

# Top quark pair production and top quark properties at CDF

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on behalf of CDF collaboration

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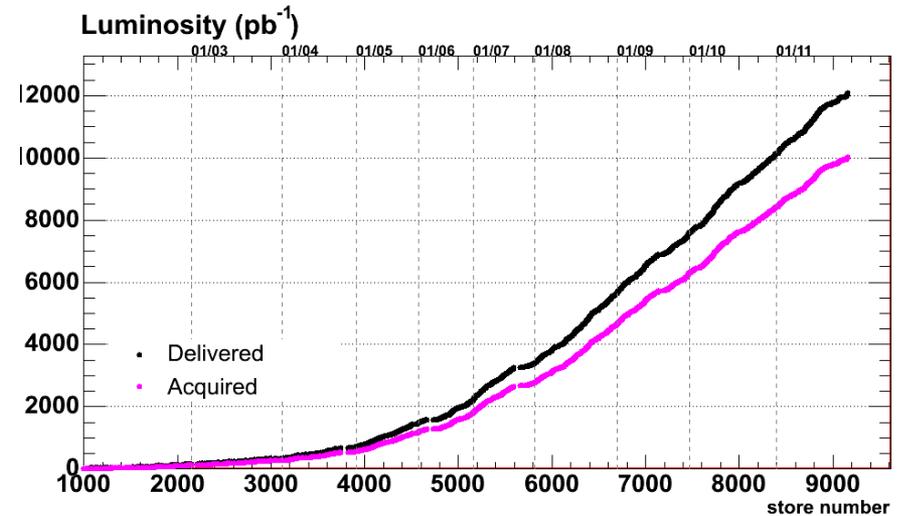
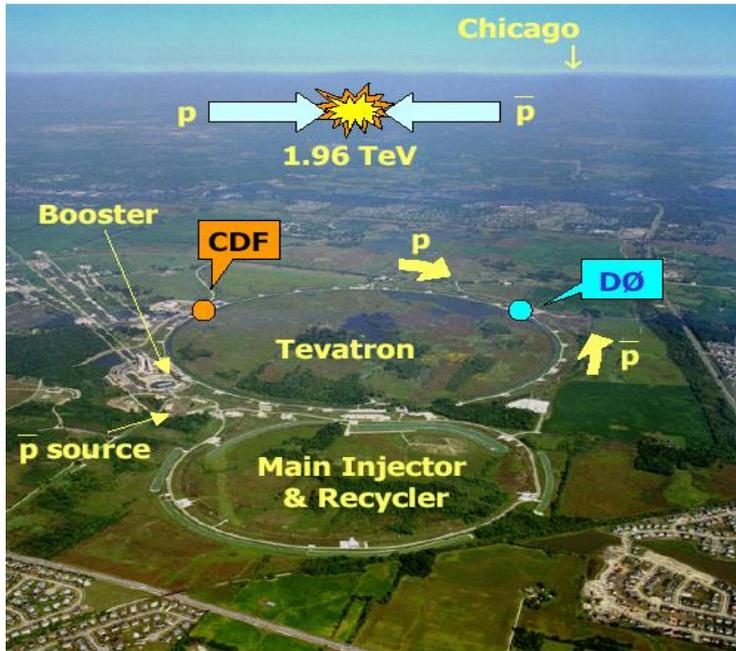


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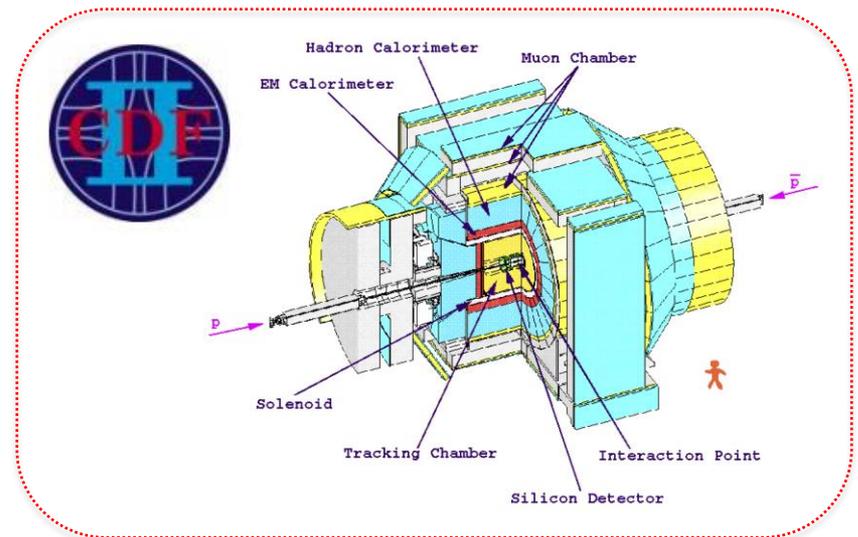


\* Supported by the EU Marie Curie IIF project 302103, "TauKitForNewPhysics"

# CDF Experiment and Dataset



- 1 km Radius Ring
- 2 million proton-antiproton collisions per second
- Run I (1992~1996):  $\sim 110 \text{ pb}^{-1}$ , 1.8 TeV
- Run II (2001~2011):  $\sim 10 \text{ fb}^{-1}$ , 1.96 TeV

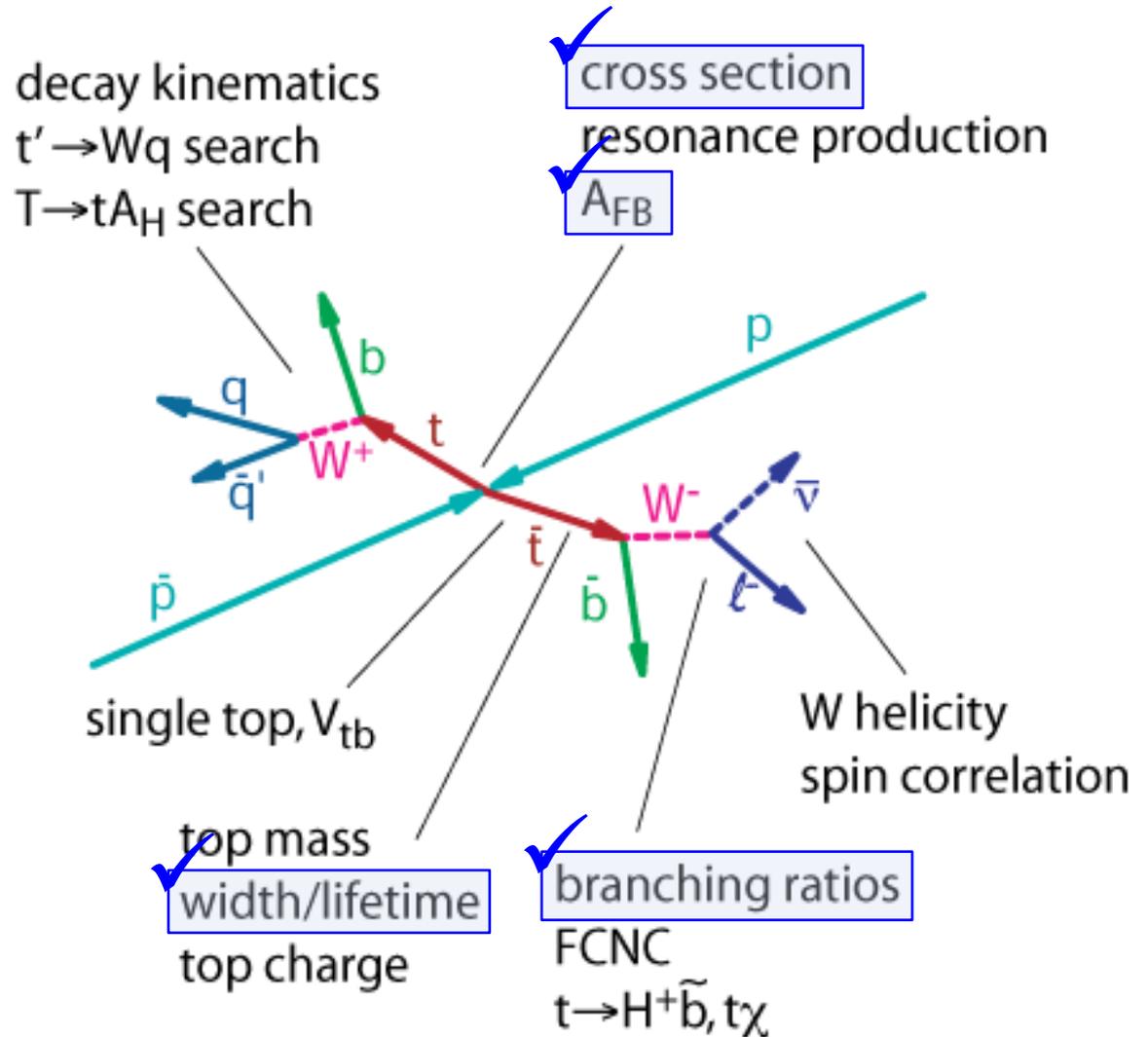




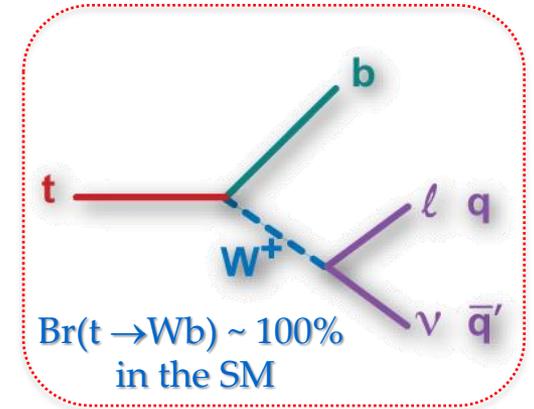
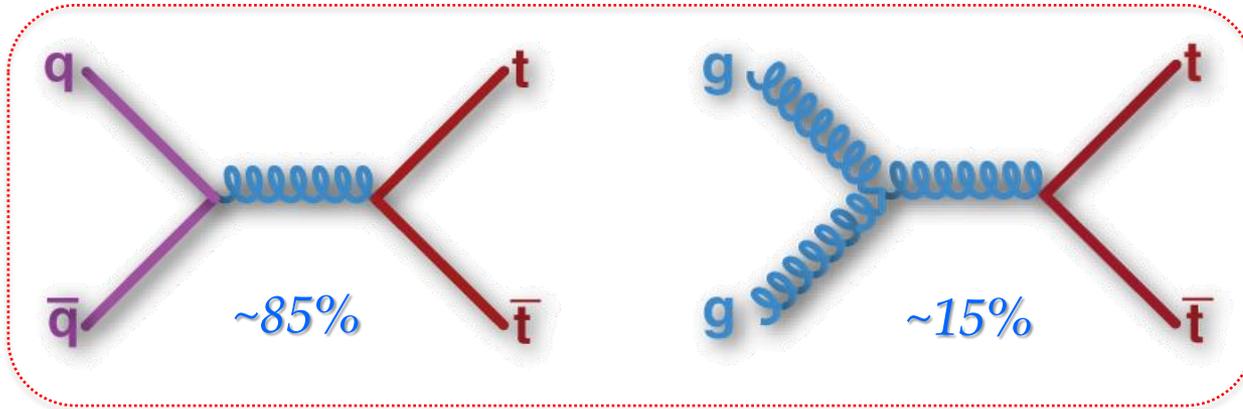
# Top quark properties

Checked topics will be covered in this talk

Any deviation from SM could indicate **New Physics** signal indirectly



# Top Pair Production and decay



## Top Pair Decay Channels

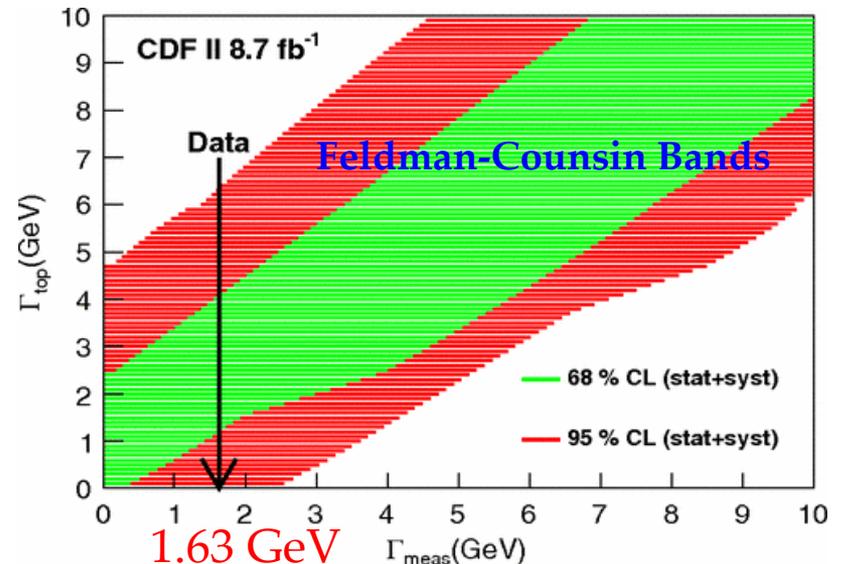
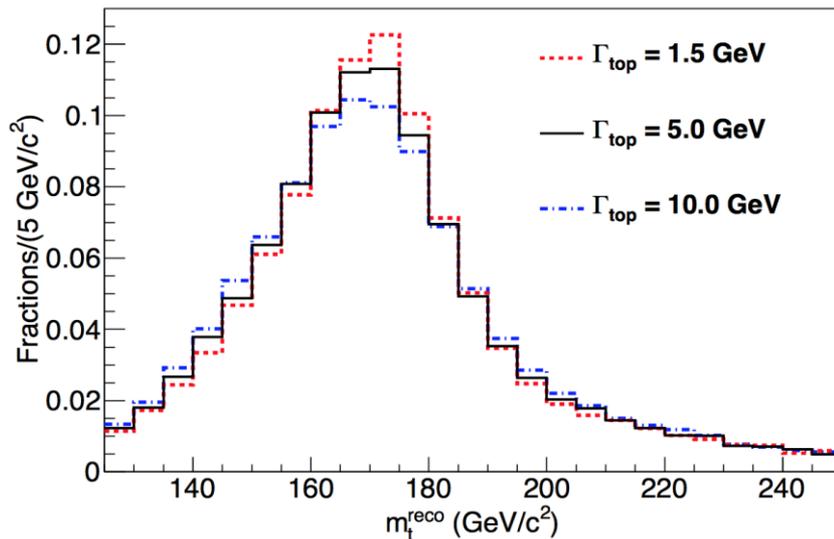
$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic			
$u\bar{d}$							
$\tau^-$	$e\tau$	$\mu\tau$	$\tau\tau$			tau+jets	
$\mu^-$	$e\mu$	$\mu\mu$	$\mu\tau$			muon+jets	
$e^-$	$e\tau$	$e\mu$	$e\tau$	electron+jets			
$W$ decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$	$c\bar{s}$		

- Most top pair production by Strong interaction at the Tevatron
- One top pair each  $10^{10}$  inelastic collisions at  $\sqrt{s} = 1.96$  TeV
  - Observed thousands of events in Run II
- Decay channels classified by W decays
- Top pair decay channels (l=e, $\mu$ )
  - Dilepton:  $l\nu l\nu b\bar{b}$  (5%)
  - Lepton+jets:  $l\nu qq\bar{b}\bar{b}$  (30%)
  - All-hadronic:  $qqqq\bar{b}\bar{b}$  (45%)

# Top quark width

Phys. Rev. Lett. 111, 202001 (2013)

- ✓ Top quark has the largest decay width of the known fermions in the SM prediction. ( $\Gamma_{\text{top}} \sim 1.3 \text{ GeV}$  at  $M_{\text{top}} = 172.5 \text{ GeV}/c^2$ )
- ✓ Direct measurement of the top-quark width is performed in fully reconstructed lepton + jets events by using the full CDF Run II data set



- ✓ Results are consistent with SM prediction. No evidence of non-SM physics in the top-quark decay.
  - $1.10 \text{ GeV} < \Gamma_{\text{top}} < 4.05 \text{ GeV}$  at 68% C.L.
  - $\Gamma_{\text{top}} < 6.38 \text{ GeV}$  at 95% C.L.

# Top quark Branching Ratio $B(t \rightarrow Wb) / B(t \rightarrow Wq)$



Published in PRL 2 June 2014

- ✓ Branching Ratio (BR) top decaying to bottom quark

$$R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

(PDG), Phys. Rev. D 86, 010001 (2012)

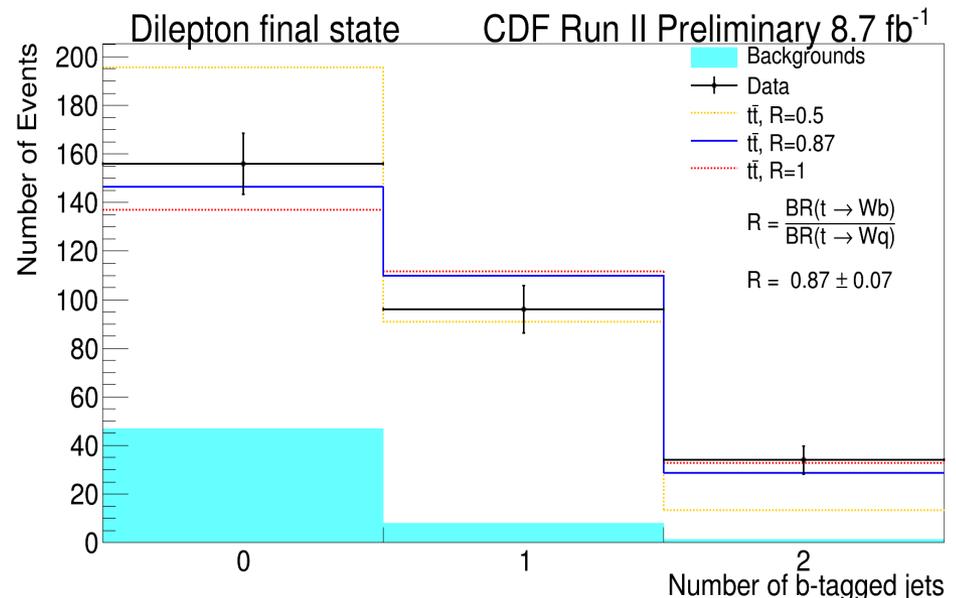
- ✓ In the SM,  $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$ ,  $|V_{tb}| = 0.999146^{+0.000021}_{-0.000046}$  PDG : PRD 86, 010001 (2012)
- ✓ Comparison between observed data and expectations in 9 subsamples: (ee,  $\mu\mu$ ,  $e\mu$ ) \* 3 b-tagging categories (0,1,2)

- ✓ BR is measured using the Maximum Likelihood estimator and the CKM Matrix element is extracted:

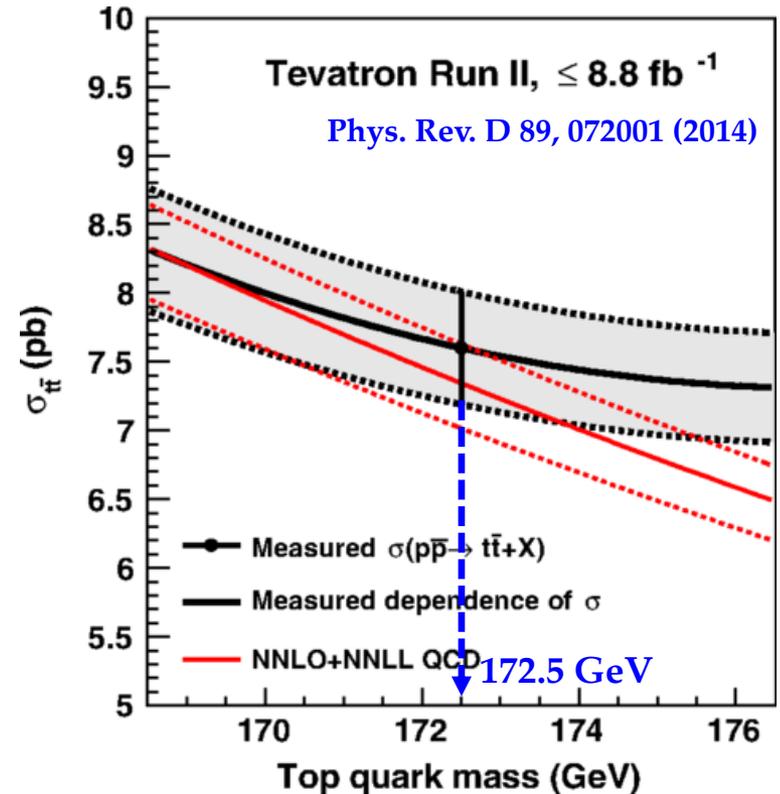
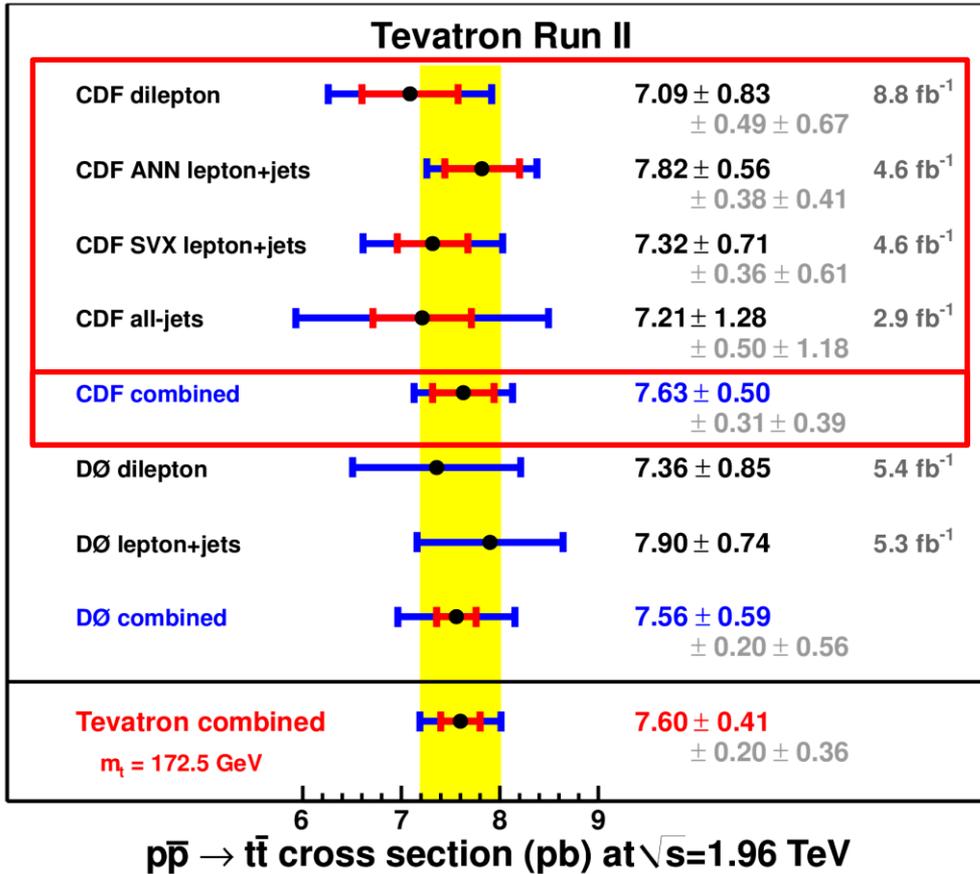
$$\mathcal{L} = \prod_i \mathcal{P}(\mu_{exp}^i(R, \sigma_{p\bar{p} \rightarrow t\bar{t}}, x_j) | N_{obs}^i) \prod_j G(x_j | 0, 1)$$

CDF Run II Preliminary,  $\mathcal{L} = 8.7 \text{ fb}^{-1}$

Parameter	Result
$R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$	$0.87 \pm 0.07$
$ V_{tb} $	$0.93 \pm 0.04$



# Top Pair Production Cross Section

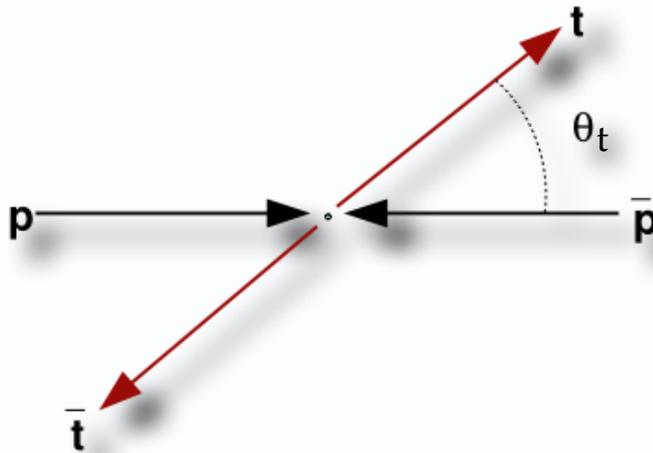


- ✓ CDF results contribute to Tevatron combination by 60%.
- ✓ Only CDF dilepton results used the full dataset.

- ✓ Theoretical prediction (**Precision ~ 4%**)  
 $\sigma = 7.35^{+0.11}_{-0.21} \text{ (scales)} + {}^{0.17}_{-0.12} \text{ (PDF)}$
- ✓ CDF combination (**Precision ~ 6.5%**)  
 $\sigma = 7.63 + 0.50 \text{ (stat+syst) pb}$

# Differential $d\sigma/d\cos\theta_t$ $t\bar{t}$ cross section

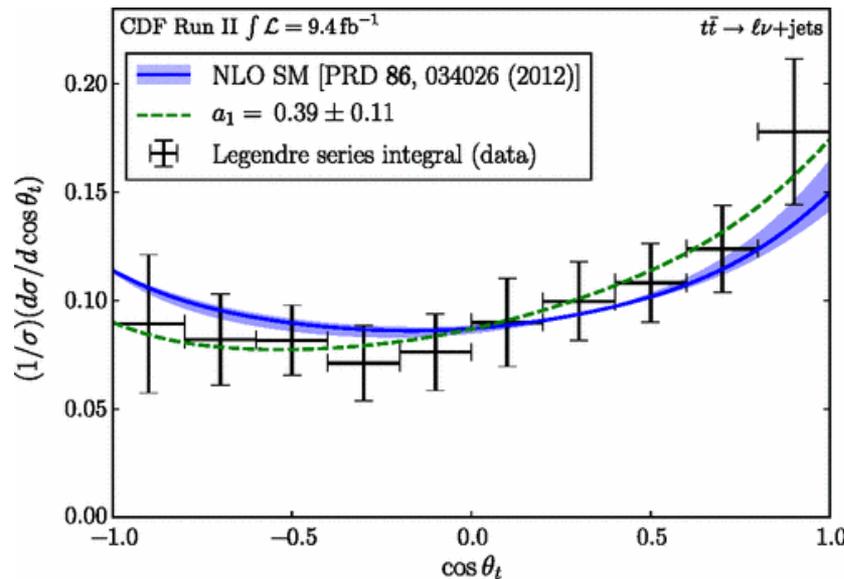
Phys. Rev. Lett. 111, 182002 (2013)



- ✓ Differential  $t\bar{t}$  cross section,  $d\sigma/d\cos\theta_t$  where  $\theta_t$  is the angle between the top quark momentum and the incoming proton momentum as measured in the  $t\bar{t}$  center-of-mass-frame
- ✓ Characterize the shape of  $d\sigma/d\cos\theta_t$  by expanding in the Legendre polynomials

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

- ✓ where  $P_{\ell}$  is the Legendre polynomial of degree  $\ell$ , and  $a_{\ell}$  is the Legendre moment of degree  $\ell$

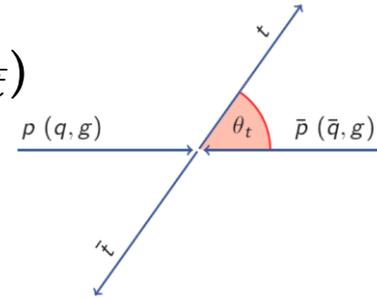


**~2  $\sigma$  deviation from NLO prediction**

$\ell$	$a_{\ell}$ (obs)	$a_{\ell}$ (pred)
1	$0.40 \pm 0.12$	$0.15^{+0.066}_{-0.033}$
2	$0.44 \pm 0.25$	$0.28^{+0.053}_{-0.030}$
3	$0.11 \pm 0.21$	$0.030^{+0.014}_{-0.007}$
4	$0.22 \pm 0.28$	$0.035^{+0.016}_{-0.008}$
5	$0.11 \pm 0.33$	$0.0048^{+0.002}_{-0.001}$
6	$0.24 \pm 0.40$	$0.0060^{+0.002}_{-0.003}$
7	$-0.15 \pm 0.48$	$-0.0028^{+0.001}_{-0.001}$
8	$0.16 \pm 0.65$	$-0.0019^{+0.0003}_{-0.0003}$

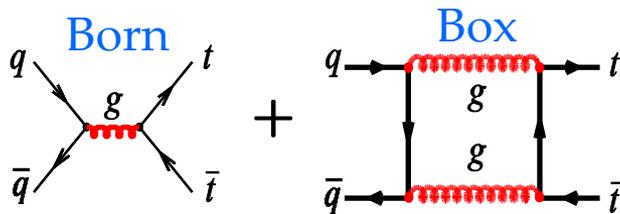
# Top $A_{FB}$ in Standard Model

✓ FB Asymmetry is defined by  $A_{FB} = \frac{N_{\Delta y > 0} - N_{\Delta y < 0}}{N_{\Delta y > 0} + N_{\Delta y < 0}}$  ( $\Delta y = y_t - y_{\bar{t}}$ )

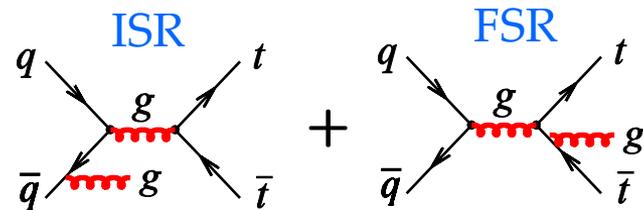


✓ Inclusive NLO prediction (QCD+EWK) :  $A_{FB} = 8.8 \pm 0.6\%$ \*

- \* W. Bernreuther and Z.-G. Si, Phys.Rev. D86, 034026 (2012)
- Terms of order  $\alpha_s^3$  in the partonic cross section  $d\hat{\sigma}(q\bar{q} \rightarrow t\bar{t}X)$
- Interference of the Born diagram with the 1-loop box and crossed box diagrams
- Interference of initial and final state radiation



Positive asymmetry



Negative asymmetry

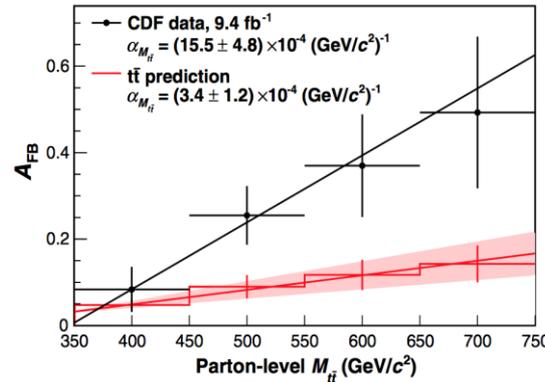
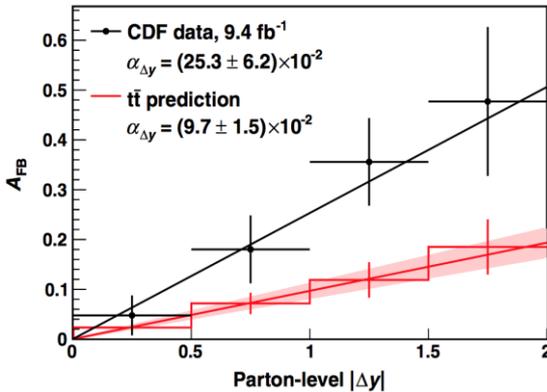
✓ Presence of new physics could make asymmetry

- Axial vector exotic gluon  $G'$  coupling
- $Z'$  exchange,  $W'$  interaction
- Things to have to explain by BSM
  - Measured  $t\bar{t}$  cross section ( $\sigma$ ) and  $d\sigma/dM_{t\bar{t}}$  are in good agreement with SM at Tevatron and LHC
  - Tiny  $A_C$  at LHC and No other indications related to  $A_{FB}$

# Dependency checks of $t\bar{t}$ $A_{FB}$ in Lep+Jets events

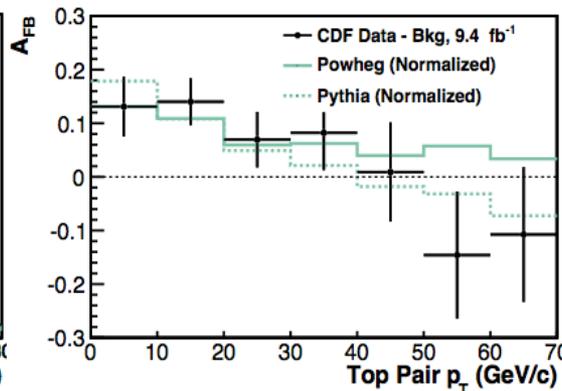
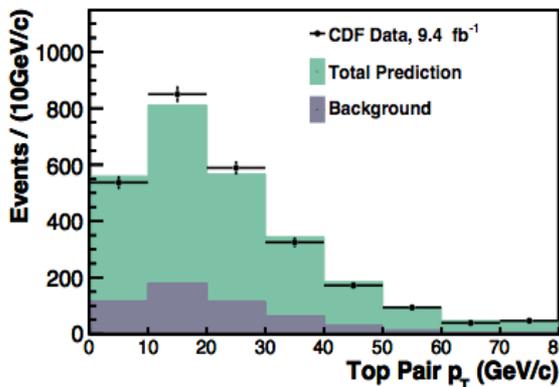
Phys. Rev. D 87, 092002 (2013)

- ✓ Observed  $A_{FB} = 6.6 \pm 2.0\%$ , **Parton-level  $A_{FB} = 16.4 \pm 4.7\%$**  with  $9.4 \text{ fb}^{-1}$ .
- ✓ Mass and Rapidity dependence



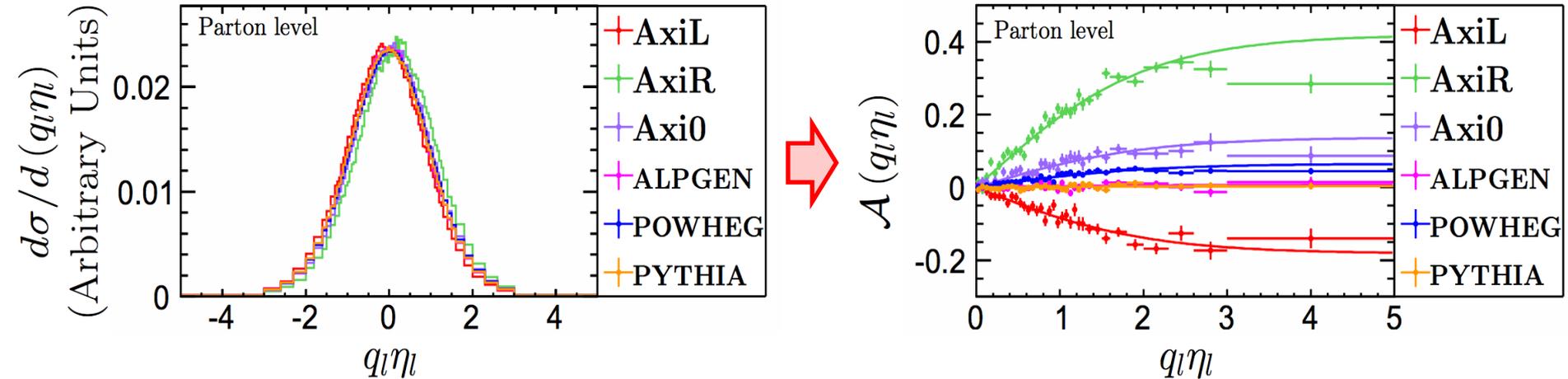
- ✓ Asymmetry linearly increases as a function of parton-level  $M_{t\bar{t}}$  and  $|\Delta y|$
- ✓ Slopes are  $3\sigma$  from zero and  $\sim 2.3\sigma$  from SM prediction

- ✓  $p_T(t\bar{t})$  dependence



- ✓ NLO (QCD+EW)  $t\bar{t}$  + Background prediction agrees with data in top pair  $p_T$  distribution
- ✓  $A_{FB}$  in the background subtracted data depends on the  $t\bar{t}$   $p_T$  spectrum
- ✓ The normalized shapes from Powheg(NLO) and Pythia(LO) describes well data, but the total asymmetry are not
- ✓ Reconstruction and modeling of the  $p_T(t\bar{t})$  dependence of the asymmetry is robust, and that the excess asymmetry in the data is consistent with being independent of  $p_T(t\bar{t})$

# Leptonic Asymmetry in $t\bar{t}$ Production



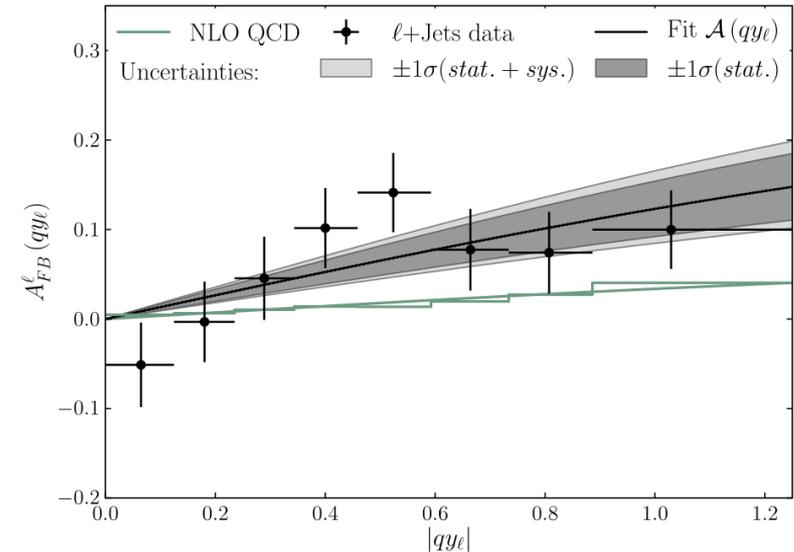
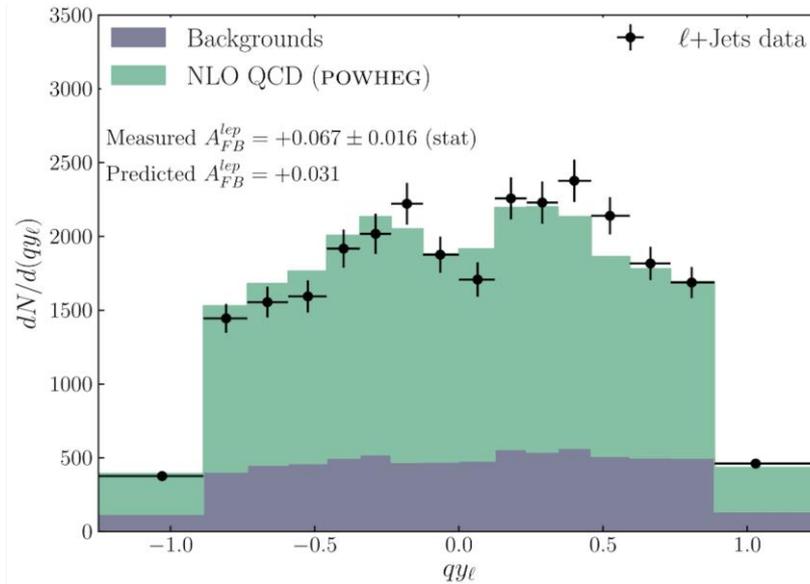
- ✓ The generator-level distributions of  $q_l\eta_l$  for different models are shown in the left plot. Shapes almost identical and a little shift of means.
- ✓ The asymmetric part is decomposed from the  $q_l\eta_l$  distribution at parton level with various physics models.  $\mathcal{A}(q_l\eta_l)$  is parametrized with an functional form of  $a \cdot \tanh(1/2 \cdot q_l\eta_l)$

$$A_{\text{FB}}^l = \frac{N(q_l\eta_l > 0) - N(q_l\eta_l < 0)}{N(q_l\eta_l > 0) + N(q_l\eta_l < 0)}$$

- ✓ Leptonic  $A_{\text{FB}}$  kinematically correlated with top  $A_{\text{FB}}$  and manifestation of  $A_{\text{FB}}$  in the lepton from polarized tops.

# Leptonic Asymmetry in Lep+Jets channel

Phys. Rev. D. 88.072003 (2013)

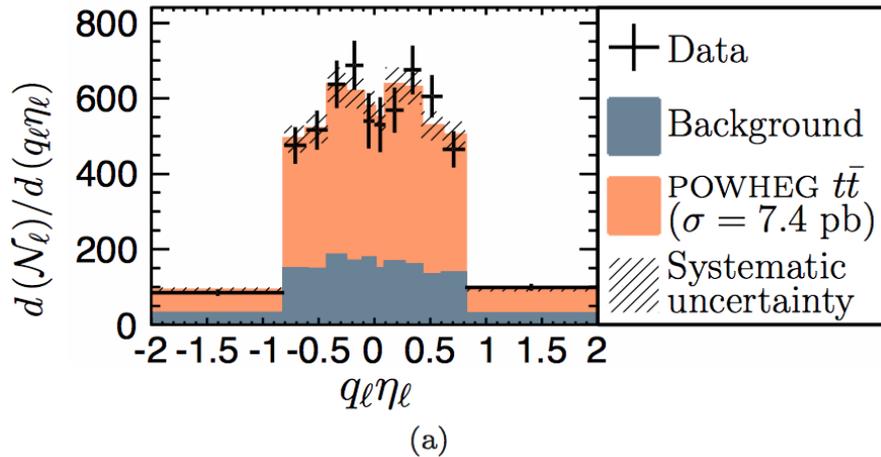


- ✓ **Observed  $A_{FB}^{lep} = 9.4^{+3.2}_{-2.9}\%$  (SM Prediction:  $3.8 \pm 0.3\%$ )**
- ✓ The observed distribution of events vs  $qy_\ell$  in the signal region (left) compared to the NLO QCD prediction of POWHEG and backgrounds
- ✓ The binned asymmetry  $A_{FB}^{lep}(qy_\ell)$  after correcting for acceptance (right), compared to the NLO QCD prediction of POWHEG. The best fit for each is shown as the smooth curve of the same color. The dark (light) gray bands indicate the statistical (total) uncertainty on the fit curve to the data.

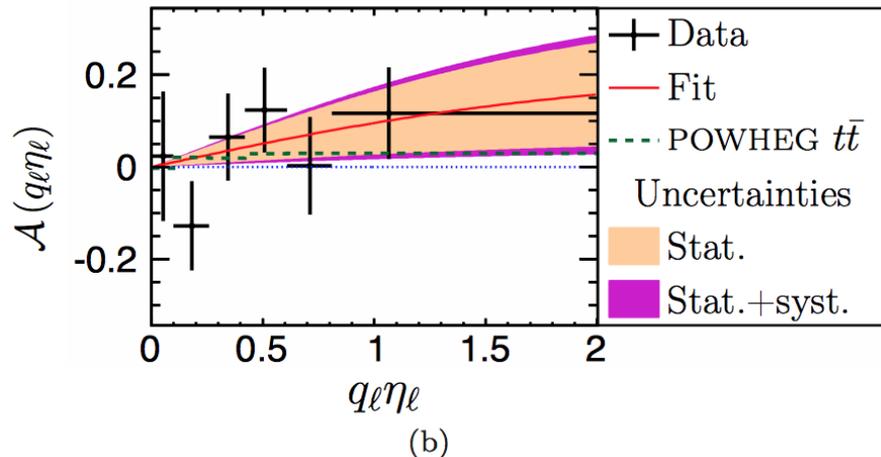
# Leptonic Asymmetry in Dilepton channel

New Accepted by PRL at last week!

arXiv:1404.3698



(a): Comparison of the observed number of leptons as a function of  $q_l \eta_l$  with the SM expectations.



(b): Asymmetric part of the distribution from data with the best fit and the expectations from the powheg MC model.

The bands indicate the one standard deviation uncertainty (statistical + systematic).

## ✓ Result :

$$A_{\text{FB}}^{\text{lep}} = 7.2 \pm 5.2(\text{stat}) \pm 3.0(\text{syst})\% \\ = 7.2 \pm 6.0\% \text{ (SM Prediction: } 3.8 \pm 0.3\%)$$

✓ Secondary result:  $A_{\text{FB}}$  of  $\Delta\eta$  between the two leptons in each event.

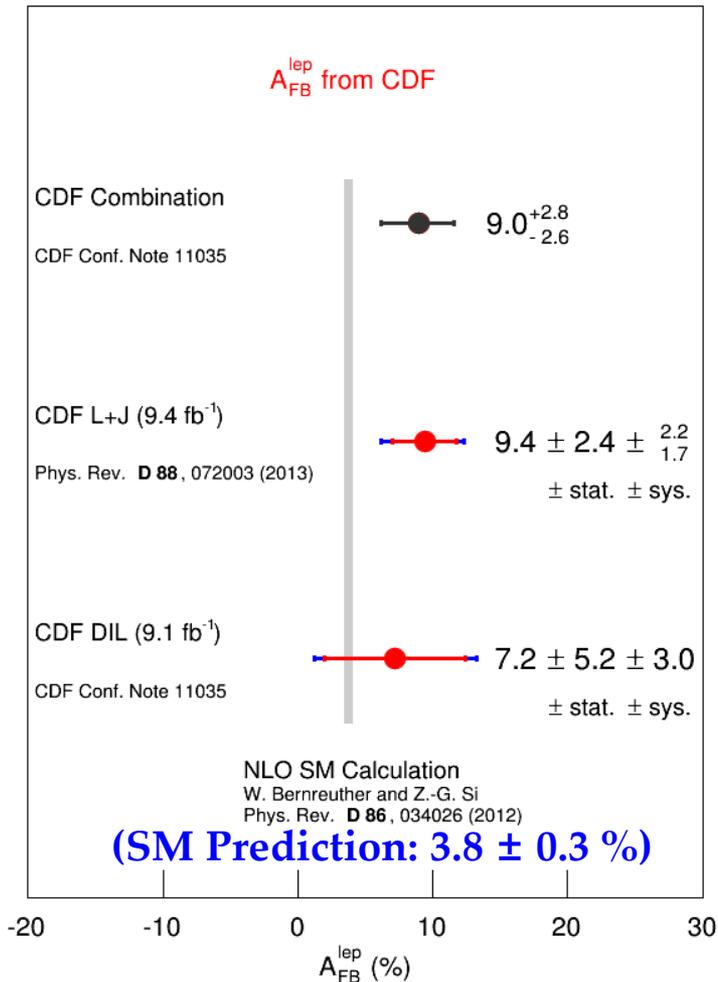
$$A_{\text{FB}}^{\Delta\eta} = 7.6 \pm 7.2(\text{stat}) \pm 3.9(\text{syst})\% \\ = 7.6 \pm 8.1\%$$

# CDF Combination of $t\bar{t}$ Leptonic $A_{FB}$

New

Accepted by PRL at last week!

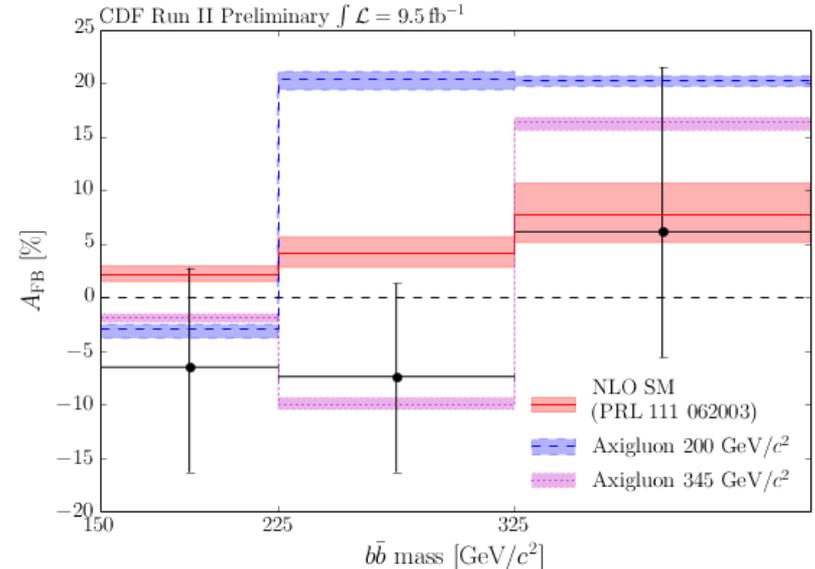
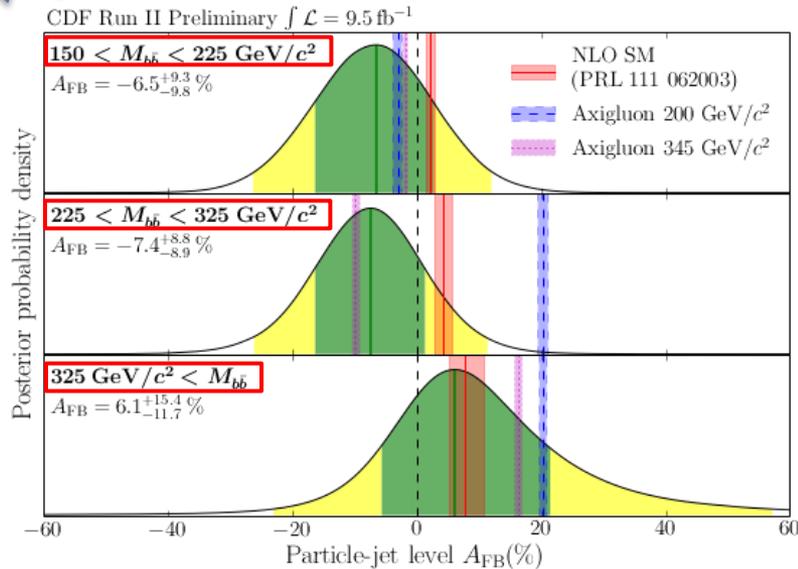
arXiv:1404.3698



- ✓ Combined the two measurements using BLUE method.
- ✓ Measurements in Lep+Jets channel using 3864 events, signal purity: 72.8%, at least one b-tagging:
  - $A_{FB}^{\text{lep}} = 9.4^{+3.2}_{-2.9}$  %
- ✓ Measurements in DIL channel using 569 events, signal purity: 71.8%, no b-tagging):
  - $A_{FB}^{\text{lep}} = 7.2 \pm 6.0$  %
- ✓ Combined result :
  - ✓  $A_{FB}^{\text{lep}} = 9.0^{+2.8}_{-2.6}$  %  
(Weight: Lep+Jets 80%; DIL 20%. Correlation: 2.6%)
- ✓ Result is  $2\sigma$  larger than NLO SM prediction:

# Forward-backward asymmetry in $b\bar{b}$ pairs

New



- ✓  $A_{\text{FB}}$  in  $b\bar{b}$  pairs at large  $b\bar{b}$  mass using jet-triggered data and jet charge to identify  $b$  from  $\bar{b}$ .
- ✓ The asymmetry is consistent with both zero and with the SM predictions as a function of  $m(b\bar{b})$ . And excluded a Axigluon model ( $M_{\text{Axigluon}} = 200 \text{ GeV}/c^2$ ). ([arXiv:1401.2443](https://arxiv.org/abs/1401.2443))
  - $A_{\text{FB}}$  only changes sign when  $M_{\text{Axigluon}} > M(b\bar{b})$ .
- ✓ CDF is working on  $A_{\text{FB}}$  in  $b\bar{b}$  pairs at low mass.
- ✓ More information in the CDF public page and public note 11092.
  - <http://www-cdf.fnal.gov/physics/new/top/2014/Afbpub/index.html>

# Conclusion

- ✓ Recent top quark pairs production and properties results from CDF are shown
  - Most measurements are consistent with the SM prediction.
- ✓ Top  $A_{\text{FB}}$  still there at CDF
  - Many various experimental checks are done.
  - Inconsistent with SM calculation.
    - The Top asymmetry grows as a function of  $t\bar{t}$  mass and rapidity
    - Leptonic asymmetry measurement show  $2\sigma$  deviation from SM prediction.
  - Tevatron combination of  $A_{\text{FB}}$  in progress.
- ✓ More information and results in the public webpage : CDF Top Groups and Tevatron Electroweak Working Group
  - <http://www-cdf.fnal.gov/physics/new/top/top.html>
  - <http://tevewwg.fnal.gov>