

# Measurement of Forward-Backward Asymmetries at the Tevatron

*European Physical Society Conference on High Energy Physics  
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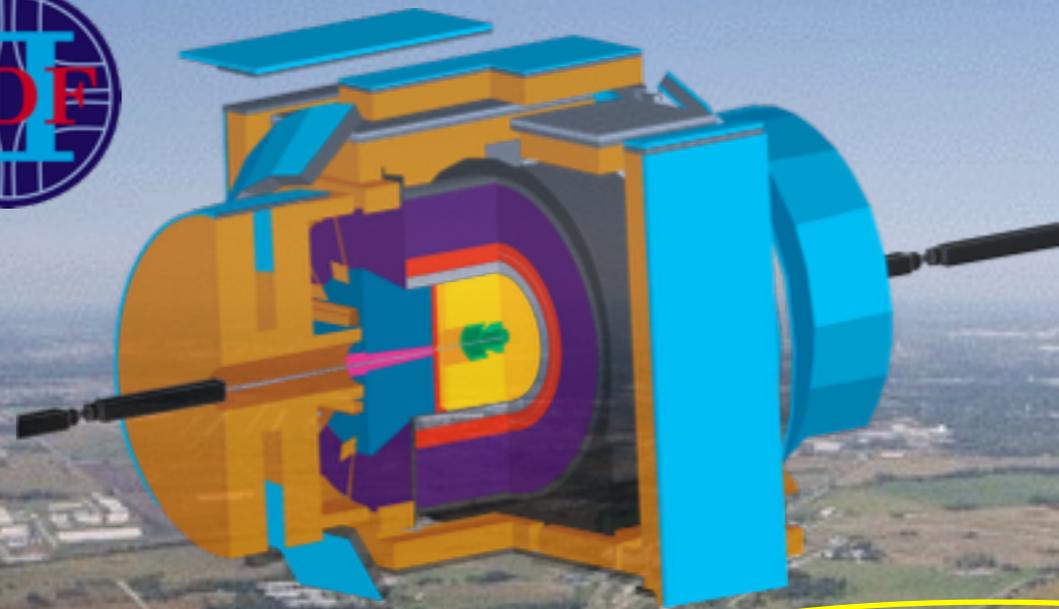
ULRICH HUSEMANN on behalf of the CDF and DØ Collaborations



# Fermilab Tevatron: 1985–2011

Fermi National Accelerator Laboratory – Aerial View

[Fermilab Visual Media Service]



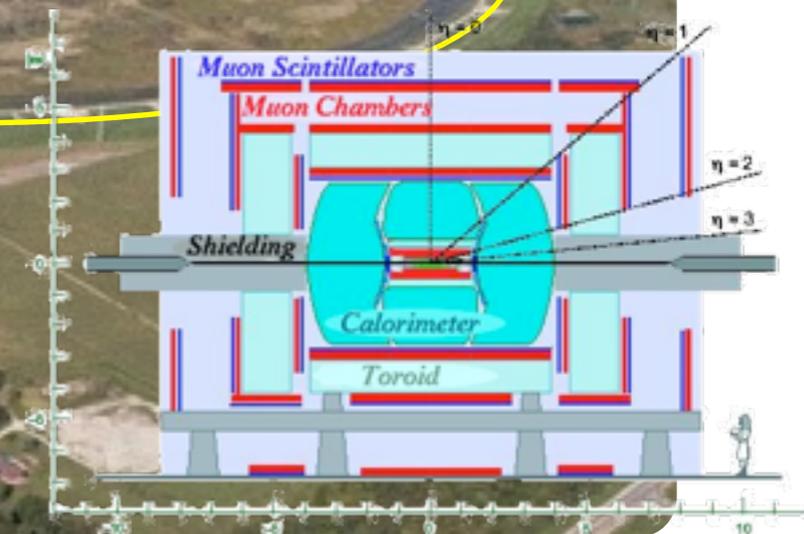
Tevatron

2 km



## ■ The Tevatron

- Proton-antiproton collider
- Run II:  $\sqrt{s} = 1.96$  TeV
- Two general-purpose experiments: **CDF**, **DØ**
- Total integrated luminosity:  $10 \text{ fb}^{-1}$  per experiment



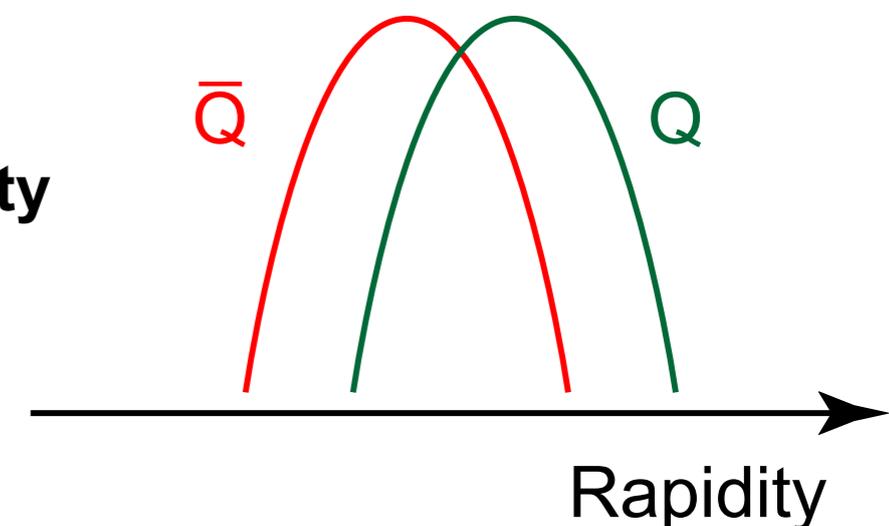
# Forward-Backward Asymmetry

- Heavy quark pair production in  $p\bar{p}$  collisions
  - Leading order QCD: **symmetric** under  $Q \leftrightarrow \bar{Q}$
  - **NLO QCD**: production process  $q\bar{q} \rightarrow Q\bar{Q}$  asymmetric  $\rightarrow$  **interference** between Born/box diagrams and initial/final state radiation (Kühn, Rodrigo, 1999)
  - Production process  $gg \rightarrow Q\bar{Q}$  remains symmetric
  - Additional asymmetry contributions: **electroweak** effects

- **Forward-backward asymmetry  $A_{FB}$**

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

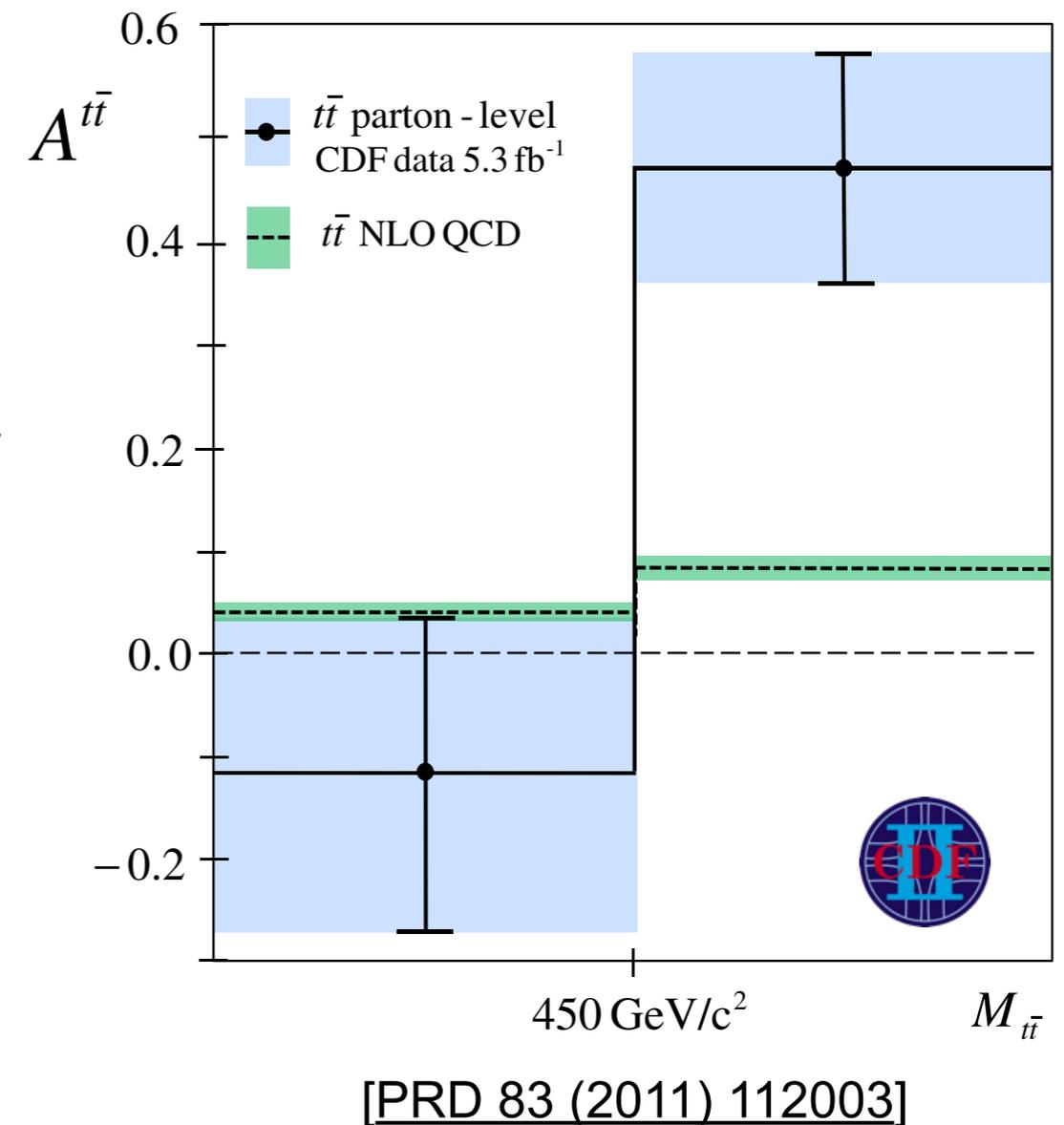
- Forward/backward usually defined in terms of **rapidity difference** of quarks and antiquarks  $\Delta y = y_Q - y_{\bar{Q}}$   
 $\rightarrow$  invariant under boosts in beam direction
- LHC: **symmetric** pp collisions  $\rightarrow A_{FB} = 0$ ,  
 measure charge asymmetry  $A_C$



Recent review: [Aguilar-Saavedra, Amidei, Juste, Pérez-Victoria, Rev. Mod. Phys. 87 \(2015\) 421](#)

# History of Top $A_{FB}$

- 2008: first Tevatron Run II measurements ( $1-2 \text{ fb}^{-1}$ ) indicate **large  $A_{FB}$**
- 2011: results on about half of Run II dataset → **discrepancies** between data and NLO expectation at level of 3 SD for large  $t\bar{t}$  **invariant mass** (CDF)
- Triggered **extensive measurement program** (Tevatron & LHC)
- O(150) **theory papers**: improved standard model calculations, many BSM ideas



Inclusive and differential  $t\bar{t}$  asymmetry

Leptonic  $t\bar{t}$  asymmetry

$b\bar{b}$  asymmetry at low and high energies

# A<sub>FB</sub>: Observables

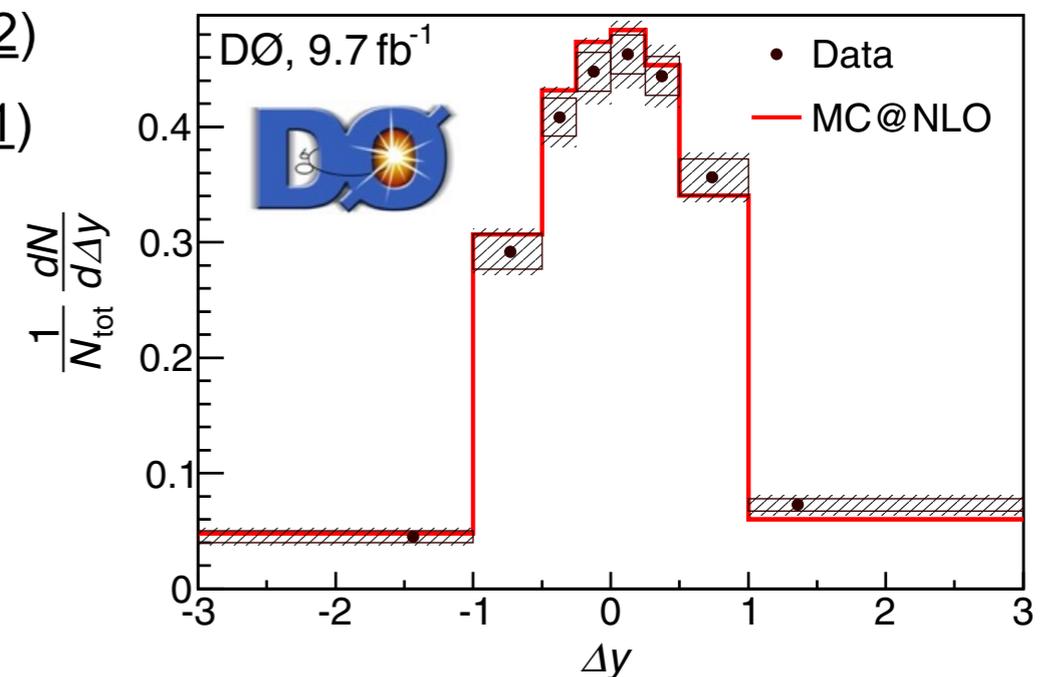
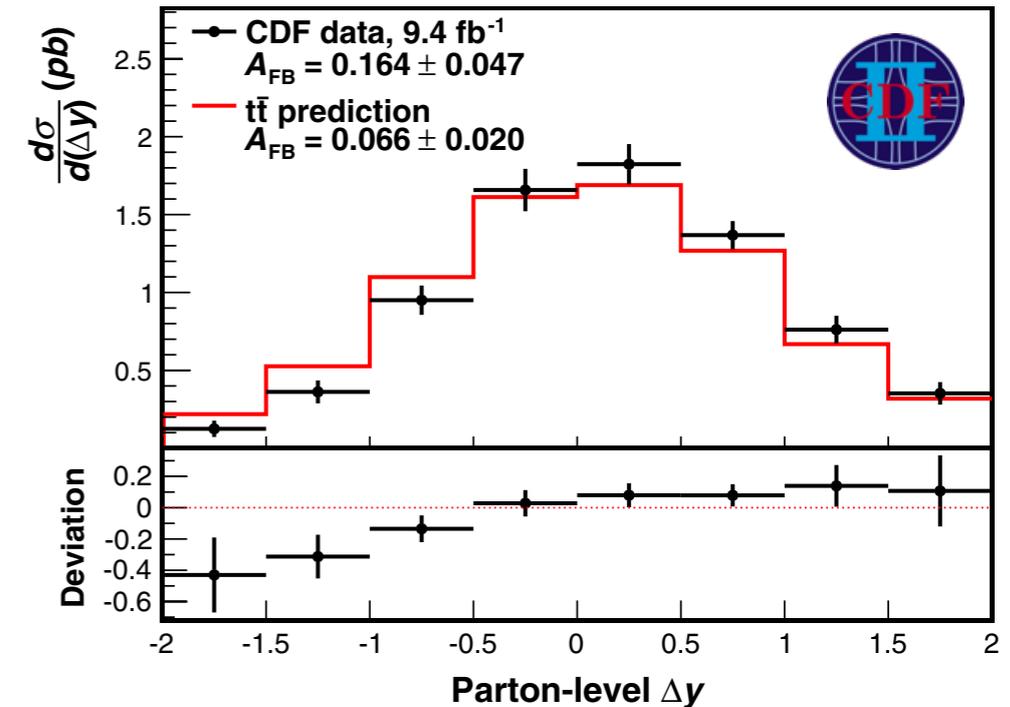
- **Raw asymmetry:** asymmetry as reconstructed  
→ **detector-dependent** (different phase space coverage)
- **t $\bar{t}$  asymmetry at parton level** (also: “production level”)
  - Correction of observables to parton level: **unfolding** using NLO MC simulation
  - Results directly **comparable to calculations**, but some model dependence
  - **Inclusive** or **differential** in kinematics of t $\bar{t}$  system (e.g. m<sub>t $\bar{t}$</sub> , production angle)
- **Leptonic asymmetry:**
  - Charge asymmetry of **leptons from top decay** → clean, small migration effects (but dependence on top polarization in addition to asymmetry → **complementary**)

$$A_{\text{FB}}^{\ell} = \frac{N_{\ell}(q_{\ell}\eta_{\ell} > 0) - N_{\ell}(q_{\ell}\eta_{\ell} < 0)}{N_{\ell}(q_{\ell}\eta_{\ell} > 0) + N_{\ell}(q_{\ell}\eta_{\ell} < 0)}$$

- **Dileptonic asymmetry** A<sup>ℓℓ</sup>: asymmetry in Δη = η<sub>ℓ+</sub> – η<sub>ℓ-</sub> of lepton pair

# Top: Inclusive Asymmetry

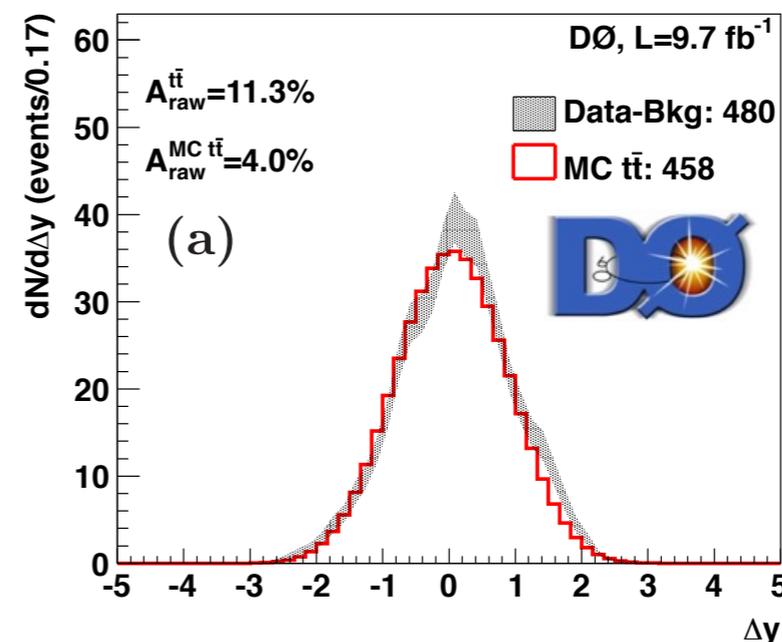
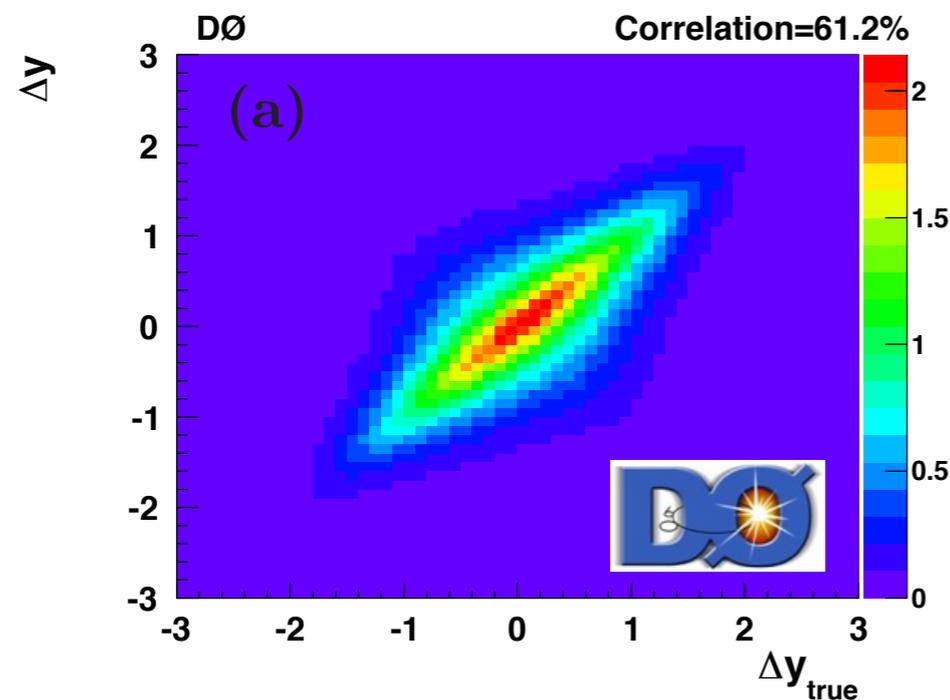
- Inclusive  $A_{\text{FB}}$  in **lepton+jets** channel
  - **Kinematic reconstruction** of  $t\bar{t}$  system
  - $t$  and  $\bar{t}$  distinguished by **lepton charge** in leptonically decaying top
  - Correction to parton level: **matrix unfolding**
  - $D\emptyset$ : include lepton + 3 jet final states
  
- Tevatron results on full Run II datasets:
  - CDF:  $A_{\text{FB}} = 0.164 \pm 0.047$  ([PRD 87 \(2013\) 092002](#))
  - $D\emptyset$ :  $A_{\text{FB}} = 0.106 \pm 0.030$  ([PRD 90 \(2014\) 072011](#))
  
- Most recent standard model predictions:
  - $A_{\text{FB}} = 0.095 \pm 0.007$  (NNLO QCD + NLO EW, Czakon et al., [arXiv:1411.3007](#))
  - $A_{\text{FB}} = 0.100 \pm 0.006$  (aN<sup>3</sup>LO QCD + NLO EW, Kidonakis, [PRD 91 \(2015\) 071502 \(R\)](#))



# Top: Inclusive Asymmetry

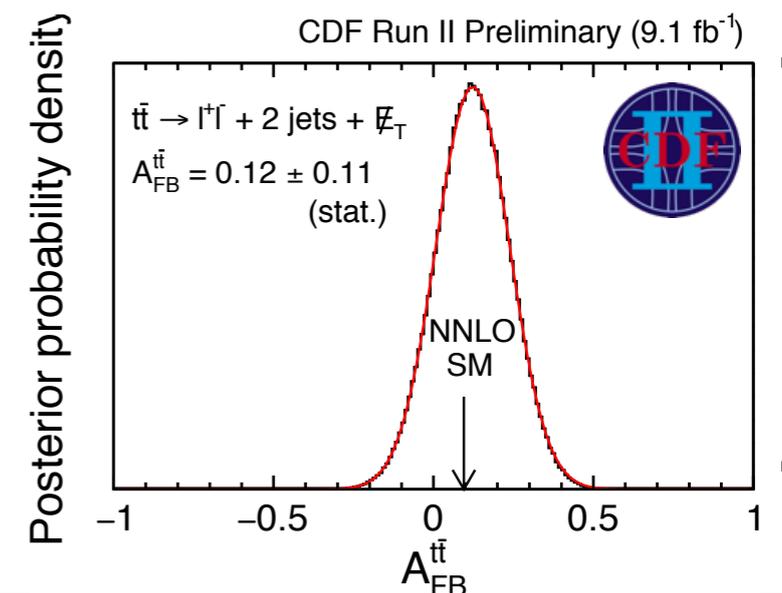


- Inclusive  $A_{FB}$  in **dilepton** channel (see also talk by B. Tuchming)
  - DØ: modified **matrix-element method** to determine parton-level  $A_{FB}$ 
    - measure correlated observables  **$A_{FB}$  and top polarization simultaneously**



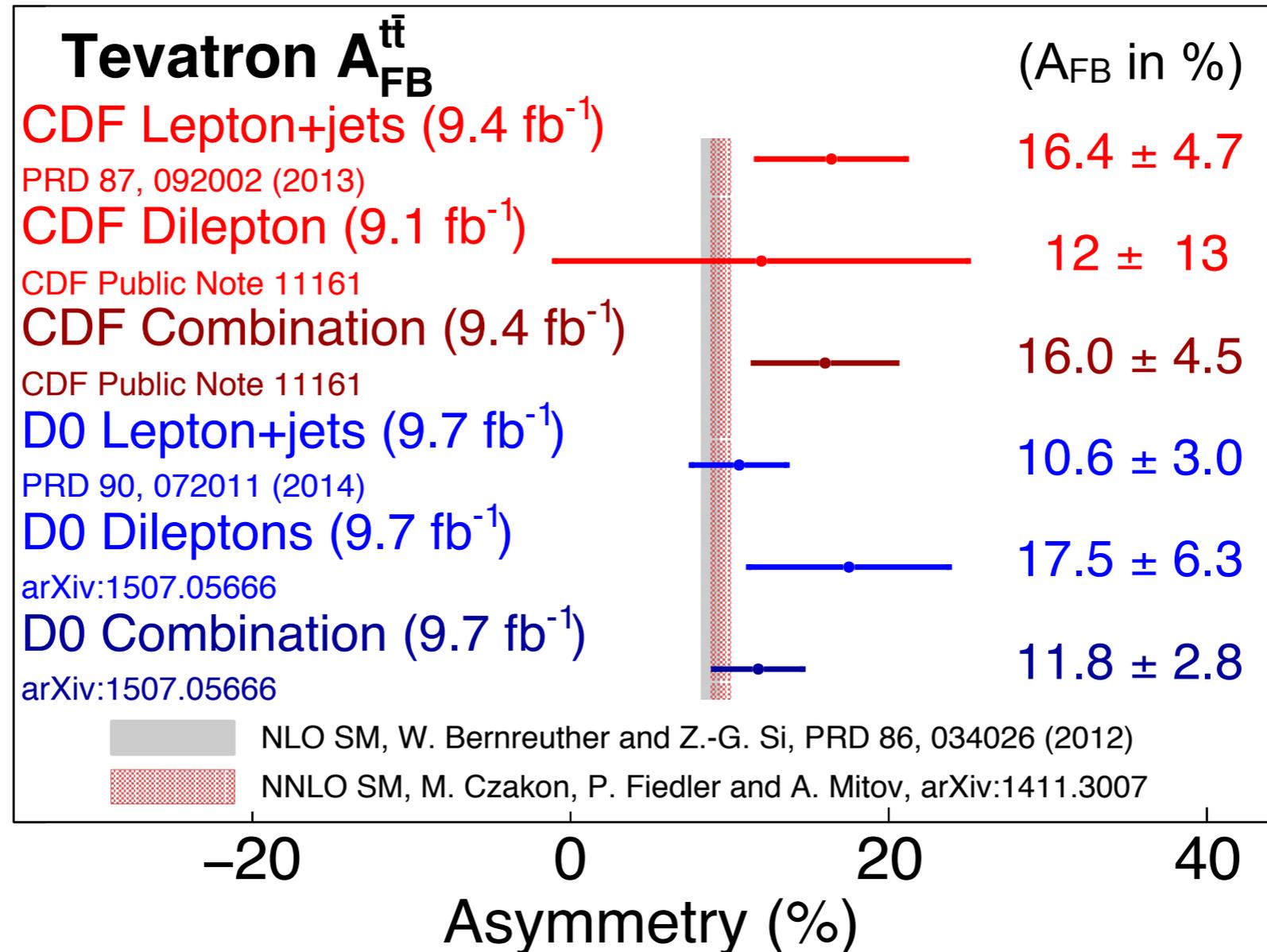
[arXiv:1507.05666,  
submitted to PRD]

- Challenge: model-independent **calibration** of analysis method
  - additional model uncertainty
- CDF: **likelihood-based  $t\bar{t}$  reconstruction**, **Bayesian model** to extract parton-level  $A_{FB}$



[CDF Note 11161]

# Top: Inclusive Asymmetry



All inclusive measurements compatible with standard model predictions within  $\leq 1.5$  standard deviations.

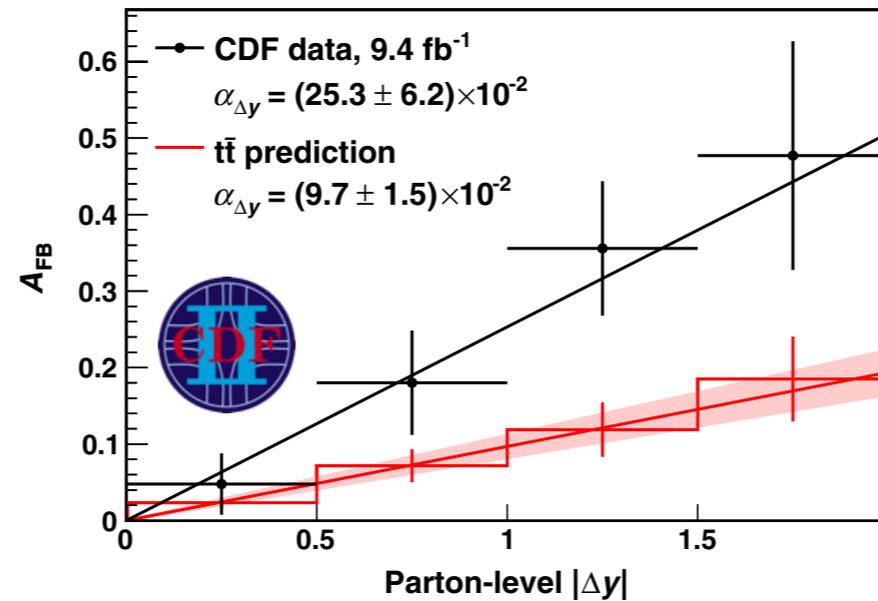
# Top: Differential Asymmetry

- Differential parton-level asymmetries

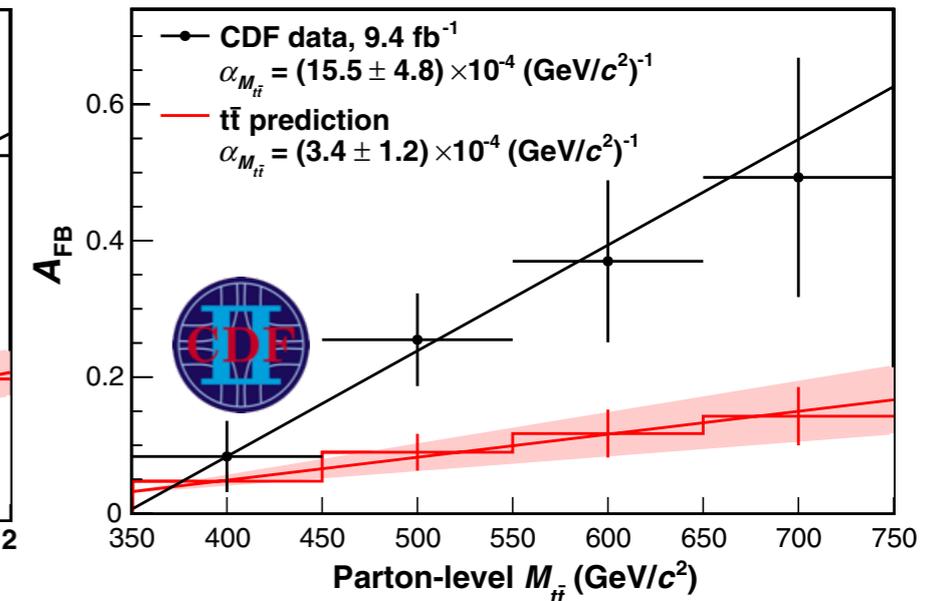
- $|\Delta y|$  dependence

- Expect **linear** increase, slope  $\alpha$

- CDF: **strong increase** ( $>2$  SD above NLO QCD)



[PRD 87 (2013) 092002]

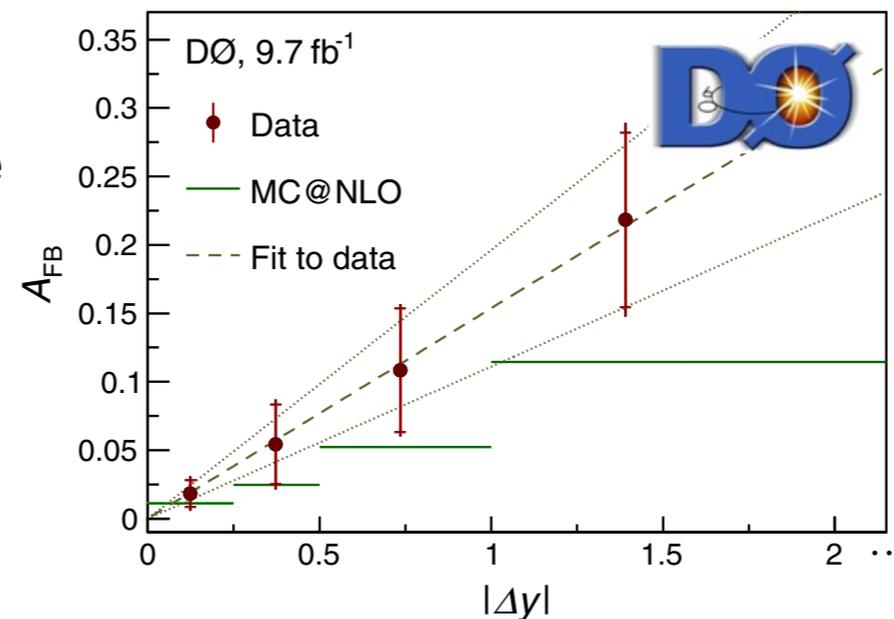


- $m_{t\bar{t}}$  dependence

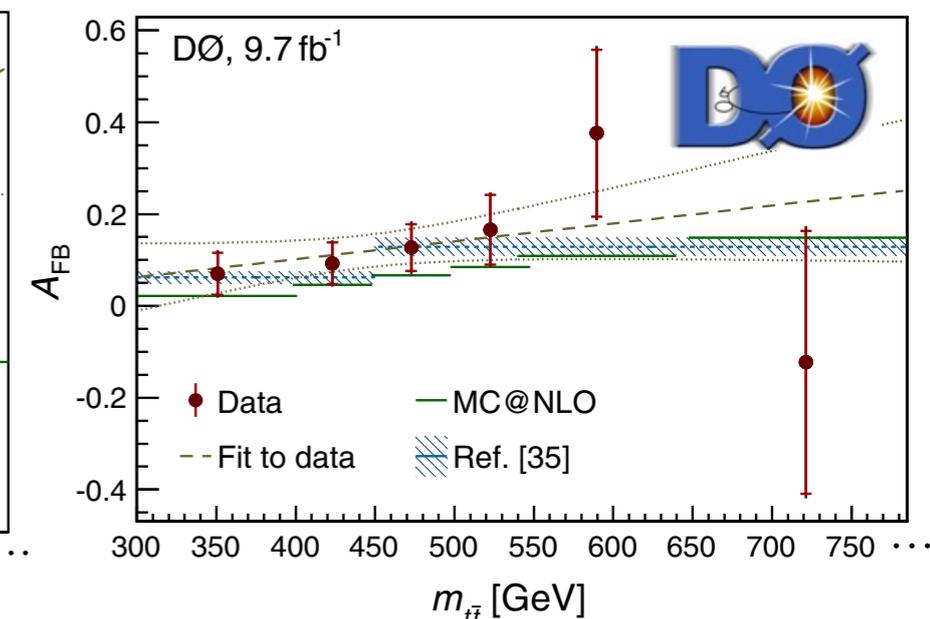
- Expect mild increase

- CDF: **strong increase** ( $>2$  SD above NLO QCD)

- DØ:  $<1$  SD above NLO predictions, little  $m_{t\bar{t}}$  dependence



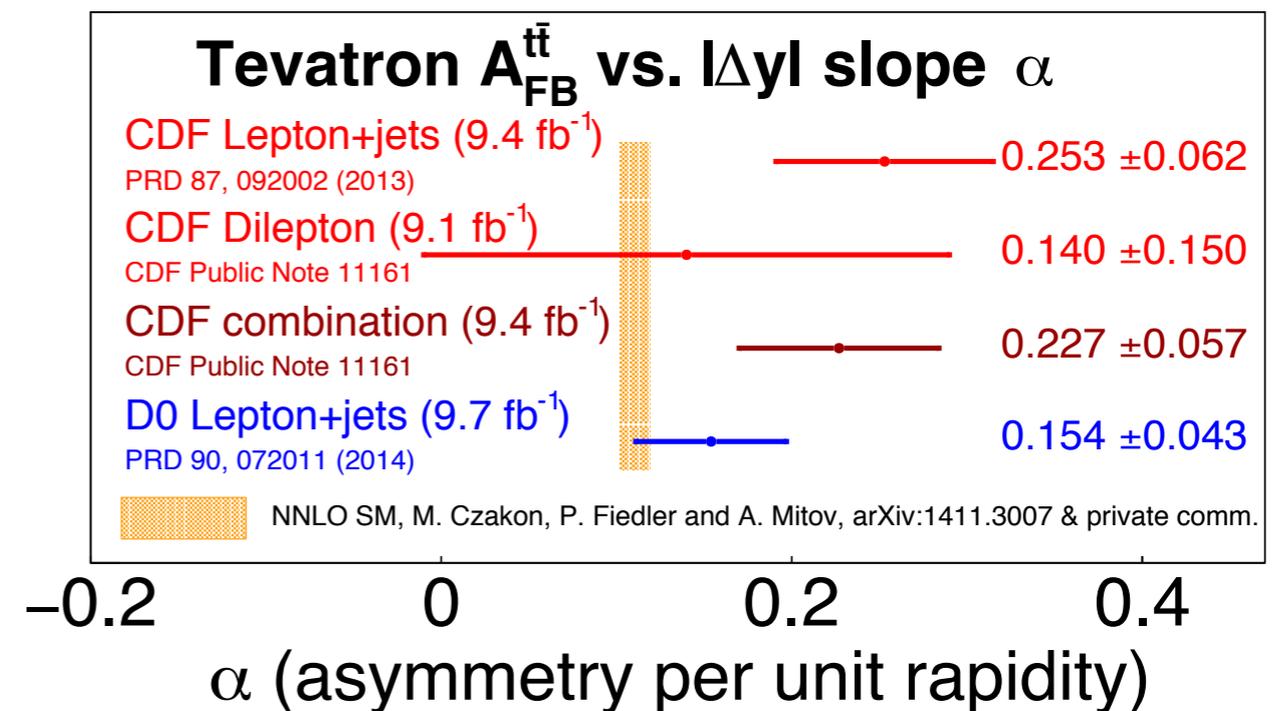
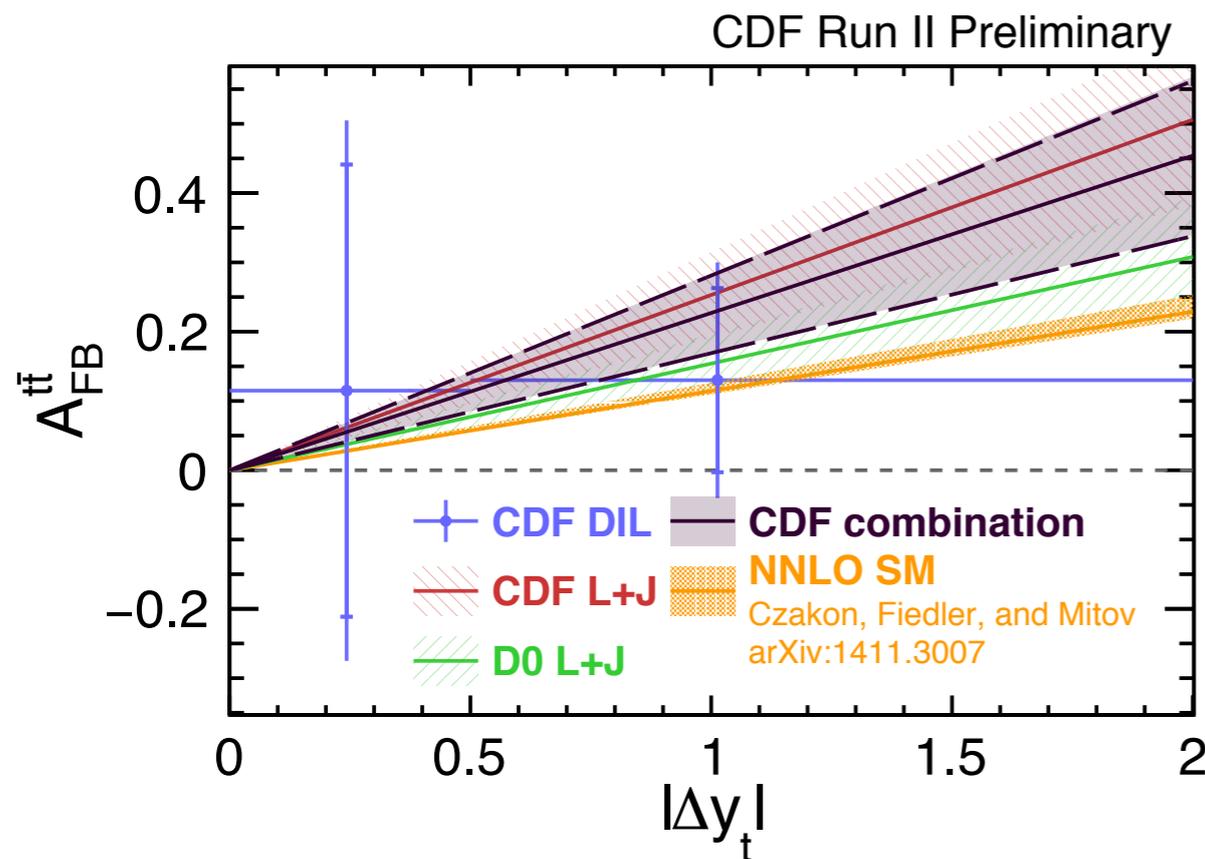
[PRD 90 (2014) 072011]



# Top: Differential Asymmetry



- Comparison with state-of-the-art standard model calculations (**NNLO+EW**)
- Both CDF and DØ: slope parameter  $\alpha$  **larger than predicted**
- **Reasonable** agreement, largest deviation: CDF lepton+jets analysis (2 SD)



[CDF Note 11161]

# Top: Production Angle



- Normalized differential cross section in **top production angle**

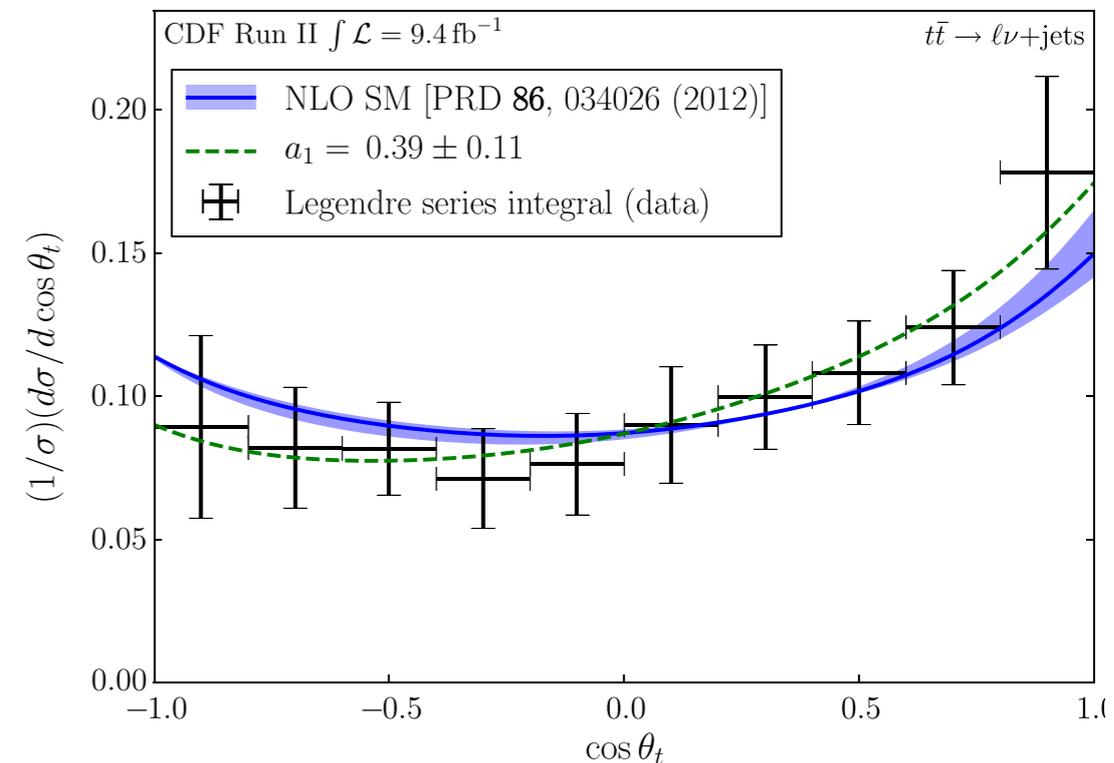
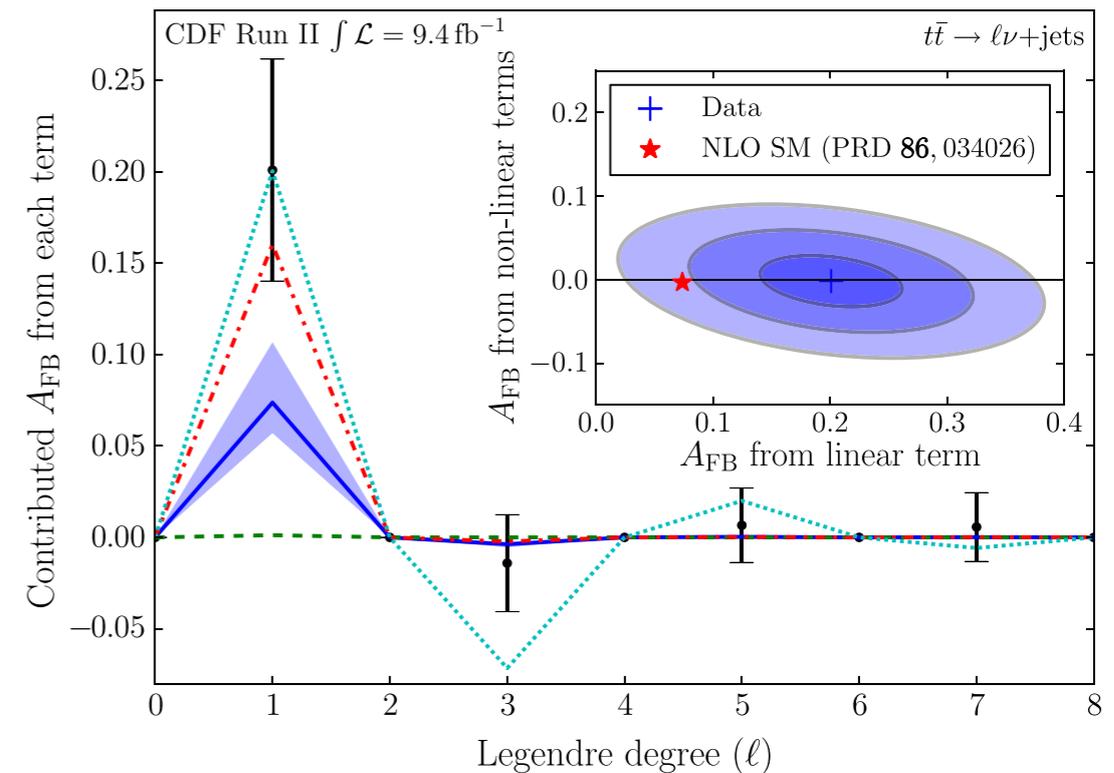
- Decomposition in orthonormal **Legendre polynomials**

$$\frac{d\sigma}{d\cos\theta_t} = \sum_{\ell=0}^{\infty} a_{\ell} P_{\ell}(\cos\theta_t)$$

- Legendre moments  $a_{\ell}$ :**  
sensitivity to underlying **dynamics**  
(s-channel: only  $a_1$ , t-channel: all  $a_{\ell}$ )

- CDF result in lepton+jets channel

- $A_{FB}$  entirely **due to  $a_1$**   
→ new physics in s-channel?
- Preliminary comparison with NNLO calculation (M. Czakon, private communication):  **$a_{\ell}$  agree with NNLO** with  $\chi^2$  probability of 75%



[PRL 111 (2013) 182002]

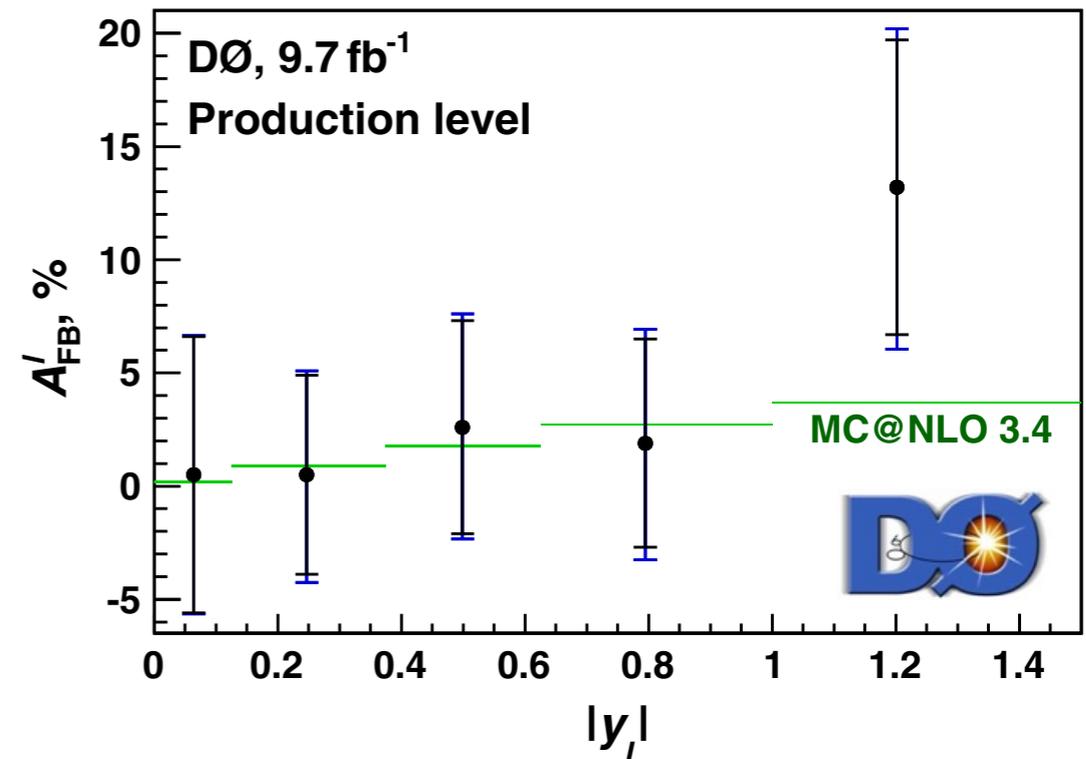
# Top: Leptonic Asymmetry

## ■ Leptonic asymmetry in lepton + jets channel

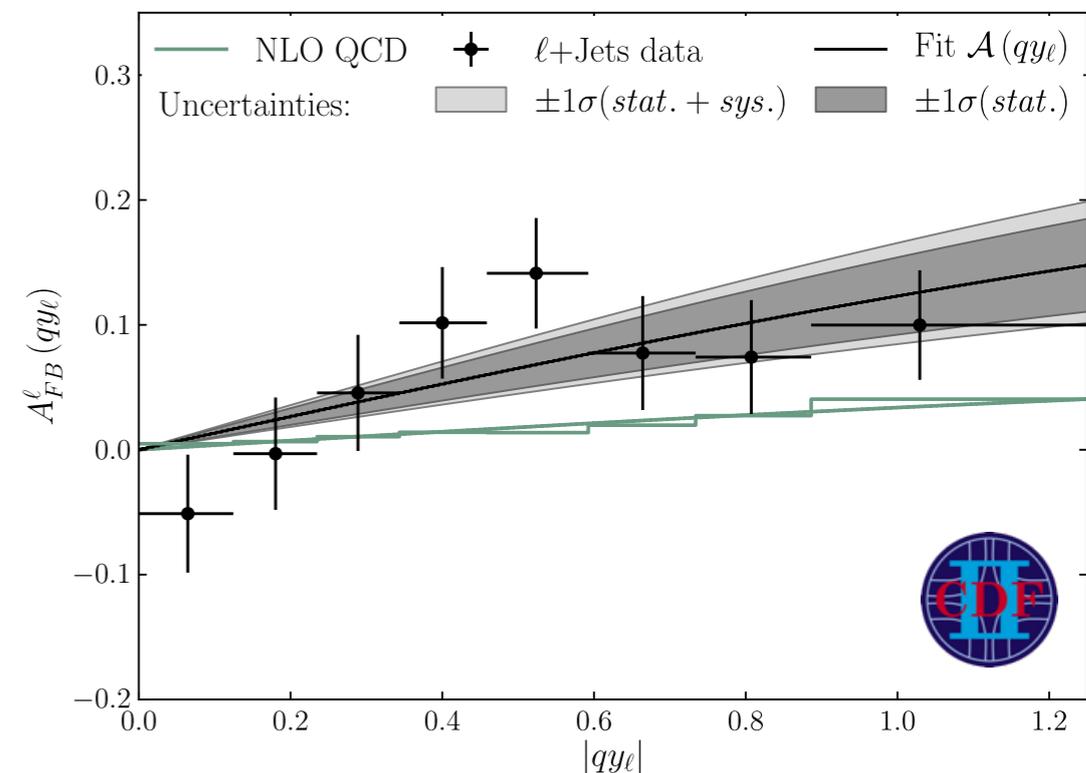
- Asymmetry in  $q_\ell \eta_\ell$  within detector acceptance
- Extrapolation to unmeasured  $\eta$  with empirical model
- Calculations including lepton acceptance cuts (NLO QCD + EW)  
→ very small model dependence  
(Bernreuther, Si, [PRD86 \(2012\) 034026](#))

## ■ Challenges:

- Control of **asymmetric background** from W+jets
- **Model-independent** extrapolation to full phase space



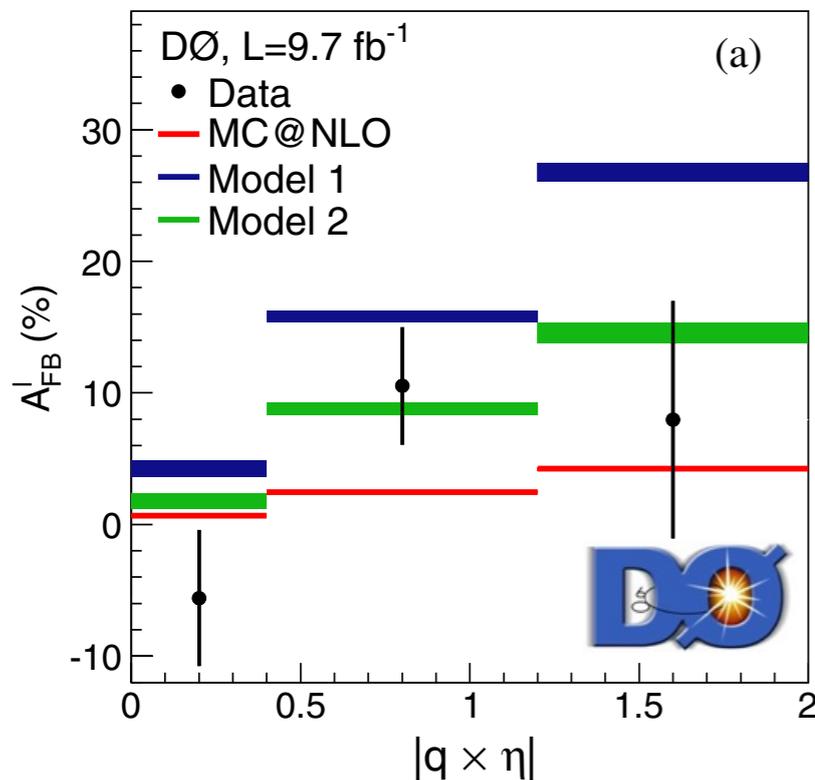
[PRD 90 (2014) 072001]



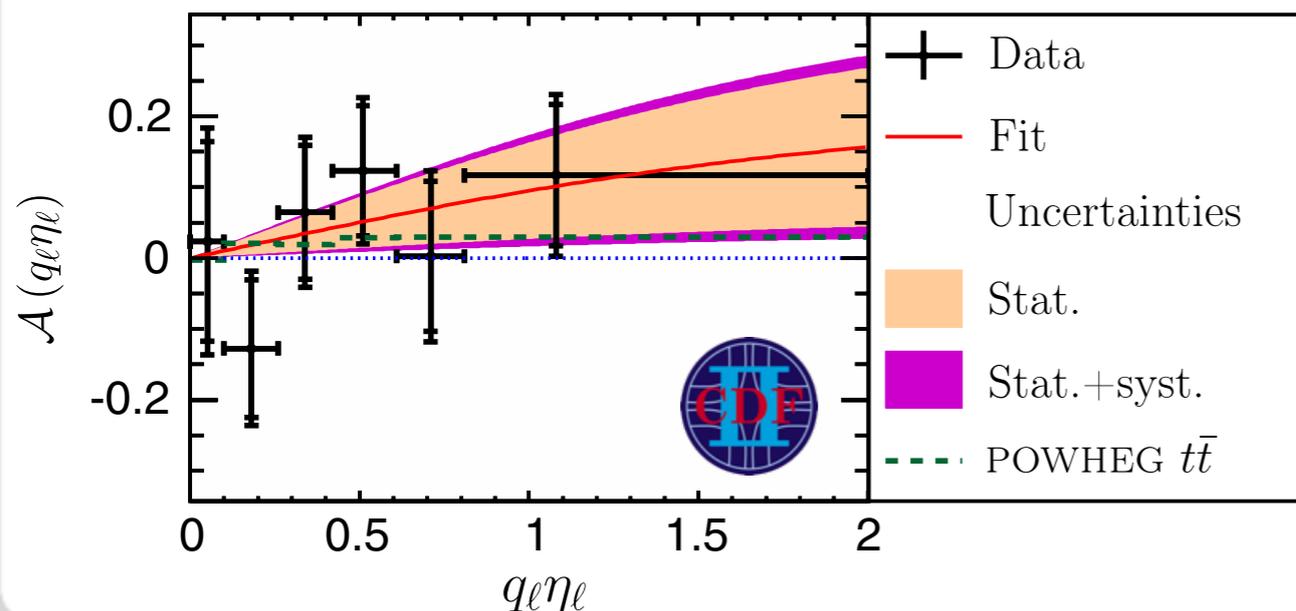
[PRD 88 (2013) 072003]

# Top: Leptonic Asymmetry

## Leptonic asymmetry in dilepton channel: observables $q_\ell \eta_\ell$ and $\Delta\eta$

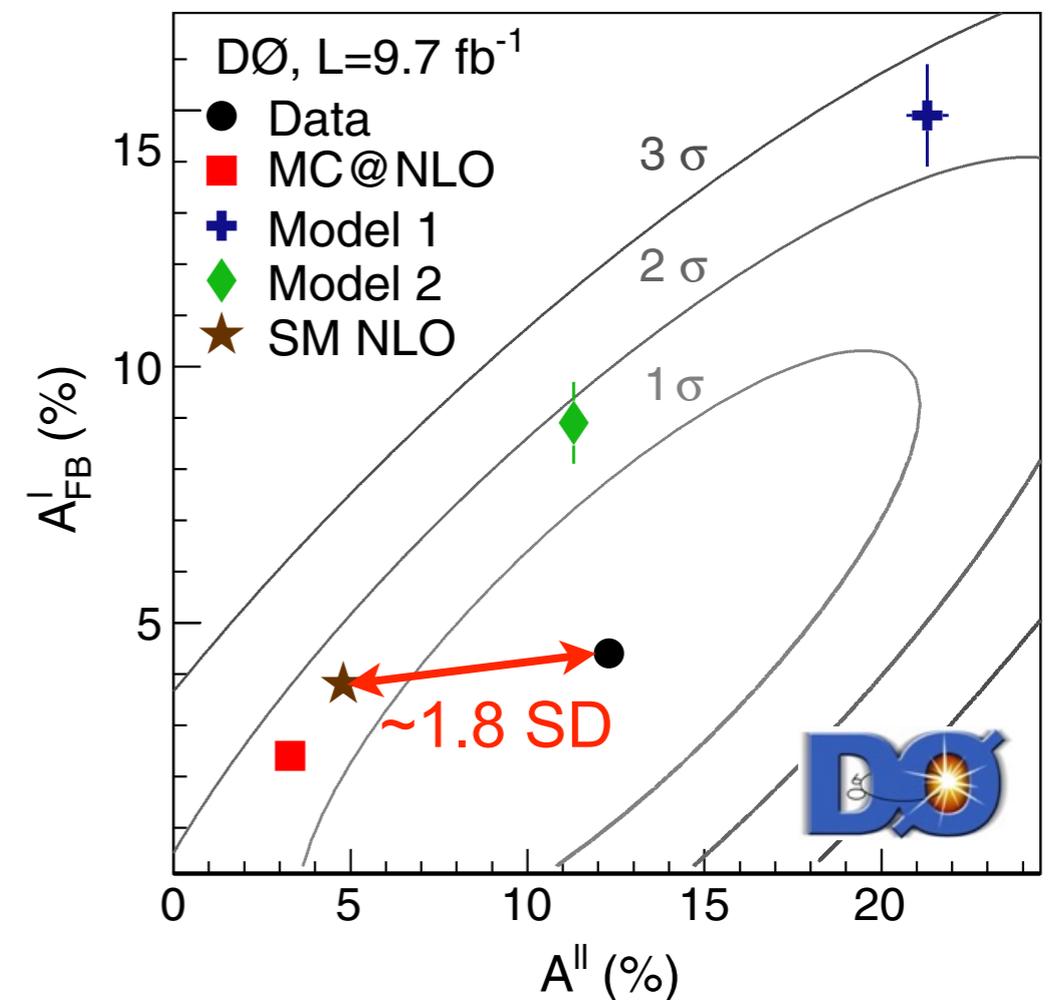


[PRD 88 (2013) 112002]



[PRL 113 (2014) 042001]

## Correlation of Asymmetries: $q_\ell \eta_\ell$ vs. $\Delta\eta$



[PRD 88 (2013) 112002]

SM NLO: QCD + EW

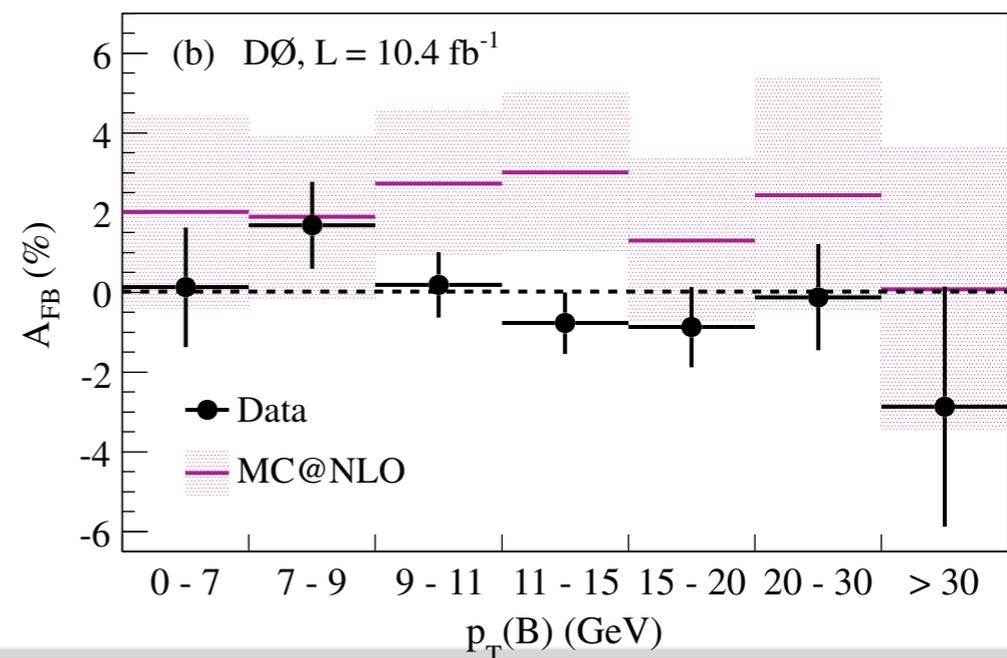
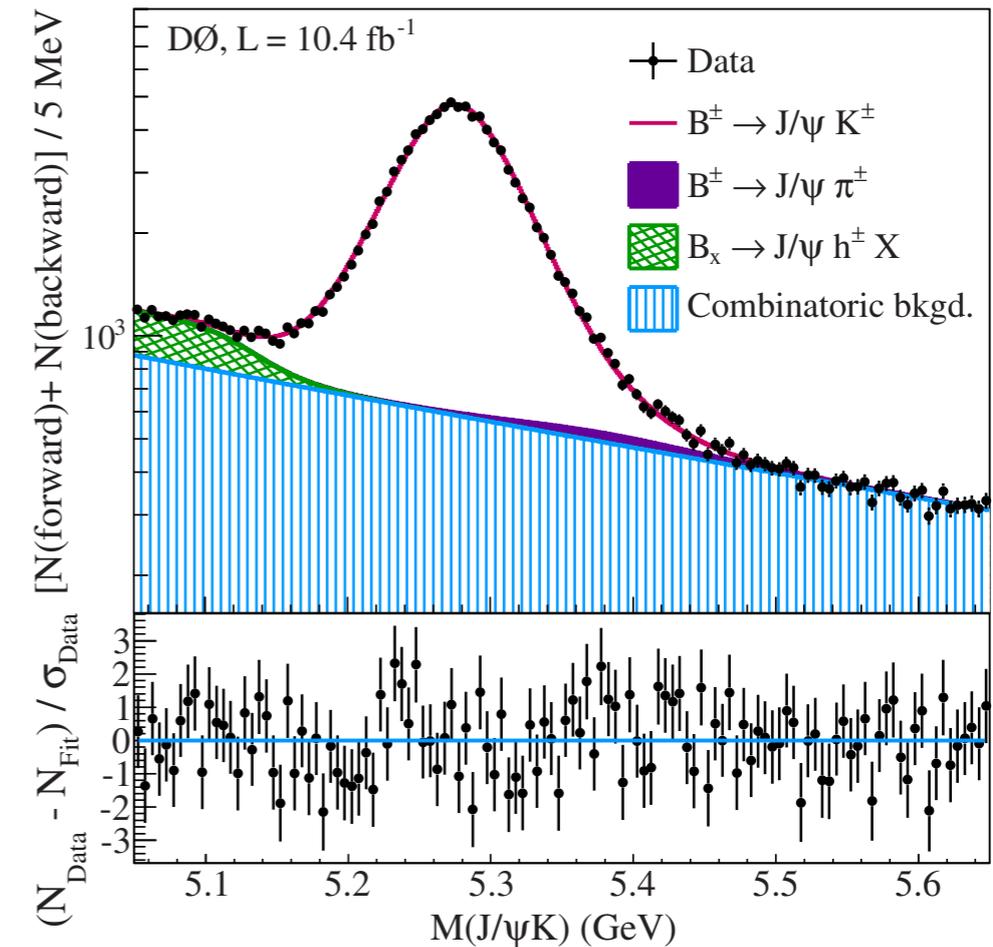
Model 1: 200-GeV axigluon RH SM couplings

Model 2: 2-TeV axigluon, strong coupling to top

# Bottom Asymmetry



- Idea: probe **same physics** that leads to top  $A_{FB}$  at **lower energies** than  $t\bar{t} \rightarrow$  study  $b\bar{b}$  system
- DØ: very low energies,  $p_{T,b} < 35$  GeV
  - **Full reconstruction** of charged B meson decays  $B^\pm \rightarrow J/\psi (\rightarrow \mu\mu) K^\pm$
  - **Unique** flavor assignment via kaon, no dilution from flavor oscillations
- **Result:**
  - Data consistent with **zero asymmetry**
  - Below NLO MC prediction, but confirmed by recent NLO QCD+EW calculation (Murphy, [arXiv:1504.02493](https://arxiv.org/abs/1504.02493))

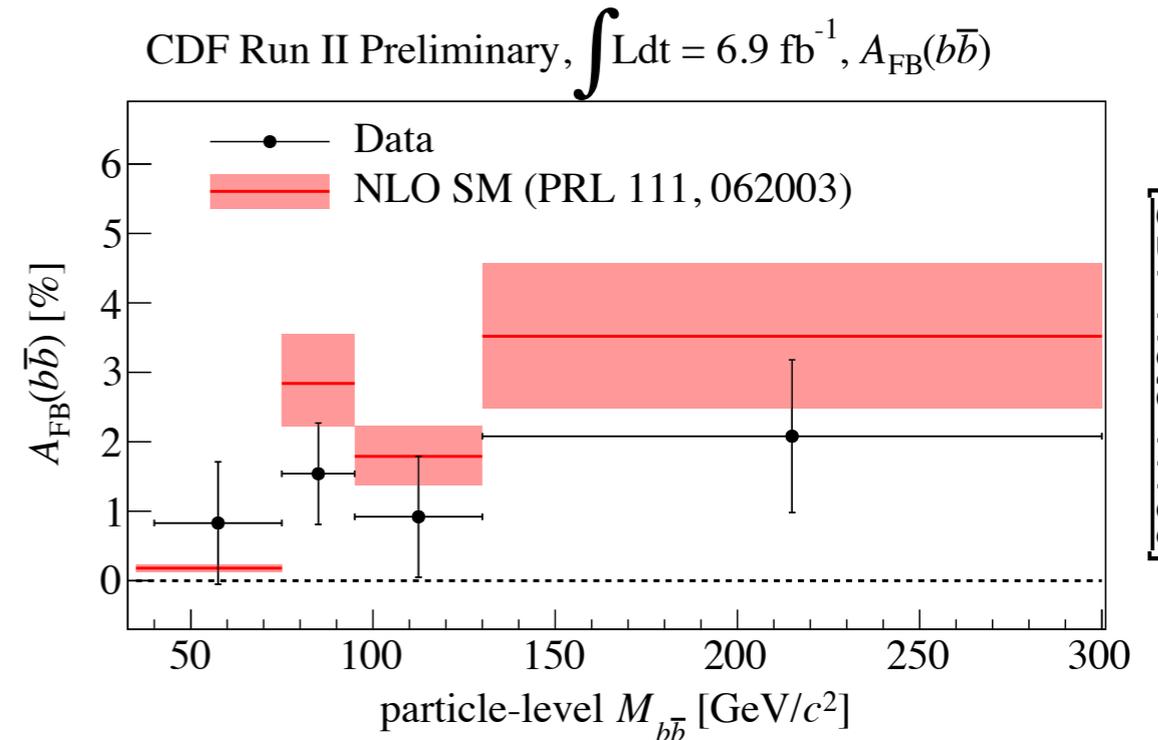


[PRL 114 (2015) 051803]

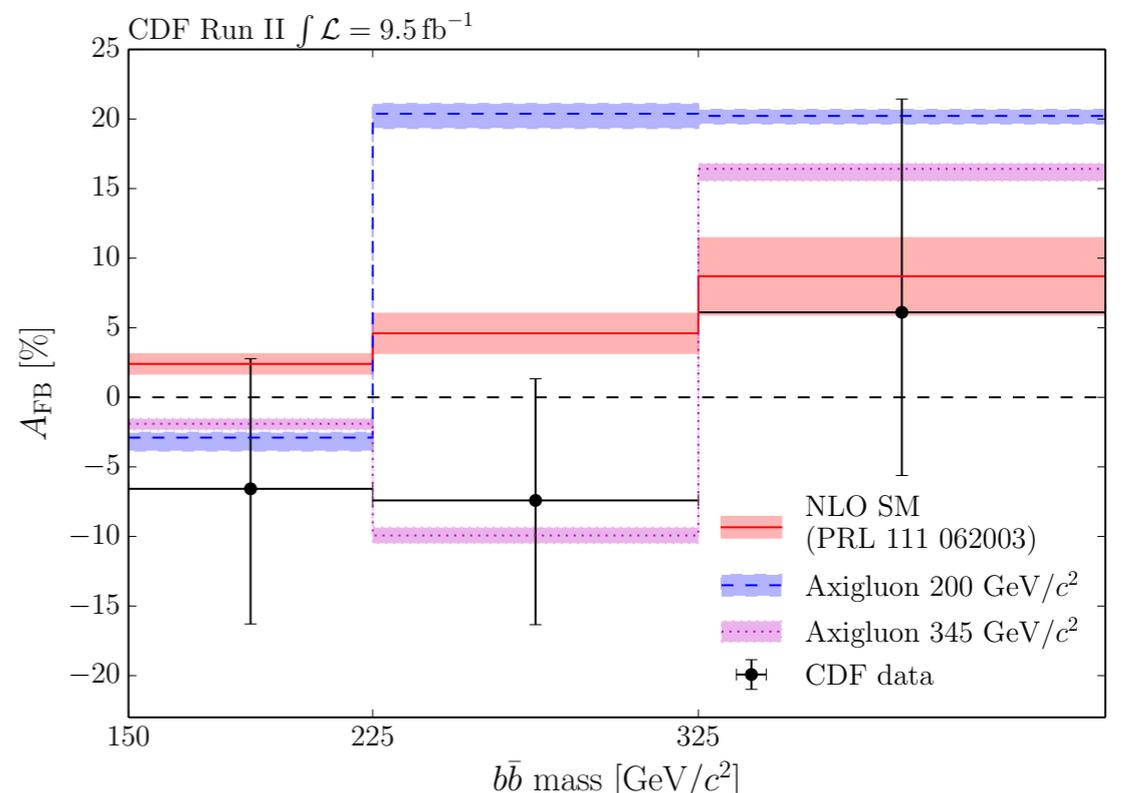
# Bottom Asymmetry



- Medium energy:  $m_{b\bar{b}} < \text{few } 100 \text{ GeV}$ 
  - Reconstruction of  $b\bar{b}$  jet pair: two b-tags, one jet with **soft muon**
  - Asymmetry from soft muon charge
  - **Consistent with standard model prediction**  
(Grinstein, Murphy, [PRL 111 \(2013\) 062003](#))
  
- High energy  $m_{b\bar{b}} > 150 \text{ GeV}$ 
  - Asymmetry from binned difference in **jet charge**
  - **Consistent with zero asymmetry and standard model, start to exclude first models** (low mass axigluon)
  
- Challenge for both analyses: **dilution** through  $B^0\bar{B}^0$  oscillations and cascade decays



[CDF Note 11156]

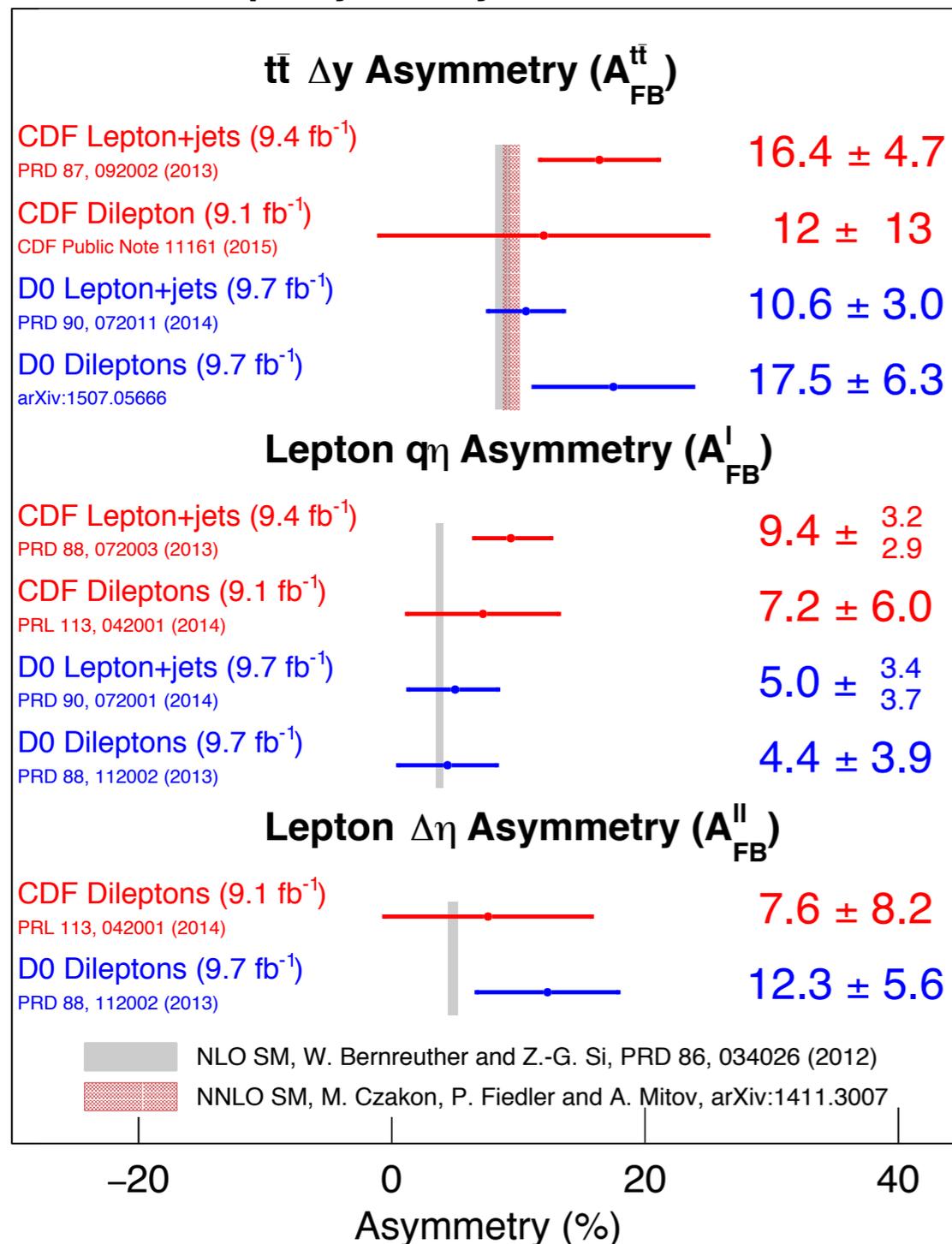


[arXiv:1504.06888, accepted by PRD]

# Summary & Conclusions



## Tevatron Top Asymmetry



- Full suite of measurements with full Tevatron Run II dataset
  - Lepton + jets and dilepton channels
  - Inclusive and differential top  $A_{FB}$
  - Leptonic  $A_{FB}$
  - Tremendous effort by CDF and DØ to settle  $A_{FB}$  question
- Conclusion: “the thrill is gone...”
  - No strong hints of new physics in  $A_{FB}$
  - Overall good agreement with standard model (NNLO + EW)
  - Independent look into **bottom**  $A_{FB}$ : no “smoking gun” either
- Tevatron **combination** ongoing