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

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IP3

INFN-UNIMI-UNIMIB Pheno Seminar

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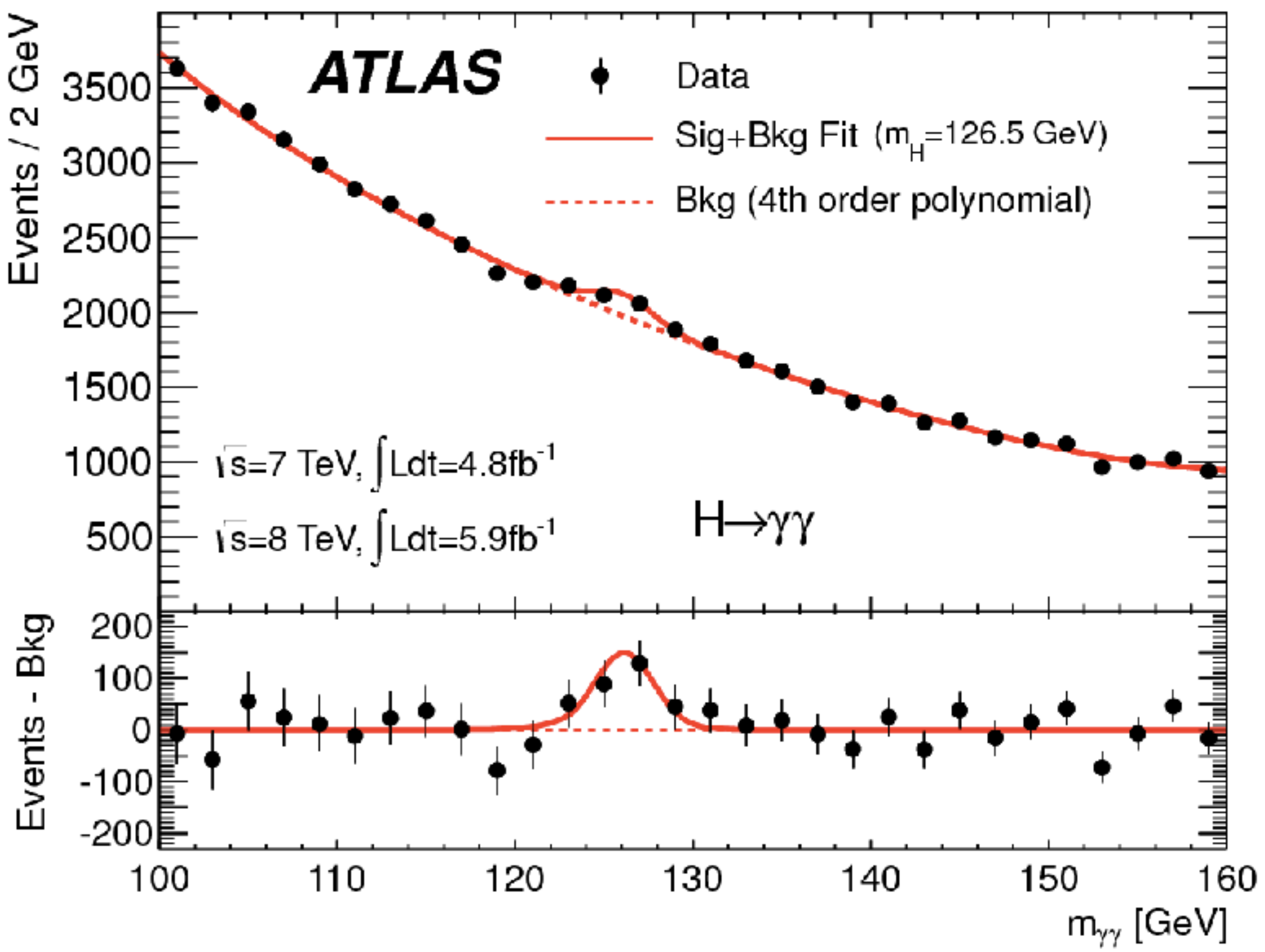
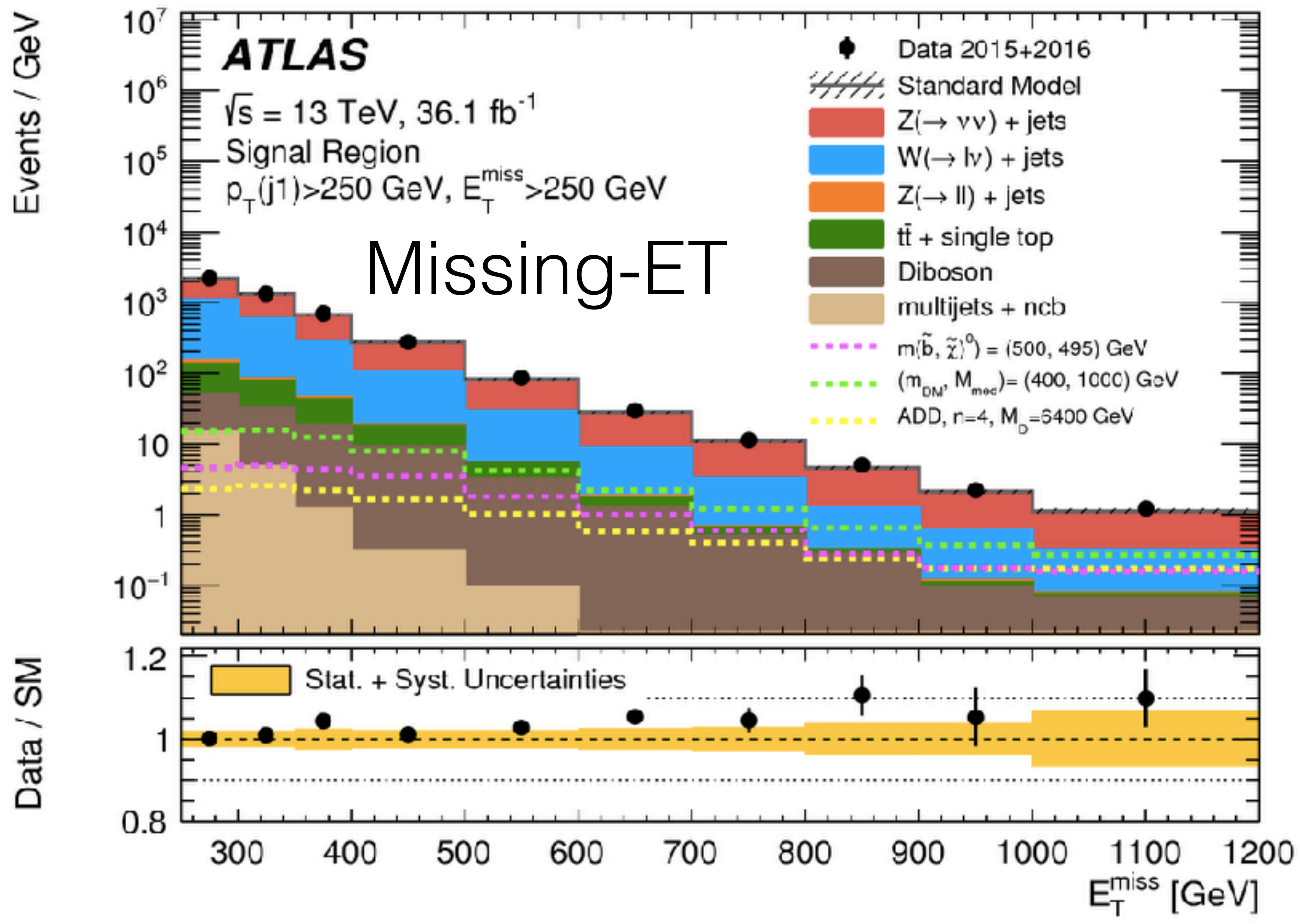
EA-01-2474

From a pheno perspective
finding the Higgs was "easy"…



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

…finding new physics might be very tough.



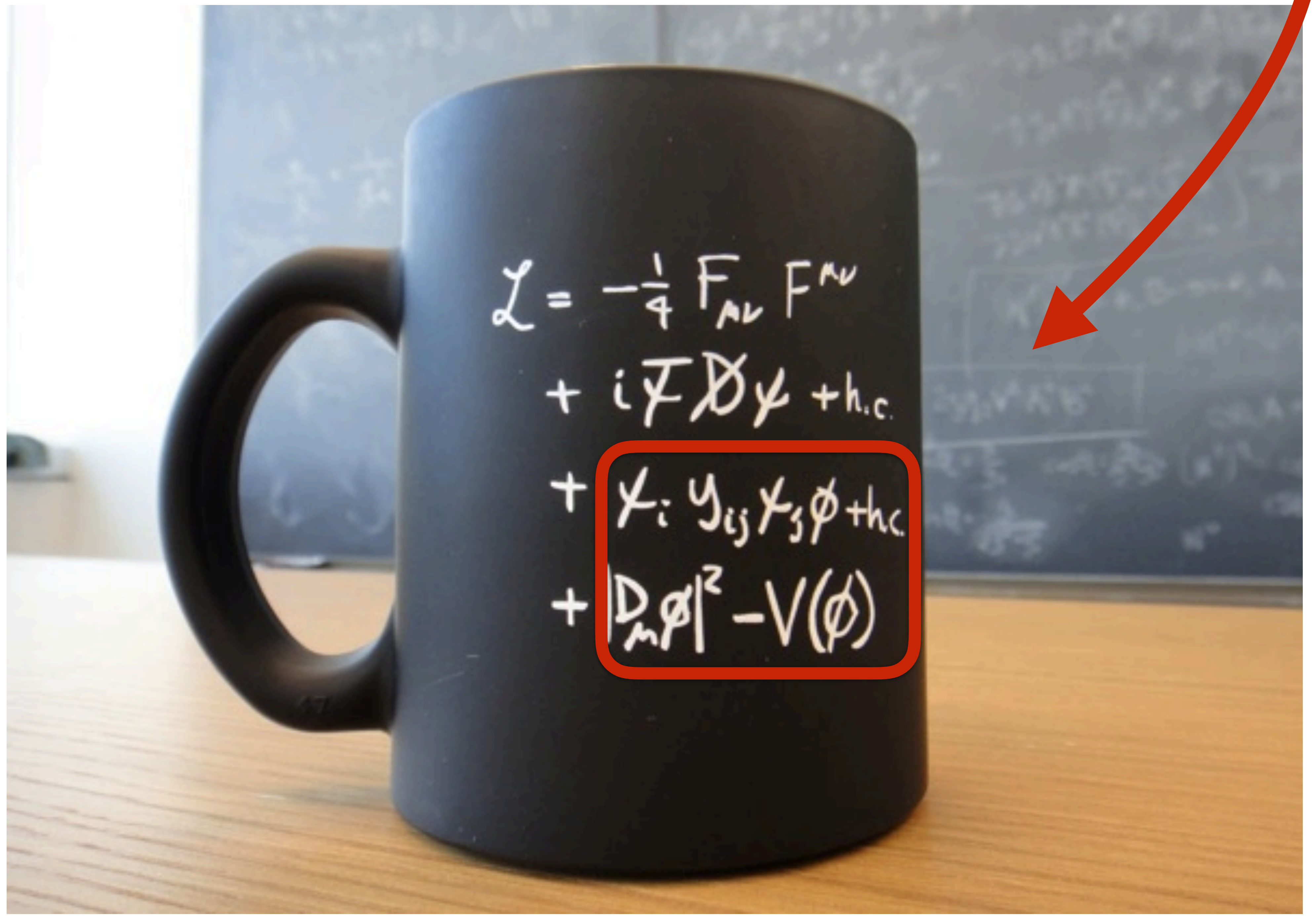
- Dark Matter particles produced at the LHC leave the detectors unobserved: signature missing transverse energy
- large irreducible SM backgrounds

→ **good control on theory necessary!**

…understanding the Higgs and its properties is tough!

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

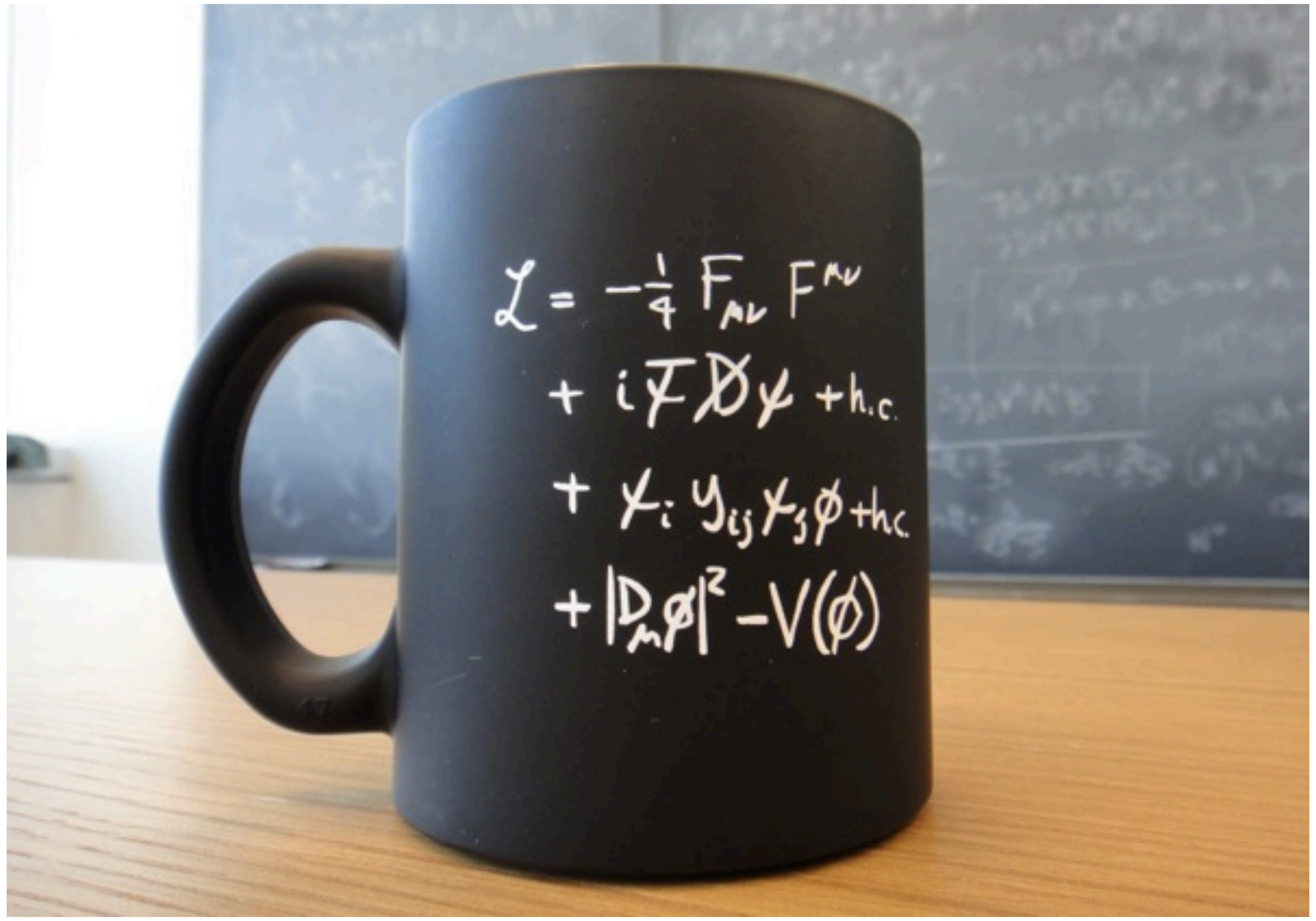
- CP properties? Is there a CP-odd admixture?
- couplings with vector-bosons/fermions as in SM?
- what is the Higgs width? Is there a significant invisible decay?
- only one Higgs doublet?
- what is the Higgs potential? self-coupling?



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

➡ precision is key!

Theoretical Predictions for the LHC

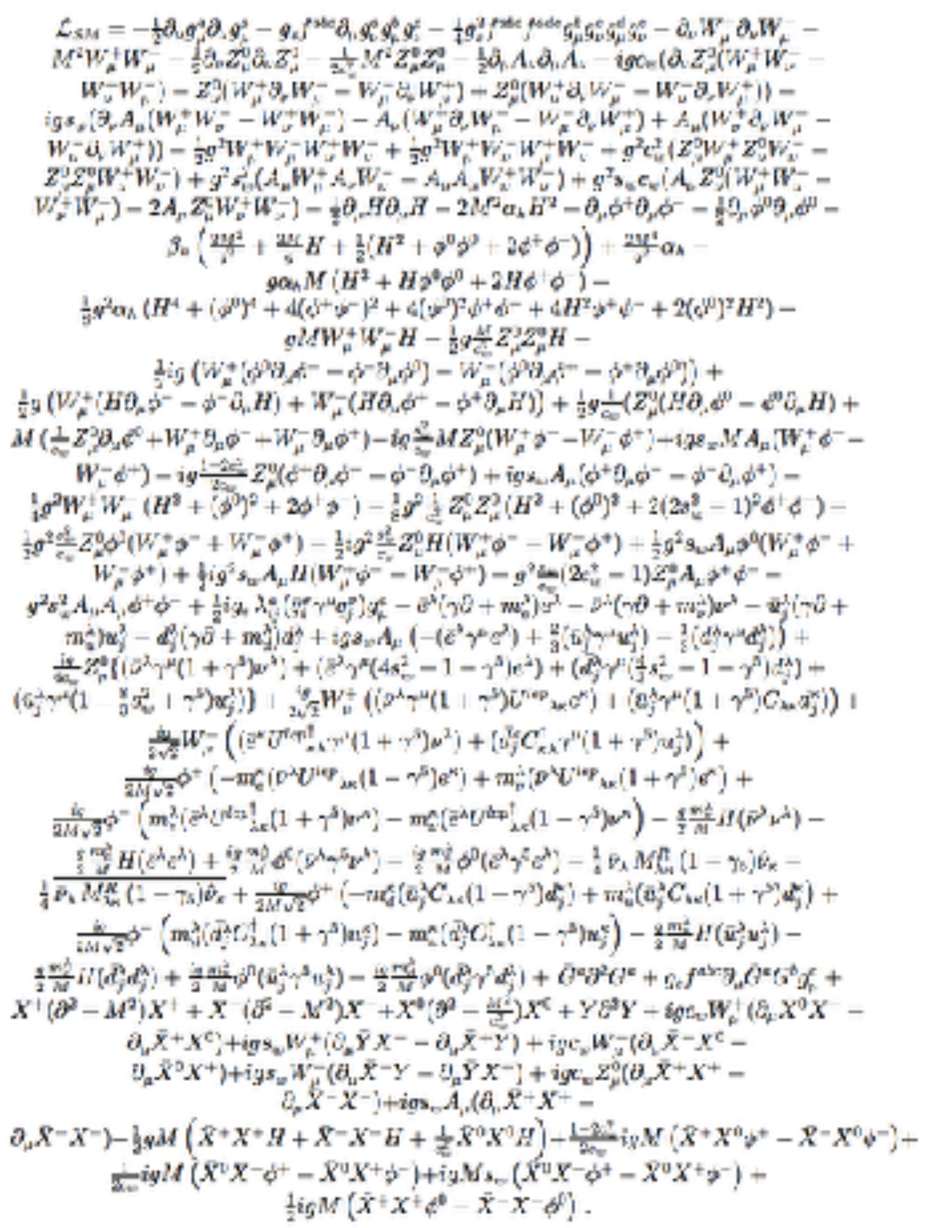


$$\hookrightarrow |\mathcal{M}|^2 \rightarrow \sigma$$

Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_S\, d\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NLO\,EW}}$$
$$+\alpha_S^2\, d\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, d\sigma_{\mathrm{NNLO\,EW}} + \alpha_S\alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NNLO\,QCDxEW}}$$



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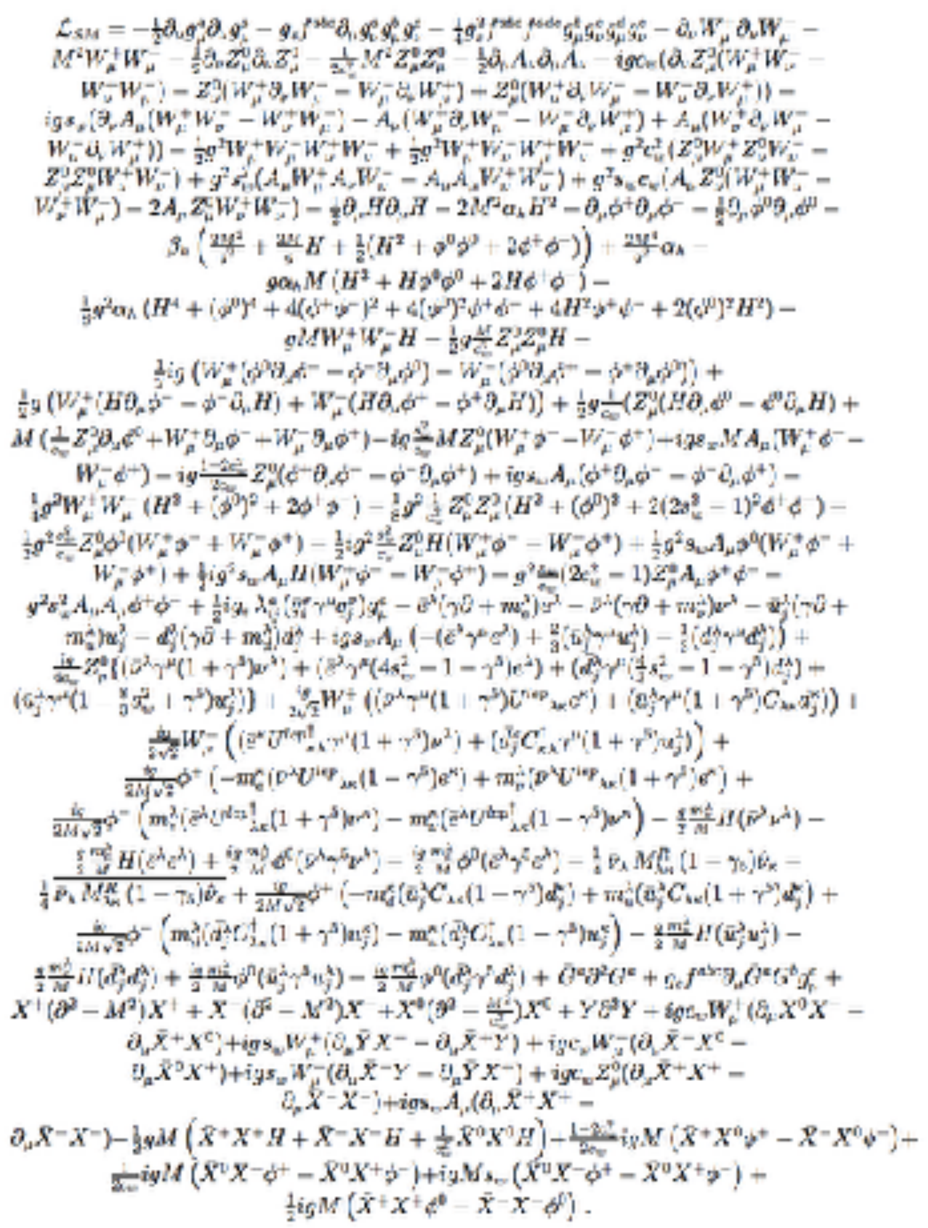

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$$\mathrm{d}\sigma_{\mathrm{NLO}} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\mathrm{LO}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\} + I\right] + \frac{1}{2s}\int d\Phi_{n+1}|\mathcal{M}_{\mathrm{NLO,R}}|^2 - S$$

OpenLoops

[JML, Maierhöfer, Pozzorini]

Sherpa

[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]

MUNICH:

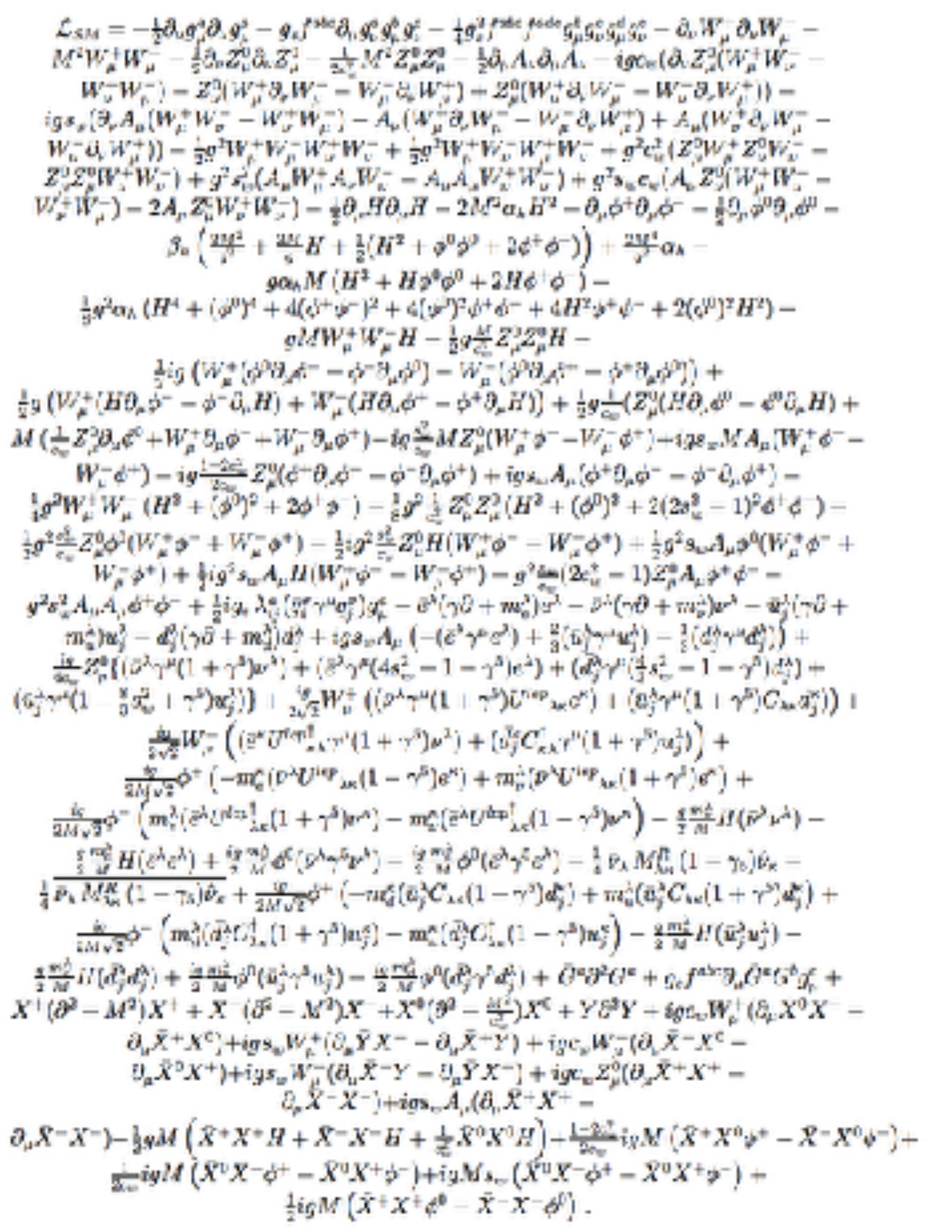
MUlti-chaNnel Integrator at swiss (CH) precision

[Kallweit]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, et. al.]

Theoretical Predictions for the LHC



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POWHEG-BOX

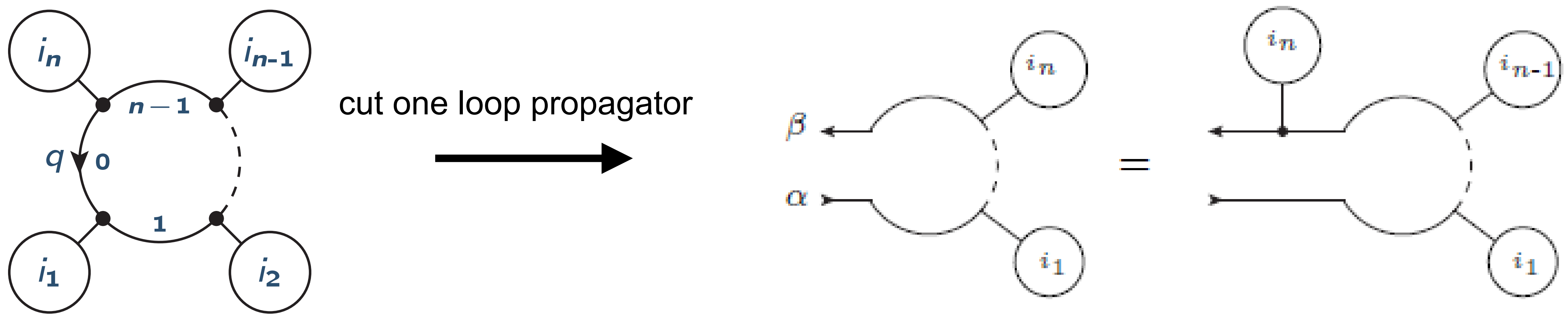
[Alioli, Nason, Oleari, Re, et. al.]

- 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

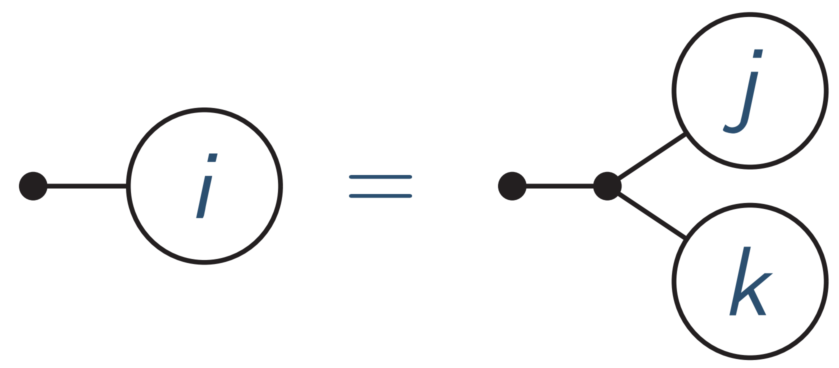


- Publicly available at **`http://openloops.hepforge.org`**
- Amplitudes for any 2 ➞ 4(5) NLO QCD process in the SM available:
  tree & (renormalized) virtual amplitudes, color correlations, spin correlations.
- Installation (Requirements: gfortran ≥ 4.6, Python 2.x, x ≥ 4): `$ cd ./OpenLoops && ./scons`
- 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]

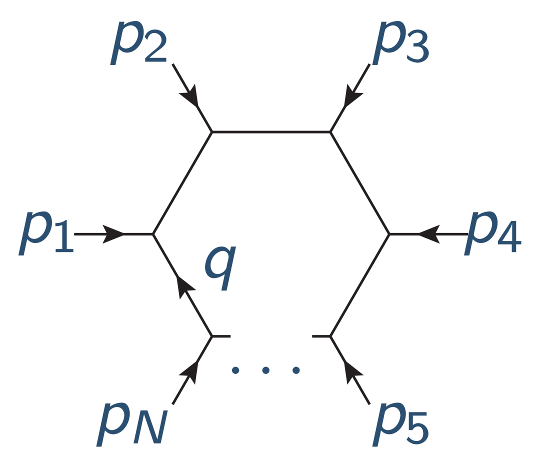
- Recursive construction of tree wave functions
  - start from wave functions w^{α} f external legs.
  - connect wave functions with vertices $X^{\beta}_{\gamma\delta}$ and propagators to recursively build "sub-trees".
  - recycle identical structures
  - wave functions of sub-trees are 4-tuples of complex numbers (for the spinor/Lorentz index).



(external lines not shown)

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

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



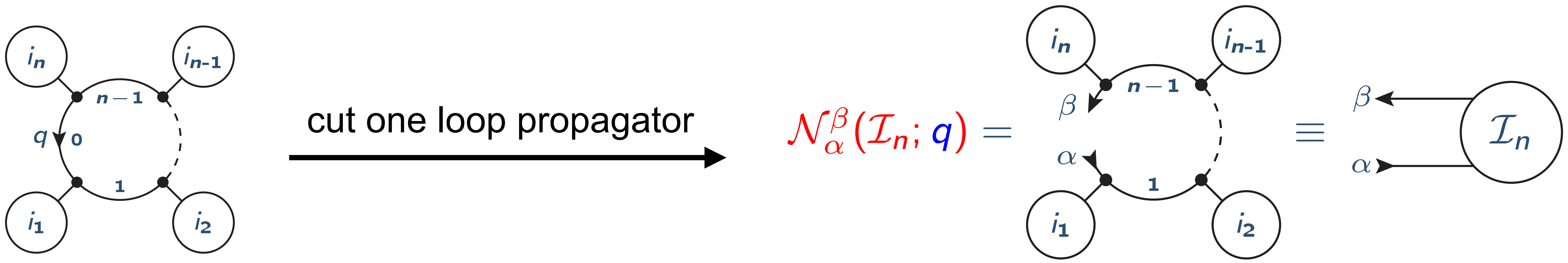
$$= \mathcal{C} \cdot \underbrace{\sum_{r=0}^{R} \mathcal{N}_r^{\mu_1 \ldots \mu_r}}_{\text{numerical recursion [OpenLoops]}} \cdot \underbrace{\int d^d q \, \frac{q_{\mu_1} \ldots q_{\mu_r}}{D_0 \, D_1 \, \ldots \, D_{N-1}}}_{\text{tensor integrals [Collier]}}$$

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

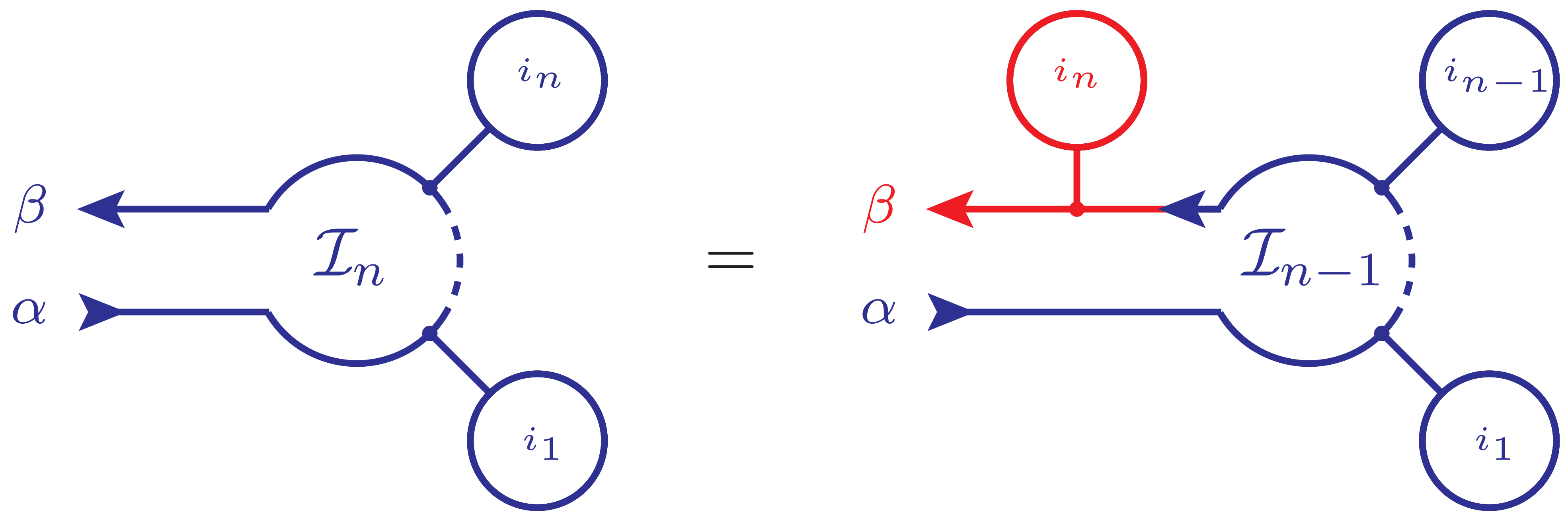
The Open Loops algorithm:
From tree recursion to loop diagrams

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

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



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



$$\mathcal{N}^\beta_\alpha(\mathcal{I}_n; q) = X^\beta_{\gamma\delta}(q)\, \mathcal{N}^\gamma_\alpha(\mathcal{I}_{n-1}; q)\, w^\delta(i_n)$$

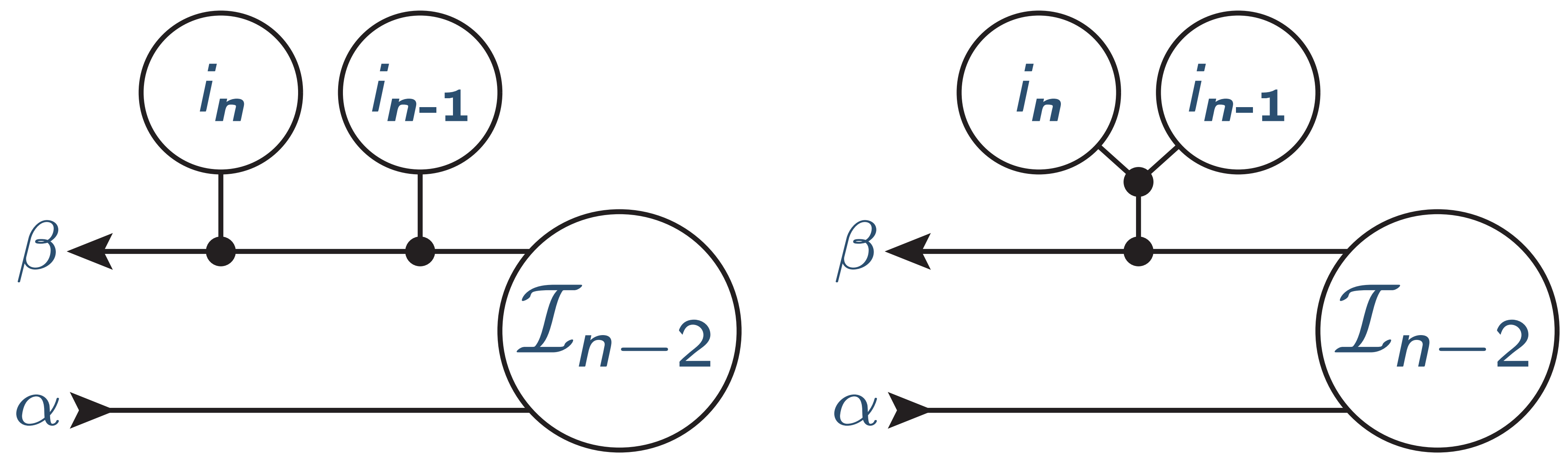
$$X^\beta_{\gamma\delta} = Y^\beta_{\gamma\delta} + q^\nu Z^\beta_{\nu;\gamma\delta}$$

$$\mathcal{N}^\beta_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n) = \left[Y^\beta_{\gamma\delta}\, \mathcal{N}^\gamma_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z^\beta_{\mu_1;\gamma\delta}\, \mathcal{N}^\gamma_{\mu_2\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\right] w^\delta(i_n)$$

$\Rightarrow$ very fast!

The (original) Open Loops algorithm: recycle loop structures

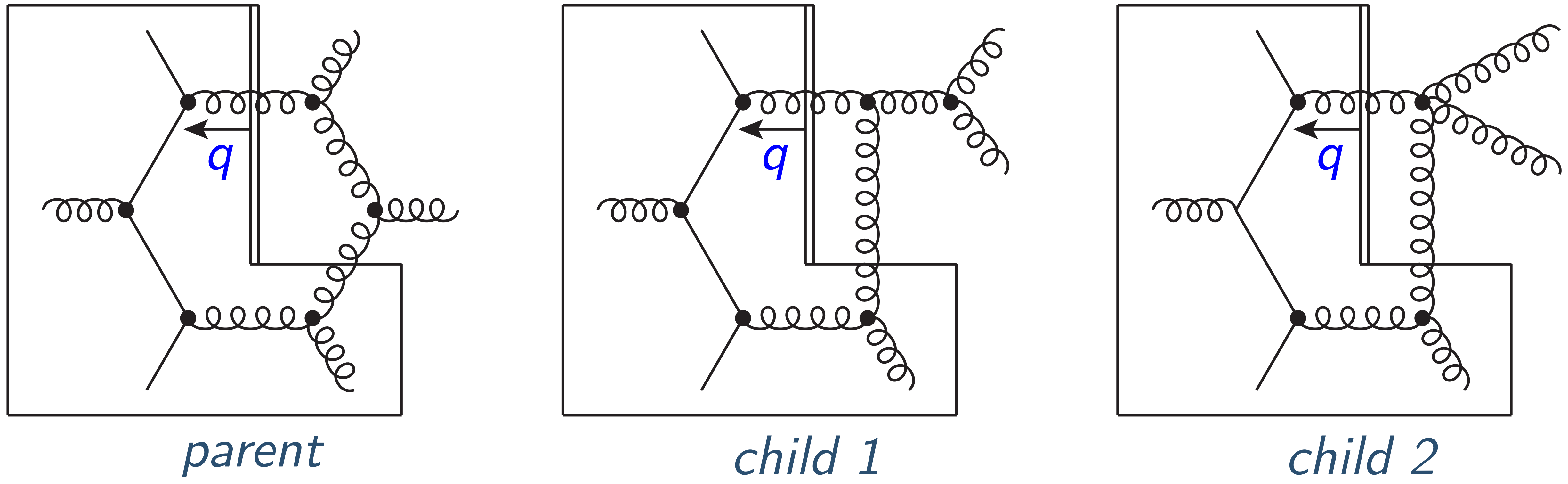
OpenLoops recycling:



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

- cut is put appropriately
- direction chosen to maximise recyclability

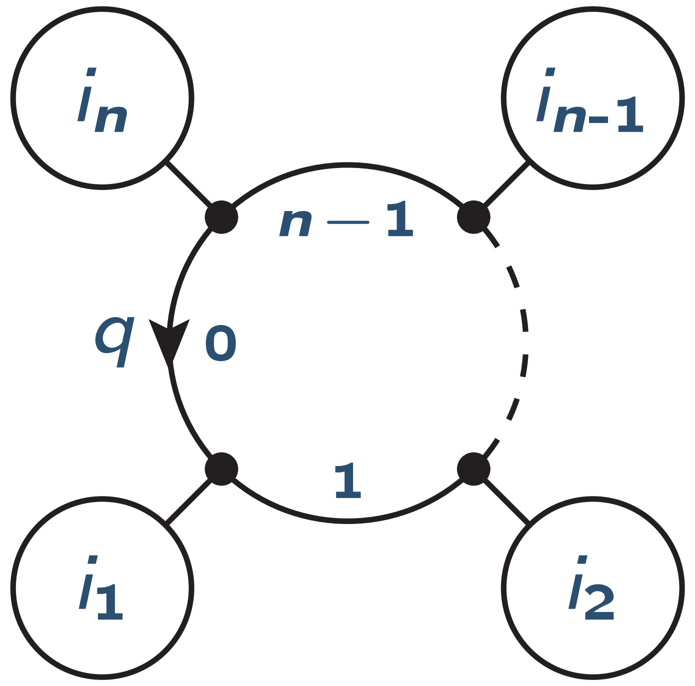
Illustration:



Complicated diagrams require only "last missing piece"

The (original) Open Loops algorithm: one loop amplitudes

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



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

- Tensorial coefficients $\mathcal{N}^{\alpha}_{\mu_1 \ldots \mu_r;\alpha}$ can directly be contracted with Tensor Integrals evaluated with **COLLIER** [Denner, Dittmaier, Hofer; '16]

- Fast evaluation of $\mathcal{N}(q) = \sum \mathcal{N}_{\mu_1 \ldots \mu_r} q^{\mu_1} \ldots q^{\mu_r}$ at multiple q-values allows for efficient application of OPP reduction methods e.g. with **CutTools** *[Ossola, Papadopolous, Pittau; '07]*

On-the-fly OpenLoops reduction

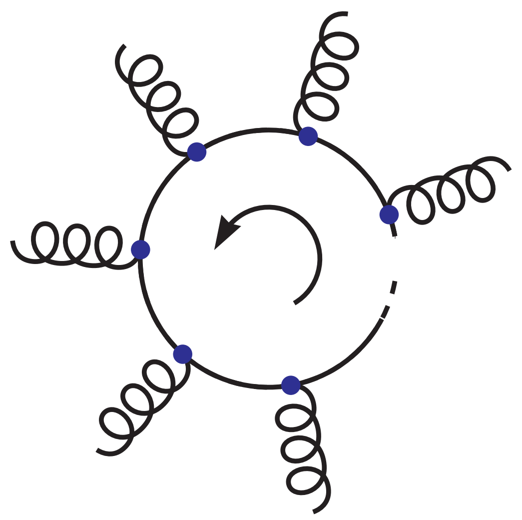
New!

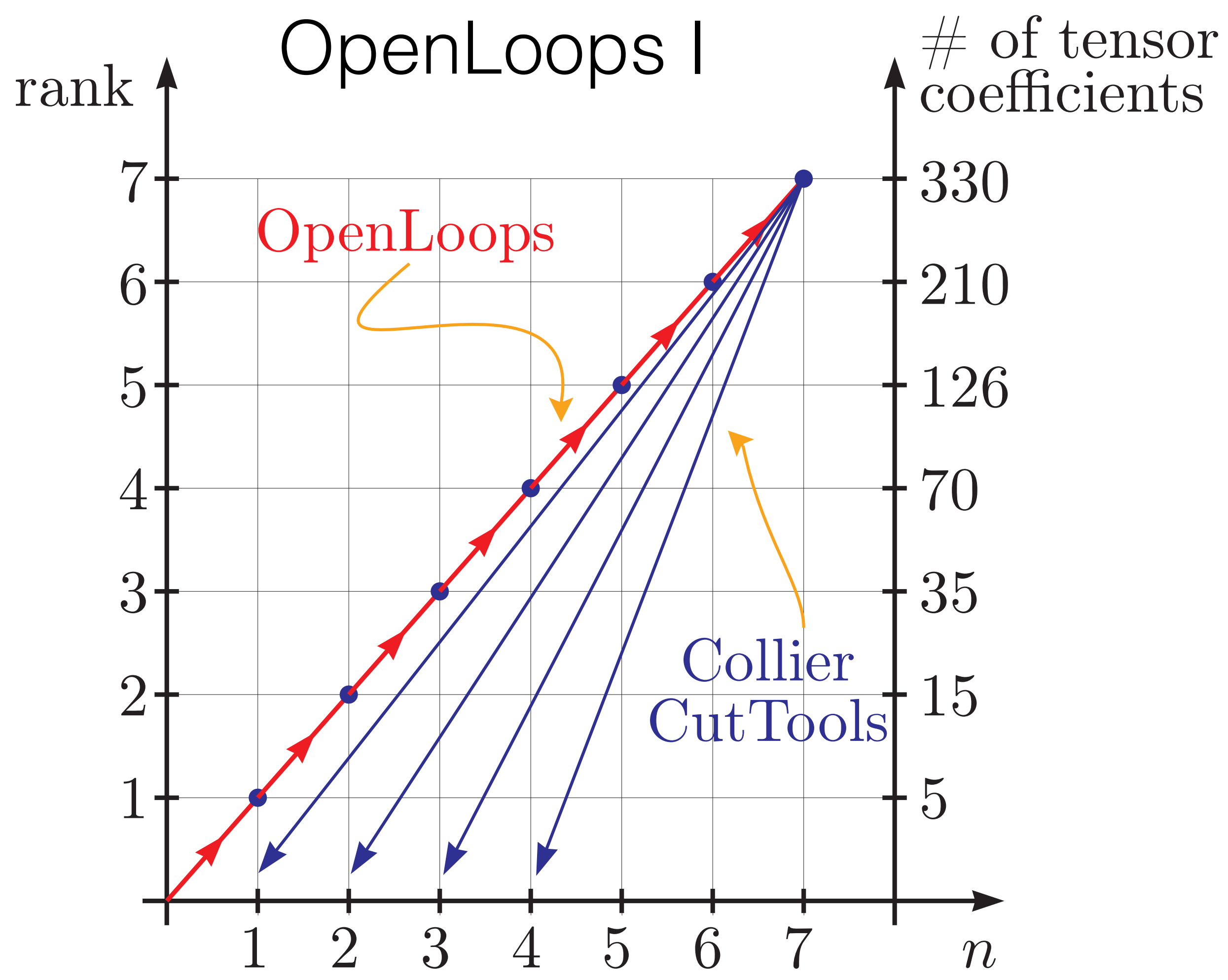
[F. Buccioni, S. Pozzorini, M. Zoller '17]

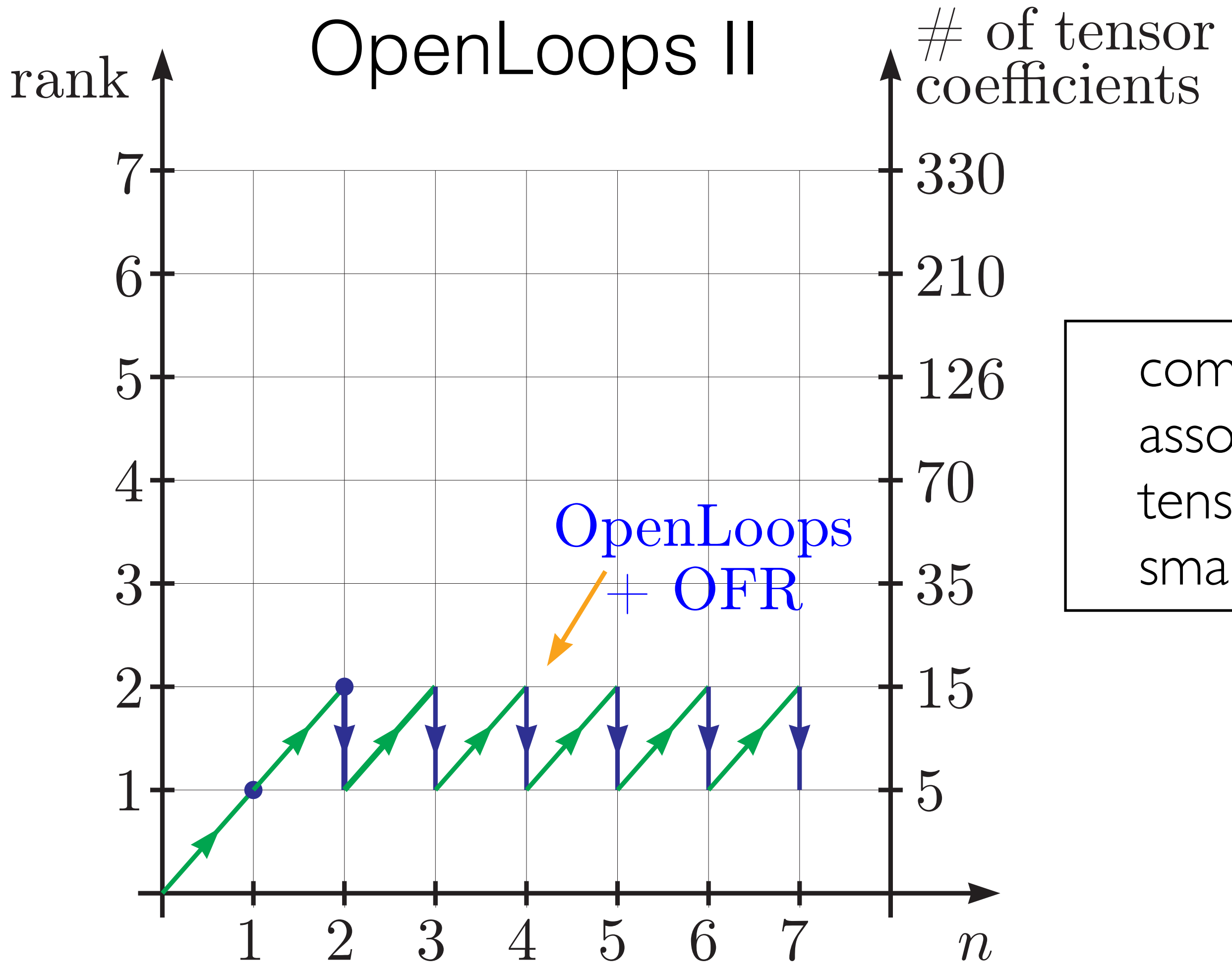
- Amplitude construction and integrand reduction merged ⇒ "on-the-fly" (OFR) reduction
- At each Open Loops step perform "on-the-fly" rank=2 ⇒ rank=1 reduction:

$$
\begin{aligned}
q^\mu q^\nu &= A^{\mu\nu} + B^{\mu\nu}_\lambda q^\lambda \\
&= \left[A^{\mu\nu}_{-1} + A^{\mu\nu}_0 D_0\right] + \left[B^{\mu\nu}_{-1,\lambda} + \sum_{i=0}^{3} B^{\mu\nu}_{i,\lambda} D_i\right] q^\lambda, \qquad D_i = (q+p_i)^2 - m_i^2
\end{aligned}
$$

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







complexity associated with tensor rank remains small!

- problem: huge proliferation of topologies due to necessary pinching of propagators.
- solution: new helicity and colour treatment at M² level allows for merging of pinched topologies.

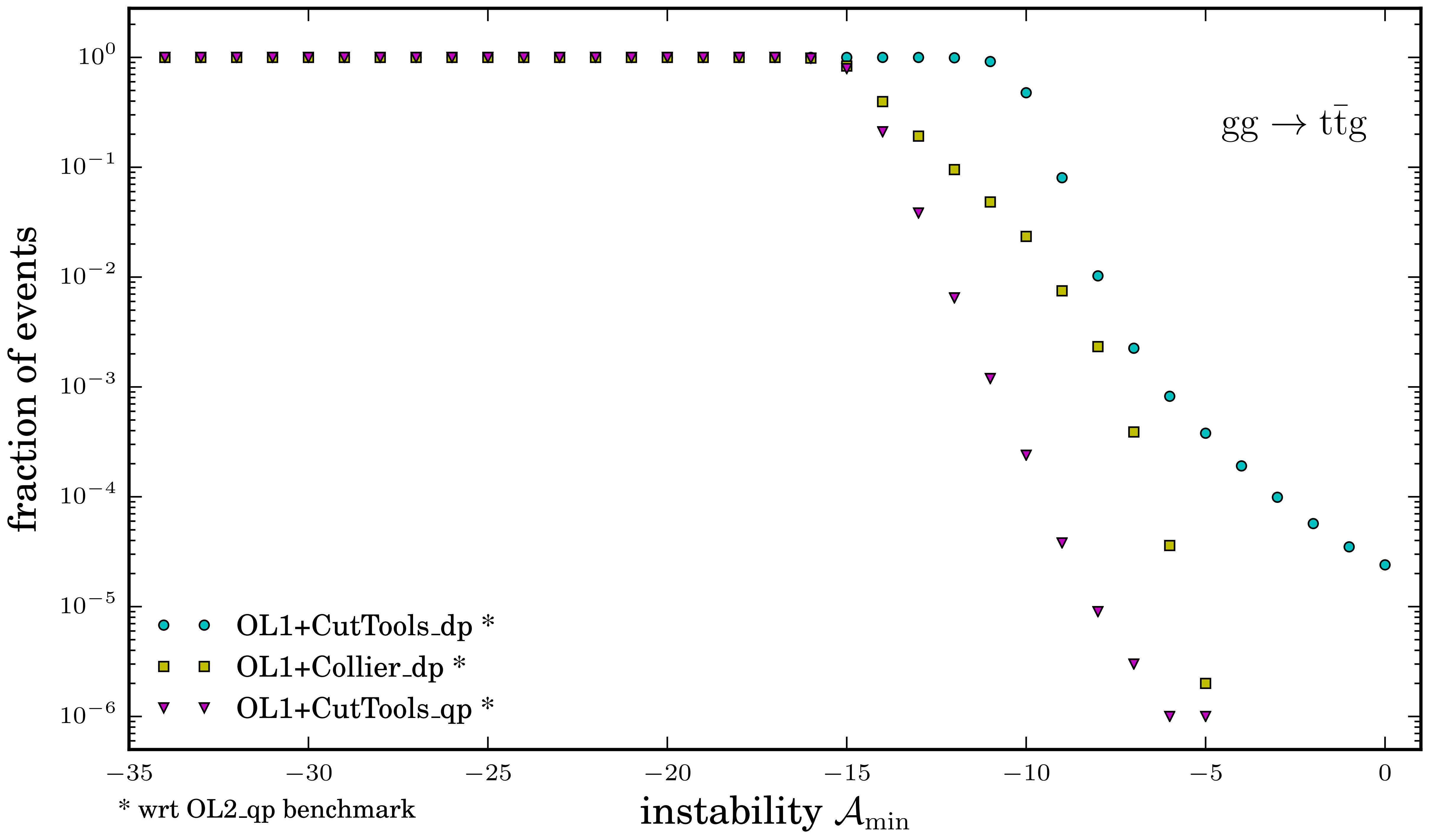
⇒ as fast as OpenLoops1+Collier

New!

On-the-fly OpenLoops reduction

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

- Huge advantage: allows for systematic treatment of numerical instabilities



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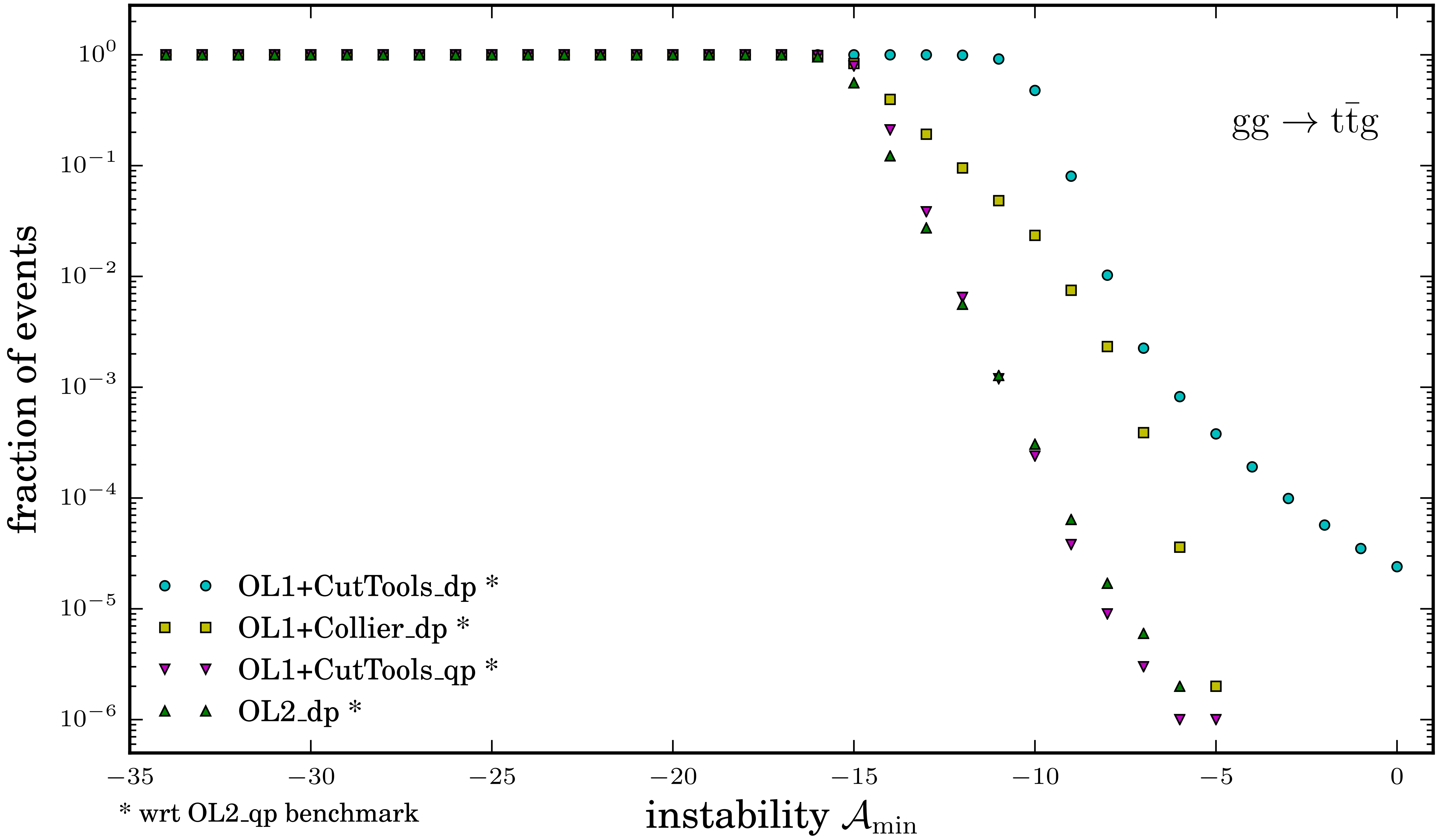

- unprecedented numerical stability (always as least as stable as OpenLoops1+Collier)
- crucial in unresolved limits of **real-virtual contributions** in NNLO calculations

On-the-fly OpenLoops reduction

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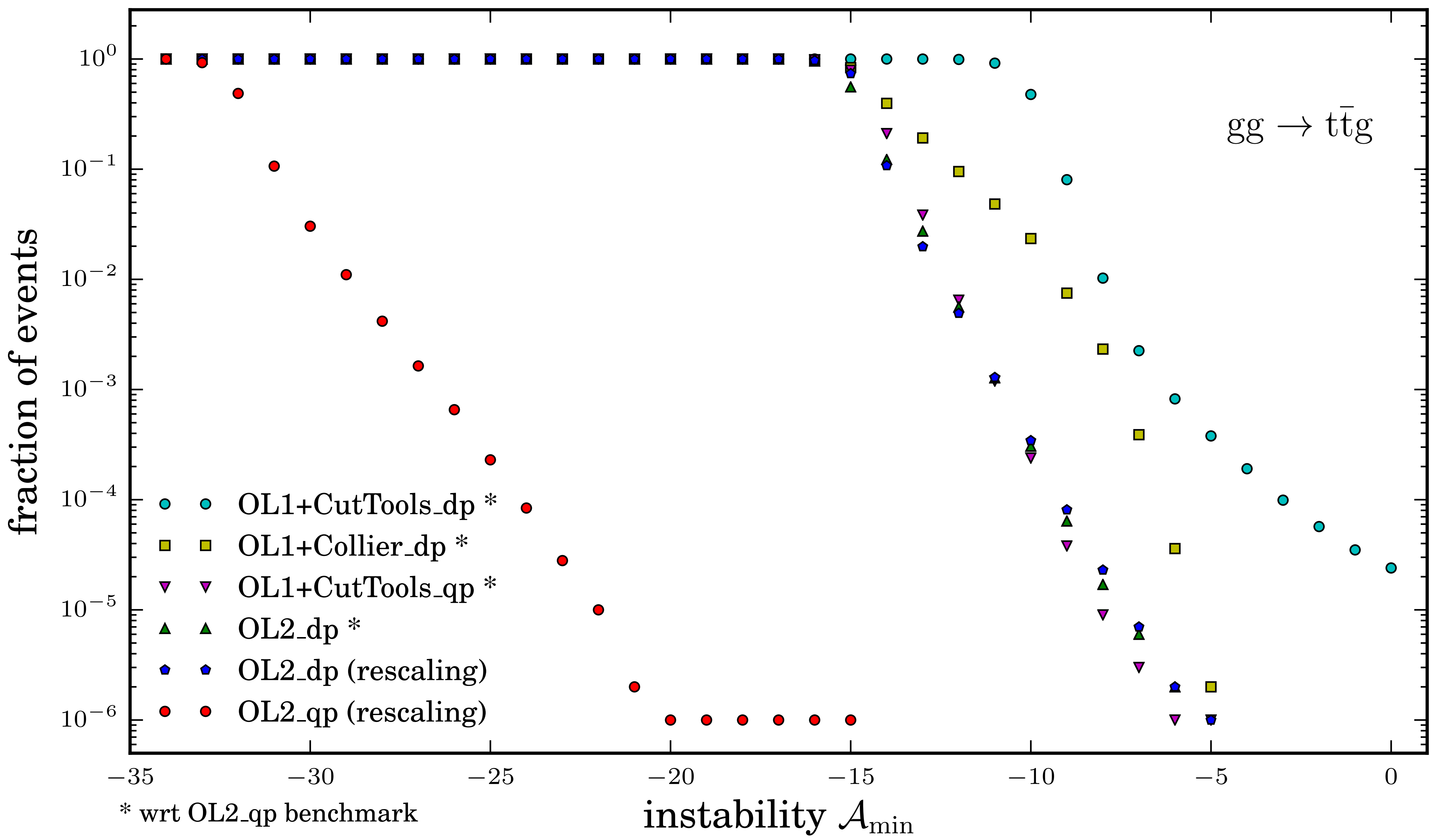
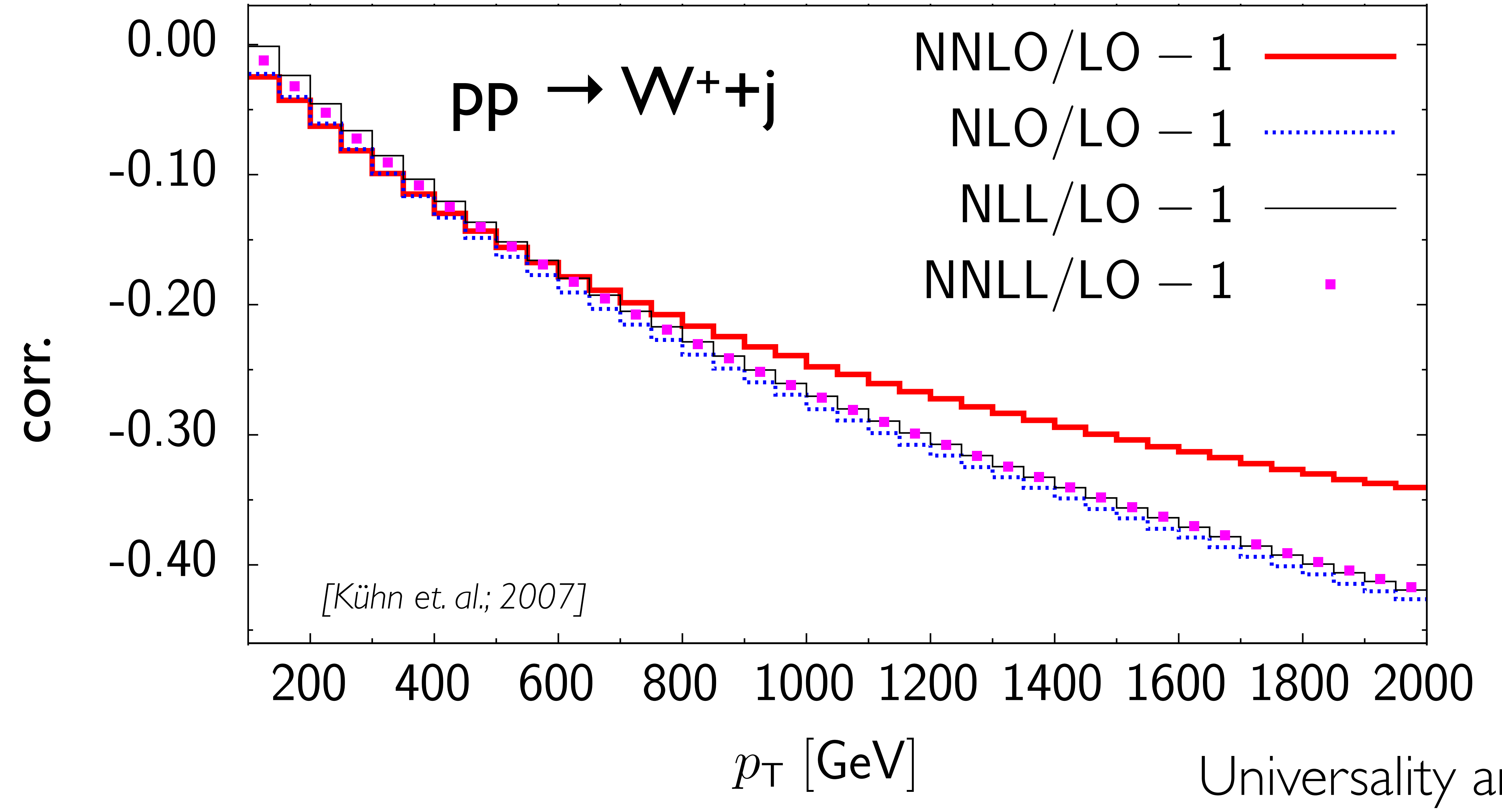


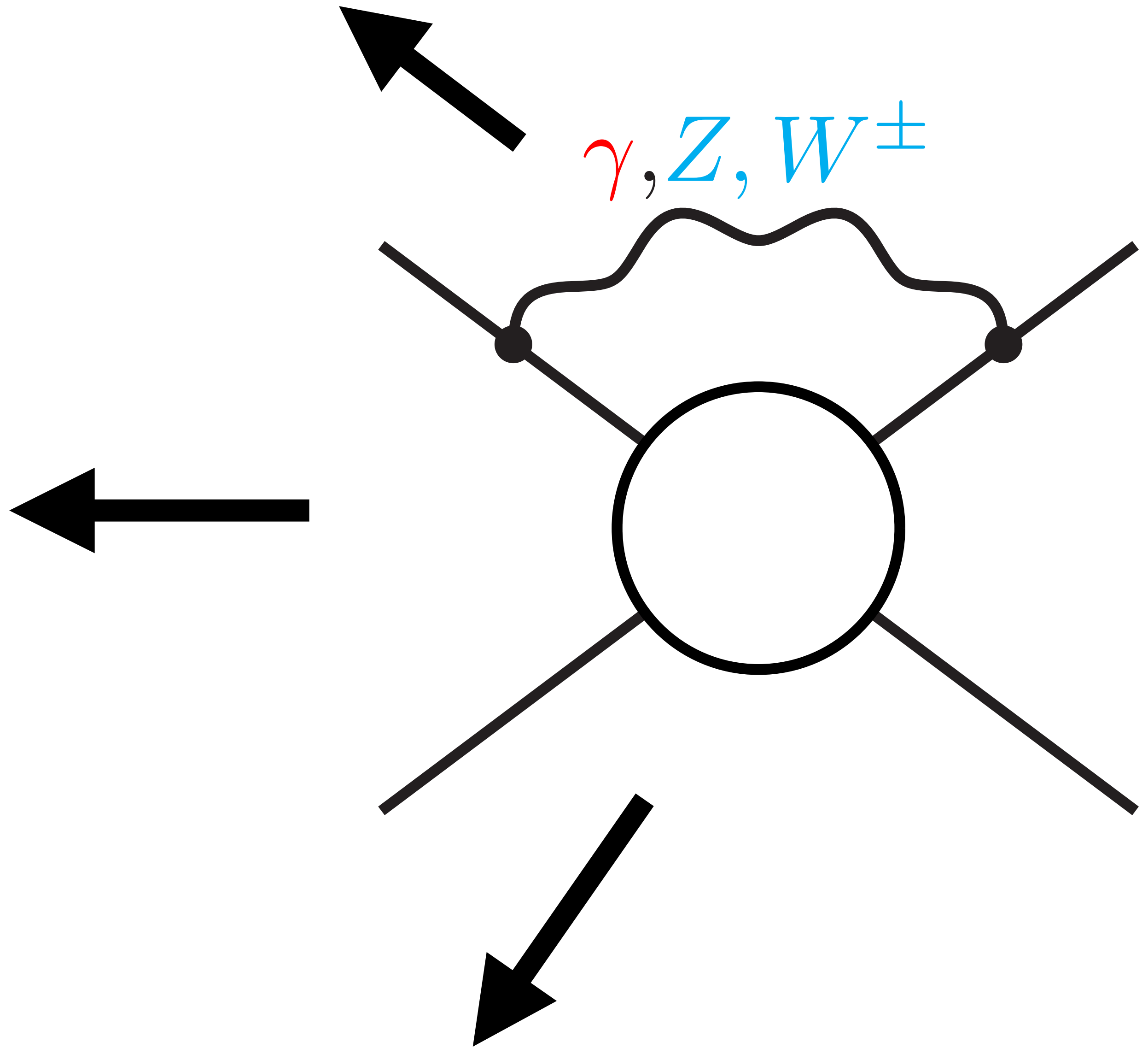
- unprecedented numerical stability (always as least as stable as OpenLoops1+Collier)
- crucial in unresolved limits of **real-virtual contributions** in NNLO calculations
- ultimate stability: OFR @ qp (based on all-order expansions)
- soon to be public in **OpenLoops2** *[F. Buccioni, JML, P. Maierhöfer, 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**

1. 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]*

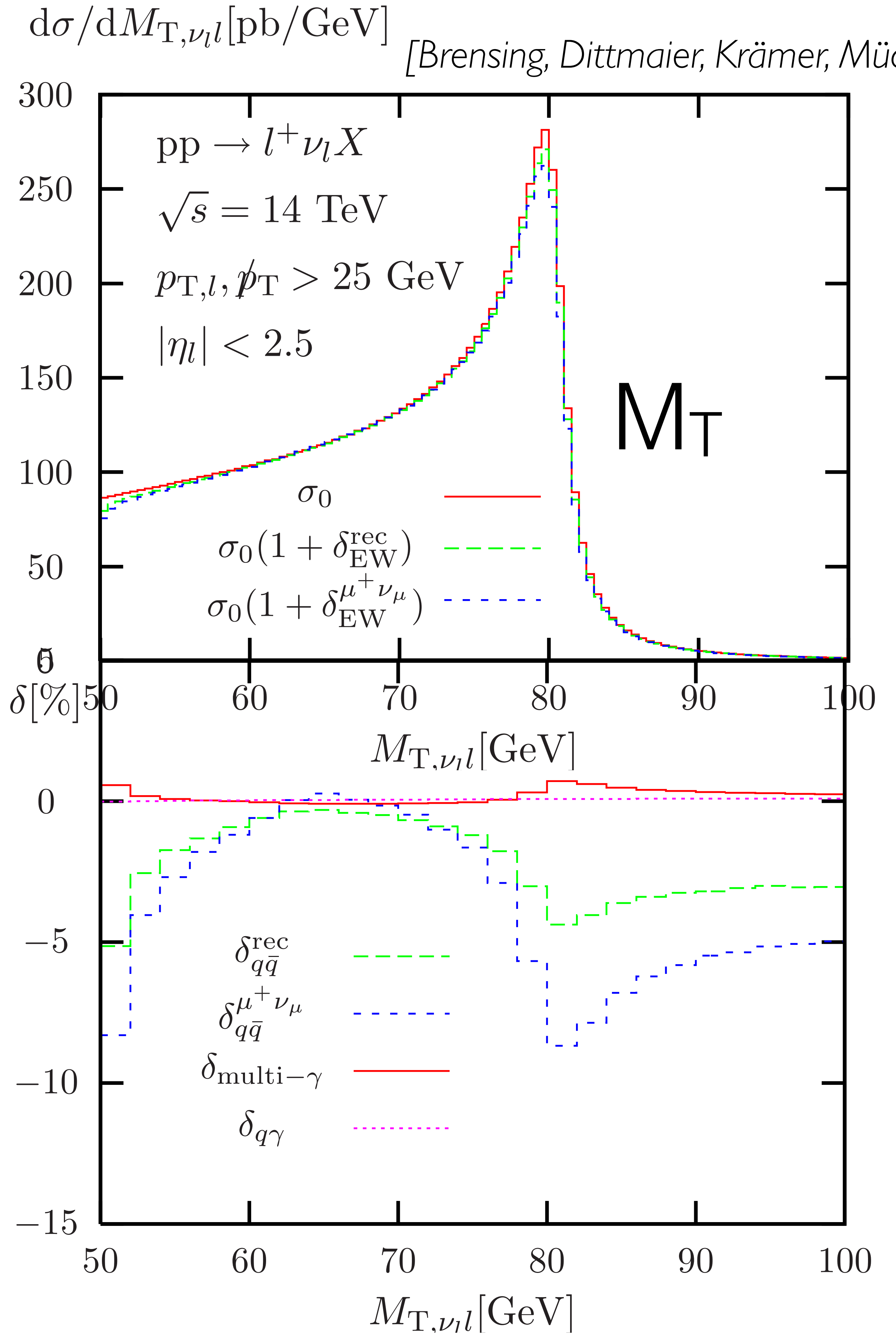
$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

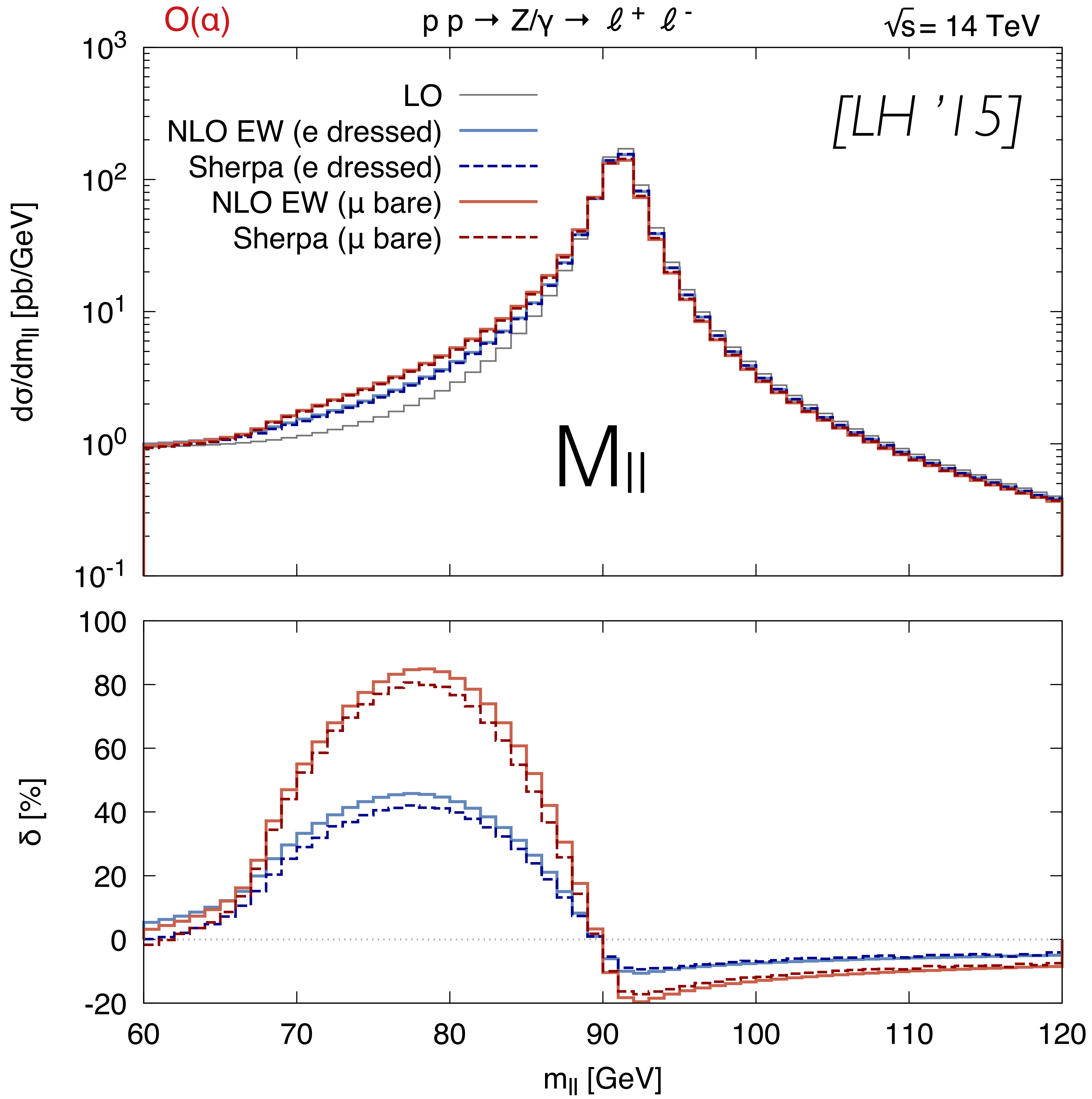
➜ overall large effect in the tails of distributions: p_T, m_{inv}, H_T,… (relevant for BSM searches!)

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.

[Brensing, Dittmaier, Krämer, Mück; '08]

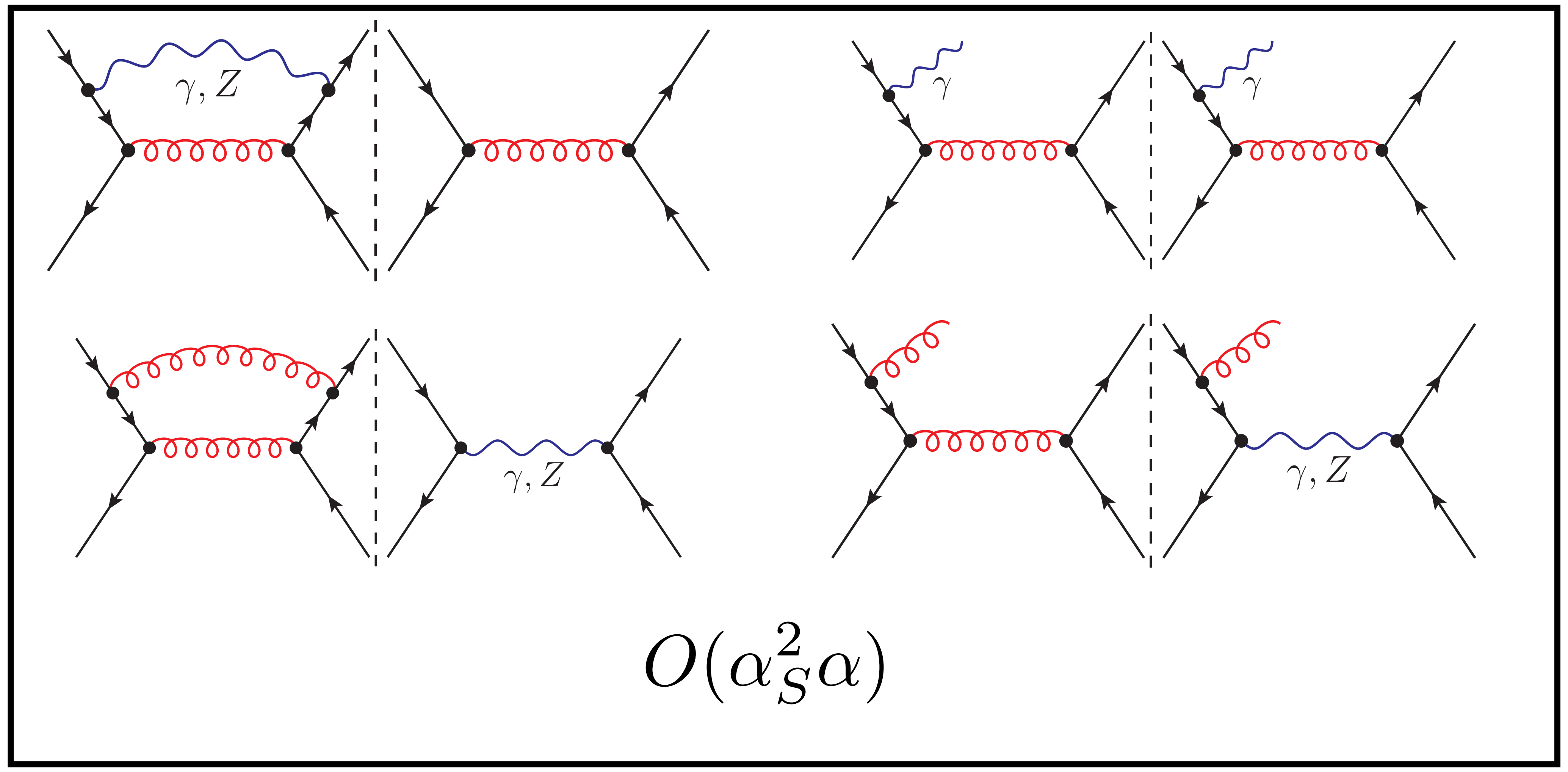




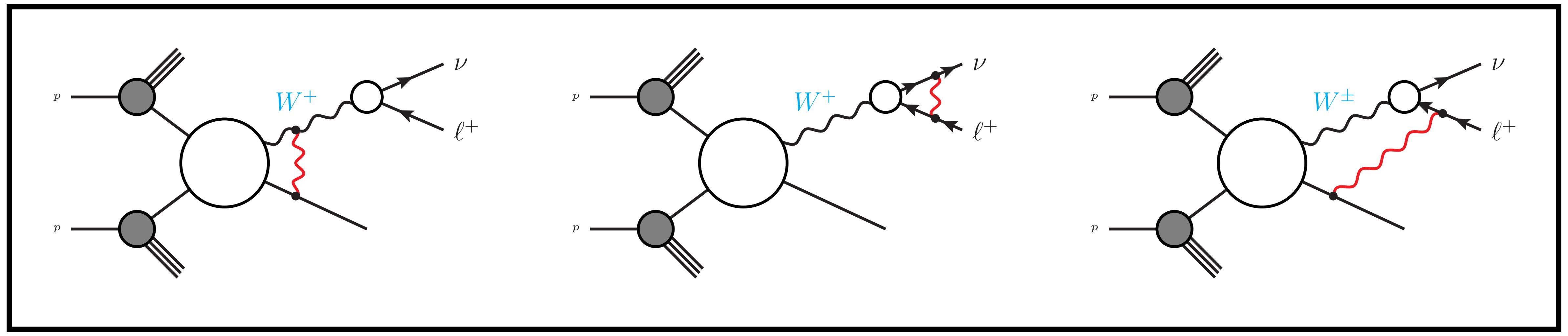
➜ **important for various precision observables, e.g. for determination of M_W in DY**

Nontrivial features in NLO QCD → NLO EW

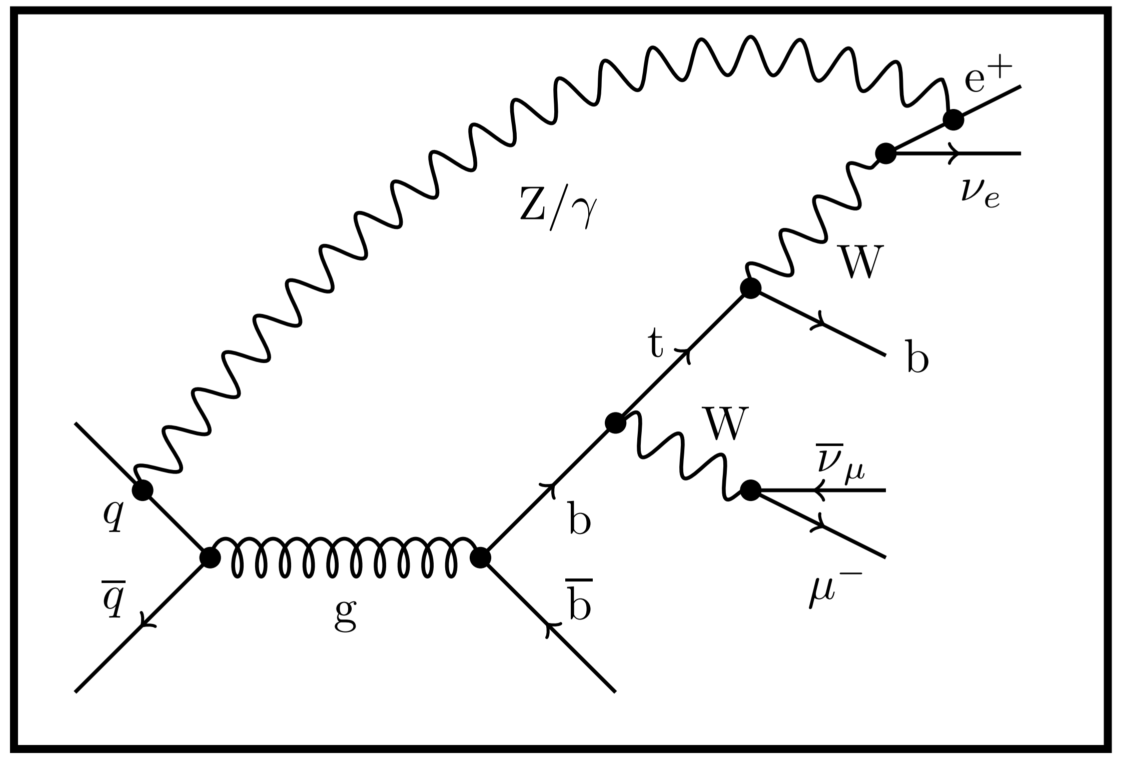
1. **QCD-EW interplay**



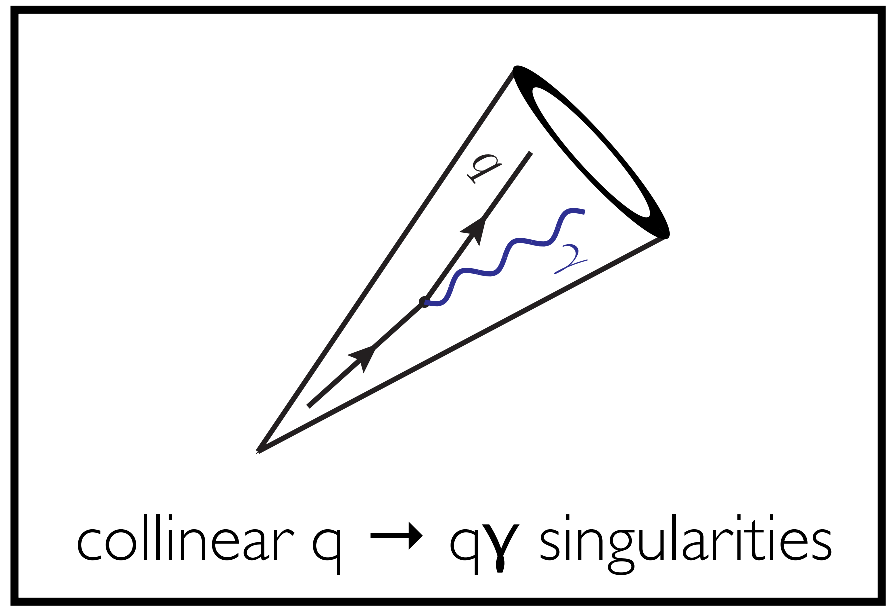
2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays
→ **complex-mass-scheme**



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

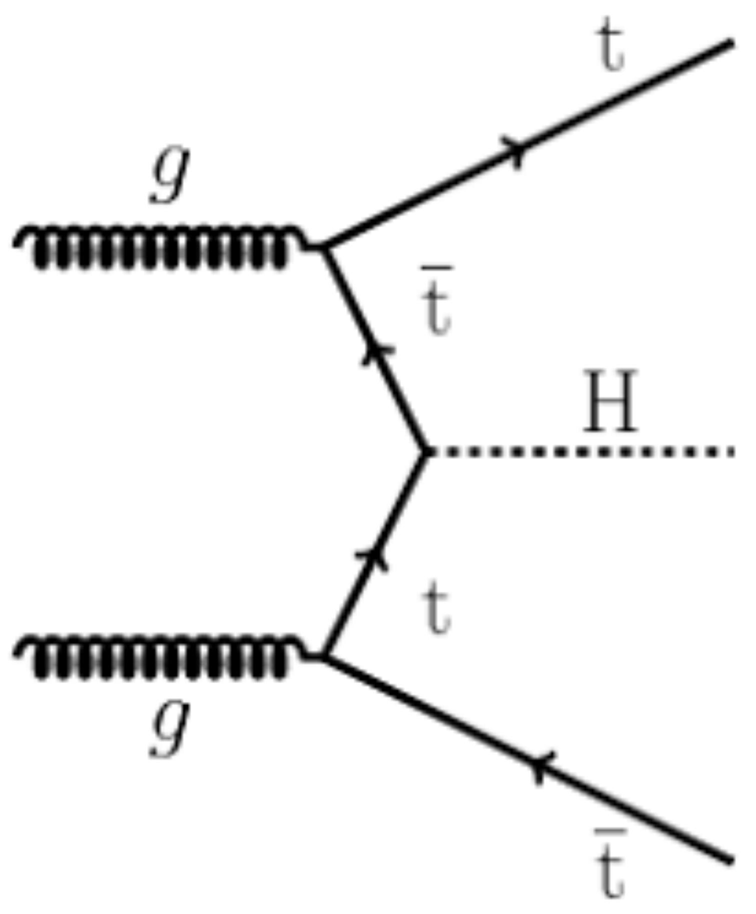


4. photon contributions in jets and proton
→ **photon-jet separation, γPDF**

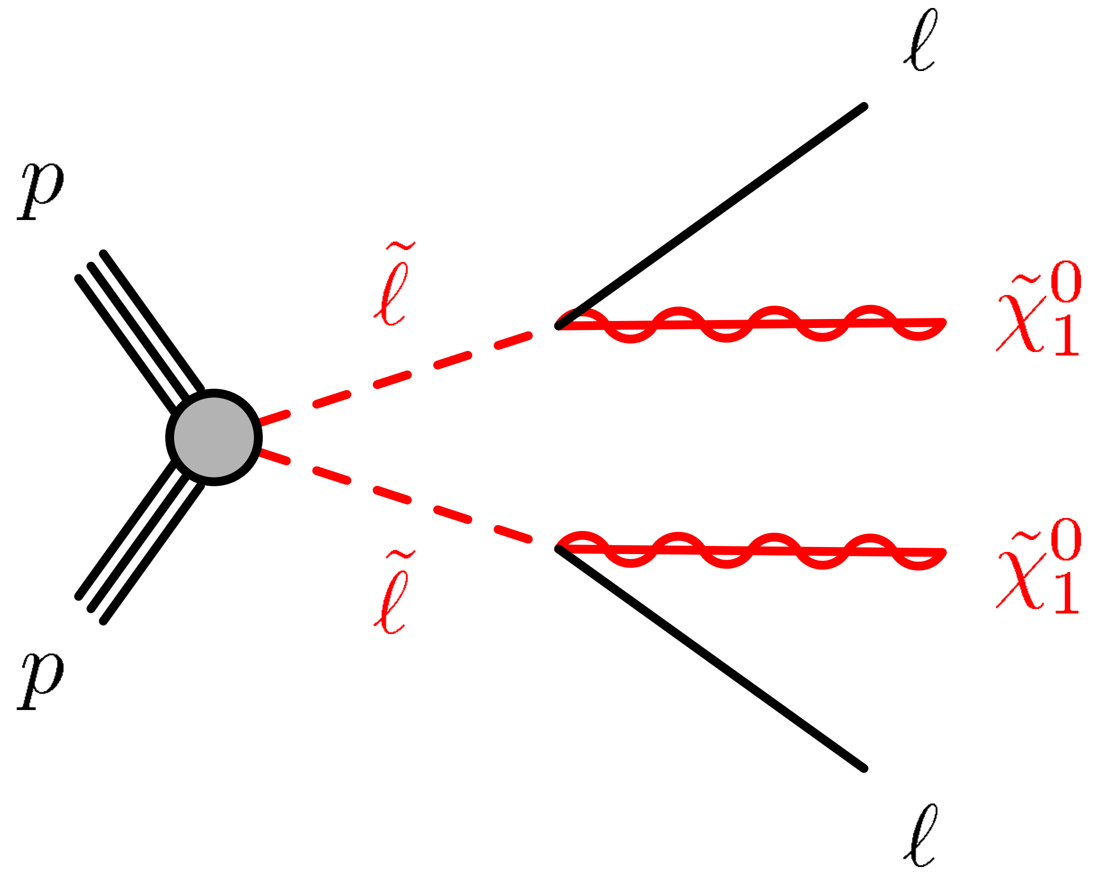


A few examples where theory precision is crucial:

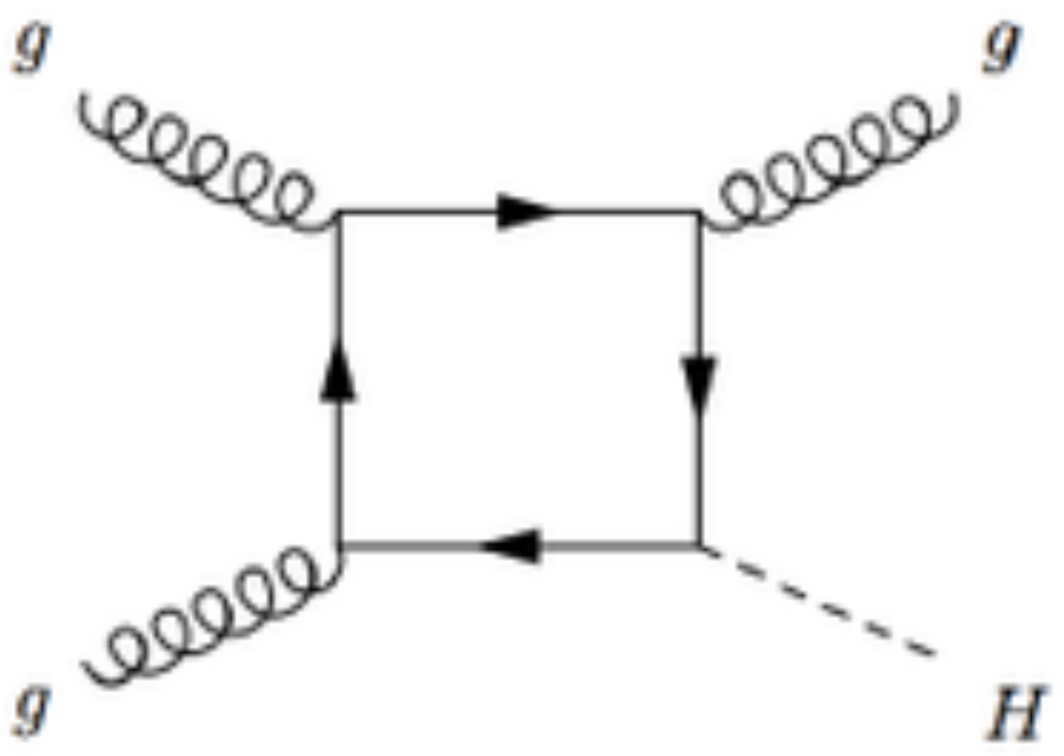
$t\bar{t}H$



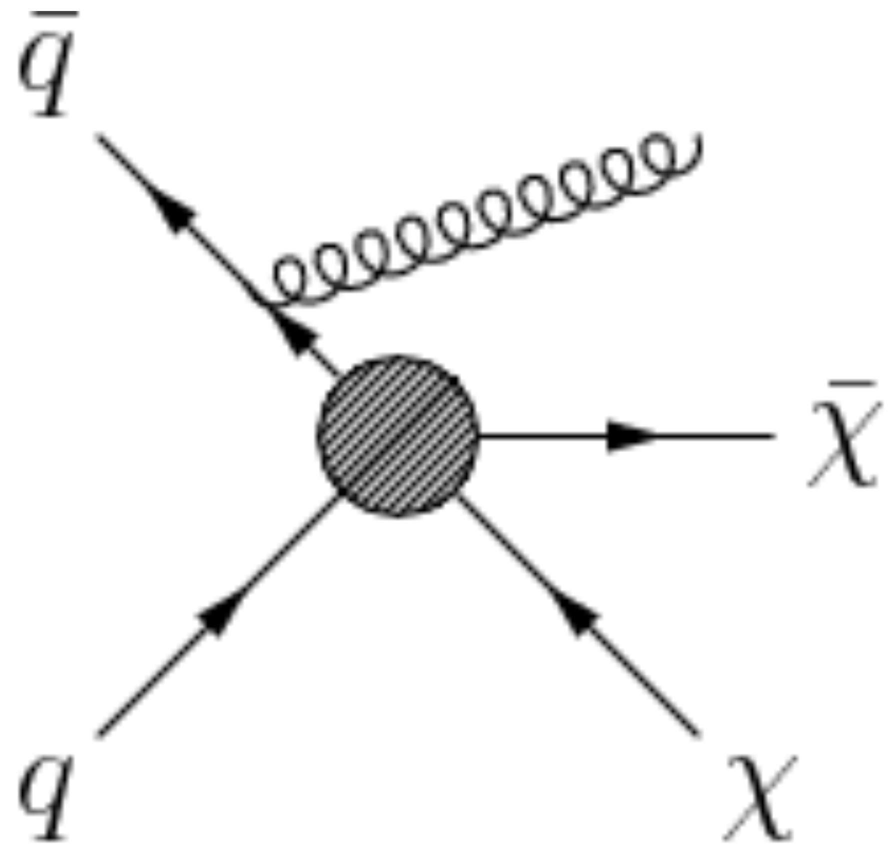
EW SUSY searches



Higgs-pT



Dark Matter searches



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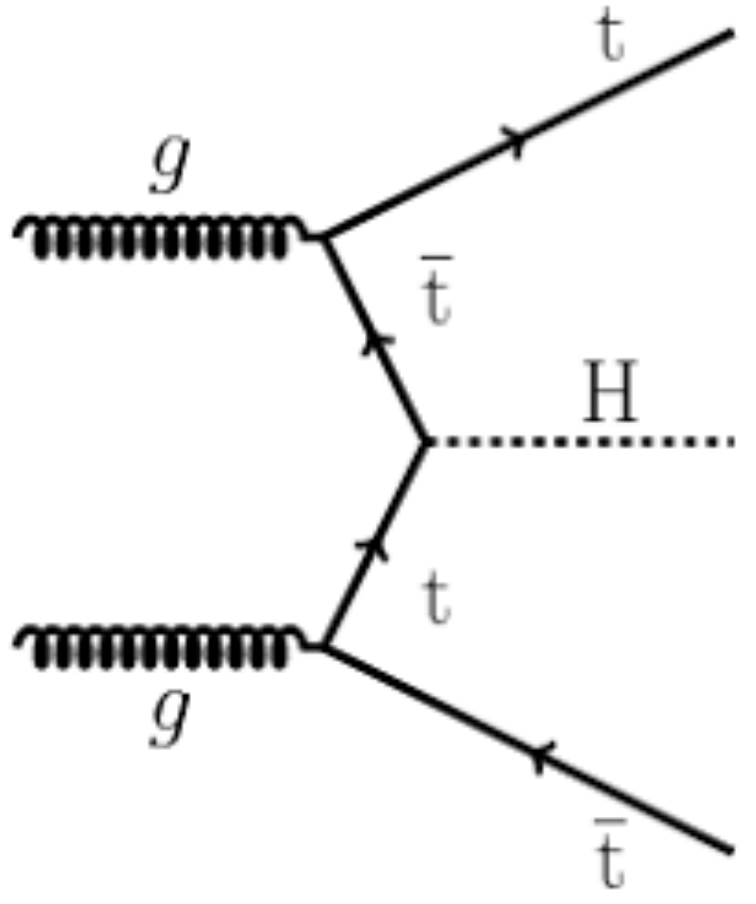
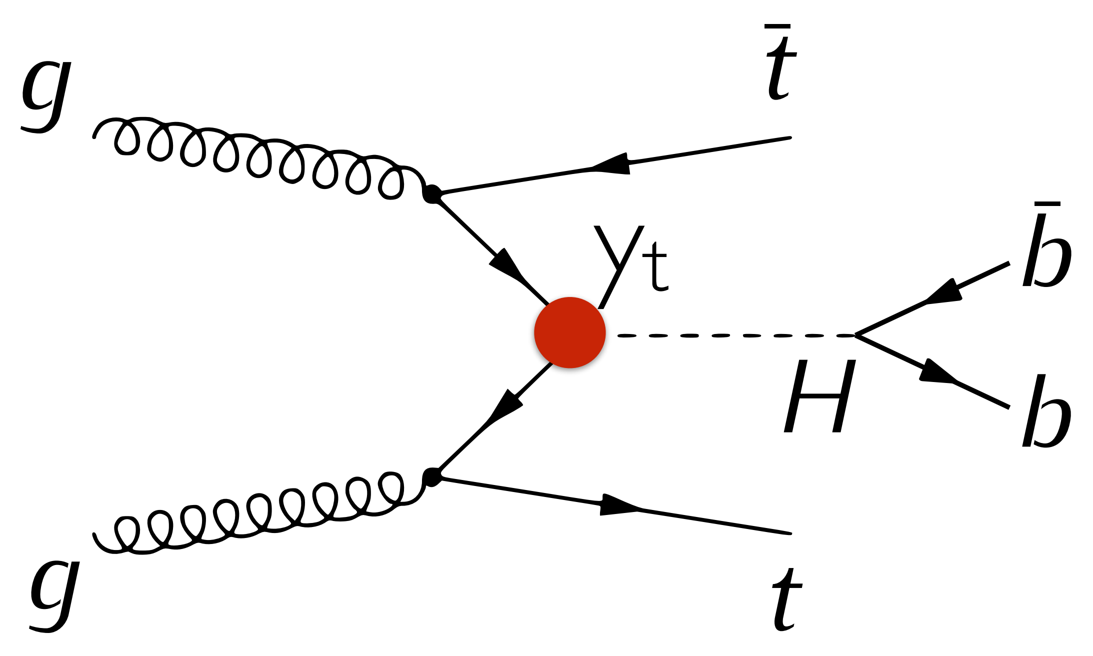


EW SUSY searches

Higgs-pT

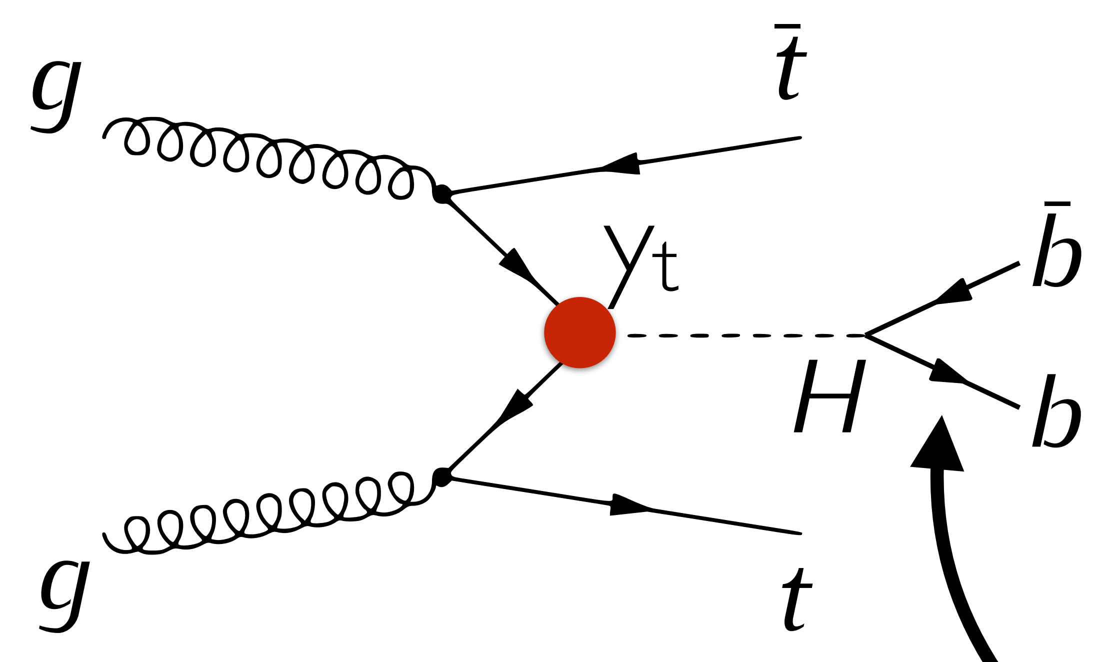
Dark Matter searches

Taming $t\bar{t}H$ backgrounds



➡ direct probe of the top Yukawa coupling

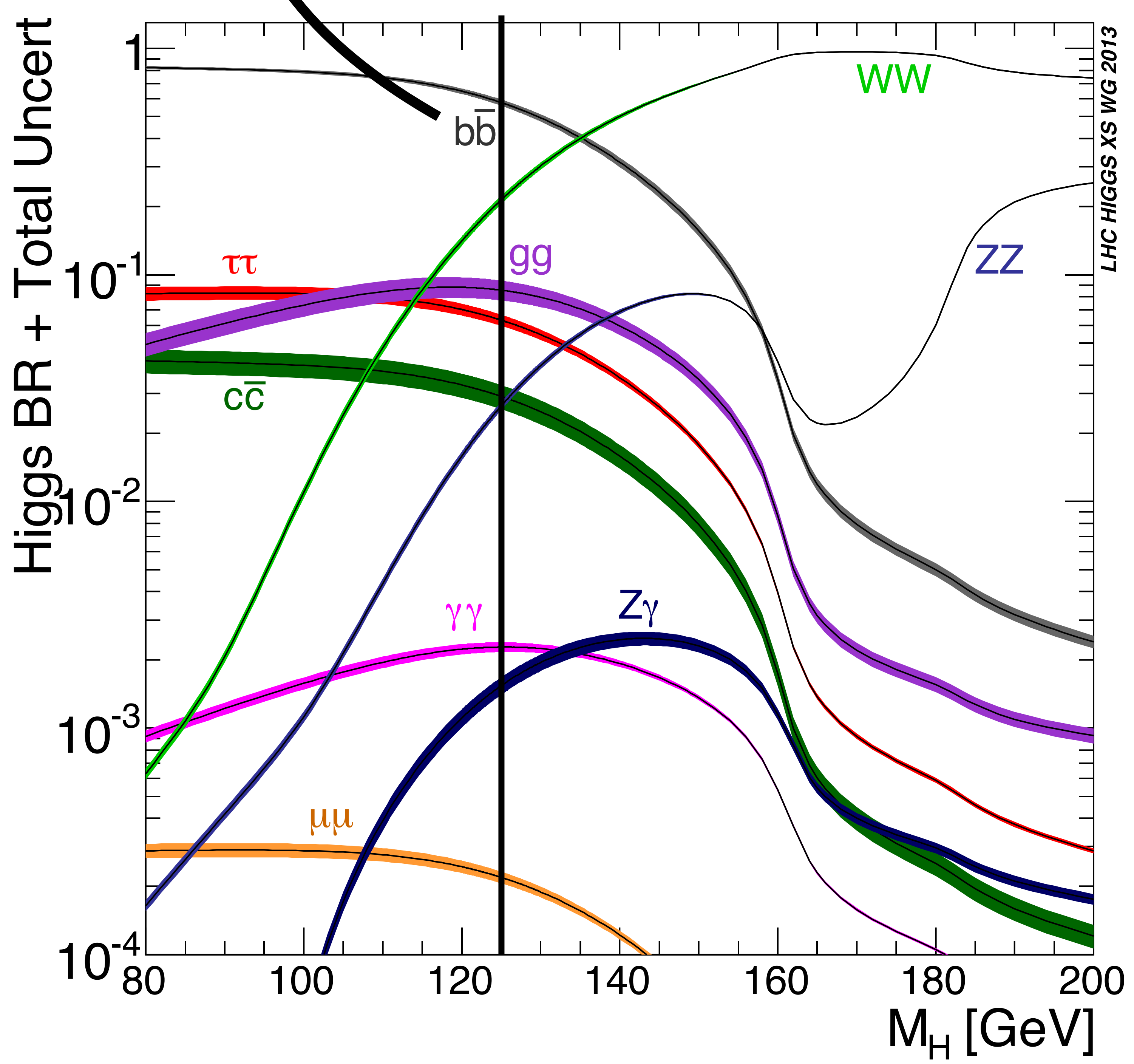
Taming $t\bar{t}H$ backgrounds

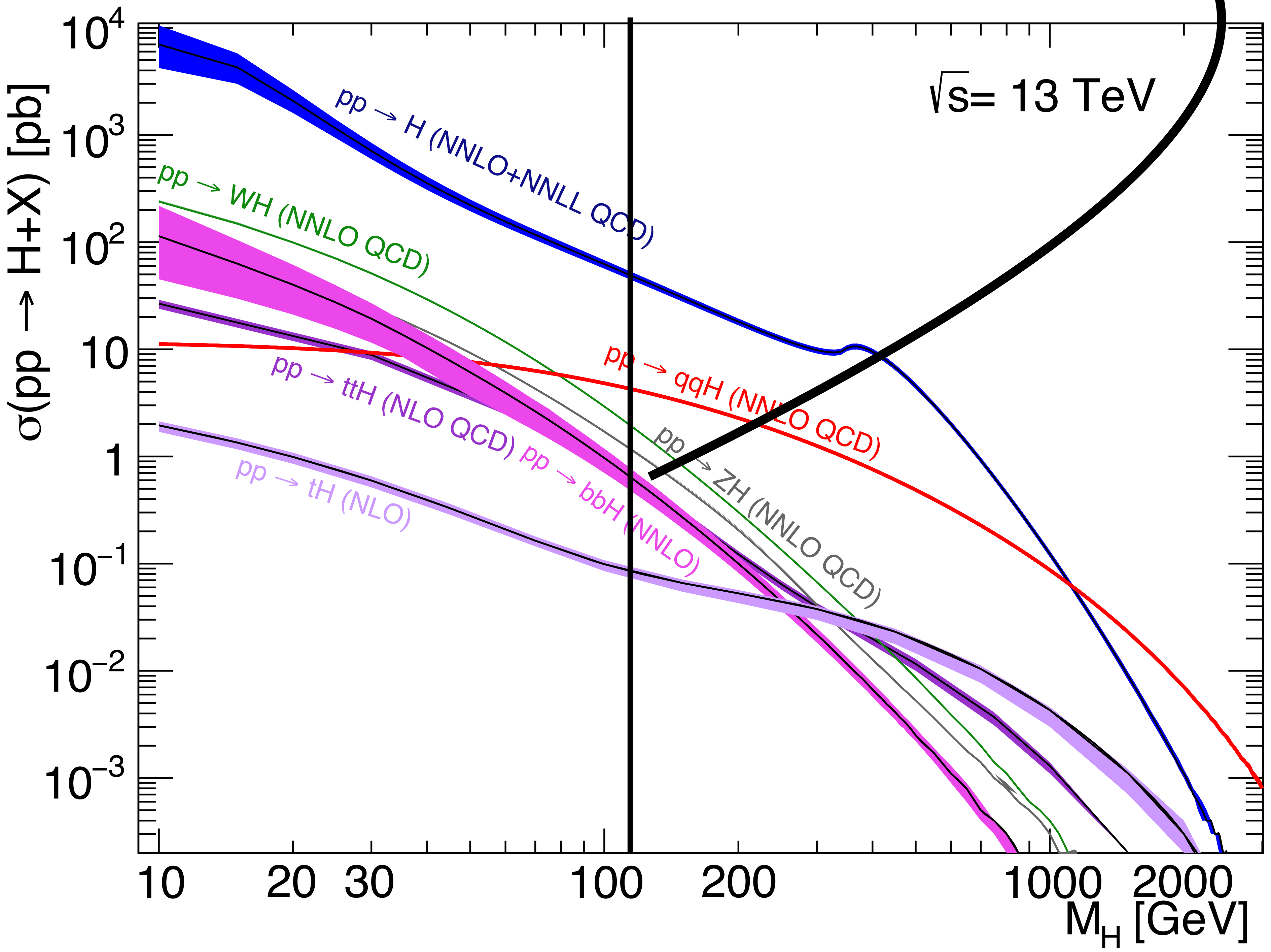


➡ direct probe of the top Yukawa coupling

➡ unfortunately very small cross section

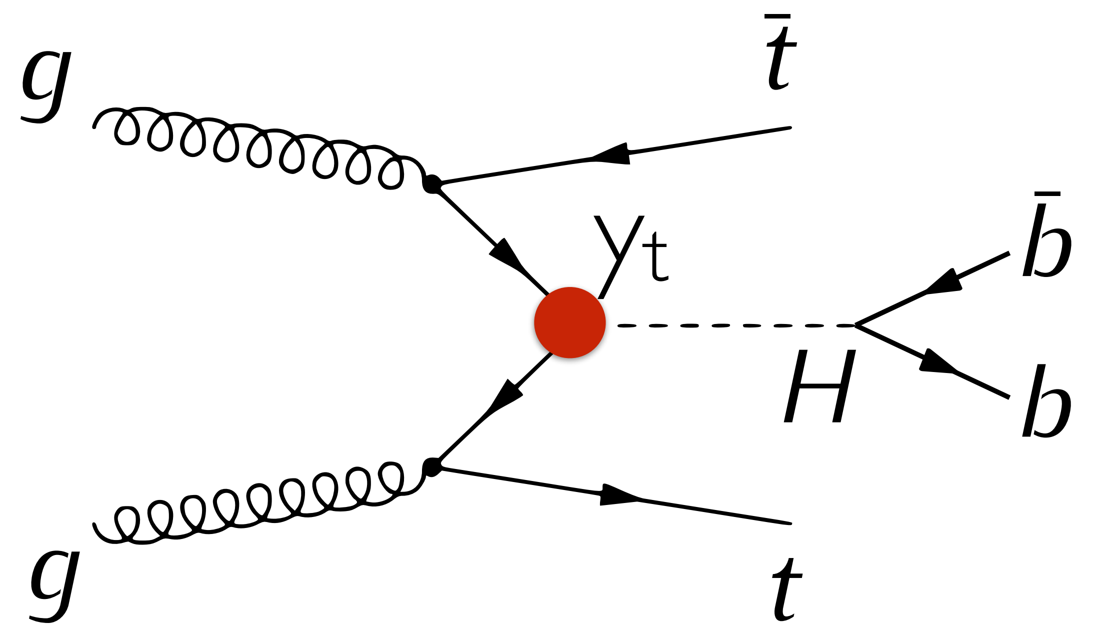
➡ have to consider $H \to b\bar{b}$ decay with large BR





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

Taming $t\bar{t}H$ backgrounds



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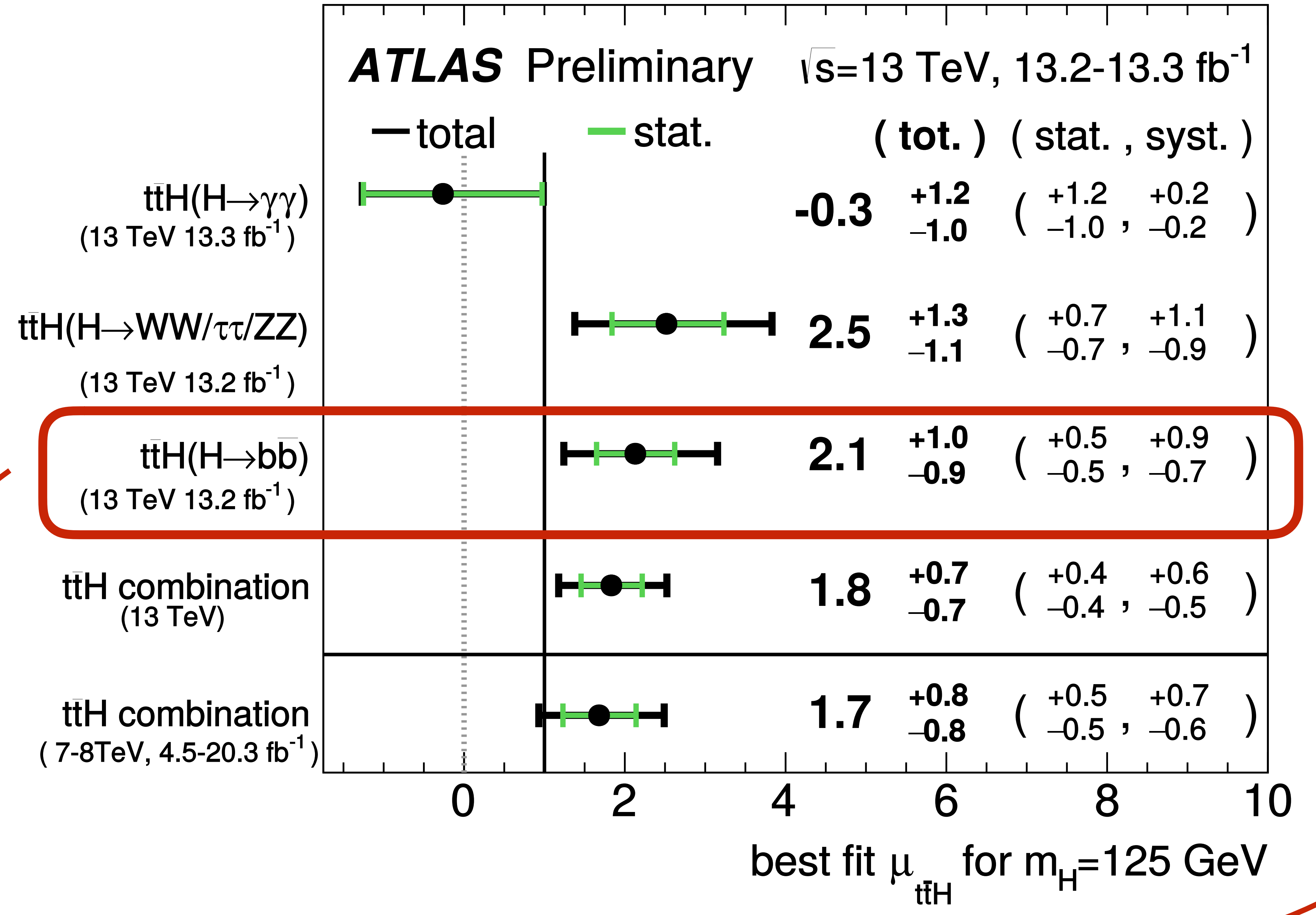
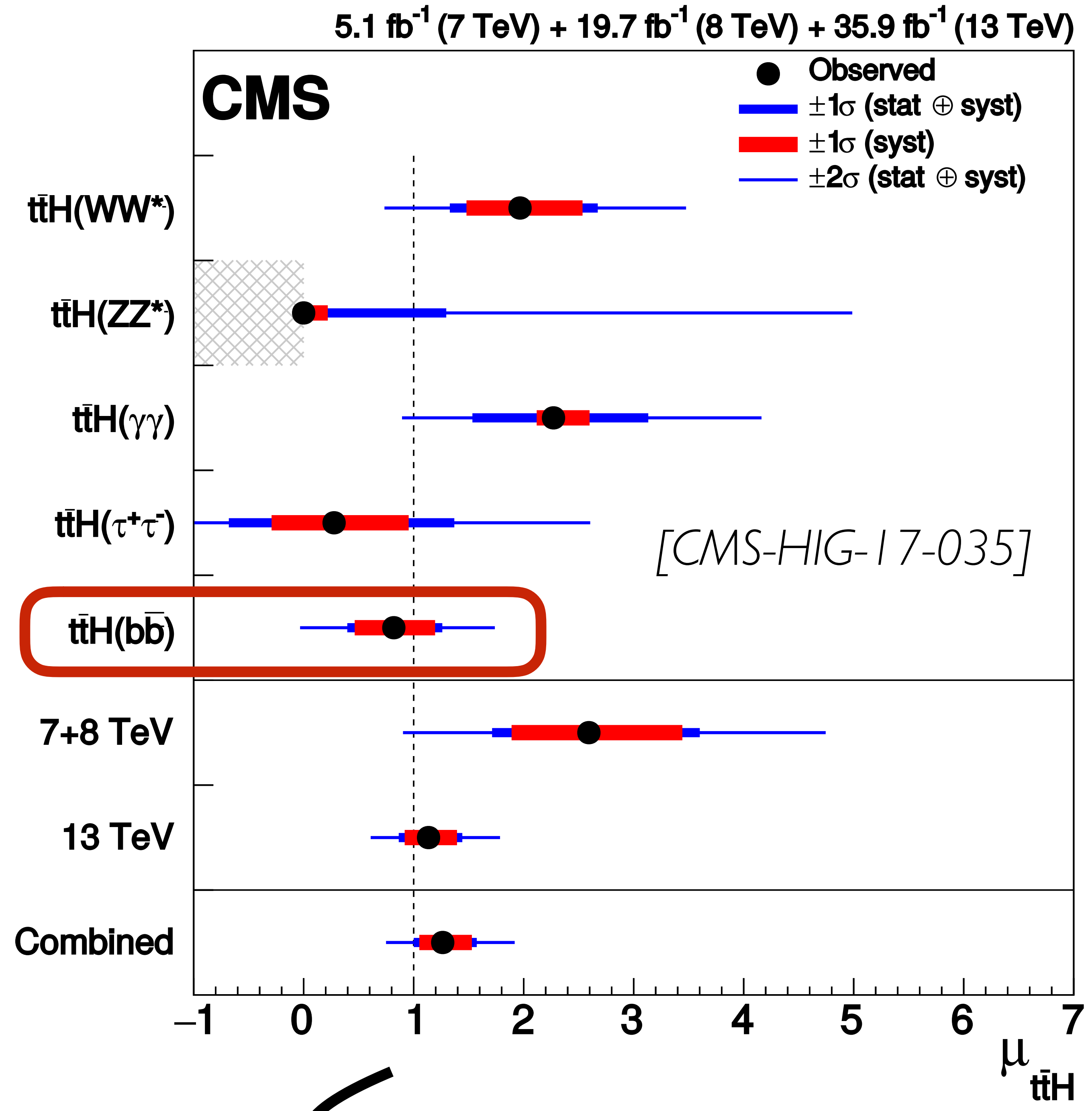


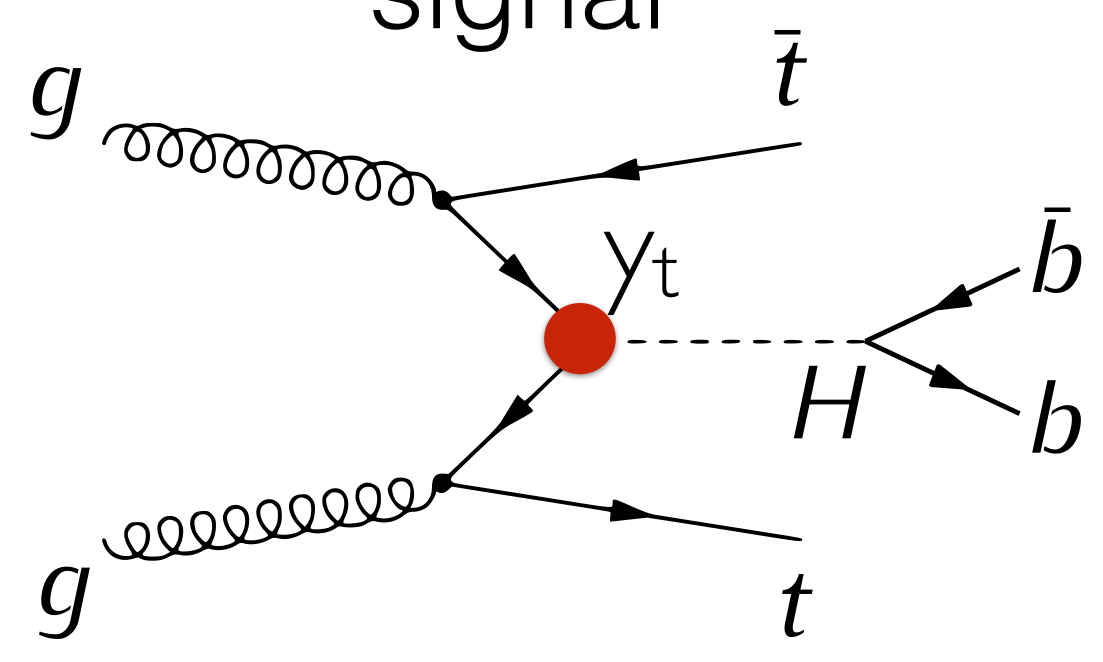


dominated by systematics!

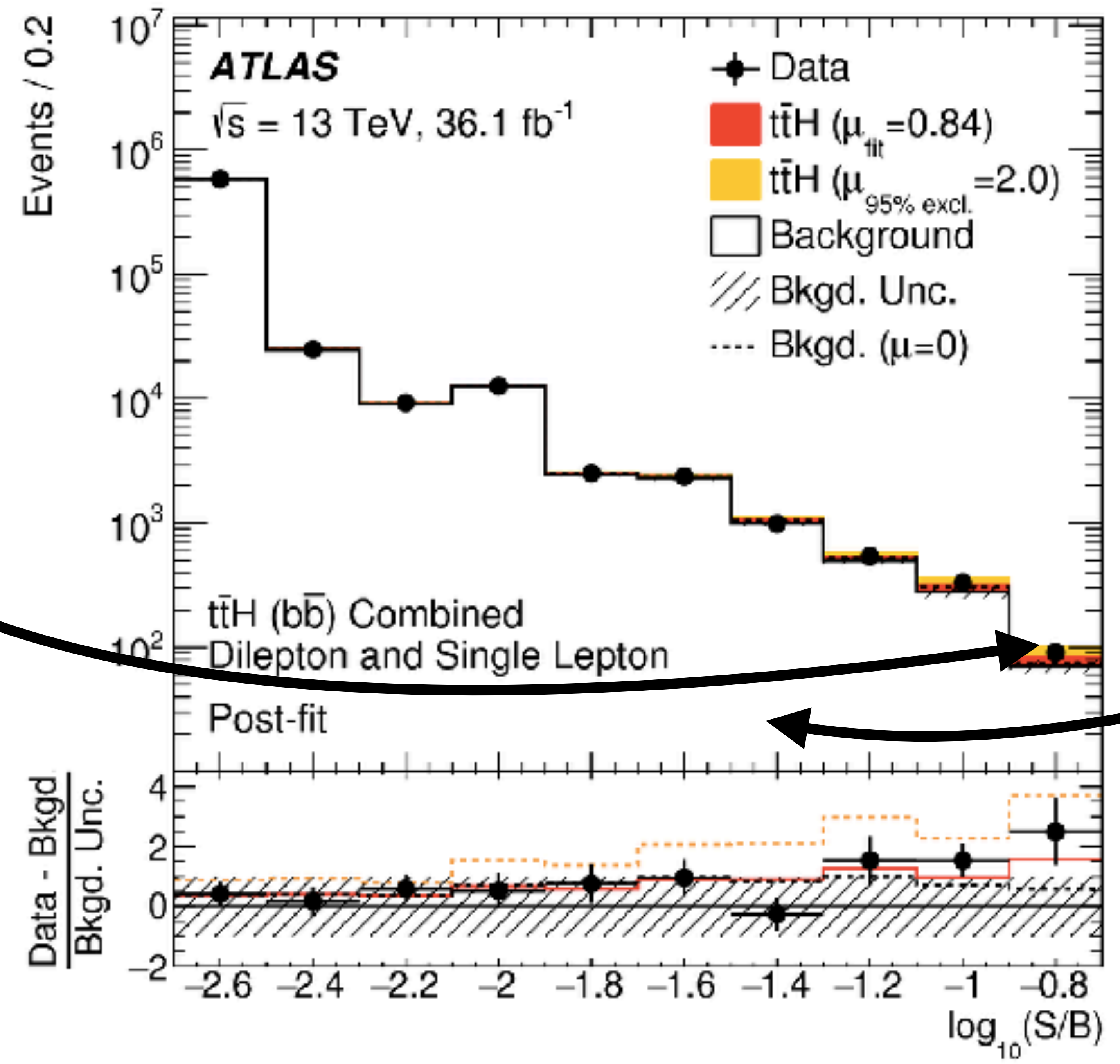
combined significance: 5.2σ!

Taming $t\bar{t}H$ backgrounds

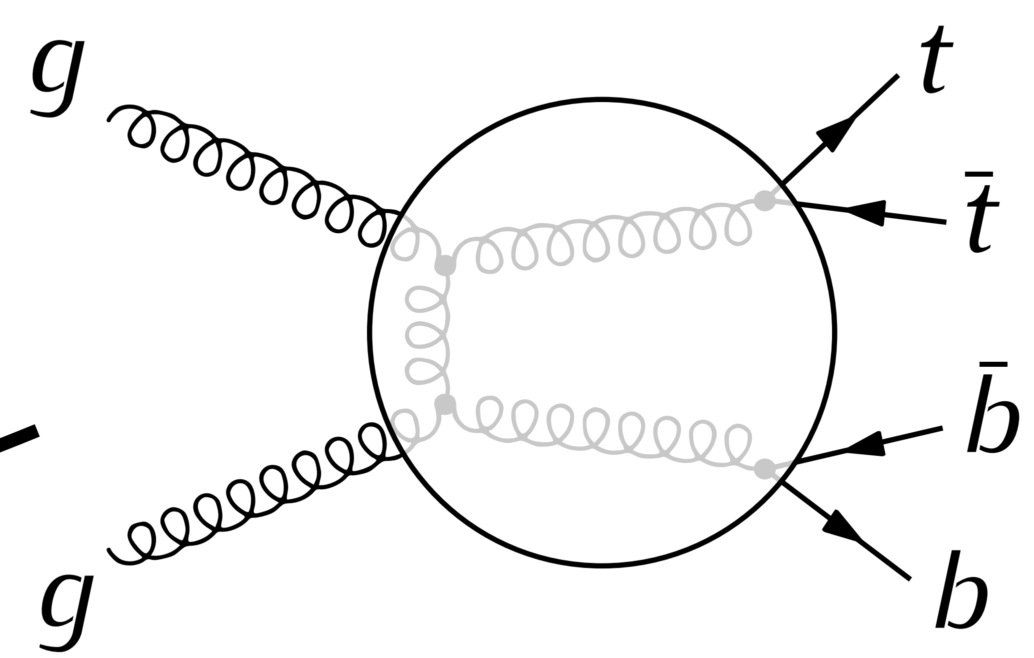
signal



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

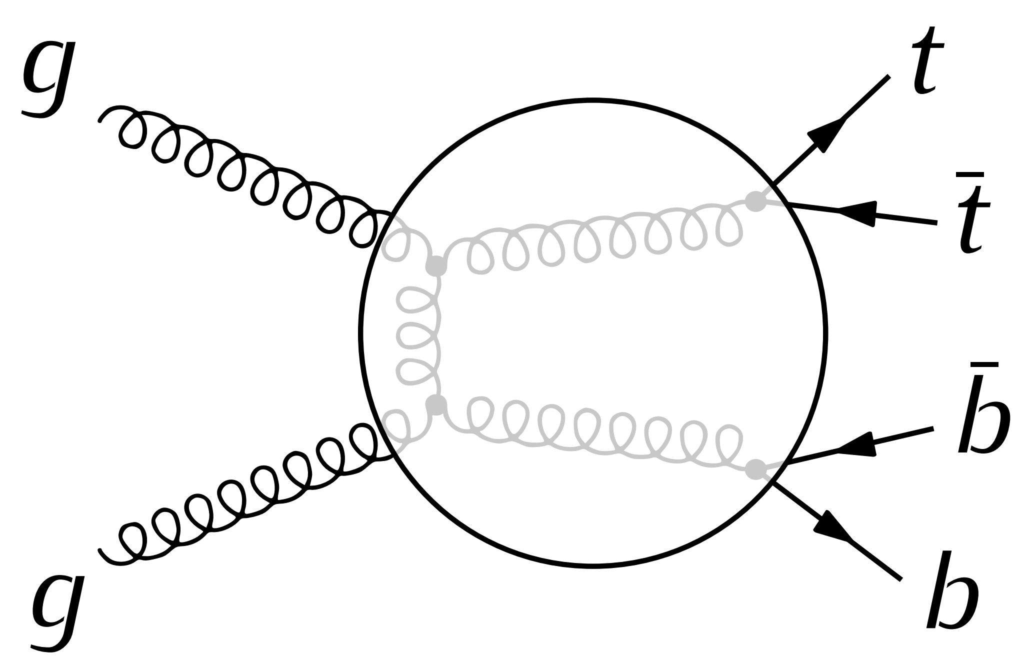


background

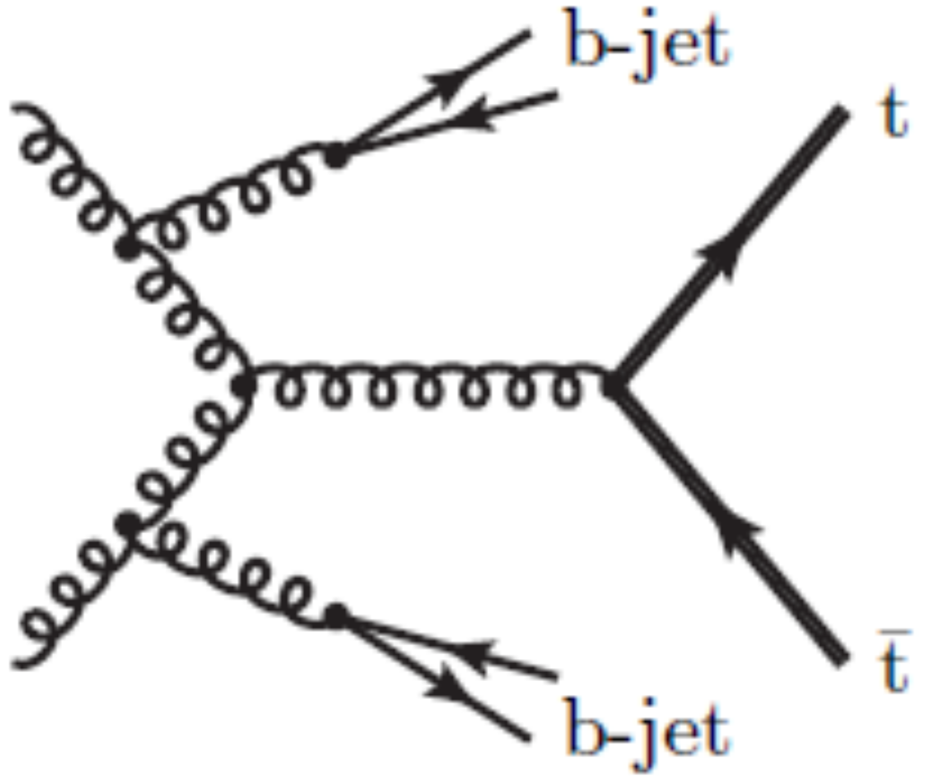


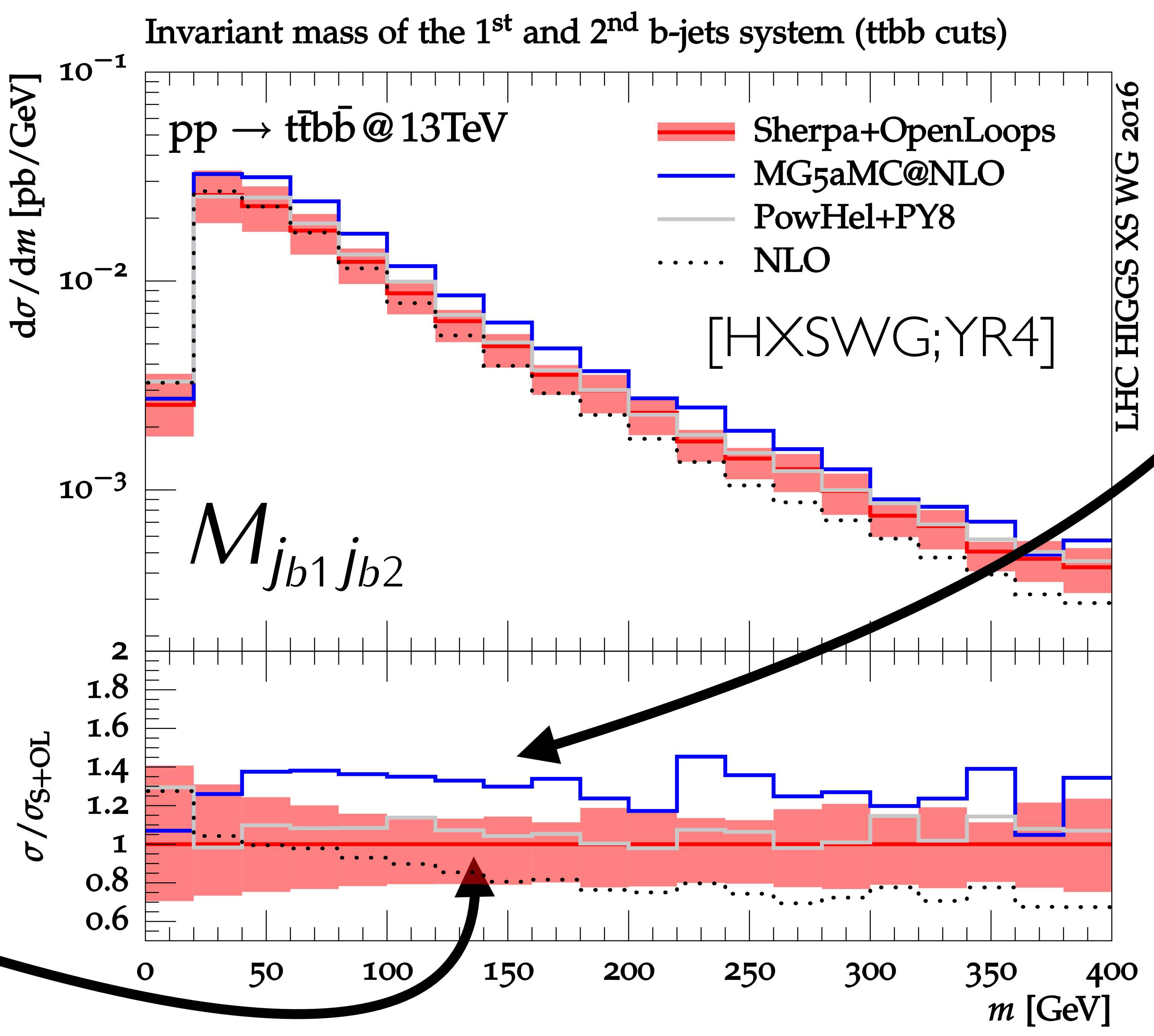
Taming $t\bar{t}H$ backgrounds

background



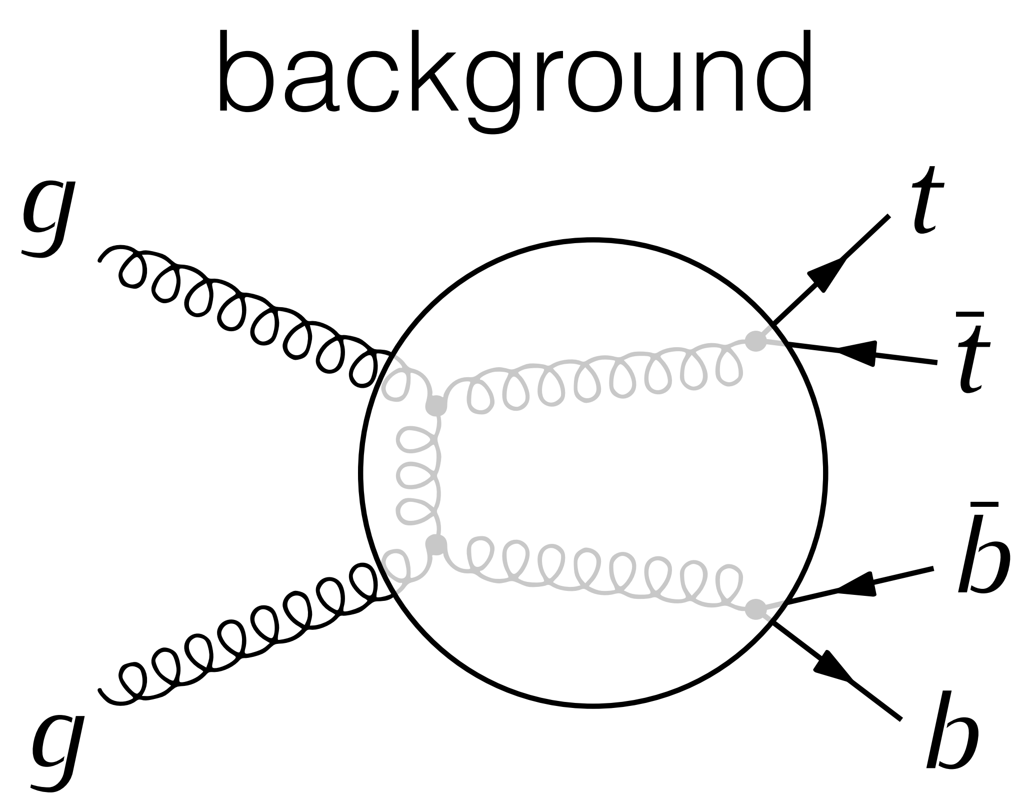
- ➡ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%
- ➡ However: notoriously difficult multi-scale problem: ET_t, $ET_{\bar{t}}$, ET_b, $ET_{\bar{b}}$
- ➡ Large shower effects, in particular from double $g \to b\bar{b}$ splittings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





~20% in the signal region

Taming $t\bar{t}H$ backgrounds



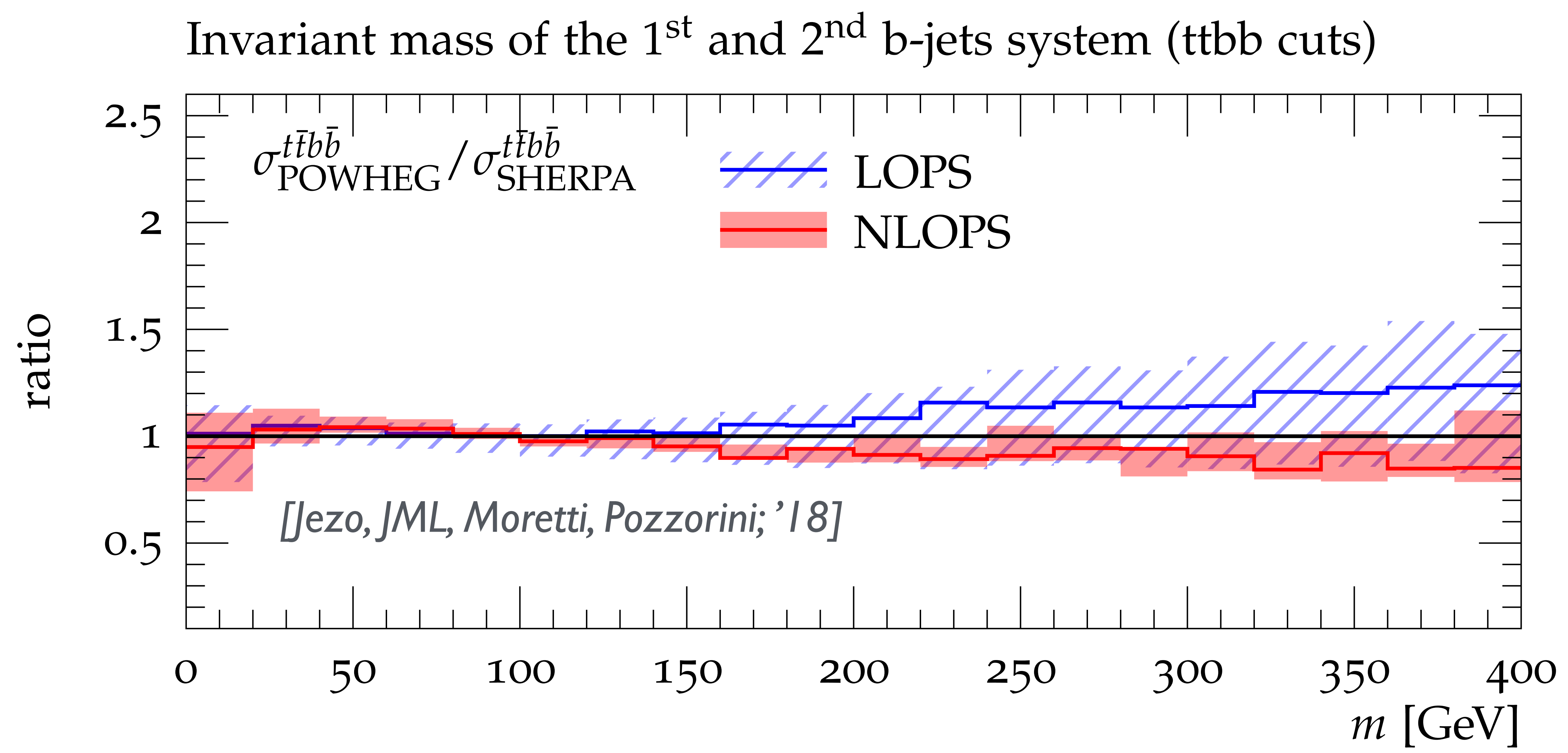
➡ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%

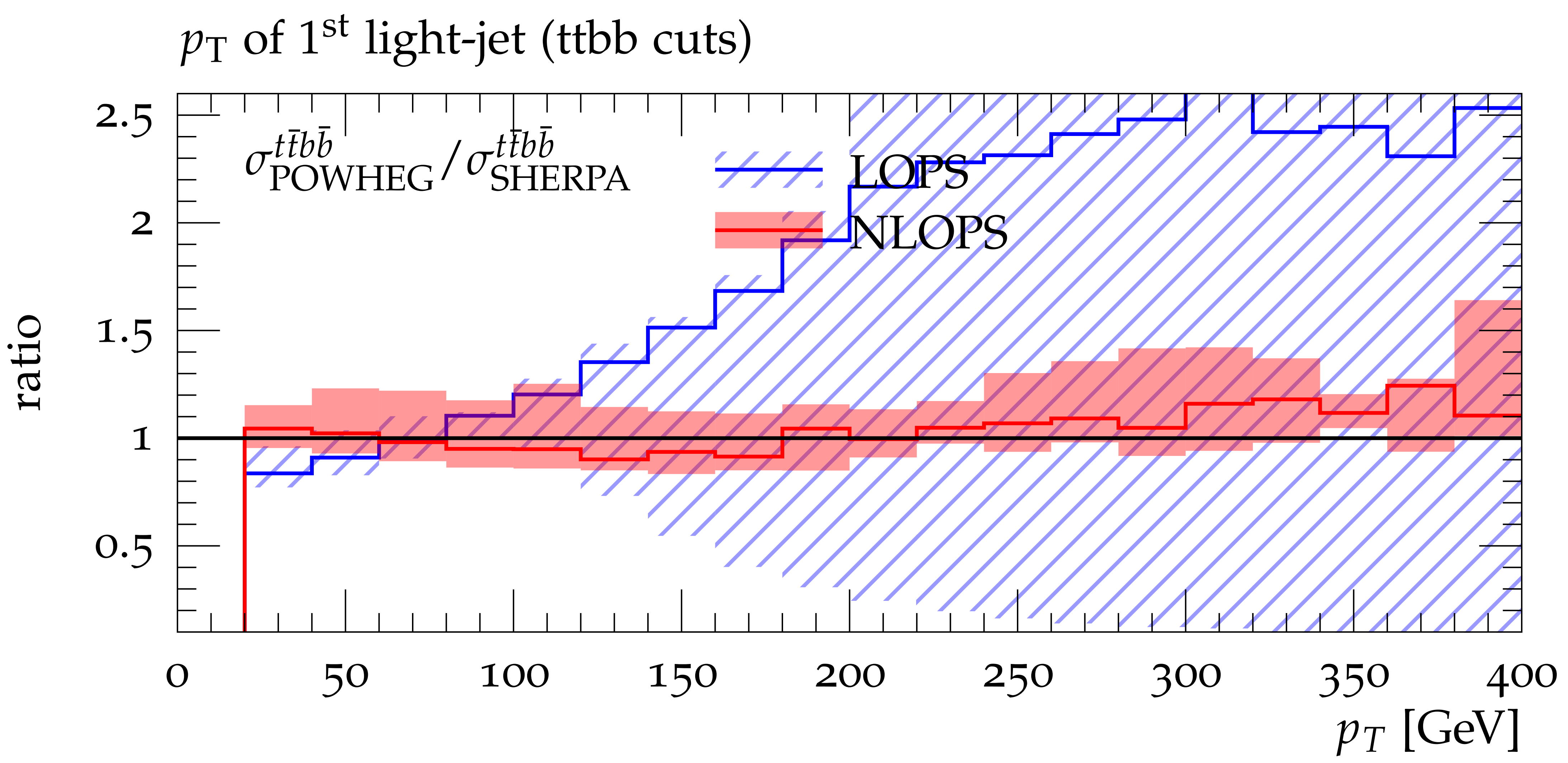
➡ However: notoriously difficult multi-scale problem: E_{T_t}, $E_{T_{\bar{t}}}$, E_{T_b}, $E_{T_{\bar{b}}}$

➡ Large shower effects, in particular from double $g \to b\bar{b}$ splittings

➡ Large systematic uncertainties from parton shower matching

➡ Careful study required to understand these systematics

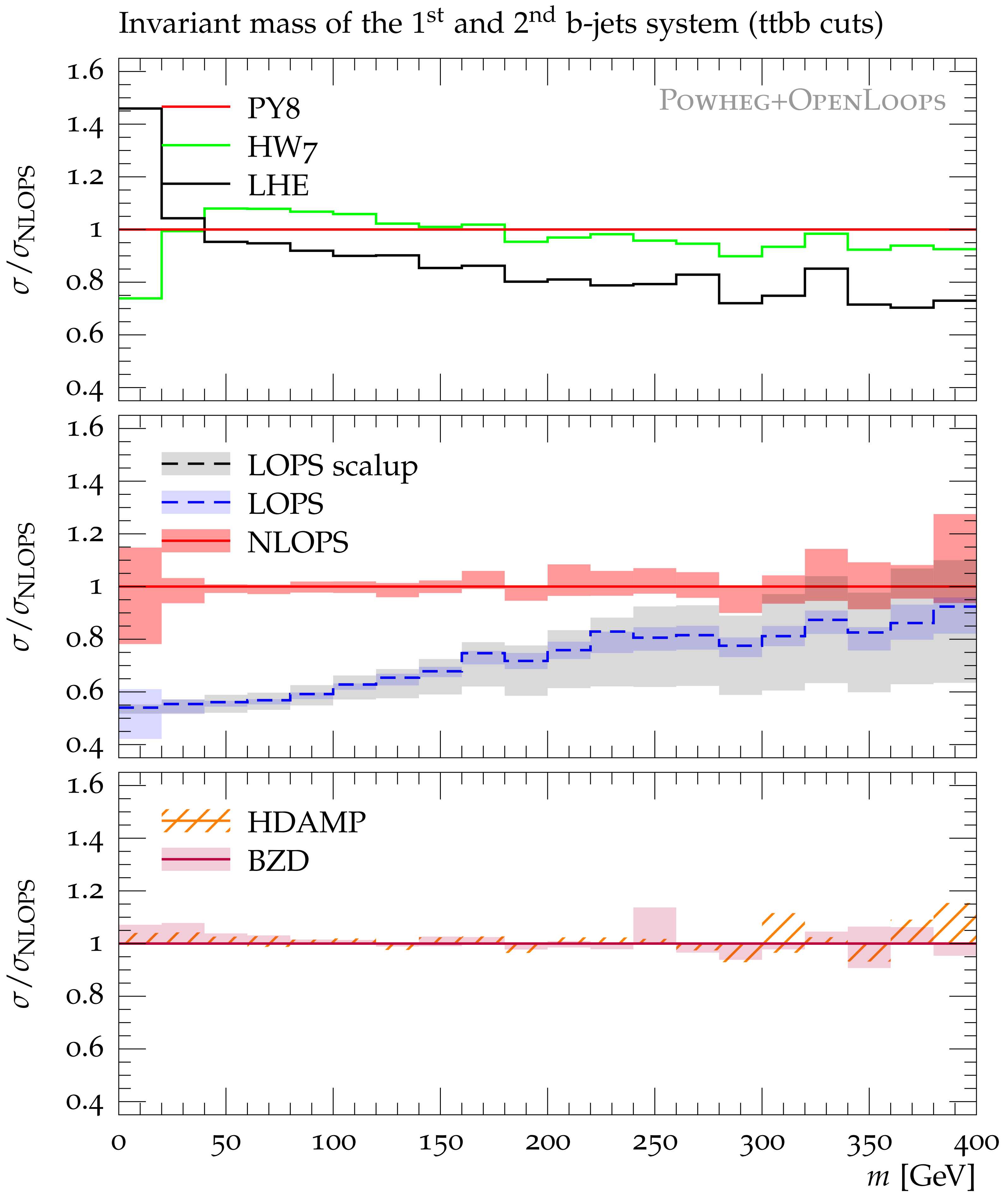


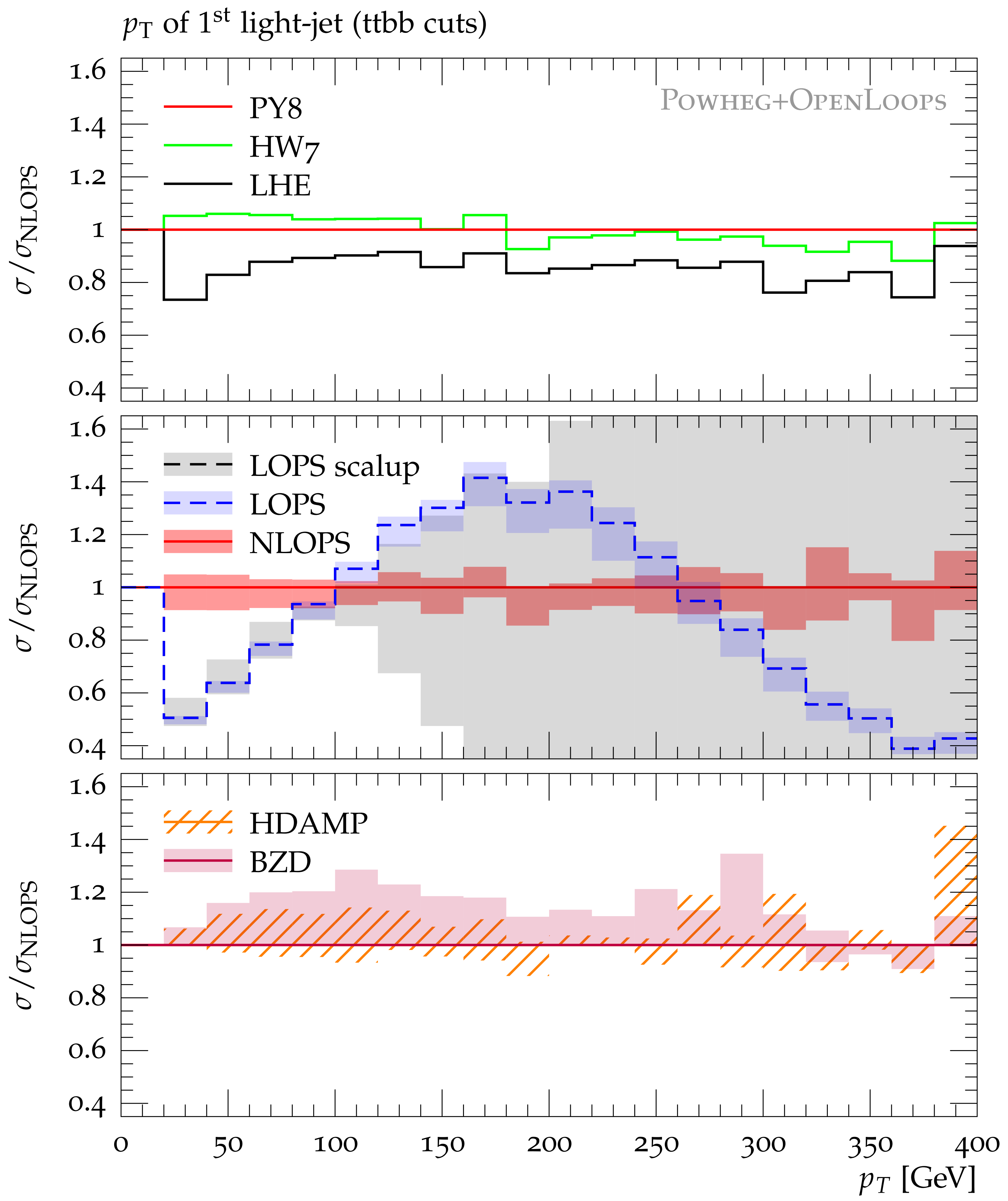


➡Sherpa vs. POWHEG+PY8 (both in 4-FS) in very good agreement

Taming $t\bar{t}H$ backgrounds

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



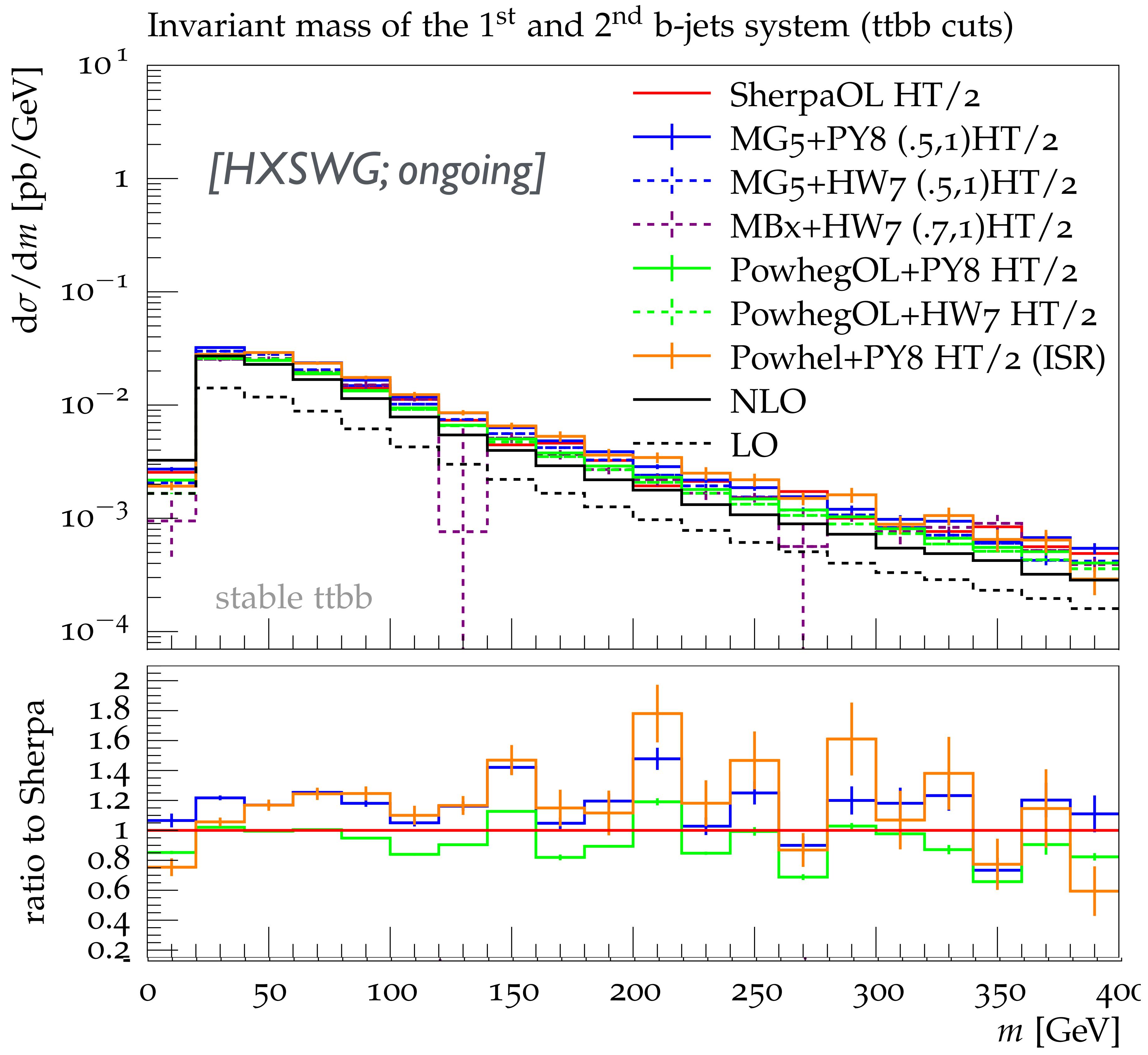


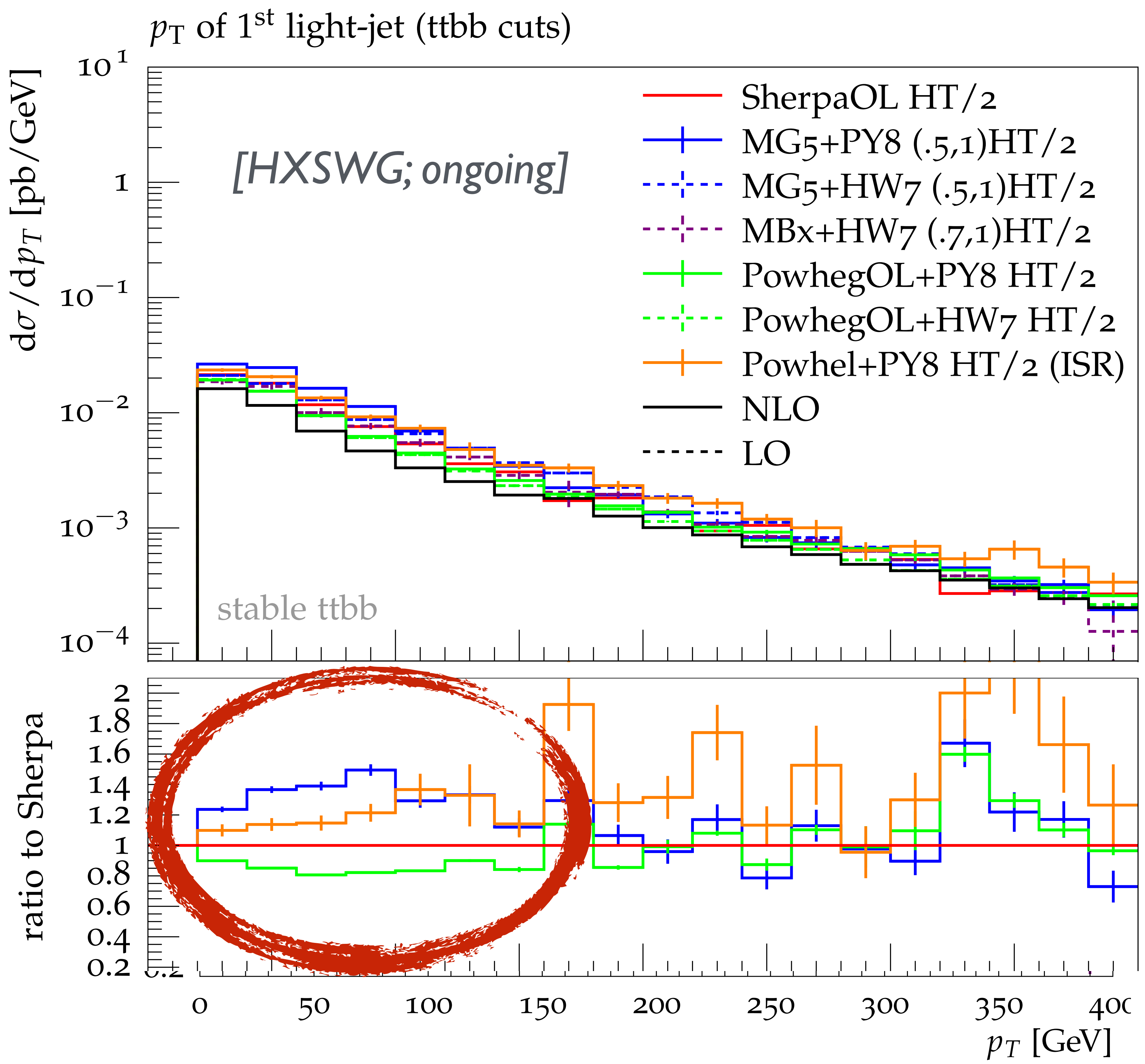
- Shower variations
- α_S & $g \to b\bar{b}$ variations
- hdamp & bzd variations

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

➡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

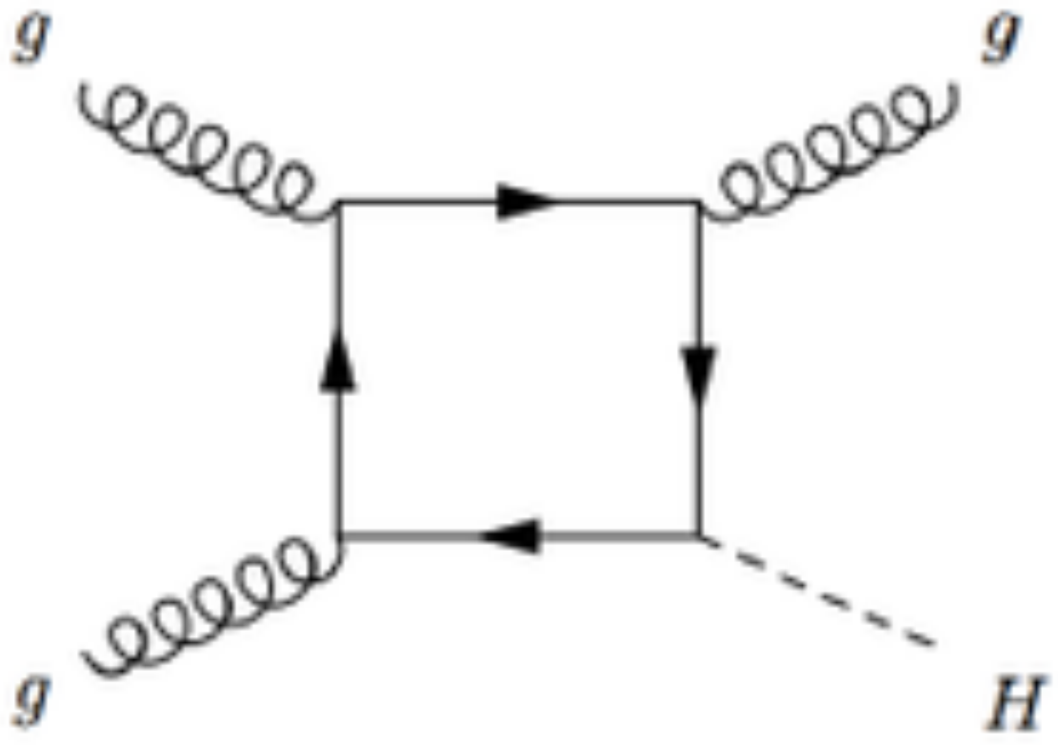
➡ Careful look inside the NLO+PS black-boxes necessary: ongoing within HXSWG!

A few examples where theory precision is crucial:

ttH

EW SUSY searches

Higgs-pT



Dark Matter searches

Higgs-pT: two regimes

$p_\perp \ll m_t$ $\qquad\qquad$ $p_\perp > m_t$

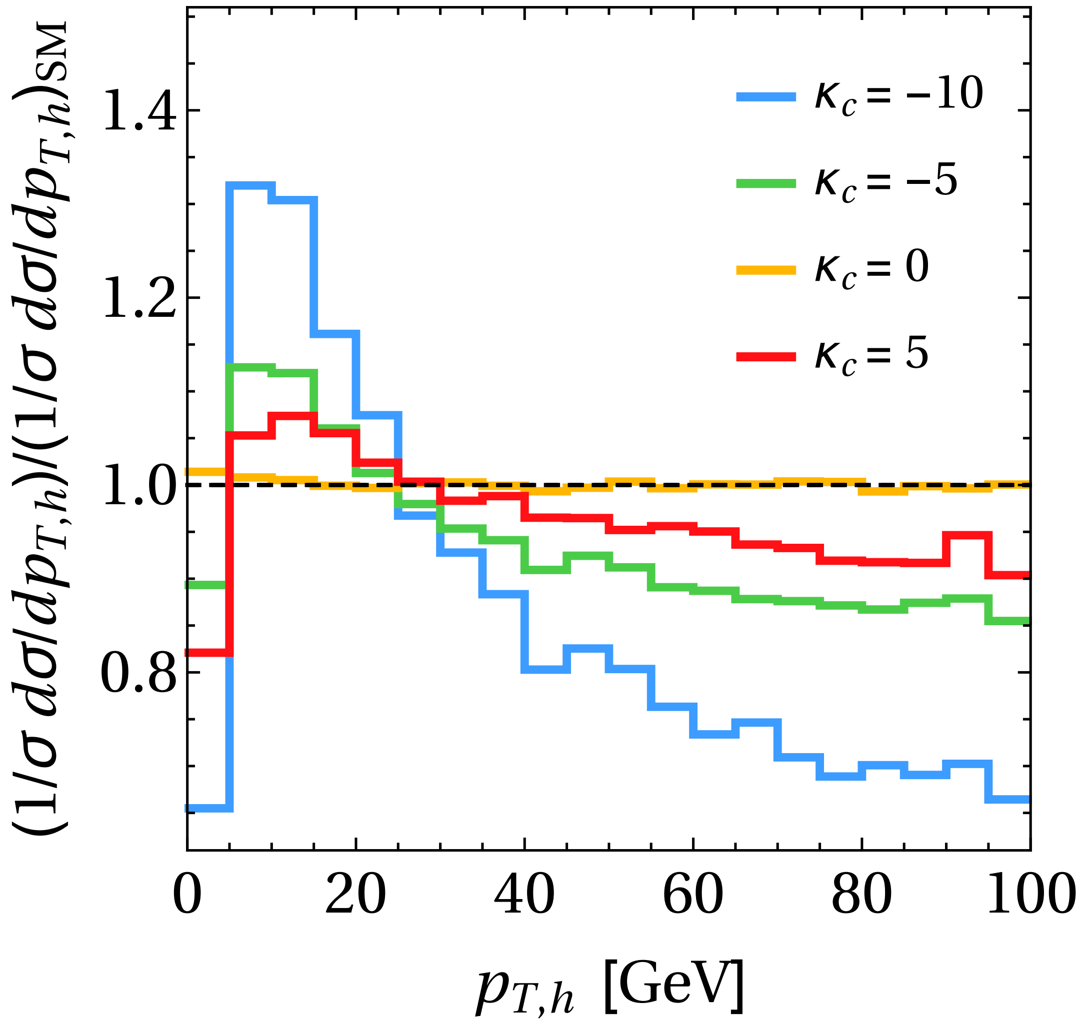
Possibility to constrain the charm-Yukawa coupling

$$\mathrm{d}\sigma/\mathrm{d}p_\perp \propto y_t^2 + y_t y_b + y_b^2 + y_t y_c + \ldots$$

for $p_\mathrm{T} \ll m_H$: ~10% $\quad$ ~1% $\quad$ <<1%

$$A^Q_{gg\to Hg} \sim m_Q^2/m_H^2 \log^2\left(p_\perp^2/m_Q^2\right)$$

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



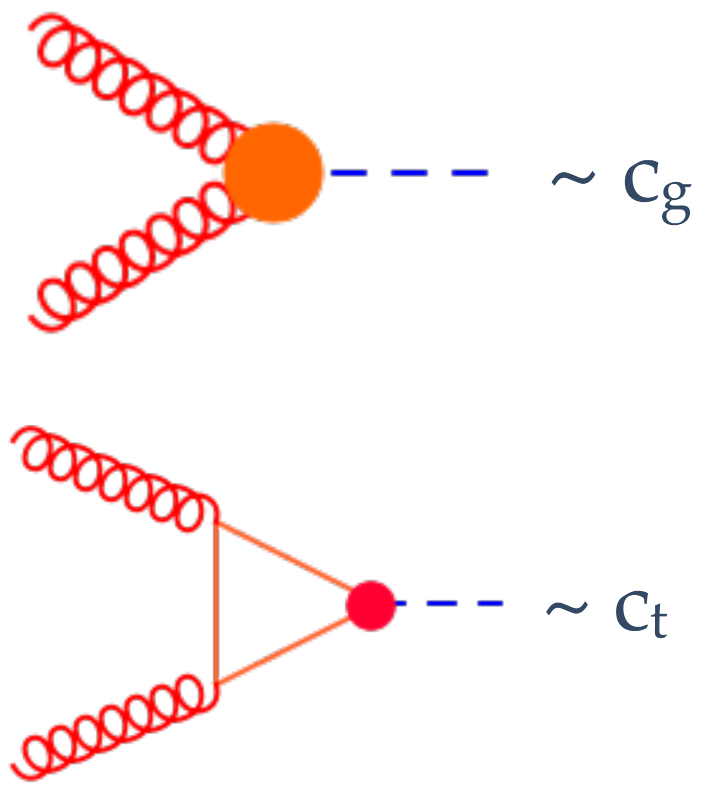
[Bishara, Haisch, Monni, Re; '16]

Sensitive probe of New Physics

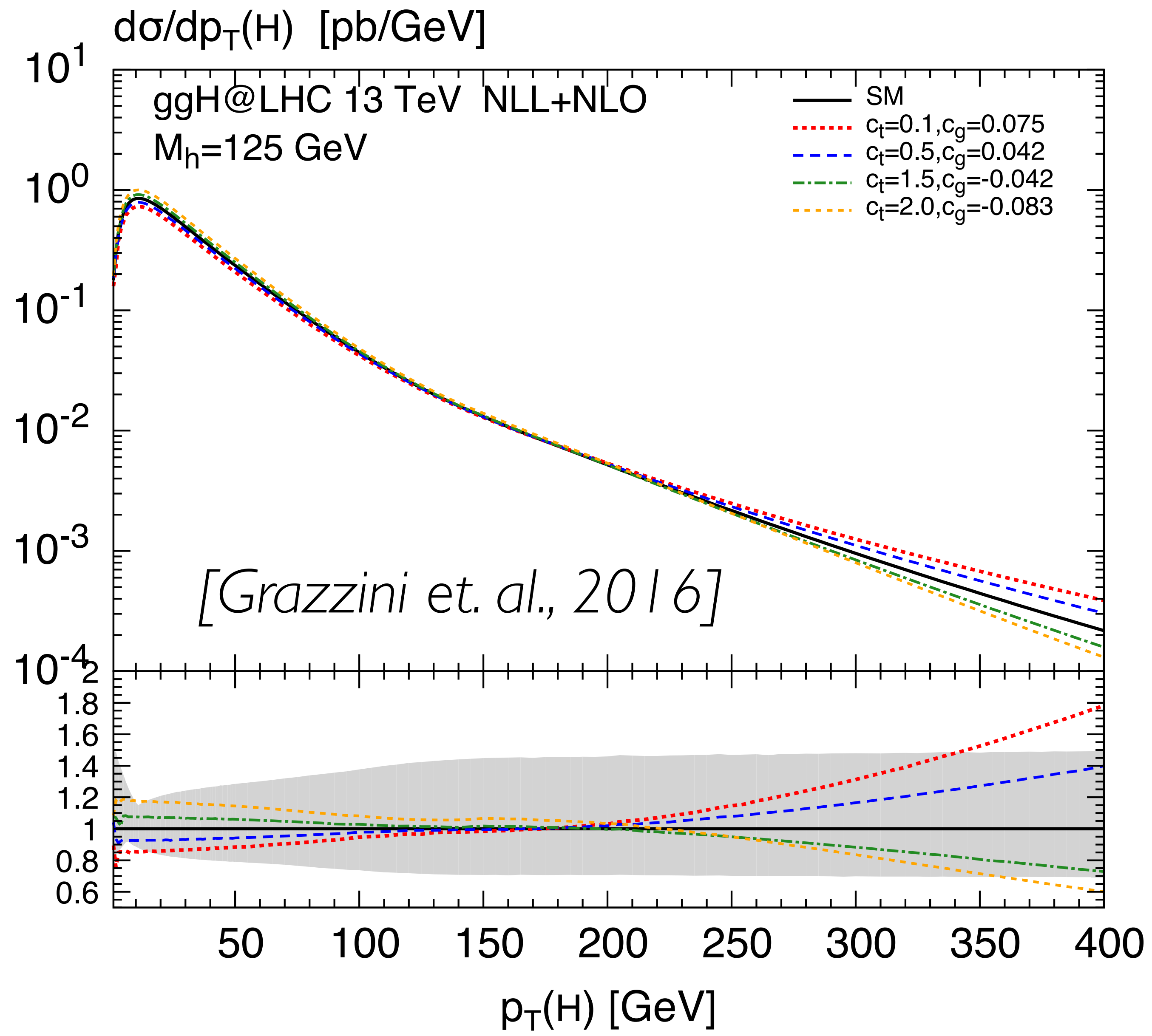
➜ In particular: disentangle c_g vs. c_t,:

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

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



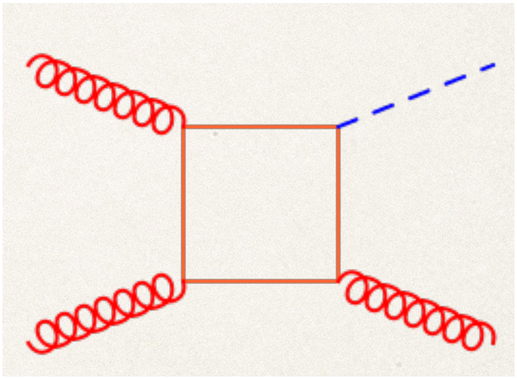
SM: $c_g=0$, $c_t=1$



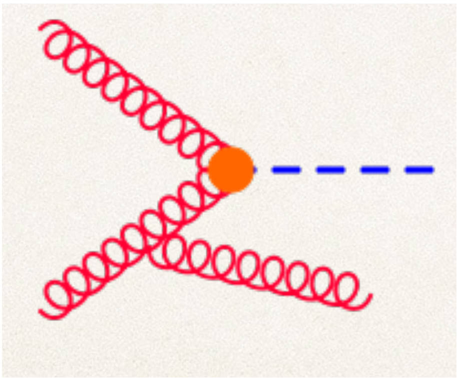
[Grazzini et. al., 2016]

Higgs-pT: higher-order corrections

full theory: loop-induced

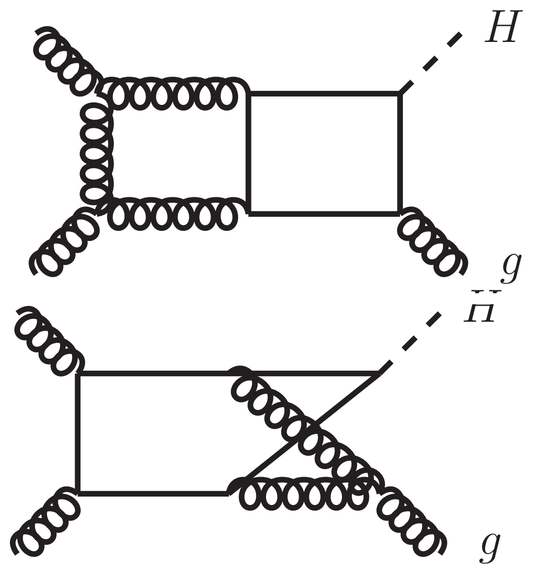


integrate-out → heavy quarks



HEFT: tree-level at LO

Bottleneck:
massive two-loop amplitudes

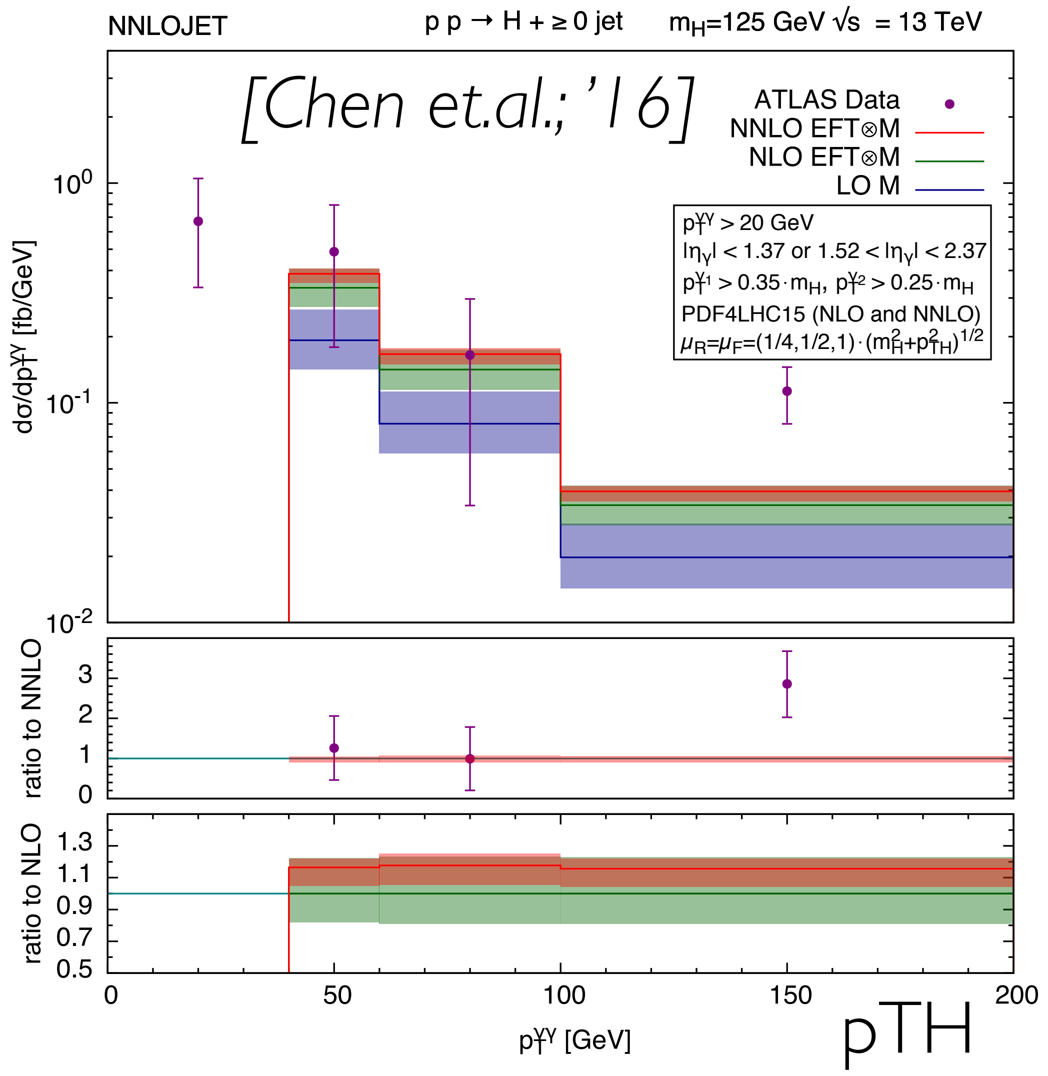


NLO

NNLO

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

Bottleneck: IR subtraction



perturb. uncertainties in HEFT under very good control:

- ~10% scale variation
- stable shapes

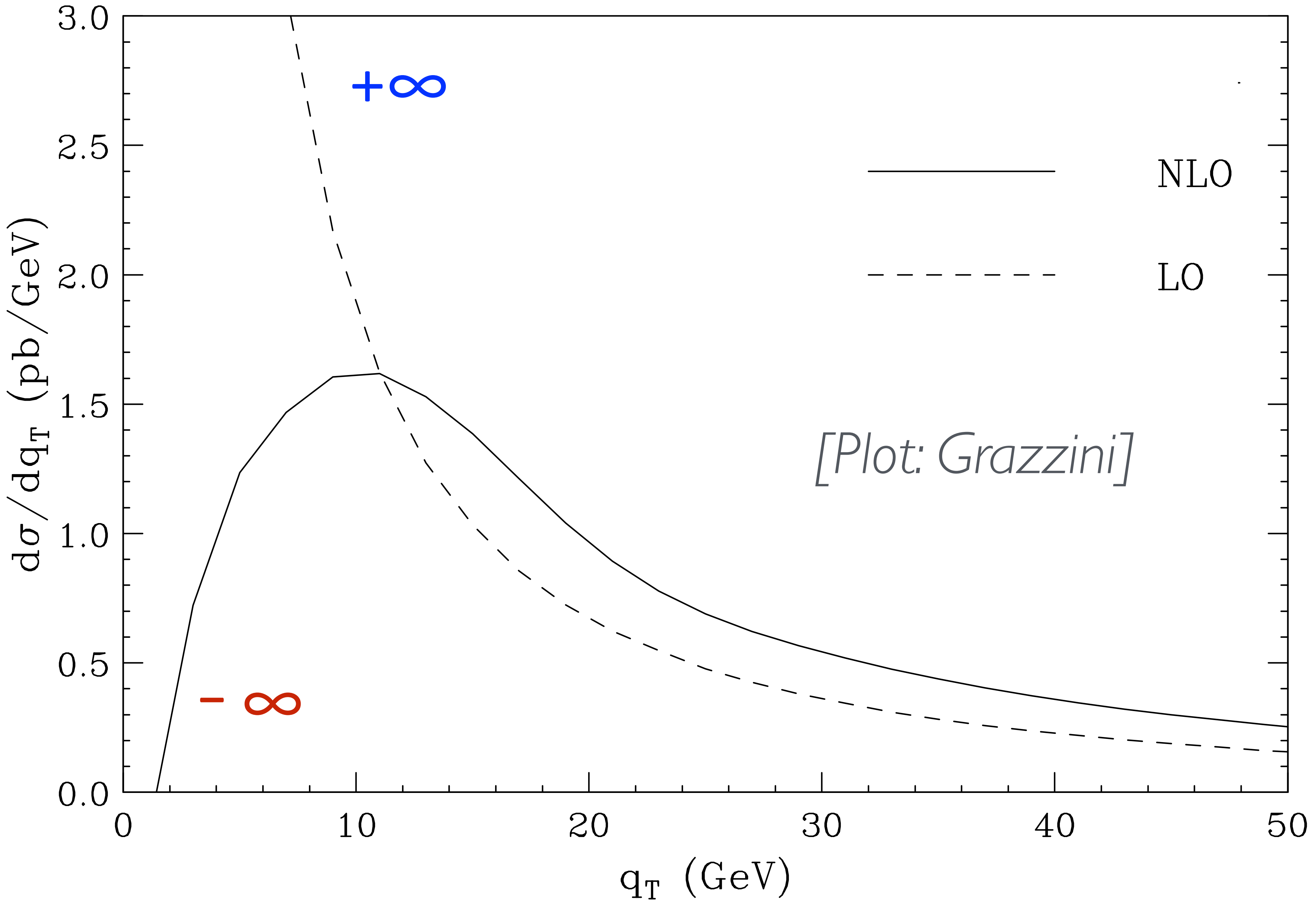
Ansätze:

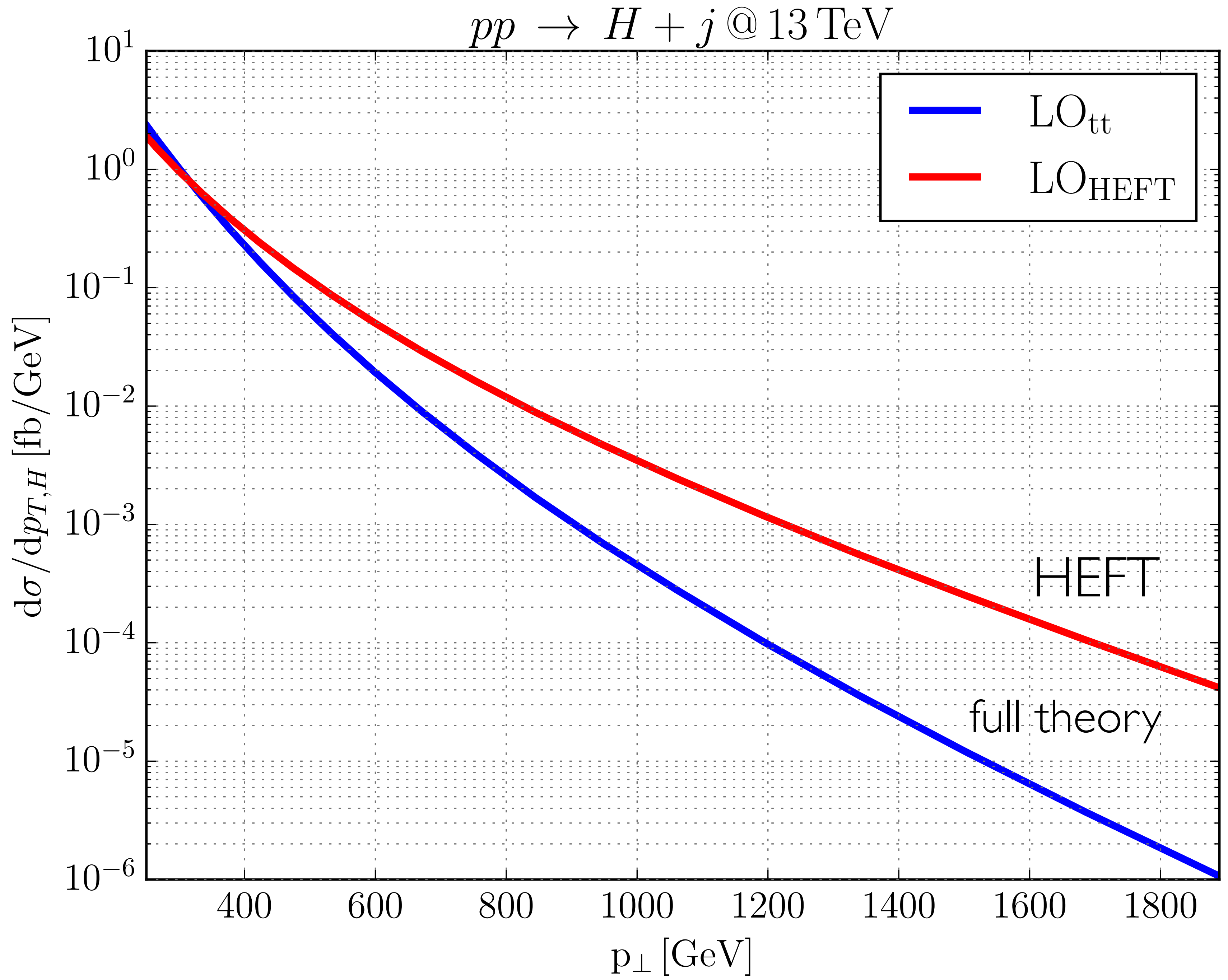
- analytical: very hard, planar MI known *[Bonciani et. al., '16]*
- numerical: very ~~CPU/~~GPU intensive *[Jones et. al., '18]*
- expansions: has to be performed carefully, very versatile *[Melnikov et. al., '16+'17]*

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

Higgs-pT: two regimes

$p_\perp \ll m_t$ $\qquad$ $p_\perp > m_t$





$\sim p_T^{-2}$

$\sim p_T^{-4}$

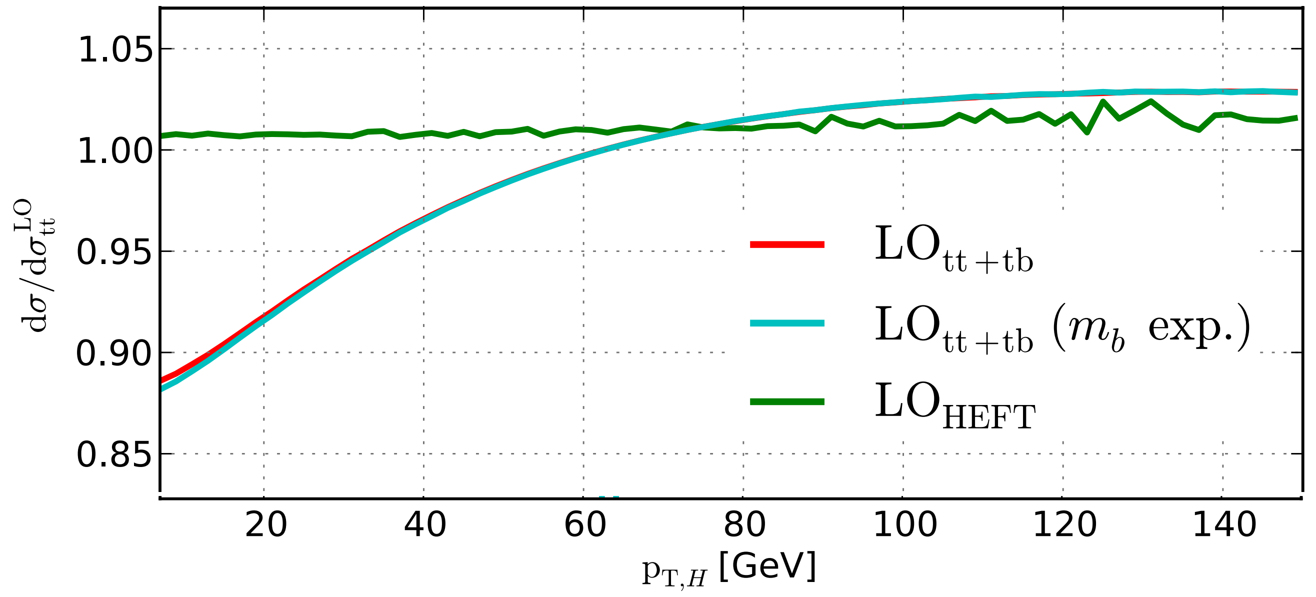
- Fixed-order breaks down at low pT

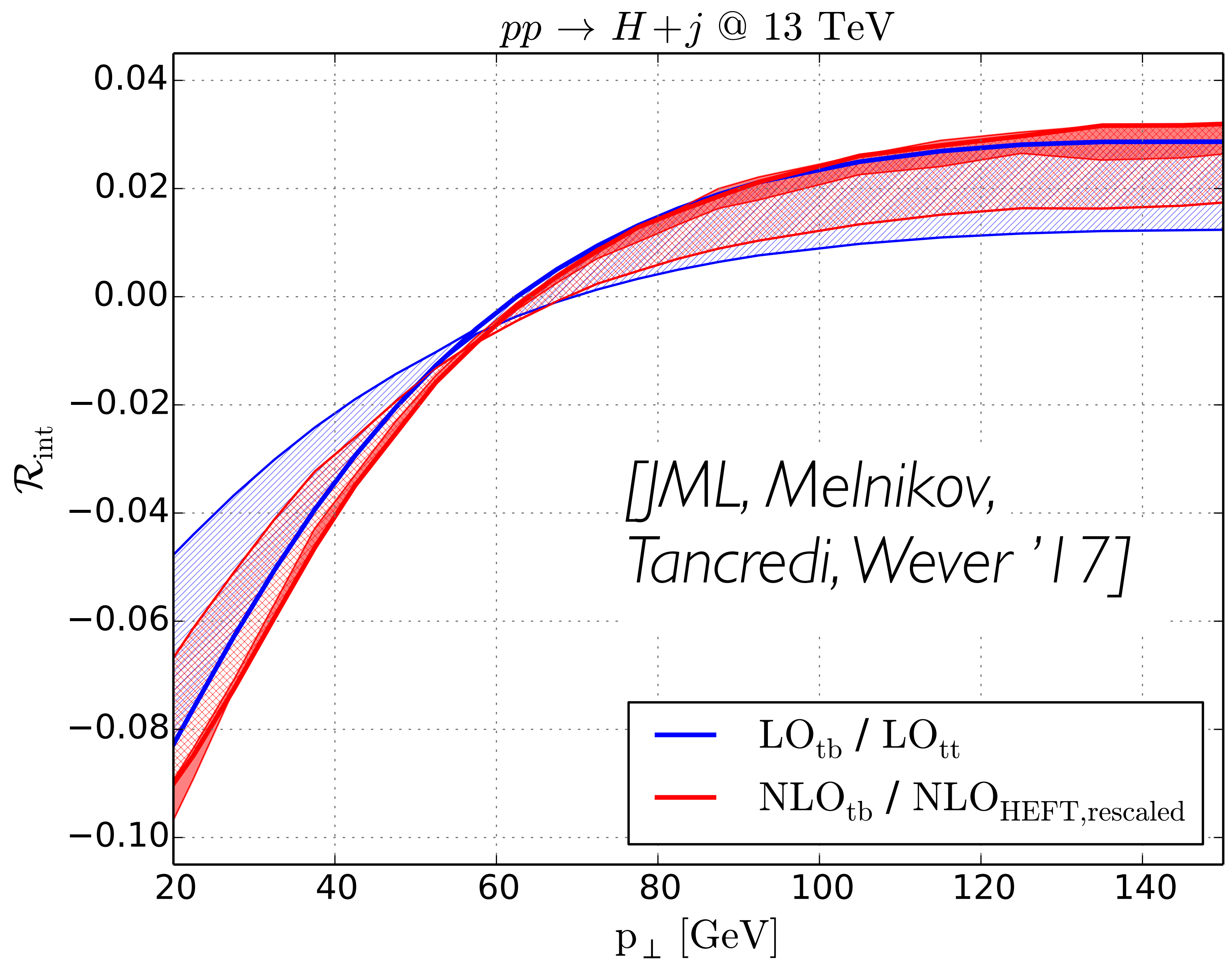
➡ Resummation mandatory

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

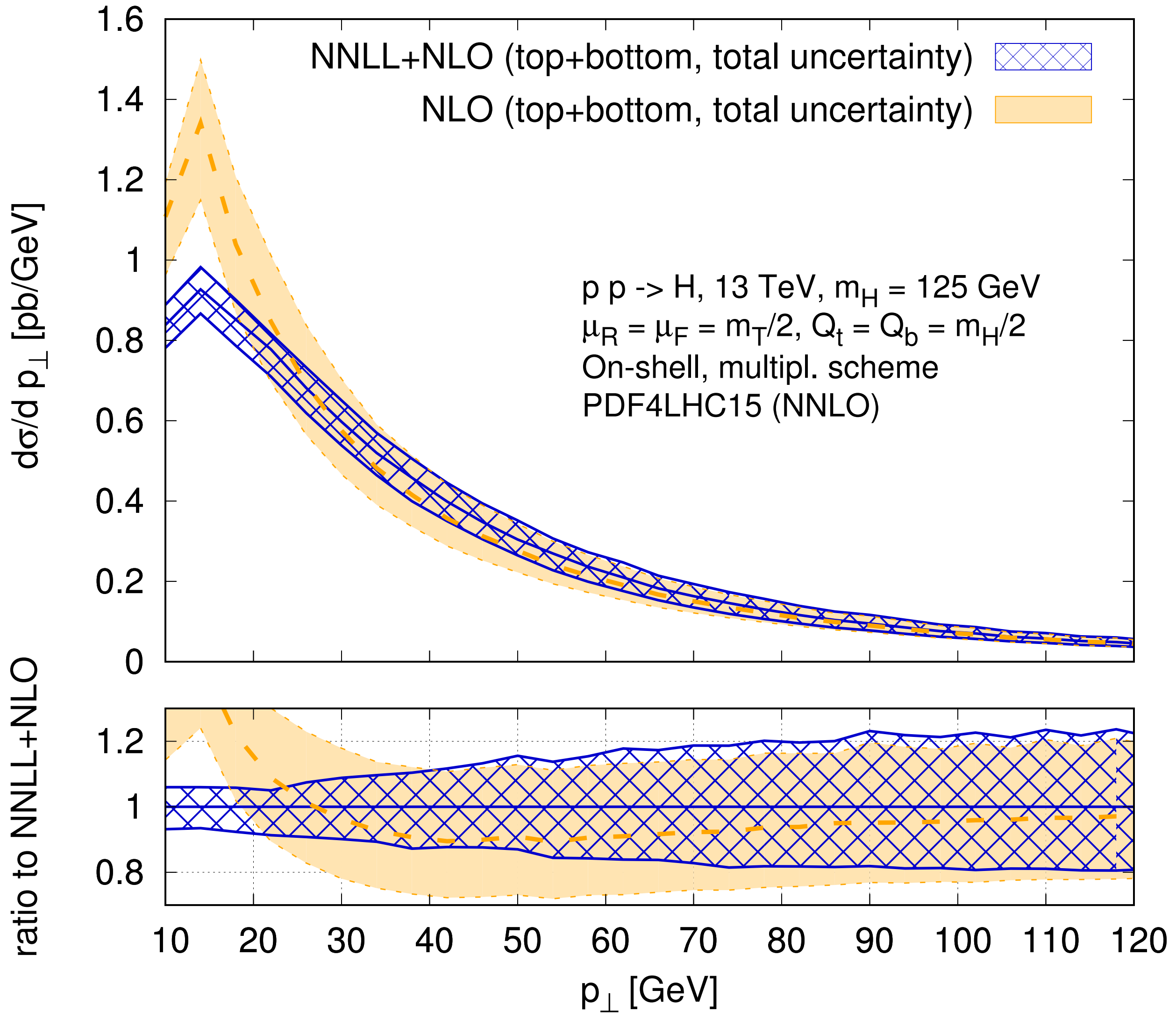
$p_\perp \ll m_t$: bottom mass effects at NLO+NNLL

- expansion of the two-loop integrals in (m_b^2/p_T^2)
  [Melnikov, Tancredi, Wever; '16+'17]
- valid at %-level down to pT~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 yt²

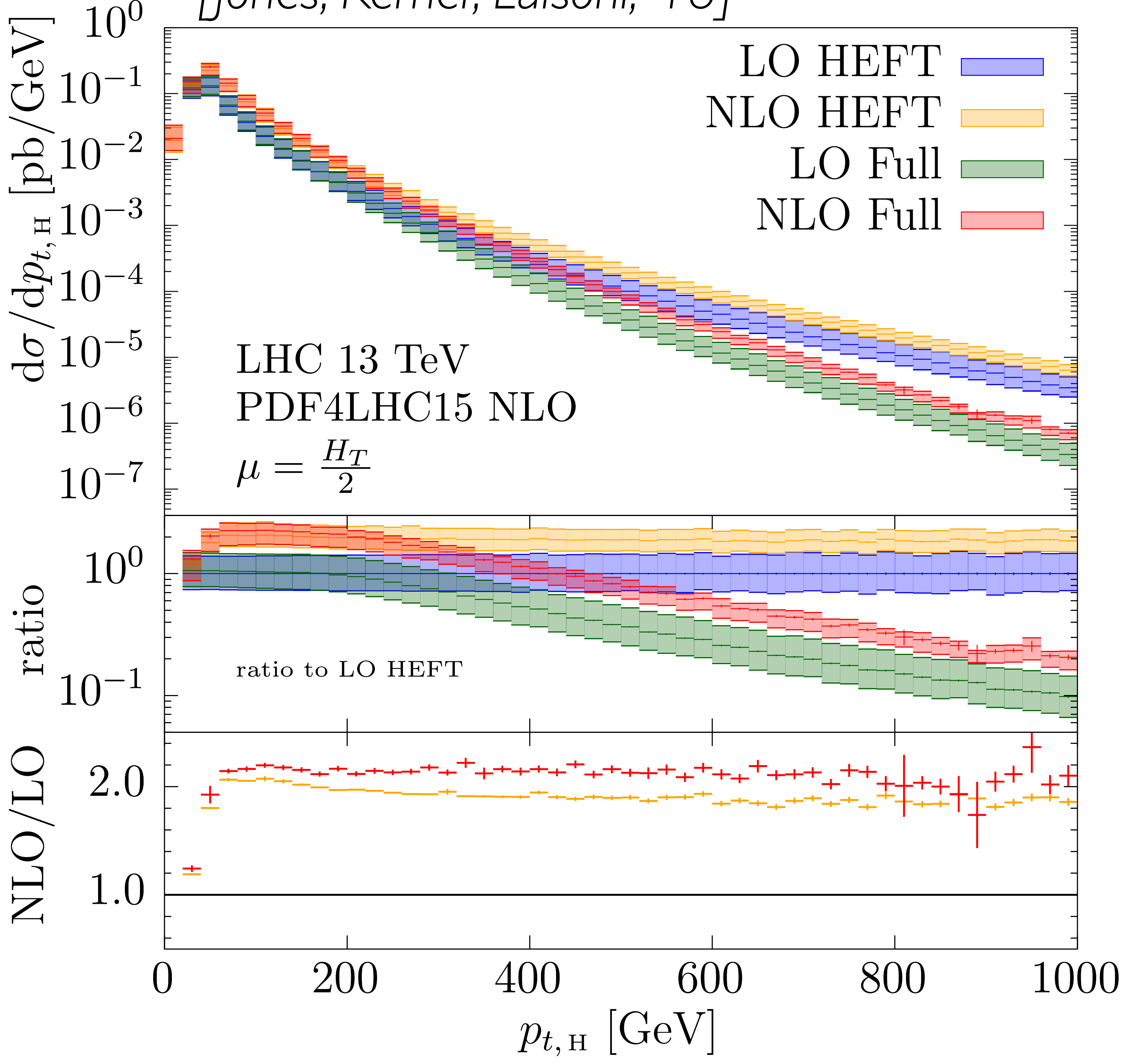
- -(5-10)% for pT=20-40 GeV at LO and NLO
- Despite (large) corrections, the interference shape stable under QCD corrections
- **large mb-renormalisation scheme dependence tamed at NLO**

resum!

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

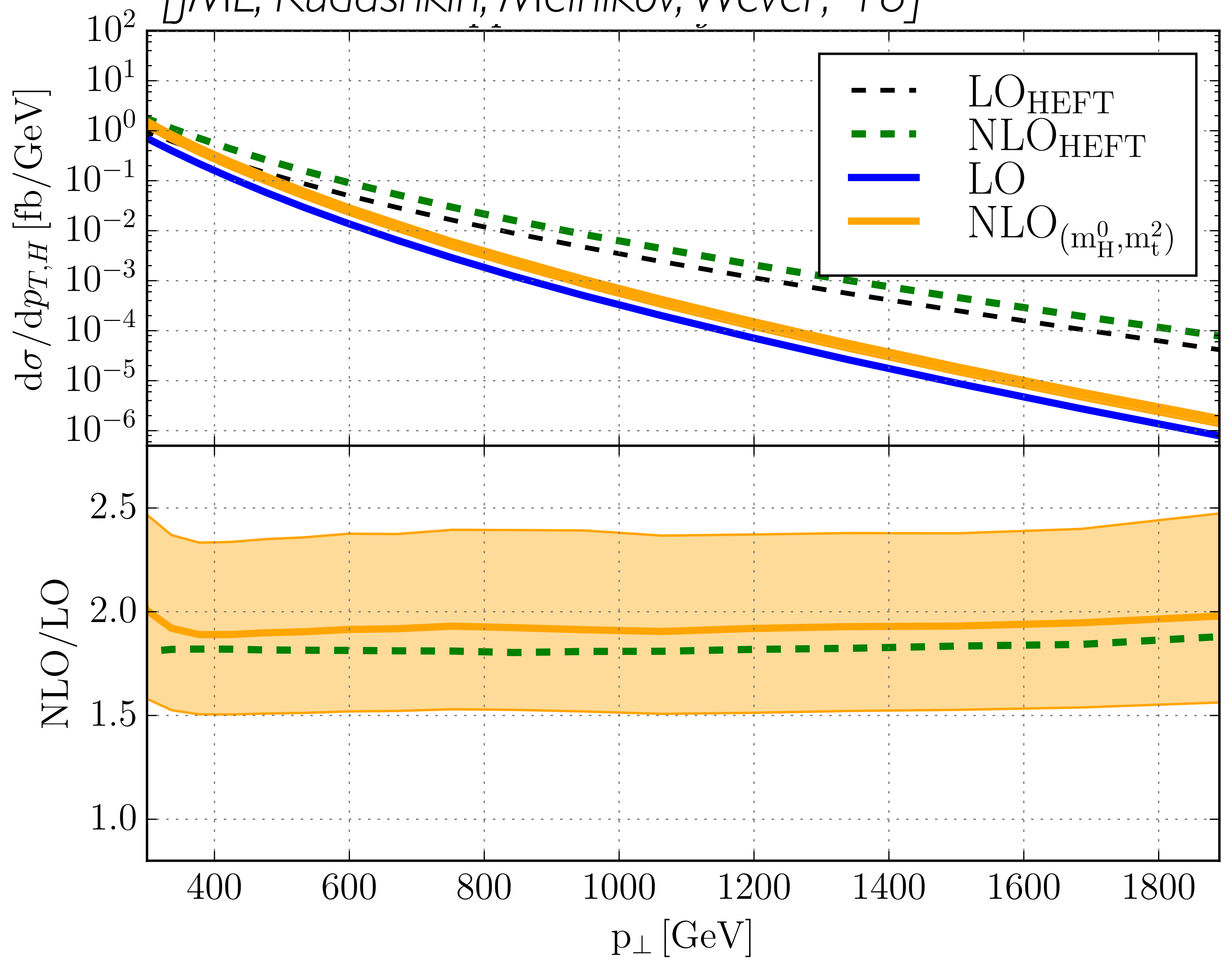
- numerical integration of two-loop integrals based on `SecDec` *[Borowka et.al.]*
- valid in all of the phase-space

[Jones, Kerner, Luisoni; '18]



- 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 pT

[JML, Kudashkin, Melnikov, Wever; '18]



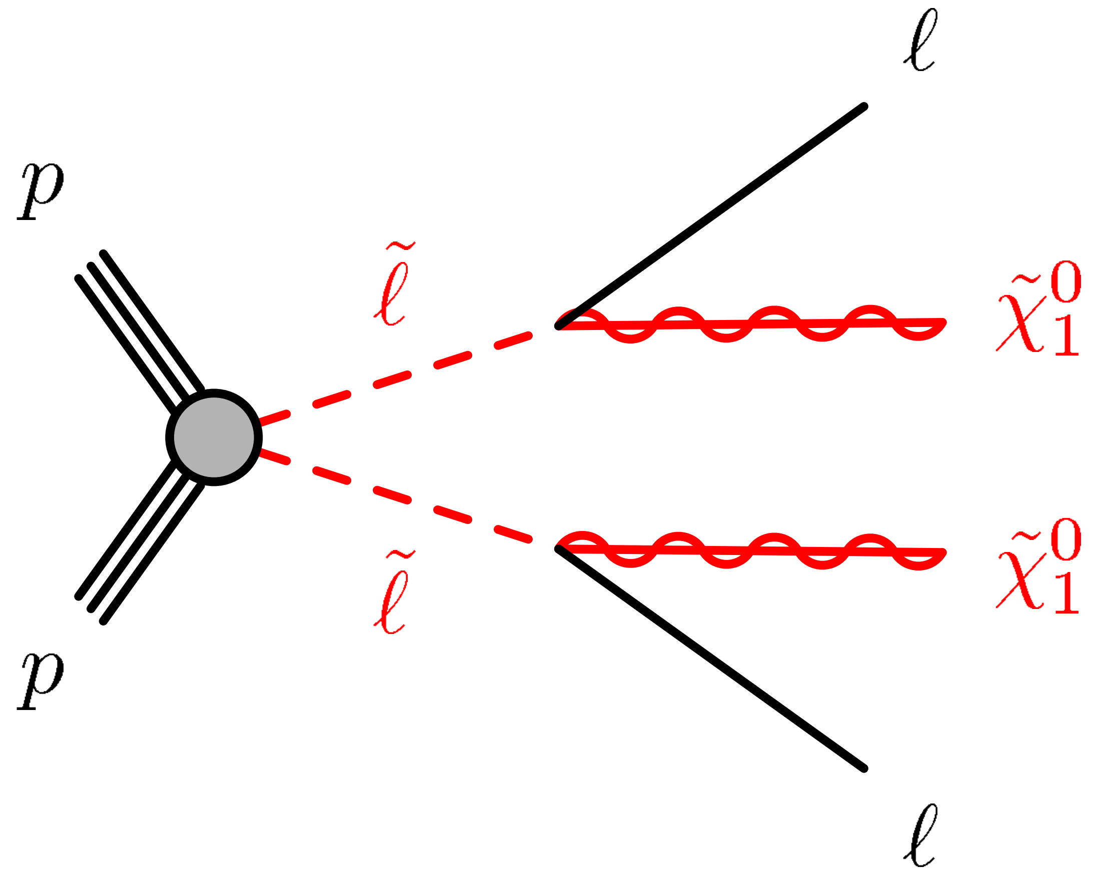
- NLO corrections very similar as in HEFT: K~2 with remaining scale uncertainties ~20-25%
- hardly any shape dependence

→Control of the high-H-pT 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



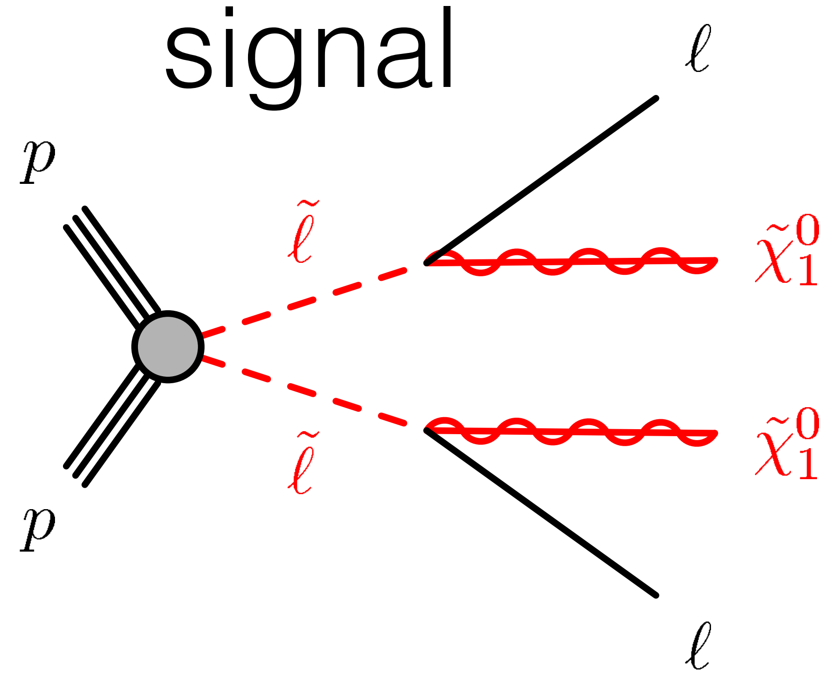
Higgs-pT

Dark Matter searches

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

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

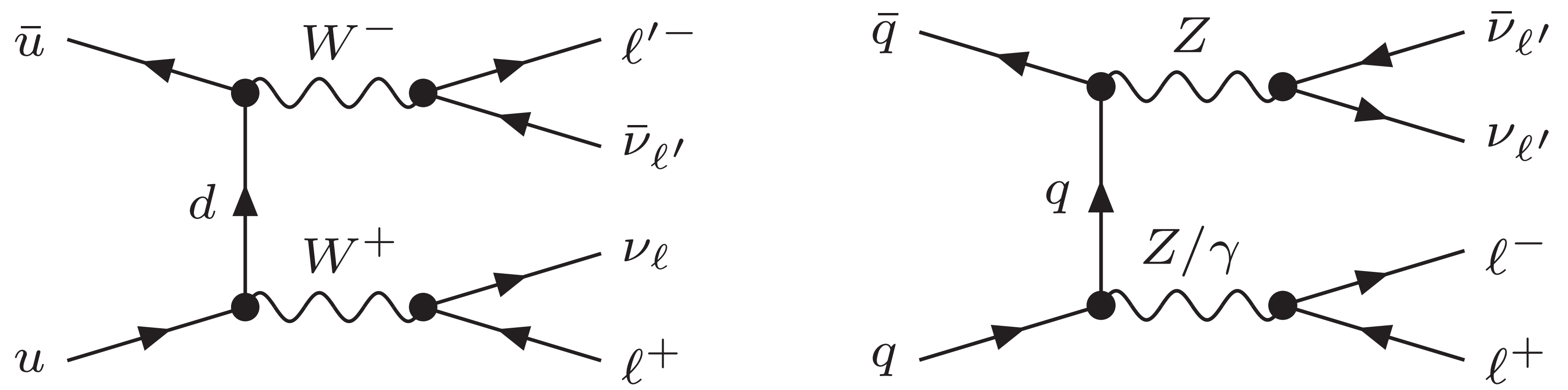
signal



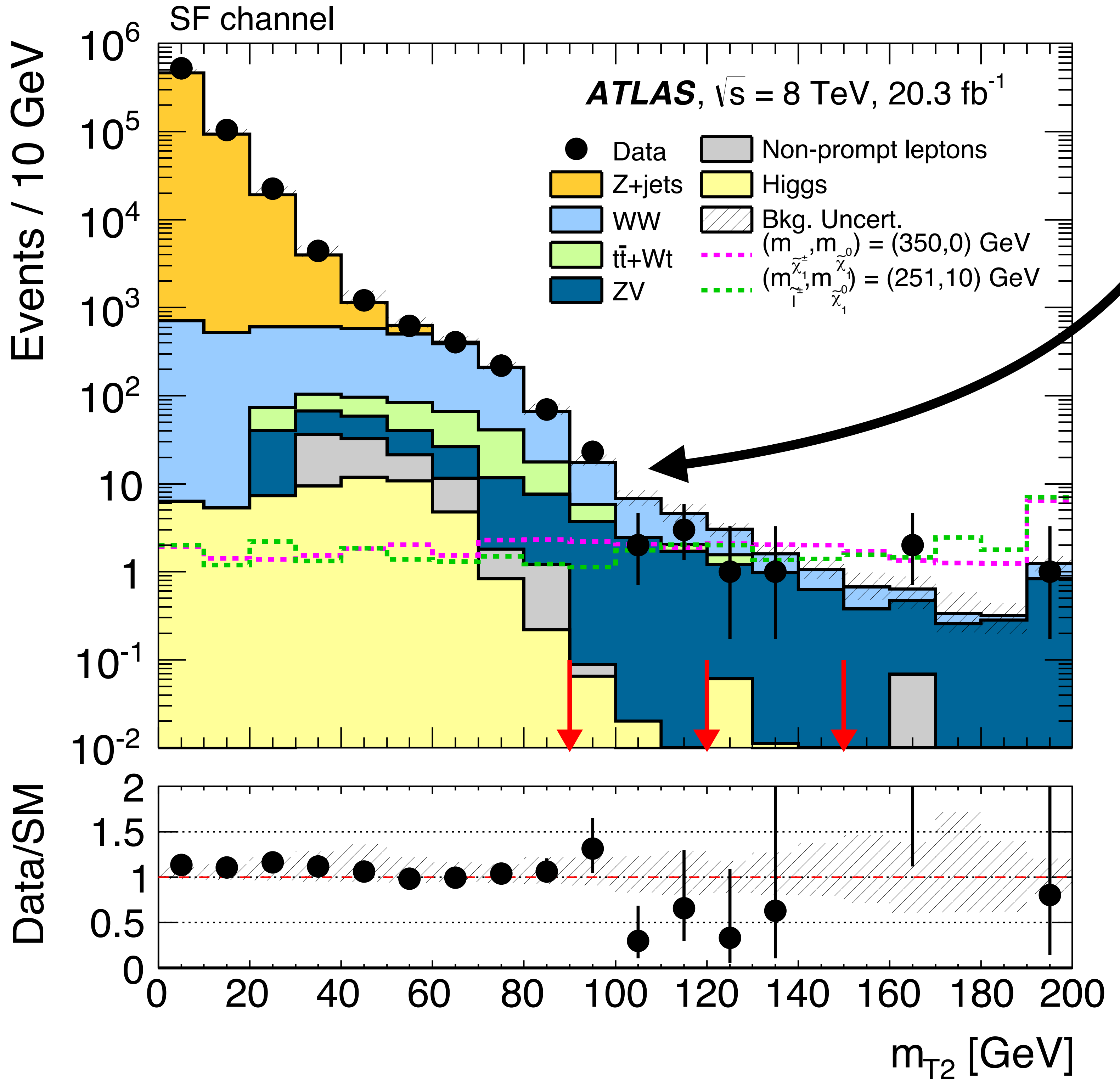
Direct Slepton pair production

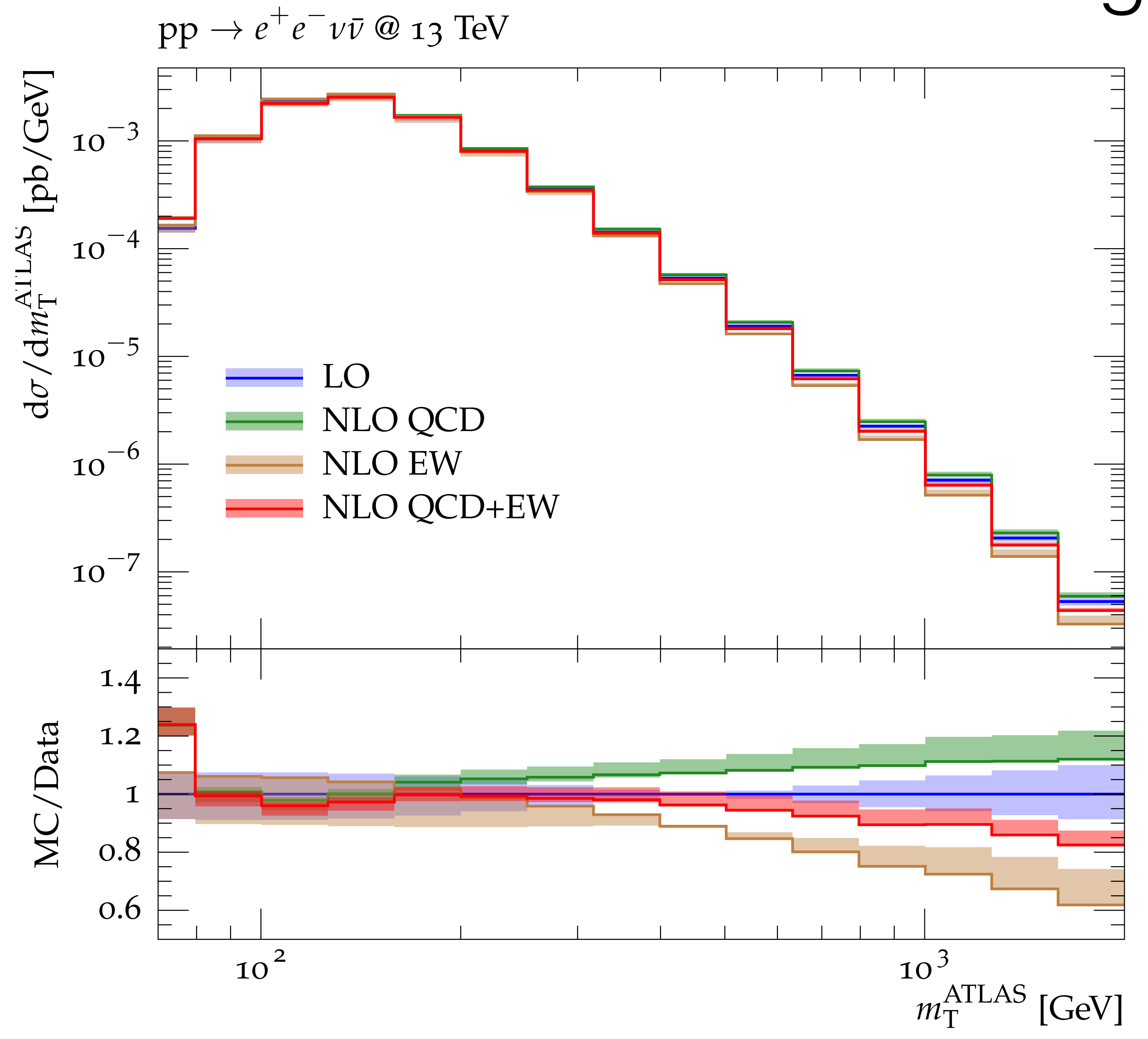
Signature: **2 OS-SF leptons + MET**

Background: $W^+W^-/ZZ \to 2l2\nu$



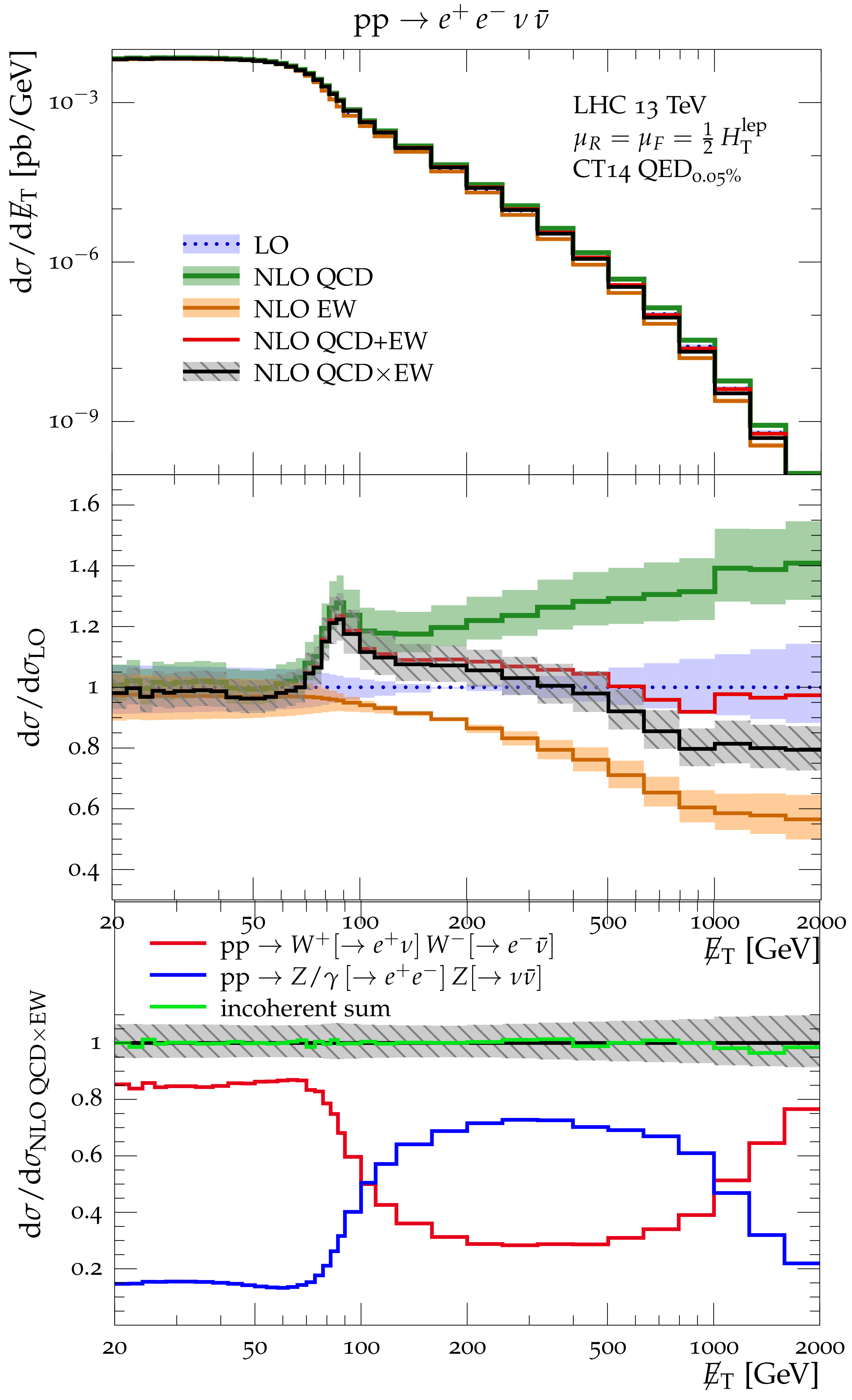
background





- EW corrections: -10(-20)% for mT2=200-300 GeV(1 TeV)
- important to include in the future to avoid fake signals
- **also crucial as $H \to W^+W^-$ background!**

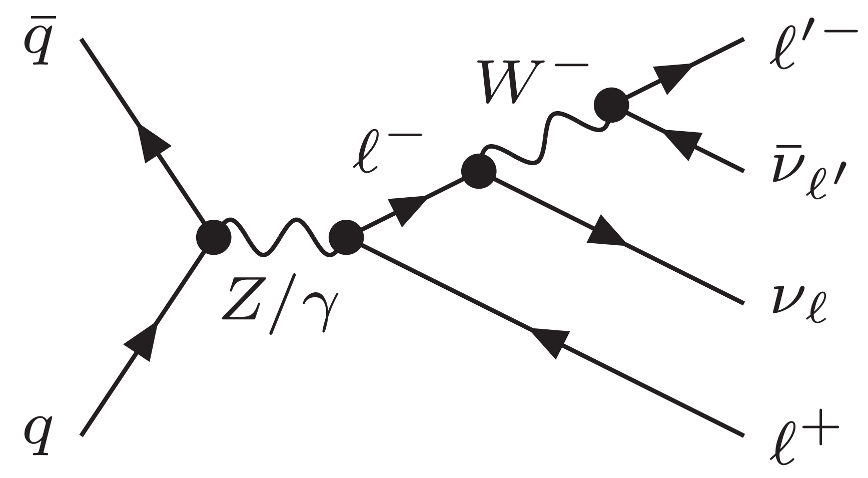
off-shell vector-boson pair production at NLO QCD+EW



Effect of EW corrections strongly depends on the observable.

MET

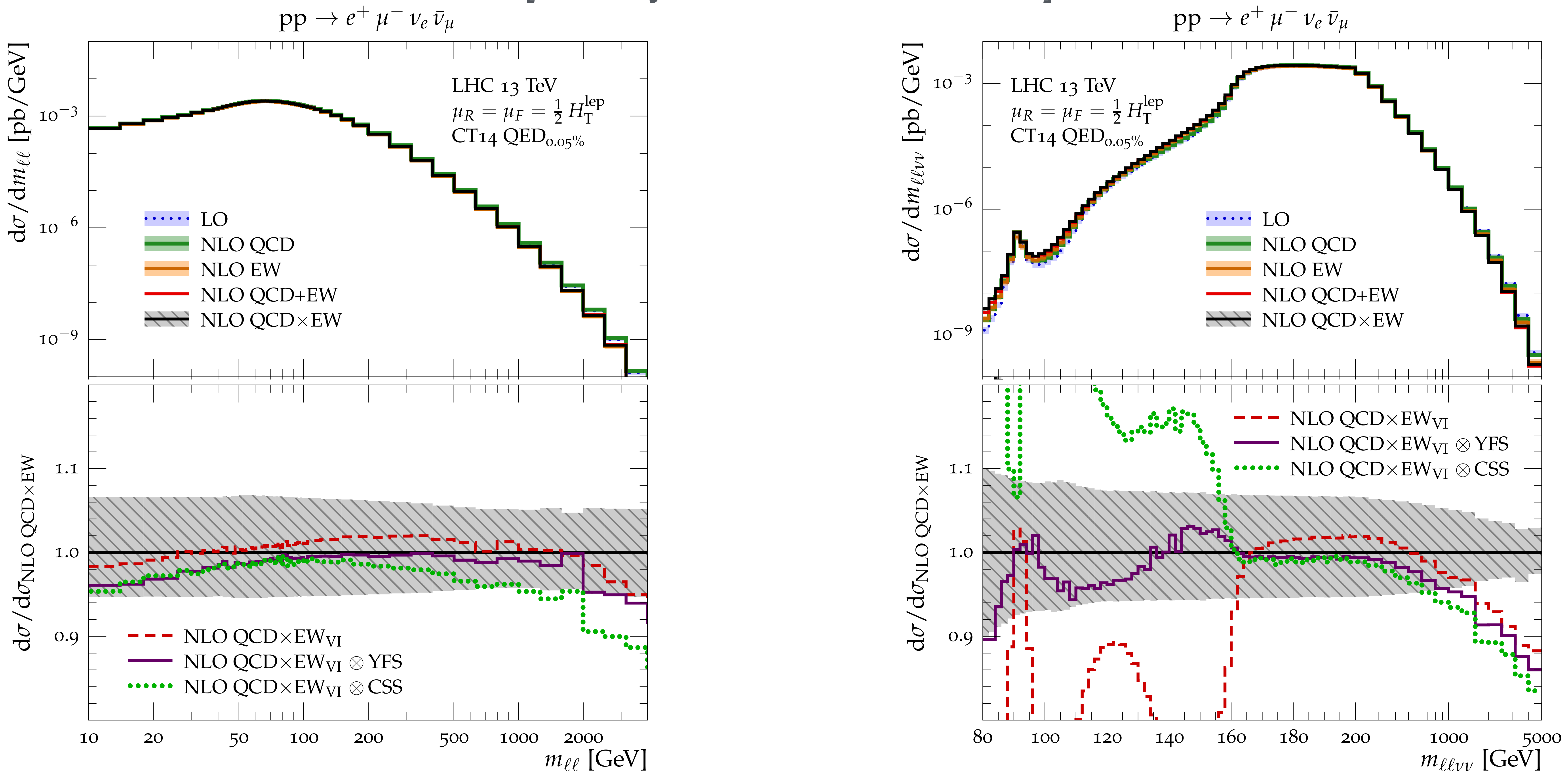
- at large MET>M_W: W's are forced off-shell



- 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]



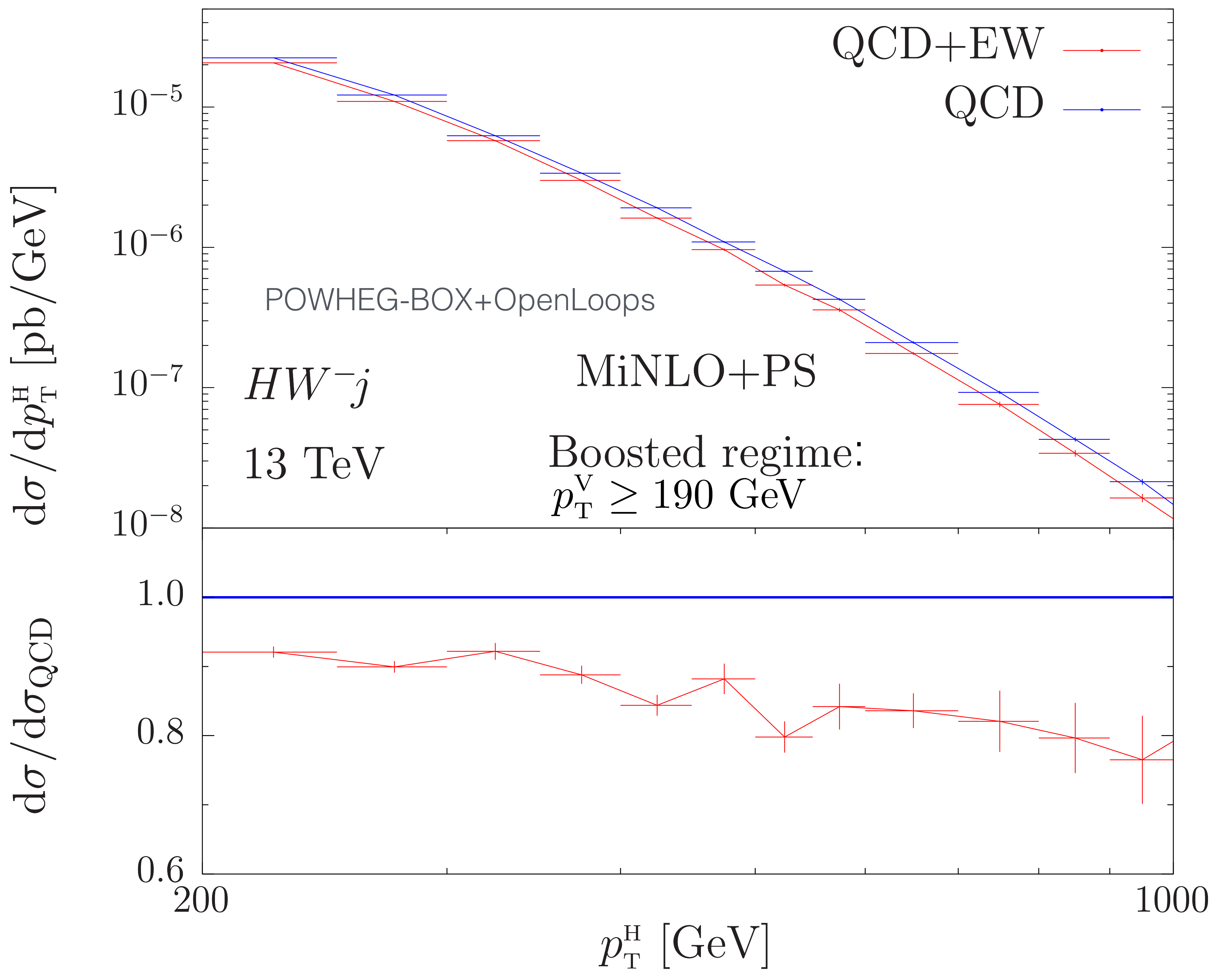
Naive NLO EW+PS matching in Sherpa+OpenLoops (applicable at particle level)

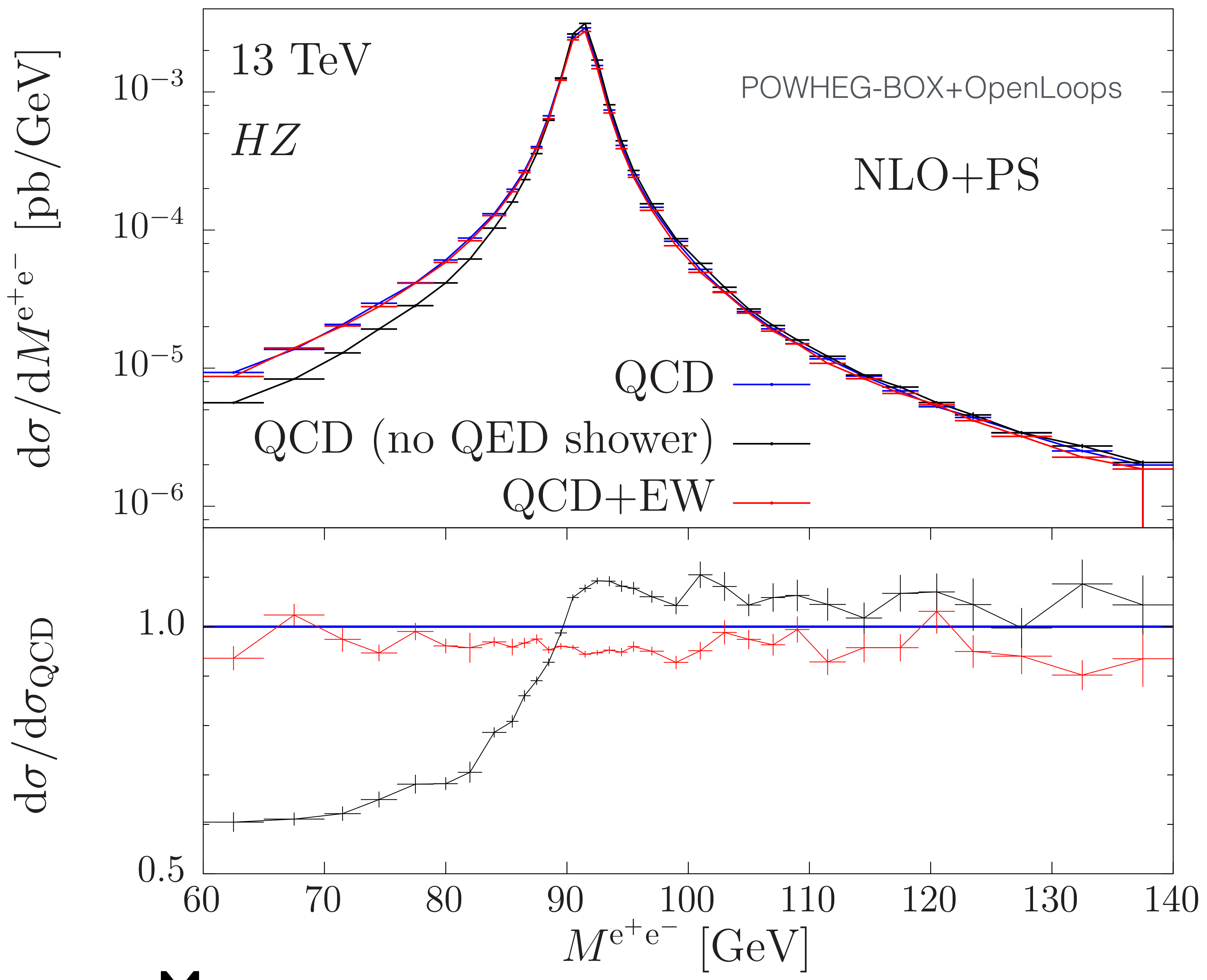
- CSS dipole shower (not resonaonce aware) ⇒ significant mismodelling
- YFS resummation (resonaonce aware) ⇒ valid approximation

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

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

Motivation:
- HV in boosted regime allows to constrain H→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**

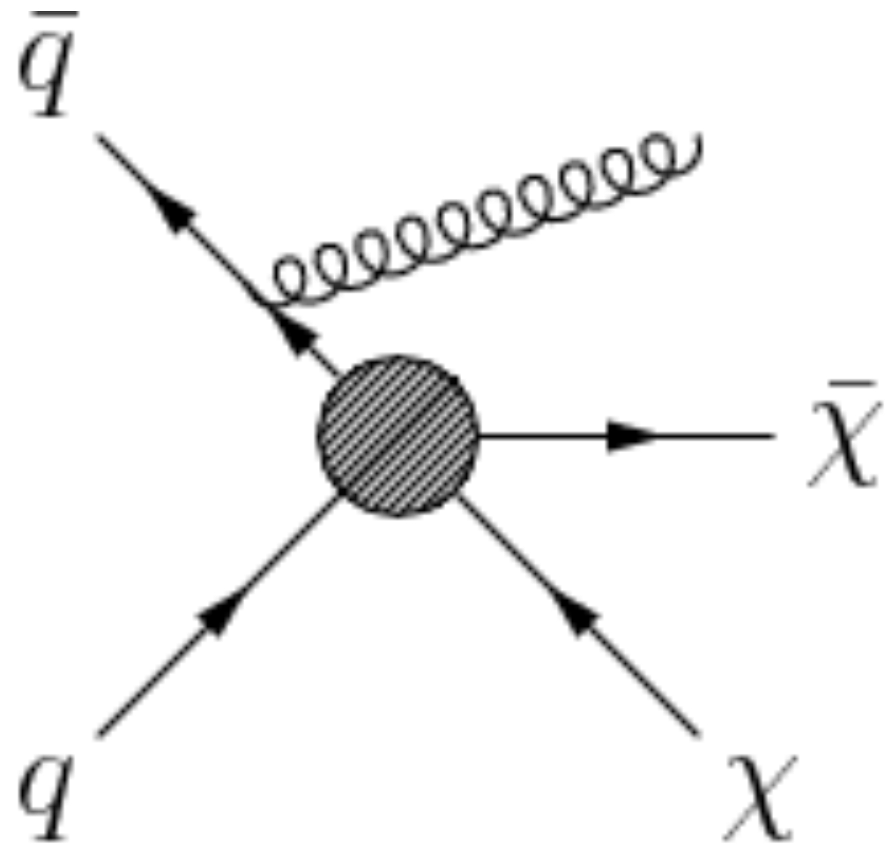
A few examples where theory precision is crucial:

ttH

EW SUSY searches

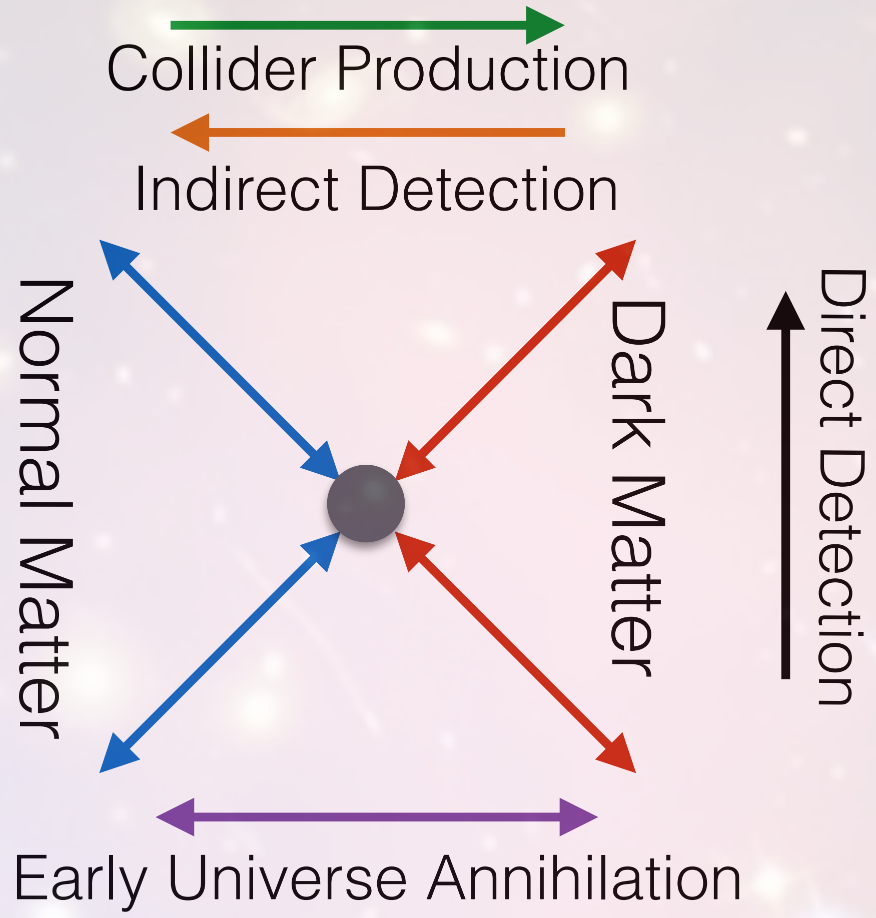
Higgs-pT

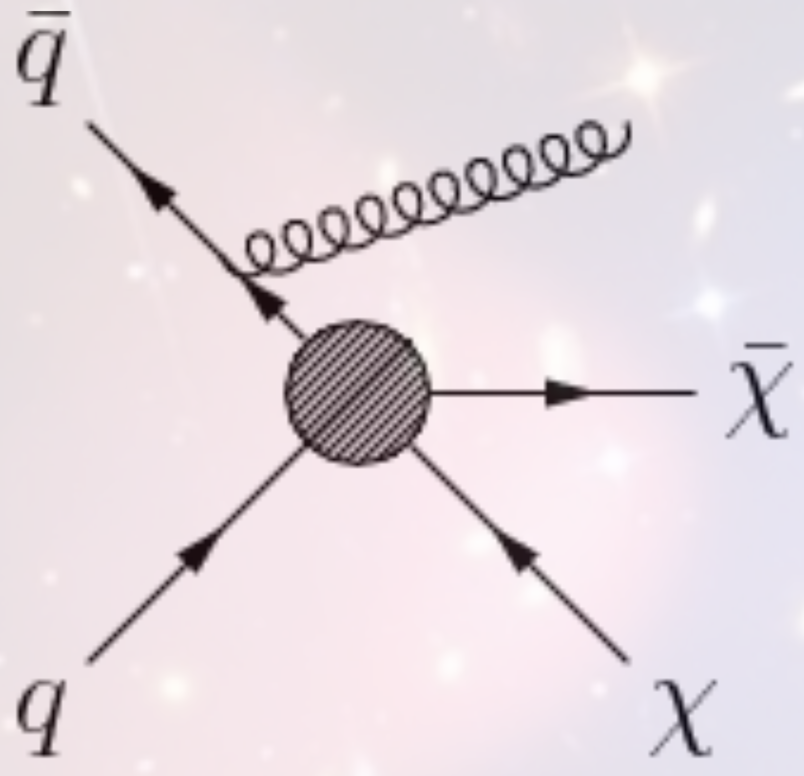
Dark Matter searches



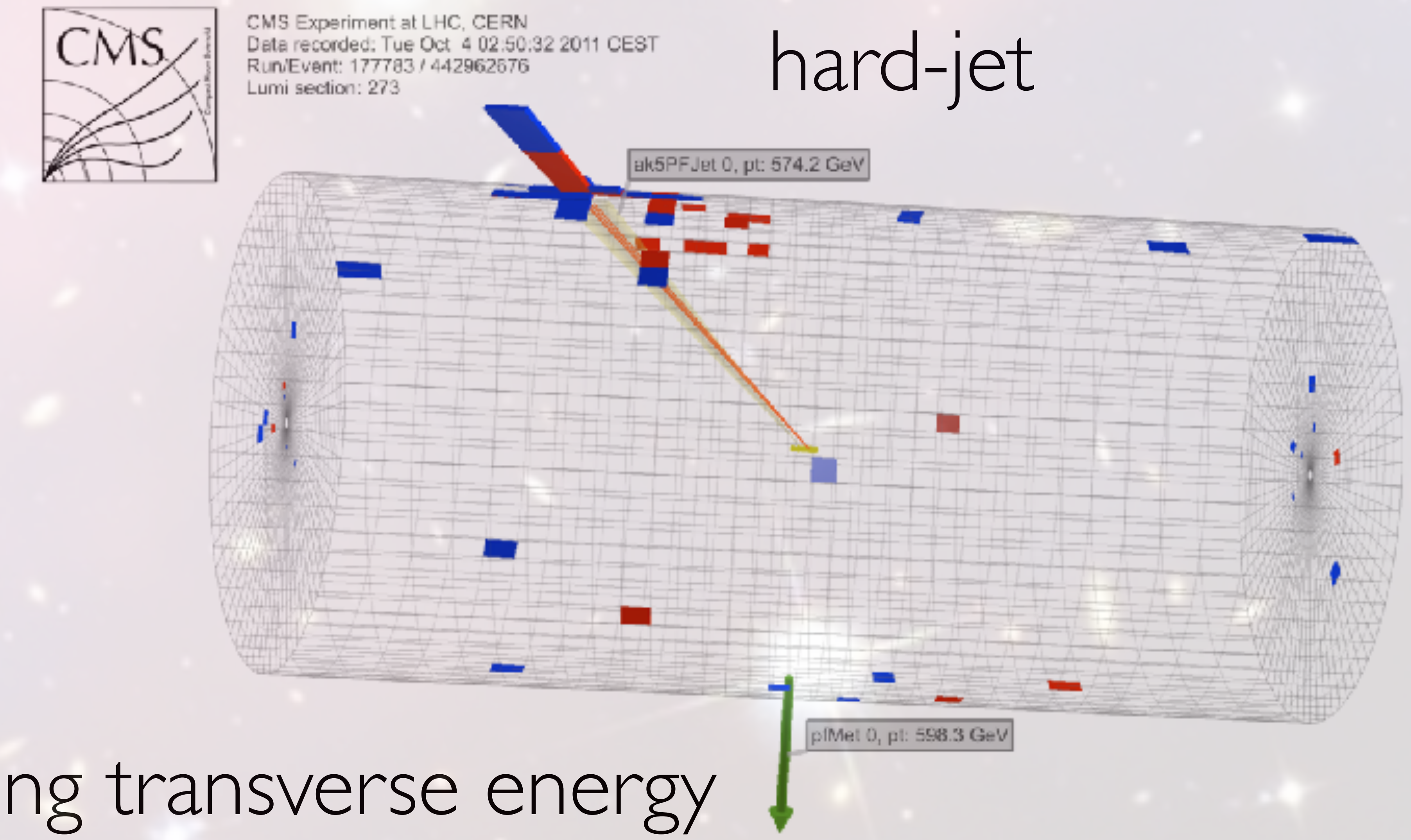
Canonical Dark Matter signature at the LHC: monojets / MET+jets

we hope to see:





experimental signal:



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

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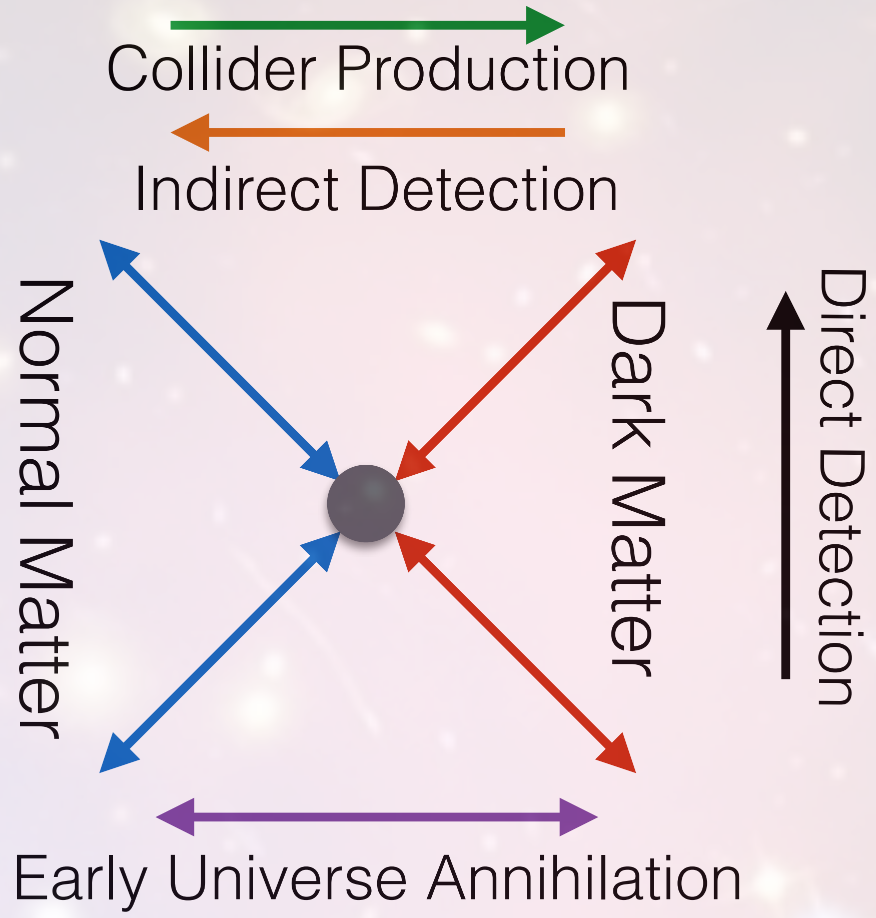
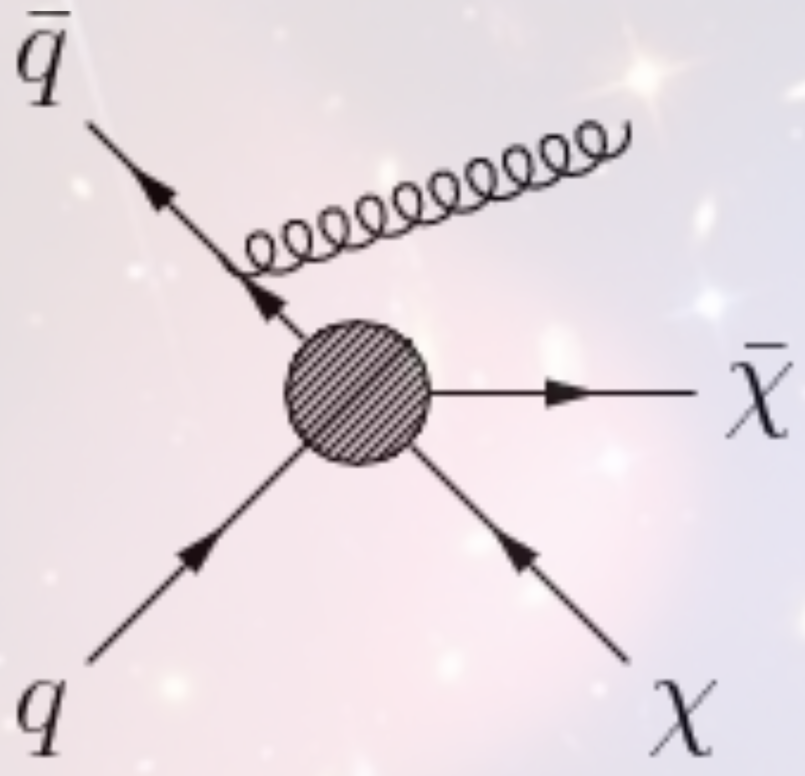
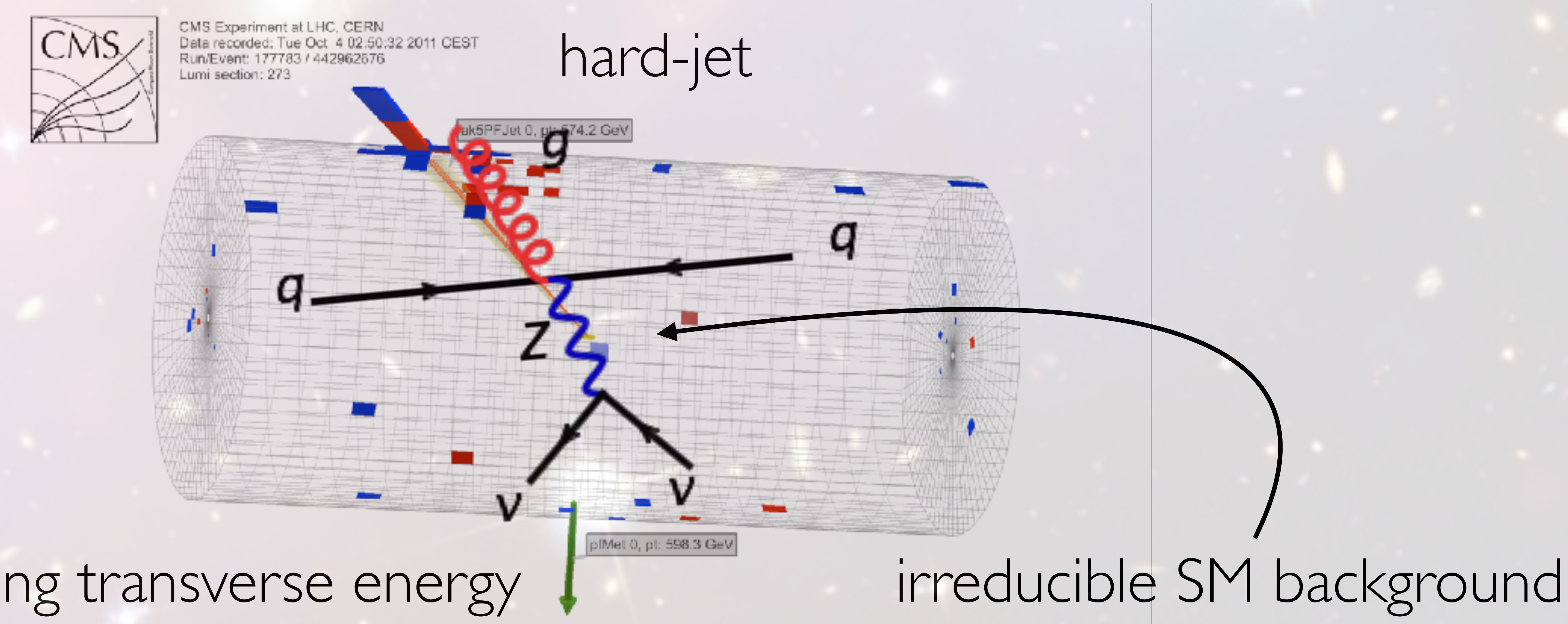


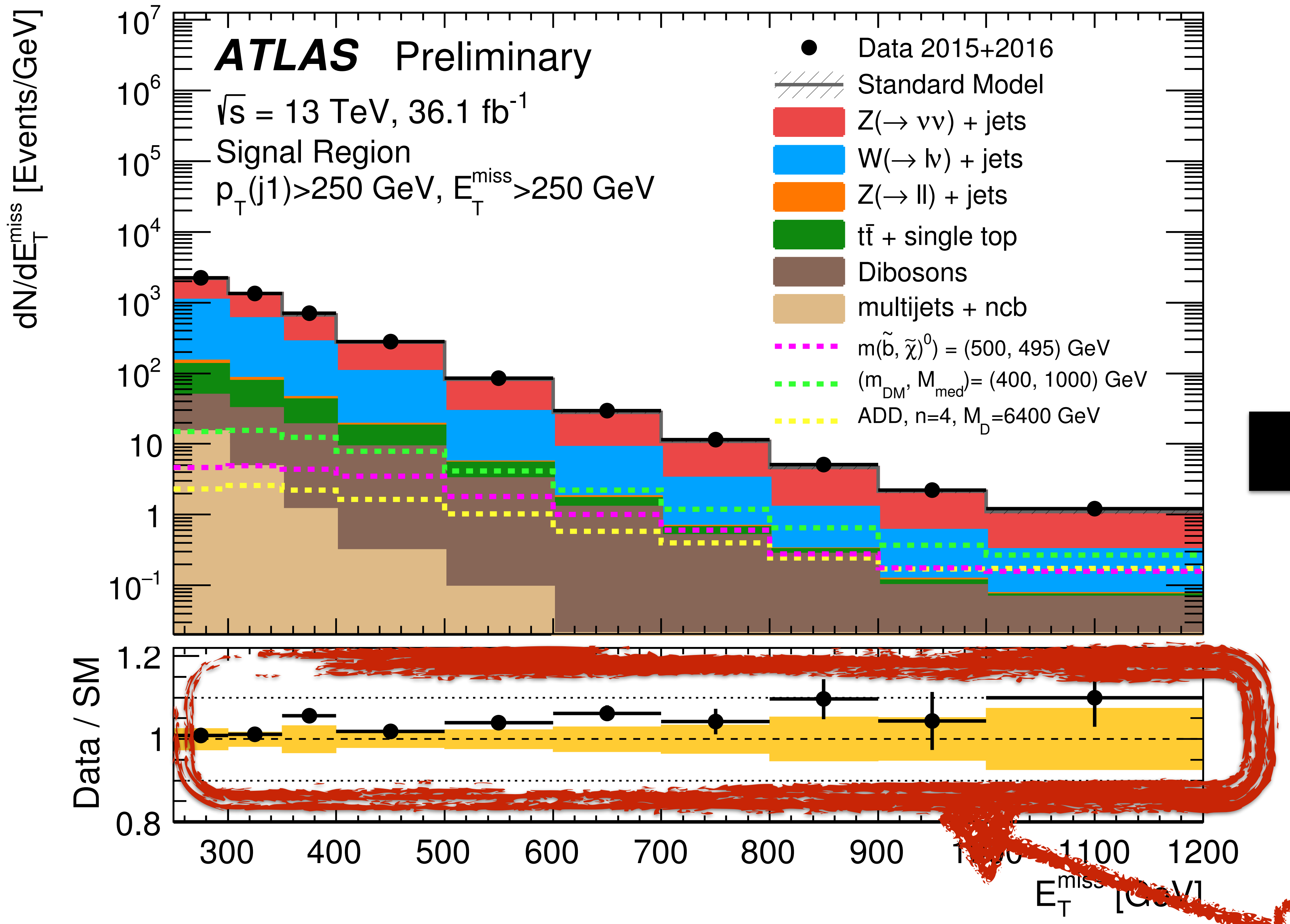


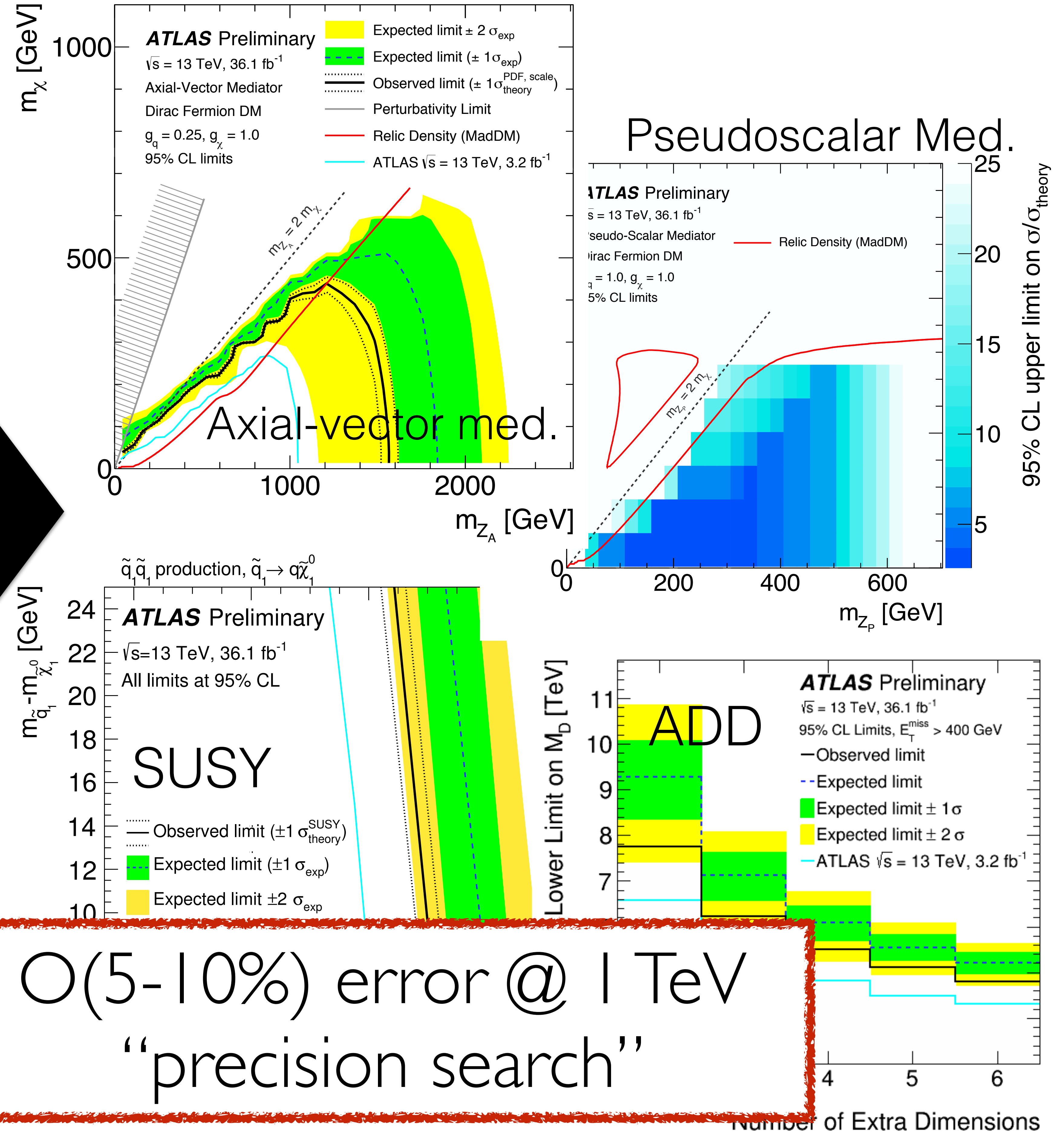
experimental signal:



SM backgrounds in monojet / MET+X searches

[ATLAS-CONF-2017-060]





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

irreducible SM backgrounds:

pp→Z(→νν̄)+jets ⟹ MET + jets

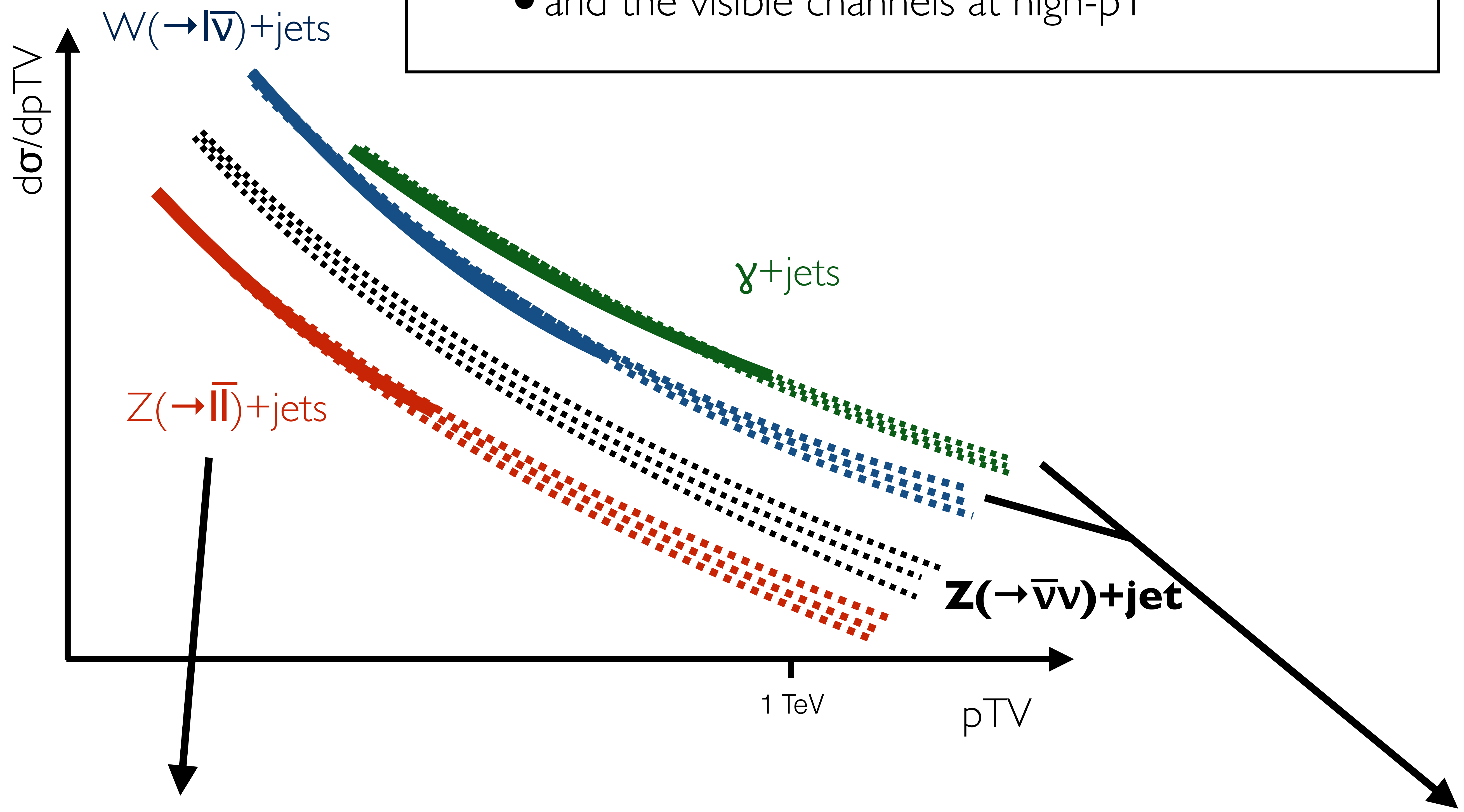
pp→W(→lν)+jets ⟹ MET + jets (lepton lost)

} V + jets

Determine V+jets DM backgrounds

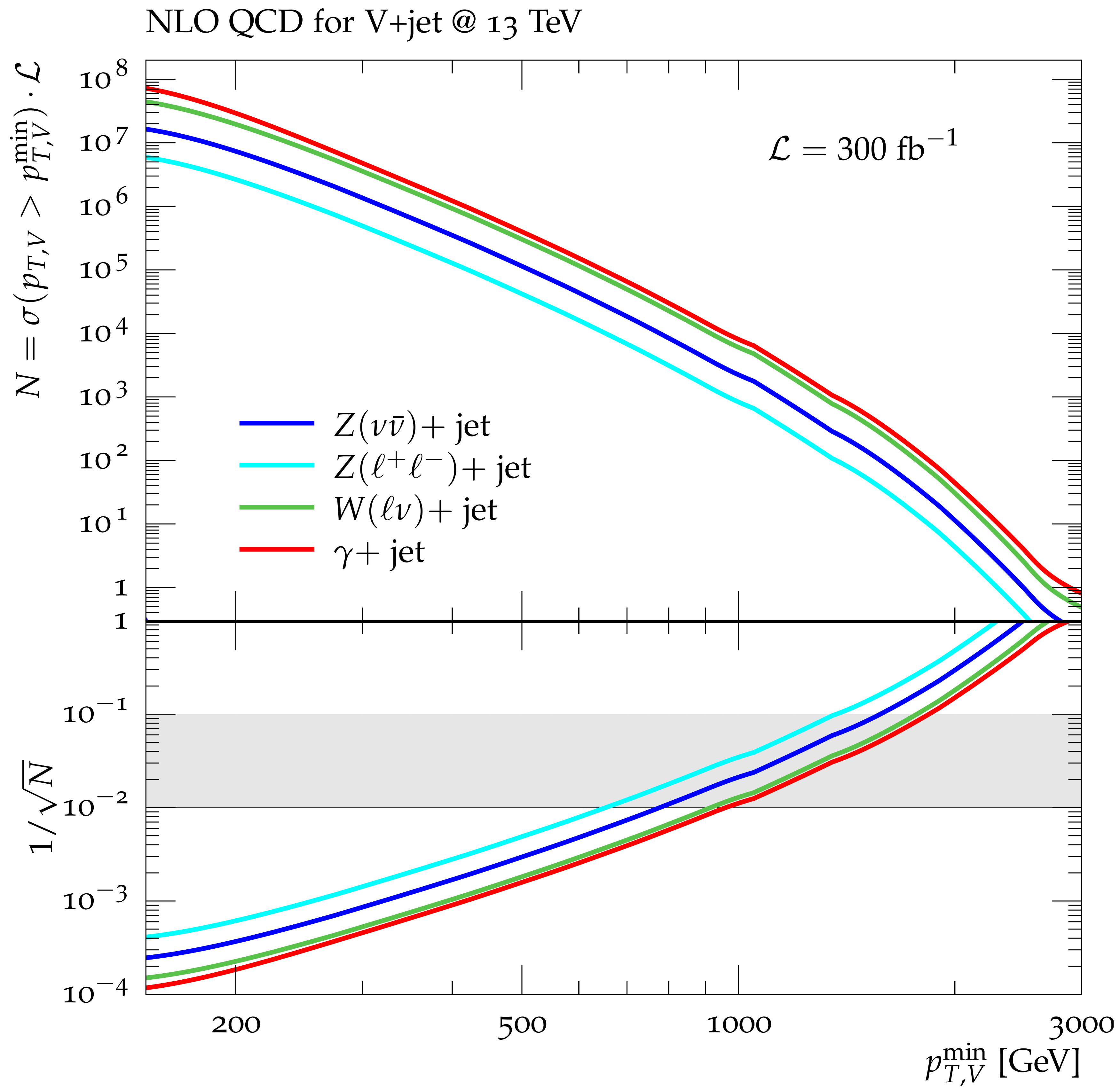
global fit of Z(→$l\bar{l}$)+jets, W(→$l\bar{\nu}$)+jets and γ+jets measurements

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



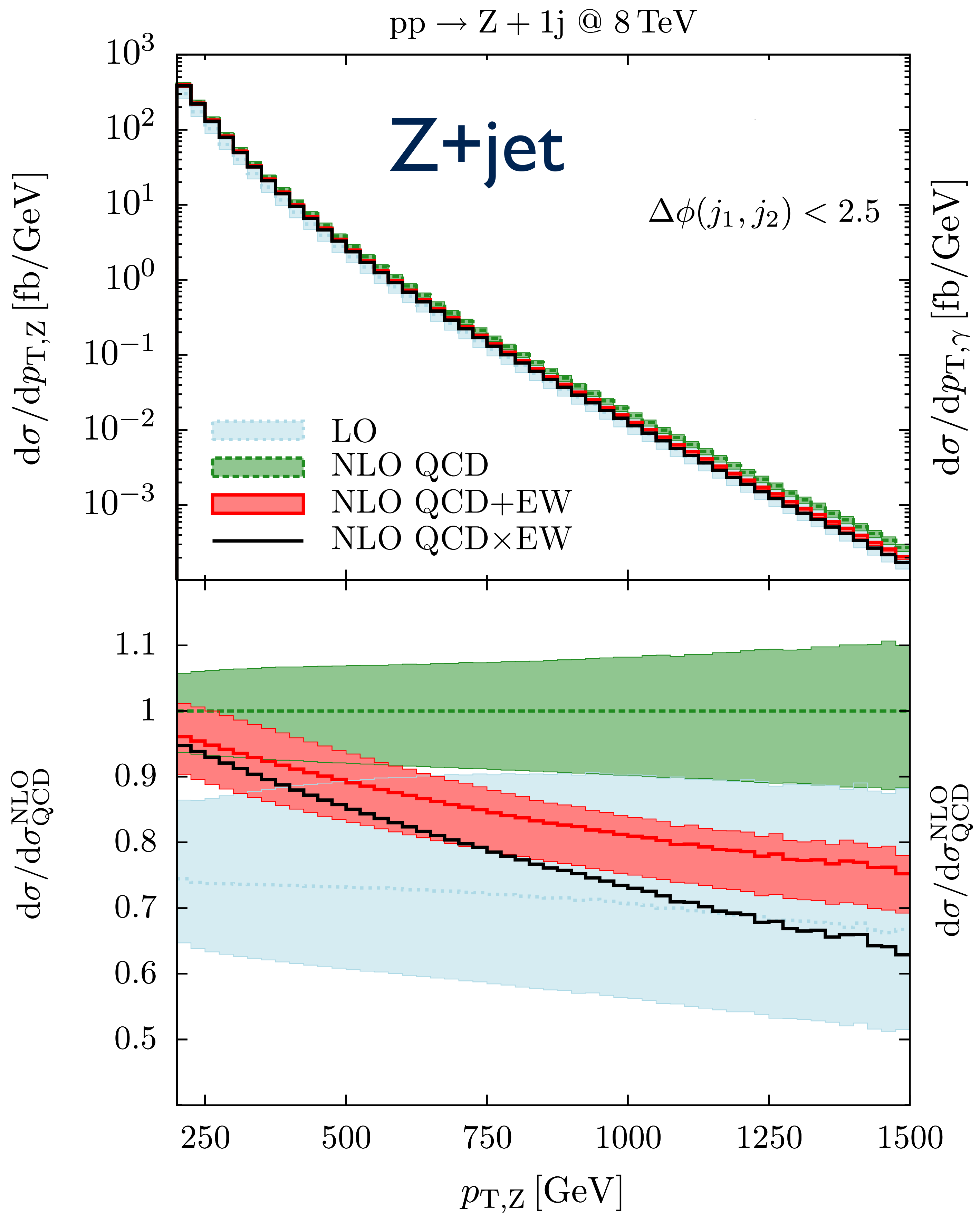
- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT

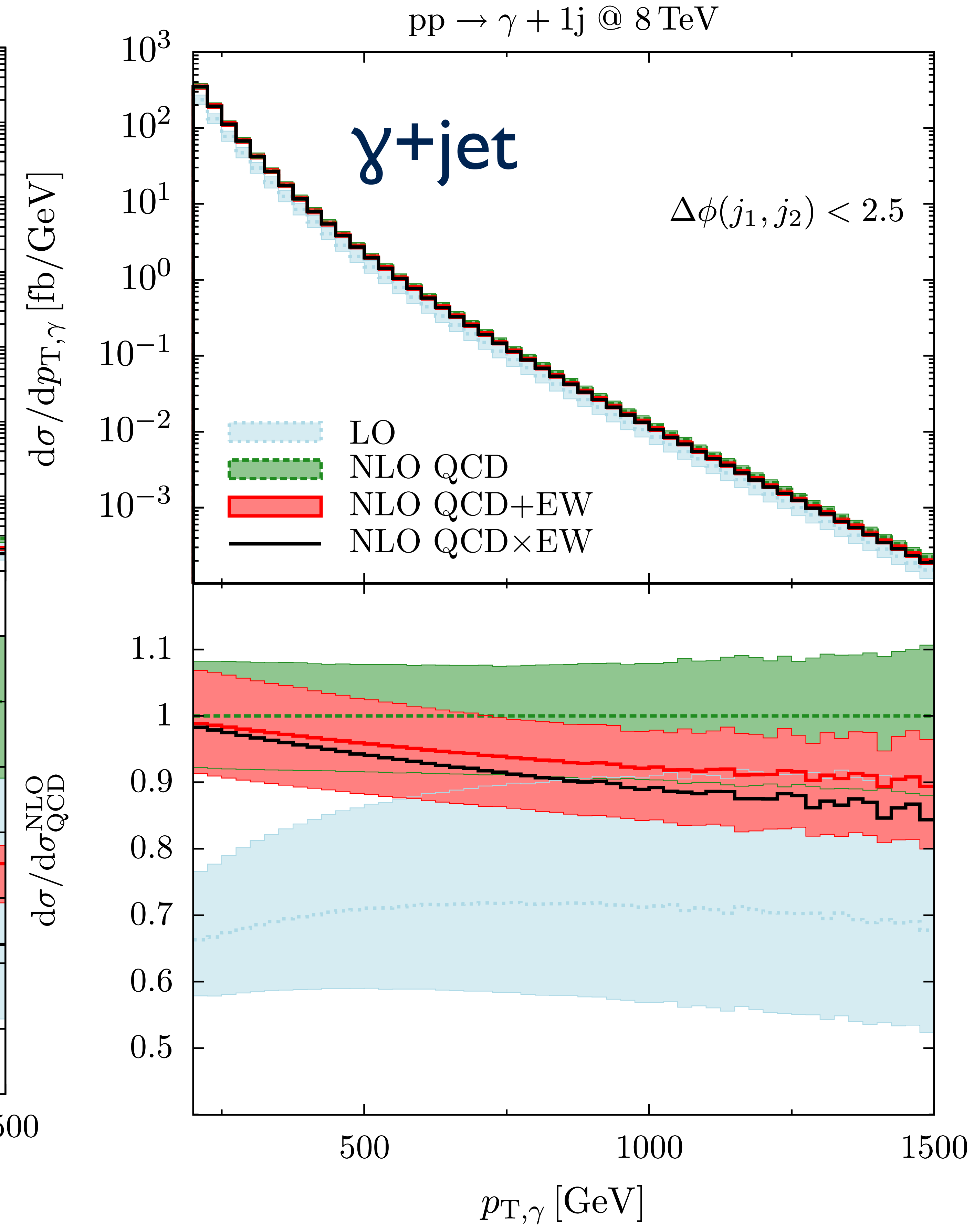
- fairly large data samples at large pT
- systematics from transfer factors



- for 500 GeV < pTV < 1000 GeV: background statistics will be at **1% level**
- this level of precision is theoretically possible @ NNLO QCD + NNLO EW

Prelude: Z+jet vs. γ + 1 jet





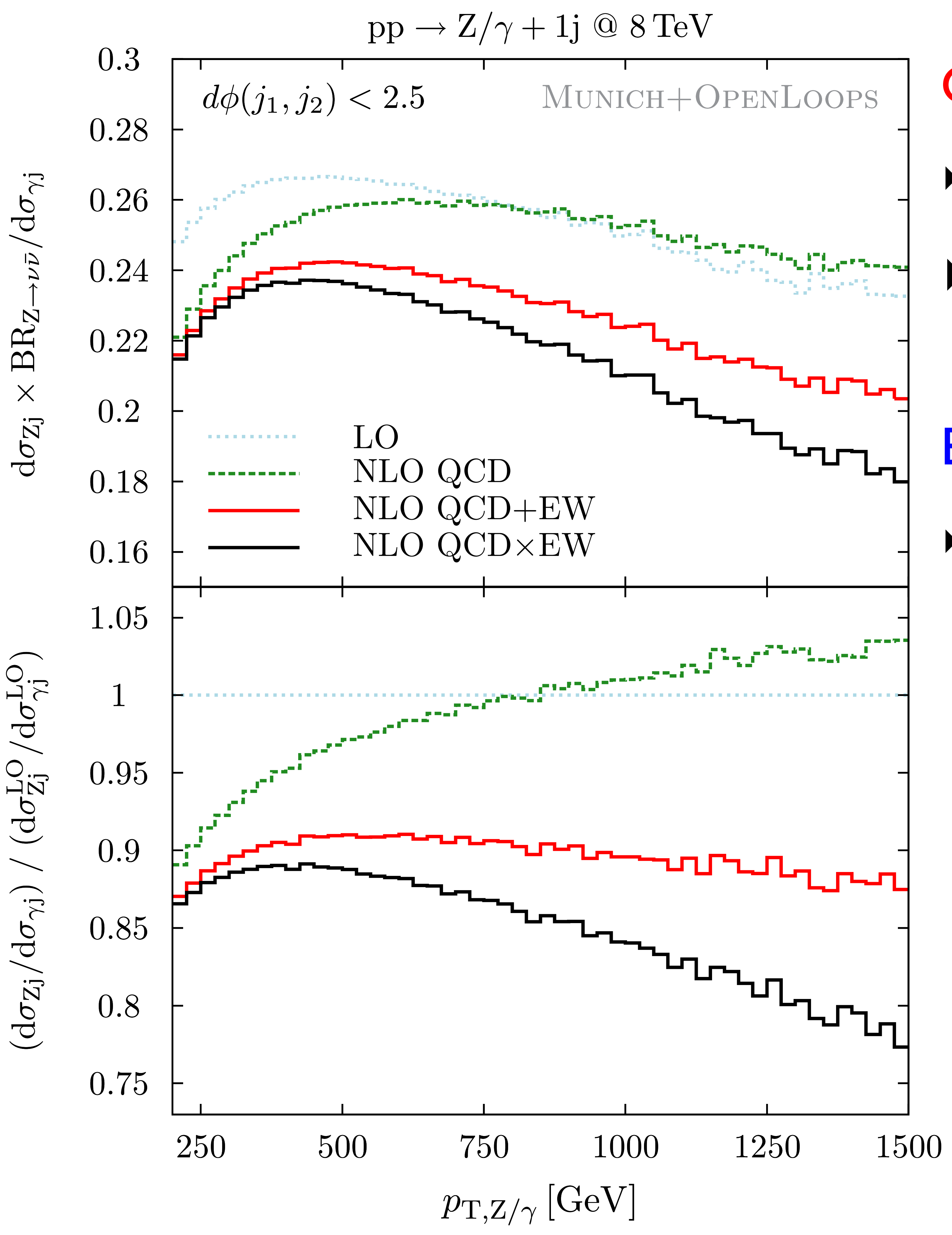
QCD corrections

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

EW corrections

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

Prelude: Z/γ pT-ratio



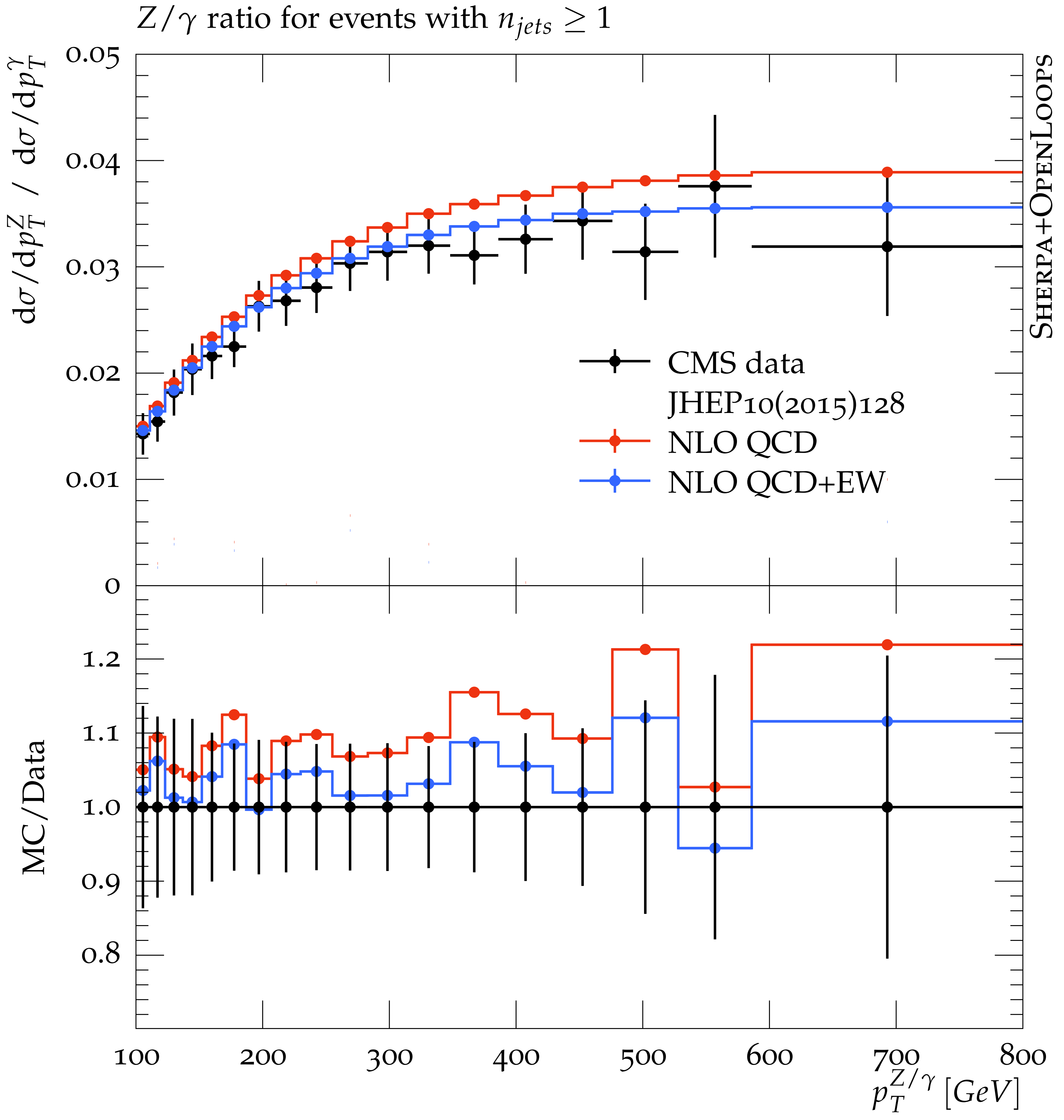
QCD corrections

- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

EW corrections

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

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



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

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

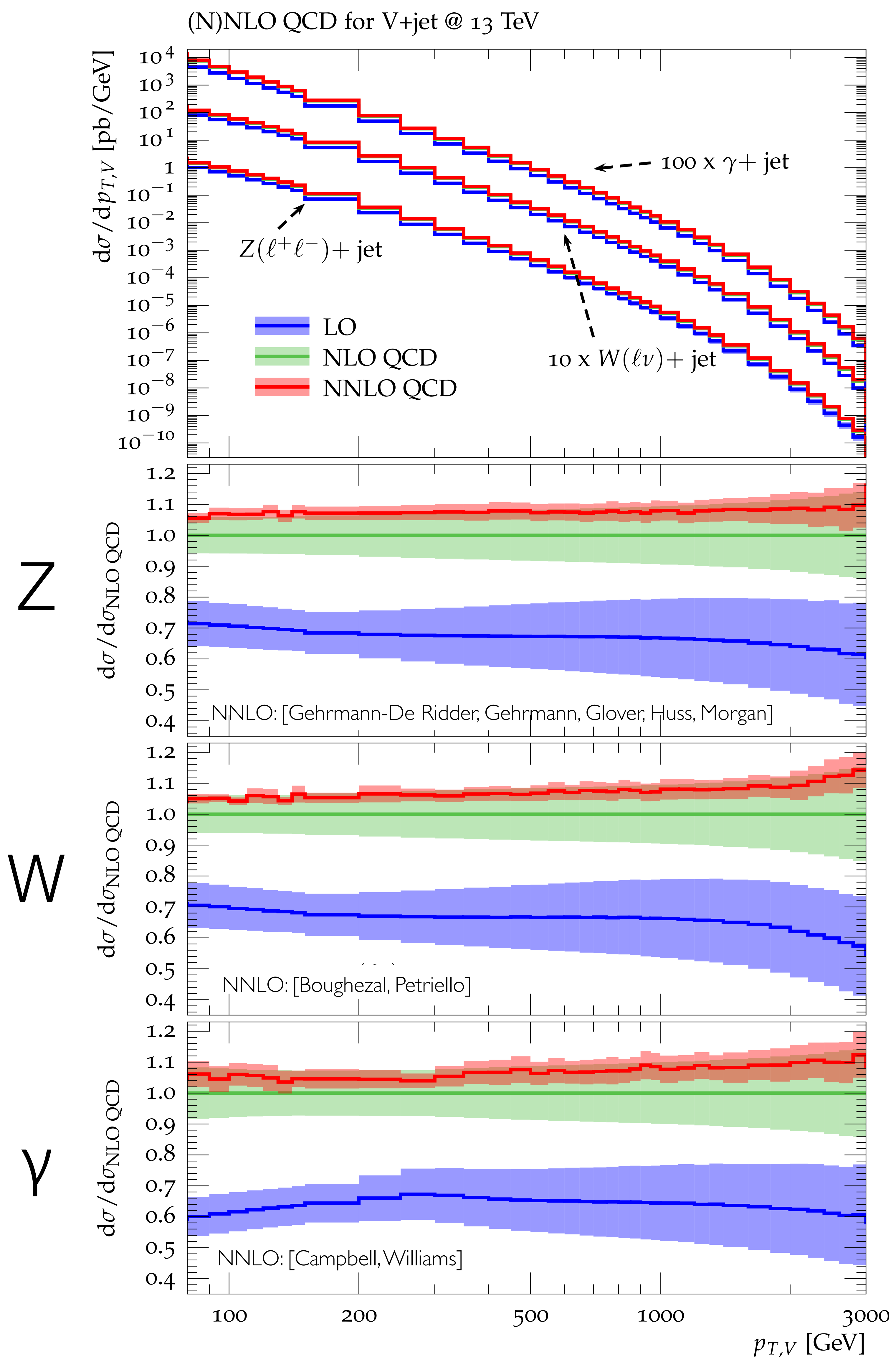
how to correlate scale uncertainties in ratios?

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]



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

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

this is a ‘good’ scale for V+jets

- at large pTV: HT’/2 ≈ pTV
- modest higher-order corrections
- sufficient convergence

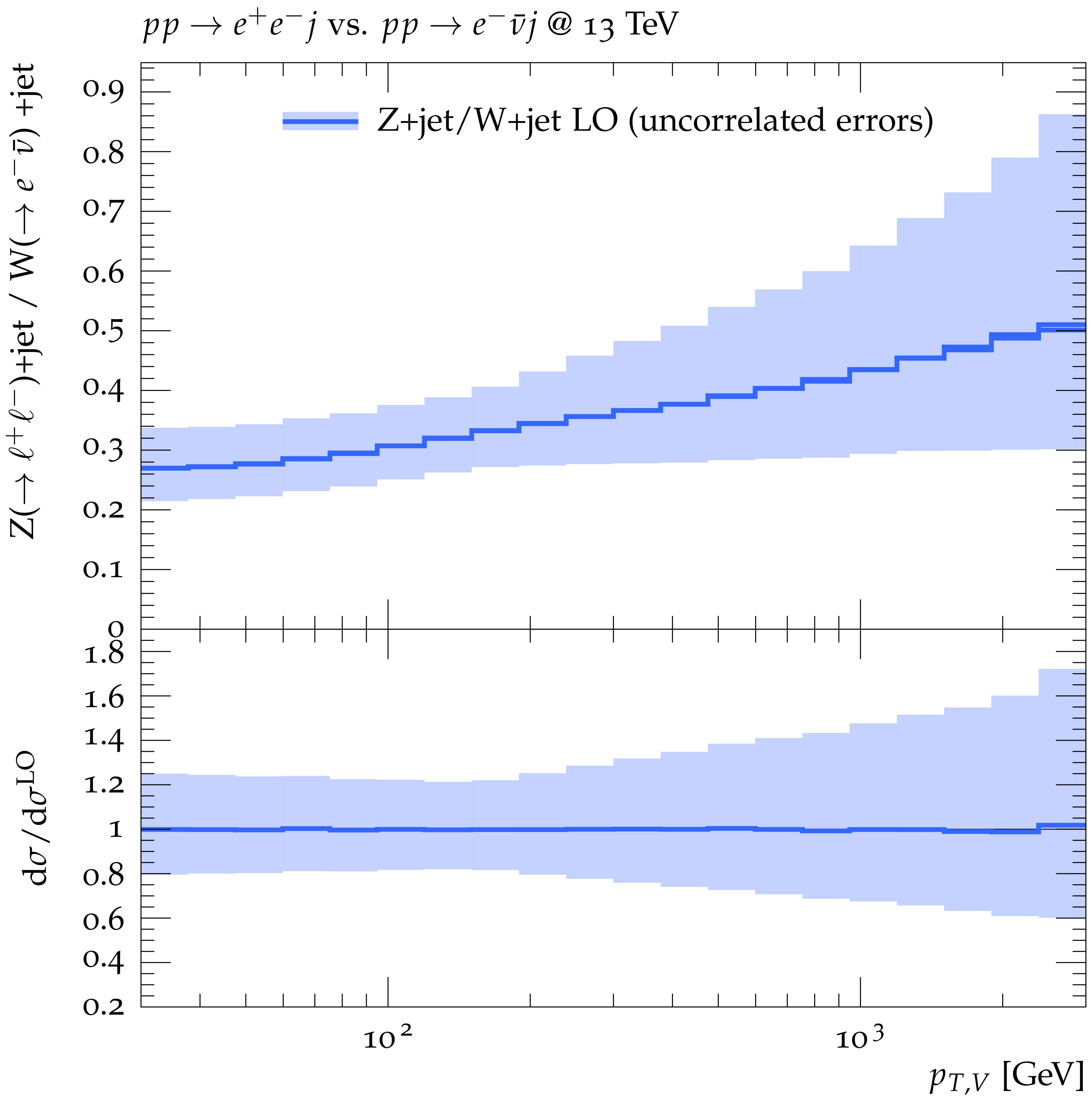
scale uncertainties due to 7-pt variations:

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

with minor shape variations

How to correlate these uncertainties across processes?

How to correlate QCD uncertainties across processes?

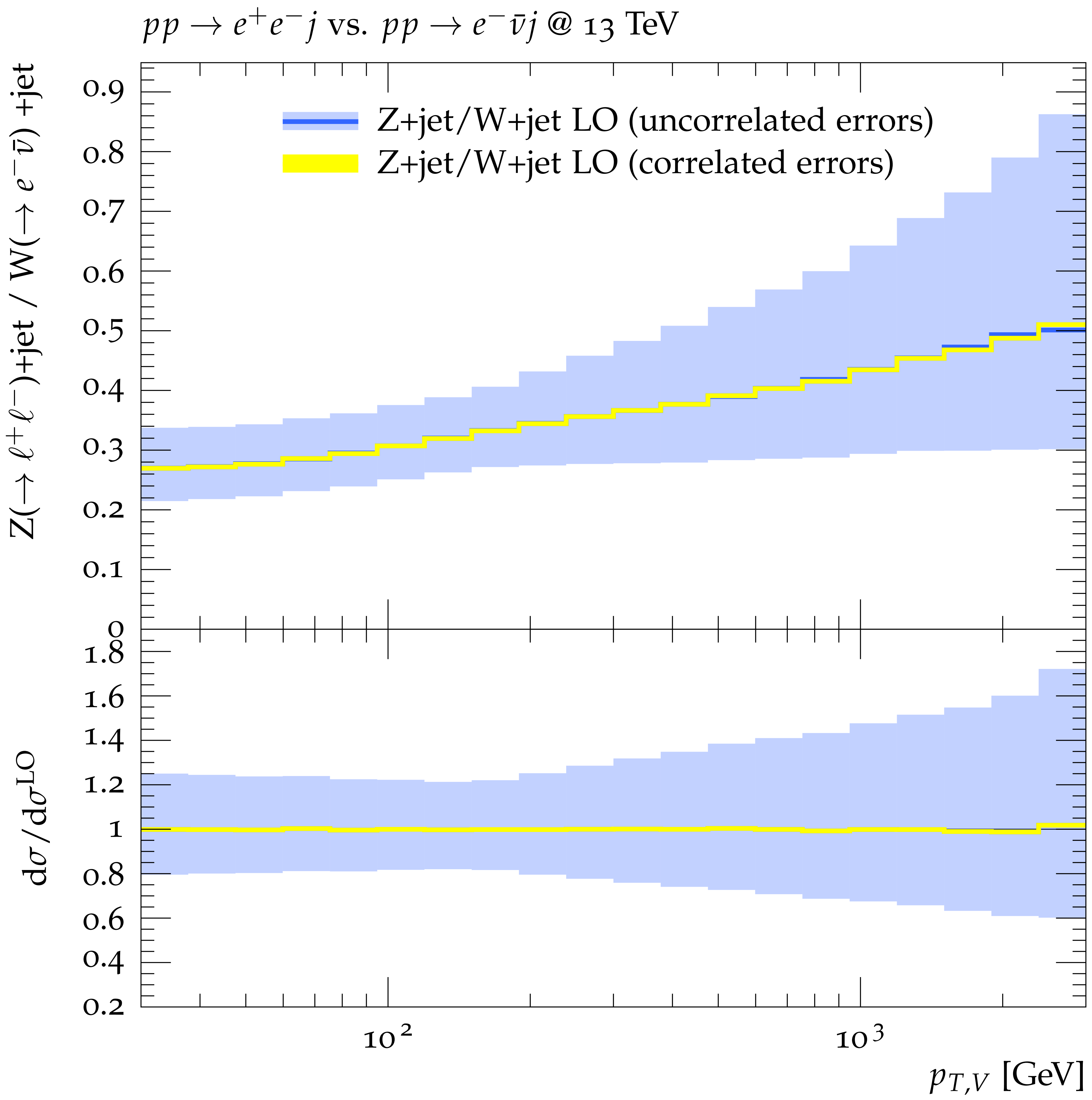


consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

How to correlate QCD uncertainties across processes?

[1705.04664]



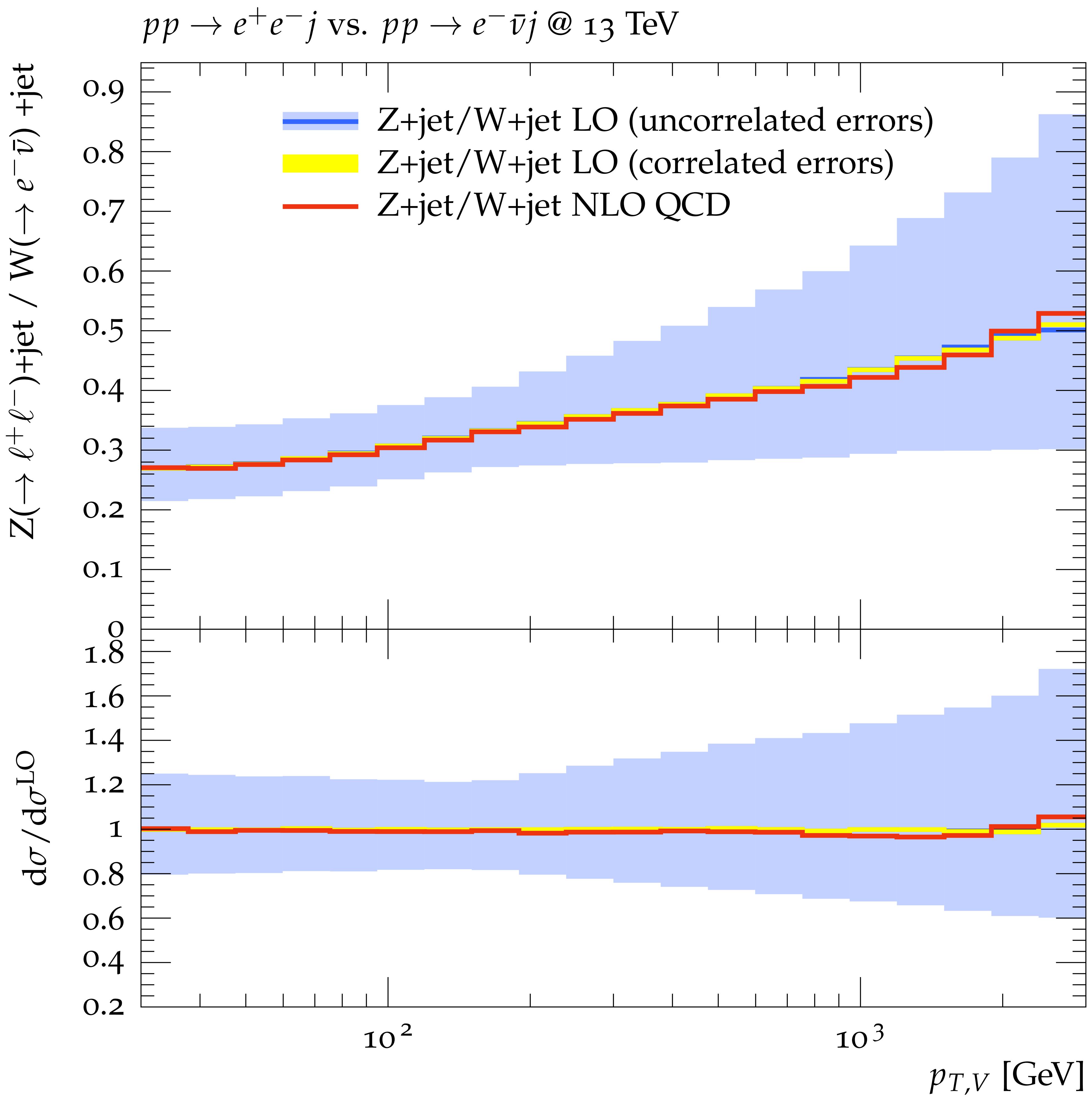
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

correlated treatment yields tiny O(<~ 1%) uncertainties

How to correlate QCD uncertainties across processes?

[1705.04664]



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

uncorrelated treatment yields O(40%) uncertainties

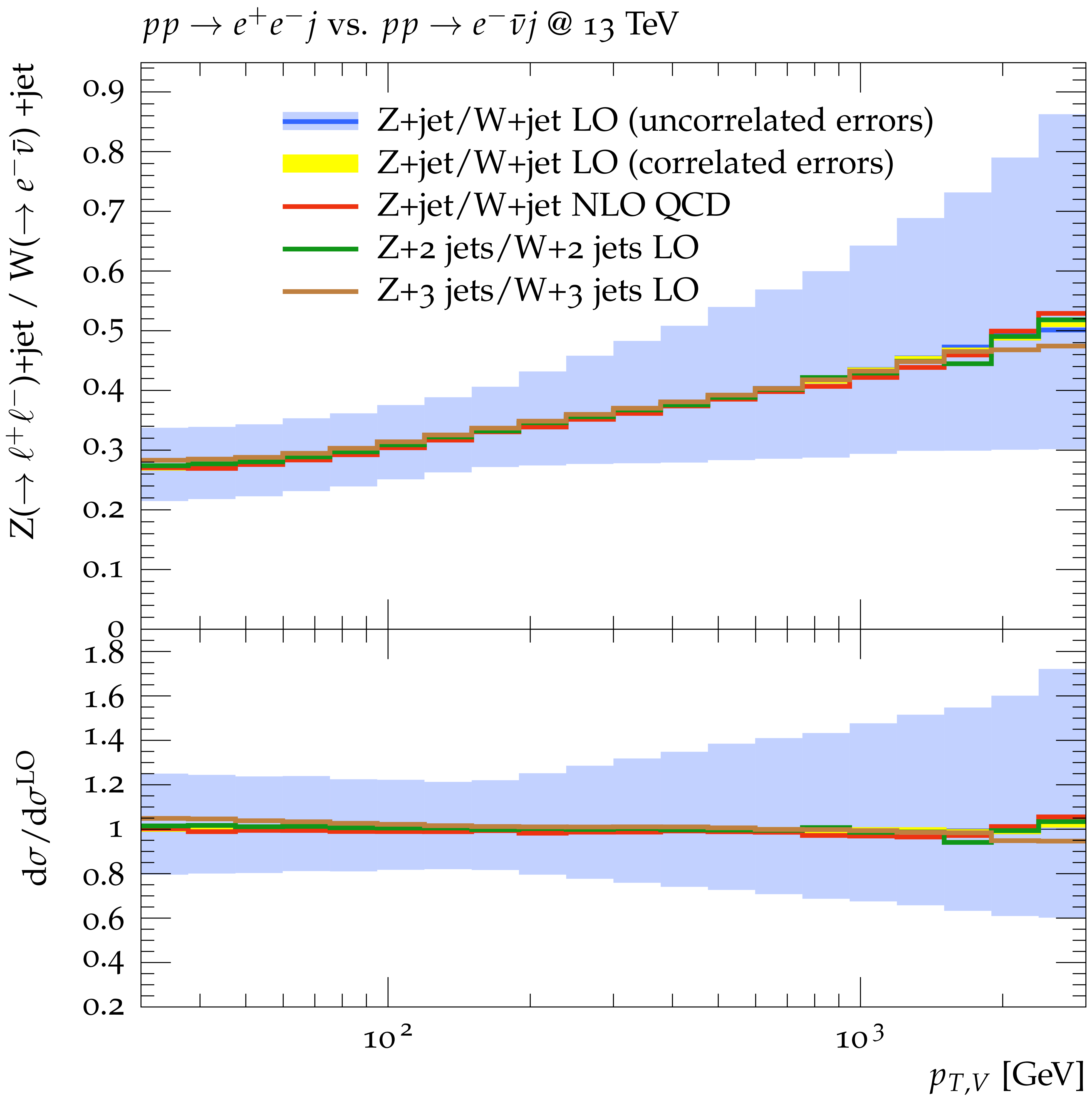
correlated treatment yields tiny O(<~ 1%) uncertainties

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 O(40%) uncertainties

correlated treatment yields tiny O(<~ 1%) uncertainties

check against NLO QCD!

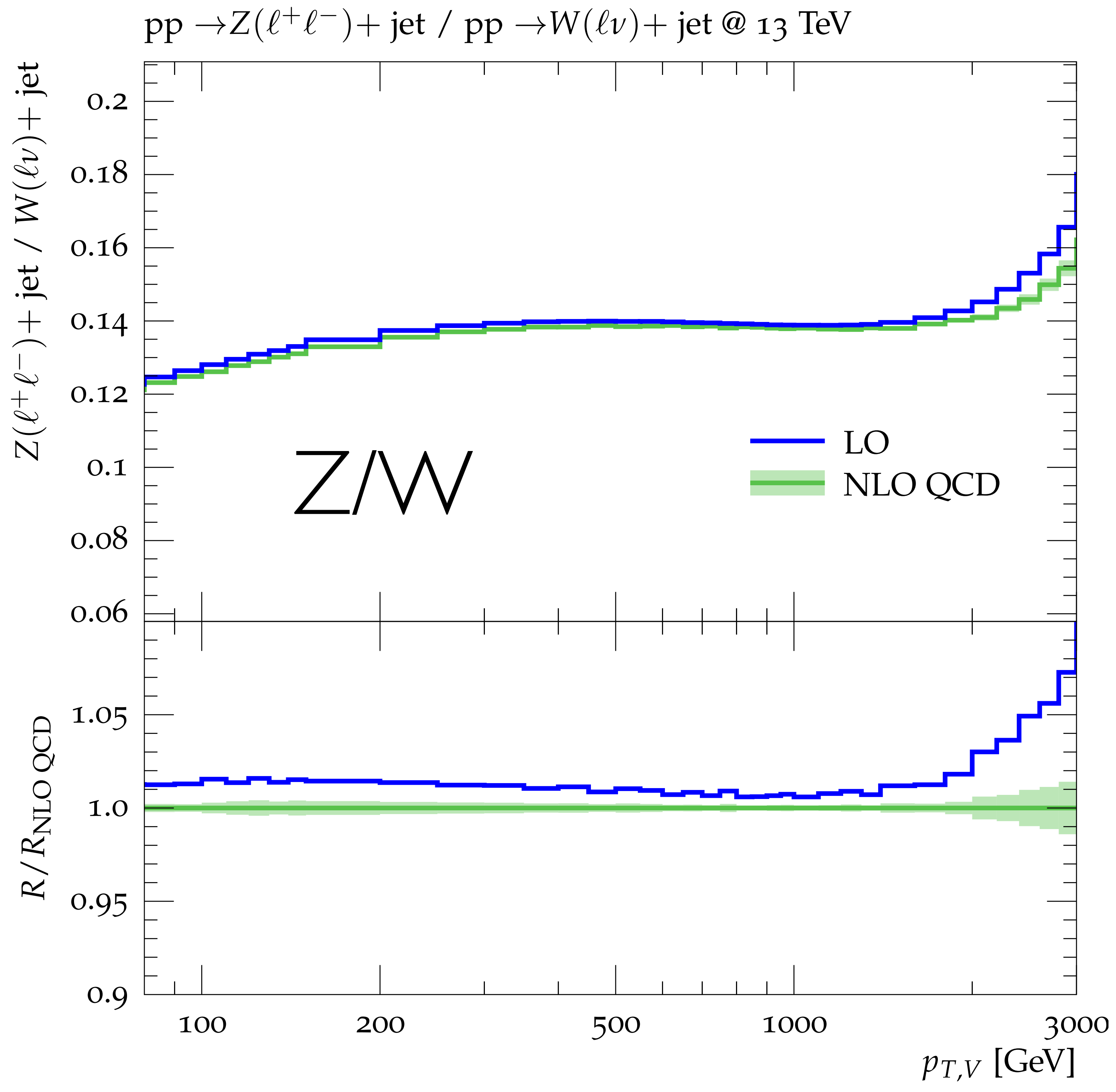
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

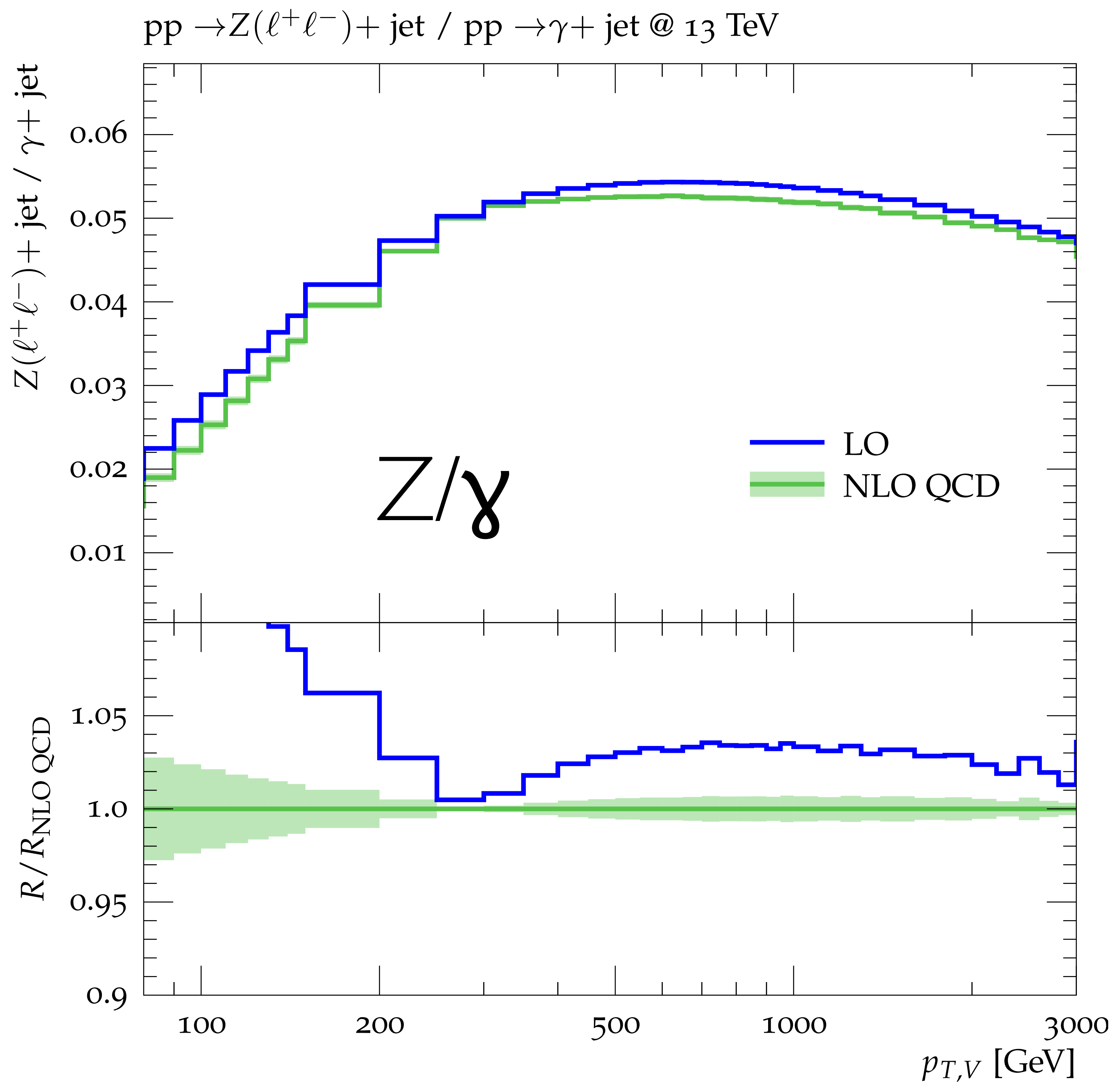
Also holds for higher jet-multiplicities
→ indication of correlation also in higher-order corrections beyond NLO!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level

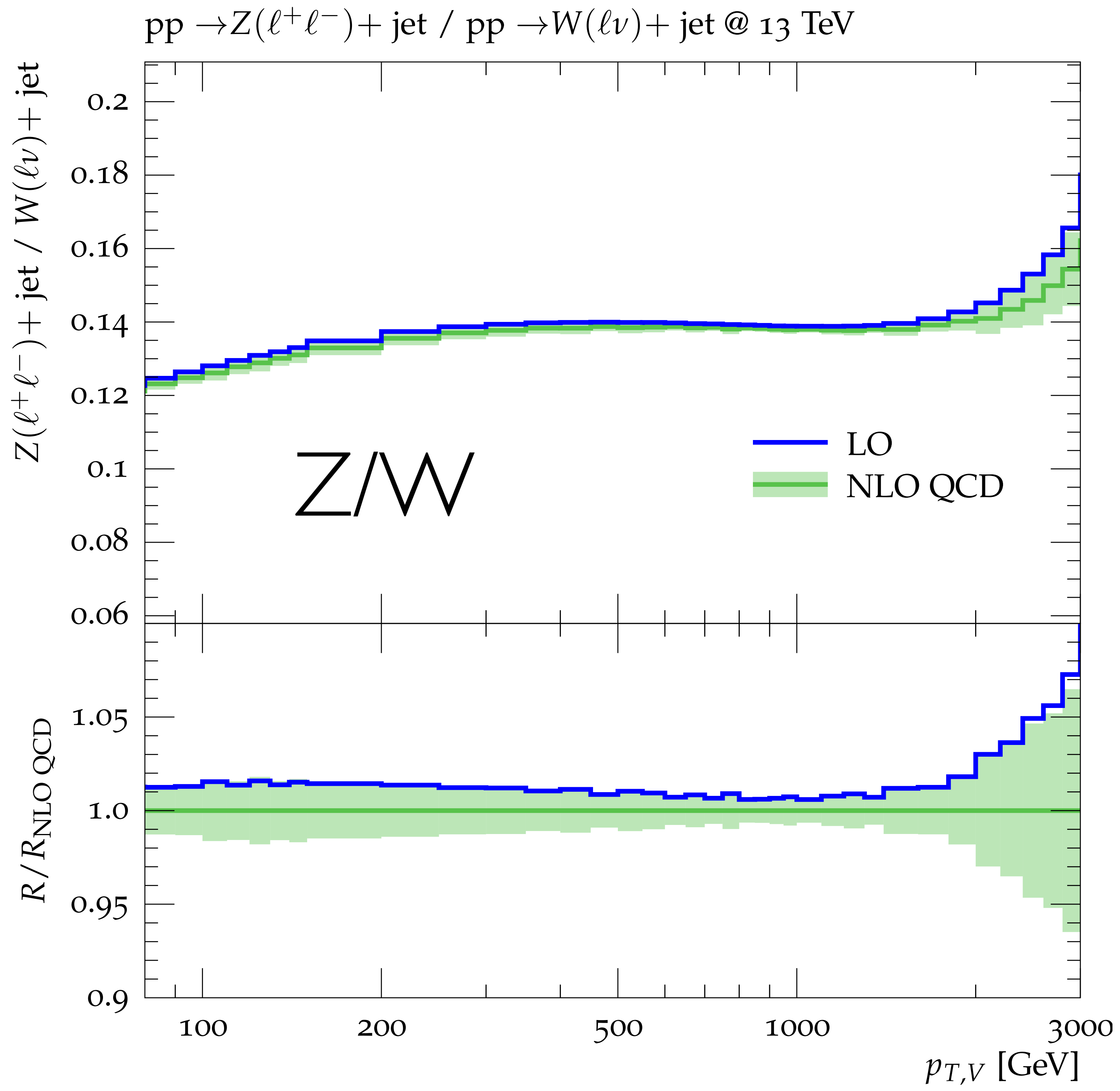




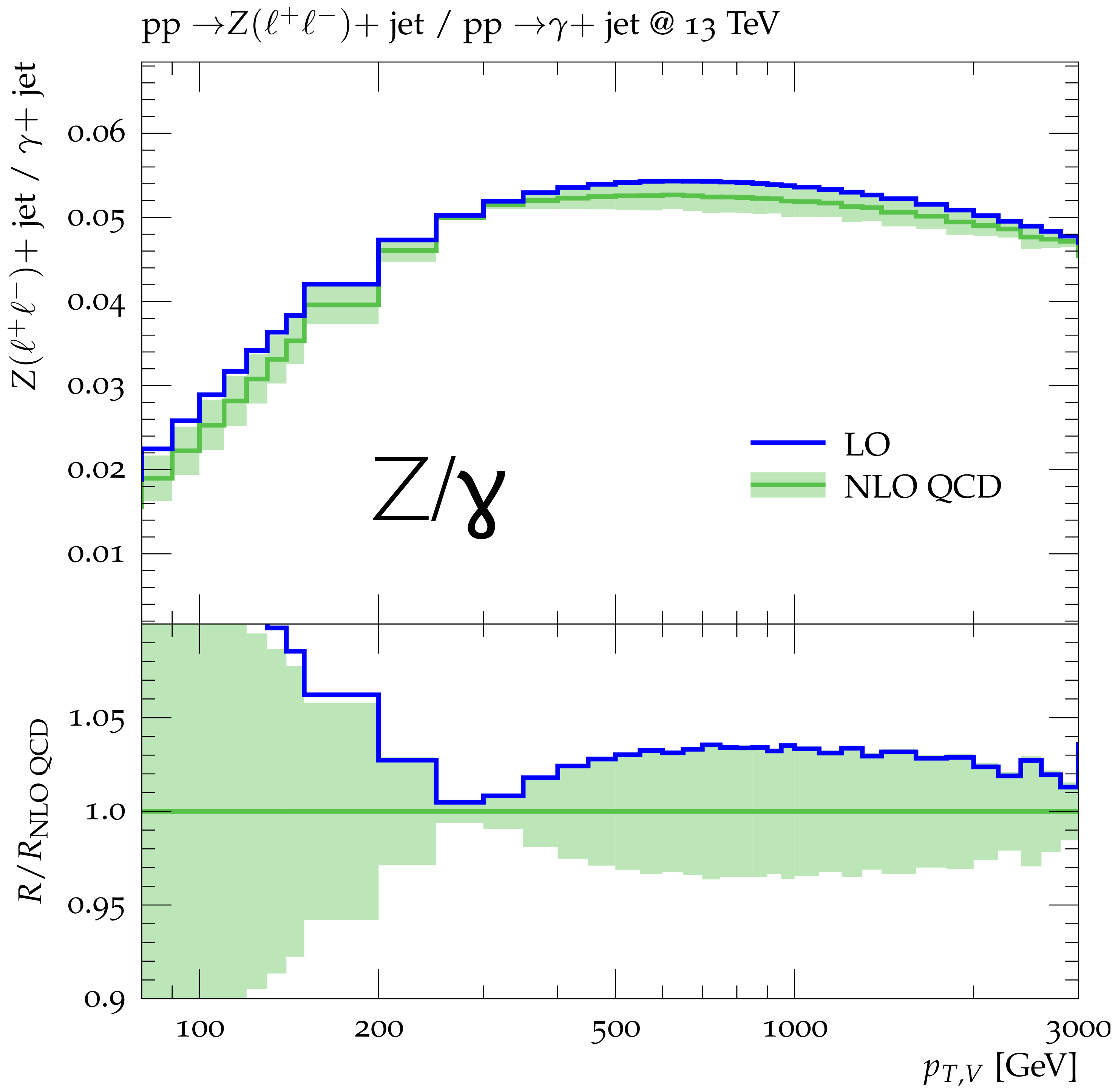
QCD uncertainties: ratios

How to correlate these uncertainties across processes?

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



δ < 2 %

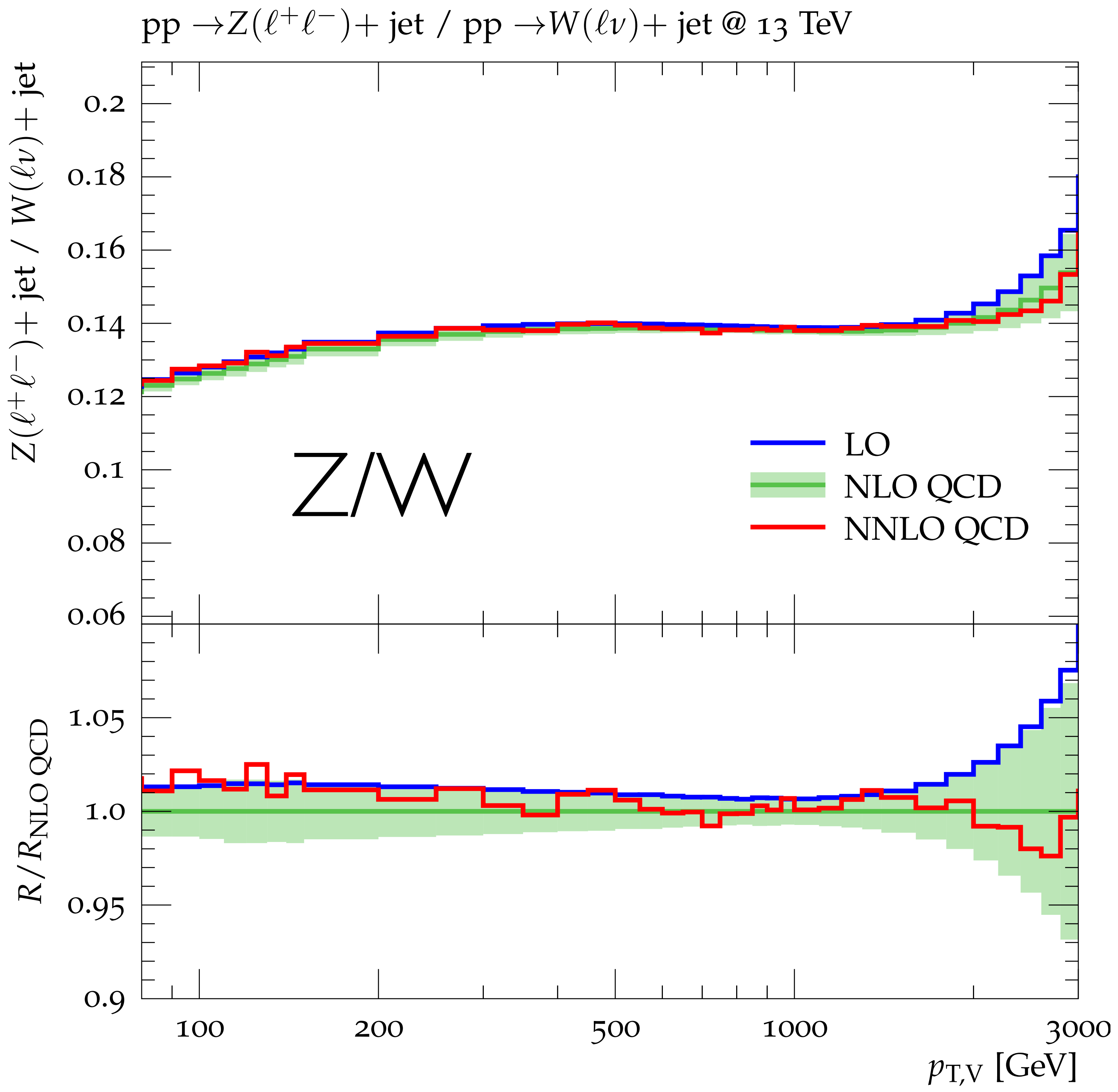


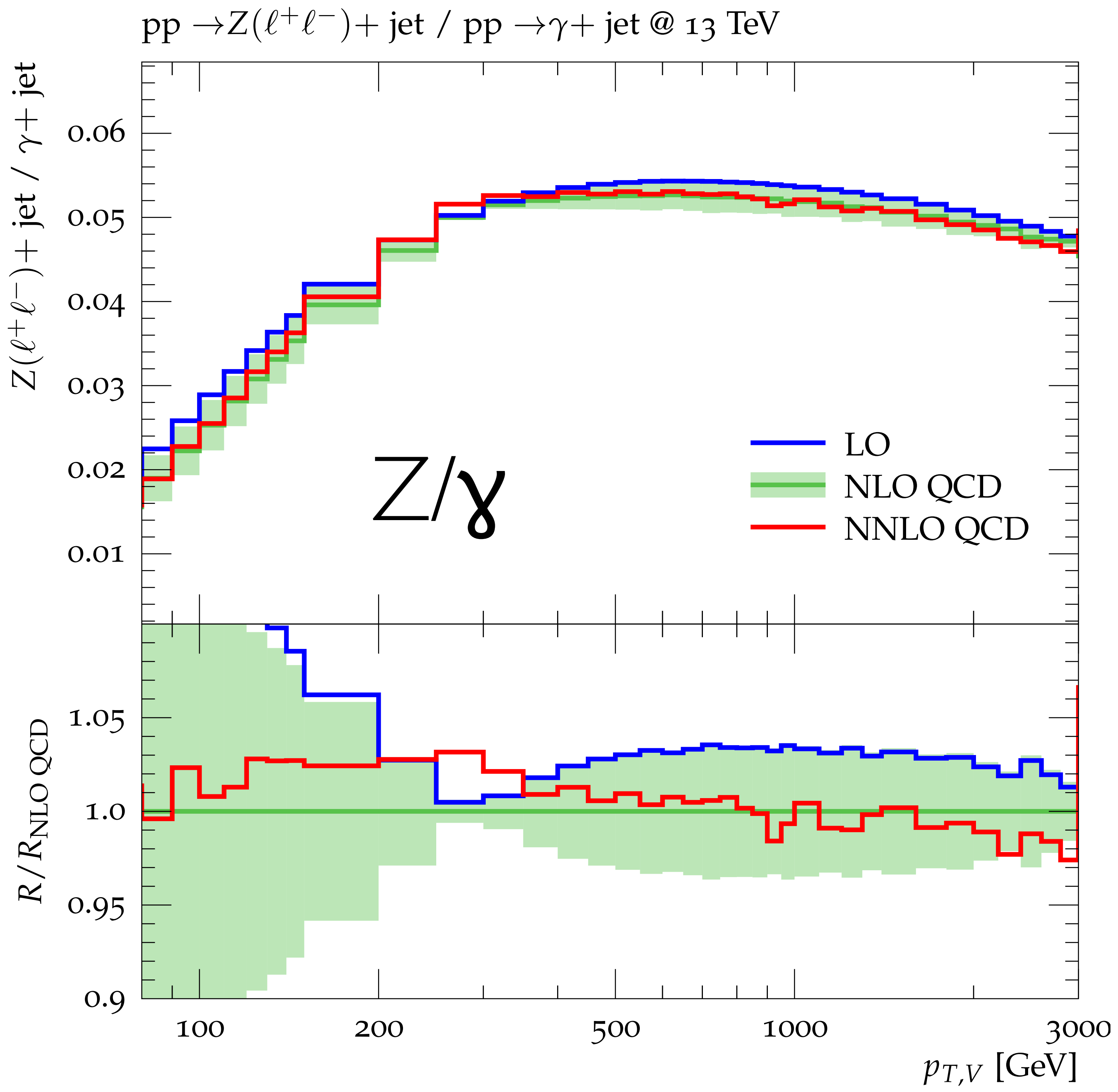
δ < 3-4 %

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

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



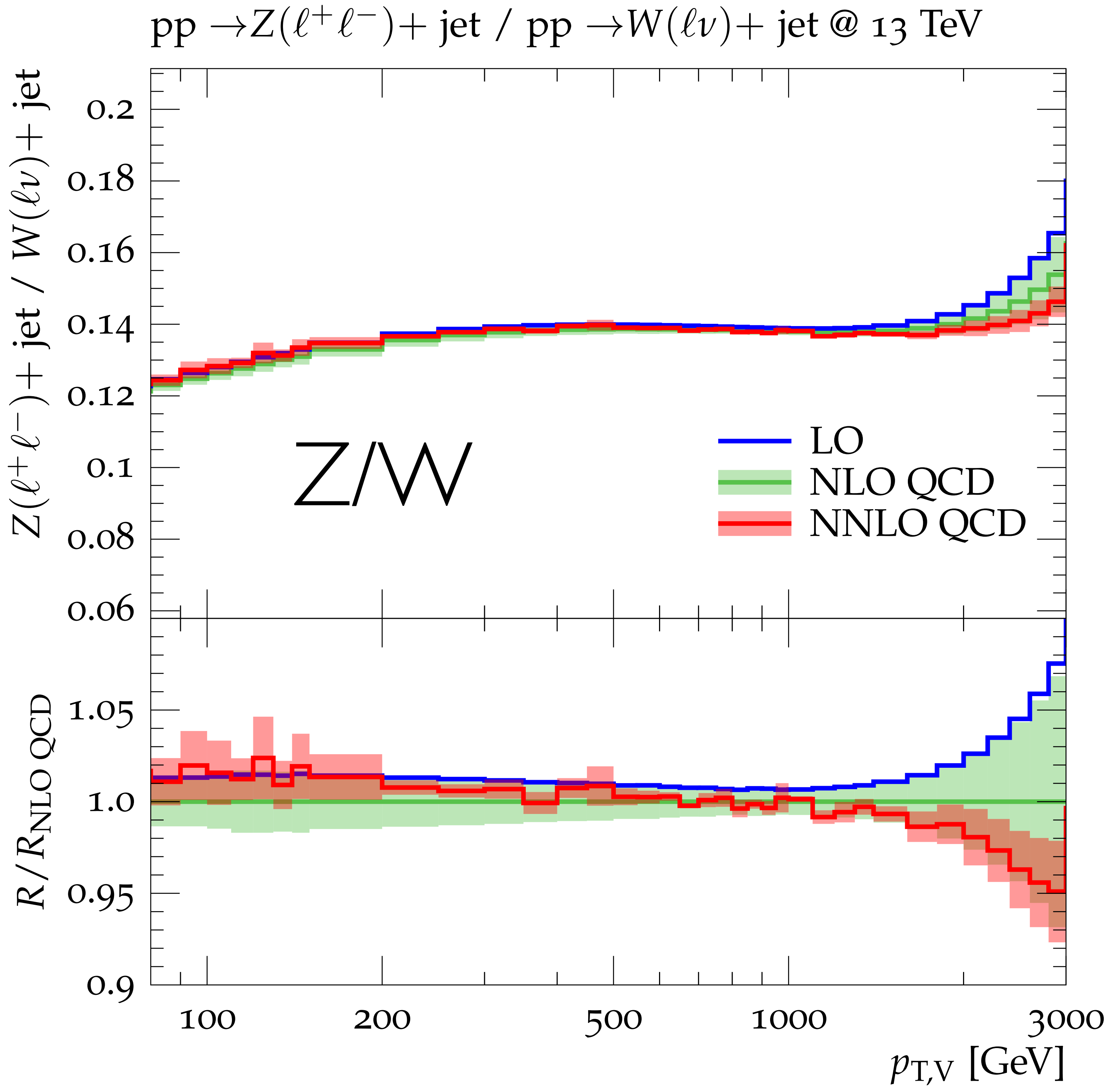


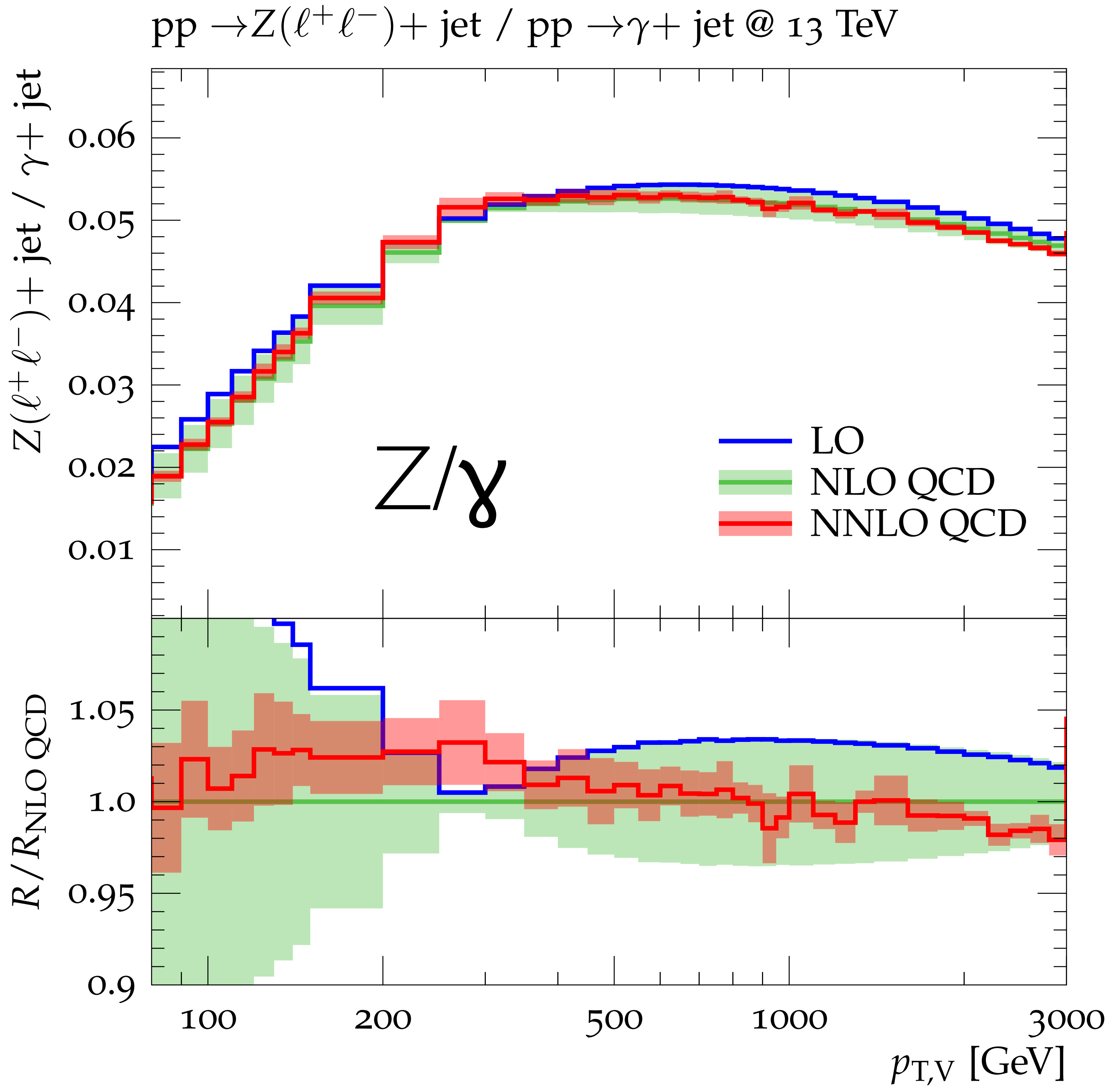
check against NNLO QCD!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

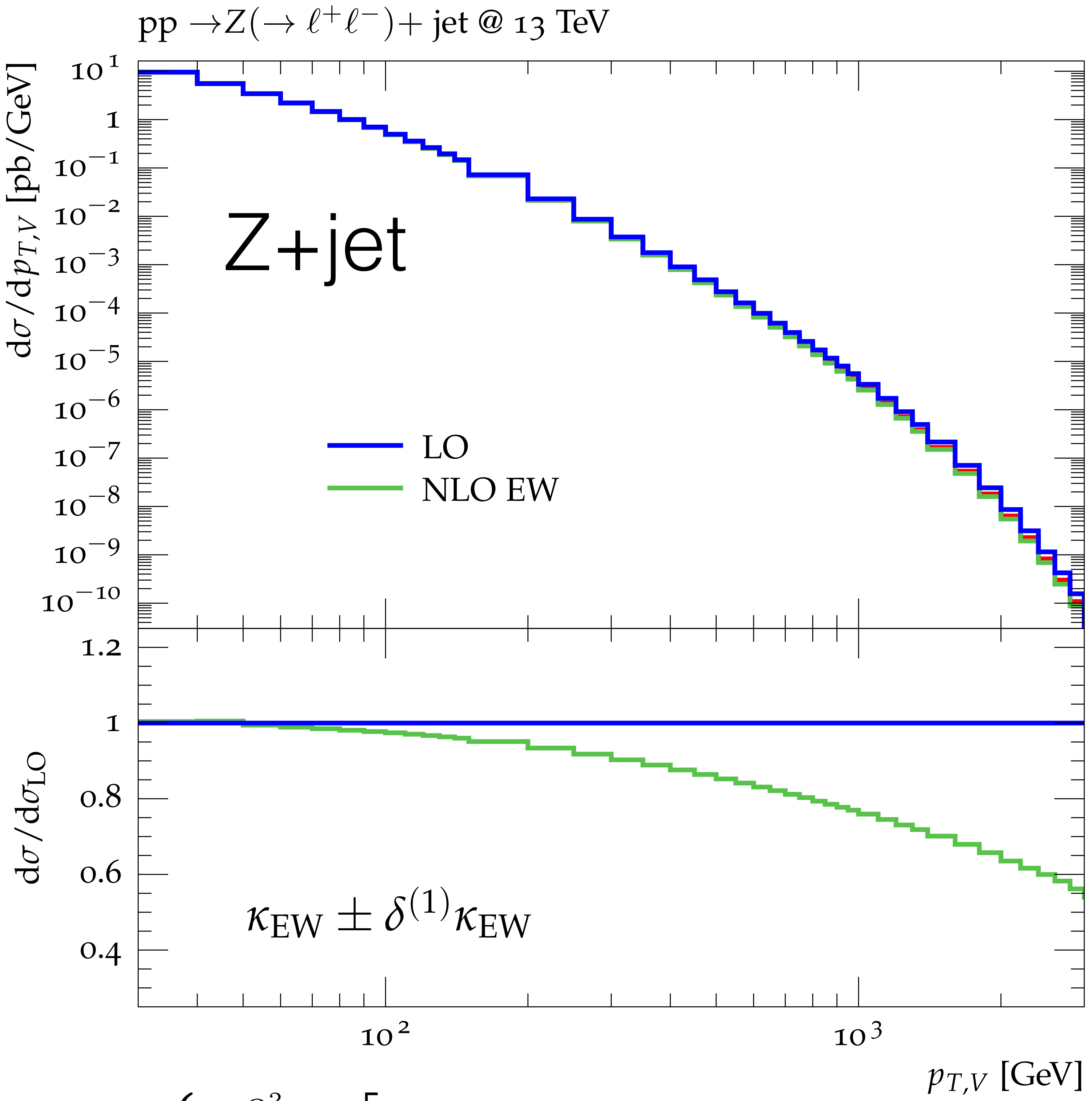
- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{(N)NLO}} = K^{V}_{\mathrm{(N)NLO}} - K^{Z}_{\mathrm{(N)NLO}}$
  →effectively degrades precision of last calculated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





Uncertainty estimates at NNLO QCD

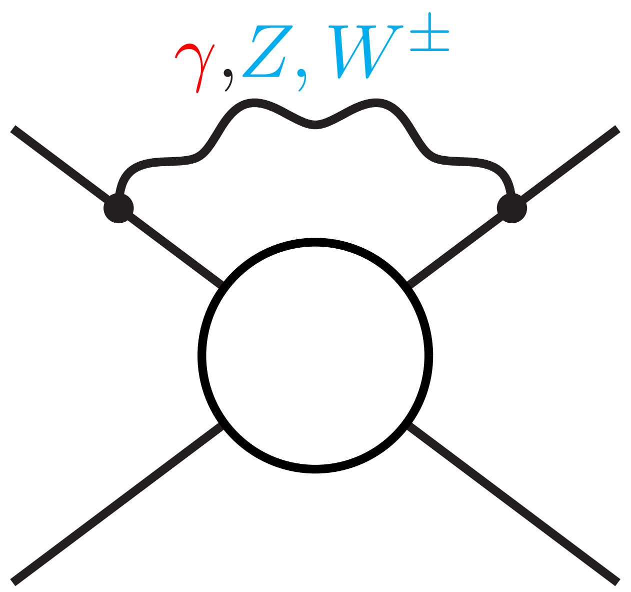
Pure EW uncertainties



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 $\mathcal{O}(\alpha^2)$?



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

$$
= \left(1 + \frac{\alpha}{\pi}\delta^{(1)}_{\mathrm{Sud}} + \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{Sud}} + \dots\right)\left(1 + \frac{\alpha}{\pi}\delta^{(1)}_{\mathrm{hard}} + \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{hard}} + \dots\right) d\sigma_{\mathrm{Born}}
$$

$\to \alpha^m \ln^n\left(Q^2/M_W^2\right)$ $\quad\to$ finite in limit $Q^2/M_W^2 \to \infty$.

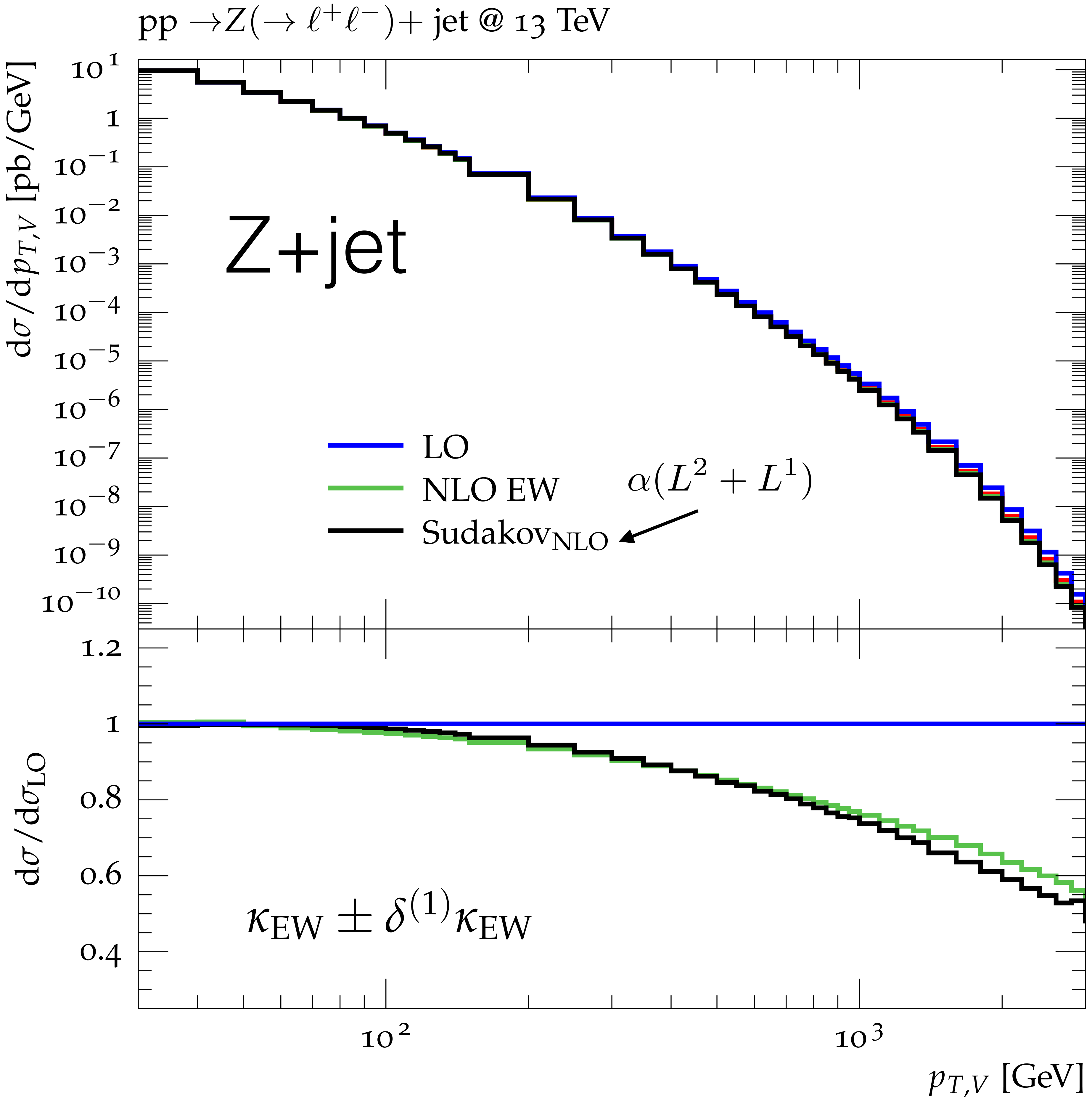
with

$$
\delta^{(1)}_{\mathrm{Sud}} = \sum_{i,j} C^{(1)}_{2,ij} \ln^2\left(\frac{Q^2_{ij}}{M^2}\right) + C^{(1)}_1 \ln^1\left(\frac{Q^2}{M^2}\right),
$$

$$
\delta^{(2)}_{\mathrm{Sud}} = \sum_{i,j} C^{(2)}_{4,ij} \ln^4\left(\frac{Q^2_{ij}}{M^2}\right) + C^{(2)}_3 \ln^3\left(\frac{Q^2}{M^2}\right) + \mathcal{O}\left[\ln^2\left(\frac{Q^2}{M^2}\right)\right]
$$

Pure EW uncertainties

[JML et. al.: 1705.04664]



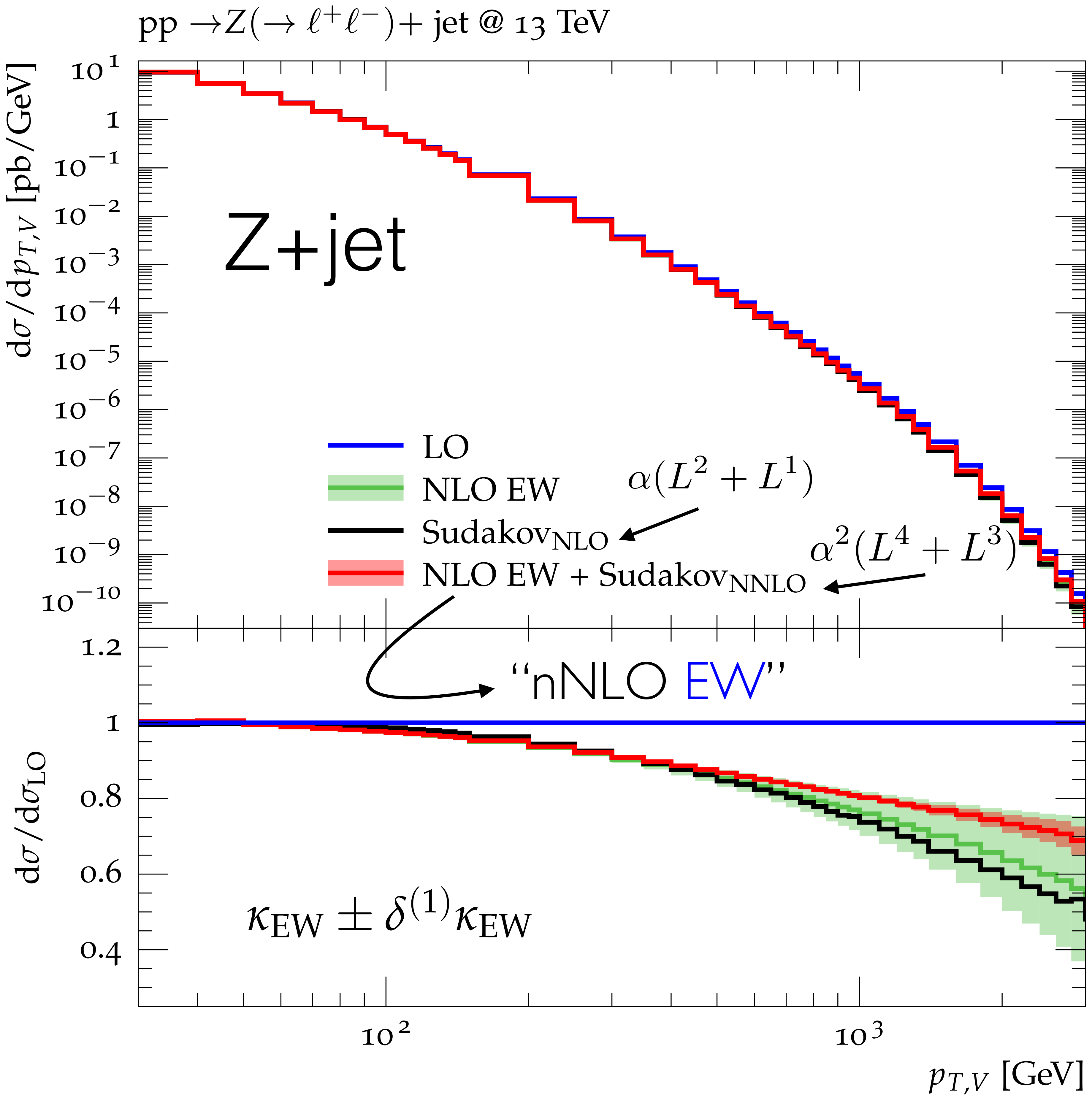
$$\kappa_{\text{nLO EW}} = \frac{\alpha}{\pi}\left[\delta(1)_{\text{Sud}}\right]$$

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

Large EW corrections dominated by Sudakov logs!

Pure EW uncertainties

[JML et. al.: 1705.04664]



Large EW corrections dominated by Sudakov logs!

↓

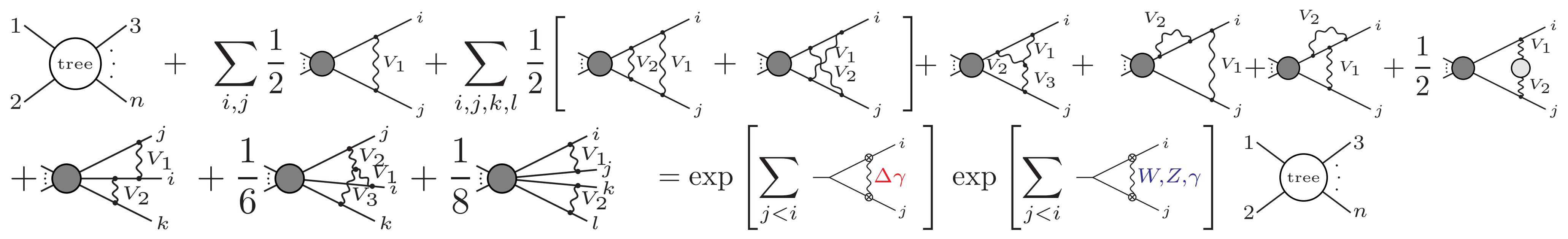
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

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

↓

check against two-loop Sudakov logs

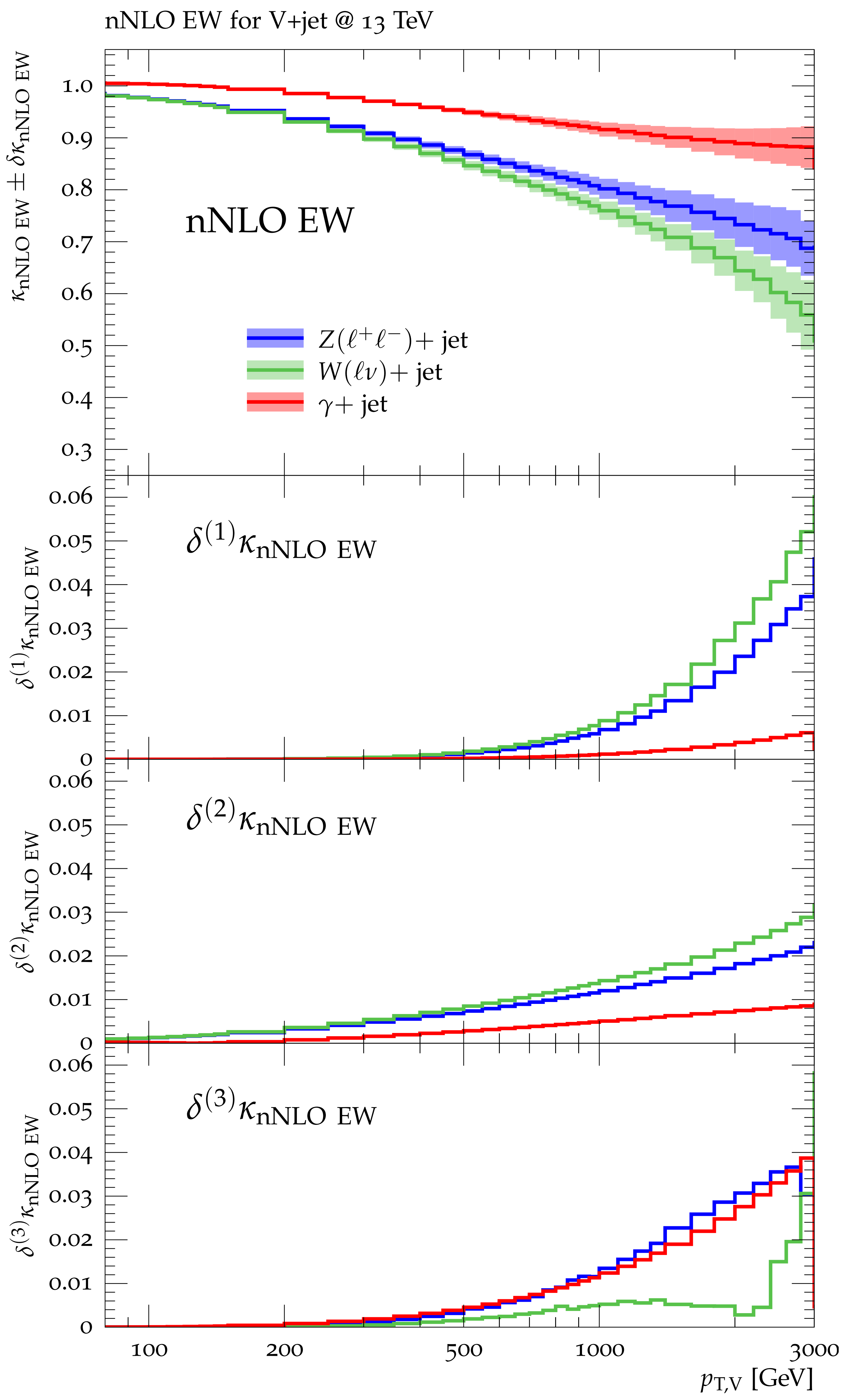
[Kühn, Kulesza, Pozzorini, Schulze; 05-07]



$$\kappa_{\mathrm{nLO\,EW}} = \frac{\alpha}{\pi}\left[\delta(1)_{\mathrm{Sud}}\right] \qquad \kappa_{\mathrm{NNLO\,Sud}} = \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{Sud}}$$

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

Pure EW uncertainties



nNLO EW corrections at 1 TeV

- -10% for γ+jets
- -20% for Z+jet
- -25% for W+jet

$$d\sigma_{\mathrm{EW}} = \left[1 + \frac{\alpha}{\pi}\left(\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right) + \left(\frac{\alpha}{\pi}\right)^2 \left(\delta^{(2)}_{\mathrm{Sud}} + \delta^{(1)}_{\mathrm{Sud}}\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{hard}}\delta^{(1)}_{\mathrm{hard}} + \delta^{(2)}_{\mathrm{hard}}\right) + \left(\frac{\alpha}{\pi}\right)^3 \left(\delta^{(3)}_{\mathrm{Sud}} \ldots\right)\right]$$

- 'higher-order Sudakov logs'

$$\delta^{(1)}\kappa^{(V)}_{\mathrm{EW}}(x) \quad := \frac{2}{3}\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)\,\kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x)$$

(correlated)

Additional uncorrelated uncertainties:

- 'hard non-log NNLO EW effects I'

(uncorrelated)

$$\delta^{(2)}\kappa^{(V)}_{\mathrm{EW}}(x) = 0.05\,\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)$$

$$\Leftrightarrow \quad \delta^{(2)}_{\mathrm{hard}} \leq \frac{0.05\pi}{\alpha}\delta^{(1)}_{\mathrm{hard}} \simeq 20\,\delta^{(1)}_{\mathrm{hard}}$$

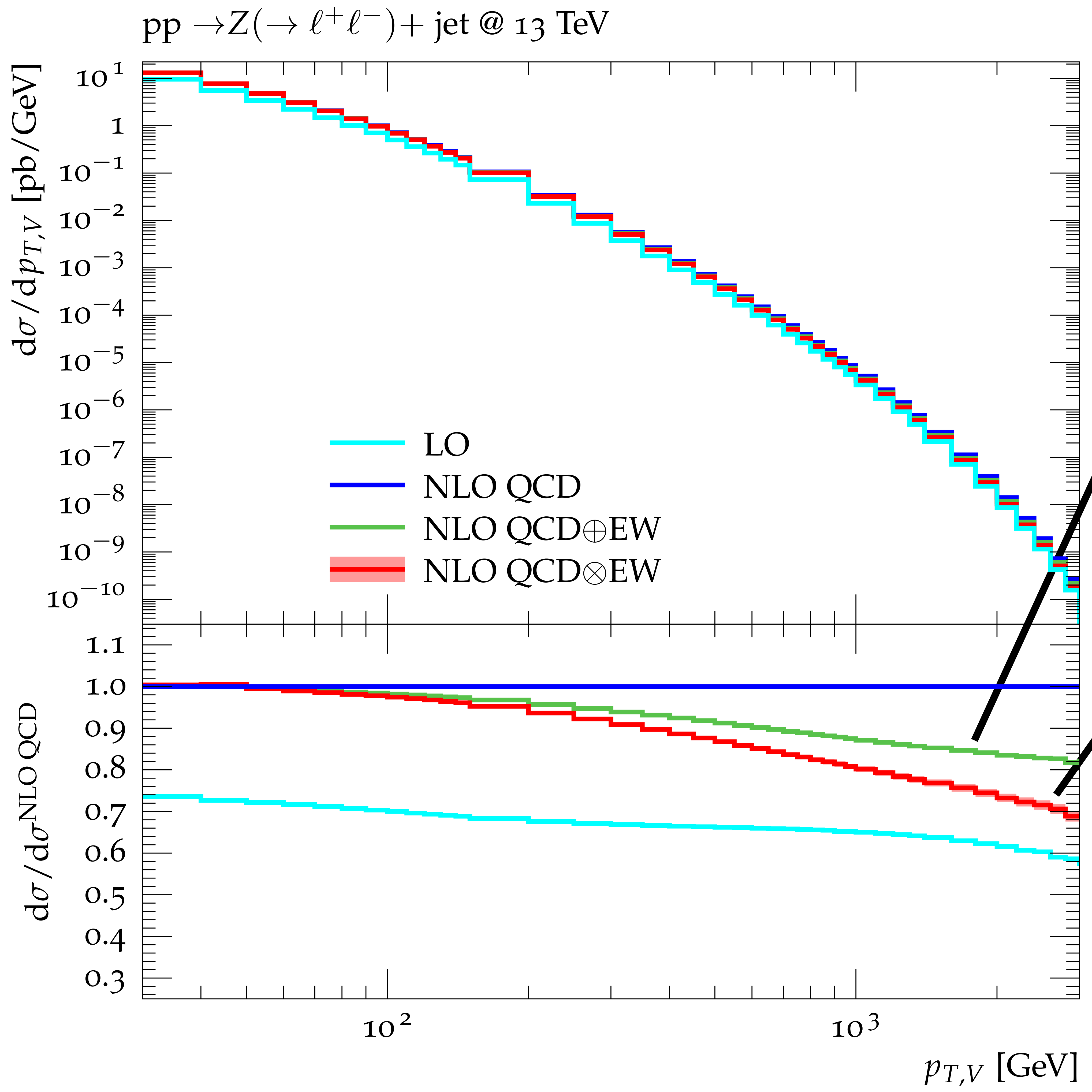
- 'hard non-log NNLO EW effects II'

$$\delta^{(3)}\kappa^{(V)}_{\mathrm{EW}}(x) \quad = \quad \kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x) - \frac{1}{2}[\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)]^2$$

(uncorrelated)

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

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

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$$

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

Multiplicative combination

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

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

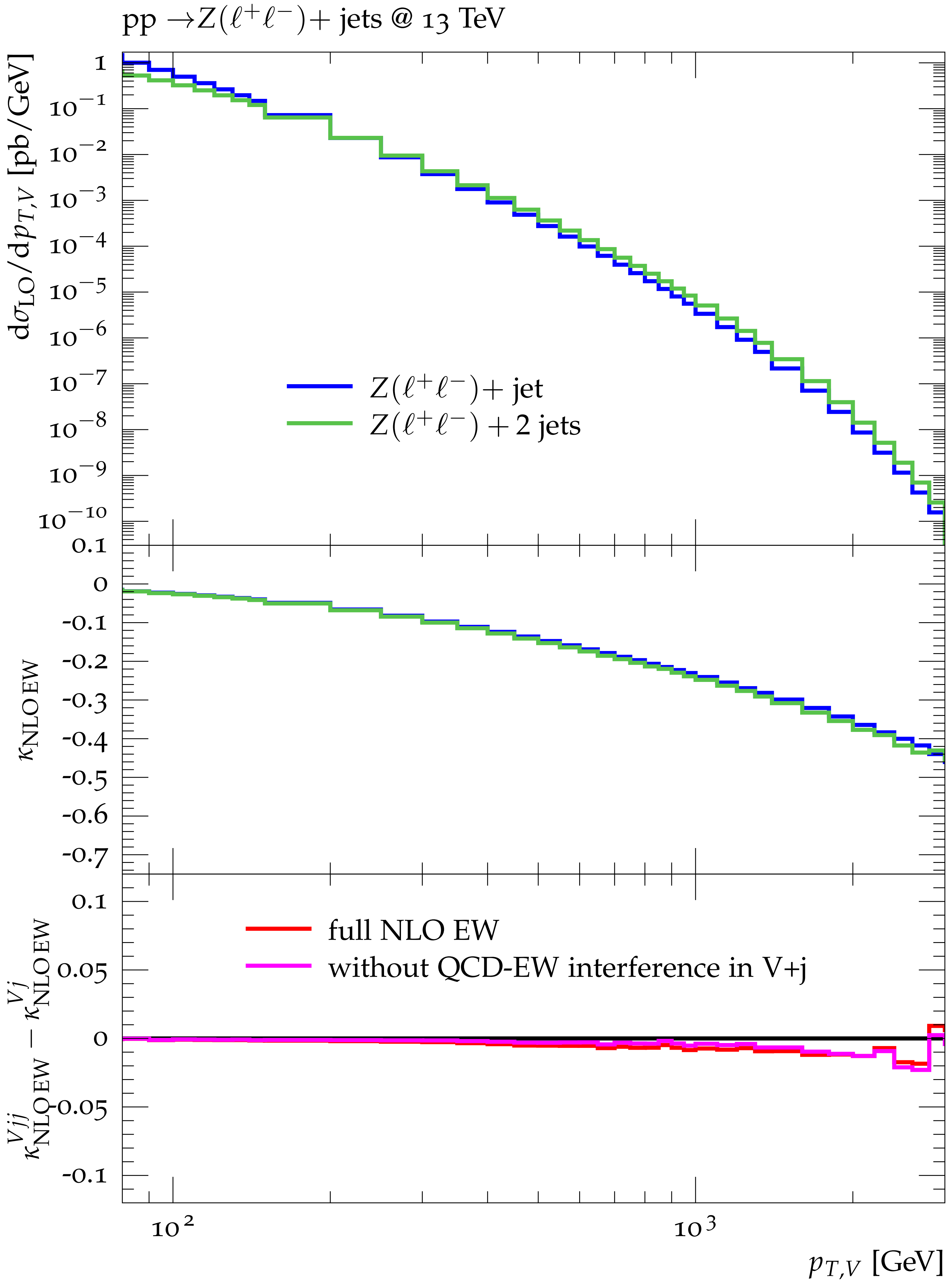
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

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

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

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

strong support for
- factorization
- multiplicative QCD x EW combination

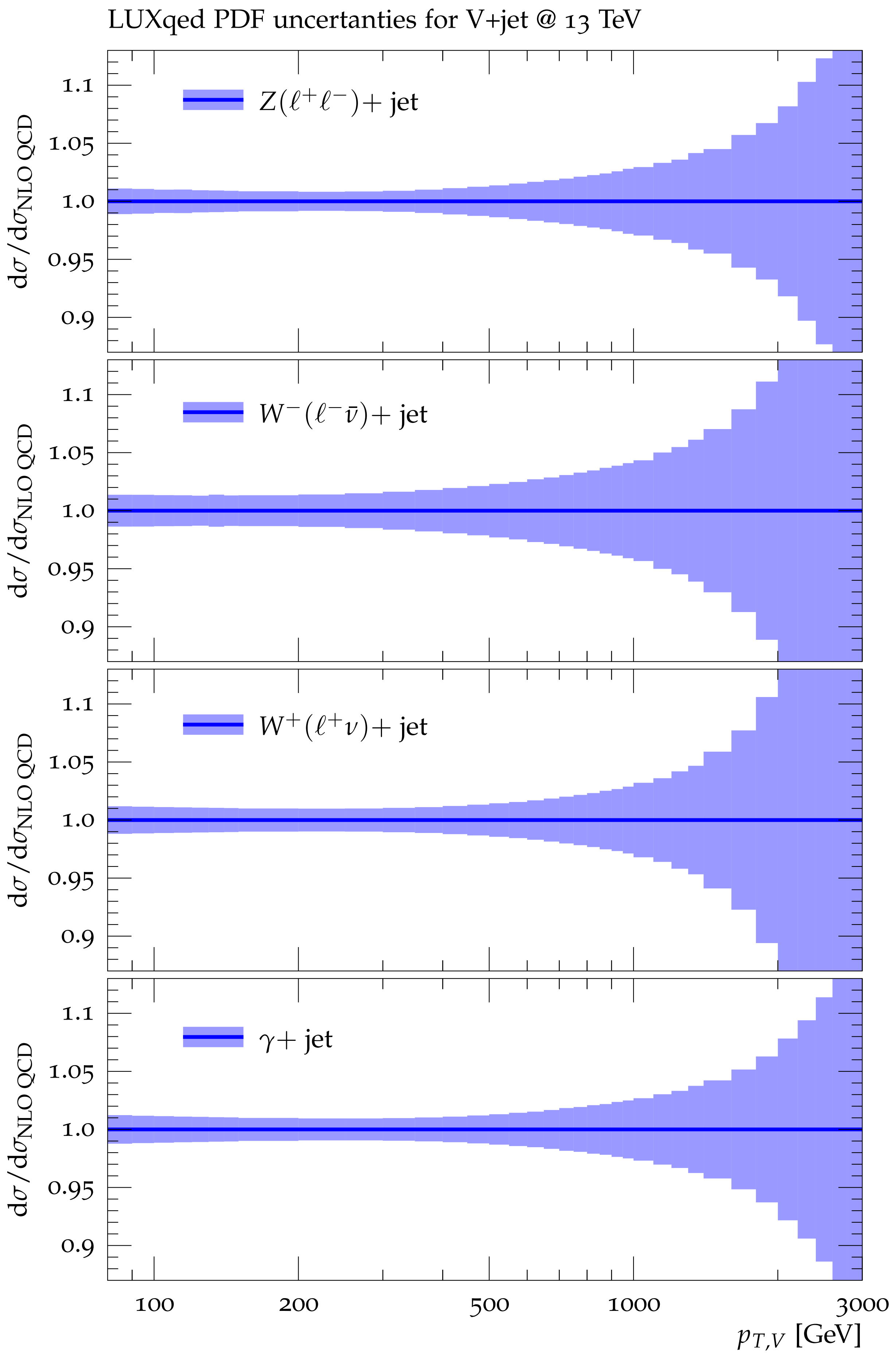
Estimate of non-factorising contributions

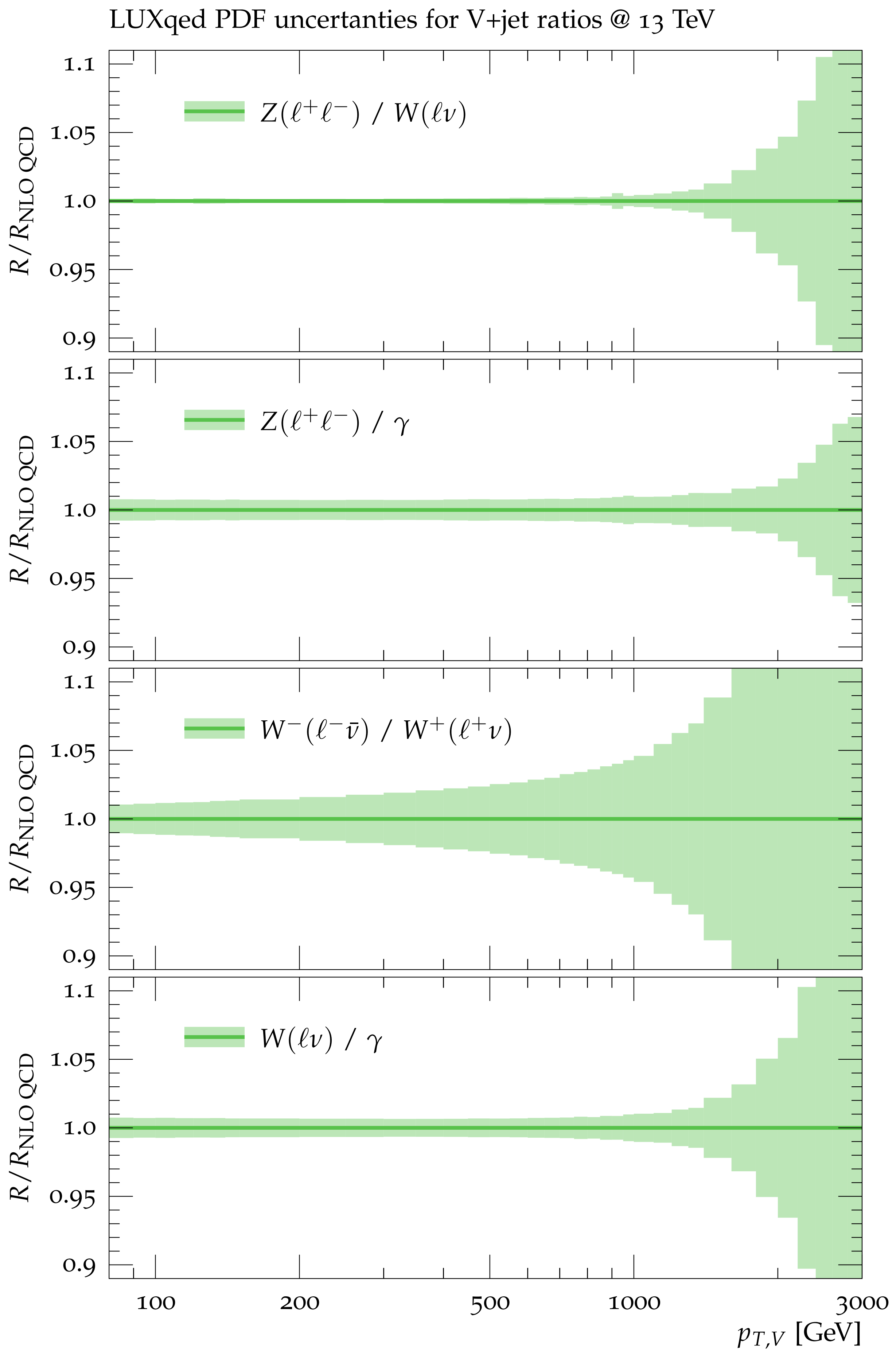
(correlated)

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

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

PDF uncertainties (LUXqed=PDF4LHC)

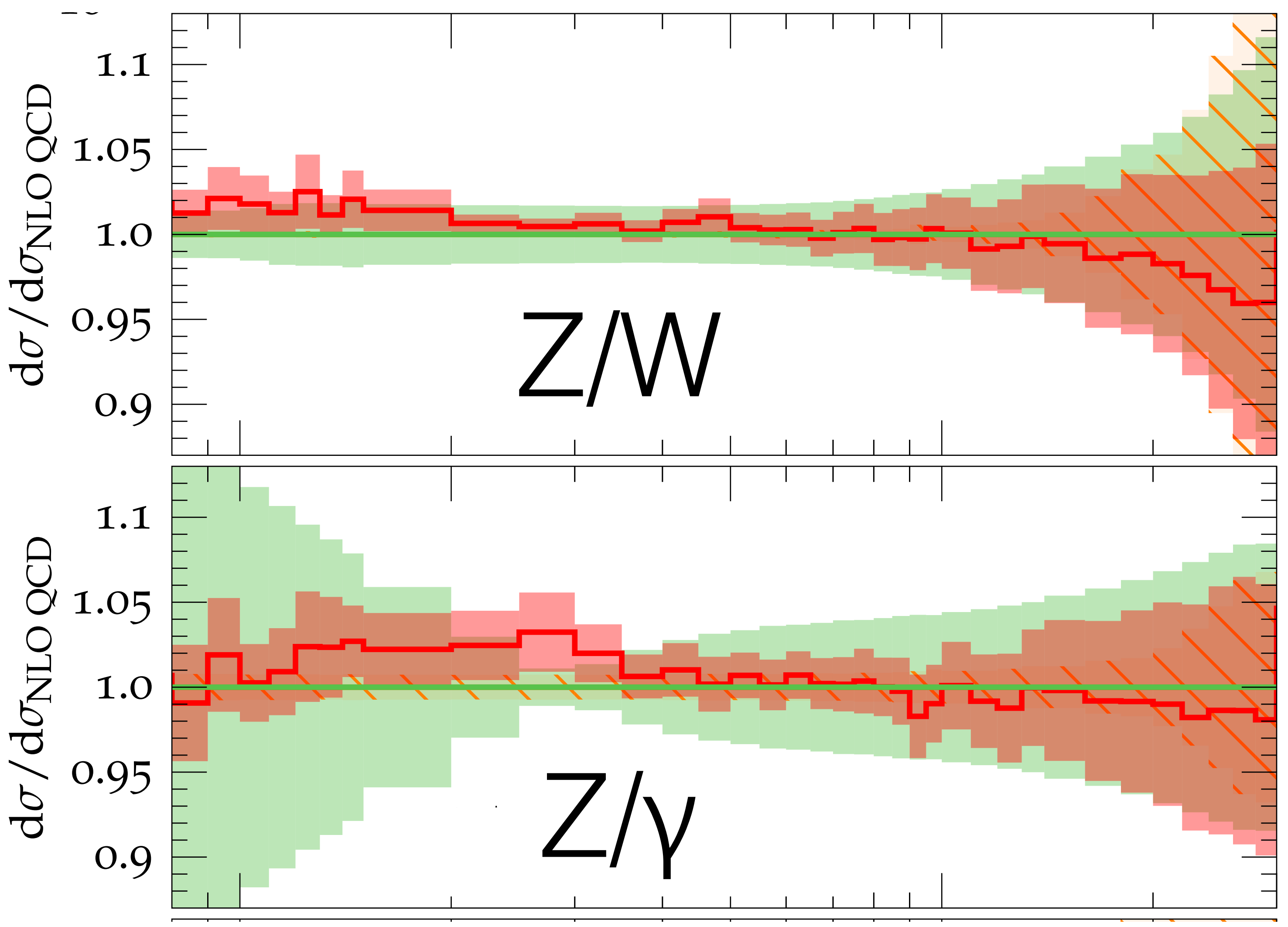




- δ_{PDF} < 2 % for pT,V < 800 GeV
- δ_{PDF} < 5 % for pT,V < 1500 GeV

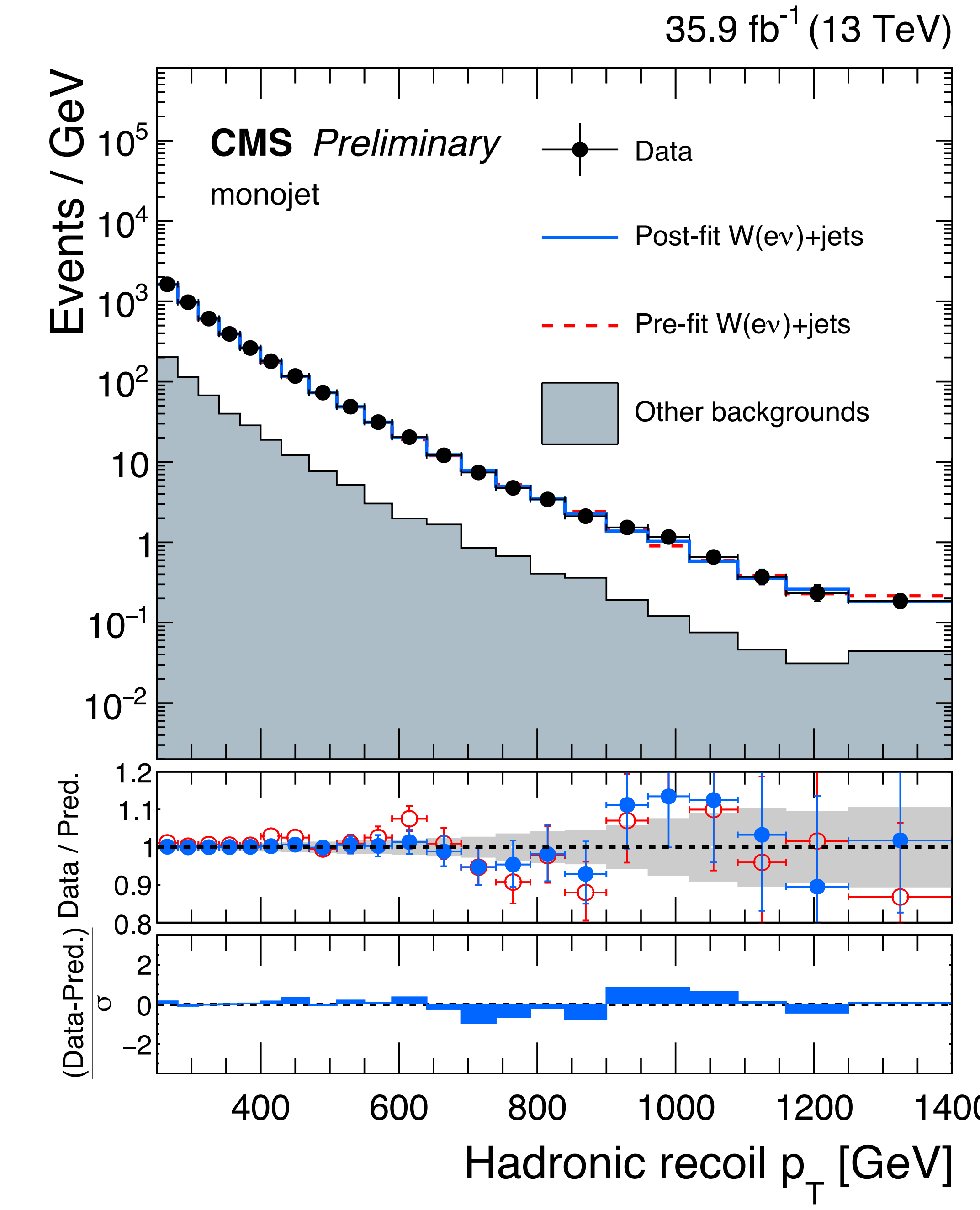
- Z/W: δ_{PDF} < 0.5%(2%) for pT,V < 800 GeV(1.5 TeV)
- Z/**γ** & W/**γ**: δ_{PDF} < 2% for pT,V < 1.3 TeV
- W^-/W^+: δ_{PDF} > 5% for pT,V < 1 TeV
  (due to large uncertainties on u/d ratio at large Bjorken-x)

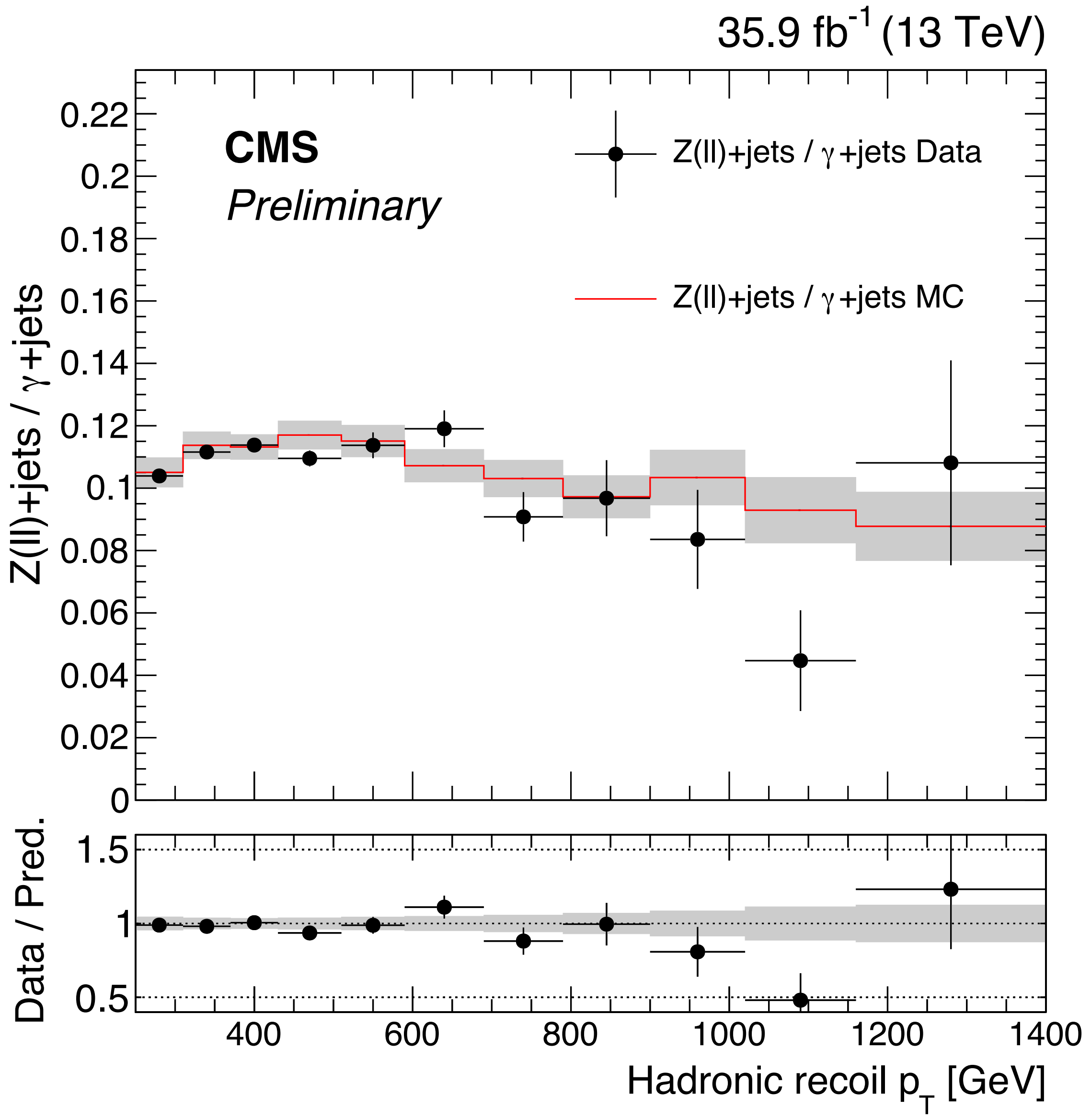
Combined uncertainties on V+jets ratios



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

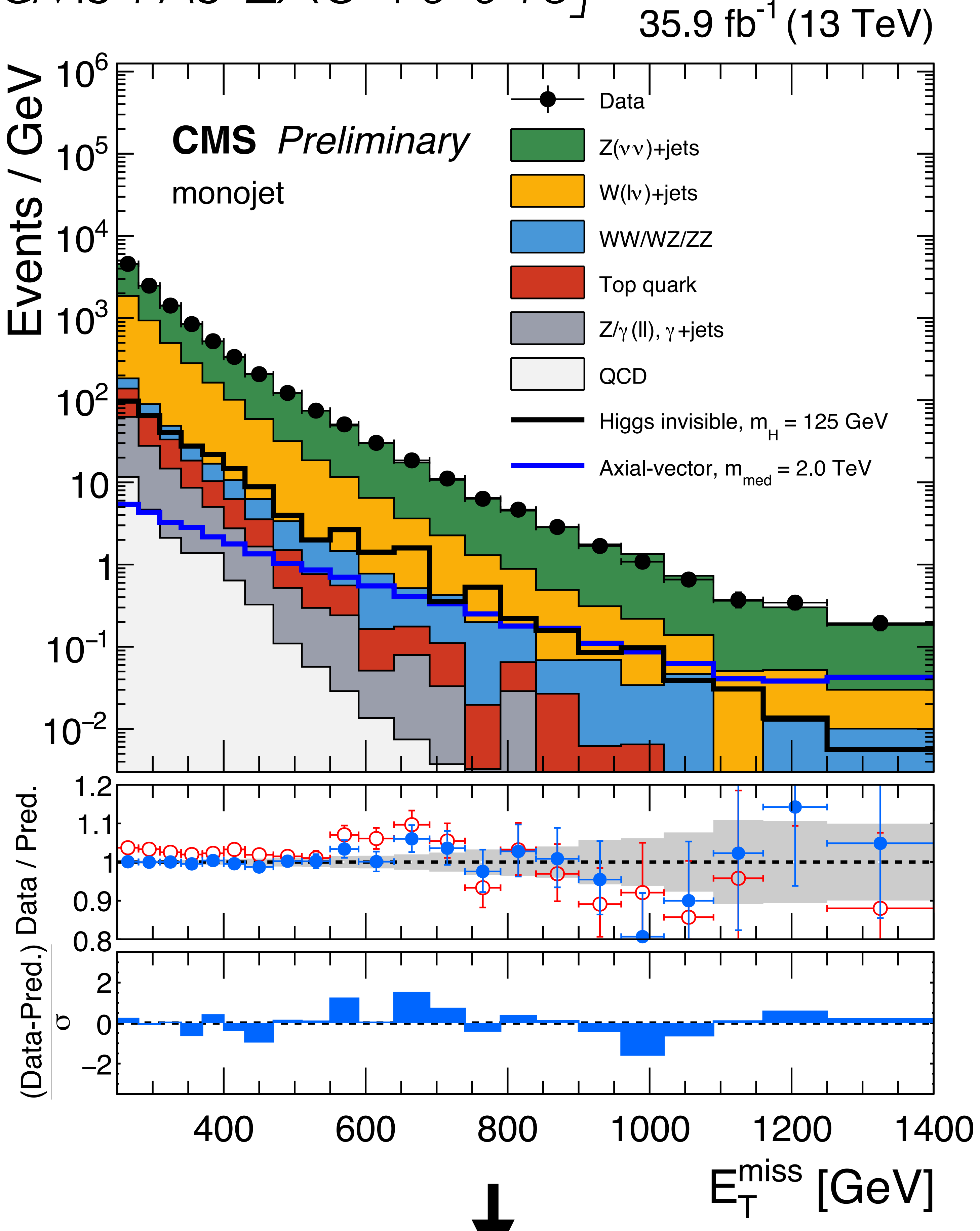
CR





SR

[CMS PAS EXO-16-048]



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 $\mathcal{N}^{\beta}_{\mu_1 \dots \mu_r;\alpha}$
  - disentangle loop momentum q from the coefficients

$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) = \sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1 \dots \mu_r;\alpha}(\mathcal{I}_n)\, q^{\mu_1} \dots q^{\mu_r} \qquad X^{\beta}_{\gamma\delta} = Y^{\beta}_{\gamma\delta} + q^{\nu} Z^{\beta}_{\nu;\gamma\delta}$$

  - recursion in d=4:

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

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

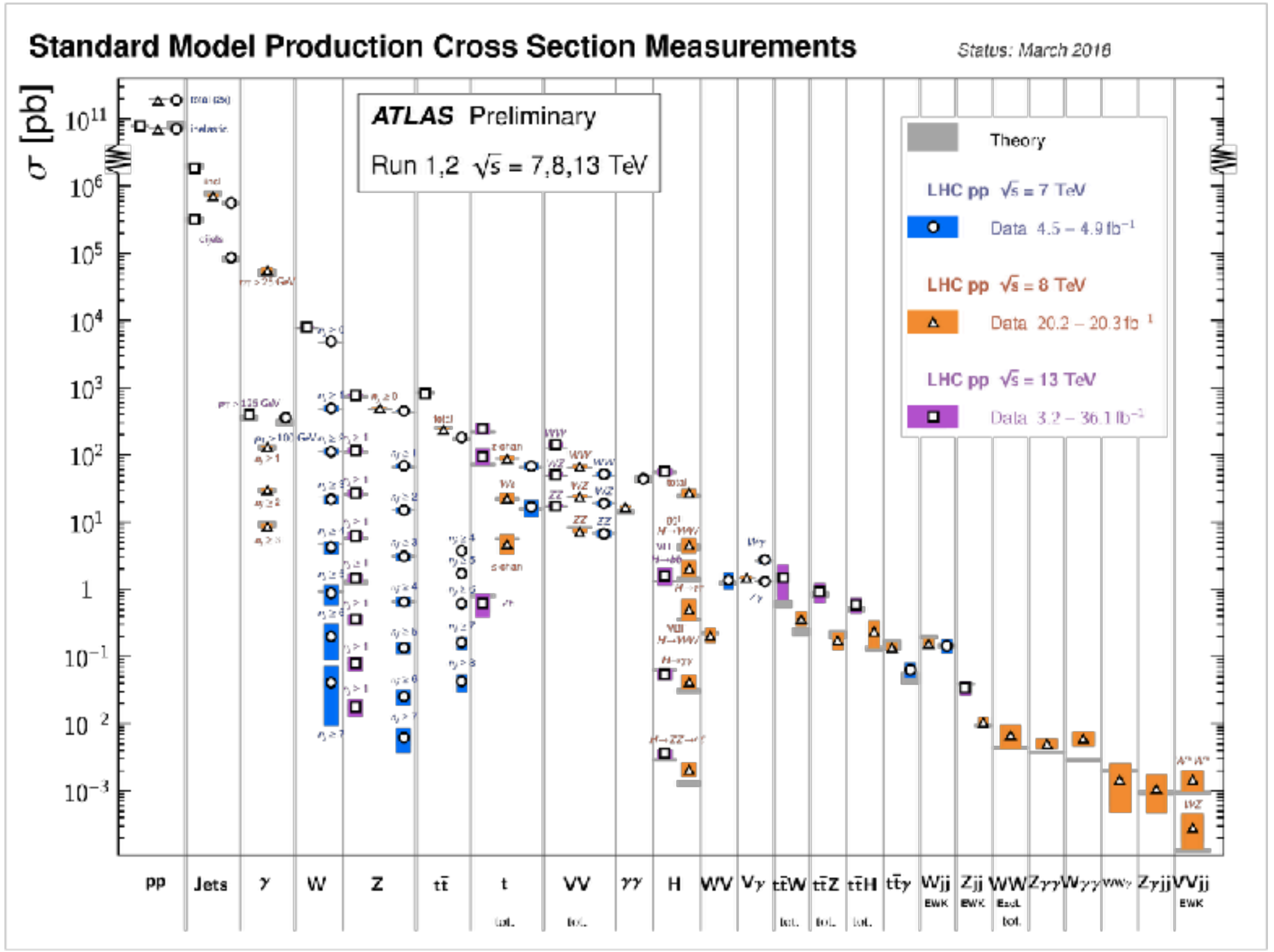
- ε-dimensional part of the numerator x poles of the tensor integrals yield R_2 rational terms

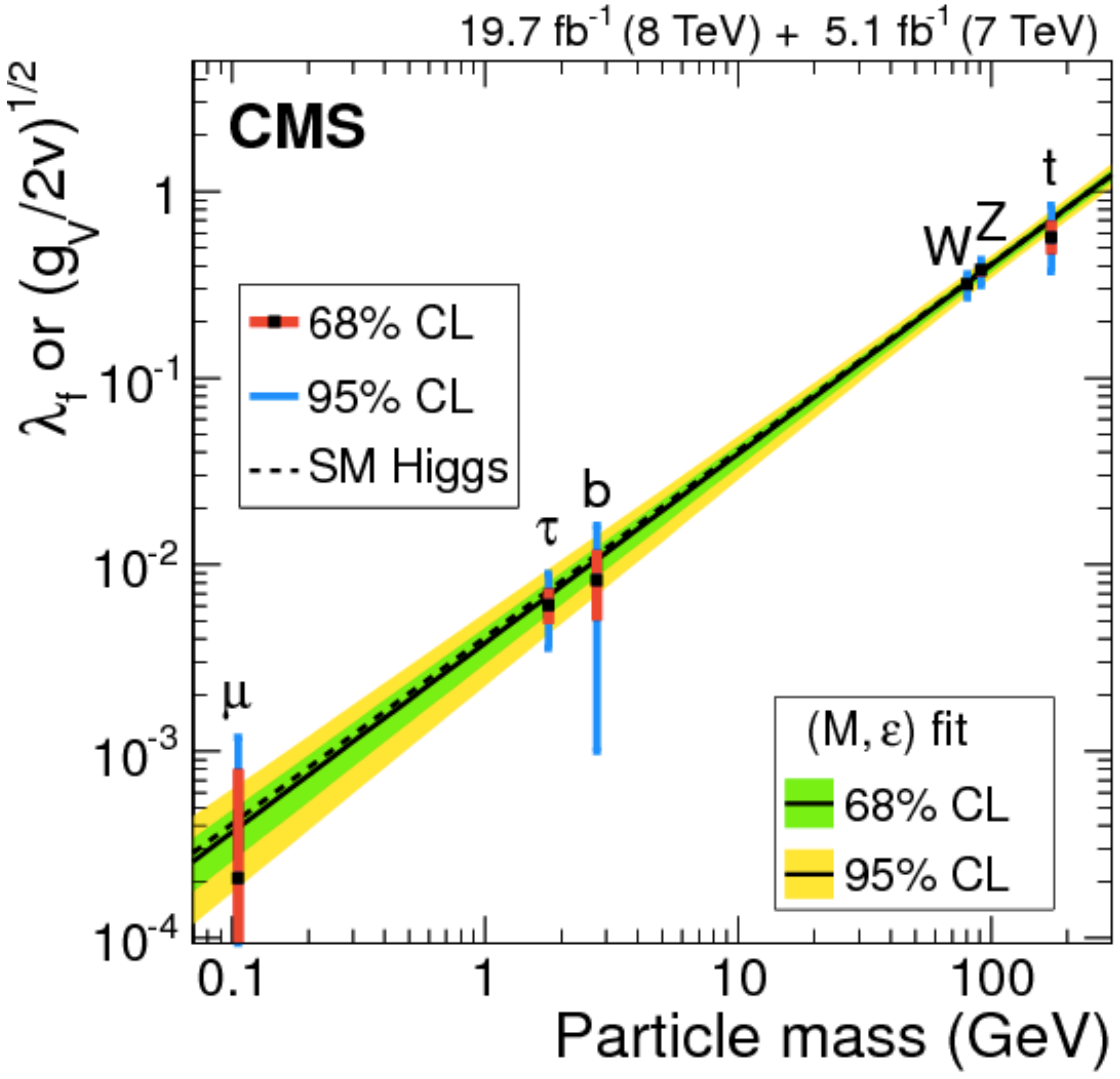
$$R_2 = \left([\mathcal{N}]_{d=4-2\epsilon} - [\mathcal{N}]_{d=4}\right) \cdot [TI]_{UV}$$

  - numerical recursion in D=4 ➞ 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

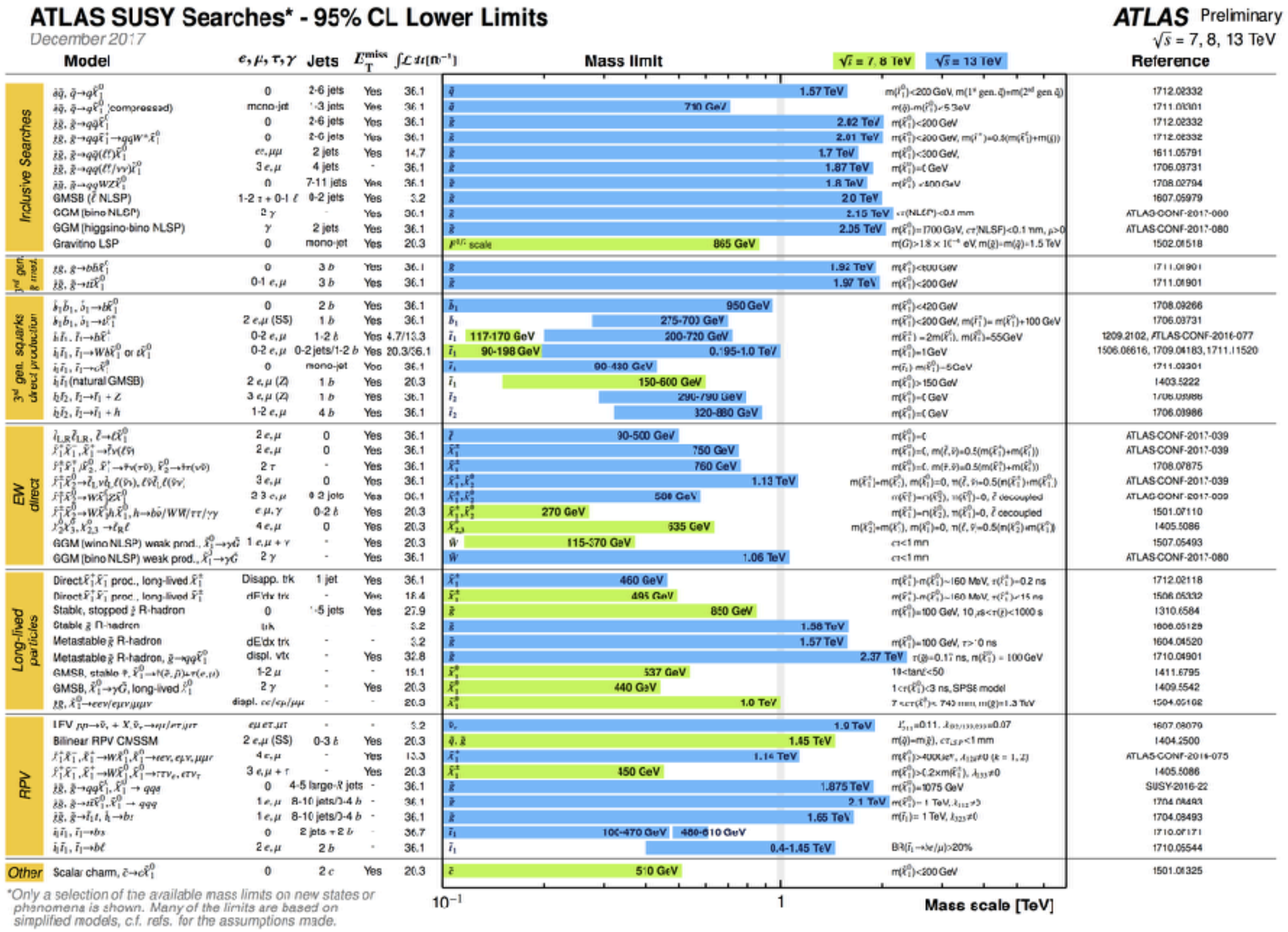


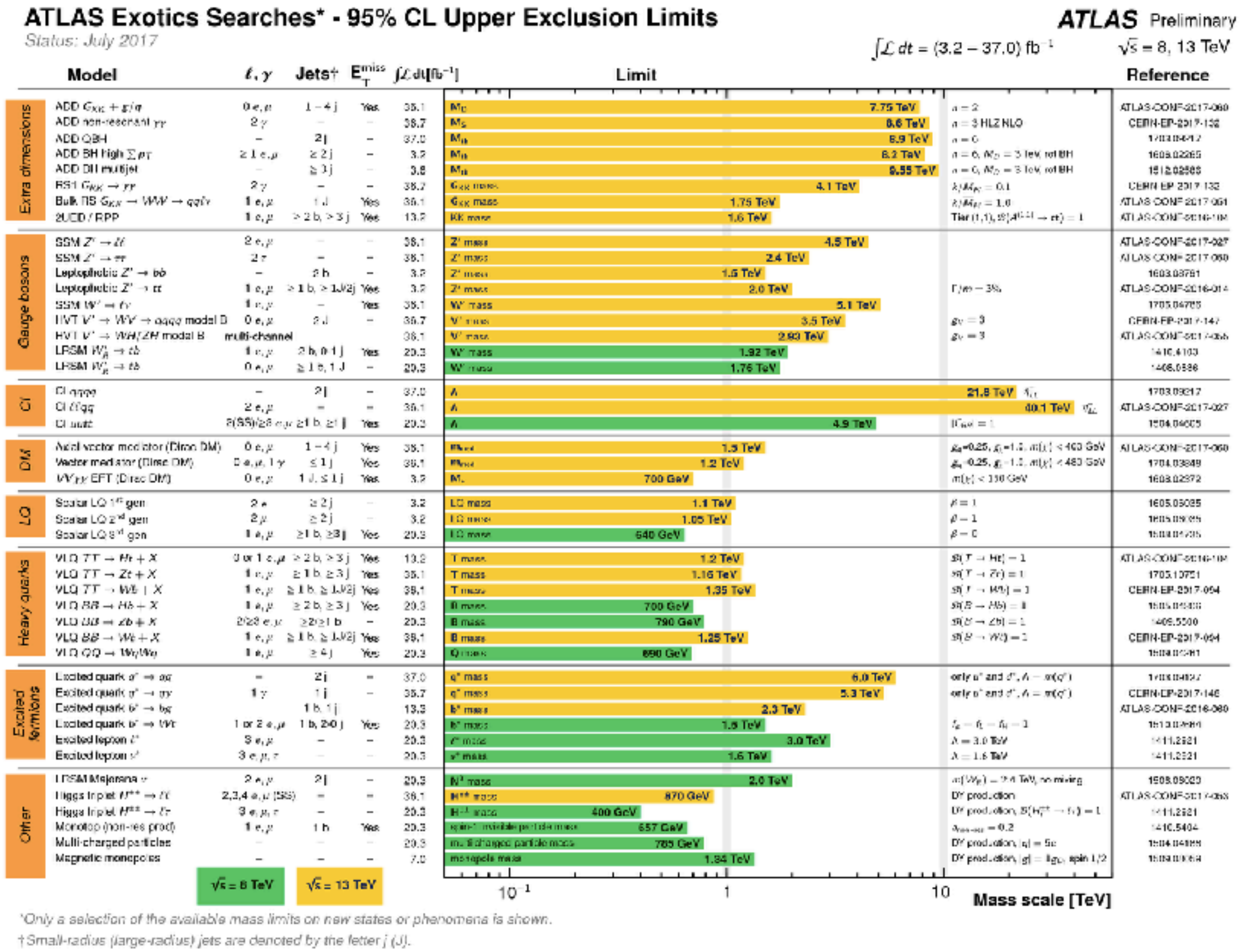


Overall remarkable data vs. theory agreement

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

Search limits





➡ BSM certainly not ‘around the corner’

➡ Leave no stone unturned

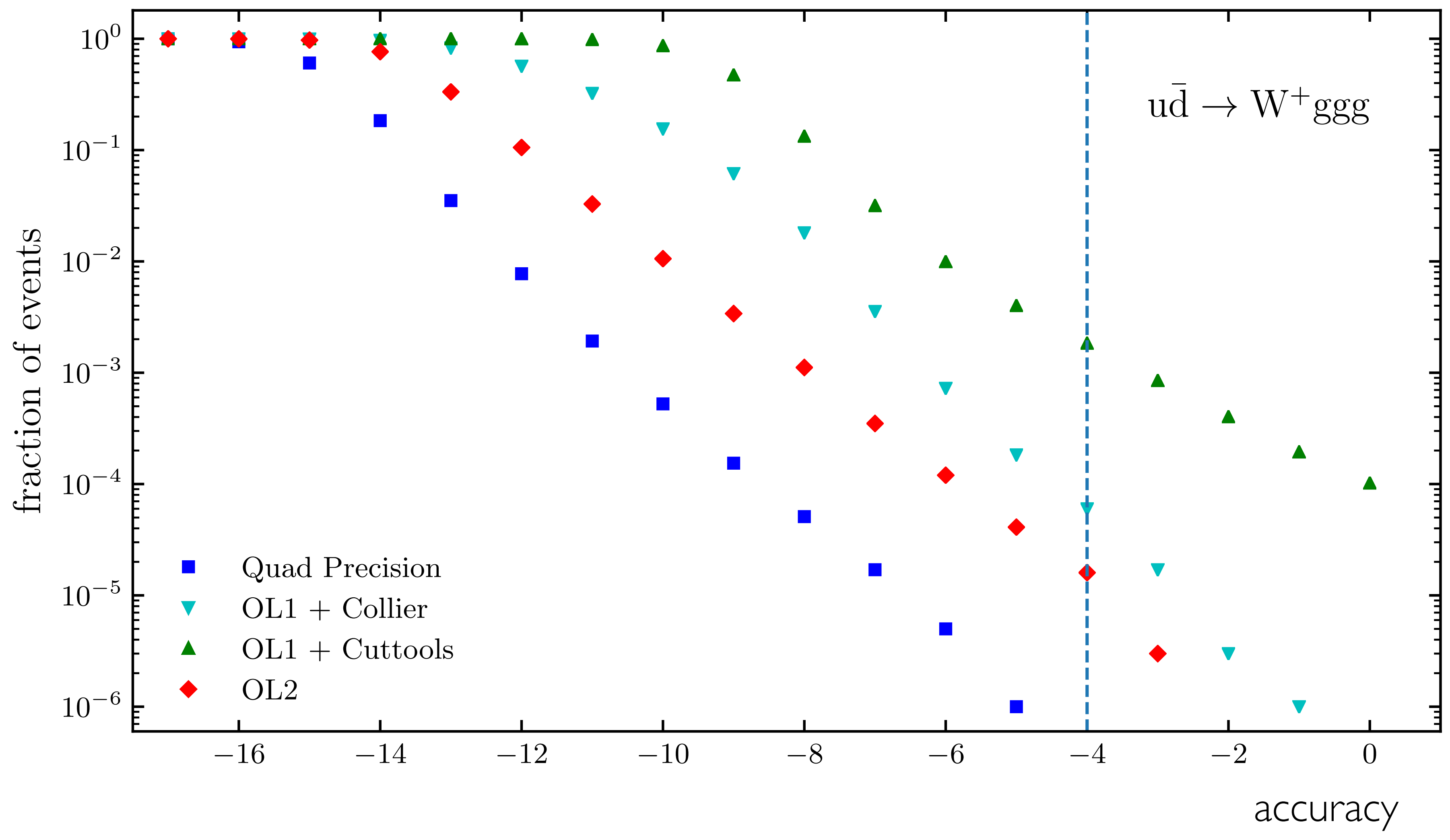
➡ Push towards smaller couplings / exotic signatures

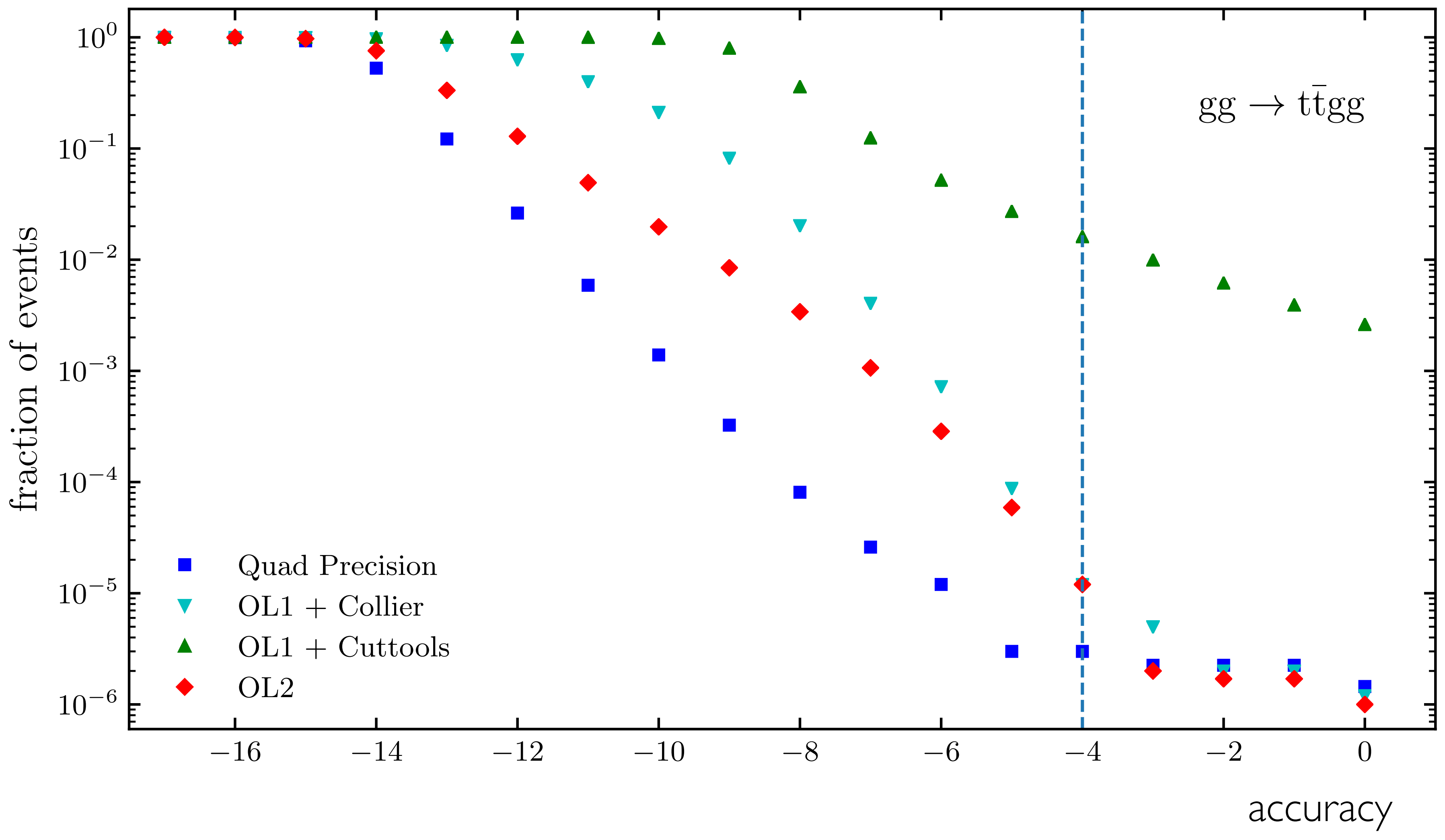
On-the-fly OpenLoops reduction

New!

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

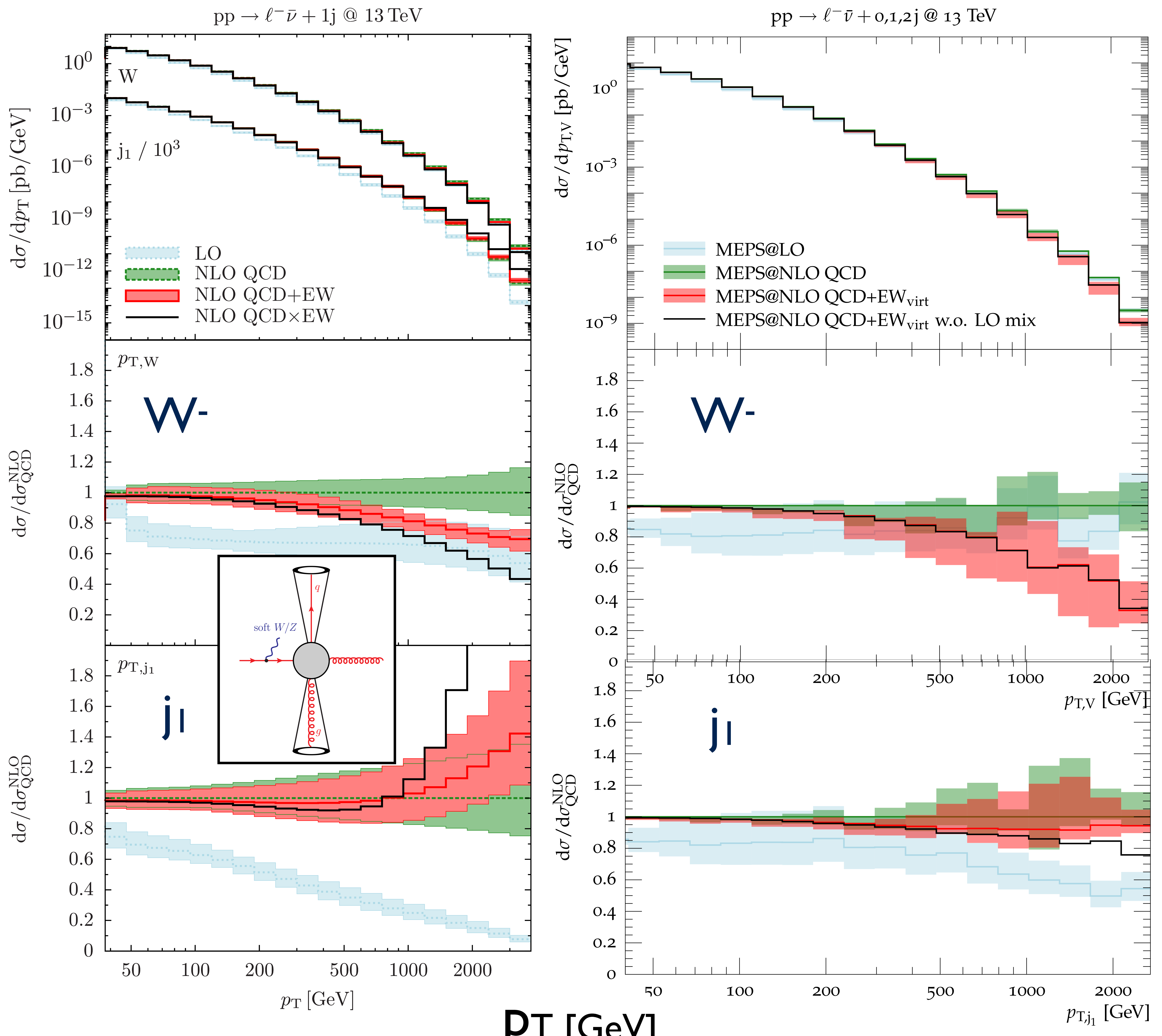
- Huge advantage: allows for systematic treatment of numerical instabilities in





- unprecedented numerical stability (always as least as stable as OpenLoops1+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_{virt}



pT [GeV]

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

- 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

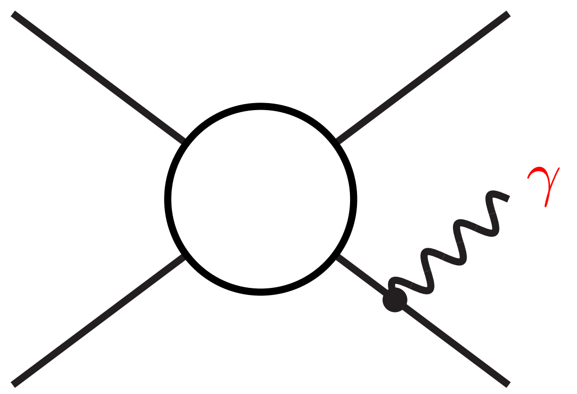
- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$:
  - merging ensures stable results (dijet topology at LO)
  - compensation between negative Sudakov and LO mix

Automation of NLO EW

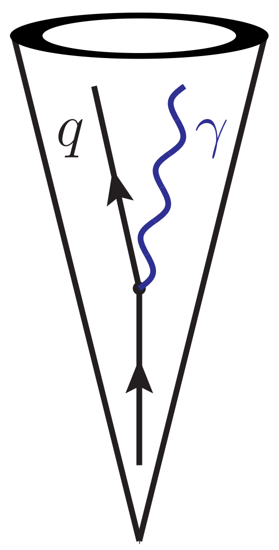
MoCaNLO+Recola	pp → ll + 2 jets	[1411.0916]
	pp → $e^+e^-\mu^+\mu^-$ / $\mu^+\mu^-\ \mu^+\mu^-$ / $e^+\nu_e\mu^-\nu_\mu$	[1601.07787] [1611.05338
	pp → $e^+\nu_e\mu^-\nu_\mu$ bb (tt)	[1607.05571]
	pp → $e^+\nu_e\mu^+\nu_\mu$ + 2 jets (VBS)	[1611.02951] [1708.00268]
	pp → $e^+\nu_e\mu^-\nu_\mu$ bbH (ttH)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

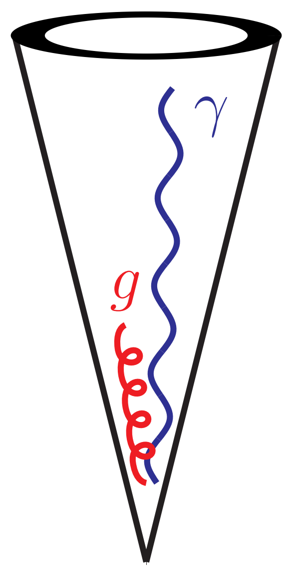
Treatment of Photons



- 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 ≡ photons)



collinear q → qγ singularities cancelled clustering q, g, γ on same footing



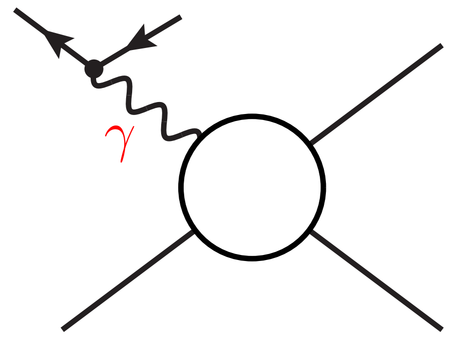
soft gluon singularities ↔ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

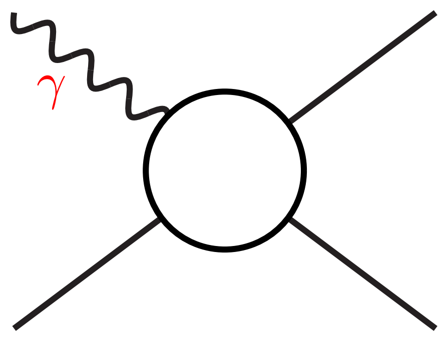
  - Separation of jets from photons through $E_\gamma/E_{jet} < z_{thr}$ inside jets
    - *rigorous approach*: absorb q → qγ singularity into fragmentation function
    - *approximation*: cancel singularity via qγ recombination in small cone

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

difference < 1% for typical z_{thr}!

- QED factorisation for IS photons and PDF evolution *[MRST2004, NNPDF2.3]*
- γ-induced processes → possible TeV scale enhancements (However large uncertainties!)

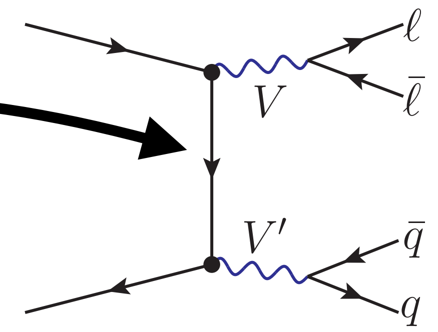




MEPS@NLO QCD+EW$_{\text{virt}}$

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

$$\tilde{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) \longrightarrow \tilde{\mathrm{B}}_{n,\mathrm{QCD+EW}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$



$$d\sigma = d\sigma(\alpha_S^2\alpha) + d\sigma(\alpha_S\alpha^2) + d\sigma(\alpha^3)$$

QCD EW QCD EW QCD EW

$$+\, d\sigma(\alpha_S^3\alpha) + d\sigma(\alpha_S^2\alpha^2) + d\sigma(\alpha_S\alpha^3) + d\sigma(\alpha^4)$$

- Validated at fixed-order level (using exclusive sums for merging): percent-level agreement
- exlusive QED corrections could be readded via the parton shower
- use CKKW scale setting with EW clustering and

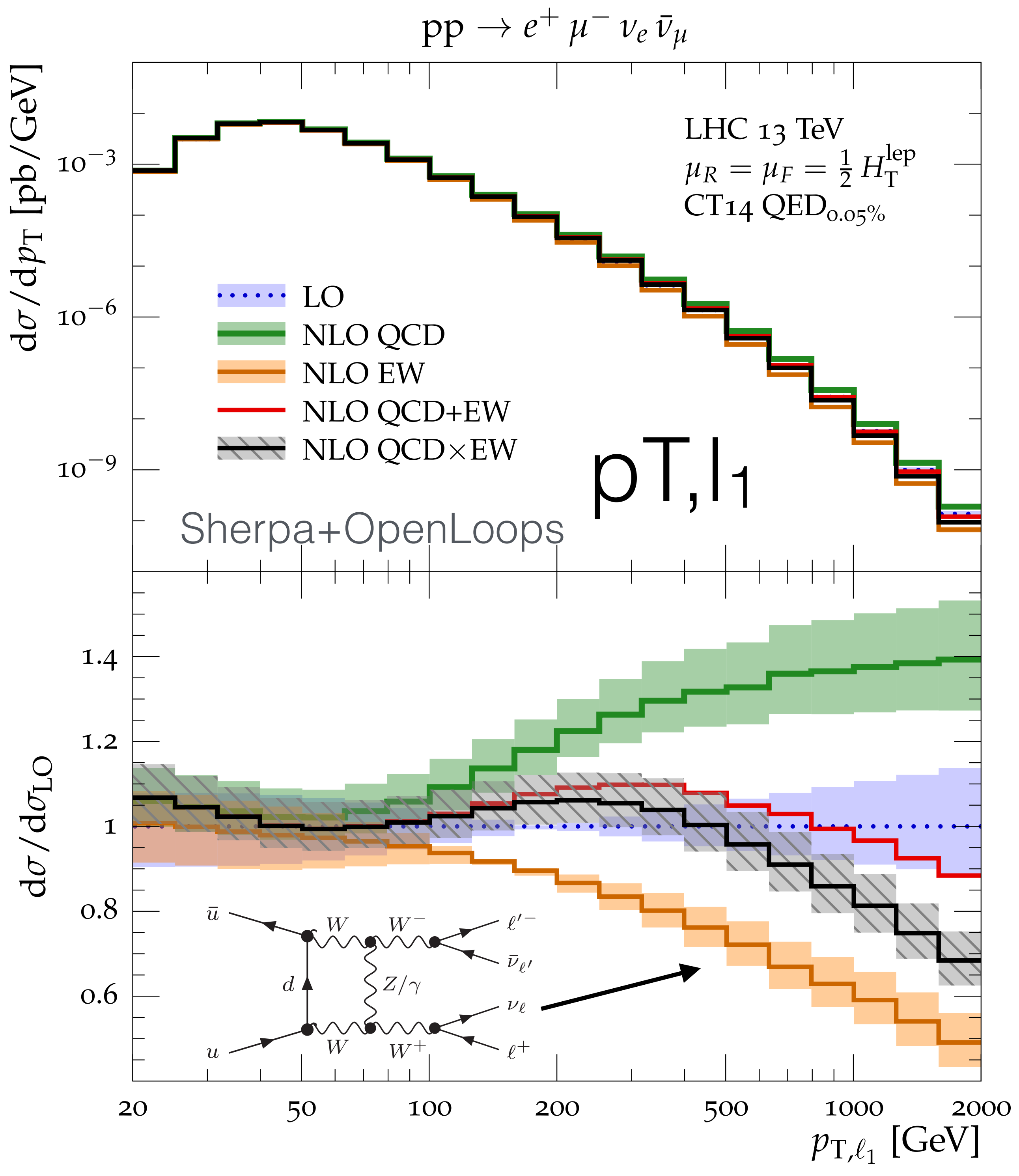
$$\alpha_S^N(\mu_{\mathrm{CKKW}}^2) = \alpha_S^{N-M}(\mu_{\mathrm{core}}^2)\,\alpha_S(t_1)\ldots\alpha_S(t_M)$$

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

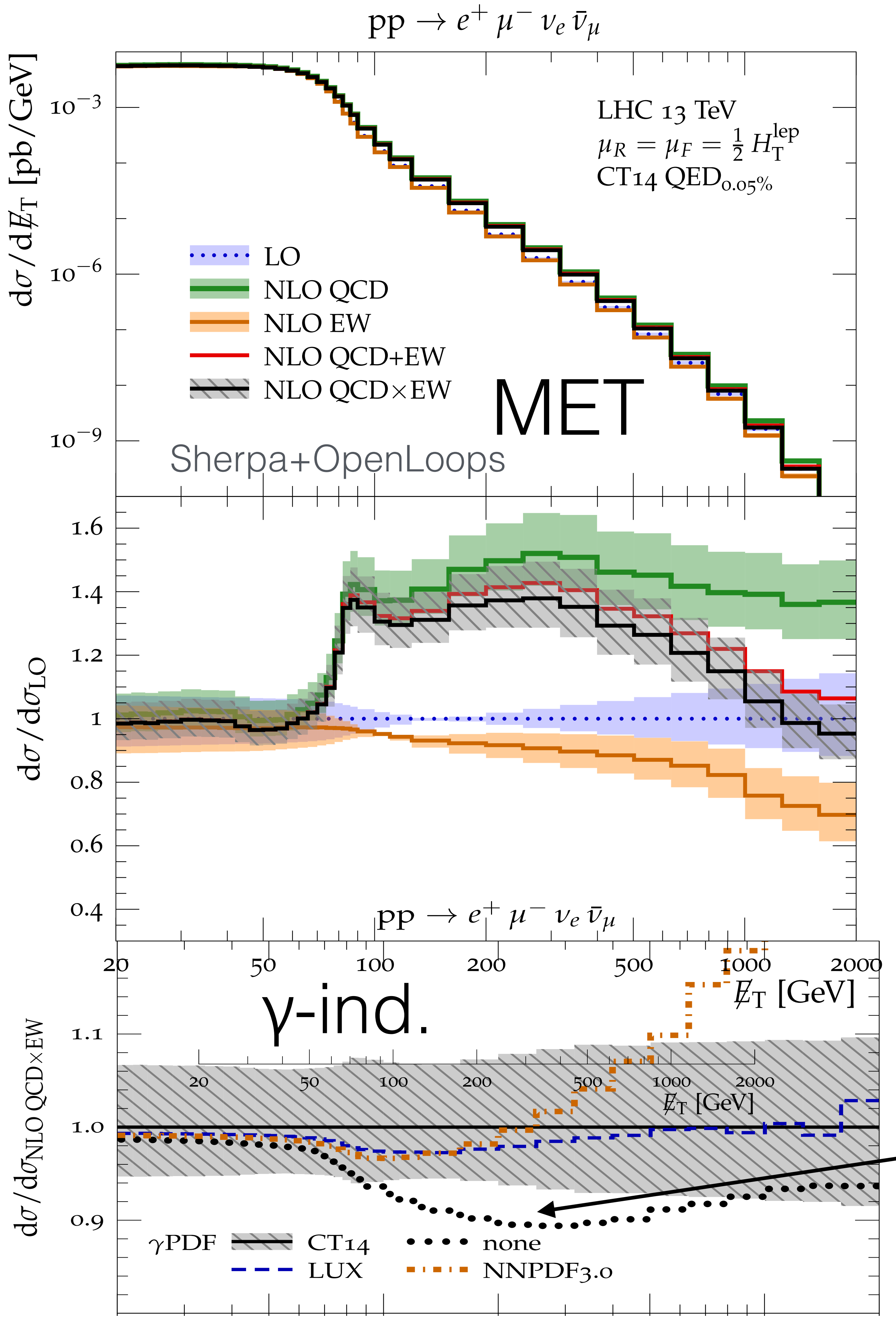
off-shell vector-boson pair production: WW-DF

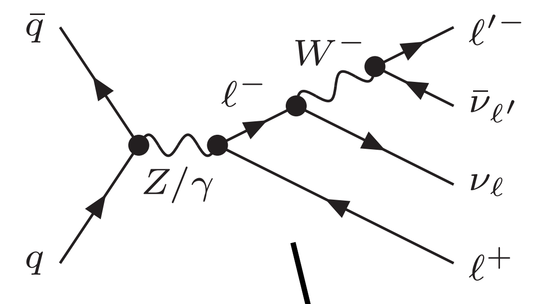
Motivation:
- important BSM background: **2 OS-DF leptons + MET**
- dominant H→ WW → 2l2ν background
- Search for aTGC's

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

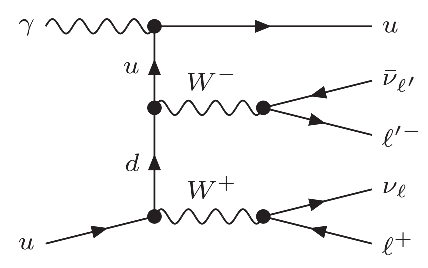


p_T of hardest lepton
- +40 % QCD corrections in the tail (Note: slight jet veto applied)
- LARGE negative EW corrections due to **Sudakov behaviour:** -40% @ 1 TeV

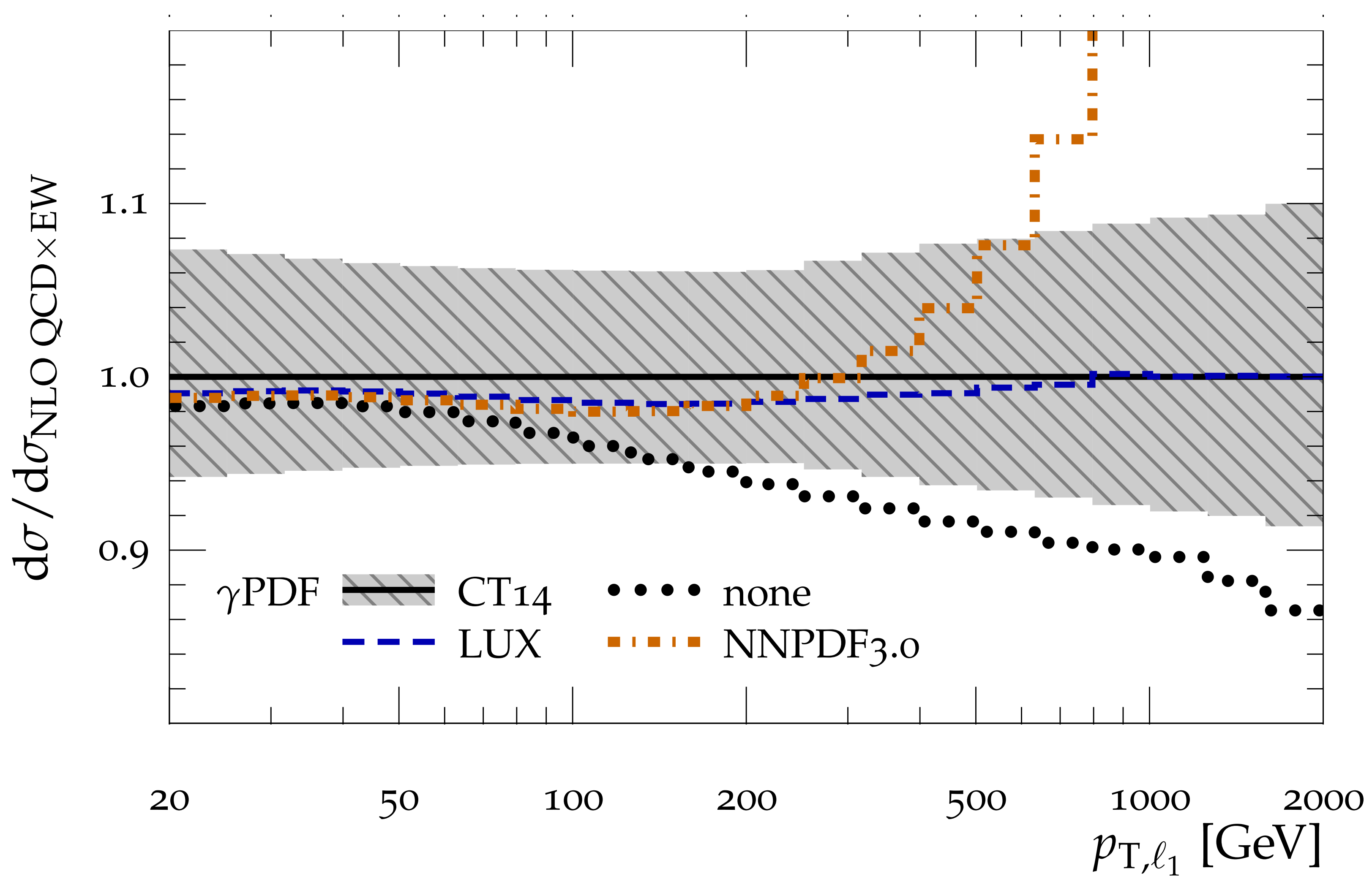


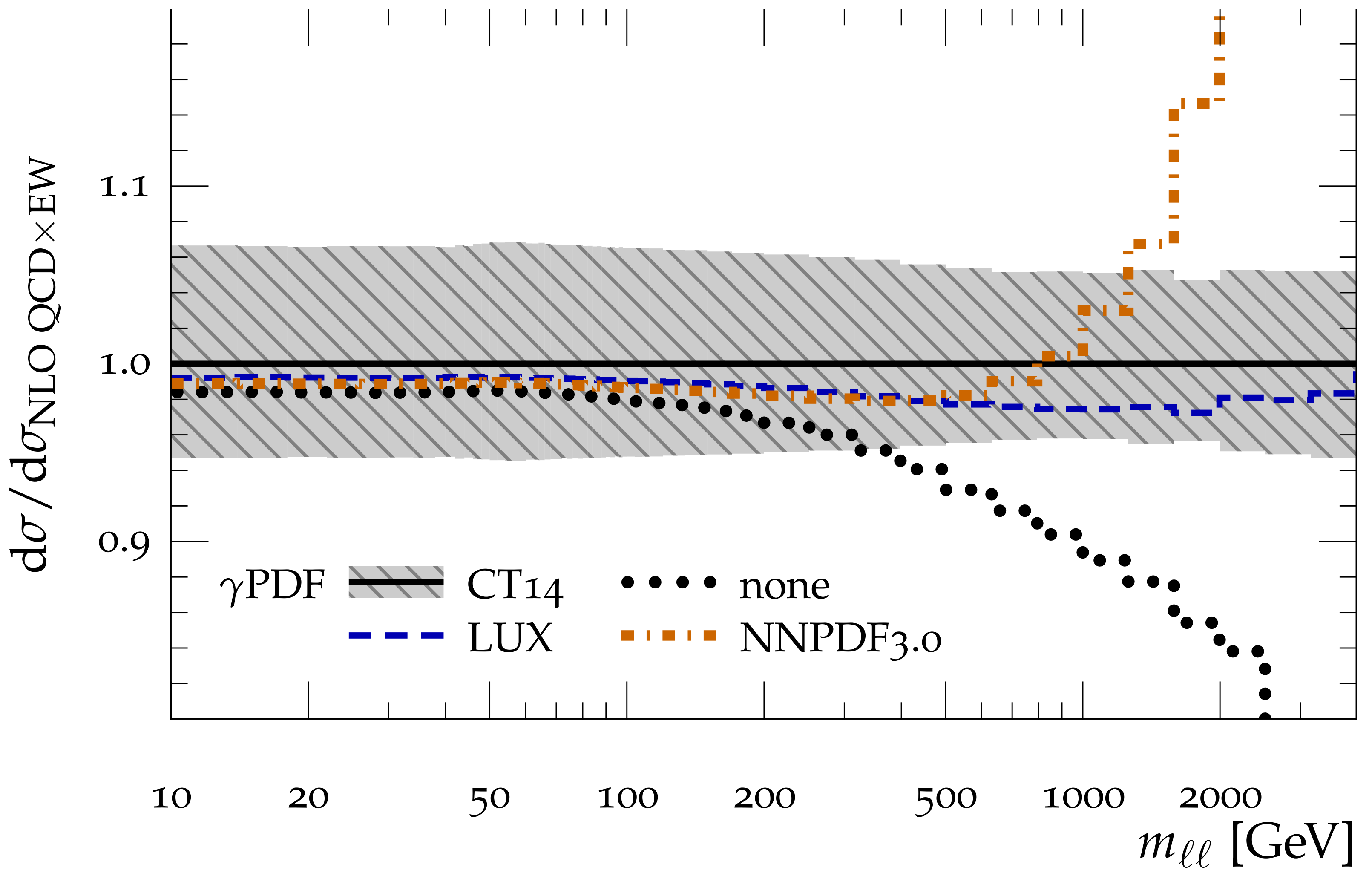


MET
- at large MET>MW: W's are forced off-shell
- jump in QCD corrections (extra jet unlocks back-to-back)
- relatively small EW corr.: -10% @ 1 TeV
- sizeable photon-induced contrib.: 10% for MET > 200 GeV

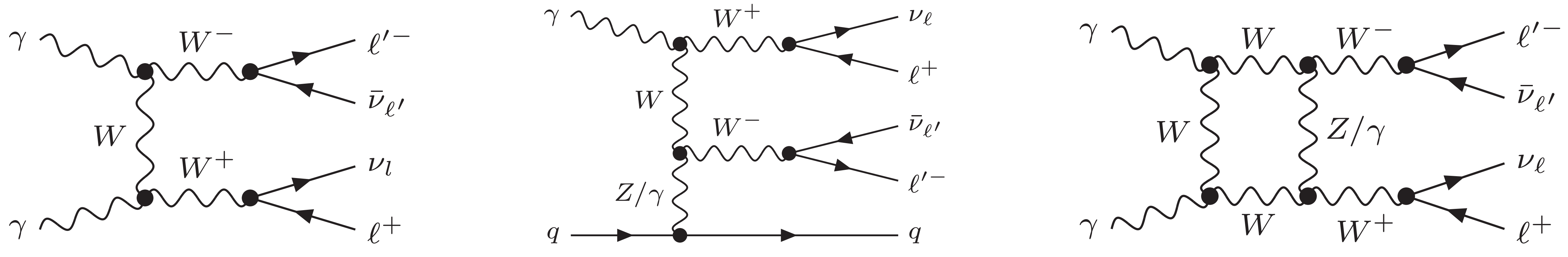


off-shell vector-boson pair production at NLO QCD+EW

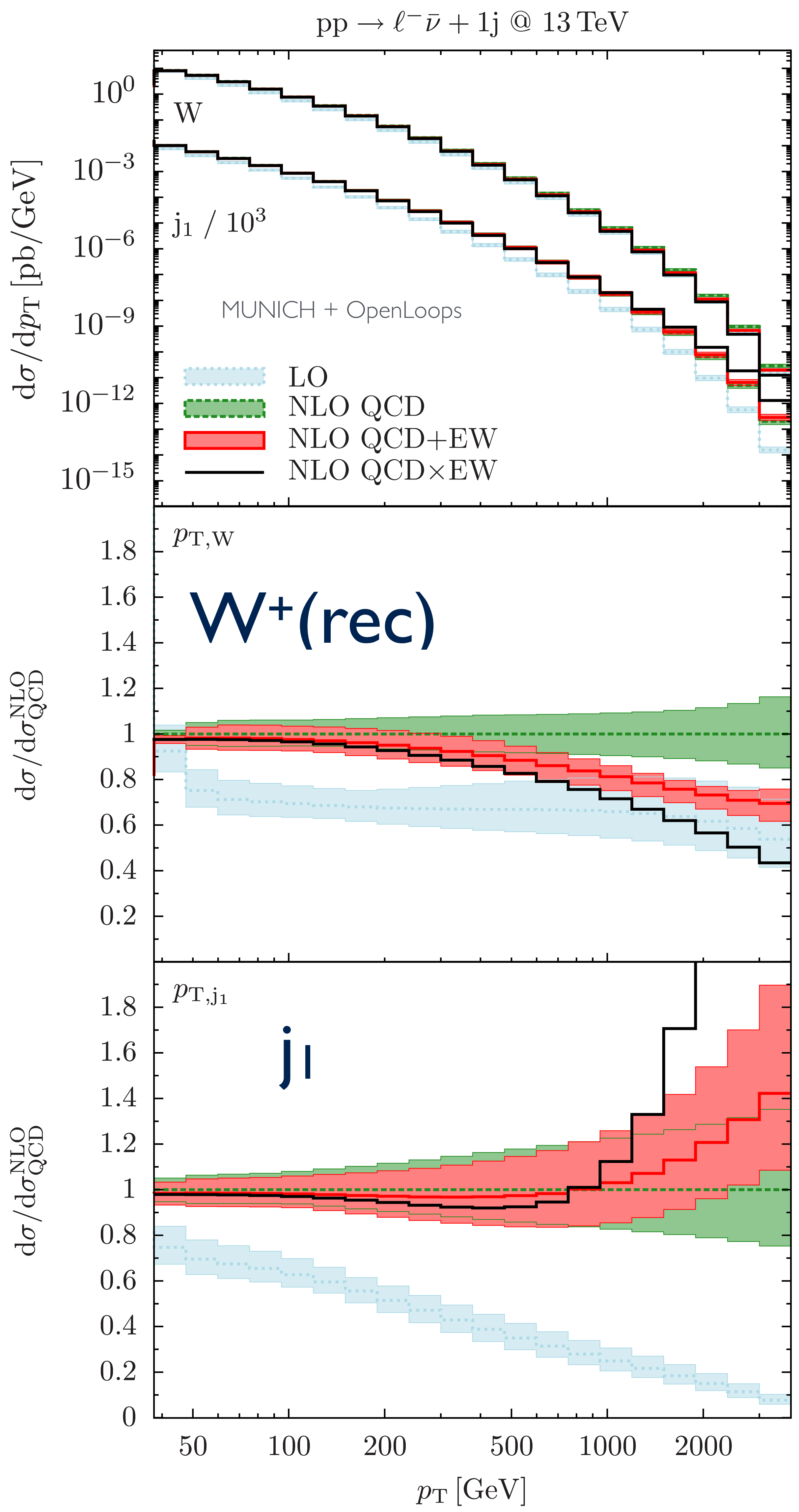




Effects of photon-induced production



l-ν + 1 jet: inclusive



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

Setup:
$\sqrt{S} = 13$ TeV
$p_{T,j} > 30$ GeV, $|\eta_j| < 4.5$
$p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$, $E_T^{miss} > 25$
$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

inclusive

$\lesssim$ 1% EW corrections

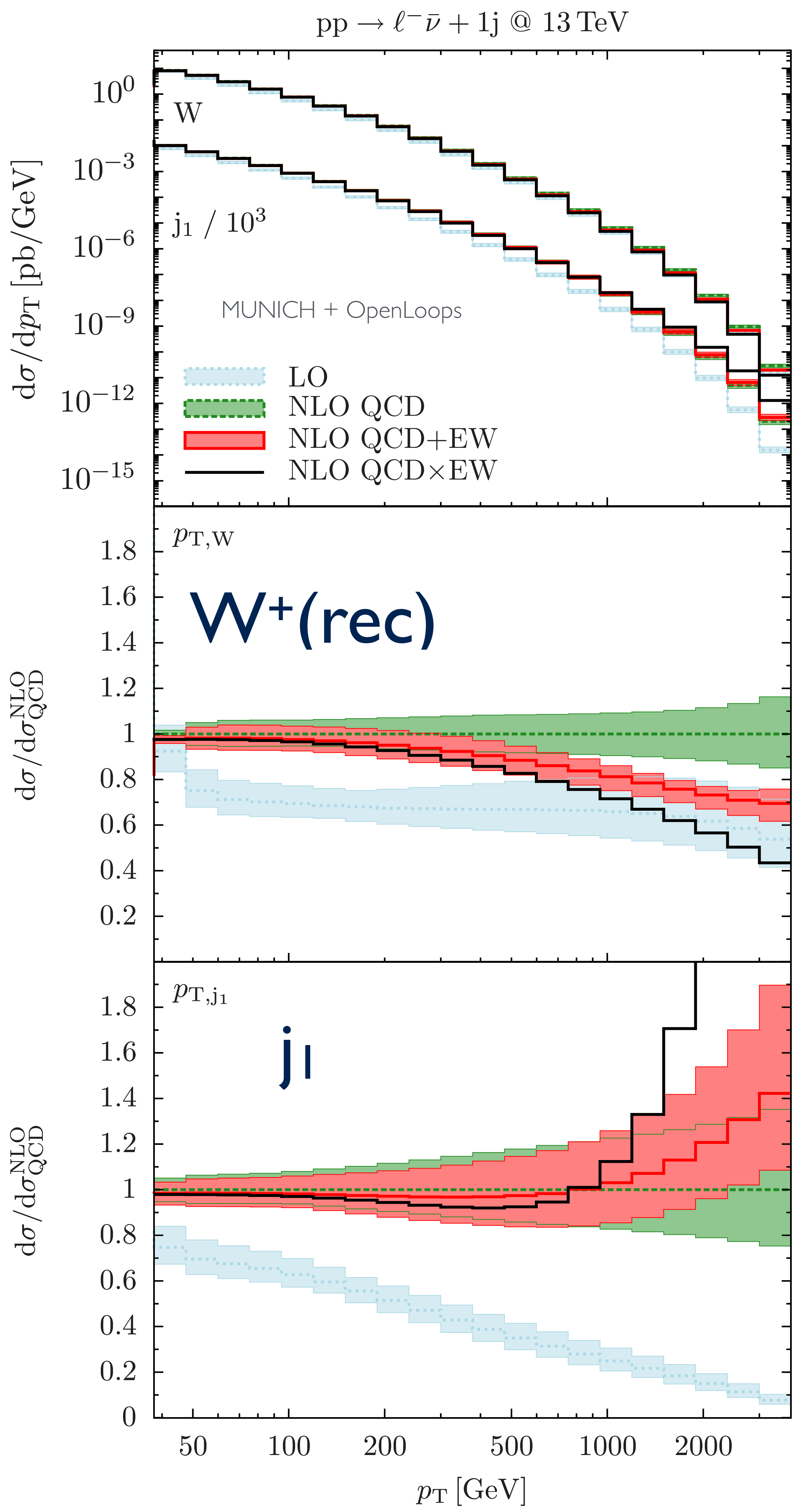
p_T of W-boson

- +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

l-ν + 1 jet: inclusive



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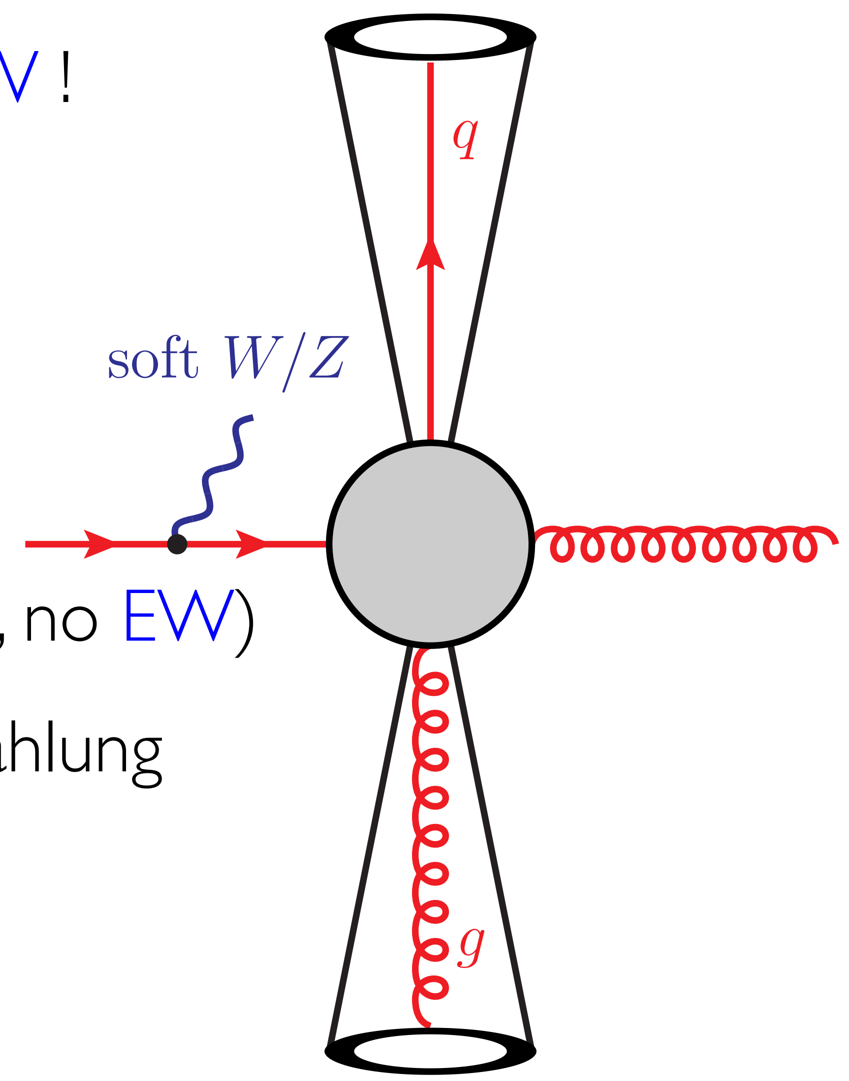

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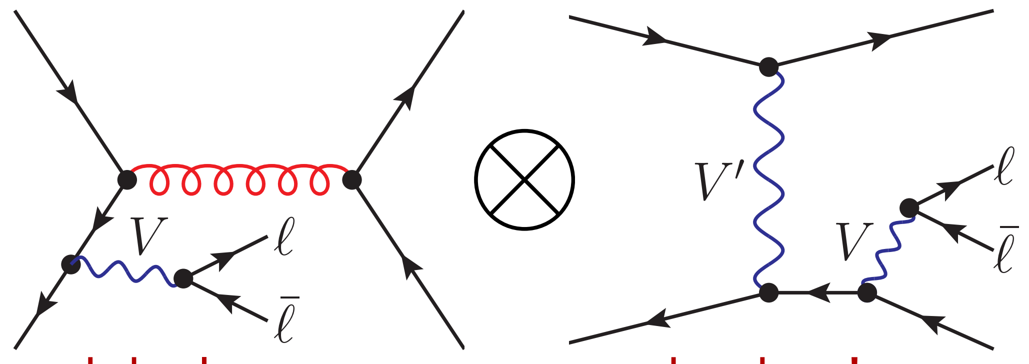
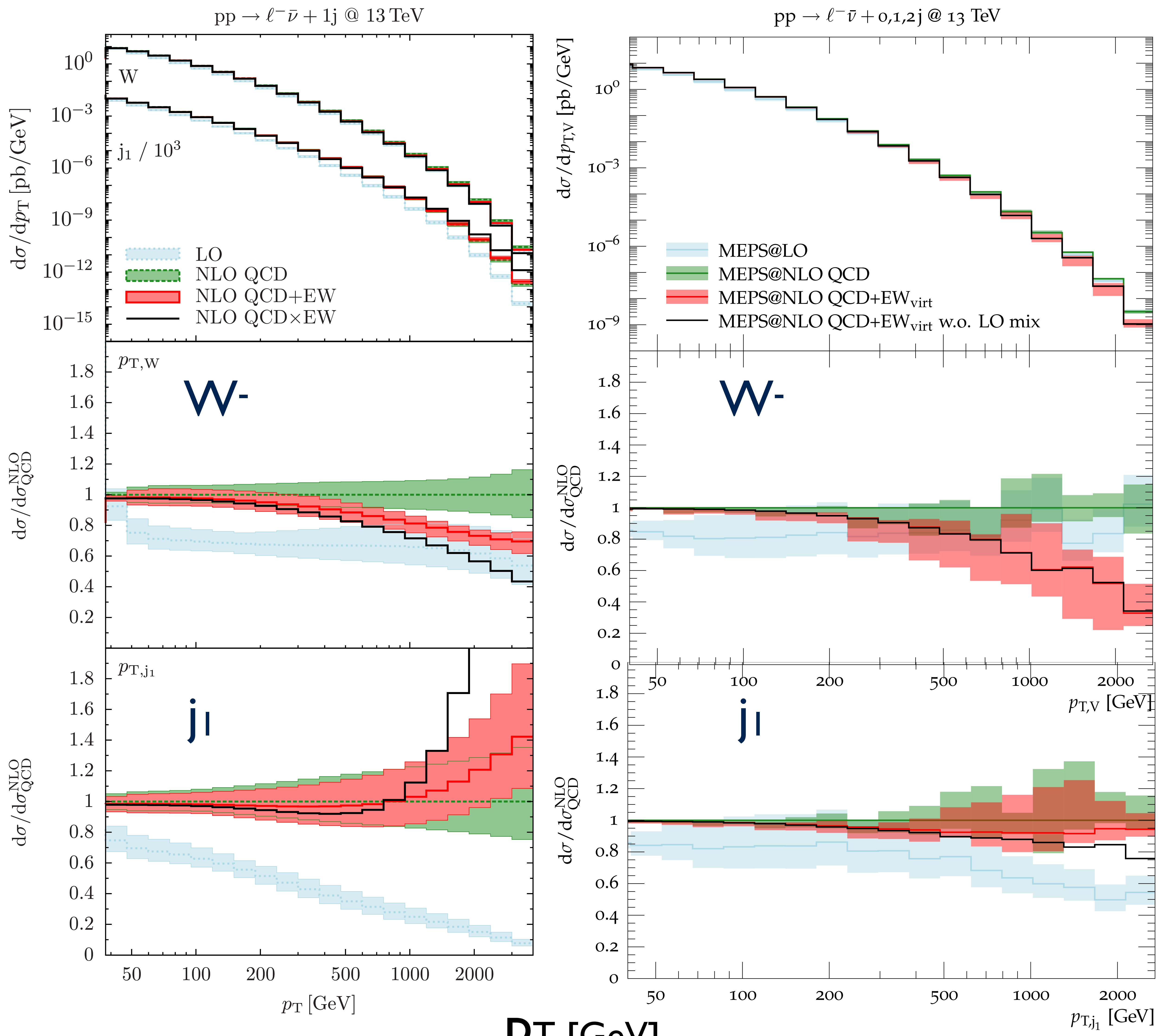


⟹ pathologic with large uncertainties!

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

NNLO QCD: *[Boughezal, Focke, Liu, Petriello '15]*

inclusive V: MEPS@NLO QCD+EW_{virt}



pT [GeV]

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- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$: compensation between negative Sudakov and LO mix

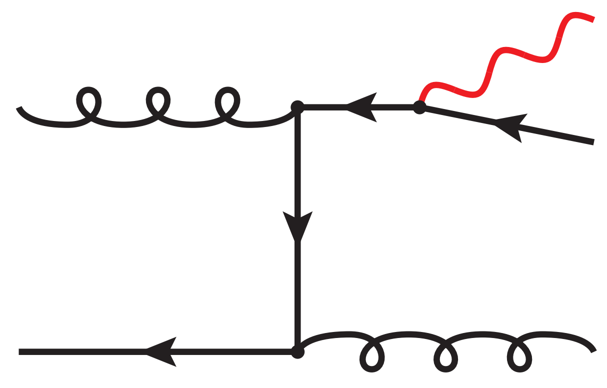
Caveat: γ+jet

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

$$\left|\frac{\sigma^{(V)}_{\rm NLO}}{\sigma^{(V)}_{\rm LO}} - \frac{\sigma^{(Z)}_{\rm NLO}}{\sigma^{(Z)}_{\rm LO}}\right| \ll \left|\frac{\sigma^{(Z)}_{\rm NLO}}{\sigma^{(Z)}_{\rm LO}}\right|$$

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

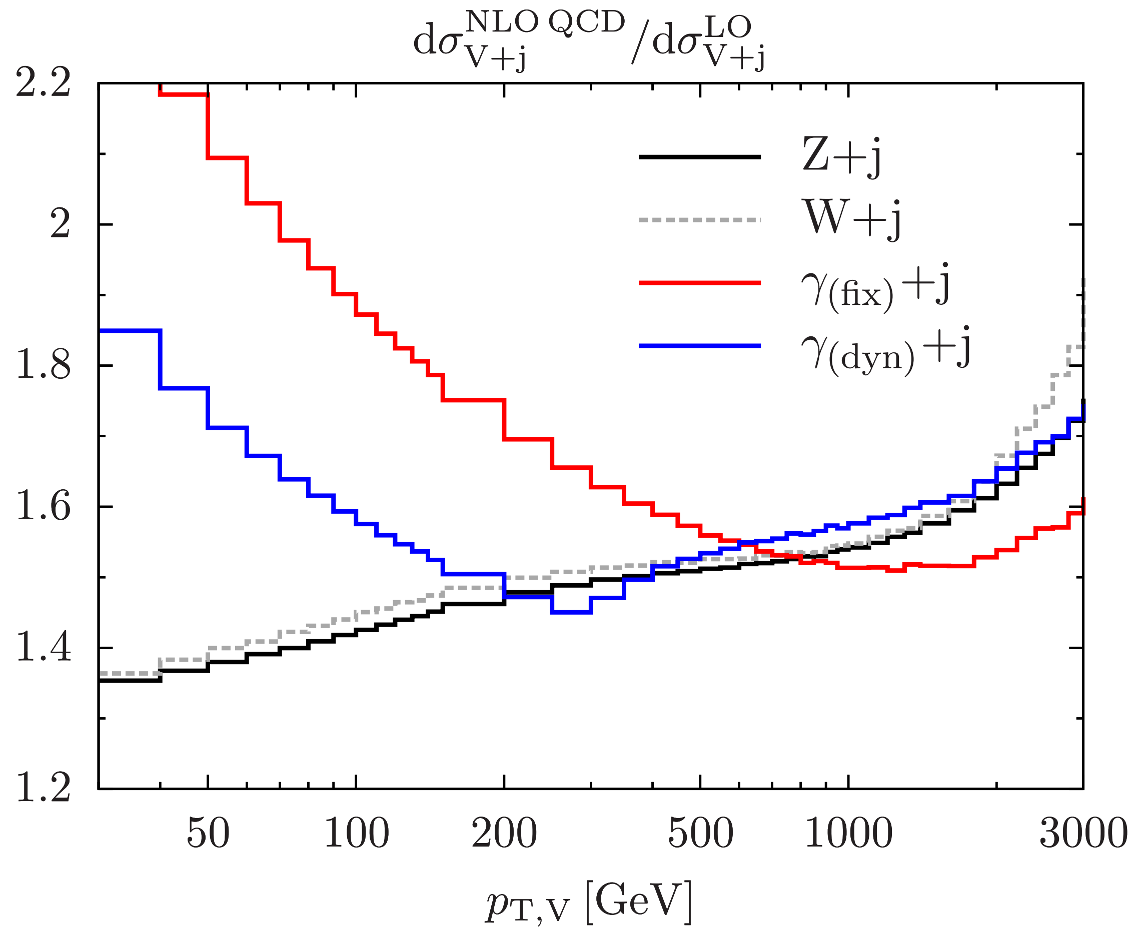
BUT: different logarithmic effects from fragmentation even at pT≫ M_V



W/Z+jet: mass cut-off → log(pT/M_V)

γ+ jet: Frixione-isolation cone of radius R_0 → log(R_0)

Consider dynamic γ-isolation with $R_{\rm dyn}(p_{{\rm T},\gamma}, \varepsilon_0) = \frac{M_Z}{p_{{\rm T},\gamma}\sqrt{\varepsilon_0}}$



- $\gamma_{\rm dyn}$ behaves like W or Z at pT > M_V

  ⇒justifies process-correlation estimate

- Additional uncertainty: remnant part $\gamma_{\rm fix} - \gamma_{\rm dyn}$ (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)

$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}(\vec{\varepsilon}_{\mathrm{MC}},\vec{\varepsilon}_{\mathrm{TH}}) := \frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})\left[\frac{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}}(\vec{\varepsilon}_{\mathrm{TH}})}{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})}\right]$$

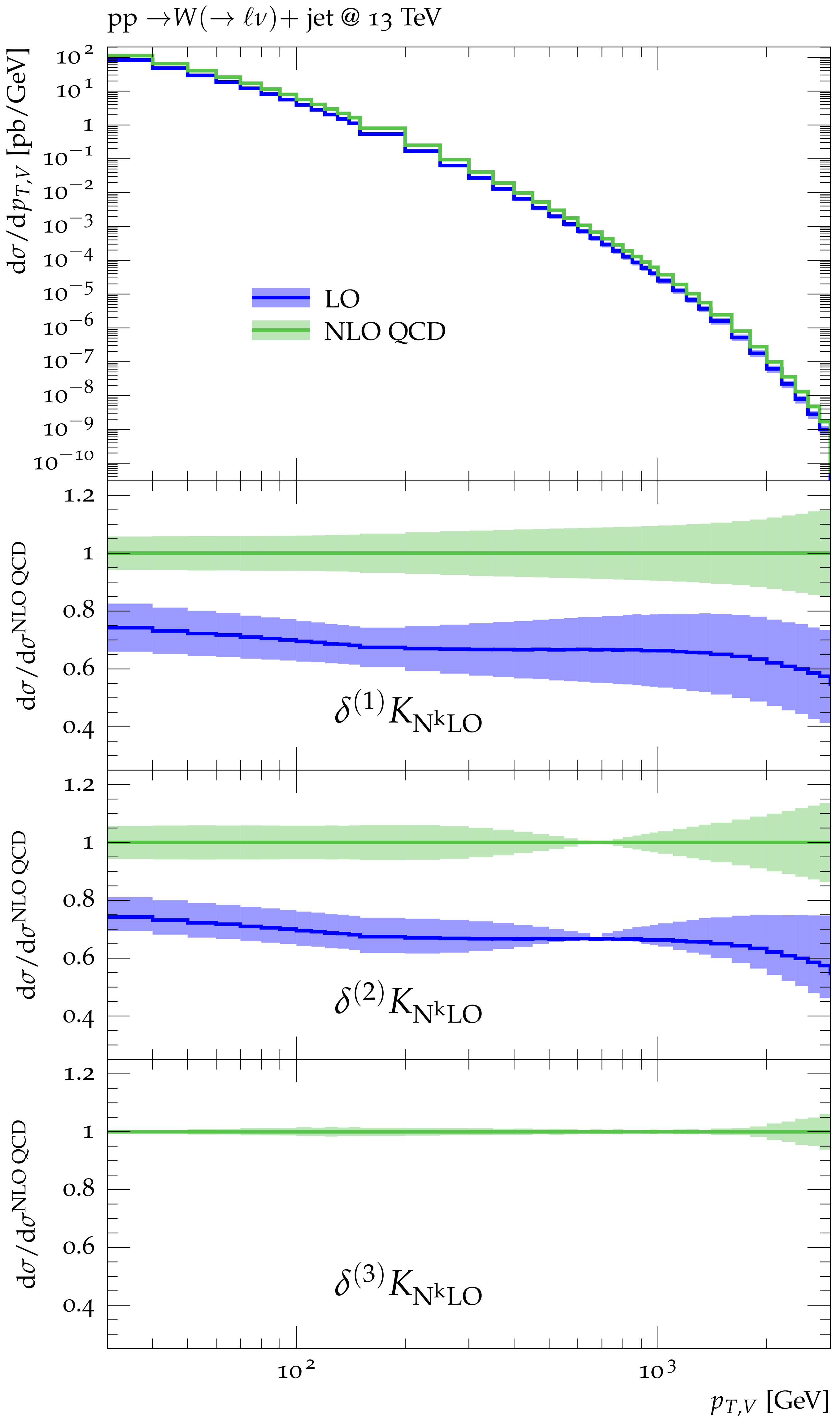
one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

with $$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{mix}} + \frac{\mathrm{d}}{\mathrm{d}x}\Delta\sigma^{(V)}_{\mathrm{EW}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}$$

- **Robust uncertainty estimates including**
  1. **Pure QCD uncertainties**
  2. **Pure EW uncertainties**
  3. **Mixed QCD-EW uncertainties**
  4. **PDF, γ-induced uncertainties ….**

- Prescription for **correlation** of these uncertainties
  - within a process (between low-pT and high-pT)
  - across processes

QCD uncertainties



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N^kLO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[K^{(V)}_{\mathrm{N^kLO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N^kLO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

nuisance parameters:

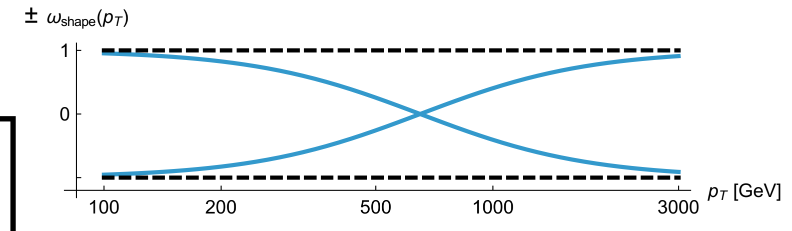
interpreted as 1σ Gaussian

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

- correlated across processes
- correlated across pT bins

- $$\delta^{(1)}K^V_{\mathrm{N^kLO}} = \frac{1}{2}\left[K^{V,\max}_{\mathrm{N^kLO}} - K^{V,\min}_{\mathrm{N^kLO}}\right]$$ *(correlated)*

  symmetrized **scale uncertainty**



- $$\delta^{(2)}K^V_{\mathrm{N^kLO}} = \frac{p_{\mathrm{T}}^2 - 650\ \mathrm{GeV}}{p_{\mathrm{T}}^2 + 650\ \mathrm{GeV}}\,\delta^{(1)}K^V_{\mathrm{N^kLO}}$$

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

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

- $$\delta^{(3)}K^V_{\mathrm{N^kLO}} = \frac{K^V_{\mathrm{N^kLO}}}{K^V_{\mathrm{N^{k-1}LO}}} - \frac{K^Z_{\mathrm{N^kLO}}}{K^Z_{\mathrm{N^{k-1}LO}}}$$ *(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, '93] Available schemes: on-shell, G_μ and $\alpha(mZ)$
- R_2 rational terms
- Treatment of unstable particles: complex-mass-scheme

✓ Real radiation, subtraction, subprocess bookkeeping

✓ **Sherpa**

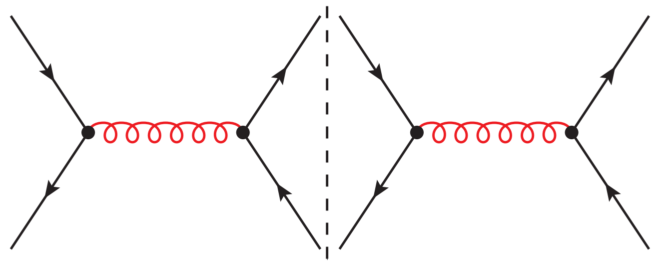
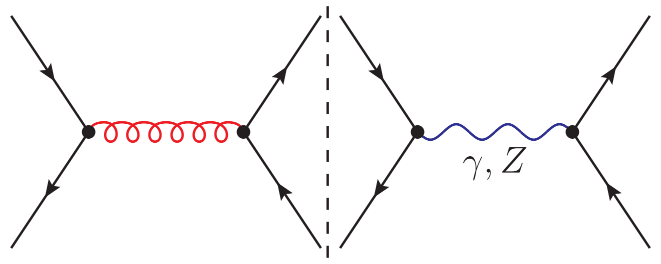
✓ **MUNICH**:

- Based on the well established NLO QCD dipole subtraction framew… …ements for QCD → QED

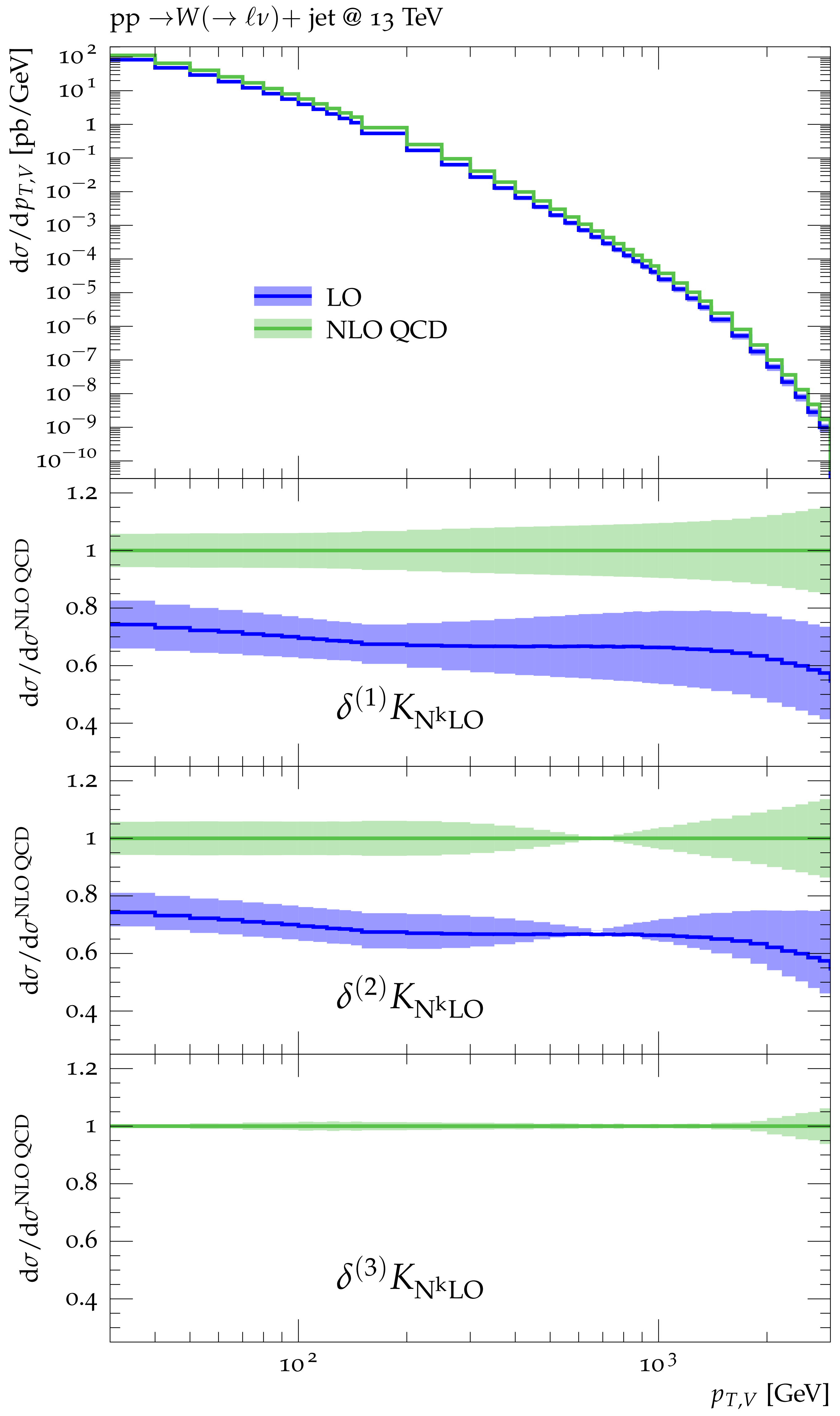
$$\alpha_s \longrightarrow \alpha, \qquad C_F \longrightarrow Q_f^2, \qquad T_R \longrightarrow N_{c,f} Q_f^2, \qquad T_R N_f \longrightarrow \sum_f N_{c,f} Q_f^2, \qquad C_A \longrightarrow 0$$

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

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

$$I \propto \sum \int_1 V_{\text{QED}} \otimes$$

$$+ \int_1 V_{\text{QCD}} \otimes$$


QCD uncertainties



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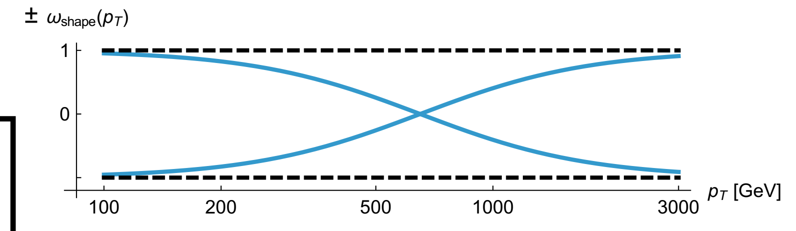
- $$\delta^{(1)}K^V_{\mathrm{N^kLO}} = \frac{1}{2}\left[K^{V,\max}_{\mathrm{N^kLO}} - K^{V,\min}_{\mathrm{N^kLO}}\right]$$ *(correlated)*

symmetrized **scale uncertainty**



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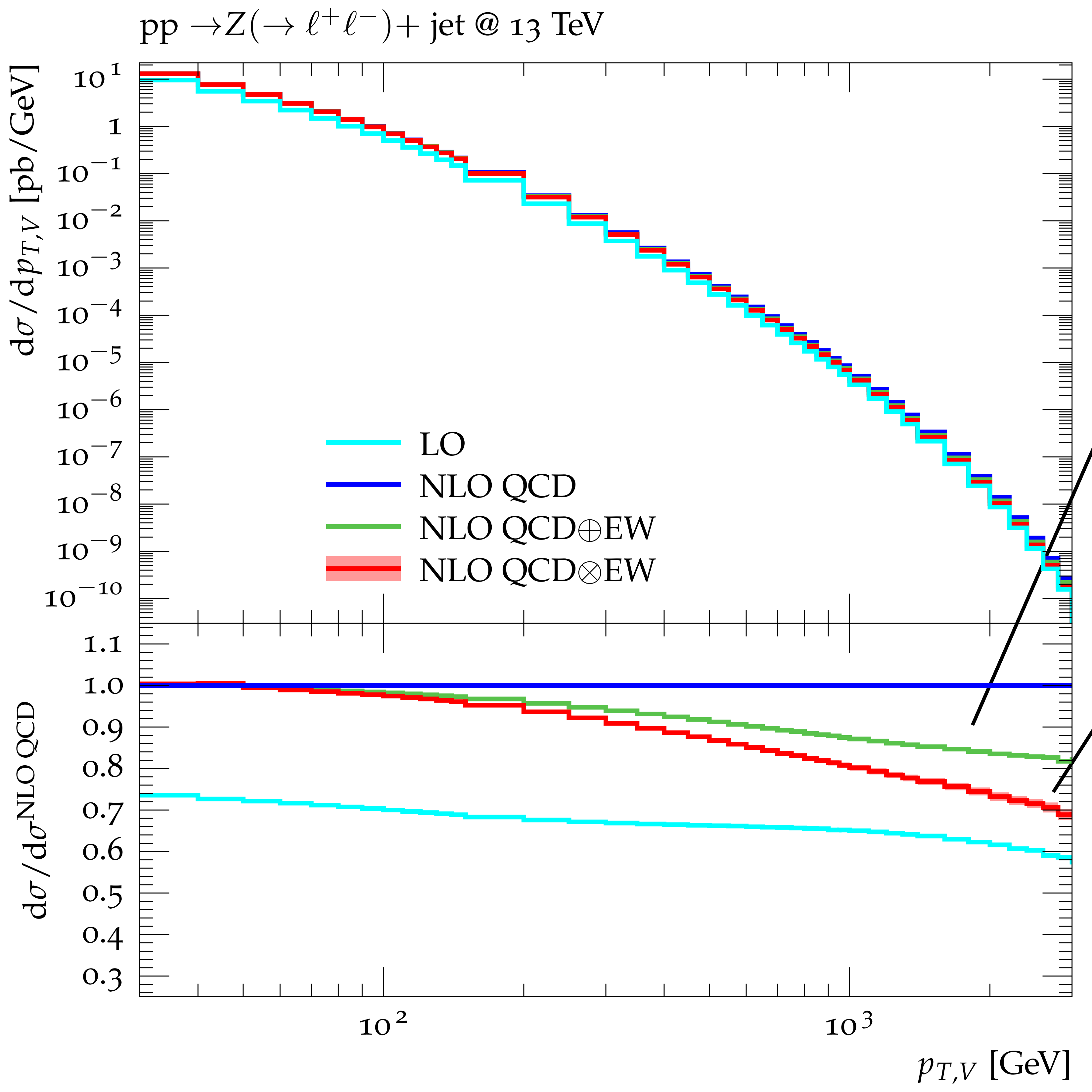
Difference of (N)NLO corrections as **process correlation uncertainty**

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

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm LO} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

Multiplicative combination

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

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

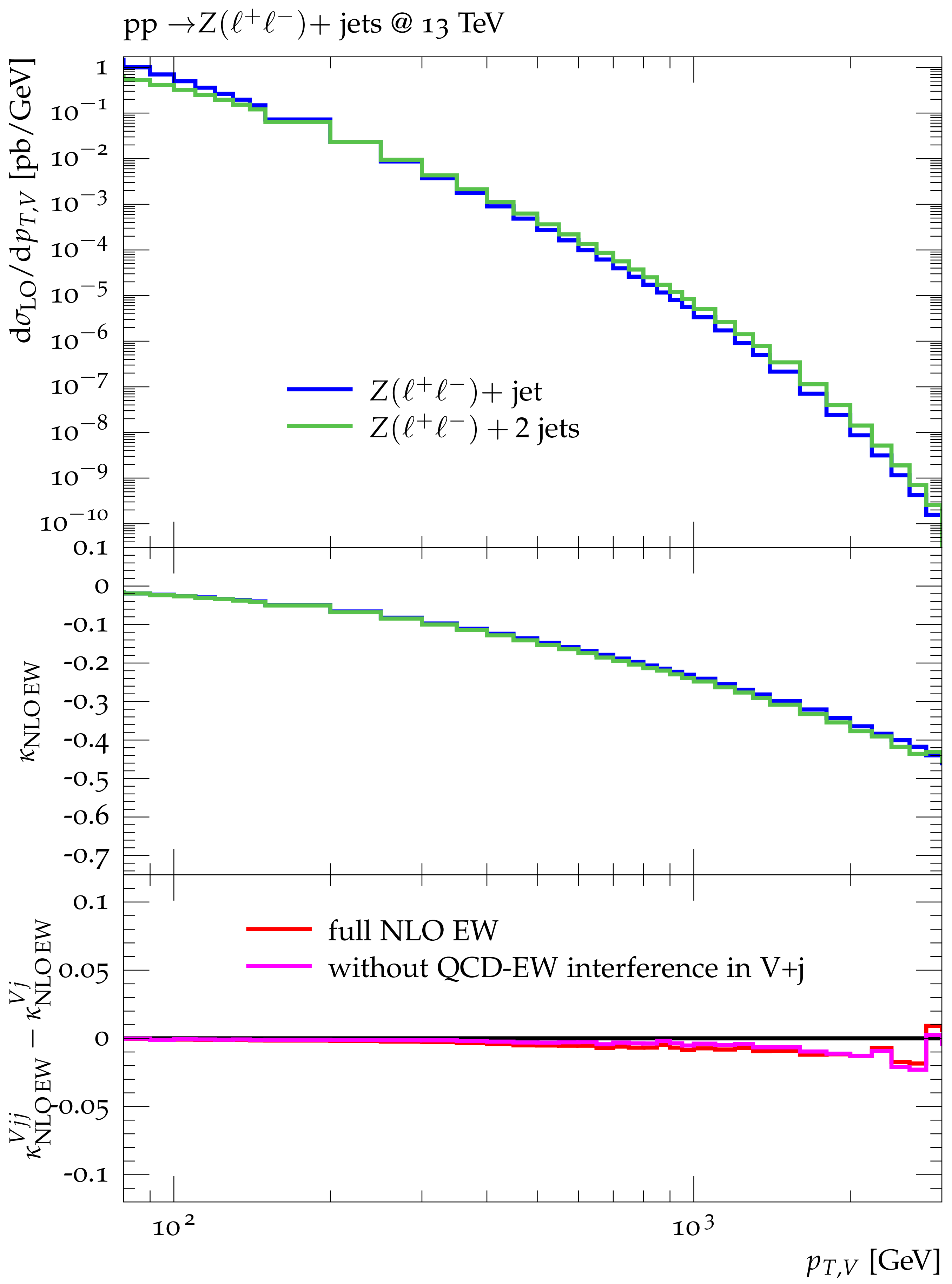
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

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

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

Mixed QCD-EW uncertainties



pT$_{j,2}$ > 30 GeV

Bold estimate:

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

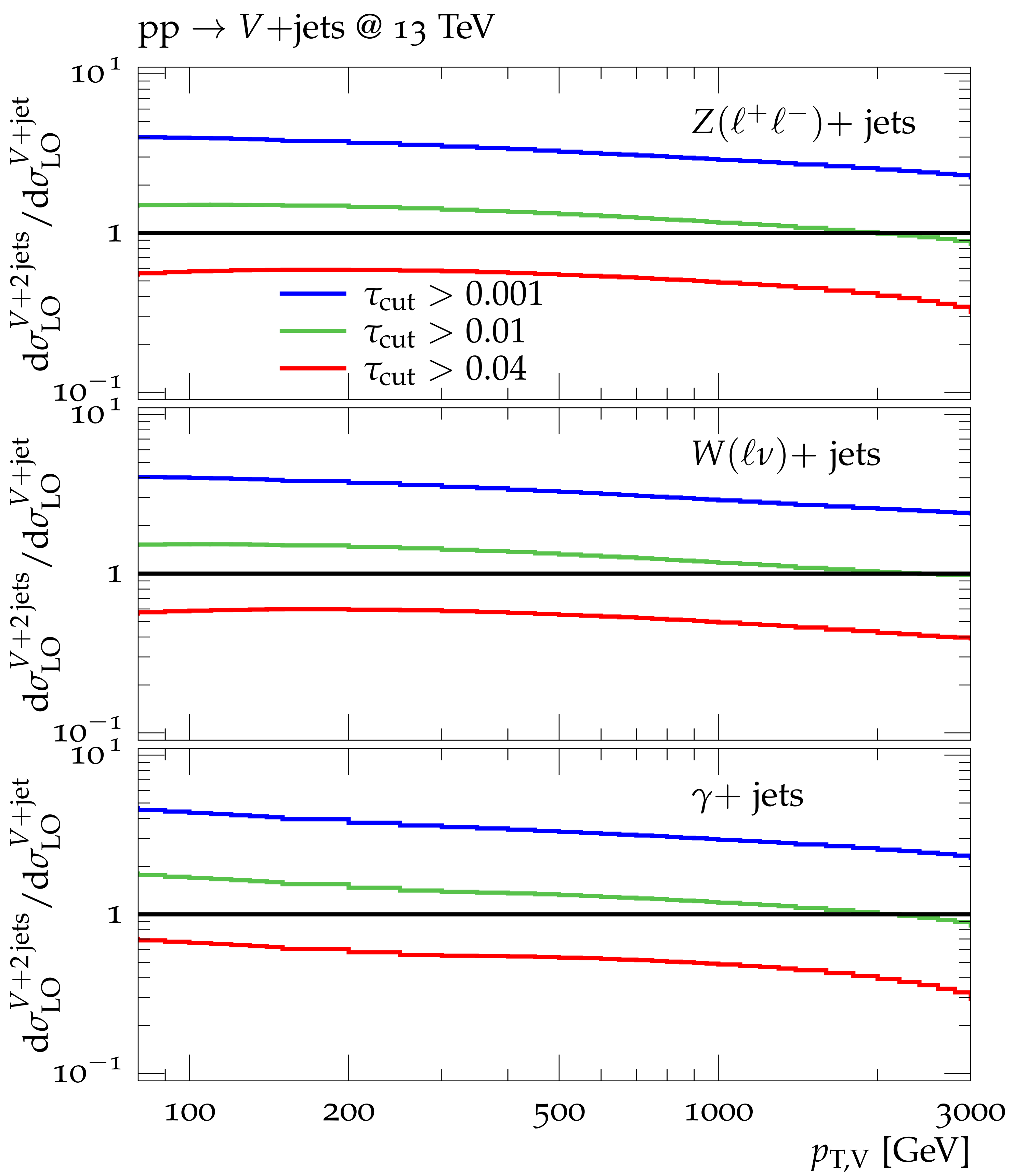
and we observe

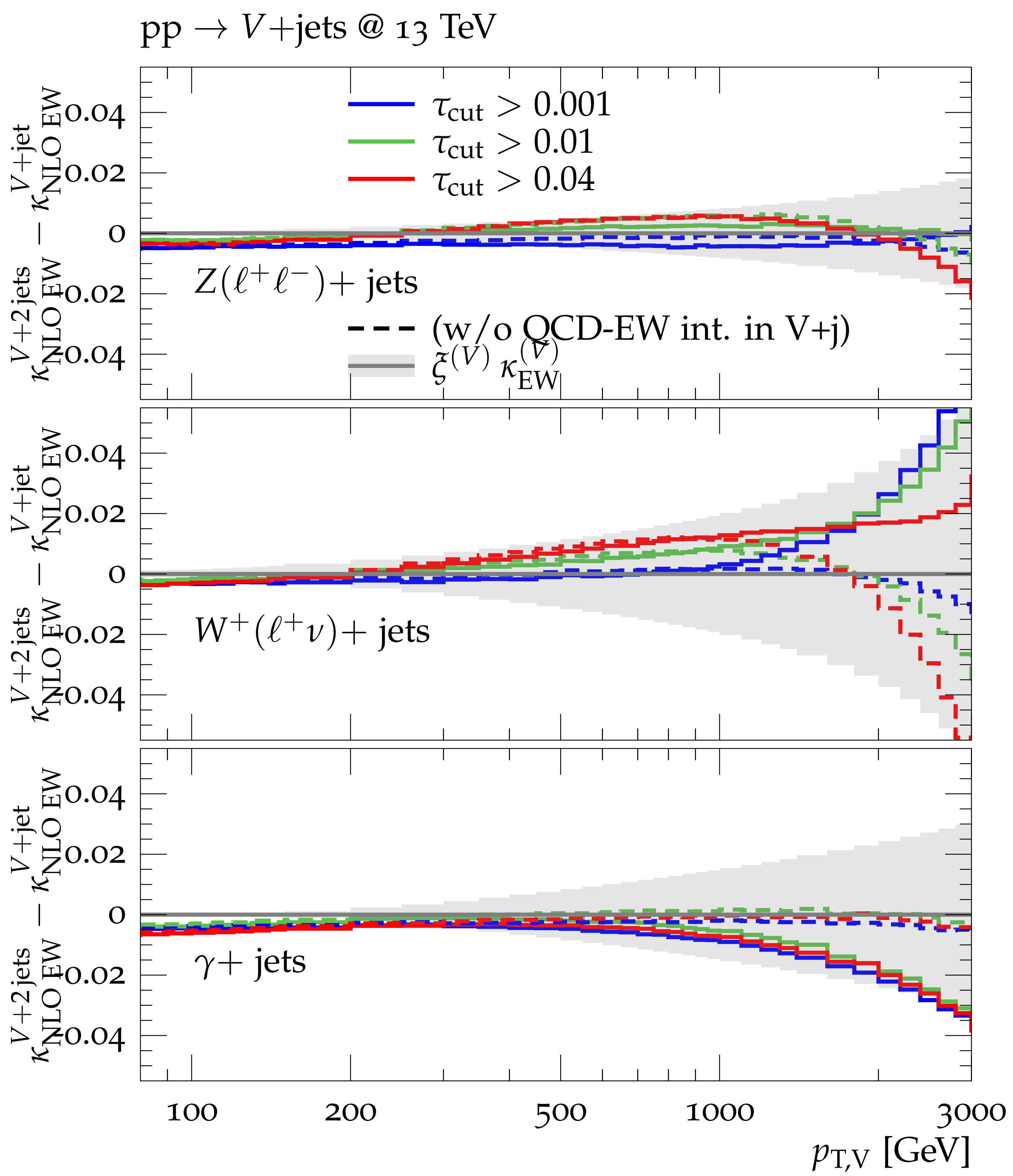
$$\left.\frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}}\right|_{V+2\text{jet}} - \left.\frac{d\sigma_{\text{NLO EW}}}{d\sigma_{\text{LO}}}\right|_{V+1\text{jet}} \lesssim 1\%$$

strong support for
- factorization
- multiplicative QCD x EW combination

Mixed QCD-EW uncertainties

Estimate of non-factorising contributions





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

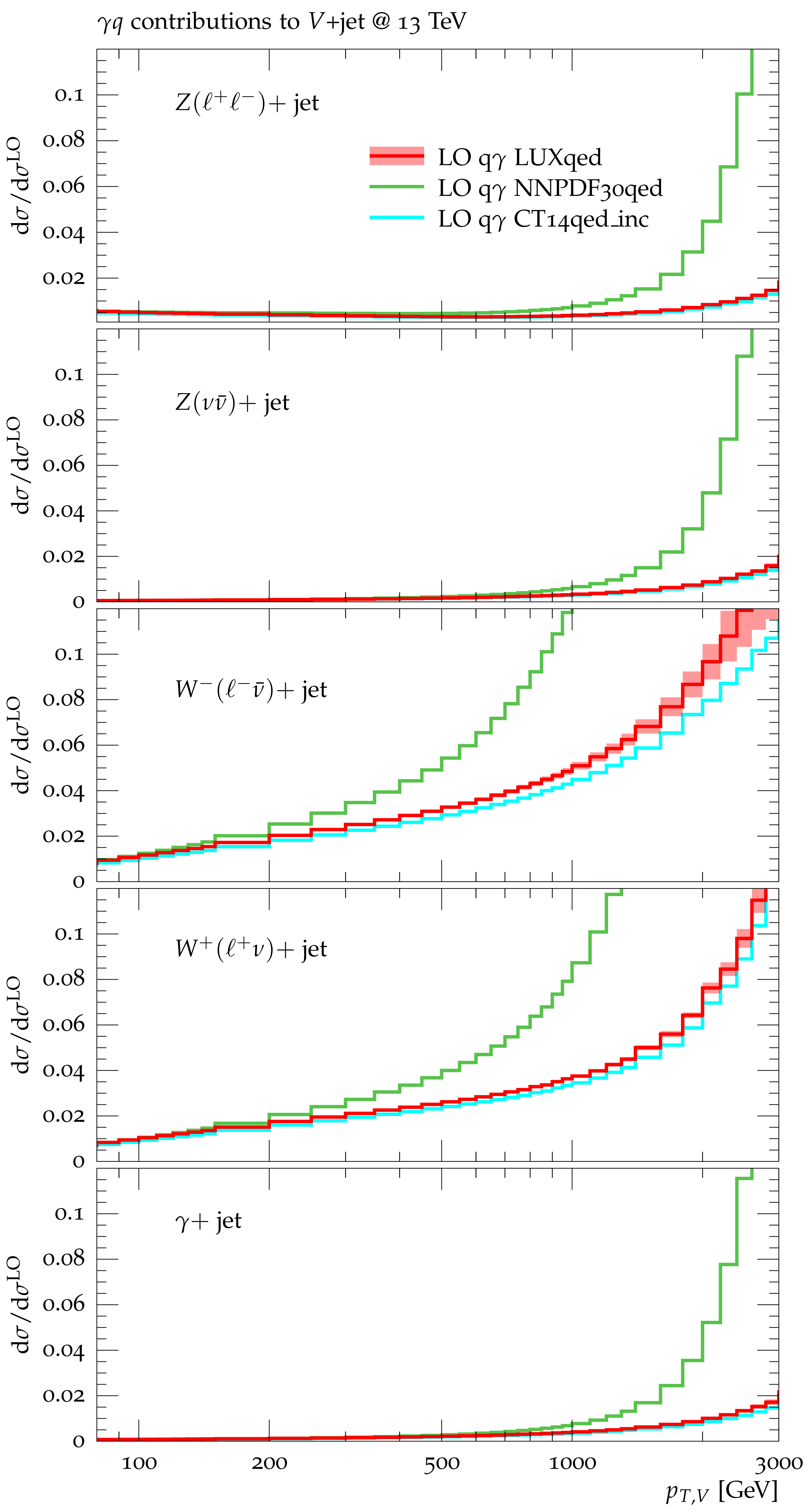
$$\tau_1 = \sum_k \min_i \left\{ \frac{2 p_i \cdot q_k}{Q_i \sqrt{\hat{s}}} \right\}$$

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

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

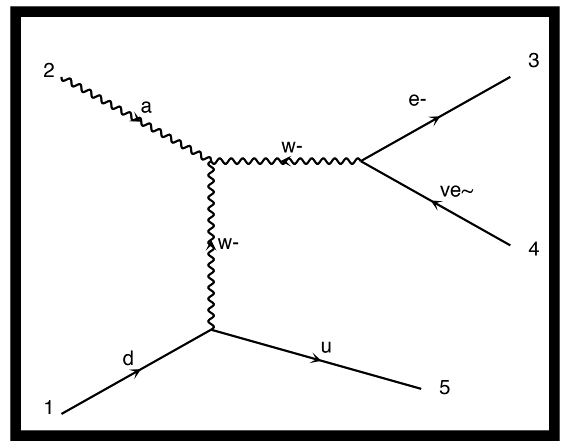
(tuned to cover above difference of EW K-factors)

Photon-induced production



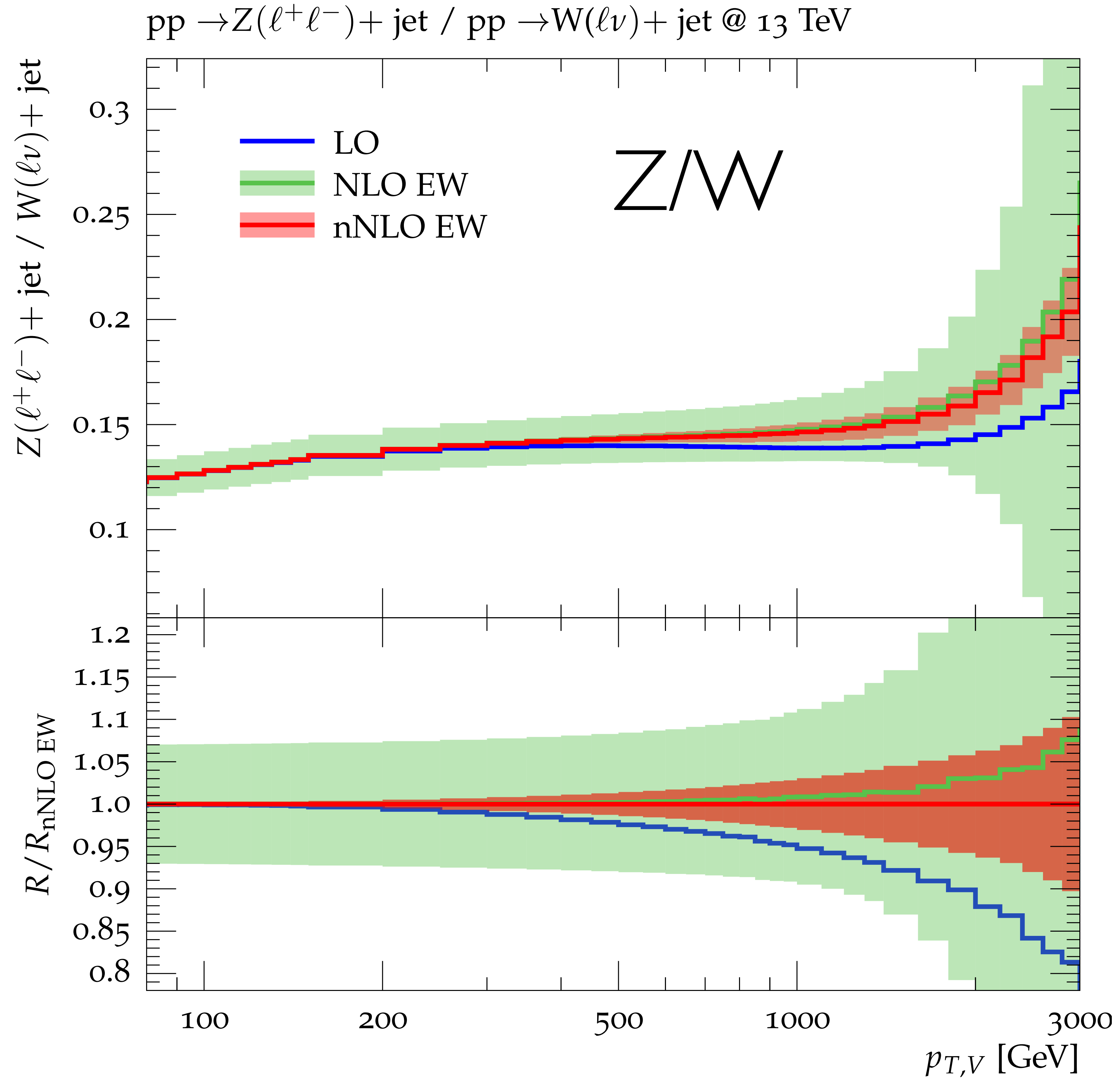
- suppressed by relative factor α/α_S
- irrelevant for Z+jet (and **γ**+jet)
- in W+jet O(5%) contribution with LUXqed, consistent with CT14qed

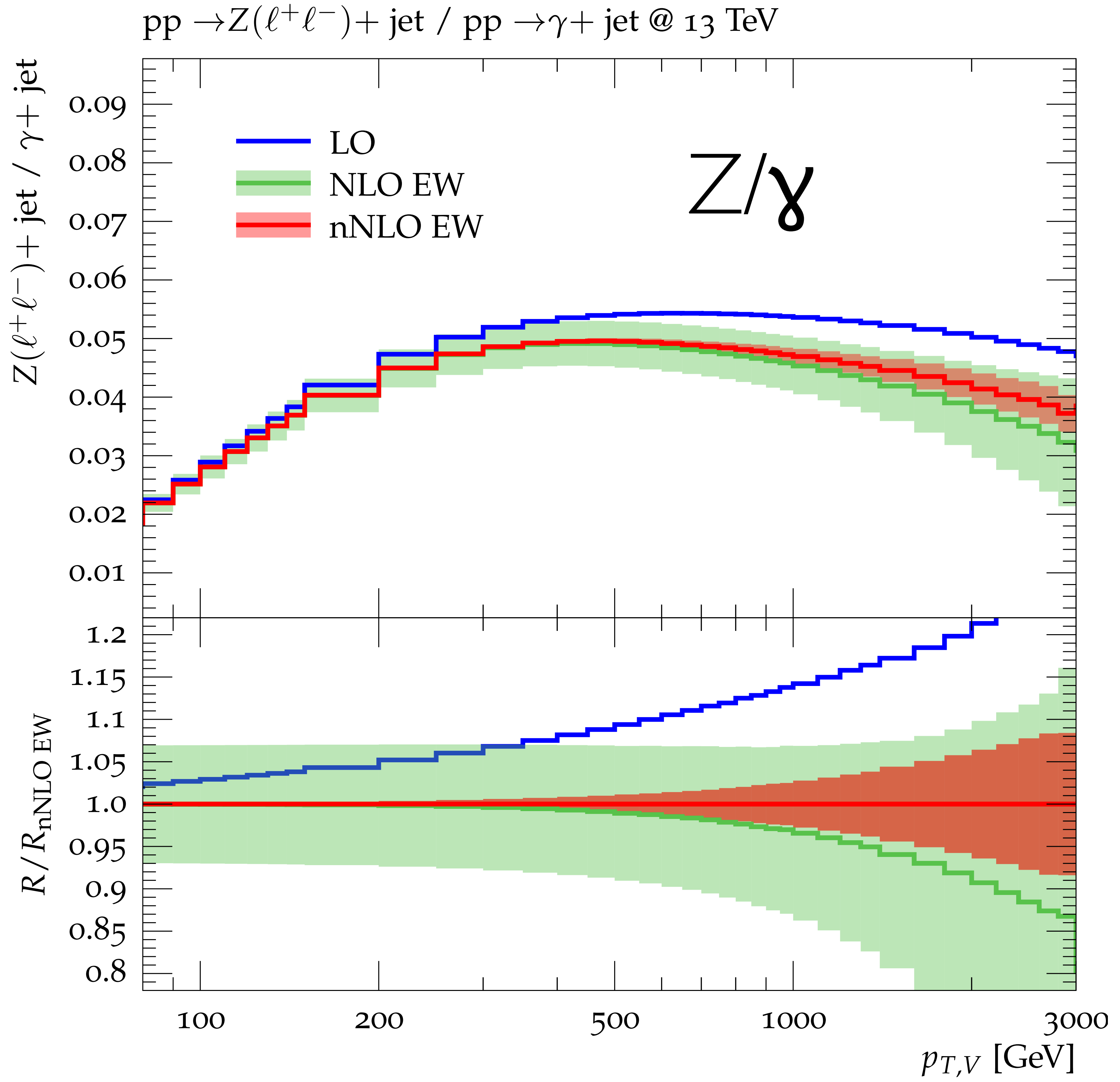
  (due to t-channel enhancement)



- ~1% uncertainties in photon PDFs due to LUXqed

Pure EW uncertainties: ratios





- NLO EW: ~5% for pT=1 TeV
- nNLO EW: ~1% for pT=1 TeV

- NLO EW: ~15% for pT=1 TeV
- nNLO EW: ~4% for pT=1TeV

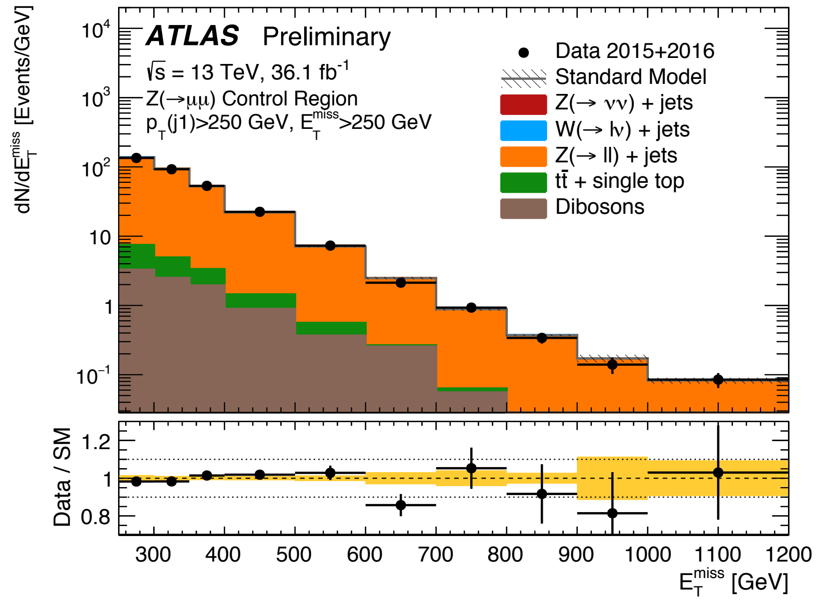
δ(R) < 3-5% for pT < 1-2 TeV

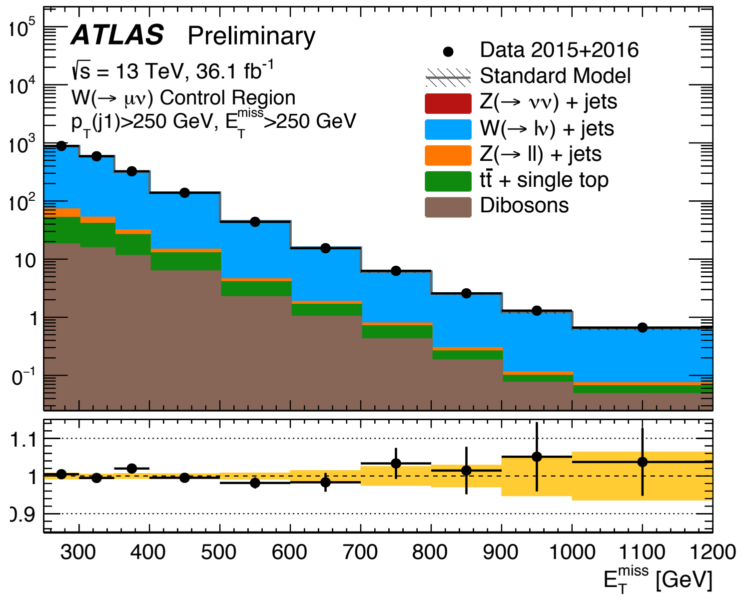
Experimental closure tests
in recent ATLAS & CMS monojet searches

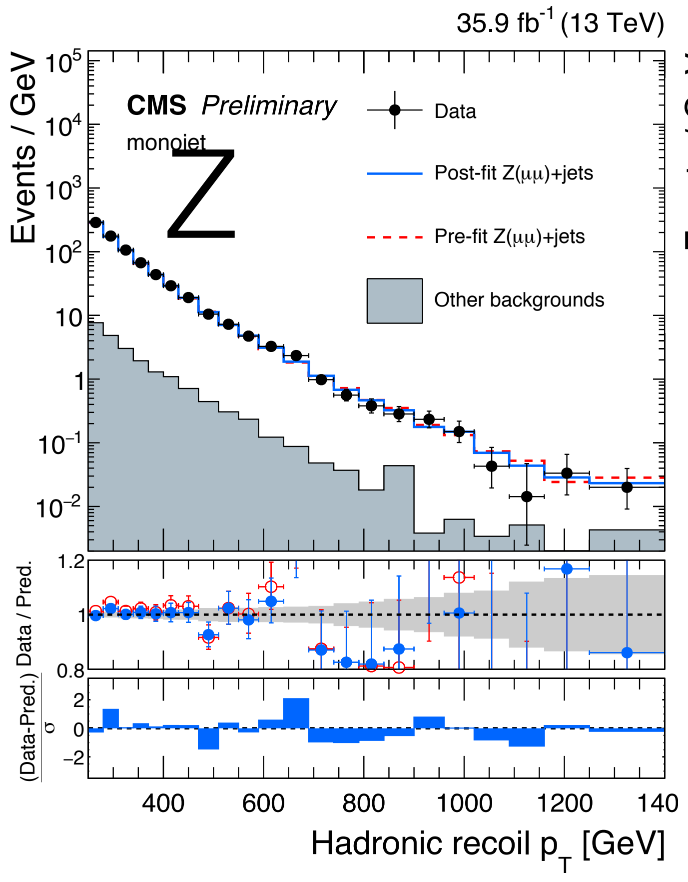
[ATLAS-CONF-2017-060]

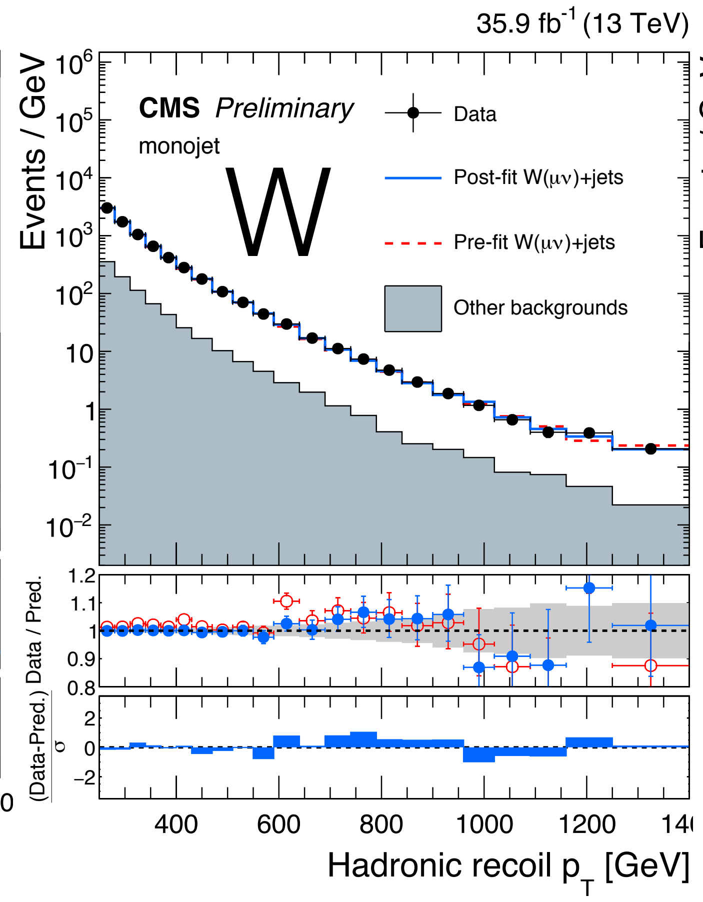
[CMS PAS EXO-16-048]

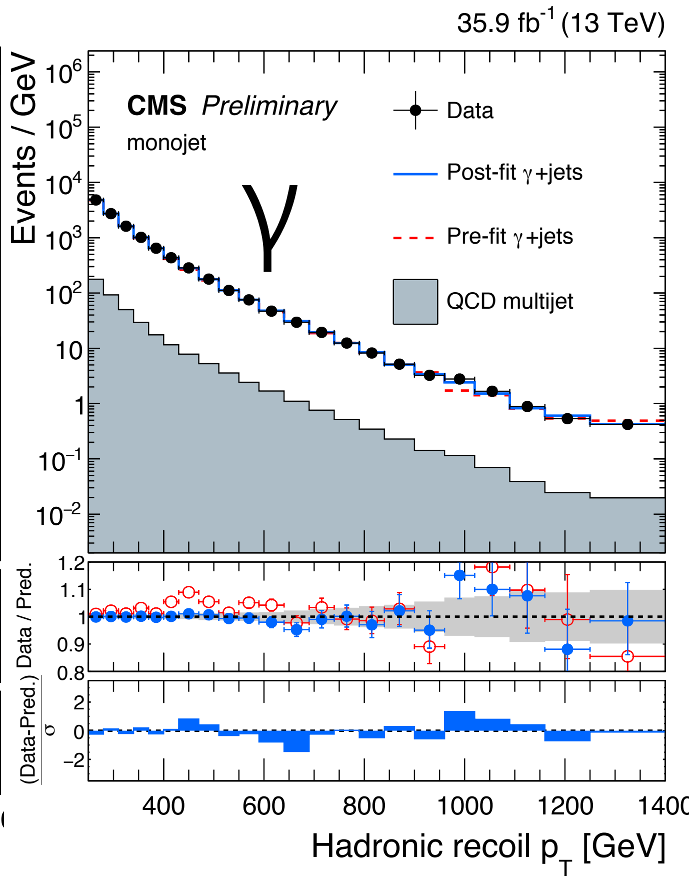
Nominals



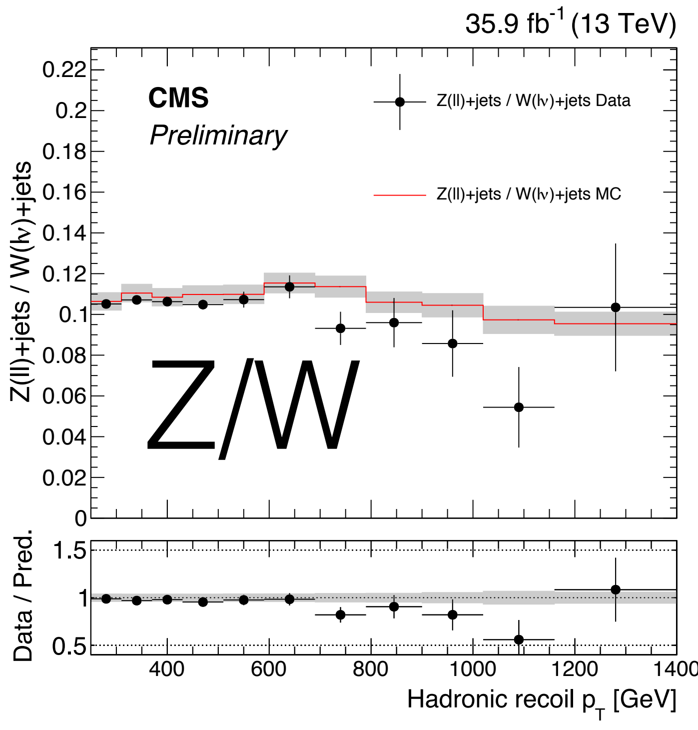


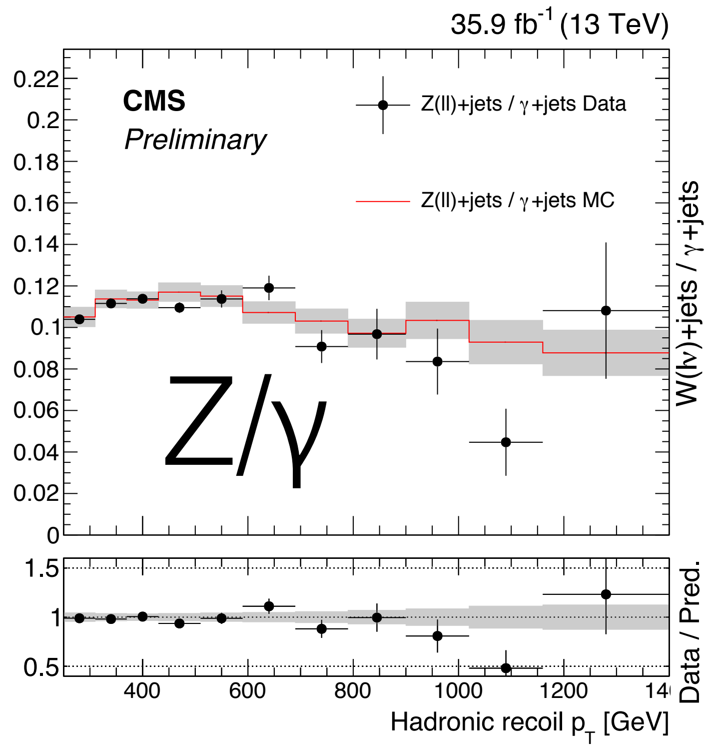


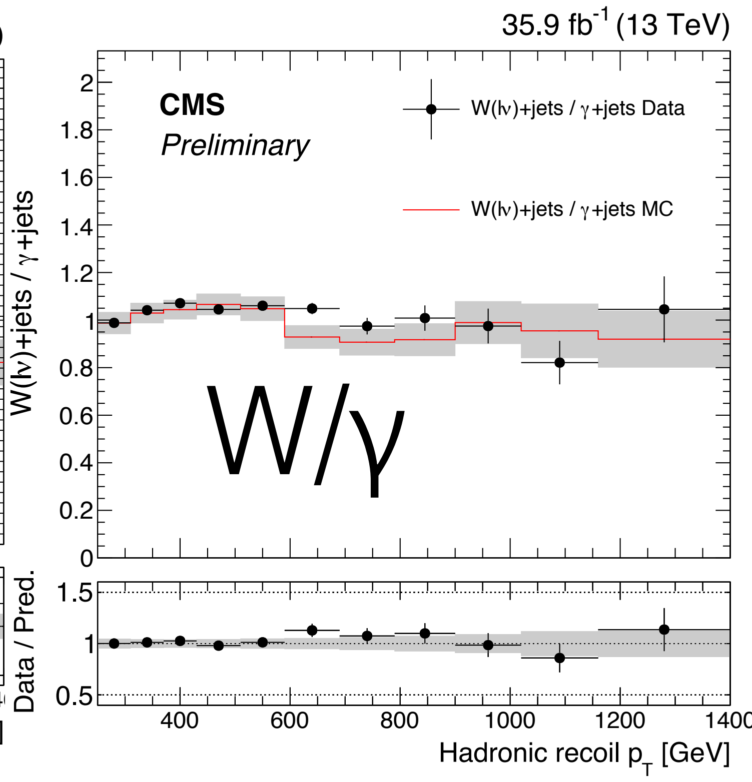




Ratios

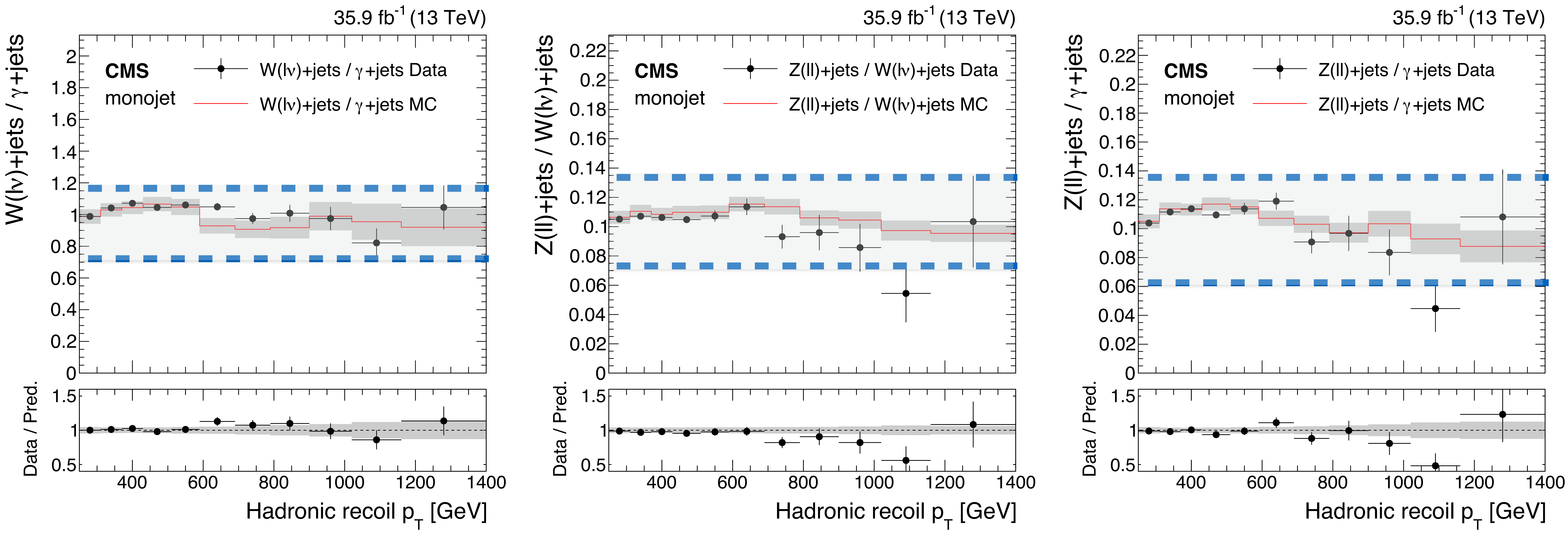






Experimental closure tests
CMS monojet searches

[Zeynep Demiragli, DM@LHC 2018]



Black ratio from data and statistical uncertainties / Red from MC

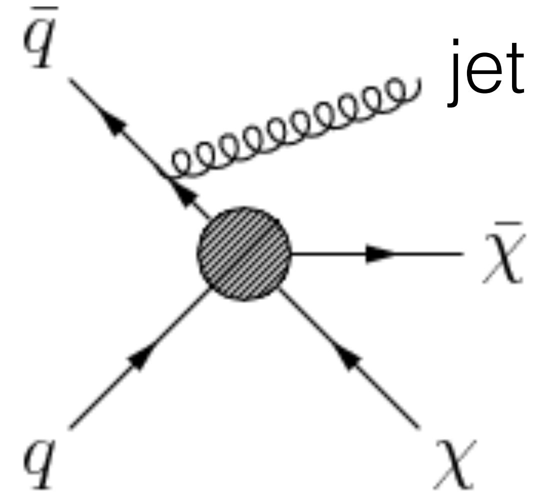
Grey band includes theoretical uncertainties

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

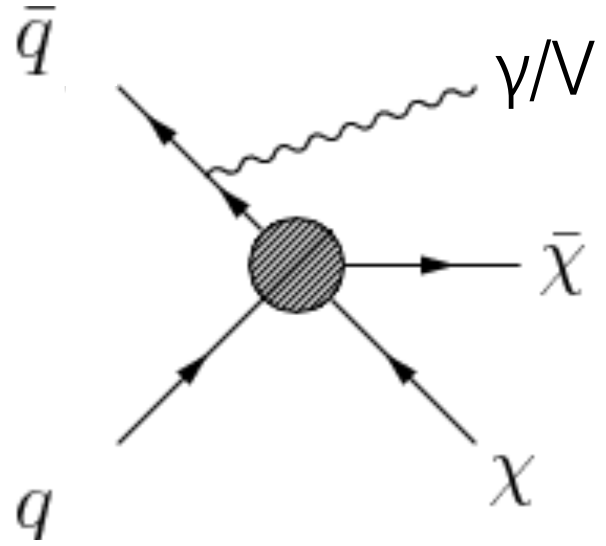
The Zoo of MET+X searches

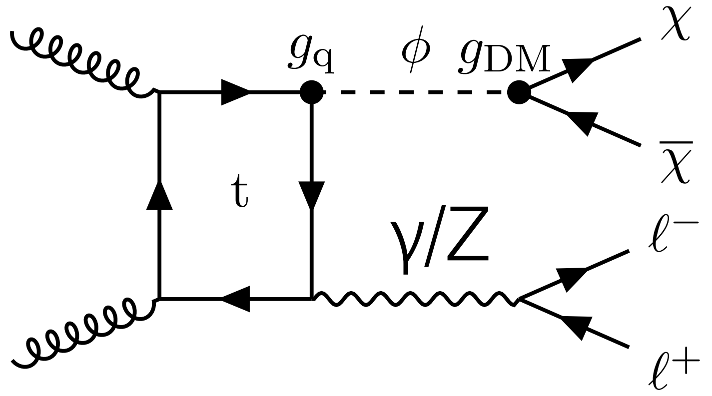
ISR

Mono-jet



Mono-γ/V

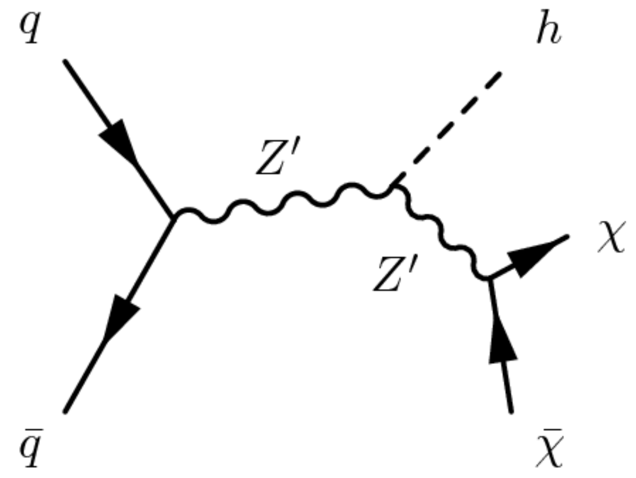




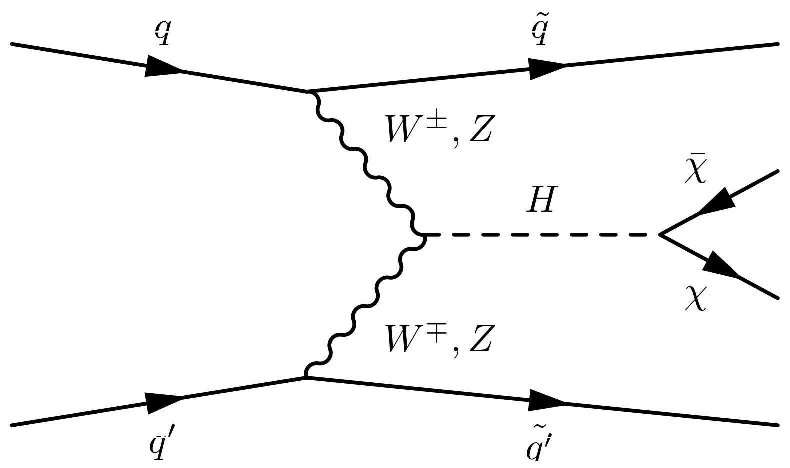
Loop-induced

Higgs-Strahlung

Mono-H

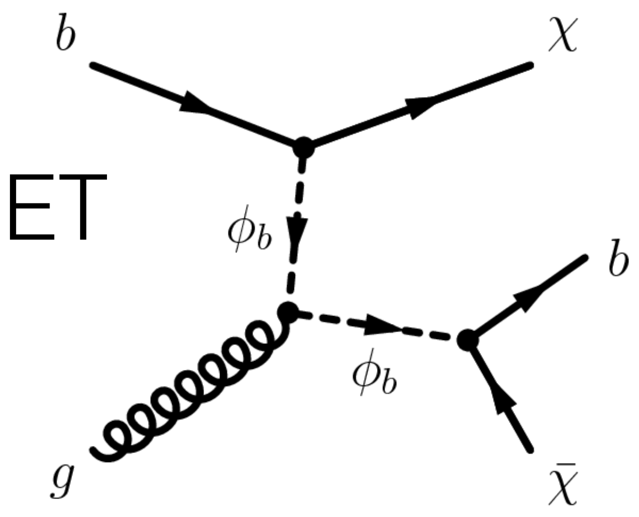


VBF

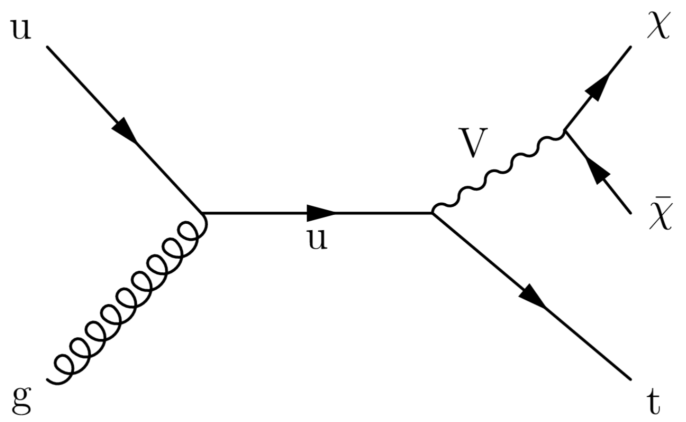


HF-associated

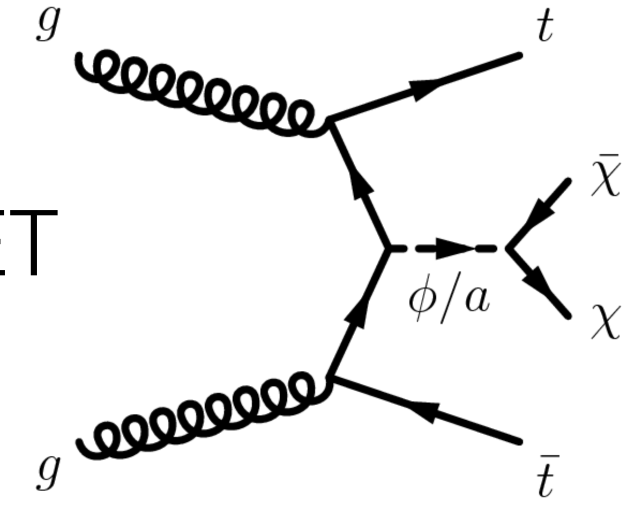
b+MET



t+MET



tt+MET

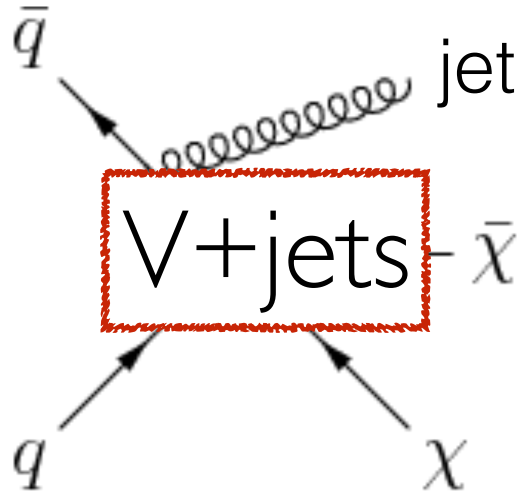


and many more….

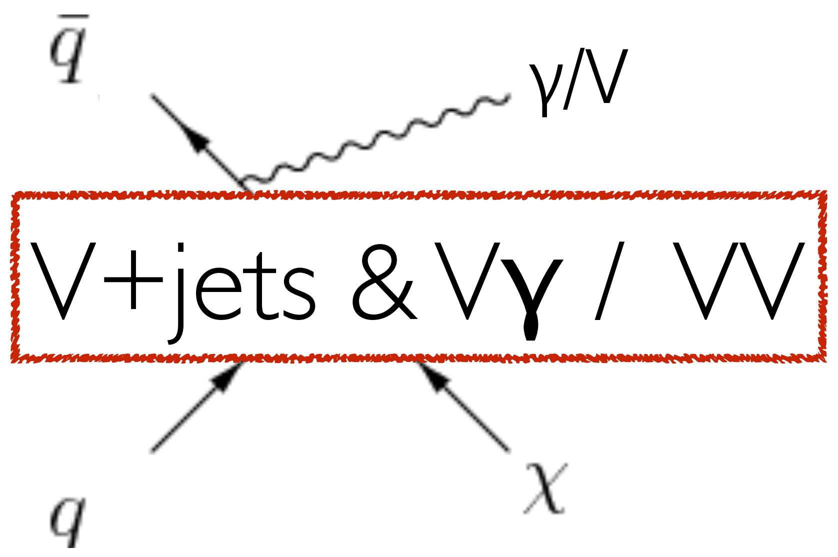
The Zoo of MET+X searches: backgrounds

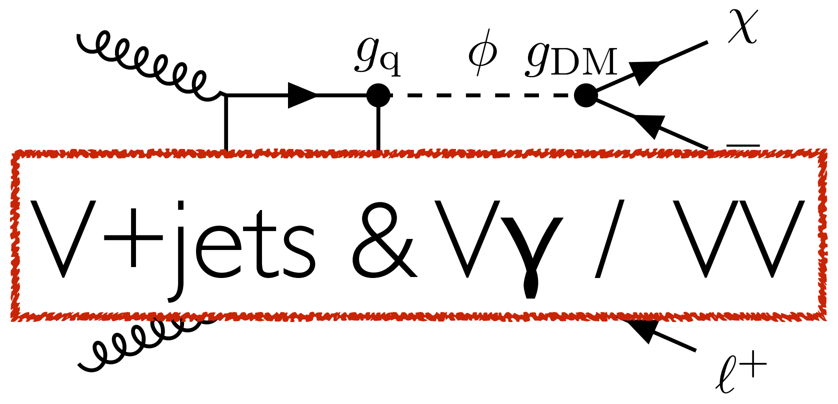
ISR

Mono-jet



Mono-γ/V

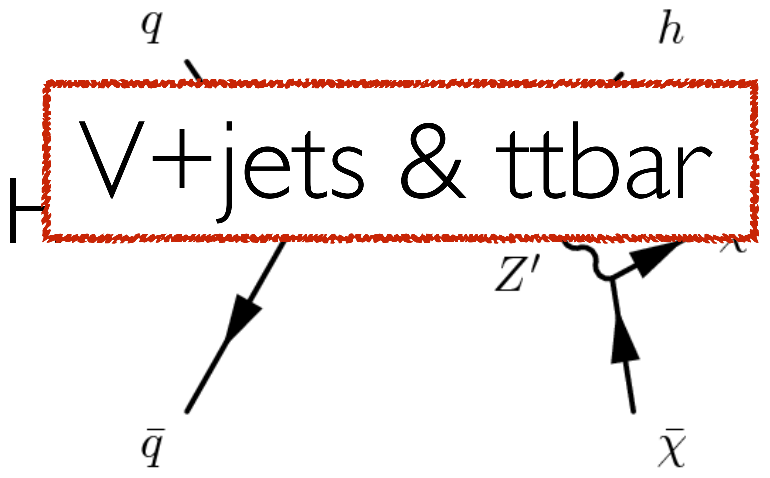




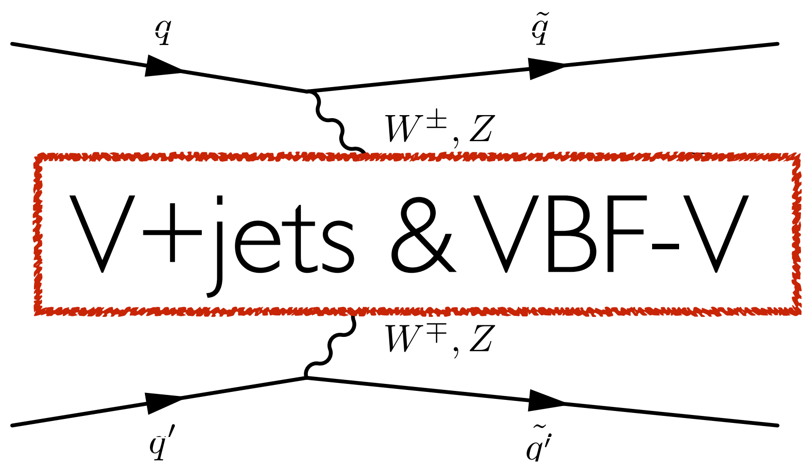
Loop-induced

Higgs-Strahlung

Mono-H

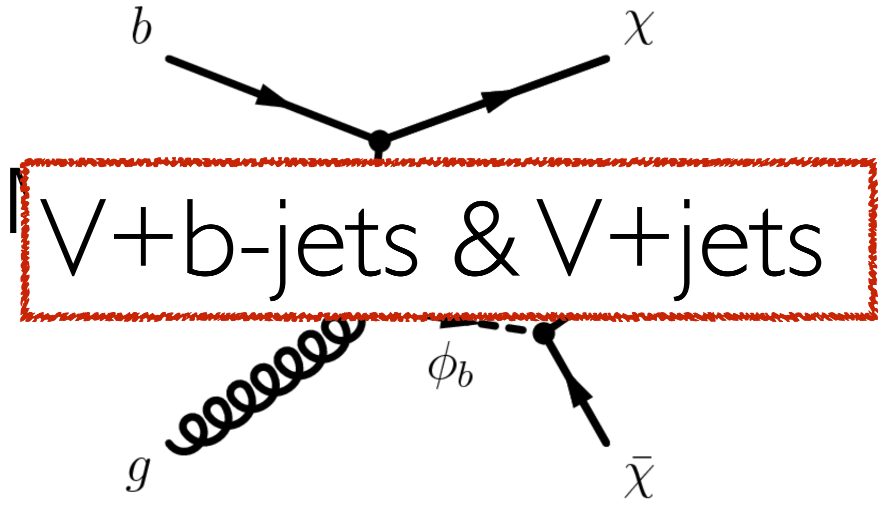


VBF

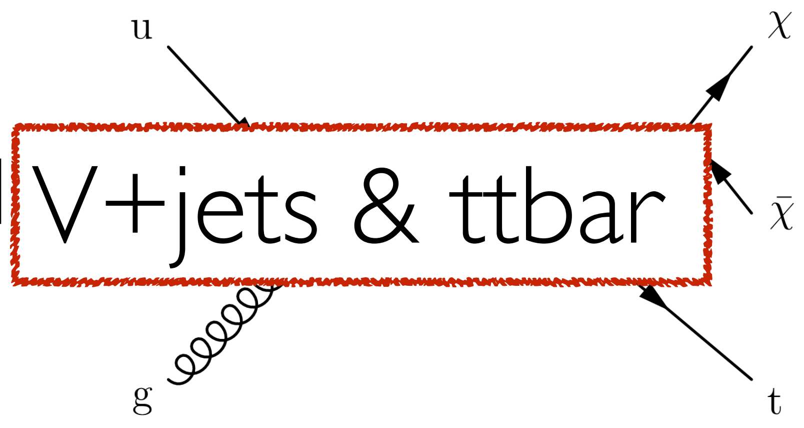


HF-associated

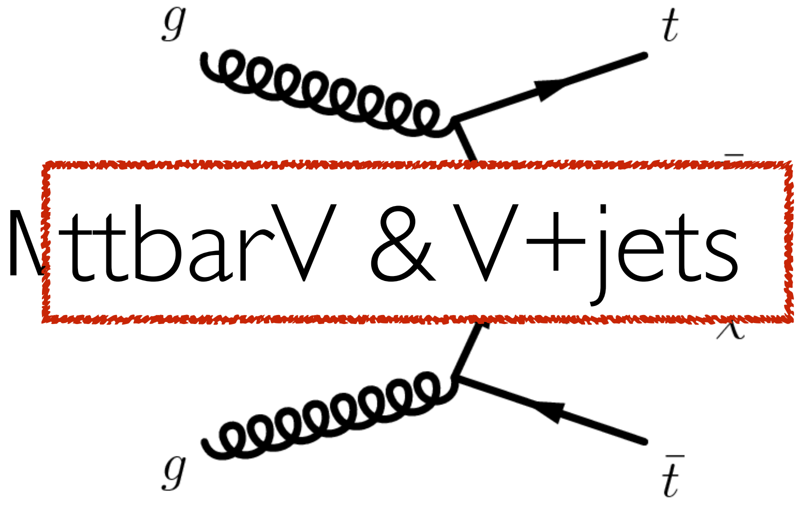
b+M



t+M



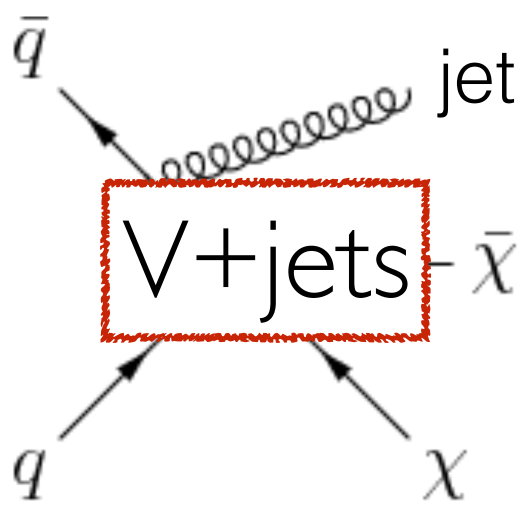
tt+M



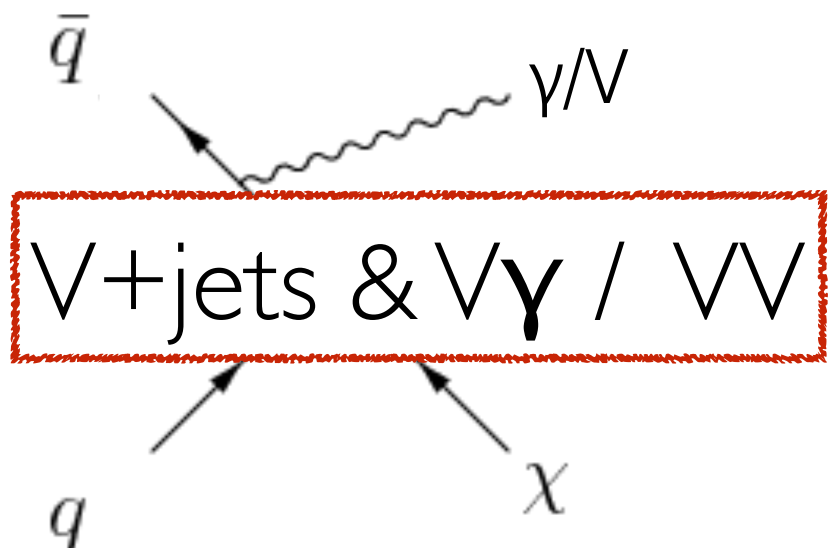
The Zoo of MET+X searches: backgrounds

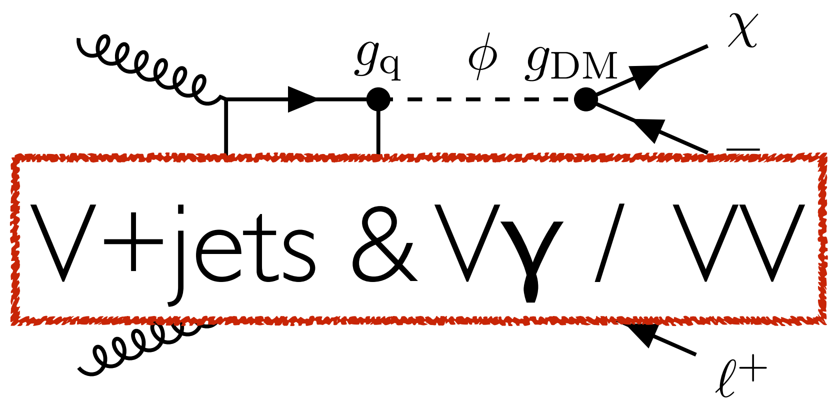
ISR

Mono-jet



Mono-γ/V

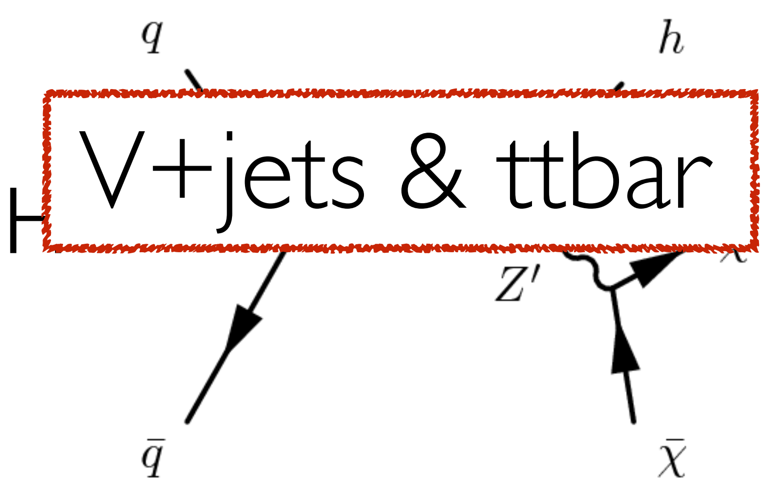




Loop-induced

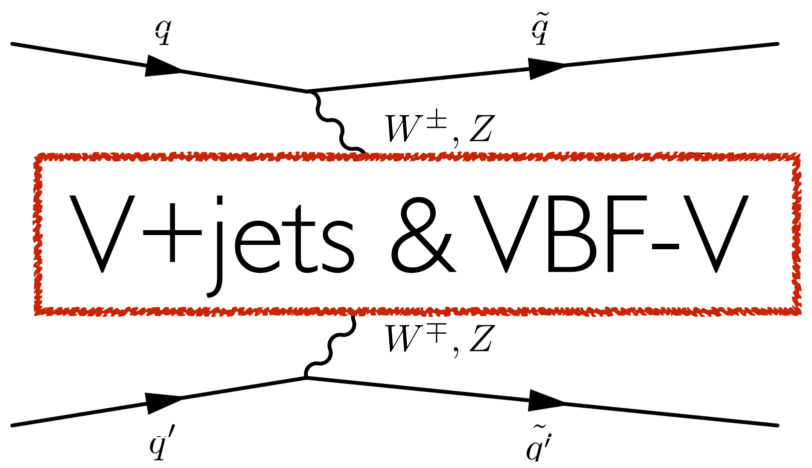
Higgs-Strahlung

Mono-H



VV ratios

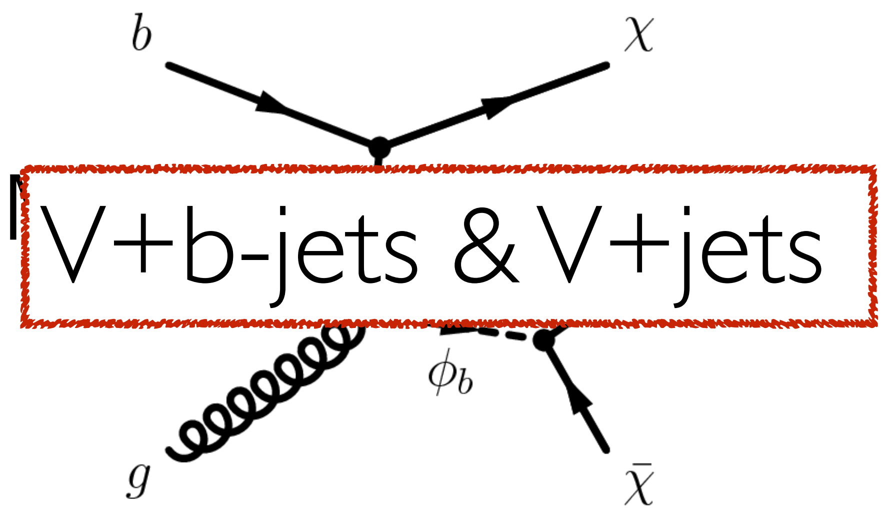
VBF



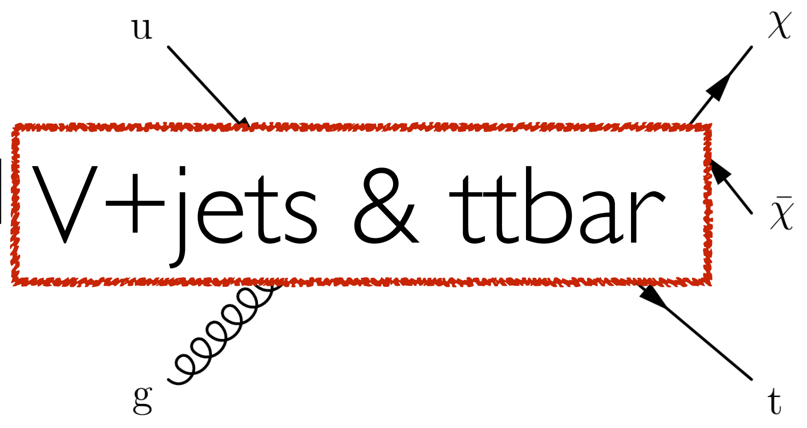
VBF-V ratios

HF-associated

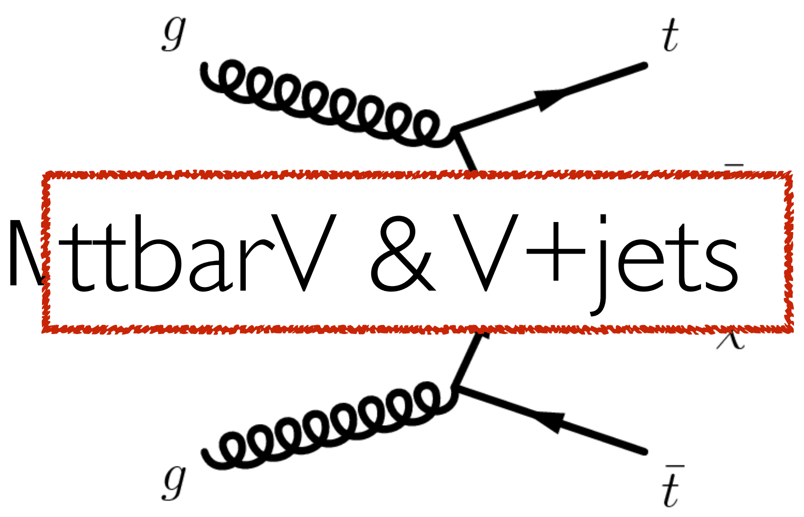
b+MET



t+MET



tt+MET



…work in progress…stay tuned!