Top Quark Results from LHC

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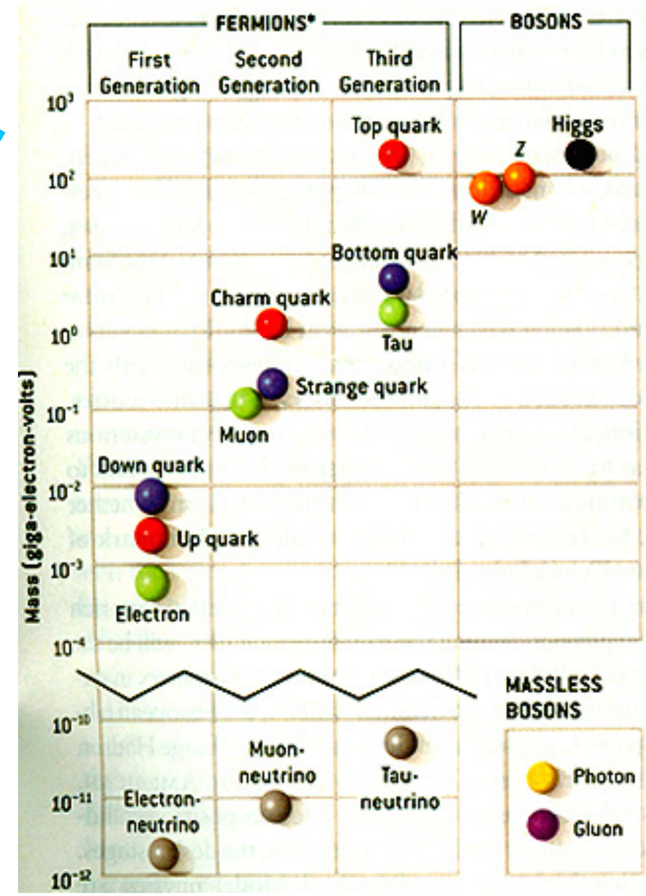
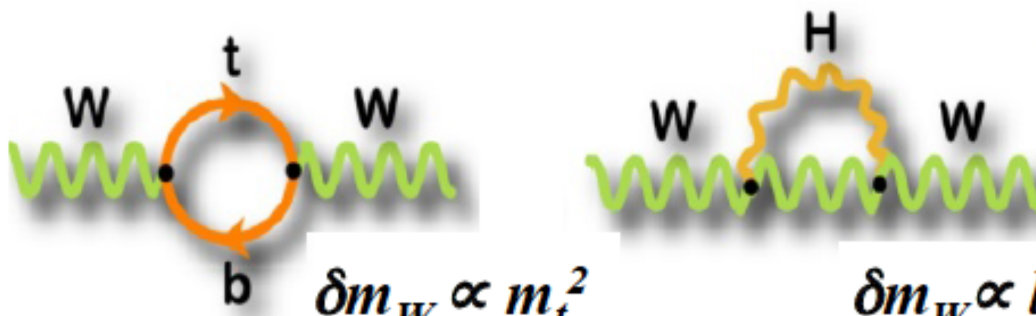
(On behalf of ATLAS and CMS Collaborations)

Why bother about top?

- It is special in many accounts
  - Heaviest know elementary particle
  - Largest coupling to the Higgs boson
  - Decays much before it can hadronize
  - Spin properties are transferred to decay products

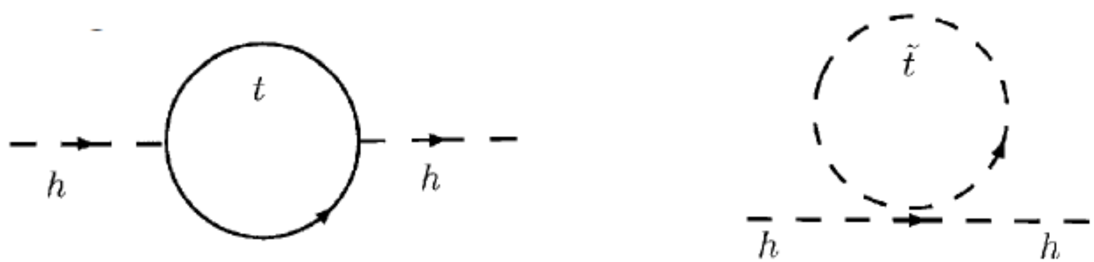


- An excellent benchmark to check self-consistency of the standard model (SM)

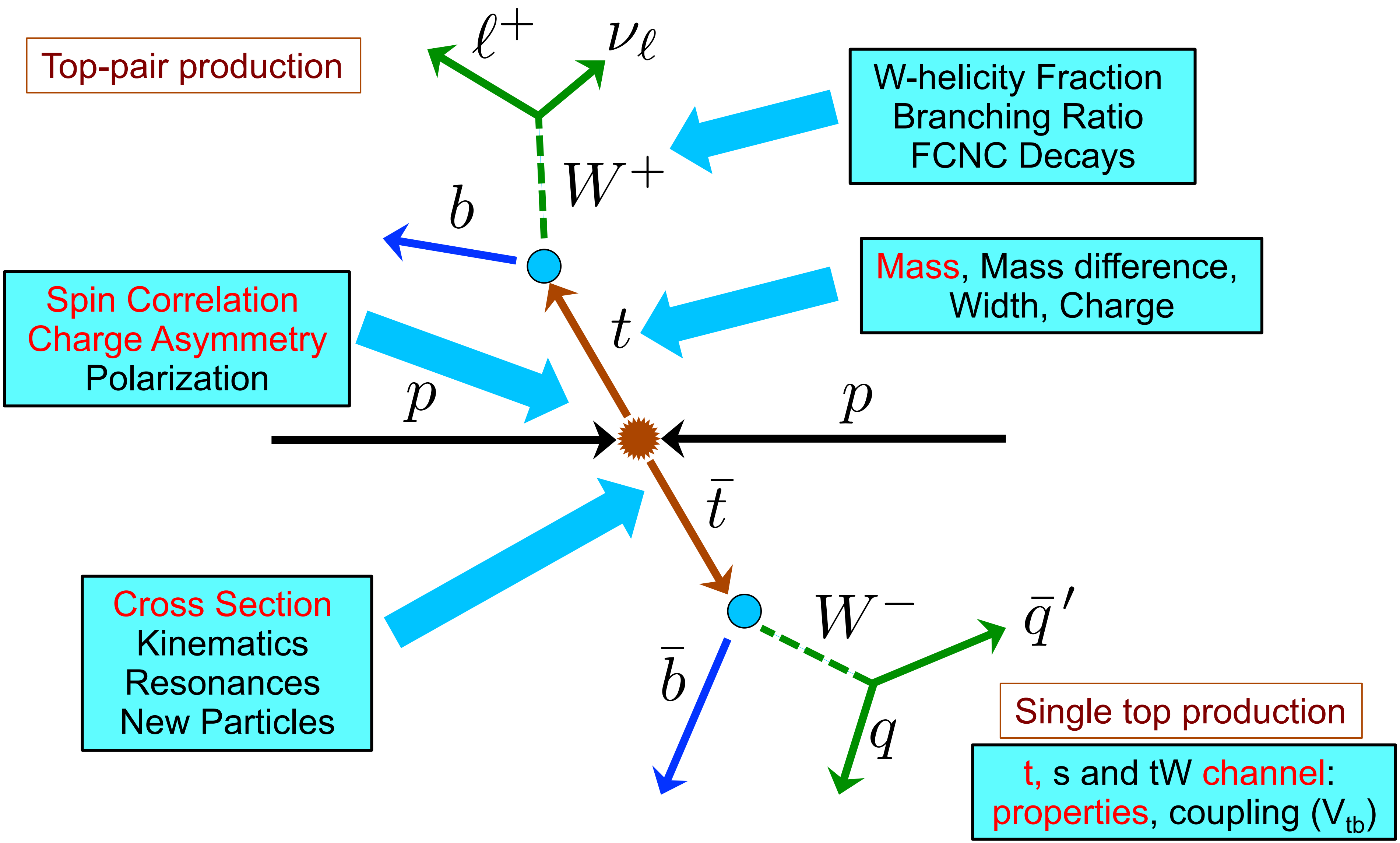


$\delta m_W \propto m_t^2$ $\qquad$ $\delta m_W \propto \ln(m_H)$

- Expect to have a good connection with new physics (NP)



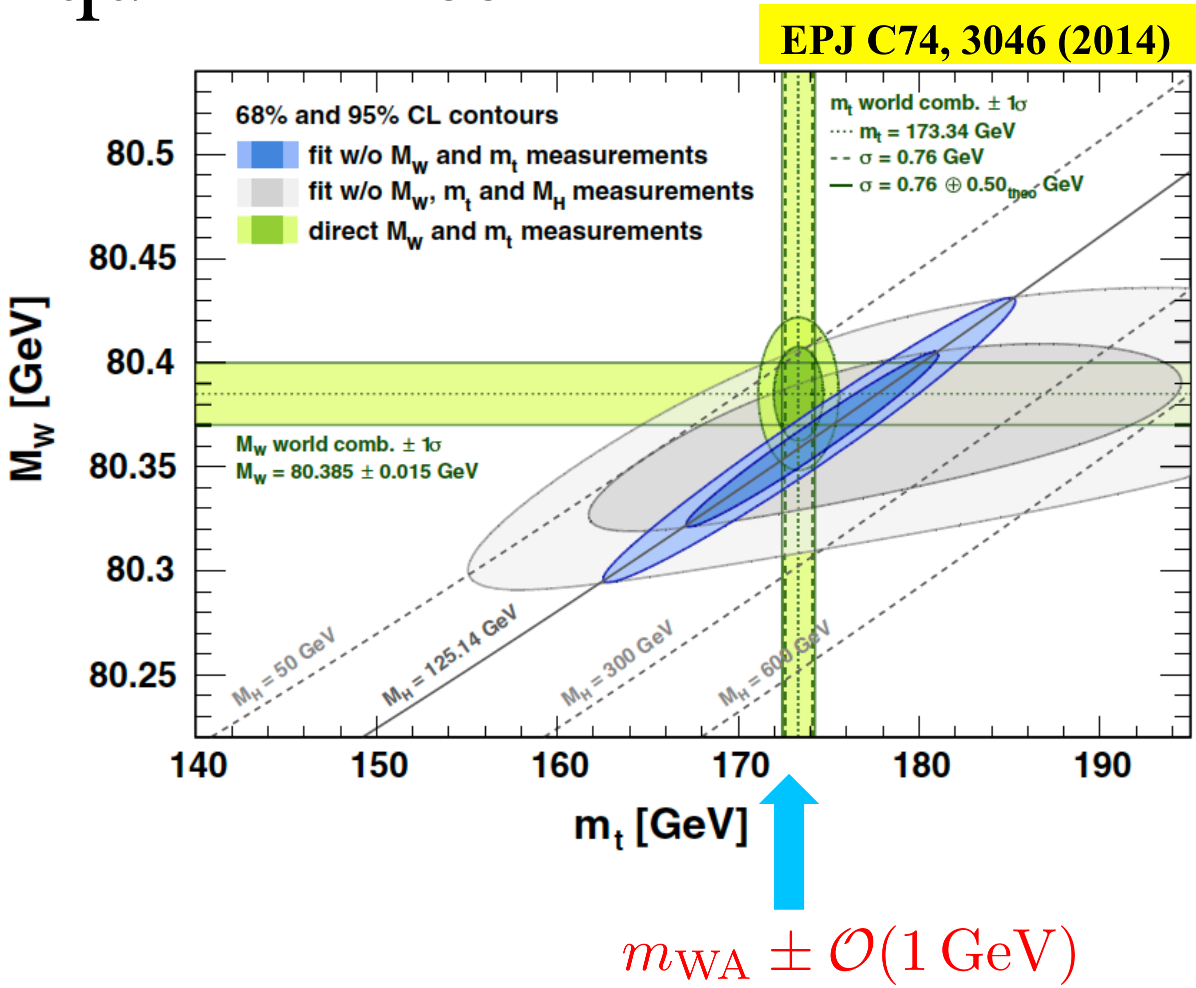
Top properties: production and decay



➢ Shall cover a selected set of results from LHC on the red coloured items

Top-quark mass

- **Top-quark mass is scheme dependent**
  - ‘Pole mass’: view the top as a free particle
  - Other schemes e.g, $\overline{\mathrm{MS}}$ scheme yield different results

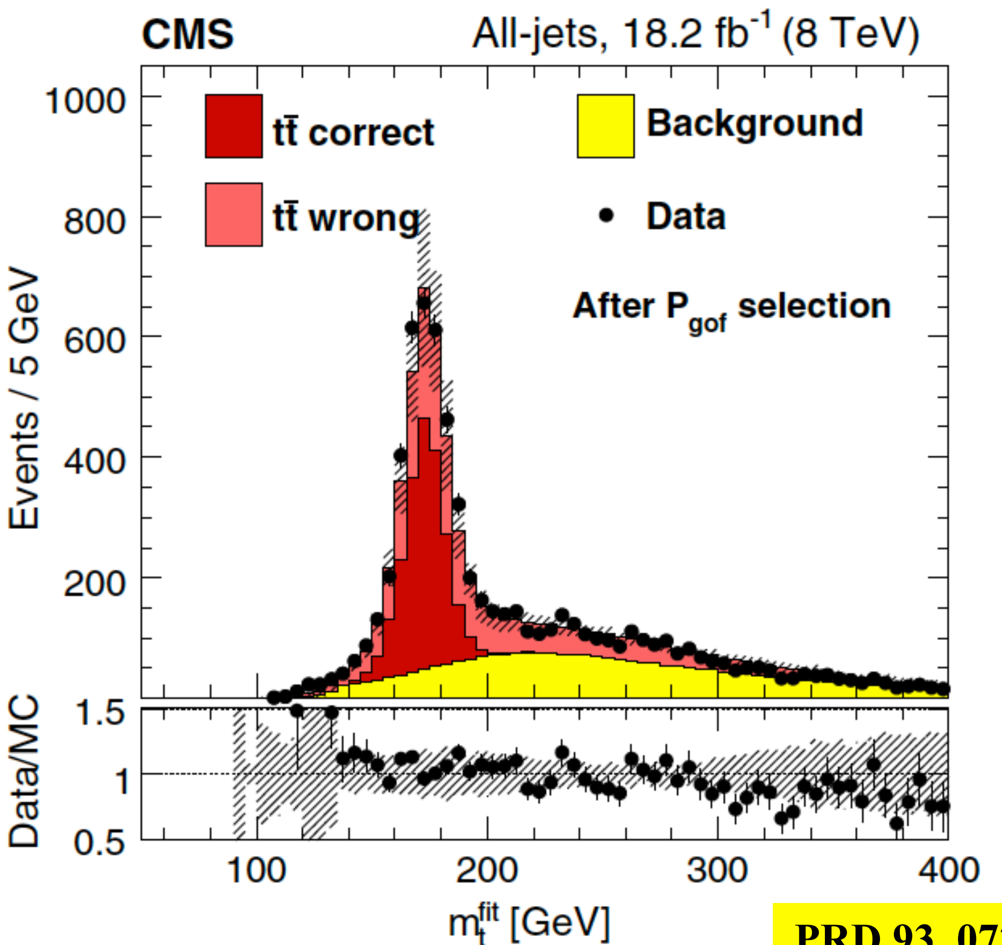


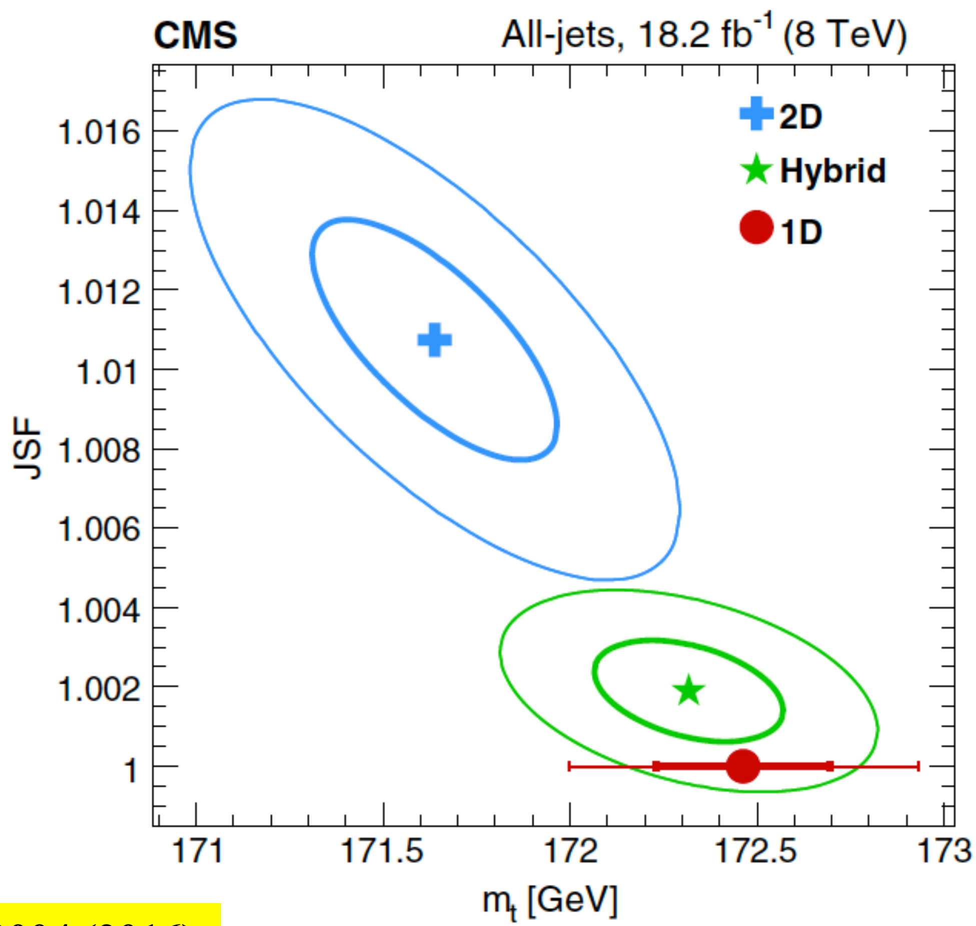
- **‘Direct’ mass measurement**
  - First reconstruct m_t(rec) and then extract the m_t(true) value
  - Most precise experimentally
  - Limitations are flavour-dependent jet energy scale (JSF) uncertainty, hadronization, fragmentation and colour reconnection

- **‘Alternative’ mass measurement**
  - Complementary experimental and theoretical uncertainties
  - Can further pin-down the global error when combined with ‘direct’ mass results

Results from the all-jets final state

- Three approaches: 2D fit to extract m_t and jet energy scale factor (JSF), 1D fit to m_t fixing JSF to unity, and hybrid approach using a Gaussian constraint for JSF with a variance related to the total jet energy correction (JEC) uncertainty





PRD 93, 072004 (2016)

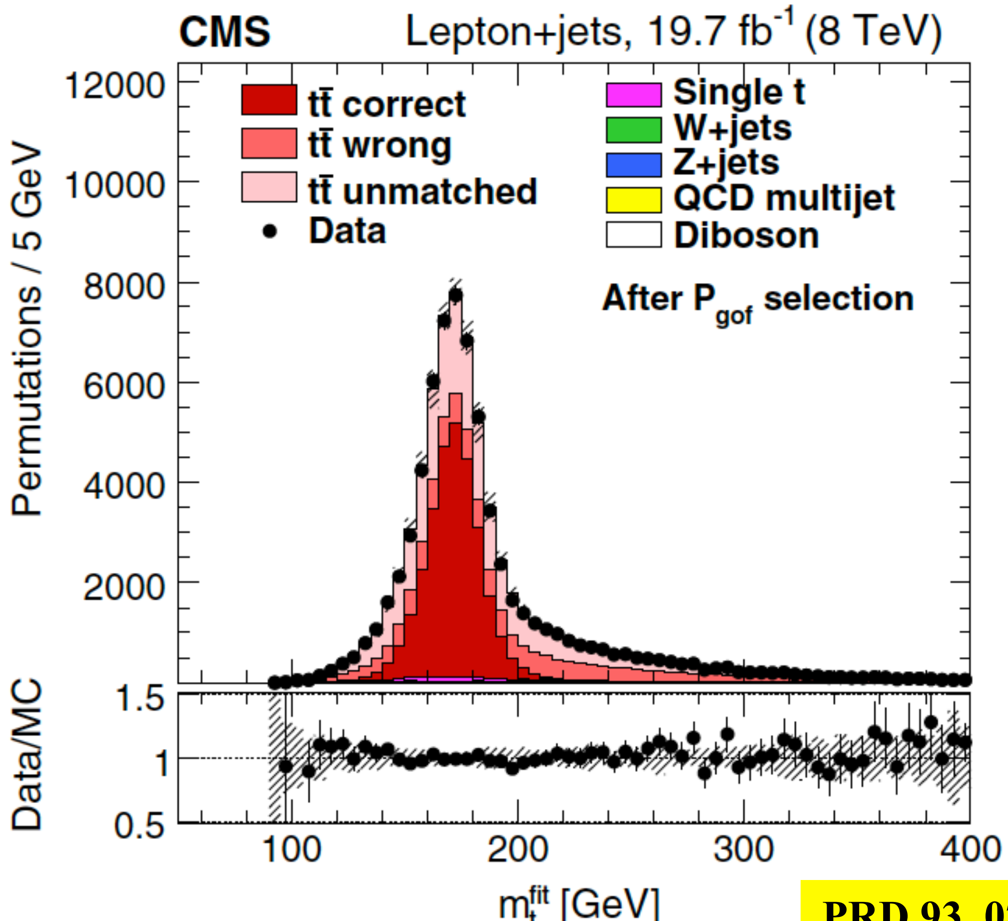
$$m_t^{2D} = 171.64 \pm 0.32(\mathrm{stat+JSF}) \pm 0.95(\mathrm{syst})\ \mathrm{GeV}$$
$$\mathrm{JSF}^{2D} = 1.011 \pm 0.003(\mathrm{stat}) \pm 0.011(\mathrm{syst})$$

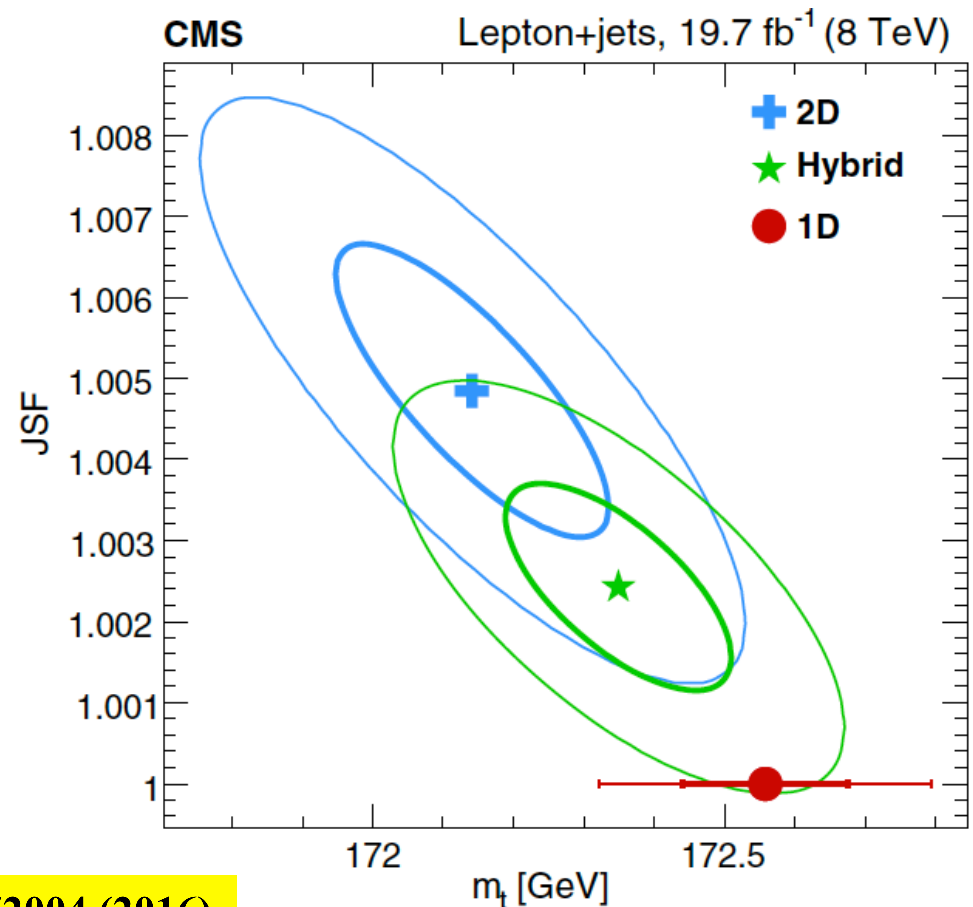
$$m_t^{hyb} = 172.32 \pm 0.25(\mathrm{stat+JSF}) \pm 0.59(\mathrm{syst})\ \mathrm{GeV}$$
$$\mathrm{JSF}^{hyb} = 1.002 \pm 0.001(\mathrm{stat})$$

$$m_t^{1D} = 172.46 \pm 0.23(\mathrm{stat}) \pm 0.62(\mathrm{syst})\ \mathrm{GeV}$$

Results from the lepton+jets final state

- Similar three approaches as all-jets final state analysis
- JSF for 2D and hybrid are within 0.5% of one
- Compatible results in individual electron+jets and muon+jets channel





PRD 93, 072004 (2016)

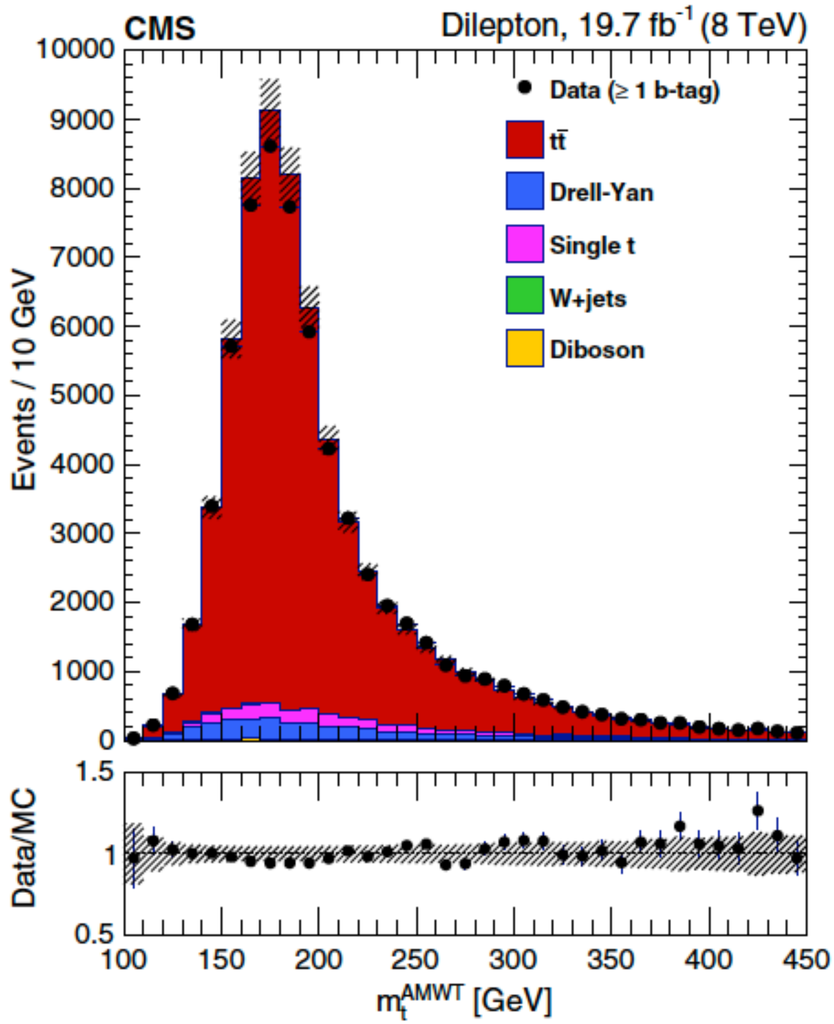
$$m_t^{2D} = 172.14 \pm 0.19(\text{stat}+\text{JSF}) \pm 0.59(\text{syst})\ \text{GeV}$$
$$\text{JSF}^{2D} = 1.005 \pm 0.002(\text{stat}) \pm 0.007(\text{syst})$$

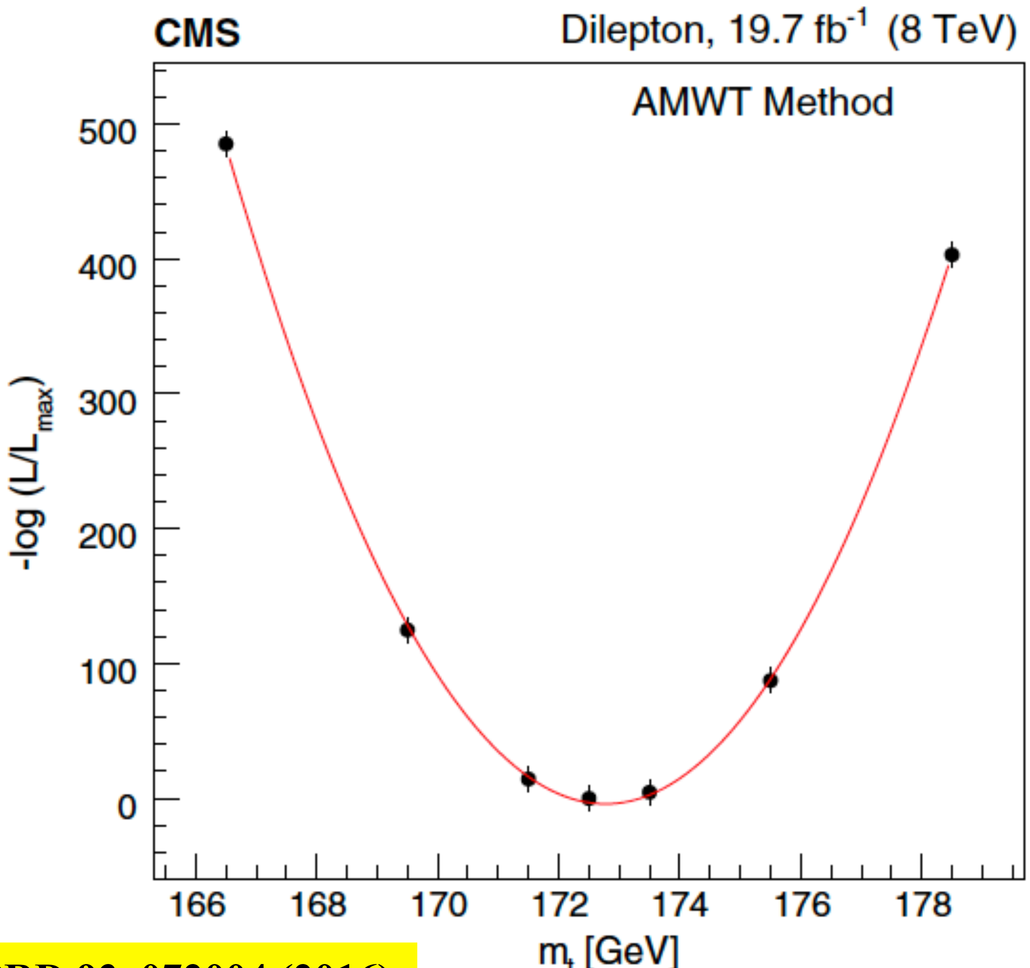
$$m_t^{hyb} = 172.35 \pm 0.16(\text{stat}+\text{JSF}) \pm 0.48(\text{syst})\ \text{GeV}$$
$$\text{JSF}^{hyb} = 1.002 \pm 0.001(\text{stat})$$

$$m_t^{1D} = 172.56 \pm 0.12(\text{stat}) \pm 0.62(\text{syst})\ \text{GeV}$$

Results from the dilepton final state

- Use analytical matrix weighting technique (AMWT) that allows determination of m_t with the assumption of JSF = 1
- Mass estimator obtained using several kinematical variables e.g., momentum of two charged leptons and of two b-jets



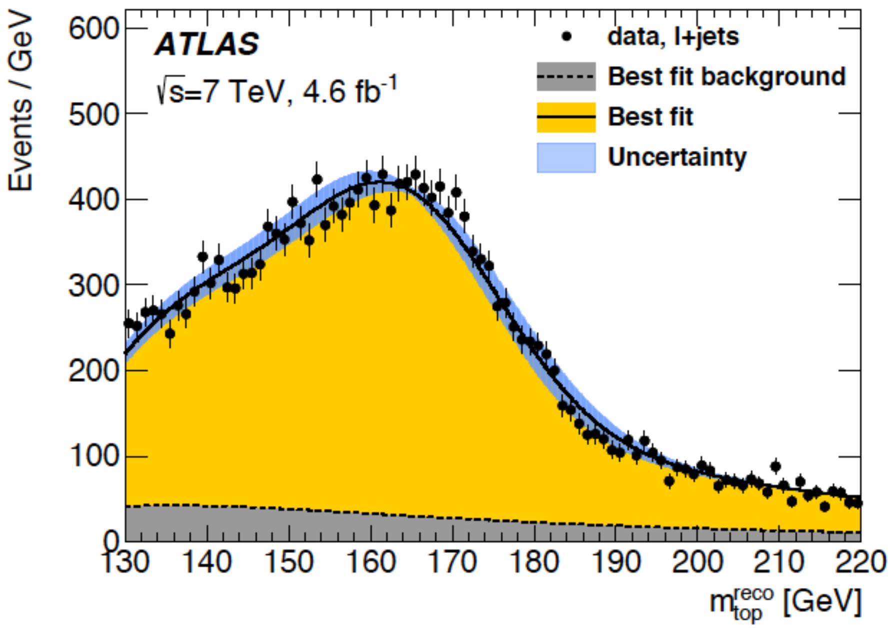


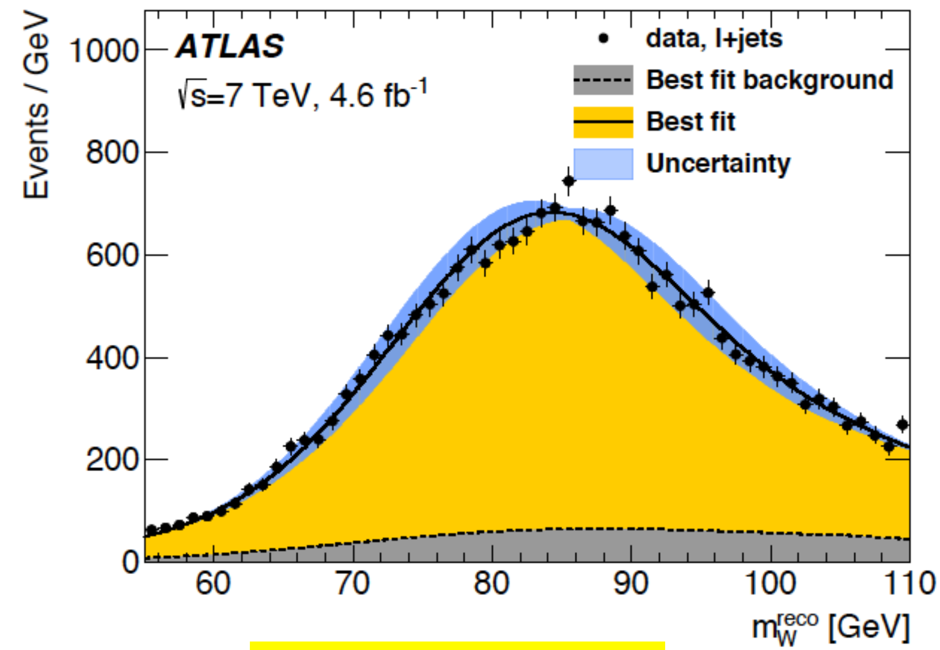
PRD 93, 072004 (2016)

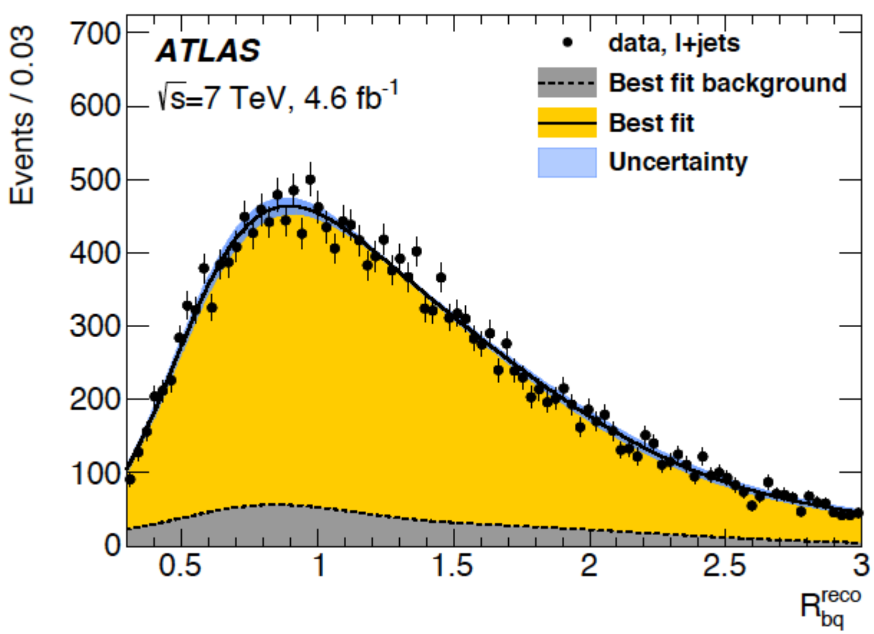
$$m_t = 172.82 \pm 0.19(\text{stat}) \pm 1.22(\text{syst})\ \text{GeV}$$

Results from lepton+jets and dilepton channels

- 3D template fit to extract m_{top}, jet energy scale and b-jet energy scale
- For the dilepton channel, the m_{top}-sensitive observable m_{lb} has been used







EPJ C75, 330 (2015)

$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\ (\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\ (\mathrm{syst})\ \mathrm{GeV},$$

$$m_{\mathrm{top}}^{\mathrm{dil}} = 173.79 \pm 0.54\ (\mathrm{stat}) \pm 1.30\ (\mathrm{syst})\ \mathrm{GeV}$$

$$\boxed{m_{\mathrm{top}} = 172.99 \pm 0.48(\mathrm{stat}) \pm 0.78(\mathrm{syst})\ \mathrm{GeV}}$$

- Will benefit from more statistics at 8 TeV as well as Run II

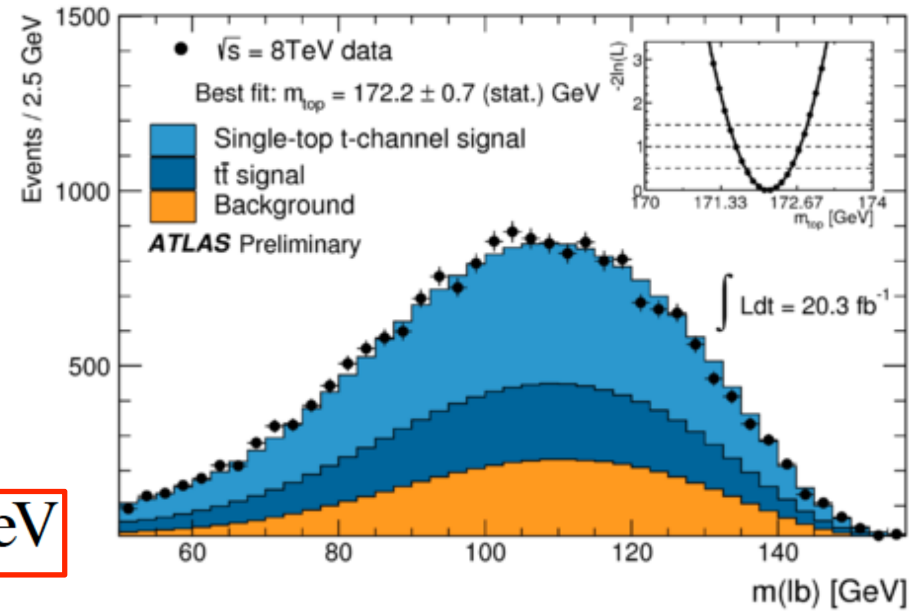
Results from single top events

ATLAS-CONF-2014-055

- Use events dominated by t-channel single top quark topologies
- Employ a Neural Network to enhance the signal purity
- 1D template fit to the invariant mass of the lepton and b-tagged jet

$$m_{\mathrm{top}} = 172.2 \pm 0.7\,(\mathrm{stat.}) \pm 2.0\,(\mathrm{syst.})\ \mathrm{GeV}$$

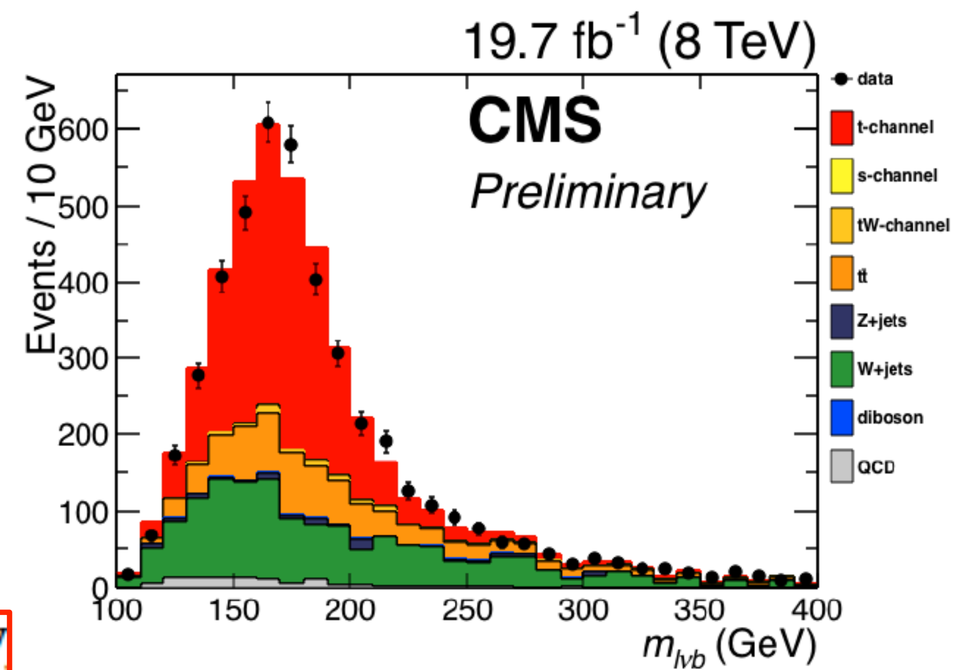
- ➤ JSF is the dominant source of systematic



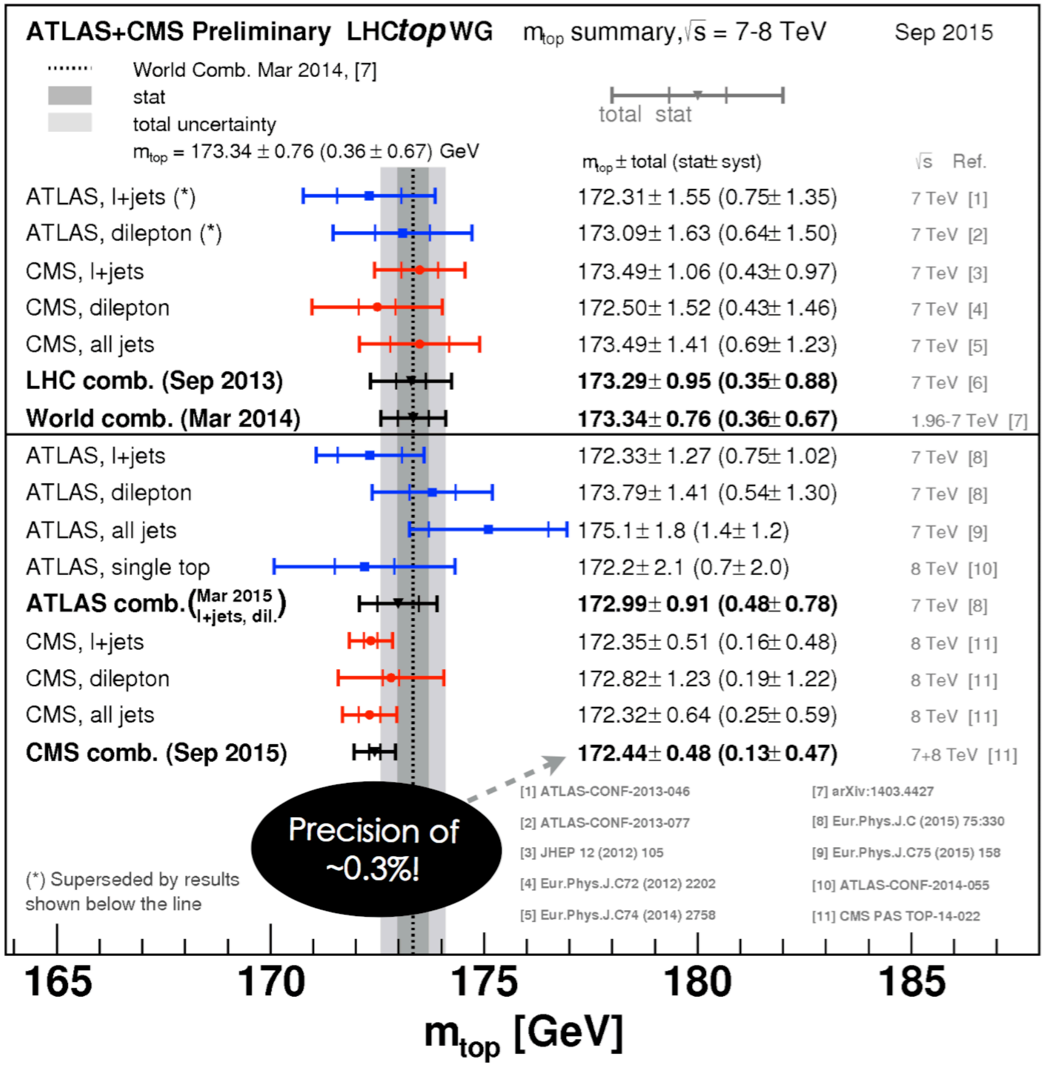
CMS PAS TOP-16-001

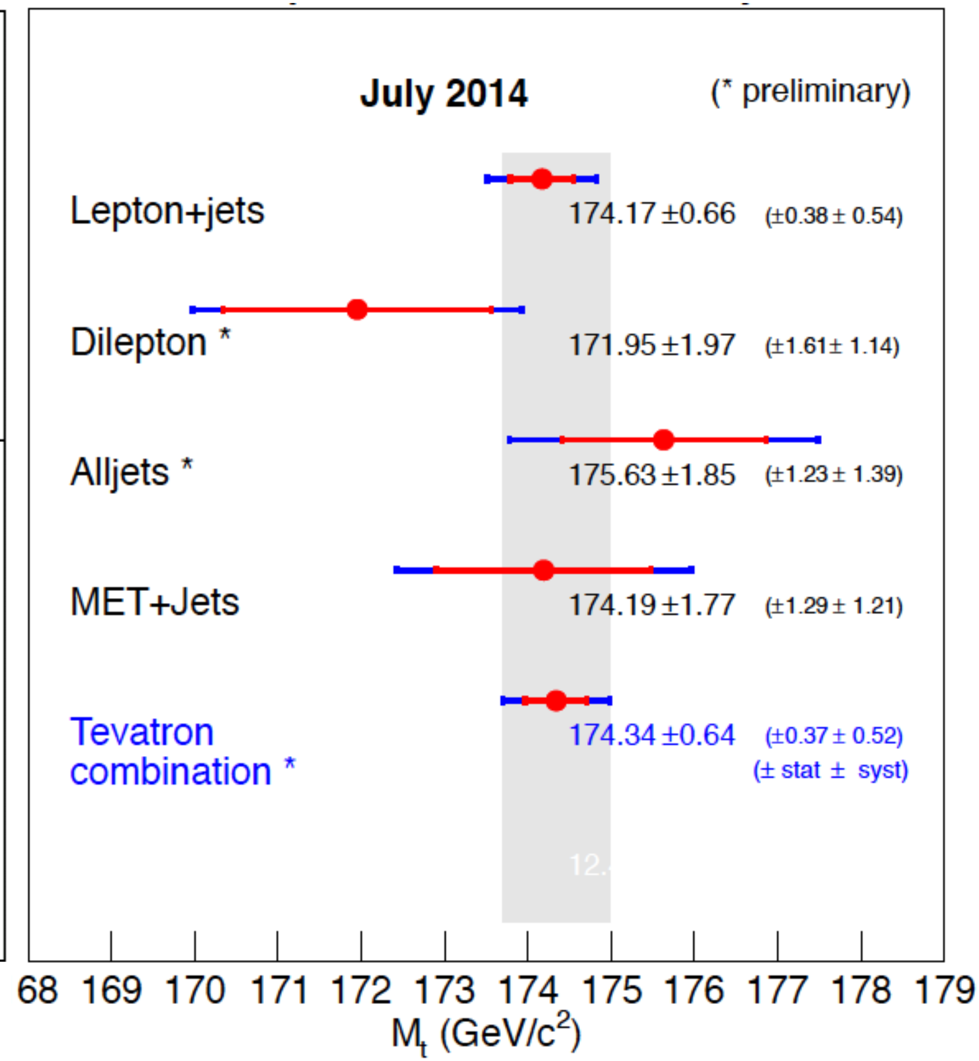
- Event topology and kinematic properties used to cut down background, especially top pair production
- Extended unbinned maximum likelihood fit to the m(lυb) distribution

$$m_{\mathrm{t}} = 172.60 \pm 0.77\ (\mathrm{stat})\ {}^{+0.97}_{-0.93}\ (\mathrm{syst})\ \mathrm{GeV}$$



Summary on the top-quark mass





$$\boxed{m_{top} = 172.44 \pm 0.48\,\mathrm{GeV}}$$

$$\boxed{m_{top} = 172.99 \pm 0.91\,\mathrm{GeV}}$$

$$\boxed{m_{top} = 174.34 \pm 0.64\,\mathrm{GeV}}$$

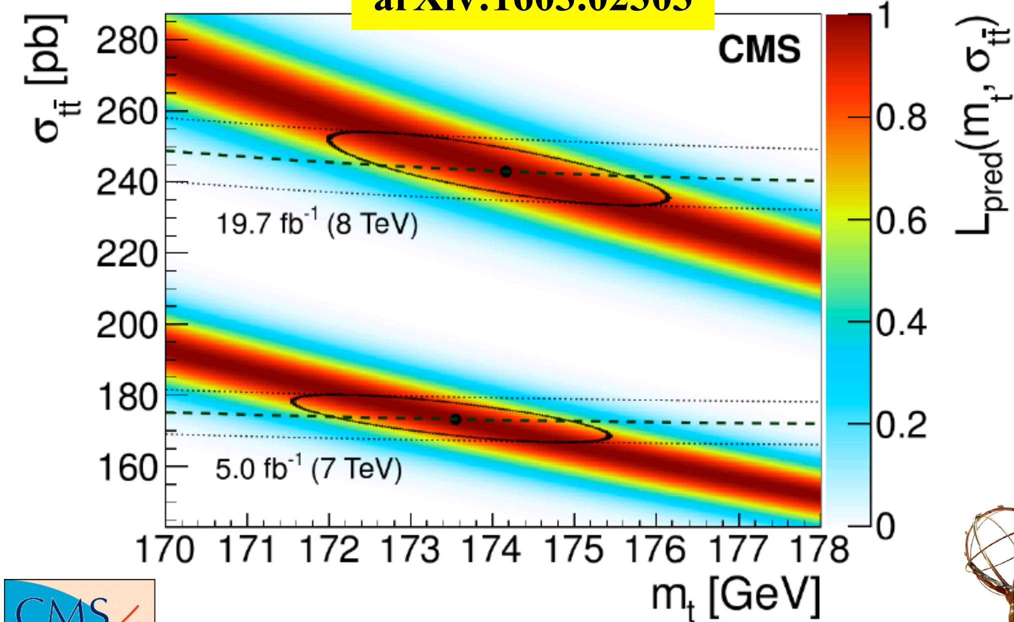
Results on m_{pole} from CMS and ATLAS

- Measure σ_{tt} (7+8 TeV) using a template fit to b-jet multiplicity, multiplicity and p_T of other jets

$$\sigma_{t\bar{t}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb}$$
$$\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\,\text{pb}$$

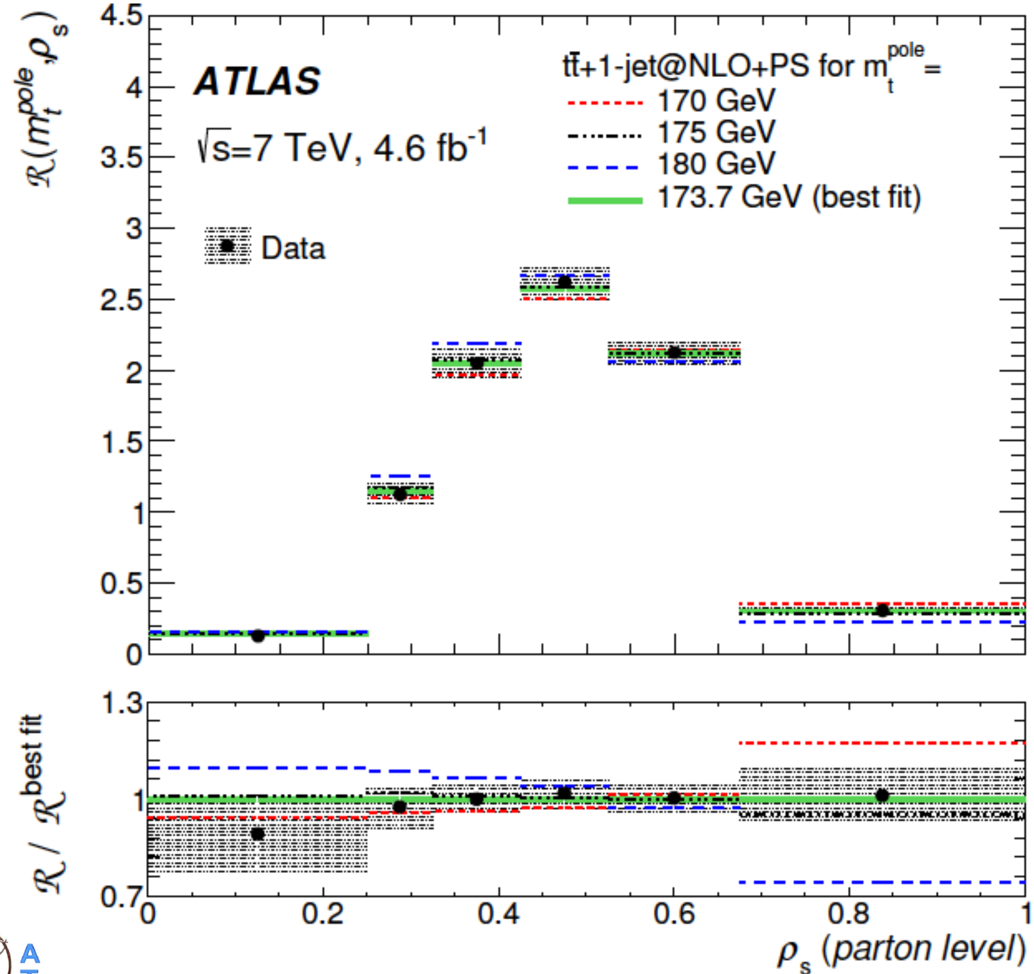
- Extract m_{pole} by comparing σ_{tt} with NNLO (+NNLL) computations

arXiv:1603.02303



$$m_{pole} = 173.8^{+1.7}_{-1.8}\,\text{GeV}$$

- tt+1-jet distribution (NLO+PS) pole mass via threshold & cone effects

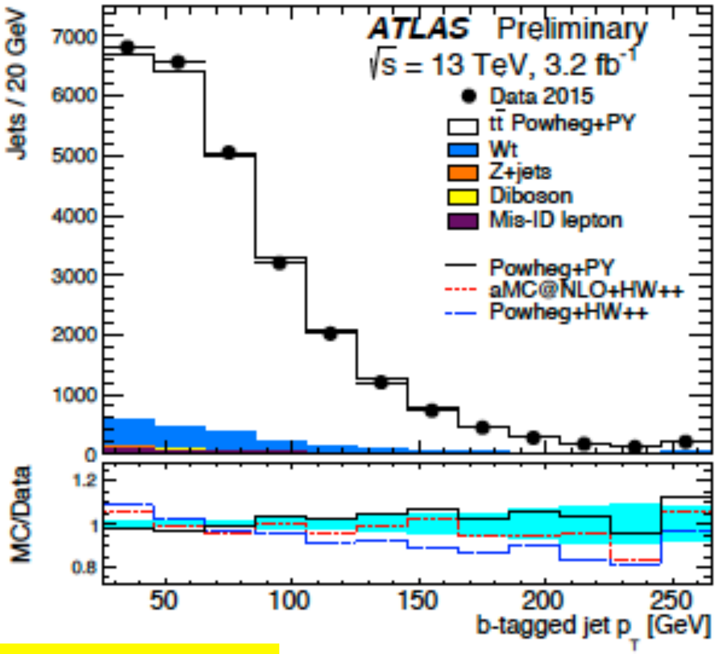


JHEP 1510, 121 (2015)

$$m_{pole} = 173.7 \pm 1.5(\text{stat}) \pm 1.4(\text{syst})^{+1.0}_{-0.5}(\text{theo})\,\text{GeV}$$

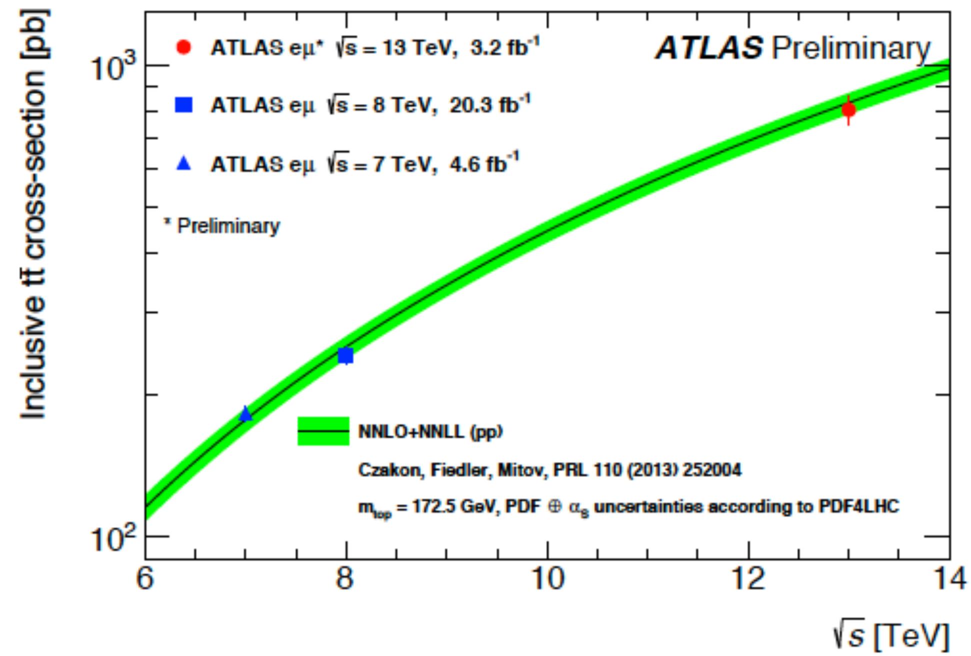
➢ First one is the single most precise m_{pole} measurement

Top-pair cross section @ 13 TeV



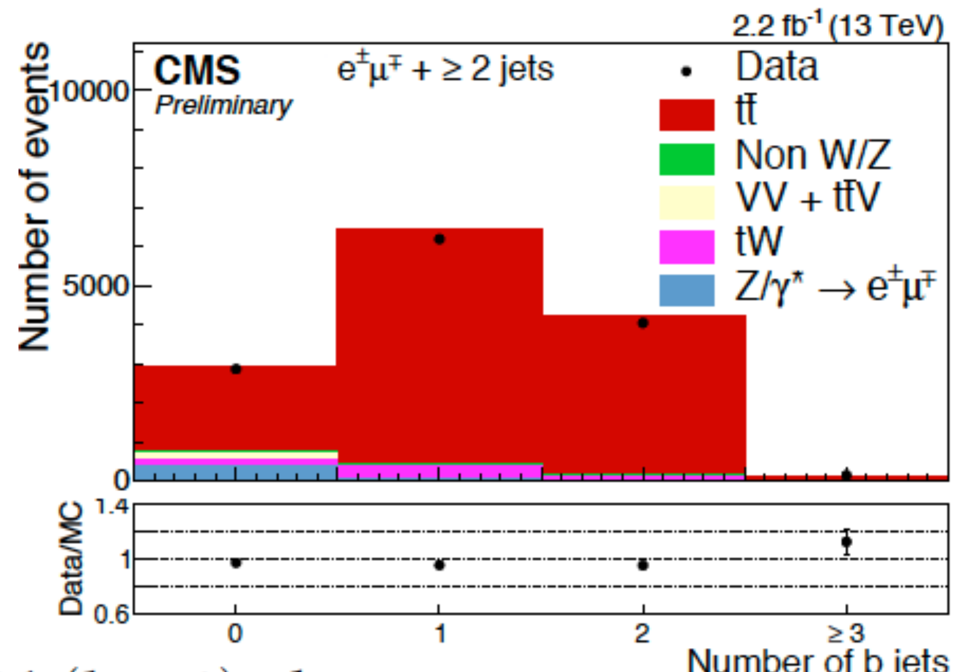
ATLAS-CONF-2016-005

- Count # of b-jets in the dilepton sample



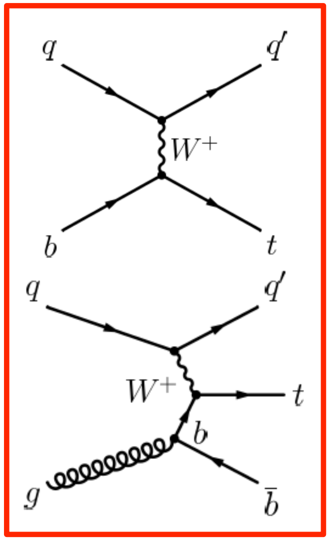
CMS PAS TOP-16-005

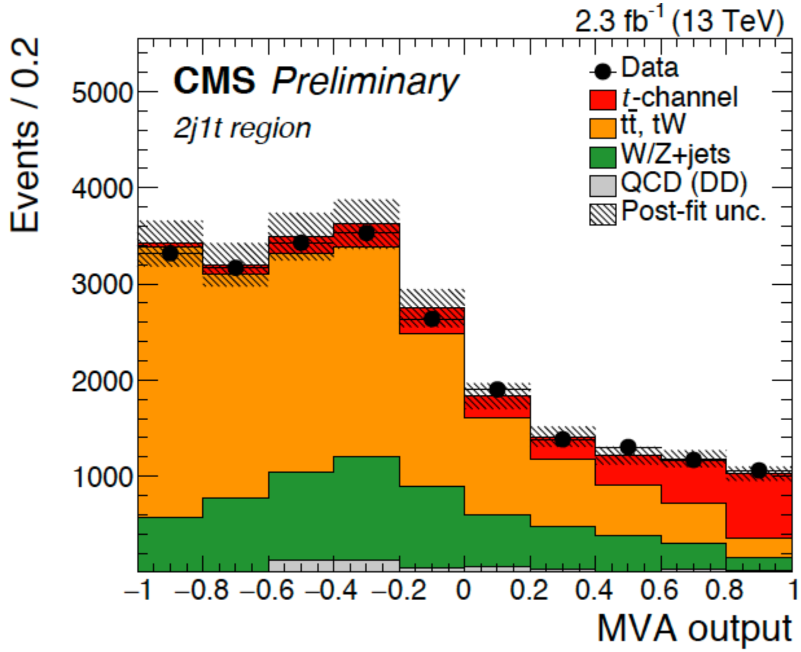
- Measurement performed through an event-counting method



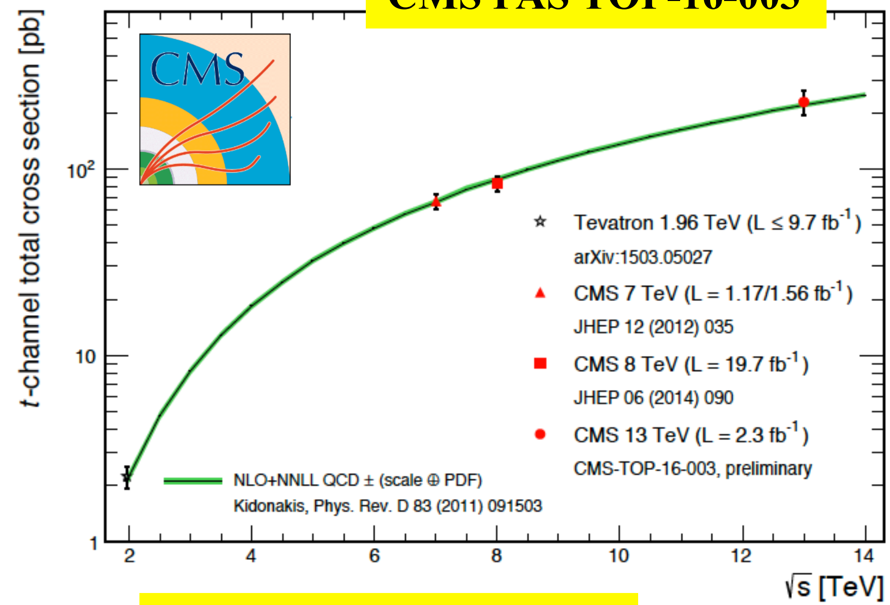
$$\sigma_{t\bar{t}} = 793 \pm 8\,(\mathrm{stat}) \pm 38\,(\mathrm{syst}) \pm 21\,(\mathrm{lumi})\ \mathrm{pb}$$

Single top production cross section @ 13 TeV

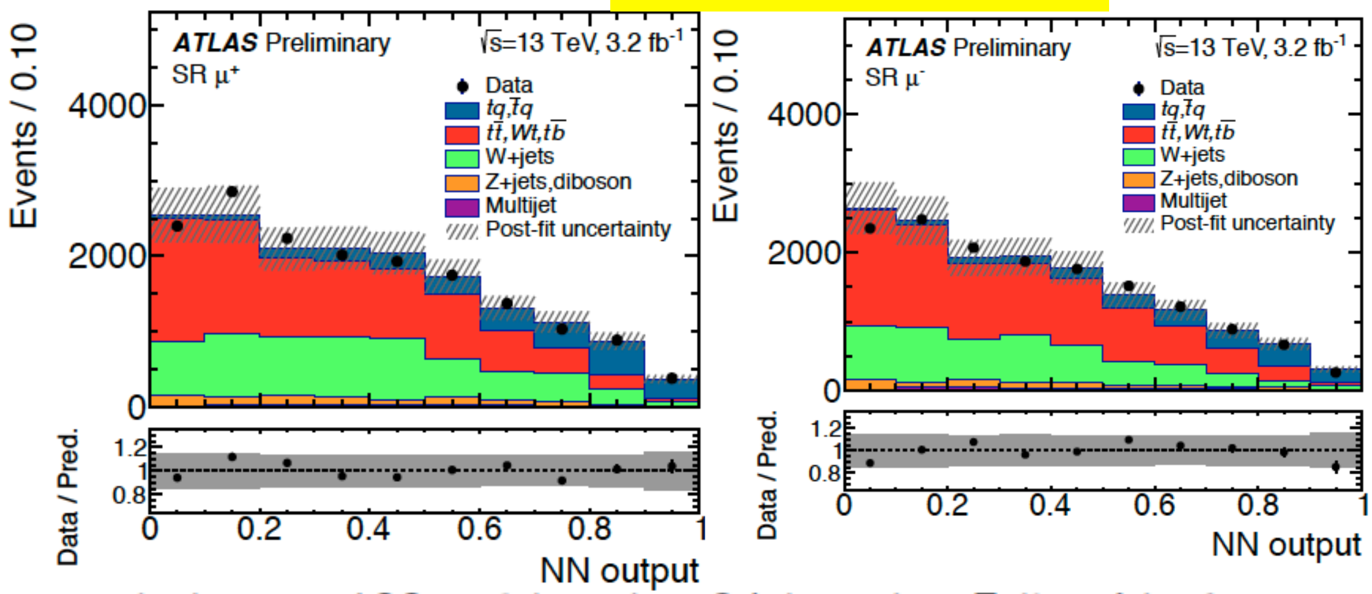




CMS PAS TOP-16-003



ATLAS-CONF-2015-079



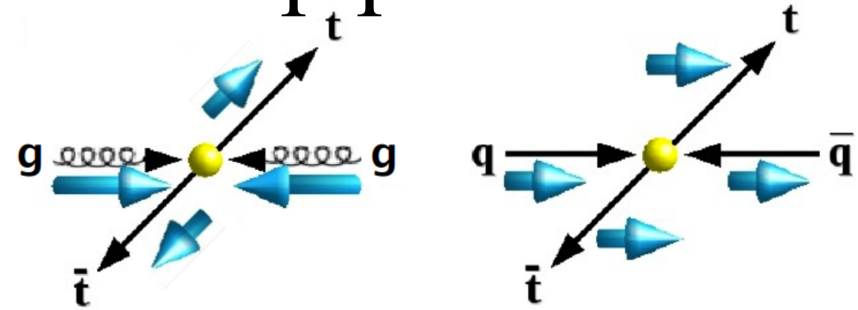
- CMS (ATLAS) obtains the cross section by fitting to a MVA (NN) o/p distribution

$$\sigma(tq) = 133 \pm 6\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lumi.})\ \text{pb}$$

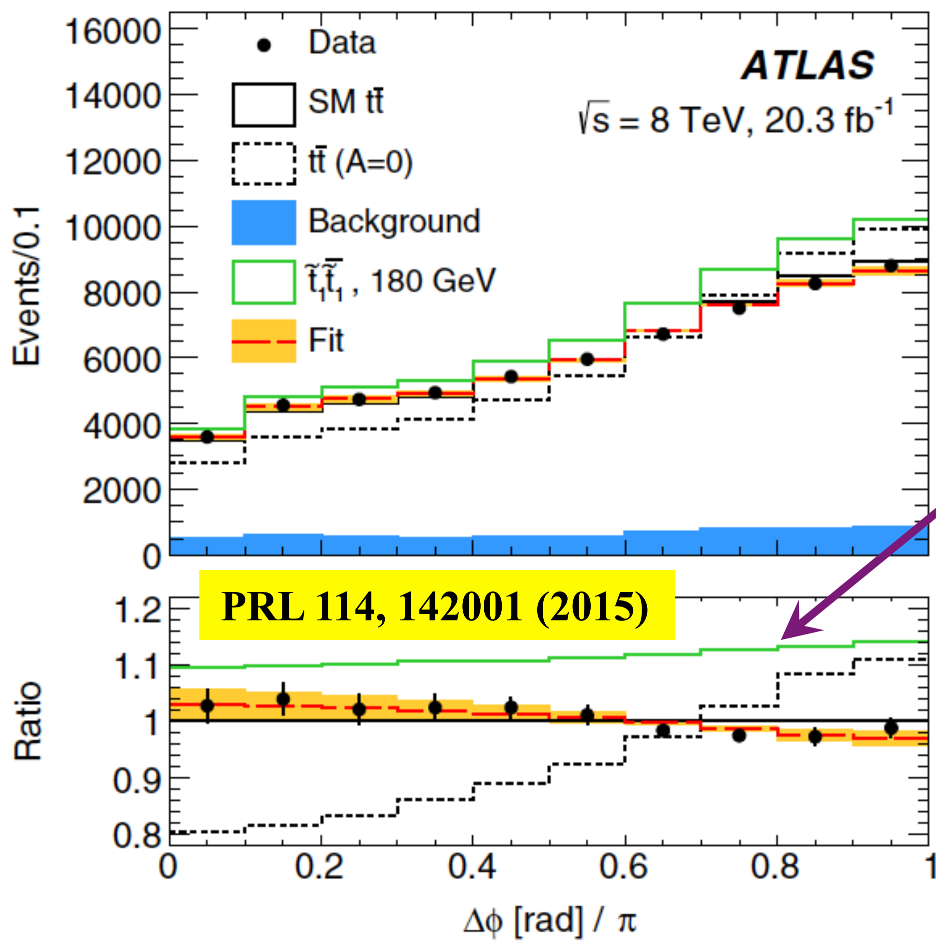
$$\sigma(\bar{t}q) = 96 \pm 5\,(\text{stat.}) \pm 23\,(\text{syst.}) \pm 5\,(\text{lumi.})\ \text{pb}$$

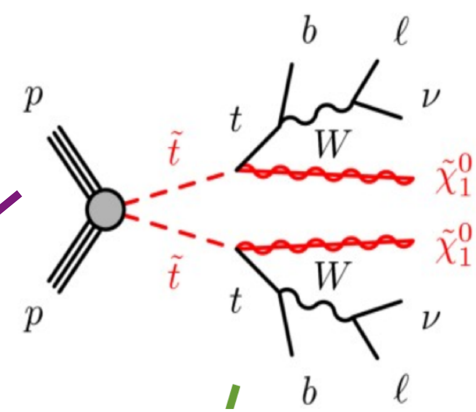
Spin correlation results from top pair events

- Top quarks decay before their spins can de-correlate ➔ spin correlation
- Use dilepton channel: access the above via azimuthal angle difference of two leptons in the laboratory frame



$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$

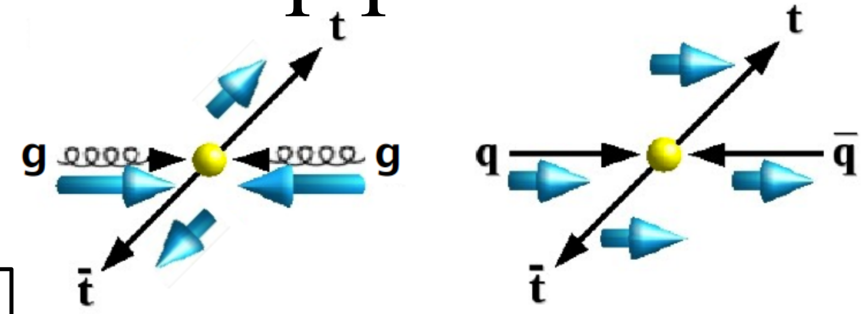




- Exclude top squark masses between m_{top} and 191 GeV at 95% CL

$$f_{SM} = 1.20 \pm 0.05(\mathrm{stat}) \pm 0.13(\mathrm{syst})$$

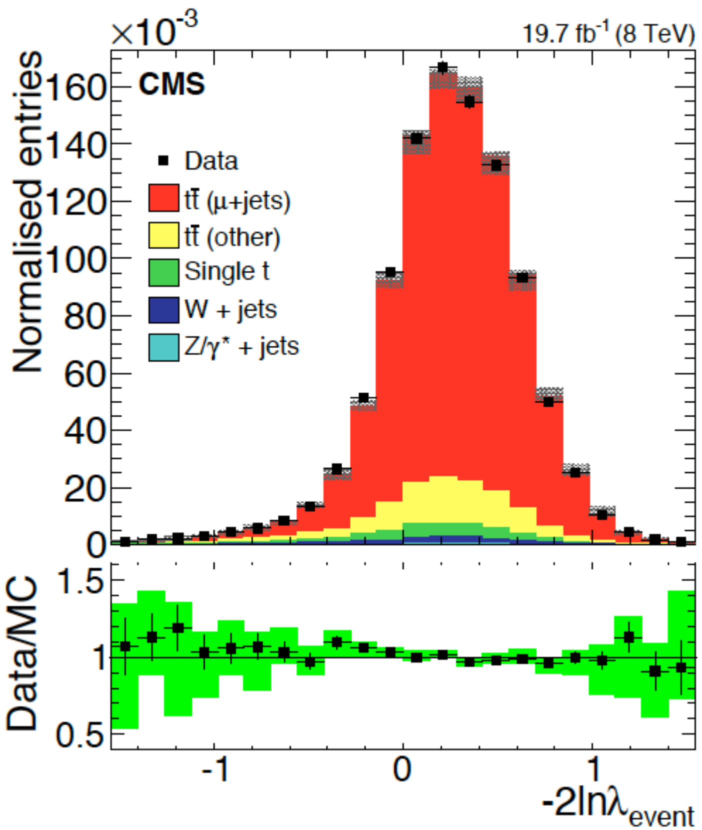
Spin correlation results from top pair events

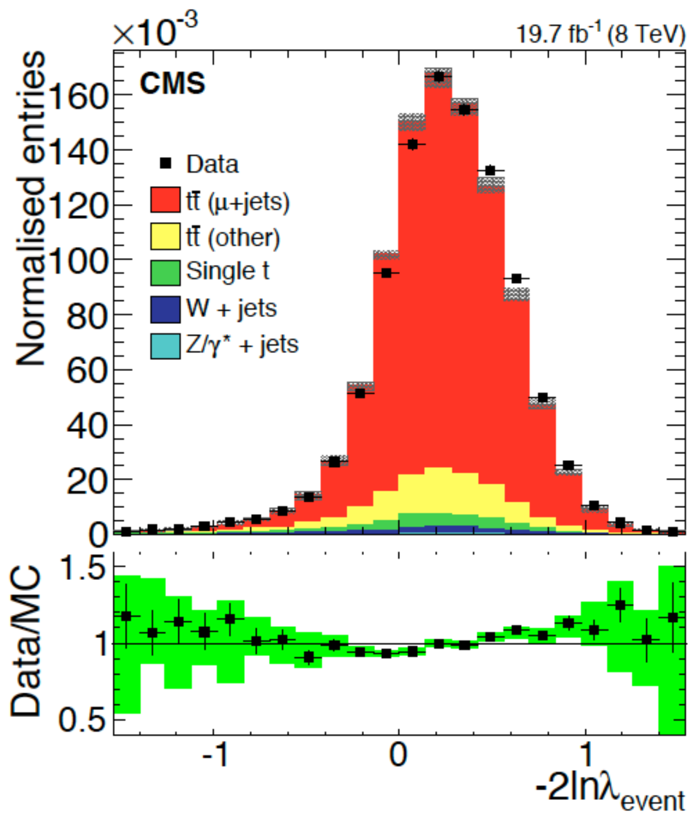


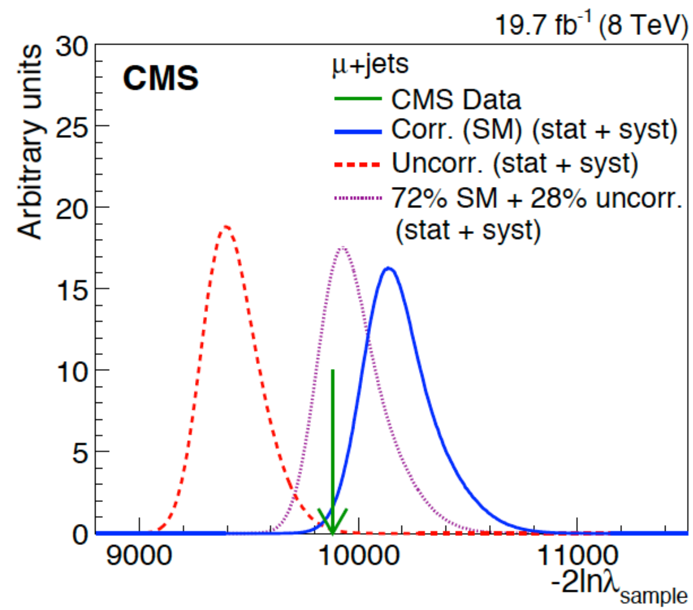
- Use the muon+jets channel ➔ require full top-pair event reconstruction
- Employ the full matrix element method

$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$

arXiv:1511.06170







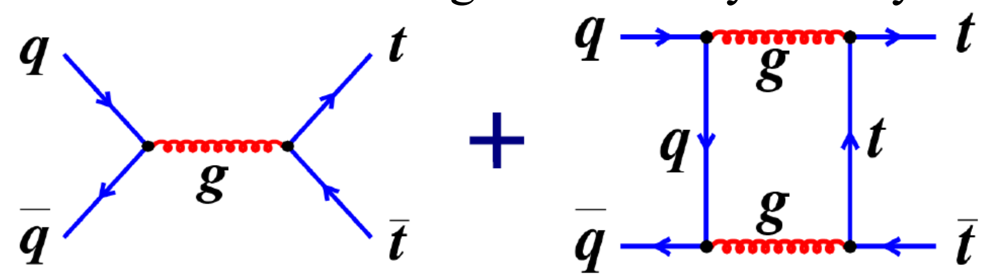
$$f = 0.72 \pm 0.08\,(\mathrm{stat})^{+0.15}_{-0.13}\,(\mathrm{syst})$$

- Data are more compatible with the SM hypothesis

Forward-backward and charge asymmetries

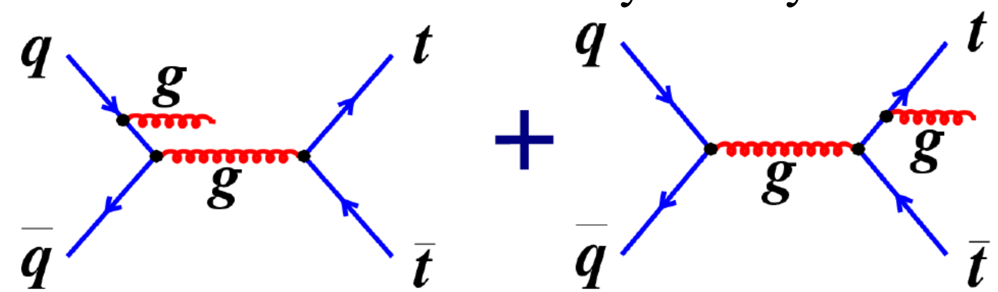
- LO: do not expect any asymmetry
- NLO: arises due to interference between the qq diagram
- Diluted at LHC owing to large gg fraction coupled with unknown quark direction

tree-level and box diagram: +ve asymmetry

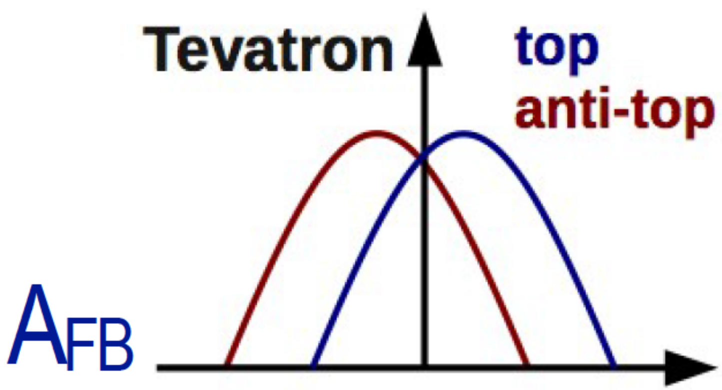


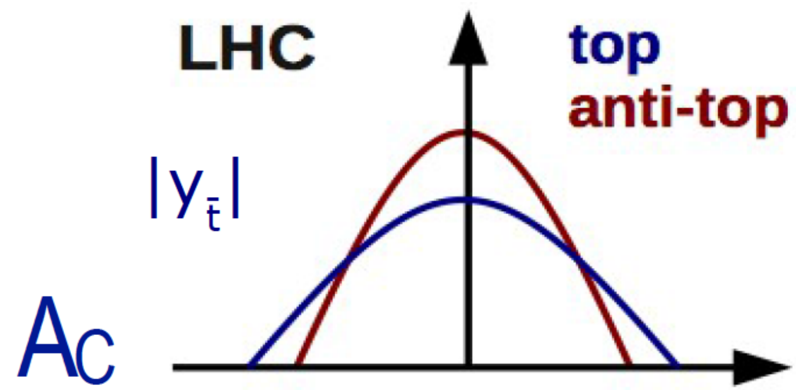
- Recent NNLO prediction for Tevatron: $A_{FB} = 0.095 \pm 0.007$ **PRL 115, 052001 (2015)**

ISR and FSR: −ve asymmetry



➢ Agrees with latest D0 measurement and 1.5σ below the CDF value





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

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

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

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

Results on charge asymmetry

- Differential AC measurement as a function of rapidity, p_T and invariant mass of the tt system
- Also performed the measurement in a fiducial phase space
- Template method exploits the shape of Δ|η| distribution as well

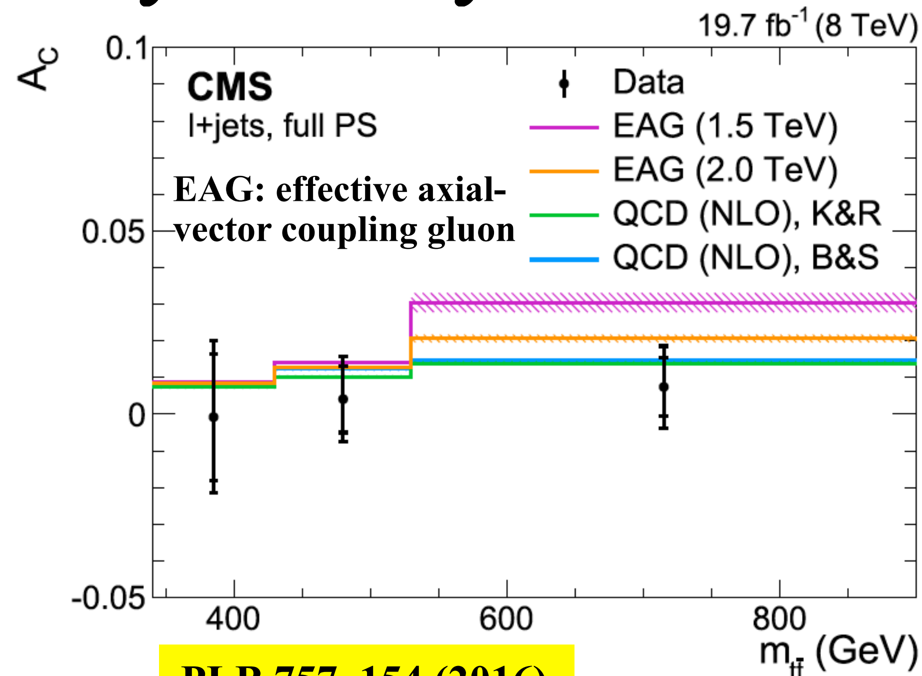
Full phase space:

$A_C = [0.10 \pm 0.68(\text{stat}) \pm 0.37(\text{syst})]\%$

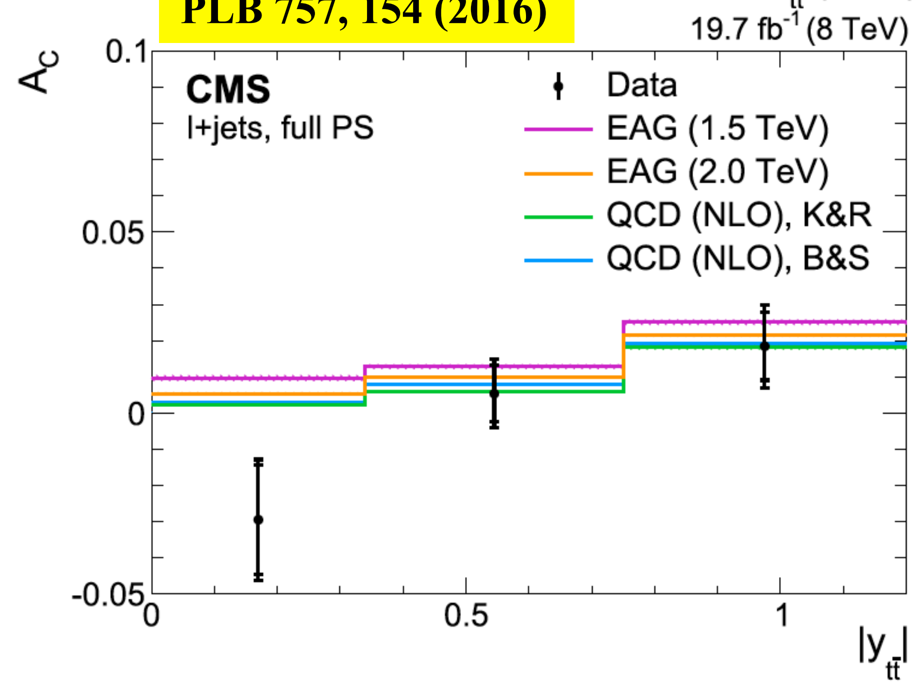
Fiducial phase space:

$A_C = [-0.35 \pm 0.72(\text{stat}) \pm 0.31(\text{syst})]\%$

➢ Are consistent with zero asymmetry as well as SM predictions (~1%)



PLB 757, 154 (2016)



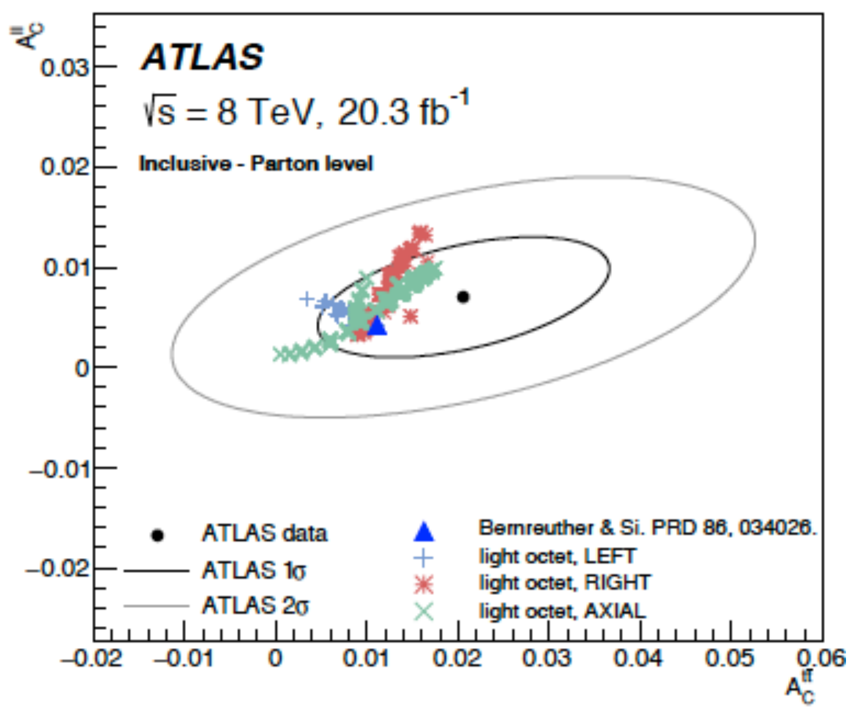
Results on charge asymmetry

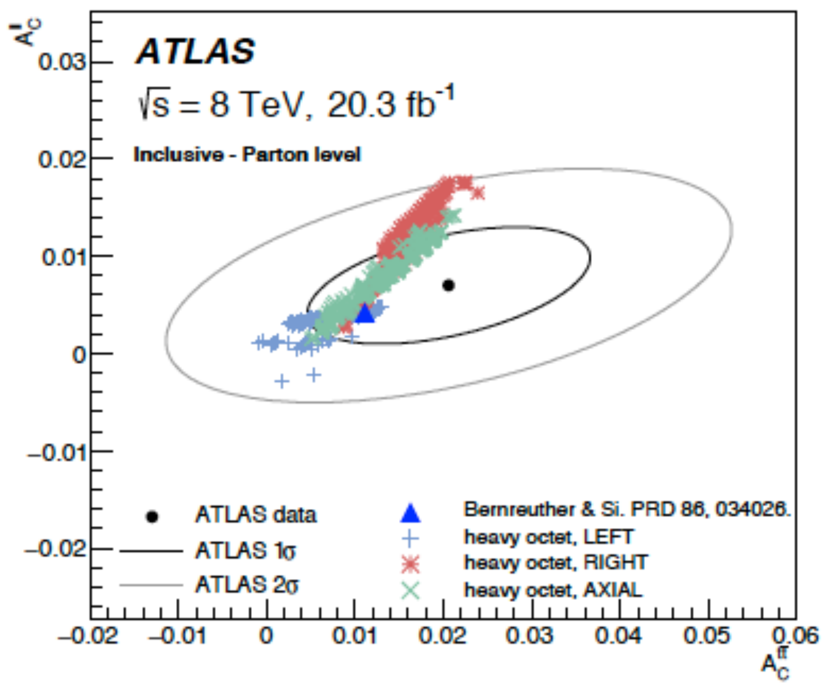
arXiv:1604.05538

- Inclusive as well as differential measurement in m_{tt}, $p_{T,tt}$ and $|\beta_{tt}|$ ➔enhanced sensitivity to NP
- Two observables are studied based on the selected leptons and reconstructed top-pair final state

$$A_C^{\ell\ell} = 0.008 \pm 0.006$$
$$A_C^{t\bar{t}} = 0.021 \pm 0.016$$

➢ Good agreement with SM predictions and constraints on NP (light and heavy octet)





Summary and Outlook

- Top physics is indeed 'top physics': it is everywhere (QCD, electroweak and NP)
  - ✓ LHC is mostly providing complementary info w.r.t. Tevatron
  - ✓ A detailed picture of the beast(!) has been established
  - ✓ ATLAS and CMS are finishing up legacy publication

- What do we expect at Run II? 100 fb^{-1} per experiment by 2018
  - ✓ 80×10^{6} top-pair and 20×10^{6} single top events (>10 Hz at 10^{34} $cm^{-2}s^{-1}$)
  - ✓ 80,000 tt+Z and t+Z events, each

- Statistics ➔ systematics and reach
  - ✓ Beat down systematics using statistics and combining different methods
  - ✓ Ultimate precision also would call for advances in theory (e.g, top mass)

- Top as a NP probe
  - ✓ Direct and indirect searches
  - ✓ Couplings, FCNC, asymmetries, angular distributions

➢ Remain positive for (un)known unknowns