Non-Relativistic Top Quark Pairs

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

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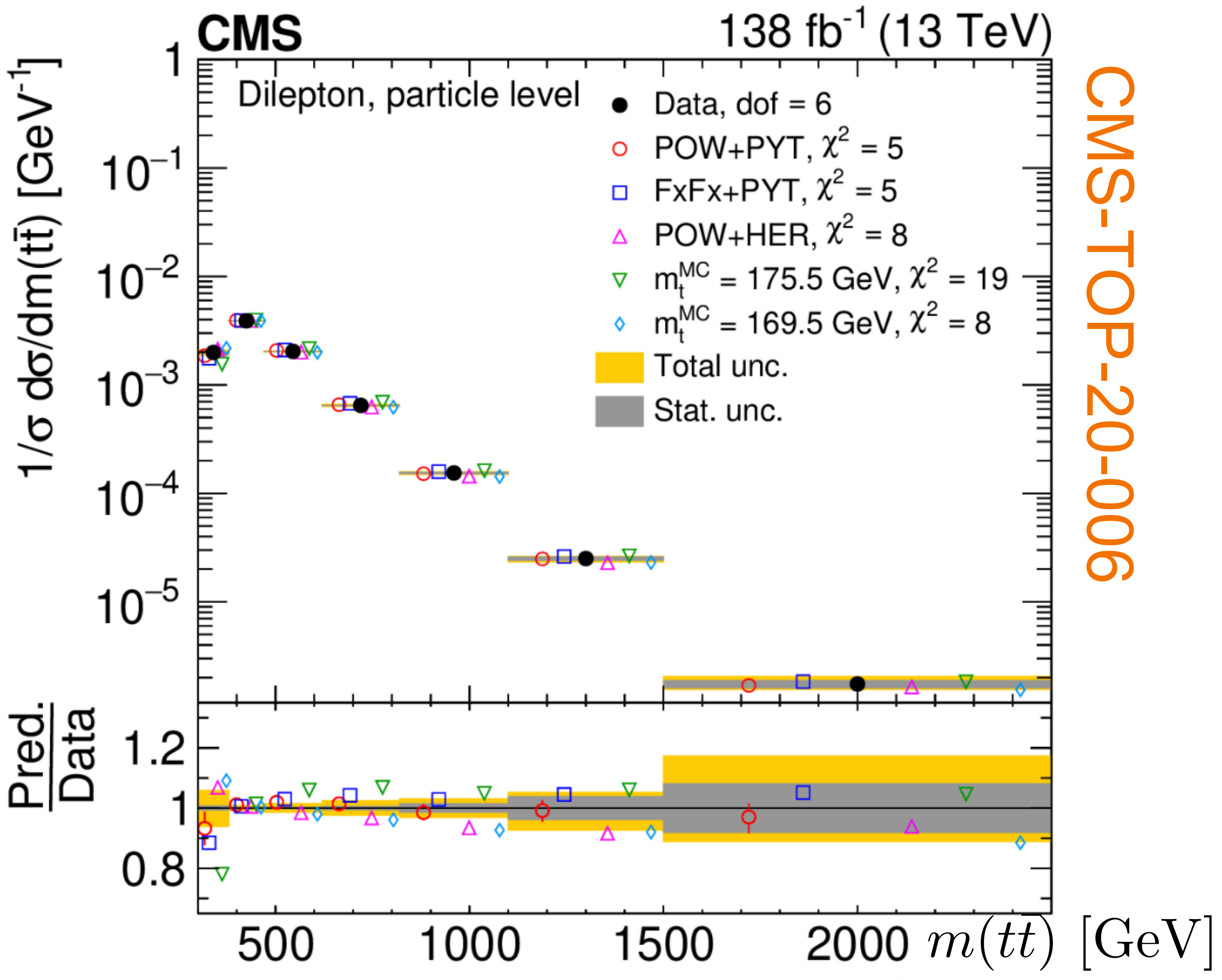
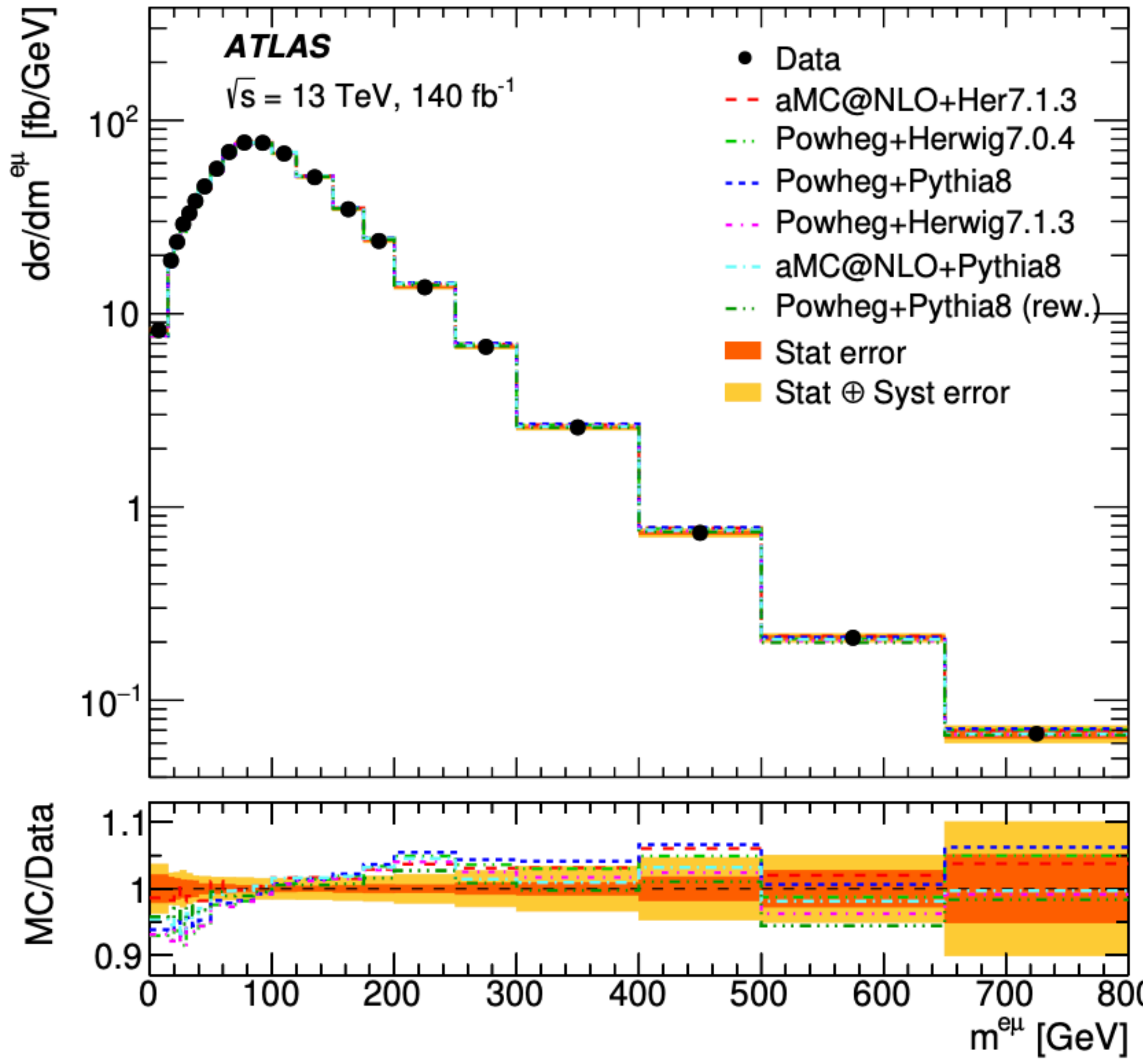
Introduction

- Significant excess in the invariant mass $M_{t\bar{t}} \simeq 2m_t$ from a recent CMS and ATLAS analysis
- New heavy Beyond Standard Model (BSM) Higgs boson decaying into $t\bar{t}$?
- Enhanced cross section $\mathrm{d}\sigma/\mathrm{d}M_{t\bar{t}}$ strictly related to bound states effects

Accurate SM theoretical predictions are crucial for reliable BSM searches



CMS-TOP-20-006



ATLAS [JHEP07(2023)141]

Theory Framework

$$\mathrm{d}\sigma_{P_1 P_2 \to X} = \sum_{i,j} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_{i,P_1}(x_1, \mu_f^2) f_{j,P_2}(x_2, \mu_f^2) \mathrm{d}\hat{\sigma}_{ij} \left(1 + \text{NP Effects}\right)$$

- $\mathrm{d}\hat{\sigma}_{ij}$ computable with perturbative QCD
- Factorization scale μ_f to separate the long distance effects from short distance dynamics
- Non-Perturbative inputs coming from Parton distribution functions $f_{i,j}$, quark masses, α_s (fit from experimental measurements, lattice computations…)

Theory Framework: $t\bar{t}+X$ @LHC

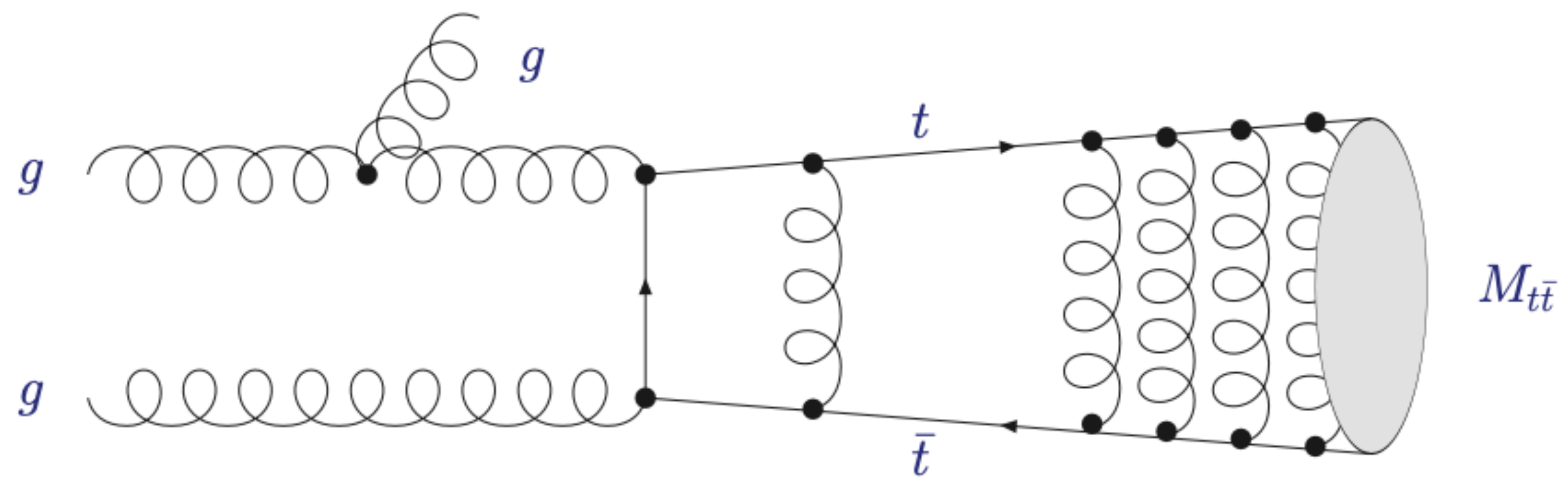
- Most of the $t\bar{t}$ pairs produced in the threshold region (non-relativistic effects play a crucial role)
- Invariant mass distribution is the choice at Hadron Colliders
- QCD factorization allows a simple expression

$$M_{t\bar{t}}\frac{\mathrm{d}\sigma_{P_1P_2\to T}}{\mathrm{d}M_{t\bar{t}}}(S,M_{t\bar{t}}^2)=\sum_{i,j}\int_{\rho}^{1}\mathrm{d}\tau\left[\frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}\tau}\right](\tau,\mu_f^2)M_{t\bar{t}}\frac{\mathrm{d}\hat{\sigma}_{ij\to T}}{\mathrm{d}M_{t\bar{t}}}(\hat{s},M_{t\bar{t}}^2,\mu_f^2)$$

Theory Framework: $t\bar{t} + X$ @LHC

- How to describe bound state effects?
- Non-Relativistic QCD is the way

$$\beta_t = \sqrt{1 - 4m_t^2/M_{t\bar{t}}^2} << 1$$



- NR QCD allows a factorization of $\mathrm{d}\hat{\sigma}_{ij}/\mathrm{d}M_{t\bar{t}}$

Kiyo, Kuhn, Moch, Steinhauser, Uwer (EPJC 60 (2009) 375-286)

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

Theory Framework: $t\bar{t} + X$ @LHC

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

- Hard function for production of a state

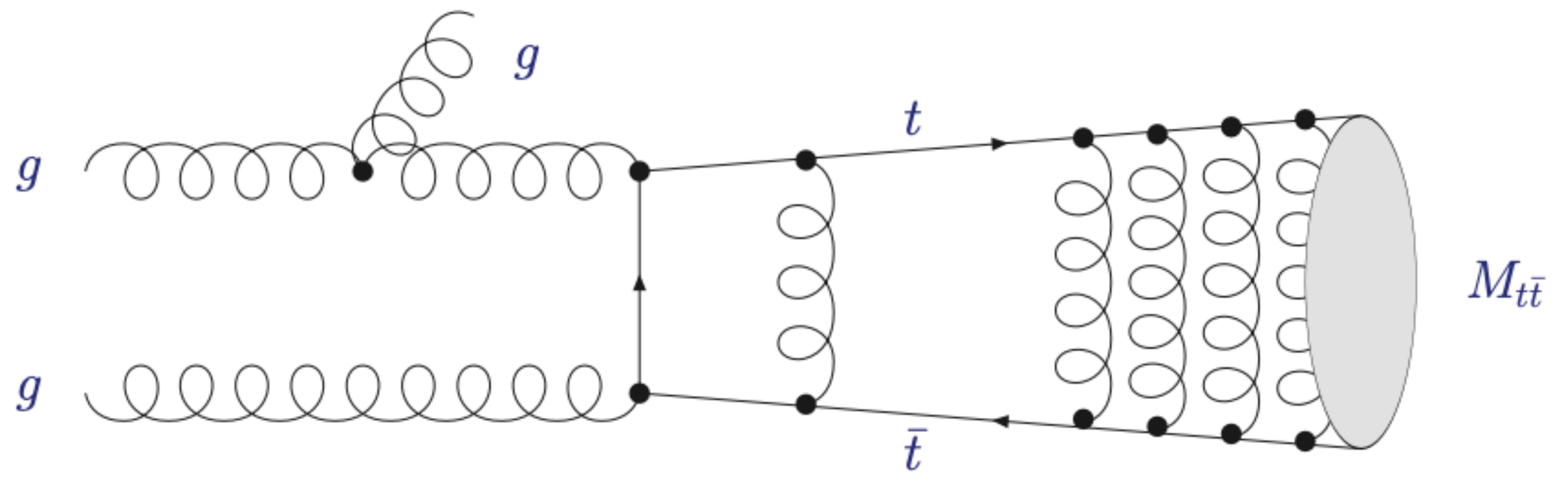
$$T = {}^{2S+1} L_J^{[1,8]}$$

Singlet (1), Octet (8) Color State

Spin

Orbital angular momentum

- Non-Relativistic Green Function Responsible for bound state formation



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

F_{ij} contribution

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

- Evaluated with pQCD at NLO accuracy
- Threshold logarithms from soft regions $z = \rho/\tau \to 1$ dominating the contribution $\mathcal{L} \otimes F$
- Resummation up to NLL accuracy for $gg \to {}^1S_0^{[1]}$ $({}^1S_0^{[8]})$, $q\bar{q} \to {}^3S_1^{[8]}$ in the Mellin Space for $\mathcal{L} \otimes F$

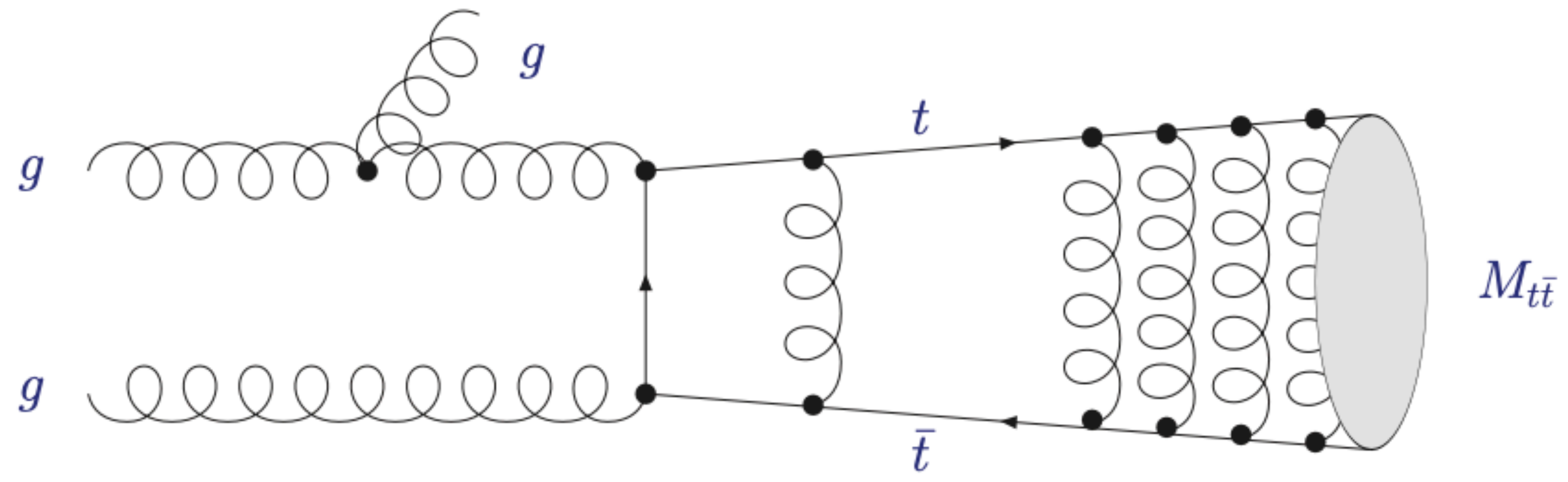
$$M_N[F_{ij}] = F_{ij\to T}^N(M_{t\bar{t}}^2, \mu_f^2) = \int_0^1 dz\, z^{N-1} F_{ij\to T}(\hat{s}, M_{t\bar{t}}^2, \mu_f^2)$$

$M_N^{-1}[\mathcal{L} \otimes F]$ → NLO+NLL accuracy

Green Function Contribution

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

- Responsible for bound state formation due to multiple gluons exchange
- Only dependent on $M_{t\bar{t}}$ and $\Gamma_t >> \Lambda_{\mathrm{QCD}}$
- Evaluated at NLO in QCD
- The nature of QCD potential strictly depends on the colour structure of T



Impact of soft gluon resummation

- Run2@LHC

$\sqrt{S} = 13$ TeV

$m_t = 172.5$ GeV (pole mass scheme)

$\Gamma_t = 1.4$ GeV

`NNPDF_3.1_NNLO_as_0118`

$\alpha_s(M_Z) = 0.1180$

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

	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

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

No large threshold logarithms from the S-wave channels

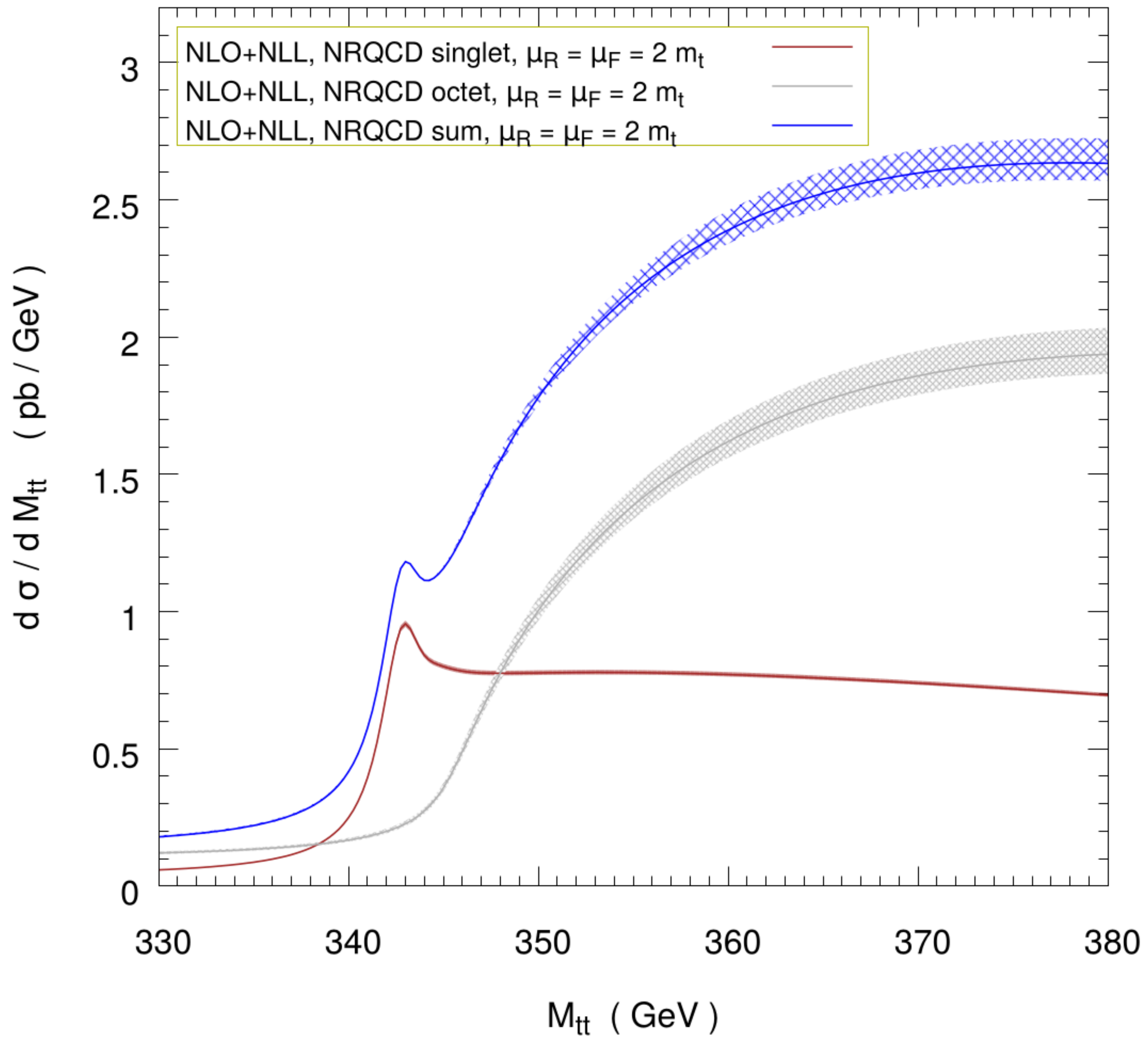
$$gg \to {}^3S_1^{[1,8]} + q\bar{q} \to {}^1S_0^{[1,8]} + gq \to {}^1S_0^{[1,8]} + gq \to {}^3S_1^{[8]} = \mathcal{O}(5\%)$$

Theoretical Predictions at $\sqrt{S} = 13 \text{ TeV}$

- $gg \rightarrow {}^1S_0^{[1]}$ shows a resonance peak for *toponium* formation

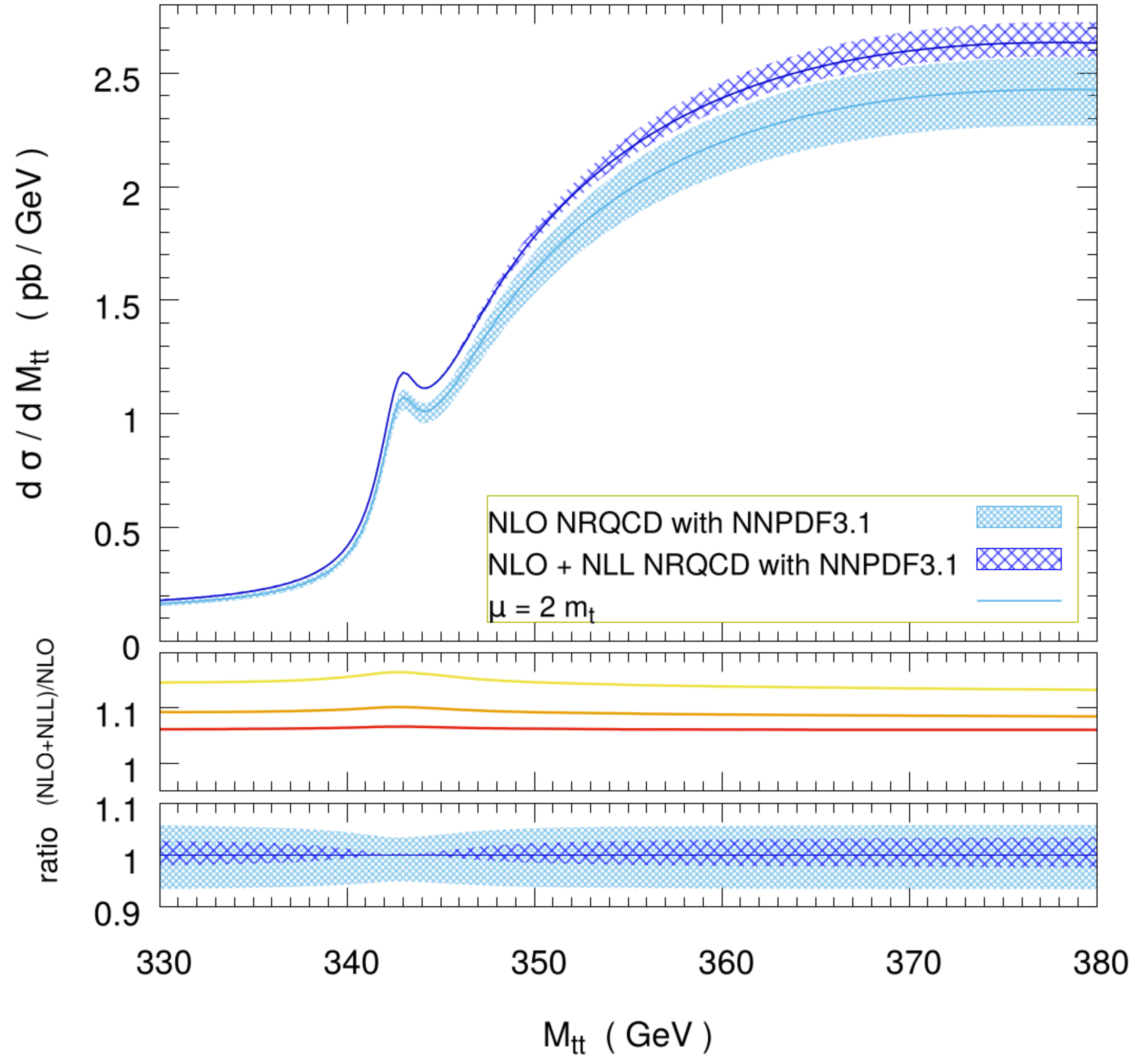
- $gg \rightarrow {}^1S_0^{[8]} + q\bar{q} \rightarrow {}^3S_1^{[8]}$ shows the repulsive effect at the threshold $M_{t\bar{t}} \simeq 2m_t$

- Strong impact on the shape coming from Γ_t below the threshold



Theoretical Predictions at $\sqrt{S} = 13\ \text{TeV}$

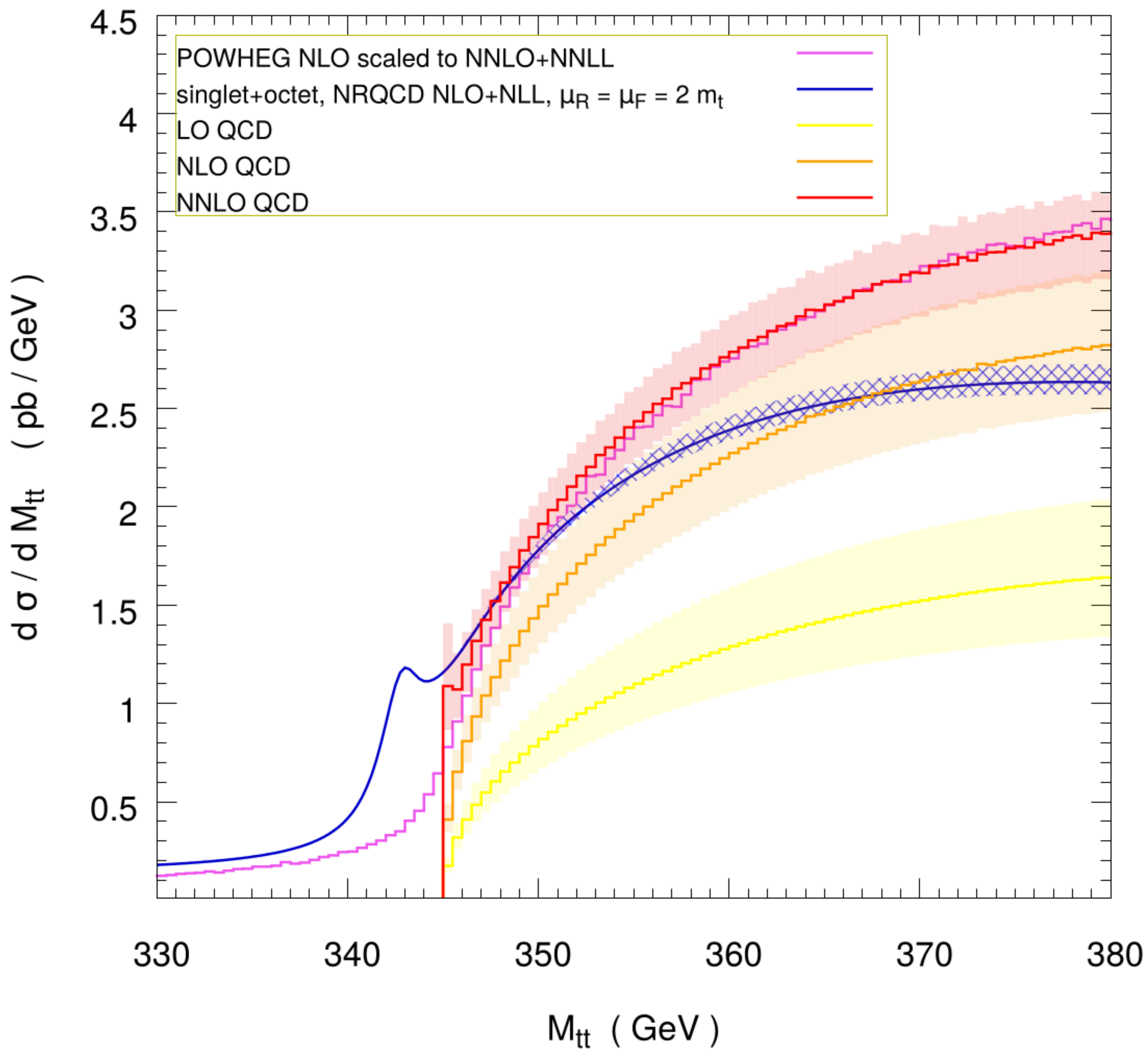
- Approximately $+\,10\%$ from soft gluon resummation in the whole $M_{t\bar{t}}$ range
- Reduction of scale dependence, in particular in the peak region
- Scale stability improved



Comparison with CMS analysis

- NLO+NLL with NRQCD
- Fixed-Order terms at LO, NLO and NNLO
  (Garzelli, Mazzitelli, Moch, Zenaiev [2311.05509])
- NLO POWHEG rescaled to NNLO+NNLL
  (Thanks to Anuar, Grohsjean, Jeppe, Schwanenberger)
- NRQCD only valid for $|M_{t\bar{t}} - 2m_t| \lesssim 5$ GeV

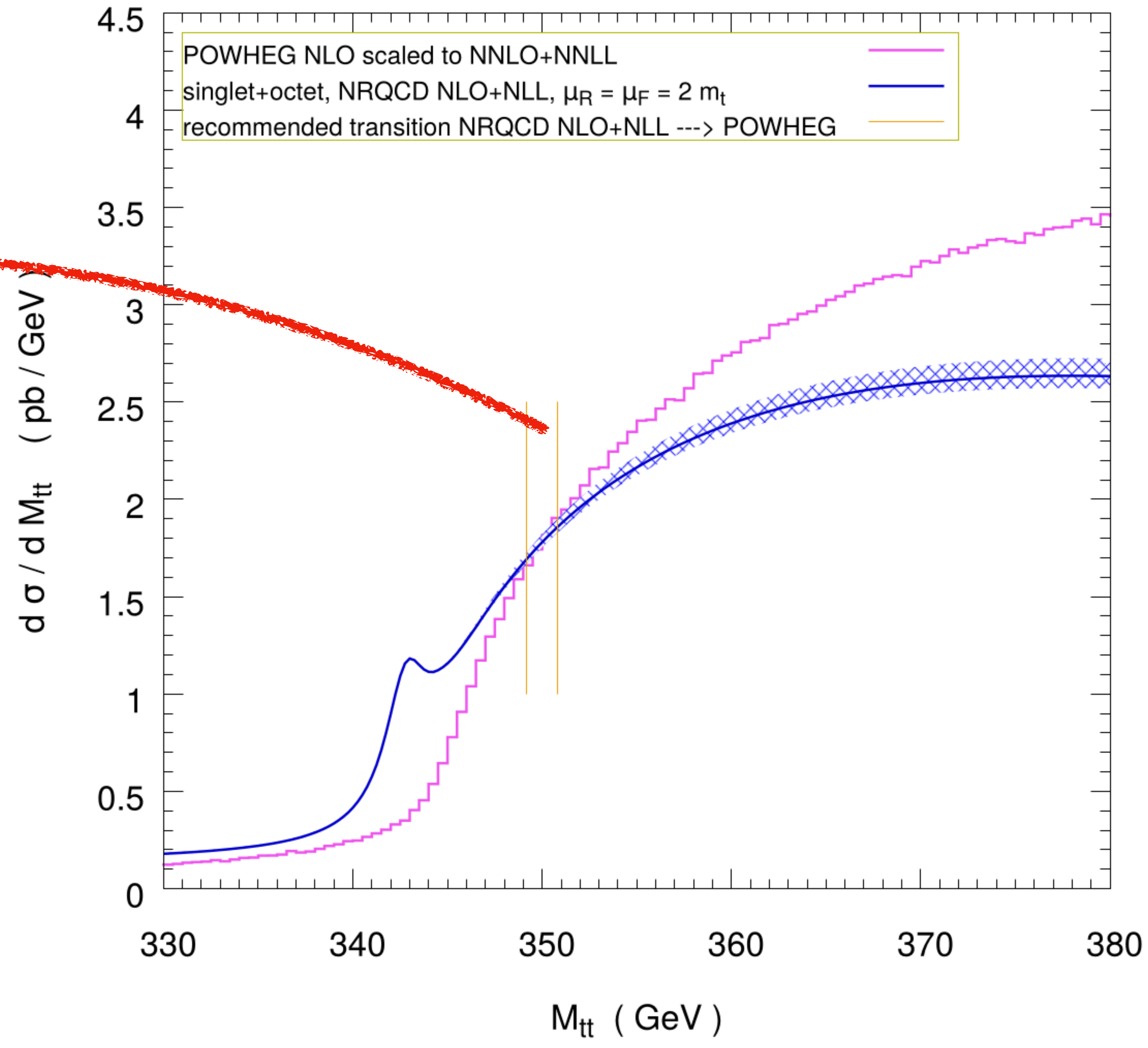
A matching is required!



From NRQCD to NNLO

Additive matching for
$M_{t\bar{t}} \gtrsim 350$ GeV
where NRQCD stops to be valid

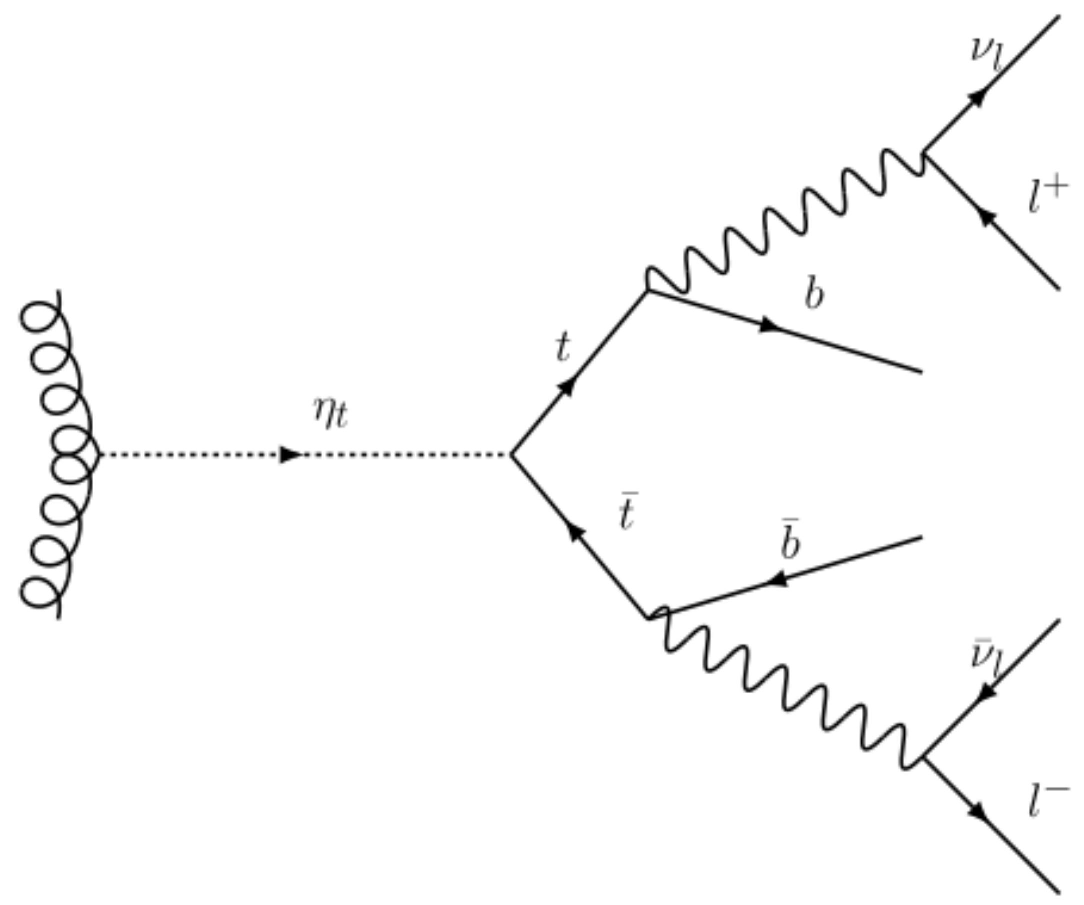
POWHEG predictions only applicable for
$M_{t\bar{t}} \gg 2m_t$



Modelling $t\bar{t}$ resonances

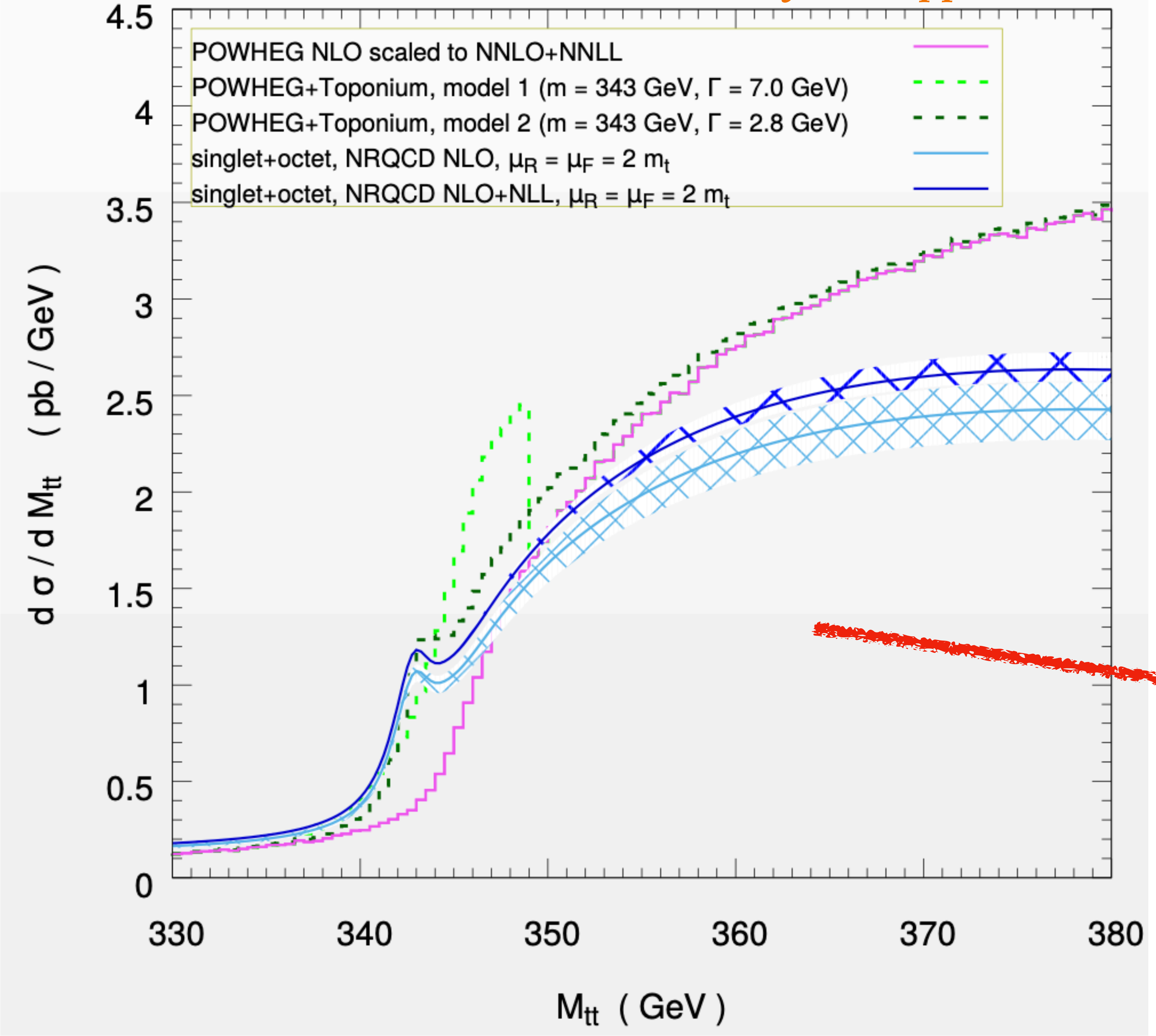
- CMS analysis based on NLO POWHEG predictions rescaled at NNLO+NNLL
- Bound states simulated by introducing a new particle η_t with mass and decay fitted for $M_{t\bar{t}} \in [337, 349]$ GeV (Fuks, Hagiwara, Ma, Zheng [2102.11281])
- Matrix element re-weigthing with NRQCD Green Function (Fuks, Hagiwara, Ma, Zheng [2411.18962]) not yet implemented for analysis

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



Modelling $t\bar{t}$ resonances

Thanks to Anuar, Garzelli, Grohsjean, Jeppe, Schwanenberger



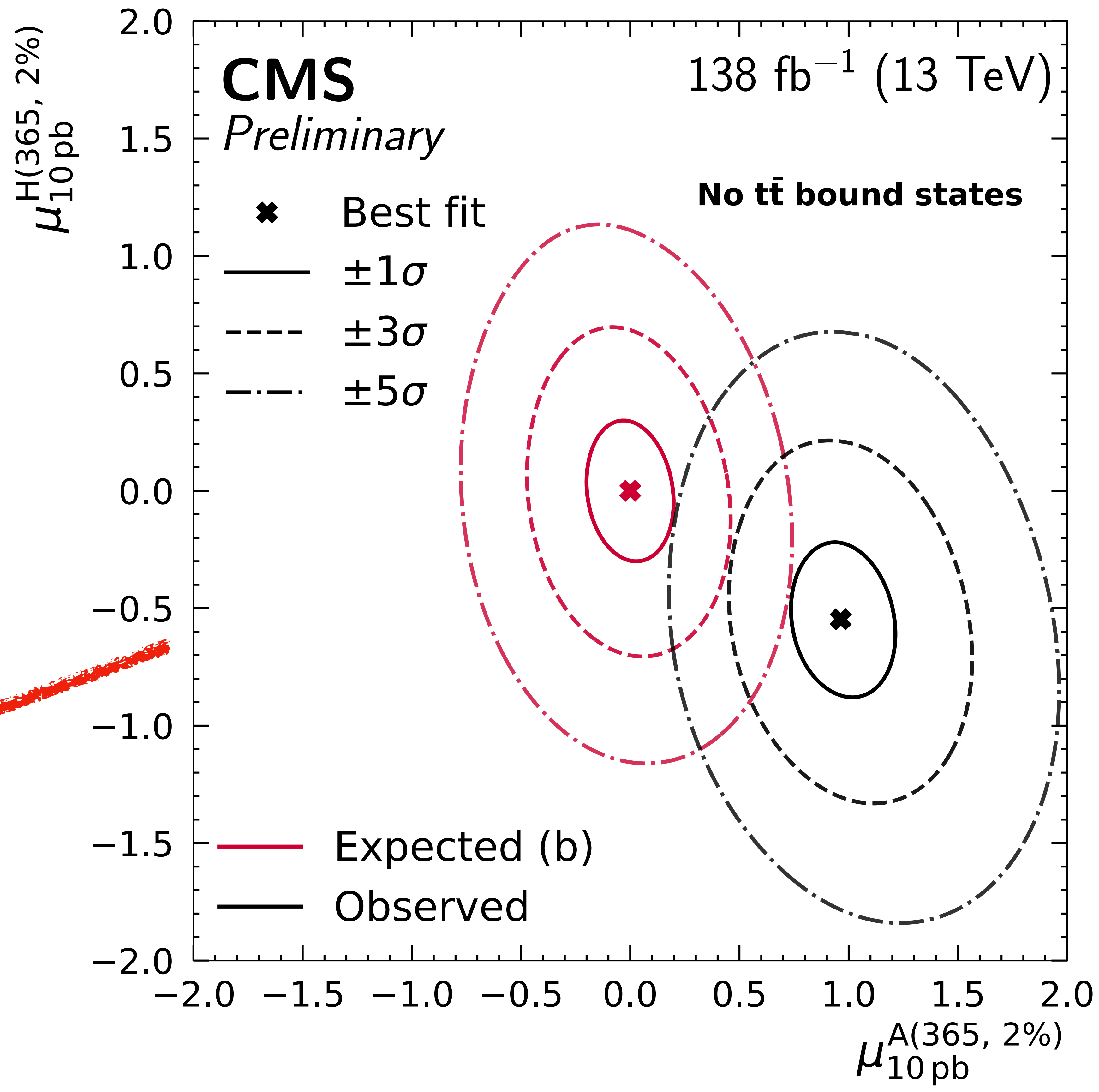
- No accounting for QCD higher orders effects
- Repulsive interaction for color octet states, other S - and P - wave singlet states are not considered
- NRQCD with Coulomb and threshold resummation to fill this gap in $M_{t\bar{t}} \in [340, 350]$ GeV

- CMS Fuks model implementation ($\Gamma_{\eta_t} = 7$ GeV) does not match with NRQCD
- Improved agreement moving from $\Gamma_{\eta_t} = 7$ GeV to $\Gamma_{\eta_t} = 2\Gamma_t = 2.8$ GeV (*Maltoni et al.* [JHEP 03, 2024, 099])

Modelling $t\bar{t}$ resonances

- Is the excess in the data related to a scalar or a pseudoscalar?
- 2D fit with arbitrary signal strength
- Scalar term compatible with zero

CMS-PAS-HIG-22-013



Data point towards a pure pseudoscalar!

Conclusions and Outlooks

- NRQCD methods highly useful to provide reliable theoretical inputs for the experimental analysis
- Pseudoscalar particle to model “toponium" formation below the threshold
- NNLO corrections to Green Function ($\mathcal{O}(10\%)$) in the peak region
- NNLO corrections to hard function F_{ij} ($\mathcal{O}(10\%)$) at the threshold
- Lower bound estimate on $\mathrm{d}\sigma/\mathrm{d}M_{t\bar{t}}$ for $M_{t\bar{t}} \simeq 2m_t$
- Forthcoming refined study about the impact of parameters settings ($m_t,\ \alpha_s(M_Z),\ \mu_r,\ \mu_f$, PDFs sets)
- More accurate matching prescription
- Other observables to be considered, kinematic cuts…

Thank you for the attention!!!