Top quark properties at the Tevatron

- (Introduction)
- Production
- Asymmetries & Polarization
- Spin correlations
- Conclusions & Outlook

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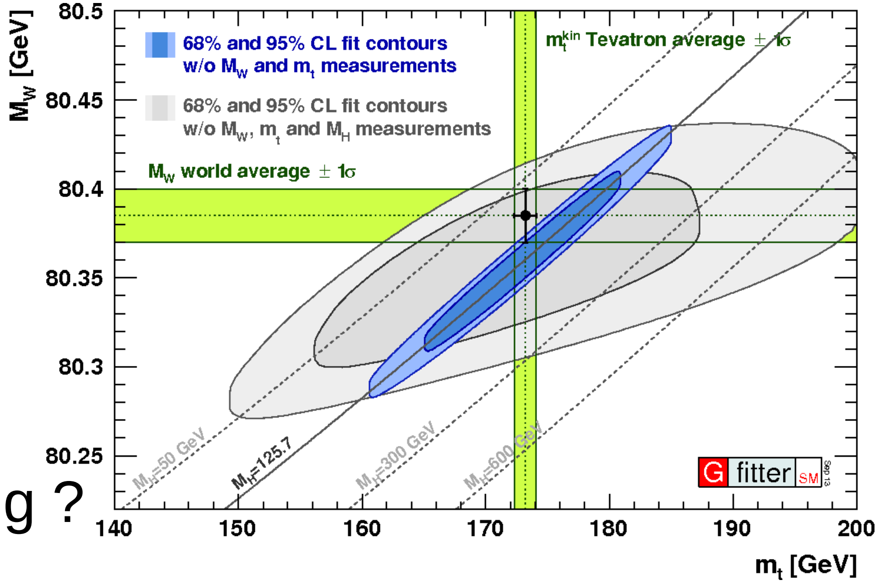
ICHEP, 3rd - 10th August, Chicago

Top quark introduction

- Top is the heaviest fundamental particle discovered so far

  m_t = 173.34 ± 0.76 GeV

  [arxiv:1403.4427]



- Lifetime: $\tau \sim 5\text{x}10^{-25}$ s << Λ_{QCD}

  Observe bare quark properties

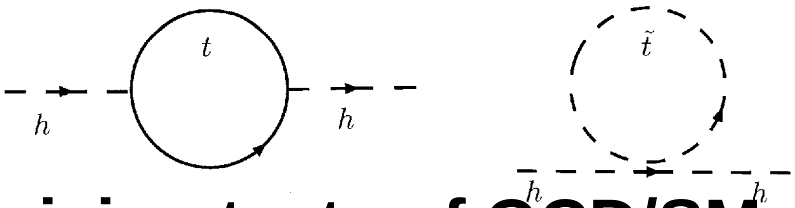
- Large Yukawa coupling to Higgs boson

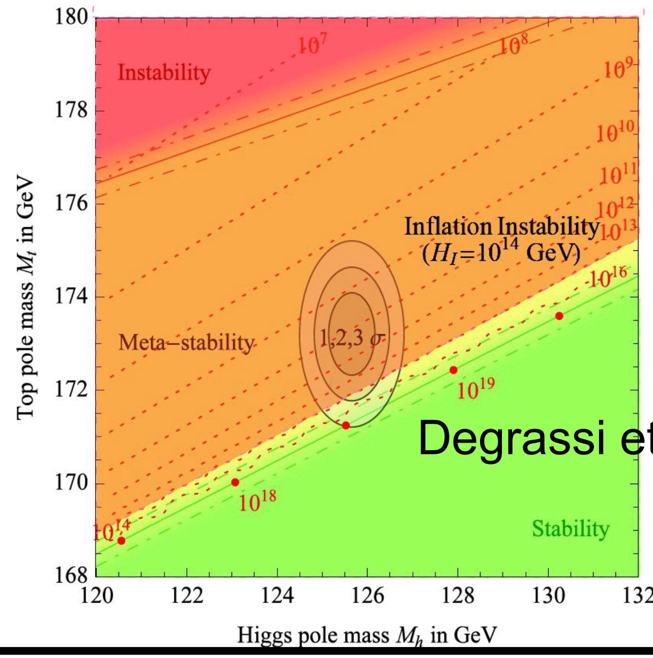
  $\lambda_t \sim 1$

  special role in electroweak symmetry breaking ?

- If we could calculate the Higgs mass:

  Large corrections to the Higgs mass from top quark “loops” (Hierarchy problem)

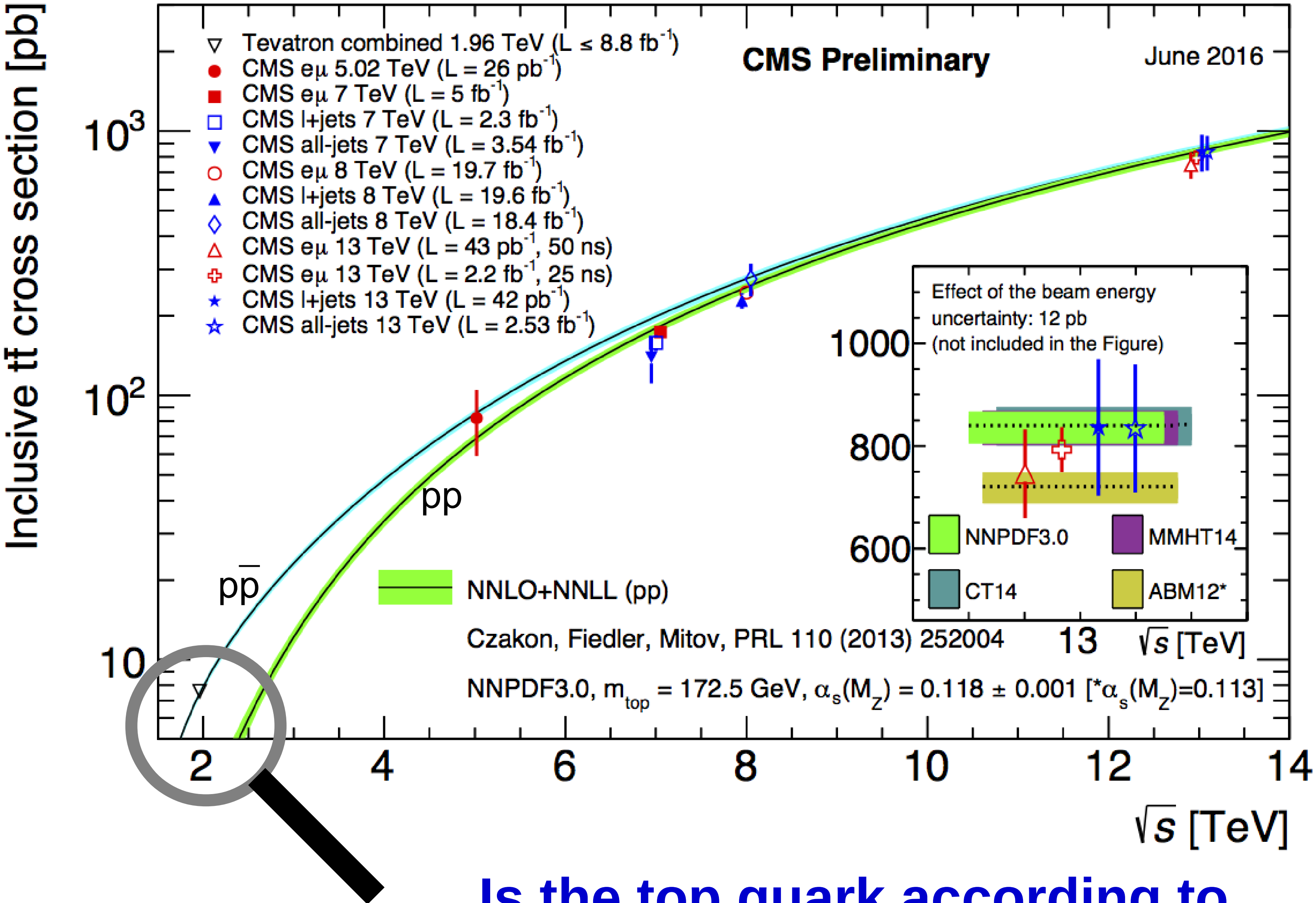




Degrassi et al.

High precision tests of QCD/SM
Tops are background to many searches
Top quarks as window to new physics

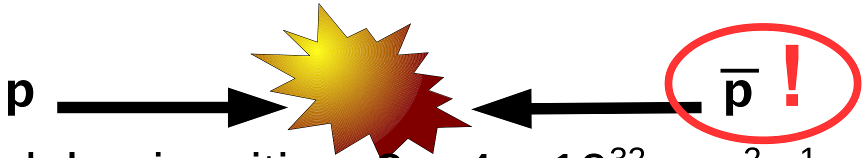
Top quark production



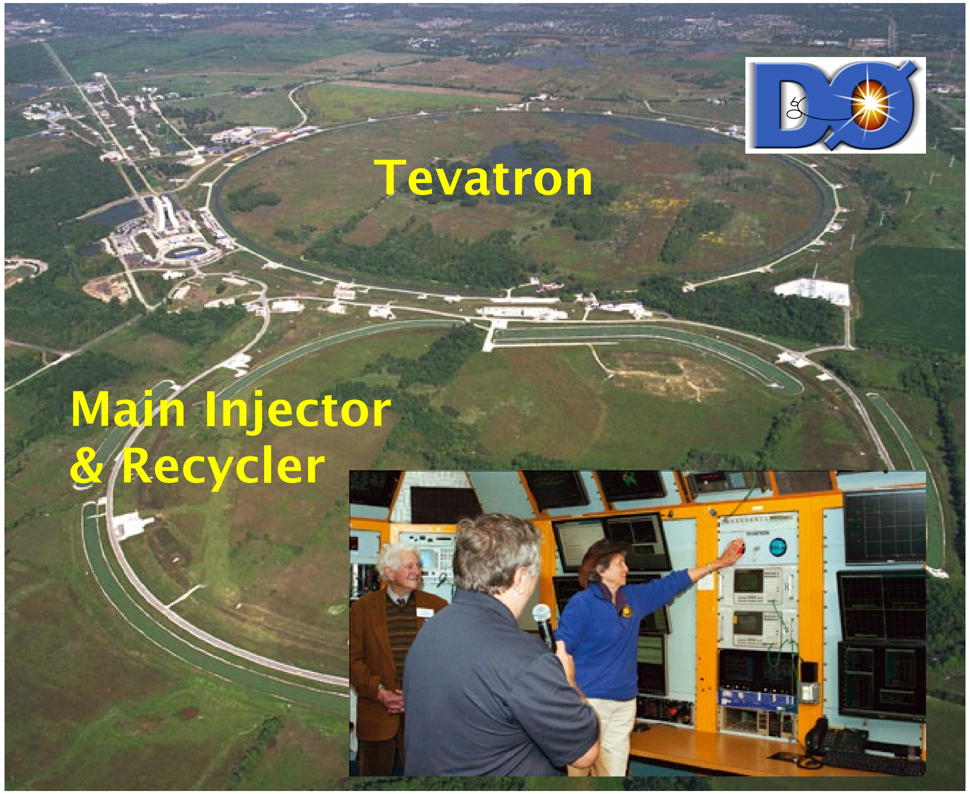
Is the top quark according to what we expect in the SM ?

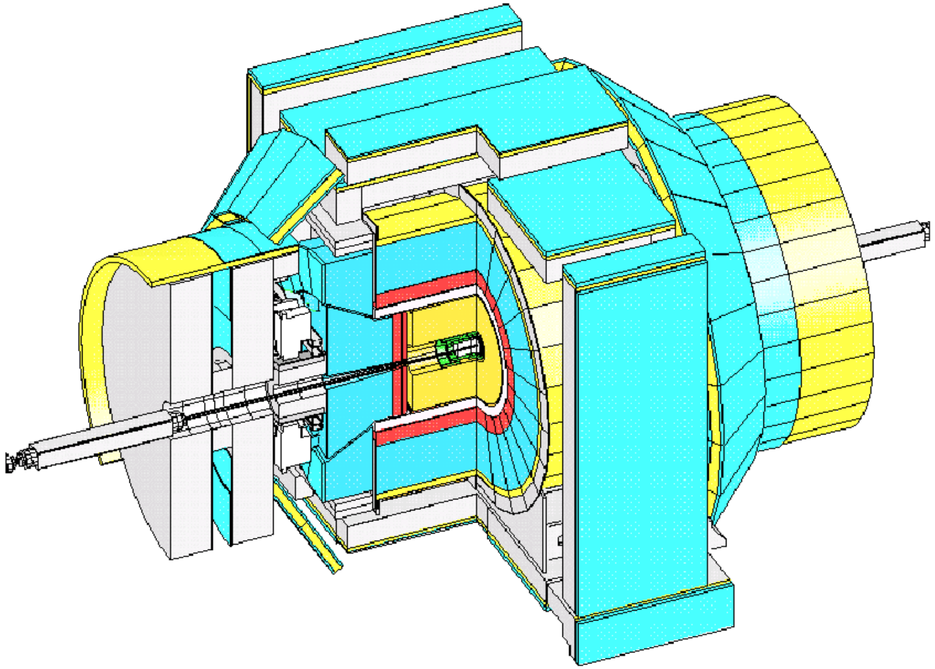
The Tevatron: CDF & D0

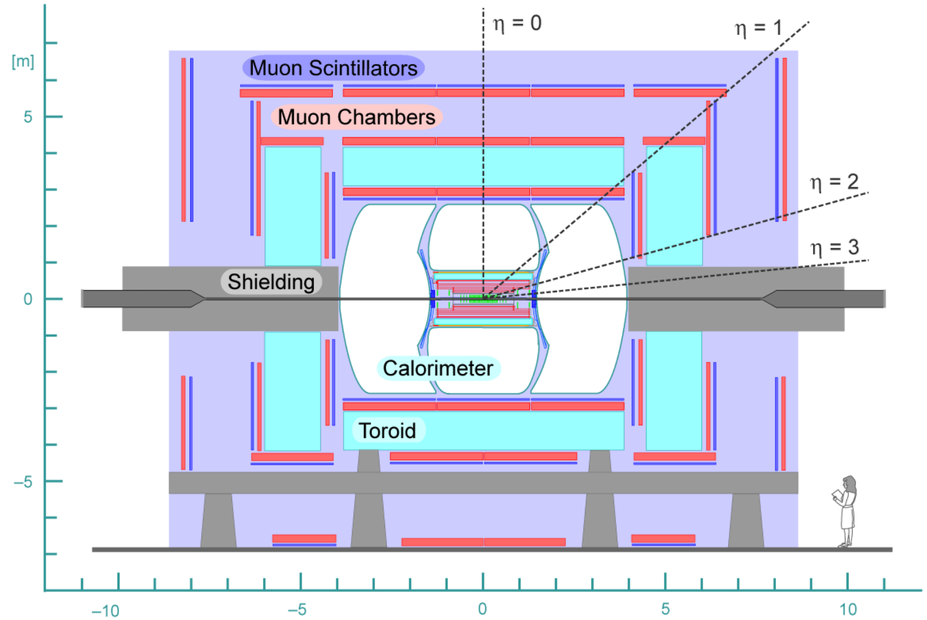
$\sqrt{s}$=1.96 TeV



- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- Tevatron operation from 1983 till shutdown in September 2011







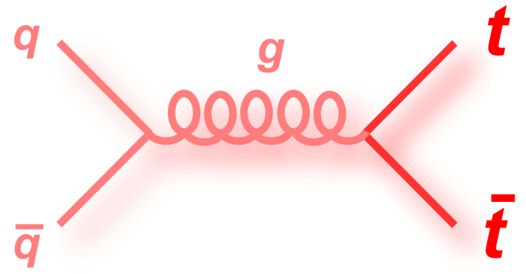
Top quark production

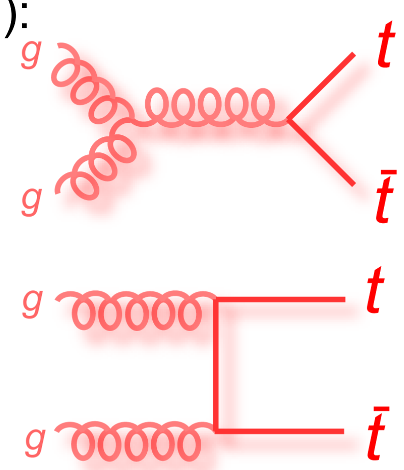
- Strong interaction: Top pairs

Tevatron vs. LHC (13 TeV):

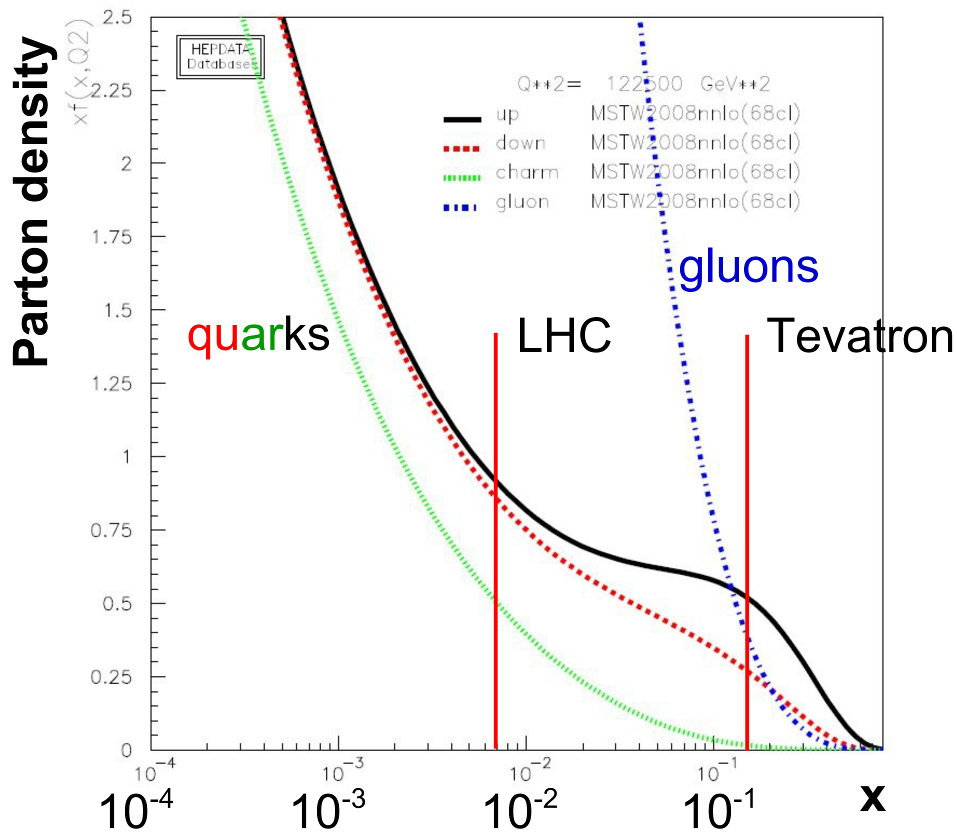
$q\bar{q}$: 85% vs ~10%

gg: 15% vs. ~90%



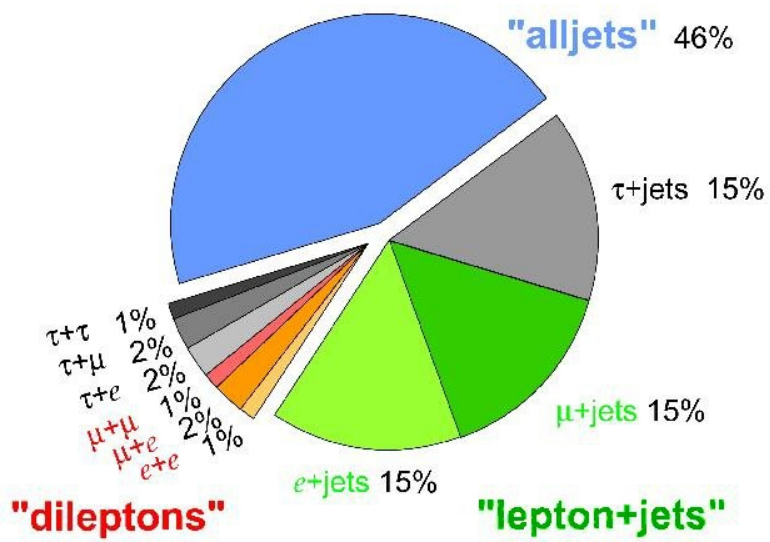


gg fusion



- Decay channels:

Top Pair Branching Fractions



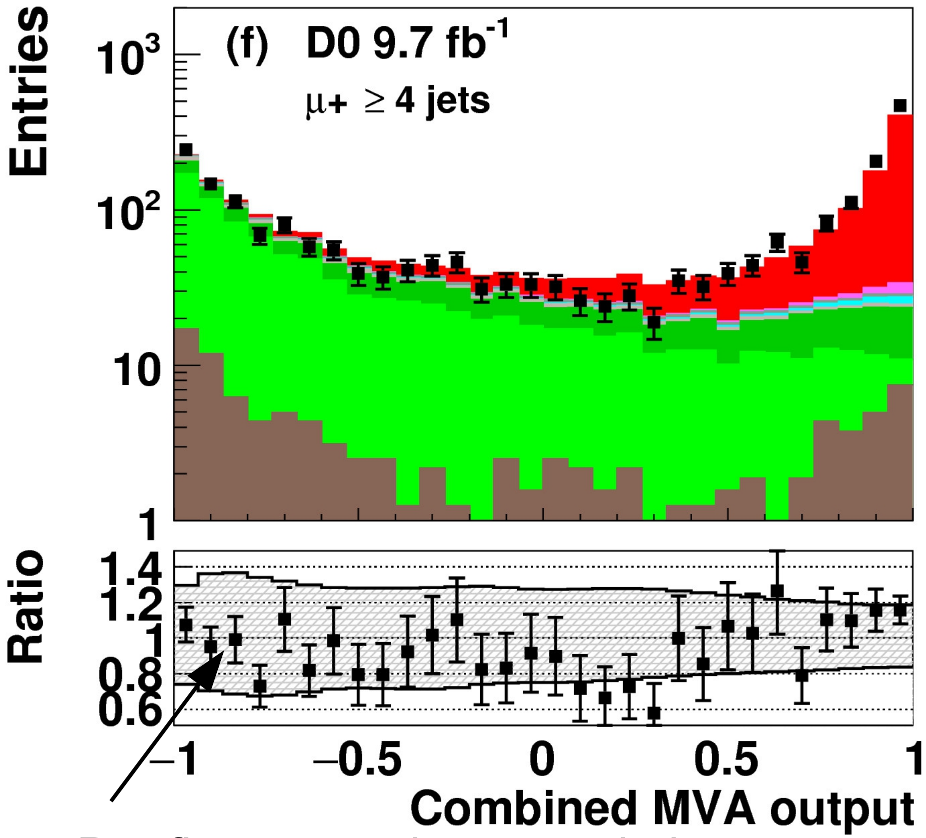
Theory (NNLO+NNLL):

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)

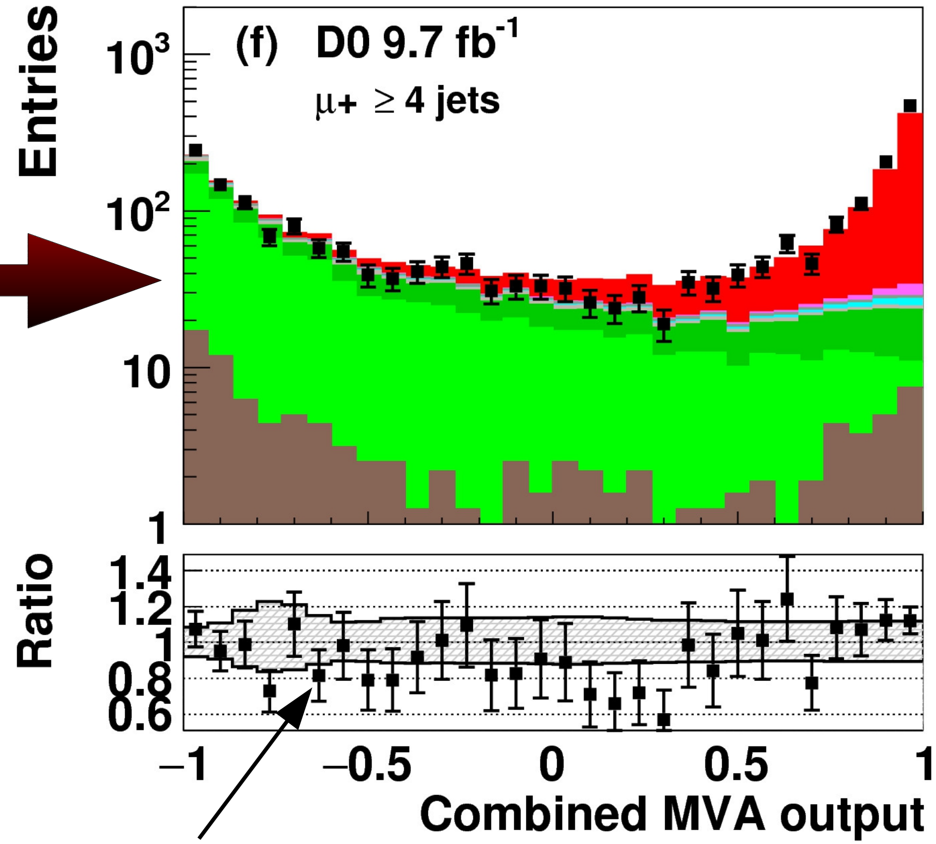
LHC 13 TeV $\sigma = 832^{+40}_{-46}$ pb

- Profile log-LH fit by D0 – final measurement at Tevatron
  - 3 individual log-LH fits for dilepton, l+jets and combination
  - Employ BDT (w gradients) discriminant, optimized to extract m(top)
  - **Reduced uncertainties** despite adding “hadronization” category

D0 [arxiv:1605.06168]



Pre-fit systematic uncertainties

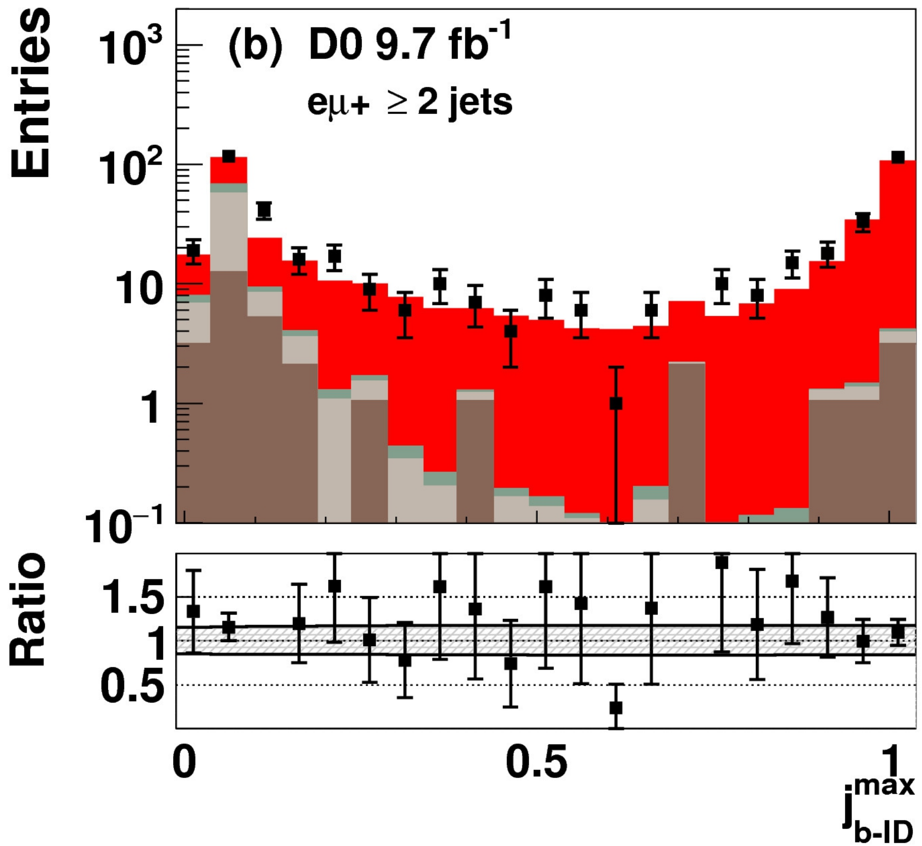


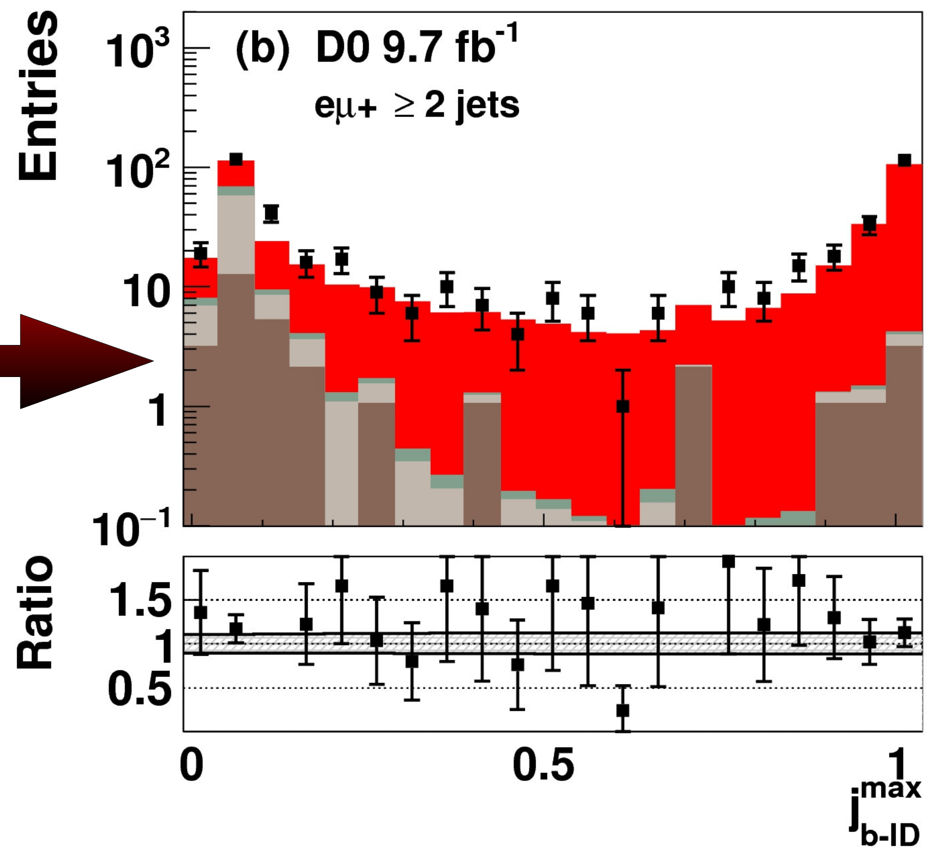
Post-fit systematic uncertainties

Top quark production

- Final Tevatron combination is work in progress
- Luminosity uncertainty: 4.3% (long effort in understanding paid of)

D0 [arxiv:1605.06168]





Leading jet in b-ID discriminant

Combination of dilepton & l+jets:

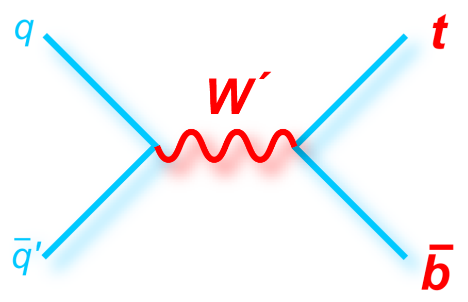
$\boxed{\sigma = 7.26 \pm 0.13 \text{ (stat.)} \pm 0.57/0.50 \text{ (syst.) pb}}$

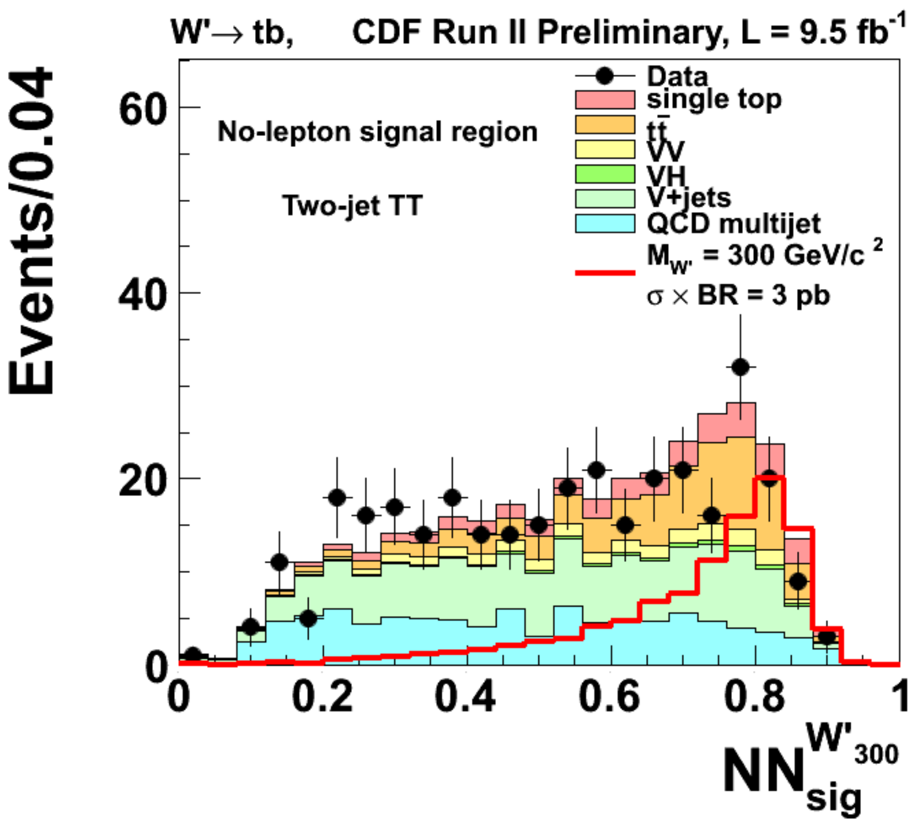
$\delta\sigma/\sigma$ = 7.6% Subm. to PRD

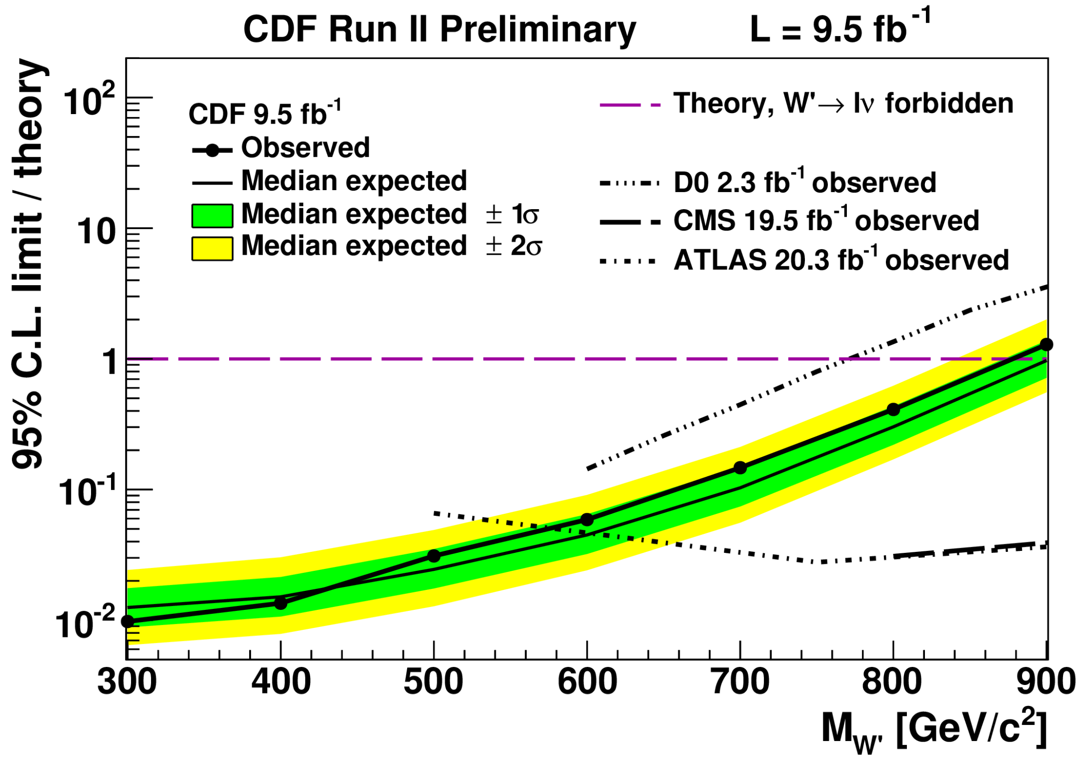
Theory (NNLO+NNLL, top++):
7.16 pb ± 3.5%

Pole mass extraction:
→ see Frederic Deliot

- **New physics ? e.g. *W'***





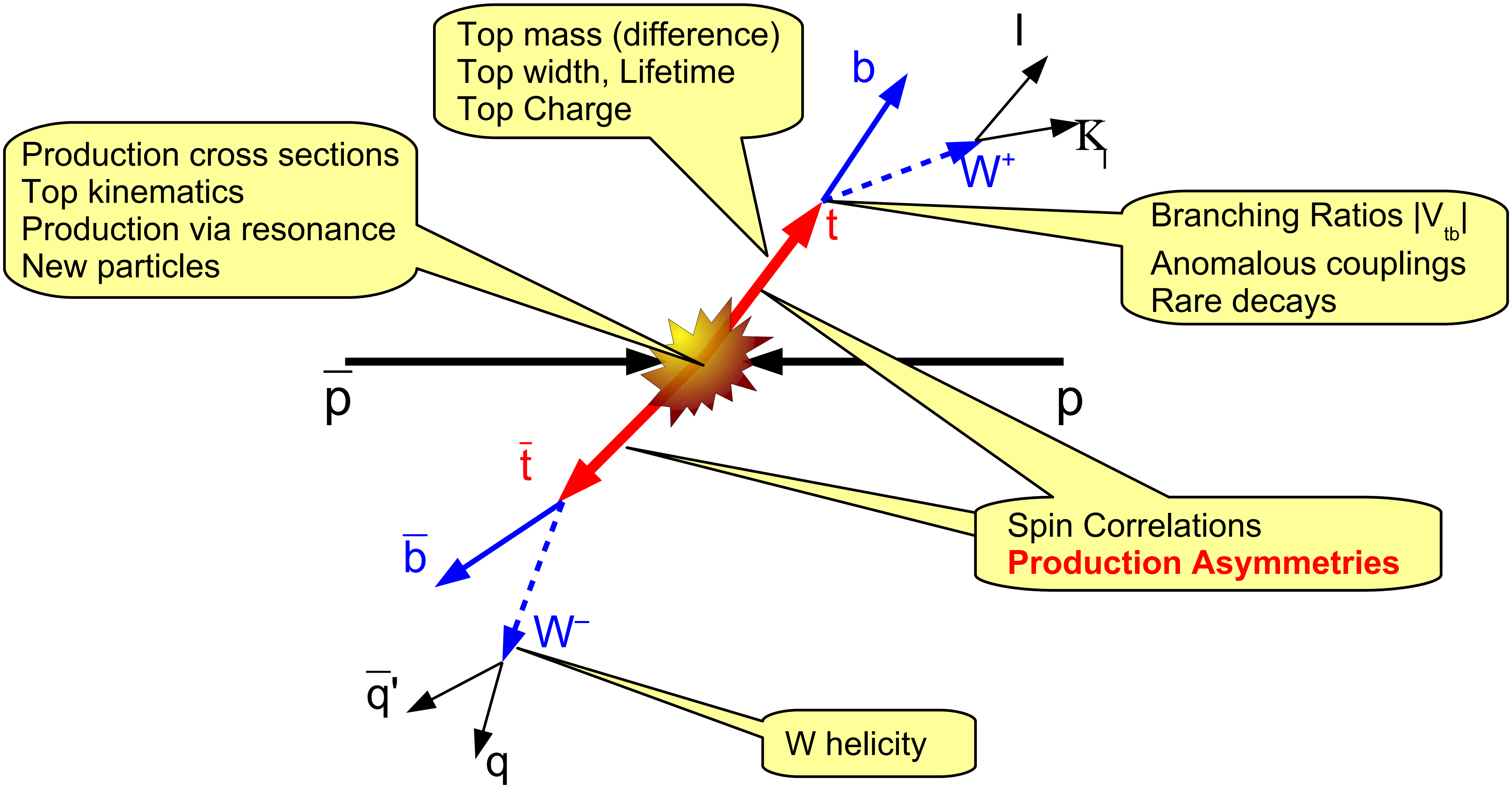


→ missing E_T and 2-3 jets

→ extending LHC exclusions into low mass region PRL 115 061801

No new physics....

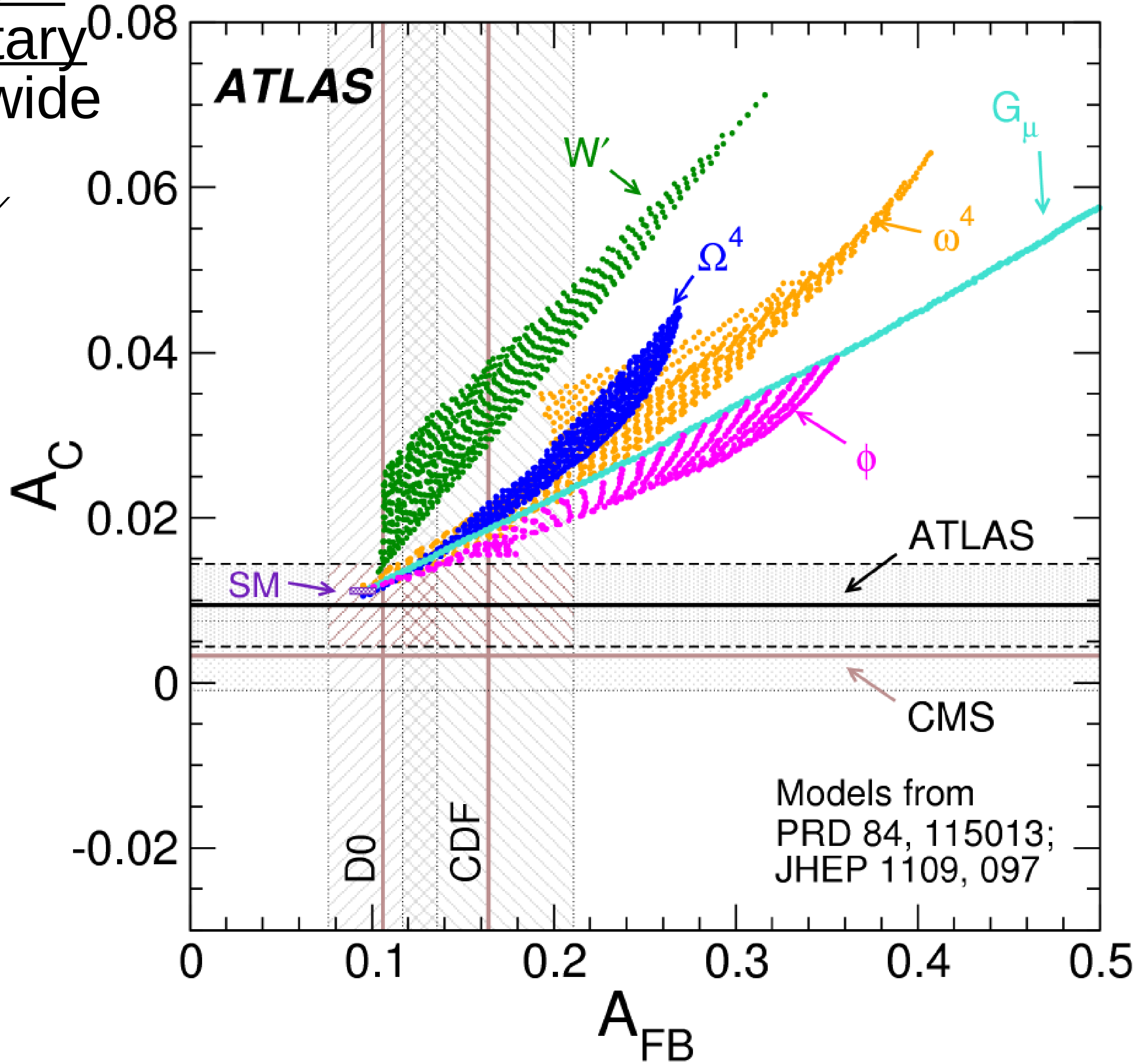
Top quark physics



Top quark asymmetries

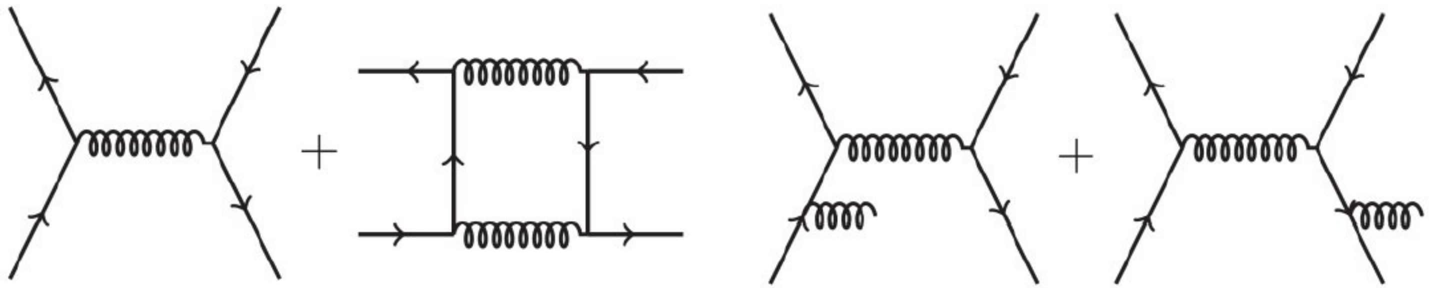
- Measurements at Tevatron & LHC are complementary
  - Variety of models with wide parameter space still allowed W', G, $\mathcal{T}$, Z'

JHEP 1402 (2014)

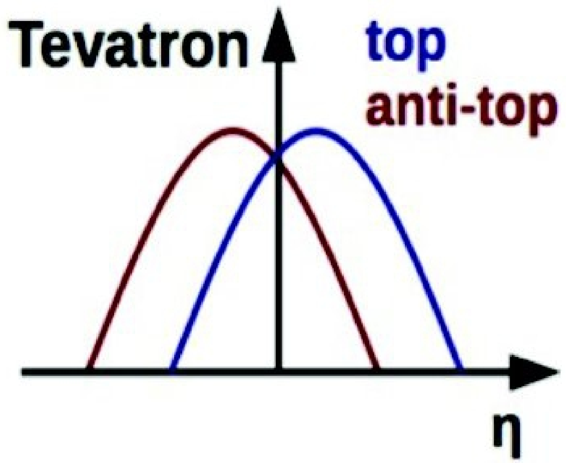


Top quark asymmetries

- <u>Interference appears at NLO QCD:</u>

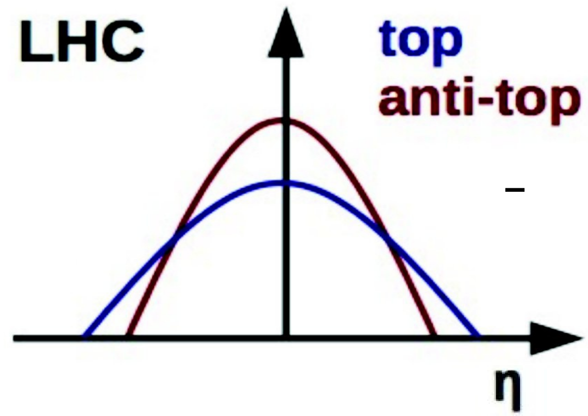


Positive asymmetry   Negative asymmetry



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



- <u>SM predictions at NLO (QCD+EWK)</u>

  Tevatron: $\mathbf{A_{FB}}$ **~ 10 %** vs. LHC: $\mathbf{A_C}$ **~ 1 %**

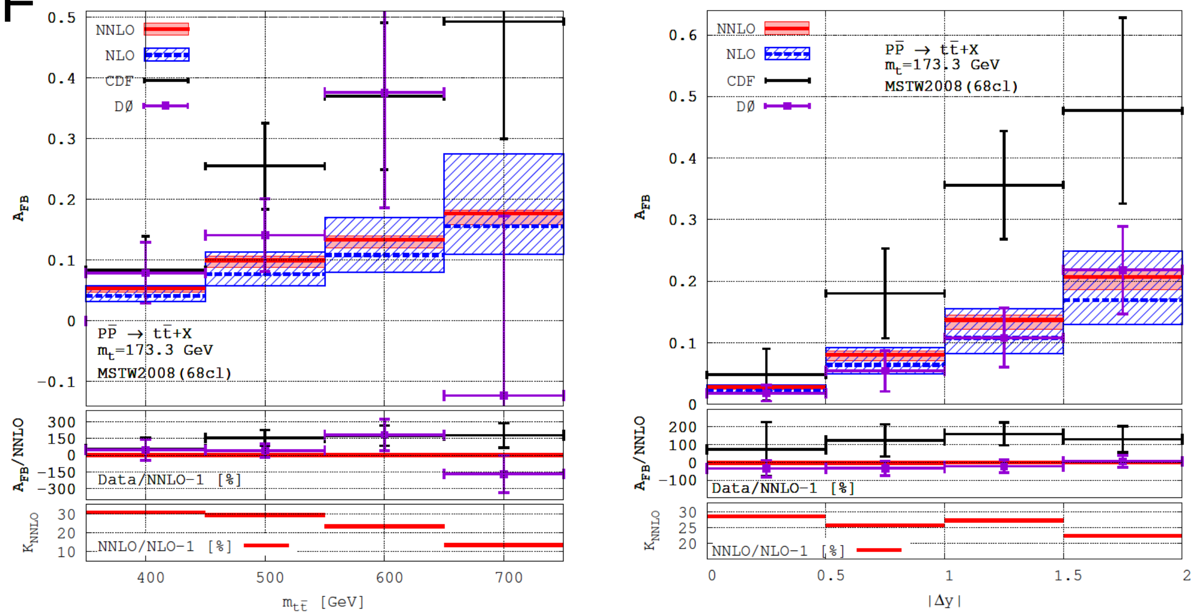
  NNLO+NNLL

- Experimentally: Asymmetries based on <u>decay leptons</u>
  or fully <u>reconstructed top quarks</u>   "easier"

  "harder"

Top quark asymmetries

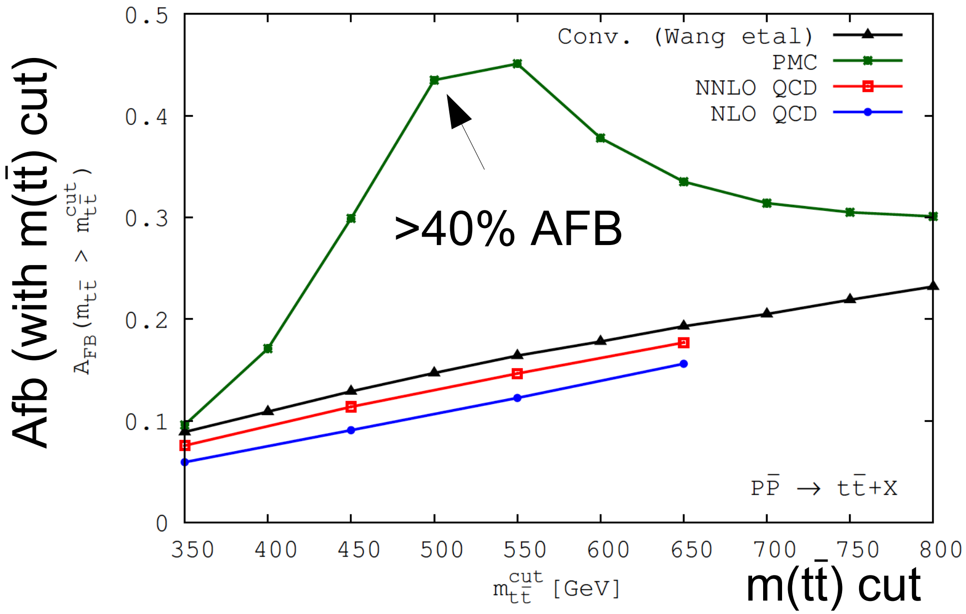
- Differential measurements by CDF and D0: PRD 87 092002
  Phys. Rev. D 90, 072011 (2014)



- Differential theory calculation by Czakon et al.: [arXiv:1601.05375]
  - NNLO+NNLL agrees with differential measurements by D0
  - CDF agrees within < 2 s.d.

- Results at aN3LO by Kidonakis agree with D0 (same caveat for CDF)

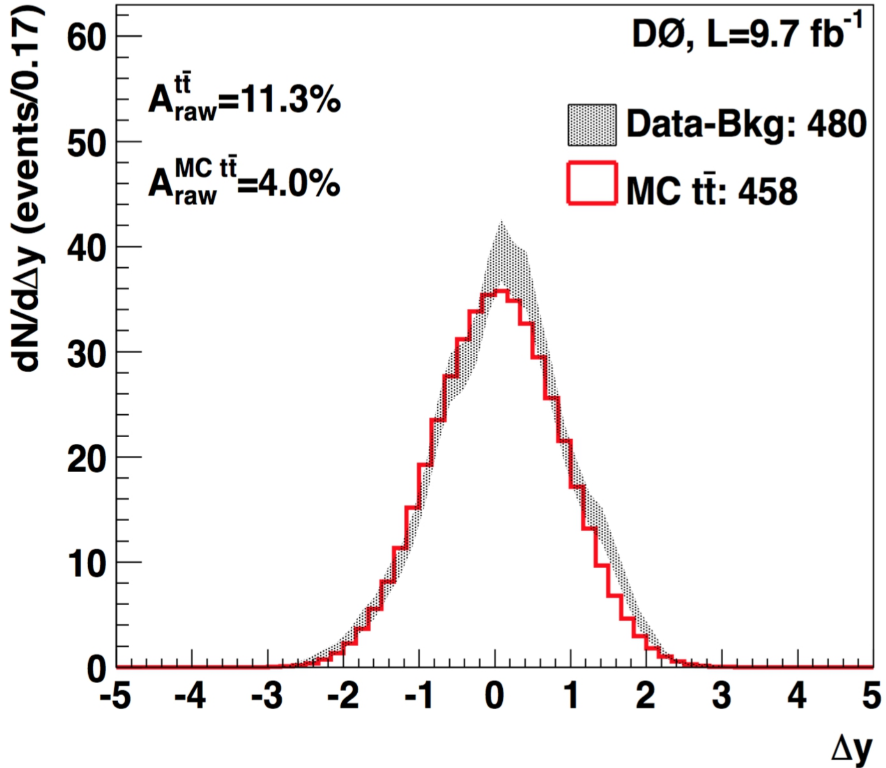
  PRD 91 071502



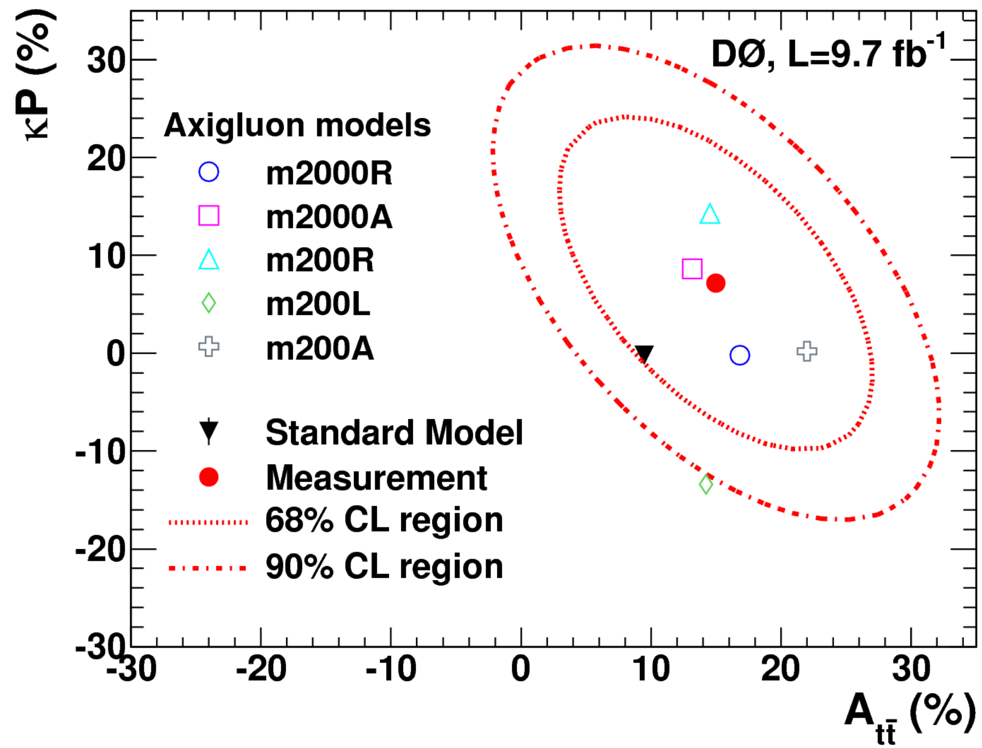
- Scale choice can have large impact on size of Afb
  - Keep in mind for LHC ?!

Top quark asymmetries

- Dilepton channel: Likelihood per event for correct Δy assignment



$$\sum_{events} L_{z_i}(\Delta y_{t\bar{t}}) \text{ vs } \Delta y_{t\bar{t}} \text{ true}$$



- Simultaneous 2D measurement:

A_{FB} = 15.0 ± 8.0 (tot.) %

κP = 7.2 ± 11.3 (tot.) %

Constrain *P* to SM value:

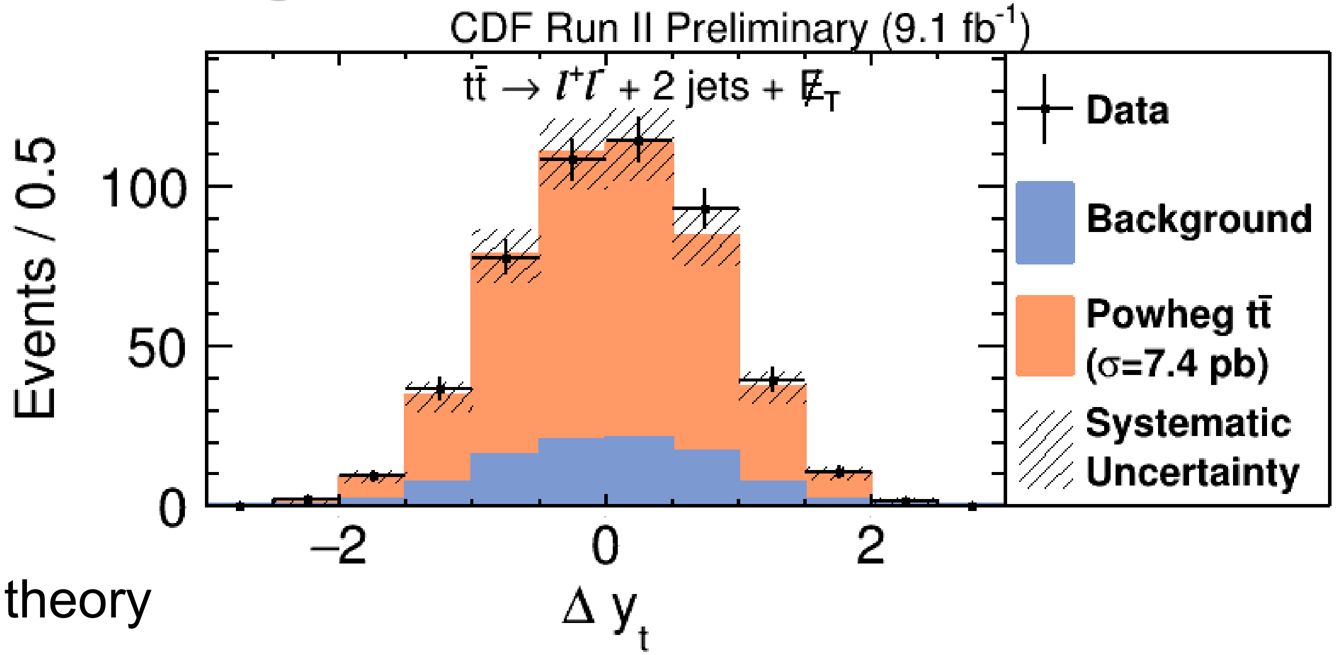
A_{FB} = 17.5 ± 6.4 (tot.) %

(SM polarization essentially 0)

Phys. Rev. D 92, 052007 (2015)

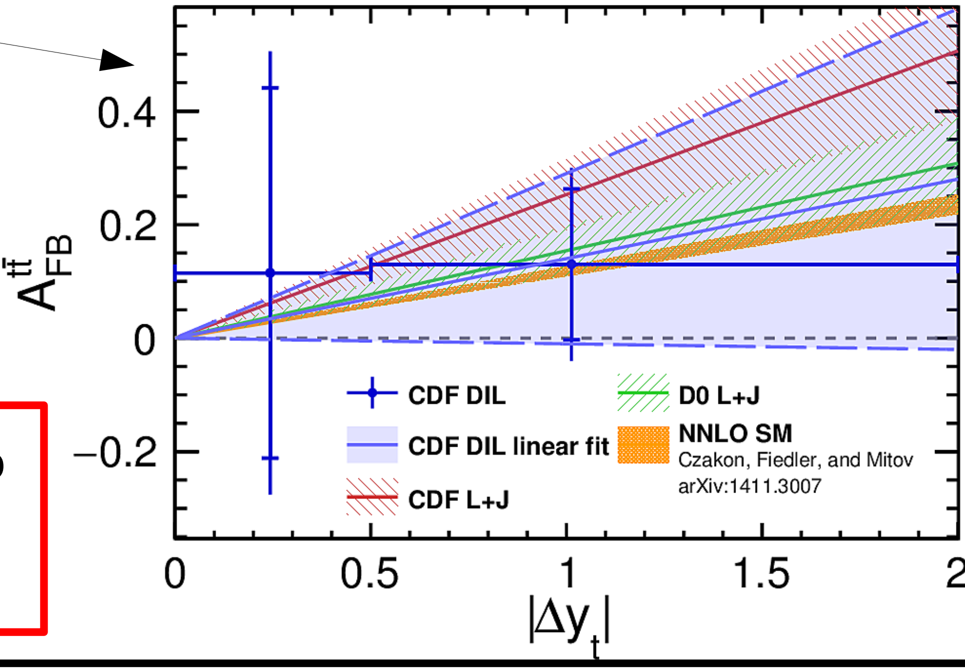
Top quark asymmetries

- Reconstruct in A_{FB} in dilepton events
- Likelihood based kin. Reconstruction
- Probability density dist for each solution



Slope in |Δy| agrees with theory and D0 result in l+jets

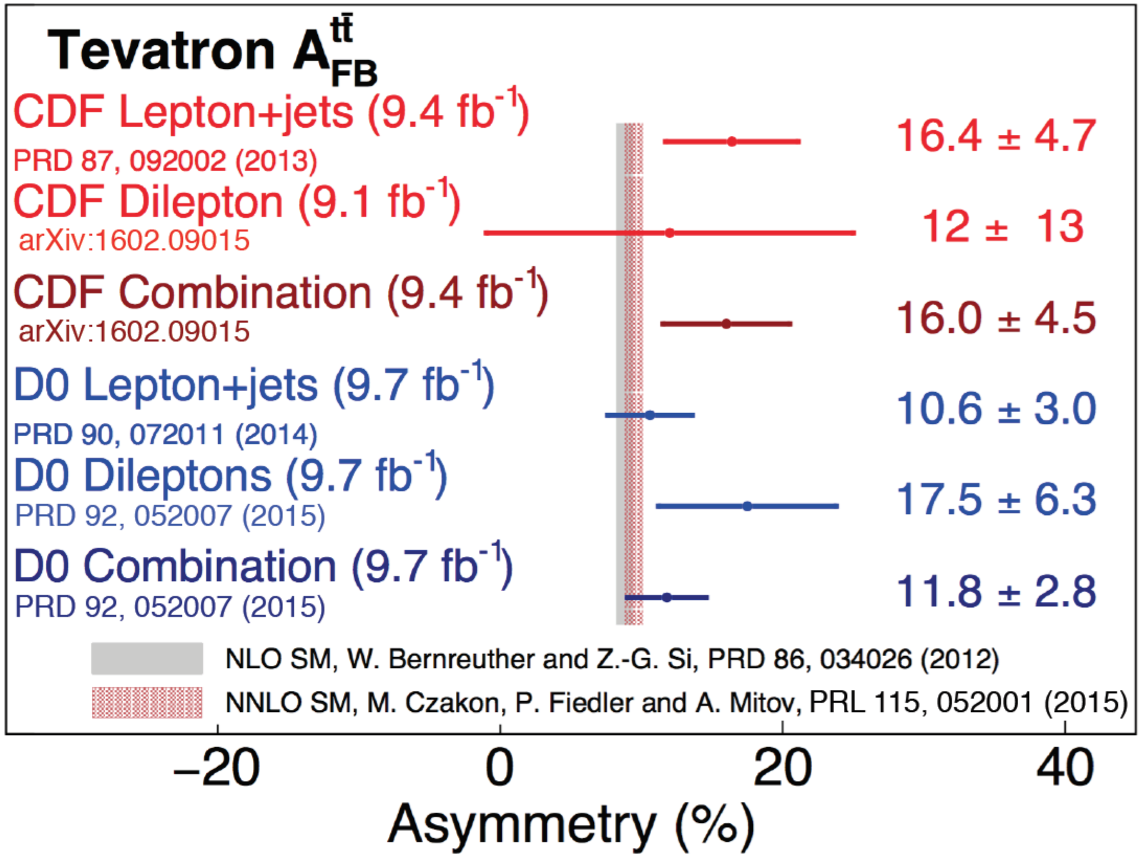
CDF note 11161 (2015)

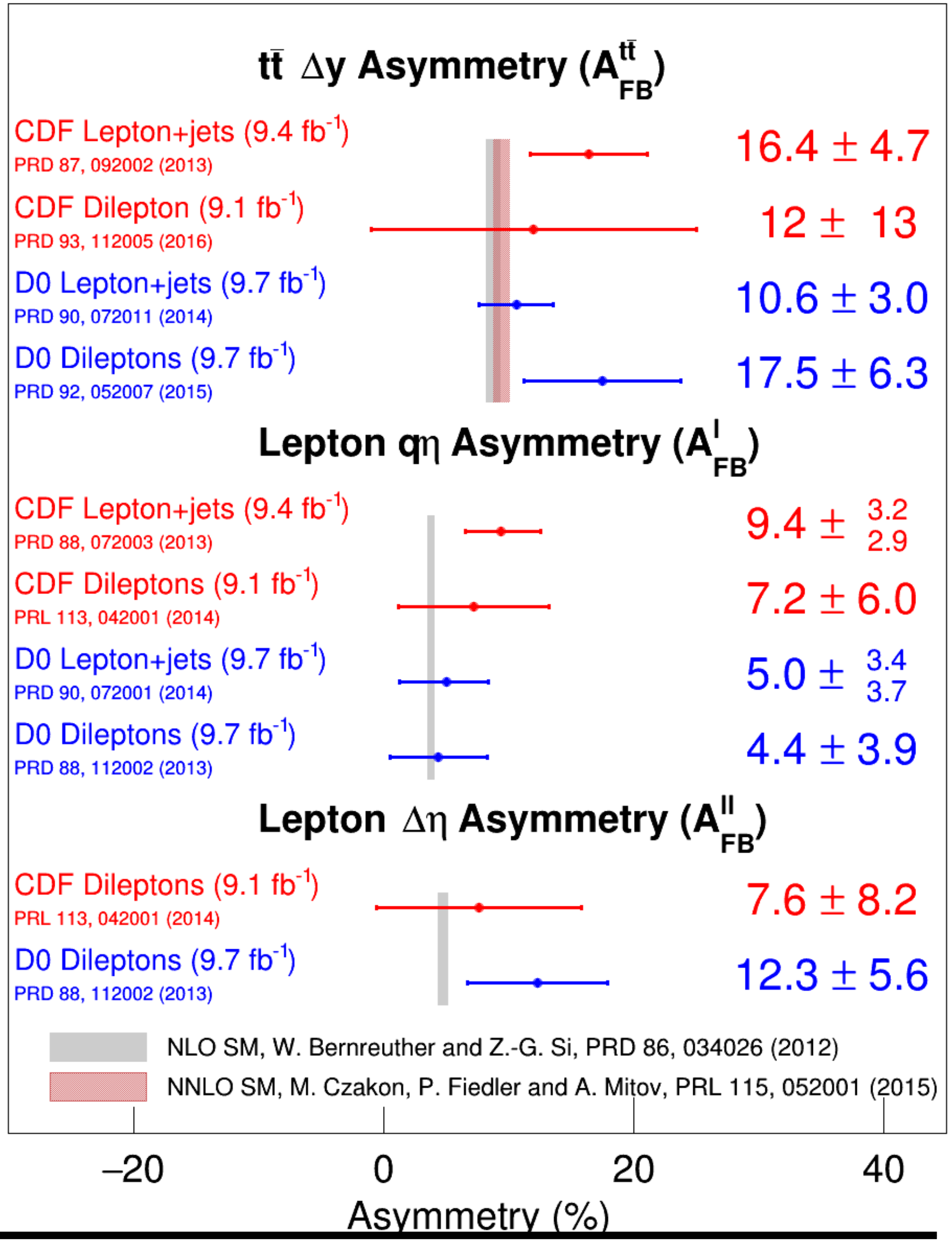


- Agreement with the SM

$$A_{FB} = 12 \pm 11\ (\text{stat.}) \pm 7\ (\text{syst.})\ \%$$
$$A_{FB} = 12 \pm 13\ (\text{tot.})\ \%$$

- Latest combinations:



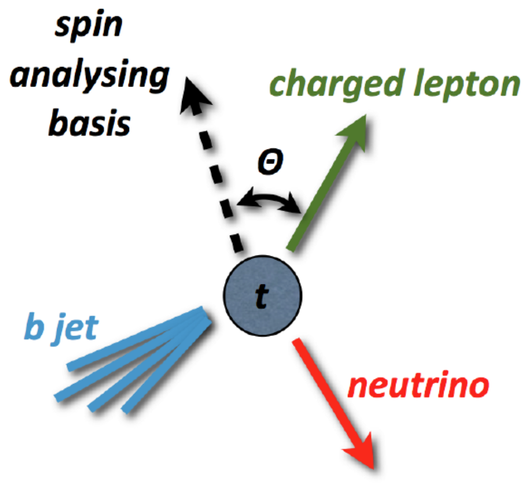


→ Agreement with SM

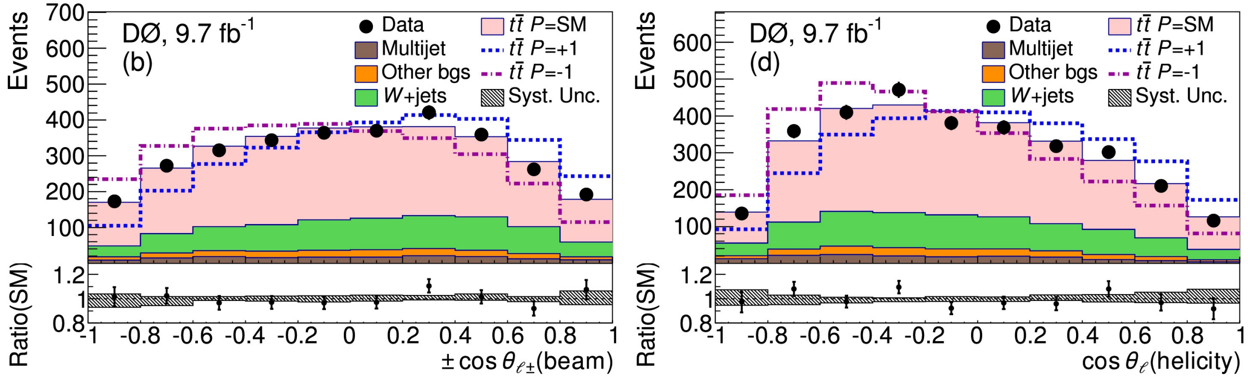
→ Tevatron combination is underway!

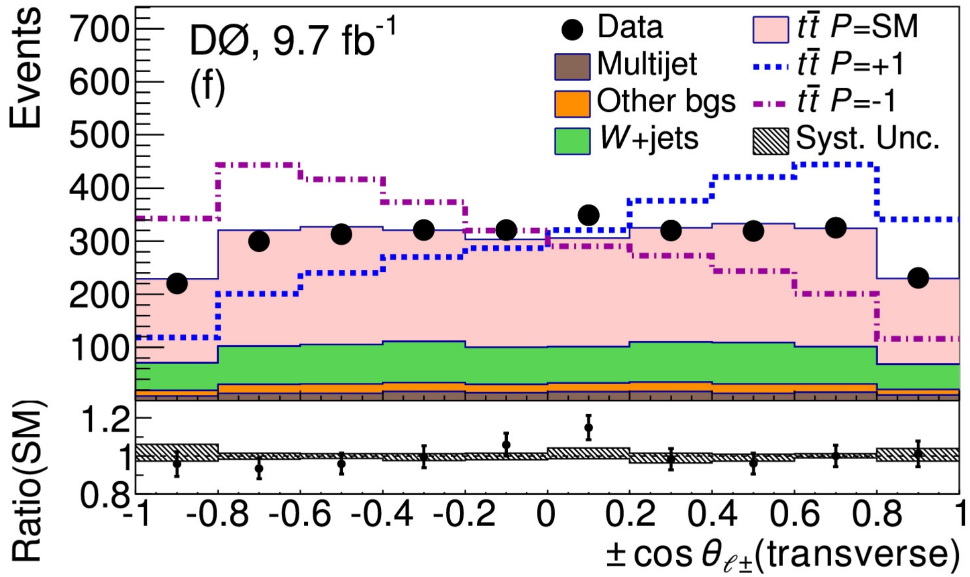
Top quark polarization

- Measure polarization of the top quark:



Subm. to PRL [arXiv:1607.07627]





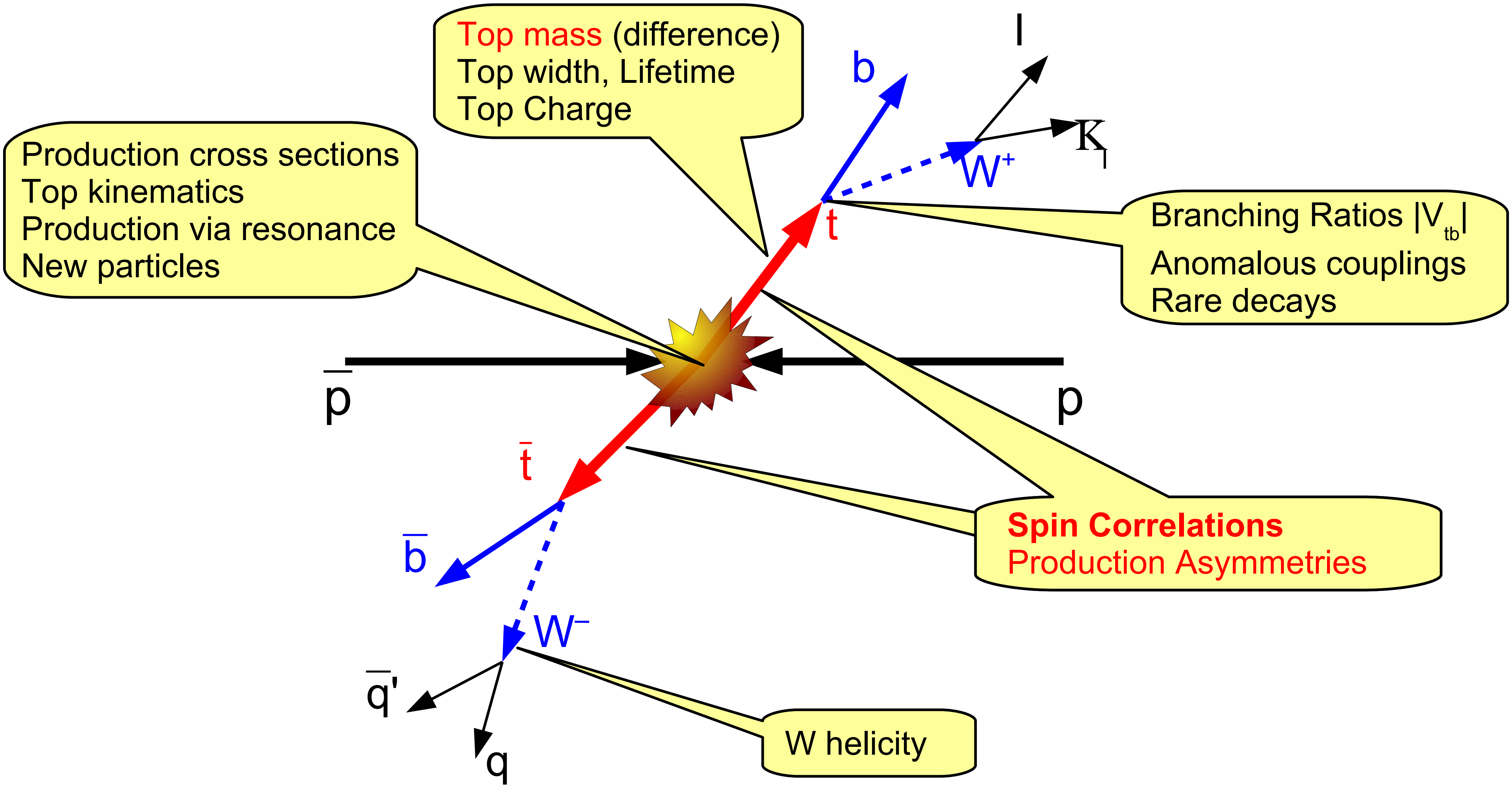
- 1st measurement of the transverse polarization
  - SM expectation is 0
- SM almost 0 for helicity and beam as well

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

→ dilepton & l+jets combination: *P* = 0.081 ± 0.048

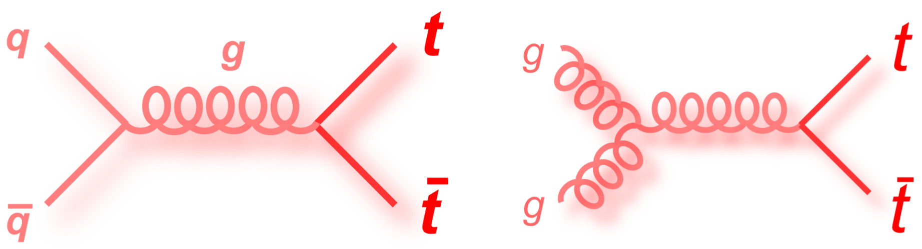
→ In agreement with the SM

Top quark physics



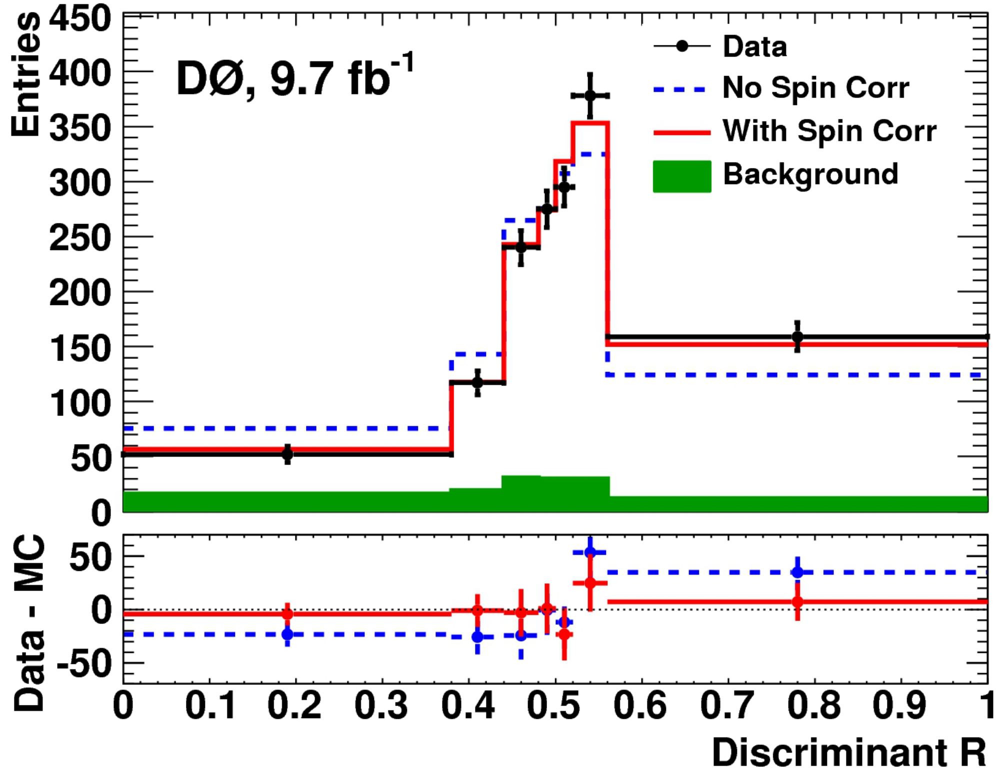
Top quark spin correlations

- This is a different quantity at Tevatron and LHC:
  - Production at threshold and well above
  - *pp* versus *p*$\bar{p}$ collisions



- Complementary to the LHC results
  - e.g. light top quark partners modifies SM spin correlation expectation
- Matrix element technique (ll + l+jets)
  - Optimized off-diagonal basis

Phys. Lett. B 757, 199 (2016)



$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u)+P_{\rm sgn}(H=c)}$$

O_{off} = 0.89 ± 0.22 (tot.)

$O_{off,\ MC@NLO}$ = 0.766

Evidence for spin correlation:
4.2 s.d. (observed)

Summary & Outlook

- Very successful Tevatron top quark program
- Precision measurements of Top Quark properties at Tevatron (all employing full Run II data set)
  - All results at 1.96 TeV in $p\bar{p}$ **confirm that top quark behaves as expected in SM**
- **Complementary** results at different energy and initial state!
- More legacy Tevatron combinations (mass, Afb, cross section) to come...plus a new mass extraction from differential cross sections

Only small limited selection of results shown, more information:

CDF Top Web pages   D0 Top Web pages

Thank you!

Backup

Top quark production

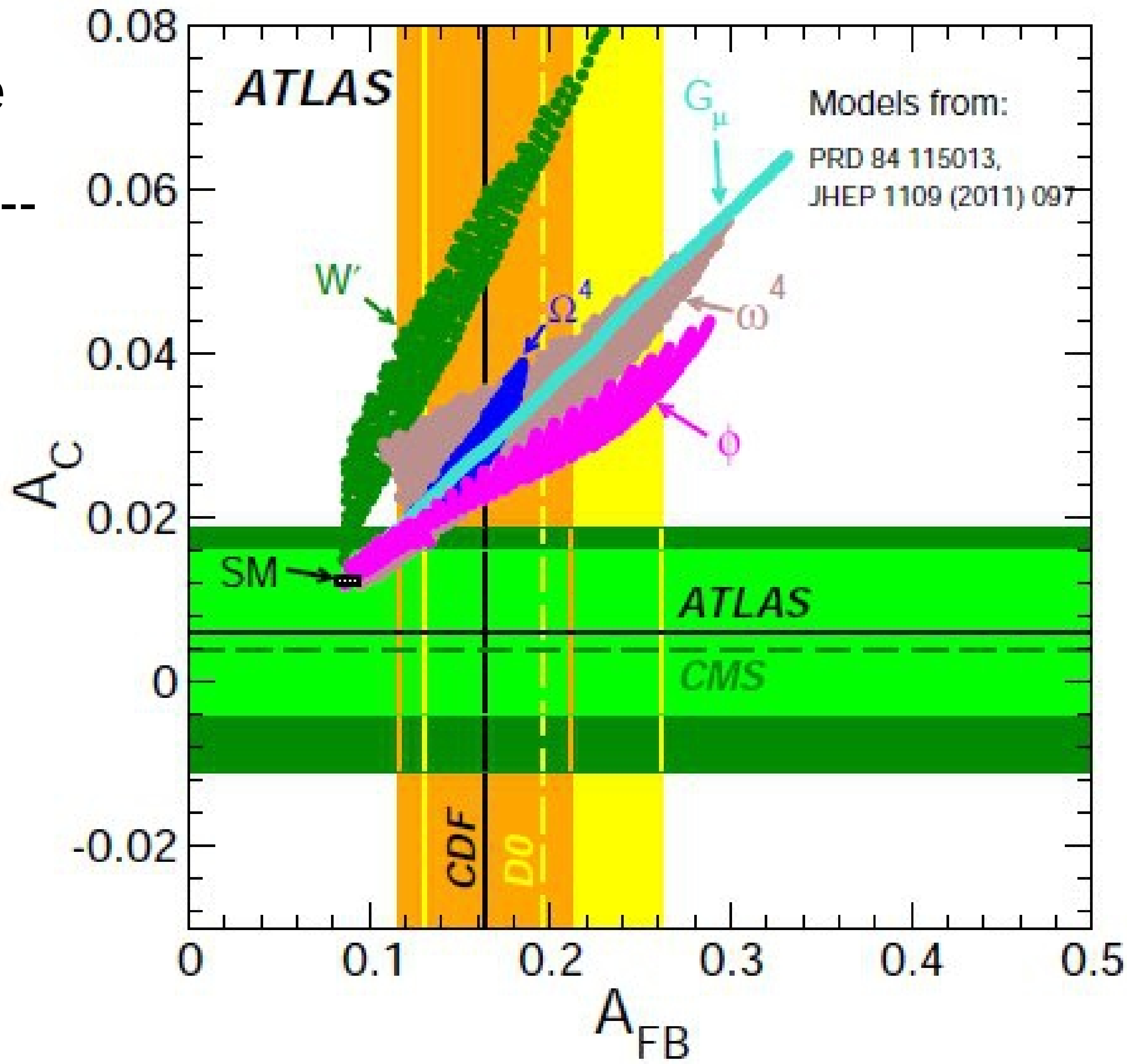
- List of systematic uncertainties, dominant are luminosity, hadronization, jet modeling, signal generator

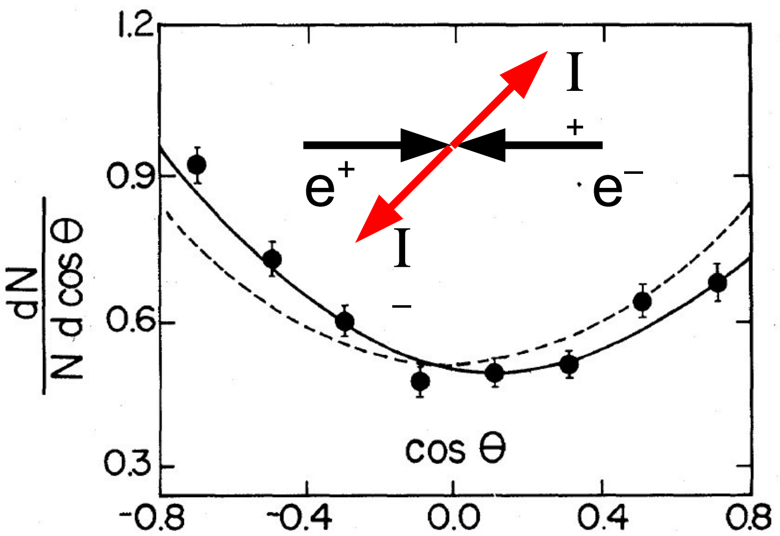
D0 [arxiv:1605.06168]

Source of uncertainty	$\delta_{\ell+\text{jets}}$, pb	$\delta_{\ell\ell}$, pb	$\delta_{\text{comb},}$, pb	Shift, pb
Signal modeling				
Signal generator	±0.21	±0.05	±0.17	$+0.08$
Hadronization	±0.26	±0.33	±0.25	$+0.12$
Color reconnection	±0.08	±0.05	±0.09	$+0.02$
ISR/FSR variation	±0.08	±0.04	±0.06	-0.05
PDF	±0.04	±0.03	±0.02	-0.01
Detector modeling				
Jet modeling & ID	±0.11	±0.08	±0.04	$+0.07$
b-jet modeling & ID	±0.27	±0.26	±0.23	-0.15
Lepton modeling & ID	±0.20	±0.26	±0.17	-0.11
Trigger efficiency	±0.32	±0.08	±0.16	$+0.01$
Luminosity	±0.30	±0.30	±0.27	$+0.10$
Sample Composition				
MC cross sections	±0.07	±0.13	±0.09	$+0.01$
Multijet contribution	±0.11	±0.02	±0.10	$+0.10$
W+jets scale factor	±0.21	±0.01	±0.15	-0.50
Z/γ^*+jets scale factor	±0.07	±0.11	±0.12	$+0.12$
MC statistics	±0.01	±0.01	±0.02	$+0.00$
Total systematic uncertainty (quadratic sum)	±0.70	±0.64	±0.60	
Total systematic uncertainty (central COLLIE)	±0.67	±0.73	±0.55	

Top quark asymmetries

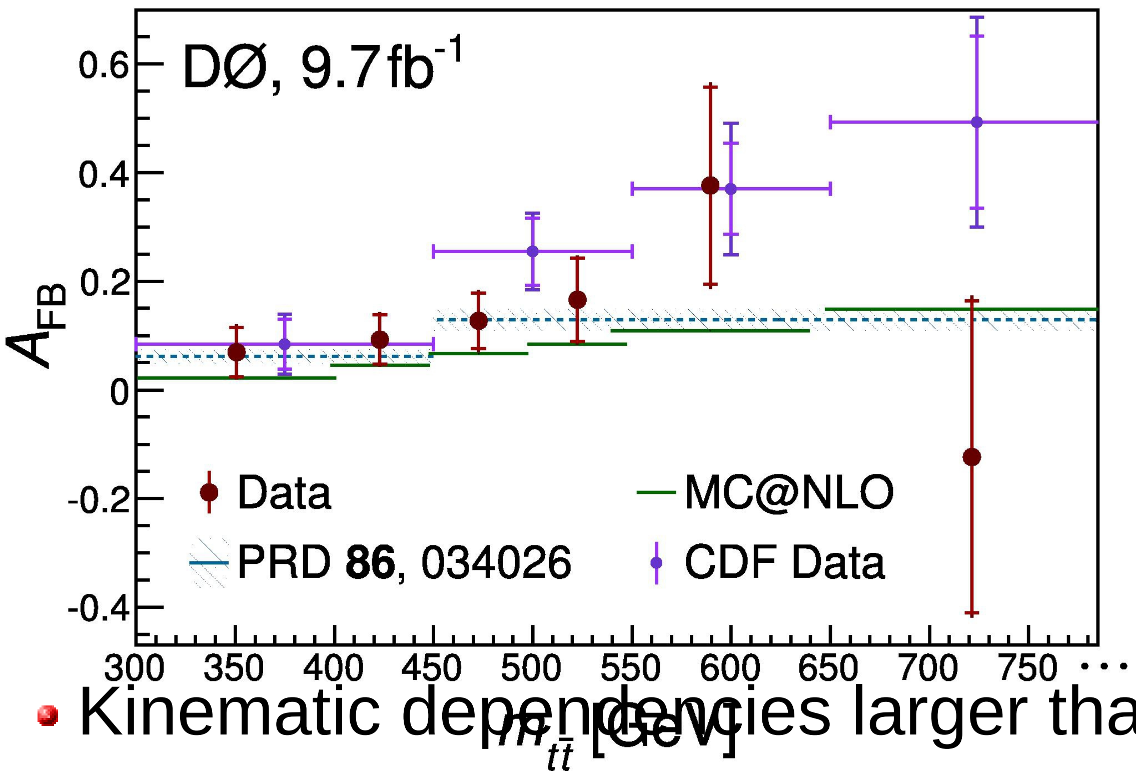
- Measurements at Tevatron & LHC are complimentary
  - Variety of models with wide parameter space still allowed
    > *W′*, *G*, *T*, *Z*′
- MARK-J at √s = 34.6 GeV

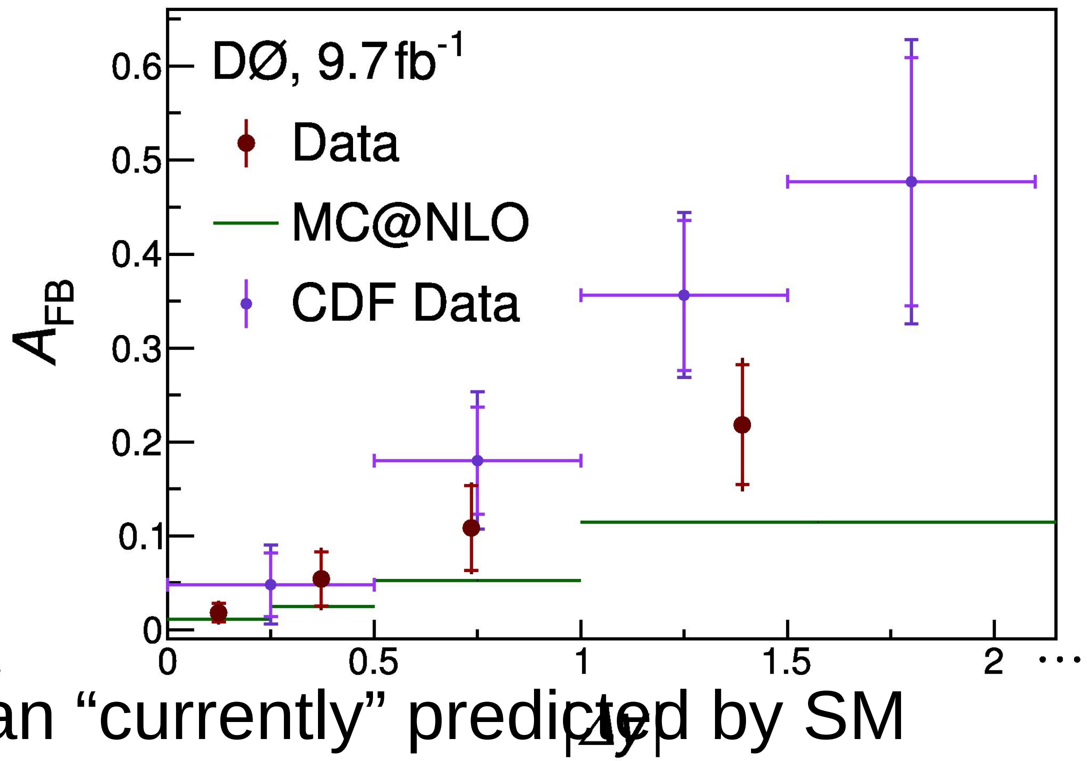




Top quark asymmetries

- Updated D0 measurement (improvements beyond "lumi-scaling")
- Existing CDF measurement in l+jets decay channel also measured kinematic dependence of A_{FB} PRD 87 092002





- Kinematic dependencies larger than "currently" predicted by SM

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

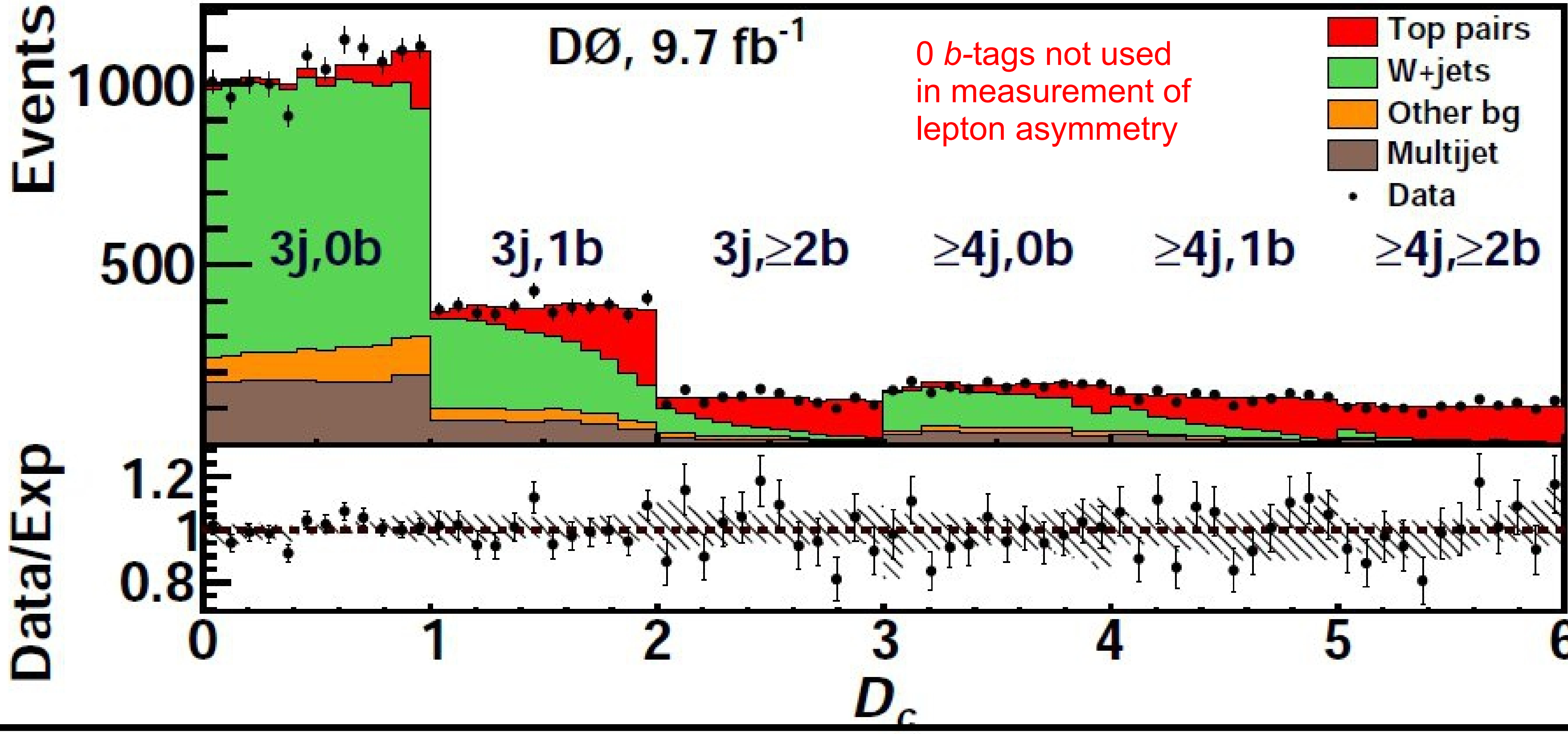
D0 agrees with SM within uncertainties
CDF higher than SM predictions

Lepton asymmetries

[arxiv:1403:1294]

Reminder: Leptonic asymmetries less affected by reconstruction effects

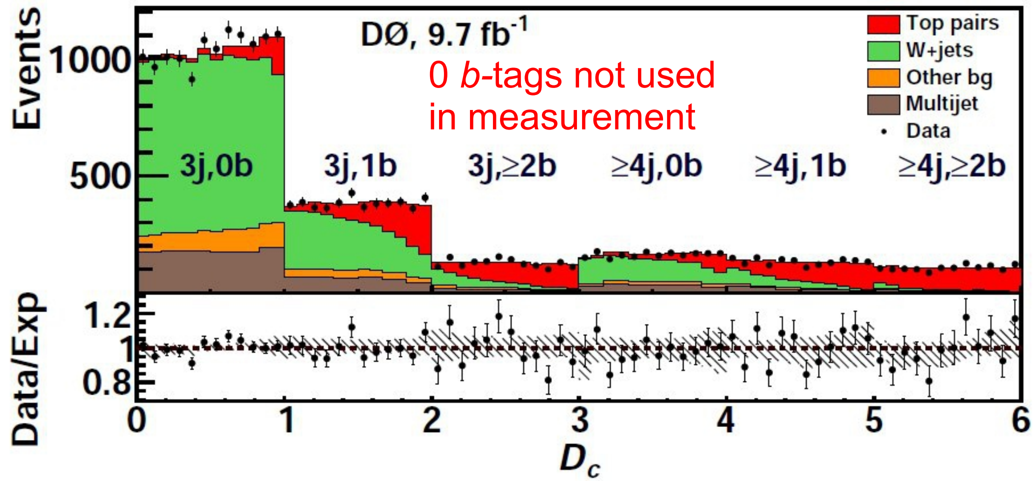
- lepton+jets, updated measurement of leptonic asymmetries
- Discriminant D_c to determine sample composition
- **Final measurements**, need to maximize acceptance & precision
  Include the 3 jet bin
  - Larger contribution of backgrounds in 3 jet bin
    need to calibrate W+jets, use 0*b*-tag

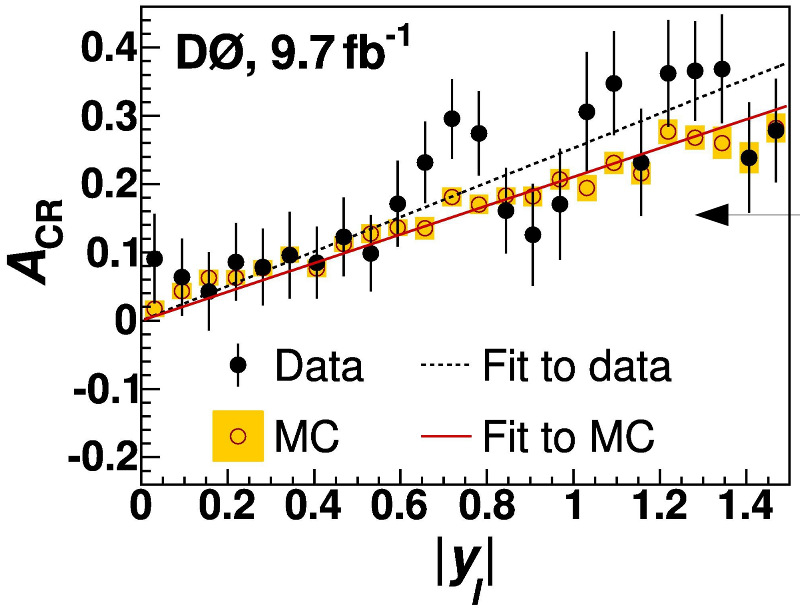


Lepton asymmetries

[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



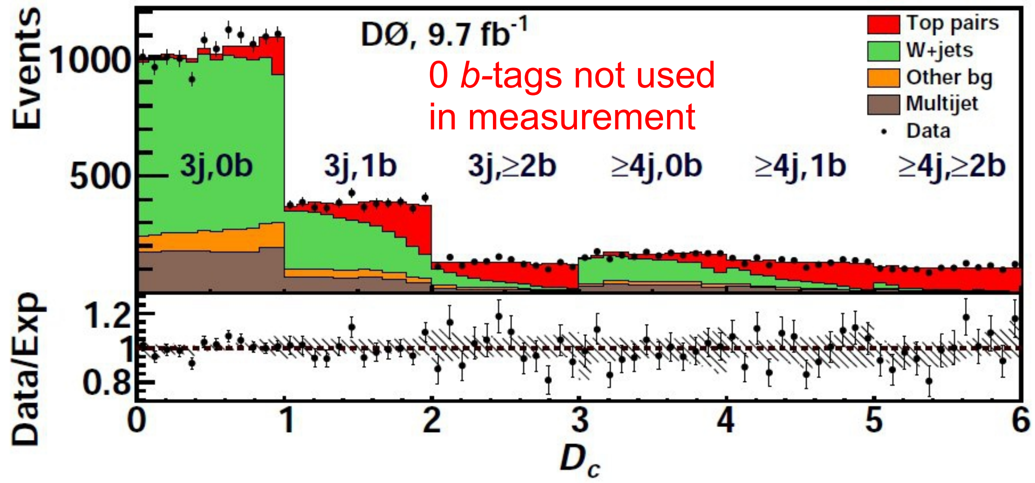


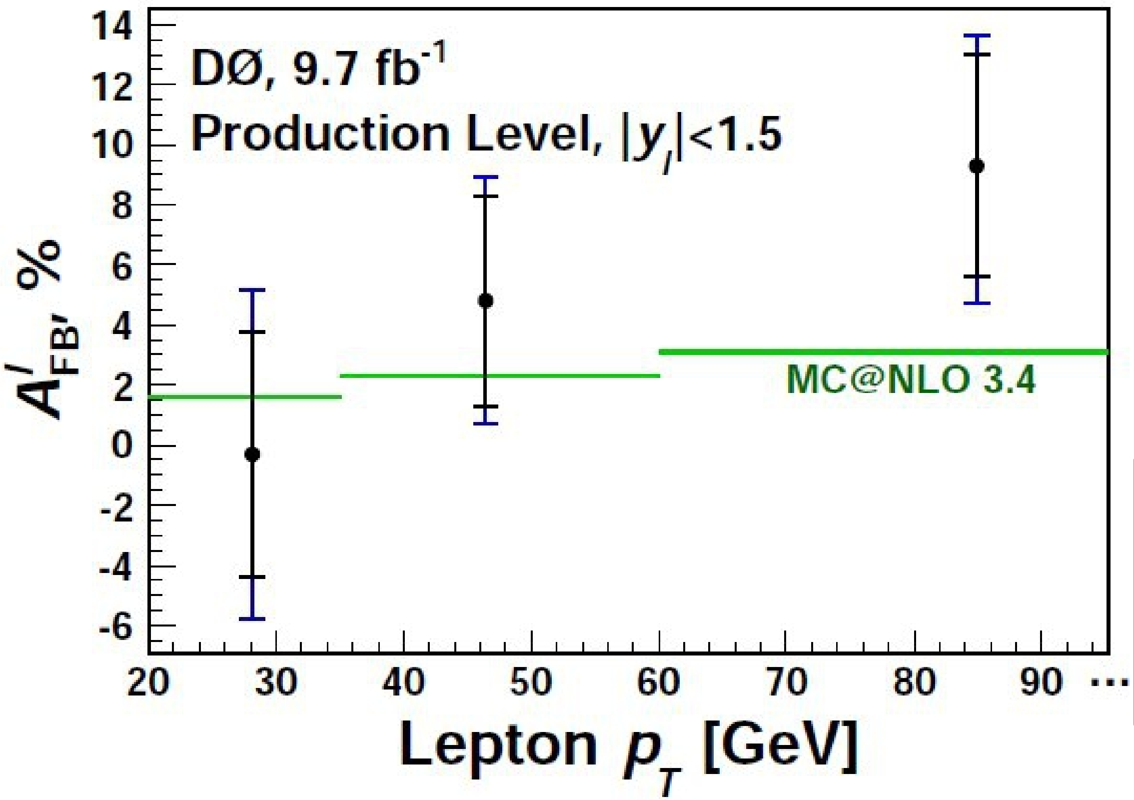
- Asymmetry in W+jets control region (CR) different from MC
- PDF uncertainty shown by yellow bars
- Full difference between data and MC slope taken as systematic uncertainty

Lepton asymmetries

[arxiv:1403:1294]

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





In agreement with SM:

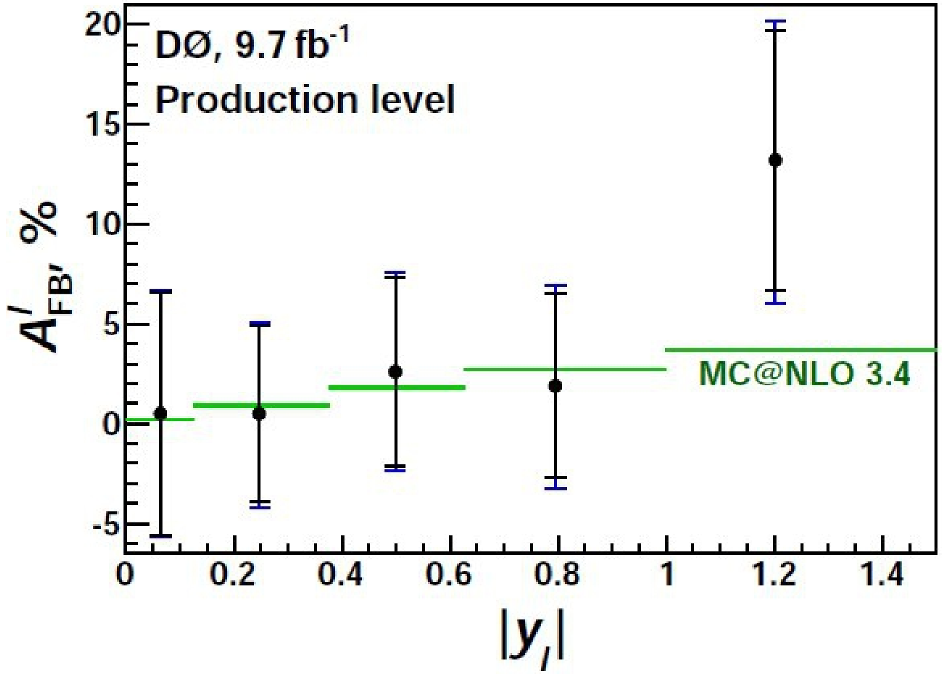
$A_l = 4.2 \pm 2.3$ (stat.) $\pm^{1.7}_{2.0}$ (syst)

Combined l+jets & dilepton:

$A_l = 4.2 \pm 2.0$ (stat.) ± 1.4 (syst.) %

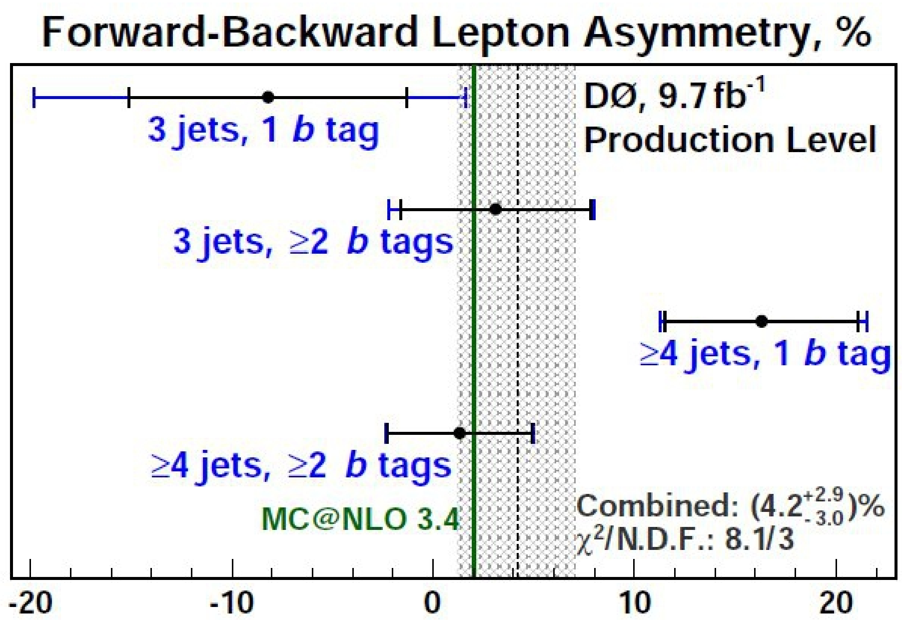
MC@NLO: 2%

Top quark 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	$-6.8 \pm 6.0\,(\mathrm{stat.})^{+6.1}_{-5.6}\,(\mathrm{syst.})$	2.7 ± 0.4
l+3 jets, ≥2 b tags	$3.7 \pm 4.3\,(\mathrm{stat.})^{+1.1}_{-1.2}\,(\mathrm{syst.})$	2.8 ± 0.3
l+≥4 jets, 1 b tag	$14.8 \pm 4.2\,(\mathrm{stat.})^{+1.1}_{-1.2}\,(\mathrm{syst.})$	0.5 ± 0.3
l+≥4 jets, ≥2 b tags	$-0.9 \pm 3.2\,(\mathrm{stat.})^{+0.3}_{-0.9}\,(\mathrm{syst.})$	1.1 ± 0.2
Total	$2.9 \pm 2.1\,(\mathrm{stat.})^{+1.5}_{-1.7}\,(\mathrm{syst.})$	1.6 ± 0.2



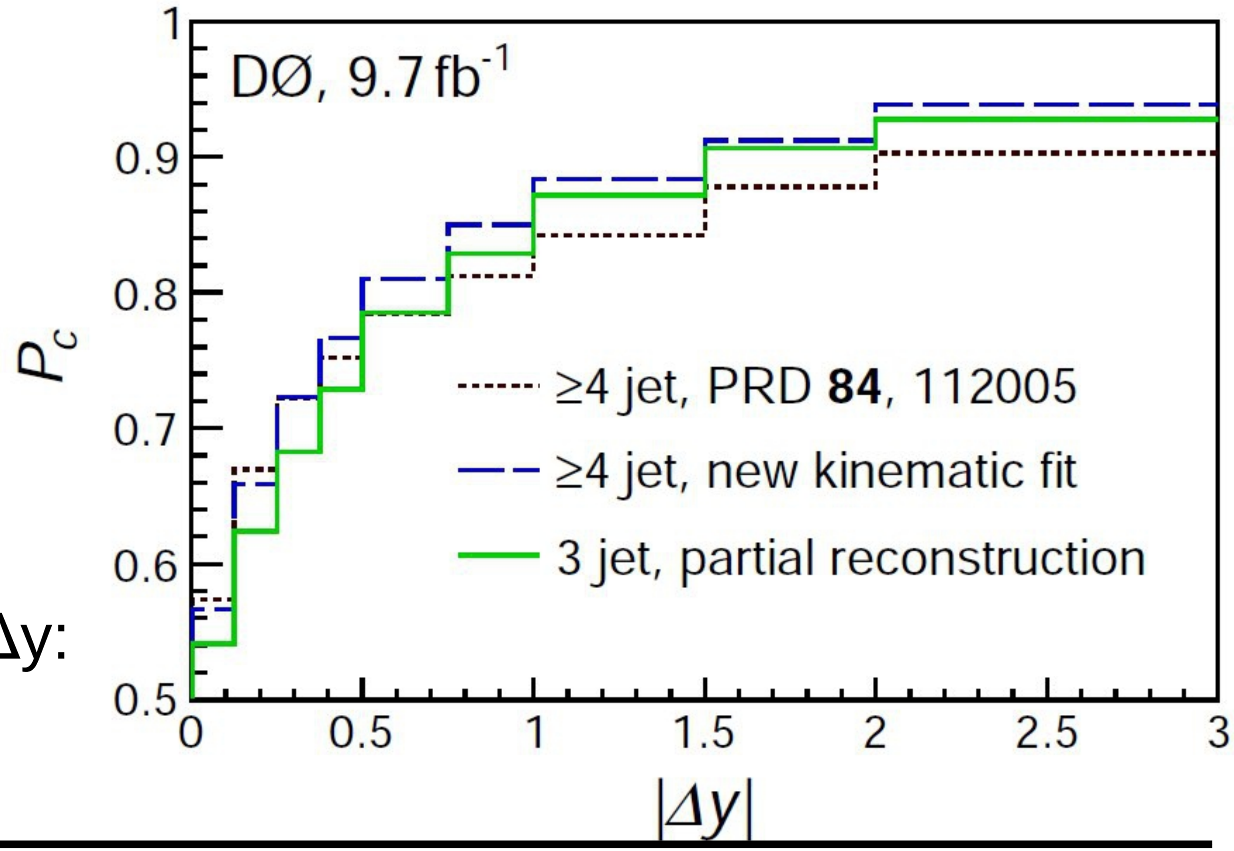
Top quark asymmetries

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

Partial $t\bar{t}$ reconstruction:

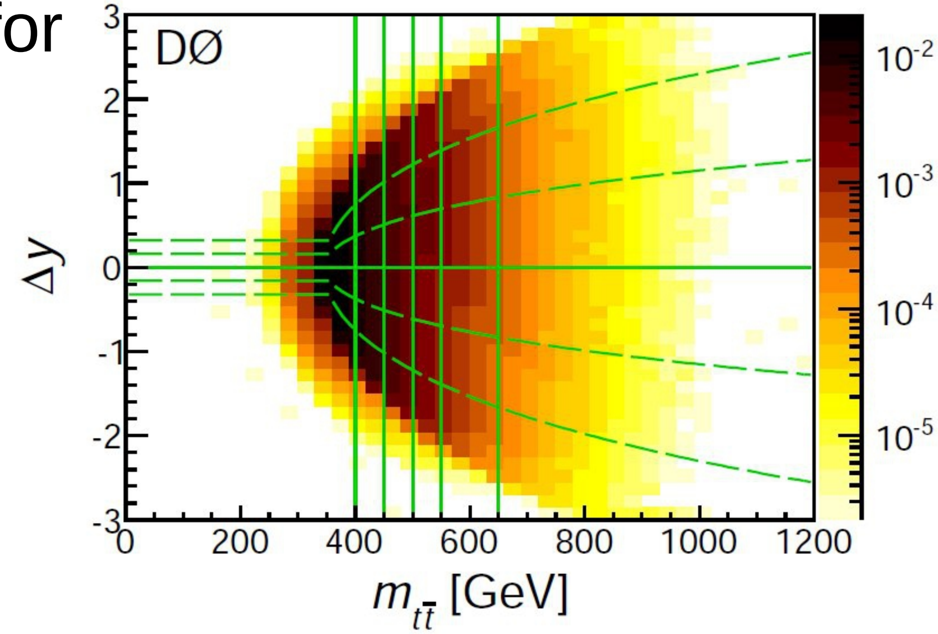
- Lost jet is from hadronic top decay (80%)
- Reconstruct leptonically decaying top and one jet
- Use a proxy for hadronically decaying top using two other jets
- Construct a likelihood & correctly reconstruct sign of Δy:

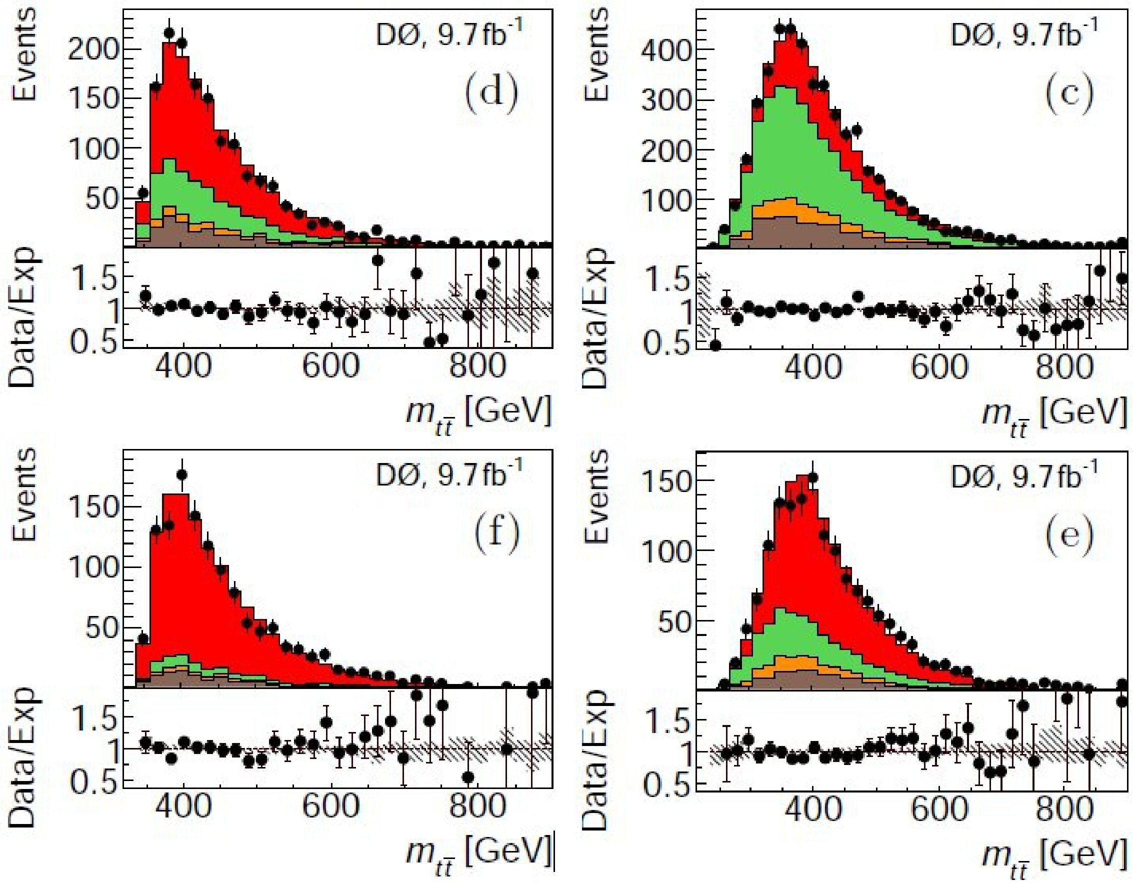
→ P_C (≥ 4j) = 77.6 %
P_C (= 3j) = 74.5 %

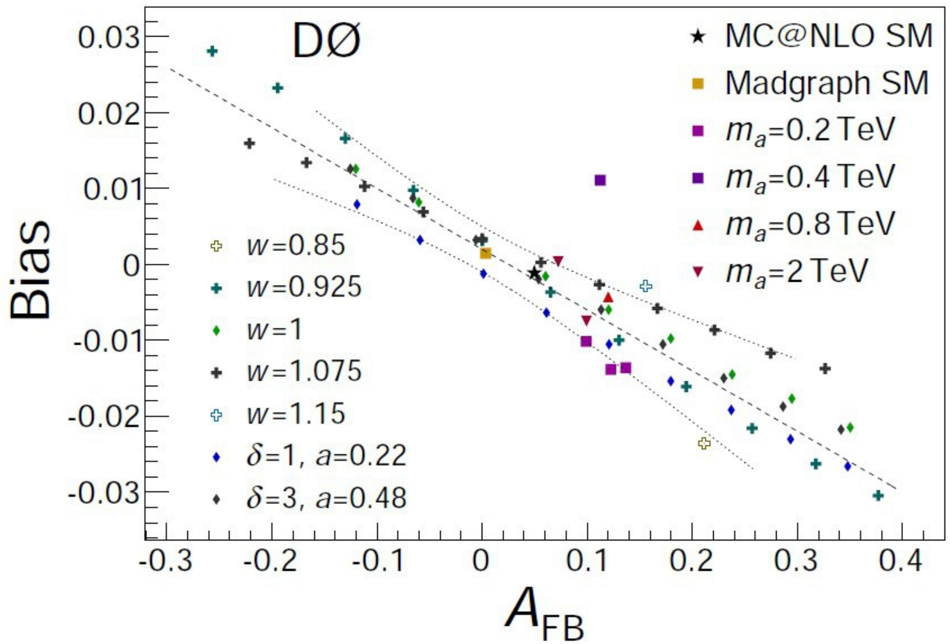


Top quark asymmetries

- Shares sames selection as the one for the leptonic asymmetry
- Get the mass dependence of A_{FB}:
  - Need 2D regularized unfolding





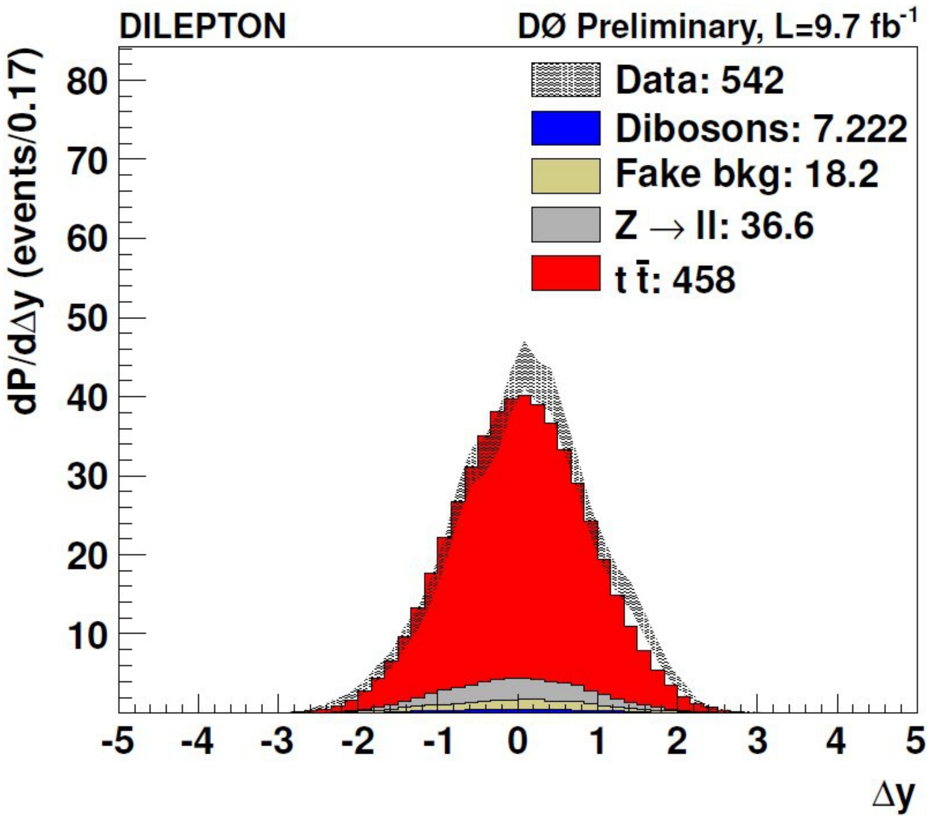


Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method:

  assign a likelihood per event for most probably Δy value

$$\sum_{events} L_{z_i}(\Delta y_{t\bar{t}}) \text{ vs } \Delta y_{t\bar{t}} \text{ true}$$

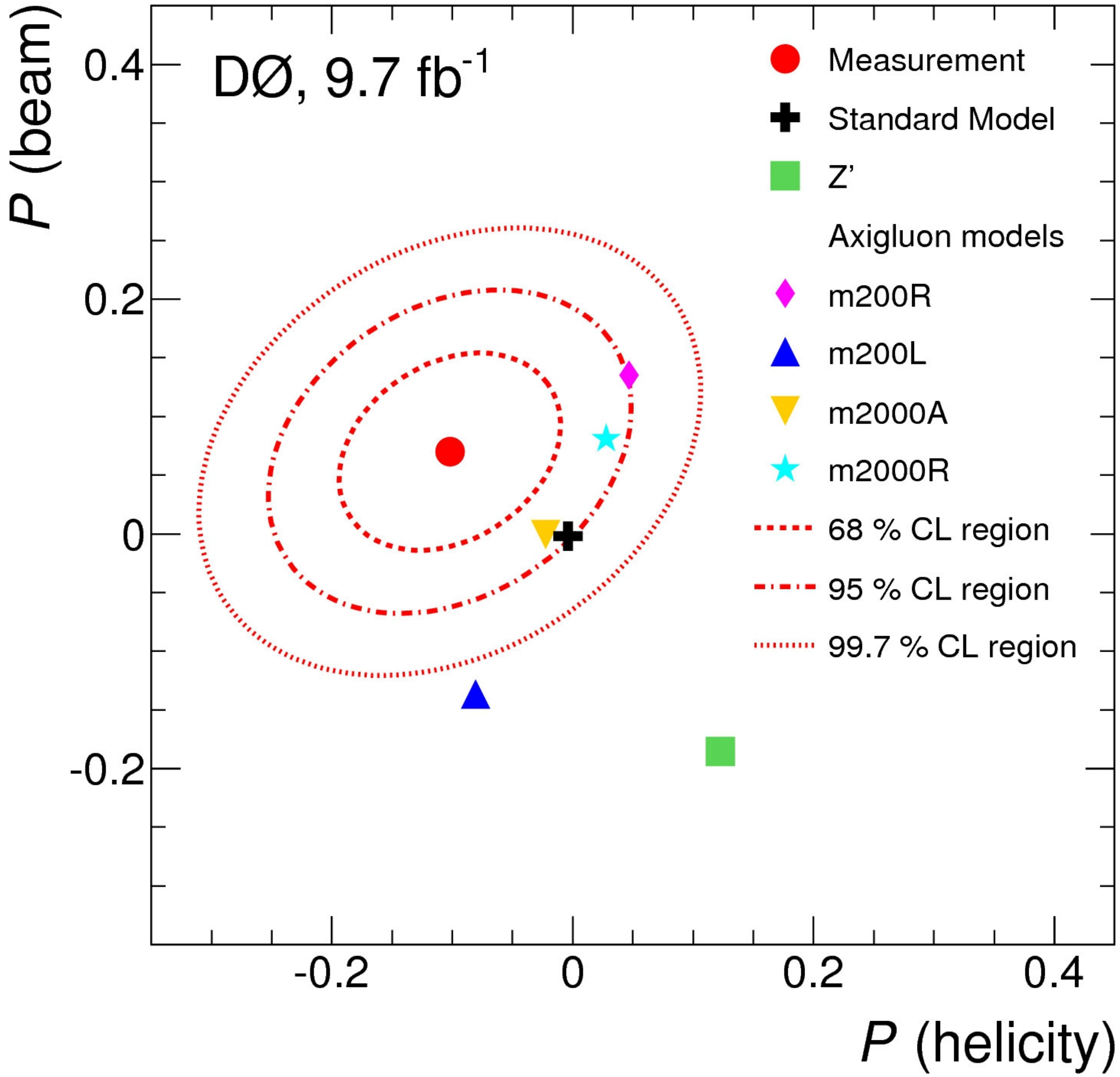


Source of uncertainty	Uncertainty on $A_{\mathrm{FB}}^{t\bar{t}}$ (%)
Detector modeling	
jet energy scale	0.14
jet energy resolution	0.17
flavor-dependent jet response	0.03
b-tagging	0.11
Signal modeling	
ISR/FSR	0.32
forward/backward ISR	0.36
hadronisation and showering	1.08
higher order correction	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

- Control distributions show reasonable modeling by MC extract asymme

Top quark polarization

Subm. to PRL [arXiv:1607.07627]



Source	Beam	Helicity	Transverse
Jet reconstruction	±0.010	±0.008	±0.008
Jet energy measurement	±0.010	±0.023	±0.006
b tagging	±0.009	±0.014	±0.005
Background modeling	±0.007	±0.021	±0.004
Signal modeling	±0.016	±0.020	±0.008
PDFs	±0.013	±0.011	±0.003
Methodology	±0.013	±0.007	±0.004
Total systematic uncertainty	±0.030	±0.042	±0.015
Total statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.061	±0.034

Axi gluon & 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

	$\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [pb]
Data	$8.27^{+0.92}_{-0.91}$ (stat. + syst.)
NNLO pQCD (SM)	$7.24^{+0.23}_{-0.27}$ (scales + pdf)

	$\Delta\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [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)

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

Acc. by PRD [arxiv:1309.7570]

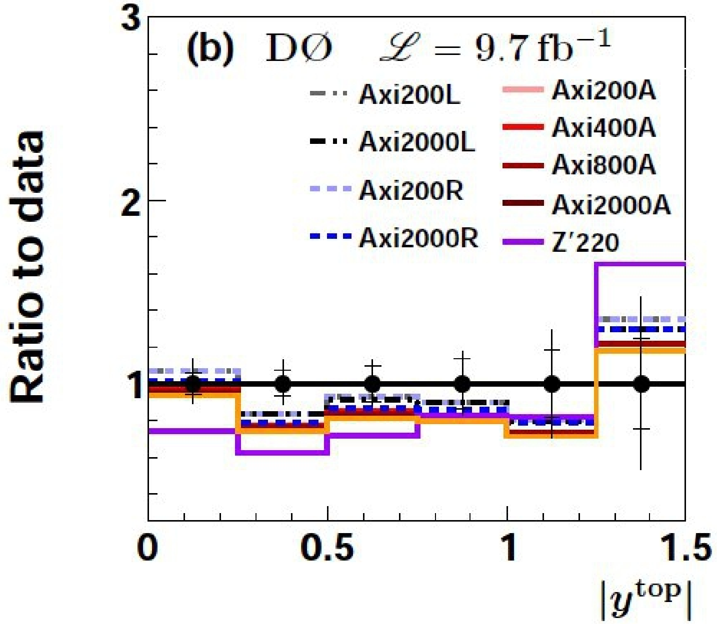
CMS [arxiv:1309.2030]

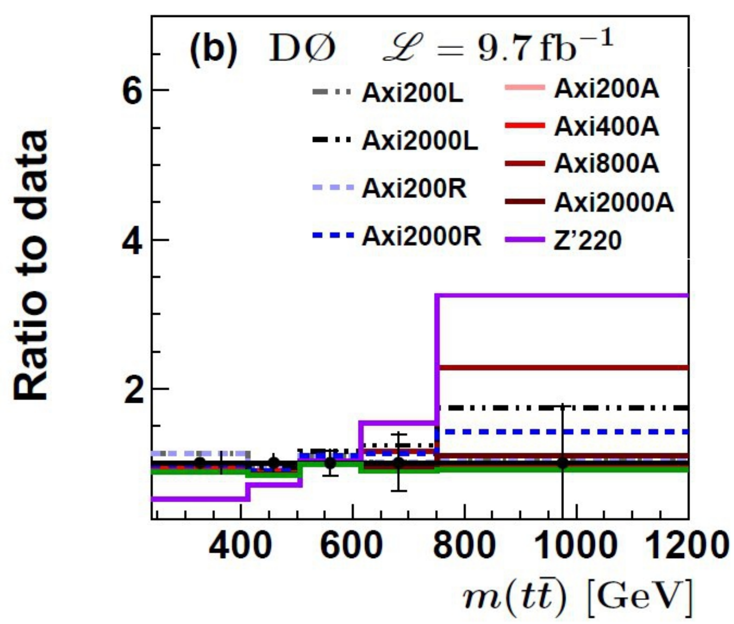
D0 [arxiv:1401.5785]

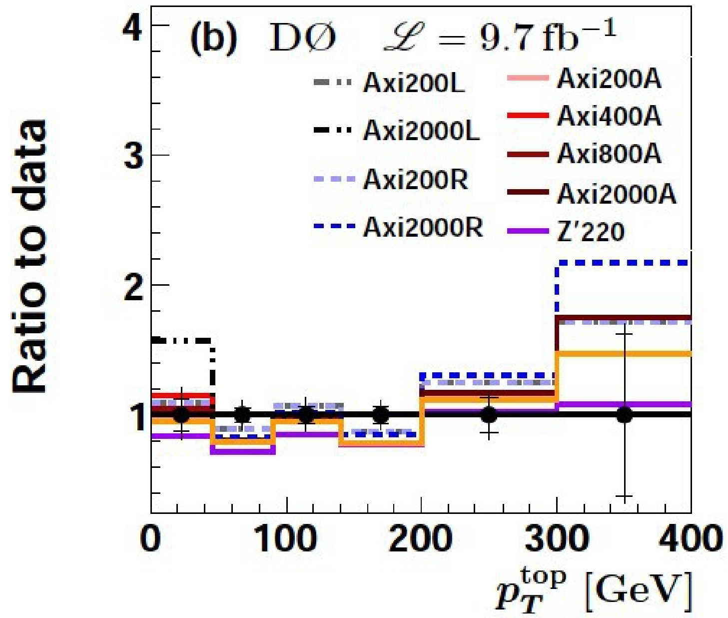
CDF PRL 102 222003

Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Reminder: High tail is used to constrain models
- Reminder: Bins are correlated, needs to be taken into account: χ^2 based on full covariance matrix
- Clearly some models are in tension with the presented data !
  - Z'
  - Various axi gluons







Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Reminder: High tail is used to constrain models
- Reminder: Bins are correlated, needs to be taken into account: ↺ based on full covariance matrix
- Clearly some models are in tension with the presented data !
  - Z'
  - Various axi gluons

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

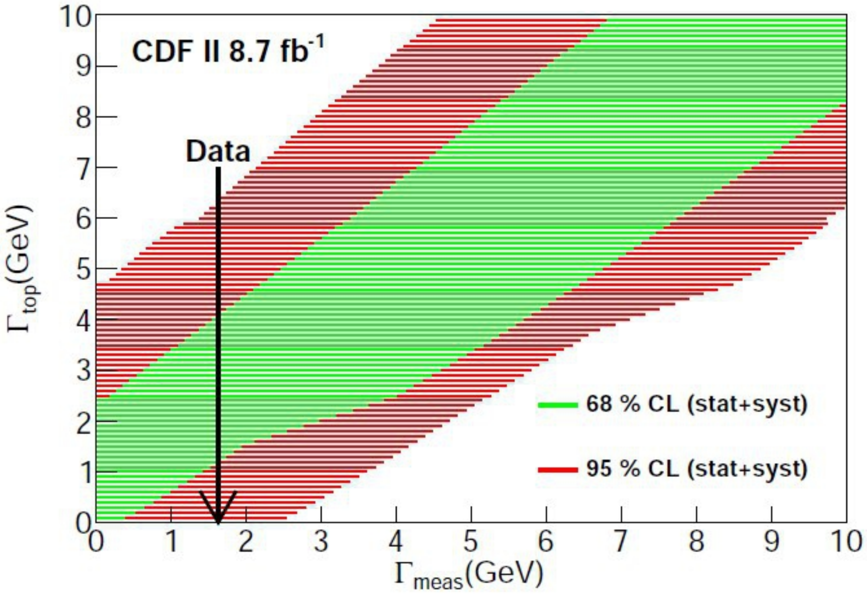
	$M(t\bar{t})$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$	$\lvert y^{\mathrm{top}}\rvert$ $[\chi^2/ndf]$
axi200L	0.96	1.07	1.20
axi200R	0.96	1.07	1.20
axi200A	0.85	3.55	3.88
axi400A	0.44	2.65	3.26
axi800A	0.97	2.86	3.23
axi2000L	0.58	1.27	3.78
axi2000R	0.43	1.94	2.75
axi2000A	0.88	3.56	4.11
Z'220	4.95	8.27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

→ Tevatron data adds sensitivity at low mass
Specific models heavily constrained

Top quark width

Source	Uncertainty (%)
Single-top quark t-channel cross section	9.2
μ_R / μ_F	4.3
JES	0.7
pileup	0.8
ME-PS	0.8
μ_R / μ_F	0.8
top-quark mass	0.6
Other sources	1.5
Total systematic	10.4

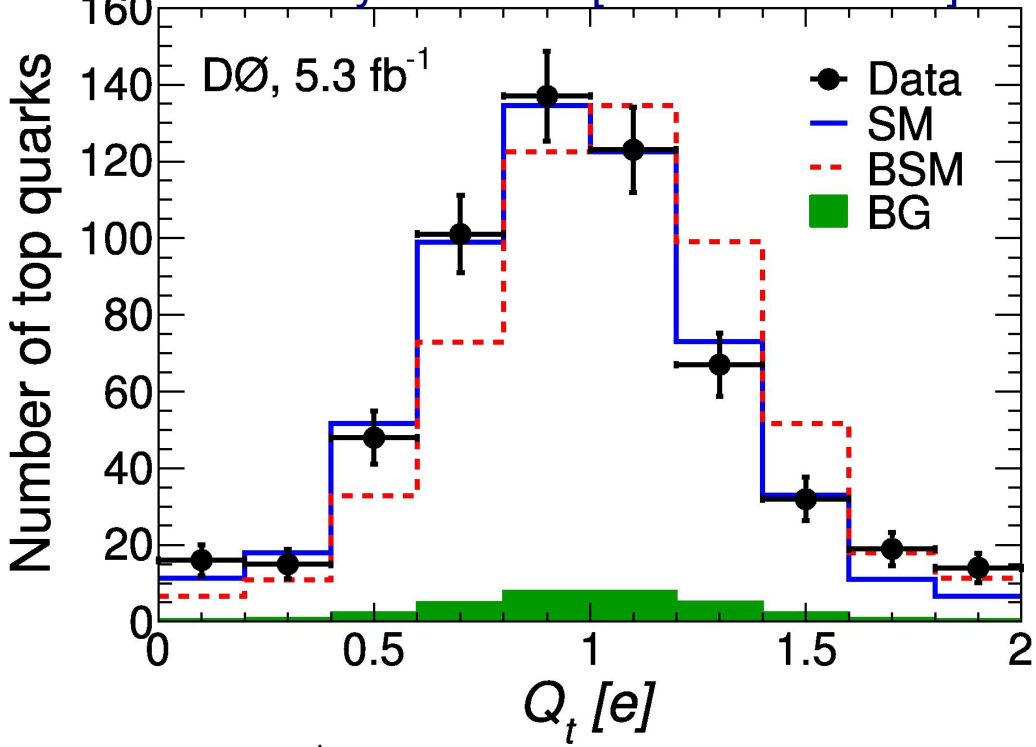
$$\Gamma_t = 1.36 \pm 0.02\,(\text{stat.})^{+0.14}_{-0.11}\,(\text{syst.})\,\text{GeV}$$

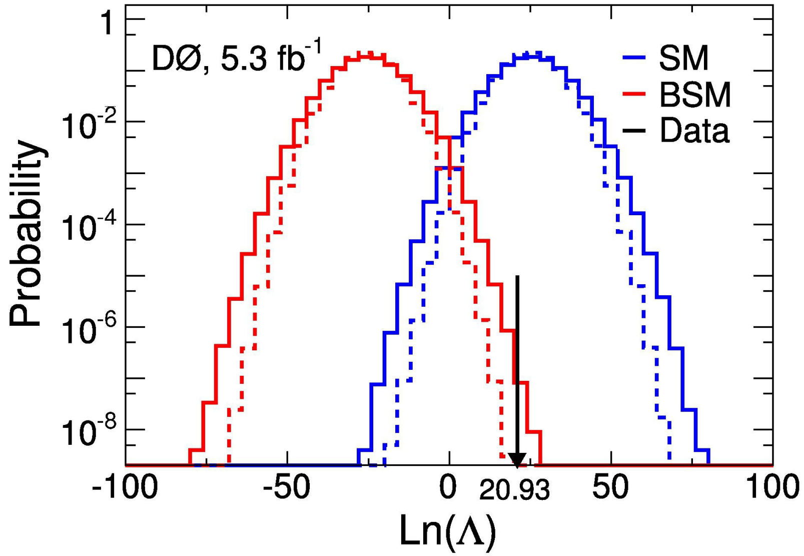


Top charge

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

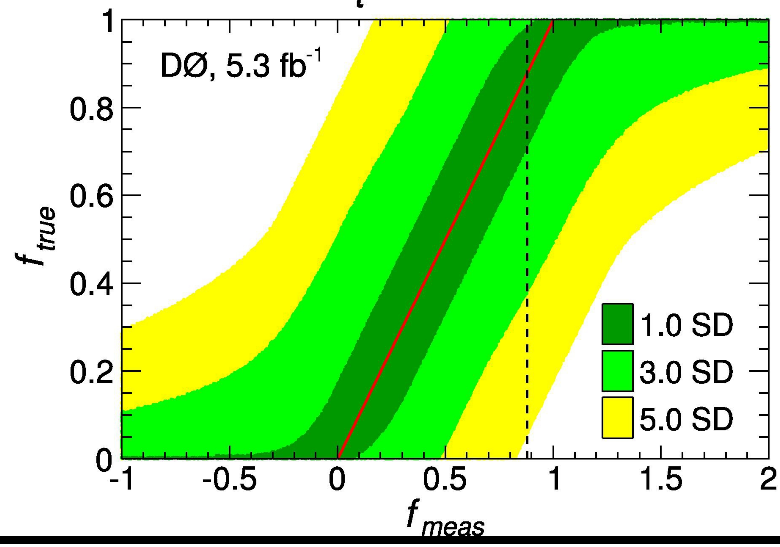
Acc. by PRD-RC [arxiv:1407.4837]





- Fraction of BSM quarks

→ $\boxed{F_{BSM} < 0.46 \text{ @ } 95\% \text{ C.L.}}$



- Conf rmed earlier measurements