Top Production at the Fermilab Tevatron

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Outline

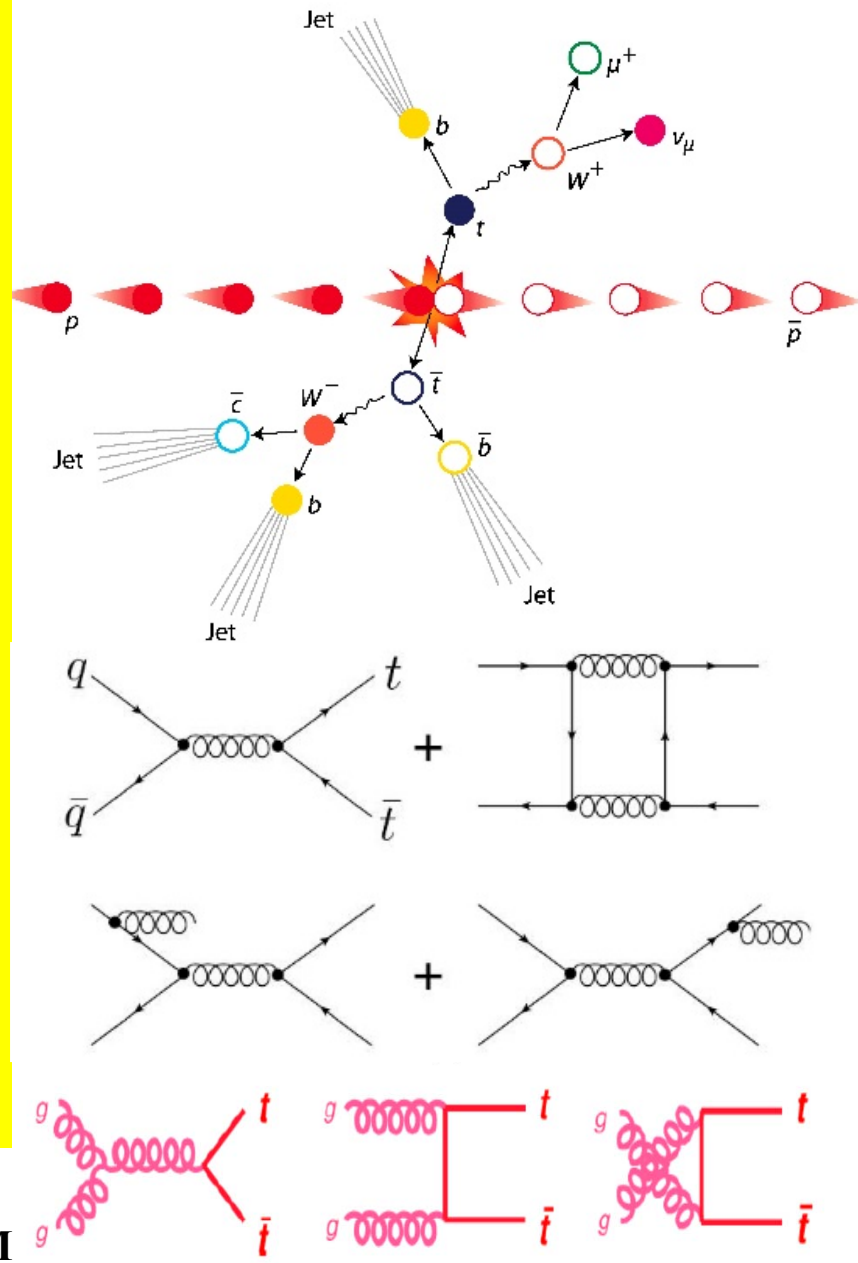
- **Total and Differential Cross Sections**
- **Angular distributions to determine the amount of Spin Correlation and Polarization**
- **Legacy result for the Forward-Backward Asymmetry (A_{FB})**
- **Conclusions**

Top Production at the Tevatron

- $p\bar{p}$ collision
  - Asymmetric initial state
- Dominant process is top quark pair production

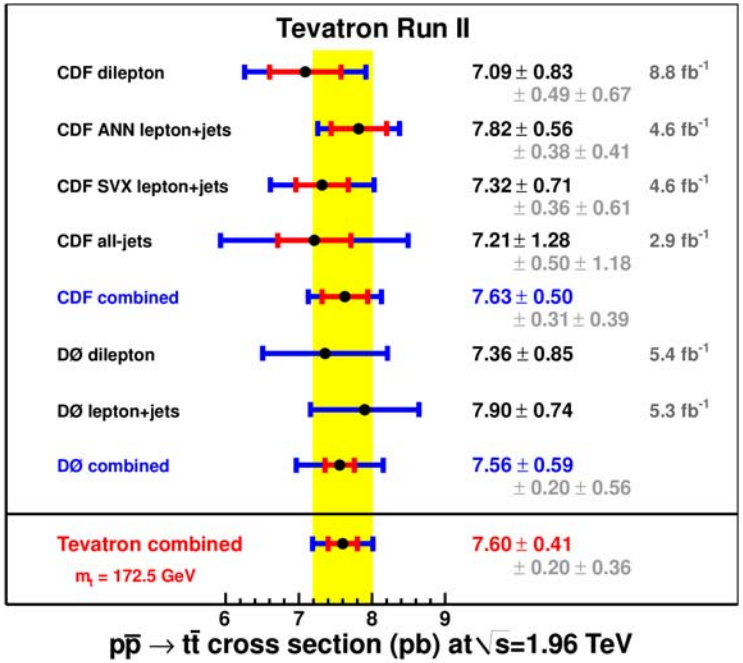
  ~85% quark annihilation
  - Important NLO contributions

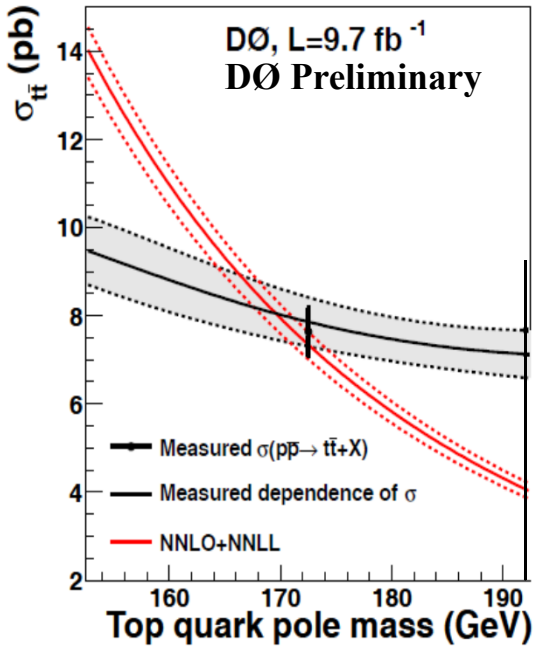
  ~15% gluon fusion
- ~70,000 $t\bar{t}$ produced/expt
  - ~3,000 reconstructed/expt



Total Cross Section Measurements

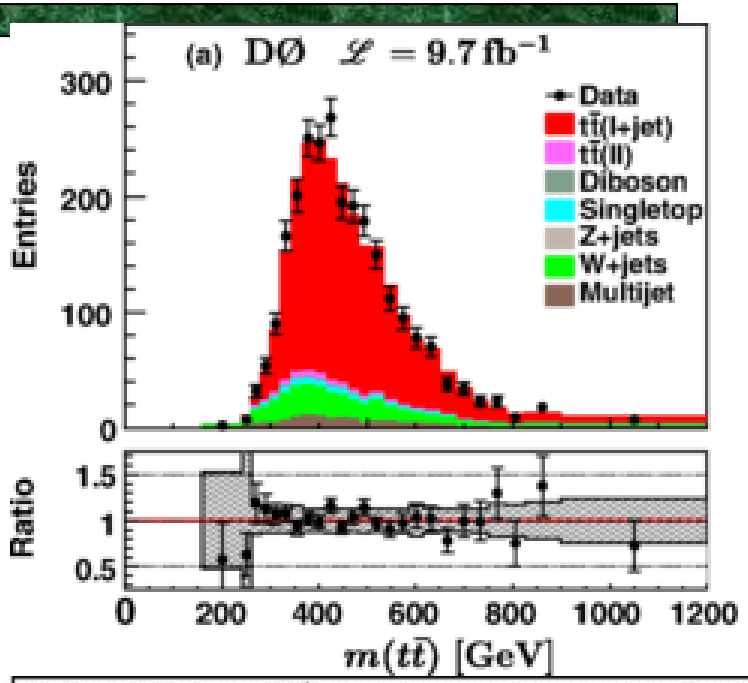
- **Tevatron combination:**
  - $\sigma_{t\bar{t}} = 7.60 \pm 0.41$pb
  - PRD 89, 072001 (2014)
- **New result from DZero (Lep+Jets & Dilepton)**
  - $\sigma_{t\bar{t}} = 7.73 \pm 0.13$ (stat.) ± 0.55 (syst.) pb,
  - D0 Note 6453-CONF (2015)
- **Theory Comparison:**
  - Fully resummed NNLO QCD calculation
    - » $\sigma_{t\bar{t}}^{Res} = 7.35^{+0.23}_{-0.27}$ (scale + pdf) pb
    - » Bernreuther, Czakon and Mitov, PRL 109 132001 (2012)
  - aNNNLO
    - » $\sigma_{t\bar{t}}^{Res} = 7.37 \pm 0.39$ (scale+pdf) pb
    - » Kidonakis, PRD 90, 014006 (2014)

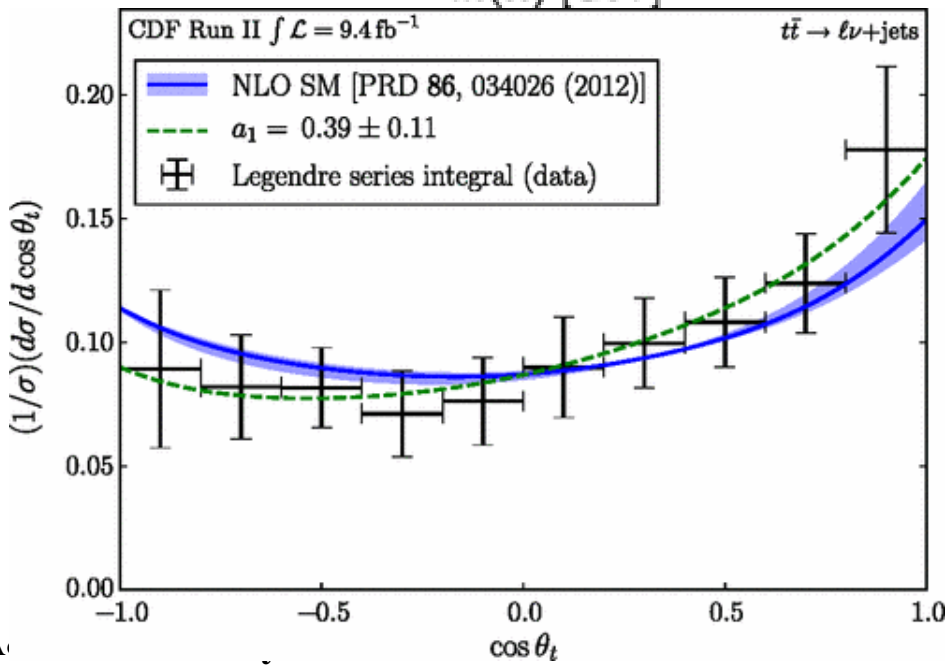




Differential Production Cross Sections

- Can look at the cross section as a function of $M_{t\bar{t}}$
  - E.g. DZero PRD 90, 092006 (2014)
- Similarly, look at it as a function of $\mathrm{Cos}(\theta_t)$
  - E.g. CDF PRL 111, 182002 (2013)
- No evidence for new physics, but the deviations as a function of $\mathrm{Cos}(\theta_t)$ are the source of the A_{FB} story





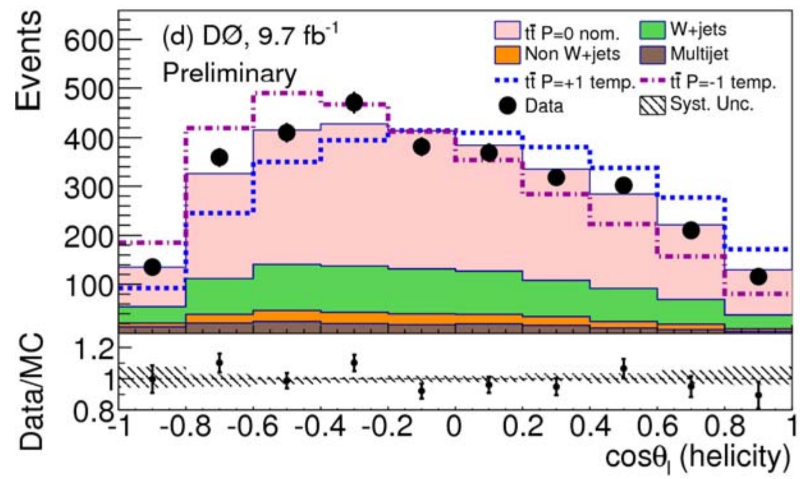
Polarization in $t\bar{t}$ Events

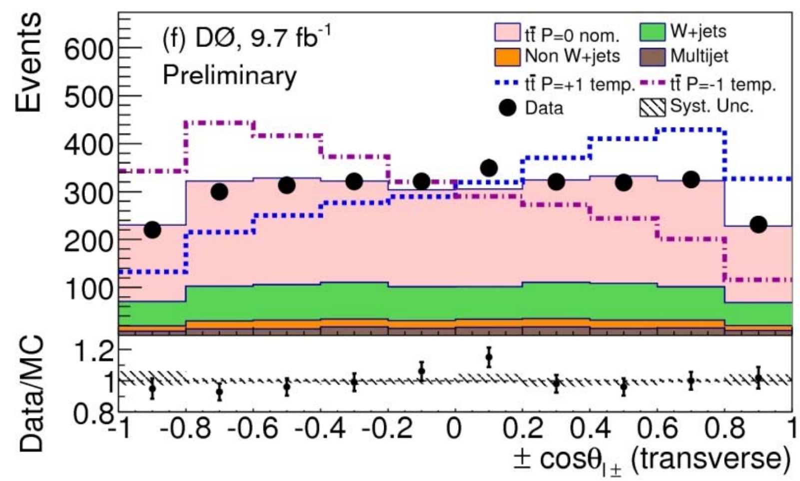
- **Tops are almost un-polarized at the Tevatron**
  - **Small longitudinal polarization from parity-violating weak interactions**
  - **Transverse polarization is allowed in strong interactions**
  - **BSM can make these bigger**
- **Since the top lifetime (~5×10^{-25} s) is smaller than the spin-decorrelation time from spin-spin interactions (~3×10^{-21} s) tops transfer their spin properties to their decay products**
- **Can measure polarization through the final angular distributions with respect to a chosen axis**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}(1 + P_{\hat{n}}\kappa_i \cos\theta_{i,\hat{n}})$$

Top Quark Polarization Cont…

- **After full reconstruction the final angle distributions gives the amount of polarization in three different configurations**
- **Data are consistent with zero polarization, and with the predicted SM values**
- **First measurement of polarization along the transverse axis at a hadron collider**





Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

DZero Conference Note 6471 (2015)

Spin Correlations

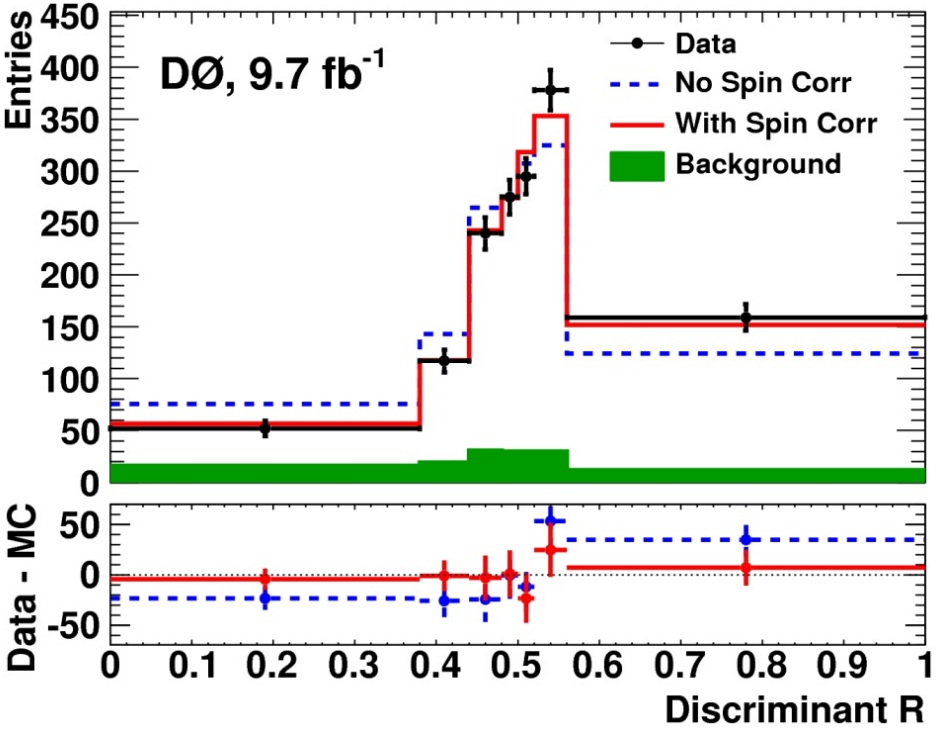
- **While QCD processes yield mostly unpolarized top and anti-top, the spins of the top and anti-top are highly correlated**
- **Define the Spin Correlation as:**

$$O_{ab} = \langle 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b}) \rangle = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)},$$

- **$O_{off} = 0.80^{+0.01}_{-0.02}$ predicted in the off-diagonal spin basis (maximal at the Tevatron)**
  - **$q\bar{q}$ annihilation has a spin correlation strength of ~0.99**
  - **gluon-gluon fusion has a typical strength of ~-0.36**

Spin Correlation Data

- Create an event-by-event discriminant for the probability "With Spin Correlations" and for "No Spin Correlations"
- Fit the data allowing the total cross section and the fraction of "With Spin Correlations" to float



Dzero arXiv:1512.08818, Submitted to PLB

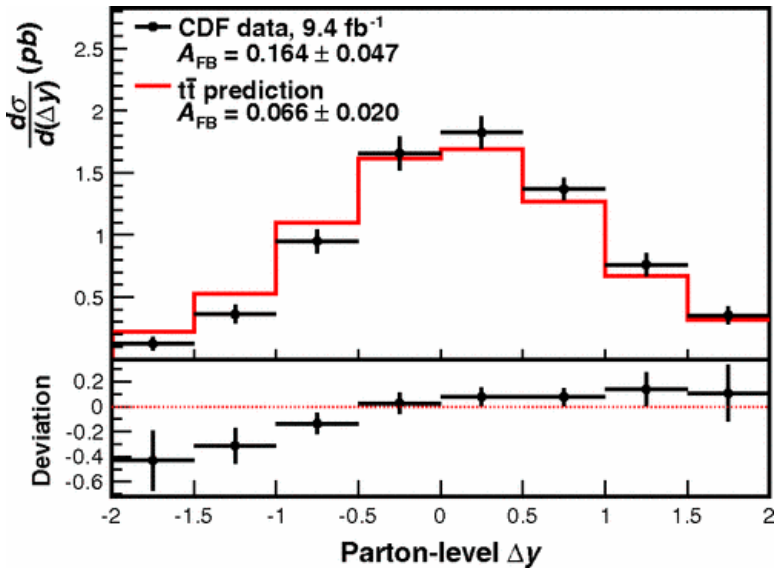
Spin Correlation Conclusions

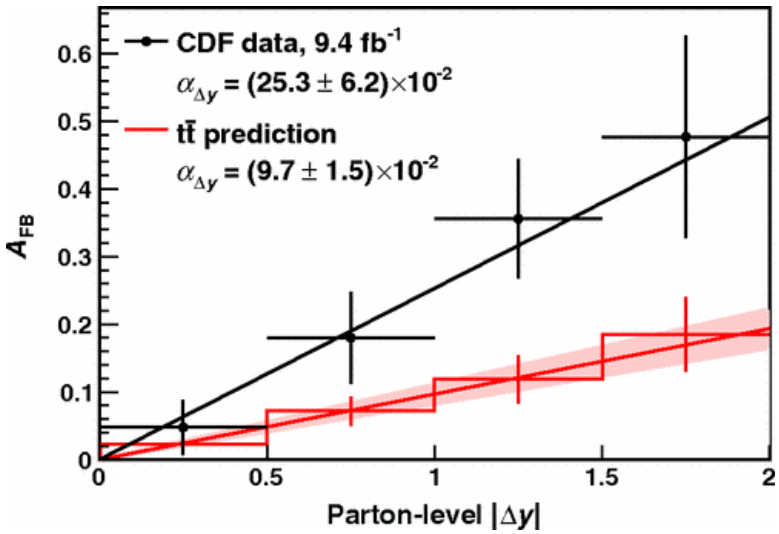
Results:

- O_{off} = 0.89 ±0.16 (stat)±0.15 (syst)
- Exclude the Uncorrelated scenario
  - P-value is 2.5×10^{-5} for obtaining a spin correlation larger than the observed value (4.2σ)
- Assuming no BSM contributions, constrain the fraction of events from gluon fusion to f_{gg}=0.08±12(stat) ±0.11(sys) which is in agreement with the NLO prediction of 0.135

Last of the A_{FB} Measurements in $t\bar{t}$ at the Tevatron

- The forward-backward asymmetry has been a hot topic since a larger-than-expected asymmetry was observed in 2012
- Not just the total asymmetry, but the asymmetry as a function of Δy and as a function of $M_{t\bar{t}}$ were larger as well
- Original results from CDF in Lep+Jets:
  - $A_{FB} = 0.164 \pm 0.047$
  - $Slope_{\Delta Y} = 0.253 \pm 0.062$
    - PRD 87, 092002 (2012)
- Note large change in SM predictions:
  - A_{FB} (NNLO SM) = 0.095±0.007
    - Czakon, Fiedler & Mitov, PRL 115, 052001 (2015)
  - $Slope_{\Delta Y}$ (NNLO)= $0.114^{+0.006}_{-0.012}$
    - Czakon, Fiedler, Heimes & Mitov, arXiv:1601.05375

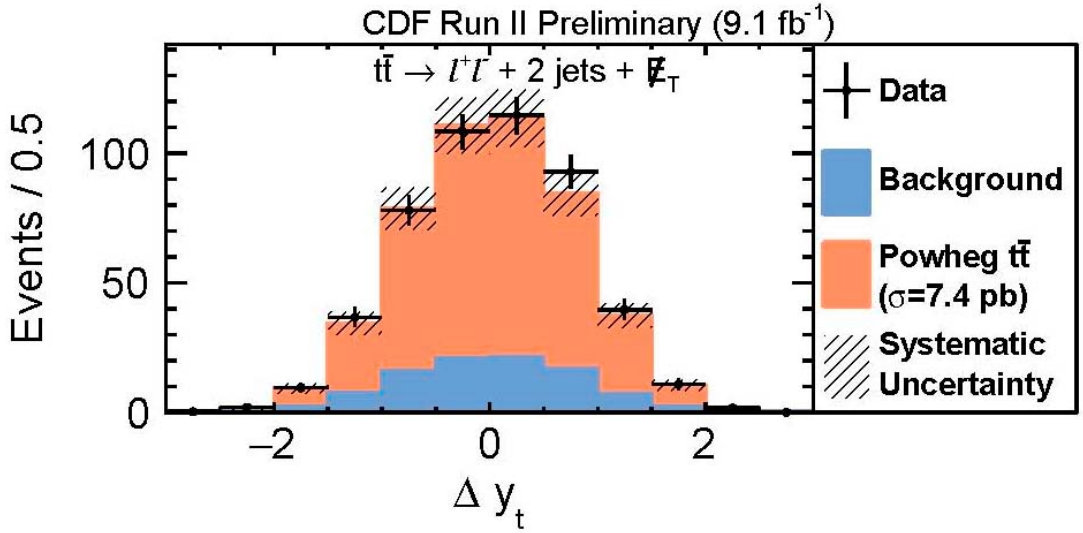




New A_{FB} Results from CDF

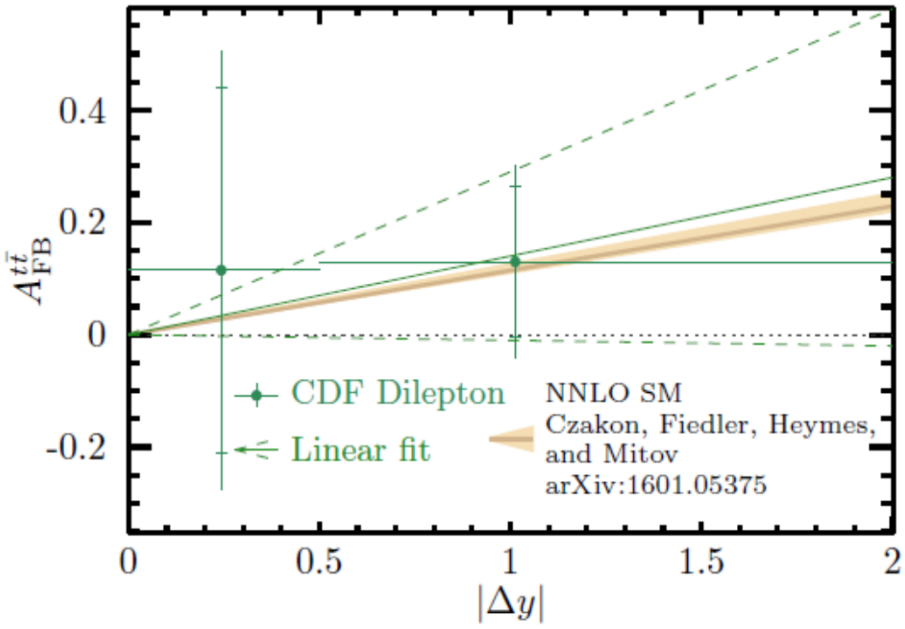
- **Results with dilepton data:**
  - $A_{FB} = 0.12 \pm 0.11(stat) \pm 0.07(syst) = 0.12 \pm 0.13$
- **Combined with CDF result in lepton+jets**
  - $A_{FB} = 0.160 \pm 0.045$
- **Consistent with SM and DZero**
  - A_{FB} (NNLO SM) $= 0.095 \pm 0.007$ within 1.5σ
  - $A_{FB} = 0.118 \pm 0.028$ DZero, PRD 92 052007 (2015)

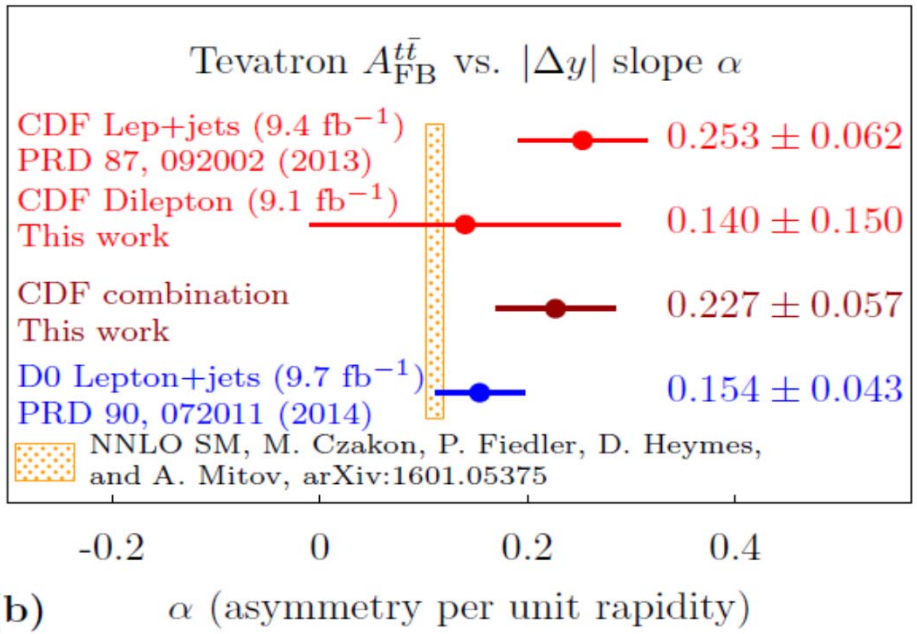
CDF arXiv: 1602.09015, Submitted to PRD



Look at Differential Distributions

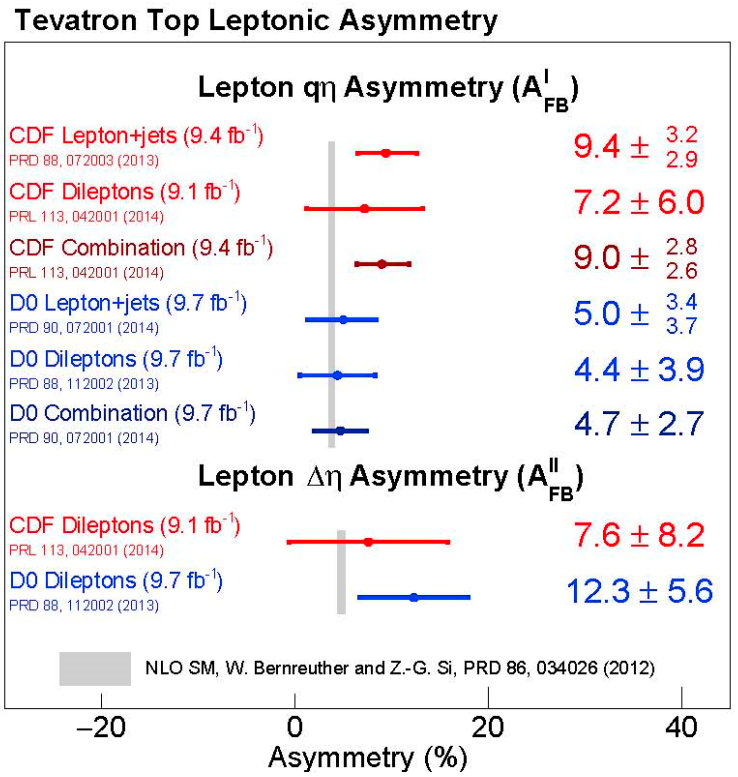
- Measure the slope of A_{FB} vs. $|\Delta y|$
  - $\text{Slope}_{\Delta Y} = 0.14 \pm 0.16$
- Combine with Lep+Jets results
  - $\text{Slope}_{\Delta Y} = 0.227 \pm 0.057$
  - 2.0σ from NNLO SM
  - Not enough statistics to make a meaningful slope vs. $M_{t\bar{t}}$ measurement
- Again consistent between CDF and DZero

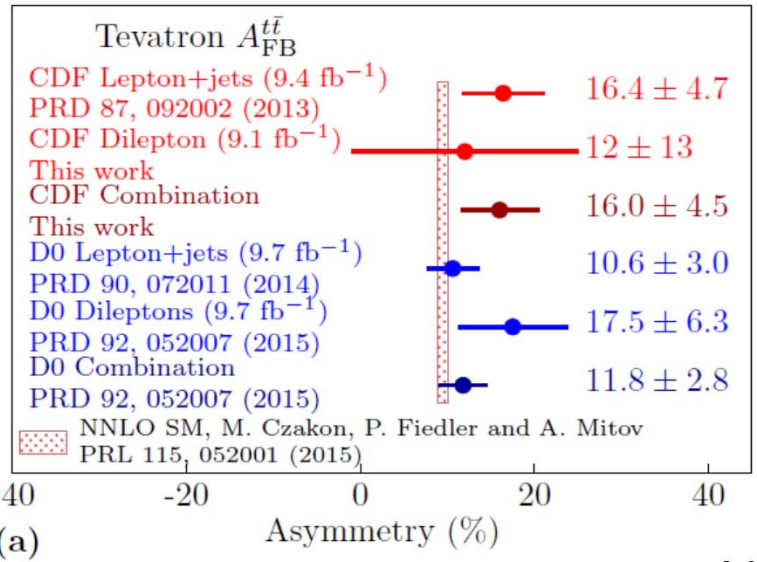




Legacy A_{FB} Tevatron Results

- **Final individual results on A_{FB} from Tevatron**
- **All the results, including from DZero, are consistent with SM predictions**
- **Notice that all of them are above…**
- **A combination of CDF+DZero results is in the works**





Conclusions

- Top production at the Tevatron has yielded a wealth of important information about the heaviest known fundamental particle
- While many of the distributions have shown to be similar to SM predictions, the measured precisions have pushed well beyond LO, to NLO and NLO+
- Indeed, many of the corrections have been larger than expected, and appear to have been the cause of some of exciting hunts for new physics while we figured it out
- The legacy results from the Tevatron are nearing completion, bringing this long, wonderful story to a close