Measurement of Forward-Backward Asymmetries at the Tevatron

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ULRICH HUSEMANN on behalf of the CDF and DØ Collaborations

Fermilab Tevatron: 1985–2011

Fermi National Accelerator Laboratory – Aerial View
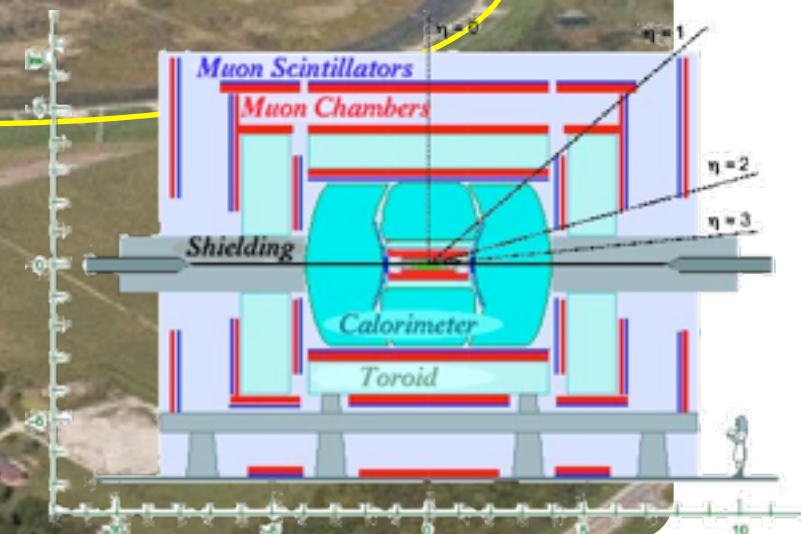
[Fermilab Visual Media Service]

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

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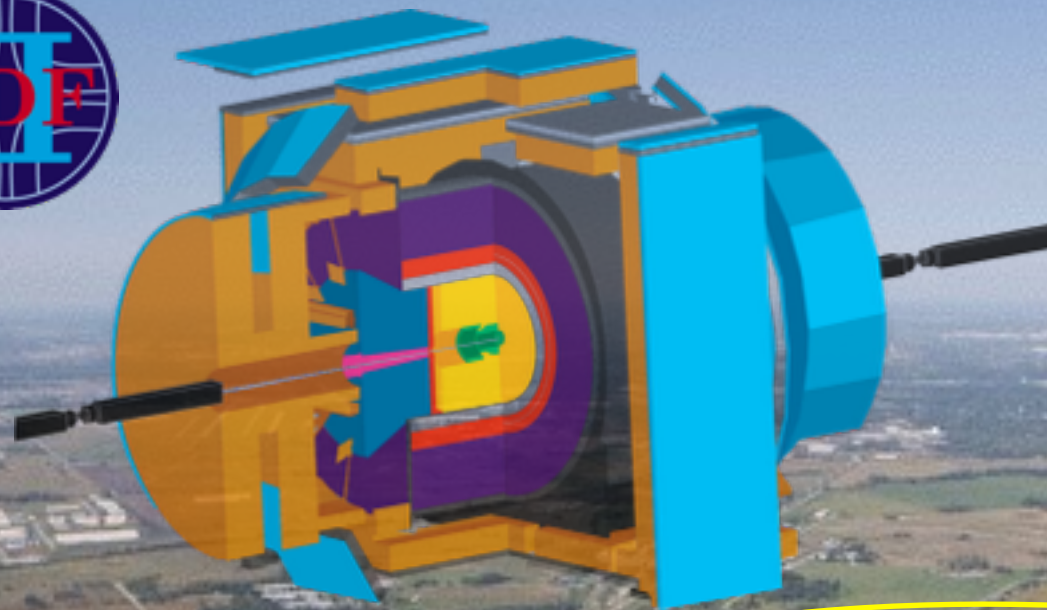
Forward-Backward Asymmetry

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

- **Forward-backward asymmetry A$_{FB}$**
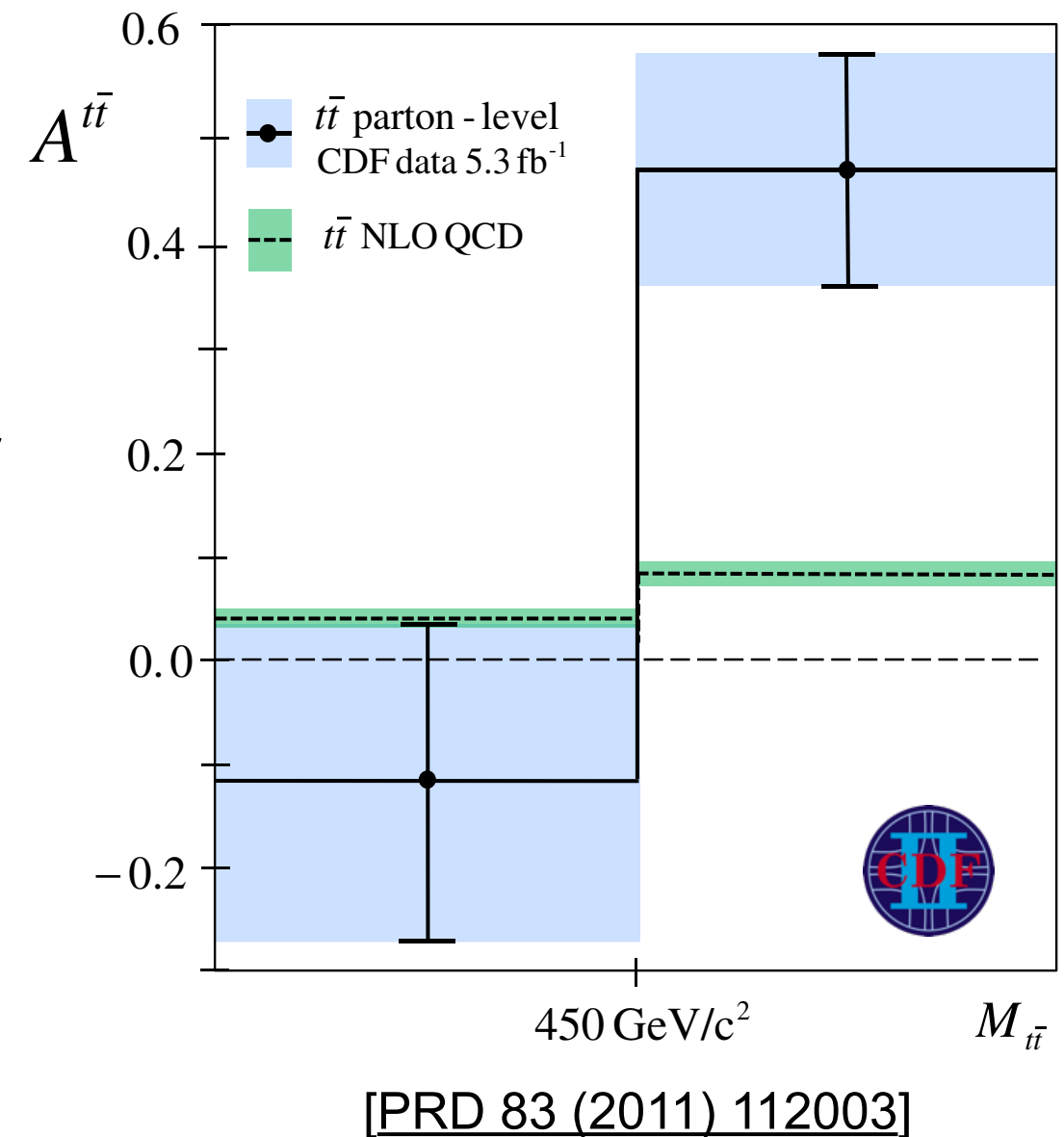
$$A_{\text{FB}} = \frac{N_F - N_B}{N_F + N_B}$$

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

$\bar{Q}$ Q

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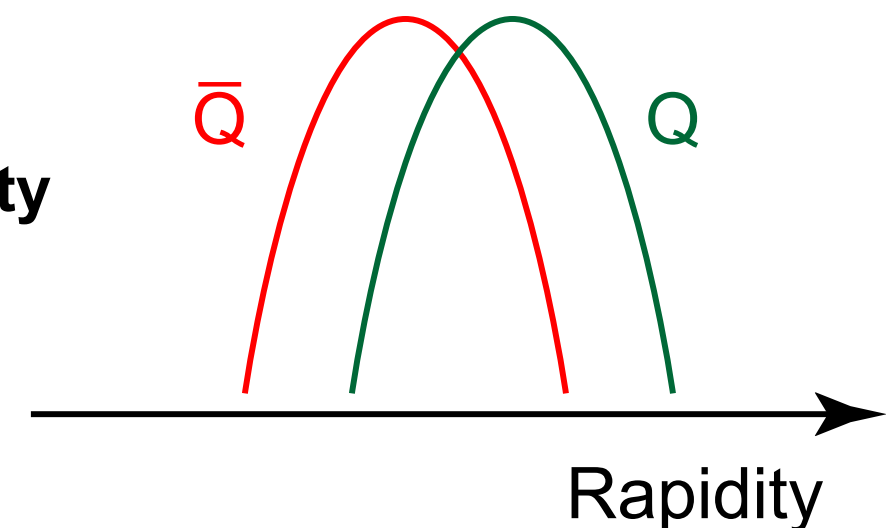
Recent review: Aguilar-Saavedra, Amidei, Juste, Pérez-Victoria, Rev. Mod. Phys. 87 (2015) 421

History of Top A_{FB}

- **2008**: first Tevatron Run II measurements (1–2 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

[PRD 83 (2011) 112003]

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Outline

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

Leptonic $t\bar{t}$ asymmetry

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

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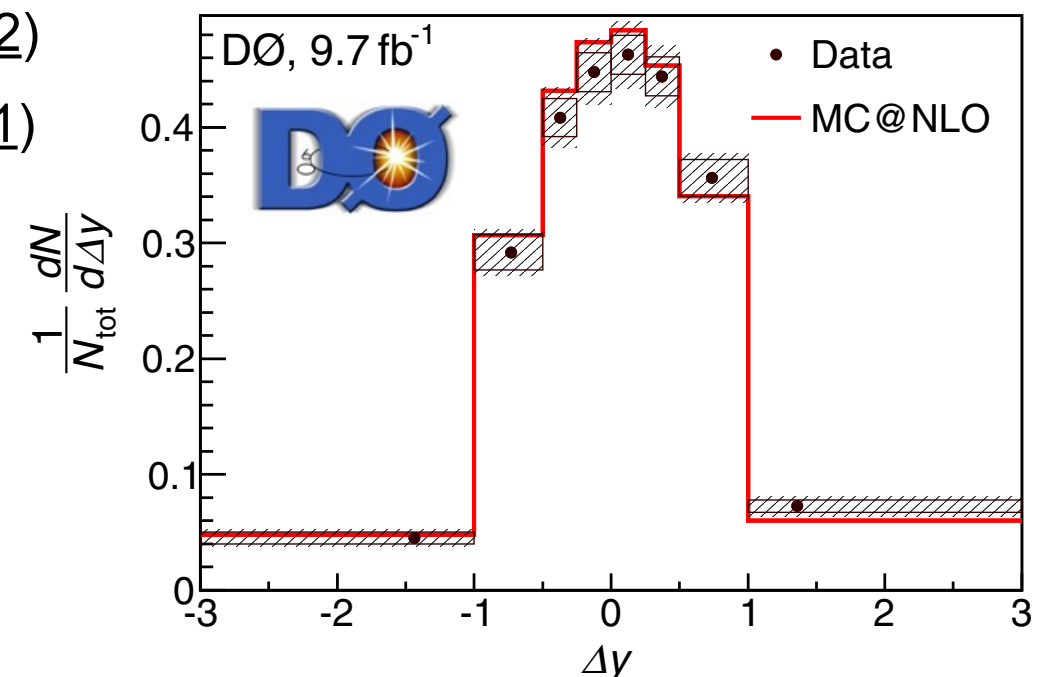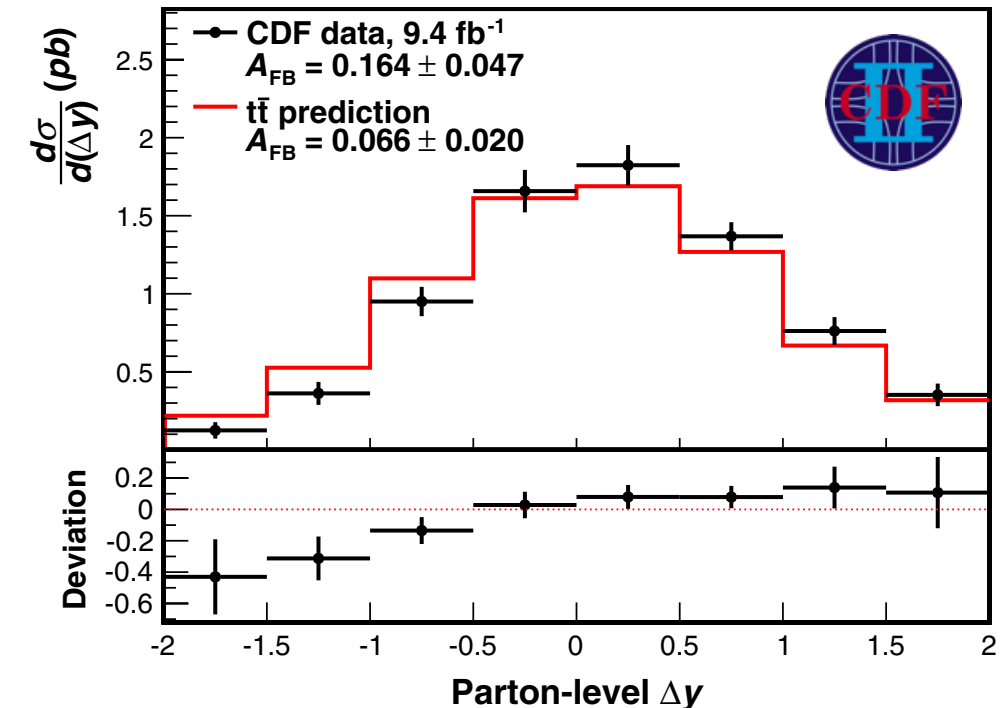
A_{FB}: Observables

- **Raw asymmetry**: asymmetry as reconstructed
  → **detector-dependent** (different phase space coverage)

- **t$\bar{\text{t}}$ 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$\bar{\text{t}}$ 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 $A^{\ell\ell}$: asymmetry in $\Delta\eta = \eta_{\ell+} - \eta_{\ell-}$ 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**
  - DØ: include lepton + 3 jet final states

- Tevatron results on full Run II datasets:
  - CDF: **A_{FB} = 0.164 ± 0.047** (PRD 87 (2013) 092002)
  - DØ: **A_{FB} = 0.106 ± 0.030** (PRD 90 (2014) 072011)

- Most recent standard model predictions:
  - **A_{FB} = 0.095 ± 0.007** (NNLO QCD + NLO EW, Czakon et al., arXiv:1411.3007)
  - **A_{FB} = 0.100 ± 0.006** (aN^{3}LO QCD + NLO EW, Kidonakis, PRD 91 (2015) 071502 (R))

CDF data, 9.4 fb^{-1}
A_{FB} = 0.164 ± 0.047
$t\bar{t}$ prediction
A_{FB} = 0.066 ± 0.020

Parton-level Δy

DØ, 9.7 fb^{-1}
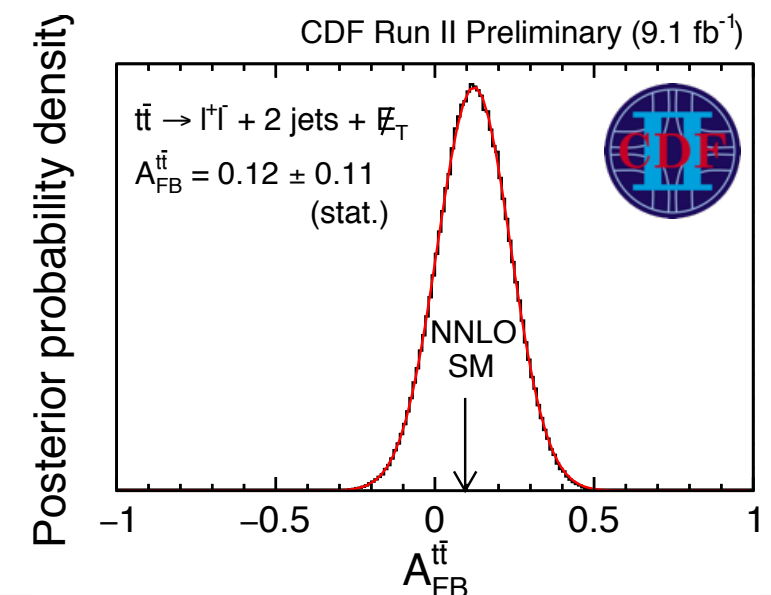Data
MC@NLO
Δy

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**
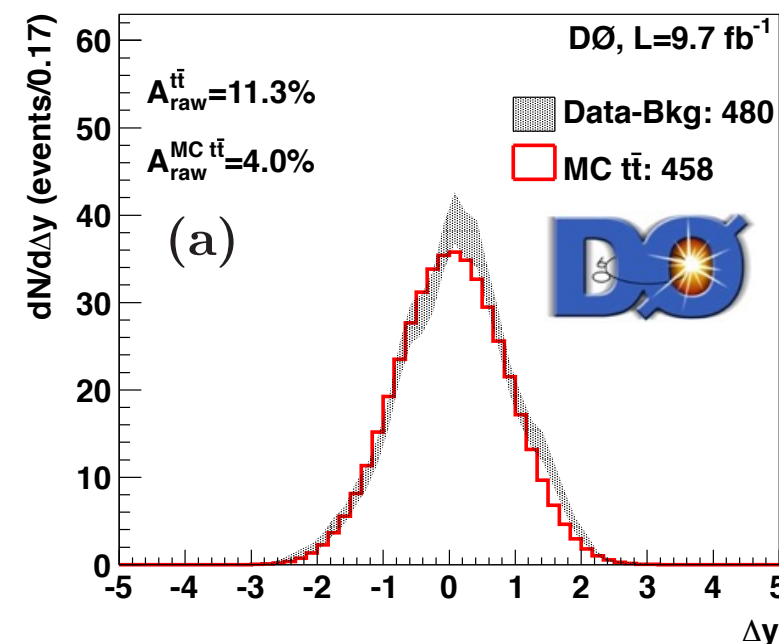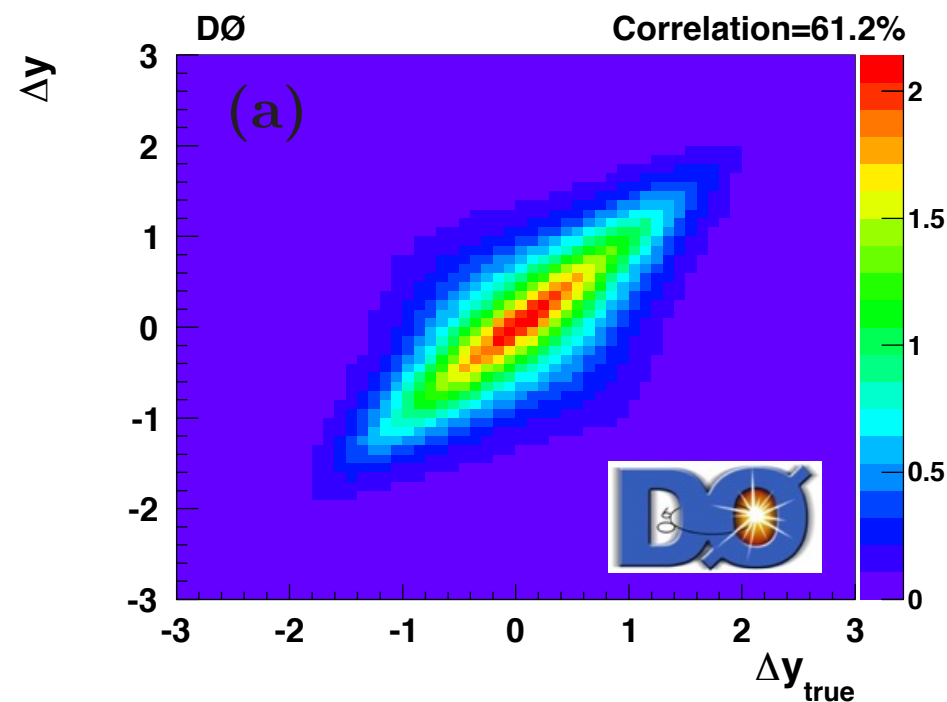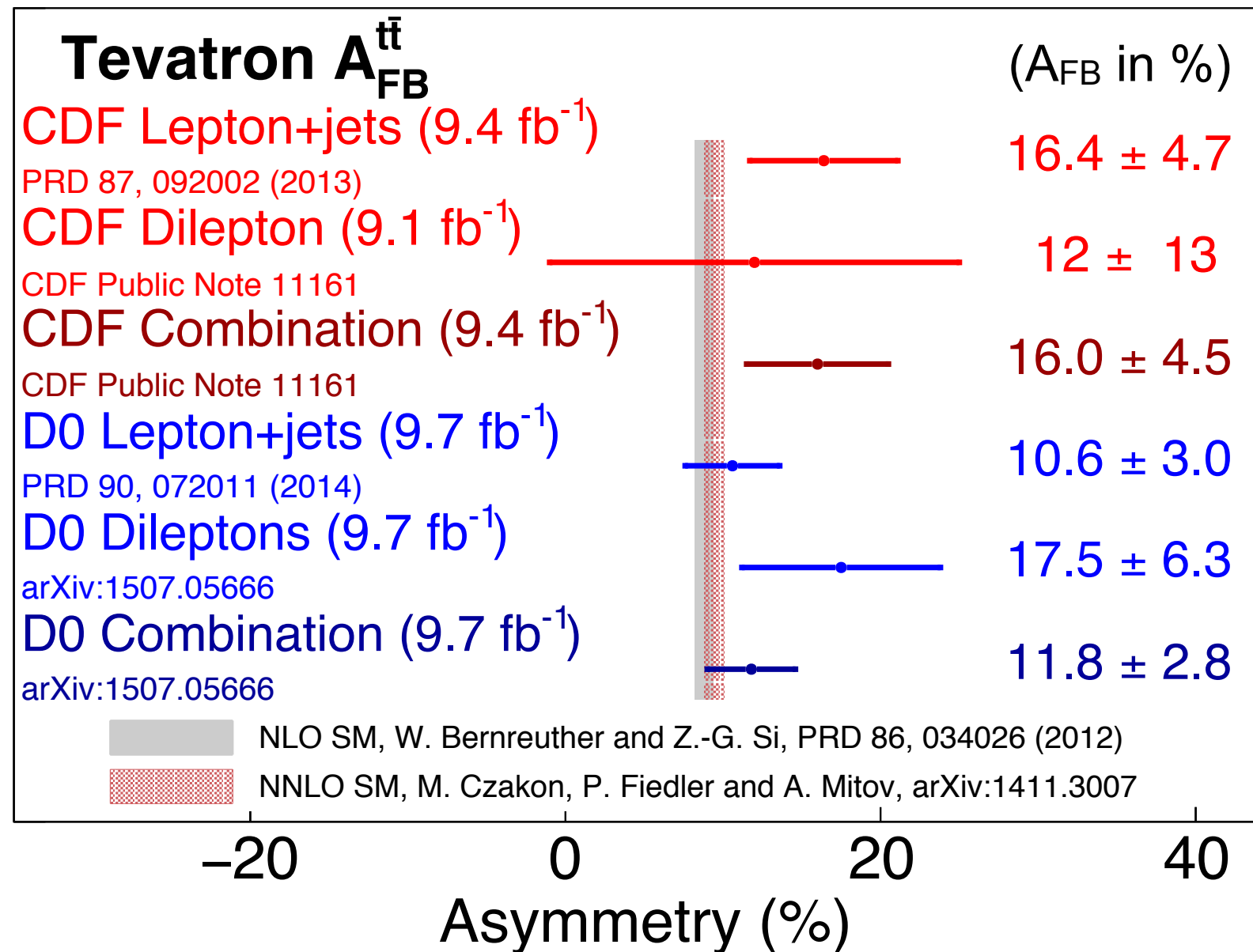

- Challenge: model-independent **calibration** of analysis method
  → additional model uncertainty

- CDF: **likelihood-based** $t\bar{t}$ reconstruction, **Bayesian model** to extract parton-level A_{FB}

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Top: Inclusive Asymmetry

Tevatron $A_{FB}^{t\bar{t}}$

(A_{FB} in %)

CDF Lepton+jets (9.4 fb⁻¹) PRD 87, 092002 (2013)	16.4 ± 4.7
CDF Dilepton (9.1 fb⁻¹) CDF Public Note 11161	12 ± 13
CDF Combination (9.4 fb⁻¹) CDF Public Note 11161	16.0 ± 4.5
D0 Lepton+jets (9.7 fb⁻¹) PRD 90, 072011 (2014)	10.6 ± 3.0
D0 Dileptons (9.7 fb⁻¹) arXiv:1507.05666	17.5 ± 6.3
D0 Combination (9.7 fb⁻¹) arXiv:1507.05666	11.8 ± 2.8

NLO SM, W. Bernreuther and Z.-G. Si, PRD 86, 034026 (2012)

NNLO SM, M. Czakon, P. Fiedler and A. Mitov, arXiv:1411.3007

Asymmetry (%)

All inclusive measurements **compatible with standard model** predictions within ≤1.5 standard deviations.

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Top: Differential Asymmetry

- Differential parton-level asymmetries
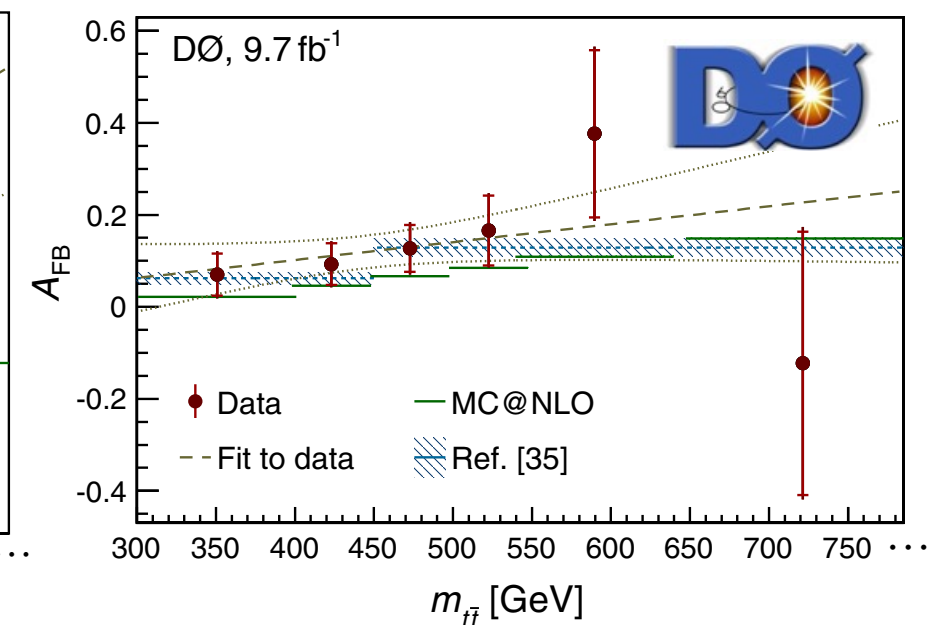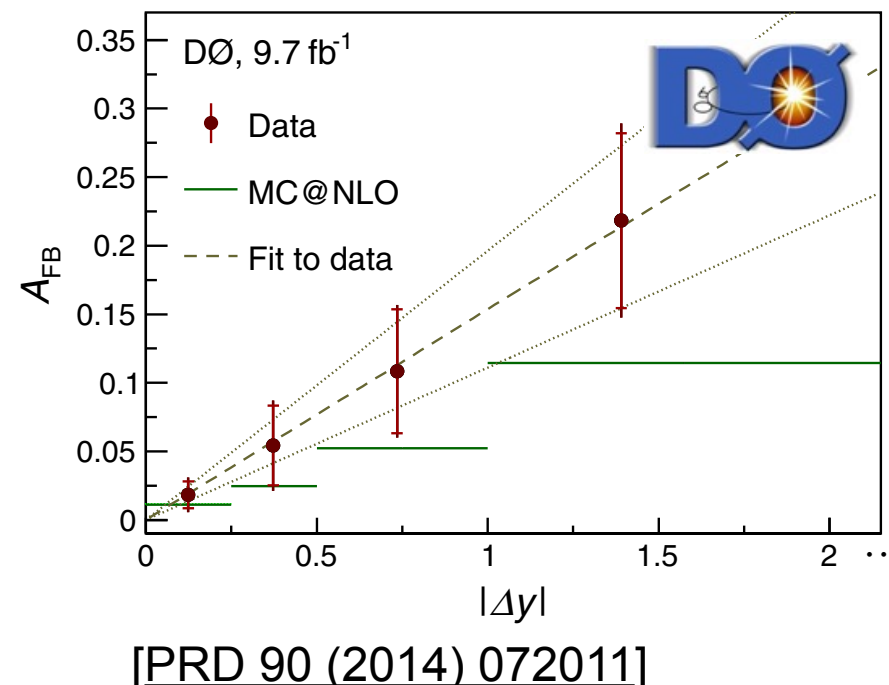
- $|\Delta y|$ dependence
  - Expect **linear** increase, slope α
  - CDF: **strong increase** (>2 SD above NLO QCD)
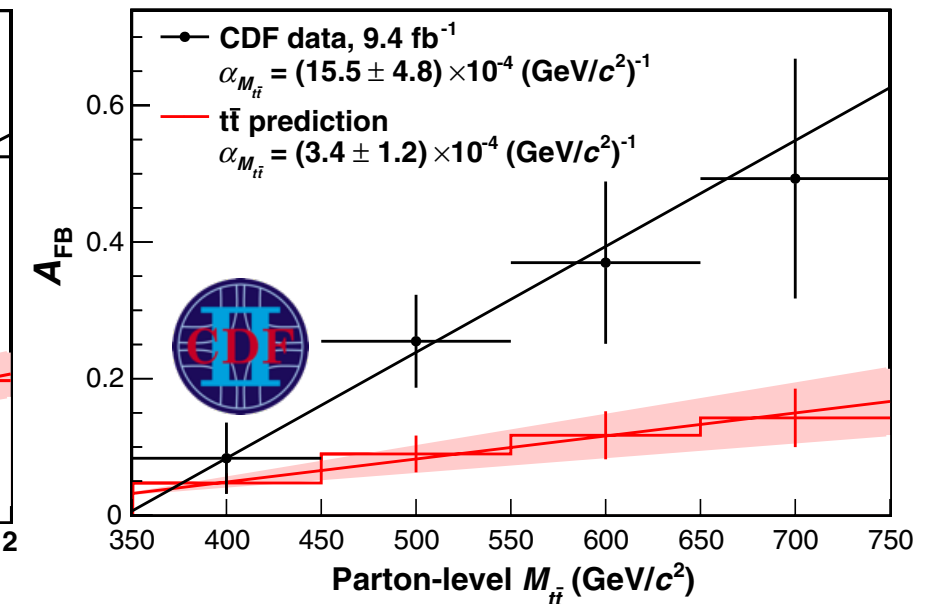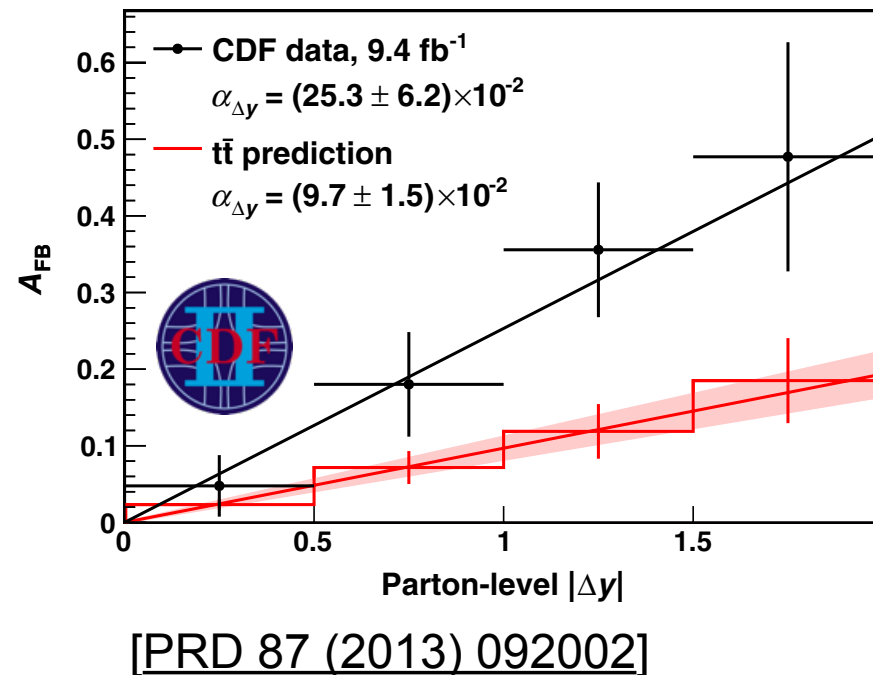
- $m_{t\bar{t}}$ dependence
 - Expect mild increase
  - CDF: **strong increase** (>2 SD above NLO QCD)
  - DØ: <1 SD above NLO predictions, little $m_{t\bar{t}}$ dependence

[PRD 87 (2013) 092002]

[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 Run II Preliminary
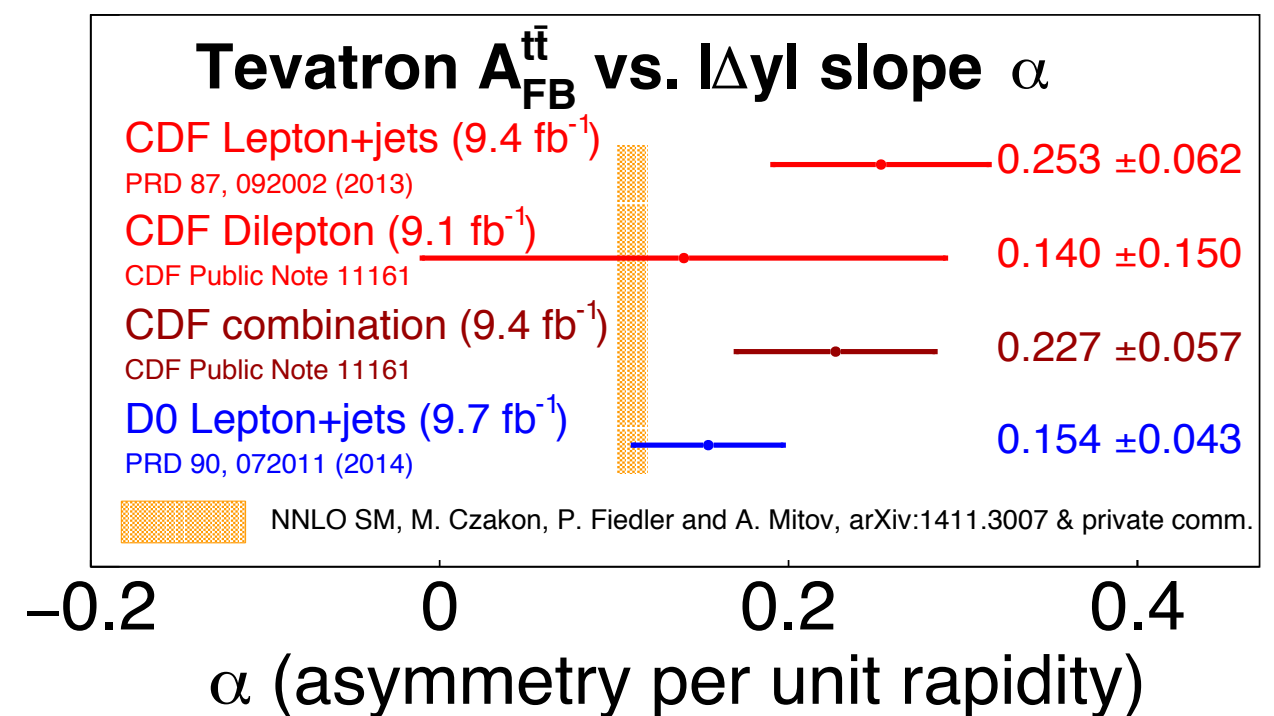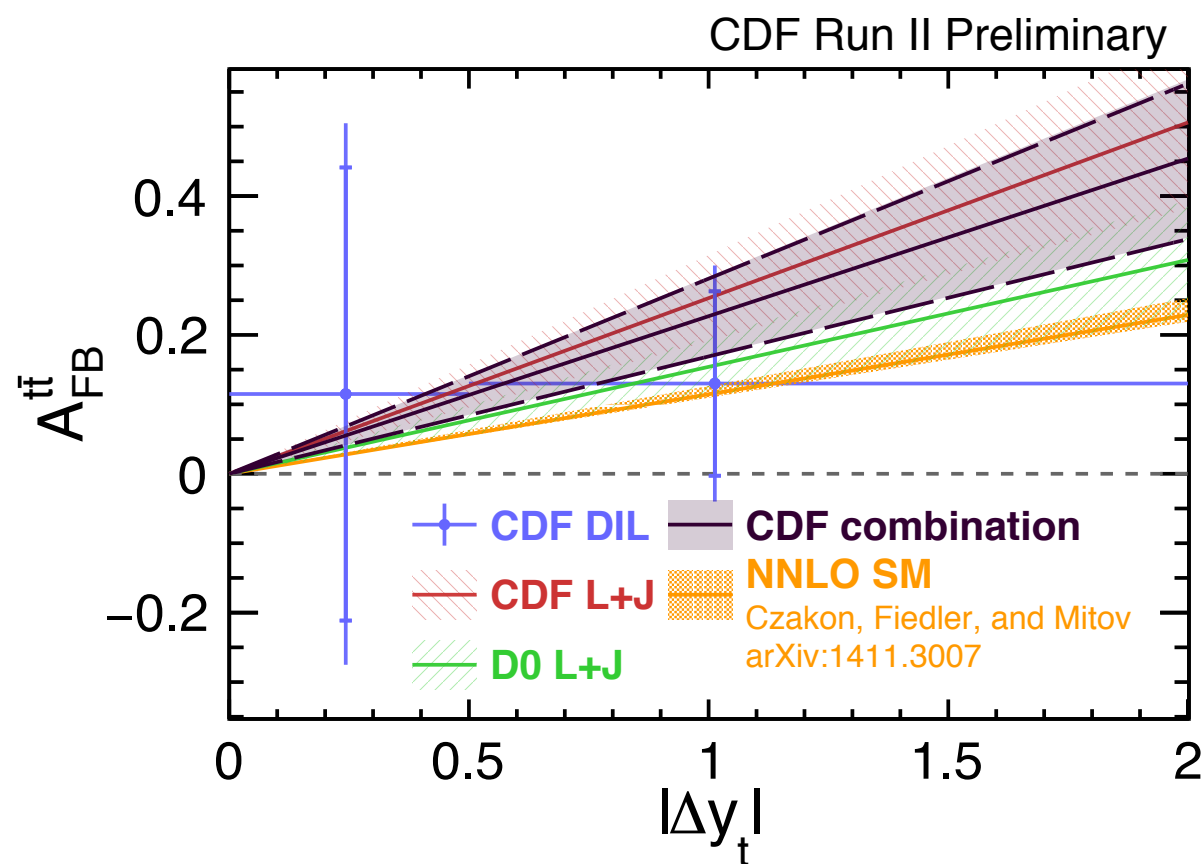
[CDF Note 11161]

Top: Production Angle

- Normalized differential cross section in **top production angle**
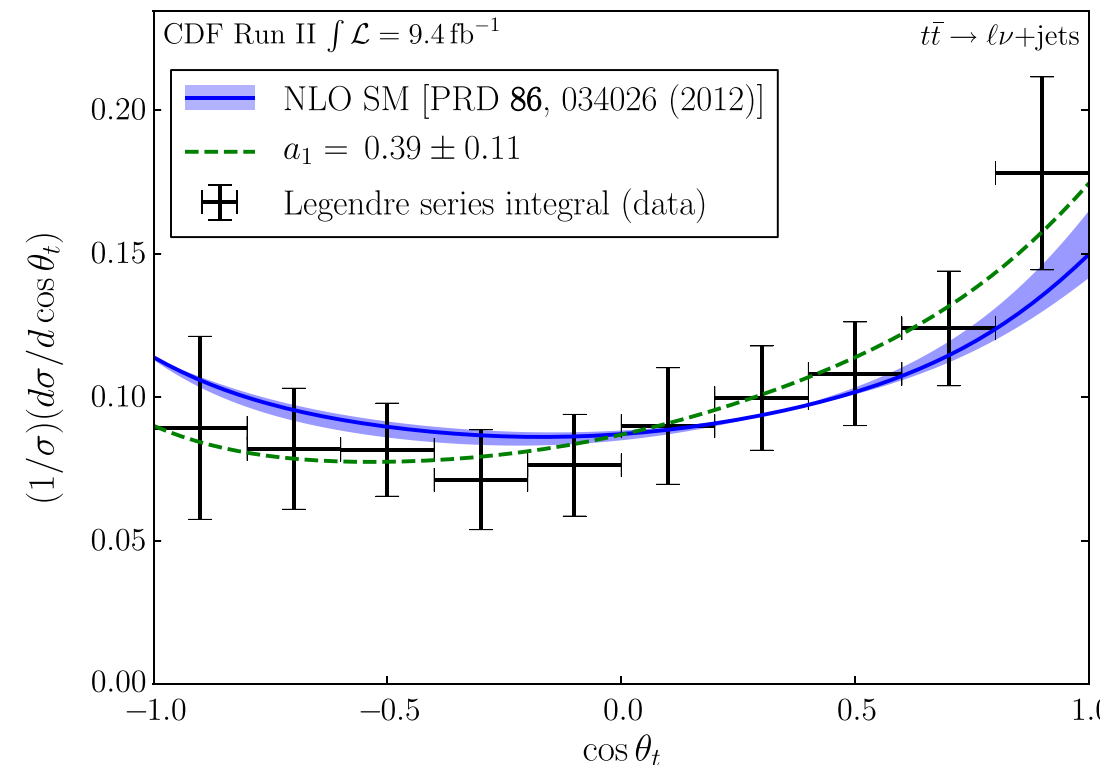 - Decomposition in orthonormal **Legendre polynomials**

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

  - **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%
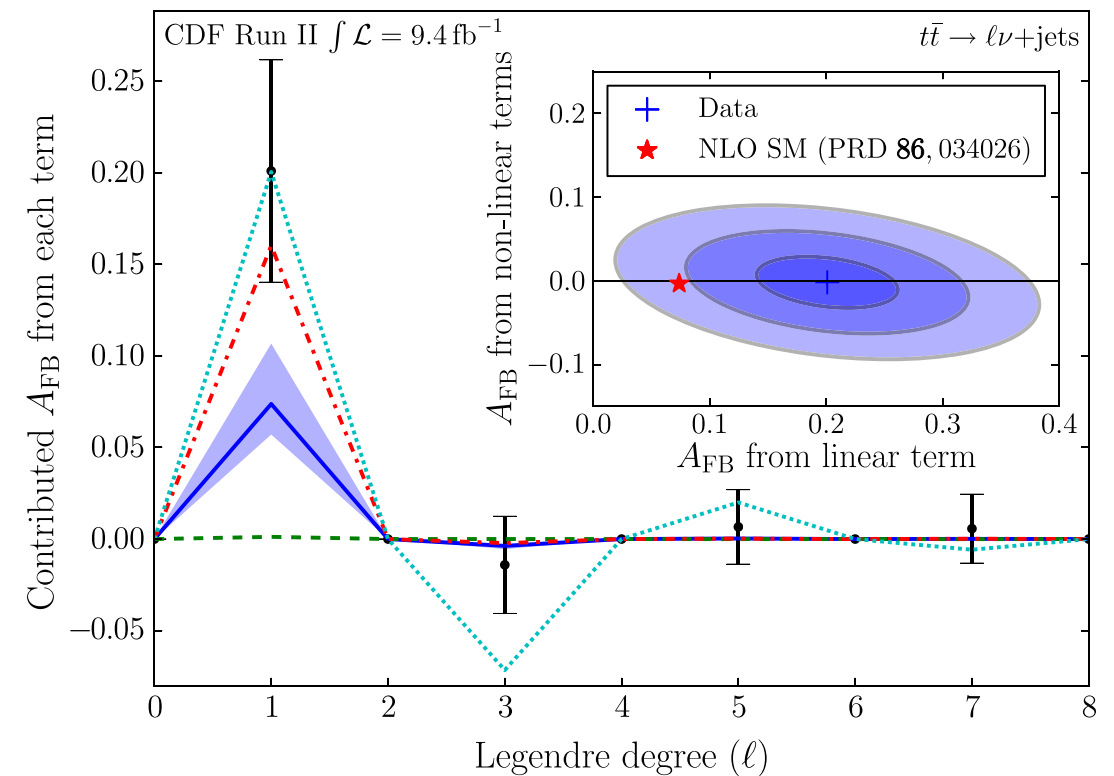
[PRL **111** (2013) 182002]

Top: Leptonic Asymmetry

- **Leptonic** asymmetry in **lepton + jets** channel
  - Asymmetry in $q_\ell \eta_\ell$ within detector acceptance
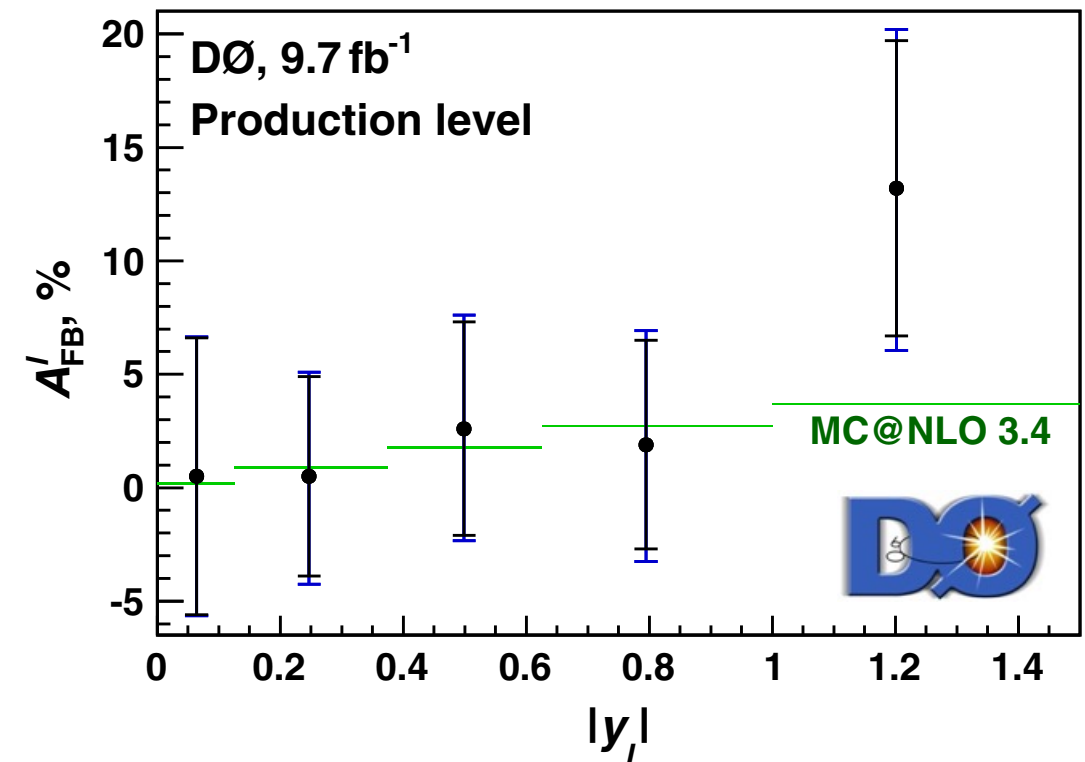 - Extrapolation to unmeasured η with empirical model
  - Calculations including lepton acceptance cuts (NLO QCD + EW)
    $\rightarrow$ very small model dependence (Bernreuther, Si, PRD86 (2012) 034026)

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

DØ, 9.7 fb^{-1}
Production level
MC@NLO 3.4
A^l_{FB}, %
$|y_l|$

[PRD 90 (2014) 072001]

NLO QCD ℓ+Jets data   Fit $\mathcal{A}(qy_\ell)$
Uncertainties: $\pm 1\sigma(stat. + sys.)$ $\pm 1\sigma(stat.)$
$A^\ell_{FB}(qy_\ell)$
$|qy_\ell|$
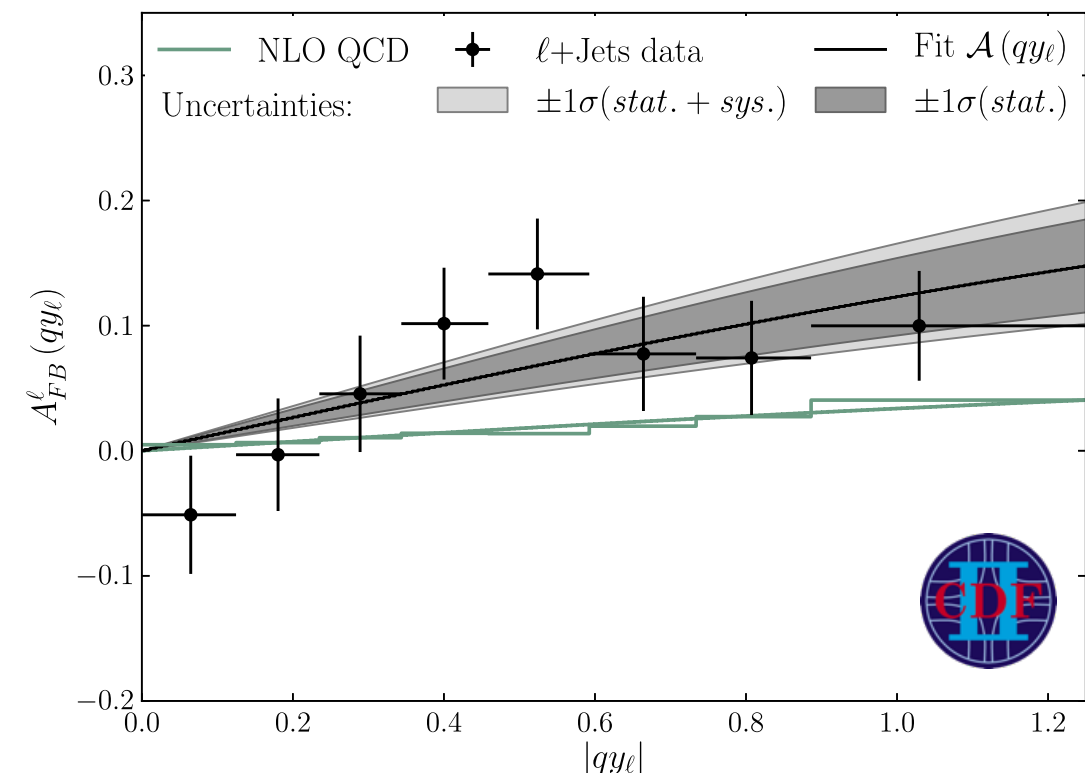
[PRD 88 (2013) 072003]

Top: Leptonic Asymmetry

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

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

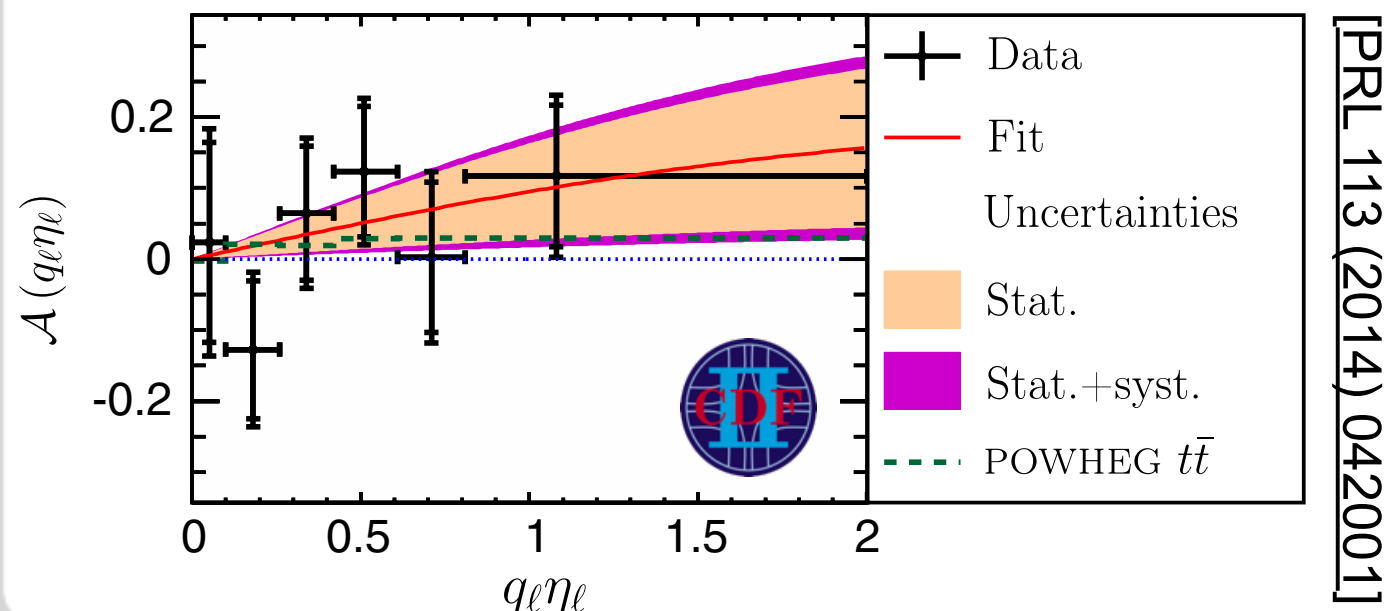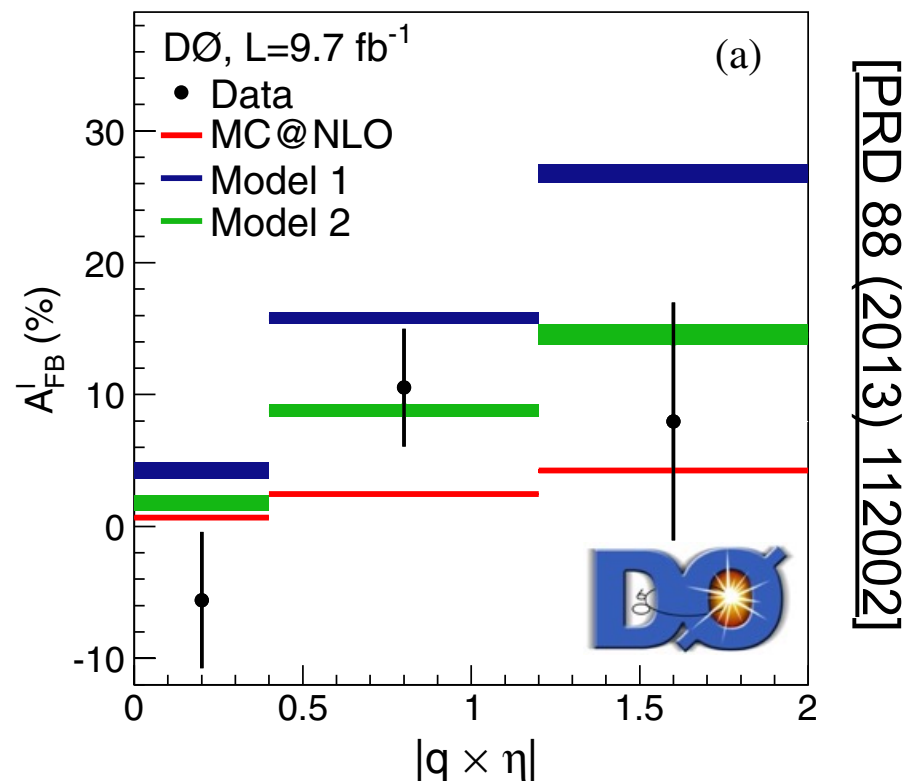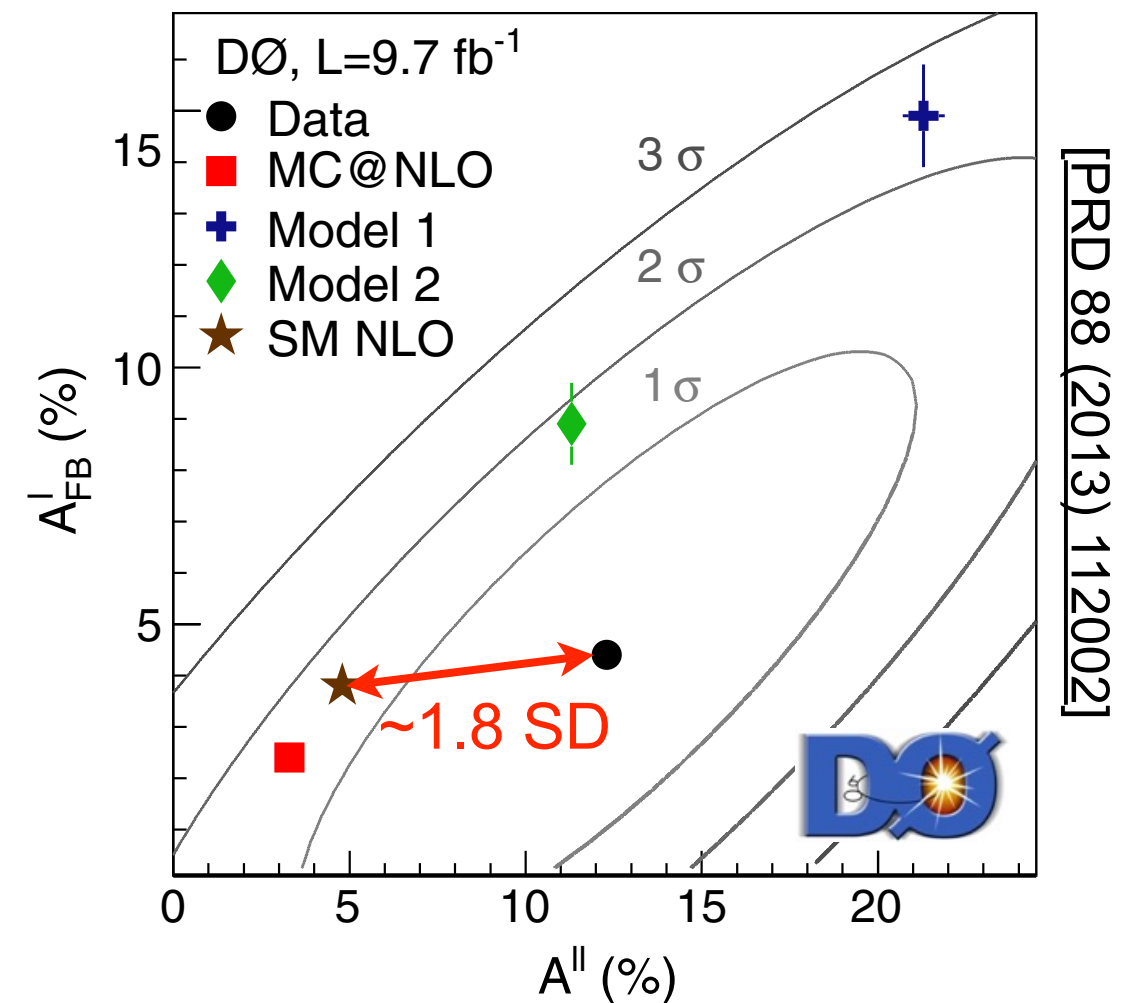SM NLO: QCD + EW
Model 1: 200-GeV axigluon RH SM couplings
Model 2: 2-TeV axigluon, strong coupling to top

Bottom Asymmetry

- Idea: probe **same physics** that leads to top A_{FB} at **lower energies** than $t\bar{t}$ → study $b\bar{b}$ system

- DØ: very low energies, $p_{T,b}$ < 35 GeV
  - **Full reconstruction** of charged B meson decays $B^{\pm} \to J/\psi (\to \mu\mu) K^{\pm}$
  - **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)

[PRL 114 (2015) 051803]

EPS-HEP 2015: Measurements of Forward-Backward Asymmetries at the Tevatron

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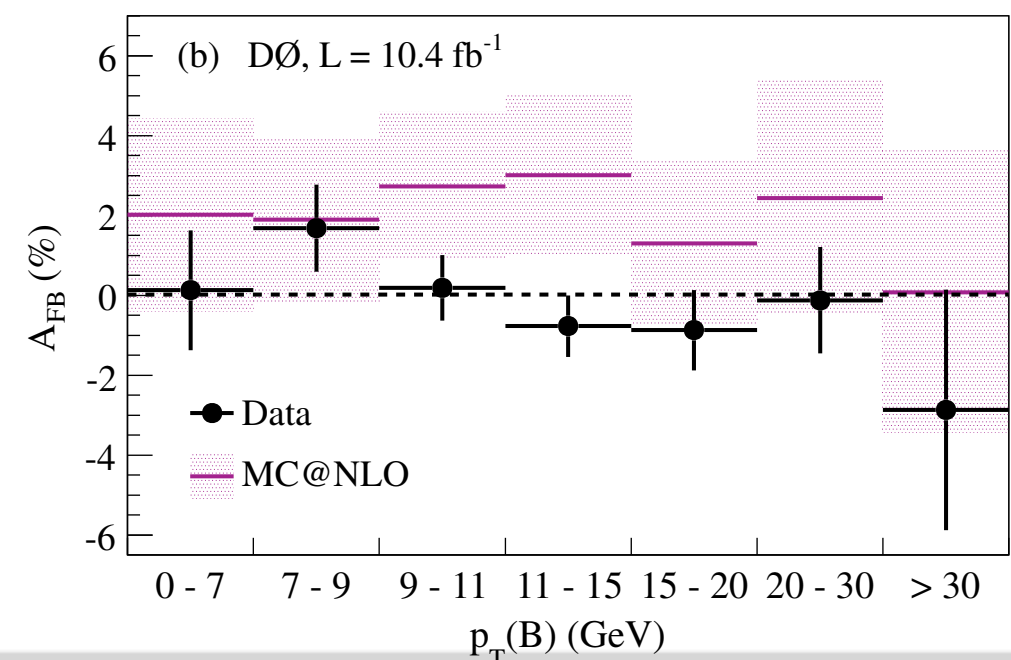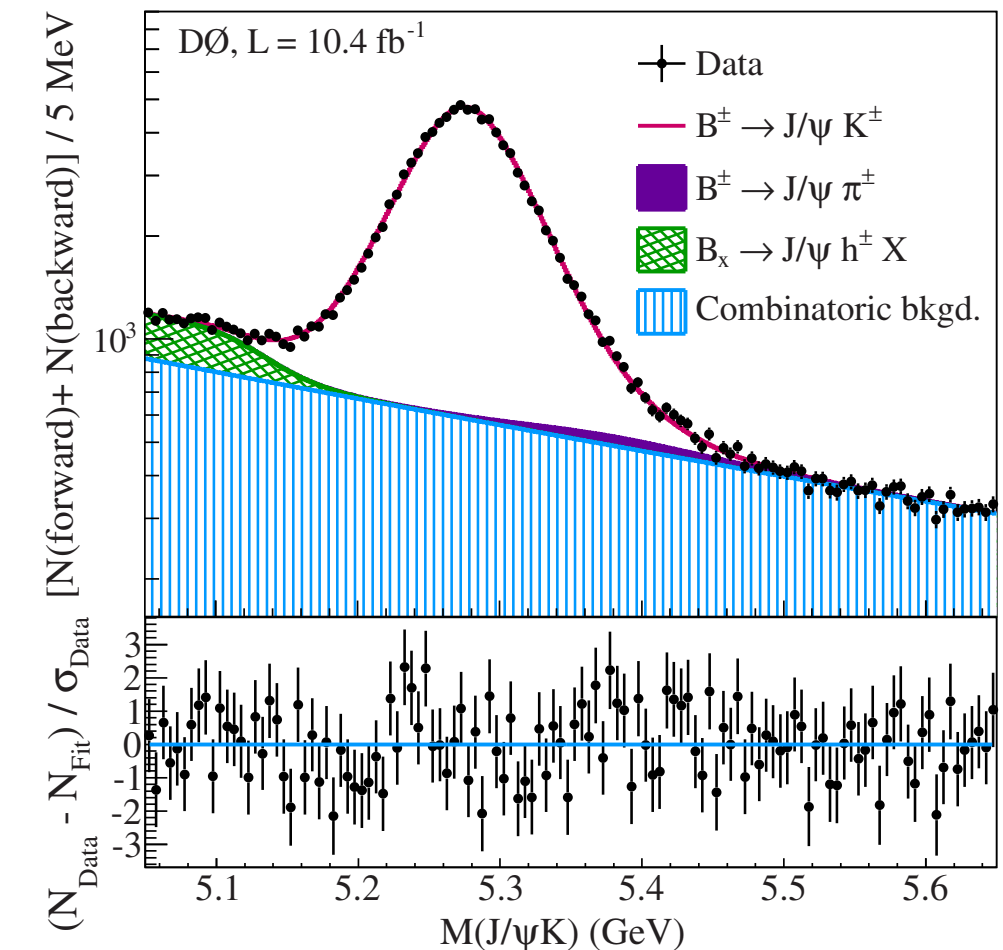
Bottom Asymmetry

- Medium energy: $m_{b\bar{b}}$ < few 100 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 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 Run II Preliminary, $\int Ldt = 6.9\ fb^{-1}$, $A_{FB}(b\bar{b})$

- Data
- NLO SM (PRL 111, 062003)

$A_{FB}(b\bar{b})$ [%]

particle-level $M_{b\bar{b}}$ [GeV/c^2]

[CDF Note 11156]

CDF Run II $\int \mathcal{L} = 9.5\ fb^{-1}$

A_{FB} [%]

NLO SM (PRL 111 062003)
Axigluon 200 GeV/c^2
Axigluon 345 GeV/c^2
CDF data

$b\bar{b}$ mass [GeV/c^2]
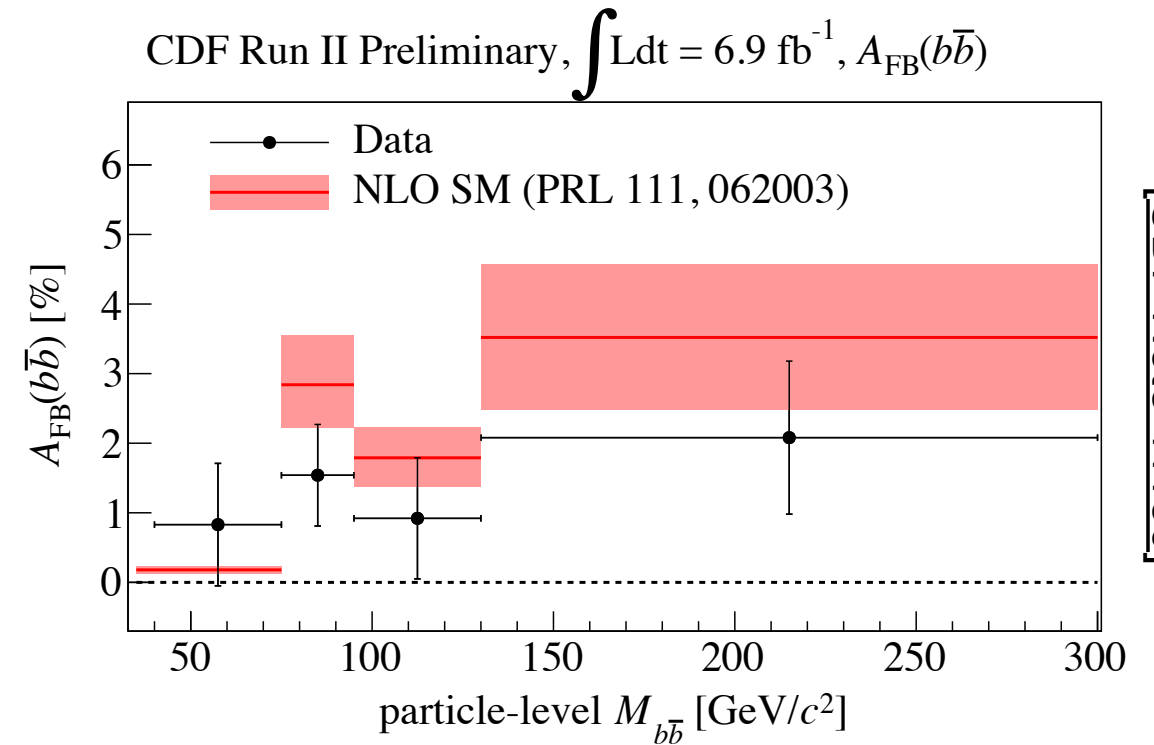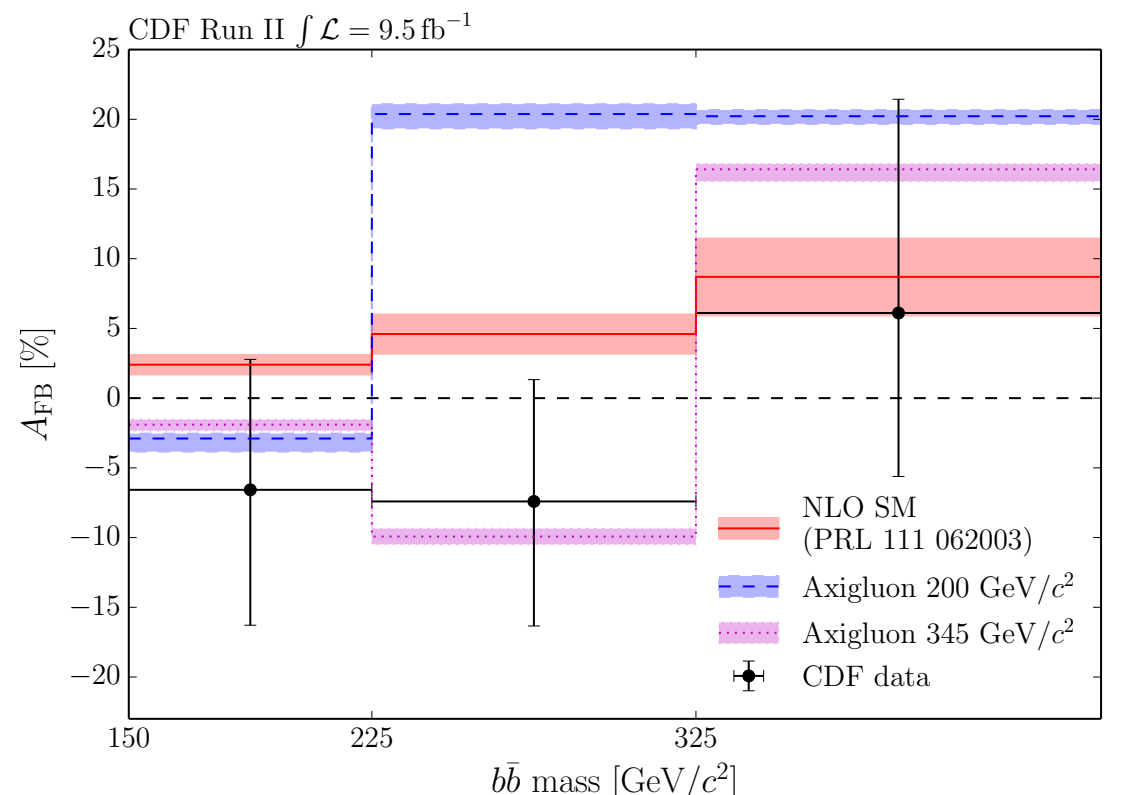
[arXiv:1504.06888, accepted by PRD]

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Summary & Conclusions

Tevatron Top Asymmetry

$t\bar{t}$ Δy Asymmetry ($A_{FB}^{t\bar{t}}$)

CDF Lepton+jets (9.4 fb^{-1})
PRD 87, 092002 (2013) — 16.4 ± 4.7

CDF Dilepton (9.1 fb^{-1})
CDF Public Note 11161 (2015) — 12 ± 13

D0 Lepton+jets (9.7 fb^{-1})
PRD 90, 072011 (2014) — 10.6 ± 3.0

D0 Dileptons (9.7 fb^{-1})
arXiv:1507.05666 — 17.5 ± 6.3

Lepton $q\eta$ Asymmetry (A_{FB}^{l})

CDF Lepton+jets (9.4 fb^{-1})
PRD 88, 072003 (2013) — $9.4 \pm ^{3.2}_{2.9}$

CDF Dileptons (9.1 fb^{-1})
PRL 113, 042001 (2014) — 7.2 ± 6.0

D0 Lepton+jets (9.7 fb^{-1})
PRD 90, 072001 (2014) — $5.0 \pm ^{3.4}_{3.7}$

D0 Dileptons (9.7 fb^{-1})
PRD 88, 112002 (2013) — 4.4 ± 3.9

Lepton $\Delta\eta$ Asymmetry (A_{FB}^{ll})

CDF Dileptons (9.1 fb^{-1})
PRL 113, 042001 (2014) — 7.6 ± 8.2

D0 Dileptons (9.7 fb^{-1})
PRD 88, 112002 (2013) — 12.3 ± 5.6

NLO SM, W. Bernreuther and Z.-G. Si, PRD 86, 034026 (2012)
NNLO SM, M. Czakon, P. Fiedler and A. Mitov, arXiv:1411.3007

Asymmetry (%): –20, 0, 20, 40

- **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

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