

Selected topics from angular distributions in $t\bar{t}b\bar{b}$ events

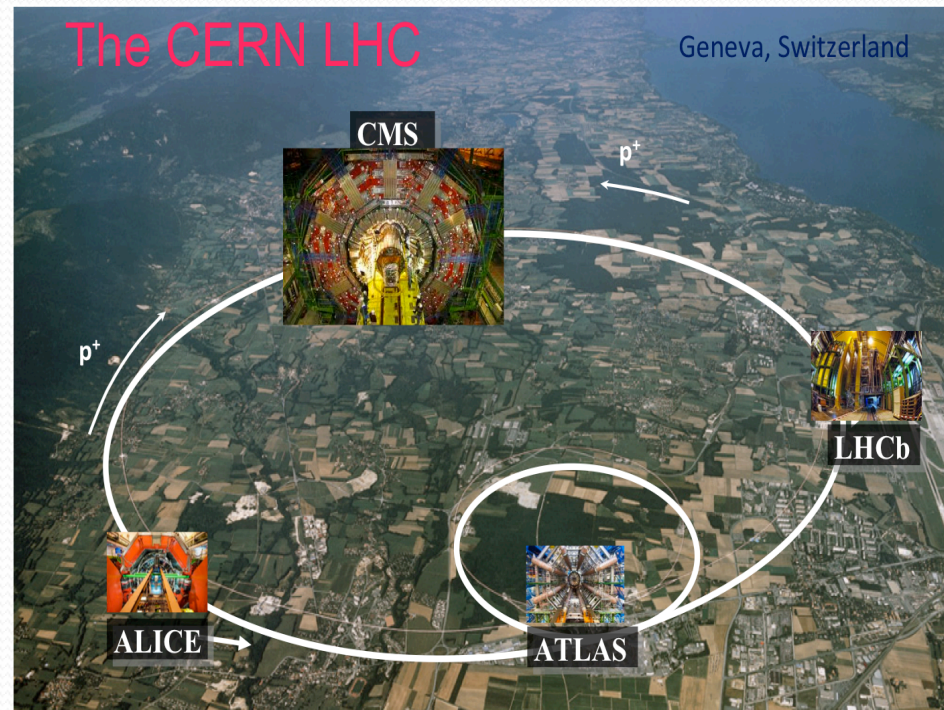
Cecilia E. Gerber

University of Illinois
at Chicago

(on behalf of the ATLAS and CMS
Collaborations)

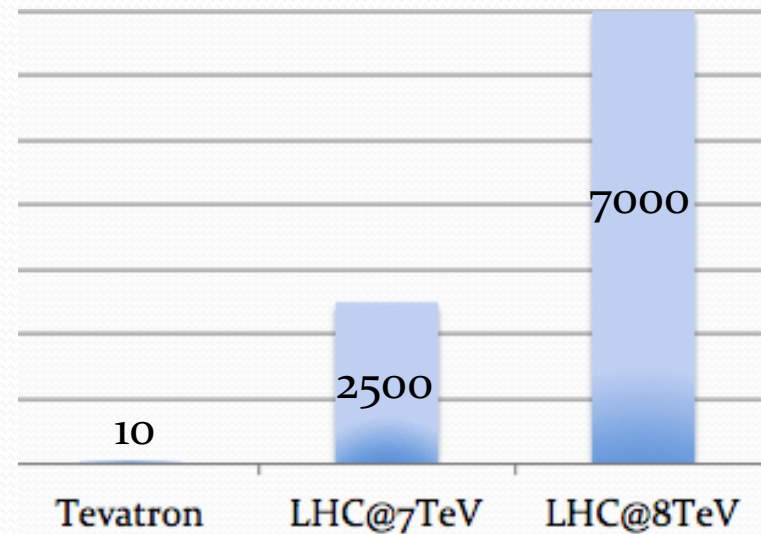
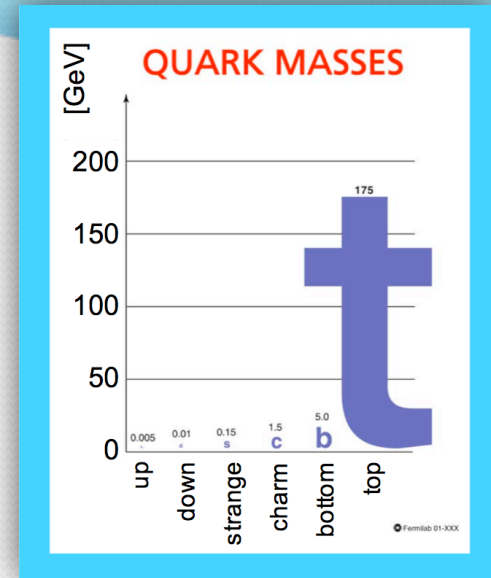
3rd Annual Large Hadron Collider
Physics Conference

St. Petersburg, Russia, August 31 – September 5, 2015



Introduction

- Top quark is special in the Standard Model:
 - VERY heavy
 - Decays before hadronization – we study bare quark
- Probe of new physics beyond electroweak scale
 - Production – top can be produced in decays of new particles (incl. virtual)
 - Decay – top can decay into new particles
- LHC is a top factory



Top quark pairs per hour at peak luminosity

Measuring top properties

- This talk is focused on **top pair** production

Production:

- Charge Asymmetry
- Color flow
- t-tbar Spin Correlation

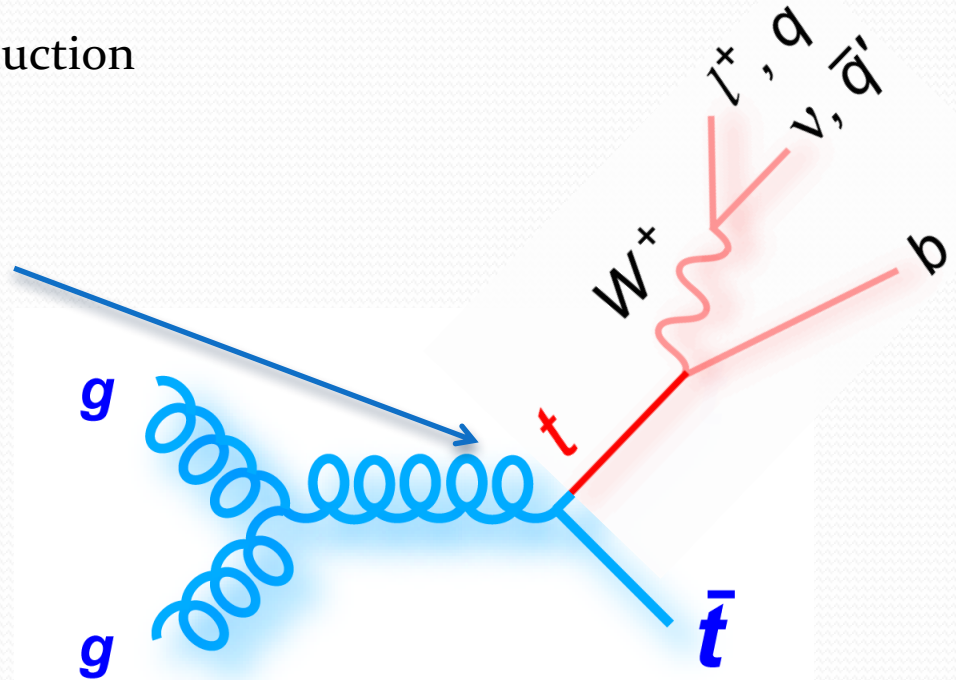


Decay:

- Branching ratios
- W polarization in top decays

Other measurements:

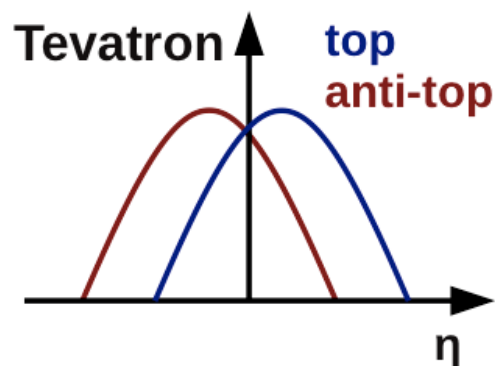
- Top mass & production (ttbar and single top), BSM Searches



Charge Asymmetry

- NLO effect originating from interference of q-qbar diagrams producing top pairs
- Can be largely enhanced by new physics, such as W' or axigluon models

Tevatron (p-pbar machine) top quarks are preferentially emitted in the direction of the incoming quark, anti-tops in the direction of the incoming anti-quark.

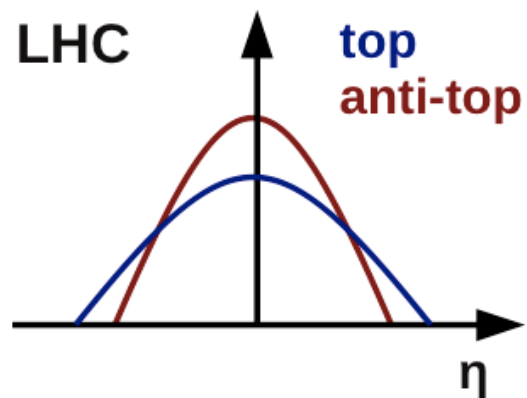


$$A_{\text{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

LHC has symmetric initial state (pp):

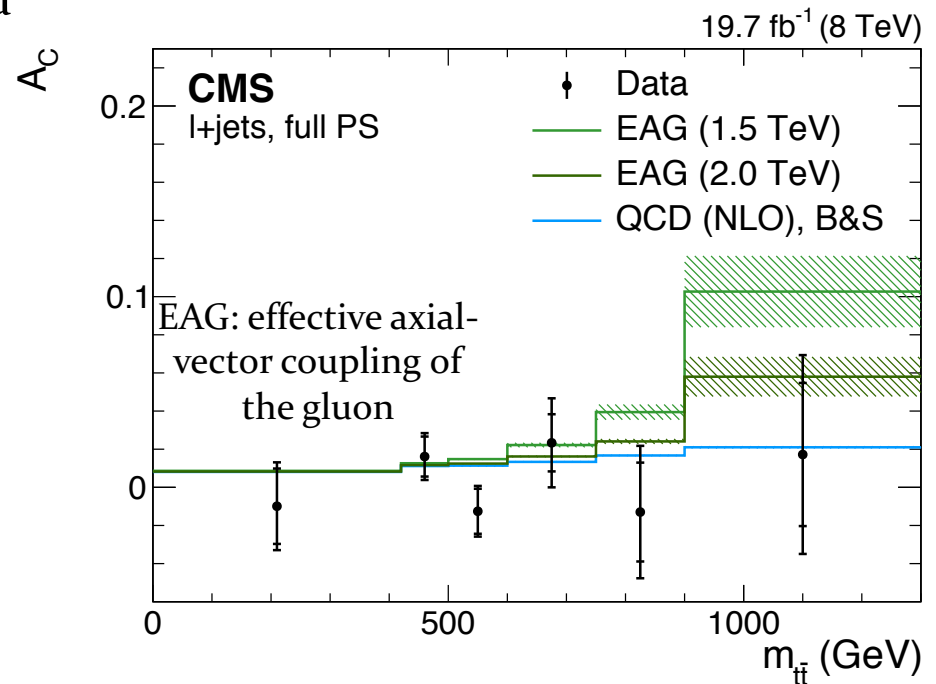
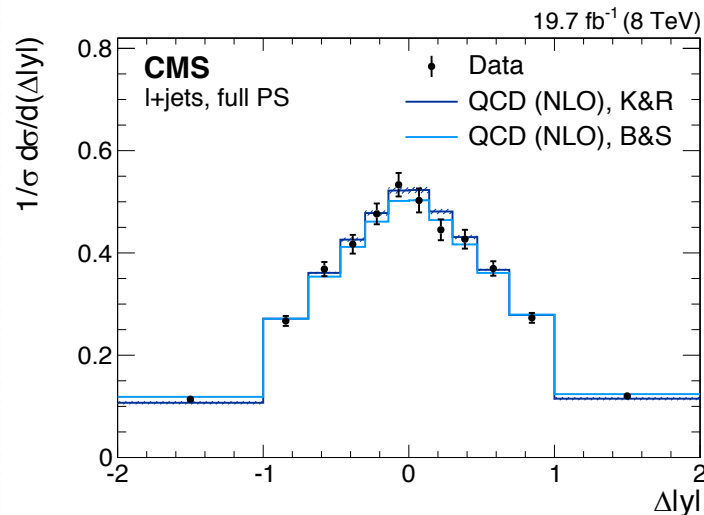
- Quarks are mostly valence and anti-quarks are from the sea
- The PDF's are not symmetric – quarks carry more momentum than anti-quarks
- Rapidity distribution of tops is broader



$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

A_C in lepton + jets events

- Full 8 TeV CMS dataset ($\sim 19.7 \text{ fb}^{-1}$)
- One lepton (e or μ), $\geq 4j$, $\geq 1b$ -tag
- $t\bar{t}$ association based on likelihood
- Unfolded to parton level
- Differential distributions (in $m_{t\bar{t}}$, $y_{t\bar{t}}$, $p_{t\bar{t}}^T$) sensitive to BSM physics



Full phase space

Theoretical prediction [Kühn, Rodrigo] [9]

Theoretical prediction [Bernreuther, Si] [39]

$0.0010 \pm 0.0068 \text{ (stat.)} \pm 0.0037 \text{ (syst.)}$

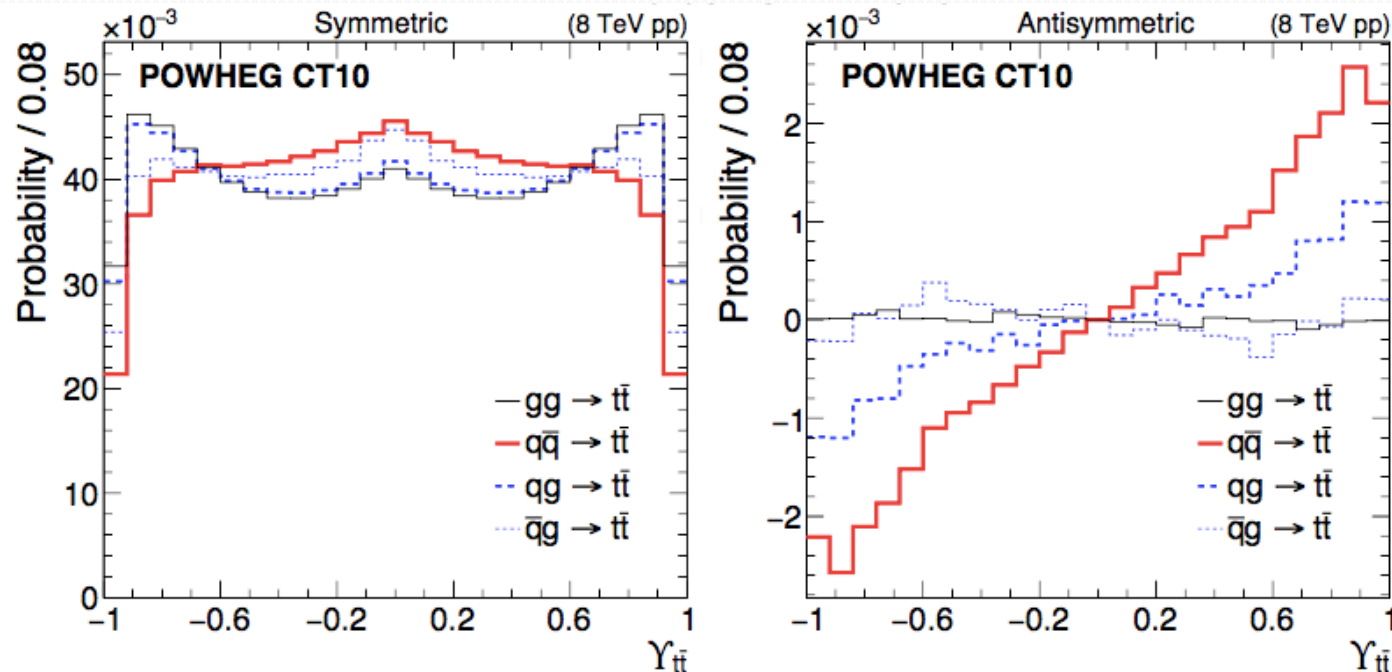
0.0102 ± 0.0005

0.0111 ± 0.0004

Submitted to PLB
arXiv:1507.03119

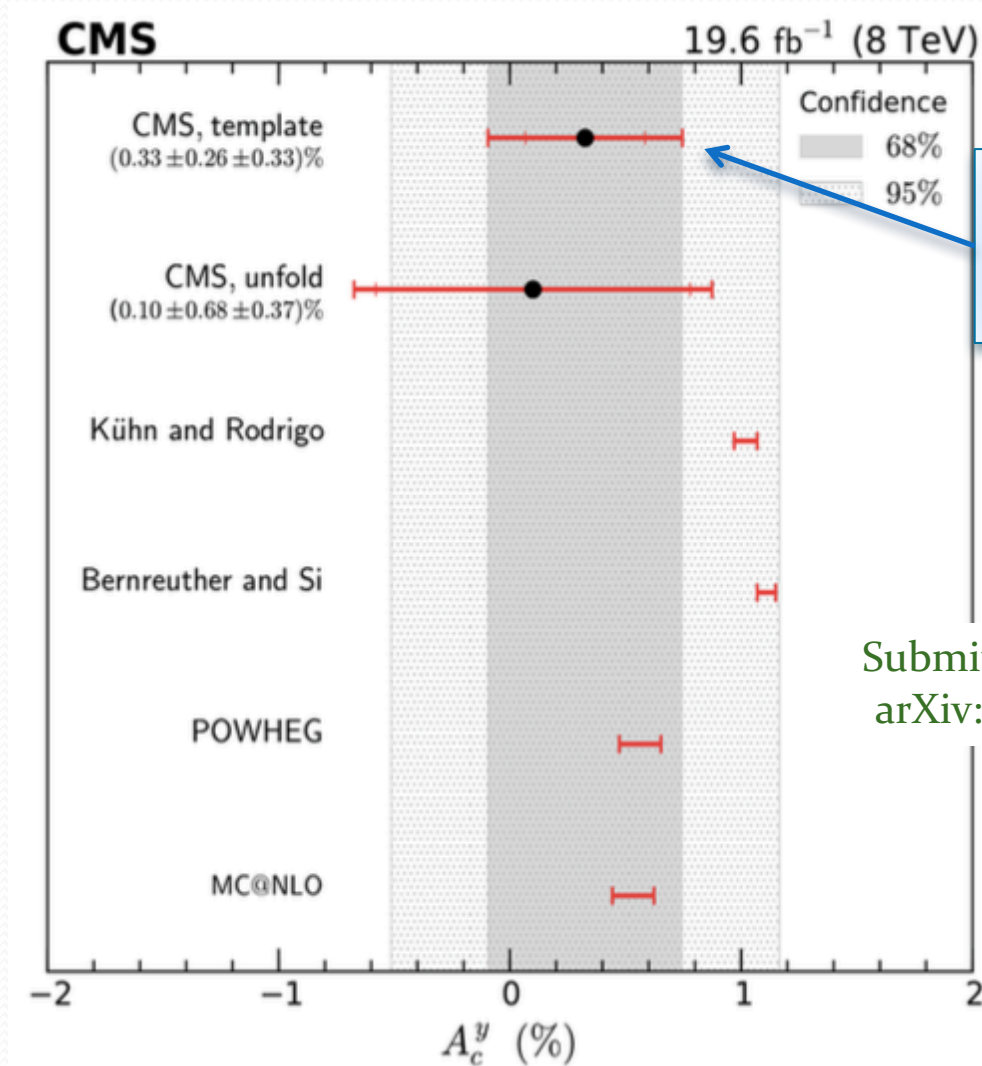
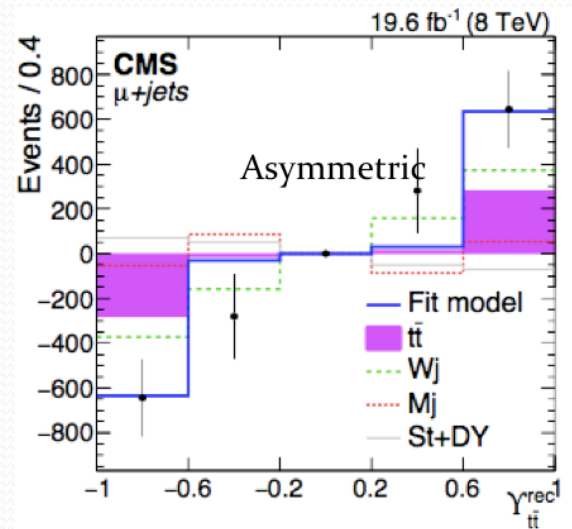
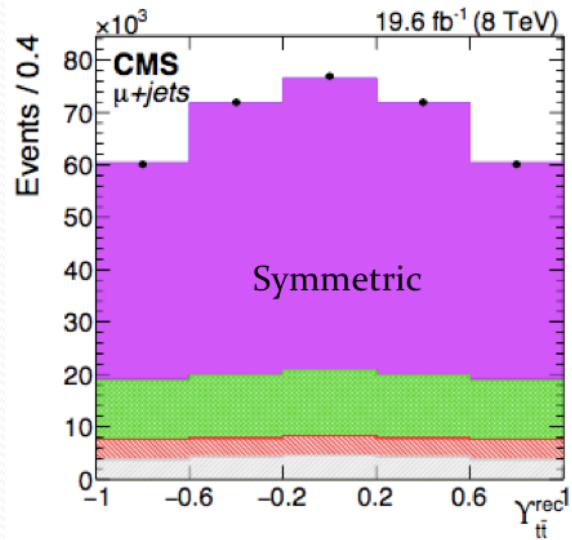
A_C (l+jets) - Template Method

- 8TeV data, looser cuts, larger sample
- Two-stage maximum-likelihood fit used sequentially for sample composition and A_C .
- Two templates for different initial states constructed from POWHEG with CT10 PDFs
- Template fit to bounded sensitive variable $\Upsilon_{t\bar{t}} = \tanh\Delta|y_{t\bar{t}}|$
- Alternative to unfolding: fit data to linear combination of symmetric and anti-symmetric templates at reconstruction level



Significantly smaller statistical uncertainties with slightly larger model dependence than traditional unfolding methods

$A_C(l+jets)$ - Template Method

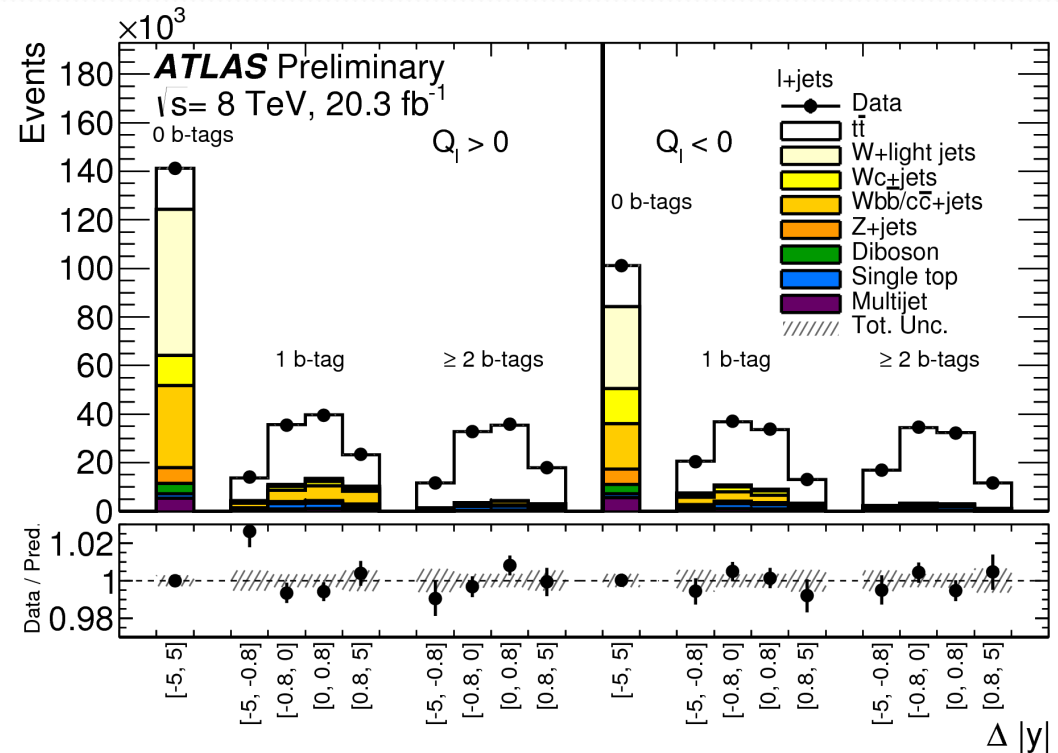


Much improved uncertainty

Submitted to PRD
arXiv:1508.03862

A_C (l+jets) – Brand New from ATLAS

- 8 TeV ATLAS dataset (20.3 fb⁻¹)
- One lepton (electron or muon), at least 4 jets
- ttbar association based on likelihood
- Measurement performed in 18 channels based on lepton charge, number of b-jets (0, 1 ≥ 2), and rapidity bins
- Simultaneous Bayesian unfolding and in-situ W+jets calibration
- Main uncertainty is data statistics, followed by JES/JER and MC statistics

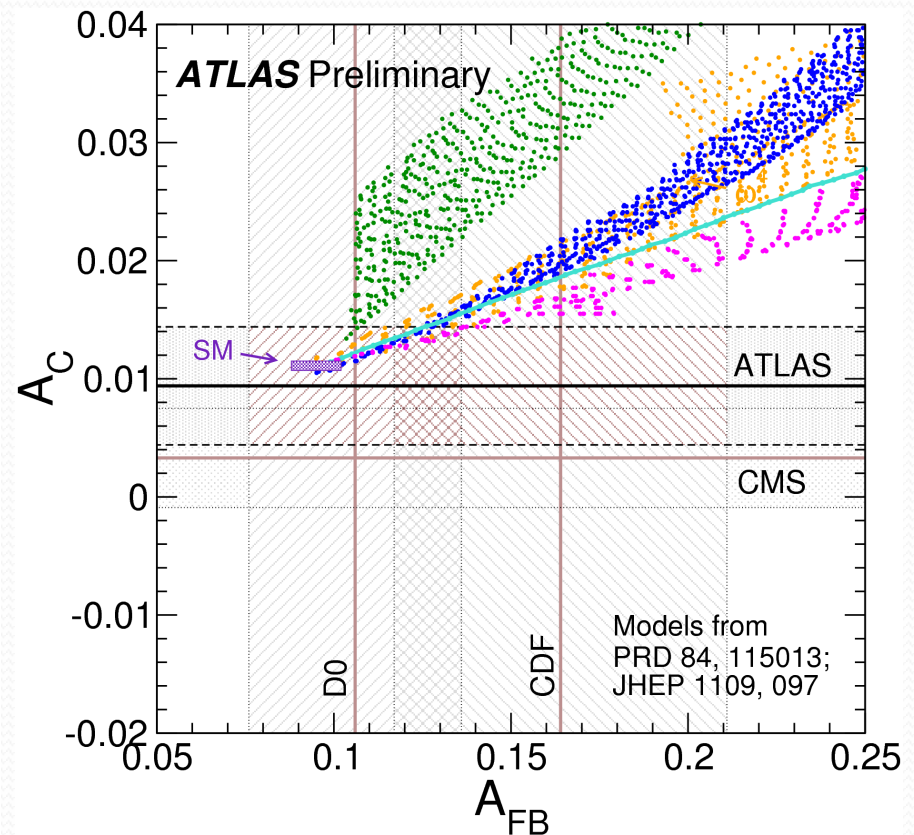
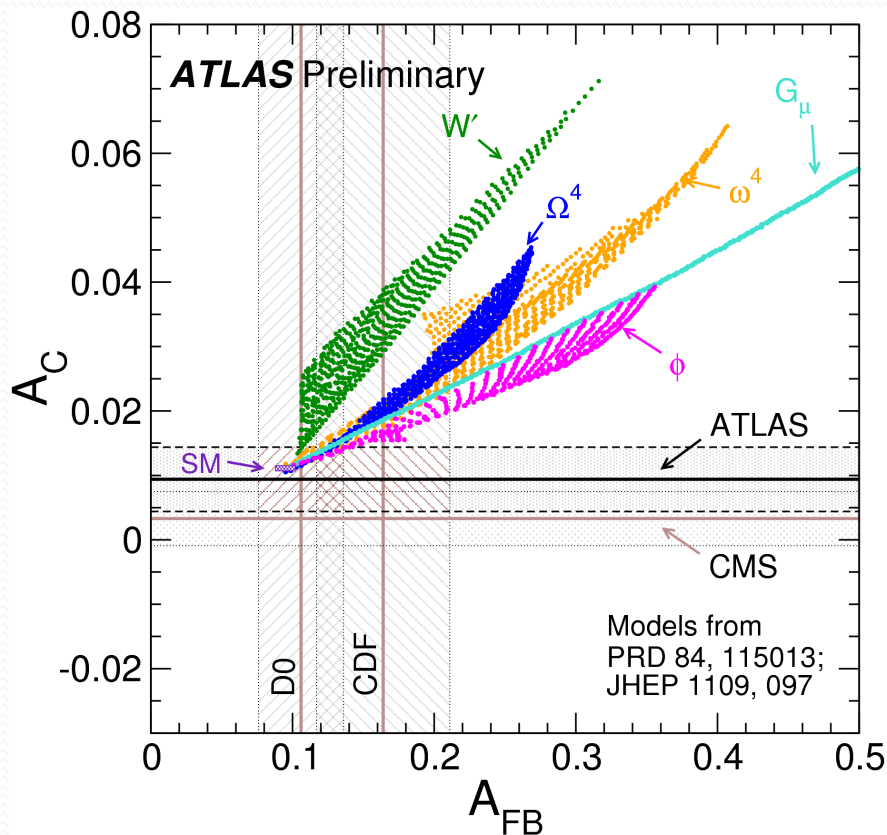


ATLAS: $A_C = 0.009 \pm 0.005$

Prediction : $A_C = 0.0111 \pm 0.0004$ PRD 86, 034026(2012)

Differential measurements as a function of the invariant mass, transverse momentum and longitudinal boost of the ttbar system compatible with SM predictions

A_C (l+jets) – Brand New from ATLAS

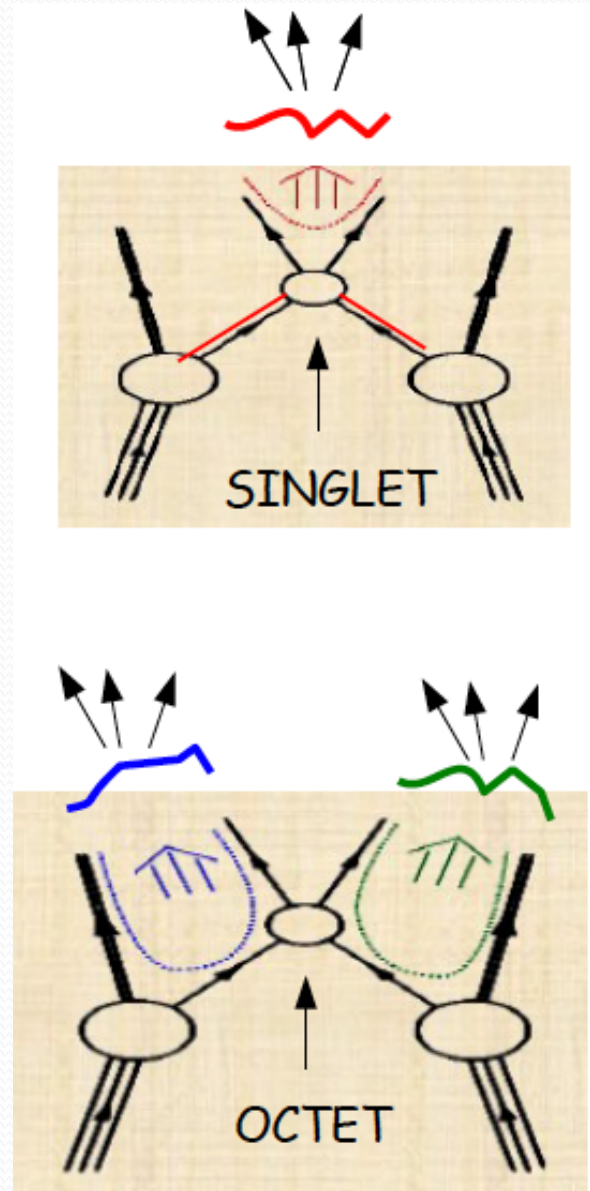


Large phase-space of parameters describing various BSM models is excluded

To be submitted to EPJC

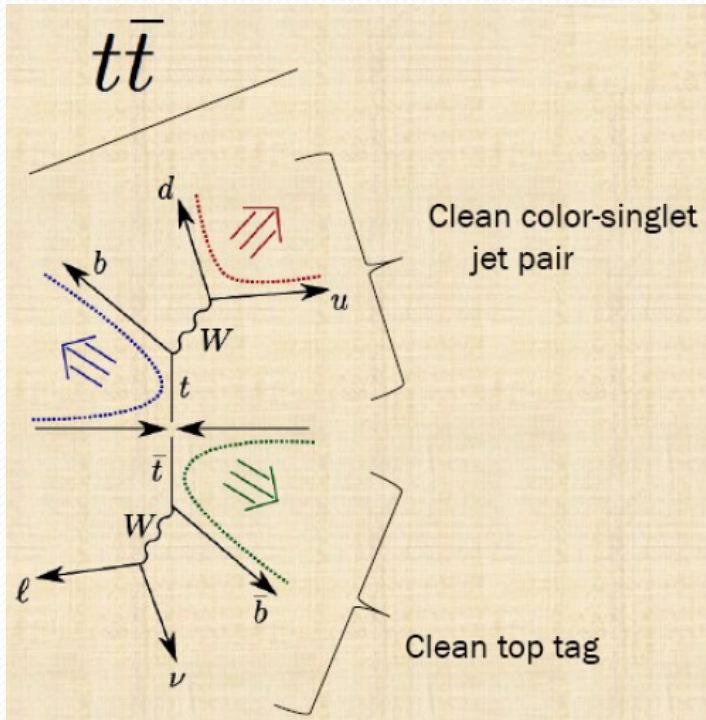
Color Flow

- QCD color charge is conserved locally, i.e. it “flows” just like electric charge
- Quarks carry one color (triplet)
- Gluons carry a color and an anti-color (octet)
- Others (W, Z, H, etc.) carry no color (singlet)
- Pulling apart a color from its anti-color requires lot of energy ($\sim 1\text{GeV/fm}$)
 - Described through a color string or color connection picture
- Eventually color strings “break” by pulling quarks out of the vacuum
- **Particles created during hadronization should be concentrated along angular region spanned by the color connected partons**



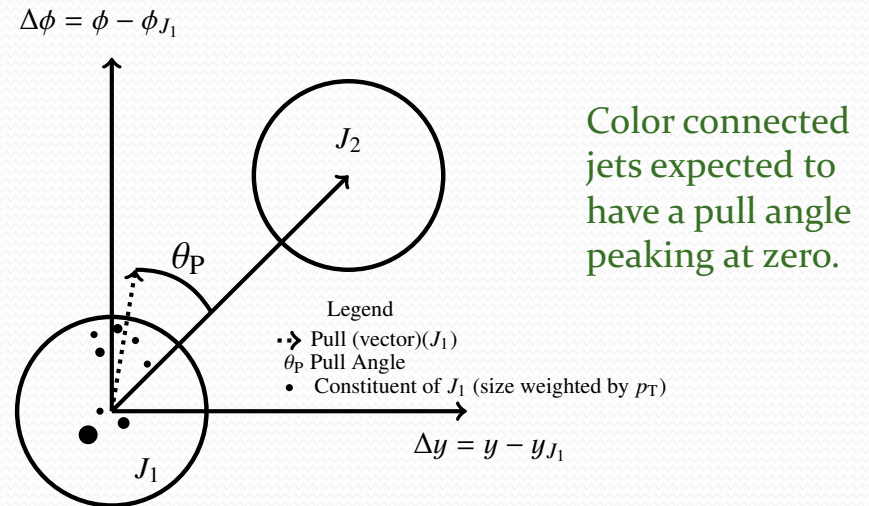
Color Flow

- $t\bar{t}$ lepton+jets sample ideal for the study of color flow

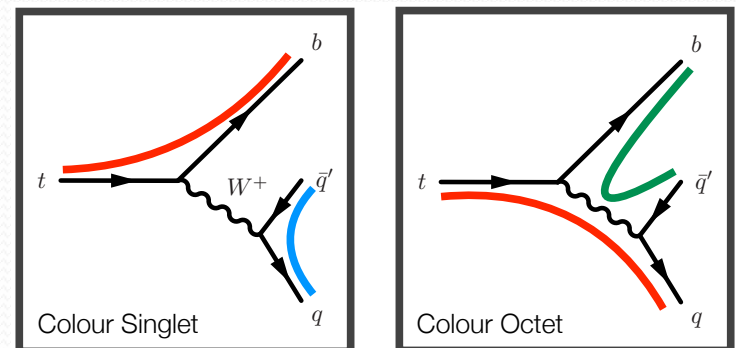


- $W \rightarrow jj$ decay is pure color singlet
- Each of the two b quarks is color connected to one of the beam remnants in a color-octet pattern

- Jet pull angle sensitive to color flow



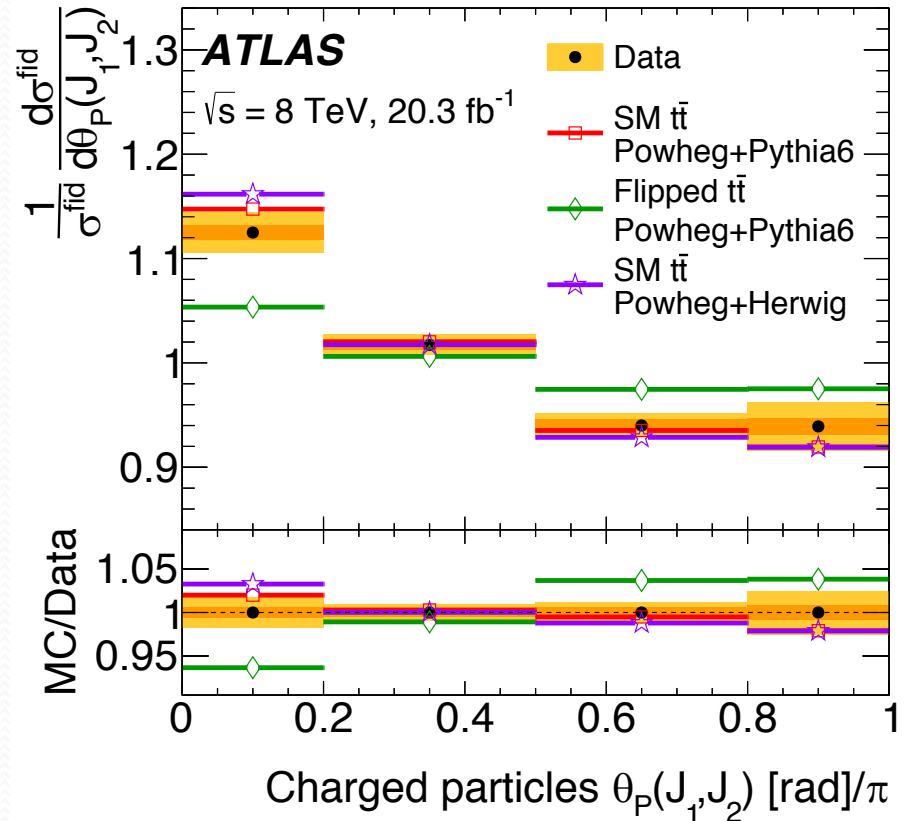
- Color flow pattern is tested comparing data to two $t\bar{t}$ MC models: SM and one in which the W boson is a color octet



Color Flow

- Full 8TeV ATLAS dataset (20.3fb⁻¹)
- One lepton (electron or muon)
- At least four jets (2 tagged as originating from b-quark)
- Large MET
- Pull angle measured using all particles and charged particles only
- Measurement unfolded for detector acceptance and resolution
- Jet pull angle presented as a normalized $t\bar{t}$ differential x-sec

Submitted to PLB
arXiv:1506.05629v1



- Color octet model disfavored at the 3 SD level
- Jet pull angle useful variable in future SM measurements and BSM searches.

Spin correlations

- Spins of top and anti-top are correlated in SM

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4} \left(1 + \overset{\approx 0}{\alpha_+ P_+} \cos\theta_+ + \overset{\approx 0}{\alpha_- P_-} \cos\theta_- + \overset{\text{Correlation}}{A \alpha_+ \alpha_-} \cos\theta_+ \cos\theta_- \right)$$

- Top lifetime < hadronization timescale < spin decorrelation timescale
 - Top quarks decay before their spins decorrelate
 - Spin correlation propagated to the decay products
 - Precise measurement gives information on the strength of the SM couplings and relative contribution of production modes of $t\bar{t}$ bar pairs

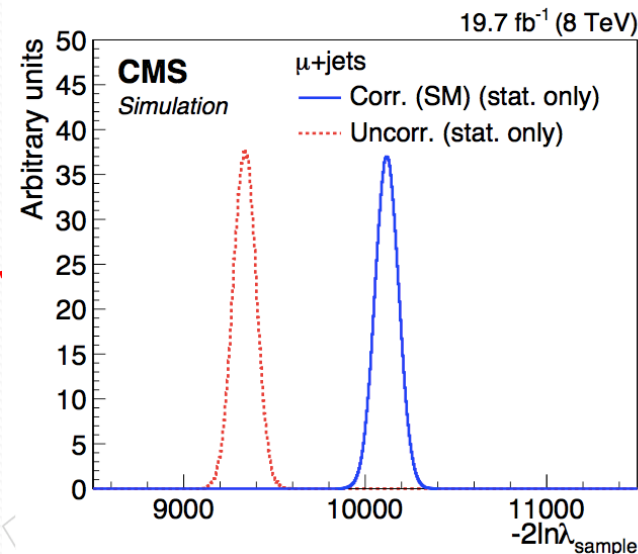
- Spin correlation strength

$$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

Asymmetry between the number of $t\bar{t}$ bar pairs with aligned and anti-aligned spins

- Use a ME method with separate matrix elements for the correlated SM and uncorrelated cases

- Calculate likelihoods for each event under the two hypotheses
- Test statistics based on the ratio $\lambda_{\text{event}} = P(H_{\text{uncor}})/P(H_{\text{cor}})$

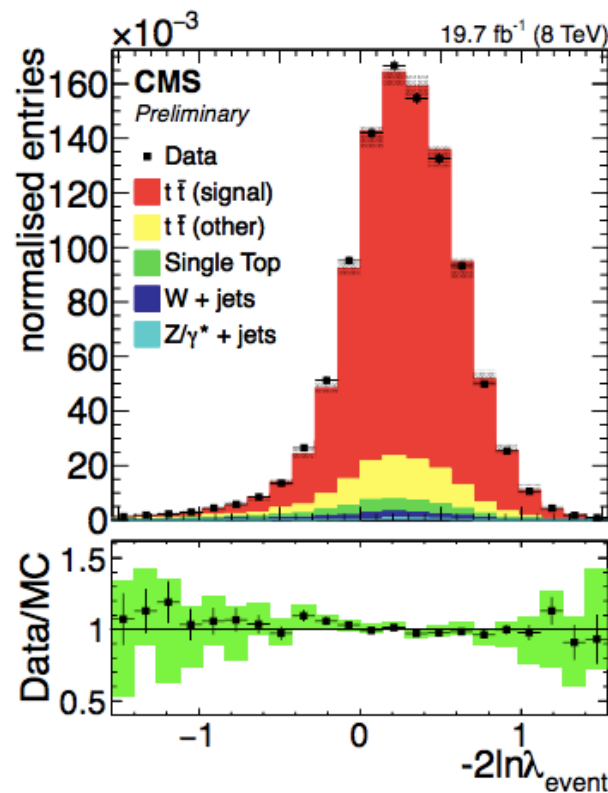


Spin correlations

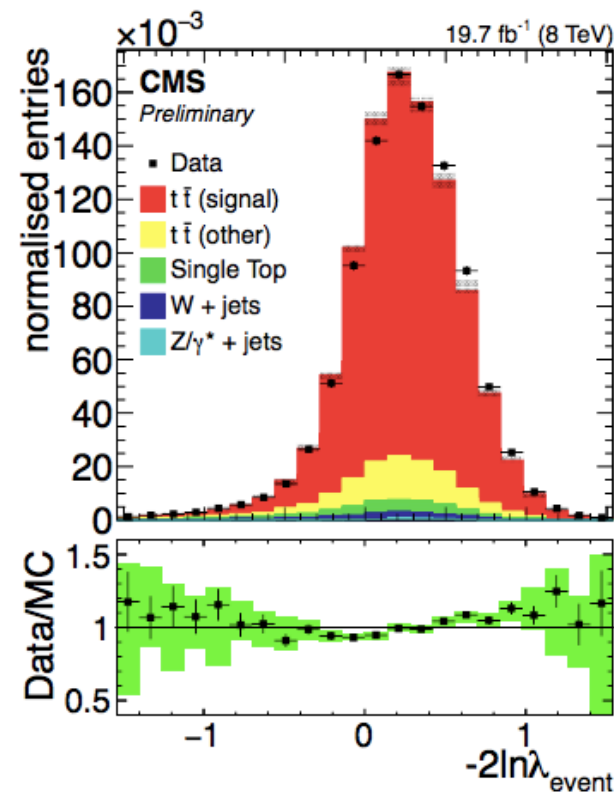
- Full 8TeV CMS dataset (19.7fb^{-1})
- One muon
- At least four jets (2 tagged as originating from b-quark)
- Kinematic fitter to reconstruct $t\bar{t}$ pairs (W mass, $m_{\text{top}}=m_{\text{antitop}}$)
- Keep only events with $\chi^2/\text{dof}<5$

Process	Yield
W+jets	722 ± 20
Z/ γ^* +jets	139 ± 18
t, $\bar{t}$, s channel	41 ± 3
t, $\bar{t}$, t channel	314 ± 10
t, $\bar{t}$, tW	935 ± 20
$t\bar{t}$ other	3896 ± 24
$t\bar{t}$ signal	31992 ± 69
Total simulation	38039 ± 81
Data	37775

Test statistics compared with correlated and uncorrelated simulations



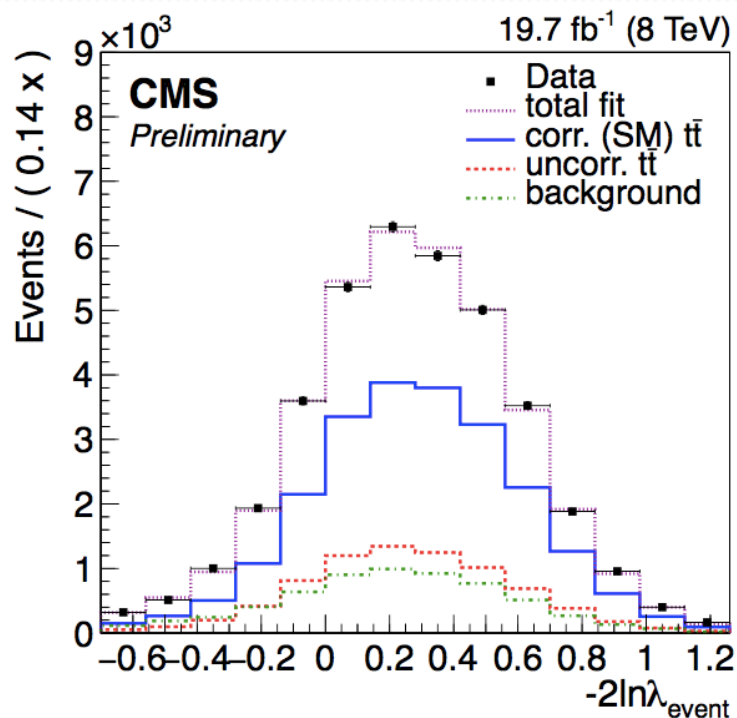
(a) $t\bar{t}$ SM correlated



(b) $t\bar{t}$ uncorrelated

Spin correlations

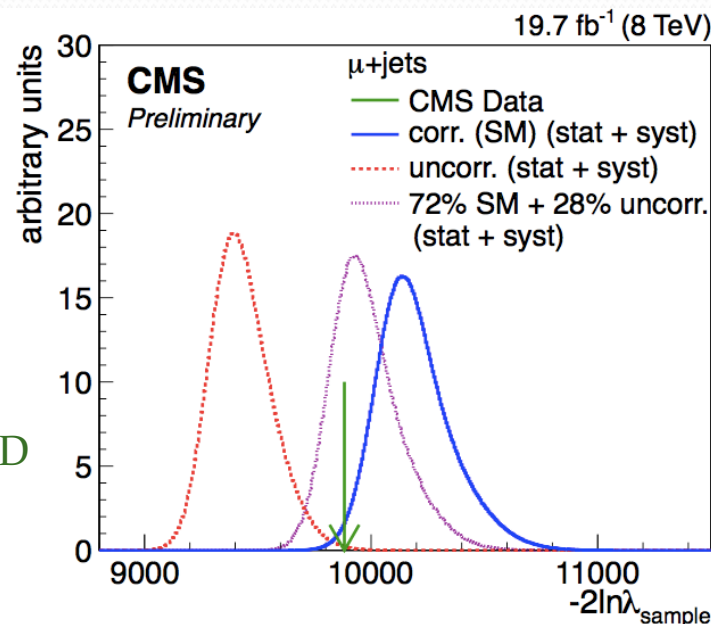
- Fraction of events with SM spin correlation from template fit to $-2\ln\lambda_{\text{event}}$



$$f = 0.72 \pm 0.09(\text{stat})^{+0.15}_{-0.13}(\text{syst})$$

TOP-13-015
Submitted to PRD
arXiv:xx.xx

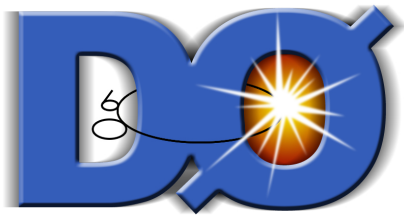
- Compatibility test using sample with measured SM fraction



- Data agree with SM hypothesis within 2.2SD and with uncorrelated hypothesis within 2.9SD
- ATLAS dilepton also agrees with SM within 2 SD – PRL 114, 142001 (2015)

Conclusions:

- Top quark is truly a unique particle in the SM
 - Measurements of its production and decay properties allow for precision tests of the SM as well as indirect window to the BSM world
- ATLAS and CMS have a very rich program of top properties:
 - Presented new results on Charge Asymmetry, Color Flow and Spin correlations
 - Results are most precise to-date and use new/alternative methods
- LHC Run-II started. Most of the analyses will benefit from larger datasets, some will also benefit from higher energy.
- **Stay tuned for updates**



Selected Tevatron Measurements of Top quark Properties

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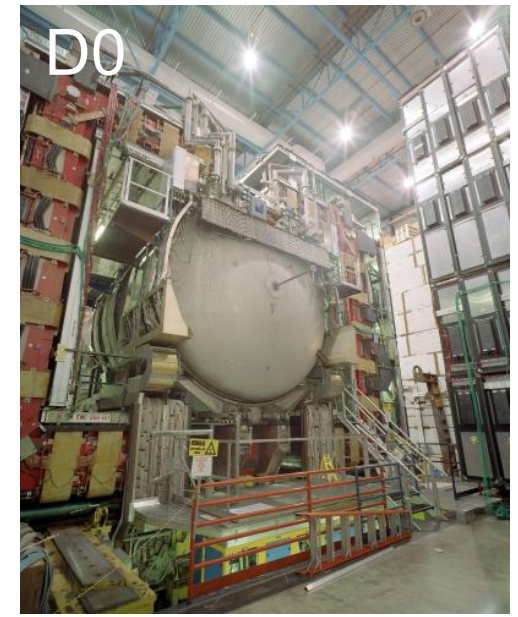
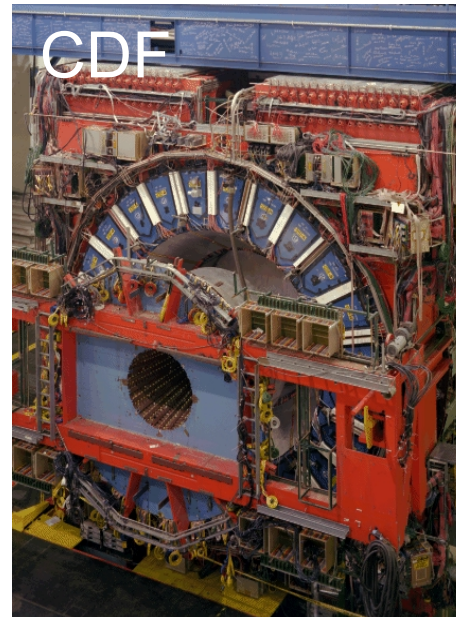
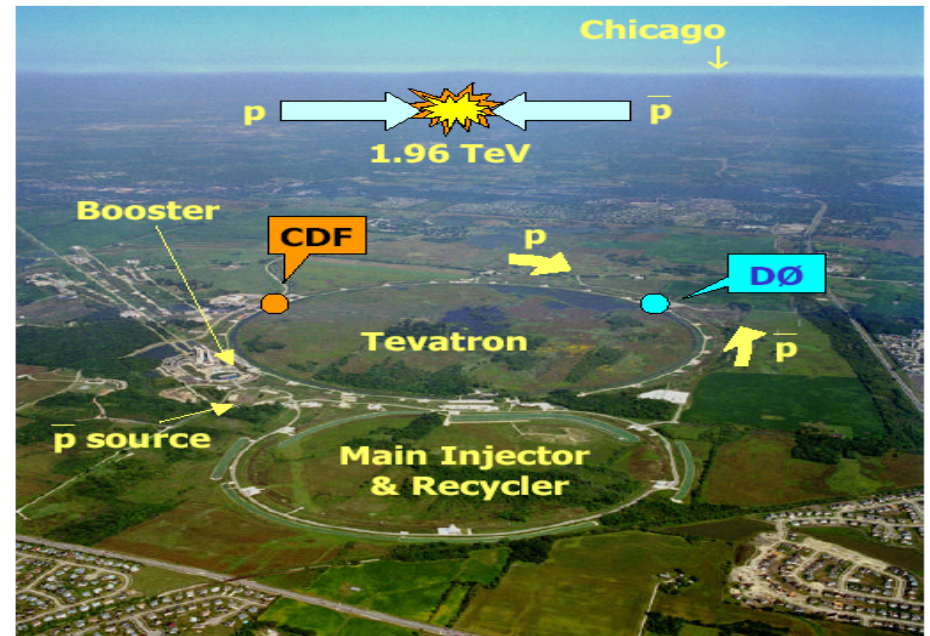
for the CDF & D0 Collaborations

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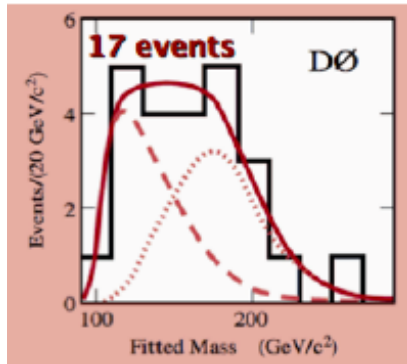
Outline

- Motivation
- Introduction to observables
- Recent results on A_{FB} and polarization (full Run II data)
- Conclusions

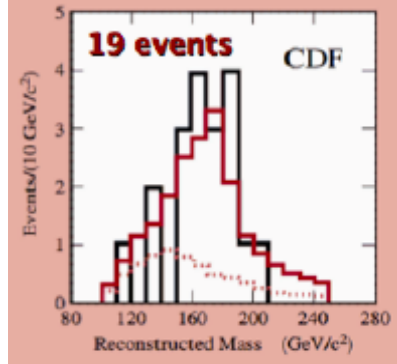


Top Quark

1995: Discovered @ the Tevatron

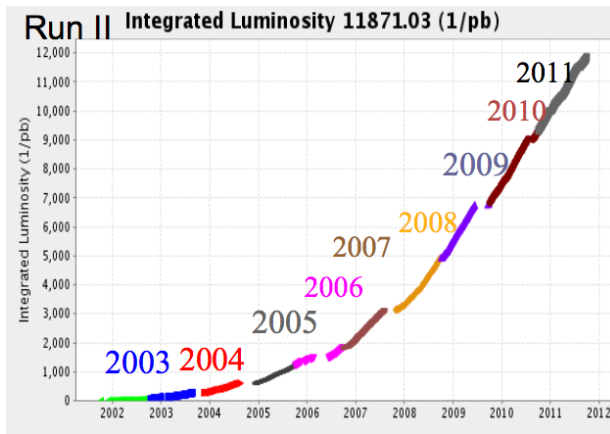


PRL 74, 2632 (1995)

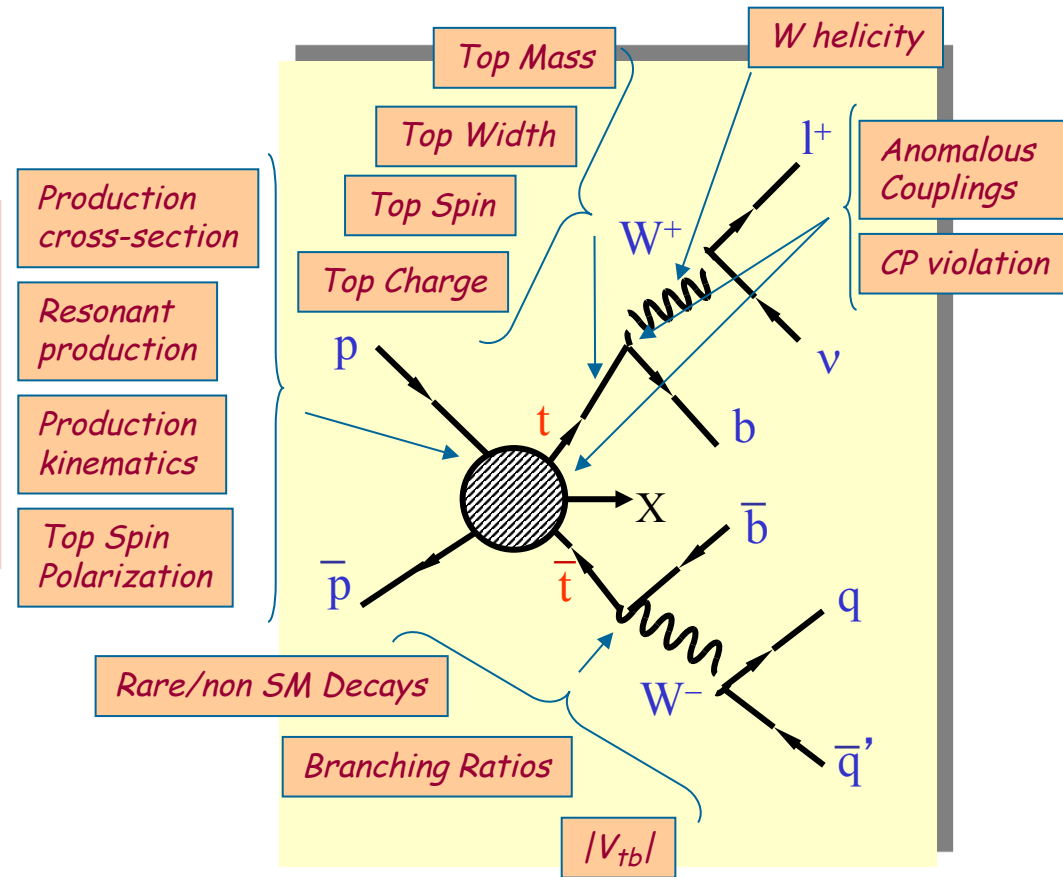


PRL 74, 2626 (1995)

Today: thousands of events used for precision measurements & searches

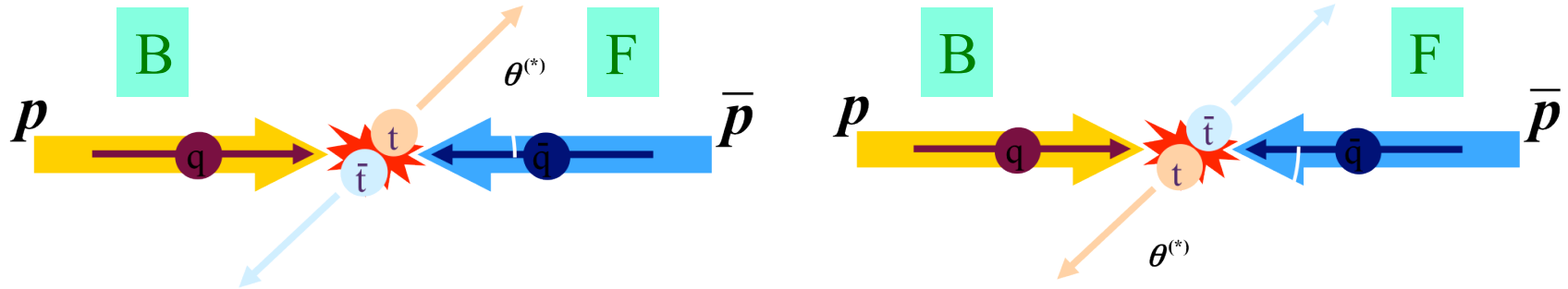


Cecilia E. Gerber (UIC) – LHCP 2015



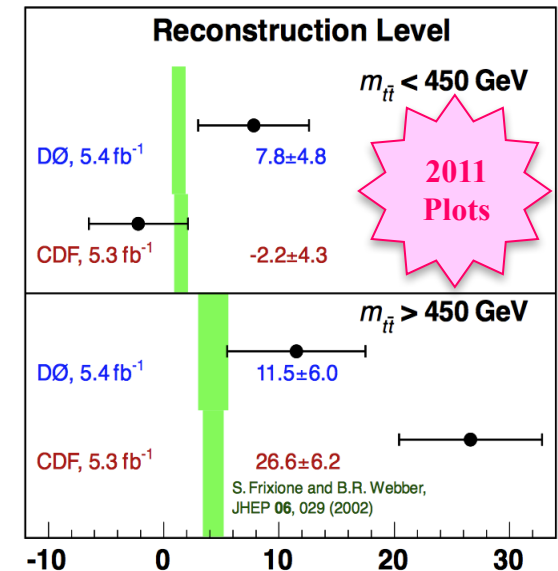
- Successful Tevatron program
- Pioneering of analysis techniques
- Complementary to LHC thanks to $p\bar{p}$ initial state
- Less pile-up effects than LHC
- Excellent agreement with SM predictions

One Excitement: Top FB Asymmetry



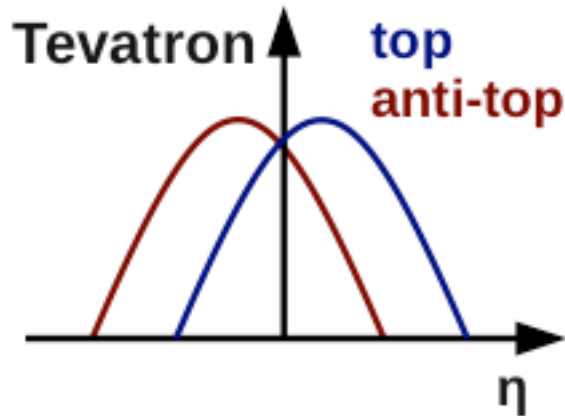
- Top quarks are preferentially emitted in the direction of the incoming quark, anti-tops in the direction of the incoming anti-quark. **No asymmetry in gg production.**
- SM predicts small asymmetry from interference between LO and NLO box diagrams & between ISR and FSR. Interference with EW processes increase the asymmetry.
- BSM production mechanisms that exchange new bosons could significantly enhance the asymmetry
- Inclusive asymmetries measured using $\sim 5\text{fb}^{-1}$ of Tevatron data exceeded SM predictions by 1.5-2SD
- Larger ($\sim 3\text{SD}$) mass and rapidity dependence than predicted by the SM
 - Resulted in aggressive measurement program & hundreds of possible BSM explanations

Forward-Backward Top Asymmetry, %



A_{FB} Definitions

- $t\bar{t} \Delta y$ Asymmetry
 - based on top rapidities



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

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

$$A_{FB}^{t\bar{t}} \approx 10\%$$

NNLO QCD + NLO EW

- Leptonic FB Asymmetry
 - based on the rapidities of the charged leptons from top decay
 - Lepton rapidity well measured
 - Free from complications of combinatorics and jet resolutions

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

Measured in
l+jets and
dilepton

$$A_{FB}^l \approx 4\%$$

NLO with LO denominator

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

Measured in
dilepton

$$\Delta y_l = y_{l^+} - y_{l^-}$$

$$A_{FB}^{ll} \approx 5\%$$

NLO with LO denominator

Top Quark Polarization

- Top quarks decay before hadronization: Spin is transferred to decay products
- SM predicts weak polarization
 - <1% QCD induced transverse polarization
 - <0.5% longitudinal polarization due to parity-violating EW contributions to the production process.
- Couplings of top to BSM particles can result in much larger polarization
- Models with new parity violating interactions (axigluons) predict a sizable polarization together with a large A_{FB}
- Measuring polarization and $A_{\text{FB}}^{t\bar{t}}$ simultaneously can shed light on the underlying dynamics of top quark production
- Simplest observable: lepton angular distribution relative to quantization axis $\hat{n}$

$$\frac{d\sigma}{d\cos\theta^\pm} = \frac{1}{2} (1 + \kappa^\pm P_{\hat{n}}^\pm \cos\theta^\pm)$$
- Polarization term can be obtained as asymmetry in the lepton angular distribution

$$\kappa P = A^{l+} - A^{l-}$$

$$A^{l^\pm} = \frac{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}{N(\cos\theta^\pm > 0) + N(\cos\theta^\pm < 0)}$$

κ : spin analyzing power of lepton ~ 0.99 in QCD

$\cos\theta^\pm$: angle between lepton $^\pm$ and $\hat{n}$

Helicity basis: $t\bar{t}$ axis in $t\bar{t}$ rest frame

Analysis Strategy

- Start with candidate samples dominated by $t\bar{t}$ events
- top and anti-top quarks are reconstructed from their decay products by means of kinematic fitting or ME techniques
- Reconstruction-level (raw) measurements are obtained after background subtraction – detector dependent
- Production-level (partonic) measurements are obtained after correcting for detector acceptance and resolution (unfolding)
 - Use NLO MC – minimal model dependence addressed using alternative signal MC samples as systematic uncertainties
 - Unfolded measurement can be compared among experiments and with theoretical predictions
 - Measurements are presented for the inclusive quantities, as well as differentially vs $m_{t\bar{t}}$, production angle, etc.



$A_{FB}^{t\bar{t}}$ lepton + jets channel



- Charge of the lepton (e or μ) identifies the charge of the leptonic top. Opposite charge assumed for the hadronic top.
- Kinematic reconstruction of the $t\bar{t}$ system - partial for events with 3 jets
D0 NIM A 788:128-136, July 2015.

Tevatron Run II inclusive results

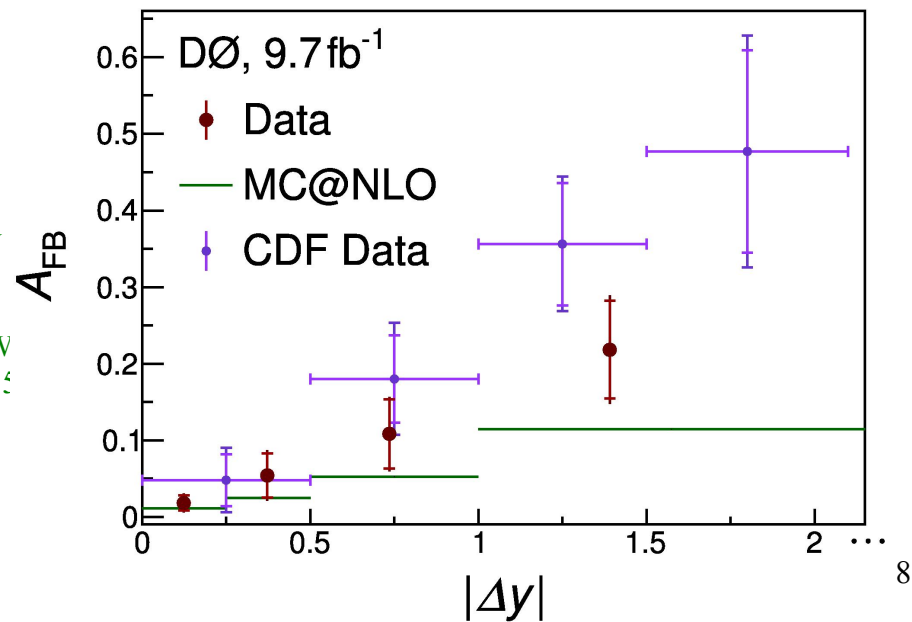
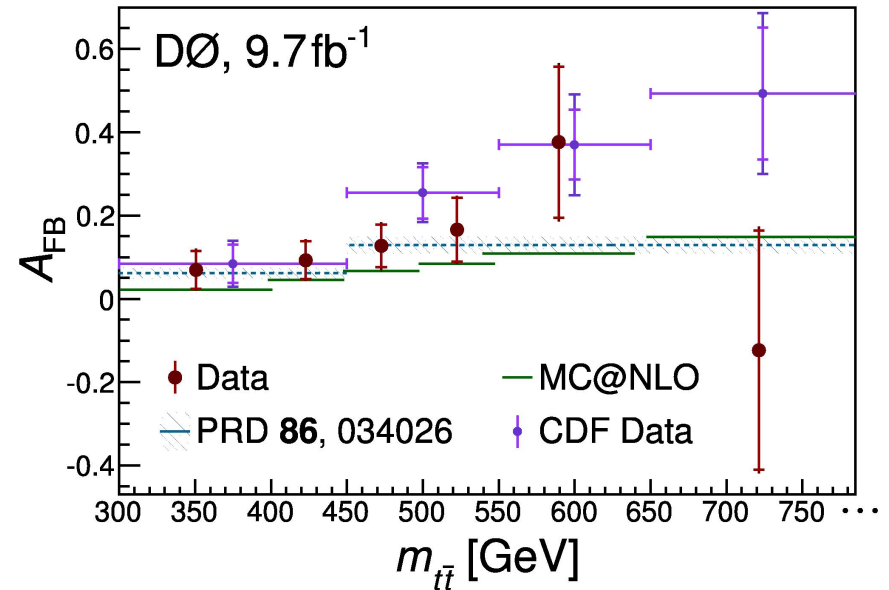
CDF $(16.4 \pm 4.7)\%$ PRD 87, 0920022 (2013)

D0 $(10.6 \pm 3.0)\%$ PRD 90, 072011 (2014)

SM predictions

Czakon $(9.5 \pm 0.7)\%$ NNLO QCD + NLO EW arXiv:1411.3007

Kidonakis $(10.0 \pm 0.6)\%$ aN³NLO QCD + NLO EW PRD 91, 071502(R) 2014



Inclusive $A_{\text{FB}}^{\text{tt}}$ dilepton channel



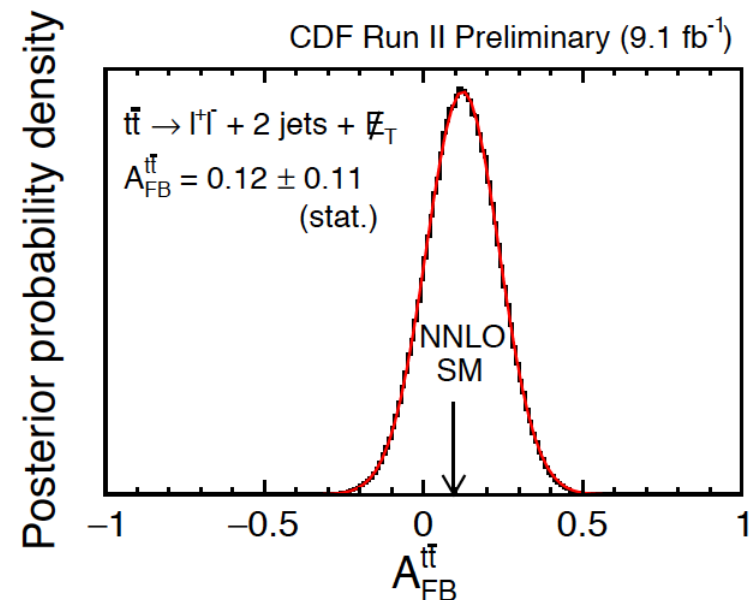
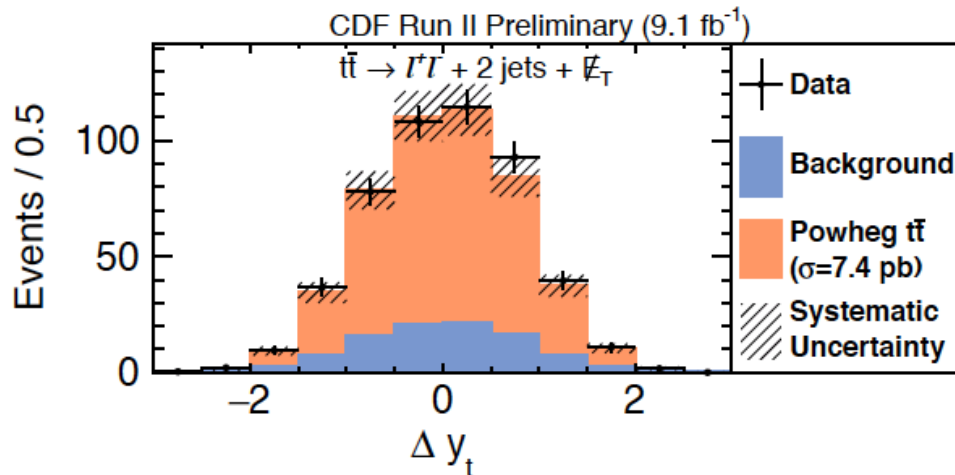
- Two opposite charge leptons ($e\bar{e}$, $e\mu$, $\mu\mu$), two jets and MET
- Likelihood-based $t\bar{t}$ reconstruction
- Event-by-event reconstruction with 4 constraints: two W boson masses, two top quark masses & energy-momentum conservation equations
- Bayesian model to extract parton-level A_{FB} in 4 bins in Δy_t

Combination with the inclusive l +jets result using BLUE

Dilepton: $(12 \pm 13)\%$

Combination: $(16.0 \pm 4.5)\%$

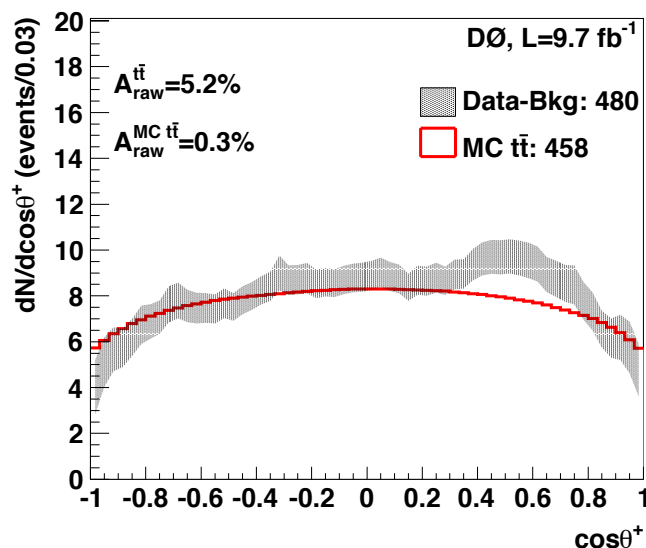
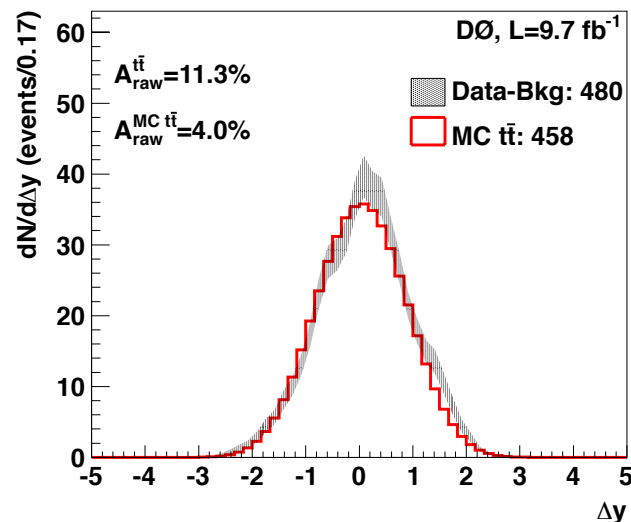
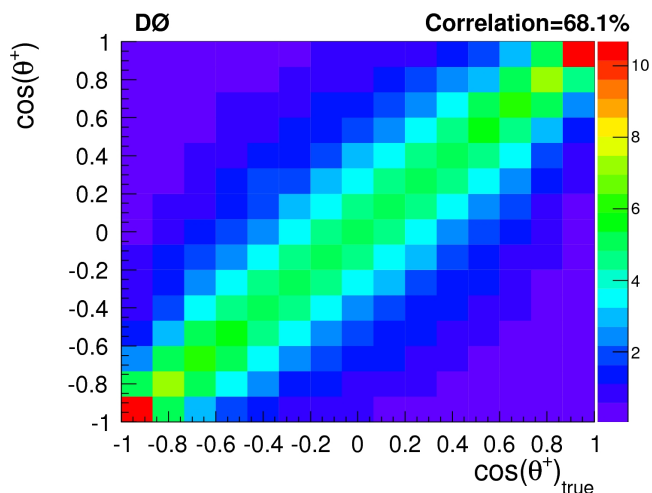
CDF Public Note
11161 (June 2015)





Simultaneous measurement of A_{FB}^{tt} and top polarization

- Dilepton channel (ee, eμ, μμ)
- Matrix Element integration method used to reconstruct events
 - LO, no $gg \rightarrow tt$, two jets
 - Modified to reconstruct Δy , $\cos\theta^+$, and $\cos\theta^-$
- Accumulation of event-by-event likelihood functions gives an estimate of the true distribution



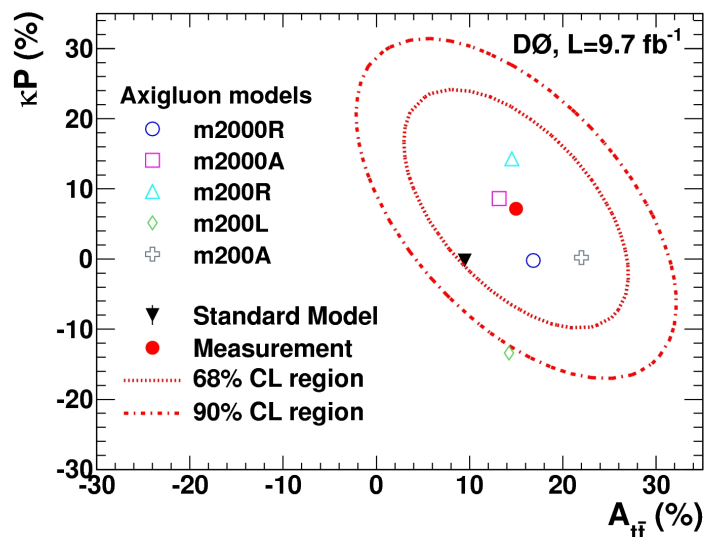
Background-subtracted accumulation of likelihoods gives the raw distributions.



Simultaneous measurement of $A_{FB}^{t\bar{t}}$ and top polarization

Raw measurements corrected using calibration $t\bar{t}$ MC test samples

- Events are reweighted according to the parton-level Δy , $\cos\theta^+$, and $\cos\theta^-$
- 30 weighted samples are produced for $\kappa P = (-0.2, -0.1, 0.0, 0.1, 0.2)$ and $A_{FB} = (-0.1, 0.0, 0.1, 0.15, 0.2, 0.25)$
- Partonic A_{FB} and κP extracted from the raw measurements simultaneously by inverting the calibration



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

$$\kappa P = 7.2 \pm 10.5(stat) \pm 4.2(syst)\%$$

Correlation due to acceptance and resolution $(A_{FB}, \kappa P) = -56\%$

- Results when separately constraining A_{FB} and κP to their SM values:

$$A_{FB}^{t\bar{t}} = 17.5 \pm 5.6(stat) \pm 3.1(syst)\%$$

$$\kappa P = 11.3 \pm 9.1(stat) \pm 1.9(syst)\%$$

First top polarization measurement at the Tevatron

- Combination with 1+jets A_{FB} result

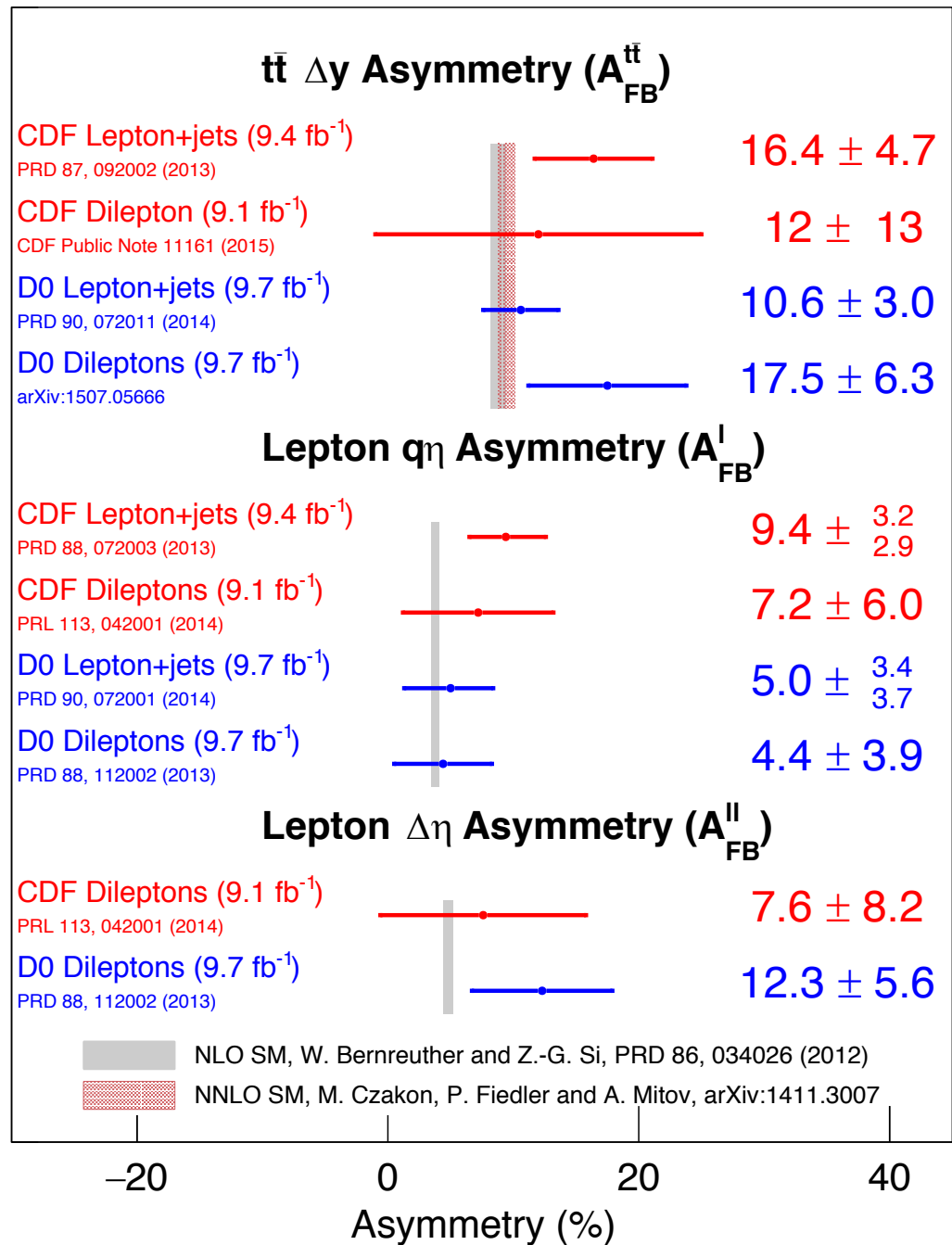
$$A_{FB}^{t\bar{t}} = 11.8 \pm 2.5(stat) \pm 1.3(syst)\%$$

All results agree with SM expectations

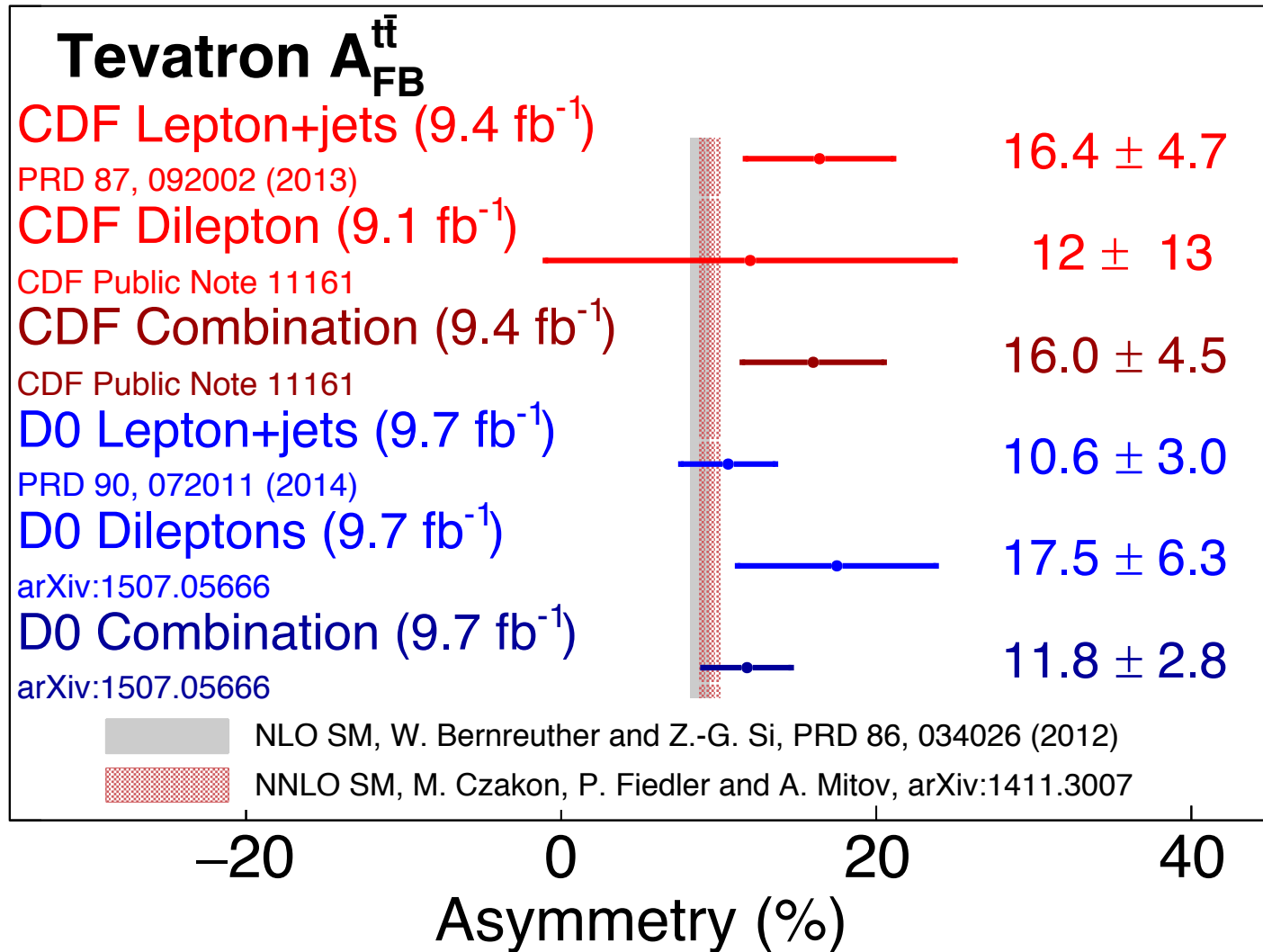
arXiv:1507.05666, submitted to PRD

- Final measurements with entire Run II dataset
 - Lepton + jets and dilepton channels
 - Top and leptonic asymmetries
 - Inclusive and Differential measurements
- Systematic effort by CDF and D0 to settle the A_{FB} discrepancy issue.
- Overall good agreement with SM prediction (QCD NNLO + EW)

Tevatron Top Asymmetry



Inclusive $A_{FB}^{t\bar{t}}$ Summary



Combination forthcoming

Conclusions

- Tevatron had a very successful SM top quark program
 - Observation
 - Development of analysis techniques
 - Precision Measurements
 - BSM Exclusions
- Legacy results on the full dataset complement LHC
 - pp initial state
 - less pileup



LHC

Tevatron



LHC opens a new era of high statistics and BSM discoveries