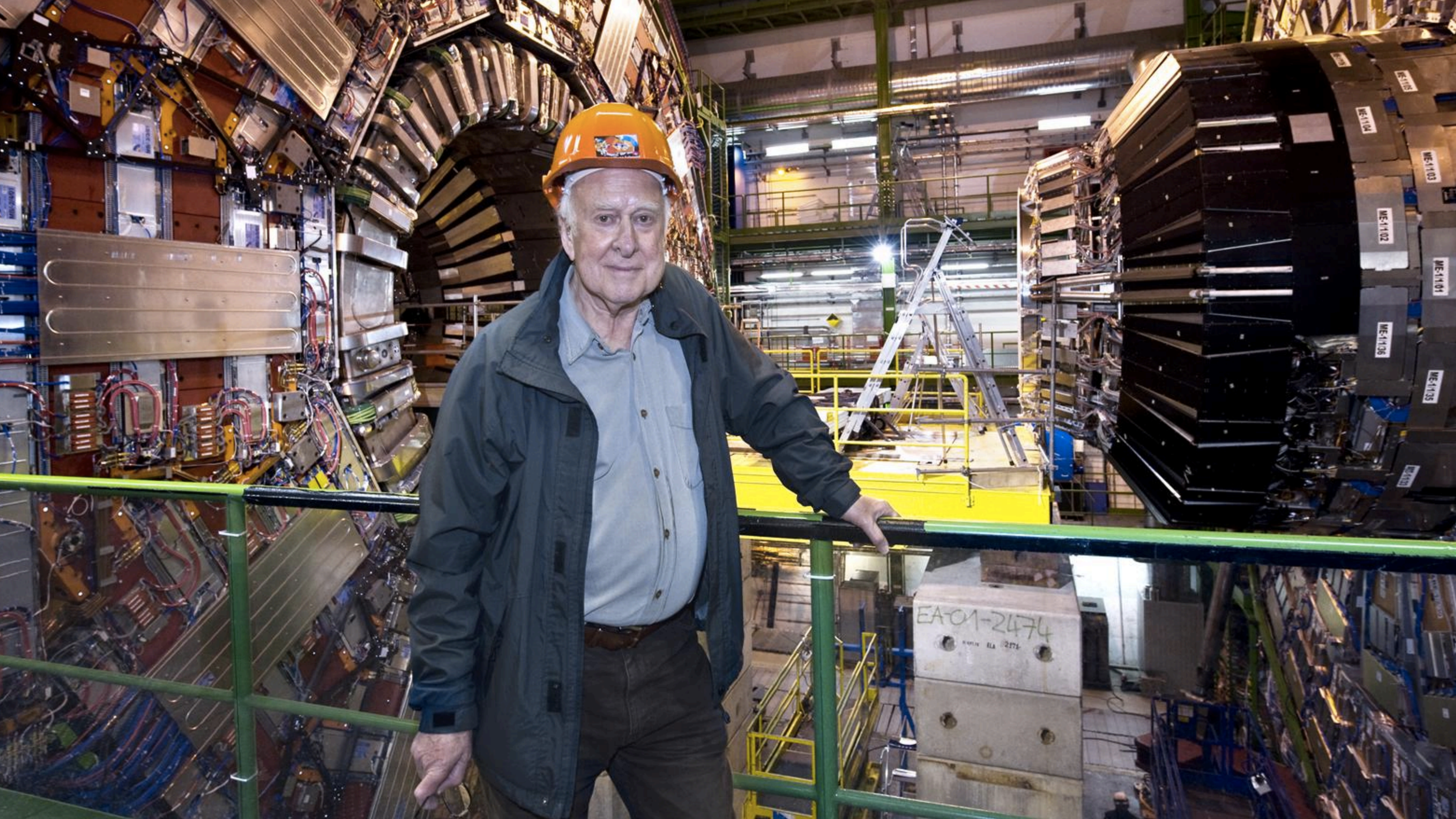


# From Higgs physics to dark matter searches: the quest for precision at the LHC

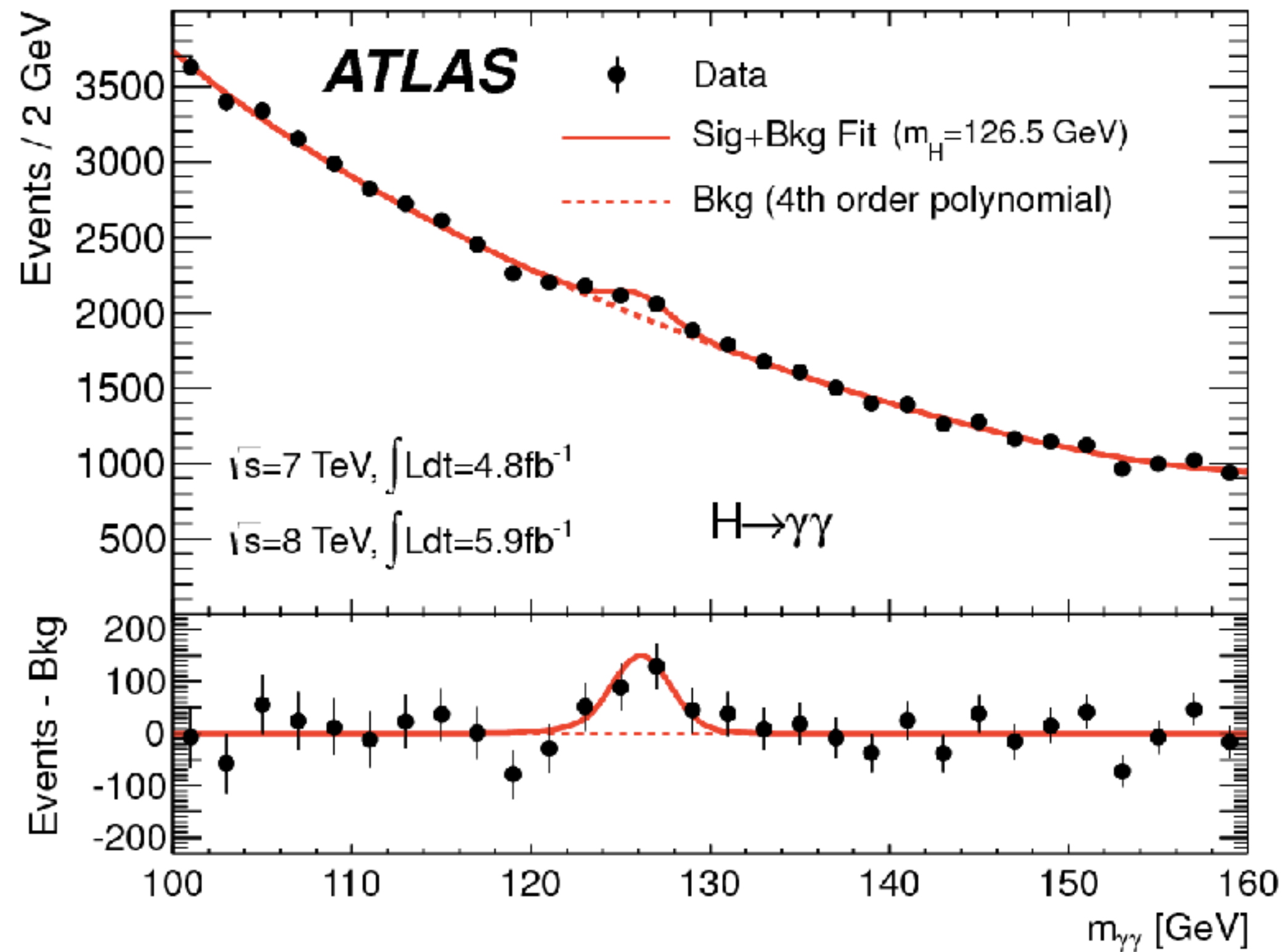
Jonas M. Lindert



INFN-UNIMI-UNIMIB Pheno Seminar  
Milan University, 24. May 2018

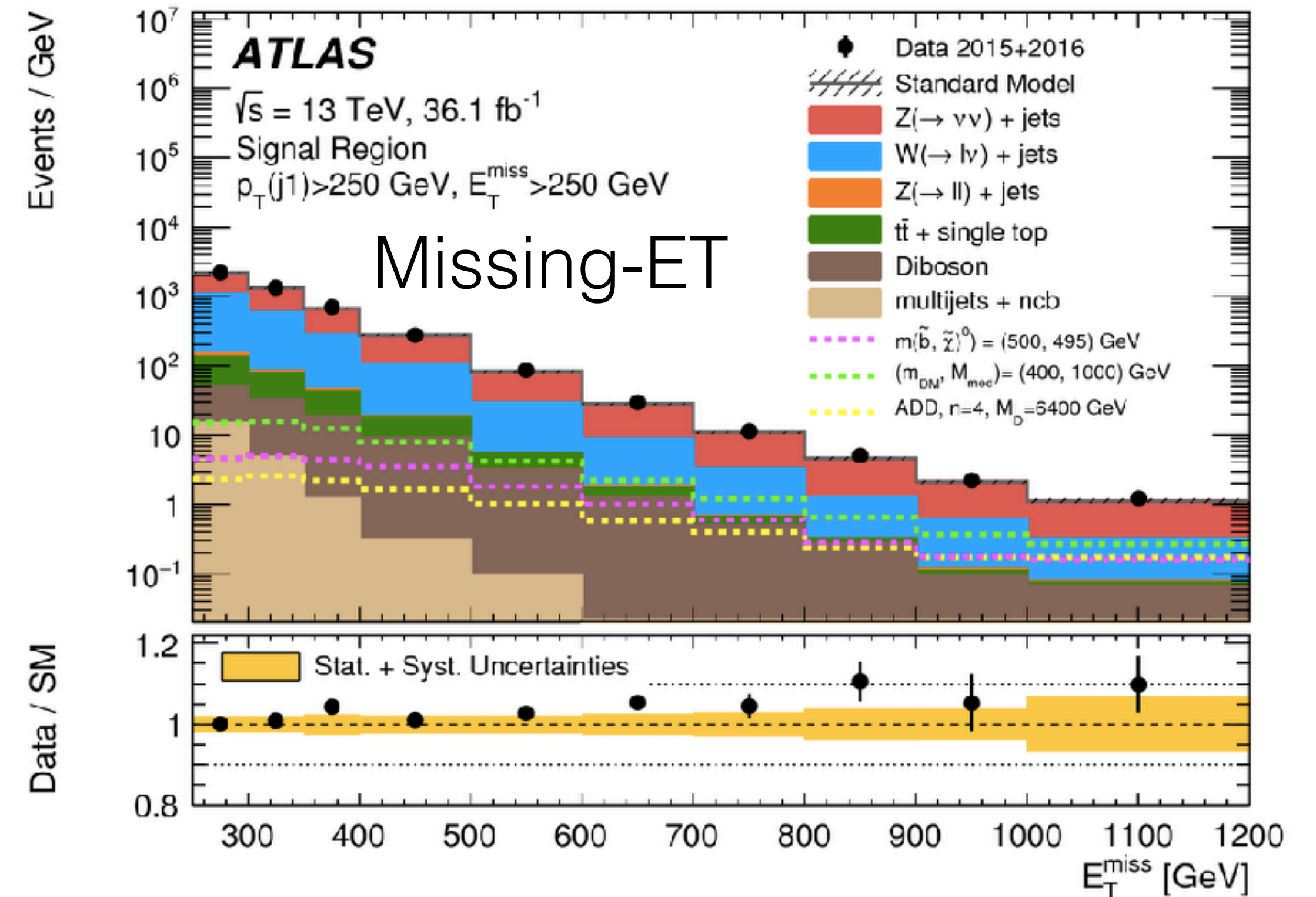


From a pheno perspective  
finding the Higgs was “easy” ...



- Higgs at 125 GeV allowed for very clean discovery in  $\gamma\gamma$  &  $4l$  channels
- Bump hunting: little to no theoretical input needed.

...finding new physics might  
be very tough.



- Dark Matter particles produced at the LHC leave the detectors unobserved: signature missing transverse energy
- large irreducible SM backgrounds  
→ **good control on theory necessary!**

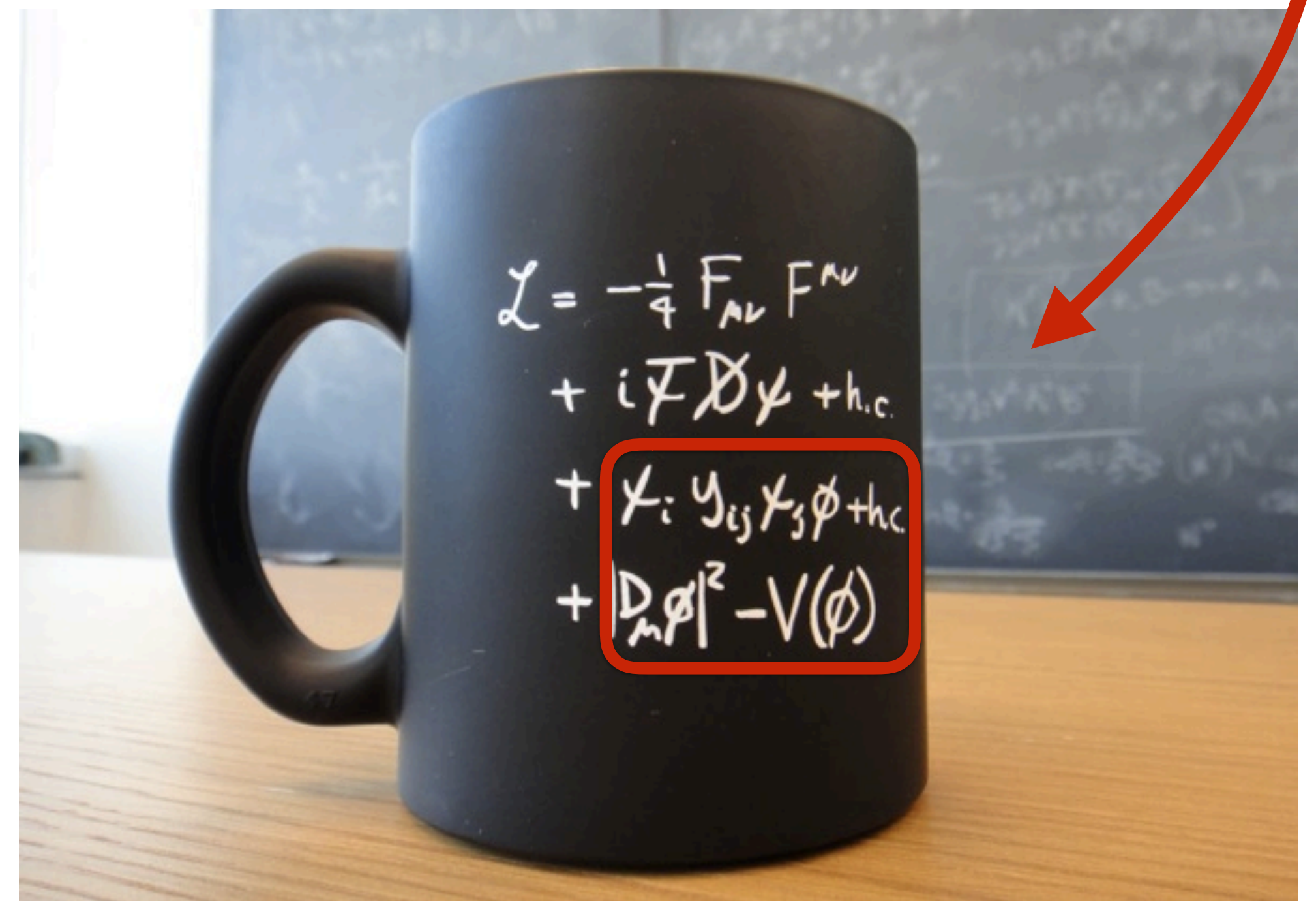
...understanding the Higgs and its properties is tough!

Is the S(125 GeV) really the SM Higgs?

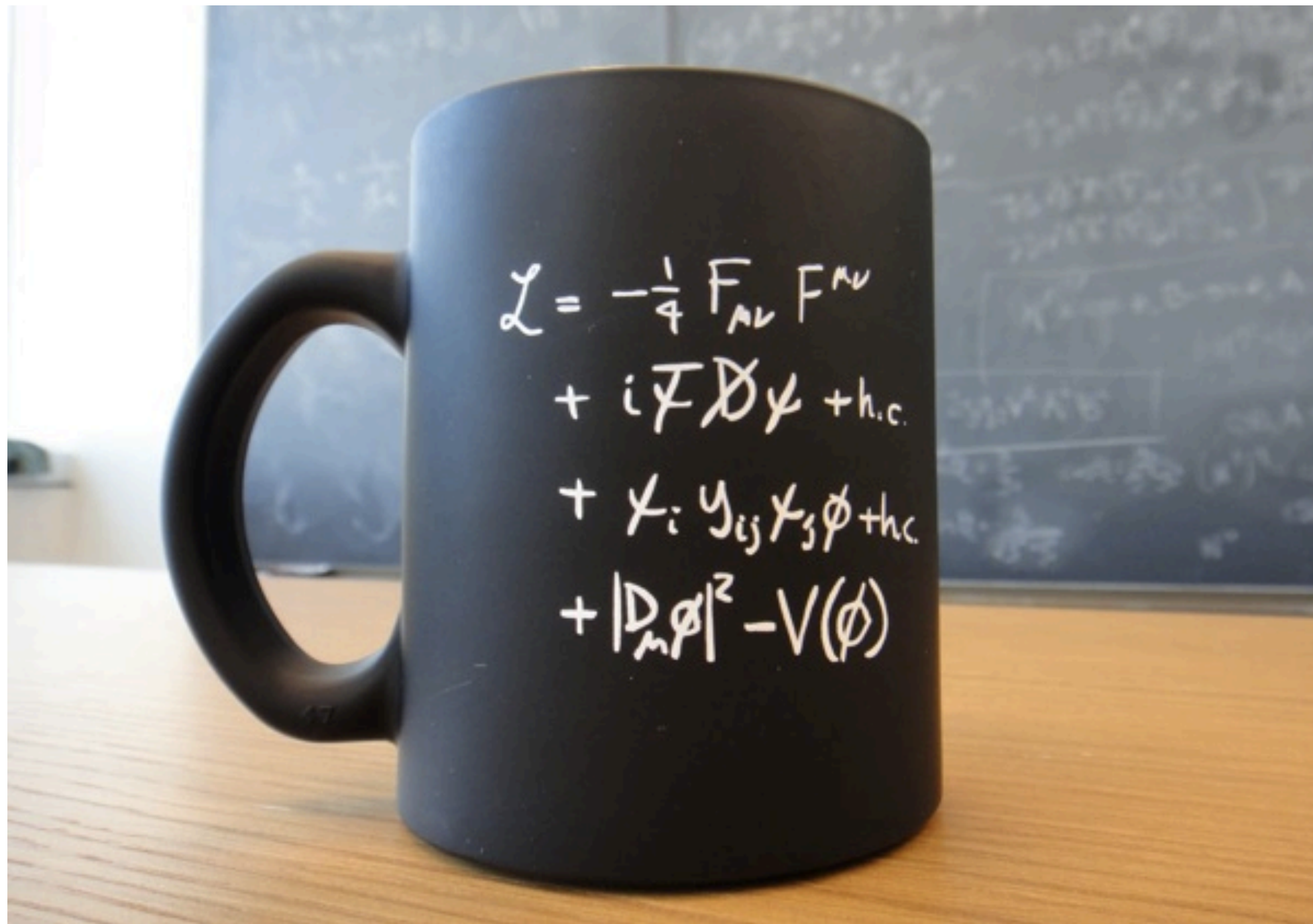
- CP properties? Is there a CP-odd admixture?
- couplings with vector-bosons/fermions as in SM?
- what is the Higgs width? Is there a significant invisible decay?
- only one Higgs doublet?
- what is the Higgs potential? self-coupling?

➔ the hunt to pin down the SM has just started.

➔ precision is key!



# Theoretical Predictions for the LHC



$$\hookrightarrow |\mathcal{M}|^2 \curvearrowright \sigma$$

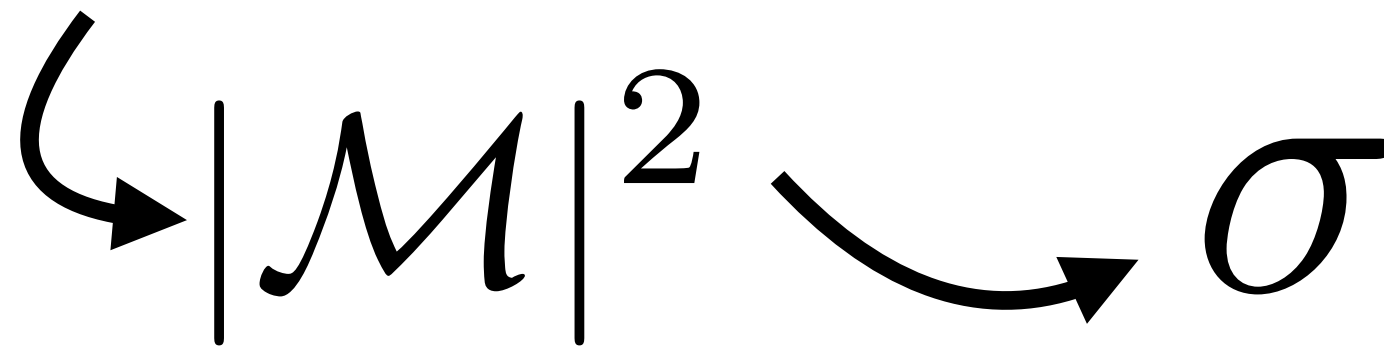
# Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

$$+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCD} \times \text{EW}}$$

$$\begin{aligned} \mathcal{L}_{\text{SM}} = & -\frac{1}{4} \partial_\mu \phi^a \partial^\mu \phi^a - g_s f^{abc} \partial_\mu \psi_i^a \partial^\mu \psi_i^b - \frac{1}{2} g_s^2 f^{abc} f^{ade} g_\mu^c g_\nu^d g_\rho^e \phi^a \phi^b \phi^c - \partial_\mu W_\nu^a \partial^\mu W_\nu^a - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\mu Z_\nu^a \partial^\mu Z_\nu^a - \frac{1}{2} M^2 Z_\mu^a Z_\mu^a - \frac{1}{2} \partial_\mu A_\nu \partial^\mu A_\nu - ig_{\text{EW}} (\partial_\mu Z_\nu^a (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - Z_\mu^a (W_\mu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\nu W_\nu^+) + Z_\mu^a (W_\mu^+ \partial_\nu W_\nu^+ - W_\mu^- \partial_\nu W_\nu^-)) - \\ & ig_{\text{EW}} (\partial_\mu A_\nu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\nu W_\nu^+) + A_\nu (W_\mu^+ \partial_\nu W_\nu^+ - \\ & W_\mu^- \partial_\nu W_\nu^-)) - \frac{1}{2} g^2 W_\mu^+ W_\nu^+ W_\mu^- W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ - g^2 \phi^\dagger (Z_\mu^a W_\nu^+ Z_\mu^a W_\nu^- - \\ & Z_\mu^a Z_\nu^a W_\mu^+ W_\nu^-) + g^2 \phi^\dagger (A_\mu W_\nu^+ A_\mu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_{\text{EW}} c_{\text{EW}} (A_\mu Z_\mu^a (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - 2A_\mu Z_\mu^a W_\nu^+ W_\nu^-) - \frac{1}{2} \partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^\dagger \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^a \partial^\mu \phi^a + \\ & \beta_0 \left( \frac{3g_s^2}{4} + \frac{3g_s^2}{4} H + \frac{1}{2} (H^2 + \phi^a \phi^a) + 2\phi^\dagger \phi \right) + \frac{23}{12} \alpha_h - \\ & \frac{1}{2} g^2 \alpha_h (H^4 + (\phi^a)^4 + 4(\phi^a \phi^a)^2 + 4(\phi^a)^2 \phi^\dagger \phi + 4H^2 \phi^\dagger \phi + 2(\phi^a)^2 H^2) - \\ & \frac{1}{2} g^2 M^2 W_\mu^+ W_\mu^- H - \frac{1}{2} g^2 Z_\mu^a Z_\mu^a H - \\ & \frac{1}{2} ig (W_\mu^+ \partial^\mu \psi_i \psi_i^\dagger - \psi_i^\dagger \partial^\mu \psi_i \psi_i) - \frac{1}{2} ig (W_\mu^+ \partial^\mu \psi_i \psi_i^\dagger - \psi_i^\dagger \partial^\mu \psi_i \psi_i) + \\ & \frac{1}{2} ig (W_\mu^+ \partial^\mu \psi_i \psi_i^\dagger - \psi_i^\dagger \partial^\mu \psi_i \psi_i) + W_\mu^+ (H \partial_\mu \phi - \phi^\dagger \partial_\mu H) + \frac{1}{2} ig \frac{2g}{M} (Z_\mu^a H \partial_\mu \phi - \phi^\dagger \partial_\mu H) + \\ & M \left( \frac{1}{2} Z_\mu^a \partial_\nu \phi^a + W_\mu^+ \partial_\nu \phi^- + W_\mu^- \partial_\nu \phi^+ \right) - ig \frac{2g}{M} M Z_\mu^a (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig s_{\text{EW}} M A_\mu (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) - ig \frac{1-2c_{\text{EW}}^2}{2s_{\text{EW}}} Z_\mu^a (\phi^- \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^-) + ig s_{\text{EW}} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{2} g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^a)^2 + 2\phi^\dagger \phi) - \frac{1}{2} g^2 \frac{1}{2} Z_\mu^a Z_\mu^a (H^2 + (\phi^a)^2 + 2(2c_{\text{EW}}^2 - 1)\phi^\dagger \phi) - \\ & \frac{1}{2} g^2 \frac{2g}{M} Z_\mu^a \phi^a (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{2g}{M} Z_\mu^a H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2} g^2 s_{\text{EW}} A_\mu \phi^a (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_{\text{EW}} A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 s_{\text{EW}} (2c_{\text{EW}}^2 - 1) Z_\mu^a A_\mu \phi^a \phi^a - \\ & g^2 s_{\text{EW}}^2 A_\mu A_\nu \phi^a \phi^a + \frac{1}{2} ig s_{\text{EW}} \lambda_{\text{EW}}^a (g_{\text{EW}}^a)^2 \phi^a - \partial^2 (\gamma \bar{u} + m_{\text{EW}}^2) \bar{u} - \partial^2 (\gamma \bar{d} + m_{\text{EW}}^2) \bar{d} - \partial^2 (\gamma \bar{e} + m_{\text{EW}}^2) \bar{e} - \\ & m_{\text{EW}}^2 \bar{u} - \partial^2 (\gamma \bar{u} + m_{\text{EW}}^2) \bar{u} + ig s_{\text{EW}} A_\mu (-\partial^2 \gamma \bar{u} + \frac{2}{3} (\bar{u}) \gamma u) - \frac{1}{2} (\bar{d}) \gamma d) + \\ & \frac{1}{2} \partial_\mu^2 (\bar{u} \gamma u (1 + \gamma^5) u^2) + (\bar{e}) \gamma e (4c_{\text{EW}}^2 - 1 - \gamma^5) e^2) + (\bar{d}) \gamma d (\frac{2}{3} c_{\text{EW}}^2 - 1 - \gamma^5) d^2) + \\ & (g_{\text{EW}}^2 (1 - \frac{2}{3} c_{\text{EW}}^2 + \gamma^5) u^2) + \frac{1}{2} g_{\text{EW}}^2 (\bar{u} \gamma u (1 + \gamma^5) u^2) + (\bar{e}) \gamma e (1 + \gamma^5) e^2) + \\ & \frac{1}{2} g_{\text{EW}}^2 W_\mu^+ (i \bar{e} \gamma u^c (1 + \gamma^5) u^2) + (\bar{d}) \gamma d (1 + \gamma^5) d^2) + \\ & \frac{1}{2} g_{\text{EW}}^2 W_\mu^- (-m_{\text{EW}}^2 (i \bar{u} \gamma u^c (1 - \gamma^5) u^2) + m_{\text{EW}}^2 (i \bar{e} \gamma e^c (1 + \gamma^5) e^2) + \\ & \frac{1}{2} m_{\text{EW}}^2 (i \bar{u} \gamma u^c (1 + \gamma^5) u^2) - m_{\text{EW}}^2 (i \bar{e} \gamma e^c (1 - \gamma^5) e^2) - \frac{1}{2} g_{\text{EW}}^2 H (i \bar{u} \gamma u^c) - \\ & \frac{1}{2} g_{\text{EW}}^2 H (i \bar{e} \gamma e^c) + \frac{1}{2} g_{\text{EW}}^2 \phi^a (i \bar{u} \gamma u^c) - \frac{1}{2} g_{\text{EW}}^2 \phi^a (i \bar{e} \gamma e^c) - \frac{1}{2} g_{\text{EW}}^2 M (i \bar{u} \gamma u^c) - \\ & \frac{1}{2} g_{\text{EW}}^2 M (i \bar{e} \gamma e^c) + \frac{1}{2} g_{\text{EW}}^2 \phi^a (-m_{\text{EW}}^2 (i \bar{u} \gamma u^c (1 - \gamma^5) u^2) + m_{\text{EW}}^2 (i \bar{e} \gamma e^c (1 + \gamma^5) e^2) + \\ & \frac{1}{2} m_{\text{EW}}^2 (i \bar{u} \gamma u^c (1 + \gamma^5) u^2) - m_{\text{EW}}^2 (i \bar{e} \gamma e^c (1 - \gamma^5) e^2) - \frac{1}{2} g_{\text{EW}}^2 H (i \bar{u} \gamma u^c) - \\ & \frac{1}{2} g_{\text{EW}}^2 H (i \bar{e} \gamma e^c) + \frac{1}{2} g_{\text{EW}}^2 \phi^a (i \bar{u} \gamma u^c) + \frac{1}{2} g_{\text{EW}}^2 \phi^a (i \bar{e} \gamma e^c) + g_{\text{EW}}^2 \partial_\mu \phi^a (i \bar{u} \gamma u^c) + \\ & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{2}) X^0 + Y^2 Y^2 + ig_{\text{EW}} W_\mu^+ (\partial_\mu X^0 X^+ - \\ & \partial_\mu X^+ X^0) + ig_{\text{EW}} W_\mu^+ (\partial_\mu X^0 X^- - \partial_\mu X^- X^0) + ig_{\text{EW}} W_\mu^- (\partial_\mu X^0 X^- - \\ & \partial_\mu X^- X^0) + ig_{\text{EW}} W_\mu^- (\partial_\mu X^+ X^- - \partial_\mu X^- X^+) + ig_{\text{EW}} Z_\mu^a (\partial_\mu X^+ X^+ - \\ & \partial_\mu X^+ X^+) - \frac{1}{2} ig M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H) - \frac{1}{2} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2} ig M (\bar{X}^0 X^+ \phi^+ - \bar{X}^0 X^+ \phi^-) + ig M_{\text{EW}} (\bar{X}^0 X^+ \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2} ig M (\bar{X}^+ X^+ \phi^+ - \bar{X}^- X^- \phi^-) . \end{aligned}$$



# Theoretical Predictions for the LHC

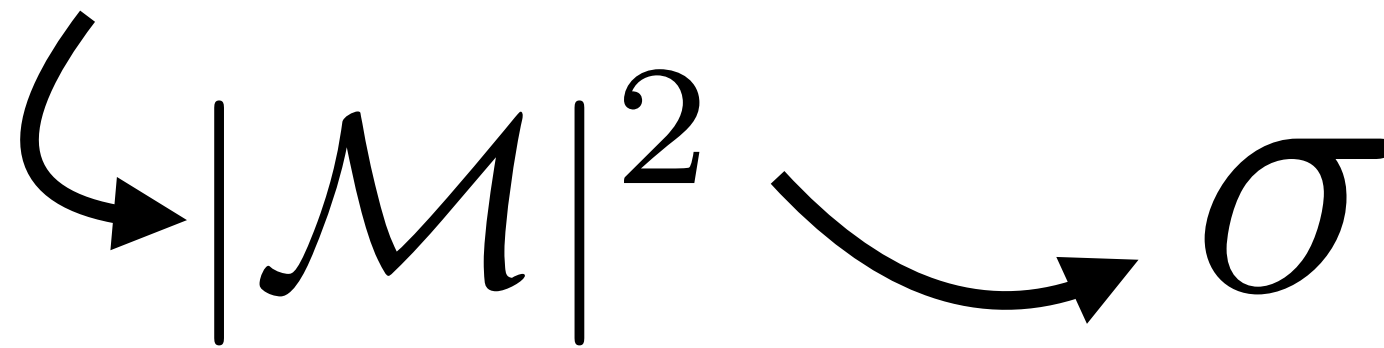
Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

$$+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCD} \times \text{EW}}$$

$$\begin{aligned} \mathcal{L}_{\text{SM}} = & -\frac{1}{4} \partial_\mu \hat{a}^i \partial^\mu \hat{a}^i - g_s f^{abc} \partial_\mu \hat{a}^i \partial^\mu \hat{a}^j - \frac{1}{2} g_s^2 f^{abc} f^{ade} \hat{a}^i \hat{a}^j \hat{a}^k \hat{a}^l - \partial_\mu \hat{W}_\nu^i \partial^\mu \hat{W}^\nu - \\ & M^2 \hat{W}_\mu^i \hat{W}^\mu - \frac{1}{2} \partial_\mu \hat{Z}_\nu^i \partial^\mu \hat{Z}^\nu - \frac{1}{2} M^2 \hat{Z}_\mu^i \hat{Z}^\mu - \frac{1}{2} \partial_\mu \hat{A}_\nu \partial^\mu \hat{A}_\nu - ig_{\text{EW}} (\partial_\mu \hat{Z}_\nu^i \hat{W}_\mu^j - \\ & \hat{W}_\mu^i \partial_\nu \hat{W}_\mu^j) - 2Z_0^i \hat{W}_\mu^i \partial_\nu \hat{W}_\mu^j - W_\mu^i \partial_\nu \hat{W}_\mu^j + 2Z_0^i \hat{W}_\mu^i \partial_\nu \hat{W}_\mu^j - W_\mu^i \partial_\nu \hat{W}_\mu^j + \\ & ig_{s_1} (\partial_\mu \hat{A}_\nu (\hat{W}_\mu^+ \hat{W}_\nu^- - \hat{W}_\mu^- \hat{W}_\nu^+) - A_\nu (\hat{W}_\mu^+ \partial_\mu \hat{W}_\nu^- - \hat{W}_\mu^- \partial_\mu \hat{W}_\nu^+) + A_\nu (\hat{W}_\mu^+ \partial_\mu \hat{W}_\nu^- - \\ & \hat{W}_\mu^- \partial_\mu \hat{W}_\nu^+)) + \frac{1}{2} g^2 \hat{W}_\mu^+ \hat{W}_\nu^- \hat{W}_\mu^+ \hat{W}_\nu^- + \frac{1}{2} g^2 \hat{W}_\mu^- \hat{W}_\nu^+ \hat{W}_\mu^- \hat{W}_\nu^+ - g^2 Z_0^i (Z_0^j \hat{W}_\mu^i \hat{W}_\mu^j - \\ & Z_0^j \hat{W}_\mu^i \hat{W}_\mu^j) + g^2 Z_0^i (A_\nu \hat{W}_\mu^+ \hat{W}_\nu^- - A_\nu \hat{W}_\mu^- \hat{W}_\nu^+) + g^2 s_{\text{EW}} (A_\nu Z_0^i \hat{W}_\mu^+ \hat{W}_\nu^- - \\ & \hat{W}_\mu^+ \hat{W}_\nu^-) - 2A_\nu Z_0^i \hat{W}_\mu^+ \hat{W}_\nu^- - \frac{1}{2} \partial_\mu \hat{H} \partial_\mu \hat{H} - 2M^2 \alpha_\mu \hat{H}^2 - \partial_\mu \hat{\phi}^+ \partial_\mu \hat{\phi}^- - \frac{1}{2} \partial_\mu \hat{\phi}^0 \partial_\mu \hat{\phi}^0 + \\ & \beta_0 \left( \frac{3g_s^2}{4} + \frac{3g_s^2}{4} H^2 + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{23}{12} \alpha_s - \\ & \frac{9\alpha_s M^2 (H^2 + H^2 \phi^0 \phi^0 + 2H\phi^+ \phi^-)}{4} - \\ & \frac{1}{2} g^2 \alpha_s (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & \frac{1}{2} g^2 M^2 \hat{W}_\mu^+ \hat{W}_\nu^- \hat{H} - \frac{1}{2} g^2 Z_0^i Z_0^j \hat{H} - \\ & \frac{1}{2} ig (W_\mu^+ (\partial^\mu \hat{H} \hat{\phi}^- - \partial^\nu \hat{H} \hat{\phi}^\nu) - W_\mu^- (\partial^\mu \hat{H} \hat{\phi}^+ - \partial^\nu \hat{H} \hat{\phi}^\nu)) + \\ & \frac{1}{2} ig (W_\mu^+ (\partial^\mu \hat{H} \hat{\phi}^- - \partial^\nu \hat{H} \hat{\phi}^\nu) + W_\mu^- (\partial^\mu \hat{H} \hat{\phi}^+ - \partial^\nu \hat{H} \hat{\phi}^\nu)) + \frac{1}{2} g^2 Z_0^i (Z_0^j \hat{H} \partial_\mu \hat{\phi}^k - \partial^\mu \hat{H} \partial_\mu \hat{\phi}^k) + \\ & M \left( \frac{1}{2} Z_0^i Z_0^j \hat{H} \partial_\mu \hat{\phi}^k + W_\mu^i \partial_\nu \hat{\phi}^j - W_\mu^j \partial_\nu \hat{\phi}^i \right) - ig_{\text{EW}} M Z_0^i (W_\mu^+ \hat{\phi}^- - W_\mu^- \hat{\phi}^+) - ig_{\text{EW}} M A_\nu (W_\mu^+ \hat{\phi}^- - \\ & W_\mu^- \hat{\phi}^+) - ig_{\text{EW}} M Z_0^i (\hat{\phi}^- \partial_\mu \hat{\phi}^+ - \hat{\phi}^+ \partial_\mu \hat{\phi}^-) + ig_{\text{EW}} A_\nu (\hat{\phi}^+ \partial_\mu \hat{\phi}^- - \hat{\phi}^- \partial_\mu \hat{\phi}^+) - \\ & \frac{1}{2} g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{2} g^2 Z_0^i Z_0^j (H^2 + (\phi^0)^2 + 2(2\phi^0 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2} g^2 Z_0^i Z_0^j \phi^0 (\hat{W}_\mu^+ \hat{\phi}^- + \hat{W}_\mu^- \hat{\phi}^+) - \frac{1}{2} g^2 Z_0^i Z_0^j \hat{H} (W_\mu^+ \hat{\phi}^- - W_\mu^- \hat{\phi}^+) - \frac{1}{2} g^2 s_{\text{EW}} A_\nu \phi^0 (W_\mu^+ \hat{\phi}^- + \\ & W_\mu^- \hat{\phi}^+) + \frac{1}{2} ig^2 s_{\text{EW}} A_\nu (W_\mu^+ \hat{\phi}^- - W_\mu^- \hat{\phi}^+) - g^2 s_{\text{EW}} (2\phi^0 - 1) Z_0^i A_\nu \hat{\phi}^+ \hat{\phi}^- - \\ & g^2 s_{\text{EW}}^2 A_\nu A_\mu \hat{\phi}^+ \hat{\phi}^- + \frac{1}{2} ig_{\text{EW}} \lambda_0 (\hat{\phi}^+ \hat{\phi}^0 \hat{\phi}^0) \hat{\phi}^+ - \partial^2 (\gamma \hat{\phi}^0 + m_0^2) \hat{\phi}^+ - \partial^2 (\gamma \hat{\phi}^0 + m_0^2) \hat{\phi}^- - \partial^2 (\gamma \hat{\phi}^0 + m_0^2) \hat{\phi}^0 - \partial^2 (\gamma \hat{\phi}^0 + \\ & m_0^2) \hat{\phi}^0 - \partial^2 (\gamma \hat{\phi}^0 + m_0^2) \hat{\phi}^0 + ig_{\text{EW}} A_\nu (-\partial^2 \hat{\phi}^+ \hat{\phi}^0) + \frac{1}{2} (\partial^2 \hat{\phi}^+ \hat{\phi}^0) + \frac{1}{2} (\partial^2 \hat{\phi}^+ \hat{\phi}^0) + \\ & \frac{1}{2} g^2 Z_0^i (\partial^2 \hat{\phi}^+ (1 + \gamma) \hat{\phi}^0) + (\partial^2 \hat{\phi}^+ (4\phi^0 - 1 - \gamma) \hat{\phi}^0) + (\partial^2 \hat{\phi}^+ (\frac{1}{2} \phi^0 - 1 - \gamma) \hat{\phi}^0) + \\ & (\partial^2 \hat{\phi}^+ (1 - \frac{1}{2} \phi^0 + \gamma) \hat{\phi}^0)) + \frac{1}{2} g^2 W_\mu^+ (\partial^\mu \hat{\phi}^+ (1 + \gamma) \hat{W}_\nu^0 \hat{\phi}^0) + (\partial^2 \hat{\phi}^+ (1 + \gamma) \hat{W}_\nu^0 \hat{\phi}^0) + \\ & \frac{1}{2} g^2 W_\mu^- (\partial^\mu \hat{\phi}^- (1 + \gamma) \hat{W}_\nu^0 \hat{\phi}^0) + (\partial^2 \hat{\phi}^- (1 + \gamma) \hat{W}_\nu^0 \hat{\phi}^0) + \\ & \frac{1}{2} g^2 W_\mu^+ (-m_0^2 \partial^\mu \hat{W}_\nu^0 \hat{\phi}^0 (1 - \gamma) \hat{\phi}^0) + m_0^2 \partial^\mu \hat{W}_\nu^0 \hat{\phi}^0 (1 + \gamma) \hat{\phi}^0) + \\ & \frac{1}{2} g^2 W_\mu^- (-m_0^2 \partial^\mu \hat{W}_\nu^0 \hat{\phi}^0 (1 - \gamma) \hat{\phi}^0) + m_0^2 \partial^\mu \hat{W}_\nu^0 \hat{\phi}^0 (1 + \gamma) \hat{\phi}^0) - \\ & \frac{1}{2} g^2 H (\partial^2 \hat{\phi}^0) + \frac{1}{2} g^2 \partial^2 \hat{\phi}^0 (\partial^2 \hat{\phi}^0 \hat{\phi}^0) - \frac{1}{2} g^2 \partial^2 \hat{\phi}^0 (\partial^2 \hat{\phi}^0 \hat{\phi}^0) - \frac{1}{2} \partial_\mu M_\nu^0 (1 - \gamma) \hat{\phi}^0 - \\ & \frac{1}{2} \partial_\mu M_\nu^0 (1 - \gamma) \hat{\phi}^0 + \frac{1}{2} \partial_\mu M_\nu^0 (-m_0^2 \hat{\phi}^0 C_{\text{EW}} (1 - \gamma) \hat{\phi}^0) + m_0^2 (\hat{\phi}^0 C_{\text{EW}} (1 + \gamma) \hat{\phi}^0) + \\ & \frac{1}{2} \partial_\mu M_\nu^0 (m_0^2 (\hat{\phi}^0)^2 (1 + \gamma) \hat{\phi}^0) - m_0^2 (\hat{\phi}^0 C_{\text{EW}} (1 - \gamma) \hat{\phi}^0) - \frac{1}{2} \partial_\mu H (\hat{\phi}^0 \hat{\phi}^0) - \\ & \frac{1}{2} \partial_\mu H (\hat{\phi}^0 \hat{\phi}^0) + \frac{1}{2} \partial_\mu H (\hat{\phi}^0 \hat{\phi}^0) - \frac{1}{2} \partial_\mu H (\hat{\phi}^0 \hat{\phi}^0) + \partial_\mu \hat{Y} \hat{Y} C^0 + \partial_\mu \hat{Y} \hat{Y} C^0 + \partial_\mu \hat{Y} \hat{Y} C^0 + \\ & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{2}) X^0 + Y^0 \hat{Y} Y^0 + ig_{\text{EW}} W_\mu^i (\partial_\mu X^0 X^0 - \\ & \partial_\mu X^+ X^0) + ig_{\text{EW}} W_\mu^i (\partial_\mu X^0 X^- - \partial_\mu X^- X^0) + ig_{\text{EW}} W_\mu^i (\partial_\mu X^- X^0 - \partial_\mu X^0 X^-) - \\ & \partial_\mu X^0 X^+ + ig_{\text{EW}} W_\mu^i (\partial_\mu X^- X^0 - \partial_\mu X^0 X^-) + ig_{\text{EW}} Z_0^i (\partial_\mu X^+ X^+ - \\ & \partial_\mu X^- X^-) + ig_{\text{EW}} A_\nu (\partial_\mu X^+ X^- - \\ & \partial_\mu X^- X^+) - \frac{1}{2} ig M (\hat{X}^+ X^+ H + \hat{X}^- X^- H + \frac{1}{2} \hat{X}^0 X^0 H) - \frac{1}{2} ig M (\hat{X}^+ X^0 \hat{\phi}^+ - \hat{X}^- X^0 \hat{\phi}^-) + \\ & \frac{1}{2} ig M (\hat{X}^0 X^0 \hat{\phi}^+ - \hat{X}^0 X^0 \hat{\phi}^-) + ig M_\nu (\hat{X}^0 X^0 \hat{\phi}^+ - \hat{X}^0 X^0 \hat{\phi}^-) + \\ & \frac{1}{2} ig M (\hat{X}^+ X^+ \hat{\phi}^0 - \hat{X}^- X^- \hat{\phi}^0) . \end{aligned}$$

$$d\sigma_{\text{NLO}} = \frac{1}{2s} \int d\Phi_n [ |\mathcal{M}_{\text{LO}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{LO}} \mathcal{M}_{\text{NLO,V}}^*\} + I ] + \frac{1}{2s} \int d\Phi_{n+1} |\mathcal{M}_{\text{NLO,R}}|^2 - S$$



**OpenLoops**  
[JML, Maierhöfer, Pozzorini]

**Sherpa**  
[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siebert, Winter et. al.]

**MUNICH:**  
**MULTI-chaNnel Integrator at swiss (CH) precision**  
[Kallweit]

**POWHEG-BOX**  
[Alioli, Nason, Oleari, Re, et. al.]

# Theoretical Predictions for the LHC

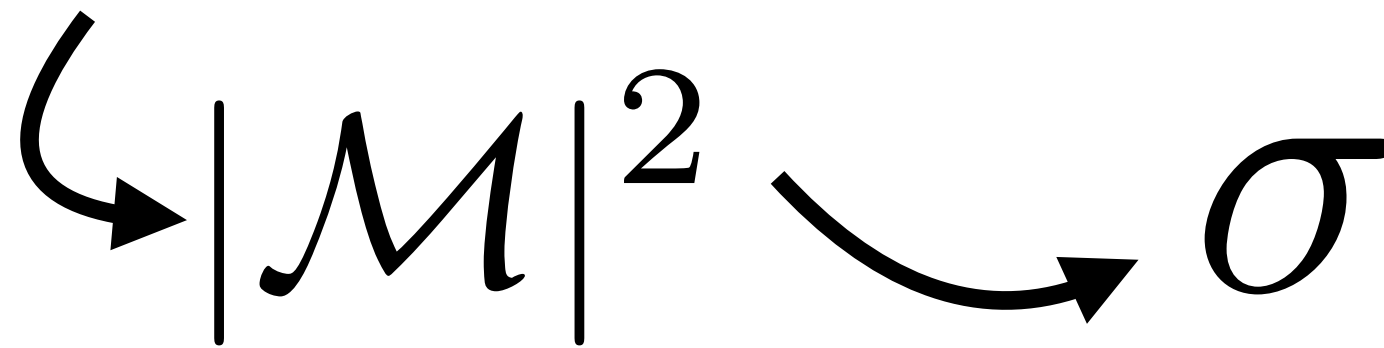
Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

$$+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCD} \times \text{EW}}$$

$$\begin{aligned} \mathcal{L}_{\text{SM}} = & -\frac{1}{4} \partial_\mu \phi^a \partial^\mu \phi^a - g_s f^{abc} \partial_\mu \psi_i^a \partial^\mu \psi_i^b - \frac{1}{2} g_s^2 f^{abc} f^{ade} \psi_i^a \psi_j^b \psi_k^c \psi_l^d - \partial_\mu W_\nu^a \partial^\mu W_\nu^a - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\mu Z_\nu^a \partial^\mu Z_\nu^a - \frac{1}{2} M^2 Z_\mu^a Z_\mu^a - \frac{1}{2} \partial_\mu A_\nu \partial^\mu A_\nu - ig_{\text{EW}} (\partial_\mu Z_\nu^a W_\mu^+ W_\nu^- - \\ & W_\mu^+ W_\nu^-) - 2Z_\mu^a W_\mu^+ W_\nu^- - W_\mu^+ \partial_\nu W_\nu^- + 2Z_\mu^a W_\mu^+ \partial_\nu W_\nu^- + A_\mu (\partial_\nu W_\nu^+ W_\mu^- - \\ & ig_s g_s (\partial_\nu A_\mu W_\nu^+ W_\mu^- - W_\mu^+ W_\nu^-) - A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\ & W_\mu^- \partial_\nu W_\nu^+)) - \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ - g^2 Z_\mu^a (Z_\nu^a W_\mu^+ Z_\nu^a W_\mu^- - \\ & Z_\nu^a Z_\mu^a W_\mu^+ W_\nu^-) + g^2 Z_\mu^a (A_\nu W_\nu^+ A_\mu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_{\text{EW}} (A_\mu Z_\mu^a W_\nu^+ W_\nu^- - \\ & W_\nu^+ W_\nu^-) - 2A_\mu Z_\mu^a W_\nu^+ W_\nu^- - \frac{1}{2} \partial_\mu H \partial_\mu H - 2M^2 \phi^+ \phi^- - \partial_\mu \phi^+ \partial^\mu \phi^- - \frac{1}{2} \partial_\mu \phi^+ \partial^\mu \phi^+ - \\ & \beta_0 \left( \frac{3}{4} g_s^2 + \frac{3}{4} g^2 + \frac{1}{2} (H^2 + \phi^+ \phi^- + 2\phi^+ \phi^-) \right) + \frac{23}{12} \alpha_s - \\ & \frac{9\alpha_s M (H^2 + H\phi^+ \phi^- + 2H\phi^+ \phi^-)}{2} - \\ & \frac{1}{2} g^2 \alpha_s (H^4 + (\phi^+)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^+)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^+)^2 H^2) - \\ & \frac{1}{2} g^2 M W_\mu^+ W_\nu^- H - \frac{1}{2} g^2 Z_\mu^a Z_\nu^a H - \\ & \frac{1}{2} ig (W_\mu^+ \partial^\mu W_\nu^- - \partial^\mu W_\nu^- W_\mu^+) - W_\mu^+ \partial^\mu W_\nu^- - \partial^\mu W_\nu^- W_\mu^+) + \\ & \frac{1}{2} ig (W_\mu^+ \partial^\mu W_\nu^- - \partial^\mu W_\nu^- W_\mu^+) + W_\mu^+ (H \partial_\mu \phi^- - \partial^\mu H \phi^-) + \frac{1}{2} ig (Z_\mu^a (H \partial_\mu \phi^+ - \partial^\mu H \phi^+) - \\ & M (\frac{1}{2} Z_\mu^a \partial_\nu \phi^+ + W_\mu^+ \partial_\nu \phi^- - W_\mu^- \partial_\nu \phi^+) - ig \frac{3}{2} M Z_\mu^a (W_\nu^+ \phi^- - W_\nu^- \phi^+) - ig s_{\text{EW}} M A_\mu (W_\nu^+ \phi^- - \\ & W_\nu^- \phi^+) - ig \frac{1-2s_{\text{EW}}^2}{2} Z_\mu^a (\phi^- \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^-) + ig s_{\text{EW}} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{2} g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^+)^2 + 2\phi^+ \phi^-) - \frac{1}{2} g^2 \frac{1}{2} Z_\mu^a Z_\nu^a (H^2 + (\phi^+)^2 + 2(2s_{\text{EW}}^2 - 1)\phi^+ \phi^-) - \\ & \frac{1}{2} g^2 \frac{1}{2} Z_\mu^a Z_\nu^a (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2} g^2 \frac{1}{2} Z_\mu^a Z_\nu^a H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2} g^2 s_{\text{EW}} A_\mu (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_{\text{EW}} A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 s_{\text{EW}} (2s_{\text{EW}}^2 - 1) Z_\mu^a A_\nu \phi^+ \phi^- - \\ & g^2 s_{\text{EW}}^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2} ig s_{\text{EW}} \lambda_0 (g^2 \gamma^0 \gamma^0) \phi^+ \phi^- - \partial^2 (\gamma^0 + m_0^2) \phi^+ - \partial^2 (\gamma^0 + m_0^2) \phi^- - \partial^2 (\gamma^0 + \\ & m_0^2) \phi^+ - \partial^2 (\gamma^0 + m_0^2) \phi^- + ig s_{\text{EW}} A_\mu (-\partial^2 \gamma^0 \phi^+ + \frac{1}{2} (\partial^2 \gamma^0 \phi^+)) + \\ & \frac{1}{2} g^2 Z_\mu^a ((\partial^2 \gamma^0 (1 + \gamma^0) \phi^+) + (\partial^2 \gamma^0 (4s_{\text{EW}}^2 - 1 - \gamma^0) \phi^+) + (\partial^2 \gamma^0 (\frac{1}{2} s_{\text{EW}}^2 - 1 - \gamma^0) \phi^+) + \\ & (\partial^2 \gamma^0 (1 - \frac{1}{2} s_{\text{EW}}^2 + \gamma^0) \phi^+)) + \frac{1}{2} g^2 W_\mu^+ ((\partial^2 \gamma^0 (1 + \gamma^0) \phi^+ \phi^+) + (\partial^2 \gamma^0 (1 + \gamma^0) \phi^+ \phi^-)) + \\ & \frac{1}{2} g^2 W_\mu^- ((\partial^2 \gamma^0 (1 + \gamma^0) \phi^+) + (\partial^2 \gamma^0 C_{\text{EW}} (1 + \gamma^0) \phi^+)) + \\ & \frac{1}{2} g^2 W_\mu^- ((\partial^2 \gamma^0 (1 + \gamma^0) \phi^-) + m_0^2 (\partial^2 \gamma^0 \phi^- (1 + \gamma^0) \phi^-) + \\ & \frac{1}{2} g^2 H (\partial^2 \phi^+) + \frac{1}{2} g^2 \partial^2 \phi^+ (\partial^2 \gamma^0 \phi^+) - \frac{1}{2} g^2 \partial^2 \phi^+ (\partial^2 \gamma^0 \phi^+) - \frac{1}{2} \partial_\mu M_\mu^0 (1 - \gamma_5) \phi^- - \\ & \frac{1}{2} \partial_\mu M_\mu^0 (1 - \gamma_5) \phi^+ + \frac{1}{2} g^2 \partial^2 \phi^+ (-m_0^2 (\partial^2 \gamma^0 C_{\text{EW}} (1 - \gamma^0) \phi^+) + m_0^2 (\partial^2 \gamma^0 C_{\text{EW}} (1 + \gamma^0) \phi^+) + \\ & \frac{1}{2} g^2 \partial^2 \phi^+ (m_0^2 (\partial^2 \gamma^0 (1 + \gamma^0) \phi^+) - m_0^2 (\partial^2 \gamma^0 C_{\text{EW}} (1 - \gamma^0) \phi^+) - \frac{1}{2} g^2 H (\partial^2 \phi^+) - \\ & \frac{1}{2} g^2 H (\partial^2 \phi^+) + \frac{1}{2} g^2 \partial^2 \phi^+ (\partial^2 \gamma^0 \phi^+) - \frac{1}{2} g^2 \partial^2 \phi^+ (\partial^2 \gamma^0 \phi^+) + \partial^2 \gamma^0 C^0 + \partial^2 \gamma^0 C^0 + \partial^2 \gamma^0 C^0 + \\ & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{2}) X^0 + Y^0 Y^0 + ig_{\text{EW}} W_\mu^+ (\partial_\nu X^0 X^\nu - \\ & \partial_\nu X^+ X^\nu) + ig_{\text{EW}} W_\mu^+ (\partial_\nu X^- X^\nu - \partial_\nu X^0 X^\nu) + ig_{\text{EW}} W_\mu^- (\partial_\nu X^- X^\nu - \partial_\nu X^0 X^\nu) - \\ & \partial_\nu X^0 X^\nu + ig_{\text{EW}} W_\mu^- (\partial_\nu X^+ X^\nu - \partial_\nu X^0 X^\nu) + ig_{\text{EW}} Z_\mu^a (\partial_\nu X^+ X^\nu - \\ & \partial_\nu X^- X^\nu) + ig_{\text{EW}} A_\mu (\partial_\nu X^+ X^\nu - \\ & \partial_\nu X^- X^\nu) - \frac{1}{2} ig M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H) - \frac{1}{2} g^2 ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2} ig M (\bar{X}^0 X^+ \phi^+ - \bar{X}^0 X^- \phi^-) + ig M_{\text{EW}} (\bar{X}^0 X^+ \phi^+ - \bar{X}^0 X^- \phi^-) + \\ & \frac{1}{2} ig M (\bar{X}^+ X^+ \phi^+ - \bar{X}^- X^- \phi^-) . \end{aligned}$$

$$d\sigma_{\text{NLO}} = \frac{1}{2s} \int d\Phi_n [|\mathcal{M}_{\text{LO}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{LO}} \mathcal{M}_{\text{NLO,V}}^*\} + I] + \frac{1}{2s} \int d\Phi_{n+1} |\mathcal{M}_{\text{NLO,R}}|^2 - S$$



**OpenLoops**  
[[ML, Maierhöfer, Pozzorini]]

**Sherpa**  
[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siebert, Winter et. al.]

**MUNICH:**  
**M**ulti-**ch**annel **I**ntegrator at **swiss (CH)** precision  
[Kallweit]  
**POWHEG-BOX**  
[Alioli, Nason, Oleari, Re, et. al.]

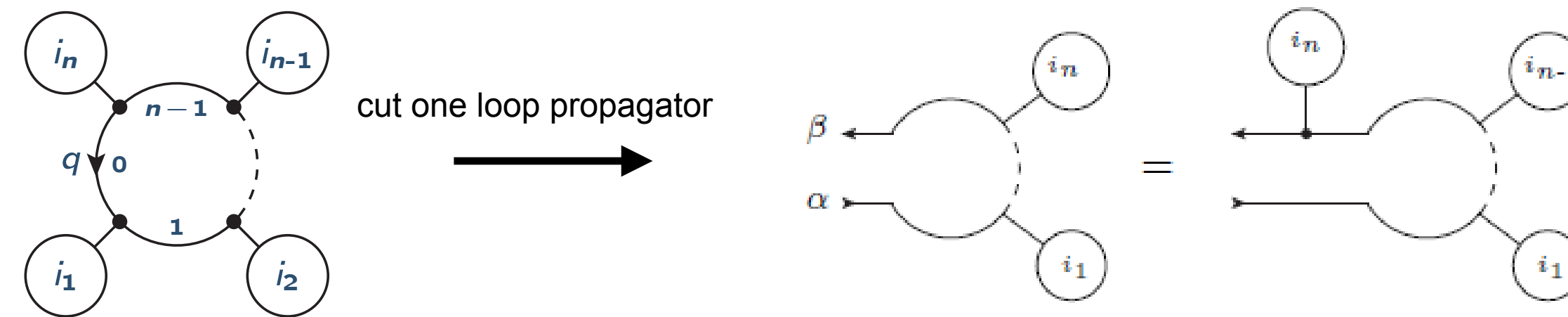
- NLO corrections in the full SM (QCD & EW) are automated in OpenLoops+Sherpa/MUNICH
- NLO EW + PS matching available in OpenLoops+POWHEG-BOX
- Automation allows for detailed phenomenological applications!



# The OpenLoops program

[F. Cascioli, JML, P. Maierhöfer, S. Pozzorini, '14]

- ▶ **FAST** and flexible implementation of the Open Loops algorithm [F. Cascioli, P. Maierhöfer, S. Pozzorini, '12]:  
a process- and model-independent numerical recursion for the calculation of one-loop amplitudes



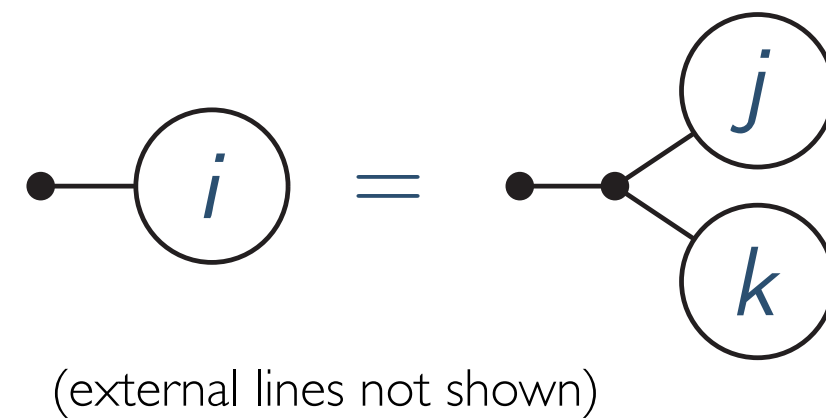
- ▶ Publicly available at <http://openloops.hepforge.org>
- ▶ Amplitudes for any  $2 \rightarrow 4(5)$  NLO QCD process in the SM available:  
tree & (renormalized) virtual amplitudes, color correlations, spin correlations.
- ▶ Installation (Requirements: gfortran  $\geq 4.6$ , Python 2.x, x  $\geq 4$ ): `$ cd ./OpenLoops && ./scons`
- ▶ Interfaces to reduction/scalar integral libraries:
  - [CutTools](#) [Ossola, Papadopolous, Pittau; '07] + [OneLoop](#) [van Hameren], [COLLIER](#) [Denner, Dittmaier, Hofer], [Samurai](#) [Mastrolia, Ossola, Reiter, Tramontano; '10]
- ▶ Interfaces to Monte Carlos:
  - Native, BLHA, [Sherpa](#), [MUNICH](#), [Herwig++](#), [POWHEG-BOX](#), [Whizard](#)

# The Open Loops algorithm: From tree recursion to loop diagrams

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

► Recursive construction of tree wave functions

- start from wave functions  $w^\alpha$  of external legs.
- connect wave functions with vertices  $X_{\gamma\delta}^\beta$  and propagators to recursively build “sub-trees”.
- recycle identical structures
- wave functions of sub-trees are 4-tuples of complex numbers (for the spinor/Lorentz index).



$$w^\beta(i) = \frac{X_{\gamma\delta}^\beta}{p_i^2 - m_i^2} w^\gamma(j) w^\delta(k)$$

► Factorize one-loop amplitude into colour factors, tensor coefficients and tensor integrals

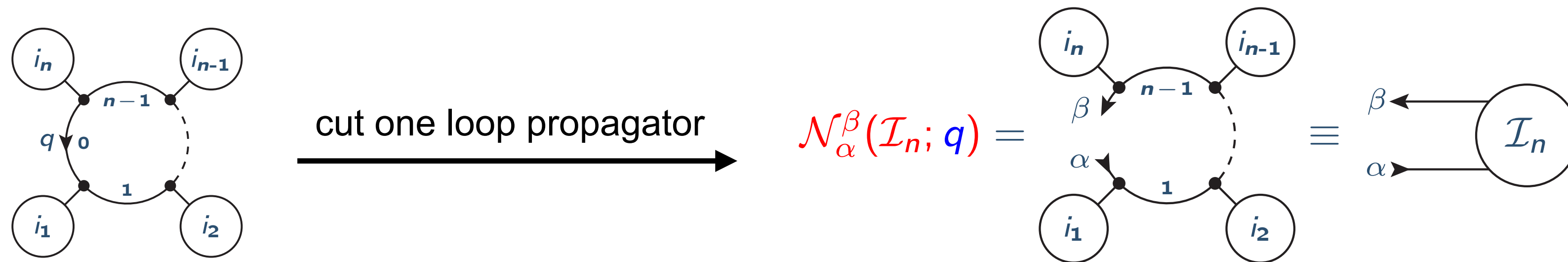
$$\begin{aligned}
 & \text{Diagram} = \underbrace{C \cdot \sum_{r=0}^R \mathcal{N}_r^{\mu_1 \dots \mu_r}}_{\text{numerical recursion [OpenLoops]}} \cdot \underbrace{\int d^d q \frac{q_{\mu_1} \dots q_{\mu_r}}{D_0 D_1 \dots D_{N-1}}}_{\text{tensor integrals [Collier]}}
 \end{aligned}$$

$D_i = (q + \sum_{\ell=0}^i p_\ell)^2 - m_i^2$

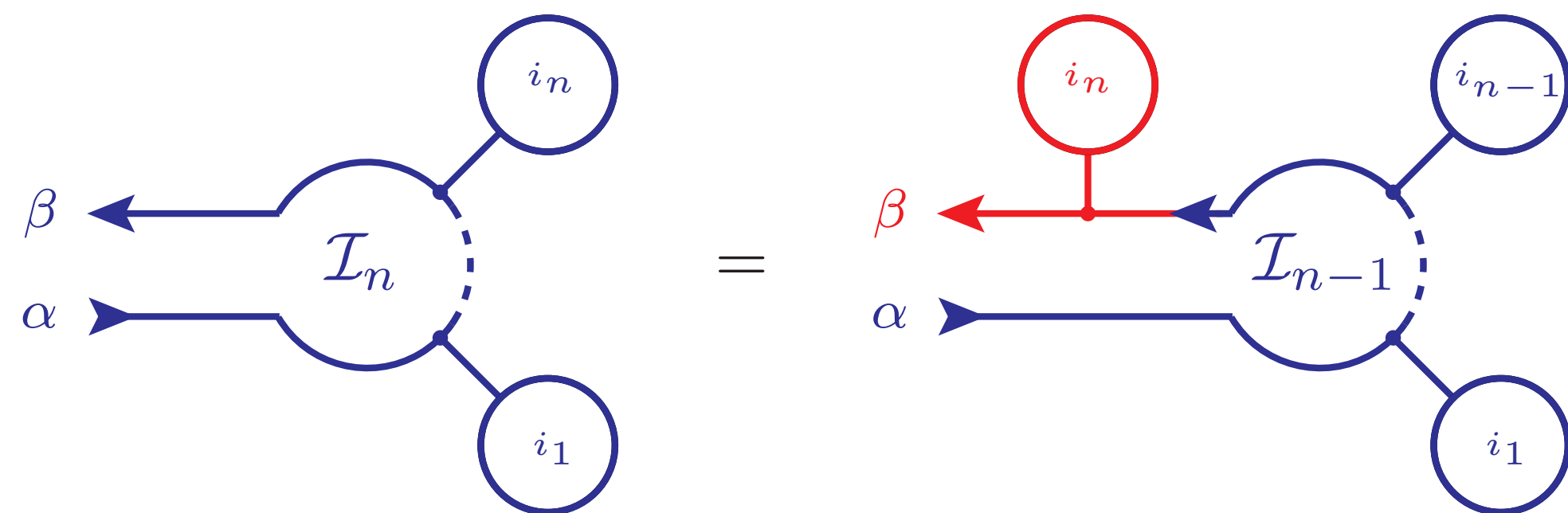
# The Open Loops algorithm: From tree recursion to loop diagrams

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

- ▶ Treat one-loop diagram as ordered set of sub-trees  $\mathcal{I}_n = \{i_1, \dots, i_n\}$  connected by propagators



- ▶ Build numerator recursively connecting subtrees along the loop keeping the  $q$  dependence



$$\mathcal{N}_\alpha^\beta(\mathcal{I}_n; q) = X_{\gamma\delta}^\beta(q) \mathcal{N}_\alpha^\gamma(\mathcal{I}_{n-1}; q) w^\delta(i_n)$$

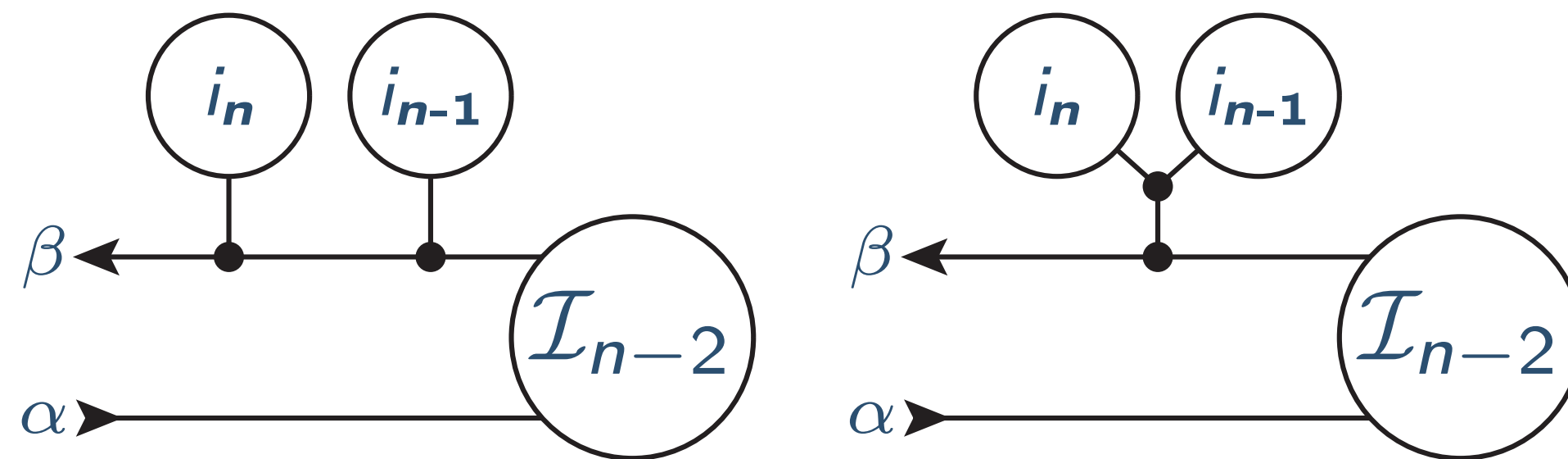
$$X_{\gamma\delta}^\beta = Y_{\gamma\delta}^\beta + q^\nu Z_{\nu;\gamma\delta}^\beta$$

$\Rightarrow$  very fast!

$$\mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\beta(\mathcal{I}_n) = \left[ Y_{\gamma\delta}^\beta \mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\gamma(\mathcal{I}_{n-1}) + Z_{\mu_1; \gamma\delta}^\beta \mathcal{N}_{\mu_2 \dots \mu_r; \alpha}^\gamma(\mathcal{I}_{n-1}) \right] w^\delta(i_n)$$

# The (original) Open Loops algorithm: recycle loop structures

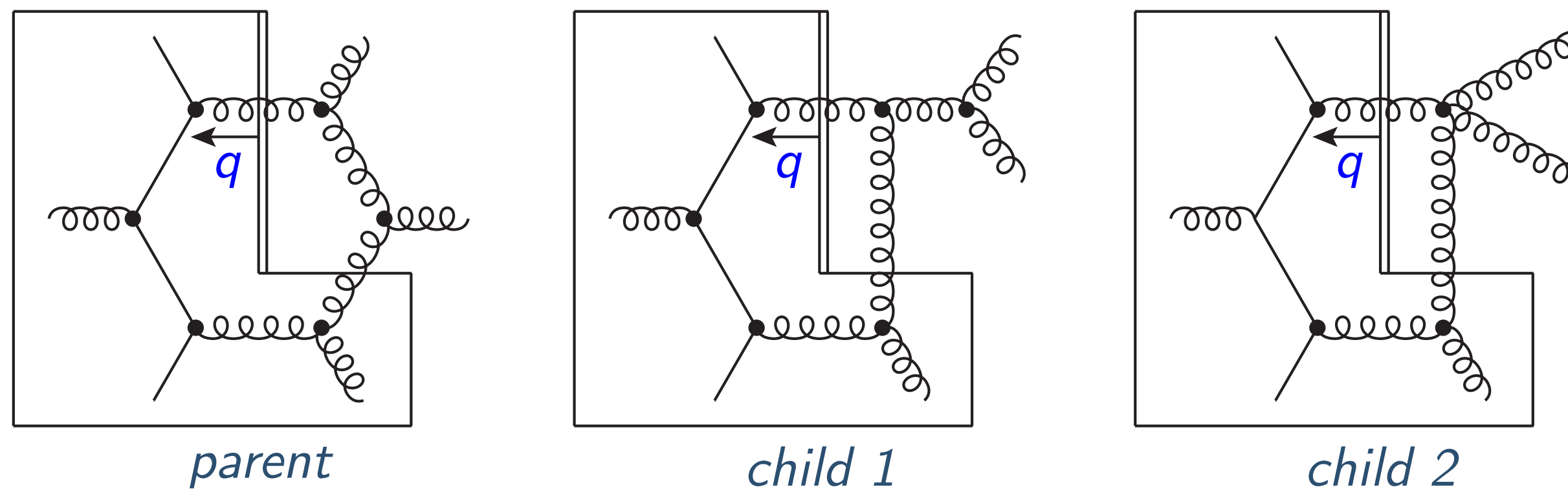
OpenLoops recycling:



Lower-point open-loops can be shared between diagrams if

- cut is put appropriately
- direction chosen to maximise recyclability

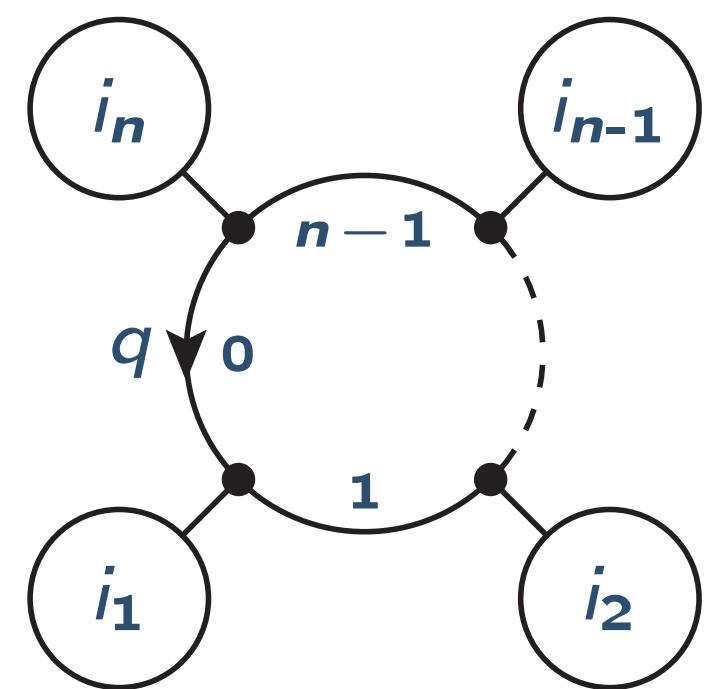
Illustration:



Complicated diagrams require only “last missing piece”

# The (original) Open Loops algorithm: one loop amplitudes

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]



$$= \int \frac{d^D \mathcal{N}(q)}{D_0 D_1 \dots D_{n-1}} = \sum_{r=0}^R \mathcal{N}_{\mu_1 \dots \mu_r} \underbrace{\int \frac{q^{\mu_1} \dots q^{\mu_r}}{D_0 D_1 \dots D_{n-1}}}_{\text{tensor integral}}$$

- Tensorial coefficients  $\mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\alpha$  can directly be contracted with Tensor Integrals evaluated with **COLLIER** [Denner, Dittmaier, Hofer; '16]
- Fast evaluation of  $\mathcal{N}(q) = \sum \mathcal{N}_{\mu_1 \dots \mu_r} q^{\mu_1} \dots q^{\mu_r}$  at multiple q-values allows for efficient application of OPP reduction methods e.g. with **CutTools** [Ossola, Papadopolous, Pittau; '07]

New!

# On-the-fly OpenLoops reduction

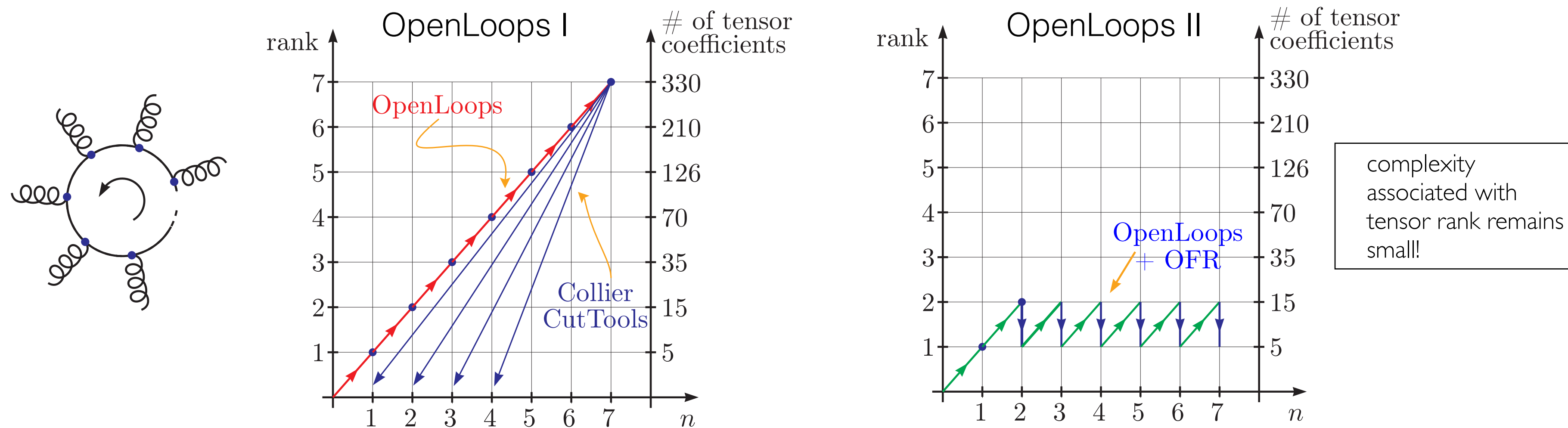
[F. Buccioni, S. Pozzorini, M. Zoller '17]

- Amplitude construction and integrand reduction merged  $\Rightarrow$  “on-the-fly” (OFR) reduction
- At each Open Loops step perform “on-the-fly” rank=2  $\Rightarrow$  rank=1 reduction:

$$q^\mu q^\nu = A^{\mu\nu} + B_\lambda^{\mu\nu} q^\lambda$$

[F. del Aguila and R. Pittau; '04]

$$= [A_{-1}^{\mu\nu} + A_0^{\mu\nu} D_0] + [B_{-1,\lambda}^{\mu\nu} + \sum_{i=0}^3 B_{i,\lambda}^{\mu\nu} D_i] q^\lambda, \quad D_i = (q + p_i)^2 - m_i^2$$



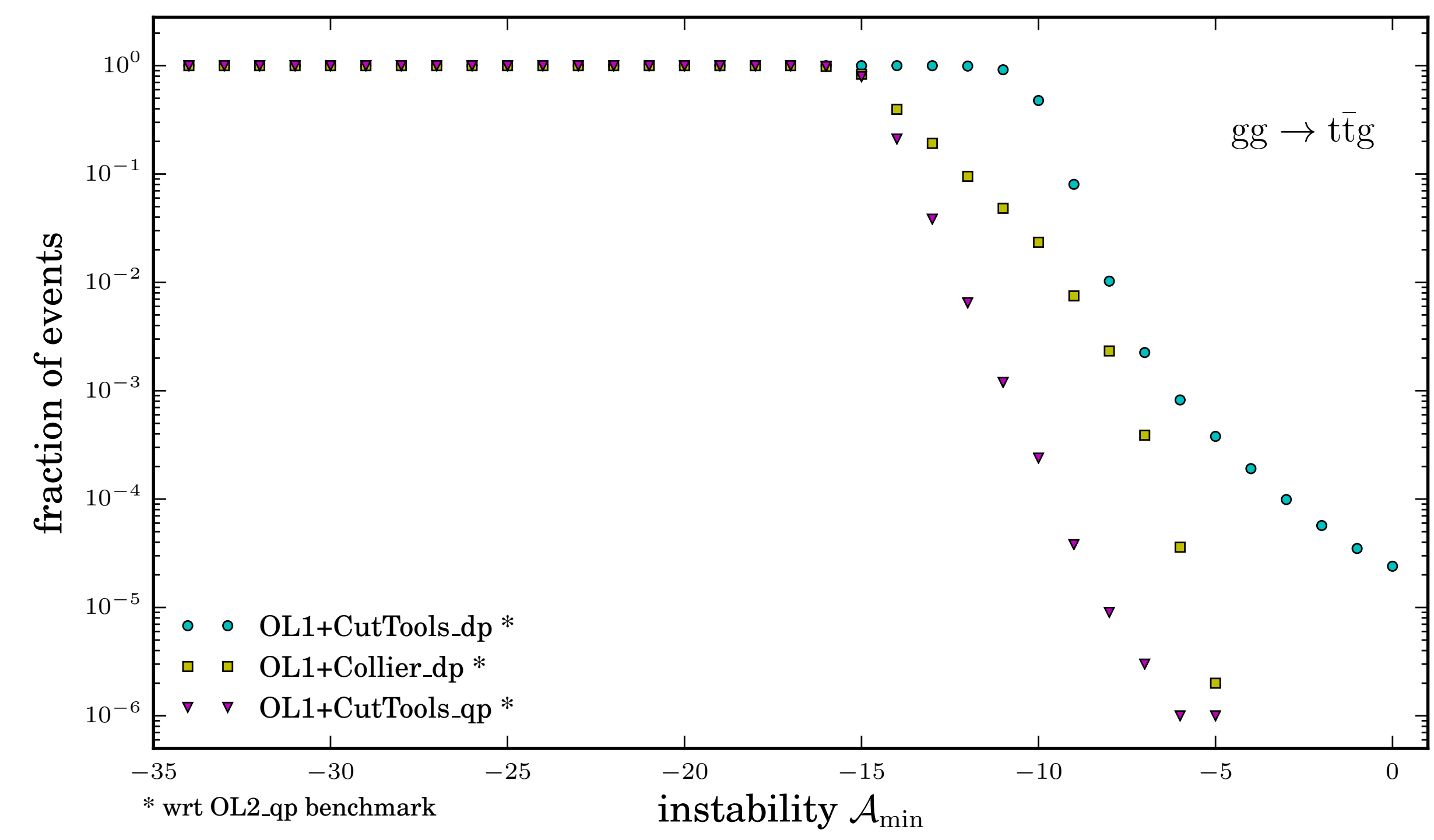
- **problem:** huge proliferation of topologies due to necessary pinching of propagators.
  - **solution:** new helicity and colour treatment at M<sup>2</sup> level allows for merging of pinched topologies.
- $\Rightarrow$  as fast as OpenLoops I + Collier

New!

# On-the-fly OpenLoops reduction

[F. Buccioni, S. Pozzorini, M. Zoller '17]

- Huge advantage: allows for systematic treatment of numerical instabilities

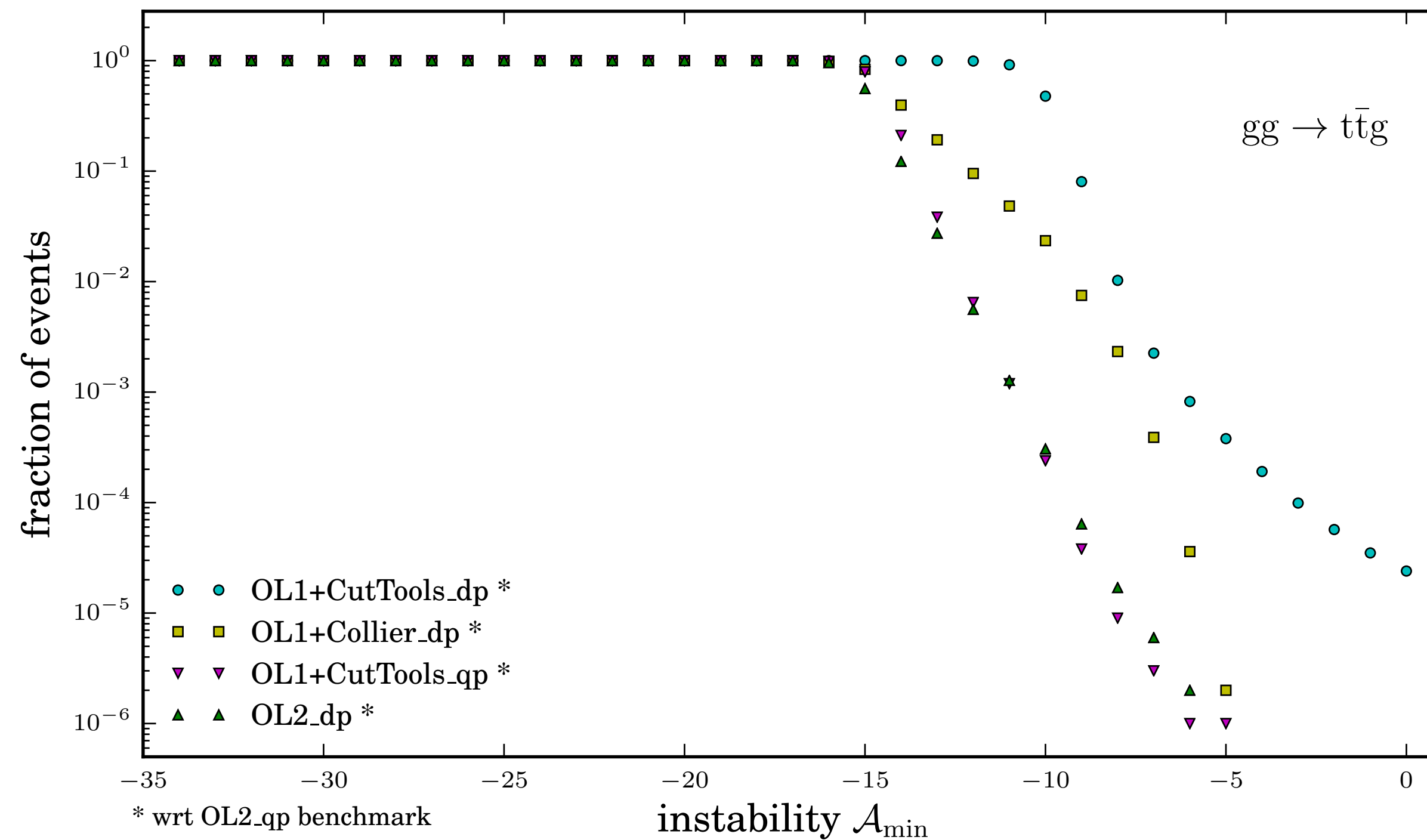


# On-the-fly OpenLoops reduction

[F. Buccioni, S. Pozzorini, M. Zoller '17]

New!

- Huge advantage: allows for systematic treatment of numerical instabilities



- unprecedented numerical stability (always as least as stable as OpenLoops I + Collier)
- crucial in unresolved limits of **real-virtual contributions** in NNLO calculations

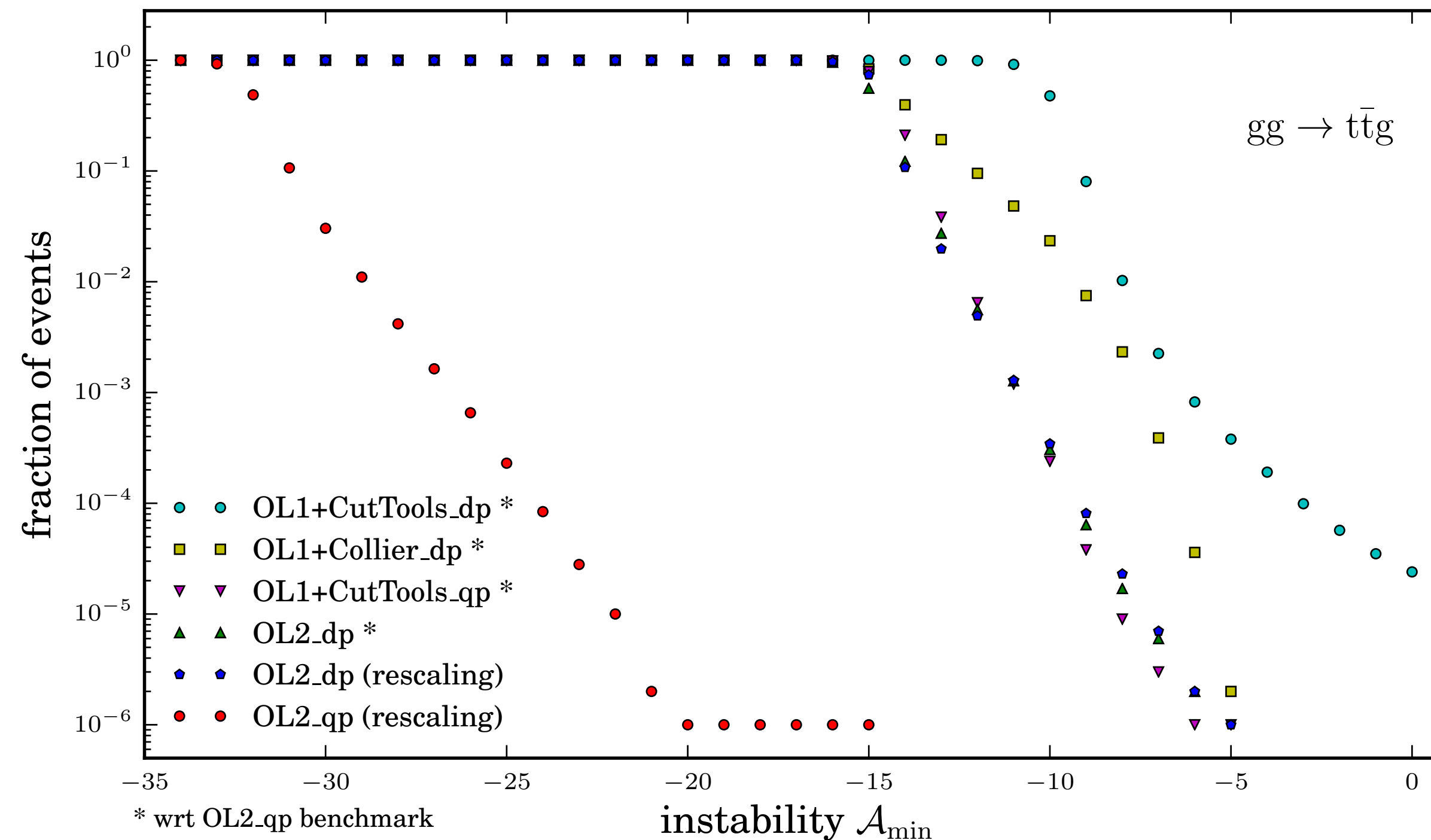


# On-the-fly OpenLoops reduction

New!

[F. Buccioni, S. Pozzorini, M. Zoller '17]

- Huge advantage: allows for systematic treatment of numerical instabilities

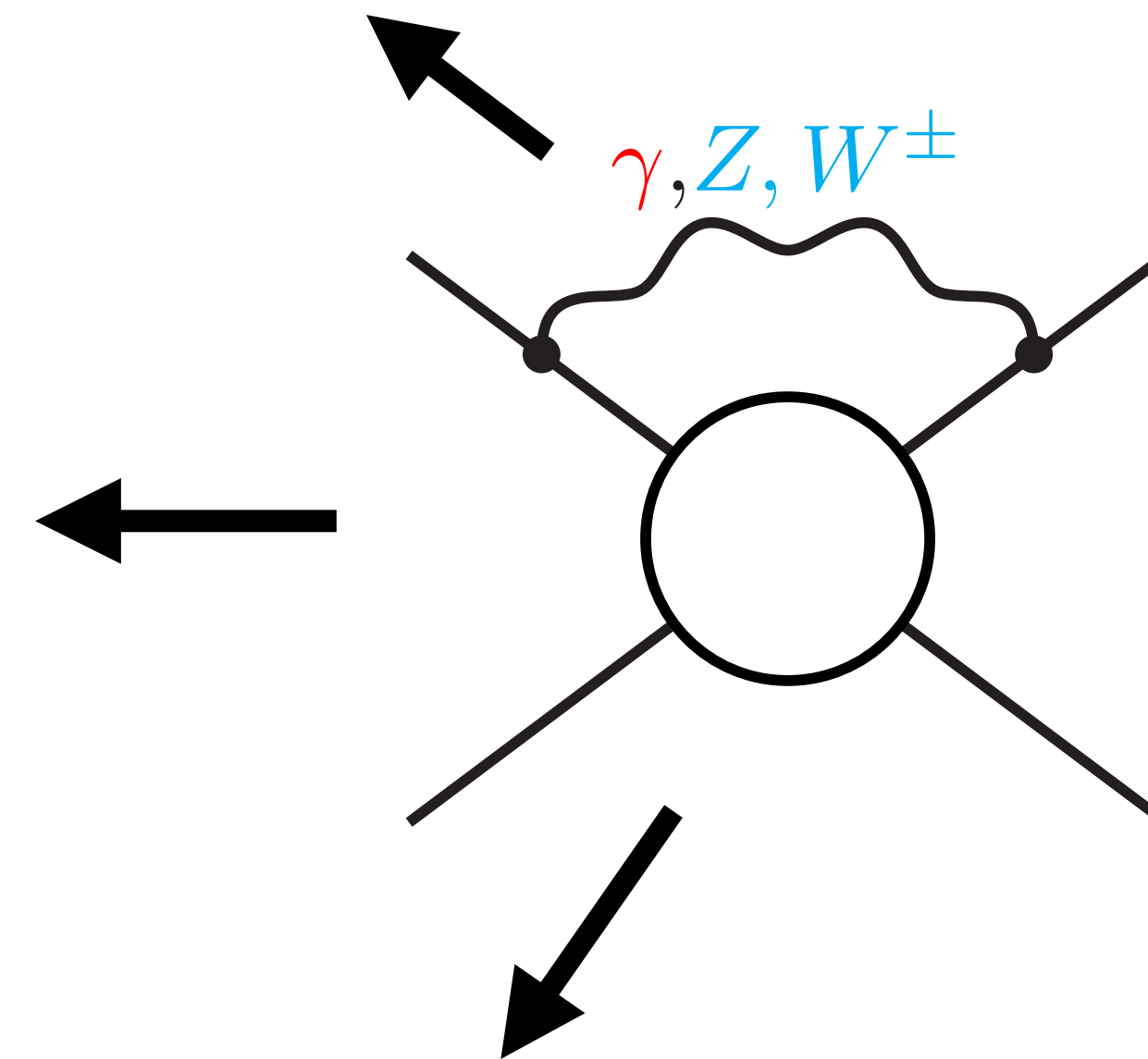
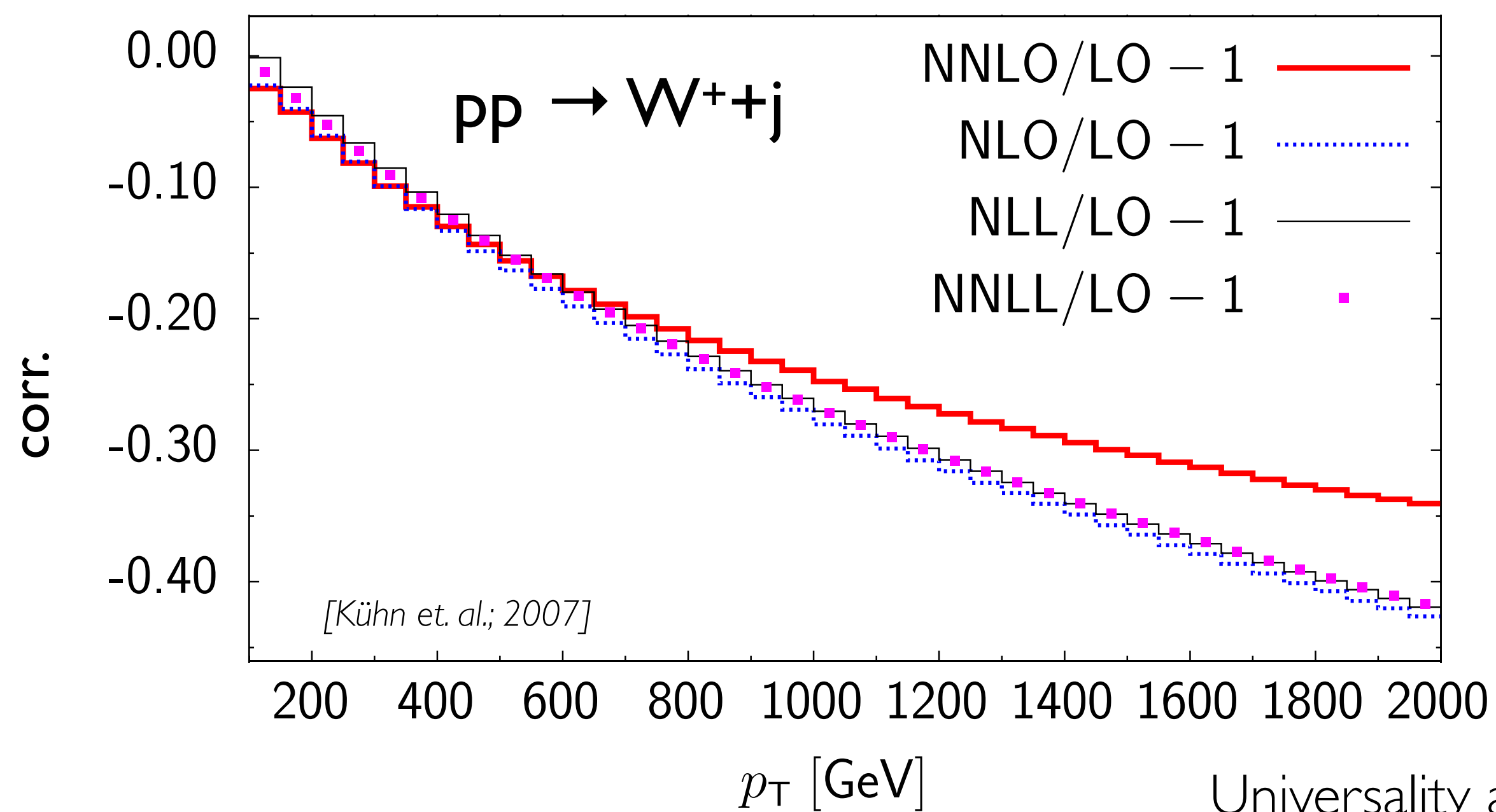


- unprecedented numerical stability (always as least as stable as OpenLoops I + Collier)
- crucial in unresolved limits of **real-virtual contributions** in NNLO calculations
- ultimate stability: OFR @ qp (based on all-order expansions)
- soon to be public in **OpenLoops2** [F. Buccioni, JML, P. Maierhöfer, S. Pozzorini, M. Zoller]

# Relevance of EW higher-order corrections I

Numerically  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$  **NLO EW ~ NNLO QCD**

I. Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:



[Ciafaloni, Comelli, '98;  
Lipatov, Fadin, Martin, Melles, '99;  
Kuehen, Penin, Smirnov, '99;  
Denner, Pozzorini, '00]

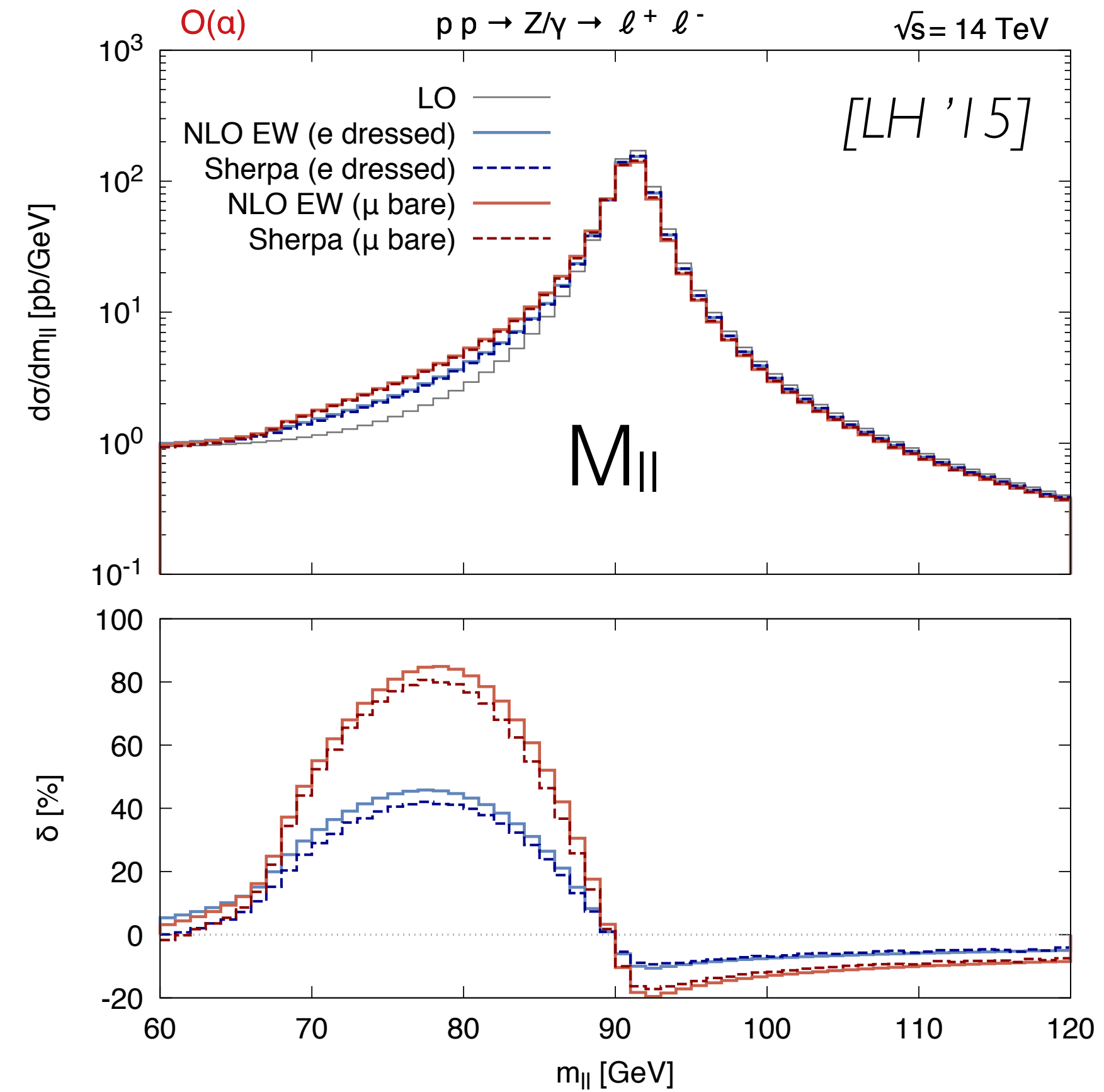
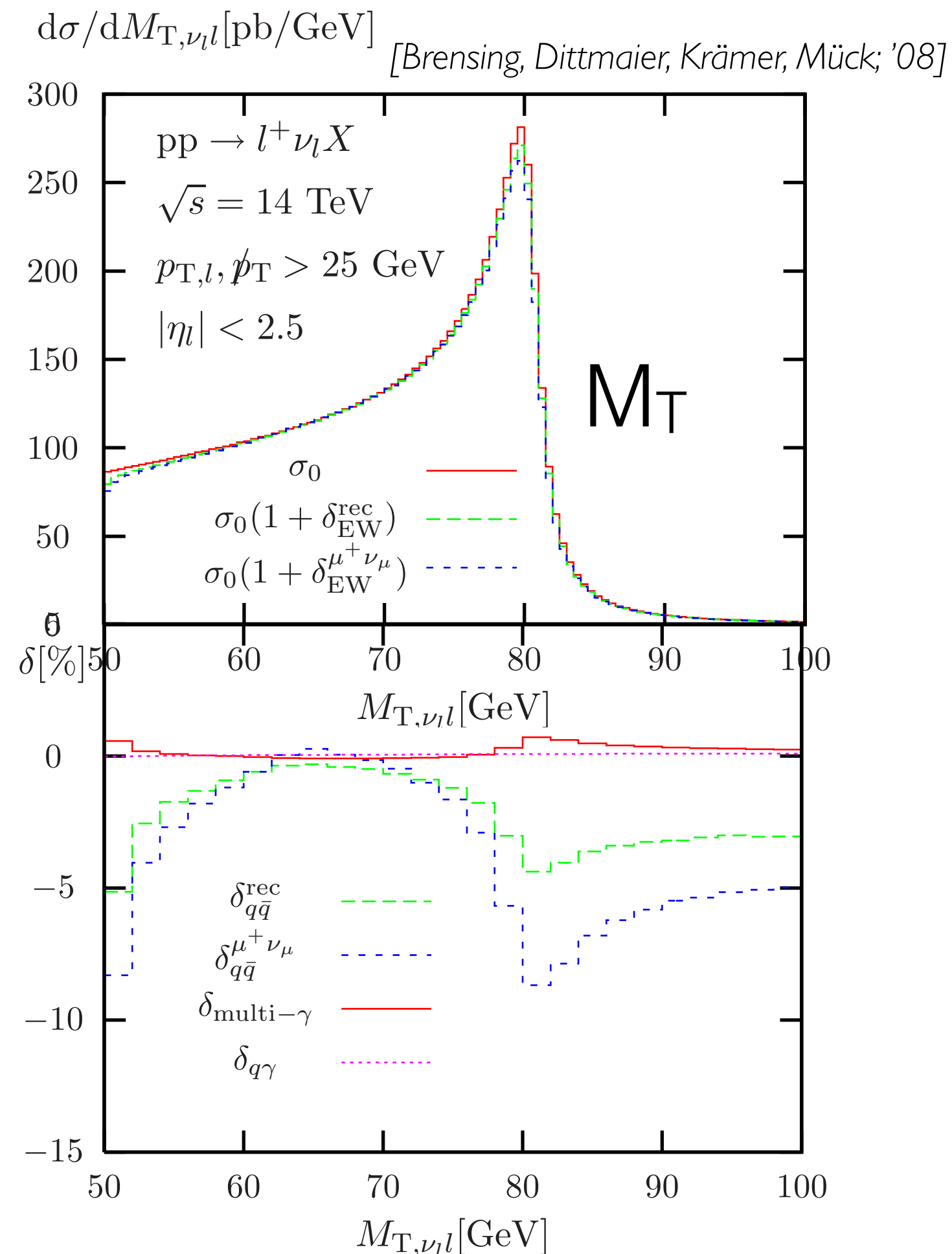
Universality and factorisation: [Denner, Pozzorini; '01]

$$\delta\mathcal{M}_{\text{LL+NLL}}^{1\text{-loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^n \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^\pm} I^a(k) I^{\bar{a}}(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\hat{s}}{M^2} \right\} \mathcal{M}_0$$

$\rightarrow$  overall large effect in the tails of distributions:  $p_T, m_{\text{inv}}, H_T, \dots$  (relevant for BSM searches!)

# Relevance of EW higher-order corrections II

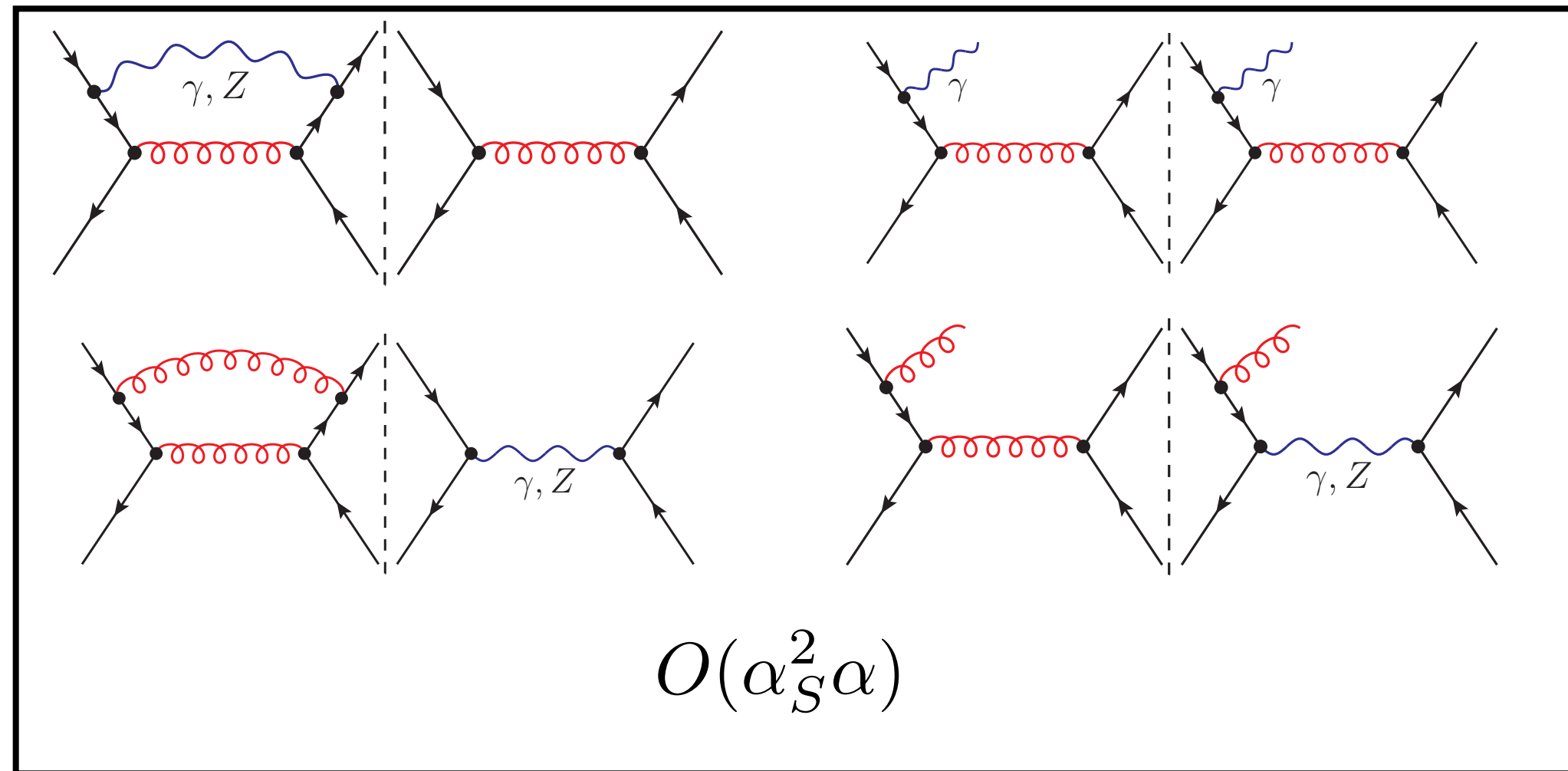
2. Possible large enhancement due to soft/collinear **logs** from photon radiation  $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$  in sufficiently exclusive observables.



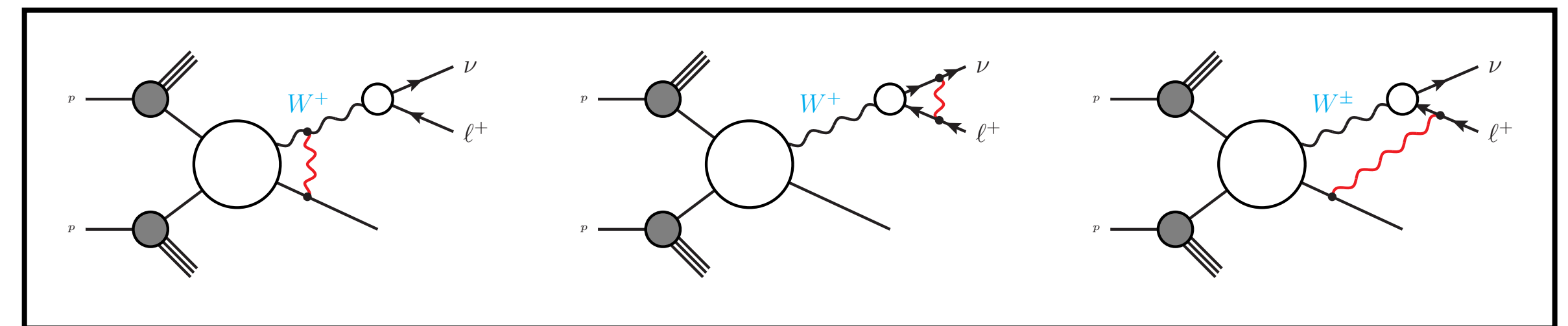
→ important for various precision observables, e.g. for determination of  $M_W$  in DY

# Nontrivial features in NLO QCD → NLO EW

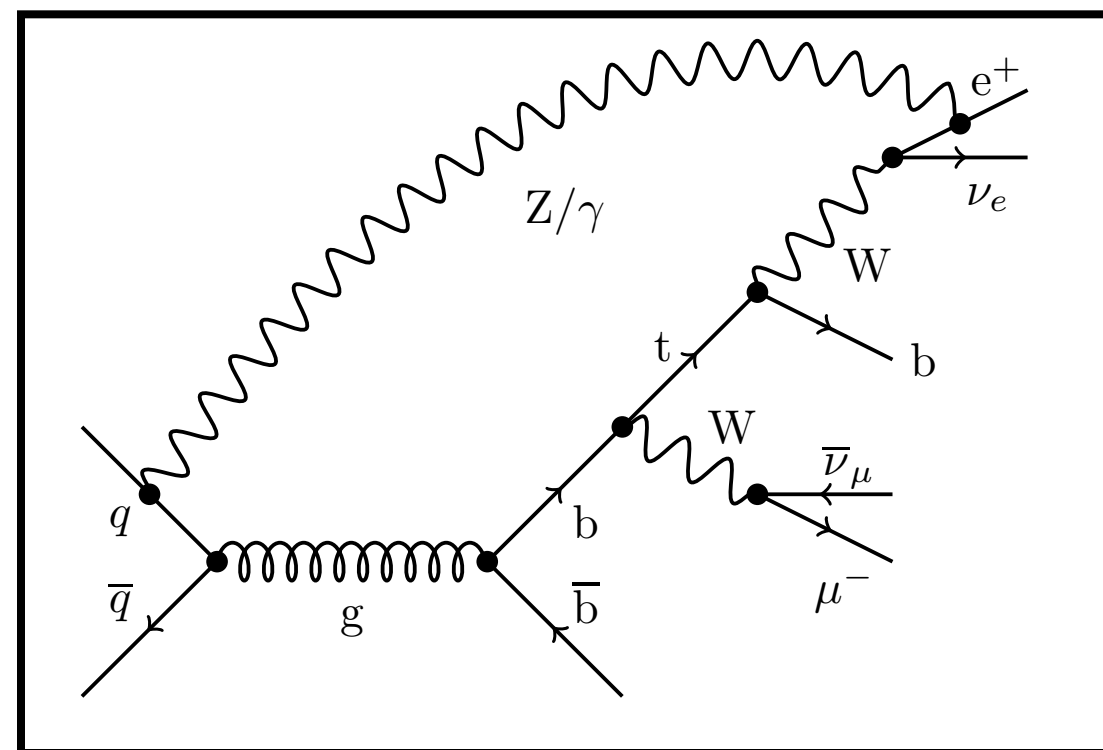
## 1. QCD-EW interplay



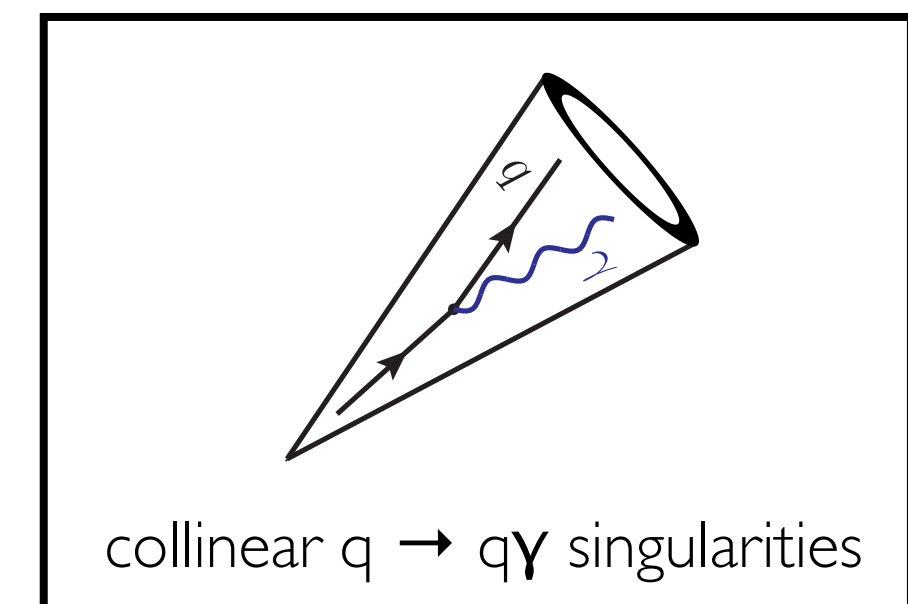
2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays  
→ **complex-mass-scheme**



3. **virtual EW corrections** more involved than QCD (many internal masses)

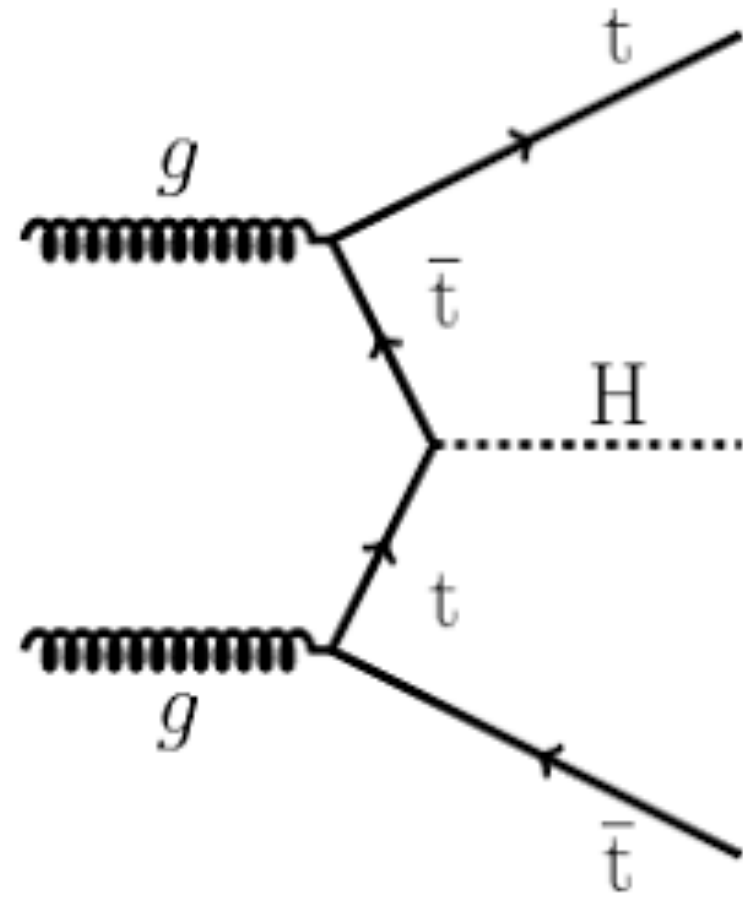


4. photon contributions in jets and proton  
→ **photon-jet separation, γPDF**

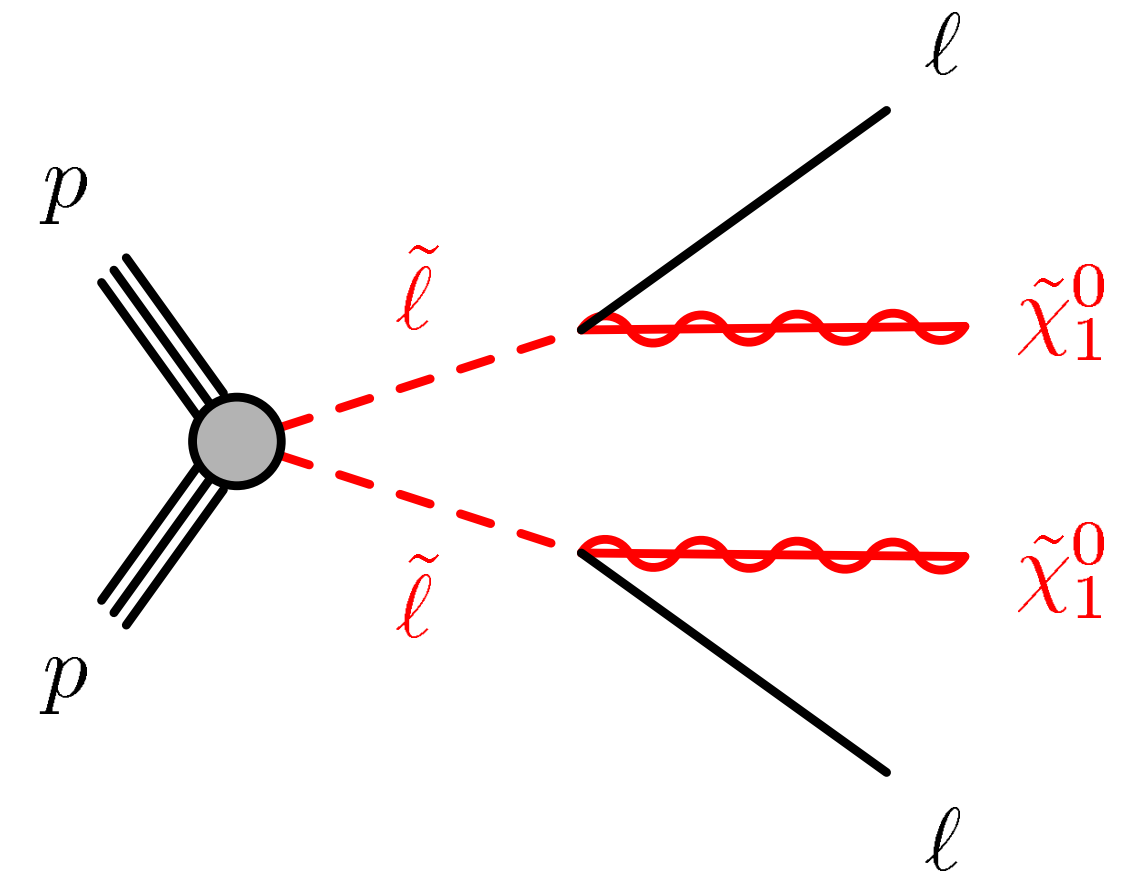


A few examples where theory precision is crucial:

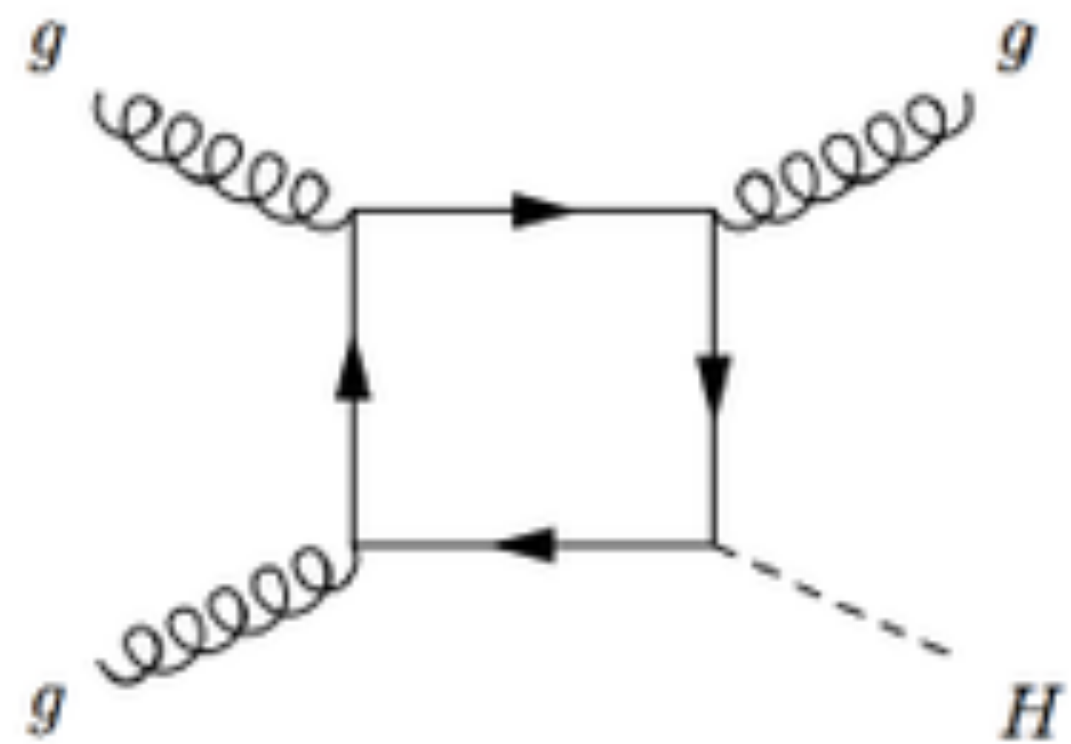
$t\bar{t}H$



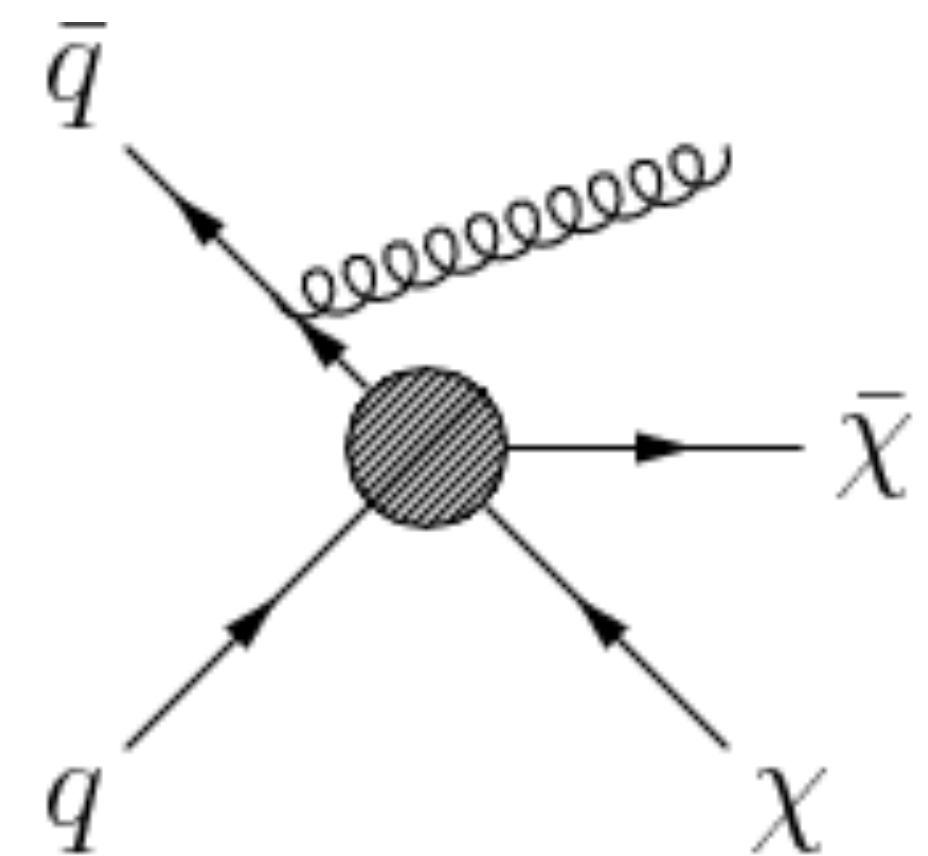
EW SUSY searches



Higgs-pT

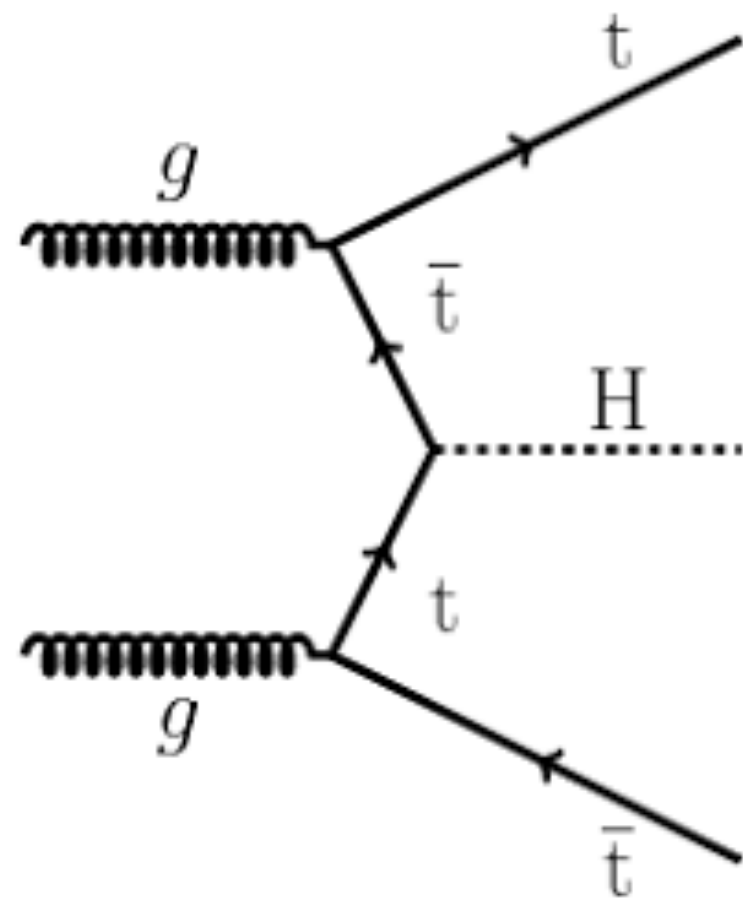


Dark Matter searches

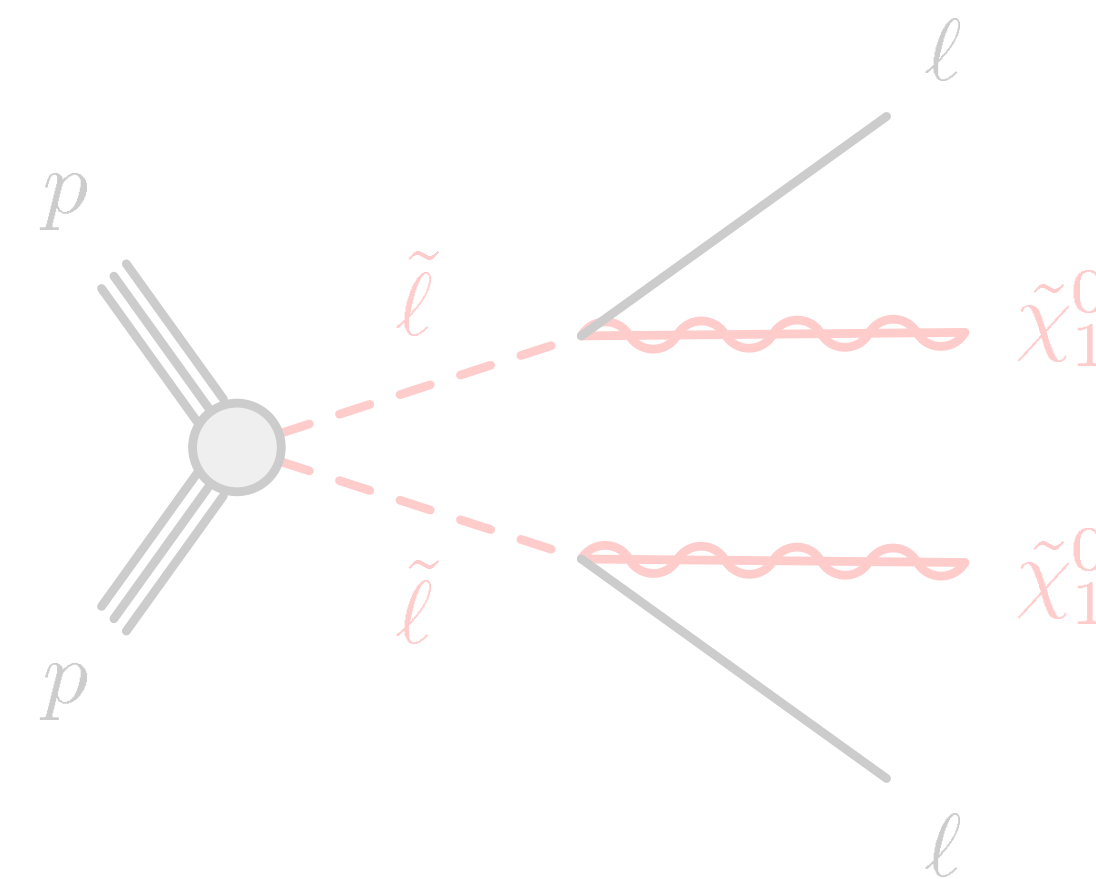


A few examples where theory precision is crucial:

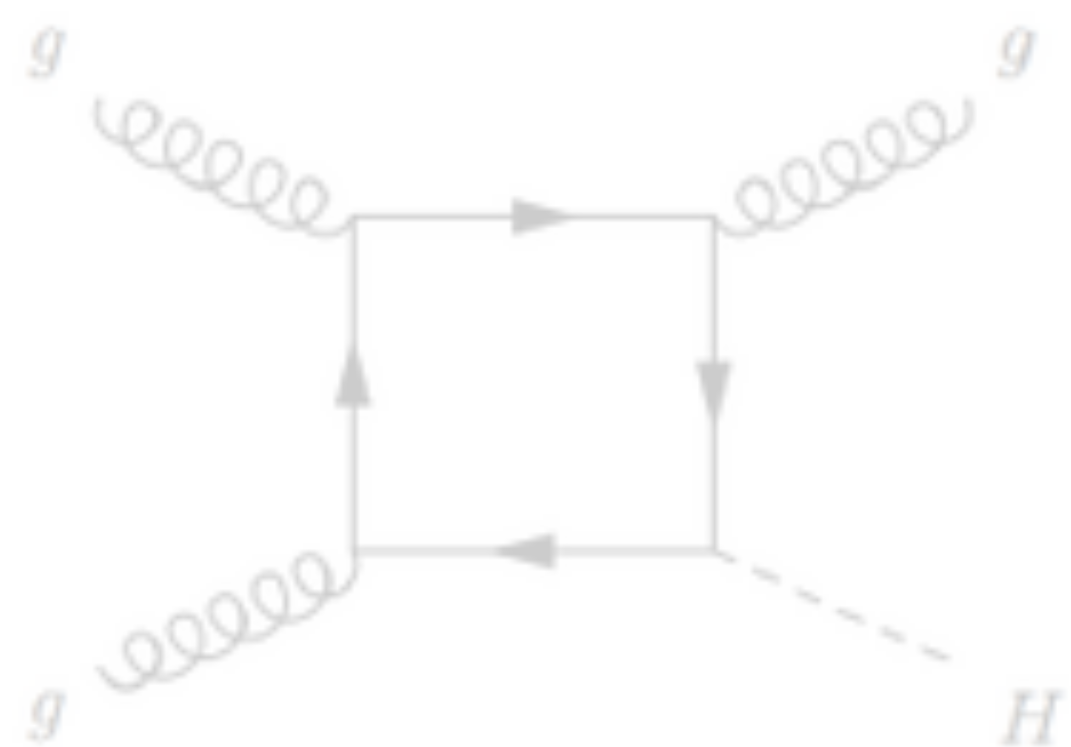
$t\bar{t}H$



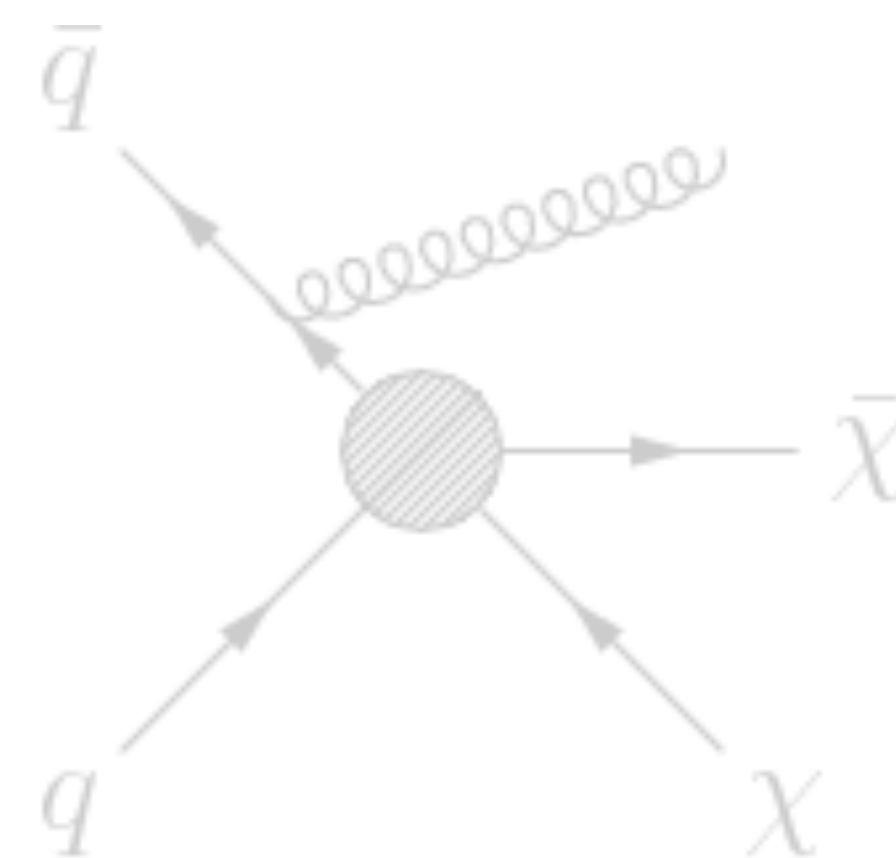
EW SUSY searches



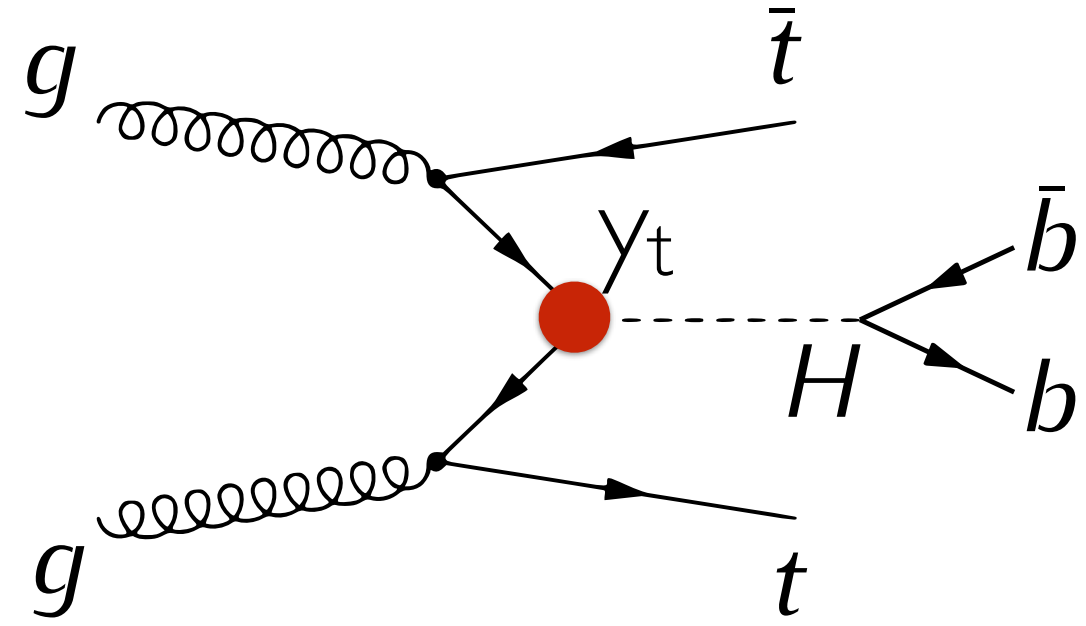
Higgs-pT



Dark Matter searches

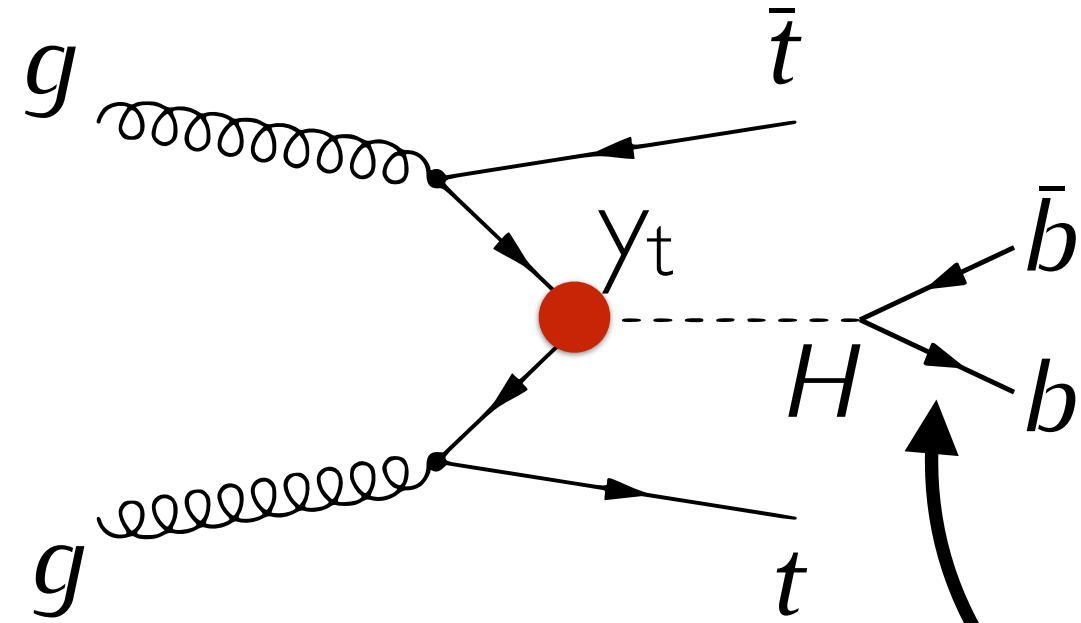


# Taming $t\bar{t}H$ backgrounds

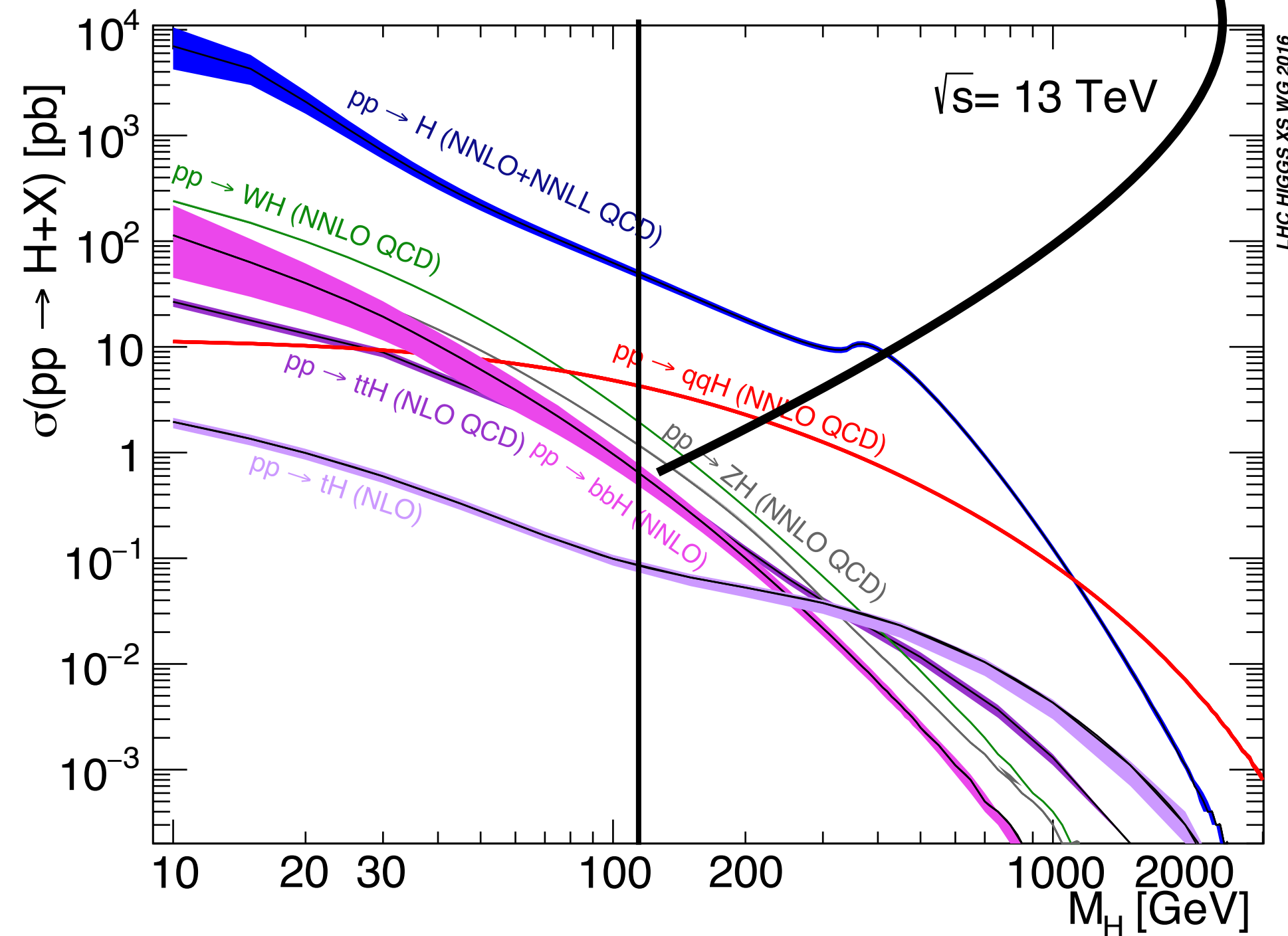
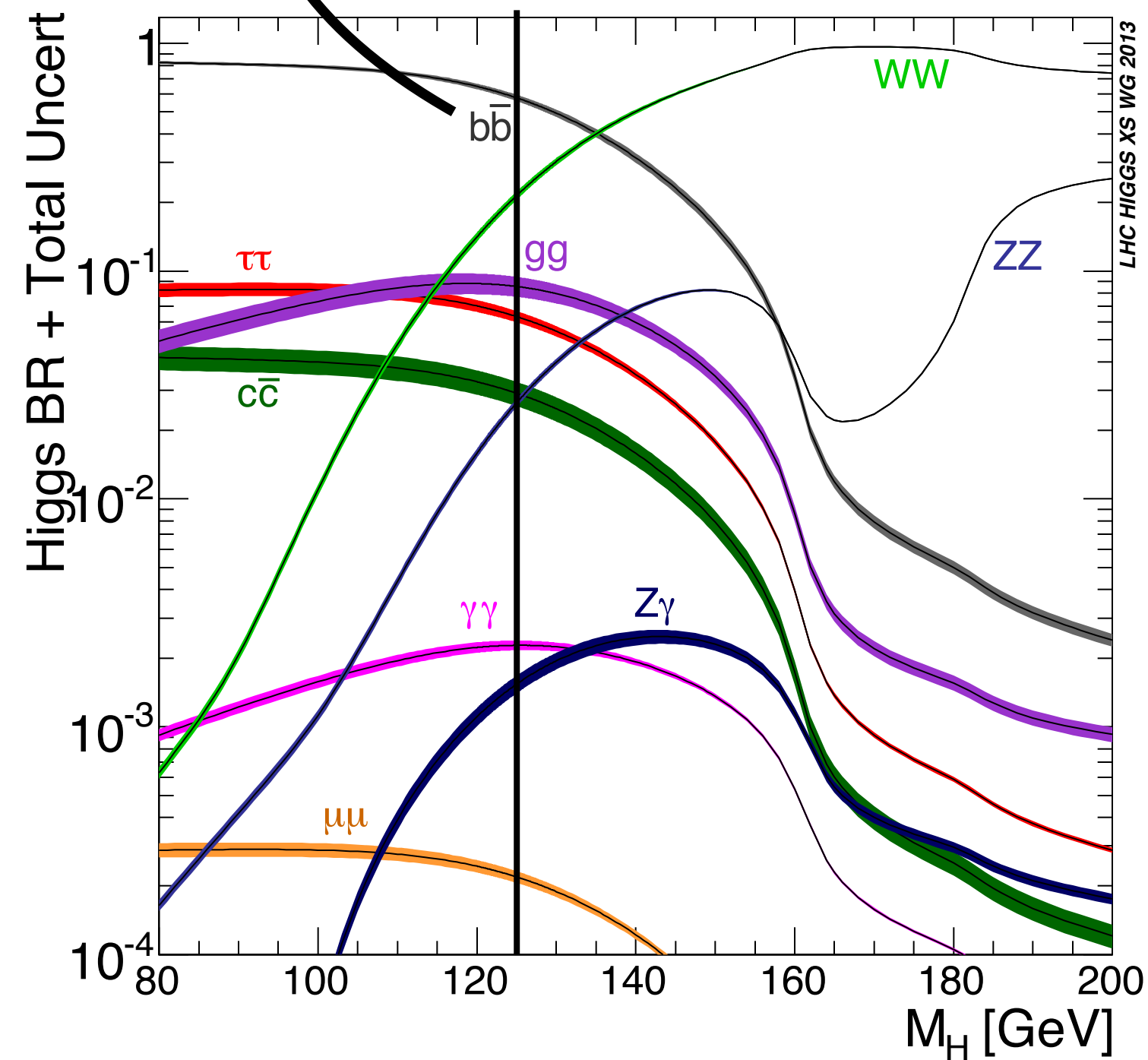


➡ direct probe of the top Yukawa coupling

# Taming $t\bar{t}H$ backgrounds



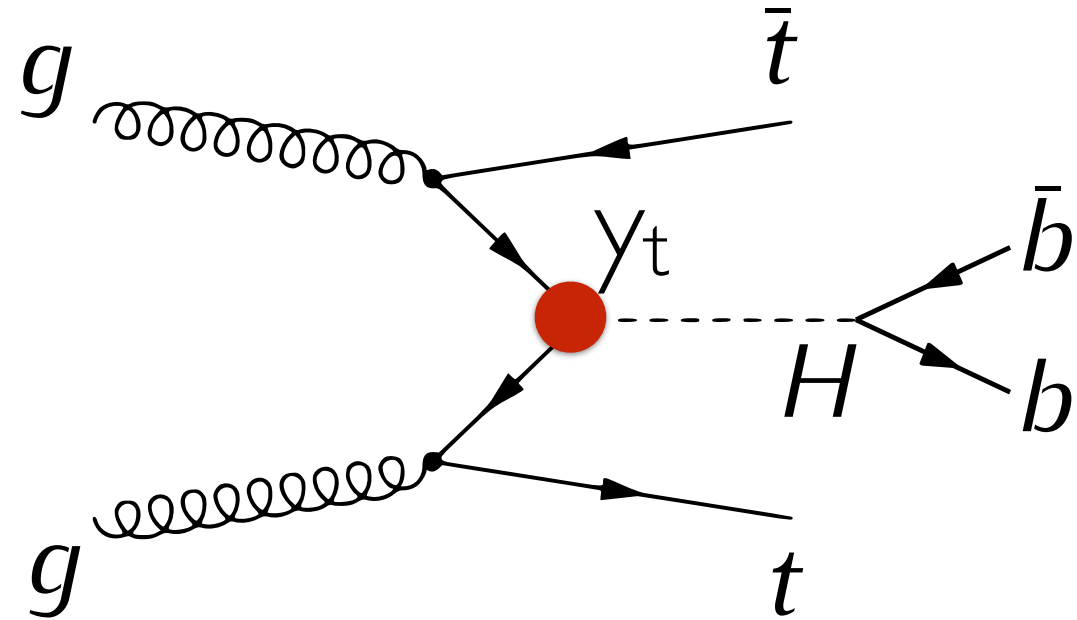
- ➔ direct probe of the top Yukawa coupling
- ➔ unfortunately very small cross section
- ➔ have to consider  $H \rightarrow b\bar{b}$  decay with large BR



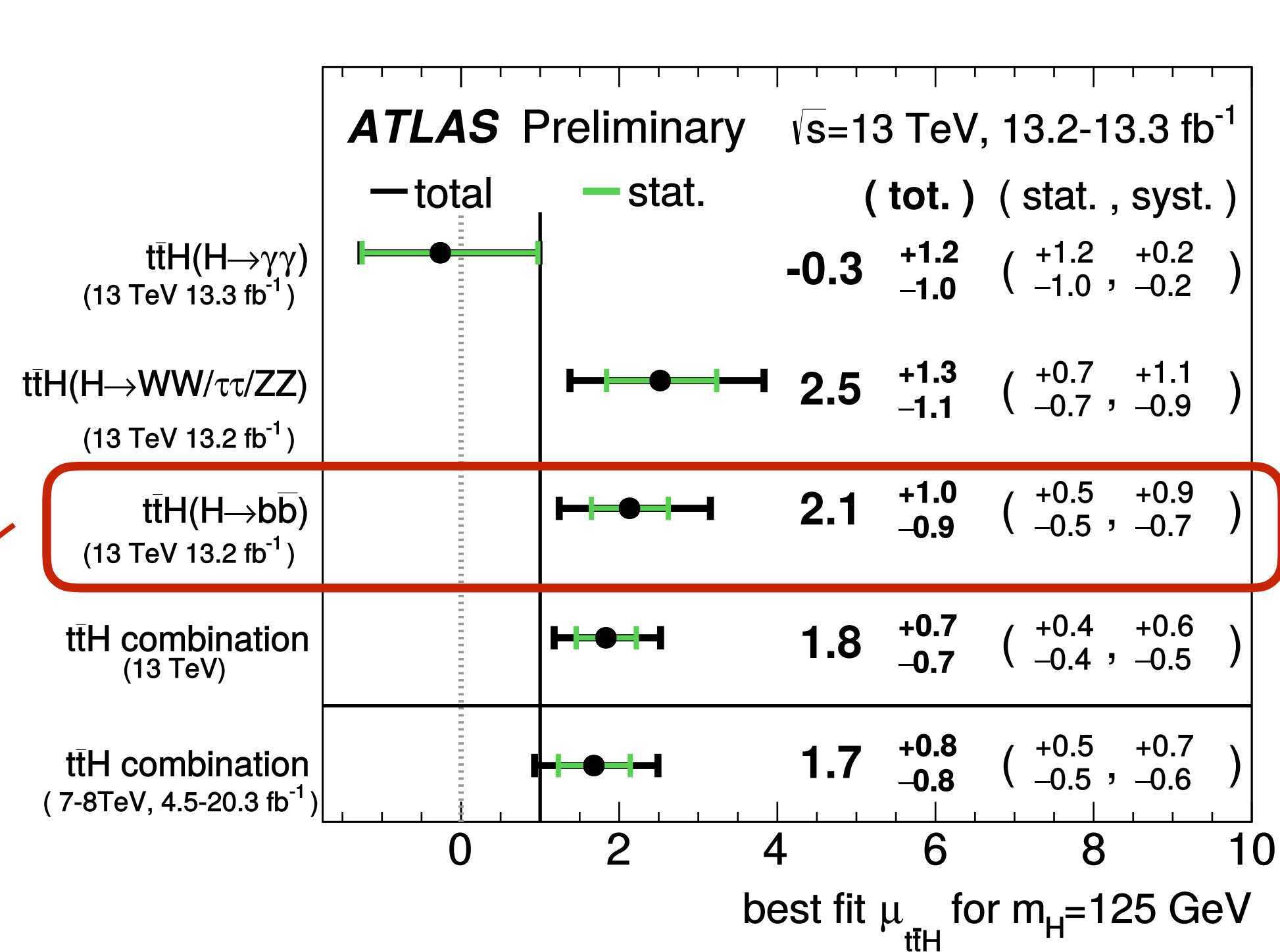
$$\sigma_{t\bar{t}H}^{\text{NLO QCD+EW}} = 0.507 \text{ pb}$$



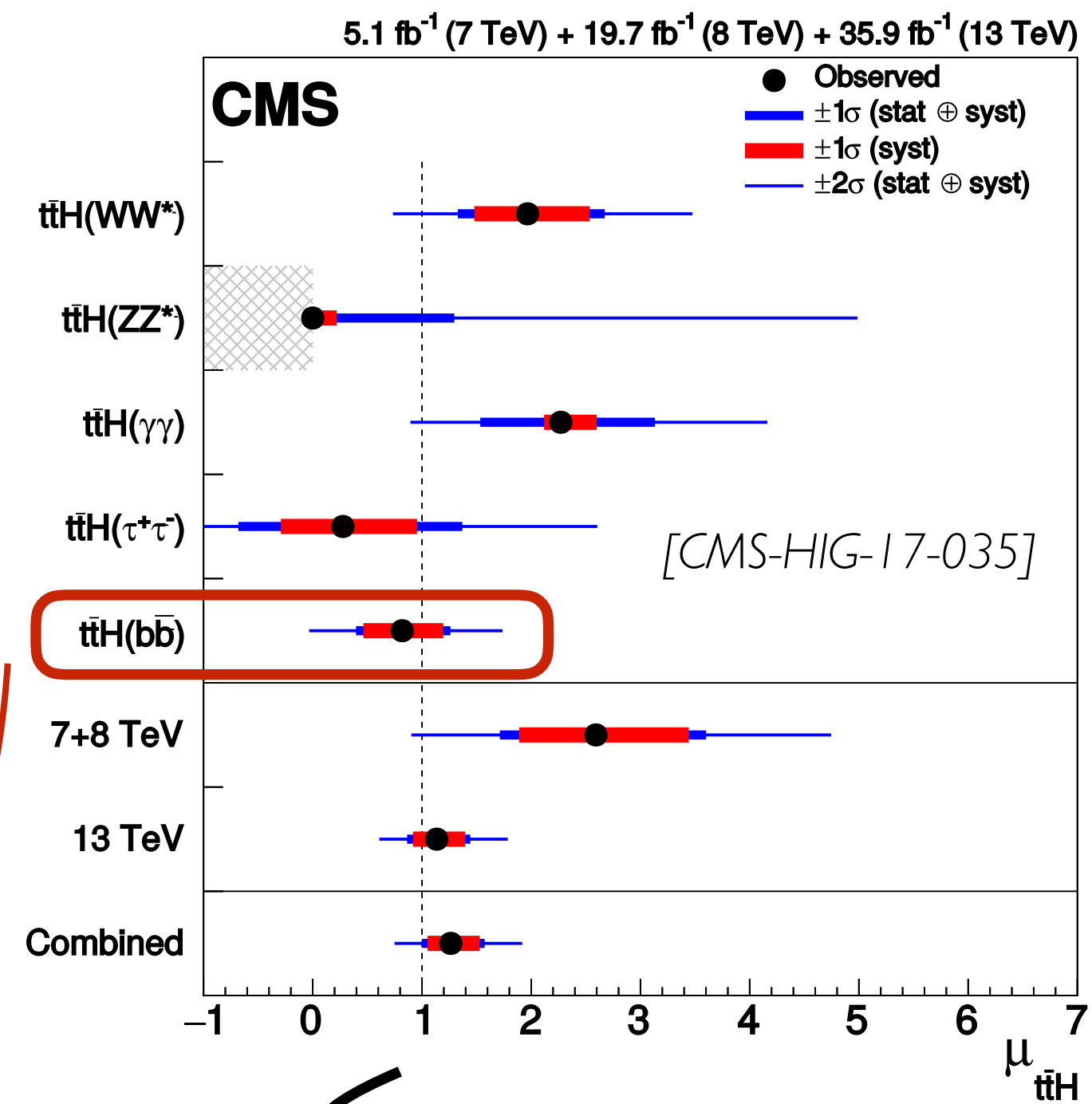
# Taming $t\bar{t}H$ backgrounds



- ➔ direct probe of the top Yukawa coupling
- ➔ unfortunately very small cross section
- ➔ have to consider  $H \rightarrow b\bar{b}$  decay with large BR

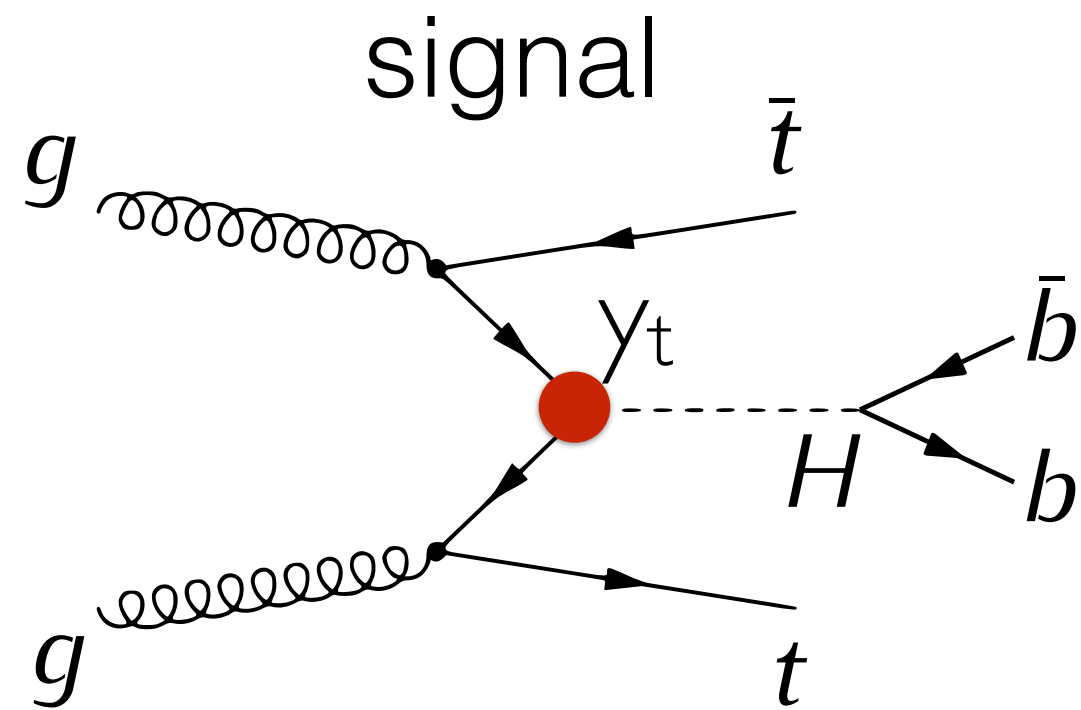


dominated by systematics!

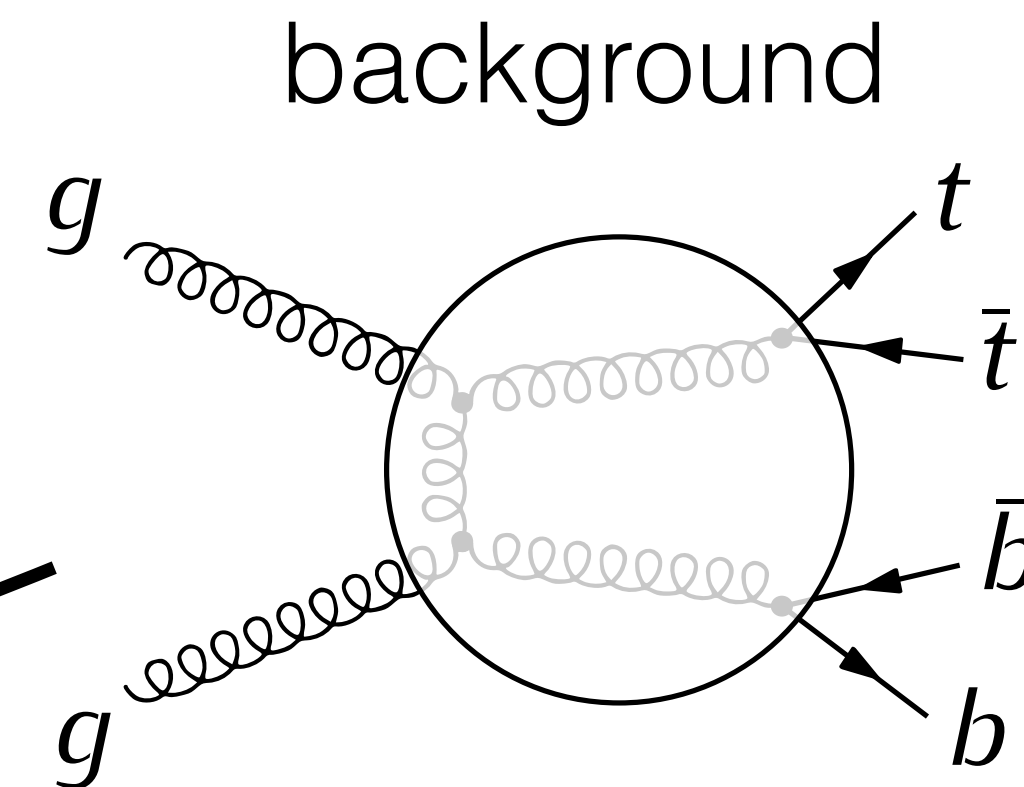
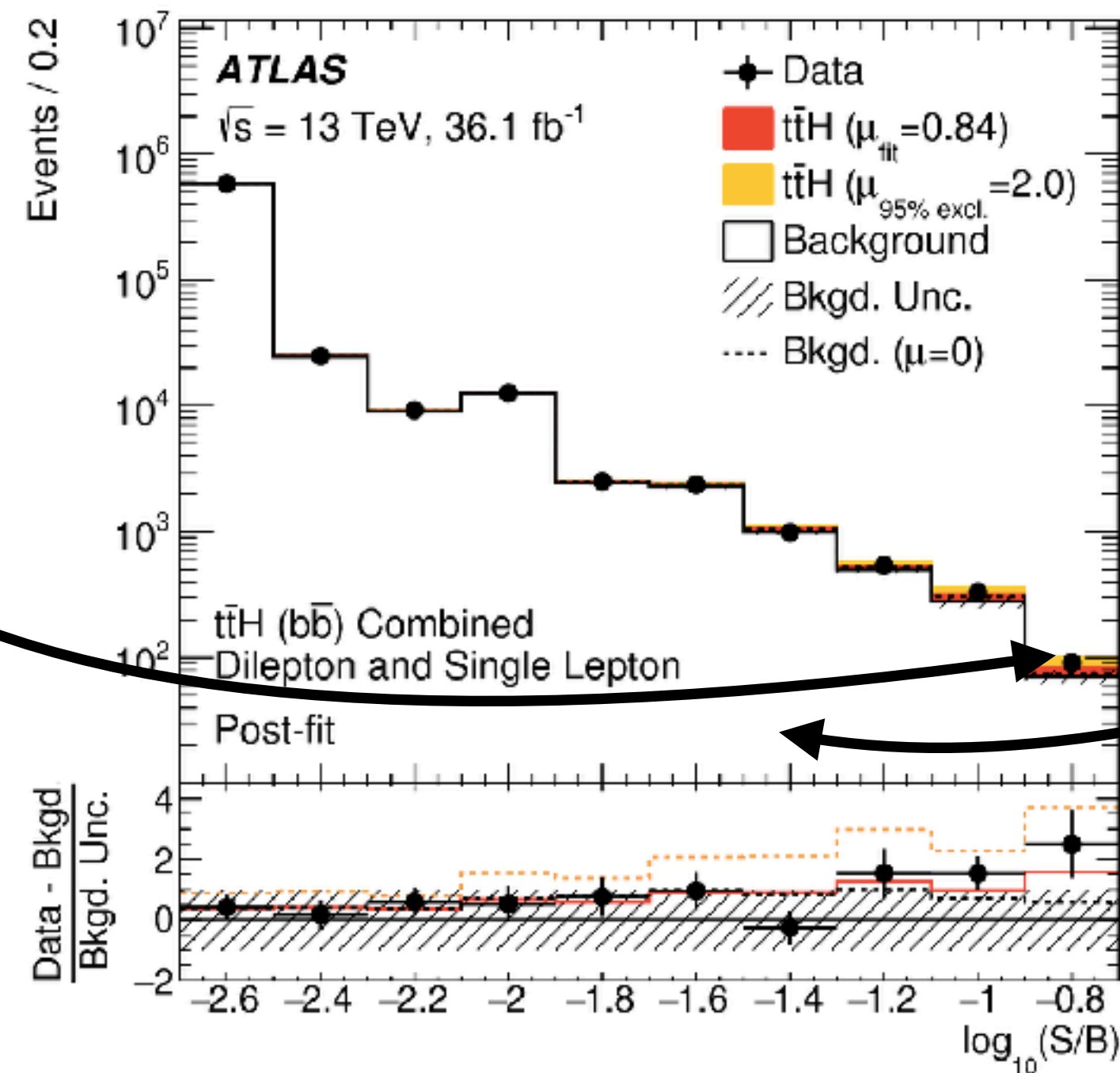


combined significance: 5.2σ!

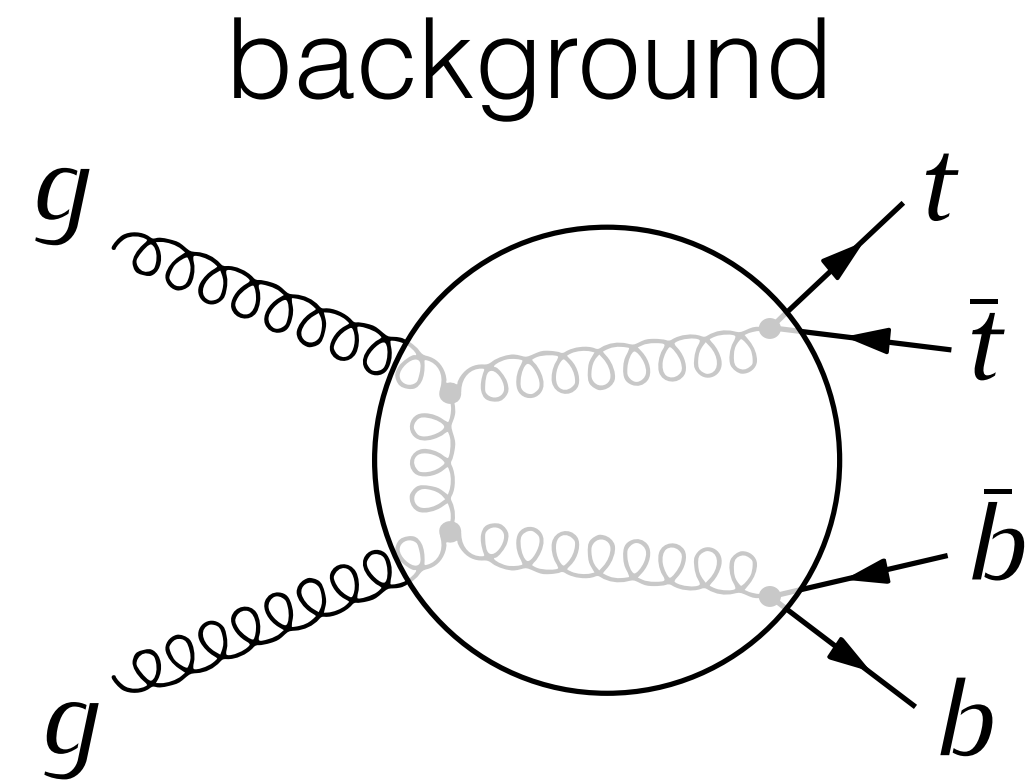
# Taming $t\bar{t}H$ backgrounds



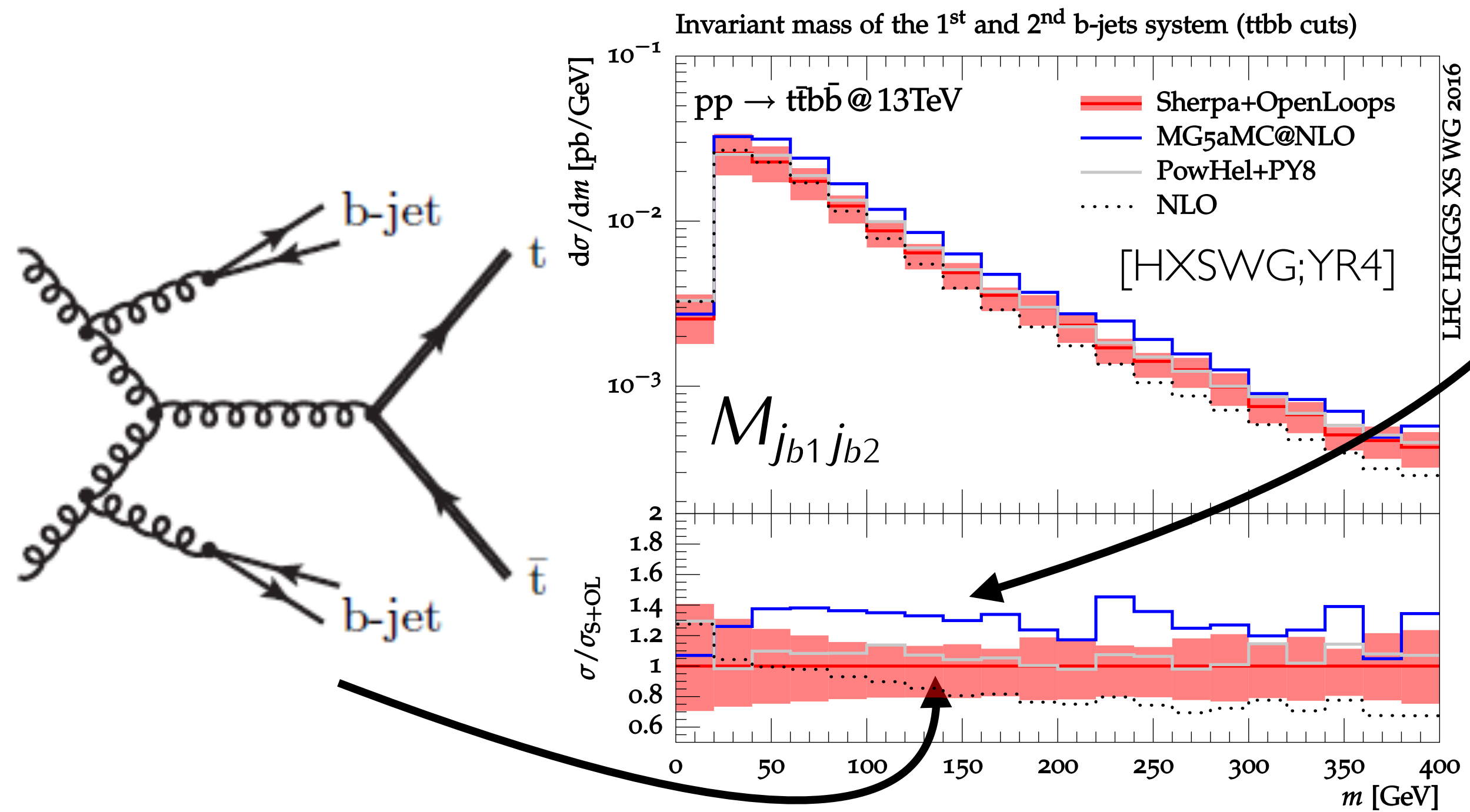
- ➔ direct probe of the top Yukawa coupling
- ➔ unfortunately very small cross section
- ➔ have to consider  $H \rightarrow b\bar{b}$  decay with large BR
- ➔ large QCD background:  $t\bar{t}+b$ -jets with sizeable uncertainties



# Taming $t\bar{t}H$ backgrounds

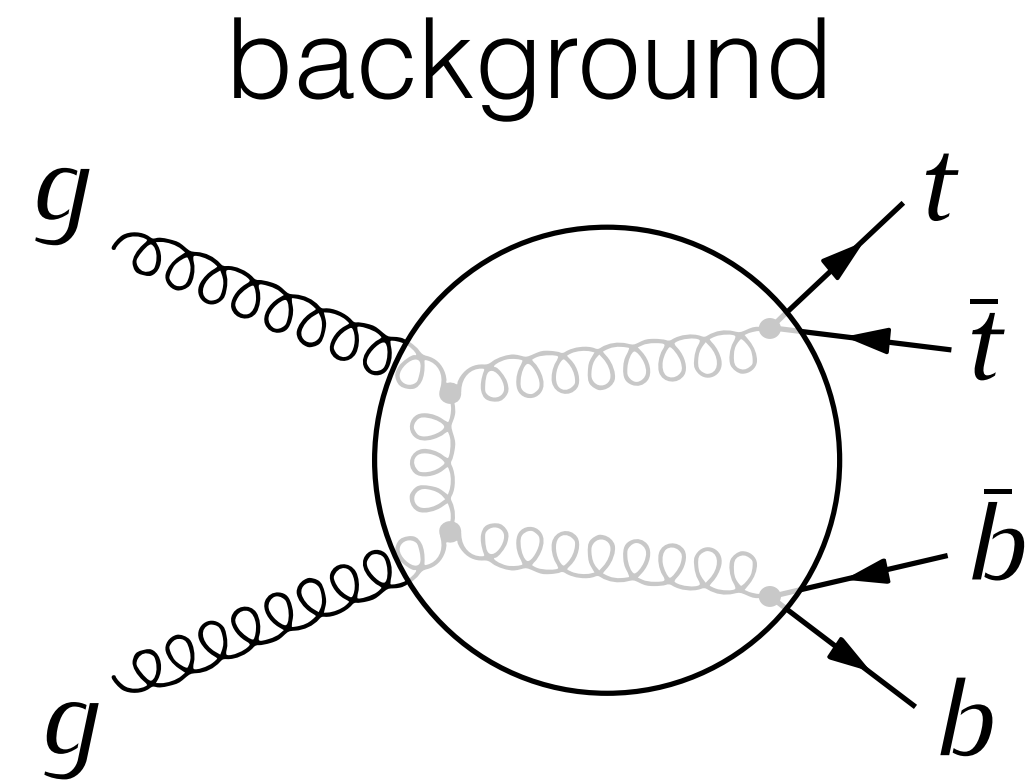


- ➔ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%
- ➔ However: notoriously difficult multi-scale problem:  $ET_t, ET_{\bar{t}}, ET_b, ET_{\bar{b}}$
- ➔ Large shower effects, in particular from double  $g \rightarrow b\bar{b}$  splittings
- ➔ Large systematic uncertainties from parton shower matching

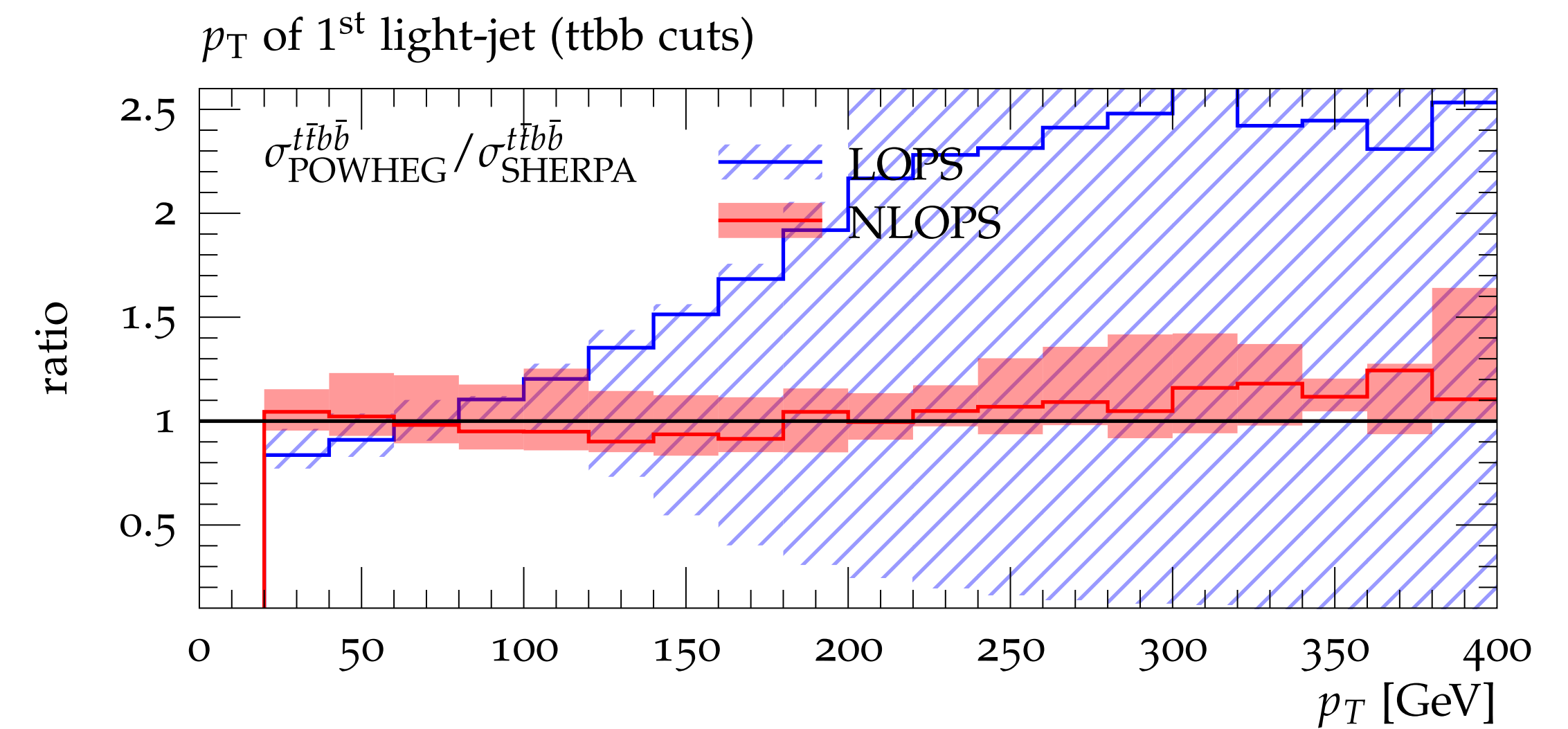
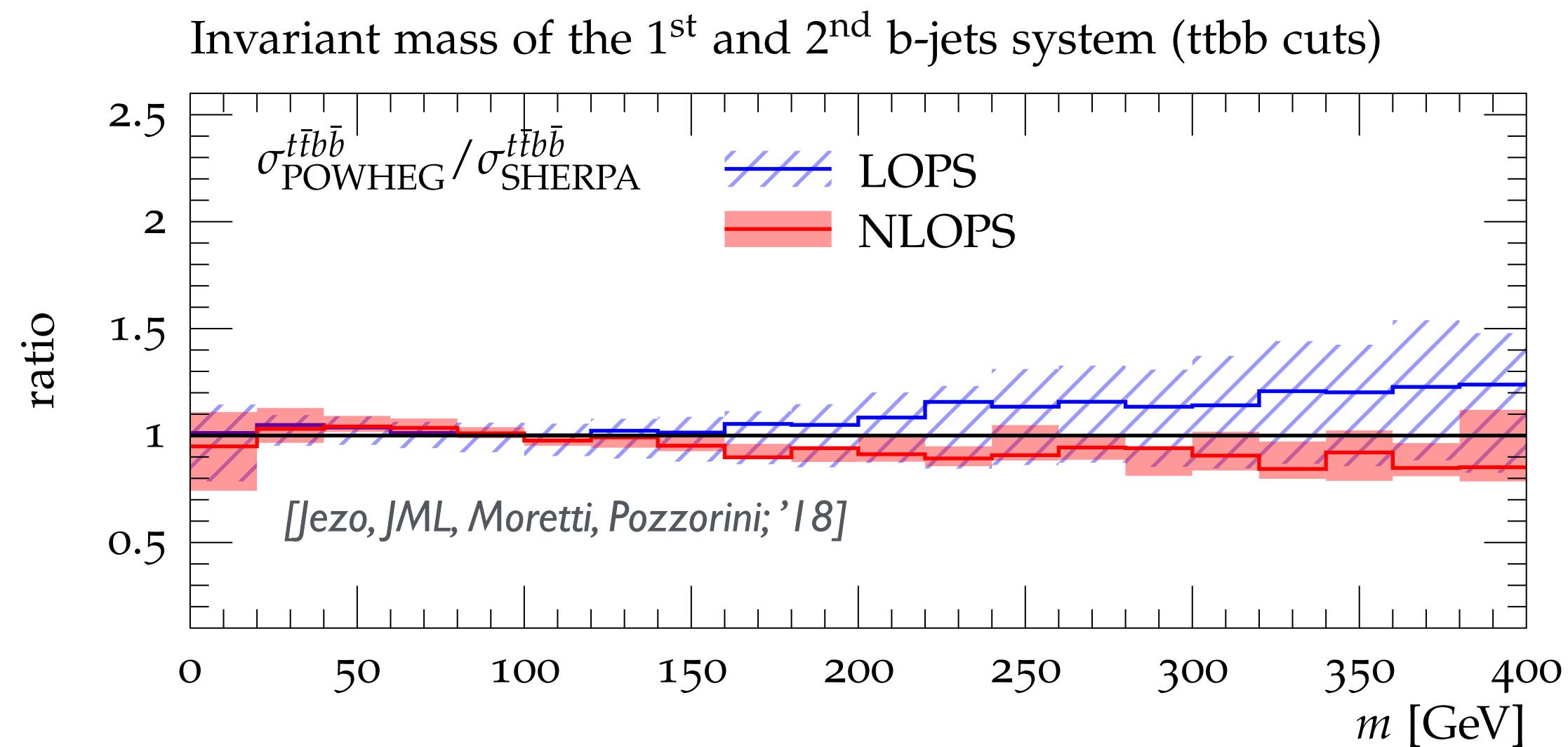


~20% in the signal region

# Taming $t\bar{t}H$ backgrounds



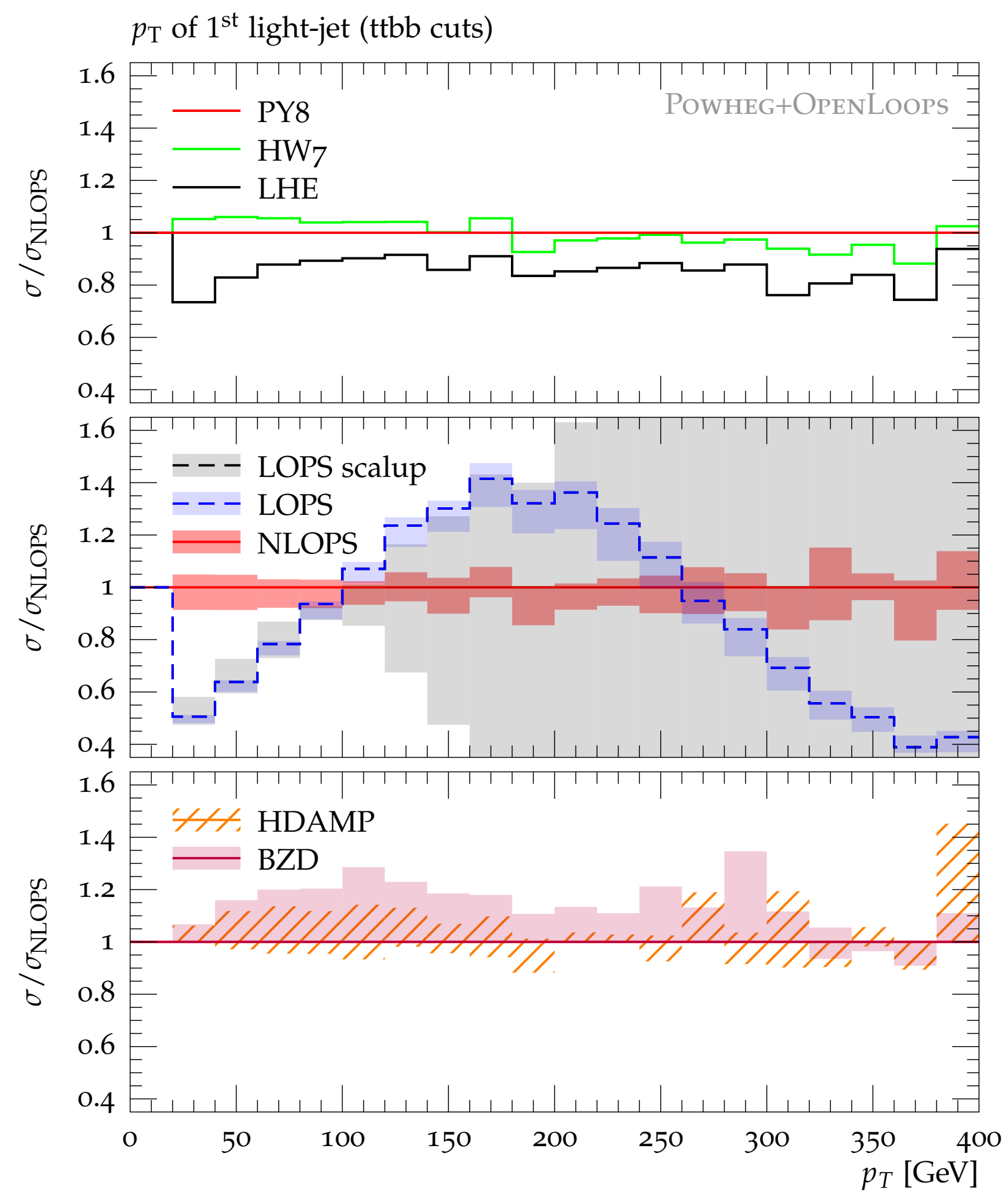
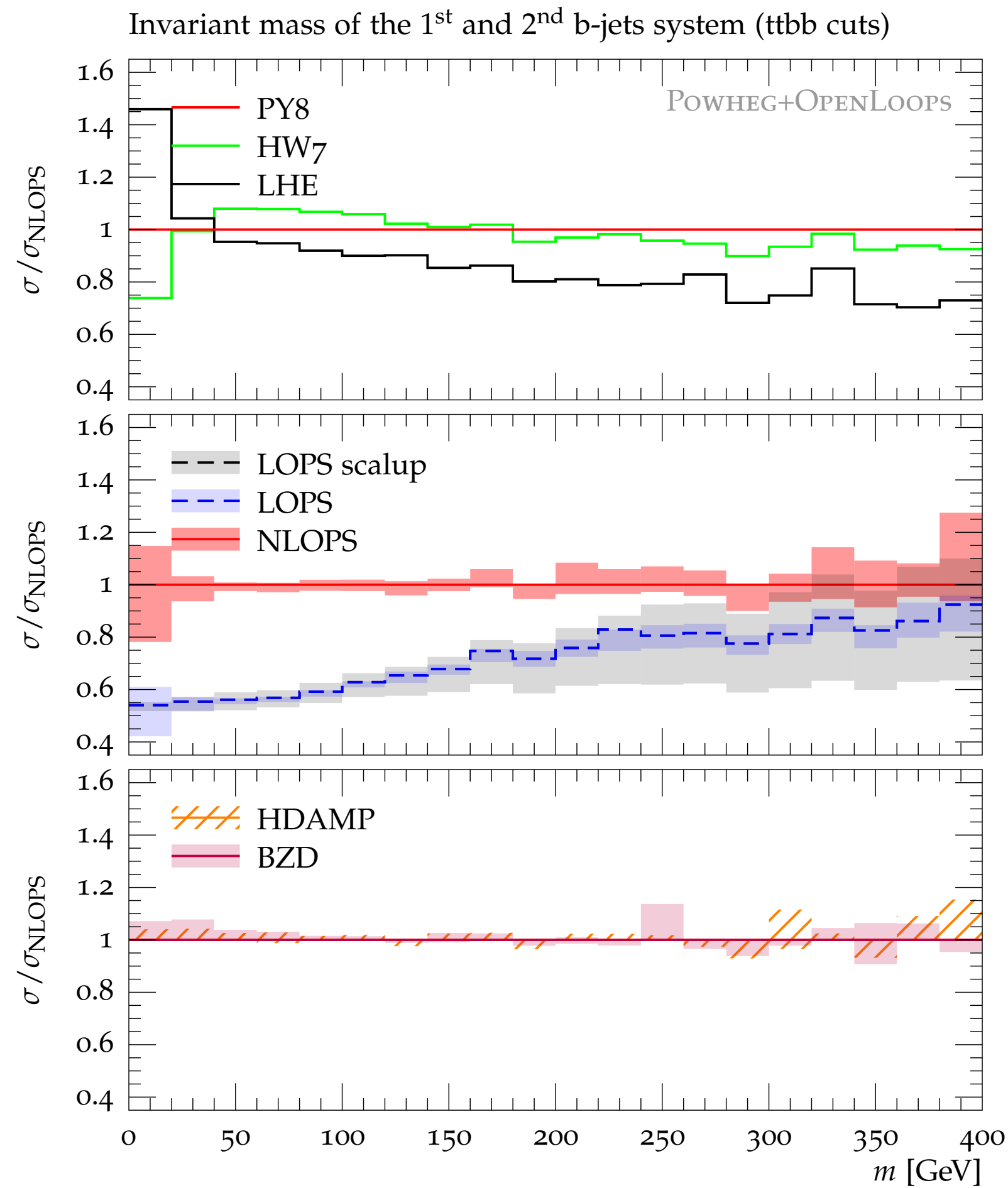
- ➔ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%
- ➔ However: notoriously difficult multi-scale problem:  $ET_t, ET_{\bar{t}}, ET_b, ET_{\bar{b}}$
- ➔ Large shower effects, in particular from double  $g \rightarrow b\bar{b}$  splittings
- ➔ Large systematic uncertainties from parton shower matching
- ➔ Careful study required to understand these systematics



➔ Sherpa vs. POWHEG+PY8 (both in 4-FS) in very good agreement

# Taming $t\bar{t}H$ backgrounds

[Jezo, JML, Moretti, Pozzorini; '18]



► Shower variations

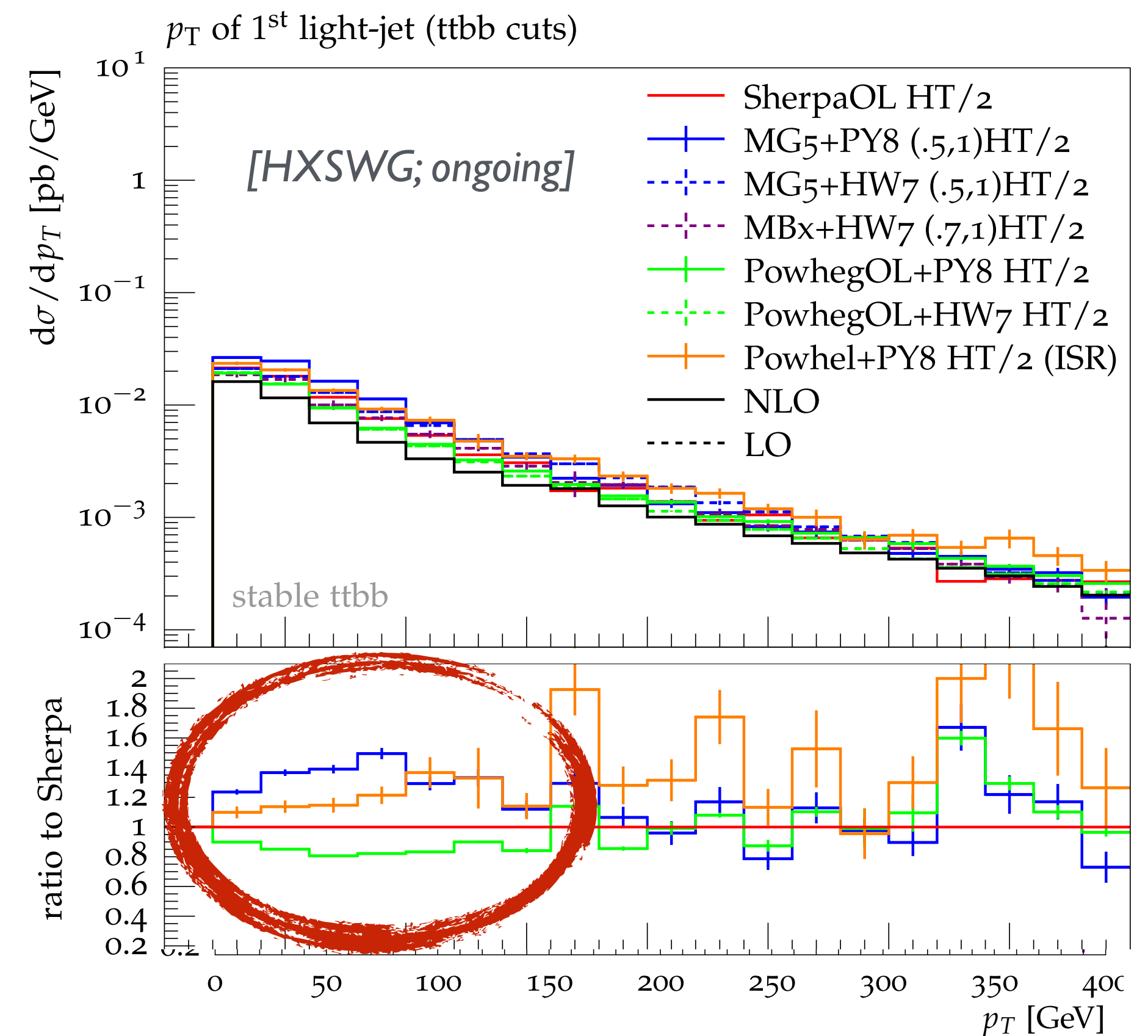
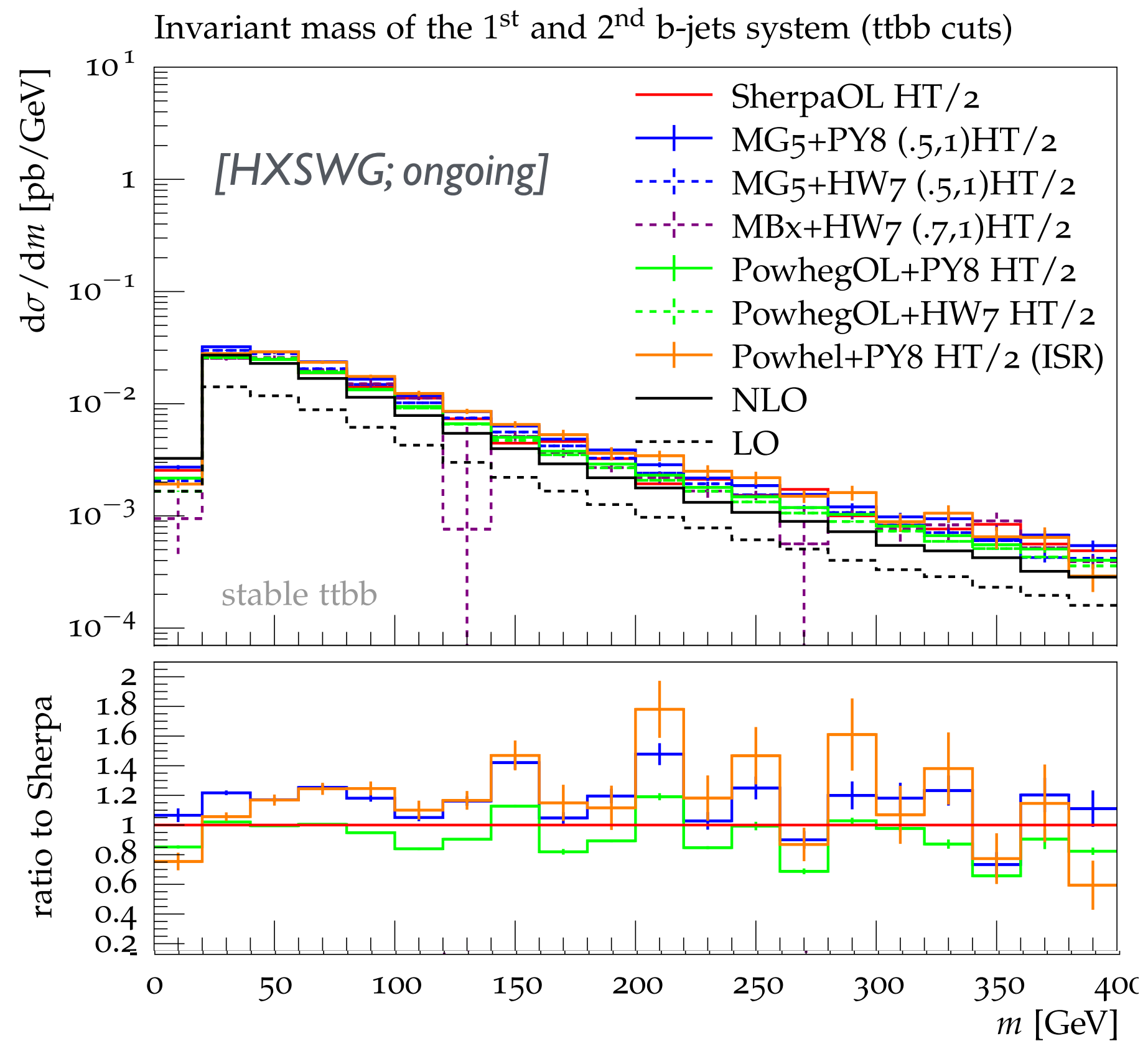
►  $\alpha_s$  &  $g \rightarrow b\bar{b}$  variations

► hdamp & bzd variations

$$g_{\text{soft}}(\Phi_{\text{rad}}, h_{\text{damp}}, h_{\text{bzd}}) = \frac{h_{\text{damp}}^2}{h_{\text{damp}}^2 + k_T^2} \theta\left(h_{\text{bzd}} B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) - R(\Phi_R)\right)$$

► Intrinsic shower systematics in POWHEG+PY8/HW7 under very good control

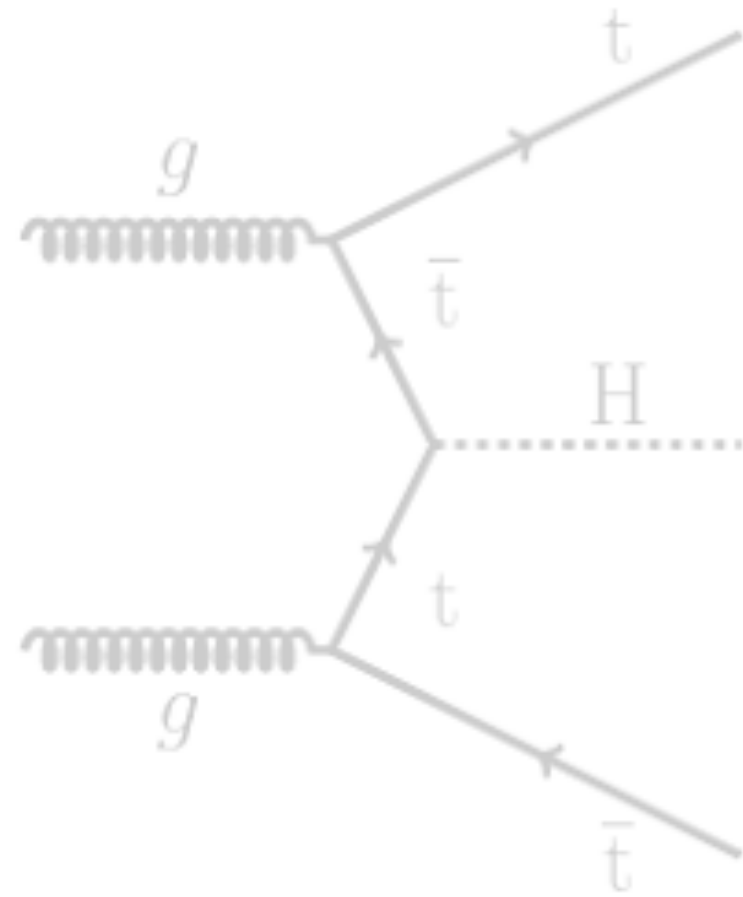
# Taming $t\bar{t}H$ backgrounds



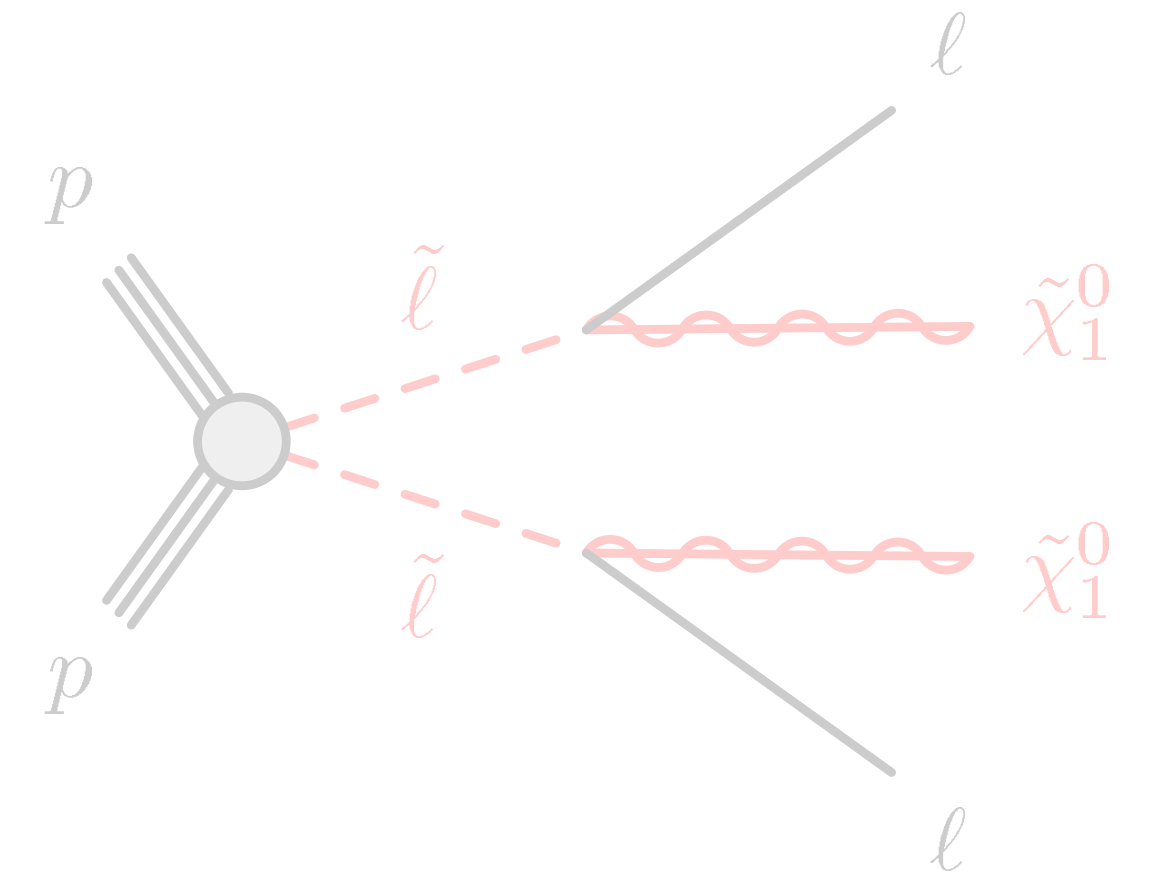
- ➔ Sizable differences between different generators: in particular in radiation/recoil spectrum
- ➔ hypothesis: distortion of jet-spectrum due to **large local K-factor** and **different S/H separation**
- ➔ Careful look inside the NLO+PS black-boxes necessary: ongoing within HXS WG!

A few examples where theory precision is crucial:

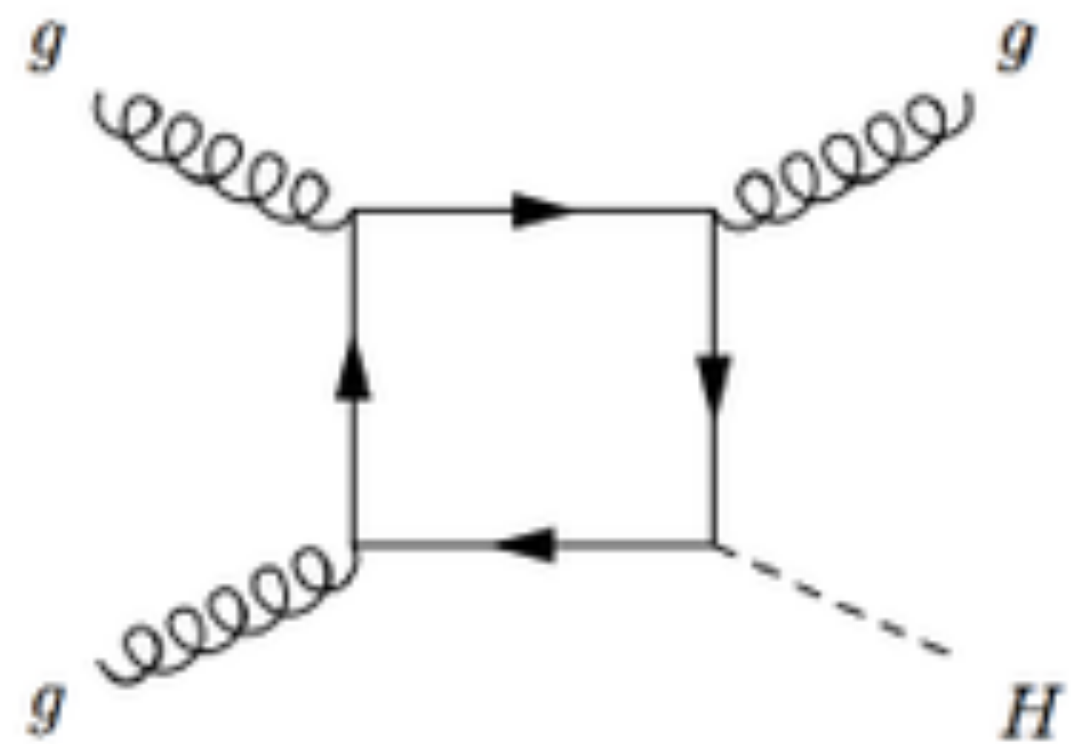
ttH



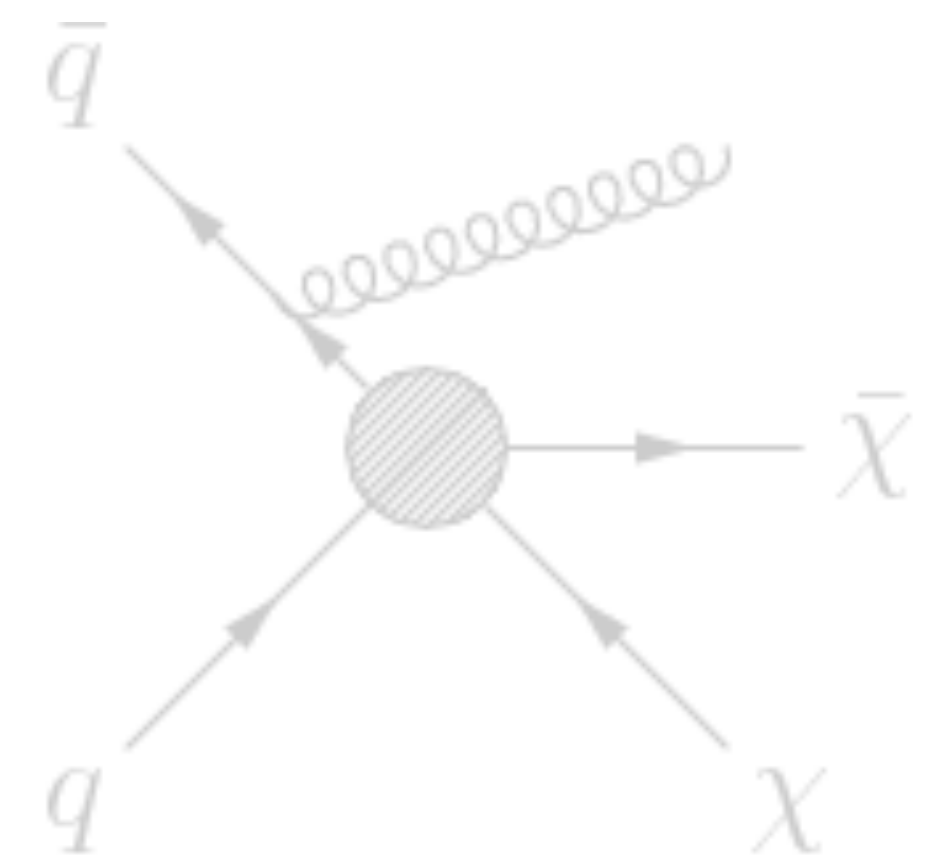
EW SUSY searches



Higgs-pT



Dark Matter searches



# Higgs-pT: two regimes

$p_{\perp} \ll m_t$

$p_{\perp} > m_t$

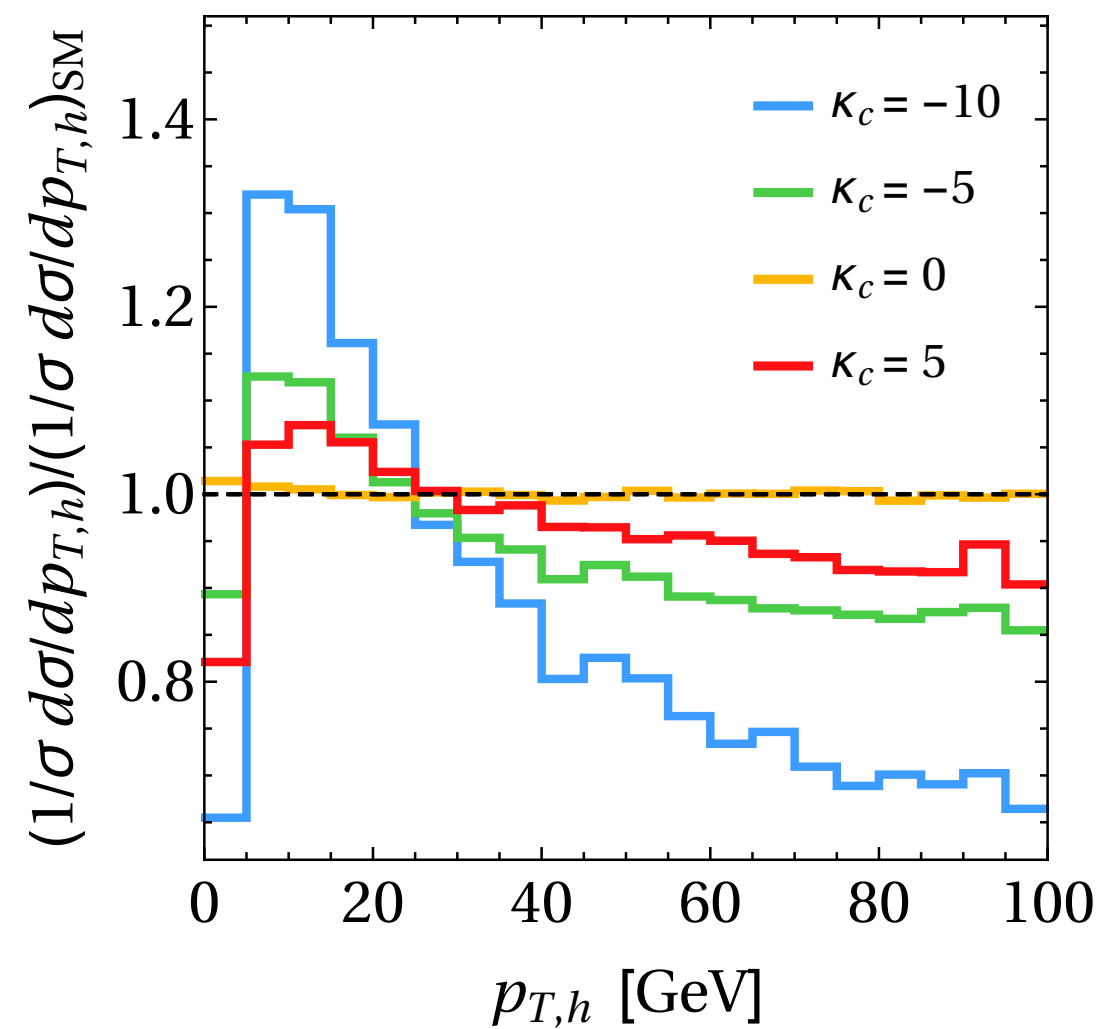
Possibility to constrain the charm-Yukawa coupling

$$d\sigma/dp_{\perp} \propto y_t^2 + y_t y_b + y_b^2 + y_t y_c + \dots$$

for  $p_T \ll m_H$ :  $\sim 10\%$      $\sim 1\%$      $\ll 1\%$

$$A_{gg \rightarrow Hg}^Q \sim m_Q^2/m_H^2 \log^2(p_{\perp}^2/m_Q^2)$$

→ Sudakov-like logarithmic enhancement of light-quark contribution at small pT



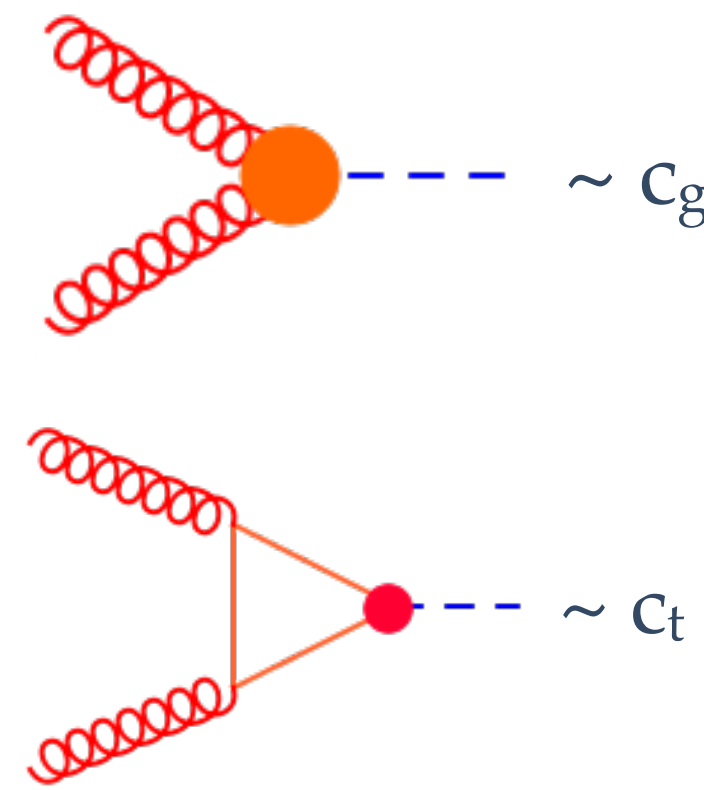
[Bishara, Haisch, Monni, Re; '16]

Sensitive probe of New Physics

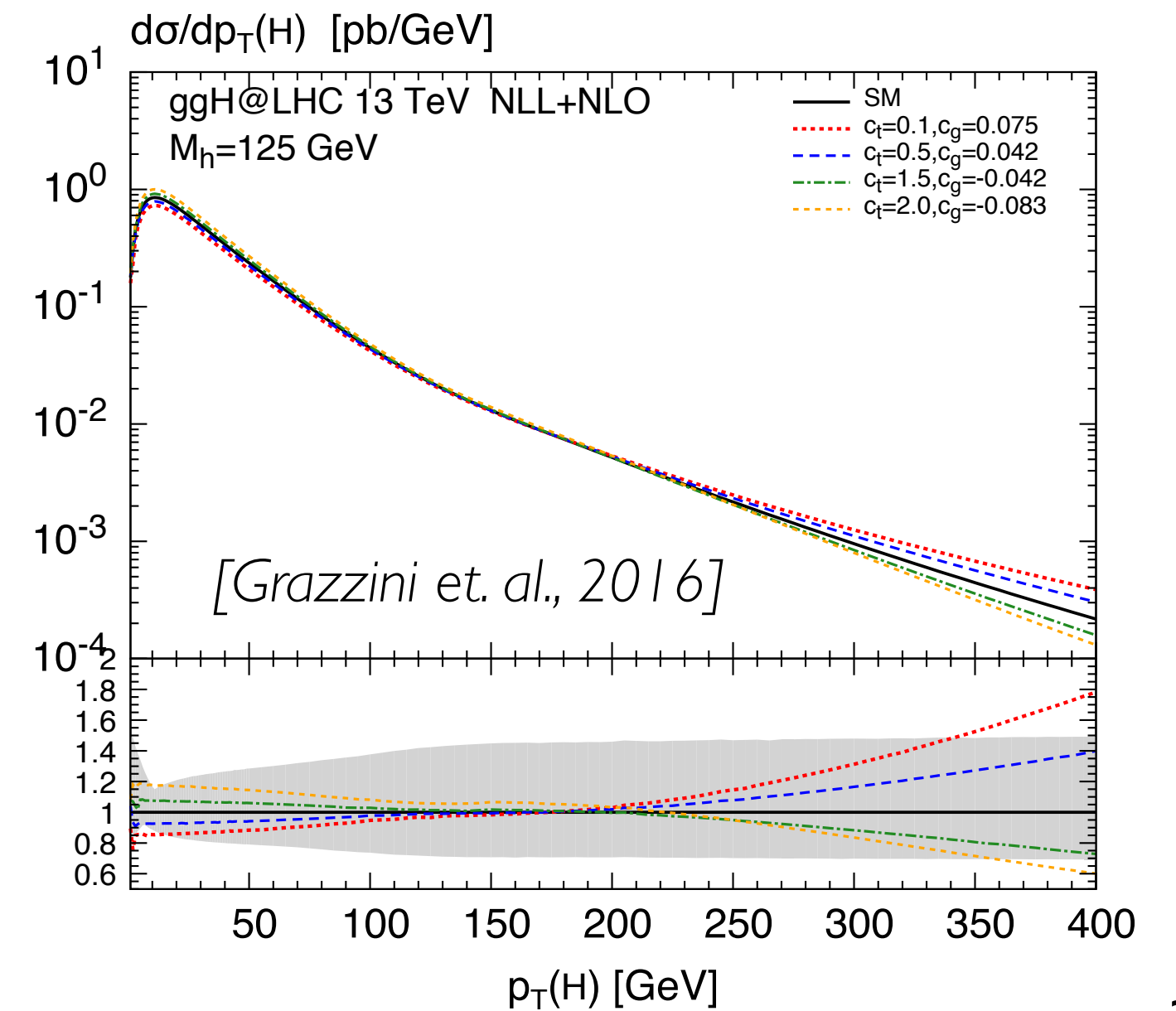
→ In particular: disentangle  $c_g$  vs.  $c_t$ :

$$\frac{d\sigma_H}{dp_{\perp}^2} \sim \frac{\sigma_0}{p_{\perp}^2} \begin{cases} (c_g + c_t)^2, & p_{\perp}^2 < 4m_t^2, \\ \left(c_g + c_t \frac{4m_t^2}{p_{\perp}^2}\right)^2, & p_{\perp}^2 > 4m_t^2. \end{cases}$$

Note: inclusive measurements only allow to constrain  $(c_g + c_t)^2$



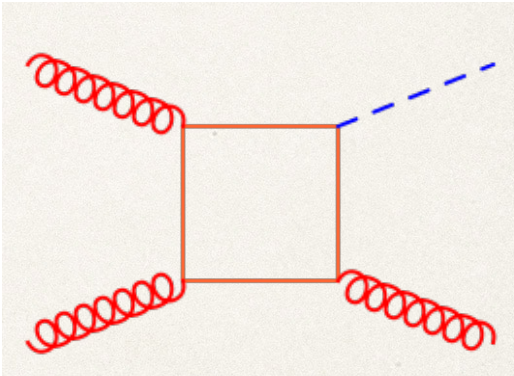
SM:  $c_g=0, c_t=1$



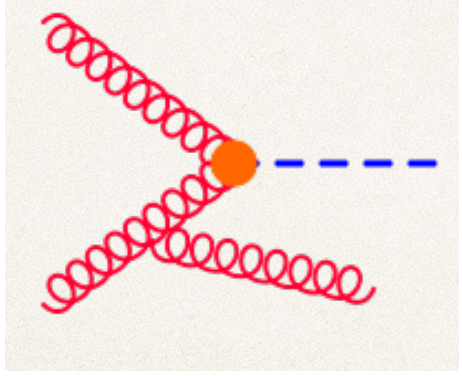


# Higgs-pT: higher-order corrections

full theory: loop-induced

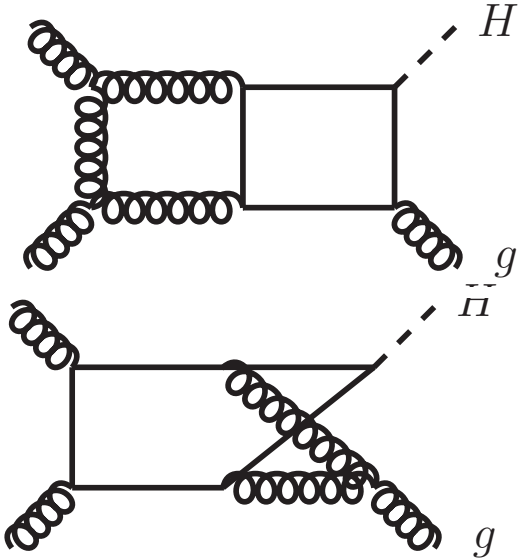


integrate-out  
heavy quarks



HEFT: tree-level at LO

Bottleneck:  
massive two-loop amplitudes



NLO

NNLO

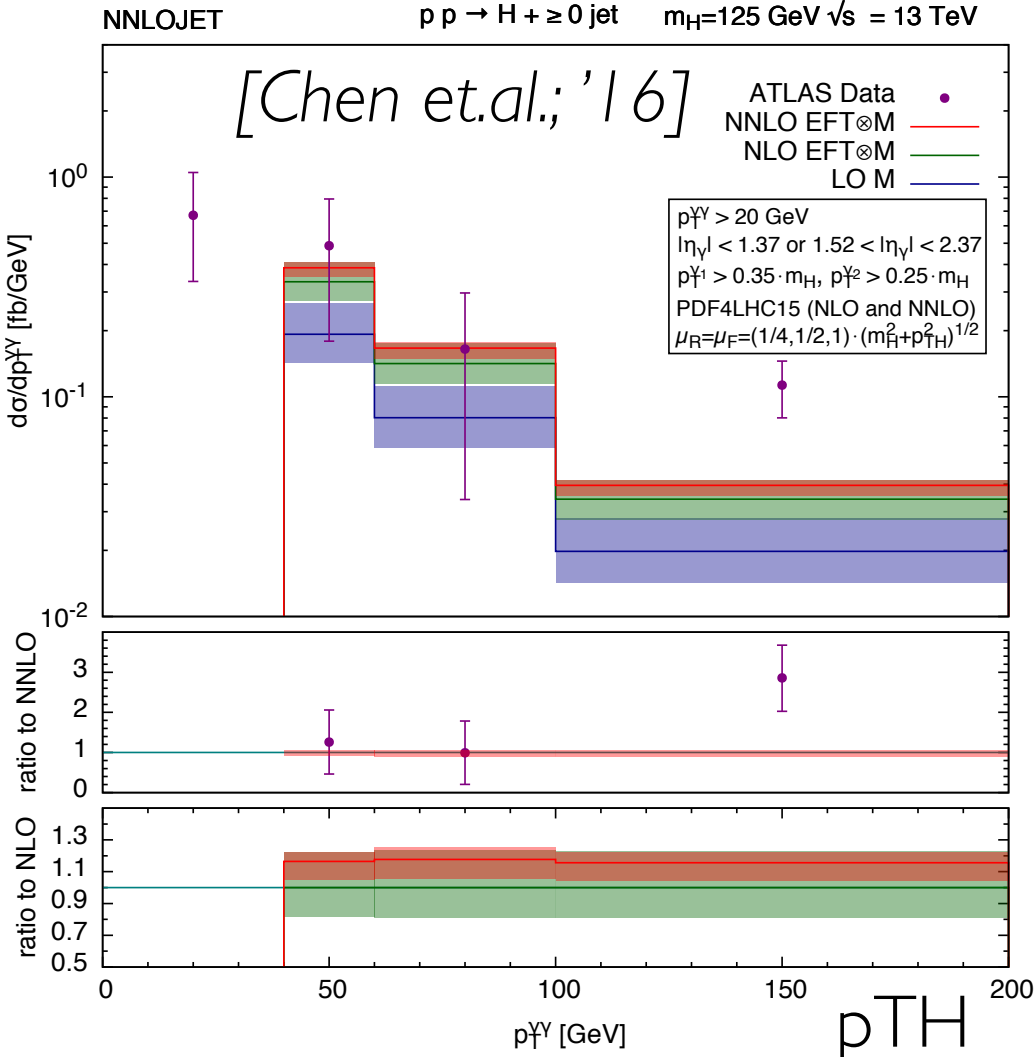
[Chen et.al.; '14+'16  
Boughezal et. al.; '15,  
Caola et.al.; '15]

Ansätze:

- analytical: very hard, planar MI known [Bonciani et. al., '16]
- numerical: very CPU/GPU intensive [Jones et. al., '18]
- expansions: has to be performed carefully, very versatile [Melnikov et. al., '16+'17]

Idea: QCD corrections factorize  
 → apply K-factors from HEFT to lower order predictions in full theory  
 → check!!

Bottleneck: IR subtraction

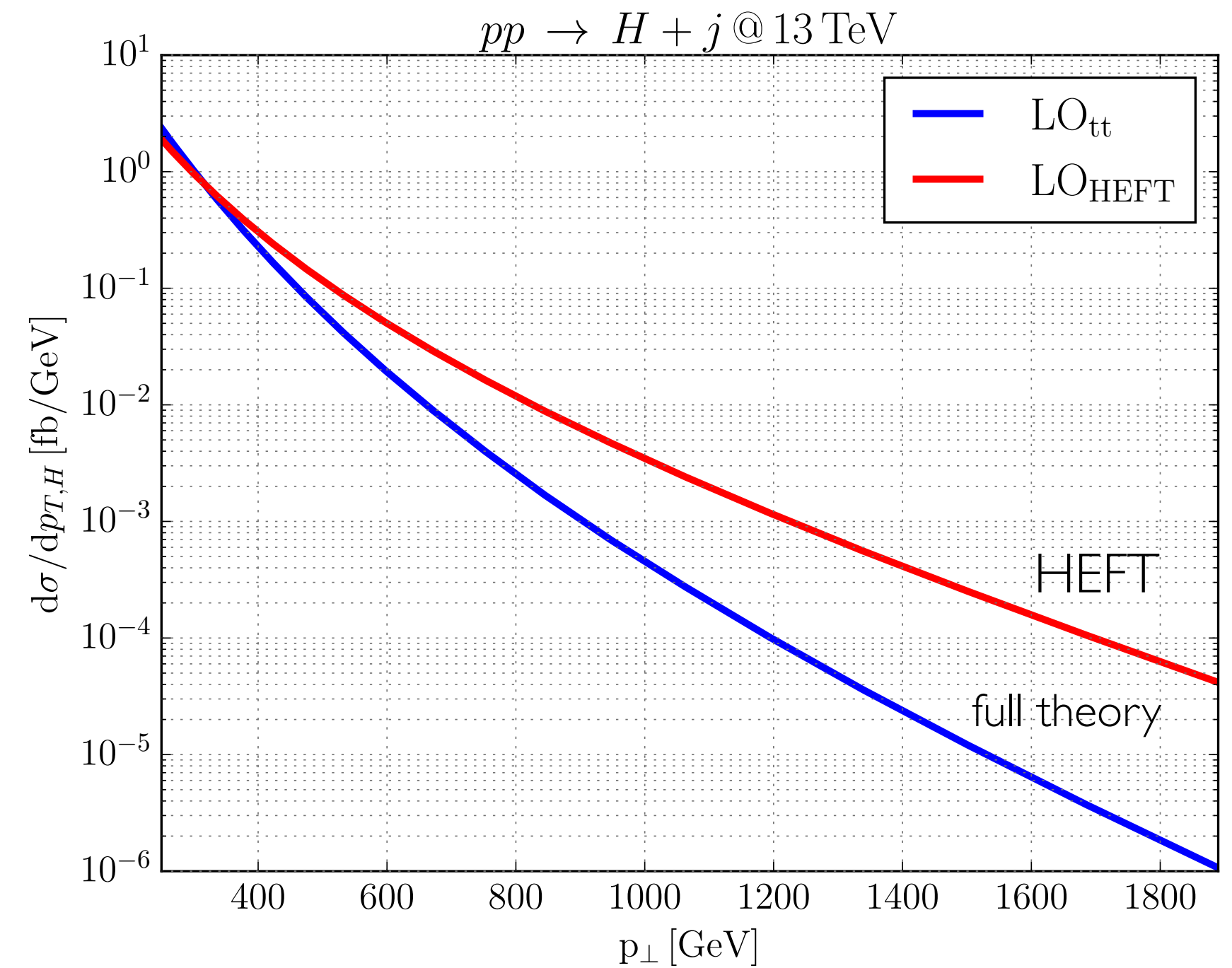
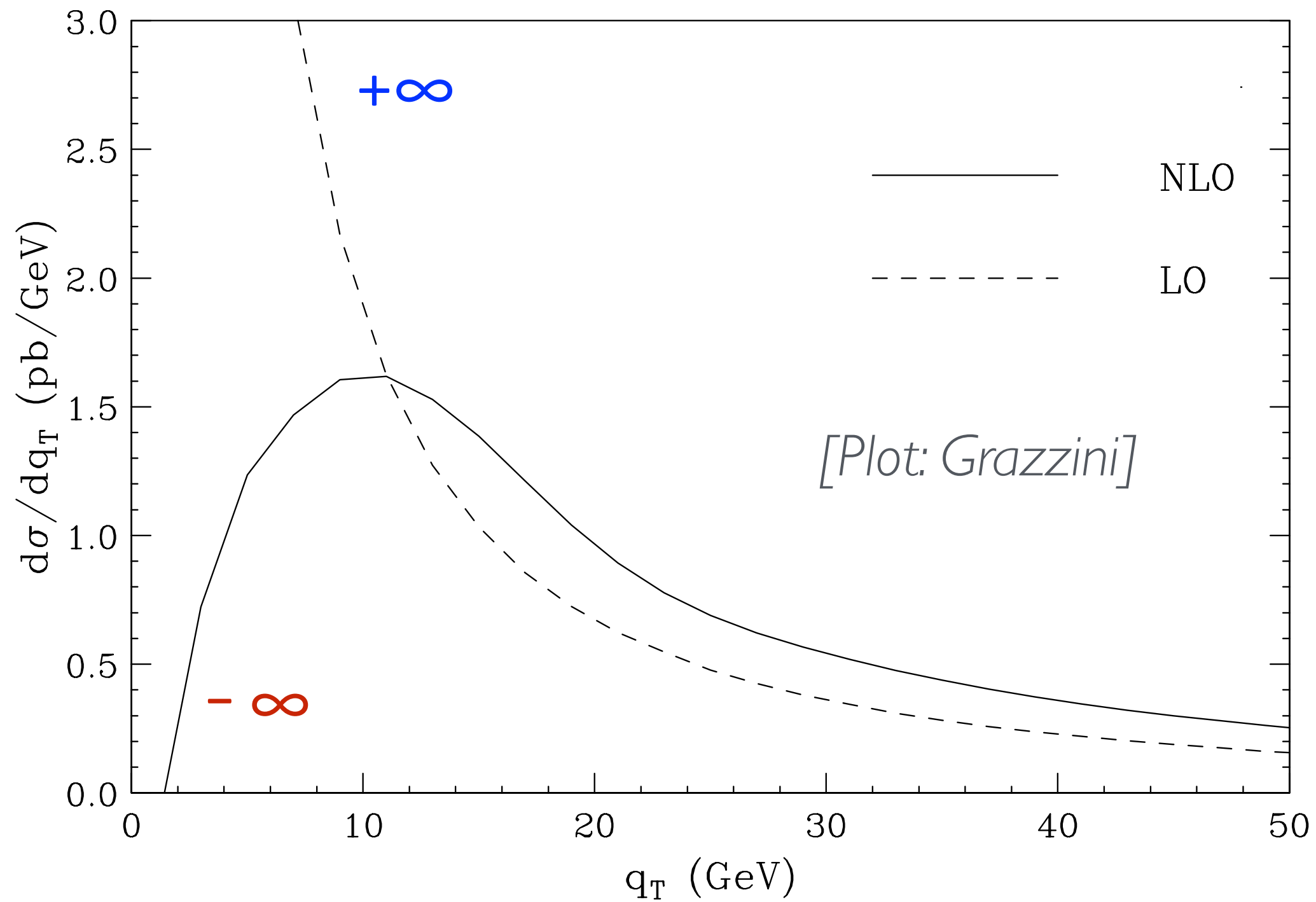


perturb. uncertainties in HEFT  
 under very good control:  
 ▶ ~10% scale variation  
 ▶ stable shapes

# Higgs- $p_T$ : two regimes

$p_{\perp} \ll m_t$

$p_{\perp} > m_t$



$$\sim p_T^{-2}$$

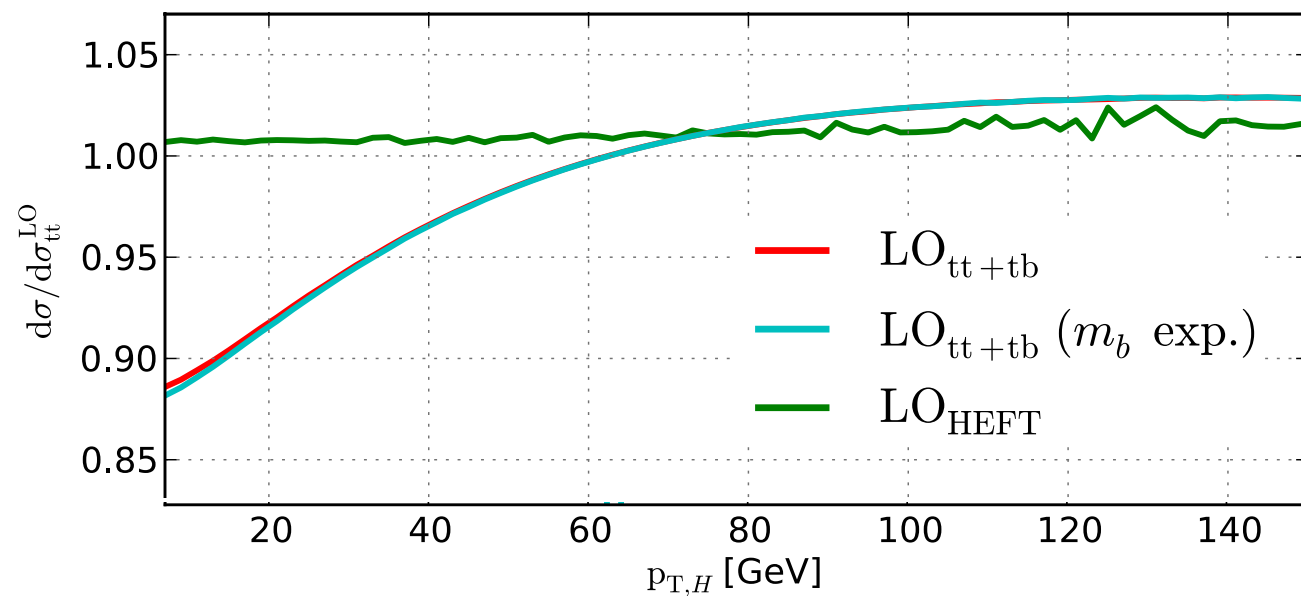
$$\sim p_T^{-4}$$

- Fixed-order breaks down at low  $p_T$
- ➔ Resummation mandatory

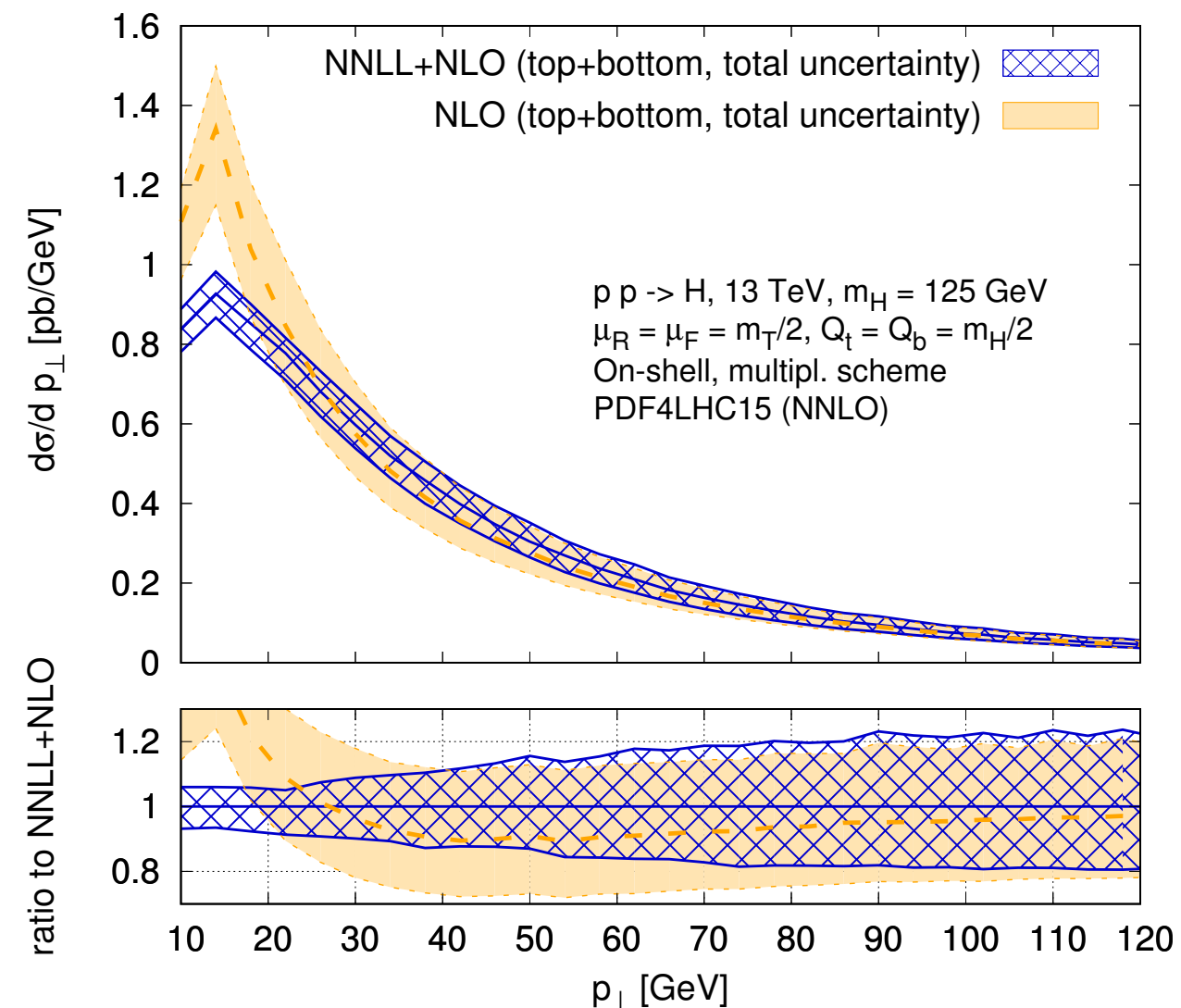
- point-like ggH (HEFT) and full theory have very different high energy behaviour.

# $p_{\perp} \ll m_t$ : bottom mass effects at NLO+NNLL

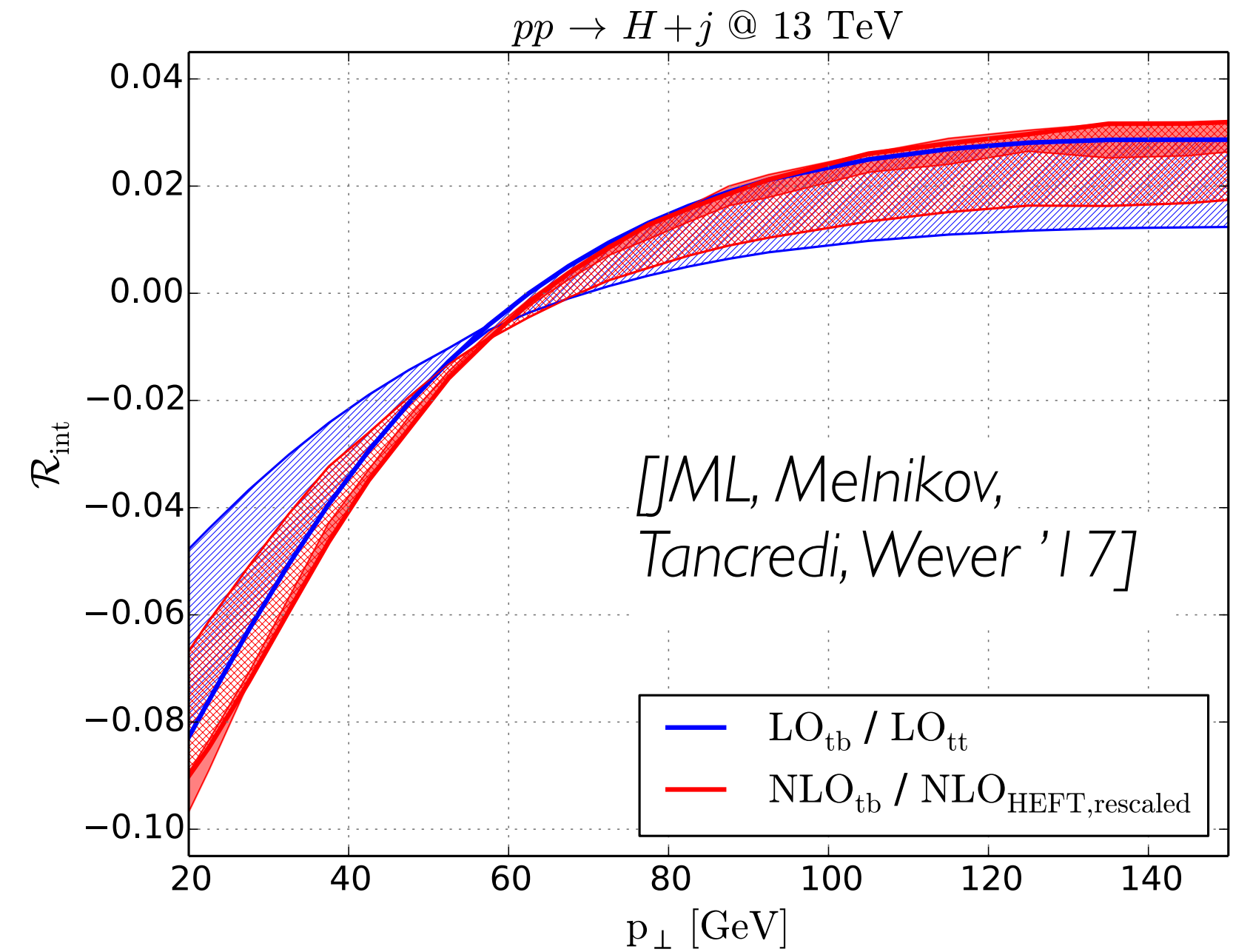
- expansion of the two-loop integrals in  $(m_b^2/p_T^2)$  [Melnikov, Tancredi, Wever; '16+'17]
- valid at %-level down to  $p_T \sim 10$  GeV
- real radiation treated exact with **OpenLoops**



[Caola, JML, Melnikov, Monni, Tancredi, Wever '17]



- uncertainties at the level of 5-20%
- further improvement when combined with NNLO for  $yt^2$



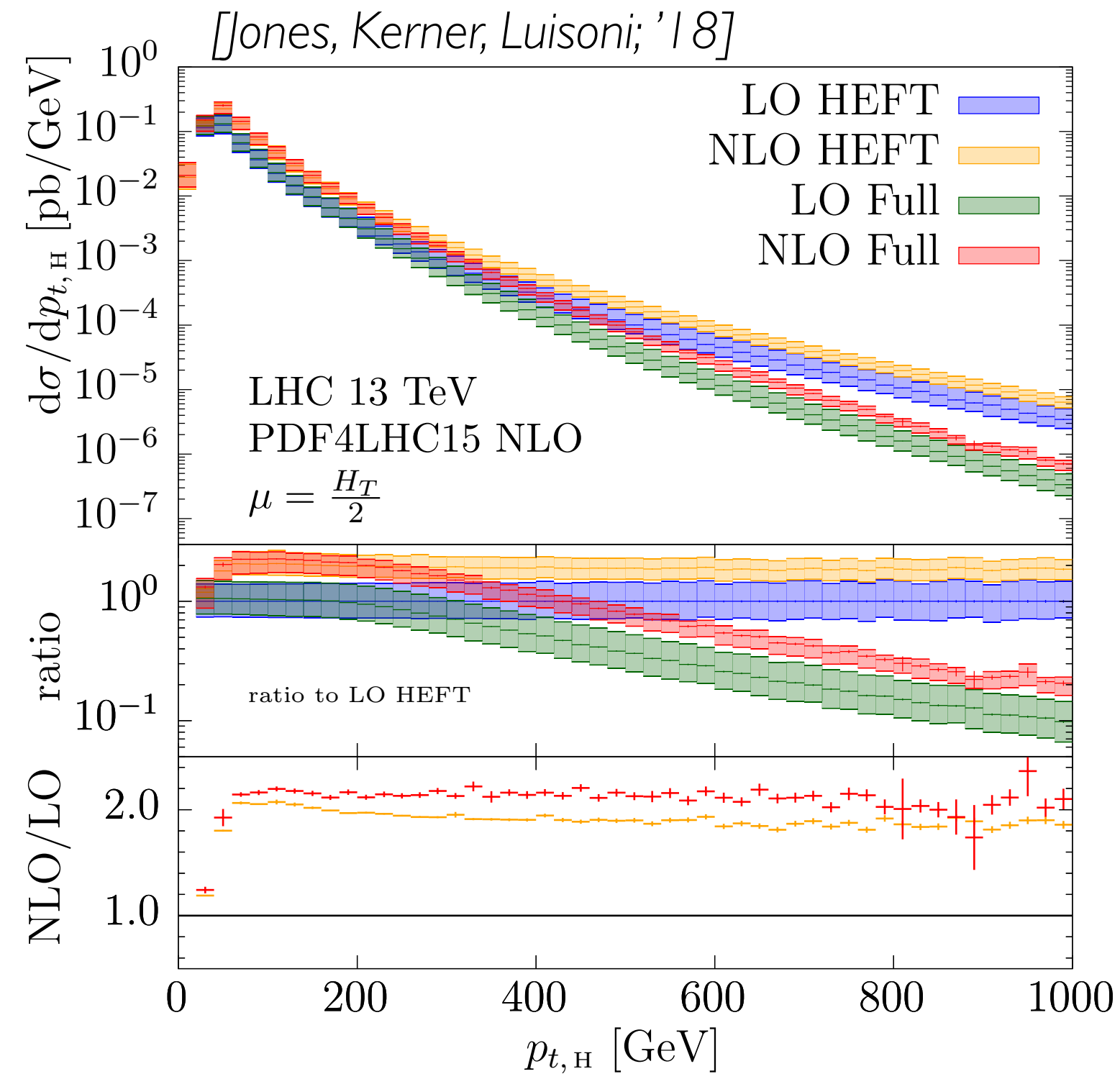
[JML, Melnikov, Tancredi, Wever '17]

- -(5-10)% for  $p_T=20-40$  GeV at LO and NLO
- Despite (large) corrections, the interference shape stable under QCD corrections
- **large mb-renormalisation scheme dependence tamed at NLO**

resum!

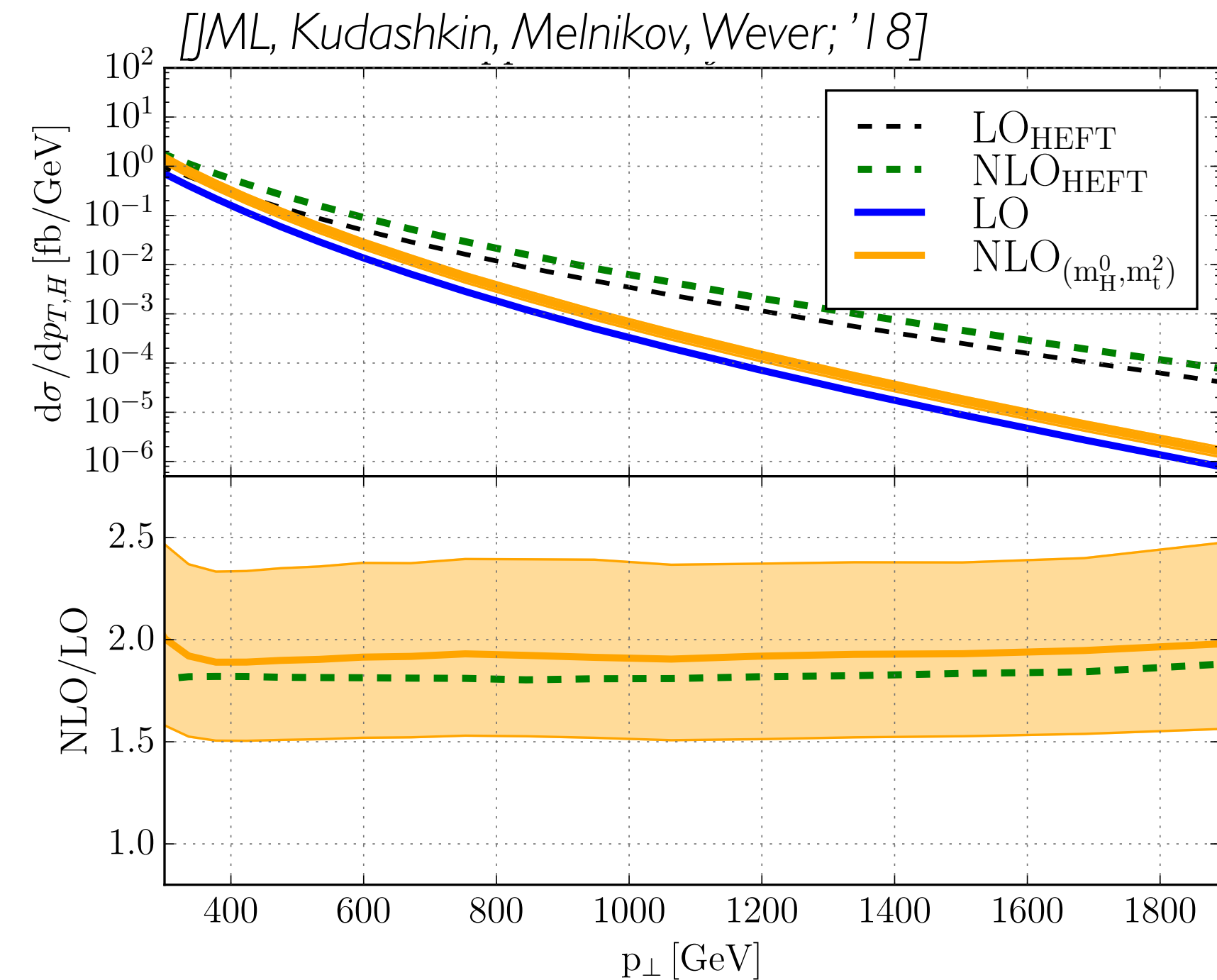
# $p_{\perp} > m_t$ : top mass effects at NLO

- numerical integration of two-loop integrals based on **SecDec** [Borowka et.al.]
- valid in all of the phase-space



- NLO corrections very similar as in HEFT:  $K \sim 2$  with remaining scale uncertainties  $\sim 20-25\%$
- hardly any shape dependence

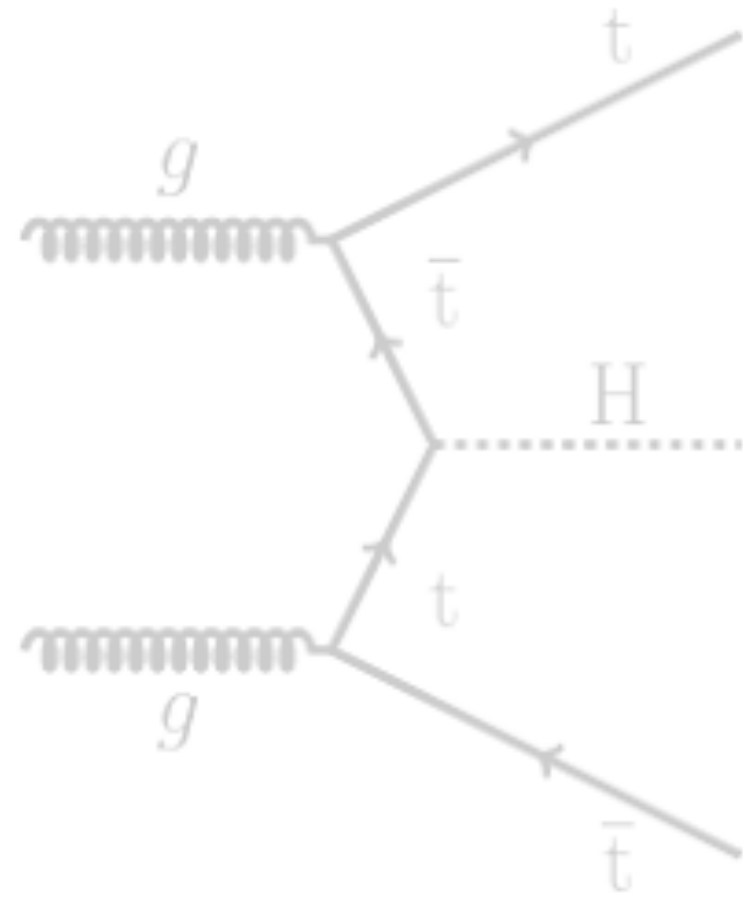
- expansion of the two-loop integrals up to  $(m_t^2/p_T^2)^1$ ,  $(m_H^2/p_T^2)^0$  at the level of the DE [Kudashkin, Melnikov, Wever; '17]
- valid at %-level for large  $p_T$



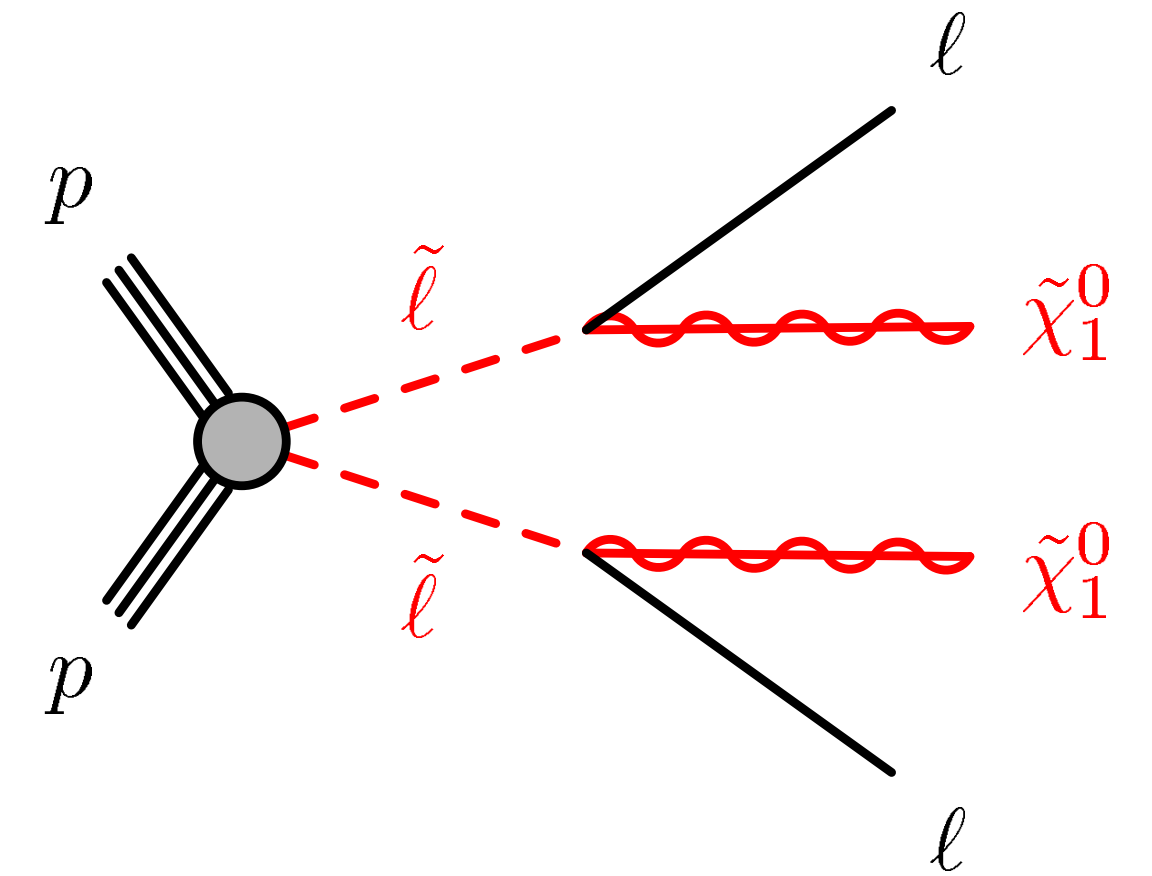
→ Control of the high- $H$ - $p_T$  tail at NLO opens the door for new physics searches in this regime!

A few examples where theory precision is crucial:

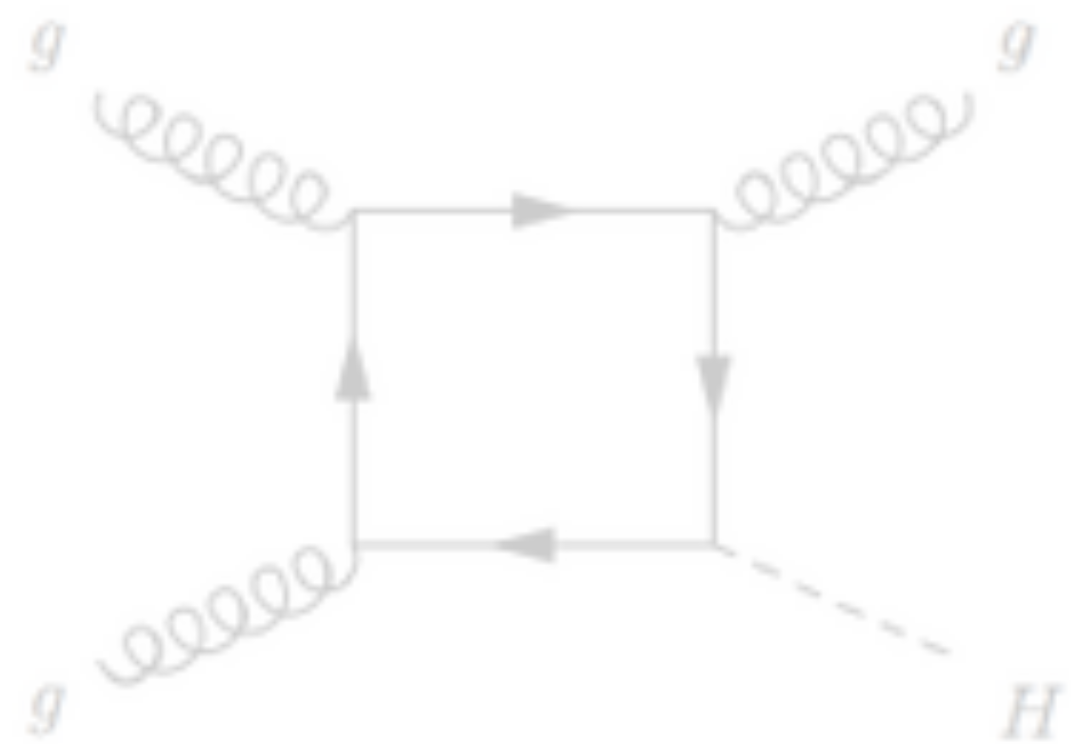
ttH



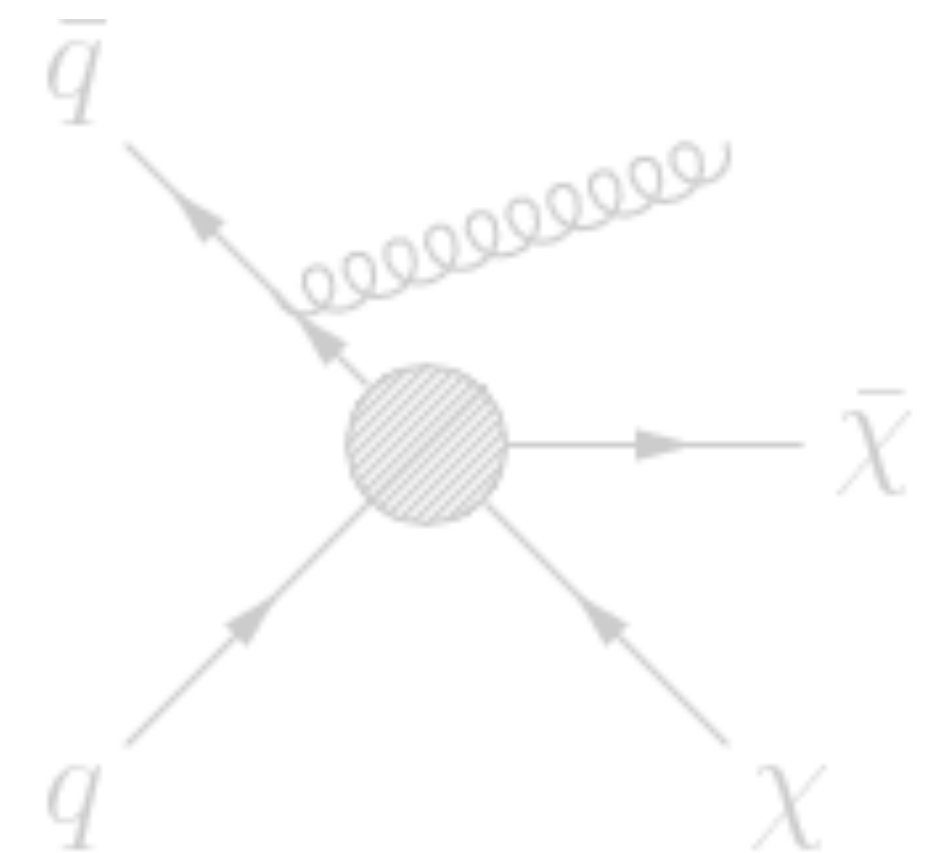
EW SUSY searches



Higgs-pT

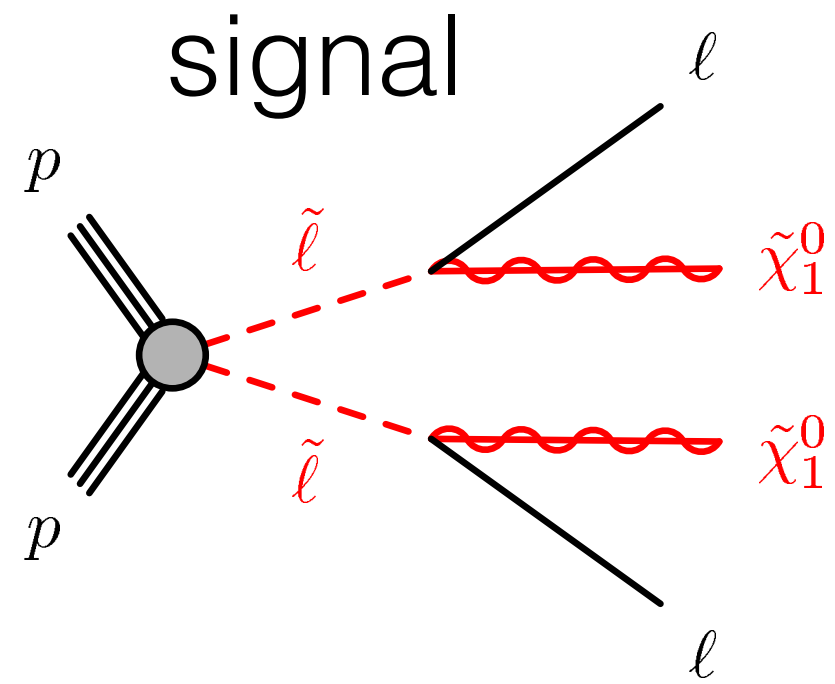


Dark Matter searches

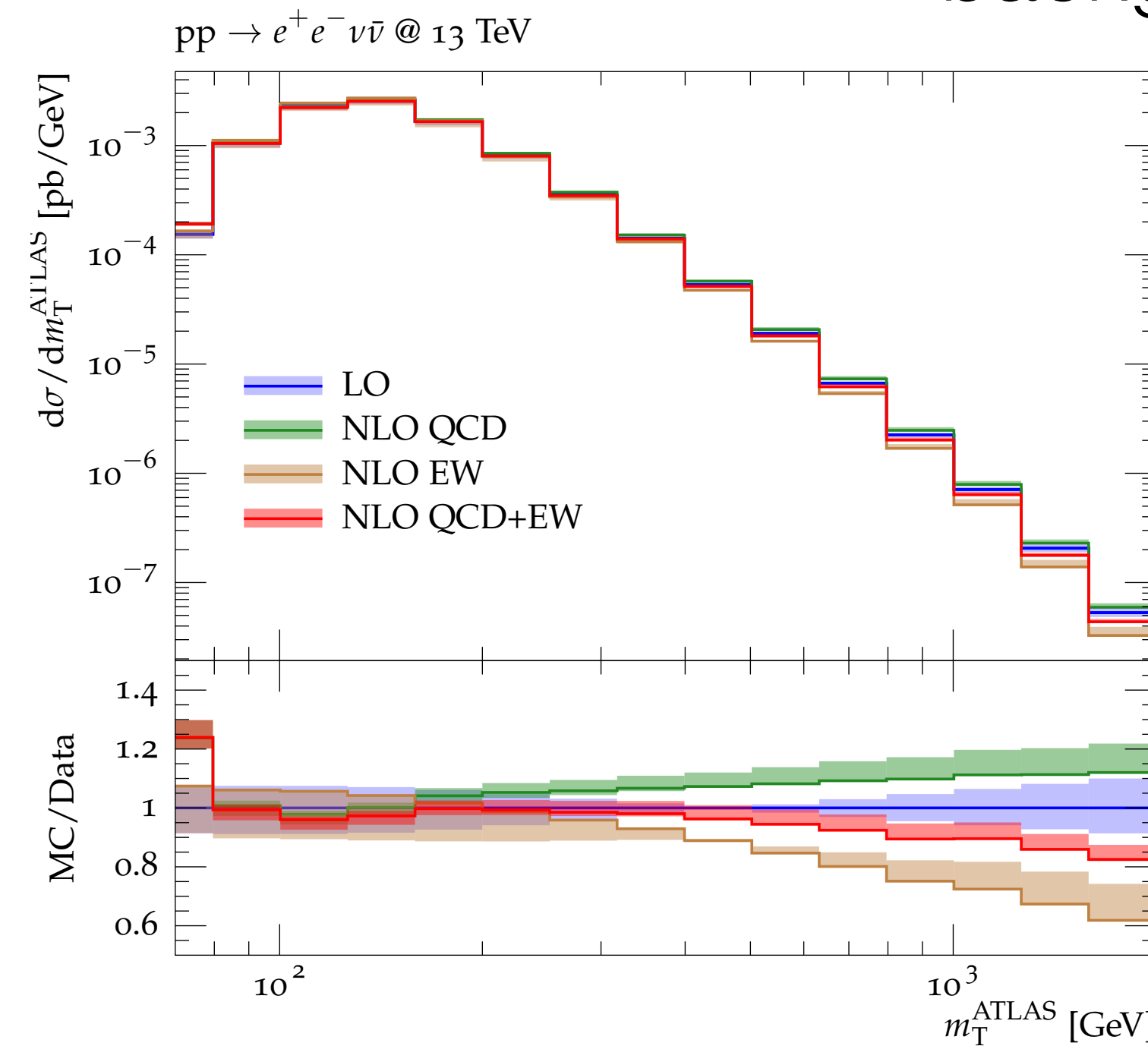
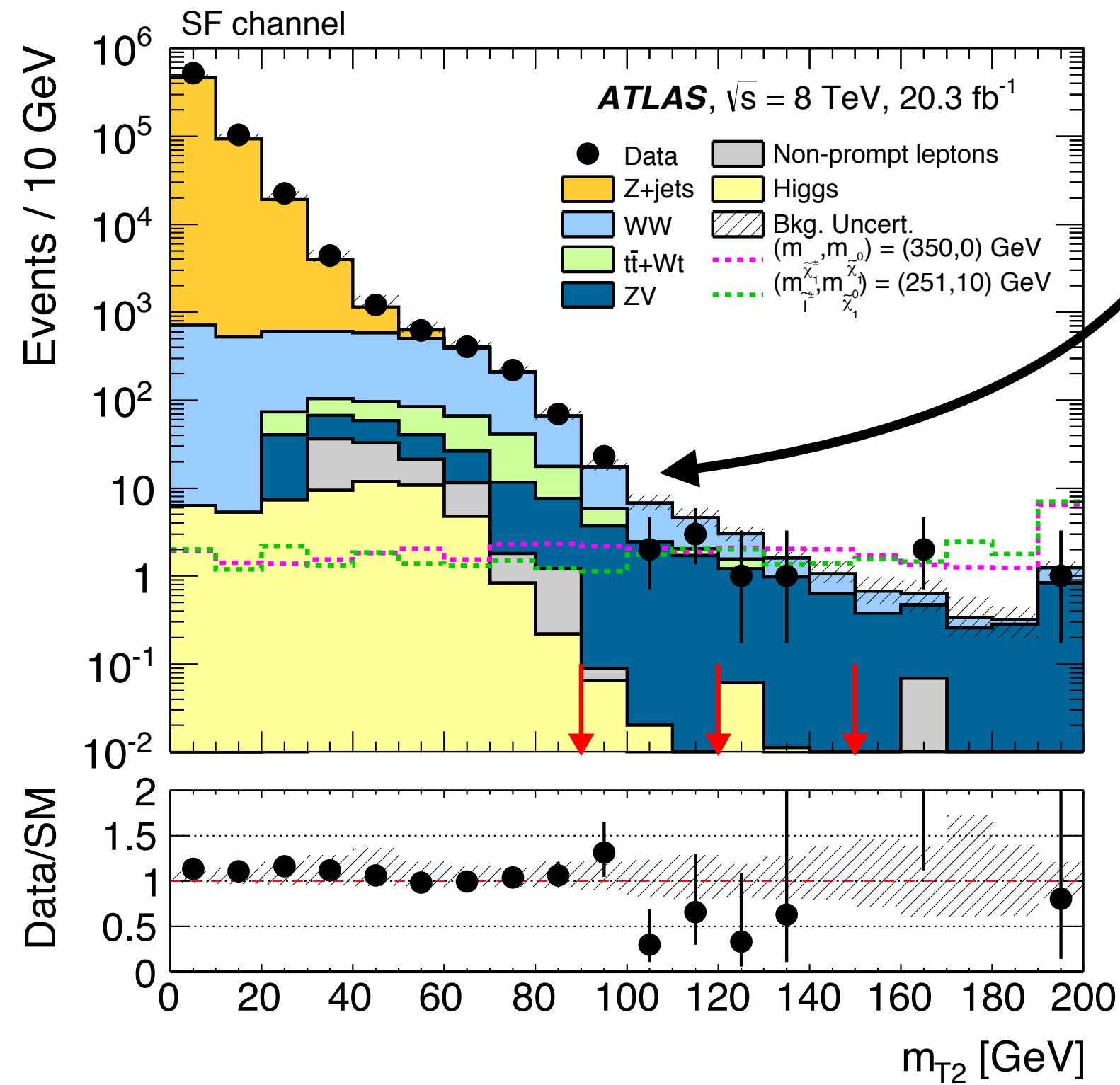
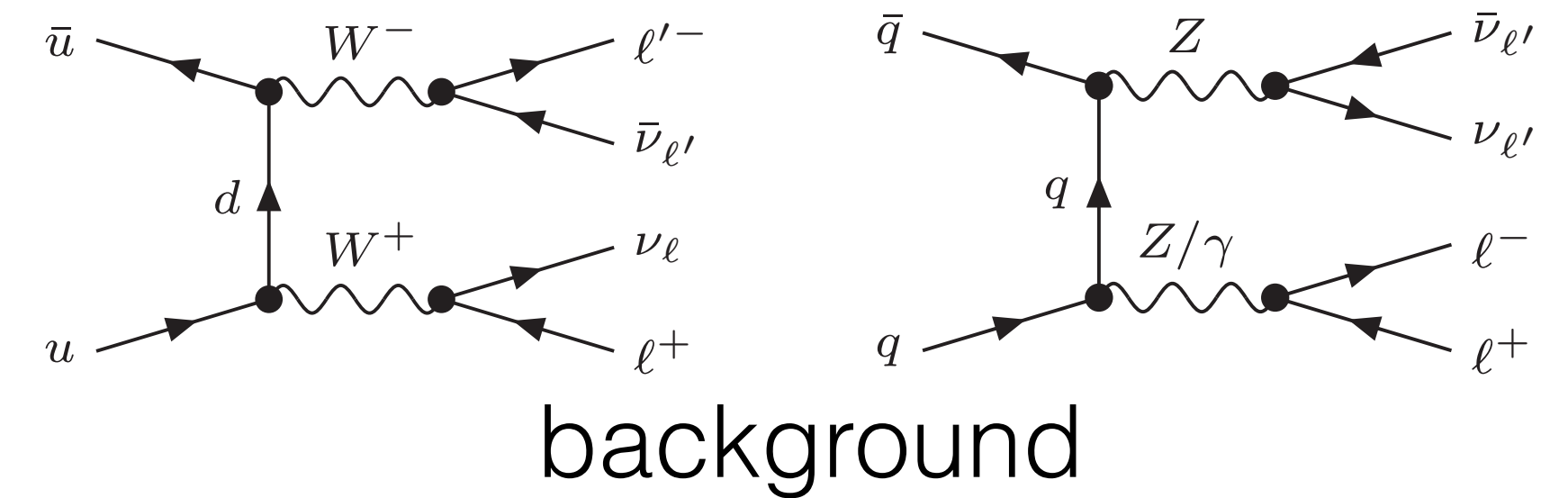


# off-shell vector-boson pair production at NLO QCD+EW

[Kallweit, JML, Pozzorini, Schönherr; '17]

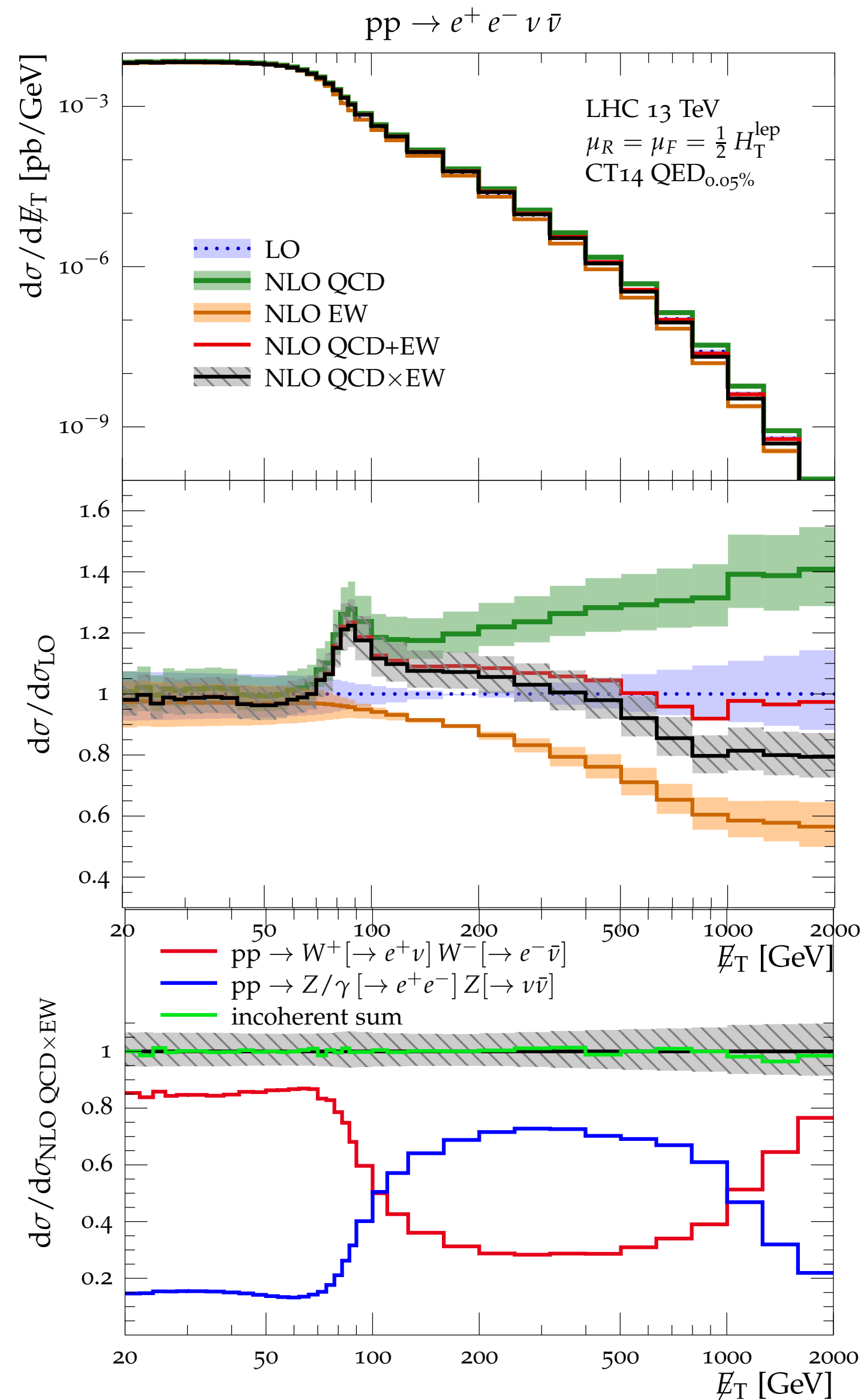


Direct Slepton pair production  
Signature: **2 OS-SF leptons + MET**  
Background:  $W^+W^-/ZZ \rightarrow 2l2\nu$



- EW corrections: -10(-20)% for  $m_{T2}=200-300 \text{ GeV}$  (1 TeV)
- important to include in the future to avoid fake signals
- also crucial as  $H \rightarrow W^+W^-$  background!

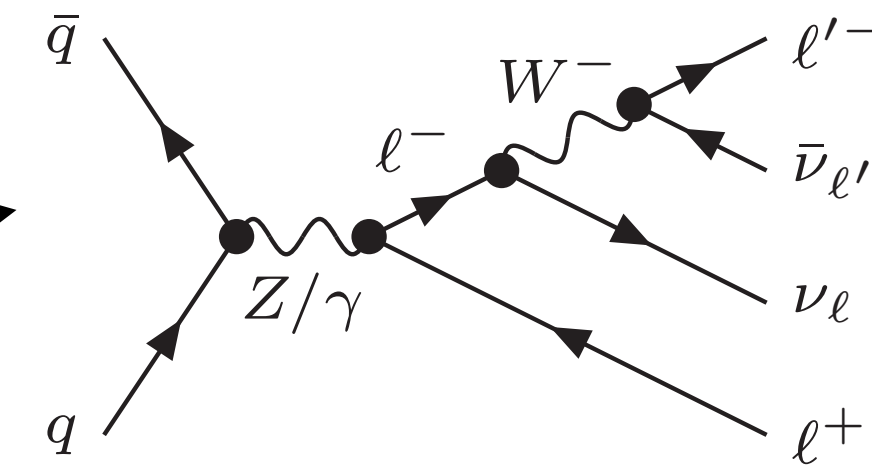
# off-shell vector-boson pair production at NLO QCD+EW



Effect of EW corrections strongly depends on the observable.

MET

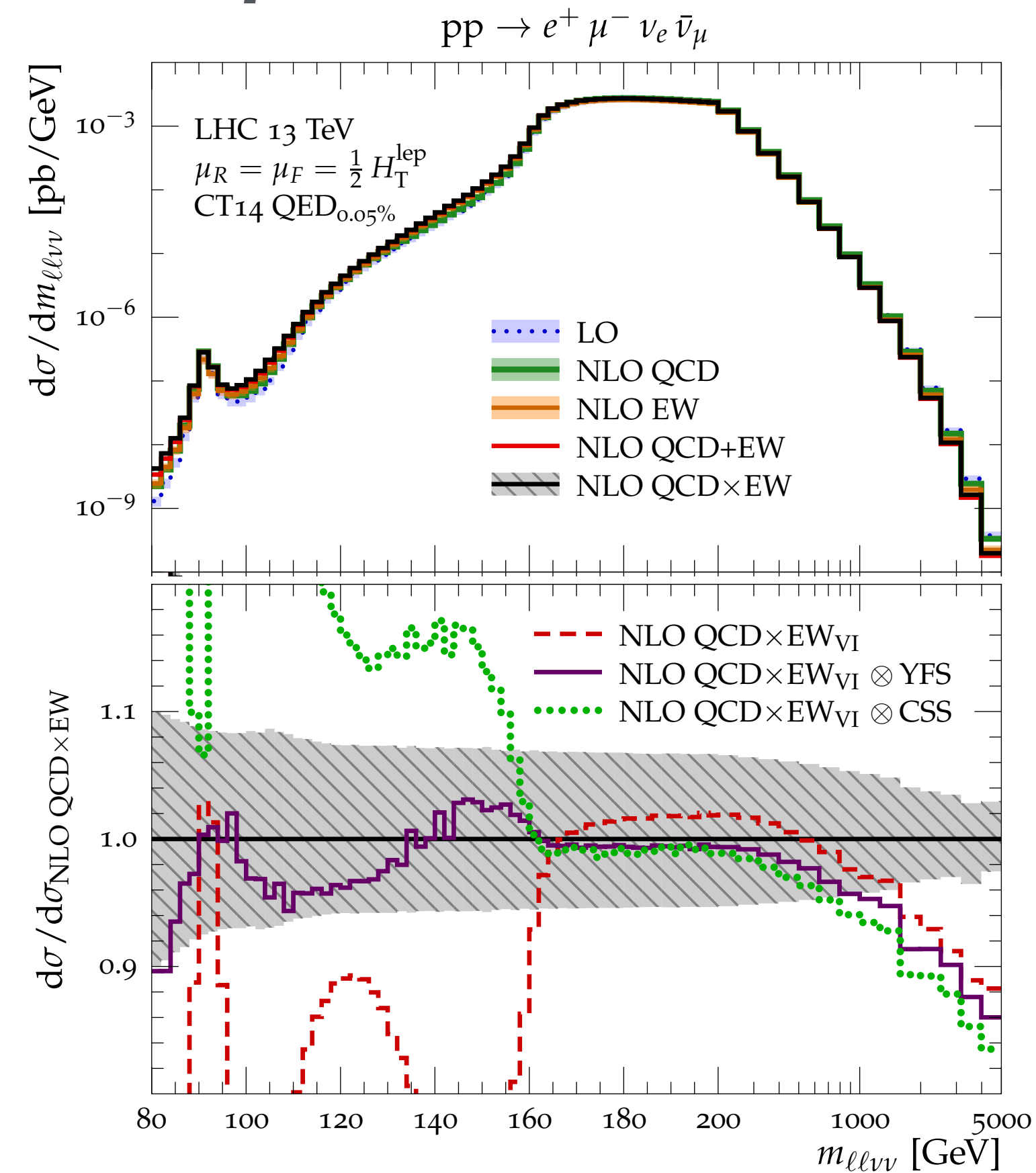
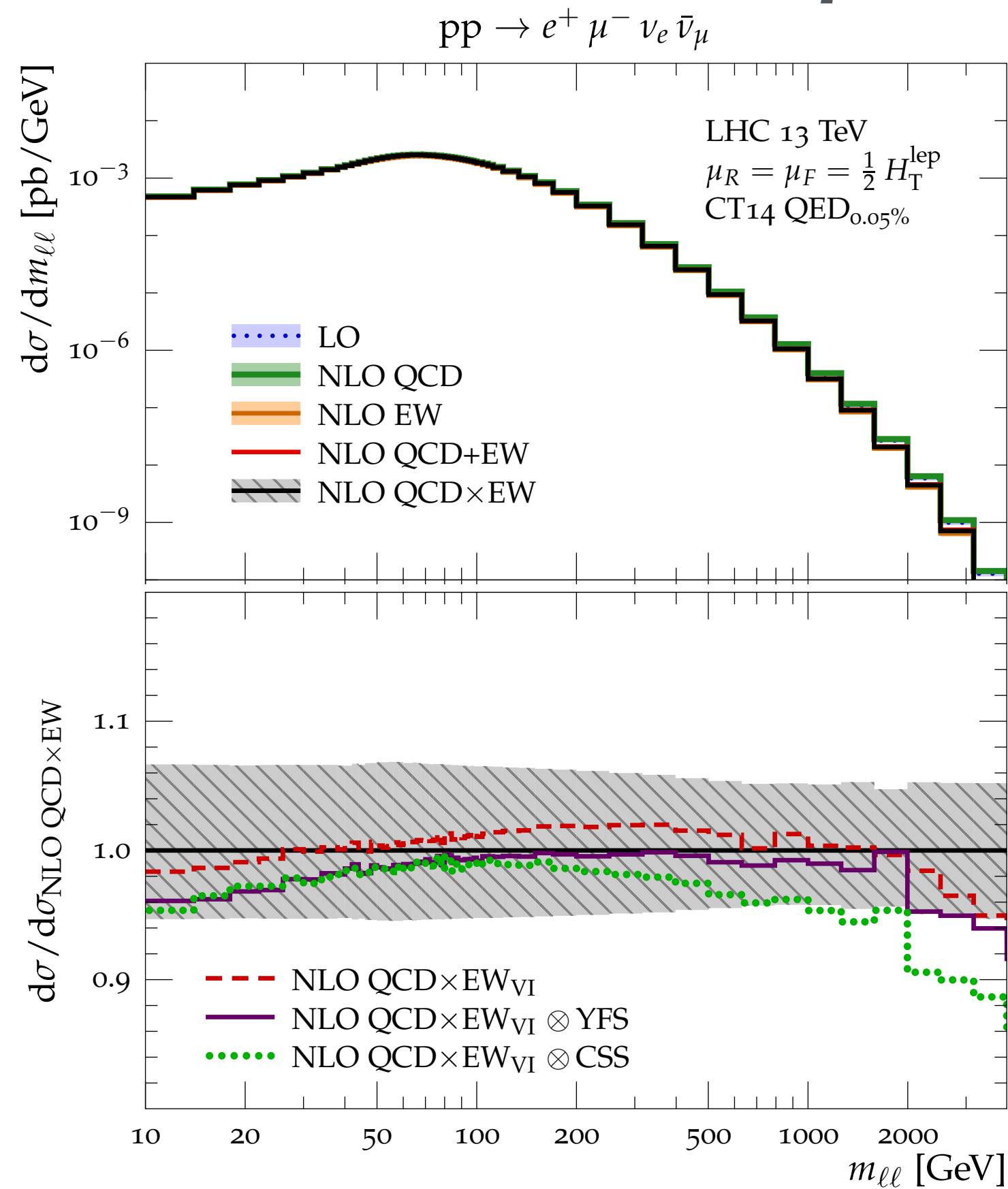
- ▶ at large MET > M<sub>W</sub>:  
W's are forced off-shell



- ▶ jump in QCD corrections  
(extra jet unlocks back-to-back configuration)
- ▶ very large EW corrections: up to 50% (WW/ZZ dependent!)
- ▶ WW-ZZ interference very suppressed (as expected from LO)

# off-shell vector-boson pair production at NLO QCD+EW

[Kallweit, JML, Pozzorini, Schönherr; '17]



Naive NLO EW+PS matching in Sherpa+OpenLoops (applicable at particle level)

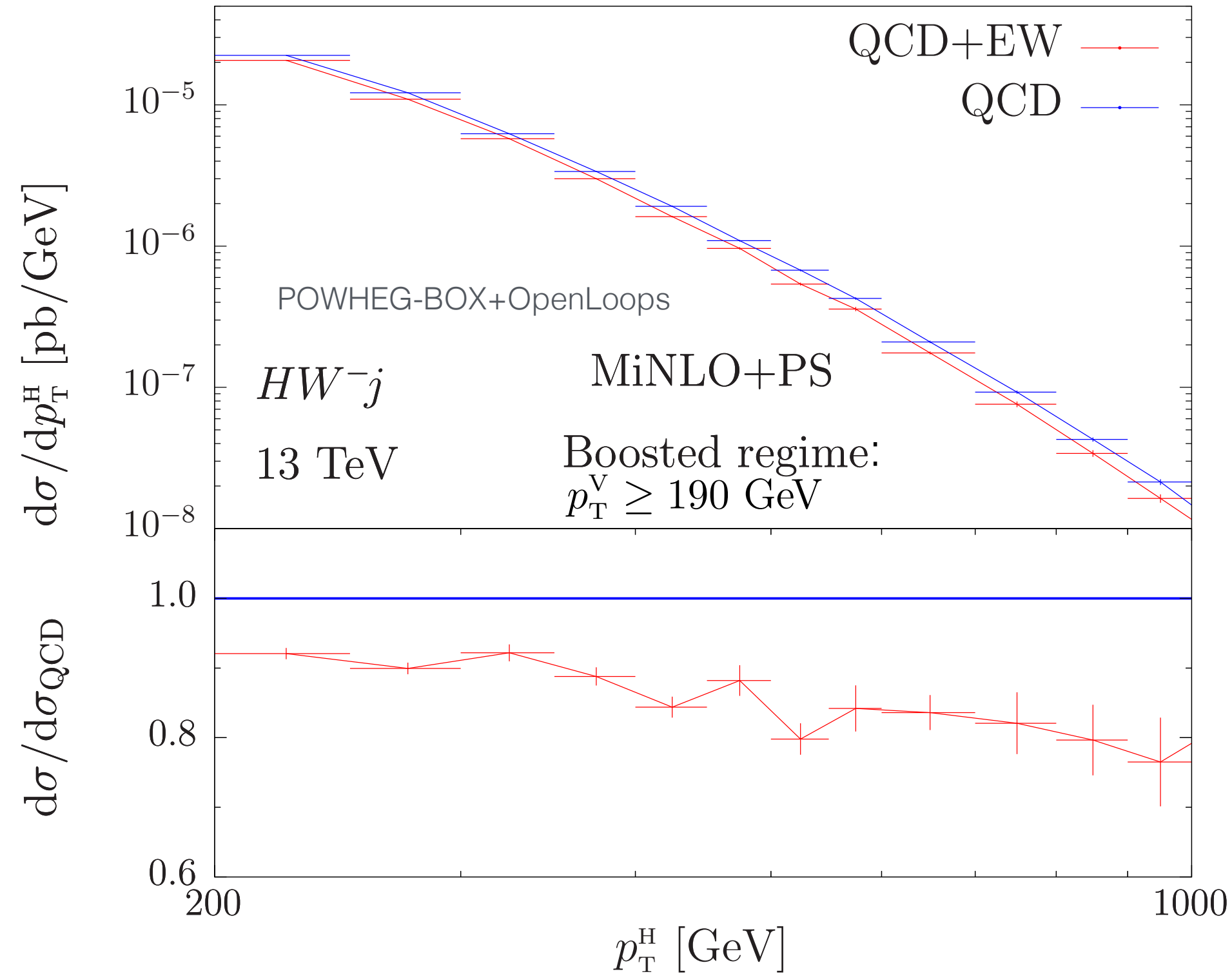
- CSS dipole shower (not resonance aware)  $\Rightarrow$  significant mismodelling
- YFS resummation (resonance aware)  $\Rightarrow$  valid approximation



# HV(+jet) at NLO+PS QCD + EW

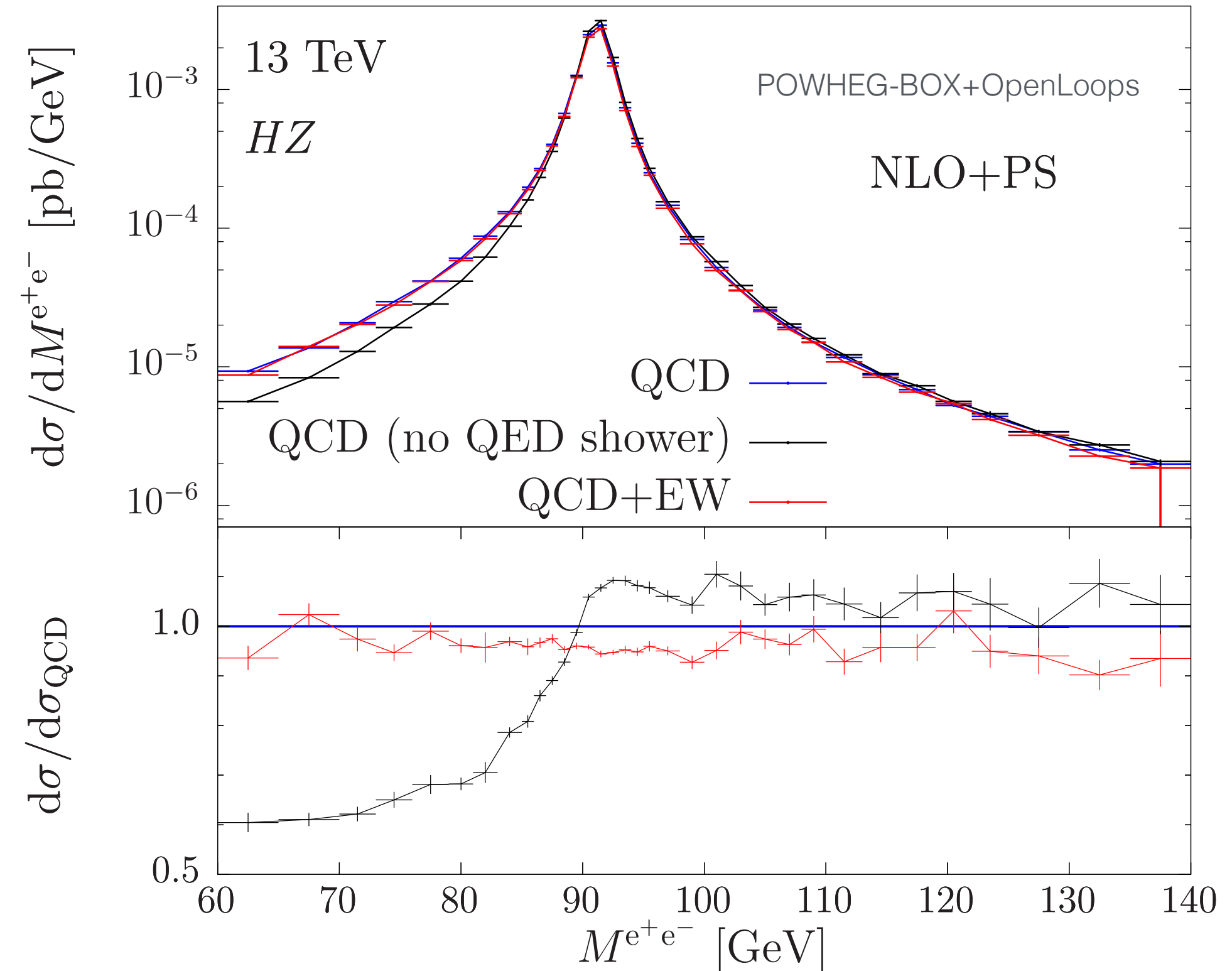
[Granata, JML, Oleari, Pozzorini, '17]

- Motivation:
- HV in boosted regime allows to constrain  $H \rightarrow bb$
  - background in mono-Higgs searches



## $p_T$ of Higgs

- ▶ NLO EW: -20 % > 800 GeV
- ▶ MiNLO ensures NLO QCD and NLO EW accuracy in the whole phase-space

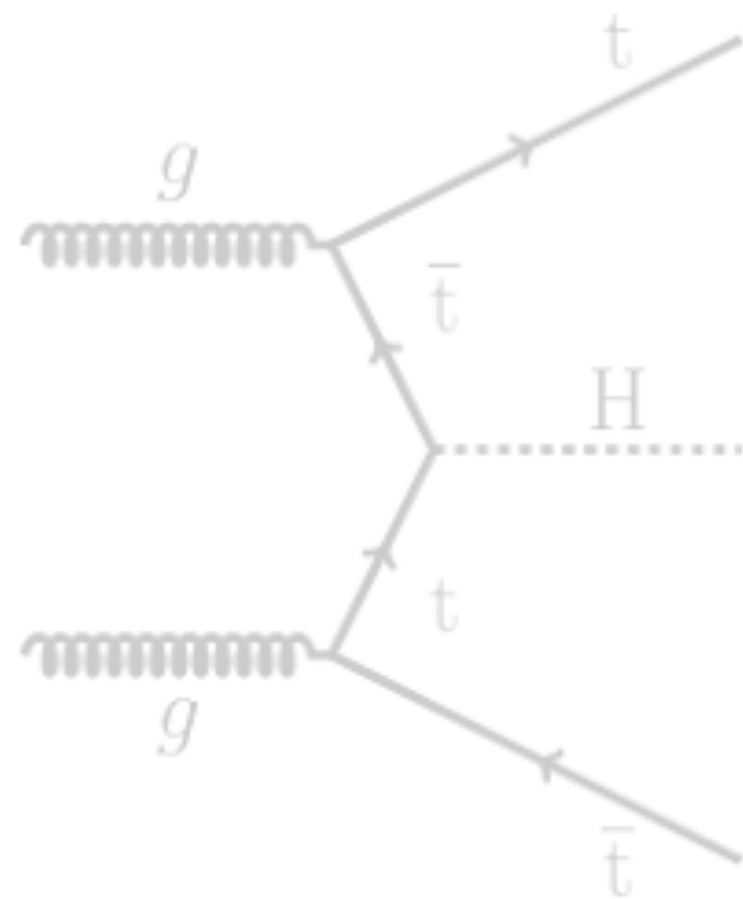


## $M_{ll}$

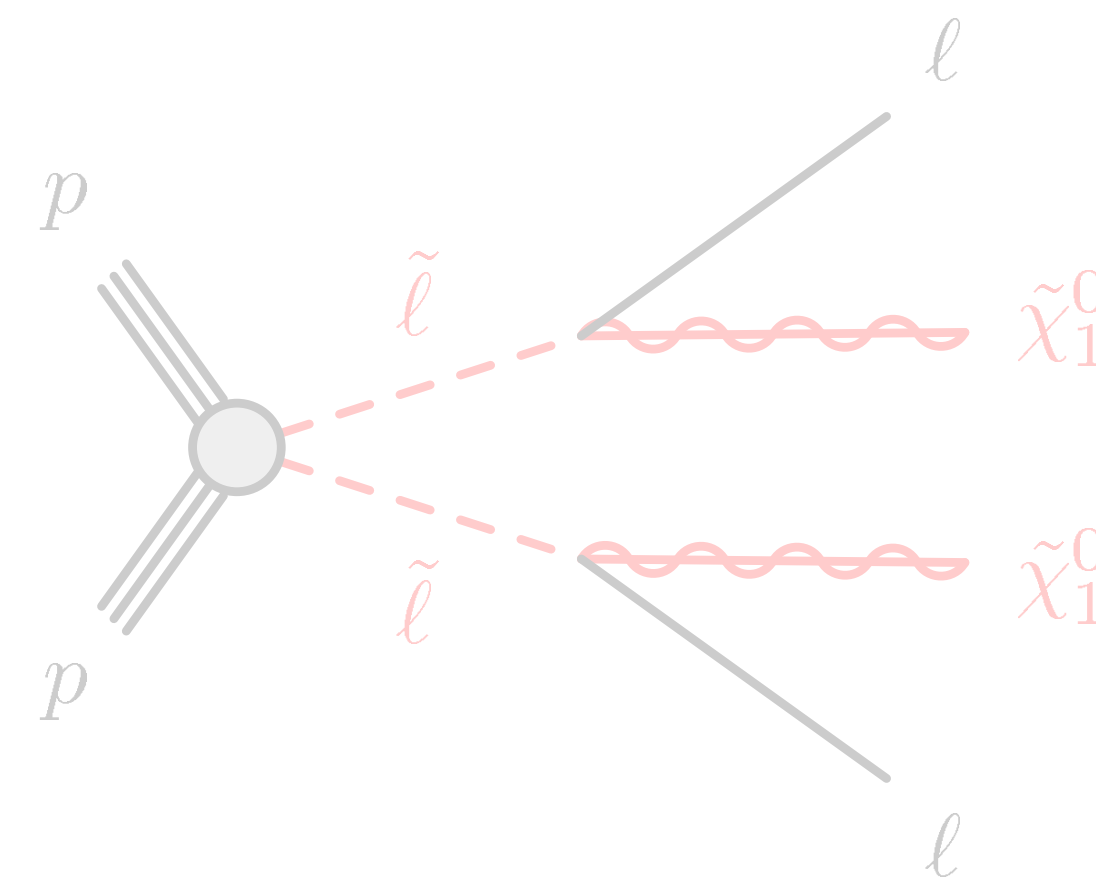
- ▶ large QED effects due to radiative tail...
- ▶ ...reliably modelled by QED-PS
- ▶ matching at NLO EW has to be resonance-aware

A few examples where theory precision is crucial:

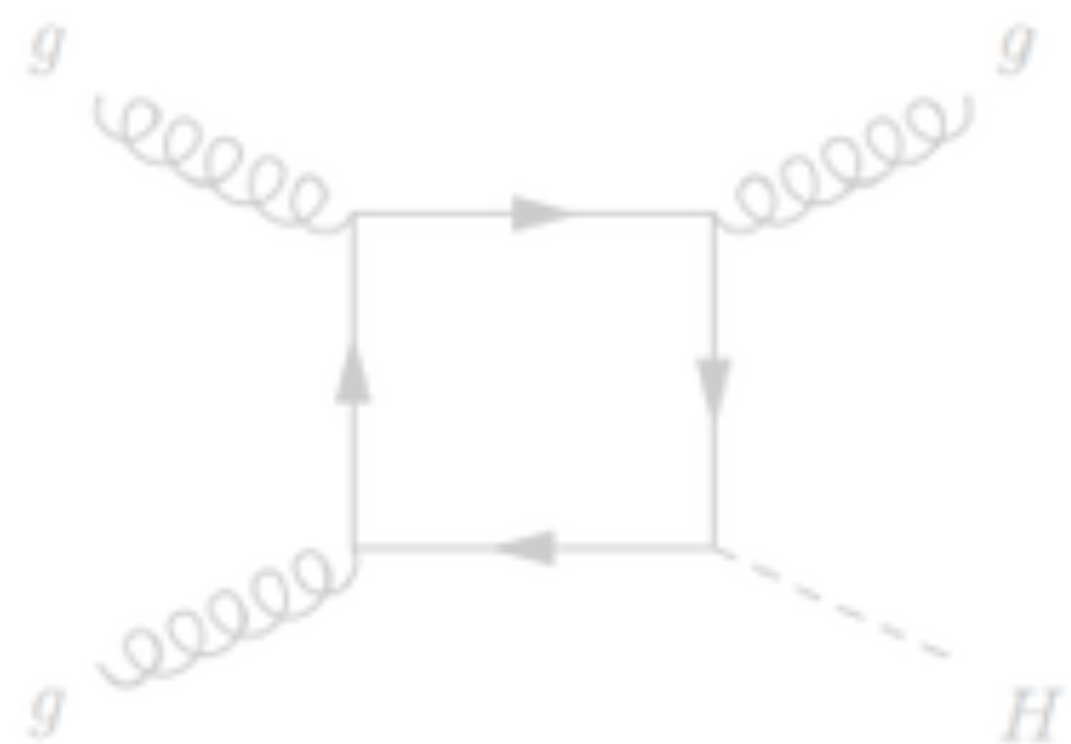
ttH



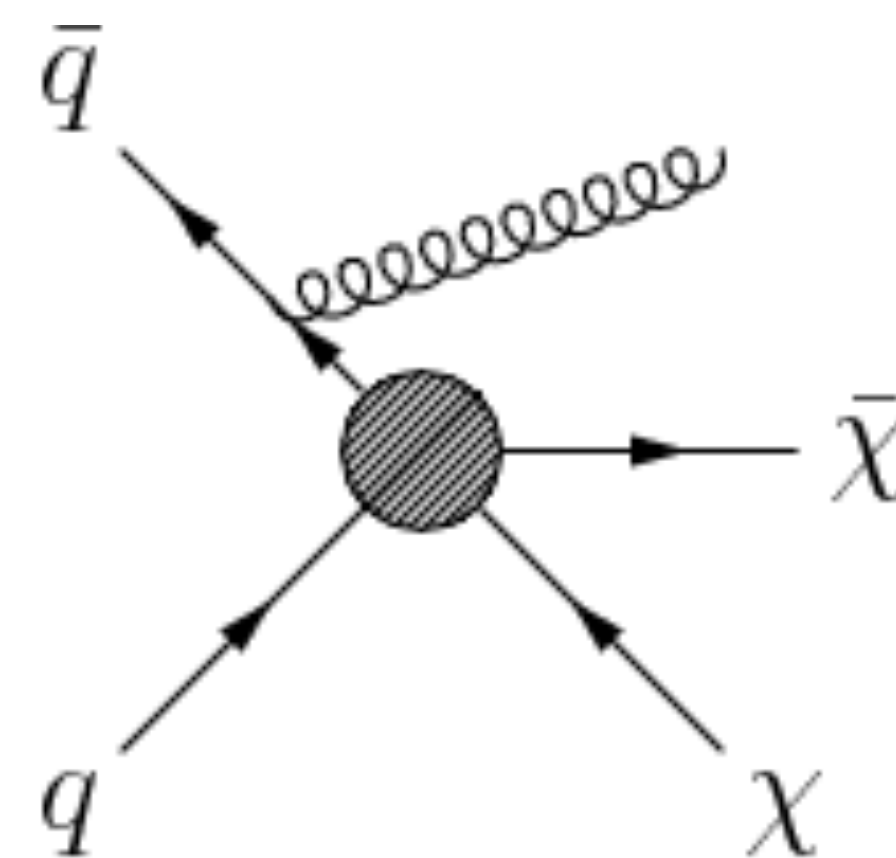
EW SUSY searches



Higgs-pT



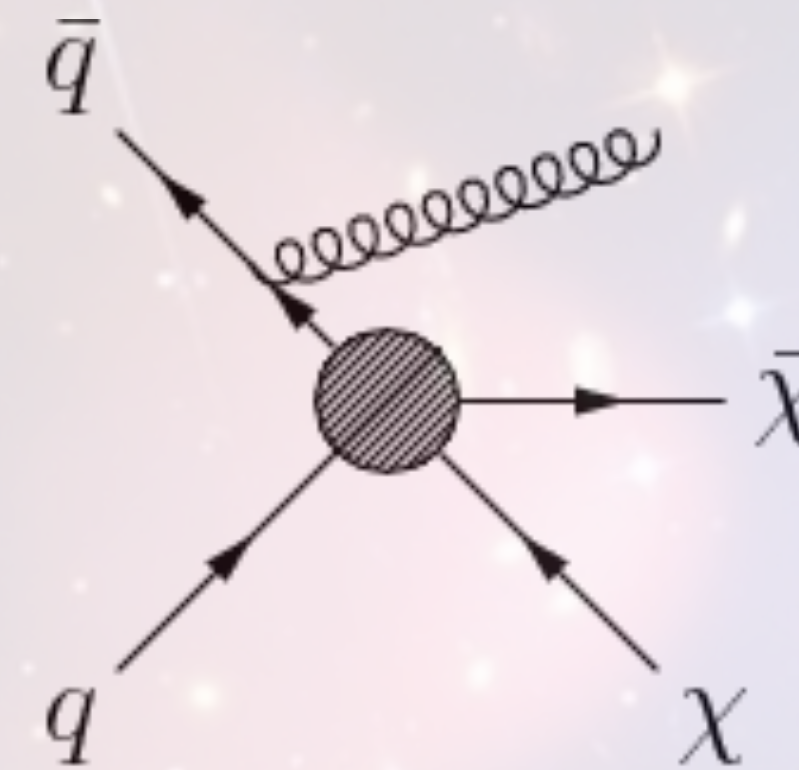
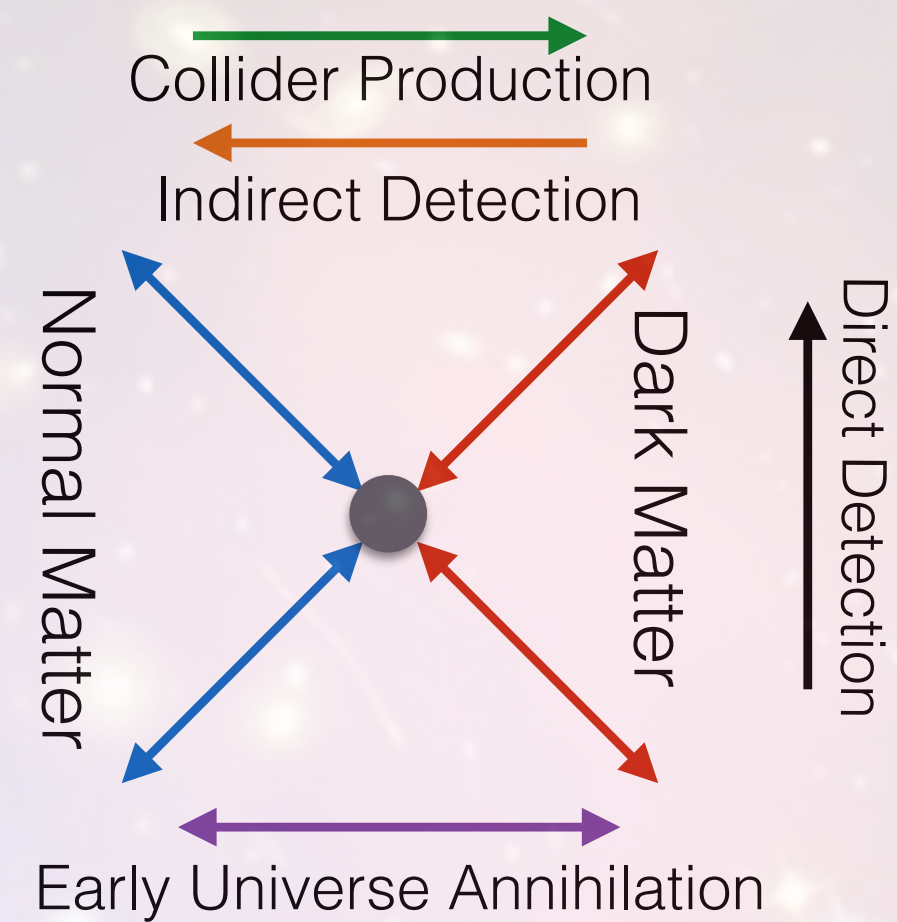
Dark Matter searches



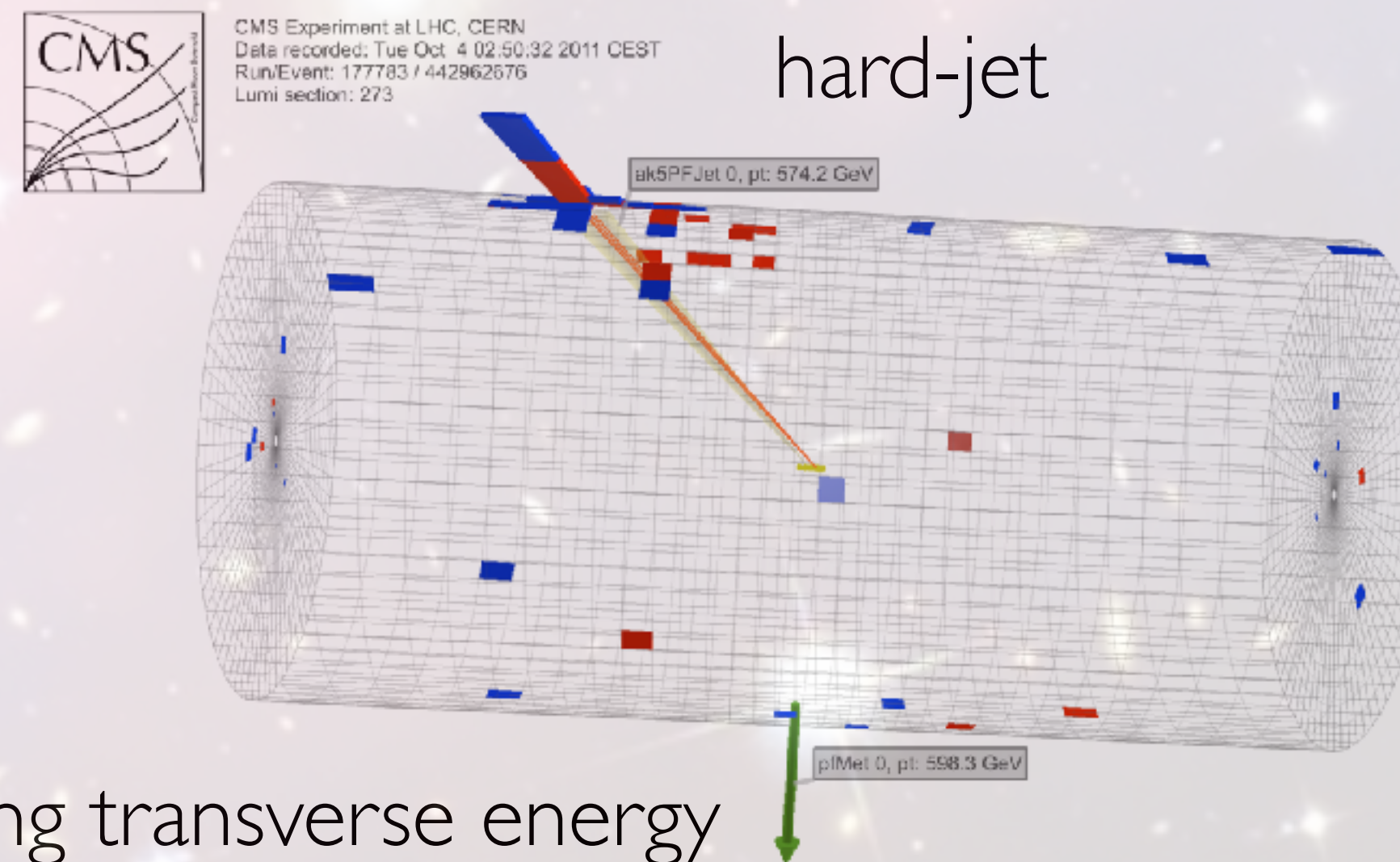


# Canonical Dark Matter signature at the LHC: monojets / MET+jets

we hope to see:

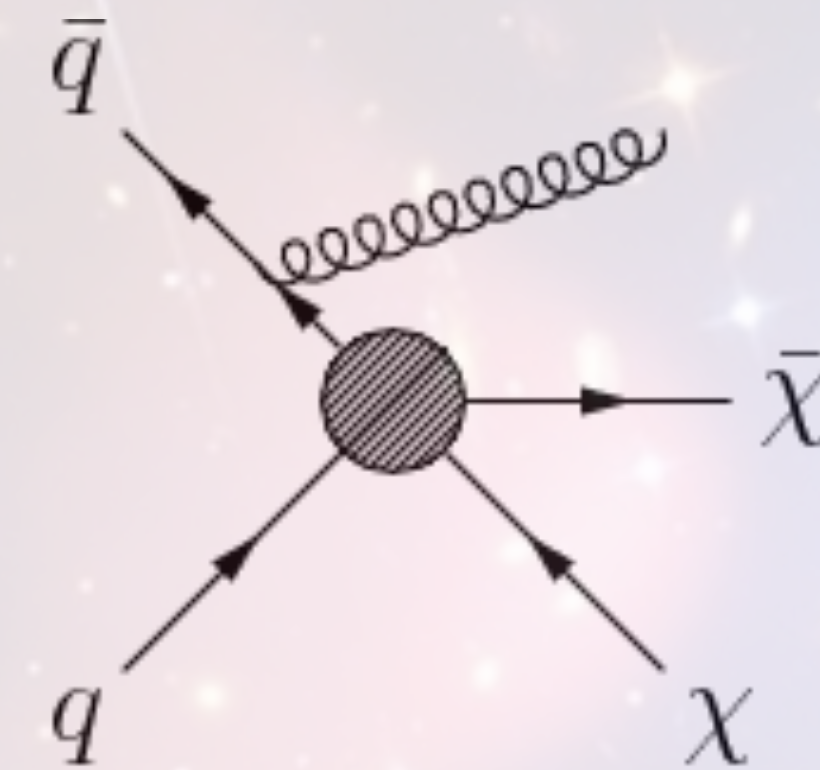
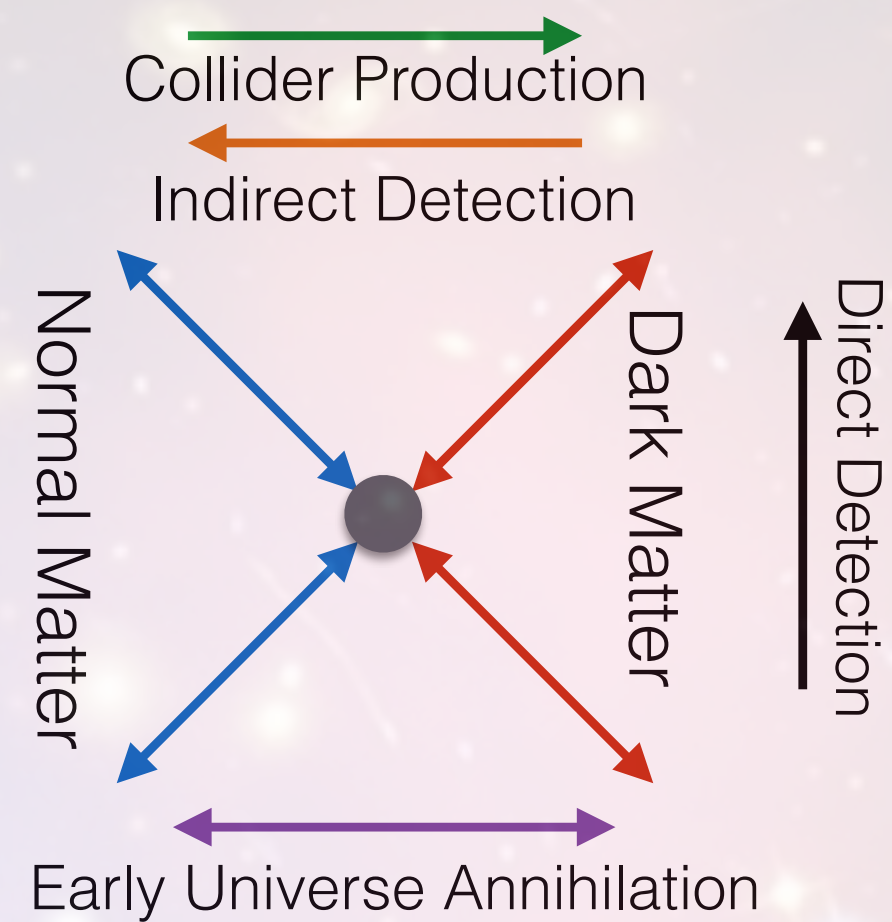


experimental signal:

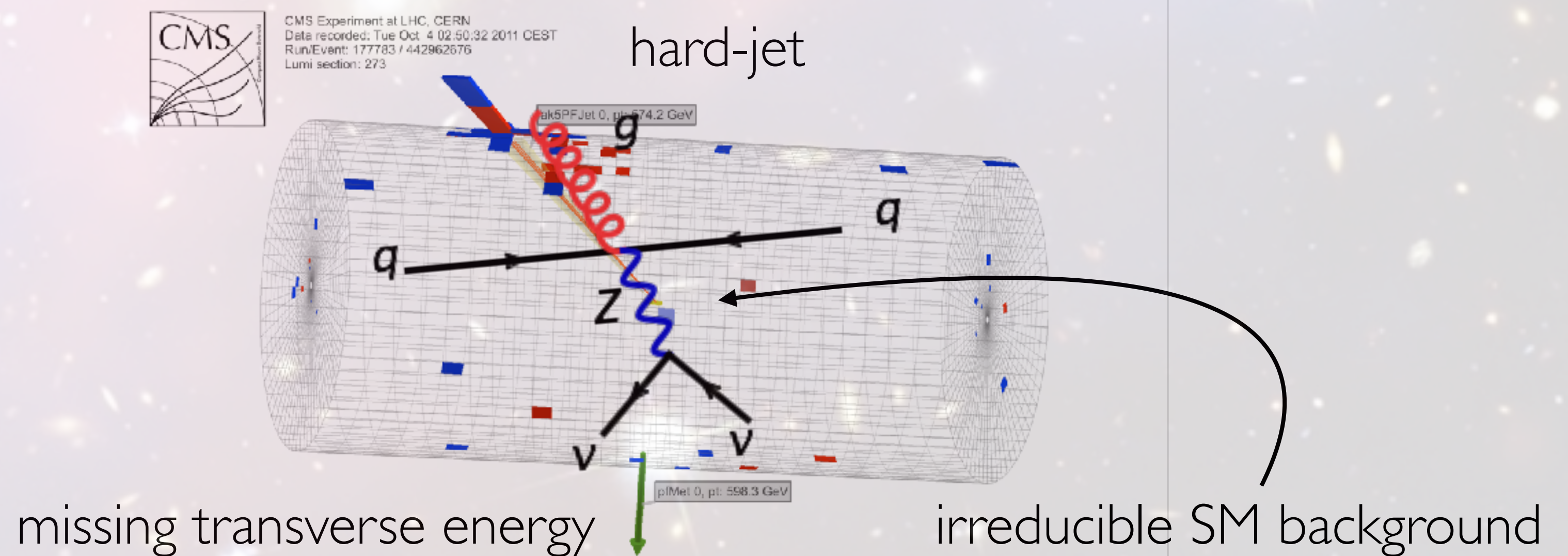


# Canonical Dark Matter signature at the LHC: monojets / MET+jets

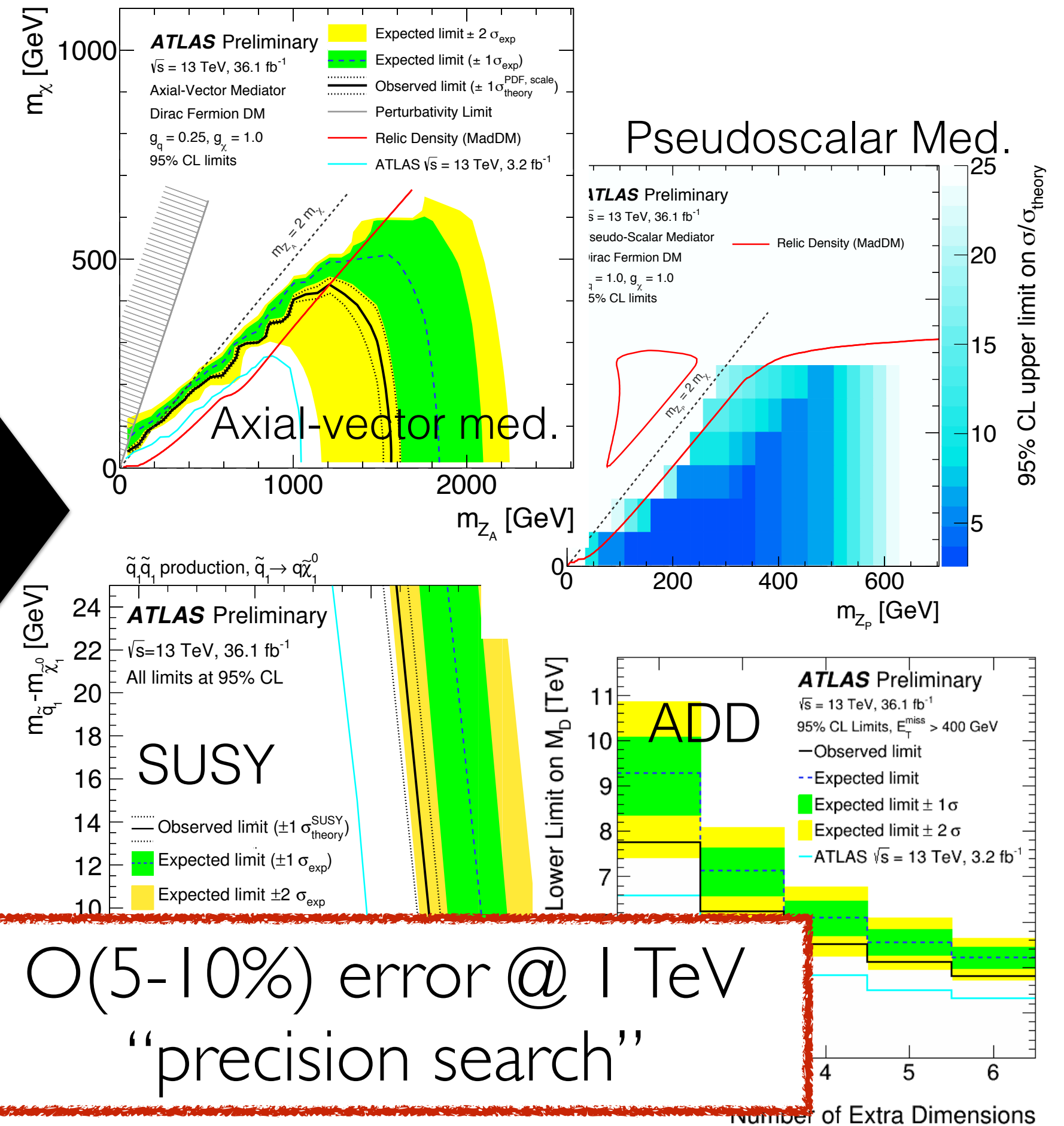
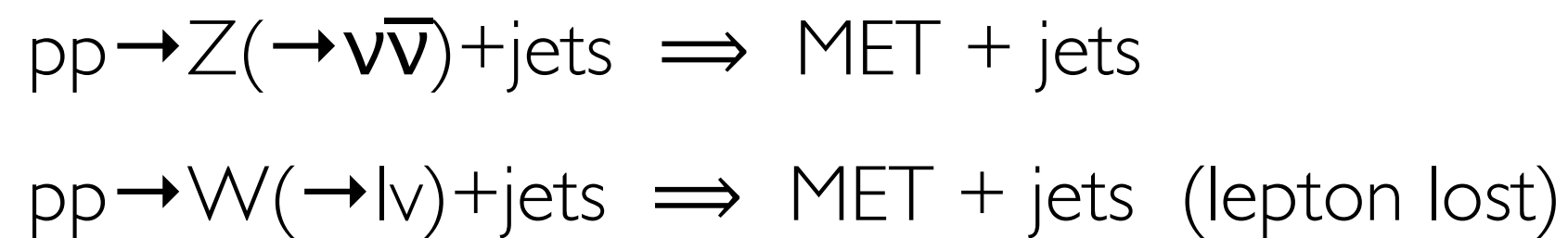
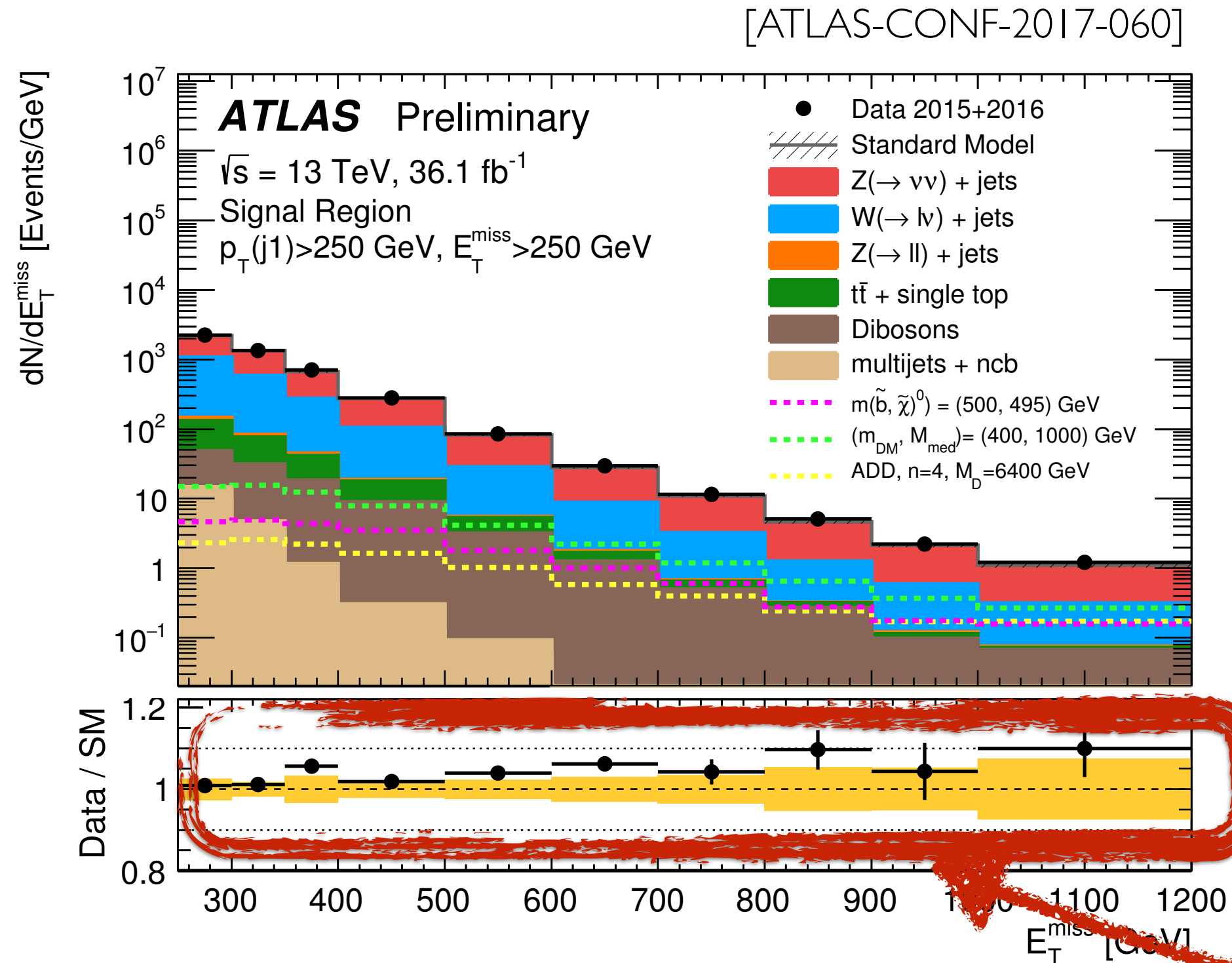
we hope to see:



experimental signal:



# SM backgrounds in monojet / MET+X searches



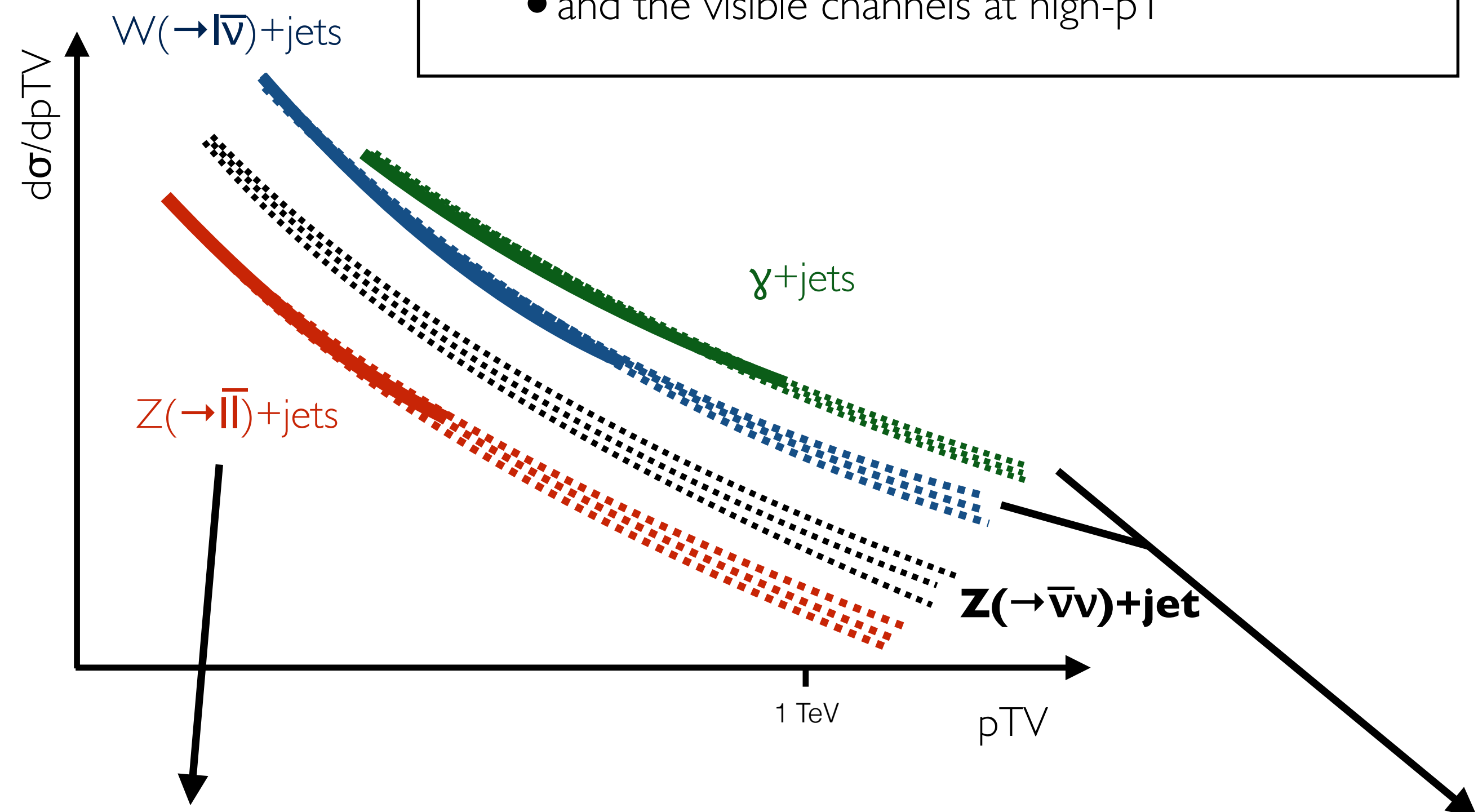
O(5-10%) error @ 1 TeV  
 "precision search"

} V + jets

# Determine V+jets DM backgrounds

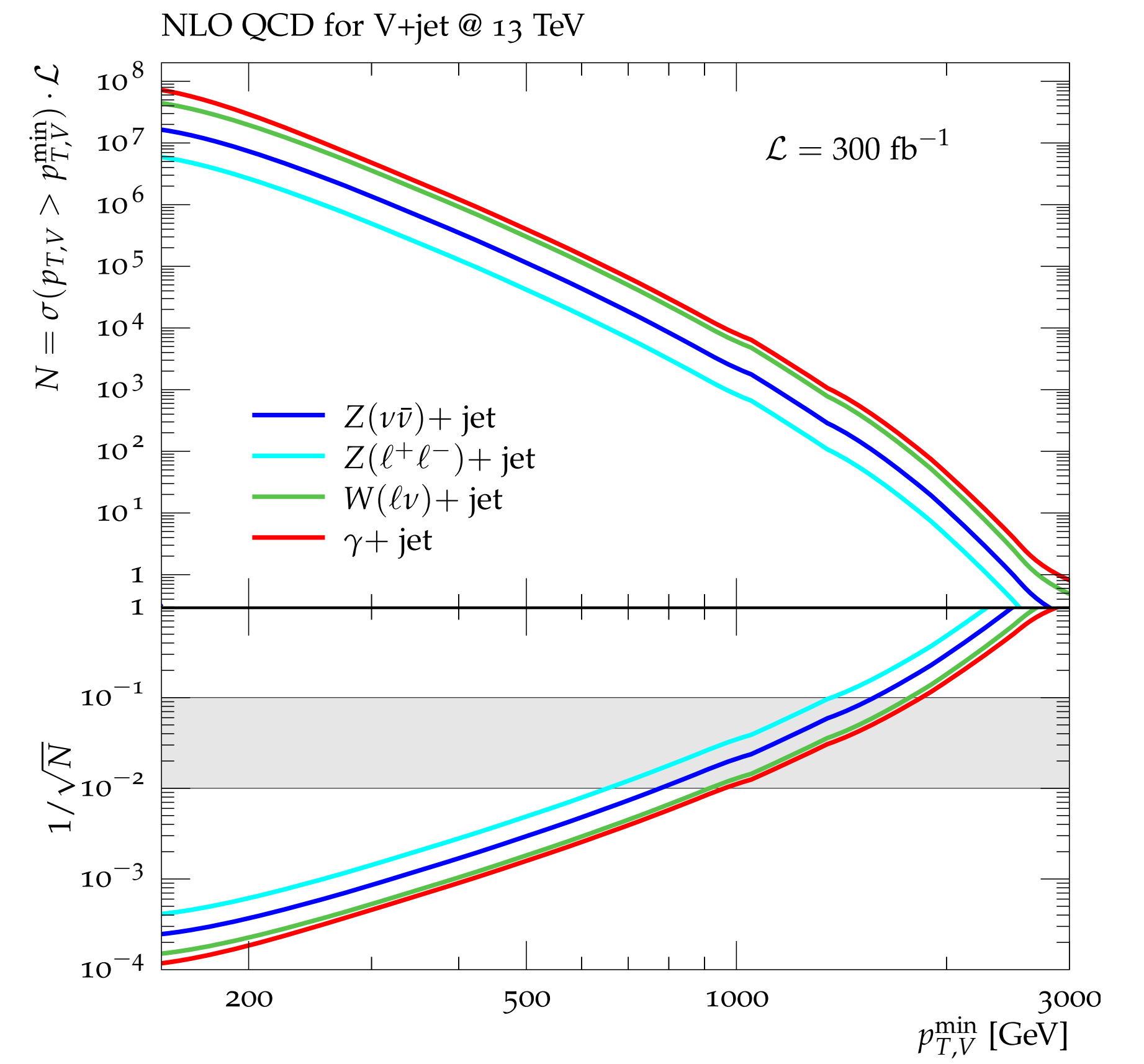
**global fit** of  $Z(\rightarrow \bar{l}l)+\text{jets}$ ,  $W(\rightarrow \bar{l}V)+\text{jets}$  and  $\gamma+\text{jets}$  measurements

- to determine  $Z(\rightarrow \bar{\nu}\nu)+\text{jet}$
- and the visible channels at high- $p_T$



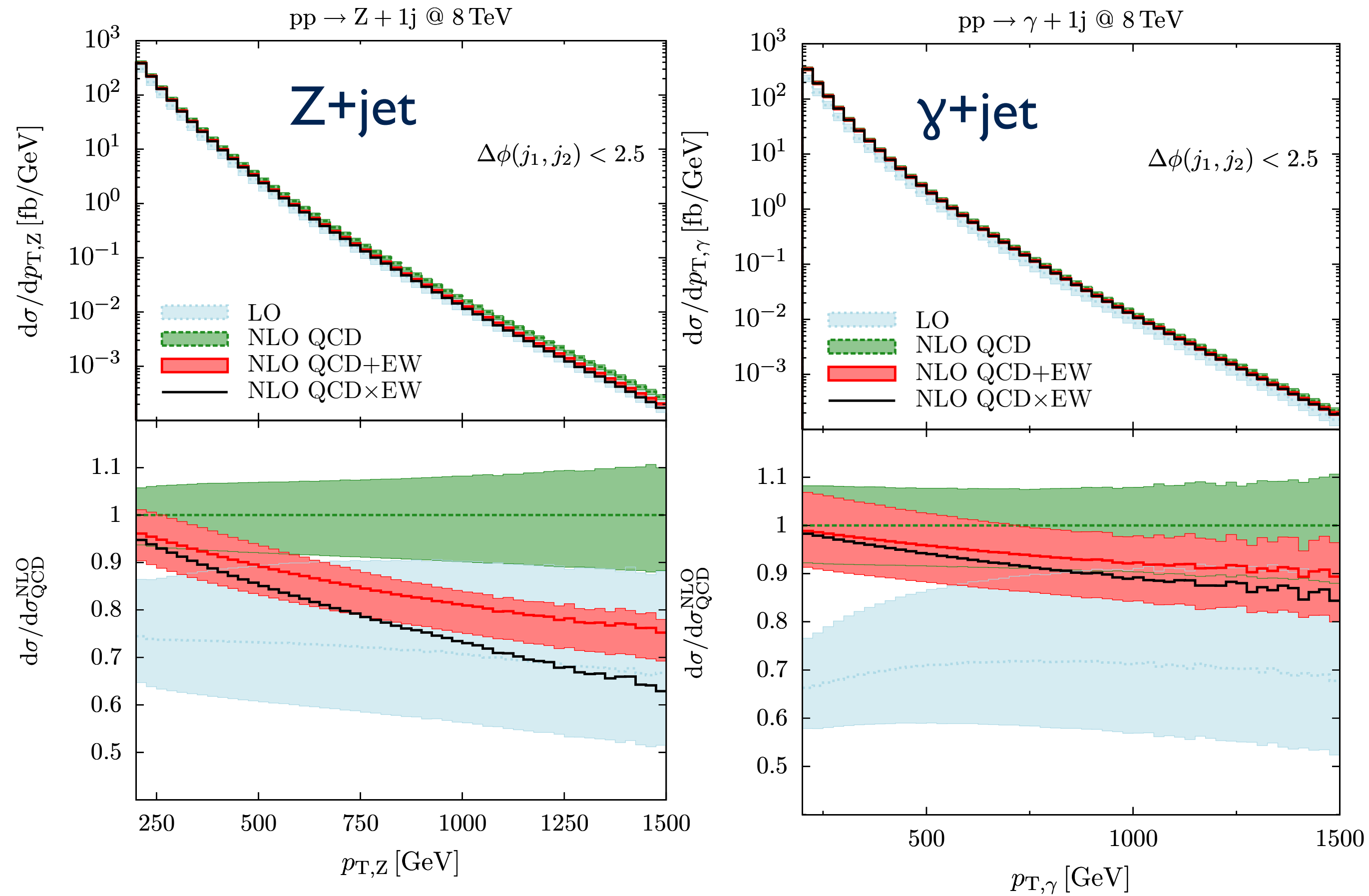
- hardly any systematics (just QED dressing)
- very precise at low  $p_T$
- but: limited statistics at large  $p_T$

- fairly large data samples at large  $p_T$
- systematics from transfer factors



- for  $500 \text{ GeV} < p_{TV} < 1000 \text{ GeV}$ : background statistics will be at **1% level**
- this level of precision is theoretically possible @ **NNLO QCD + NNLO EW**

# Prelude: Z+jet vs. $\gamma$ + 1 jet



## QCD corrections

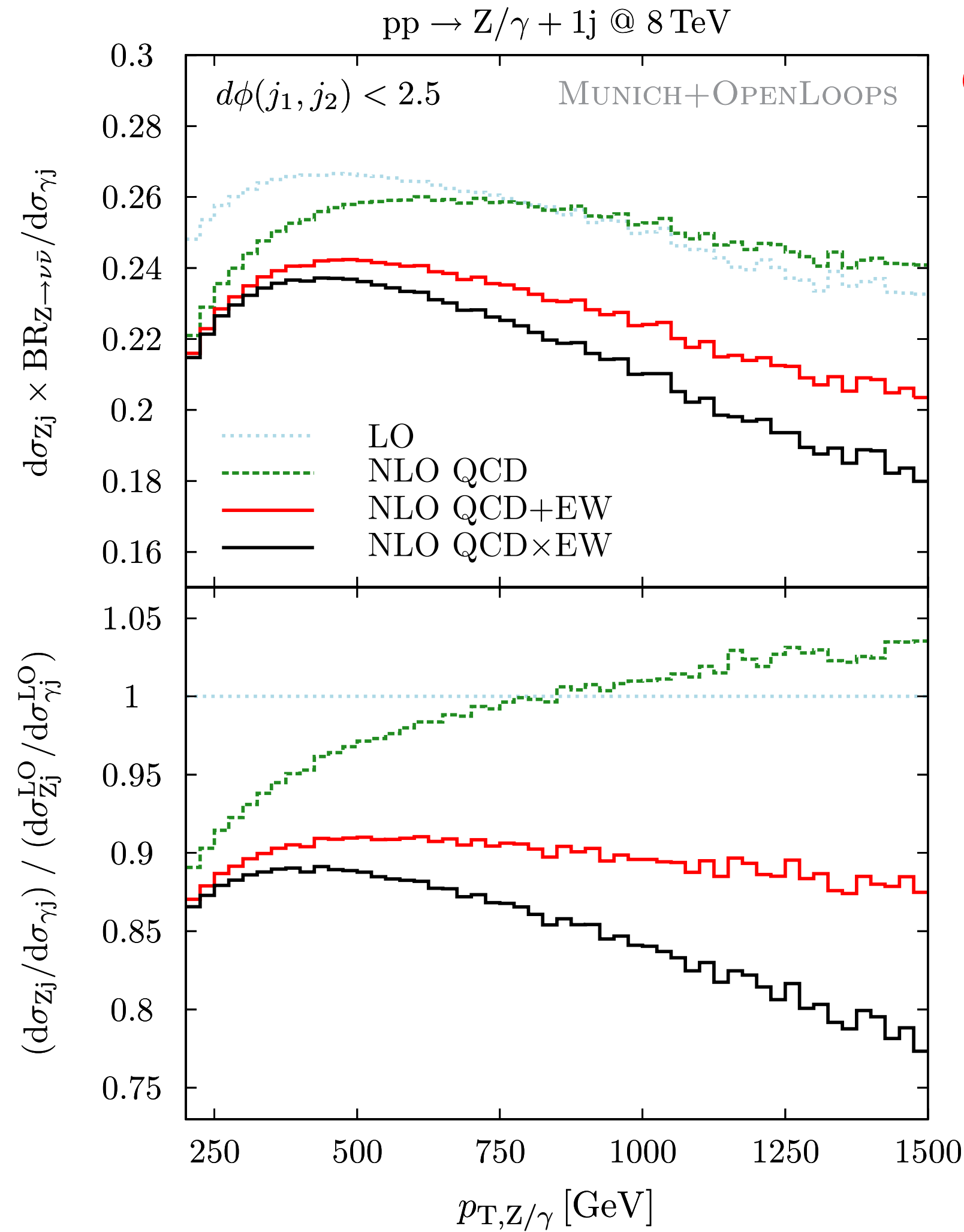
- ▶ mostly moderate and stable QCD corrections
- ▶ (almost) **identical QCD corrections in the tail**, sizeable differences for small  $p_T$

## EW corrections

- ▶ **correction in  $p_T(Z) >$  correction in  $p_T(\gamma)$**
- ▶ **-20/-8%** for Z/ $\gamma$  at 1 TeV
- ▶ EW corrections  $>$  QCD uncertainties for  $p_{T,Z} > 350$  GeV



# Prelude: $Z/\gamma$ pT-ratio



## QCD corrections

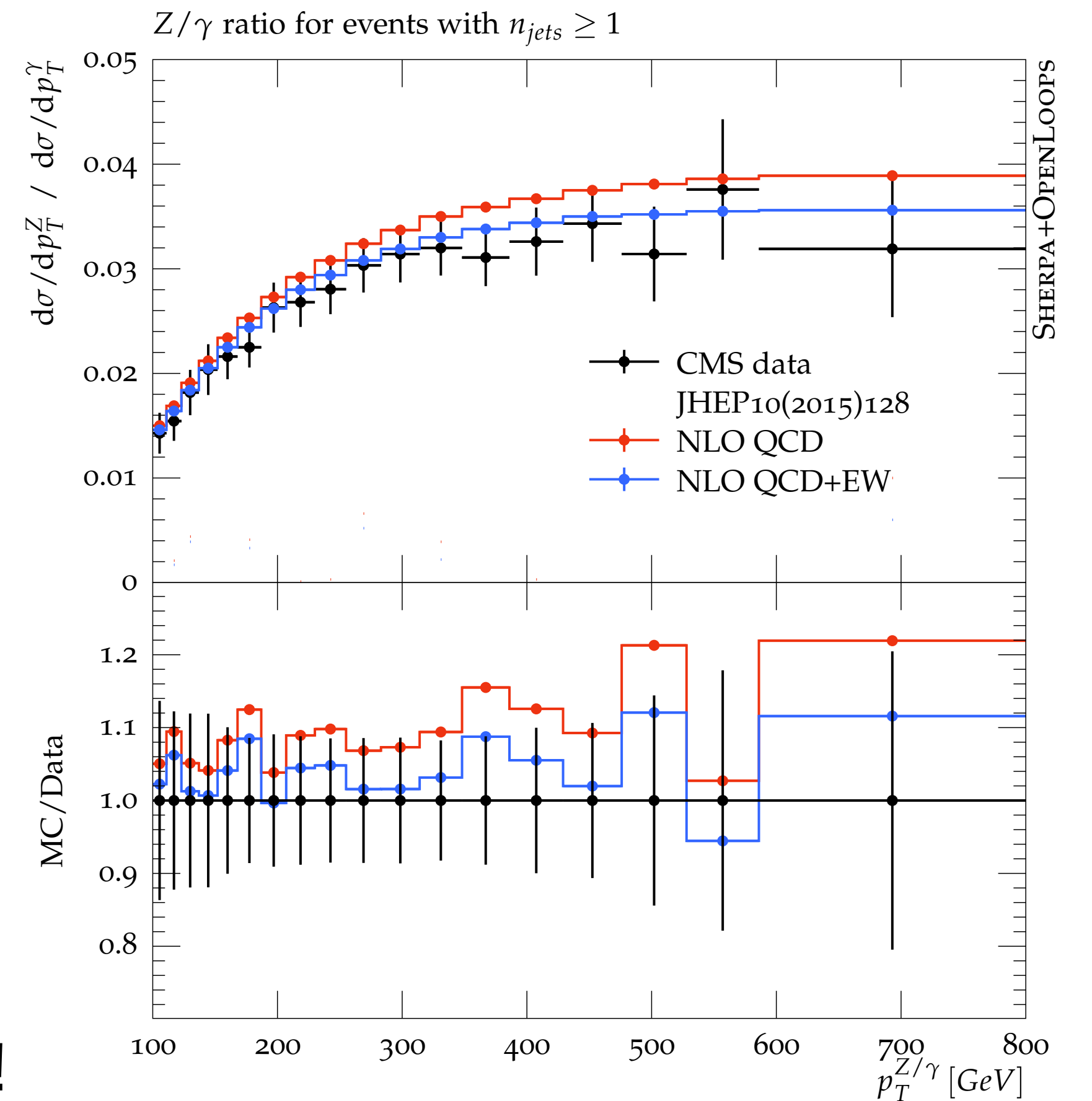
- ▶ 10-15% below 250 GeV
- ▶  $\approx$  5% above 350 GeV

## EW corrections

- ▶ sizeable difference in EW corrections results in 10-15% corrections at several hundred GeV

- ▶ remarkable agreement with data at @ NLO **QCD+EW**!

[Ciulli, Kallweit, JML, Pozzorini, Schönherr for **LesHouches'15**]



Uncertainty estimates  
at  
(N)NLO QCD + (n)NLO EW

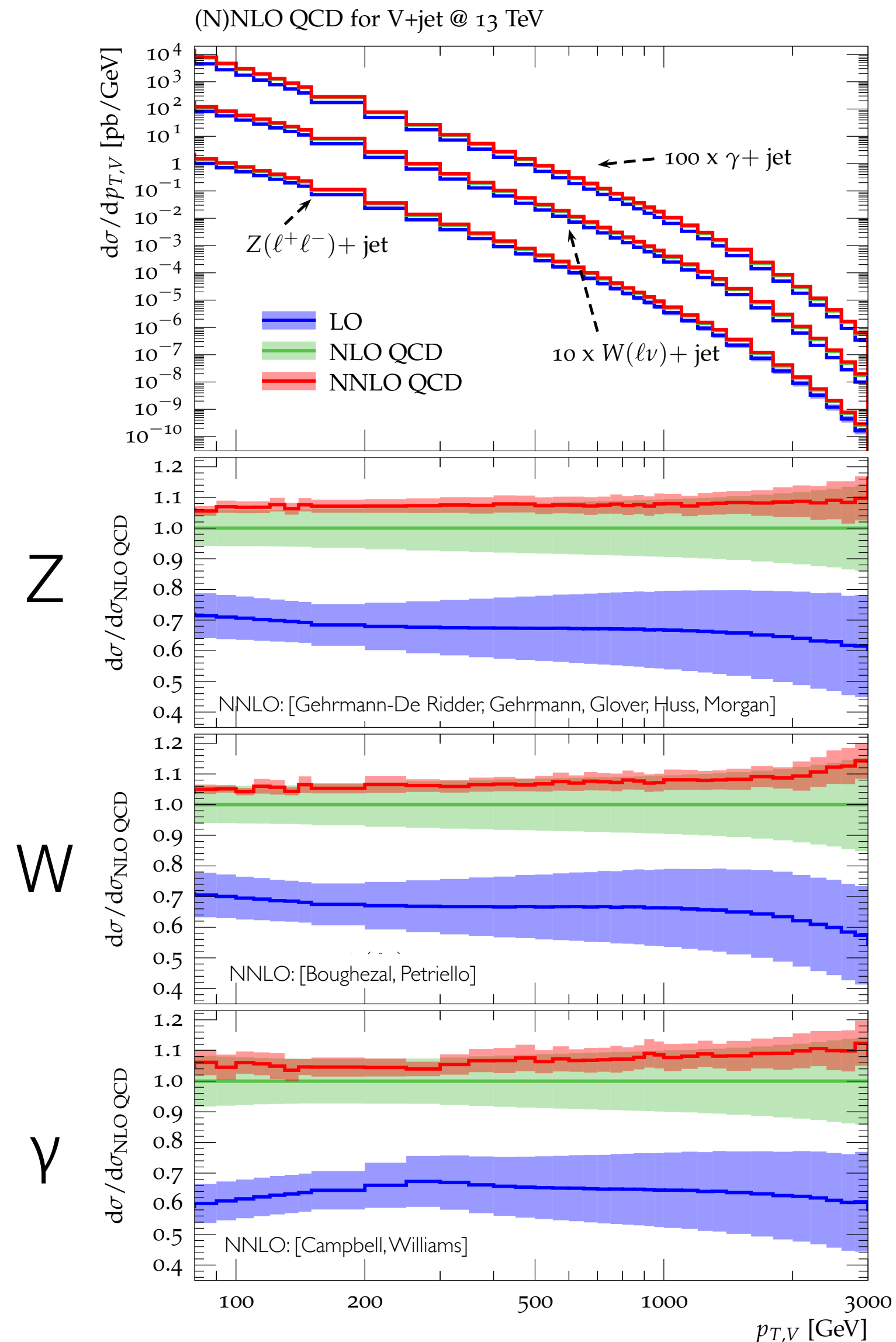
how to correlate scale uncertainties in ratios?

how to estimate uncertainties due to missing higher-order EW?

how to combine higher-order QCD and EW correction?  
what is the related uncertainty?

# Pure QCD uncertainties

[JML et. al.: 1705.04664]



$$\frac{d}{dx} \sigma_{\text{QCD}}^{(V)} = \frac{d}{dx} \sigma_{\text{LO QCD}}^{(V)} + \frac{d}{dx} \sigma_{\text{NLO QCD}}^{(V)} + \frac{d}{dx} \sigma_{\text{NNLO QCD}}^{(V)}$$

$$\mu_0 = \frac{1}{2} \left( \sqrt{p_{T,\ell+\ell-}^2 + m_{\ell+\ell-}^2} + \sum_{i \in \{q,g,\gamma\}} |p_{T,i}| \right)$$

this is a 'good' scale for V+jets

- at large  $p_{TV}$ :  $HT'/2 \approx p_{TV}$
- modest higher-order corrections
- sufficient convergence

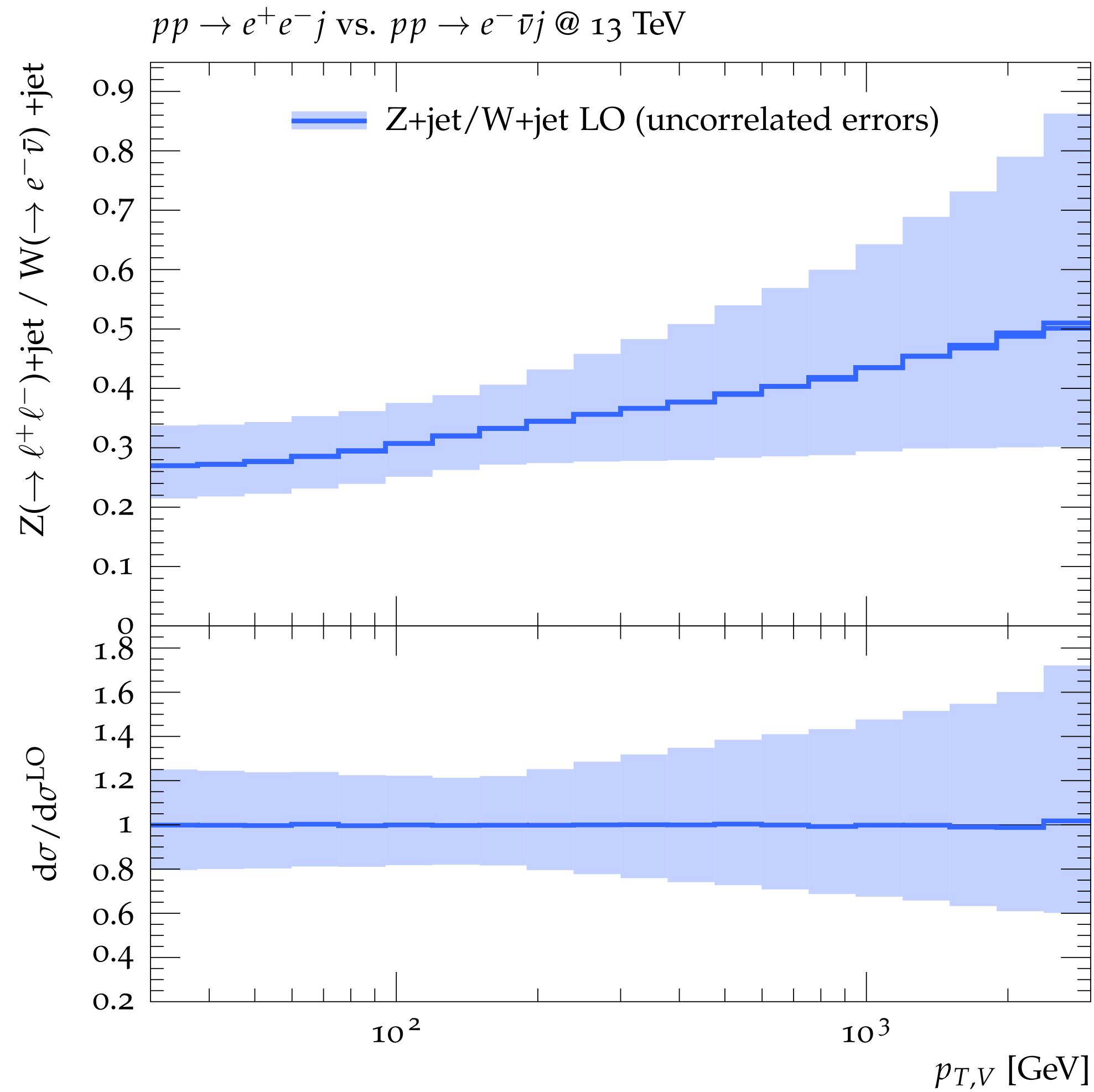
scale uncertainties due to 7-pt variations:

- (20%) uncertainties at LO
- (10%) uncertainties at NLO
- (5%) uncertainties at NNLO

with minor shape variations

How to correlate these uncertainties across processes?

# How to correlate QCD uncertainties across processes?



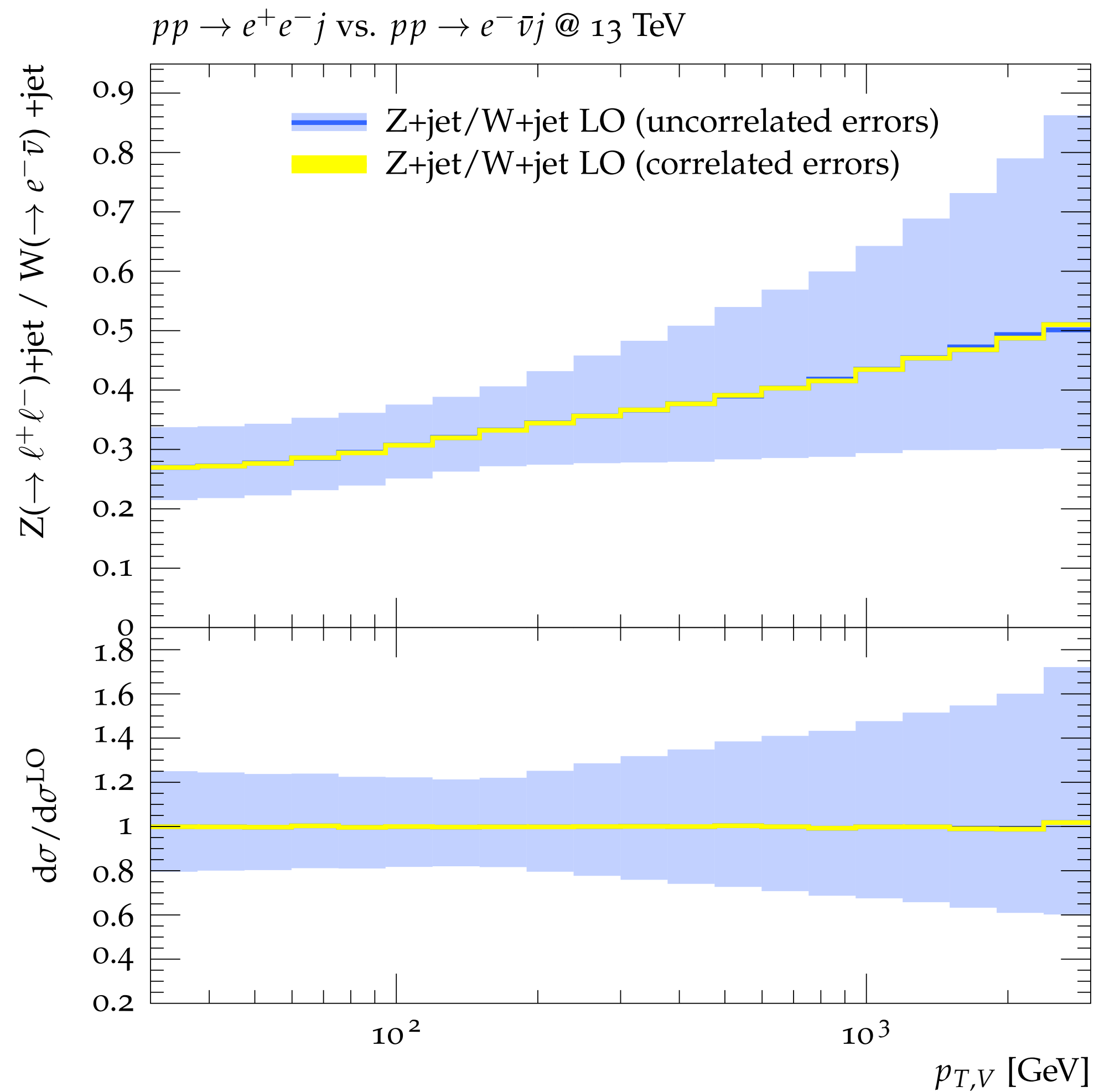
consider Z+jet / W+jet  $p_{T,V}$ -ratio @ LO

uncorrelated treatment yields

O(40%) uncertainties

# How to correlate QCD uncertainties across processes?

[1705.04664]



consider Z+jet / W+jet  $p_{T,V}$ -ratio @ LO

uncorrelated treatment yields

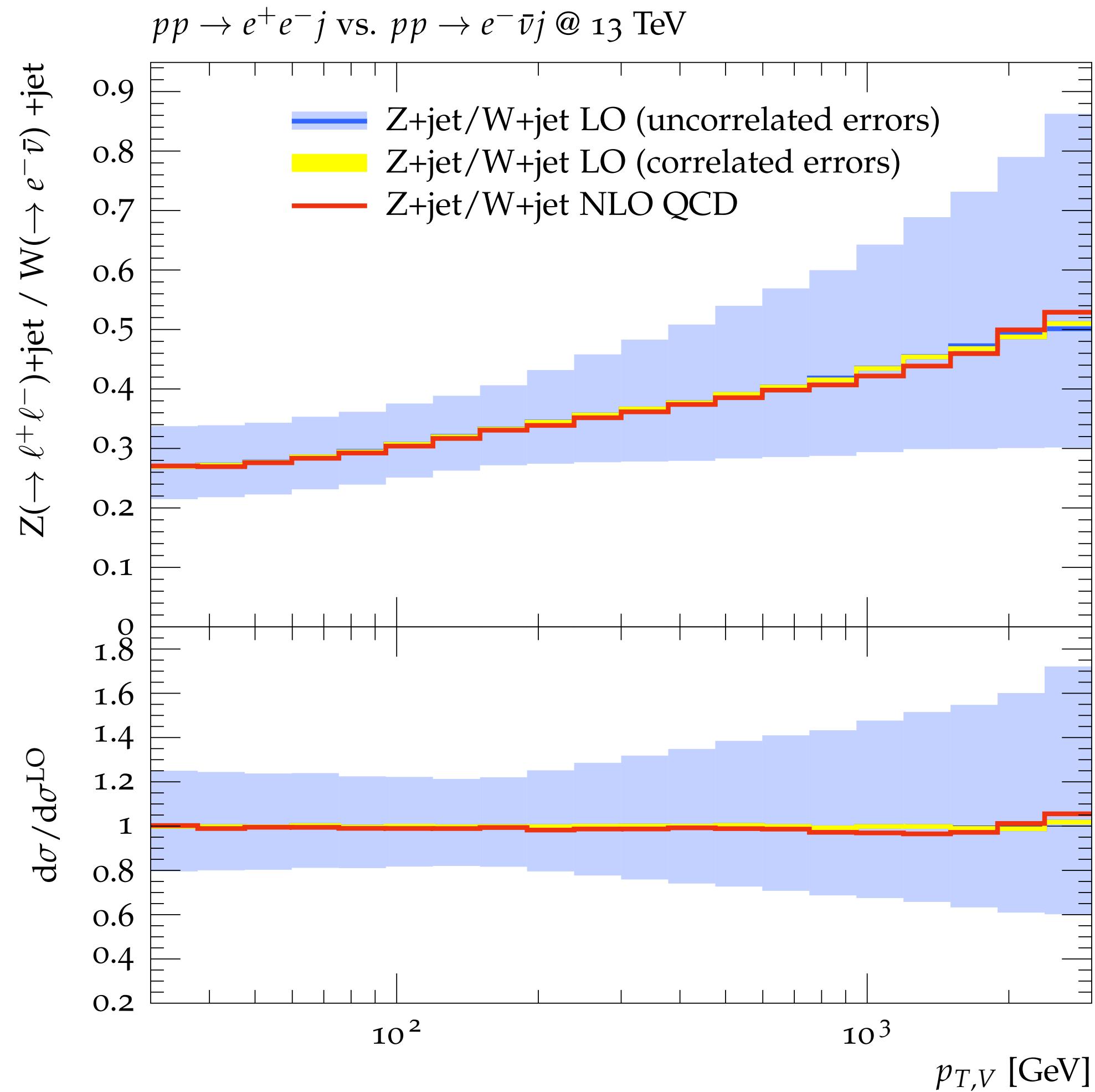
$\mathcal{O}(40\%)$  uncertainties

correlated treatment yields tiny

$\mathcal{O}(<\sim 1\%)$  uncertainties

# How to correlate QCD uncertainties across processes?

[1705.04664]



consider Z+jet / W+jet  $p_{T,V}$ -ratio @ LO

uncorrelated treatment yields

$\mathcal{O}(40\%)$  uncertainties

correlated treatment yields tiny

$\mathcal{O}(<\sim 1\%)$  uncertainties

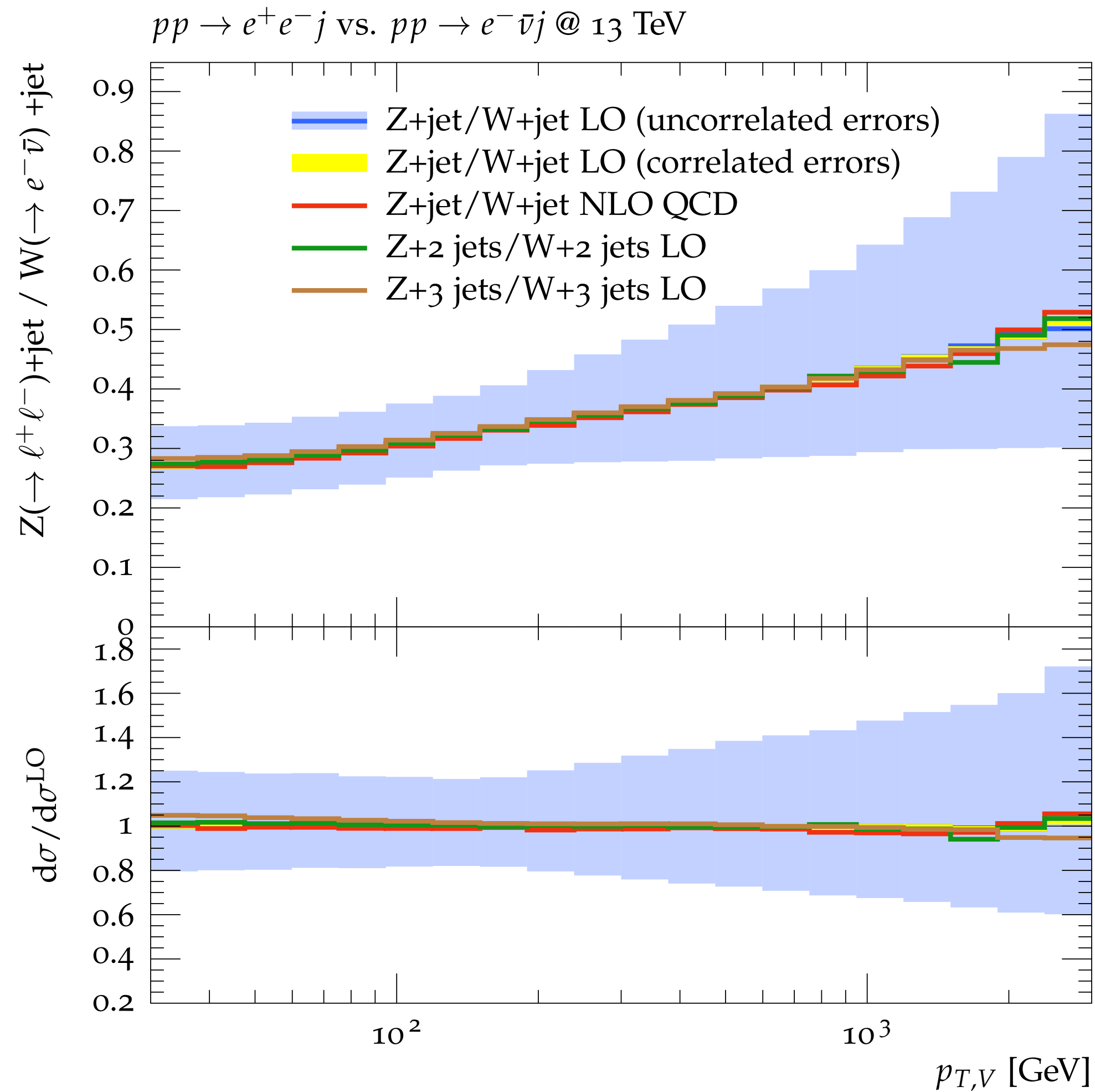
check against NLO QCD!

NLO QCD corrections remarkably flat  
in Z+jet / W+jet ratio!

→ supports correlated treatment of  
uncertainties!

# How to correlate QCD uncertainties across processes?

[1705.04664]



consider Z+jet / W+jet  $p_{T,V}$ -ratio @ LO

uncorrelated treatment yields

$\mathcal{O}(40\%)$  uncertainties

correlated treatment yields tiny

$\mathcal{O}(<\sim 1\%)$  uncertainties

check against NLO QCD!

NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!

→ supports correlated treatment of uncertainties!

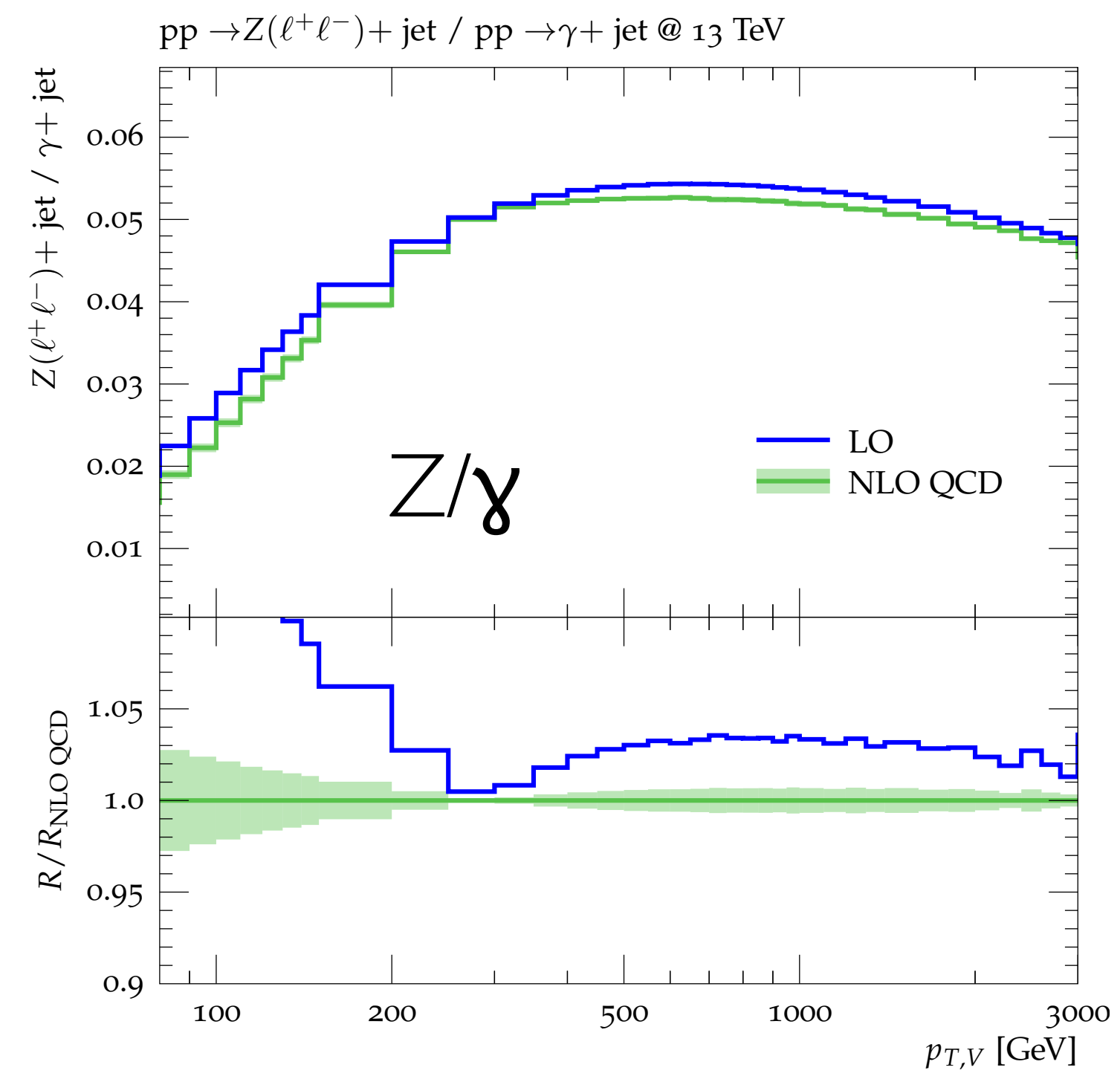
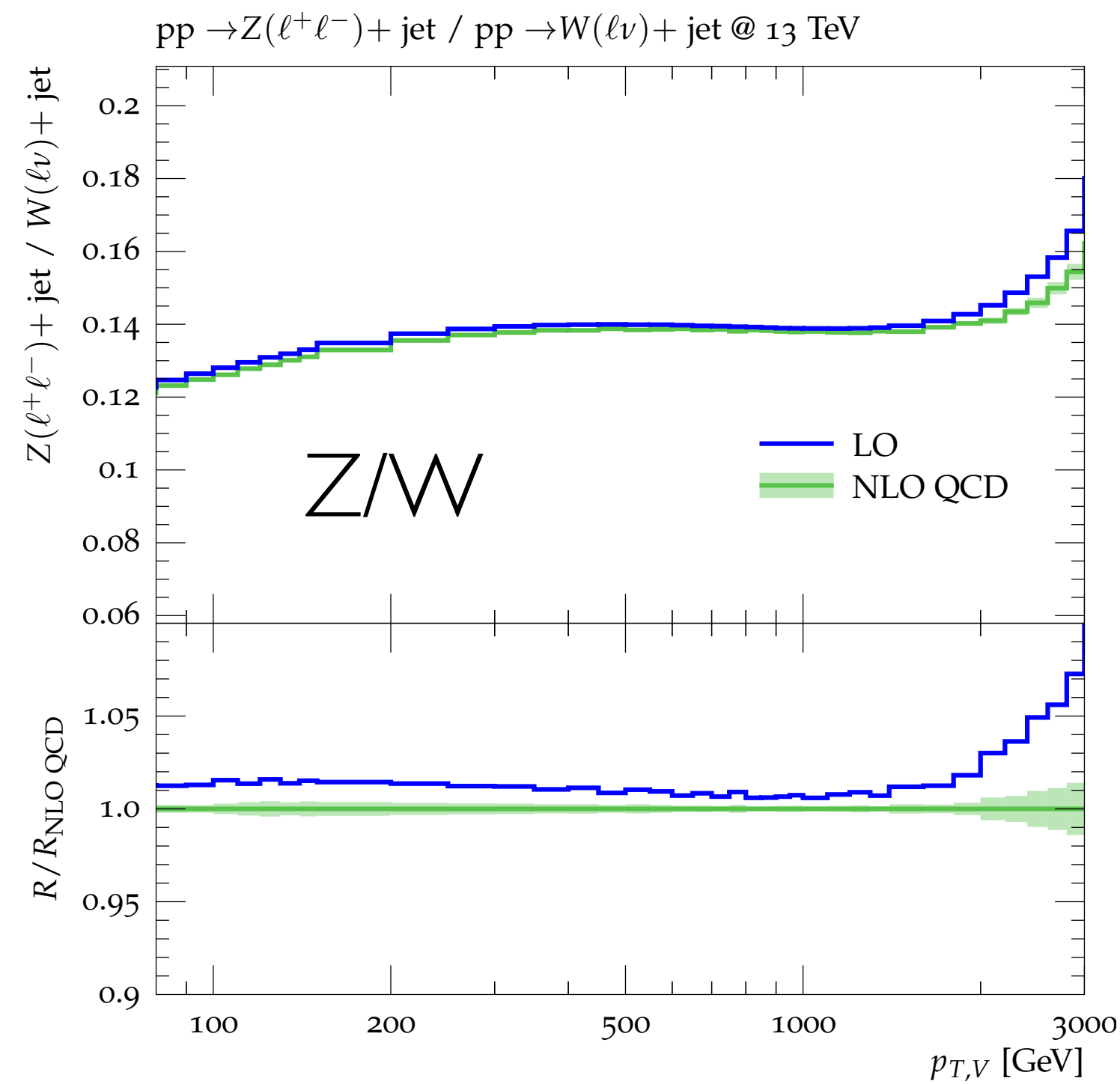
Also holds for higher jet-multiplicities

→ indication of correlation also in higher-order corrections beyond NLO!

# QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:  
NLO QCD uncertainties cancel at the  $\sim 1\%$  level

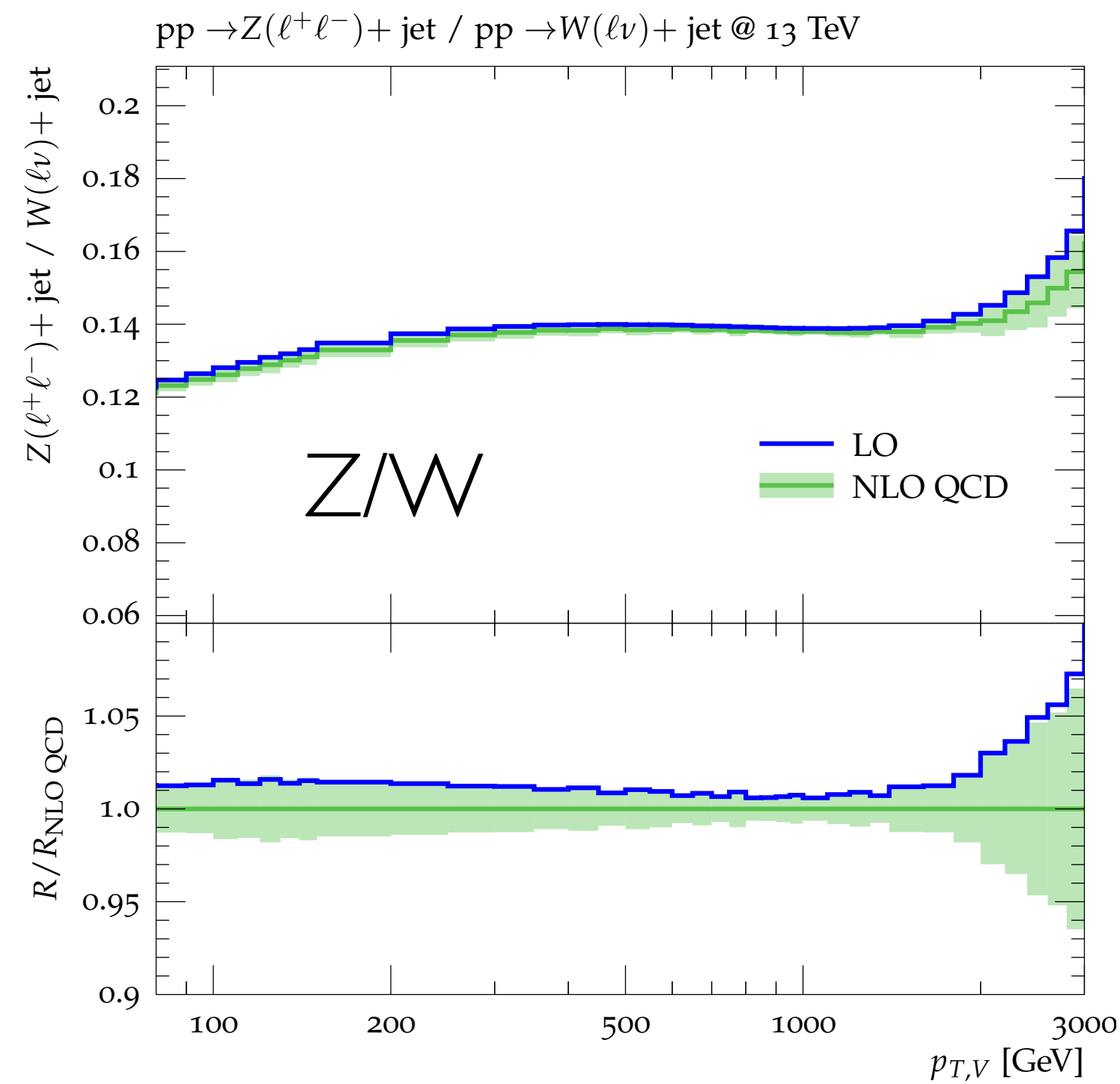




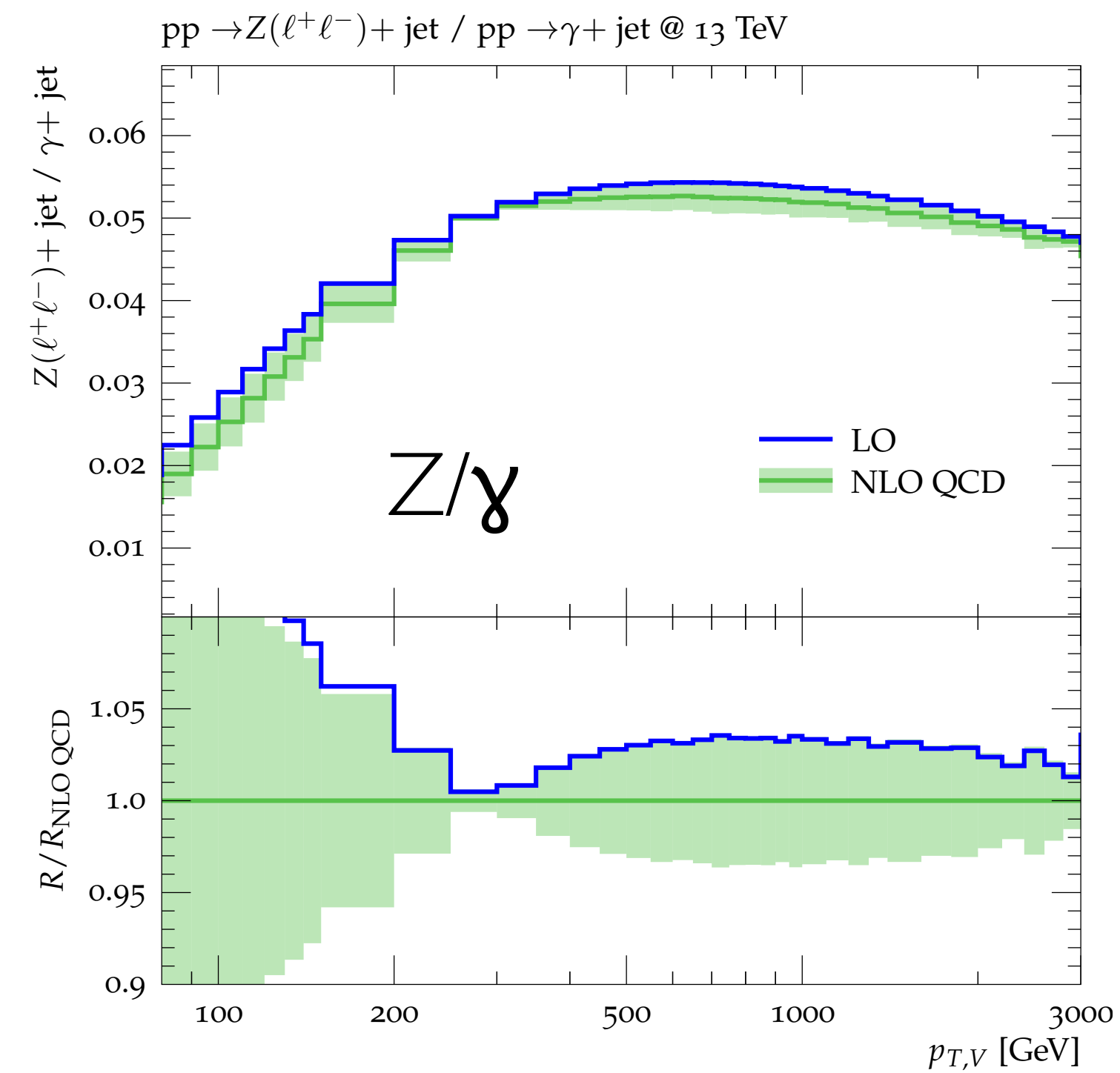
# QCD uncertainties: ratios

## How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:  
NLO QCD uncertainties cancel at the  $< \sim 1\%$  level
- introduce **process correlation uncertainty** based on K-factor difference:  $\delta K_{\text{NLO}} = K_{\text{NLO}}^V - K_{\text{NLO}}^Z$   
→ effectively degrades precision of last calculated order



$\delta < 2\%$

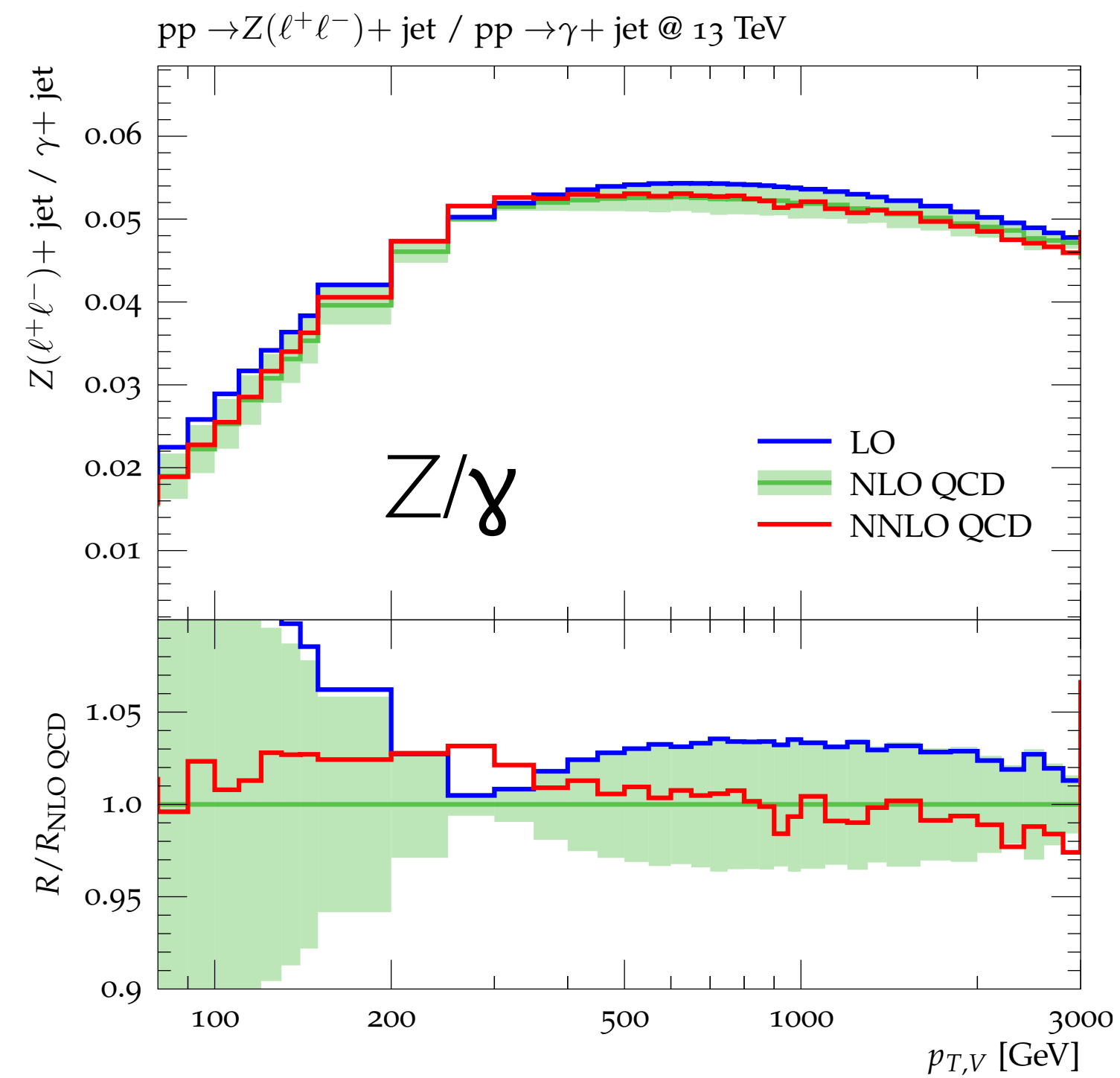
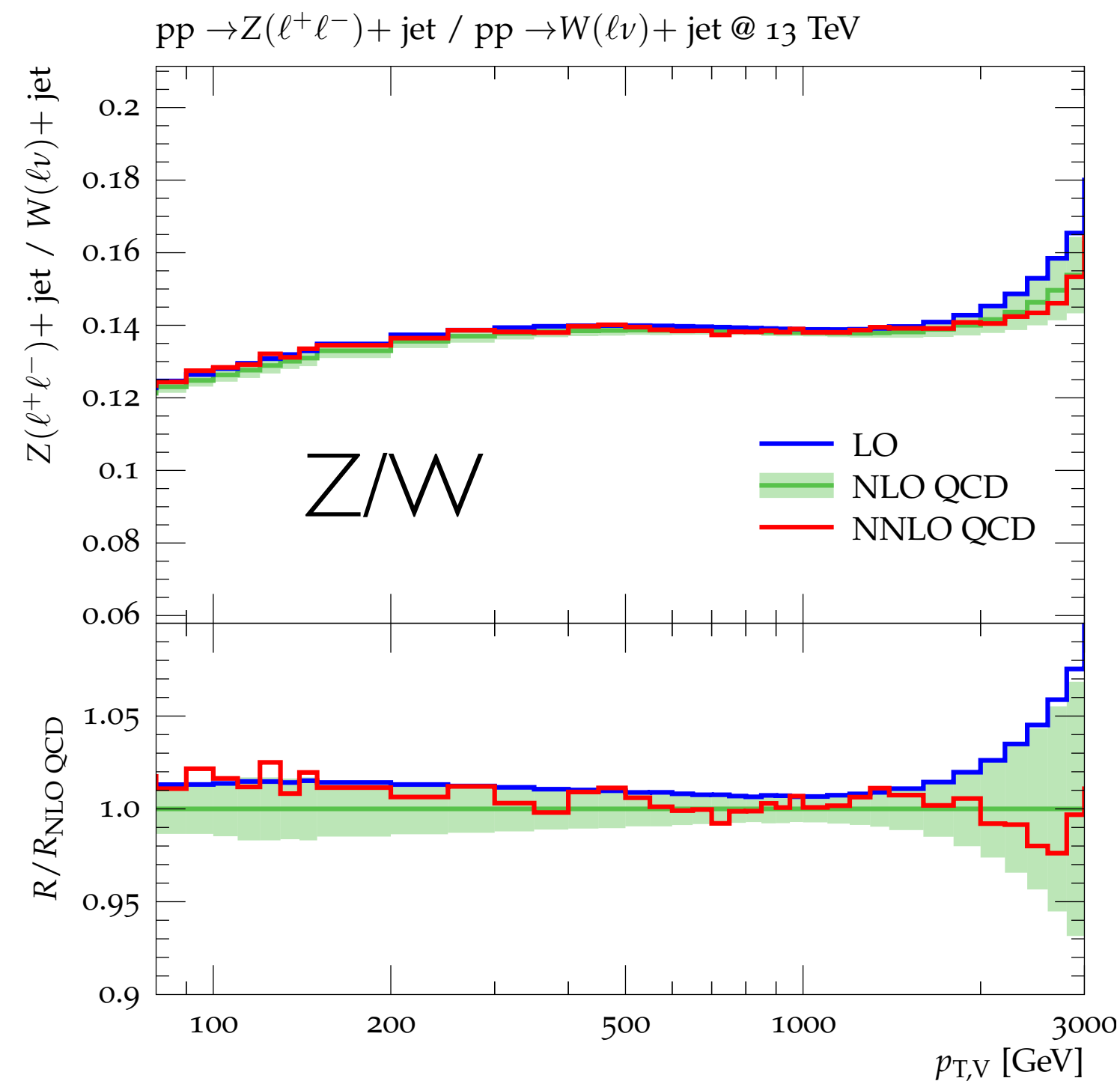


$\delta < 3-4\%$

# QCD uncertainties: ratios

## How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:  
NLO QCD uncertainties cancel at the  $< \sim 1\%$  level
- introduce **process correlation uncertainty** based on K-factor difference:  $\delta K_{\text{NLO}} = K_{\text{NLO}}^V - K_{\text{NLO}}^Z$   
→ effectively degrades precision of last calculated order

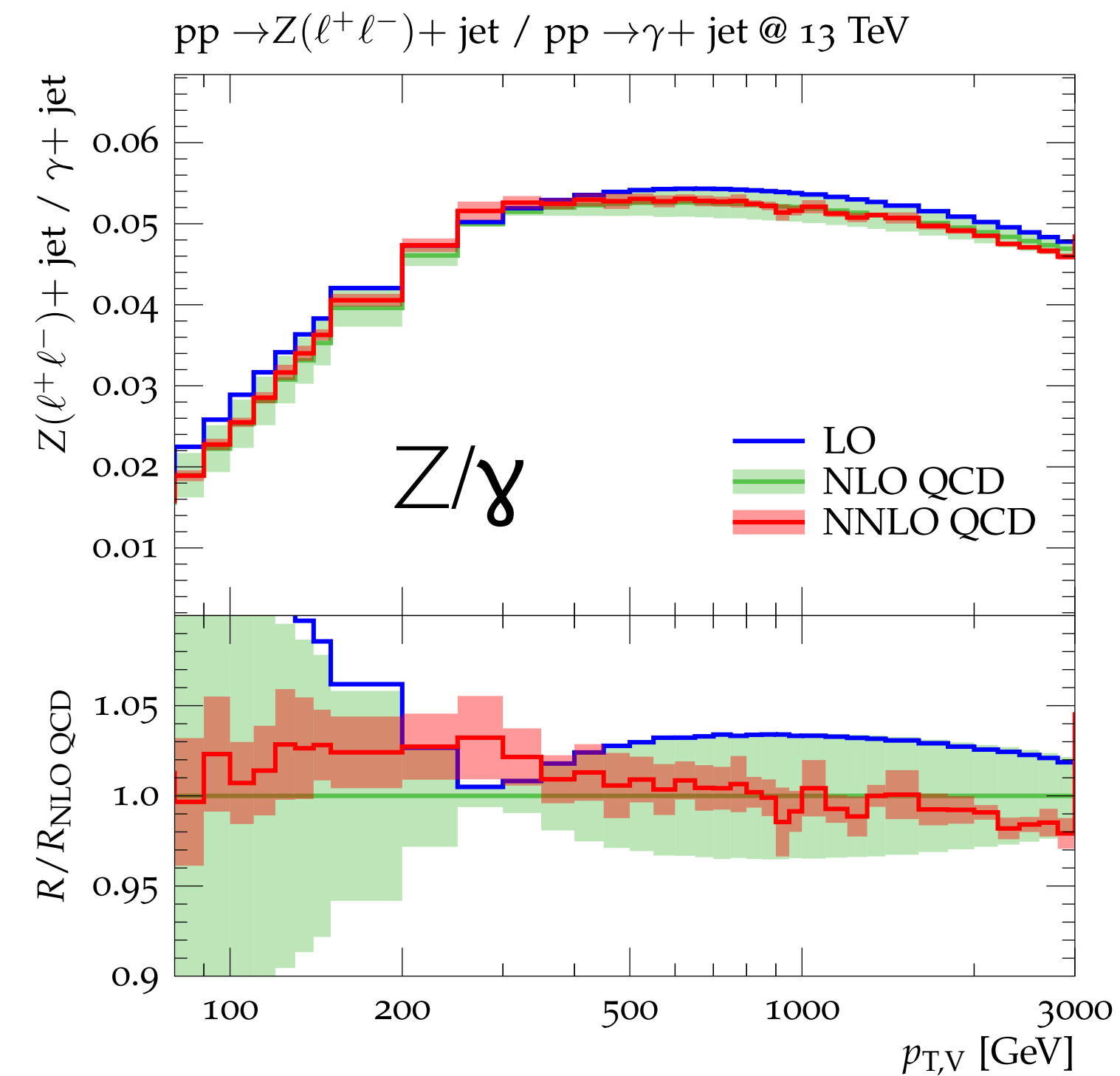
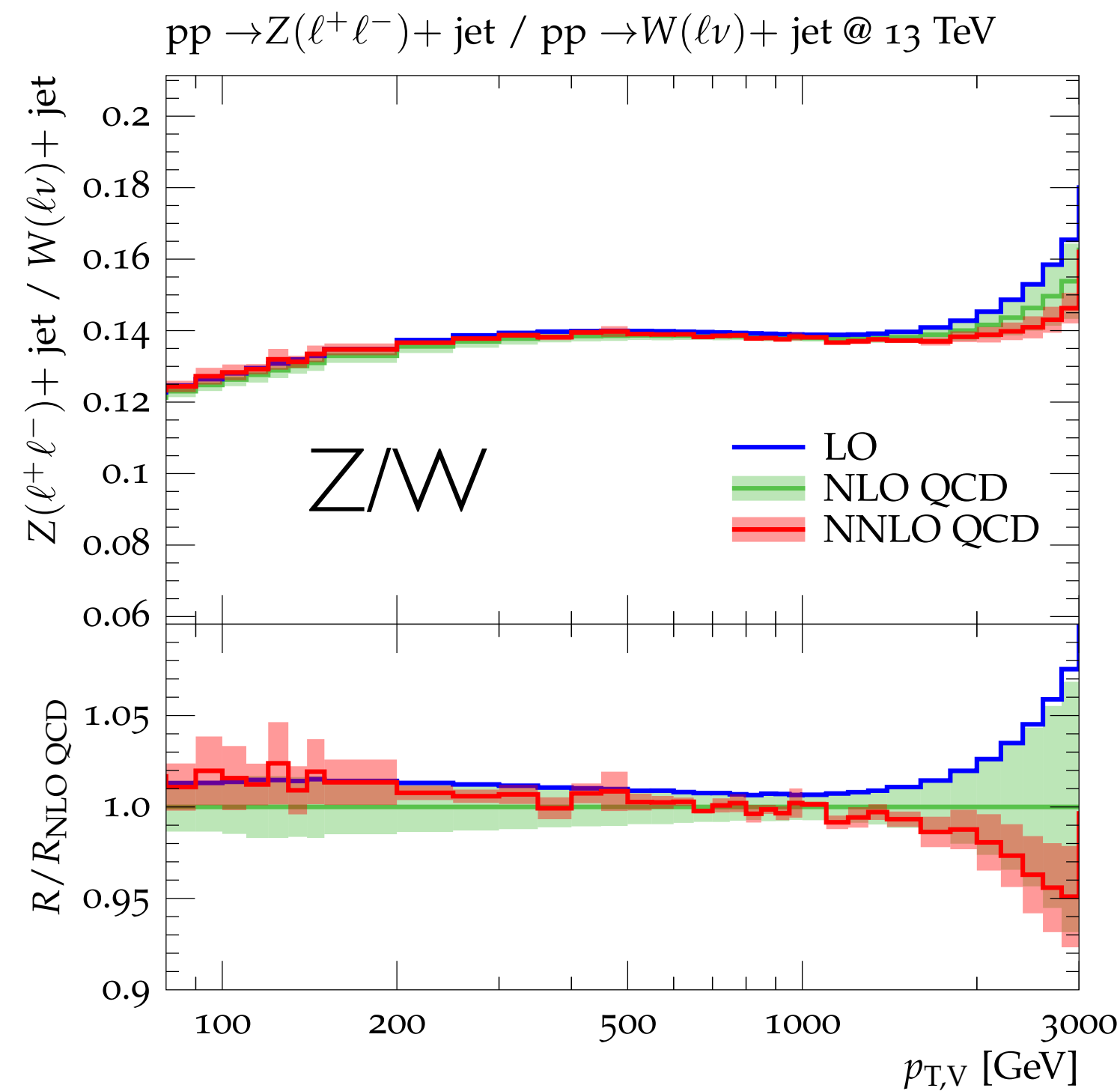


check against NNLO QCD!

# QCD uncertainties: ratios

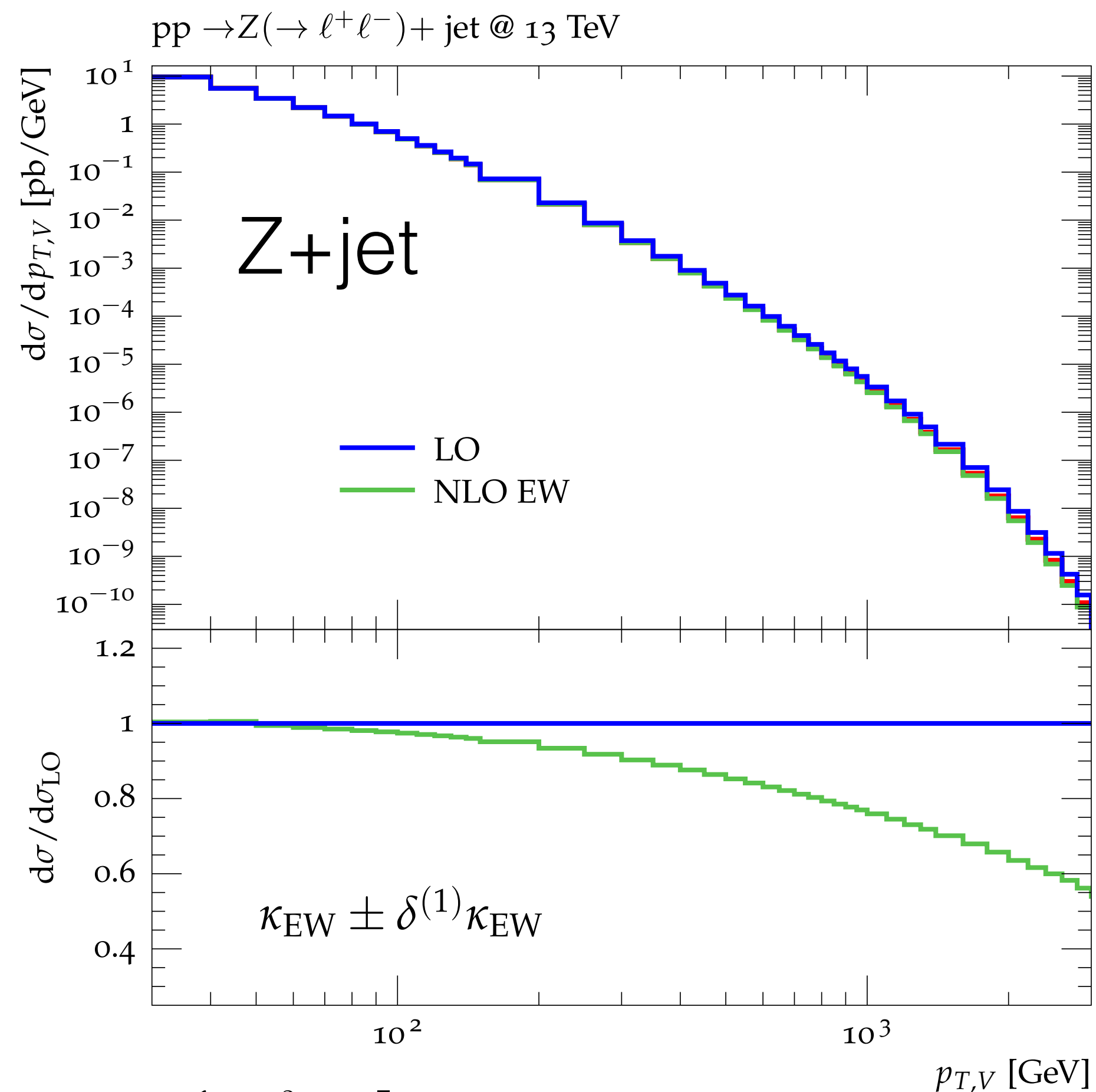
## How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:  
NLO QCD uncertainties cancel at the  $< \sim 1\%$  level
- introduce **process correlation uncertainty** based on K-factor difference:  $\delta K_{(N)NLO} = K_{(N)NLO}^V - K_{(N)NLO}^Z$   
→ effectively degrades precision of last calculated order



Uncertainty estimates at NNLO QCD

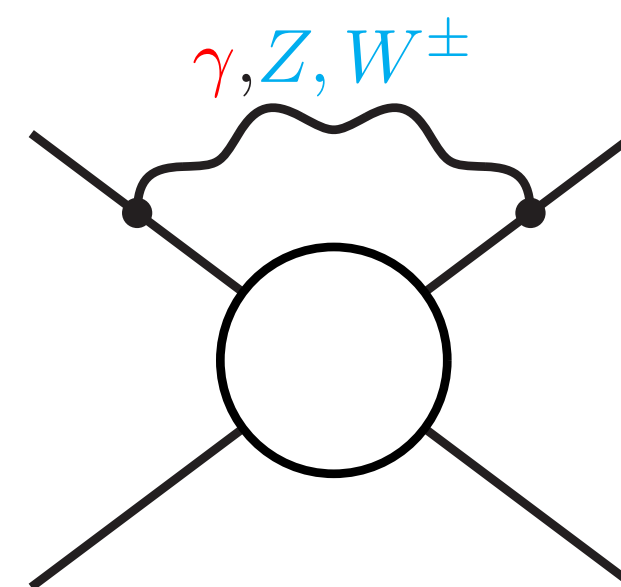
# Pure EW uncertainties



EW corrections become sizeable at large  $p_{T,V}$ : -30% @ 1 TeV

Origin: virtual EW Sudakov logarithms

How to estimate corresponding pure EW uncertainties of relative  $\mathcal{O}(\alpha^2)$ ?



$$d\sigma_{EW} = \exp \left\{ \int_{M_W^2}^{Q^2} \frac{dt}{t} \left[ \int_{M_W^2}^t d\tau \frac{\gamma(\alpha(\tau))}{\tau} + \chi(\alpha(t)) + \xi(\alpha(M_W^2)) \right] \right\} d\sigma_{\text{hard}},$$

$$= \left( 1 + \frac{\alpha}{\pi} \delta_{\text{Sud}}^{(1)} + \left( \frac{\alpha}{\pi} \right)^2 \delta_{\text{Sud}}^{(2)} + \dots \right) \left( 1 + \frac{\alpha}{\pi} \delta_{\text{hard}}^{(1)} + \left( \frac{\alpha}{\pi} \right)^2 \delta_{\text{hard}}^{(2)} + \dots \right) d\sigma_{\text{Born}} \quad \text{with}$$

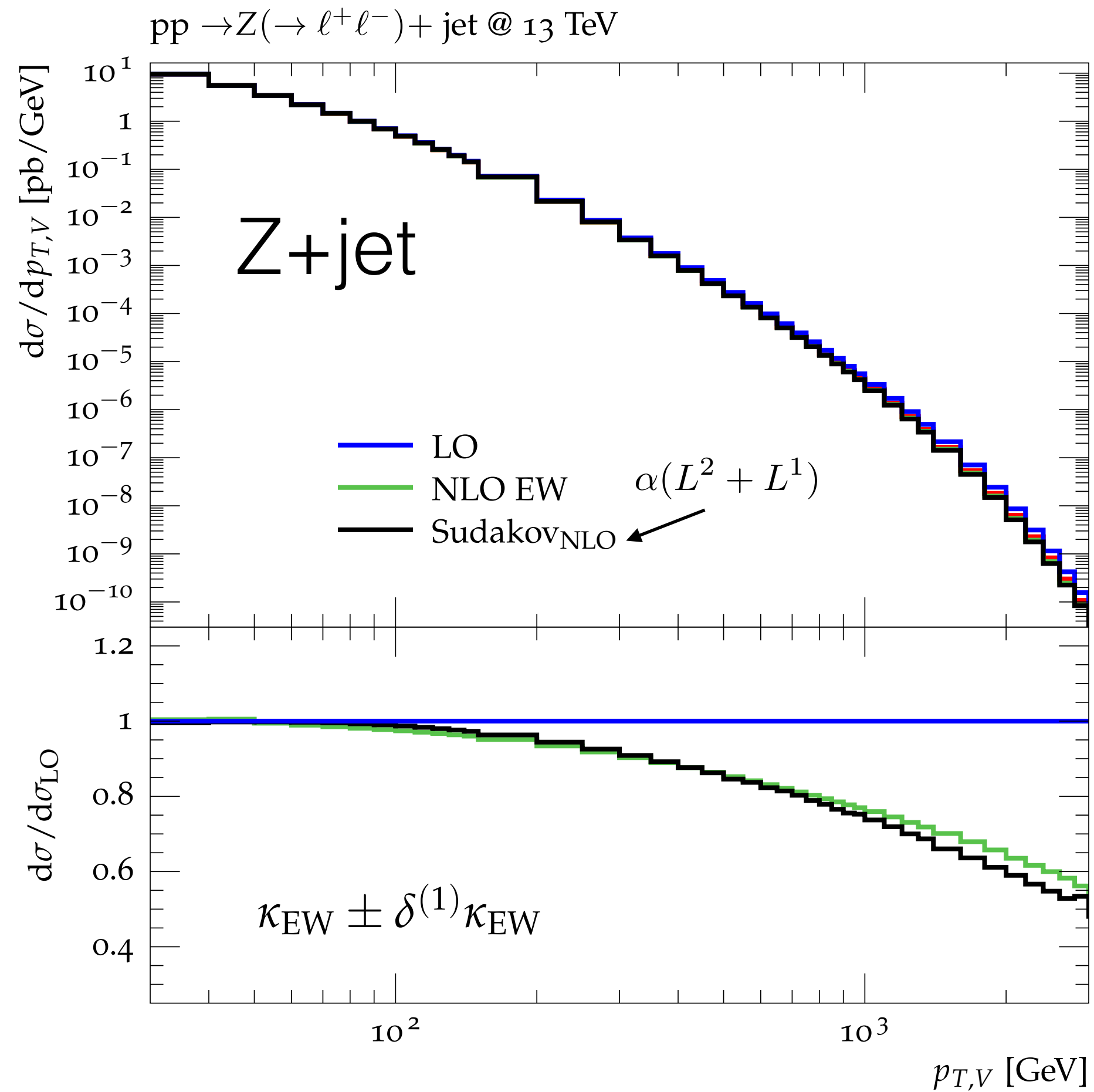
$\rightarrow \alpha^m \ln^n(Q^2/M_W^2) \quad \rightarrow \text{finite in limit } Q^2/M_W^2 \rightarrow \infty,$

$$\delta_{\text{Sud}}^{(1)} = \sum_{i,j} C_{2,ij}^{(1)} \ln^2 \left( \frac{Q_{ij}^2}{M^2} \right) + C_1^{(1)} \ln^1 \left( \frac{Q^2}{M^2} \right),$$

$$\delta_{\text{Sud}}^{(2)} = \sum_{i,j} C_{4,ij}^{(2)} \ln^4 \left( \frac{Q_{ij}^2}{M^2} \right) + C_3^{(2)} \ln^3 \left( \frac{Q^2}{M^2} \right) + \mathcal{O} \left[ \ln^2 \left( \frac{Q^2}{M^2} \right) \right]$$

# Pure EW uncertainties

[JML et. al.: 1705.04664]



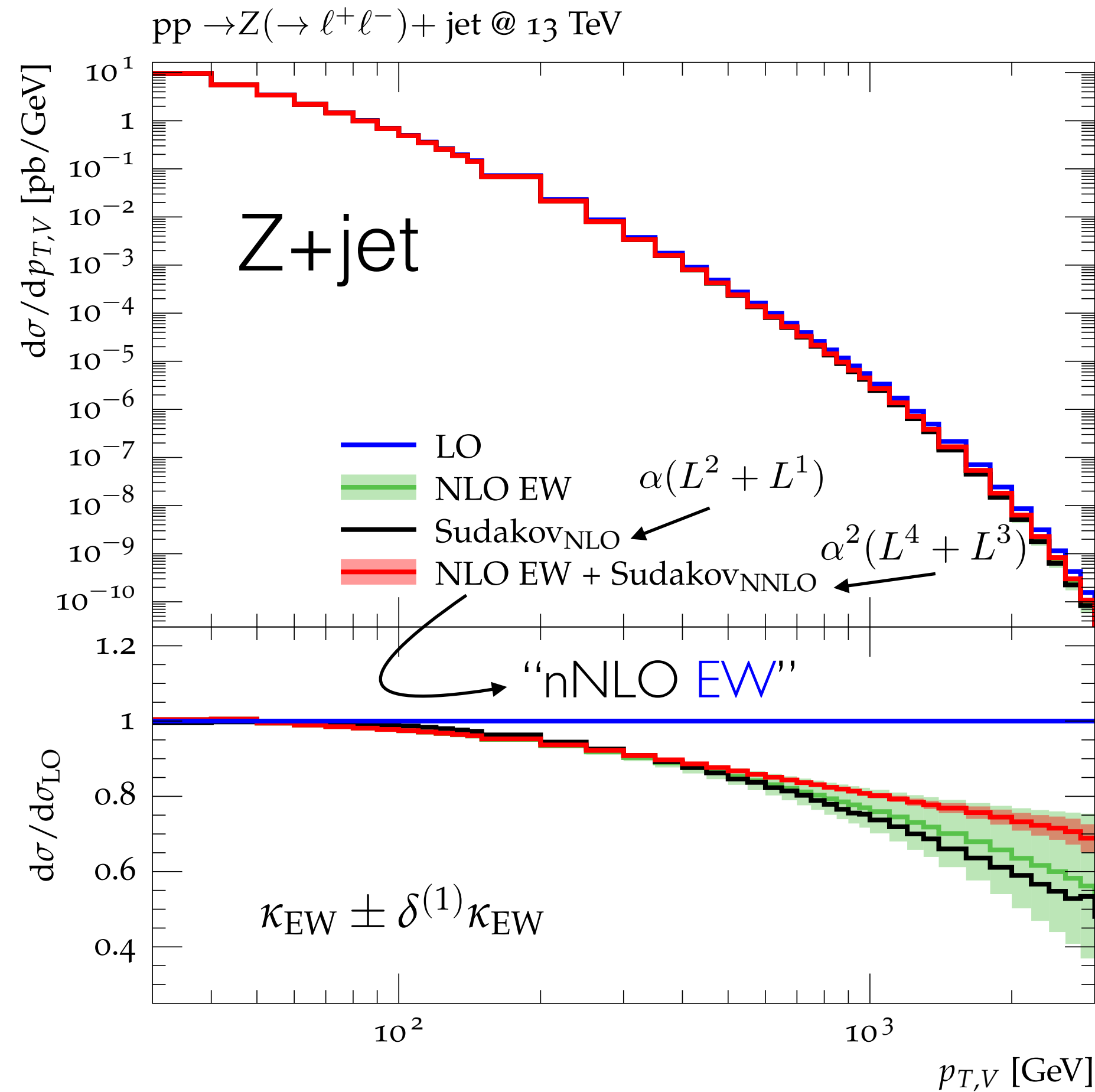
Large EW corrections dominated by Sudakov logs!

$$\kappa_{\text{nLO EW}} = \frac{\alpha}{\pi} [\delta^{(1)}_{\text{Sud}}]$$

$$\kappa_{\text{NLO EW}} = \frac{\alpha}{\pi} [\delta^{(1)}_{\text{hard}} + \delta^{(1)}_{\text{Sud}}]$$

# Pure EW uncertainties

[JML et. al.: 1705.04664]



Large EW corrections dominated by Sudakov logs!



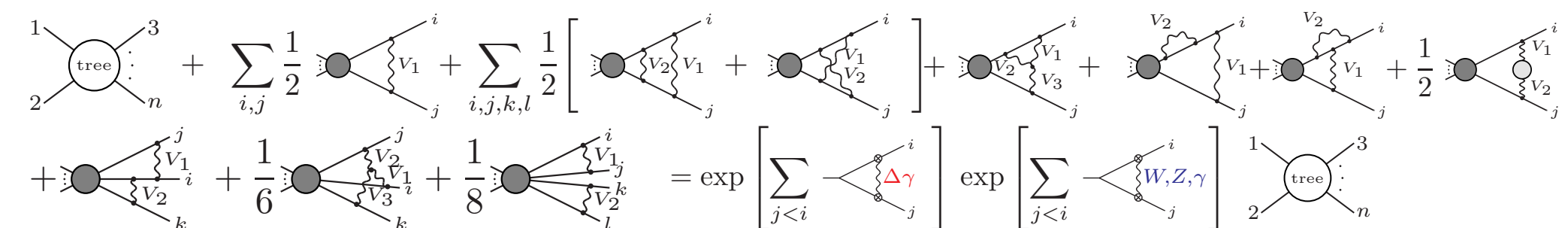
Uncertainty estimate of (N)NLO EW from naive exponentiation  $\times 2$ :

$$\delta^{(1)}\kappa_{EW} \simeq \frac{2}{k!} \left( \kappa_{NLO,EW} \right)^k \quad (\text{correlated})$$



check against two-loop Sudakov logs

[Kühn, Kulesza, Pozzorini, Schulze; 05-07]



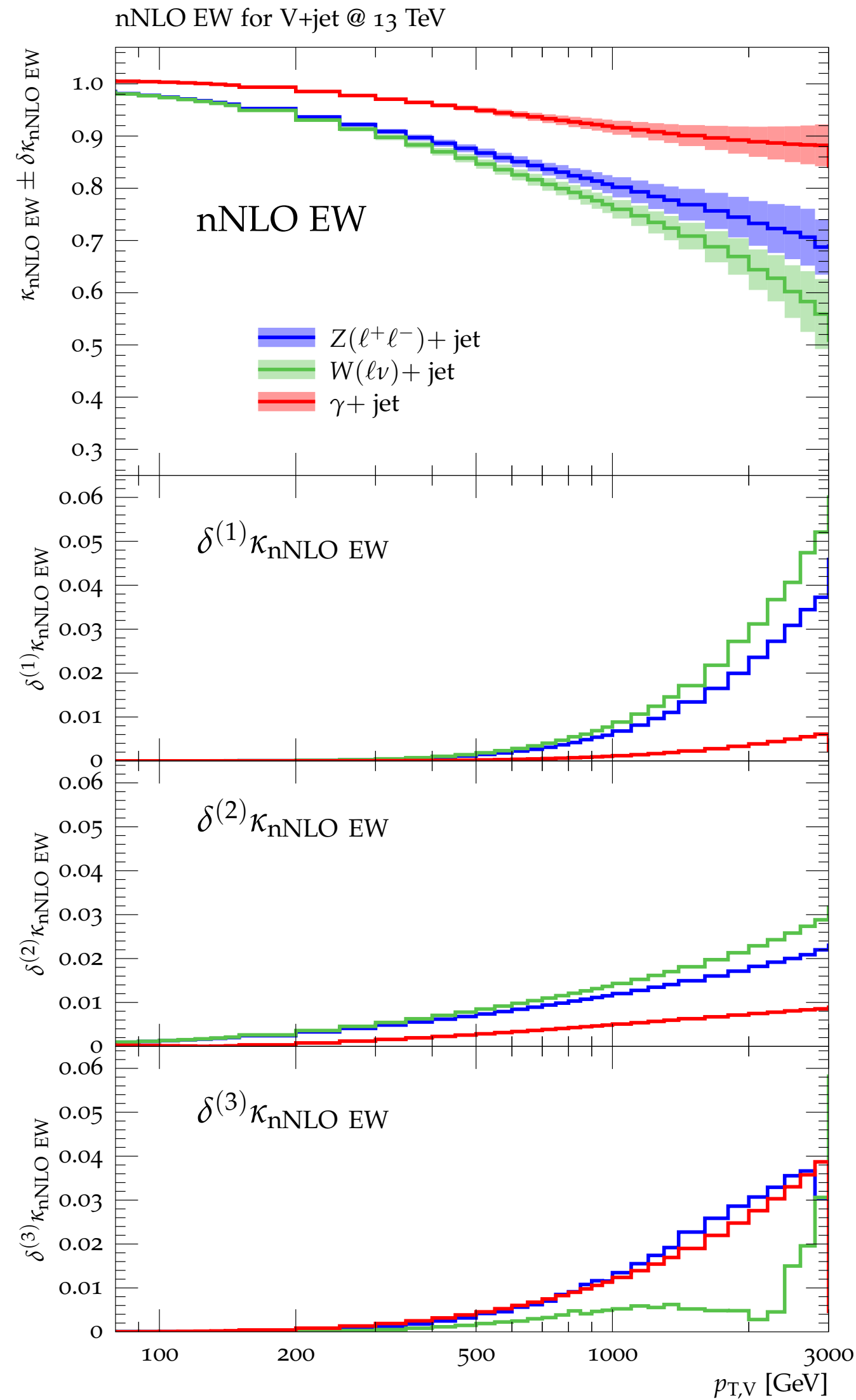
$$\kappa_{nLO\ EW} = \frac{\alpha}{\pi} [\delta^{(1)}_{Sud}]$$

$$\kappa_{NNLO\ Sud} = \left( \frac{\alpha}{\pi} \right)^2 \delta^{(2)}_{Sud}$$

$$\kappa_{NLO\ EW} = \frac{\alpha}{\pi} \left[ \delta^{(1)}_{hard} + \delta^{(1)}_{Sud} \right]$$

$$\kappa_{nNLO\ EW} = \kappa_{NLO\ EW} + \kappa_{NNLO\ Sud}$$

# Pure EW uncertainties



## nNLO EW corrections at 1 TeV

- ▶ -10% for  $\gamma$ +jets
- ▶ -20% for Z+jet
- ▶ -25% for W+jet

$$d\sigma_{\text{EW}} = \left[ 1 + \frac{\alpha}{\pi} \left( \delta_{\text{hard}}^{(1)} + \delta_{\text{Sud}}^{(1)} \right) + \left( \frac{\alpha}{\pi} \right)^2 \left( \delta_{\text{Sud}}^{(2)} + \delta_{\text{Sud}}^{(1)} \delta_{\text{hard}}^{(1)} + \delta_{\text{hard}}^{(1)} \delta_{\text{hard}}^{(1)} + \delta_{\text{hard}}^{(2)} \right) + \left( \frac{\alpha}{\pi} \right)^3 \left( \delta_{\text{Sud}}^{(3)} \dots \right) \right]$$

- 'higher-order Sudakov logs'

$$\delta^{(1)} \kappa_{\text{EW}}^{(V)}(x) = \frac{2}{3} \kappa_{\text{NLO EW}}^{(V)}(x) \kappa_{\text{NNLO Sud}}^{(V)}(x) \quad (\text{correlated})$$

Additional uncorrelated uncertainties:

- 'hard non-log NNLO EW effects I'

$$\delta^{(2)} \kappa_{\text{EW}}^{(V)}(x) = 0.05 \kappa_{\text{NLO EW}}^{(V)}(x) \quad (\text{uncorrelated})$$

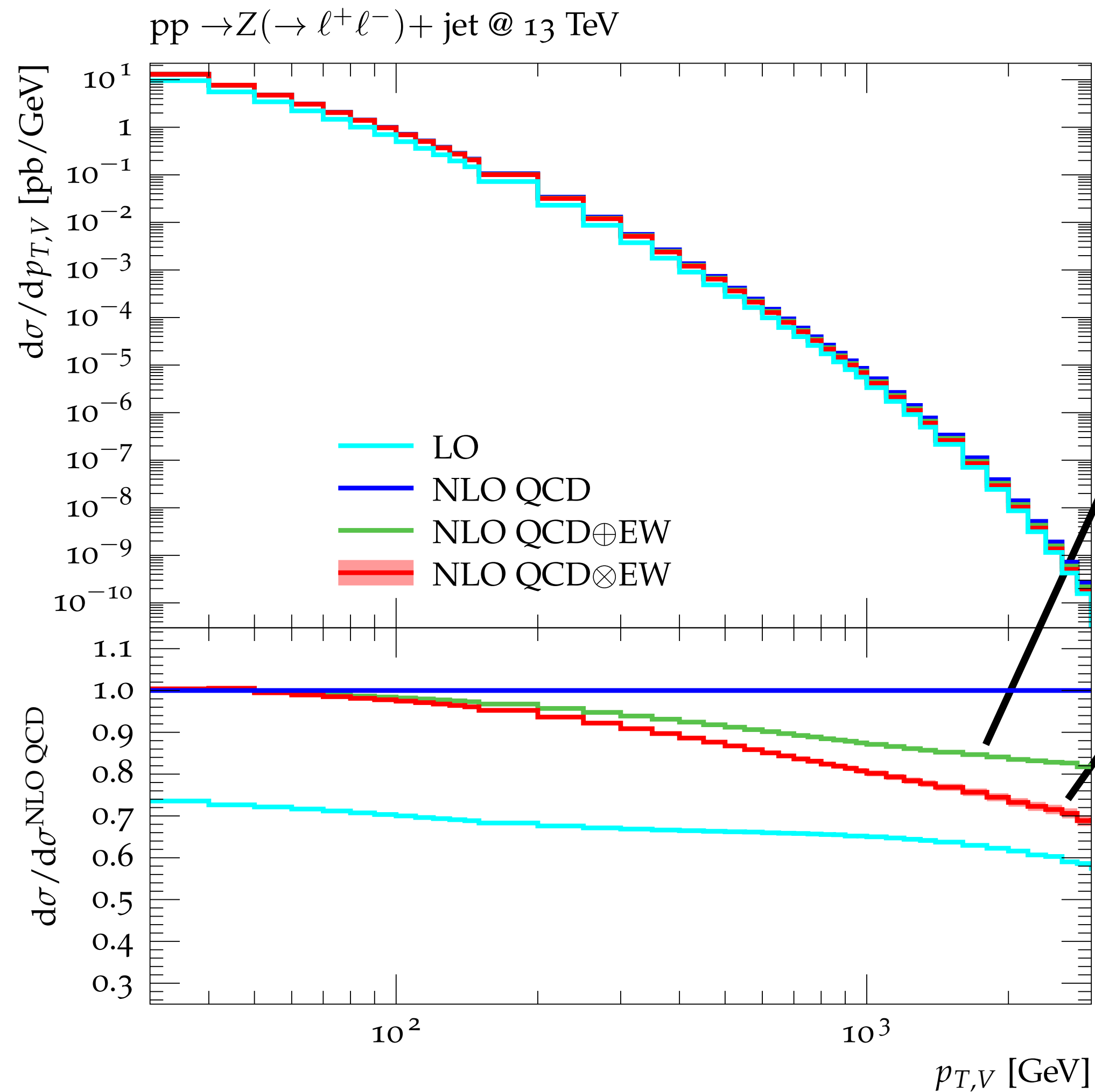
$$\Leftrightarrow \delta_{\text{hard}}^{(2)} \leq \frac{0.05\pi}{\alpha} \delta_{\text{hard}}^{(1)} \simeq 20 \delta_{\text{hard}}^{(1)}$$

- 'hard non-log NNLO EW effects II'

$$\delta^{(3)} \kappa_{\text{EW}}^{(V)}(x) = \kappa_{\text{NNLO Sud}}^{(V)}(x) - \frac{1}{2} [\kappa_{\text{NLO EW}}^{(V)}(x)]^2 \quad (\text{uncorrelated})$$

estimate of typical size of  $\left[ \delta_{\text{hard}}^{(1)} \right]^2$  or  $\delta_{\text{hard}}^{(1)} \times \delta_{\text{Sud}}^{(1)}$ .

# Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative  $\mathcal{O}(\alpha\alpha_s)$  have to be considered.

## Additive combination

$$\sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma^{\text{LO}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} + \delta\sigma_{\text{EW}}^{\text{NLO}}$$

(no  $\mathcal{O}(\alpha\alpha_s)$  contributions)

## Multiplicative combination

$$\sigma_{\text{QCD} \times \text{EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left( 1 + \frac{\delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right)$$

(try to capture some  $\mathcal{O}(\alpha\alpha_s)$  contributions, e.g. EW Sudakov logs  $\times$  soft QCD)

Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

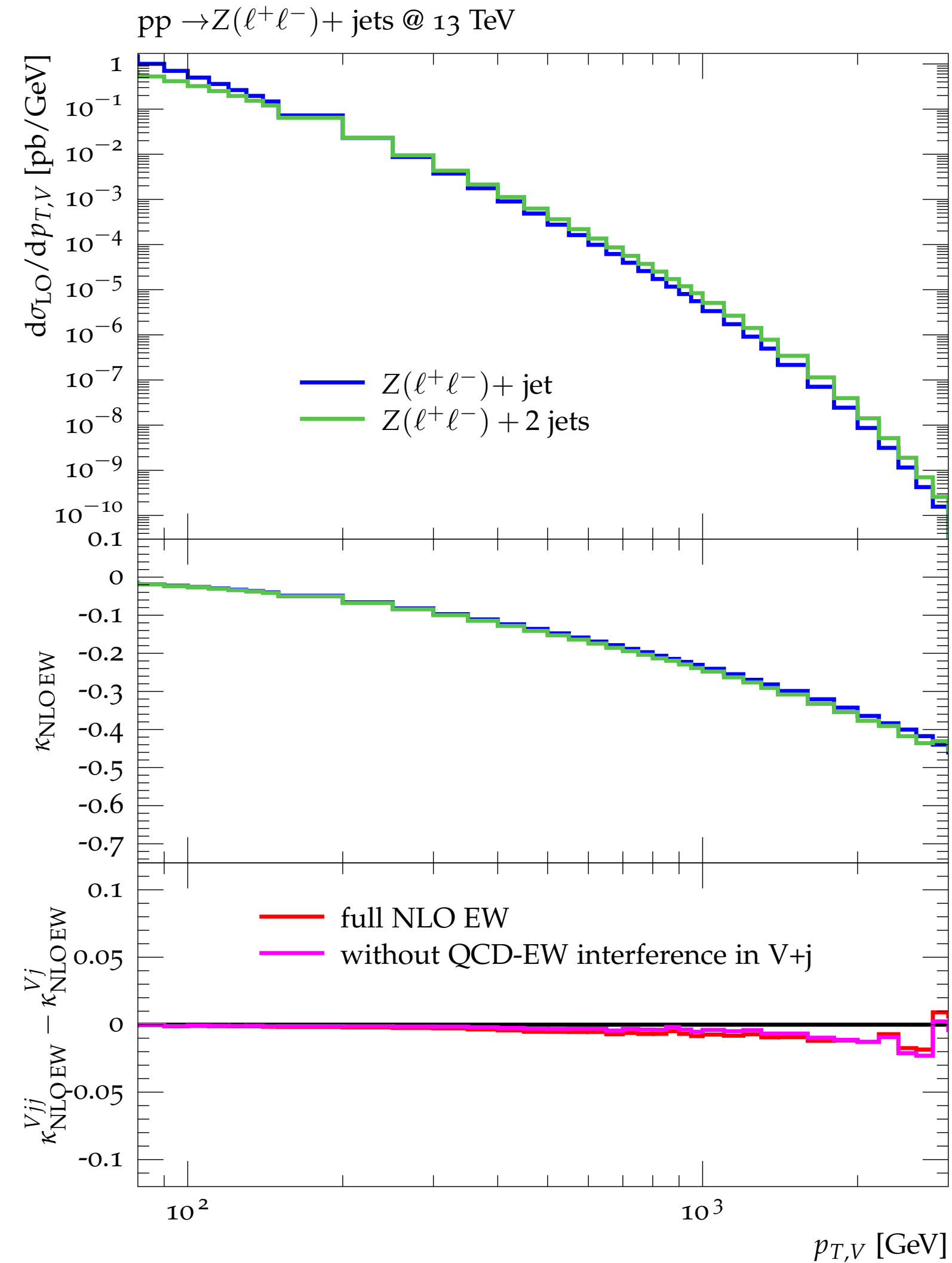
$$K_{\text{QCD} \otimes \text{EW}} - K_{\text{QCD} \oplus \text{EW}} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!



# Mixed QCD-EW uncertainties



Bold estimate:

Consider real  $\mathcal{O}(\alpha\alpha_s)$  correction to V+jet

$\simeq$  NLO EW to V+2jets

and we observe

$$\left. \frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}} \right|_{V+2\text{jet}} - \left. \frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}} \right|_{V+1\text{jet}} \lesssim 1\%$$

strong support for

- factorization
- multiplicative QCD  $\times$  EW combination

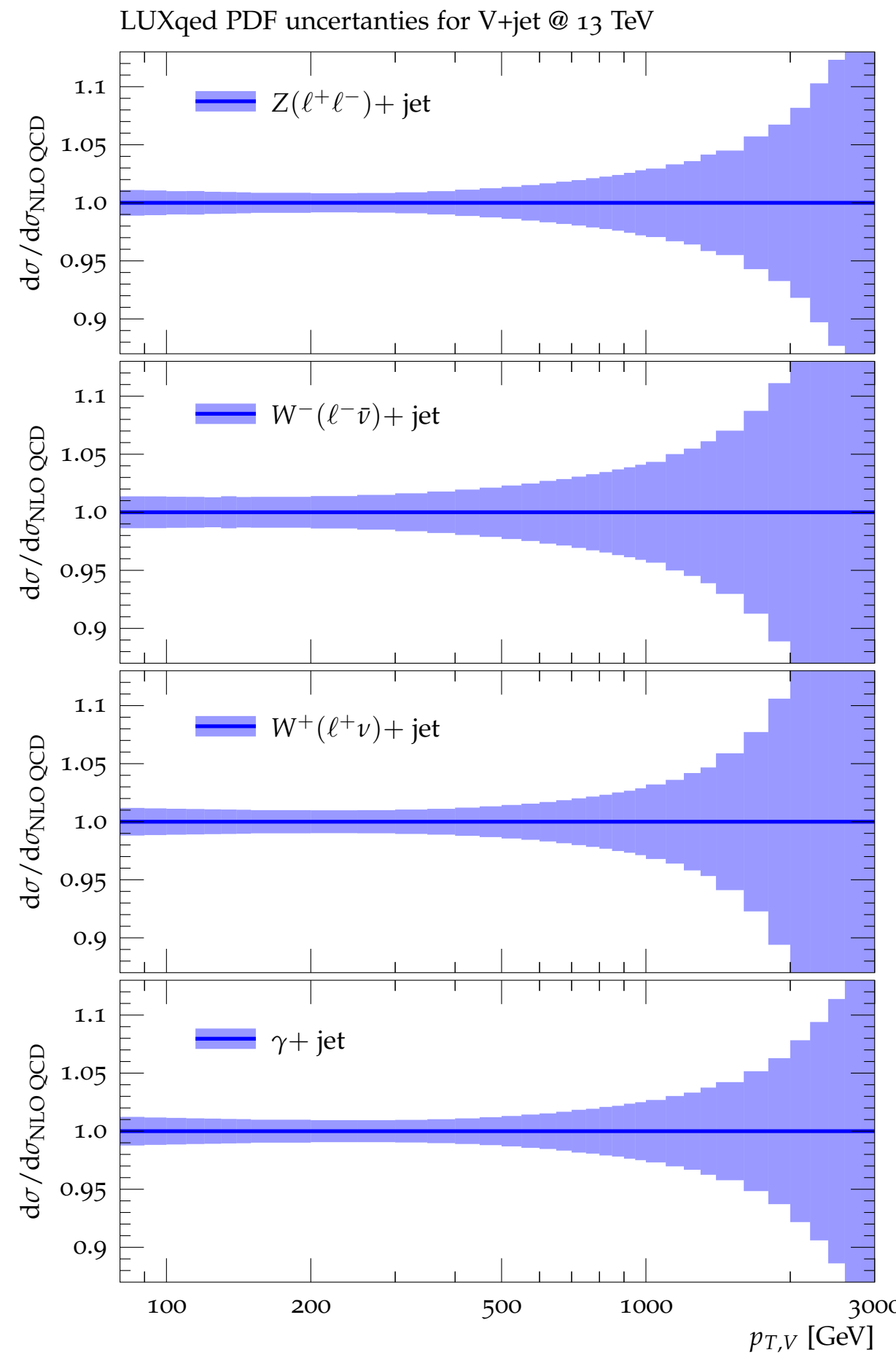
Estimate of non-factorising contributions

(correlated)

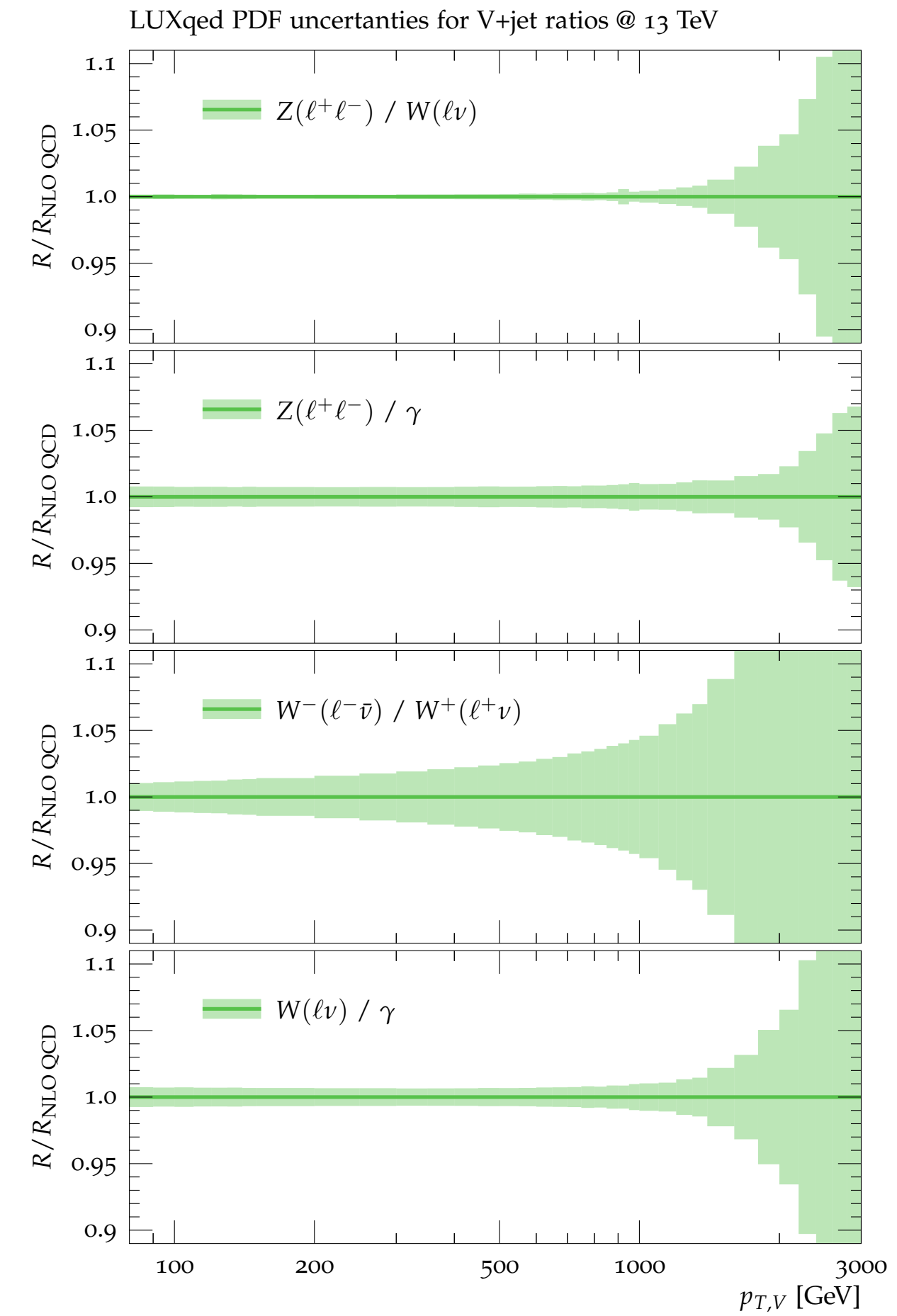
$$\delta K_{\text{mix}}^{(V)}(x) = 0.1 \left[ K_{\text{TH},\oplus}^{(V)}(x, \vec{\mu}_0) - K_{\text{TH},\otimes}^{(V)}(x, \vec{\mu}_0) \right]$$

(tuned to cover above difference of EW K-factors )

# PDF uncertainties (LUXqed=PDF4LHC)

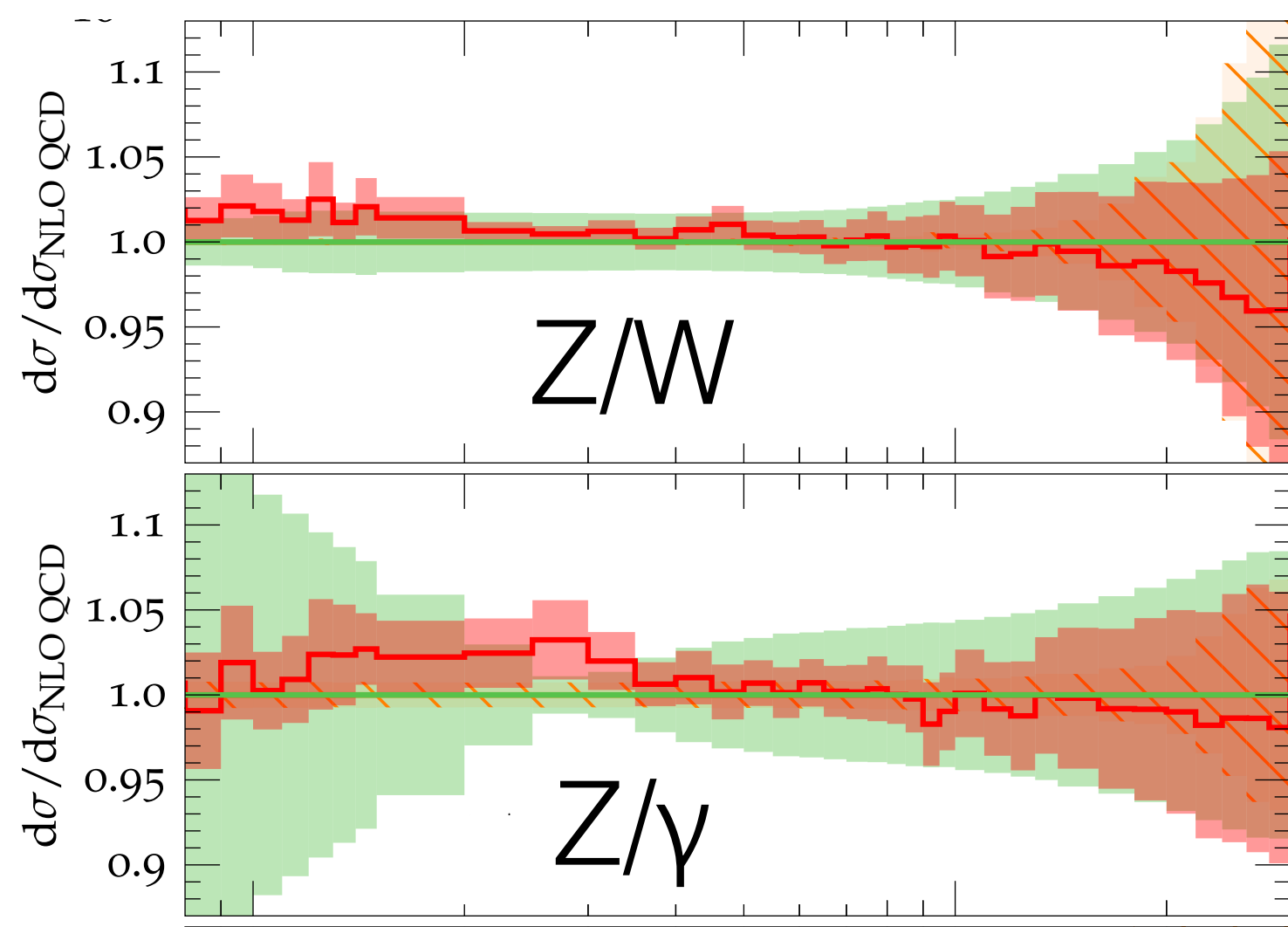


- $\delta_{\text{PDF}} < 2\%$  for  $p_{T,V} < 800$  GeV
- $\delta_{\text{PDF}} < 5\%$  for  $p_{T,V} < 1500$  GeV



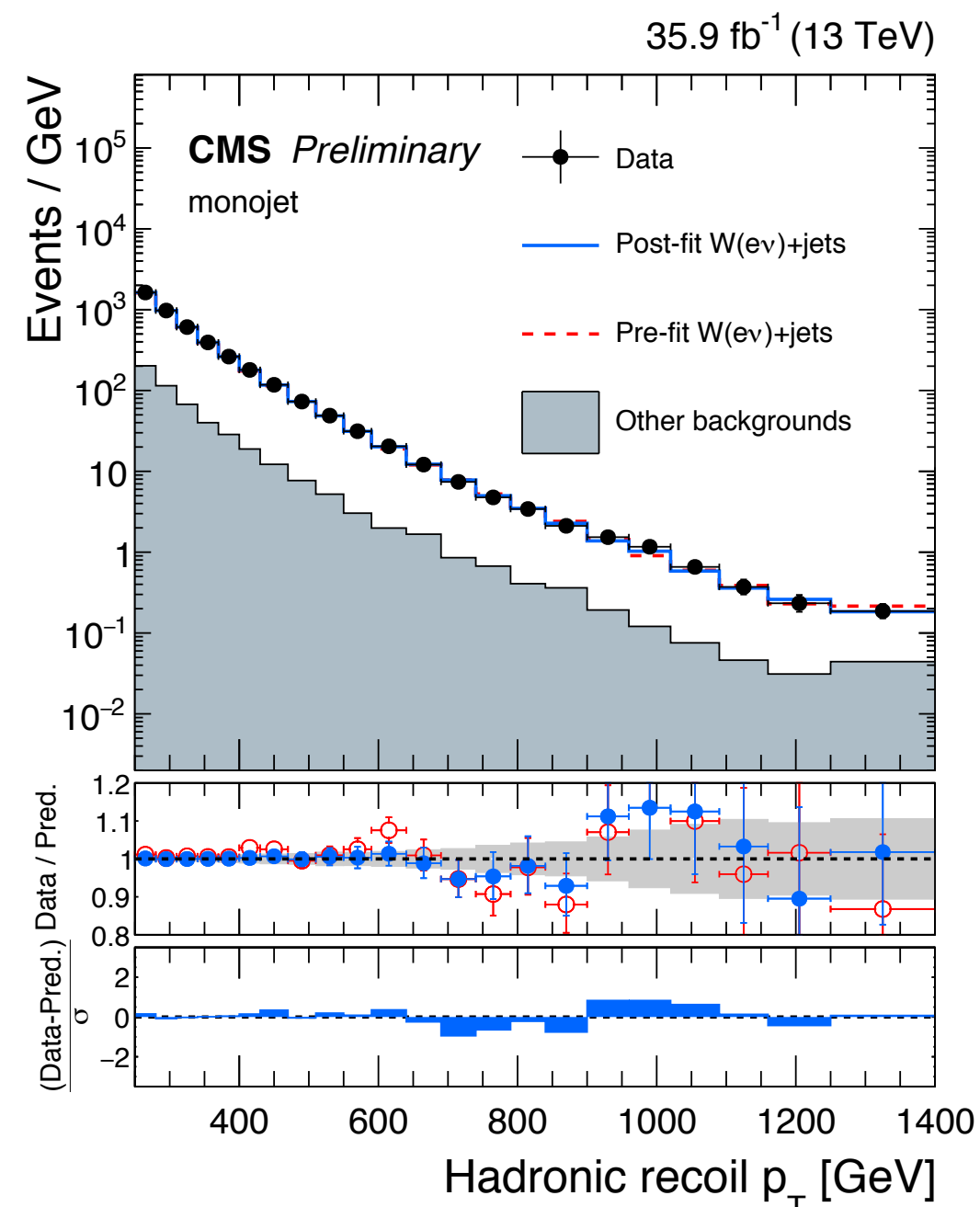
- Z/W:  $\delta_{\text{PDF}} < 0.5\%(2\%)$  for  $p_{T,V} < 800$  GeV(1.5 TeV)
- Z/γ & W/γ:  $\delta_{\text{PDF}} < 2\%$  for  $p_{T,V} < 1.3$  TeV
- W-/W+:  $\delta_{\text{PDF}} > 5\%$  for  $p_{T,V} < 1$  TeV  
(due to large uncertainties on u/d ratio at large Bjorken-x)

# Combined uncertainties on $V$ +jets ratios



- $\delta_{Z/W} = 1-3\%$  for  $p_T < 1$  TeV
- $\delta_{Z/\gamma} = 3-5\%$  for  $p_T < 1$  TeV

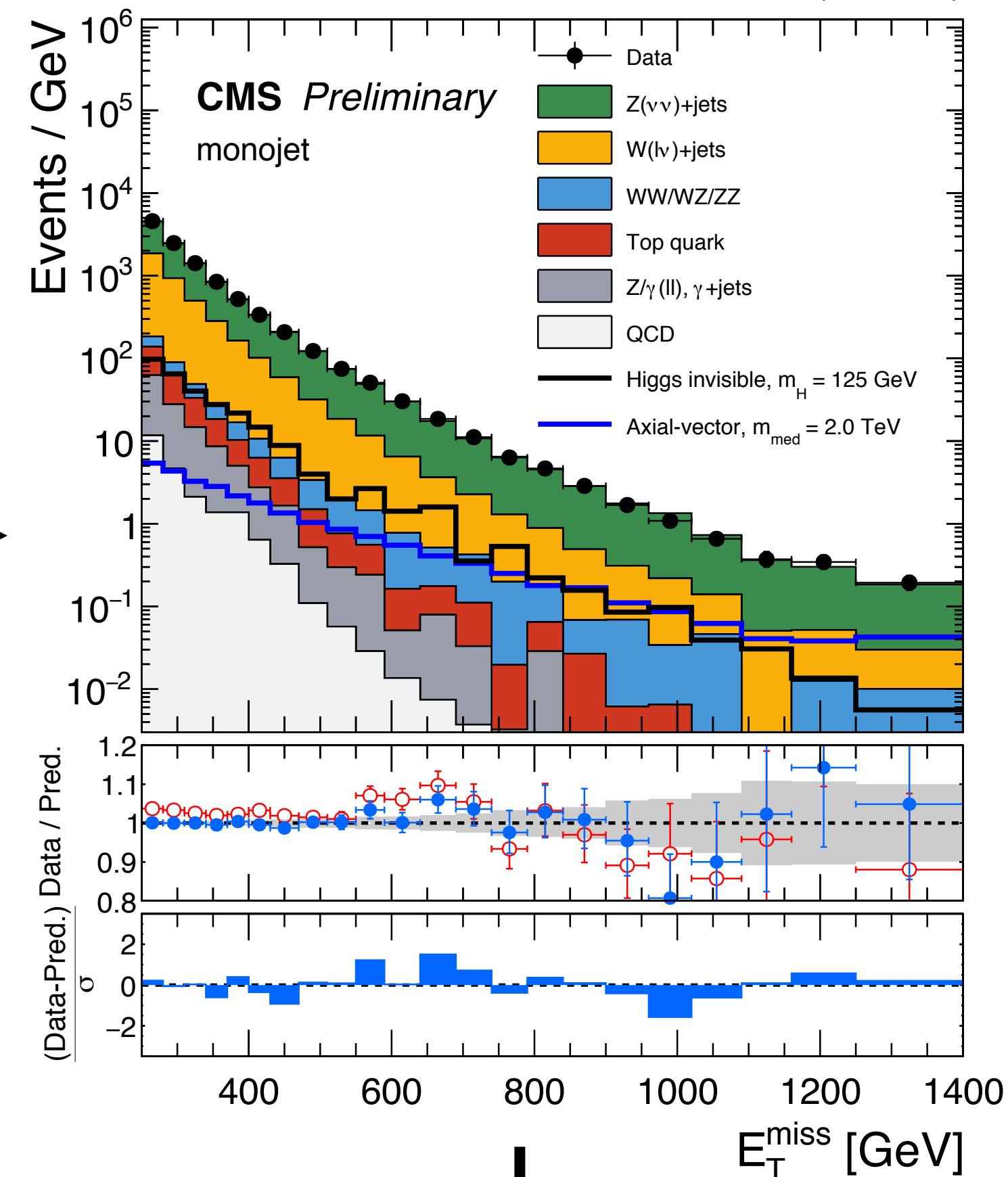
CR



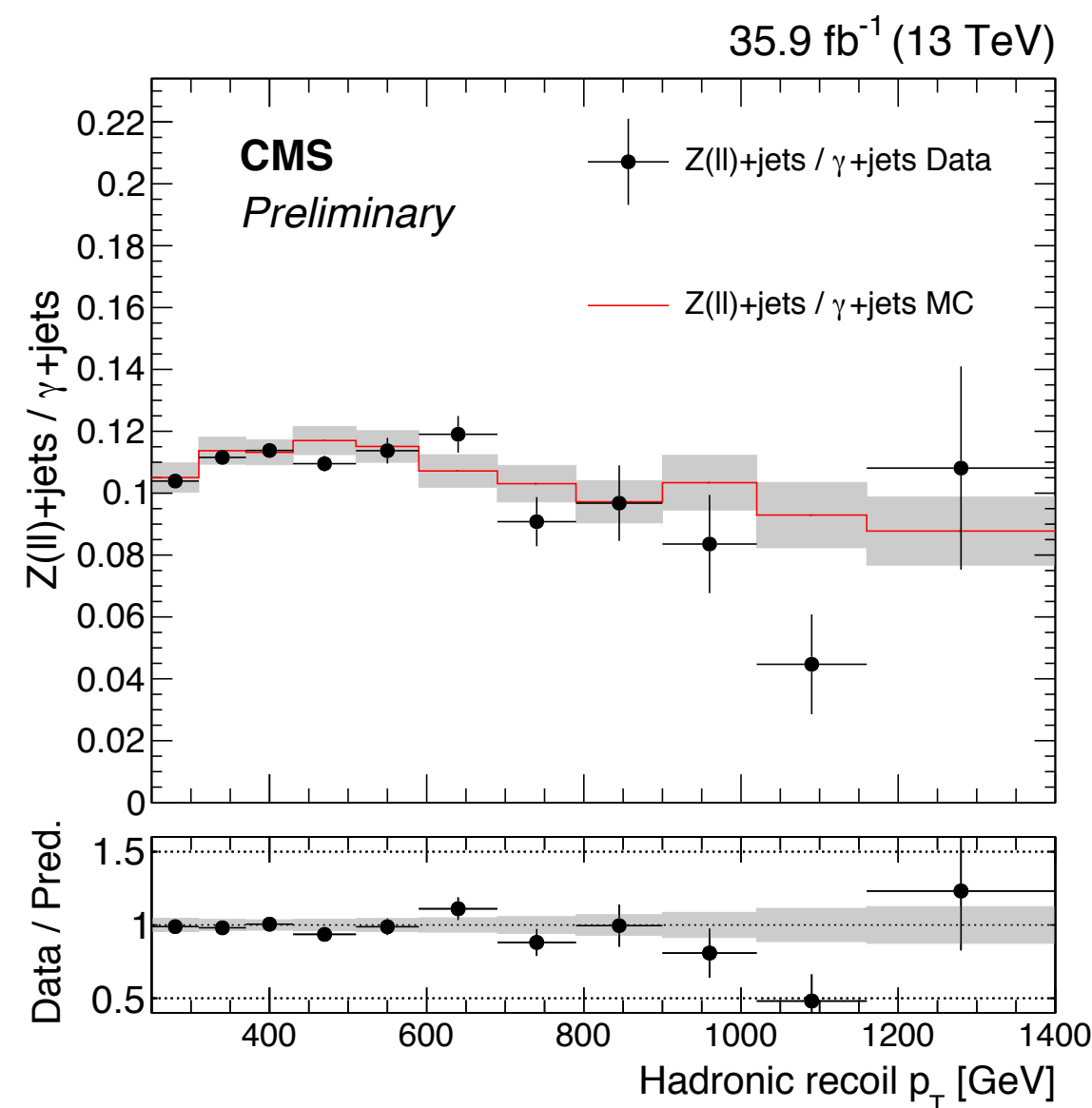
SR

[CMS PAS EXO-16-048]

35.9 fb<sup>-1</sup> (13 TeV)



Unprecedented limits on monojet DM production!



# Conclusions

- ▶ There is no clear scale/signature for new physics effects:  
Let's explore the unknown leaving no stone unturned!
- ▶ Precision is key for SM(+Higgs) measurements,  
as well as for BSM searches.
- ▶ Detailed understanding of theory systematics is  
becoming pivotal.
- ▶ At high energies inclusion of **EW** corrections *crucial*  
due to large Sudakov logs
- ▶ Automation of higher-order corrections allows for  
detailed phenomenological analyses for a multitude of  
process. But: need to look inside the black box.
- ▶ Let's push the precision frontier!



BACKUP

# The Open Loops algorithm: one-loop recursion

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

► Recursively build “open loops” polynomials  $\mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\beta$

- disentangle loop momentum  $q$  from the coefficients

$$\mathcal{N}_\alpha^\beta(\mathcal{I}_n; q) = \sum_{r=0}^n \mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\beta(\mathcal{I}_n) q^{\mu_1} \dots q^{\mu_r}$$

$$X_{\gamma\delta}^\beta = Y_{\gamma\delta}^\beta + q^\nu Z_{\nu; \gamma\delta}^\beta$$

- recursion in  $d=4$ :

$$\mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\beta(\mathcal{I}_n) = \left[ Y_{\gamma\delta}^\beta \mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^\gamma(\mathcal{I}_{n-1}) + Z_{\mu_1; \gamma\delta}^\beta \mathcal{N}_{\mu_2 \dots \mu_r; \alpha}^\gamma(\mathcal{I}_{n-1}) \right] w^\delta(i_n)$$

- model and process independent algorithm
- numerical implementation requires only universal building blocks, derived from the Feynman rules of the theory (full SM implemented; also HEFT; more BSM/EFT to come)

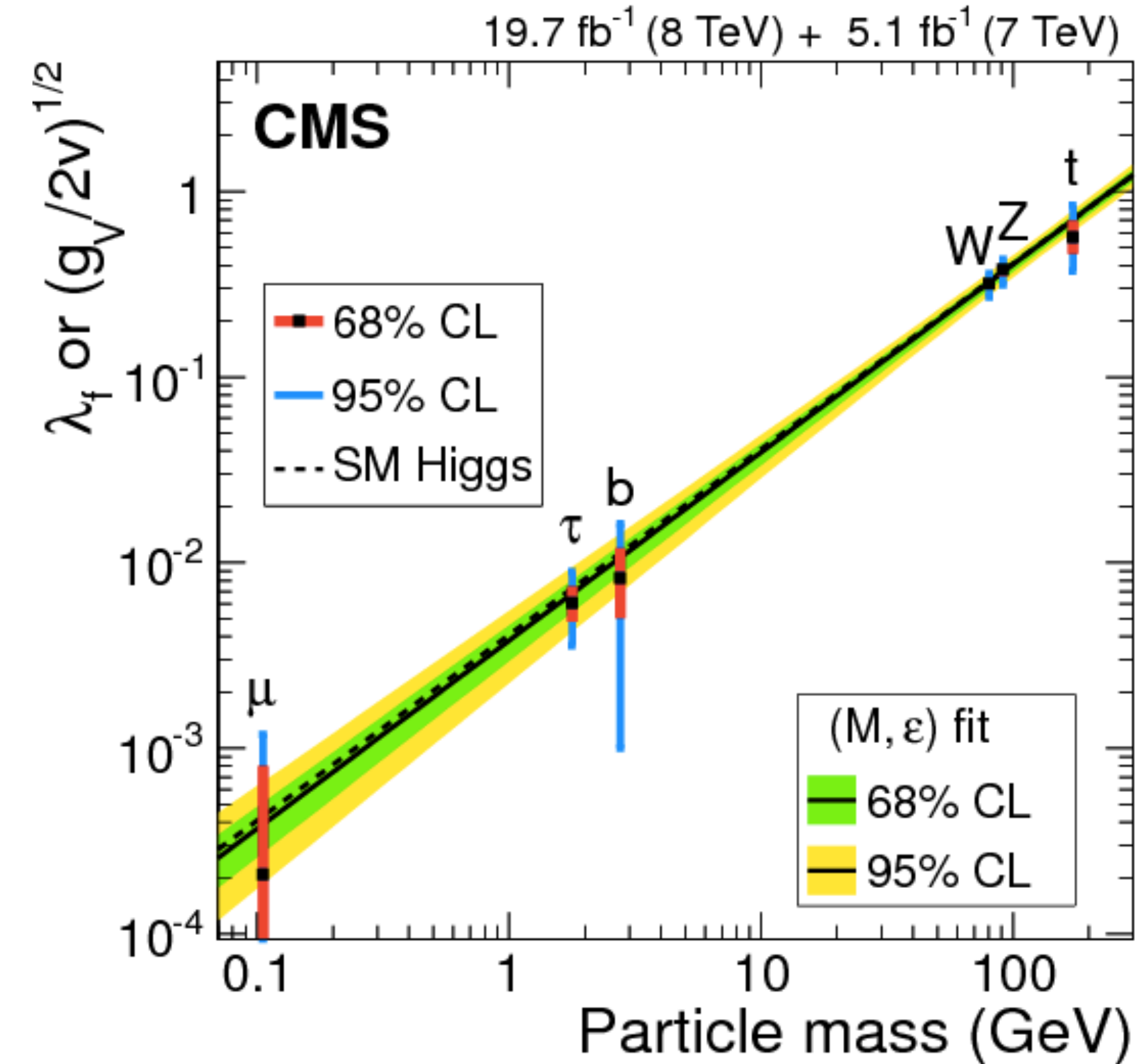
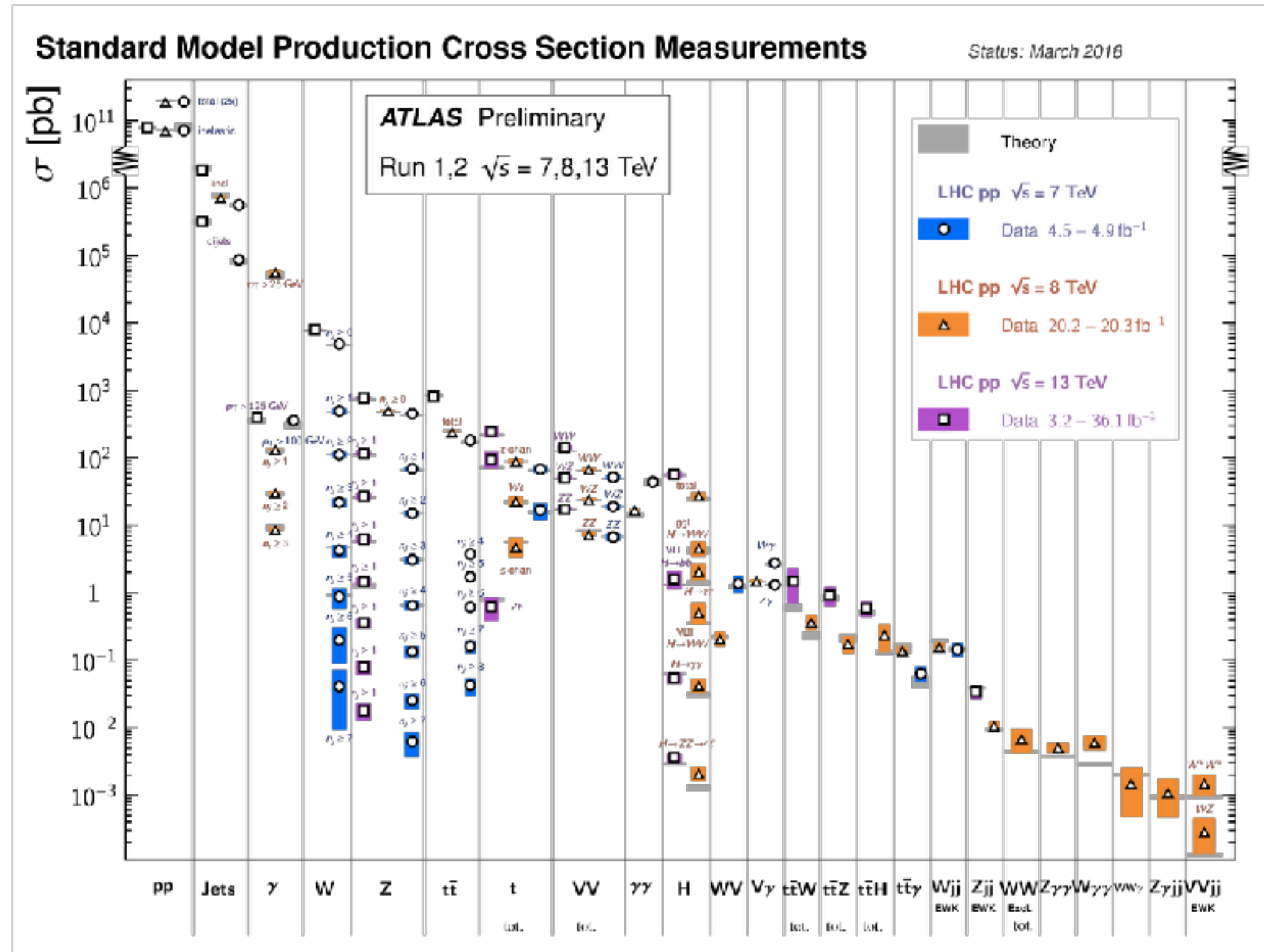
►  $\epsilon$ -dimensional part of the numerator  $\times$  poles of the tensor integrals yield  $R_2$  rational terms

$$R_2 = ([\mathcal{N}]_{d=4-2\epsilon} - [\mathcal{N}]_{d=4}) \cdot [TI]_{UV}$$

- numerical recursion in  $D=4 \rightarrow$  restore  $R_2$  via process independent counter terms

[Draggiotis, Garzelli, Malamos, Papadopoulos, Pittau '09, '10; Shao, Zhang, Chao '11]

# Success of Run-I & Run-II of the LHC



Overall remarkable data vs. theory agreement

➔ Precision tests of the SM at the quantum level in a multitude of processes

# Search limits

## ATLAS SUSY Searches\* - 95% CL Lower Limits

December 2017

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{miss}$	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
<b>Inclusive Searches</b>								
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	0	2-6 jets	Yes	36.1		1.57 TeV	$m(\tilde{g}) < 200 \text{ GeV}, m(1^{st} \text{ gen. } \tilde{q}) = m(2^{nd} \text{ gen. } \tilde{q})$	1712.02332
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	790 GeV		$m(\tilde{g}), m(\tilde{q}) < 530 \text{ GeV}$	1711.01301
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	0	2-6 jets	Yes	36.1		2.42 TeV	$m(\tilde{g}) < 200 \text{ GeV}$	1712.02332
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	0	2-6 jets	Yes	36.1		2.91 TeV	$m(\tilde{g}) < 200 \text{ GeV}, m(\tilde{q}) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1712.02332
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	$e, \mu$	2 jets	Yes	14.7		1.7 TeV	$m(\tilde{g}) < 300 \text{ GeV}$	1611.05791
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	$3e, \mu$	4 jets	-	36.1		1.87 TeV	$m(\tilde{g}) < 1 \text{ GeV}$	1706.03731
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	0	7-11 jets	Yes	36.1		1.8 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	1708.02794
GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau$ + 0-1 $\ell$	0-2 jets	Yes	3.2		2.0 TeV		1607.05979
CCM (bino NLSP)	2 $\gamma$	-	Yes	36.1		2.15 TeV	$\tau < (NLSP) < 0.1 \text{ mm}$	ATLAS-CONF-2017-060
GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	36.1		2.35 TeV	$m(\tilde{g}) = 1700 \text{ GeV}, \tau < (NLSP) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2017-080
Gravitino LSP	0	mono-jet	Yes	20.3		865 GeV	$m(\tilde{G}) > 1.8 \times 10^4 \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$	1502.01518
<b>3<sup>rd</sup> gen. squarks</b>								
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	0	2 b	Yes	36.1	950 GeV		$m(\tilde{t}_1) < 420 \text{ GeV}$	1708.02666
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$ (SS)	1 b	Yes	36.1	275-703 GeV		$m(\tilde{t}_1) < 200 \text{ GeV}, m(\tilde{t}_2) = m(\tilde{t}_1) + 100 \text{ GeV}$	1706.03731
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	0-2 $e, \mu$	1-2 b	Yes	4.7/13.3	117-170 GeV	200-720 GeV	$m(\tilde{t}_1) = 2m(\tilde{t}_2), m(\tilde{t}_1) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$ or $\tilde{t}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 b	Yes	20.3/36.1	90-198 GeV	0.195-1.0 TeV	$m(\tilde{t}_1) = 1 \text{ GeV}$	1506.06616, 1709.04163, 1711.11520
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	0	mono-jet	Yes	36.1	90-130 GeV		$m(\tilde{t}_1) = m(\tilde{t}_2) = 5 \text{ GeV}$	1711.03201
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$ (Z)	1 b	Yes	20.3	150-600 GeV		$m(\tilde{t}_1) > 150 \text{ GeV}$	1403.5222
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	3 $e, \mu$ (Z)	1 b	Yes	36.1	290-790 GeV		$m(\tilde{t}_1) < 1 \text{ GeV}$	1706.03986
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	1-2 $e, \mu$	4 b	Yes	36.1	320-880 GeV		$m(\tilde{t}_1) < 1 \text{ GeV}$	1706.03986
<b>EW direct</b>								
$\tilde{W}_2 \rightarrow W\tilde{Z}$	2 $e, \mu$	0	Yes	36.1	90-500 GeV		$m(\tilde{W}_2) < 1 \text{ GeV}$	ATLAS-CONF-2017-039
$\tilde{W}_1 \rightarrow W\tilde{Z}$	2 $e, \mu$	0	Yes	36.1	750 GeV		$m(\tilde{W}_1) < 1 \text{ GeV}, m(\tilde{Z}) = 0.5(m(\tilde{W}_1) + m(\tilde{Z}))$	ATLAS-CONF-2017-039
$\tilde{Z} \rightarrow \nu\tilde{\nu}$	2 $\tau$	-	Yes	36.1	760 GeV		$m(\tilde{Z}) < 1 \text{ GeV}, m(\tilde{\nu}) = 0.5(m(\tilde{Z}) + m(\tilde{\nu}))$	1708.07875
$\tilde{Z} \rightarrow \nu\tilde{\nu}$	3 $e, \mu$	0	Yes	36.1	1.13 TeV		$m(\tilde{Z}) = m(\tilde{\nu}), m(\tilde{\nu}) = 0, m(\tilde{Z}) = 0.5(m(\tilde{Z}) + m(\tilde{\nu}))$	ATLAS-CONF-2017-039
$\tilde{Z} \rightarrow \nu\tilde{\nu}$	2 $e, \mu$	0-2 jets	Yes	36.1	508 GeV		$m(\tilde{Z}) = m(\tilde{\nu}), m(\tilde{\nu}) = 0, \tilde{\nu}$ occupied	ATLAS-CONF-2017-060
$\tilde{Z} \rightarrow \nu\tilde{\nu}$	3 $e, \mu, \gamma$	0-2 b	Yes	20.3	270 GeV		$m(\tilde{Z}) = m(\tilde{\nu}), m(\tilde{\nu}) = 0, \tilde{\nu}$ occupied	1501.07110
$\tilde{Z} \rightarrow \nu\tilde{\nu}$	4 $e, \mu$	0	Yes	20.3	335 GeV		$m(\tilde{Z}) = m(\tilde{\nu}), m(\tilde{\nu}) = 0, m(\tilde{Z}) = 0.5(m(\tilde{Z}) + m(\tilde{\nu}))$	1405.5086
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	115-370 GeV		$c\tau < 1 \text{ mm}$	1507.05493
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 $\gamma$	-	Yes	36.1	1.06 TeV		$c\tau < 1 \text{ mm}$	ATLAS-CONF-2017-080
<b>Long-lived particles</b>								
Direct $\tilde{t}_1, \tilde{t}_2$ proc., long-lived $\tilde{t}_1^0$	Disapp. trk	1 jet	Yes	36.1	460 GeV		$m(\tilde{t}_1) = m(\tilde{t}_2) = 160 \text{ MeV}, \tau(\tilde{t}_1^0) = 0.2 \text{ ns}$	1712.02118
Direct $\tilde{t}_1, \tilde{t}_2$ proc., long-lived $\tilde{t}_1^0$	HFV trk	-	Yes	18.4	495 GeV		$m(\tilde{t}_1) = m(\tilde{t}_2) = 160 \text{ MeV}, \tau(\tilde{t}_1^0) = 15 \text{ ns}$	1506.05332
Stable, stopped $\tilde{t}_1$ R-hadron	0	1-5 jets	Yes	27.9	850 GeV		$m(\tilde{t}_1) = 100 \text{ GeV}, 10^{-10} \text{ s} < \tau < 1000 \text{ s}$	1310.4584
Stable $\tilde{t}_1$ R-hadron	0	-	-	5.2	1.58 TeV		$m(\tilde{t}_1) = 100 \text{ GeV}, \tau > 0 \text{ ns}$	1606.05129
Metastable $\tilde{t}_1$ R-hadron	dE/dx trk	-	-	5.2	1.57 TeV		$m(\tilde{t}_1) = 100 \text{ GeV}, \tau > 0 \text{ ns}$	1604.04520
Metastable $\tilde{t}_1$ R-hadron, $\tilde{g} \rightarrow q\tilde{g}^0$	displ. vtx	-	Yes	32.8	2.37 TeV		$\tau(\tilde{g}) = 0.17 \text{ ns}, m(\tilde{g}) = 100 \text{ GeV}$	1710.04901
GMSB, stable $\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	1-2 $\mu$	-	-	19.1	537 GeV		$19 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{t}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{t}_1^0$	2 $\gamma$	-	Yes	20.3	440 GeV		$1 < \tan\beta < 3 \text{ ns}, \text{SPS6 model}$	1409.5542
$\tilde{g}, \tilde{t}_1^0 \rightarrow t\tilde{g}^0$	diapl. $ee/\mu\mu$	-	-	20.3	1.0 TeV		$7 < \tan\beta < 742 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05168
<b>RPV</b>								
RPV $\tilde{g} \rightarrow q\tilde{g}^0$	$e\mu\tau, \mu\tau$	-	-	5.2	1.9 TeV		$A_{111} = 0.11, A_{211,311,331} = 0.07$	1607.08079
Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 b	Yes	20.3	1.45 TeV		$m(\tilde{g}) = m(\tilde{q}), c\tau_{\tilde{g}} < 1 \text{ mm}$	1404.2500
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	4 $e, \mu$	-	Yes	13.3	1.14 TeV		$m(\tilde{t}_1) > 400 \text{ MeV}, A_{122} \neq 0 (k = 1, 2)$	ATLAS-CONF-2018-075
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	3 $e, \mu + \tau$	-	Yes	20.3	150 GeV		$m(\tilde{t}_1) < 2 \times m(\tilde{t}_2), A_{133} \neq 0$	1405.5086
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	0	4-5 large-R jets	-	36.1	1.875 TeV		$m(\tilde{g}) = 1075 \text{ GeV}$	SUSY-2016-22
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	1 $e, \mu$	8-10 jets/3-4 b	-	36.1	2.1 TeV		$m(\tilde{g}) = 1 \text{ TeV}, A_{122} \neq 0$	1704.04643
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}^0$	1 $e, \mu$	8-10 jets/3-4 b	-	36.1	1.65 TeV		$m(\tilde{g}) = 1 \text{ TeV}, A_{122} \neq 0$	1704.04643
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	0	2 jets + 2 b	-	36.7	106-470 GeV	480-610 GeV		1710.07171
$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$	2 b	-	36.1	0.4-1.45 TeV		$B\tau(\tilde{t}_1 \rightarrow t\tilde{t}_1^0) > 20\%$	1710.05544
<b>Other</b>								
Scalar charm, $\tilde{c} \rightarrow c\tilde{c}^0$	0	2 c	Yes	20.3	510 GeV		$m(\tilde{c}) < 200 \text{ GeV}$	1501.01325

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

## ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2017

## ATLAS Preliminary

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{miss}$	$\int \mathcal{L} dt [fb^{-1}]$	Limit	Reference
<b>Extra dimensions</b>						
ADD $G_{KK} + \tilde{g}/\tilde{q}$	0 $e, \mu$	1-4 j	Yes	35.1	7.75 TeV	$n = 2$
ADD non-resonant $\tilde{g}/\tilde{q}$	2 $\gamma$	-	-	35.7	8.6 TeV	$n = 3 \text{ HLZ NLO}$
ADD GBH	-	2 j	-	37.0	8.9 TeV	$n = 0$
ADD BH High $\Sigma p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	8.2 TeV	$n = 0, M_{pl} = 3 \text{ TeV, rot BH}$
ADD BH Low $\Sigma p_T$	-	$\geq 3 j$	-	3.8	8.5 TeV	$n = 0, M_{pl} = 3 \text{ TeV, rot BH}$
RS1 $G_{KK} \rightarrow \tilde{g}/\tilde{q}$	2 $\gamma$	-	-	38.2	4.1 TeV	$\lambda/M_{pl} = 0.1$
Bulk NS $G_{KK} \rightarrow WW \rightarrow qq\tilde{\nu}$	1 $e, \mu$	1 j	Yes	35.1	1.75 TeV	$\lambda/M_{pl} = 1.0$
2UED / RPP	1 $e, \mu$	$> 2 b, > 3 j$	Yes	13.2	1.6 TeV	$\text{Tier}(1,1), \text{St}(A^{(1)} \rightarrow e\tilde{\nu}) = 1$
<b>Gauge bosons</b>						
SSM $Z' \rightarrow \ell\ell$	2 $e, \mu$	-	-	35.1	4.5 TeV	
SSM $Z' \rightarrow \nu\nu$	2 $\tau$	-	-	35.1	2.4 TeV	
Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	3.2	1.5 TeV	$\Gamma/\text{m} = 3\%$
Leptophobic $Z' \rightarrow \tau\tau$	1 $e, \mu$	$\geq 1 b, \geq 1 W, \geq 1 j$	Yes	3.2	2.0 TeV	
SSM $W' \rightarrow \ell\nu$	1 $e, \mu$	-	Yes	35.1	5.1 TeV	$g_V = 3$
UVT $V' \rightarrow WW \rightarrow qq\tilde{q}$ model D	0 $e, \mu$	2 j	-	35.7	3.5 TeV	$g_V = 3$
HVT $V' \rightarrow WW/ZH$ model B	multi-channel	-	-	35.1	2.63 TeV	
LRSM $W'_R \rightarrow \ell\bar{\nu}$	1 $e, \mu$	2 b, 1 j	Yes	23.3	1.92 TeV	
LRSM $W'_R \rightarrow \ell\bar{\nu}$	0 $e, \mu$	$\geq 1 b, \geq 1 j$	-	23.3	1.75 TeV	
<b>CI</b>						
CI $q\bar{q}q\bar{q}$	-	2 j	-	37.0	21.6 TeV	$A_1$
CI $q\bar{q}q\bar{q}$	2 $e, \mu$	-	-	35.1	40.1 TeV	$\sqrt{G_L}$
CI $q\bar{q}q\bar{q}$	2 $e, \mu$	$\geq 1 b, \geq 1 j$	Yes	23.3	4.9 TeV	$ G_{UV}  = 1$
<b>DM</b>						
Neutral vector mediator (Dion DM)	0 $e, \mu$	1-4 j	Yes	35.1	1.3 TeV	$\mu_{\tilde{g}} = 0.25, g_{\tilde{g}} = 1.5, m(\tilde{g}) < 400 \text{ GeV}$
Vector mediator (Dion DM)	0 $e, \mu, 1 \gamma$	$\leq 1 j$	Yes	35.1	1.2 TeV	$\mu_{\tilde{g}} = 0.25, g_{\tilde{g}} = 1.5, m(\tilde{g}) < 480 \text{ GeV}$
UVFP EFT (Dion DM)	0 $e, \mu$	1 j, $\leq 1 j$	Yes	3.2	700 GeV	$m(\tilde{g}) < 130 \text{ GeV}$
<b>LO</b>						
Scalar $LQ$ 1 <sup>st</sup> gen	2 $e, \mu$	$\geq 2 j$	-	3.2	1.1 TeV	$\beta = 1$
Scalar $LQ$ 2 <sup>nd</sup> gen	2 $\mu$	$\geq 2 j$	-	3.2	1.05 TeV	$\beta = 1$
Scalar $LQ$ 3 <sup>rd</sup> gen	1 $e, \mu$	$\geq 1 b, \geq 3 j$	Yes	23.3	640 GeV	$\beta = 0$
<b>Heavy quarks</b>						
VLQ $TT \rightarrow H\ell + X$	0 or 1 $e, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	1.2 TeV	$\text{St}(T \rightarrow H\ell) = 1$
VLQ $TT \rightarrow Z\ell + X$	1 $e, \mu$	$\geq 1 b, \geq 3 j$	Yes	35.1	1.16 TeV	$\text{St}(T \rightarrow Z\ell) = 1$
VLQ $TT \rightarrow W\ell + X$	1 $e, \mu$	$\geq 1 b, \geq 1 W, \geq 1 j$	Yes	35.1	1.35 TeV	$\text{St}(T \rightarrow W\ell) = 1$
VLQ $BB \rightarrow H\ell + X$	1 $e, \mu$	$\geq 2 b, \geq 3 j$	Yes	23.3	700 GeV	$\text{St}(B \rightarrow H\ell) = 1$
VLQ $BB \rightarrow Z\ell + X$	2 or 3 $e, \mu$	$\geq 2 b, \geq 1 j$	-	23.3	790 GeV	$\text{St}(B \rightarrow Z\ell) = 1$
VLQ $BB \rightarrow W\ell + X$	1 $e, \mu$	$\geq 1 b, \geq 1 W, \geq 1 j$	Yes	35.1	1.25 TeV	$\text{St}(B \rightarrow W\ell) = 1$
VLQ $QQ \rightarrow W\ell/W\tilde{\nu}$	1 $e, \mu$	$\geq 4 j$	Yes	23.3	690 GeV	
<b>Excited fermions</b>						
Excited quark $q^* \rightarrow q\tilde{g}$	-	2 j	-	37.0	6.0 TeV	only $u^*$ and $d^*, A = m(q^*)$
Excited quark $q^* \rightarrow q\tilde{g}$	1 $\gamma$	1 j	-	35.7	5.3 TeV	only $u^*$ and $d^*, A = m(q^*)$
Excited quark $q^* \rightarrow q\tilde{g}$	-	1 b, 1 j	-	13.3	2.3 TeV	

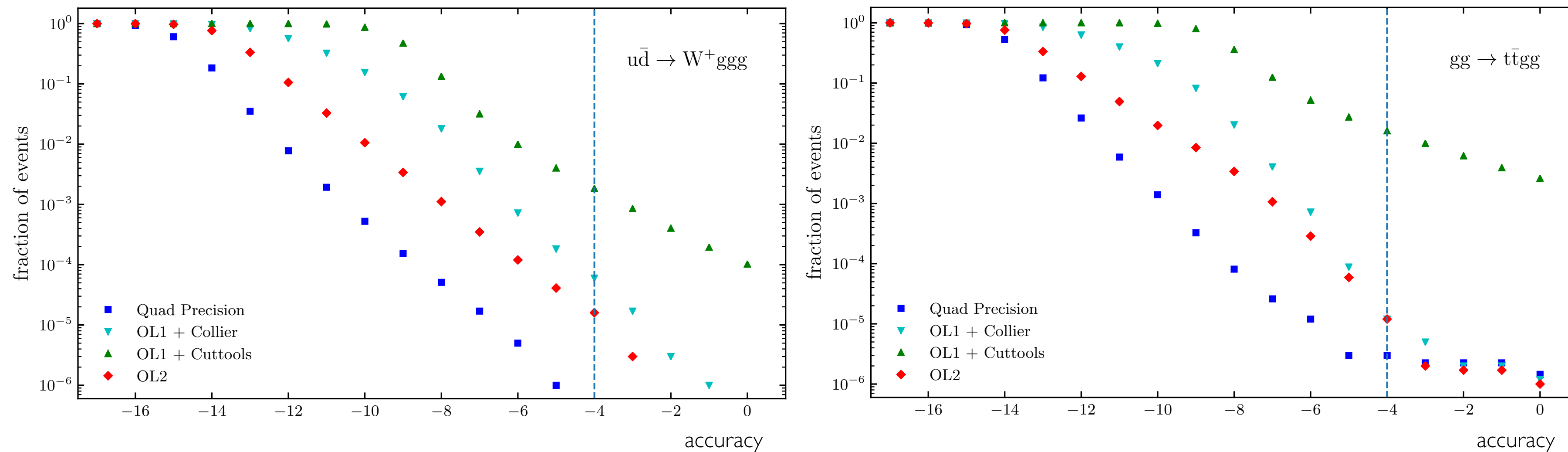


# On-the-fly OpenLoops reduction

New!

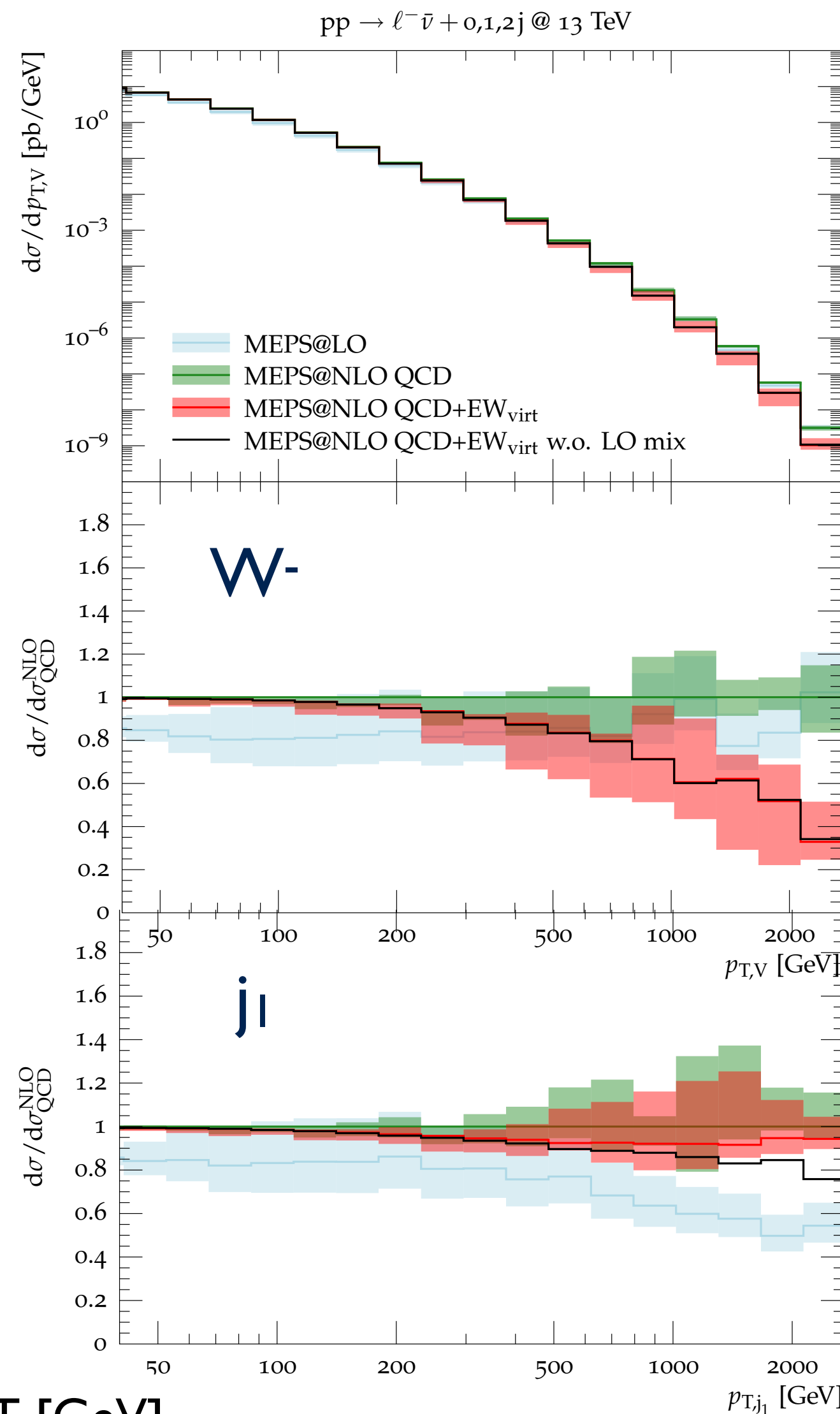
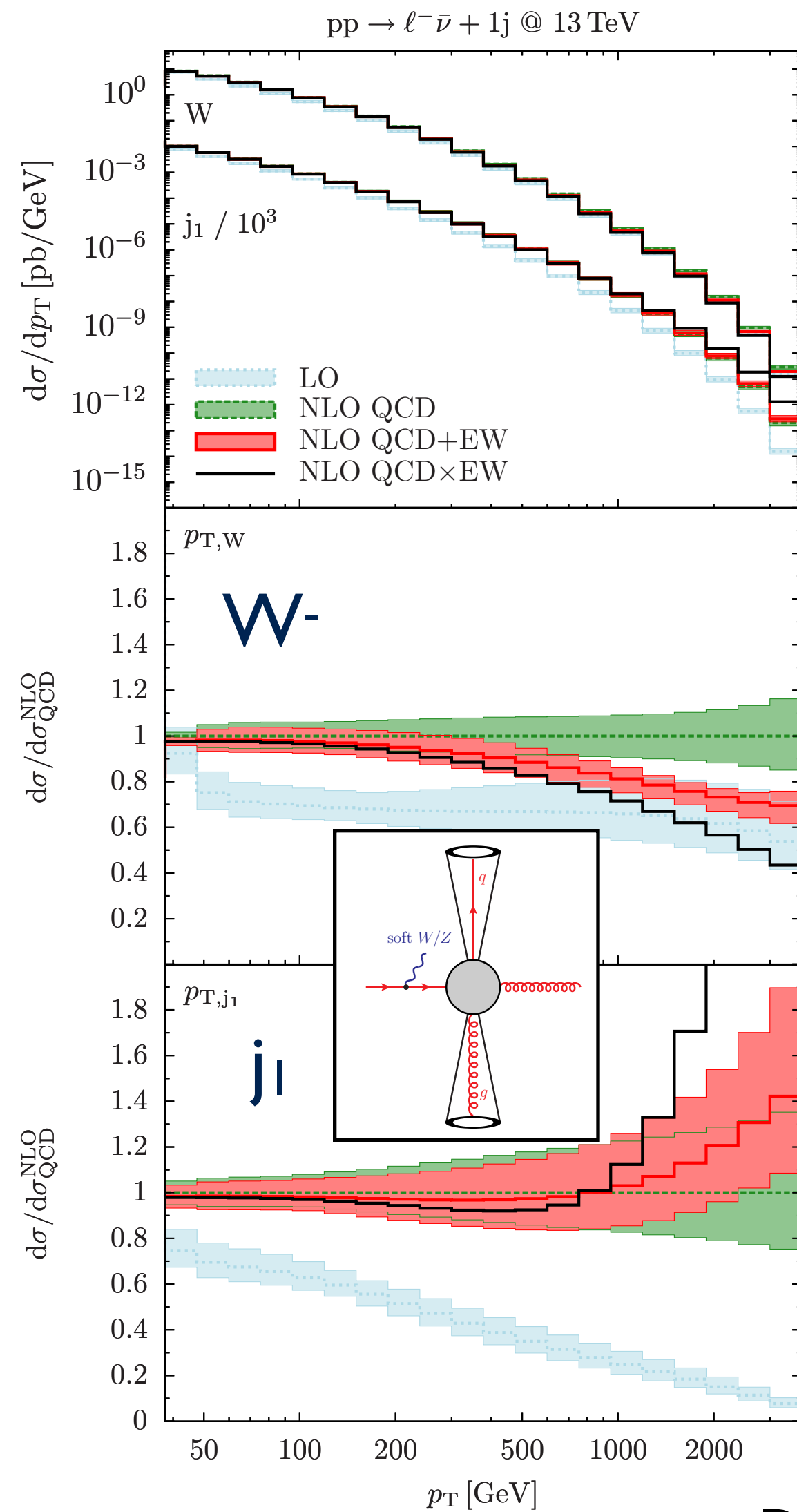
[F. Buccioni, S. Pozzorini, M. Zoller '17]

- Huge advantage: allows for systematic treatment of numerical instabilities in



- unprecedented numerical stability (always as least as stable as OpenLoops I + Collier)
- crucial in unresolved limits of **real-virtual contributions** in NNLO calculations
- ultimate stability: OFR @ qp (work in progress)
- soon to be public in **OpenLoops2** [F. Buccioni, JML, P. Maierhöfer, S. Pozzorini, M. Zoller]

# inclusive V: MEPS@NLO QCD+EW<sub>virt</sub>



- ▶ Bases on Sherpa's standard MEPS@NLO
- ▶ Stable NLO QCD+EW predictions in all of the phase-space...
- ▶ ...including Parton-Shower effects.
- ▶ Can directly be used by the experimental collaborations
- ▶  $p_{T,V}$  : MEPS@NLO QCD+EW in agreement with QCD×EW (fixed-order)
- ▶  $p_{T,j_1}$ :
  - merging ensures stable results (dijet topology at LO)
  - compensation between negative Sudakov and LO mix

PT [GeV]

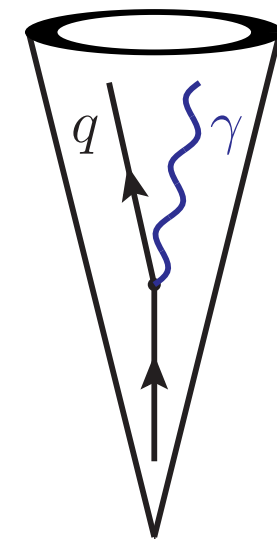
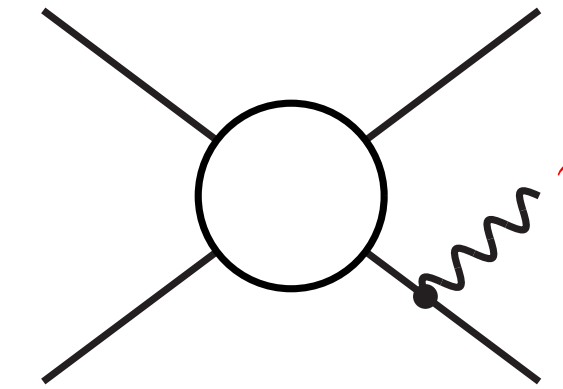
# Automation of NLO EW

MoCaNLO+Recola	$pp \rightarrow ll + 2 \text{ jets}$	[1411.0916]
	$pp \rightarrow e^+e^- \mu^+ \mu^- / \mu^+ \mu^- \mu^+ \mu^- / e^+ \nu_e \mu^- \nu_\mu$	[1601.07787] [1611.05338]
	$pp \rightarrow e^+ \nu_e \mu^- \nu_\mu \text{ bb (tt)}$	[1607.05571]
	$pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu + 2 \text{ jets (VBS)}$	[1611.02951] [1708.00268]
	$pp \rightarrow e^+ \nu_e \mu^- \nu_\mu \text{ bbH (ttH)}$	[1612.07138]
Sherpa/Munich+OpenLoops POWHEG+OpenLoops	$pp \rightarrow W+1,2,3 \text{ jets}$	[1412.5156]
	$pp \rightarrow ll/l\nu/\nu\nu + 0, 1, 2 \text{ jets (V+jets)}$	[1511.08692]
	$pp \rightarrow ll\nu\nu \text{ (VV)}$	[1705.00598]
MadGraph_aMC@NLO +MadLoop	$pp \rightarrow llH/l\nu H+0,1 \text{ jet (HV)}$	[1706.03522]
	$pp \rightarrow tt+H/Z/W$	[1504.03446]
	$pp \rightarrow tt$	[1606.01915] [1705.04105]
	$pp \rightarrow 2 \text{ jets}$	[1612.06548]
MadDipole+GoSam Sherpa+GoSam	$pp \rightarrow W+2 \text{ jets}$	[1507.08579]
	$pp \rightarrow \gamma\gamma+0,1,2 \text{ jets}$	[1706.09022]

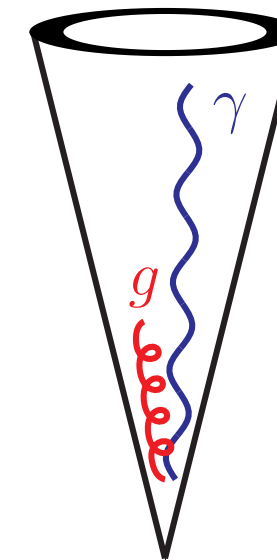
- many NLO QCD+EW calculations for **multi-particle processes** are becoming available
- NLO QCD+EW matching and merging with parton showers is under way (approximations available)
- Given the achieved automation: **attention is shifting towards detailed phenomenological applications**

# Treatment of Photons

- ▶ QED IR subtraction [Catani,Dittmaier,Seymour,Trocsanyi; Frixione, Kunszt, Signer]
- ▶ Problem of IR safeness in presence of FS QCD partons and photons:
  - ▶ Democratic jet-algorithm approach (jets  $\equiv$  photons)



**collinear  $q \rightarrow q\gamma$  singularities** cancelled  
clustering  $q, g, \Upsilon$  on same footing



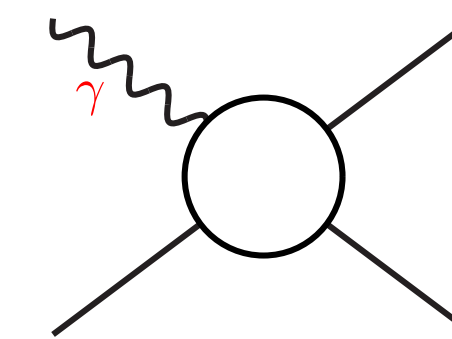
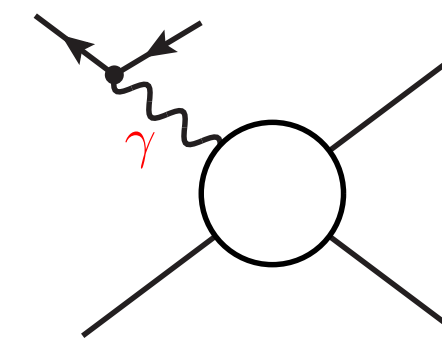
**soft gluon singularities  $\leftrightarrow$  hard photons inside jets:** cancelled in jet-production (NLO EW) +  $\Upsilon$ -production (NLO QCD)

- ▶ Separation of jets from photons through  $E_\Upsilon/E_{jet} < z_{thr}$  inside jets
  - *rigorous approach:* absorb  $q \rightarrow q\gamma$  singularity into fragmentation function
  - *approximation:* cancel singularity via  $q\gamma$  recombination in small cone

$$\Delta R_{q\gamma} < 0.1$$

*difference < 1% for typical  $z_{thr}$ !*

- ▶ QED factorisation for IS photons and PDF evolution [MRST2004, NNPDF2.3]
- ▶  $\Upsilon$ -induced processes  $\rightarrow$  possible TeV scale enhancements (However large uncertainties!)



# MEPS@NLO QCD+EW<sub>virt</sub>

- ▶ Incorporate approximate EW corrections into MEPS@NLO framework [Höche, Krauss, Schönherr, Siebert; '13]
- ▶ Idea: integrate out real photon corrections (typical at the percent level for high-energy observables)

$$\tilde{B}_{n,\text{QCD}}(\Phi_n) \longrightarrow \tilde{B}_{n,\text{QCD}+\text{EW}}(\Phi_n) = \tilde{B}_n(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

$$d\sigma = \underbrace{d\sigma(\alpha_S^2\alpha)}_{\text{QCD}} + \underbrace{d\sigma(\alpha_S\alpha^2)}_{\text{EW}} + \underbrace{d\sigma(\alpha^3)}_{\text{QCD}} + \underbrace{d\sigma(\alpha^4)}_{\text{EW}}$$

$$+ \underbrace{d\sigma(\alpha_S^3\alpha)}_{\text{QCD}} + \underbrace{d\sigma(\alpha_S^2\alpha^2)}_{\text{EW}} + \underbrace{d\sigma(\alpha_S\alpha^3)}_{\text{QCD}} + \underbrace{d\sigma(\alpha^4)}_{\text{EW}}$$

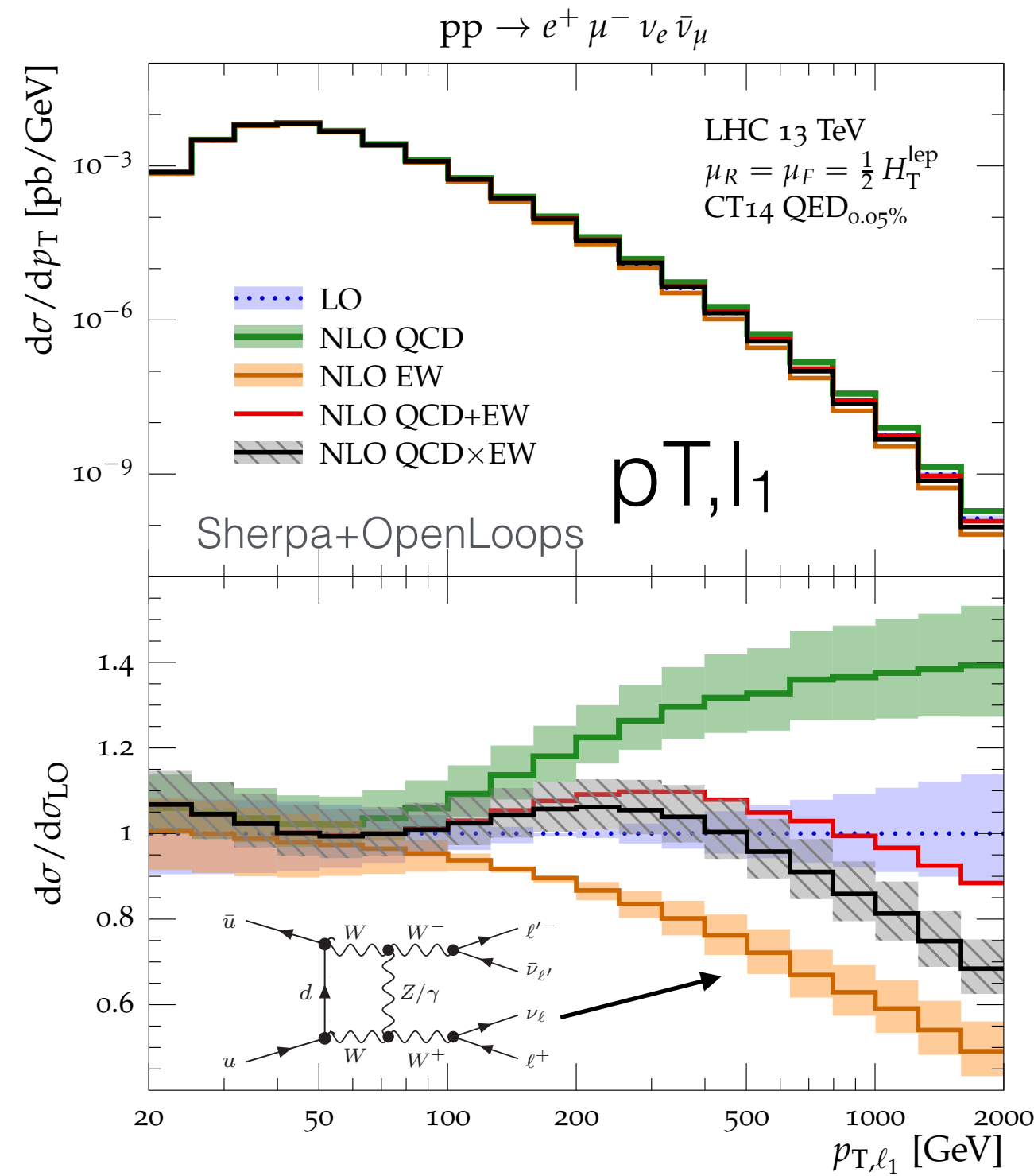
- ▶ Validated at fixed-order level (using exclusive sums for merging):  
percent-level agreement
- ▶ exclusive QED corrections could be readded via the parton shower
- ▶ use CKKW scale setting  $\alpha_S^N(\mu_{\text{CKKW}}^2) = \alpha_S^{N-M}(\mu_{\text{core}}^2) \alpha_S(t_1) \dots \alpha_S(t_M)$  with EW clustering and

$$\mu_{\text{core},\ell\ell} = m_{\ell\ell}, \quad \mu_{\text{core},Vj} = \frac{1}{2} E_{T,V} = \frac{1}{2} \sqrt{M_V^2 + p_{T,V}^2}, \quad \mu_{\text{core},jj} = \frac{1}{2} \left( \frac{1}{\hat{s}} - \frac{1}{\hat{t}} - \frac{1}{\hat{u}} \right)^{-\frac{1}{2}}$$

# off-shell vector-boson pair production: WW-DF

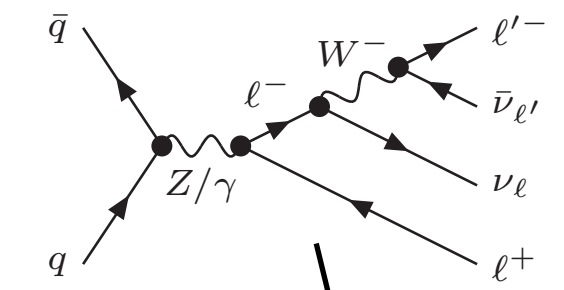
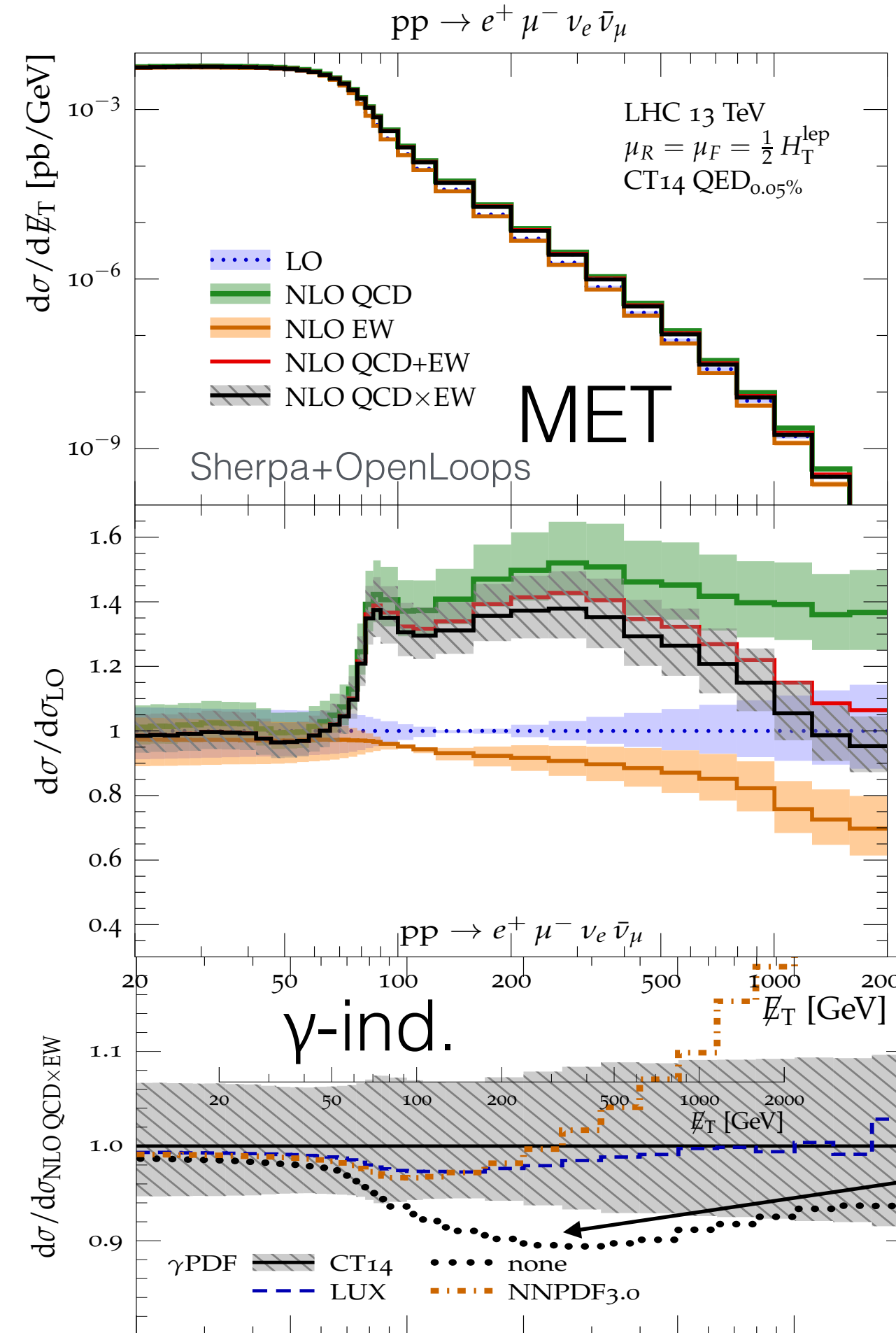
- Motivation:
- important BSM background: **2 OS-DF leptons + MET**
  - dominant  $H \rightarrow WW \rightarrow 2l2\nu$  background
  - Search for aTGC's

[Kallweit, JML, Pozzorini, Schönherr; '17]



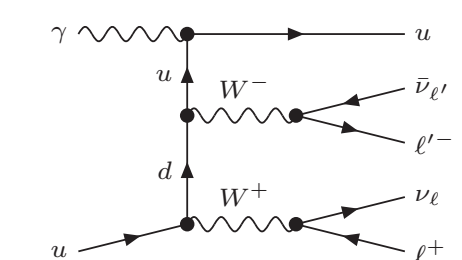
## $p_T$ of hardest lepton

- ▶ +40 % QCD corrections in the tail (Note: slight jet veto applied)
- ▶ LARGE negative EW corrections due to **Sudakov behaviour**: -40% @ 1 TeV

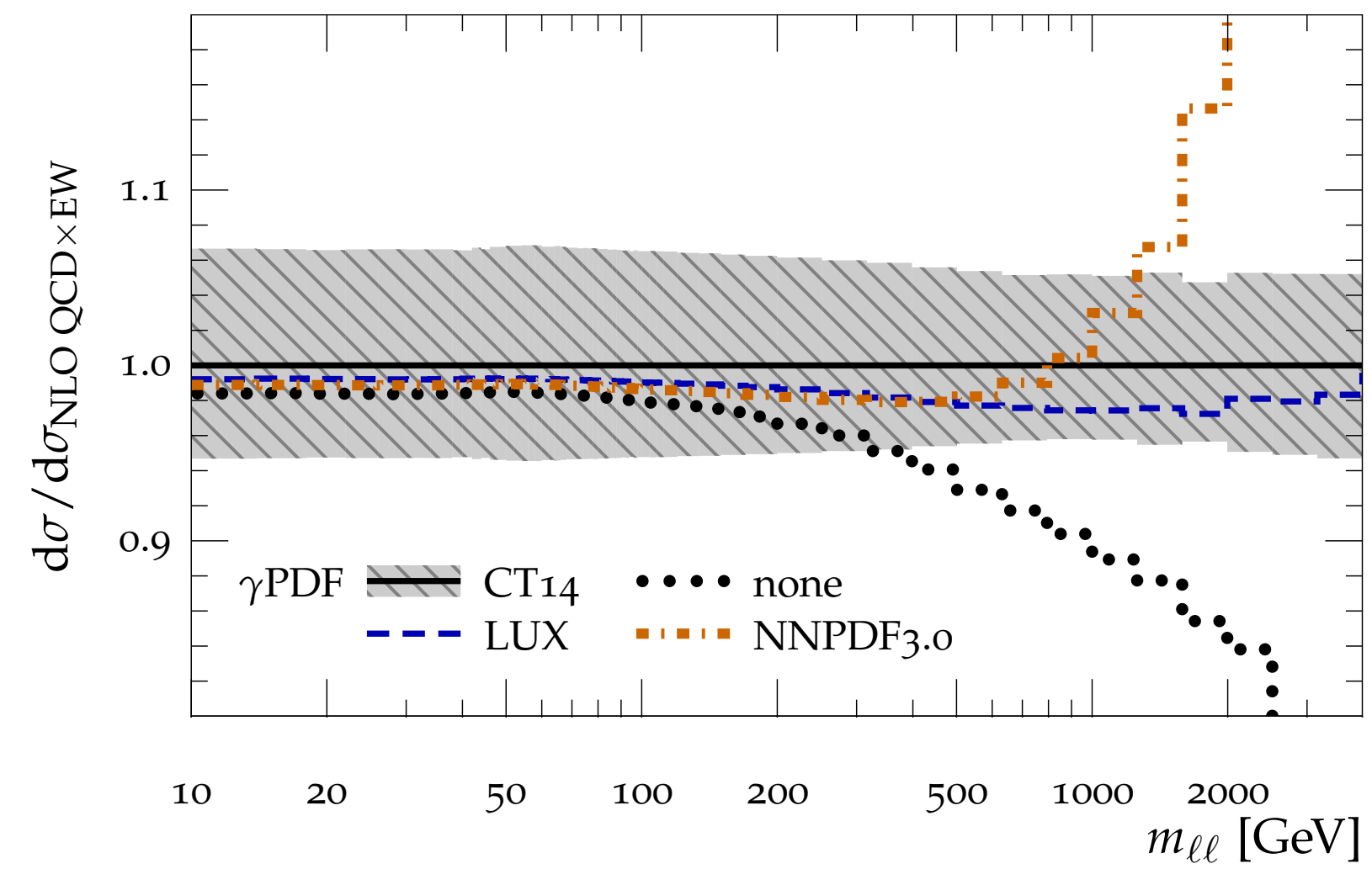
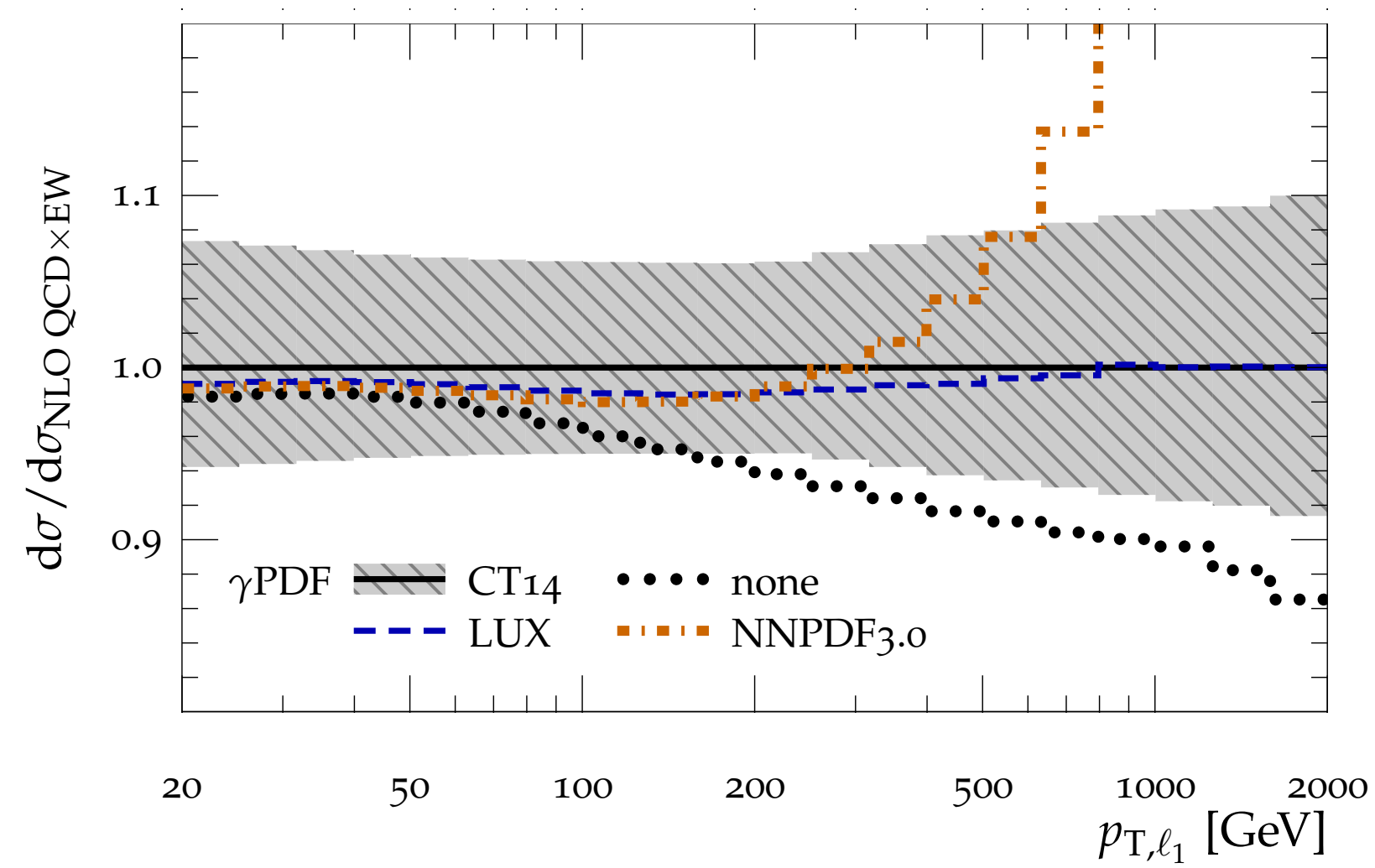


## MET

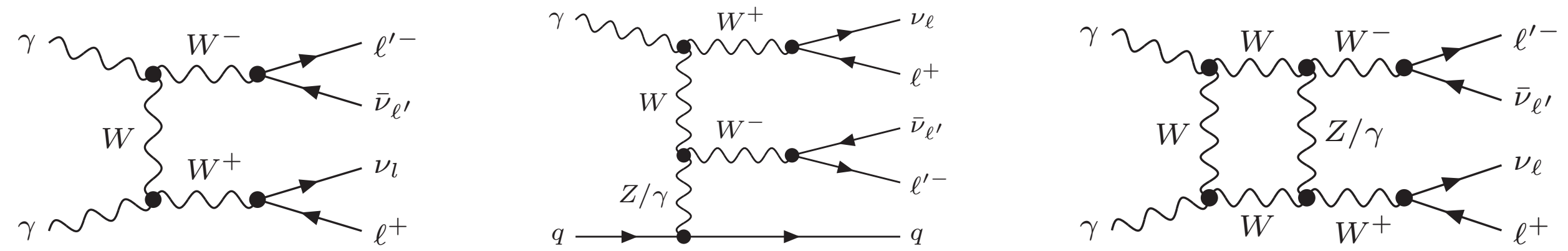
- ▶ at large MET > MW: W's are forced off-shell
- ▶ jump in QCD corrections (extra jet unlocks back-to-back)
- ▶ relatively small EW corr: -10% @ 1 TeV
- ▶ sizeable photon-induced contrib.: 10% for MET > 200 GeV



# off-shell vector-boson pair production at NLO QCD+EW



Effects of photon-induced production



# $l\nu + 1 \text{ jet}$ : inclusive

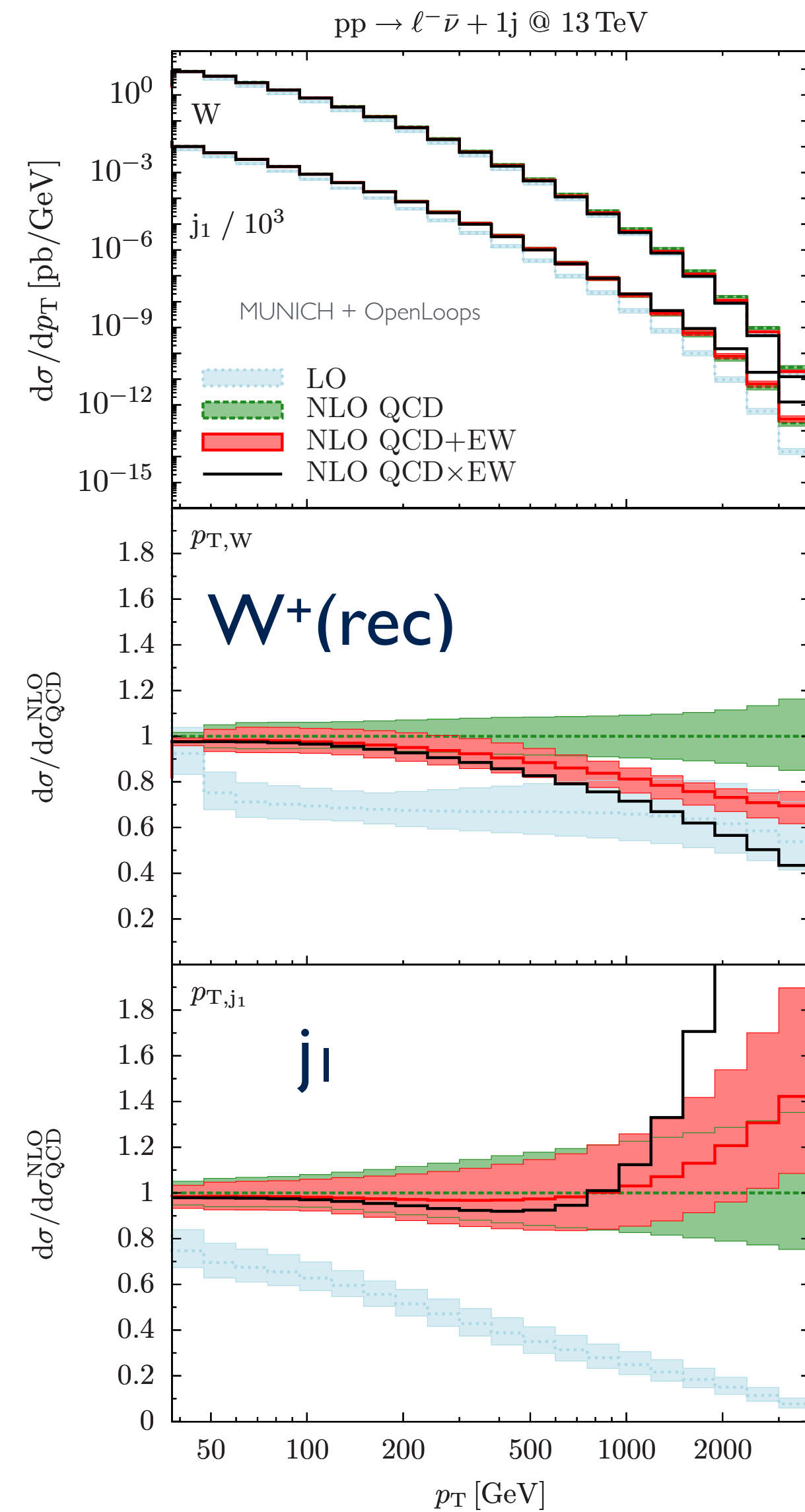
Setup:

$$\sqrt{S} = 13 \text{ TeV}$$

$$p_{T,j} > 30 \text{ GeV}, \quad |\eta_j| < 4.5$$

$$p_{T,l} > 20 \text{ GeV}, \quad |\eta_l| < 2.5, \quad E_T^{\text{miss}} > 25$$

$$\mu_0 = \hat{H}_T/2 \text{ (+ 7-pt. variation)}$$



inclusive

$\approx 1\%$  EW corrections

$p_T$  of W-boson

- ▶ +100 % QCD corrections in the tail
- ▶ large negative EW corrections due to **Sudakov behaviour**: -20–35% corrections at 1-4 TeV
- ▶ sizeable difference between QCD+EW and QCDxEW !

$p_T$  of jet

- ▶ “giant QCD K-factors” in the tail [Rubin, Salam, Sapeta '10]
- ▶ dominated by **dijet configurations** (effectively LO, no EW)
- ▶ positive 10-50% EW corrections from quark bremsstrahlung

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]



# $l\nu + 1 \text{ jet}$ : inclusive

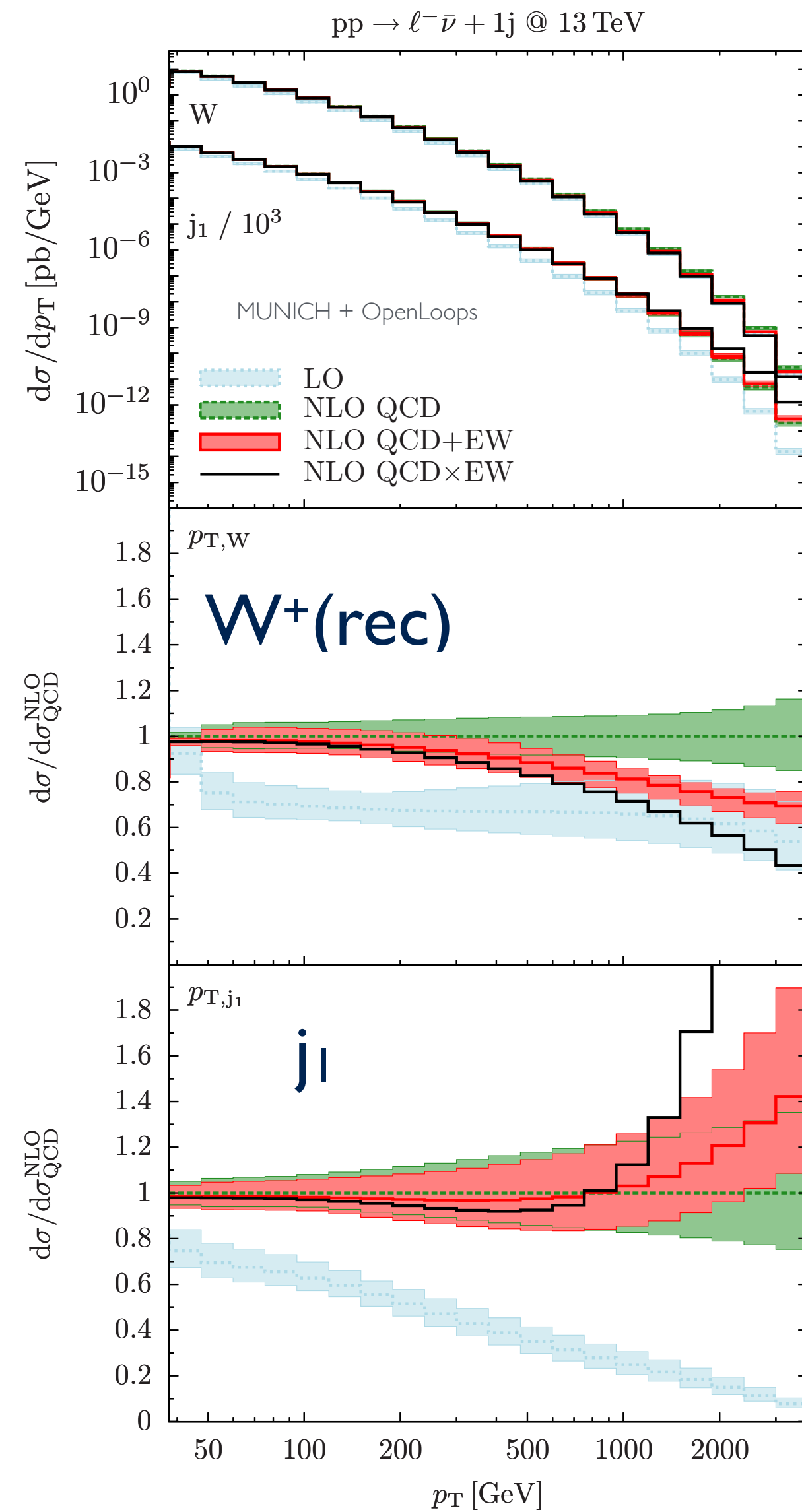
Setup:

$$\sqrt{S} = 13 \text{ TeV}$$

$$p_{T,j} > 30 \text{ GeV}, \quad |\eta_j| < 4.5$$

$$p_{T,l} > 20 \text{ GeV}, \quad |\eta_l| < 2.5, \quad E_T^{\text{miss}} > 25$$

$$\mu_0 = \hat{H}_T/2 \text{ (+ 7-pt. variation)}$$



inclusive

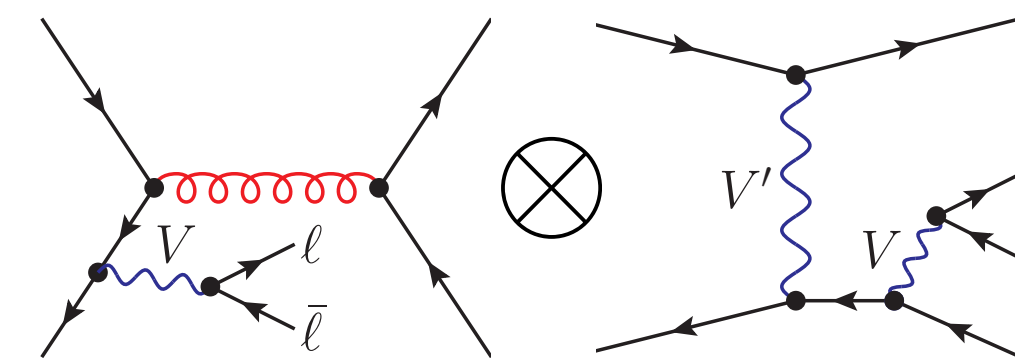
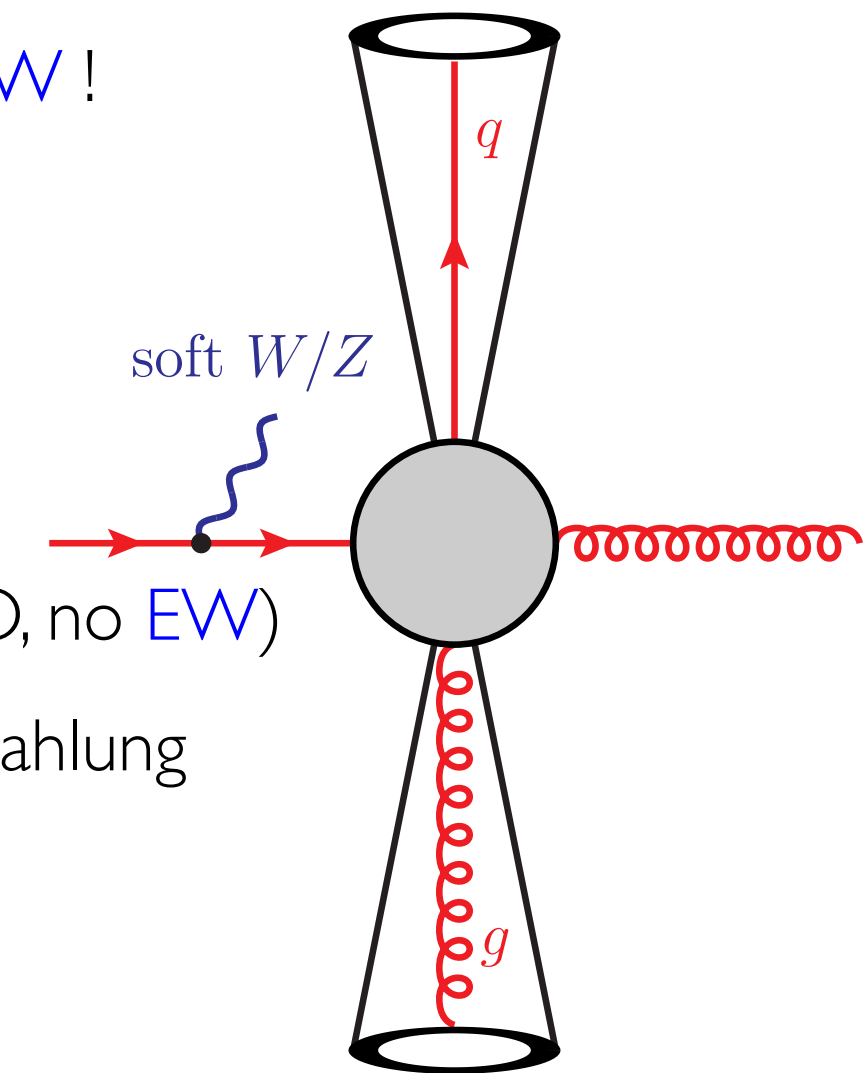
≈ 1% EW corrections

$p_T$  of W-boson

- ▶ +100% QCD corrections in the tail
- ▶ large negative EW corrections due to **Sudakov behaviour**: -20–35% corrections at 1–4 TeV
- ▶ sizeable difference between QCD+EW and QCD×EW!

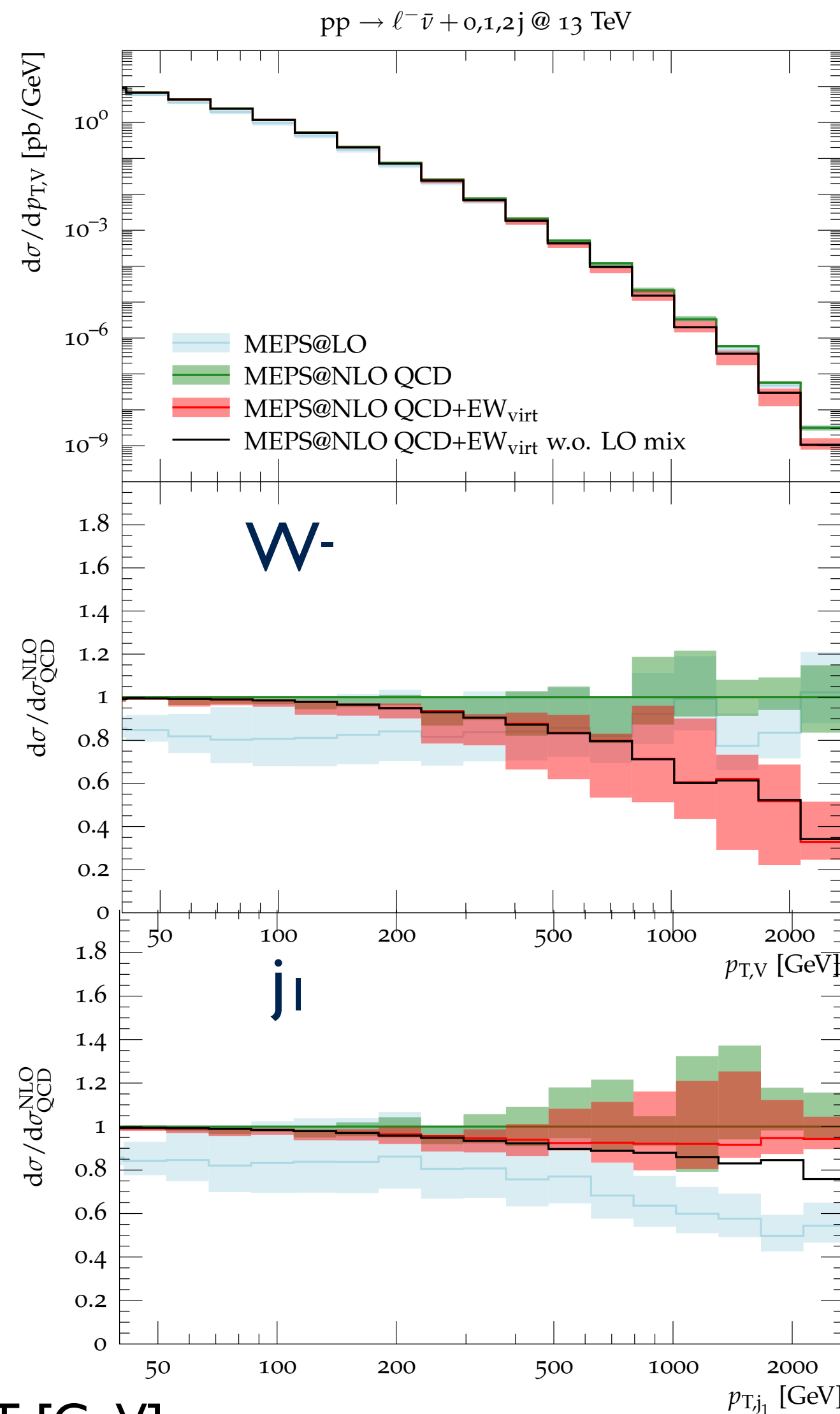
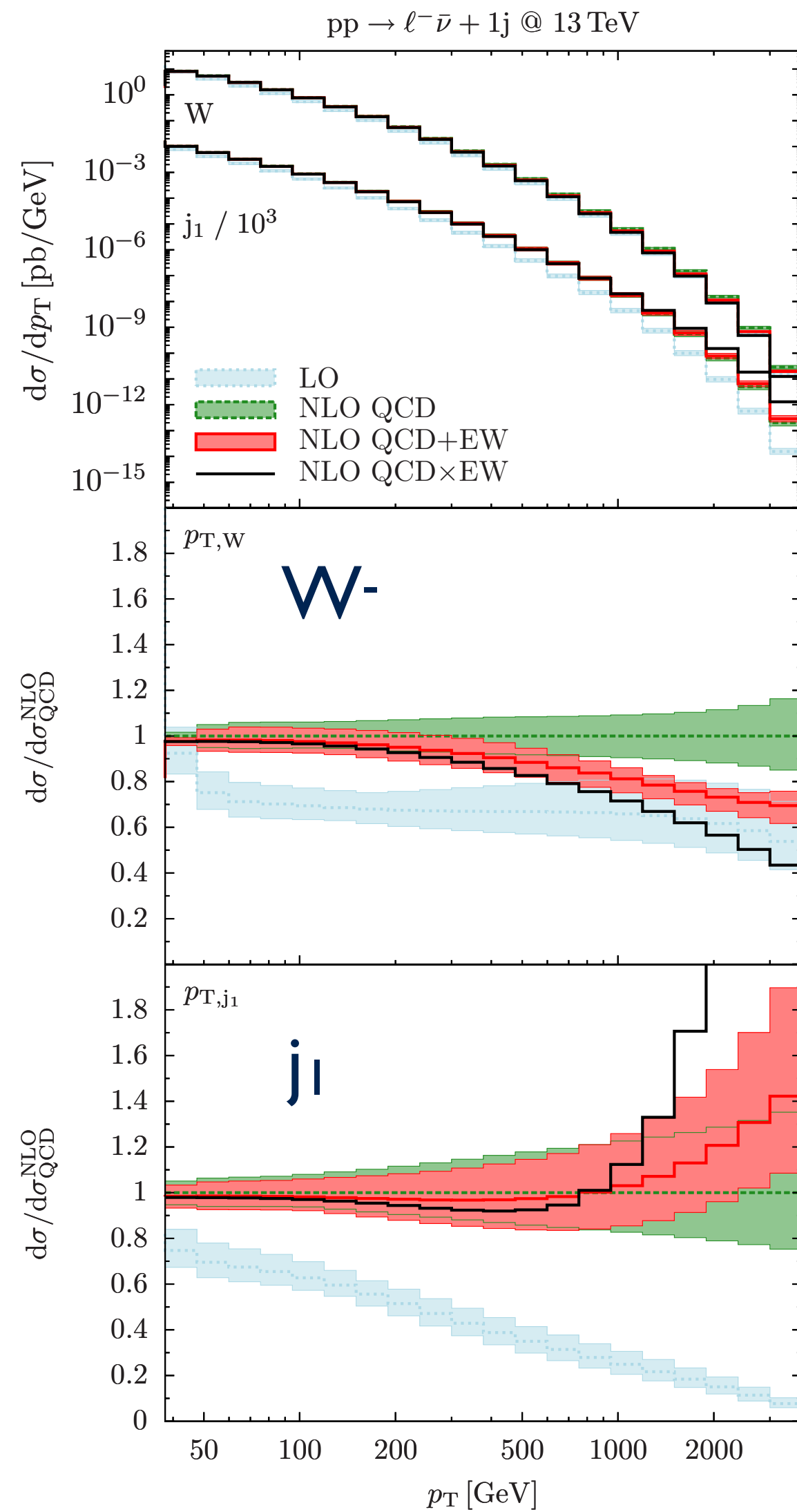
$p_T$  of jet

- ▶ “giant QCD K-factors” in the tail [Rubin, Salam, Sapeta '10]
- ▶ dominated by **dijet configurations** (effectively LO, no EW)
- ▶ positive 10–50% EW corrections from quark bremsstrahlung



⇒ pathologic with large uncertainties!

# inclusive V: MEPS@NLO QCD+EW<sub>virt</sub>



**PT [GeV]**

- ▶ Bases on Sherpa's standard MEPS@NLO
- ▶ Stable NLO QCD+EW predictions in all of the phase-space...
- ▶ ...including Parton-Shower effects.
- ▶ Can directly be used by the experimental collaborations
- ▶  $p_{T,V}$  : MEPS@NLO QCD+EW in agreement with QCD x EW (fixed-order)
- ▶  $p_{T,j_1}$  : compensation between negative Sudakov and LO mix

# Caveat: $\gamma$ +jet

Note: this modelling of process correlations assumes close similarity of QCD effects between different  $V$ +jets processes

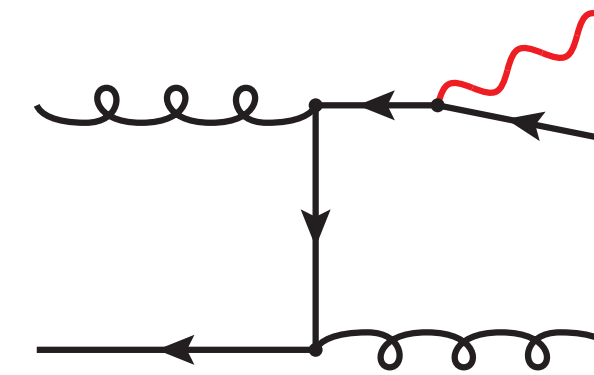
$$\left| \frac{\sigma_{\text{NLO}}^{(V)}}{\sigma_{\text{LO}}^{(V)}} - \frac{\sigma_{\text{NLO}}^{(Z)}}{\sigma_{\text{LO}}^{(Z)}} \right| \ll \left| \frac{\sigma_{\text{NLO}}^{(Z)}}{\sigma_{\text{LO}}^{(Z)}} \right|$$

- apart from PDF effects it is the case for  $W$ +jets vs.  $Z$ +jets
- at  $p_T > 200$  GeV it is in principle also the case for  $\gamma$ +jets vs.  $Z/W$ +jets

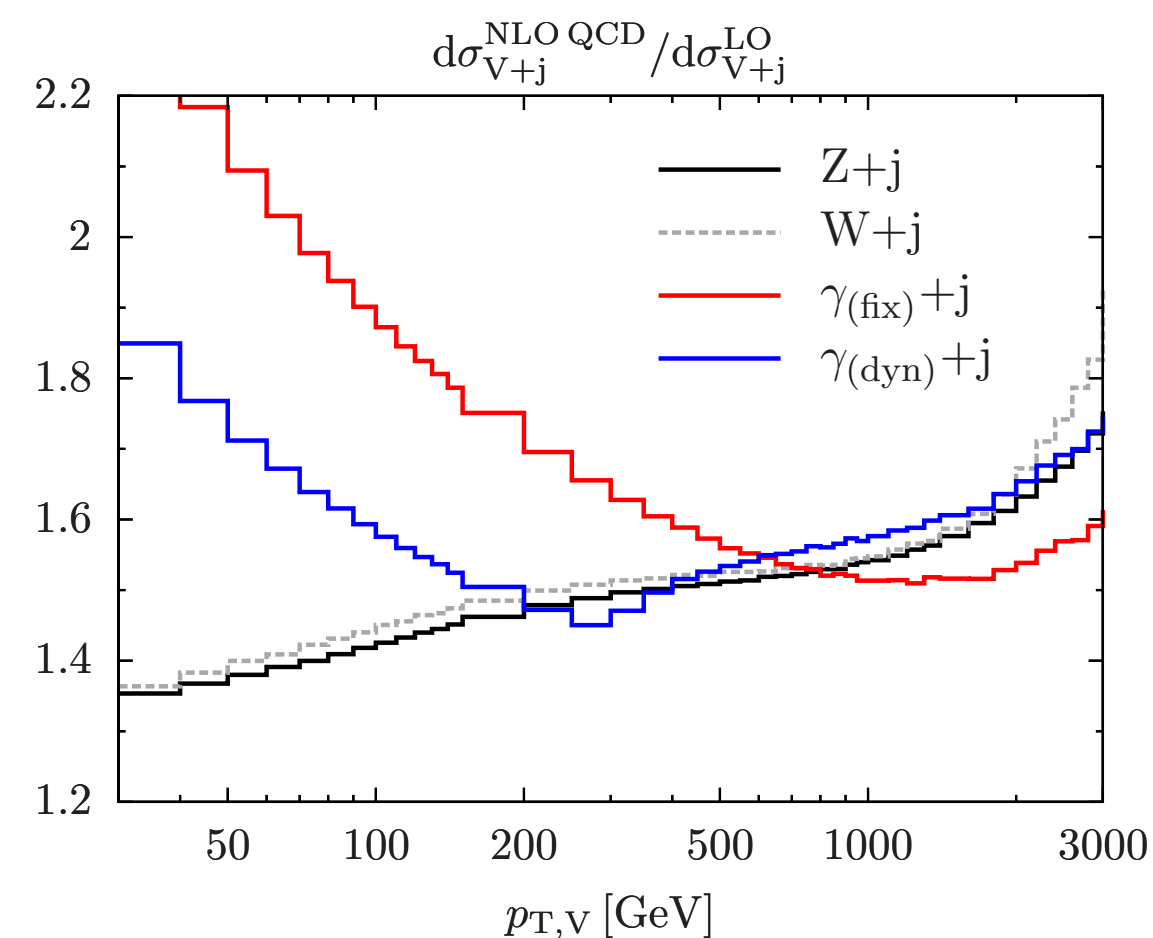
BUT: different logarithmic effects from fragmentation even at  $p_T \gg M_V$

$W/Z$ +jet: mass cut-off  $\rightarrow \log(p_T/M_V)$

$\gamma$ + jet: Frixiene-isolation cone of radius  $R_0 \rightarrow \log(R_0)$



Consider dynamic  $\Upsilon$ -isolation with  $R_{\text{dyn}}(p_{T,\gamma}, \epsilon_0) = \frac{M_Z}{p_{T,\gamma} \sqrt{\epsilon_0}}$



- $\Upsilon_{\text{dyn}}$  behaves like  $W$  or  $Z$  at  $p_T > M_V$   
 $\Rightarrow$  justifies process-correlation estimate

- Additional uncertainty: remnant part  $\Upsilon_{\text{fix}} - \Upsilon_{\text{dyn}}$   
 (through extra MC reweighting)

(uncorrelated)

# Precise predictions for V+jet DM backgrounds

[1705.04664]

work in collaboration with:

R. Boughezal, J.M. Campell, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, S. Kallweit, M. L. Mangano, P. Maierhöfer, T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam, C. Williams

- Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)

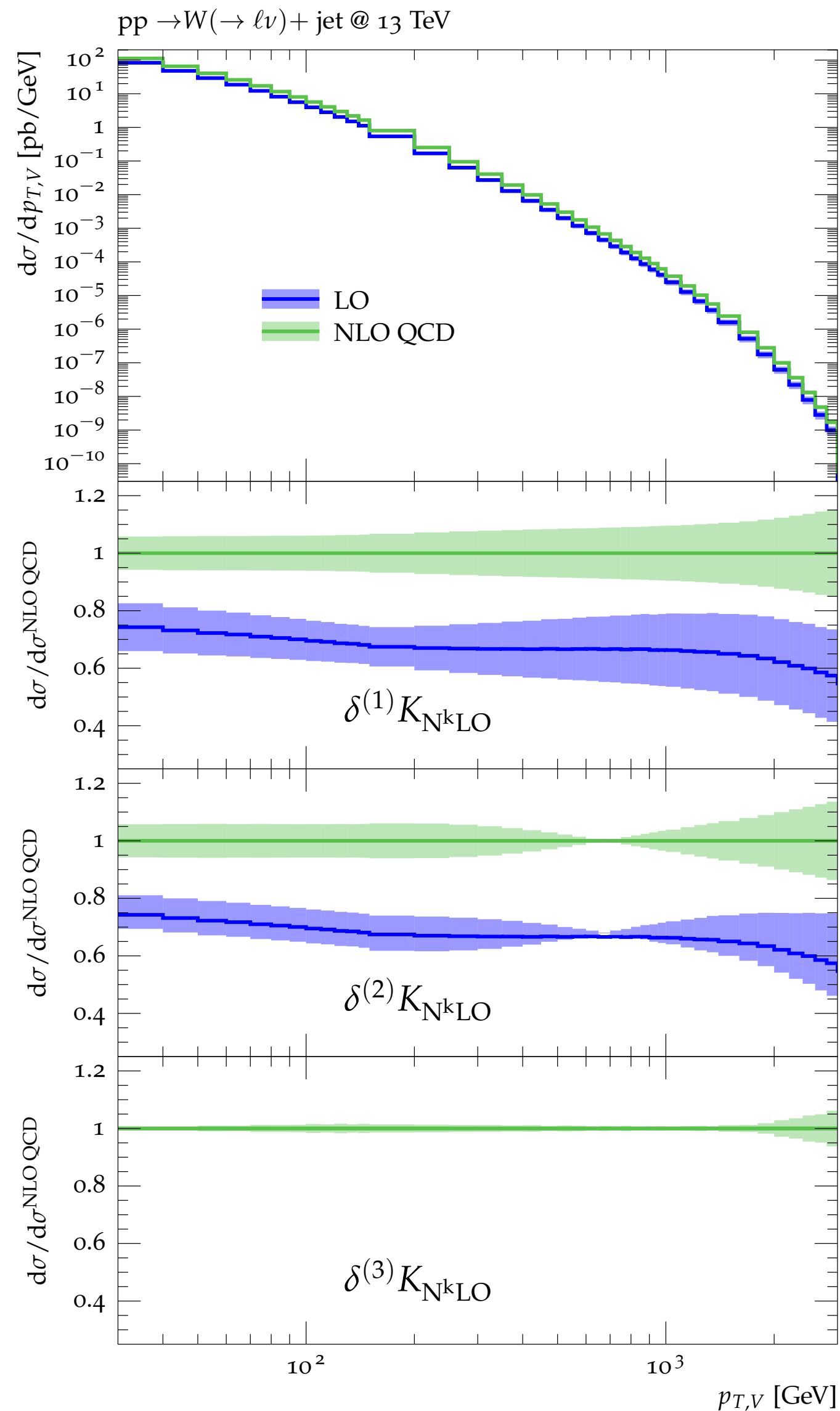
$$\frac{d}{dx} \frac{d}{dy} \sigma^{(V)}(\vec{\epsilon}_{\text{MC}}, \vec{\epsilon}_{\text{TH}}) := \frac{d}{dx} \frac{d}{dy} \sigma_{\text{MC}}^{(V)}(\vec{\epsilon}_{\text{MC}}) \left[ \begin{array}{c} \frac{d}{dx} \sigma_{\text{TH}}^{(V)}(\vec{\epsilon}_{\text{TH}}) \\ \frac{d}{dx} \sigma_{\text{MC}}^{(V)}(\vec{\epsilon}_{\text{MC}}) \end{array} \right]$$

one-dimensional reweighting of MC samples in  $x = p_{\text{T}}^{(V)}$

with 
$$\frac{d}{dx} \sigma_{\text{TH}}^{(V)} = \frac{d}{dx} \sigma_{\text{QCD}}^{(V)} + \frac{d}{dx} \sigma_{\text{mix}}^{(V)} + \frac{d}{dx} \Delta \sigma_{\text{EW}}^{(V)} + \frac{d}{dx} \sigma_{\gamma\text{-ind.}}^{(V)}$$

- Robust uncertainty estimates including
  1. Pure QCD uncertainties
  2. Pure EW uncertainties
  3. Mixed QCD-EW uncertainties
  4. PDF,  $\gamma$ -induced uncertainties ....
- Prescription for **correlation** of these uncertainties
  - ▶ within a process (between low-pT and high-pT)
  - ▶ across processes

# QCD uncertainties



$$\frac{d}{dx} \sigma_{N^k \text{LO QCD}}^{(V)}(\vec{\epsilon}_{\text{QCD}}) = \left[ K_{N^k \text{LO}}^{(V)}(x) + \sum_{i=1}^3 \epsilon_{\text{QCD},i} \delta^{(i)} K_{N^k \text{LO}}^{(V)}(x) \right] \times \frac{d}{dx} \sigma_{\text{LO QCD}}^{(V)}(\vec{\mu}_0).$$

$$\epsilon_{\text{QCD},i}^{(Z)} = \epsilon_{\text{QCD},i}^{(W^\pm)} = \epsilon_{\text{QCD},i}^{(\gamma)} = \epsilon_{\text{QCD},i}$$

- correlated across processes
- correlated across pT bins

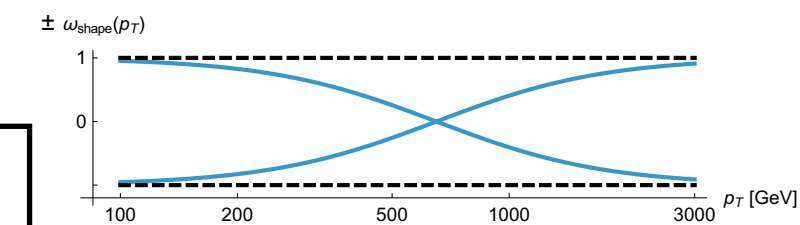
nuisance parameters:  
interpreted as  $1\sigma$  Gaussian

$$\bullet \delta^{(1)} K_{N^k \text{LO}}^V = \frac{1}{2} \left[ K_{N^k \text{LO}}^{V,\text{max}} - K_{N^k \text{LO}}^{V,\text{min}} \right] \quad (\text{correlated})$$

symmetrized **scale uncertainty**

$$\bullet \delta^{(2)} K_{N^k \text{LO}}^V = \frac{p_T^2 - 650 \text{ GeV}}{p_T^2 + 650 \text{ GeV}} \delta^{(1)} K_{N^k \text{LO}}^V$$

yields max **shape distortion** within scale variation band (correlated)



(important for extrapolation from low-pT to high-pT)

$$\bullet \delta^{(3)} K_{N^k \text{LO}}^V = \frac{K_{N^k \text{LO}}^V}{K_{N^{k-1} \text{LO}}^V} - \frac{K_{N^k \text{LO}}^Z}{K_{N^{k-1} \text{LO}}^Z} \quad (\text{correlated})$$

Difference of (N)NLO corrections as **process correlation uncertainty**

# Technical implementation of NLO EW

✓ Virtuals with OpenLoops:

- ▶ Fast numerical routines for all tree+loop vertices in the full SM
- ▶  $\mathcal{O}(\alpha)$  renormalization [Denner, 2012] Available schemes: on-shell,  $G_\mu$  and  $\alpha(m_Z)$
- ▶  $R_2$  rational terms
- ▶ Treatment of unstable particles: complex-mass-scheme

✓ Real radiation, subtraction, subprocess bookkeeping

✓ **Sherpa**

✓ **MUNICH:**



- ▶ Based on the well established NLO QCD dipole subtraction frameworks with replacements for QCD → QED

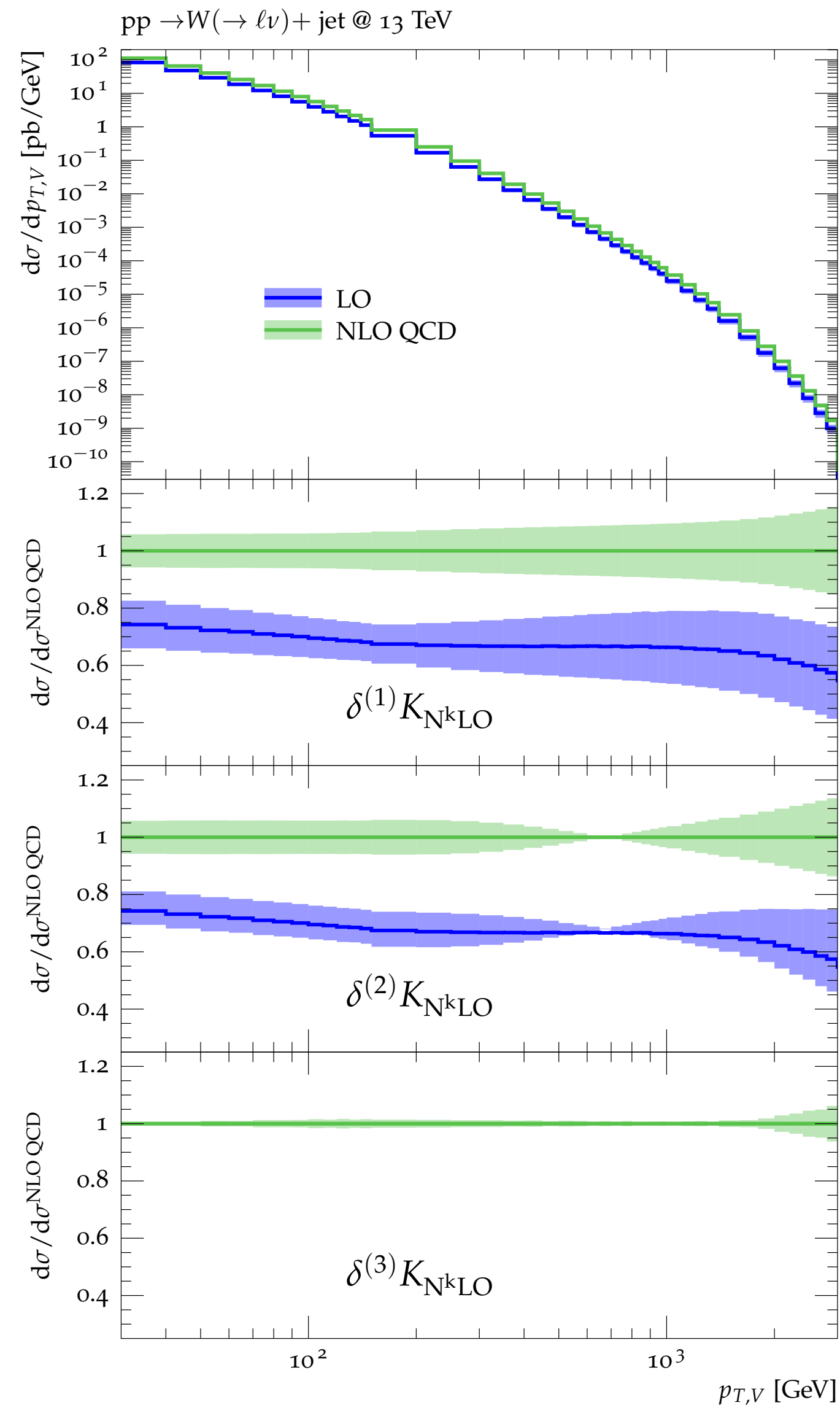
$$\alpha_s \longrightarrow \alpha, \quad C_F \longrightarrow Q_f^2, \quad T_R \longrightarrow N_{c,f} Q_f^2, \quad T_R N_f \longrightarrow \sum_f N_{c,f} Q_f^2, \quad C_A \longrightarrow 0$$

$$\frac{\mathbf{T}_{ij} \cdot \mathbf{T}_k}{\mathbf{T}_{ij}^2} \longrightarrow \begin{cases} \frac{Q_{ij} Q_k}{Q_{ij}^2} & \text{if the emitter } ij \text{ is a (anti)fermion} \\ \kappa_{ij,k} & \text{if the emitter } ij \text{ is a photon,} \end{cases}$$

- ▶ Mixed QCD-QED l-operator requires a non-trivial interplay between different Born orders

$$I \propto \sum \int_1 V_{\text{QED}} \otimes \text{[diagram with red wavy line]} + \int_1 V_{\text{QCD}} \otimes \text{[diagram with blue wavy line labeled } \gamma, Z \text{]}$$

# QCD uncertainties



$$\frac{d}{dx} \sigma_{N^k \text{LO QCD}}^{(V)}(\vec{\epsilon}_{\text{QCD}}) = \left[ K_{N^k \text{LO}}^{(V)}(x) + \sum_{i=1}^3 \epsilon_{\text{QCD},i} \delta^{(i)} K_{N^k \text{LO}}^{(V)}(x) \right] \times \frac{d}{dx} \sigma_{\text{LO QCD}}^{(V)}(\vec{\mu}_0).$$

$$\epsilon_{\text{QCD},i}^{(Z)} = \epsilon_{\text{QCD},i}^{(W^\pm)} = \epsilon_{\text{QCD},i}^{(\gamma)} = \epsilon_{\text{QCD},i}$$

- correlated across processes
- correlated across pT bins

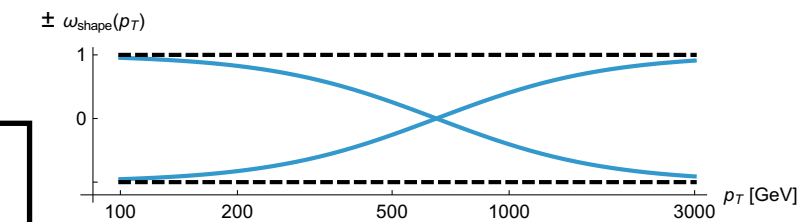
nuisance parameters:  
interpreted as  $1\sigma$  Gaussian

$$\bullet \delta^{(1)} K_{N^k \text{LO}}^V = \frac{1}{2} \left[ K_{N^k \text{LO}}^{V,\text{max}} - K_{N^k \text{LO}}^{V,\text{min}} \right] \quad (\text{correlated})$$

symmetrized **scale uncertainty**

$$\bullet \delta^{(2)} K_{N^k \text{LO}}^V = \frac{p_T^2 - 650 \text{ GeV}}{p_T^2 + 650 \text{ GeV}} \delta^{(1)} K_{N^k \text{LO}}^V$$

yields max **shape distortion** within scale variation band (correlated)

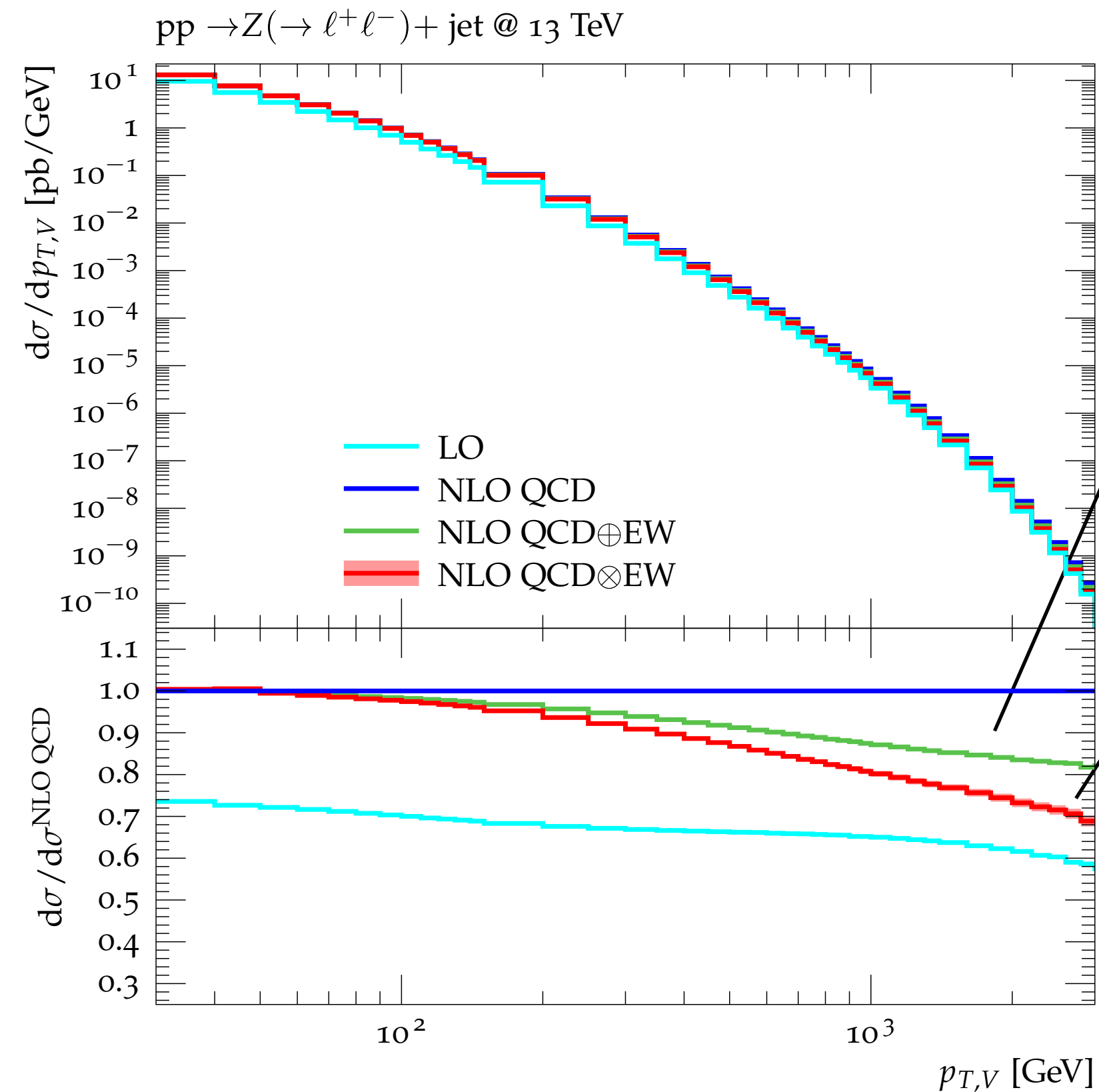


(important for extrapolation from low-pT to high-pT)

$$\bullet \delta^{(3)} K_{N^k \text{LO}}^V = \frac{K_{N^k \text{LO}}^V}{K_{N^{k-1} \text{LO}}^V} - \frac{K_{N^k \text{LO}}^Z}{K_{N^{k-1} \text{LO}}^Z} \quad (\text{correlated})$$

Difference of (N)NLO corrections as **process correlation uncertainty**

# Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative  $\mathcal{O}(\alpha\alpha_s)$  have to be considered.

## Additive combination

$$\sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma^{\text{LO}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} + \delta\sigma_{\text{EW}}^{\text{NLO}}$$

## Multiplicative combination

$$\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left( 1 + \frac{\delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right)$$

(try to capture some  $\mathcal{O}(\alpha\alpha_s)$  contributions, e.g. EW Sudakov logs  $\times$  soft QCD)

Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

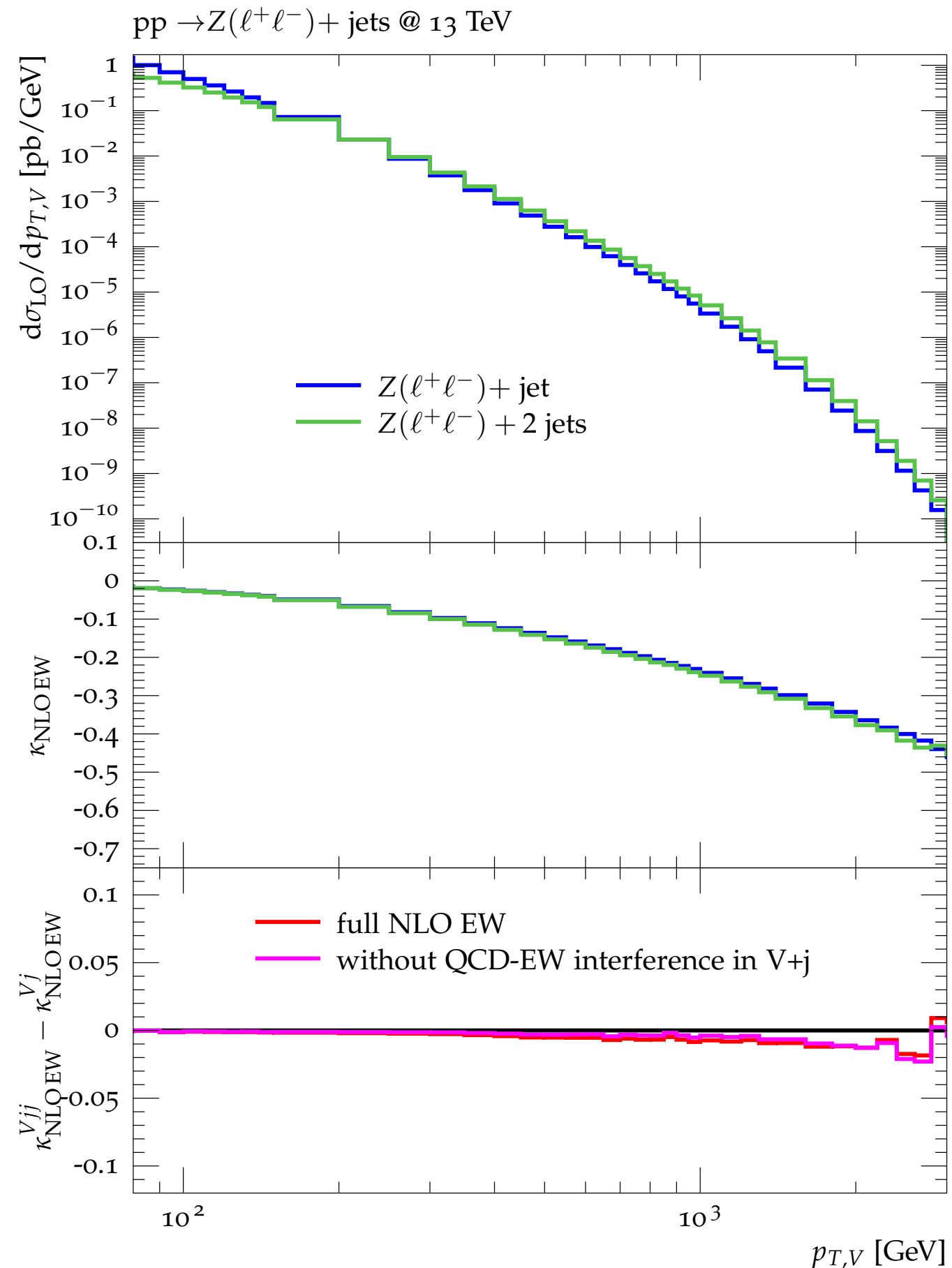
$$K_{\text{QCD}\otimes\text{EW}} - K_{\text{QCD}\oplus\text{EW}} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!



# Mixed QCD-EW uncertainties



$p_{T,j,2} > 30 \text{ GeV}$

Bold estimate:

Consider real  $\mathcal{O}(\alpha\alpha_s)$  correction to V+jet  
 $\simeq$  NLO EW to V+2jets

and we observe

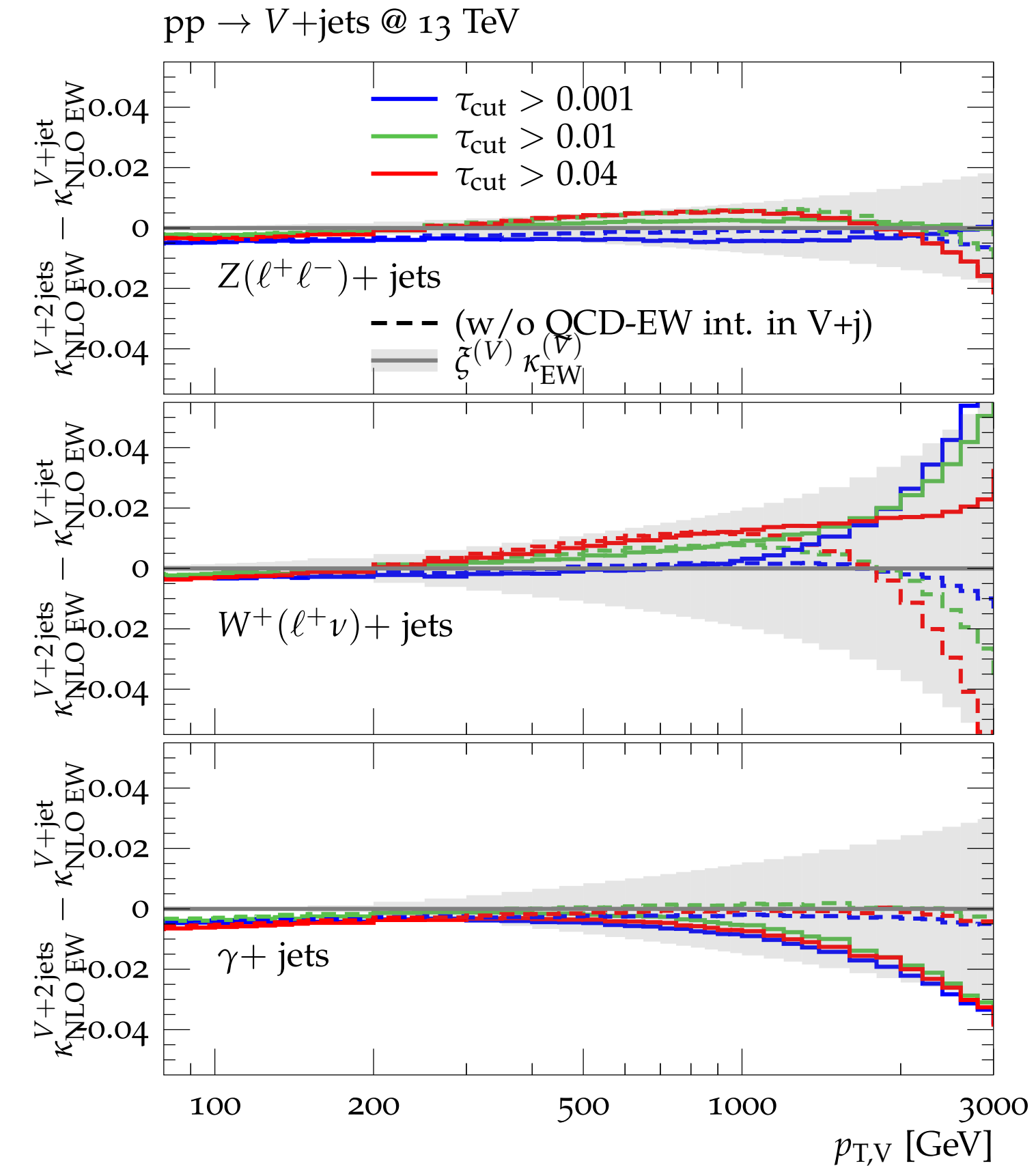
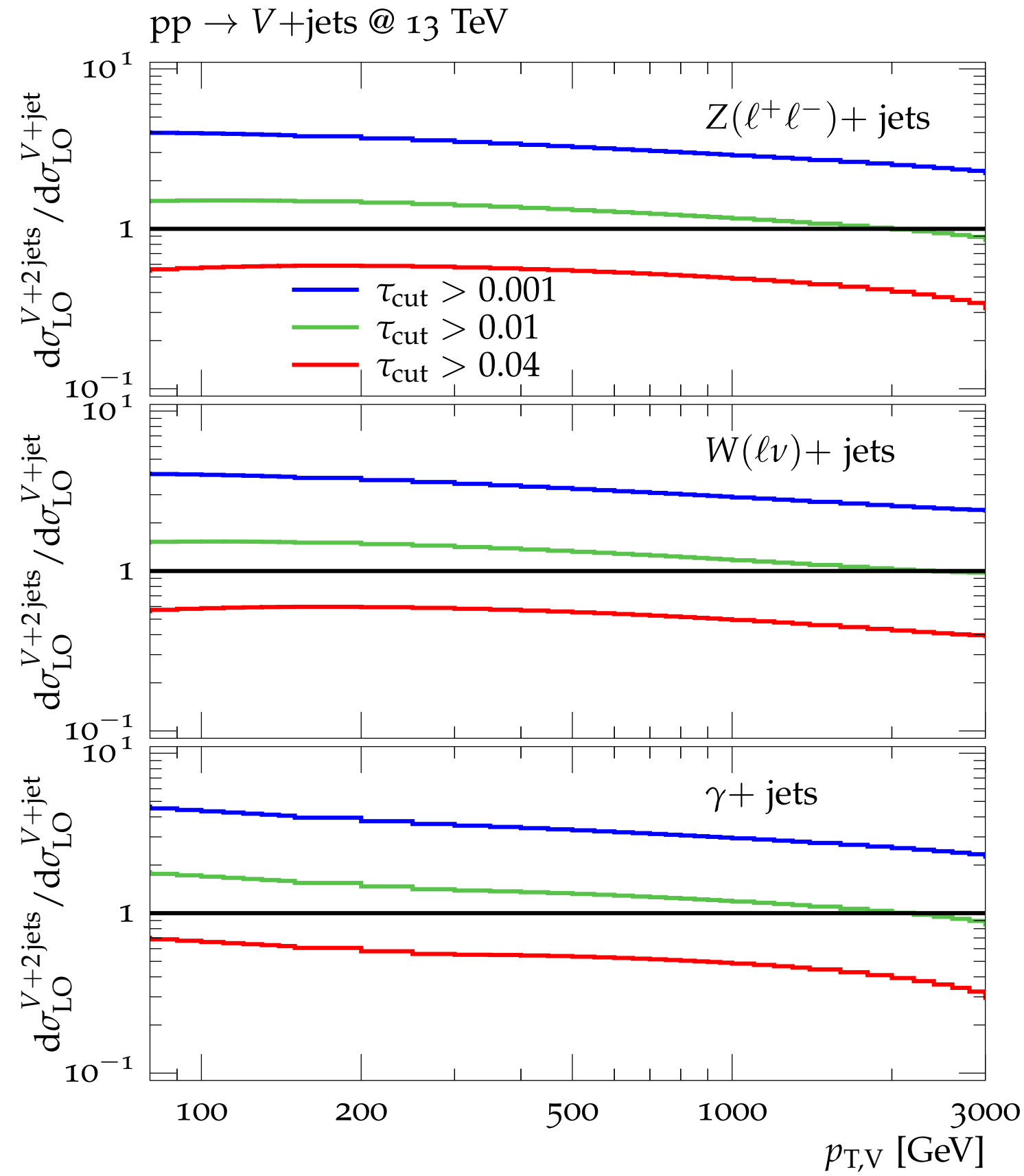
$$\frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}}\Big|_{V+2\text{jet}} - \frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}}\Big|_{V+1\text{jet}} \lesssim 1\%$$

strong support for

- factorization
- multiplicative QCD  $\times$  EW combination

# Mixed QCD-EW uncertainties

Estimate of non-factorising contributions



N-jettiness cut ensures approx. constant ratio  
V+2jets/V+jet

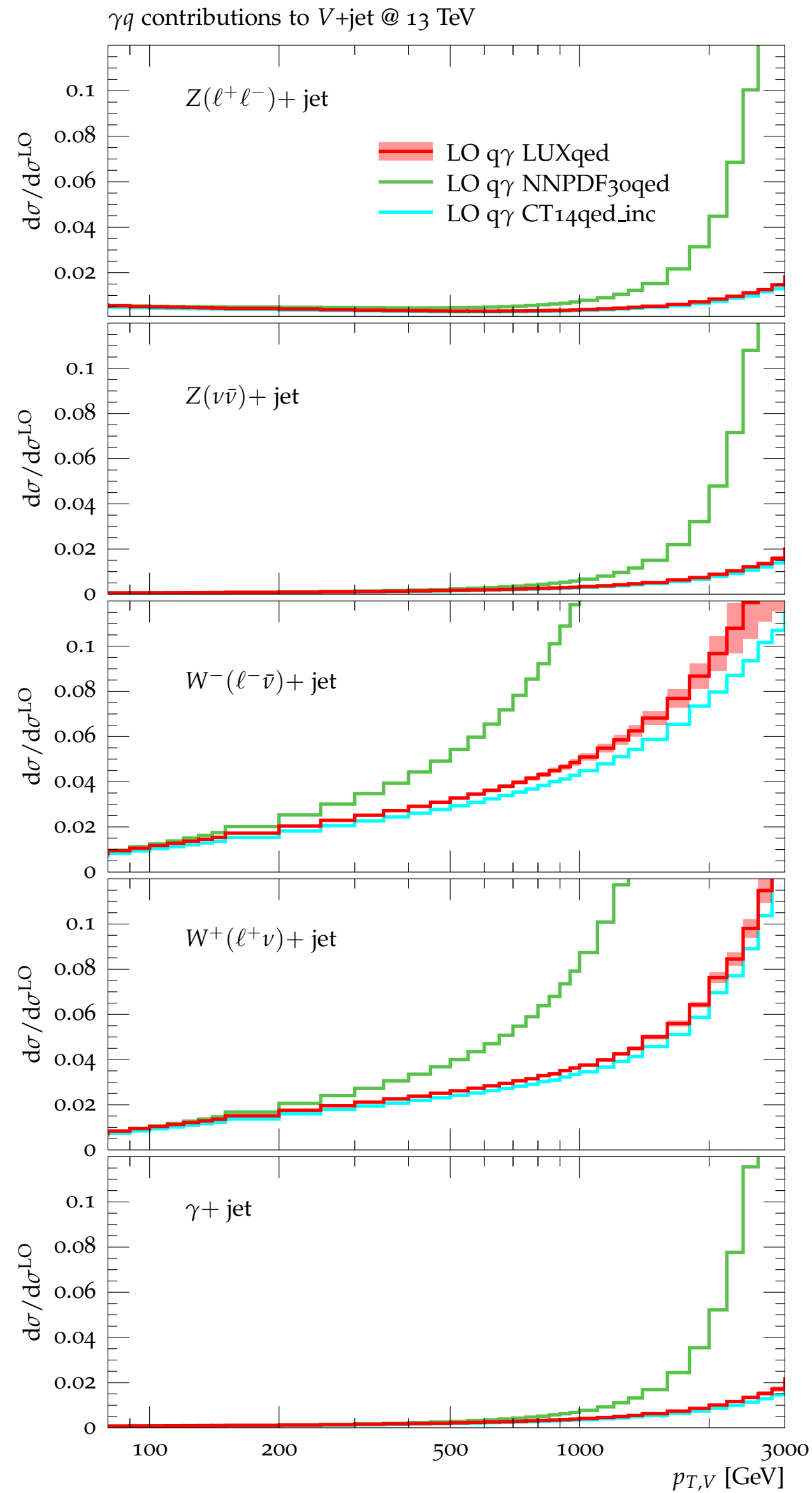
$$\tau_1 = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i \sqrt{\hat{s}}} \right\}$$

$$\delta K_{mix}^{(V)}(x, \mu) = \xi^{(V)} \left[ K_{TH,\otimes}^{(V)}(x, \mu) - K_{TH,\oplus}^{(V)}(x, \mu) \right]$$

$$\xi^Z = 0.1, \quad \xi^W = 0.2, \quad \xi^\gamma = 0.4$$

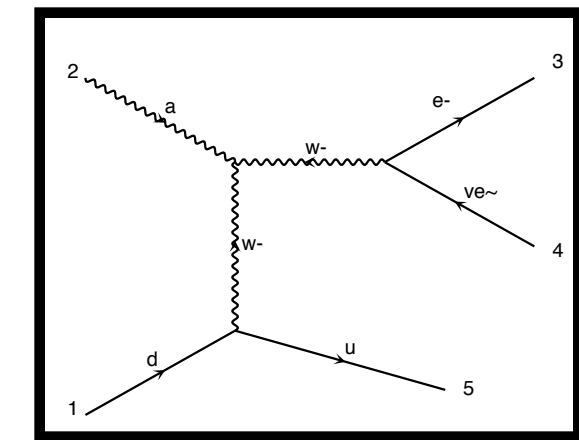
(tuned to cover above difference of EW K-factors )

# Photon-induced production



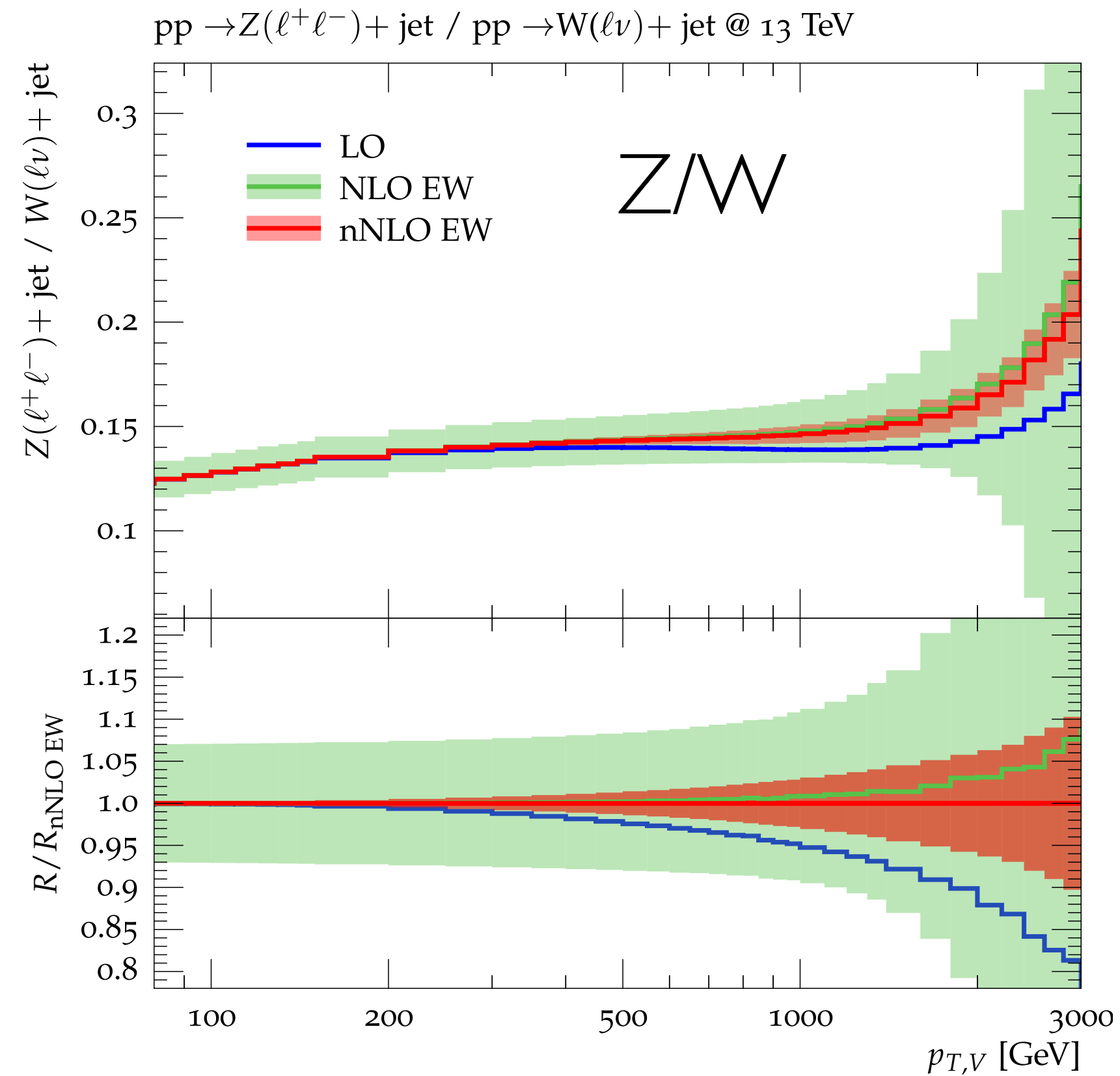
- suppressed by relative factor  $\alpha/\alpha_S$
- irrelevant for  $Z$ +jet (and  $\gamma$ +jet)
- in  $W$ +jet  $O(5\%)$  contribution with LUXqed, consistent with CT14qed

(due to t-channel enhancement)

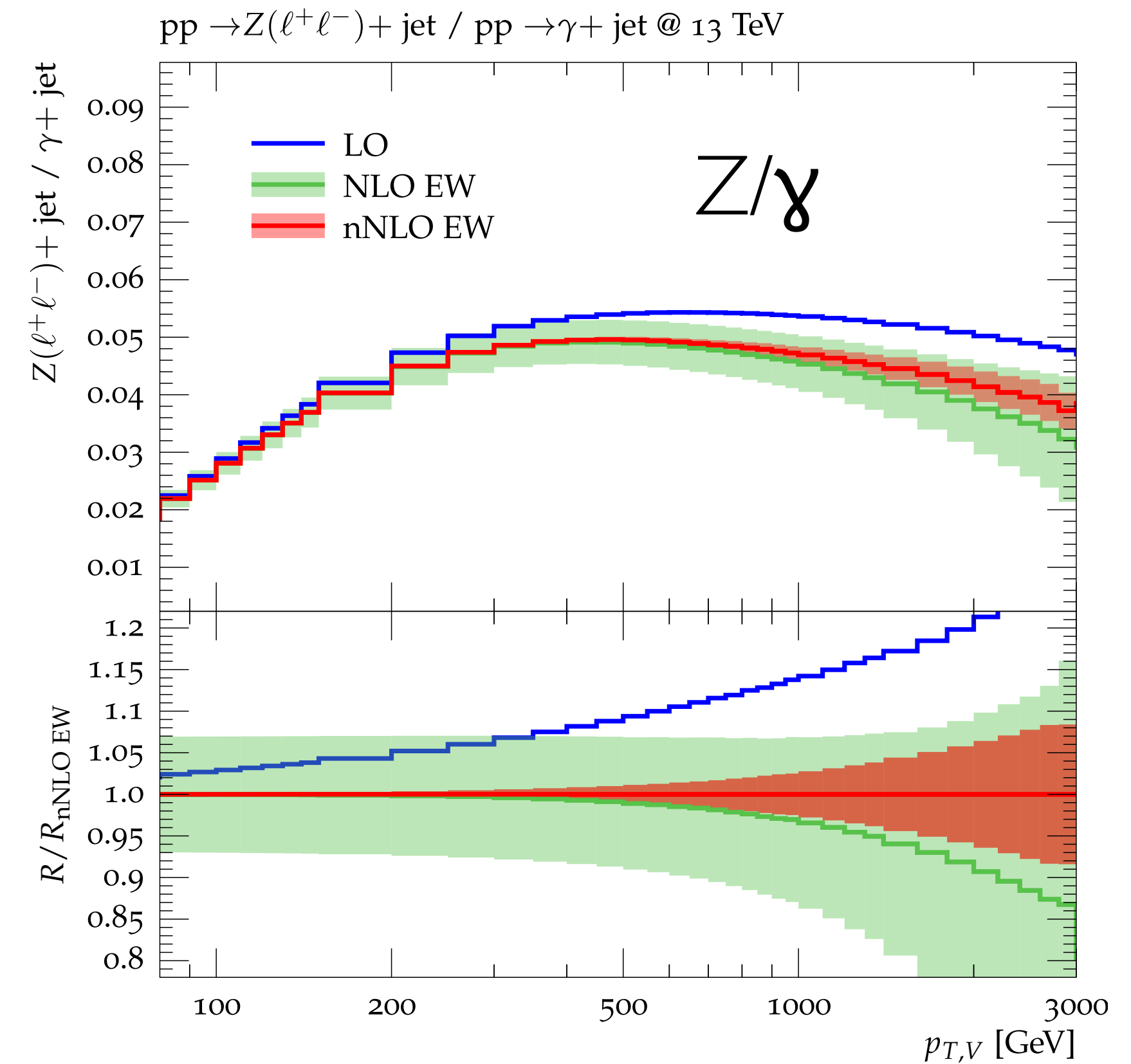


- $\sim 1\%$  uncertainties in photon PDFs due to LUXqed

# Pure EW uncertainties: ratios



- NLO EW:  $\sim 5\%$  for  $p_T=1$  TeV
- nNLO EW:  $\sim 1\%$  for  $p_T=1$  TeV



- NLO EW:  $\sim 15\%$  for  $p_T=1$  TeV
- nNLO EW:  $\sim 4\%$  for  $p_T=1$  TeV

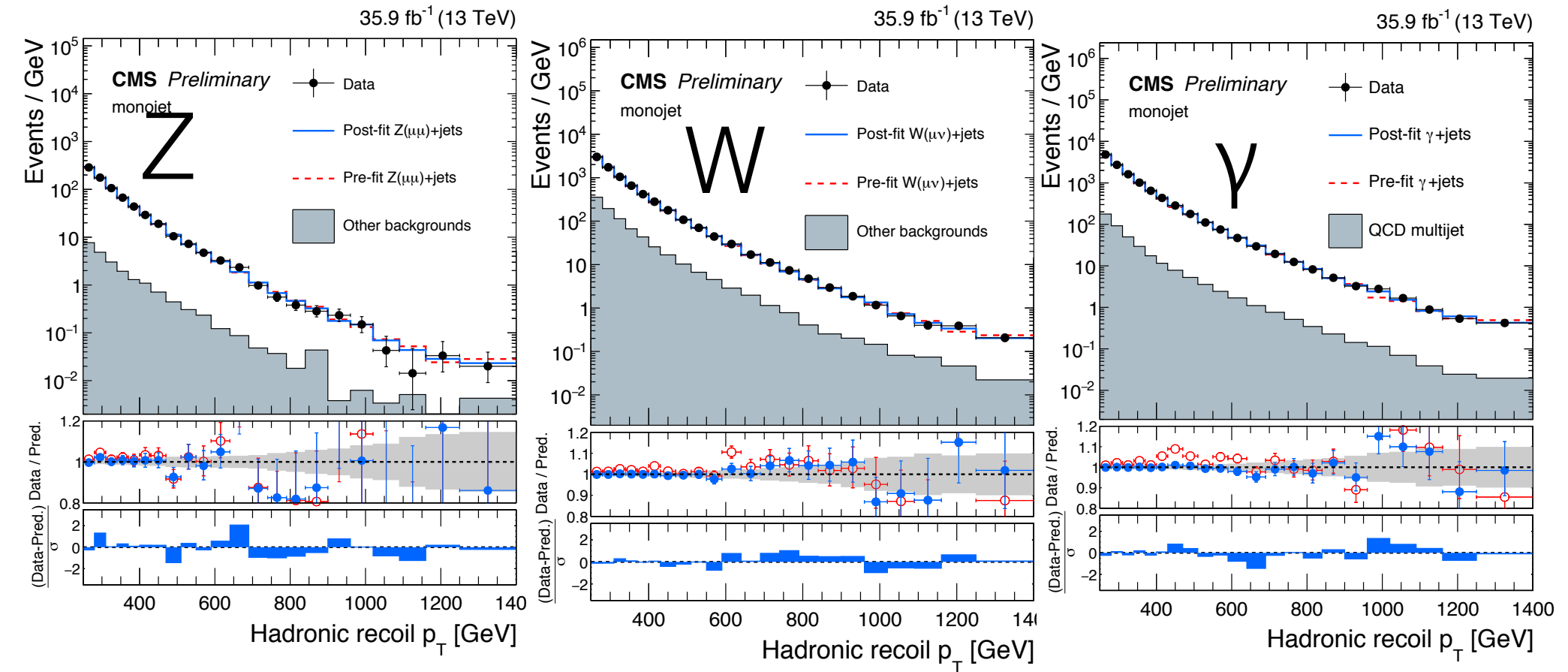
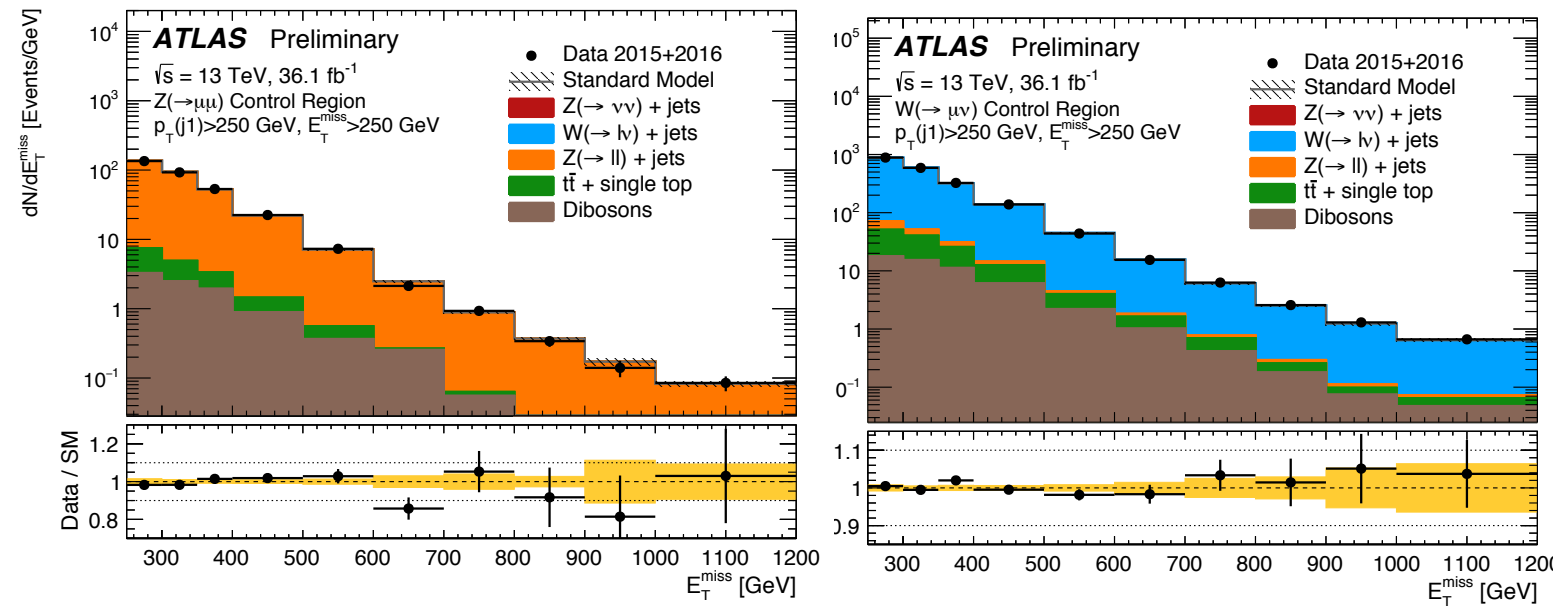
$\delta(R) < 3-5\%$  for  $p_T < 1-2$  TeV

# Experimental closure tests in recent ATLAS & CMS monojet searches

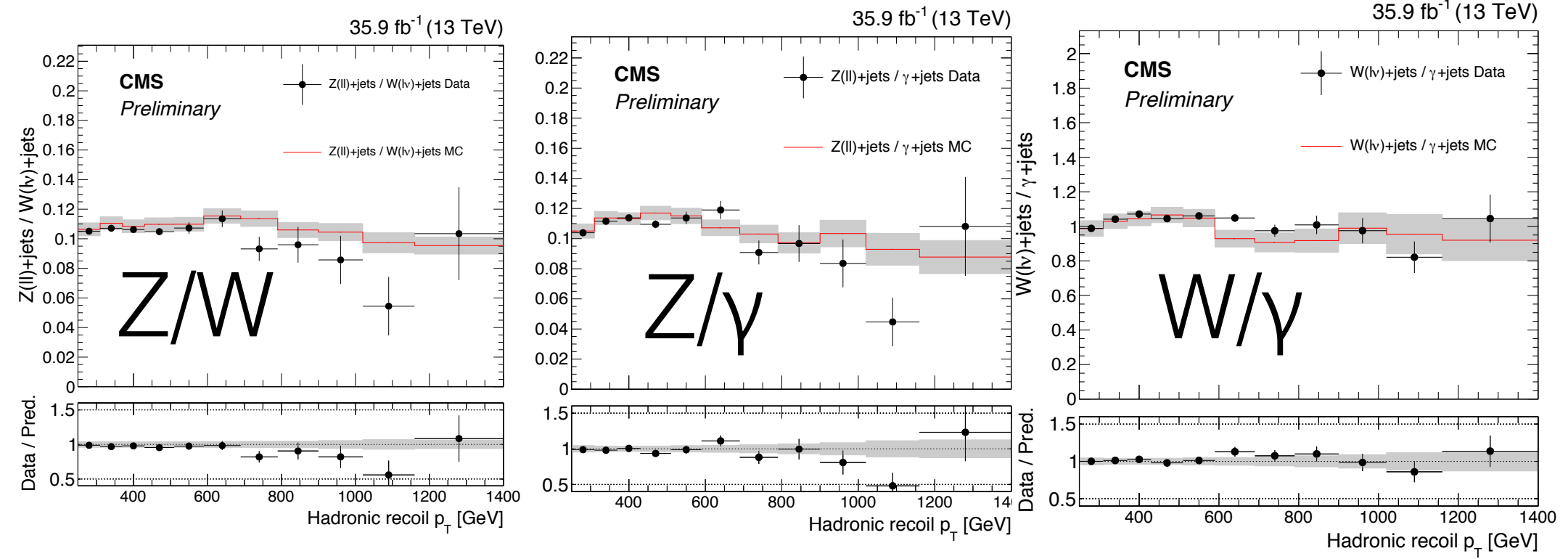
[ATLAS-CONF-2017-060]

[CMS PAS EXO-16-048]

Nominals

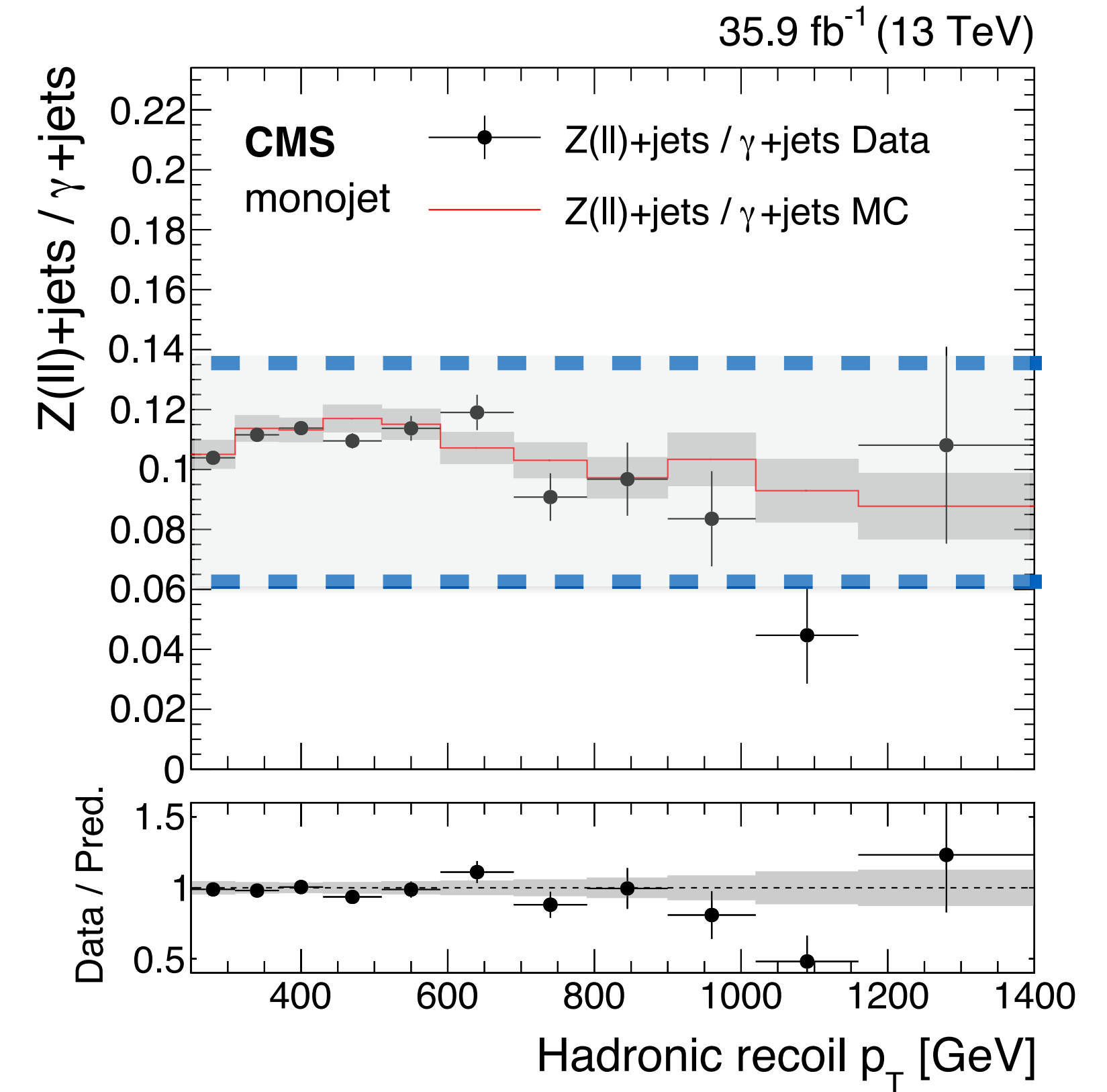
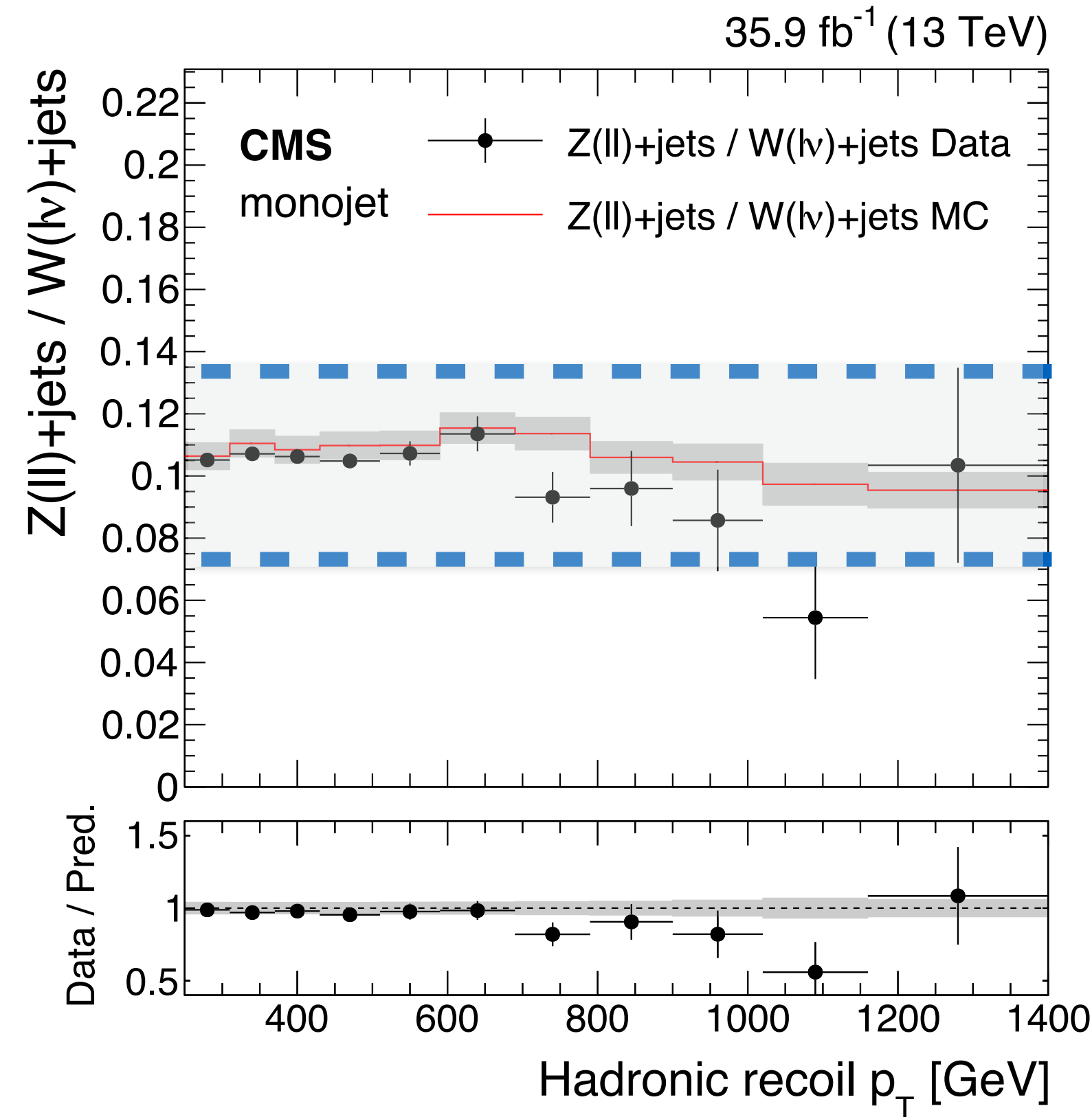
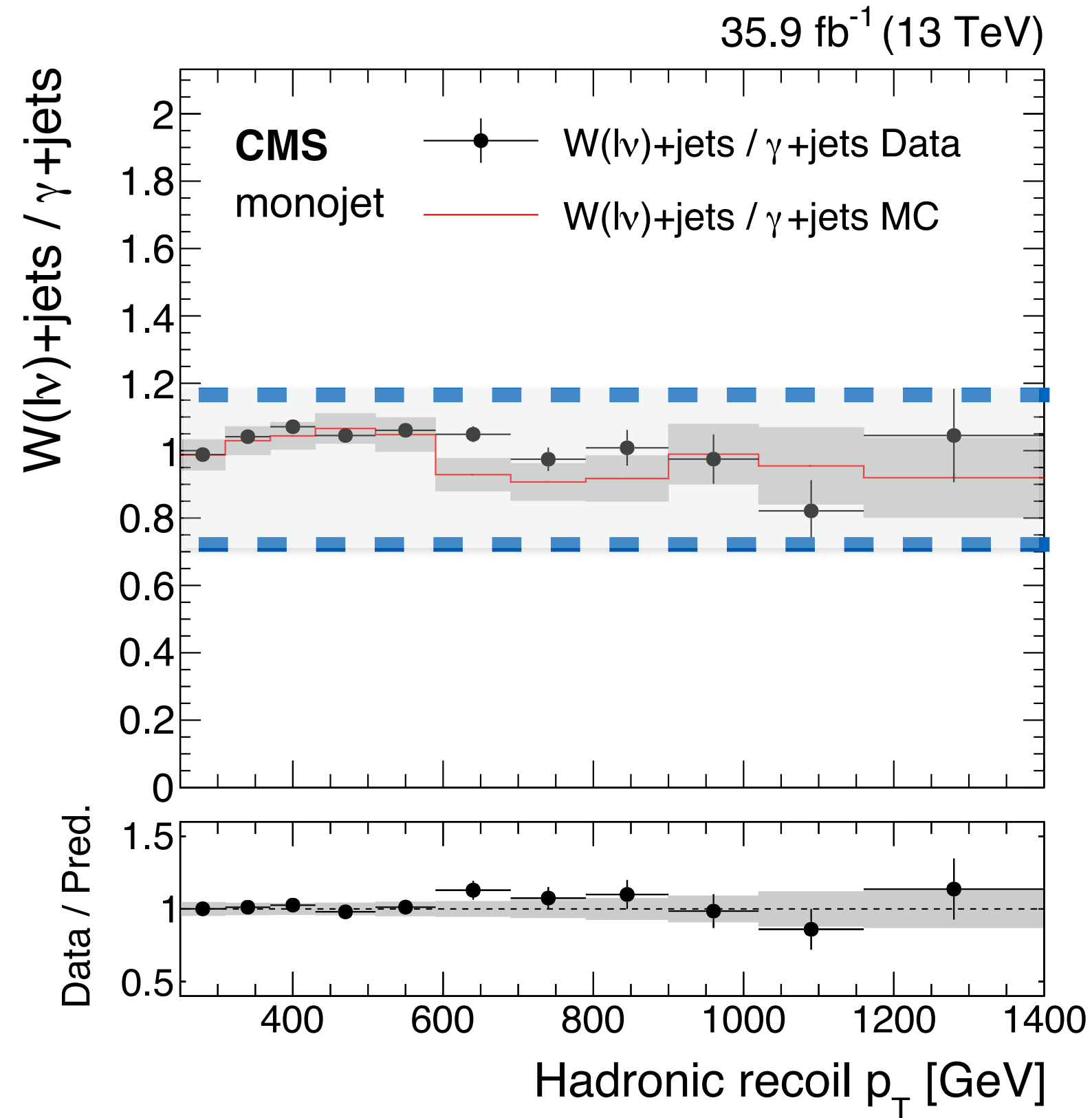


Ratios



# Experimental closure tests CMS monojet searches

[Zeynep Demiragli,  
DM@LHC 2018]



**Black ratio from data and statistical uncertainties / Red from MC**

Grey band includes theoretical uncertainties

**dashed lines -> what the uncertainties would have been without the work of the theory community**

# The Zoo of MET+X searches

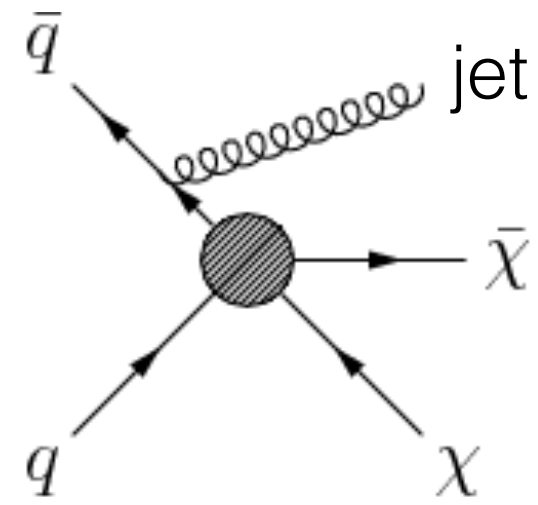
ISR

Higgs-Strahlung

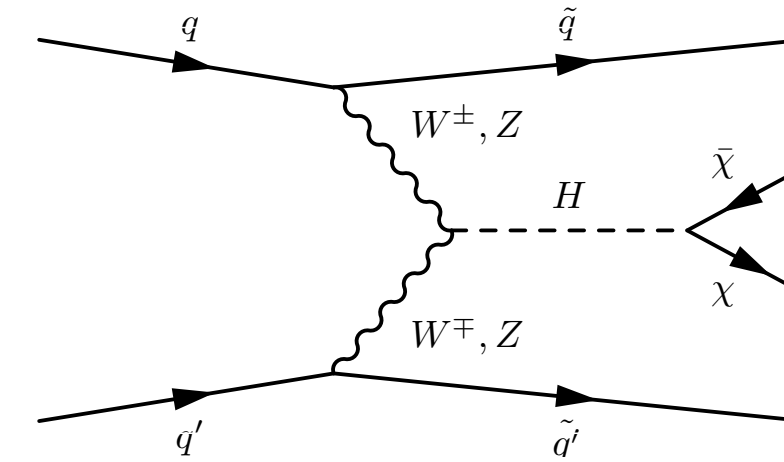
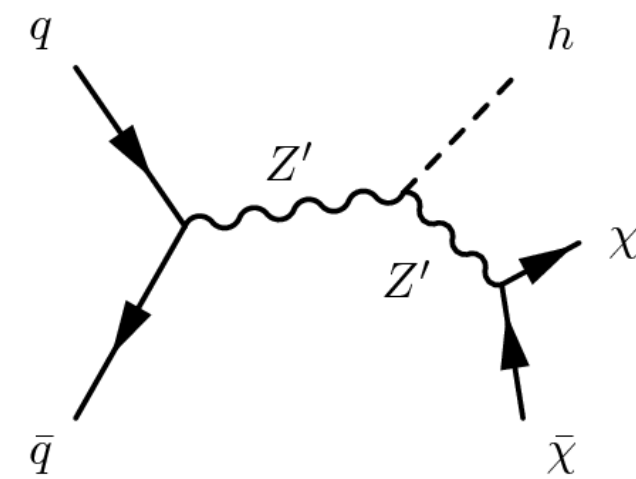
VBF

HF-associated

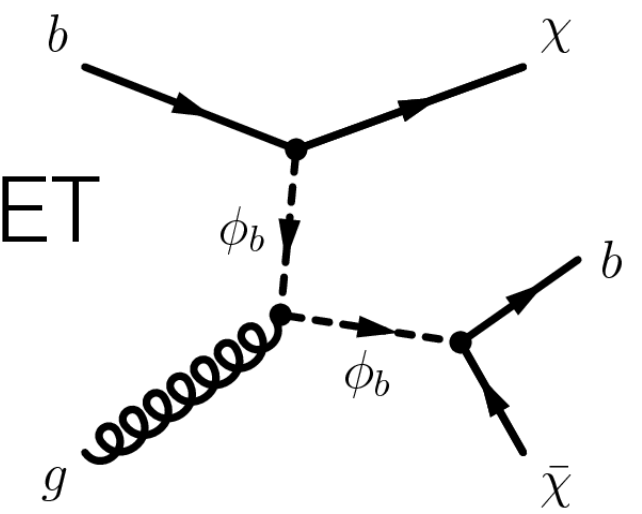
Mono-jet



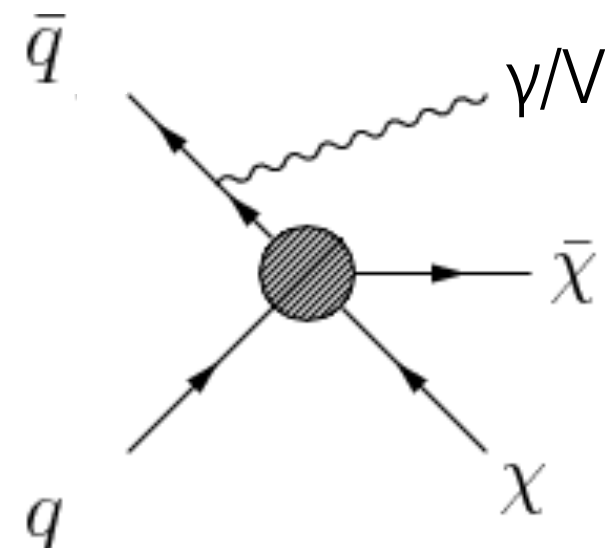
Mono-H



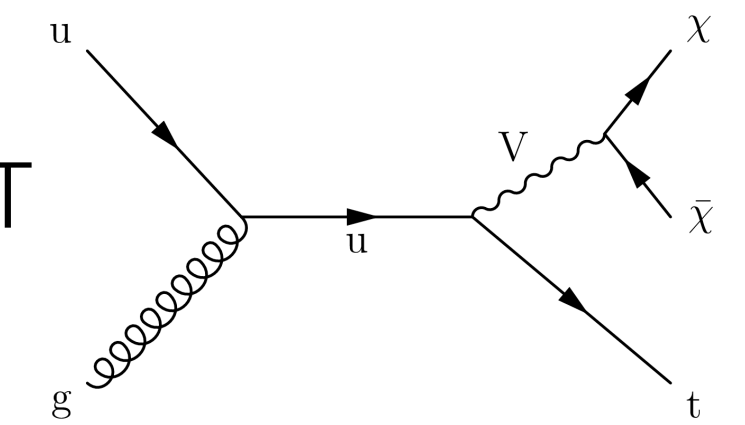
b+MET



Mono- $\gamma/V$

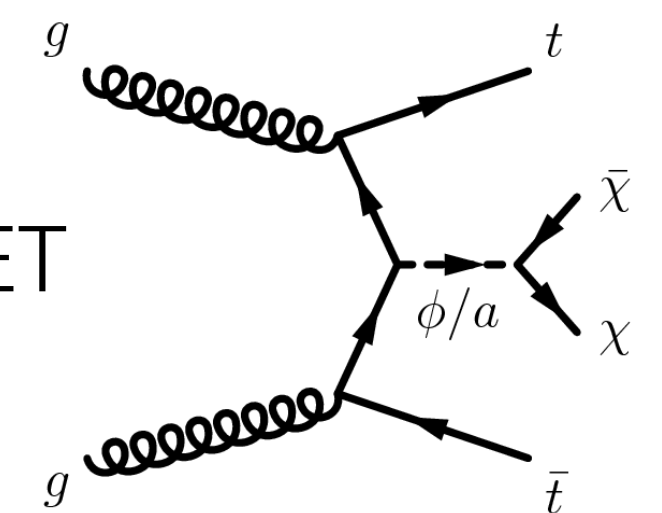


t+MET

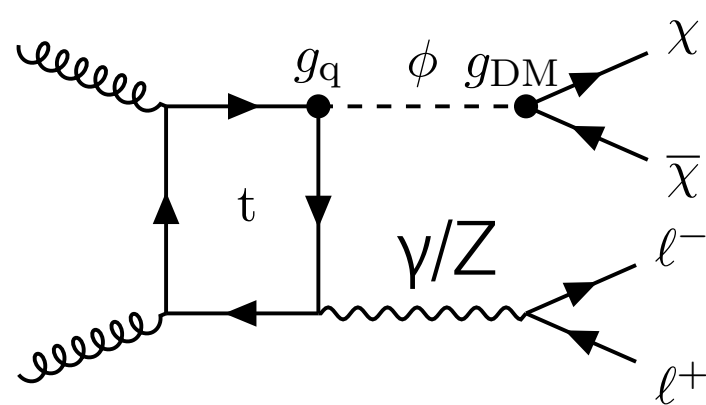


and many more....

tt+MET



Loop-induced



# The Zoo of MET+X searches: backgrounds

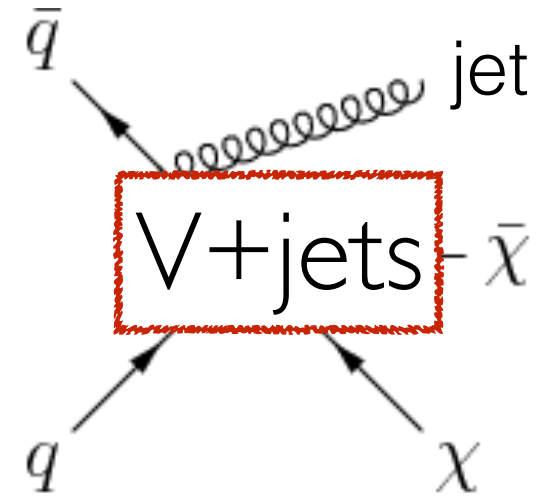
ISR

Higgs-Strahlung

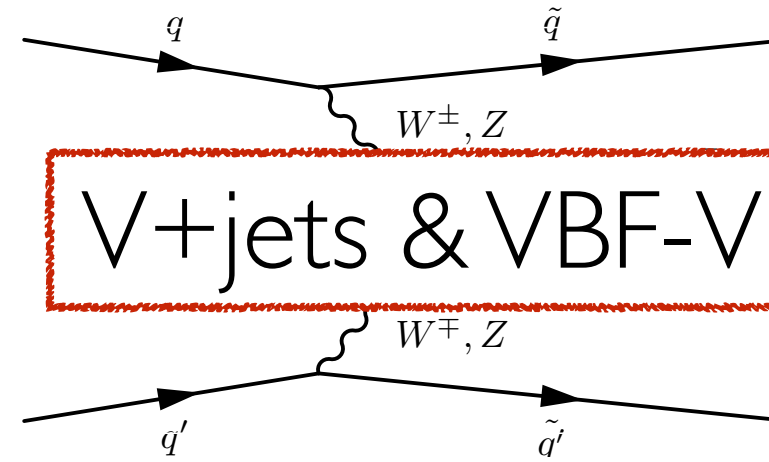
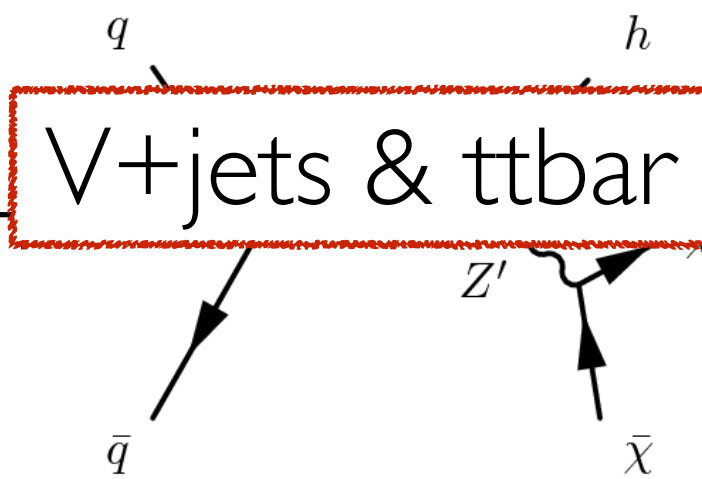
VBF

HF-associated

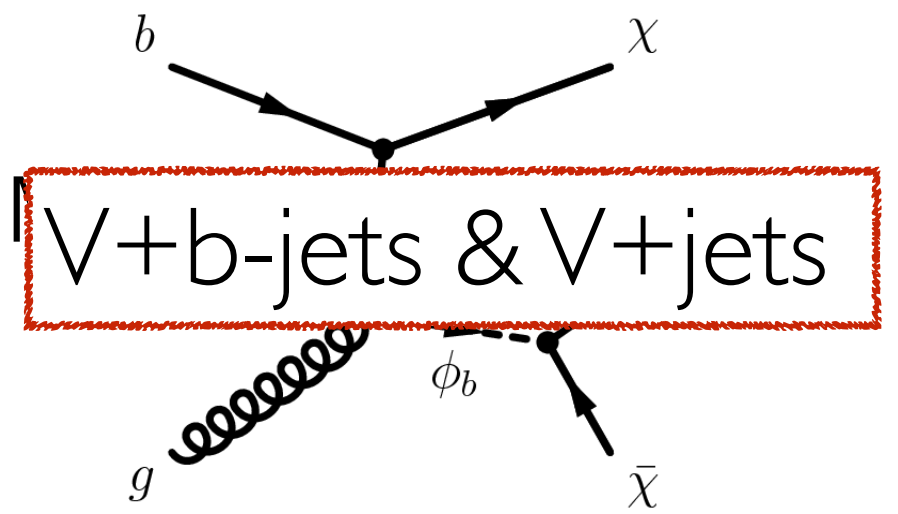
Mono-jet



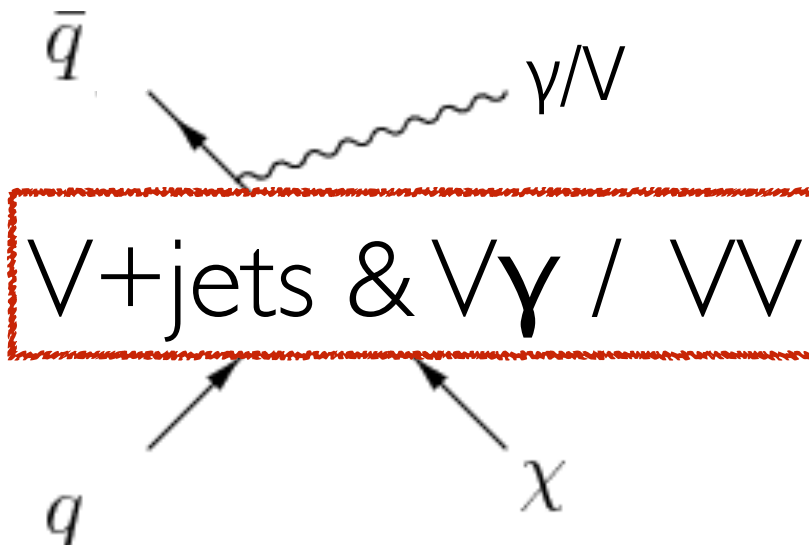
Mono-H



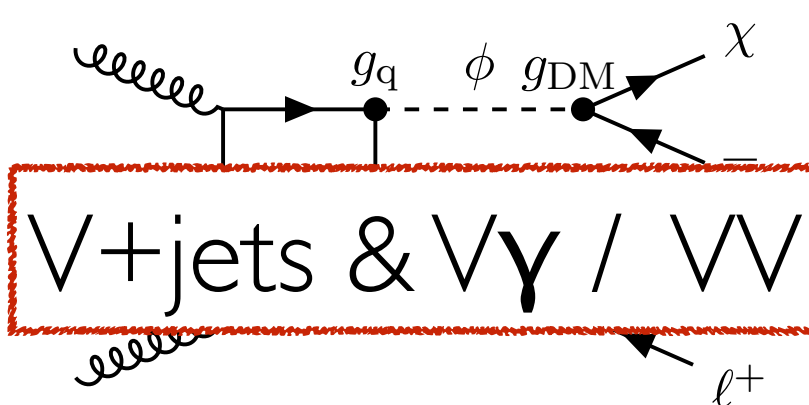
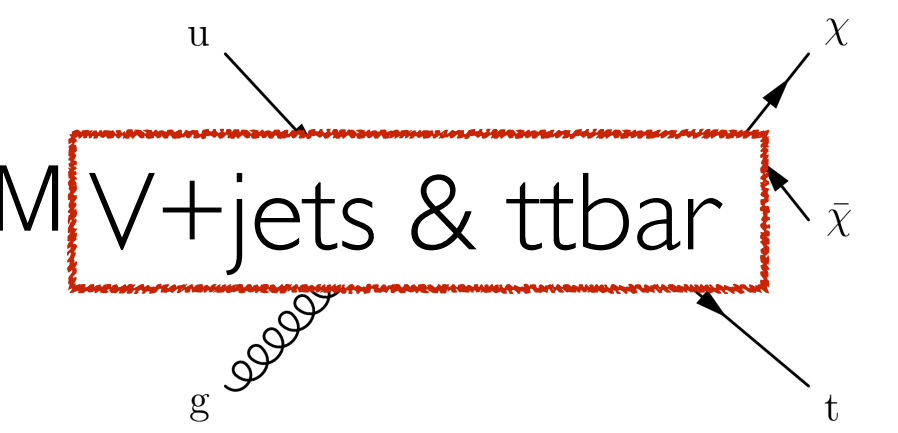
b+H



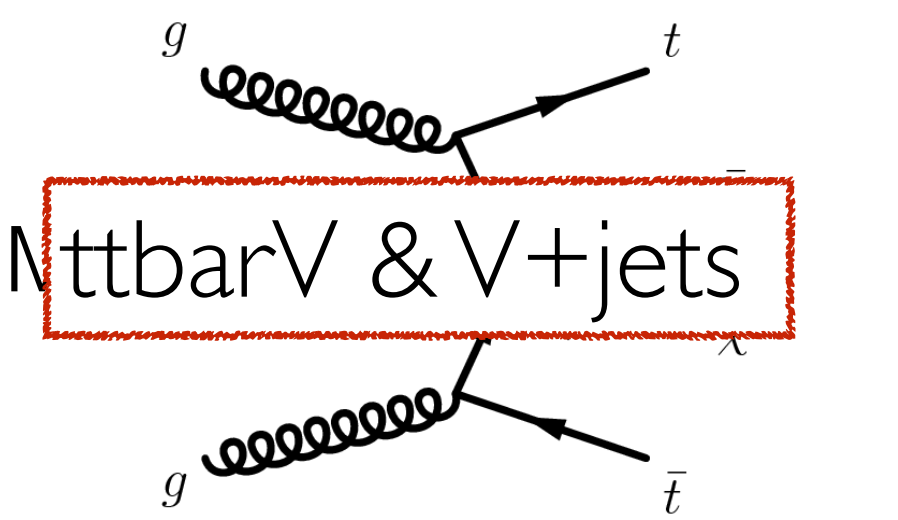
Mono- $\gamma/V$



t+M



tt+M



Loop-induced



# The Zoo of MET+X searches: backgrounds

