Top quark properties

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on behalf of the ATLAS, CDF, CMS, and DØ collaborations

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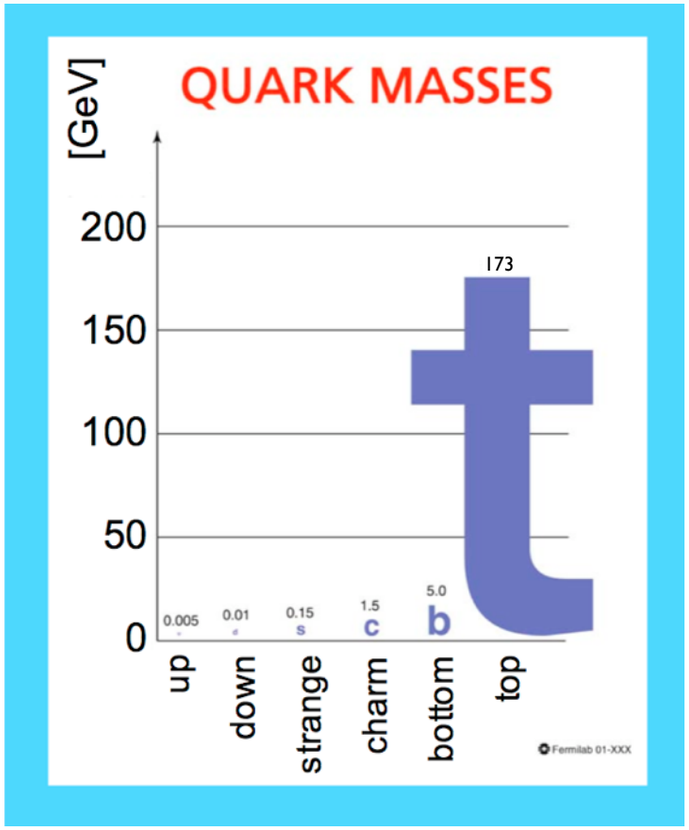
Introduction

- Why study top quark properties?
  - heaviest quark in the standard model
    - large coupling to Higgs
    - probe for new theories above the electroweak scale
  - top quark decays before hadronisation
    - study properties of a "bare"quark
  - stringent test of the SM, with many possibilities for manifestation of new physics
    - tops could be produced from decay of new particles
    - tops could decay into new particles
  - important to understand top as a background for other measurements and searches



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- $t\bar{t}$ cross-section
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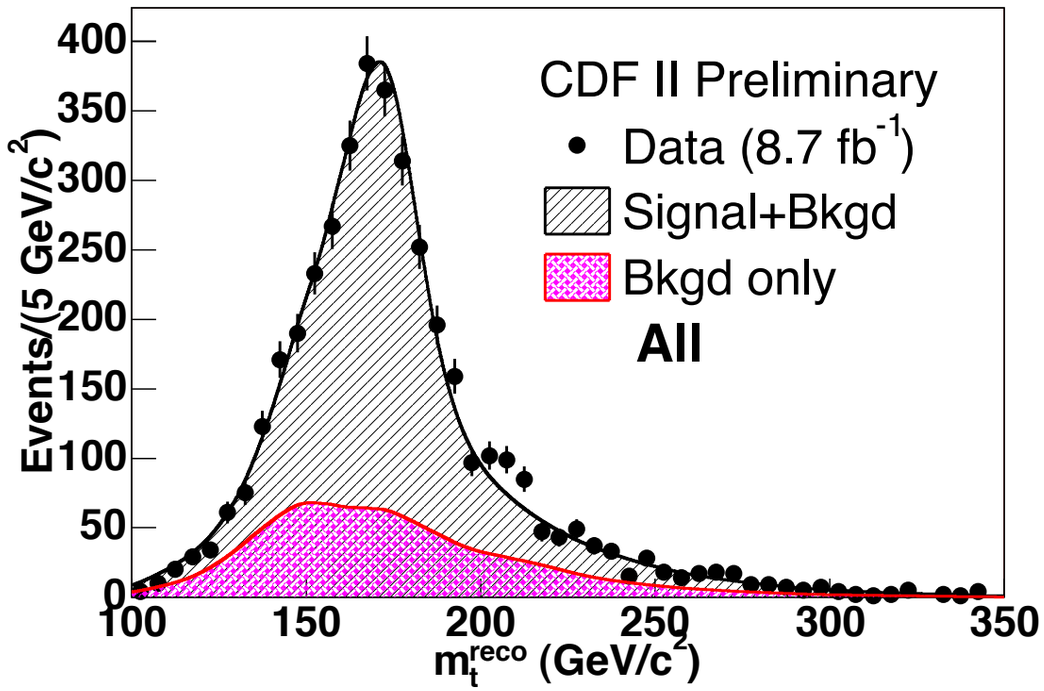
Top quark mass

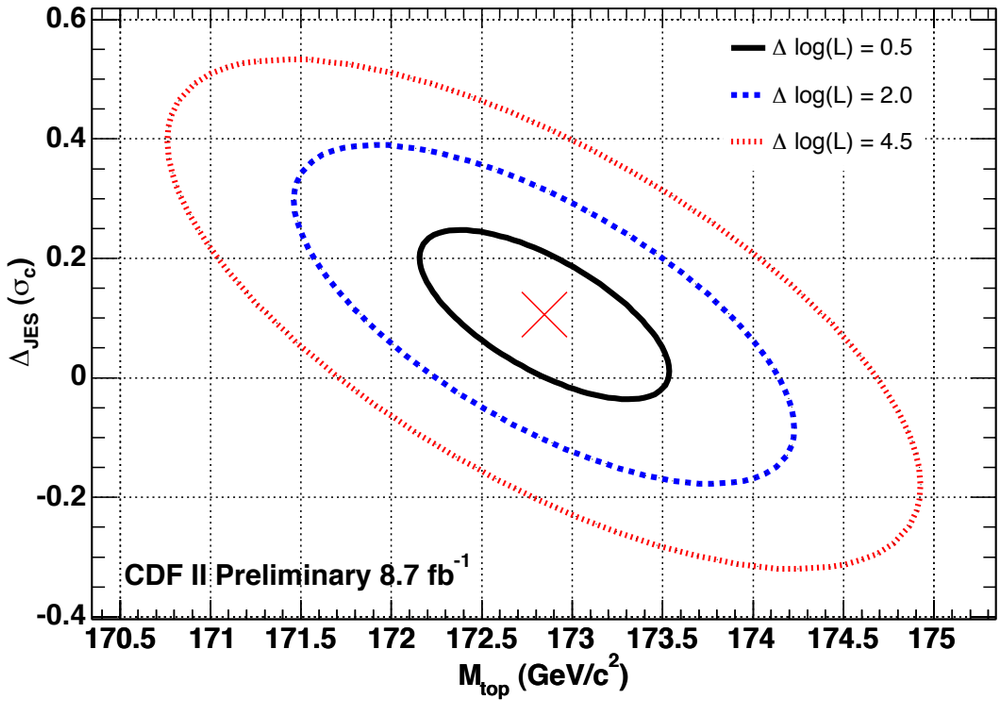
Top mass: CDF lepton+jets

PRL 109 152003

- CDF lepton+jets channel until recently most precise single measurement
  - latest result with 8.7 fb^{-1} at 1.96 TeV, e/μ + ≥4j
- jet energy scale (JES) leading systematic: reduce uncertainty by measuring residual JES simultaneously with m_t using m_W constraint
- $t\bar{t}$ system reconstructed using χ2 minimisation
- Kernel Density Estimate-based approach to forming probability density functions (pdfs) from simulated Pythia MC
  - Done for signal and background for various values of m_t and JES
- Per-event likelihood from sum of signal and background pdfs, with 3 observables:
  - m_t^{reco} from each of the 2 smallest χ2 permutations, and m_W^{reco}
- m_t = 172.85 ± 0.71 (stat.+JES) ± 0.84 GeV (syst)



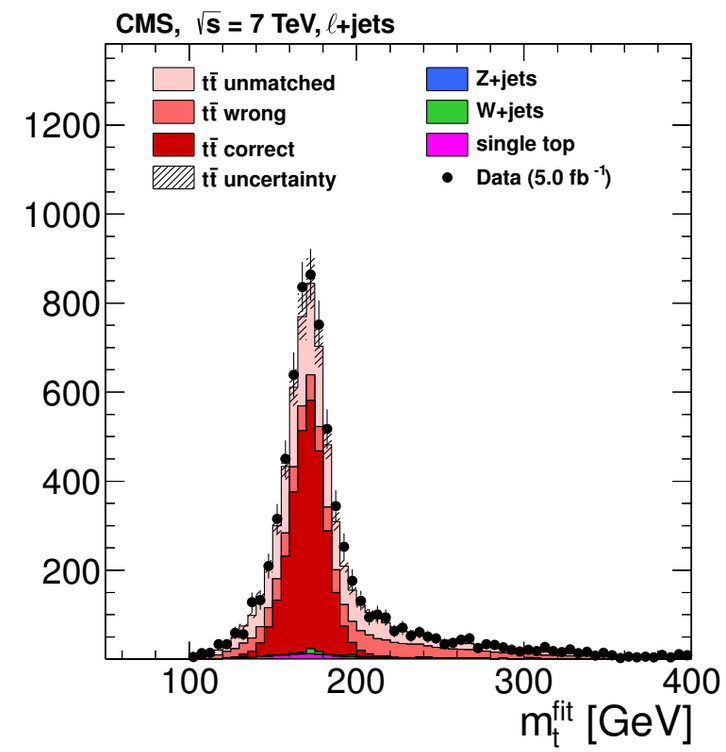
simultaneous fit for m_t and JES

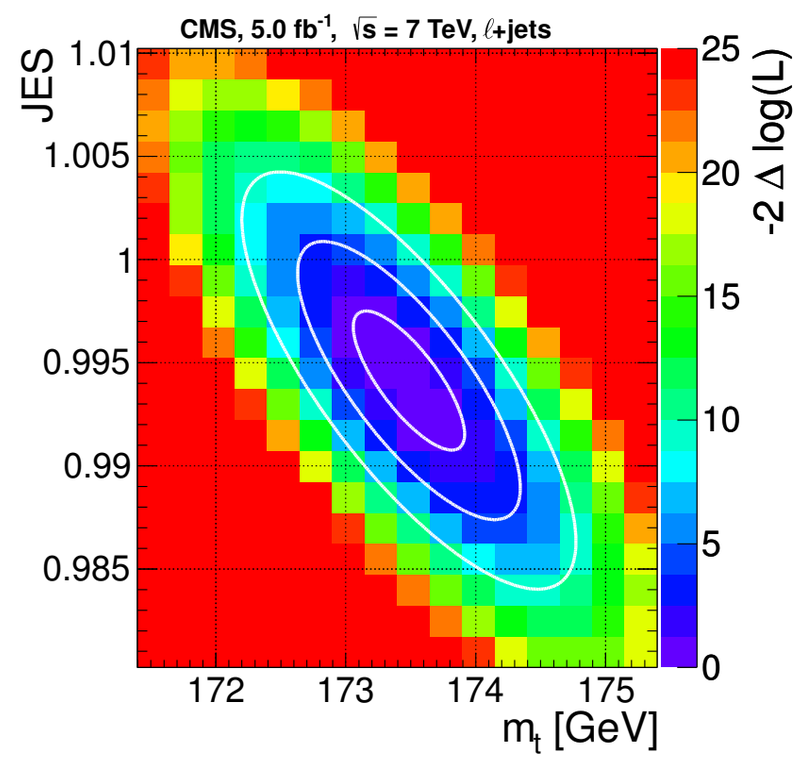


Top mass: CMS lepton+jets

JHEP 12 (2012) 105

- 5 fb^{-1} 7 TeV lepton+jets data (e/μ + ≥4j, ≥2 b-tags)
- Kinematic fit to reconstruct mass of top quarks in each event, using m_W constraint
  - 2 possible parton to b-jet assignments per event, weighted based on fit χ^2 (and with high χ^2 cut to increase fraction of correct permutations and reject background)
- Per-event likelihood for m_t and JES based on $m_{t,fit}$ and the reco-level m_W (before constraint)
  - includes sum of pdfs for $t\bar{t}$ with "correct" and "wrong" jet permutations, and also "unmatched" where the 4 jets do not correspond to the 4 partons
- Mass and JES simultaneously extracted from combined likelihood (Ideogram method):
- m_t = 173.49 ± 0.43 (stat.+JES) ± 0.98 (syst.) GeV
- JES = 0.994 ± 0.003 (stat.) ± 0.008 (syst.)





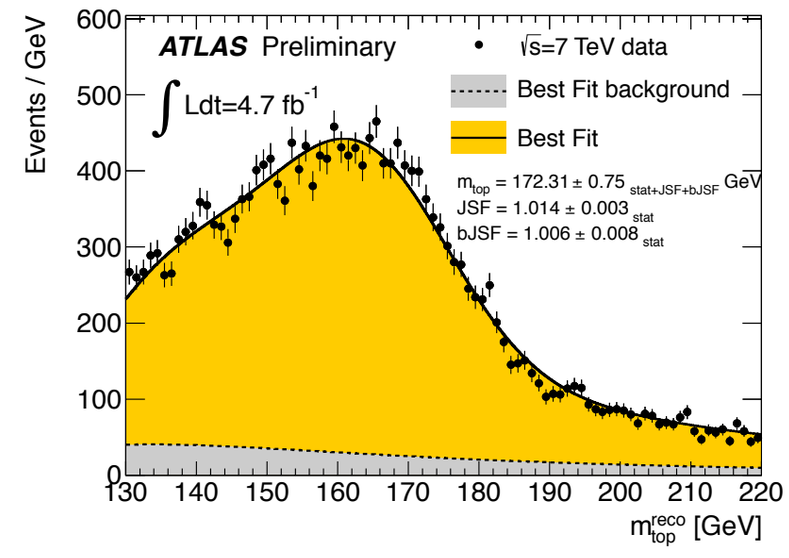
most precise single measurement to date

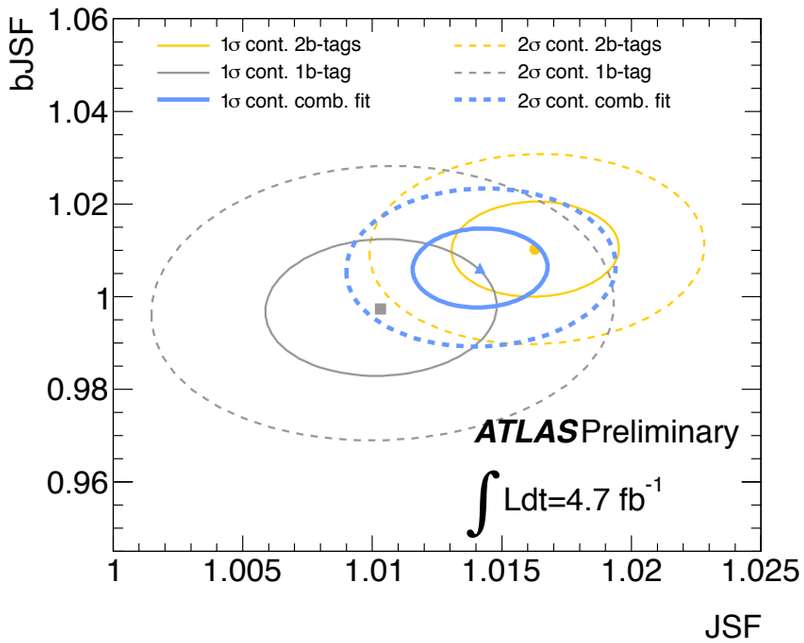
3D template fit top mass analysis

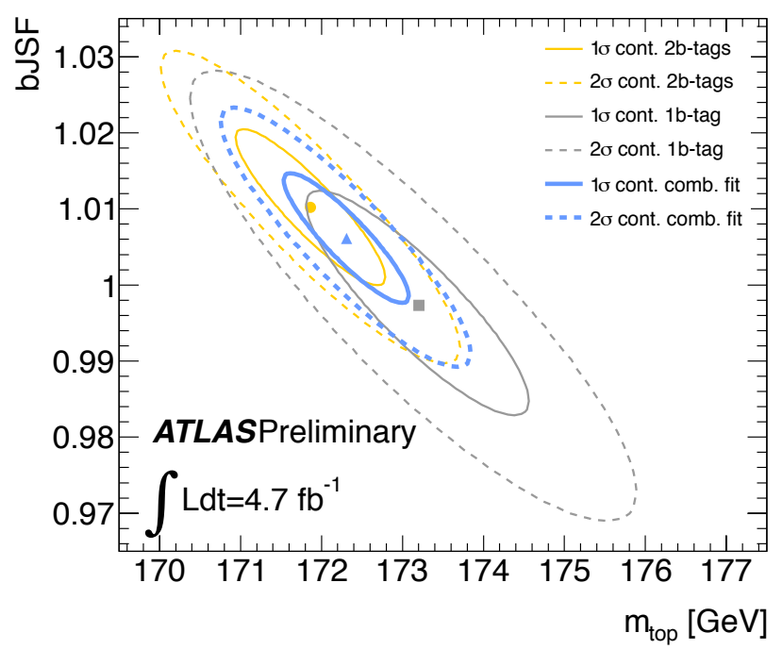
ATLAS-CONF-2013-046

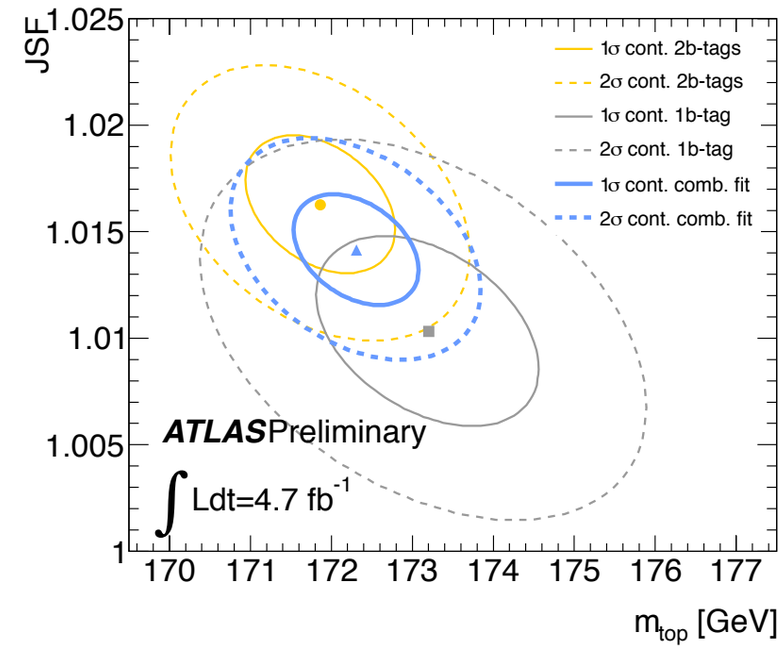
- New result from ATLAS seeks to further reduce JES systematics by adding an independent correction to the b jet scale, bJSF, so the simultaneous fit
- Template fit, using 3 variables from a kinematic fit of each event
  - m_t^{fit} templates as a function of input m_t, JSF, and bJSF
  - m_W^{reco} templates as a function of JSF
  - templates of $R_{lb}^{reco,2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}}$ as a function of m_t and bJSF

4.7 fb^{-1} 7 TeV data







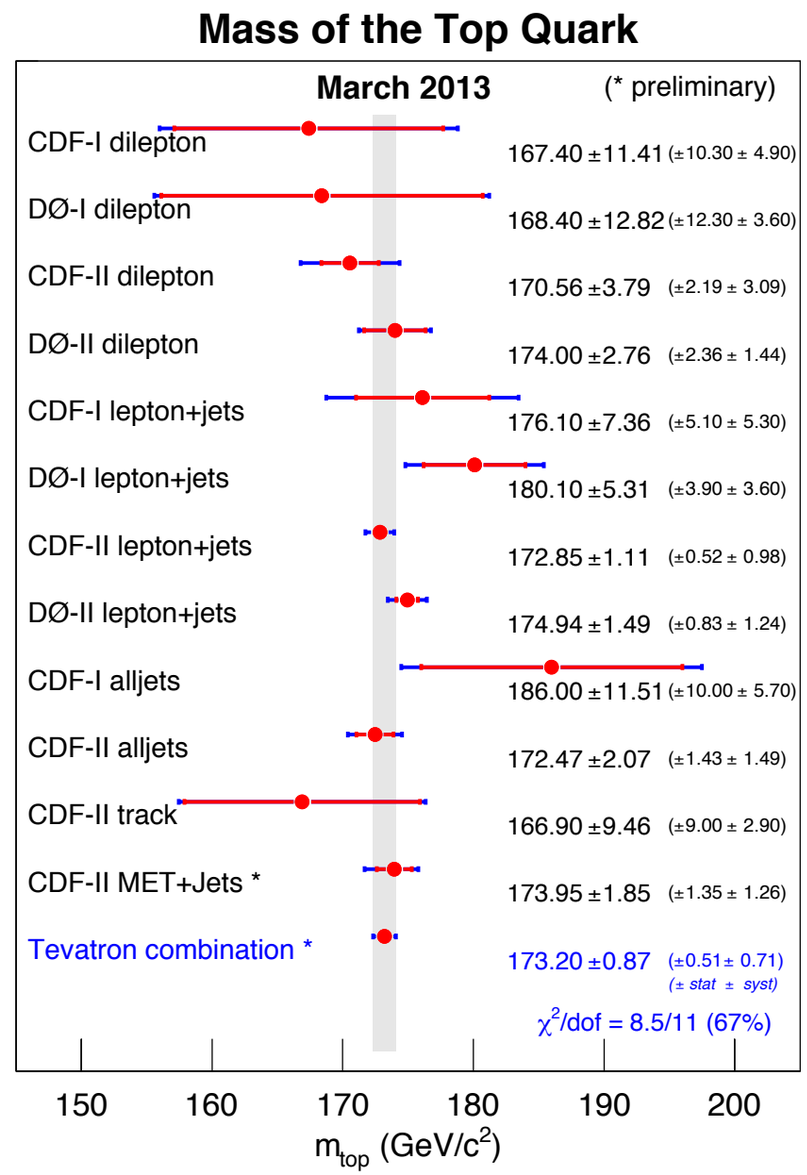


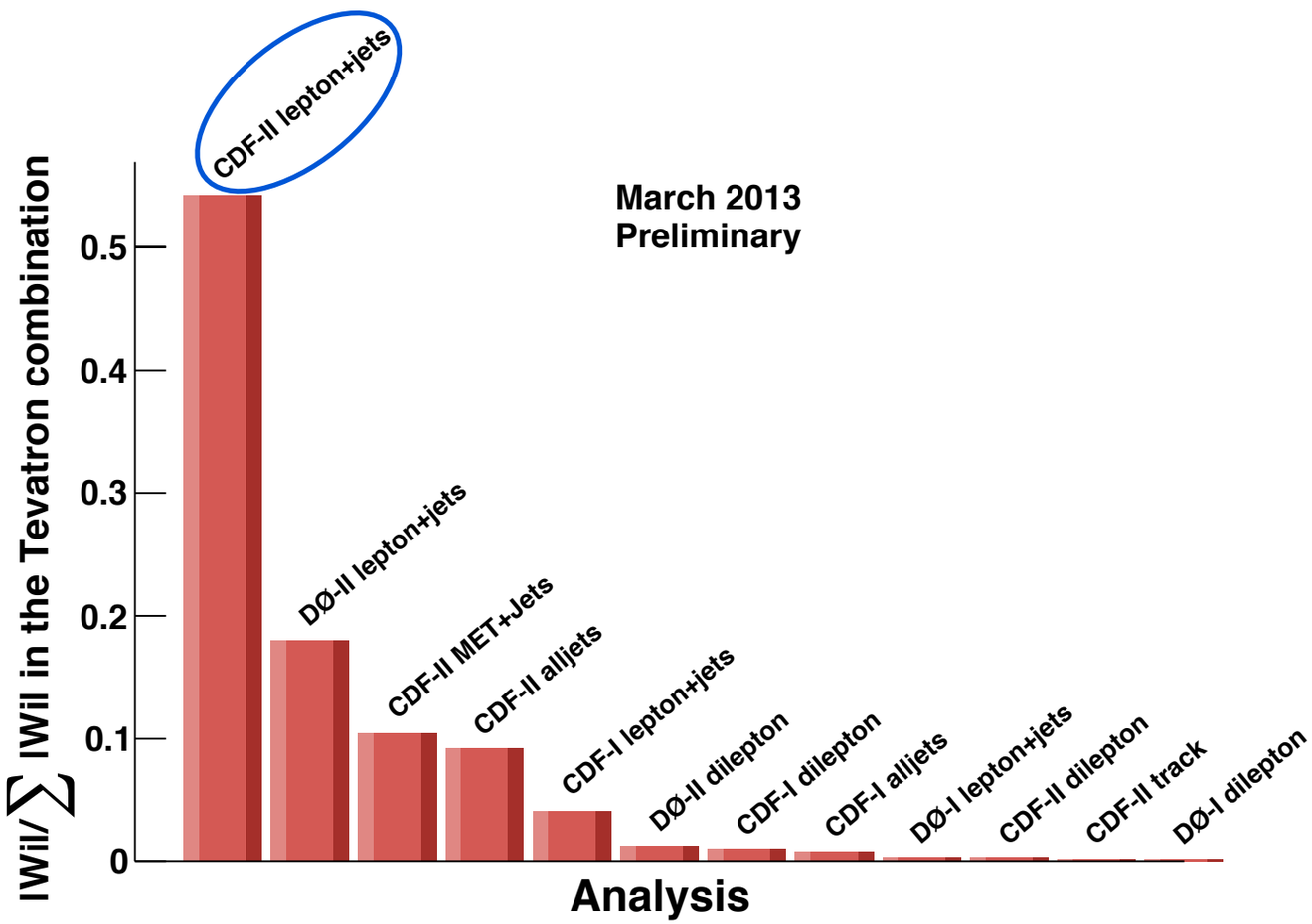
- $m_{top} = 172.31 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35\ (\text{syst})\ \text{GeV}$
  $\text{JSF} = 1.014 \pm 0.003\ (\text{stat}) \pm 0.021\ (\text{syst}),$
  $\text{bJSF} = 1.006 \pm 0.008\ (\text{stat}) \pm 0.020\ (\text{syst}).$
- total uncertainty significantly reduced compared to result using traditional 2D fit (with bJSF set = 1):
  $m_{top} = 172.80 \pm 0.35\ (\text{stat} + \text{JSF}) \pm 2.02\ (\text{syst})\ \text{GeV}$

Tevatron top quark mass combination

CDF Note 10976, DØ Note 6381

- BLUE method (best linear unbiased estimator)
- M_{top} = 173.20 ± 0.51 (stat) ± 0.71 (syst) GeV
- M_{top} = 173.2 ± 0.9 (syst) GeV
  - relative uncertainty of **0.50%**
- Compared to previous (2011) combination, uses updated Run II CDF lepton+jets and MET+jets measurements
  - full 8.7 fb^{-1} of data, and improved analysis technique and jet energy resolution for lepton+jets
- Precision of 2012 LHC combination already surpassed by single results





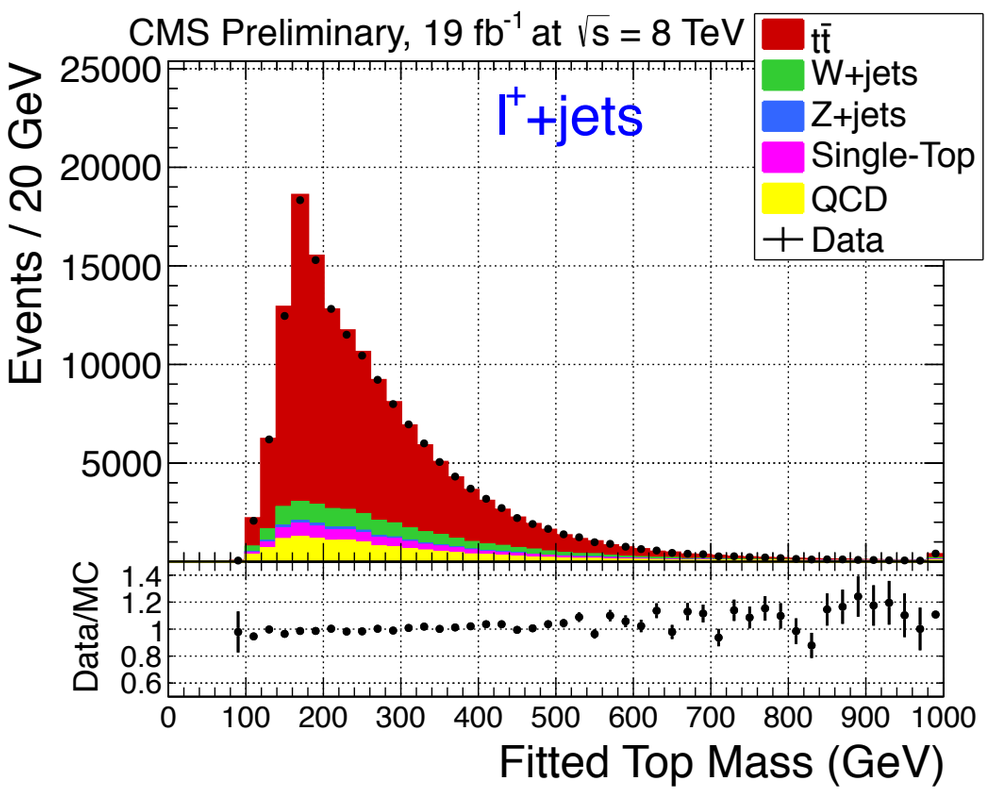
March 2013

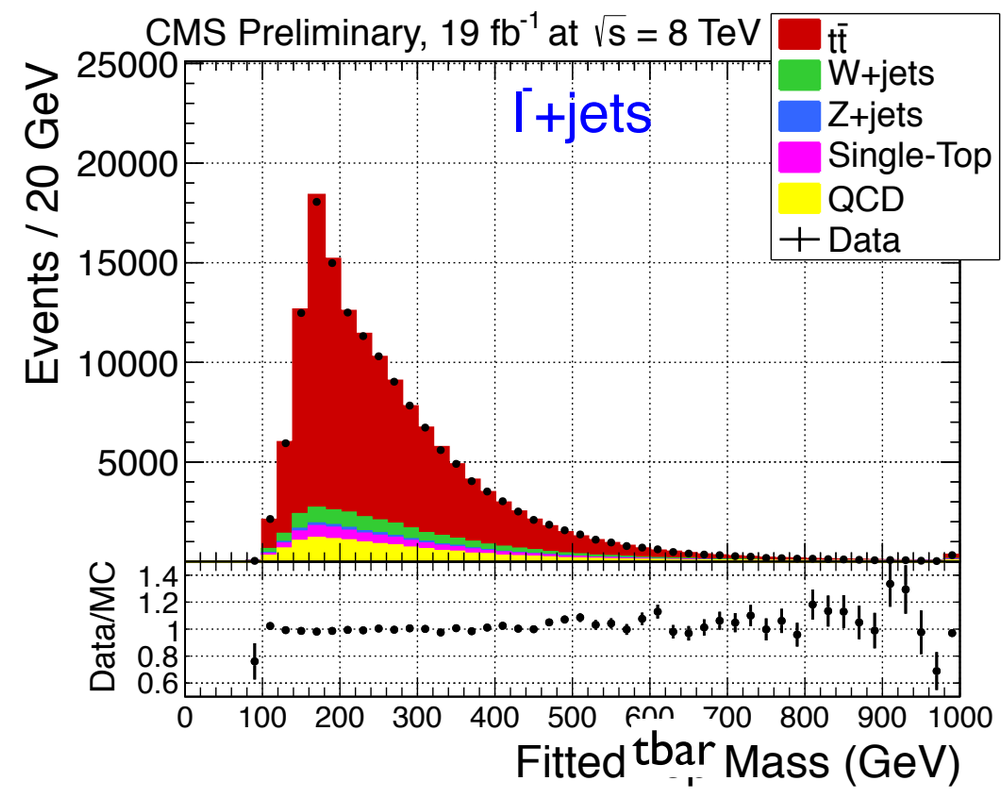
Parameter	Value (GeV/c^2)	Correlations			
		$M_t^{alljets}$	M_t^{l+j}	$M_t^{di\text{-}l}$	M_t^{MEt}
$M_t^{alljets}$	172.7 ± 1.9	1.00			
M_t^{l+j}	173.2 ± 0.9	0.25	1.00		
$M_t^{di\text{-}l}$	170.0 ± 2.1	0.19	0.41	1.00	
M_t^{MEt}	173.8 ± 1.8	0.13	0.26	0.18	1.00

top - antitop mass difference

CMS PAS TOP-12-031

- SM invariance under CPT predicts equality of particle and antiparticle masses
  - test by measuring the mass difference between t and tbar, $\Delta m_t = m_t - m_{tbar}$
  - 19 fb^{-1} 8 TeV lepton+jets data (e/μ + ≥4j, ≥1b-tag)
- Kinematic fit to reconstruct mass of hadronically decaying top in each event, using M_W constraint
  - jet energies first corrected to parton-level
- Mass extracted from combined likelihood (Ideogram method)
  - per-event likelihood terms for signal with correct and incorrect jet combinations, and for background
- Event sample split in two based on lepton charge:





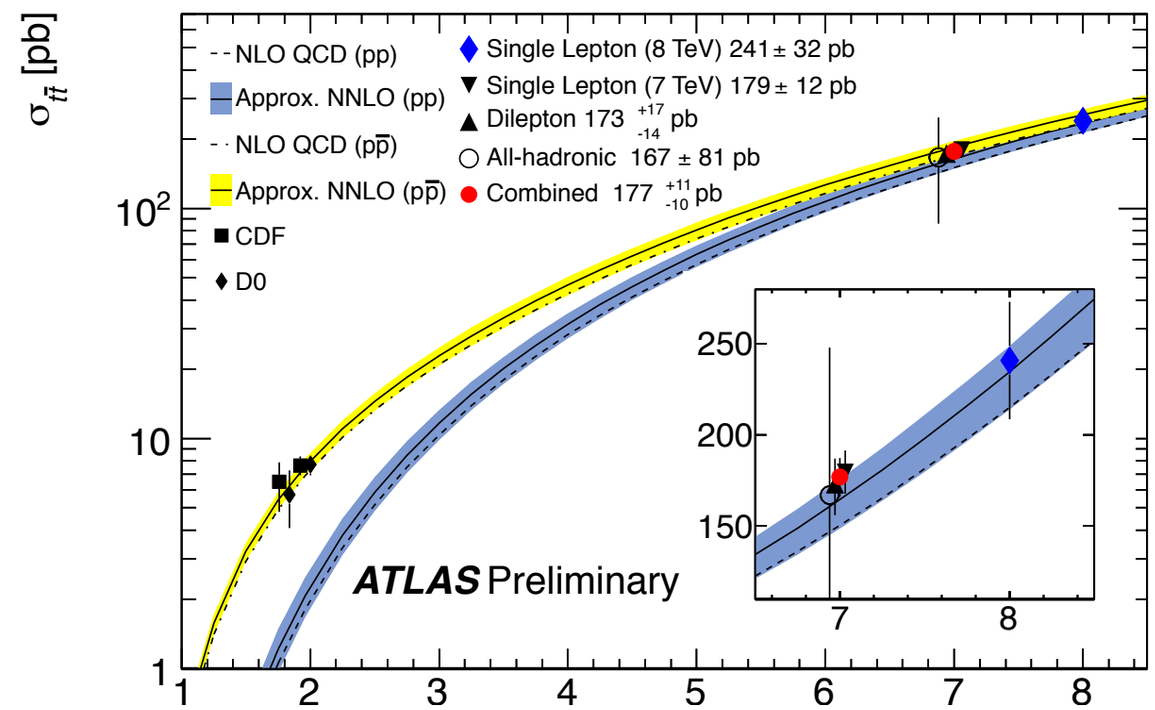
- $$\Delta m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.) MeV}$$
  - By far the most precise measurement to date

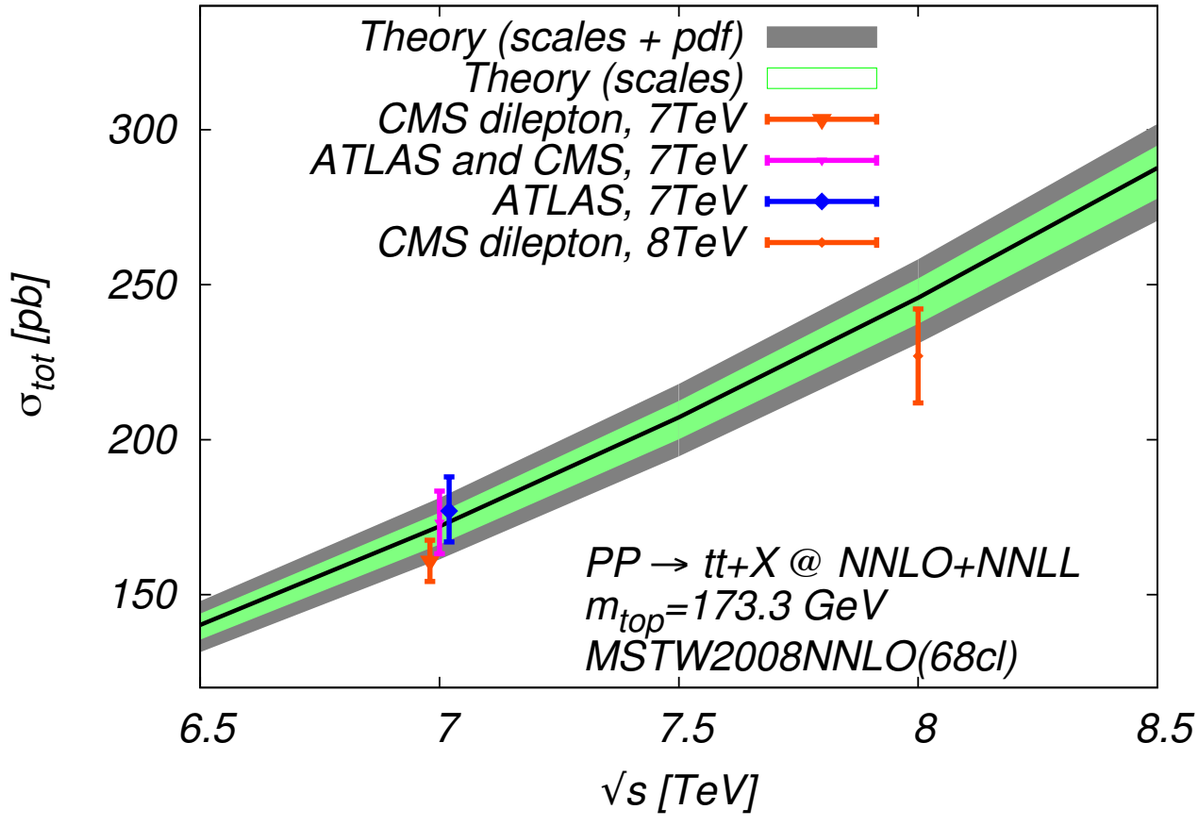
average fitted top-quark mass is found to be m_t = 172.51 ± 0.10 (stat.) GeV (no syst.)

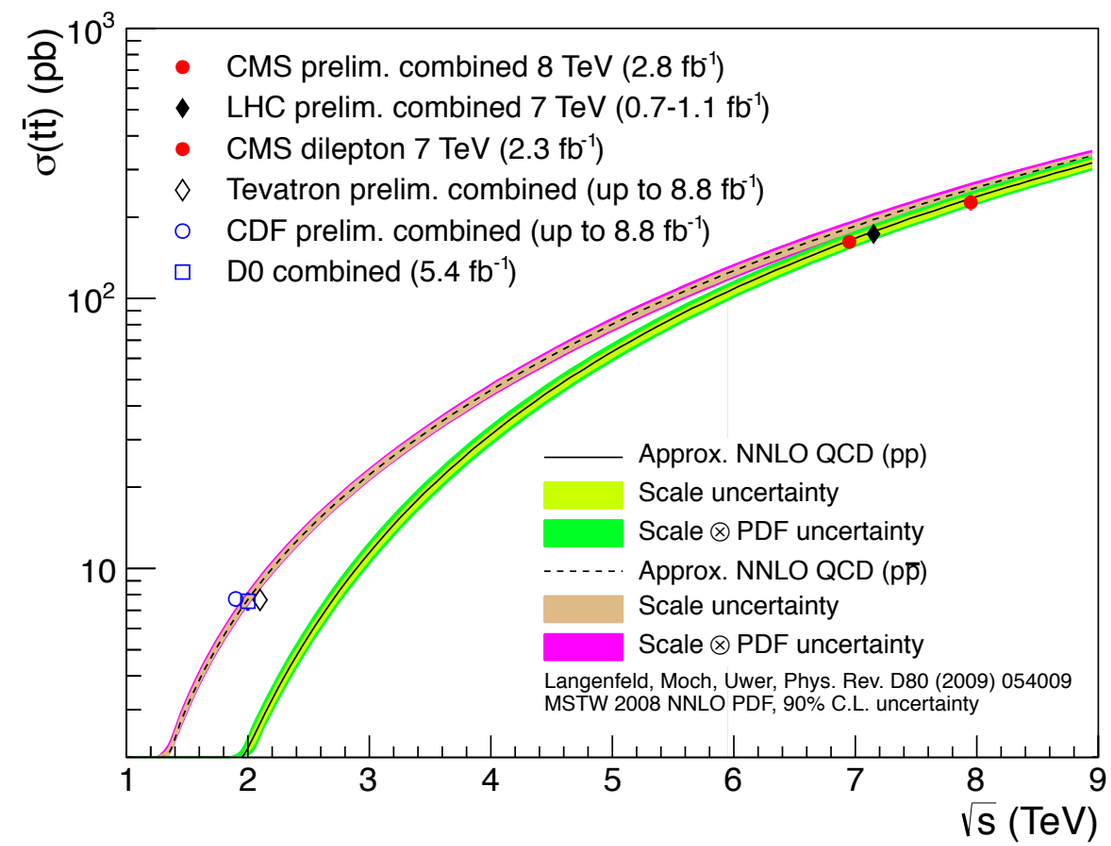
$t\bar{t}$ cross section

$t\bar{t}$ cross section

- Similar event selection as for mass analyses
- Measurements typically using kinematic fits to distinguish signal and background, with a likelihood fit to estimate N_{ttbar}
- Measured cross-section in good agreement with theory
  - exact NNLO calculation recently completed: arXiv:1303.6254 [hep-ph]







Differential cross section

- ATLAS results in 2 fb^{-1} 7 TeV data
- CMS lepton+jets and dilepton channel results in 12 fb^{-1} 8 TeV data
- consistent with SM, but NNLO required to describe top p_T dependence

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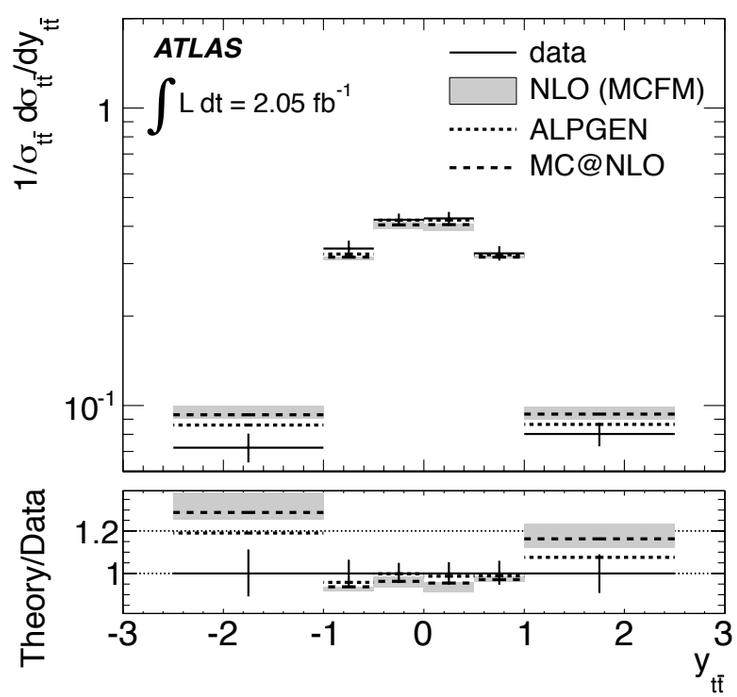
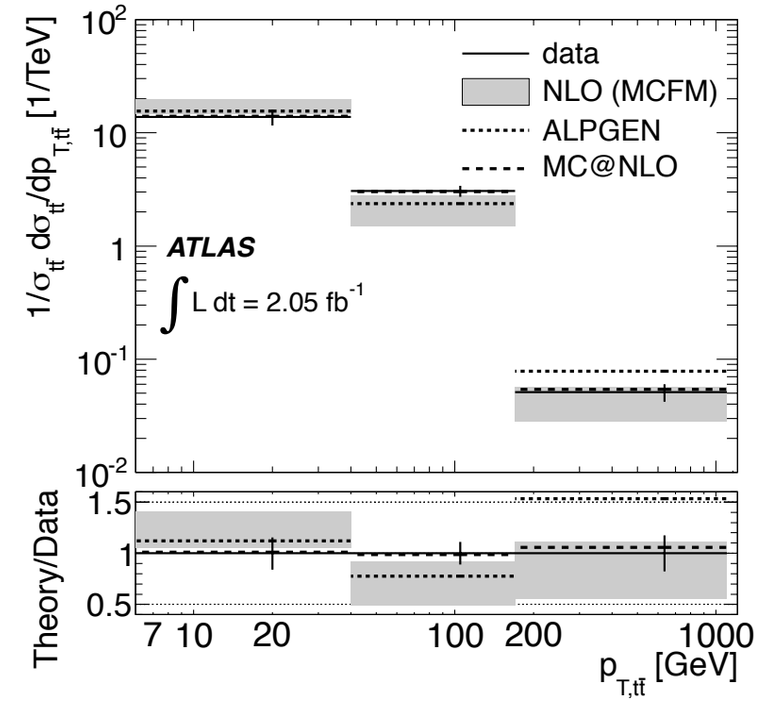
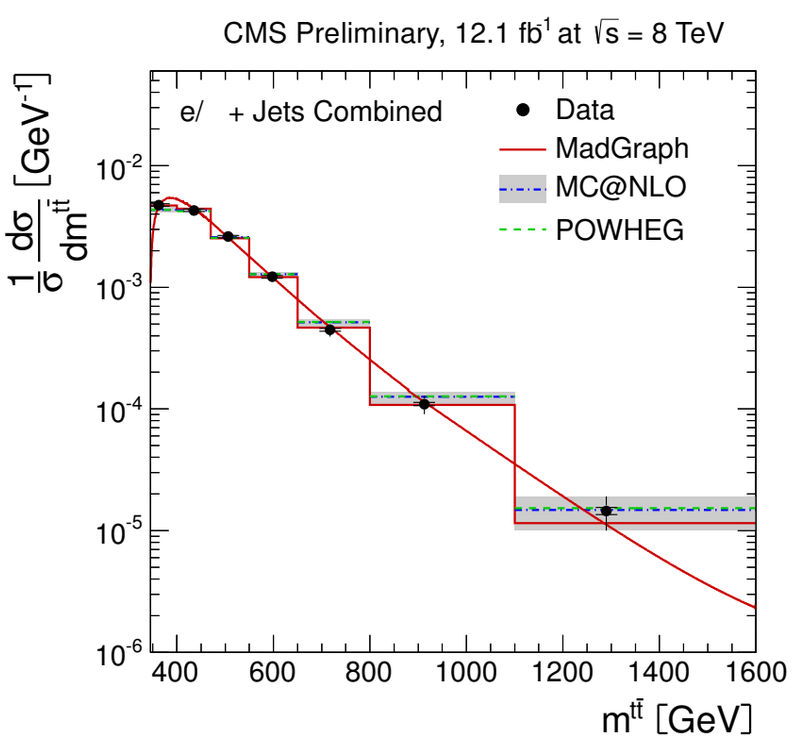
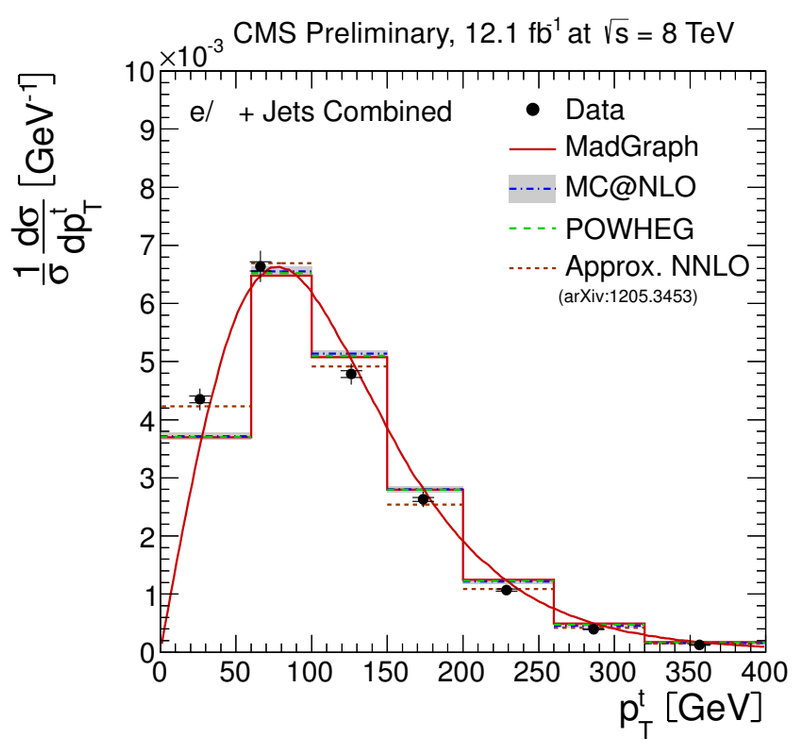


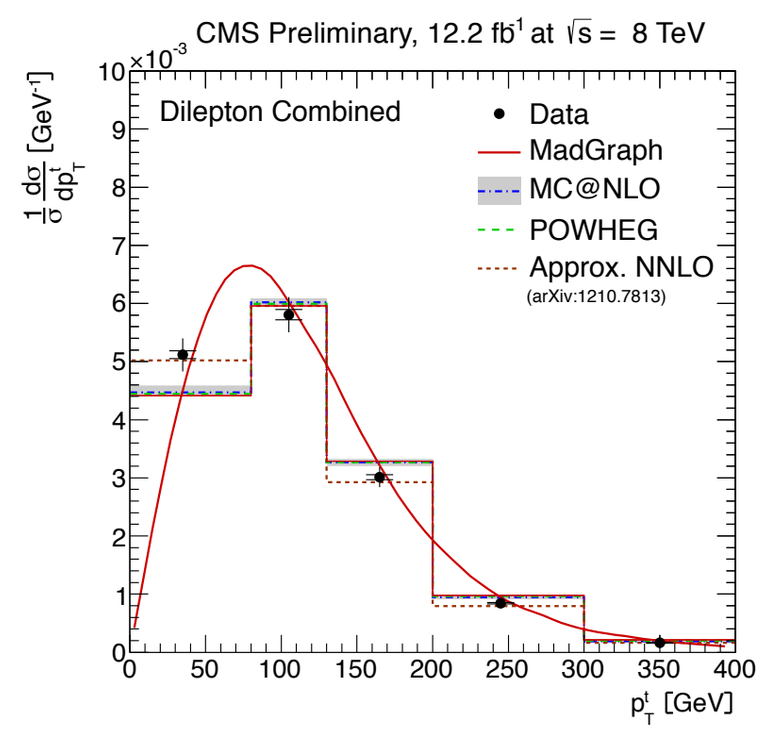


CMS PAS TOP-12-027





CMS PAS TOP-12-028

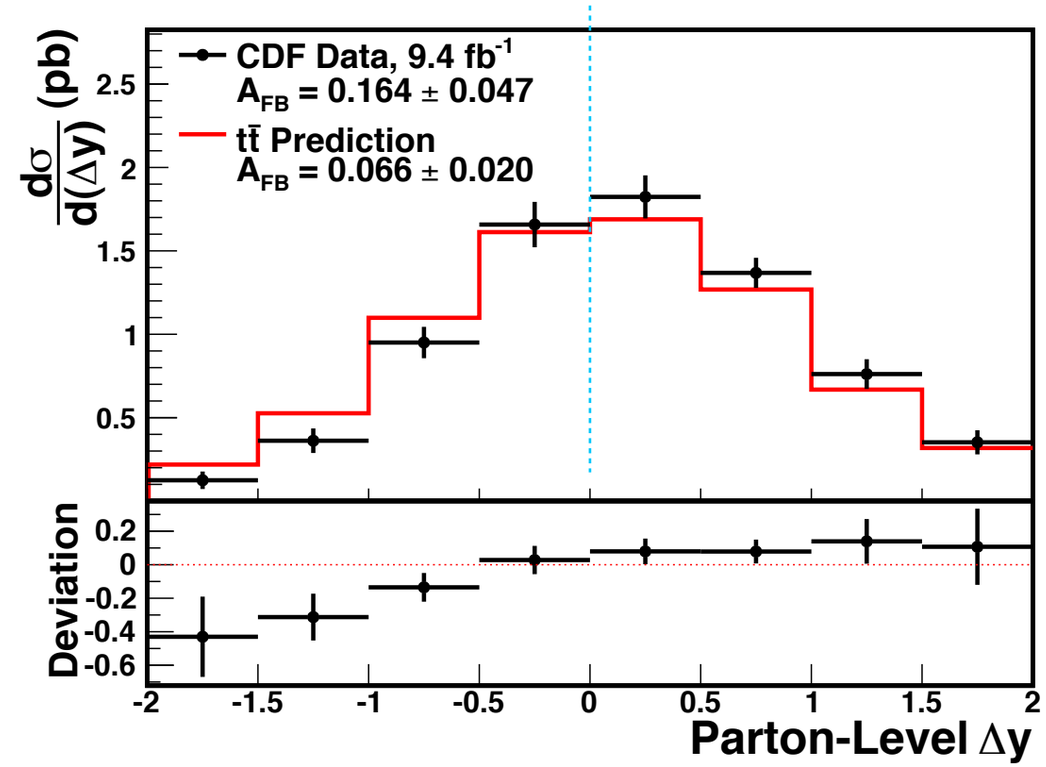


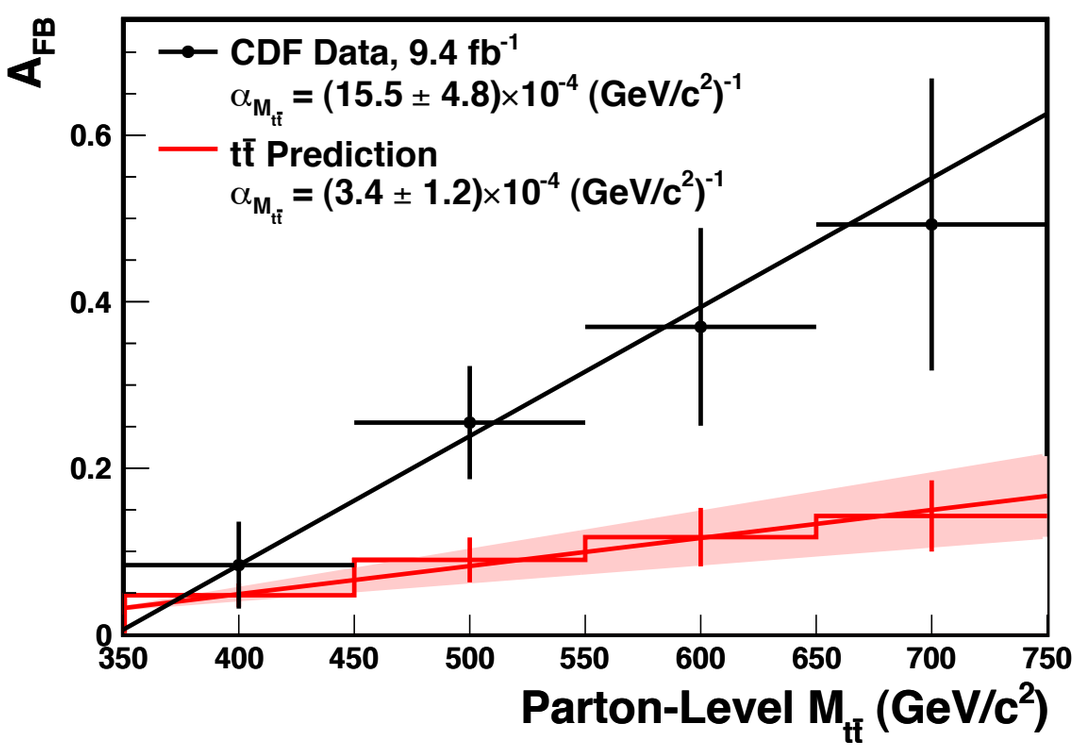
top charge asymmetry

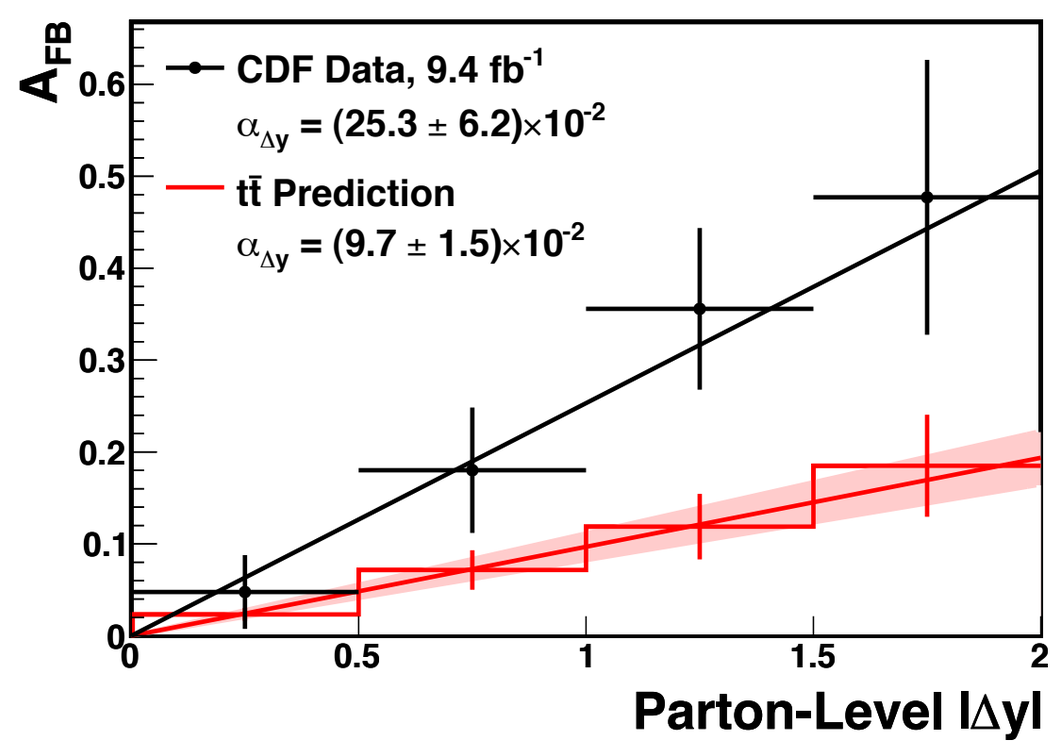
Top charge asymmetry

PRD: arXiv:1211.1003

- Great interest in the tension between the Tevatron measurements and the SM prediction for charge asymmetry
  - $A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$ where $\Delta y = y_t - y_{tbar}$
- Plots show latest CDF l+jets result with 8.7 fb^{-1} at 1.96 TeV
  - distributions bkg-subtracted and unfolded to parton level
- The SM calculation has been improved
  - electroweak processes that contribute to the asymmetry
  - studies of the choice of renormalisation scale
  - progress on NNLO calculation
  - small increase in the expected asymmetry, but not enough to resolve the tension with observation.



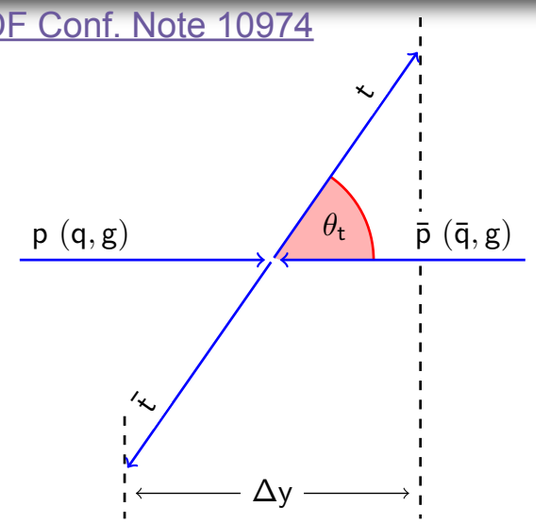


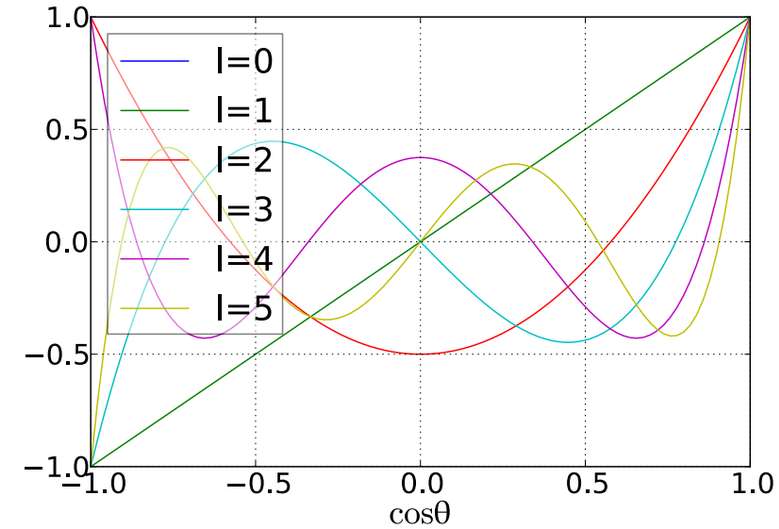


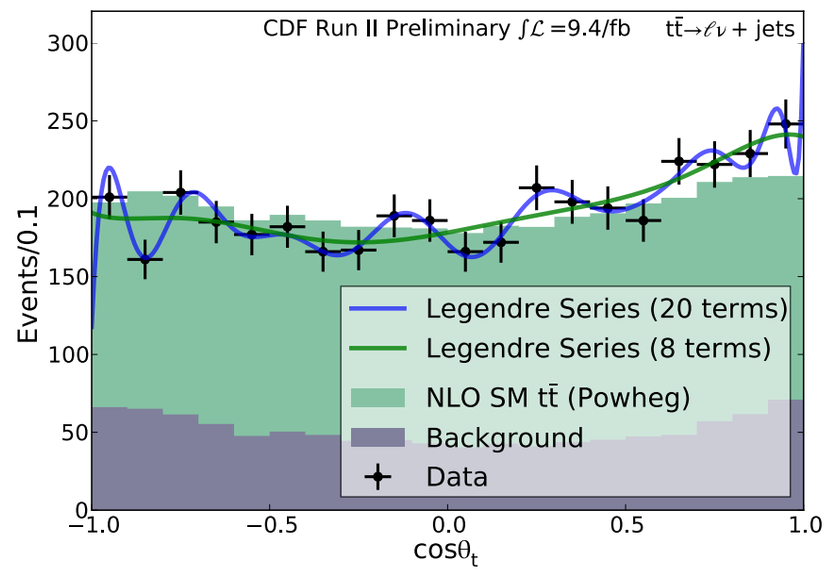
Characterisation of $d\sigma/d\cos\theta_t$

- $A_{FB}(\Delta y) \sim= A_{FB}(\cos\theta_t)$ (equal when p_T(ttbar)=0)
- Angular dependence of qq->tt scattering in CM completely characterised by sum of Legendre polynomials
  - contributing polynomials determined by angular momentum J of intermediate states
- LO SM: contributions only from ℓ =0,2. Non-zero A_{FB} comes from odd moments (ℓ =1,3,5)
- Results from fit to $\cos\theta_t$ in data, background subtracted and corrected to parton level
- Observed A_{FB} all comes from ℓ =1 term

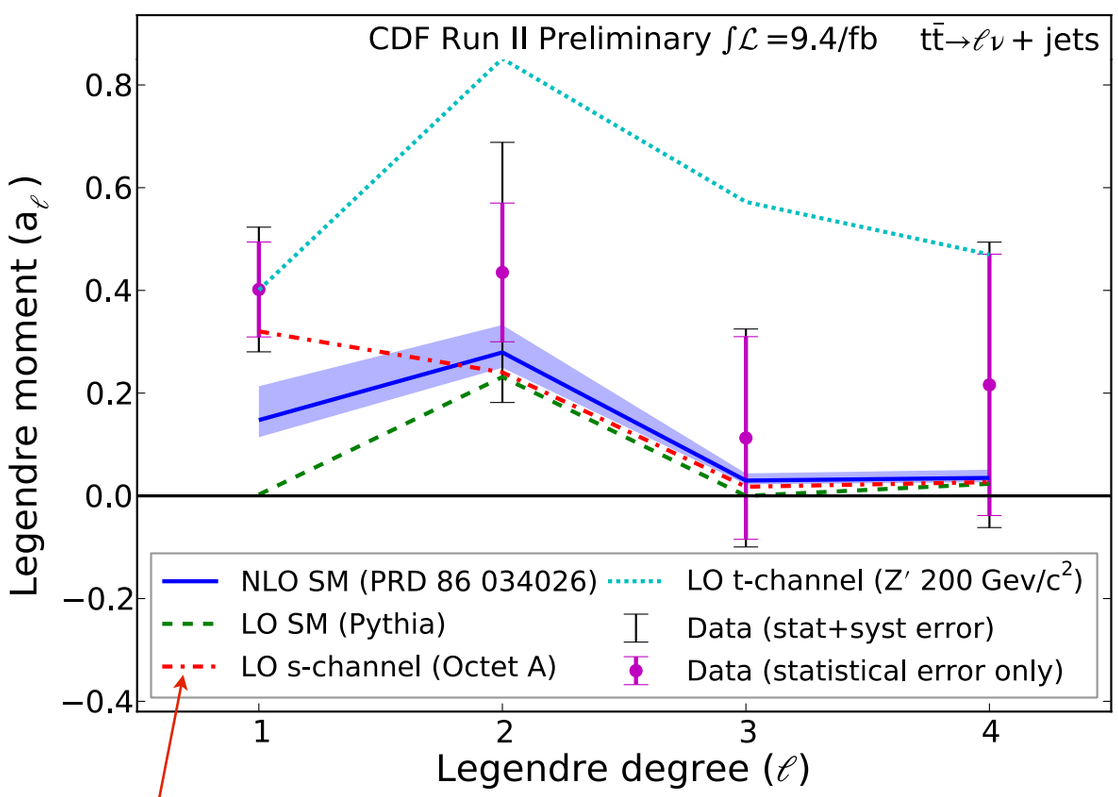
CDF Conf. Note 10974



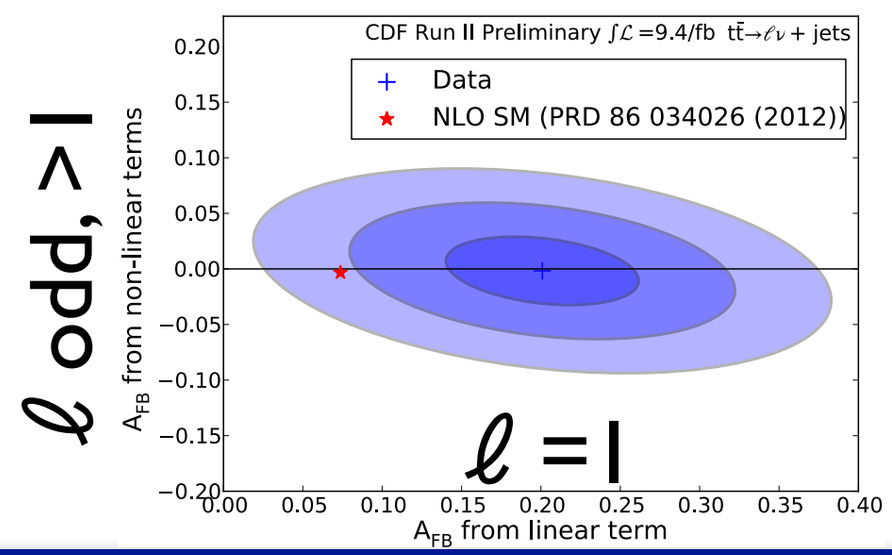




ℓ	$P_\ell(x)$
0	1
1	x
2	$\frac{1}{2}(3x^2-1)$
3	$\frac{1}{2}(5x^3-3x)$
4	$\frac{1}{8}(35x^4-30x^2+3)$
5	$\frac{1}{8}(63x^5-70x^3+15x)$

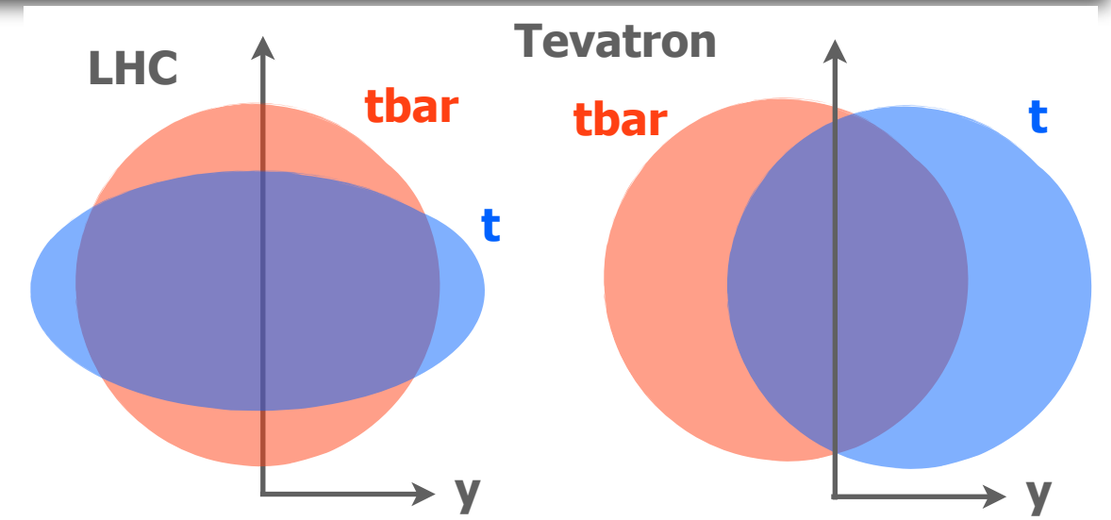


s-channel model with axigluon of mass 2 TeV



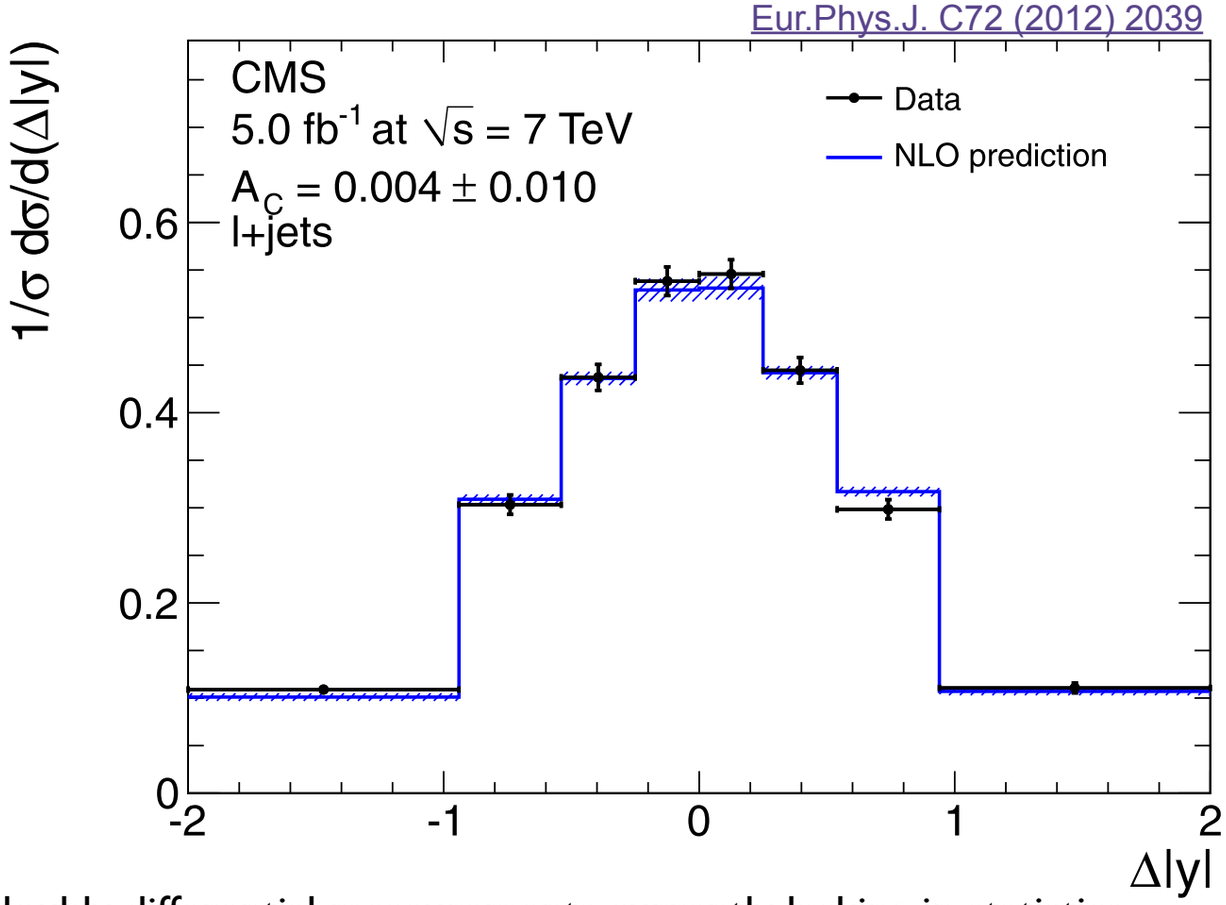
Charge asymmetry at the LHC

- A_{FB} variable not useful at LHC because initial state is symmetric (qq)
- If top quark preferentially emitted along the direction of q, expect tops to be more forward than antitops, i.e. $|y_t|>|y_{tbar}|$
- LHC measurements consistent with SM
  - same is true for lepton charge asymmetry, which can be measured in dilepton events
- But this is possible for some NP models



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

Eur.Phys.J. C72 (2012) 2039



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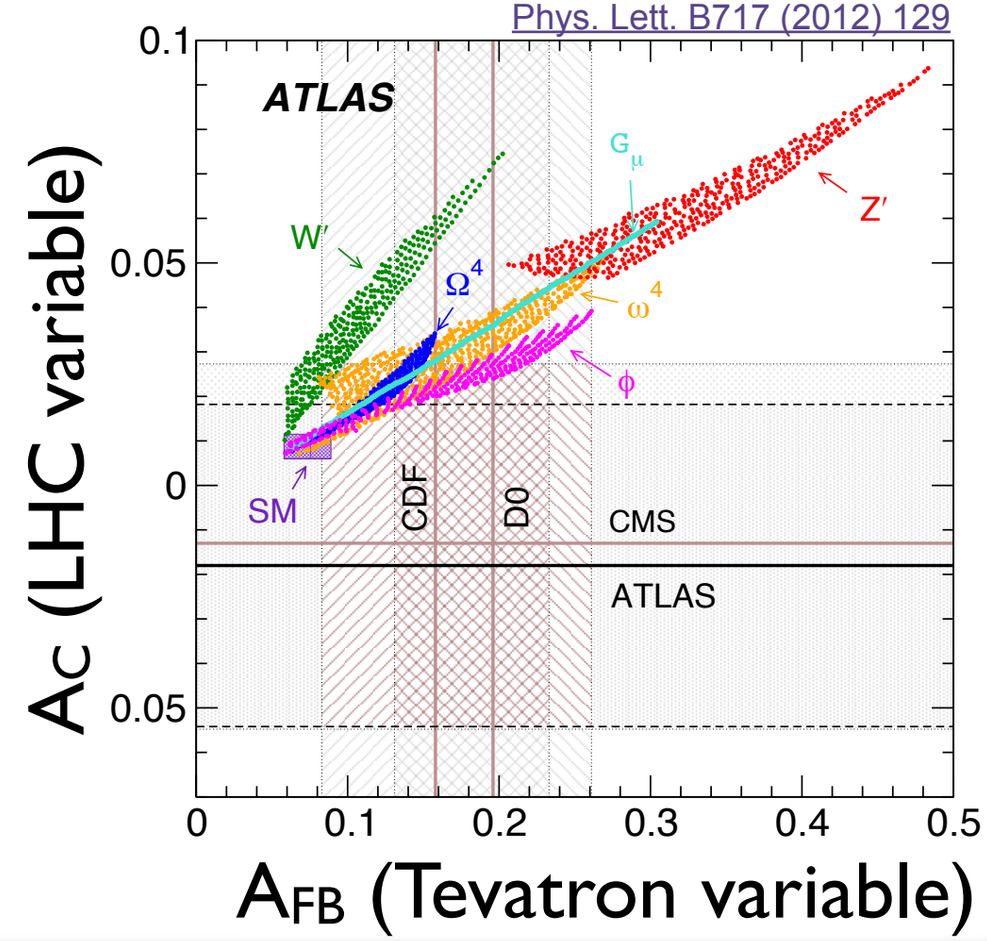
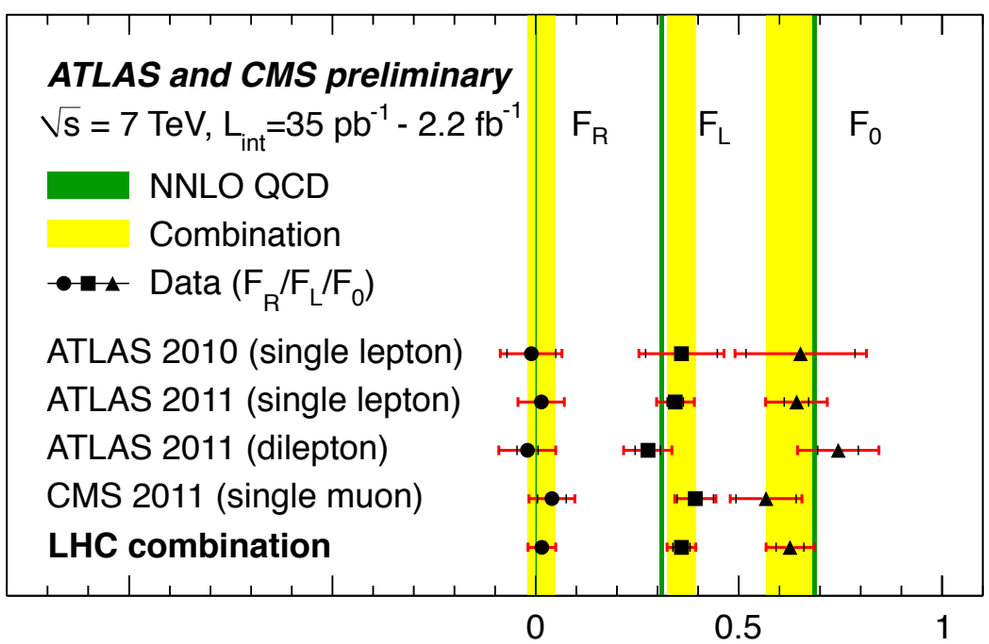


doubly differential measurements currently lacking in statistics

W helicity and anomalous Wtb couplings

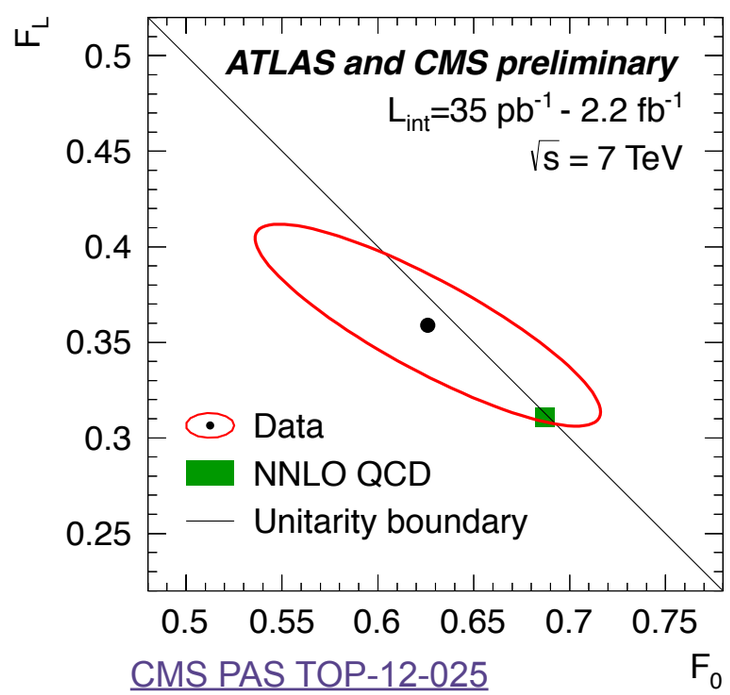
W helicity fractions in top decays (LHC combination)

- Fractions of events containing W bosons with right-handed (F_R), left-handed (F_L), and longitudinal (F_0) polarisation
- measured using θ* distribution in $t\bar{t}$ events: angle of the lepton in the W rest frame, measured wrt the W momentum in top rest frame (helicity basis)
  - ATLAS measurements using template fitting method and acceptance-corrected angular asymmetries
  - CMS measurement based on reweighting MC in a likelihood technique to find F_i preferred in data
- $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2\, F_R + \frac{3}{8}(1-\cos\theta^*)^2\, F_L + \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0$$
- CMS and ATLAS results combined using BLUE



ATLAS-CONF-2013-033

W boson helicity fractions



CMS PAS TOP-12-025

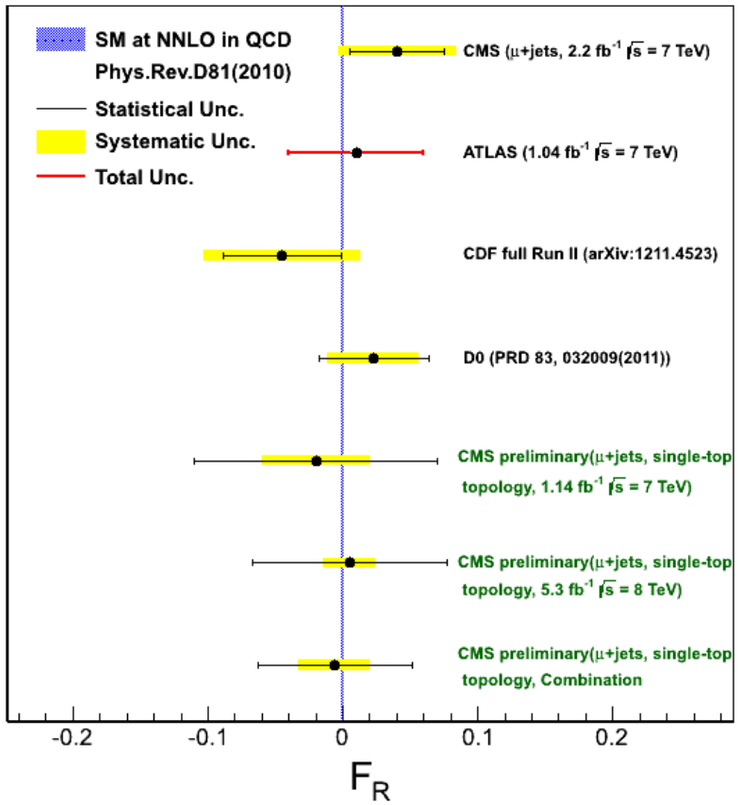
$F_0 = 0.626 \pm 0.034\ (\text{stat.}) \pm 0.048\ (\text{syst.})$

$F_L = 0.359 \pm 0.021\ (\text{stat.}) \pm 0.028\ (\text{syst.})$

=> $F_R = 0.015 \pm 0.034$ (unitarity)

- Also measured in single-top events

CMS PAS TOP-12-020



Limits on anomalous couplings

- The combined helicity fractions are in agreement with NNLO QCD predictions and can be used to set limits on new physics contributing to the Wtb vertex.
- Start with most general Wtb vertex:

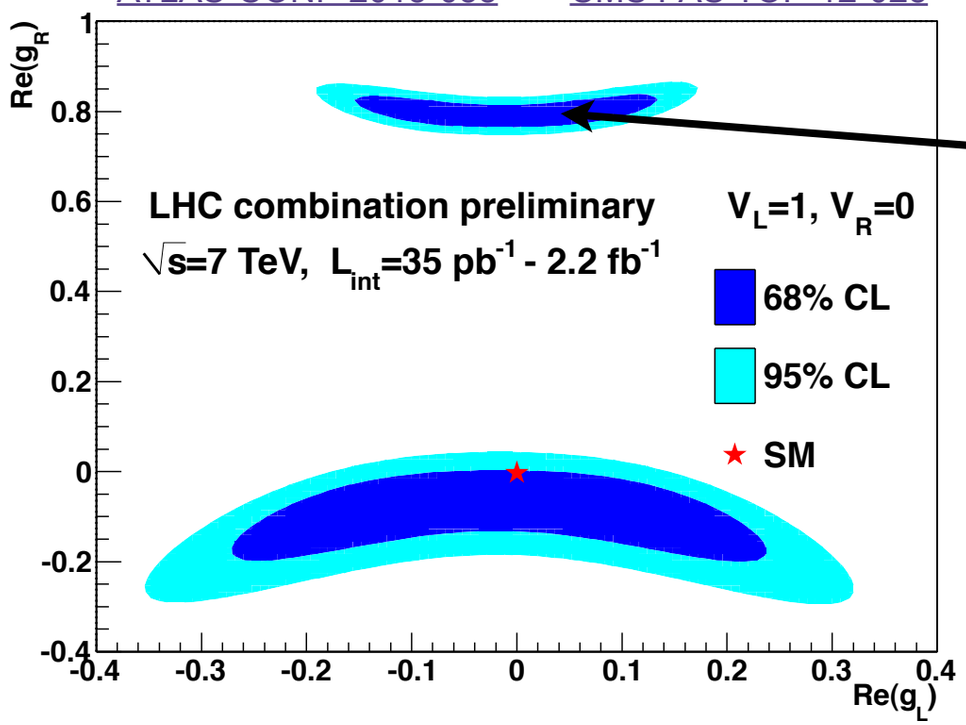
left and right handed vector couplings — left and right handed tensor couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-} + \text{h.c.}$$

SM part, $V_L = V_{tb}$ — anomalous couplings (zero in SM)

- Assuming V_L=1 and V_R = 0, set limits on real parts of g_L and g_R

ATLAS-CONF-2013-033 CMS PAS TOP-12-025



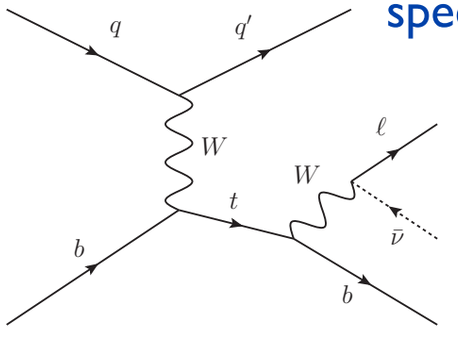
region highly disfavoured by single top cross-section measurements

- Assuming g_L=0:

$$\mathrm{Re}(g_R) = -0.10 \pm 0.06\ (\text{stat.})\ ^{+0.07}_{-0.08}\ (\text{syst.})$$

Search for CP violation in single top quark events

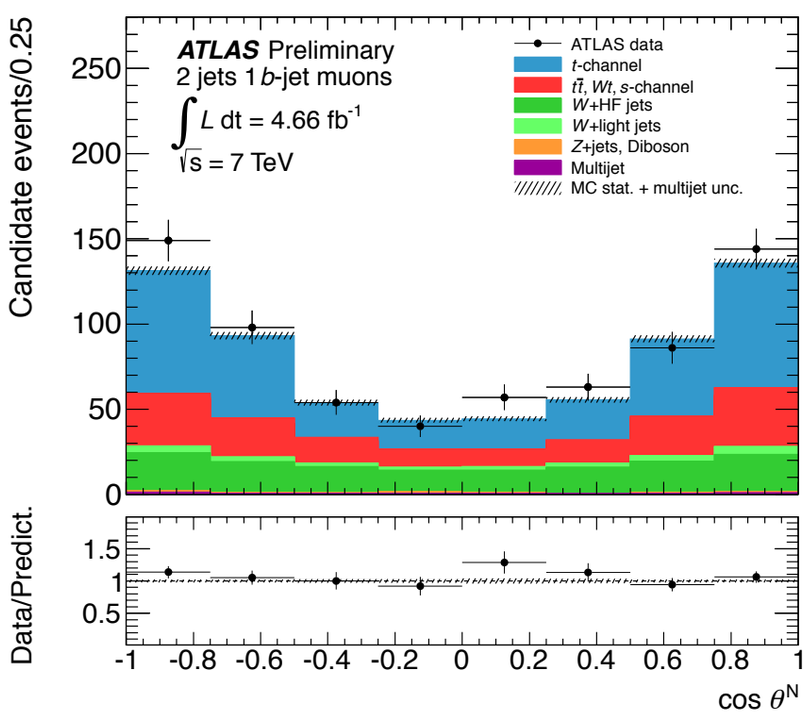
- CP violation has been observed in the decays of kaons and B mesons but not at higher energies (i.e. top)
- helicity fractions measured using θ^* not sensitive to all anomalous couplings
  - limits apply to real part of coupling, not the complex phases that would imply that the top quark decay has a CP-violating component
- Single-top quarks produced in the t channel predicted to be highly polarised (P~0.9) in direction of spectator quark
- Define θ_N: similar to θ^*, but angle measured wrt normal to W direction and spectator quark direction (top spin direction)



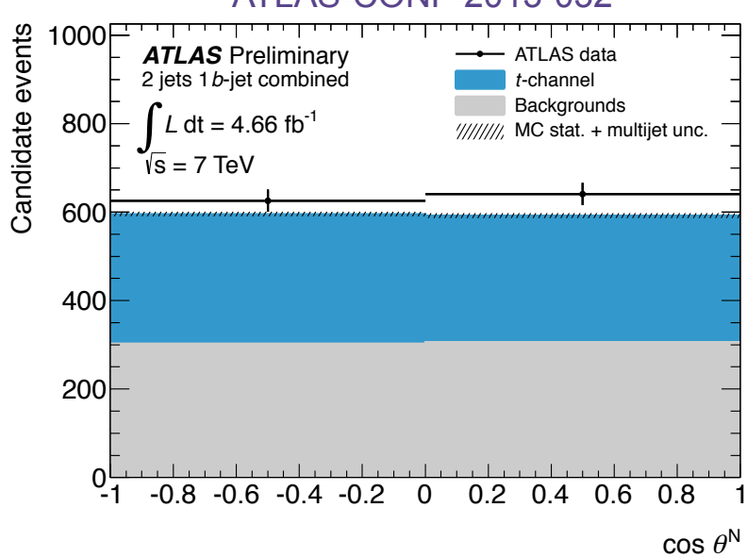
spectator quark

Require exactly 1 lepton, 1 b-tagged jet, 1 untagged jet, and MET

- forward-backward asymmetry in the normal direction, A^N_{FB}, very sensitive to imaginary part of g_R:
  - $A^N_{FB} = 0.64\, P\, \mathbb{I}(g_R)$ (for small values of g_R and with $V_L = 1$ and $V_R = g_L = 0$)
- $\cos\theta_N$ distribution unfolded to parton level for comparison with theory

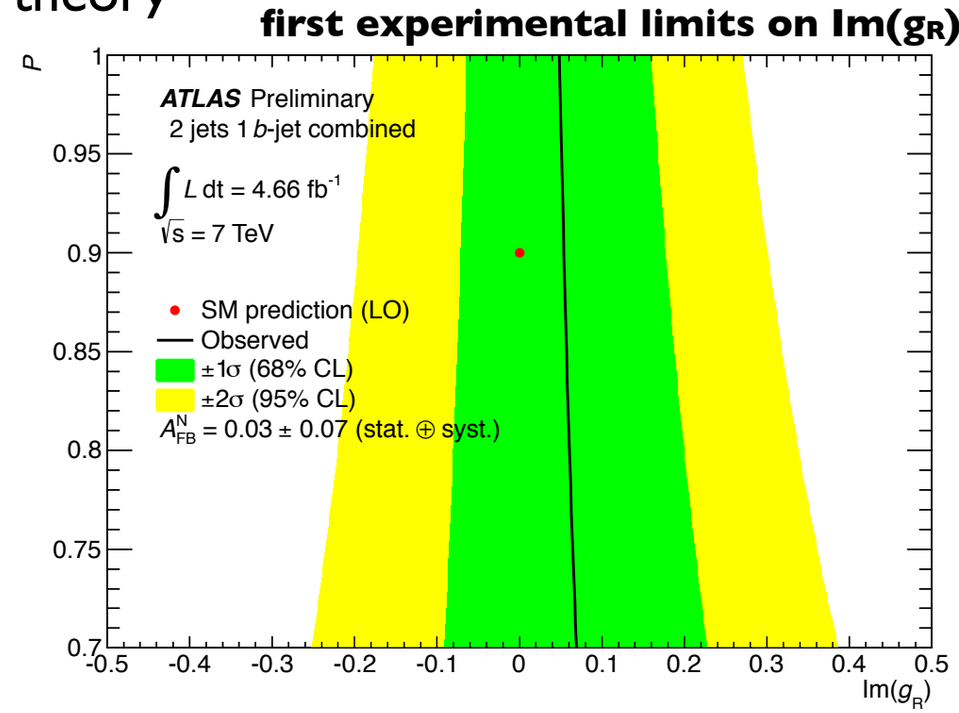


ATLAS-CONF-2013-032



$A^N_{FB} = 0.03 \pm 0.07 \pm 0.03$

first experimental limits on Im(g_R)

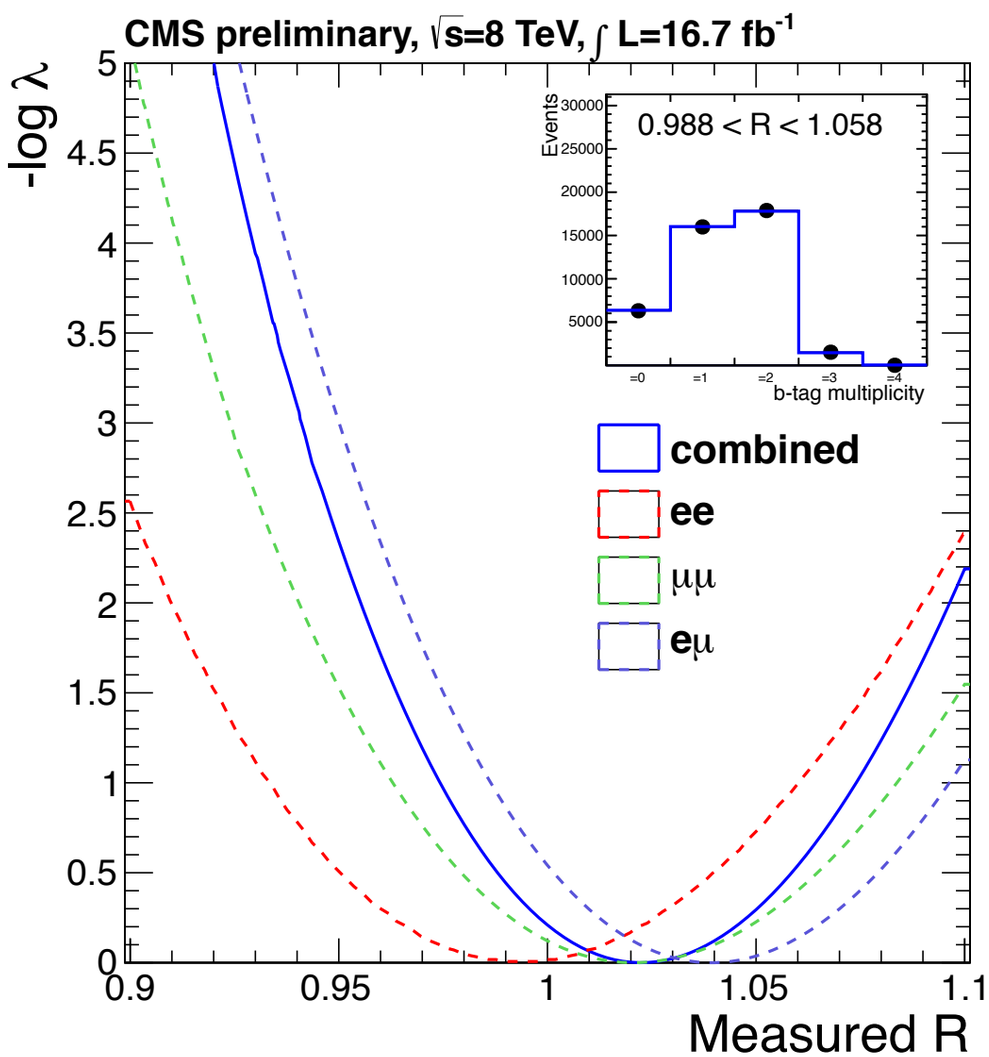


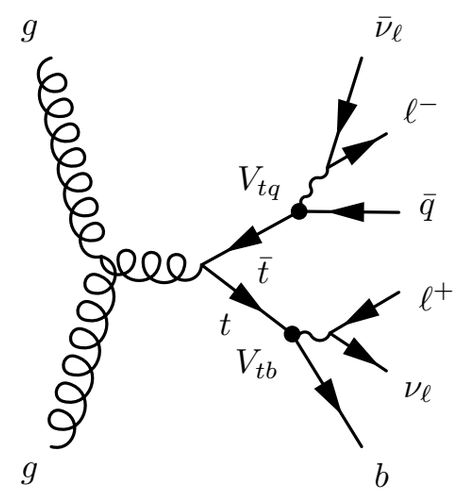
$95\%\text{C.L.} \Rightarrow Im(g_R) \in [-0.20, +0.30]$ for P=0.9

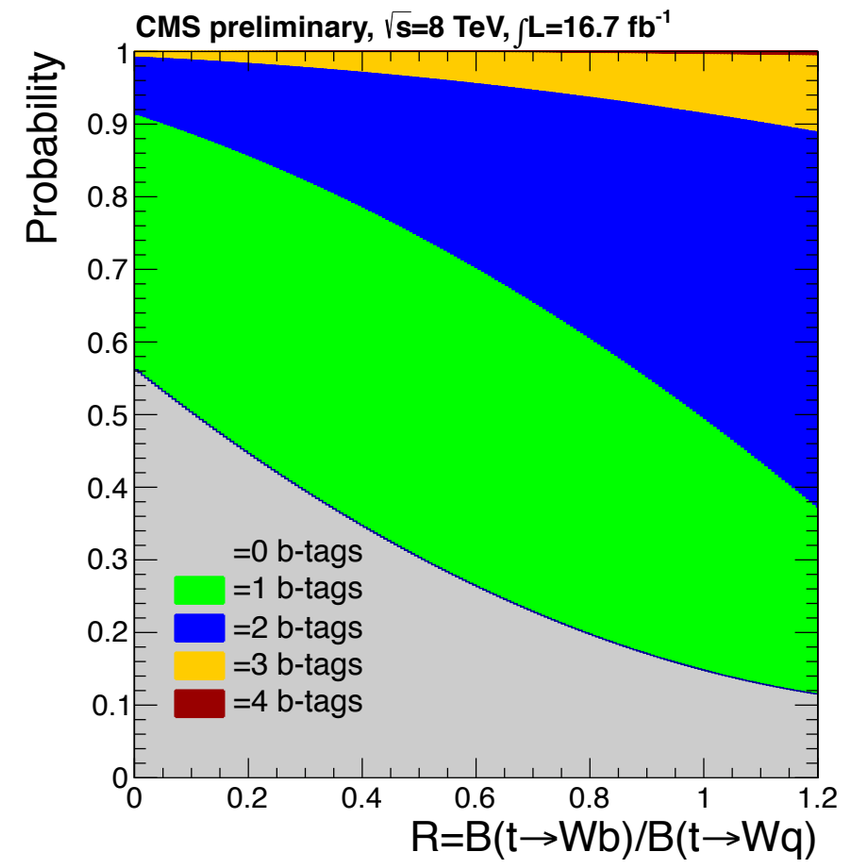
Ratio B(t → Wb)/B(t → Wq)

CMS PAS TOP-12-035

- Measurement in dilepton final state with 16.7 fb^{-1} 8 TeV data
- Construct probability model for expected b-tag multiplicities vs R where $\mathcal{R} = B(t \to Wb)/B(t \to Wq)$
  - done separately for different event categories based on channel (ee, eμ, μμ) and jet multiplicity
- Likelihood fit for R using observed b-tag multiplicity distribution





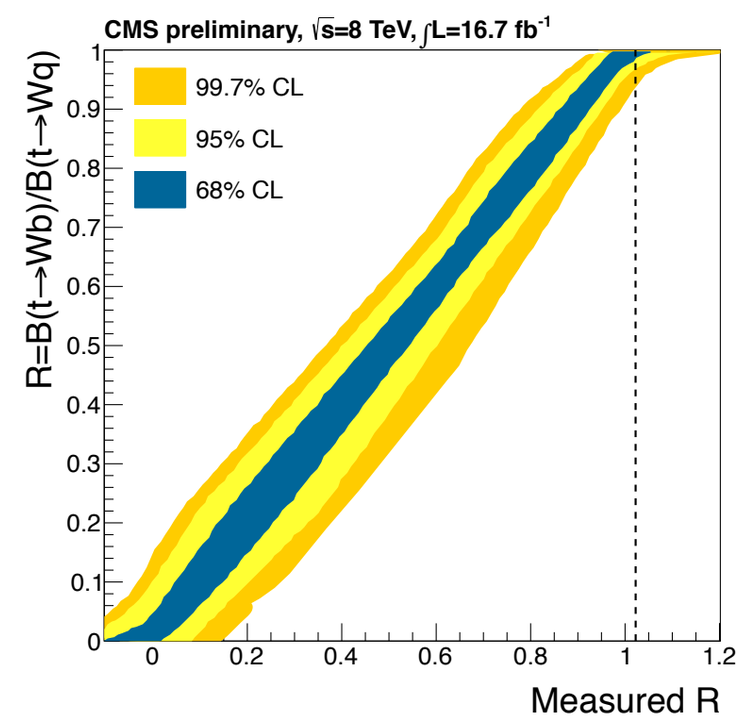


$$\mathcal{R} = 1.023^{+0.036}_{-0.034}\ \text{(stat+syst)}$$

$$\mathcal{R} > 0.945 \text{ at 95\% CL}$$

$$|V_{tb}| > 0.972 \text{ at 95\% CL}$$

most precise measurement to date



Search for FCNC in top decay

Search for FCNC in top decays

- Flavour changing neutral currents highly suppressed in SM
- Search for $t\bar{t}$ events with FCNC decay, $t \to Zq$
  - $tt \to Zq + Wb \to \ell\ \ell\ q + \ell\ \nu b$
- Require two opposite-sign, isolated leptons (e or μ) consistent with a Z-boson decay and an extra charged lepton consistent with W decay, also ≥2 jets (no b-tagging)
- Less likely Z-j combinations vetoed by cut on $\sum p_{T\ell} + \sum p_{Tj} + \not{E}_T$, then $t\bar{t}$ pair with largest Δphi selected
- Perform counting experiment: $\mathcal{B}(t \to Zq) < 0.21\%$

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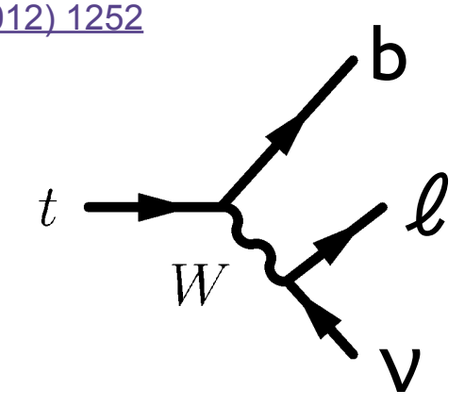
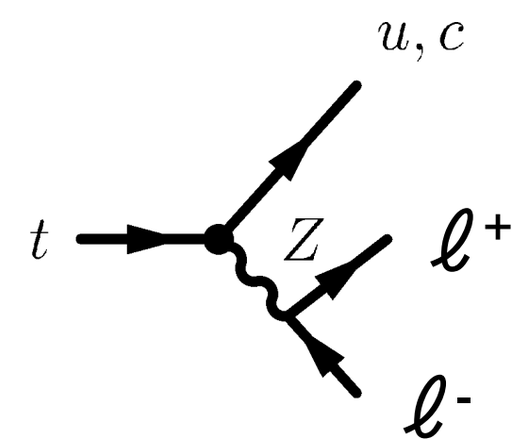
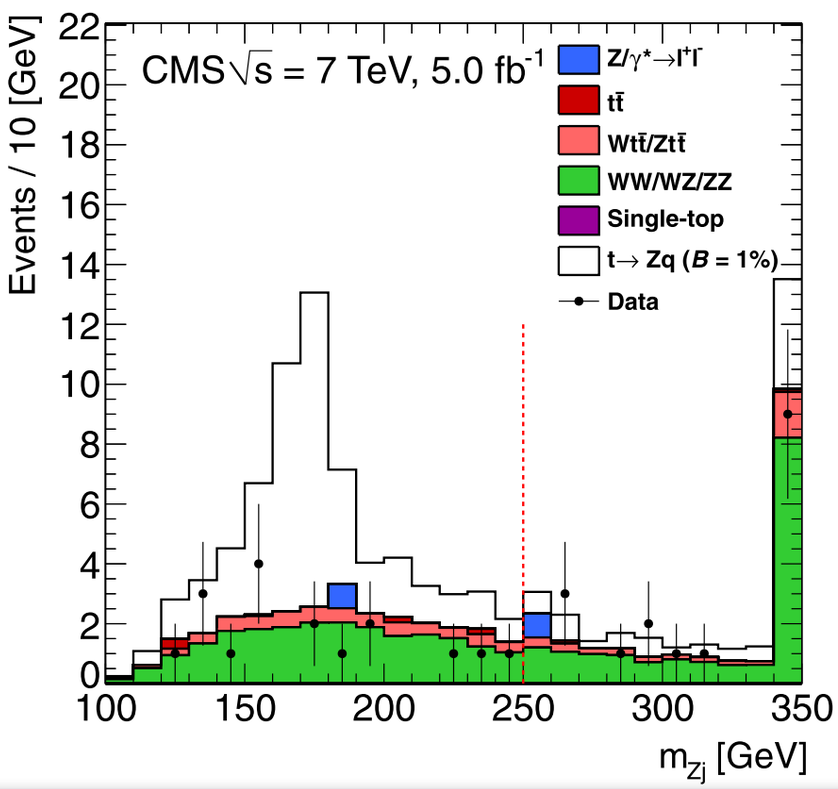
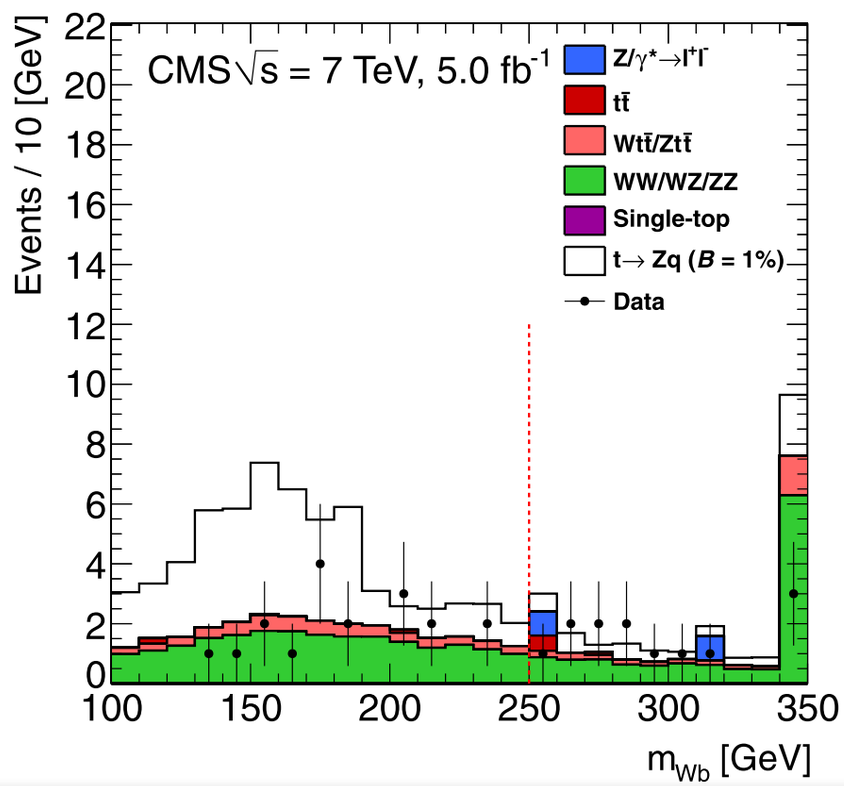


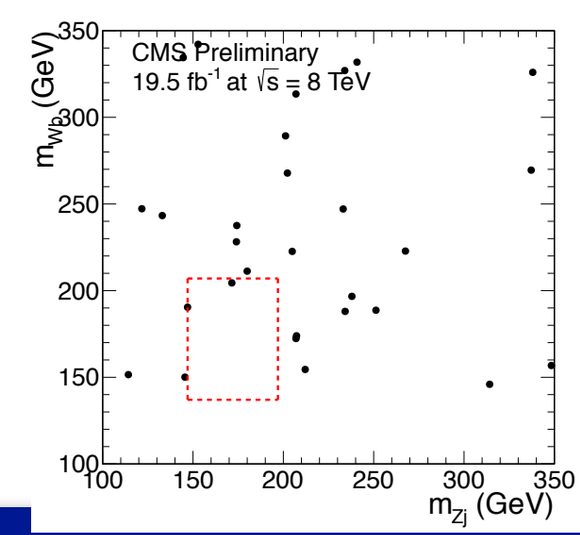






slide to be updated for new result (19/fb 8 TeV):

CMS PAS TOP-12-037



Conclusions and prospects for 13 TeV

- LHC mass measurements matching precision of Tevatron

- Abundance of tops at LHC allows for more detailed studies of top quark properties compared to Tevatron
  - differential cross-section compared to theory at NNLO
  - top, antitop mass difference and limits on V_{tb} and FCNC far exceed Tevatron precision

- Tevatron A_{FB} result still the only hint at new physics (good agreement with SM elsewhere)

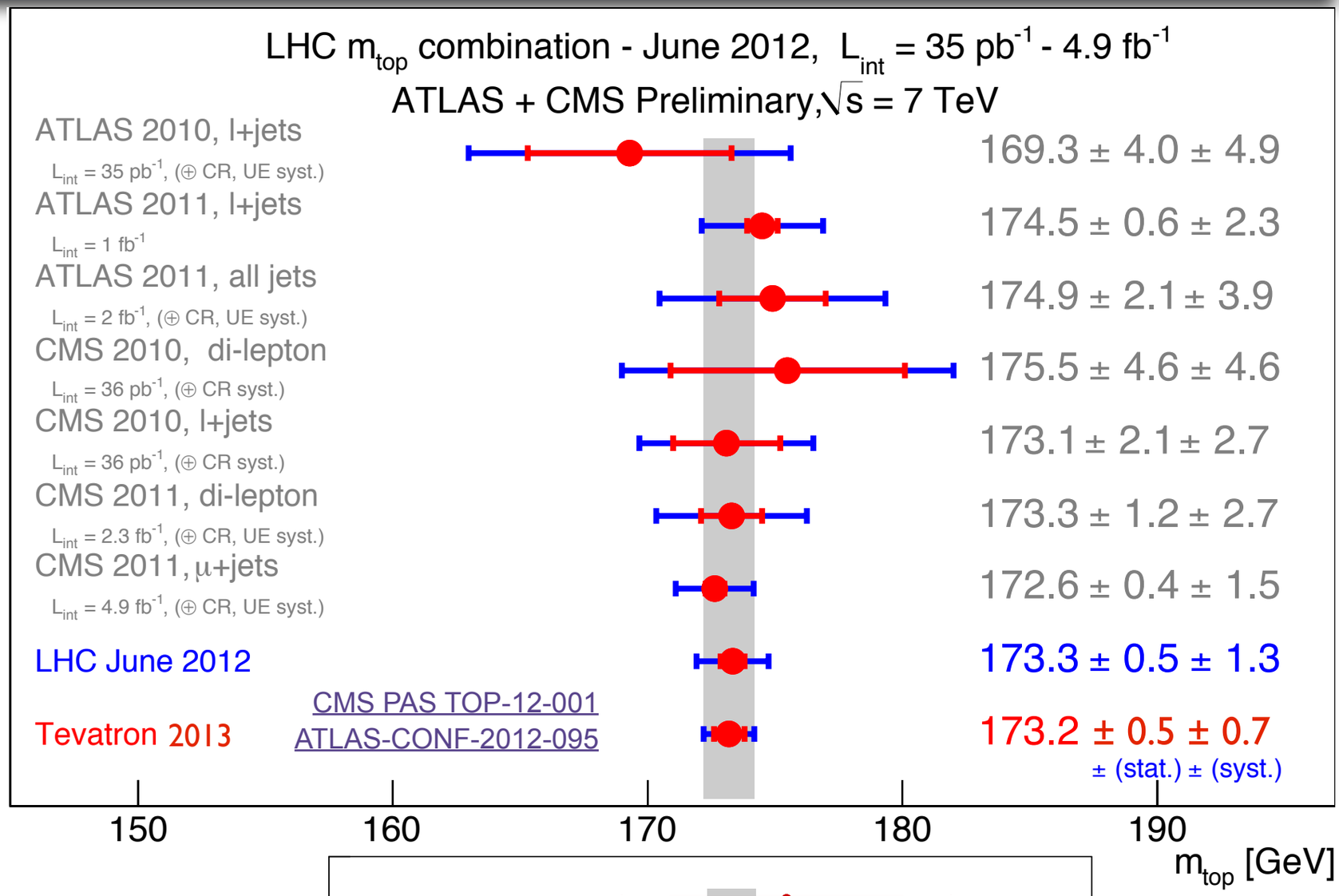
- Many results for full LHC dataset at 8 TeV still to come!

- $t\bar{t}$ cross section increases by factor of ~3 from 8 TeV to 13 TeV
  - uncertainties will quickly be dominated by systematics
  - good understanding of top background very important at 13 TeV

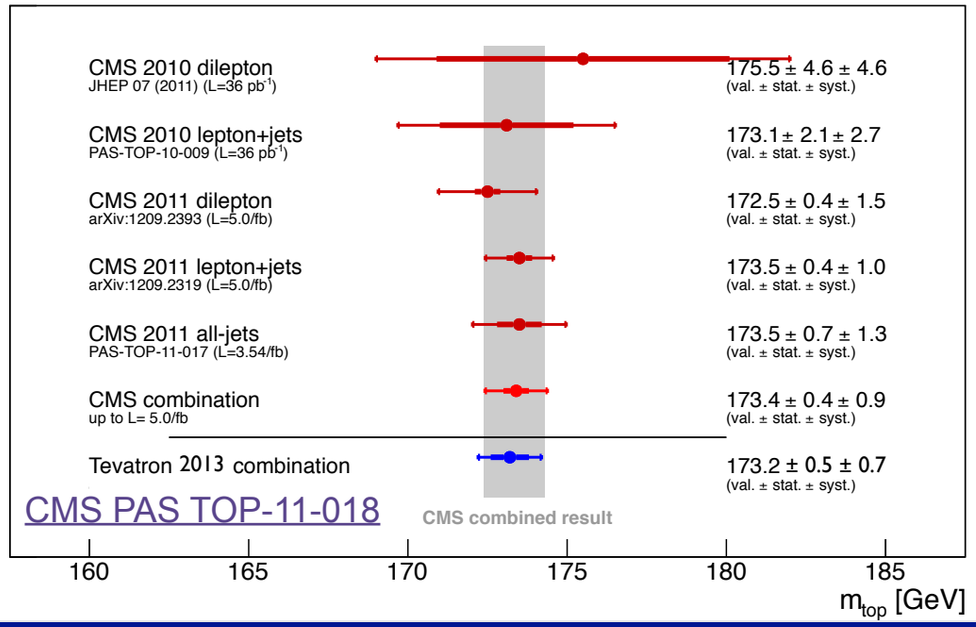
Backup

Mass combination at the LHC

- June 2012 combination, using BLUE
- Lepton+jets channel best sensitivity
  - smallest syst. unc.



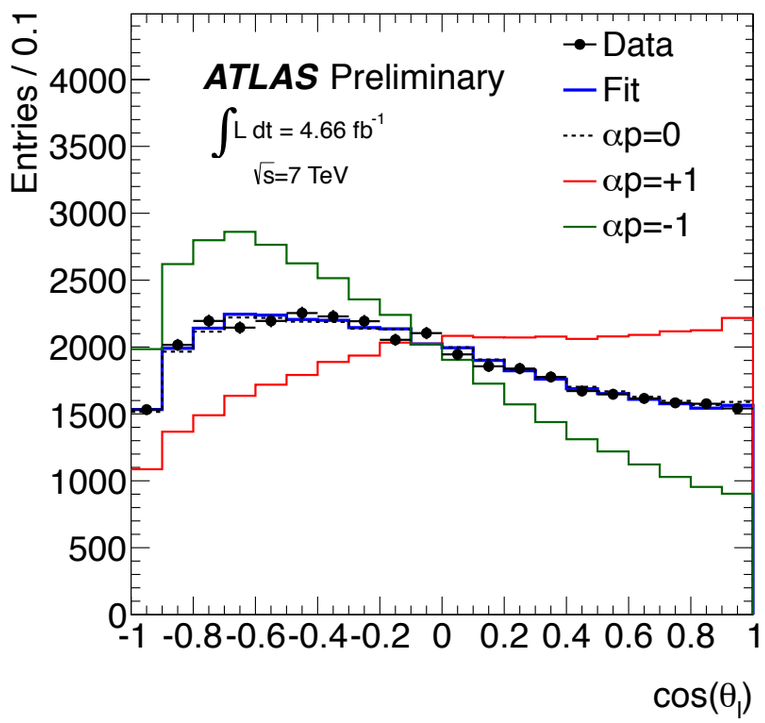
- CMS results updated since combination
- CMS combination:
  - m_t = 173.4±0.4±0.9 GeV
- Consistent with Tevatron

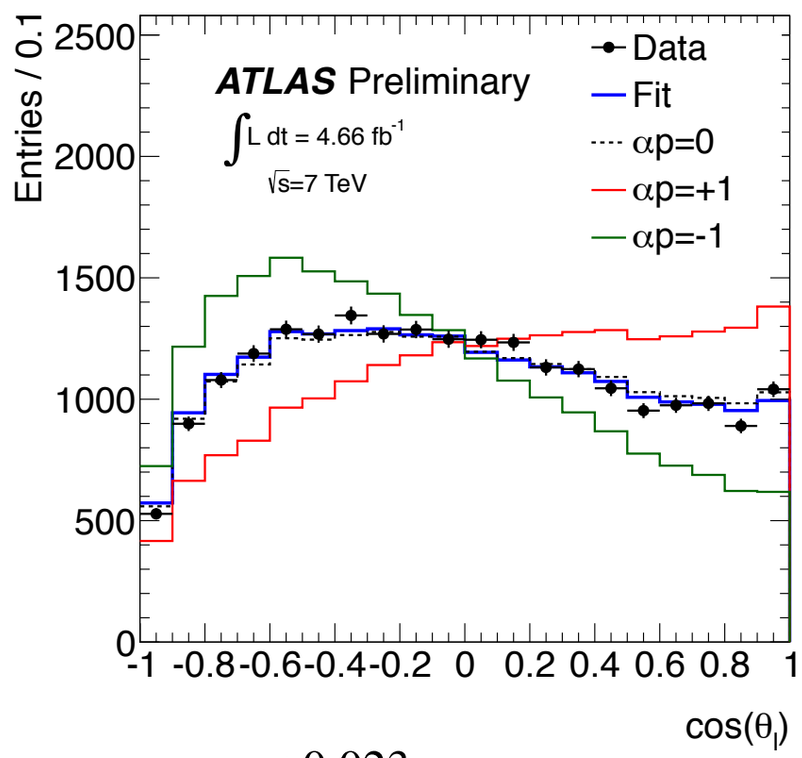


Top polarisation

- Atlas: lepton+jets, template fit ATLAS-CONF-2012-133 CMS PAS TOP-12-016
- CMS: dilepton, unfolded to parton level
- Distribution of angle of lepton in top CM (helicity basis) $\propto 1 + \alpha_i p \cos\theta_i$
- alpha=1 in SM at LO
- fraction of + polarised tops: $f = \frac{1}{2} + \frac{N(\cos\theta_l > 0) - N(\cos\theta_l < 0)}{N(\cos\theta_l > 0) + N(\cos\theta_l < 0)}$

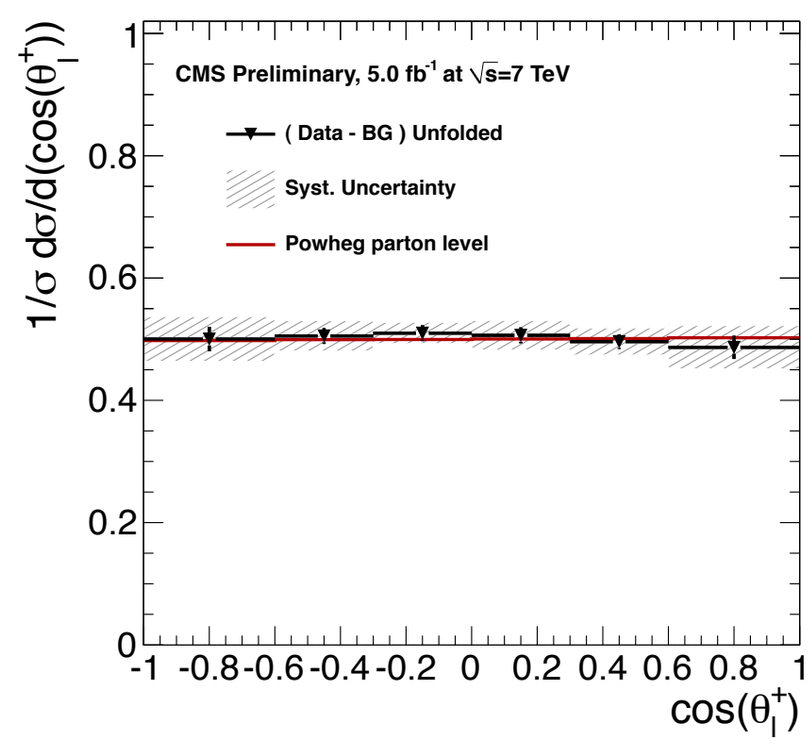
Reco level





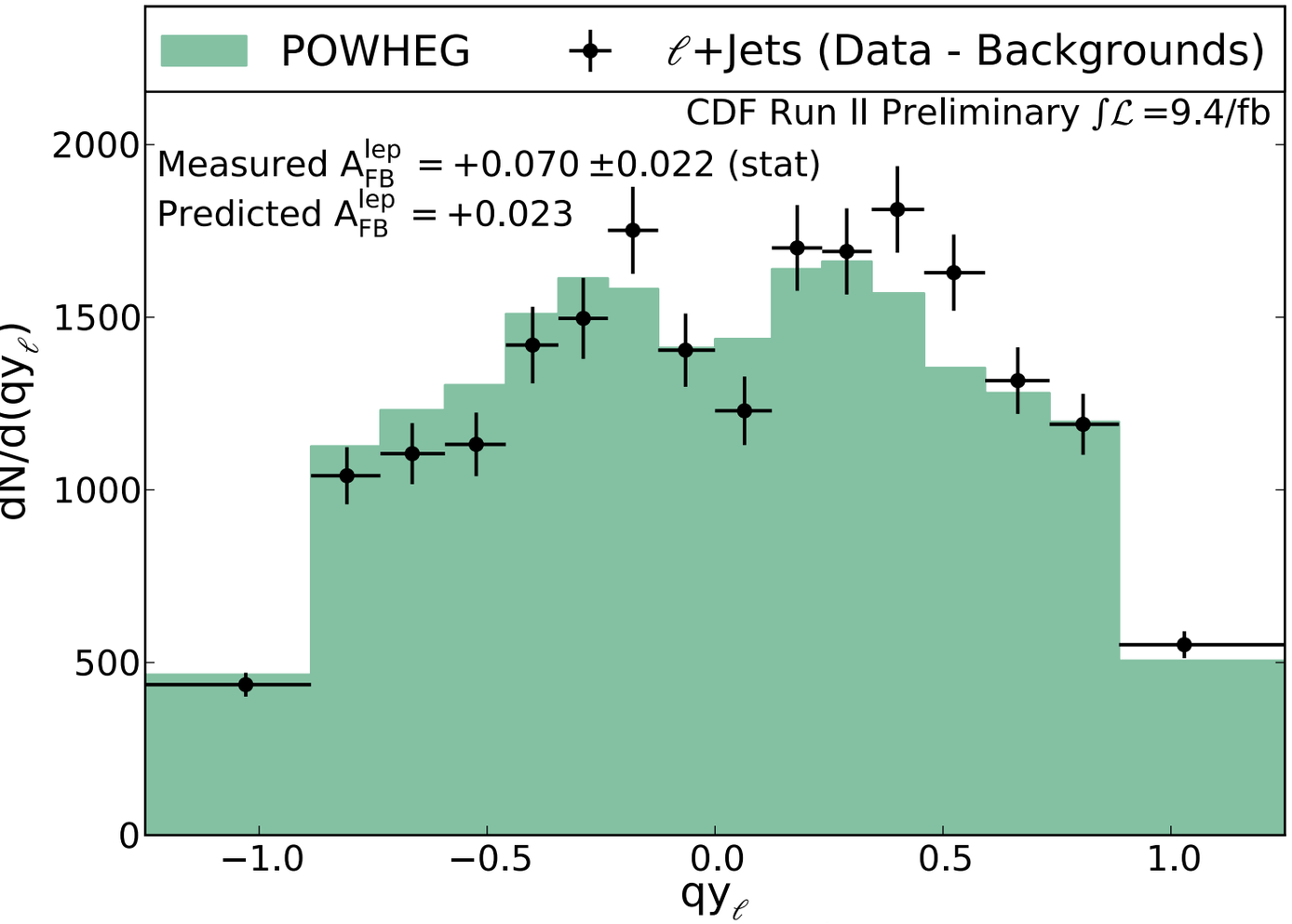
$$f = 0.470 \pm 0.009(\text{stat})^{+0.023}_{-0.032}(\text{syst})$$

Parton level



f = 0.491±0.029±0.041

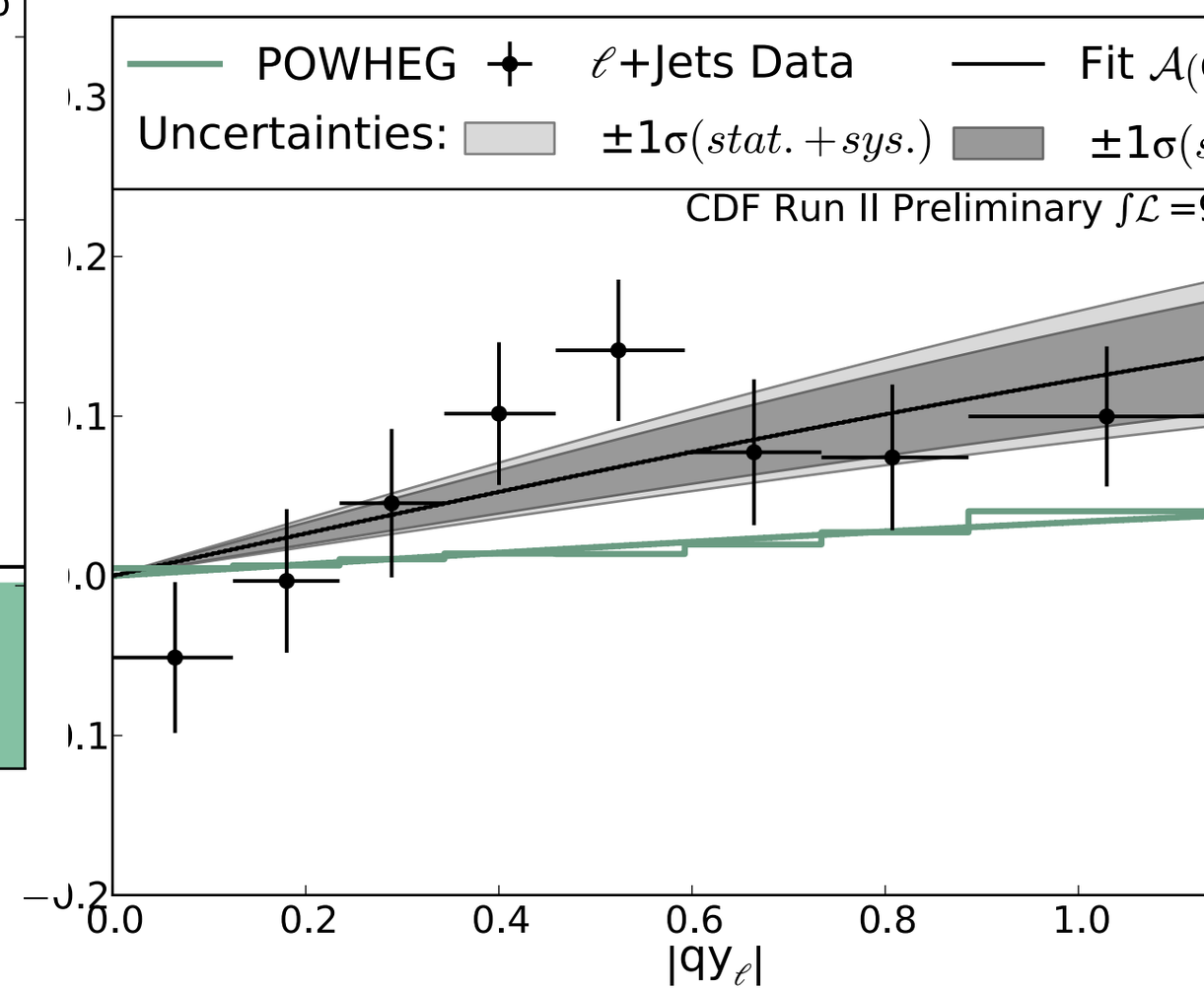
Lepton charge asymmetry



CDF Run II Preliminary $\int \mathcal{L} = 9.4/fb$

Correction Level	CDF Data	POWHEG
Data Only	0.067±0.016	0.032
Backgrounds Subtracted	0.070±0.019 ± 0.011	0.023
Fully Extrapolated	$0.094 \pm 0.024^{+0.022}_{-0.017}$	0.027

CDF Conf. Note 10975



more top mass

Study of the dependence of the top-quark mass measurement on event kinematics
5.0 /fb
link

CMS PAS TOP-12-029

Top mass with the kinematic endpoints method
5.0 /fb
link

CMS PAS TOP-11-027

top width

top mass systematics

Top spin correlation