Top quark properties at Tevatron

On behalf of the CDF and D0 collaborations

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Top Workshop 2016, Olomouc, 19-23 Sep 2016

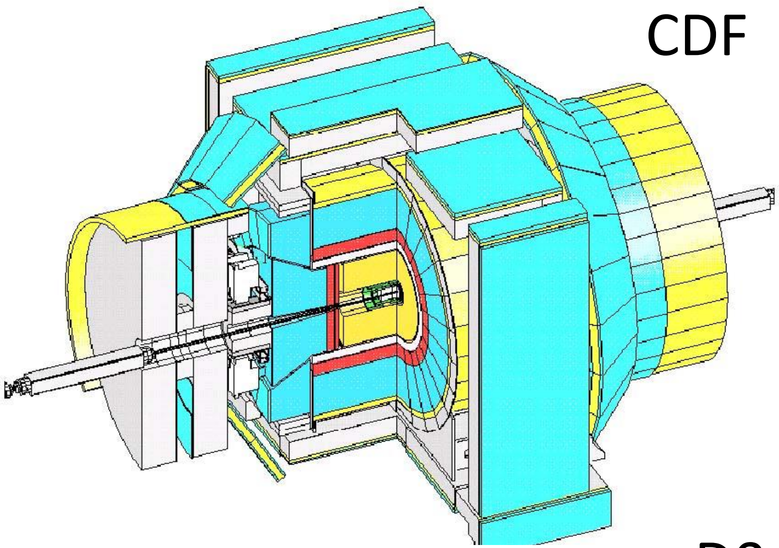
Topics in This Talk

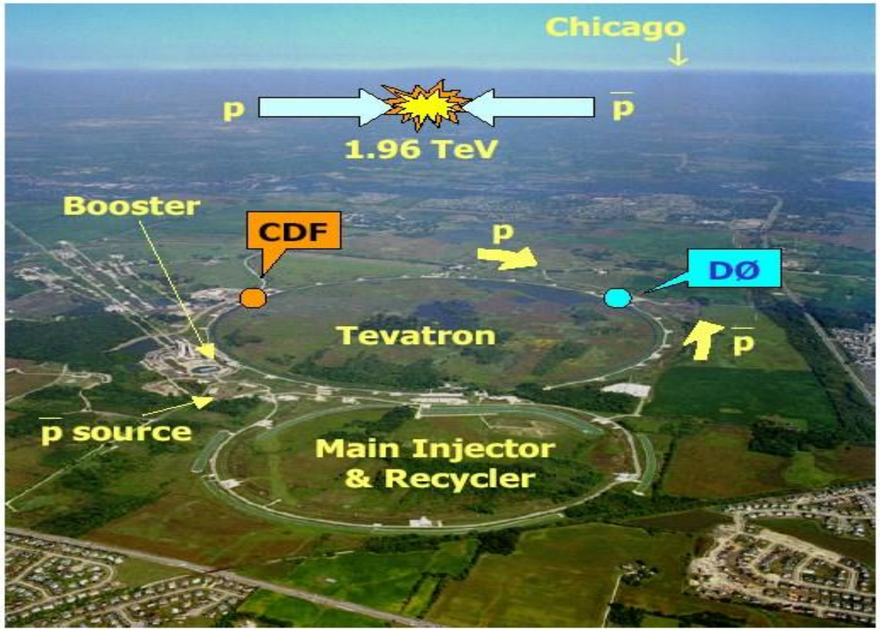
- About Tevatron and its experiments (CDF, D0)
- Top pair production cross section
- Forward-Backward/Charge $t\bar{t}$ production asymmetries
- Polarization of *W* boson from top decay
- Top quark spin correlations
- Decay width of top quark
- Top quark charge determination

The Tevatron: CDF and D0

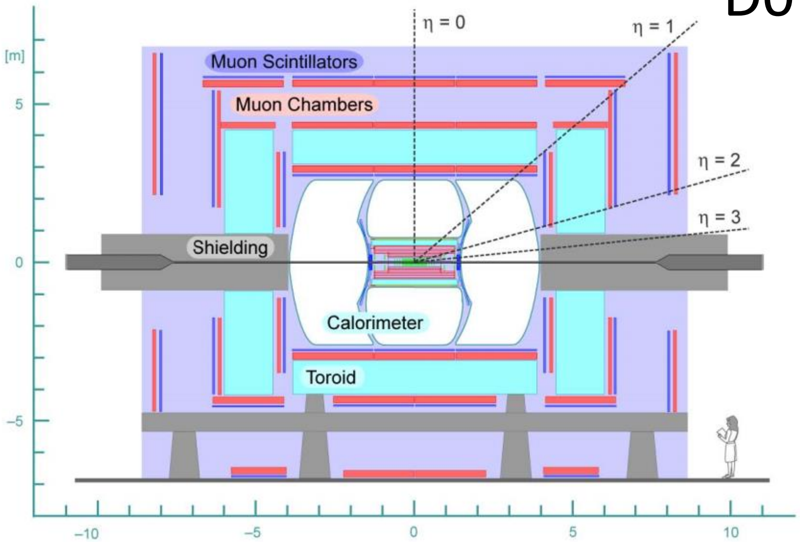
- collisions: $p \rightarrow \leftarrow \bar{p}$, $\sqrt{s}$ = 1.96 TeV
- Peak luminosities: 3 - $4\times10^{32}cm^{-2}s^{-1}$.
- $10fb^{-1}$/ experiment recorded
- Tevatron operation: 1983 – 2011
- Top quark discovery (1995)

CDF



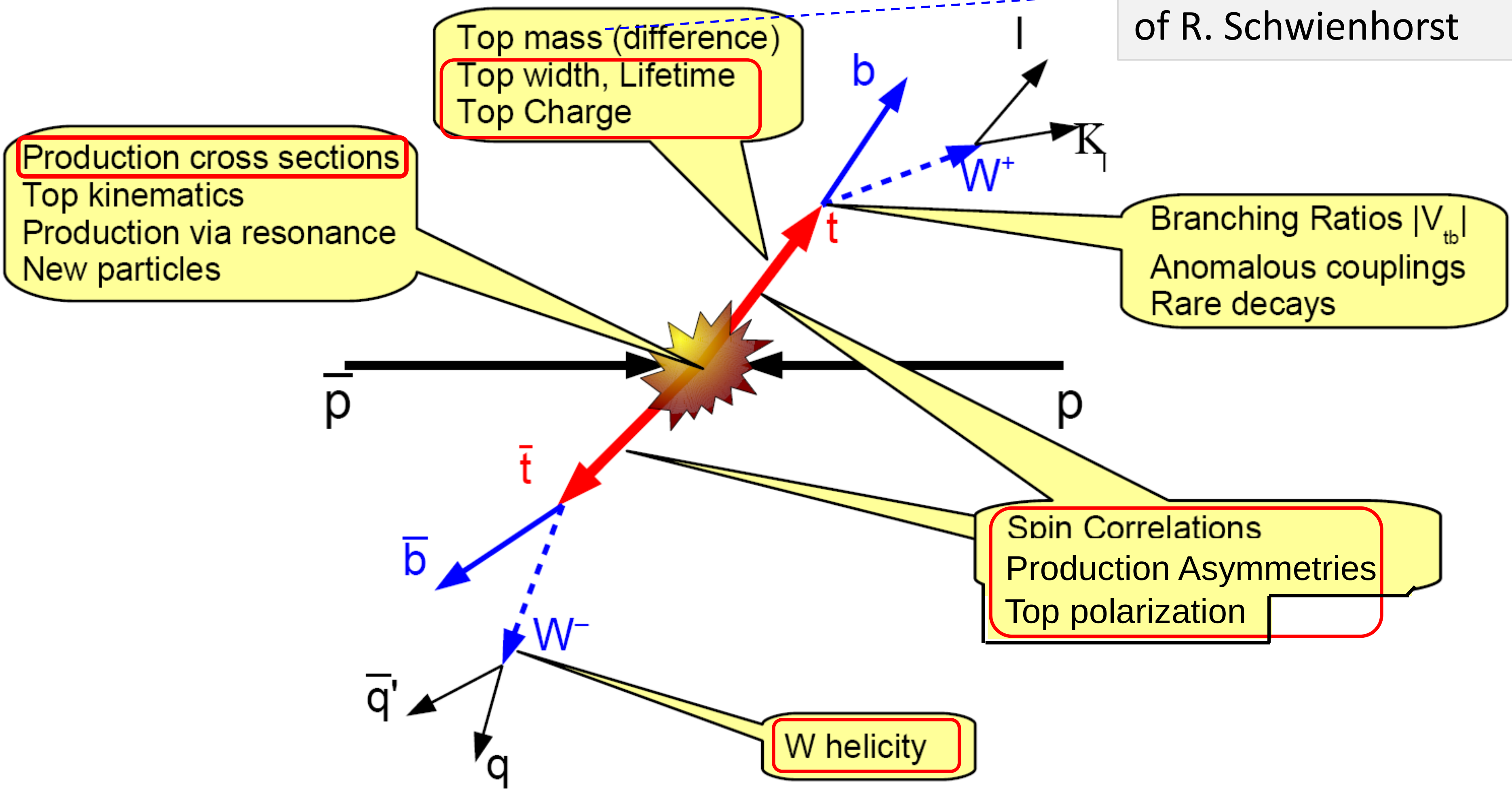


D0



Physics of top quark at Tevatron

On top mass see talk of R. Schwienhorst



Top pair production cross section

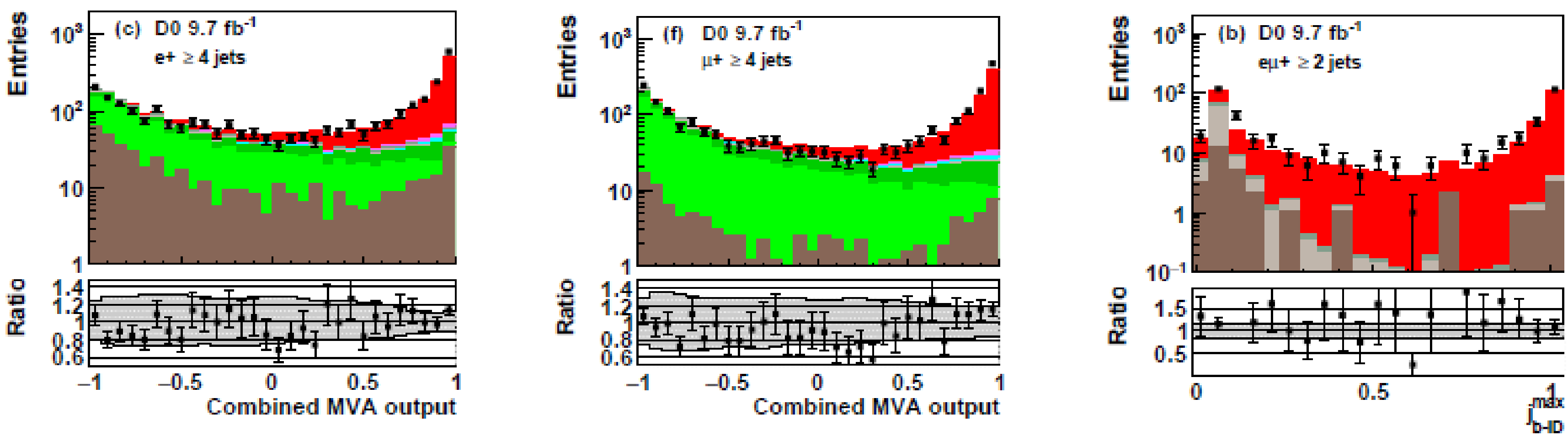
Inclusive $t\bar{t}$ production cross section measured combining ℓ+jets and $\ell\ell$ channels;

$p\bar{p}$ collision at $\sqrt{s} = 1.96\,\text{TeV}$, $\int L dt = 9.7\,\text{fb}^{-1}$ archiv.1605.06168, sub. to PRD

Different MVA techniques used for ℓ+jets and $\ell\ell$ channels see event classif., s.24

ℓ+jets: 6 event groups (ℓ type, n_{jets} =2, 3, ≥4), for MVA discriminant: ≥ 24 variables

$\ell\ell$ channel: due to small bkgd var. $j^{\text{max}}_{b\text{-ID}}$ (max. b-ID value) is used to separate signal



Combined likelihood: the product of binned likelihoods for the individual channels

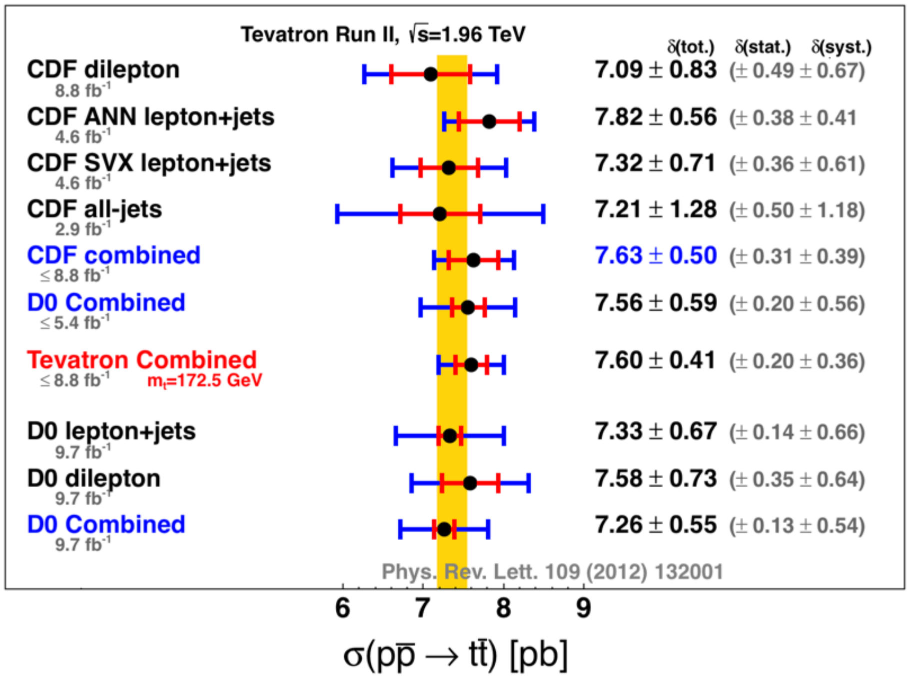
- prior probability densities on systematic uncertainties included.

Combined Cross section: $\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat})\,^{+0.57}_{-0.50}(\text{syst})\,\text{pb}, \quad \varepsilon = 7.6\%$

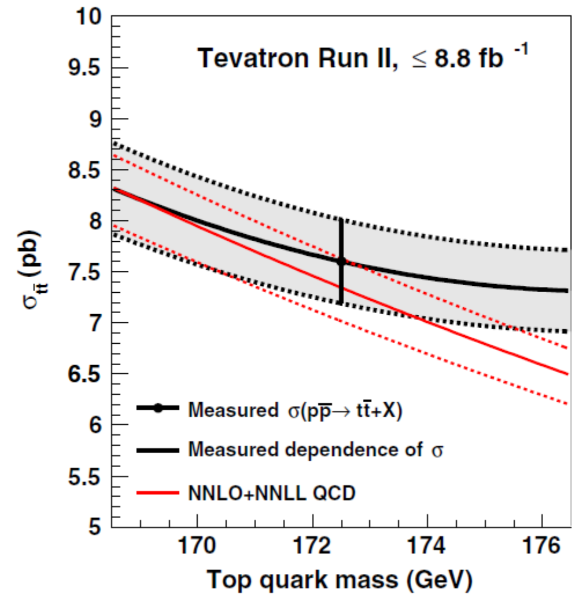
see J.Franc's talk

Tevatron σ_{tt} combination

Combination of measurements of $\sigma_{t\bar{t}}$ in the dilepton, ℓ + jets, and all-jets final states, using data collected by the CDF and D0 collaborations, $p\bar{p}$ collision at $\sqrt{s} = 1.96\,\mathrm{TeV}$



PRD 89, 072001 (2014)*



Combined Cross section: $\sigma_{t\bar{t}} = 7.60 \pm 0.41\ \mathrm{pb}$ **5.4% rel. uncertainty**

- ✓ The latest D0 result not included in Tevatron combination
- ✓ The CDF full statistics result is in preparation!

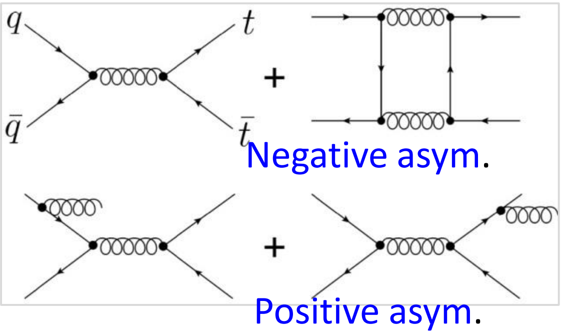
New combination is expected !

Asymmetries in top quark production

SM: at LO of strong interaction processes: no F-B/Charge asymmetries !

A_{FB} sources: interference of amplitudes with the same initial and final state particle $\Rightarrow$ appears in

- ✓ higher orders with $q\bar{q}$ and qg initial states;
- ✓ gg fusion is fully symmetric in all orders.



At partonic level: charge asymmetry — forward-backward asymmetry

$$A_C(\cos\theta^*) = \frac{N_Q(\cos\theta^*) - N_{\bar{Q}}(\cos\theta^*)}{N_Q(\cos\theta^*) + N_{\bar{Q}}(\cos\theta^*)}$$

$$A_{FB}(\cos\theta^*) = \frac{N_Q(\cos\theta^*) - N_Q(-\cos\theta^*)}{N_Q(\cos\theta^*) + N_Q(-\cos\theta^*)}$$

$\theta^* \equiv Q$ quark production angle *wrt* proton direction in $q\bar{q}$ rest frame.

Assuming CP conservation: $N_{\bar{Q}}(\cos\theta^*) = N_Q(-\cos\theta^*) \Rightarrow A_C = A_{FB}$

Integrated FB asymmetry:

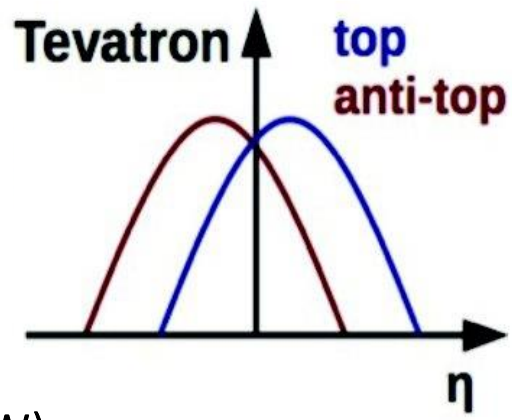
Instead of $\theta^* \Rightarrow$ rapidity difference $\Delta y = y_Q - y_{\bar{Q}}$

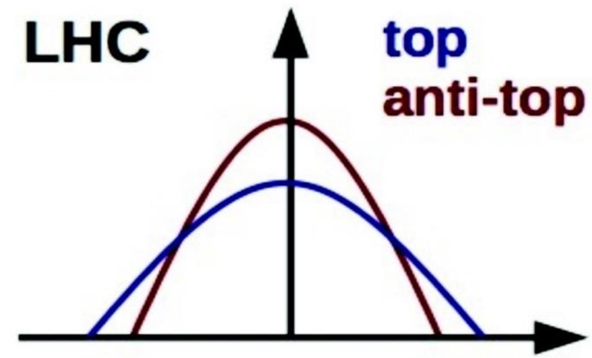
$$A_{FB} = \frac{N_Q(\cos\theta^* > 0) - N_Q(-\cos\theta^* < 0)}{N_Q(\cos\theta^* > 0) + N_Q(-\cos\theta^* < 0)} \longrightarrow A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

Contribution of Electroweak processes gives: around 20% effect!

Top asymmetries: Tevatron vs LHC

Distribution of t and $\bar{t}$ in pseudorapidity *wrt* respect of proton direction $\Rightarrow$ Tevatron vs LHC complement.



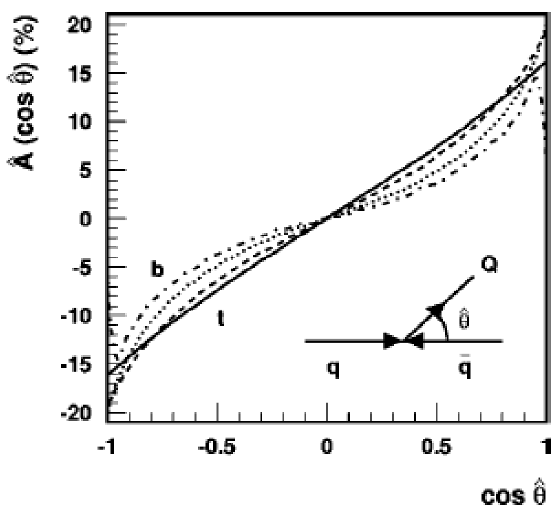


PRD 86, 034026 (2012)

SM prediction at NLO (QCD+EW)
Tevatron: A_{FB} ~9% vs LHC: A_C ~ 1%
Now available: NNLO+NNLL

PRL 115, 052001 (2015)

Experimentally: Asymmetries based on
- ✓ fully reconstructed tops ($A_{FB}^{t\bar{t}}$) or
- ✓ Leptons from top decays (A_{FB}^{ℓ} , $A_{FB}^{\ell\ell}$)

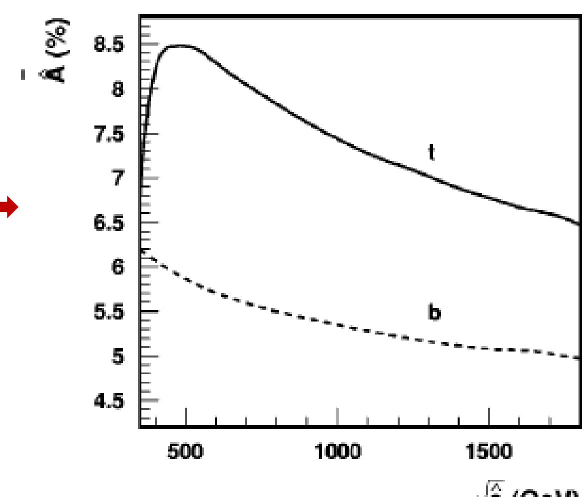


SM prediction for $Q\bar{Q}$ A_{FB} ($q\bar{q}$ rest frame, only QCD):

Integrated A_{FB} →

← Differential A_{FB}: maximum at cosθ = ±1

PRD 59, 054017(1999)



CDF: Top quark asymmetries

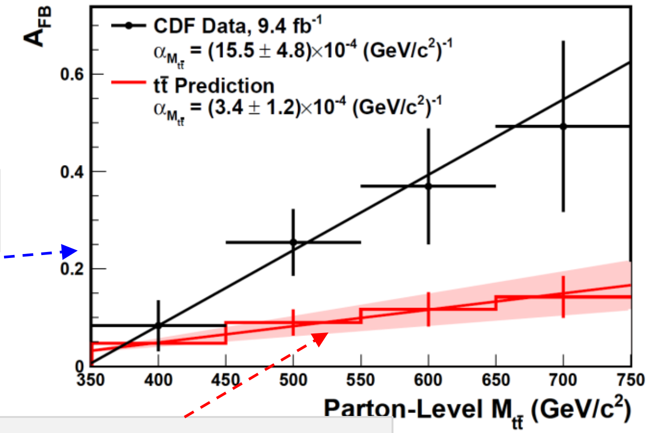
PRD 87, 092002 (2013)

CDF studied FB asymmetry in $t\bar{t}$ production using $\Delta y\ (= y_t - y_{\bar{t}})$; ℓ+jets channel; $\int L dt = 9.4\,\mathrm{fb}^{-1}$

Measured asymmetry after correction to parton level:

$A_{FB}^{t\bar{t}} = (16.4 \pm 4.7)\%$ SM NLO: $A_{FB}^{t\bar{t}} = (8.8 \pm 0.9)\%$

$A_{\rm FB}^{t\bar{t}}$ linearly depends on $|\Delta y|$ and $M_{t\bar{t}}$



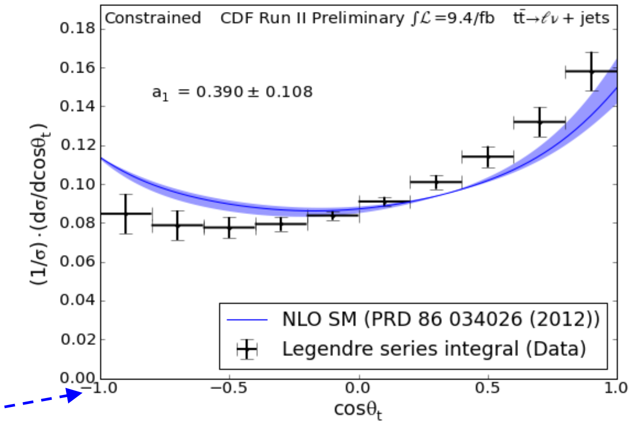
POWHEG prediction

Background: W+jets, Non-W, Single top, ...
Expected bkg: 530 ± 124, expected signal: 2186 ± 314
Total SM expected: 2716 ± 314 ⇔ observed: 2653

CDF: $d\sigma/d\cos\theta^*$ - $t\bar{t}$ x-section *vs* top production angle *wrt* proton direction – θ^* in $t\bar{t}$ rest frame ;
expansion into Legedre series; ℓ+jets channel

⇒ Measured asymmetry: $A_{\rm FB}^{t\bar{t}} = (19.9 \pm 5.7)\%$

⇒ A_{FB} as a function of $\cos\theta^*$ *vs* SM NLO prediction



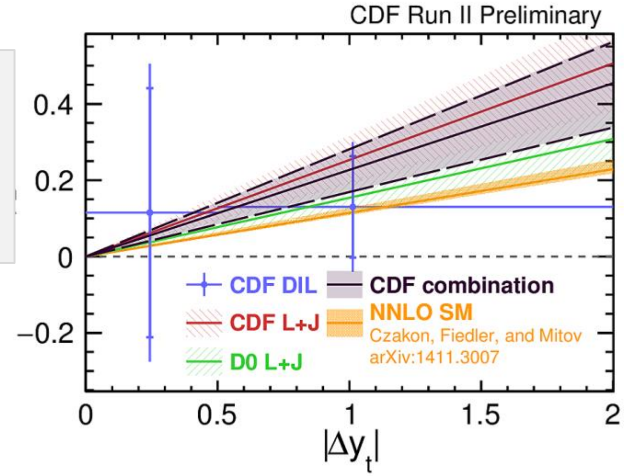
PRL 111, 182002 (2013)

CDF: Top quark asymmetries

A_{FB} measured in $\ell\ell$ channel; $\int L dt = 9.1 \text{fb}^{-1}$, $\Delta y = y_t - y_{\bar{t}}$

PRD 93, 112005 (2016)

Kinematic fitter used to reconstruct $t\bar{t}$ topology



Expect. background: 96±18 Expect. signal: 386±18
(Diboson, Z/γ*+jets, W+jets)
Total SM expected: 482±36 ⇔ observed: 495

Extracted parton-level asymmetry:

$$A_{FB}^{t\bar{t}} = (12 \pm 11(\text{stat}) \pm 7(\text{syst}))\% = (12 \pm 13)\%$$

SM NNLO: $A_{FB}^{t\bar{t}} = (10.0 \pm 0.6)\%$ PRD 91, 071502 (2015).

NEW!

A_{FB} combination of ℓ+jets and $\ell\ell$ channels; correlations of stat. and syst. uncertainties taken into account (BLUE technique applied):

$$A_{FB}^{t\bar{t}} = (16.0 \pm 4.5)\%$$

The best fit of $A_{FB}^{t\bar{t}} = \alpha \cdot |\Delta y_t|$ yields a slope of $\alpha = 0.14 \pm 0.15$

SM NNLO: $\alpha = 0.114^{+0.006}_{-0.012}$ arXiv:1601.05375.

D0: Top quark asymmetries

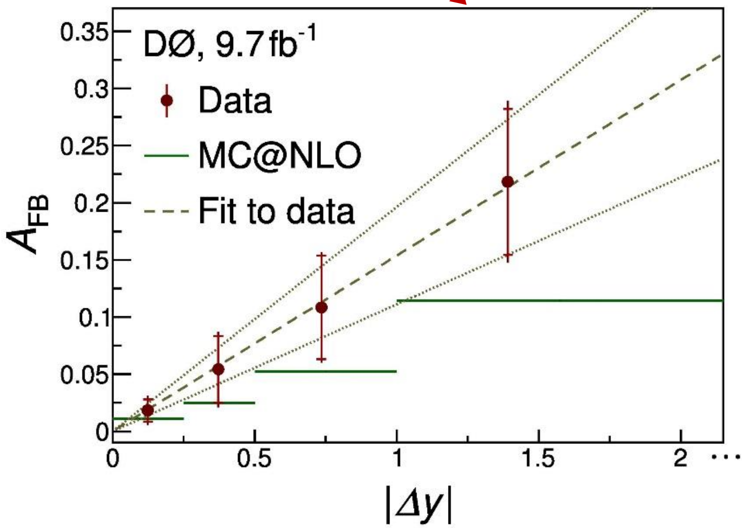
D0 measurement of FB asymmetry in ℓ+jets of $t\bar{t}$, $\int L dt = 9.7\,\text{fb}^{-1}$

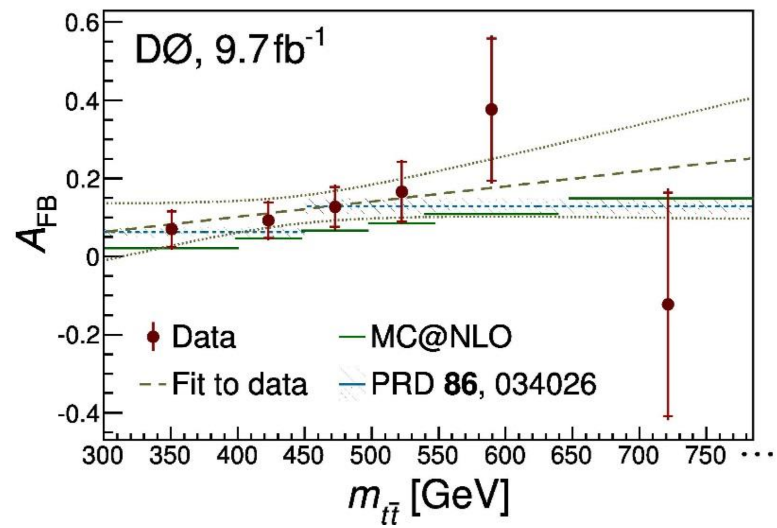
- ✓ Kinematic reconstr. of $t\bar{t} \Rightarrow$ rapidity difference $\Delta y = y_t - y_{\bar{t}}$ between t and $\bar{t}$ used
- ✓ Selected events: ℓ + ≥4 jets and : ℓ + 3 jets (partial reconstruction)
- ✓ Background: W+jets, multijet, other bkg
- ✓ Measured background-subtracted A_{FB} 1D-distrib. in Δy and 2D-distrib. in $(\Delta y, m_{t\bar{t}})$ unfolded to parton level $\Rightarrow$

Measured asymmetry: $A_{FB}^{t\bar{t}} = (10.6 \pm 3.0)\%$

PRD 90, 072011 (2014)

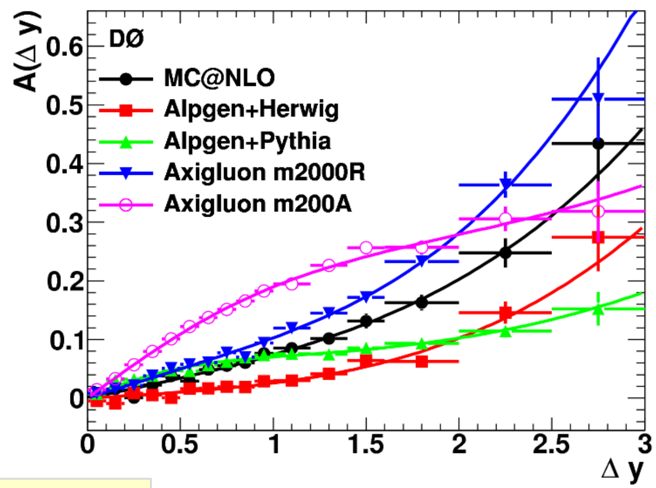
A_{FB} a function of $|\Delta y|$ and $t\bar{t}$ invariant mass $m_{t\bar{t}}$





D0: Top quark A_{FB} + polarization

D0 simultaneous measurement of asymmetry A_{FB} and top-quark polarization κP in the beam axis



- ✓ A_{FB} measured using $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$
- ✓ Polarization κP using angular distribution of ℓ^+ and ℓ^-

$$\frac{d\sigma}{d\cos\theta^{\pm}} = \frac{1}{2}\left(1+\kappa^{\pm} P\cos\theta^{\pm}\right)$$

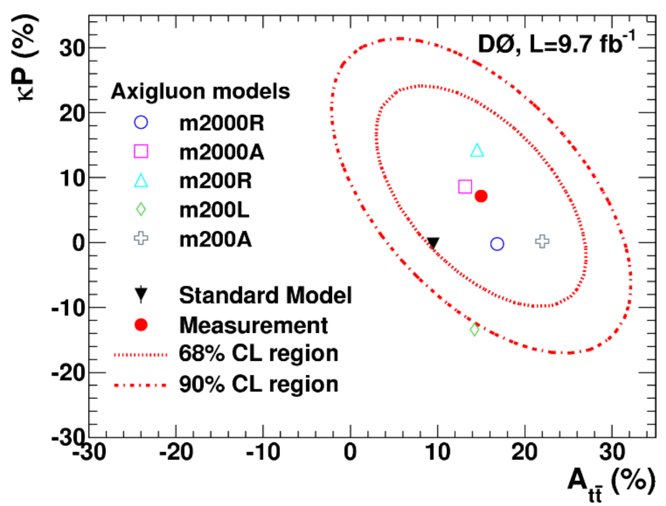
- ✓ Dilepton channel with $\int L dt = 9.7\,\text{fb}^{-1}$
- ✓ Measured A_{FB} and κP :

PRD 92, 052007 (2015)

$$A_{FB}^{t\bar{t}} = \left(15.0 \pm 6.4(\text{stat}) \pm 4.9(\text{syst})\right)\%$$

$$\kappa P = \left(7.2 \pm 10.5(\text{stat}) \pm 4.2(\text{syst})\right)\%$$

correlation: -56%



Assuming NNLO A_{FB} (=9.5±0.7 %): $\kappa P = (11.3 \pm 9.3)\%$

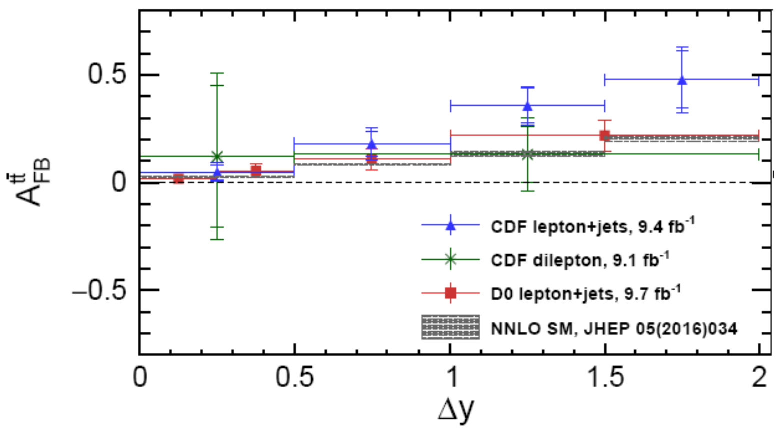
Assuming SM polarization: $A_{FB}^{t\bar{t}} = (17.5 \pm 6.3)\%$

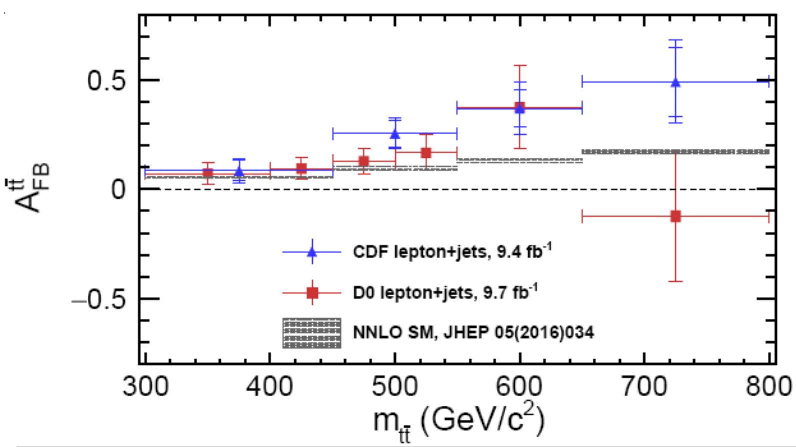
Combination of A_{FB} for dilepton and in ℓ+jets channels (BLUE techniqe): $A_{FB}^{t\bar{t}} = (11.8 \pm 2.8)\%$

Compatibility with the SM prediction!

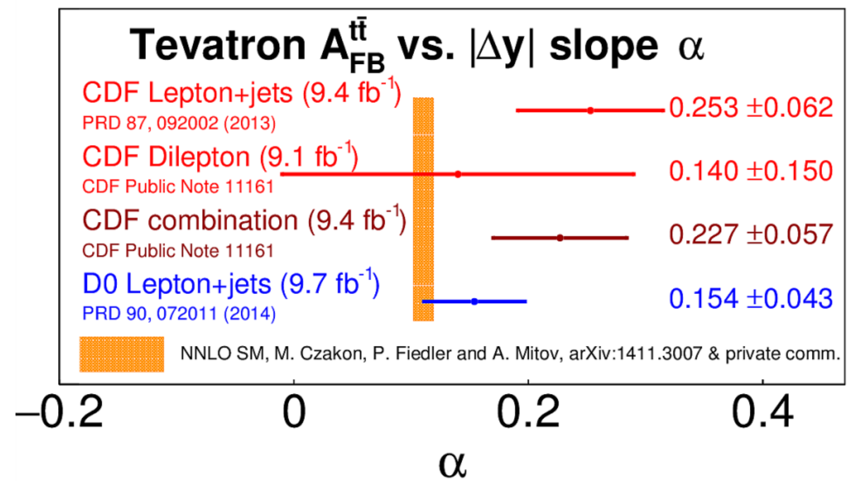
Summary of A_{FB} measurements (1)

Asymmetry $\boldsymbol{A}_{FB}$ in $t\bar{t}$ production, reconstructed via rapidity difference Δy, measured by CDF and D0 compared with SM NNLO predictions.





Slope α of $A_{FB}^{t\bar{t}}$ *vs* Δy dependence extracted by CDF and D0 compared with SM NNLO predictions



...not bad agreement with SM NNLO

Measured $\boldsymbol{A}_{FB}$ in $t\bar{t}$ production: compatibility between CDF and D0

CDF: leptonic top quark asymmetries

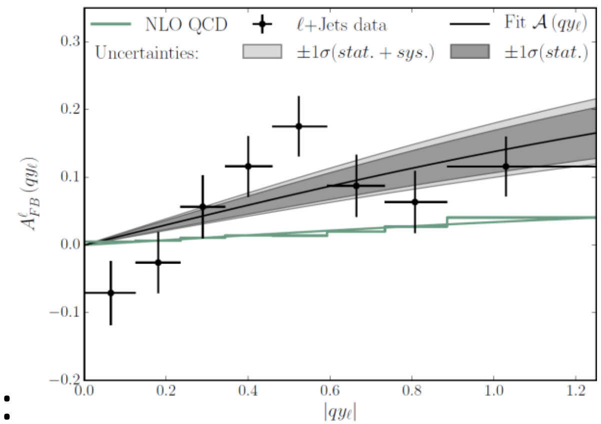
Idea behind: correlation between top direction and its decay products.

Lepton asymmetry A_{FB}^{ℓ} depends on top pair prod. asymmetry and top polarization

- A_{FB}^{ℓ} in ℓ+jets channel, 9.4 fb^{-1}:

PRD 88, 072003 (2013)

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



Measured: $A_{FB}^{\ell} = 10.5^{+3.2}_{-2.9}\,\%$ NLO SM: $A_{FB}^{\ell} = (3.8 \pm 0.3)\%$

- Dilepton ($\ell\ell$ +jets) channel, 9.1 fb^{-1} → the observable:

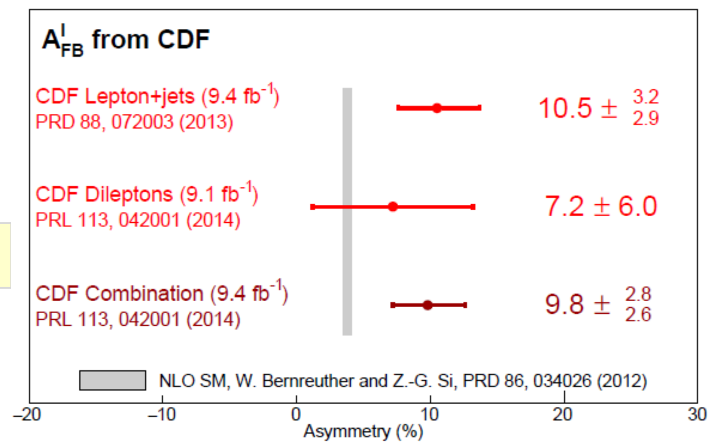
$$A_{FB}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}, \quad \Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$$

PRD 86, 034026 (2012)

NLO SM prediction: $A_{FB}^{\ell\ell} = (4.8 \pm 0.4)\%$

Measured: $A_{FB}^{\ell} = 7.6 \pm 6.0\%$ $A_{FB}^{\ell\ell} = (7.2 \pm 6.0)\%$

PRL 113, 042001 (2014)*



- Combination of ℓ+jets channel and $\ell\ell$ channels,

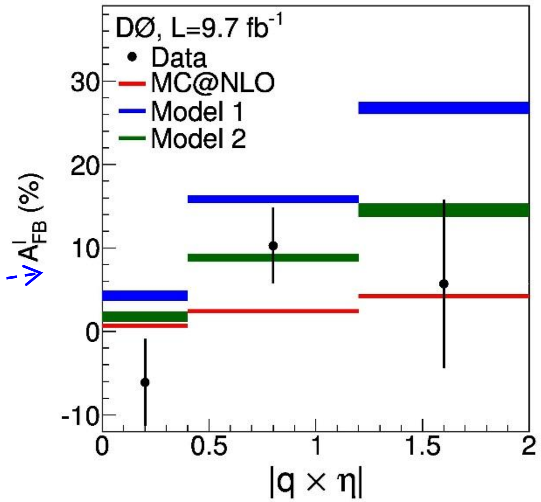
BLUE technique used: $A_{FB}^{\text{lep}} = 9.8^{+2.8}_{-2.6}\,\%$

D0: leptonic top quark asymmetry

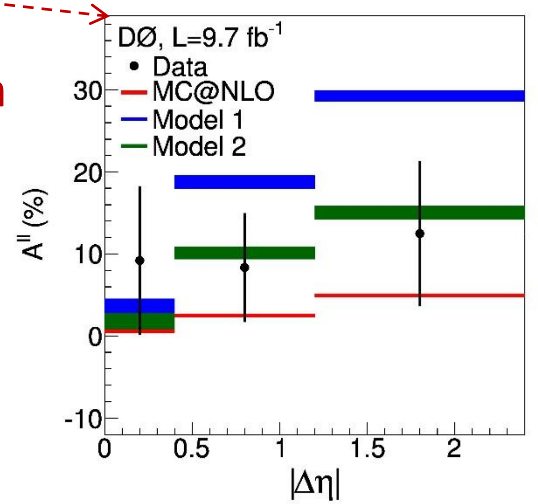
Dilepton ($\ell\ell$ +jets) channel, 9.7 fb^{-1}

PRD 88, 112002(2013)

- ✓ the observables: $q\times\eta$ and $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$
- ✓ 1ℓ ($A^{\ell}_{\rm FB}$) and 2ℓ ($A^{\ell\ell}_{\rm FB}$) asymmetries reconstructed
- ✓ Sensitivity to BSM physics ⇒ comparison with axigluon BSM models giving a large AFB at tree level



Asymmetries $A^{\ell}_{\rm FB}$ and $A^{\ell\ell}_{\rm FB}$ after bkg subtraction and correction for selection eff.



Extracted A_{FB} after unfolding to parton level vs SM prediction

$$A^{\ell}_{\rm FB} = \left(4.4 \pm 3.7({\rm stat}) \pm 1.1({\rm syst})\right)\%$$

$$A^{\ell\ell}_{\rm FB} = \left(10.5 \pm 5.4({\rm stat}) \pm 1.5({\rm syst})\right)\%$$

$$A^{\ell}_{\rm FB} = \left(3.8 \pm 0.3\right)\%$$

$$A^{\ell\ell}_{\rm FB} = \left(4.8 \pm 0.4\right)\%$$

❑ Asymmetry in ℓ +jets channel, 9.7 fb^{-1}

PRD 90, 072001(2014)

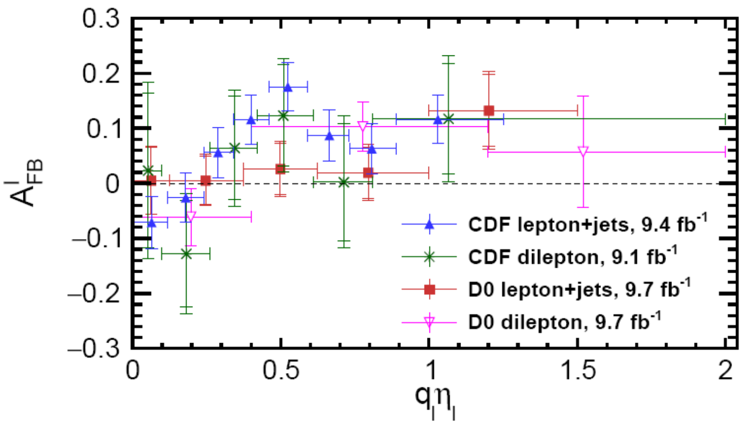
$$A^{\ell}_{\rm FB} = \left(4.2 \pm 2.3({\rm stat})\ ^{+1.7}_{-2.0}\ ({\rm syst})\right)\%$$

Combination for $|y_\ell| \leq 1.5$: $A^{\ell}_{\rm FB} = \left(4.2 \pm 2.3\right)\%$

Tevatron A_{FB} combinations & Summary

Asymmetry A_{FB} in $t\bar{t}$ production, reconstructed via Δy, and leptonic A_{FB}, measured by CDF and D0 were combined (BLUE) and compared with SM NLO and NNLO predictions.

$A_{FB}^{t\bar{t}} = (12.8 \pm 2.5)\%$ within 1.5σ of $(9.5 \pm 0.7)\%$

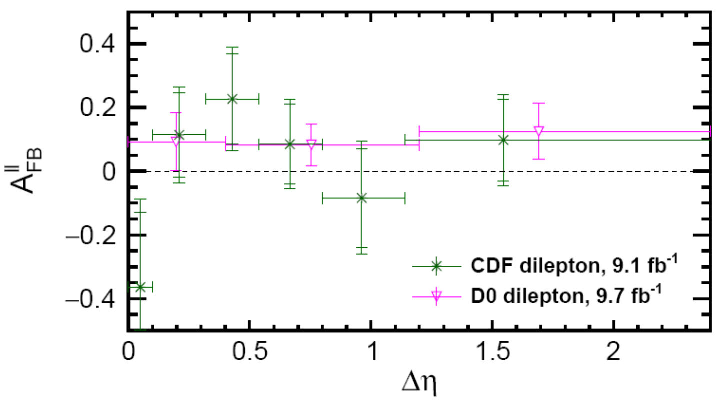


$A_{FB}^{\ell} = (7.3 \pm 2.0)\%$

1.7σ larger than

SM: $(3.8 \pm 0.3)\%$

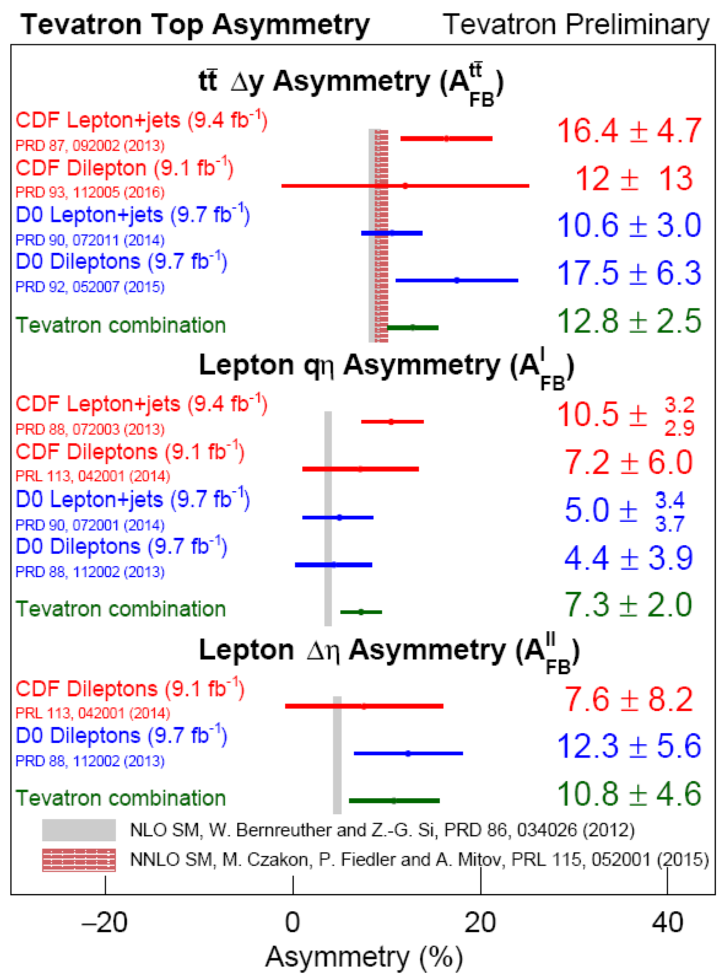
NEW!



$A_{FB}^{\ell\ell} = (10.8 \pm 4.6)\%$

within 1.5σ of

SM: $(4.8 \pm 0.4)\%$



CDF: polarization of *W* boson from top

SM: top quark decays before hadronization mainly to ***Wb*** via weak interaction (V-A structure) $\Rightarrow$ ***tWb*** coupling and ***W***-boson polarization

- ✓ SM prediction for longitudinal, left- and right-handed polarizations:

$$f_0 = 0{,}696,\quad f_- = 0.303 \quad \text{and} \quad f_+ = 3.8\times10^{-4}$$

- ✓ Main background: ***W***+jets, diboson, single top, multijet events
- ✓ Fractions f_0, f_- and f_+ determined using an unbinned likelihood technique

$\Rightarrow$ LO matrix element of $q\bar{q} \to t\bar{t}$ can be expressed via f_0, f_- and f_+

Model-independent measurement in ℓ +jets channel, 9.1 fb^{-1} . simultaneously determined f_0 and f_+:

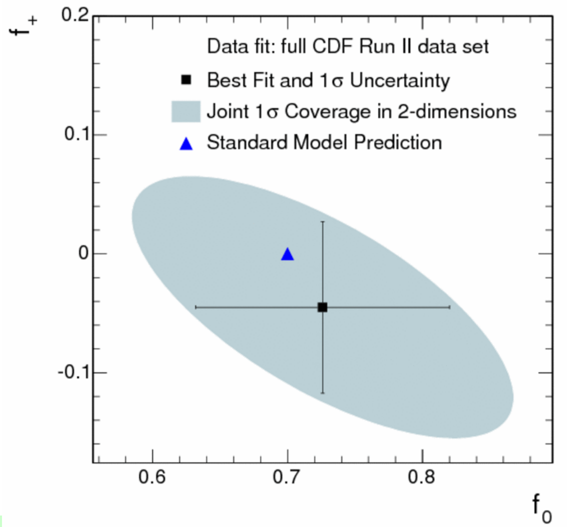
PRD87, 031104(R) (2013)

$$f_0 = \;\; 0.726 \pm 0.066\,(\text{stat}) \pm 0.067(\text{syst})$$
$$f_+ = -0.045 \pm 0.044\,(\text{stat}) \pm 0.058(\text{syst})$$

correlation f_0 vs f_+ : -0.69

fixing $f_+ = 0$ $\Rightarrow f_0 = \;\; 0.683 \pm 0.042\,(\text{stat}) \pm 0.040\,(\text{syst})$

Fixing $f_0 = 0.7 \Rightarrow f_+ = -0.025 \pm 0.024\,(\text{stat}) \pm 0.040\,(\text{syst})$



D0: top quark polarization

Top polarization measured along 3 quantization axes: beam, helicity and transverse.

- ✓ Measurement in ℓ +jets - final state contains a lepton + ≥3 jets
- ✓ Measured polarization: using distributions of leptons along the mentioned 3 axes.

Cos of lepton/*d*-quark angle vs axis ***n***

$$\frac{1}{\Gamma}\frac{d\Gamma}{dc_{\theta 1}dc_{\theta 2}} = \frac{1}{4}\left(1 + \kappa_1 P_{\vec{n}} c_{\theta 1} + \rho\kappa_2 P_{\vec{n}} c_{\theta 2} - \kappa_1\kappa_2 C\, c_{\theta 1} c_{\theta 2}\right)$$

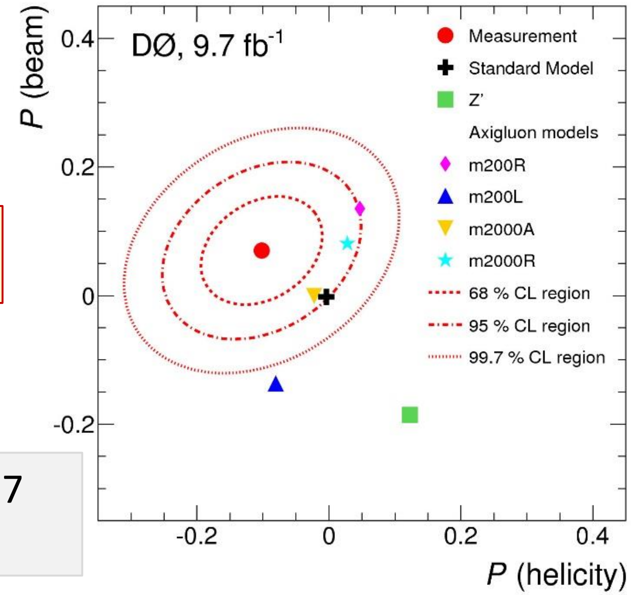
Polarization *wrt* ***n***

Spin correlation → from SM

	3 jets		≥ 4 jets	
Source	e+jets	μ+jets	e+jets	μ+jets
W+jets	1741 ± 26	1567 ± 15	339 ± 3	295 ± 3
Multijet	494 ± 7	128 ± 3	147 ± 4	49 ± 2
Other Bkg	446 ± 5	378 ± 2	87 ± 1	73 ± 1
$t\bar{t}$ signal	1200 ± 25	817 ± 20	1137 ± 24	904 ± 23
Sum	3881 ± 37	2890 ± 25	1710 ± 25	1321 ± 23
Data	3872	2901	1719	1352

NEW!

arXiv:1607.07627
subm. to PRL



Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Beam - D0 comb.	$+0.081 \pm 0.048$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

2D visualization of longitudinal top polarizations in ℓ+jets ch. along beam and helicity axes compared with SM and BSM

D0: Top quark spin correlations

Top quark lifetime, $\tau_t \approx 5 \cdot 10^{-25} s$ << spin-decorrelation time, $\tau_{\text{spin}} \approx 3 \cdot 10^{-21} s$

$\Rightarrow$ QCD: unpolarized t and $\bar{t}$ quarks, but the spins of t and $\bar{t}$ are correlated.

Spin correlation observable:

$$O = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

σ(..) ≡ cross section referred to spin state of q and $\bar{q}$ relative to quantization axes

NEW!

- ✓ Matrix element technique applied to dilepton ($\ell\ell$) and ℓ+jets final state
- ✓ Tevatron vs LHC spin correlations: $q\bar{q}$ annihil. vs like-helicity ***gg*** fusion (complement.)
- ✓ Spin correlation discriminant event-by-event:

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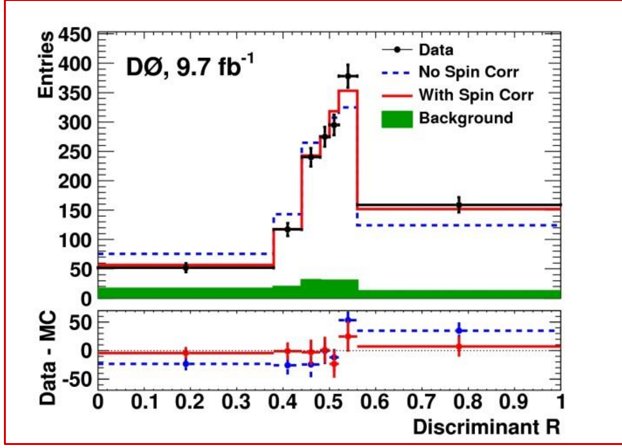
$$R(x) = \frac{P_{t\bar{t}}(x, \text{SM})}{P_{t\bar{t}}(x, \text{SM}) + P_{t\bar{t}}(x, \text{null})}$$

Probability for SM/null (uncorrelated) hypotesis



- ✓ Off-diagonal spin basis (max. correlations for $p\bar{p}$)

$O_{\text{off}} = 0.89 \pm 0.16(\text{stat}) \pm 0.15(\text{syst})$ SM: $O_{\text{off}} = 0.80^{+0.01}_{-0.02}$

Significance from zero: 4.2 σ

Assuming absence of non-SM → fraction of gg fusion:

$f_{gg} = 0.08 \pm 0.16(\text{stat+syst})$ SM (NLO): $f_{gg} = 0.135$

CDF: Top quark decay width

SM NNLO: assuming M_{top} =172.5 GeV/c^2 $\Rightarrow$ Top quark width Γ_{top} = 1.32 GeV

- ✓ D0 determined $\Gamma_{top} = 2.00^{+0.47}_{-0.43}$, data set of 5.4 fb^{-1}, using a model-dependent indirect measurement that assumes SM couplings.
- ✓ CDF: more model-independent measurement using a direct shape comparison of the reconstructed M_{top} with data set of 8.7 fb^{-1}
- ✓ Analysis carried out in ℓ+jets channel
- ✓ 5 samples: 0, 1 and 2 b-tags – soft and tight tags
- ✓ Main background: W+jets and multijets

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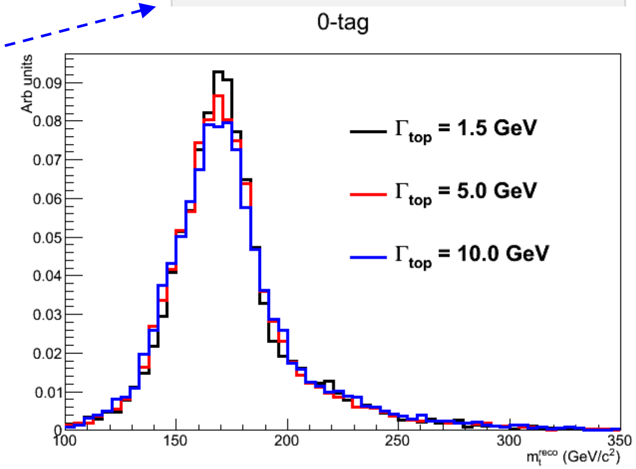
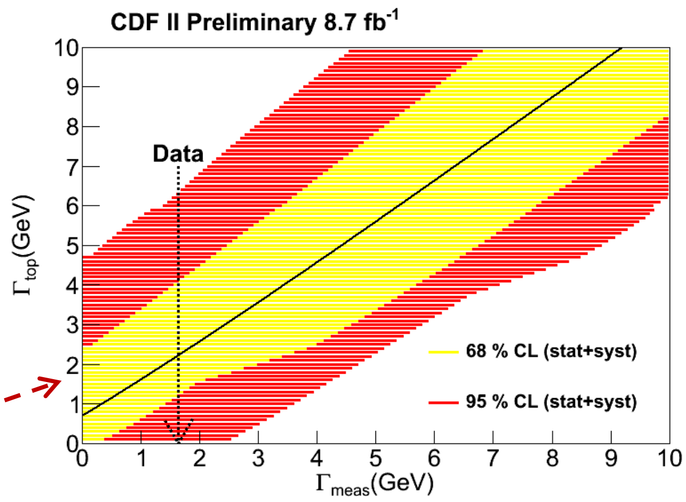


Likelihood fit applied to 5 data samples used to extract Γ_{top} width:

Γ_{meas} = 1.63 GeV, upper limit of Γ_{top} < 6.38 GeV

1.10 < Γ_{top} < 4.05 GeV 68% C.L.



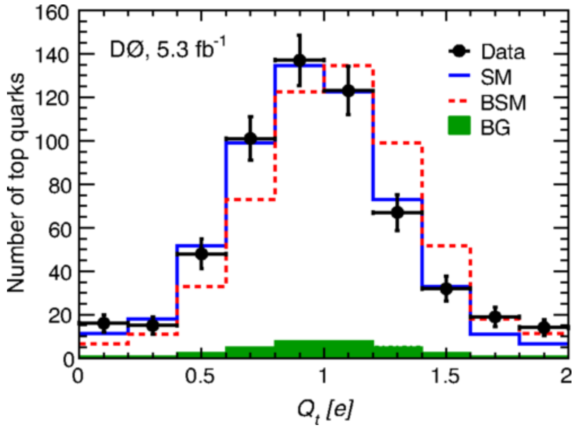
Confidence bands of Γ_{top} as a function of Γ_{meas} for 68% and 95% C.L. limits.

Top quark charge determination

PRD 90, 051101(R)

SM: $t \to W^+ b$ vs BSM: $t \to W^- b_{BSM}(-4/3)$

Fully reconstructed $t\bar{t}$ pairs in ℓ +jets jets channel, 5.3 fb^{-1}



b-jet charge calculated : $Q_j = \left(\sum_i Q_i (p_{Ti})^{0.5}\right) / \left(\sum_i (p_{Ti})^{0.5}\right)$

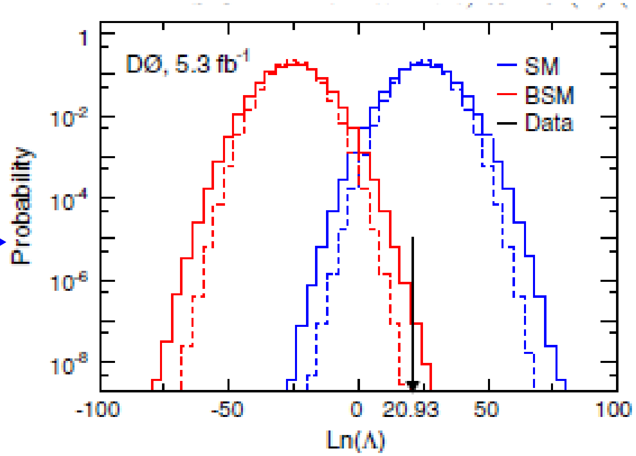
Top charge observable → charges of W boson and b-quark combined : $Q_t^\ell = \left|Q_\ell + Q_b^\ell\right|$ and $Q_t^h = \left|-Q_\ell + Q_b^h\right|$

Discrimination between SM and BSM → likelihood ratio:

$$\Lambda = \left[\prod_i P^{SM}(Q_t^i)\right] / \left[\prod_i P^{BSM}(Q_t^i)\right]$$

Probability to observe top charge Q_i under SM (BSM) hypothesis

Pseudoexperiments: carried out for **SM** and **XM** hypothesis, all uncertainties included.



Maximum likelihood fit to data top-charge distribution:

fraction of SM tops : $f = 0.88 \pm 0.13(\text{stat}) \pm 0.11(\text{syst})$

- ✓ All top quarks in data are BSM quarks: excluded at the level of > 5 SD.
- ✓ An upper limit on the fraction of BSM quarks: 0.46 at a 95% C.L

CDF: Top quark charge

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Data sample: $p\bar{p}$ at $\sqrt{s}$ = 2TeV, L_{int} = 5.6 fb^{-1}

Event selection: $t\bar{t}$ events, l+jets channel

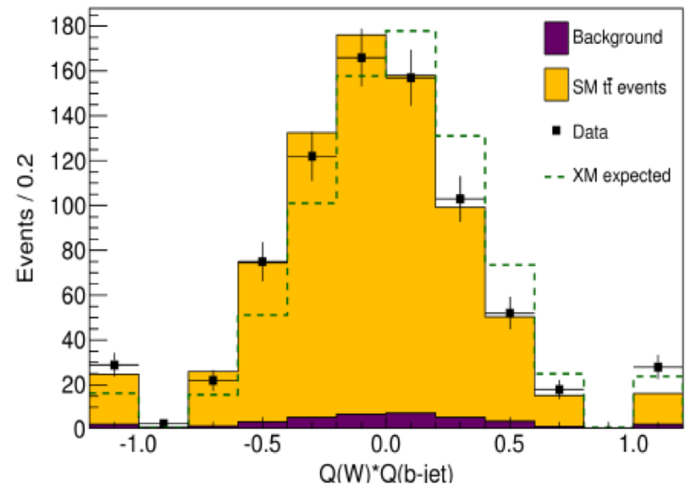
Decision observable: combined charge $\Rightarrow Q_l \times Q_{bjet}$

Pairing of ℓ and b-jet: kinematic fitter (max. χ^2)

Candidate events: SM(XM)-like: $Q_l \times Q_{bjet}$ < 0 (>0)

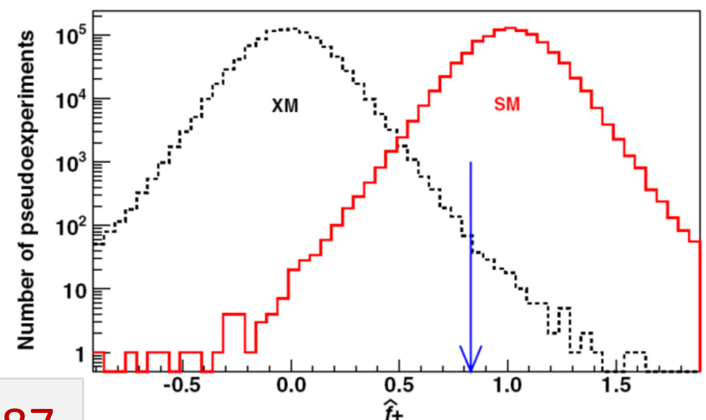
Sensitive variable: $f_+ \equiv$ fraction of SM pairs among all data pairs is used to test SM hypothesis (f_+=1) vs XM one (f_+=0).

Maximal likelihood used to extract SM-fraction $\hat{f}_+$ for observed SM- and XM- data pairs.



Obtained from data:

- Electron branch (N_{SM}=206, N_{XM}=156): $\hat{f}_+ = 1.11$
- Muon branch (N_{SM}=210, N_{XM}=203): $\hat{f}_+ = 0.57$



Combined results: $\hat{f}_+ = 0.87$

Result of statistical analysis:

- hypothesis of exotic quark is excluded at 99% CL.
- Bayes factor, 2ln(BF) = 19.6: strong prefer. for SM.

Pseudoexperiments: carried out for **SM** and **XM** hypothesis, all uncertainties incl.

Summary

- Tevatron experiments (CDF and D0) provided us with remarkable results on the top quark properties – in (good) agreement with SM
- At Tevatron have been measured not only the basic characteristics of top quarks (cross section or mass), but also
  - ✓ Asymmetries in $t\bar{t}$ production
  - ✓ Top quark spin correlations
  - ✓ Helicity of *W* bosons from top decay
  - ✓ Top quark charge, decay width
- Some results (asymmetries, spin correlations...) are unique due to complementarity connected with $p\bar{p}$ collisions.
- Results from CDF and D0 are still coming...
- Heritage of the Tevatron experiments in different experimental techniques is of a great significance for LHC.

Thank you!

D0: ttbar cross section - signal & background

Process	ℓ+jets decay channel					
	$e+2$ jets	$e+3$ jets	$e+\geq 4$ jets	$\mu+2$ jets	$\mu+3$ jets	$\mu+\geq 4$ jets
Multijet	9160 ± 2350	2266 ± 550	464 ± 120	1546 ± 630	418 ± 170	99 ± 40
Single top	471 ± 60	129 ± 20	27 ± 5	331 ± 40	92 ± 10	20 ± 3
Wlp + jets	$37937 \pm^{1350}_{700}$	$5544 \pm^{200}_{100}$	$850 \pm^{30}_{20}$	$32701 \pm^{1150}_{600}$	$5313 \pm^{200}_{100}$	$835 \pm^{30}_{15}$
$(Wc\bar{c} + Wb\bar{b})$+jets	$6020 \pm^{1000}_{1400}$	$1502 \pm^{250}_{350}$	$329 \pm^{60}_{80}$	$4998 \pm^{850}_{1150}$	$1391 \pm^{250}_{300}$	$315 \pm^{50}_{70}$
$Z/\gamma^* lp$+jets	2031 ± 400	390 ± 80	57 ± 10	2557 ± 500	422 ± 80	49 ± 10
$(Z/\gamma^* c\bar{c} + Z/\gamma^* b\bar{b})$+jets	369 ± 70	114 ± 20	24 ± 5	485 ± 100	120 ± 20	21 ± 5
Diboson	1926 ± 140	338 ± 20	52 ± 5	1417 ± 100	249 ± 20	40 ± 5
$t\bar{t}$, $\ell\ell$	566 ± 30	182 ± 10	31 ± 5	345 ± 20	118 ± 10	22 ± 5
$\sum$ bknd	58479 ± 2900	10465 ± 650	1834 ± 140	44381 ± 1650	8123 ± 350	1402 ± 80
$t\bar{t}$, ℓ+jets	669 ± 30	1460 ± 70	1177 ± 60	393 ± 20	1002 ± 50	909 ± 50
$\sum$ (sig + bknd)	59148 ± 2900	11925 ± 650	3011 ± 140	44773 ± 1650	9125 ± 350	2310 ± 80
Data	59122	11905	3007	44736	9098	2325

Process	dilepton decay channel			
	$ee+\geq 2$ jets	$\mu\mu+\geq 2$ jets	$e\mu+1$ jets	$e\mu+\geq 2$ jets
Multijet	$5.7 \pm^{0.9}_{0.9}$	$7.0 \pm^{3.3}_{2.6}$	$28.3 \pm^{6.6}_{6.6}$	$32.5 \pm^{7.4}_{7.4}$
$Z/\gamma^* \to \ell\ell$+jets	$66.6 \pm^{17.9}_{17.2}$	$107.6 \pm^{22.1}_{22.0}$	$74.6 \pm^{15.8}_{15.8}$	$57.5 \pm^{13.8}_{13.4}$
Diboson	$9.9 \pm^{2.4}_{2.2}$	$12.6 \pm^{2.8}_{3.0}$	$38.5 \pm^{4.6}_{4.2}$	$14.7 \pm^{3.7}_{3.5}$
$\sum$ bknd	82.2 ± 18	172.2 ± 22	141.4 ± 18	104.7 ± 15
$t\bar{t}$, $\ell\ell$	107.7 ± 15	101.5 ± 12	86.5 ± 11	313.7 ± 38
$\sum$ (sig + bknd)	190 ± 23	229 ± 25	228 ± 21	418 ± 42
Data	215	242	236	465

CDF: Top quark asymmetries

A_{FB} in $\ell\ell$ channel; $\int L dt = 9.1 \mathrm{fb}^{-1}$, using Δy

Extracted parton-level asymmetry:

$$A_{FB}^{t\bar{t}} = (12 \pm 11(\mathrm{stat}) \pm 7(\mathrm{syst}))\% = (12 \pm 13)\%$$

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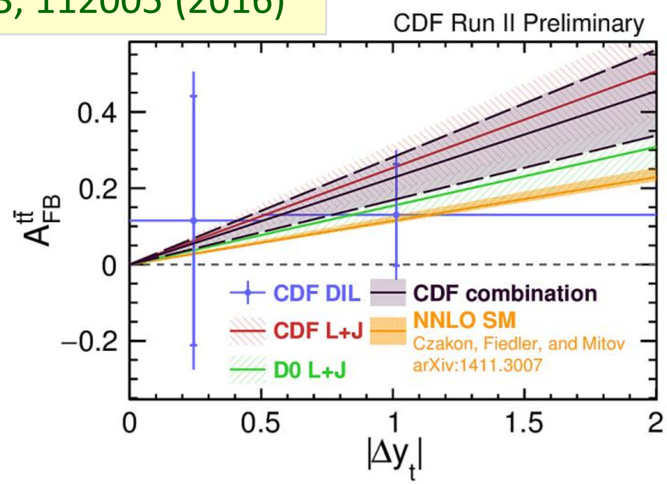


Expect. background: 96±18 Expect. signal: 386±18

(Diboson, Z/γ*+jets, W+jets)

Total SM expected: 482±36 ⇔ observed: 495

A_{FB} combination ℓ+jets and $\ell\ell$ channels; correlations of stat. and syst. uncertainties taken into account (BLUE technique applied): $A_{FB}^{t\bar{t}} = (16.0 \pm 4.5)\%$

The best fit of

$$A_{FB}^{t\bar{t}} = \alpha \cdot |\Delta y_t|$$

With measurements from both ℓ+jets and $\ell\ell$ final states. All correlations taken into account.

CDF Run II Preliminary (9.4 fb^{-1})

		Bin centroid $|\Delta y|$	$A_{FB}^{t\bar{t}}$ ($|\Delta y|$)	Covariance matrix						
				λ	0.156	0.0296	0.0251	0.00732	0.000682	0.000476
L+J	$|\Delta y| < 0.5$	0.24	0.048	Eigenvectors	-0.018	0.064	-0.012	-0.371	0.904	-0.201
L+J	$0.5 < |\Delta y| < 1.0$	0.73	0.180	Eigenvectors	0.001	-0.030	-0.014	-0.840	-0.235	0.487
L+J	$1.0 < |\Delta y| < 1.5$	1.22	0.356	Eigenvectors	0.008	-0.440	-0.172	-0.344	-0.281	-0.761
L+J	$|\Delta y| > 1.5$	1.82	0.477	Eigenvectors	0.030	-0.830	-0.286	0.193	0.219	0.378
DIL	$|\Delta y| < 0.5$	0.24	0.11	Eigenvectors	-0.984	-0.087	0.155	0.005	-0.008	0.006
DIL	$|\Delta y| > 0.5$	1.01	0.13	Eigenvectors	0.174	-0.322	0.930	-0.023	0.024	-0.021

D0: leptonic top quark asymmetry

Dilepton ($\ell\ell$ +jets) channel, 9.7 fb^{-1} $\rightarrow$ the observables: $q\times\eta$ and $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$
And single lepton ($A_{\rm FB}^{\ell}$) and dilepton ($A_{\rm FB}^{\ell\ell}$) asymmetries are reconstructed

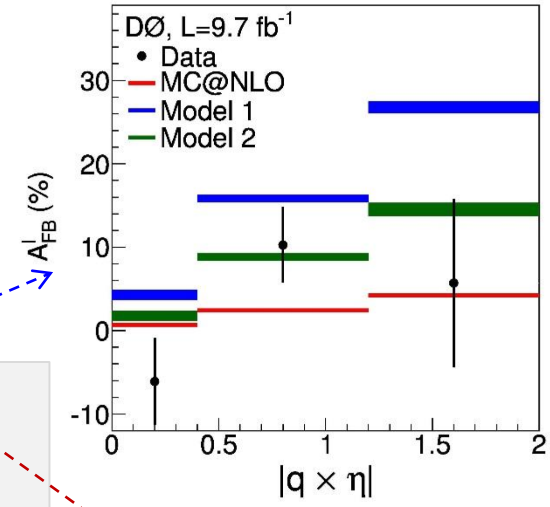
✓ Sensitivity to BSM physics $\Rightarrow$ comparison with axigluon BSM models giving a large AFB at tree level

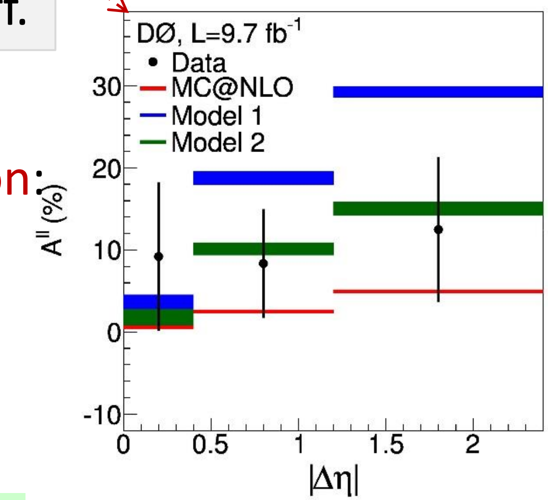
Systematic uncertainties

PRD 88, 112002(2013)

	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

Asymmetries $A_{\rm FB}^{\ell}$ and $A_{\rm FB}^{\ell\ell}$ after bkg subtraction and correction for selection eff.





Extracted $A_{\rm FB}$ after unfolding to parton level vs SM prediction:

$$A_{\rm FB}^{\ell} = (4.4 \pm 3.7({\rm stat}) \pm 1.1({\rm syst}))\%$$

$$A_{\rm FB}^{\ell} = (3.8 \pm 0.3)\%$$

$$A_{\rm FB}^{\ell\ell} = (10.5 \pm 5.4({\rm stat}) \pm 1.5({\rm syst}))\%$$

$$A_{\rm FB}^{\ell\ell} = (4.8 \pm 0.4)\%$$