



Alexander von
HUMBOLDT
STIFTUNG



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Threshold Top Quark pair production: Cross sections and key uncertainties

[Based on 2412.16685, 2604.09485, in collaboration with Garzelli, Moch, Steinhauser, Zenaiev]

Giovanni Limatola
Universität Hamburg

QCD@LHC
University of Oxford
29th September 2026

The Top Quark

- The heaviest known fundamental particle $m_t \simeq 172.5$ GeV

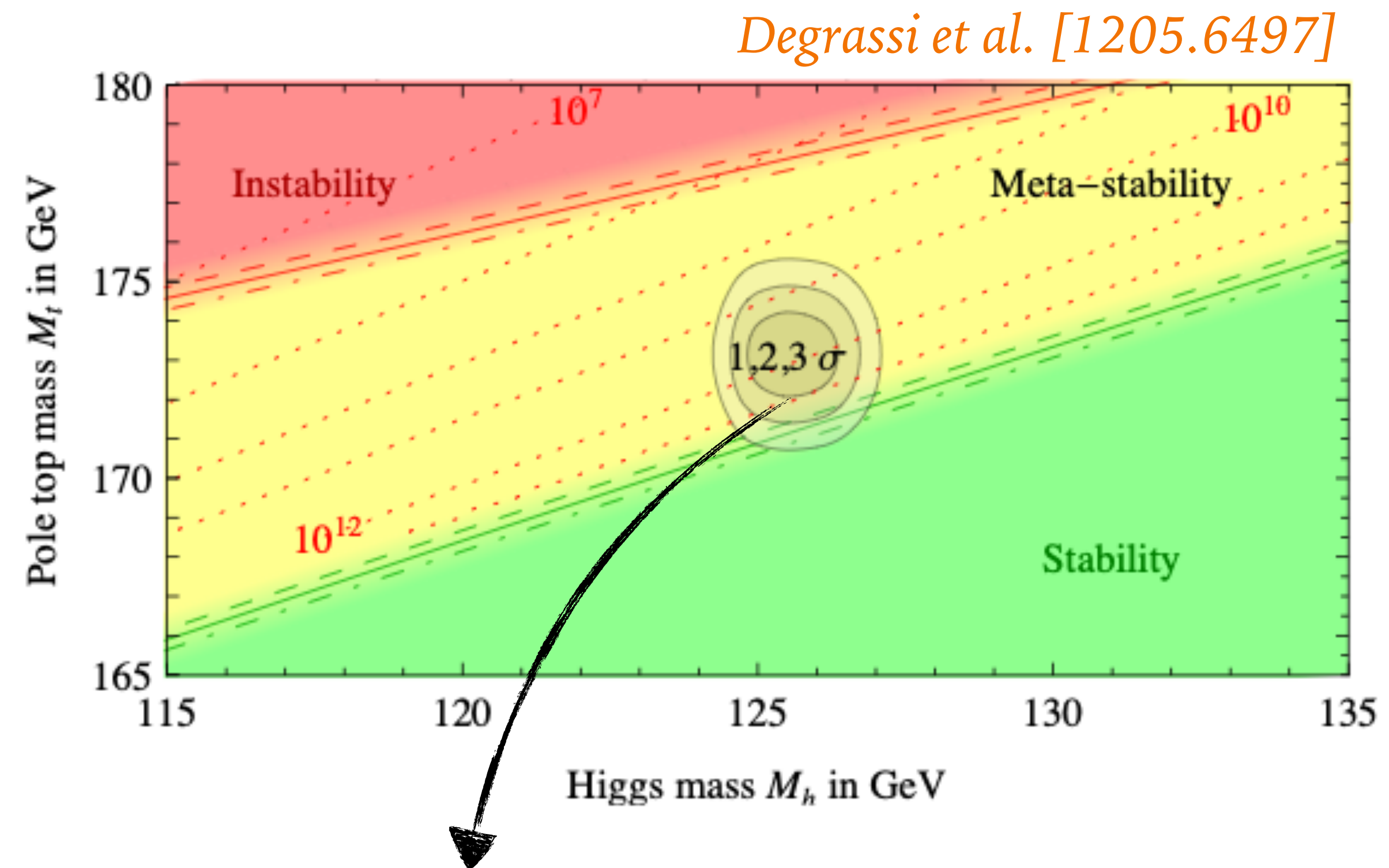
- $\Gamma_t(t \rightarrow Wb) \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}} \sim 1.6 \text{ GeV} \gg \Lambda_{\text{QCD}}$

Too heavy to hadronise before decaying

- Strong Yukawa coupling $y_t(m_t) \sim 1$
- Plays a key role in assessing the vacuum stability

Degrassi et al. [1205.6497]

$$M_h [\text{GeV}] > 129.4 + 1.4 \left(\frac{M_t [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$



Stable Vacuum excluded at 2σ level for $M_H < 126$ GeV

The Top Quark

- The heaviest known fundamental particle $m_t \simeq 172.5$ GeV

$$\Gamma_t(t \rightarrow Wb) \simeq \frac{G_F \boxed{m_t^3}}{8\pi\sqrt{2}} \sim 1.6 \text{ GeV} \gg \Lambda_{\text{QCD}}$$

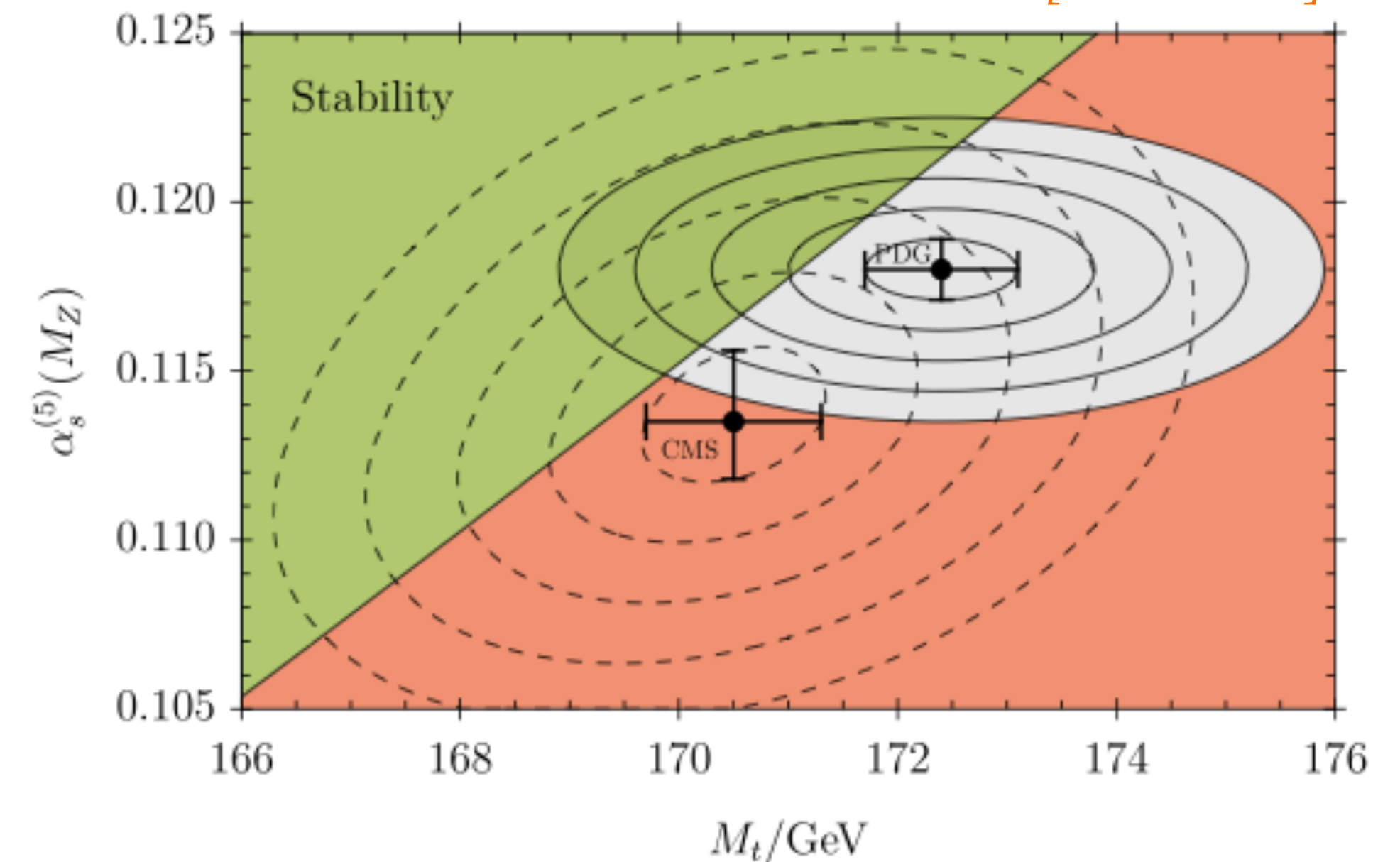
Too heavy to hadronise before decaying

- Strong Yukawa coupling $y_t(m_t) \sim 1$
- Plays a key role in assessing the vacuum stability

Degrassi et al. [1205.6497]

$$M_h [\text{GeV}] > 129.4 + 1.4 \left(\frac{M_t [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$

Hiller et al. [2401.08811]



Vacuum stability can be excluded at 5σ level with m_t uncertainty of ~ 200 MeV

Target for HL-LHC!

Top Quark production at the LHC

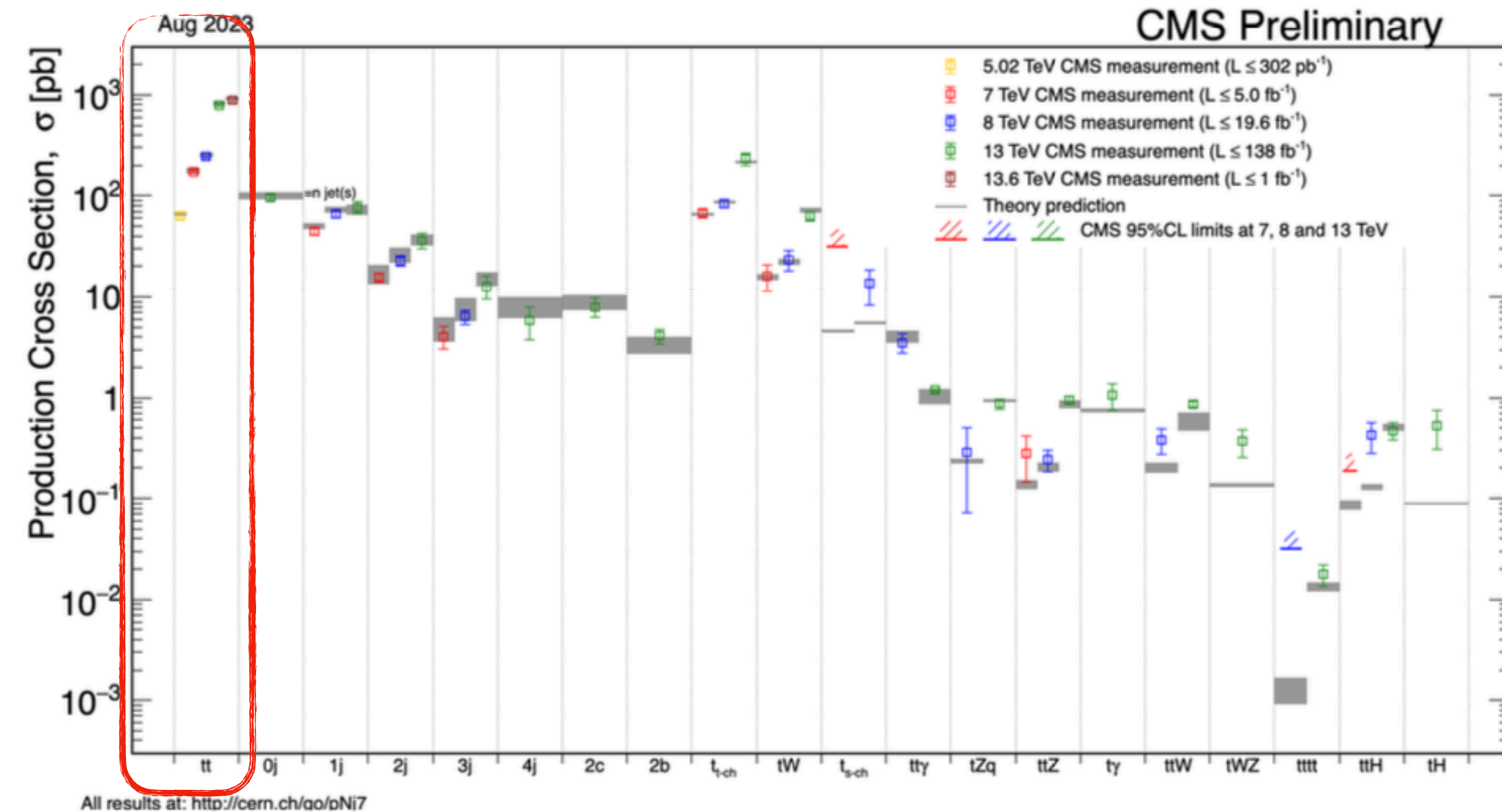
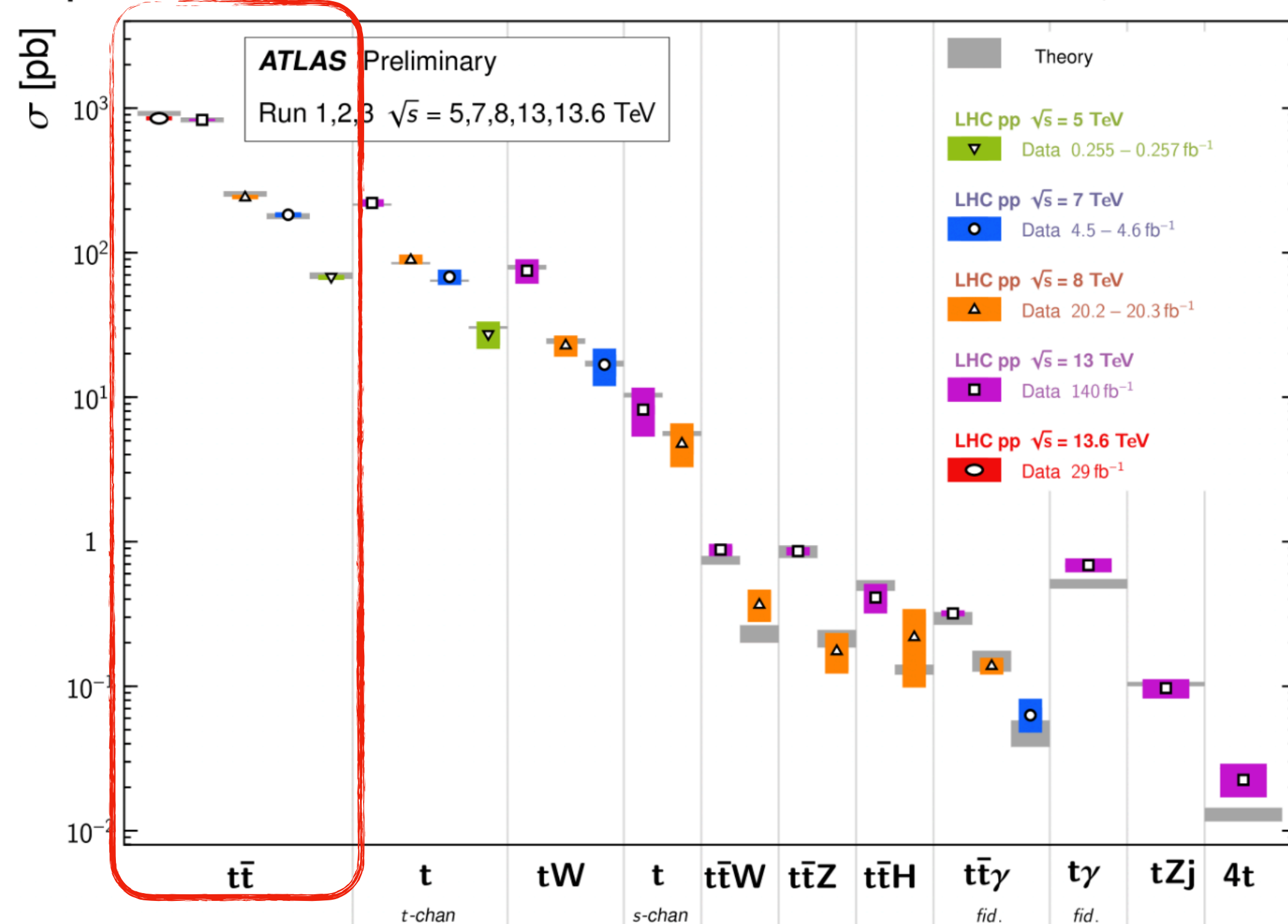


Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Top Quark Production Cross Section Measurements

Status: May 2025



- 4-5 orders of magnitude are spanned for top production cross section
- $t\bar{t}$ production essential for top quark properties and to reduce the background

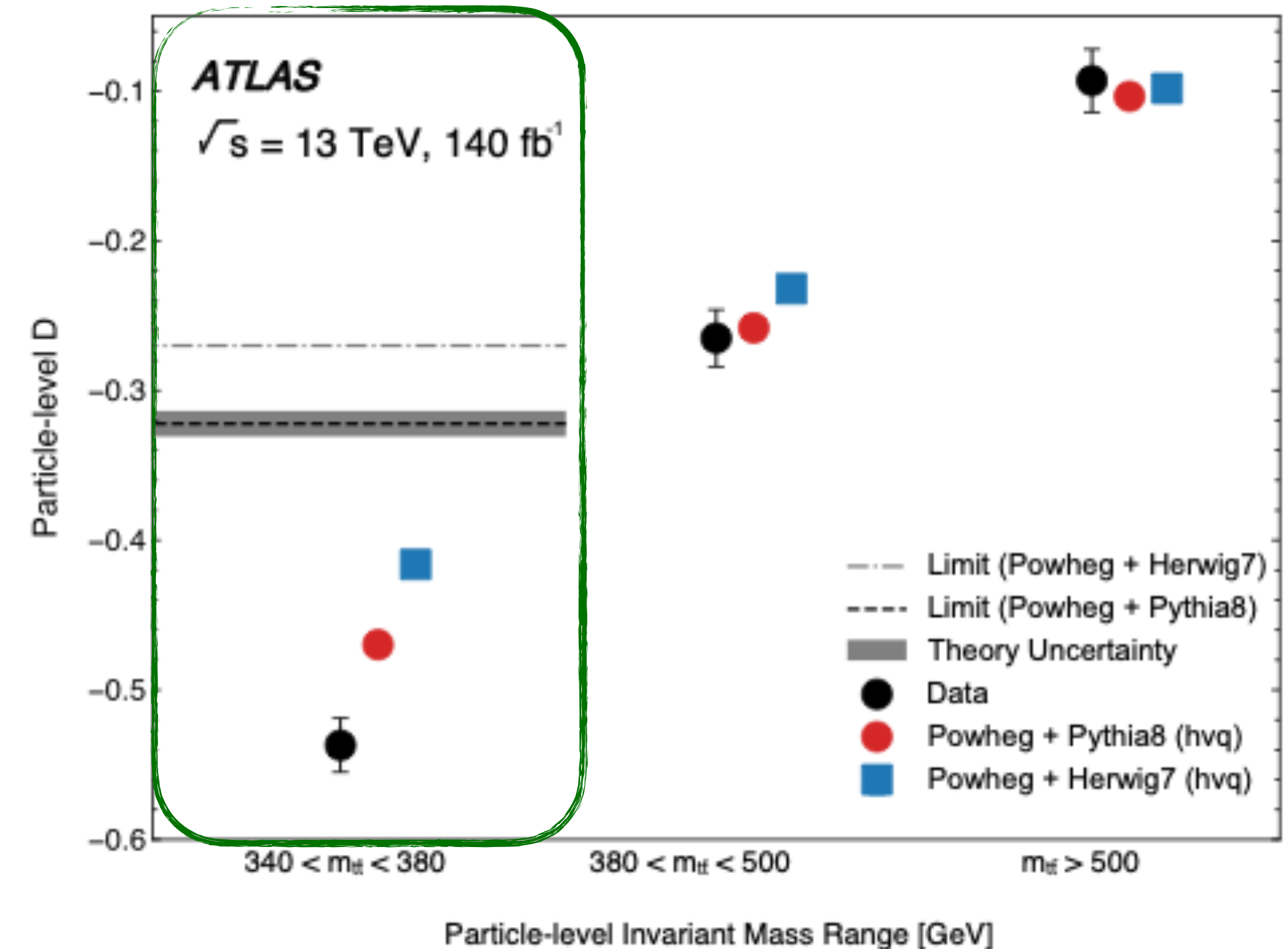
Entanglement in $t\bar{t}$ pair

- $t\bar{t}$ pair mostly produced in the threshold region $M_{t\bar{t}} \simeq 2m_t$
- The spin information of $t\bar{t}$ is entirely transferred to its charged leptonic decay product l^+l^-
- Large fraction of $t\bar{t}$ produced in a spin-singlet state and *maximally entangled*
[Kiyo, Kühn, Moch, Steinhauser, Uwer '08, Afik, de Nova '20]
- Entanglement only survives close to the threshold because of rotational invariance

Existence of an entangled state if $D = -3\langle \hat{l}^- \cdot \hat{l}^+ \rangle < -1/3$

[Peres '96, Horodecki '97, ...]

ATLAS Collaboration, [2311.07288]



$$D^{\text{expected}} = -0.470 \pm 0.002 \text{ [stat]} \pm 0.017 \text{ [syst]}$$

$$D^{\text{observed}} = -0.537 \pm 0.002 \text{ [stat]} \pm 0.019 \text{ [syst]}$$

$t\bar{t}$ excess at the threshold

Observation of a pseudoscalar excess at the top quark pair production threshold

The CMS Collaboration*

Abstract

A search for resonances in top quark pair ($t\bar{t}$) production in final states with two charged leptons and multiple jets is presented, based on proton-proton collision data collected by the CMS experiment at the CERN LHC at $\sqrt{s} = 13$ TeV, corresponding to 138 fb^{-1} . The analysis explores the invariant mass of the $t\bar{t}$ system and two angular observables that provide direct access to the correlation of top quark and antiquark spins. A significant excess of events is observed near the kinematic $t\bar{t}$ threshold compared to the nonresonant production predicted by fixed-order perturbative quantum chromodynamics (pQCD). The observed enhancement is consistent with the production of a color-singlet pseudoscalar ($^1S_0^{[1]}$) quasi-bound toponium state, as predicted by nonrelativistic quantum chromodynamics. Using a simplified model for $^1S_0^{[1]}$ toponium, the cross section of the excess above the pQCD prediction is measured to be $8.8^{+1.2}_{-1.4} \text{ pb}$.

Observation of a cross-section enhancement near the $t\bar{t}$ production threshold in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

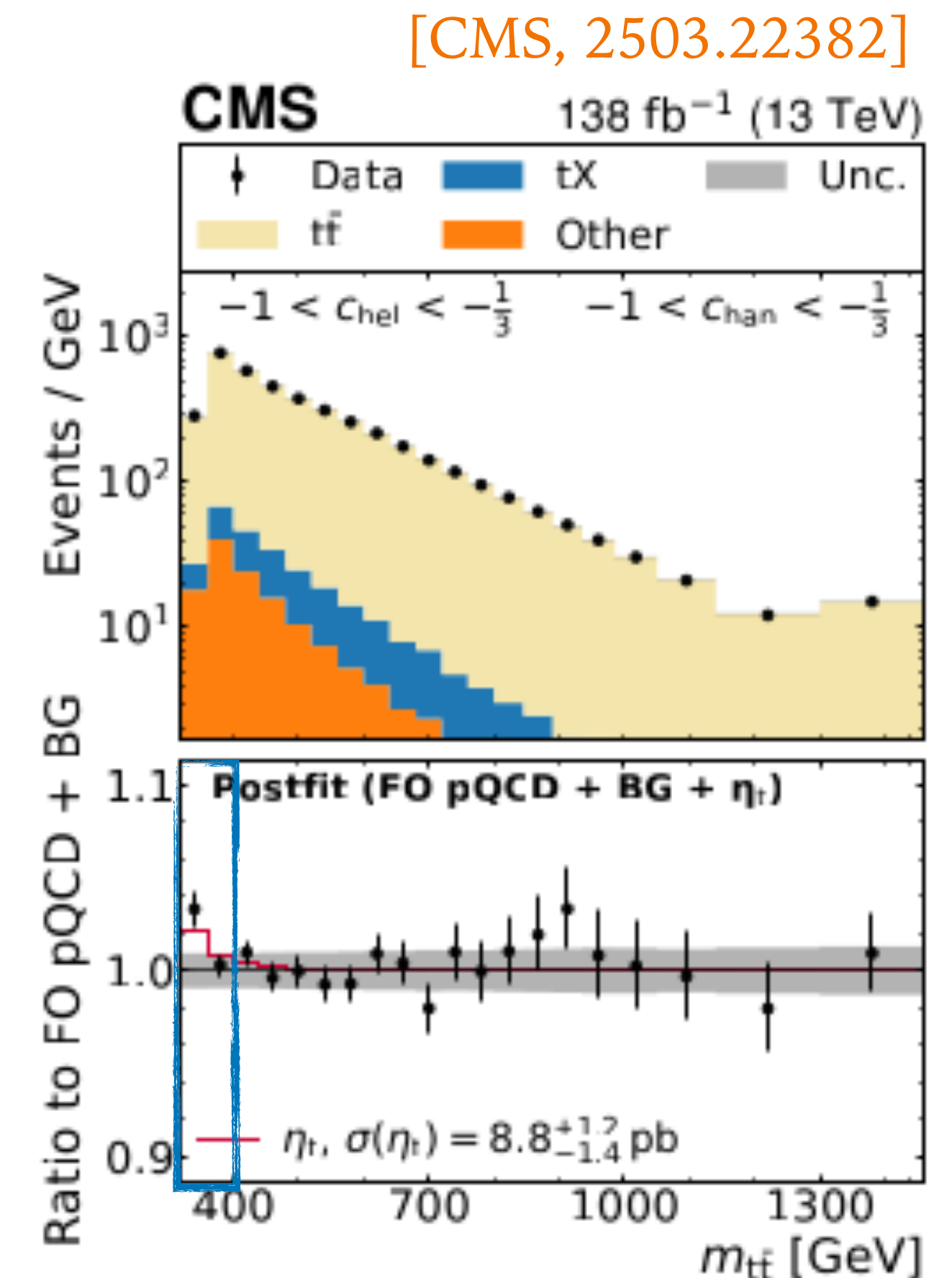
A measurement of $t\bar{t}$ production is presented in the invariant-mass region near the pair production threshold, $m_{t\bar{t}} \sim 345$ GeV, in final states with two charged leptons and multiple jets. The measurement is based on 140 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. The data are compared to two models of $t\bar{t}$ production: a baseline model including only perturbative QCD predictions for the hard process, and an extended model that, in addition, incorporates non-relativistic QCD simulations of colour-singlet quasi-bound-state formation near the $t\bar{t}$ threshold. The agreement between the data and the models is quantified via a profile-likelihood fit to the reconstructed $m_{t\bar{t}}$ distributions, in bins of two angular observables sensitive to spin-correlations in the $t\bar{t}$ system. An excess of events is observed over the baseline perturbative QCD prediction, with an observed significance over 8 standard deviations. This excess is consistent with the formation of colour-singlet and spin-singlet S -wave quasi-bound $t\bar{t}$ states, as predicted by non-relativistic QCD, and corresponds to an observed cross-section of $9.3^{+1.4}_{-1.3} \text{ pb}$.

- Significant excess of events from ATLAS and CMS for $M_{t\bar{t}} \simeq 2m_t$ w.r.t. FO pQCD

$$\sigma_{\text{CMS}} = 8.8^{+1.2}_{-1.4} \text{ pb} \quad [\text{CMS}, 2503.22382]$$

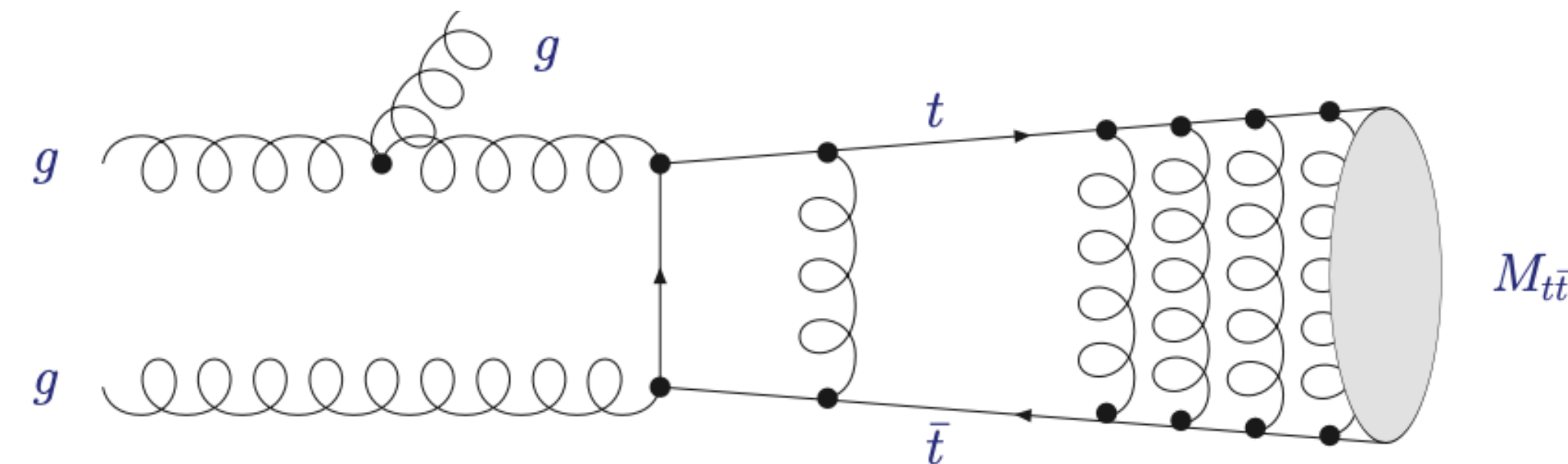
$$\sigma_{\text{ATLAS}} = 9.3^{+1.4}_{-1.3} \text{ pb} \quad [\text{ATLAS}, 2601.11780]$$

Are we observing quasi-bound-state effects?



$t\bar{t}$ production at the threshold

- In the threshold region the top quark velocity
 $\beta_t = \sqrt{1 - 4m_t^2/M_{t\bar{t}}^2} \sim \alpha_s \sim 0.1$ in the $t\bar{t}$ CM frame
- Significant QCD Coulomb corrections scaling as $(\alpha_s/\beta_t)^k$ due to quasi-bound state interactions at all orders
- Quasi-bound state effects can be modelled as multiple soft gluon exchanges between top quarks
 - First hypotheses before top quark discovery
 [Fadin, Khoze '87 + Sjostrand '90]
 [Sumino, Fujii, Hagiwara, Murayama, Ng '93]
- The whole $M_{t\bar{t}}$ spectrum smeared by the finite value of Γ_t



*EFT Non-Relativistic QCD
to factorise $(\alpha_s/\beta_t)^k$ at all orders*

[Caswell, Lepage '86]

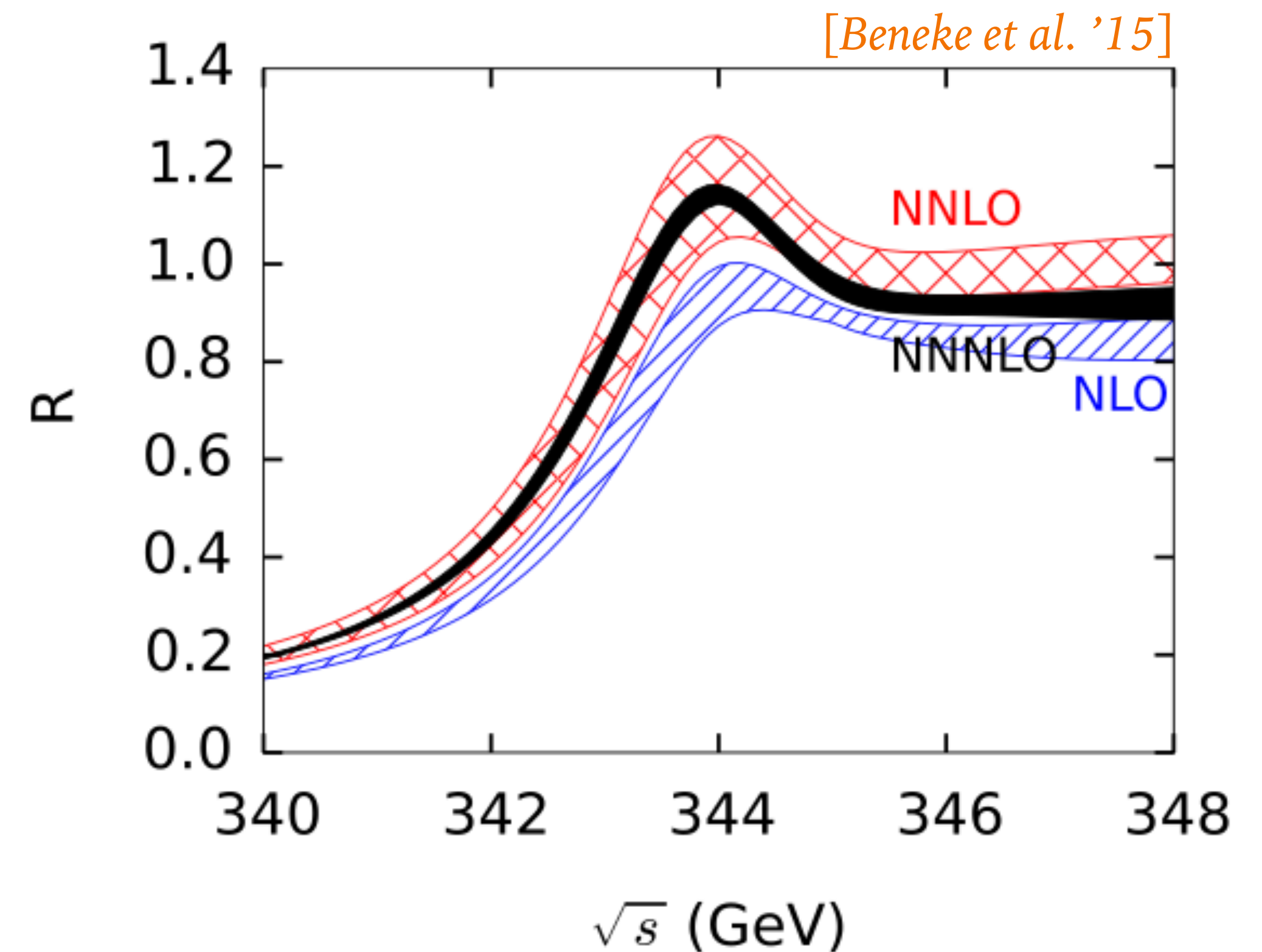
[Bodwin, Braaten, Lepage '94]

$t\bar{t}$ production at the threshold

$$R = \frac{\sigma_{e^+e^- \rightarrow t\bar{t}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}} = \beta \sum_k \left(\frac{\alpha_s}{\beta} \right)^k \{1(\text{LO}); \alpha_s, \beta(\text{NLO}); \alpha_s^2, \alpha_s\beta, \beta^2(\text{NNLO}); \dots\}$$

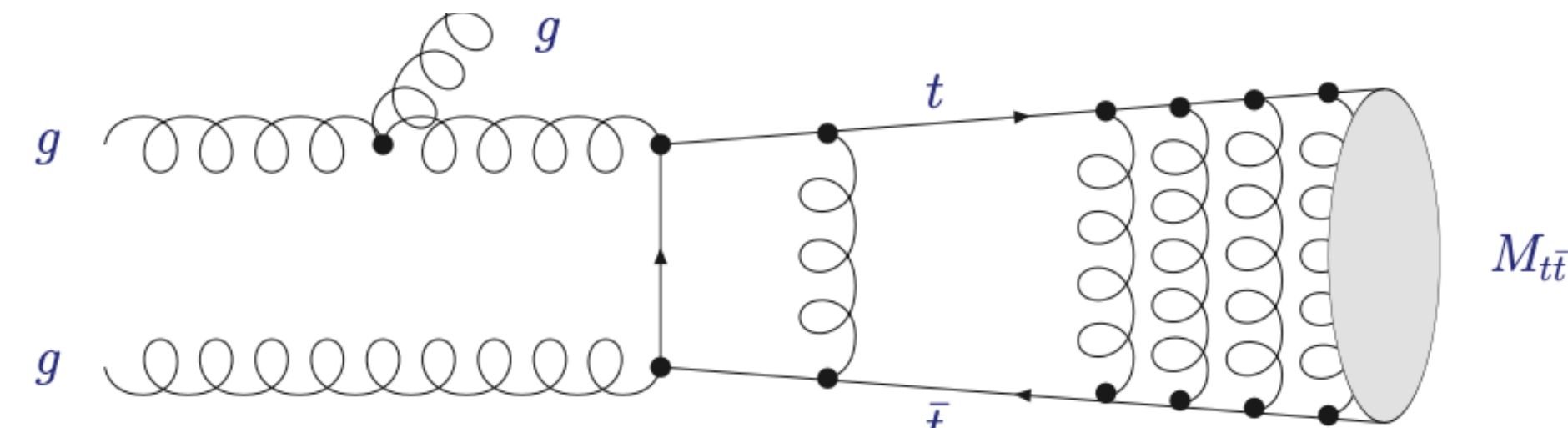
- Well studied in e^+e^- collisions → Colour-singlet state
- Large corrections to σ from NNLO results
[Hoang, Teubner '98, '99]
[Melnikov, Yelkhovsky '98]
[Penin, Pivovarov '99]
[Beneke et al. '99, Nagano et al. '99]
- $\mathcal{O}(\pm 3\%)$ uncertainty on the cross section normalisation from N3LO results [Beneke et al., '15]

Less developed predictions at hadron colliders



$t\bar{t}$ production at the threshold @ LHC

- $t\bar{t}$ produced in mixed singlet [1] and octet [8] colour configuration
- Effects of ISR need to be considered
[Hagiwara, Sumino, Yokoya '08]
[Sumino, Yokoya '10]
- Resummation of soft and collinear gluons emission at the threshold



- Final state $M_{t\bar{t}}$ described as $T \equiv {}^{2S+1} L_J^{[c]}$

$L = 0$ @ NLO NRQCD

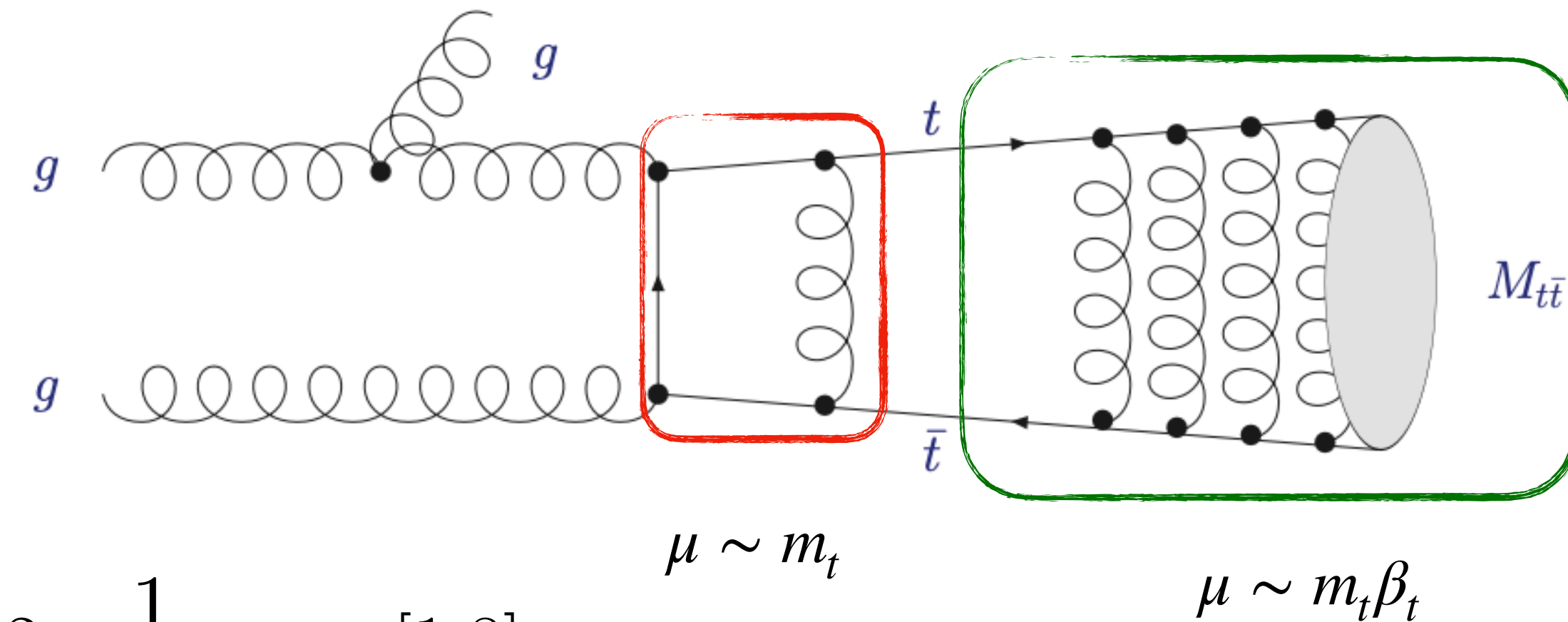
$S = 0, 1$

$$M_{t\bar{t}} \frac{d\sigma_{P_1 P_2 \rightarrow T}}{dM_{t\bar{t}}} (S, M_{t\bar{t}}^2) = \sum_{ij} \int_{\rho}^1 d\tau \left[\frac{d\mathcal{L}_{ij}}{d\tau} \right] M_{t\bar{t}} \frac{d\hat{\sigma}_{ij \rightarrow T}}{dM_{t\bar{t}}} (\hat{s} = \tau S, M_{t\bar{t}}^2)$$

$t\bar{t}$ production at the threshold @ LHC

Multi-scale problem

- $t\bar{t}$ hard-production at $\mu \sim m_t$ at NLO in pQCD
- Multiple soft-gluons exchange at $\mu \sim m_t\beta_t < m_t$



$$M_{t\bar{t}} \frac{d\hat{\sigma}_{ij \rightarrow T}}{dM_{t\bar{t}}}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) = F_{ij \rightarrow T}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) \frac{1}{m_t^2} \text{Im} G^{[1,8]}(M_{t\bar{t}} + i\Gamma_t)$$

Zero-distance Green's Function
for a Coulomb QCD potential

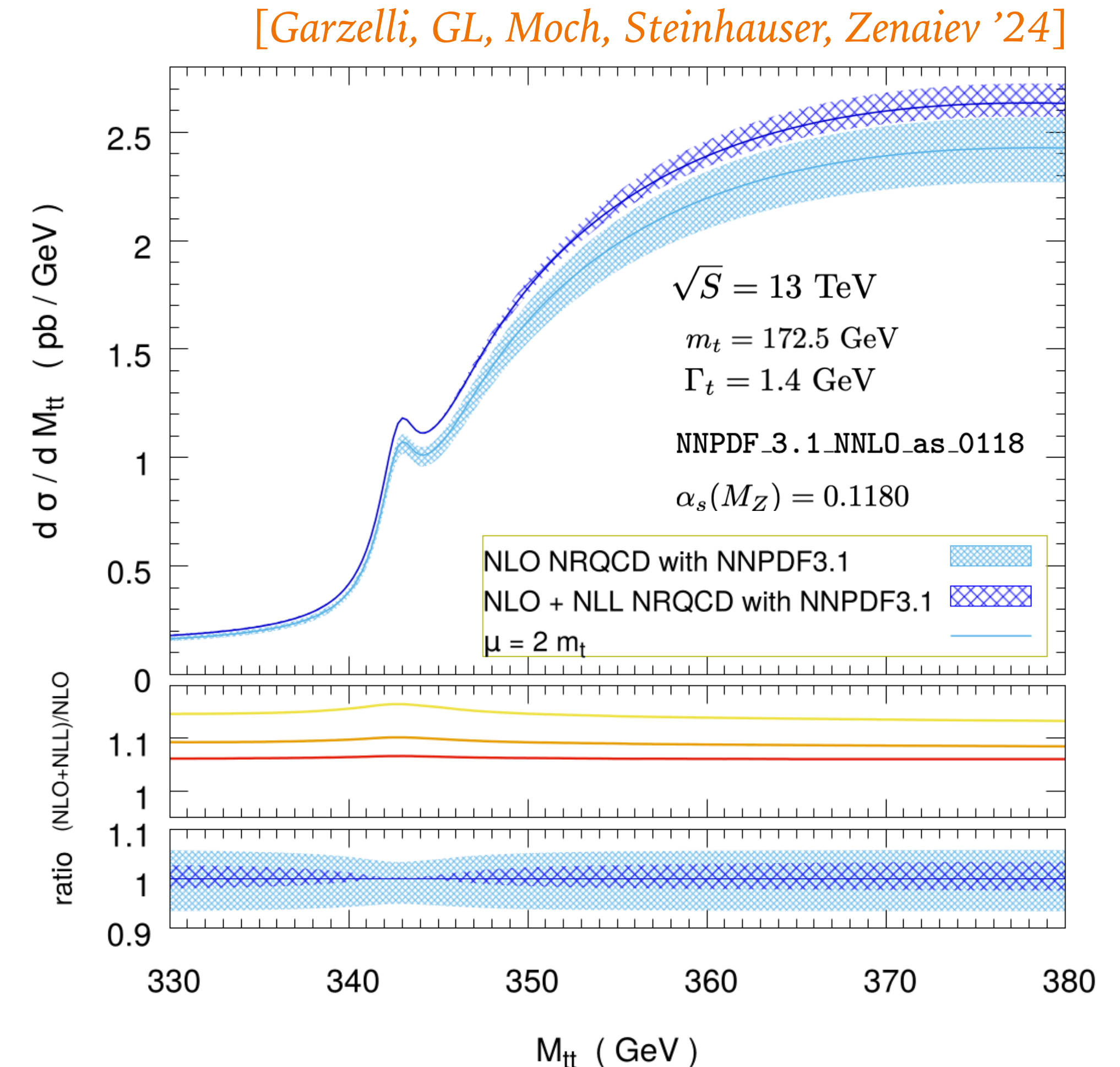
$$F_{ij \rightarrow T}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) = \mathcal{N}_{ij} \frac{\pi^2 \alpha_s^2(\mu_r)}{3\hat{s}} \left(1 + \frac{\alpha_s(\mu_r)}{\pi} \mathcal{C}_h \right) \\ \times \left[\delta_{ij \rightarrow T} \delta(1-z) + \frac{\alpha_s(\mu_r)}{\pi} (\mathcal{A}_c + \mathcal{A}_{nc}) \right]$$

$$V_C^{[1,8]} = -\frac{4\pi\alpha_s(\mu) \mathcal{C}^{[1,8]}}{\vec{q}^2} \left[1 + \frac{\alpha_s(\mu)}{4\pi} \left(\beta_0 \ln \frac{\mu^2}{\vec{q}^2} + a_1 \right) \right]$$

$t\bar{t}$ production at the threshold @ LHC

- $\mu = m_t, 2m_t, 4m_t$
- NLL soft-gluon threshold resummation for leading channels
- Scale stability improved in the threshold region $M_{t\bar{t}} \simeq 2m_t$
- + $\mathcal{O}(10\%)$ from NLL predictions at the central scale choice

$M_{t\bar{t}} = 2m_t$	NLO [pb]			resummed [pb]		
$gg \rightarrow {}^1S_0^{[1]}$	18.2	18.7	18.3	19.4	20.5	21.1
$gg \rightarrow {}^1S_0^{[8]}$	55.8	55.2	52.8	60.0	61.5	62.0
$q\bar{q} \rightarrow {}^3S_1^{[8]}$	21.7	22.3	22.0	22.4	22.4	22.0



From threshold to continuum

- ATLAS and CMS observed excess for $M_{t\bar{t}} \leq 400$ GeV
- NRQCD predictions cease to be valid in the *continuum*

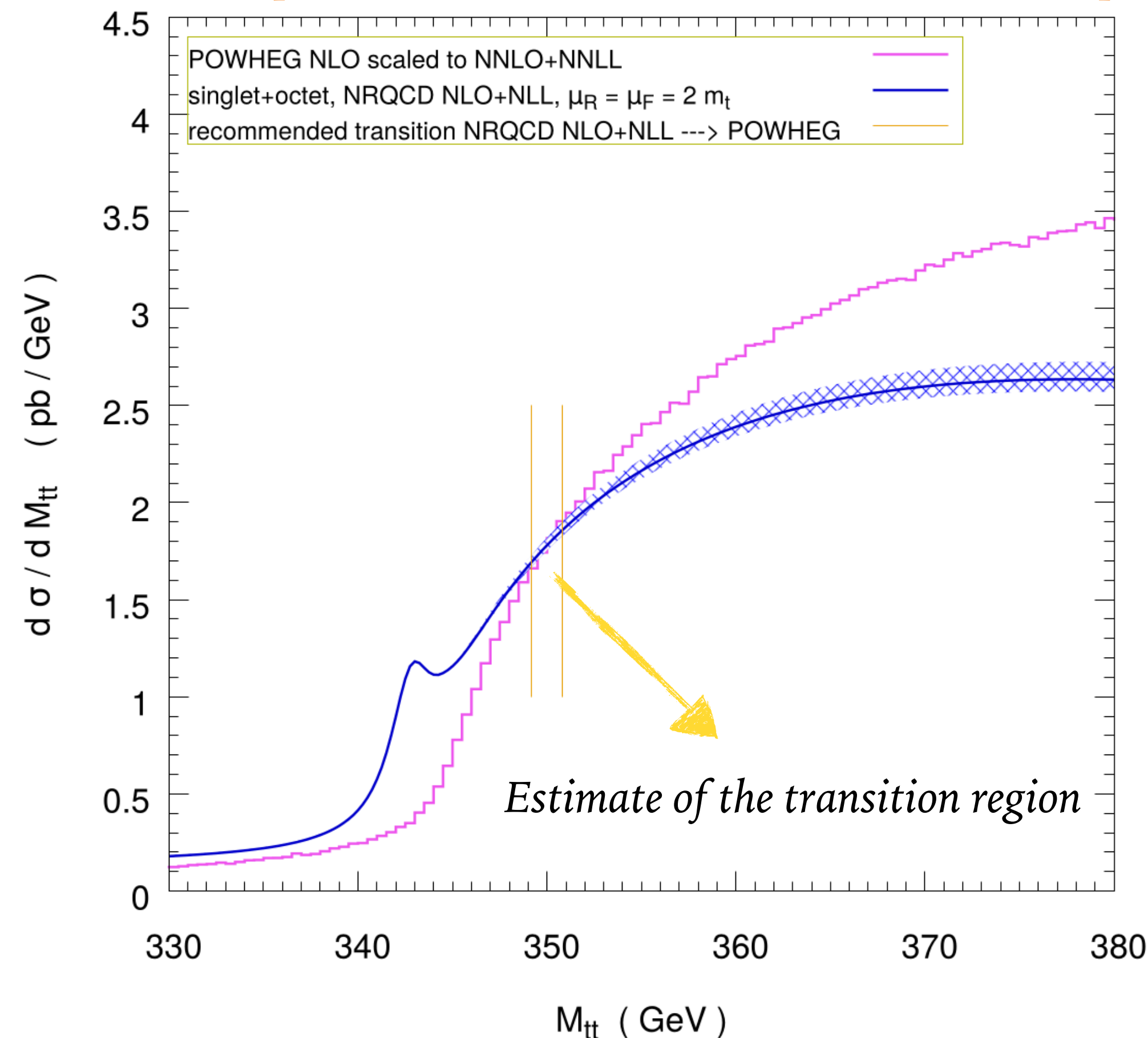
$$|M_{t\bar{t}} - 2m_t| \gtrsim 5 \text{ GeV}$$

TODO

- Matching prescription from threshold to pQCD regime
- Higher orders in NRQCD expansion
- Estimate of uncertainties for σ_{NRQCD}

[Garzelli, GL, Moch, Steinhauser, Zenaiev '26]

[Garzelli, GL, Moch, Steinhauser, Zenaiev '24]



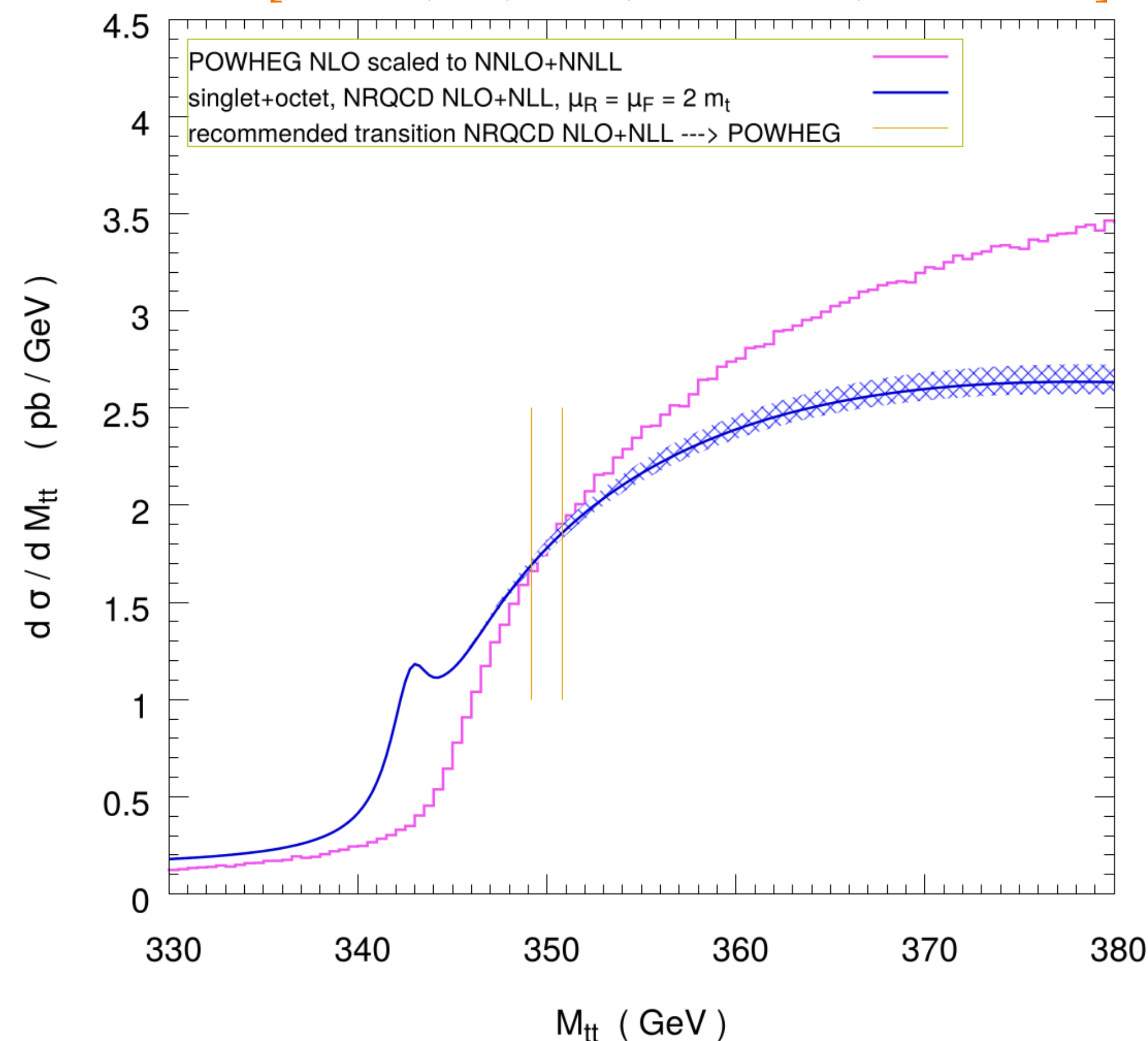
$t\bar{t}$ production at the threshold @ LHC

$$\sigma^{\text{NRQCD}} = \int_{M_{t\bar{t}} \simeq 2m_t} dM_{t\bar{t}} \frac{d\sigma_{P_1 P_2 \rightarrow T}}{dM_{t\bar{t}}} \pm \Delta\sigma^{\text{NRQCD}}$$

$\Delta\sigma^{\text{NRQCD}}$ estimated through variations of input parameters

- Renormalisation and factorisation scales $\mu_R = \mu_F$
 - Soft-scale μ_s variations in $G^{[1,8]}$
 - $\alpha_s(M_Z)$
 - PDFs
- } Correlation is accounted for
- Top quark decay width Γ_t
 - Top quark mass m_t

[Garzelli, GL, Moch, Steinhauser, Zenaiev '24]

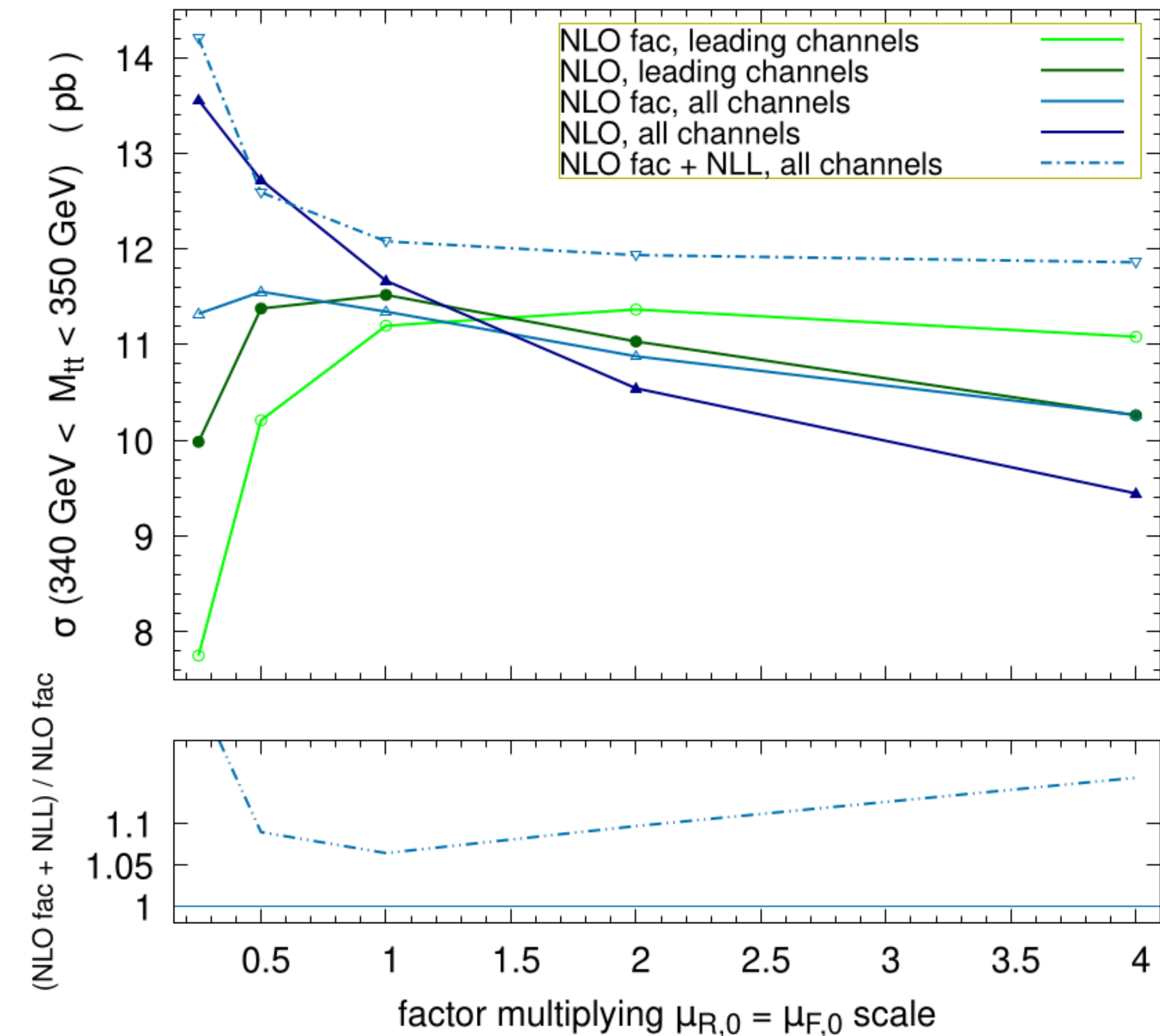


σ^{NRQCD} and uncertainties

$$F_{ij \rightarrow T}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) = \mathcal{N}_{ij} \frac{\pi^2 \alpha_s(\mu_r)^2}{3\hat{s}} \left[\left(1 + \frac{\alpha_s(\mu_r)}{\pi} \mathcal{C}_h \right) \delta_{ij \rightarrow T}(1 - z) + \frac{\alpha_s(\mu_r)}{\pi} \left(\mathcal{A}_c(z) + \mathcal{A}_{nc}(z) \right) \right]$$

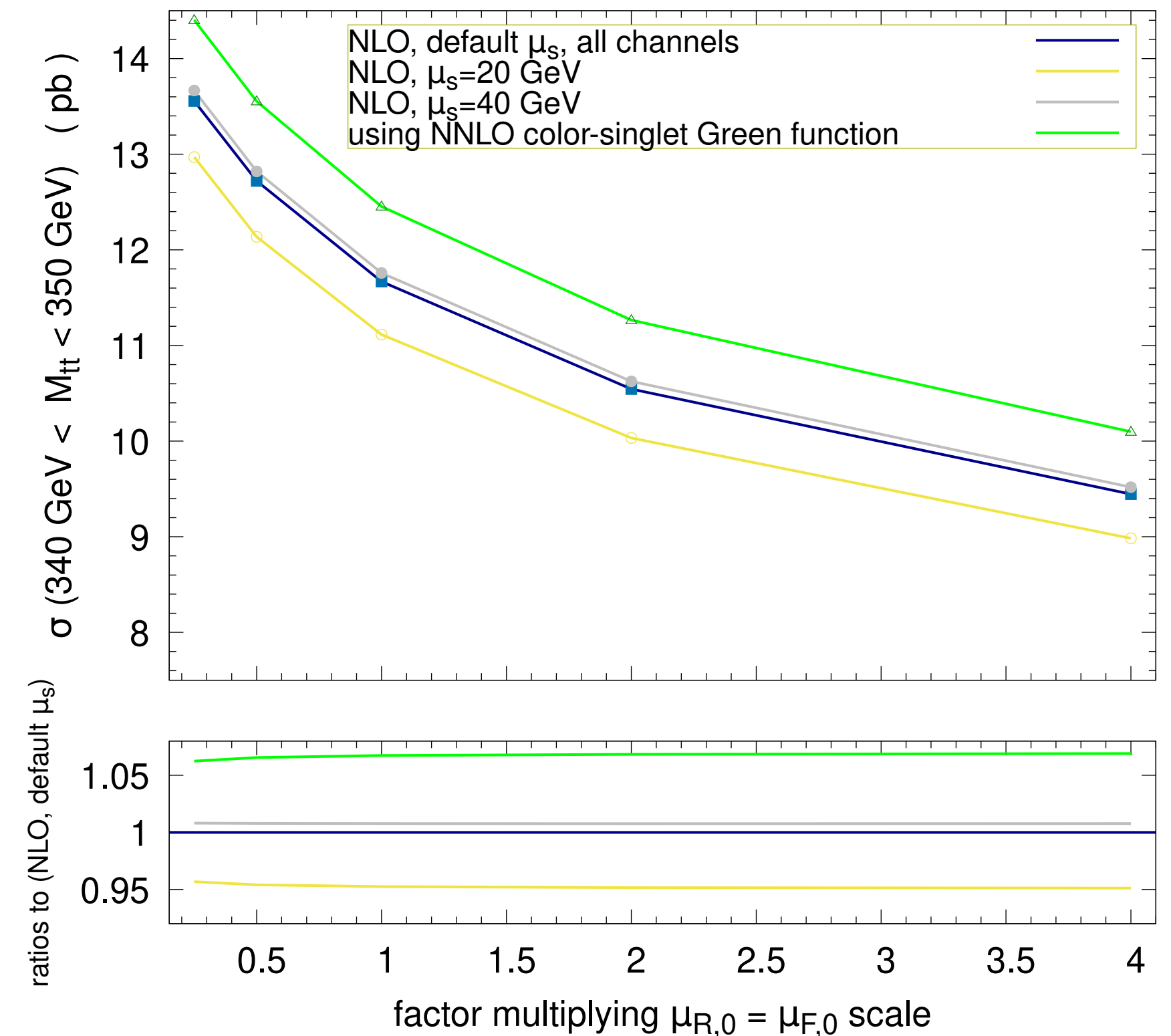
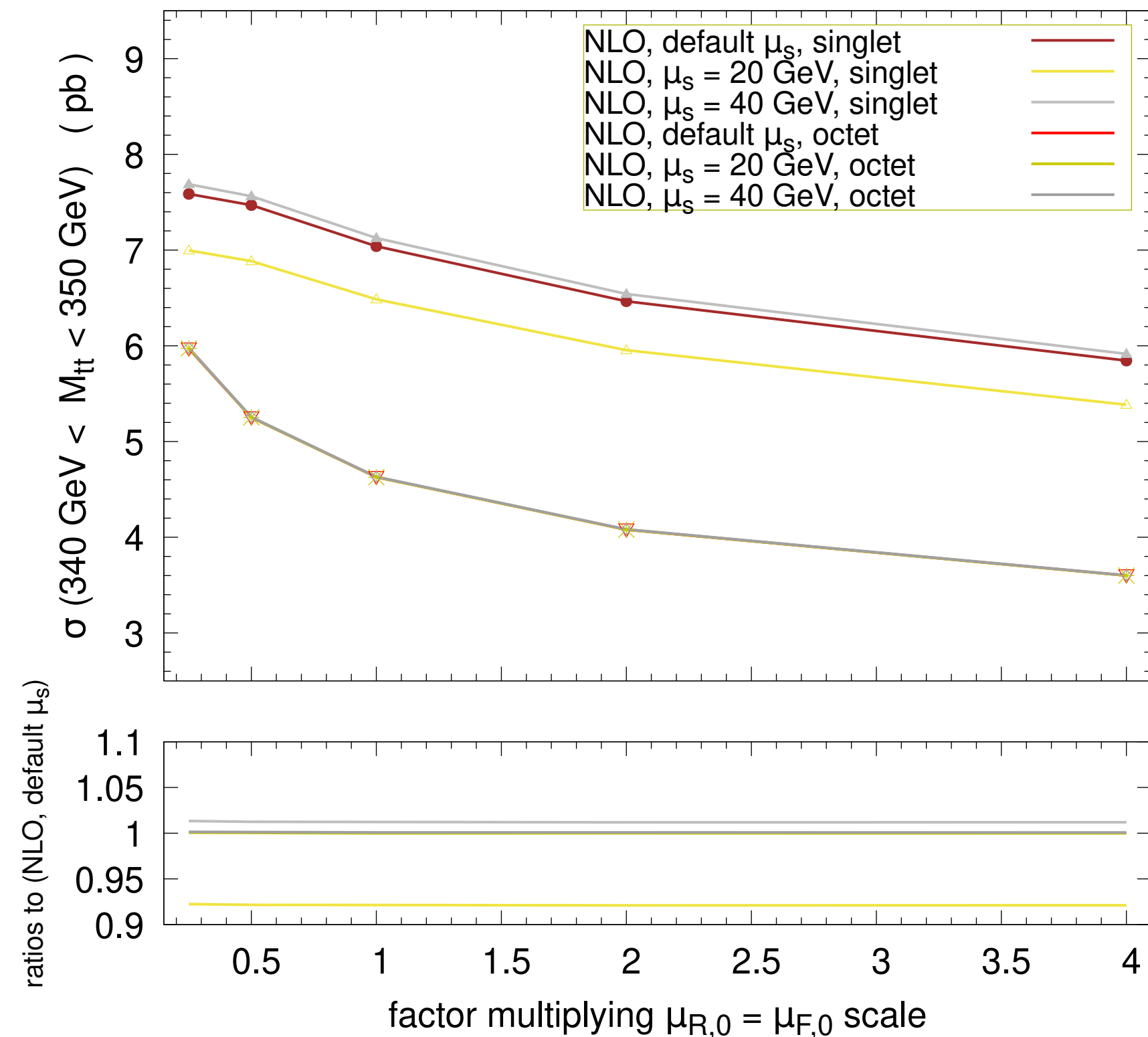
- Stable predictions for σ^{NRQCD} with central scale $\mu_{R,0} = \mu_{F,0} = m_t$
- Reduction by $\mathcal{O}(10\%)$ up to $\mathcal{O}(30\%)$ from neglecting subleading channels at $\mu_R = m_t/2, m_t/4$
- $\sim +5\%$ from NLL resummation at $\mu_R = m_t$

[Garzelli, GL, Moch, Steinhauser, Zenaiev '26]



σ^{NRQCD} and uncertainties

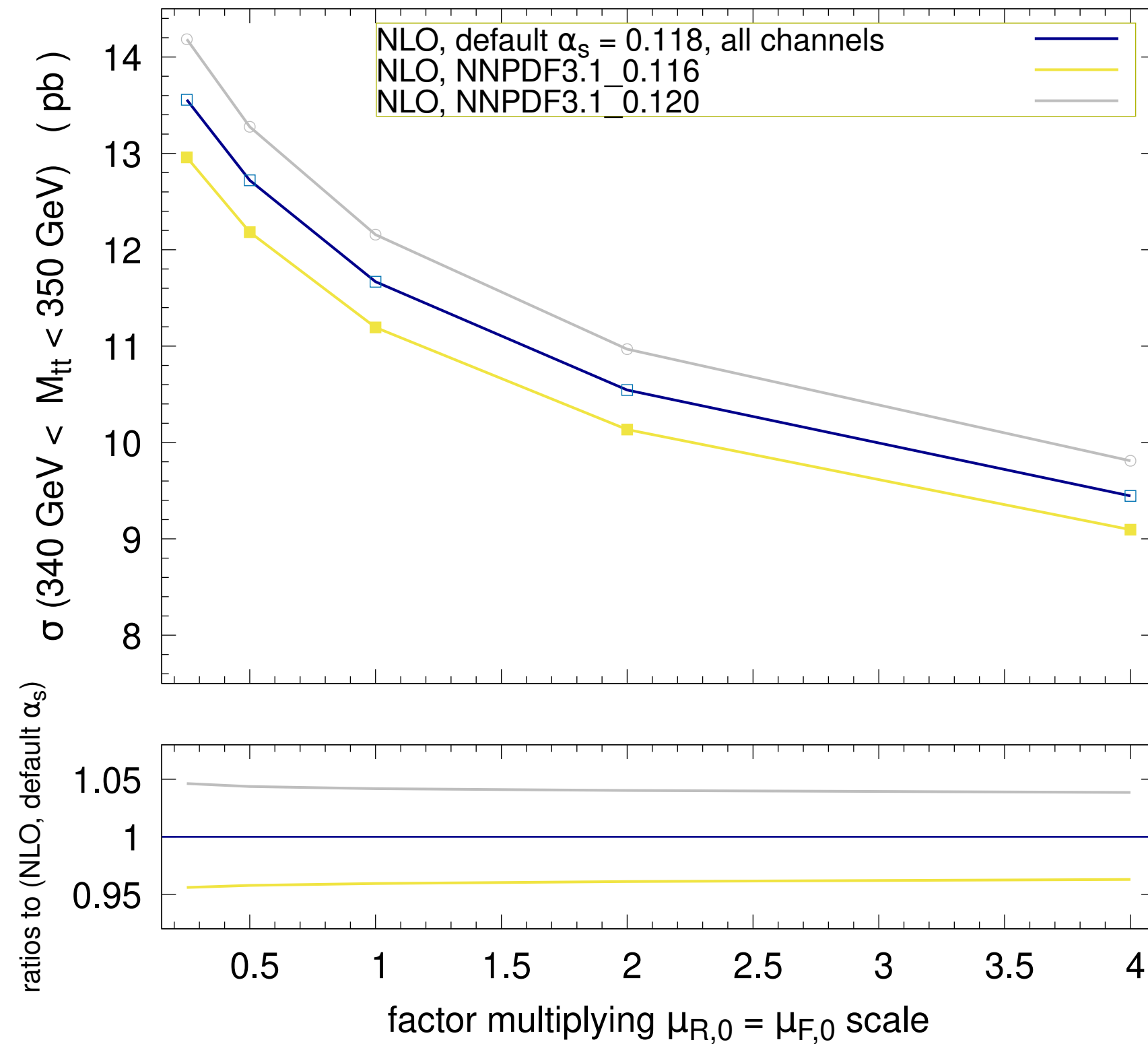
[Garzelli, GL, Moch, Steinhauser, Zenaiev '26]



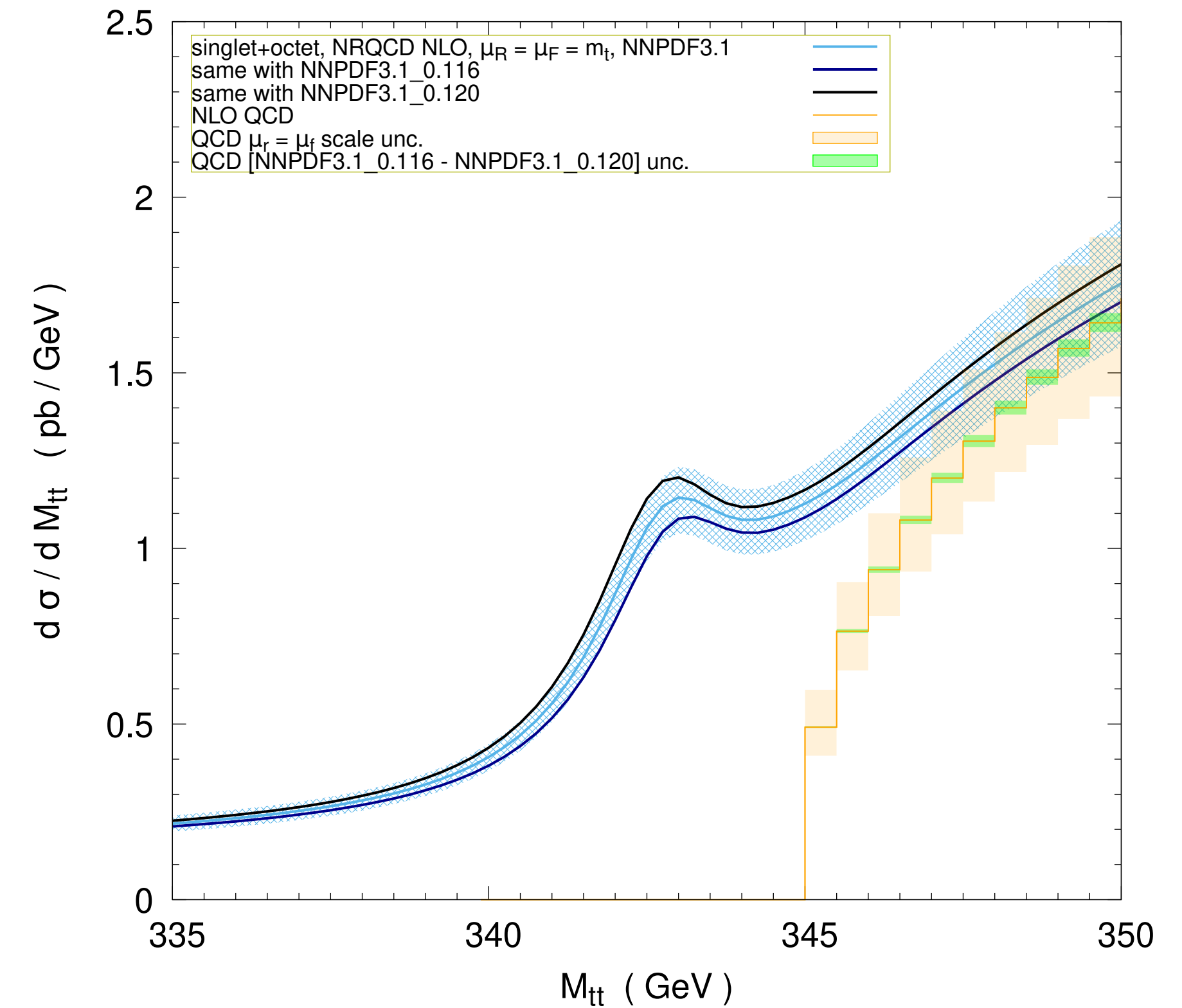
- Quasi-bound state dynamics at the scale $1/r_B = \mu_s = m_t C_F \alpha_s(\mu_s) \simeq 32 \text{ GeV}$
- $\mu_s \in [20, 40] \text{ GeV}$ with $+3\% - 9\%$ effects for $M_{t\bar{t}} \simeq 2m_t - 2 \text{ GeV}$
- Sensitivity to μ_s only from colour-singlet terms

Trivial dependence from $\mu_R = \mu_F$ variations

σ^{NRQCD} and uncertainties



Trivial dependence on $\mu_{R,0} = \mu_{F,0}$ variations

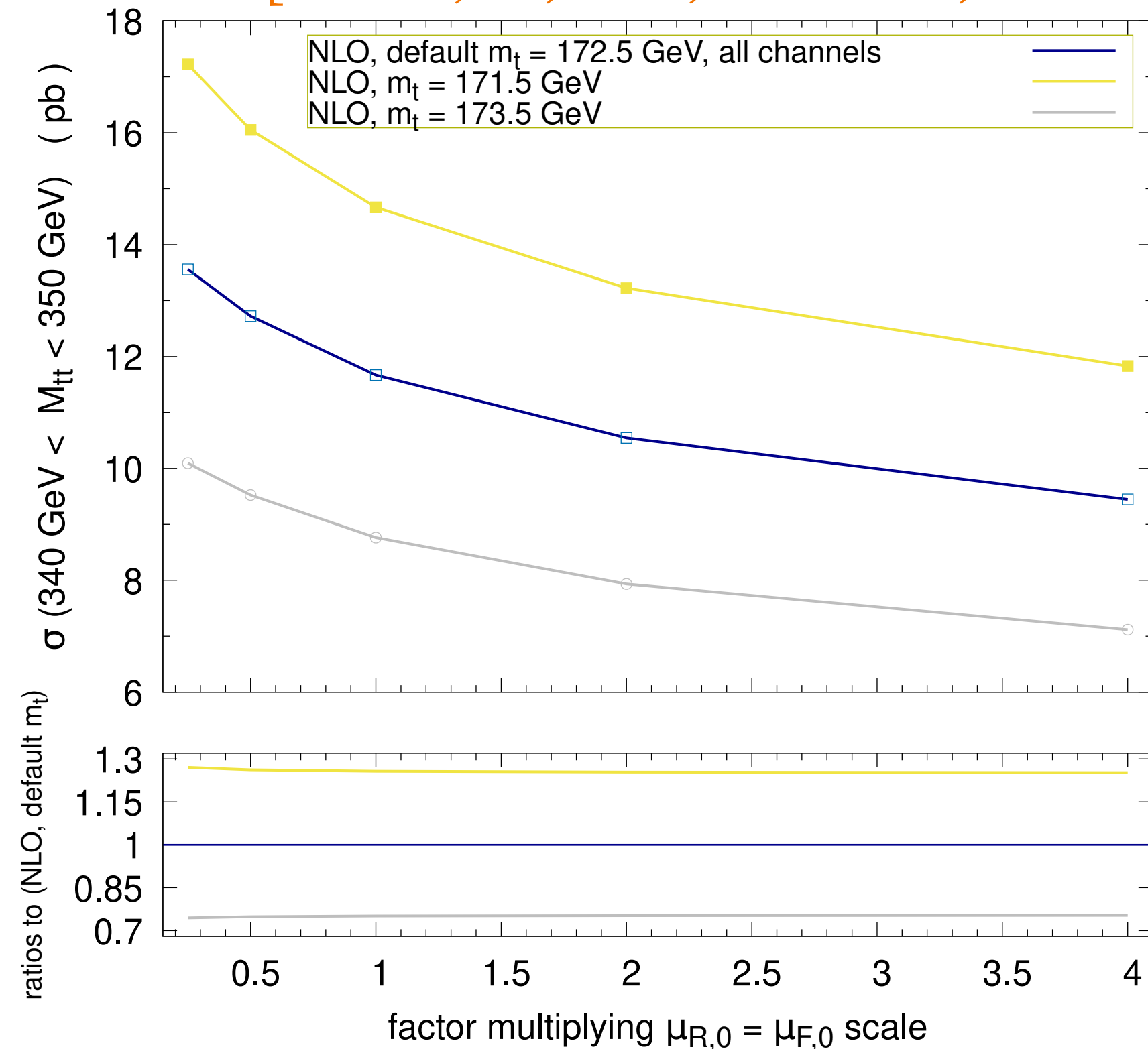


Differences stay within than scale uncertainties

- ± 0.002 variations w.r.t. the central predictions $\alpha_s(M_Z) = 0.118$, NNPDF3.1 PDF_set
- $\alpha_s(M_Z)$, PDFs correlations is accounted for
- Few percent effects in the region $M_{t\bar{t}} \in [340, 350] \text{ GeV}$

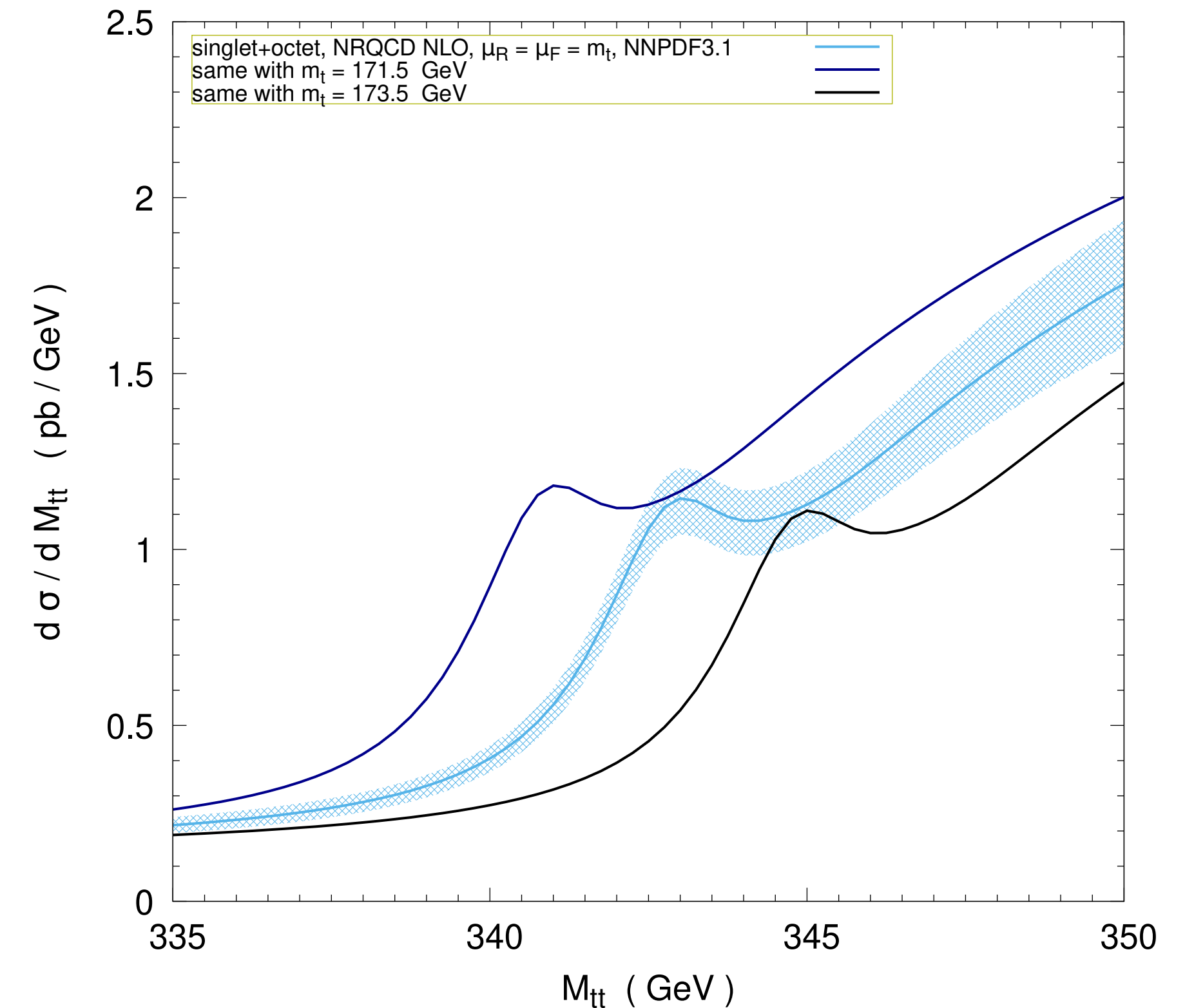
σ^{NRQCD} and uncertainties

[Garzelli, GL, Moch, Steinhauser, Zenaiev '26]



- $\pm 1 \text{ GeV}$ variations for $m_t = 172.5 \text{ GeV}$
- Smaller σ^{NRQCD} from larger m_t values
- $\pm 25 \%$ effects on σ^{NRQCD} in the selected range

Larger than scale uncertainties



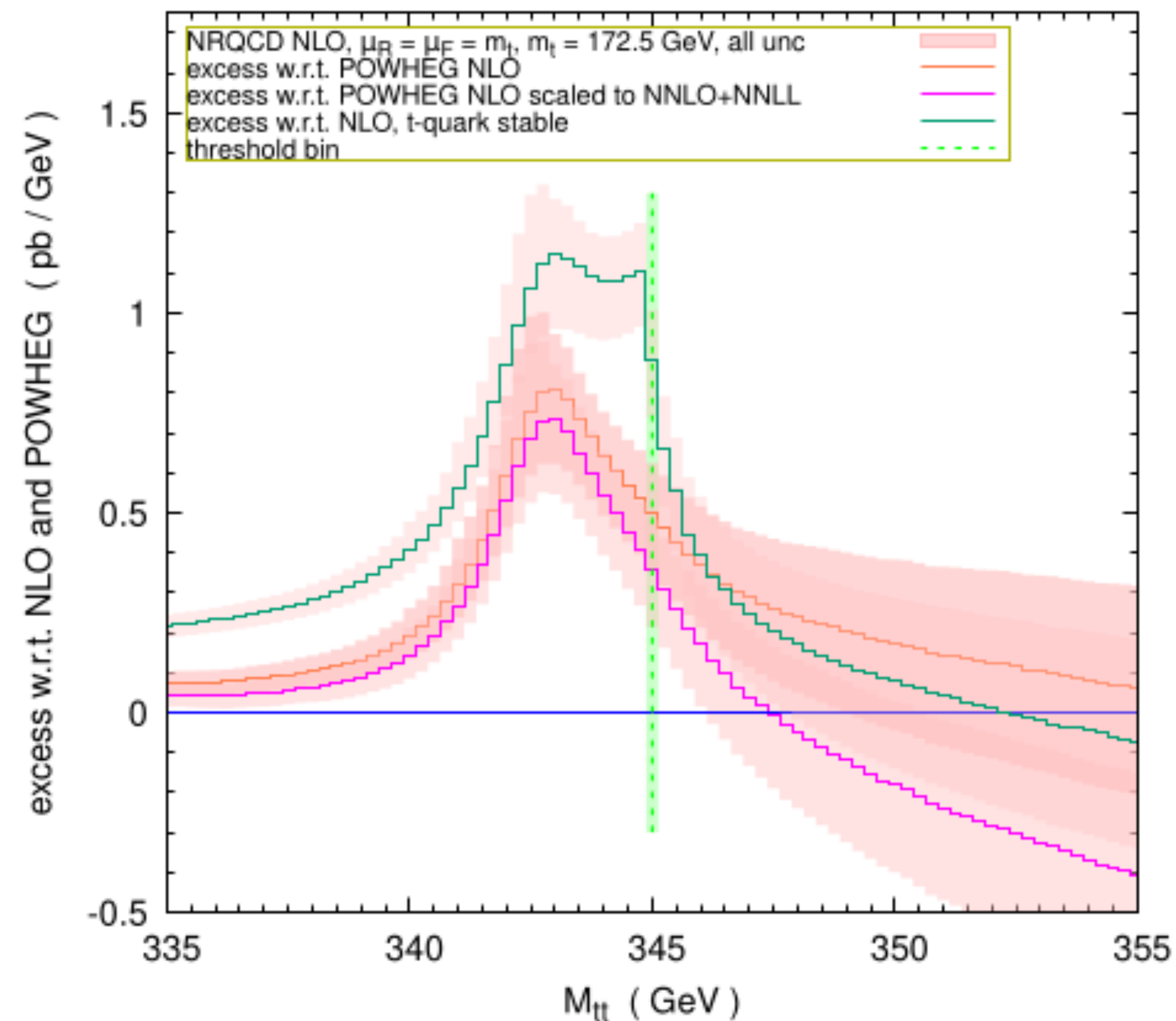
m_t determinations from $d\sigma/dM_{t\bar{t}}$
with improved experimental accuracy from HL-LHC

Phenomenology at the threshold

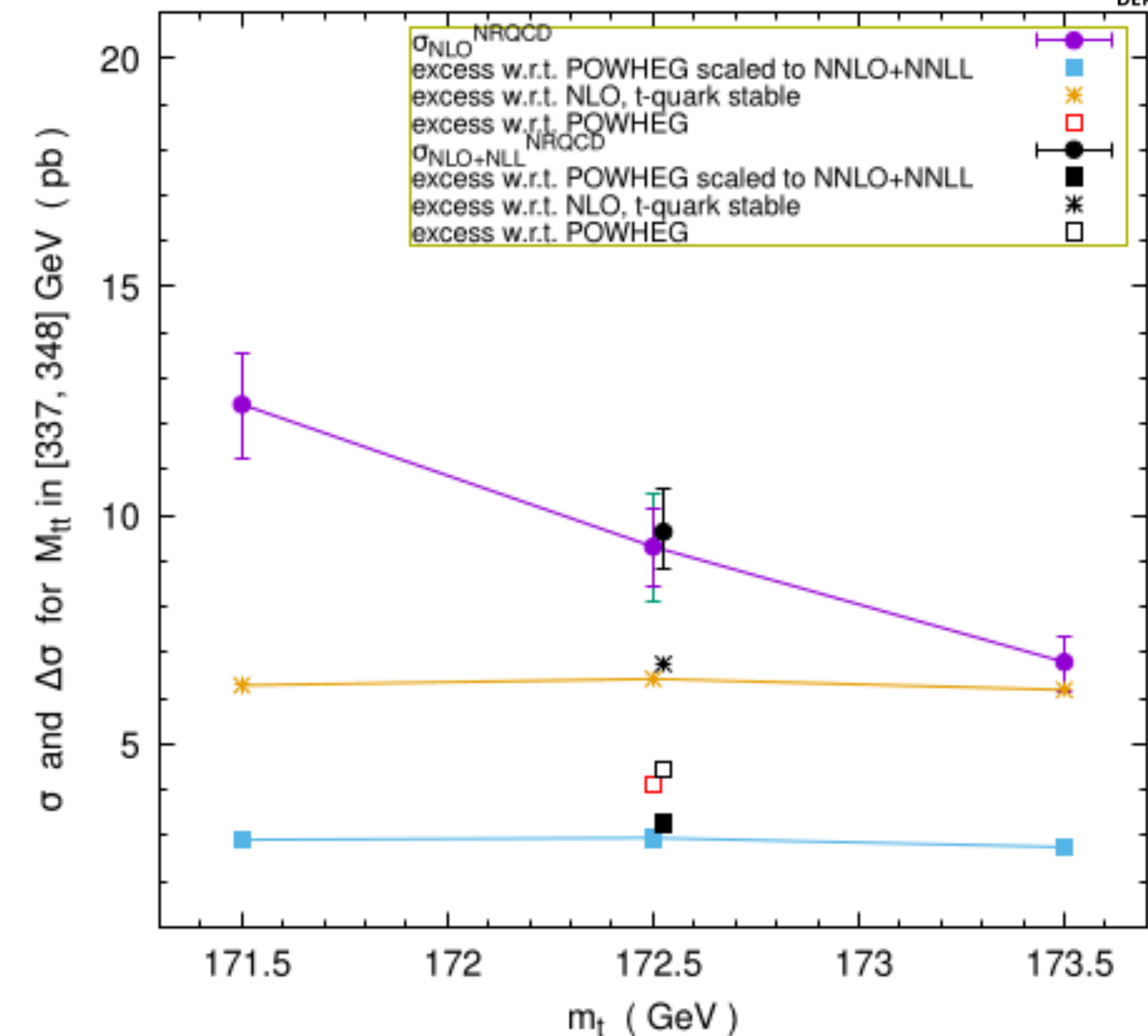
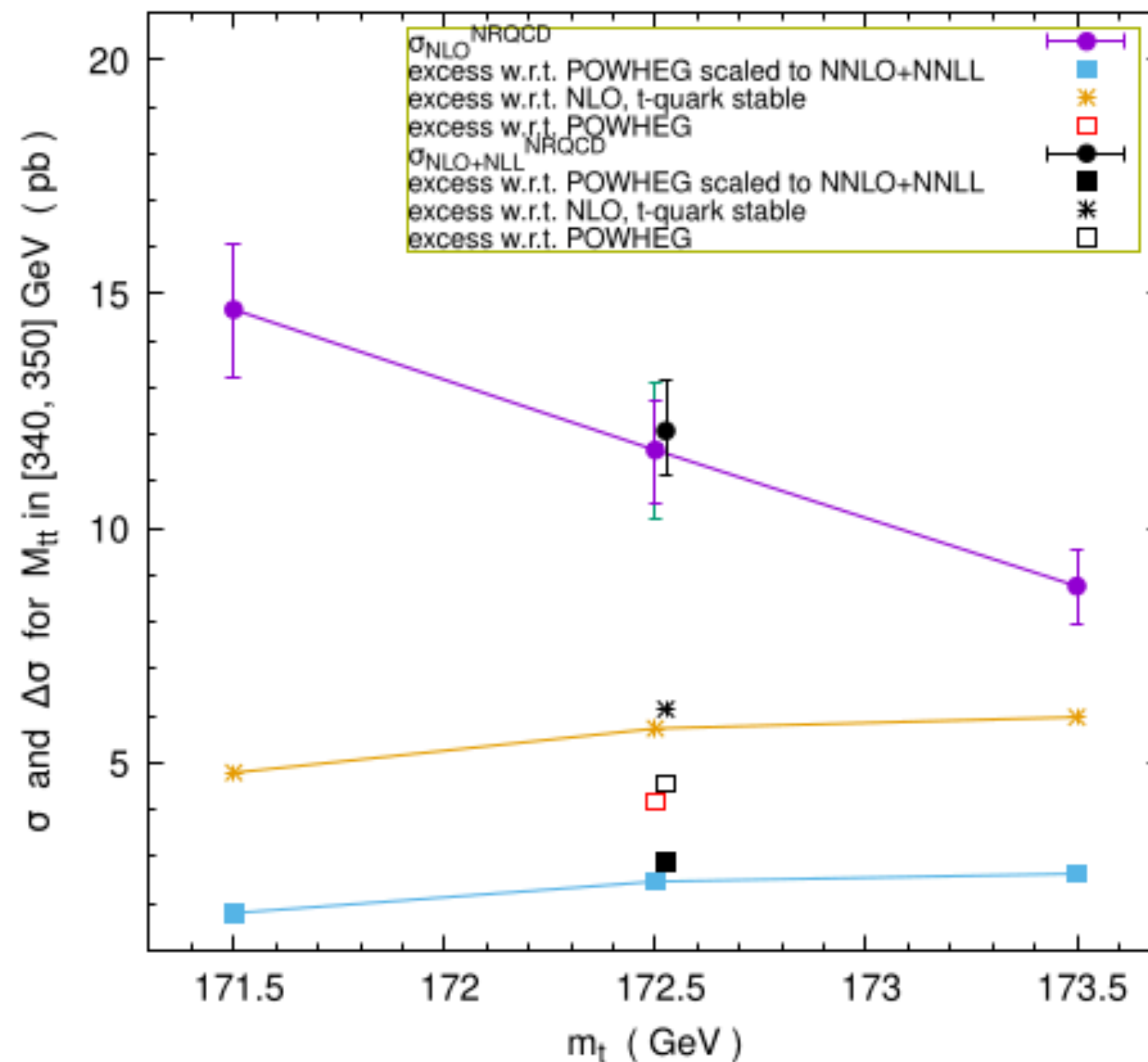
[Garzelli, GL, Moch, Steinhauser, Zenaiev '26]

- Sum in quadrature of Δ_μ , Δ_{μ_s} , Δ_{Γ_t} , Δ_{PDFs} , Δ_{α_s}
- $\Delta\sigma^{\text{NRQCD}}/\sigma^{\text{NRQCD}} \sim \pm 12\%$
- NLO pQCD results from POWHEG-hvq generator
[Frixione, Nason, Ridolfi, 0707.3088]
- NLO pQCD rescaled to NNLO+NNLL cross section
[CMS, 2503.22382]
- Excess extracted as $\sigma^{\text{excess}} = \sigma^{\text{NRQCD}} - \sigma^{\text{pQCD}}$

$$\sigma^{\text{excess}}(340 \text{ GeV} \leq M_{t\bar{t}} \leq 350 \text{ GeV}) = 4.15^{+1.43}_{-1.47} \text{ pb}$$



Phenomenology at the threshold



- $\mathcal{O}(\pm 10\%)$ from m_t variations on $\sigma^{\text{excess}}(340 \text{ GeV} \leq M_{t\bar{t}} \leq 350 \text{ GeV})$
- Further $\mathcal{O}(10\%)$ from resummation for $m_t = 172.5 \text{ GeV}$
- σ^{excess} independent on m_t variations for $M_{t\bar{t}} \in [337, 348] \text{ GeV}$

NRQCD matching to rigorously identify the integration range

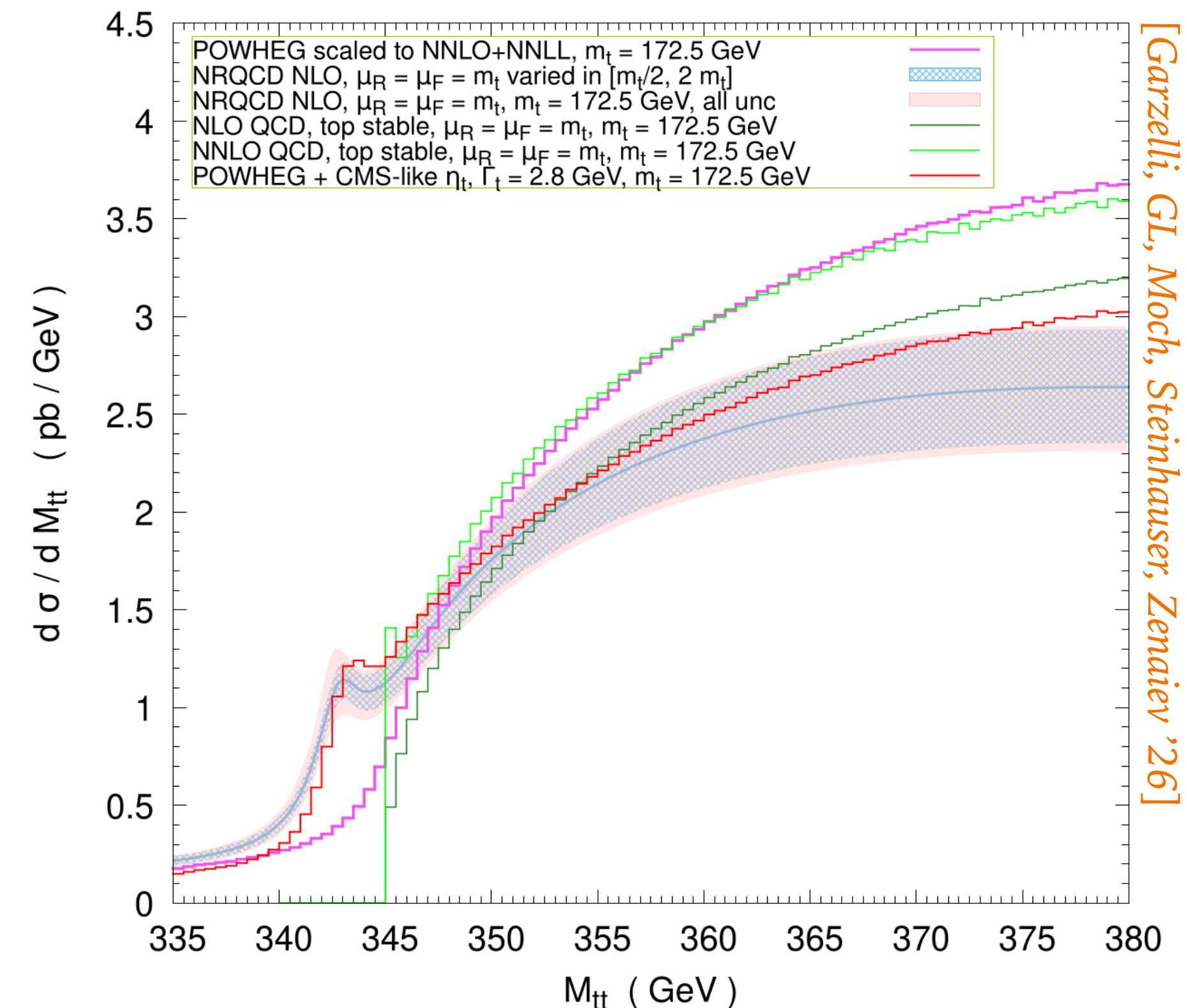
Modelling $t\bar{t}$ resonances

- Theoretical baseline for ATLAS and CMS based on NLO+PS within POWHEG-hvq+PYTHIA8
- Two-dimensional reweighting to NNLO QCD+NLO EW
- Quasi-bound state with colour-singlet Green's Function reweighting *Fuks, Hagiwara, Ma, Zheng [2102.11281]*

$$i\mathcal{M} \rightarrow i\mathcal{M} \times \frac{G(E; p^*)}{G_{\text{free}}(E; p^*)}$$

- Pseudoscalar-resonance particle η_t *Maltoni et al. [2401.08751]*

$$\mathcal{L}_{\eta_t} = \frac{1}{2} \partial_\mu \phi_{\eta_t} \partial^\mu \phi_{\eta_t} - \frac{1}{2} m_{\eta_t} \phi_{\eta_t}^2 - \frac{1}{4} g_{gg\eta_t} \phi_{\eta_t} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} - i g_{t\bar{t}\eta_t} \phi_{\eta_t} \bar{t} \gamma_5 t$$



Quasi-bound state or h.o. QCD?

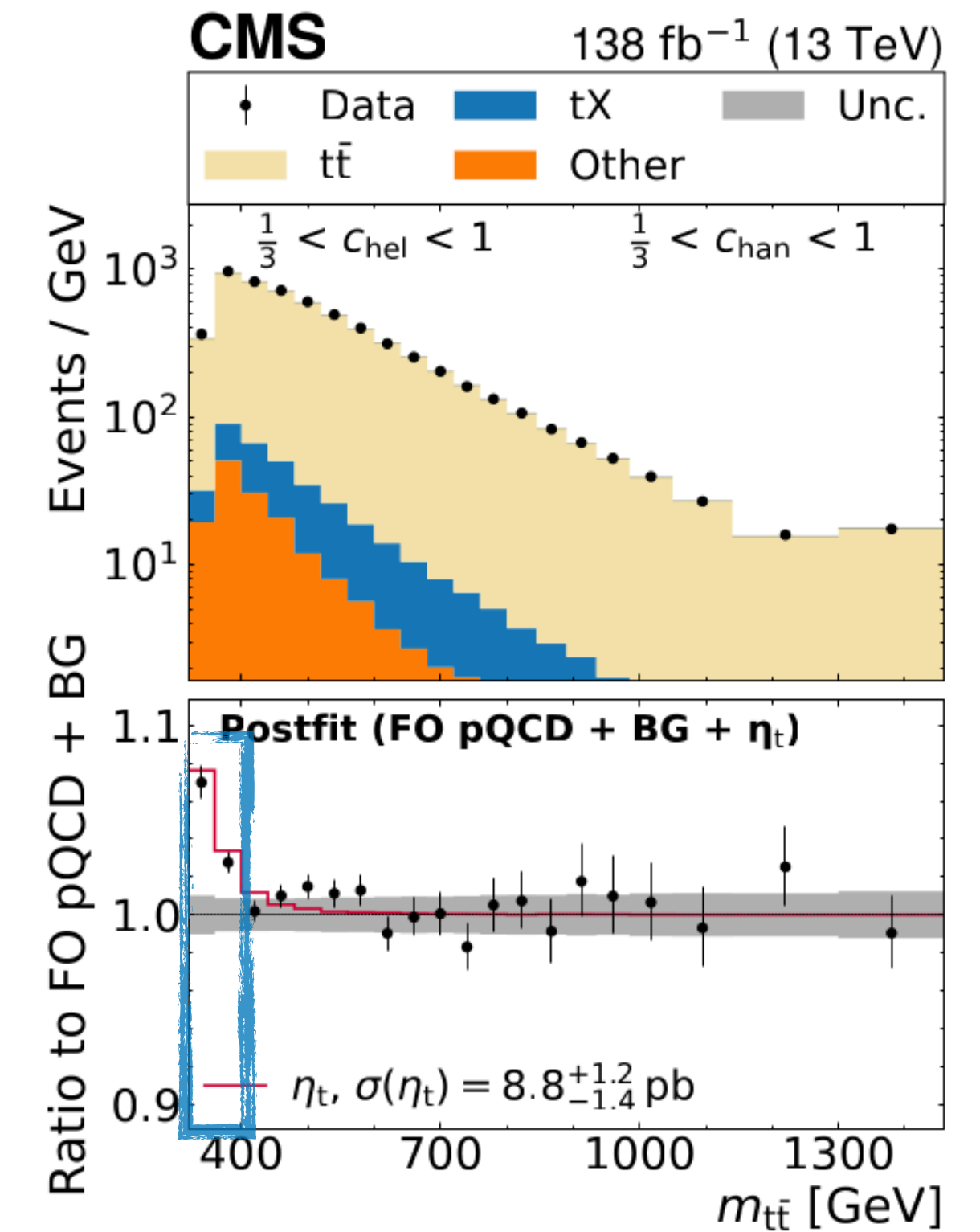
- Cross section enhancement observed for $M_{t\bar{t}} < 400$ GeV
- With large $M_{t\bar{t}}$ binning quasi-bound state and continuum contributions merge into pQCD predictions
- Threshold-enhanced effects encoded in NLO+PS POWHEG generators including finite-width effects [\[Nason, Re, Rottoli '25+Pelliccioli '26\]](#)
- Finite width-effects also included in a recent PYTHIA version [\[Sjöstrand, Khoze, Preuss '26\]](#)

[\[Nason, Re, Rottoli '25+Pelliccioli '26\]](#)

thr2 NLO results, no widths corr., $340 \text{ GeV} < m_{t\bar{t}} < M_{\text{cut}}$

M_{cut}	Δ from [32]	Basel.	central	Δ
345	2.73 ± 0.61	1.41(1)	3.91(1)	2.50(2)
346	3.16 ± 0.75	1.95(1)	5.24(1)	3.29(2)
347	3.48 ± 0.90	2.74(1)	6.66(2)	3.92(2)
348	3.74 ± 1.08	3.78(1)	8.21(2)	4.43(2)
349	3.97 ± 1.27	5.03(1)	9.88(2)	4.84(2)
350	4.15 ± 1.47	6.48(1)	11.67(2)	5.20(2)

Fairly compatible results within the errors



Conclusions

- Top quark essential sector for precision SM and BSM physics
 - Many progresses in fixed-order computation for $t\bar{t}$ pair production and off-shell effects
 - Efforts in multi-loop and multi-scale scattering amplitudes
 - Excess of events in $M_{t\bar{t}}$ distribution from ATLAS and CMS
 - Many approaches to model threshold effects in $M_{t\bar{t}}$ distribution
 - NRQCD corrections at the threshold to be matched to pQCD predictions in the *continuum*
 - Towards NNLO NRQCD
- NRQCD
 - Green's Function reweighting
 - New PYTHIA release
 - Fixed-order pQCD computations

BACKUP

Top Quark production at the LHC

$t\bar{t}$ production

- NNLO QCD at inclusive and differential level [Czakon et al. '13, '15, '16, Catani et al. '19]
↳ +NNLL threshold resummation [Czakon et al. '18]
- aNNLO QCD production + NNLO QCD decay [Gao, Papanastasiou '17]
- NNLO QCD+NLO EW [Czakon et al. '20, Huss et al. '25]
- NNLO QCD matched to PS in MiNNLO [Mazzitelli et al. '20, '21]

$t\bar{t}$ production and decay

- NLO QCD (full off-shell) [Denner et al. '10, Bevilacqua et al. '10, Denner et al. '12]
+NLO EW [Denner, Pellen '16]
- NLO+PS in the NWA [Campbell '14] and for
full off-shell $bb4l$ state [Jezo et al. '16]

Dilepton channel

- NNLO QCD (DPA) [Buonocore et al. '25]

- NLO QCD [Denner, Pellen '17] + PS [Jezo et al. '23]

- NNLO+PS in MiNNLO [Mazzitelli et al. '21]

$l + j$ channel

- Complete NLO QCD+full off-shell effects [Mans et al. '25]

process	known	desired
$pp \rightarrow t\bar{t}$	NNLO _{QCD} + NLO _{EW} (w/o decays) NLO _{QCD} + NLO _{EW} (off-shell) NNLO _{QCD} (w/ decays)	N ³ LO _{QCD}
$pp \rightarrow t\bar{t} + j$	NLO _{QCD} (off-shell effects) NLO _{EW} (w/o decays)	NNLO _{QCD} + NLO _{EW} (w decays)
$pp \rightarrow t\bar{t} + 2j$	NLO _{QCD} (w/o decays)	NLO _{QCD} + NLO _{EW} (w decays)
$pp \rightarrow t\bar{t} + V'$	NLO _{QCD} + NLO _{EW} (w decays)	NNLO _{QCD} + NLO _{EW} (w decays)
$pp \rightarrow t\bar{t} + \gamma$	NLO _{QCD} (off-shell)	
$pp \rightarrow t\bar{t} + Z$	NLO _{QCD} + NLO _{EW} (off-shell)	
$pp \rightarrow t\bar{t} + W$	NLO _{QCD} + NLO _{EW} (off-shell)	
$pp \rightarrow H + t\bar{t}$	NLO _{QCD} + NLO _{EW} NNLO _{QCD} (approx.)	NNLO _{QCD}
$pp \rightarrow H + t/\bar{t}$	NLO _{QCD} + NLO _{EW}	NNLO _{QCD}

Les Houches 2023 — Physics at TeV Colliders:

Report on the Standard Model Precision Wishlist [2504.06689v2]

$t\bar{t}$ production at the threshold @ LHC

[Kiyo, Kühn, Moch, Steinhauser '08]

- Logarithmic enhanced terms from $\mathcal{A}_c$ and $\mathcal{A}_{nc}$ due to soft gluon emissions
- Impact over $\mathcal{L} \otimes F$ as long as $z = \rho/\tau \rightarrow 1$
- Working in the Mellin space

$$F_{ij}^N = \int_0^1 dz z^{N-1} F_{ij}$$

- NLL soft-gluons threshold resummation

$$F_{ij}^{\text{res}} = \int \frac{dN}{2\pi i} x^{-N} \left(F_{ij}^N - F_{ij}^N|_{\text{NLO}} \right) + F_{ij}^{\text{NLO}}$$

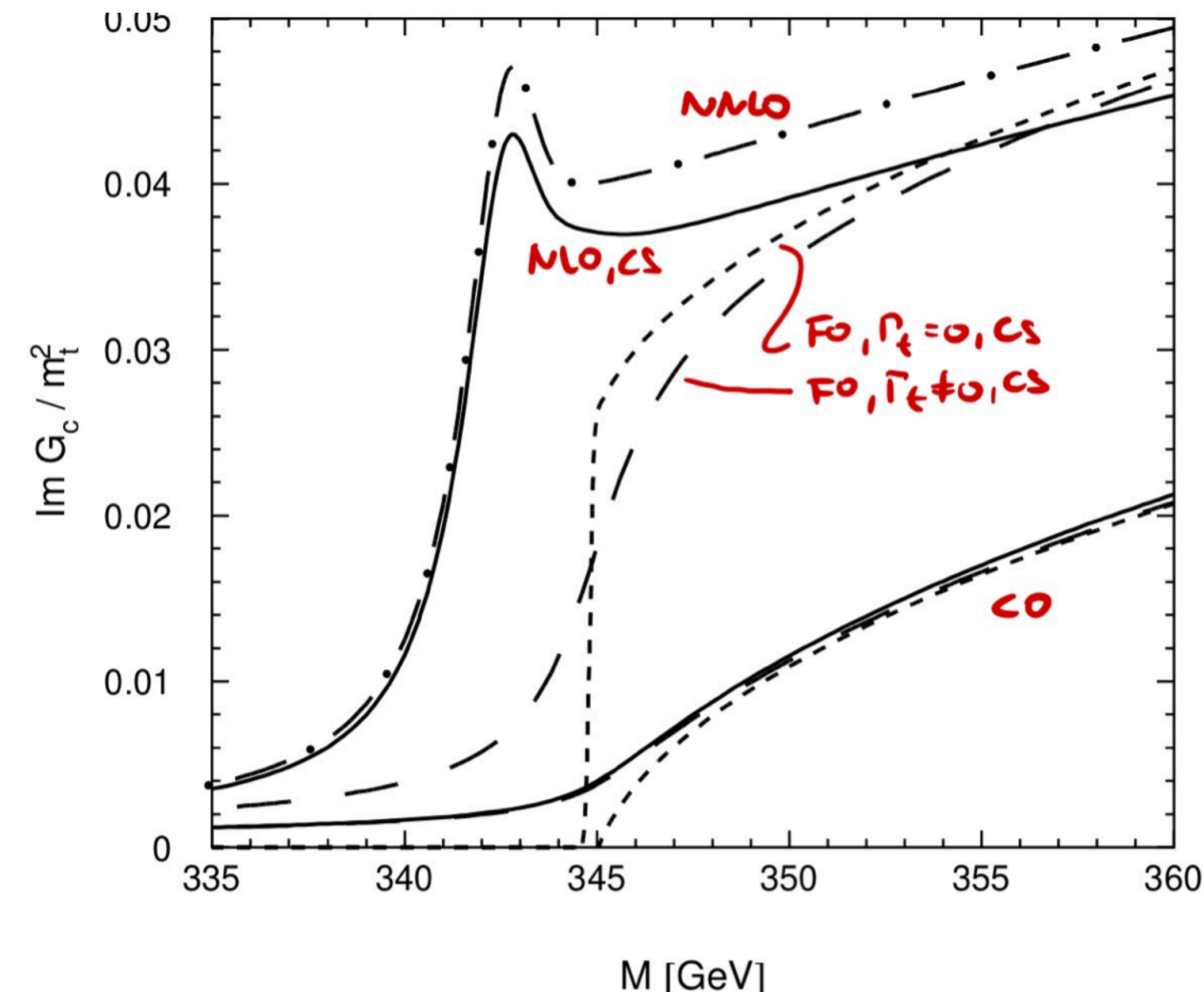
$$F_{ij \rightarrow T}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) = \mathcal{N}_{ij} \frac{\pi^2 \alpha_s^2(\mu_r)}{3\hat{s}} \left(1 + \frac{\alpha_s(\mu_r)}{\pi} \mathcal{C}_h \right) \\ \times \left[\delta_{ij \rightarrow T} \delta(1-z) + \frac{\alpha_s(\mu_r)}{\pi} (\mathcal{A}_c + \mathcal{A}_{nc}) \right]$$

Soft threshold logarithms only for

$$gg \rightarrow^1 S_0^{[1,8]}, q\bar{q} \rightarrow^3 S_1^{[8]}$$

$G(M + i\Gamma_t)$ contribution

$$\left\{ 2m_t + \left[\frac{(-i\nabla)^2}{m_t} + V_C^{[1,8]}(\vec{r}) \right] - (M + i\Gamma_t) \right\} G^{[1,8]}(\vec{r}; M + i\Gamma_t) = \delta^{(3)}(\vec{r})$$



$$V_C^{[1,8]} = -\frac{4\pi\alpha_s(\mu)C^{[1,8]}}{\vec{q}^2} \left[1 + \frac{\alpha_s(\mu)}{4\pi} \left(\beta_0 \ln \frac{\mu^2}{\vec{q}^2} + a_1 \right) \right]$$

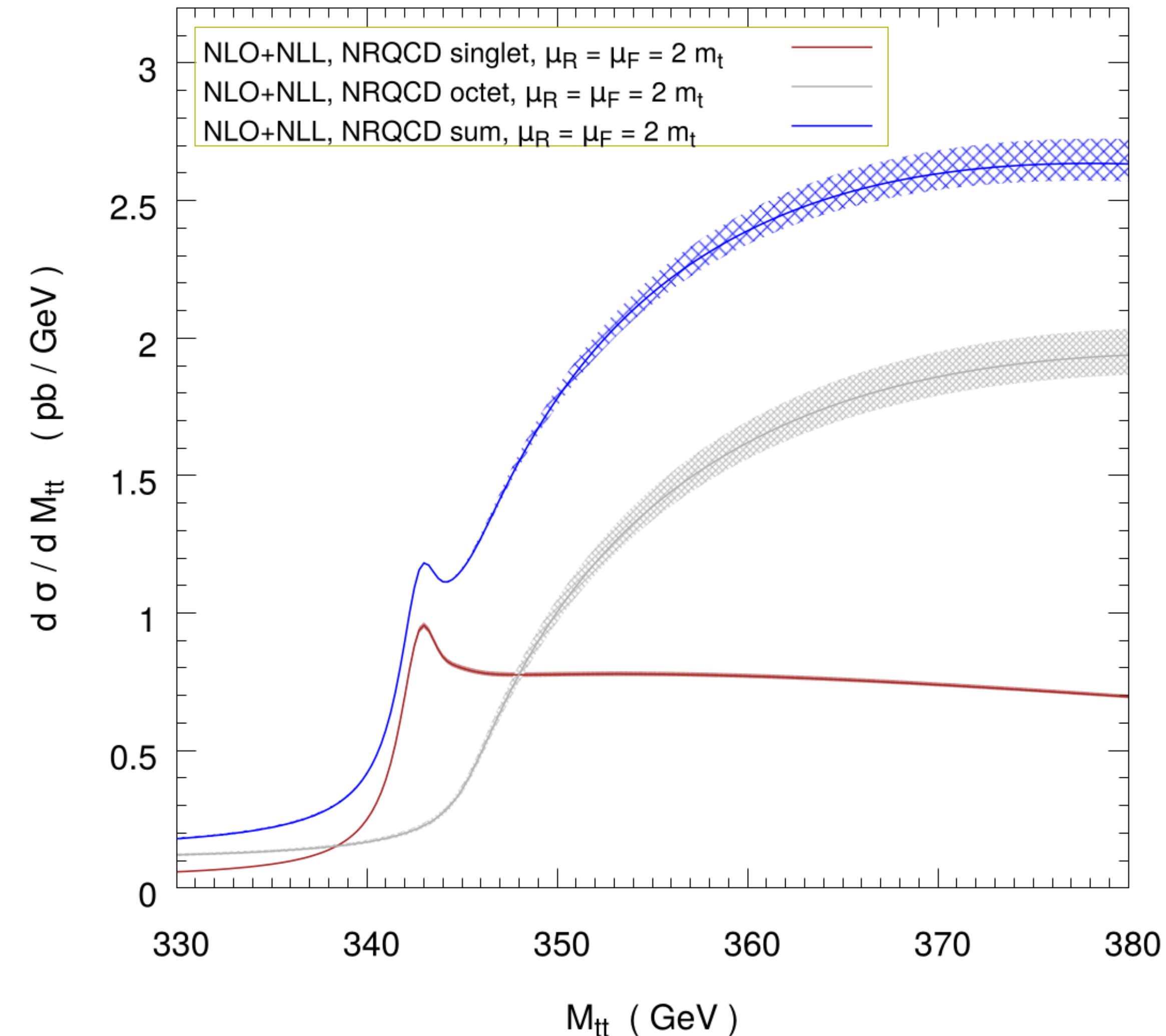
$$C^{[1]} = C_F = 4/3$$

$$C^{[8]} = C_F - C_A/2 = -1/6$$

Thanks to Matthias Steinhauser

NRQCD Predictions

[Garzelli, GL, Moch, Steinhauser, Zenaiev '24]



- $gg \rightarrow {}^1S_0^{[1]}$ shows a resonance peak in the kinematic region $M_{t\bar{t}} \simeq 2m_t$
- Depletion in the $gg \rightarrow {}^1S_0^{[8]} + q\bar{q} \rightarrow {}^3S_1^{[8]}$ due to the repulsive nature of $V_C^{[8]}$
- Impact of Γ_t in the region below the threshold due to falling off slowly in this region $G^{[8]}(M_{t\bar{t}} + i\Gamma_t)$

Modelling $t\bar{t}$ resonances

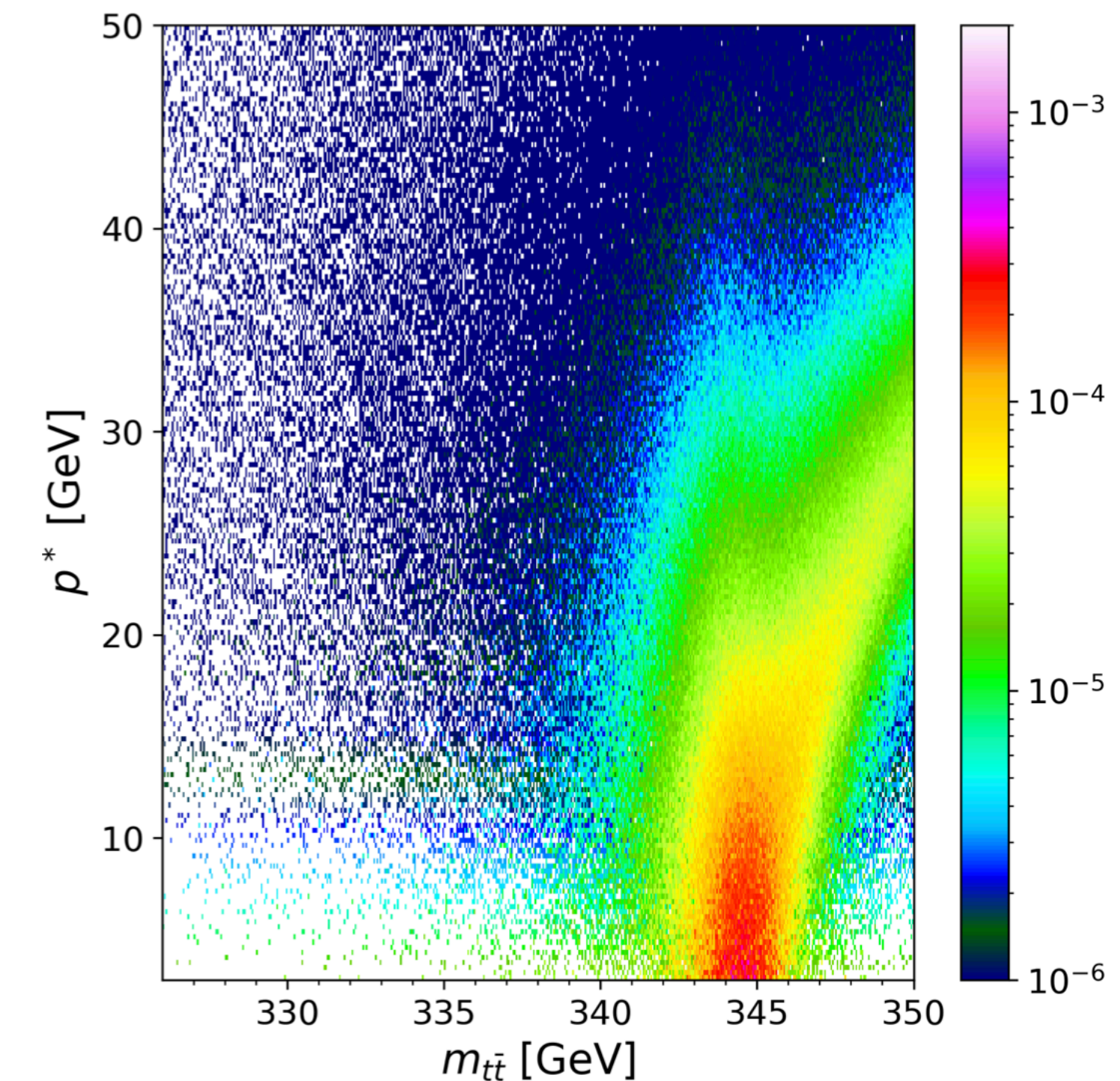
- Theoretical baseline for ATLAS and CMS based on NLO+PS within POWHEG-hvq+PYTHIA8
- Two-dimensional reweighting to NNLO QCD+NLO EW
- Quasi-bound state with colour-singlet Green's Function reweighting

$$i\mathcal{M} \rightarrow i\mathcal{M} \times \frac{G(E; p^*)}{G_{\text{free}}(E; p^*)} \quad \text{Fuks, Hagiwara, Ma, Zheng [2102.11281]}$$

- Pseudoscalar-resonance particle η_t *Maltoni et al. [2401.08751]*

$$\mathcal{L}_{\eta_t} = \frac{1}{2} \partial_\mu \phi_{\eta_t} \partial^\mu \phi_{\eta_t} - \frac{1}{2} m_{\eta_t} \phi_{\eta_t}^2 - \frac{1}{4} g_{gg\eta_t} \phi_{\eta_t} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} - i g_{t\bar{t}\eta_t} \phi_{\eta_t} \bar{t} \gamma_5 t$$

[Fuks '24 + Hagiwara, Ma, Zheng '25]

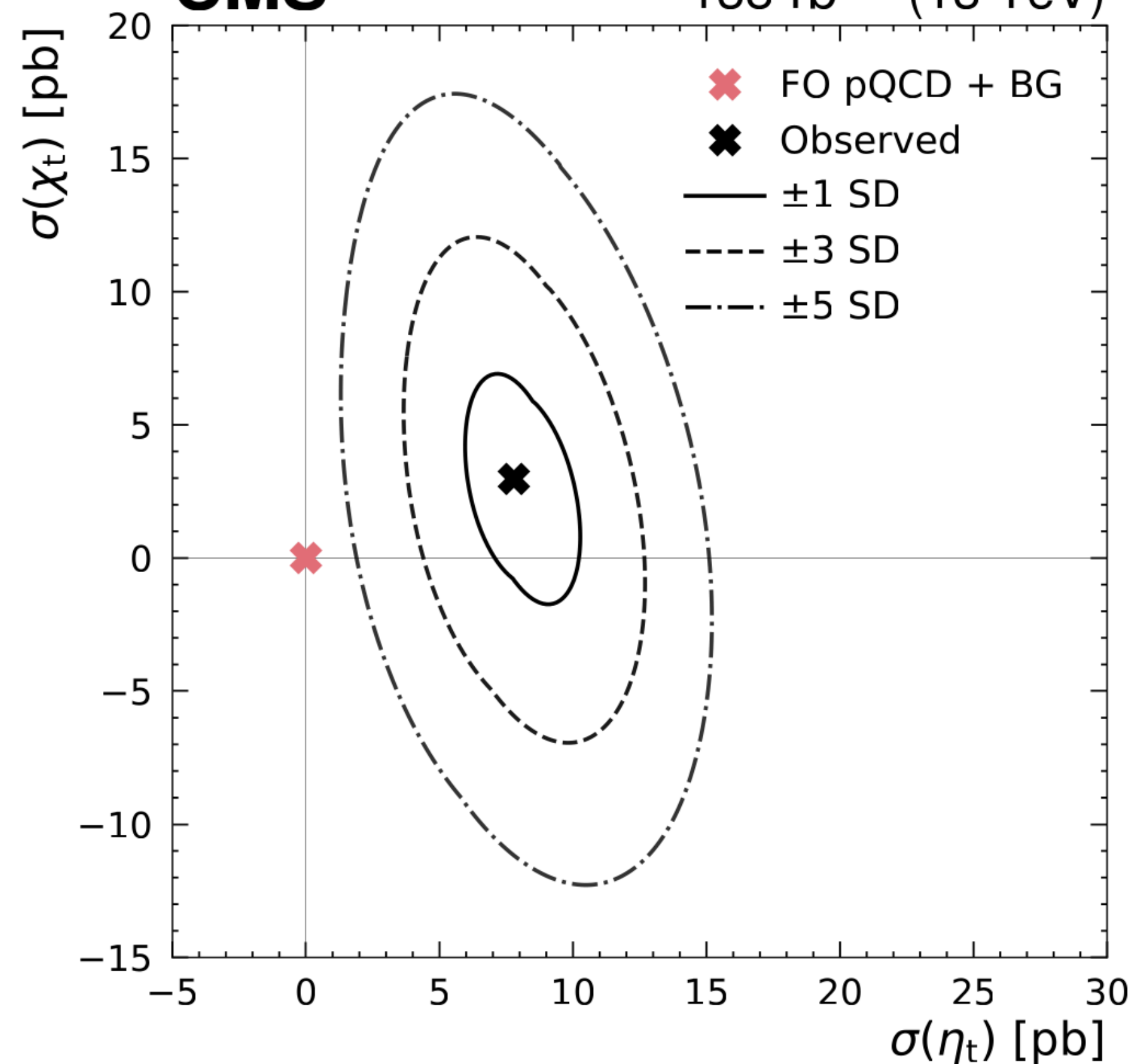


Conclusions and Outlooks

[CMS-TOP-24-007]

CMS

138 fb⁻¹ (13 TeV)



- Simultaneous fit including scalar χ_t and pseudoscalar η_t contributions

$\sigma(\chi_t)$ compatible with zero within one SD