

Scales for differential top-quark pair production through NNLO

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Based on: Czakon, Heymes, Mitov 1606.03350

Study of dynamic scales

- Stable top quark pair production at the LHC
 - Considering stable tops allows us to pinpoint the production dynamics
 - Decay will be discussed later (talk by M. Worek)
- Dynamic scales needed. How to choose them?
- Various things used in the past; typically $E_T=(m_t^2+p_T^2)^{1/2}$ is involved.
- It is unclear what even constitutes “best” scale choice.
- Some obvious constraints:
 - For $P_T=0$ scale has to be $\sim m_t$
 - For large P_T should be $\sim P_T$
- The coefficients of these leading powers should be fixed somehow.
- We have done quite some experimentation, looking for the following criteria:
 - Get maximally fast convergence from NLO to NNLO (also from LO to NLO)
 - The low P_T part is constrained by the total x-section
- There is no experimental handle at large P_T .

The Logic of the study

1. We consider the variation of factorisation and renormalisation scales as a proxy for missing higher order terms. The scale variation procedure we use is not *ad hoc*; its applicability to the total inclusive cross-section has been validated.
2. As a prerequisite to scale variation, one needs to specify a default central scale μ_0 . The main goal of this paper is to identify the functional form of μ_0 . We choose such a scale based on the criterium of *perturbative convergence*. In doing so we account for LO, NLO and NNLO corrections as well as, where available, NNLO plus soft-gluon resummation.
3. We assume that the sought default scale μ_0 is the same for both the renormalisation and factorisation scales, i.e. $\mu_{R,0} = \mu_{F,0} = \mu_0$. Scale variation, however, is done independently for μ_F and μ_R [29]:

$$\mu_{F,R} \in (\mu_0/2, 2\mu_0) \quad \text{with} \quad 0.5 \leq \mu_R/\mu_F \leq 2 . \quad (1.1)$$

4. A dynamic scale is, *a priori*, better than a fixed scale. However, the spread among various dynamic scales can be comparable in size to scale variation and therefore a *sensible* choice among possible dynamic scales has to be made.

Perturbative convergence is an indicator of the reliability of perturbative predictions

How to identify the dynamic scale?

- By performing a number of fully differential calculations for top-pair production at the LHC based on the following set of functional forms:

$$\mu_0 \sim m_t ,$$

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} ,$$

$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} ,$$

$$\mu_0 \sim H'_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} ,$$

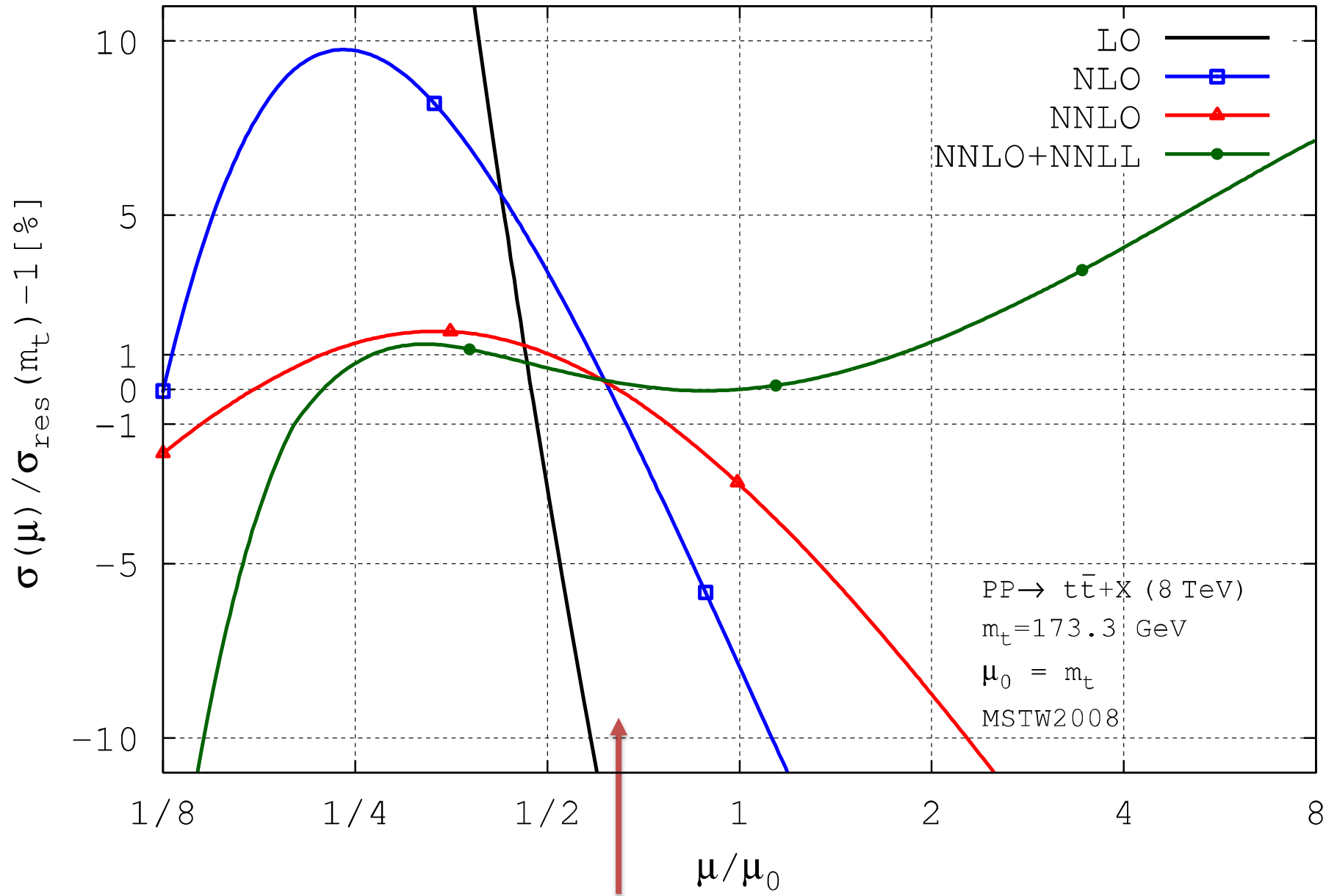
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2} \sqrt{m_t^2 + p_{T,\bar{t}}^2}} ,$$

$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} ,$$

$$\mu_0 \sim m_{t\bar{t}} ,$$

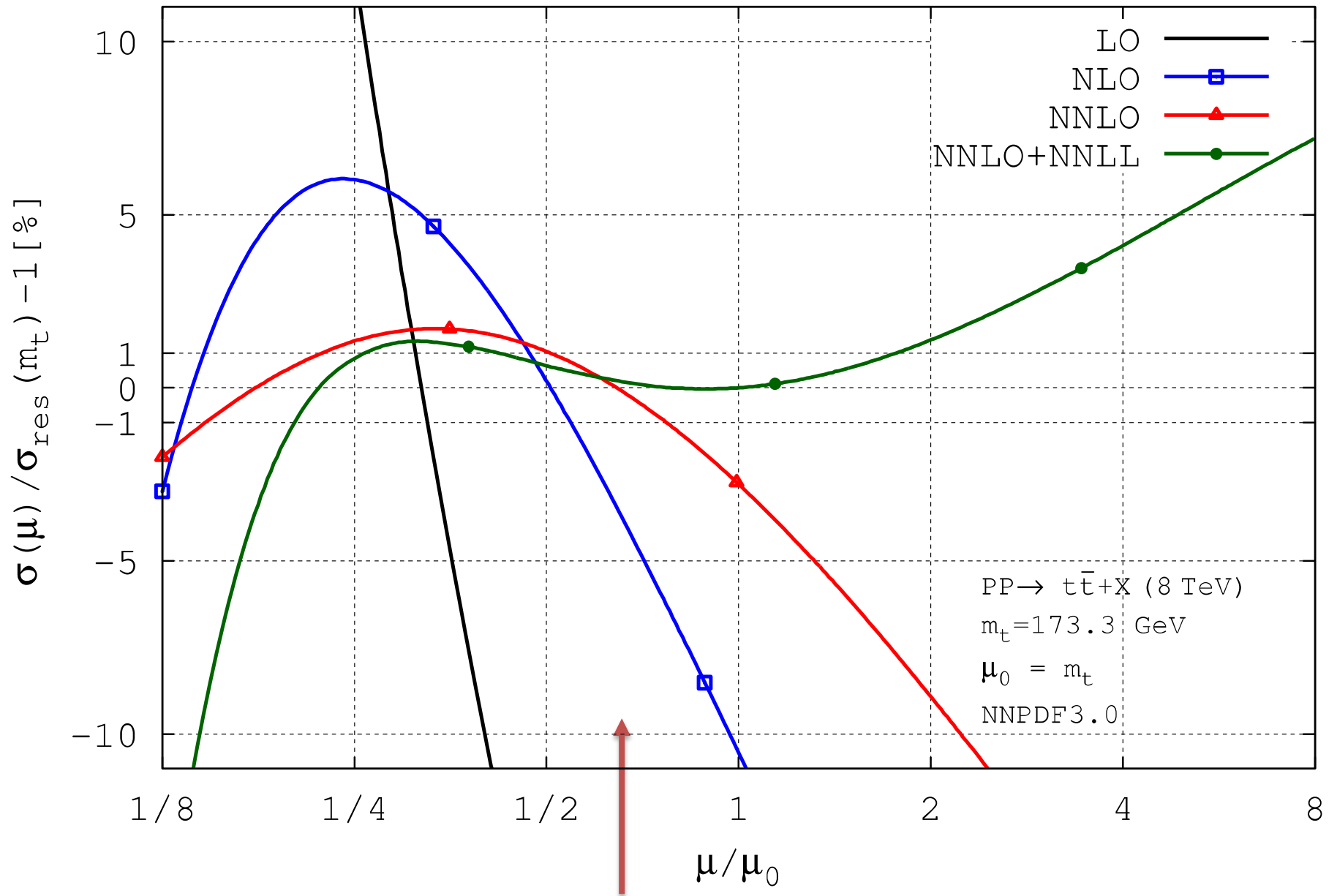
NOTE: the coefficients above are arbitrary and should be fixed together with the functional form!

Total cross-section



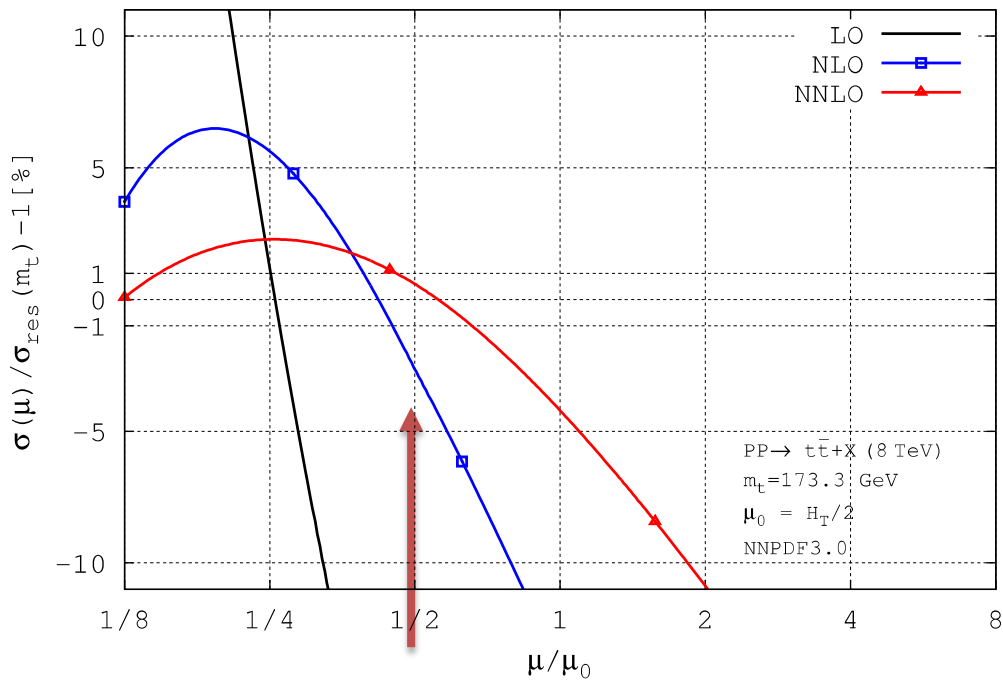
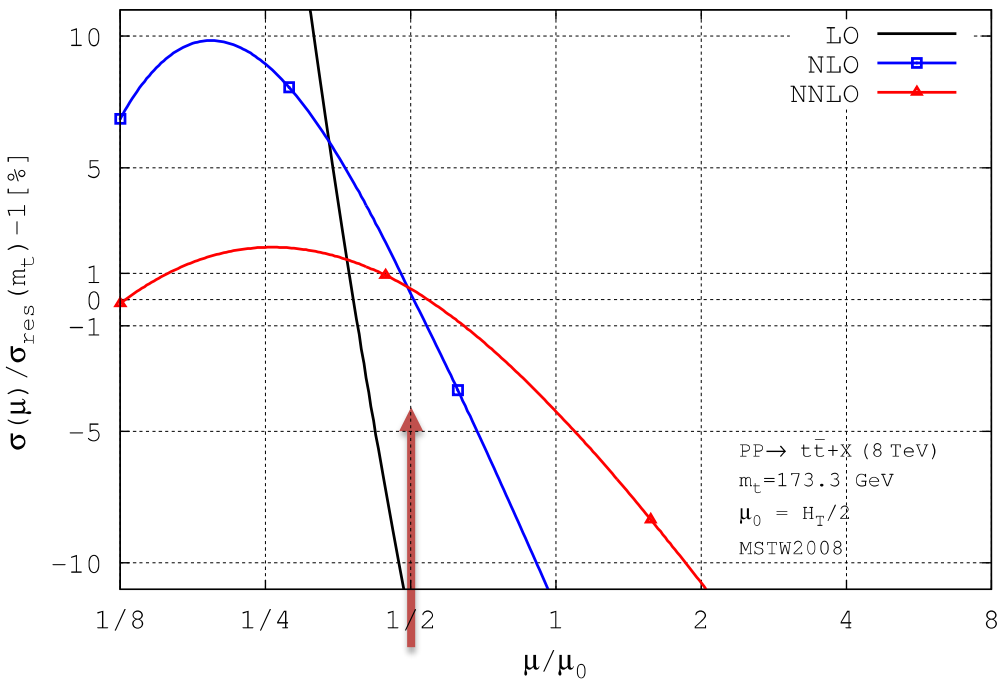
Smaller scale is preferred

Total cross-section



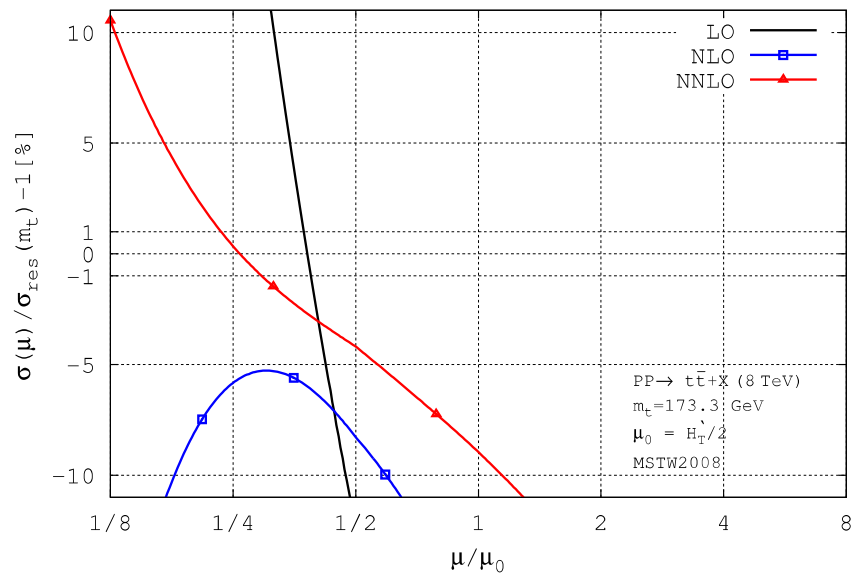
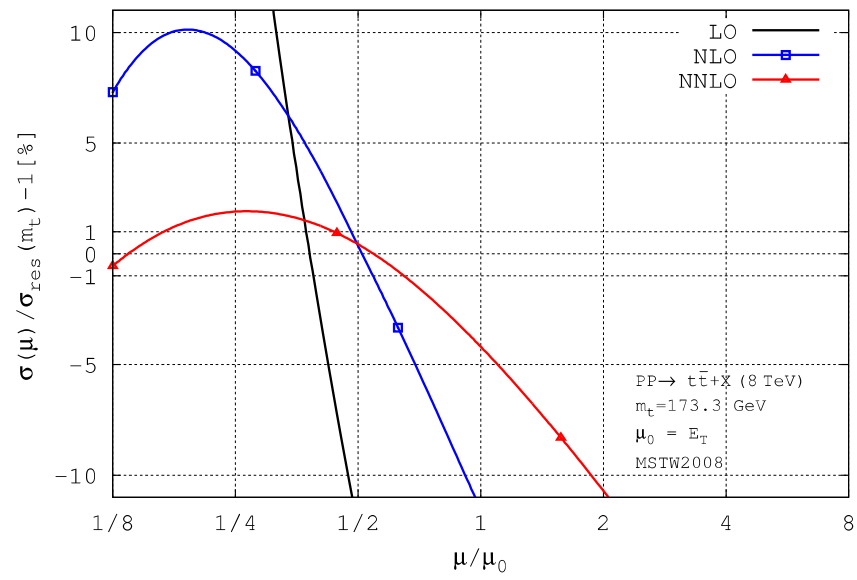
Smaller scale is preferred

• Total cross-section with various dynamic scales and for different PDF's



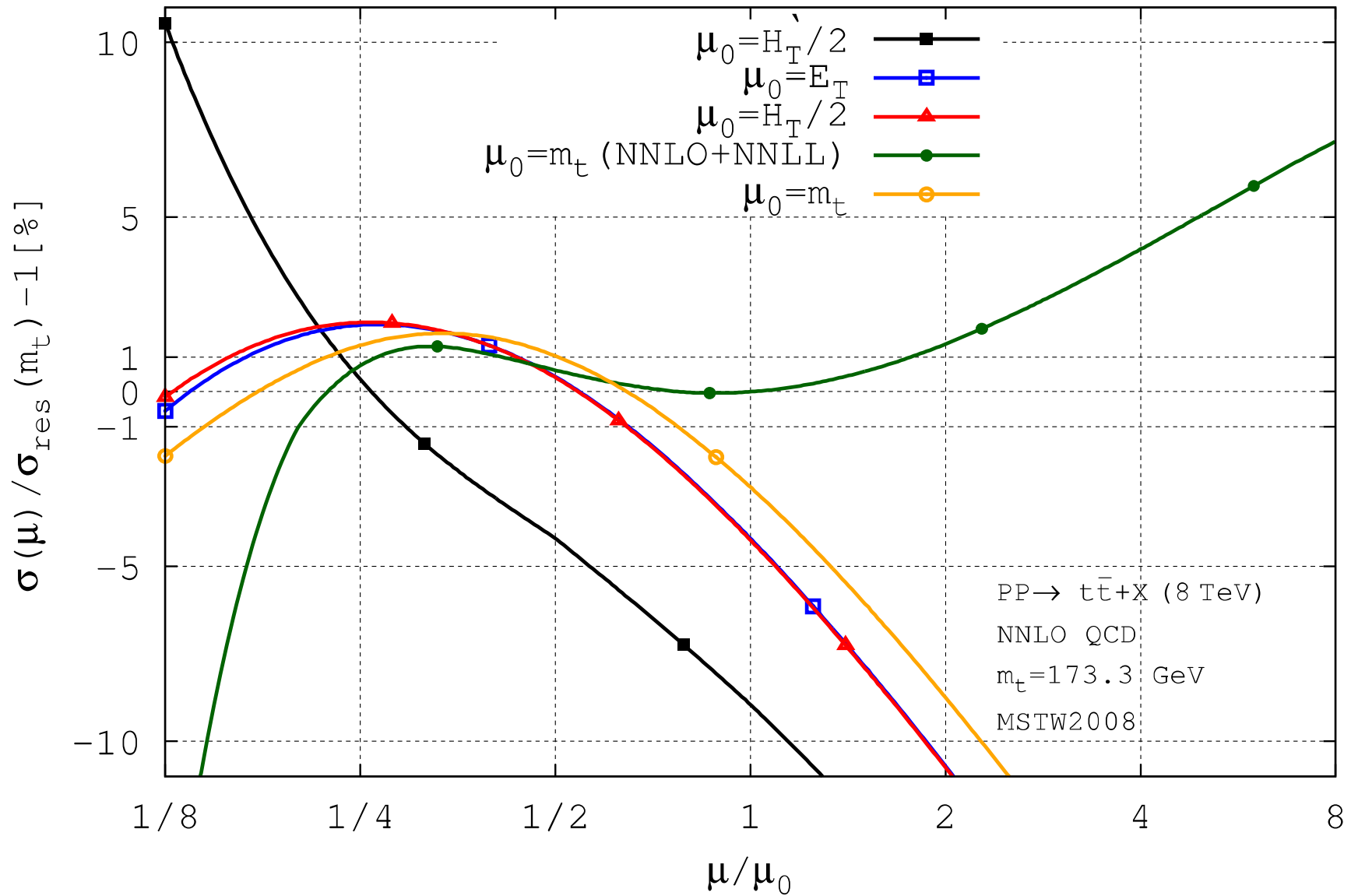
- The total x-section with dynamic scale == resummed x-section with fixed scale
 - Effect of resummation for 'best' scale is negligible (0.5% effect)

Two less-optimal scales:



Total cross-section

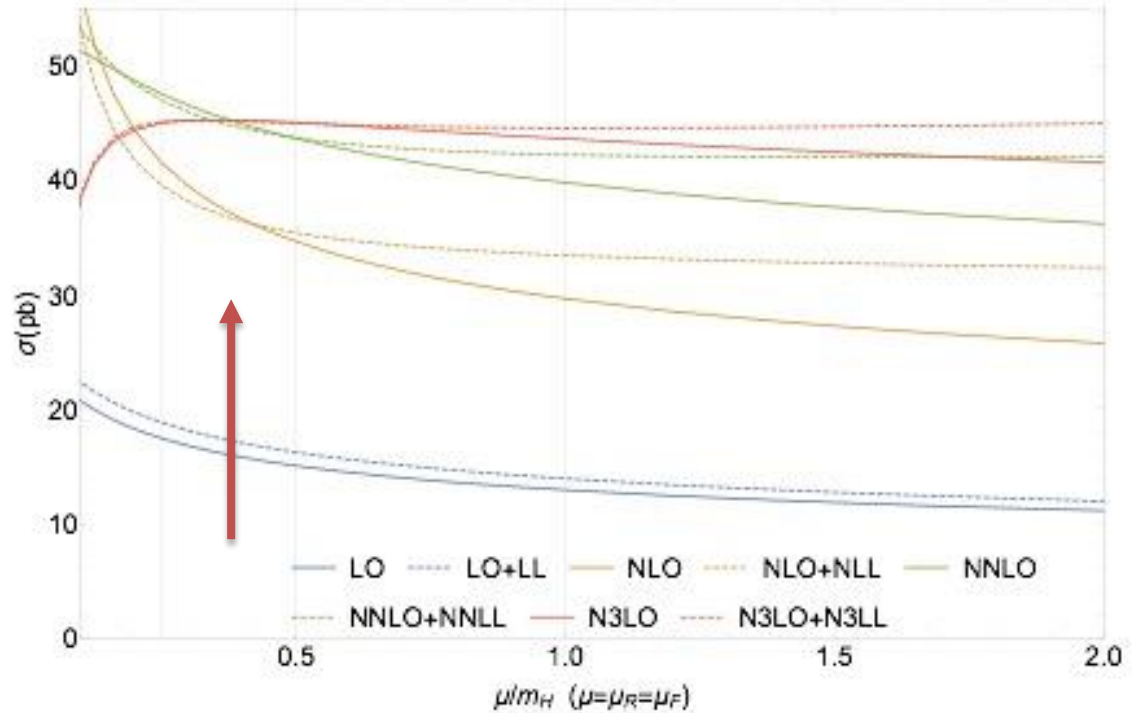
- Total cross-section with various dynamic scales and for different PDF's



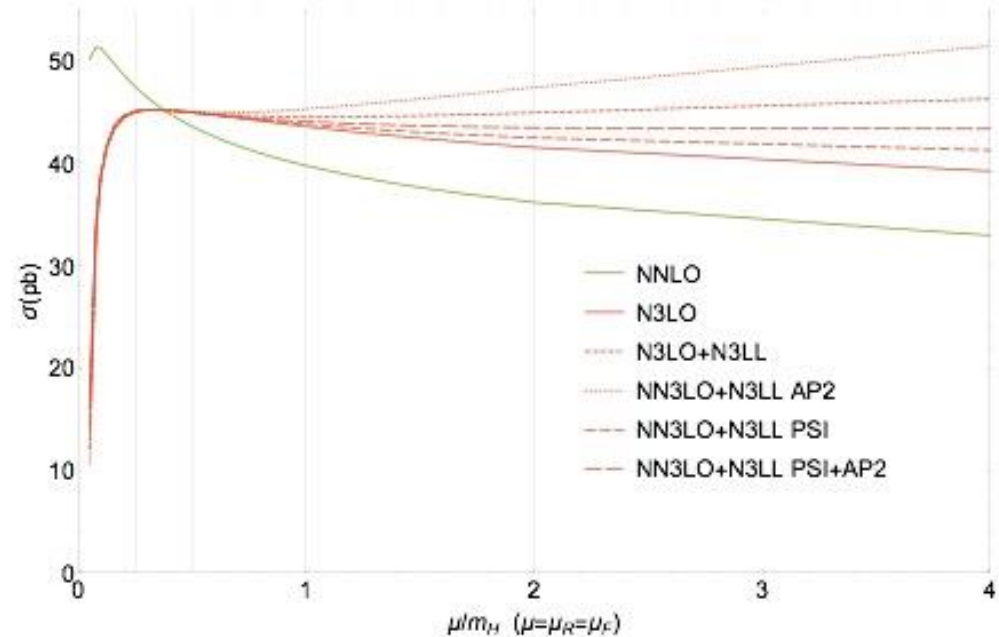
- Comparison of various scales at NNLO and NNLO+NNLL

Total cross-section

- The total x-section at N^2O behaves very similarly to the Higgs x-section at N^3LO



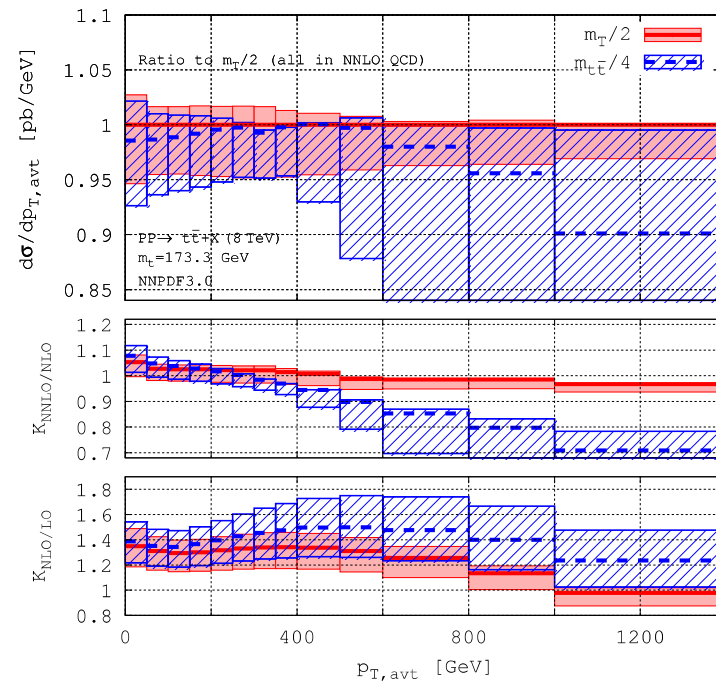
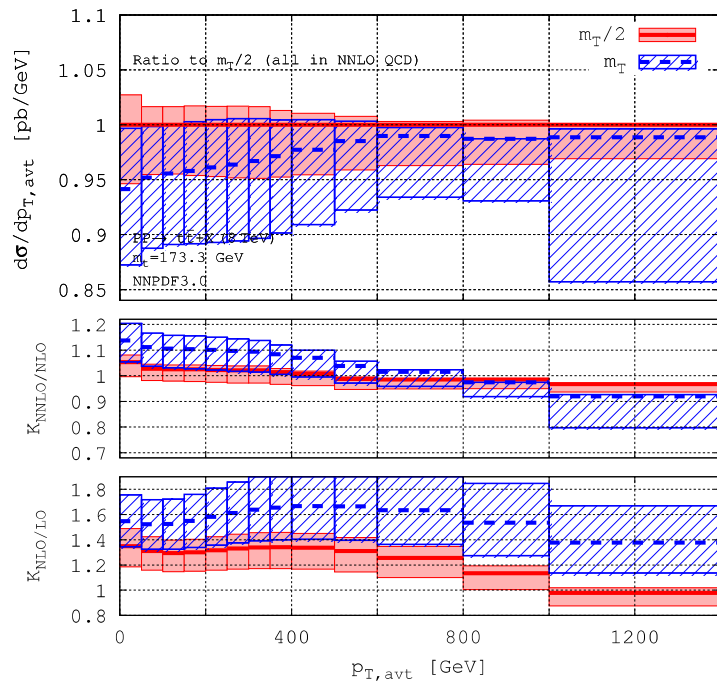
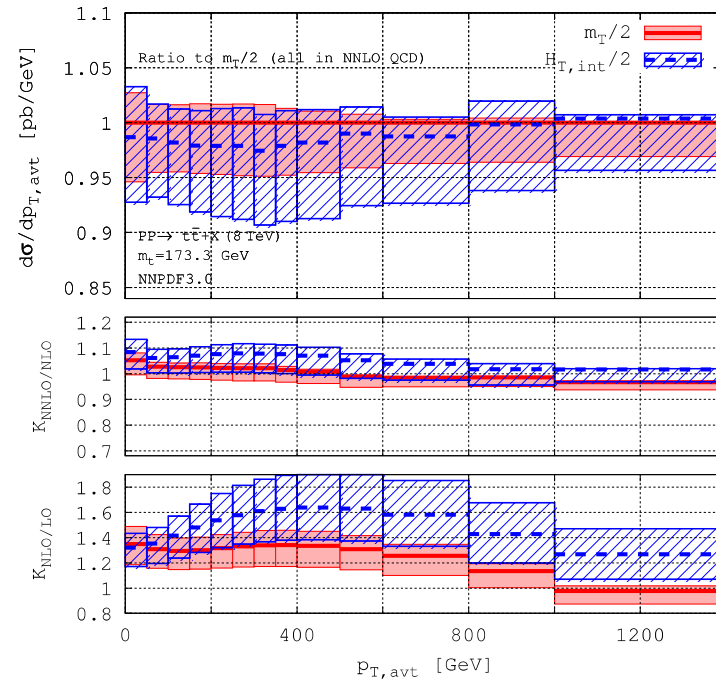
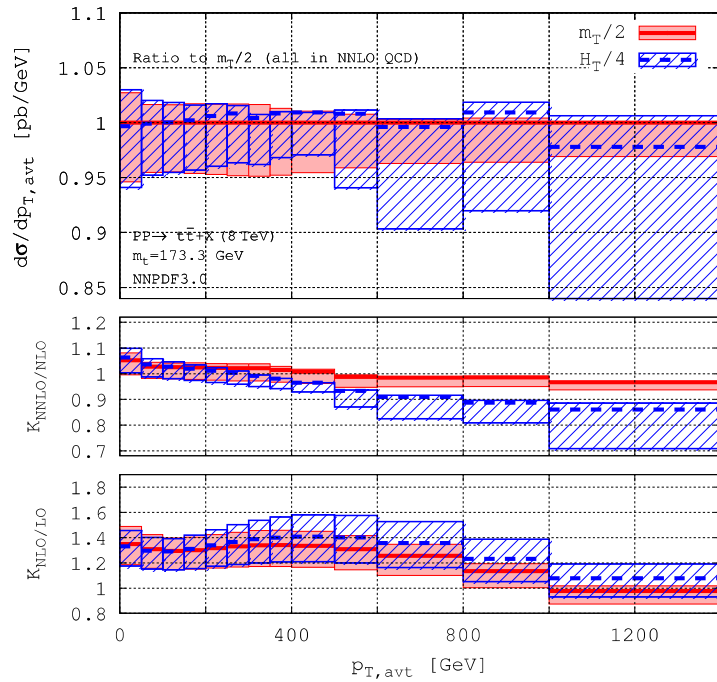
- Preference towards smaller scales



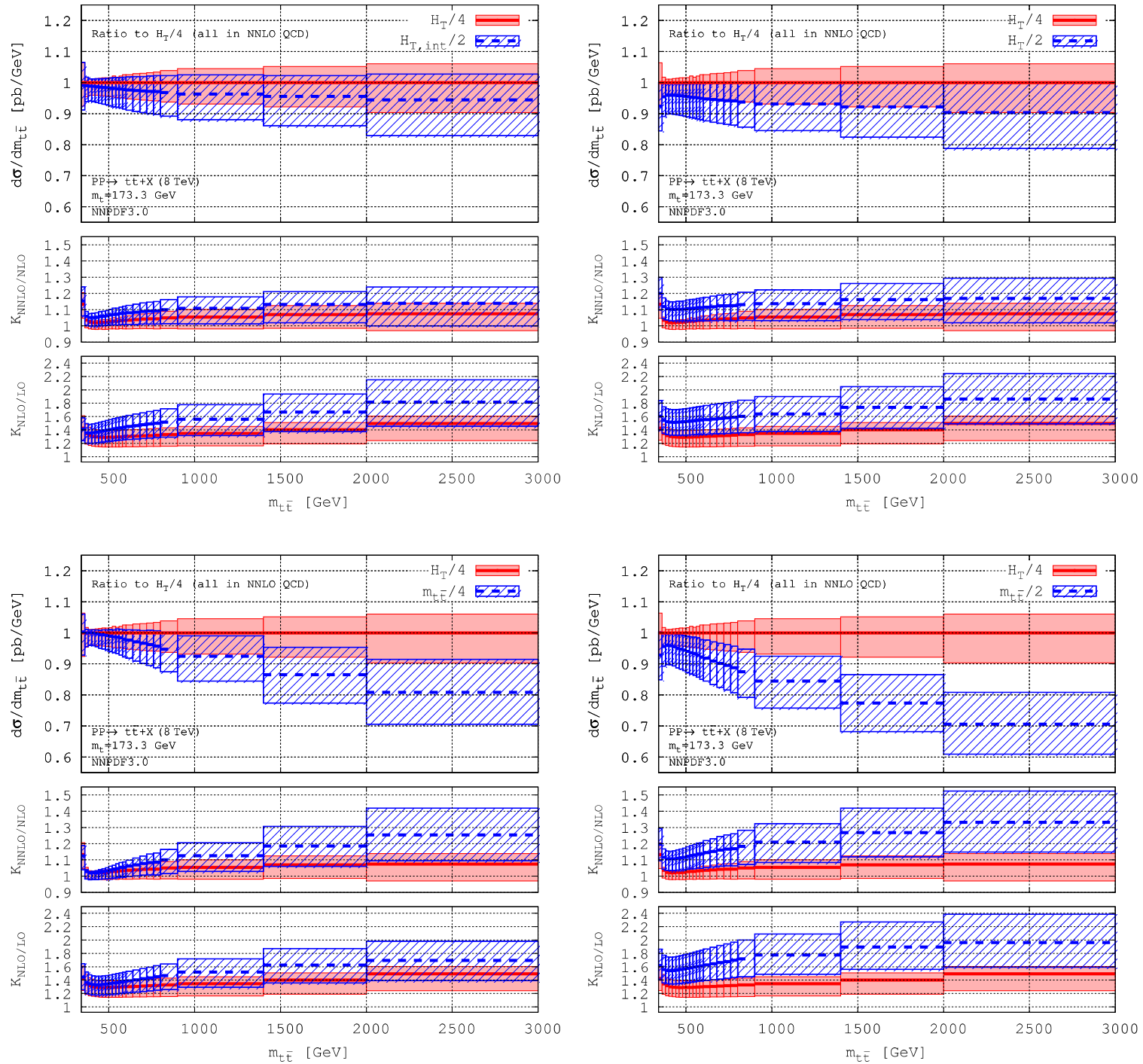
- Resummed result grows at large scales

Anastasiou et al arXiv:1602.00695v1

The P_T distribution



The M_{tt} distribution



Conclusions about “best” scales

- Differential cross-section with various fixed scale choices and for different PDF's
- Use the following dynamic scales:

$$\mu = H_T/4 \quad \text{for} \quad m_{t\bar{t}}, y_t, y_{\bar{t}}, y_{\text{avet}}, y_{t\bar{t}}, \dots$$

$$\mu = \frac{1}{2} m_T(t/\bar{t}) : \quad \text{for} \quad p_{T,t}, p_{T,\bar{t}}, p_{T,\text{avet}}$$

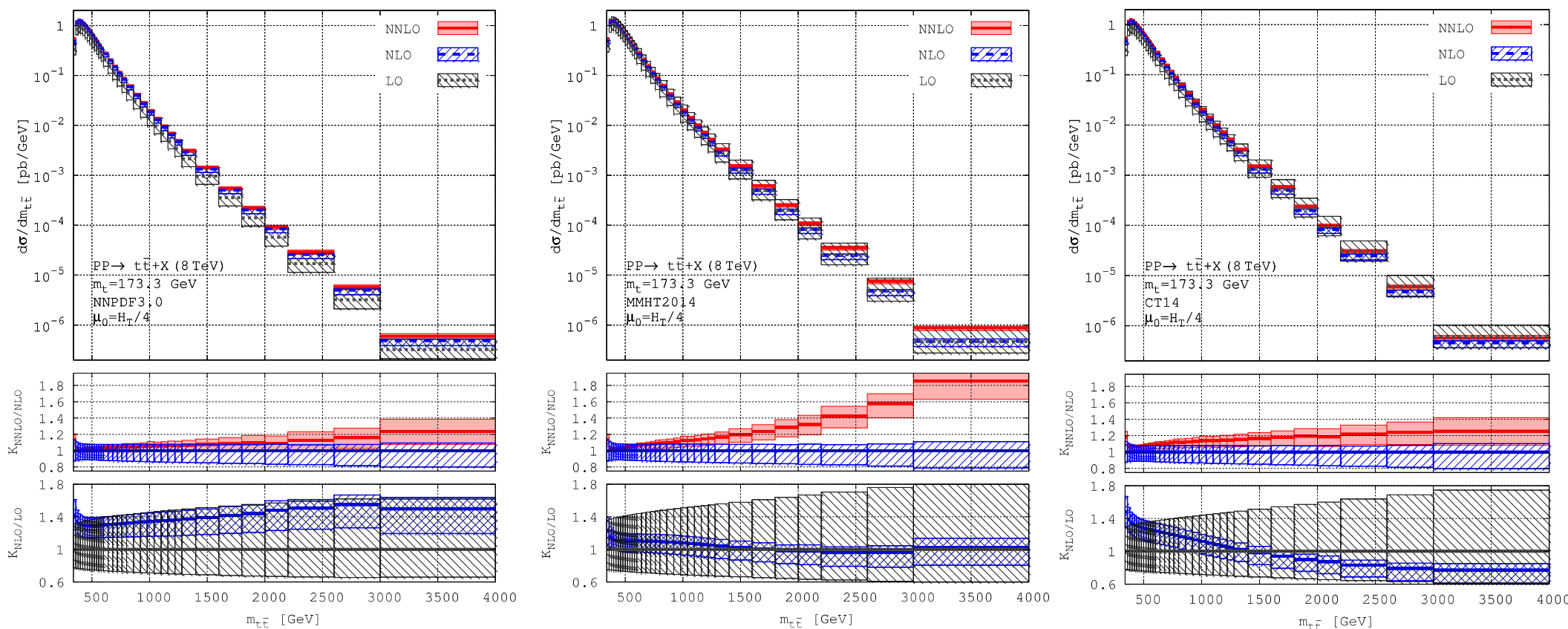
$$H_T = \sqrt{m_t^2 + p_{Tt}^2} + \sqrt{m_{\bar{t}}^2 + p_{T\bar{t}}^2}$$

Scales $\mu \propto m_{t\bar{t}}$ do not work well

- Tried also:
 - geometric average of the two tops m_T (similar results to H_T)
 - H'_T (sum over all final state partons): not as good
- Same conclusions for 8 TeV and 13 TeV

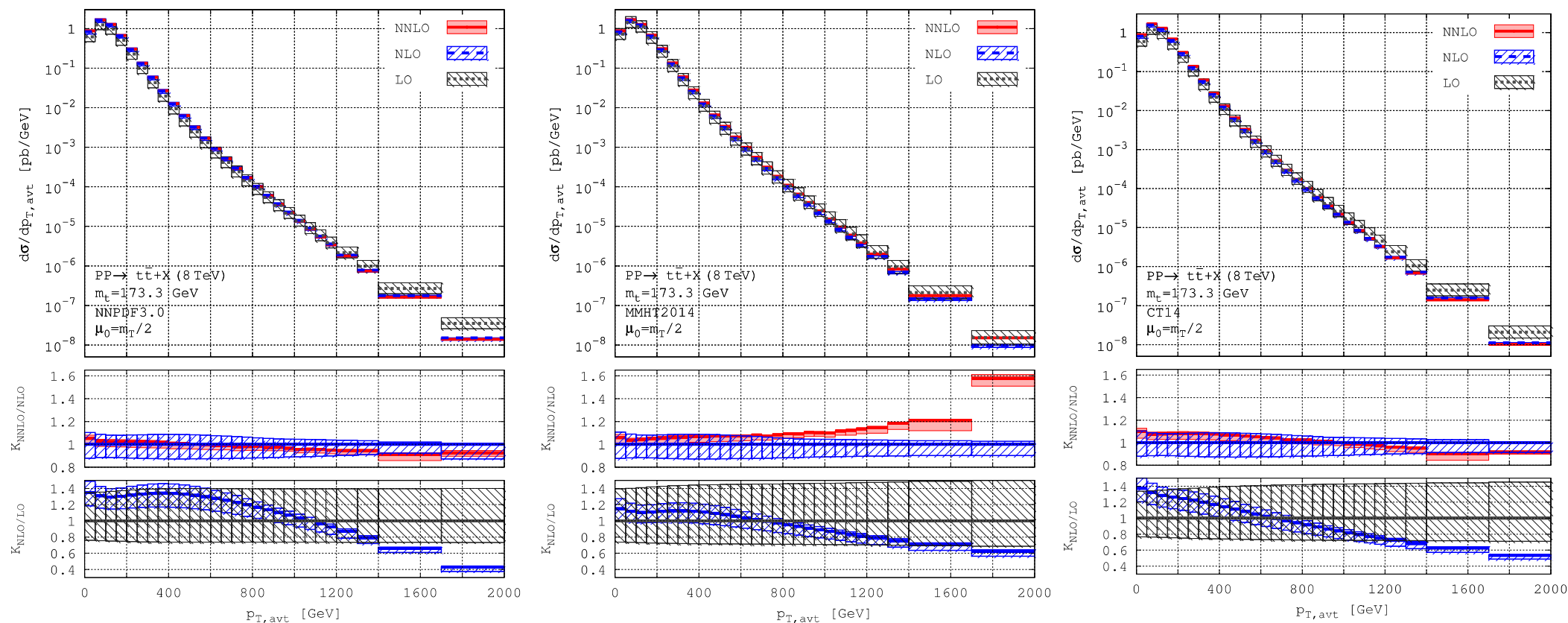
PDF dependence: the $M_{t\bar{t}}$ distribution

- Are the conclusions affected by PDF's?



- Differences above are genuinely due to PDF's.
- We checked it is not due to perturbative x-sections or scales

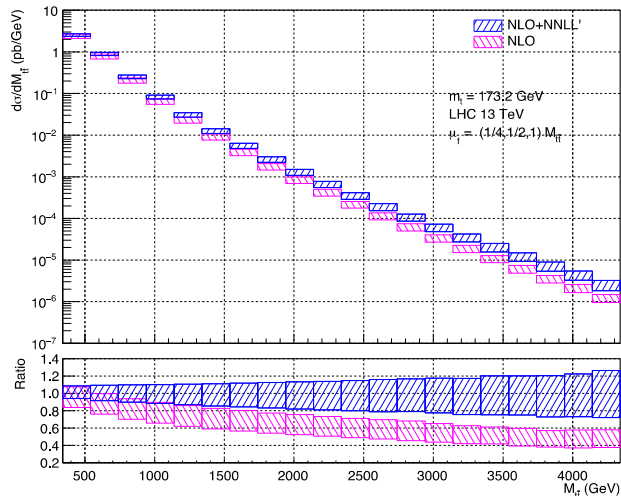
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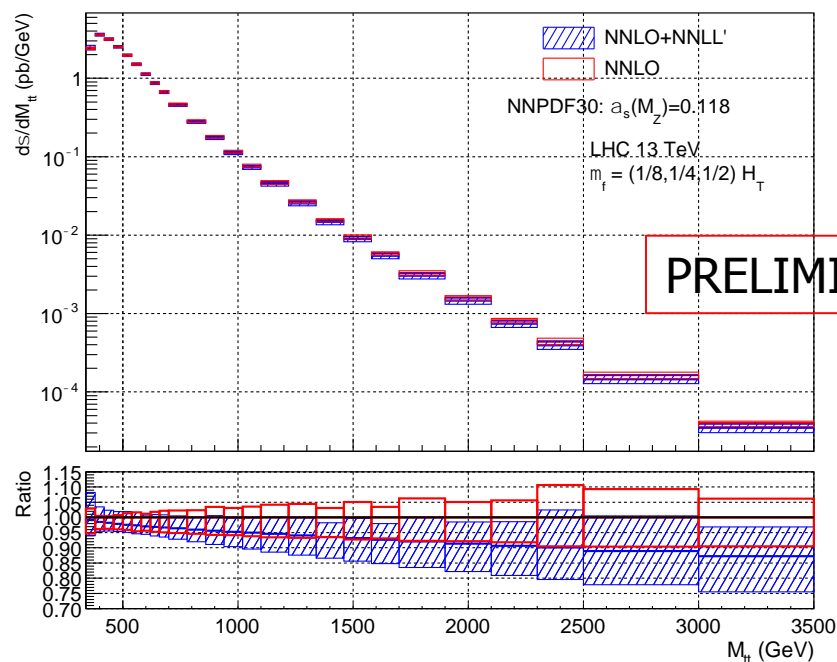
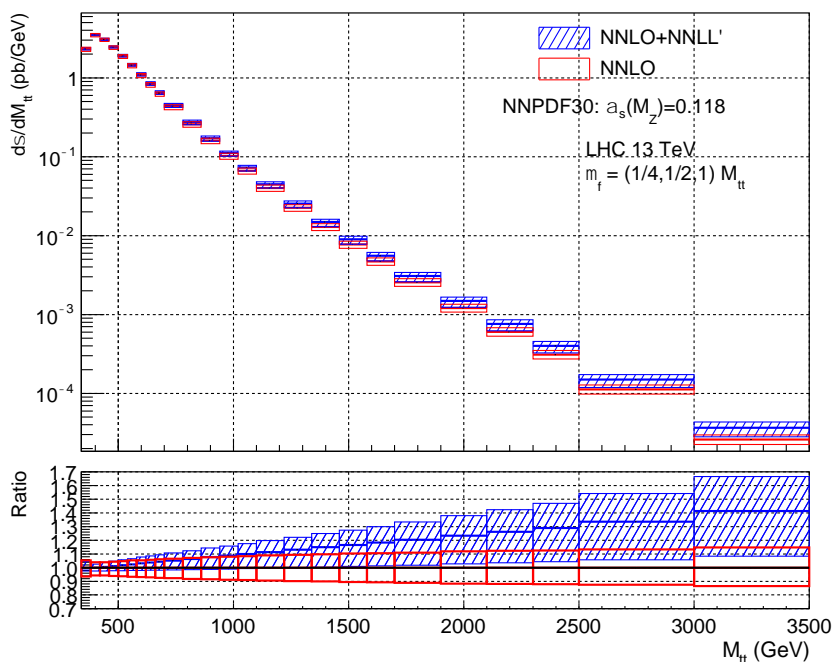
Adding soft-gluon resummation

- Recent result of NNLL resummation with sub-optimal scale $\sim M_{tt}$ shows large corrections



Pecjak, Scott, Wang, Yang 1601.07020v2

- Matching to NNLO and using optimal scale leads to small corrections

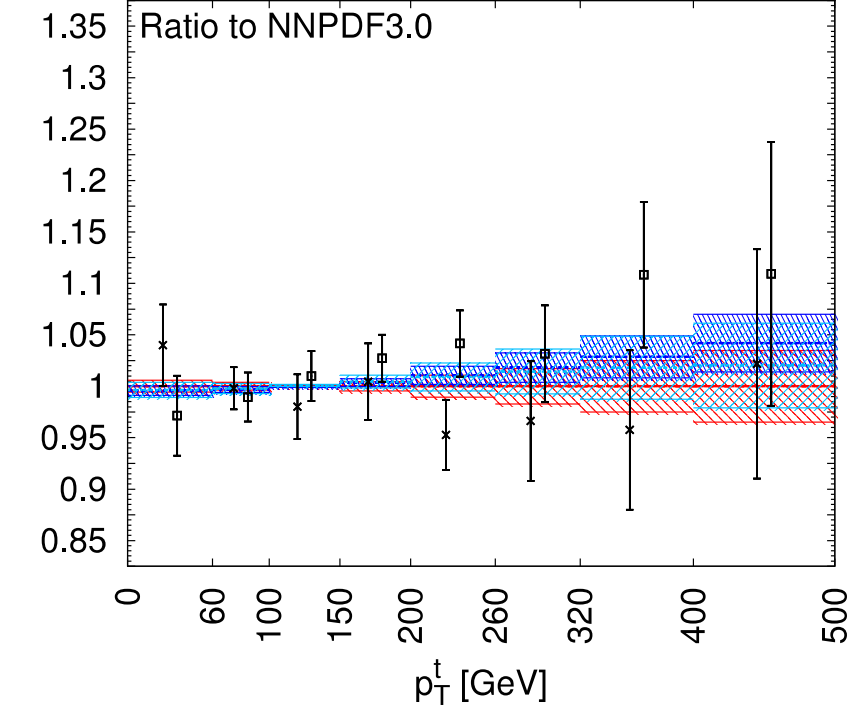
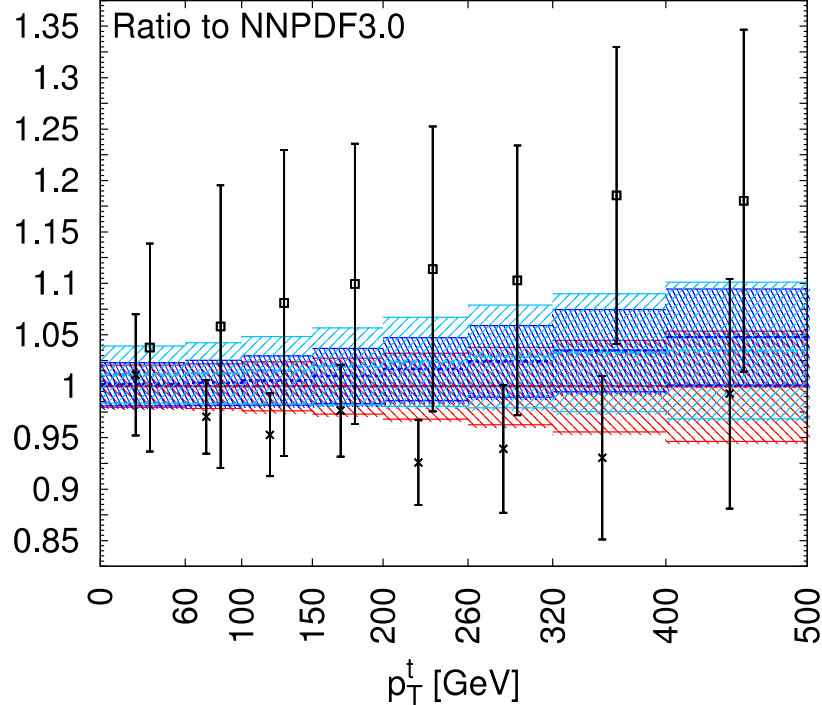
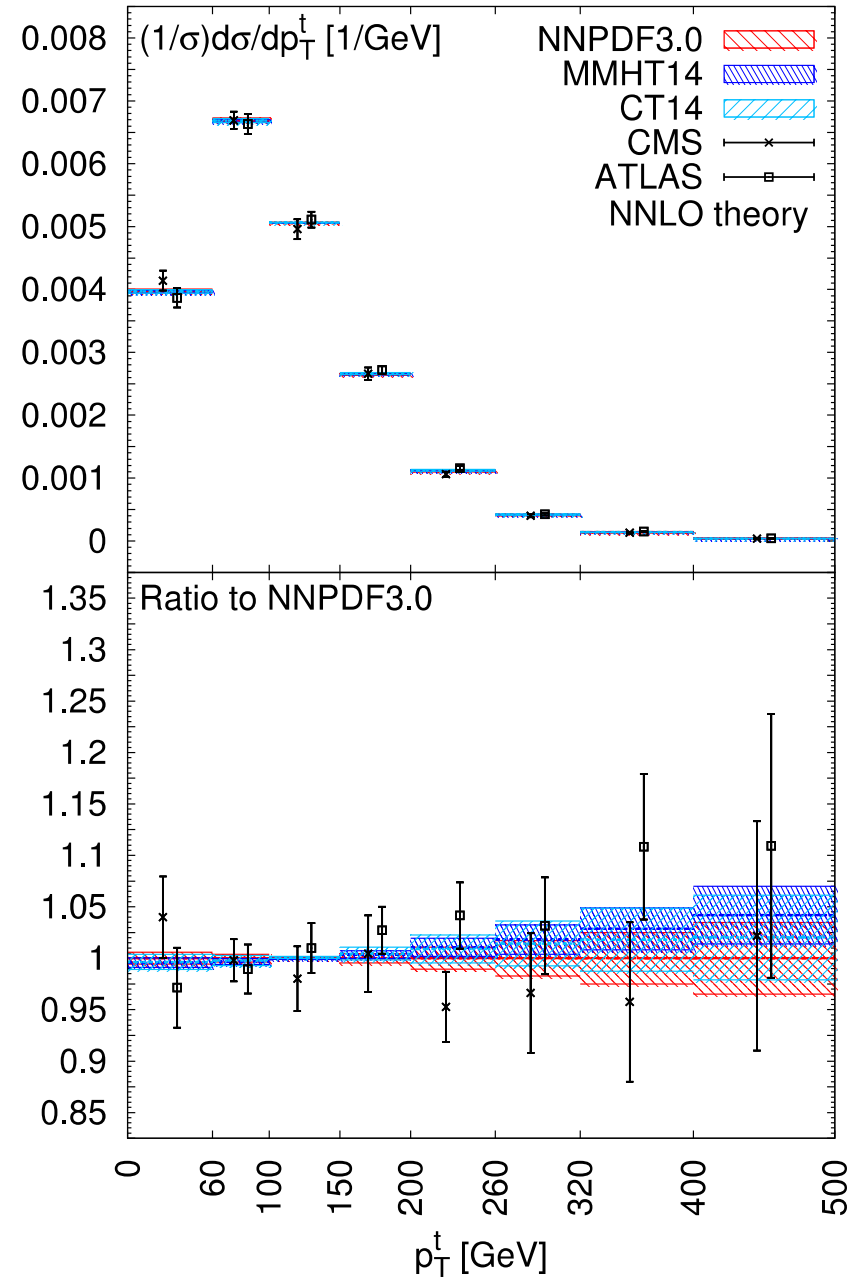
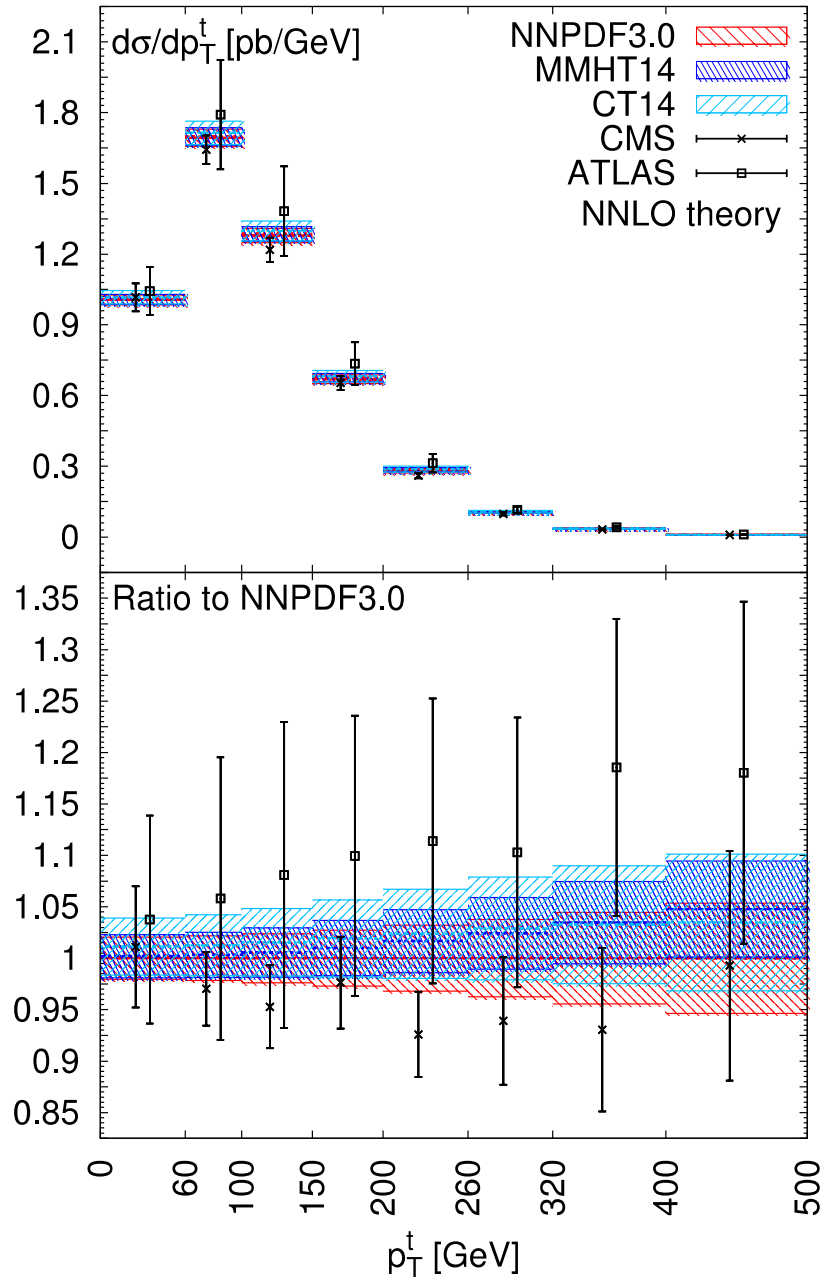


PRELIMINARY

Comparison with data

- The differences due to PDF set and data are now more important
- Seems the scales we use do a good job

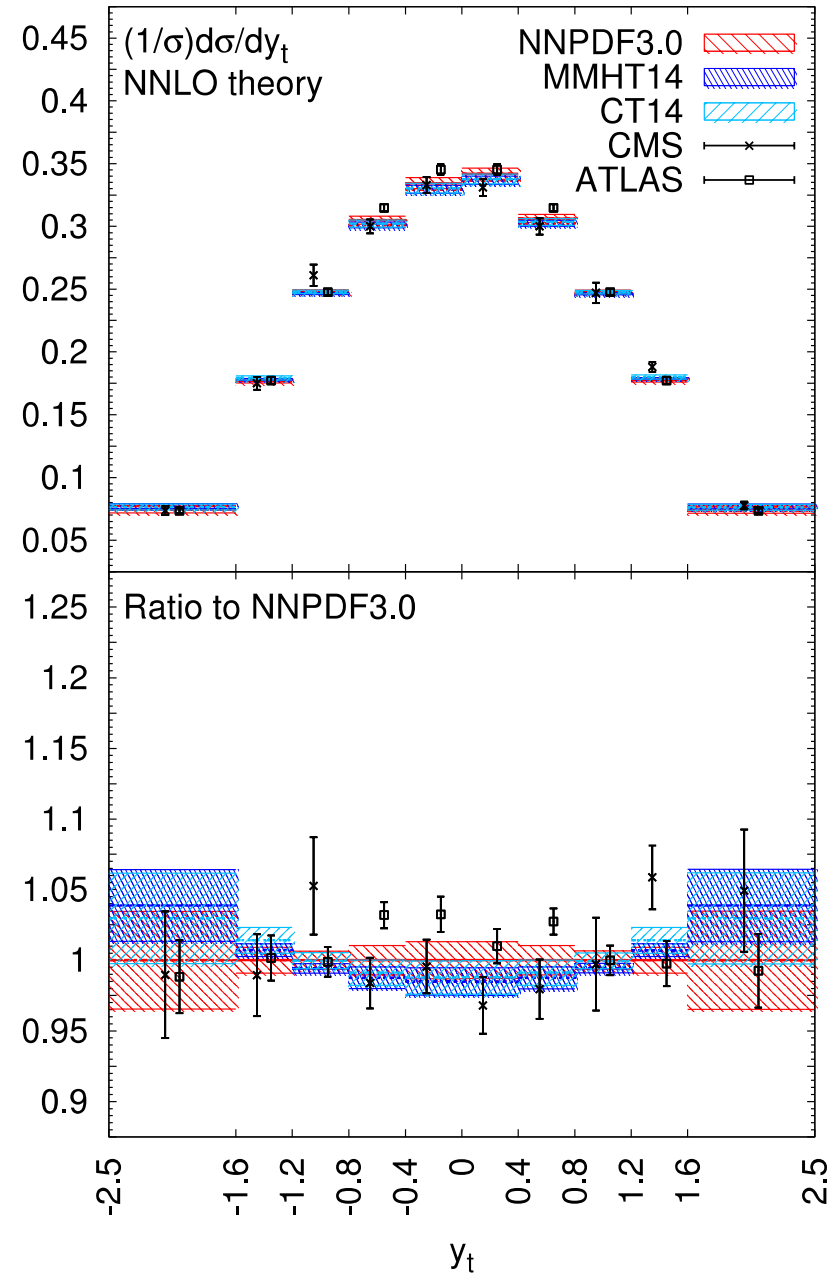
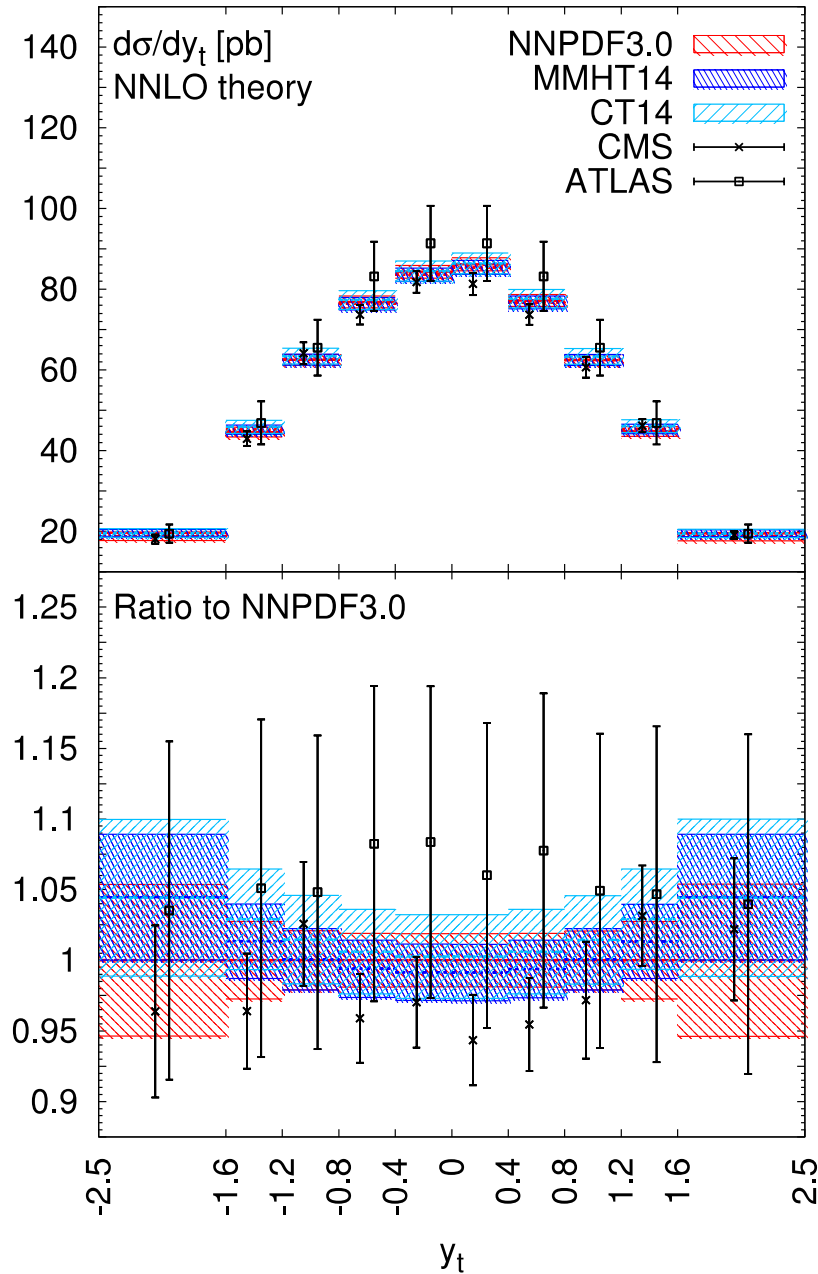
Czakon et al arXiv:1611.08609v2



Comparison with data

Czakon et al arXiv:1611.08609v2

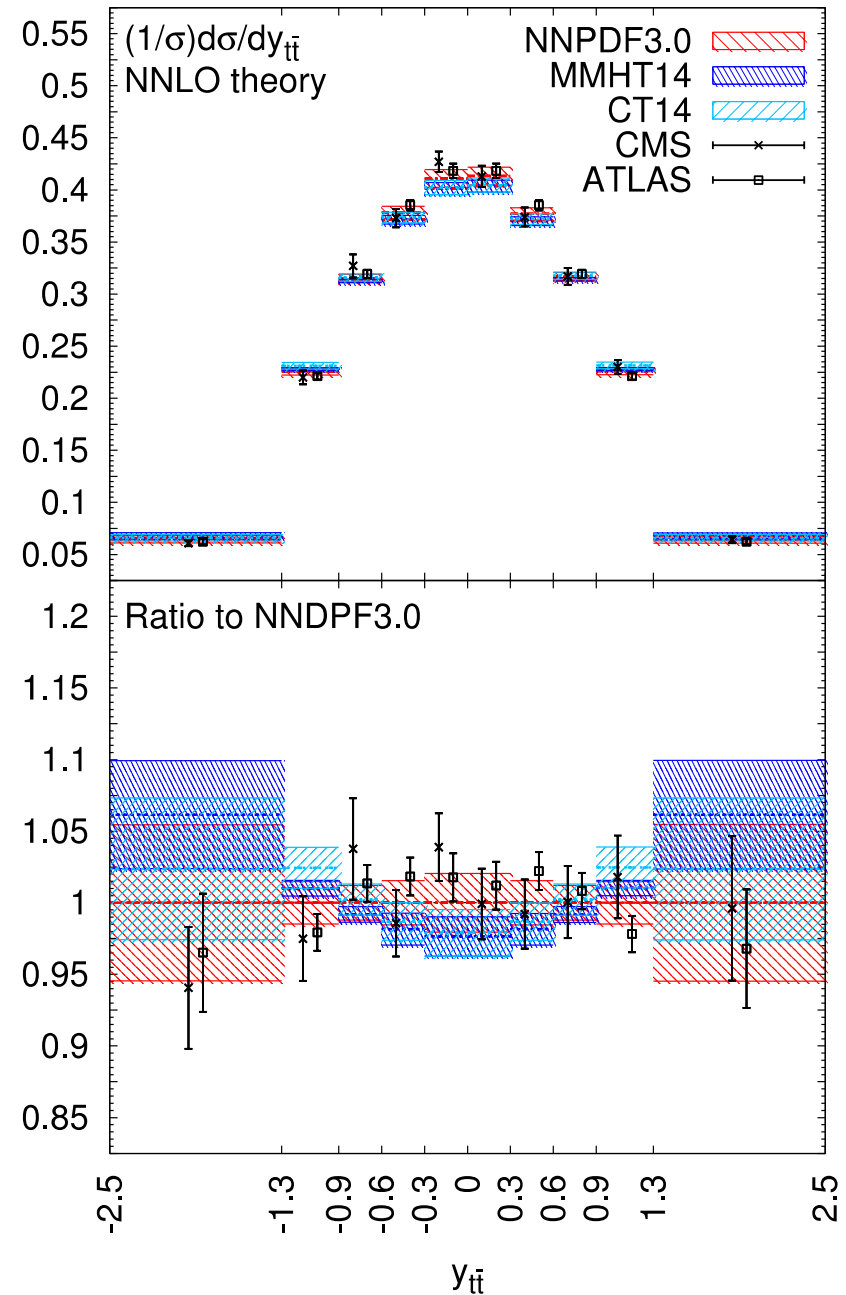
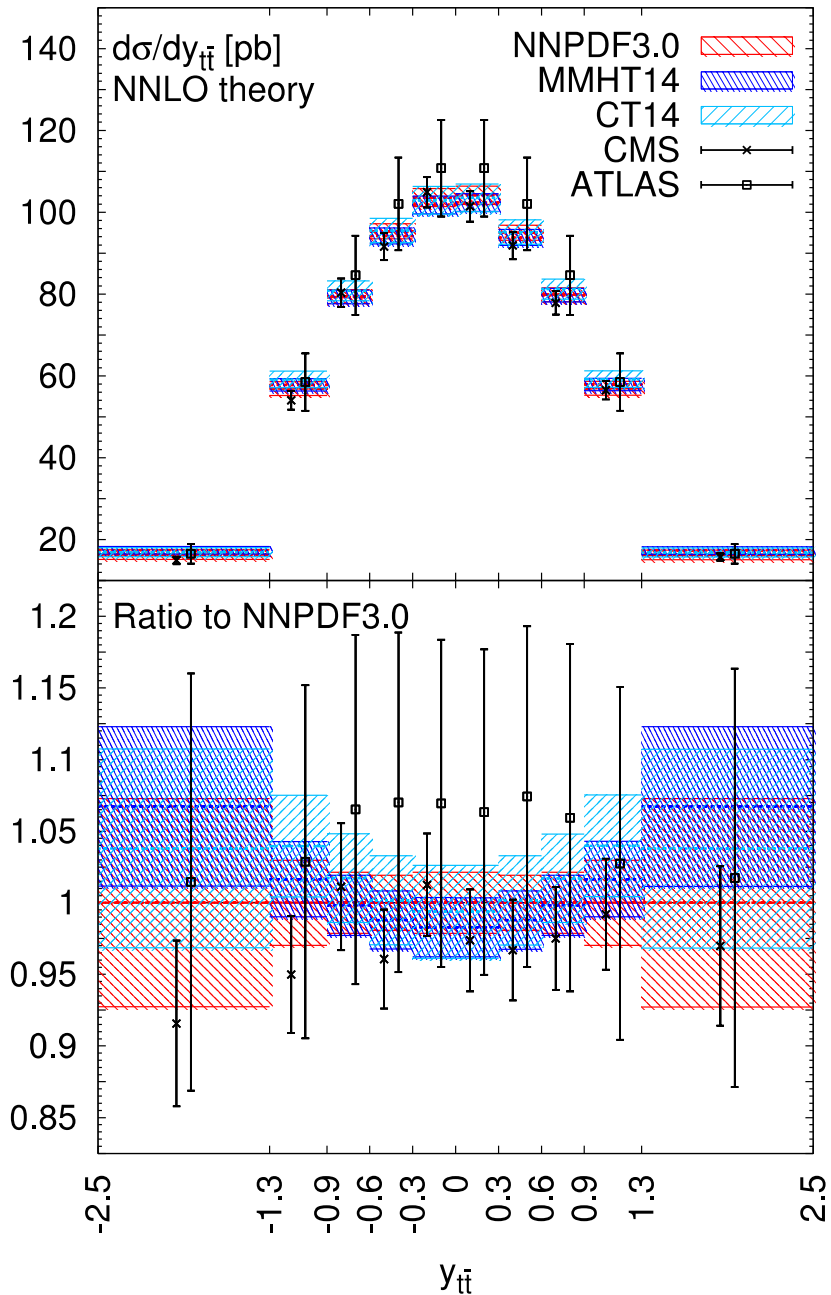
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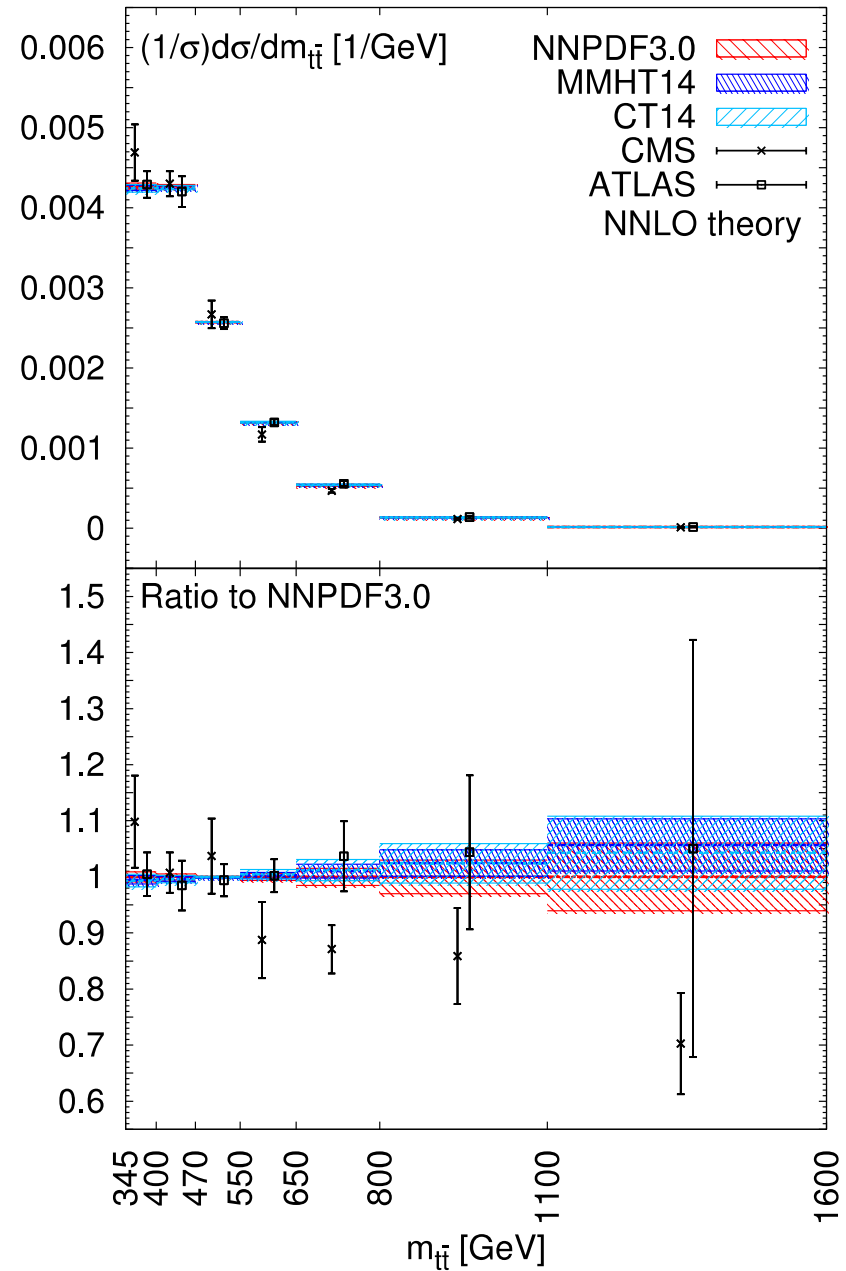
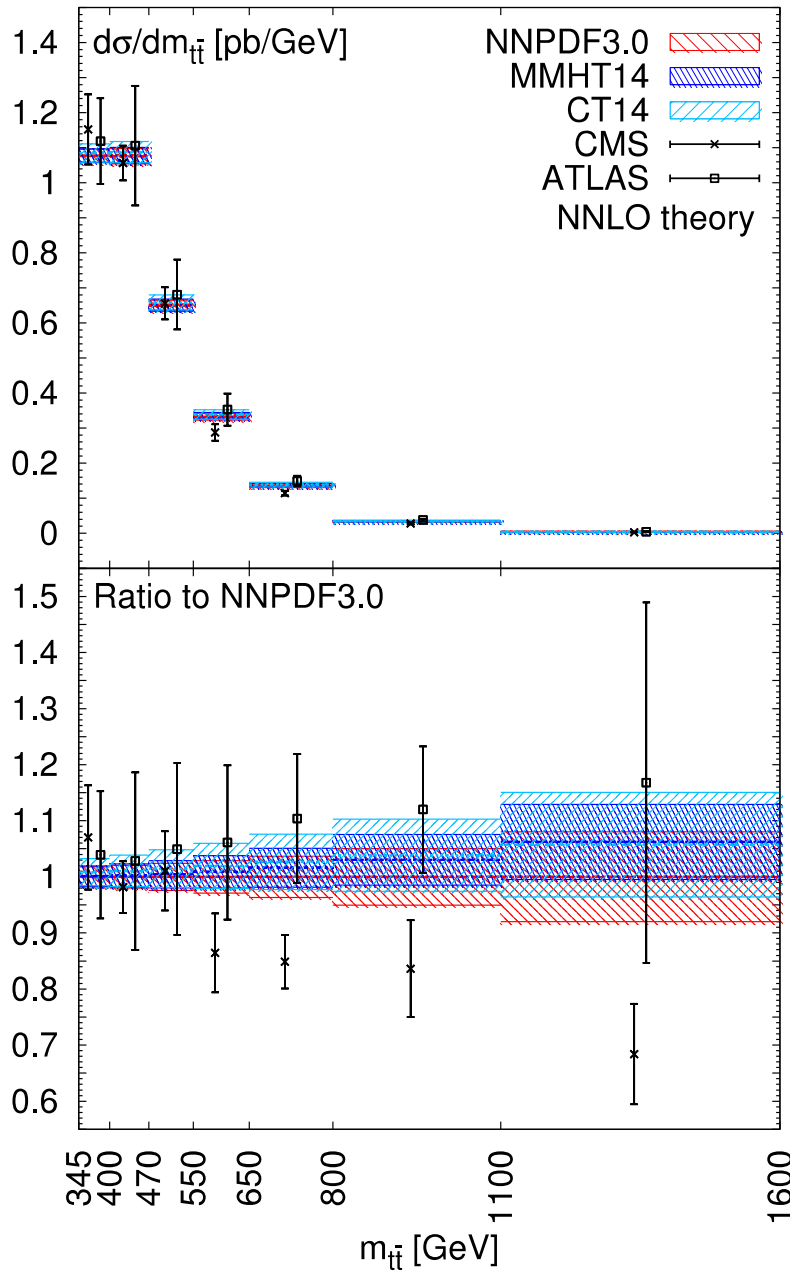
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Comparison with data

Czakon et al arXiv:1611.08609v2

- The differences due to PDF set and data are important
- Seems the scales we use do a good job



Conclusions

- We have investigated choices of dynamical scales for stable top pair production
- We find that:
 - m_T and H_T based scales work best
 - Coefficients are typically $1/2$ of what's been used in the past. This leads, among others, to agreement for the total x-section with soft-gluon resummation (as in Top++)
 - We find that scales that involve additional radiation – not part of the Born final state – do not work as well.
- Future developments: reconcile with other predictions – especially event generator based ones.
- Typical question we often get is: “Can you compute with the Powheg scales?”
 - Is this possible
 - Or a good idea?