Precision over the top

latest on precision in top production and lessons for the broader precision program

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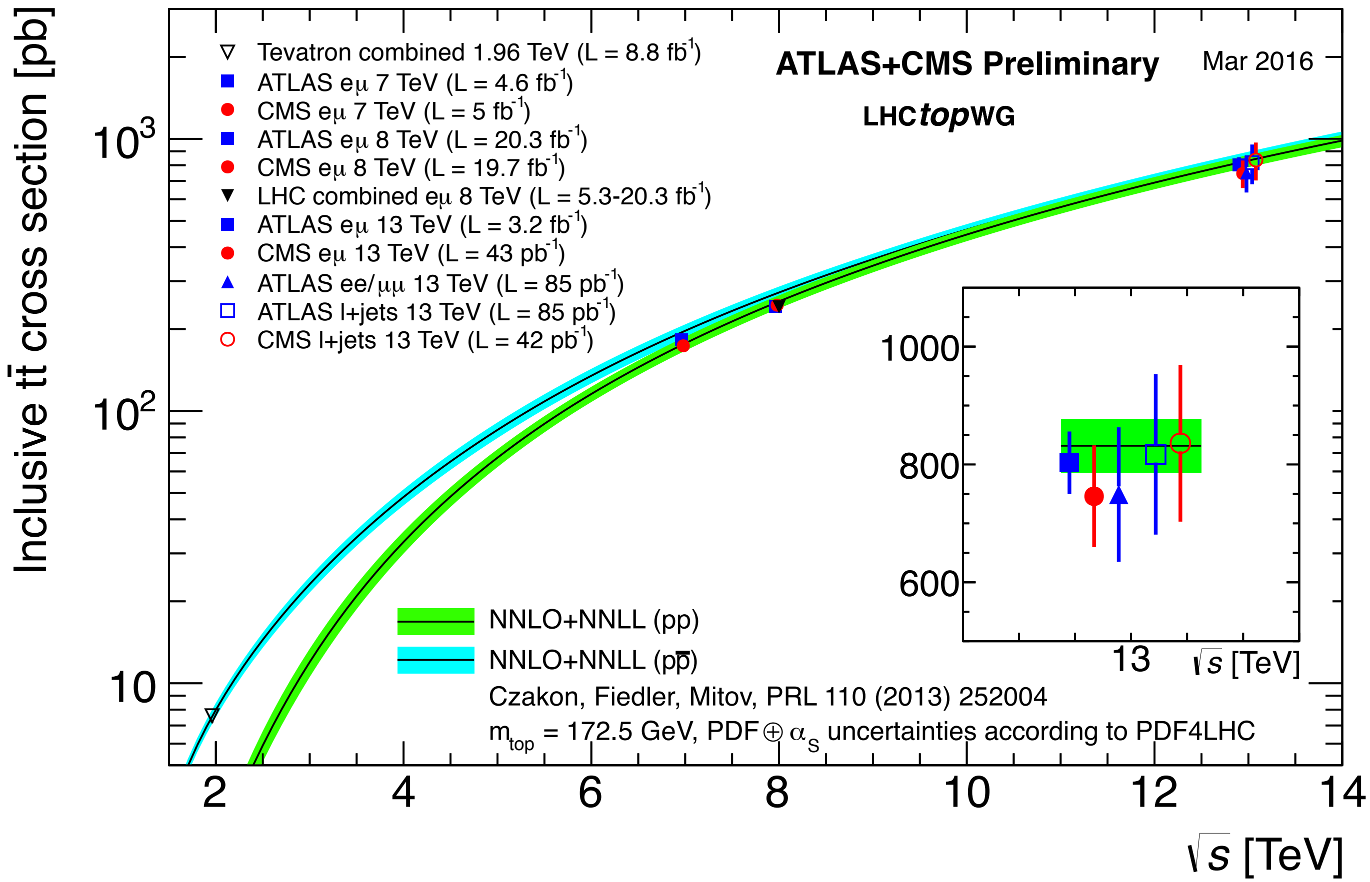
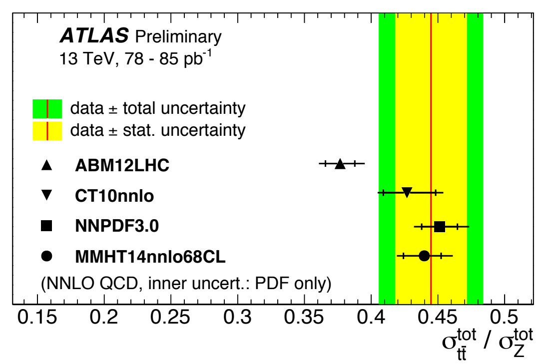
Top-pair production at NNLO

- Impressive agreement for the total cross-section (level of 4-5%)



✓ Notable: luminosity is the dominant error!

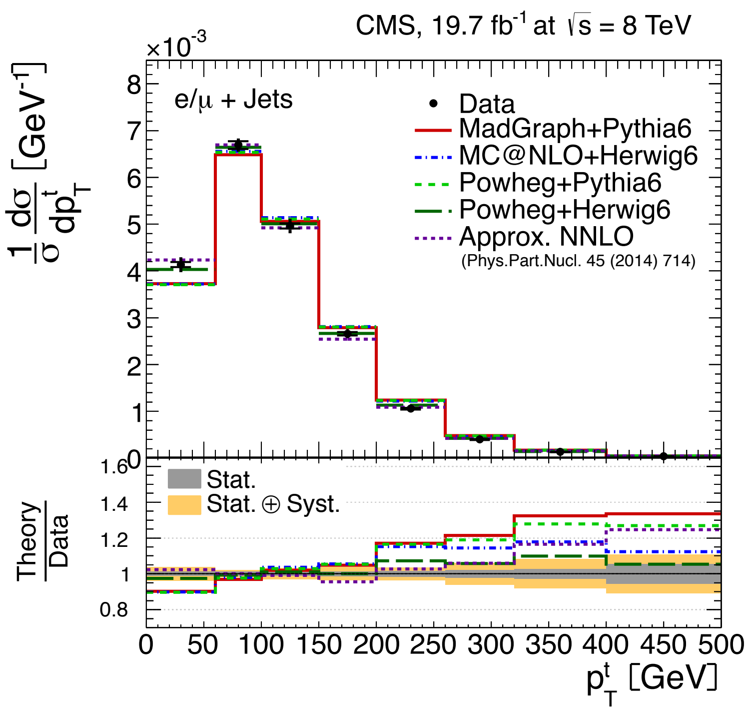
✓ Cancels in the tt/Z ratio. Excellent agreement with NNLO SM.

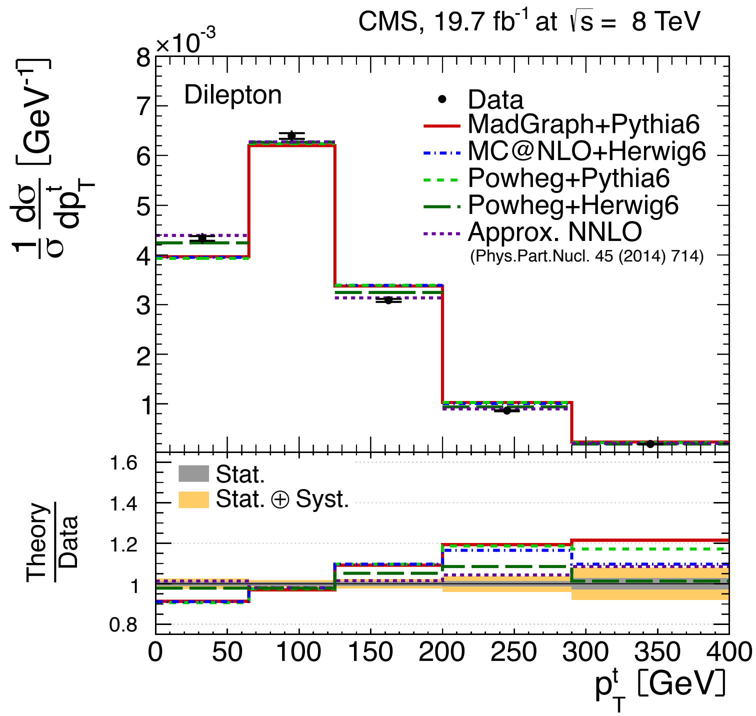


- The total x-section is one number; how much mileage can we get out of it?
- Surprisingly much:
    - Total x-section comparison
    - Top mass extraction
    - α_S extraction
    - PDF constraining
    - Constraining/excluding new physics models
    - Normalization for tt background in most searches
- The main contributors of error are:
    - Missing higher order corrections (from scale variation): 3%
    - pdf (at 68%cl): 2-3%
    - α_S : 1.5%
    - m_{top} : 3%

The LHC top P_T discrepancy

- ✓ Since 2012 there has been a consistent discrepancy between top quark measurements and SM



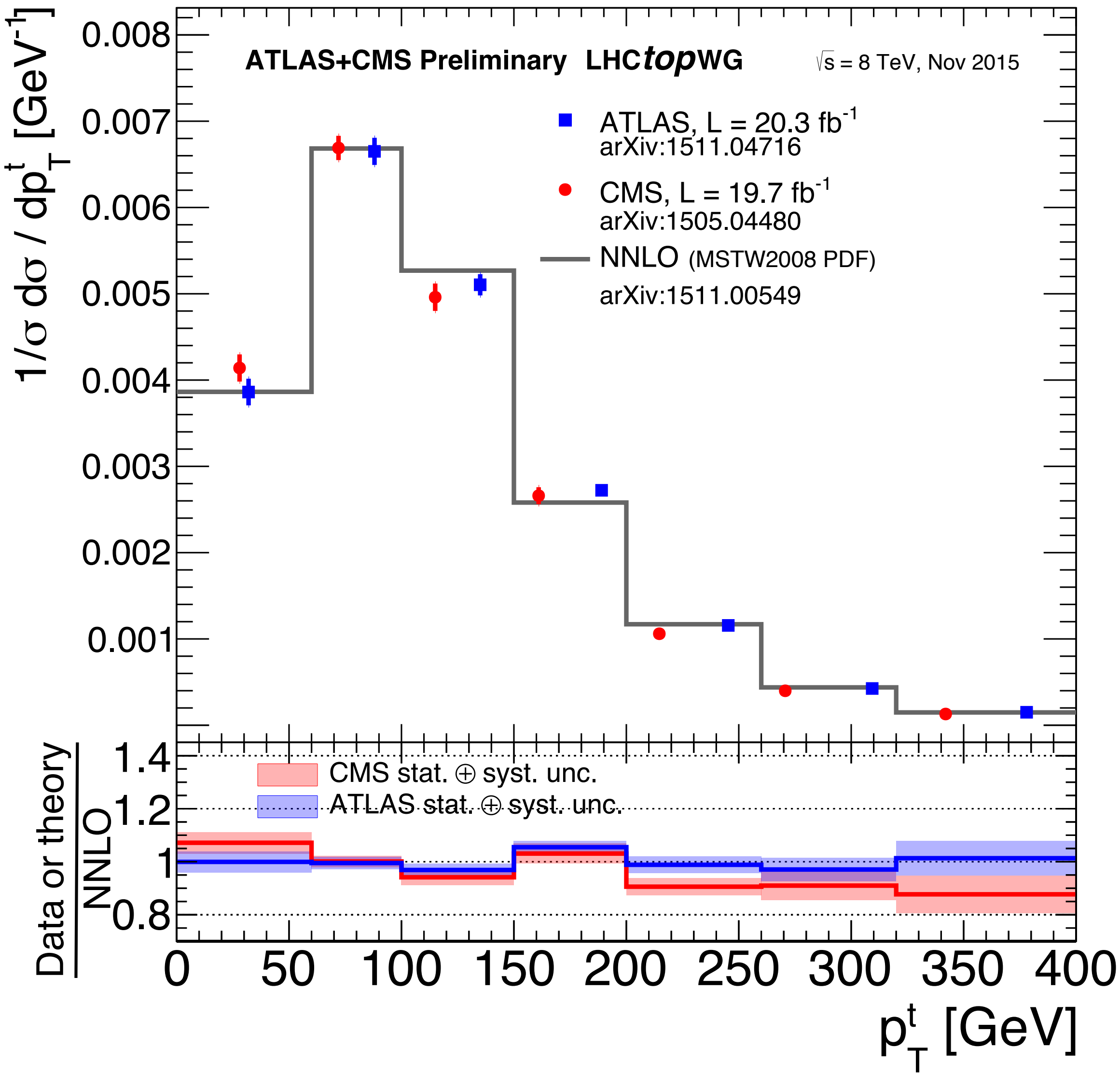


- ✓ Several qualifications:
  - ✓ Top quark-level observables show some deviation.
  - ✓ But tops are not measured; they are “inferred” from data using MC’s.
  - ✓ Therefore, any discrepancy between SM top quark predictions and ‘measurements’ are testing how well current MC’s describe top production.
  - ✓ Implications beyond top physics.

Inclusion of NNLO QCD corrections

✓ There are two obvious theory sources:

- Higher order corrections that we know are not inside MC's (NNLO QCD for example)
- Further tuning of MC's: treatment of color, recoil, hadronization, etc.

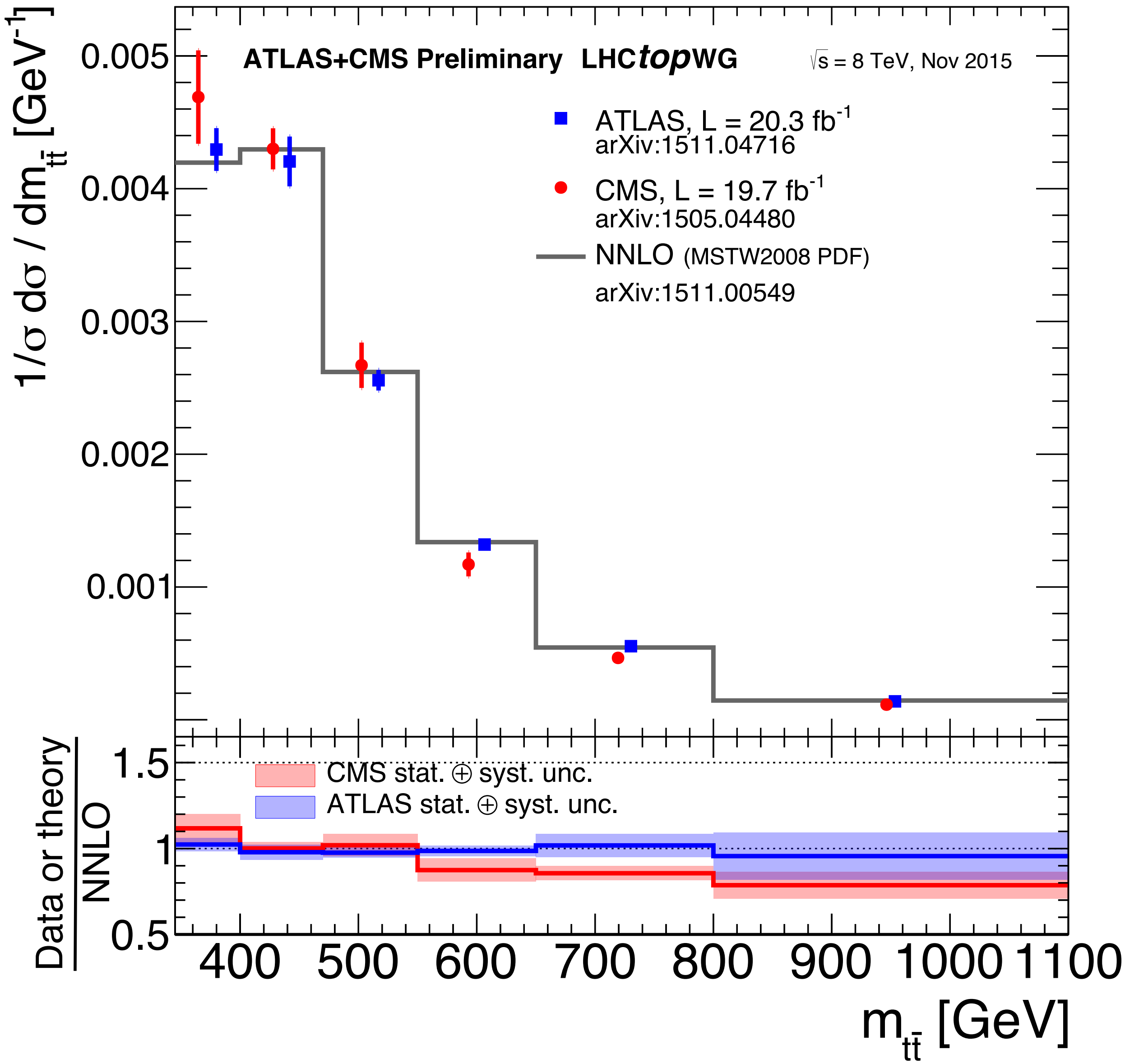


✓ The goal of this work is to clarify the role of NNLO QCD (before we start tuning MC's!)

✓ NNLO QCD corrections systematically improve the agreement with data

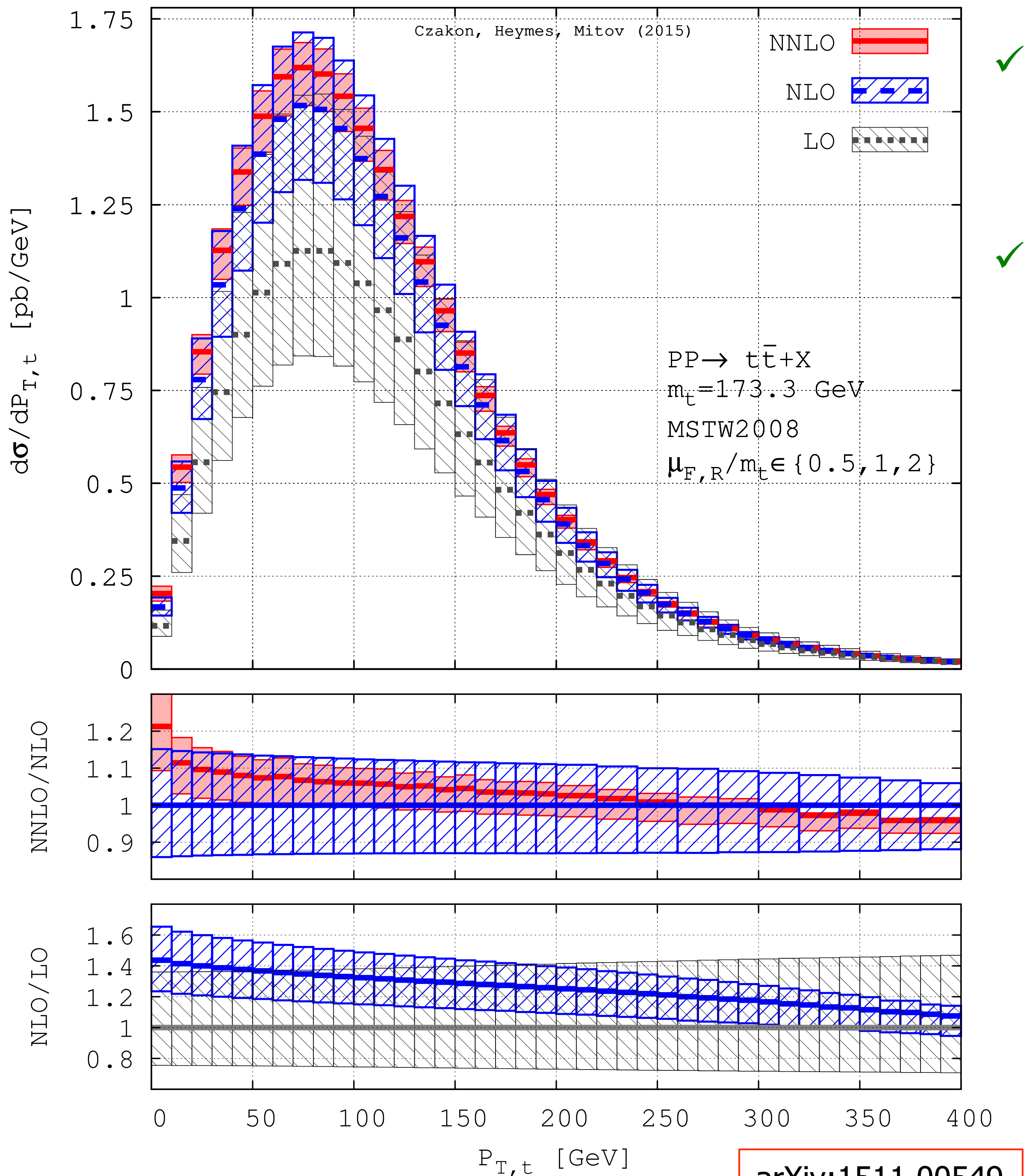
- Pdf error not included

Inclusion of NNLO QCD corrections



- NNLO QCD corrections systematically improve the agreement with data

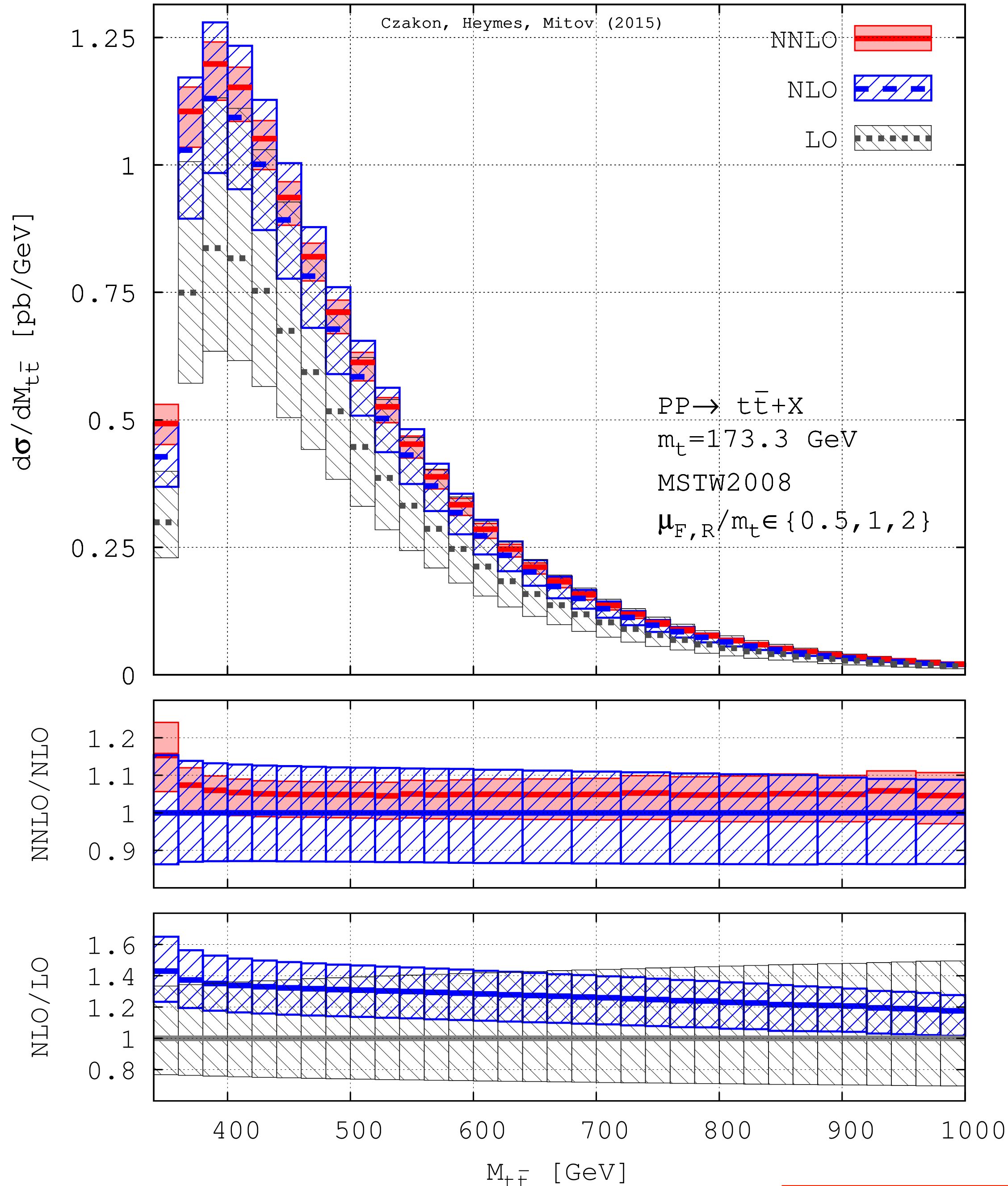
Inclusion of NNLO QCD corrections



arXiv:1511.00549

- ✓ The quality of the calculation is high:
  - ✓ Fine binning
- ✓ NNLO does what one normally expects:
  - Convergence
  - Decrease of scale error
  - Pdf error not included
  - Threshold effects can be seen

Inclusion of NNLO QCD corrections



arXiv:1511.00549

- ✓ The quality of the calculation is high:
  - ✓ Fine binning
- ✓ NNLO does what one normally expects:
  - Convergence
  - Decrease of scale error
  - Pdf error not included
  - Threshold effects can be seen
  - Note the extreme stability of the shape: no change from NLO to NNLO (within 0.5% or so)
  - An opportunity for searches?

Study of dynamic scales

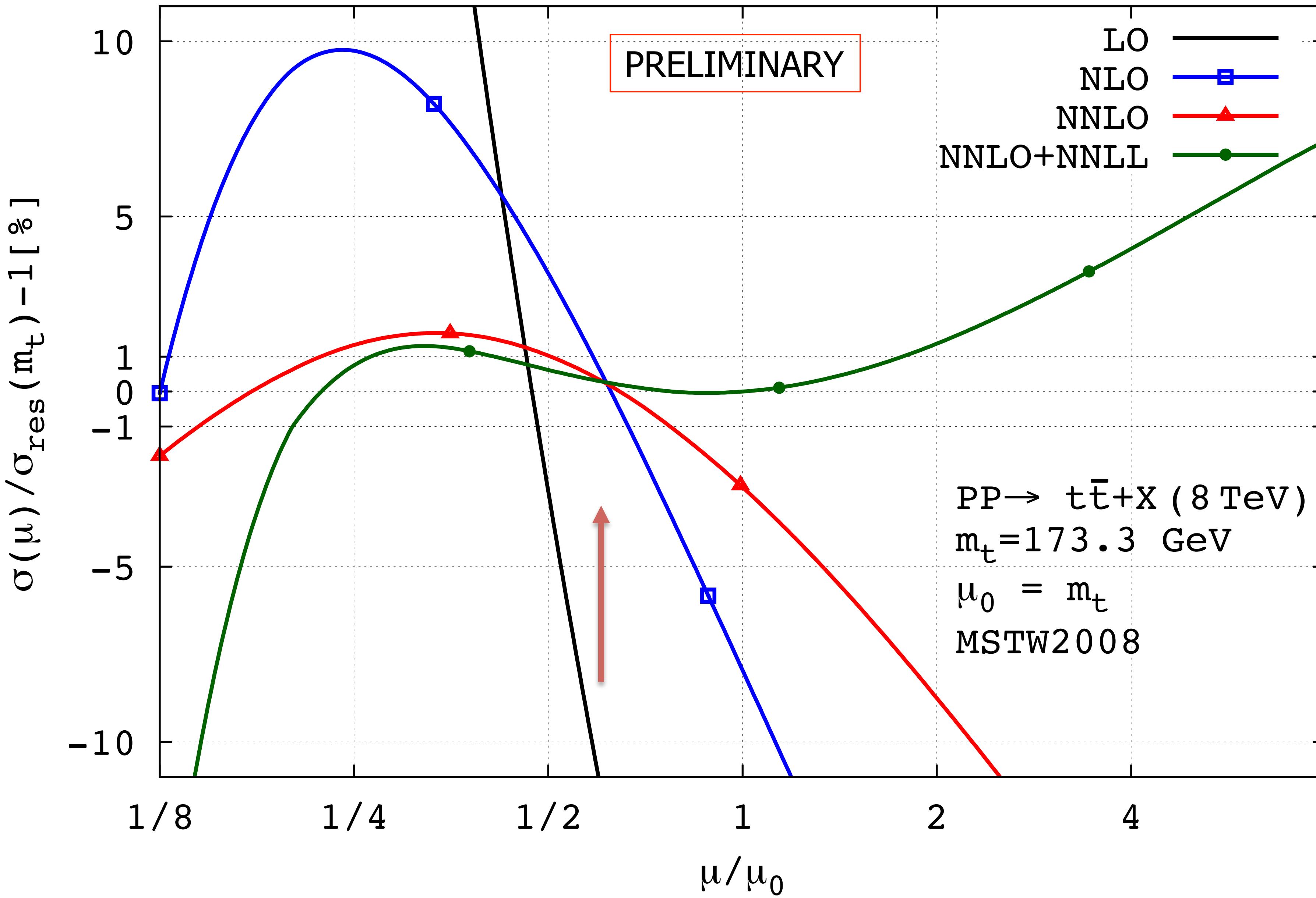
Czakon, Heymes, Mitov, to appear

- Main critique for prior results: used "static" scales $\mu_F=\mu_R=m_t$
- This is OK in restricted kinematic ranges (for example PT<400)
- Going in the TeV range requires dynamic scales. 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 constitutes "best" scale choice.
  - For PT=0 scale has to be ~mt
  - For large PT should be ~PT
- The coefficients of these leading powers should be somehow fixed.
- 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 PT part is constrained by the total x-section
- There is no experimental handle at large PT.

Beyond that: if we are to do precision, then the scale choice must also be optimized!

Study of dynamic scales

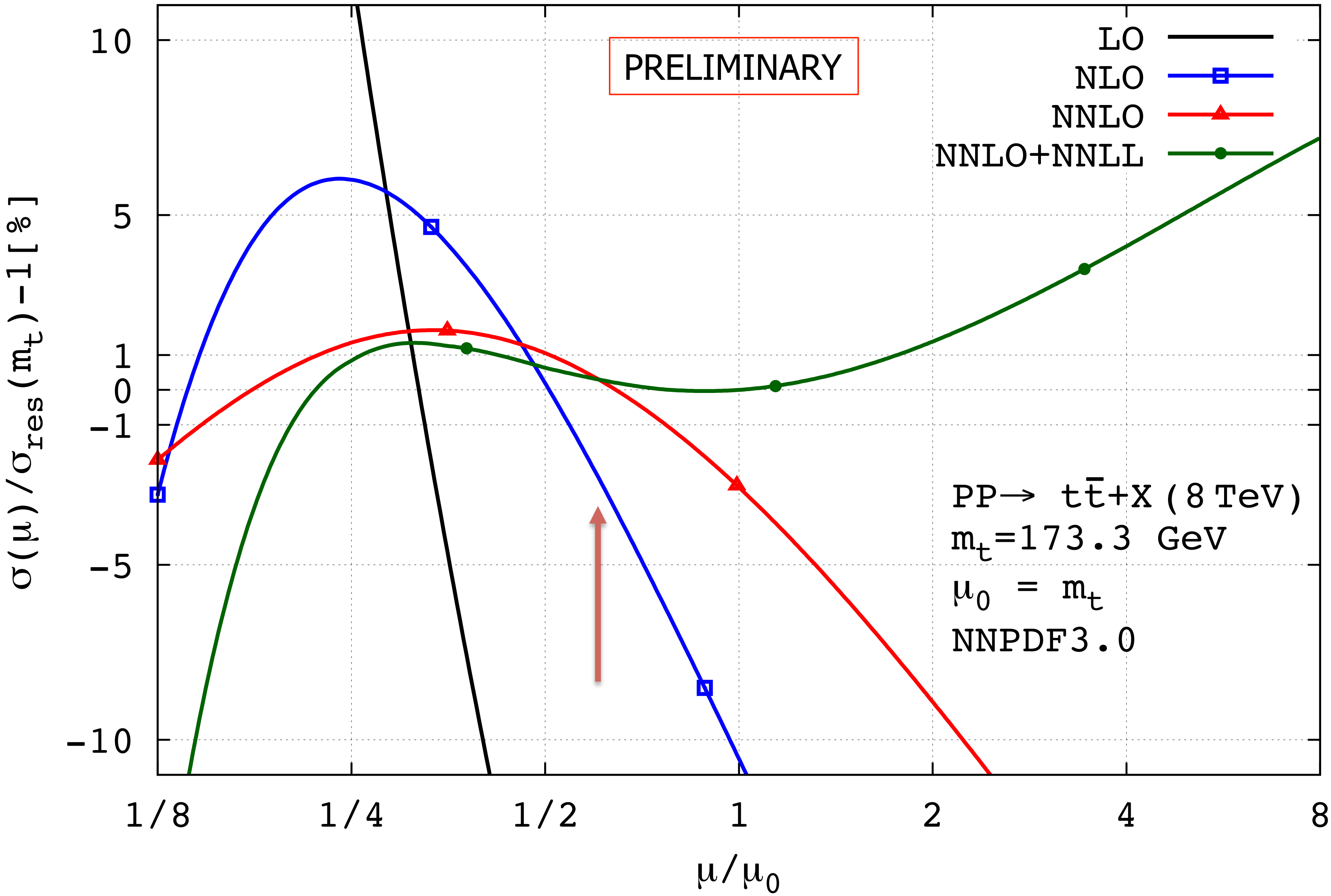
- Total cross-section with various fixed scale choices and for different PDF's



Smaller scale is preferred

Study of dynamic scales

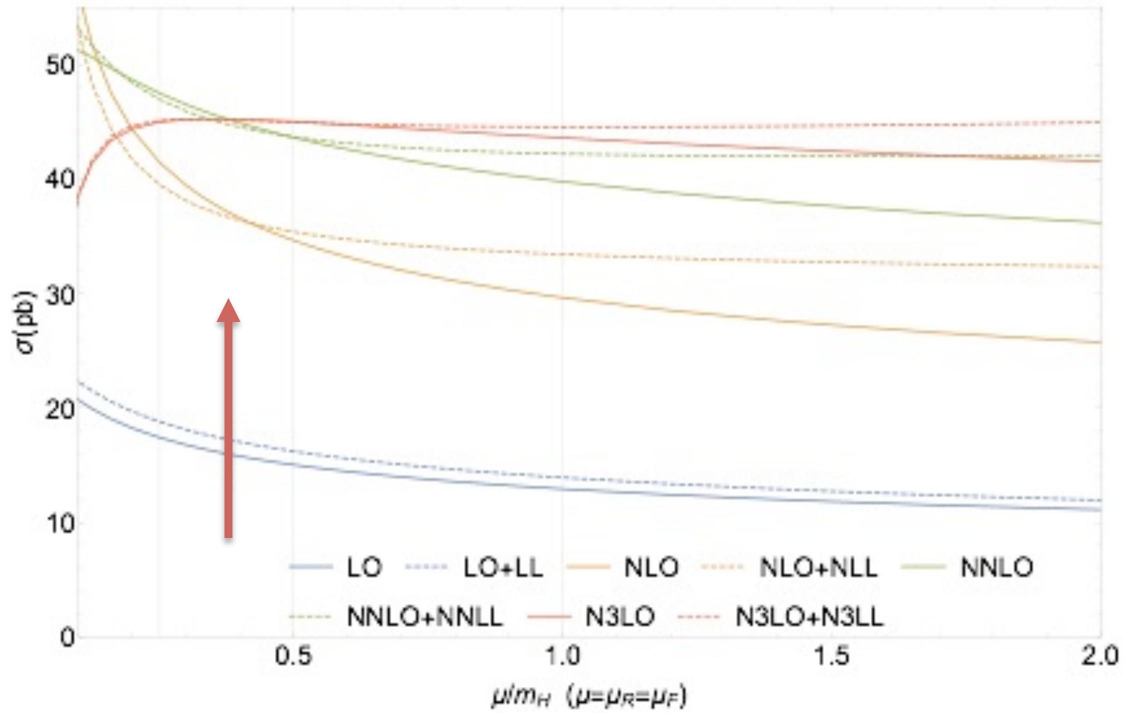
- Total cross-section with various fixed scale choices and for different PDF's



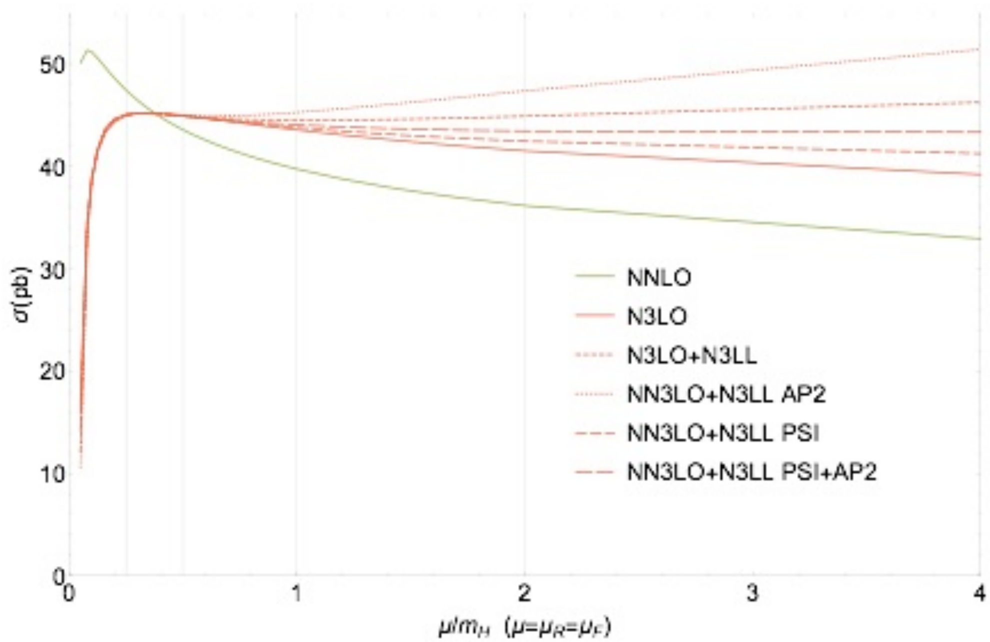
Smaller scale is preferred

Study of dynamic scales

- The total x-section at N^2LO 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

Study of dynamic scales

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

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

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

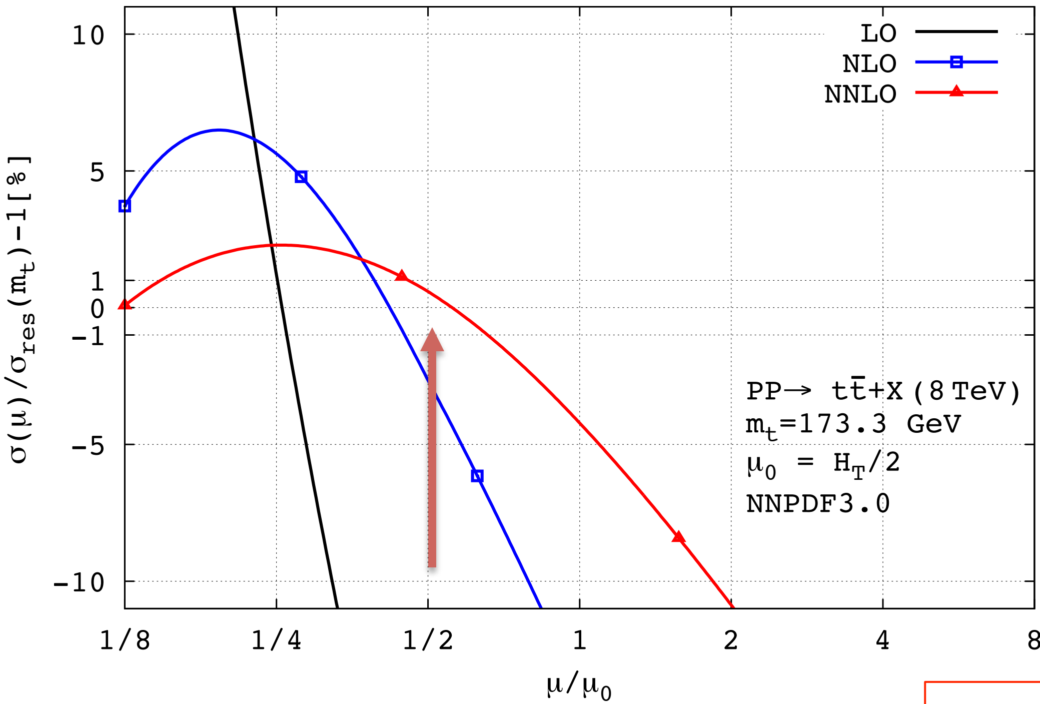
$$H_T = \sqrt{m_t^2 + p_{\mathrm{T}t}^2} + \sqrt{m_t^2 + p_{\mathrm{T}\bar{t}}^2}$$

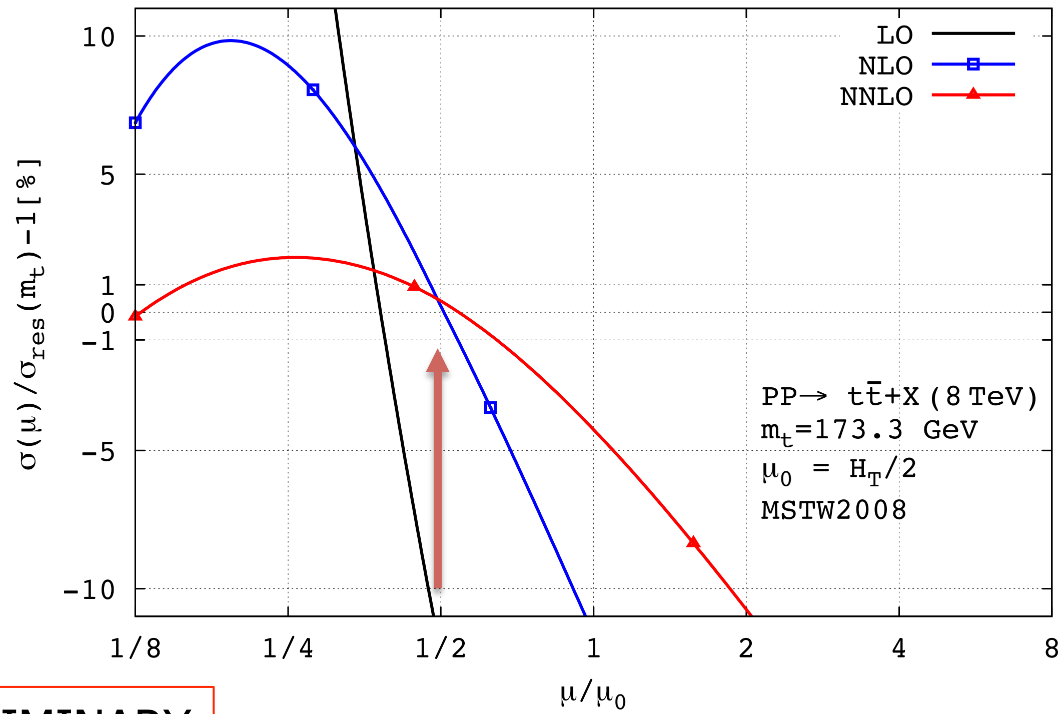
Scales $\mu \propto m_{t\bar{t}}$ do not work well

- 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

Study of dynamic scales

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



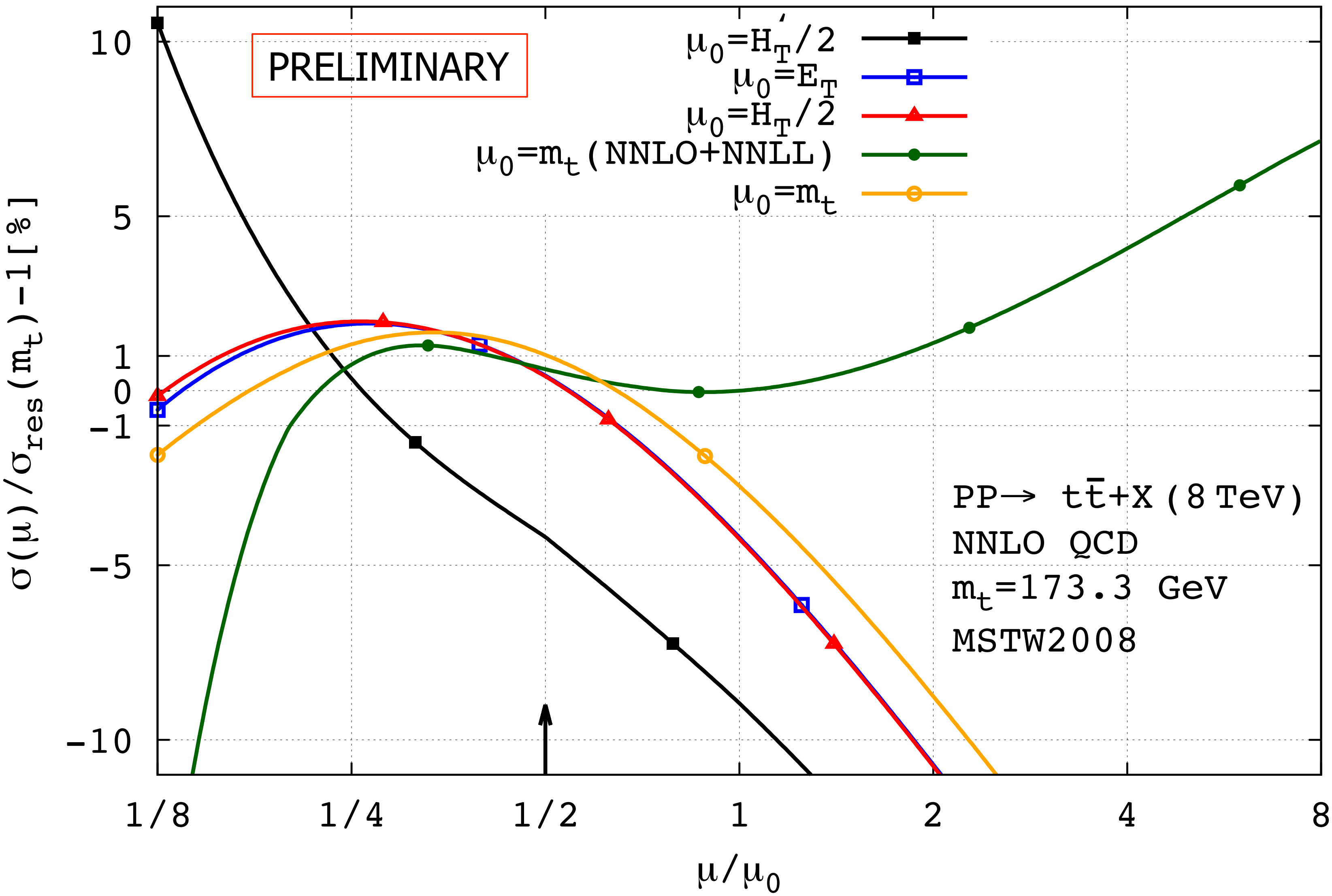


PRELIMINARY

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

Study of dynamic scales

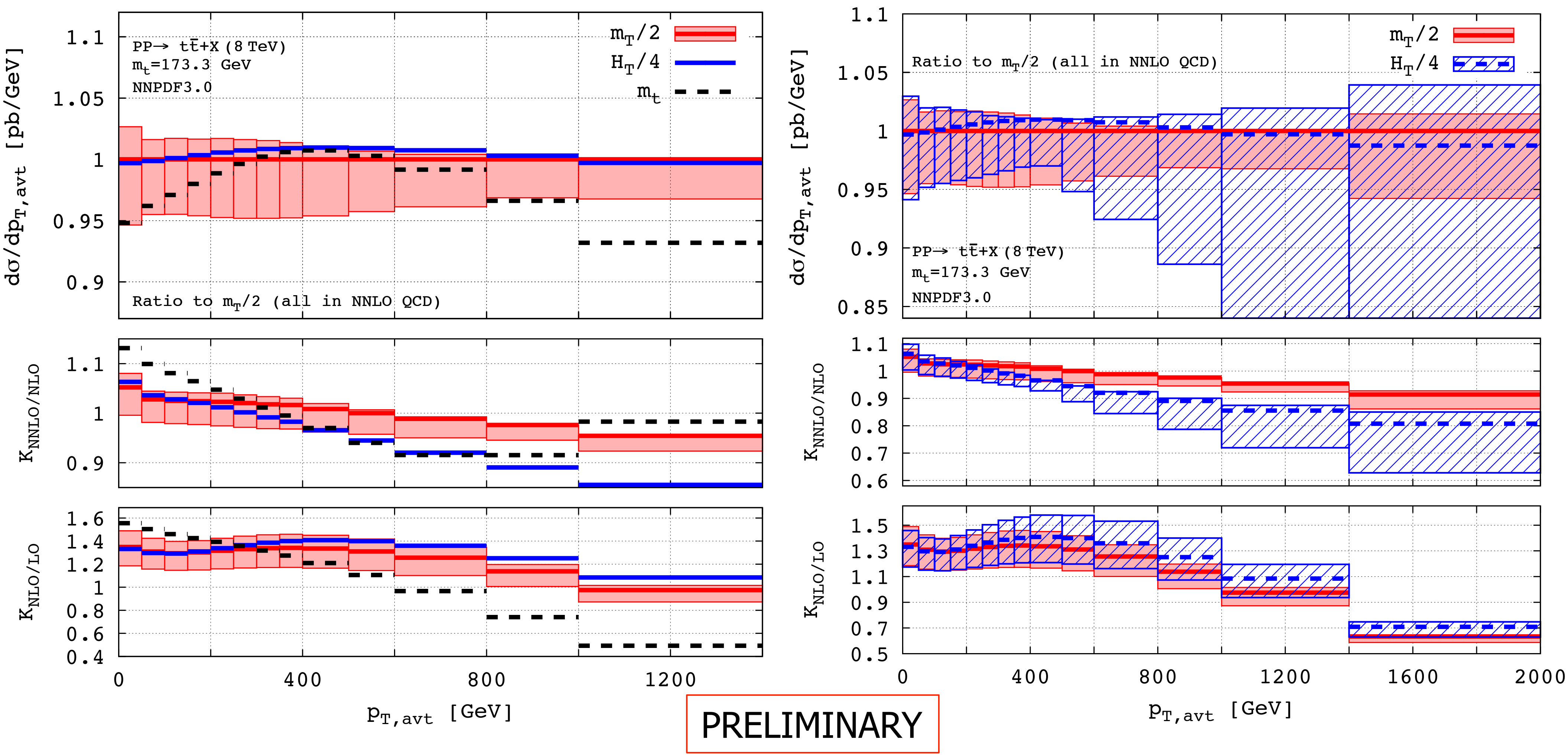
- Total cross-section with various dynamic scales and for different PDF's



- Comparison of various scales at NNLO and NNLO+NNLL

Study of dynamic scales

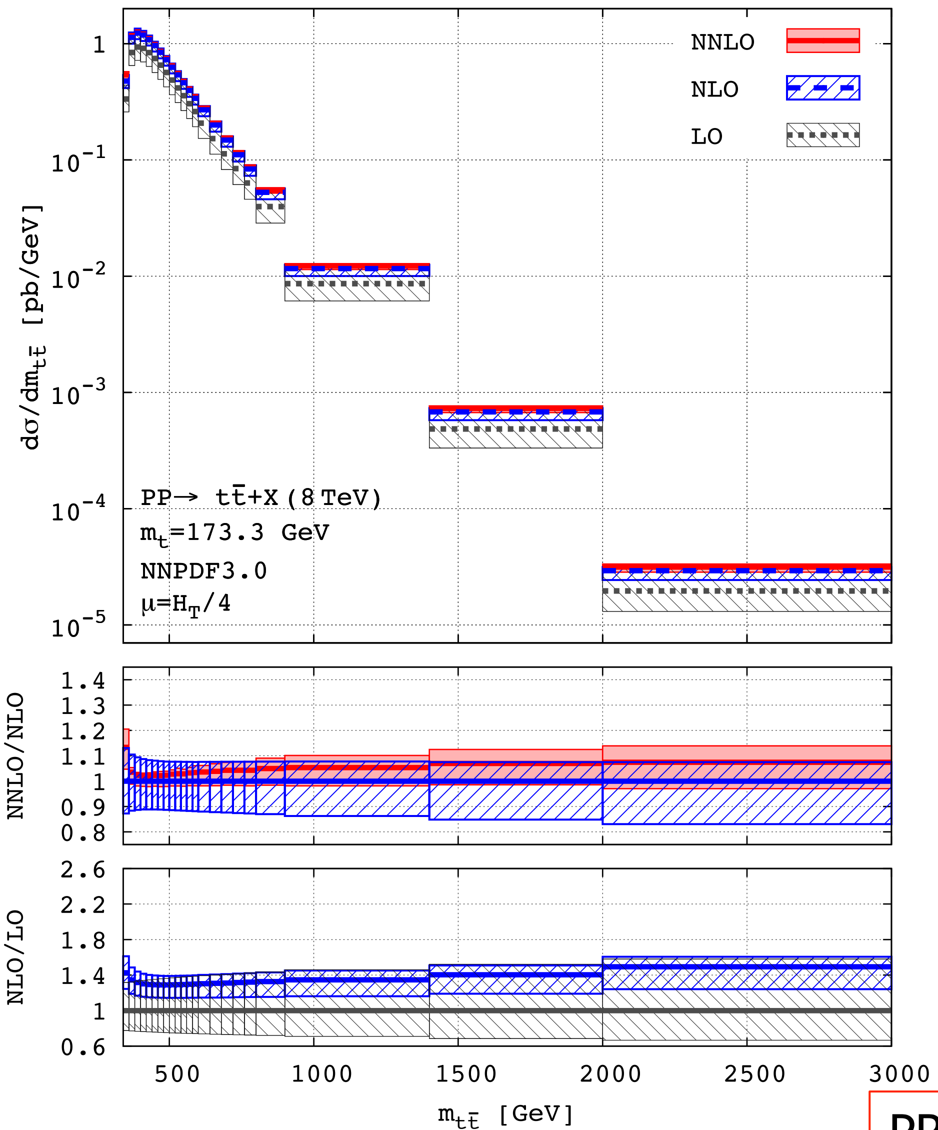
- Total P_T x-section with various dynamic scales and for different PDF's

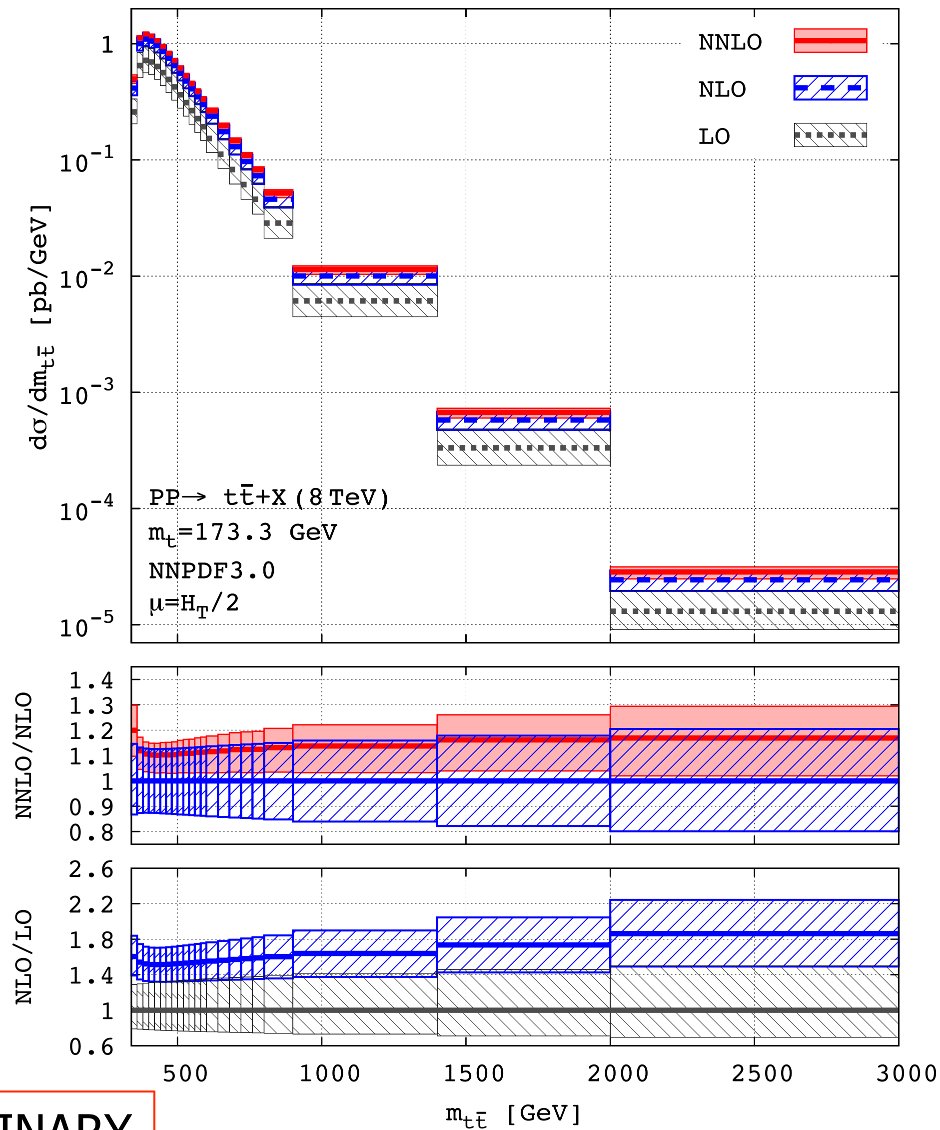


- Dedicated effort to populate the tails. Multi TeV predictions possible.
- $H_T/4$ and $M_T/2$ are compatible within 2% but return very different scale errors
- Fixed scale (m_{top}) is compatible within scale errors up to 1 TeV (a curiosity)

Study of dynamic scales

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



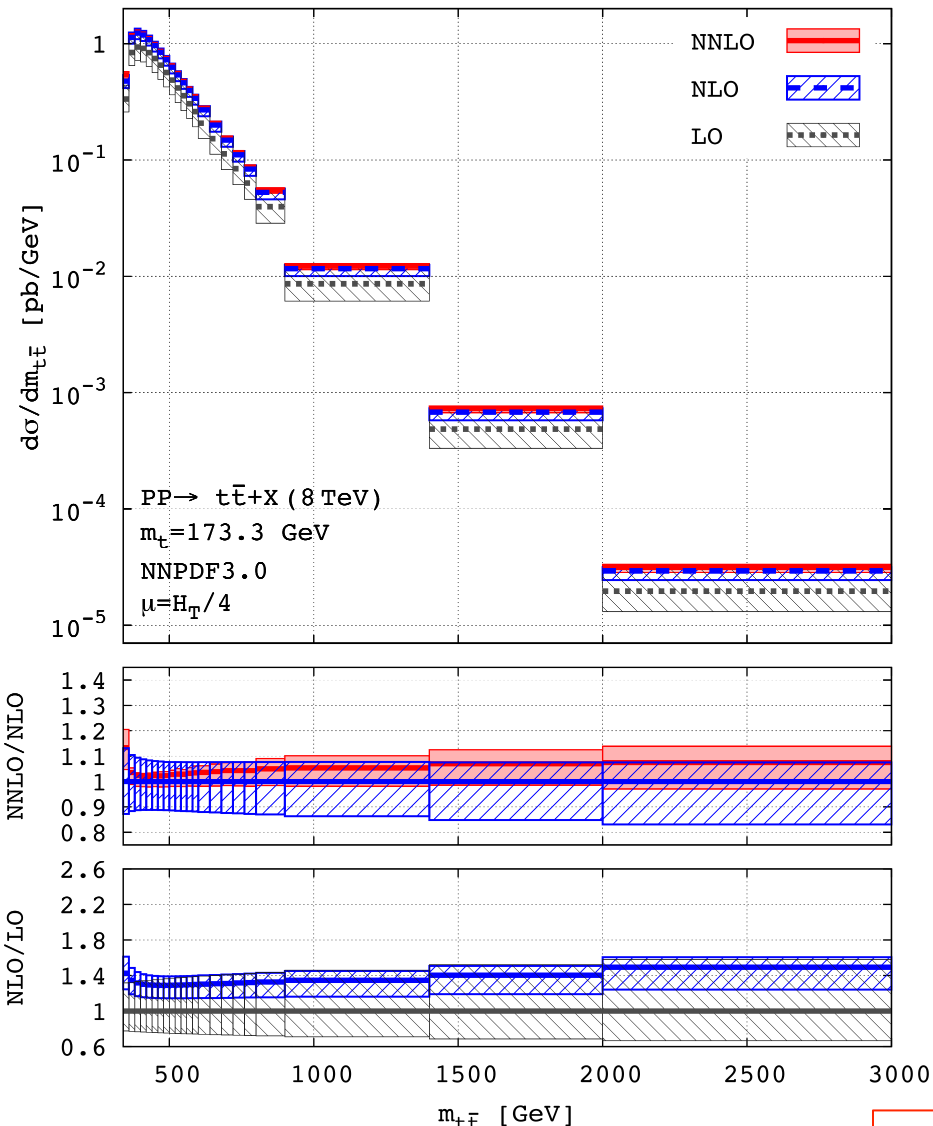


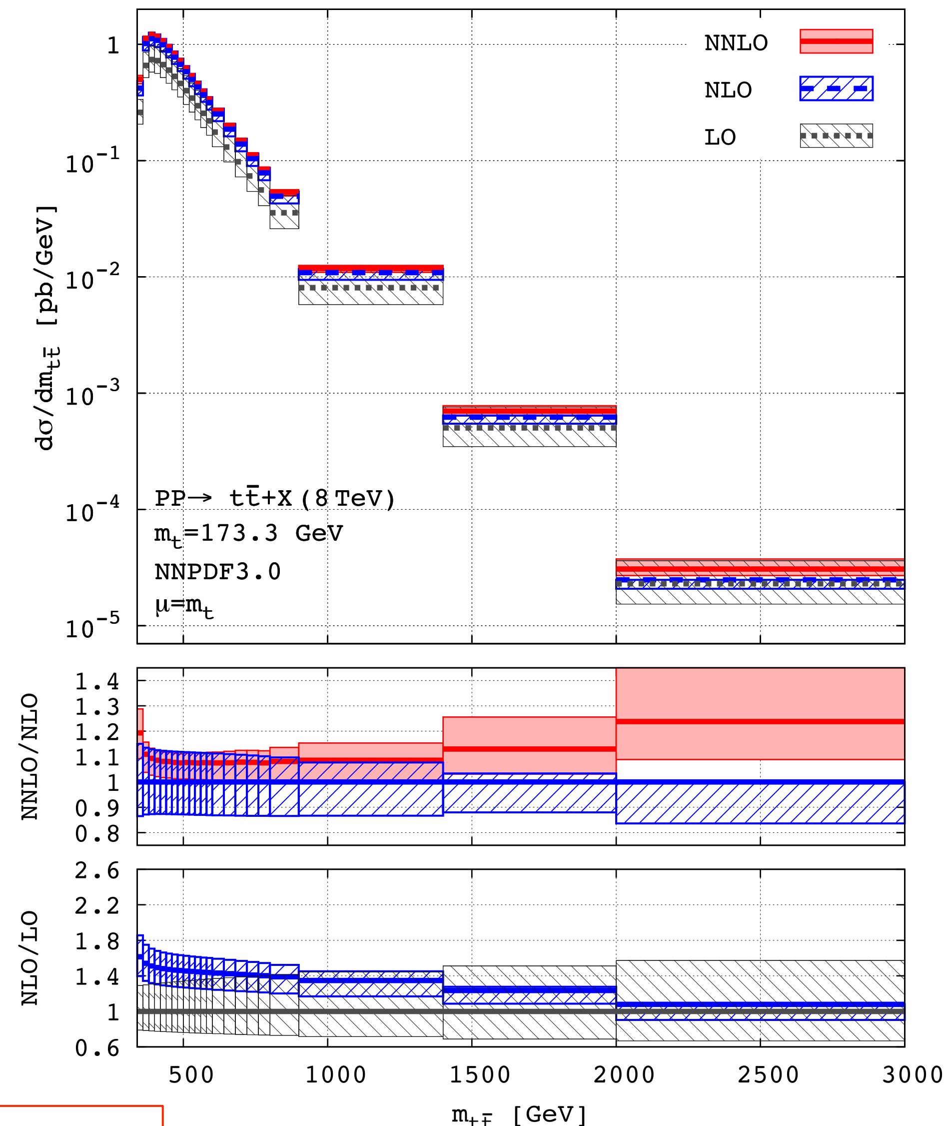
PRELIMINARY

- HT/4 (left) and HT/2 (right)

Study of dynamic scales

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



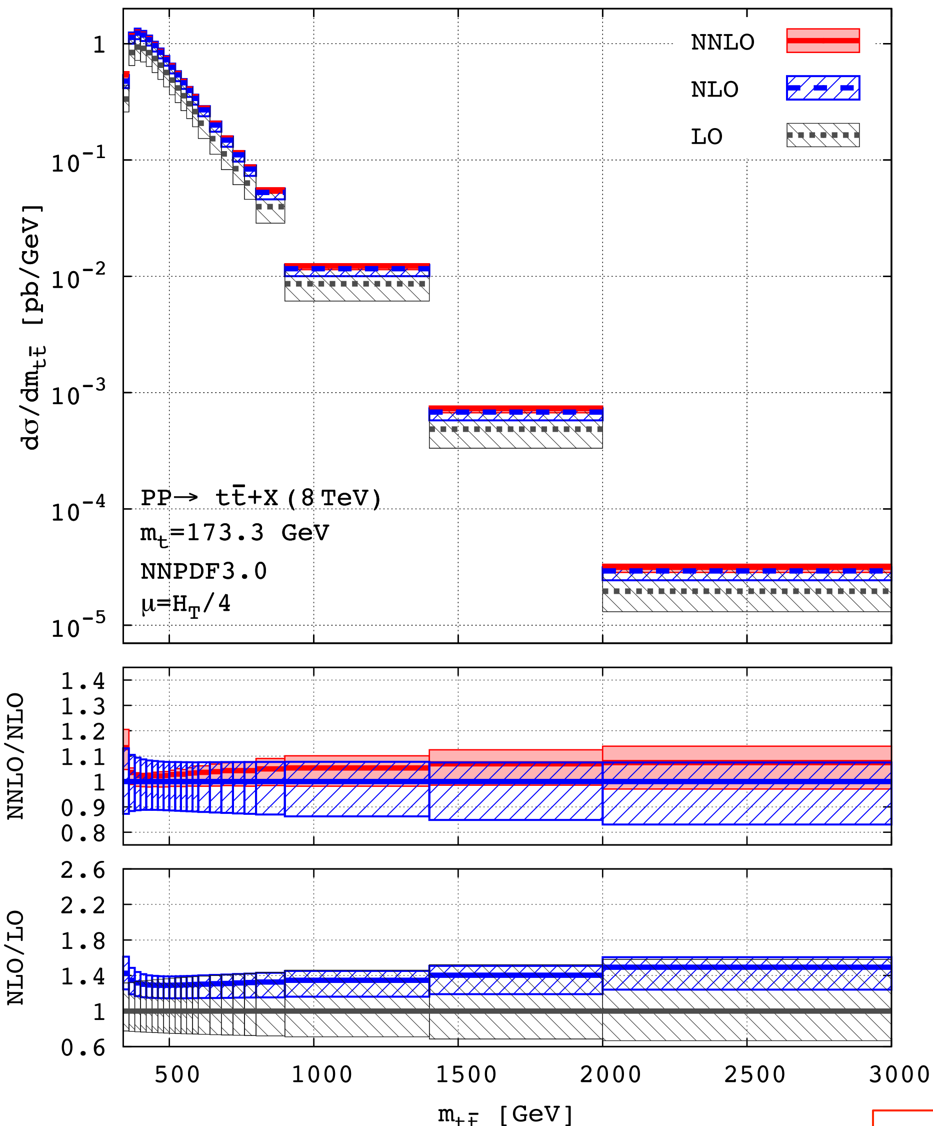


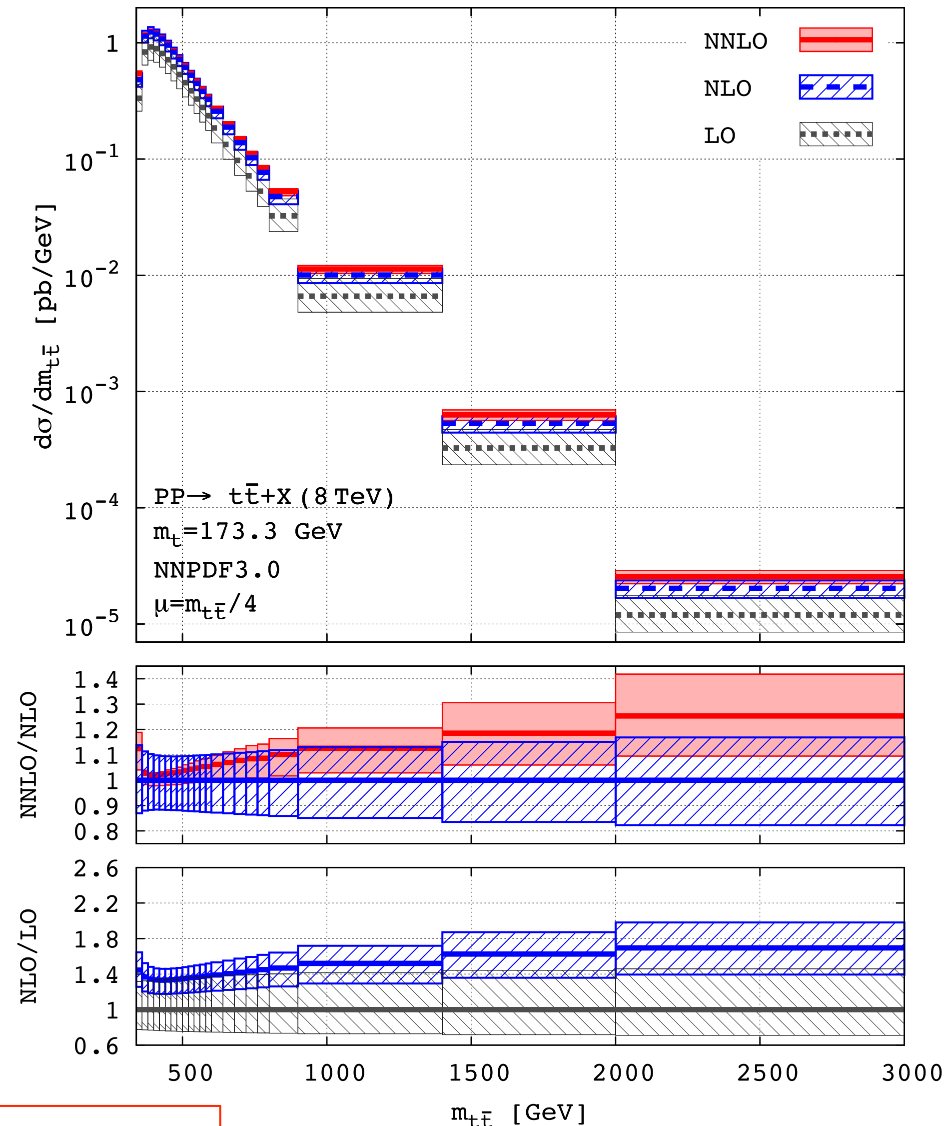
PRELIMINARY

- HT/4 (left) and mtop (right)

Study of dynamic scales

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



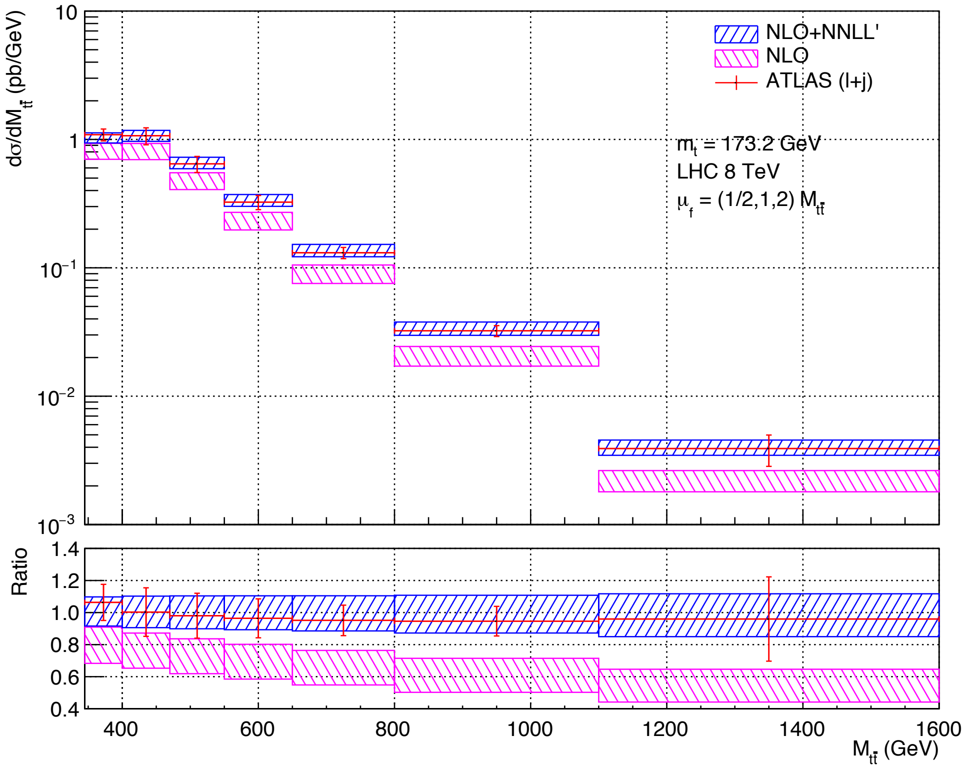


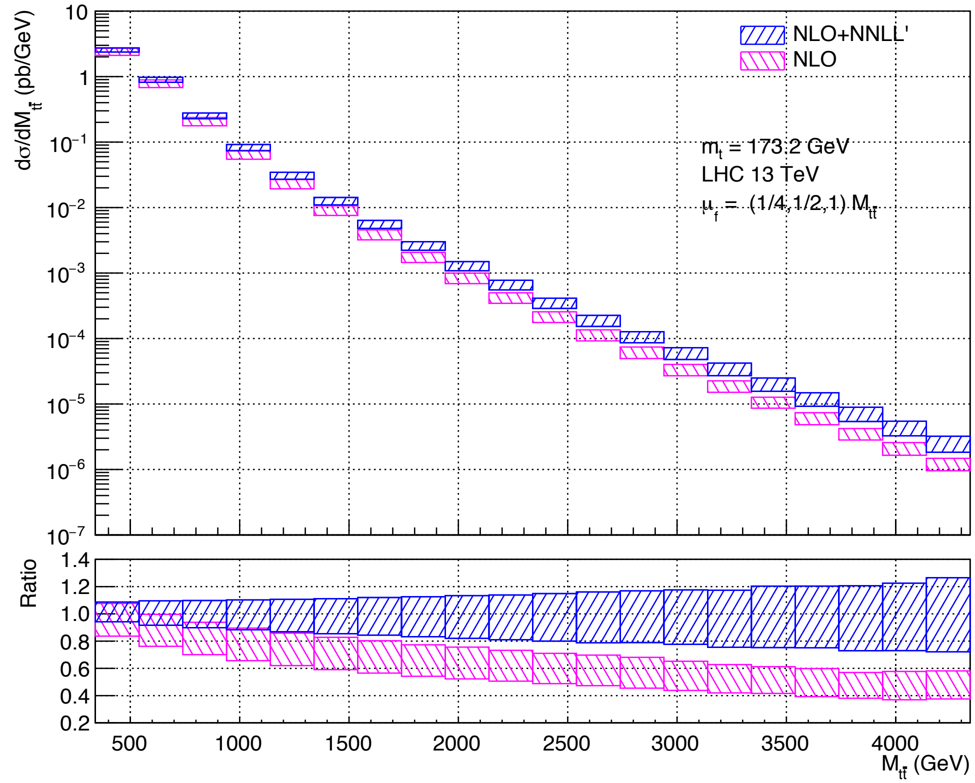
PRELIMINARY

- $H_T/4$ (left) and $M_{tt}/4$ (right). $M_{tt}/2$ is even worse.

Study of dynamic scales

- Recent result of NNLL resummation (soft and soft-collinear) of differential top production





Pecjak, Scottb, Wang, Yang arXiv:1601.07020v2

- Effect due to resummation may be obscured by scale choice !
(which is different between 8/13 TeV)

What about PDF dependence?

- We notice not-so-small shifts from pdf set to pdf set in various observables.
- Not quantitative changes but effects are interesting
- We saw some examples for the total x-section
- For the differential all is preliminary
- To illustrate the point look at some Tevatron plots

Czakon, Fiedler, Heymes, Mitov ‘16

PDF dependence: absolute normalization at the Tevatron

Czakon, Fiedler, Heymes, Mitov '16

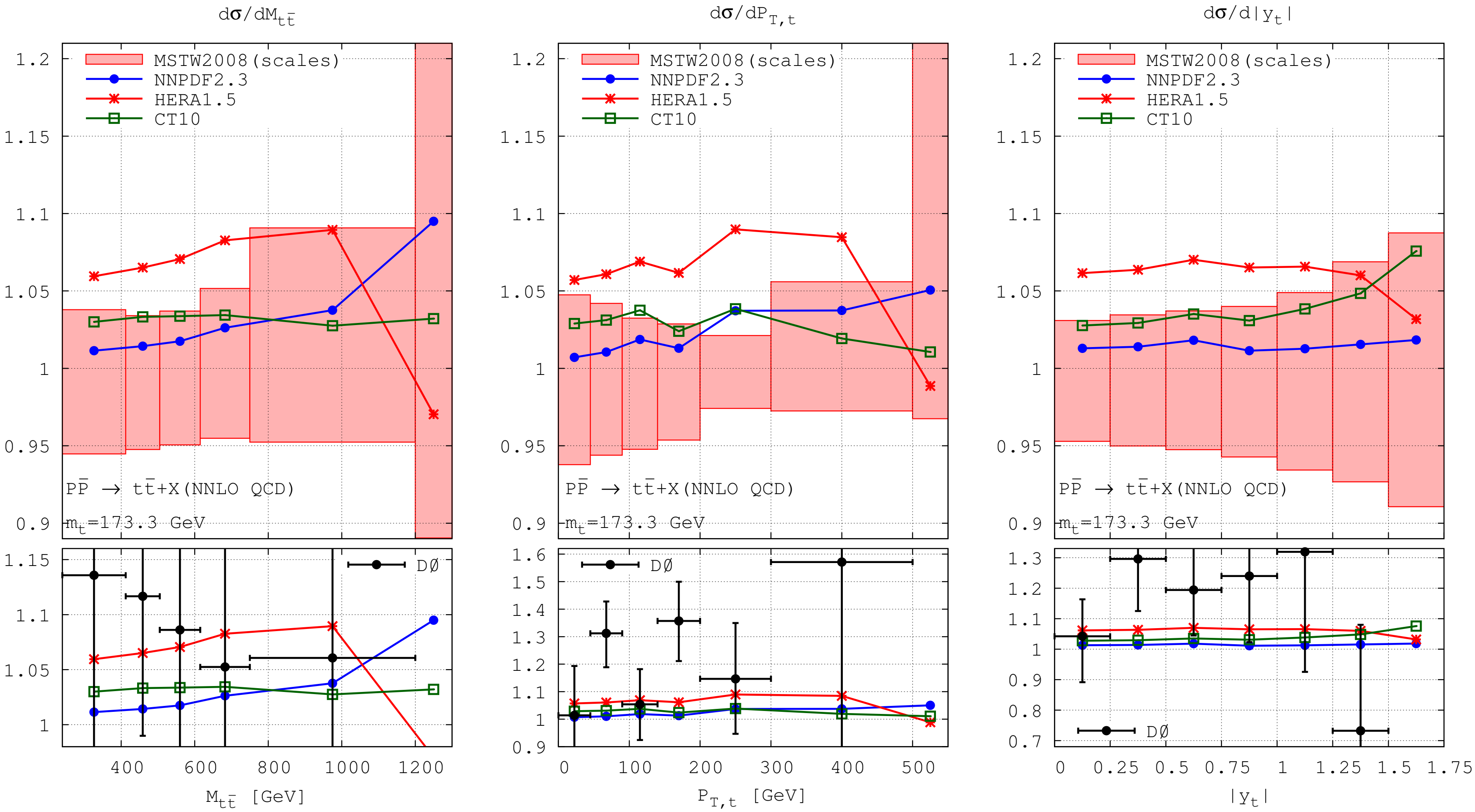


Figure 10. NNLO QCD prediction for three differential distributions (in $M_{t\bar{t}}$, $P_{T,t}$ and $|y_t|$) with four pdf sets. Given are the ratios of the CT10, HERA 1.5 and NNPDF 2.3 based predictions with respect to MSTW2008. For reference also the scale dependence of the MSTW2008 prediction is shown (red band). For improved visibility, in the lower plots we compare the same predictions with the available data from the DØ Collaboration [15].

PDF dependence: normalized distributions at the Tevatron

Czakon, Fiedler, Heymes, Mitov '16

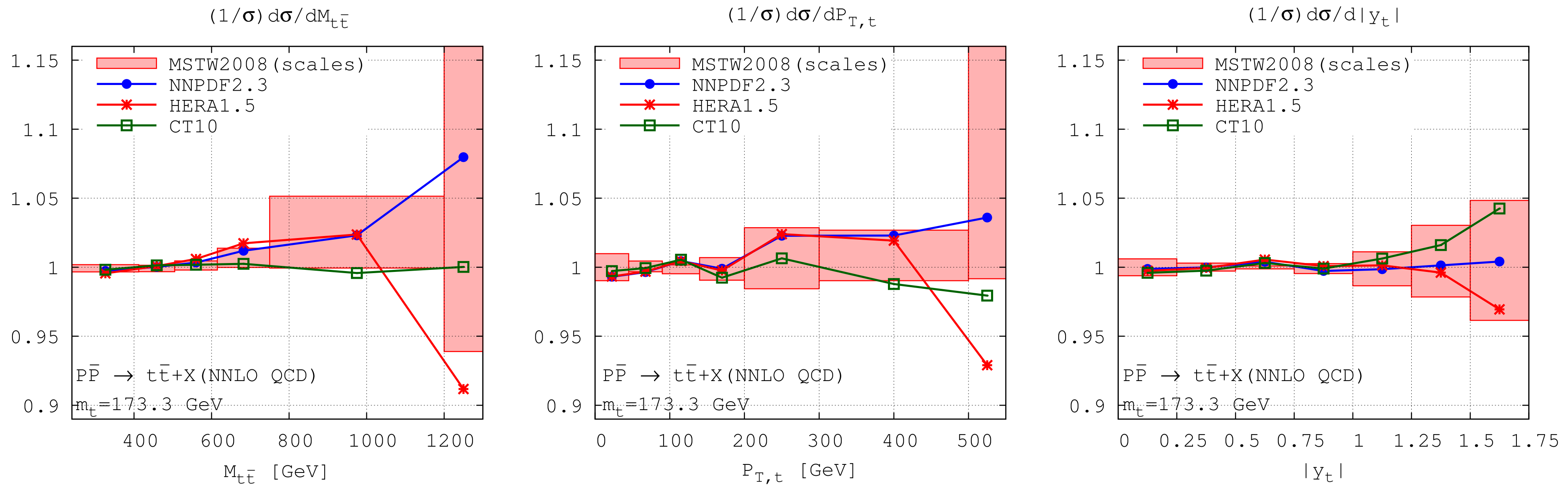
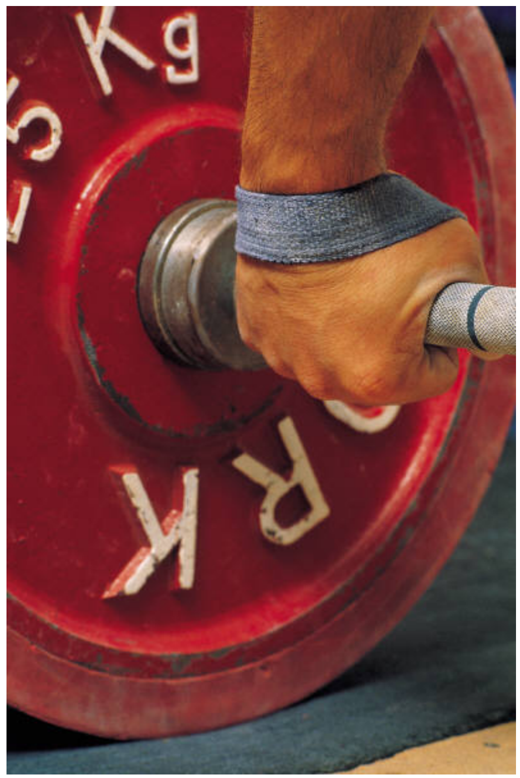


Figure 11. As in fig. 10 but for the normalised to unity distributions.

- ✓ Very impressive consistency between pdf's once the normalization ambiguity is taken out.
- ✓ Good news for m_{top} extractions from differential distributions.
- ✓ All for fixed scales

Top quark mass



Top quark mass

- Look at the spread across some current measurements:
  - m_t = 173.34 ± 0.76 GeV [World Average]
  - m_t = 172.04 ± 0.77 GeV [CMS Collaboration]
  - m_t = 174.98 ± 0.76 GeV [D0 Collaboration]

- Comparable uncertainties; rather different central values!

- Can it be that this spread is due to different theory systematics? Overview of methods:

Juste et al arXiv:1310.0799
Moch et al arXiv:1405.4781

- The important question the paper raises is how well do we control theory systematics in top mass determination

Frixione, Mitov '14

- I would single out leptonic observables since they are cleaner and, supposedly, under better theory control (at least as far as MC's are concerned)

- While we sure want precise m_{top} extraction, the main motivation is reliable estimate of errors, not necessarily a "most precise" method.

- ✓ The top mass is extracted from the ***shapes, not normalizations***, of the following distributions:

kinematic distribution
$p_T(\ell^+)$
$p_T(\ell^+\ell^-)$
$M(\ell^+\ell^-)$
$E(\ell^+) + E(\ell^-)$ ← Studied before by: Biswas, Melnikov, Schulze '10
$p_T(\ell^+) + p_T(\ell^-)$

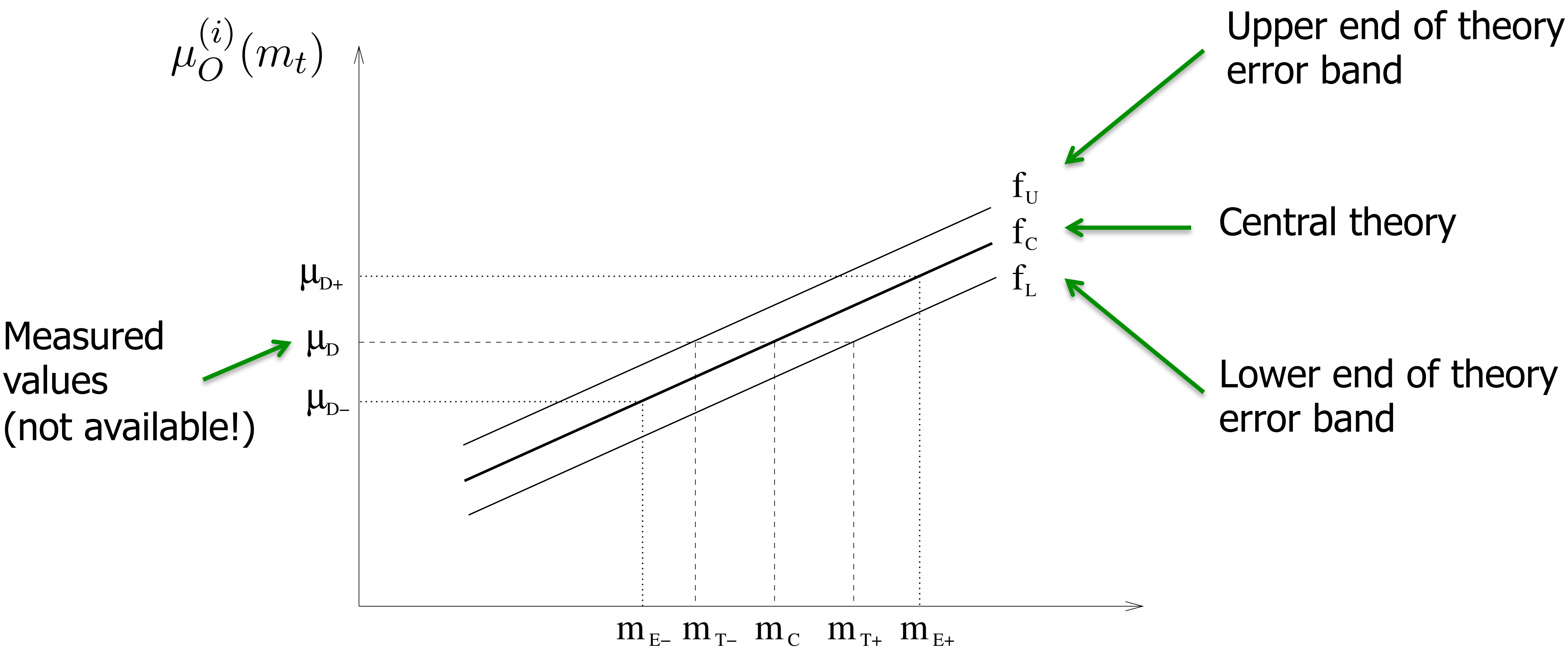
- ✓ Working with distributions directly is cumbersome.
- ✓ Instead, utilize the first 4 moments of each distribution

$$\sigma = \int d\sigma \qquad \mu_O^{(i)} = \frac{1}{\sigma}\int d\sigma\, O^{\,i} \qquad \mu_O^{(0)} = 1\,, \qquad \mu_O^{(1)} = \langle O \rangle$$

Note: both are subject to cuts (or no cuts); we tried both.

- Here is how it all works:

1) Compute the dependence of the moments $\mu_O^{(i)}(m_t)$ on the top mass
2) Measure the moment
3) Invert 1) and 2) to get the top mass (would be the pole mass, since this is what we use)

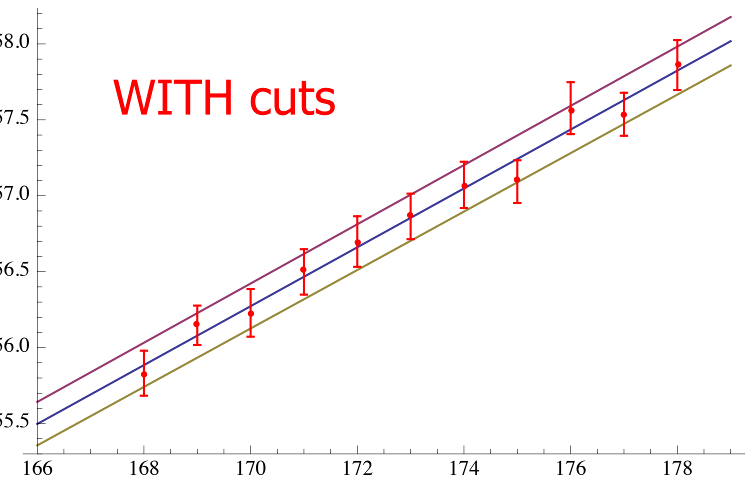


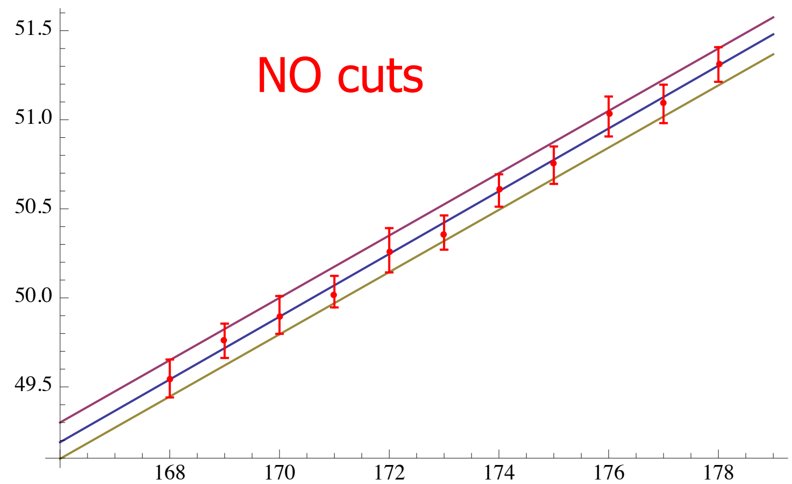
How to compute the theory error band for $\mu_O^{(i)}(m_t)$?

➢ Compute $\mu_O^{(i)}(m_t)$ for a finite number of m_t values: $m_t = (168, 169, \ldots, 178)$ GeV

Then get best straight line fit (works well in this range).

Example:
- Single lepton P_T
- Subject to cuts





✓ Errors: pdf and scale variation; restricted independent variation

$$0.5 \leq \xi_F, \xi_R \leq 2 \qquad \xi_{F,R} = \mu_{F,R}/\hat{\mu} \text{ and } \hat{\mu} \text{ is a reference scale}$$

✓ There are statistical fluctuation (from MC event generation) No issue for lower moments 1M events; 30% pass the cuts.

Top quark mass

- Analysis just performed by CMS (at LO+PS)

Available on the CERN CDS information server **CMS PAS TOP-16-002**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch 2016/03/14

Determination of the top quark mass from leptonic observables using $e\mu$+jets final states selected in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

Abstract

A novel technique for measuring the top quark mass using only leptonic observables is discussed. Top quark pair events with one electron and one muon and at least one jet in the final state are selected in proton-proton collision data collected by the CMS experiment at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. Several observables are studied and the transverse momentum distribution of the charged lepton pair originating from the decay of the top quark pair is chosen to extract the top quark mass. After the calibration with simulated events $m_{\mathrm{t}} = 171.7 \pm 1.1\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{exp.})^{+2.5}_{-3.1}\,(\mathrm{th.})^{+0.8}_{-0.0}\,(p_T(\mathrm{t}))$ GeV is measured, where the dominant systematic uncertainties stem from signal modeling.

Top quark mass

- Analysis just performed by CMS (at LO+PS)

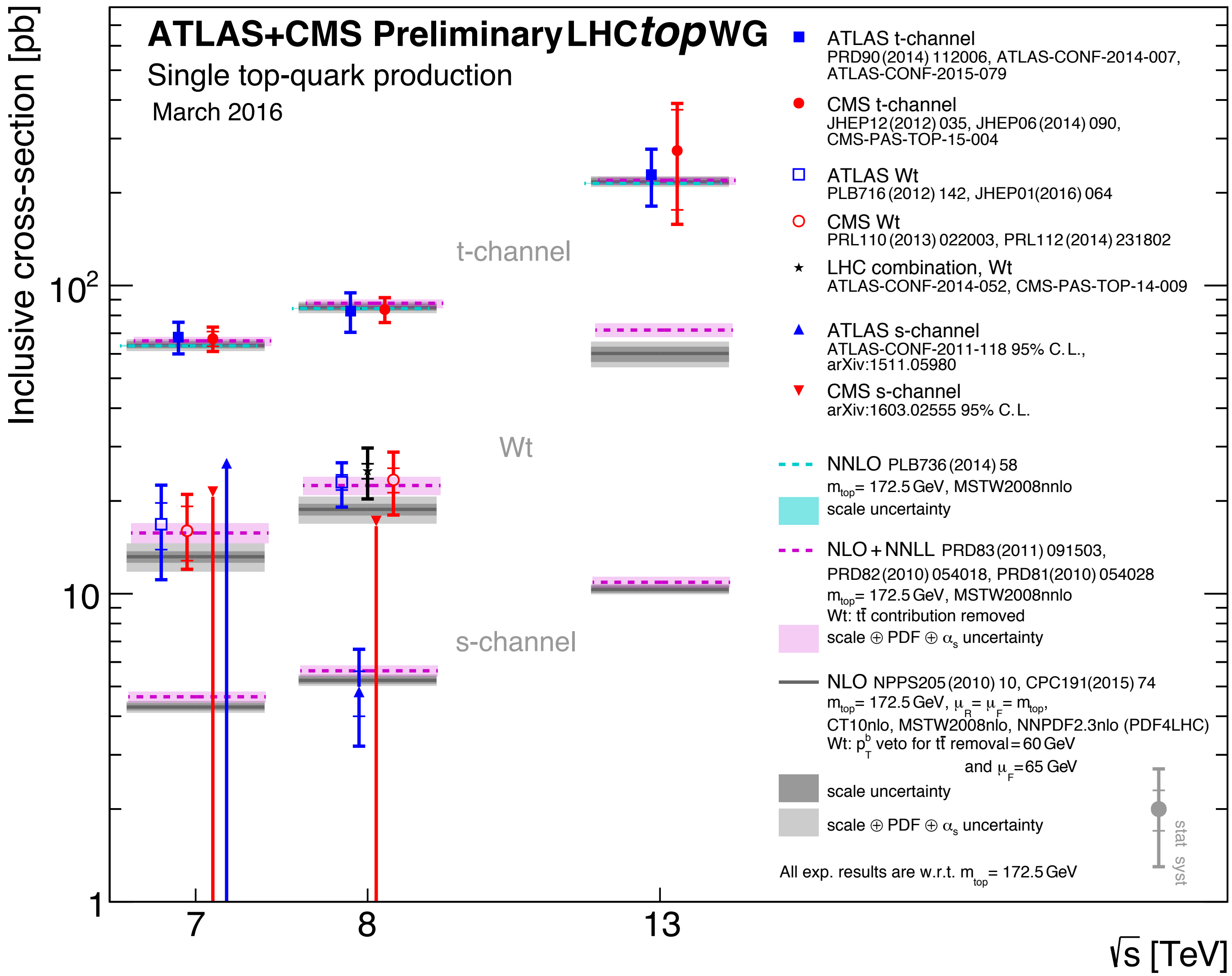
Source	$\Delta m_t{}^{fit}$ [GeV]	$\Delta m_t{}^{O^{(1)}}$ [GeV]	$\Delta m_t{}^{O^{(2)}}$ [GeV]
Theory uncertainties			
μ_R/μ_F scales $t\bar{t}$	$\{^{+1.61}_{-2.29}$	$\{^{+1.70}_{-2.91}$	$\{^{+1.79}_{-2.71}$
μ_R/μ_F scales tW	$\{^{+0.06}_{-0.05}$	$\{^{+0.08}_{-0.11}$	$\{^{+0.07}_{-0.09}$
ME-PS matching scale	$\{^{+0.91}_{-1.06}$	$\{^{+0.99}_{-0.99}$	$\{^{+1.08}_{-0.79}$
Parton density functions	±0.35	±0.38	±0.37
Top quark p_T	$+0.78$	$+0.85$	$+1.15$
Underlying event	±0.82	±0.56	±0.57
Color reconnection	±0.48	±0.66	±0.51
Signal model	±1.29	±0.71	±0.61
$t\bar{t}$/tW interference	±0.48	±0.55	±0.60
tW normalization	±0.05	±0.07	±0.07
Total theory	$\{^{+2.63}_{-3.05}$	$\{^{+2.50}_{-3.34}$	$\{^{+2.67}_{-3.07}$
Experimental uncertainties			
Jet energy scale	±0.05	±0.05	±0.05
Jet energy resolution	$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Lepton energy scale	±0.37	$\{^{+0.24}_{-0.48}$	$\{^{+0.22}_{-0.51}$
Lepton selection efficiency	±0.04	±0.08	±0.08
b tagging	±0.02	±0.02	±0.02
Misidentification efficiency	±0.03	±0.09	±0.09
Pileup	±0.16	±0.24	±0.27
Background normalization	±0.33	±0.45	±0.35
Total experimental	±0.53	$\{^{+0.60}_{-0.73}$	$\{^{+0.51}_{-0.69}$
Total systematic	$\mathbf{+2.68 - 3.09}$	$\mathbf{+2.57 - 3.42}$	$\mathbf{+2.72 - 3.14}$

- Small experimental errors (great)
- Very large theory error (but is LO – will improve)
- MC related errors are large O(1 GeV) even in this "cleanest" observable…

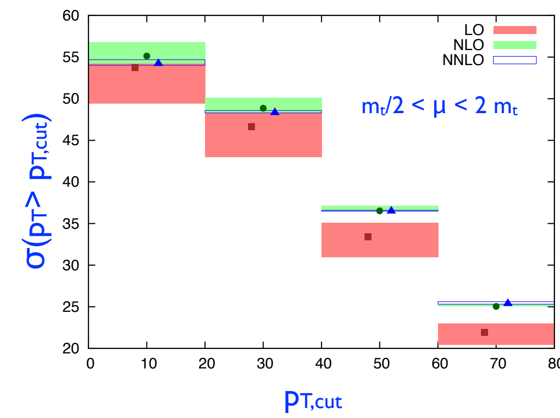
Single top and associated top-pair production

Single top

- Latest LHC comparison



LHC 7 TeV



Brucherseifer, Caola, Melnikov ‘14

- Newest work: NLO+offshell+shower

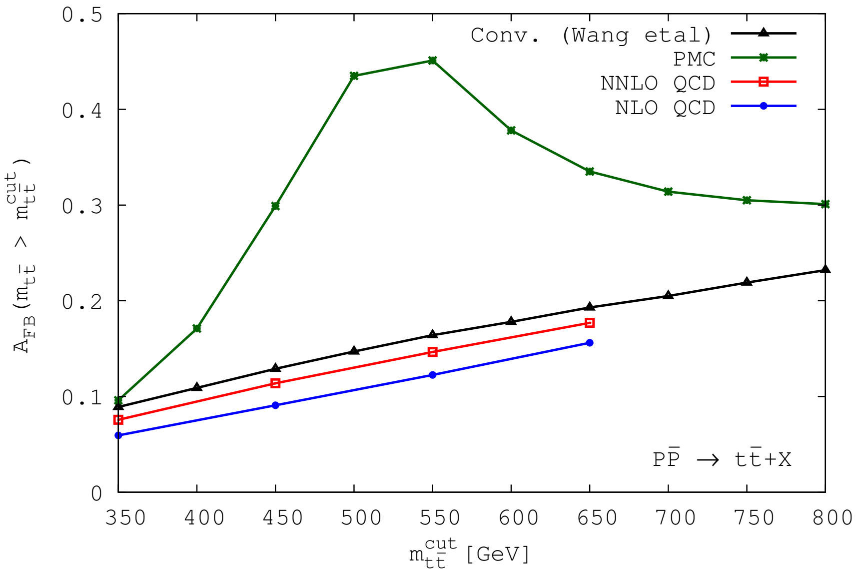
Frederix, Frixione, Papanastasiou, Prestel, Torrielli
arXiv:1603.01178v1

- Precision comparison only down the road at 13 TeV

Conclusions

- Precision requires understanding of scales in the "usual" scale approach (BLM approach not considered here but there could be serious differences→)

$A_{FB}(M_{tt})$:
BLM/PMC versus usual scales
from arXiv:1601.05375v1



- We have performed such a study and find that indeed, not all scales "are equal".

- We believe that our motivation, as well as many of the conclusions, would be applicable to more processes that are now known at NNLO (and beyond).

- The above is needed in order to "quantify" precision.

- Future promises:
  - Top production + decay at NNLO
  - NNLO QCD + EW (needed in multi TeV range)
  - Top jets for TeV tops

- Top quark mass: made the point that increased precision needs good understanding of theory uncertainties. IMHO, there is much work left to do there…