Top quark pairs in the threshold at the LHC

(Based on 2412.16685, in collaboration with Garzelli, Moch, Steinhauser, Zenaiev)

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DESY

Workshop on Top Quark Mass Measurement
Valencia
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Introduction

- The LHC has provided astonishing results in testing the Standard Model
- No clear signal of Beyond the Standard Model effects (yet!)
- The upcoming High-Luminosity regime at the LHC is expected to improve both the statistical accuracy and the coverage of phase space
- This poses a significant challenge to the theory community
- Emphasis on high multiplicity processes and/or massive particles production

The Top Quark

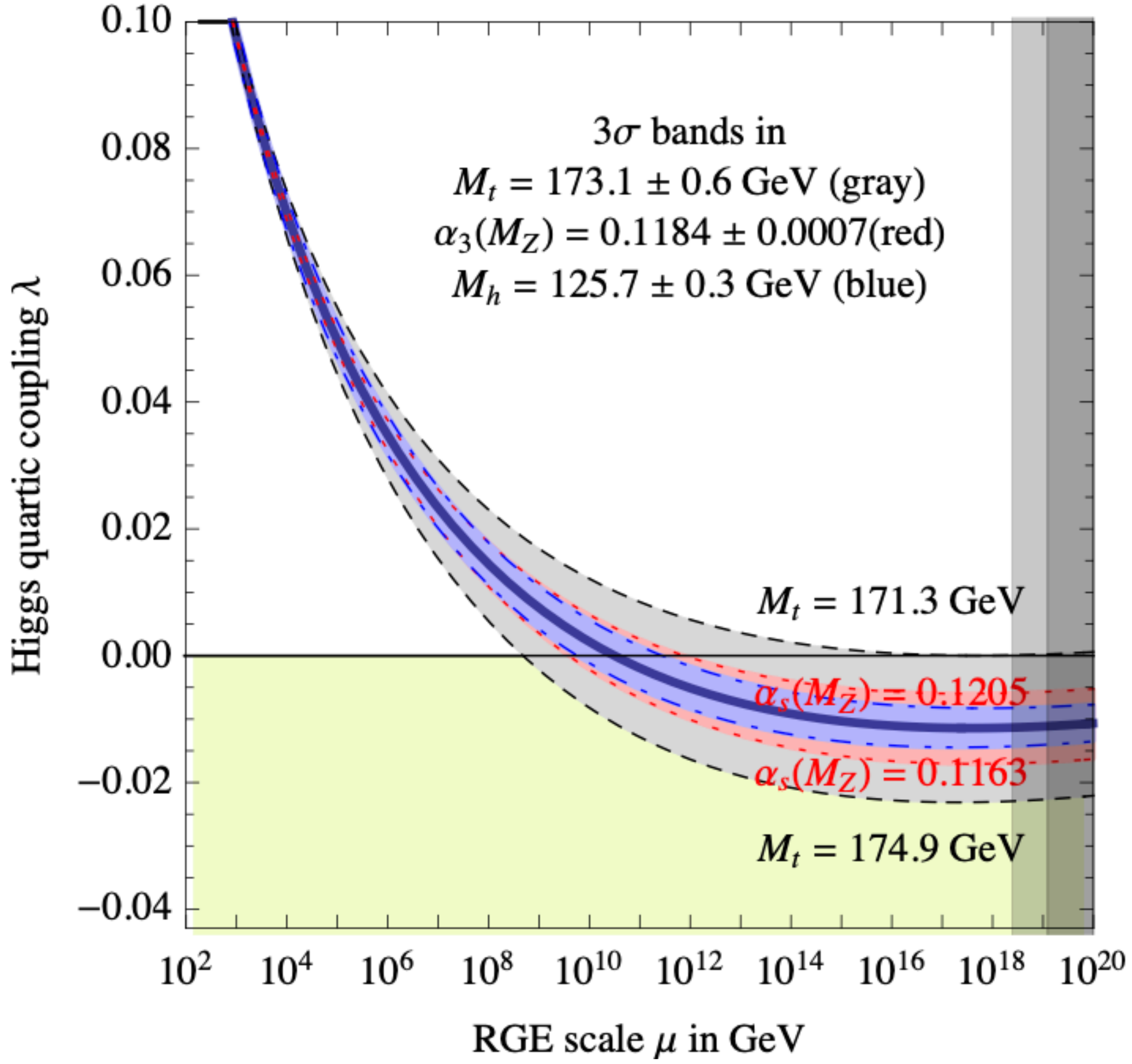
[PDG 2018]

- The heaviest known fundamental particle $m_t = 172.9 \pm 0.4\ \mathrm{GeV}$
- Large Yukawa coupling to the Higgs Boson λ_t
- m_t plays a key role in the stability of the Universe
- $\Gamma_t(t \to Wb) \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}} \sim 1.6\ \mathrm{GeV} \gg \Lambda_{\mathrm{QCD}}$

Life-time too short for hadron formation

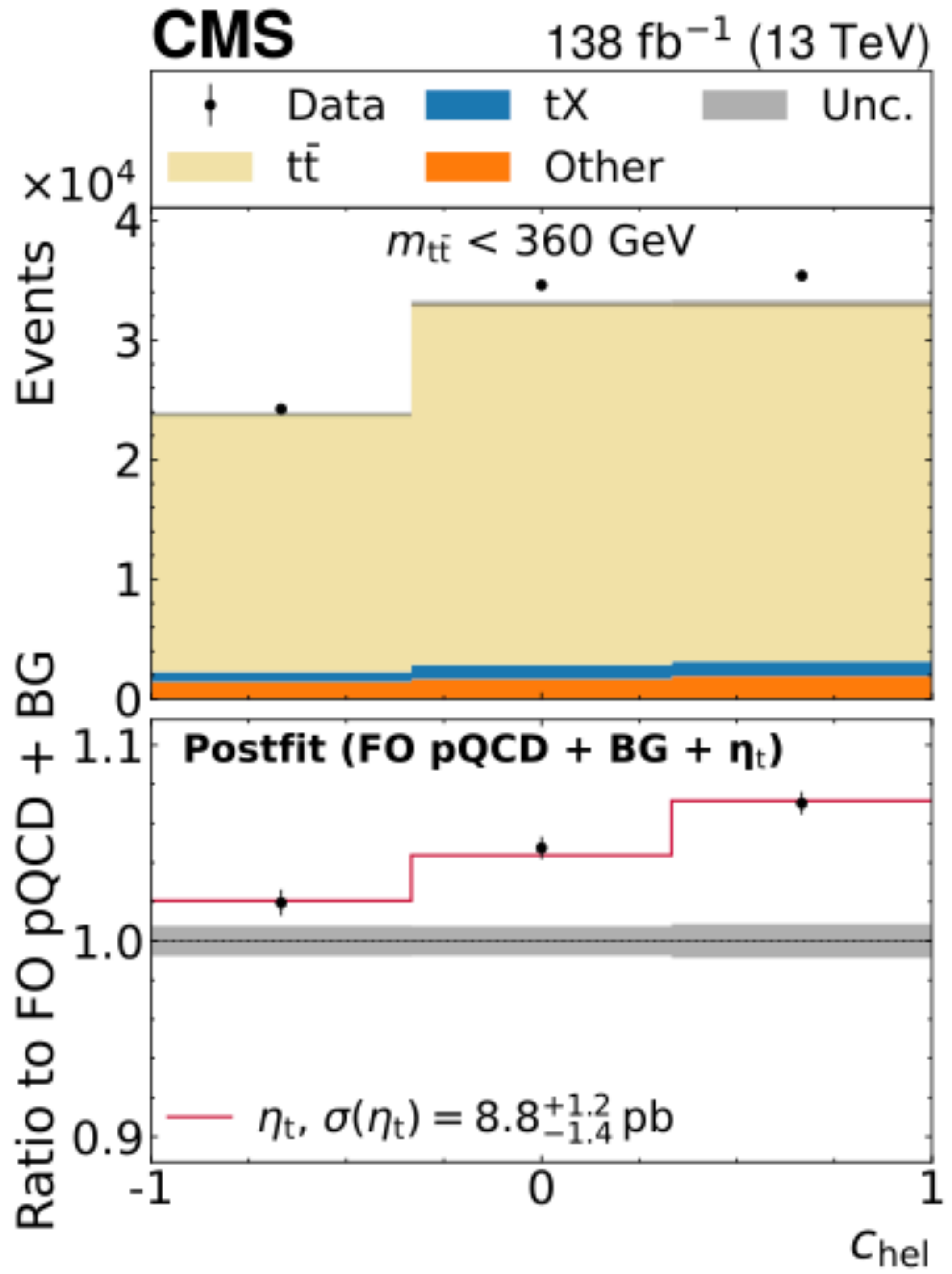
Top quark properties can be studied directly!

Degrassi et al. [1205.6497]



Results from CMS and ATLAS

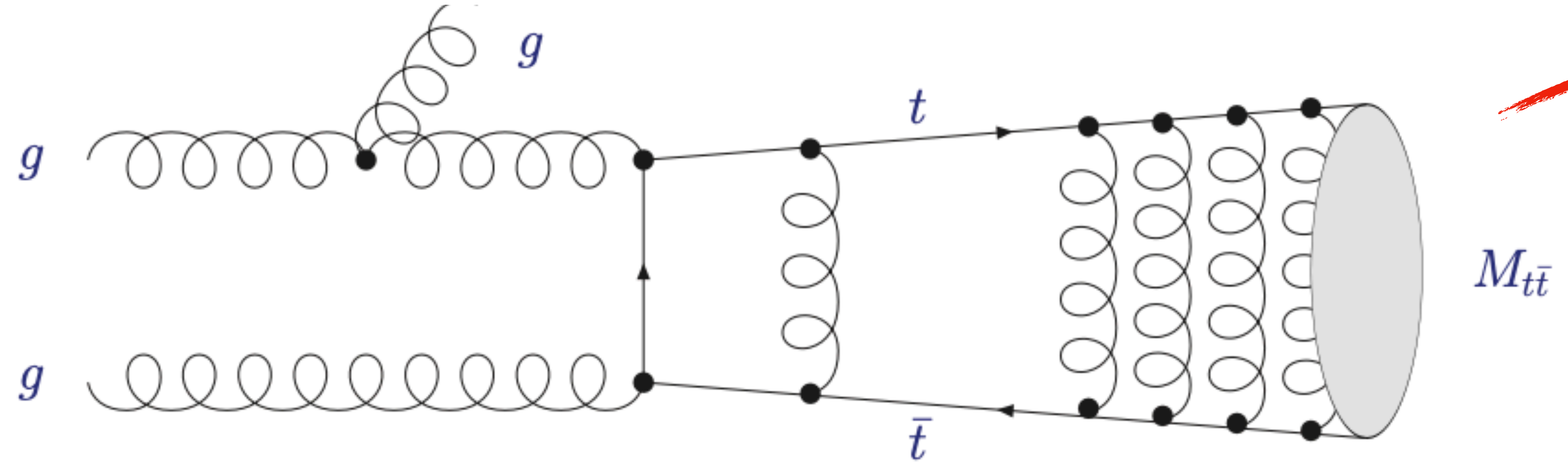
- The spin information of the top quark is entirely transferred to its leptonic decay product
- Spin correlation measurements performed introducing two angular observables $\hat{c}_{\text{hel}}$, $\hat{c}_{han}$
- Observation of a significant excess of events in the threshold region $M_{t\bar{t}} \simeq 2m_t$ w.r.t. to pQCD predictions
- $\sigma_{\text{CMS}} = 8.8^{+1.2}_{-1.4}$ pb [CMS, 2503.22382]
  $\sigma_{\text{ATLAS}} = 9.0 \pm 1.3$ pb [ATLAS-CONF-2025-008]
- BSM pseudoscalar effects?
  Quasi-bound state effects?



Threshold enhanced effects require dedicated studies!

$t\bar{t}$ 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
- Quasi-bound state effects can be modelled as multiple soft gluon exchanges between top quarks

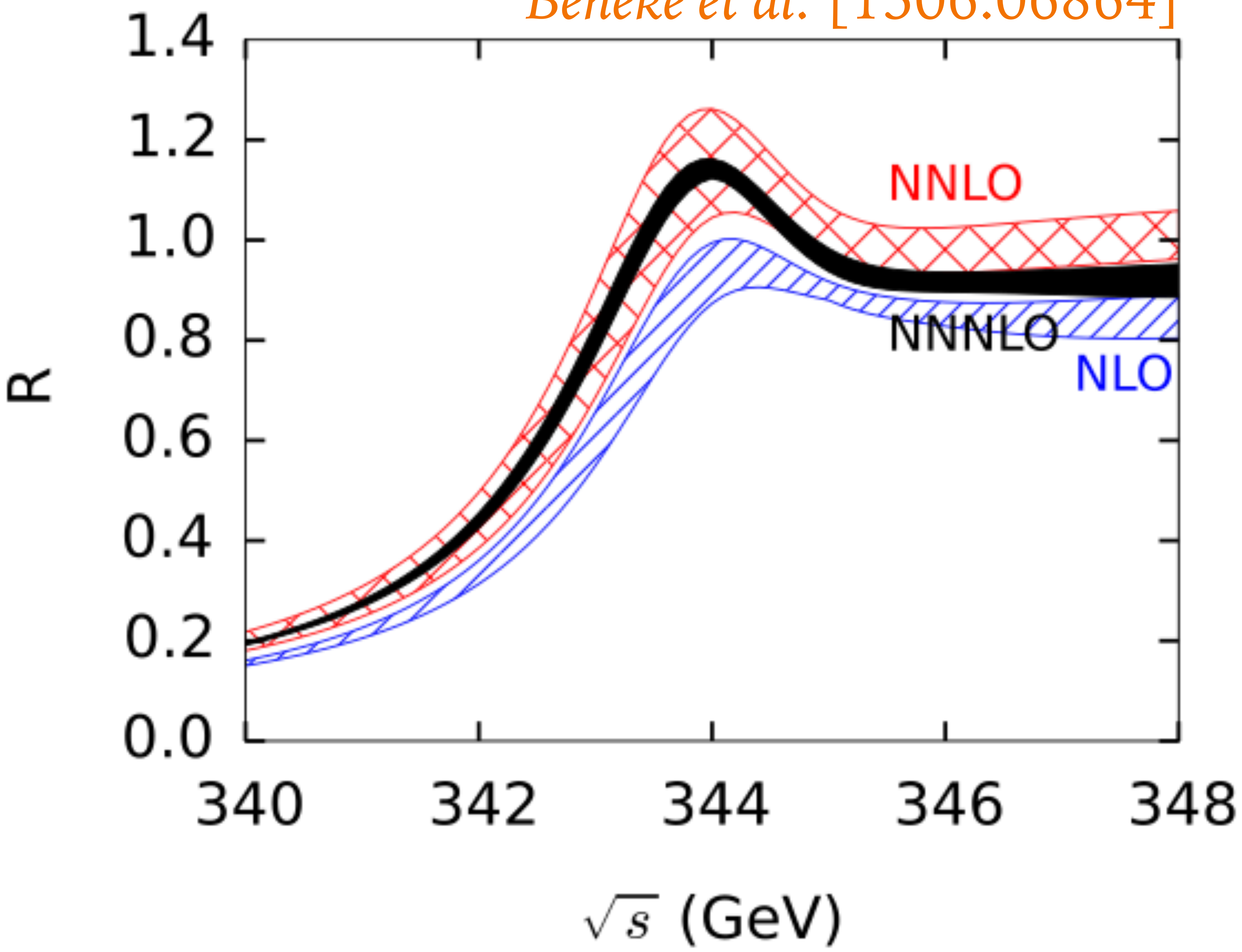


EFT Non-Relativistic QCD
to factorise $(\alpha_s/\beta_t)^k$ at all-orders

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

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

Beneke et al. [1506.06864]



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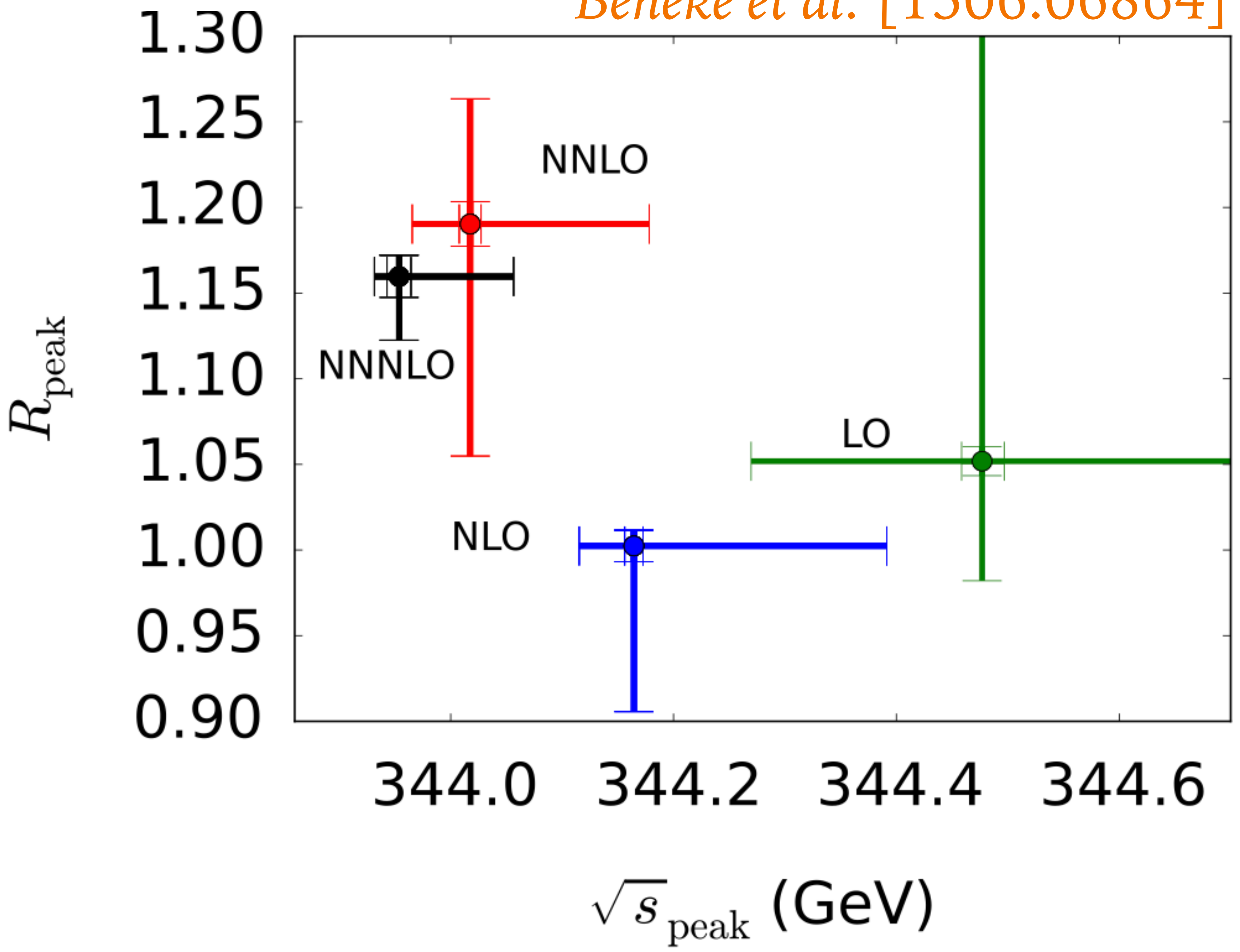
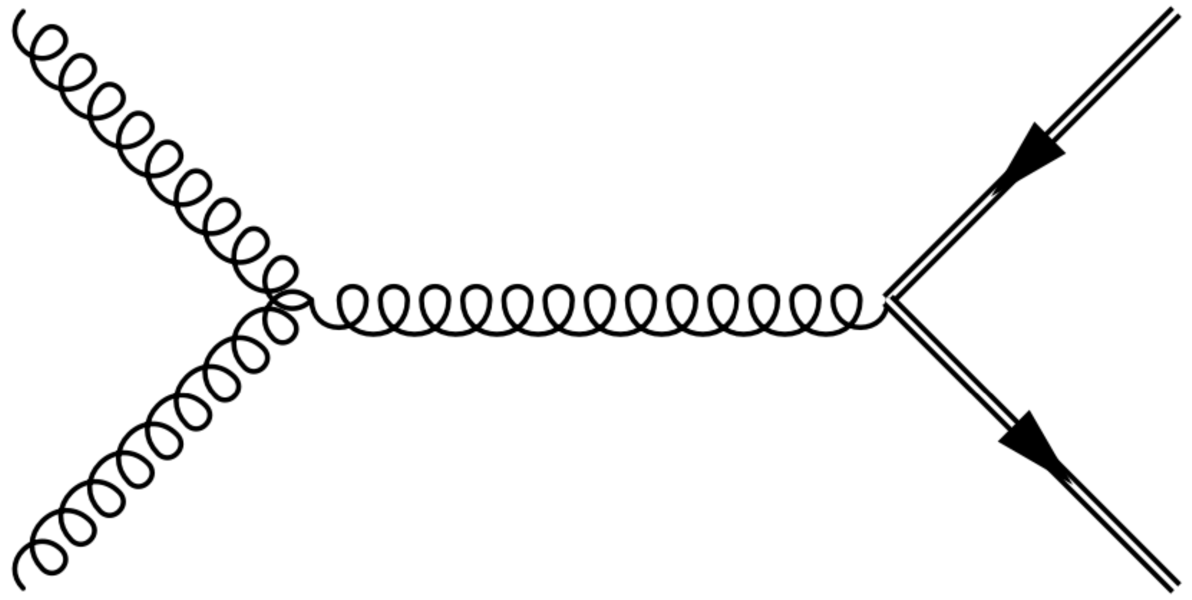
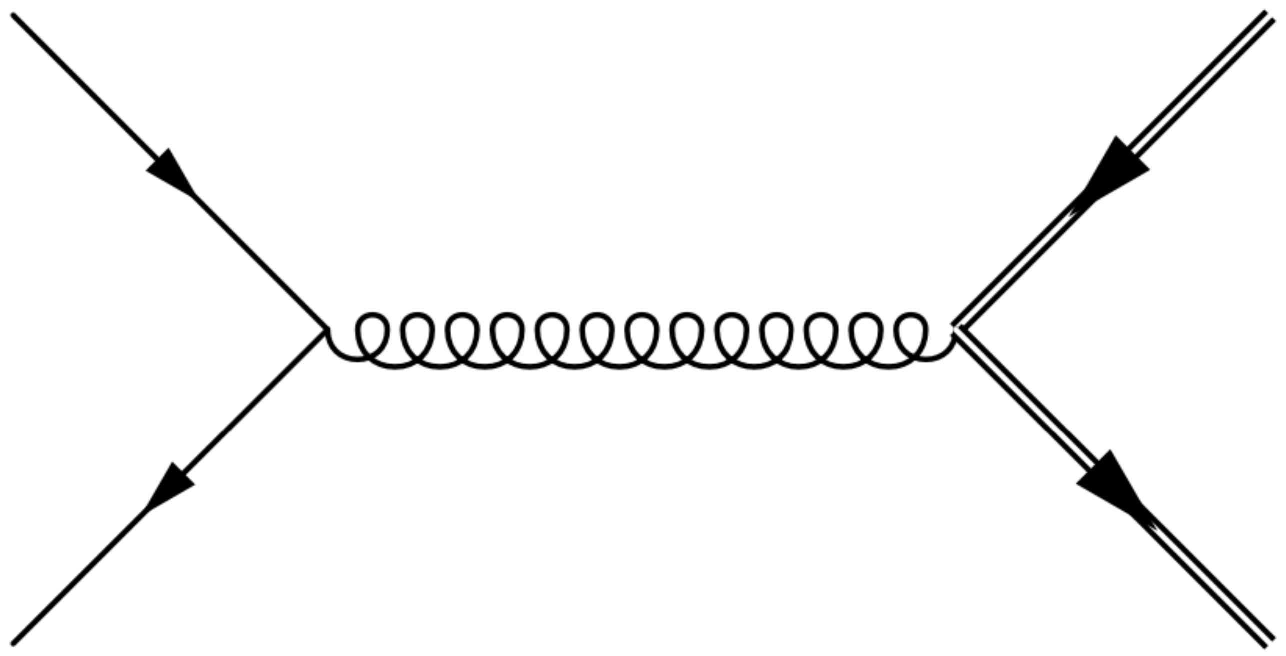


$t\bar{t}$ production at the threshold @ LHC

- $t\bar{t}$ pairs predominantly produced at the threshold
- Threshold scan of the invariant mass distribution $M_{t\bar{t}}$ for top mass extraction
- NRQCD predictions for colour singlet/octet state $t\bar{t}$ formation
- Radiative corrections from initial state region need to be considered
  [Hagiwara, Sumino, Yokoya ’08],[Kiyo, Kühn, Moch, Steinhauser ’08], [Sumino, Yokoya '10]
  [Garzelli, GL, Moch, Steinhauser, Zenaiev '24]





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

- $t\bar{t}$ in the quasi-bound state in terms of the Spin S, the orbital L, the total J angular momentum and the colour state c of the $t\bar{t}$ pair

$$\boxed{T = {}^{2S+1}\, L_J^{[c]}}$$

- Zero orbital angular momentum in the threshold region $J = S$

- $S = 0{,}1$ states are possible

- $c = 1, 8$ for the colour state

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

- Invariant mass distribution for $h_1(P_1)\ h_2(P_2) \to T$

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

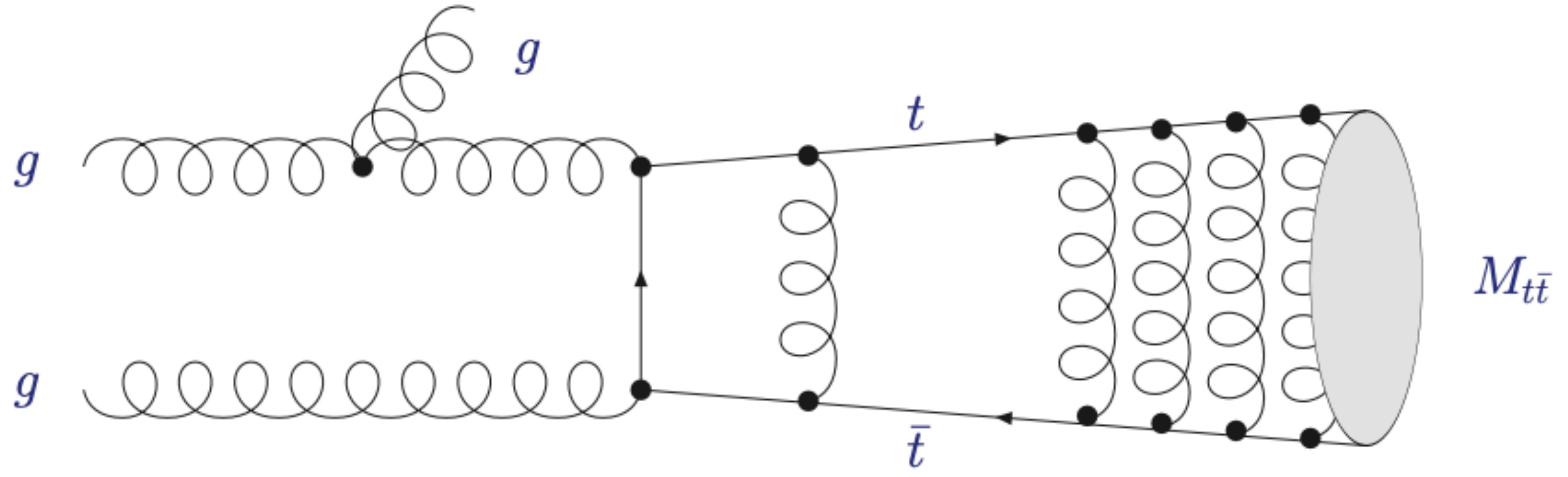
$$\left[\frac{d\mathcal{L}_{ij}}{d\tau}\right] = \int_0^1 dx_1 \int_0^1 dx_2 f_{i/P_1}(x_1, \mu_f^2) f_{j/P_2}(x_2, \mu_f^2) \delta(\tau - x_1 x_2)$$

Parton Luminosity

$$\frac{d\hat{\sigma}_{ij \to T}}{dM_{t\bar{t}}}(\hat{s}, M_{t\bar{t}}^2)$$

Partonic Cross Section

Quasi-bound state in NRQCD



- Multiscale problem
- Hard production at the scale $\sim m_t$
- Quasi-bound state formation at the scale $\sim m_t \beta_t < m_t$
- NRQCD allows the factorisation

$$\frac{d\hat{\sigma}_{ij\to T}}{dM_{t\bar{t}}}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2) = \underbrace{F_{ij\to T}}_{\text{Hard Production}}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2)\frac{1}{m_t^2}\underbrace{\mathrm{Im}G^{[1,8]}}_{\text{Quasi-bound state effects}}(M + i\Gamma_t)$$

Separately independent from μ_r

F_{ij} contribution

- Hard production cross section for a state T with invariant mass $M_{t\bar{t}}$
- Evaluated at NLO within pQCD

Hard Correction

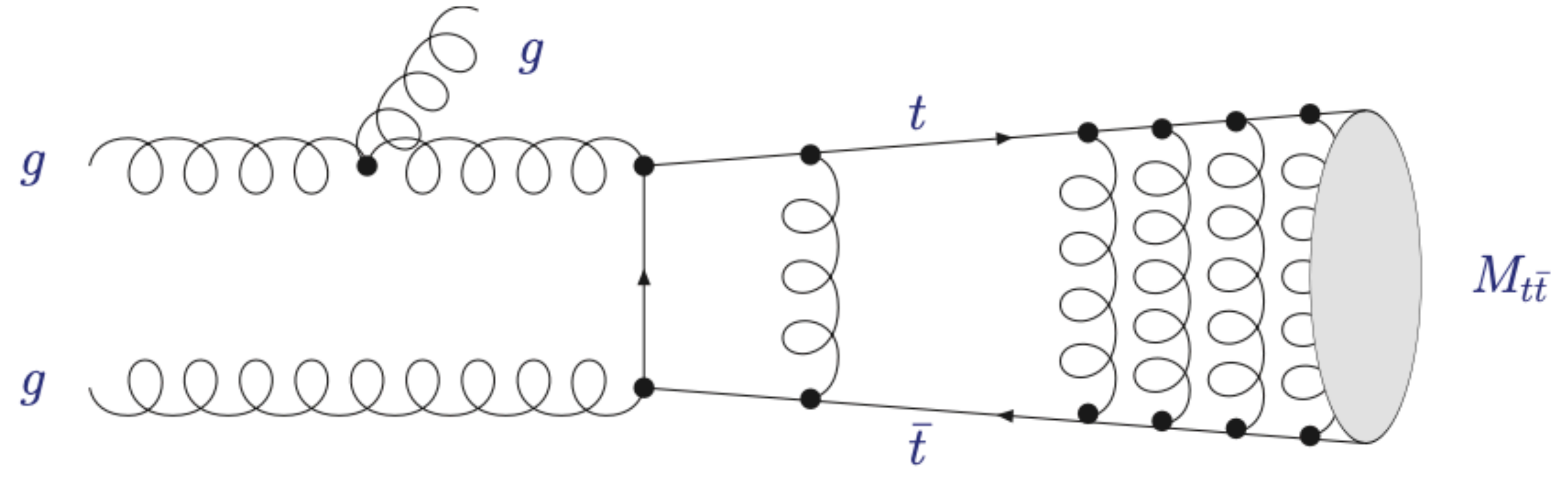
$$F_{ij\to T}(\hat{s}, M^2_{t\bar{t}}, \mu_f^2) = \mathcal{N}_{ij}\frac{\pi^2\alpha_s^2(\mu_r)}{3\hat{s}}\left(1+\frac{\alpha_s(\mu_r)}{\pi}\mathcal{C}_h\right)$$

$$\times\left[\delta_{ij\to T}\,\delta(1-z)+\frac{\alpha_s(\mu_r)}{\pi}\left(\mathcal{A}_c+\mathcal{A}_{nc}\right)\right]$$

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

Real Correction from (non) collinear emission

$G(M + i\Gamma_t)$ contribution



- Quasi-bound state due to long-distance effects at the scale $m_t\beta_t$
- Multiple soft gluon exchange modelled with the introduction of a zero-distance Green Function

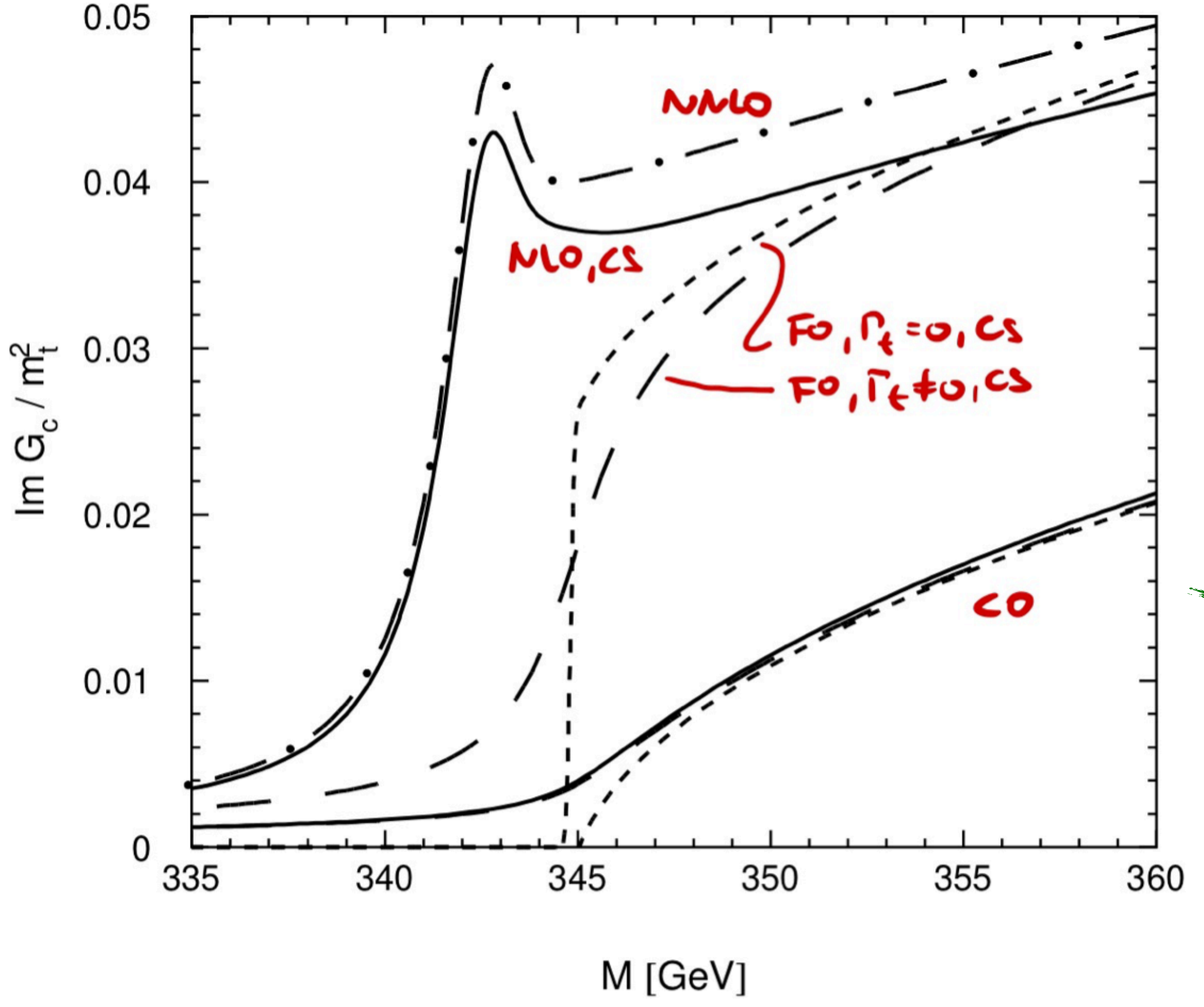
$$\left\{2m_t + \left[\frac{(-i\nabla)^2}{m_t} + V_C^{[1,8]}(\vec{r})\right] - (M + i\Gamma_t)\right\} G^{[1,8]}(\vec{r}; M + i\Gamma_t) = \delta^{(3)}(\vec{r})$$

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

Coulomb-like QCD potential at NLO

$G(M + i\Gamma_t)$ contribution

[Kiyo, Kühn, Moch, Steinhauser, '08]



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

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

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

Thanks to Matthias Steinhauser

F_{ij}: soft gluon resummation

- Logarithmic enhanced terms from $\mathcal{A}_c$ and $\mathcal{A}_{nc}$ due to soft gluon emissions

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

- Impact over $\mathcal{L}\otimes F$ as long as $z=\rho/\tau\to 1$
- Working in the Mellin space

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

- NLL soft-gluons threshold resummation

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

F_{ij}: soft gluon resummation

- Run2@LHC

$\sqrt{S} = 13$ TeV

$m_t = 172.5$ GeV

$\Gamma_t = 1.4$ GeV

`NNPDF_3.1_NNLO_as_0118`

$\alpha_s(M_Z) = 0.1180$

$\mu_r = \mu_f \in \{m_t, 2m_t, 4m_t\}$

$M_{t\bar{t}} = 2m_t$	NLO			resummed		
$\mu =$	m_t	$2m_t$	$4m_t$	m_t	$2m_t$	$4m_t$
$gg \to {}^1S_0^{[1]}$	18.2	18.7	18.3	19.4	20.5	21.1
$gg \to {}^1S_0^{[8]}$	55.8	55.2	52.8	60.0	61.5	62.0
$q\bar{q} \to {}^3S_1^{[8]}$	21.7	22.3	22.0	22.4	22.4	22.0

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

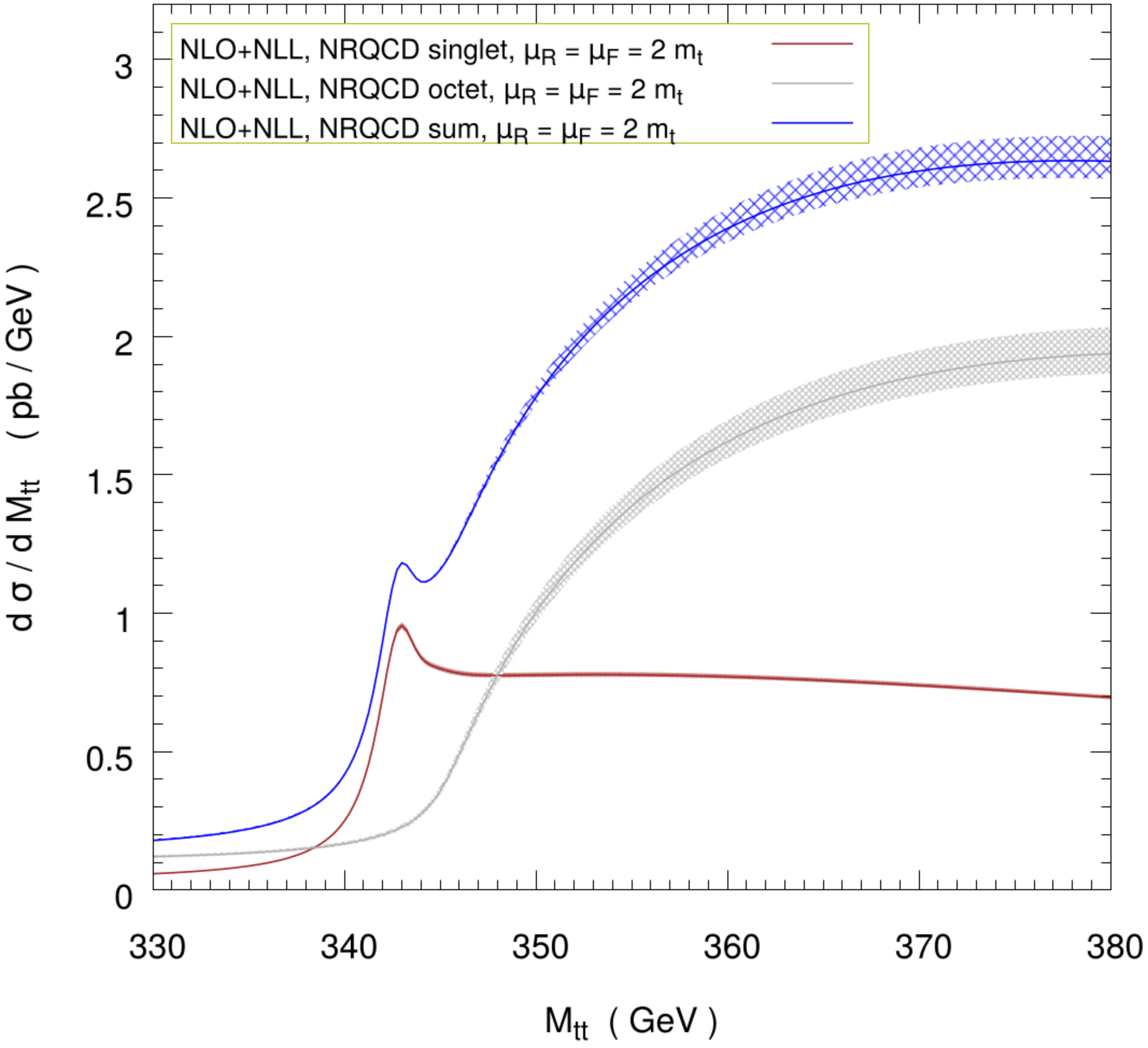
Up to 10% from soft gluon resummation for the leading channels

No large threshold logarithms from the S-wave channels

$$gg \to {}^3S_1^{[1,8]} + q\bar{q} \to {}^1S_0^{[1,8]} + gq \to {}^1S_0^{[1,8]} + gq \to {}^3S_1^{[8]} = \mathcal{O}(5\%)$$

NRQCD Predictions

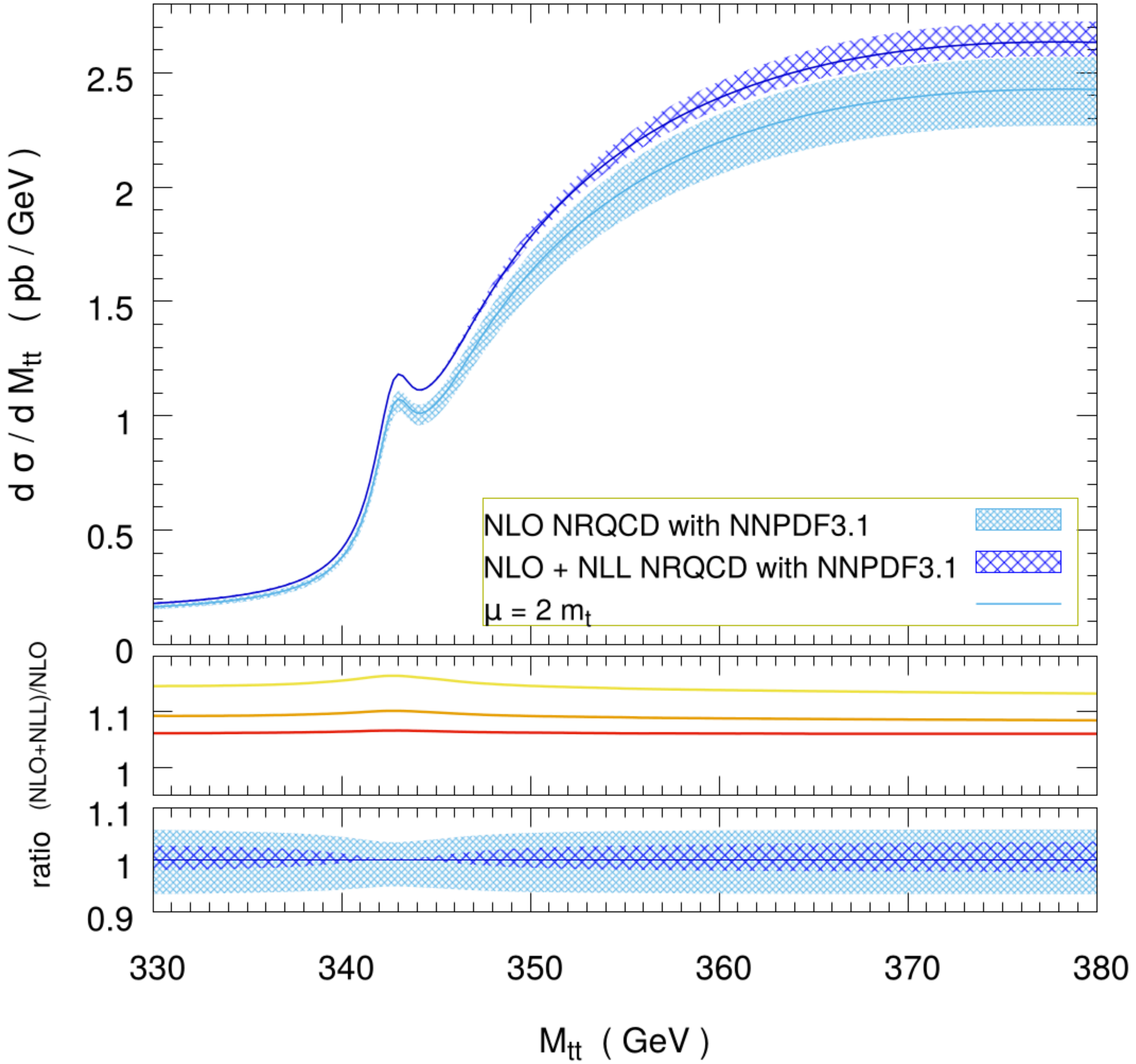
[Garzelli, GL, Moch, Steinhauser, Zenaiev '24]



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

NRQCD Predictions

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

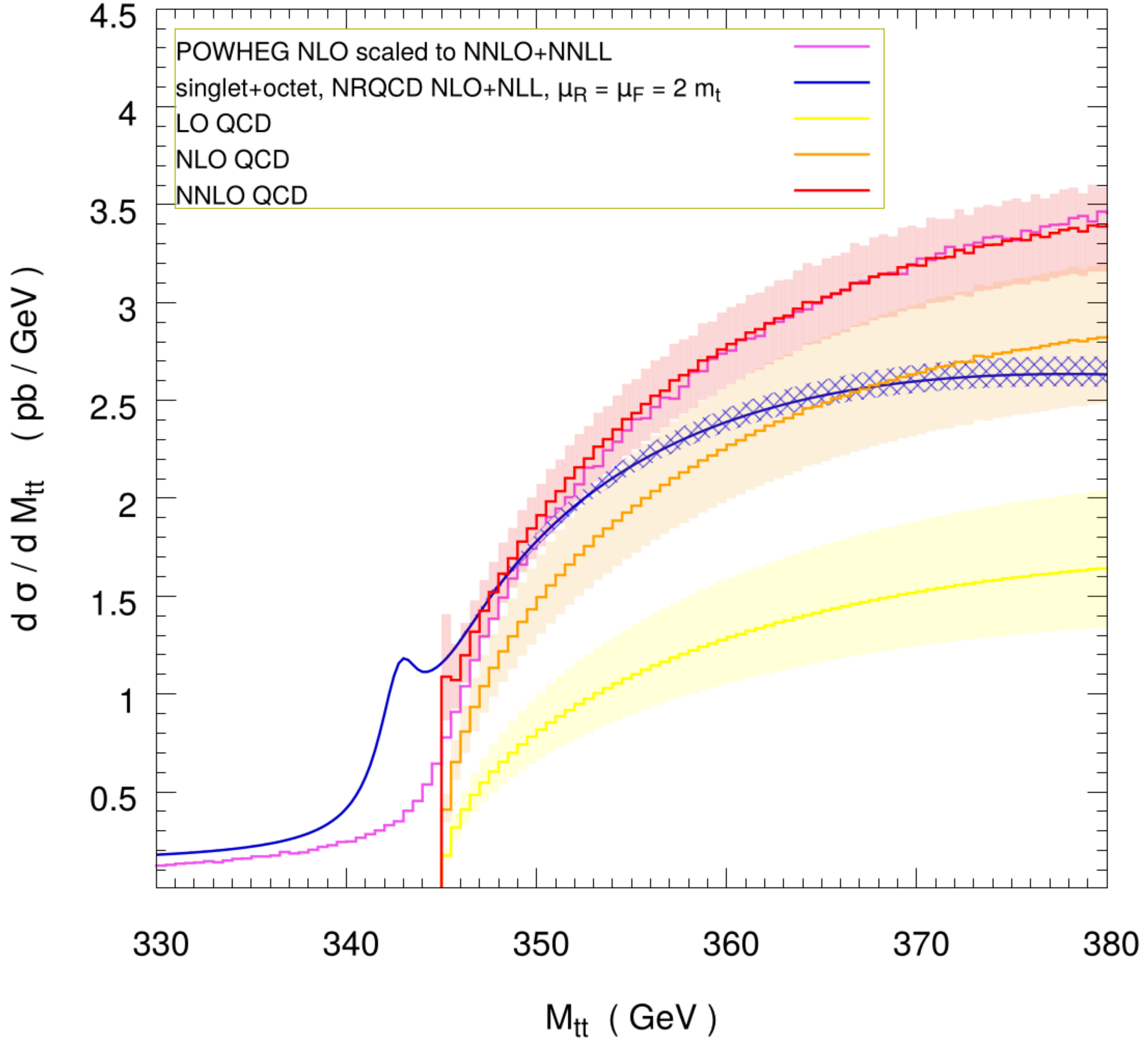


- $\mu = m_t\,,\ 2m_t\,,\ 4m_t$
- Scale stability improved in the threshold region $M_{t\bar{t}} \simeq 2m_t$
- $+\mathcal{O}(10\%)$ from resummation at the central scale choice

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

Threshold and continuum

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



- CMS-PAS-HIG-22-013 based on NLO pQCD POWHEG predictions rescaled to NNLO+NNLL also accounting for NLO EW effects

- NRQCD predictions valid in the region

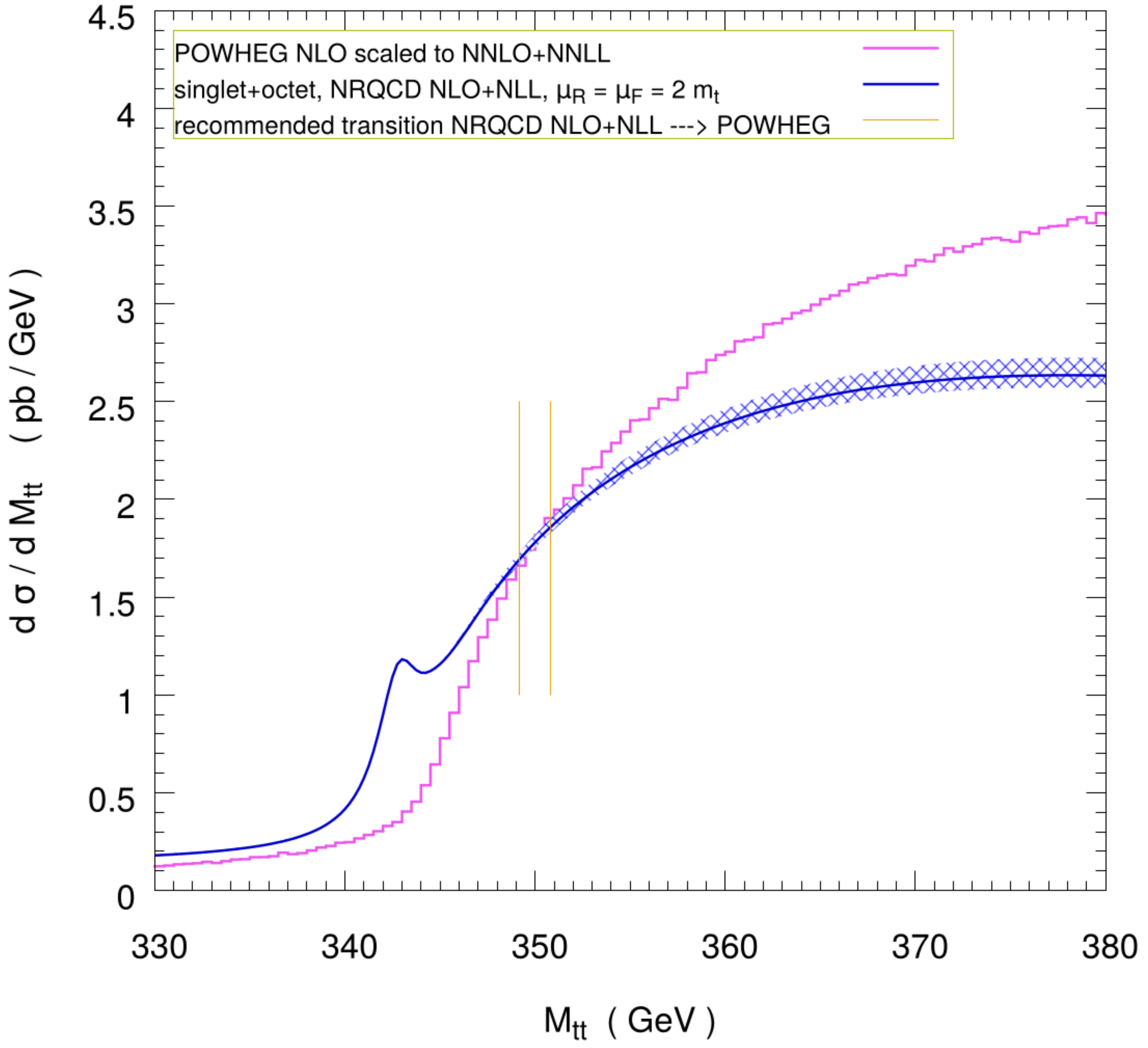
$$\boxed{|M_{t\bar{t}} - 2m_t| \lesssim 5 \text{ GeV}}$$

- Fixed-order pQCD at LO, NLO, NNLO

- The transition from the threshold to the continuum needs accurate study

Threshold and continuum

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



- NRQCD predictions cease to be valid for

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

- $\sigma_{\text{NRQCD}}(340 \text{ GeV} \lesssim M_{t\bar{t}} \lesssim 350 \text{ GeV}) = 12 \text{ pb}$
  $\sigma_{\text{POWHEG}}(340 \text{ GeV} \lesssim M_{t\bar{t}} \lesssim 350 \text{ GeV}) = 8.4 \text{ pb}$

- $\sigma_{\text{CMS}} = 8.8^{+1.2}_{-1.4} \text{ pb}$
  $\sigma_{\text{ATLAS}} = 9.0 \pm 1.3 \text{ pb}$

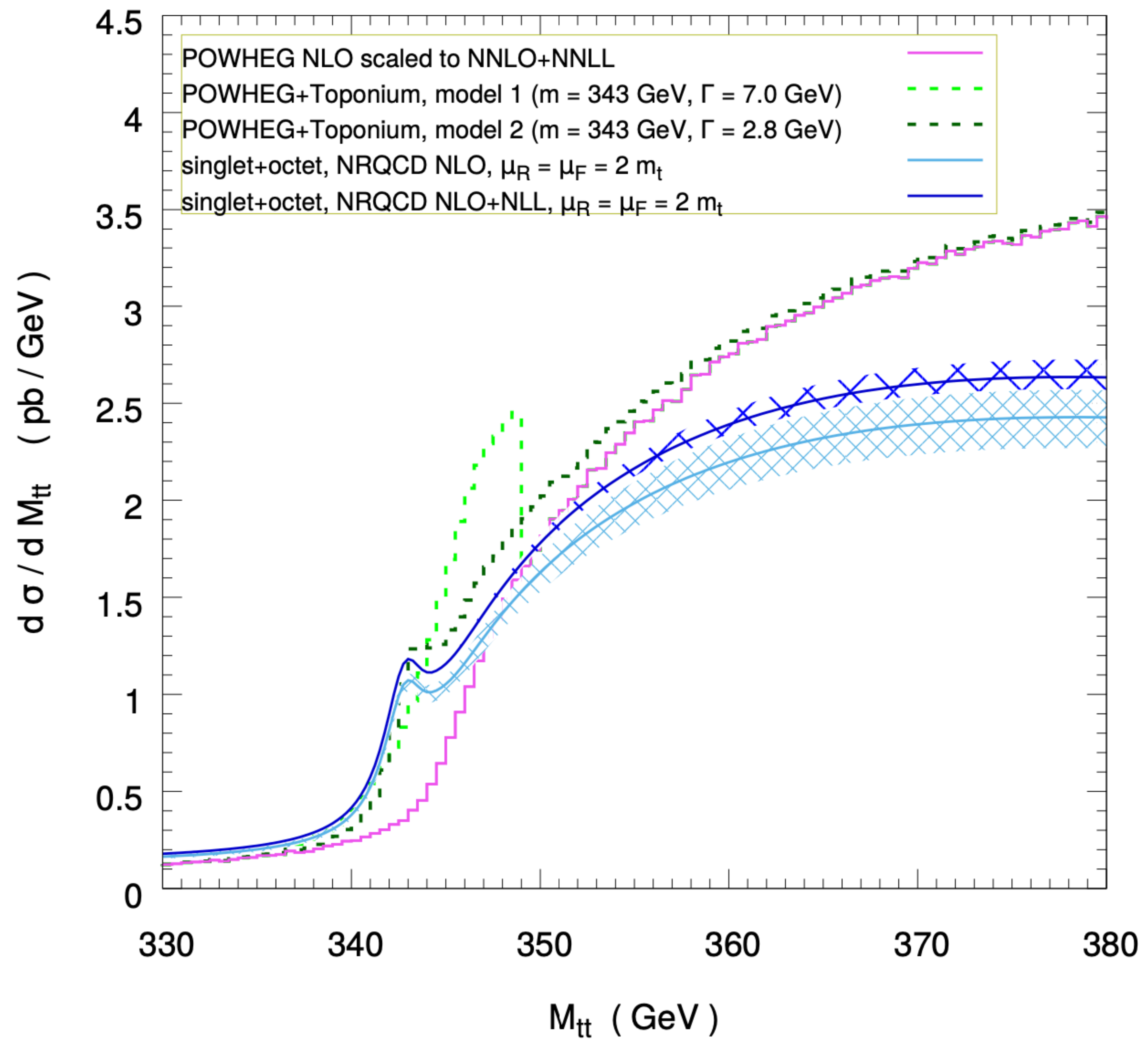
Improvements in NRQCD estimate are needed

Modelling $t\bar{t}$ resonances

- Quasi-bound state due to a pseudoscalar particle η_t
  Fuks, Hagiwara, Ma, Zheng [2102.11281],Maltoni et al. [2401.08751]
- LO MEs reweighted with the LO zero-distance Green Function
  Fuks, Hagiwara, Ma, Zheng [2411.18962]
- Resonance effect added on the FO pQCD predictions
  [CMS-TOP-24-007]
- The model only accounts for colour-singlet final states
- Colour repulsive interactions not included

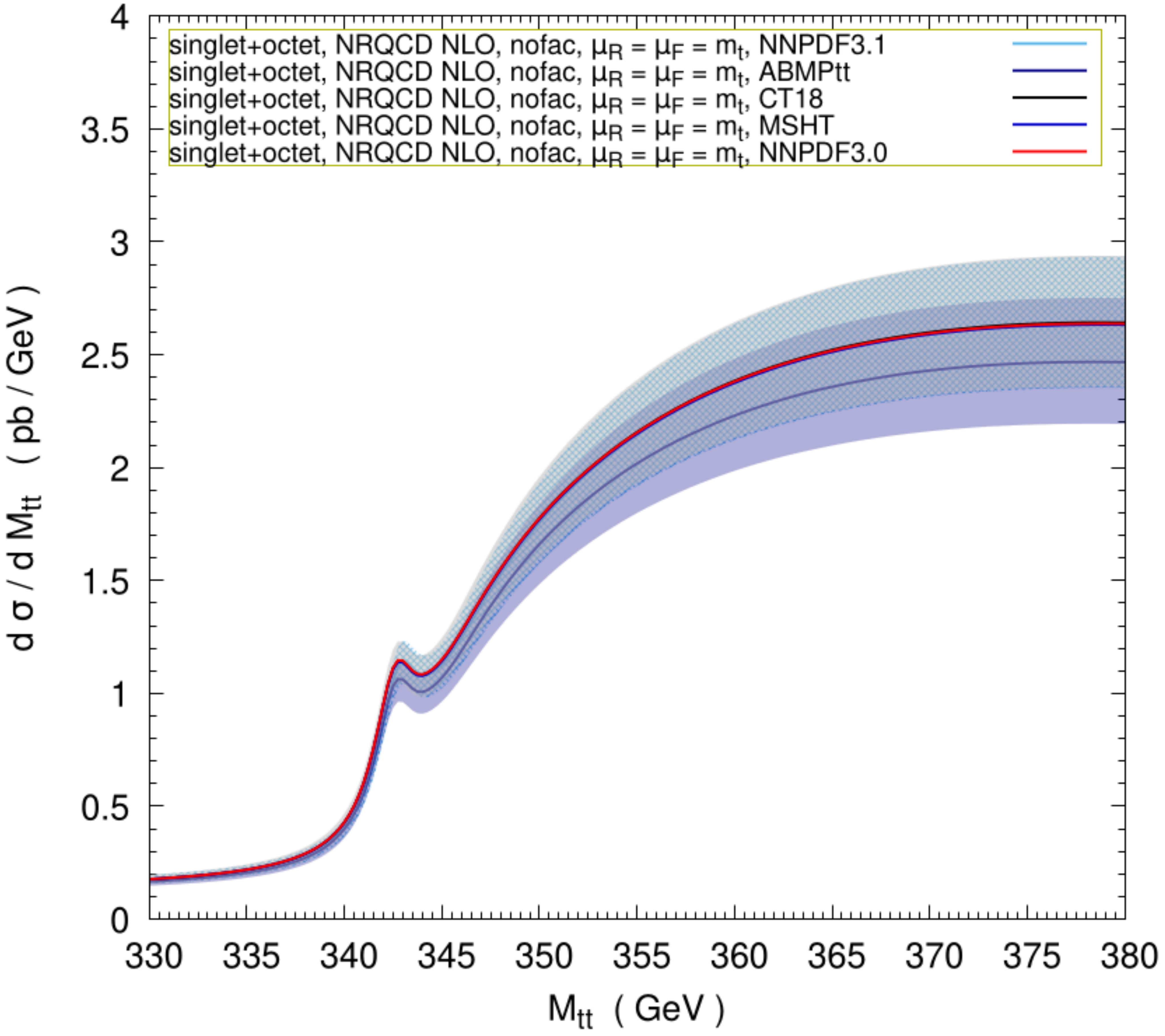
$$\mathcal{L}_{\eta_t} = \frac{1}{2}\partial_\mu\phi_{\eta_t}\partial^\mu\phi_{\eta_t} - \frac{1}{2}m_{\eta_t}\phi^2_{\eta_t} - \frac{1}{4}g_{gg\eta_t}\phi_{\eta_t}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - ig_{tt\eta_t}\phi_{\eta_t}\bar{t}\gamma_5 t$$

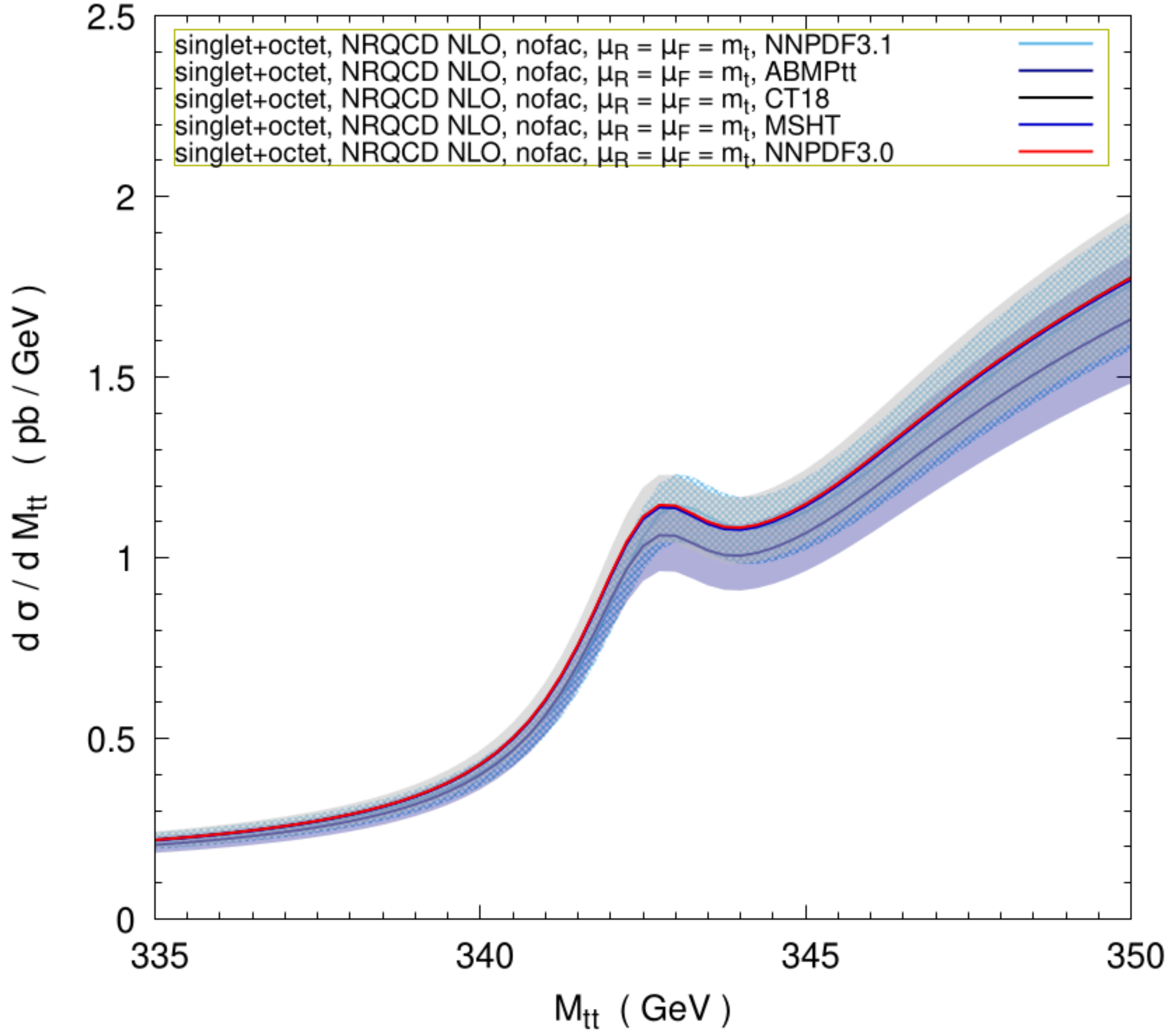
Thanks to Anuar, Garzelli, Grohsjean, Jeppe, Schwanenberger



NRQCD Predictions:PDF variations

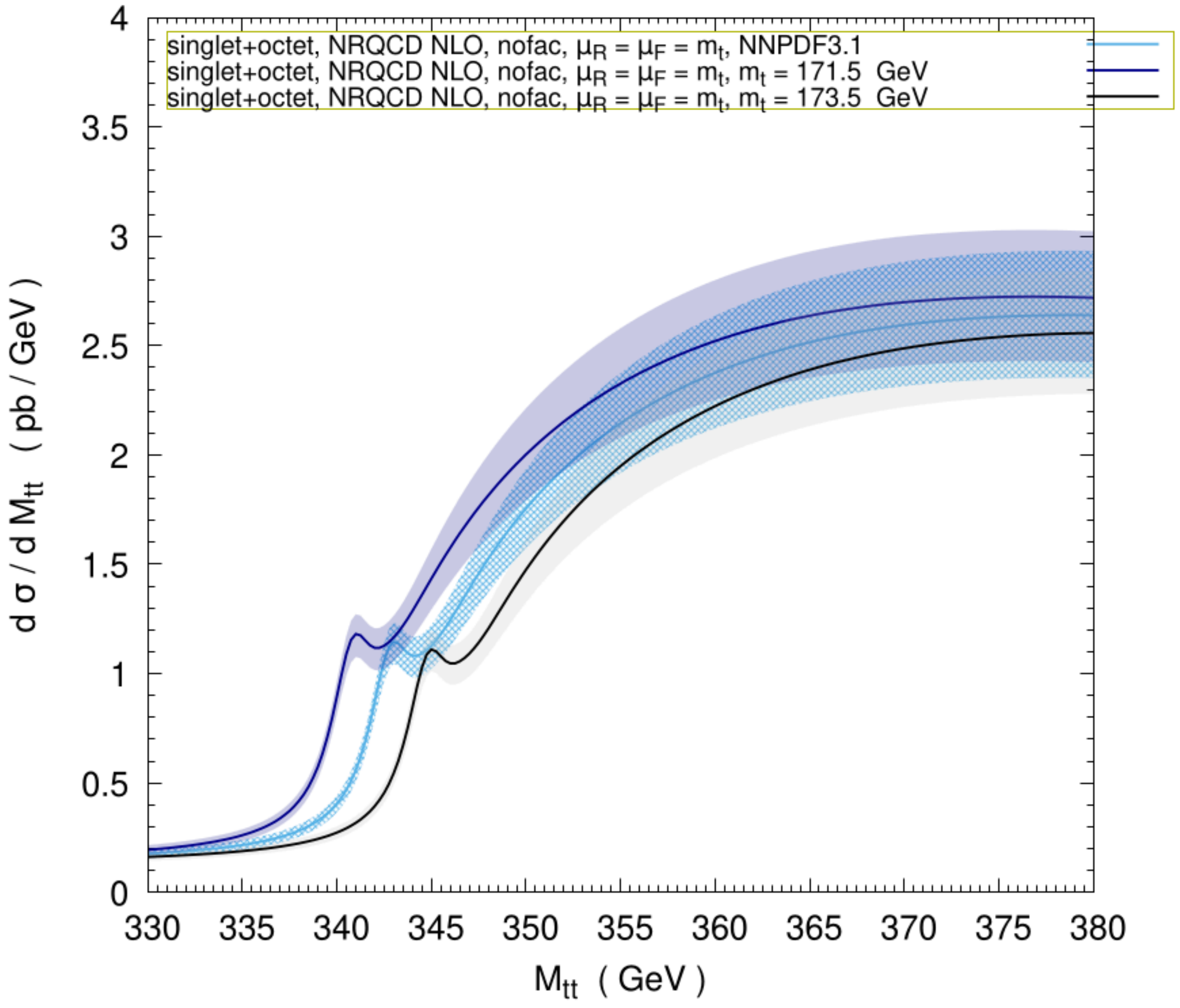
[Garzelli, GL, Moch, Steinhauser, Zenaiev to appear soon]

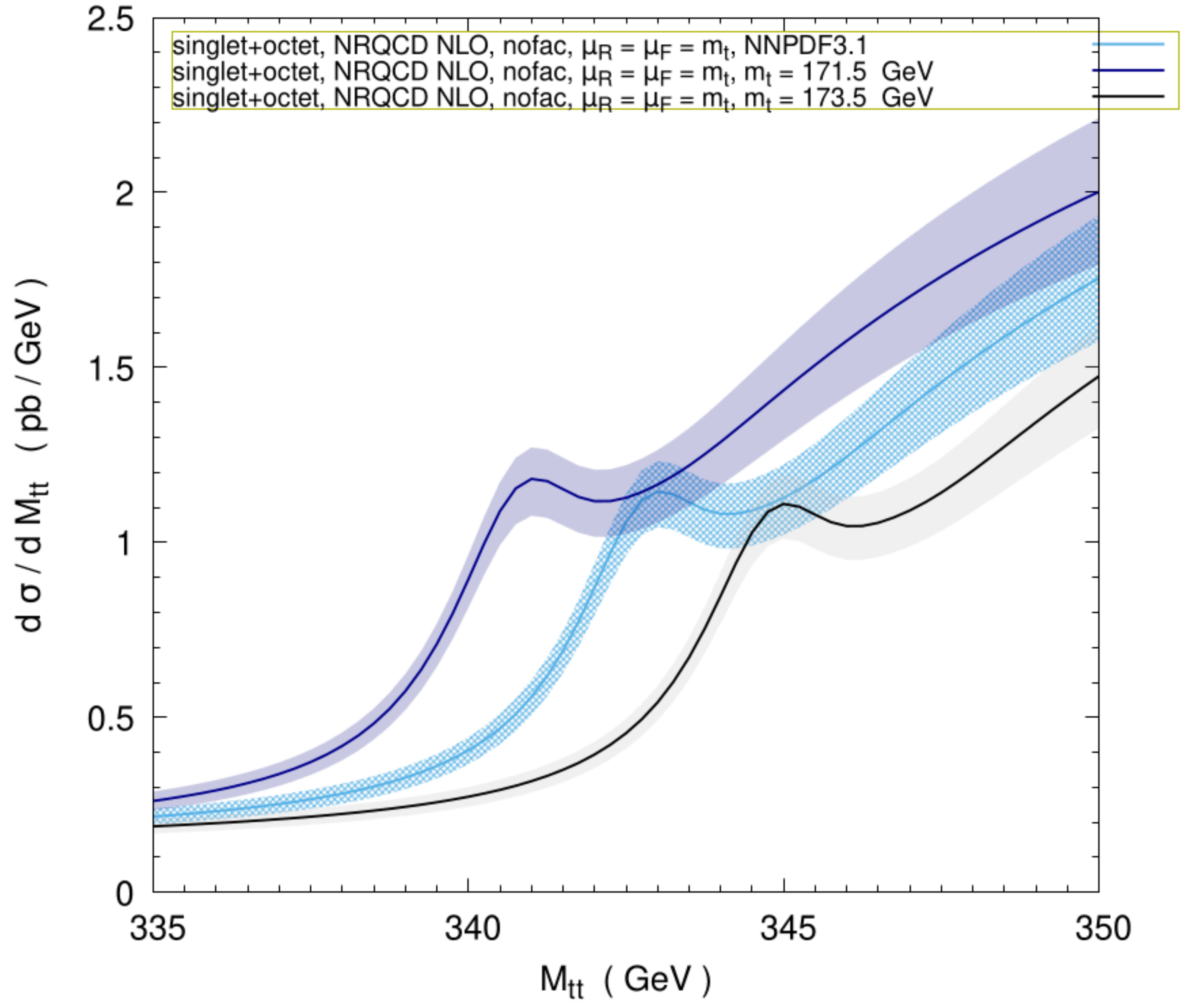




NRQCD Predictions: m_t variations

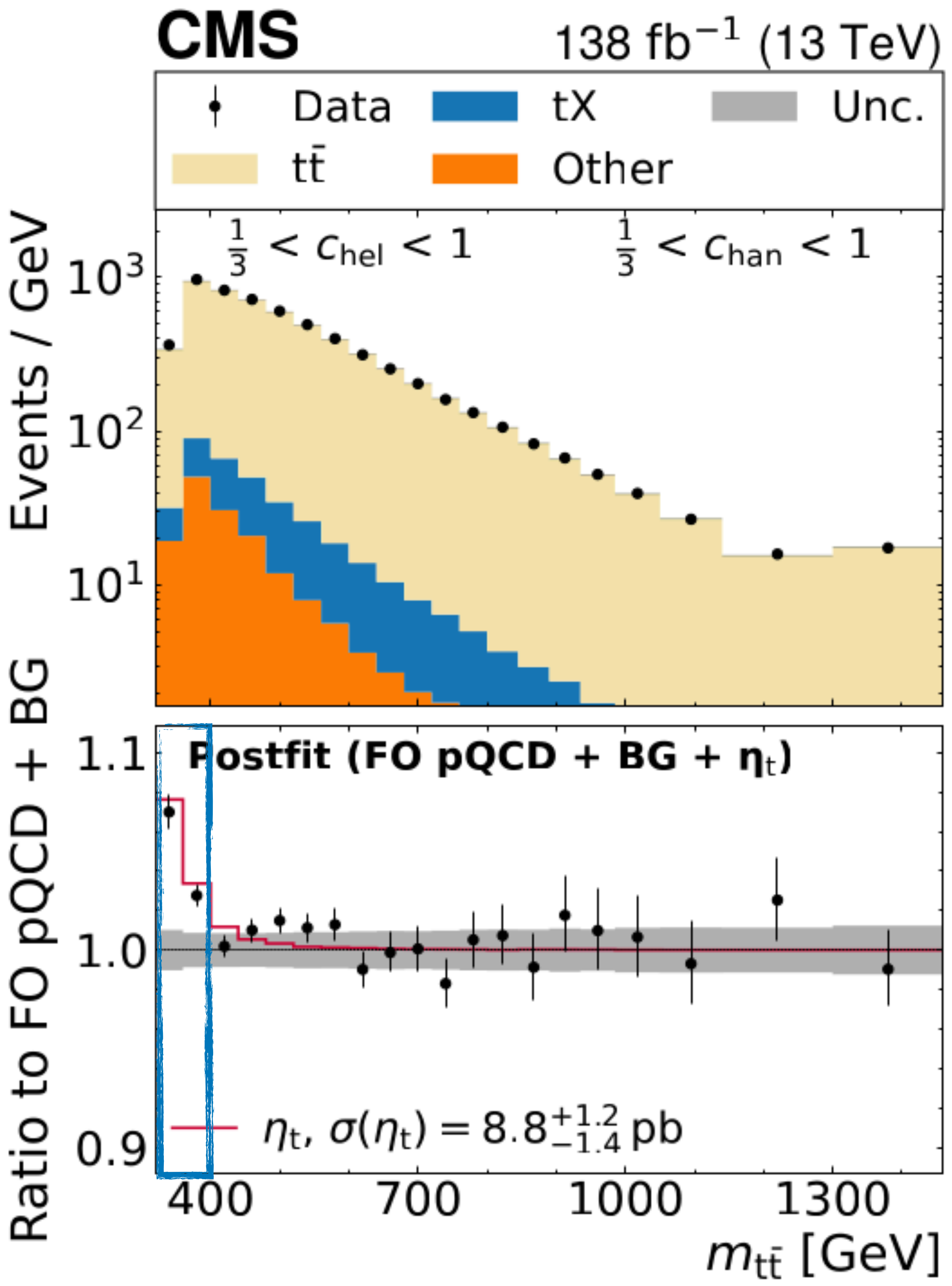
[Garzelli, GL, Moch, Steinhauser, Zenaiev to appear soon]





Other Approaches

[Nason, Re, Rottoli '25]



- Large experimental resolution
- Excess observed in the first bin $M_{t\bar{t}} \lesssim 380$ GeV
- Fixed-order pQCD can be applied
- Quasi-bound state at N3LO $\mathcal{O}(\alpha_s^3)$

Is the excess of event only related to quasi-bound state interactions?

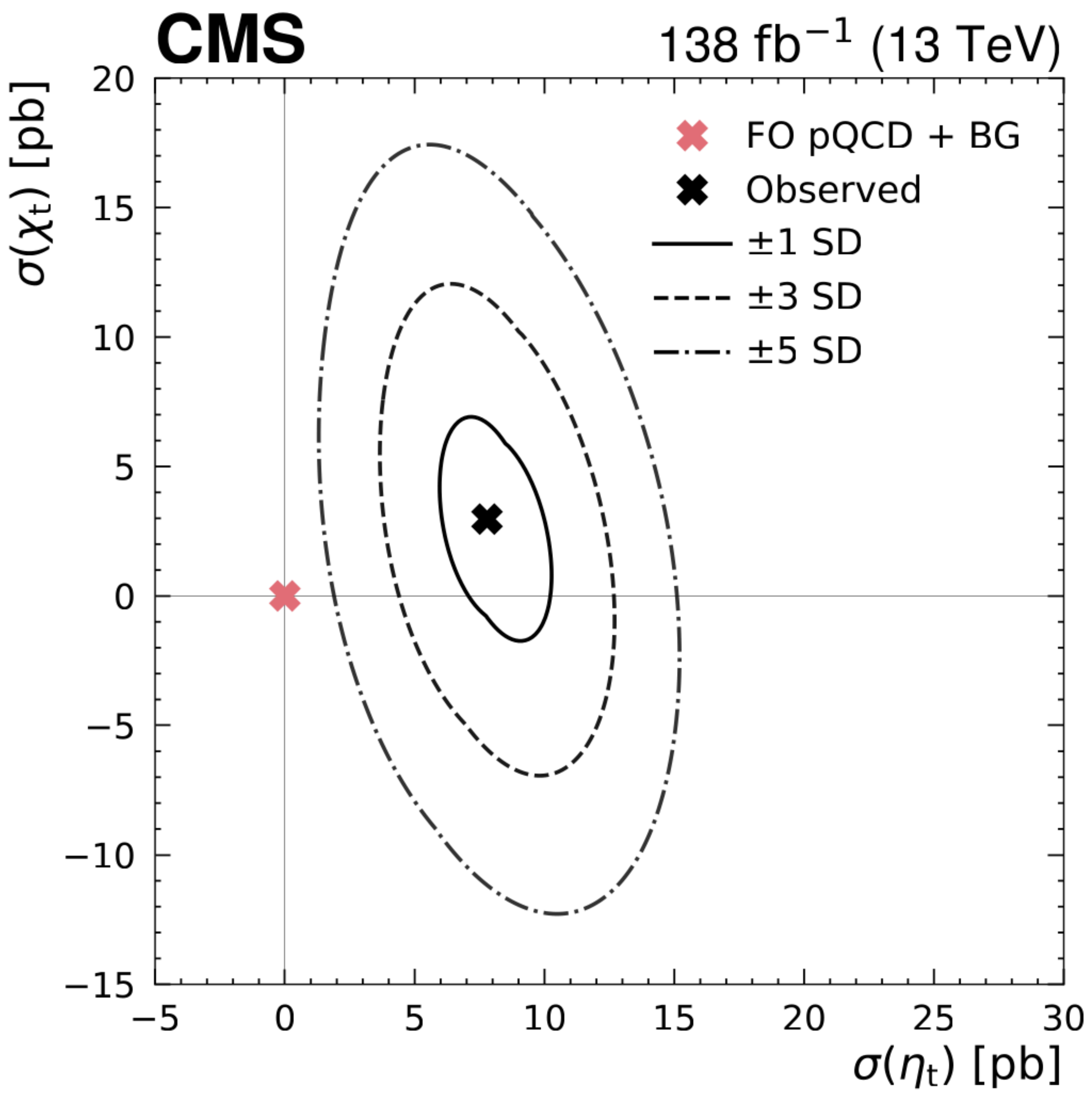
Conclusions and Outlooks

- Excess of events in $M_{t\bar{t}}$ distribution from CMS and ATLAS
- NRQCD to study threshold effects in $t\bar{t}$ pair production at the LHC
- Uncertainties due to missing higher orders effects in the NRQCD expansion
- Well formulated matching prescription is demanded
- NRQCD predictions for other observables than $M_{t\bar{t}}$

BACKUP

Conclusions and Outlooks

[CMS-TOP-24-007]



- Simultaneous fit including scalar χ_t and pseudoscalar η_t contributions

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