Differential distributions of top-quark pair productions at NNLO+NNLL' in QCD

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1803.07623

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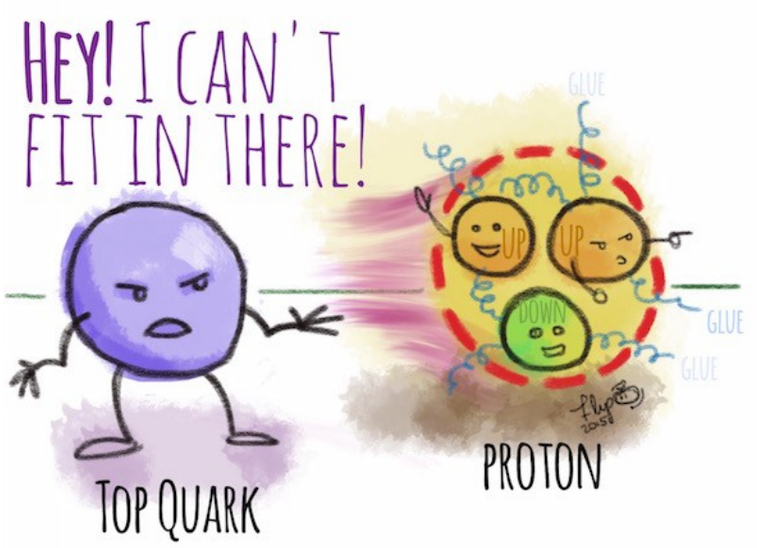
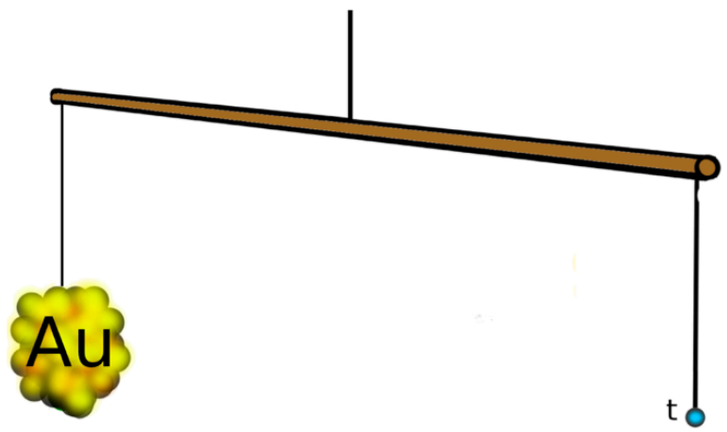
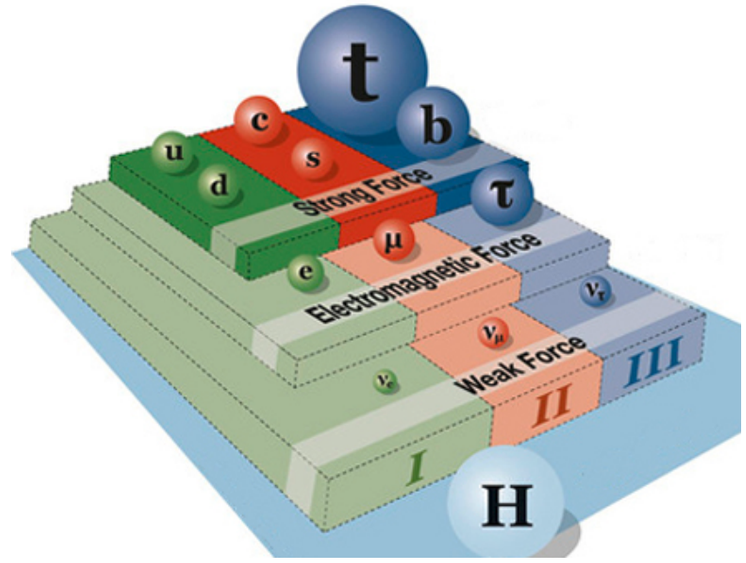
and **1811.xxxxx**, with B. D. Pecjak, D. J. Scott and L.L. Yang

HFCPV–2018@郑州





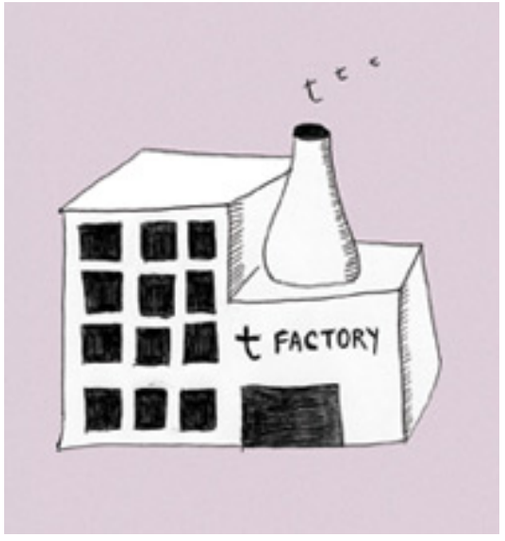


- **Heaviest in SM:** $m_t \approx 173.3$ **GeV**
- **Strong Yukawa coupling:** $y_t \sim 1$

- **Crucial to SM? i.e. EW SSB.**
- **A window to BSM**

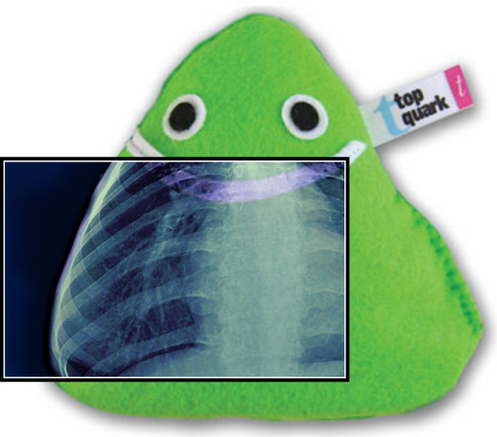
- **Decay before hadronization!** → **pQCD dominates!**

Top pair productions at LHC



- LHC is a top pair factory(gluon channel dominates)
  - Entire phase space detection is possible

Boosted region and threshold region?

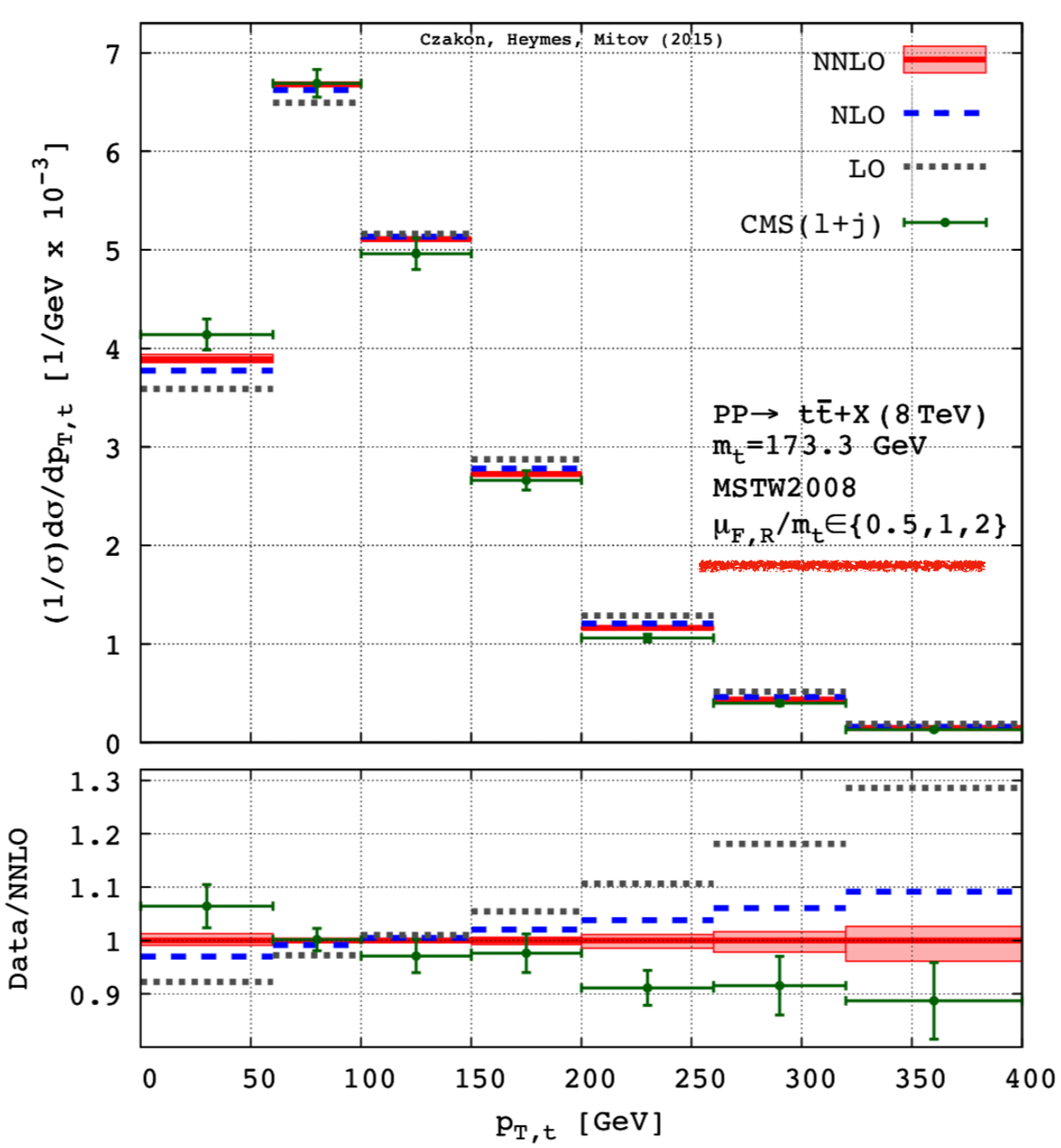


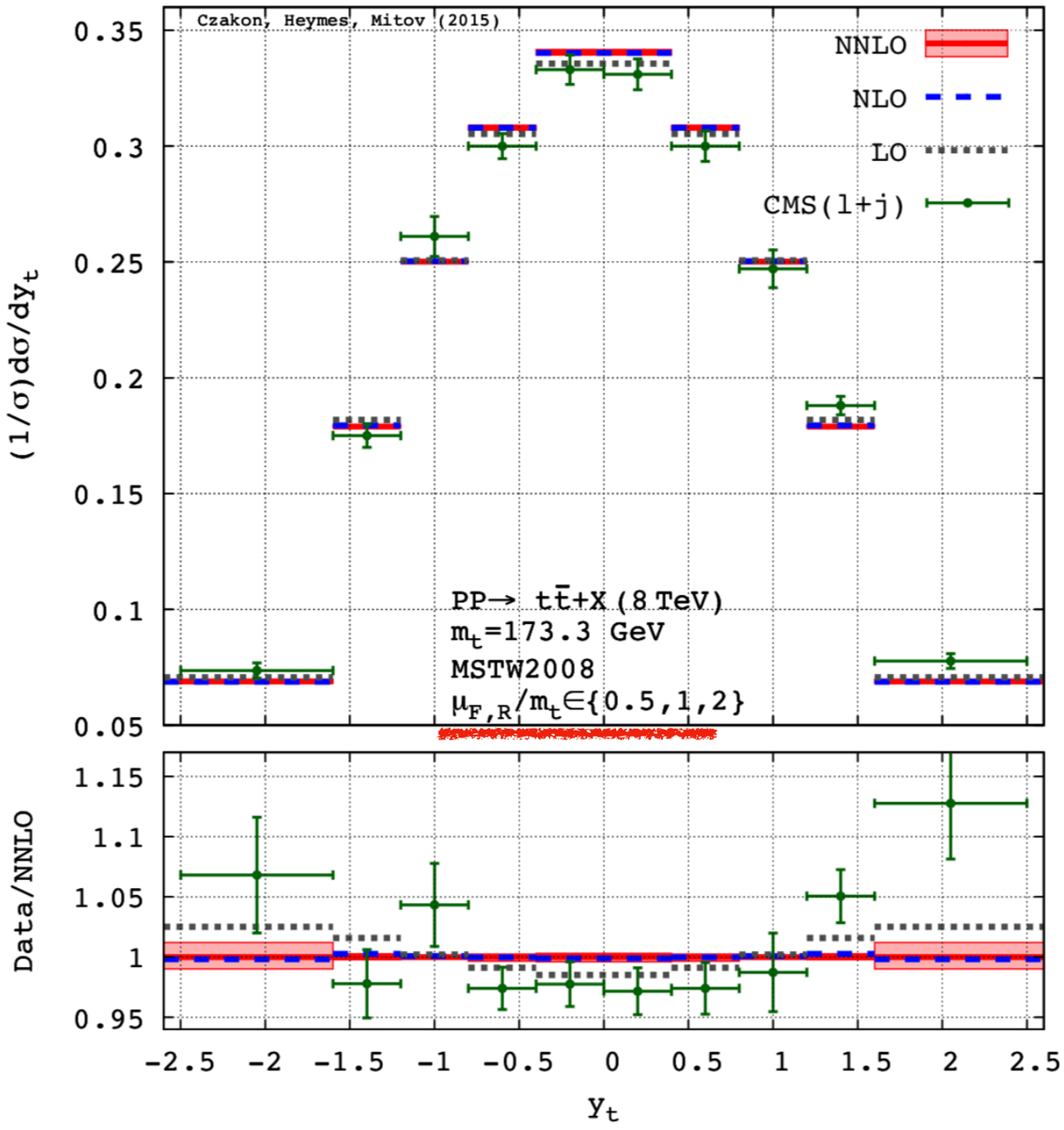
- Precision era has been coming...
  - Differential Xs are more and more important
    - Test and constrain SM at the energy frontier
    - Provide more accurate background estimates for BSM
    - Deviations may hint BSM signals!

i.e. rapidity dists help to constrain gluon PDFs at large x

Differential dists @NNLO QCD

Czakon, Heymes, Mitov: 1511.00549(fixed scale choice)



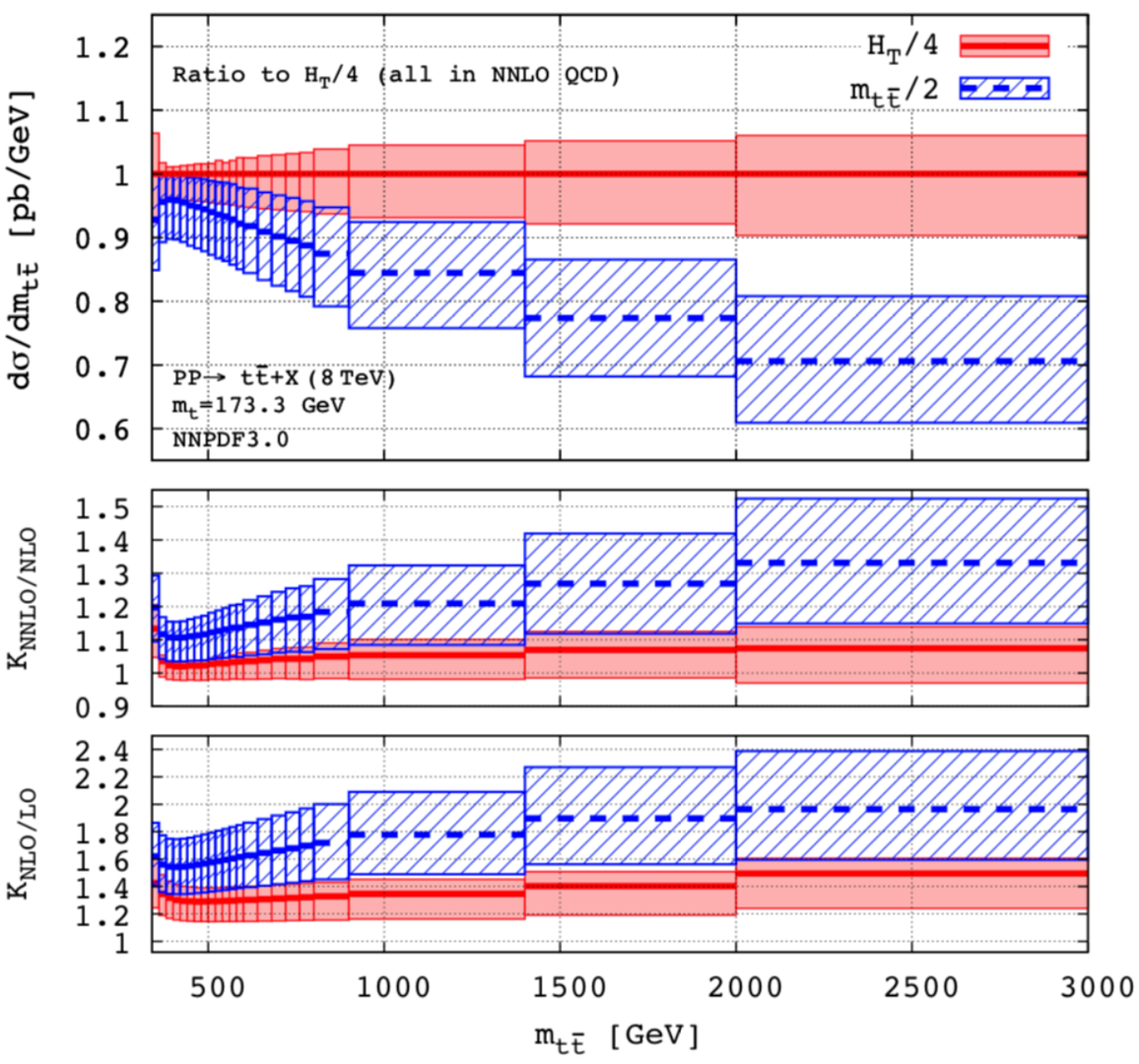


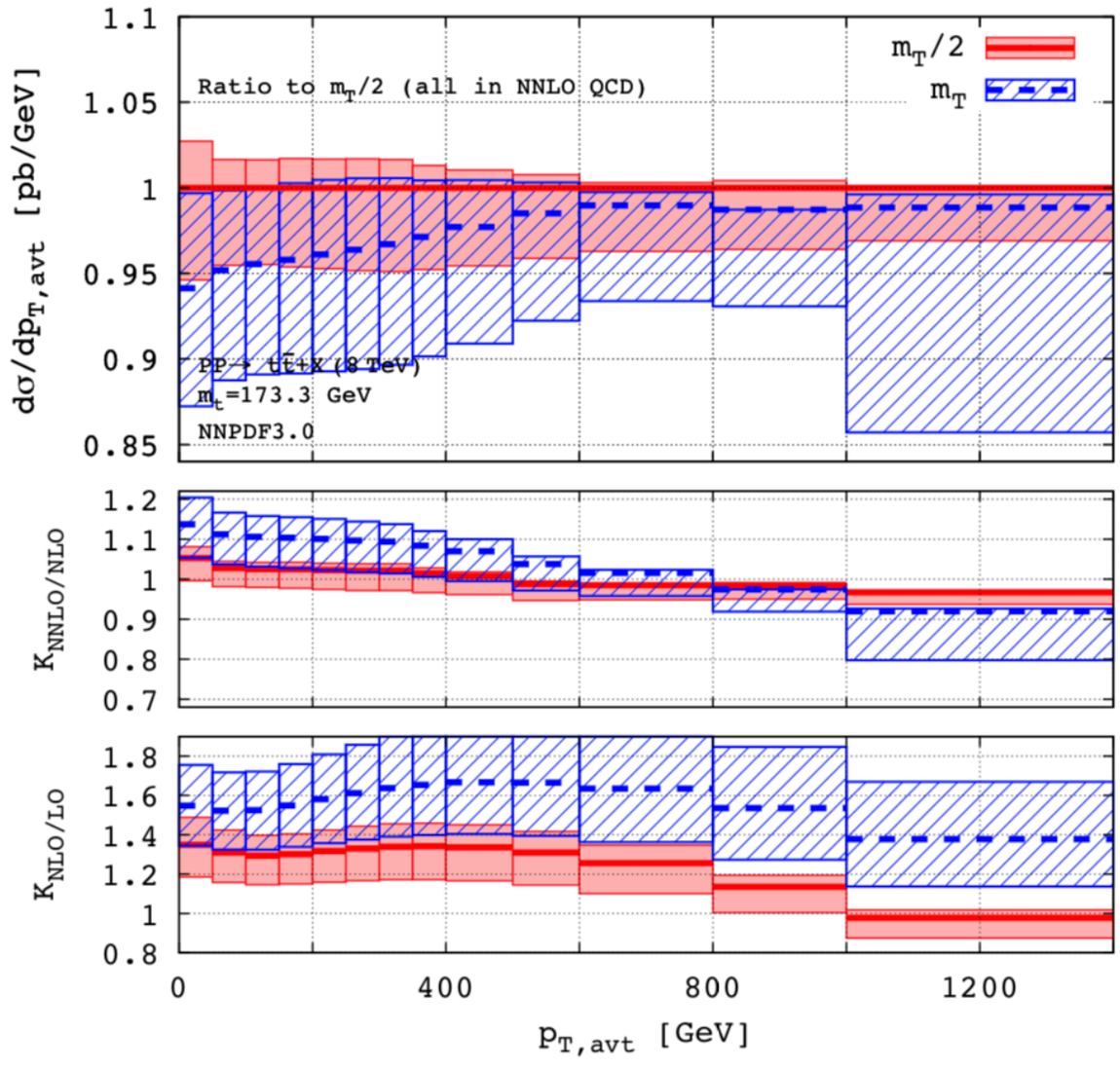
- **NNLO improves tremendously, but has some tension in boosted region.**

Differential dists @NNLO QCD

Czakon, Heymes, Mitov: 1606.03350(**dynamical scale choice**)

Based on perturbative series convergence





- **However, results depend on different choice dramatically, especially in boosted region.**

Kinematics in boosted region

Many wide-separated scales emerge:

$$\hat{s},\ M_{t\bar{t}},\ |t_1|,\ m_T^{t/\bar{t}},\ m_t,\ \cdots$$

Soft gluons → $\ln \dfrac{\hat{s} - M_{t\bar{t}}^2}{\hat{s}}$

Quasi-collinear gluons → $\ln \dfrac{m_t}{M_{t\bar{t}}}$

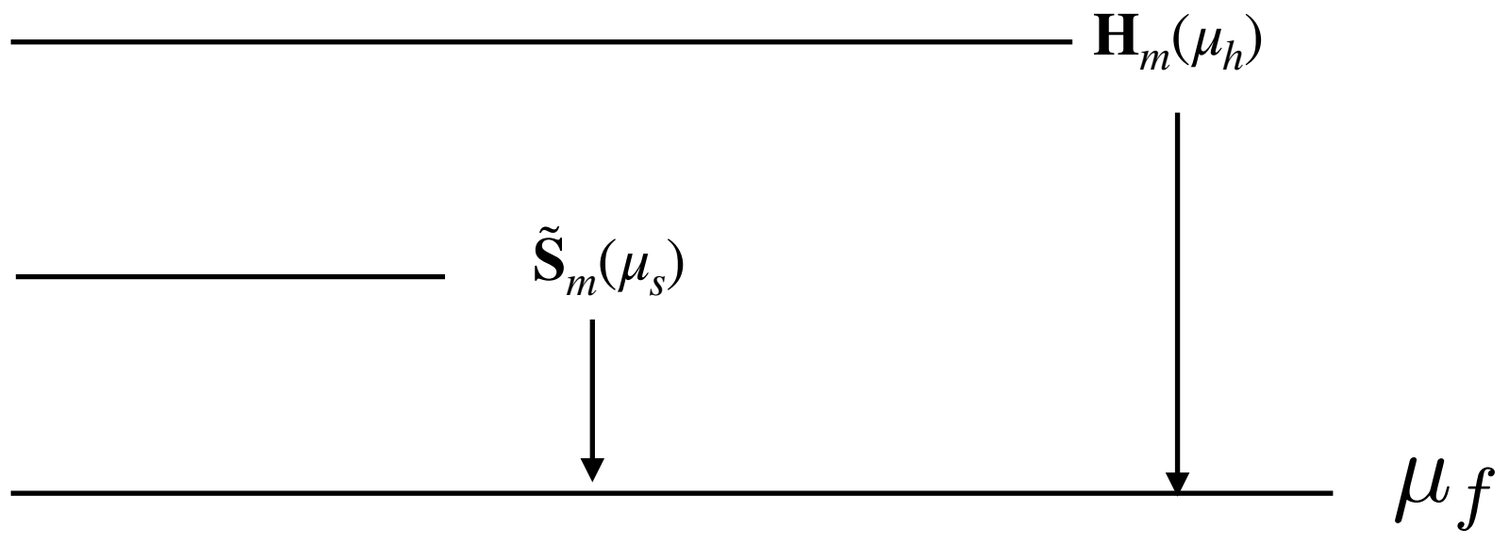
✱ **Resummation is called for to relieve those tensions here;**

✱ **And to reduce scheme dependence of scale choice for boosted tops.**

Factorization and resummation in Mellin space

soft limit: $\hat{s}, |t| \sim M_{t\bar{t}},\ m_t \gg M_{t\bar{t}}/N$

$$\frac{d\hat{\sigma}(N,\mu_f)}{dX} \propto \mathbf{Tr}[\mathbf{H}_m(\mu_f)\tilde{\mathbf{S}}_m(\mu_f)] + \mathcal{O}(1/N)$$



$$\frac{d\sigma(N,\mu_f)}{dX} = L(N,\mu_f)\mathrm{Tr}[\mathbf{U}_m(N,\mu_f,\mu_s,\mu_h)\mathbf{H}_m(\mu_h)\mathbf{U}_m^\dagger(N,\mu_f,\mu_s,\mu_h)\tilde{\mathbf{S}}_m(\mu_s)] + \mathcal{O}(1/N)$$

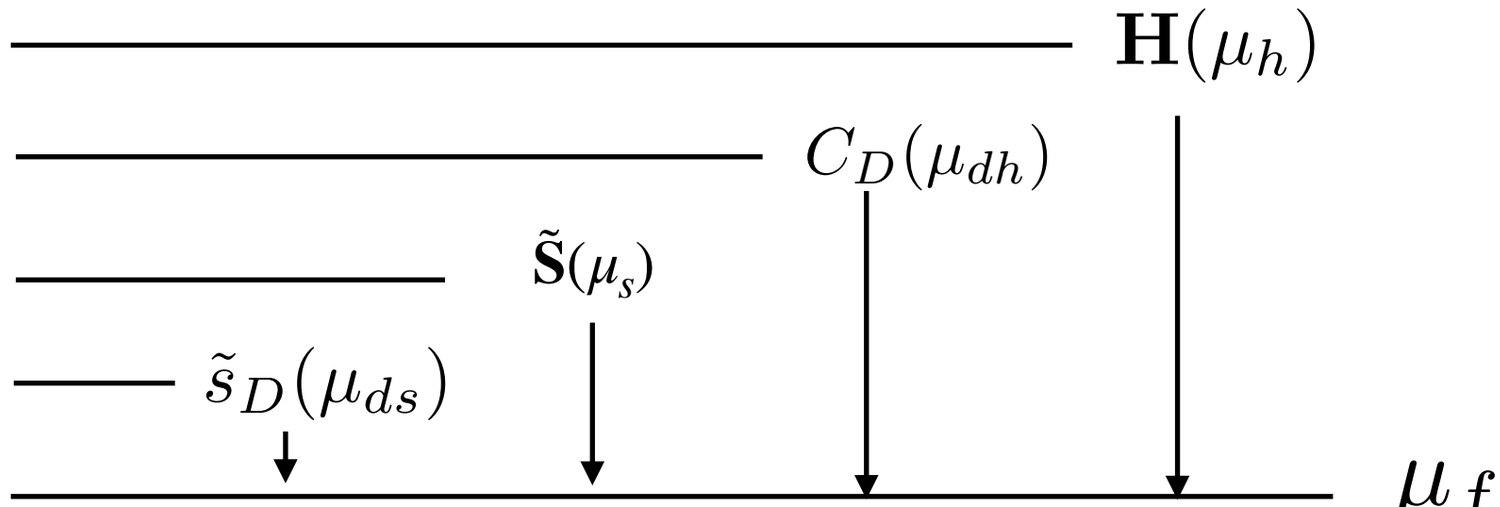
Only soft logs resummed

Kidonakis, Sterman: hep-ph/9705234; Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1003.5827

Factorization and resummation in Mellin space

boosted-soft limit: $\hat{s}, |t| \sim M_{t\bar{t}} \gg m_t \gg M_{t\bar{t}}/N \gg m_t/N$

$$\frac{d\hat{\sigma}(N,\mu_f)}{dX} \propto \mathbf{Tr}[\mathbf{H}(\mu_f)\tilde{\mathbf{S}}(\mu_f)]C_D^2(\mu_f)\tilde{s}_D^2(\mu_f) + \mathcal{O}(1/N) + \mathcal{O}(m_t/M_{t\bar{t}})$$



$$\frac{d\sigma(N,\mu_f)}{dX} = L(N,\mu_f)\mathrm{Tr}[\mathbf{U}(N,\mu_f,\mu_s,\mu_h)\mathbf{H}(\mu_h)\mathbf{U}^\dagger(N,\mu_f,\mu_s,\mu_h)\tilde{\mathbf{S}}(\mu_s)]$$
$$U_D^2(N,\mu_f,\mu_{dh},\mu_{ds})C_D^2(\mu_{dh})\tilde{s}_D^2(\mu_{ds}) + \mathcal{O}(1/N) + \mathcal{O}(m_t/M_{t\bar{t}})$$

Different distributions have different luminosity functions

Both logs resummed

Ferroglia, Pecjak, LLY: 1205.3662

Matching:
avoid double or triple counting

soft+small-mass resummation(b)

soft resummation(m)

(N)NLO

- matching with soft-gluon resummation

$$d\sigma^{\mathrm{NNLL}'_{b+m}} = d\sigma^{\mathrm{NNLL}'_{b}} + (d\sigma^{\mathrm{NNLL}_{m}} - d\sigma^{\mathrm{NNLL}_{m}}|_{m_t \to 0})$$

- matching with fixed order

$$d\sigma^{(\mathrm{N})\mathrm{NLO+NNLL}'} = d\sigma^{\mathrm{NNLL}'_{b+m}} + (d\sigma^{(\mathrm{N})\mathrm{NLO}} - d\sigma^{\mathrm{NNLL}'_{b+m}}|_{(\mathrm{N})\mathrm{NLO}})$$

Hard and soft scale choice

In boosted region, new effective scale emerges in hard and soft functions:

$$-t_1\,|_{m_t\to 0} \approx \frac{M_{t\bar{t}}^2}{2}(1-\cos\theta) + m_t^2\cos\theta \xrightarrow{\cos\theta\to 1} p_T^2 + m_t^2 \equiv m_T^2 = H_T^2/4$$

$$-u_1\,|_{m_t\to 0} \approx \frac{M_{t\bar{t}}^2}{2}(1+\cos\theta) - m_t^2\cos\theta \xrightarrow{\cos\theta\to -1} p_T^2 + m_t^2 \equiv m_T^2 = H_T^2/4$$

t-, u-channel enhancement

$$\mathbf{H}(\mu_h)\,|_{t_1\to 0} \supseteq \{\ln^k\frac{-t_1}{\mu_h^2}, \ln^k x_t, \ln^k x_t \times \ln^j\frac{-t_1}{\mu_h^2}\}$$

$$\tilde{\mathbf{S}}(\mu_s)\,|_{t_1\to 0} \supseteq \{\ln^k\frac{-t_1}{\bar{N}^2\mu_s^2}, \ln^k x_t, \ln^k x_t \times \ln^j\frac{-t_1}{\bar{N}^2\mu_s^2}\}$$

$$\mu_h^0 \propto H_T$$

$$\mu_s^0 \propto H_T/\bar{N}$$

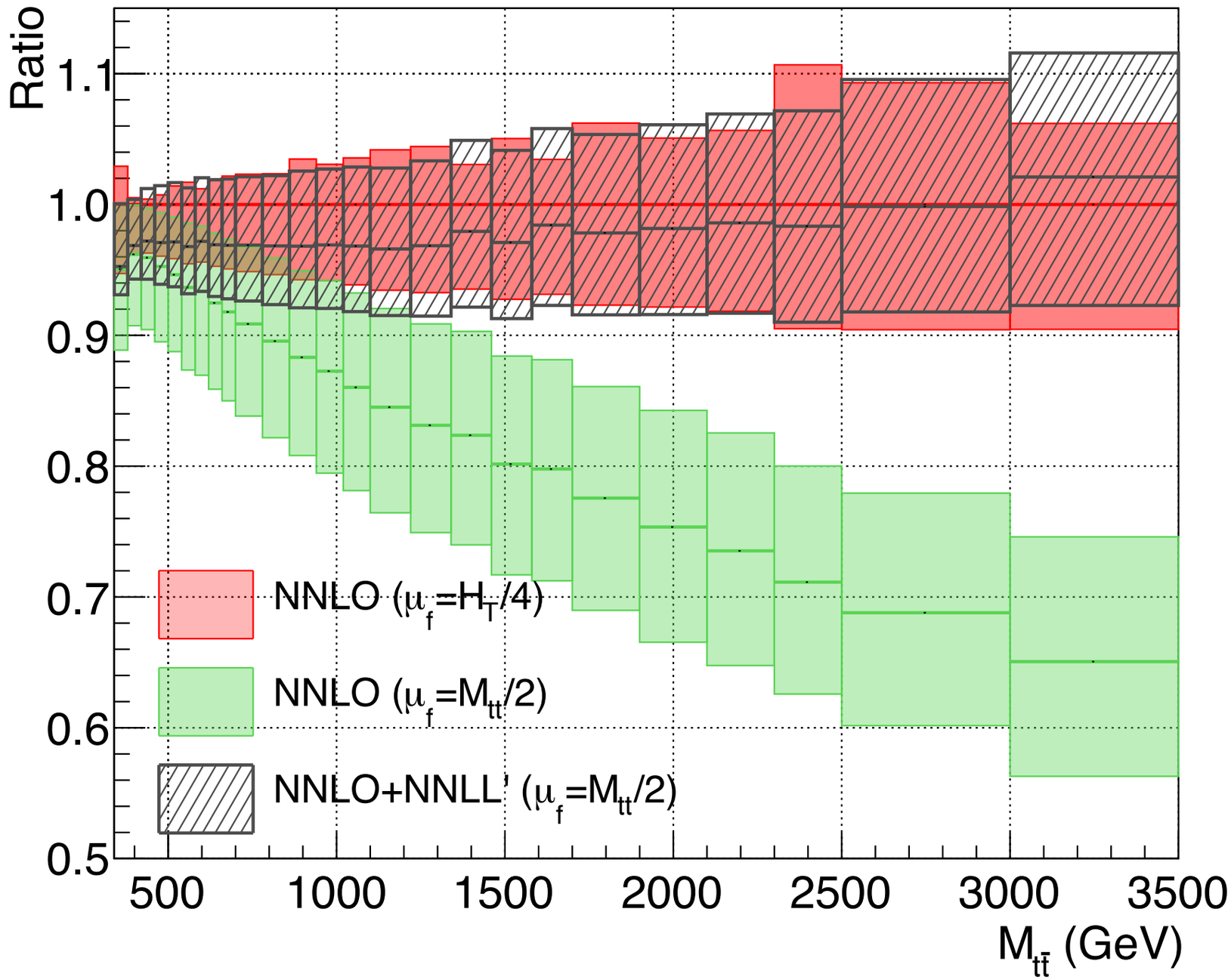
To get rid of large logs in perturbative expansions of hard and soft functions.

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, LLY: 1803.07623

Factorization scale choice

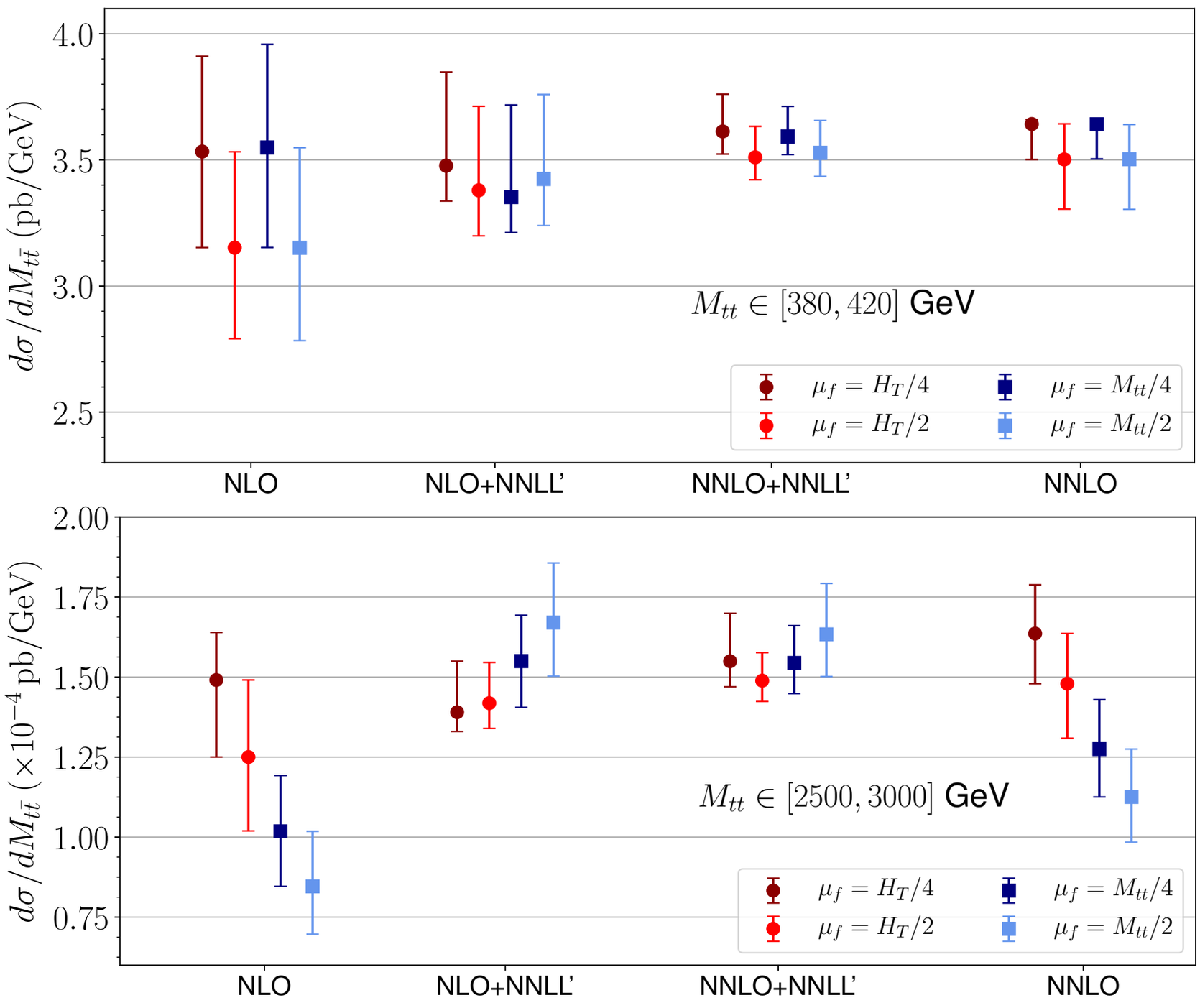
Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, LLY: 1803.07623

$$\mu_f^0 = H_T/4$$



Resummation makes the result not depend on the fac-scale so dramatically.

Factorization scale choice



Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, LLY: 1803.07623

Final results

$$\mu_f^0 = H_T/4$$
$$\mu_h^0 = H_T/2$$

$M_{t\bar{t}},\ Y_{t\bar{t}},\ y_{t/\bar{t}}:$

$$\mu_s^0 = H_T/\bar{N}$$
$$\mu_{dh}^0 = m_t$$
$$\mu_{ds}^0 = m_t/\bar{N}$$

$$\mu_f^0 = m_T/2$$
$$\mu_h^0 = m_T$$

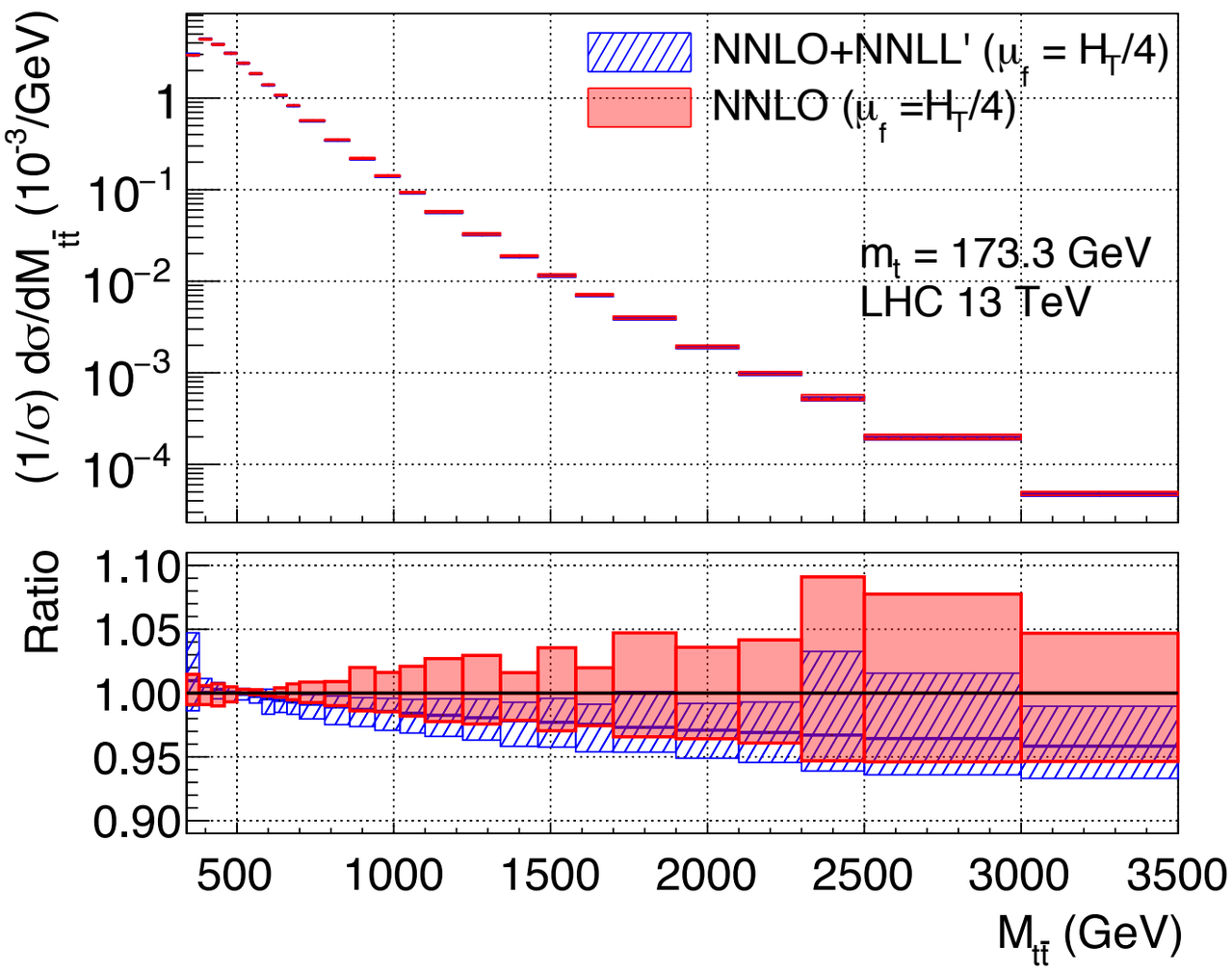
$p_{T,t/\bar{t}}:$

$$\mu_s^0 = 2m_T/\bar{N}$$
$$\mu_{dh}^0 = m_t$$
$$\mu_{ds}^0 = m_t/\bar{N}$$

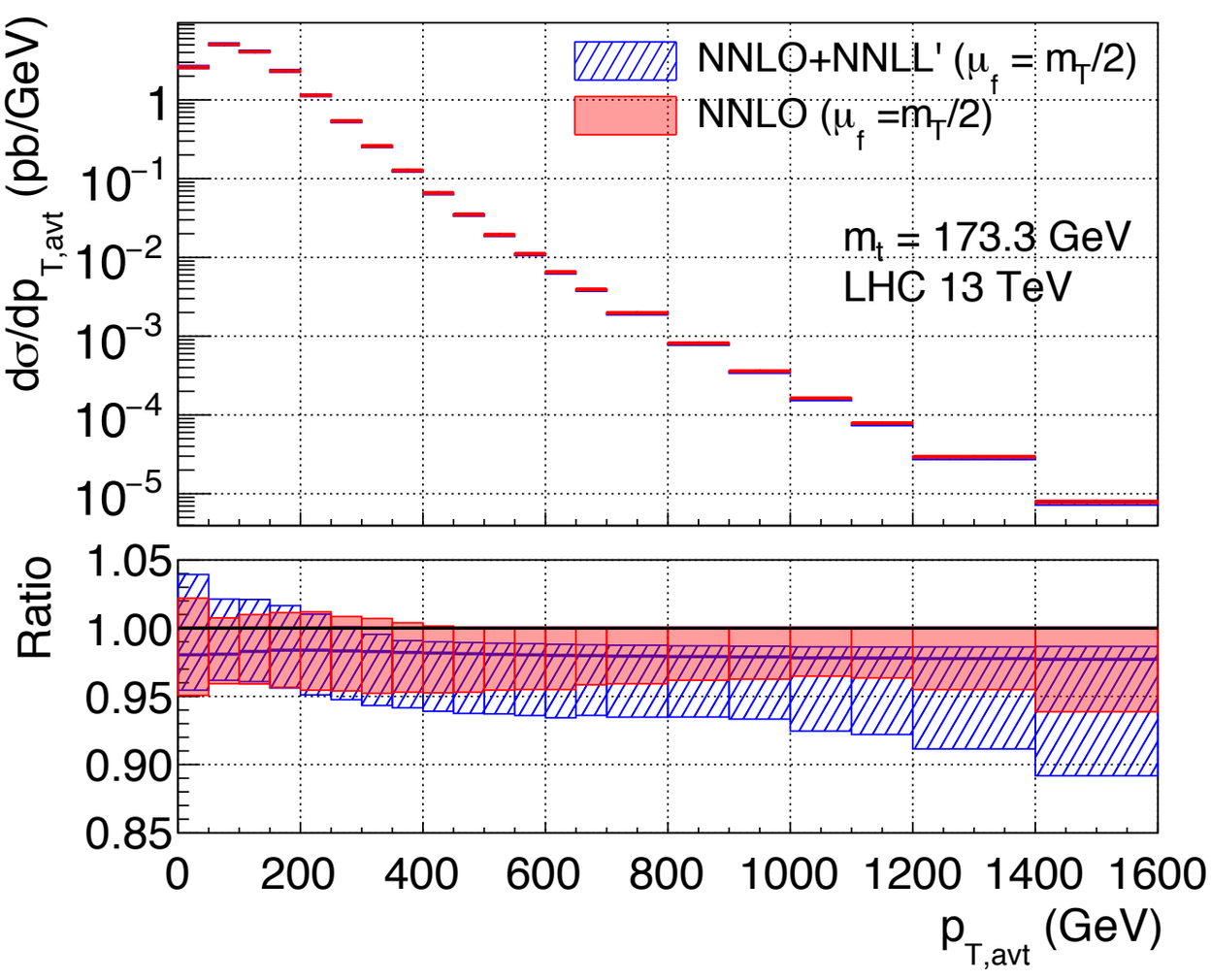
Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, LLY: 1803.07623

$M_{t\bar{t}}$ & $p_{T,t/\bar{t}}$ distribution

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, LLY: 1803.07623



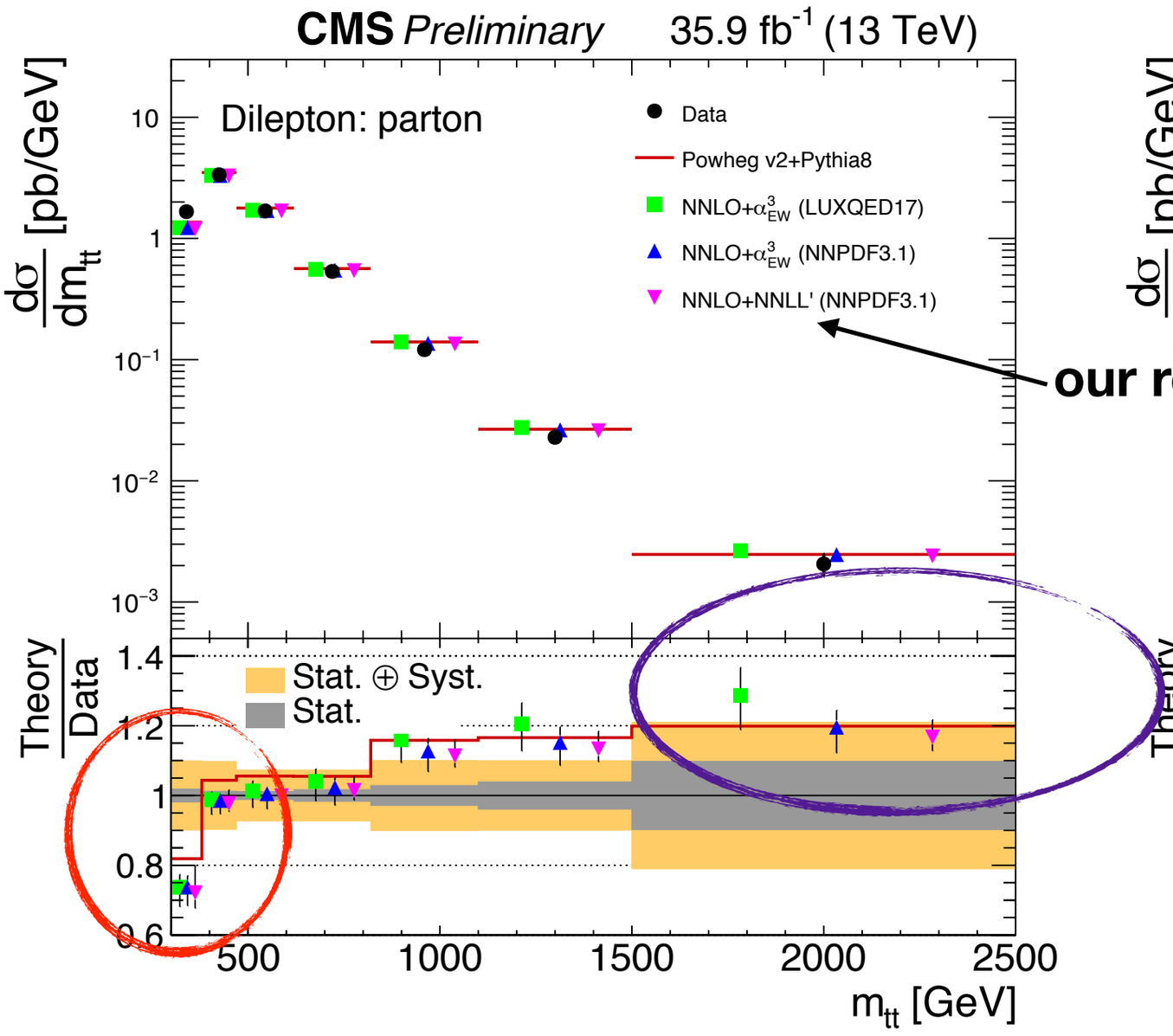
- **Reduce scale uncertainty**
- **Soften the spectrum**

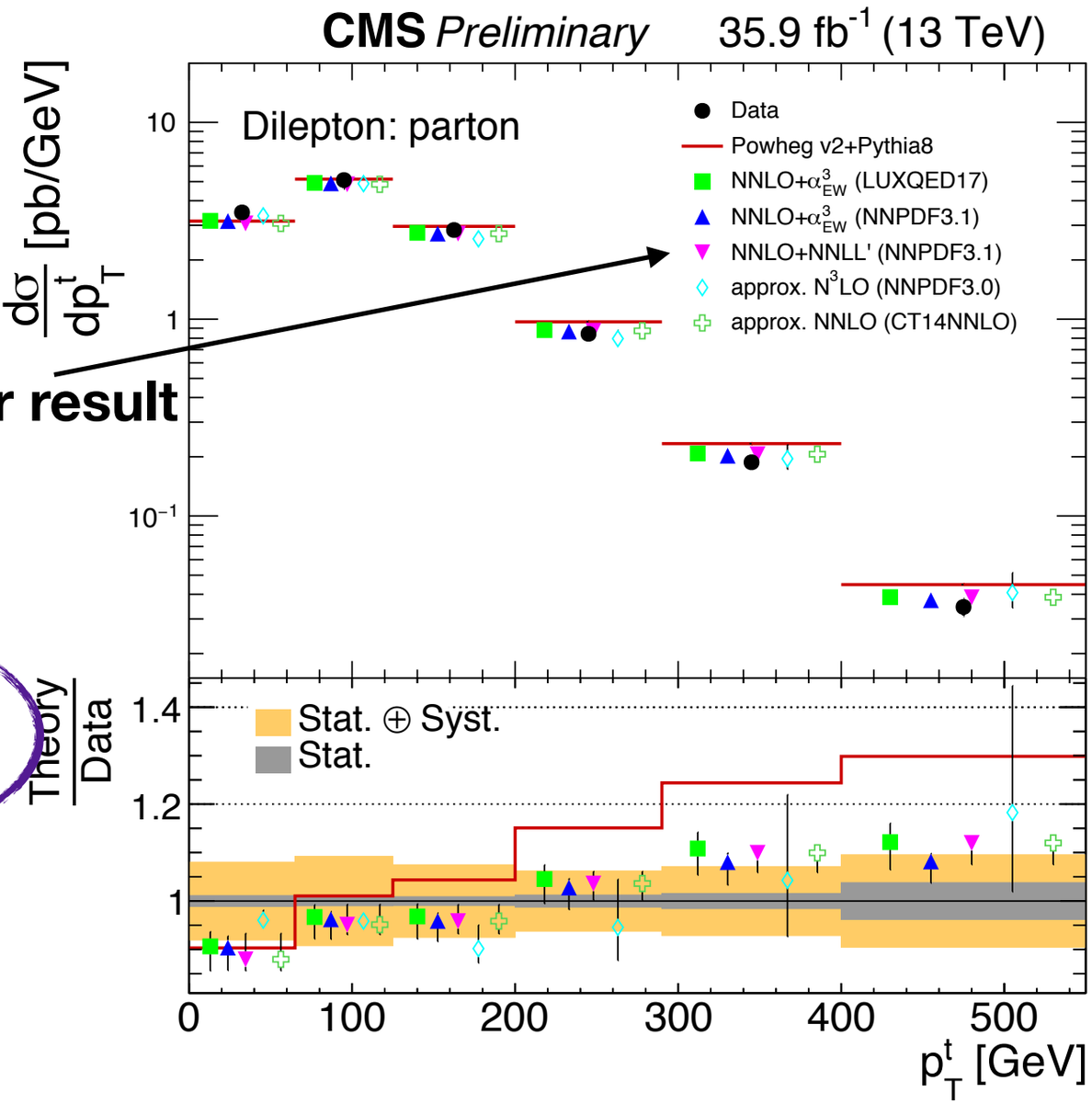


- **Soften the spectrum**

CMS PAS TOP-17-014

$M_{t\bar{t}}$ & $p_{T,t/\bar{t}}$ distribution



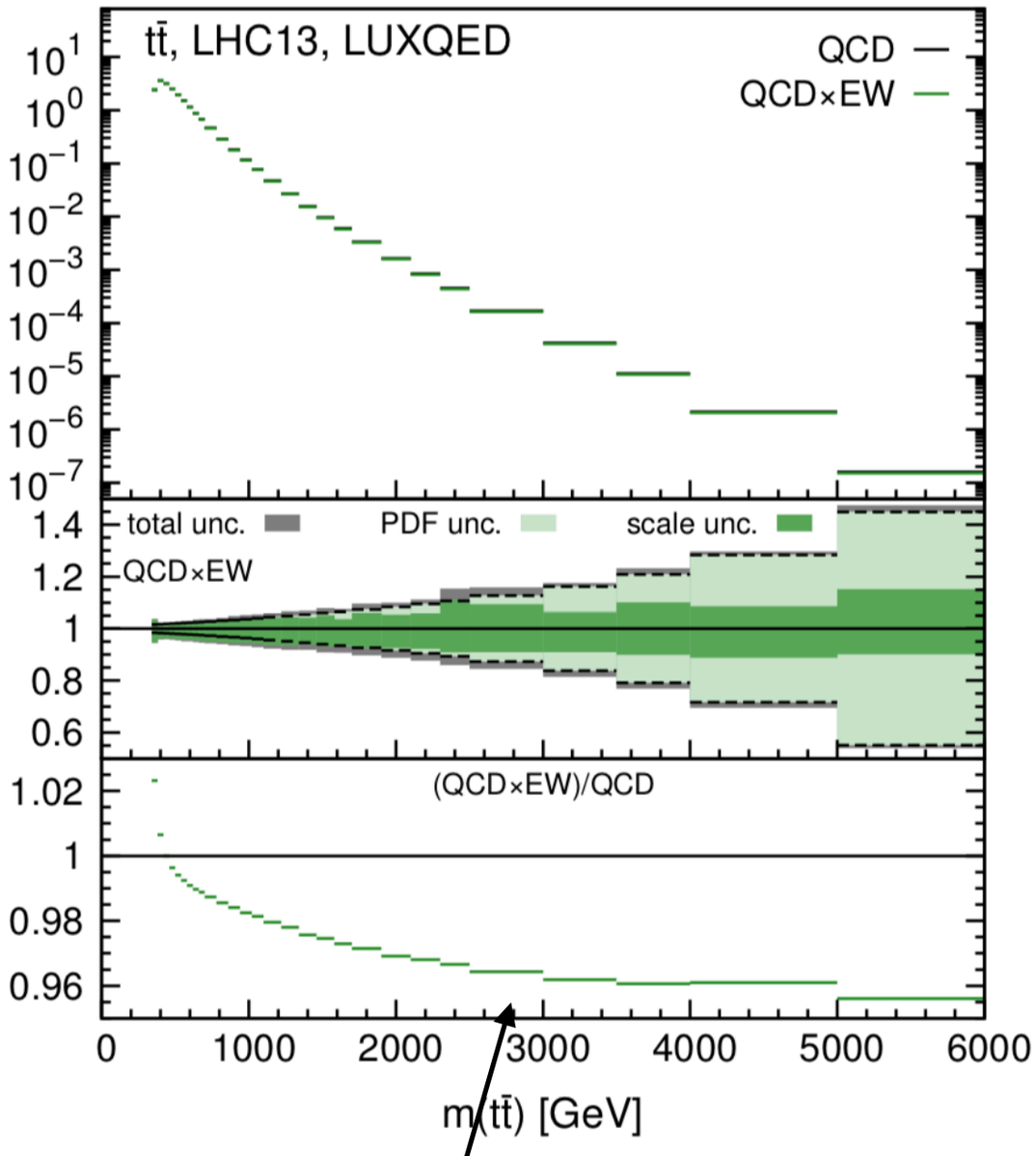


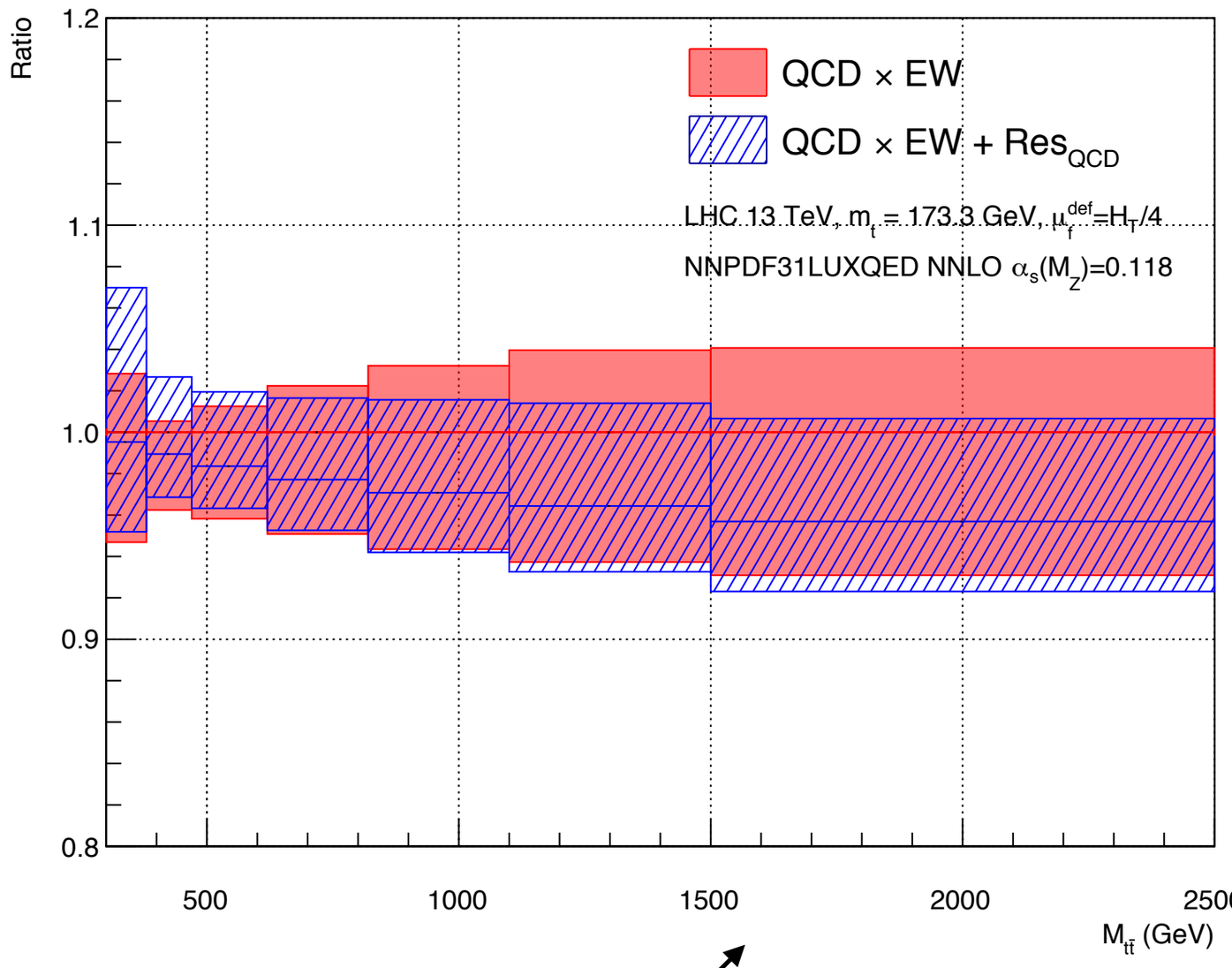
our result

- top mass effect?
- soft and Coulomb gluon?

- need to go beyond

$M_{t\bar{t}}$ & $p_{T,t/\bar{t}}$ distribution

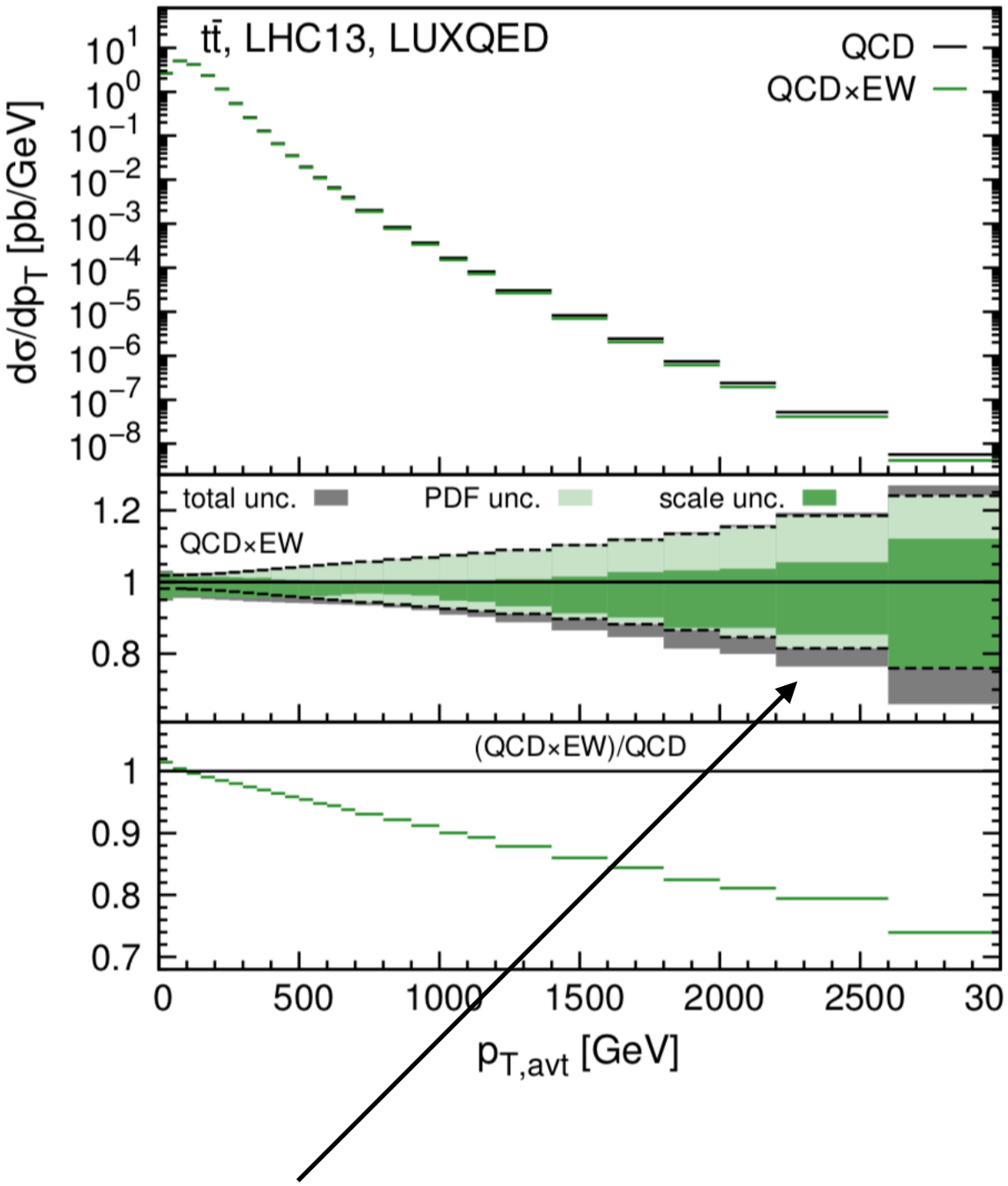




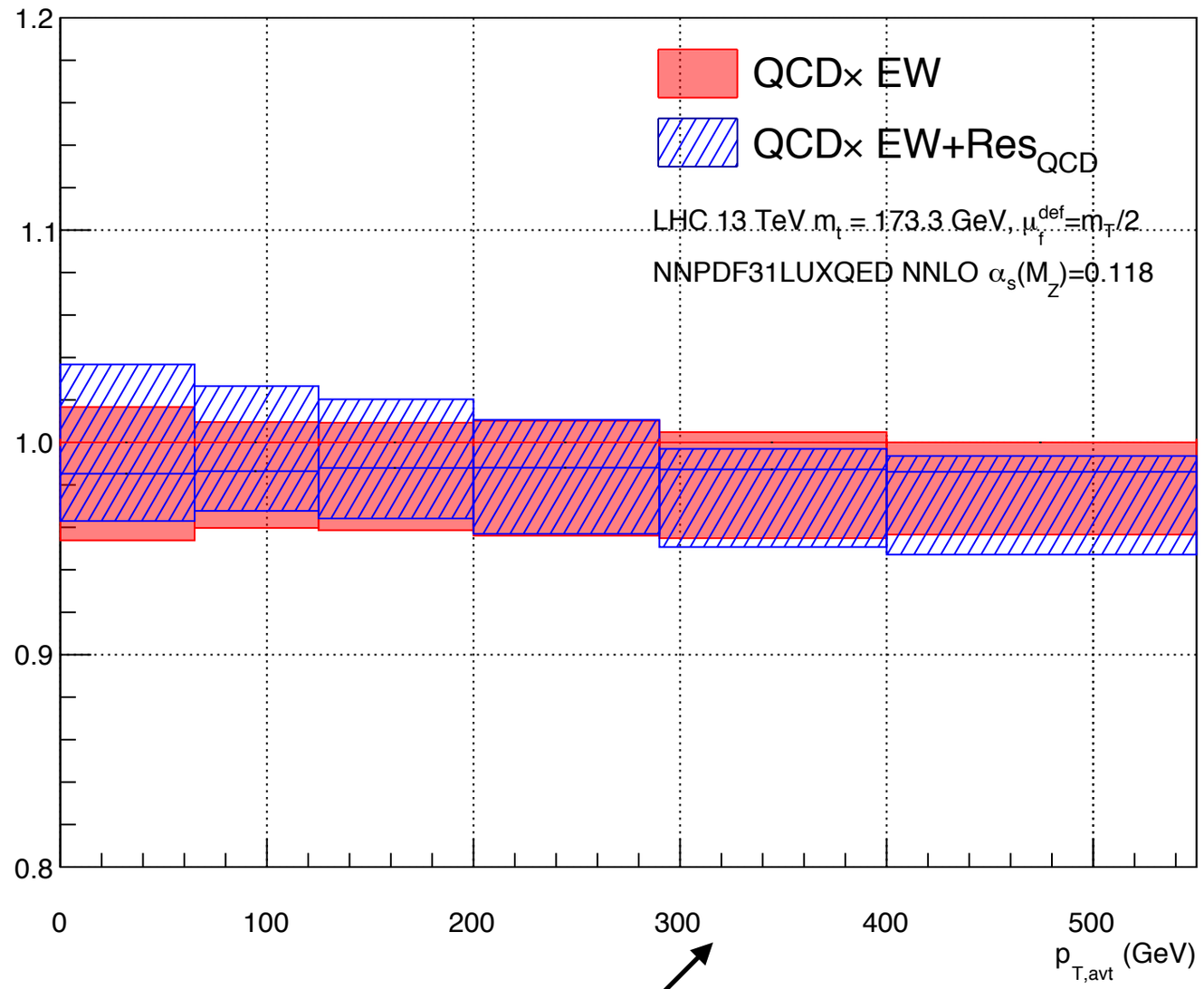
Czakon et al.: 1705.04105

Preliminary results about QCD&EW

$M_{t\bar{t}}$ & $p_{T,t/\bar{t}}$ distribution



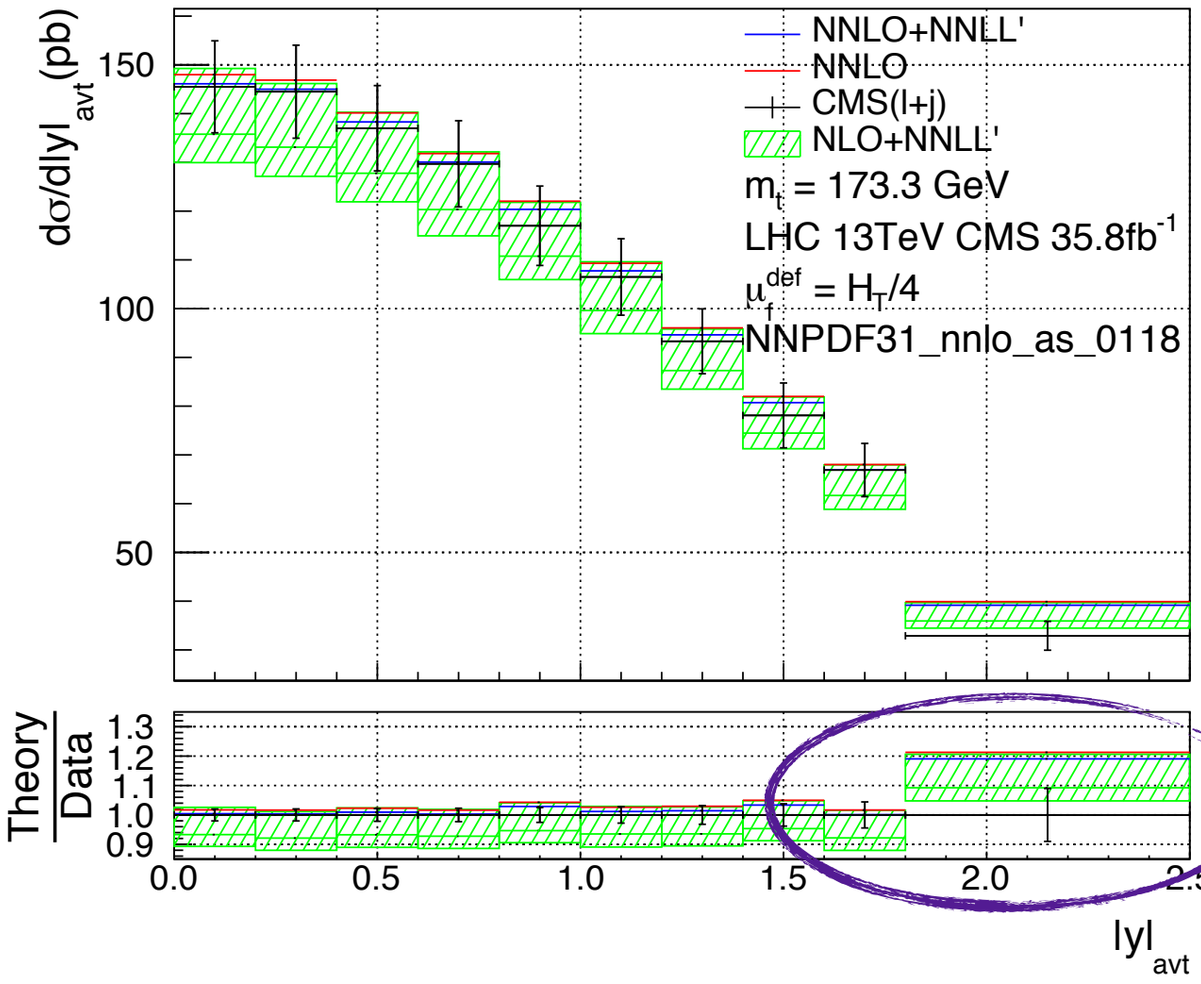
Czakon et al.: 1705.04105

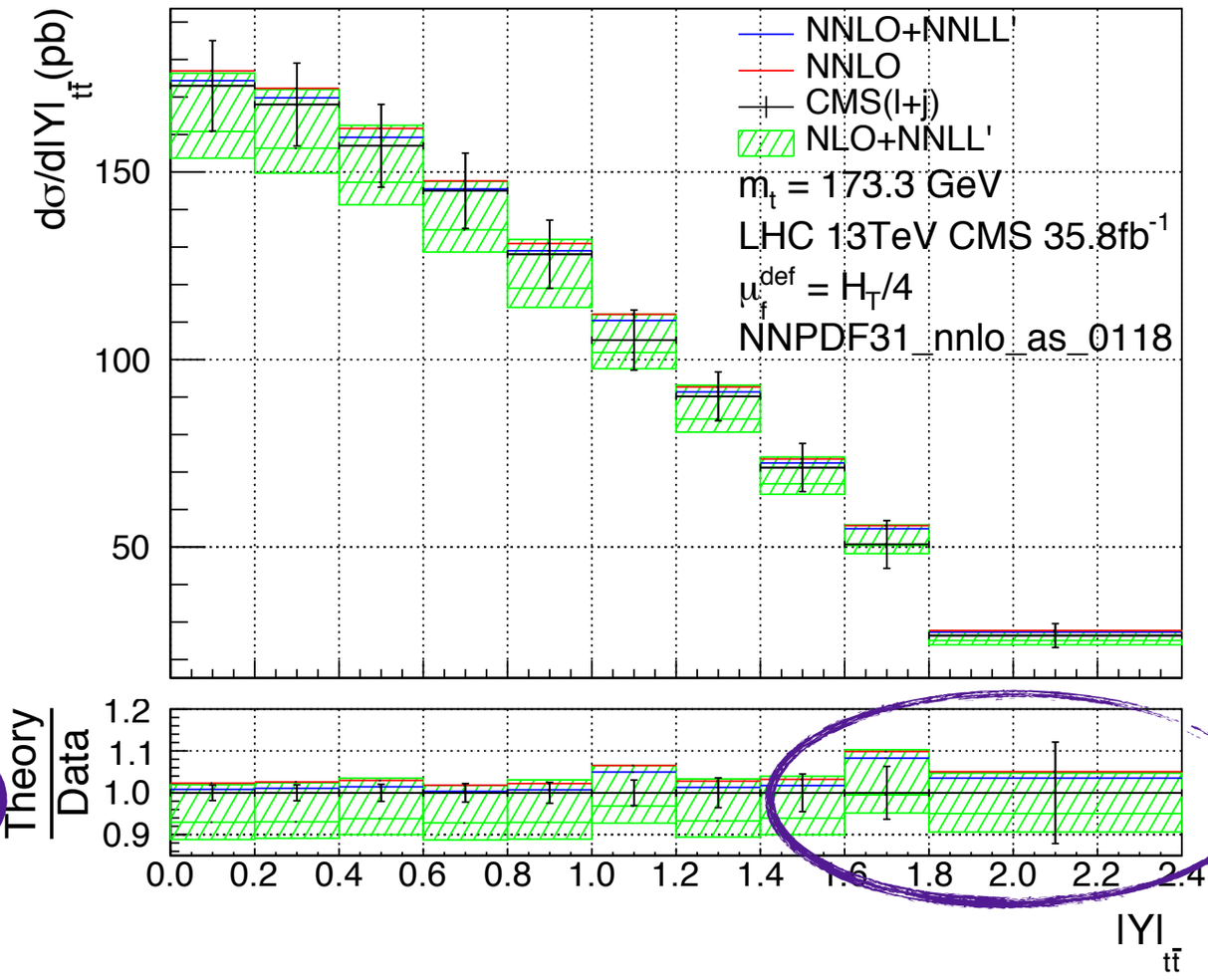


Preliminary results about QCD&EW

$Y_{t\bar{t}}$ & $y_{t/\bar{t}}$ distribution

Pecjak, Scott, Wang, LLY: to appear





- **In fact, the shape depends on different PDFs and can be used to constrain PDFs**

Summary and Outlook

☑ NNLO+NNLL' is the most precise QCD prediction for large range of PS.

☑ Resummation effects compensate for FO results in two ways.

☑ Ongoing:

- Finishing analysis on rapidity distributions.
- Collaborate with NLO EW corrections group.

☐ Outlook:

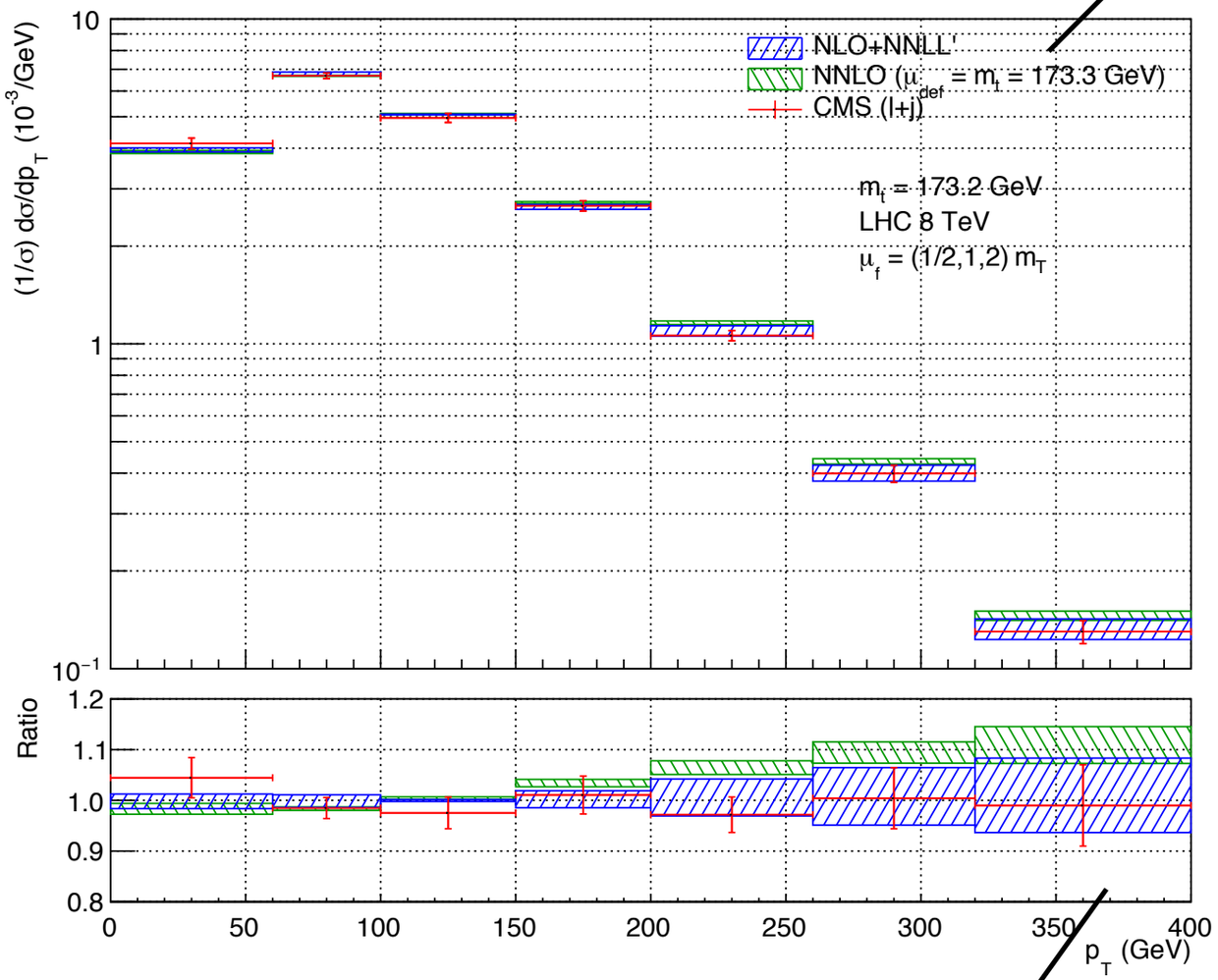
- ✱ Coulomb gluon contributions in the first bin.

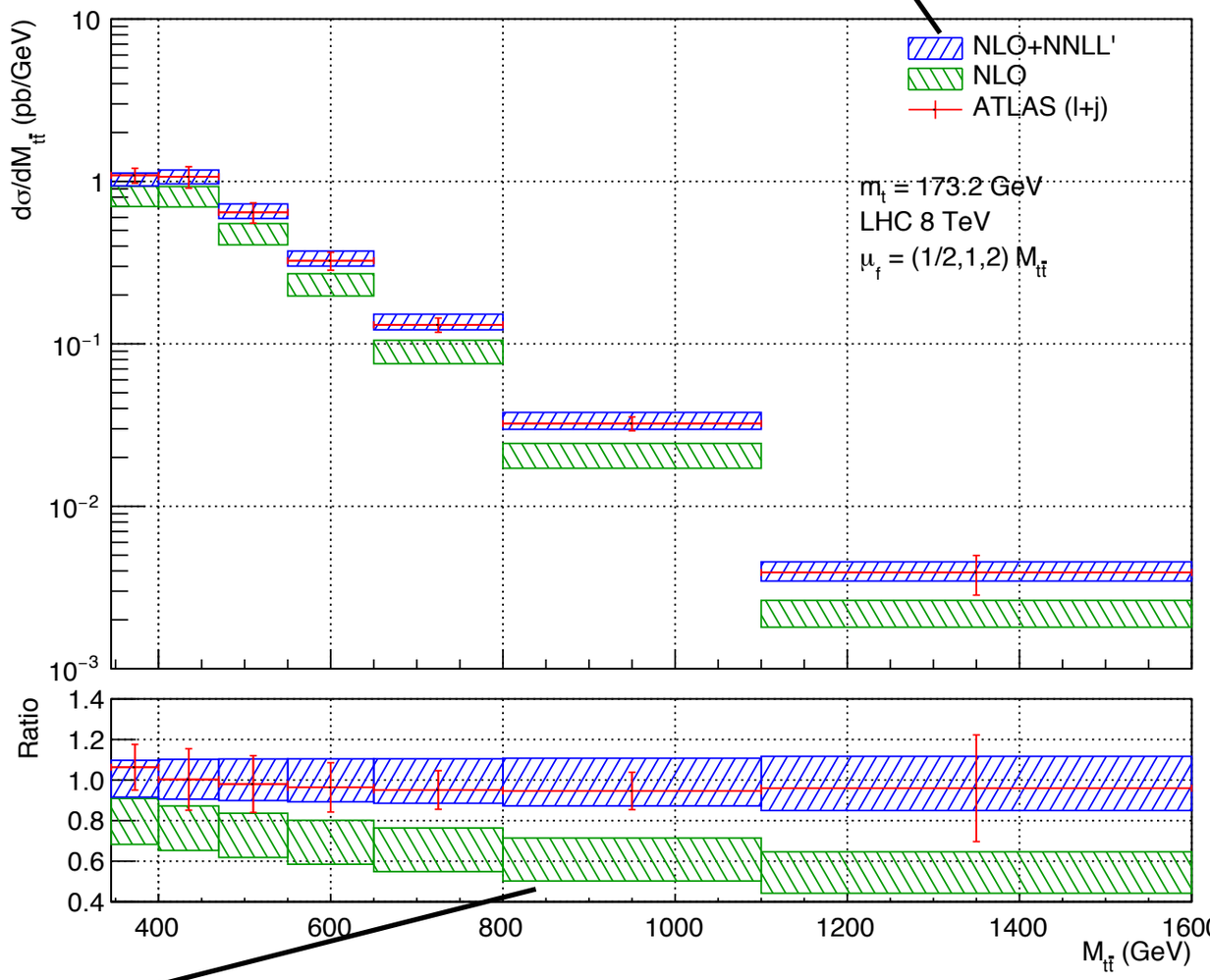
Backup

Resummation effects

Fixed scale for NNLO

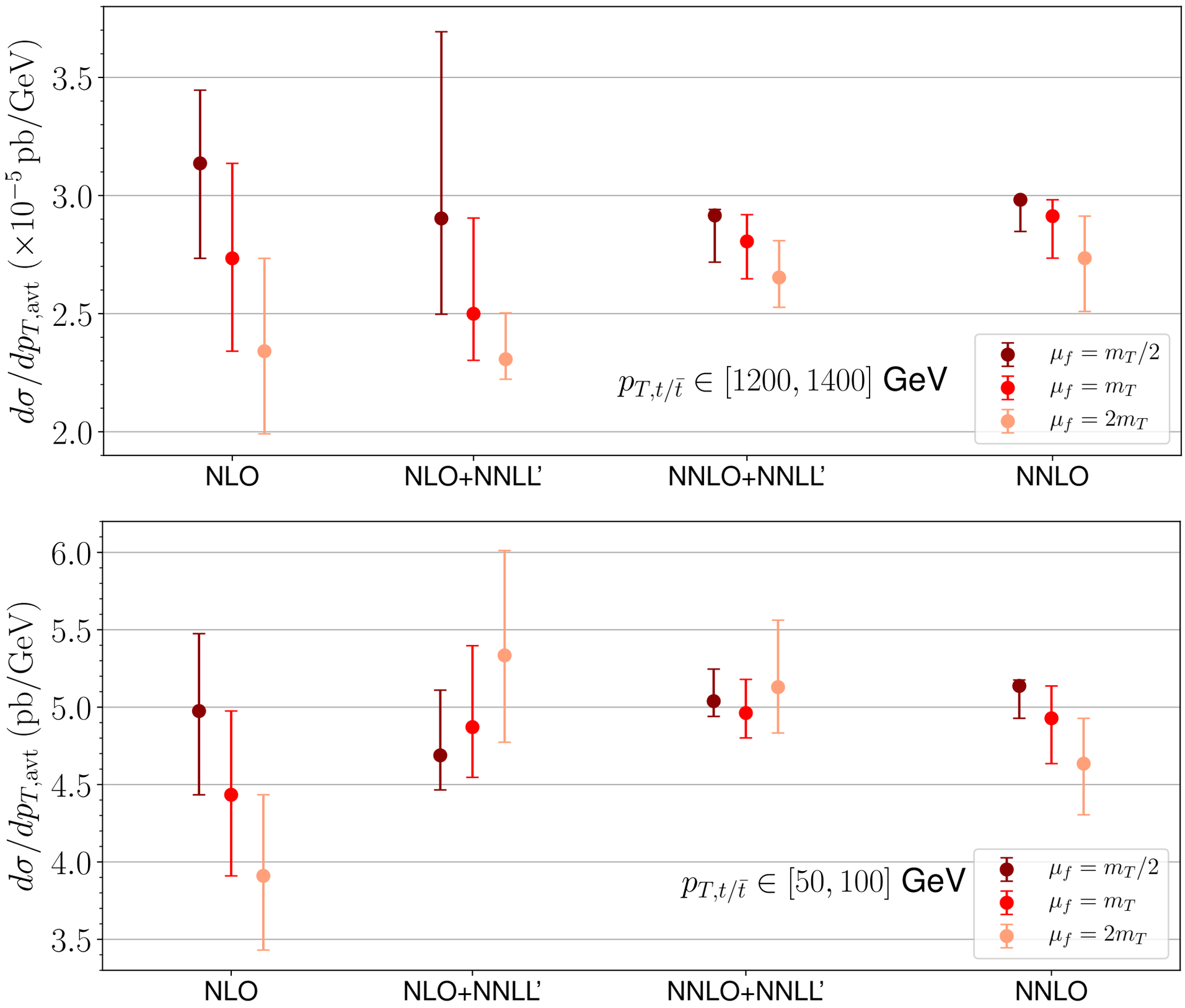
NLO+NNLL'





Resummation change the shape very apparently.

Pecjak, Scott, Wang, Yang, 1601.07020


$d\sigma/dp_{T,\mathrm{avt}}$ ($\times 10^{-5}$ pb/GeV)
3.5
3.0
2.5
2.0
$p_{T,t/\bar{t}} \in [1200, 1400]$ GeV
$\mu_f = m_T/2$
$\mu_f = m_T$
$\mu_f = 2m_T$
NLO
NLO+NNLL'
NNLO+NNLL'
NNLO
$d\sigma/dp_{T,\mathrm{avt}}$ (pb/GeV)
6.0
5.5
5.0
4.5
4.0
3.5
$p_{T,t/\bar{t}} \in [50, 100]$ GeV
$\mu_f = m_T/2$
$\mu_f = m_T$
$\mu_f = 2m_T$
NLO
NLO+NNLL'
NNLO+NNLL'
NNLO