

Measurement of Forward-Backward Asymmetries at the Tevatron

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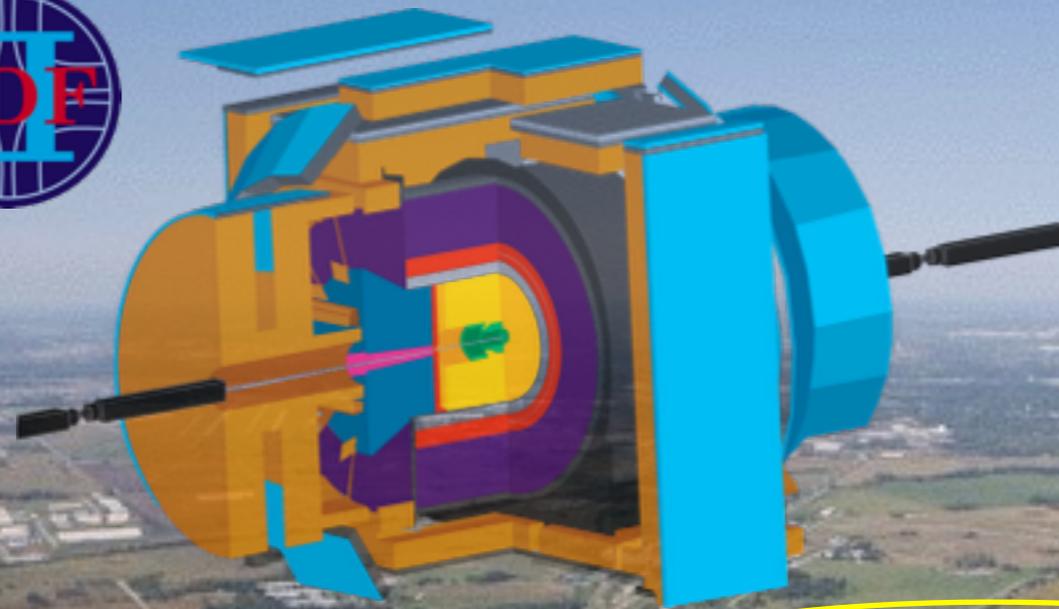
ULRICH HUSEMANN on behalf of the CDF and DØ Collaborations



Fermilab Tevatron: 1985–2011

Fermi National Accelerator Laboratory – Aerial View

[Fermilab Visual Media Service]



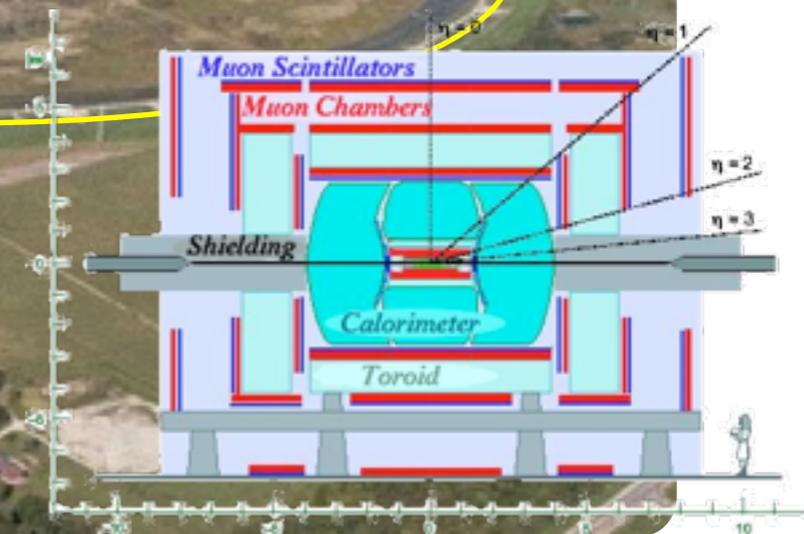
Tevatron

2 km



■ The Tevatron

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



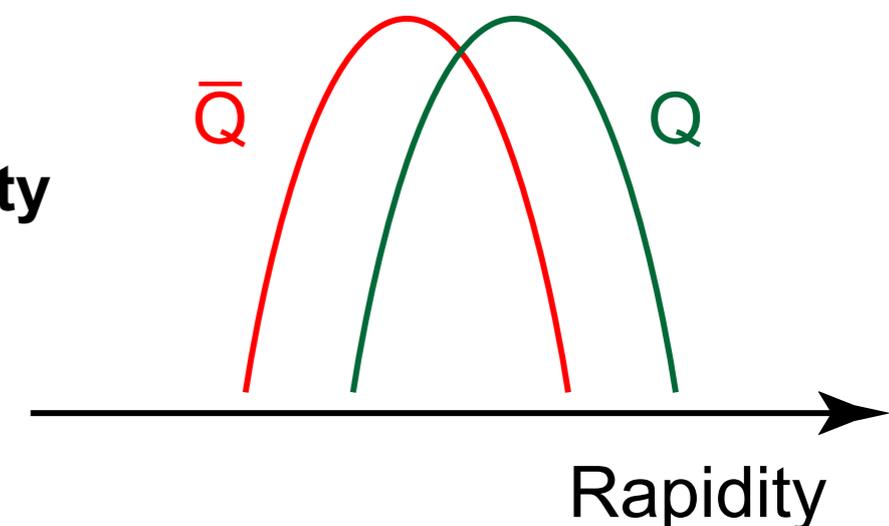
Forward-Backward Asymmetry

- 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}**

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

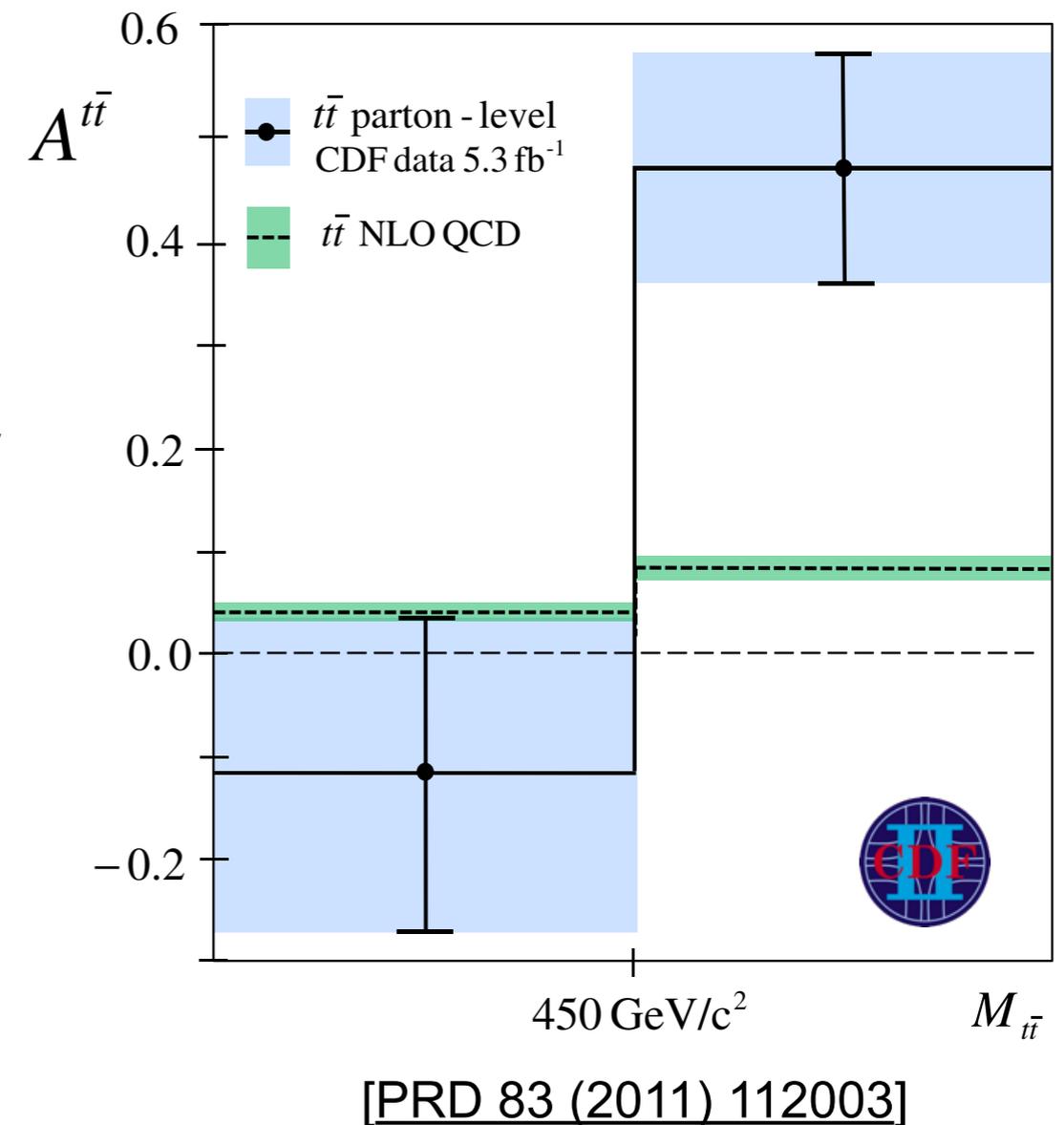
- Forward/backward usually defined in terms of **rapidity difference** of quarks and antiquarks $\Delta y = y_Q - y_{\bar{Q}}$
 \rightarrow invariant under boosts in beam direction
- LHC: **symmetric** pp collisions $\rightarrow A_{FB} = 0$,
 measure charge asymmetry A_C



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_{FB}: 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_{t \bar{t}} , 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^{ℓℓ}: asymmetry in Δη = η_{ℓ+} – η_{ℓ-} of lepton pair

Top: Inclusive Asymmetry

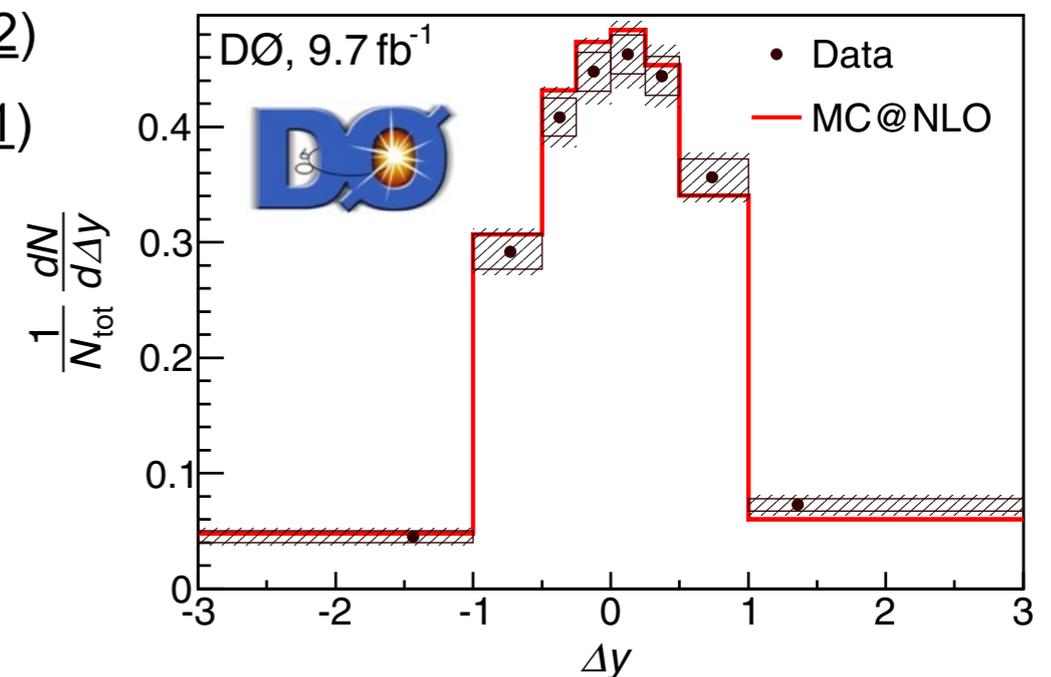
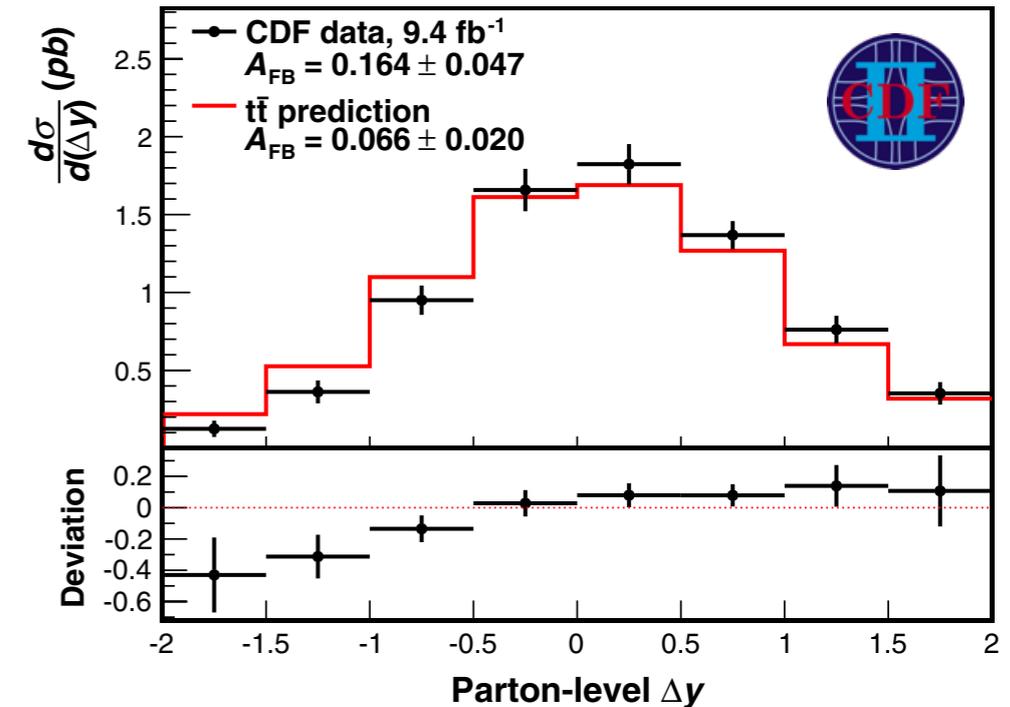
- Inclusive A_{FB} in **lepton+jets** channel
 - **Kinematic reconstruction** of $t\bar{t}$ system
 - t and \bar{t} distinguished by **lepton charge** in leptonically decaying top
 - Correction to parton level: **matrix unfolding**
 - $D\emptyset$: include lepton + 3 jet final states

- Tevatron results on full Run II datasets:

- CDF: $A_{FB} = 0.164 \pm 0.047$ ([PRD 87 \(2013\) 092002](#))
- $D\emptyset$: $A_{FB} = 0.106 \pm 0.030$ ([PRD 90 \(2014\) 072011](#))

- Most recent standard model predictions:

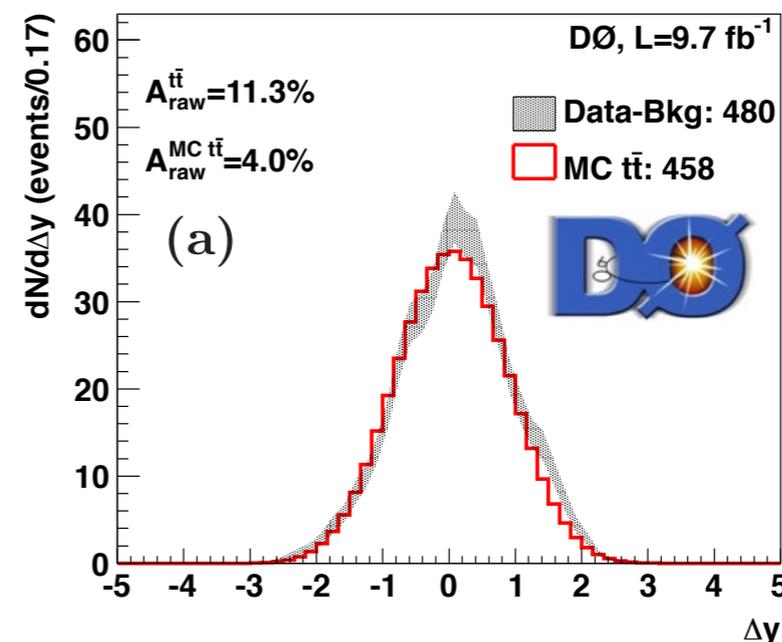
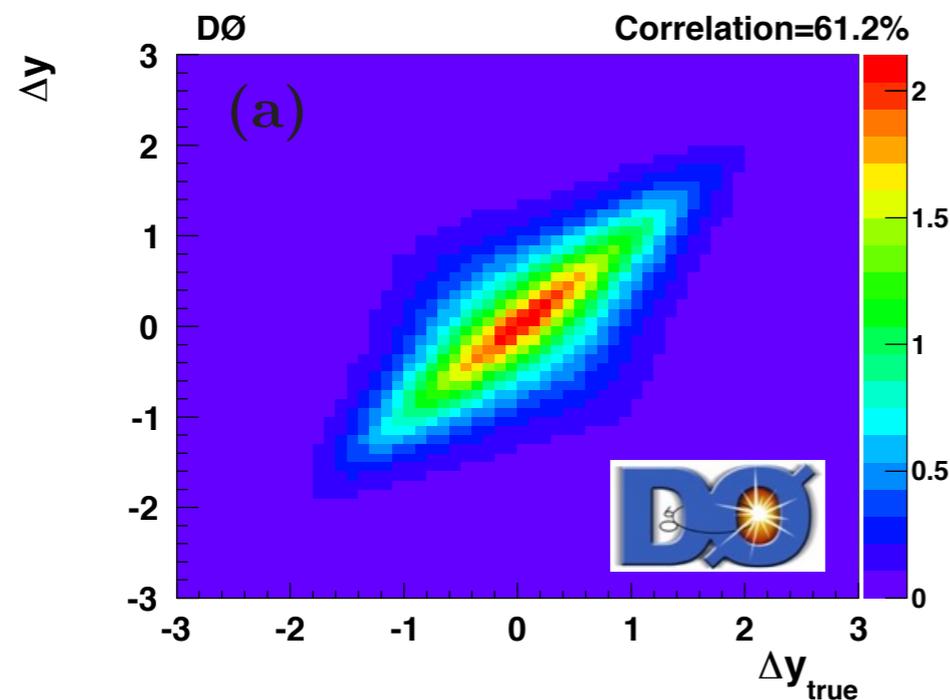
- $A_{FB} = 0.095 \pm 0.007$ (NNLO QCD + NLO EW, Czakon et al., [arXiv:1411.3007](#))
- $A_{FB} = 0.100 \pm 0.006$ (aN³LO QCD + NLO EW, Kidonakis, [PRD 91 \(2015\) 071502 \(R\)](#))



Top: Inclusive Asymmetry

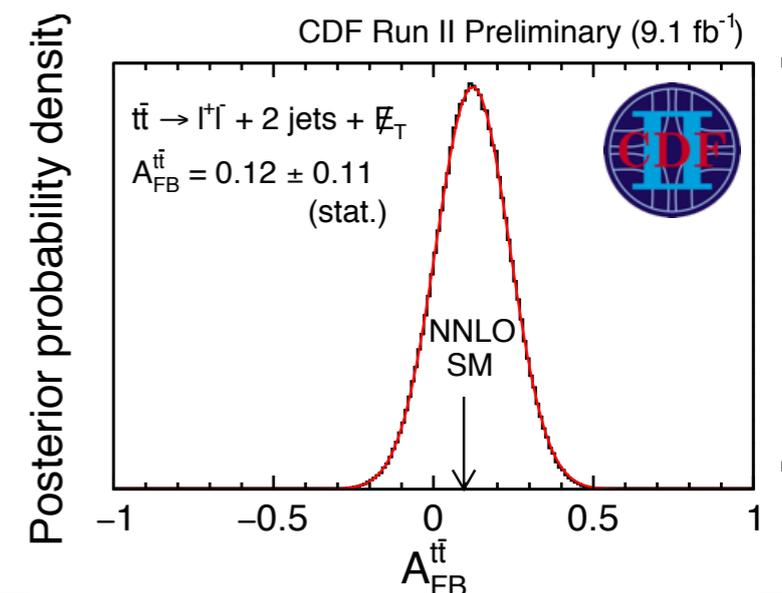


- Inclusive A_{FB} in **dilepton** channel (see also talk by B. Tuchming)
 - DØ: modified **matrix-element method** to determine parton-level A_{FB}
 - measure correlated observables **A_{FB} and top polarization simultaneously**



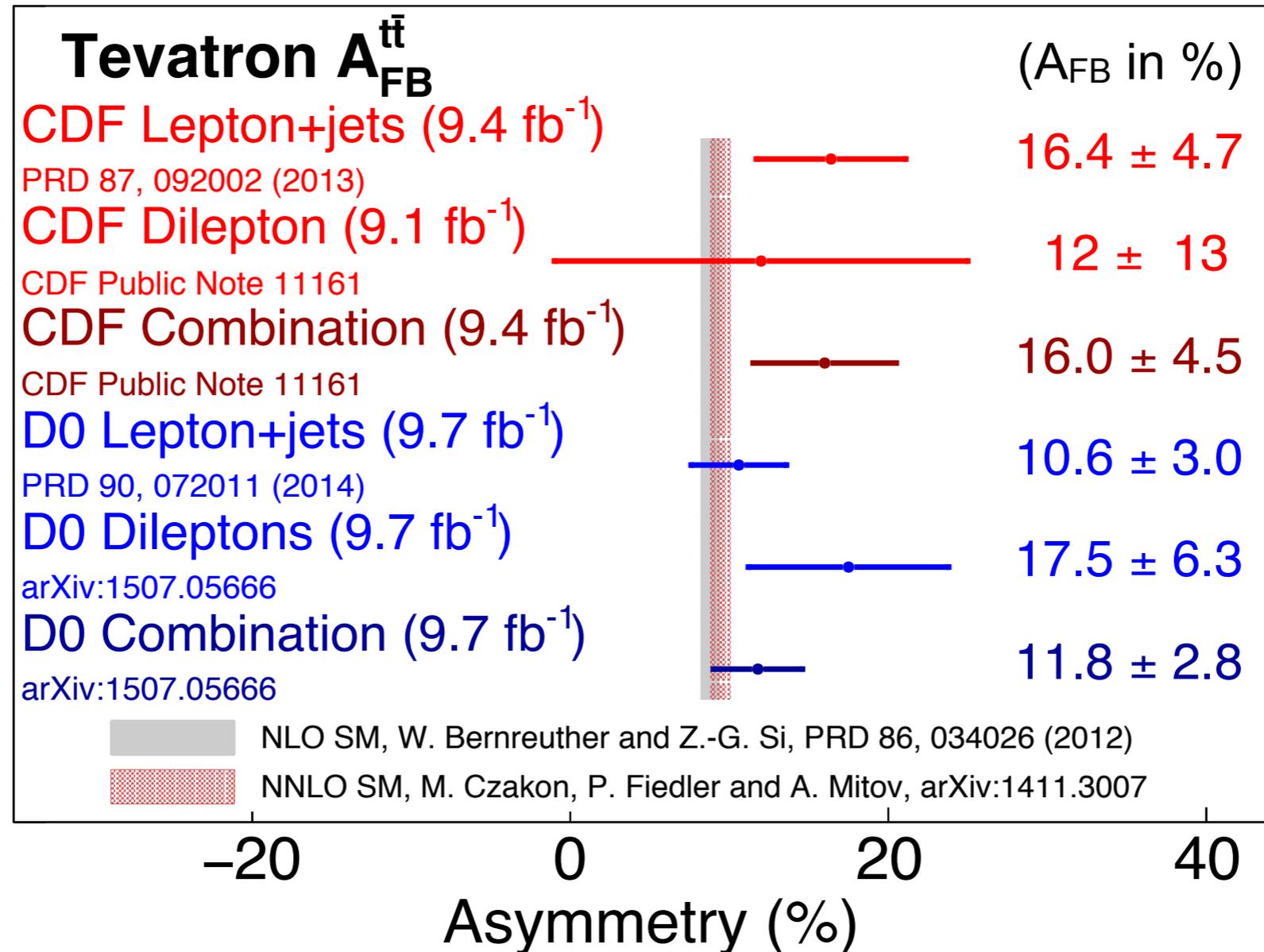
[arXiv:1507.05666,
submitted to PRD]

- 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 ≤ 1.5 standard deviations.

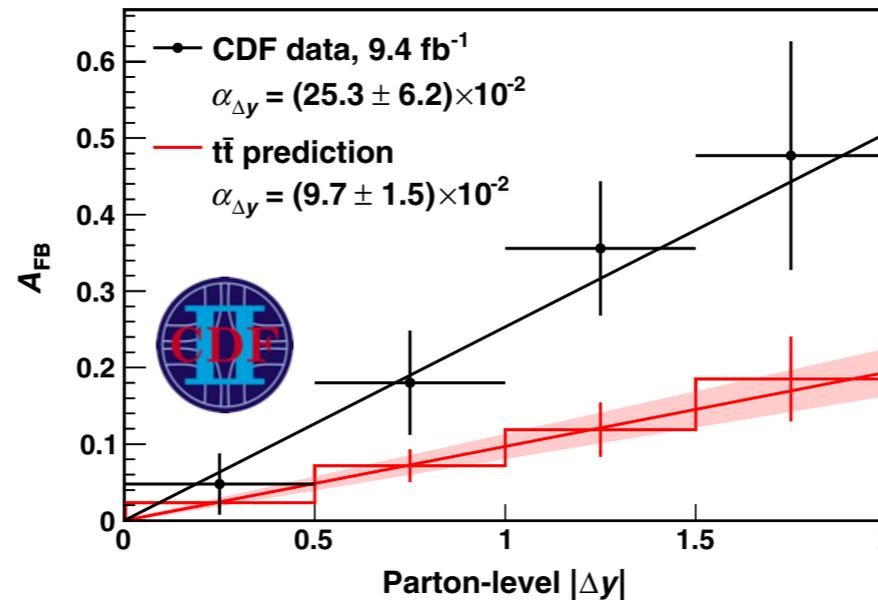
Top: Differential Asymmetry

- Differential parton-level asymmetries

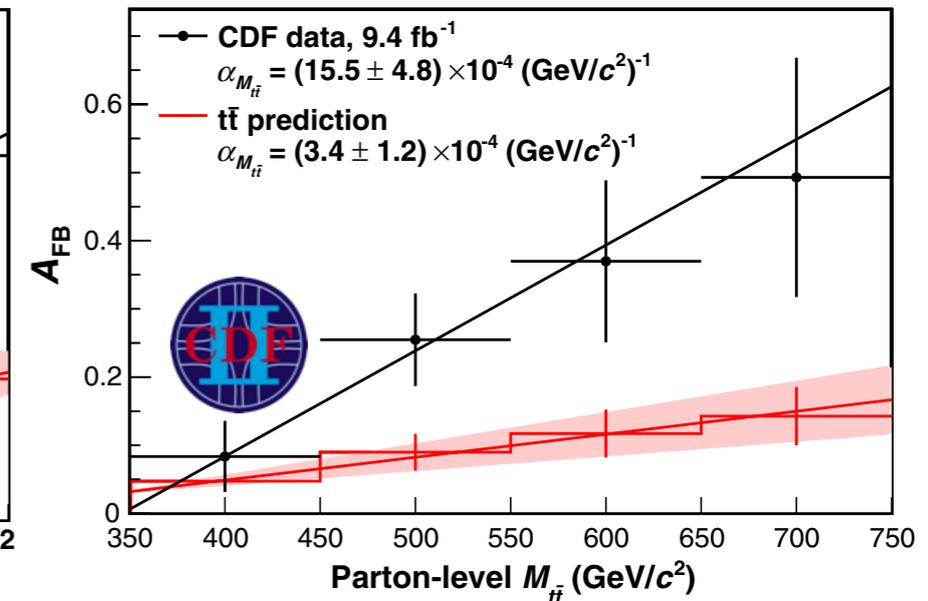
- $|\Delta y|$ dependence

- Expect **linear** increase, slope α

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



[PRD 87 (2013) 092002]

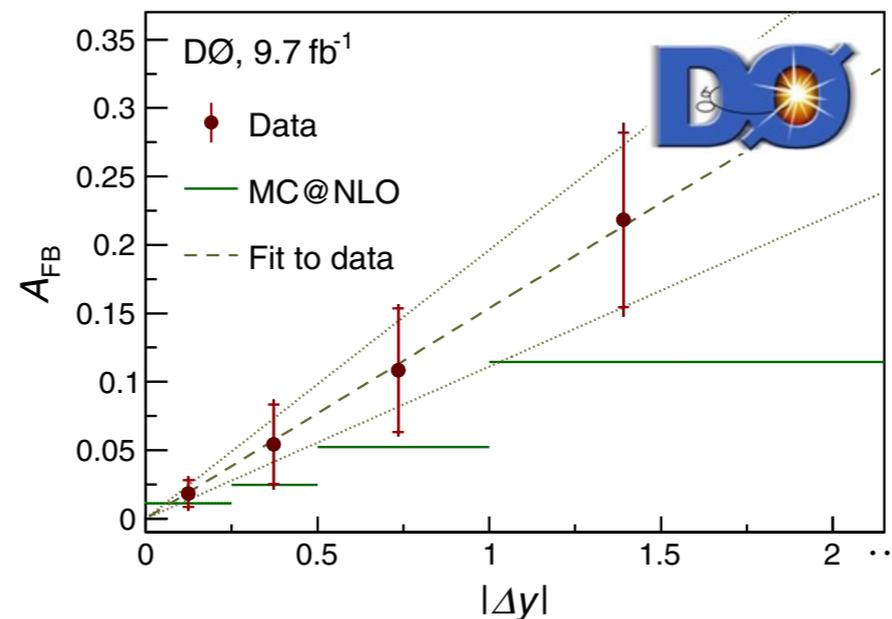


- $m_{t\bar{t}}$ dependence

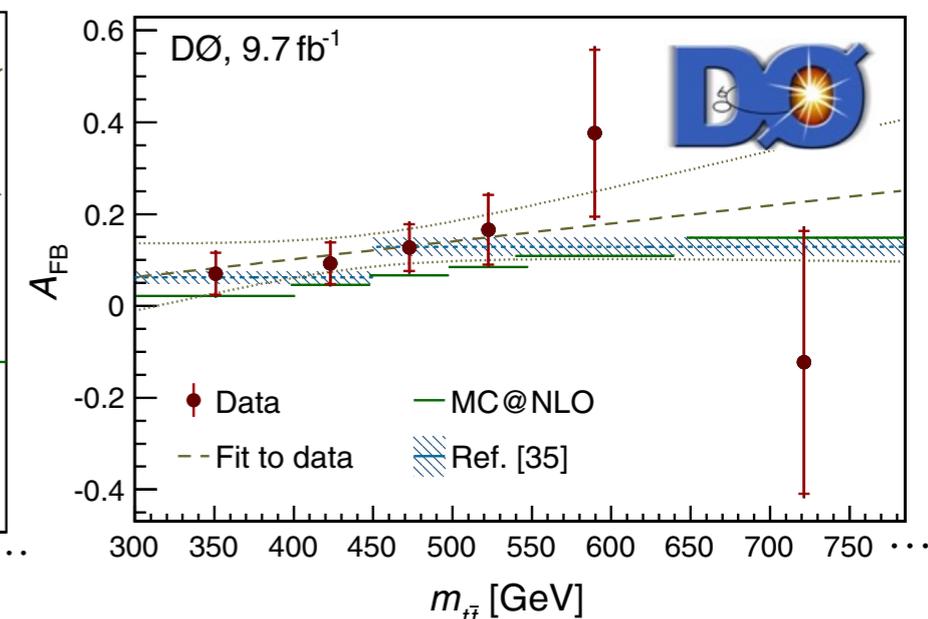
- Expect mild increase

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

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



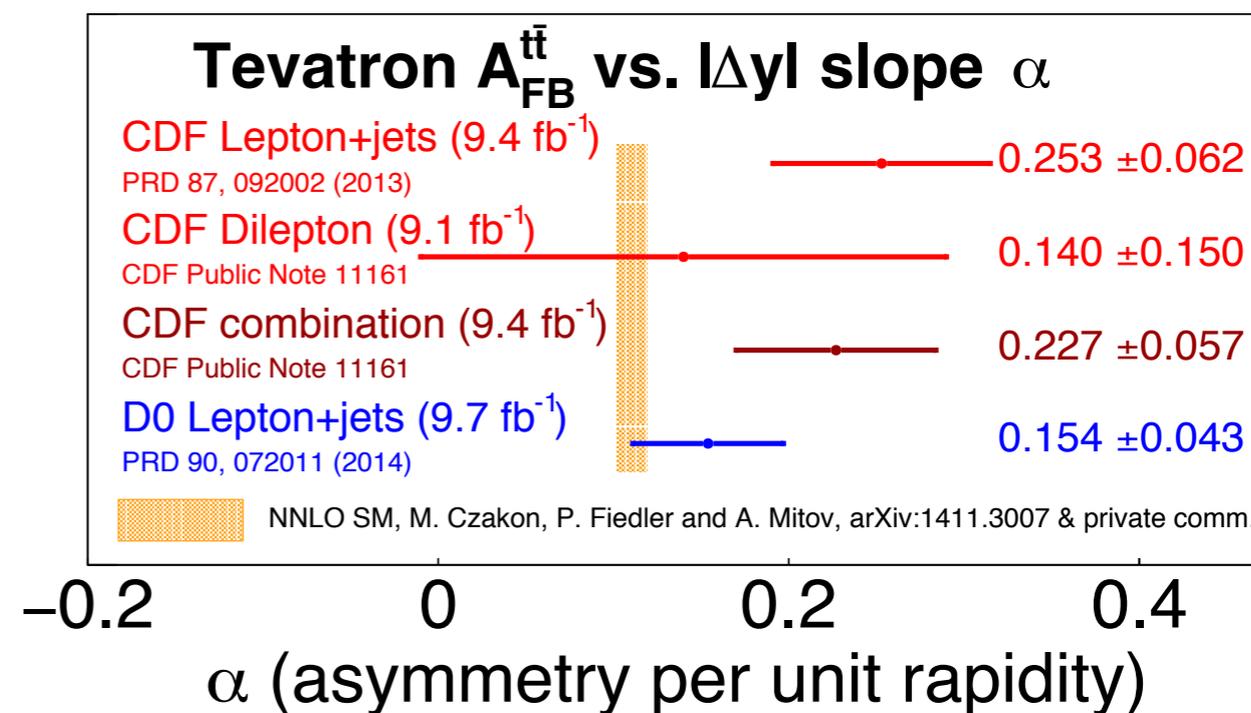
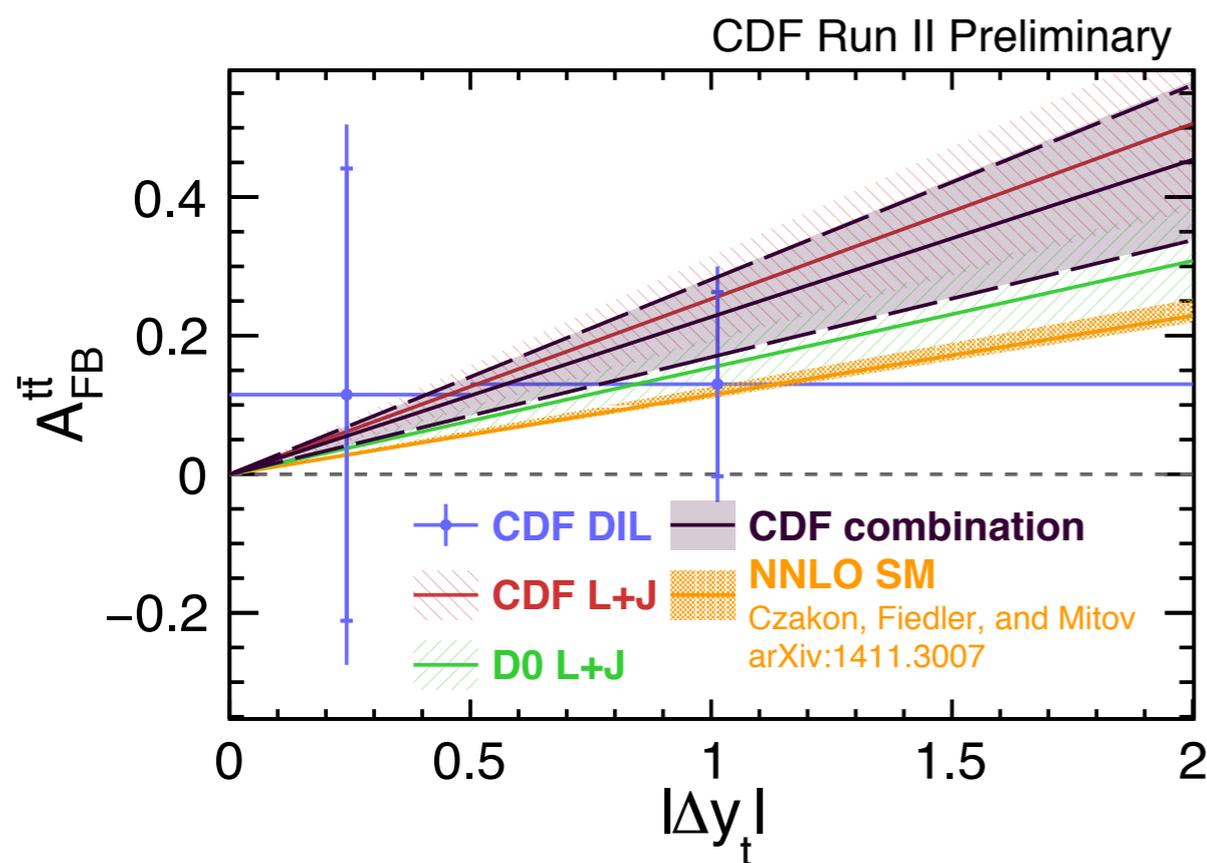
[PRD 90 (2014) 072011]



Top: Differential Asymmetry



- Comparison with state-of-the-art standard model calculations (**NNLO+EW**)
- Both CDF and DØ: slope parameter α **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**

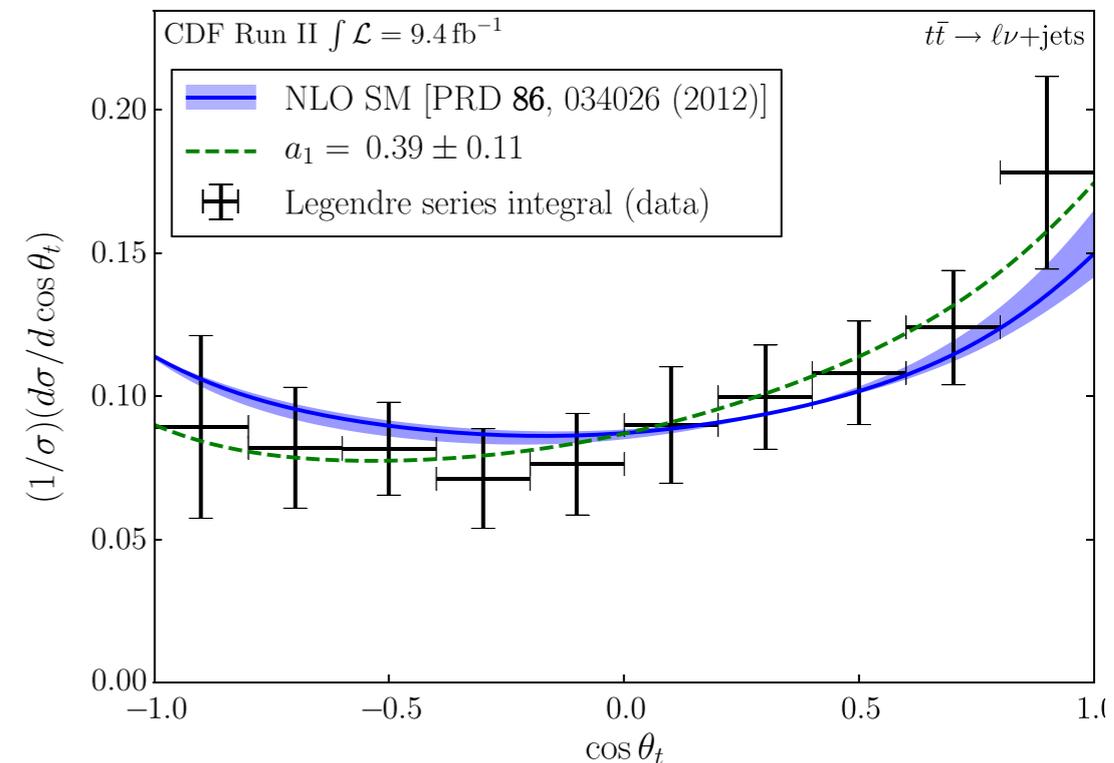
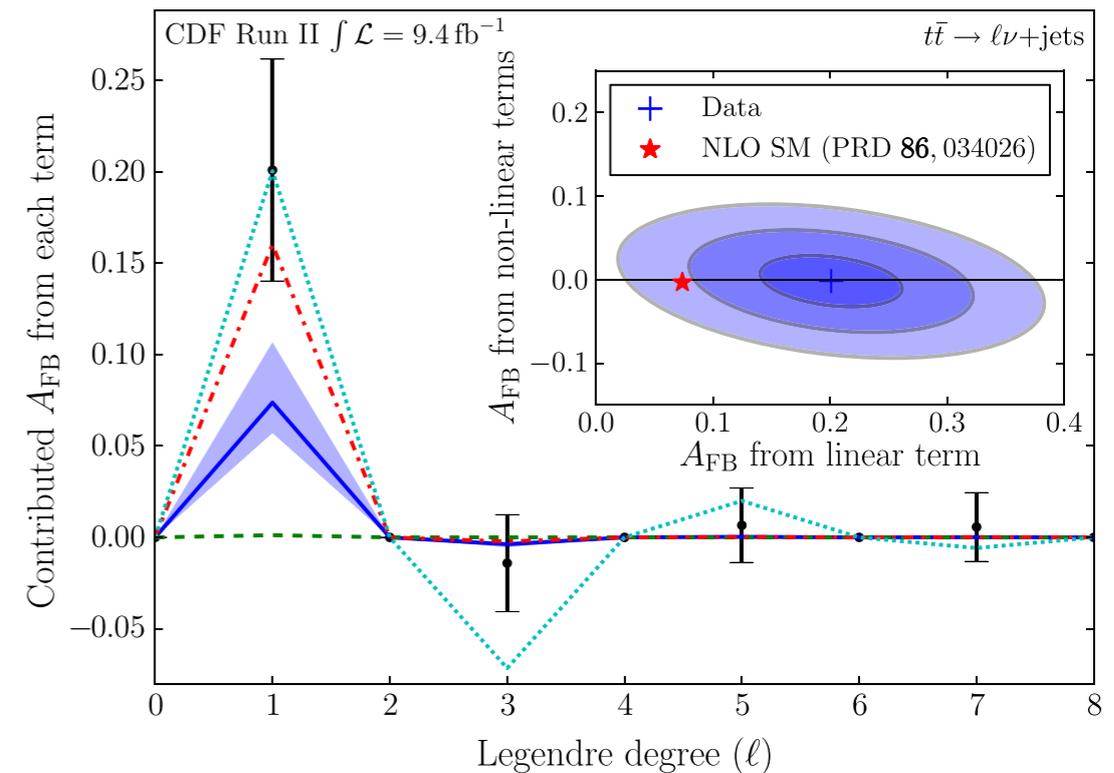
- Decomposition in orthonormal **Legendre polynomials**

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

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

- 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_{ℓ} agree with NNLO** with χ^2 probability of 75%



[PRL 111 (2013) 182002]

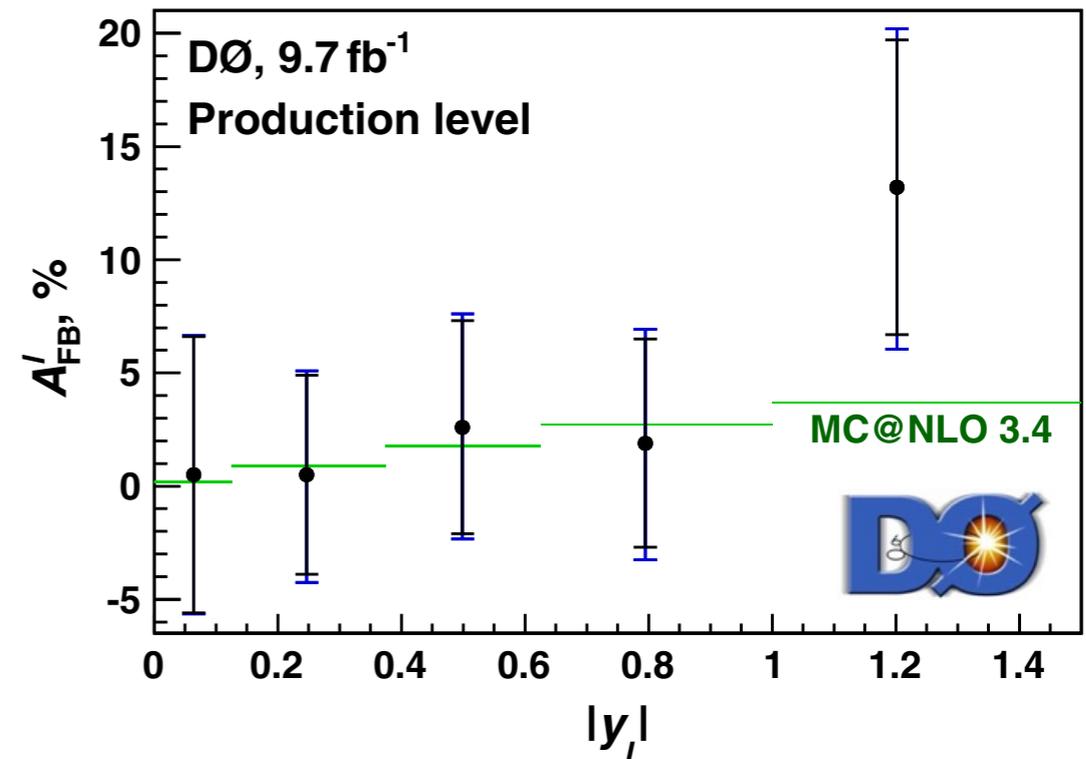
Top: Leptonic Asymmetry

■ Leptonic asymmetry in lepton + jets channel

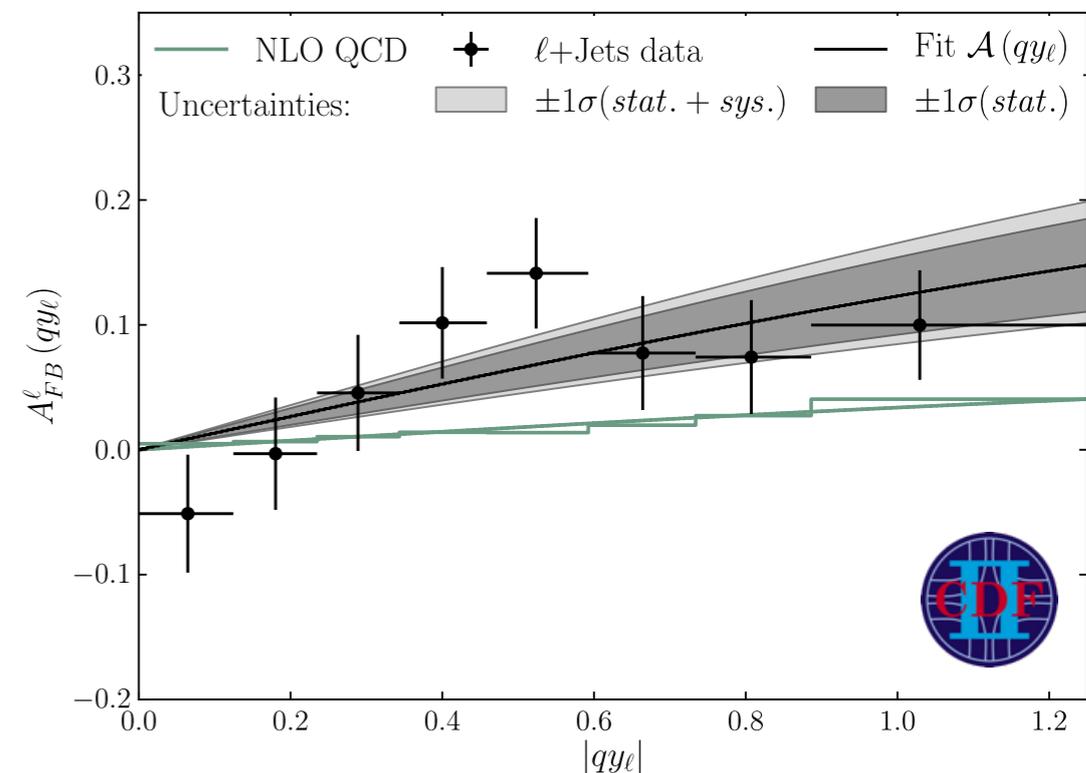
- Asymmetry in $q_\ell \eta_\ell$ within detector acceptance
- Extrapolation to unmeasured η with empirical model
- Calculations including lepton acceptance cuts (NLO QCD + EW)
→ very small model dependence
(Bernreuther, Si, [PRD86 \(2012\) 034026](#))

■ Challenges:

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



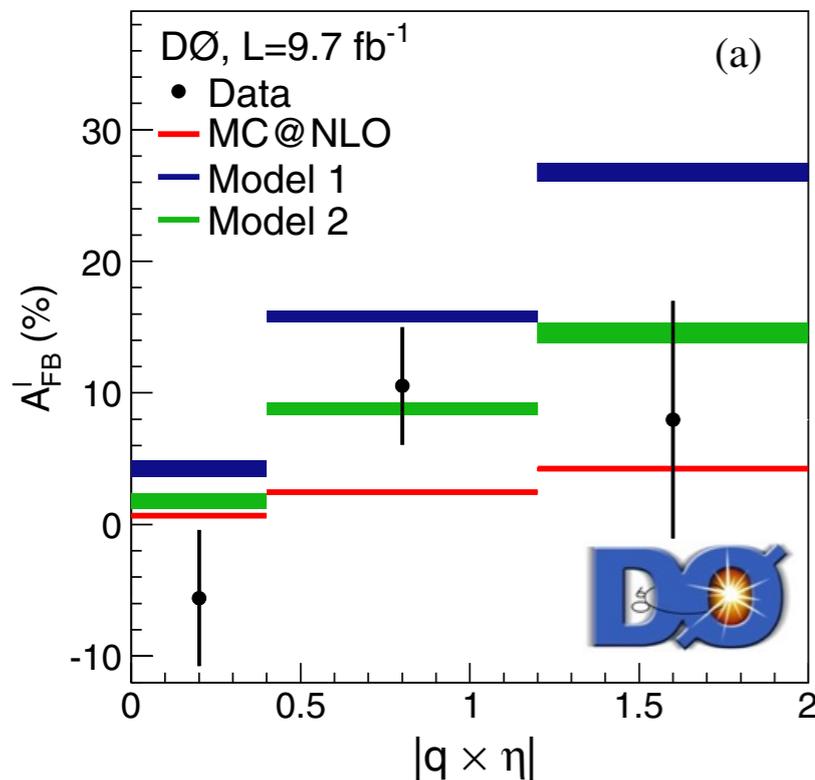
[PRD 90 (2014) 072001]



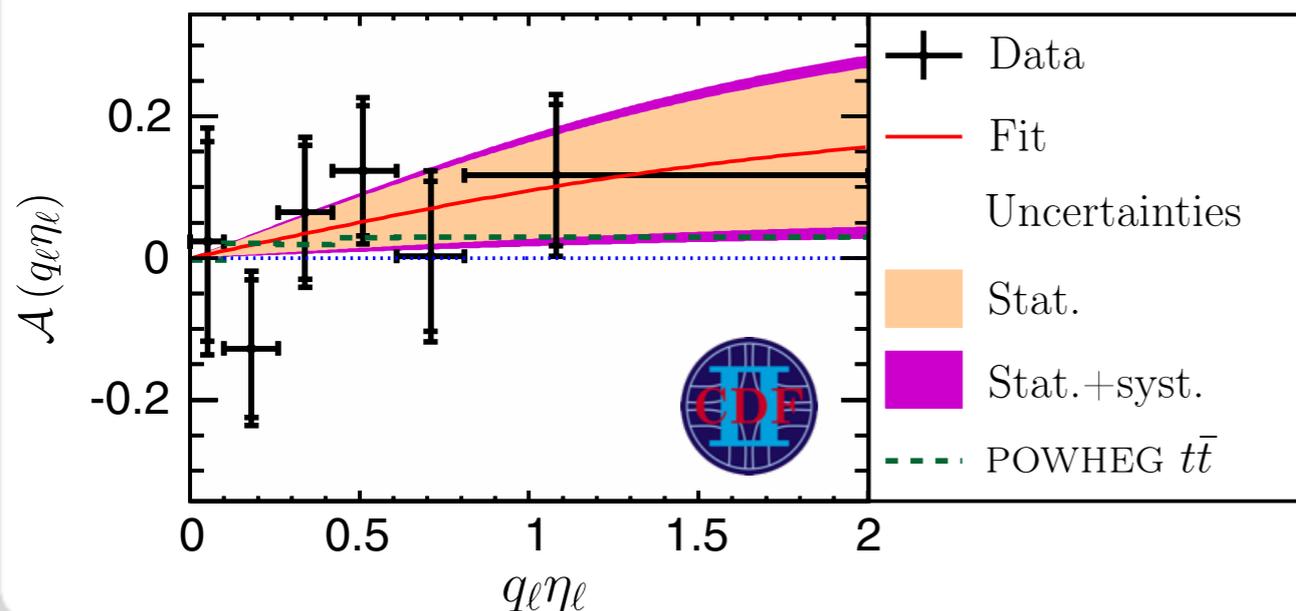
[PRD 88 (2013) 072003]

Top: Leptonic Asymmetry

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

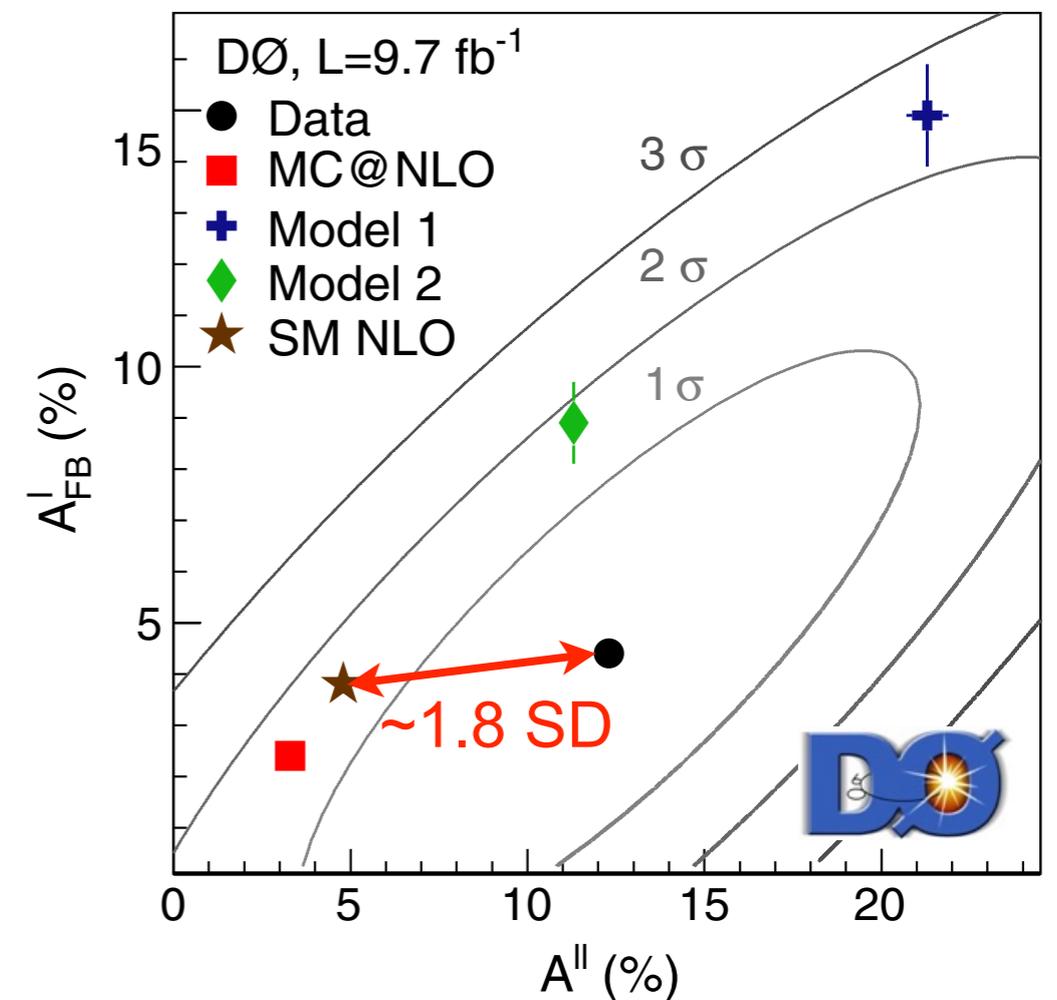


[PRD 88 (2013) 112002]



[PRL 113 (2014) 042001]

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



[PRD 88 (2013) 112002]

SM NLO: QCD + EW

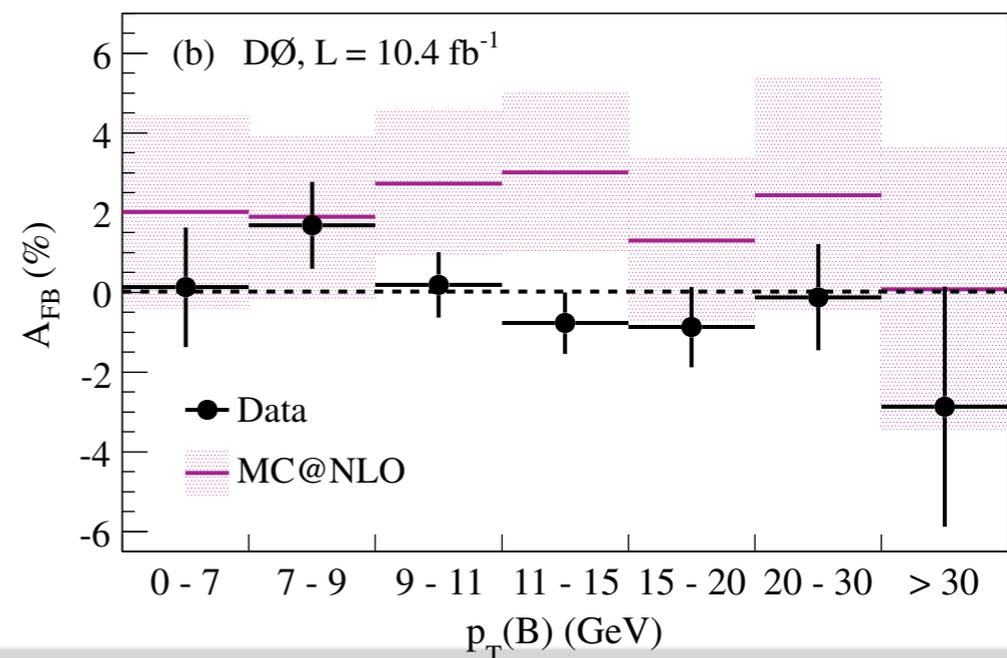
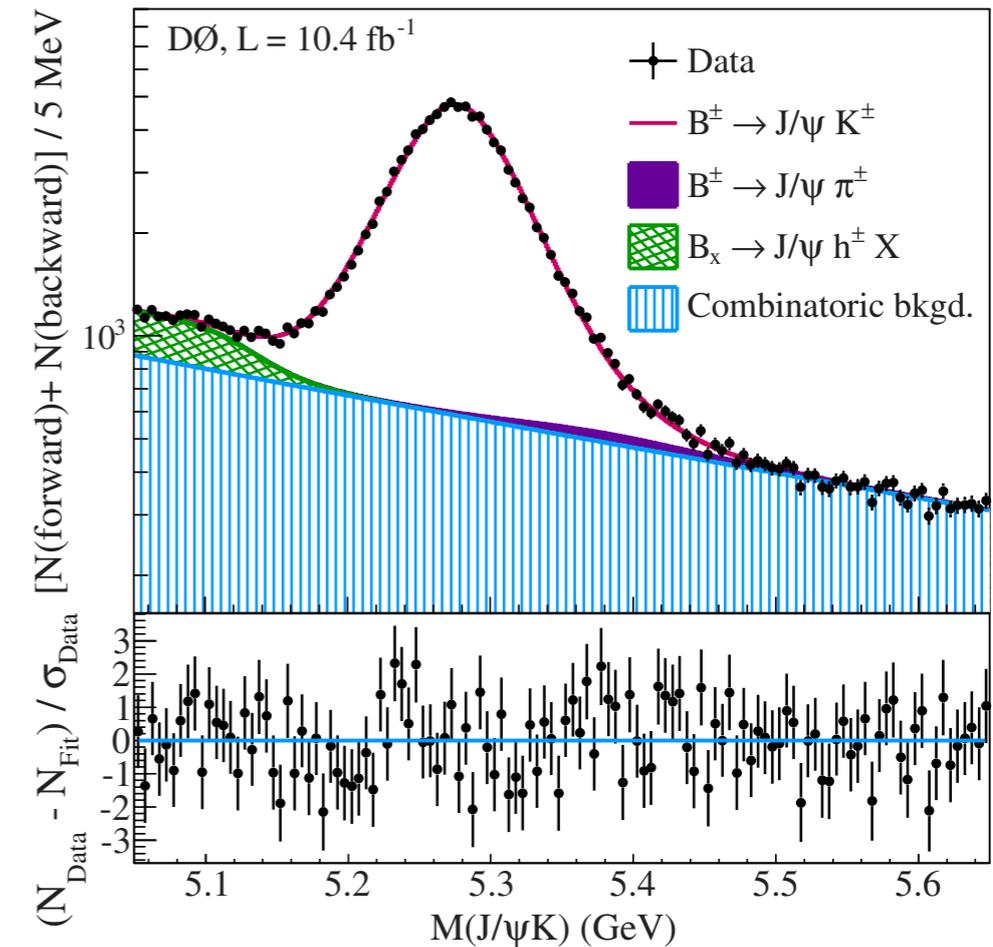
Model 1: 200-GeV axigluon RH SM couplings

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]

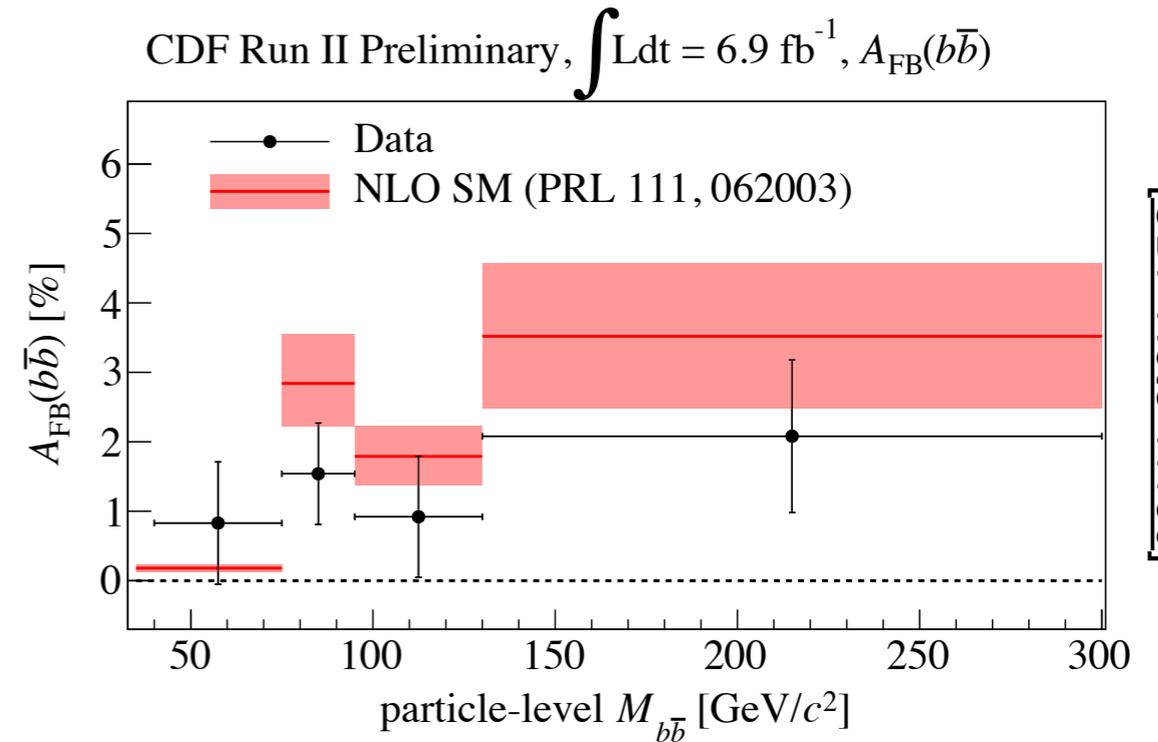
Bottom Asymmetry



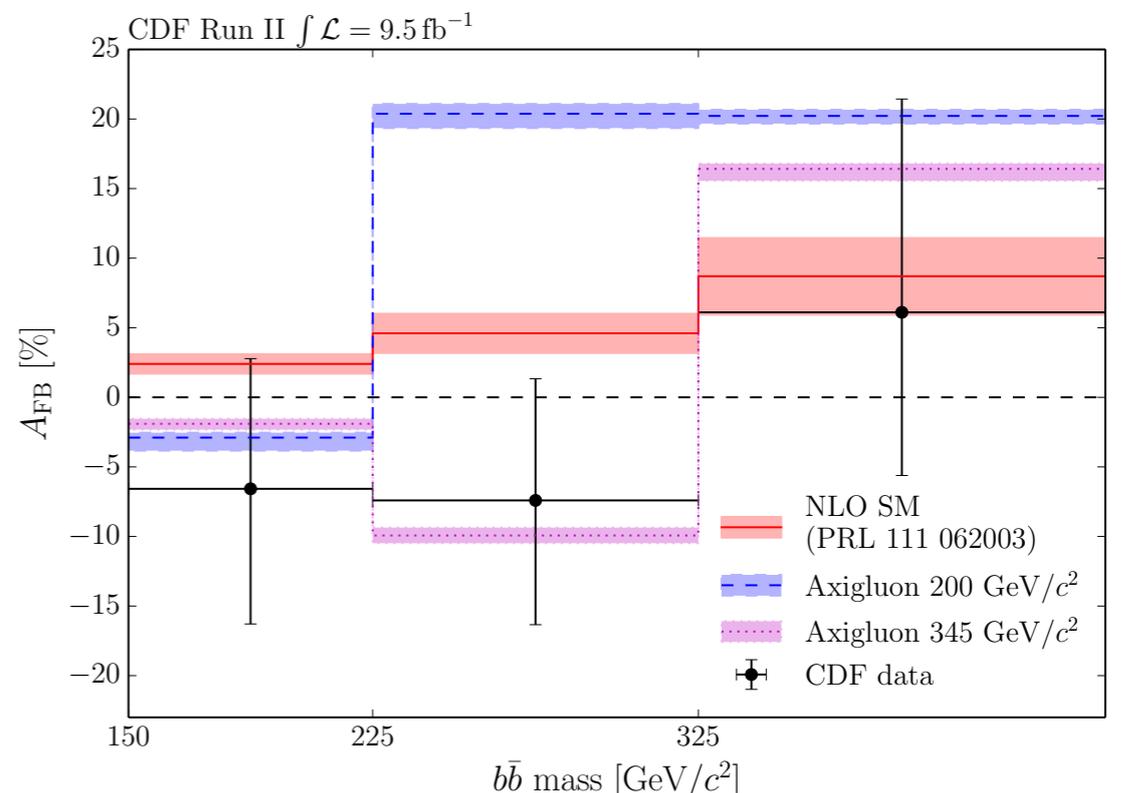
- Medium energy: $m_{b\bar{b}} < \text{few } 100 \text{ GeV}$
 - Reconstruction of $b\bar{b}$ jet pair: two b-tags, one jet with **soft muon**
 - Asymmetry from soft muon charge
 - **Consistent with standard model prediction**
(Grinstein, Murphy, [PRL 111 \(2013\) 062003](#))

- 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]

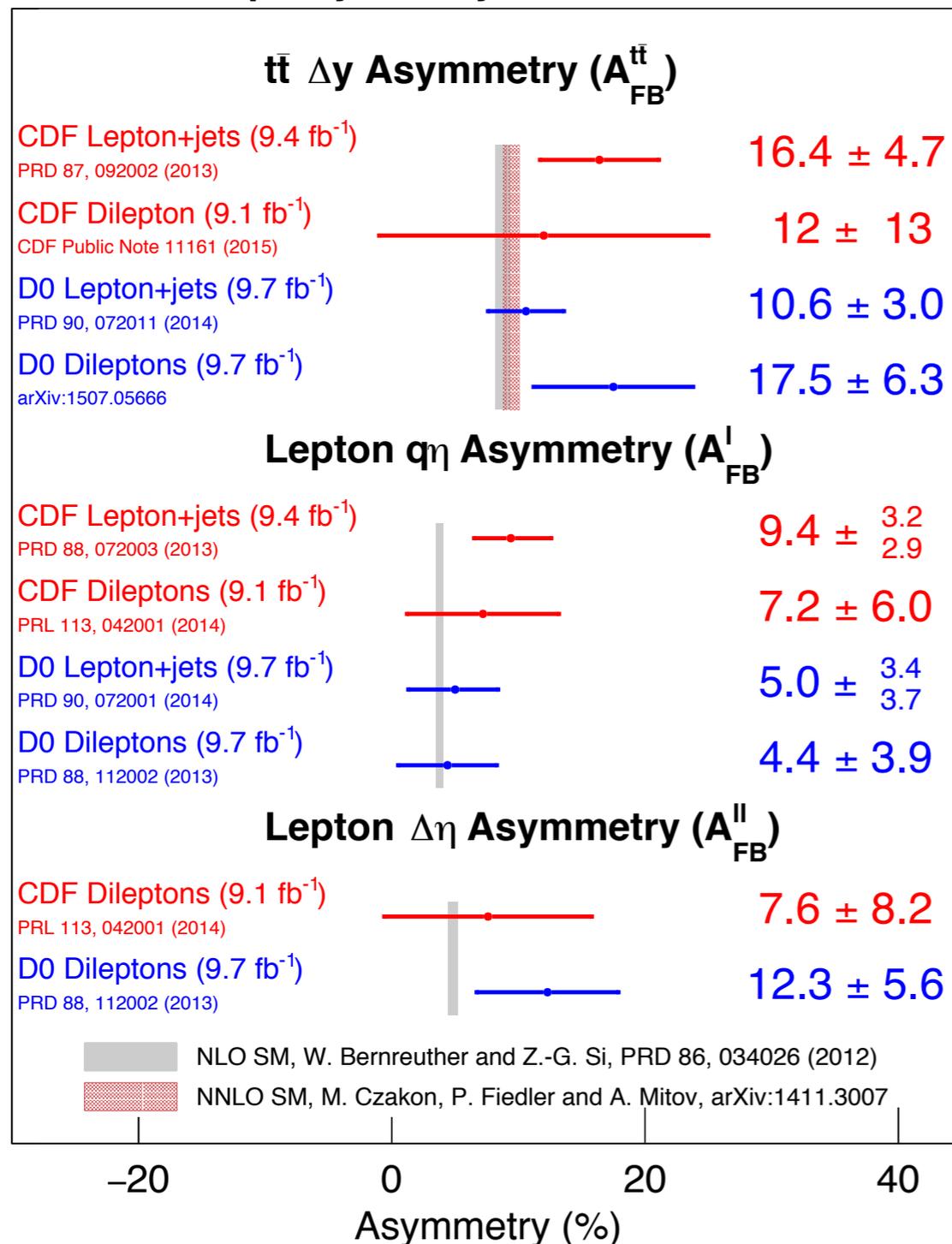


[arXiv:1504.06888, accepted by PRD]

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