Progress on top pair production at NNLO and AFB at Tevatron

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Work with:

Michael Czakon and Paul Fiedler arXiv:1411.3007

Michael Czakon and David Heymes, in progress

The whole story in a nutshell

- Fully differential top pair production at NNLO
- Everything is included – no approximations!
- Stable top quarks only. Down the road include decay but not right 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 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 (for LHC).

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

- Calculations published/available now only for Tevatron. LHC in progress (will not show).
- Any energy can be done – matter of CPU!
- 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?

Status of NNLO QCD differential distributions at LHC

Work in progress with:
Michael Czakon and David Heymes

LHC

- No public results yet
- Preliminary results shown at Top2014
- Very large number of events generated; stat fluctuations still an issue. Needs improvement (not an issue for Tevatron as we'll see shortly)
- To solve this a completely new code is being developed
  - Much faster: about a factor of 100
  - Has the options for including top decay
  - No stat fluctuations
  - Hope to complete the code development within 1 month
  - Then testing and computing etc. Should have predictions before any new LHC 13 TeV data becomes available.
  - Will use dynamic scales.

NNLO QCD corrections to A_{FB}

Work appeared:
Michael Czakon and Paul Fiedler arXiv:1411.3007

NNLO QCD corrections to A_{FB}

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

- Inclusive
- $|\Delta y|$
- M_{tt}
- $P_{T,tt}$

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

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

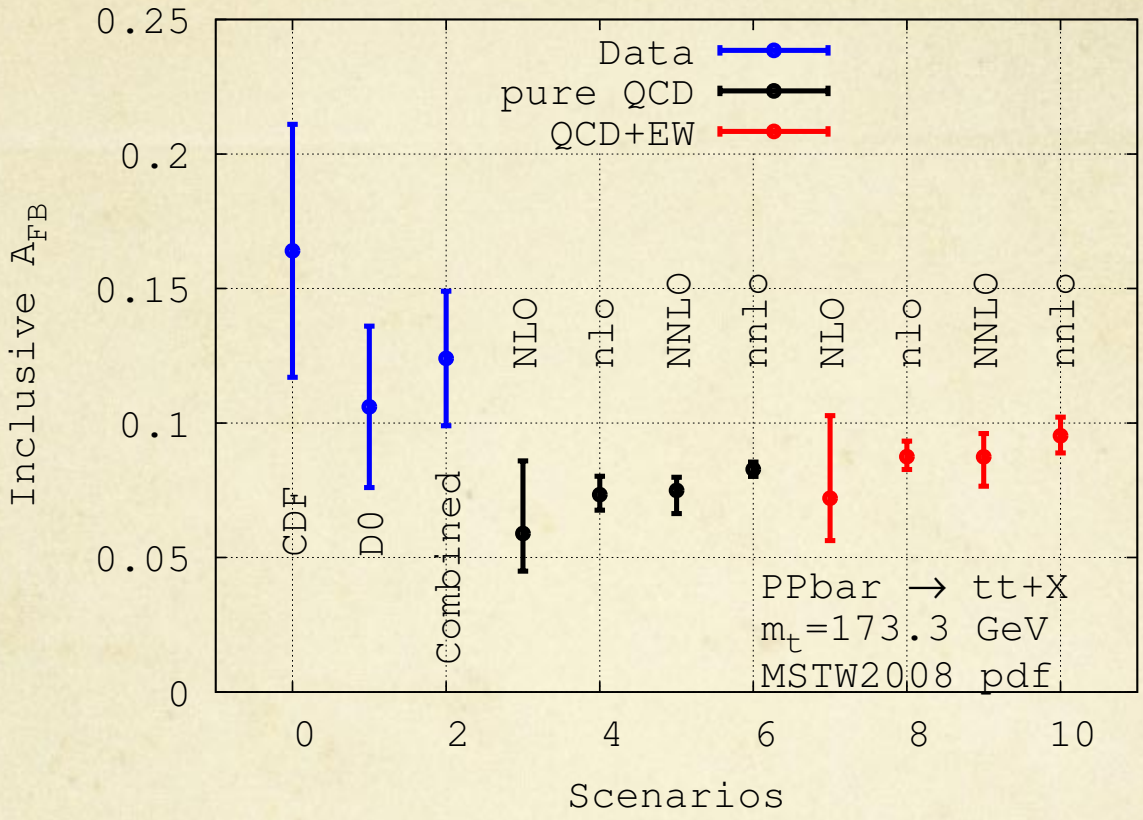
$$\begin{aligned}
\mathrm{A_{FB}} &\equiv \frac{N_{ew} + \alpha_S^3 N_3 + \kappa\alpha_S^4 N_4}{\alpha_S^2 D_2 + \alpha_S^3 D_3 + \kappa\alpha_S^4 D_4} \\
&= \alpha_S \frac{N_3}{D_2} + \kappa\alpha_S^2 \left(\frac{N_4}{D_2} - \frac{N_3}{D_2}\frac{D_3}{D_2}\right) + \mathcal{O}(\alpha_S^3) \\
&\quad +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

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}
  - ✓ We have managed to make them negligible.
  - ✓ MC error in each bin is:
    - Few permil for differential distributions
    - Below 1% for AFB in each bin; with only highest Mtt bin with 1.5%
  - ✓ MC error on inclusive AFB is few permil.
  - ✓ Agreement with sigma_{TOT} (Top++) to better than 0.5 permil (each scale)
  - ✓ Clearly, the numerical precision of the results is very high.
  - ✓ AT NLO QCD we agree with MCFM and Bernreuther & Si.
  - ✓ Another check at NNLO: consistent with $P_{T,tT}$ spectrum from ttj @ NLO
  - ✓ Computed for generic independent μ_F and μ_R (again, non-dynamic = M_{top})

Results for inclusive A_{FB}



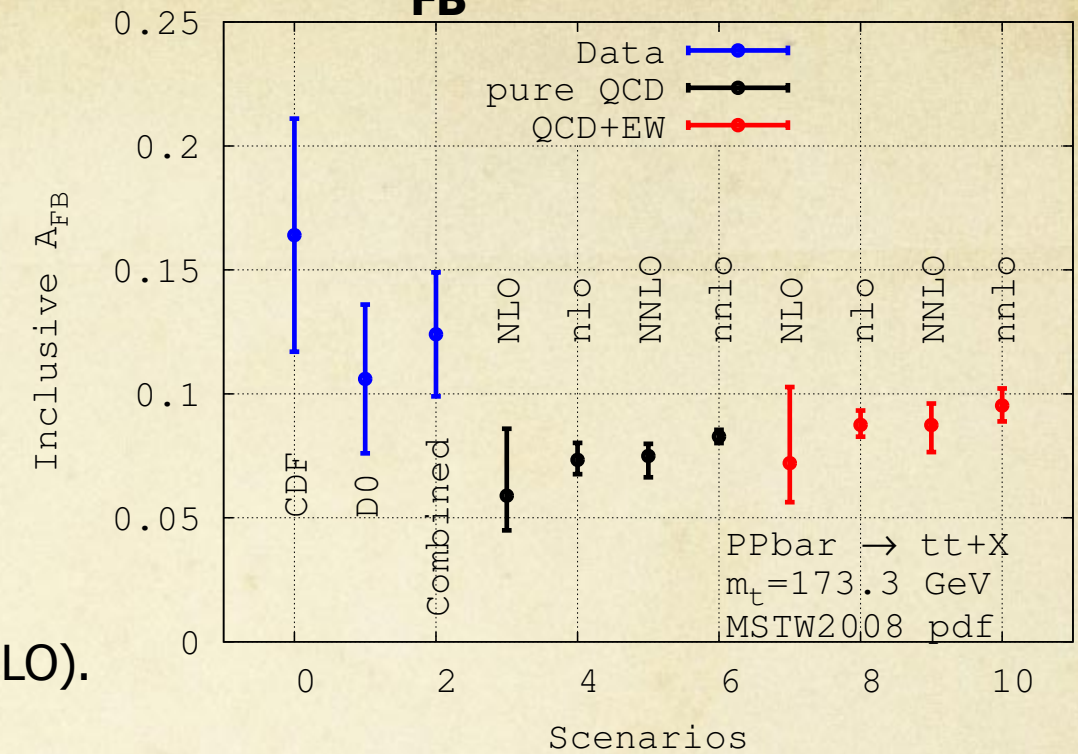
Errors due to scale variation only

How to read the above plot:

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

Results for inclusive A_{FB}

- *NLO*, *NNLO* :
  exact numerator and denominator
- *nlo*, *nnlo* : expanded in powers of a_S



✓ We find large QCD corrections:
NNLO ~ 27% of NLO (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

Rapidity dependence of A_{FB}

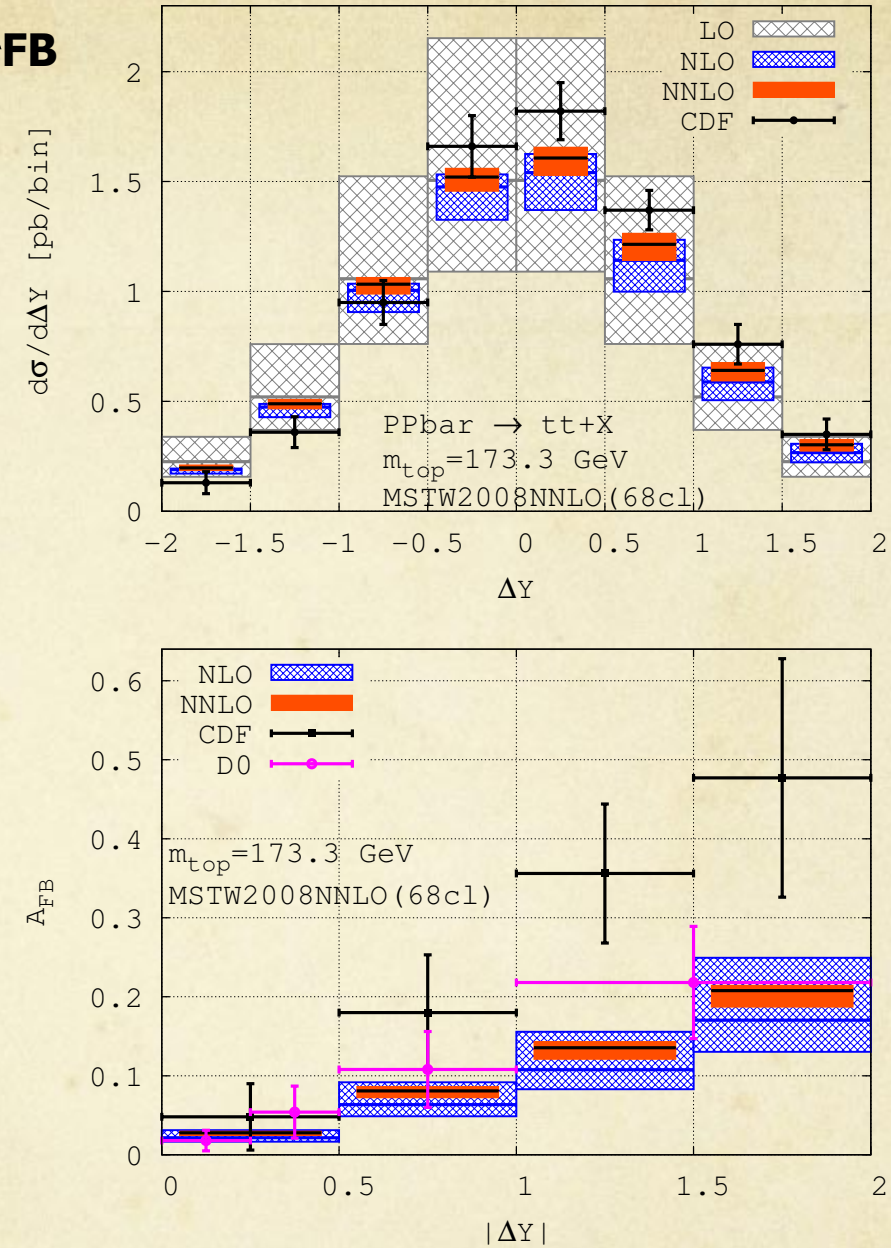
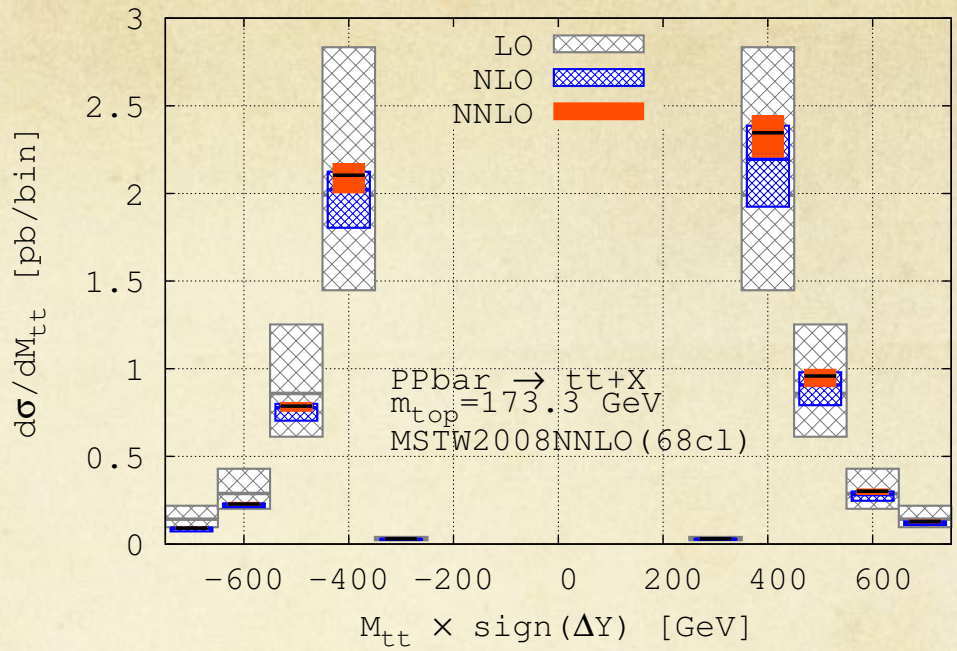


FIG. 2: The $|\Delta y|$ differential distribution (top) and asymmetry (bottom) in pure QCD at LO (grey), NLO (blue) and NNLO (orange) versus CDF [2] and D0 [1] data. Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

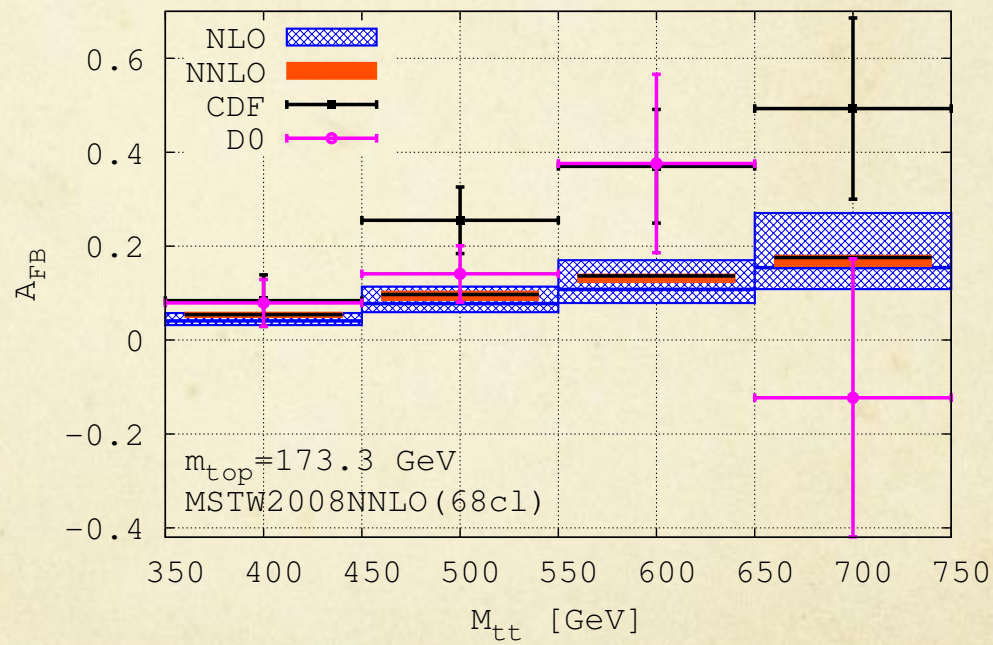
Errors due to scale variation only
- Pdf error small
- MC error negligible

- Perfect agreement with D0
- No agreement for A_{FB} with CDF
- But differential x-section reasonably close to CDF ...

M_{tt} dependence of A_{FB}



Errors due to scale variation only
- Pdf error small except in the two highest bins, where they are as large as scales (but have opposite direction)
- MC error negligible

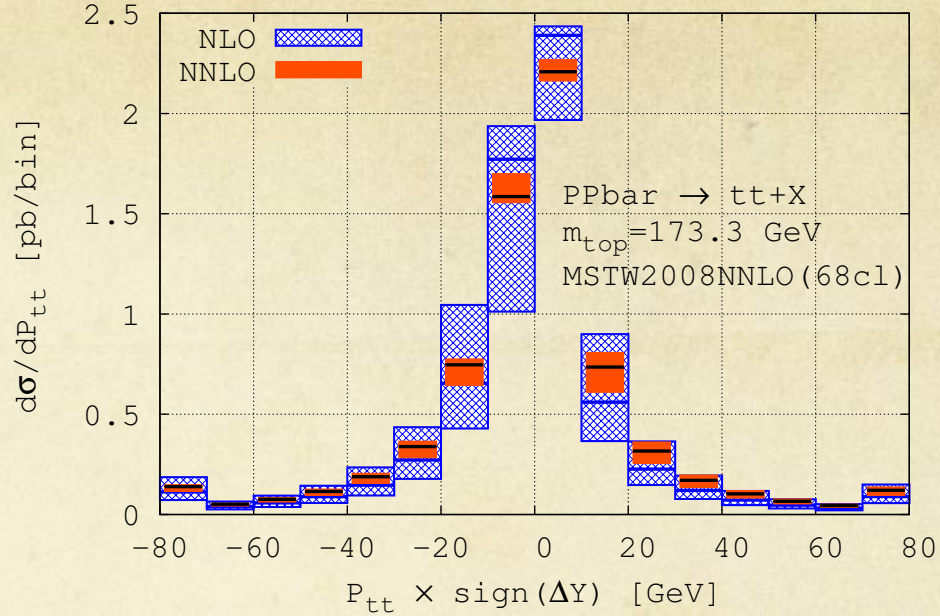


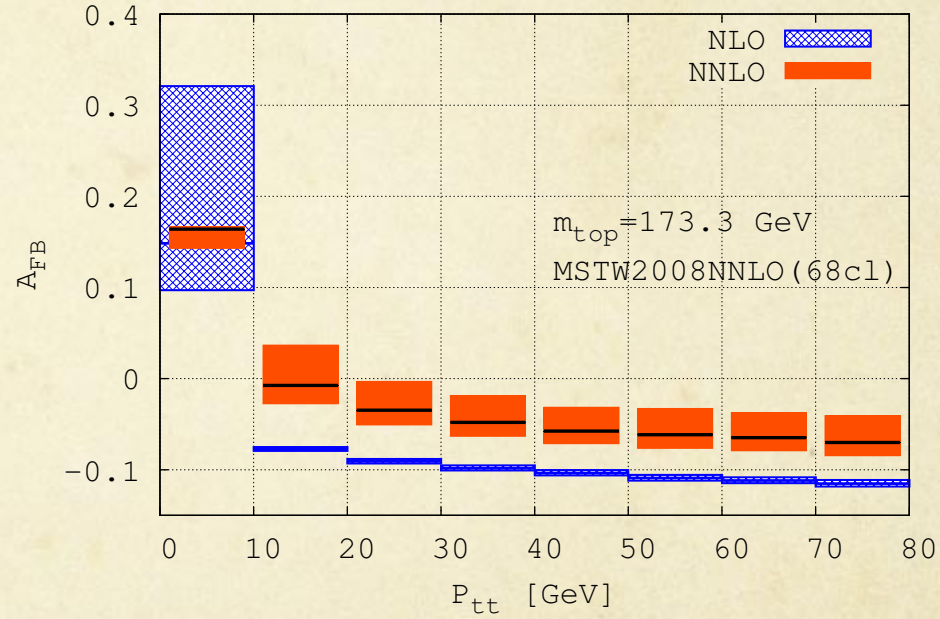
- Agreement with D0
- So-so agreement for A_{FB} with CDF

FIG. 3: As in fig. 2 but for the $M_{t\bar{t}}$ differential asymmetry. Both lowest and highest bins contain overflow events.

$P_{T,tt}$ dependence of A_{FB}

Errors due to scale variation only
- Pdf error small except
  $60 \leq P_{T,tt} \leq 70$GeV bin, where it is 1.5%
- MC error 1%, i.e. small





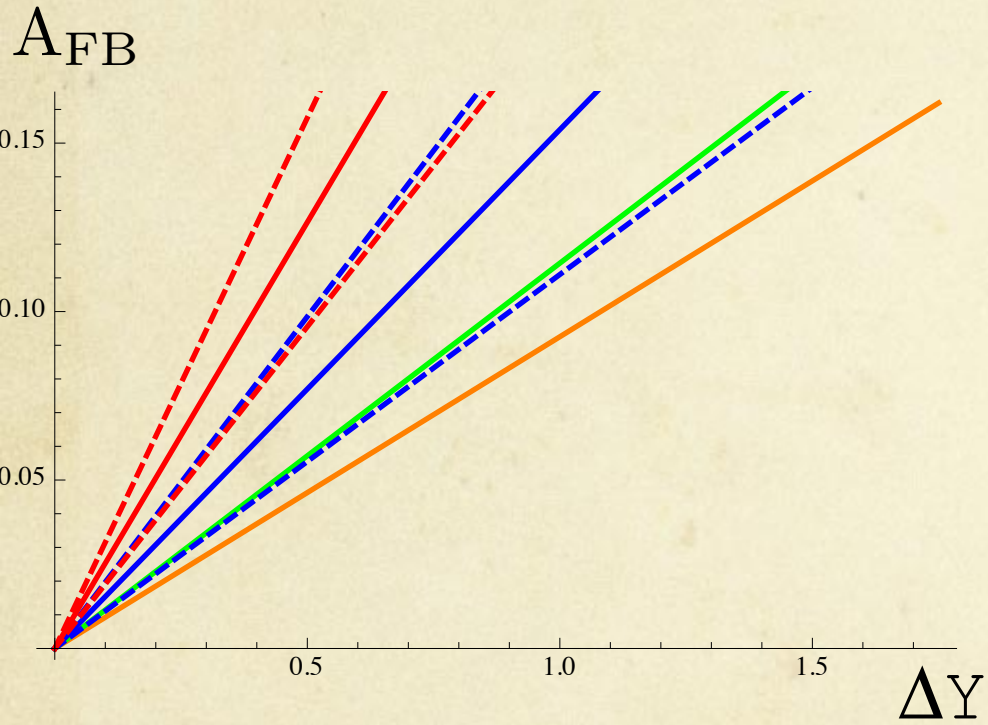
- Note the change in shape in diff x-section
- No data to compare to…
- Difference NNLO-NLO is constant like as noted already by CDF
- The NNLO/NLO correction agrees with the preferred color-octet structure of the AFB discrepancy found in

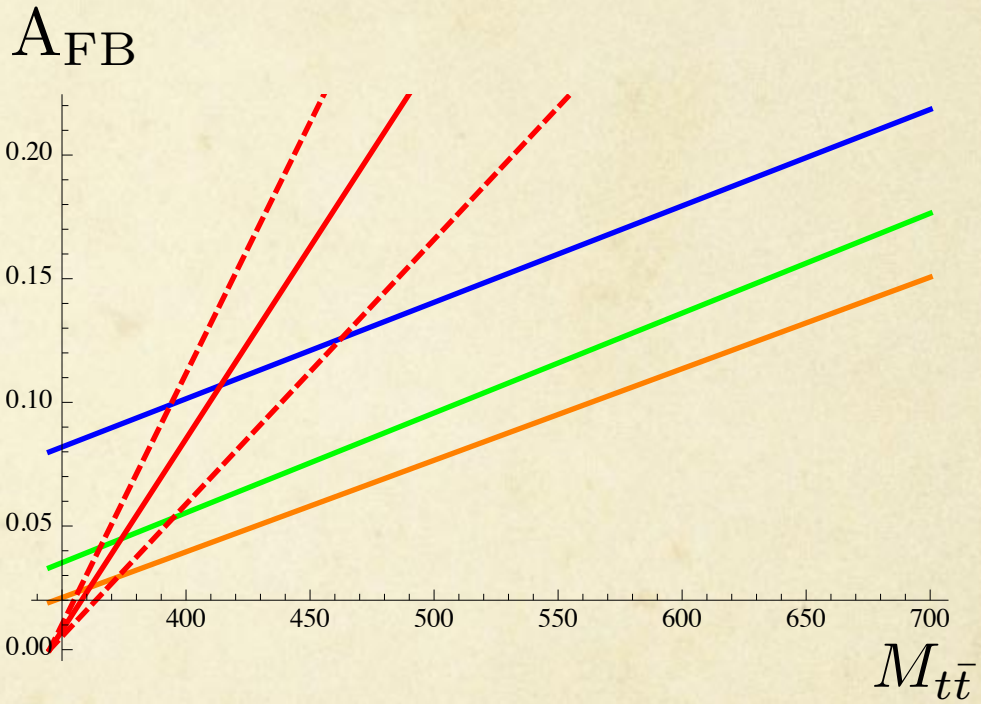
Gripaios, Papaefstathiou, Webber '13

FIG. 4: The $P_{T,t\bar{t}}$ differential asymmetry in pure QCD at NLO (blue) and NNLO (orange). Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

The slope of A_{FB}

- It was noted previously that the differential asymmetry is close to a straight line
- For the rapidity dependence it is clear it is actually slightly curved at both NLO and NNLO
- For M_{tt} at NNLO is very close to a straight line – unlike NLO





- CDF (dashes – errors)
- D0 (dashes – errors)
- NNLO
- NLO

- Agreement with D0 within errors even without EW corrections
- CDF is far off

Understanding the origin of NNLO A_{FB}

- The anatomy of A_{FB} at NNLO is similar to that at NLO but more extreme
  - Example: the contributions to the NNLO inclusive numerator

	Factorization	RR	RV	VV
(princ. contr.)/($\alpha_S^4 N_4$)	−0.47	5.34	−3.90	0.03

TABLE I: Sizes of the various principle contributions to the numerator of the inclusive A_{FB} at NNLO in pure QCD. The size of the numerator is given in table II.

  - Driven by large cancellation between RR and RV
  - Sizable Factorization
  - Tiny VV

- Contributions from partonic reactions is similar to NLO:
  - Inclusive numerator is 99% qqbar
  - qg = qqbar/10^2
  - qq'=qqbar/10^4

In line with the contributions of these reaction to the totla inclusive x-section

The difference w/r to approximate NNLO

- Large difference for the inclusive asymmetry and numerator (no comparison for differential)

$$A_{FB}^{(NNLO)}/A_{FB}^{(NLO)} \text{ is } 1.27\ (1.13)$$ For unexpaned (expanded) definition

Num_{NNLO}/Num_{NLO} = 1.34

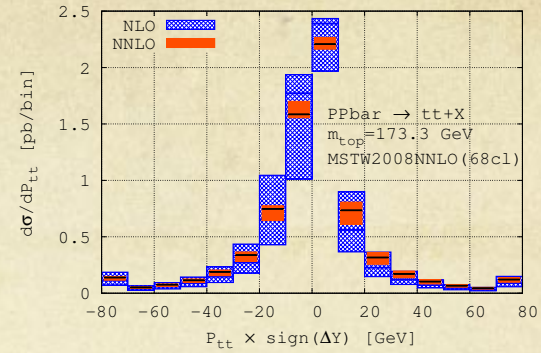
	NLO	NNLO	NLO+NNLL
$\alpha_S^3 N_3 + \alpha_S^4 N_4$ [pb]	$0.394^{+0.211}_{-0.127}$	$0.525^{+0.055}_{-0.085}$	$0.448^{+0.080}_{-0.071}$
$\alpha_S^4 N_4$ [pb]	–	0.148	–
A_{FB}[%] (eq. (3))	$7.34^{+0.68}_{-0.58}$	$8.28^{+0.27}_{-0.26}$	$7.24^{+1.04}_{-0.67}$
A_{FB}[%] (eq. (2))	$5.89^{+2.70}_{-1.40}$	$7.49^{+0.49}_{-0.86}$	–

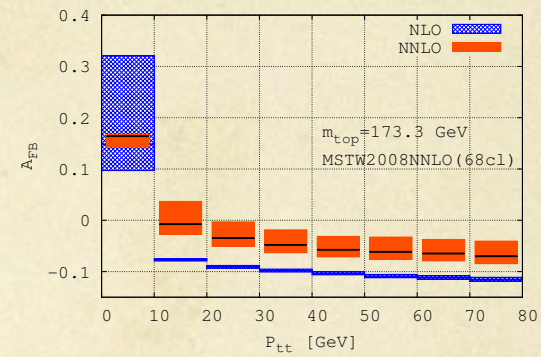
TABLE II: Comparison of the numerator in eq. (2) and the inclusive asymmetry A_{FB} computed in pure QCD at NLO (with NLO pdf set), NNLO and NLO+NNLL [20]. Only errors from $\mu_F = \mu_R$ scale variation are shown.

[20] Ahrens, Ferroglia, Neubert, Pecjak and Yang, 1106.6051

- To better understand this look at the $P_{T,tt}$ differential asymmetry

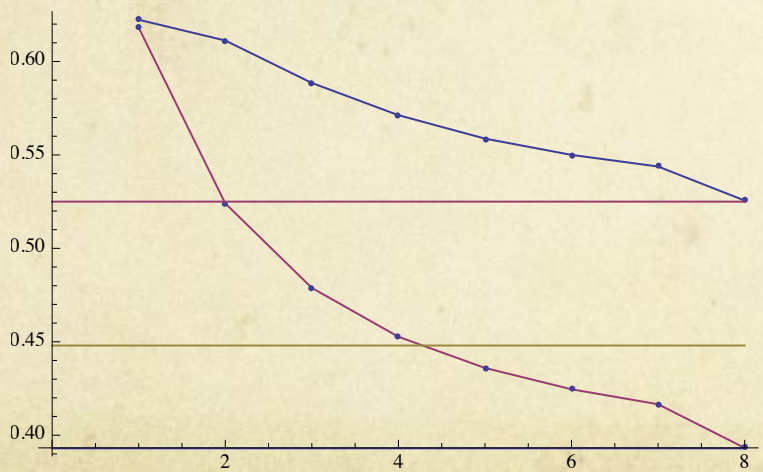
The difference w/r to approximate NNLO





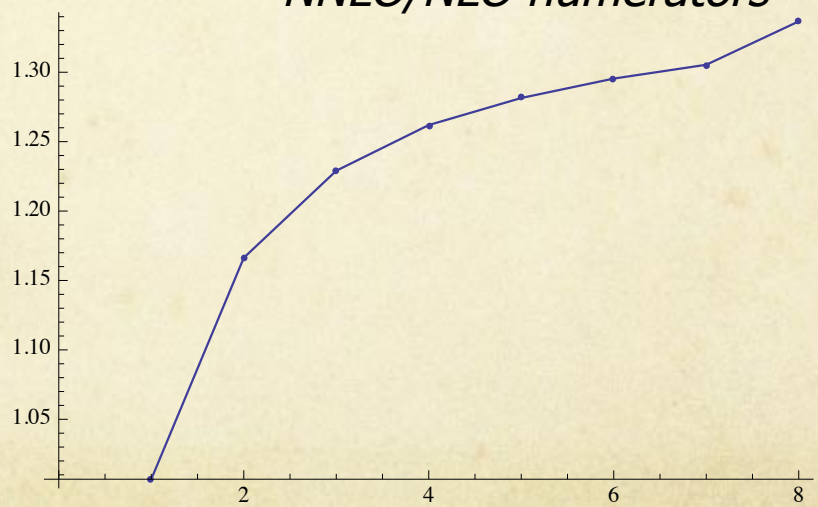
- It is better to look at the Cumulative differential asymmetry (i.e. the inclusive asymmetry with a cut on $P_{T,tt}$)
- Recall: the inclusive asymmetry is <u>not</u> an integral over the differential one …
- Soft gluon resummation "operates" near $P_{T,tt}$=0. The Cumulative asymmetry will illustrate how AFB develops
- Cumulative $P_{T,tt}$ asymmetry:

NNLO and NLO numerators



$P_{T,tt}$ bin

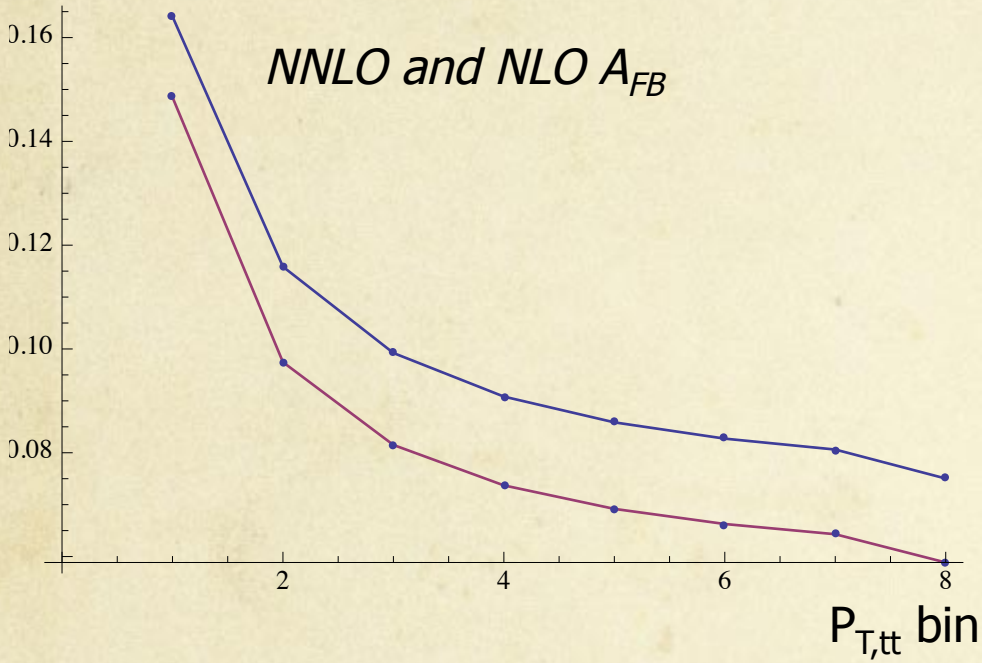
NNLO/NLO numerators

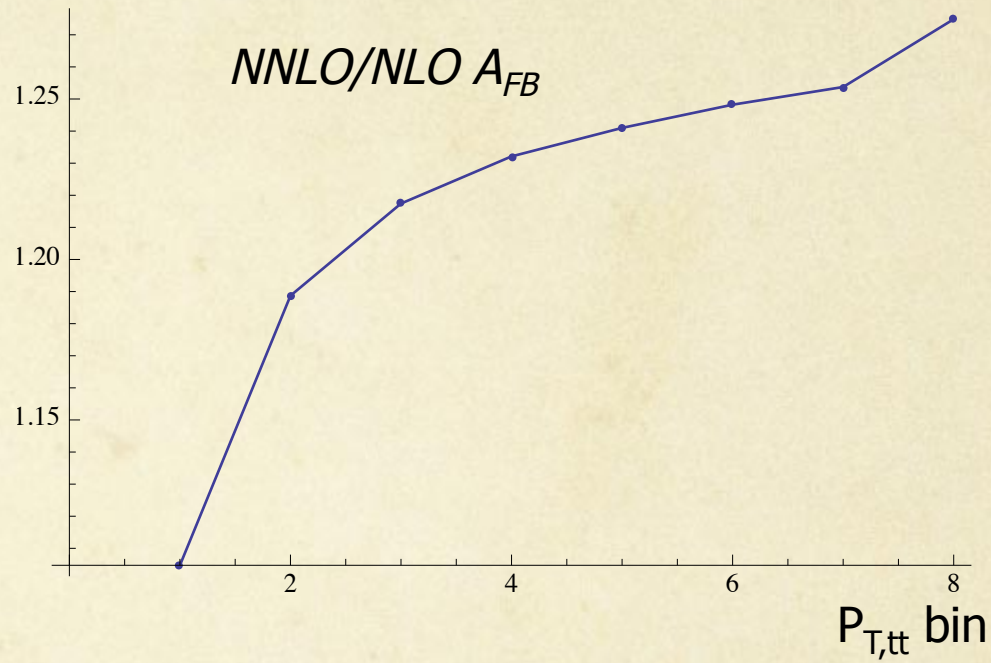


$P_{T,tt}$ bin

The difference w/r to approximate NNLO

- Cumulative $P_{T,tt}$ asymmetry:





- Equal NLO and NNLO numerators in the first bin (where soft resummation is most relevant)
- Thus, the NLO – NNLO difference in the first bin is only due to the denominator!
- They start to diverge fast afterwards
- The second bin contains already 50% of the NNLO-NLO difference in the numerator

- Clearly the difference between NLO and NNLO comes from hard emissions which cannot be described by soft-gluon resummation

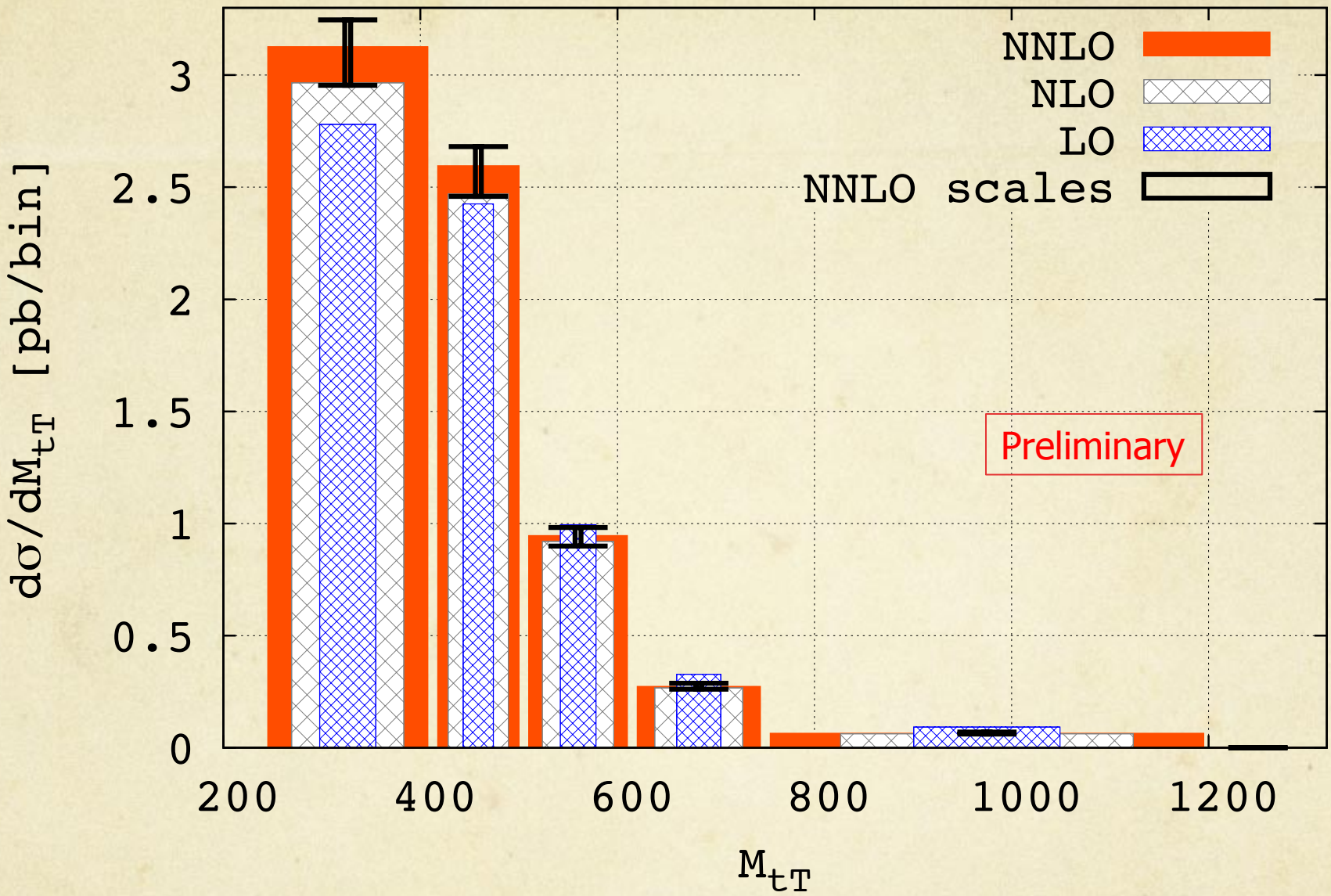
NNLO QCD differential distributions for Tevatron

Work in progress with:
Michael Czakon and Paul Fiedler

Tevatron

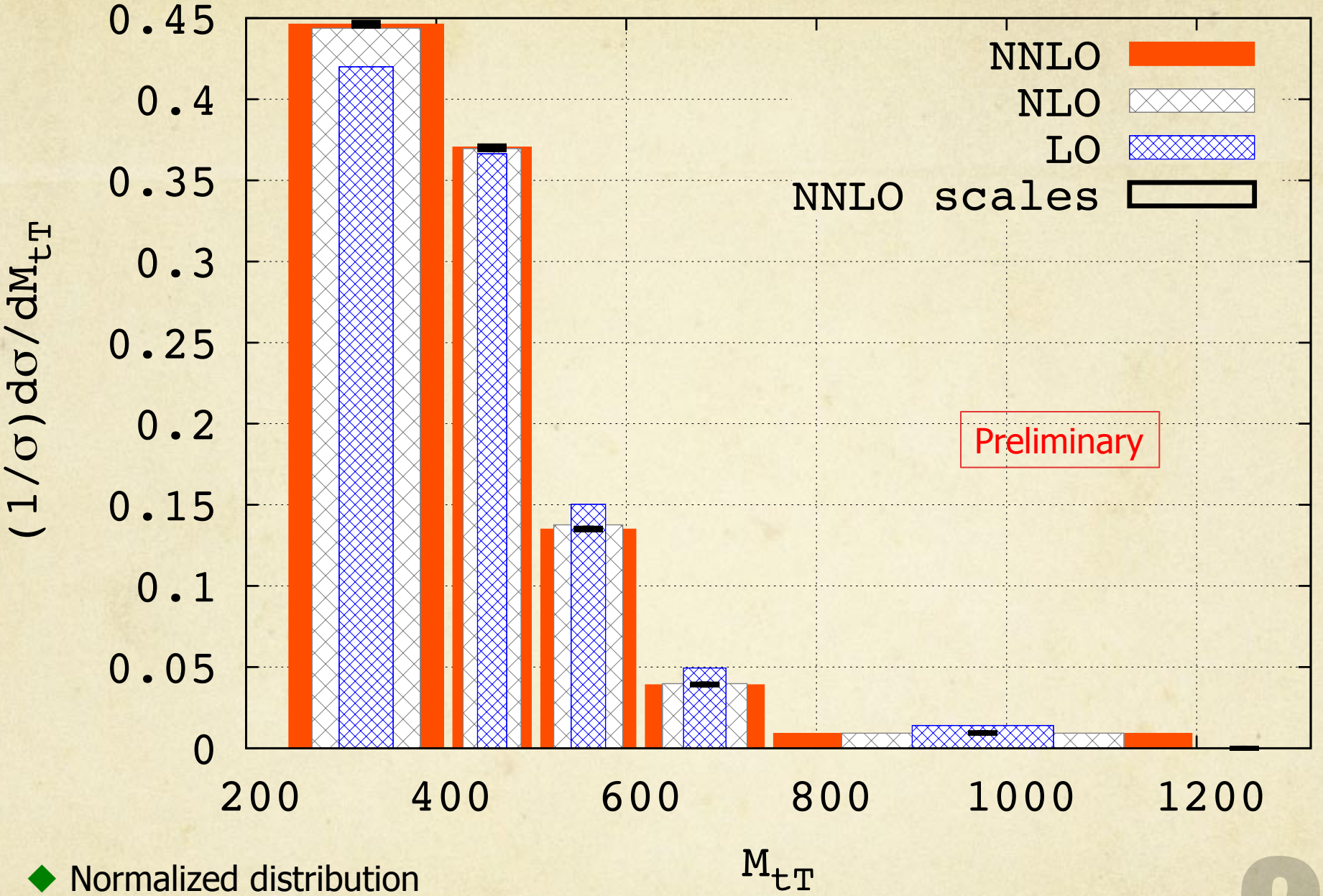
- We have computed (calculations are completed) all differential distributions that were measured at the Tevatron
- Paper being prepared. Preliminary results in the following.
- Fixed scales used (muF,muR=m_{top})
- Quality of calculation is high (relative MC error small except in the highest bins where x-section is extremely small)
- Will present results for: M_{tT}, $P_{T,top}$, $P_{T,tT}$, $y_{top,}$ cos(theta)
- Have some more distributions (relevant for the Legendre moment analysis of AFB)

Tevatron: M_{tT}



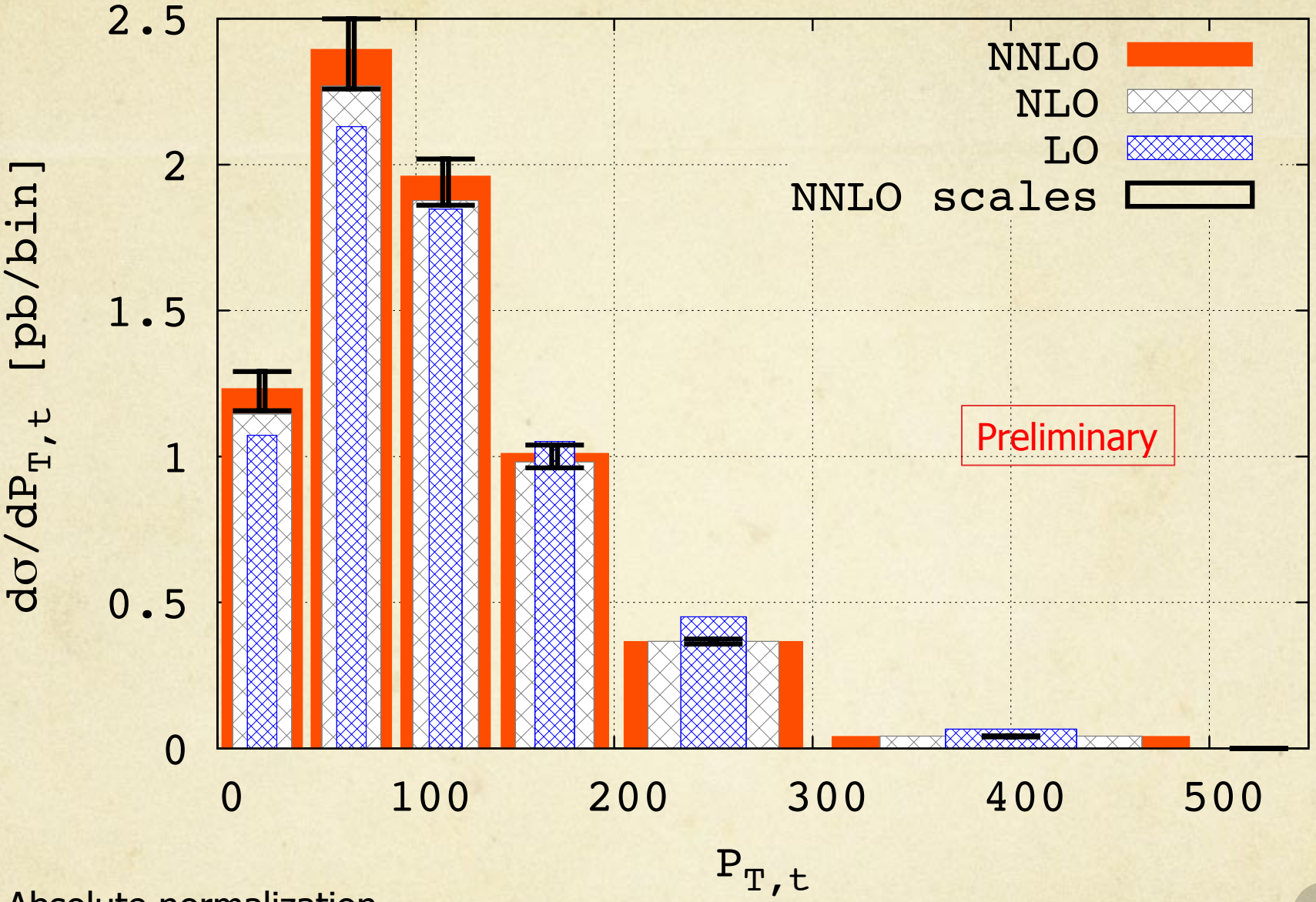
- Absolute normalization
- m_{top}=173.3GeV
- Fixed scales (muR,muF=m_{top})
- MSTW2008NNLO

Tevatron: normalized M_{tT}



- Normalized distribution
- m_{top}=173.3GeV
- Fixed scales (muR,muF=m_{top})
- MSTW2008NNLO

Tevatron: $P_{T,top}$



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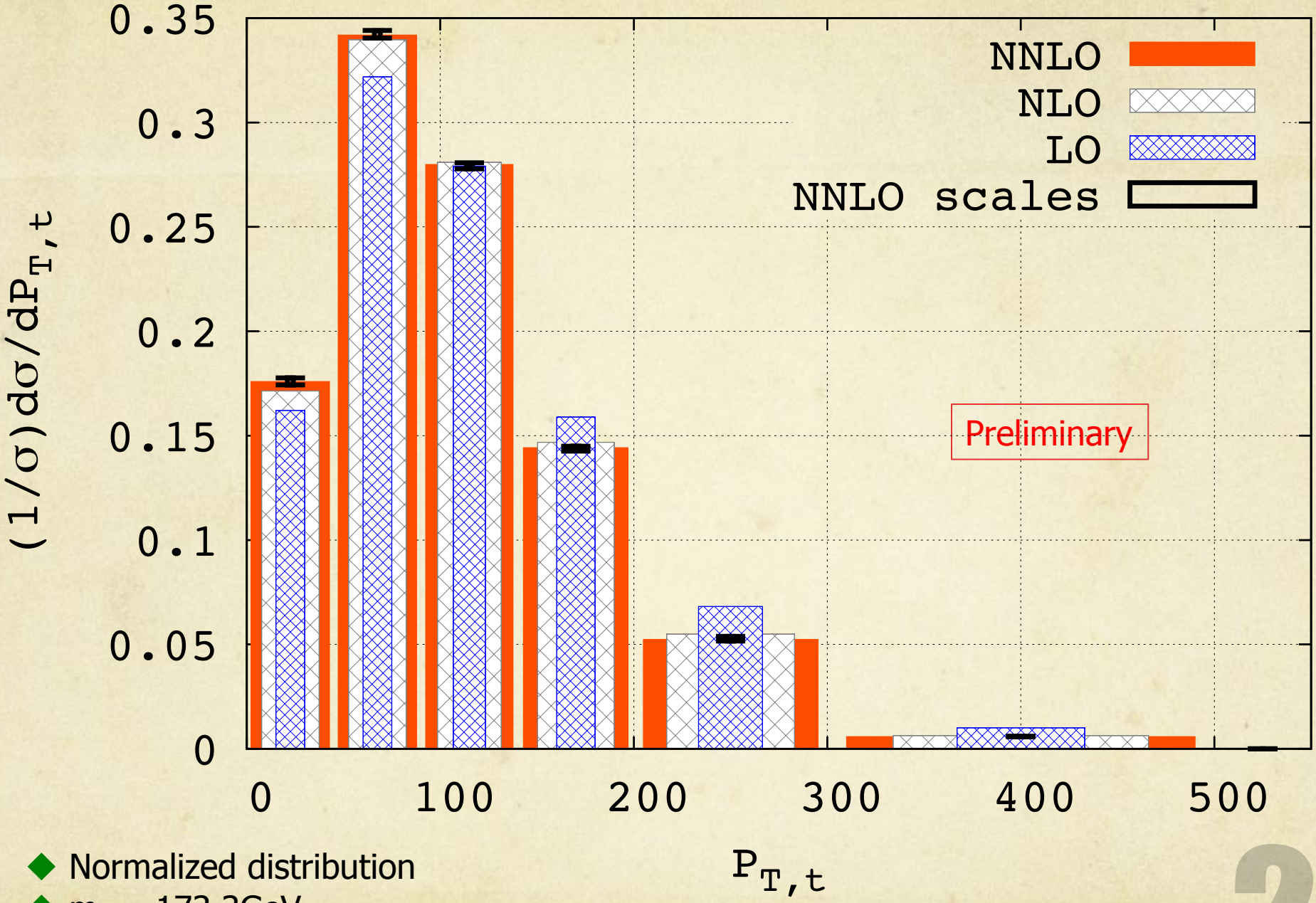
Tevatron: Normalized $P_{T,top}$



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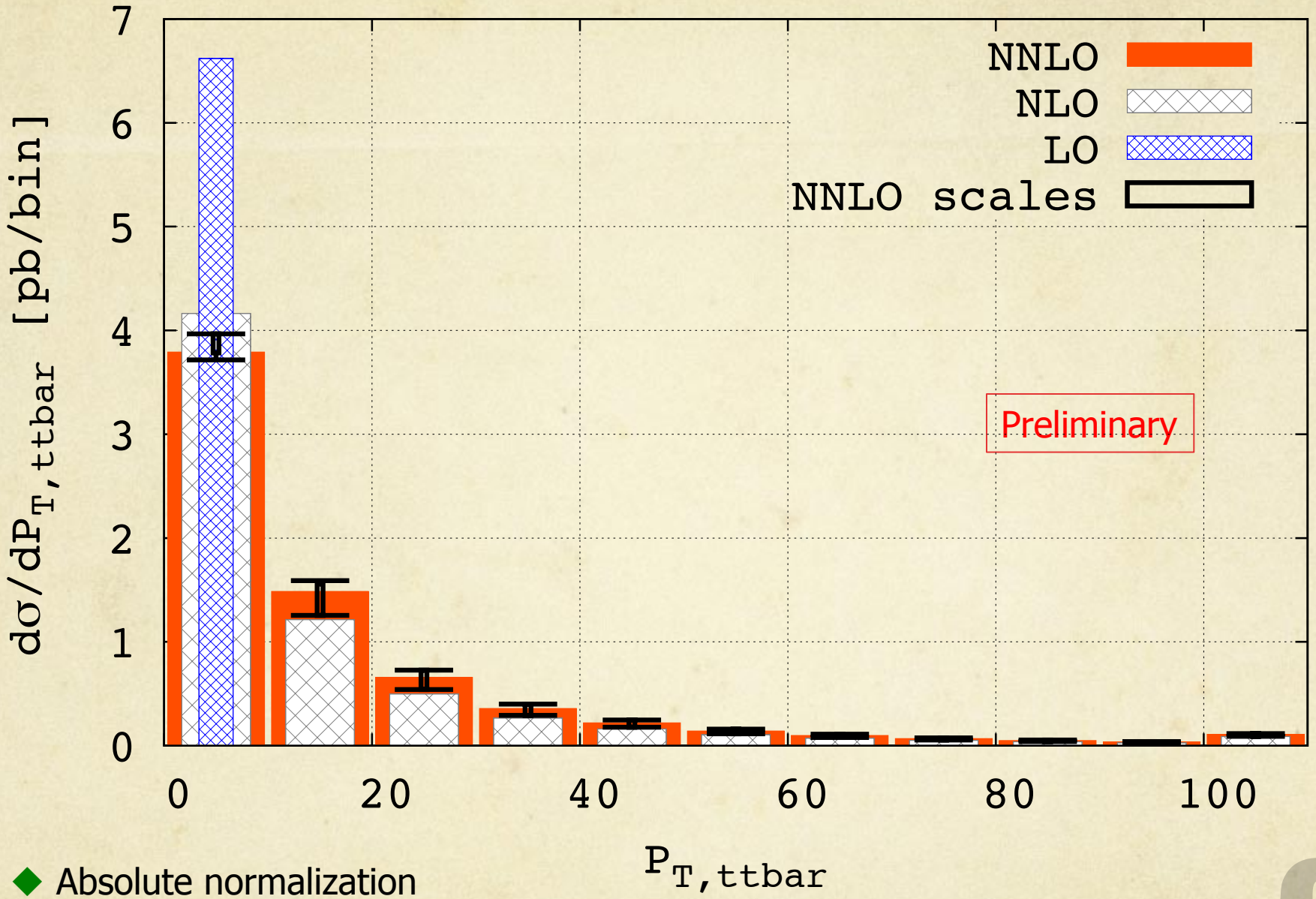
Tevatron: $P_{T,tT}$



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- Fixed scales (muR,muF=m_{top})
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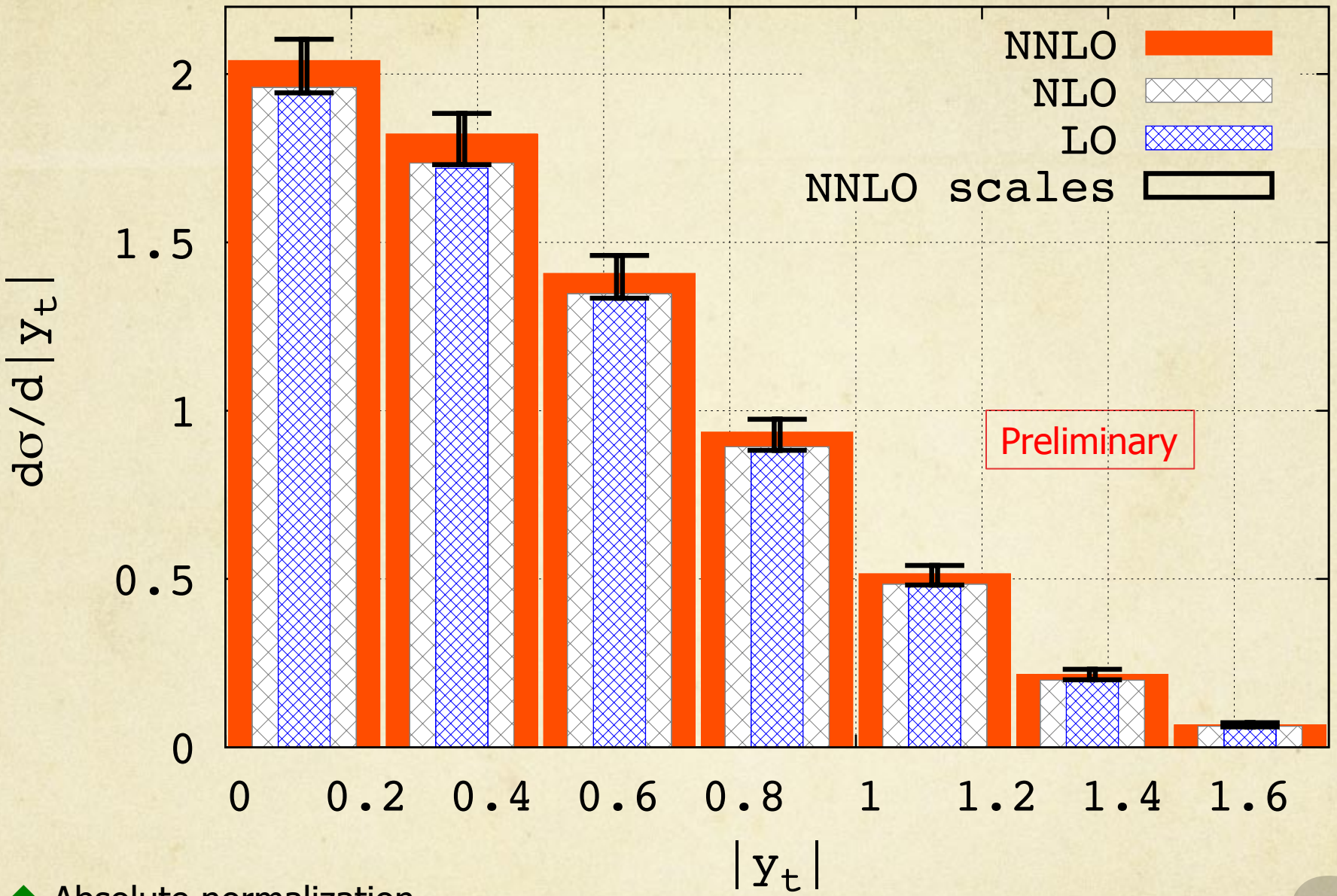
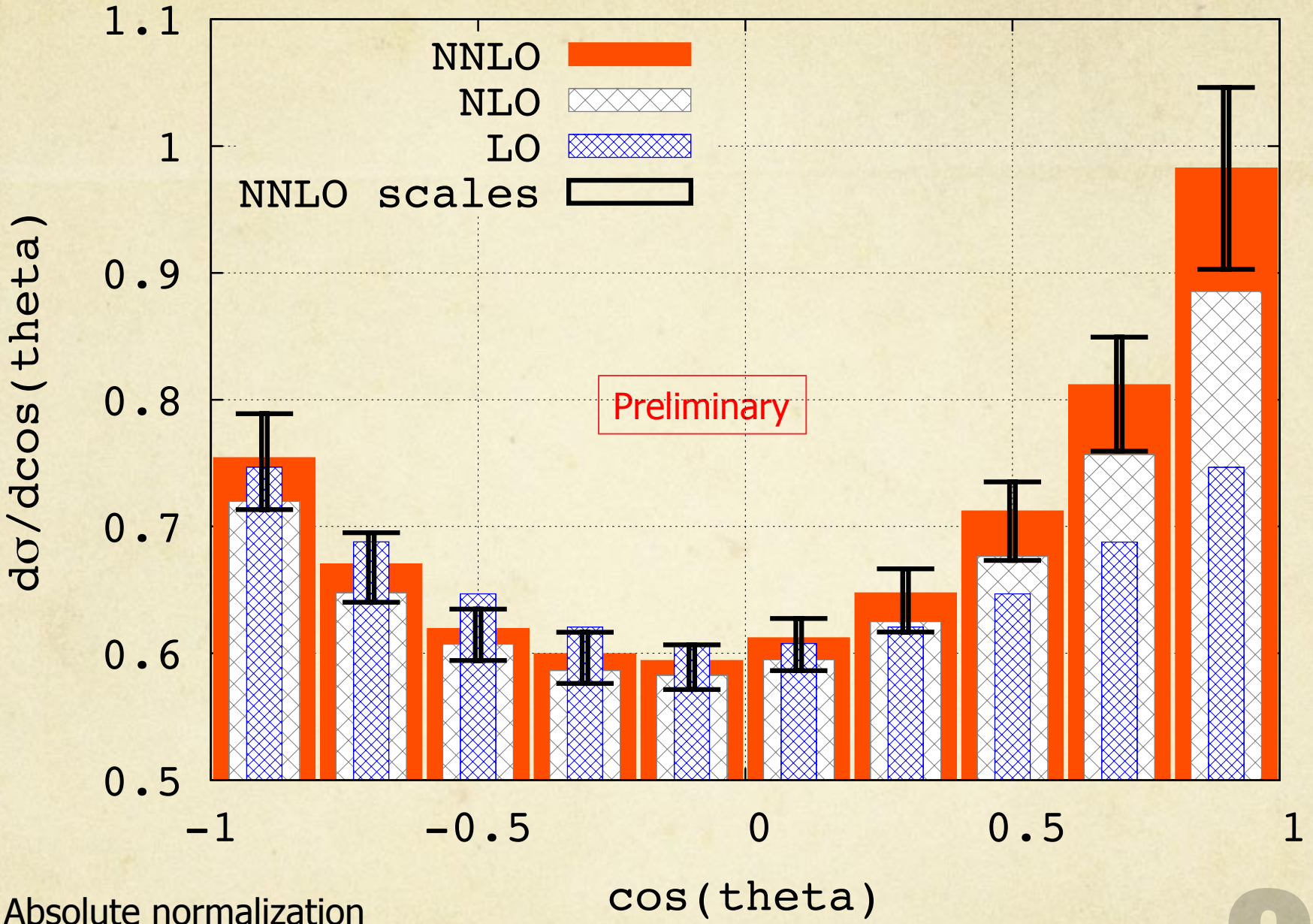
Tevatron: y_{top}



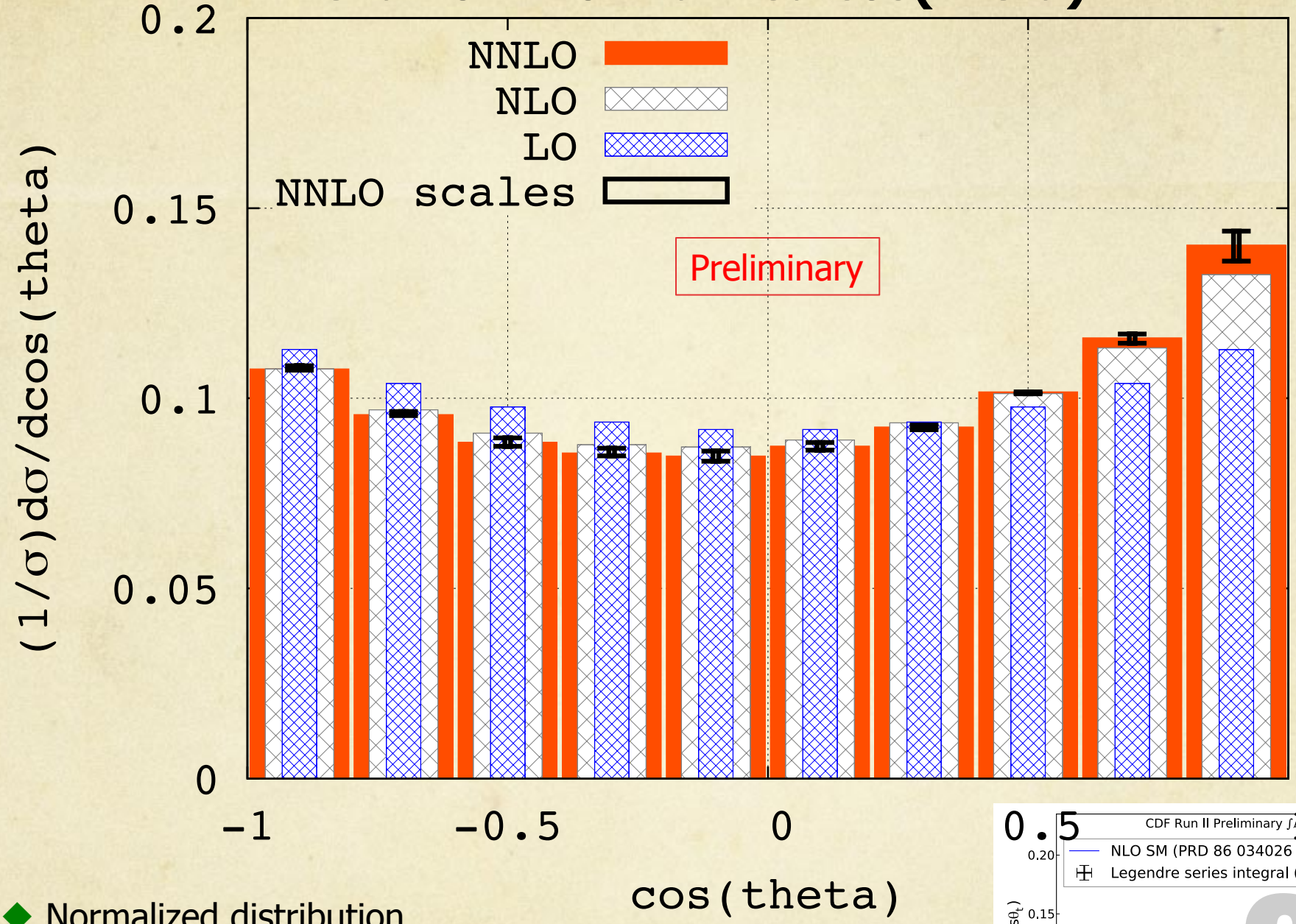
- Absolute normalization
- m_{top}=173.3GeV
- Fixed scales (muR,muF=m_{top})
- MSTW2008NNLO

Tevatron: cos(theta)



- Absolute normalization
- m_{top}=173.3GeV
- Fixed scales (muR,muF=m_{top})
- MSTW2008NNLO

Tevatron: normalized cos(theta)



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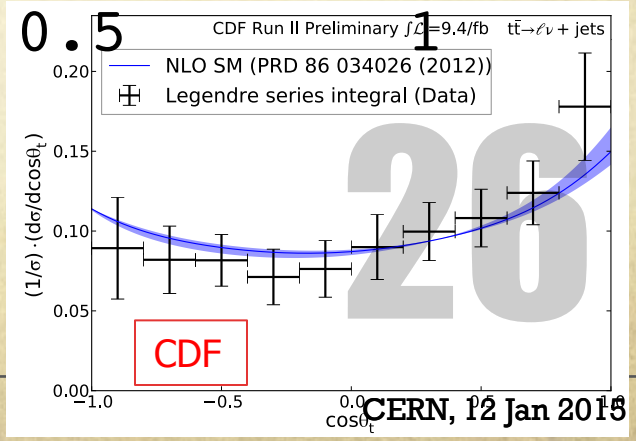

Summary and Conclusions

- We have a working code which calculates exactly the fully differential ttbar production (all channels, no approximations like leading color used)

- We have high-quality predictions for the Tevatron

- The results for AFB at Tevatron published (healthy NNLO effect found which brings SM theory closer to experiment

- We have computed all Tevatron distributions with Tevatron binning. Paper in preparation.

- LHC differential computed but not good enough.

- New code development underway which will allow a number of improvements:

  - All calculations exact
  - dynamic scales
  - O(100) speed improvement
  - Allows for top decay!

  - Anticipate LHC results before any new LHC 13 TeV results.

  - If all goes as planned this year we should also have NNLO with NNLO decayed tops.