Highlights of top-quark physics at ATLAS

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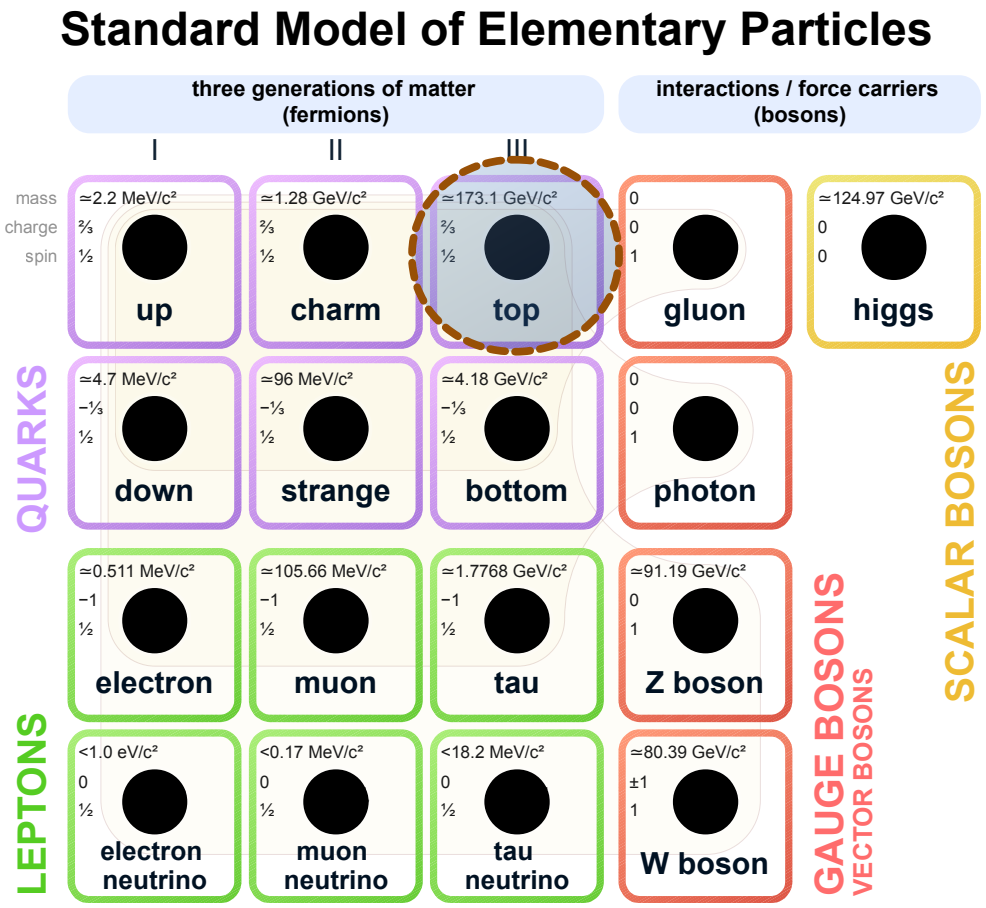
on behalf of the ATLAS collaboration

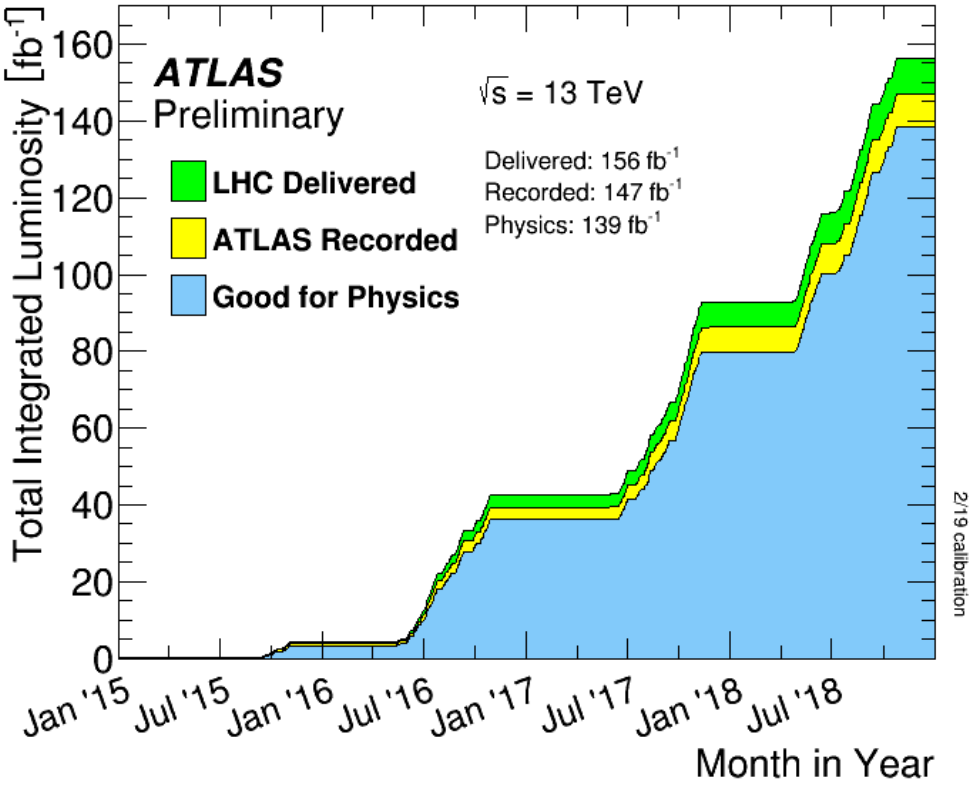
HEPMAD19

Top quark



- Property which makes top quark special: **a large mass**
  - Probing Standard Model (SM) at large energy scales
  - Unique role in potential extensions of SM
  - Important background in many searches for physics beyond SM

Top quark physics at LHC

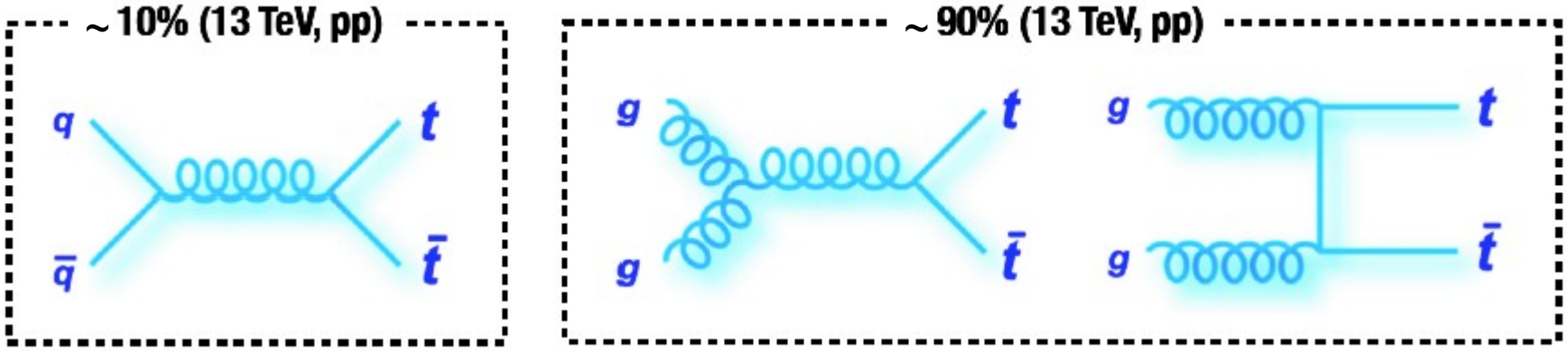


- ATLAS/CMS: ~120 millions of top-quark pair events predicted per experiment
  → **precise measurement** of production and properties (also differentially)
  → **searches** for rare production and new phenomena

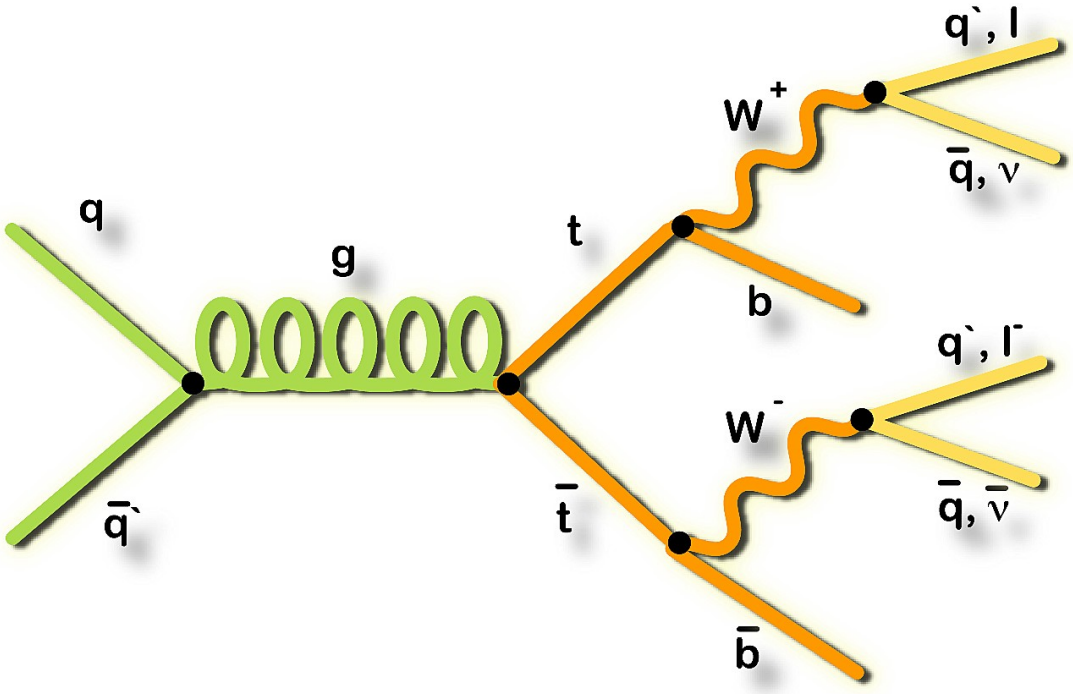
How often top quarks are produced?

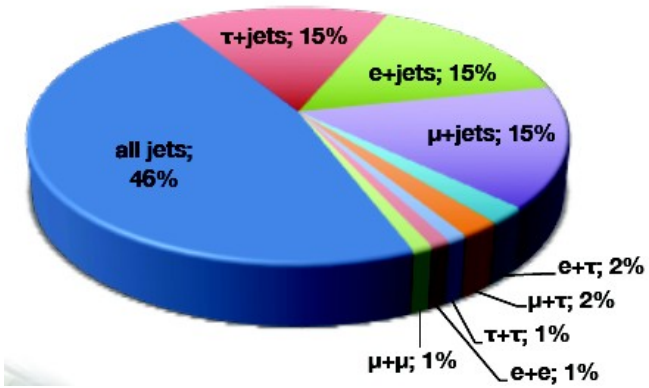
Top-quark pair production

- Dominant production in pairs via strong interaction:



- Decay chain determined by W boson decays:





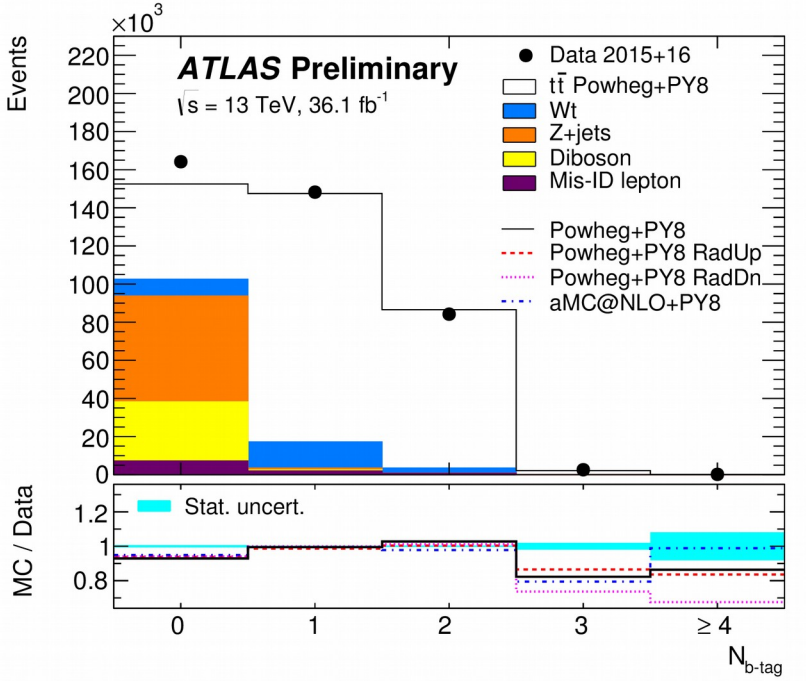
Inclusive top-quark pair cross-section

ATLAS-CONF-2019-041
ATLAS-CONF-2019-044

- Precise test of QCD at large energy scale

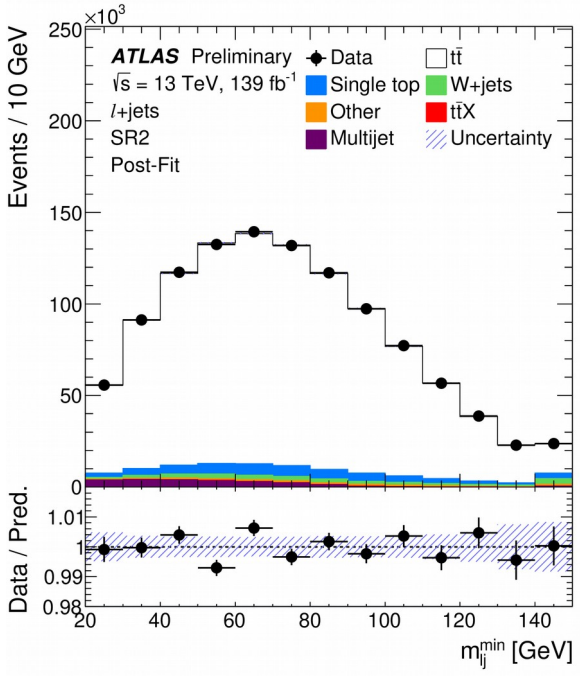
Dilepton channel:

- counting events with b-jets
- analyse 2015 and 2016 data separately



lepton+jets channel:

- fit to various distributions with small sensitivity to $t\bar{t}$ modelling



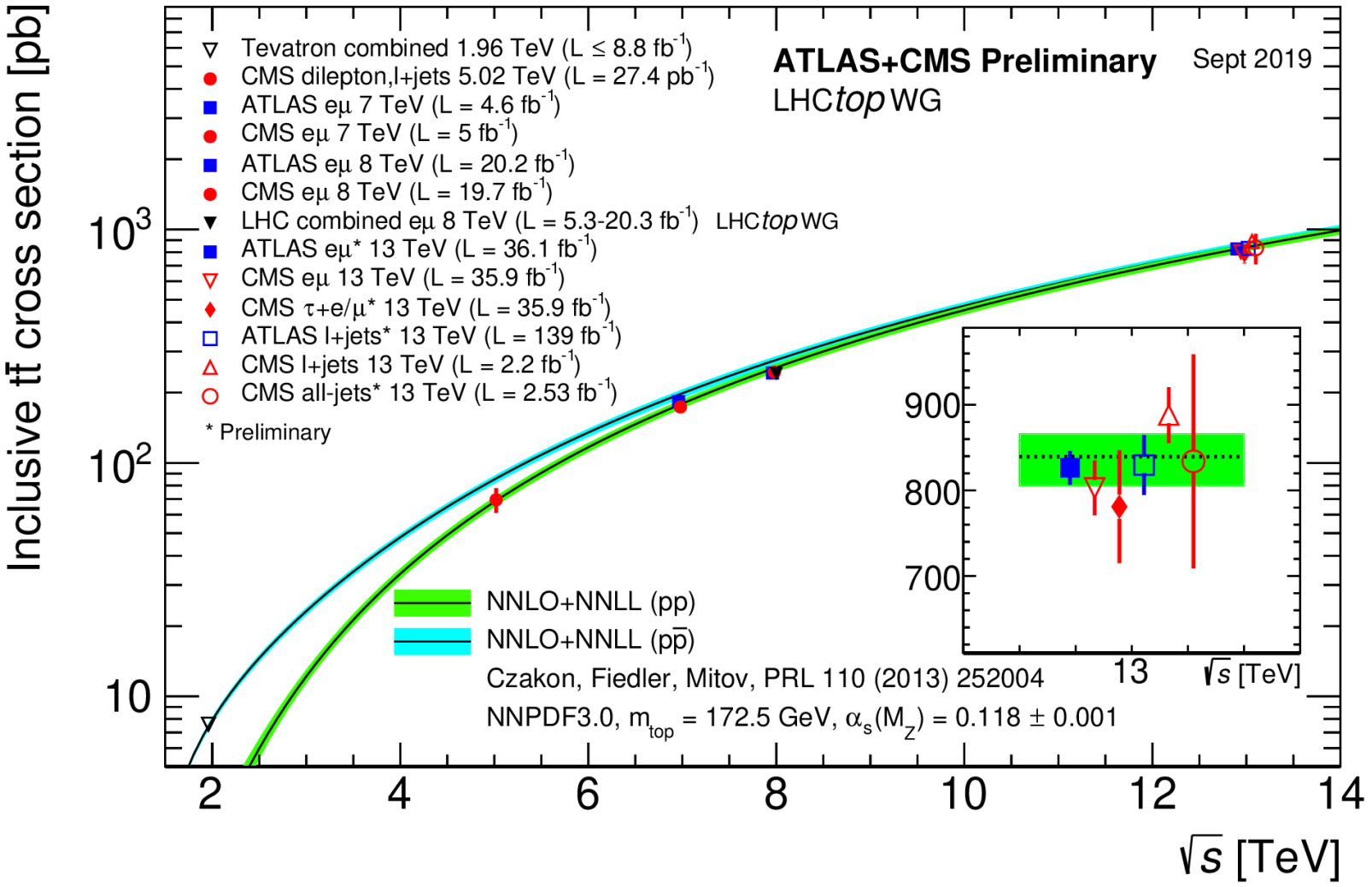
$$\sigma(dil) = 826.4 \pm 3.6(stat.) \pm 11.5(syst.) \pm 15.7(lumi.) \pm 1.9(beam)\ pb \quad 2.4\%$$

$$\sigma(l+jets) = 830.4 \pm 0.4(stat.)\ ^{+38.2}_{-37.0}(syst.)\ pb \quad 4.6\%$$

Theory prediction:

$$\sigma(NNLO+NNLL) = 832\ ^{+20}_{-29}(scale) \pm 35(PDF+\alpha_s)\ pb \quad +4.8\%\ -5.5\%$$

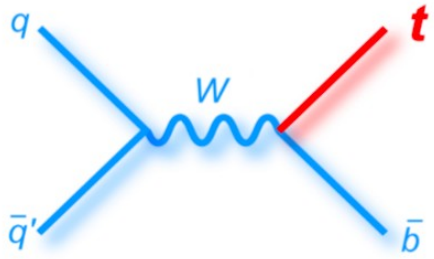
Summary of top-quark pair cross-section



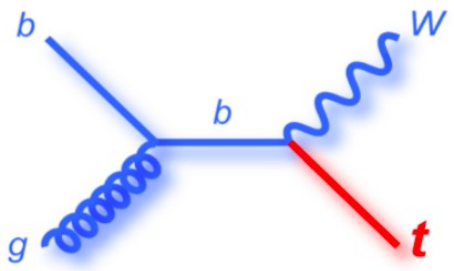
Single-top quark production

- production via electro-weak interaction:

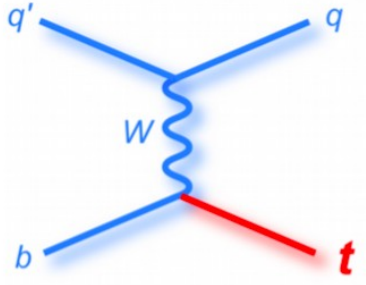
t-channel (~75% at LHC)



tW (~20% at LHC)



s-channel (~5% at LHC)



- Motivation to measure:
  - SM single-top quark cross-section directly depends on element of CKM matrix $|V_{tb}|$
  - Sensitivity to new physics mechanisms could be different compared to top pair production

Summary of single-top cross-sections

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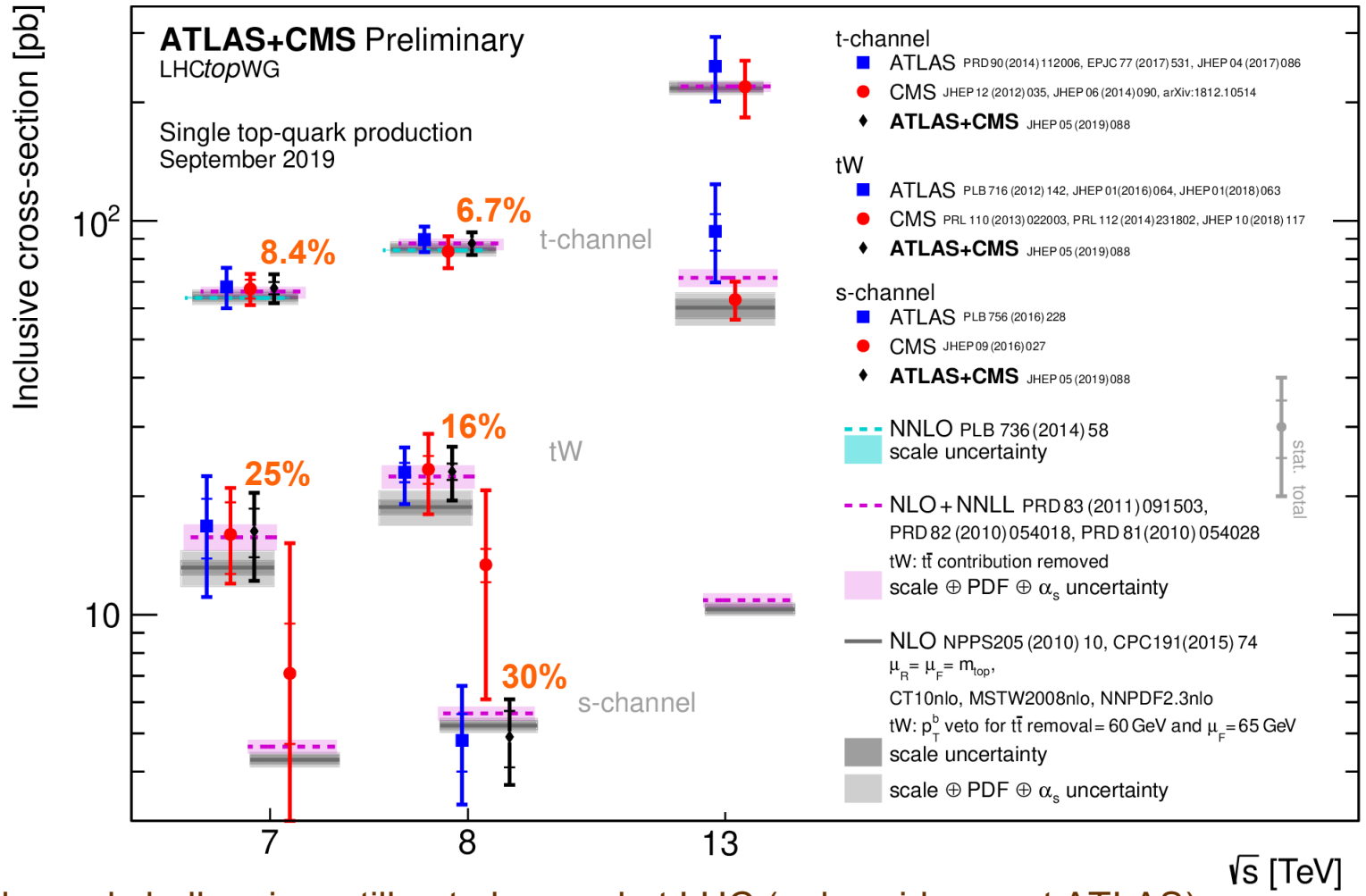
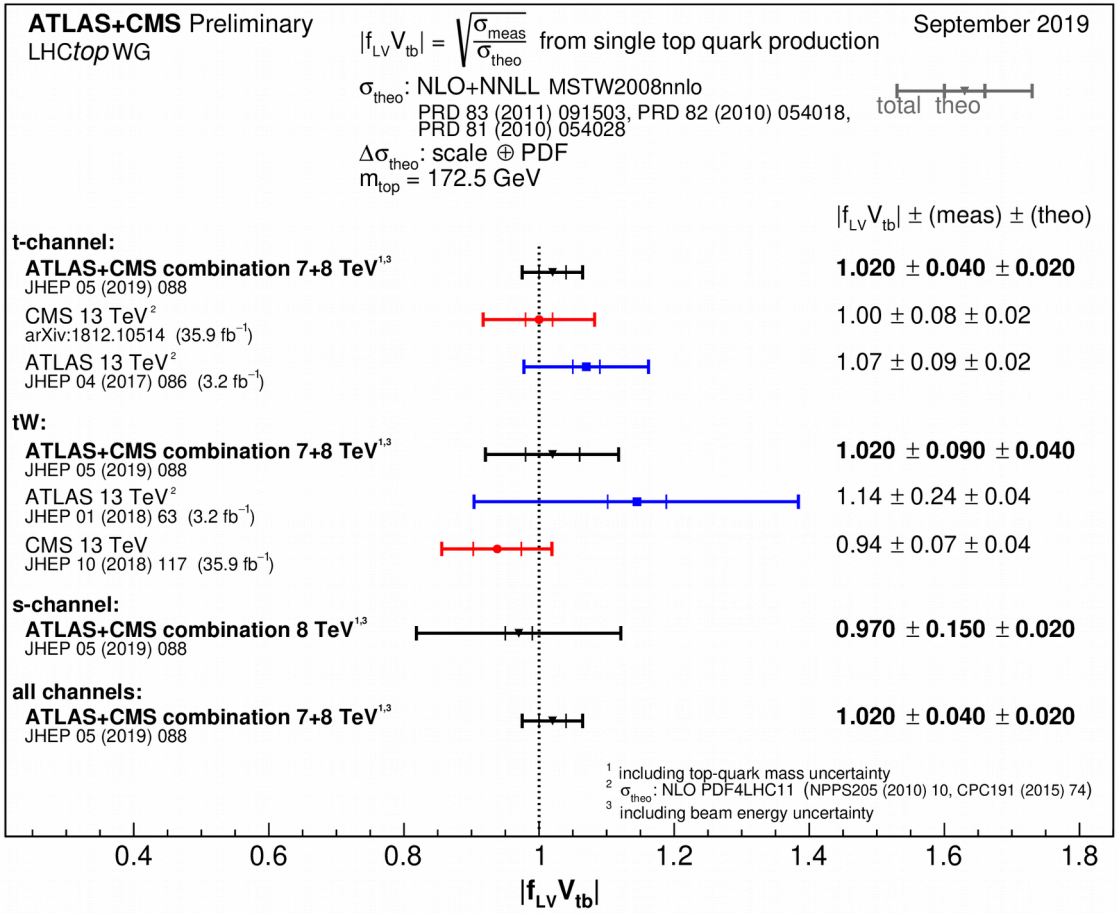
- Combination of ATLAS+CMS for each production channel at both Run 1 center-of-mass energies (7 and 8 TeV)
  - Uncertainties larger then theory prediction uncertainties (4-8%)



s-channel challenging, still not observed at LHC (only evidence at ATLAS)

Measurement of CKM matrix element V_{tb}

- single-top quark cross-section depends quadratically on $|V_{tb}|$ → $|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}\ (V_{tb}=1)}}$
- It is a direct measurement



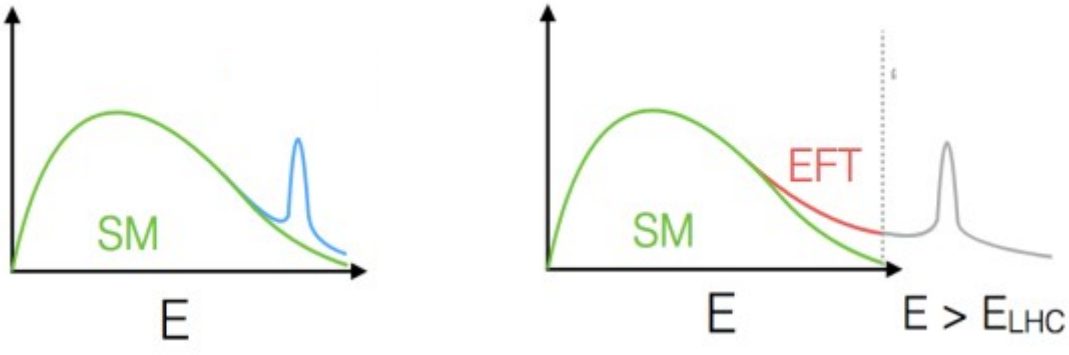
f_{LV}: form factor parametrising possible anomalous couplings

In SM: f_{LV} = 1.0

$SM: V_{tb} \simeq 1.0$

3.7%

What is kinematics of top quarks?

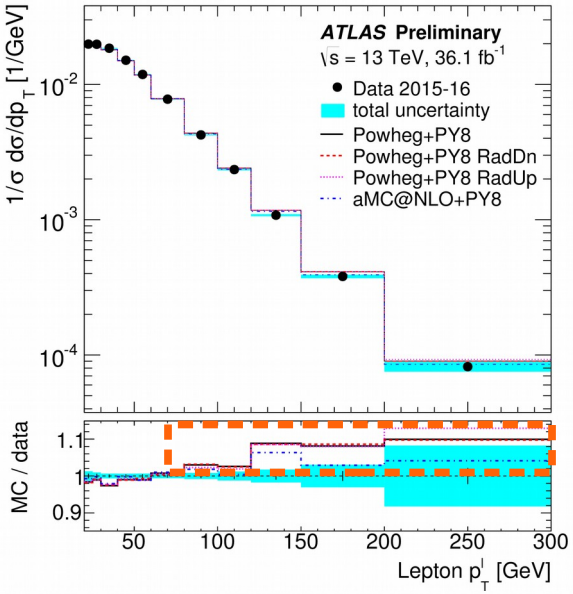


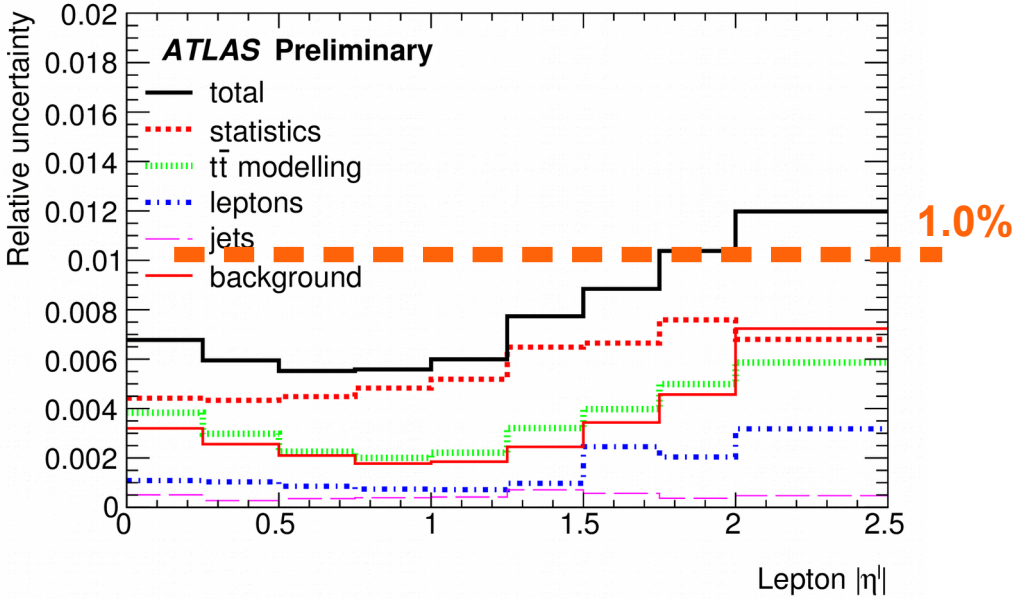
- Measuring dependence of cross-section on kinematic variables
  - Is more detailed test of SM compared to inclusive cross-section
  - Can reveal new physics in some region while not visibly changing inclusive cross-section
  - Helps to improve the simulation of tt production: MC generators tuning, PDF
  - Allows to measure SM parameters (top mass, α_s) and effective field theory couplings

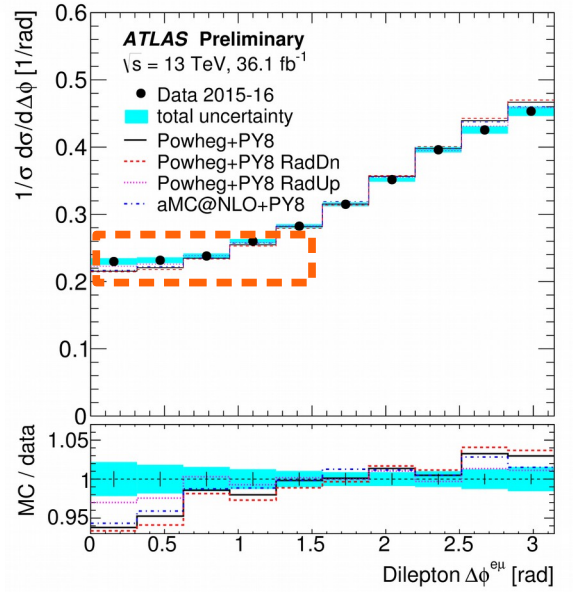
Differential cross-sections in dilepton channel

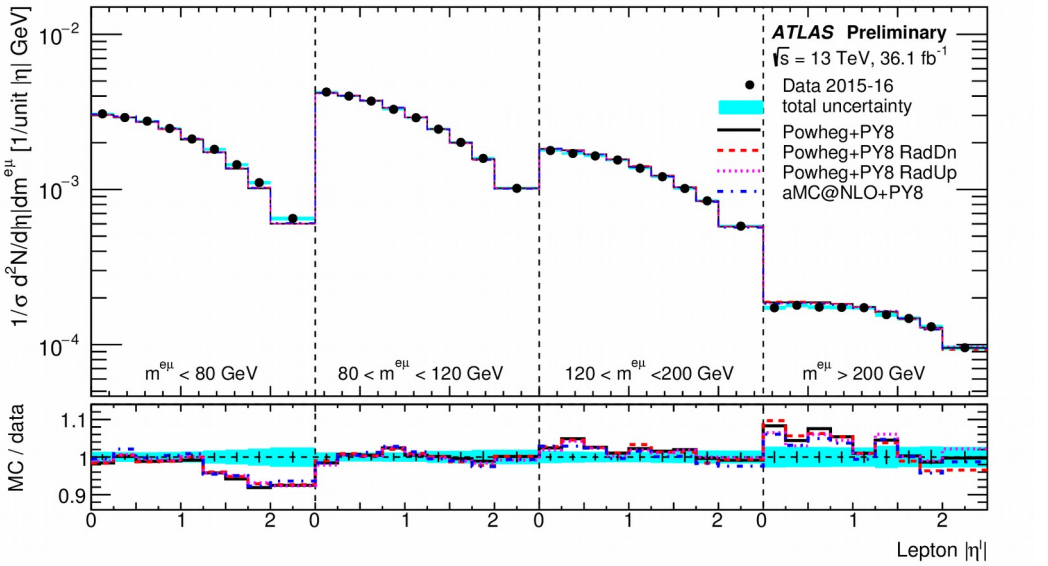
ATLAS-CONF-2019-041

- Measured precisely various lepton variables (p_T, |eta|) and their 2D combinations





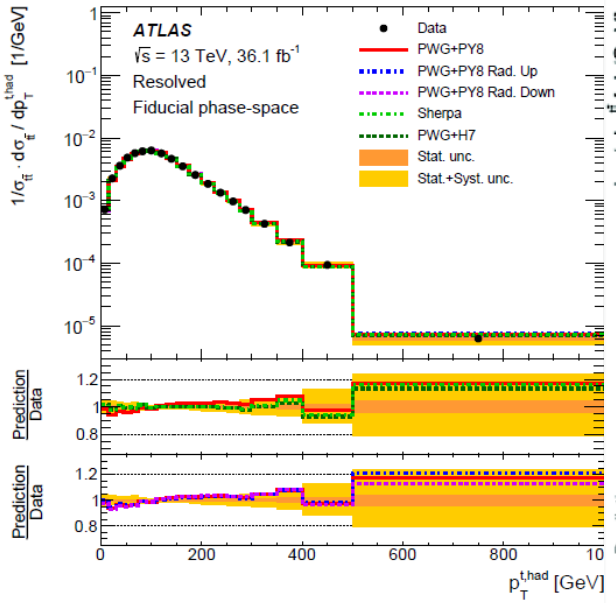


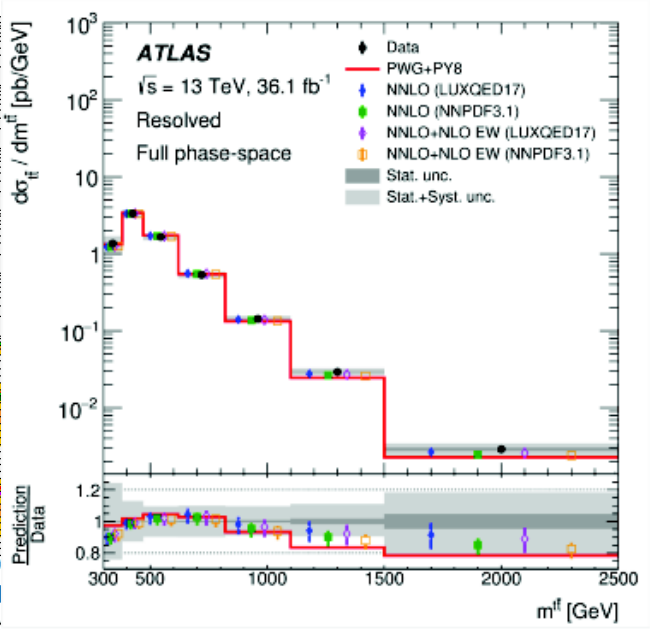


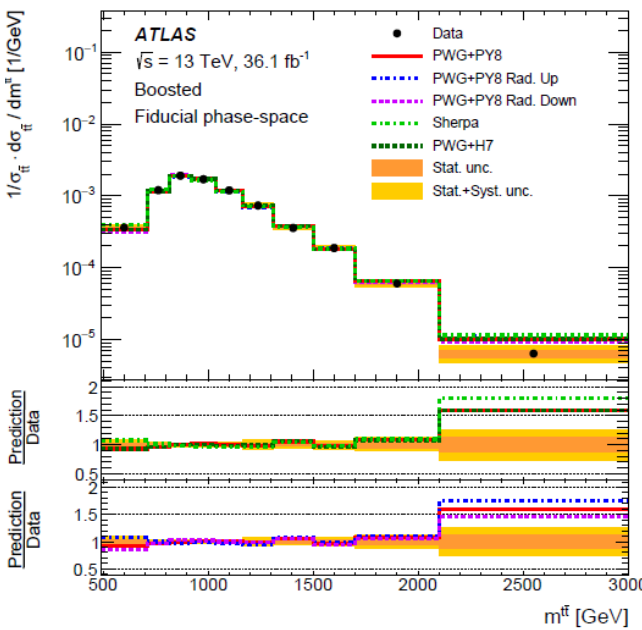
Differential cross-sections in l+jets channel

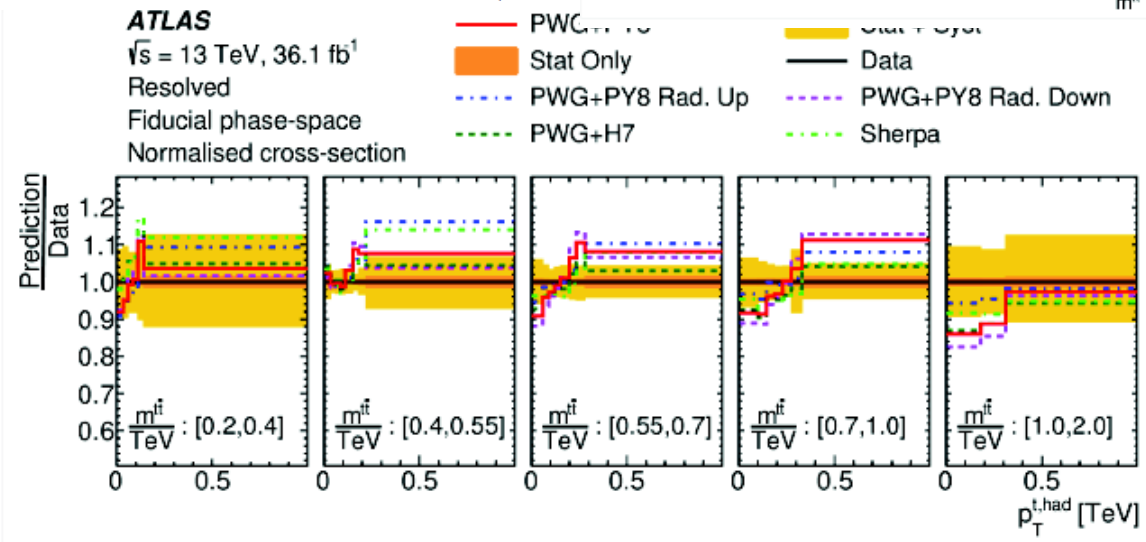
arXiv:1908.07305

- Measured lots of top and ttbar kinematics in resolved and boosted topologies







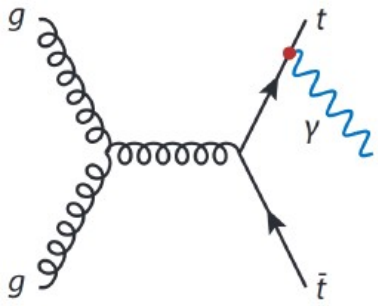


- Parton level: agreement improved for NNLO prediction comparing to NLO+PS
- Particle level:
  - 1D mostly o.k., not 2D
  - In boosted regime: normalization discrepancy

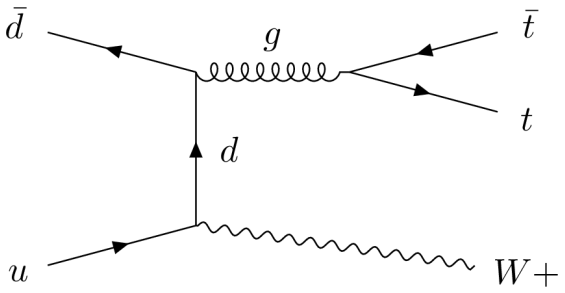
Special production of top quarks?

Top quark production with electro-weak bosons and jets

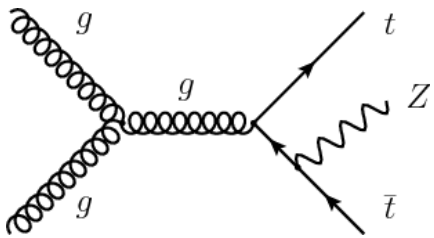
tt+γ



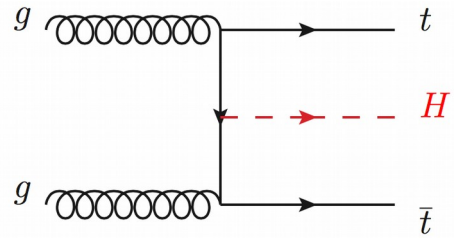
tt+W



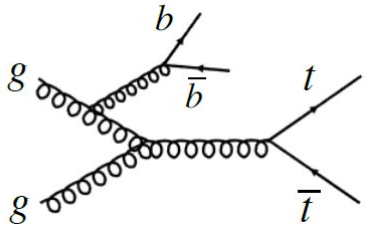
tt+Z



tt+H



tt+bb

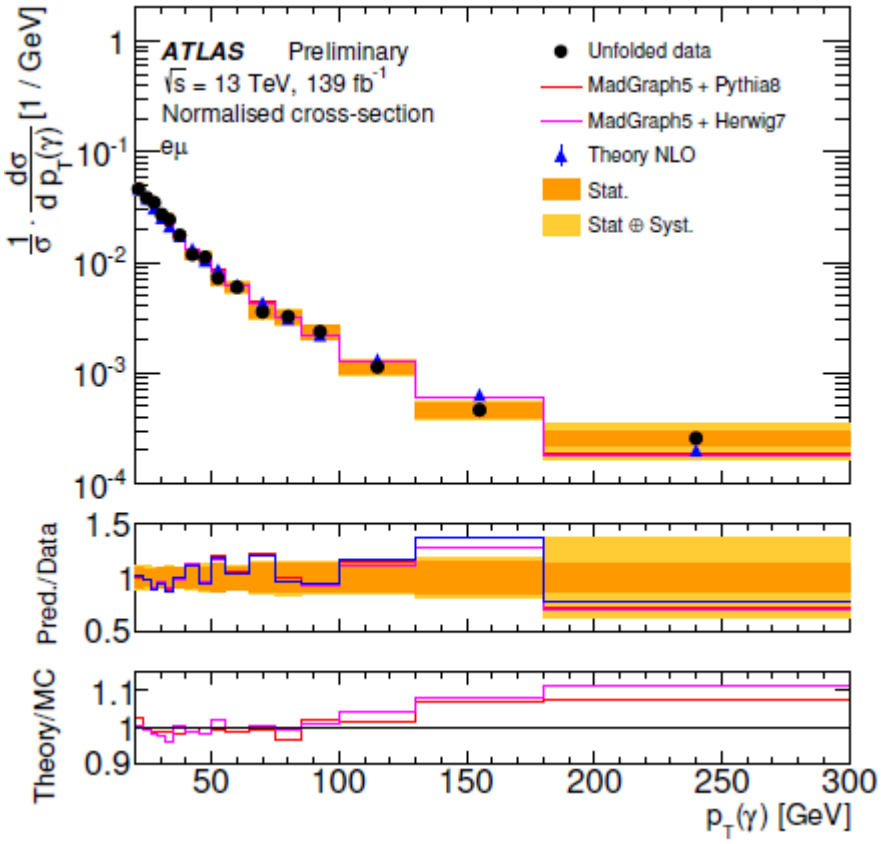


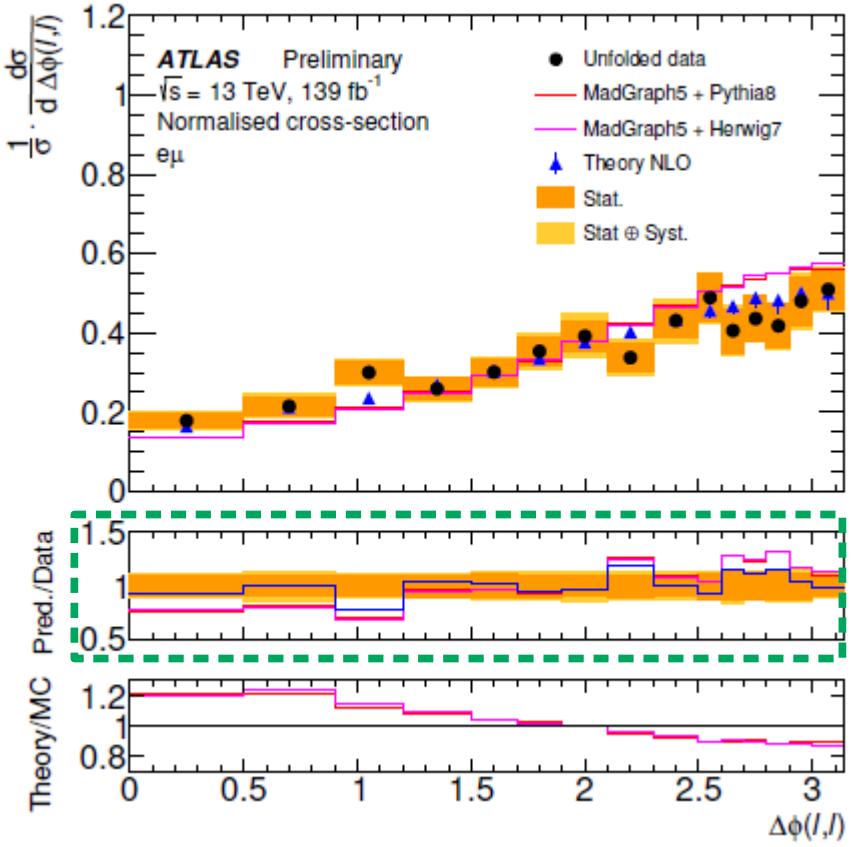
- ttH:
  - Direct measurement of top Yukawa coupling via ttH
- tt+W/Z:
  - Probe structure of EWK top-Z/gamma couplings
  - Important background for ttH and BSM searches
- tt+bb important background for ttH

ttbar + photon

ATLAS-CONF-2019-042

- Probes top-photon coupling, enhanced charge asymmetry
- Measuring inclusive and differential cross-sections





$$\sigma(tt+gamma)=44.2\pm0.9(stat.)^{+2.6}_{-2.4}(syst.)\,pb \qquad 6\,\%$$

$$theory:\sigma(NLO)=39.50^{+0.56}_{-2.18}(scale)^{+1.04}_{-1.18}\,pb \qquad ^{+3}_{-6}\,\%$$

ttbar + W/Z

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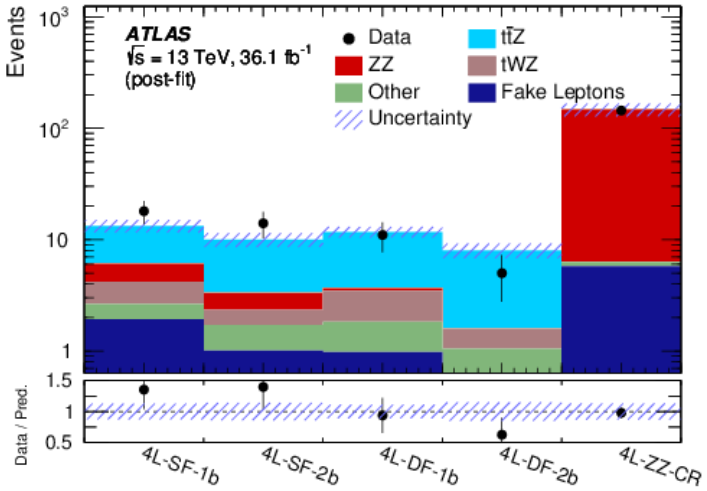
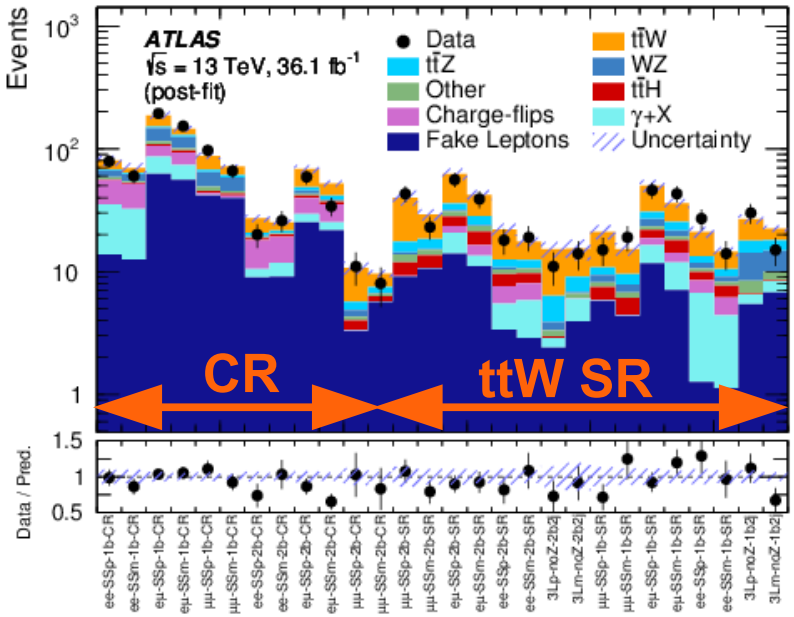
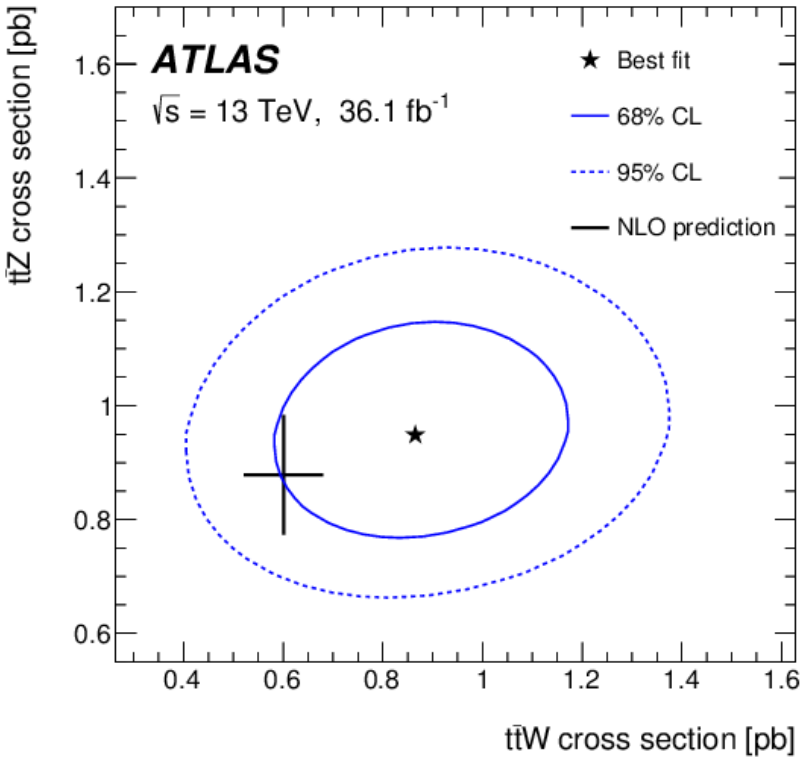
- Very sensitive to new physics
- Simultaneous fit of ttW and ttZ cross-section







$\sigma(ttZ) = 0.95 \pm 0.08\,(stat.) \pm 0.10\,(syst.)\ pb$ 13%

$\sigma(ttW) = 0.87 \pm 0.13\,(stat.) \pm 0.14\,(syst.)\ pb$ 22%

$theory: \sigma_{ttZ}^{NLO} = 0.88\,^{+0.09}_{-0.11}\ pb,\ \sigma_{ttW}^{NLO} = 0.6\,^{+0.08}_{-0.07}\ pb$ 13%

ttbar + H

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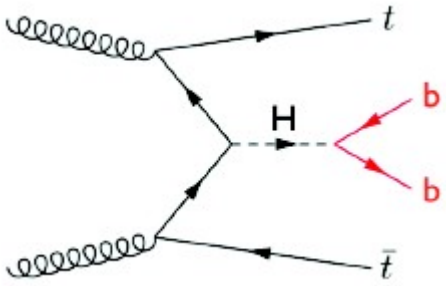
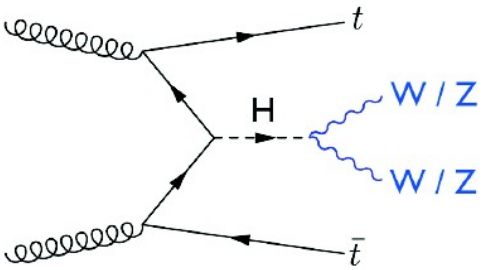
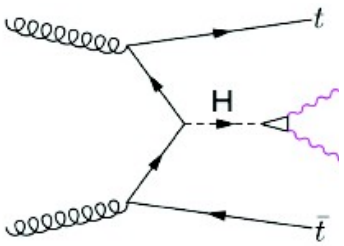
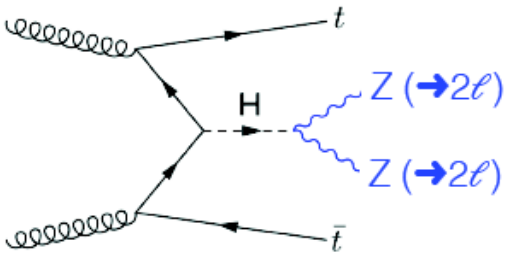
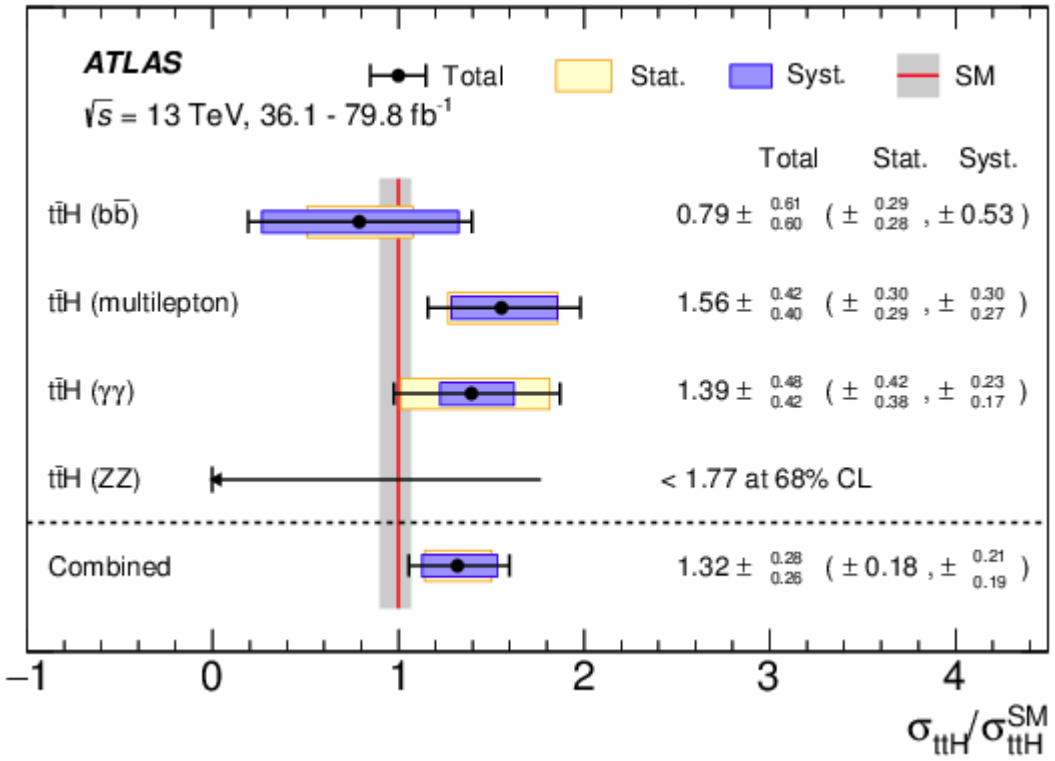






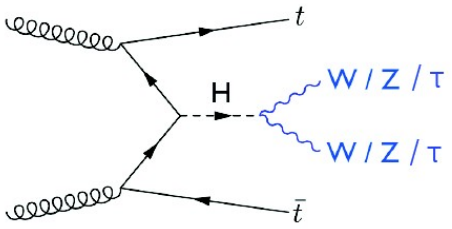


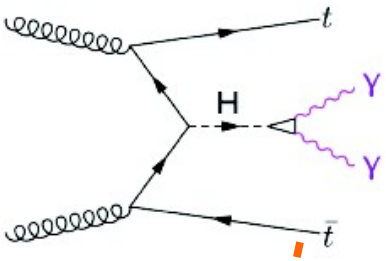


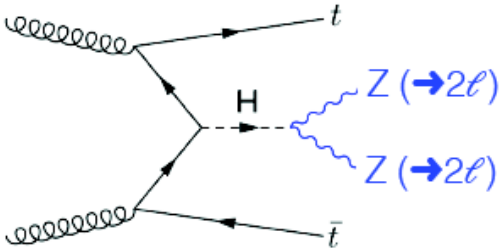
Observation (6.3σ) of ttH in combination of all channels last year

ttbar+H

ATLAS-CONF-2019-045
ATLAS-CONF-2019-025
ATLAS-CONF-2019-004





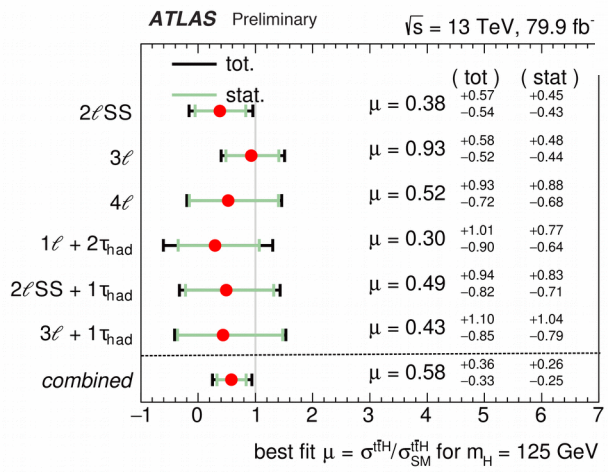


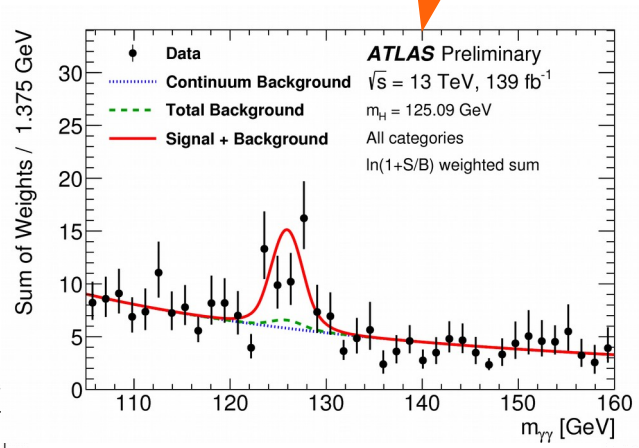
Observed/Expected significance:

1.8σ (3.1σ)

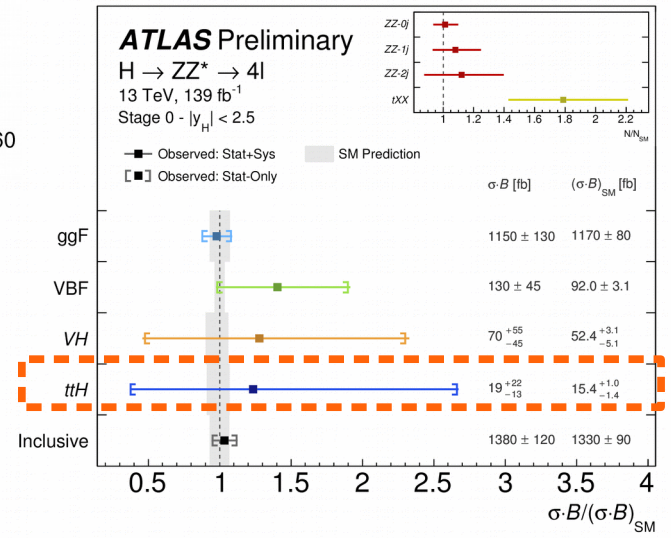
4.9σ (4.2σ)

~1.3σ

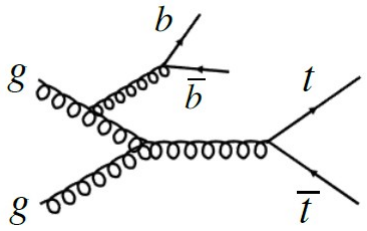




Observation of ttH in ttH → γγ !



ttbar + bbbar



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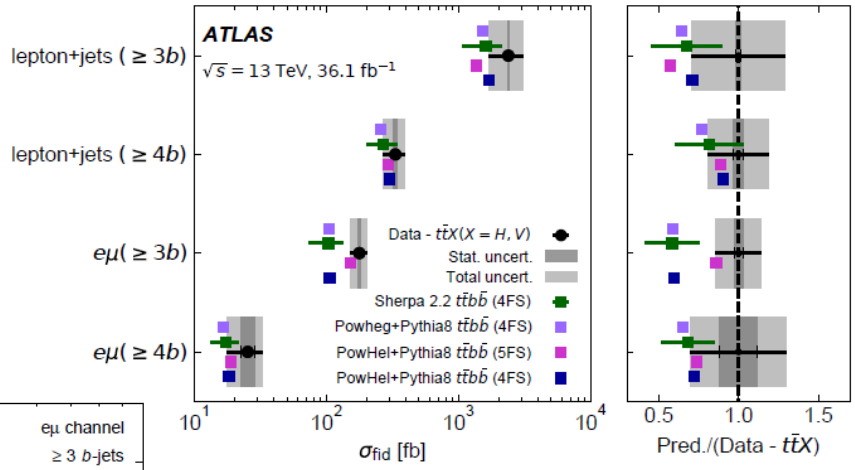
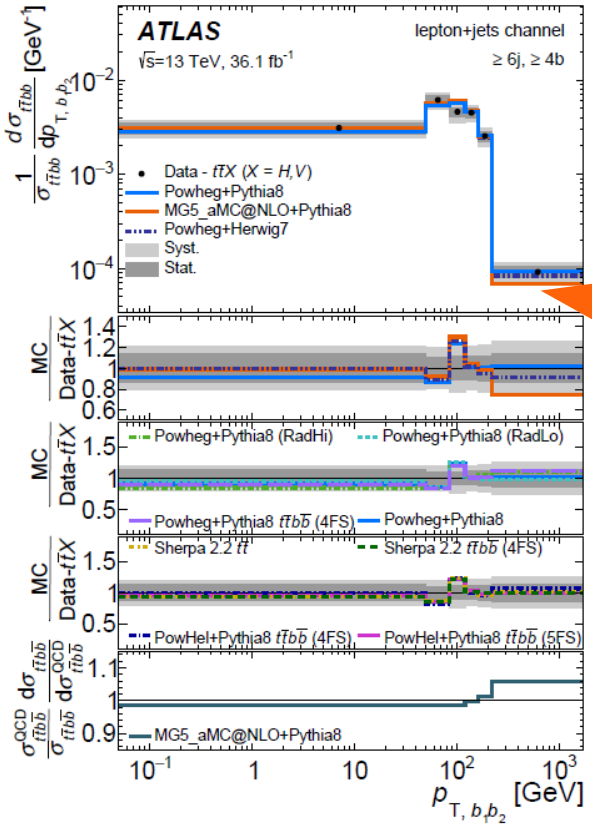
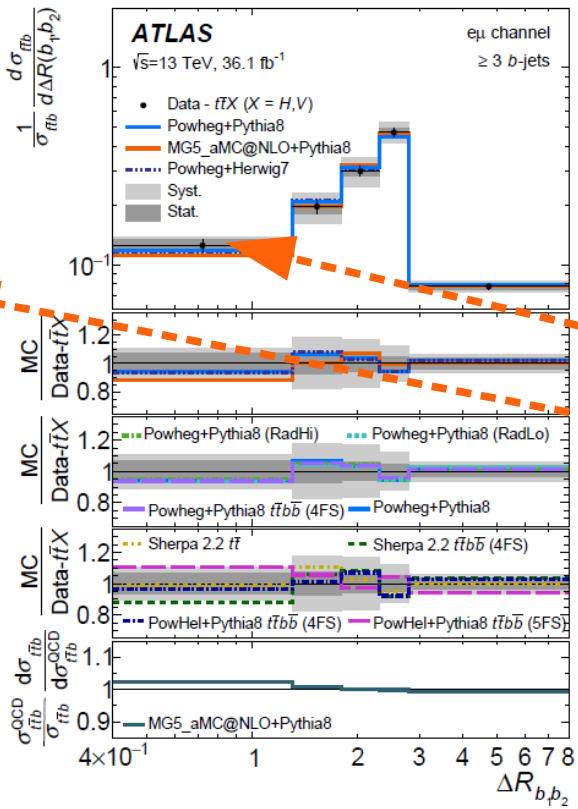
- Large uncertainties in theory (NLO) predictions (25-30%)
- Important background for ttH and many searches



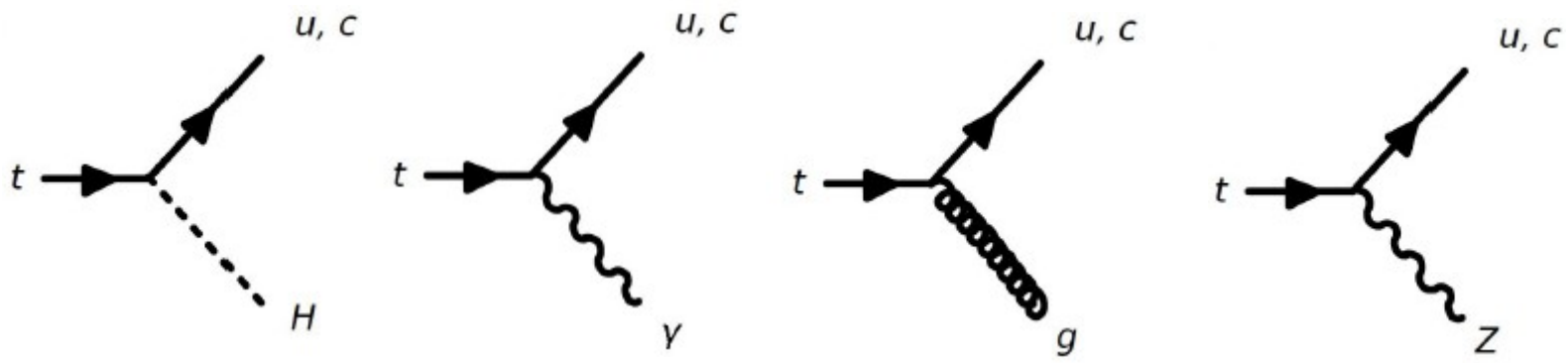
Inclusive measurements higher than various predictions





Testing b-jets from gluon splitting and from top quark production

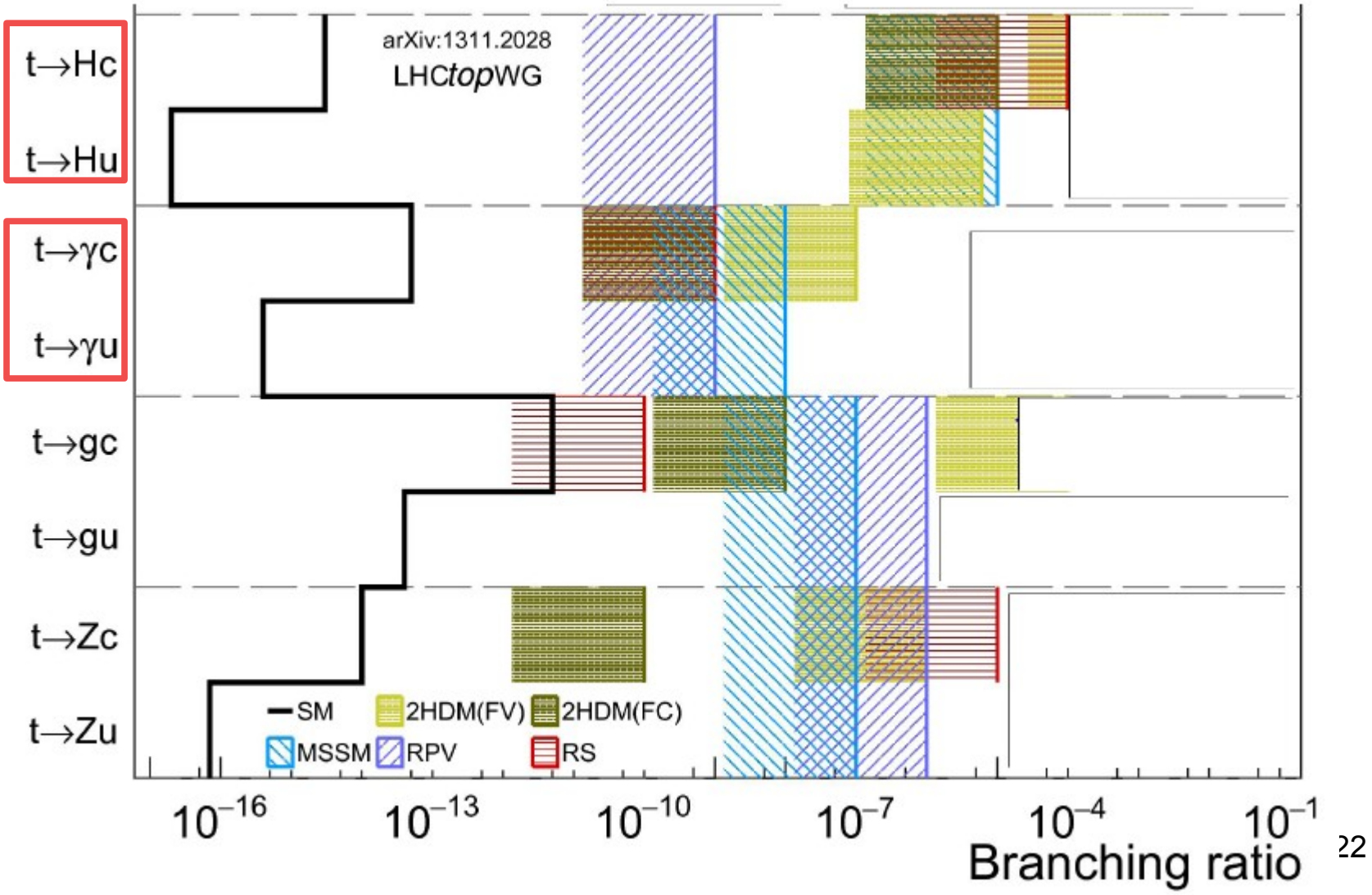
Special decay of top quark?



→ top quark searches for flavor-changing neutral currents

Flavor Changing Neutral Currents (FCNC)

- FCNC extremely rare in Standard Model
  - Significantly enhanced in various SM extensions



tqH vertex

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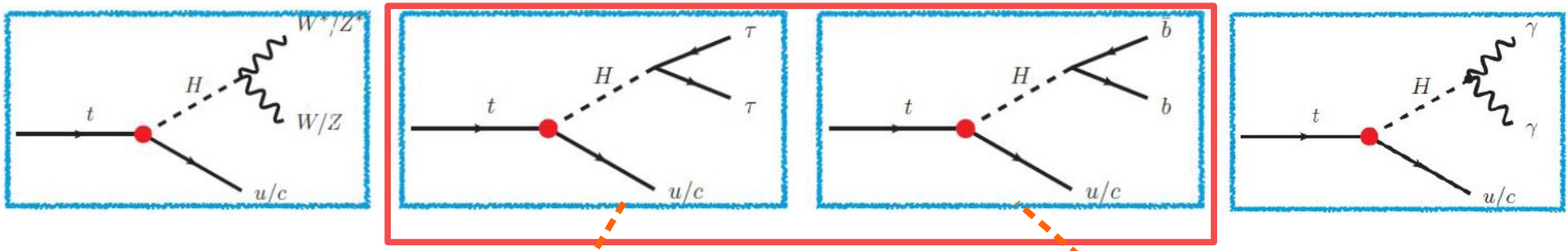

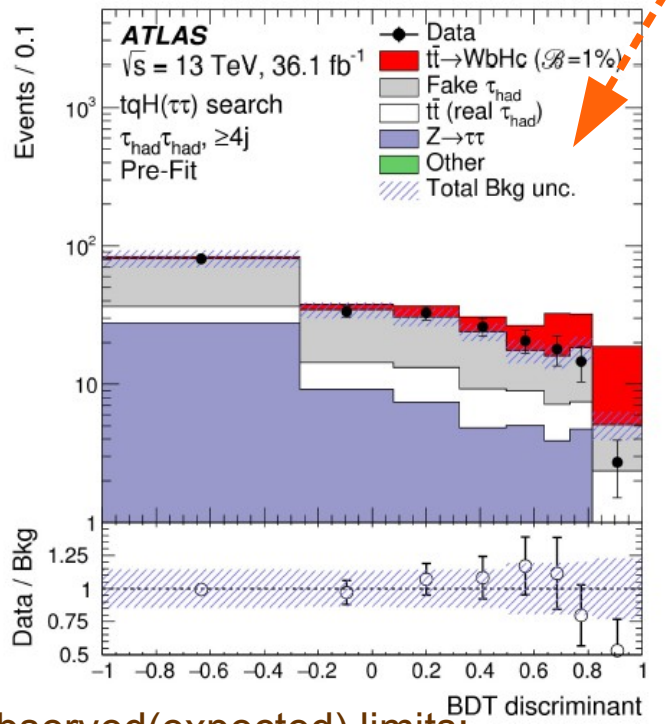

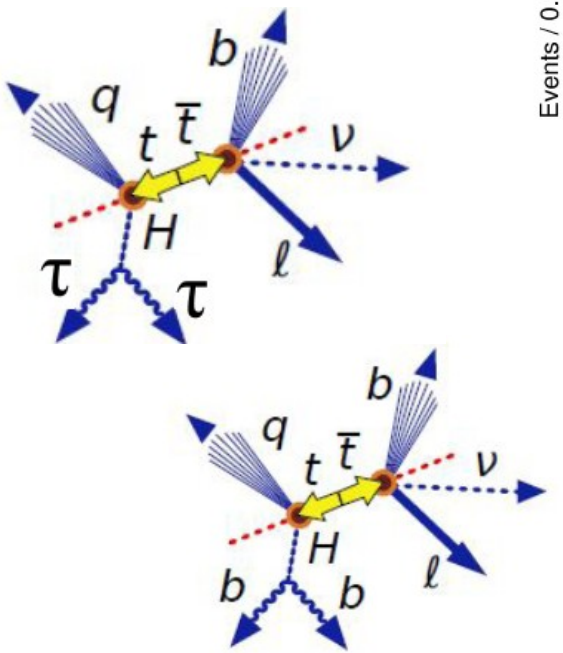

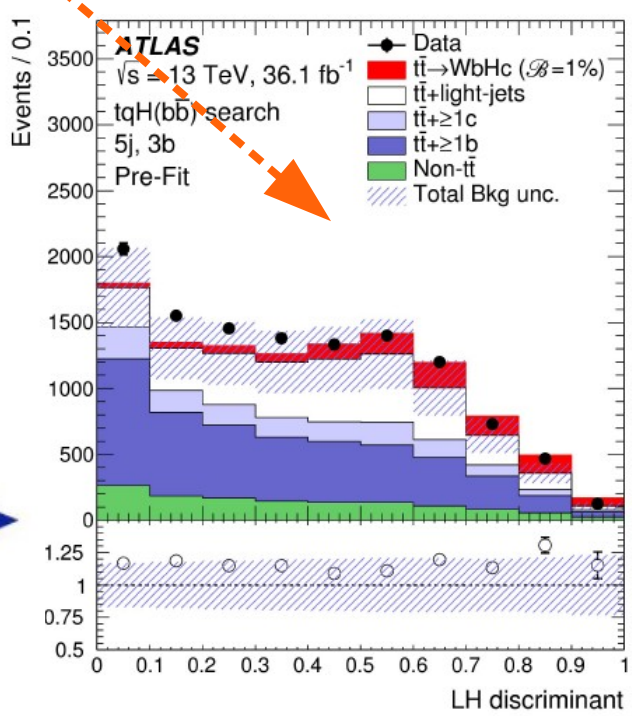

observed(expected) limits:

$BR(t \to Hu) < 1.7\,(2.0) \times 10^{-3}$

$BR(t \to Hc) < 1.9\,(2.1) \times 10^{-3}$

$BR(t \to Hu) < 5.2\,(4.9) \times 10^{-3}$

$BR(t \to Hc) < 4.2\,(4.0) \times 10^{-3}$

Combination of tqH FCNC searches

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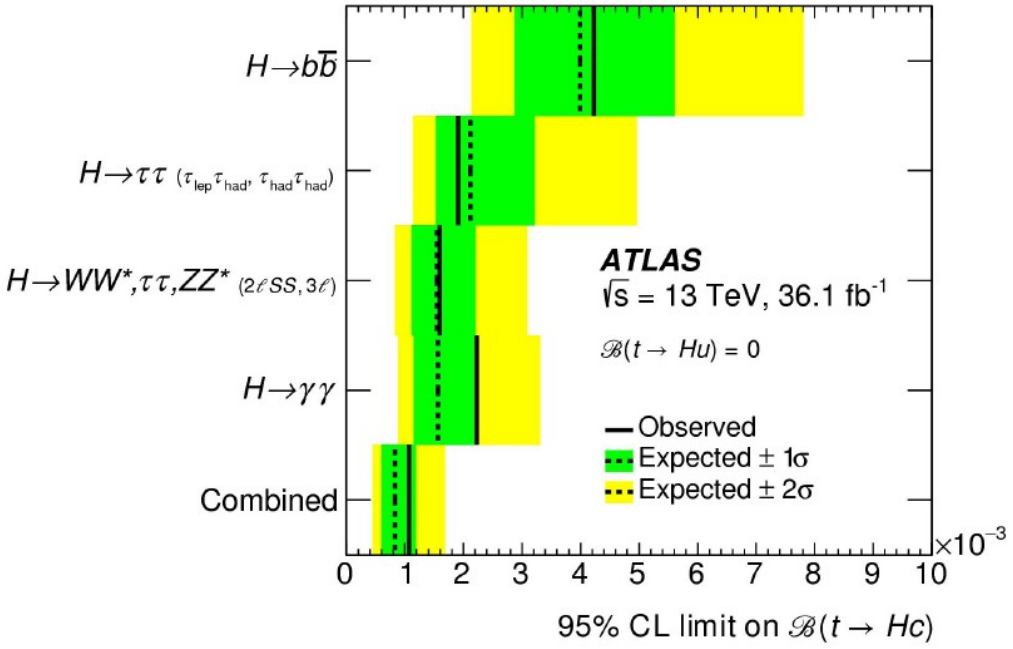
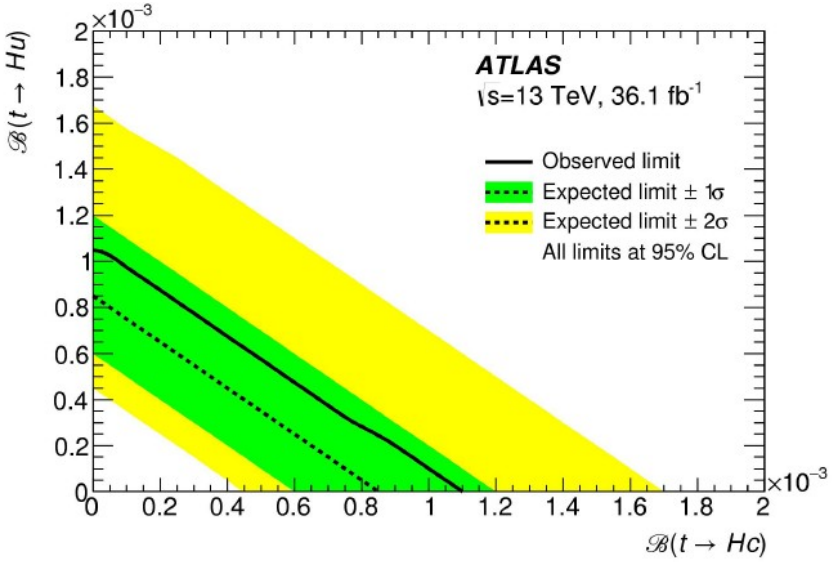




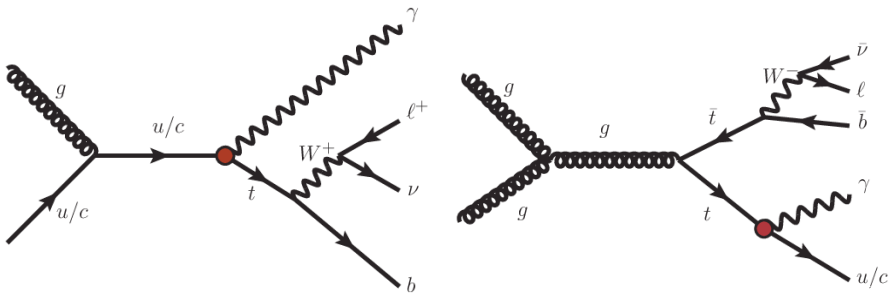
$$BR(t\to Hu)<1.2(0.83)\times10^{-3}$$

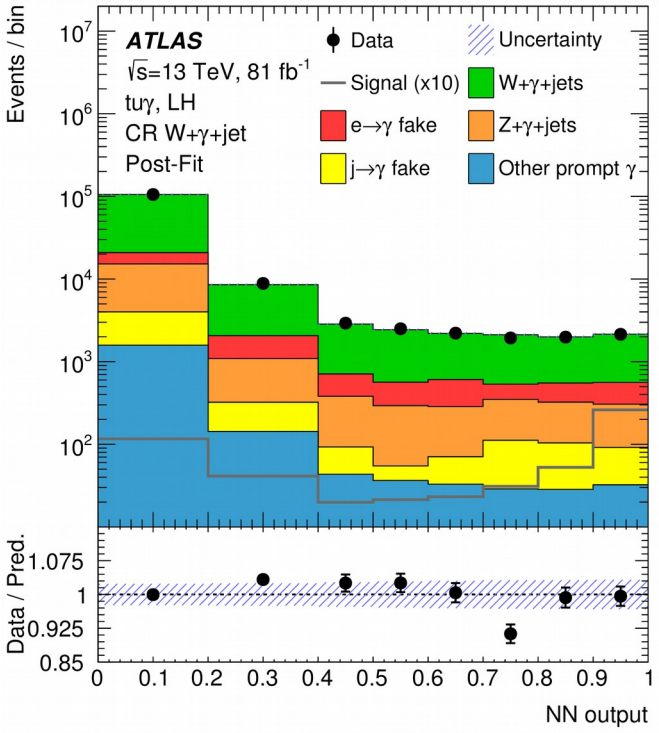
$$BR(t\to Hc)<1.1(0.83)\times10^{-3}$$

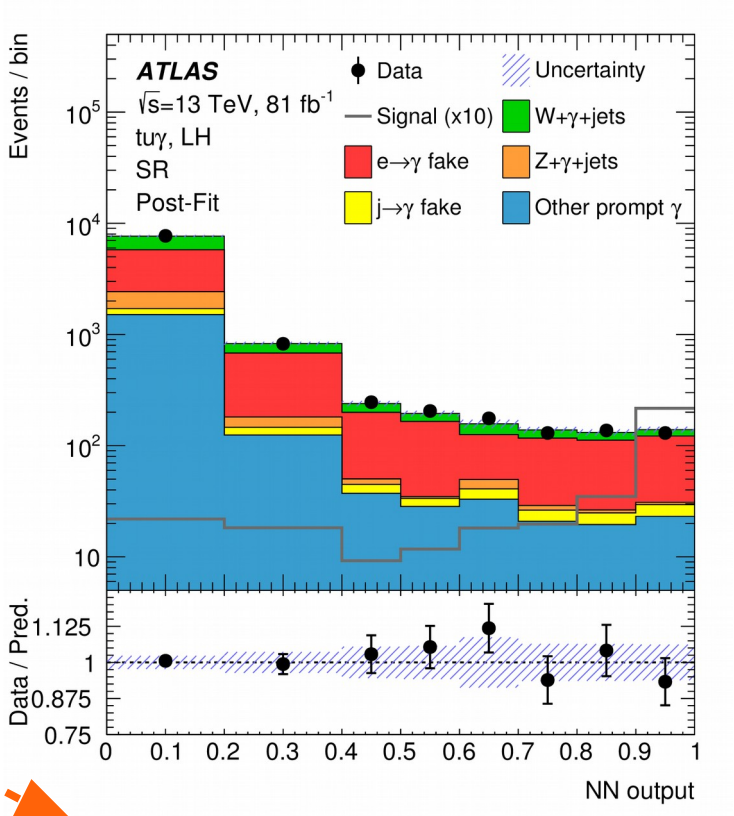
tqγ vertex

arXiv:1908.08461

- Both production and decay modes considered
- Simultaneous fit of signal and W/Z+gamma+jets





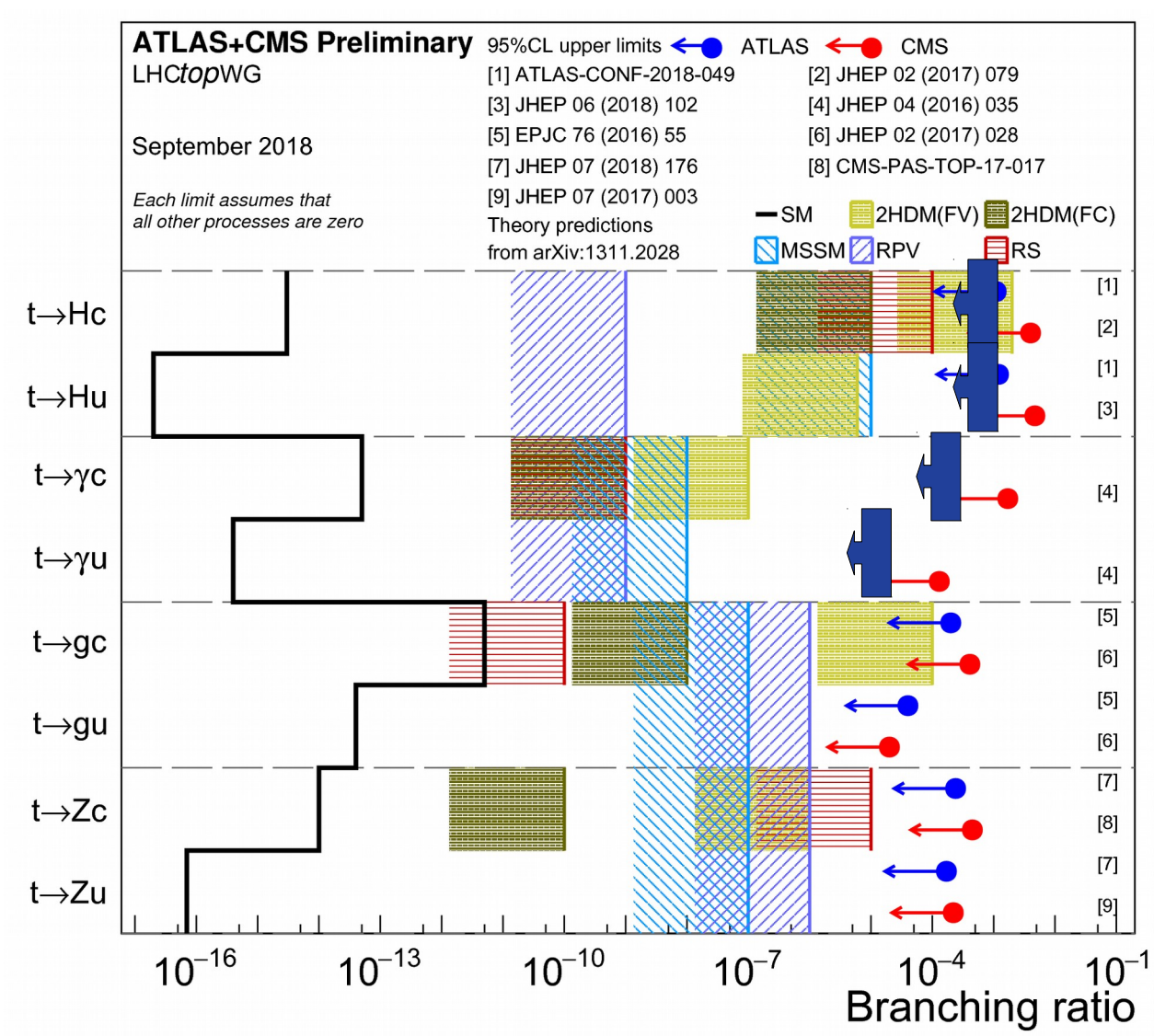


Observable	Vertex	Coupling	Obs.	Exp.
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

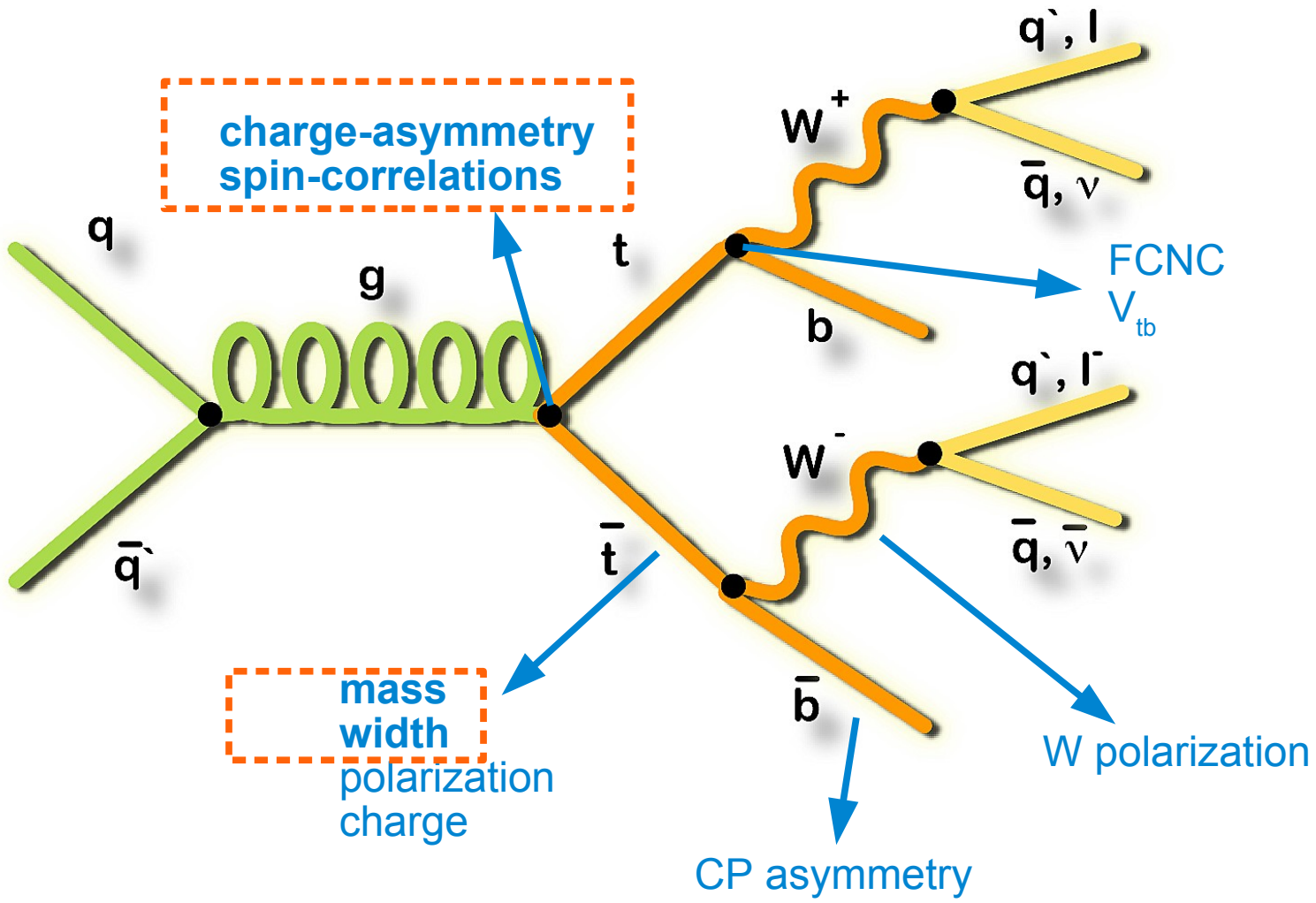
95% C.L. limits on branching ratios

Top quark FCNC summary plot

- ATLAS results shown in this talk:

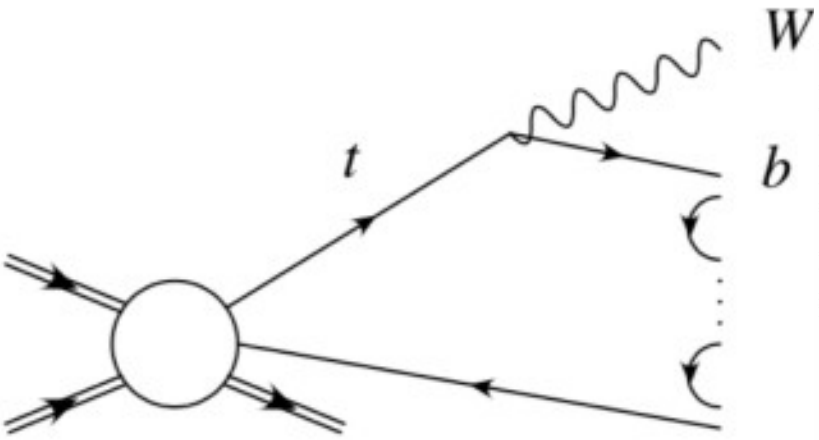


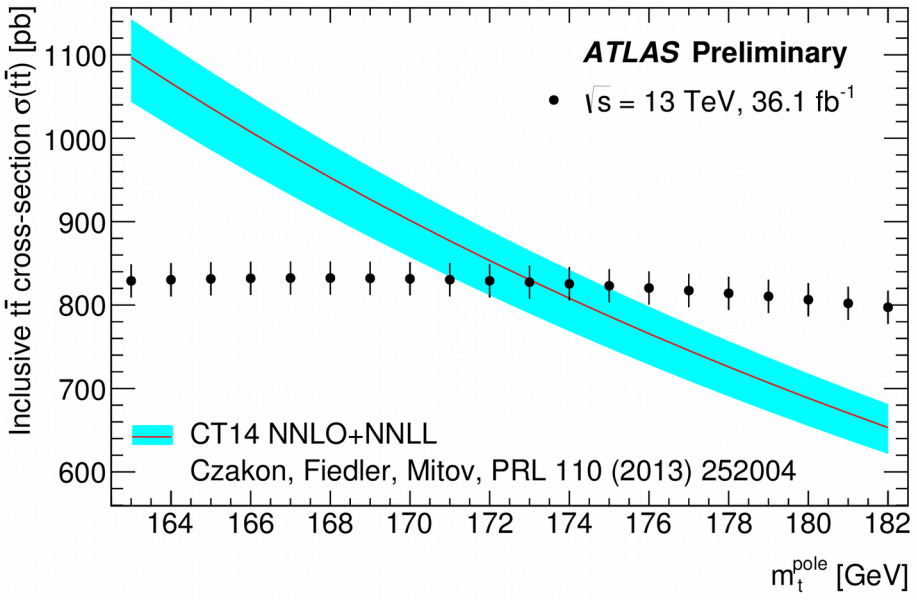
Top quark properties



Top quark mass

- Free parameter in SM, most of the top quark predictions depend on it
- Top quark not a free particle → what do we actually measure?
  - Direct measurements: using decay products of top quark
    → mass parameter in MC → does it corresponds to pole mass?
  - Indirect measurements: using cross-section dependence on mass
    → top pole mass

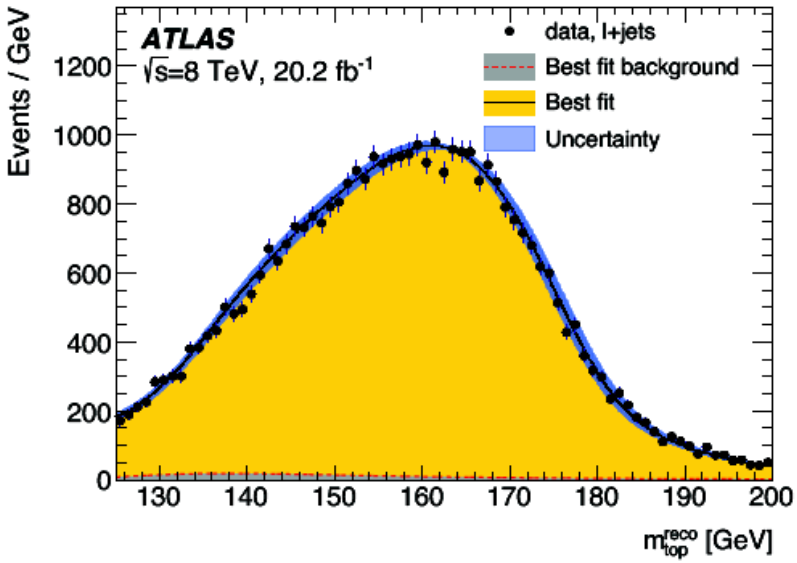


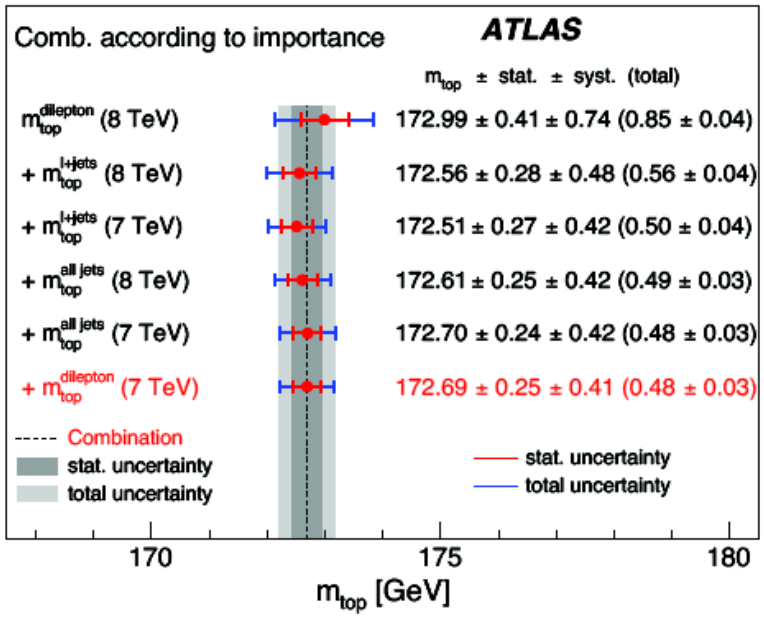


m_{top} in l+jets channel and combination

EPJC 79 (2019) 290

- Template 3D (m_{top}^{reco}, m_{W}^{reco}, R_{bq}^{reco}) method with in situ jet and b-jet calibration
- Combined with the rest of 7 and 8 TeV measurements





$$\sigma(l+jets) = 172.08 \pm 0.39\,(stat.) \pm 0.82\,(syst.)\,GeV = 172.08 \pm 0.91\,GeV\,(\pm 0.53\,\%)$$

$$\sigma(7+8\,TeV) = 172.69 \pm 0.25\,(stat.) \pm 0.41\,(syst.)\,GeV = 172.69 \pm 0.48\,GeV\,(\pm 0.28\,\%)$$

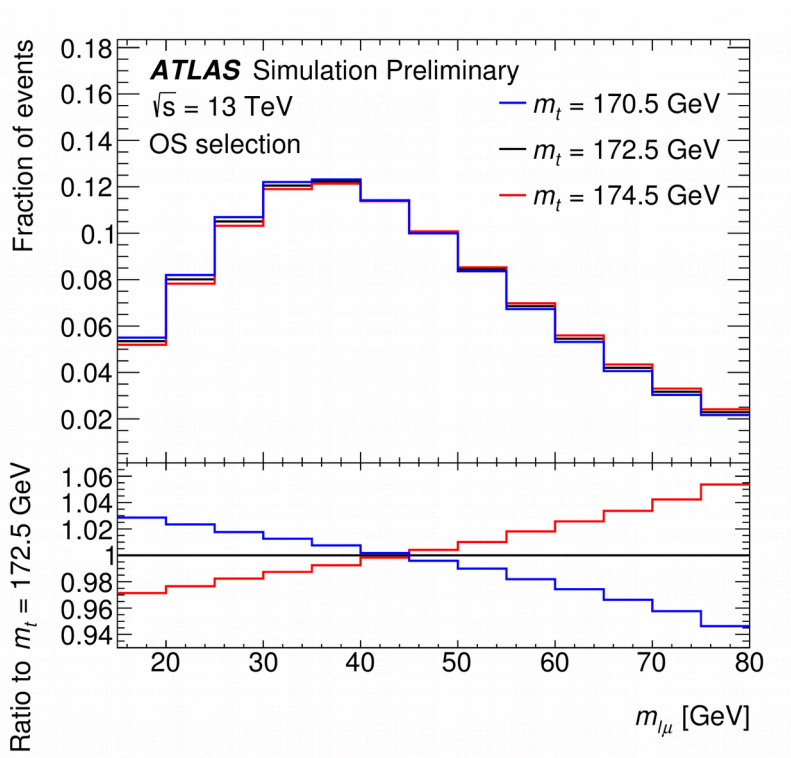
- Dominant uncertainties in combination:

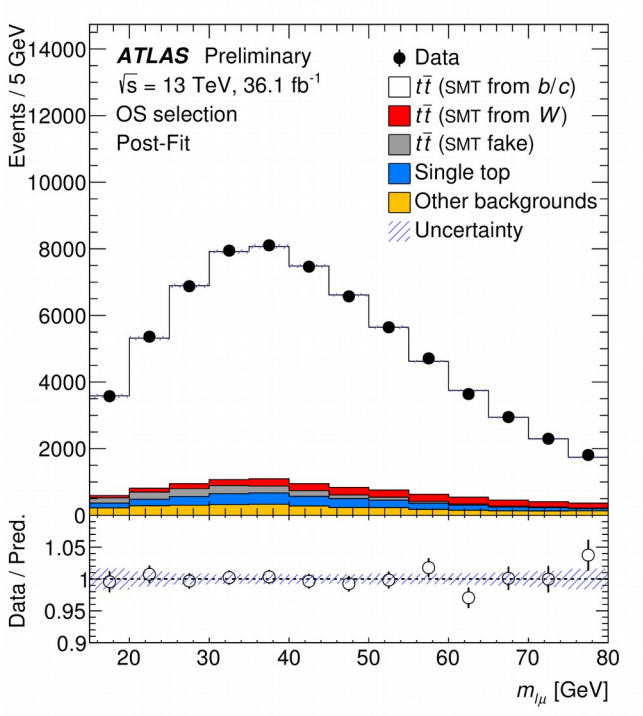
JES	0.22 GeV
b-tagging	0.17 GeV
bJES	0.17 GeV

m_{top} in lepton+jets channel with soft muon

ATLAS-CONF-2019-046

- Motivation: use method where uncertainty in jet calibration not dominant
- Template method using invariant mass of lepton and soft muon (from b-decay)



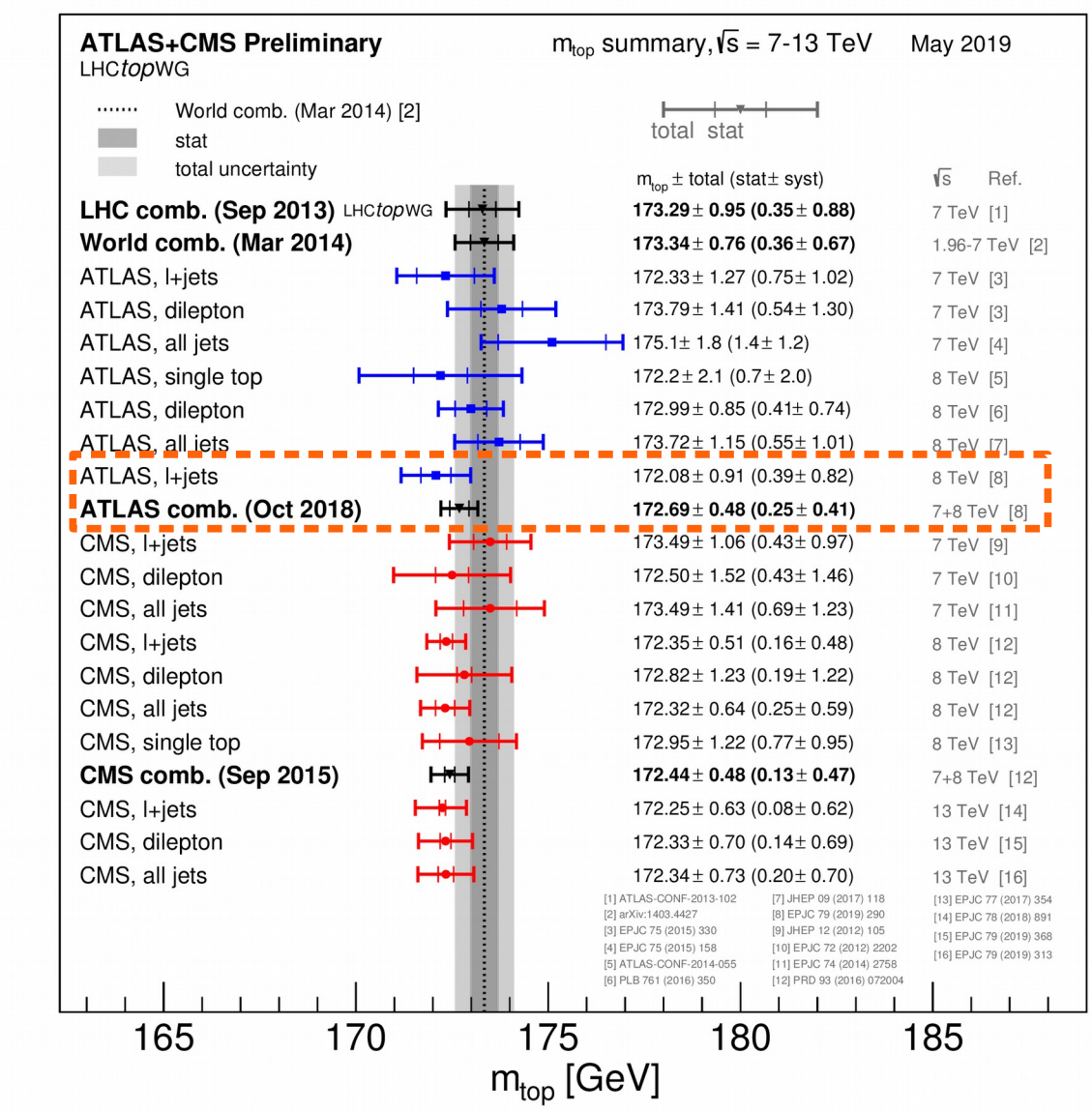


$$\sigma(l+jets+soft\,\mu) = 174.48 \pm 0.40\,(stat.) \pm 0.67\,(syst.)\,GeV = 174.48 \pm 0.78\,GeV\,(\pm 0.45\,\%)$$

most precise single direct measurement in ATLAS!

- Dominant uncertainties:
  - Modeling of b/c-quark decay: 0.39 GeV
  - pile-up modeling: 0.20 GeV

Summary of direct mtop measurements



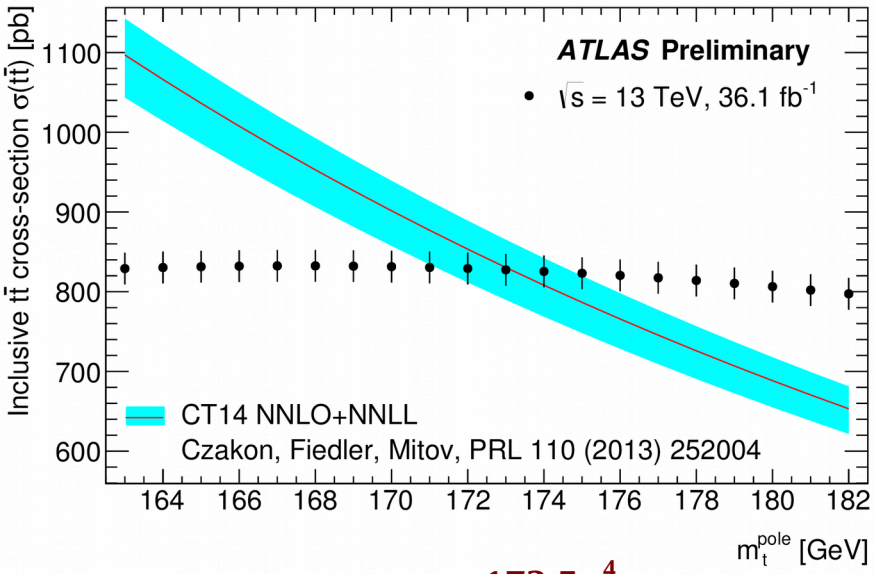
- Soft muon measurement not yet here → will help in combination

Indirect top mass measurements

- These are measuring the parameter used in calculations
  → top quark pole mass

ATLAS-CONF-2019-041
arXiv:1905.02302

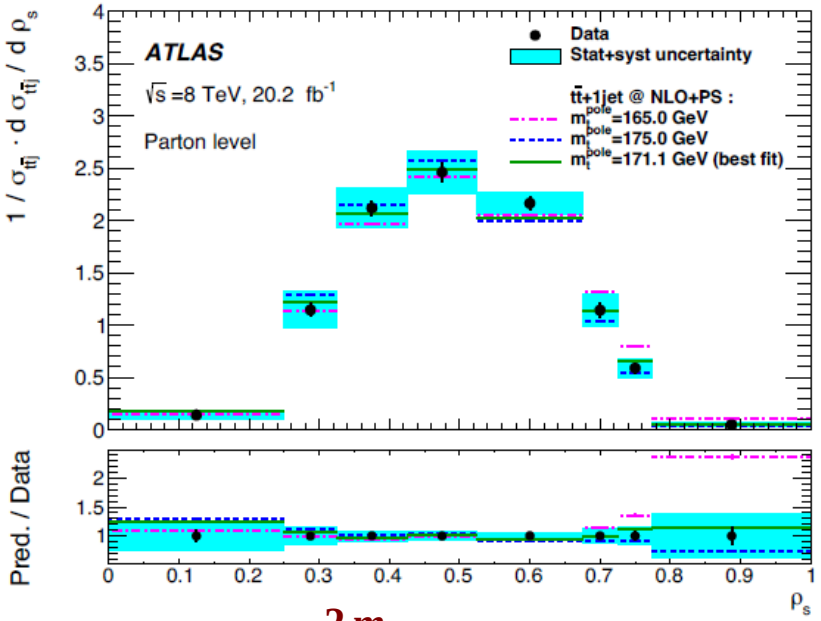
- ttbar cross-section depends on m_{top}^{pole}
  → use emu cross-section measurement



$$\sigma_{t\bar{t}}^{theory}(m_t^{pole}) = \sigma(172.5)\left(\frac{172.5}{m_t^{pole}}\right)^4 (1 + a_1 x + a_2 x^2)$$

$$x = (m_t^{pole} - 172.5)/172.5$$

- Diff. cross-section depends on m_{top}^{pole}
  - additional jet enhances the dependence on mtop → using ttbar+1 jet channel

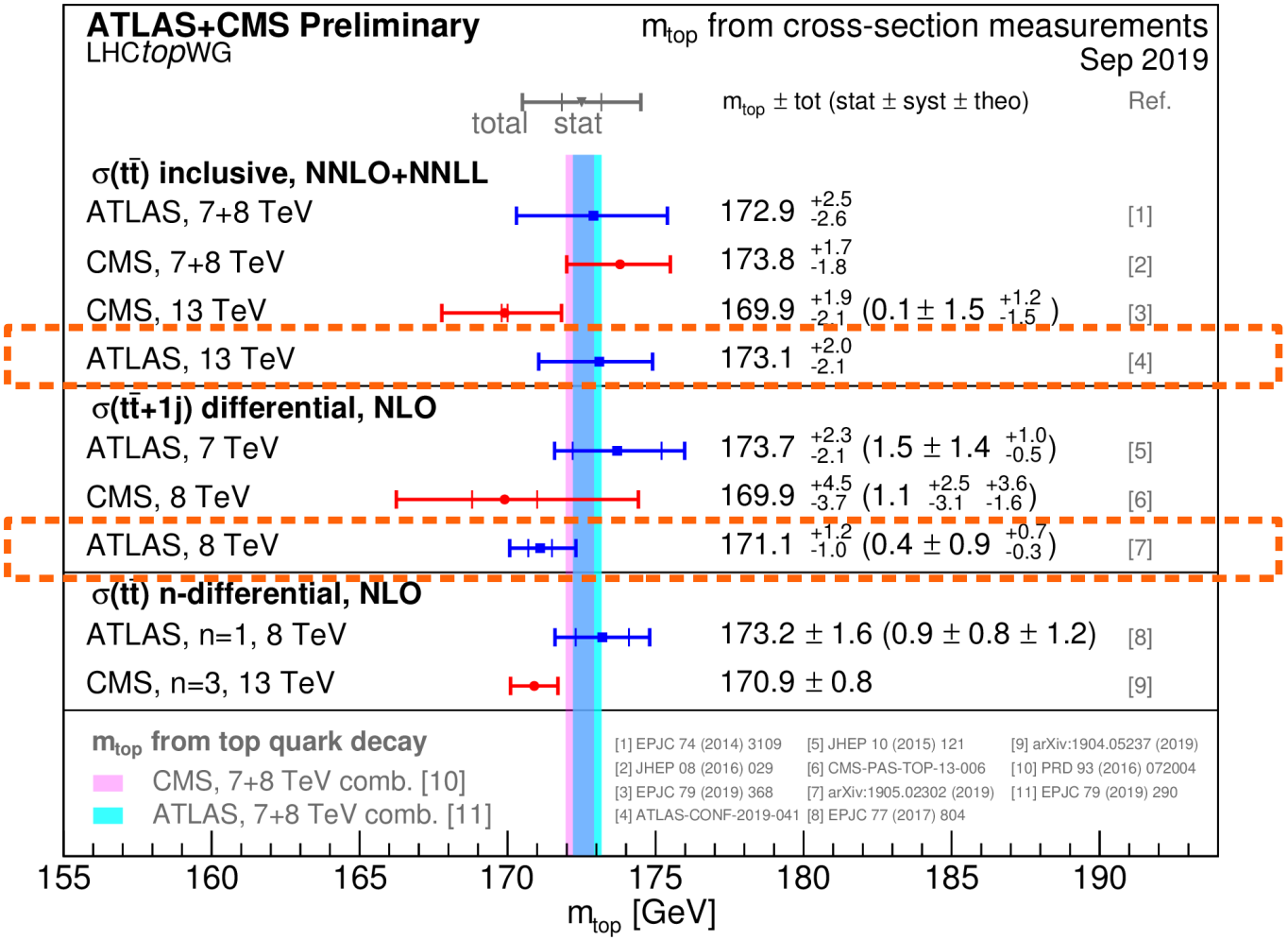


$$\rho_s = \frac{2\,m_0}{m(t\bar{t}+1\,jet)} \quad (m_0 = 170\,GeV)$$

$$m_{top}^{pole}(e\mu) = 173.1 \pm 1.0\,(exper.)^{+1.5}_{-1.4}\,(PDF+\alpha_s)^{+1.0}_{-1.5}\,(QCD\ scales)\,GeV\ (^{+2.0}_{-2.1}\,GeV)$$

$$m_{top}^{pole}(tt+1\,jet) = 171.1 \pm 0.4\,(stat.) \pm 0.9\,(syst.)^{+0.7}_{-0.3}\,(theor)\,GeV\ (^{+1.2}_{-1.0}\,GeV)$$

Summary of Top pole mass measurements



Indirect top quark mass measurements seem to be consistent with direct mass measurements at current precision

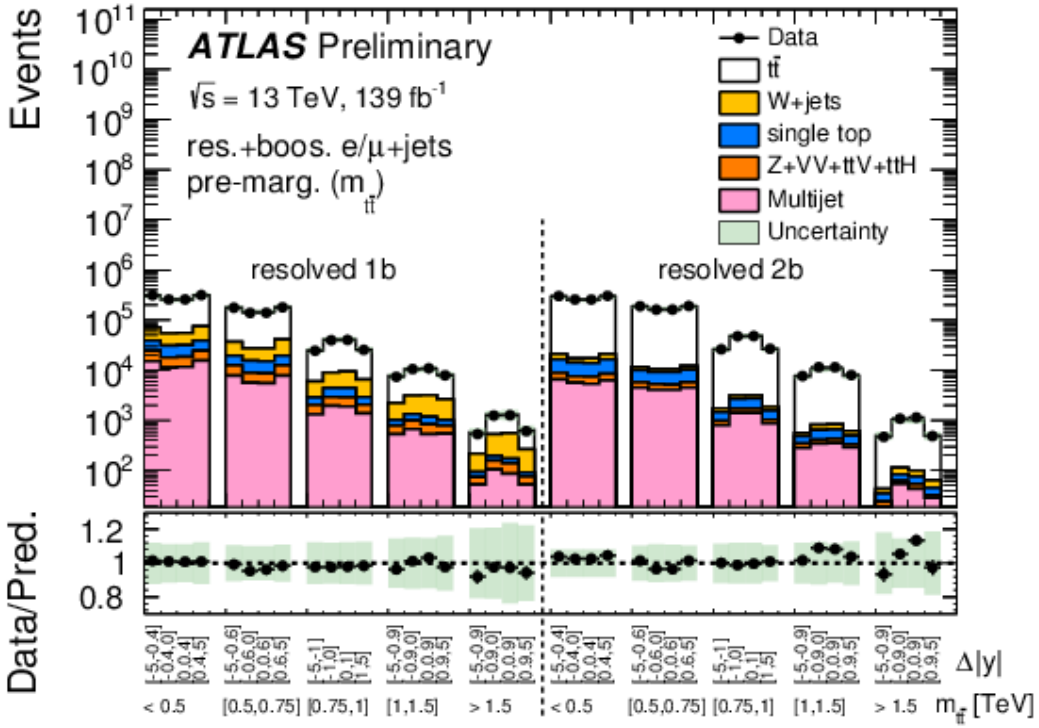
Charge asymmetry

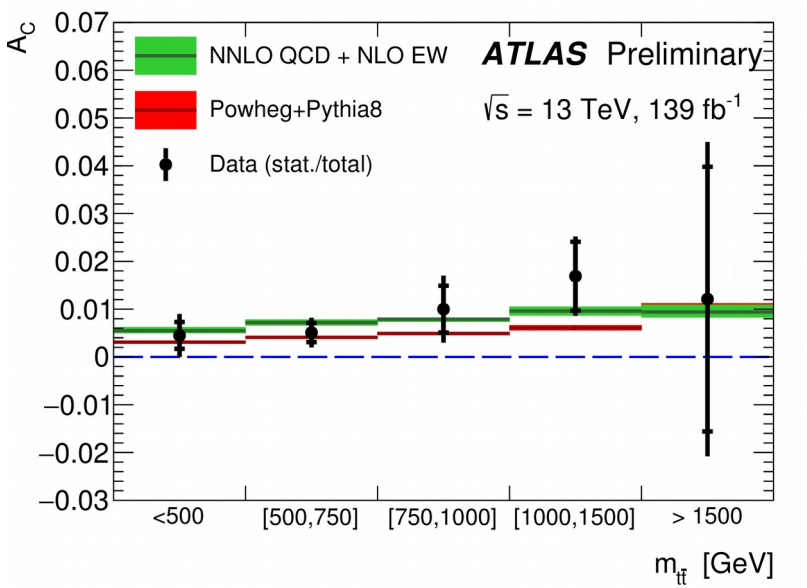
ATLAS-CONF-2019-026

- Charge asymmetry in production:
  - small effect in SM due to higher order corrections
  - Could be enhanced in extensions of SM

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

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





$$A_C = 0.0060 \pm 0.0015$$

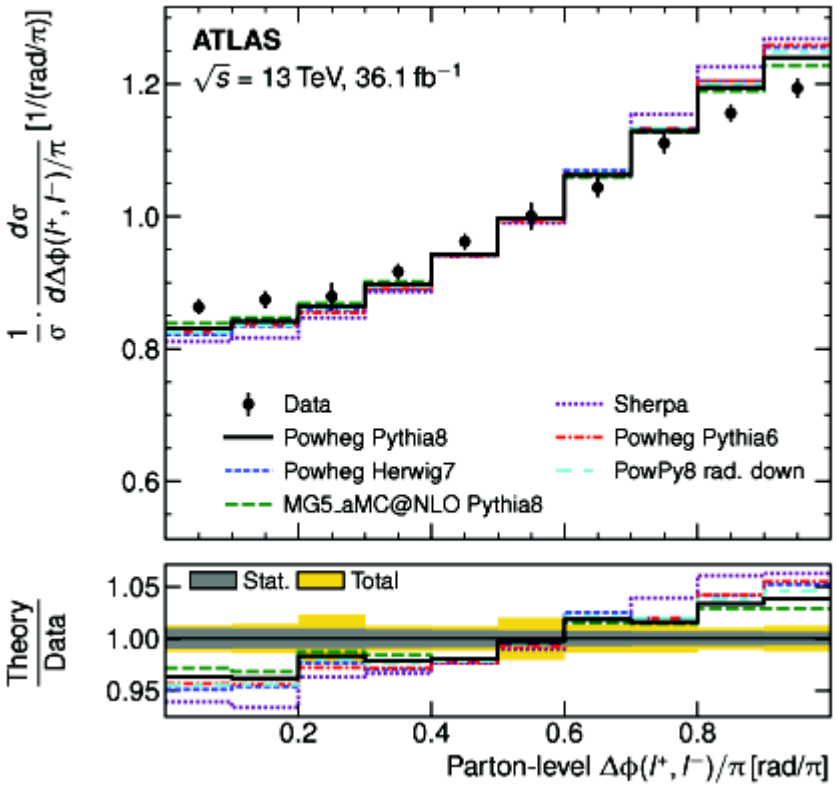
$$theory\,(NNLO\,QCD + NLO\,QED): A_C = 0.0064 \pm 0.0005$$

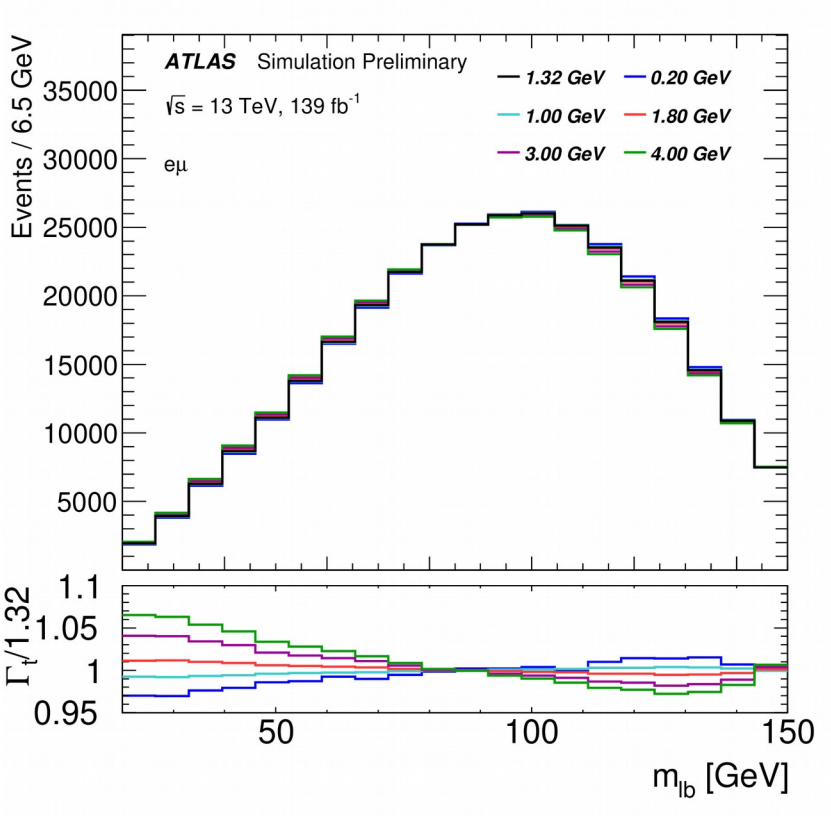
Evidence of charge asymmetry at the level of 4 standard deviations

Spin correlations & Top Width

arXiv:1903.07570
ATLAS-CONF-2019-038

- Top-antitop spin correlations:
  - Can be accessed through decay products
  - Sensitive to top quark SUSY partner
- Top width:
  - Direct measurement
  - Template method using mass of l+b





$theory: f_{SM} = 1.0$

$f_{SM} = 1.249 \pm 0.024\,(stat.) \pm 0.061\,(syst.) \pm 0.040\,(theory)$

→ 3.2 standard deviation larger than prediction from NLO+PS generators

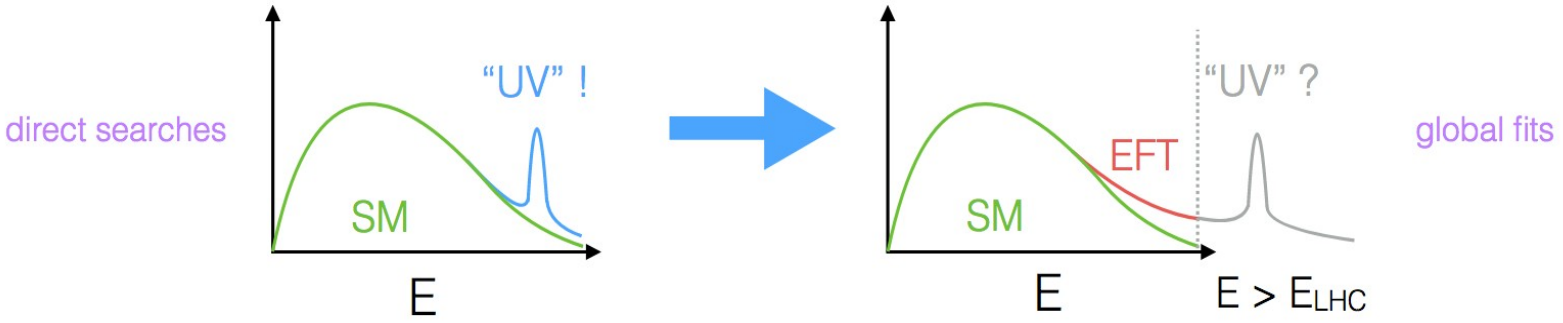
$\Gamma_{top} = 1.94^{+0.52}_{-0.49}\,GeV$

$theory: \Gamma_{top} = 1.32\,GeV$

Effective field theory interpretations

ATLAS-CONF-2019-026

- haven't seen directly new physics yet → even if beyond the reach of LHC, can reveal itself indirectly



- Can quantify the effect of new heavy mass states through model independent approach
  → effective field theory

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

Wilson coefficients; dim-D operators; scale of dim-D interactic

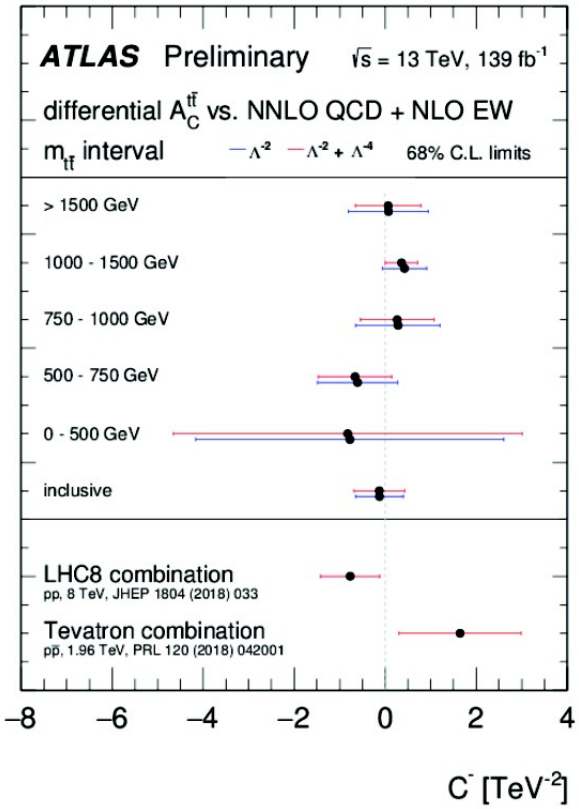
- Example: charge asymmetry measurement sensitive to 7 four-fermion operators in Warsaw basis

$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

Assumptions:

$$C_u^1 = C_d^1 = C^1$$
$$C_u^2 = C_d^2 = C^2$$

$$C^- = C^1 - C^2$$



Conclusions

- Lots of detailed and precise studies of top quark
  - Dilepton cross-section with 2.4%, some normalized differential below 1%
  - Top mass measured with precision of about 0.5 GeV
  - Evidence of charge asymmetry
- Observation of processes of top quark associated to bosons
- All top quark properties consistent with the Standard Model predictions
  - 3.2 sigma deviation from MC prediction for ttbar spin correlations
- More and more interpretations of precise top quark measurements through the effective field theory couplings restrictions

All results available on public web page:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

BACKUP

R_t measurement

R_t:

- Ratio of t-channel cross-section for top and antitop
- Sensitive to inner proton structure given by PDFs