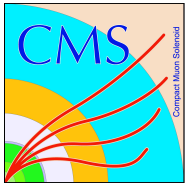
Measurement of the top quark mass and properties at the LHC

Nuno Castro

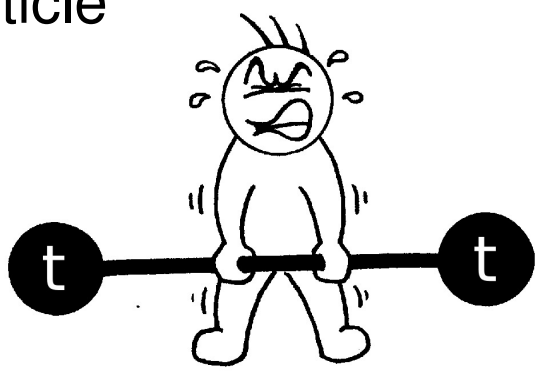
on behalf of the
ATLAS and CMS Collaborations



Rencontres de Moriond
Electroweak Interactions and Unified Theories
La Thuile, 19 March 2014

The top quark

- Top is the heaviest known fundamental particle
  $\lambda_t = \sqrt{2} m_t / v \sim 1$
  ☞ special role in EWSB?



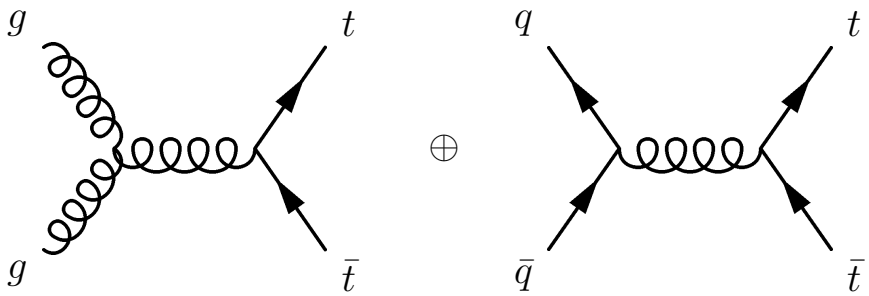
- Top quark is short lived
  ☞ decays before hadronization
  - $\Lambda_{\rm QCD}^{-1} \sim (100\ {\rm MeV})^{-1} \sim 10^{-23}$s
  - $\Gamma_t^{NLO} = 1.42$ GeV
    $\tau_t \sim 10^{-25}$ s $\ll 10^{-23}$ s
- Top decays (almost exclusively) through $t \to bW$

  $BR(t \to sW) \leq 0.18\%$, $BR(t \to dW) \leq 0.02\%$
- The measurement of the top quark properties provides a powerful test of the SM
- Top quark has often a special role in new physics models

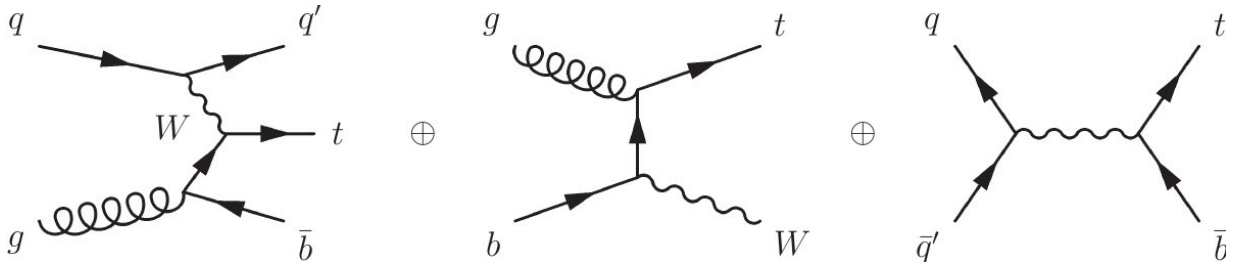
Top quark production at the LHC

- LHC is a top factory

pair production:



single production:

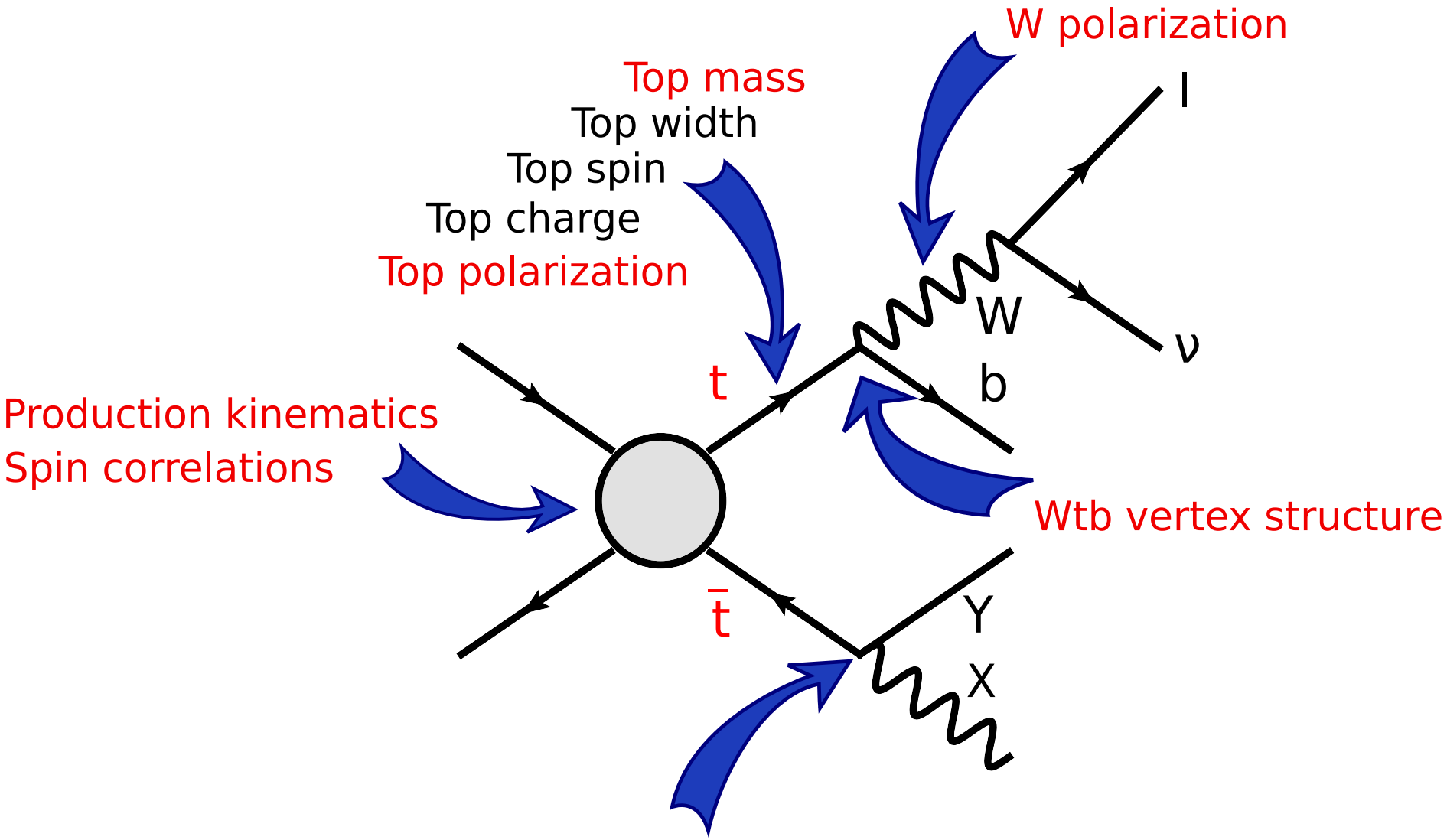


☞ pair production is dominant:

$\sim$10M ($\sim$2M) $t\bar{t}$ events produced at ATLAS and CMS at $\sqrt{s} = 8$ (7) TeV
$\sim$5M ($\sim$1M) single t events produced at ATLAS and CMS at $\sqrt{s} = 8$ (7) TeV

☞ *Top quark production at ATLAS and CMS* by Luca Lista

Measurement of the top quark properties in $t\bar{t}$ events



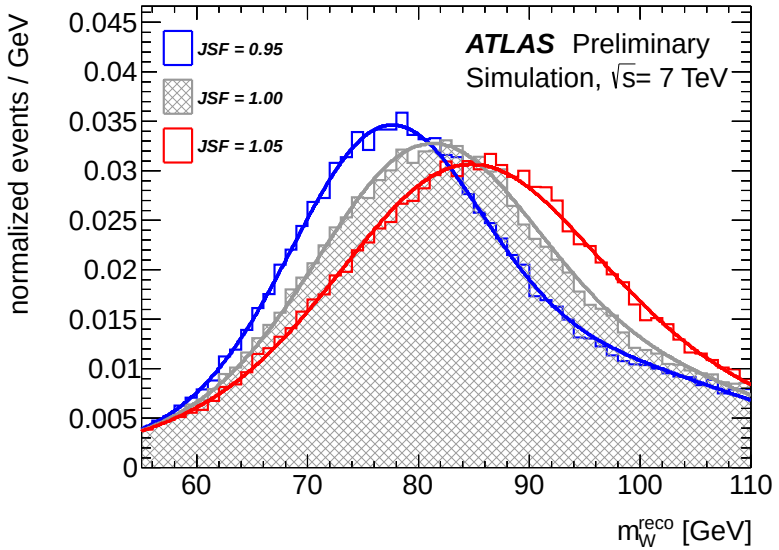
Top mass: in ℓ+jets channel

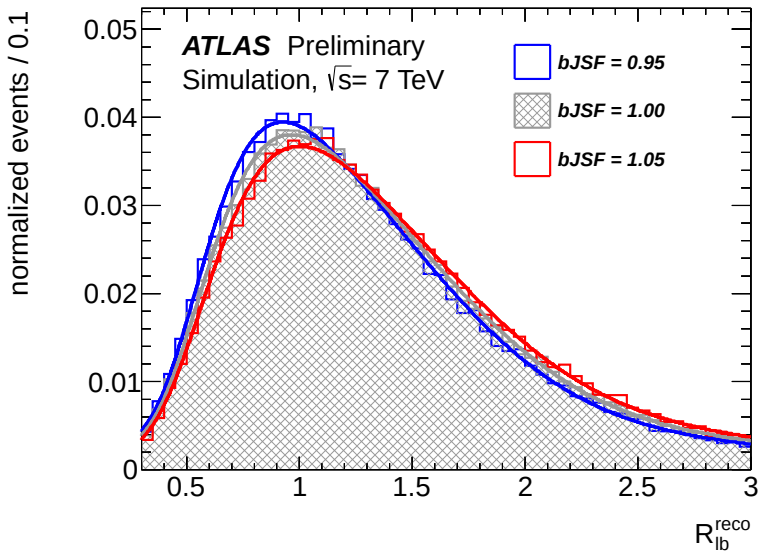
[ATLAS-CONF-2013-046]

- $\sqrt{s} = 7$ TeV data ($\int Ldt = 4.7$ fb^{-1})
- Kinematic fit used to reconstruct $t\bar{t}$
- first m_t measurement with *in-situ* b-quark JES calibration
- Fit simultaneously m_t, m_W^{had} and

$$R_{\ell b}^{\mathrm{reco}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet1}}} + p_{\mathrm{T}}^{W_{\mathrm{jet2}}}}$$

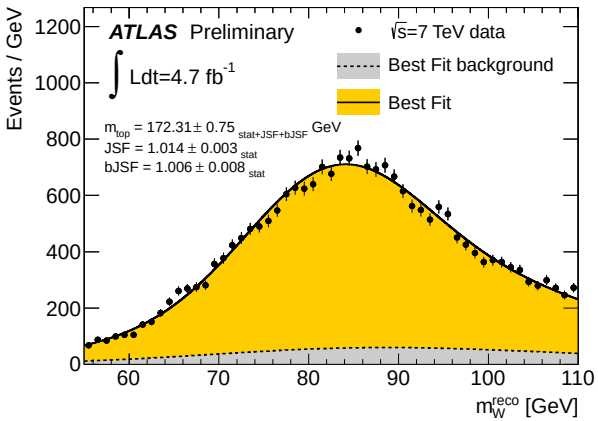
- m_W^{had} used to constrain the overall jet scale factor (JSF)
- $R_{\ell b}^{\mathrm{reco}}$ used to constrain the overall ratio of b to light-parton jet energy scale factor (bJSF)

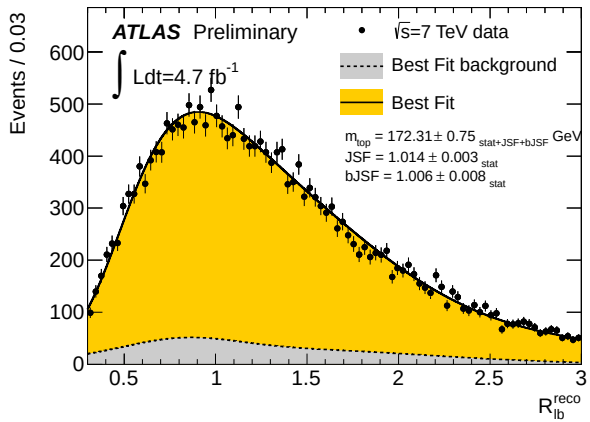


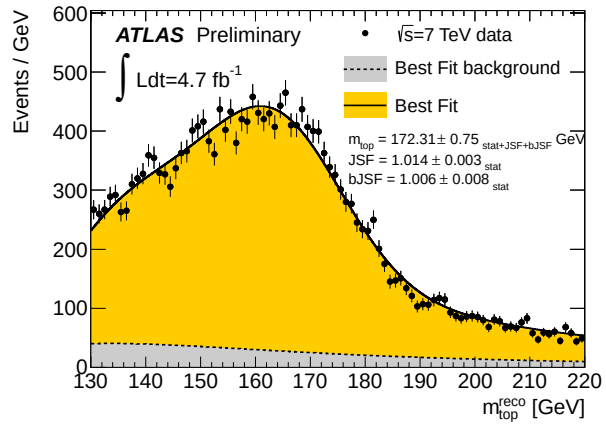


Top mass: in ℓ+jets channel

[ATLAS-CONF-2013-046]







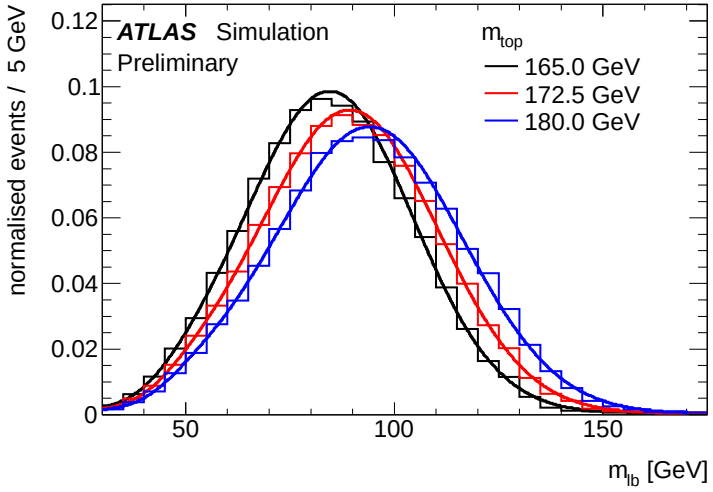
$m_t = 172.31 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35\ (\text{syst})$ GeV

dominant systematics: bJSF (stat), residual JES, *b*-tagging, $t\bar{t}$ modelling

- CMS [JHEP 12 (2012) 105]:
  $\sqrt{s} = 7$ TeV data ($\int Ldt = 5$ fb^{-1})
  $m_t = 173.49 \pm 0.43\ (\text{stat.} + \text{JES}) \pm 0.98\ (\text{syst.})$ GeV
  dominant systematics: bJES, JSF, $t\bar{t}$ modelling

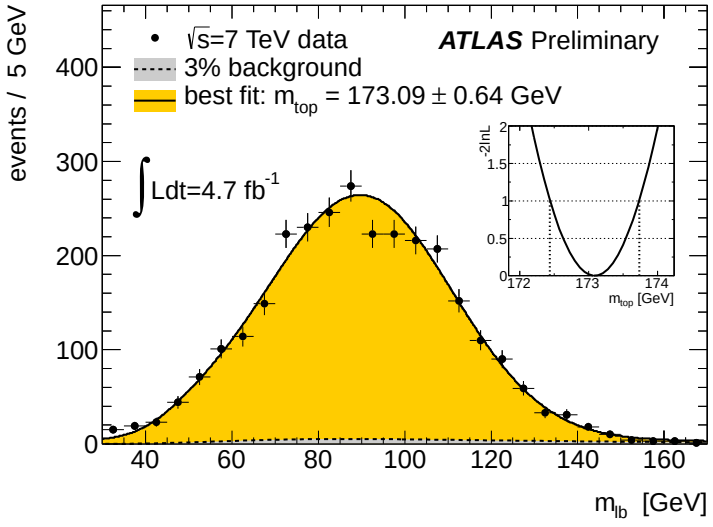
Top mass: dilepton channel

- [ATLAS-CONF-2013-077]
  - 1D template method:
    $m_{\ell b}$ as estimator for m_t
    ☞ lowest average $m_{\ell b}$ used
  - $\geq$ 2 b-tagged jets
    almost background free sample
    ($<$ 3% single top)



$m_t = 173.09 \pm 0.64\ (\text{stat}) \pm 1.50\ (\text{syst})$ GeV

dominant systematics: bJES, JES,
$t\bar{t}$ modelling, b-tag



- CMS [EPJ C72 (2012) 2202]

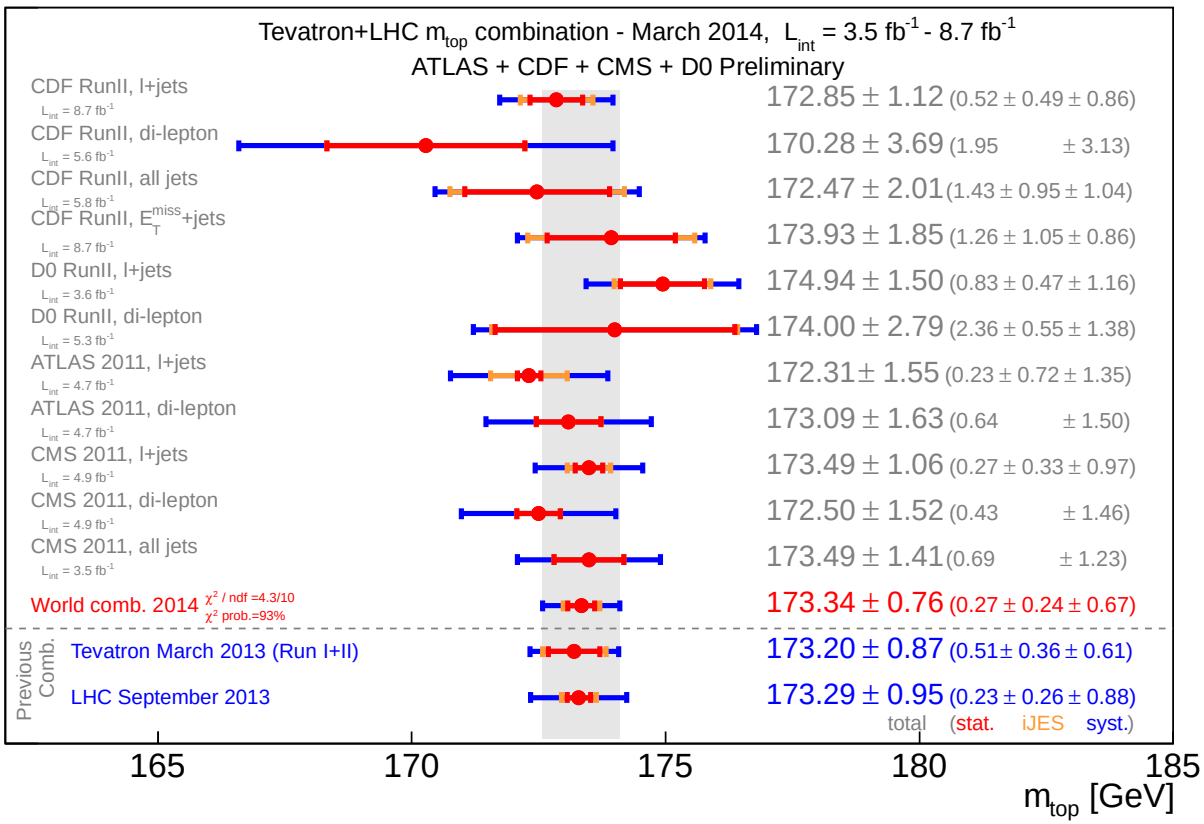
  $m_t = 172.5 \pm 0.4\ (\text{stat}) \pm 1.5\ (\text{syst})$ GeV

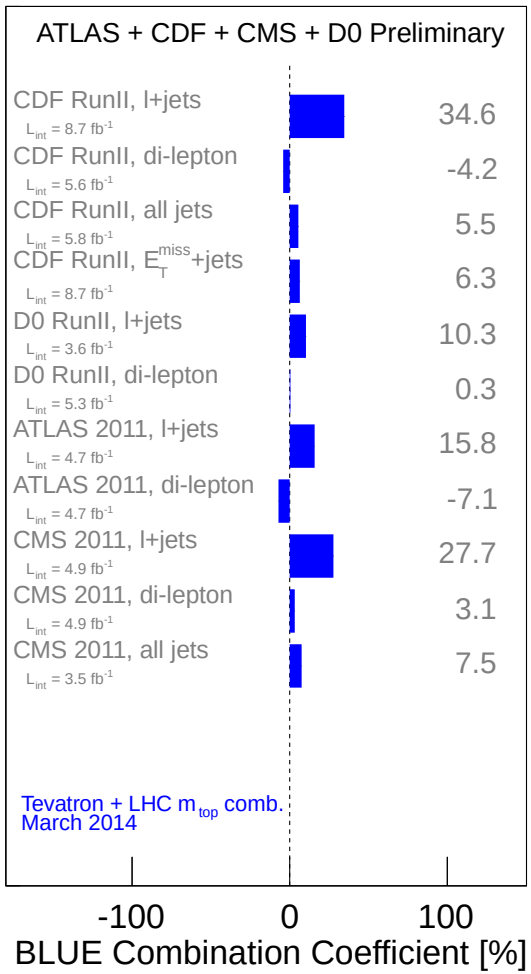
  dominant systematics: bJES, JES, renor./fact. scales

Top mass: LHC/Tevatron combination

[ATLAS-CONF-2014-008 / CDF note 11071 / CMS PAS TOP-13-014 / D0 note 6416]

- Combination done with BLUE ($\chi^2/\mathrm{ndf} = 4.3/10$)
- Stability checks performed





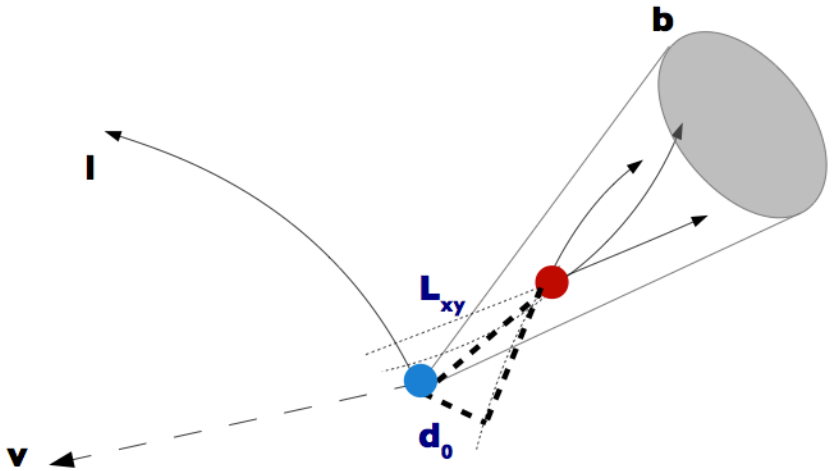
[arXiv:1403.4427]

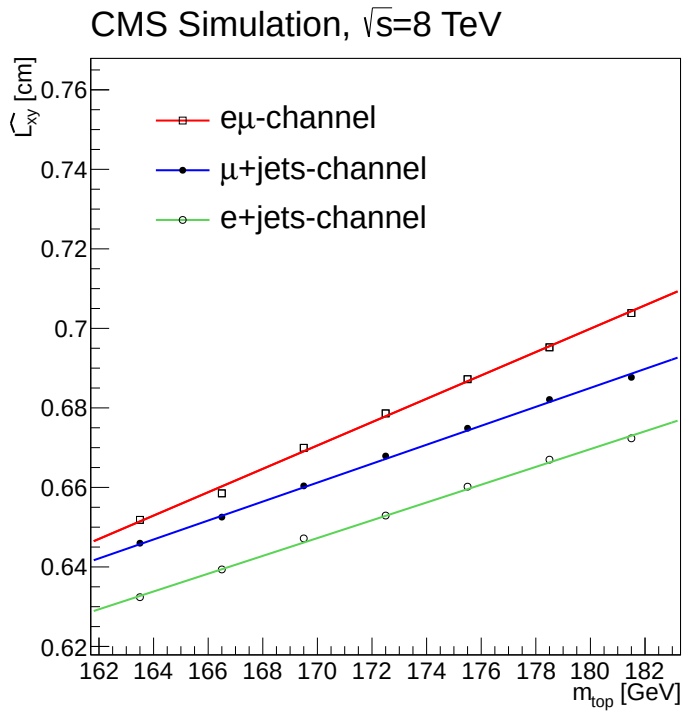
☞ Ongoing efforts to harmonise the treatment of the systematic uncertainties

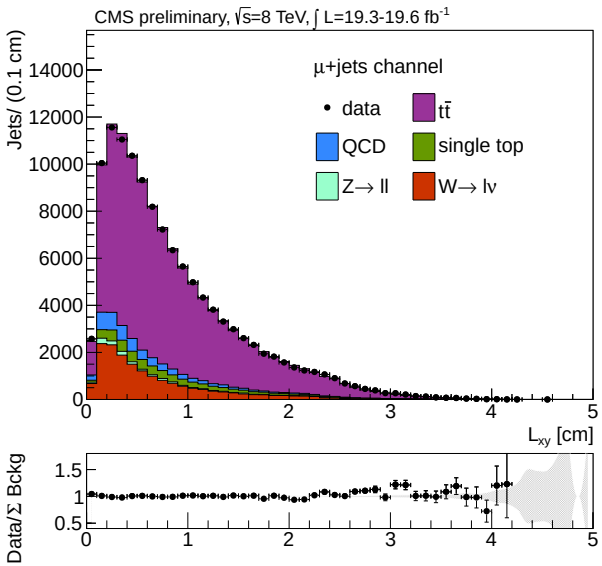
Top mass from the *B*-hadron lifetime

[CMS PAS TOP-12-030]

- transverse decay length (L_{xy}) of *B*-hadrons in $t\bar{t}$ events has a linear dependence with m_t:





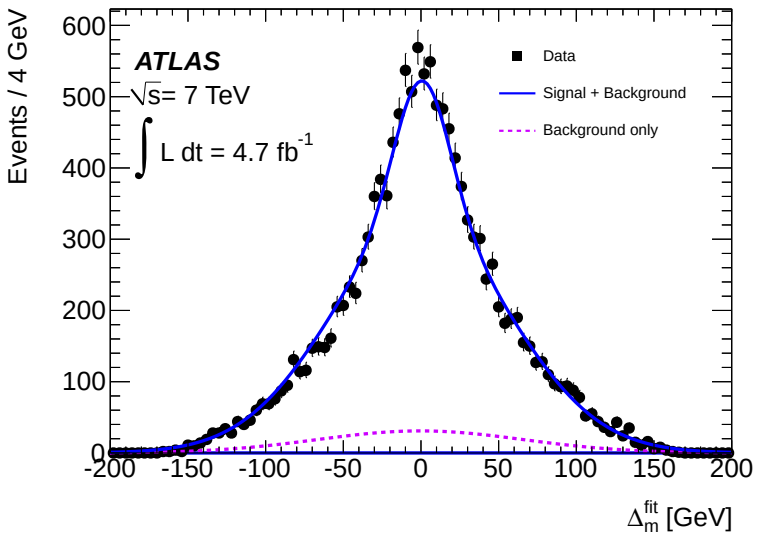


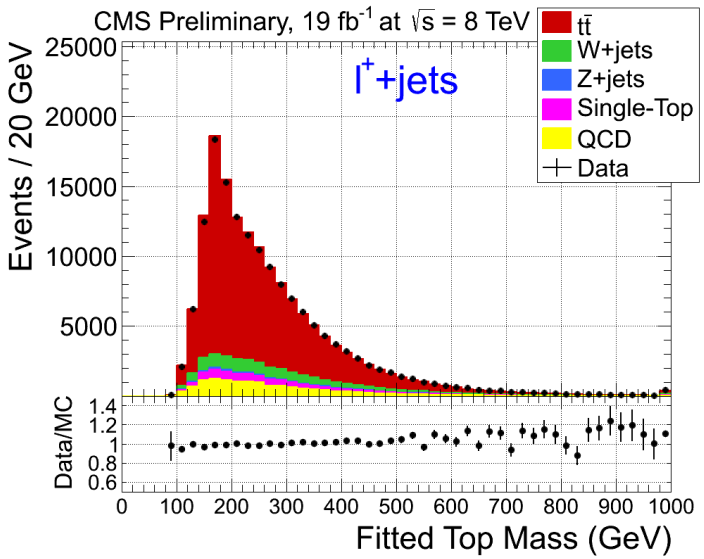
Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

$t/\bar{t}$ mass difference

[PLB 728C (2014) 363, CMS PAS TOP-12-031]

- ℓ+jets topology w/ $\geq$1 (CMS) or $\geq$2 (ATLAS) b-tagged jets
- Kinematic χ^2 (ATLAS) and a likelihood fit (CMS) used to determine t and $\bar{t}$ masses





ATLAS: $m_t - m_{\bar{t}} = 0.67 \pm 0.61\ (\text{stat}) \pm 0.41\ (\text{syst})$ GeV

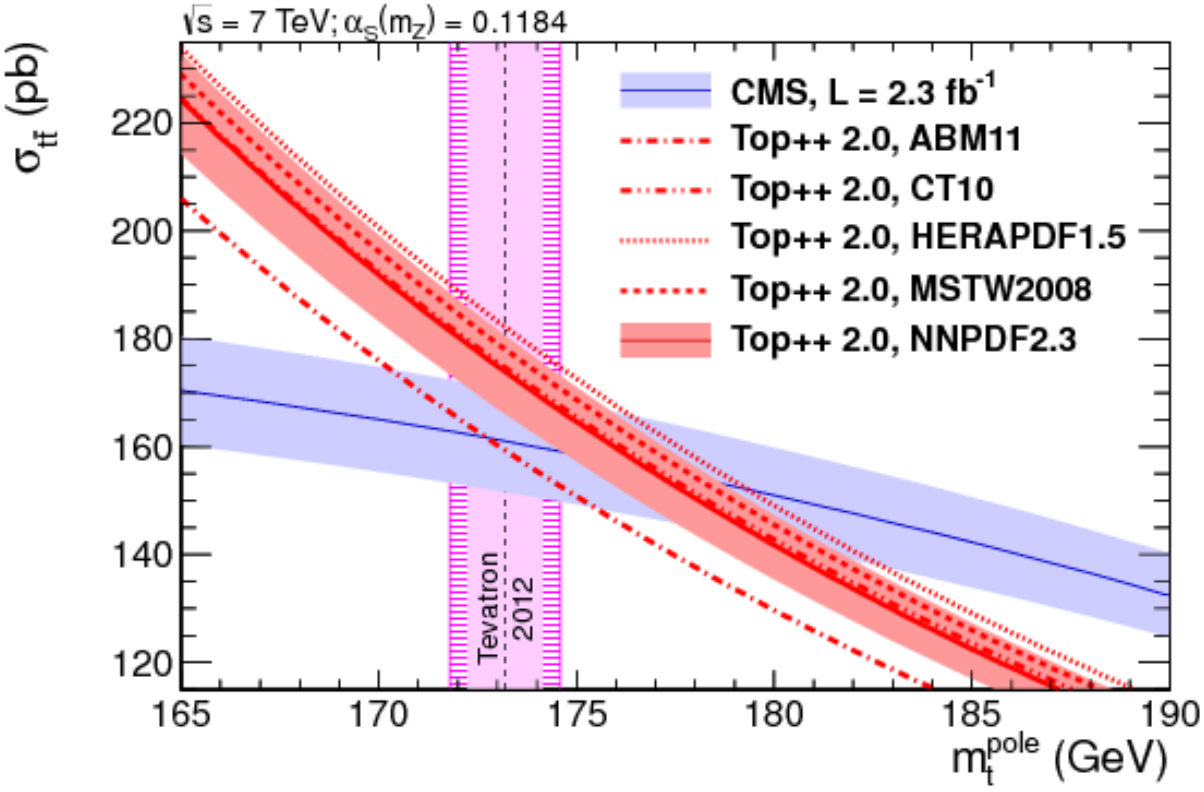
CMS: $m_t - m_{\bar{t}} = 0.272 \pm 0.196\ (\text{stat}) \pm 0.122\ (\text{syst})$ GeV

dominant uncertainties: choice of b fragmentation model (ATLAS: 0.34 GeV) and $b/\bar{b}$-jet response (CMS: 0.06 GeV; ATLAS: 0.08 GeV)

Top mass from the $t\bar{t}$ production cross-section

[PLB 728 (2013) 496]

- The mass dependence of the QCD prediction for $\sigma_{t\bar{t}}$ can be used to determine the pole mass
- NNLO prediction for $\sigma_{t\bar{t}}$ from `top++`



$$m_t^{\text{pole}} = 176.7^{+3.8}_{-3.4}\ \text{GeV}$$

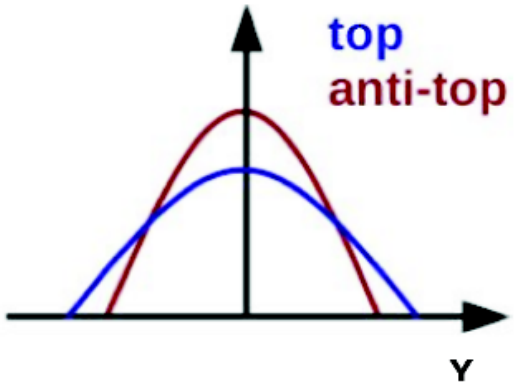
$t\bar{t}$ charge asymmetry

- In the SM at LO $t\bar{t}$ production is symmetric under charge conjugation

  ☞ at NLO (for $q\bar{q}$ and qg modes) there is a small preference to produce the t ($\bar{t}$) in the direction of the incoming q ($\bar{q}$)

  ☞ $A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$

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



- Lepton asymmetry can also be defined. In dilepton events:

  ☞ $A_C^{\ell\ell} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$

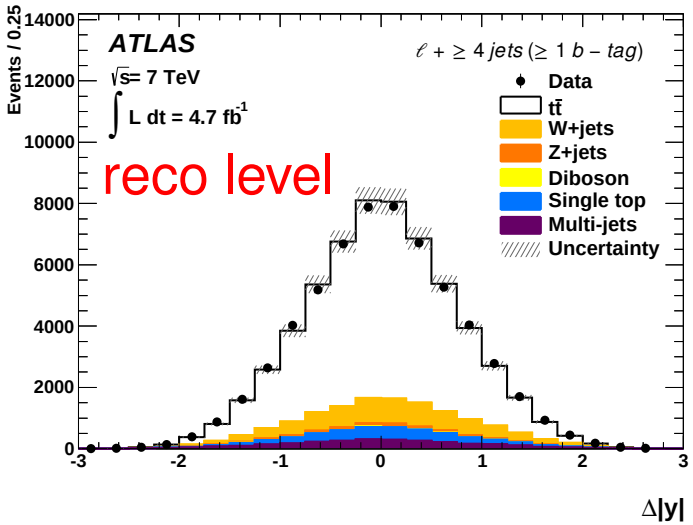
  $\Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$

	$\sqrt{s}$	topology	reference
ATLAS	7 TeV	ℓ+jets	JHEP02(2014)107
CMS	7 TeV	ℓ+jets	PLB717(2012)129
ATLAS	7 TeV	dileptonic	ATLAS-CONF-2012-057
CMS	7 TeV	dileptonic	arXiv:1402.3803
CMS	8 TeV	ℓ+jets	CMS PAS TOP-12-033

$t\bar{t}$ charge asymmetry (ℓ+jets)

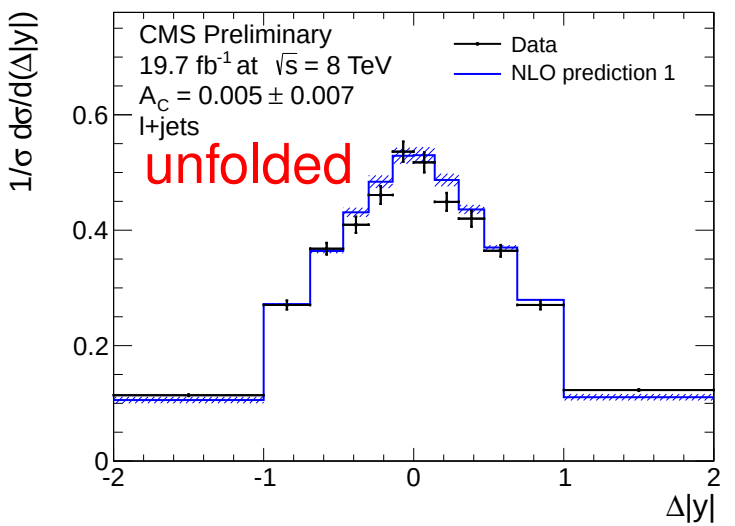
- Full reconstruction of the $t\bar{t}$ system
- Unfolding of the $\Delta|y|$ distribution
- ATLAS ($\sqrt{s} = 7$ TeV):

A_C	Data	Theory
Unfolded	0.006±0.010	0.0123±0.0005
Unfolded with $m_{t\bar{t}} > 600$ GeV	0.018±0.022	$0.0175^{+0.005}_{-0.004}$
Unfolded with $\beta_{z,t\bar{t}} > 0.6$	0.011±0.018	$0.0202^{+0.006}_{-0.007}$



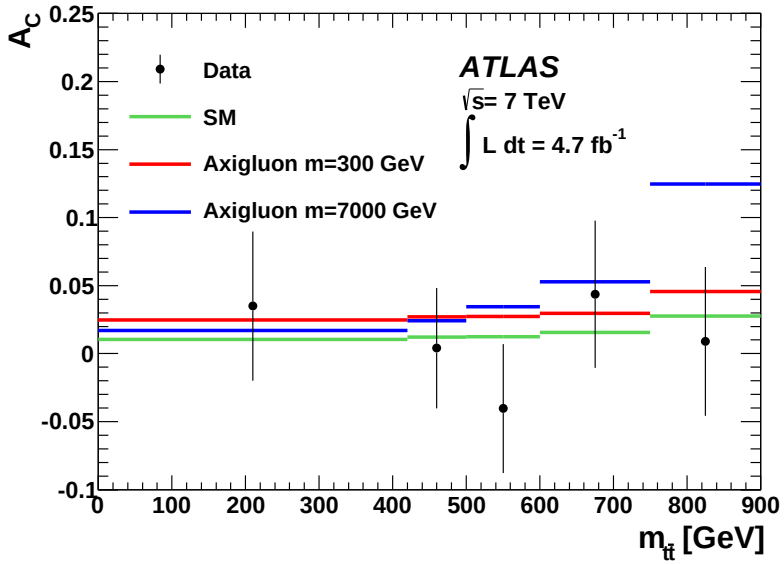
- CMS ($\sqrt{s} = 8$ TeV):

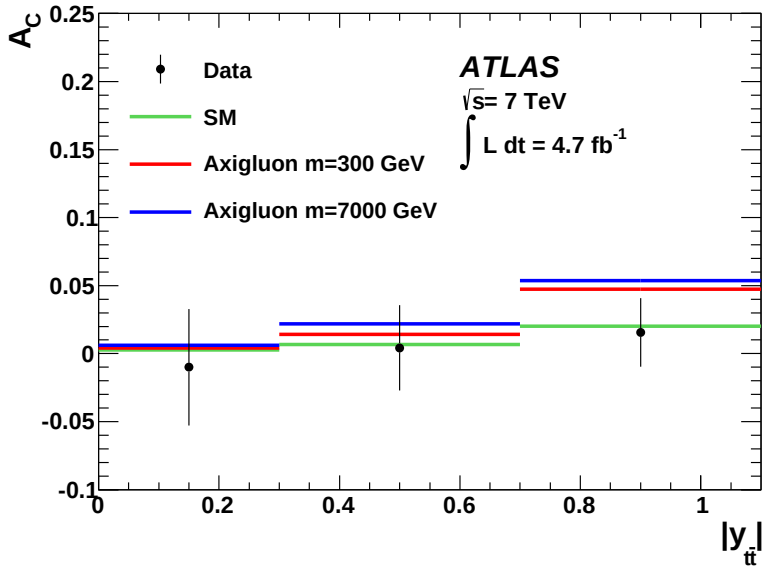
Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)

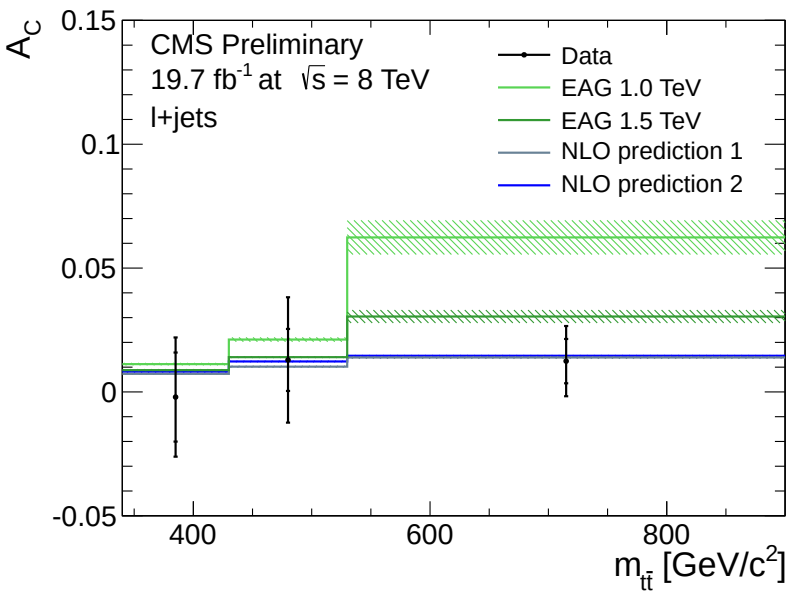


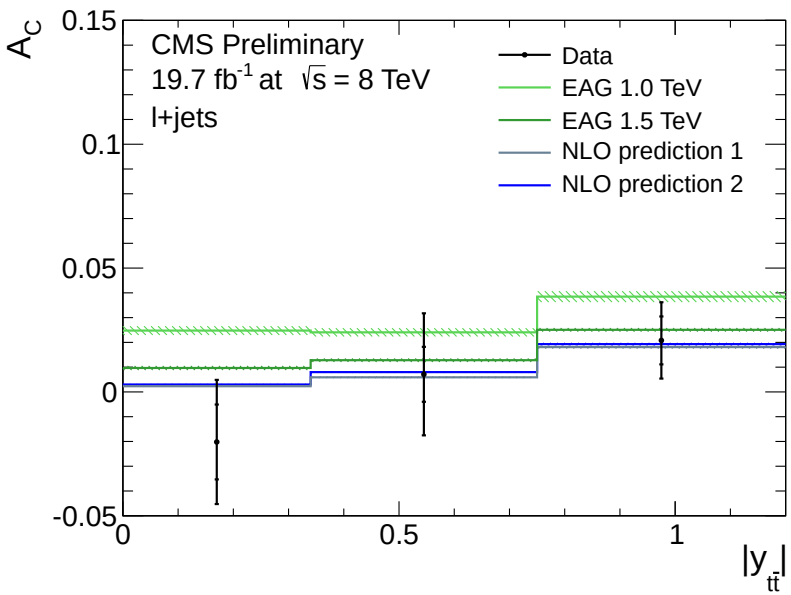
$t\bar{t}$ charge asymmetry (ℓ+jets)

- New physics might be more visible in differential distributions:





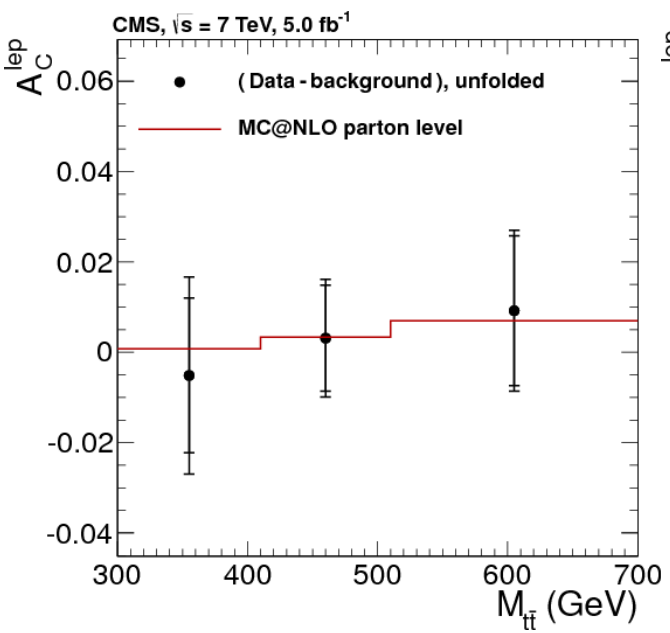


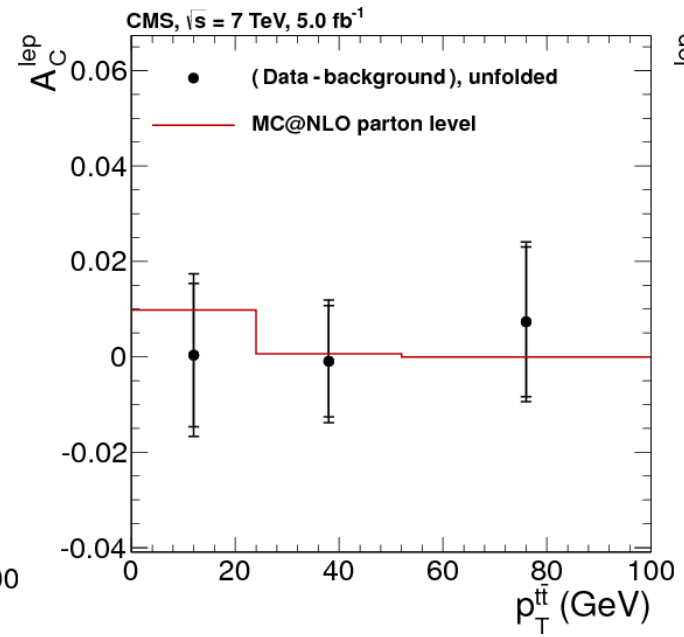


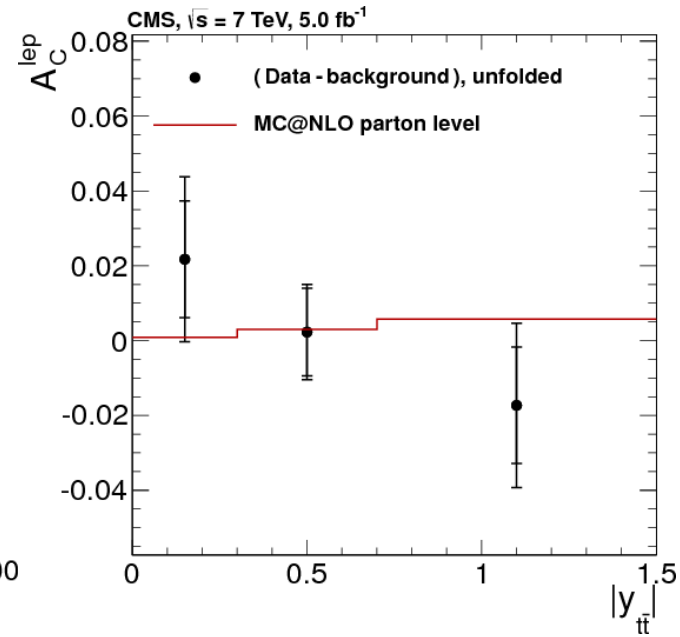
$t\bar{t}$ charge asymmetry (dileptons)

- Dilepton events: lepton asymmetry can be measured

ATLAS	$A_C^{\ell\ell} = 0.023 \pm 0.012\ (\text{stat.}) \pm 0.008\ (\text{syst.})$
CMS	$A_C^{\ell\ell} = 0.009 \pm 0.010\ (\text{stat.}) \pm 0.006\ (\text{syst.})$
SM (NLO)	$A_C^{\ell\ell} = 0.0070 \pm 0.0003$

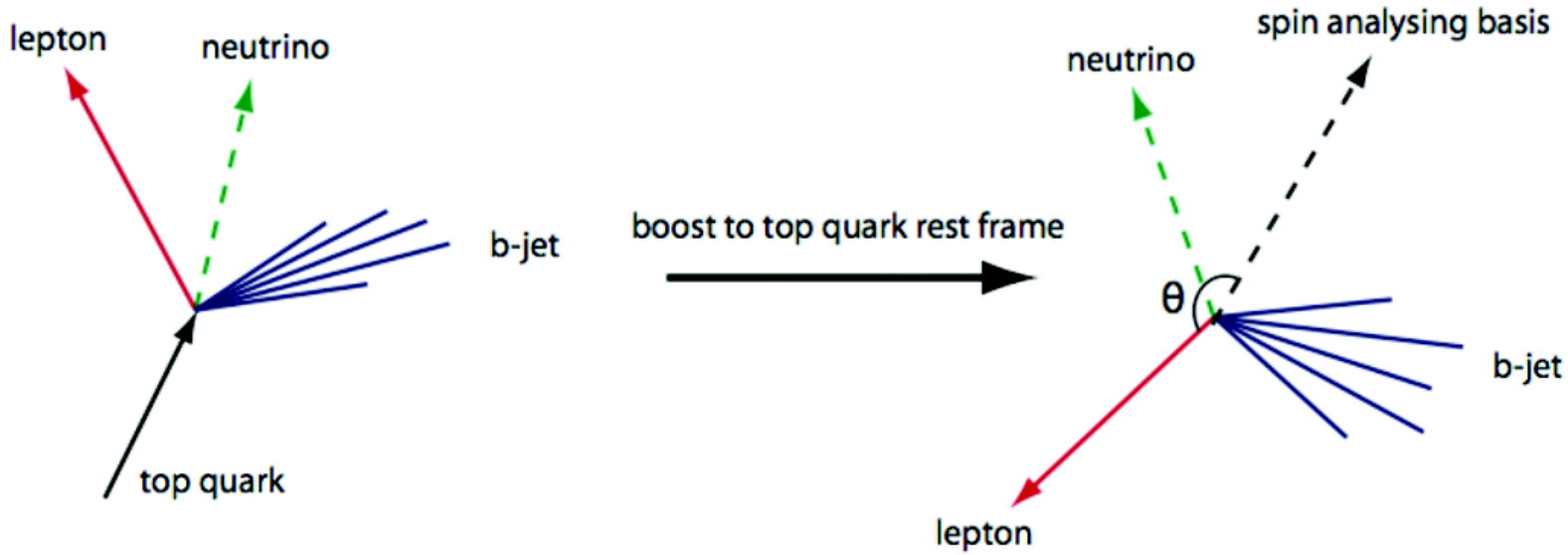






$t\bar{t}$ spin correlation

- t-quarks in $t\bar{t}$ events are produced (almost) unpolarized but their spins are correlated
- Different BSM scenarios predict different production and decay dynamics of the top quark, i.e. a different $t\bar{t}$ spin correlation



$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[cos(\theta_j)]} = \frac{1}{4}[P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

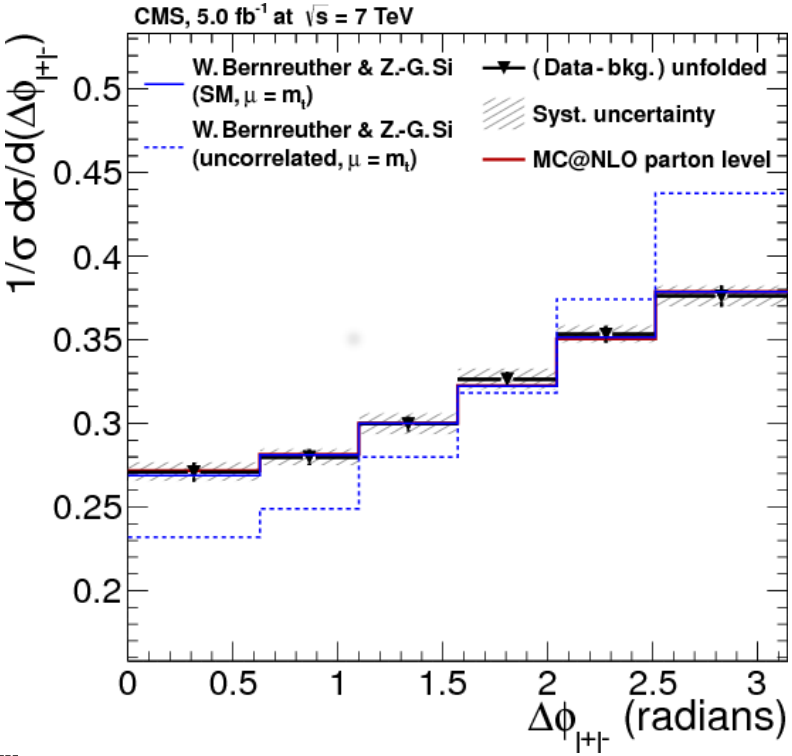
	b	ℓ	d	u
α (NLO)	-0.39	0.998	0.93	-0.31

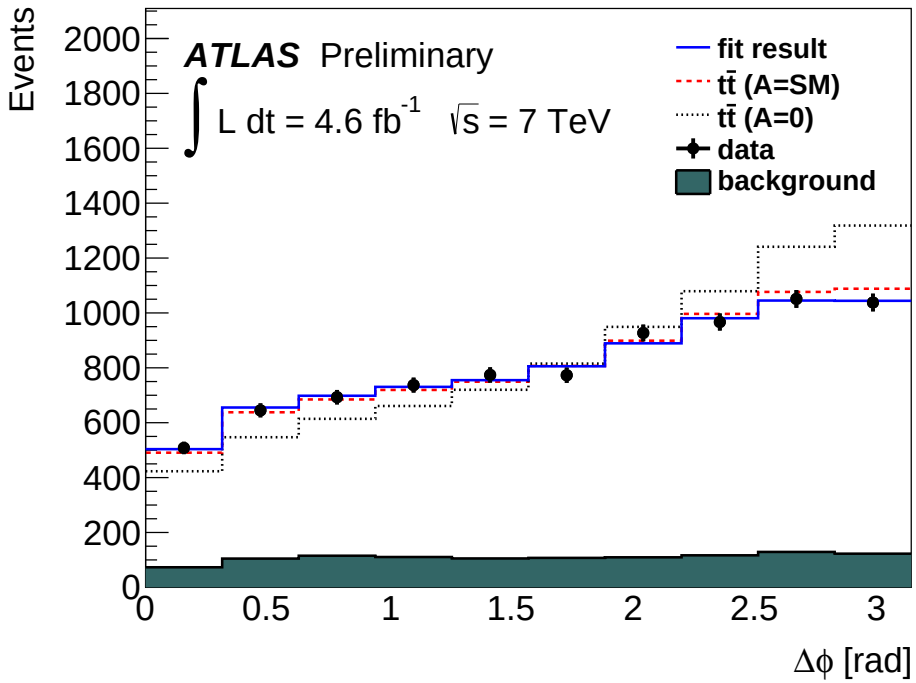
$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

$t\bar{t}$ spin correlation

[arXiv:1311.3924 (CMS), ATLAS-CONF-2013-101 (ATLAS)]

- ATLAS fits MC templates
- CMS unfolds the relevant distributions to parton level
  - $\Delta\phi$ between two spin analysers in lab frame is sensitive to spin correlations (*gg* production)

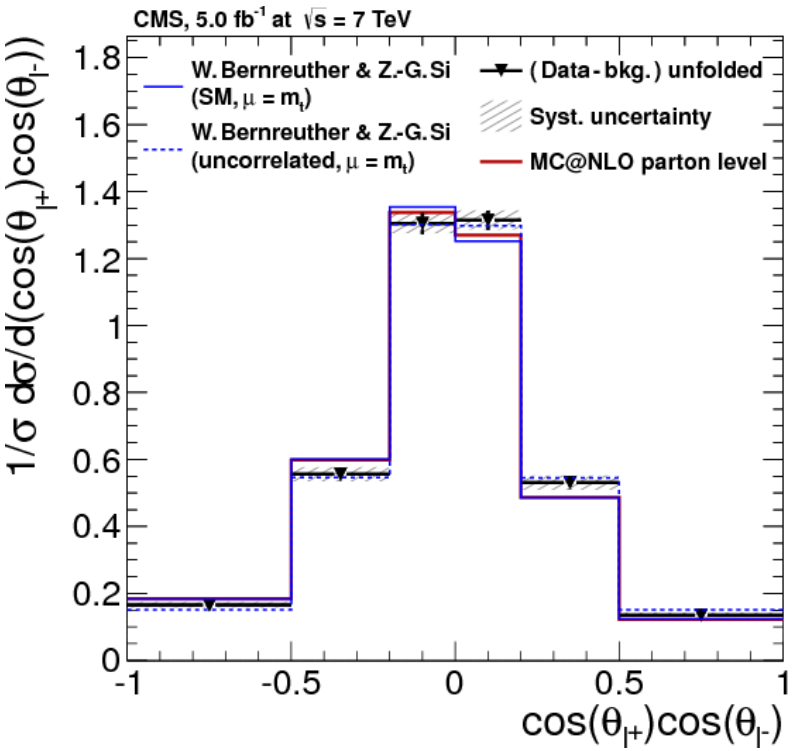


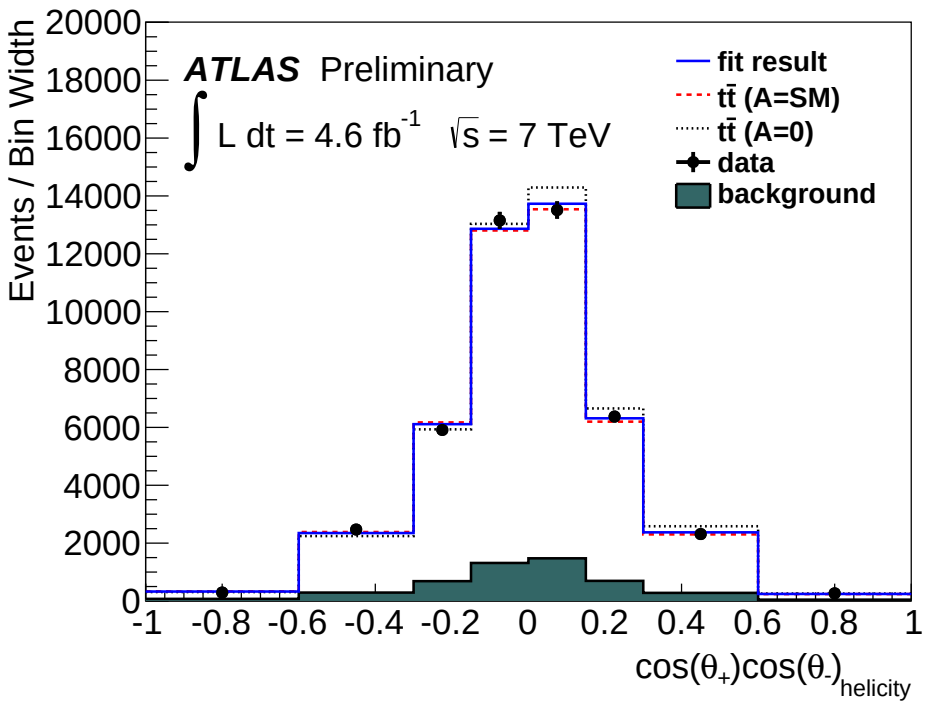


$t\bar{t}$ spin correlation

[arXiv:1311.3924 (CMS), ATLAS-CONF-2013-101 (ATLAS)]

- ATLAS fits MC templates
- CMS unfolds the relevant distributions to parton level
  - $\cos(\theta_i)\cos(\theta_j)$ probes A directly: $\alpha_i\alpha_j A = -9\langle\cos(\theta_i)\cos(\theta_j)\rangle$





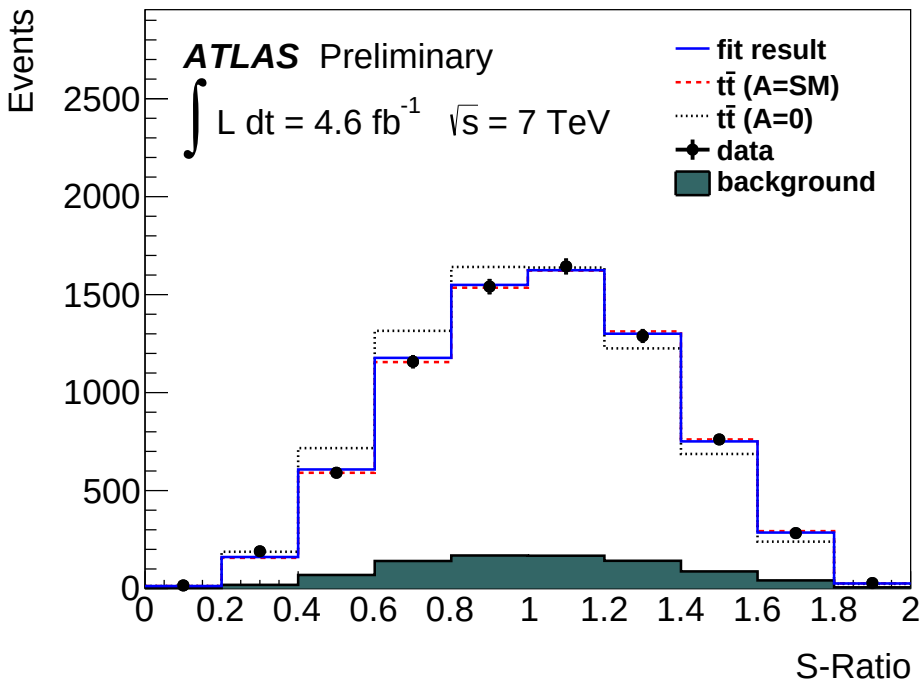
$t\bar{t}$ spin correlation

[ATLAS-CONF-2013-101]

☞ ATLAS fits MC templates

- *S*-ratio of ME from the fusion of like-helicity gluons with and without spin correlation (at LO, built from measured 4-momenta)

$$S = \frac{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{corr}}{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{uncorr}} = \frac{m_t^2\{(t \cdot l^+)(t \cdot l^-) + (\bar{t} \cdot l^+)(\bar{t} \cdot l^-) - m_t^2(l^+ \cdot l^-)\}}{(t \cdot l^+)(\bar{t} \cdot l^-)(t \cdot \bar{t})}$$



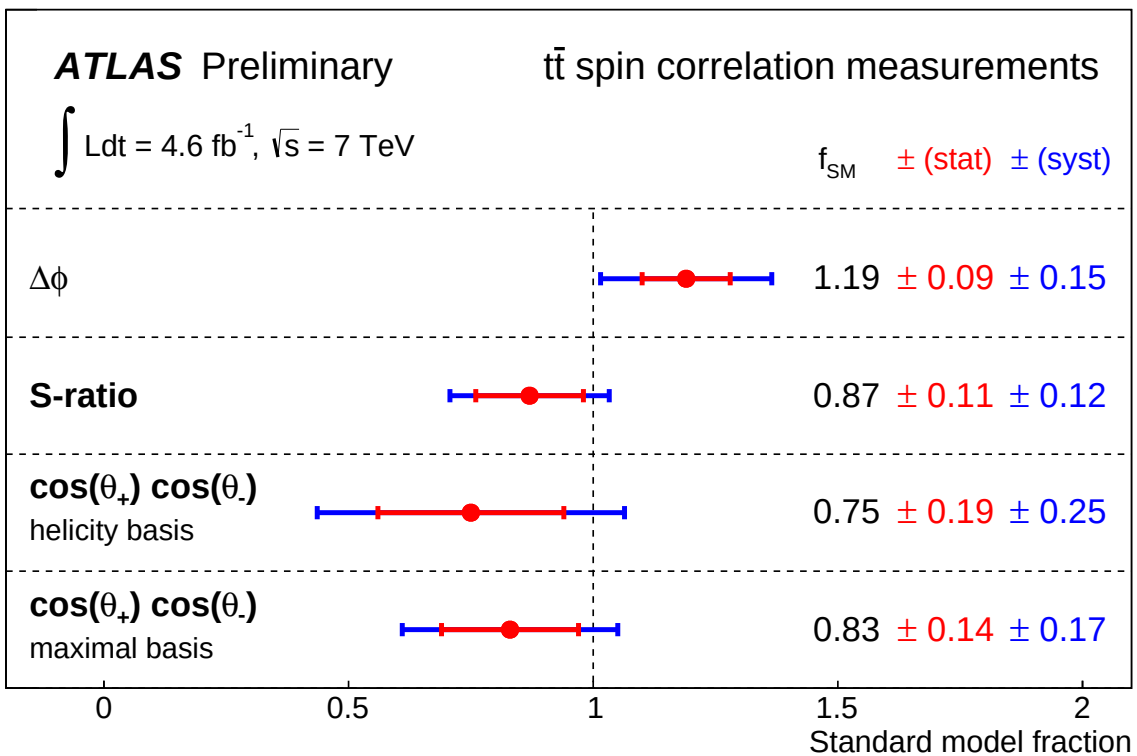
$t\bar{t}$ spin correlation

- CMS:

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)} \qquad A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)} \qquad C_{\mathrm{hel}} = -4A_{c_1c_2}$$

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.007 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.027 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0

- ATLAS:

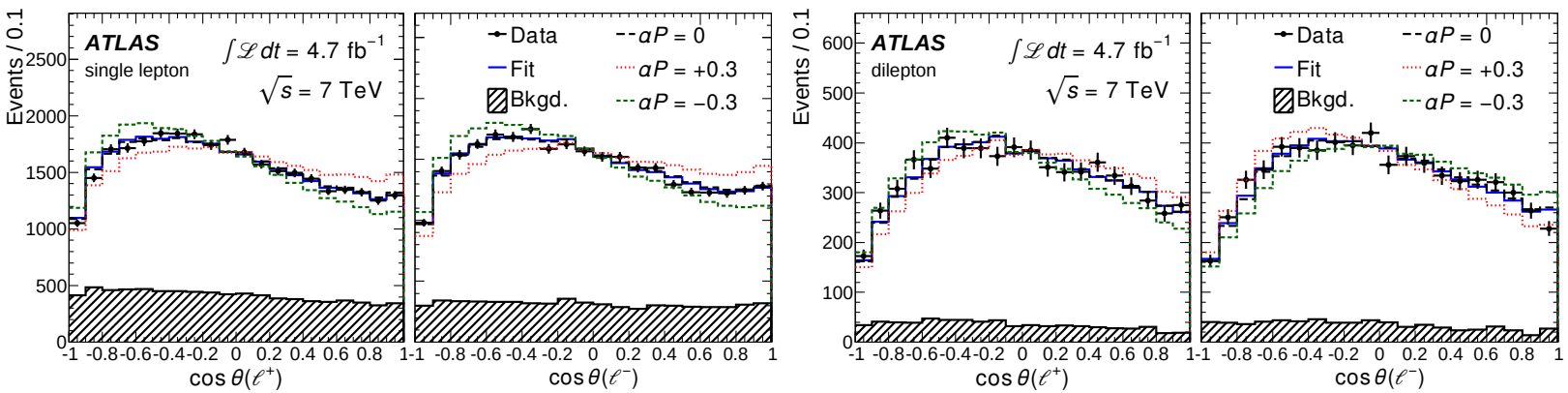


Top polarization in $t\bar{t}$ events

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

[PRL 111 (2013) 232002] $P_{\mathrm{SM}} = 0.003 \pm 0.001$ [PLB 725 (2013) 115]

- ℓ+jets (w/ *b*-tagging) and dilepton (wo/ *b*-tagging)
- Template fit to reconstruct $\cos\theta$
- Two hypotheses tested:
  - CP conserving (CPC): top and anti-top have the same P
  - CP violating (CPV): top and anti-top have opposite P



- $\alpha_\ell P_{\mathrm{CPC}} = -0.035 \pm 0.014\ (\mathrm{stat}) \pm 0.037\ (\mathrm{syst})$
  $\alpha_\ell P_{\mathrm{CPV}} = +0.020 \pm 0.016\ (\mathrm{stat})^{+0.013}_{-0.017}\ (\mathrm{syst})$

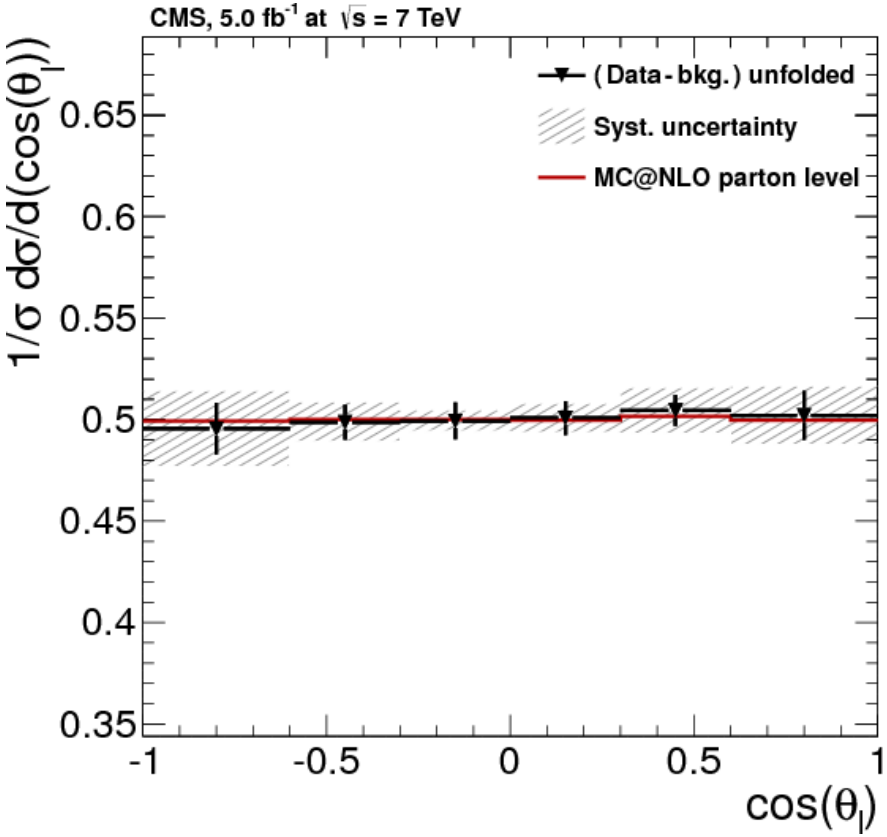
Top polarization in $t\bar{t}$ events

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[cos(\theta_j)]} = \frac{1}{4}[P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

[arXiv:1311.3924]

- Dilepton $t\bar{t}$ events
- $\cos\theta_\ell$ distribution unfolded to parton level
- $P = 2A_P$

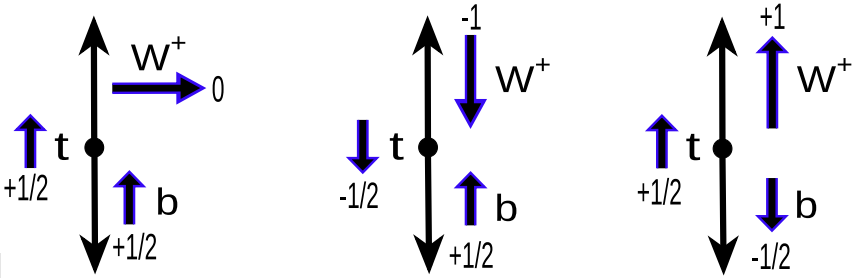
$$A_P = \frac{N(\cos\theta_\ell)>0 - N(\cos\theta_\ell)<0}{N(\cos\theta_\ell)>0 + N(\cos\theta_\ell)<0}$$



- $A_P = 0.005 \pm 0.013\ (\text{stat.}) \pm 0.020\ (\text{syst.}) \pm 0.008(p_{\text{T}}^t\ \text{reweig.})$

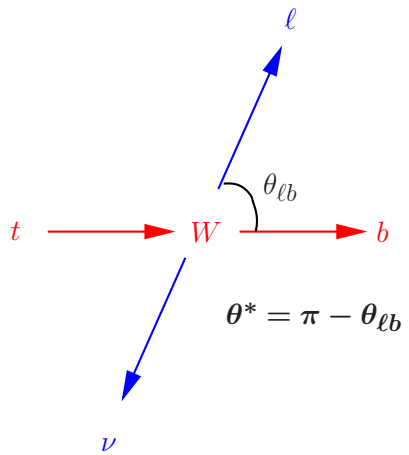
W polarization in $t \to bW$ decays

[PRD81 (2010) 111503]



longitudinal W — left-handed W — right-handed W

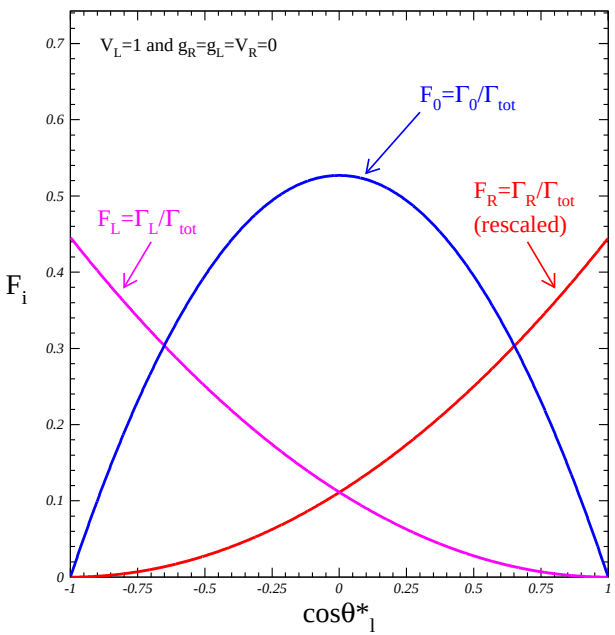
SM (NNLO): $F_0 = 0.687$ — $F_L = 0.311$ — $F_R = 0.0017$



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*}{2}\right)^2\right]$$

☞ fit of the $\cos\theta^*$ using templates

☞ BSM structure of the Wtb vertex changes W helicity fractions and angular asymmetries

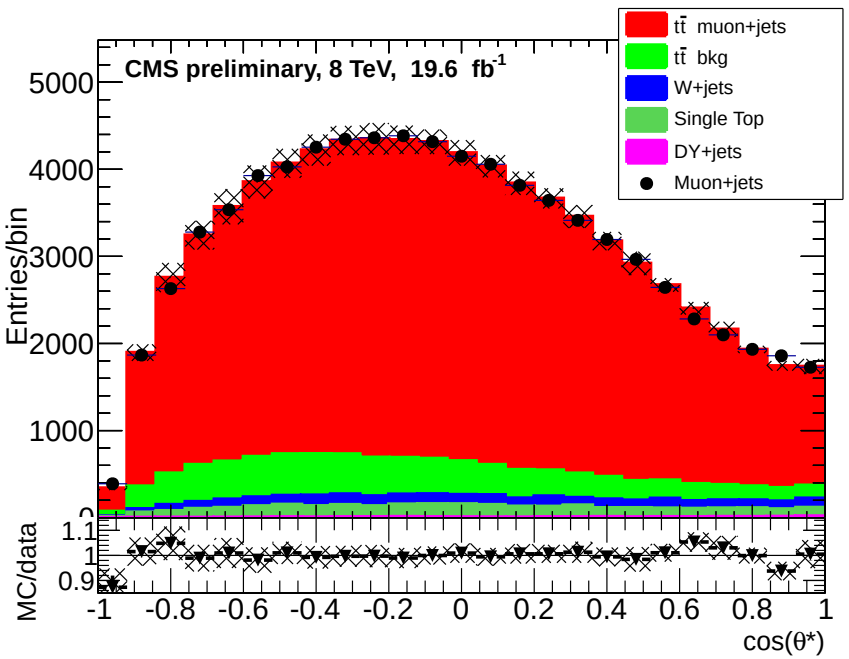


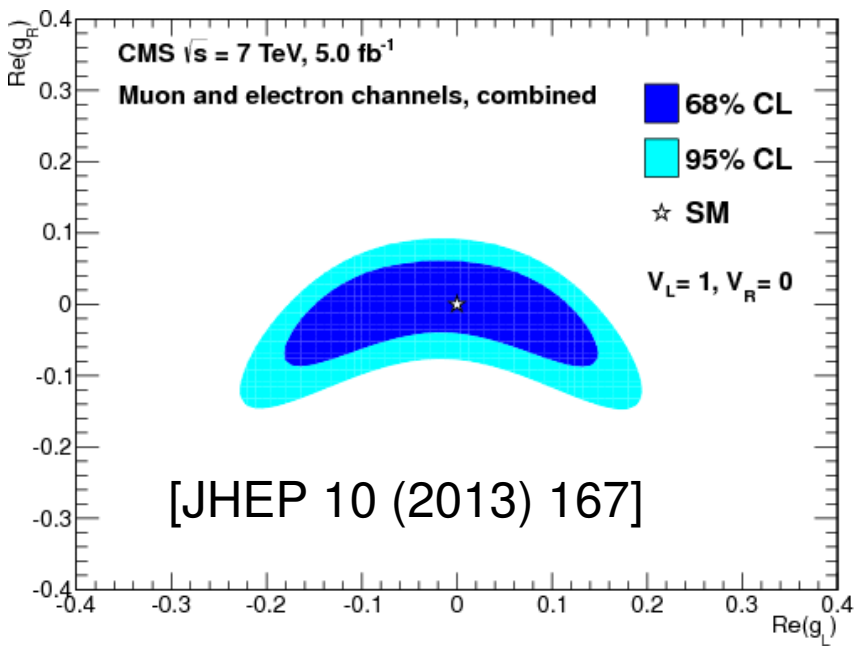
W polarization in $t \to bW$ decays

	CMS [CMS PAS TOP-13-008]	ATLAS [JHEP 1206 (2012) 088]
F_0	$0.659 \pm 0.015(\text{stat}) \pm 0.023(\text{syst})$	$0.67 \pm 0.03(\text{stat}) \pm 0.06(\text{syst})$
F_L	$0.350 \pm 0.010(\text{stat}) \pm 0.024(\text{syst})$	$0.32 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$
F_R	$-0.009 \pm 0.006(\text{stat}) \pm 0.020(\text{syst})$	$0.01 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$

dominant uncertainties: $t\bar{t}$ modelling (ATLAS+CMS), JES and template stat. (ATLAS)

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W^-_{\mu}$$





Summary

- Top quark physics has entered the precision era, testing many different properties
  - Several measurements dominated by the systematic uncertainties:
    - $t\bar{t}$ modelling
    - jet energy measurement
- Differential measurements starting
  - Still limited by statistical uncertainty
- No hint for physics beyond the SM observed so far
- Plenty of new results from 8 TeV run in preparation
  ☞ Stay tuned for news!

Backup Slides

Top mass from the 3D fit in the ℓ+jets channel

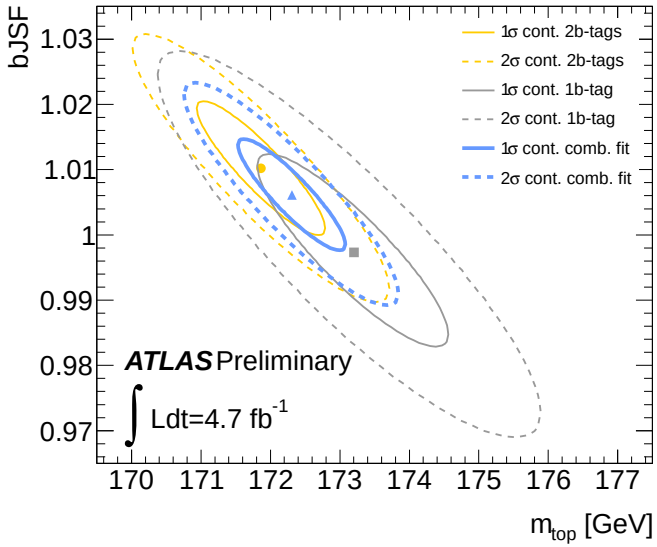
[ATLAS-CONF-2013-046]

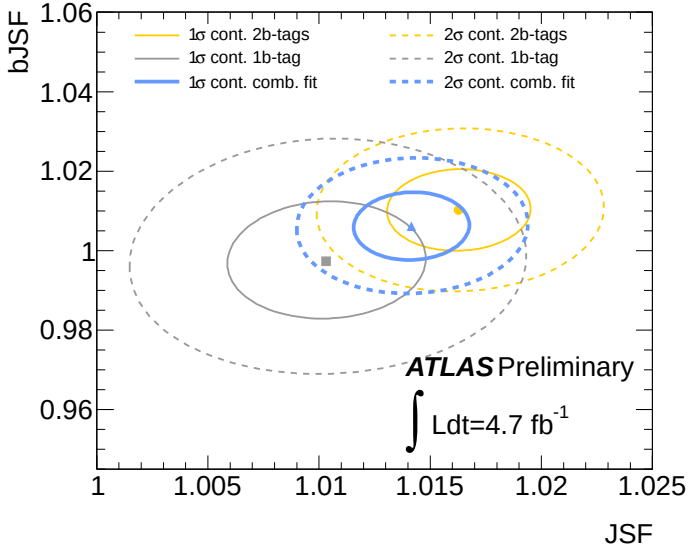
- Kinematic fit used to reconstruct $t\bar{t}$
- Fit simultaneously m_t, m_W^{had} and $R_{\ell b}^{\mathrm{reco}}$

$$R_{\ell b}^{\mathrm{reco,\ 2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet1}}} + p_{\mathrm{T}}^{W_{\mathrm{jet2}}}}$$

$$R_{\ell b}^{\mathrm{reco,\ 1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet1}}} + p_{\mathrm{T}}^{W_{\mathrm{jet2}}})/2}$$

- m_W^{had} used to constrain the overall jet scale factor (JSF)
- $R_{\ell b}^{\mathrm{reco}}$ used to constrain the overall ratio of b to light-parton jet energy scale factor (bJSF)

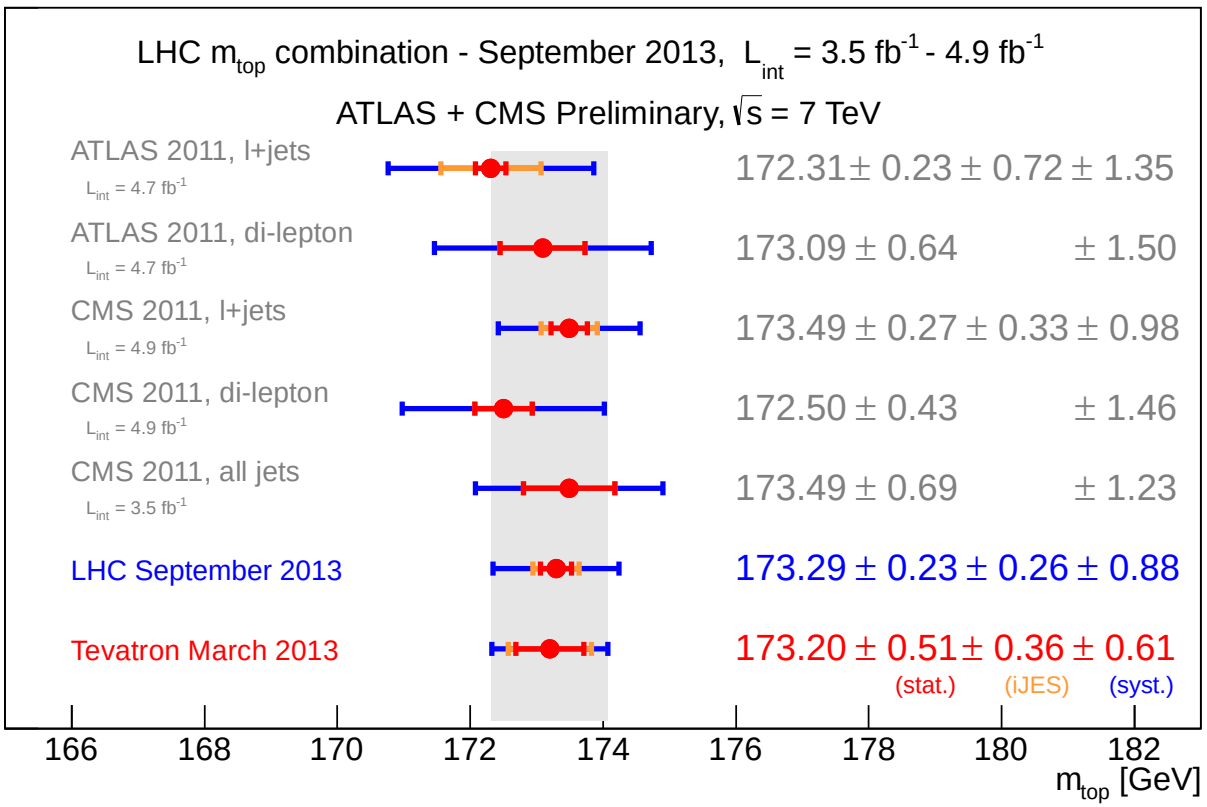


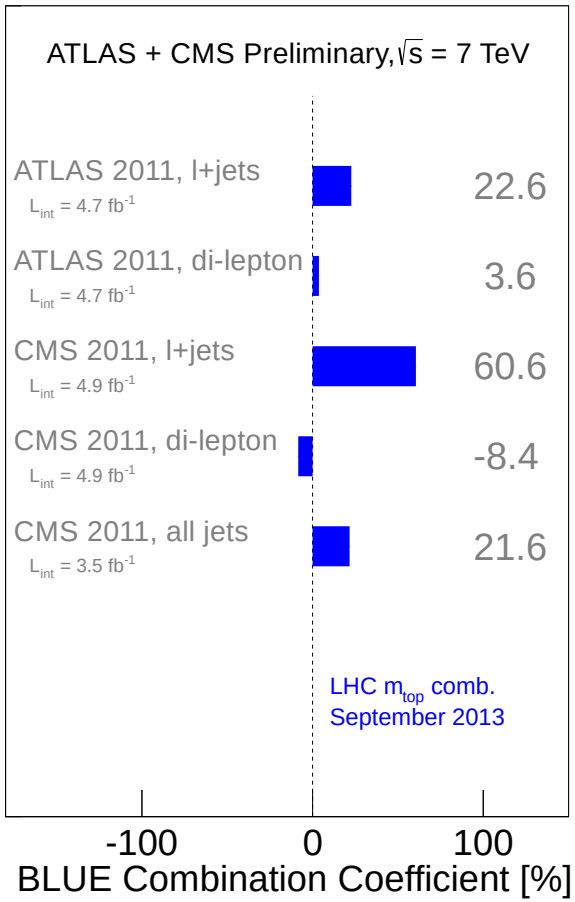


Top mass: LHC combination

TOPLHCWG [ATLAS-CONF-2013-102 / CMS PAS TOP-13-005]

- Combination done with BLUE ($\chi^2/\mathrm{ndf} = 1.8/4$)
- Stability checks performed

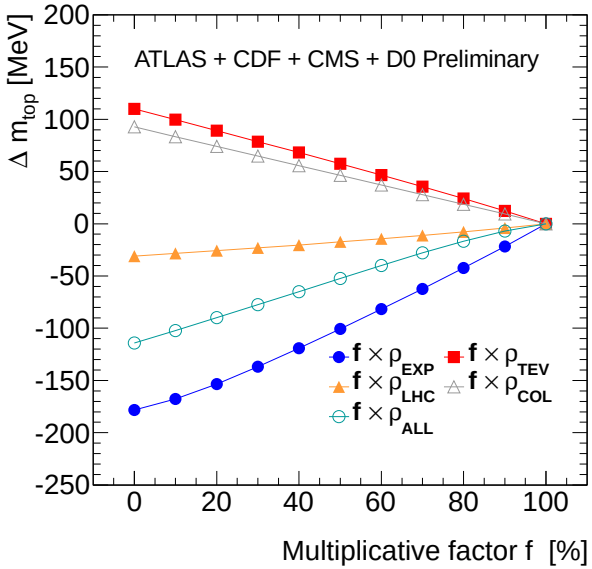


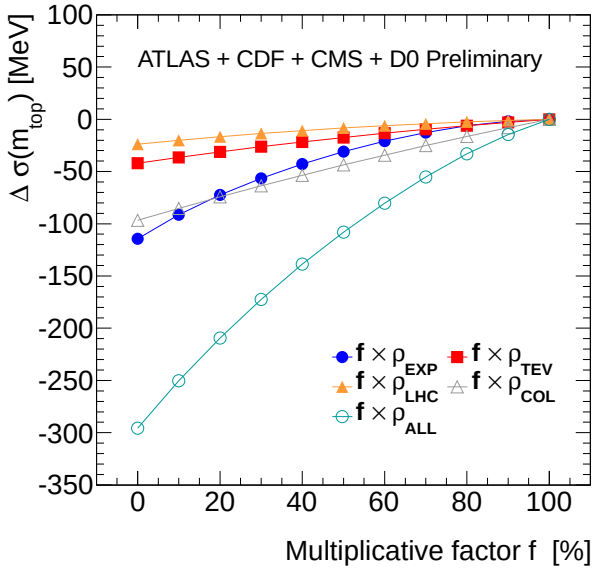


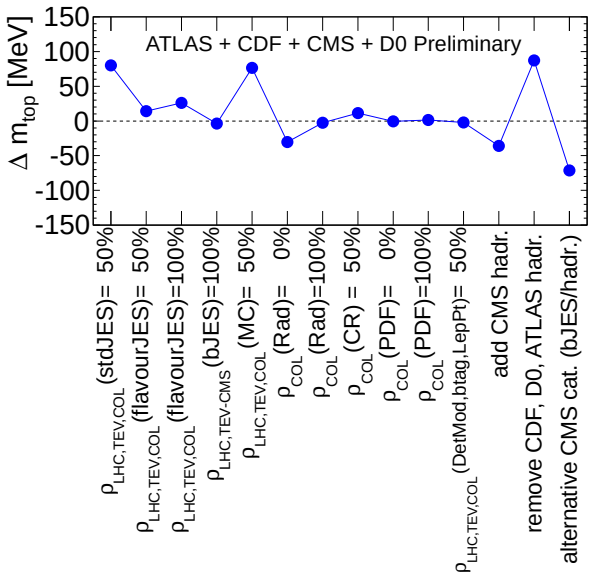
☞ Ongoing efforts to harmonise the treatment of the systematic uncertainties

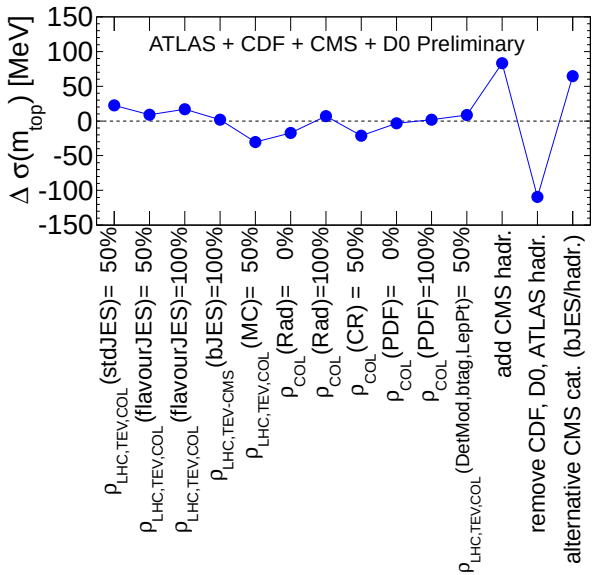
Top mass: LHC/Tevatron combination

[ATLAS-CONF-2014-008 / CDF note 11071 / CMS PAS TOP-13-014 / D0 note 6416]





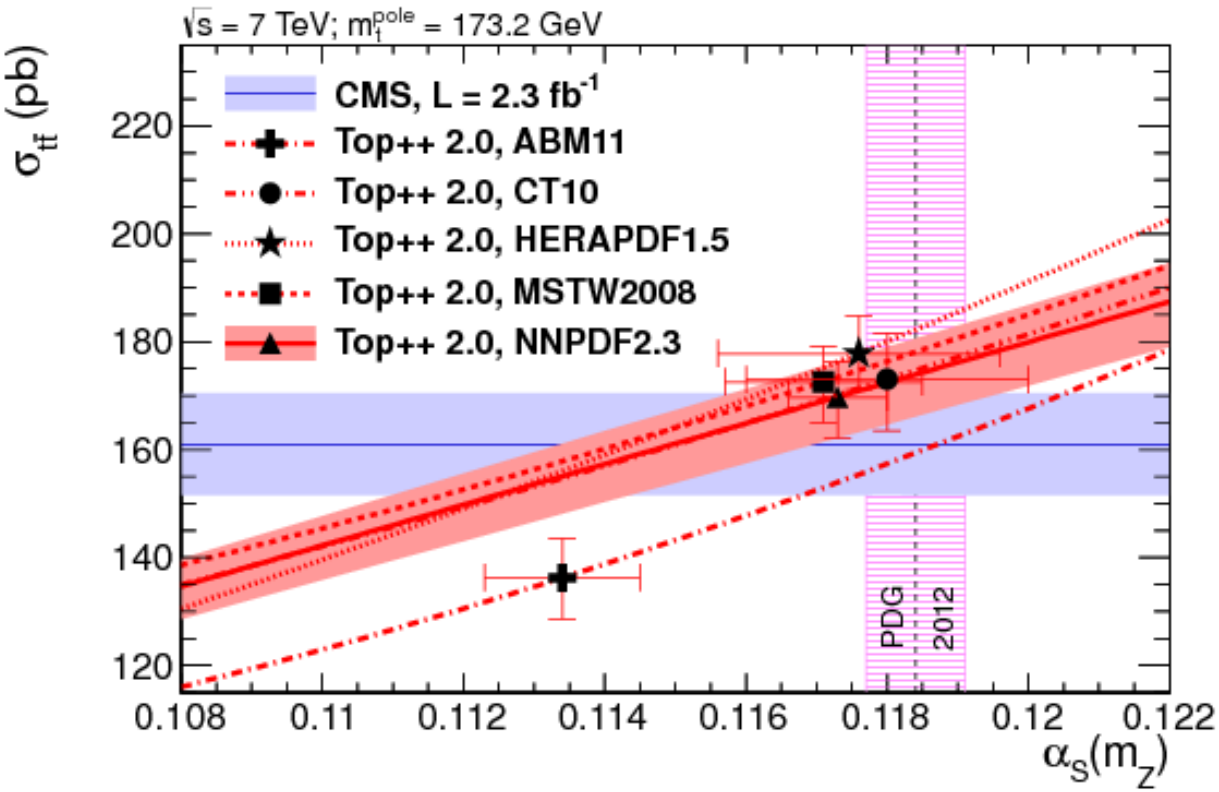




Top mass from the $t\bar{t}$ production cross-section

[PLB 728 (2013) 496]

- The mass dependence of the QCD prediction for $\sigma_{t\bar{t}}$ can be used to determine the pole mass
- NNLO prediction for $\sigma_{t\bar{t}}$ from `top++`

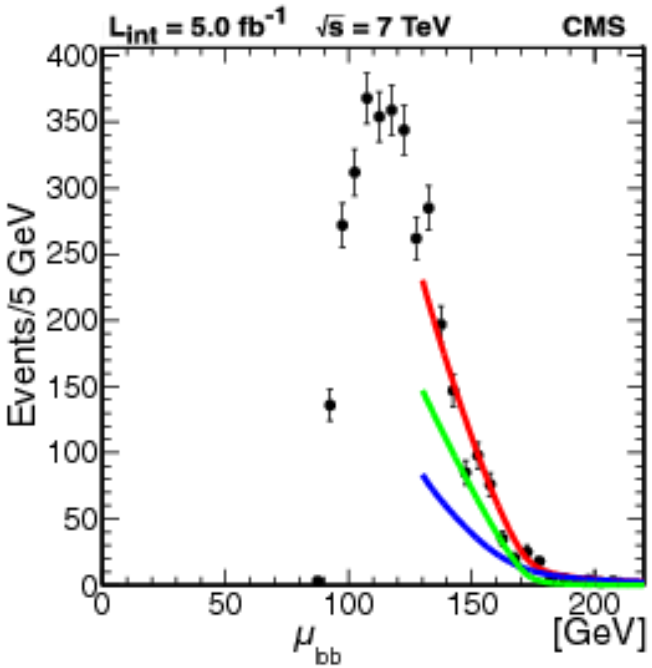


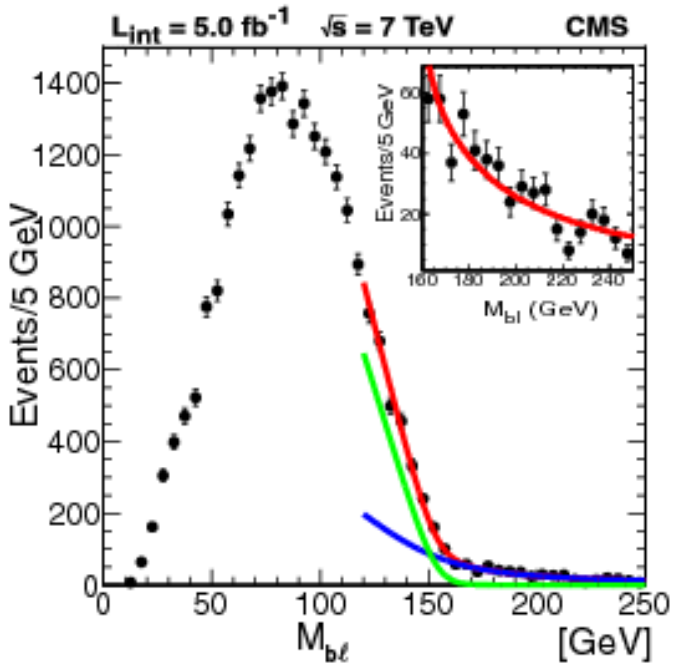
$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

Top mass from kinematic endpoints

[EPJ C73 (2013) 2494]

- Dilepton events ($e^+e^-, \mu^+\mu^-$) with ≥ 2 b-tagged jets
- m_t sensitive to the kinematic endpoints (transverse masses)
  $M_{\mathrm{T}}^2 = m_a^2 + M_a^2 + 2(E_{\mathrm{T}}^a E_{\mathrm{T}}^b - \boldsymbol{p}_{\mathrm{T}}^a \boldsymbol{p}_{\mathrm{T}}^b)$, $M_{\mathrm{T2}} = \min_{\boldsymbol{p}_{\mathrm{T}}^a + \boldsymbol{p}_{\mathrm{T}}^b} \left(\max(M_{\mathrm{T}}^a, M_{\mathrm{T}}^b)\right)$





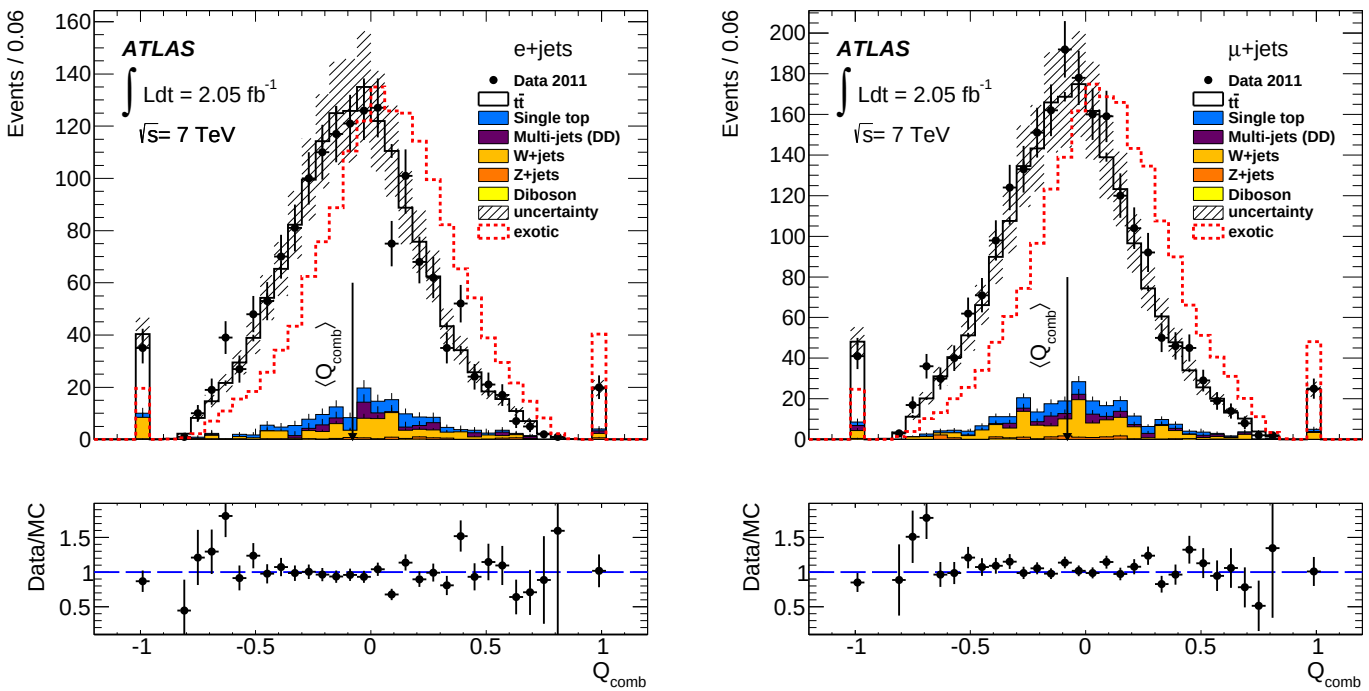
$m_t = 173.9 \pm 0.9\ (\mathrm{stat})^{+1.7}_{-2.1}\ \mathrm{syst}$

dominant systematics: JES, fit range, modelling

Top charge

[JHEP 11 (2013) 031]

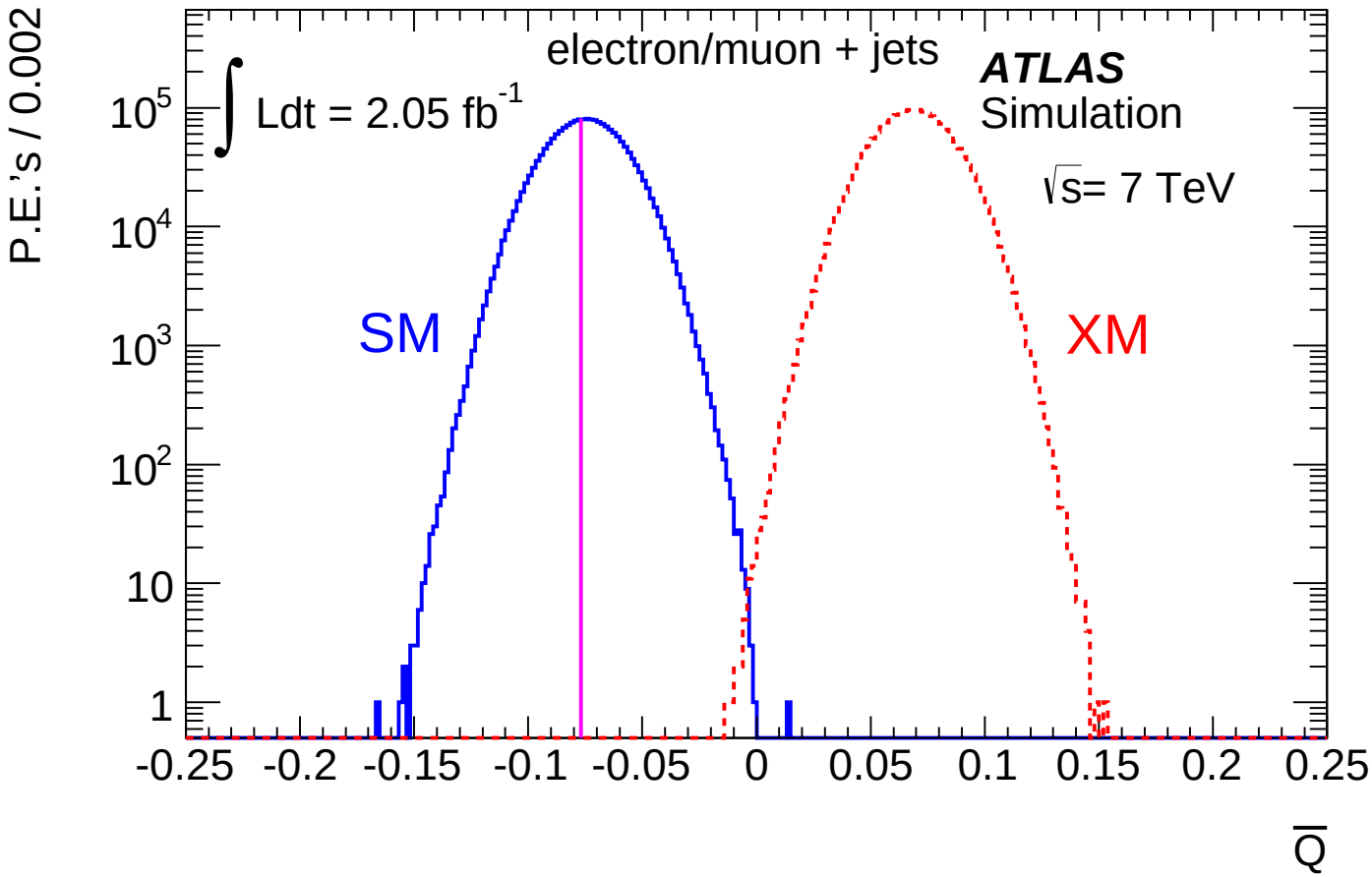
- ℓ+jets channel
- distinguish $t^{(+2/3)} \longrightarrow b^{(-1/3)}\ W^{(+1)} \longrightarrow b^{(-1/3)}\ \ell^{(+1)}\ \nu_\ell$
  $\tilde{t}^{(-4/3)} \longrightarrow b^{(-1/3)}\ W^{(-1)} \longrightarrow b^{(-1/3)}\ \ell^{(-1)}\ \bar{\nu}_\ell$
- lepton/b-tagged jet association using $m_{\ell b}$ / kin. fit
- charge of the b-jet from charge weighting / semilep. B decays



☞ $\tilde{t}^{(-4/3)}$ scenario excluded at 8 σ

Top charge

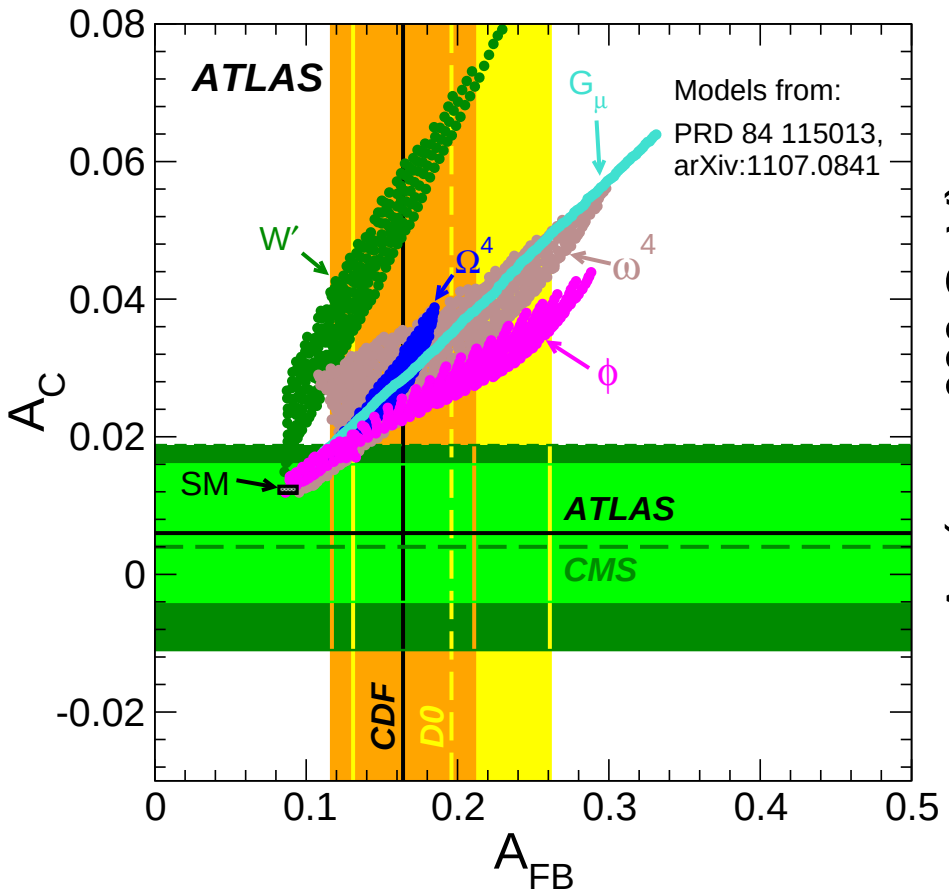
[JHEP 11 (2013) 031]

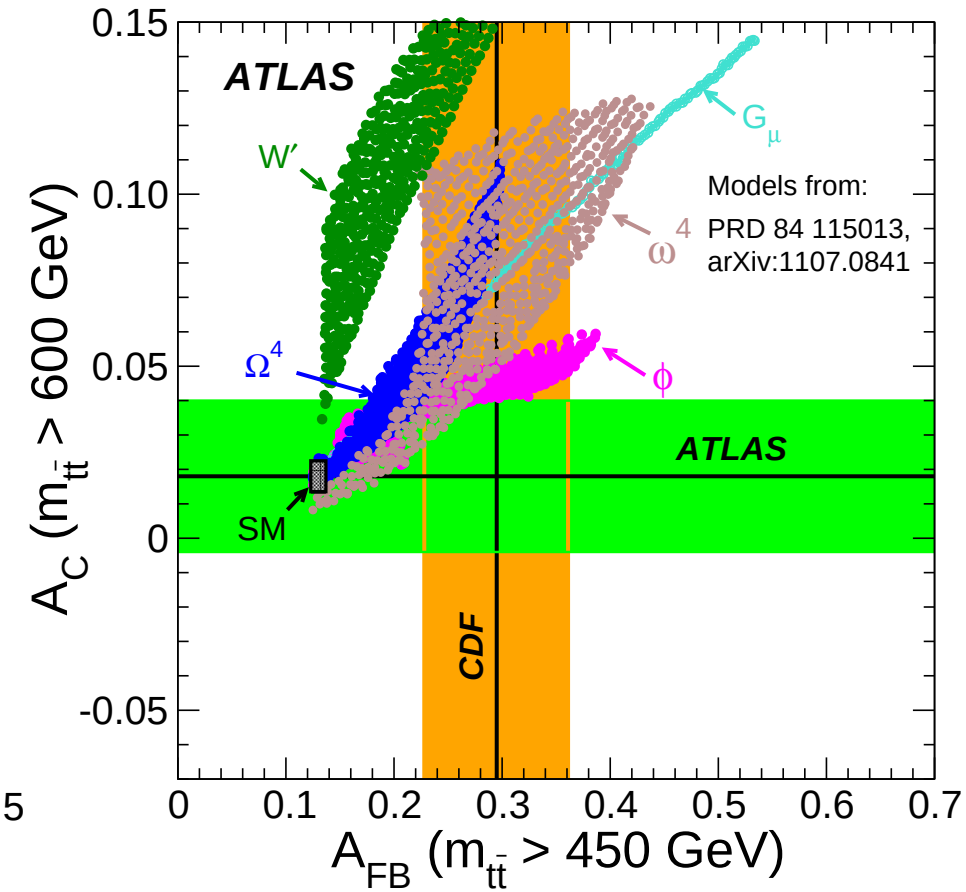


☞ $\tilde{t}^{(-4/3)}$ scenario excluded at 8 σ

Inclusive charge asymmetry and new physics

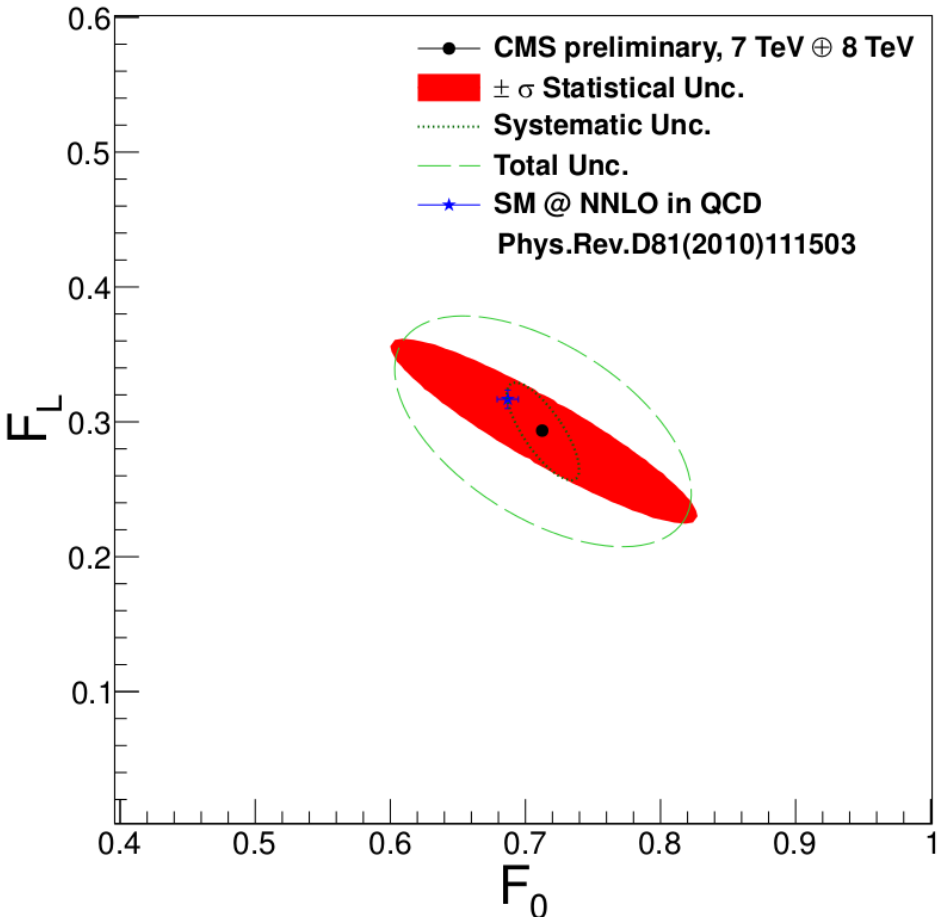
[JHEP 02 (2014) 107]

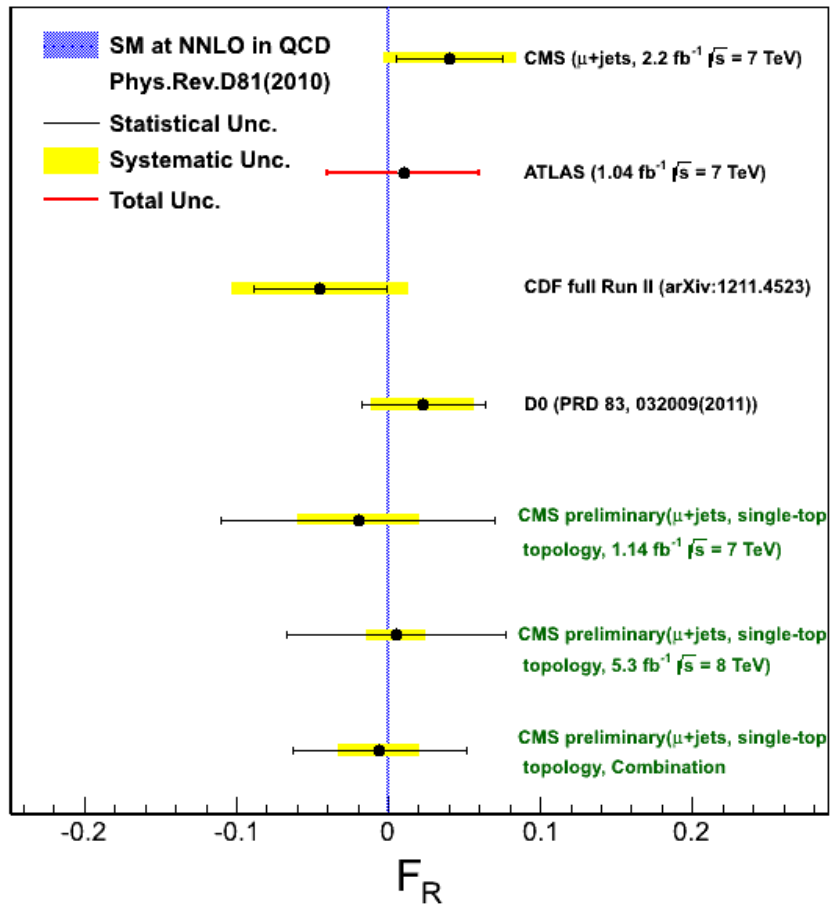




W polarization in single top events

[CMS-TOP-12-020]





LHC combination of the *W* polarization measurements

TOPLHCWG [ATLAS-CONF-2013-033]