THE ROYAL SOCIETY

University of Glasgow

Top properties at the LHC

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On behalf of the ATLAS & CMS collaborations

52nd Rencontres de Moriond EW 2017

Why the top quark?

- In the Standard Model (SM) it's the only quark:

1. With a natural mass:

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

   - Hence, large correction to the Higgs mass: $\Delta {m_H^t}^2 \sim -\frac{y_t^2}{8\pi^2}\Lambda^2$
   - Top quark could be place to see new physics!

2. That decays before hadronizing:

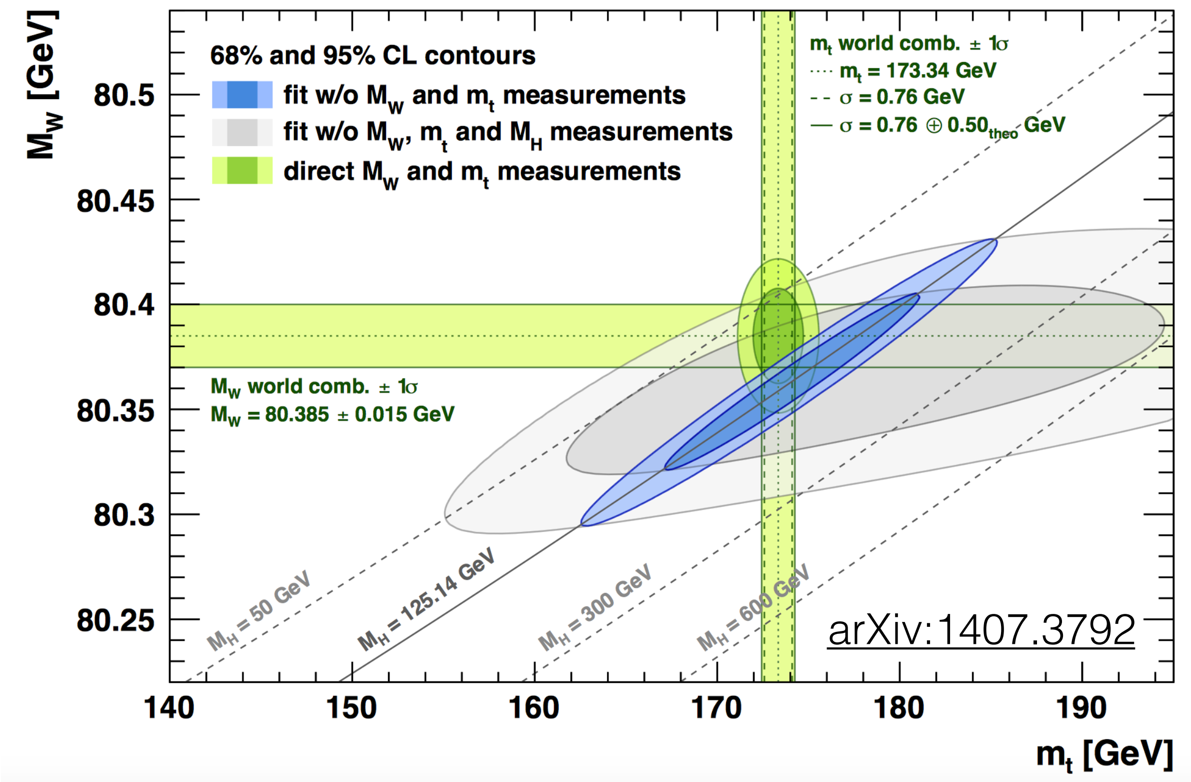
$$\tau_{had} \approx 2 \times 10^{-24} s$$

$$\tau_{top} \approx 5 \times 10^{-25} s$$

   - Chance to study a 'bare' quark.

Why top properties?

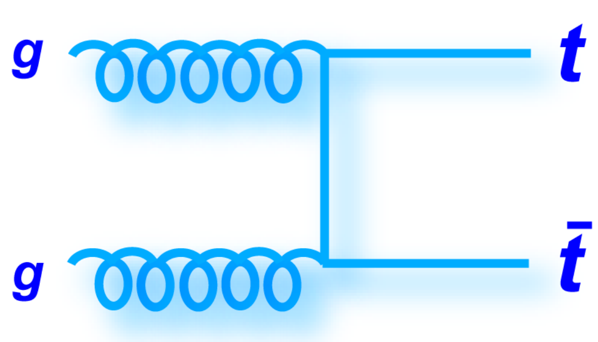
- Top quark mass is a fundamental parameter of the Standard Model:
    - Precise measurement needed for checking consistency of the SM.

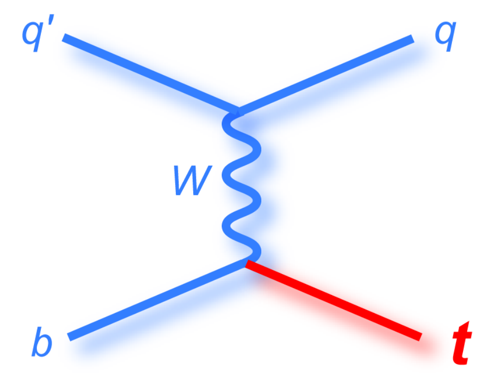


- Other properties of the top quark (electroweak coupling, production asymmetries) are predicted by SM.
    - Precise measurements could reveal the SM breaking down.

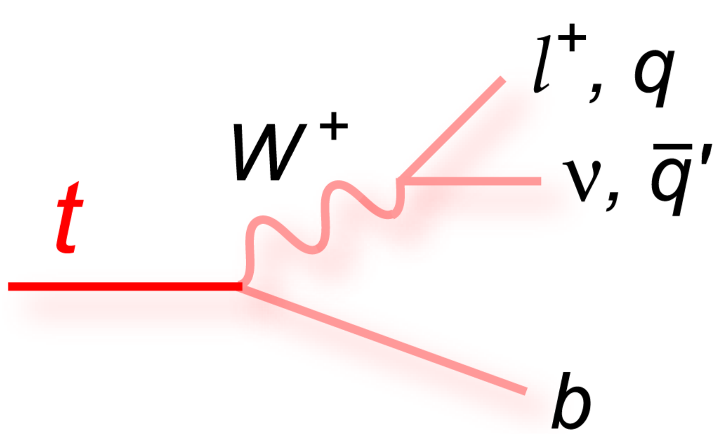
Top production & decay

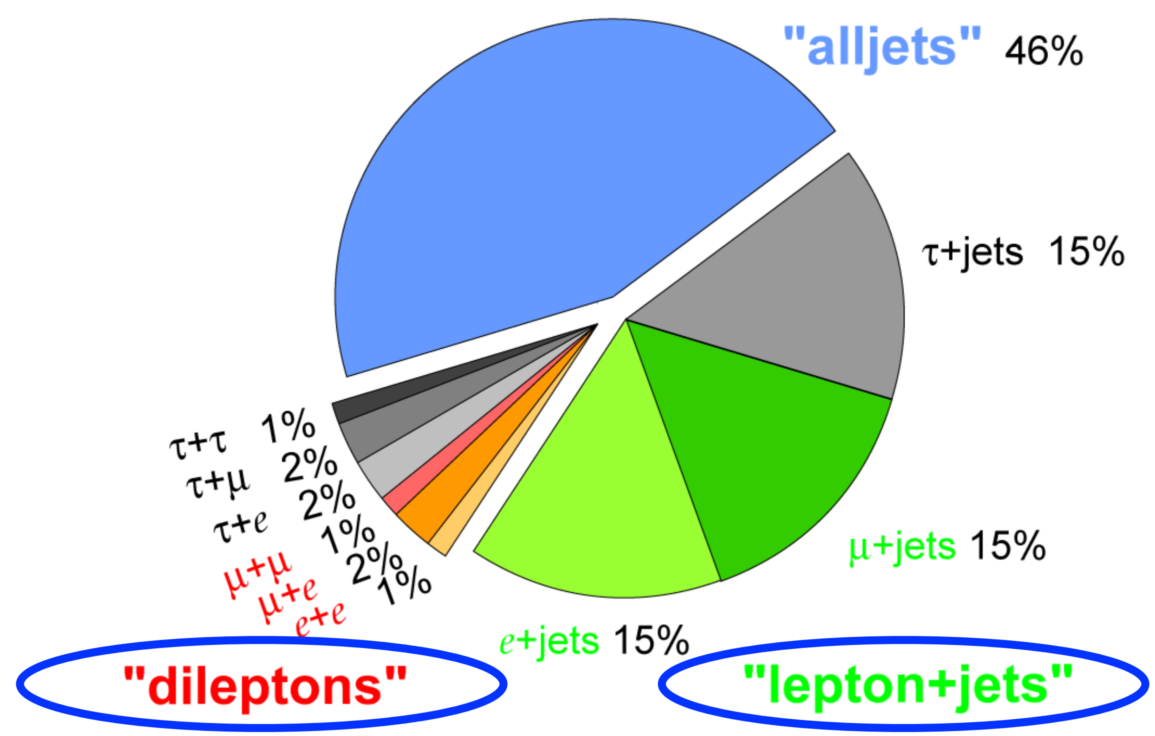
- Top production dominated by QCD production. EW production provides direct access to Wtb vertex:



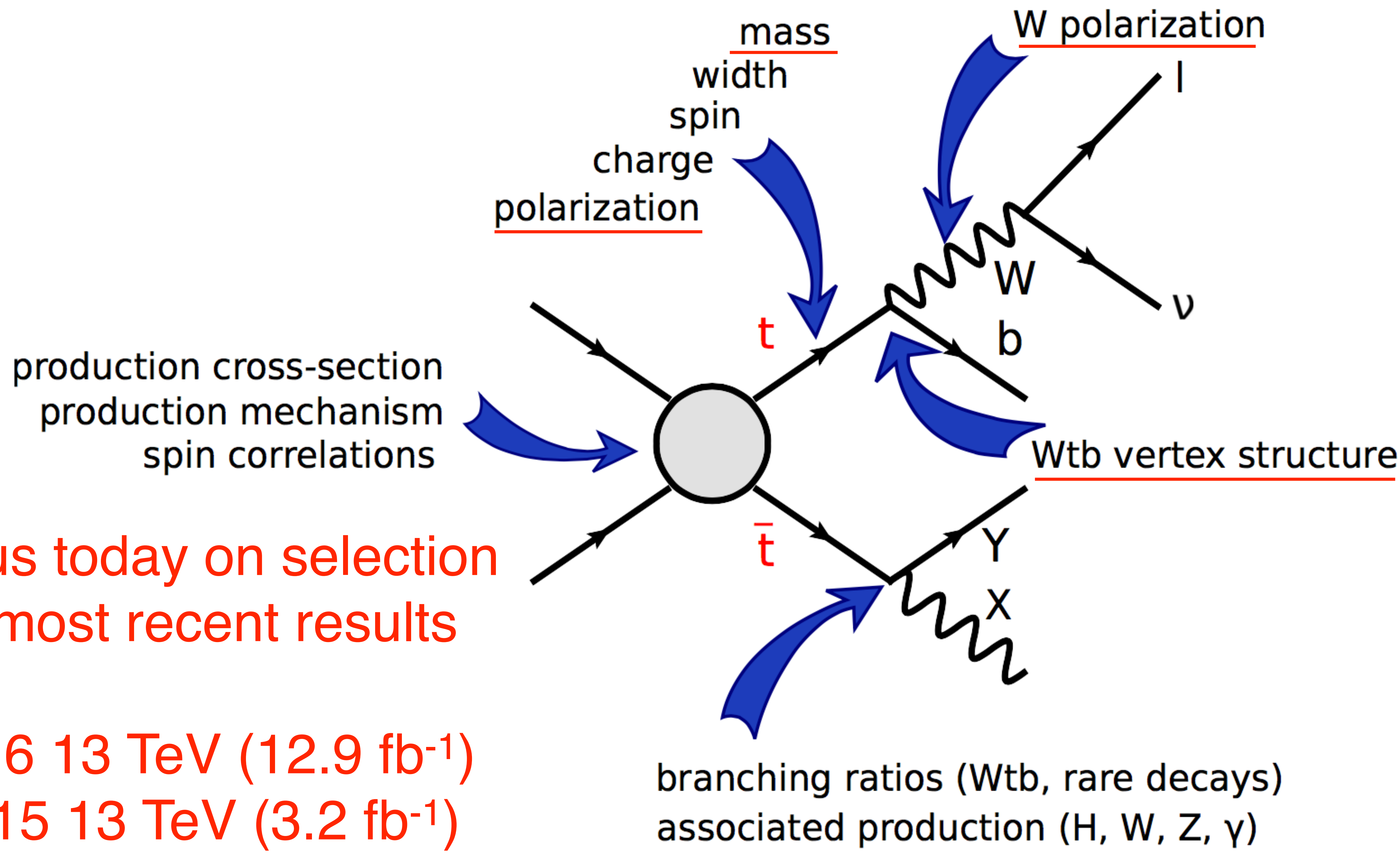


- In SM top decays to Wb:





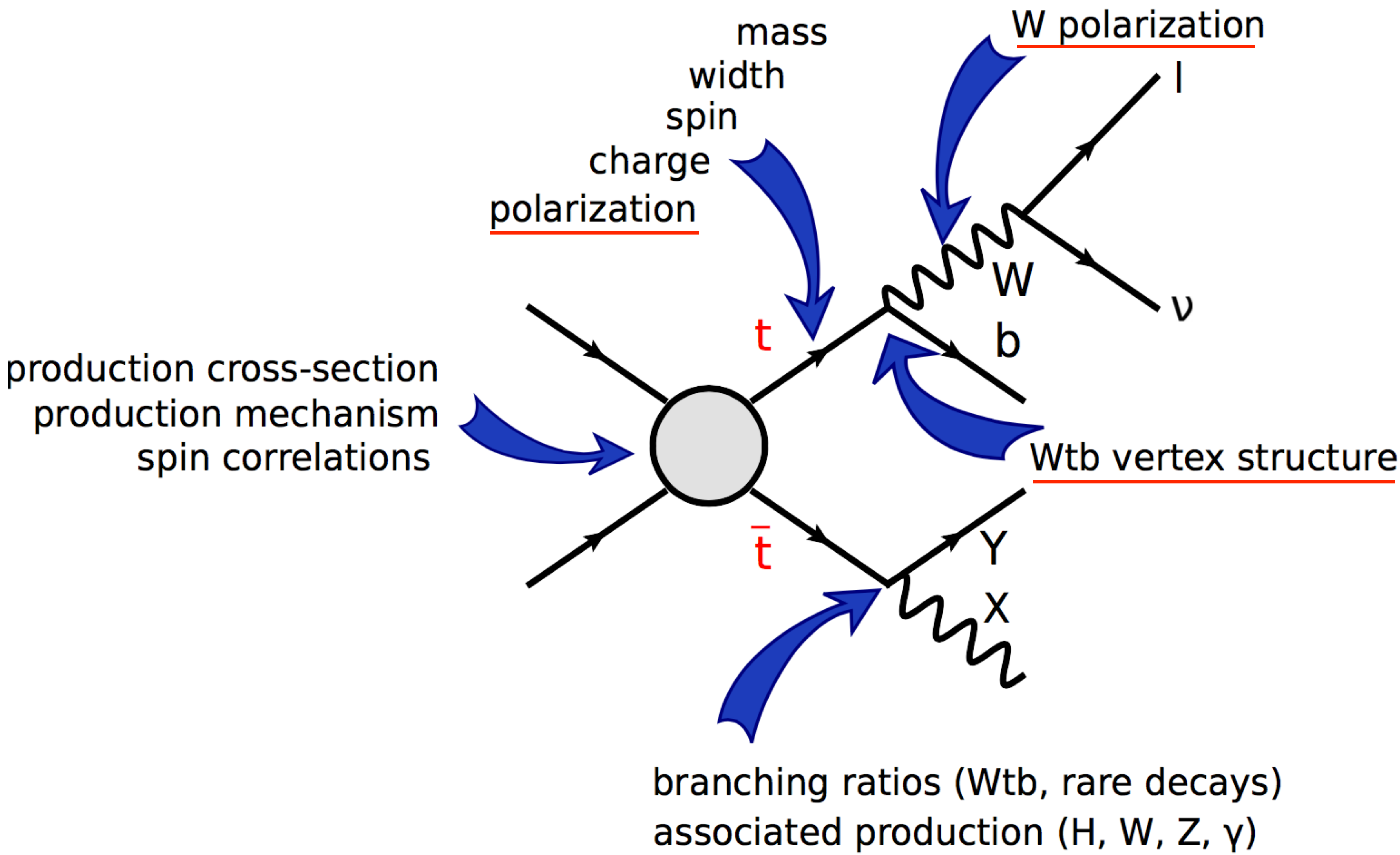
Outline



Focus today on selection of most recent results

2016 13 TeV (12.9 fb^{-1})
2015 13 TeV (3.2 fb^{-1})
2012 8 TeV (20 fb^{-1})

Outline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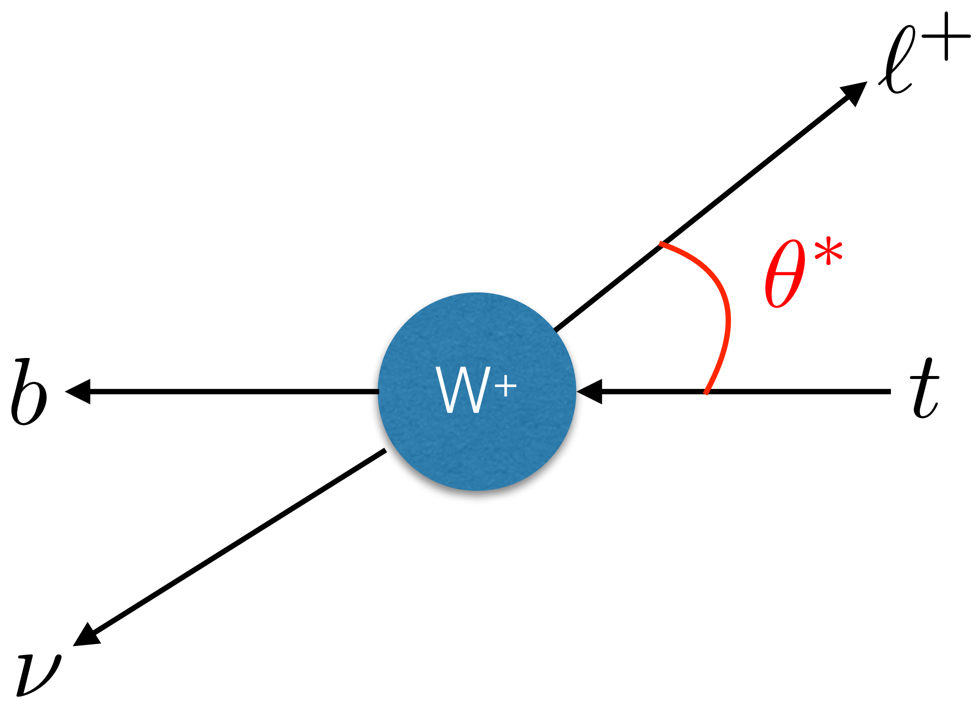
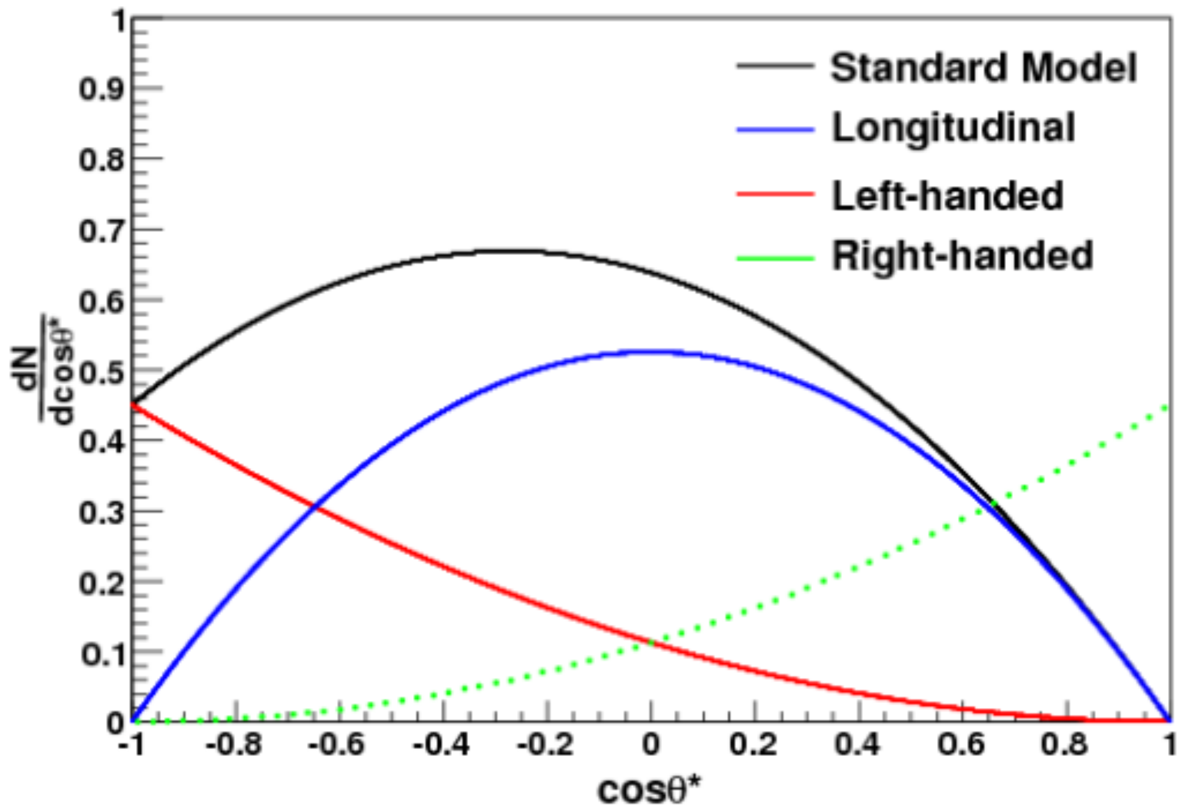
production cross-section
production mechanism
spin correlations
Wtb vertex structure
t̄
Y
X
branching ratios (Wtb, rare decays)
associated production (H, W, Z, γ)

W boson polarisation

- W bosons can be produced with left-handed, right-handed or longitudinal polarisation.
- The top decay vertex in the SM, Wtb, is characterised by the (V - A) structure → fractions of polarisation states are well predicted.
- Can probe this by measuring the angular distributions of the W boson decay products:

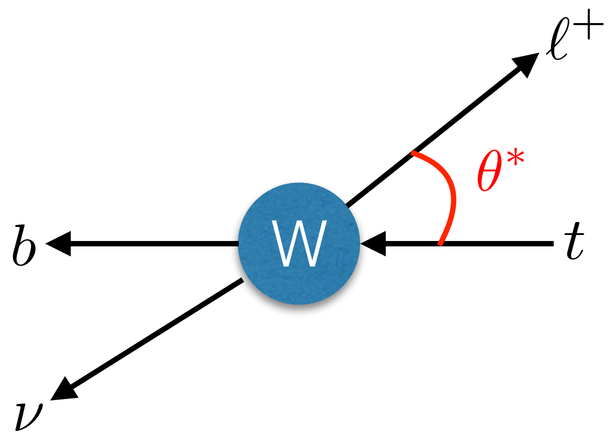


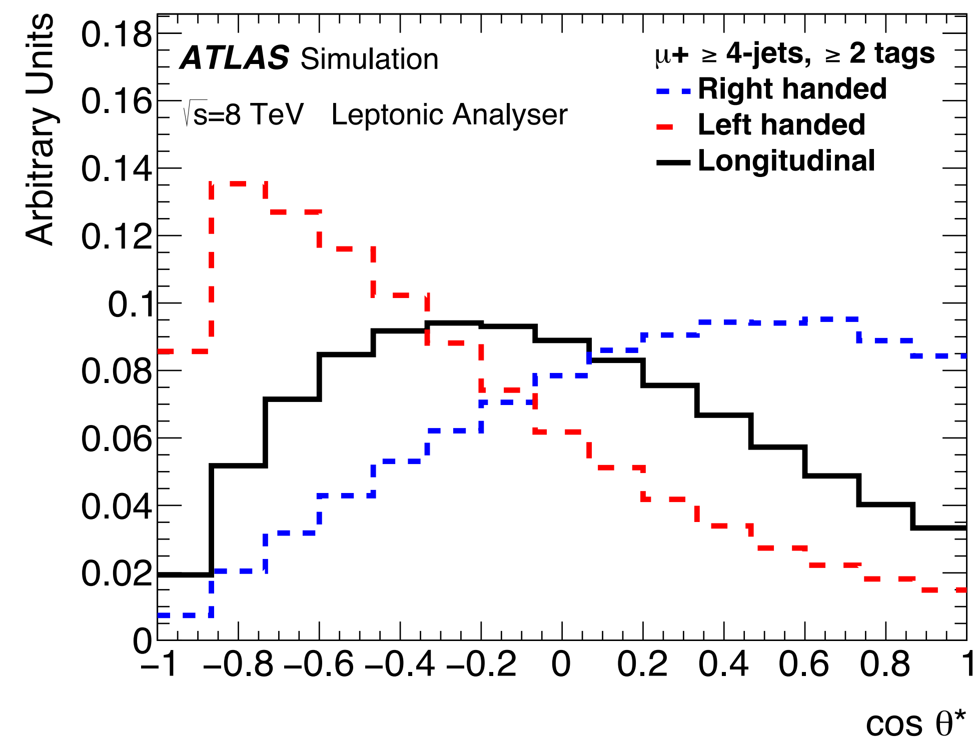


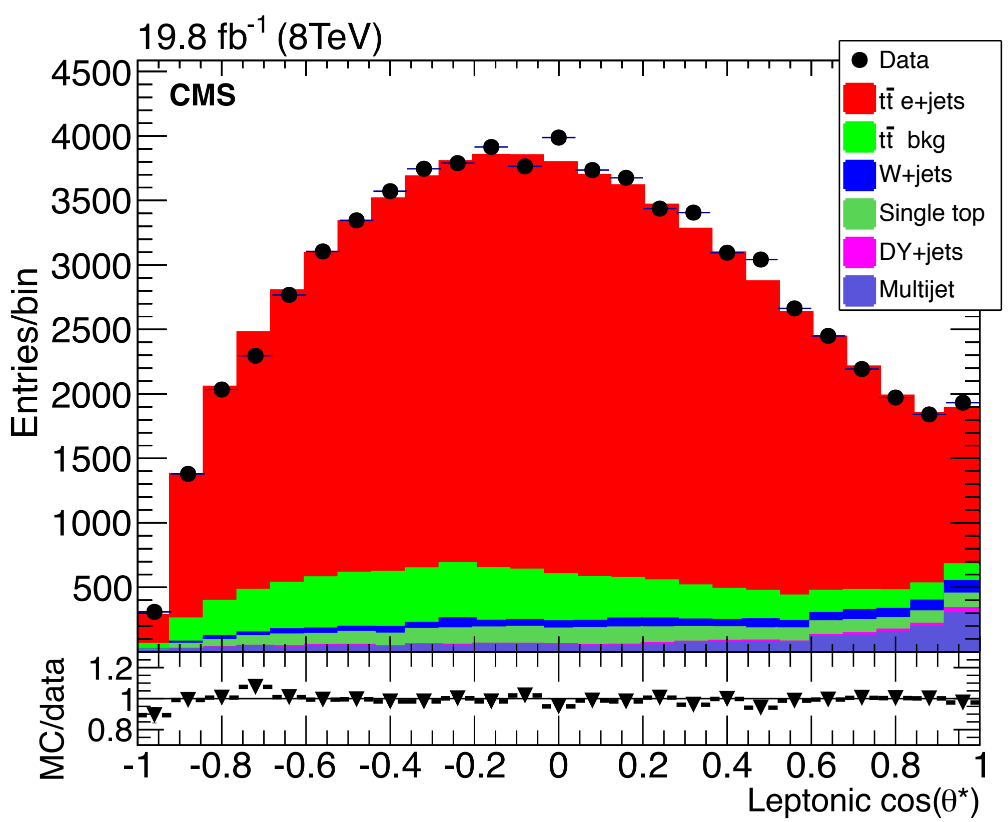
- New physics could be present in the vertex & change the produced polarisation.

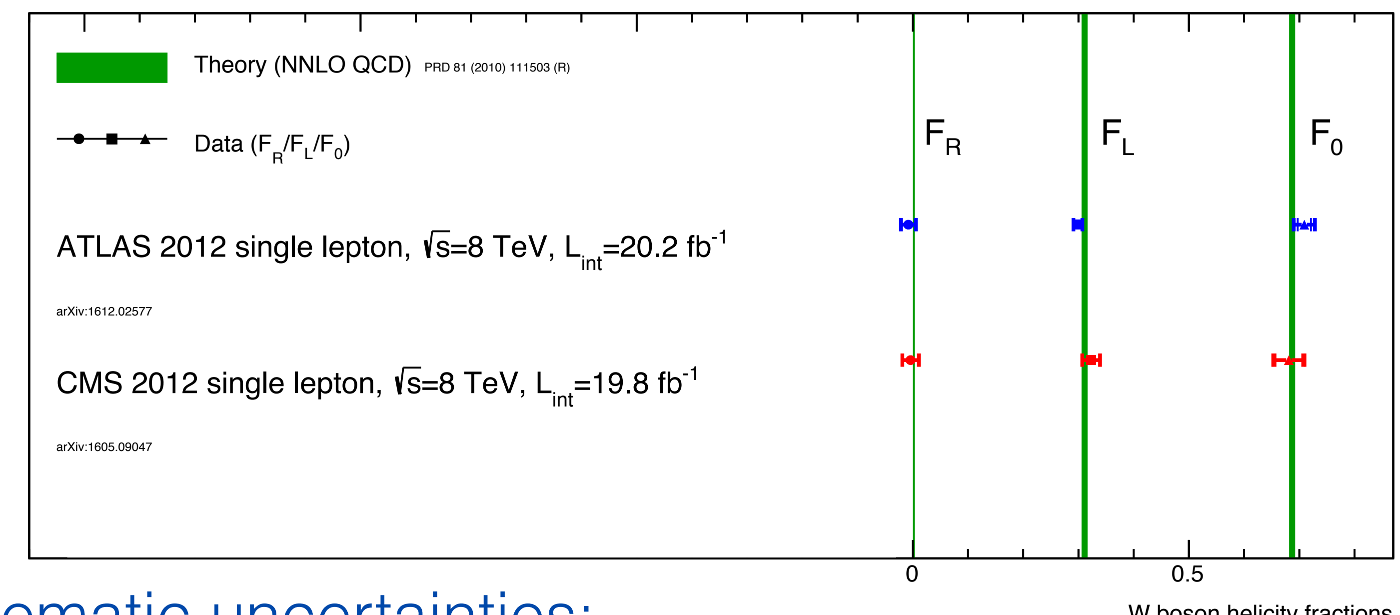
W boson polarisation

- Use top-quark pair events & reconstruct full system:







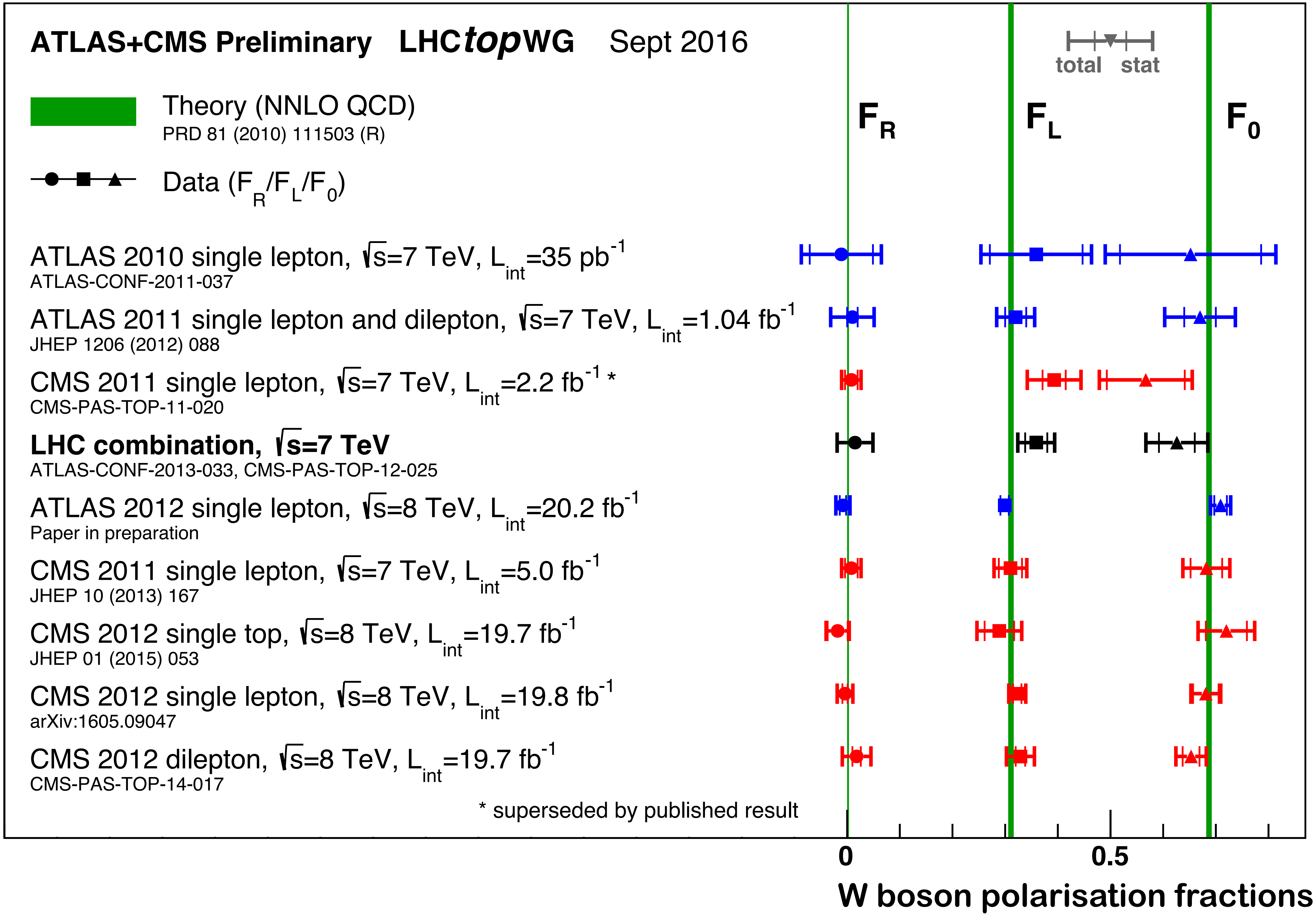


Largest systematic uncertainties:
jet energy scale (JES), Monte Carlo (MC) modelling.

arXiv:1605.09047

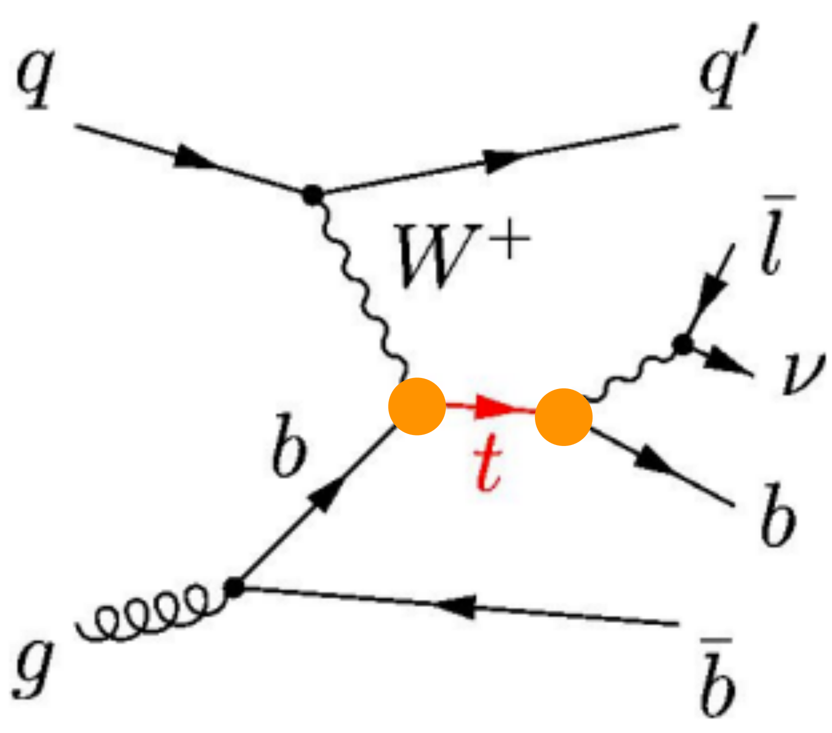
arXiv:1612.02577

W boson polarisation



Polarisation in single top

- Single-top t-channel production sensitive to Wtb vertex in both production and decay.
- SM predicts non-zero polarisation of single-top quark production. Full system can be parameterised in terms of polarisation & 6 independent W-boson spin observables.



arXiv:1702.08309

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R + F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R - F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1 - 3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

arXiv:1508.04592
arXiv:1005.5382

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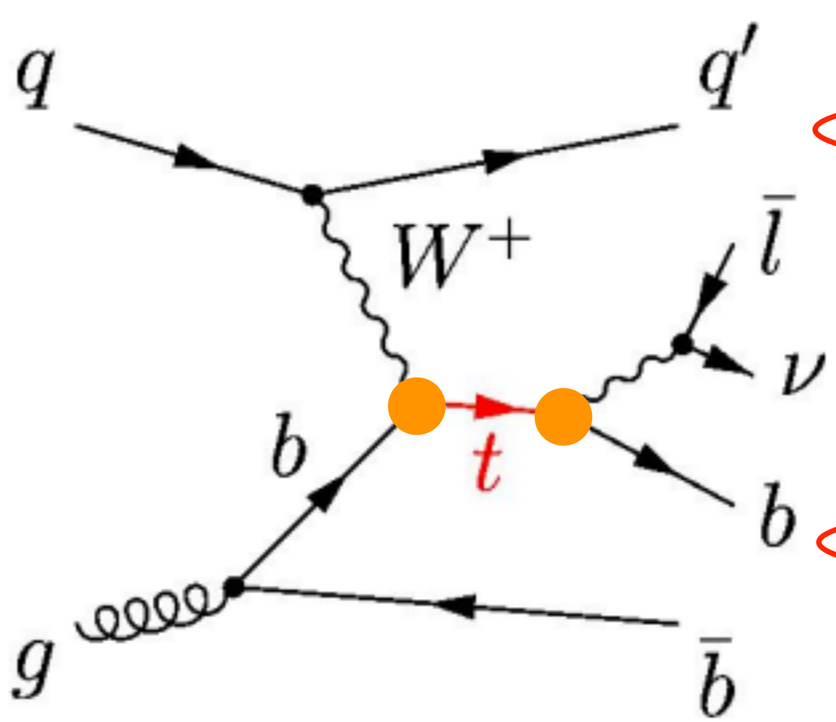

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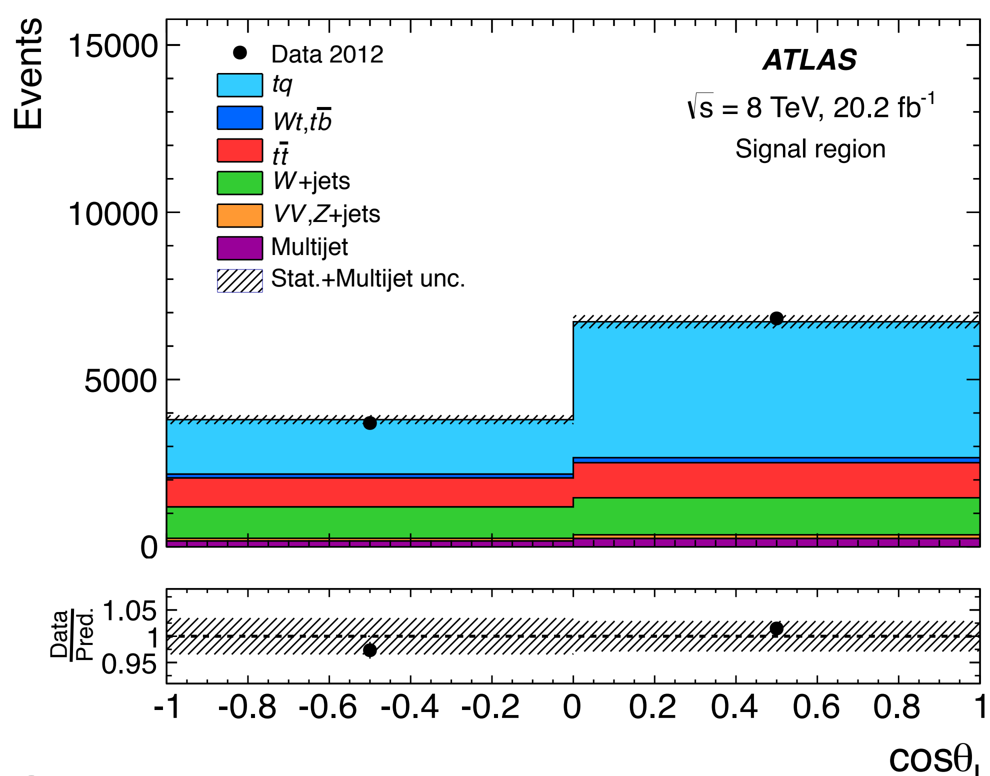
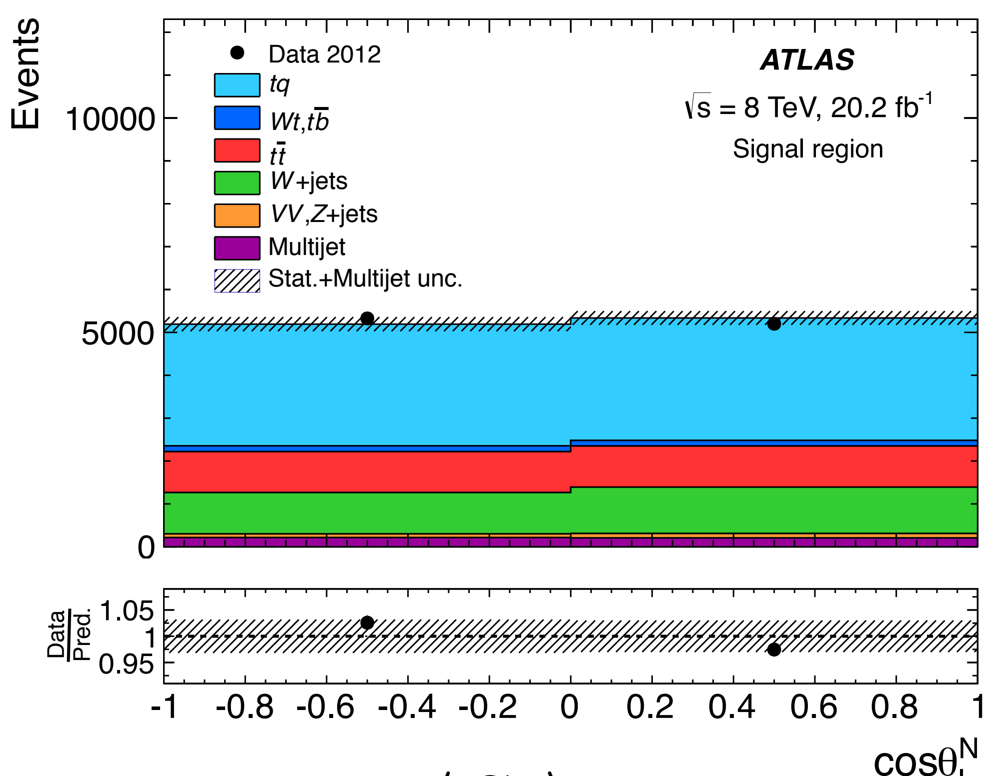
Polarisation in single top

- Kinematic cuts used to separate single-top from W and top-pair backgrounds.
- Angular asymmetries sensitive to top polarization and W boson spin observable $\langle S_2 \rangle$:





SM: $P = 0.9$ $\langle S_2 \rangle = 0$

ATLAS Data: $P = 0.97 \pm 0.12$ $\langle S_2 \rangle = 0.06 \pm 0.05$

CMS Data: $P = 0.52 \pm 0.22$

arXiv:1702.08309 arXiv:1511.02138

Largest systematic uncertainties: JER, JES, MC modelling.

Wtb vertex constraints

- Interpret these measurements by considering general expression for the Wtb vertex:

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

SM: $V_L = V_{tb}$ $V_R = 0$ $g_L = 0$ $g_R = 0$

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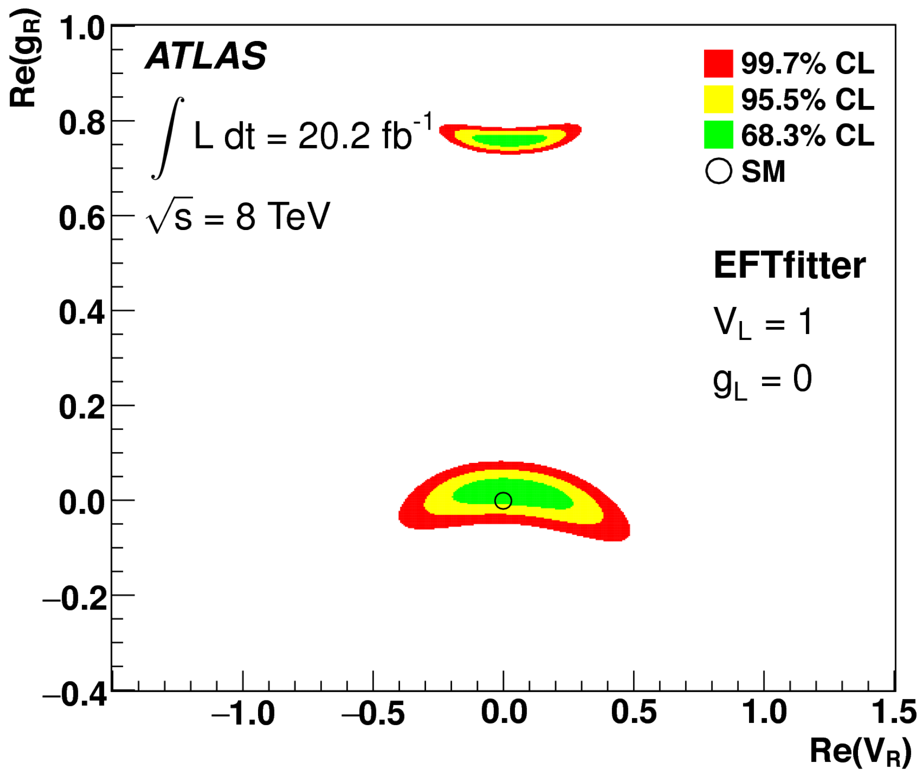
ATLAS W polarization:



arXiv:1612.02577 arXiv:1702.08309 arXiv:1610.03545

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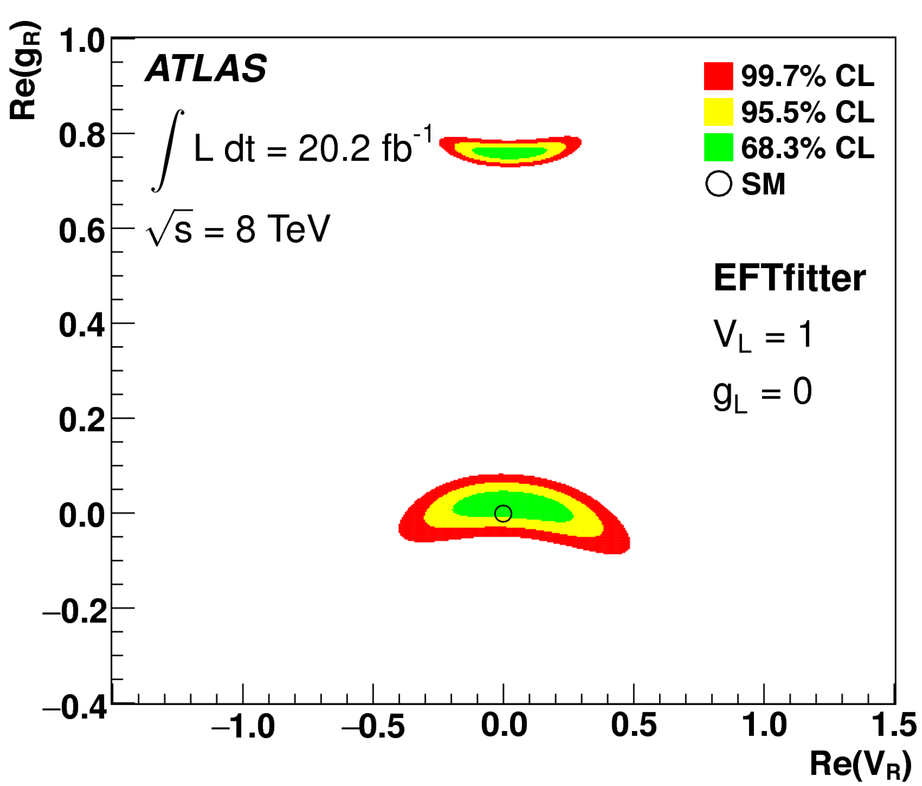

arXiv:1612.02577

ATLAS single-top: $\mathrm{Im}(g_R) \in [-0.18, 0.06]$

arXiv:1702.08309

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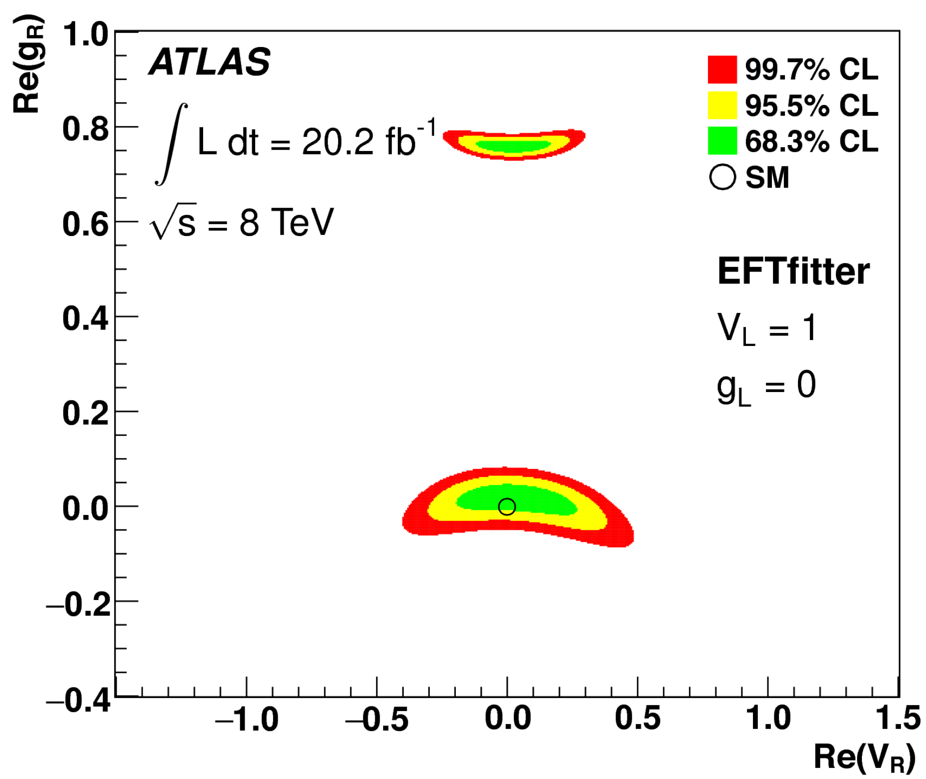

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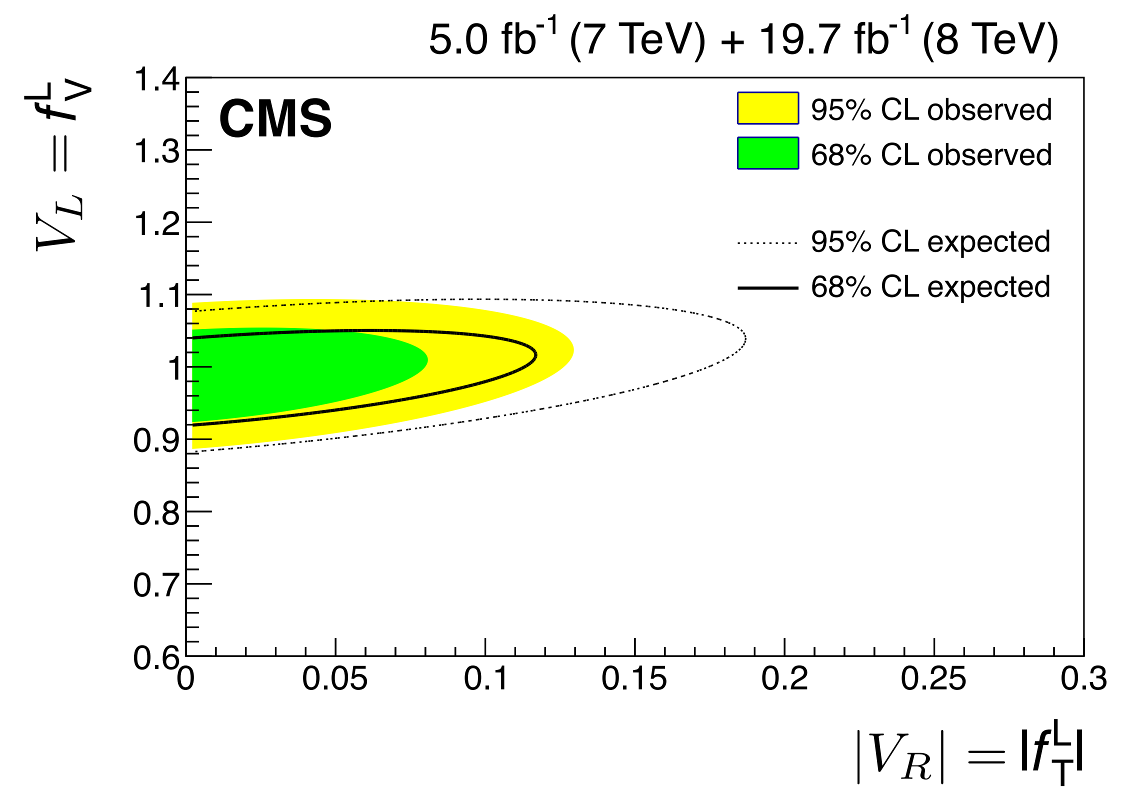
arXiv:1702.08309

CMS single-top:



arXiv:1610.03545

Wtb vertex constraints

- Interpret these measurements by considering general expression for the Wtb vertex:

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

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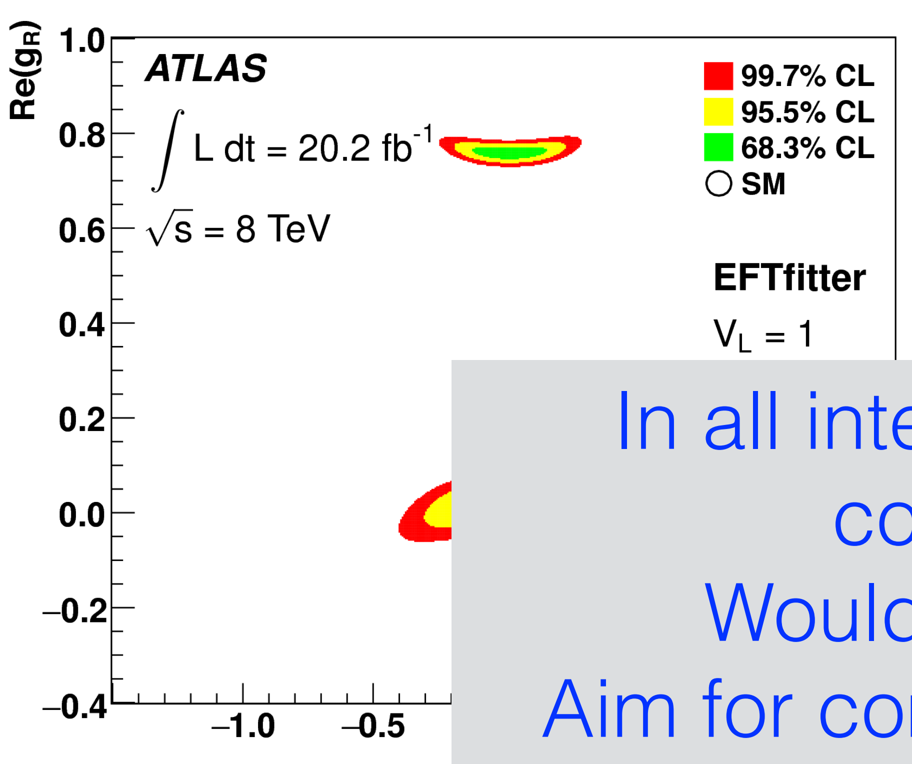
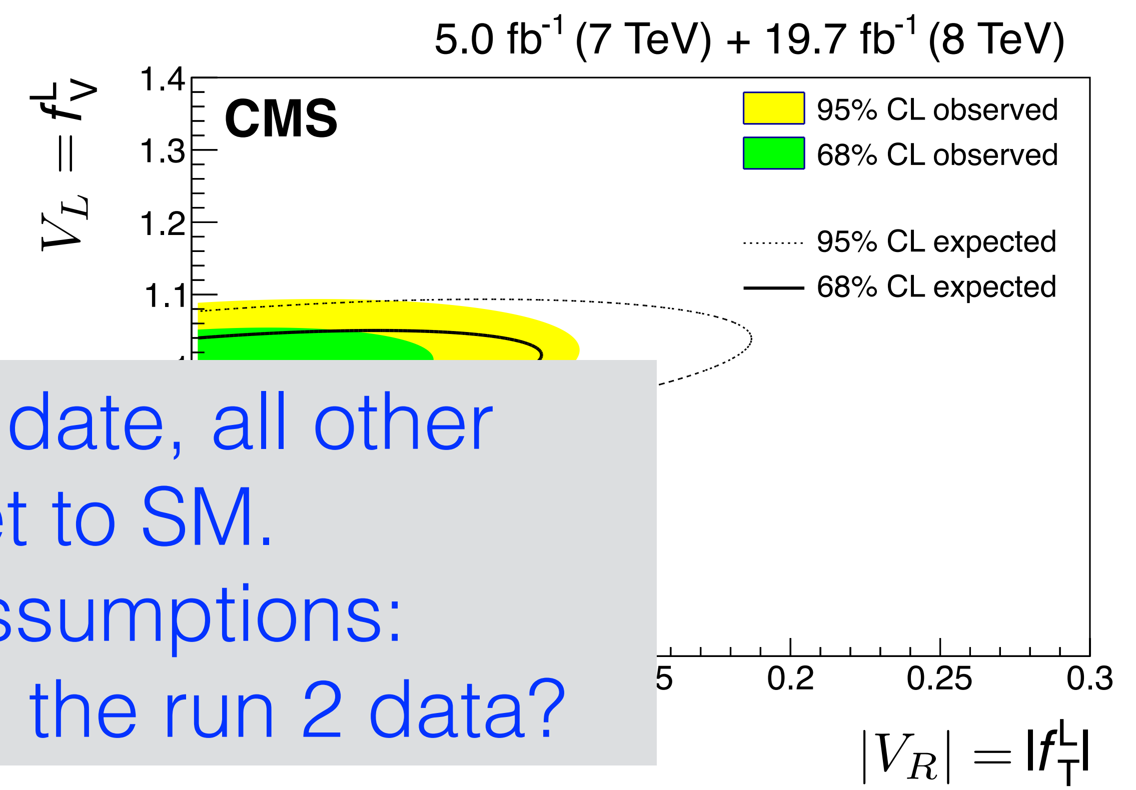


arXiv:1612.02577

CMS single-top:

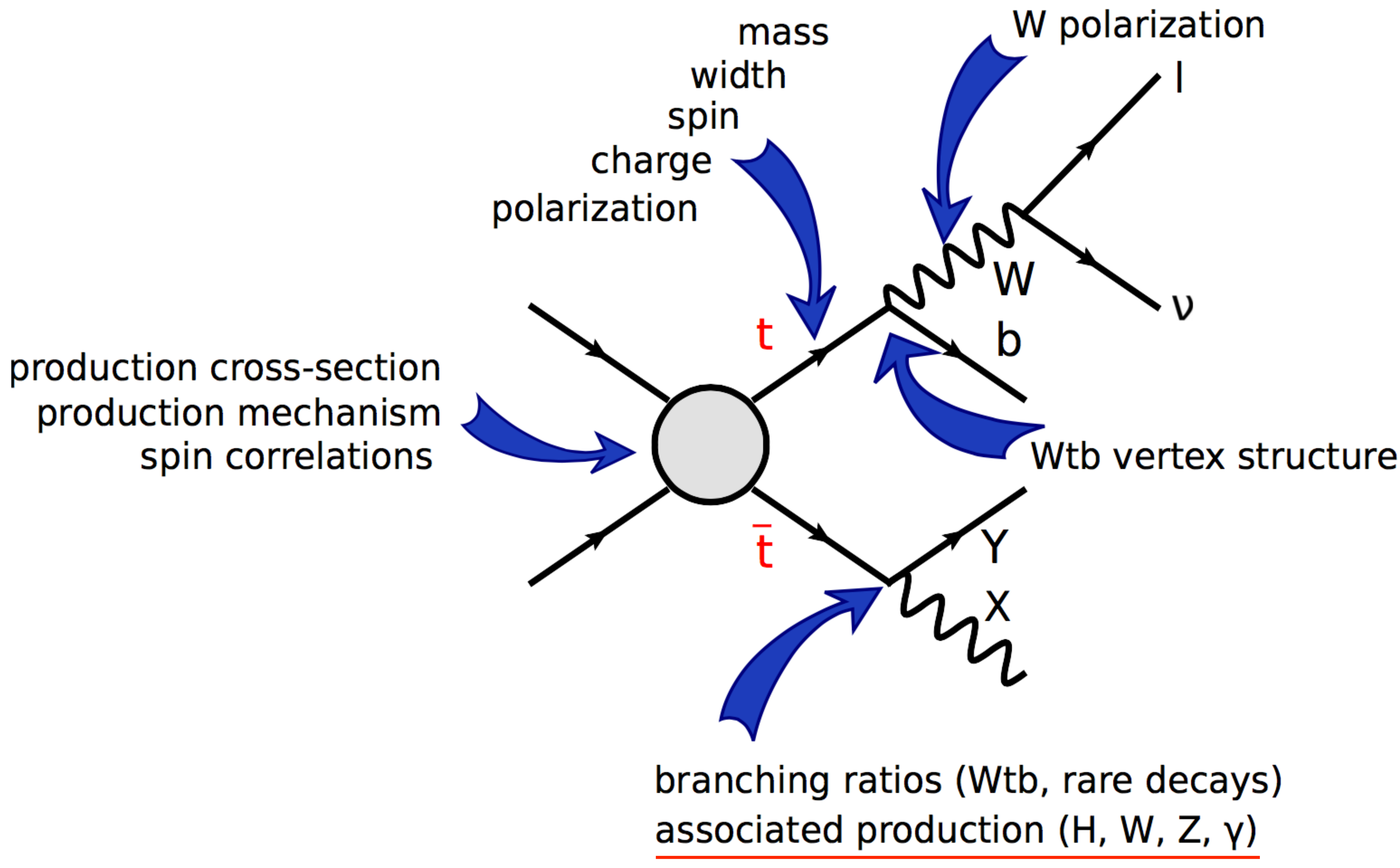
arXiv:1702.08309



arXiv:1610.03545

In all interpretations to date, all other couplings are set to SM.
Would prefer less assumptions:
Aim for combined fit with the run 2 data?

Outline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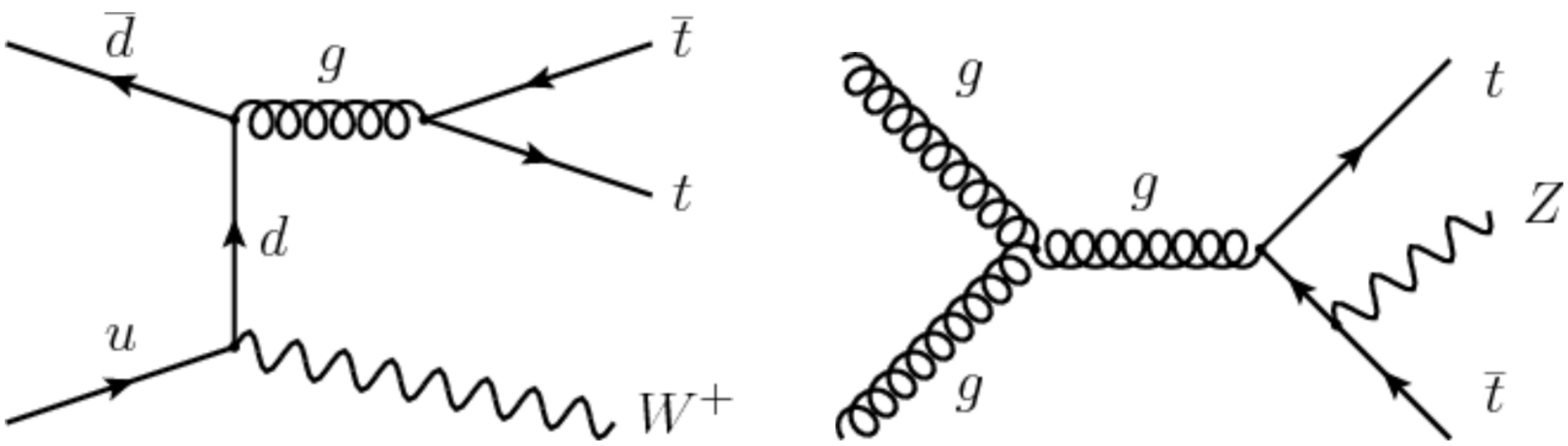
branching ratios (Wtb, rare decays)
associated production (H, W, Z, γ)

ttV Production

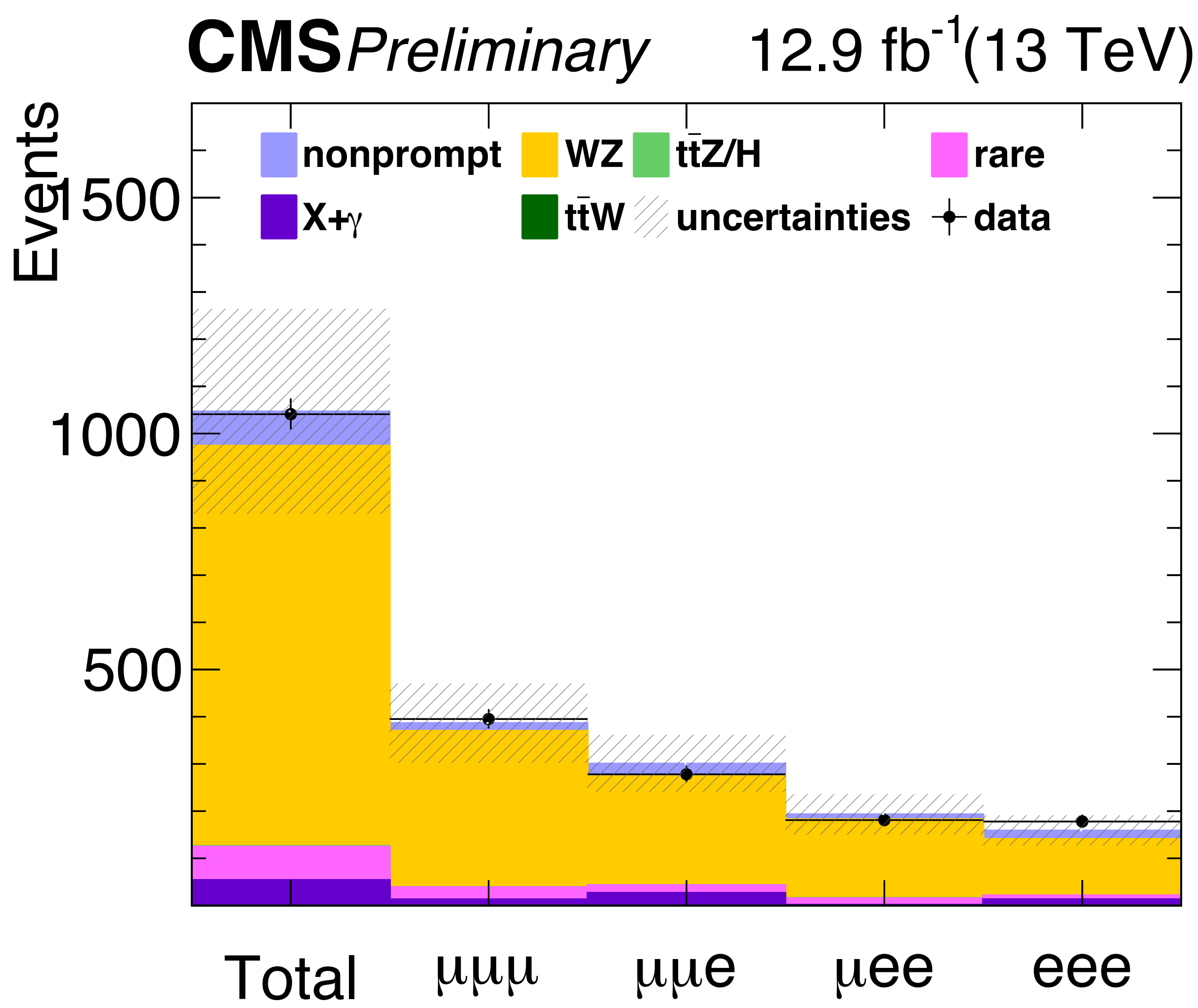
- Large datasets give access to rare tt+W and tt+Z processes.
  - ttZ: Direct probe of top-Z coupling (new physics?).
  - ttW: Important background to new physics searches.

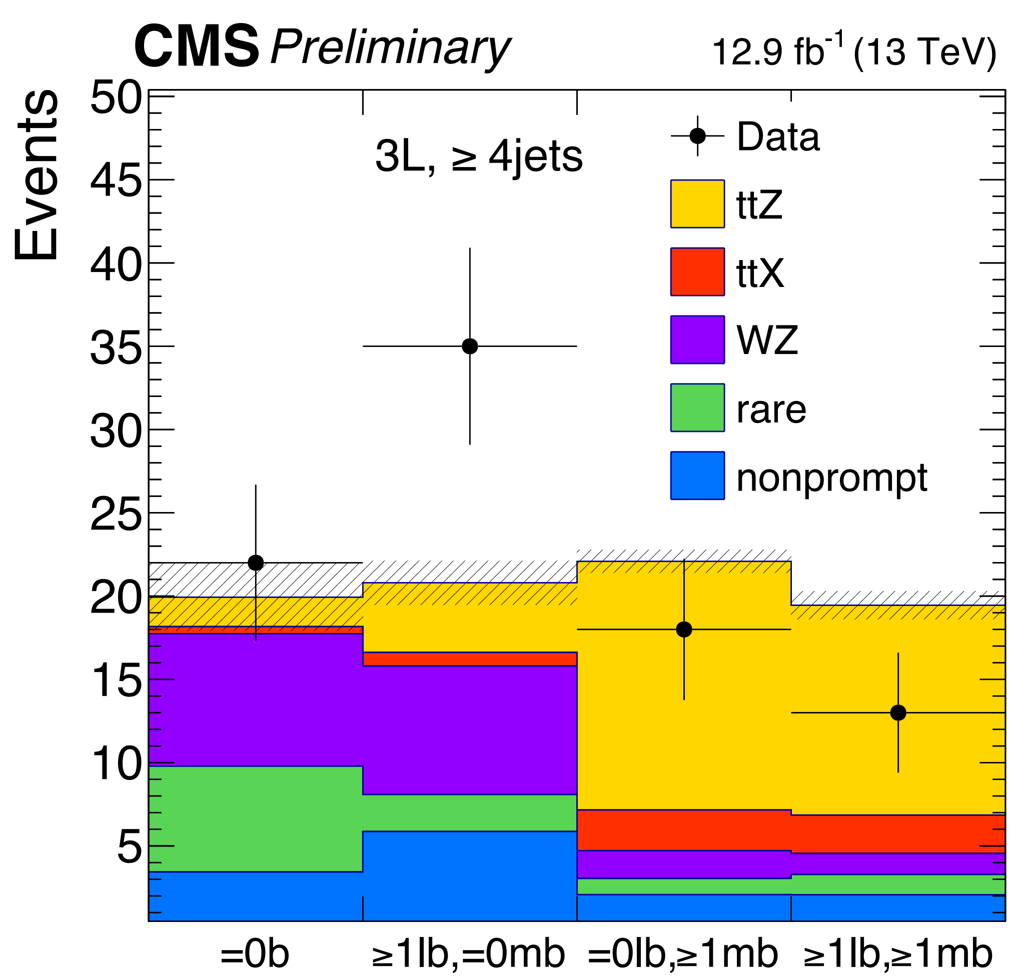


- Use multi-lepton final states to reduce background:
  - 2 same-sign charge leptons, 3 or 4 lepton final states.

ttV Production

- 2 same-sign charge leptons, 3 or 4 lepton final states.
    - Split selected events according to number of jets & b-jets.
    - Control regions used to check WZ and ZZ backgrounds.

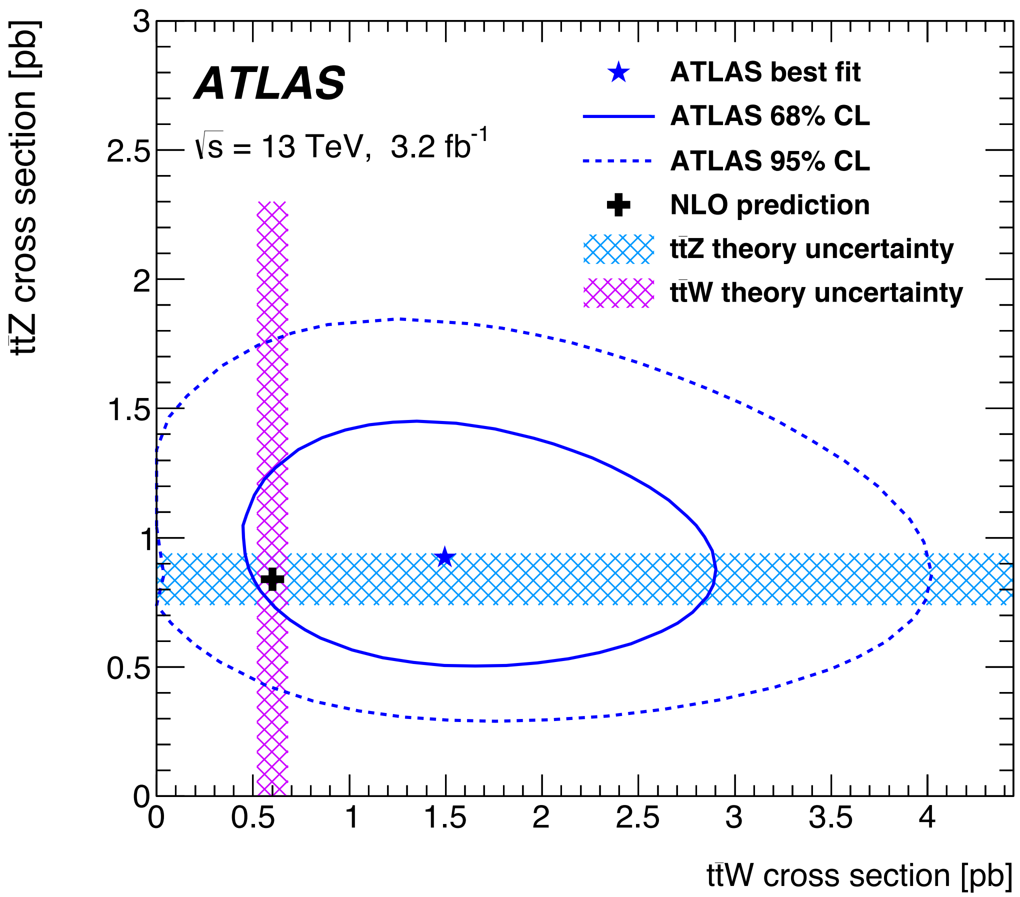


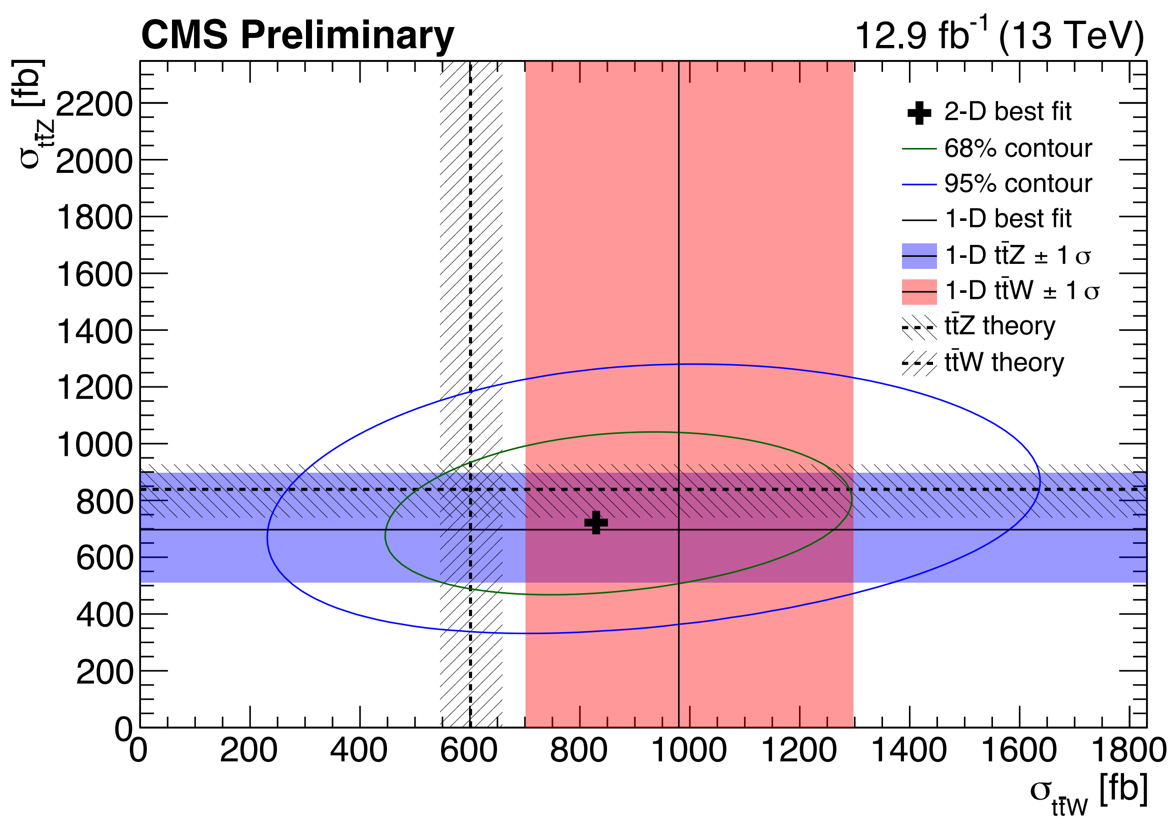


CMS-PAS-TOP-16-017

ttV Production

- Fit to the many signal-regions to simultaneously extract ttW and ttZ cross-sections:





$t\bar{t}W$: 2.2σ (expected : 1.0σ)

$t\bar{t}Z$: 3.9σ (expected : 3.4σ)

$t\bar{t}W$: 3.9σ (expected : 2.6σ)

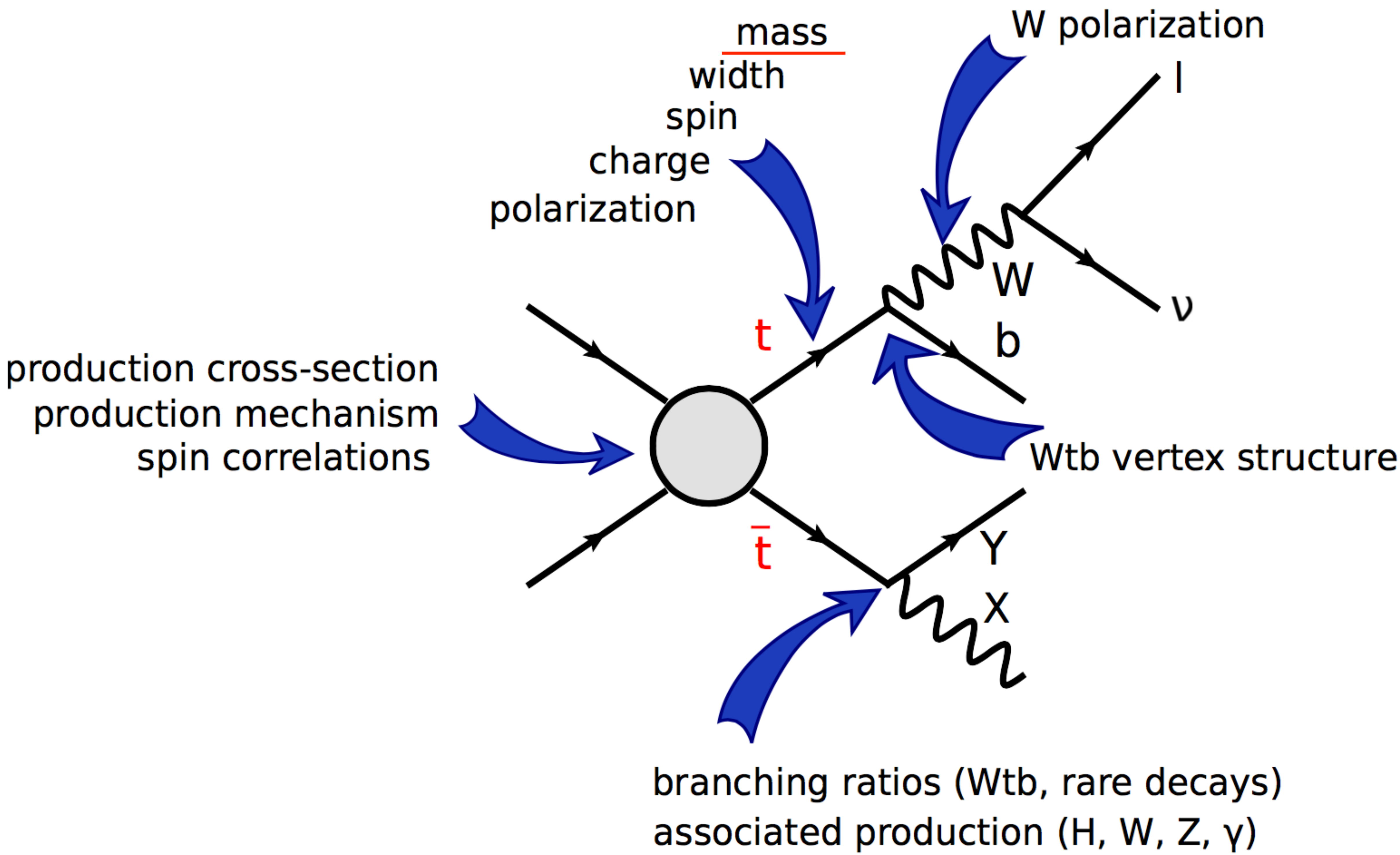
$t\bar{t}Z$: 4.6σ (expected : 5.8σ)

Measurements still statistics limited - looking forward to results with higher statistics.

arXiv:1609.01599

CMS-PAS-TOP-16-017

Outline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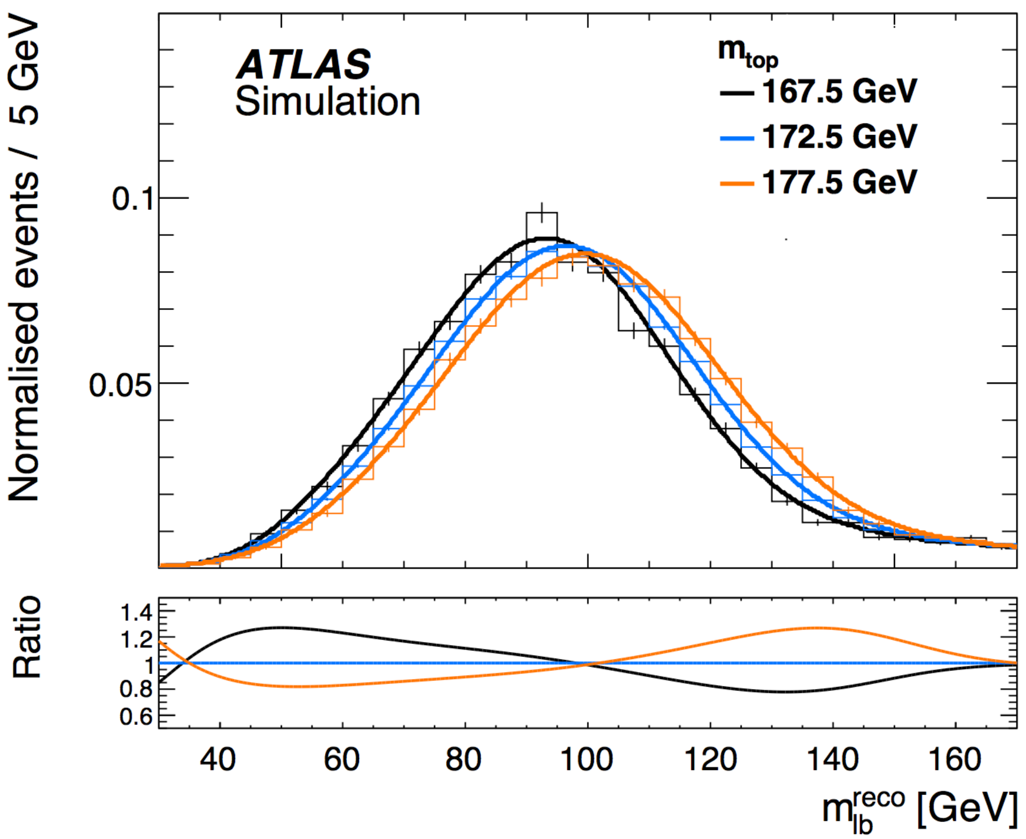
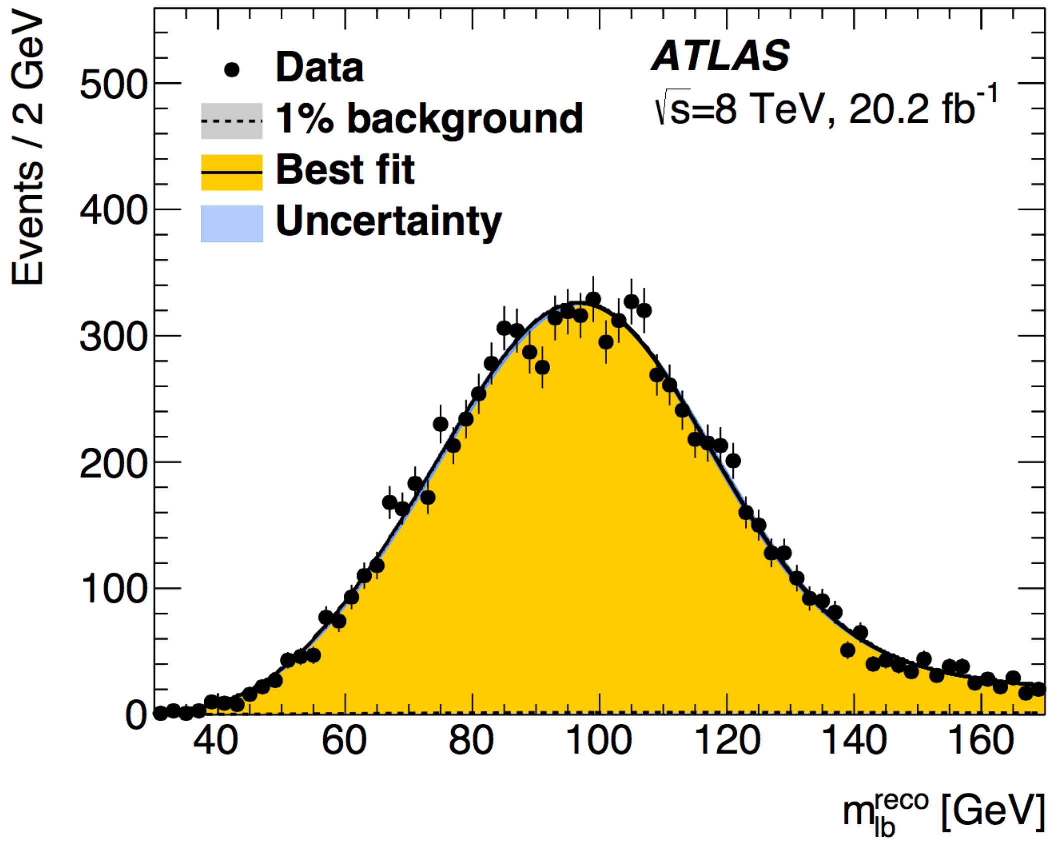
The top quark mass

- Dilepton channel: two neutrinos in the final state, system is under-constrained.
  - Optimised selection on pT(lb) to reduce uncertainties.
  - Use m(lb) as top mass sensitive variable.





Largest systematic uncertainties:
JES (0.54 GeV), MC modelling (0.35 GeV), bJES (0.3 GeV).

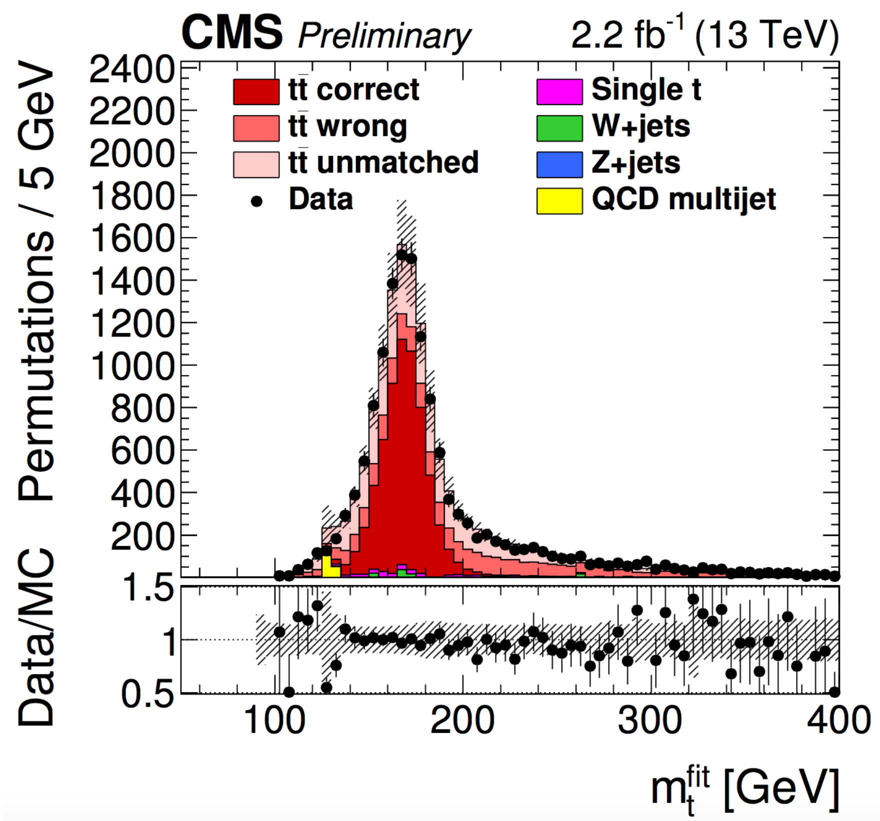
$$m_{top} = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV}$$

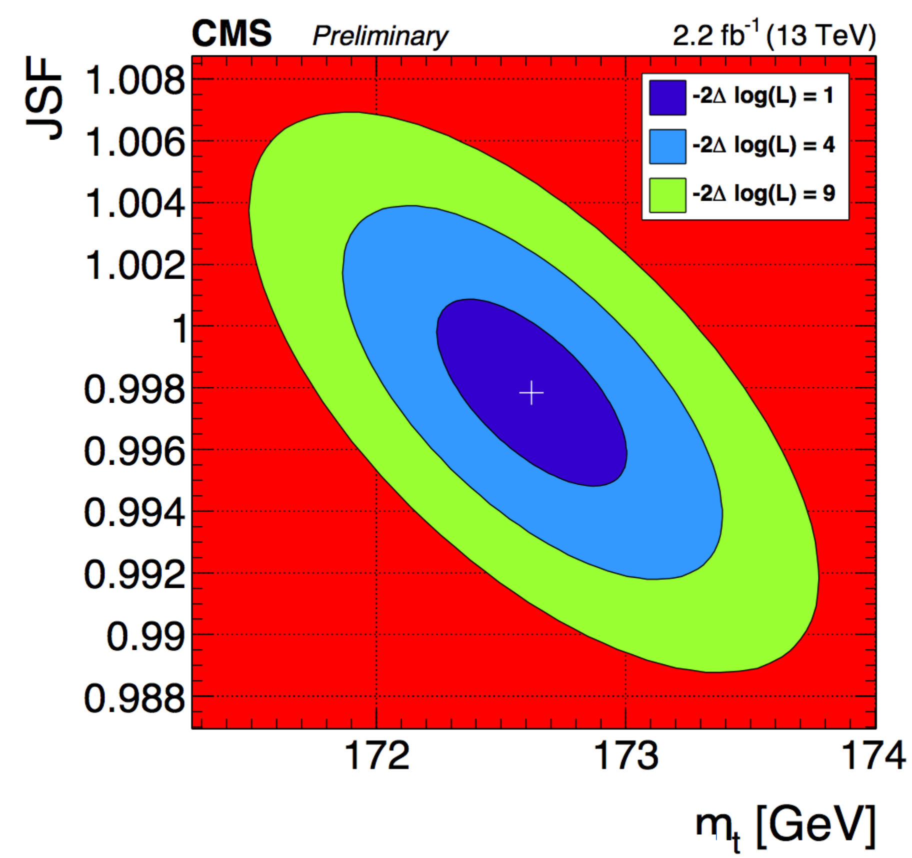
Most precise measurement in dilepton channel to date

arXiv:1606.02179

The top quark mass

- First measurement at 13 TeV - following 8 TeV lepton+jets measurement:
  - Full reconstruction of top-pair system and 2D fit for m_t and jet energy scale-factor (JSF):





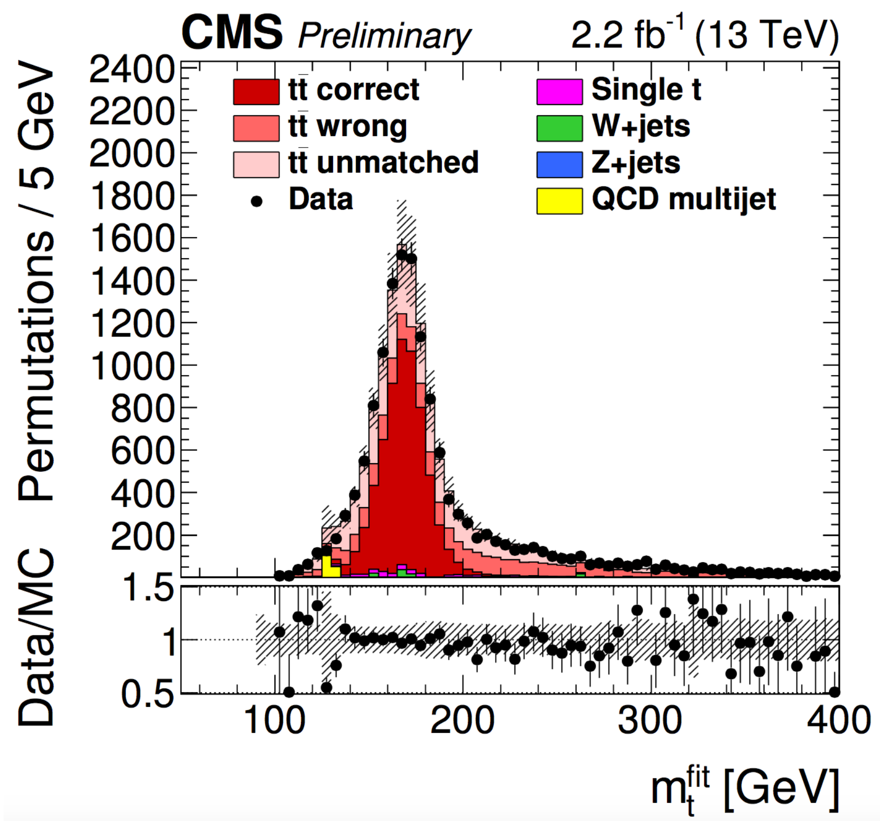
$$m_t = 172.62 \pm 0.38\ (\text{stat.+JSF}) \pm 0.70\ (\text{syst.})\ \text{GeV}$$

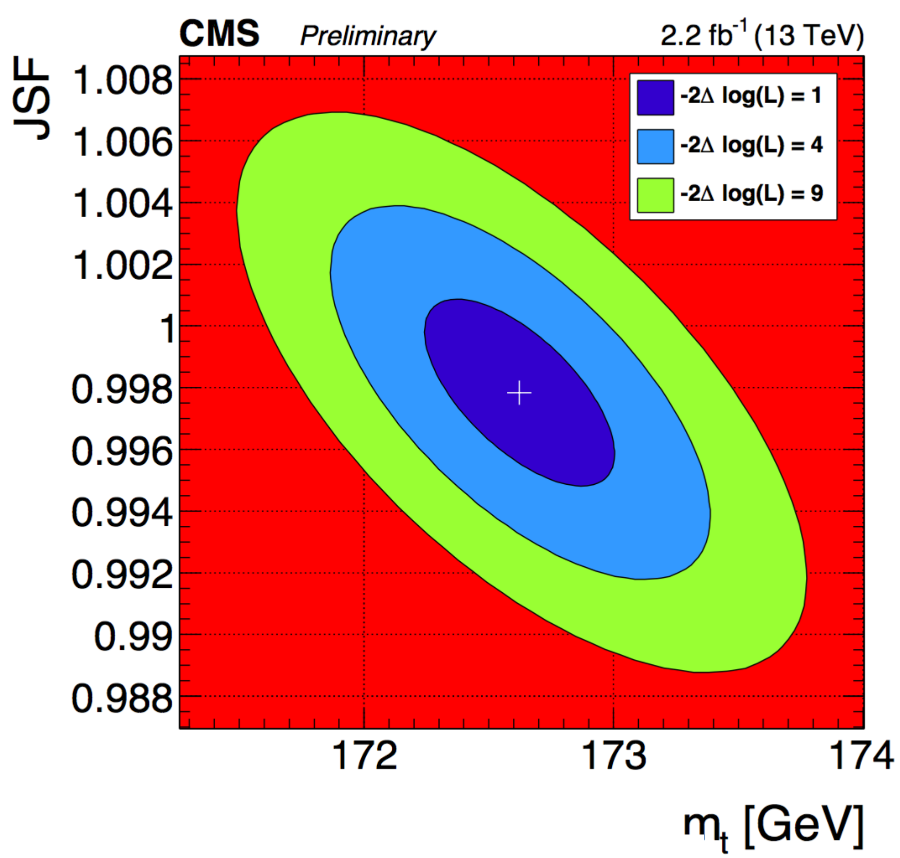
arXiv:1509.04044

CMS-PAS-TOP-16-022

The top quark mass

- First measurement at 13 TeV - following 8 TeV lepton+jets measurement:
  - Full reconstruction of top-pair system and 2D fit for m_t and jet energy scale-factor (JSF):





$$m_{\mathrm{t}} = 172.62 \pm 0.38\,(\mathrm{stat.+JSF}) \pm 0.70\,(\mathrm{syst.})\ \mathrm{GeV}$$

- Largest systematic uncertainties: JES (0.51 GeV) & MC modelling (0.40 GeV).

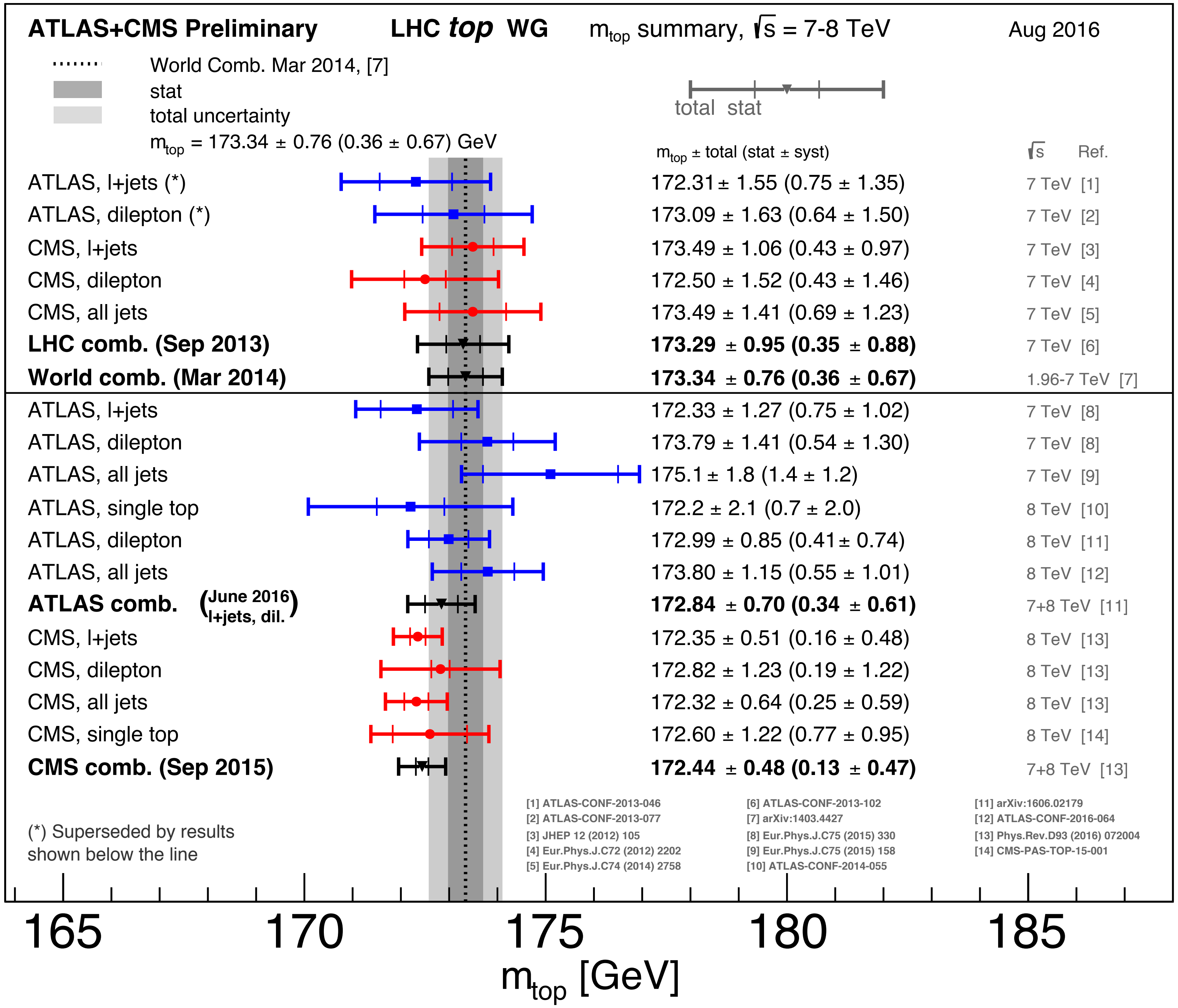
- Not yet at run 1 precision, but excellent agreement with CMS run 1 combination:

$$m_t = 172.44 \pm 0.13 \pm 0.47\ \mathrm{GeV}$$

arXiv:1509.04044

CMS-PAS-TOP-16-022

The top quark mass



- Nearing completion of run 1 results: combination needed to exploit measurements.

Summary

- Top quark is still the heaviest particle we know about.
- Provides a potential window to new physics.
- Well understood run 1 LHC dataset continues to yield precise measurements.
- First run 2 measurements available: no sign for deviations beyond the SM.
- Run 2 offers unprecedented statistics & opportunities: must exploit statistics to reduce systematics.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

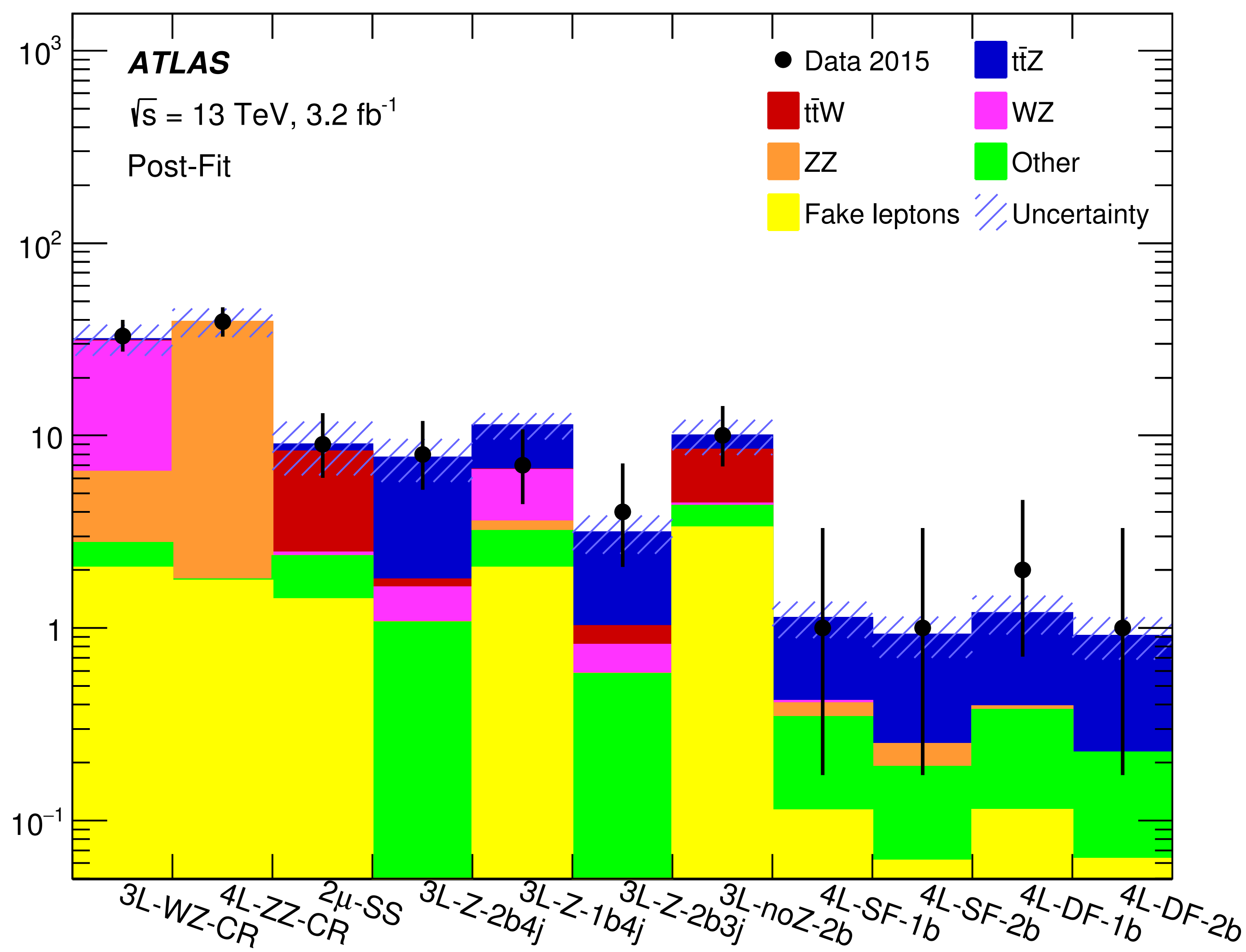
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

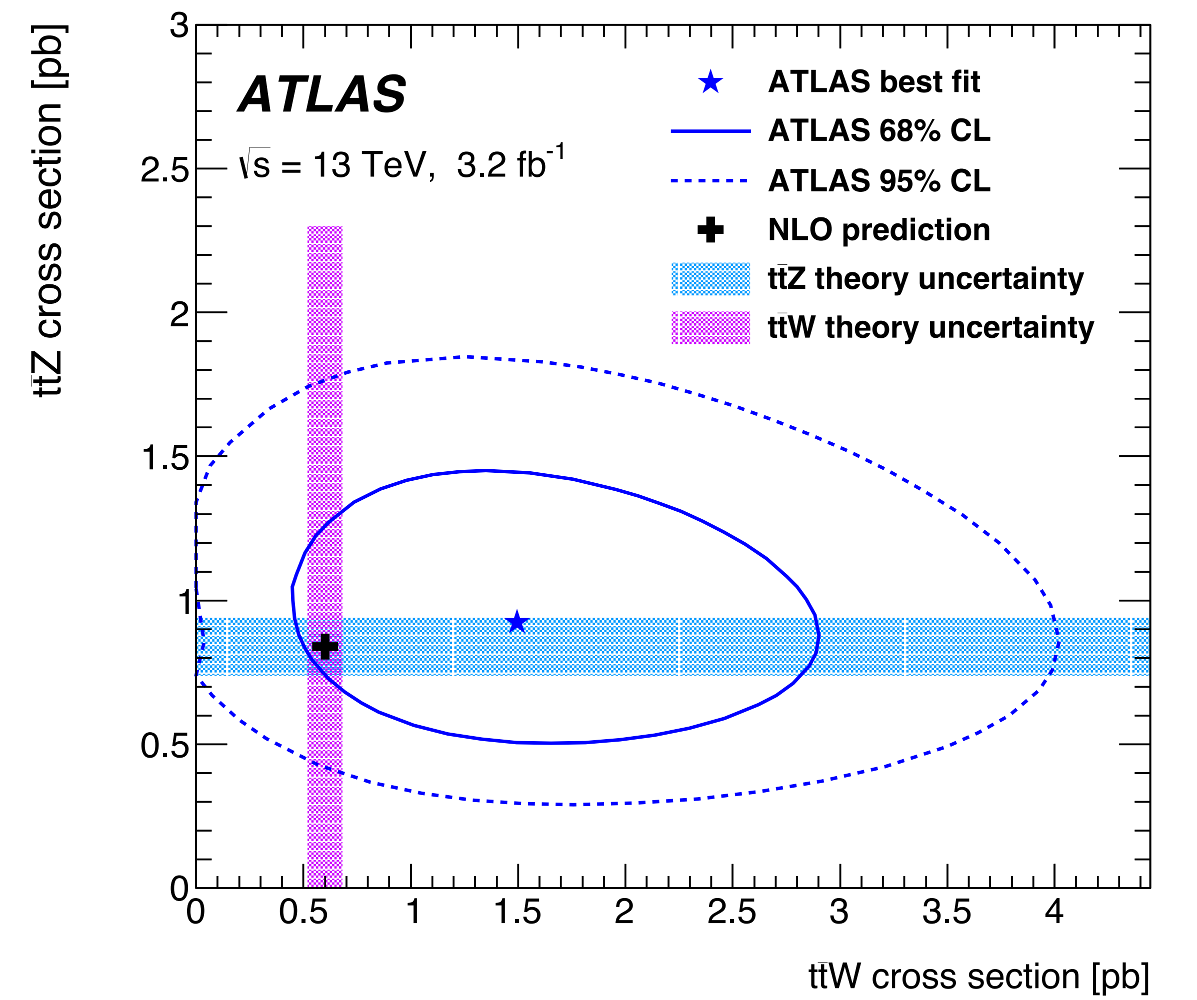
Backup

ATLAS ttV

- 2 same-sign charge leptons, 3 or 4 lepton final states.
  - Split selected events according to lepton-pairings & number of b-jets.
  - Use control regions to constrain WZ & ZZ backgrounds.

arXiv:1609.01599

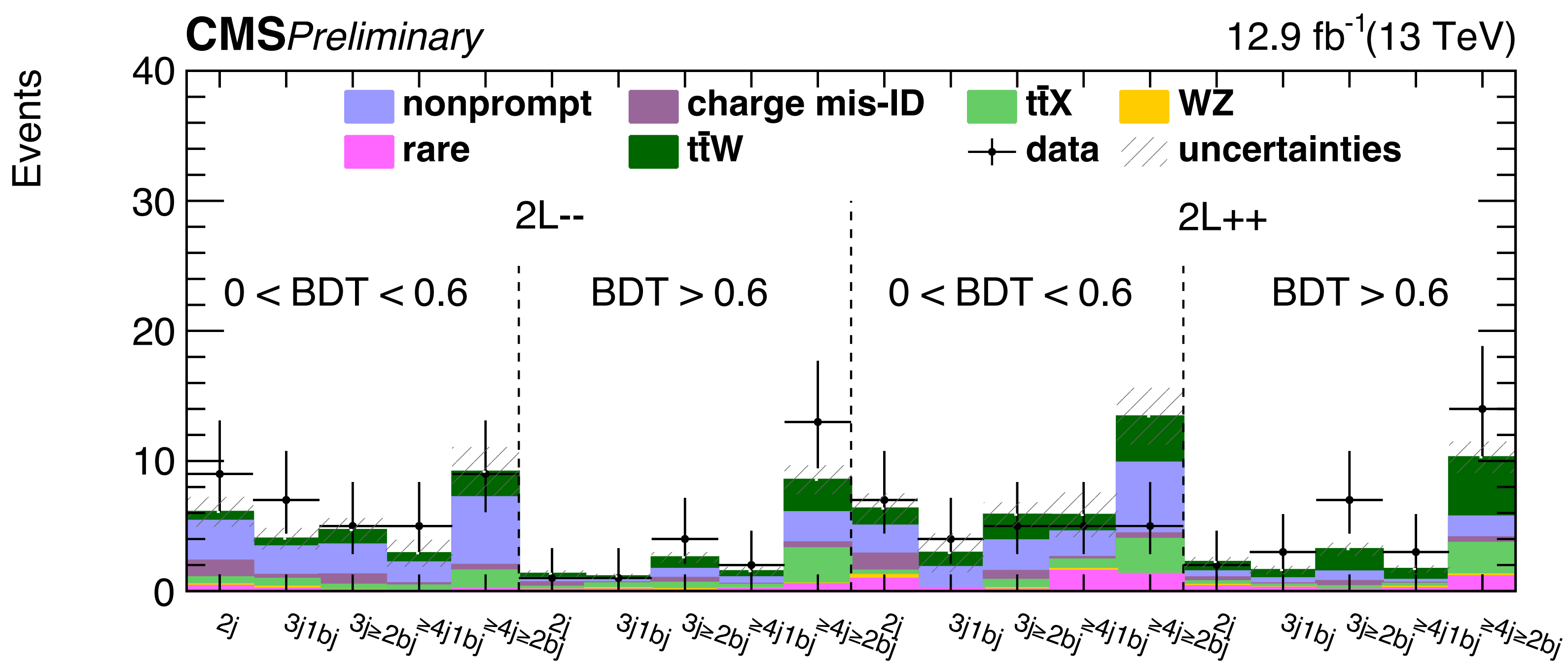


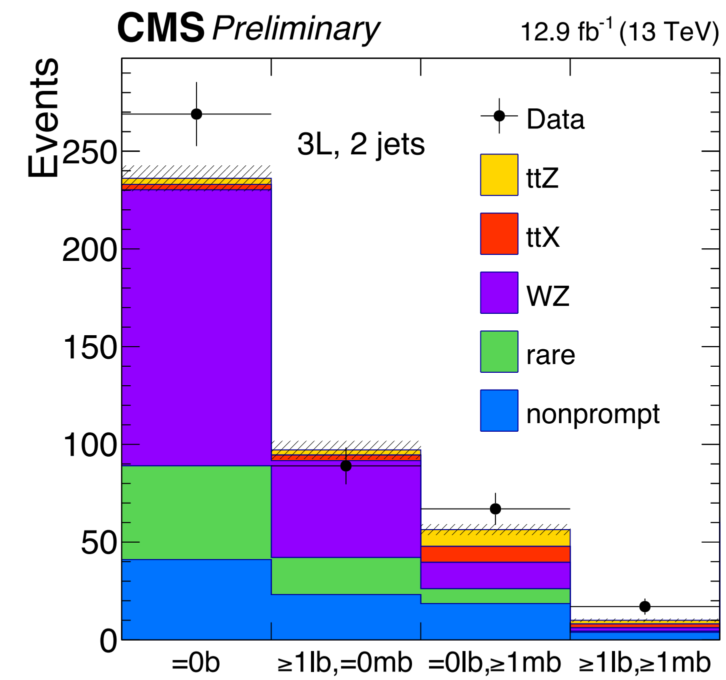


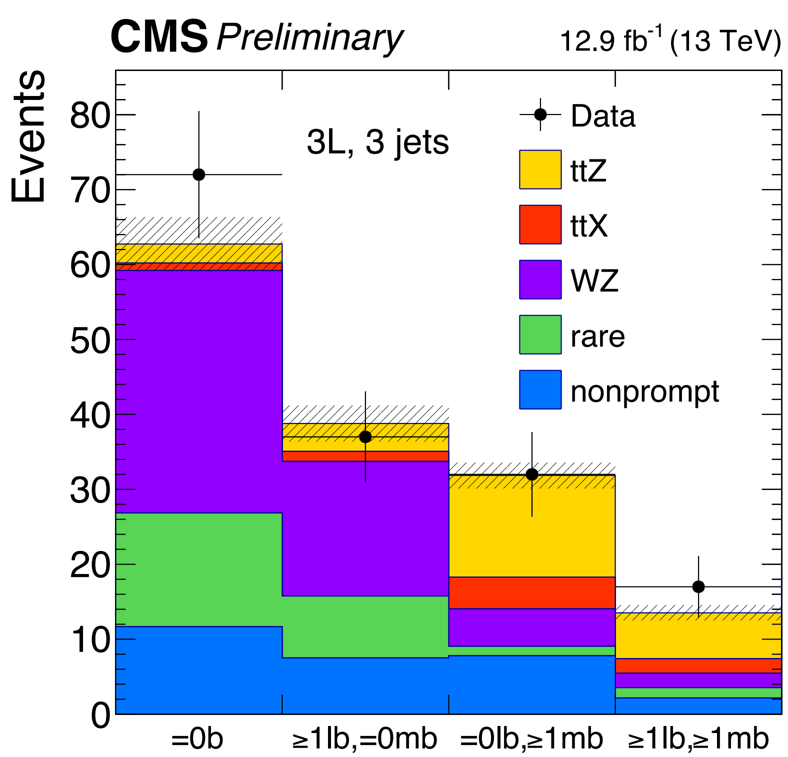
  - Statistics limited - big scope improvements with 2016 dataset.

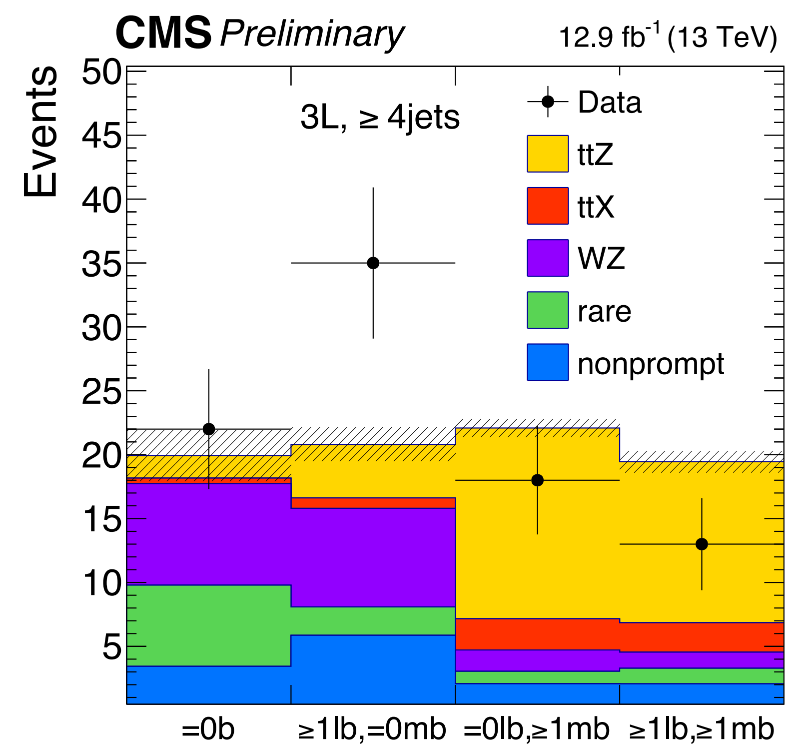
CMS ttV

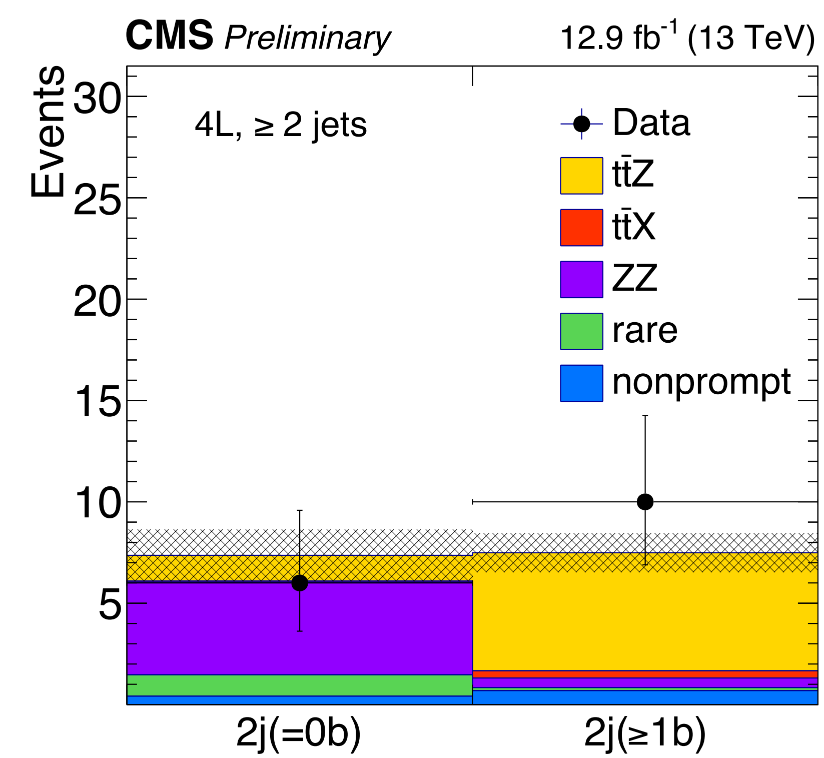
- Signal regions in CMS ttV:







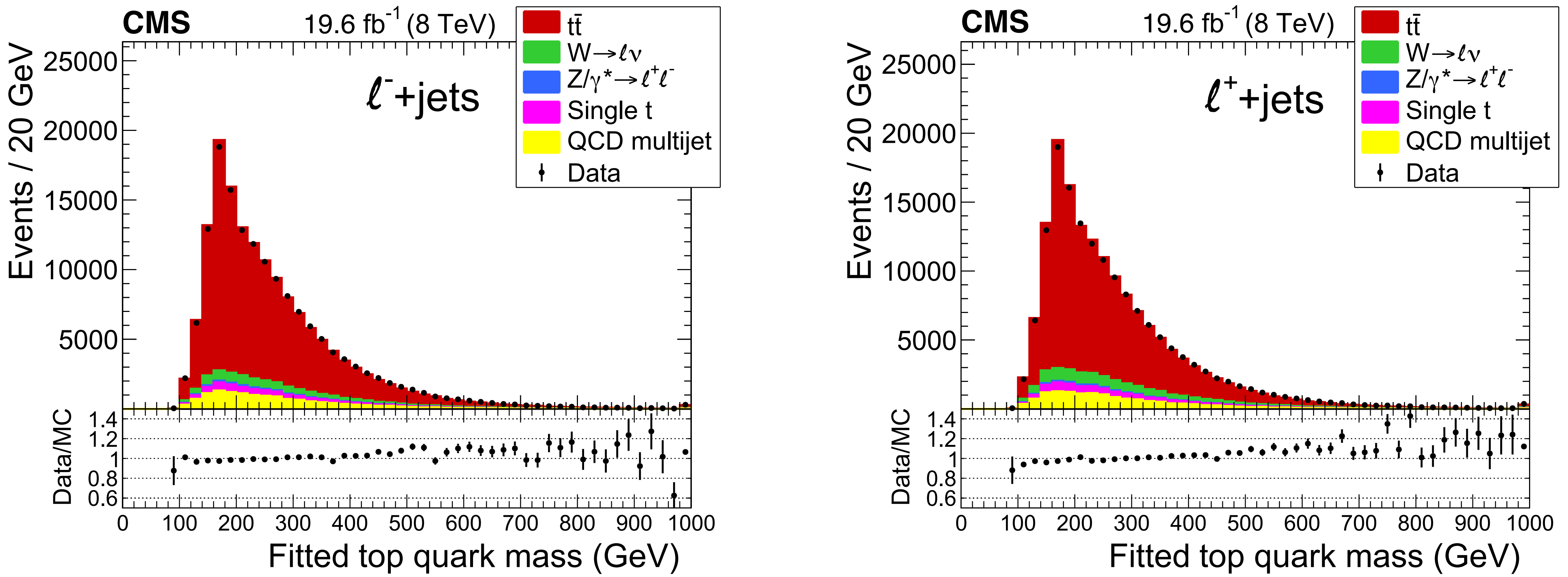




CMS-PAS-TOP-16-017

Top quark mass difference

- Test CPT invariance by measuring: $\Delta m_t = m_t - m_{\bar{t}}$
- Use charge of lepton in e/μ+jets events to tag charge of top-quark:



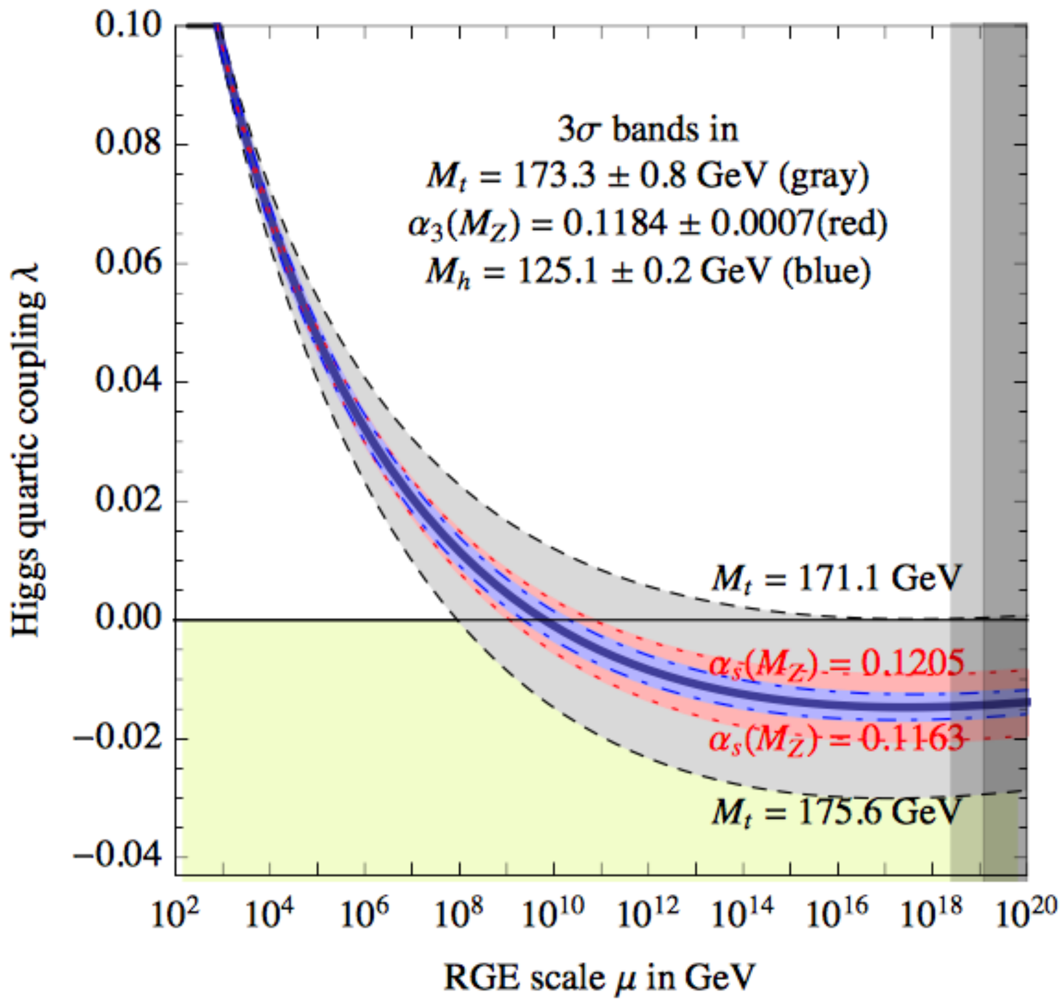
$$\Delta m_{\mathrm{t}} = -0.15 \pm 0.19\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst})\,\mathrm{GeV}$$

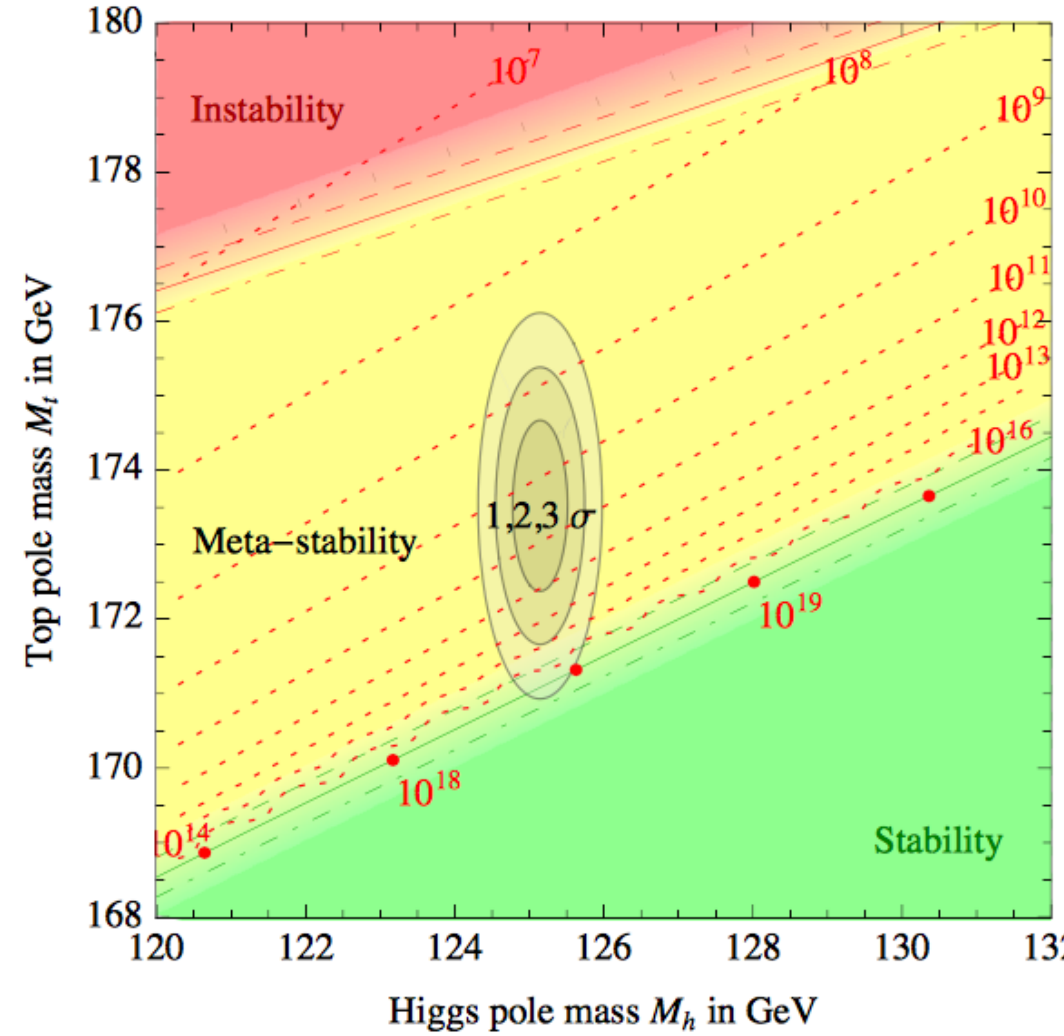
Statistics limited (largest systematic: b vs $\bar{\mathrm{b}}$ response)

arXiv:1610.09551

The top quark mass

- Top quark mass critical to understanding if SM is valid to high scales:

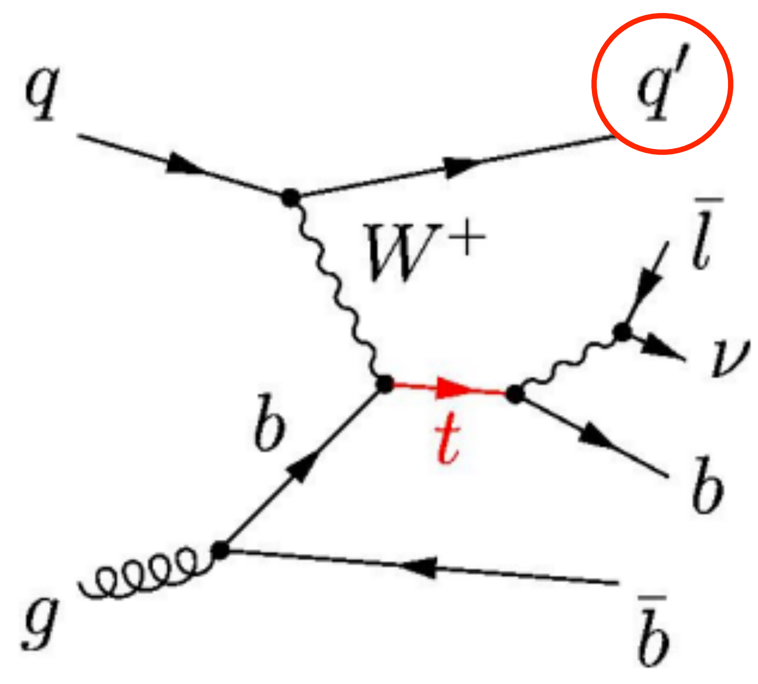


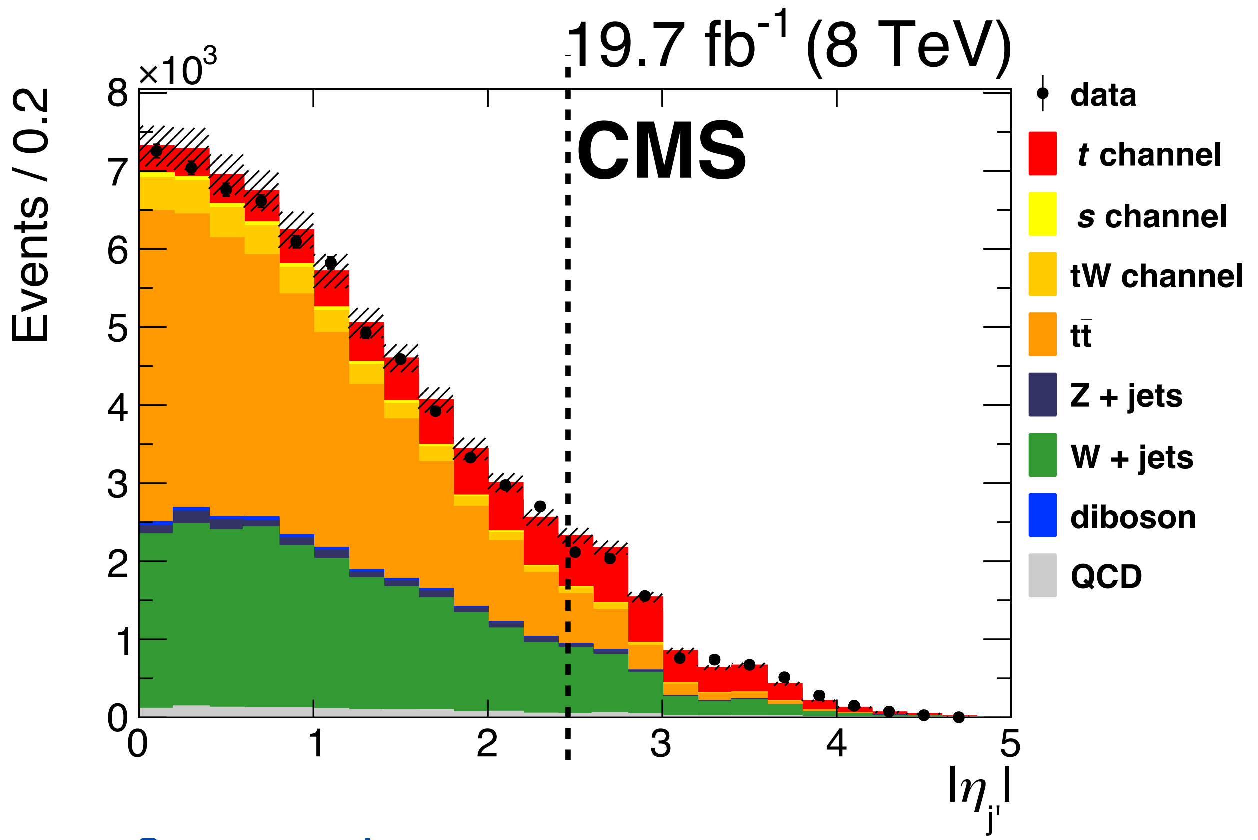


arXiv:1307.3536

CMS single top mass

- Measurement in single-top t-channel events:
    - Require presence of forward jet to enhance t-channel signal:



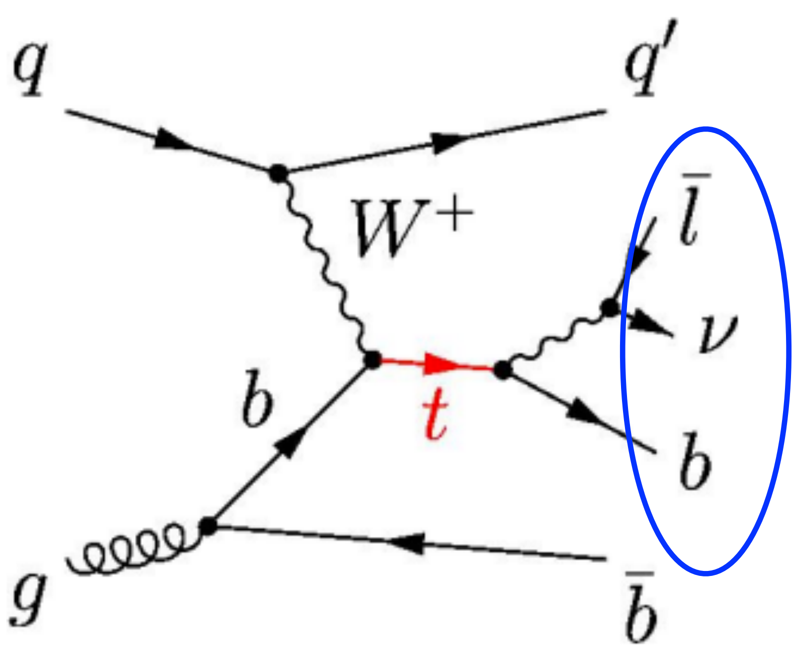


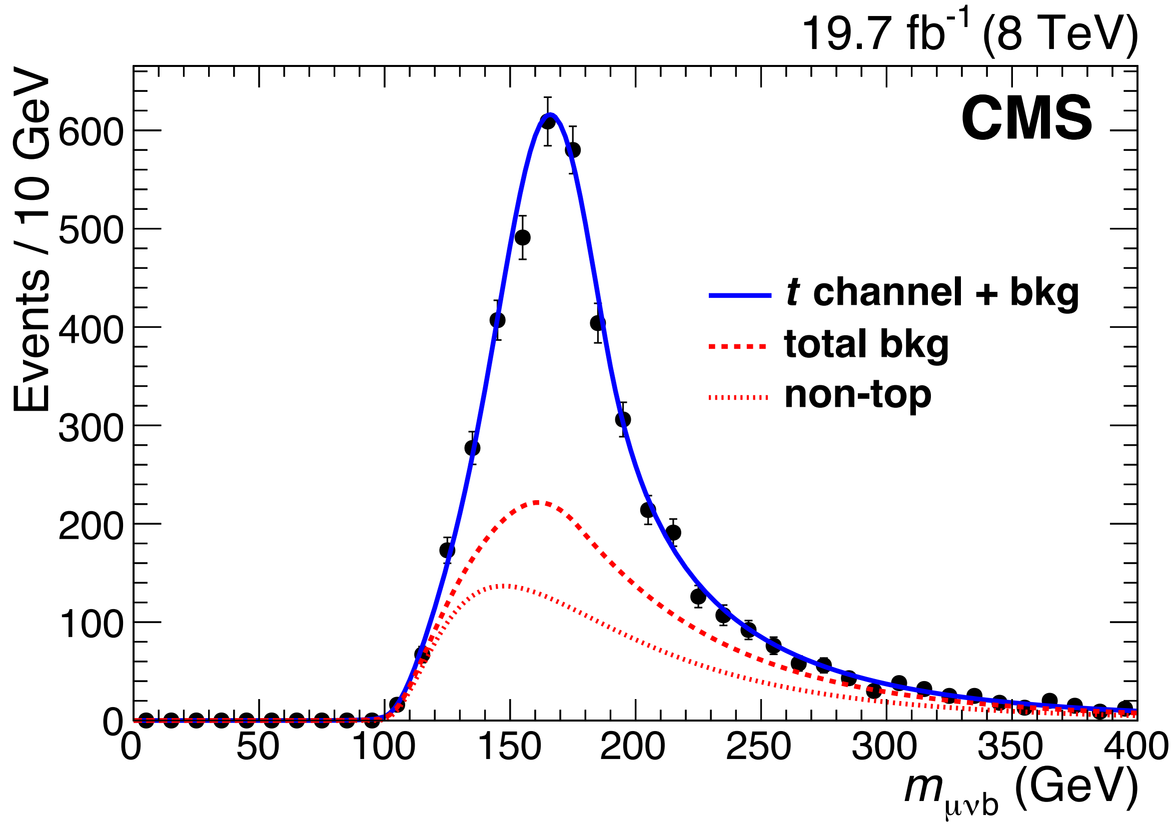
- Then reconstruct top from b, lepton & neutrino.
- Largest systematic uncertainties: JES, MC modelling, fit calibration.

arXiv:1703.02530

CMS single top mass

- Measurement in single-top t-channel events:
    - Require presence of forward jet to enhance t-channel signal:





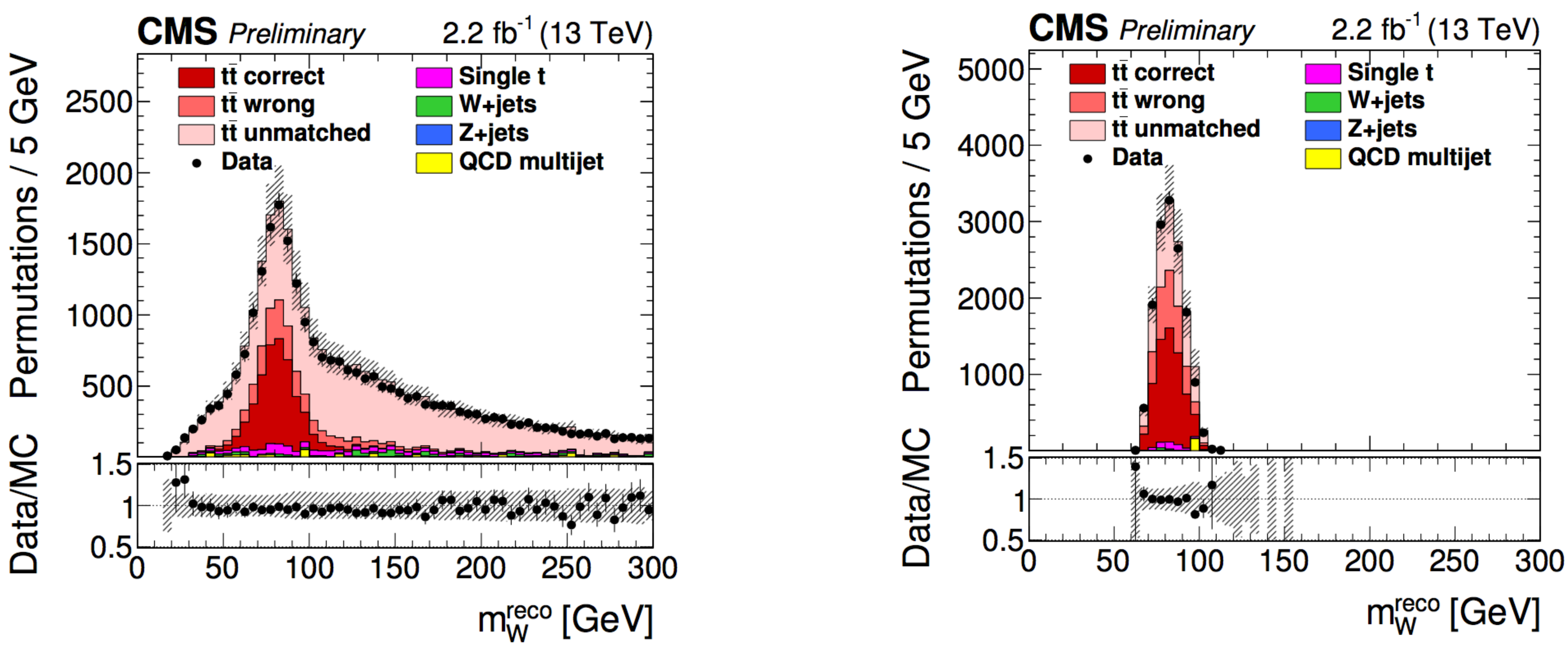
- Then reconstruct top from b, lepton & neutrino.
- Largest systematic uncertainties: JES, MC modelling, fit calibration.

$$m_t = 172.95 \pm 0.77\ (\mathrm{stat})^{+0.97}_{-0.93}\ (\mathrm{syst})\ \mathrm{GeV}$$

arXiv:1703.02530

CMS top mass 13 TeV

- 13 TeV lepton+jets measurement: requirement on goodness of kinematic fit used to select well reconstructed events:

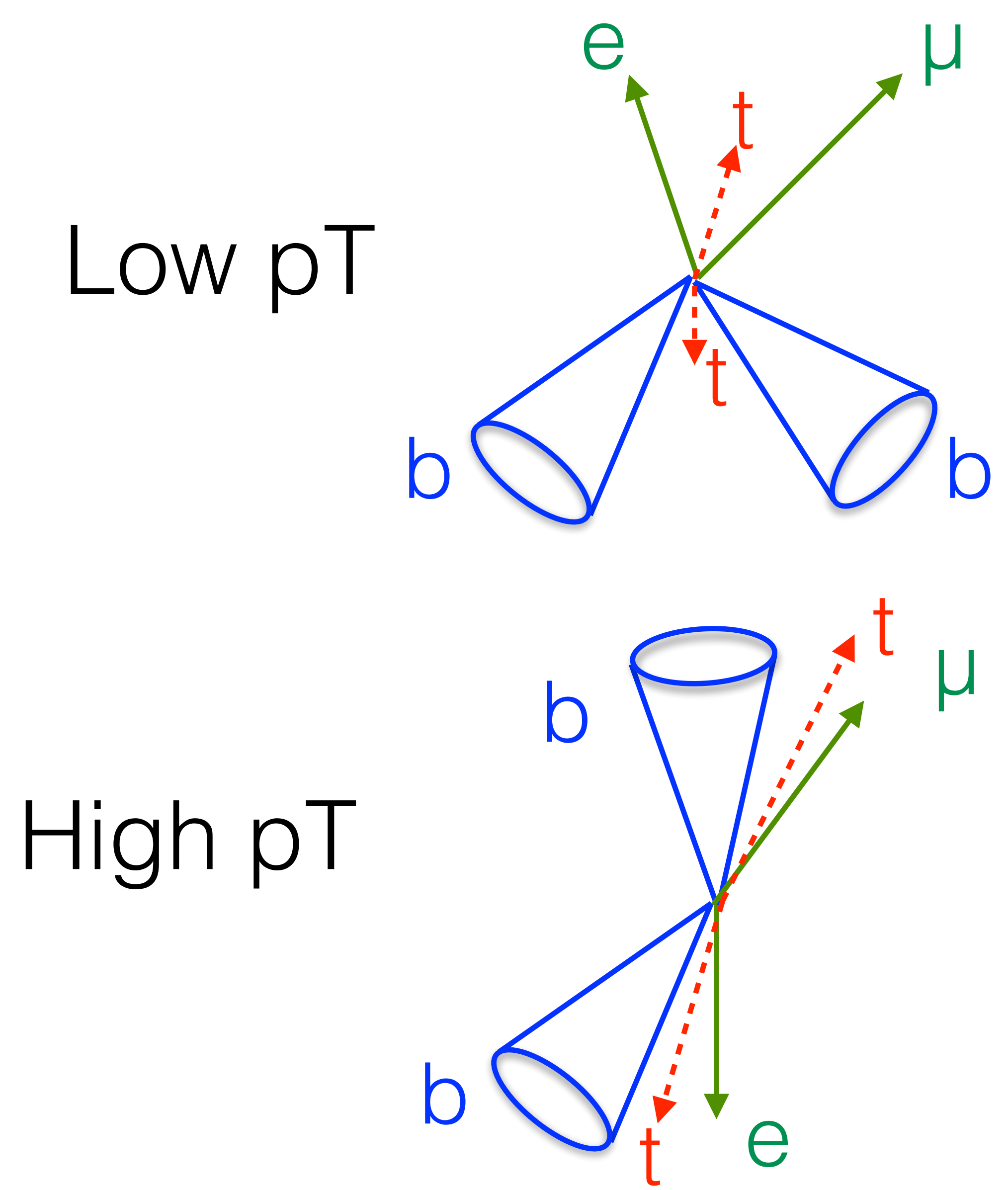


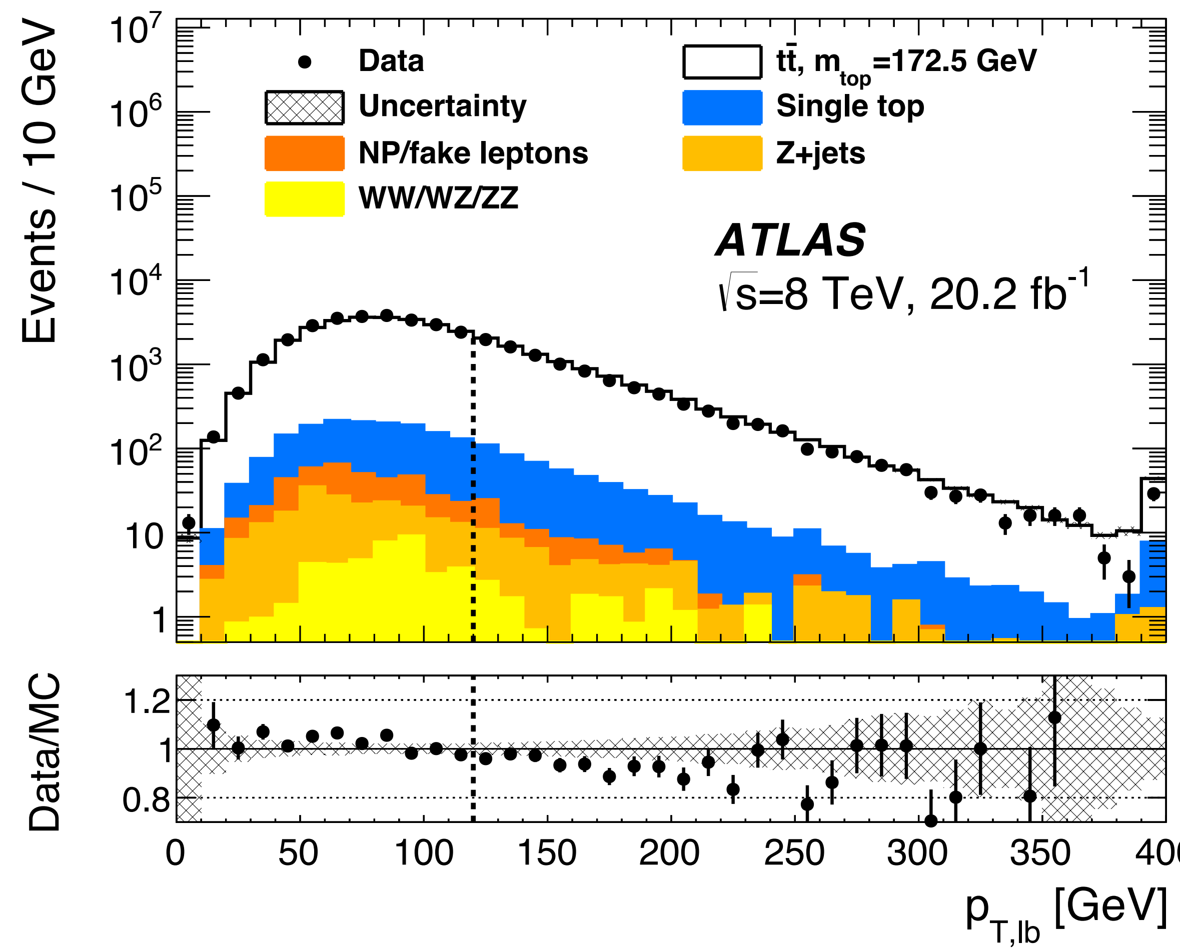
- Reconstructed W boson mass (from 2 light jets) then used to fit the jet energy scale factor.

CMS-PAS-TOP-16-022

ATLAS dilepton top mass

- New measurement in the dilepton channel at 8 TeV.
- Apply cut on pT(lb) - increases fraction of events where correct pairing of lepton & b are selected & reduces total uncertainty.

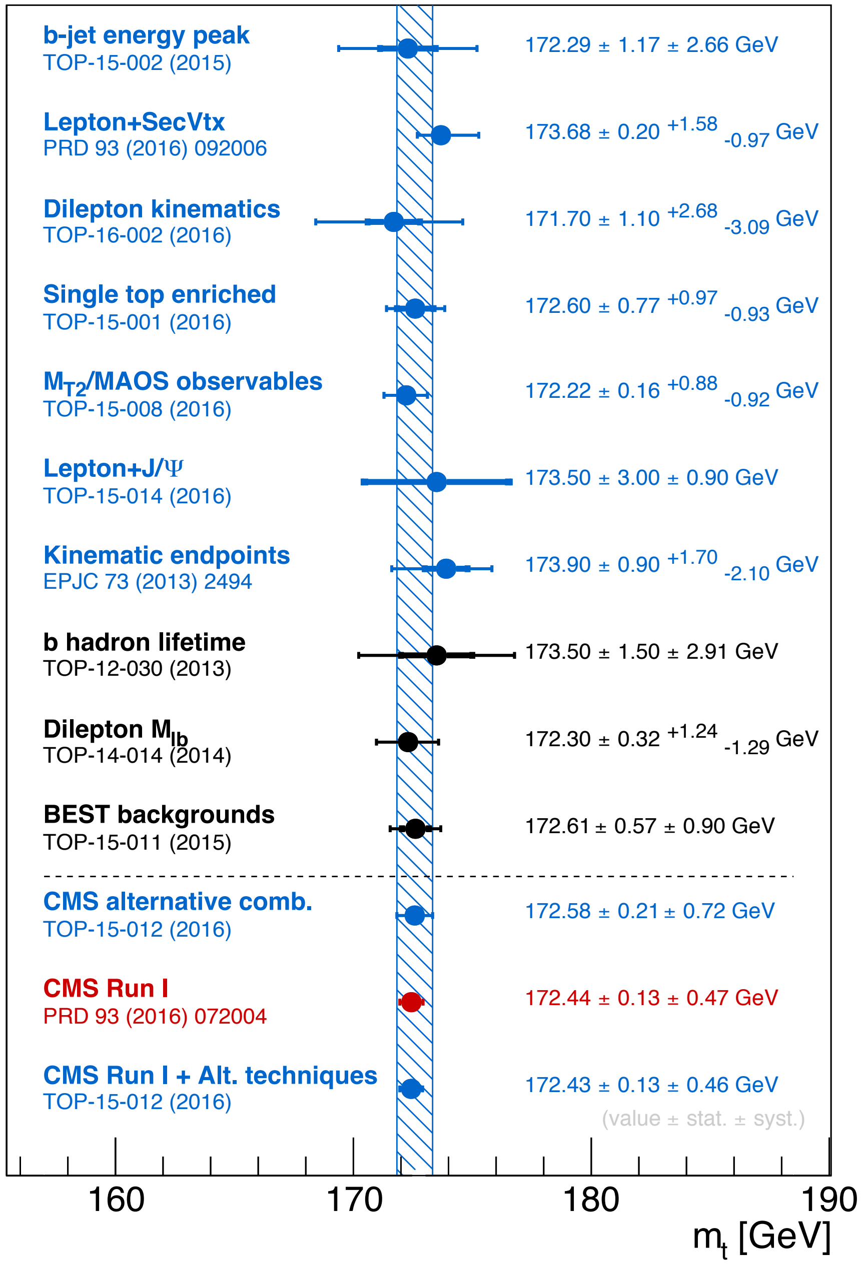


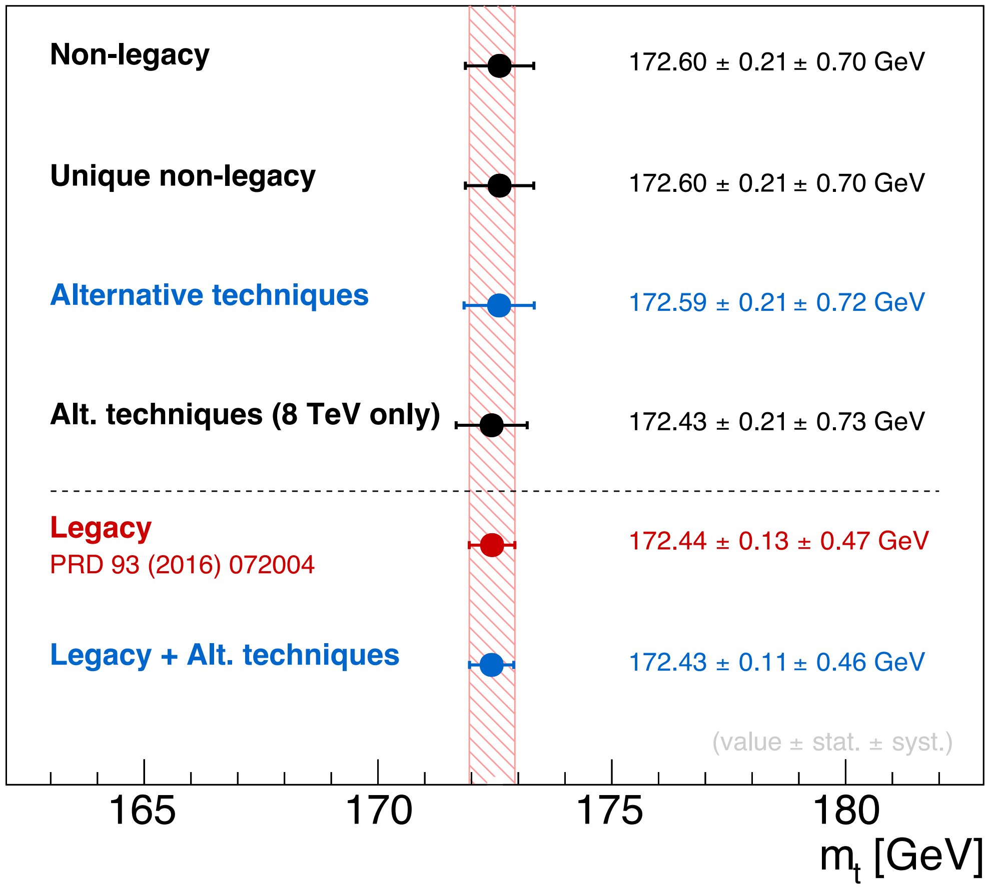


arXiv:1606.02179

CMS mass combination

- Using all ‘alternative’ measurements not included in the standard combination:





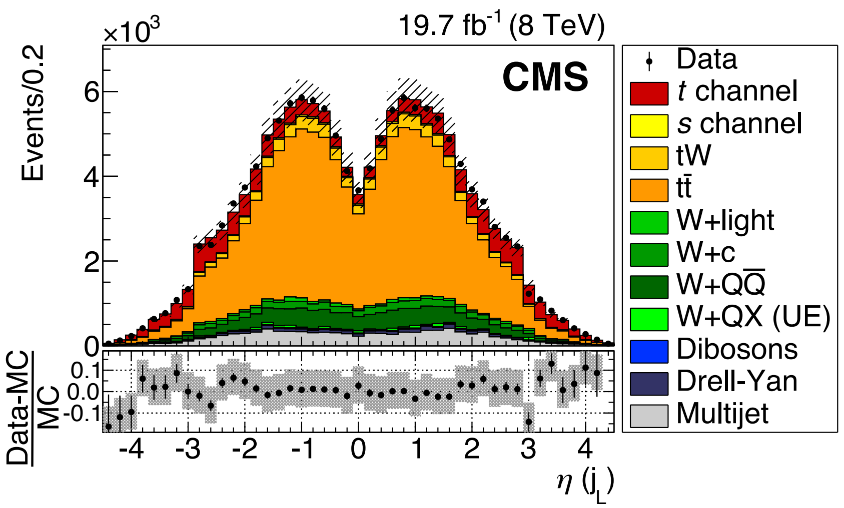
Good agreement with standard measurements.

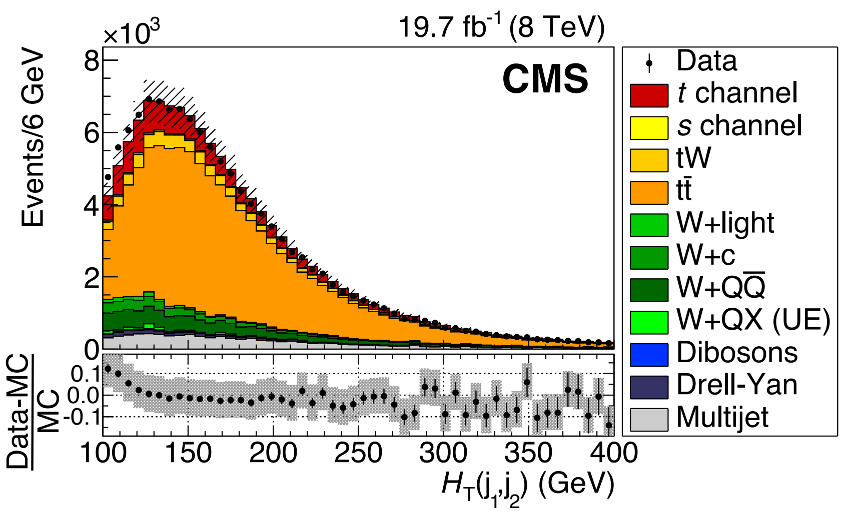
However, very small gain relative to standard combination

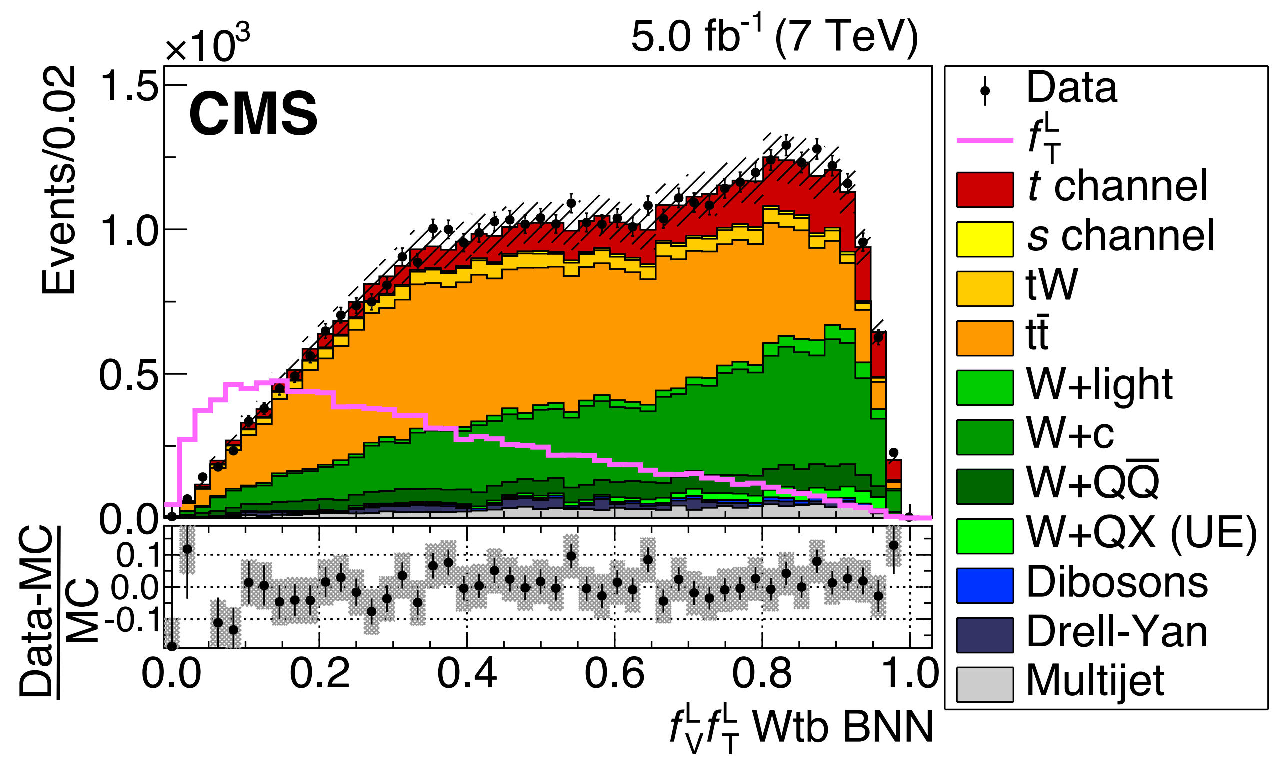
CMS-PAS-TOP-15-012

Search for anomalous Wtb couplings

- Train multivariate boosted-decision trees to separate between SM single-top and single-top with non-SM Wtb couplings:





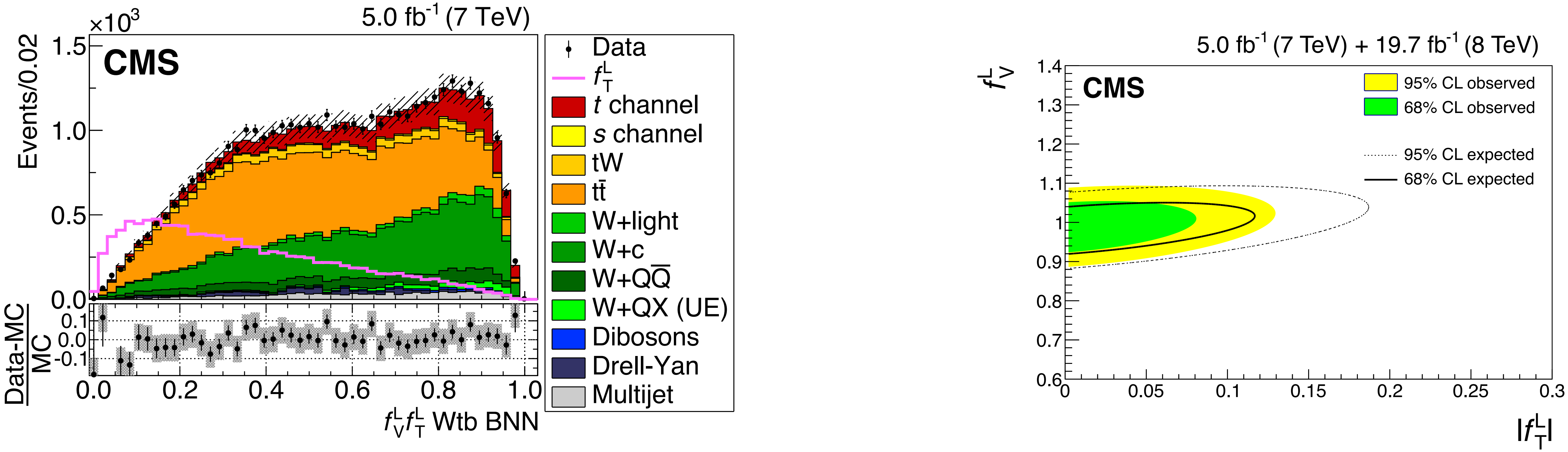


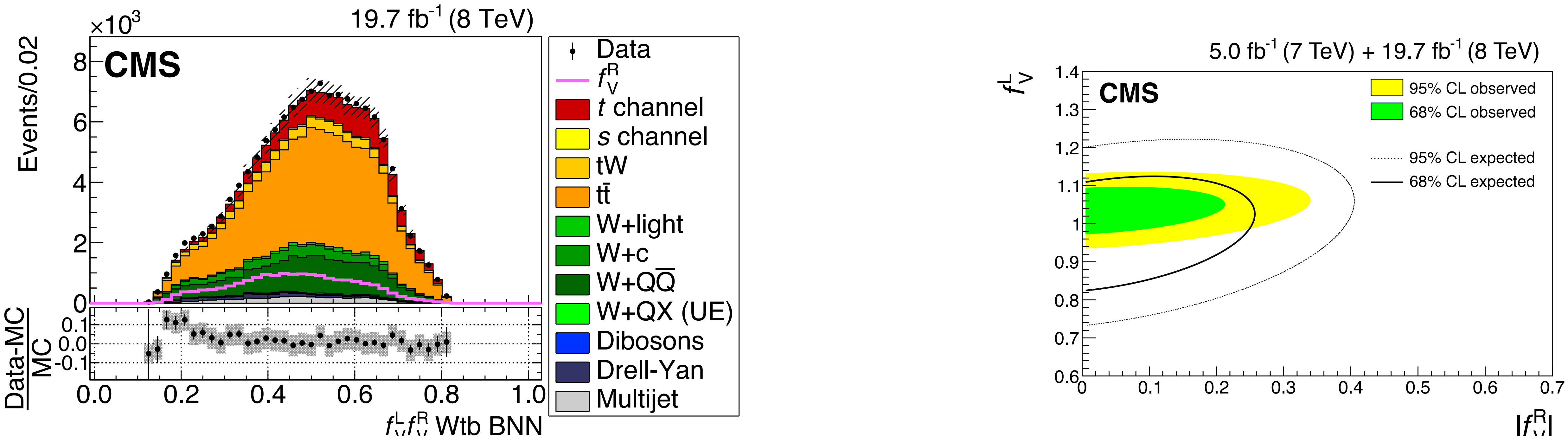
+ others

arXiv:1610.03545

Search for anomalous Wtb couplings

- Limits then extracted by fitting to the BNN distributions:

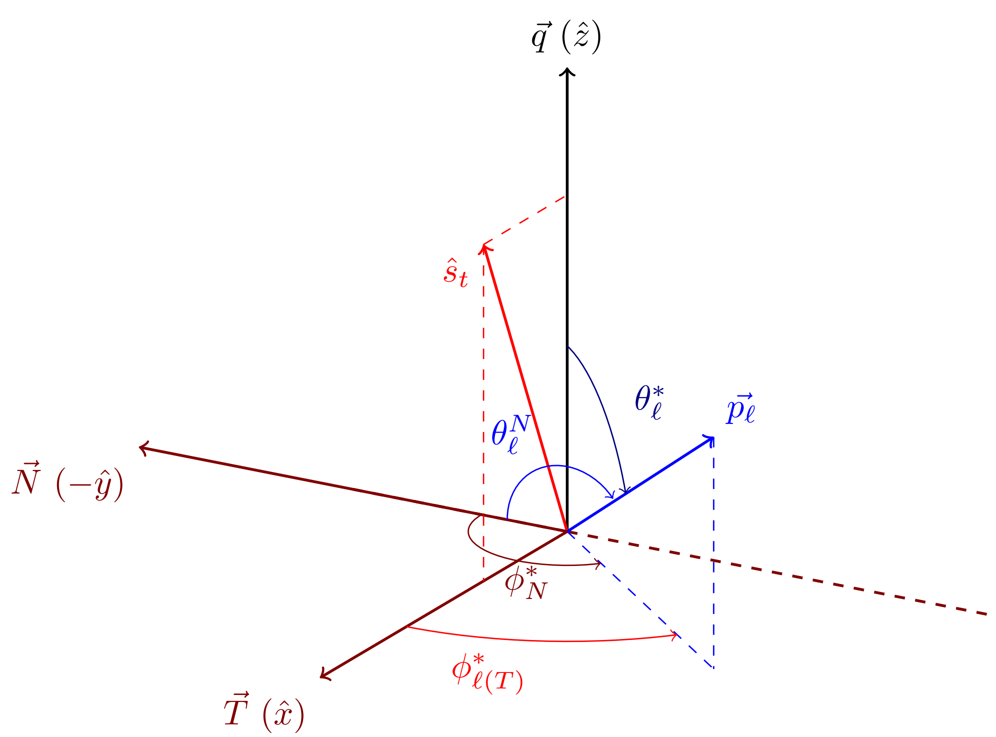




arXiv:1610.03545

Polarisation in single top

- Angular variables in single top polarisation:

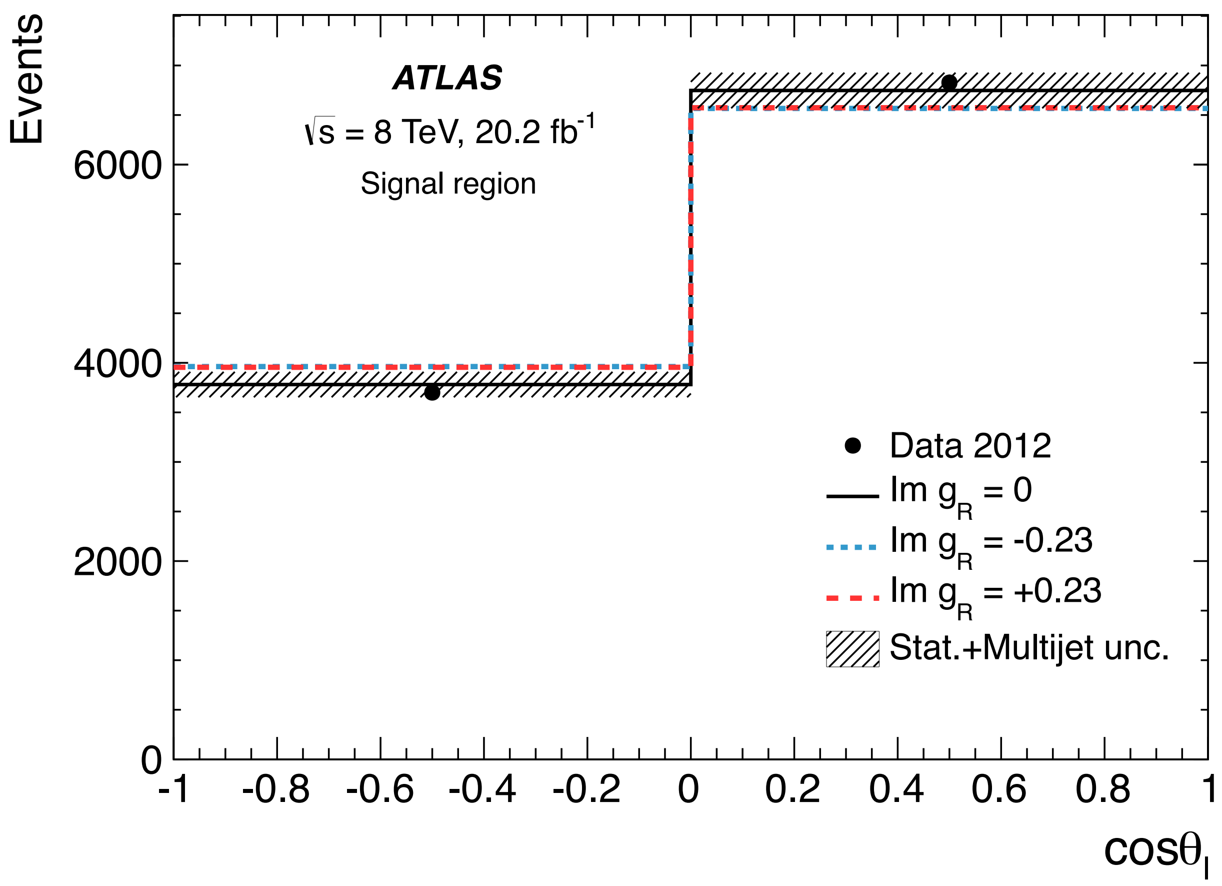


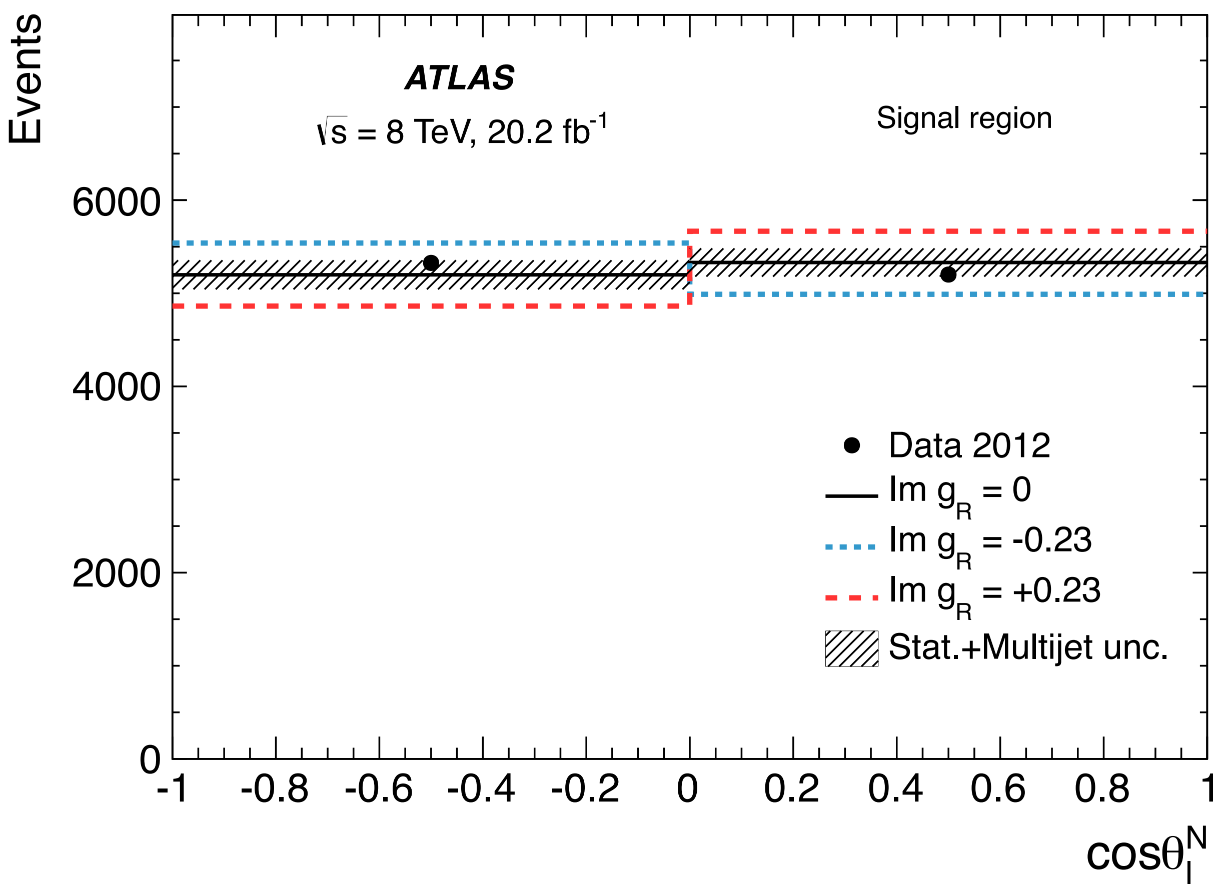
The W-boson momentum q in the top-quark rest frame defines the z-axis; the top-quark spin direction s_t, taken along the spectator-quark momentum in the top-quark rest frame, defines the x–z plane. The polar and azimuthal angles of the charged-lepton momentum p_ℓ in the W-boson rest frame are labelled θ_ℓ^* and ϕ_ℓ^*, respectively. The normal and transverse axes are defined relatively to q and st according to $N=s_t\times q$ and $T=q \times N$; they are along the -y and x axes of the coordinate system, respectively. The azimuthal angles ϕ_N^* and ϕ_T^* of the charged lepton in the W-boson rest frame are defined relatively to the N and T axes, respectively ($\phi_T^*\equiv\phi_\ell^*$), while θ_ℓ^N and θ_ℓ^T (not shown in the figure) are the relative angles between p_ℓ and the N and T axes, respectively.

arXiv:1702.08309

Polarisation in single top

- Sensitivity to anomalous couplings:



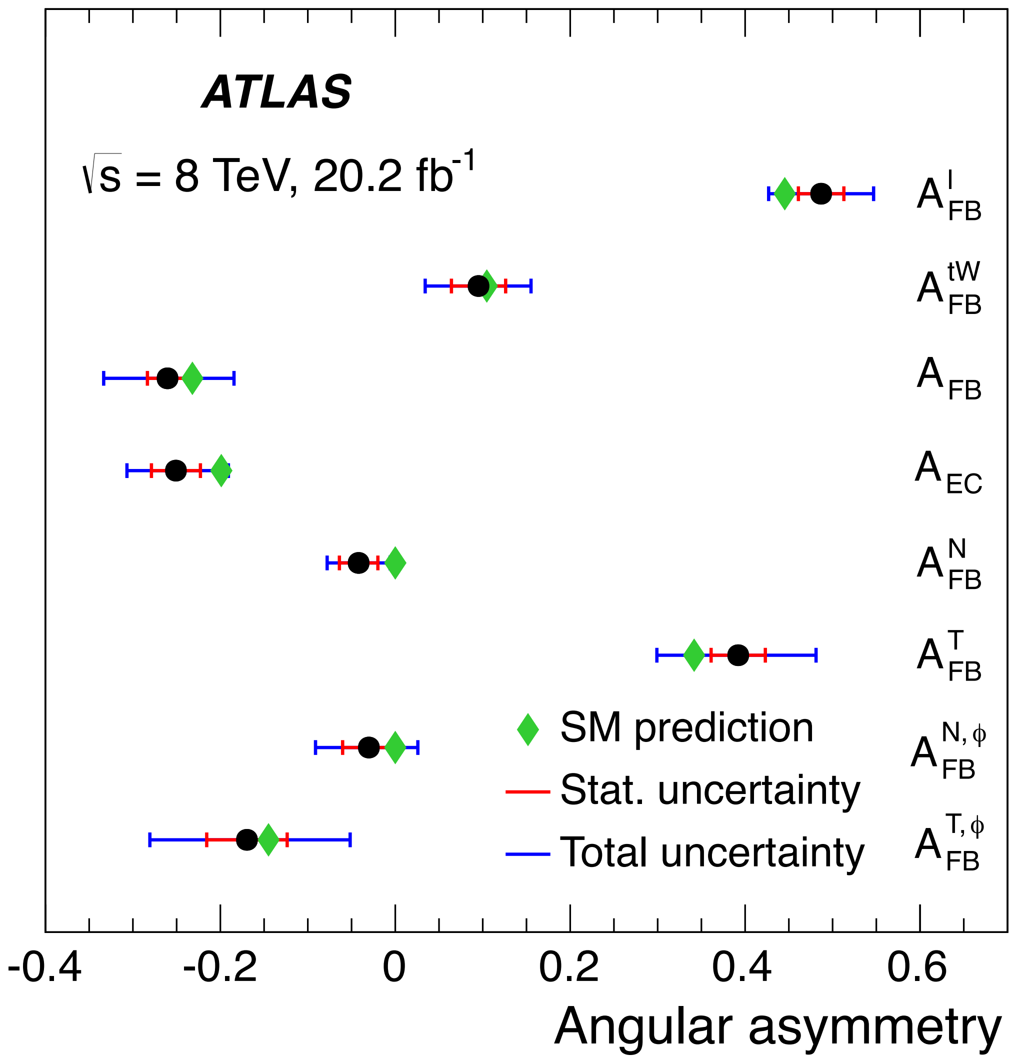


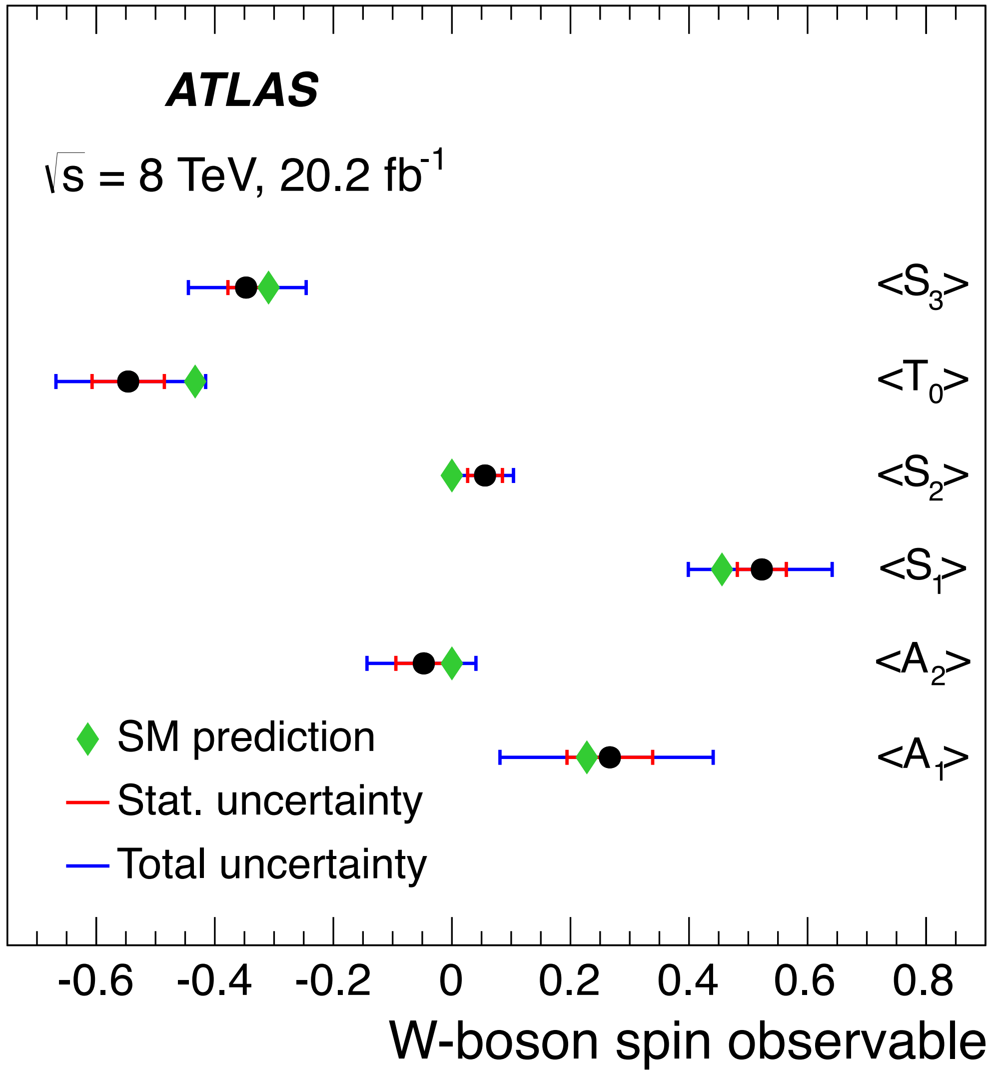
- When extracting limits on Im(g_R), correlation between observables is accounted for (-0.05).

arXiv:1702.08309

Polarisation in single top

- All measured asymmetries:

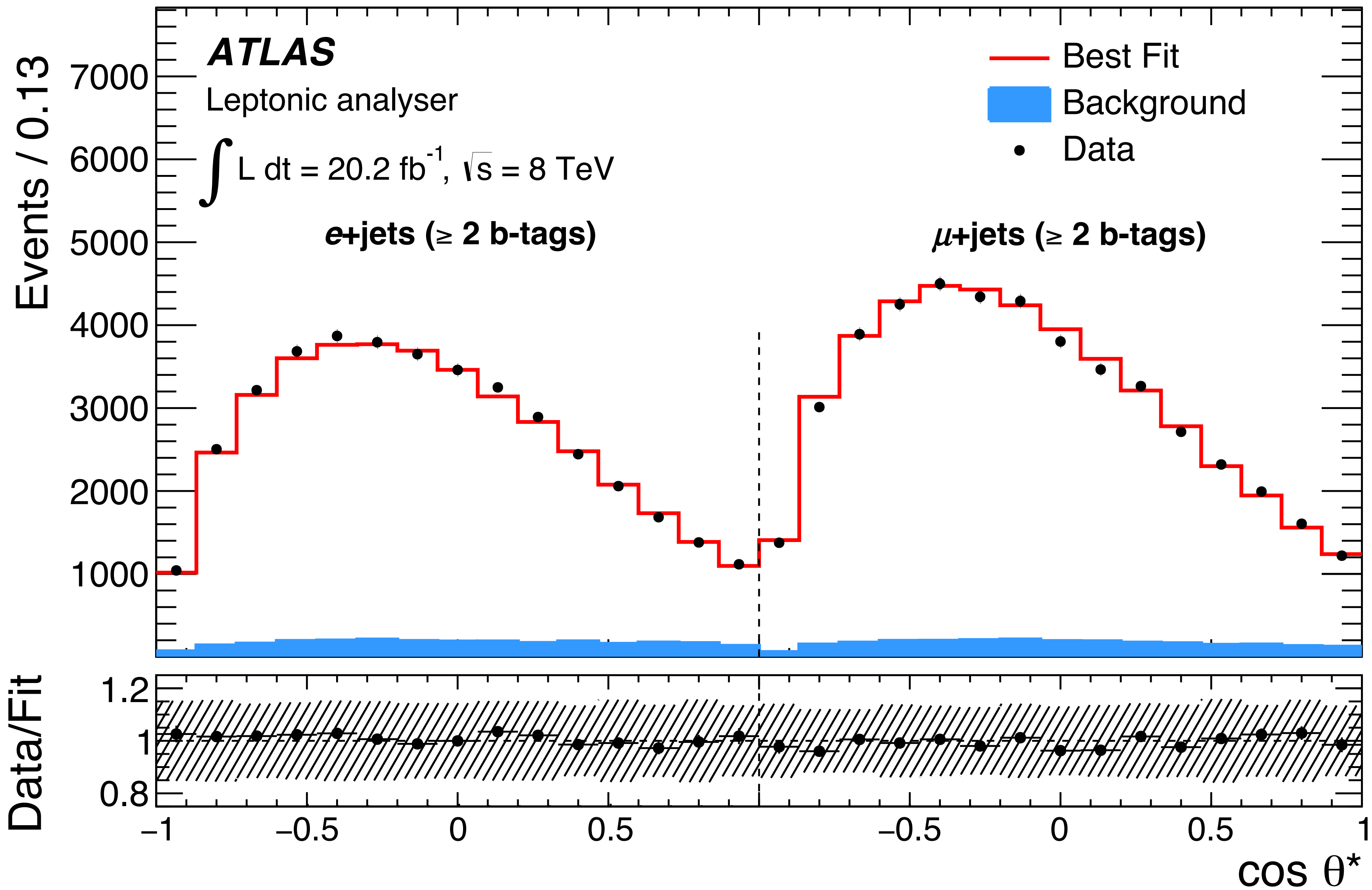




arXiv:1702.08309

W boson polarisation

- Fitted distributions for the ATLAS measurement:



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}(1-\cos\theta^*)^2\ F_L + \frac{3}{8}(1+\cos\theta^*)^2\ F_R$$

arXiv:1612.02577