Differential top pair production in NNLO QCD

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Work in progress with Michael Czakon and Paul Fiedler

The main point

- We have huge effort ongoing for the calculation of
  - Fully differential top pair production at NNLO
  - Everything is included – no approximations!
  - Stable top quarks only. Down the road include decay but not a priority now.
  - For the moment we compute only pre-decided binned distributions.
  - Cannot store events for subsequent analyses.
  - Calculations are very expensive and take long time. It is not easy at all to redo a calculation to change it "a little bit". Of course we will make the effort if the need is there

  - For the moment we compute simultaneously with several fixed scales mu_R, mu_F =(1/2,1,2)*M_{top}. Dynamical scales in the future.

  - Use mostly MSTW2008, but we also have almost everything computed also with NNPDF, CT10 and HERA.

  - Calculations for now only for LHC7 and LHC8. Any energy can be done – matter of CPU!
  - Tevatron computed, too.
  - M_{top}=173.3 GeV only. If top mass dependence is needed separate calculations will have to be done. CPU constrained. Perhaps compute for 3 M_{top} values that are 1 GeV apart and use them to approximate in a narrow window. Good enough?

The main point

- No papers yet. However:
  - Tevatron results ready to go (matter of days).
  - LHC results much less ready. Mostly will need time for more runs. Timescale ~ weeks.
- Major point to stress: the calculation is fully automated and completely generic. If it works for one collider/energy should work for all! Our Tevatron results are of very high quality and in our eyes validate what we are doing.

The remainder of the talk:

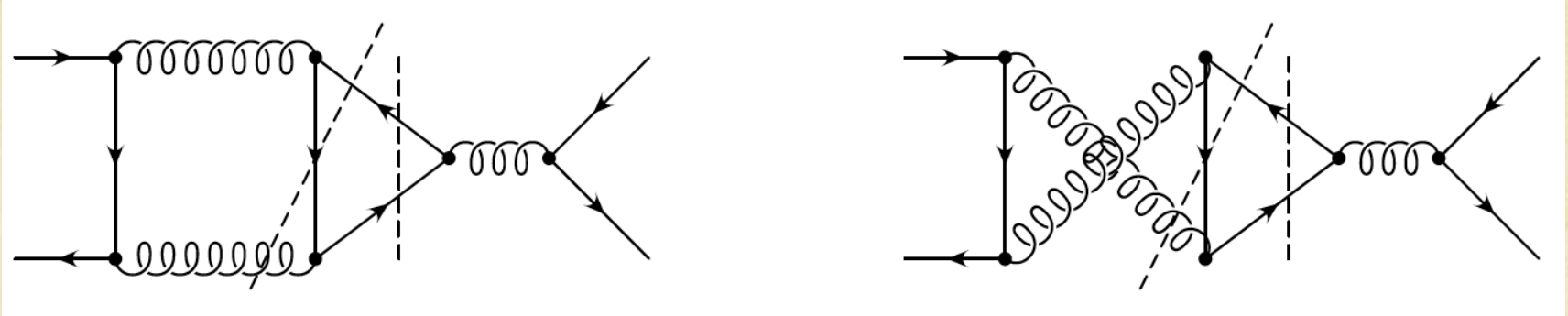
- ✓ Results for the Tevatron (in the context of A_{FB}).
  These results are still preliminary but quite settled.
- ✓ Results for LHC 7 TeV. Extremely preliminary (plotted this morning for the first time …)

The A_{FB} puzzle at the Tevatron

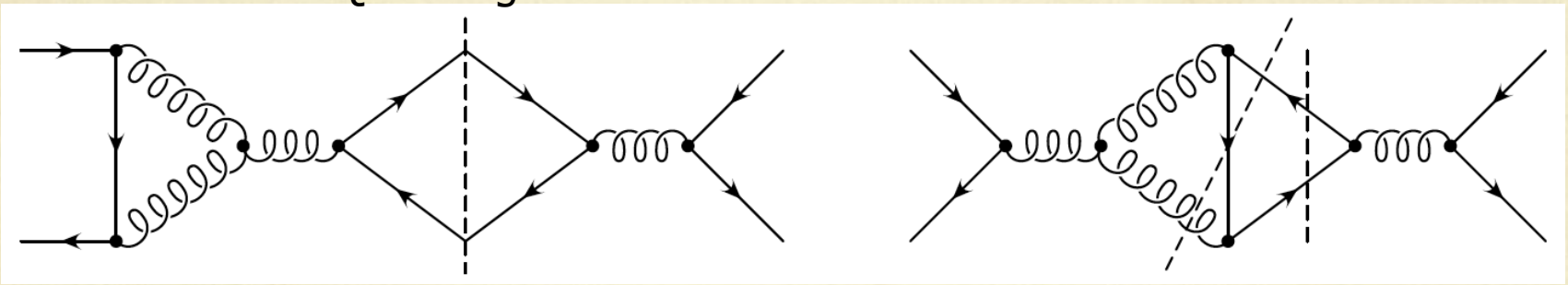
Czakon, Fiedler, Mitov, to appear

QCD diagrams that generate asymmetry:

Kuhn, Rodrigo '98



… and some QCD diagrams that do not:

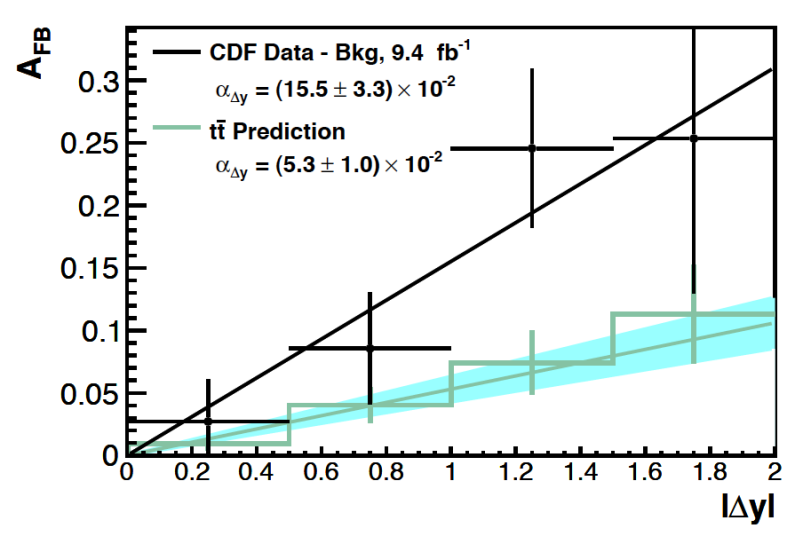


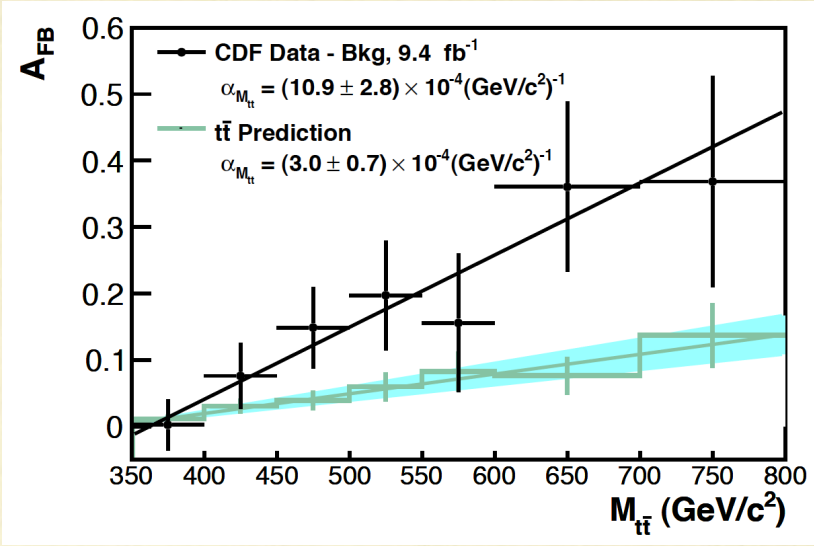
- ✓ For ttbar: charge asymmetry starts from NLO
- ✓ For ttbar + jet: starts already from LO
- ✓ Asymmetry appears when sufficiently large number of fermions (real or virtual) are present.
- ✓ The asymmetry is QED like.
- ✓ It does not need massive fermions.
- ✓ It is the twin effect of the perturbative strange (or c- or b-) asymmetry in the proton!

Definition of the asymmetry:

$$A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

… and the CDF measurement versus (known) SM:





Discrepancy ≤ 3σ

✓ New D0 measurement (2014): it is much lower than CDF and in good agreement with SM

What is known about A_{FB} ?

✓ The largest known contribution to A_{FB} is due to NLO QCD, i.e. $\sim(\alpha_S)^3$.

Kuhn, Rodrigo '98

✓ Higher order soft effects probed. No new effects appear (beyond Kuhn & Rodrigo).

Almeida, Sterman, Wogelsang '08
Ahrens, Ferroglia, Neubert, Pecjak, Yang `11
Manohar, Trott '12
Skands, Webber, Winter '12

✓ F.O. EW effects checked. ~25% effect: not as small as one might naively expect!

Hollik, Pagani '11
Bernreuther, Si '12

✓ BLM/PMC scales setting does the job? Claimed near agreement with the measurements.

Brodsky, Wu '12

✓ Higher order hard QCD corrections? Next slide.

✓ Final state non-factorizable interactions? Unlikely.

Mitov, Sterman '12
Rosner '12

NNLO QCD corrections to A_{FB}

Czakon, Fiedler, Mitov, to appear

✓ Computed AFB following the definition and binning of CDF '12

- Inclusive
- |Δy|
- M_{tt}
- $P_{T,tt}$

$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}, \quad \text{where} \quad \sigma^{\pm} \equiv \int \theta(\pm\Delta y)\, d\sigma$$

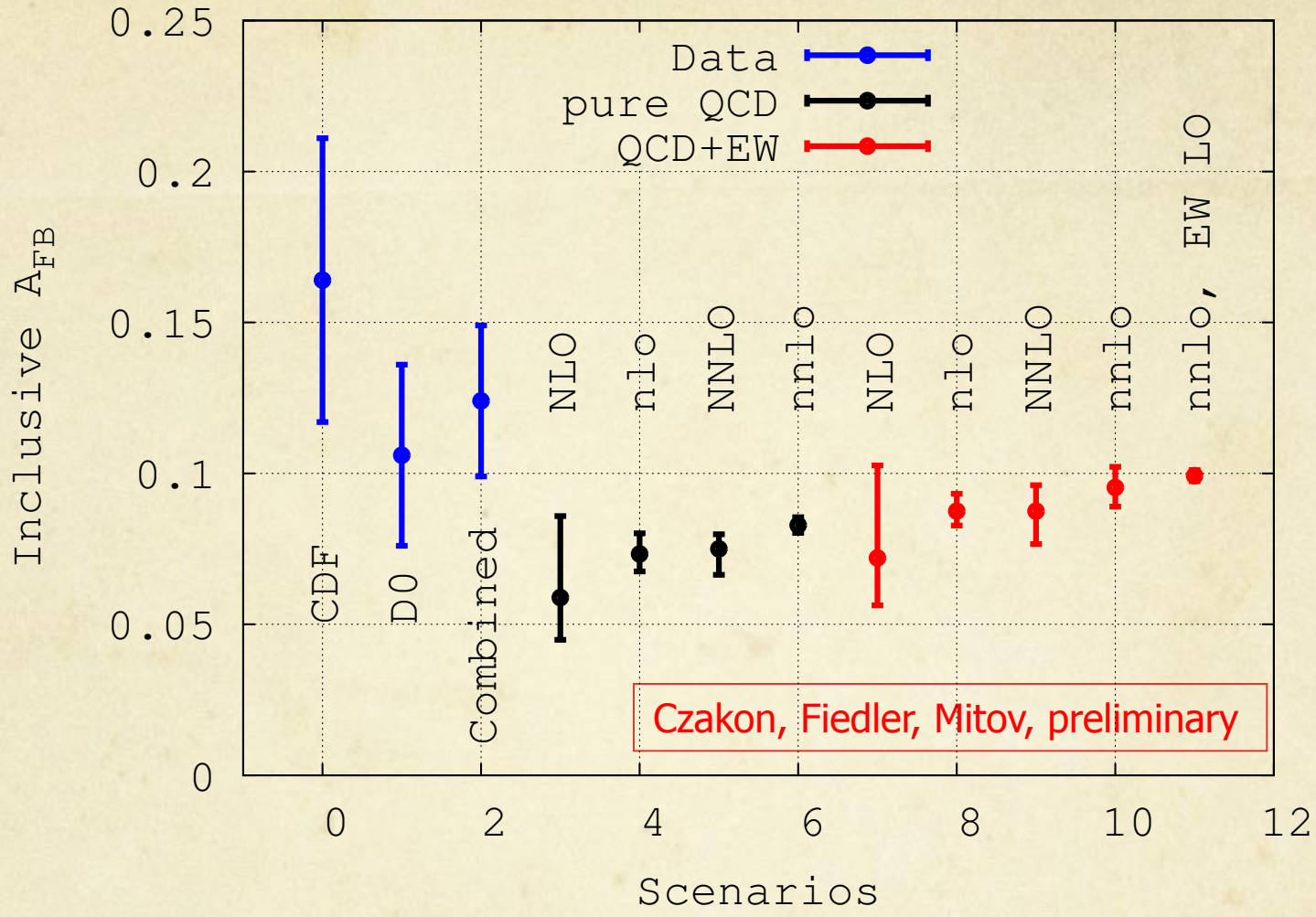
✓ The EW corrections to inclusive A_{FB} included (from Bernreuther, Si '12)

$$\begin{aligned} A_{FB} &\equiv \frac{N_{ew} + \alpha_S^3 N_3 + \kappa\alpha_S^4 N_4}{\alpha_S^2 D_2 + \alpha_S^3 D_3 + \kappa\alpha_S^4 D_4} \\ &= \alpha_S \frac{N_3}{D_2} + \kappa\alpha_S^2 \left(\frac{N_4}{D_2} - \frac{N_3}{D_2}\frac{D_3}{D_2} \right) + \mathcal{O}(\alpha_S^3) \\ &\quad + \frac{N_{ew}}{\alpha_S^2 D_2} \left(1 - \kappa \frac{\alpha_S D_3}{D_2} \right). \end{aligned}$$

Two alternative expansions

NNLO QCD corrections to A_{FB}

- ✓ Checks and quality of the results
  - ✓ Pole cancellation: in each bin, for each scale.
  - ✓ MC errors (from integration) are a big worry due to large cancellation in A_{FB}
  - ✓ Agreement with $sigma_{TOT}$ (Top++) to better than 0.5 permil (each scale)
  - ✓ MC error in each bin is:
    - Few permil for differential distributions
    - Below 1% for AFB in each bin; with only highest Mtt bin with 2%
  - ✓ MC error on inclusive AFB is few permil.
  - ✓ Clearly, the numerical precision of the results is very high.
  - ✓ AT NLO QCD we agree with MCFM and Bernreuther & Si.
  - ✓ Only one more check left at NNLO (the $P_{T,tT}$ spectrum to compare with ttj)
  - ✓ Computed for generic independent μ_F and μ_R (again, non-dynamic = M_{top})



Errors due to scale variation only

How to read the above plot:

- *NLO*, *NNLO* : exact numerator and denominator (see previous slide)
- *nlo*, *nnlo* : expanded in powers of a_S

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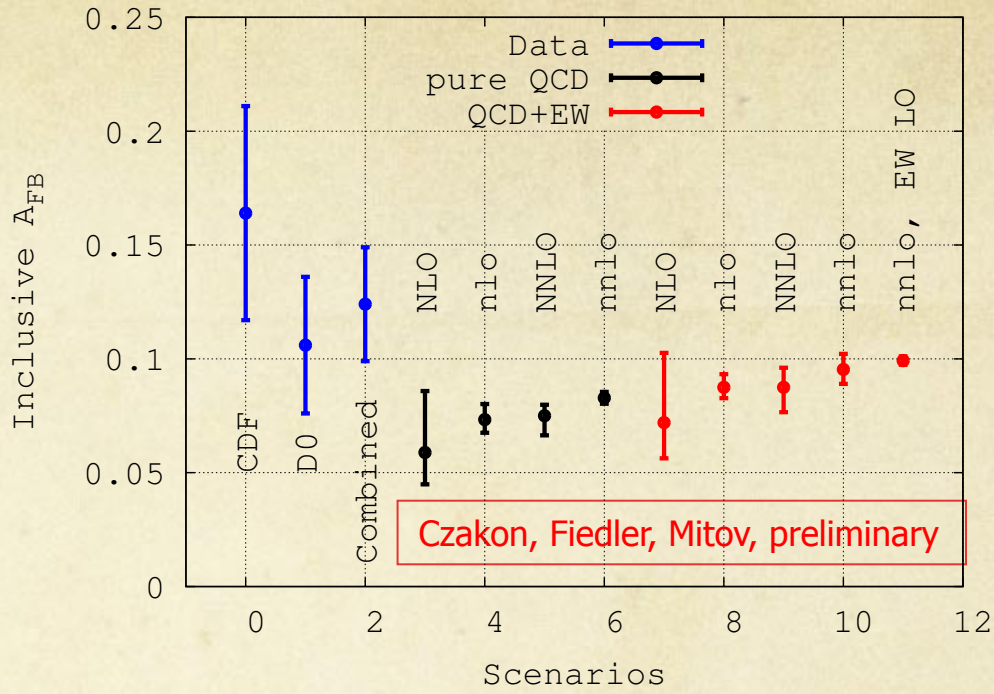


✓ We find large QCD corrections: NLO ~ 30% of LO (recall EW is 25% of LO).

➔ This was not expected, given soft-gluon resummation suggests negligible correction.

✓ Adding all corrections A_{FB} ~ 10%.

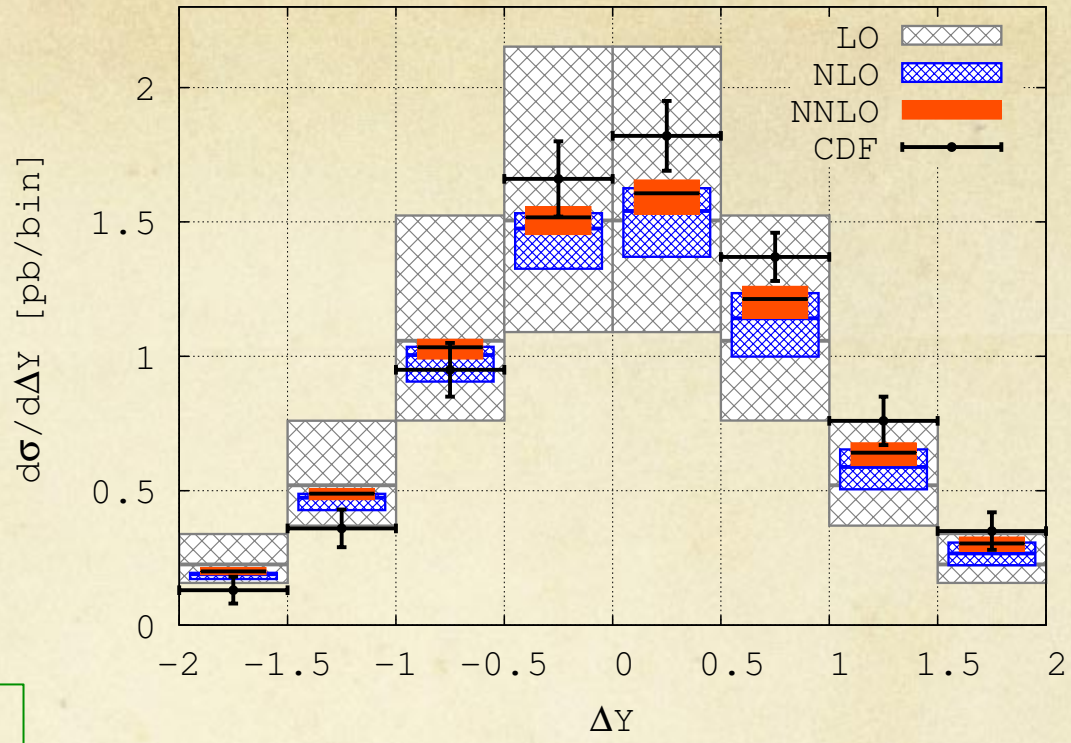
✓ Agrees with D0 and CDF/D0 naive combination
✓ Less than 1.5σ below CDF

✓ We consider this as *agreement* between SM and experiment.

✓ We observe good perturbative convergence (based on errors from scale variation)

✓ Expanded results (both *nlo* and *nnlo*) seem to have accidentally small scale variation

Czakon, Fiedler, Mitov, preliminary



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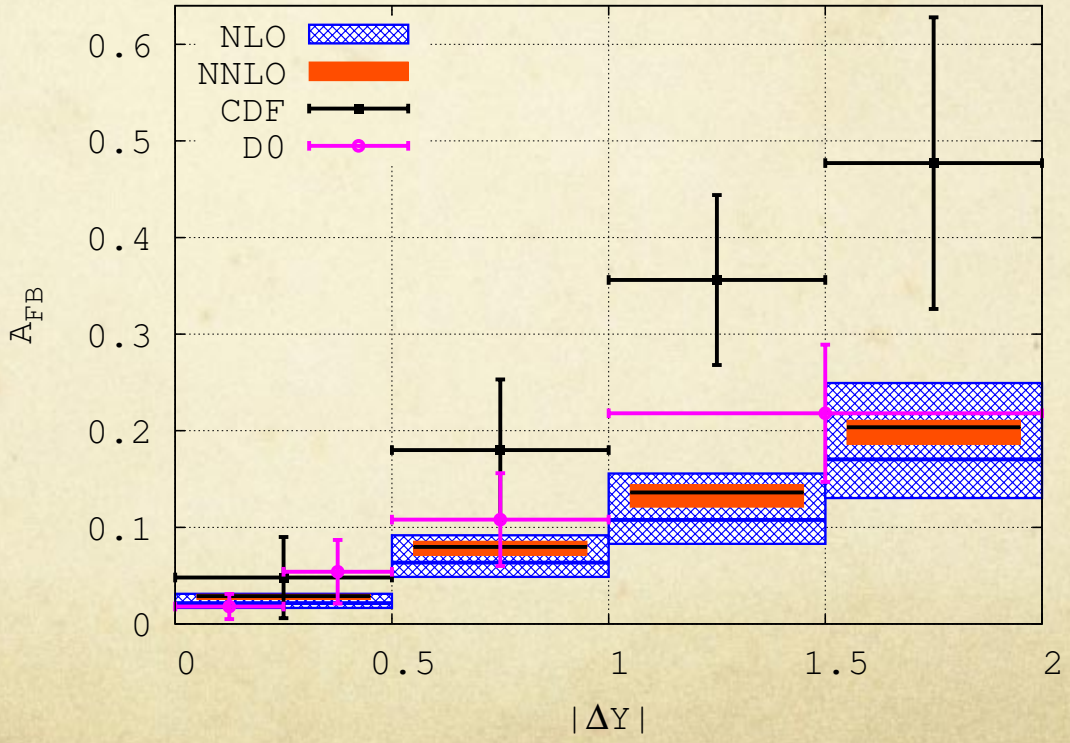

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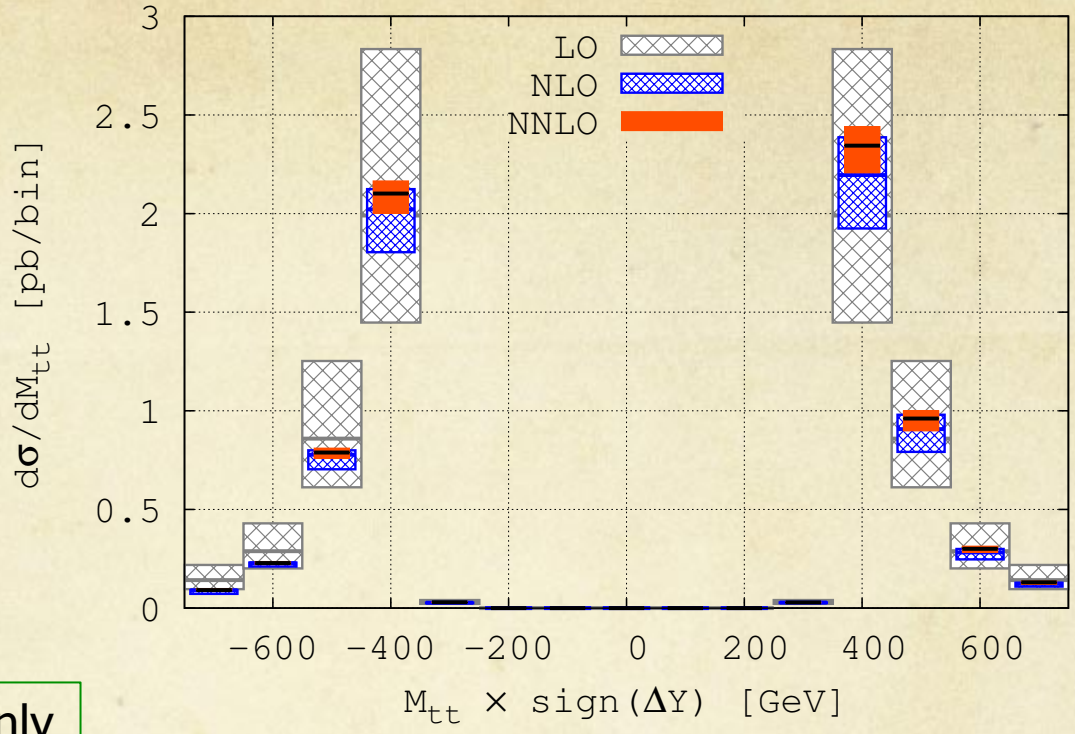

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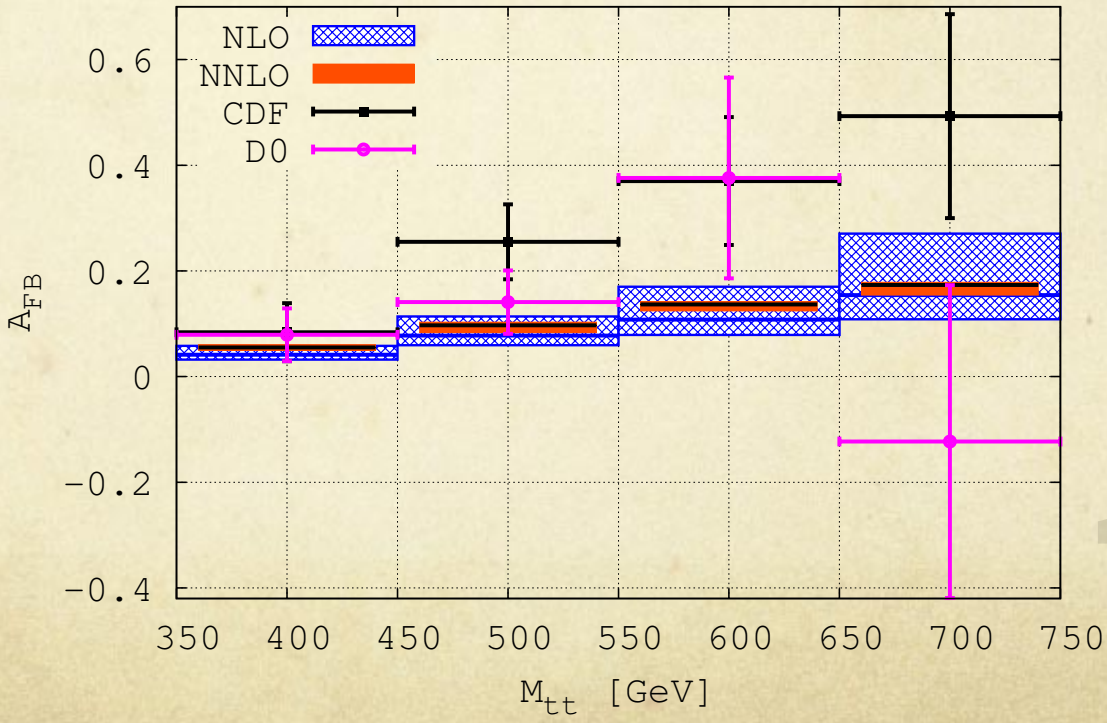

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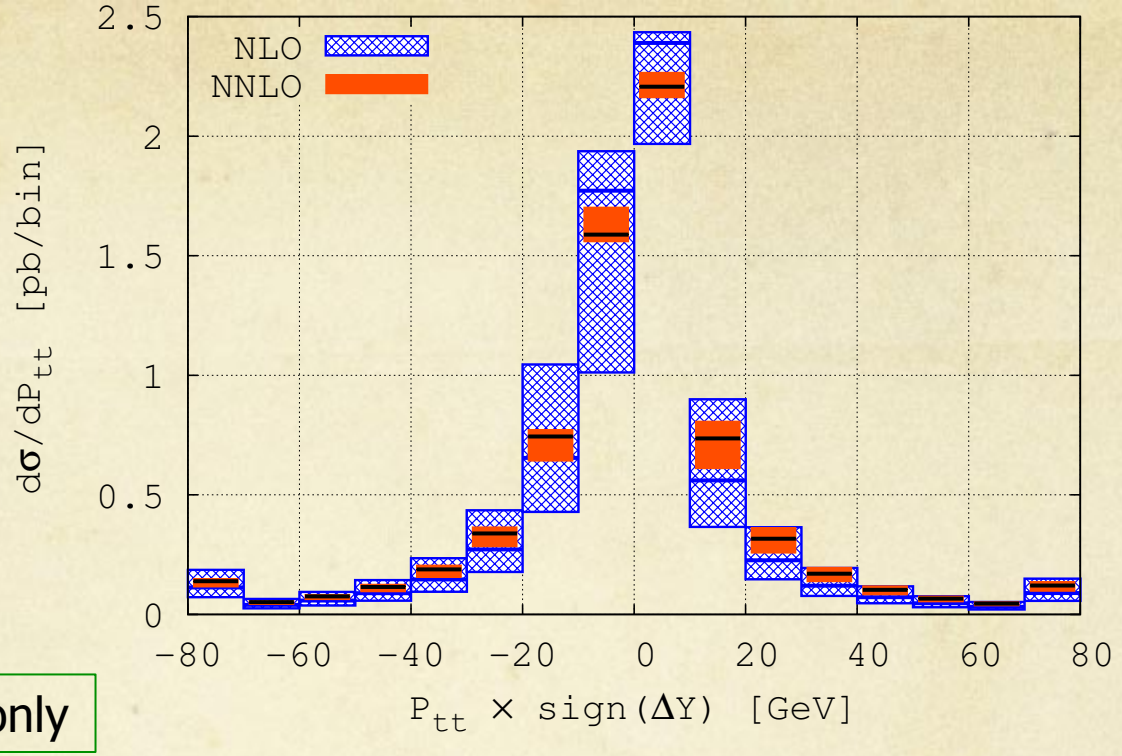

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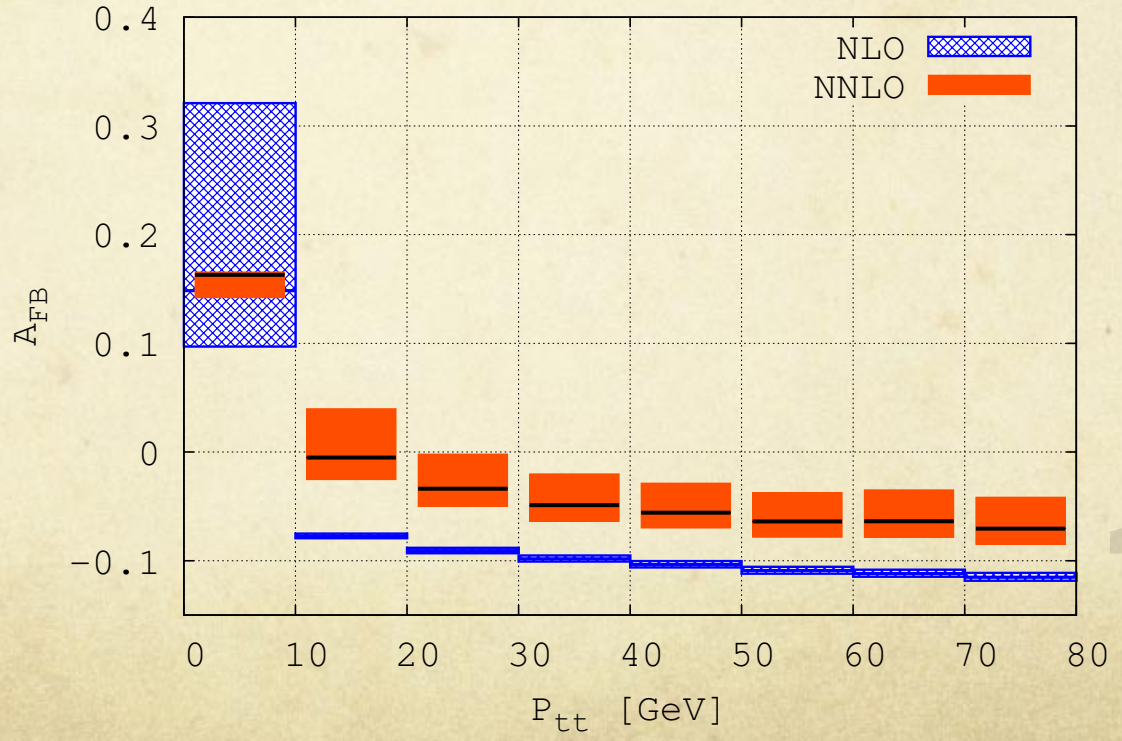

LHC 7 TeV – Super preliminary !

Czakon, Fiedler, Mitov, to appear

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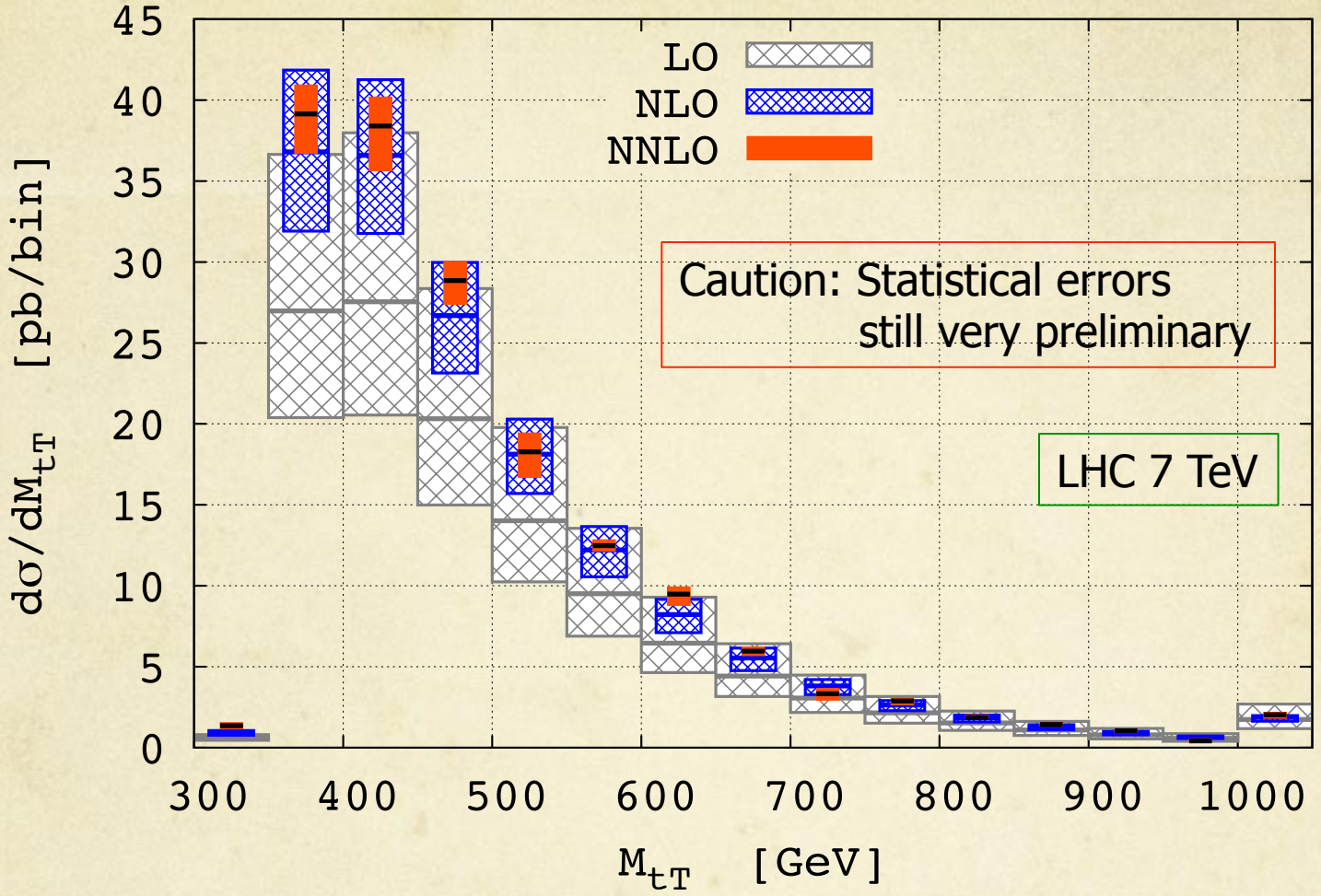

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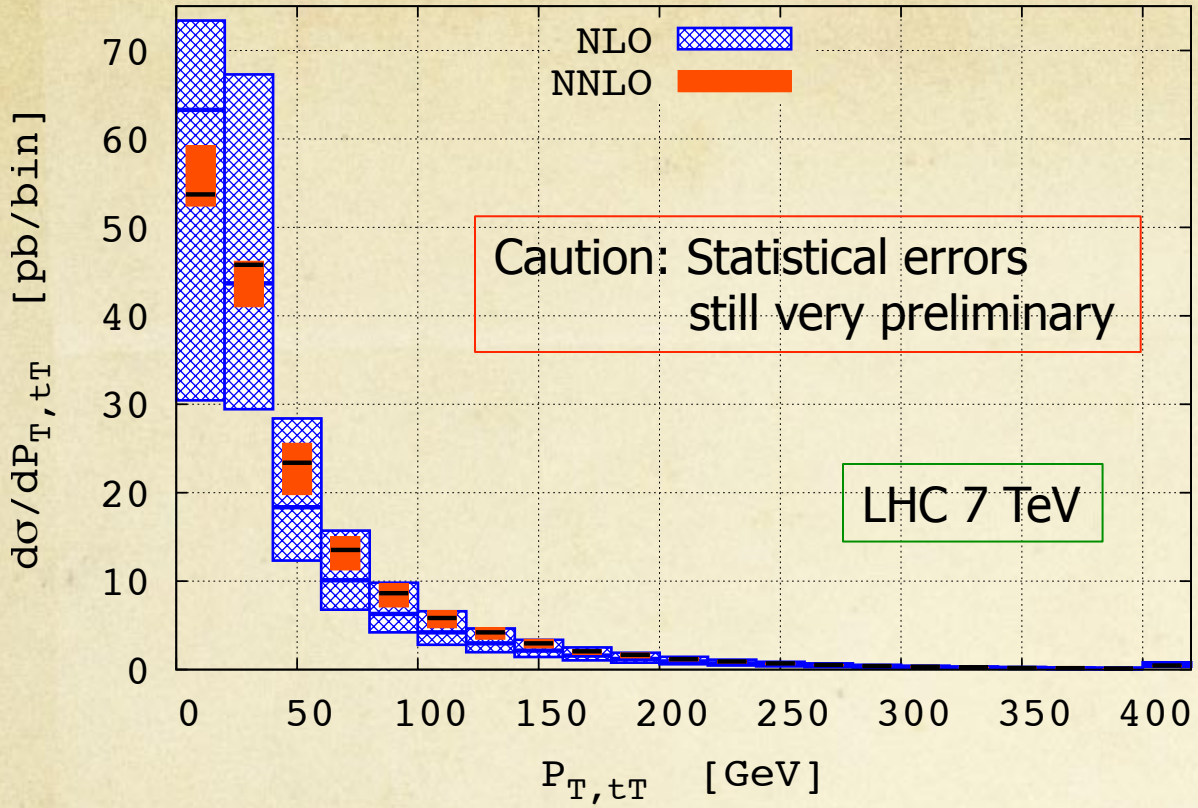

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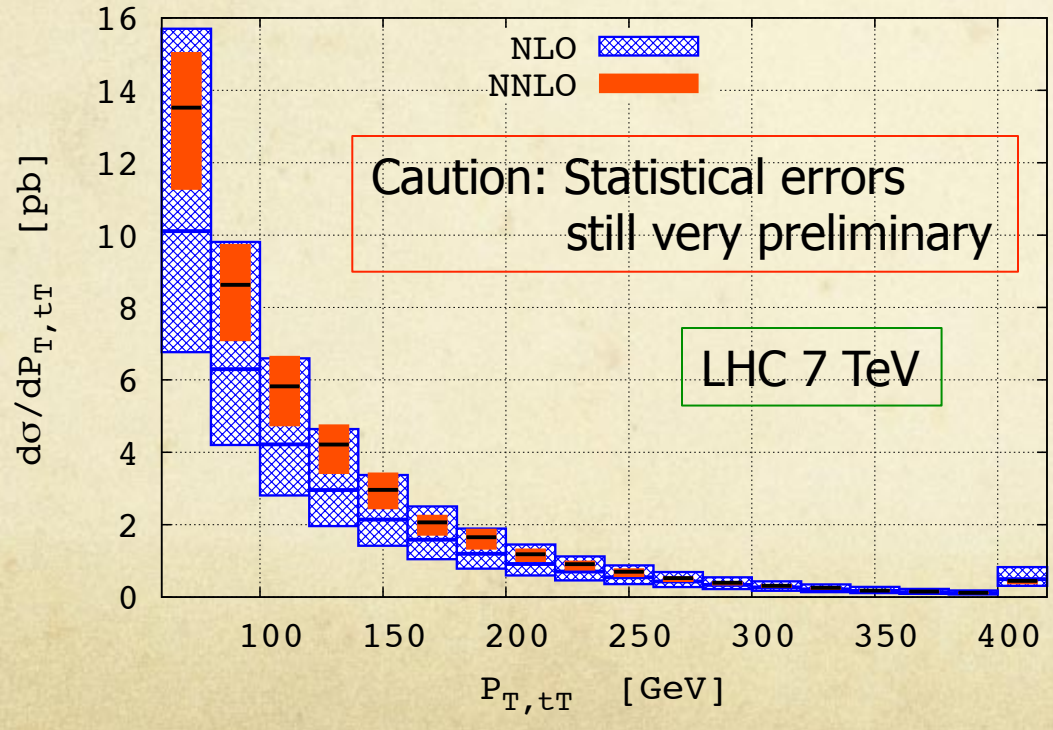

← Zoom in the above plot

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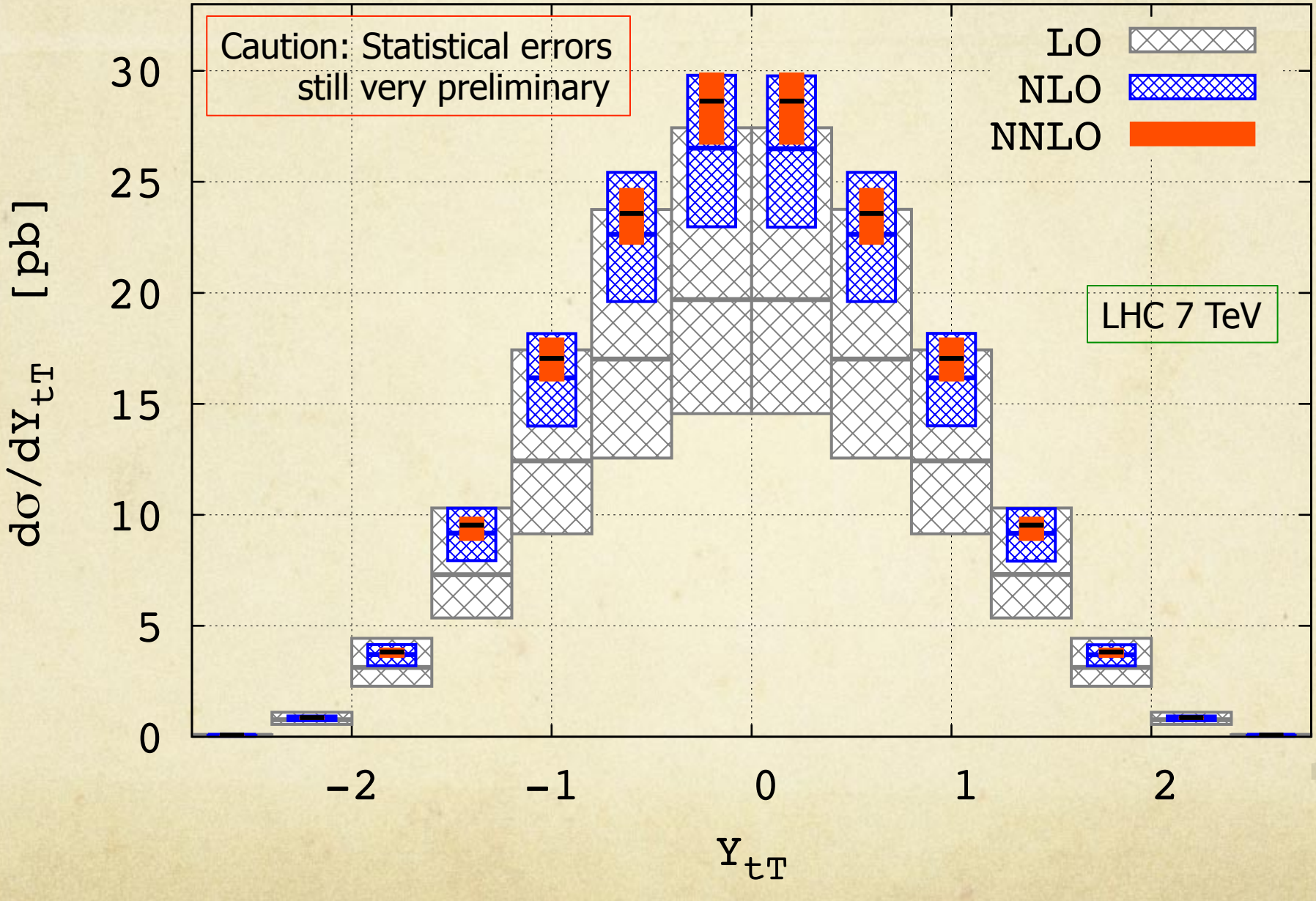

Summary and Conclusions

- Presented preliminary new results for NNLO QCD differential distributions:
- Tevatron: in the context of A_{FB}
  - We find that QCD + EW corrections bring A_{FB} ~ 10%, in agreement with D0 and near-agreement with CDF
  - The numerical results are of high quality
- LHC 7 TeV
  - Takes long time to compute
- LHC 8 in the pipeline; Extension to LHC 13/14 will follow.
- For now only Mtop=173.3 Various M_{top} values possible if needed.
- We still haven't had the chance to analyze the physics implications but this will be forthcoming
- Looking forward to many applications for these and future results!