Properties of the top quark

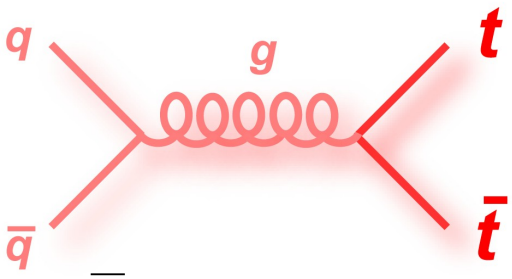
- **(Introduction)**
- **Charge,** Width & Spin correlations
- **Production Asymmetries & extras**
- **Conclusions & Outlook**

Andreas Jung (Fermilab) for the CDF and DØ collaboration

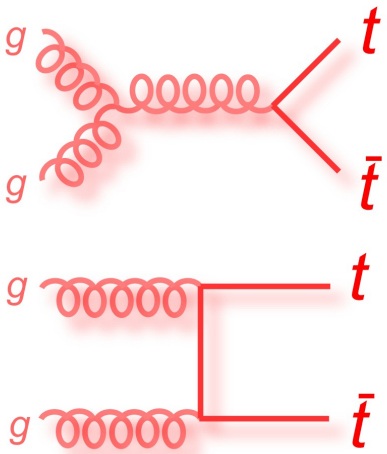
Top quark introduction

- Top is the heaviest fundamental particle discovered so far:
  → m_t = **174.3 ± 0.8 GeV** [arxiv:1407.2682]
- Top plays special role in EWSB ?
  → λ_t = **0.995 ± 0.005** (indirect)
- Lifetime: $\tau \approx 5\text{x}10^{-25}$ s << Λ_{QCD}
  → **Observe bare quark**

- Strong interaction: Top pairs



$q\bar{q}$ annihilation



gg fusion

Tevatron vs. LHC:

	(1.96 TeV	7/8 TeV)
$q\bar{q}$:	~85%	~15/13% (~10%, 14 TeV)
gg:	~15%	~85/87% (~90%, 14 TeV)

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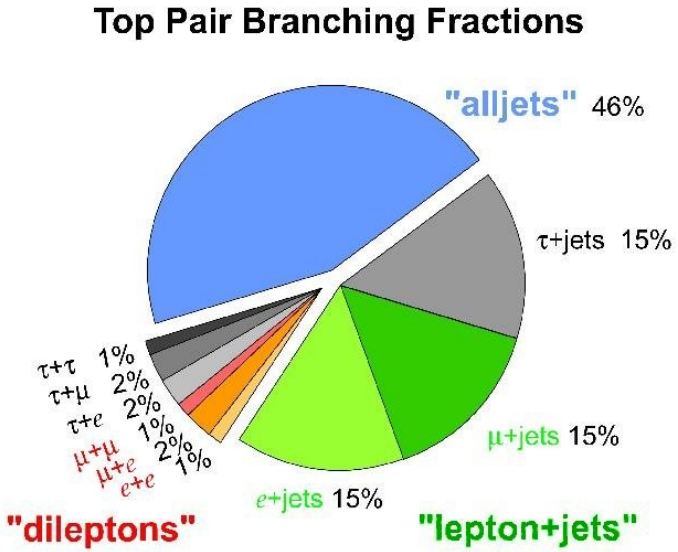
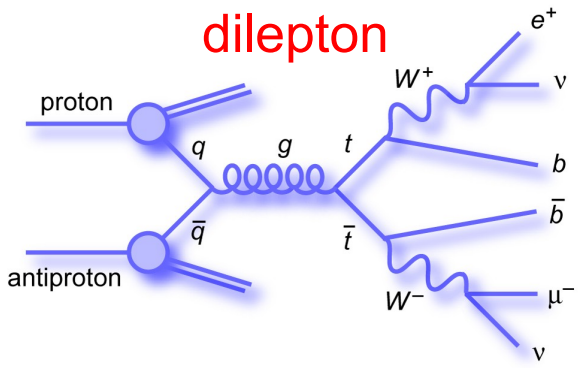
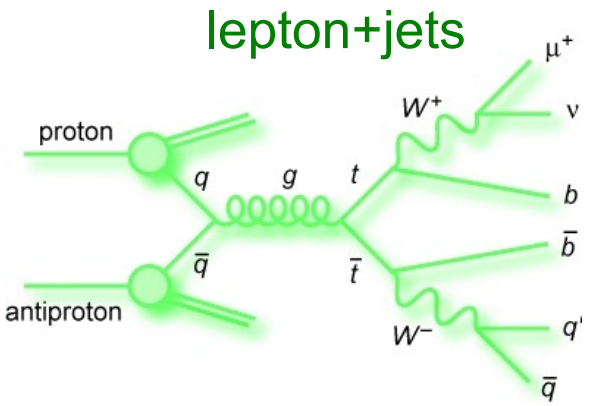
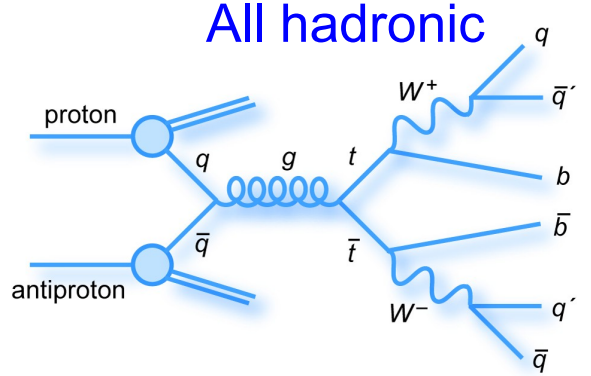
- Different decay channels:





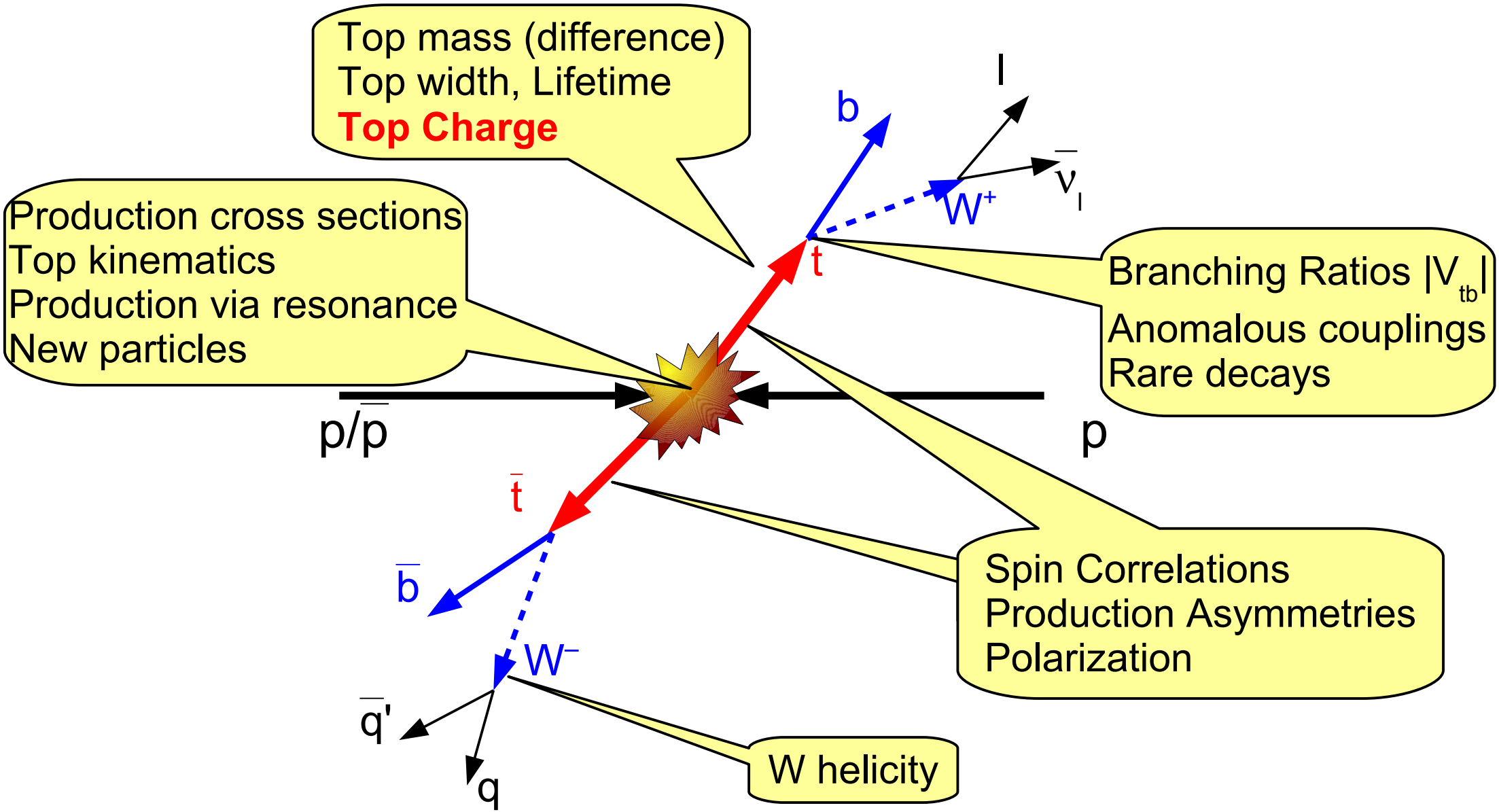




BR, bg increase

BR, bg decrease

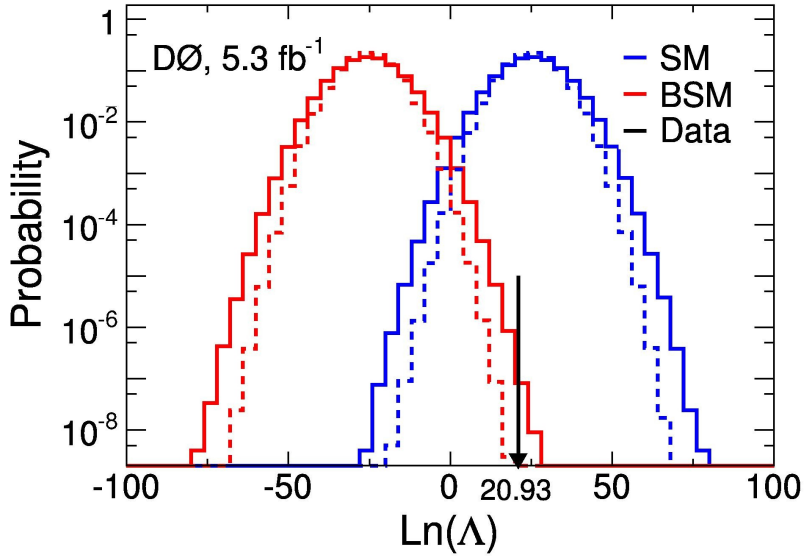
Content



→ Mass measurements at the Tevatron, see S.Sharyy
→ 2 Posters on production of top quarks, see J.Franc, J.Lim

Top charge

- Fully reconstruct top pairs in lepton+jets decay channel
- Identify *b*-jet charge by jet charge algorithm
- Exclude -4/3 hypothesis with 5 s.d.

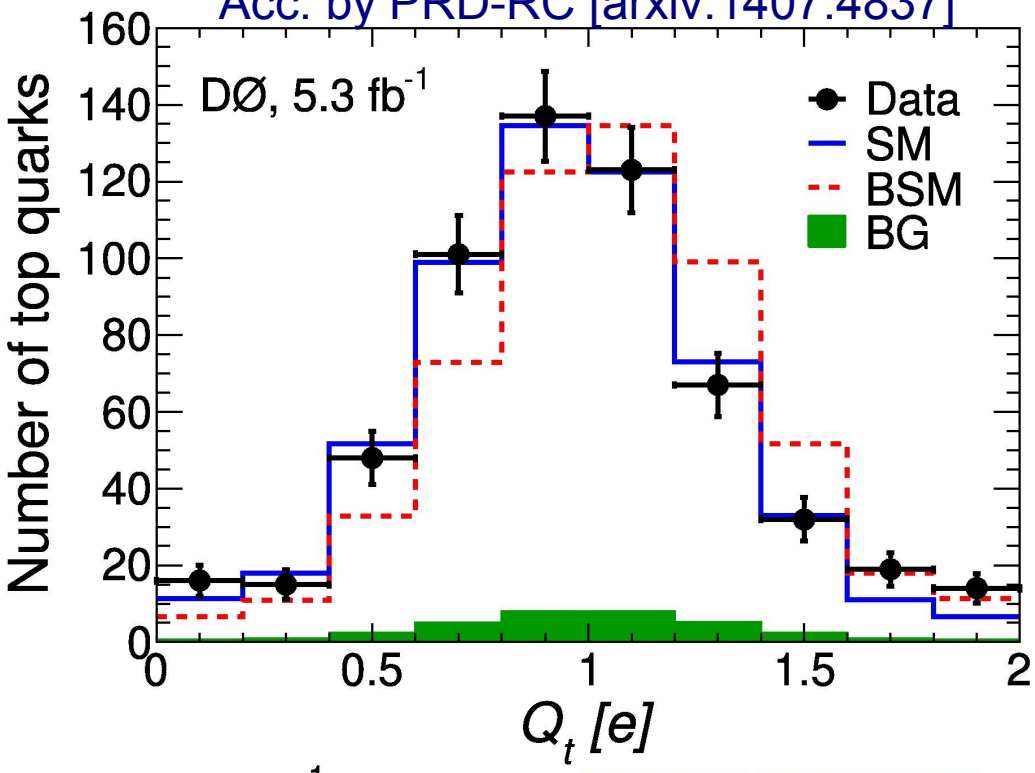


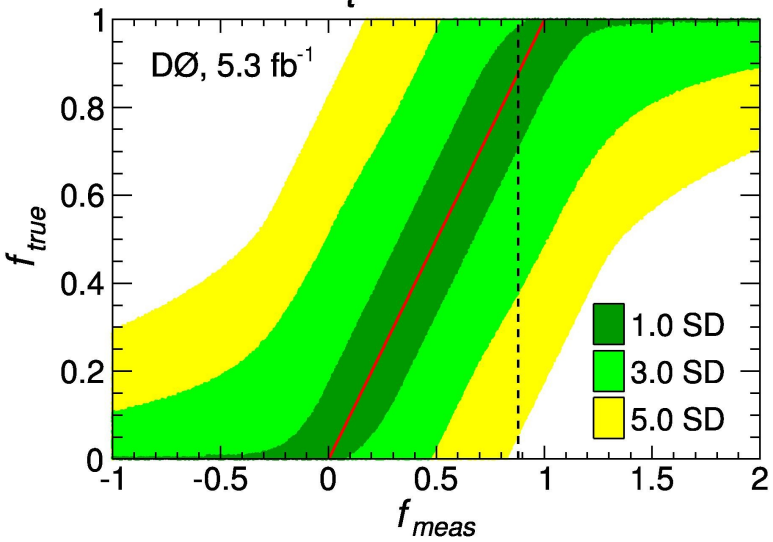
- Fraction of BSM quarks

→ $F_{BSM} < 0.46$ @ 95% C.L.

- Confirmed earlier measurements

Acc. by PRD-RC [arxiv:1407.4837]





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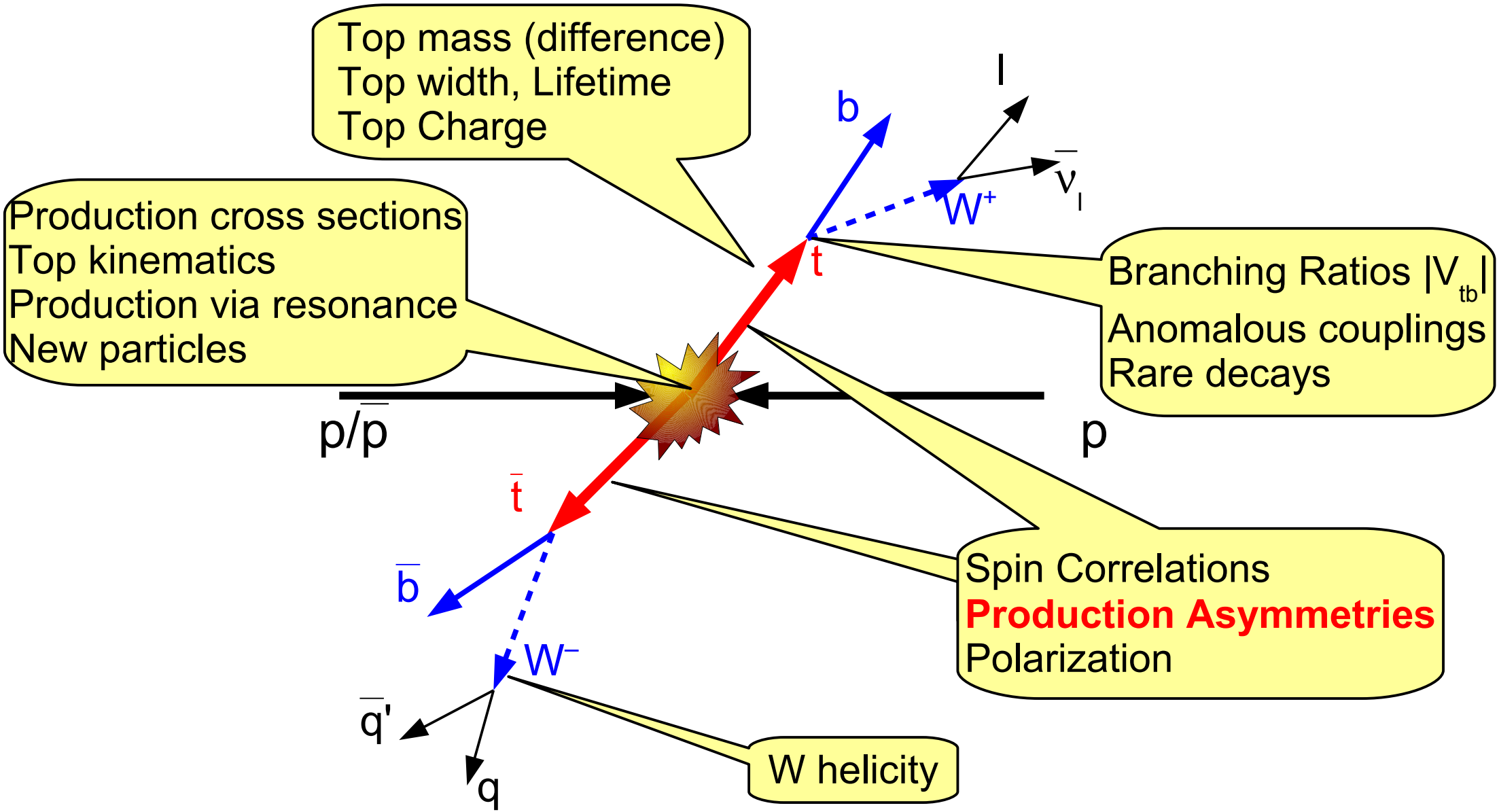
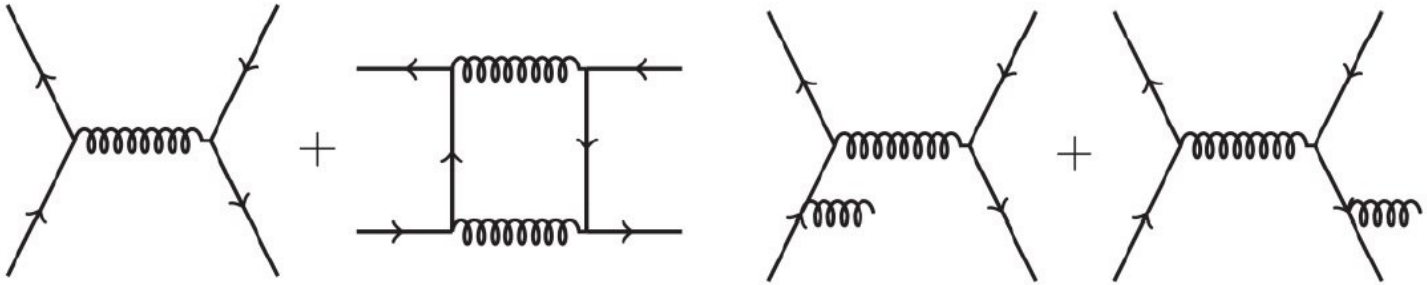

Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays
Spin Correlations
Production Asymmetries
Polarization
W helicity
p/p̄
p
b
l
ν̄l
W+
t
t̄
b̄
W−
q̄'
q

Top quark asymmetries

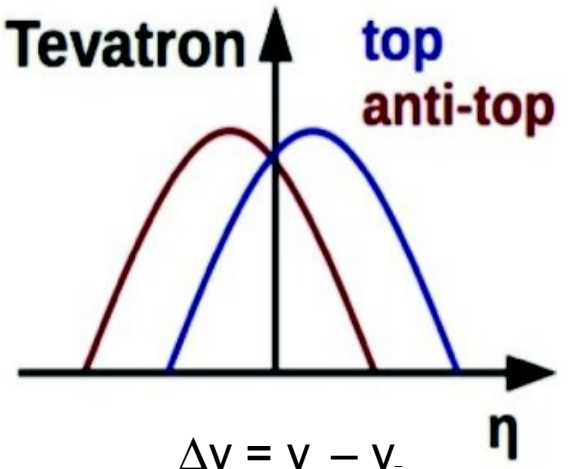
- Interference appears at NLO QCD:



Positive asymmetry Negative asymmetry

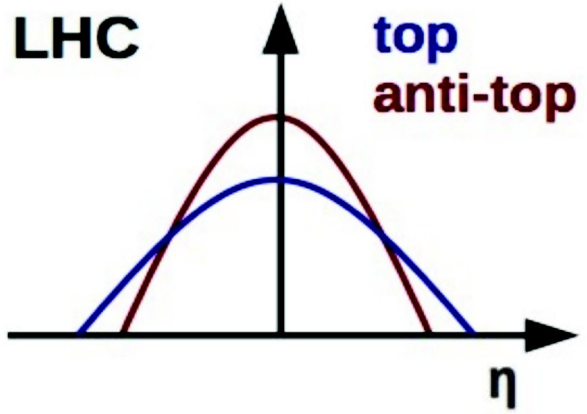
→ Only occurs in $q\bar{q}$ initial state; gg is fwd-bwd symmetric

- This is a forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → $\bar{t}$ more central



$\Delta y = y_t - y_{\bar{t}}$

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



$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

Top quark asymmetries

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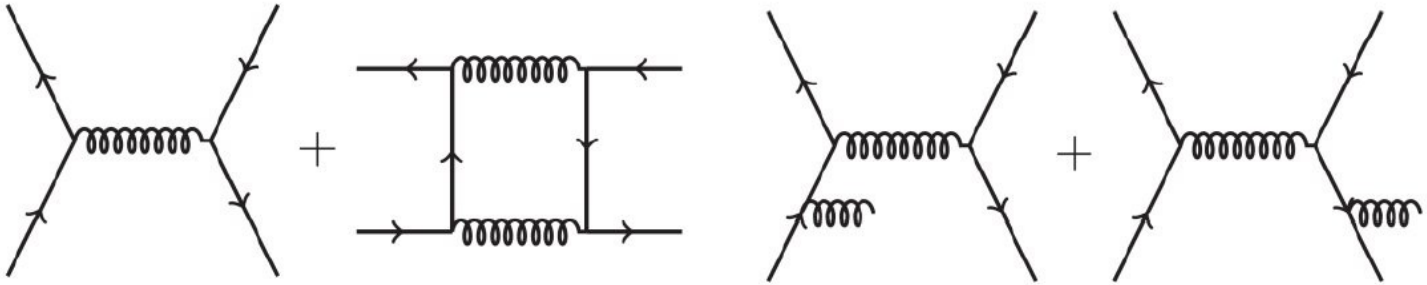

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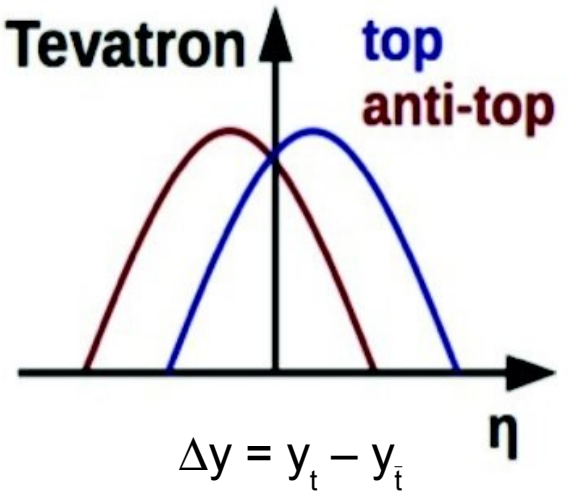

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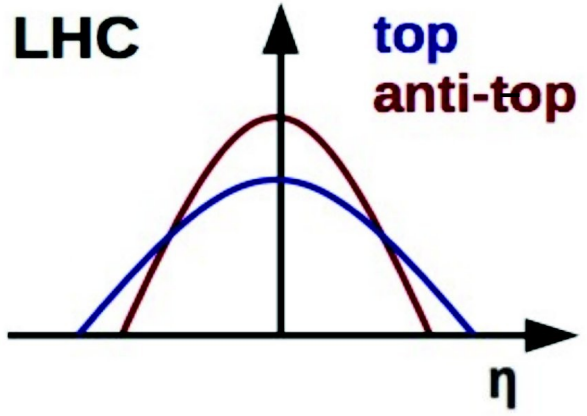
$$A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- SM predictions at NLO (QCD+EWK)

→ Tevatron: $\mathbf{A_{FB} \sim 8\text{-}9\ \%}$ vs. LHC: $\mathbf{A_C \sim 1\ \%}$

→ **Update: 10% at NNLO+NNLL**

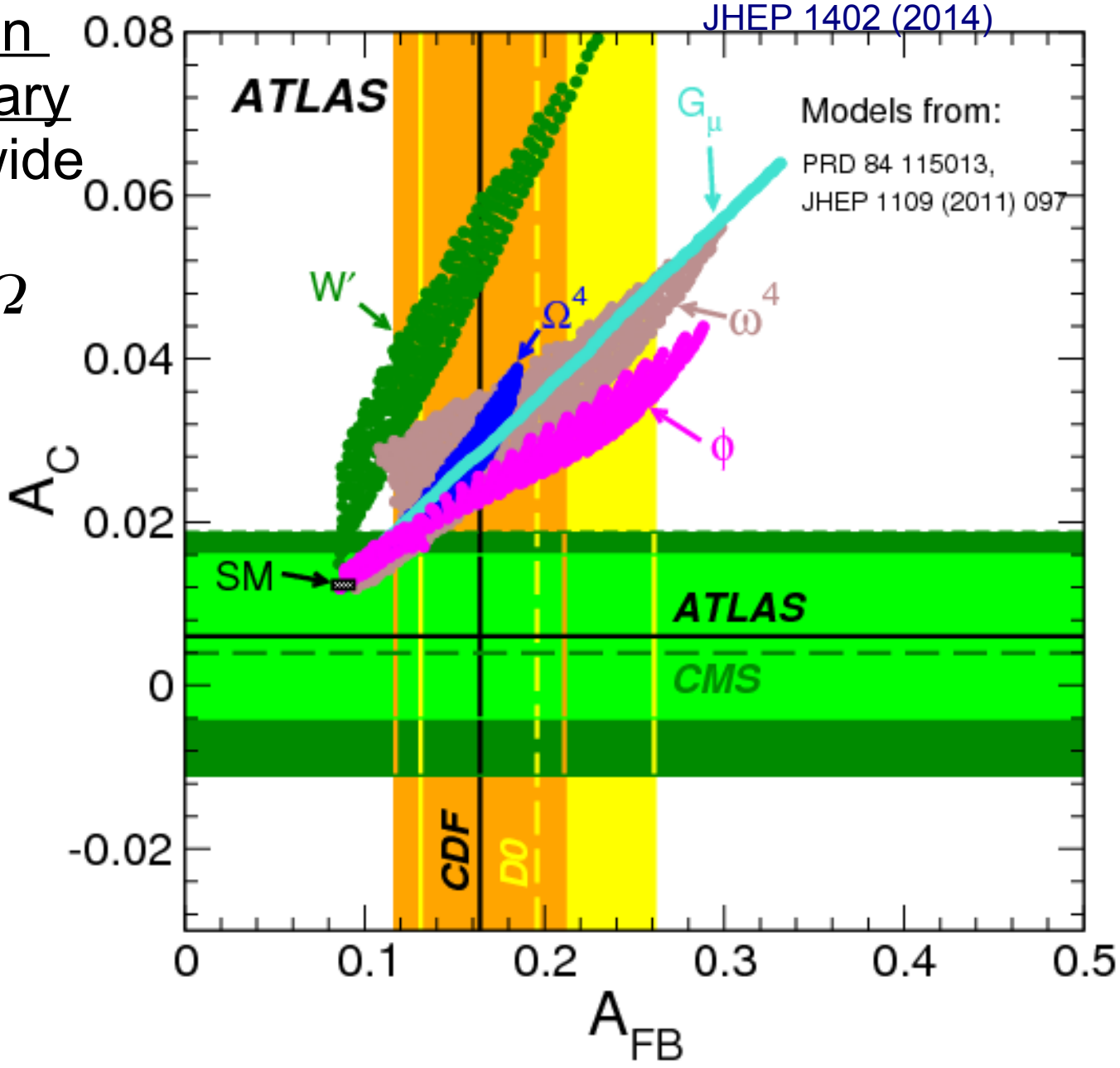


- Experimentally: Asymmetries based on decay leptons or fully reconstructed top quarks "easier" "harder"

$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

Complementarity

- Measurements at Tevatron & LHC are complementary
  - Variety of models with wide parameter space still allowed → *W′, G, ω, φ, Ω*

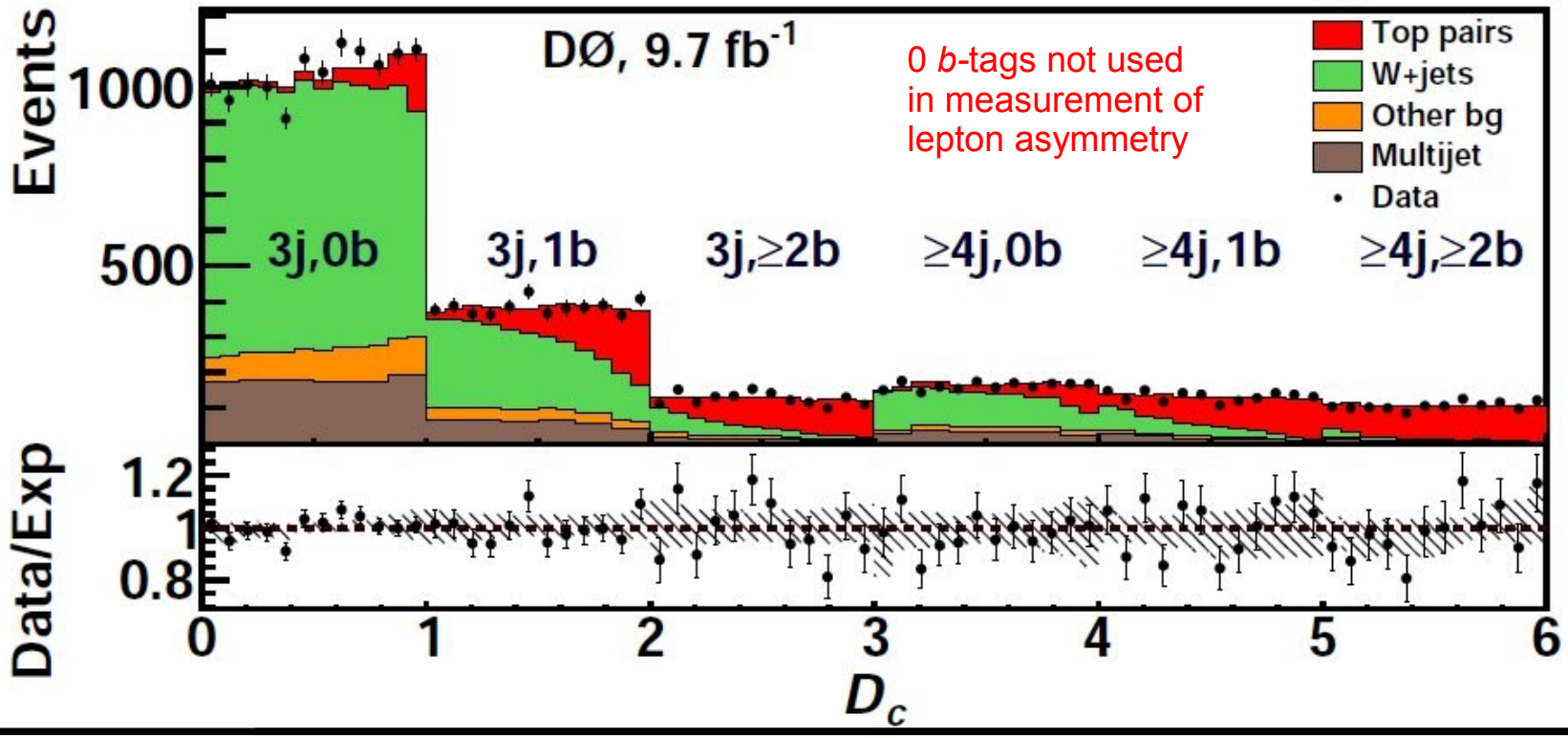


Lepton asymmetries

Acc. by PRD:
[arxiv:1403:1294]

Leptonic asymmetries less affected by reconstruction effects:

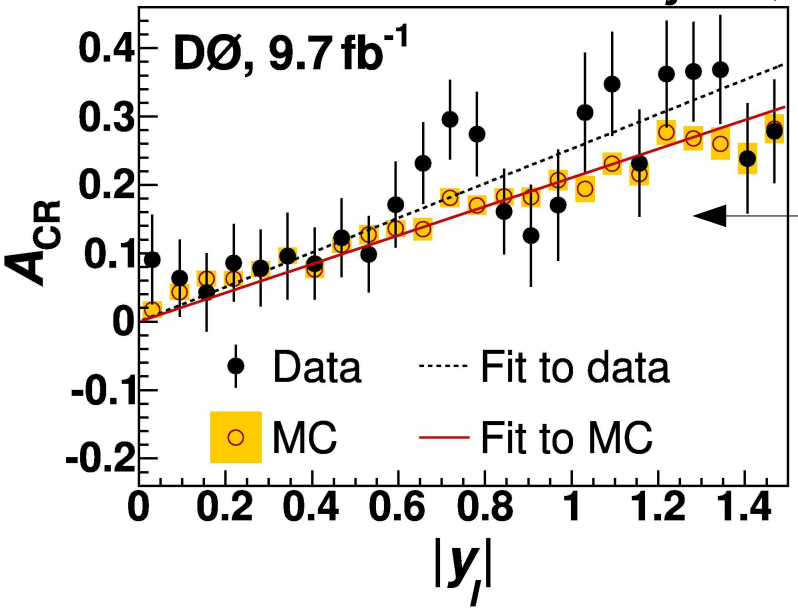
- lepton+jets, full Run II data set, **Final measurements**
  → Maximize acceptance & precision: Include the 3 jet bin
  - Larger contribution of backgrounds in 3 jet bin
    → need to calibrate W+jets, use 0 *b*-tag
    → Improved background rejection and modeling
  - Discriminant D_c to determine sample composition

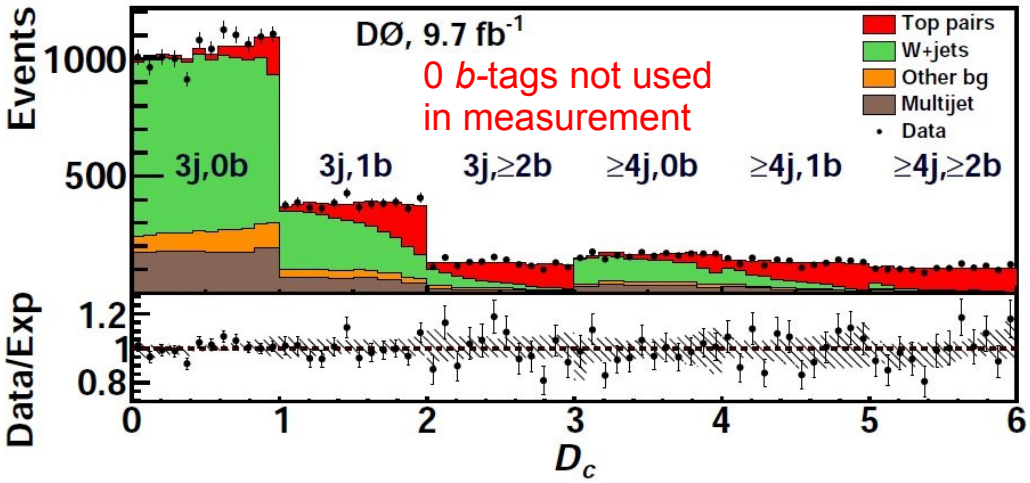


Lepton asymmetries

Acc. by PRD:
[arxiv:1403:1294]

- lepton+jets, updated measurement of leptonic asymmetries
- Discriminant D_c to determine sample composition
- Need to calibrate W+jets, use 0 *b*-tag



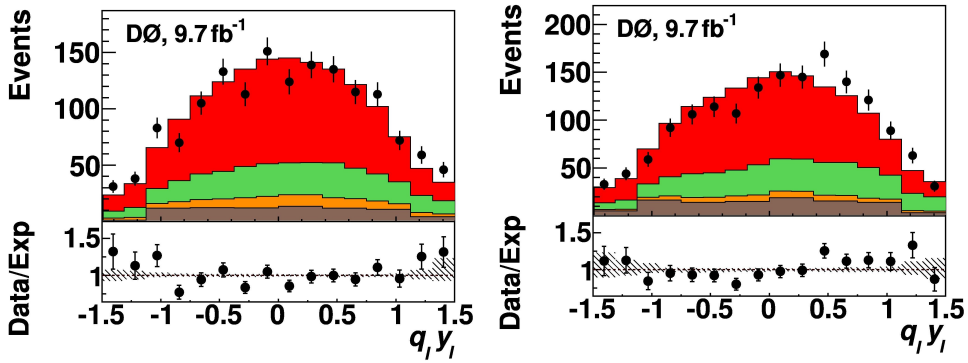


- Asymmetry in W+jets control region (CR) different from MC
- PDF uncertainty shown by yellow bars
- Full difference between data and MC slope taken as systematic uncertainty

Lepton asymmetries

Acc. by PRD: [arxiv:1403:1294]

- lepton+jets, updated measurement of leptonic asymmetries
- Discriminant D_c to determine sample composition



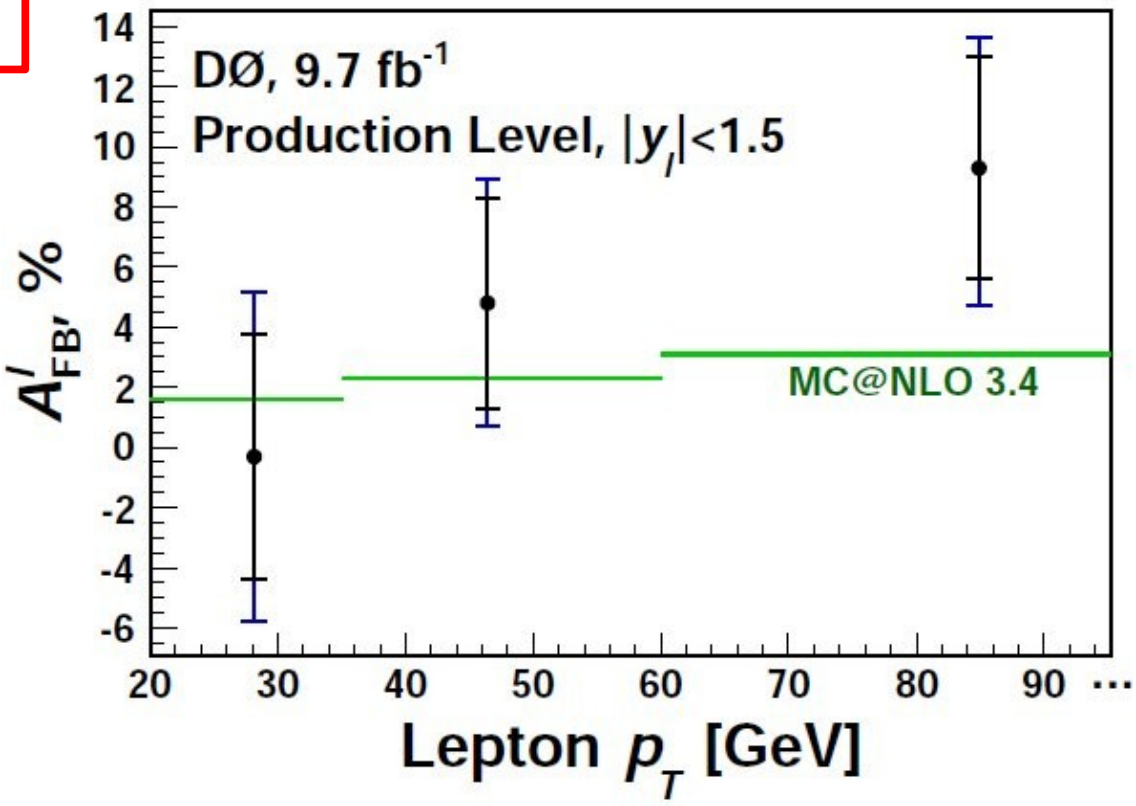
In agreement with SM:

$$A_l = 4.2 \pm 2.3\ (\text{stat.}) \pm^{1.7}_{2.0}\ (\text{syst})$$

MC@NLO: 2%

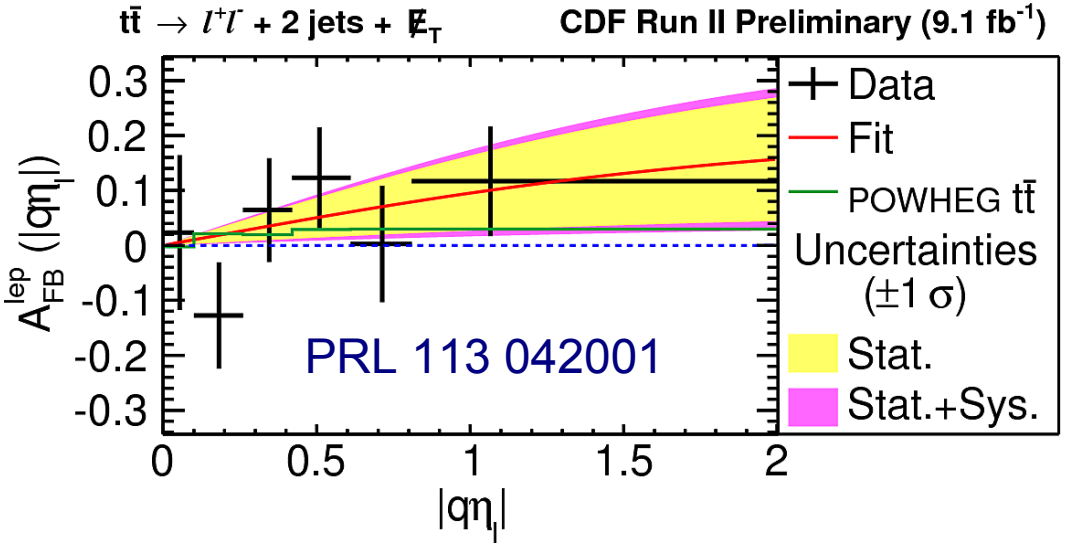
- **Differential measurement** of the leptonic asymmetry
  - A_l affected by polarization

A. Falkowski, M. L. Mangano, A.Martin, G. Perez, and J. Winter, Phys. Rev. D 87, 034039 (2013)



Lepton asymmetries

- Update in dilepton decay channel by CDF employing 9.1/fb

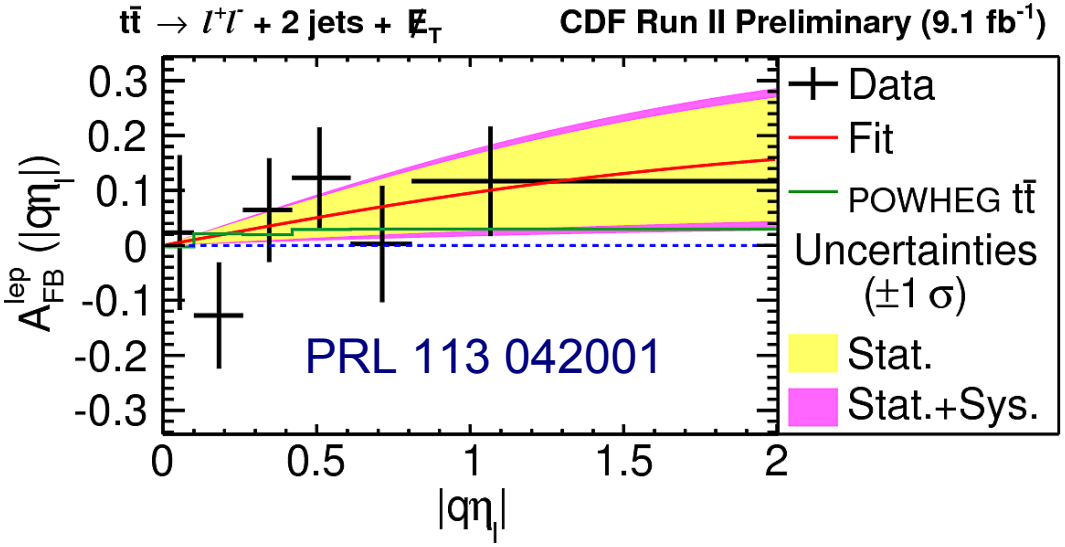


→ A_l = 7.2 ± 6.0 (tot.) %

Combined A_l = $9.0 \pm {}^{2.8}_{2.6}$ (tot.) %

Lepton asymmetries

- Update in dilepton decay channel by CDF employing 9.1/fb



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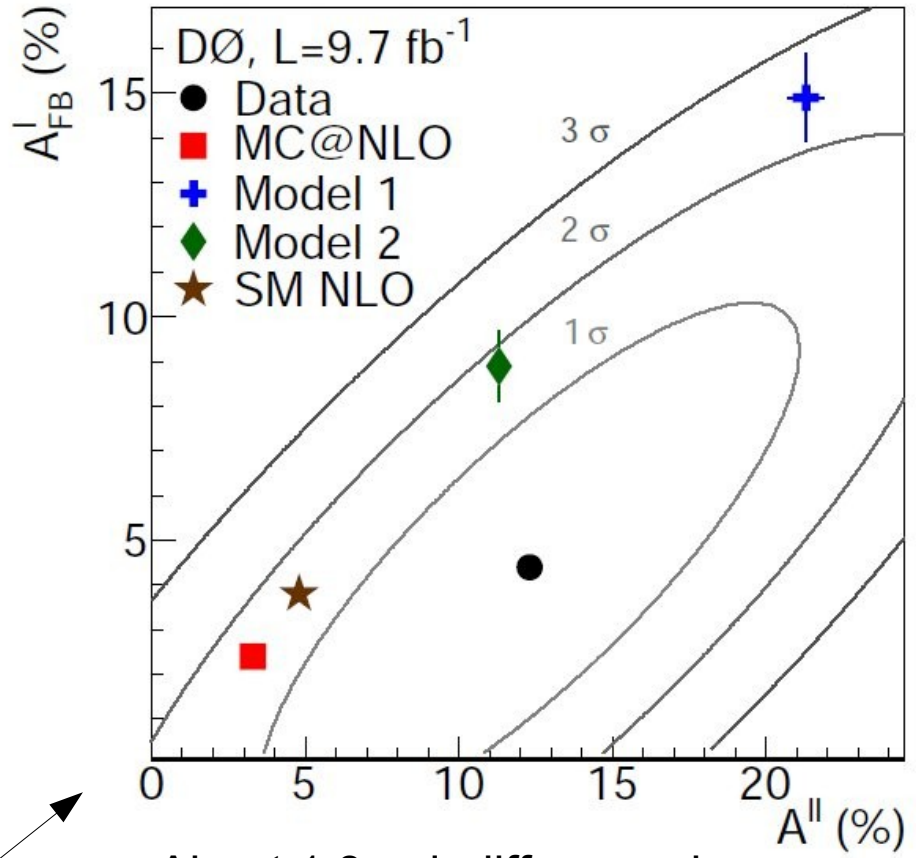


About 1.8 s.d. difference in the ratio A_l/A_{ll} to the SM

Updated D0 measurement:

- Agrees with NLO SM
- In agreement with CDF
- $|\eta| < 1.5$

PRD 88, 112002 (2013)

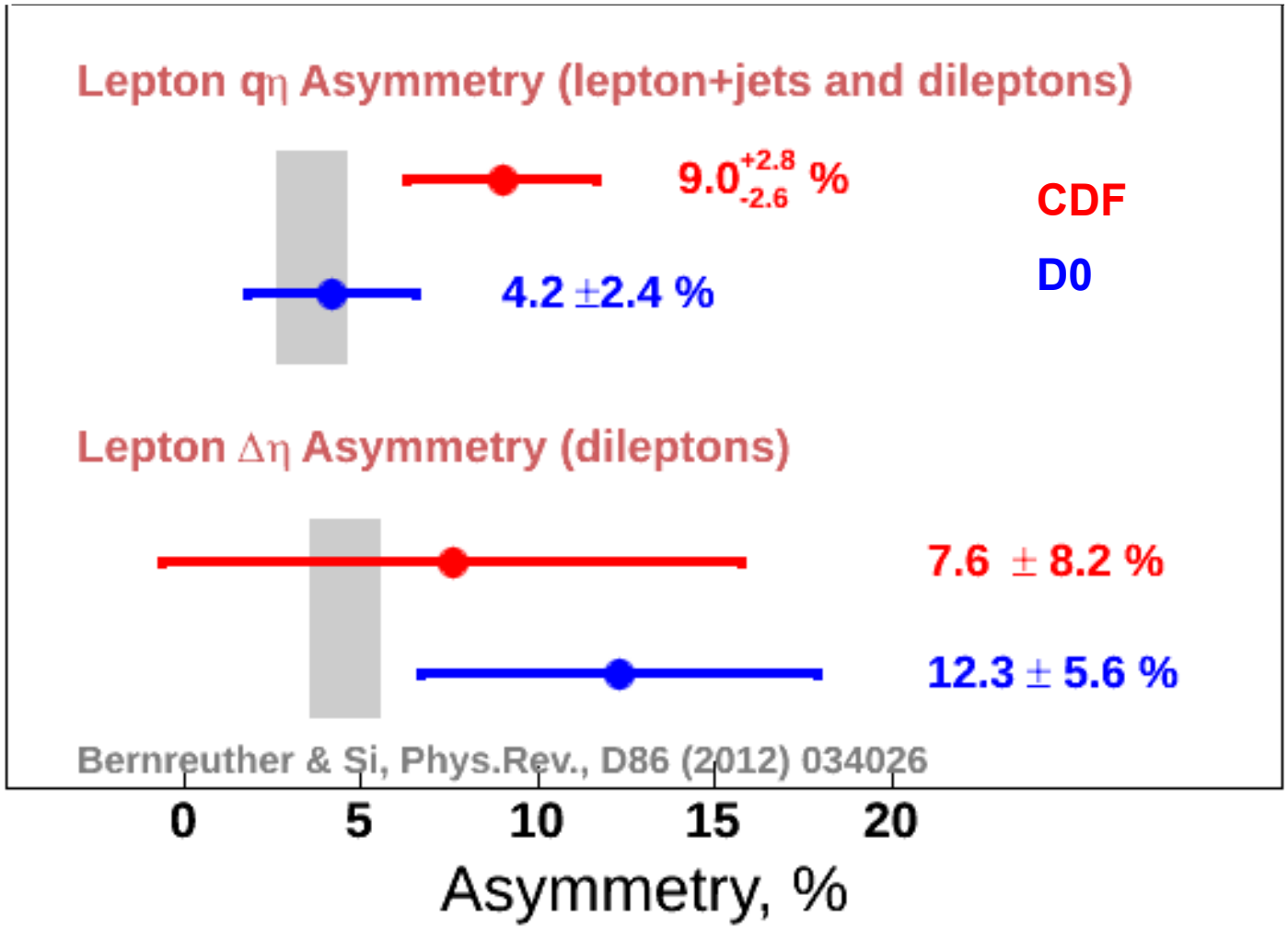
→ A_l = 4.4 ± 3.7 (stat.) ± 1.1 (syst) %
A_{ll} = 12.3 ± 5.4 (stat.) ± 1.5 (syst.) %

D0 combination:

→ A_l = 4.2 ± 2.0 (stat.) ± 1.4 (sys.) %

Lepton asymmetries

- All use full data set, D0 + CDF combinations to come



Top quark asymmetries

- Lots of effort went into maximizing expected significance:
  - → Understand & Improve systematic uncertainties
  - → Increase available sample size
    - Full Run II expected statistical uncertainty 4.6%, need 3% for 5 s.d. significance (given central value does not move) → Can we get to 3% ?

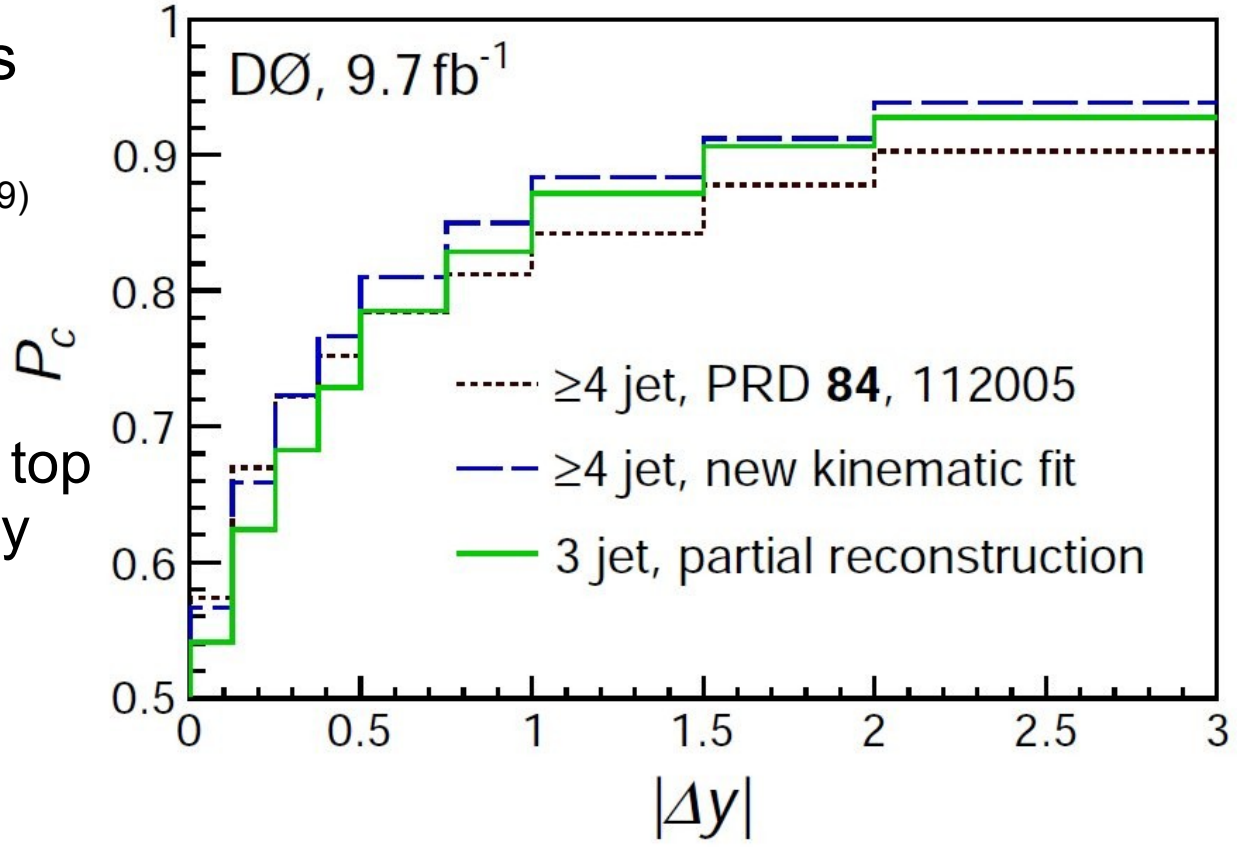
New kinematic fit:

- Flavor dependent transfer fcts
- Analytical solution for p(ν)
  (Betchart, Demina, Harel NIM A 736 (2014) 169)

Partial $t\bar{t}$ reconstruction:

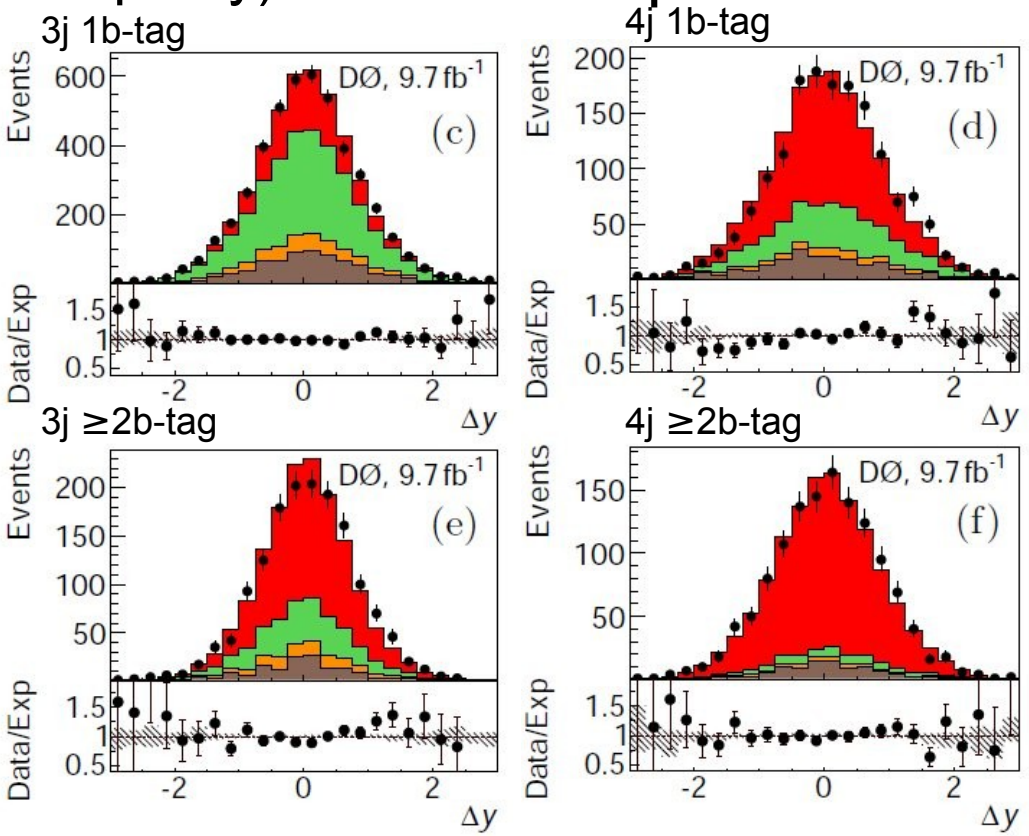
- Lost jet is in 80% from hadronic top
- Construct a likelihood & correctly reconstruct sign of Δy:

→ P_C (≥ 4j) = 77.6 %
P_C (= 3j) = 74.5 %



Top quark asymmetries

- Shares same selection as the one for the leptonic asymmetry measurement, also employs Discriminant D_c
- Combine several channels (w different purity) & unfold to parton level
  → used modified TUnfold
  → Acc. by PRD [arxiv:1405.0421]



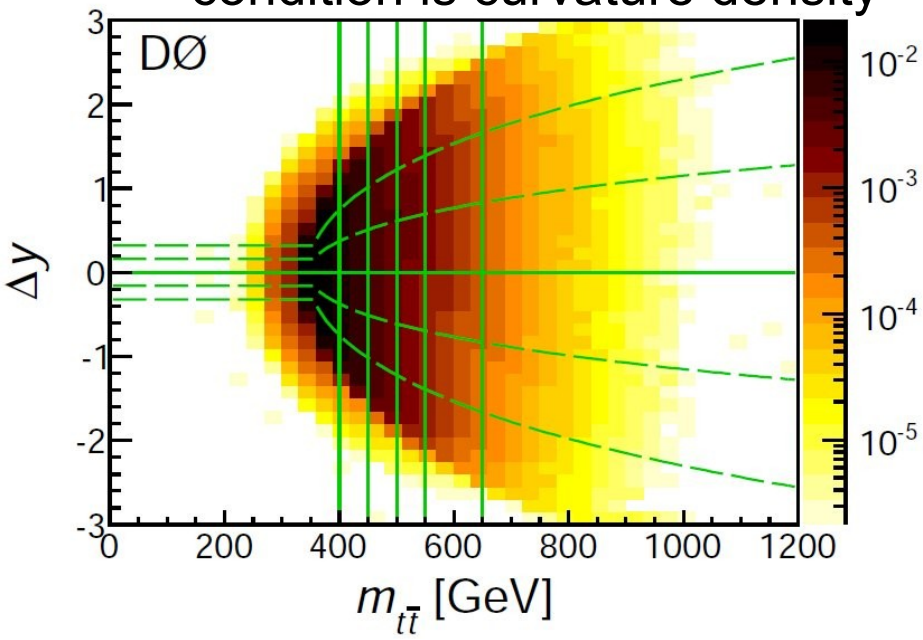
- Achieved improvement beyond luminosity scaling with 3% total uncertainty
- SM @NNLO: ~10% (Czakon, Mitov, et al.)

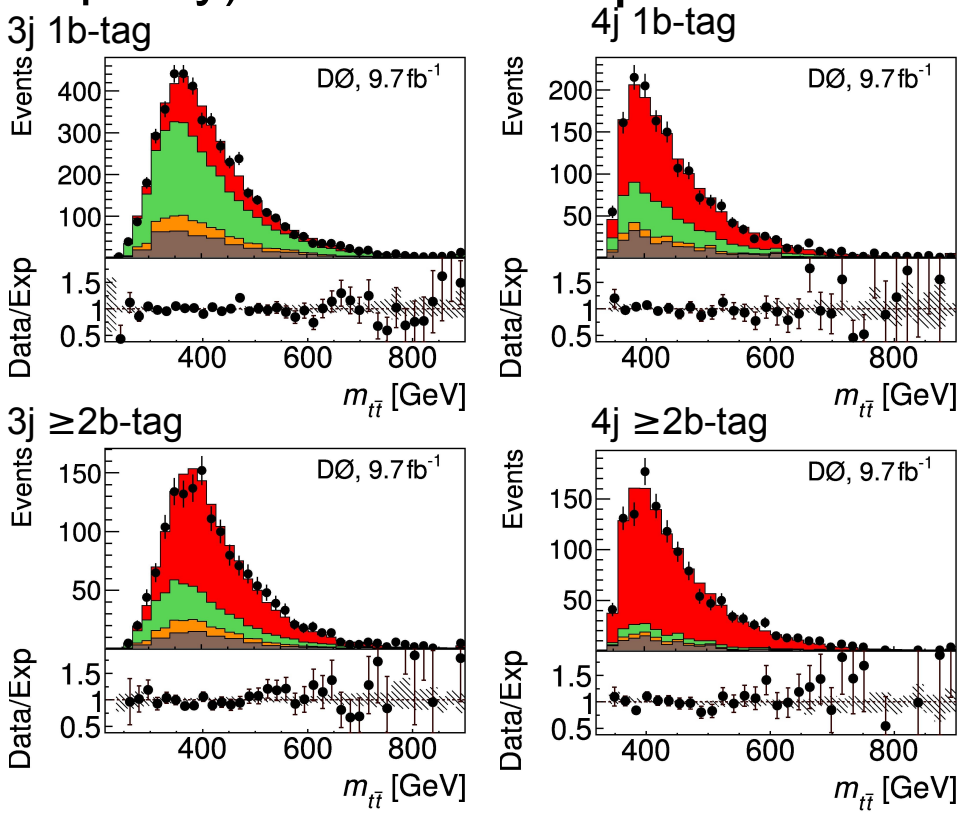
→ A_{FB} = 10.6 ± 3.0 (tot.) %
CDF: A_{FB} = 16.4 ± 4.5 (tot.) %

→ D0 agrees with SM within uncertainties
→ CDF higher than SM predictions

Top quark asymmetries

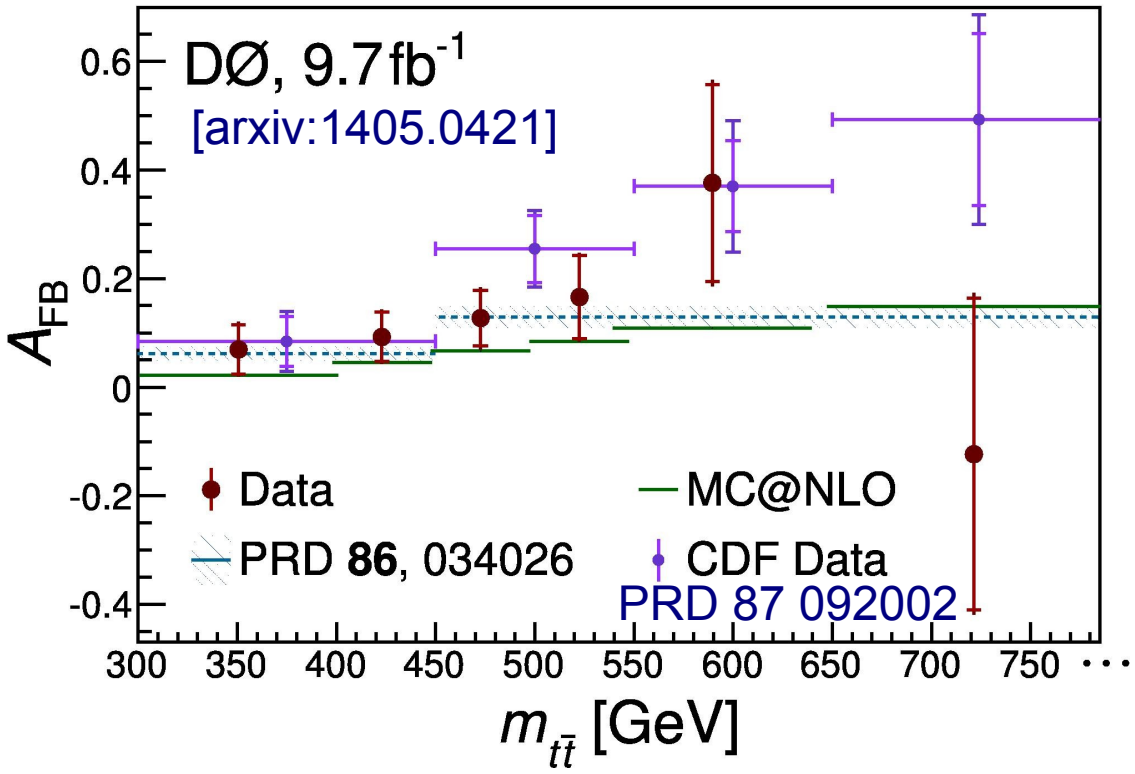
- Shares same selection as the one for the leptonic asymmetry measurement, also employs Discriminant D_c [arxiv:1405.0421]
- Combine several channels (w different purity) & unfold to parton level
  → used modified TUnfold
- $m(t\bar{t})$ dependence of A_{FB}:
  - 2D regularized unfolding
    → account for variable bin-size
    → condition is curvature density

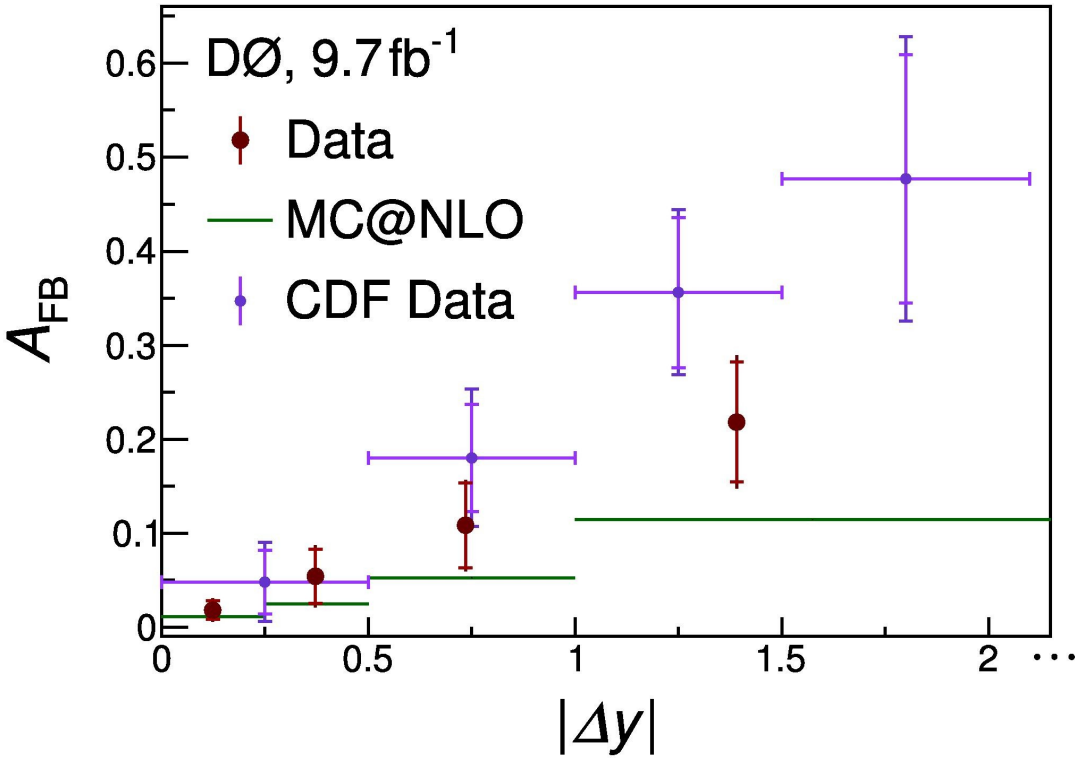




Top quark asymmetries

- Existing CDF measurement in l+jets decay channel also measured kinematic dependence of A_{FB}

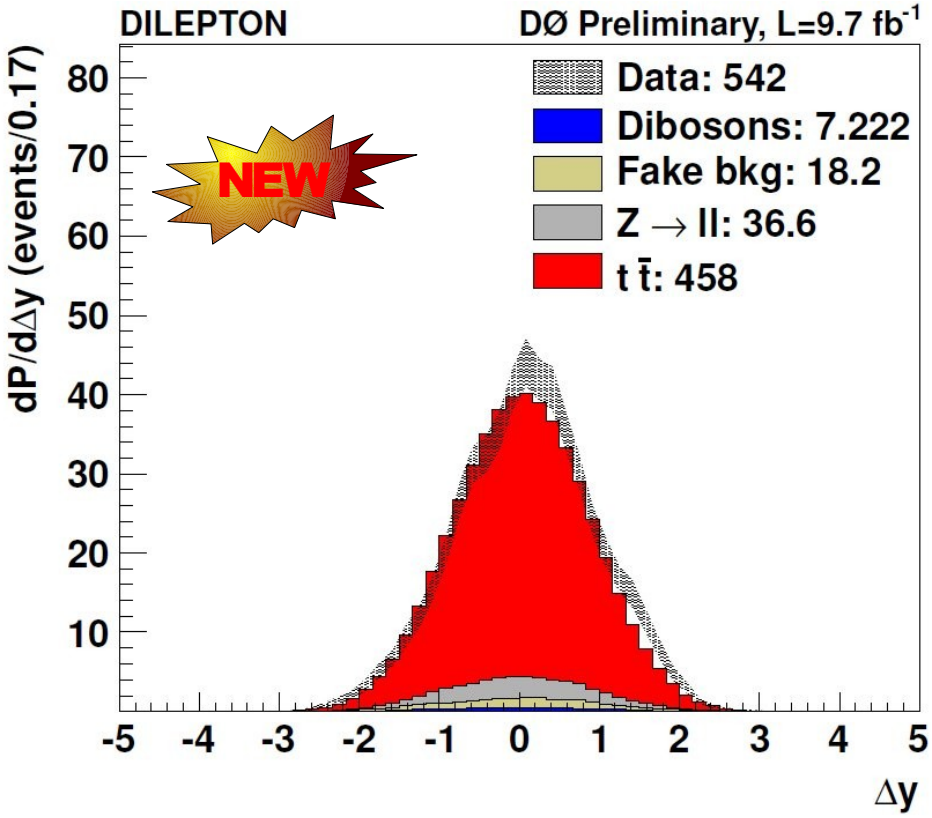


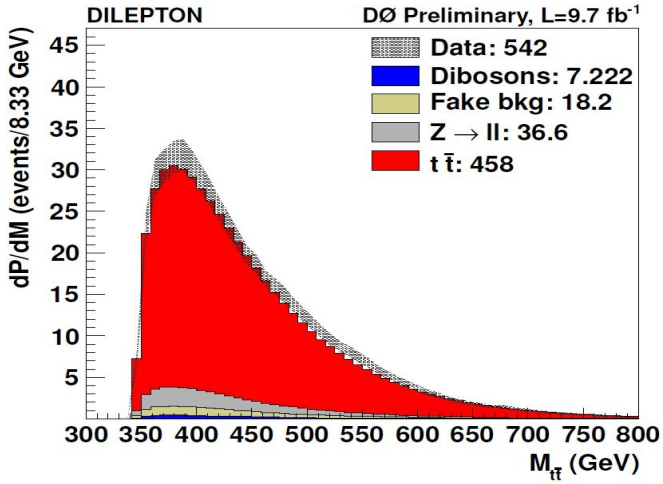


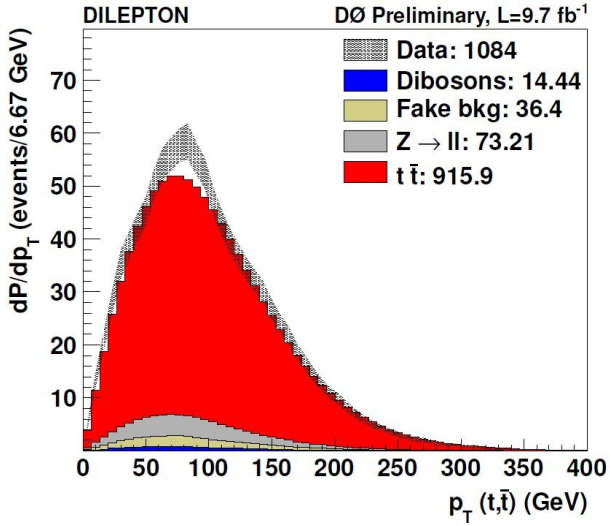
- Kinematic dependencies larger than “currently” predicted by SM
- Good agreement of D0 data with most recent pQCD @NNLO
  (see yesterdays talk by Michael Czakon)

Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method:
  → assign a likelihood per event for most probably Δy (x) value



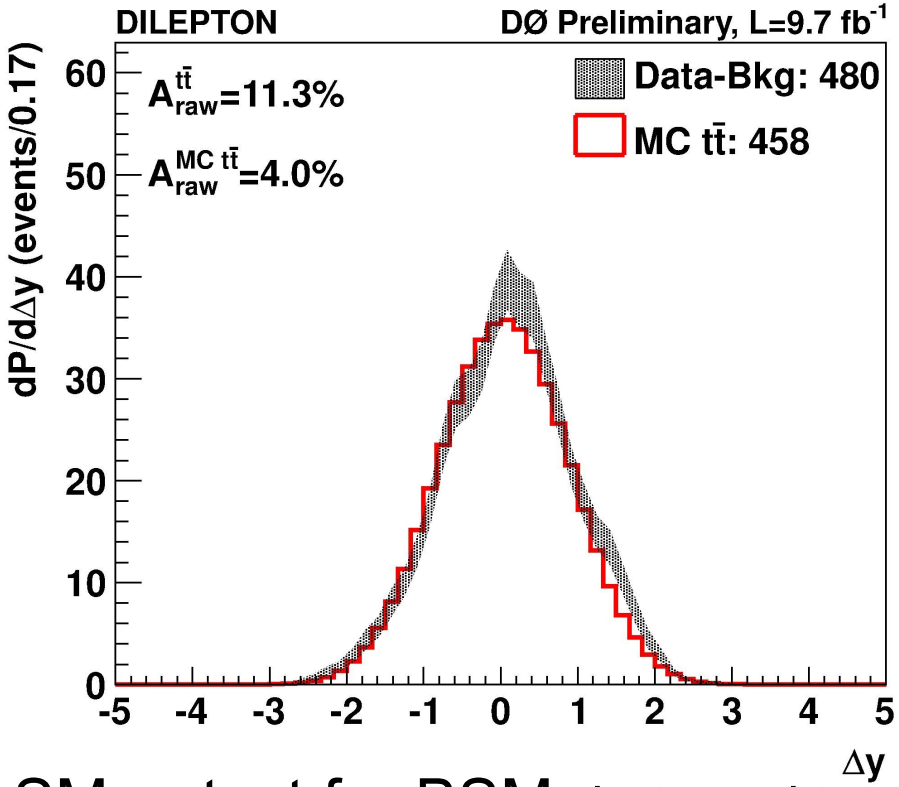




- Control distributions show reasonable data modeling by MC → extract asymmetry

Top quark asymmetries

- Systematic uncertainties dominated by signal modeling, in particular hadronization and showering and calibration



Source of uncertainty	Uncertainty on $A_{FB}^{t\bar{t}}$ (%)
Detector modeling	
jet energy scale	0.14
jet energy resolution	0.17
flavor-dependent jet response	0.03
b-tagging	0.11
Signal modeling	
ISR/FSR	0.32
forward/backward ISR	0.36
hadronisation and showering	→ 1.08
higher order correction	0.80
PDF	0.60
Background model	
fake background normalization	0.35
fake background shape	0.35
background normalization	0.53
Calibration	
$\Delta y_{t\bar{t}}$ model	→ 2.7
calibration statistics	0.4
Total	3.3

- Test SM or test for BSM, but need to consider unknown polarization in calibration

→ A_{FB} = 18.0 ± 6.9 (tot.) %

A_{FB} = 18.0 ± 6.9 (tot.) ± 5.1(model) %

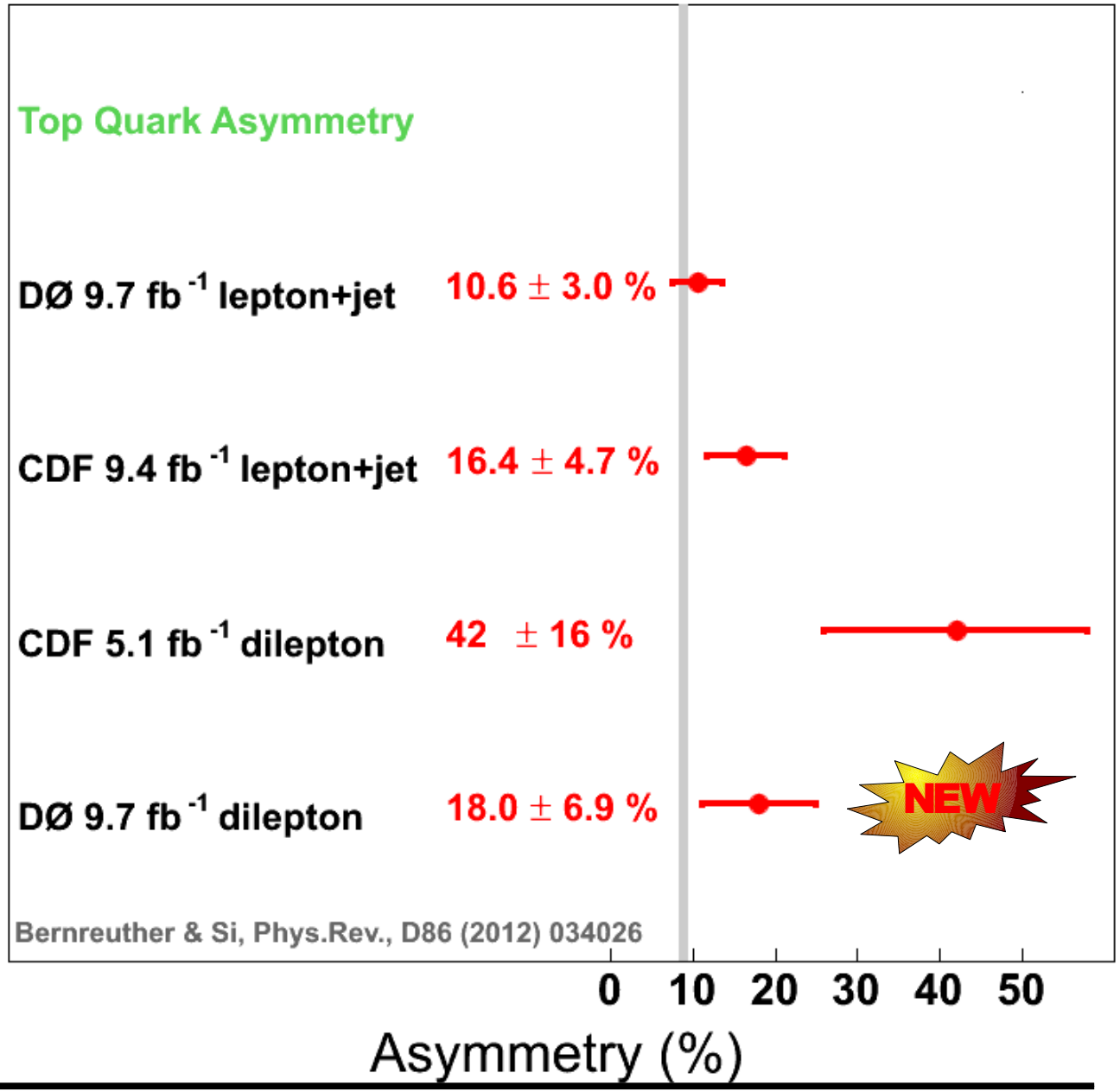
Top quark asymmetries

Summary of the current situation:

- Most Tevatron results use full data sets
- Combinations to come

Theory:

- Latest @NNLO is ≈ 10%
  → agreement with D0, while CDF little higher



Axi gluons & Z' models

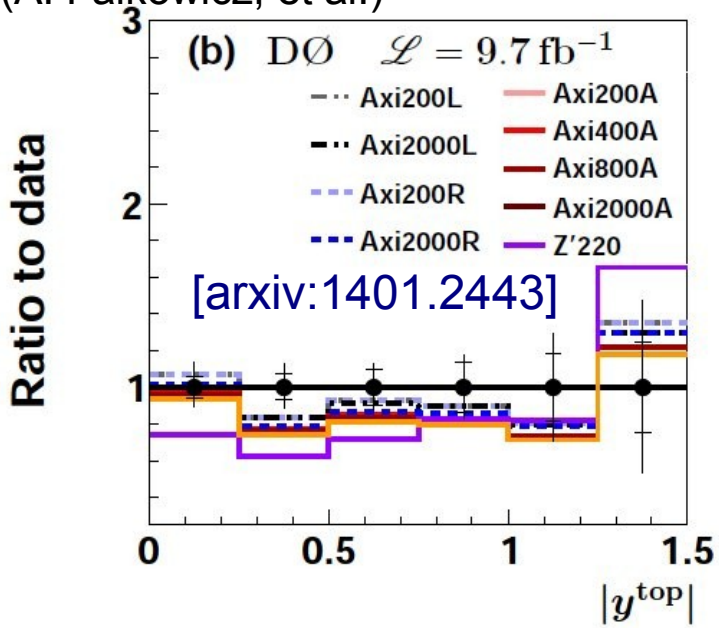
- Various axi gluon models with different couplings, differential cross section predictions (A. Falkowicz, et al.)

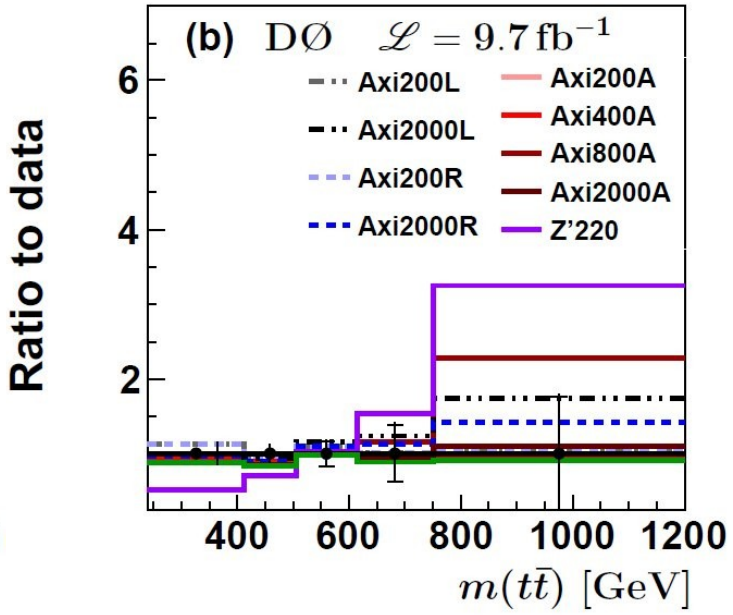
- Compare various models to unfolded cross section data using full covariance matrix:

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

- Models with masses of 0.2 to 2 TeV for L (left), R (right), A (axial)
- Models are constrained by σ(tt), A_{FB} and high tail of dσ/dm(tt) at Tevatron and LHC

- Some models are in tension with the presented data !
  → Z', some axi gluons





	$M(t\bar{t})$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$	$\lvert y^{\mathrm{top}}\rvert$ $[\chi^2/ndf]$
axi200L	0.96	1.07	1.20
axi200R	0.96	1.07	1.20
axi200A	0.85	3.55	3.88
axi400A	0.44	2.65	3.26
axi800A	0.97	2.86	3.23
axi2000L	0.58	1.27	3.78
axi2000R	0.43	1.94	2.75
axi2000A	0.88	3.56	4.11
Z'220	4.95	8.27	7.48

Tevatron data adds sensitivity at low mass
→ specific models constrained

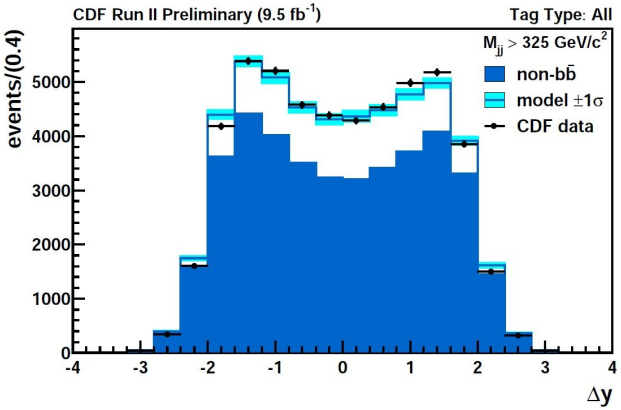
Other asymmetries...

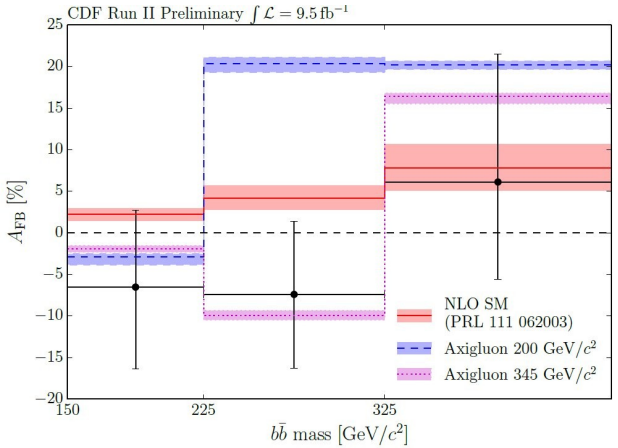
What about *b*-quark asymmetries ?

- CDF: Data side-band technique to estimate light quark asymmetry
  - Identify *b* and $\bar{b}$ employing jet charge
  - Bayesian technique to correct for detector effects
  - Results agree with SM

NEW

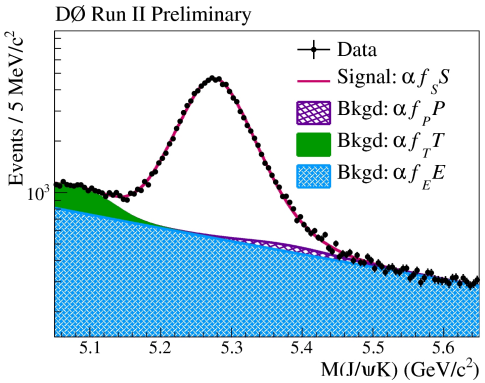
Conf. Note 11092





- D0 uses $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ to probe asymmetry of *b*-quarks
- Unbinned maximum likelihood fit

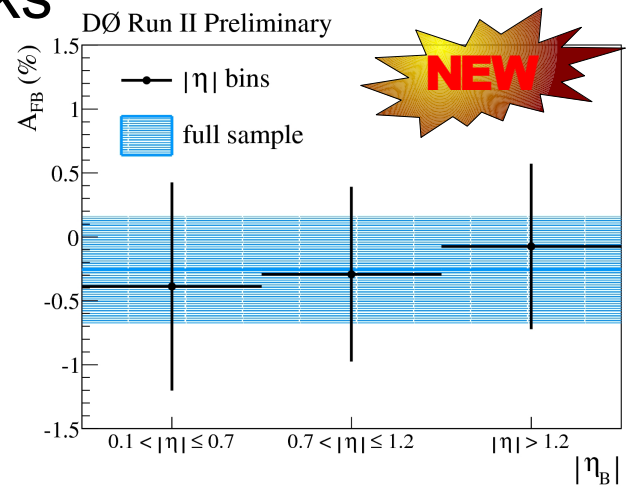
D0 Note 6441-CONF



A_{FB} = -0.26 ± 0.41 ± 017 %

MC@NLO: 1.63 ± 0.43 ± x.xx %

Stat. To come: scales,pdf



Summary & Outlook

- Final legacy measurements of top quark properties
  → Expect spin correlation & polarization measurements soon (D0)

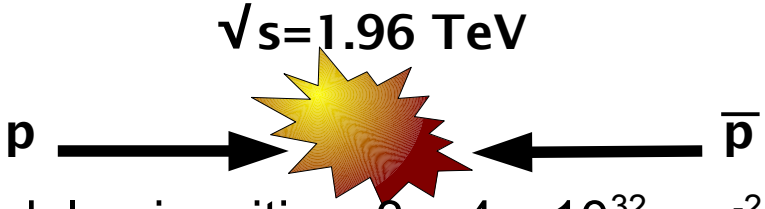
- What about the forward-backward Asymmetry ?
  → D0 closer to SM, CDF somewhat larger than SM
  → Latest: D0 consistent with A_{FB} prediction at NNLO QCD
  → *b*-quark asymmetries agree with SM expectations
  → No indication for axi gluon/Z' contributions in differential cross sections
- Tevatron combinations to come

- Focused on asymmetry results, only small selection of property results shown, more information:

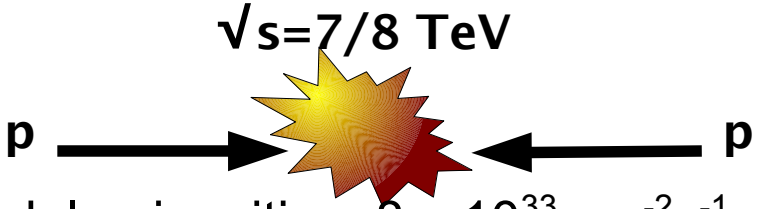
  D0 Top Web pages CDF Top Web pages

Backup

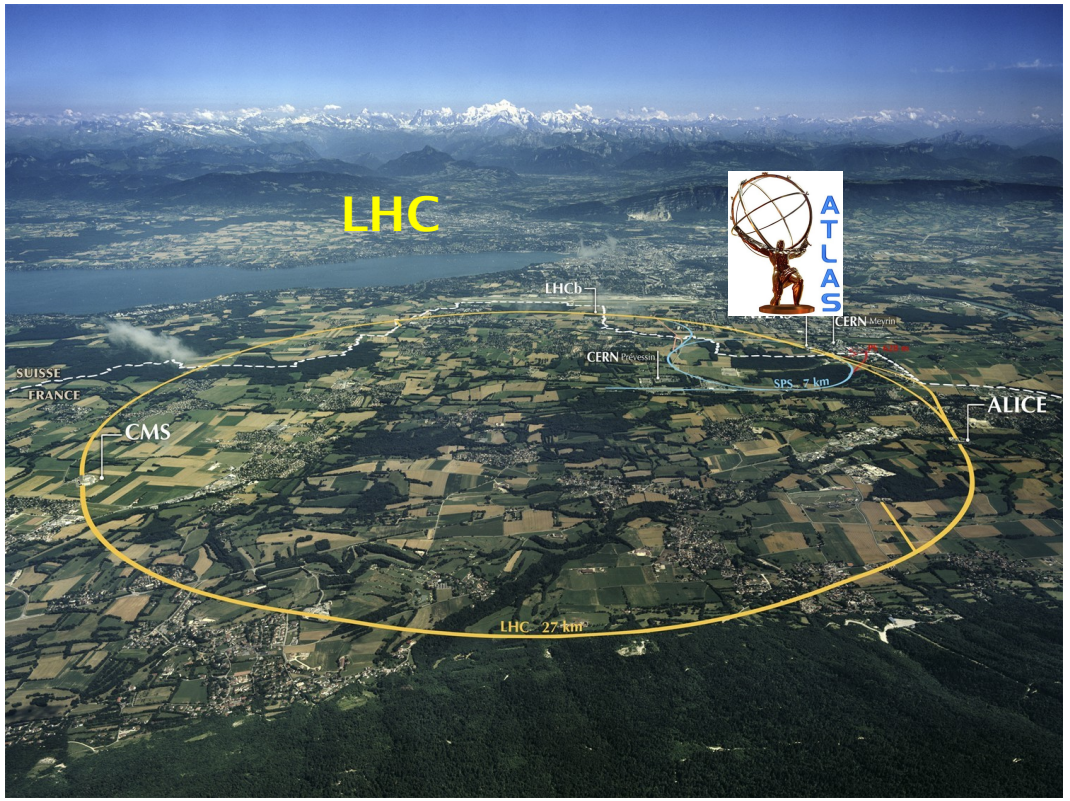
Accelerators



- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- Tevatron shutdown September 2011



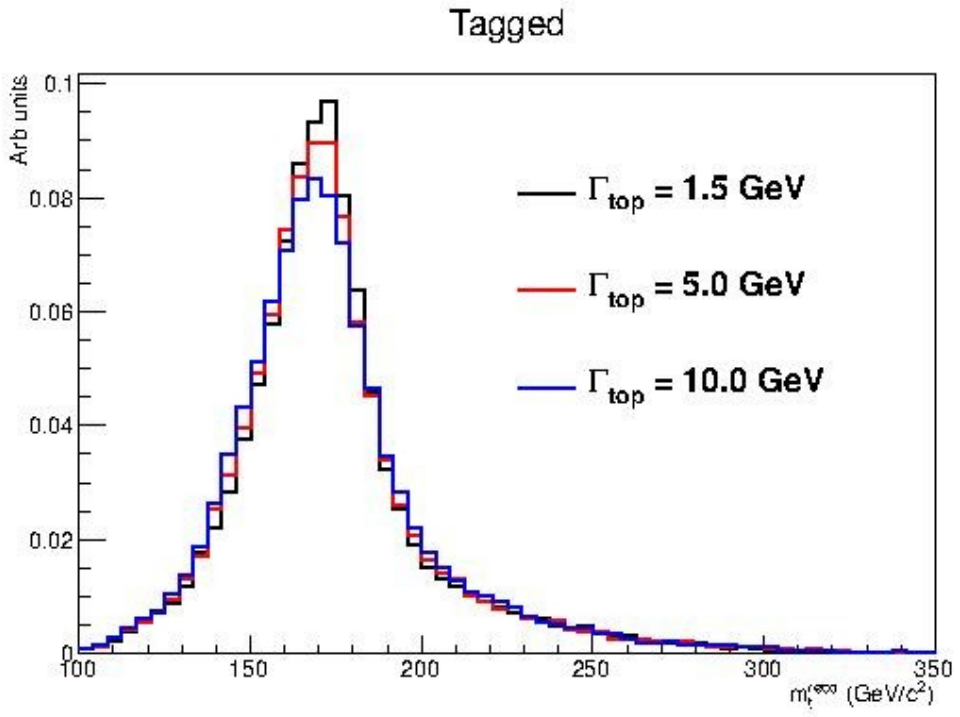
- Peak luminosities: 8 x 10^{33} $cm^{-2}s^{-1}$
- ~5 (25) fb^{-1}/experiment recorded
- LHC consolidation/upgrades till 2015

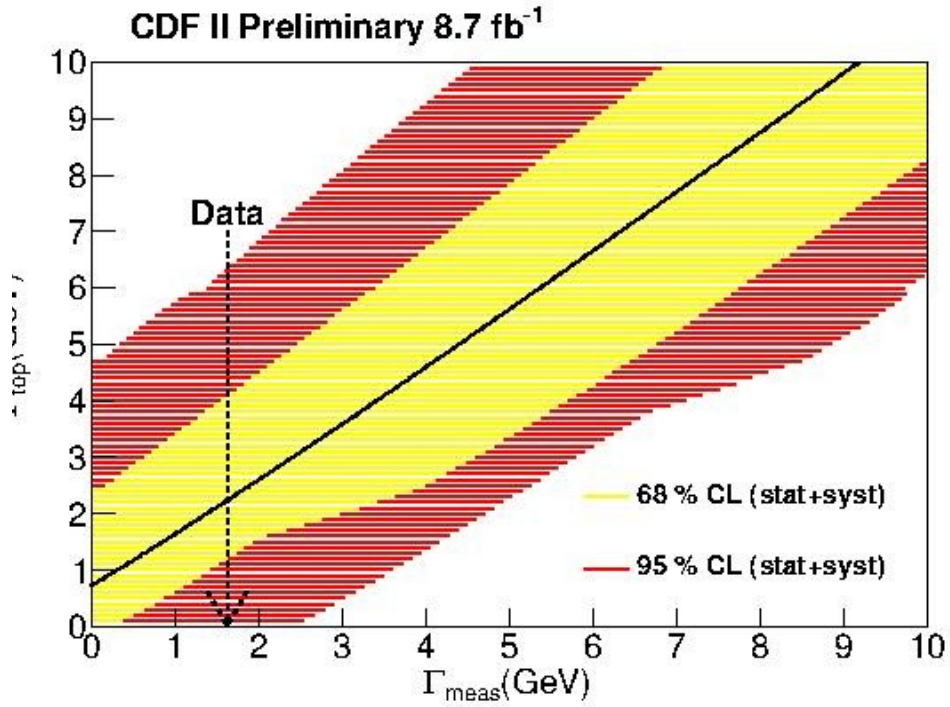


Big thanks to the Accelerator Divisions!

Top quark width

- Measurement of width



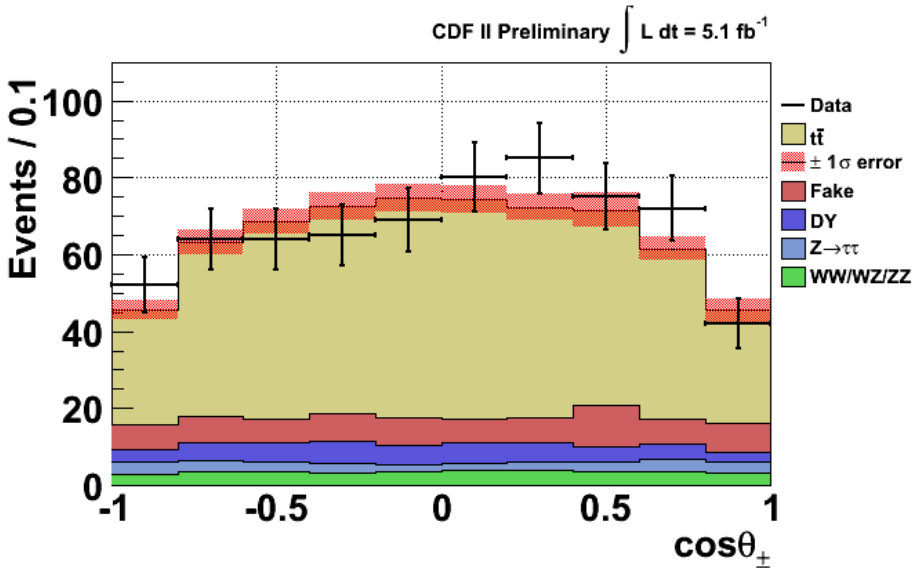


CDF Run II Preliminary 8.7 fb^{-1}

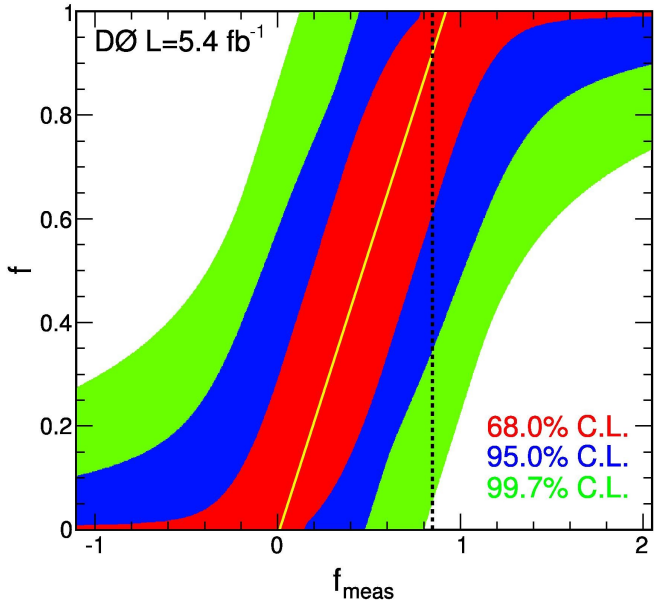
Systematic	$\Delta\Gamma_{meas}$ (GeV)
Jet Resolution	0.56
Color Reconnection	0.69
Generator	0.50
Higher Order Effect	0.21
Residual Jet Energy Scale	0.19
Parton Distribution Functions	0.24
b Jet Energy Scale	0.28
Background Shape	0.18
gg Fraction	0.26
Radiation	0.17
Lepton Energy	0.03
Multiple Hadron Interaction	0.23
Total Effect	1.22

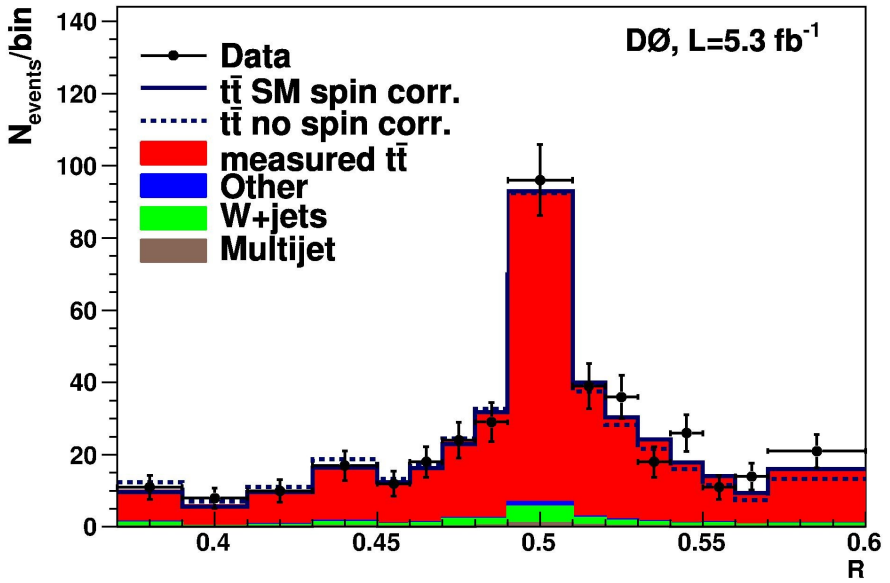
Spin correlations

- Spin correlation affect decay products, spin state of top quark is preserved
- Complementary due to initial state
- Evidence for spin correlations at D0

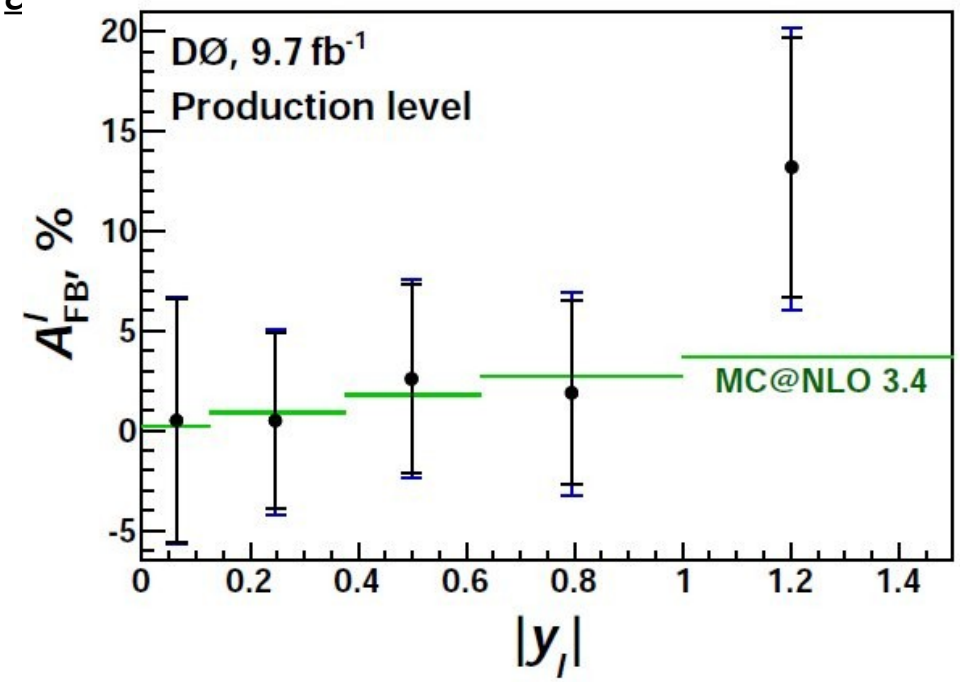


$F_{COR} = 0.85 \pm 0.29$ (stat. + syst.)



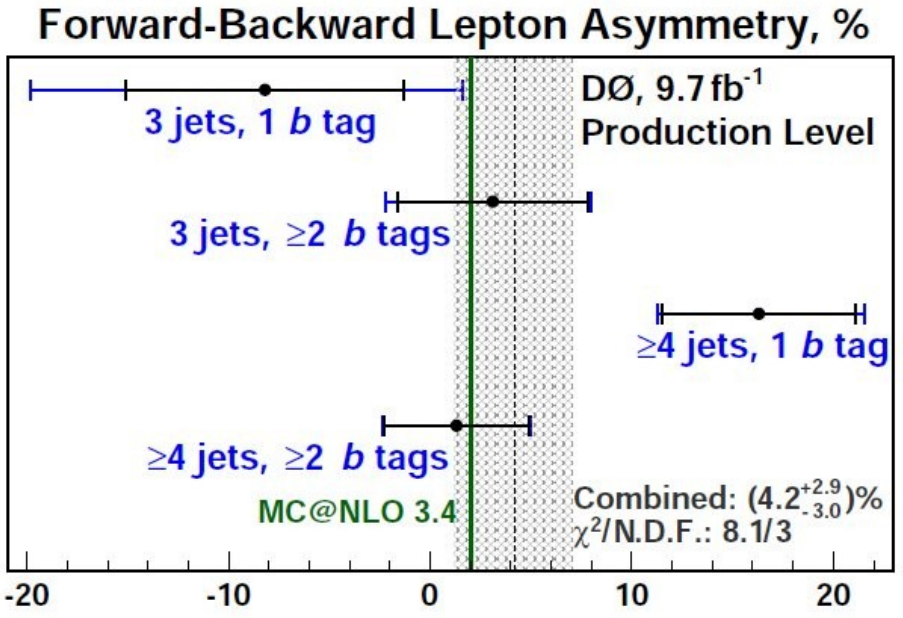


Lepton asymmetries

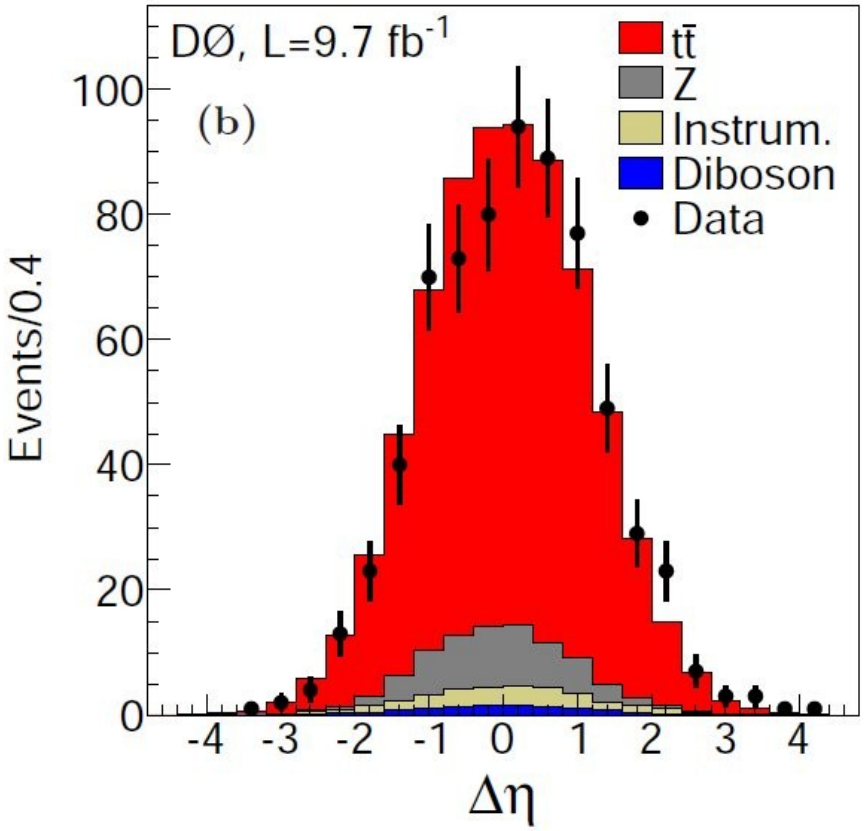


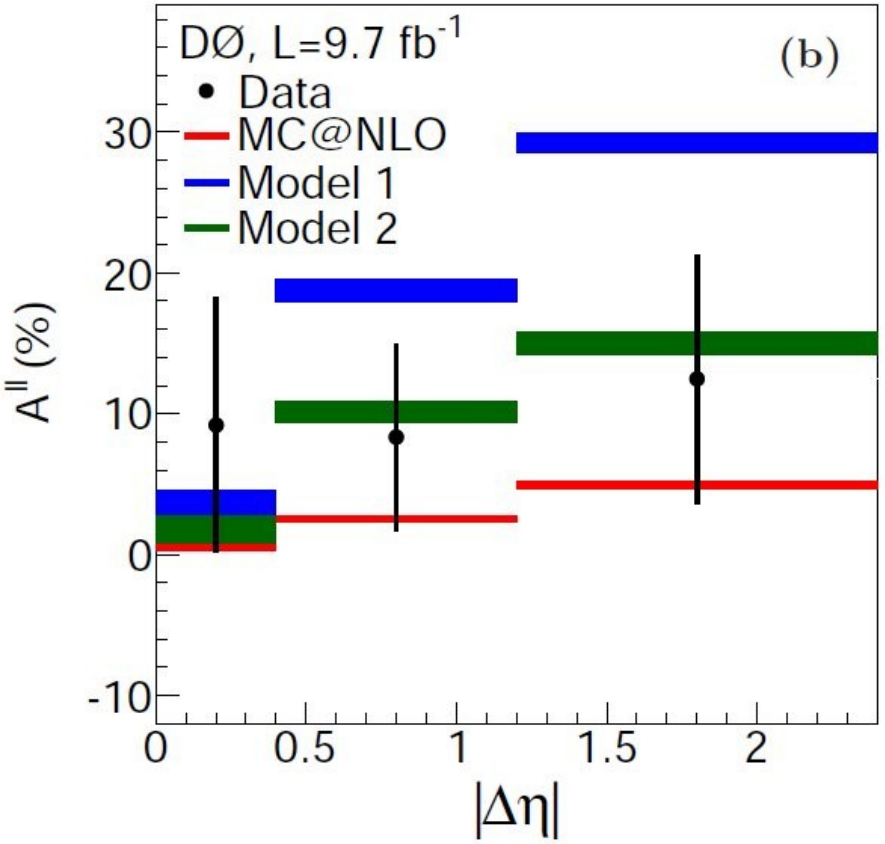
Source	Absolute uncertainty, % Reconstruction level Prediction	Reconstruction level Measurement	Prod. level Measurement
Jet reco	−0.1	–	–
JES/JER	+0.1	+0.1/−0.3	+0.2/−0.3
Signal modeling	–	−0.2	+0.6/−0.4
b tagging	±0.1	+0.5/−0.8	+0.8/−1.1
Bg subtraction	n/a	+0.1/−0.3	+0.1/−0.3
Bg modeling	n/a	+1.4/−1.5	+1.3/−1.5
PDFs	–	+0.3/−0.2	+0.1/−0.2
Total	±0.1	+1.5/−1.7	+1.7/−2.0

Channel	A^l_{FB}, % Data	MC@NLO
l+3 jets, 1 b tag	$-6.8 \pm 6.0\,(\text{stat.})^{+6.1}_{-5.6}\,(\text{syst.})$	2.7 ± 0.4
l+3 jets, ≥2 b tags	$3.7 \pm 4.3\,(\text{stat.})^{+1.1}_{-1.2}\,(\text{syst.})$	2.8 ± 0.3
l+≥4 jets, 1 b tag	$14.8 \pm 4.2\,(\text{stat.})^{+1.1}_{-1.2}\,(\text{syst.})$	0.5 ± 0.3
l+≥4 jets, ≥2 b tags	$-0.9 \pm 3.2\,(\text{stat.})^{+0.3}_{-0.9}\,(\text{syst.})$	1.1 ± 0.2
Total	$2.9 \pm 2.1\,(\text{stat.})^{+1.5}_{-1.7}\,(\text{syst.})$	1.6 ± 0.2



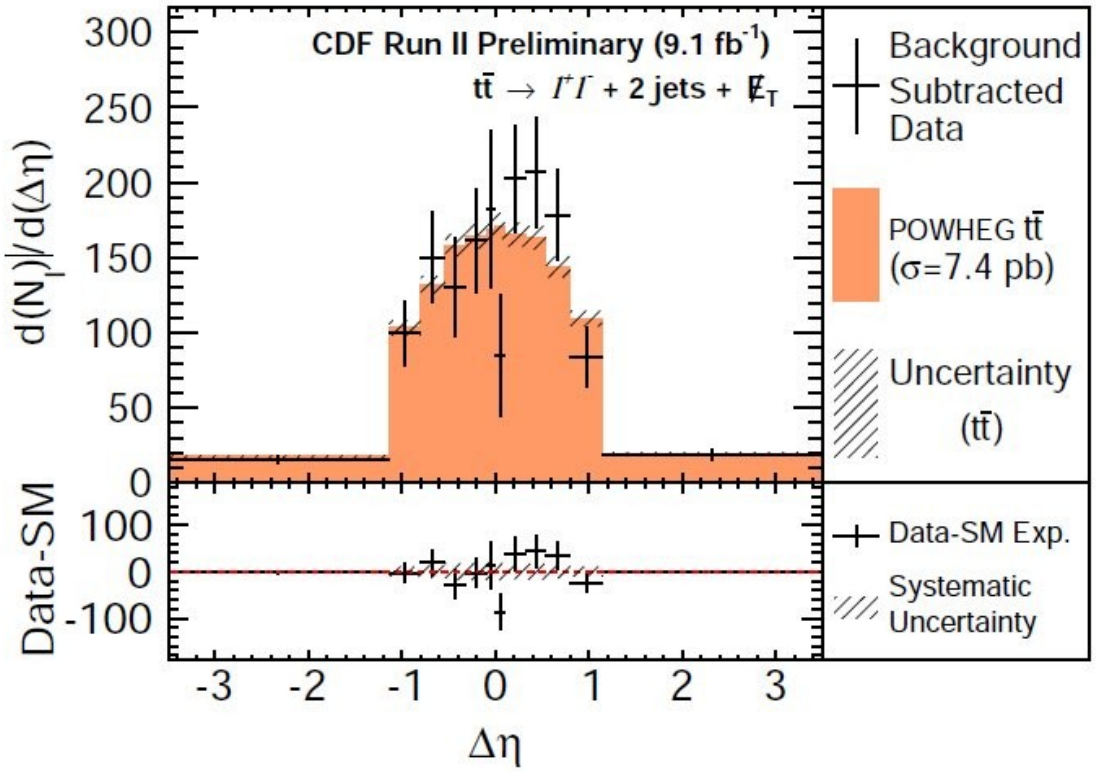
Lepton asymmetries

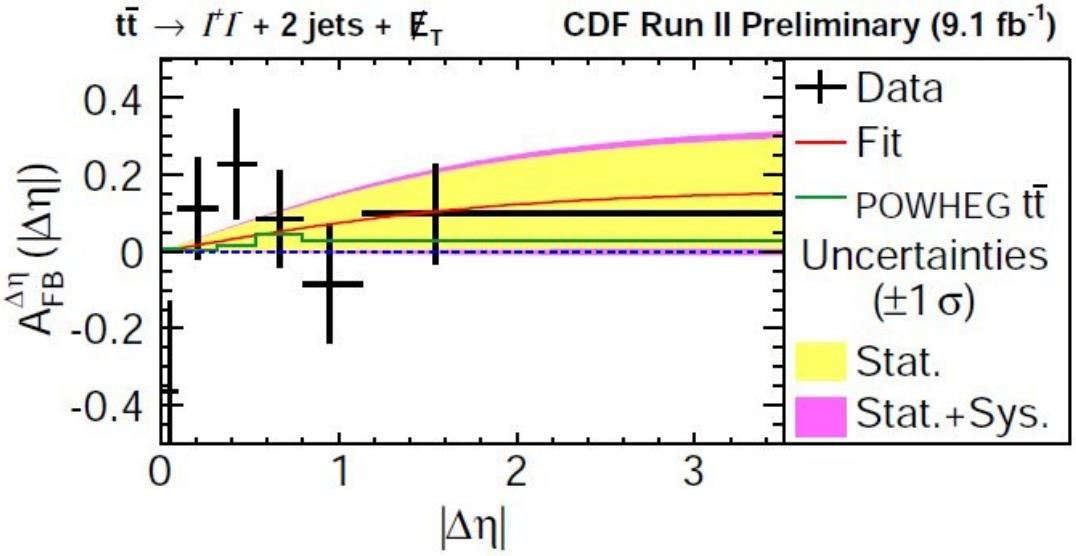




	Corrected		Extrapolated	
	$A_{\rm FB}^{\ell}$	$A^{\ell\ell}$	$A_{\rm FB}^{\ell}$	$A^{\ell\ell}$
Source				
Object ID	0.54	0.50	0.59	0.60
Background	0.66	0.74	0.72	0.88
Hadronization	0.52	0.62	0.62	0.92
MC statistics	0.19	0.23	0.23	0.37
Total	1.02	1.12	1.14	1.46

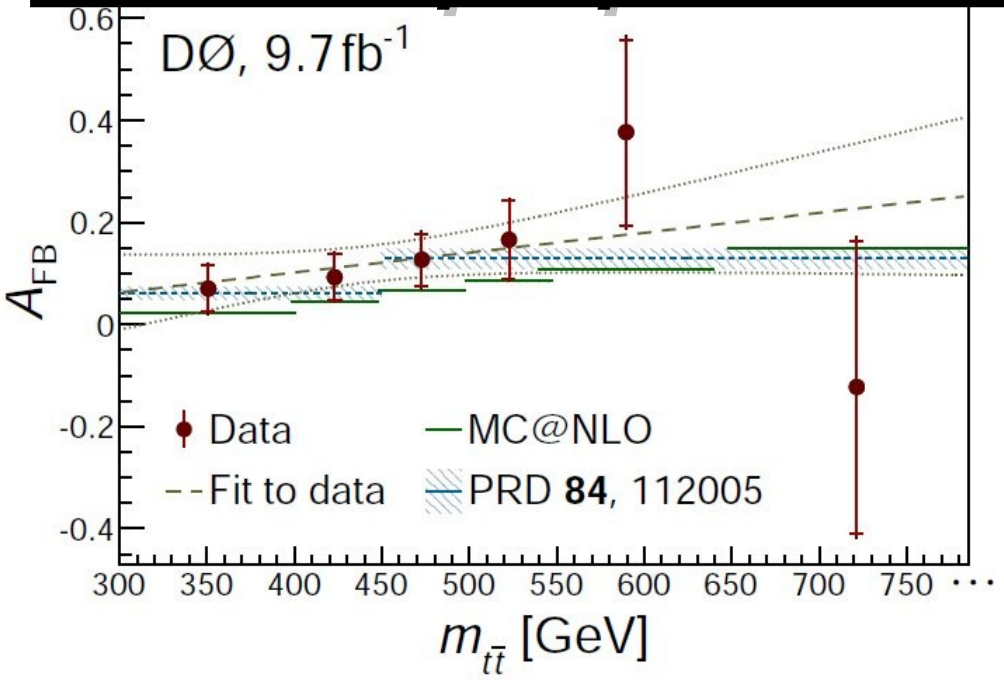
Top quark asymmetries

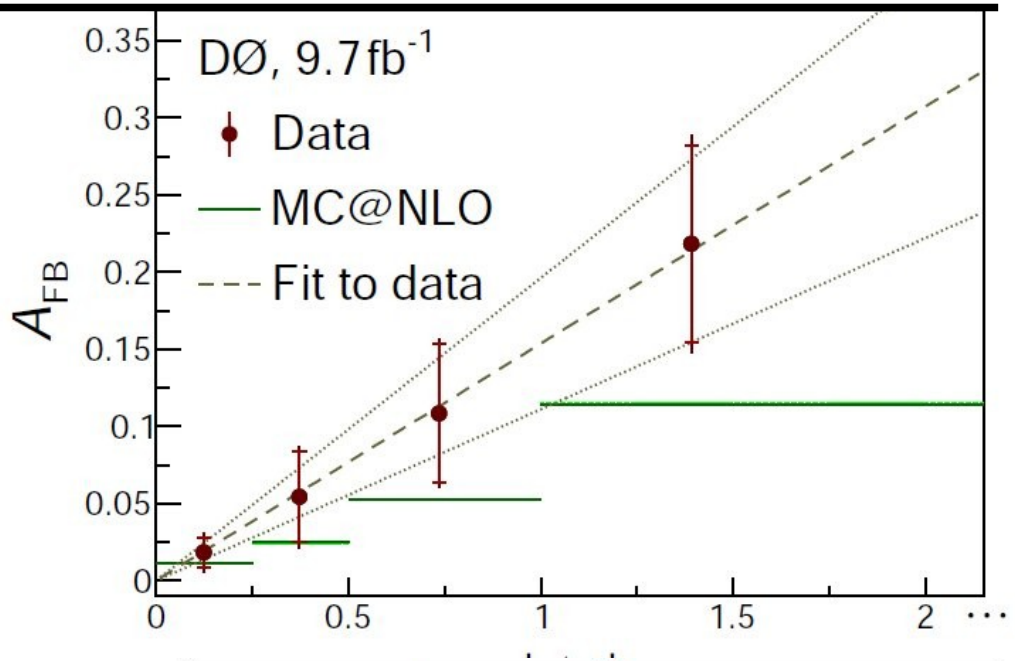




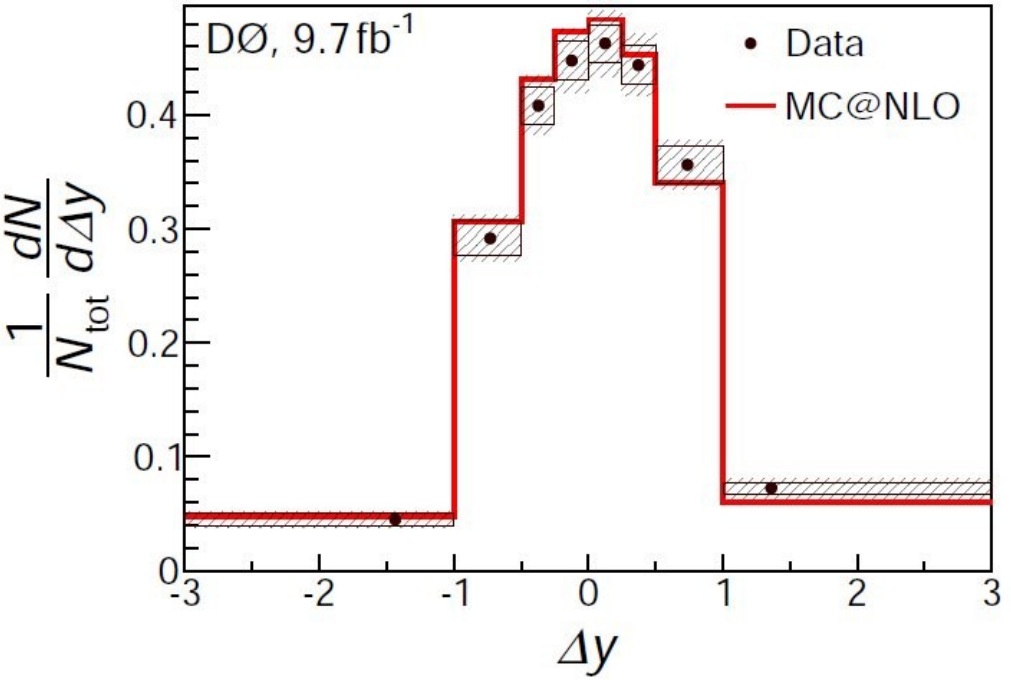
CDF Run II Preliminary (9.1 fb^{-1})	
Source of Uncertainty ($A_{FB}^{\Delta\eta}$)	Value
Backgrounds	0.037
Asymmetric Modeling	0.012
Jet Energy Scale	0.003
Symmetric Modeling	0.004
Total Systematic	0.039
Statistical	0.072
Total Uncertainty	0.082

Top quark asymmetries





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



Axi gluons & Z' models

- Various axi gluon models with different couplings, differential cross section predictions provided by A. Falkowicz [arxiv:1401.2443]

Remarks:

- Models with masses of 0.2 to 2 TeV and L (left), R (right), A (axial)
- Large masses highly constrained by LHC measurement
- Low masses not so much, but tough as effects are small
- Models use inclusive cross sections and asymmetry measurements at the Tevatron, in addition high tail of m(tt) at Tevatron and LHC

Phys. Rev. D. 88, 112002 (2013)
Phys. Rev. D 84, 112005 (2011)
CDF Conf. 11035

Acc. by PRD [arxiv:1309.7570]

CMS [arxiv:1309.2030]

D0 [arxiv:1401.5785]

CDF PRL 102 222003

	$\sigma_{\mathrm{tot}}(p\bar{p} \to t\bar{t})$ [pb]
Data	$8.27^{+0.92}_{-0.91}$ (stat. + syst.)
NNLO pQCD (SM)	$7.24^{+0.23}_{-0.27}$ (scales + pdf)
	$\Delta\sigma_{\mathrm{tot}}(p\bar{p} \to t\bar{t})$ [pb]
axi200L	0.97 ± 0.06 (scale)
axi200R	0.97 ± 0.06 (scale)
axi200A	0.06 ± 0.04 (scale)
axi400A	0.26 ± 0.04 (scale)
axi800A	0.22 ± 0.04 (scale)
axi2000L	0.87 ± 0.15 (scale)
axi2000R	0.55 ± 0.06 (scale)
axi2000A	0.05 ± 0.06 (scale)
Z'220	-1.00 ± 0.06 (scale)