NNLO corrections to top pair differential distributions at hadron colliders

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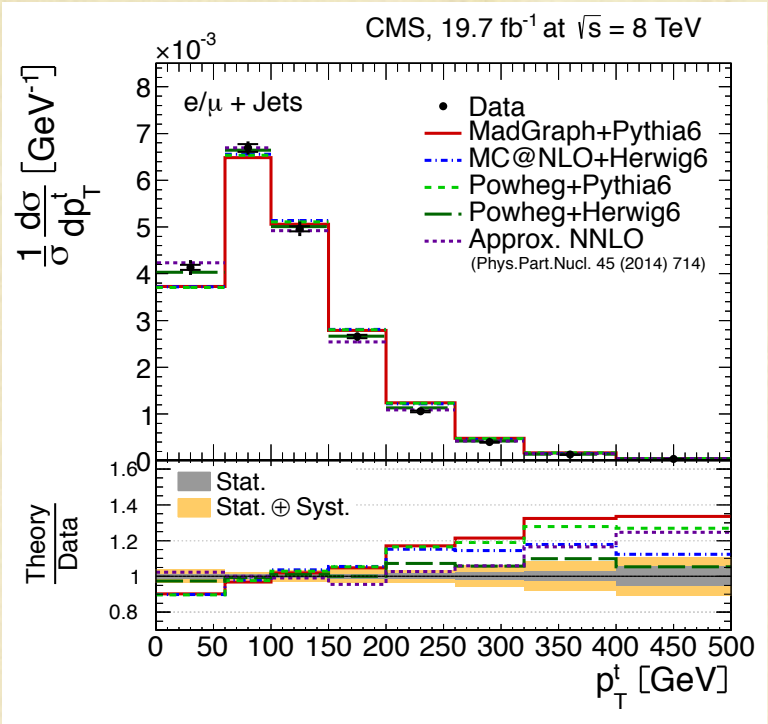
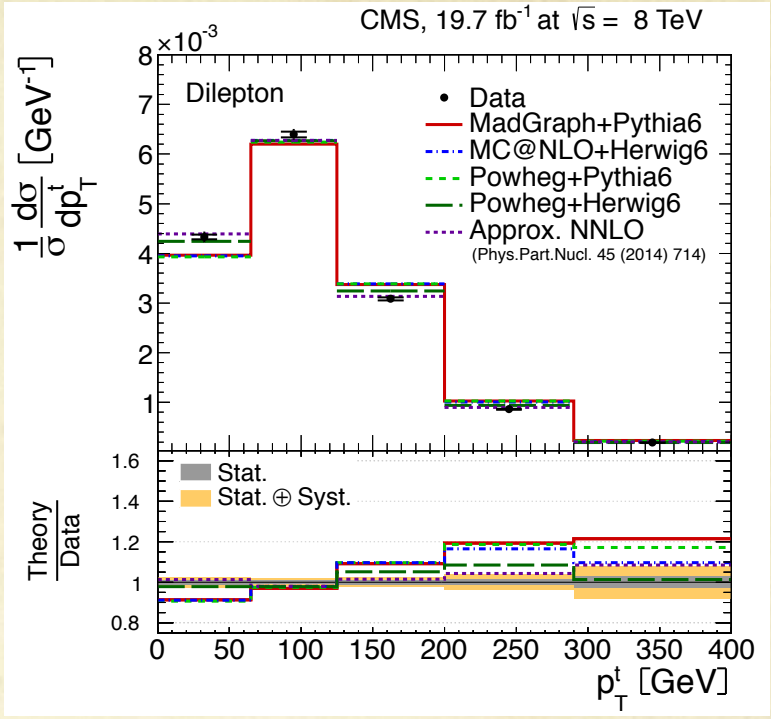
Work with Michael Czakon, Paul Fiedler and David Heymes

arXiv:1511.00549 + to appear

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.

More details about what is computed

- ✓ Calculations is complete and exact:
  - All partonic reactions
  - No approximations made (like, for example, leading color)
- ✓ Results for LHC 8 TeV
- ✓ Calculation done with fixed scales: $\mu_R=\mu_F=m_t$.
  - Done for simplicity and for cross-checks. Eventually will switch to dynamic scales
  - Pheno is OK since our ranges are not large (for example $P_T<400$ GeV)
- ✓ Scale variation: with independent $\mu_{R,F}$ variation.
- ✓ For now results with only one pdf set (MSTW2008). No pdf error computed
  - Eventually will study many pdf's (but see Tevatron results below)
  - Pdf error smaller in absolute distributions
  - In normalized distributions pdf error as large as scale

More details about the calculation

- ✓ First calculation done in the 4-dimensional STRIPPER formulation
  - Main advantage: use standard tree-level amplitudes
- ✓ Calculation done in double precision
  - Except for the evaluation of the one-loop 2-to-3 amplitude
- ✓ New implementation of STRIPPER in C++
  - Further details can be found in M. Czakon's RADCOR 2015 presentation
- ✓ Overall speedup compared to our previous code is a factor of O(100).
- ✓ Results cross-checked with earlier CDR Tevatron calculation (will show in the following)

Czakon, Heymes '14

A. van Hameren's library

S. Dittmaier's library

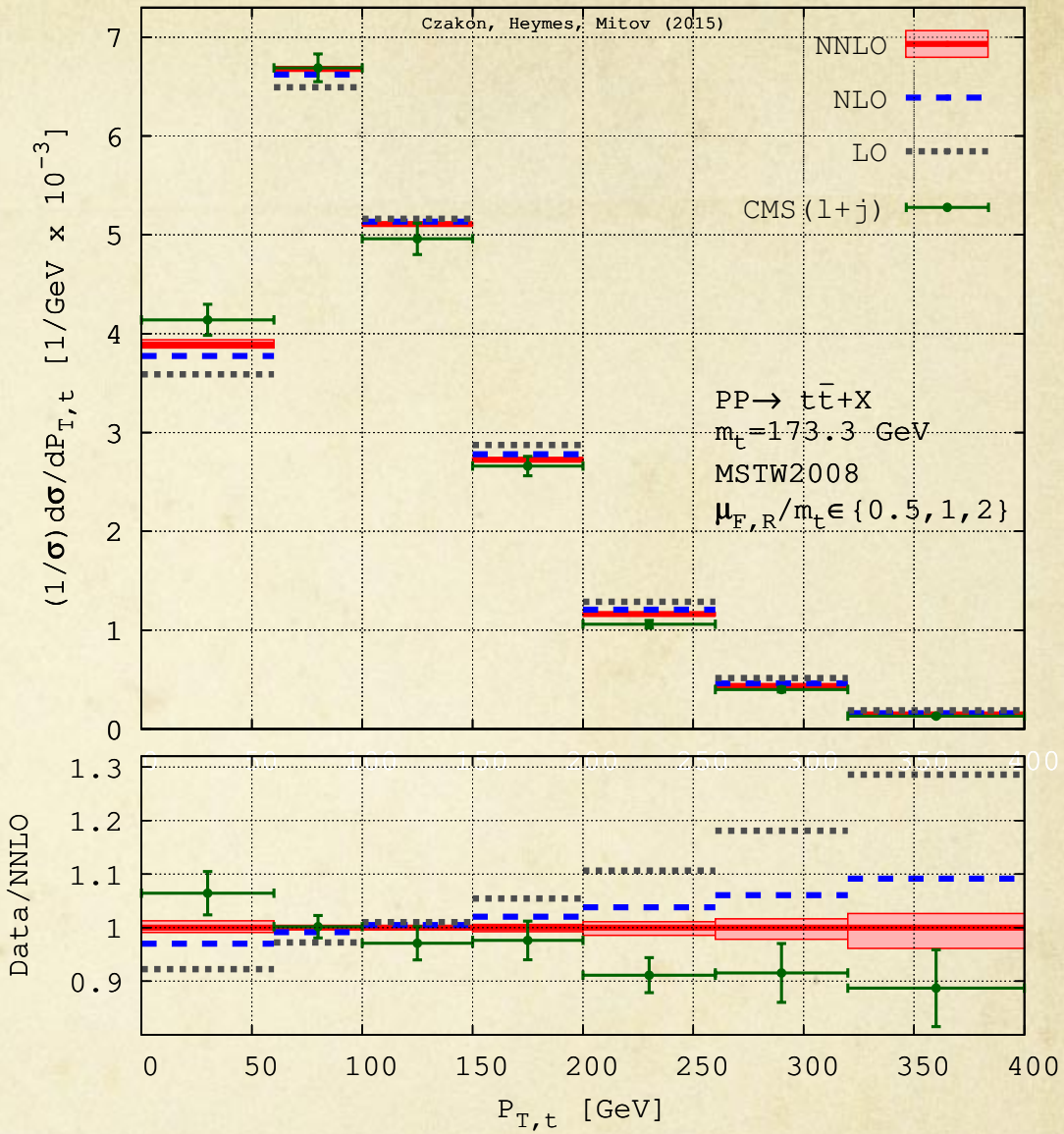
Czakon, Heymes

The LHC top P_T discrepancy

- ✓ 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.

See Peter Richardson's talk

- ✓ 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 CMS data.
  - Pdf error not included



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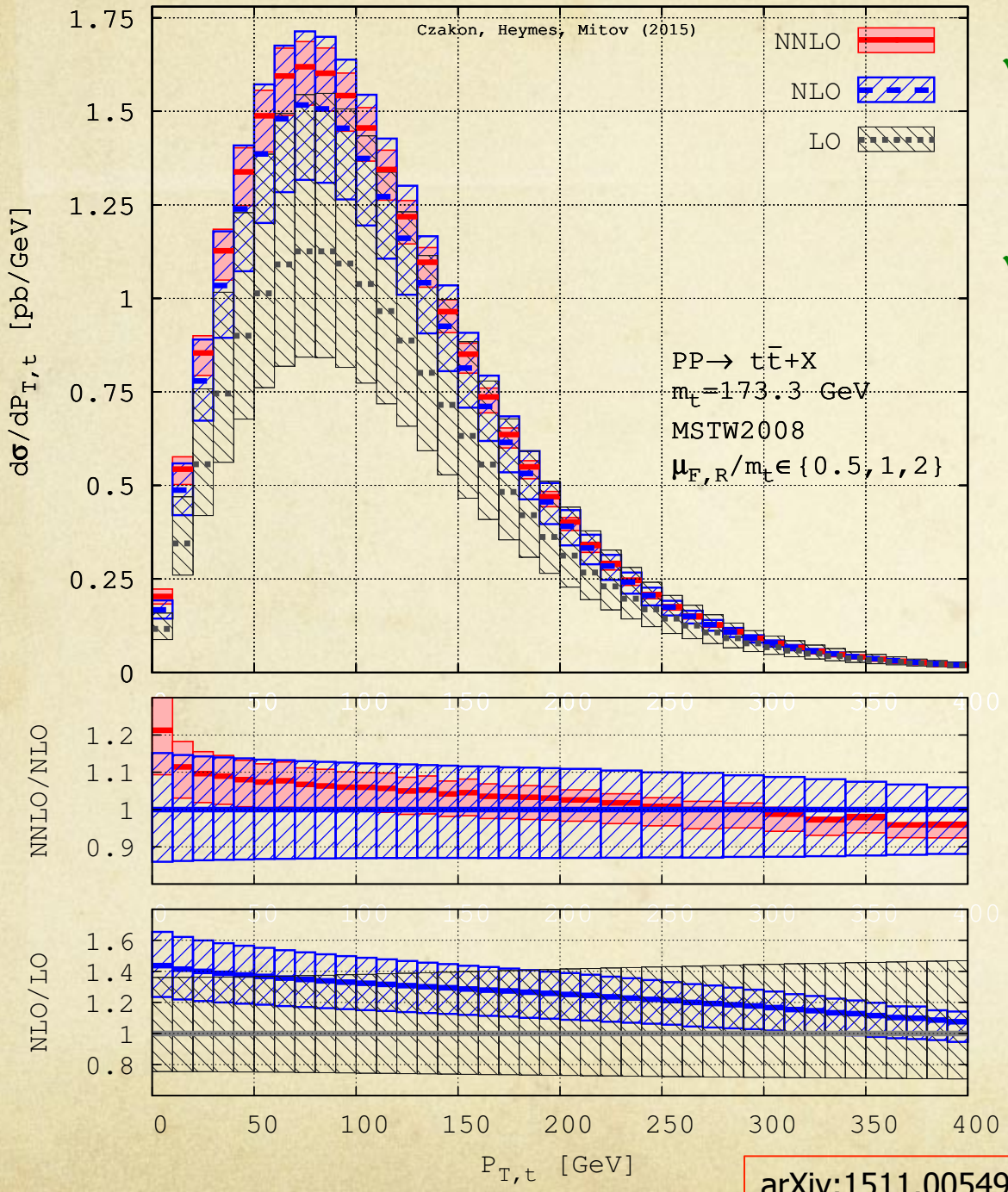
The LHC top P_T discrepancy



- ✓ 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

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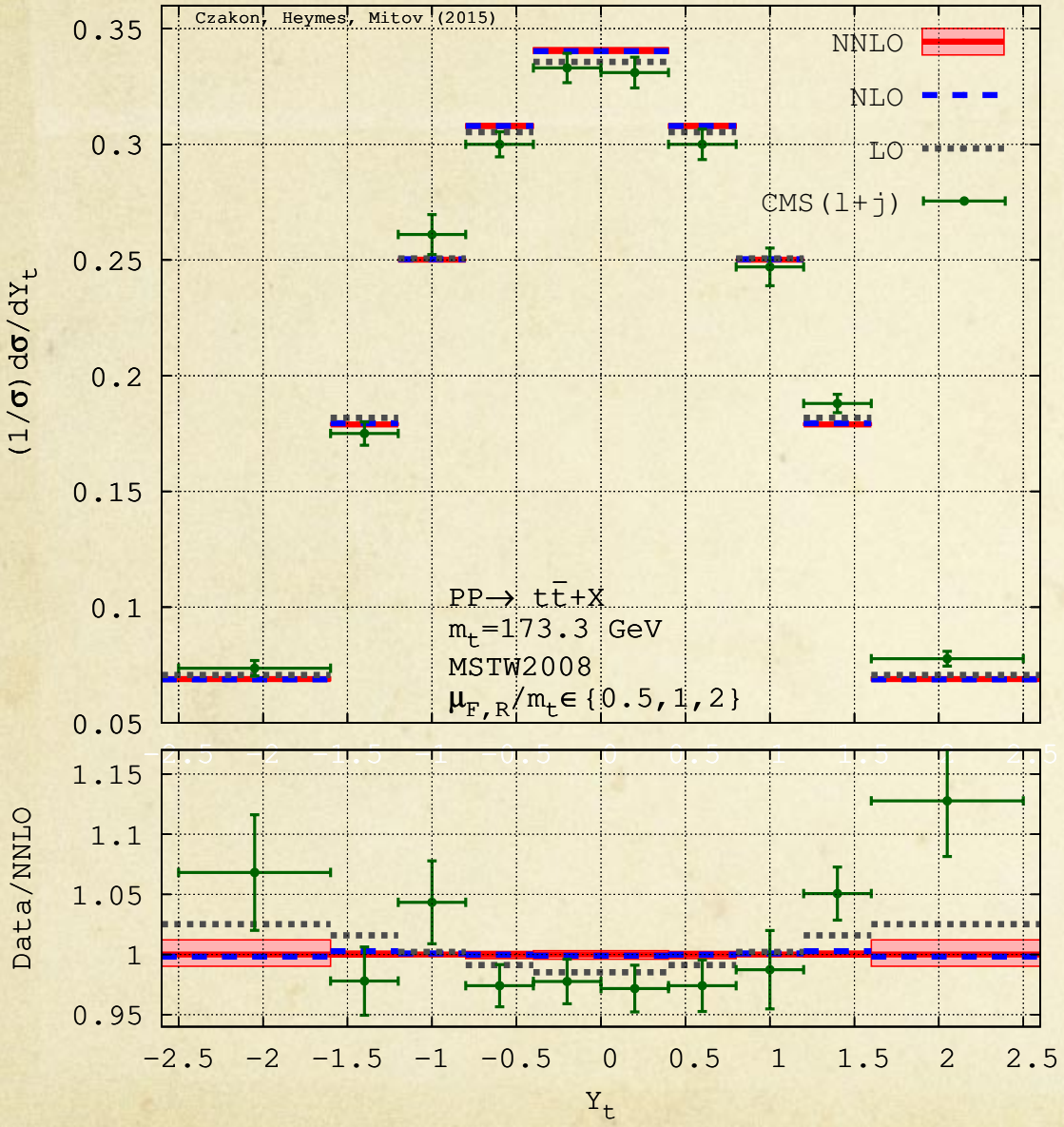
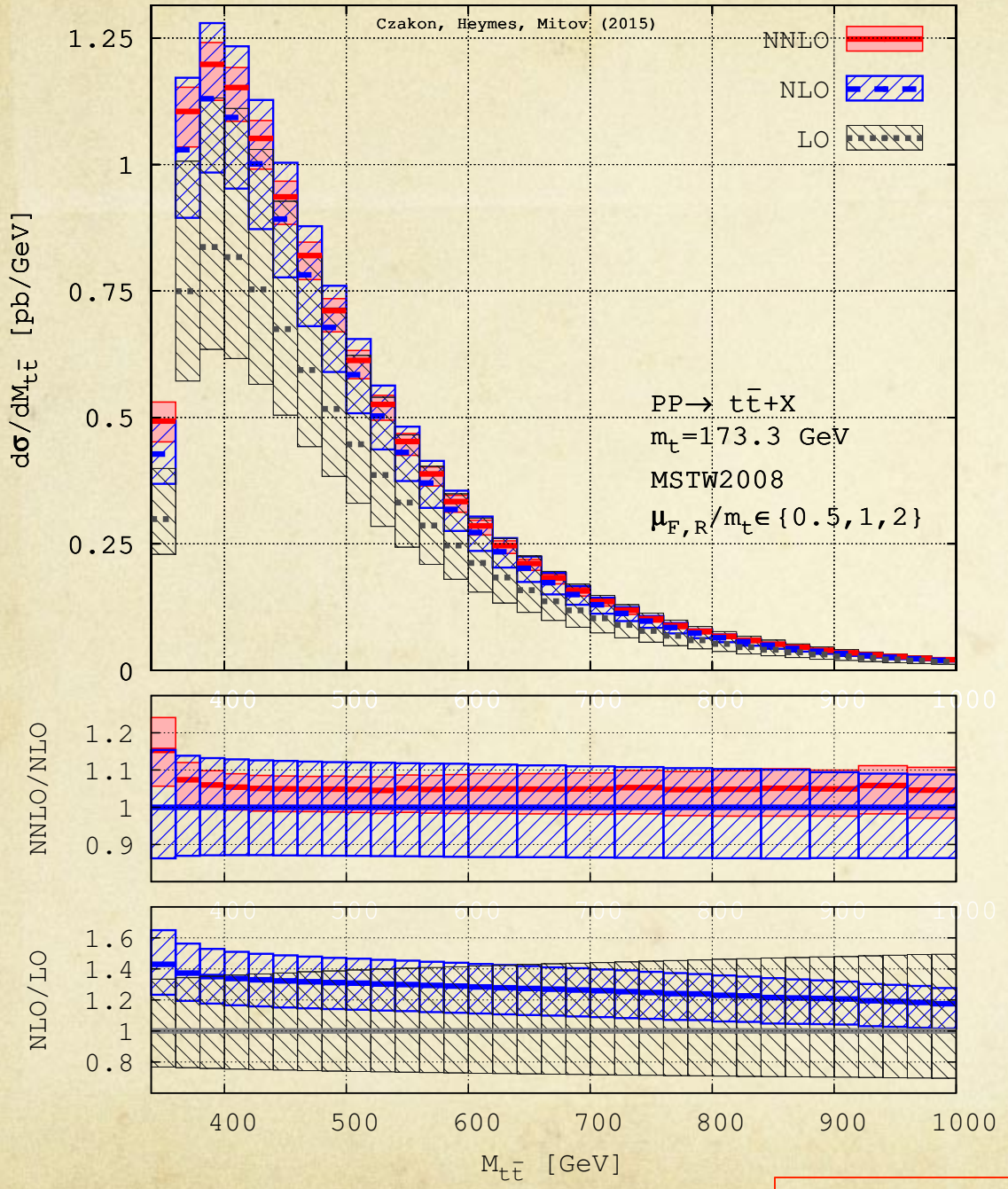
The LHC top y_t distribution



- ✓ Stable w/r to NNLO corrections
  - Partly due to bin size
- ✓ Data error is still large; can't draw serious conclusions just yet
- ✓ (Slight mismatch in sizes of the highest bin)

arXiv:1511.00549

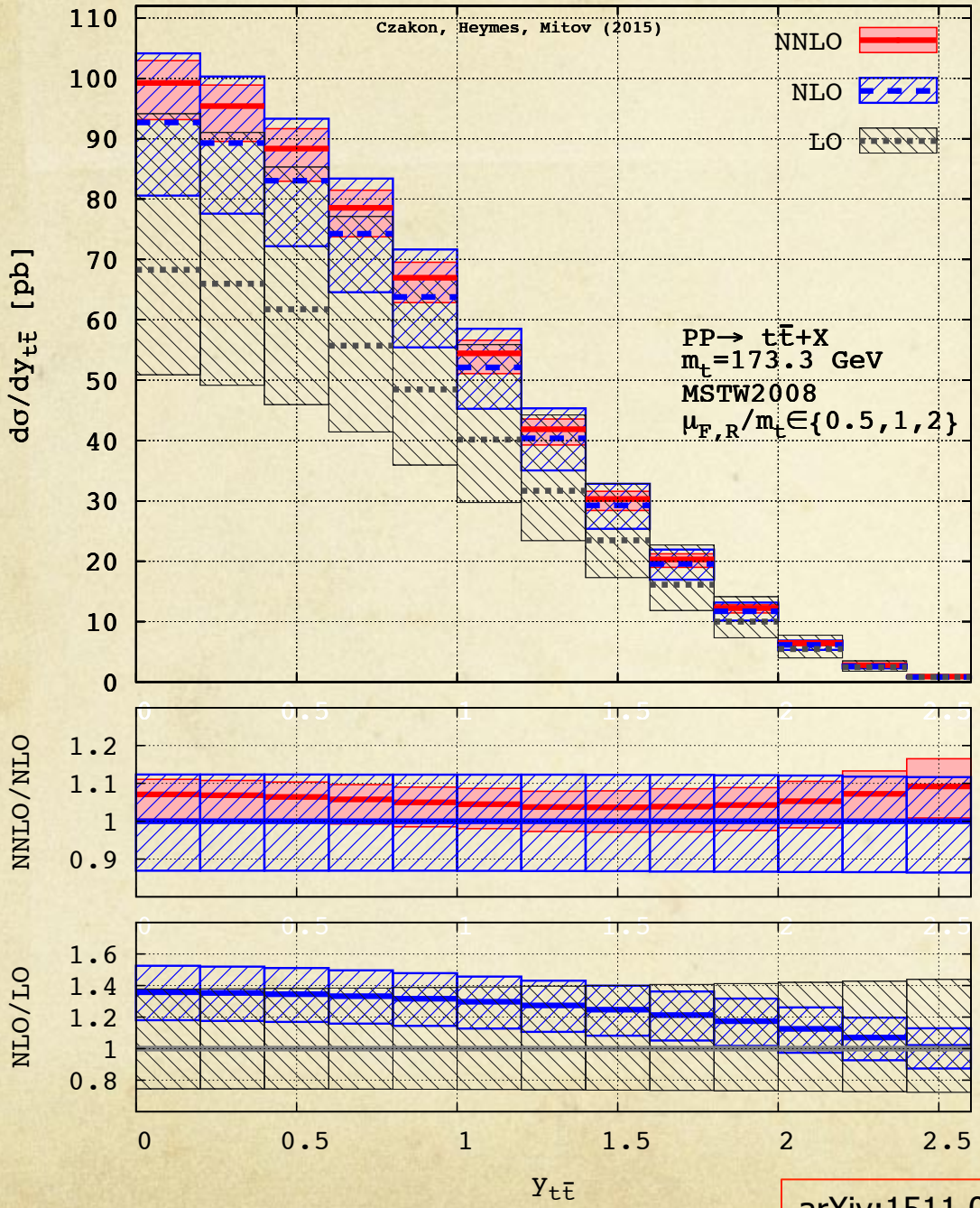
The LHC top M_{tt} distribution



- ✓ 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?

arXiv:1511.00549

The LHC top y_{tt} distribution



- ✓ The quality of the calculation is high:
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  - Convergence
  - Decrease of scale error
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Differential results for the Tevatron

- ✓ Calculations is also complete and exact
- ✓ Fixed scales and the rest similar to LHC
- ✓ Computation is older: done in CDR.

Czakon, Fiedler, Heymes, Mitov – to appear

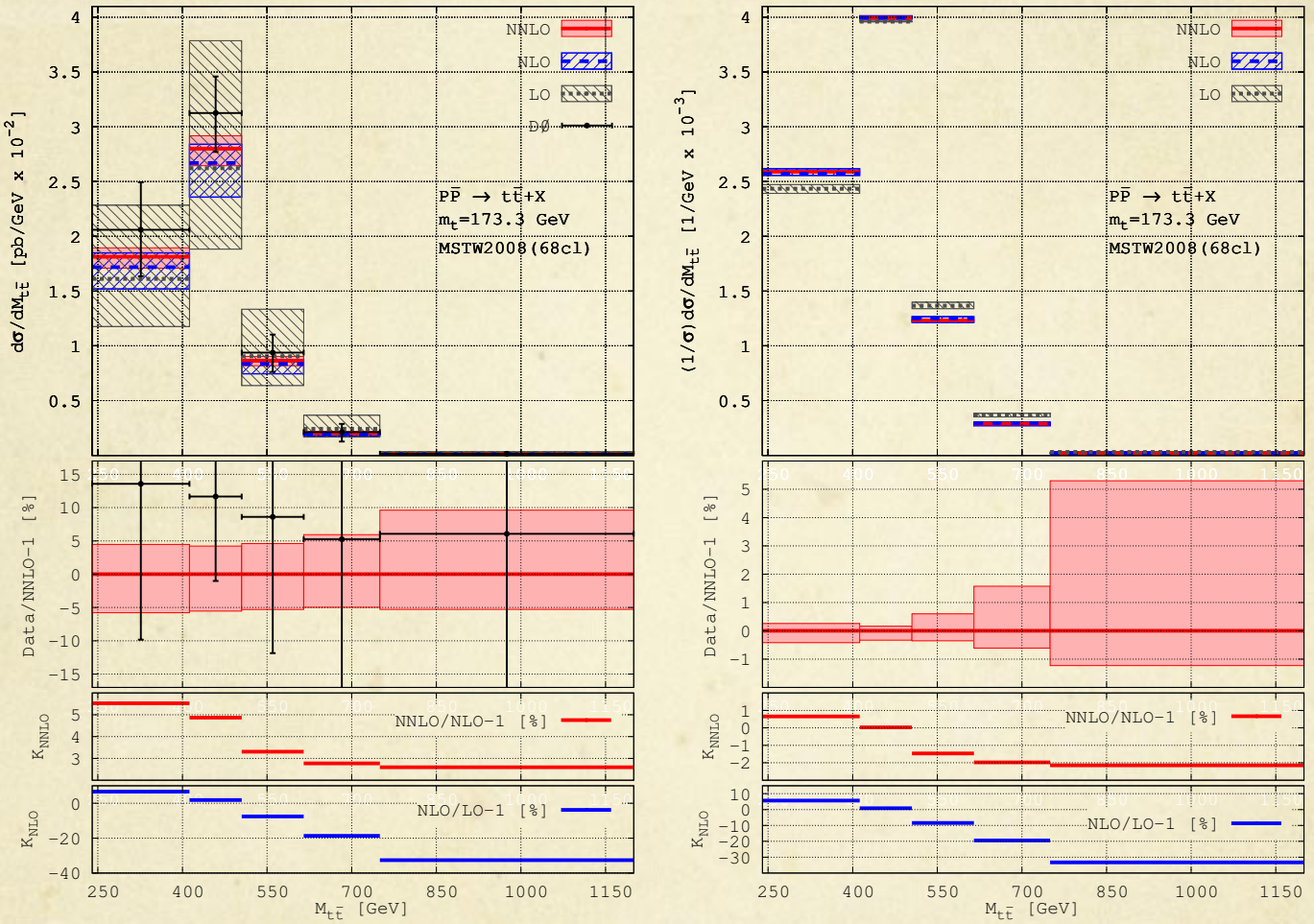

Figure 1. The $M_{t\bar{t}}$ distribution computed through NNLO in QCD and compared to data from the DØ Collaboration [15]. The plot on the left shows the absolute normalisation, while the one on the right the same distribution but normalised to unity. The plots show the ratio of data to NNLO QCD as well as the NNLO/NLO and NLO/LO K-factors $K_{\rm NNLO}$ and $K_{\rm NLO}$. The error of the theory predictions at NLO and NNLO are from adding scales and pdf in quadrature.

Differential results for the Tevatron

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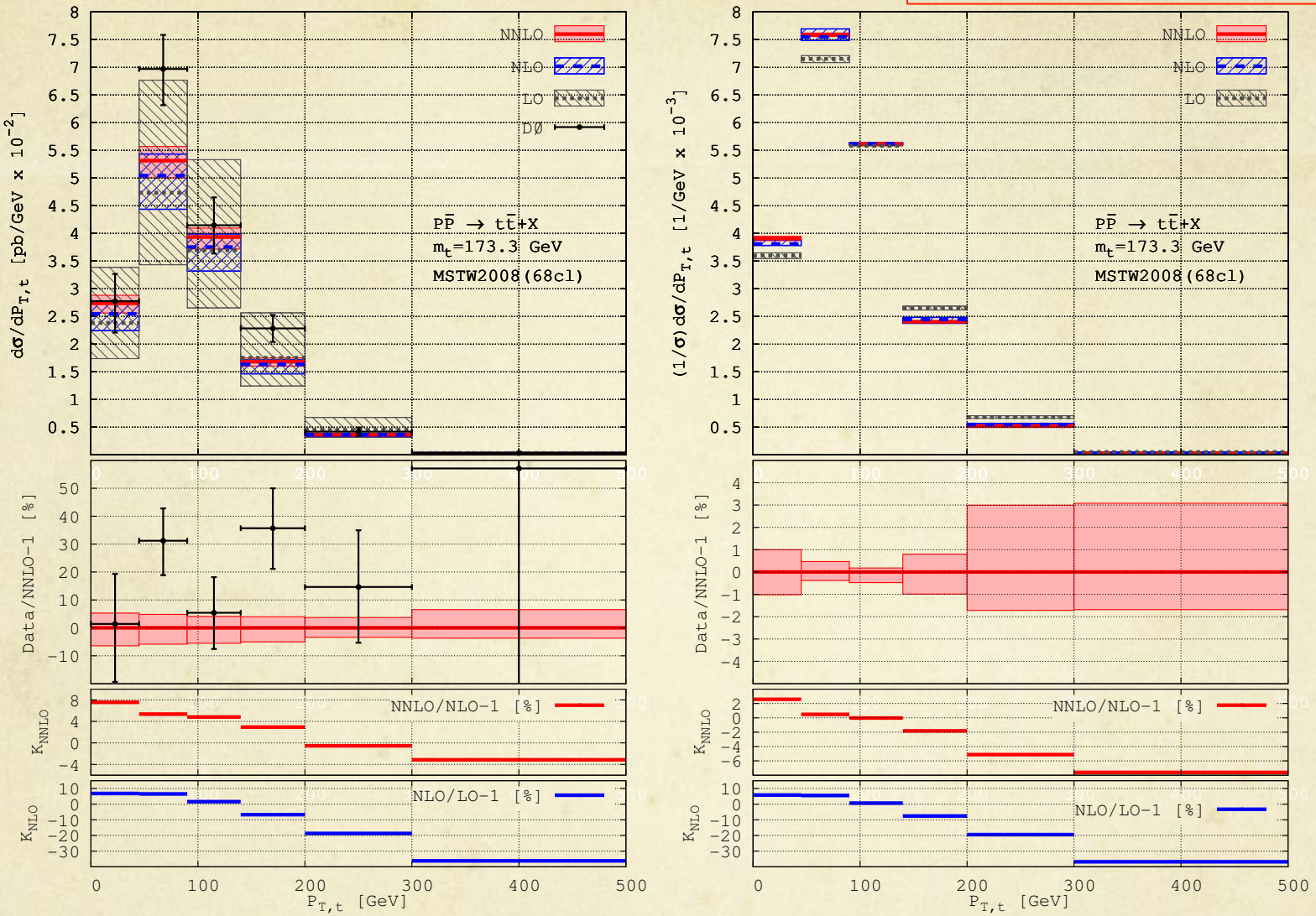

Figure 2. The $P_{T,t}$ spectrum computed through NNLO in QCD and compared to data from the DØ Collaboration [15]. The plot on the left shows its absolute normalisation, while the one on the right the same distribution but normalised to unity. The plots also show the ratio of data to NNLO QCD as well as the NNLO/NLO and NLO/LO K-factors $K_{\rm NNLO}$ and $K_{\rm NLO}$. The error of the theory predictions at NLO and NNLO is derived by adding in quadrature errors from scales and pdf.

Differential results for the Tevatron

Czakon, Fiedler, Heymes, Mitov – to appear

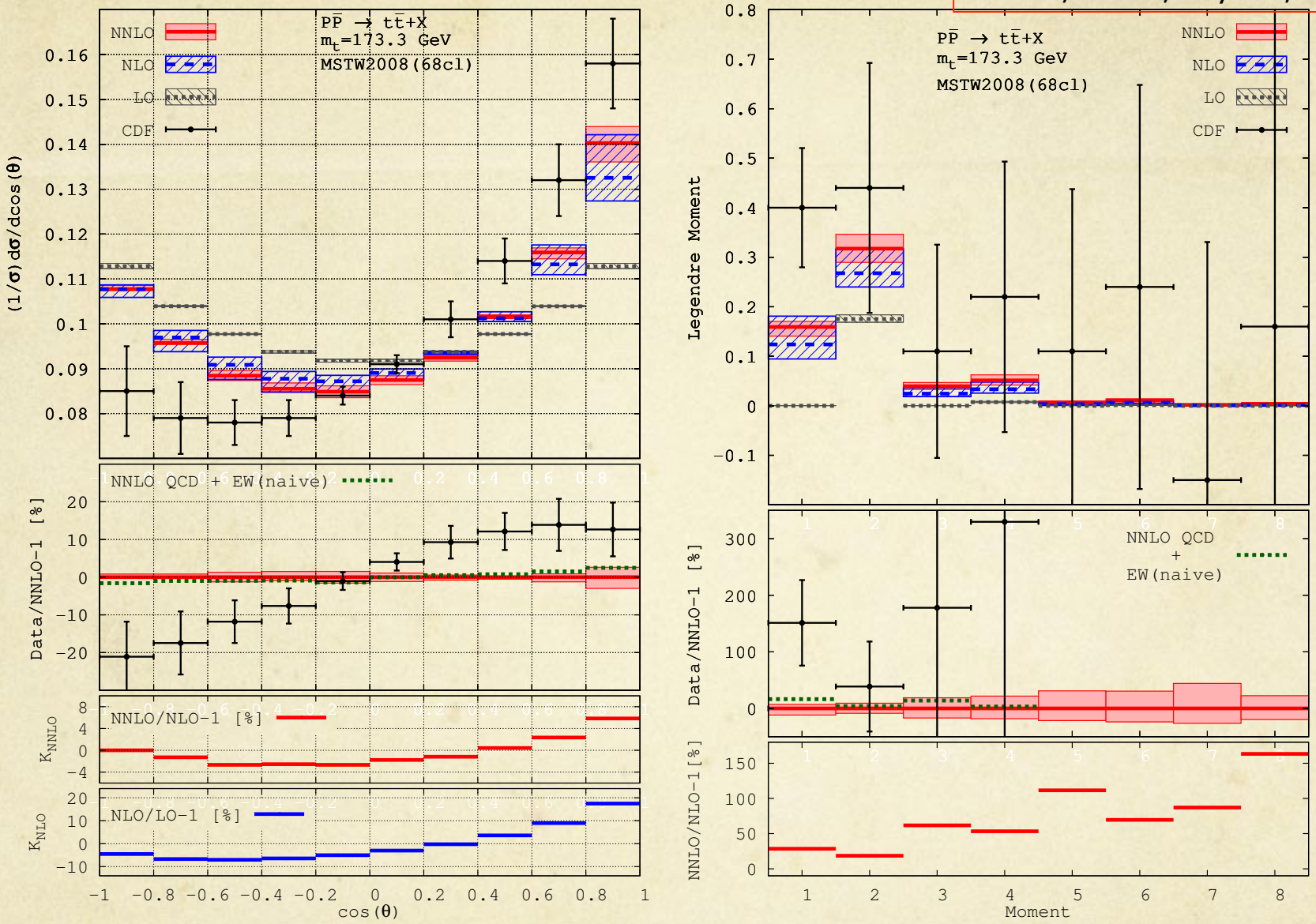

Figure 4. The normalised top quark $\cos\theta$ distribution (left) and related Legendre moments (right) through NNLO QCD compared to data from Ref. [16]. Also shown is a naive estimate of the EW corrections (see text) as well as the K-factors $K_{\rm NNLO}$ and $K_{\rm NLO}$. The error of the theory predictions is based on scale variation only.

PDF dependence: absolute normalization at the Tevatron

Czakon, Fiedler, Heymes, Mitov – to appear

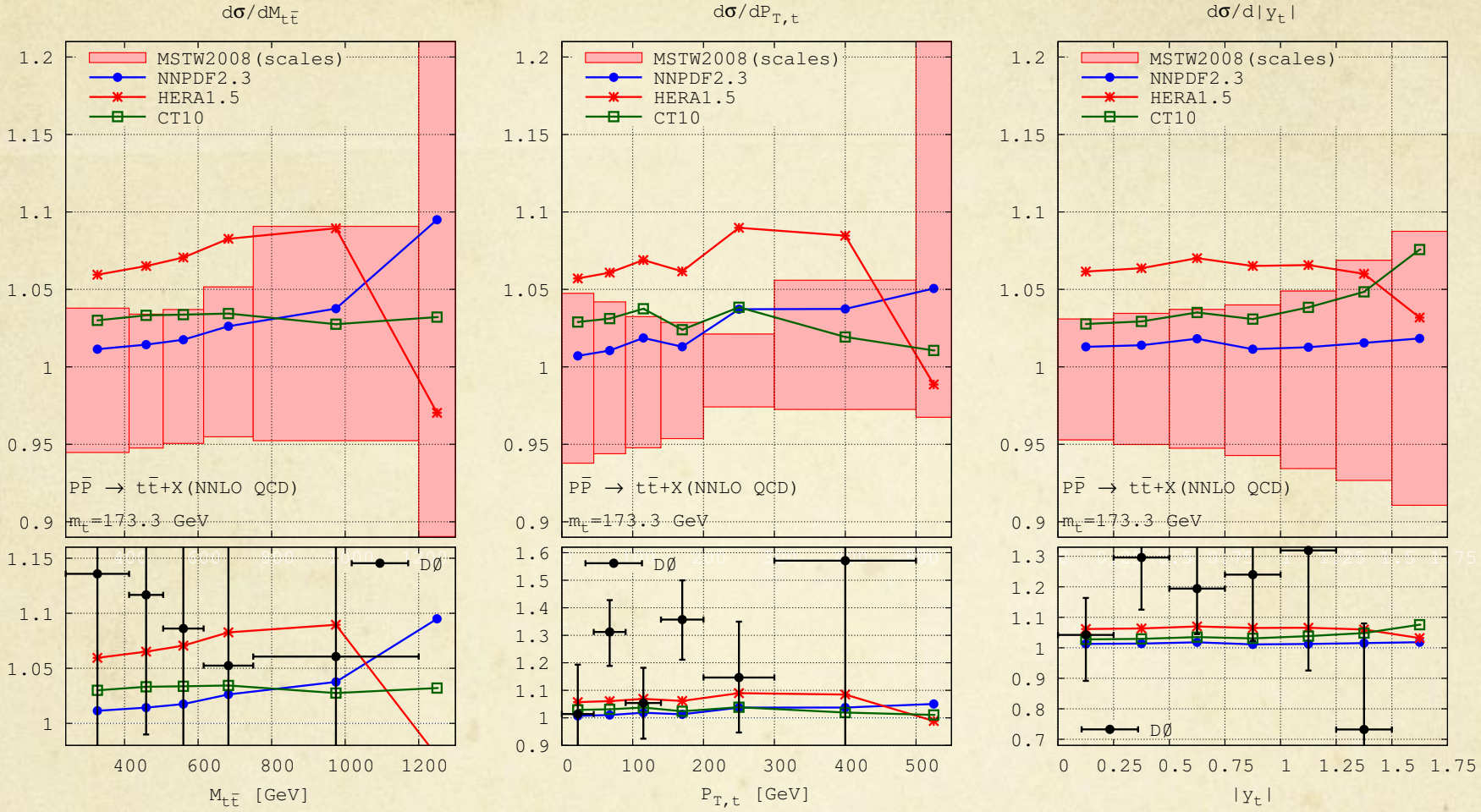

Figure 10. NNLO QCD prediction for three differential distributions (in $M_{t\bar{t}}$, $P_{T,t}$ and $|y_t|$) with four pdf sets. Given are the ratios of the CT10, HERA 1.5 and NNPDF 2.3 based predictions with respect to MSTW2008. For reference also the scale dependence of the MSTW2008 prediction is 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 – to appear

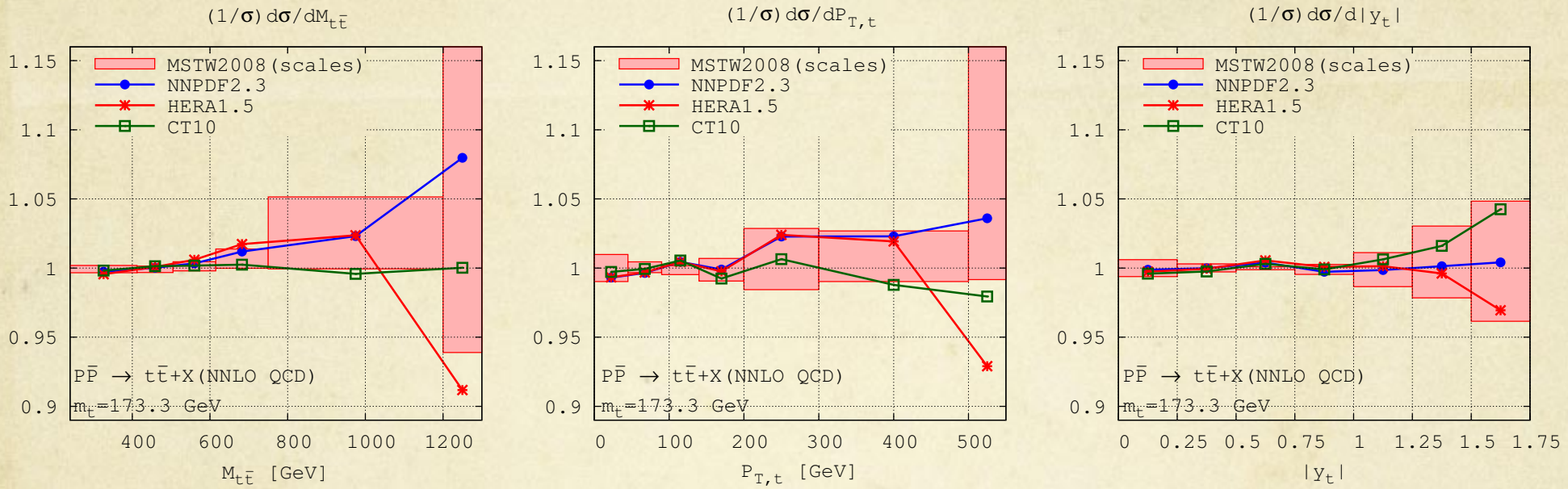

Figure 11. As in fig. 10 but for the normalised to unity distributions.

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

Summary and Conclusions

- Clearly, top physics is in precision phase
- High quality agreement between SM and Tevatron/LHC measurements at all collider energies.
- Total and differential x-section for tT production now known in full NNLO.
  - So far all is for stable tops.
- Important phenomenology ahead:
  - Constrain and improve PDF's
  - Searches for new physics
  - Very high-precision test of SM (good th/exp agreement so far!)

Future directions

- Top decay
- Combine with EW corrections
- Understand properly the TeV P_T region (large collinear logs, etc.)
  - + introduce dynamic scale setting
- Plenty of interesting phenomenology!