Asymmetries at Tevatron

Pavol Bartoš

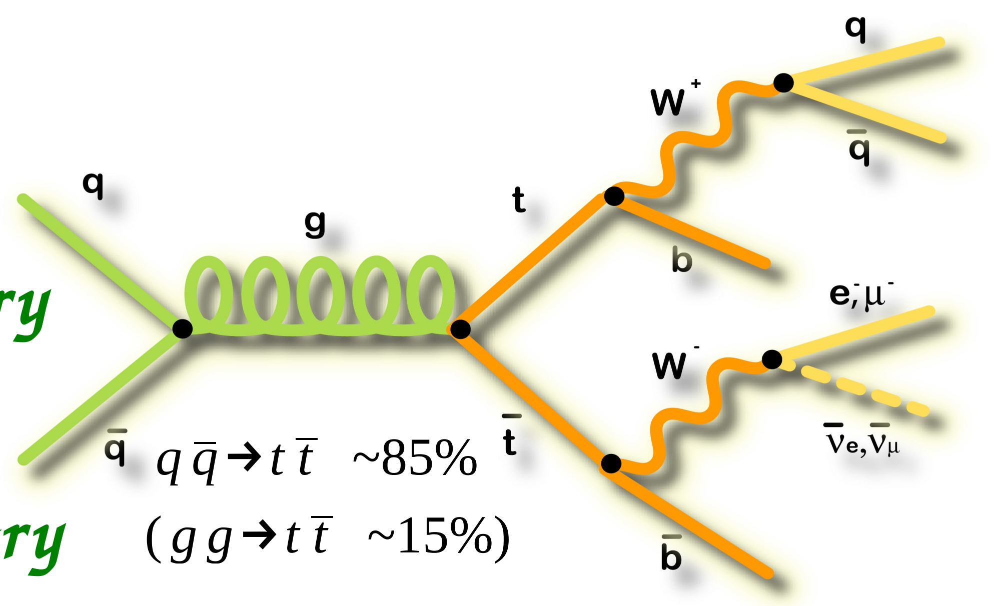
(Comenius University)

On behalf of CDF and D0 collaborations

CKM 2014, Vienna

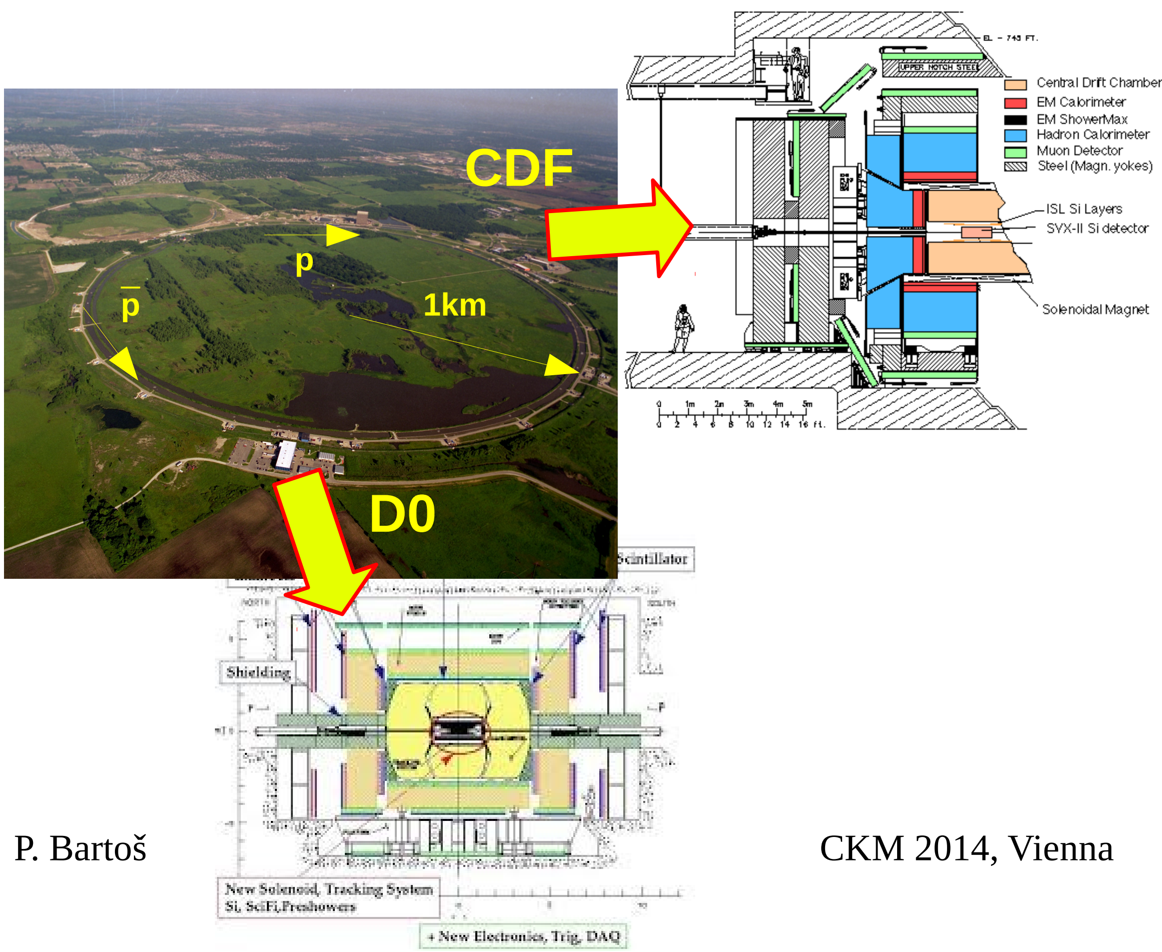
Outline

- → $t\bar{t}$ forward-backward asymmetry
- → $t\bar{t}$ lepton based asymmetry
- → $b\bar{b}$ forward-backward asymmetry



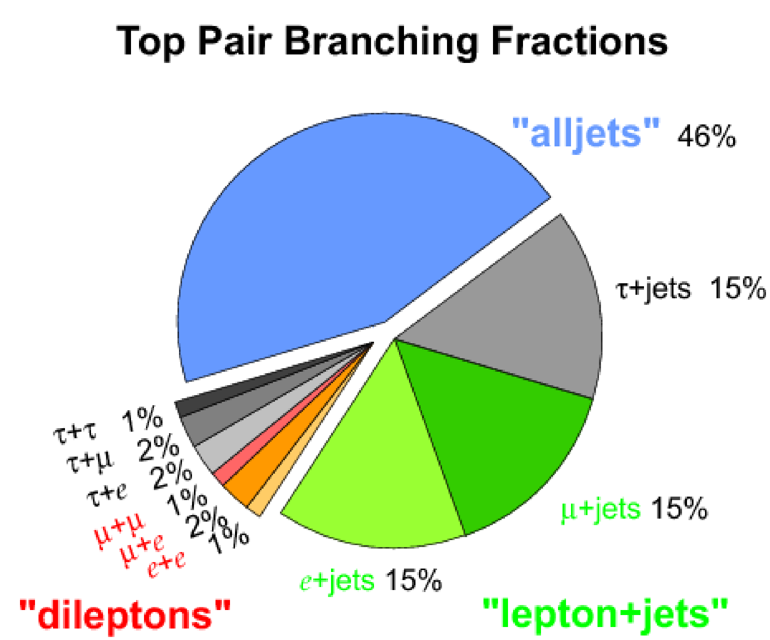
$q\bar{q} \to t\bar{t}$ ~85%

$(gg \to t\bar{t}$ ~15%)



According to SM:

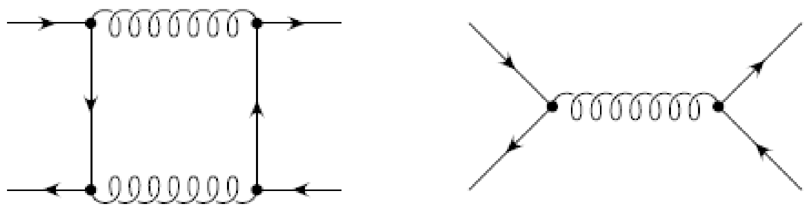
$B(t \to Wb) \sim 100\%$



$t\bar{t}$ forward-backward asymmetry

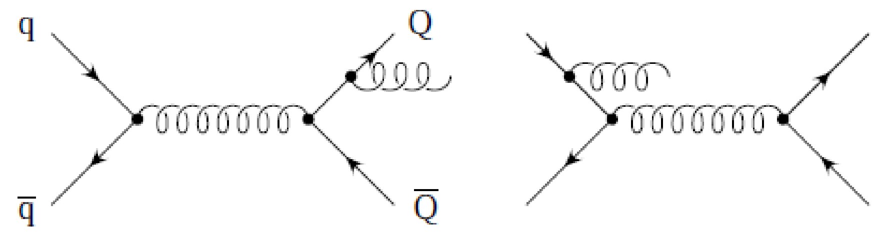
→ **at NLO, the SM predicts asymmetry** in $t\bar{t}$ production

→ asymmetry comes from events with **$q\bar{q}$ initial states**, **gg is symmetric**



positive asymmetry

+



negative asymmetry

→ **Definition:**

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$, where $\Delta y = y_t - y_{\bar{t}}$

→ **Methodology:**

→ using l+jet events (full statistics)

→ **full kinematic reconstruction** of $t\bar{t}$ final state

→ CDF: χ^2-based fit

→ D0: new kinematic fit algorithm (helps to increase statistics by factor of 2)

m_{tt} obtained from multivariate regression combining 3 algorithms

→ **correction for parton level** – using TUnfold (D0), SVD (CDF)

→ inclusive asymmetry expressed also **as function of: m_{tt}, $|\Delta y|$** – CDF, DO

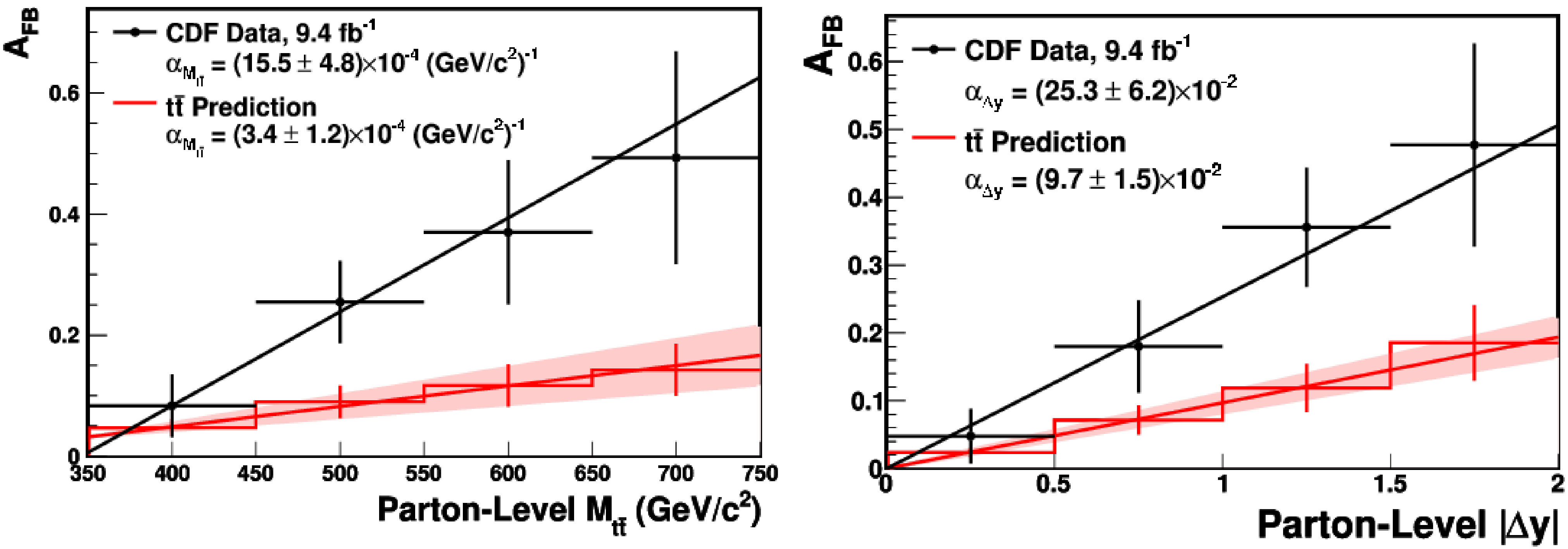
$p_T(t\bar{t})$ - CDF

$t\bar{t}$ forward-backward asymmetry

→ **CDF Results:**

$$A_{FB} = 0.164 \pm 0.039\,(\text{stat.}) \pm 0.026\,(\text{syst.})$$

PRD 87, 092002 (2013)



Slopes different w.r.t. SM predictions:

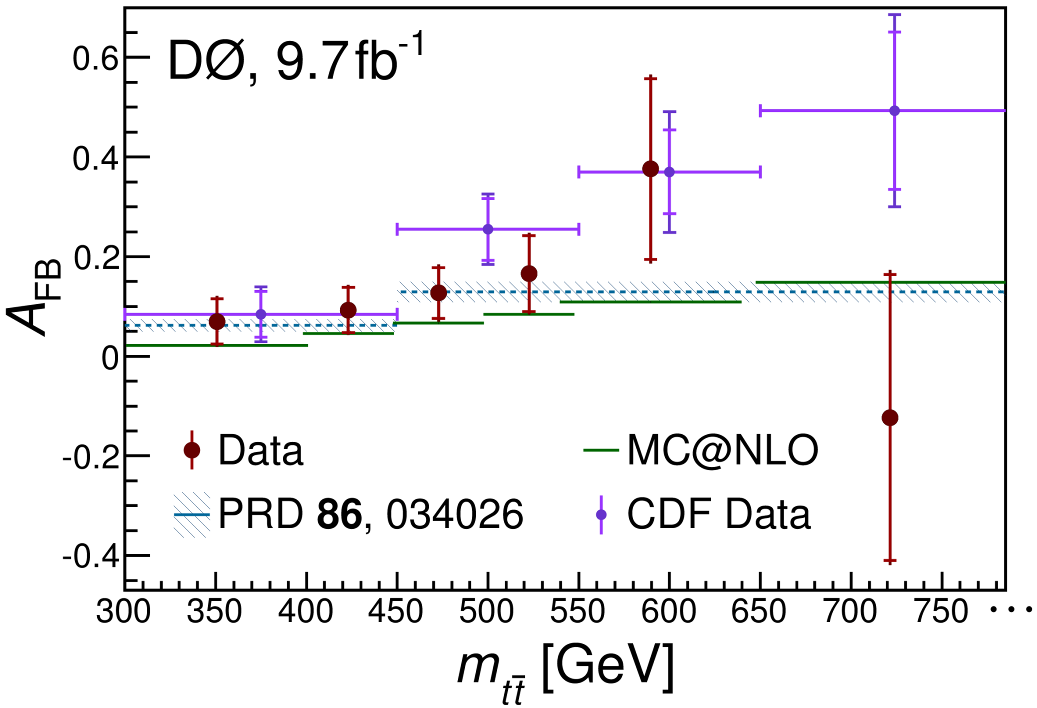
2.4σ (M_{tt}), 2.8σ (|Δy|)

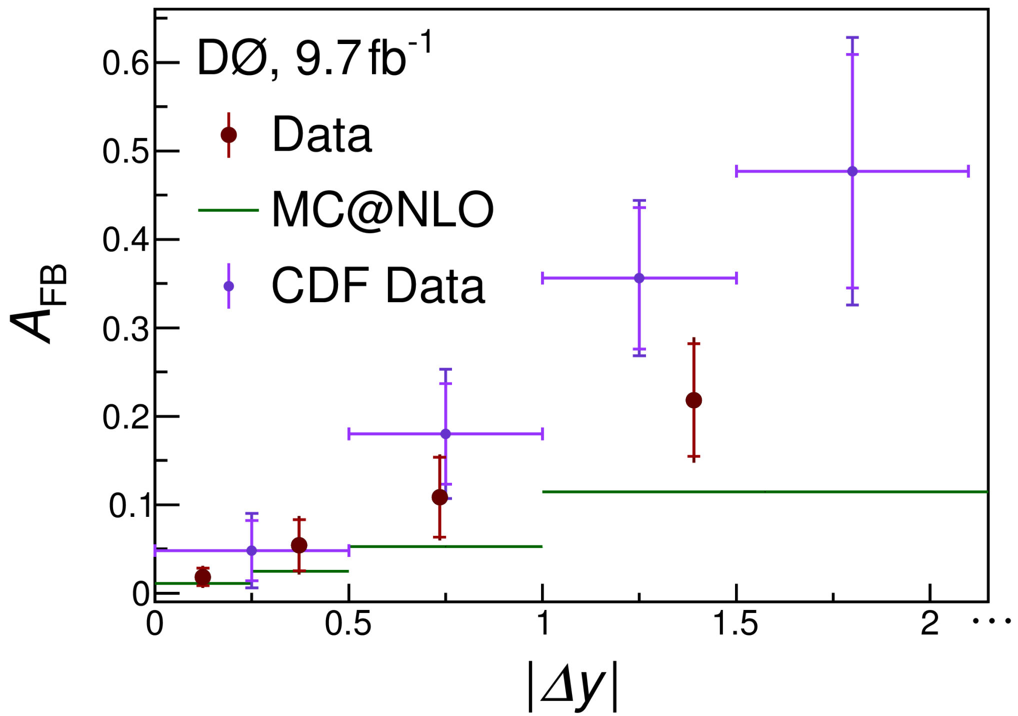
$t\bar{t}$ forward-backward asymmetry

→ **D0 results**

$$A_{FB} = 0.106 \pm 0.030$$

ArXiv:1405.0421, submitted to PRD





Slope difference w.r.t. **MC@NLO predictions** and **CDF results:**

M_{tt}: consistent withMC@NLO, 1.8σ (CDF) **|Δy|: 1.7σ (MC@NLO), 1.3σ (CDF)**

Compatible with **SM predictions** and with **CDF result !**

Differential $t\bar{t}$ cross sections

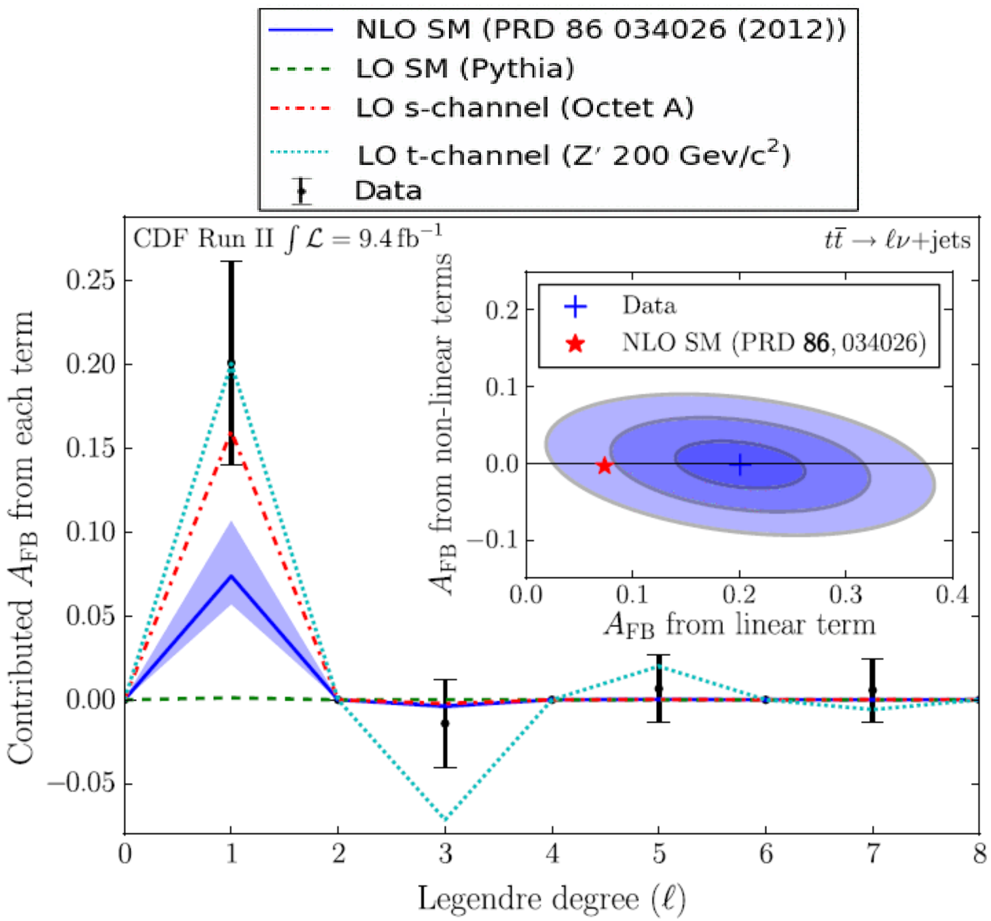
→ employ Legendre polynomials to characterize the shape of differential cross section:

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

θ_t is angle between top-quark momentum and the incoming proton momentum in $t\bar{t}$ center-of-mass frame

→ full shape has potential to discriminate among various calculations of SM and non-SM physics models

→ moment a_0 contains only total cross section, we scale all moments, (a_l), so that a_0=1



PRL 111 182002 (2013)

ℓ	a_ℓ (obs)	a_ℓ (pred)
1	0.40 ± 0.12	$0.15^{+0.07}_{-0.03}$
2	0.44 ± 0.25	$0.28^{+0.05}_{-0.03}$
3	0.11 ± 0.21	$0.030^{+0.014}_{-0.007}$
4	0.22 ± 0.28	$0.035^{+0.016}_{-0.008}$
5	0.11 ± 0.33	$0.005^{+0.002}_{-0.001}$
6	0.24 ± 0.40	$0.006^{+0.002}_{-0.003}$
7	-0.15 ± 0.48	$-0.003^{+0.001}_{-0.001}$
8	0.16 ± 0.65	$-0.0019^{+0.0003}_{-0.0003}$

~2σ difference w.r.t. predictions

result favors the asymmetry models with strong s-channel components

Differential $t\bar{t}$ cross sections (I)

→ *l+jet channel with 1 b-tag* → cross section as a function of **m_{tt} , $p_T(t)$, $|y(t)|$**

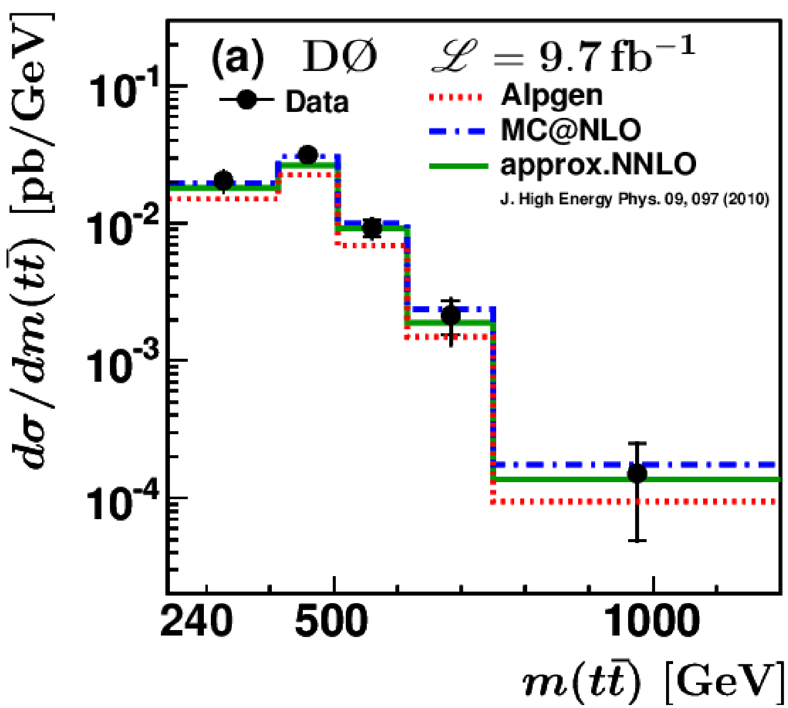
→ Different axigluon models with different couplings (used in asymmetry studies) differential cross section predictions provided by A. Falkowski (et al)

arXiv 1401.2443

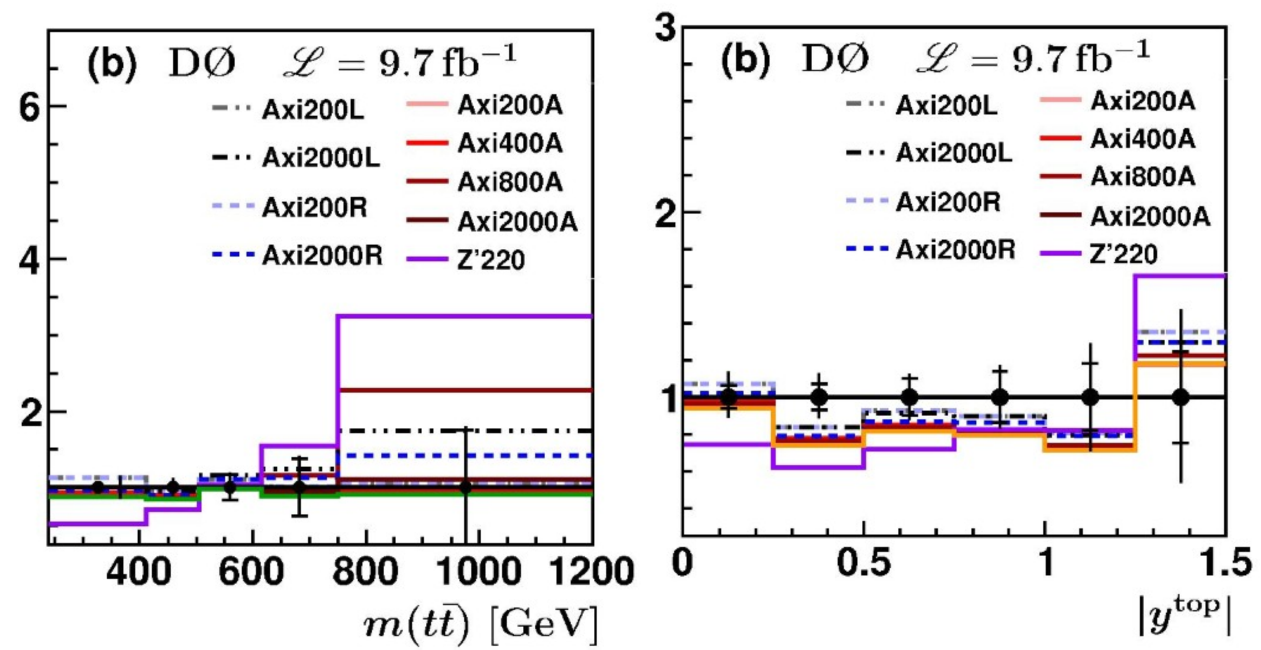
→ in these models, forward-backward asymmetry will be increased, but also the **differential cross section distributions will be changed**

→ high-mass axigluons highly constrained by LHC measurements, while low masses not so much (but the effects are small)

Some models are in tension with the presented data !



Ratio to data



Differential $t\bar{t}$ cross sections (II)

Table of χ^2/NDF values for **data** versus **approx. pQCD at NNLO** and the **various axi-gluon models** and **one Z' model.**

$$\chi^2 = \sum_{i,j} (m-\mu)_i \, cov^{-1}_{i,j} . (m-\mu)_j$$

m – measured value per bin
μ – expected value of particular model per bin
cov – covariance matrix

	$\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [pb]	$M(t\bar{t})$ $[\chi^2/ndf]$	$\lvert y^{\text{top}}\rvert$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$
Data	$8.27^{+0.92}_{-0.91}$ (stat. + syst.)	n.a.	n.a.	n.a.
pQCD NNLO	$7.24^{+0.23}_{-0.27}$ (scales + pdf)	0.98	3.71	4.05

non-SM model	$\Delta\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [pb]	$M(t\bar{t})$ $[\chi^2/ndf]$	$\lvert y^{\text{top}}\rvert$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$
$G'(l)$, $m = 0.2$ TeV	$+0.97 \pm 0.06$ (scales)	0.96	1.07	1.20
$G'(r)$, $m = 0.2$ TeV	$+0.97 \pm 0.06$ (scales)	0.96	1.07	1.20
$G'(a)$, $m = 0.2$ TeV	$+0.06 \pm 0.04$ (scales)	0.85	3.55	3.88
$G'(a)$, $m = 0.4$ TeV	$+0.26 \pm 0.04$ (scales)	0.44	2.65	3.26
$G'(a)$, $m = 0.8$ TeV	$+0.22 \pm 0.04$ (scales)	0.97	2.86	3.23
$G'(l)$, $m = 2.0$ TeV	$+0.87 \pm 0.15$ (scales)	0.58	1.27	3.78
$G'(r)$, $m = 2.0$ TeV	$+0.55 \pm 0.06$ (scales)	0.43	1.94	2.75
$G'(a)$, $m = 2.0$ TeV	$+0.05 \pm 0.06$ (scales)	0.88	3.56	4.11
Z', $m = 0.22$ TeV	-1.00 ± 0.06 (scales)	4.95	8.27	7.48

Lepton based $t\bar{t}$ asymmetry

→ **Advantage:** no need to reconstruct the $t\bar{t}$ final state.
sensitive to top quark polarization
  → lepton direction is measured with high precision + good charge determination
→ asymmetry is smaller than $t\bar{t}$ forward-backward one

→ **Definition:**

Dilepton events: $\Delta\eta = \eta_{l^+} - \eta_{l^-}$

$$A_{\mathrm{FB}}^{\ell} = \frac{N(qy_\ell > 0) - N(qy_\ell < 0)}{N(qy_\ell > 0) + N(qy_\ell < 0)}.$$

$$A_{\mathrm{FB}}^{\Delta\eta} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$

→ **CDF methodology: (same for l+jets and dilepton events)**

  → asymmetry is decomposed into symmetric and asymmetric parts:

$$\mathcal{S}(qy_\ell) = \frac{\mathcal{N}(qy_\ell) + \mathcal{N}(-qy_\ell)}{2} \qquad \mathcal{A}(qy_\ell) = \frac{\mathcal{N}(qy_\ell) - \mathcal{N}(-qy_\ell)}{\mathcal{N}(qy_\ell) + \mathcal{N}(-qy_\ell)},$$

  → symmetric part (obtained from MC) – largely insensitive to physics model
  → asymmetric part is parametrized: $\mathcal{A}(qy_\ell) = a \tanh\left(\frac{qy_\ell}{2}\right)$

  → fit of asymmetric part allows to extrapolate to unmeasured region

Lepton based asymmetry

→ **D0 methodology: (l+jets events)**

→ using l + 3 jets in addition to l + ≥4 jets – increase statistics twice
→ l+3 jets has lower S/B ratio, helps to reduce acceptance corrections

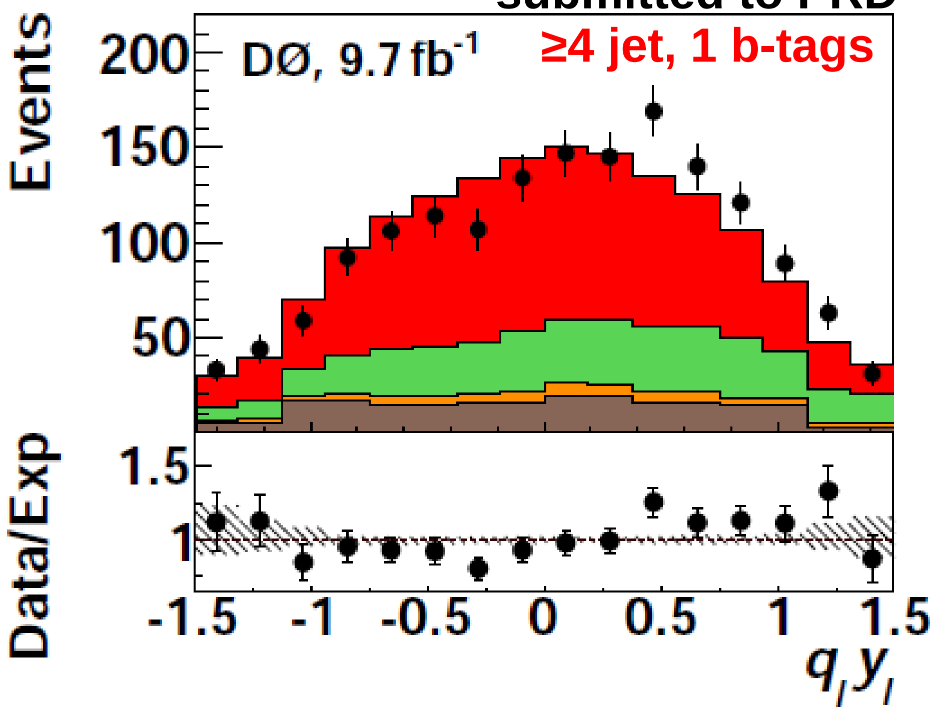
→ improve modeling of A^{l}_{FB} in W+jets using control region (3 jets+0 btag)

→ asymmetry and sample composition is extracted by likelihood fit

→ unfold for acceptance effects, study dependence on lepton p_T and y_l

l+jets channel:

arXiv 1403.1294
submitted to PRD



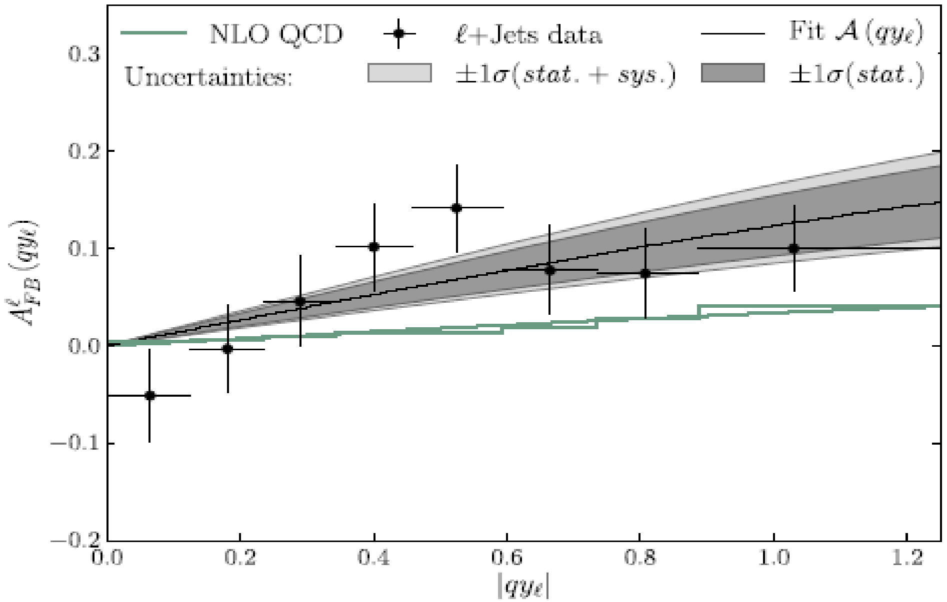
→ **D0 methodology: (dilepton events)**
→ background subtraction,
→ correction for selection effects
→ extrapolation to the full range of η

Single-lepton asymmetry results

l+jets channel

CDF: PRD 88, 072003 (2013)

$$A^{l}_{FB} = 0.094 \pm 0.024\,(\text{stat.})^{+0.022}_{-0.017}\,(\text{syst.})$$



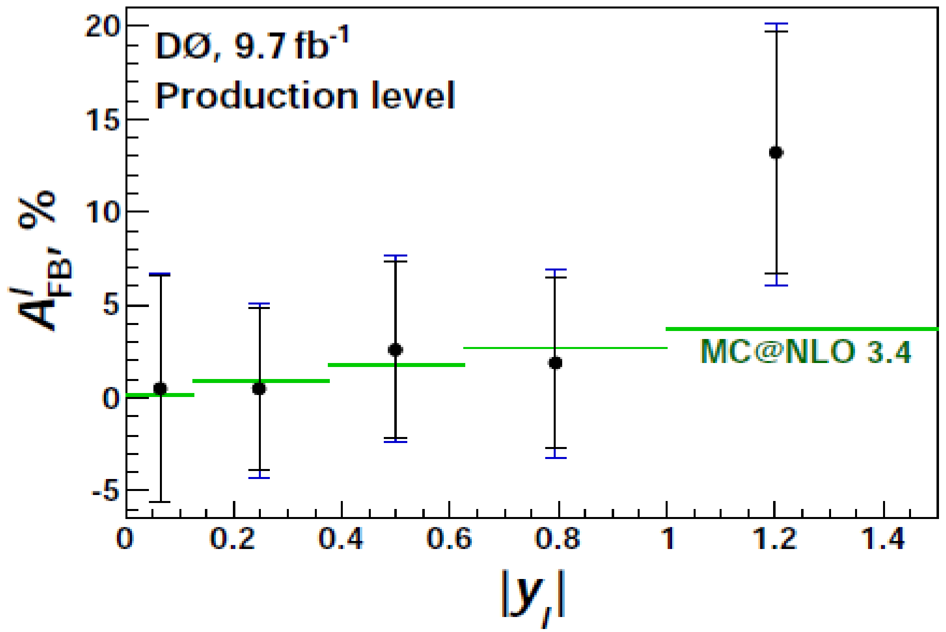
SM predicts:

$$A^{l}_{FB} = 0.038 \pm 0.003$$

D0: $|y_l|<1.5$:

arXiv 1403.1294
accepted by PRD

$$A^{l}_{FB} = 0.042 \pm 0.023\,(\text{stat.})^{+0.017}_{-0.020}\,(\text{syst.})$$



MC@NLO $|y_l|<1.5$:

$$A^{l}_{FB} = 0.020$$

Single lepton asymmetry

Dilepton channel

SM predicts:

$$A^{l}_{FB} = 0.038 \pm 0.003$$

CDF: PRL 113, 042001 (2014)

$$A^{l}_{FB} = 0.072 \pm 0.052\,(\text{stat.}) \pm 0.030\,(\text{syst.})$$

D0: PRD 88, 112002 (2013)

$$A^{l}_{FB} = 0.044 \pm 0.037\,(\text{stat.}) \pm 0.011\,(\text{syst.})$$

Combination *(l+jet, dilepton)*

→ using BLUE method

SM predicts:

$$A^{l}_{FB} = 0.038 \pm 0.003$$

CDF:

$$A^{l}_{FB} = 0.090^{+0.028}_{-0.026}$$

PRL 113, 042001 (2014)

2σ larger than the SM prediction

D0: arXiv 1403.1294, accepted by PRD

$$A^{l}_{FB} = 0.042 \pm 0.020\,(\text{stat}) \pm 0.014\,(\text{syst})$$

Dilepton asymmetry
Dilepton channel

CDF:

$$A_{FB}^{\Delta\eta} = 0.076 \pm 0.072\,(\text{stat.}) \pm 0.039\,(\text{syst.})$$

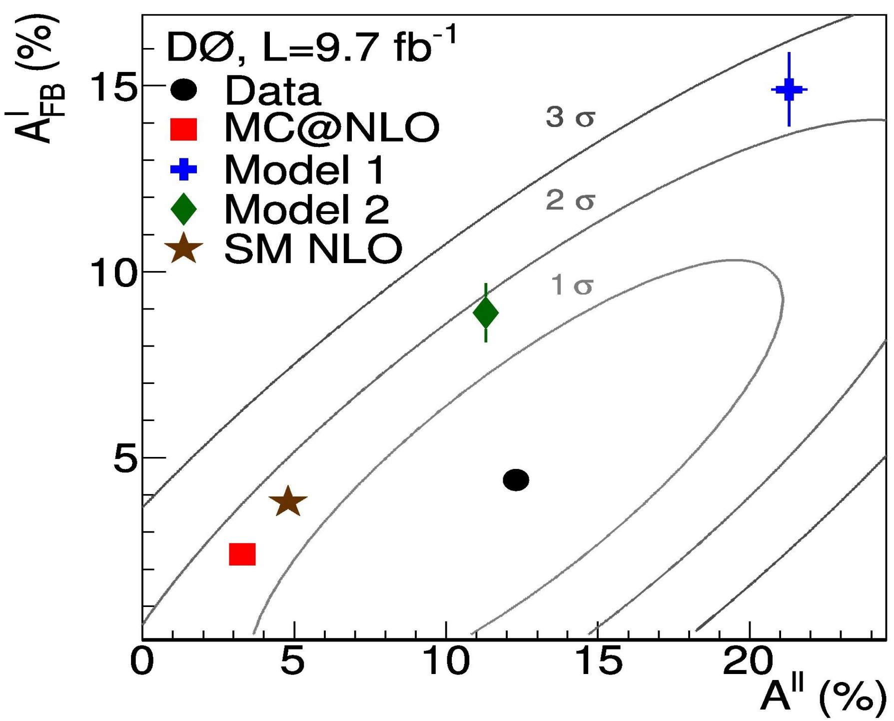
PRL 113, 042001 (2014)

D0: PRD 88, 112002 (2013)

$$A_{FB}^{\Delta\eta} = 0.123 \pm 0.054\,(\text{stat.}) \pm 0.015\,(\text{syst.})$$

SM predicts:

$$A_{FB}^{\Delta\eta} = 0.048 \pm 0.004$$



D0:

PRD 88, 112002 (2013)

$$A_{FB}^{l} / A_{FB}^{\Delta\eta} = 0.36 \pm 0.20$$

SM (NLO): 0.79 ± 0.10

2σ difference

Bottom forward-backward asymmetry at high mass

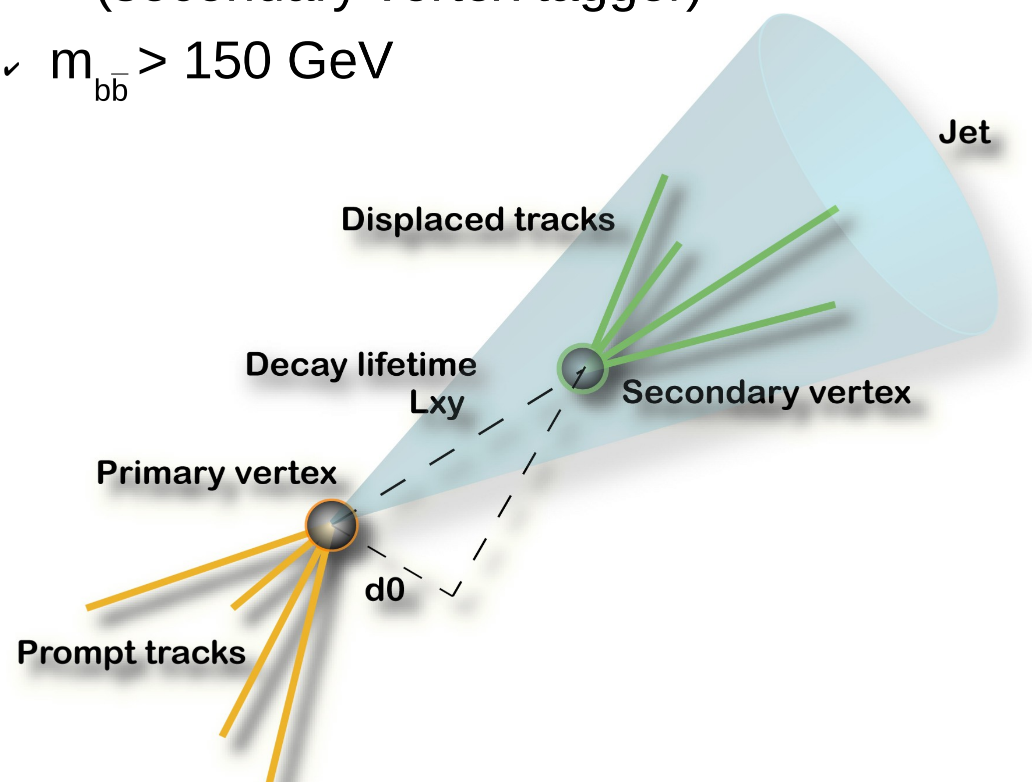
$b\bar{b}$ asymmetry at high mass (I)

→ **$b\bar{b}$ production** is almost exclusively **a QCD process**

→ one has to **select** a **kinematic region** where **$q\bar{q}$ initial state** is **significantly enhanced** over the symmetric gluon fusion background.

Event selection

- ≥ 2 jets with E_T > 20 GeV and |y|<2.
- 2 jets has to b-tagged (secondary vertex tagger)
- $m_{b\bar{b}}$ > 150 GeV



Theoretical prediction

B. Grinstein and C. W. Murphy

$m_{b\bar{b}}$ [GeV c^{-2}]	$A_{FB}(b\bar{b})$ [%]
[150, 225]	$2.2 \pm 0.7 \pm 0.2$ %
[225, 325]	$4.2 \pm 1.3^{+0.6}_{-0.5}$ %
[325, 1960]	$7.8 \pm 2.3^{+1.7}_{-1.4}$ %

PRL 111, 062003 (2013)

$b\bar{b}$ asymmetry at high mass (II)

Asymmetry definition

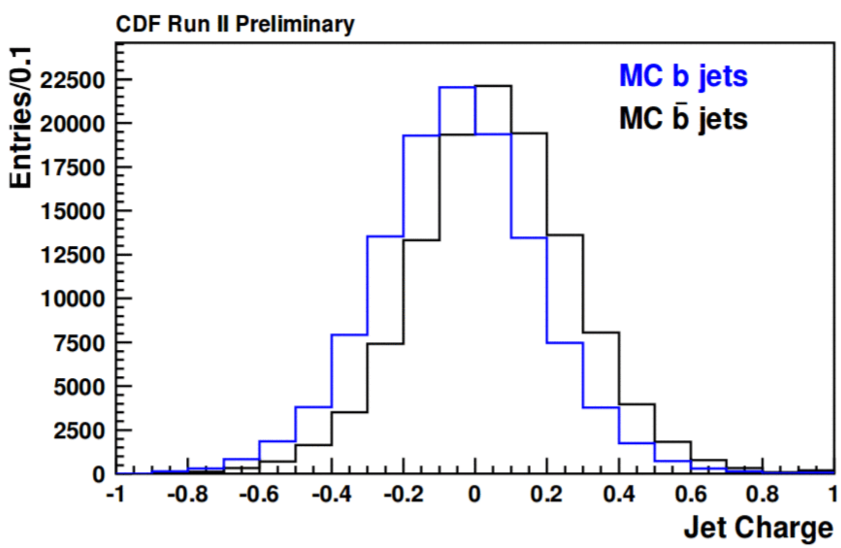
$$A_{FB} = \frac{N(\Delta y_b > 0) - N(\Delta y_b < 0)}{N(\Delta y_b > 0) + N(\Delta y_b < 0)}$$

$$\Delta y_b = y_b - y_{\bar{b}}$$

Jet charge

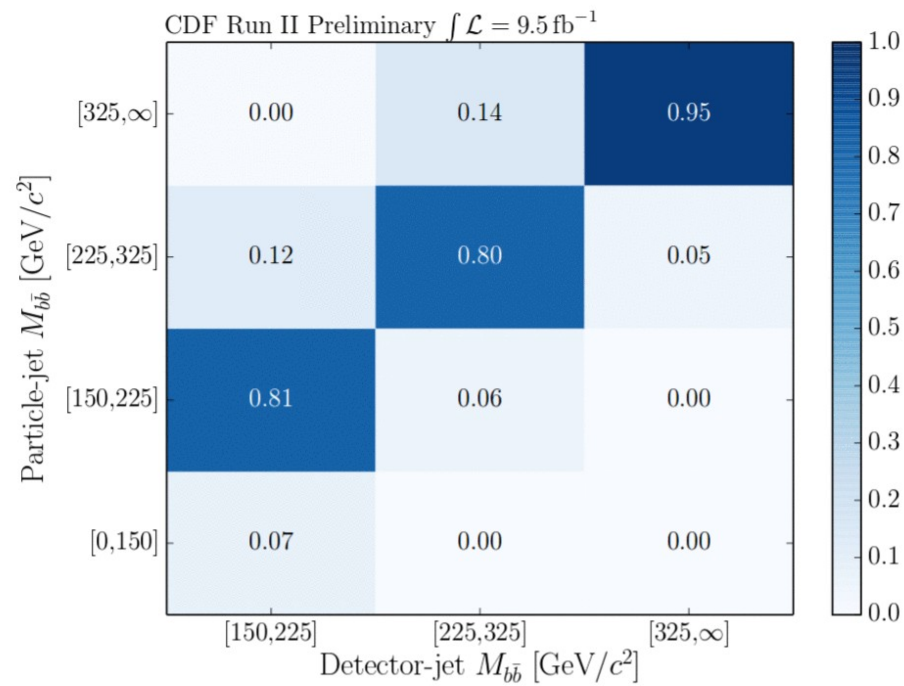
$$Q_{jet} = \frac{\sum_t q_t (\vec{p}_t \cdot \vec{p}_{jet})^{0.5}}{\sum_t (\vec{p}_t \cdot \vec{p}_{jet})^{0.5}}$$

→ is **b-jet initiated** by **b** or **$\bar{b}$** quark ?



Corrections

- → one can obtain **$b\bar{b}$ fraction** from the rate at which light jets are b-tagged
- → per event **charge confusion** derived from difference between the 2 quantized jet charges
- → **background asymmetry** estimated using data sideband
- → **$m_{b\bar{b}}$ response matrix:**



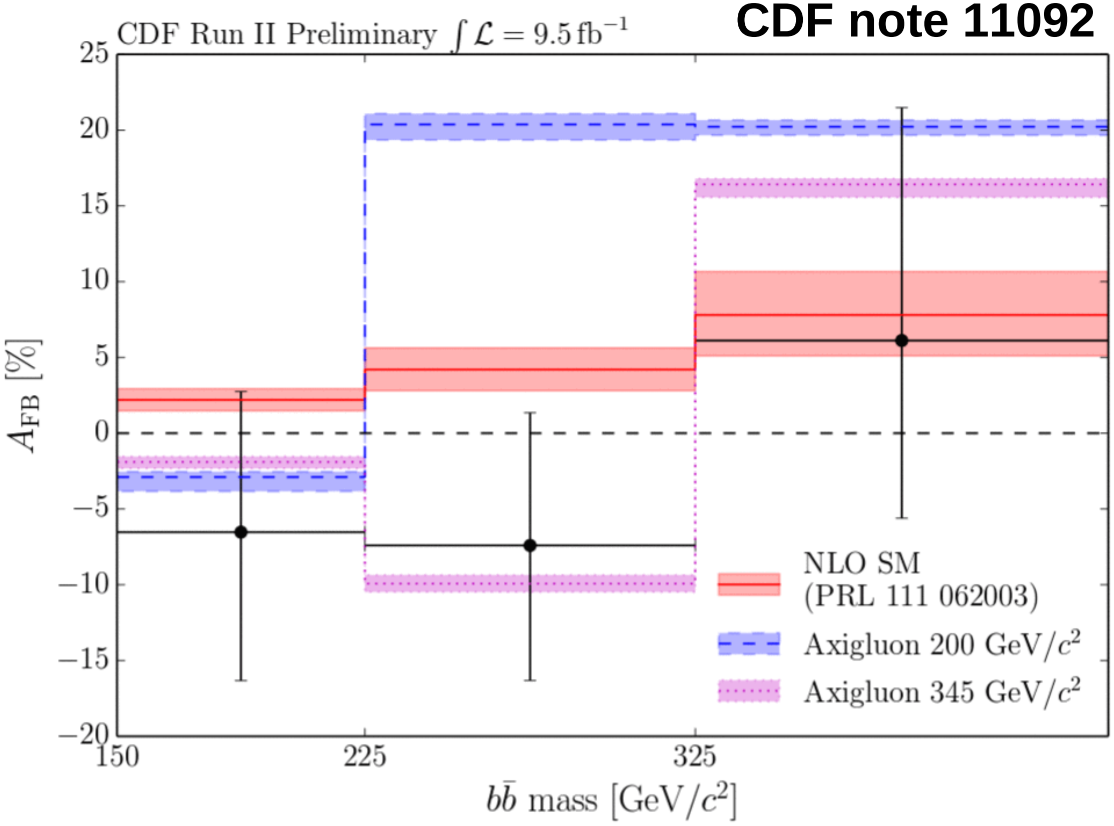
$b\bar{b}$ asymmetry at high mass (III)

Result:

→ We use a **Bayesian technique** to **extract** the **hadron-jet level result.**

→ A formula is used to relate the background asymmetry, charge confusion rate, $b\bar{b}$ fraction, mass smearing, and signal asymmetry

CDF note 11092



→ **Consistent** with **zero**, the **SM**, and the **345 GeV axigluon model.**

→ **200 GeV axigluon model** is **inconsistent** with the measurement **at more than 95%**

Conclusions

→ the measurements are mostly in agreement with SM prediction

→ CDF see higher production asymmetry in both $t\bar{t}$ inclusive and lepton-based measurements

→ D0 data compatible with SM prediction and also with CDF results

→ First measurement of bottom forward-backward asymmetry at high mass presents consistency with both zero and with the SM predictions

Plans

→Tevatron combination of production asymmetry results is on the table

→Bottom forward-backward asymmetry measurement at low mass

Thank you!

Back up slides

$t\bar{t}$ forward-backward asymmetry

→ **CDF Results:**

PRD 87, 092002 (2013)

TABLE V. Systematic uncertainties on the parton-level A_{FB} measurement.

Source	Uncertainty
Background shape	0.018
Background normalization	0.013
Parton shower	0.010
Jet energy scale	0.007
Initial- and final-state radiation	0.005
Correction procedure	0.004
Color reconnection	0.001
Parton-distribution functions	0.001
Total systematic uncertainty	0.026
Statistical uncertainty	0.039
Total uncertainty	0.047

→ **D0 results**

ArXiv:1405.0421, submitted to PRD

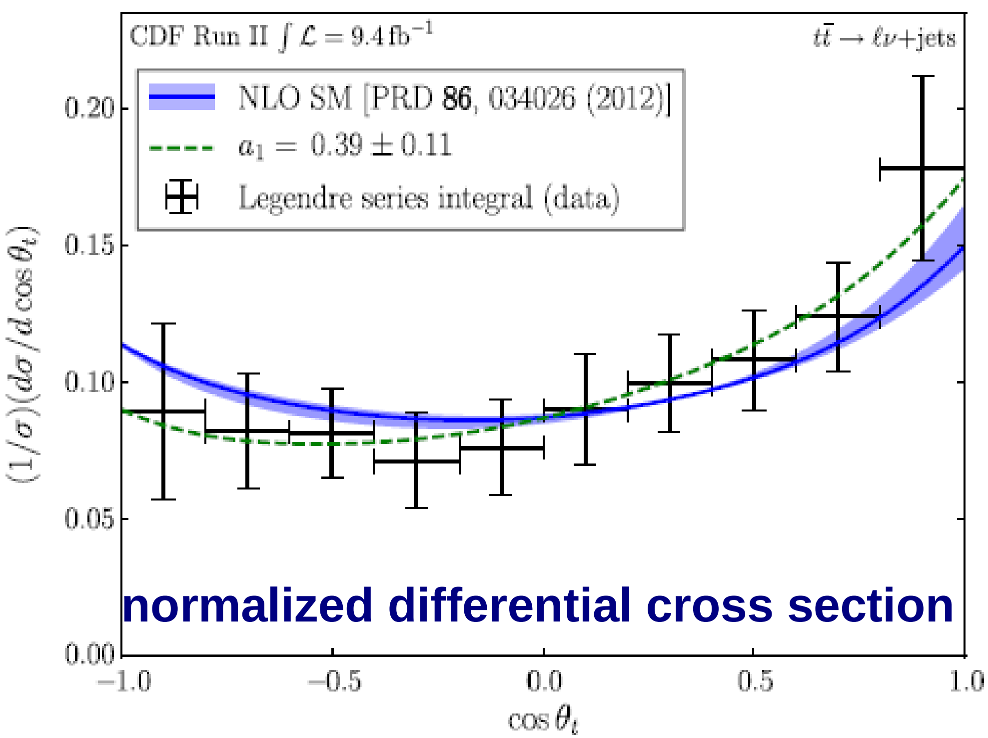
Systematic uncertainties in absolute %

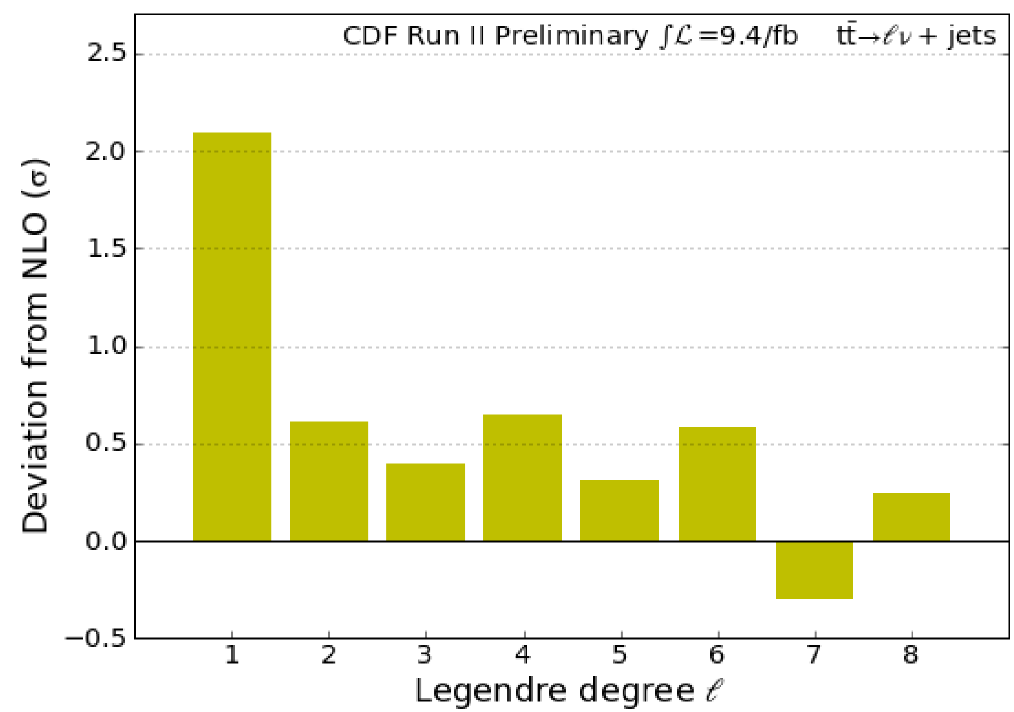
Source	Reco. level inclusive	Production level inclusive	Production level 2D
Background model	+0.7/−0.8	1.0	1.1–2.8
Signal model	< 0.1	0.5	0.8–5.2
Unfolding	N/A	0.5	0.9–1.9
PDFs and pileup	0.3	0.4	0.5–2.9
Detector model	+0.1/−0.3	0.3	0.4–3.3
Sample composition	< 0.1	< 0.1	< 0.1
Total	+0.8/−0.9	1.3	2.1–7.5

Differential $t\bar{t}$ cross sections

An s-channel model "Octet A" hypothesizes the existence of a heavy ($m_{G'}$ = 2 TeV) partner of the gluon with axial-vector couplings to quarks.
This produces an enhanced linear-term coefficient a1 in $d\sigma = d(\cos\theta_t)$.

A t-channel model "Z' 200'" contains a new, heavy ($m_{Z'}$ 200 GeV) vector boson with a flavor changing u-Z'-t coupling. The resulting additional term in the cross section has a leading dependence $\hat{s}/\hat{t} = 1/(1-\cos\theta_T)$ where $\hat{t}$ is the Mandelstam variable. This behavior produces large Legendre moments at all degrees.





Differential $t\bar{t}$ cross sections

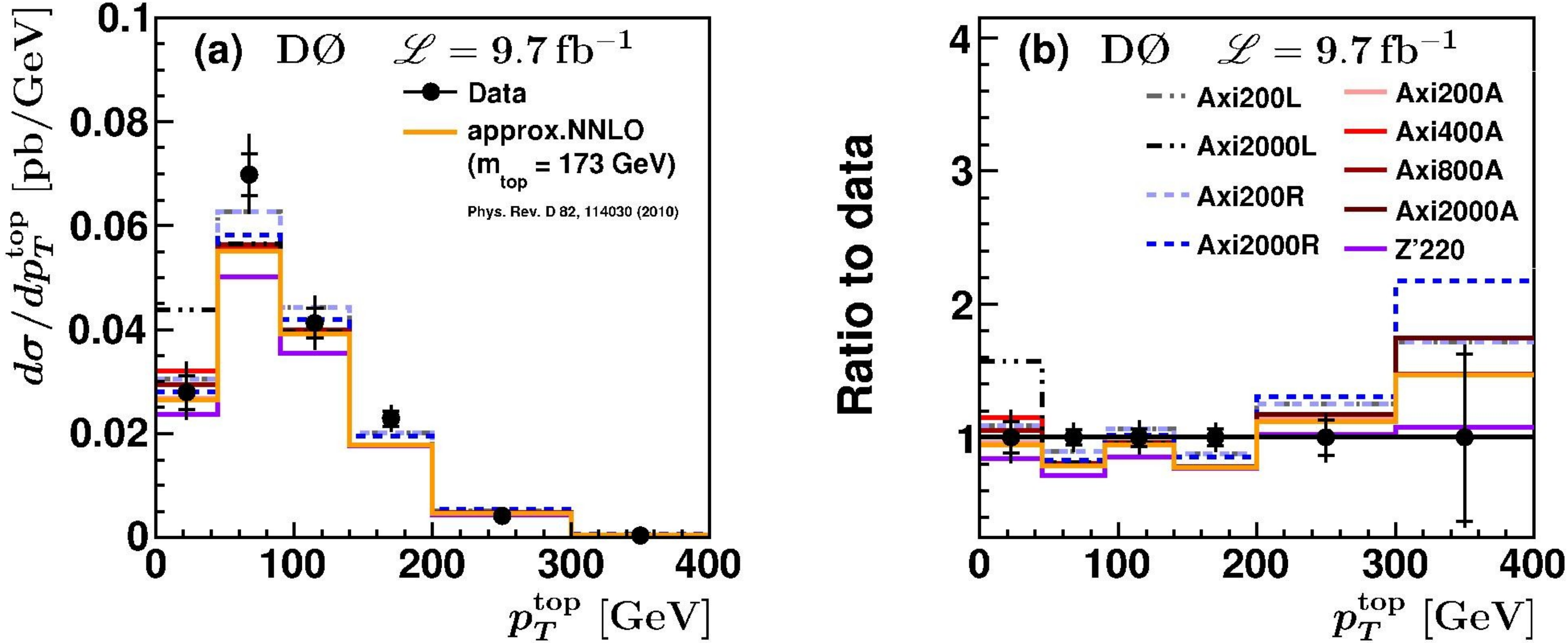


Table slide 8: The χ^2 values take into account the full covariance matrix and are calculated according to $\chi^2 = \sum_{i,j}(y-\mu)_i \cdot \mathrm{cov}_{i,j}^{-1} \cdot (y-\mu)_j$, where y is the measured value per bin, μ is the expected value of a particular model per bin and cov is the covariance matrix of the differential cross section measurement.

Lepton based asymmetry

PRD 88, 072003 (2013)

l+jets, single-lepton asymmetry

Source of uncertainty	Value
Backgrounds	0.015
Recoil modeling	+0.013 −0.000
Color reconnection	0.0067
Parton showering	0.0027
Parton distribution functions	0.0025
Jet-energy scales	0.0022
Initial- and final-state radiation	0.0018
Total systematic	+0.022 −0.017
Data sample size	0.024
Total uncertainty	+0.032 −0.029

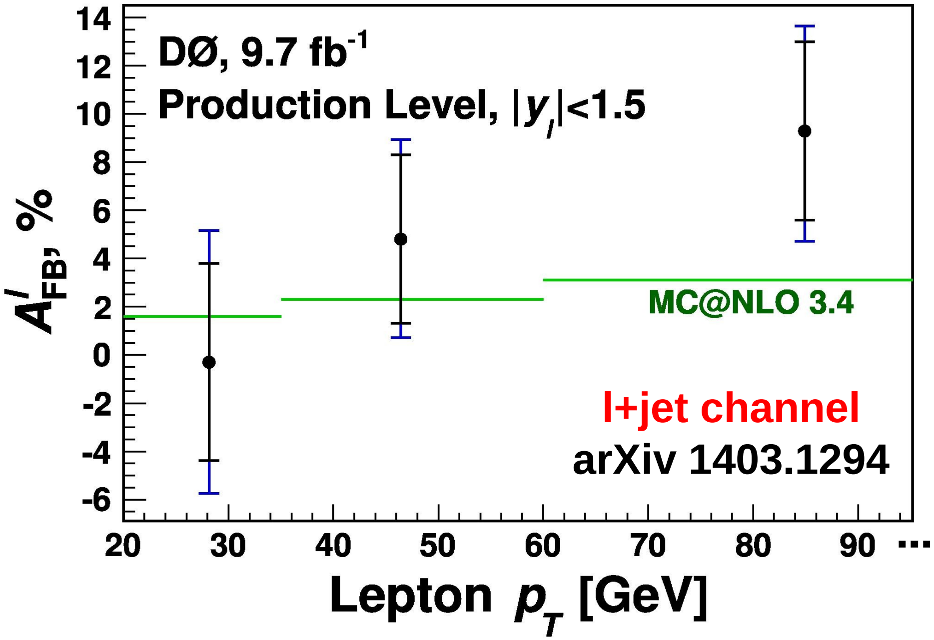
PRL 113, 042001 (2014)

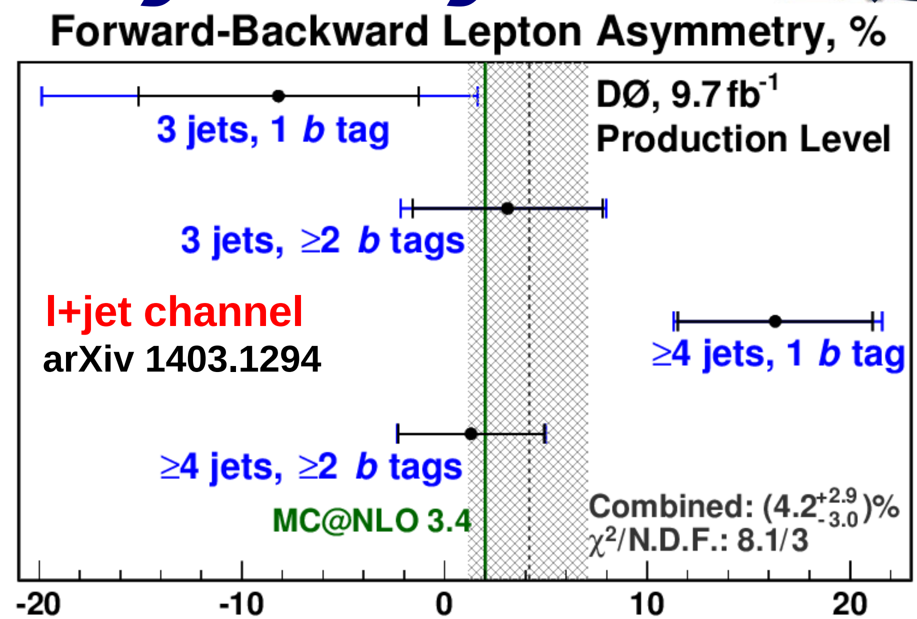
single-lepton asymmetry
l+jets + dilepton combination

CDF Run II Preliminary

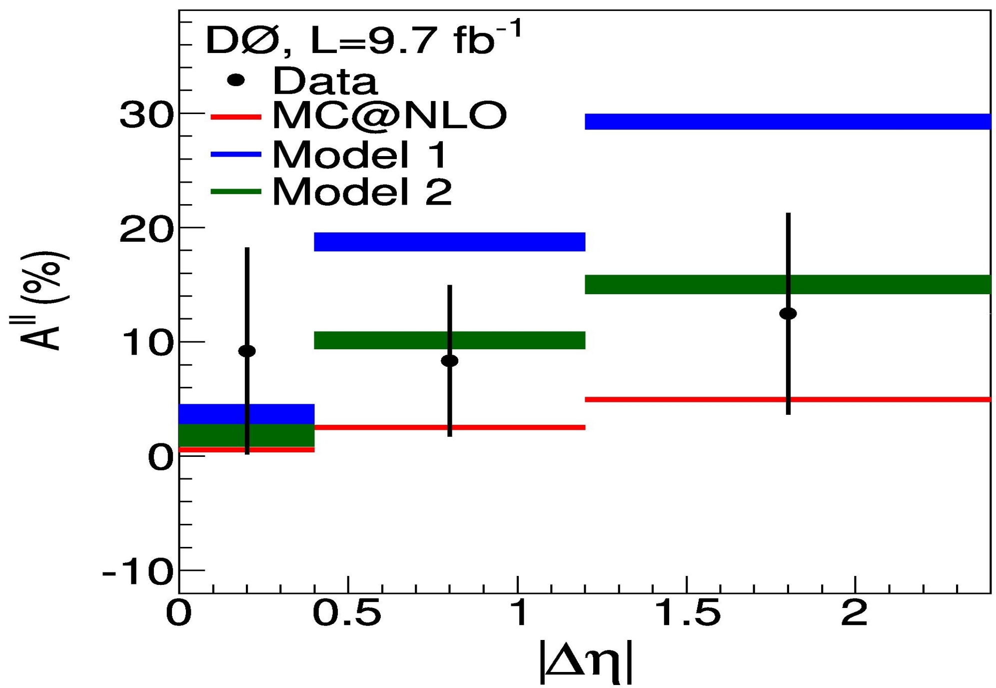
Source of uncertainty	L+J ($9.4\mathrm{fb}^{-1}$)	DIL ($9.1\mathrm{fb}^{-1}$)	Correlation
Backgrounds	0.015	0.029	0
Recoil modeling (Asymmetric modeling)	+0.013 −0.000	0.006	1
Symmetric modeling	-	0.001	
Color reconnection	0.0067	-	
Parton showering	0.0027	-	
PDF	0.0025	-	
JES	0.0022	0.004	1
IFSR	0.0018	-	
Total systematic	+0.022 −0.017	0.030	
Statistics	0.024	0.052	0
Total uncertainty	+0.032 −0.029	0.060	

Lepton based asymmetry



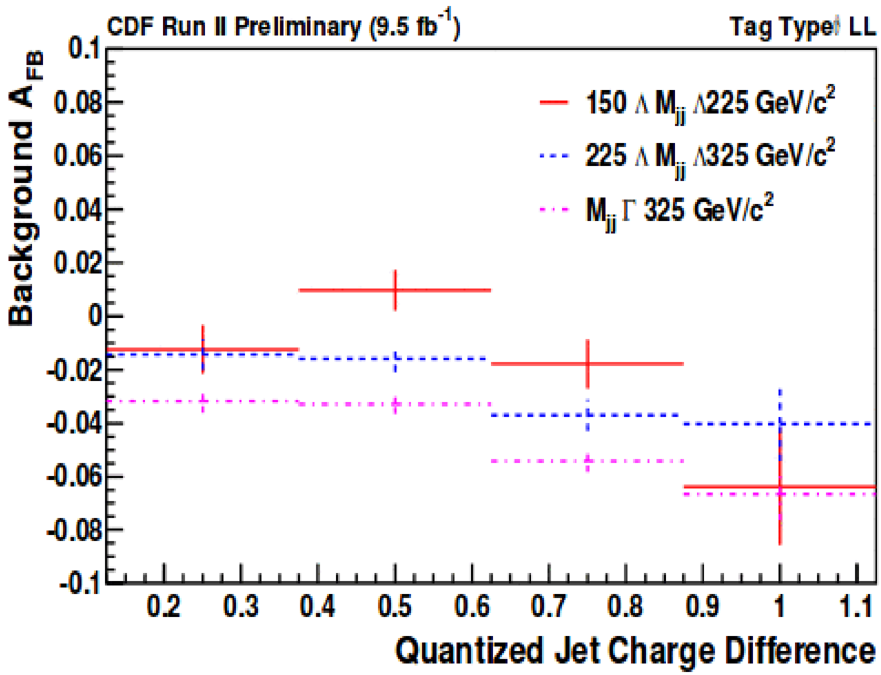


dilepton channel (PRD 88, 112002 (2013))



$\bar{b}b$ asymmetry at high mass

→ **background asymmetry** estimated using data sideband



Result: