Intrinsic Top Quark Properties

Mass, Charge, Polarization of W, FCNC

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on behalf of the ATLAS Collaboration

Warsaw, 28 Apr - 2 May 2014

Outline

- Introduction: intrinsic means…
- What a top quark is
  - Charge
  - Mass
- How a top quark behaves
  - Polarization of W in $t \rightarrow Wb$ decays
  - Flavor-Changing Neutral Currents
- Conclusions

The Arrow of ($t\bar{t}$)ime

$$\frac{1}{m_t} < \frac{1}{\Gamma_t} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda^2_{QCD}}$$

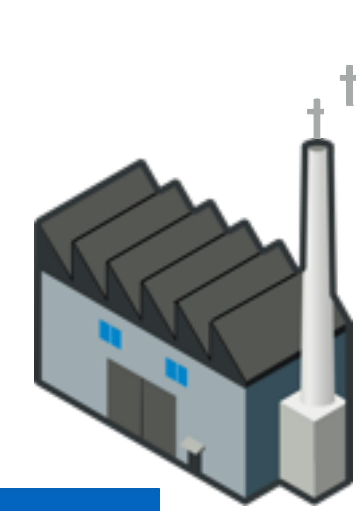
production time	lifetime	hadronization time	spin decorrelation time

Large Mass ➠ No hadronization

➠ intrinsic properties can be directly observed!

The only known quark we can observe “undressed”

The LHC is a Top Factory

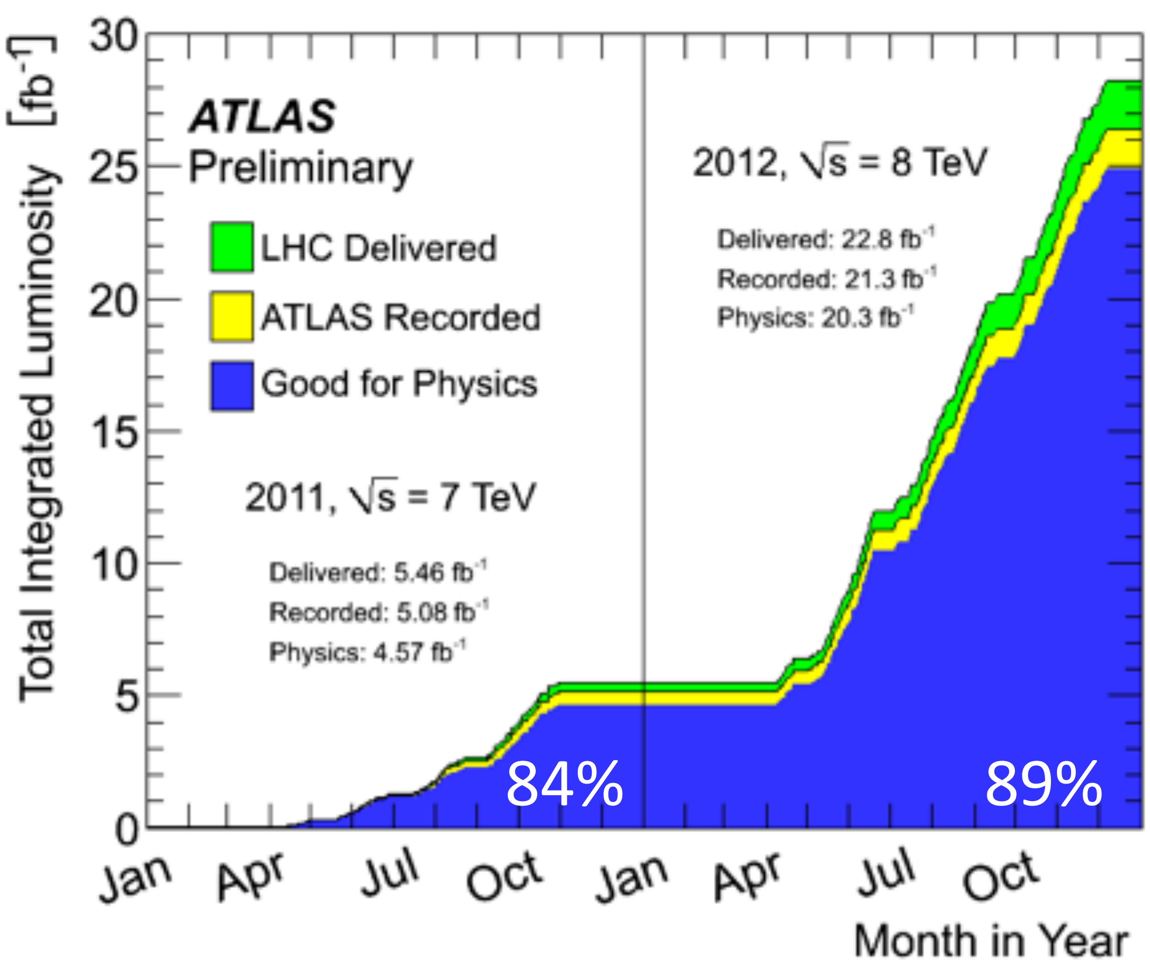


- Top perspective:
  LHC mainly a gluon collider

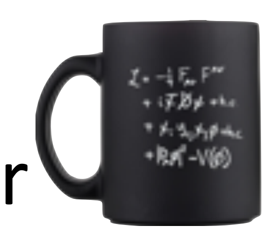
- Large production cross-section √s=8TeV
  top-antitop pairs ~ 250 pb (QCD)
  single top ~100 pb (EW)

As seen on: P. Skubic's Talk

As seen on: C. Monini's Talk



@ 8 TeV ~75 ttbar / min
8-hours shift 36,000 ttbar



8 TeV analyses: ~5 10^6 ttbar pairs
7 TeV analyses: ~1 10^6 ttbar pairs

SUISSE VISA
SWITZERLAND

VISA

Surname

Quark

Name

Top

Nationality

United States of America

Place of Birth

Batavia, IL, USA

Marital Status

Strongly coupled to Higgs Boson

Children

W Boson and Bottom Quark

TOPQUARK<<M173<<<<<<<<<<<<<<<<<
Q2/3e<<S1/2HBAR<<T1<<I1/2<<Y1/3

Electric charge

- Standard Model top quark $q = +2/3e$
  Exotic alternative model $-4/3e$

Phys.Rev.D 59 (1999) 091503

- Disfavored *but not excluded* by CDF @ 95% CL

PRL 105 (2010) 101801

		$Q_b * Ql$	Q_{comb}
SM	$t^{(2/3)} \to b^{(-1/3)} + W^{(+1)}, W^+ \to \ell^+ + \nu_\ell$	- +	= -
Exotic	$\tilde{t}^{(-4/3)} \to b^{(-1/3)} + W^{(-1)}, W^- \to \ell^- + \nu_\ell$	- -	= +

- Exploit correlation Q(b-quark) ~ <Q>(b-jet)

The charge of a b-jet is the weighted sum of its track charges

$$Q_{b-\text{jet}} = \frac{\sum_i Q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa}$$

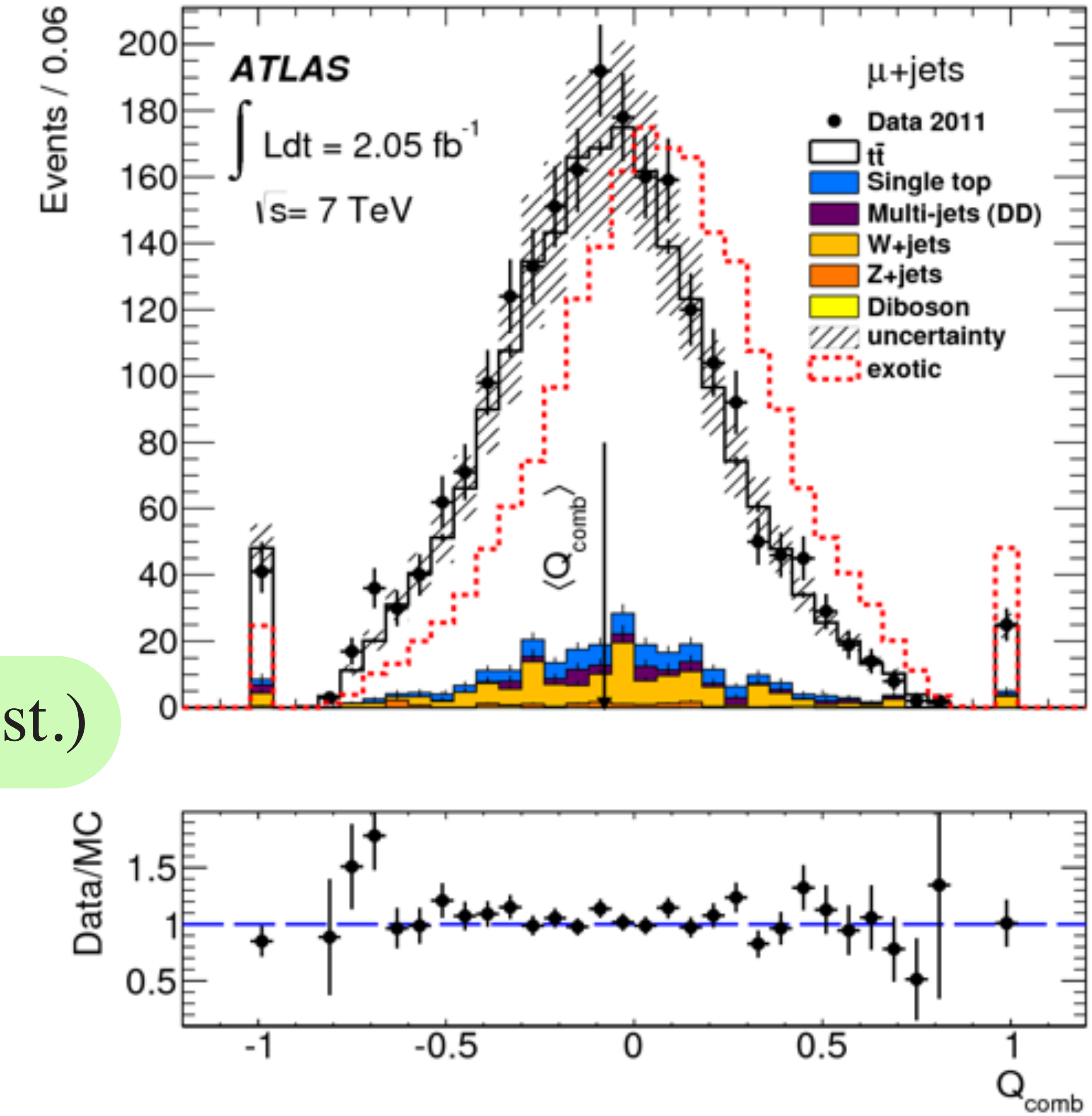
best separation
k = 0.5

Electric charge

- top-antitop pairs
- 2 b-tags and *m*(*l*,*b*) mass-cut
- Low efficiency (28%) but very high purity (87%)

$$Q_{\rm top} = 1 + Q_{\rm comb}^{\rm (data)} \times C_b\,, \qquad C_{\rm b} = Q_{\rm b}/\langle Q_{\rm comb}\rangle$$

$$Q_{top} = 0.64 \pm 0.02\ (\text{stat.}) \pm 0.08\ (\text{syst.})$$



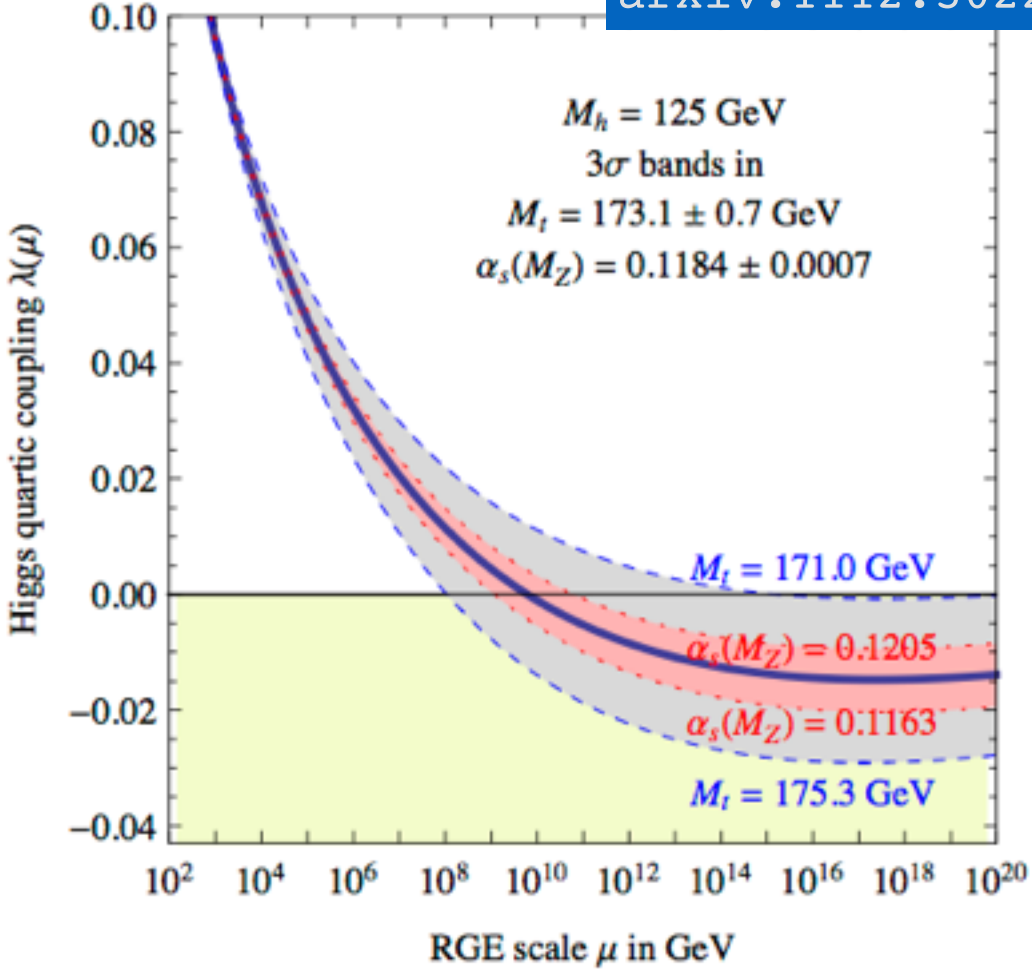
- Compatible with +(2/3)e
- Exotic *t* excluded at > 8σ

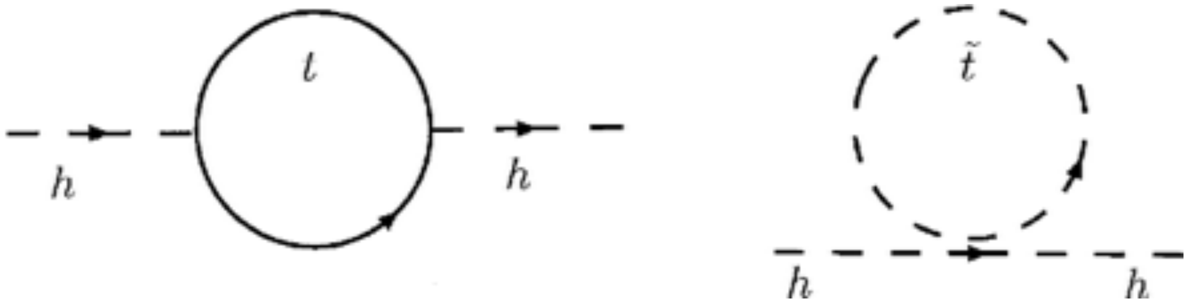
Top is an up-type quark!

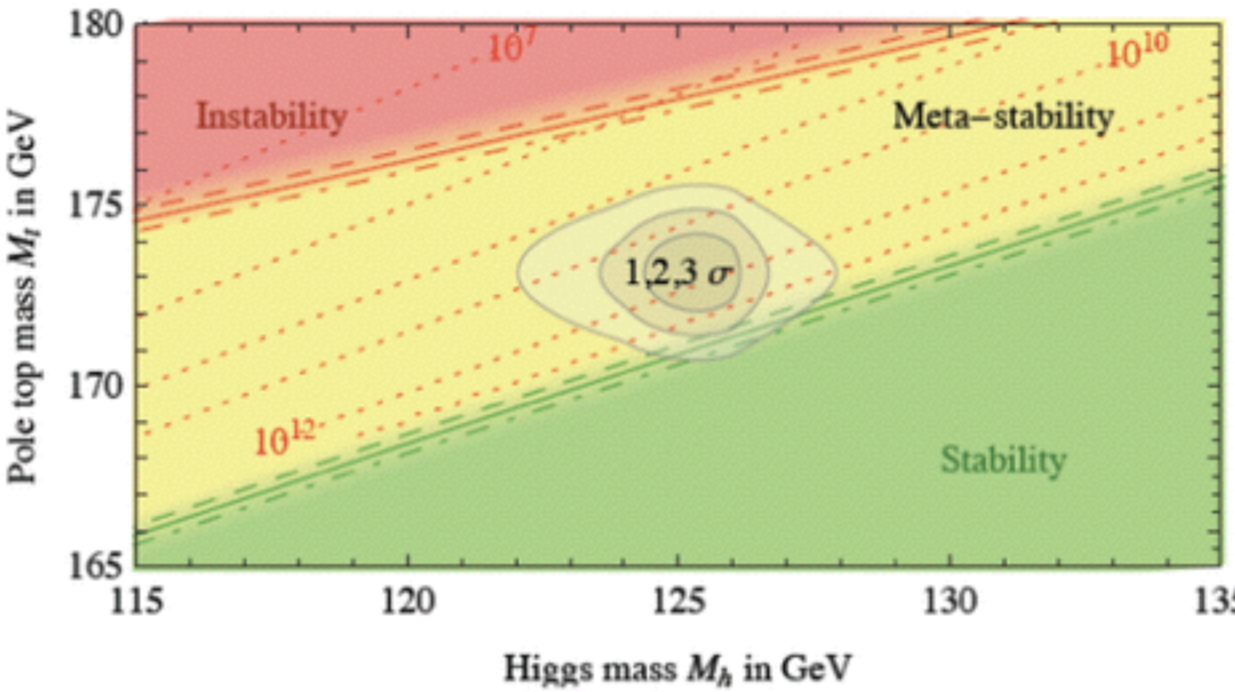
Top Mass (m_t)

- Important parameter in SM: stability of Higgs potential, B-physics
- Direct measurements: m_t^{MC} invariant mass in $t \rightarrow Wb$
  - Beyond LO QCD m_t depends on renormalization scheme
  - "Monte Carlo" top mass sensitive to m_t, but no well-defined renormalization scheme

arXiv:1112.3022v1







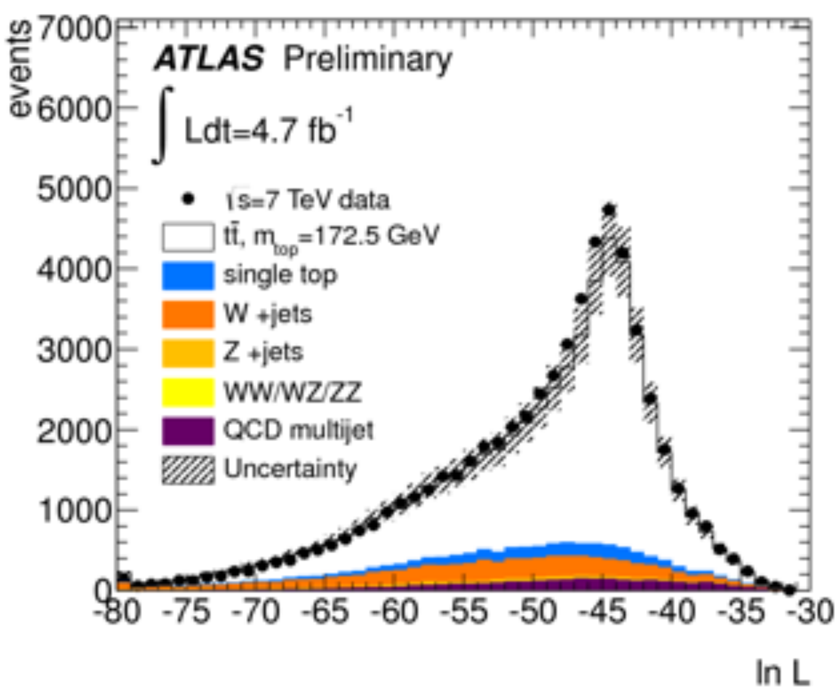
ATLAS-CONF-2013-046 | 4.7 fb^{-1} | 7 TeV

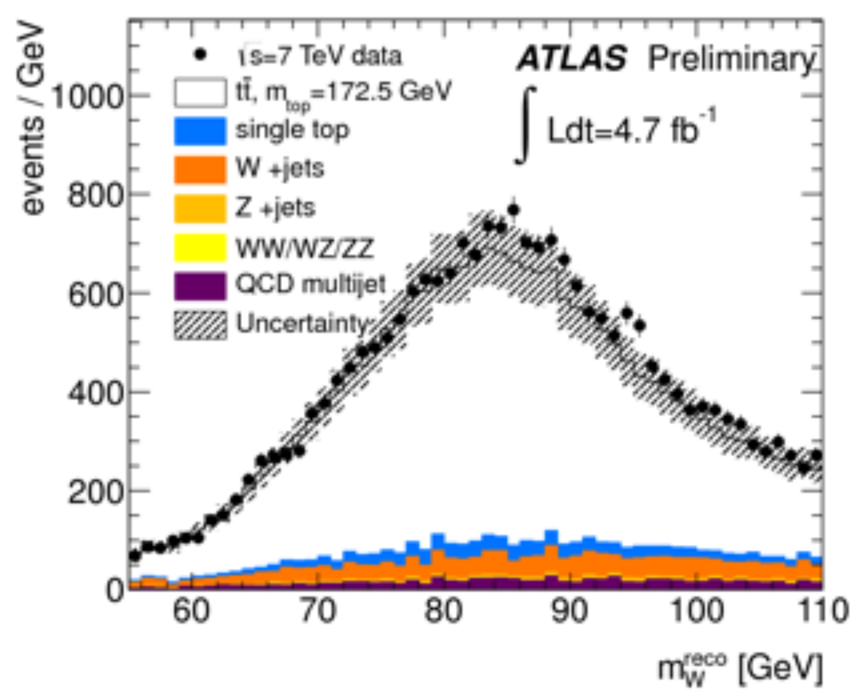
3D Fit

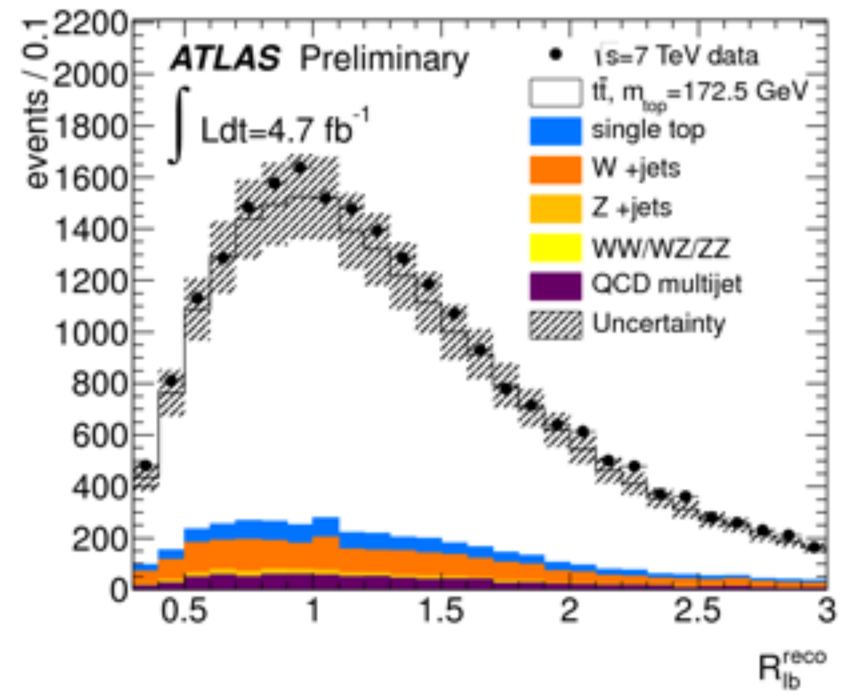
- Lepton+jets topology
- Extract 3 observables from each event:
    - m_t from kinematic likelihood fit
    - Reconstructed m_W and R_{lb} from lepton and jets (assigned from best-fit permutation)

$$R_{\mathrm{lb}}^{\mathrm{reco,2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}}},$$

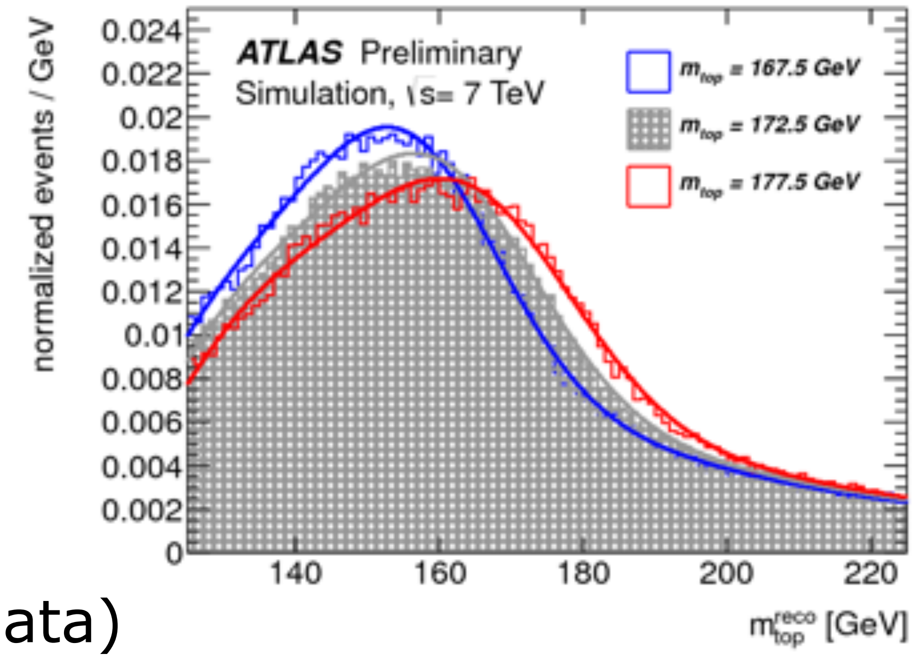
$$R_{\mathrm{lb}}^{\mathrm{reco,1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}})/2}$$





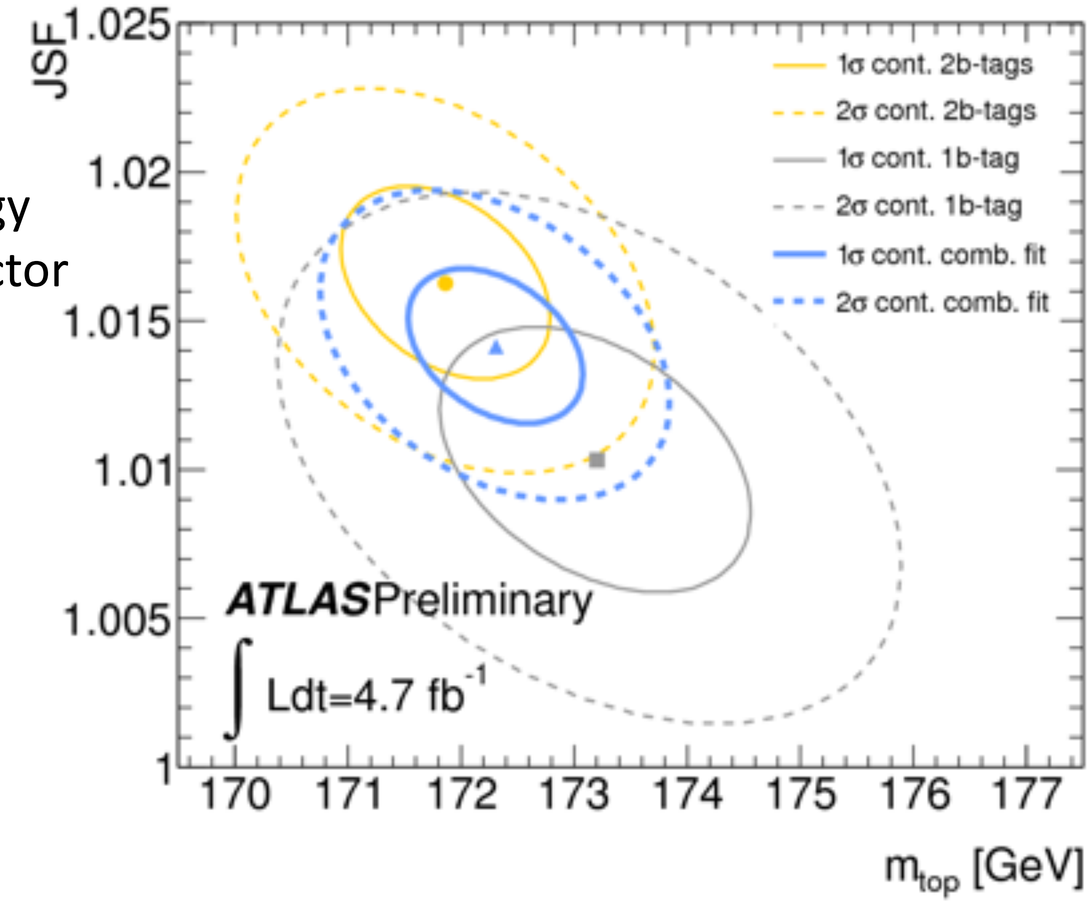


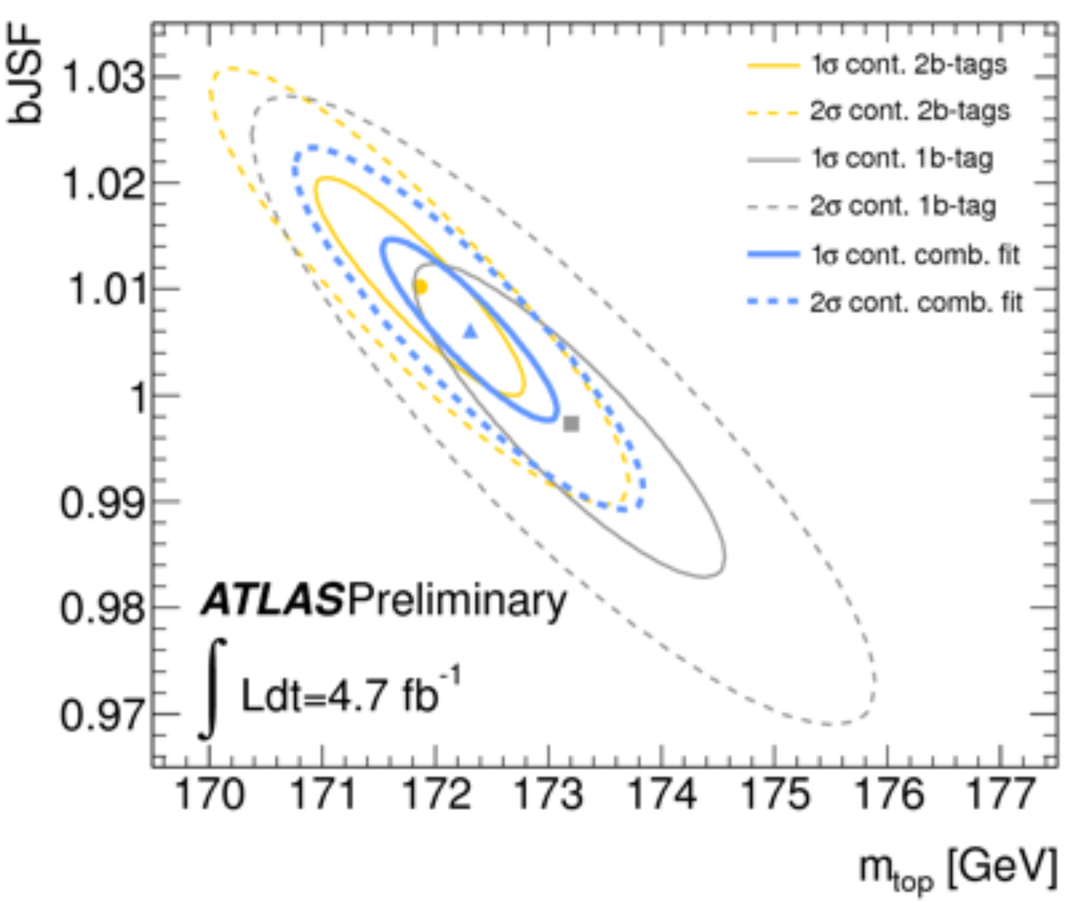
3D Fit



- Templates for m_t [167.5, 177.5] GeV ⊗ JSF ⊗ bJSF
- unbinned fit extracts m_t, JSF and bJSF
- Main unc.: b-tagging eff, JSF, bJSF(stat comp., decr. w/ data)

JSF =
Jet energy
Scale **F**actor





$$
\begin{aligned}
m_{\rm top} &= 172.31 \pm 0.75\ ({\rm stat + JSF + bJSF}) \pm 1.35\ ({\rm syst})\ \ {\rm GeV},\\
{\rm JSF} &= 1.014\ \pm 0.003\ ({\rm stat})\ \pm 0.021\ ({\rm syst}),\\
{\rm bJSF} &= 1.006\ \pm 0.008\ ({\rm stat})\ \pm 0.020\ ({\rm syst}).
\end{aligned}
$$

3D vs 2D Fit = constrain bJSF = 1

2D

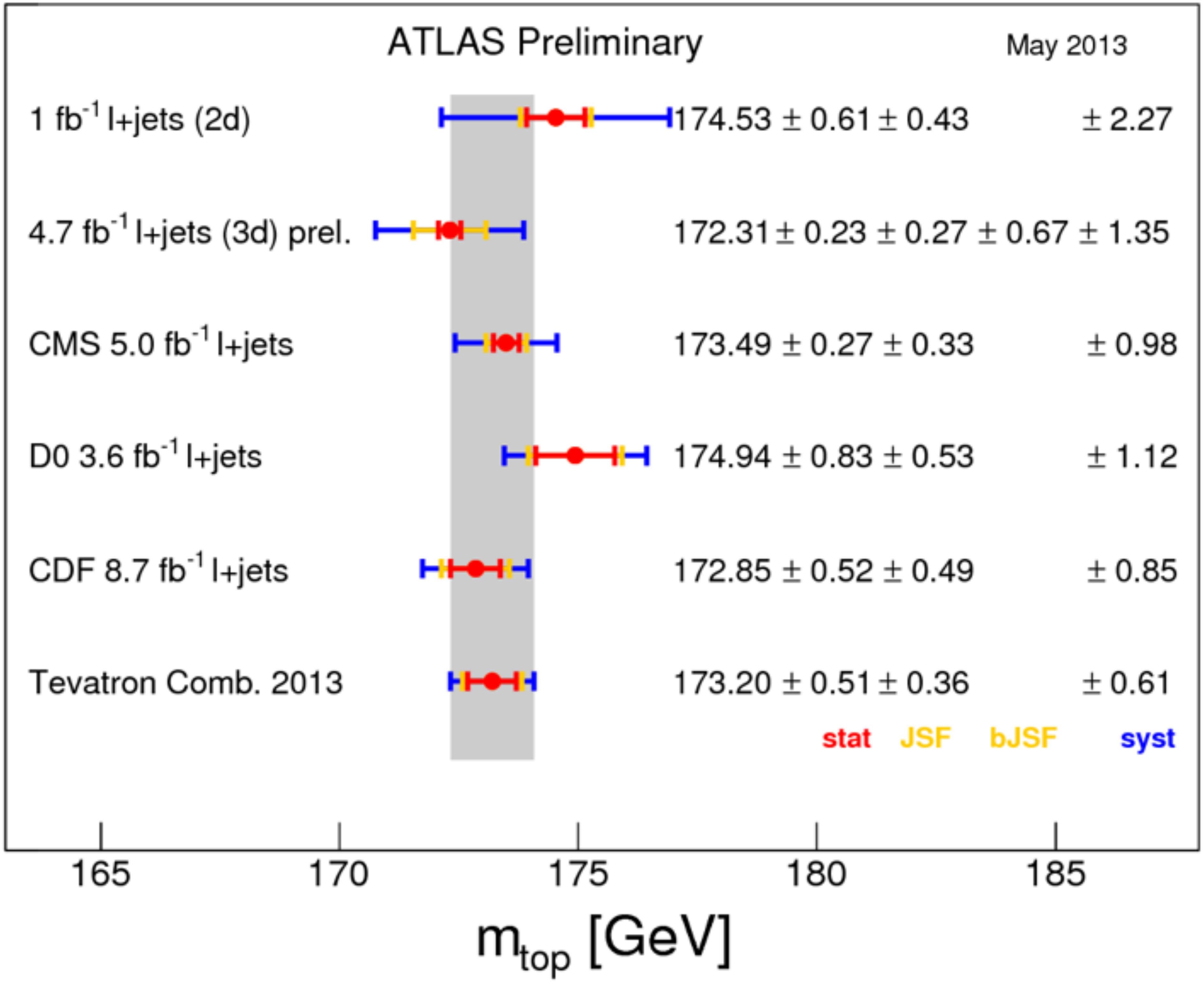
$$\begin{aligned} m_{\mathrm{top}} &= 172.80 \pm 0.35\ (\mathrm{stat} + \mathrm{JSF}) \pm 2.02\ (\mathrm{syst})\ \mathrm{GeV}, \\ \mathrm{JSF} &= 1.014 \pm 0.003\ (\mathrm{stat}) \pm 0.021\ (\mathrm{syst}). \end{aligned}$$

3D

$$\begin{aligned} m_{\mathrm{top}} &= 172.31 \pm 0.75\ (\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.35\ (\mathrm{syst})\ \mathrm{GeV}, \\ \mathrm{JSF} &= 1.014 \pm 0.003\ (\mathrm{stat}) \pm 0.021\ (\mathrm{syst}), \\ \mathrm{bJSF} &= 1.006 \pm 0.008\ (\mathrm{stat}) \pm 0.020\ (\mathrm{syst}). \end{aligned}$$

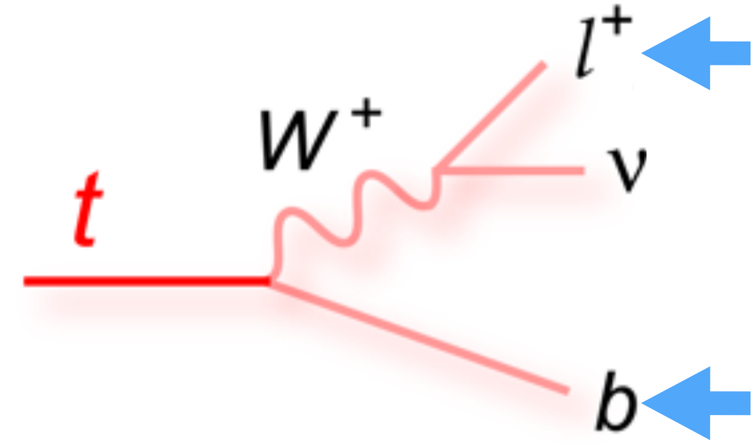
- R_{lb} (ratio) not sensitive to JSF: JSF(2D)=JSF(3D)
- Fitted m_t from the two methods agree ~ 0.5 GeV (less than bJSF ~ 0.9 GeV)
- Reduced systematics wrt previous ATLAS measurement: EPJC 72(2012)2046
  - ✓ Improved IFSR and bJSF
  - ✓ Better MC simulation modeling and higher statistics
    MC@NLO+HERWIG → POWHEG+PYTHIA Perugia 2011C tune
  - ✓ Better ttbar reconstruction (χ^2 → kinematic fit)
  - ✓ Improved analysis strategy (3D fit)

3D/2D Fit

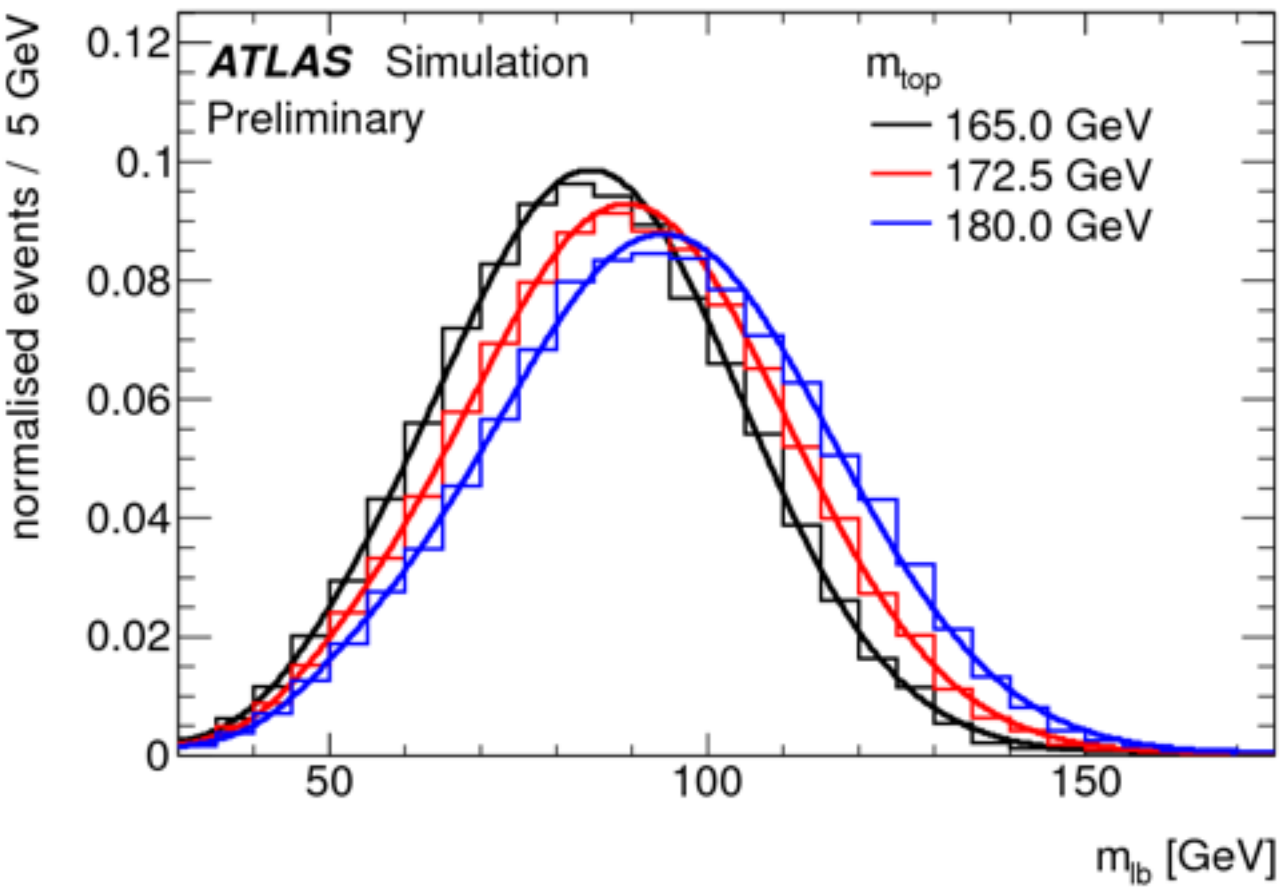

ATLAS Preliminary
May 2013
1 fb-1 l+jets (2d)
174.53 ± 0.61 ± 0.43 ± 2.27
4.7 fb-1 l+jets (3d) prel.
172.31 ± 0.23 ± 0.27 ± 0.67 ± 1.35
CMS 5.0 fb-1 l+jets
173.49 ± 0.27 ± 0.33 ± 0.98
D0 3.6 fb-1 l+jets
174.94 ± 0.83 ± 0.53 ± 1.12
CDF 8.7 fb-1 l+jets
172.85 ± 0.52 ± 0.49 ± 0.85
Tevatron Comb. 2013
173.20 ± 0.51 ± 0.36 ± 0.61
stat JSF bJSF syst
165 170 175 180 185
m_top [GeV]

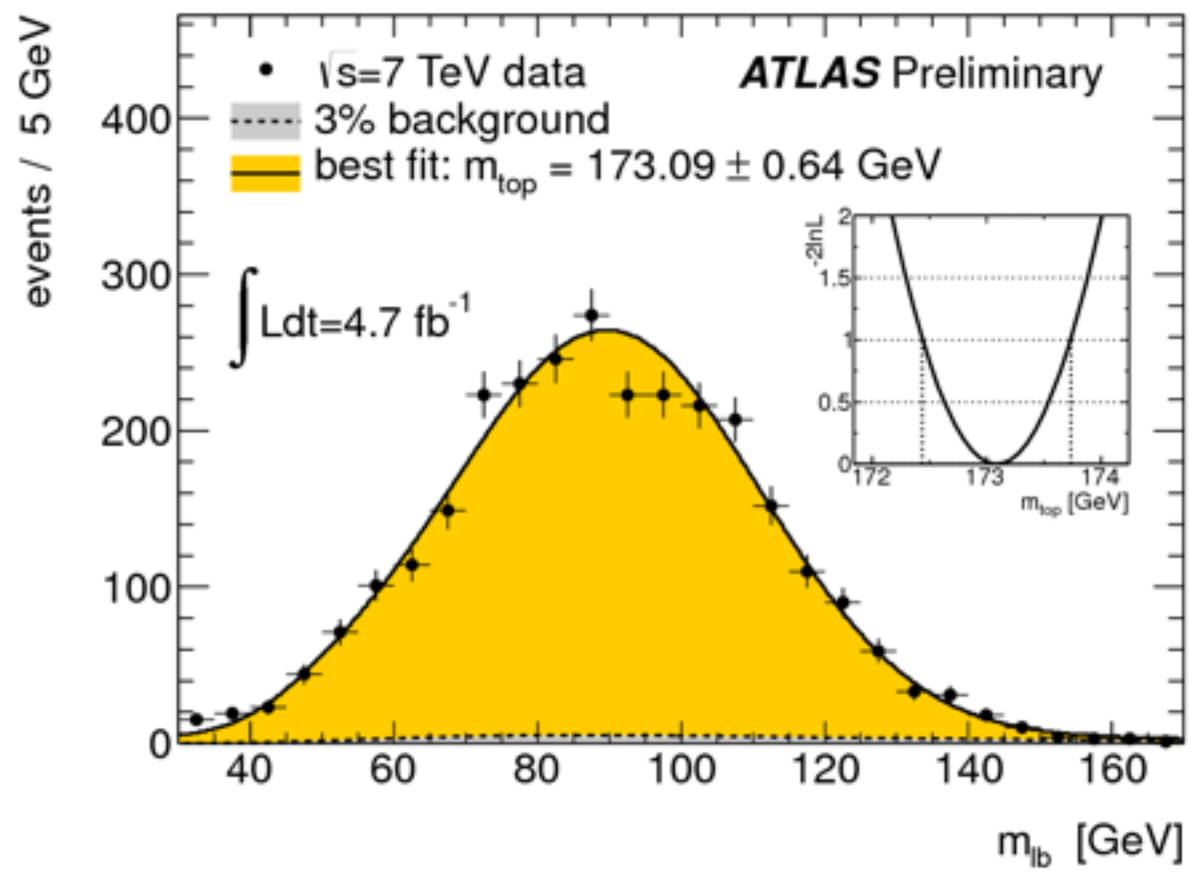
ATLAS-CONF-2013-077 | 4.7 fb^{-1} | 7 TeV

di-leptonic



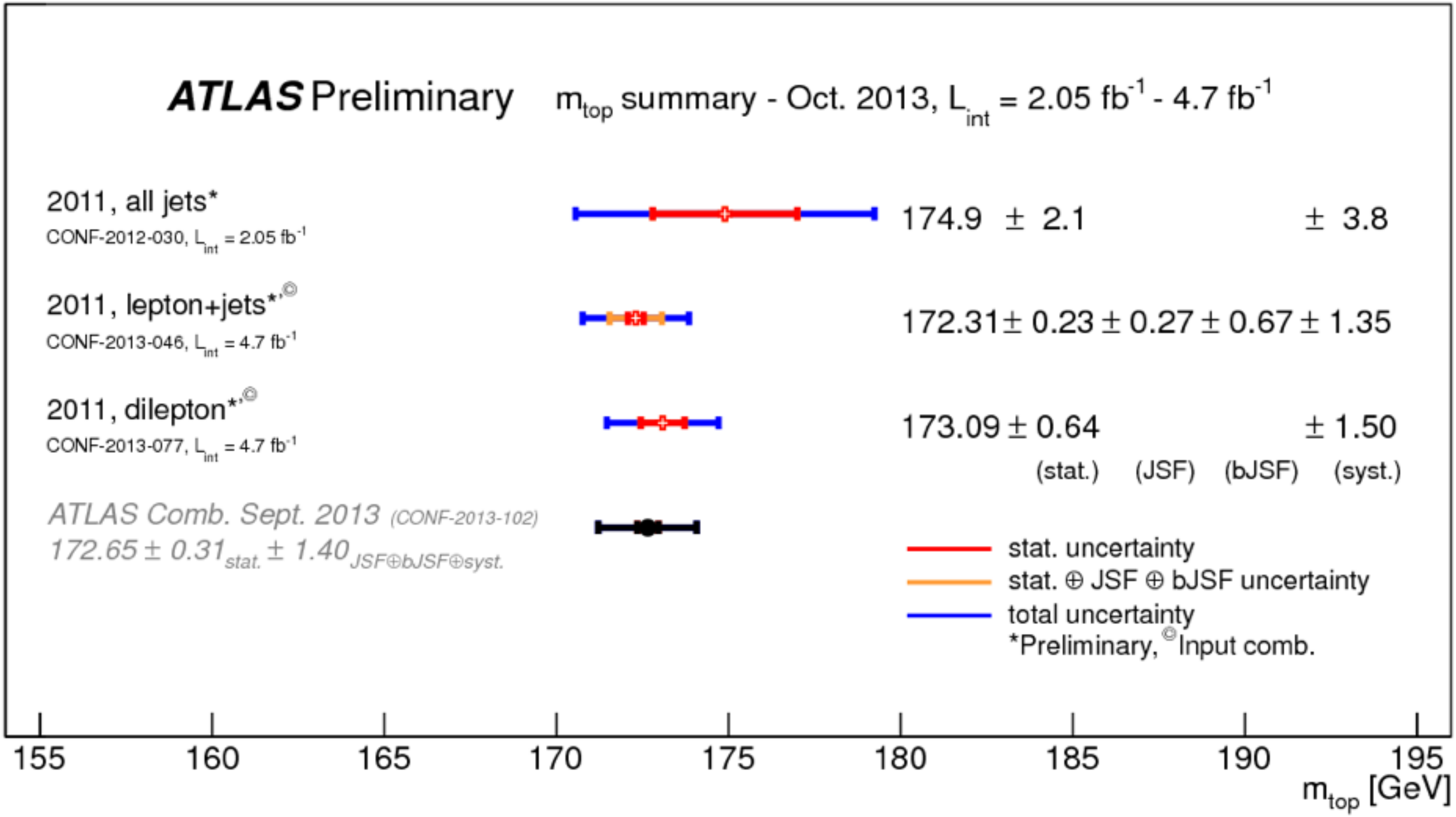
- Template method for the invariant mass lepton+bjet $m(l^{\pm}, b)$
- ttbar: 2 b-jets, correct assignment 77% of the times
- Main unc.: STAT, JES, bJES, b-tagging eff



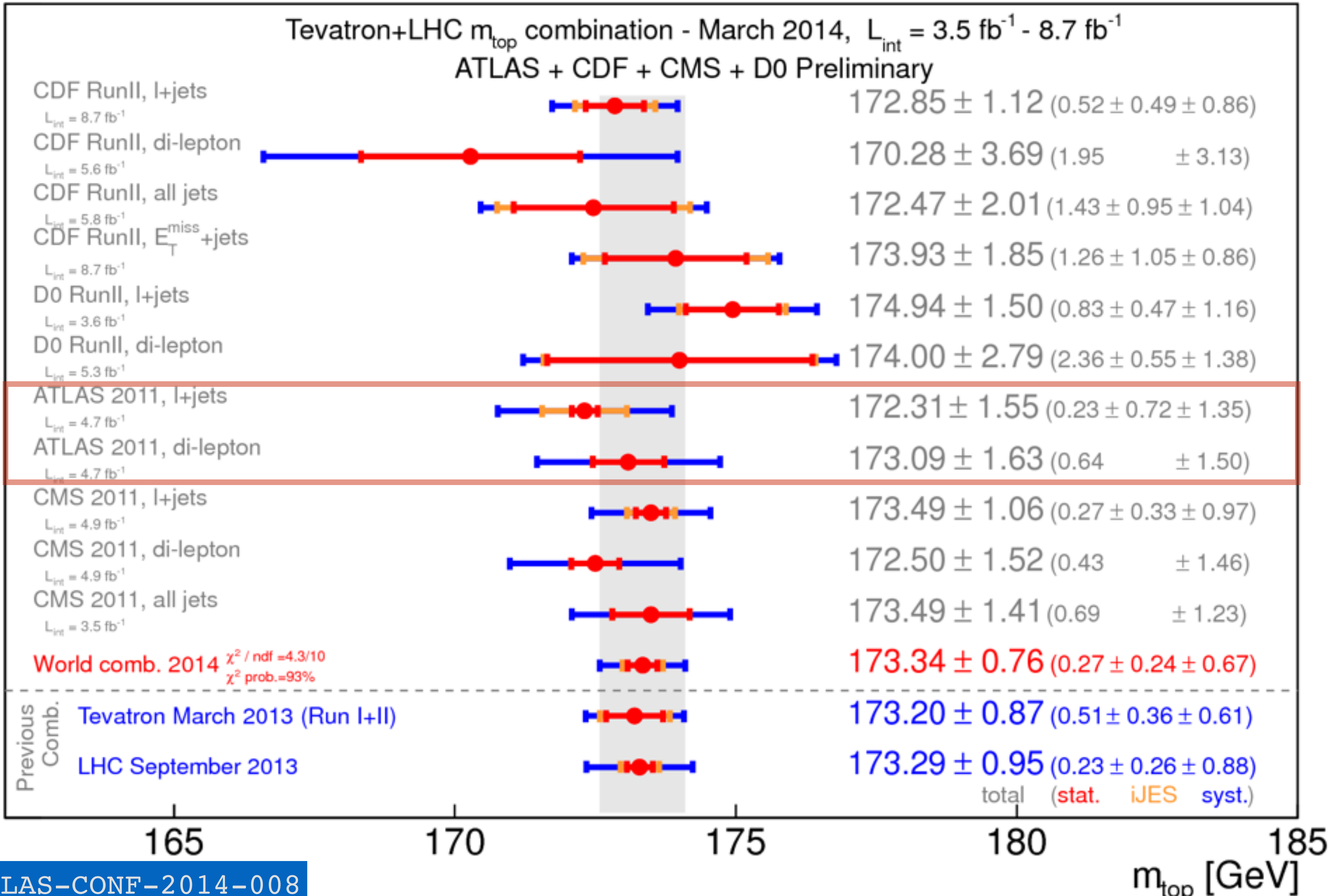


$$m_{top} = 173.09 \pm 0.64\,(\text{stat}) \pm 1.50\,(\text{syst})\ \text{GeV}$$

Main m_t measurements



m_t world combination



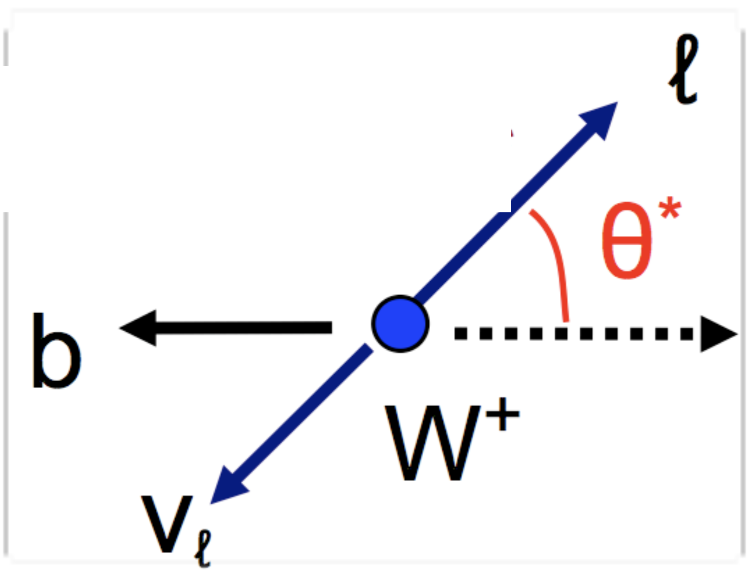
ATLAS-CONF-2014-008

Top Quark is a Handle for New Physics

Large mass ~ EW
Probe for TeV-scale physics

Anomalous production and decays hint for New Physics

Polarization of W



Are W bosons from top decays produced along a preferred direction?

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)\,F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2\,F_\mathrm{L} + \frac{3}{8}\left(1+\cos\theta^*\right)^2\,F_\mathrm{R}$$

- *Helicity fractions* calculated at QCD NNLO

Phys.Rev.D **81**(2010)111503

$F_0 = 0.687 \pm 0.005$ $F_L = 0.311 \pm 0.005$ $F_R = 0.0017 \pm 0.0001$

- Non-standard *Wtb* vertex modifies HF
  - Parametrization in Effective Field Theories

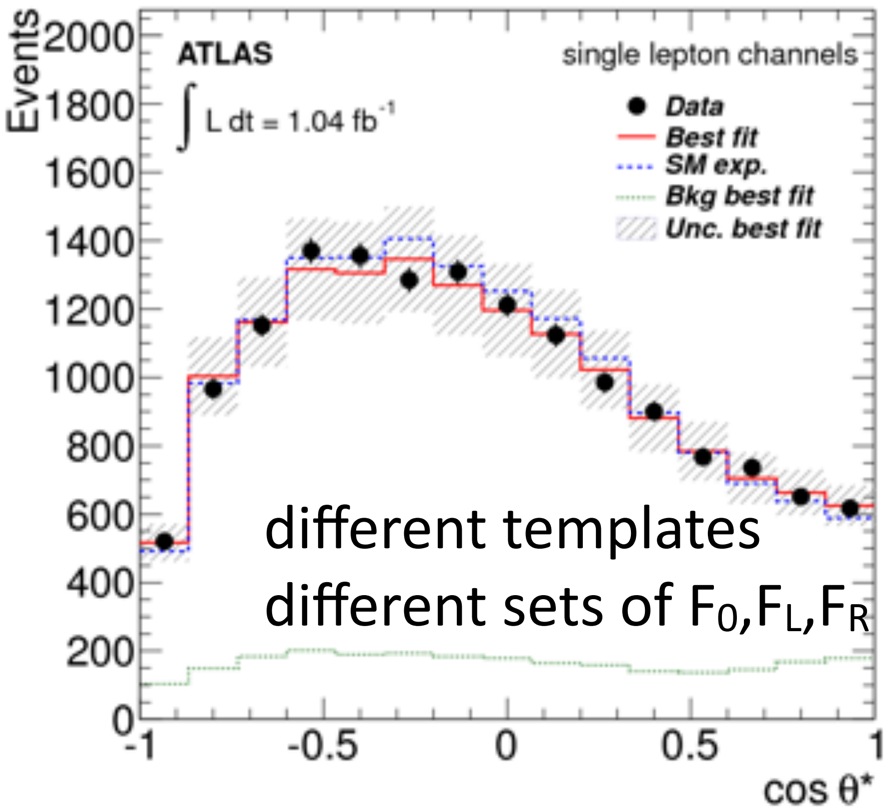
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\left(V_\mathrm{L}P_\mathrm{L} + V_\mathrm{R}P_\mathrm{R}\right)t\,W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(g_\mathrm{L}P_\mathrm{L} + g_\mathrm{R}P_\mathrm{R}\right)t\,W_\mu^- + \mathrm{h.c.}$$

$$V_\mathrm{L} = V_{tb} + C_{\phi q}^{(3,3+3)}\frac{v^2}{\Lambda^2}\,, \quad V_\mathrm{R} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_\mathrm{L} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_\mathrm{R} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

Polarization of *W*

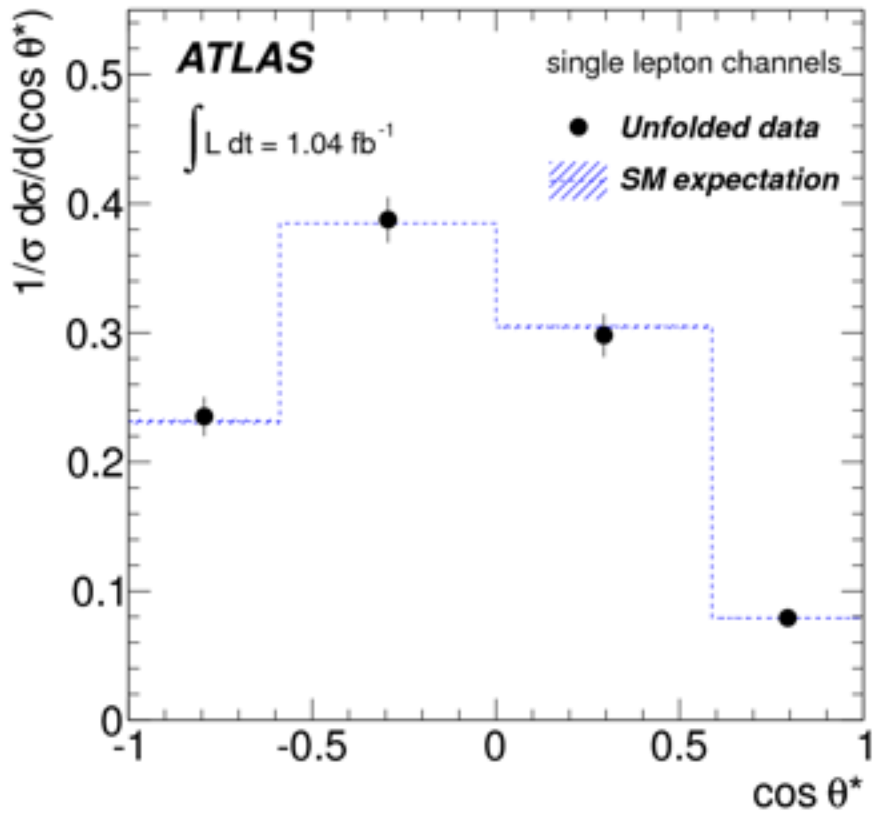
- Angular asymmetry: $$A_{\pm} = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}$$
- Combine 2 observables from 2 topologies (l+jets, dilept)

Extract helicity fractions from the best-fit template for *observed* cosθ*



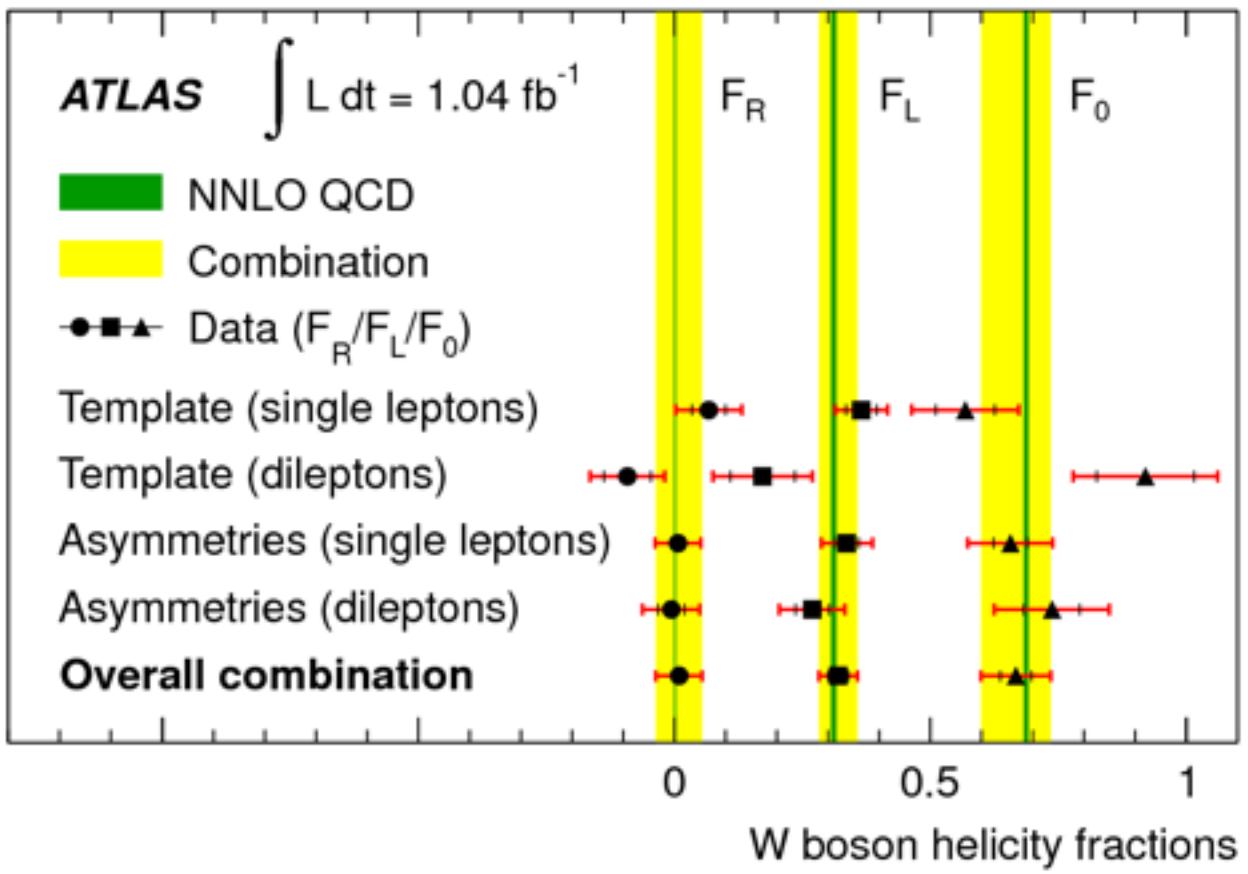
different templates
different sets of F_0, F_L, F_R

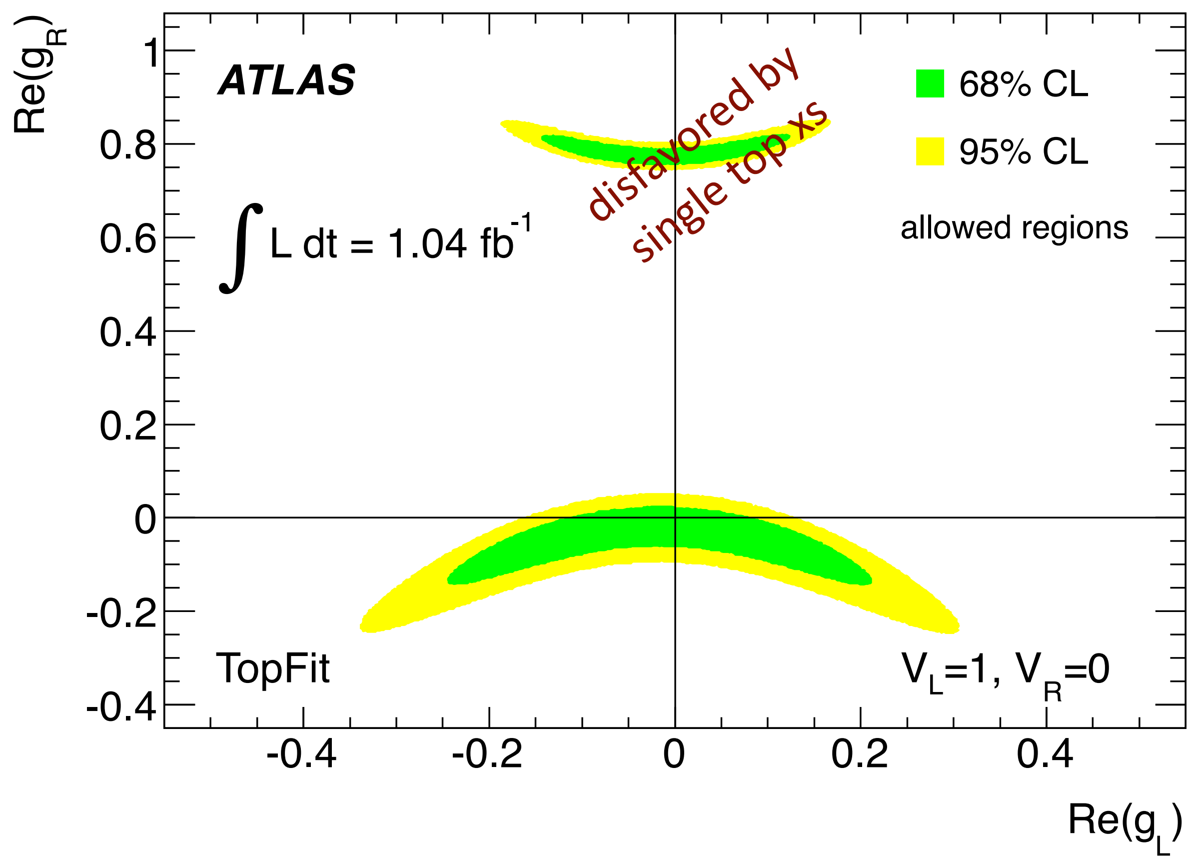
Extract angular asymmetry from the *unfolded* cosθ*



JHEP 1206(2012)088 | 1.04 fb^{-1} | 7 TeV

Polarization of W



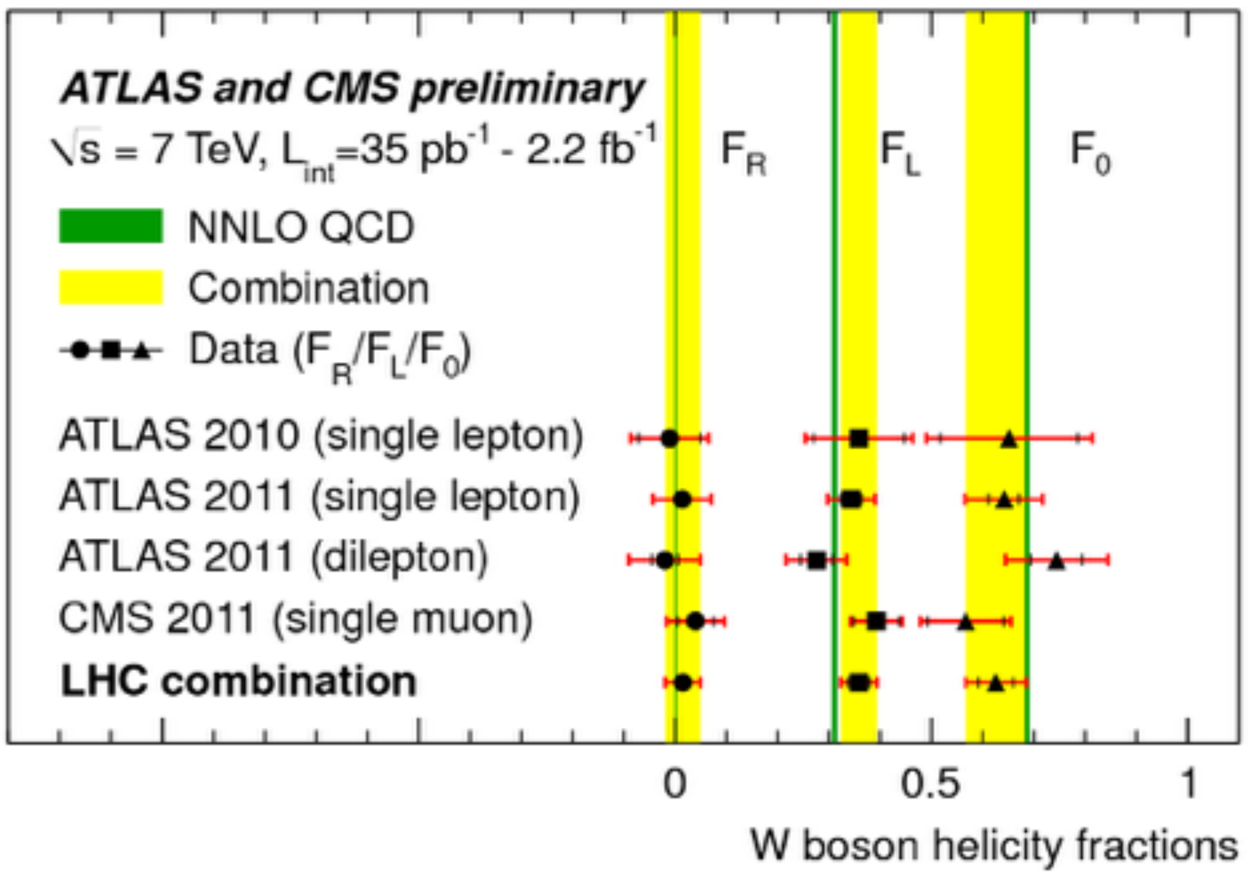


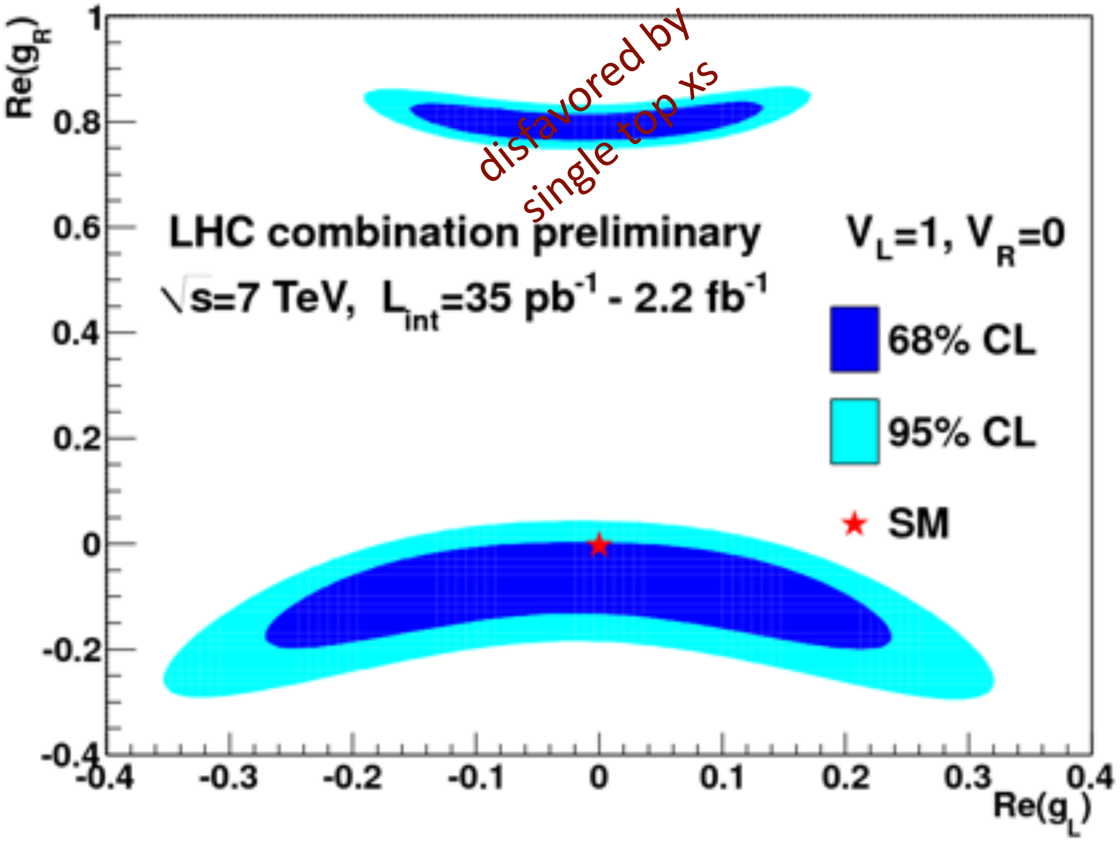
$$F_0 = 0.67 \pm 0.03\ (\text{stat.}) \pm 0.06\ (\text{syst.})\,,$$
$$F_\mathrm{L} = 0.32 \pm 0.02\ (\text{stat.}) \pm 0.03\ (\text{syst.})\,,$$
$$F_\mathrm{R} = 0.01 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{syst.})\,.$$

$$\mathrm{Re}\,(V_\mathrm{R}) \in [-0.20, 0.23] \rightarrow \frac{\mathrm{Re}\,(C_{\phi\phi}^{33})}{\Lambda^2} \in [-6.7, 7.8]\ \ \mathrm{TeV}^{-2}\,,$$
$$\mathrm{Re}\,(g_\mathrm{L}) \in [-0.14, 0.11] \rightarrow \frac{\mathrm{Re}\,(C_{dW}^{33})}{\Lambda^2} \in [-1.6, 1.2]\ \ \mathrm{TeV}^{-2}\,,$$
$$\mathrm{Re}\,(g_\mathrm{R}) \in [-0.08, 0.04] \rightarrow \frac{\mathrm{Re}\,(C_{uW}^{33})}{\Lambda^2} \in [-1.0, 0.5]\ \ \mathrm{TeV}^{-2}\,.$$

Polarization of *W*

ATLAS + CMS!



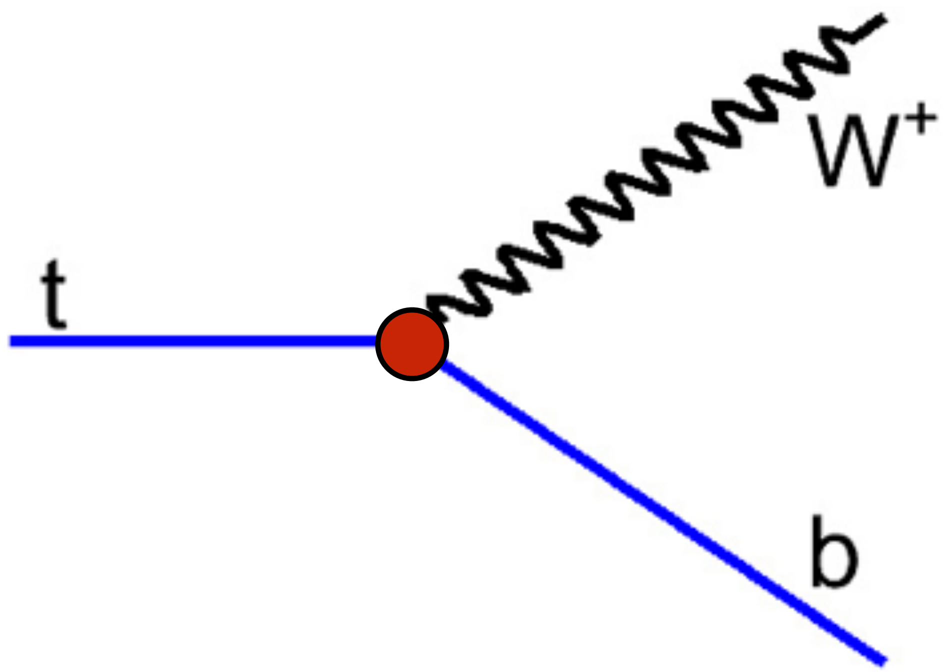


$$F_0 = 0.626 \pm 0.034\,(\text{stat.}) \pm 0.048\,(\text{syst.})$$
$$F_L = 0.359 \pm 0.021\,(\text{stat.}) \pm 0.028\,(\text{syst.})$$
$$F_R = 0.015 \pm 0.034$$

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

$$\frac{\text{Re}(C^{33}_{uW})}{\Lambda^2} = -1.1 \pm 0.6\,(\text{stat.})\,^{+0.9}_{-1.0}\,(\text{syst.})\,\text{TeV}^{-2}$$

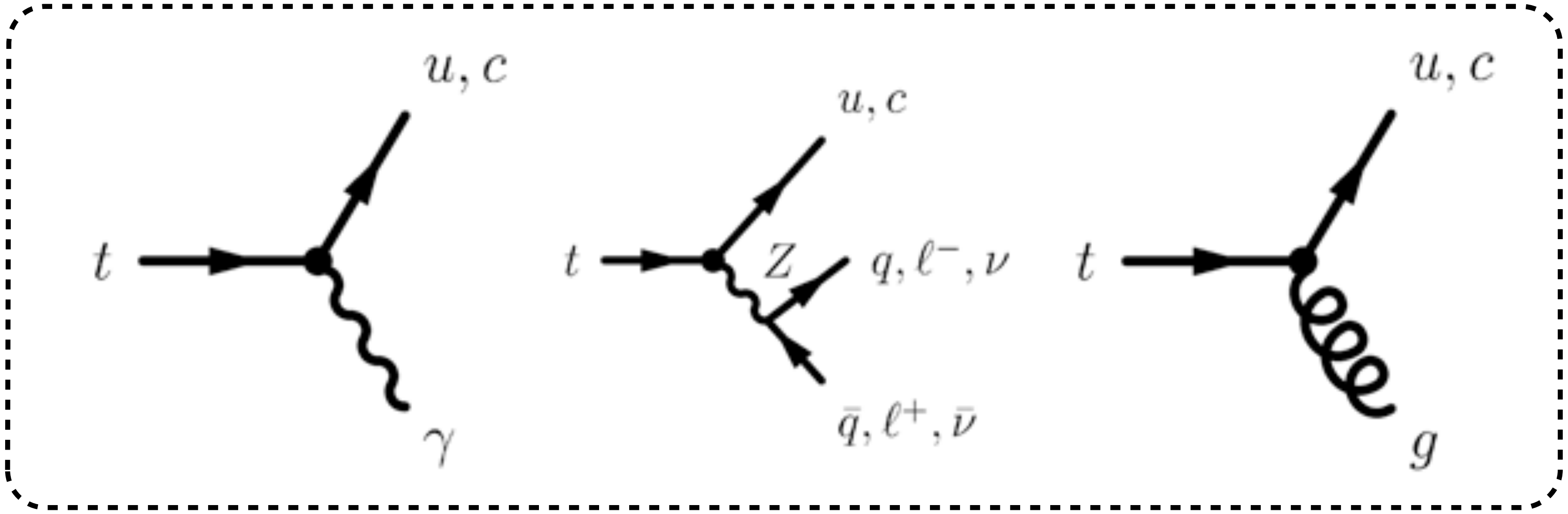
Flavor-Changing Neutral Currents



$t \rightarrow Wb$ ~100% SM ✓

Non standard couplings in decay/production?

?



No LO, GIM suppressed at higher orders

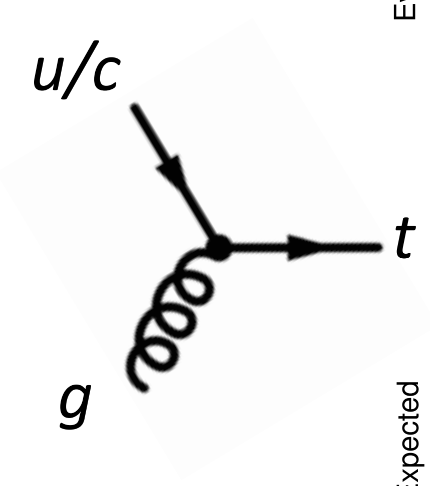
Flavor-Changing Neutral Currents

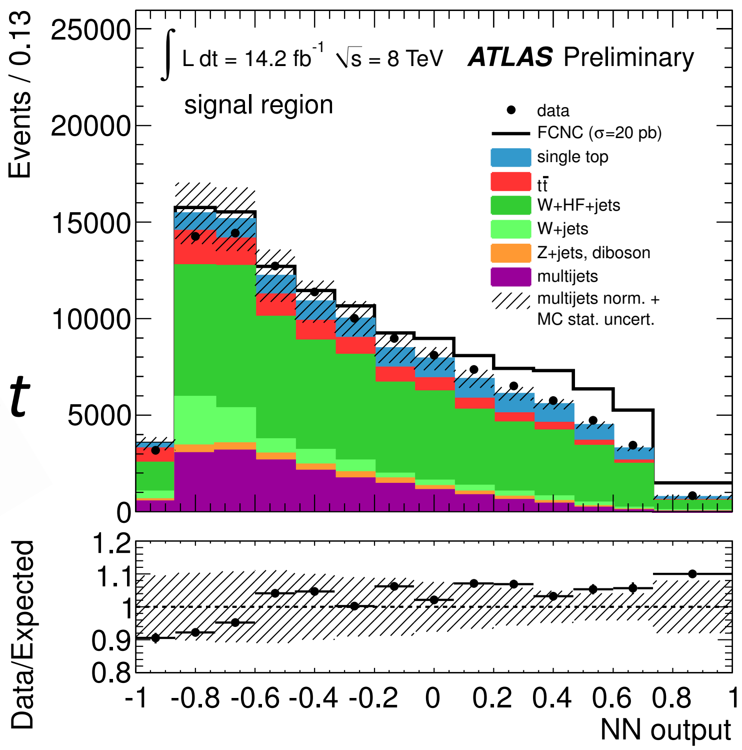
- **Production**

single top (t-channel), Neural Network

$\sigma(qg \to t)*BR(t \to bW) < 2.5$ pb 95% CL
$BR(t \to ug) < 3.1\ 10^{-5}$ $k_{ugt}/\Lambda < 5.1\ 10^{-3}$ TeV^{-1}
$BR(t \to cg) < 1.6\ 10^{-4}$ $k_{cgt}/\Lambda < 1.1\ 10^{-2}$ TeV^{-1}

ATLAS-CONF-2013-063 | 14.2 fb^{-1} | 7 TeV



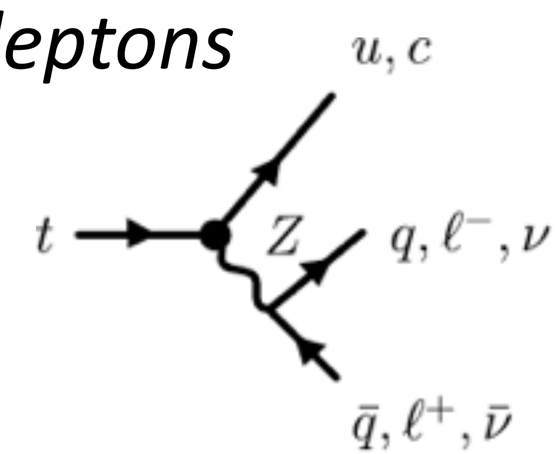


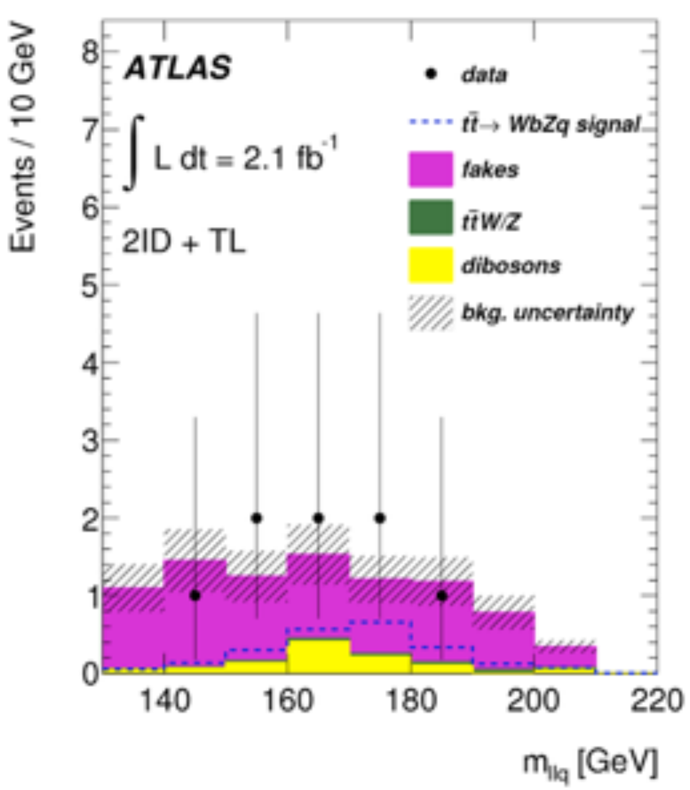
- **Decay**

ttbar production, decay w/ 3 charged leptons

$BR(t \to qZ) < 0.73\%$ 95% CL
(expected $< 0.93\%$)

JHEP 09(2012)139 | 2.1 fb^{-1} | 7 TeV



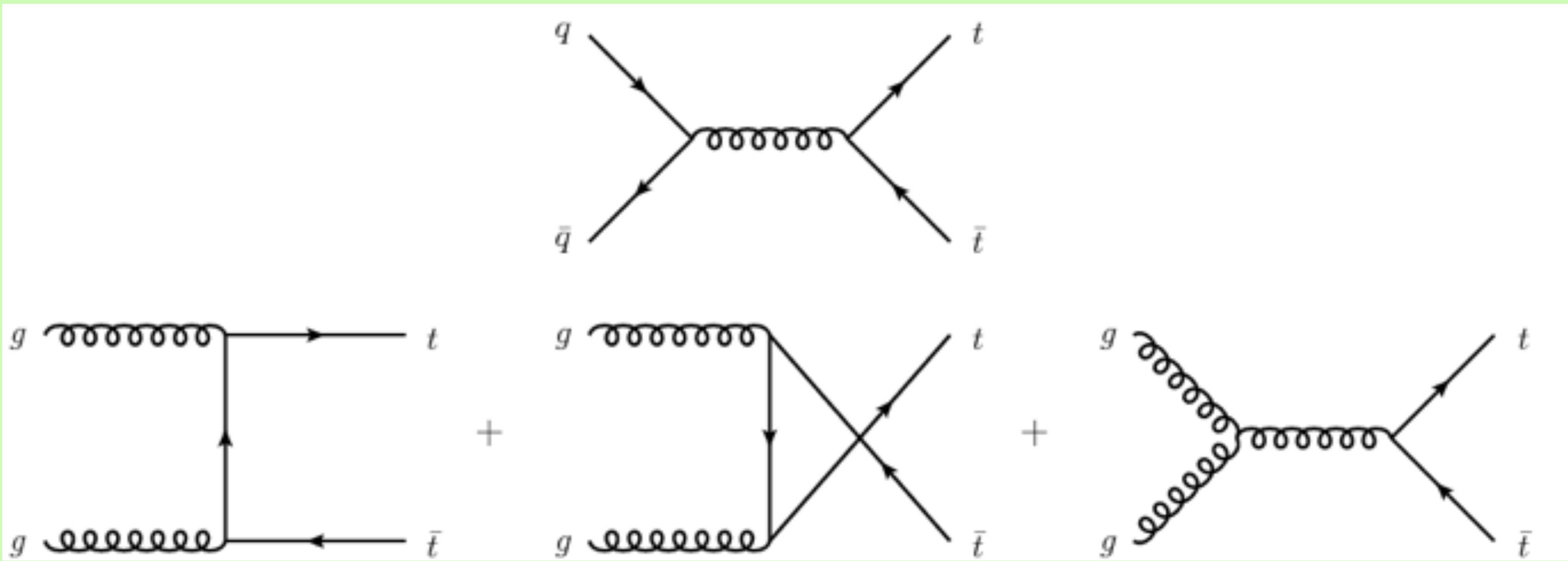


Conclusions

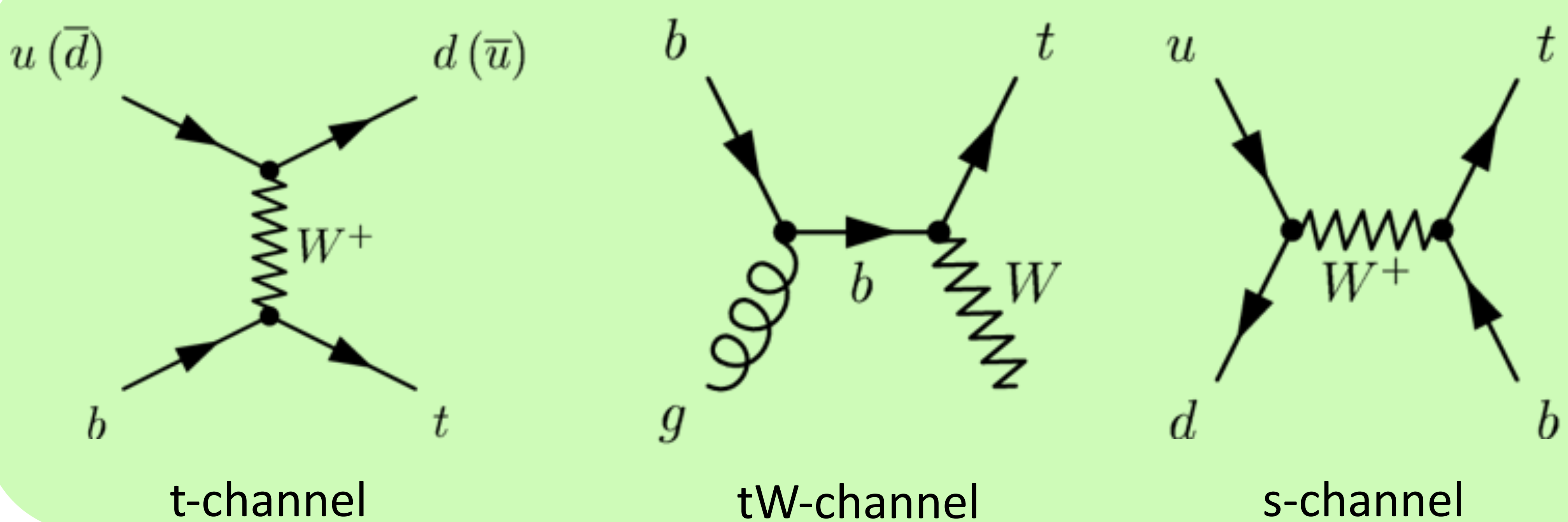
- Top physics is well into the precision era
- Most measurements dominated by systematics
  - Top quark mass measured with δm ~ 1 GeV
  - Largest systematic on m_t (stat bJSF) will decrease with more data
- Unique probe for BSM physics
  - Run1: no large deviations from SM found

Backup

The Twofold Way



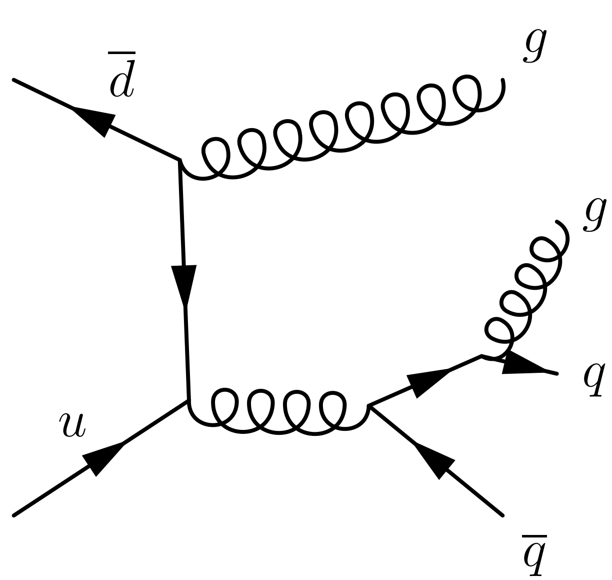
top pairs
QCD
xs ~ 250 pb



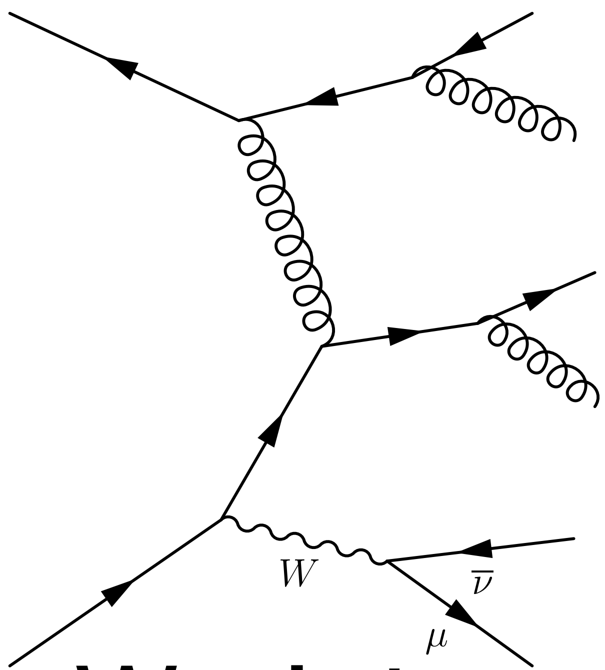
single top
EW
xs ~ 100 pb

Backgrounds

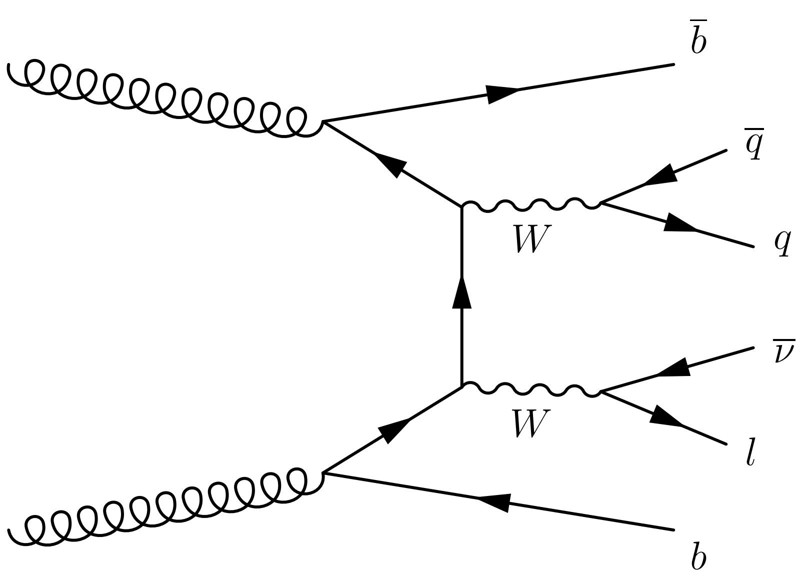
Channel	Topology	Backgrounds
Di-leptonic	2	*WW*+jets, *Z*+jets
Semi-leptonic	2 jets + 2	*W* + jets
Full-hadronic	4 jets + 2 *b*-jets	QCD Multi-jet



QCD

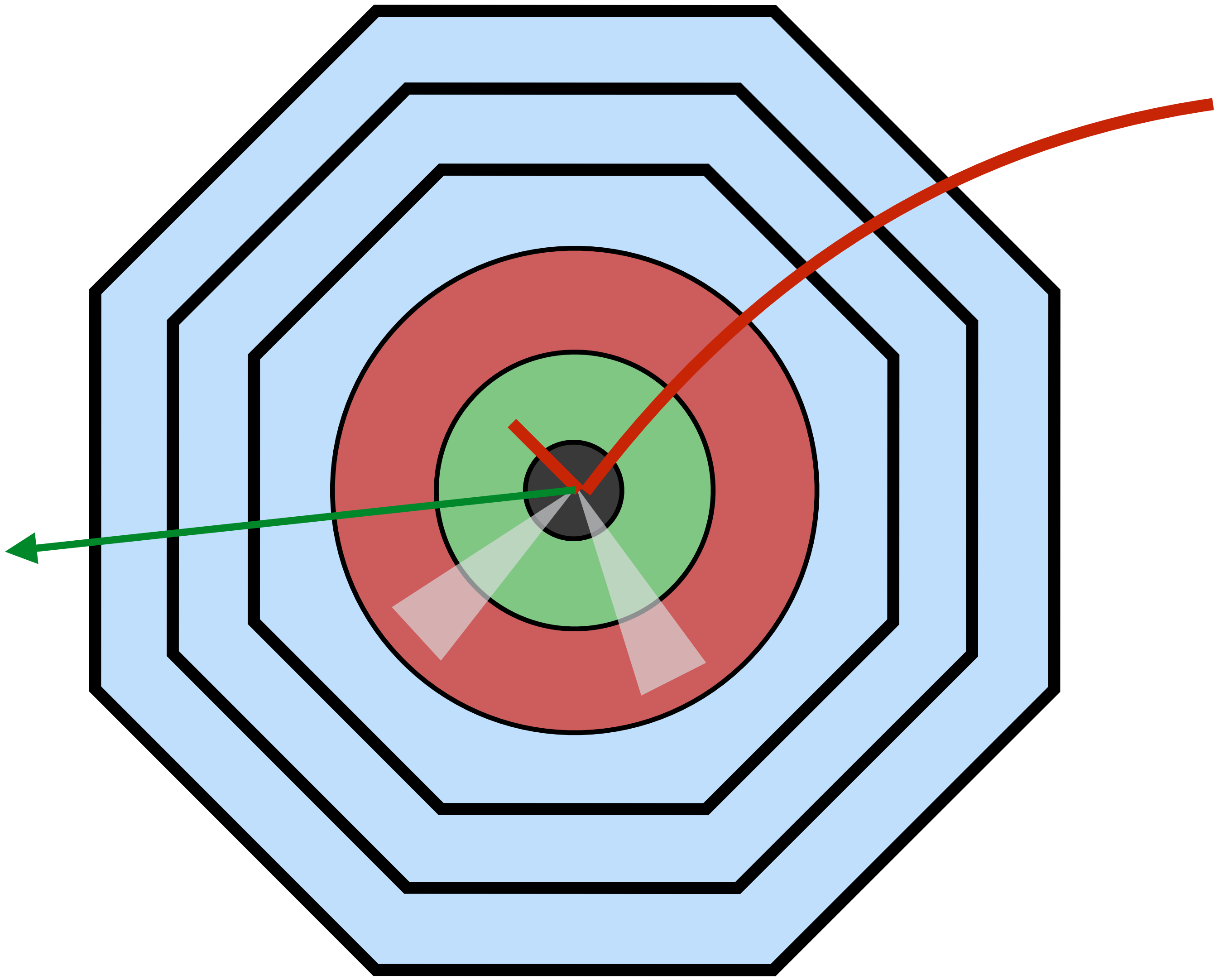


W+jets



WW+jets

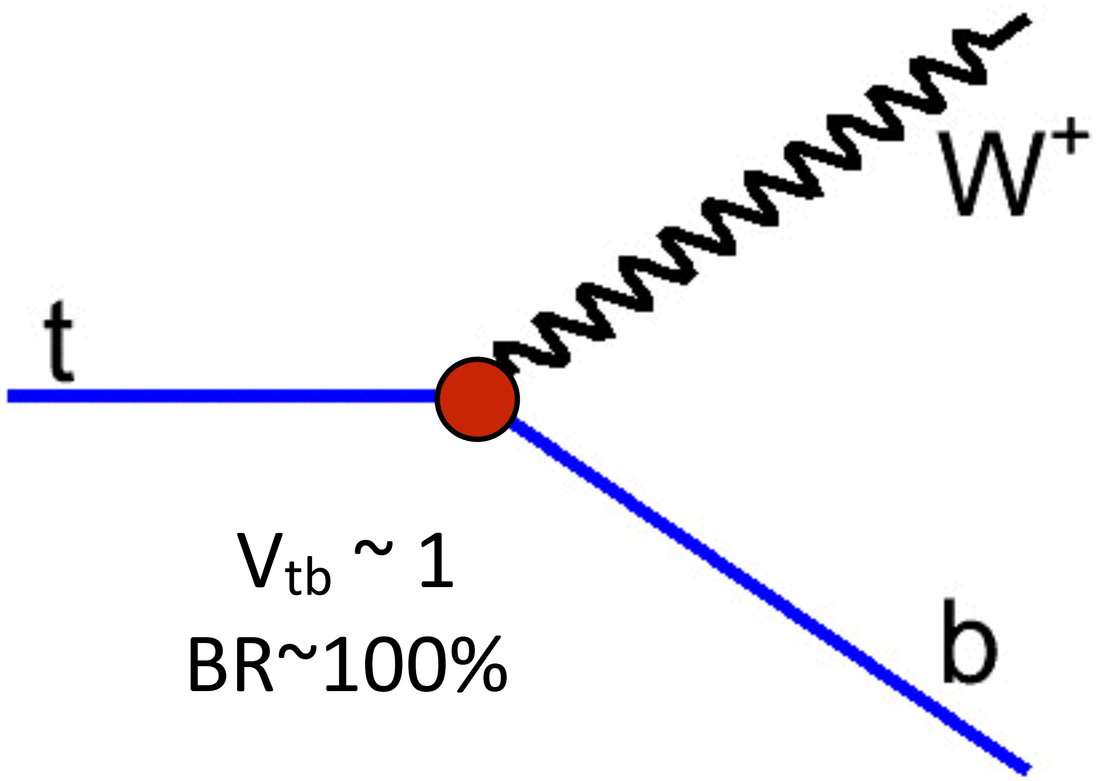
Top Physics = Full Detector ON



✓ Inner detector
reduce pileup, secondary vertices

✓ Calorimeters
electrons, jets, ETmiss

✓ Muon Spectrometer
muons, reject cosmic rays



W leptonic decays (*BR* ~ *1/3*)

trigger/bkg reduction if lepton = *e* / μ
high correlation w/ top flight direction

W hadronic decays (*BR* ~ *2/3*)

kinematic reconstruction, *in-situ* JES calibr.

b-jet tagging

background reduction (sec vtx)

Which measurement?			
	semi-leptonic (aka lepton+jets)	*full kinematic reco*	*t* mass, Δm_t, *W* polarization
	di-leptonic	*preserve angles, charge, low bkg*	*t* charge, *t* mass, *W* polarization

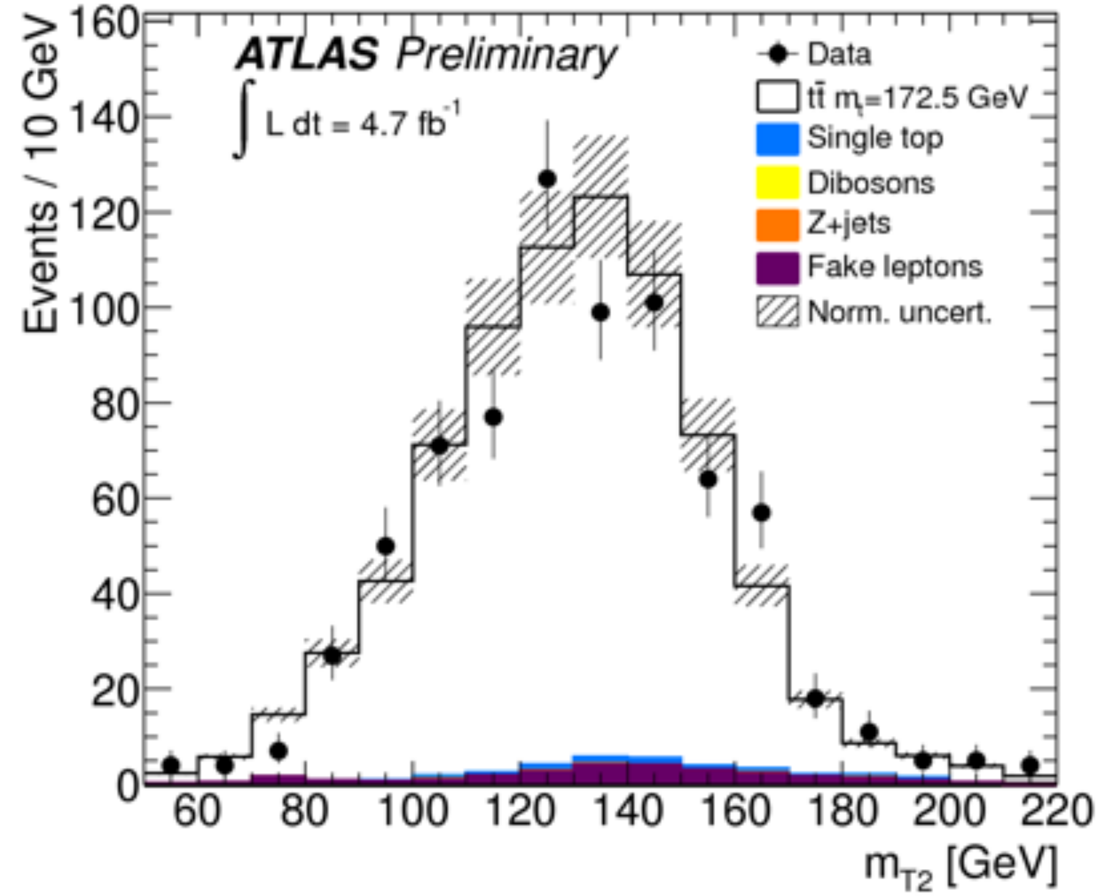
Other measurements

- “stransverse mass” m_{T2} in eμ

  invariant transverse mass, w/ missing particles

$$m_{\text{top}} = 175.2 \pm 1.6(\text{stat.})^{+3.1}_{-2.8}(\text{syst.})\ \text{GeV}$$

ATLAS-CONF-2012-077 | 4.7 fb^{-1} | 7 TeV

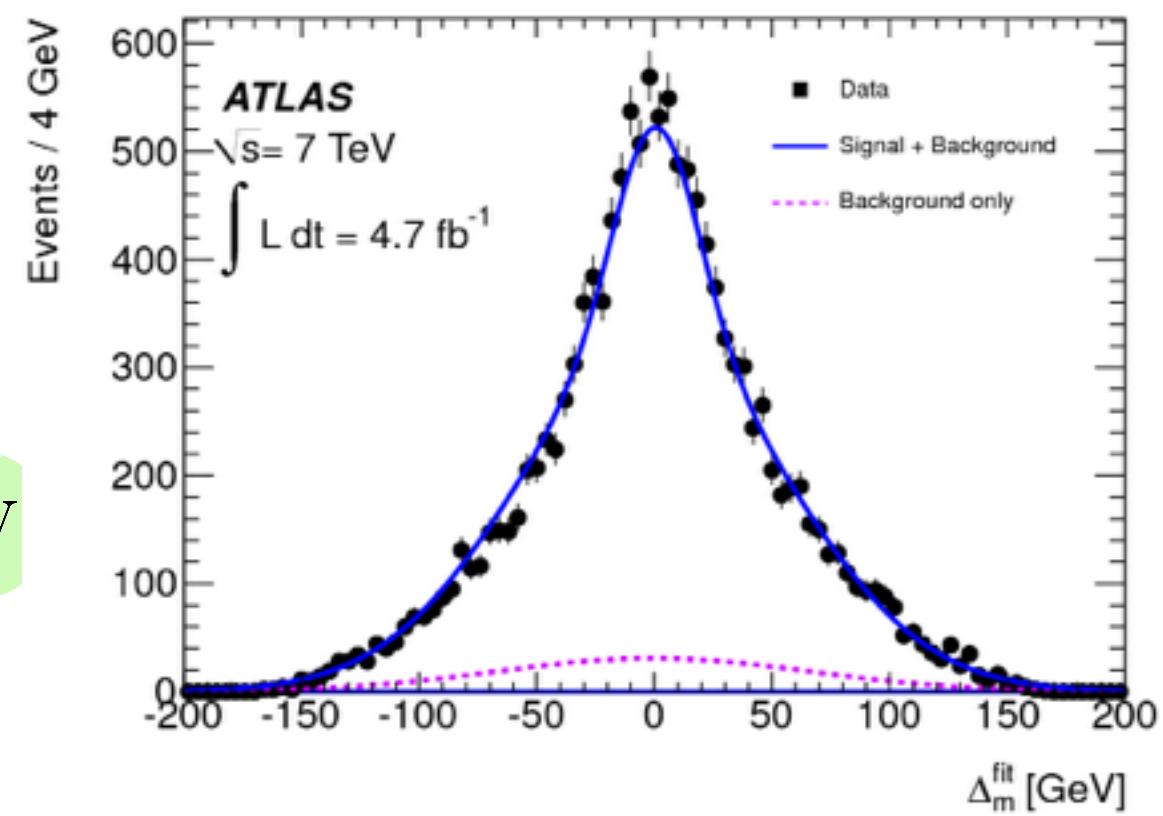


- Mass difference top-antitop

  CPT invariance: Δm = 0

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

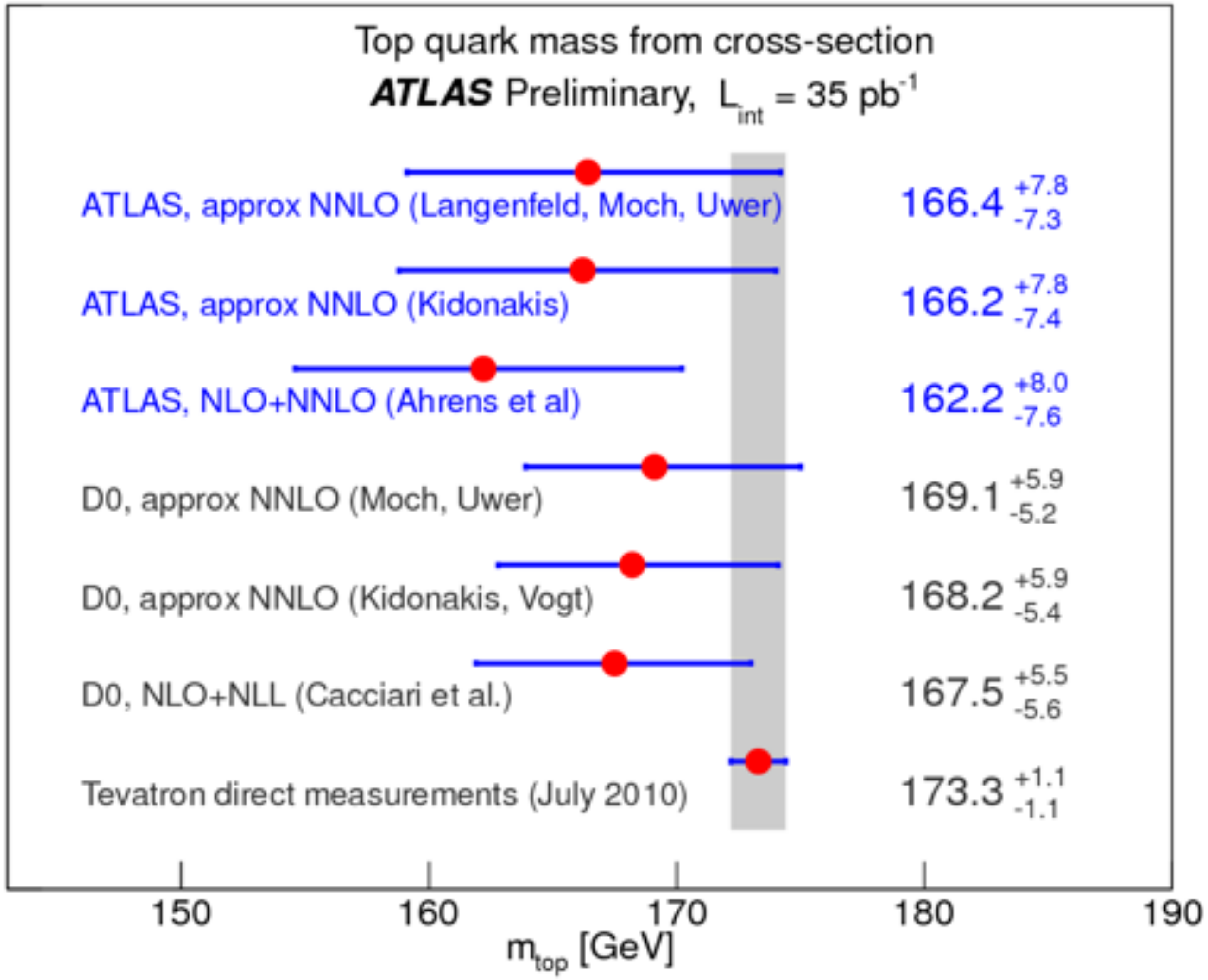
PLB 728C(2014)363-379 | 4.7 fb^{-1} | 7 TeV



Pole mass

- Extracted from cross-section
- Different parametrizations

$$\sigma_{t\bar{t}}(m_{\text{top}}^{\text{pole}}) = \left(\frac{1}{m_{\text{top}}^{\text{pole}}}\right)^4 \left(a + b(m_{\text{top}}^{\text{pole}} - 170) + c(m_{\text{top}}^{\text{pole}} - 170)^2 + d(m_{\text{top}}^{\text{pole}} - 170)^3\right) \text{ pb}$$



Flavor-Changing Neutral Currents

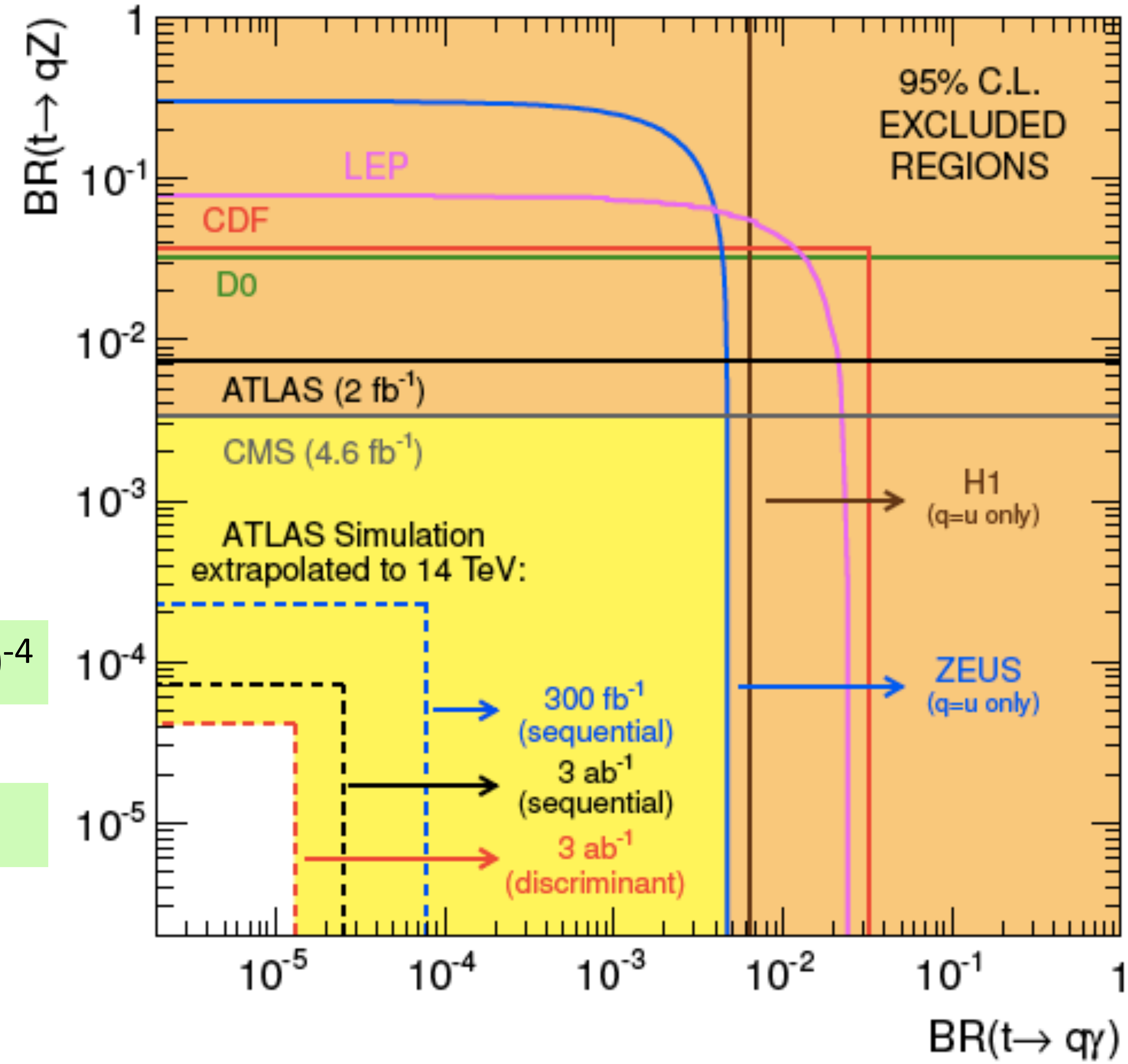
Prospect for HL-LHC

14 TeV

L_{int} 300 fb^{-1} ÷ 3000 fb^{-1}

interesting region BR < 10^{-4}

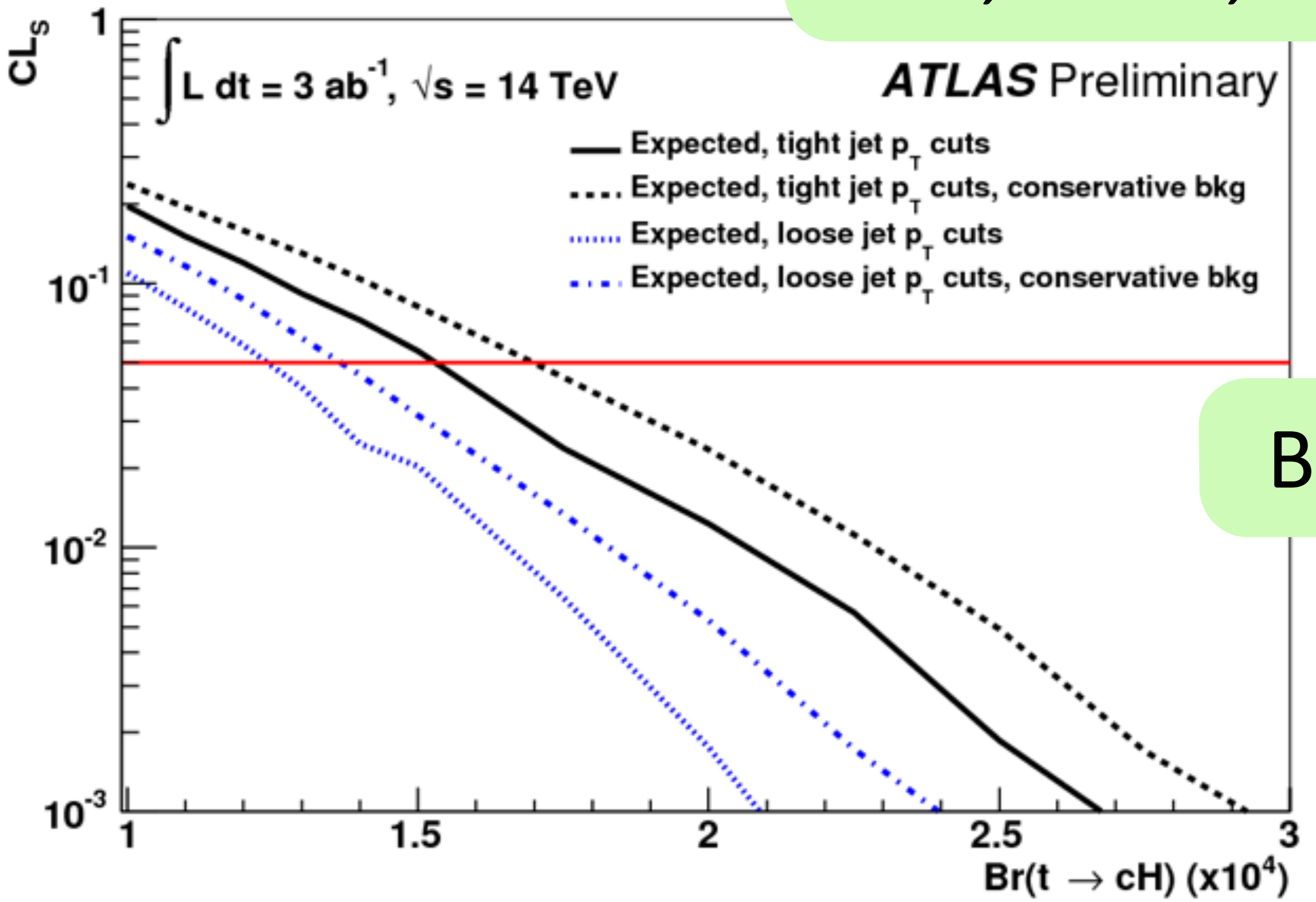
ultimate limits BR < 10^{-5}



FCNC Top decays HL-LHC

ATLAS-PHYS-PUB-2013-012

tt, t→cH, H→γγ



BR < 1.5 10^{-4} @ 95 CL