Top and ttH at the LHC

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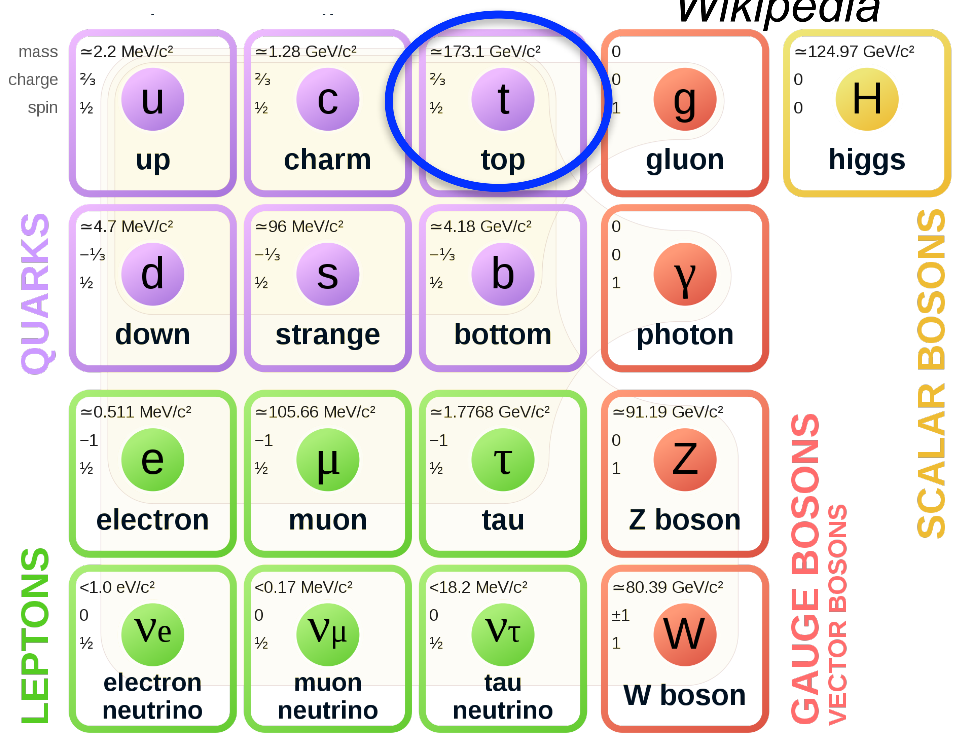
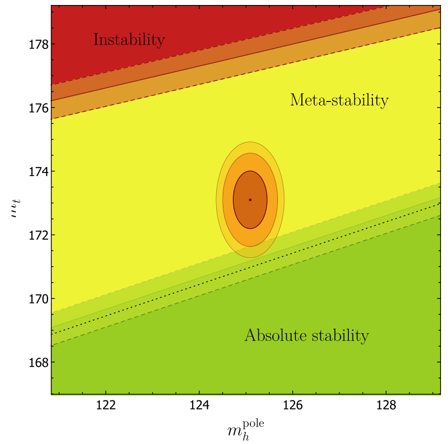
Introduction to Top Quark Physics

- Top quark is the heaviest elementary particle in the SM (m_t~173 GeV)
- Only quark decays before hadronization
- Large Yukawa coupling with Higgs boson. Important for understanding Higgs mechanism
- Large cross section at LHC. Could be used to study SM with high precision (cross section, mass measurements *etc.*)
- Search for physics beyond SM
- Top quark mass: cosmological application

Wikipedia





PRD 97 056006 (2018)

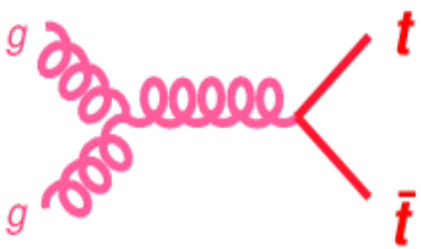
Vacuum stability

Top Quark Production and Decays at LHC

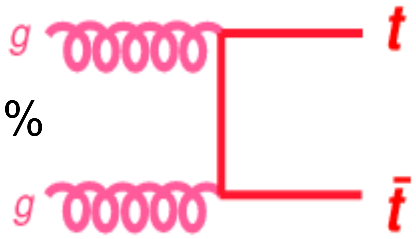
- ttbar production (strong)

ttbar σ at Tevatron @1.96 TeV: ~7 pb

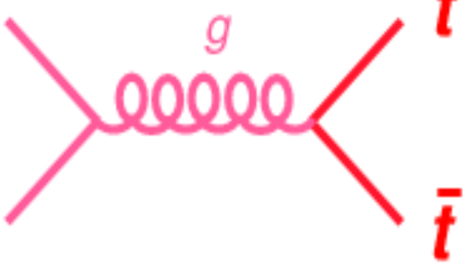
σ @13 TeV: ~830 pb



~90%

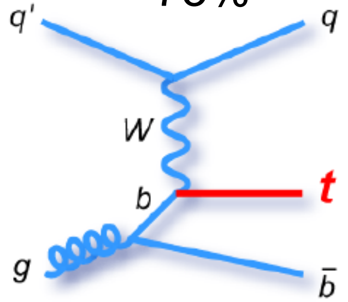


~10%



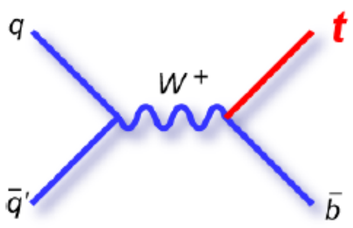
- Single-top production (EW)

~73%



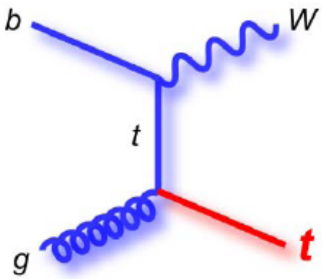
t-channel

~24%



s-channel

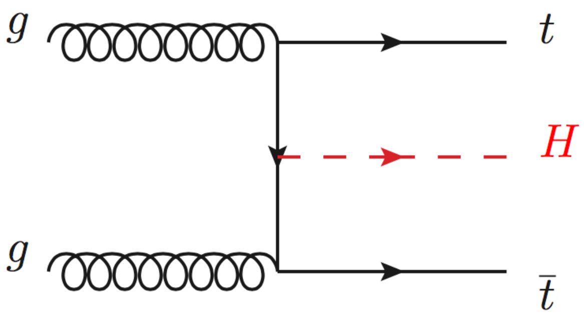
~3%



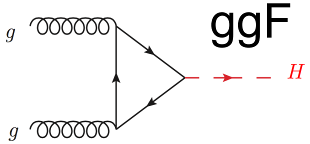
tW-channel

σ @13 TeV: ~300 pb

- 2 top quarks + Higgs (ttH)



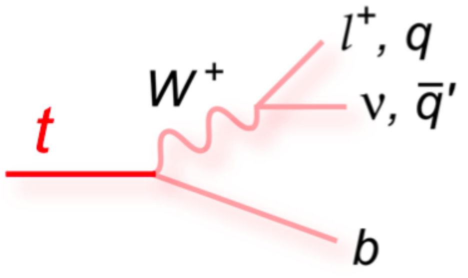
σ @13 TeV: ~0.5 pb



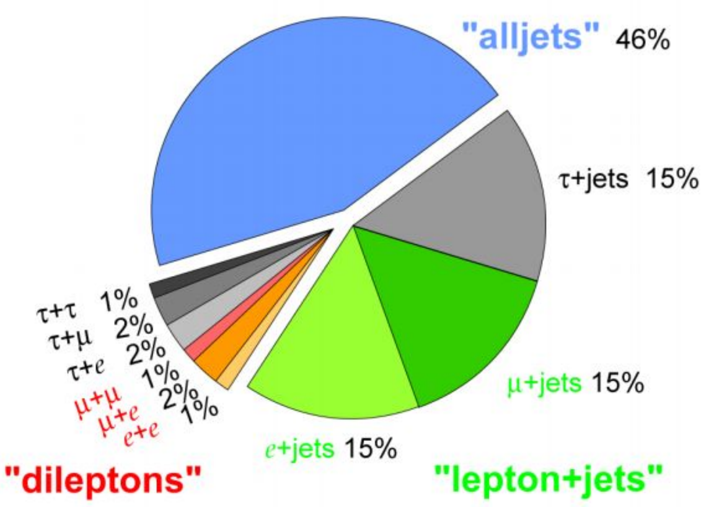
ggF

Top Quark Production and Decays at LHC

- Decay (EW)

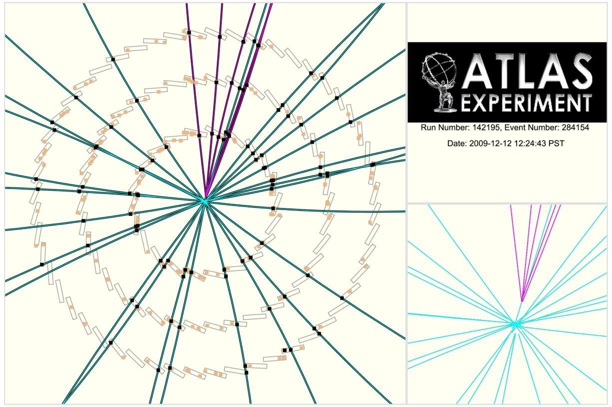


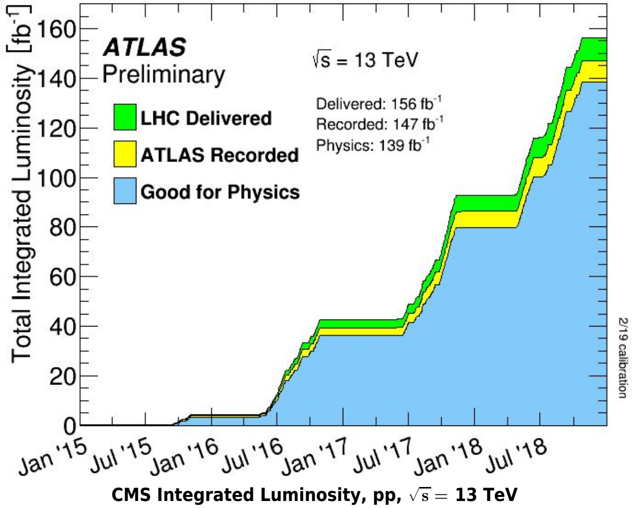
ttbar decay

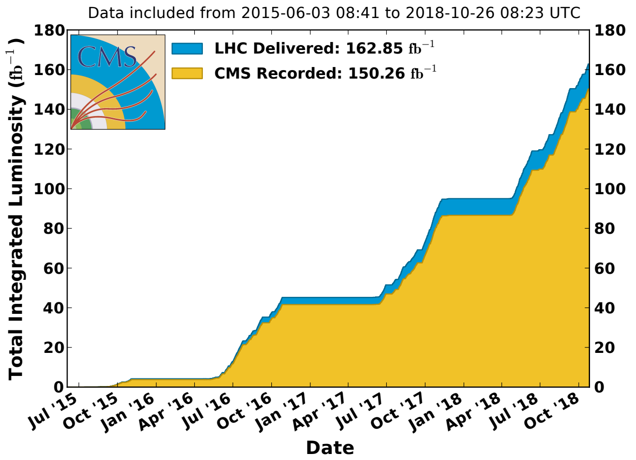


Complicated decay final states. Almost use all parts of the ATLAS detector

b-jet tagging： B hadron with p_T=50 GeV will travel 3 mm in the transverse direction







- ATLAS LHC Run 2: 139 fb-1 data
- ~115M ttbar events

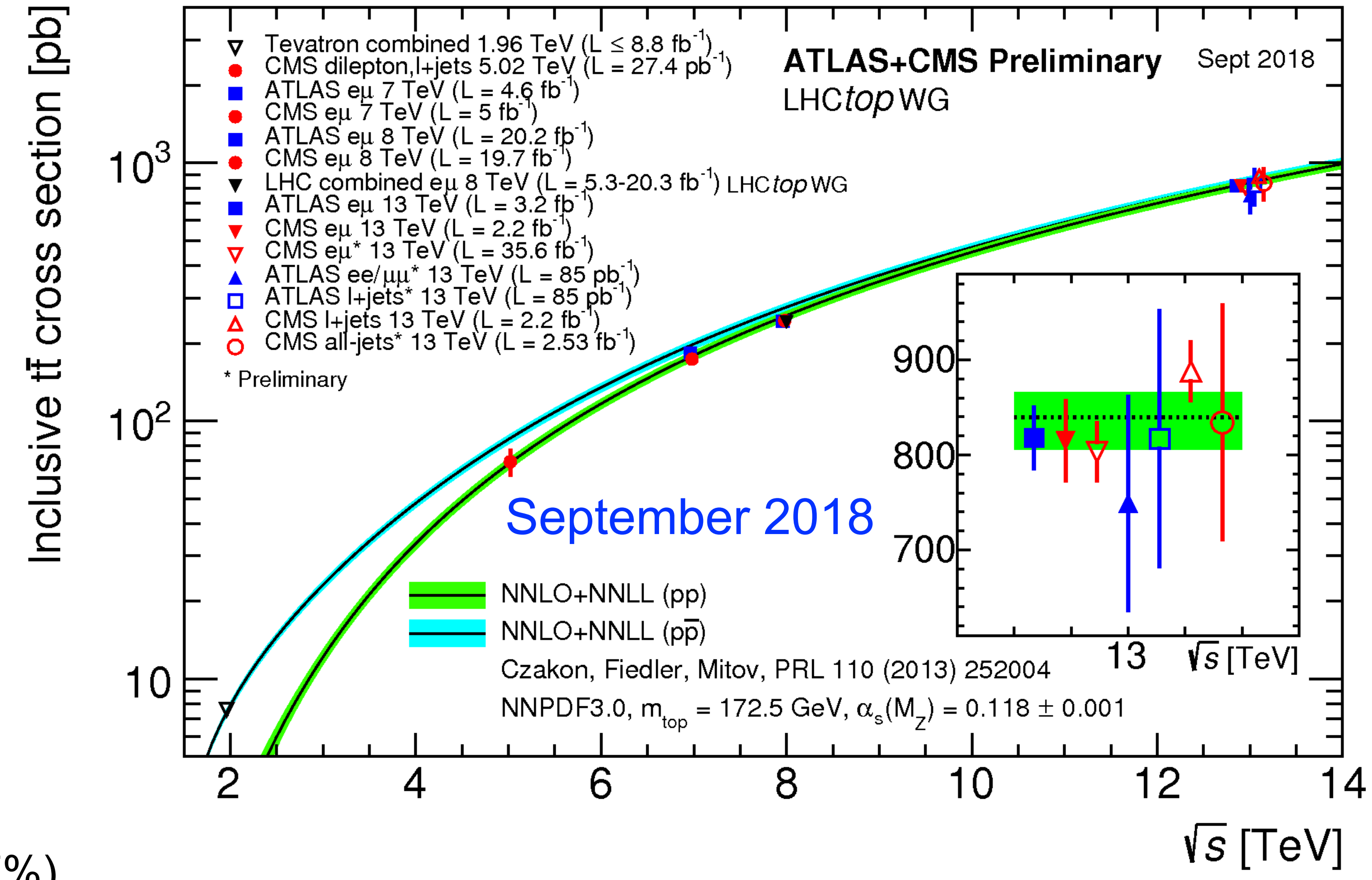
Selected Topics in Top and ttH Physics

1. ttbar cross section
2. Single-top quark cross section
3. Observation of tZq
4. Top quark mass measurement
5. ttbar spin correlation
6. Four top quarks search
7. ttH measurement

Cross Sections

Inclusive ttbar Cross Section

- Measure ttbar cross section at different center of mass energies (5.02 TeV, 7 TeV, 8 TeV and 13 TeV)
- Good agreement with NNLO+NNLL calculations



State-of-the-art calculation:

NNLO+NNLL from Top++ v2.0

$\sigma_{t\bar{t}}$(7 TeV) = 177.3 +3.7 -3.2 pb

$\sigma_{t\bar{t}}$(8 TeV) = 252.9 +15.3 -16.3 pb

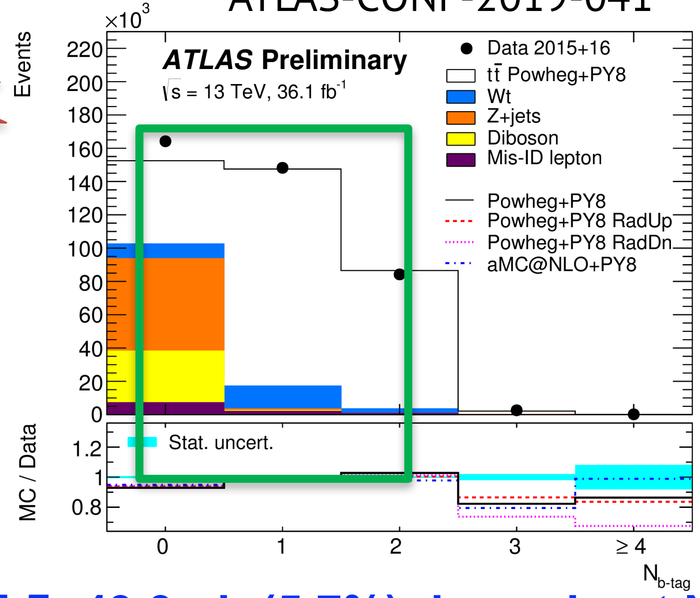
$\sigma_{t\bar{t}}$(13 TeV) = 831.8+45.5 -49.9 pb (5.7%)

Inclusive ttbar Cross Section

- ATLAS: use eμ channel to reduce systematics
- Counting events in 1 b-jet region and 2 b-jet region simultaneously
- Dominate systematics: lumi. (1.9%); bkg (tW) XS (0.5%); etc.

New

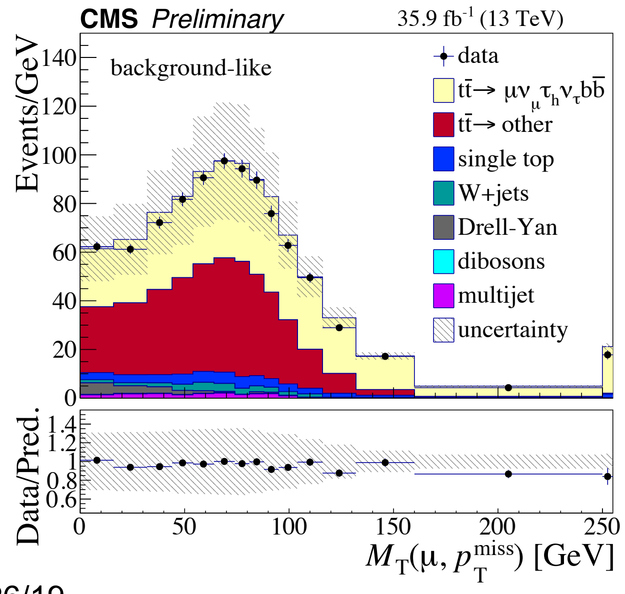
ATLAS-CONF-2019-041



$\sigma_{t\bar{t}}$=826.4±3.6 (stat)±11.5 (syst)±15.7 (lumi)±1.9 (beam) pb

Total uncertainty: 2.4%

NNLO+NNLL: σtt̄ (13 TeV) = 831.8+45.5 -49.9 pb (5.7%); how about N3LO?



- CMS: measure ttbar cross section with l+τ channel (hadronic τ)
- Fit to mT(lepton, pTmiss) in signal and background-like regions

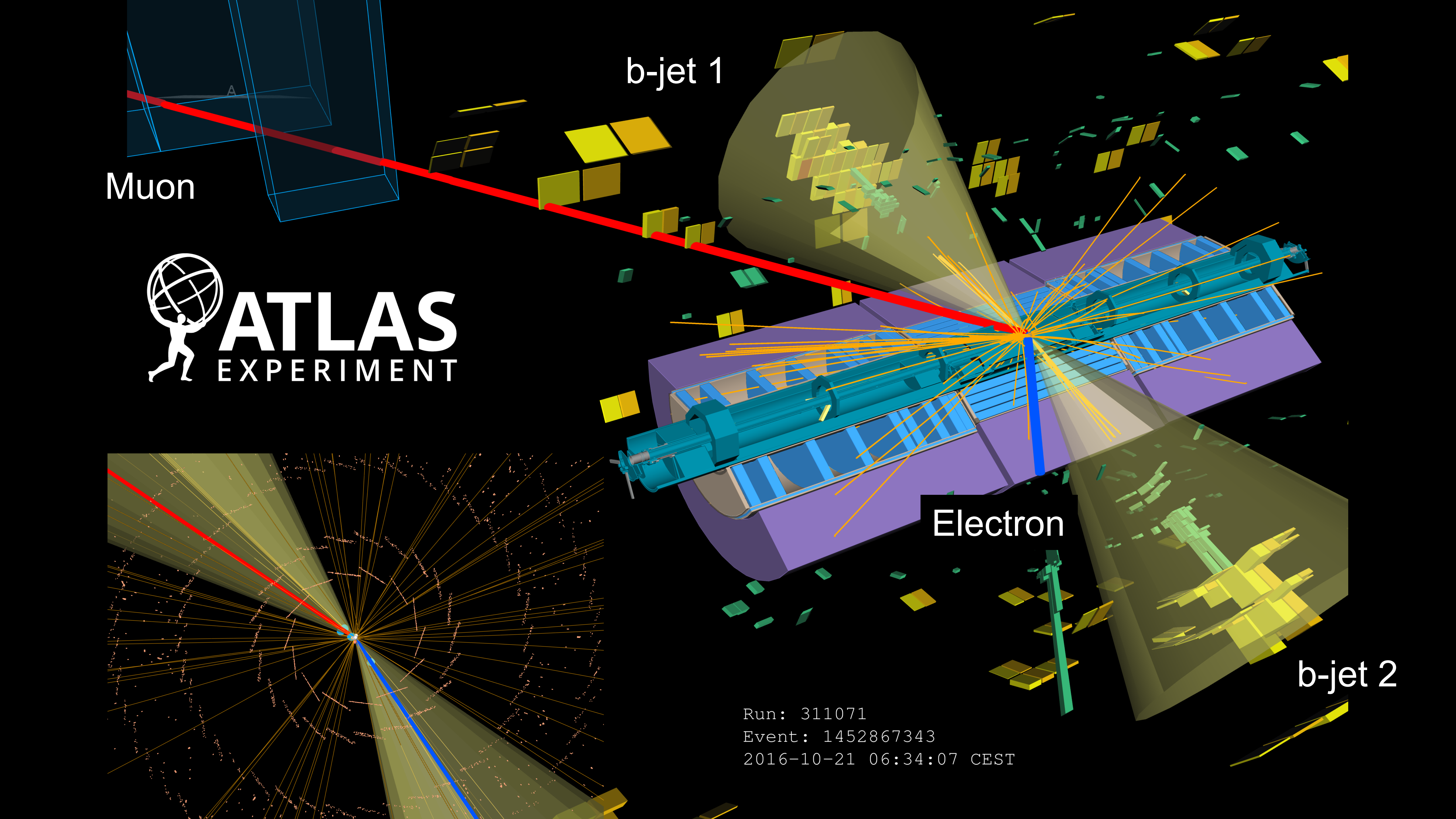
σtt = 781 ± 7 (stat) ± 62 (syst) ± 20 (lumi) pb

Uncertainty: ~8%

New

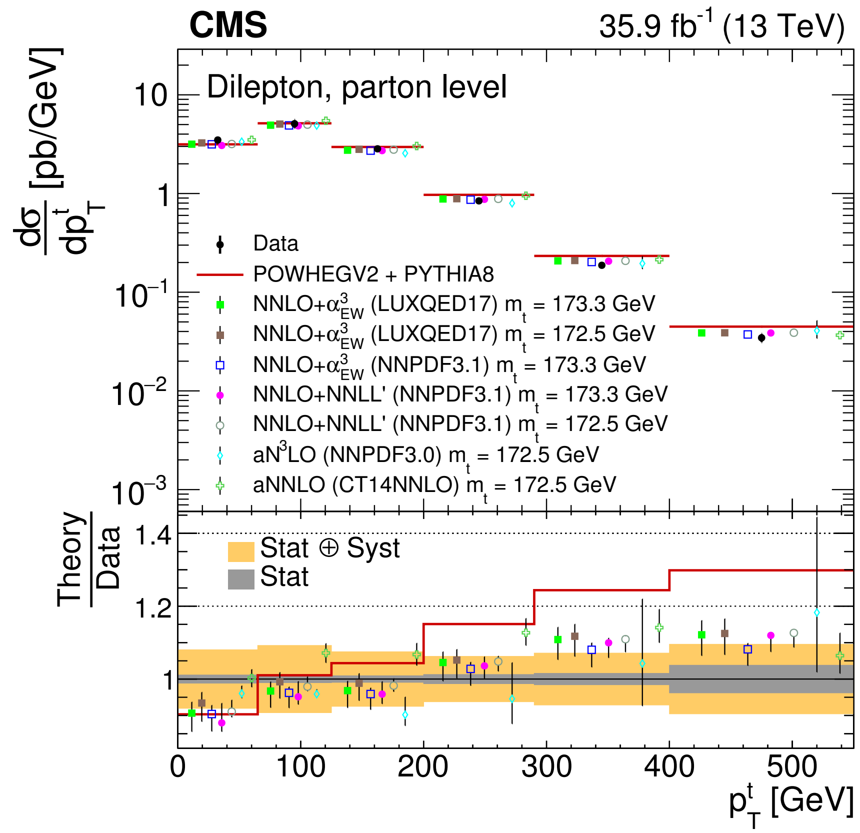
Test lepton universality

$$R_{\ell\tau_h/\ell\ell} = 0.973 \pm 0.009\,(\text{stat}) \pm 0.066\,(\text{syst})$$

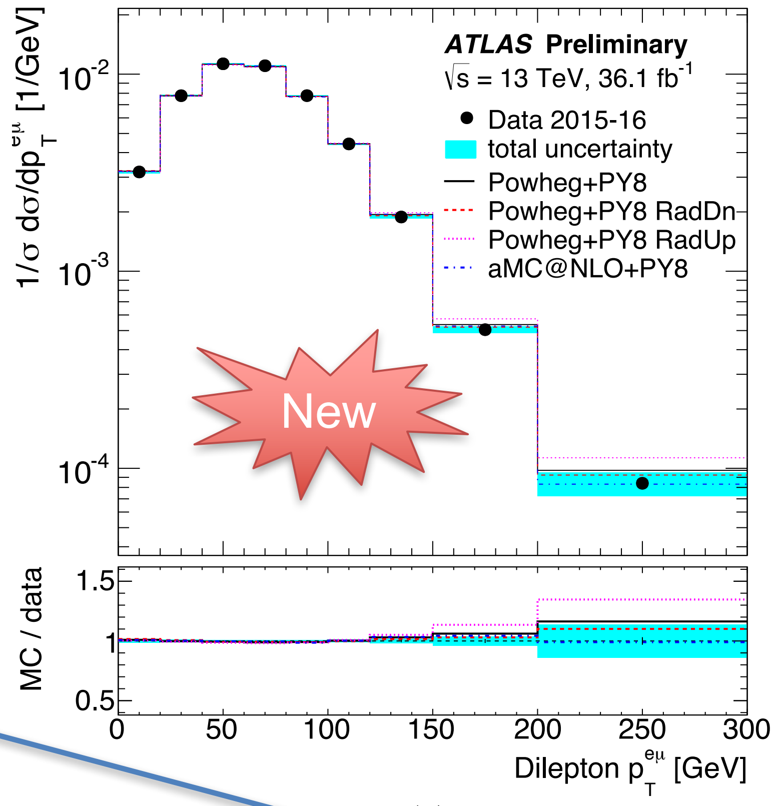

b-jet 1
Muon
ATLAS
EXPERIMENT
Electron
b-jet 2
Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST

ttbar Differential Cross Section

JHEP 02 (2019) 149



ATLAS-CONF-2019-041



Powheg predicts harder top pT distribution

- Differential cross section measurements could be used to test the QCD calculations in different phase space
- Use unfolding to correct acceptance and detect effects

- NNLO calculations are closer to data measurements

Single-top Quark Cross Section

JHEP 05 (2019) 088

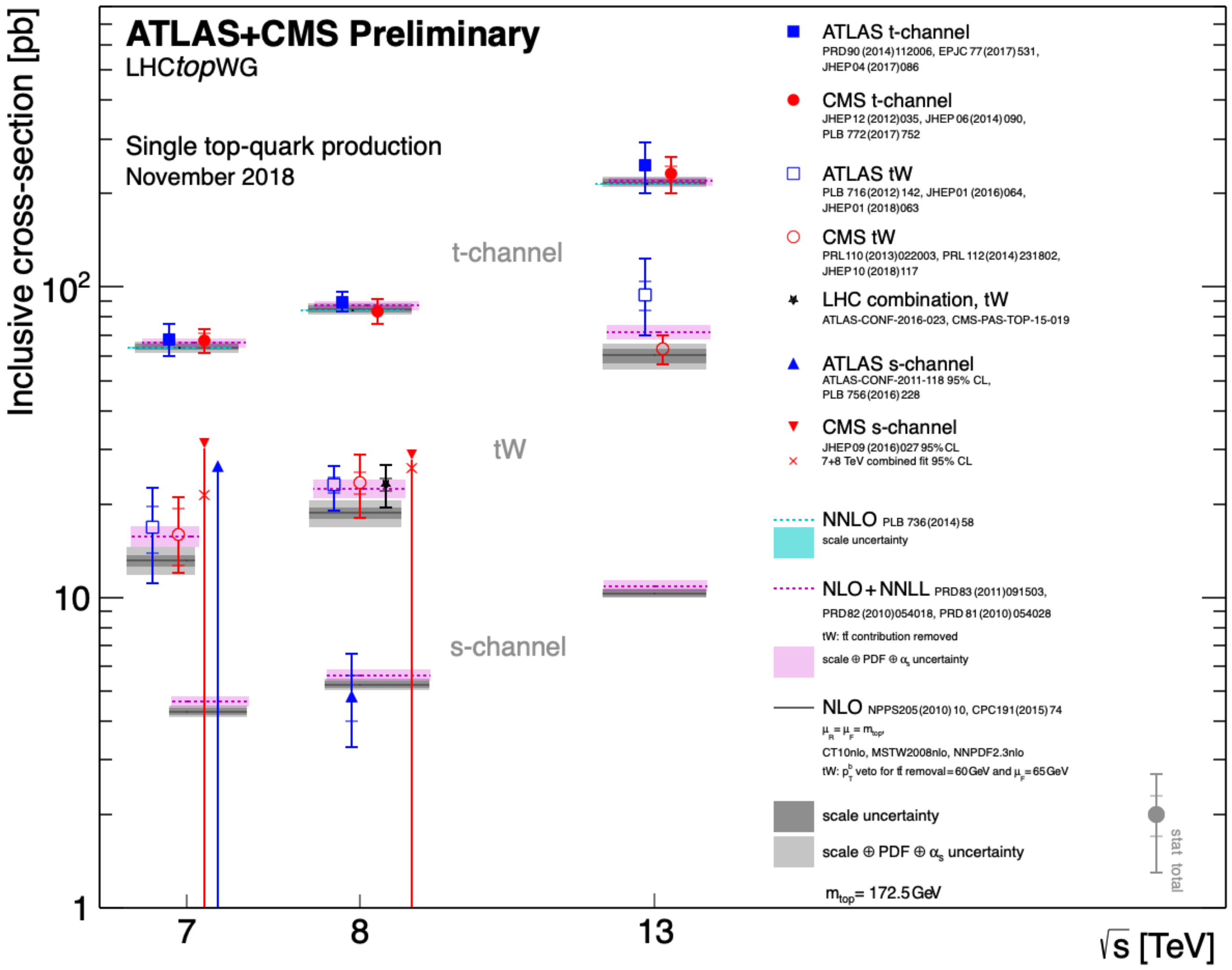
- ATLAS and CMS Run1 single-top combination
- Cross section and CKM matrix element V_{tb} measurement

$$|f_{\rm LV} V_{tb}| =$$

$$1.02 \pm 0.04\ (\text{meas.}) \pm 0.02\ (\text{theo.})$$

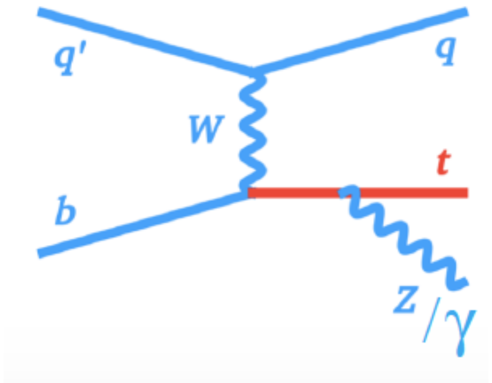
~3.7%

- With full Run2 data, measure single-top differential cross section and measure top properties in this channel



Rare Processes

Observation of tZq

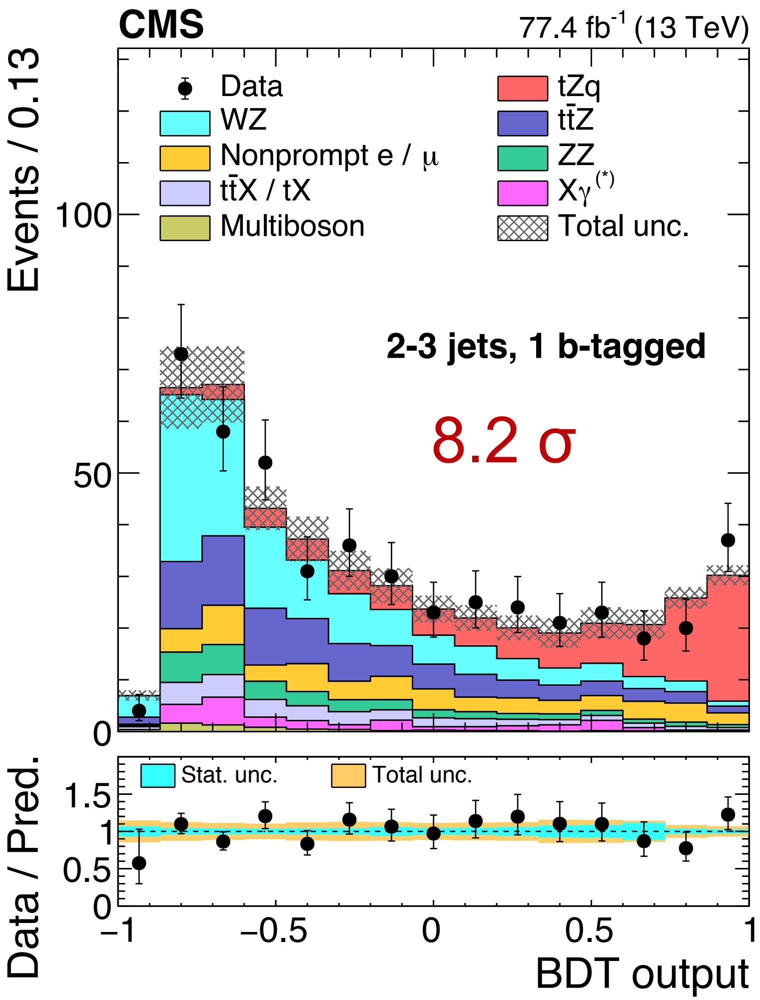


- Observation of tZq production process
- Signal cross section is consistent with SM prediction

98 ± 12 (stat.) ± 8 (syst.) fb

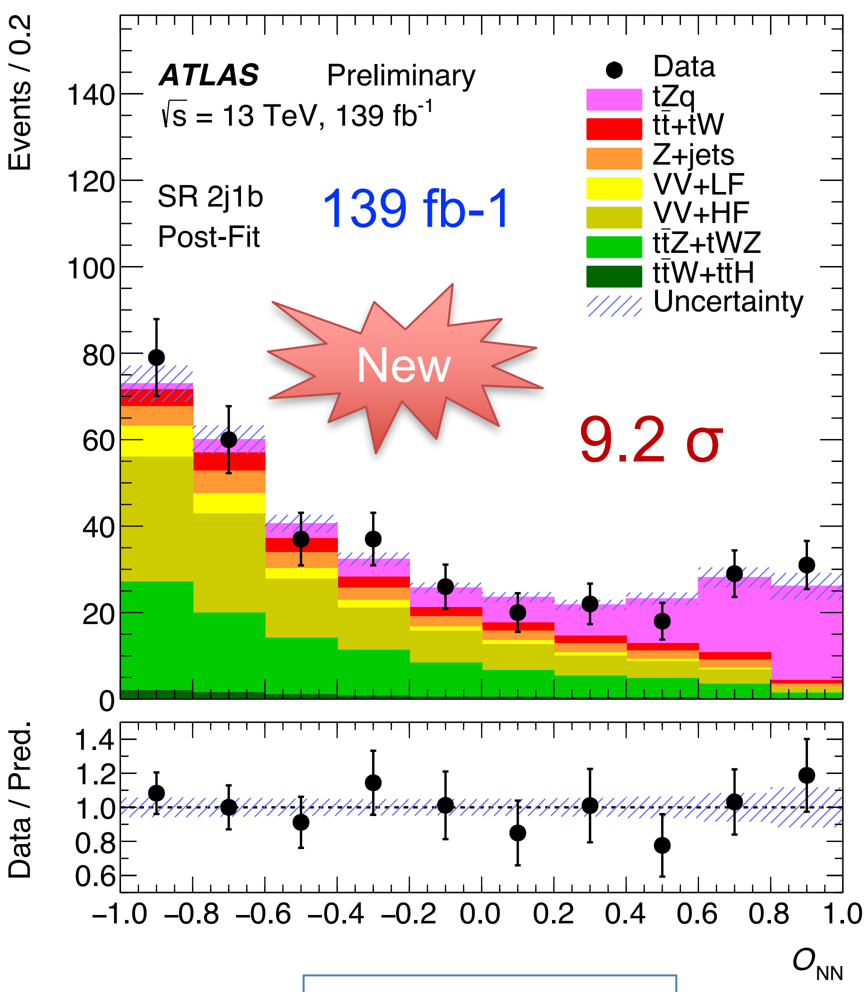
SM cross-section: 102 +5 -2 fb.

PRL 122, 132003 (2019)



Boosted Decision Trees

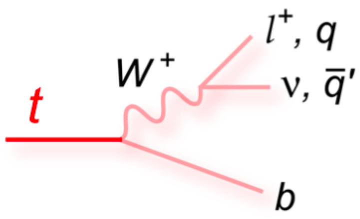
ATLAS-CONF-2019-043

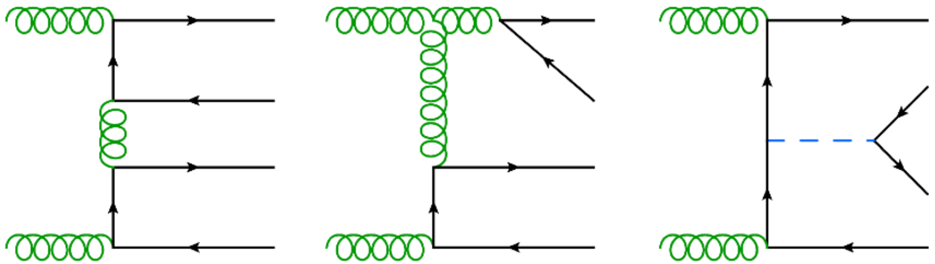


Neural Network

Search for Four Top Quark Final States

- Four quark production is a rare process at LHC
- Cross section is about 12 fb from NLO calculation
- Complicated final states

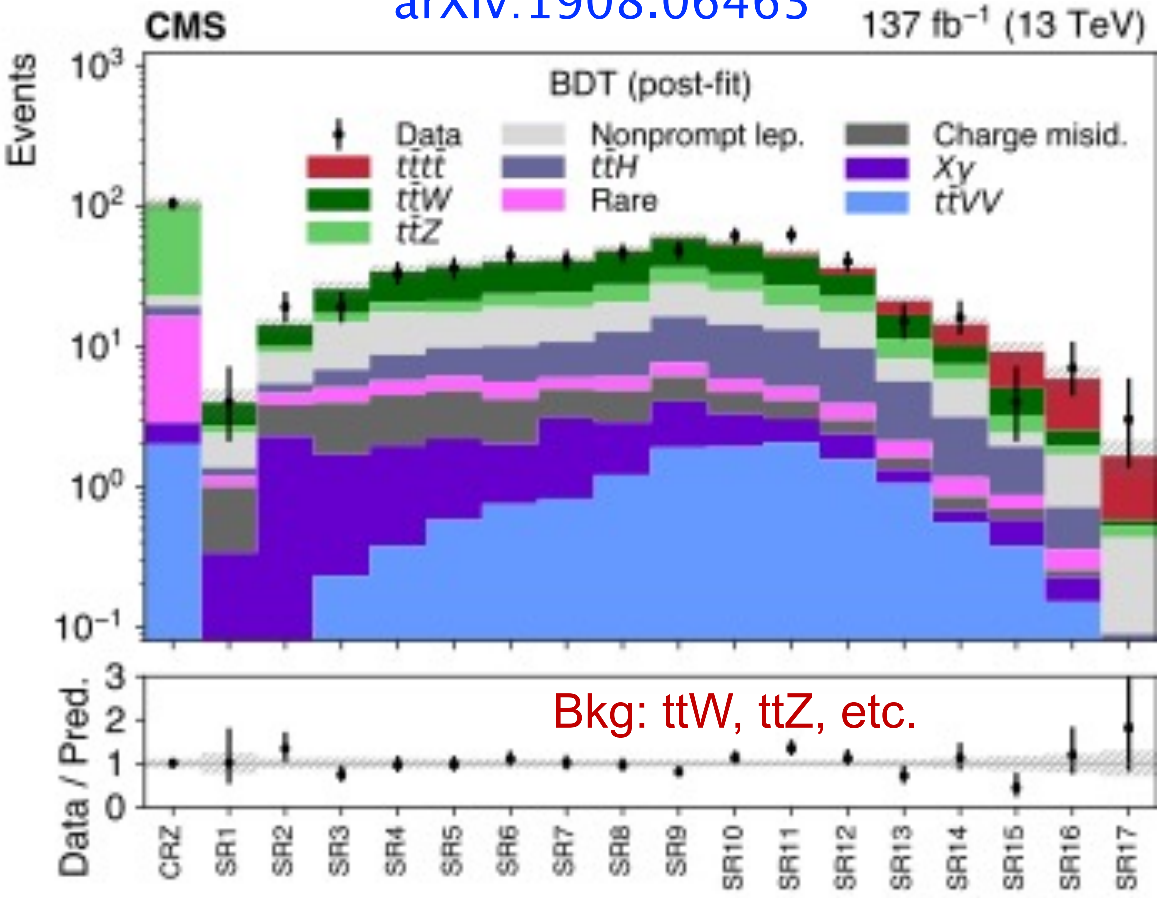




arXiv: 1611.05032

Same-sign dilepton and multilepton channels: SS/ML

arXiv:1908.06463



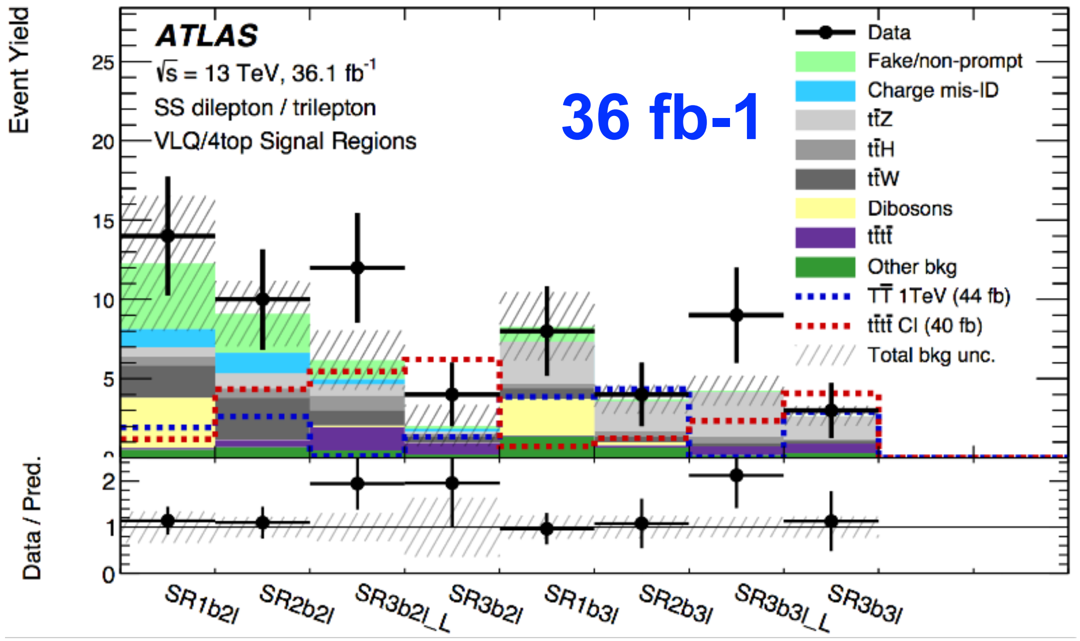
Bkg: ttW, ttZ, etc.

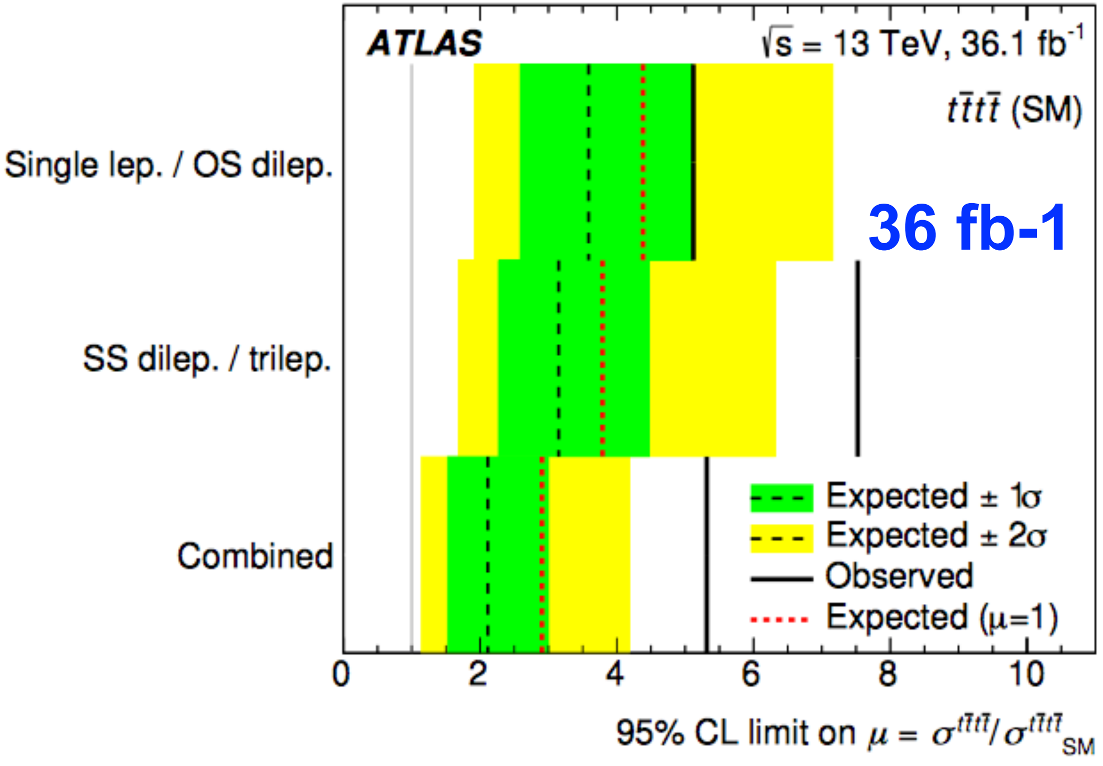
Obs. (exp.): 2.6 (2.7σ)

Search for Four Top Quark Final States

- Same-sign dilepton and multilepton channels: SS/ML
- Single-lepton and opposite-sign dilepton: 1L/OS

Phys. Rev. D 99, 052009 (2019)





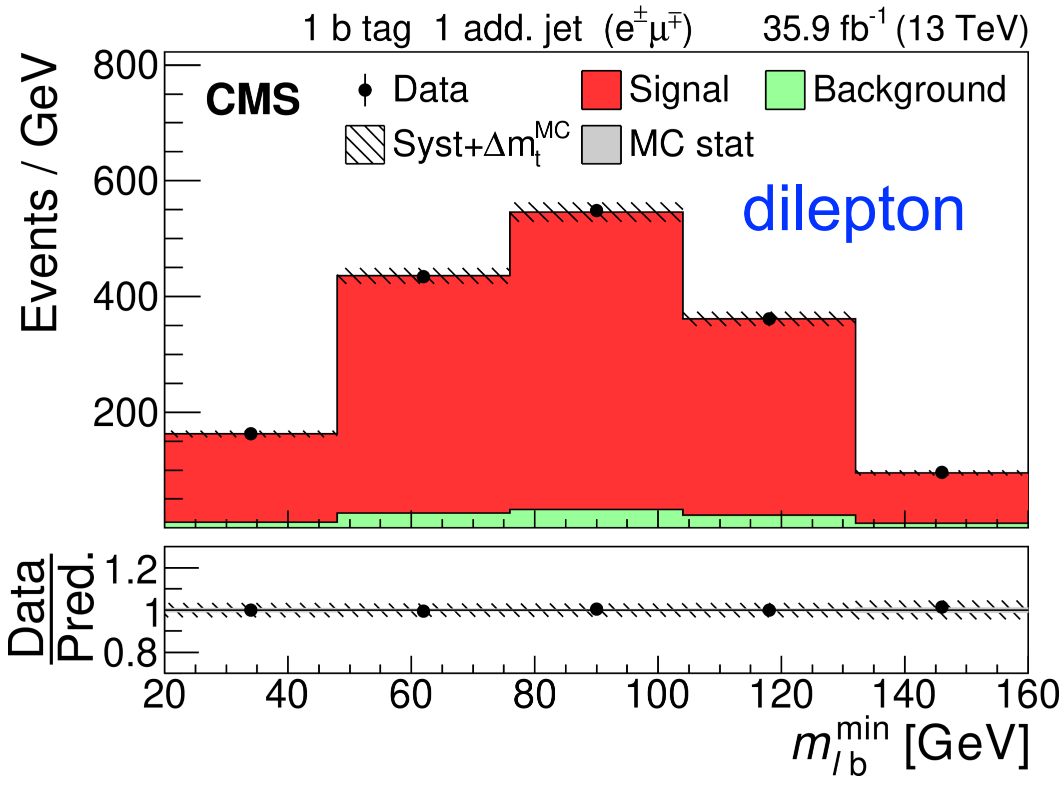
- SS/ML: 3.0 (0.8σ)
- 1L/OS: 1.0 (0.6σ)
- Combined: 2.8 (1.0σ). Obs. (exp.)

Top Quark Properties

Top Quark Mass – Direct Measurement

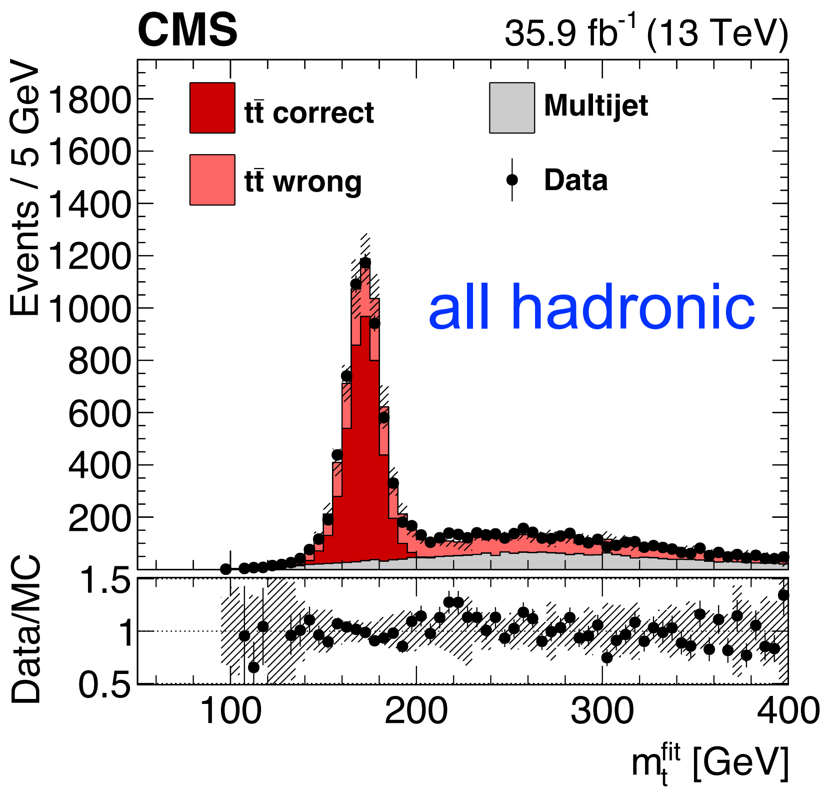
- Direct measurement: reconstruct top decay products.

EPJC 79 (2019) 368



m_t^{MC} = 172.33 ± 0.14 (stat) +0.66−0.72 (syst) GeV

EPJC 79 (2019) 313



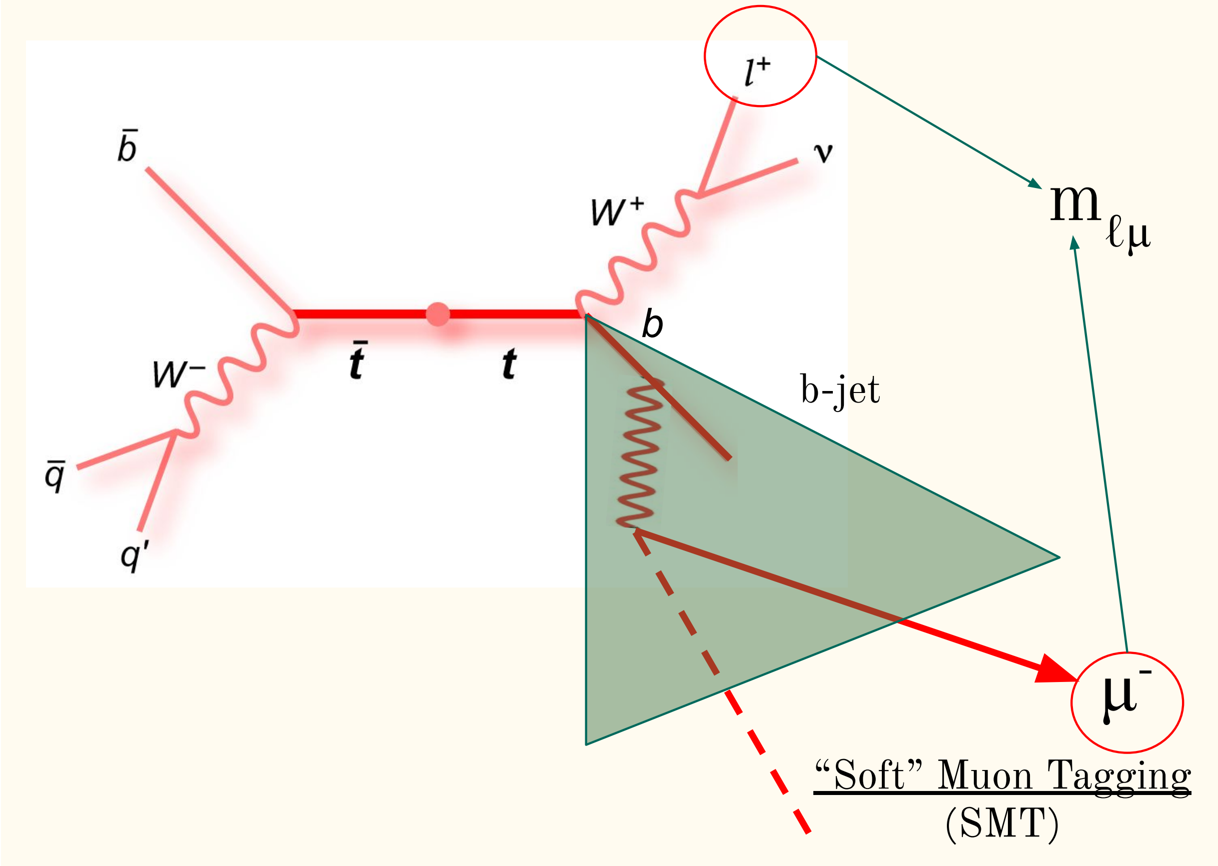
m_t=172.34±0.73 GeV

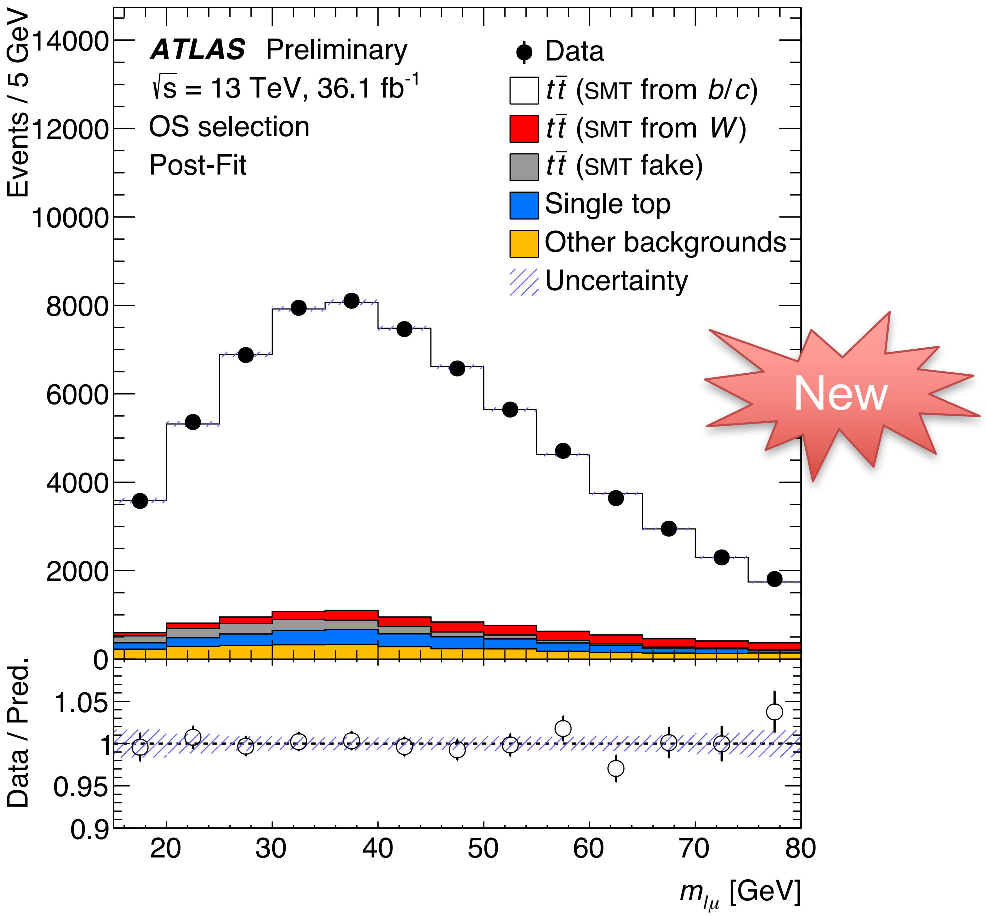
After combined with l+jet, m_t=172.26±0.61 GeV

Top Quark Mass – Direct Measurement

- Direct measurement: reconstruct top decay products.

ATLAS-CONF-2019-046 ATLAS l+jet with soft muon





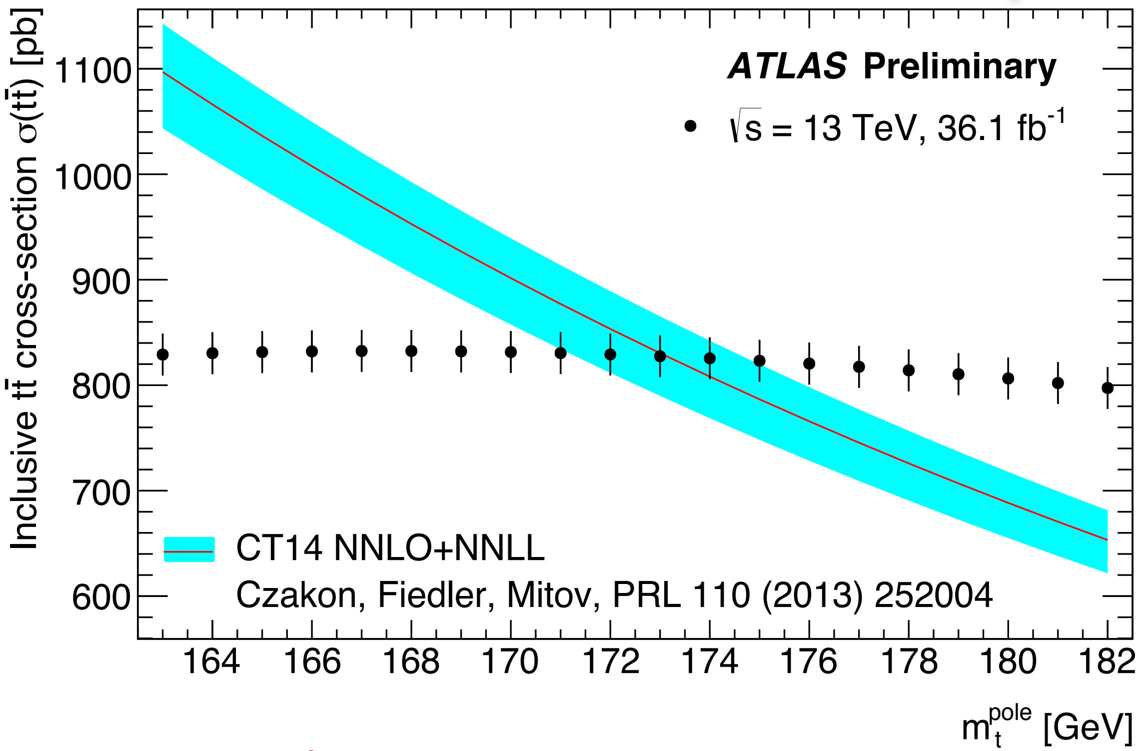
m_t=174.48±0.40(stat)±0.67(syst) GeV

Top Quark Mass

Indirect measurement

ATLAS-CONF-2019-041

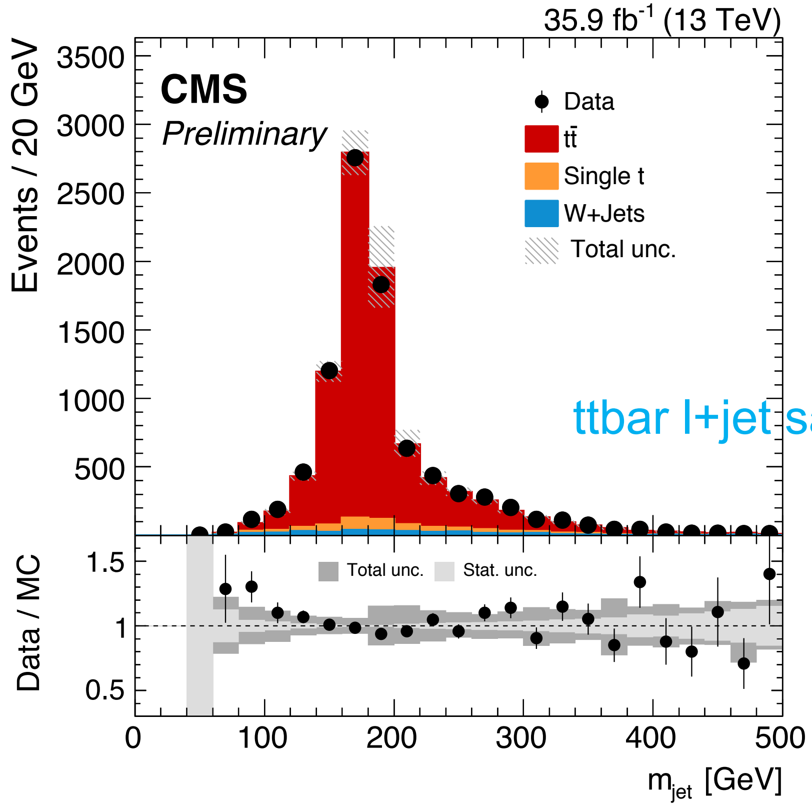
New



m_t^{pole} = 173.1+2.0 – 2.1 GeV

Top mass with boosted jets from top hadronic decay

CMS-TOP-19-005



ttbar l+jet sample

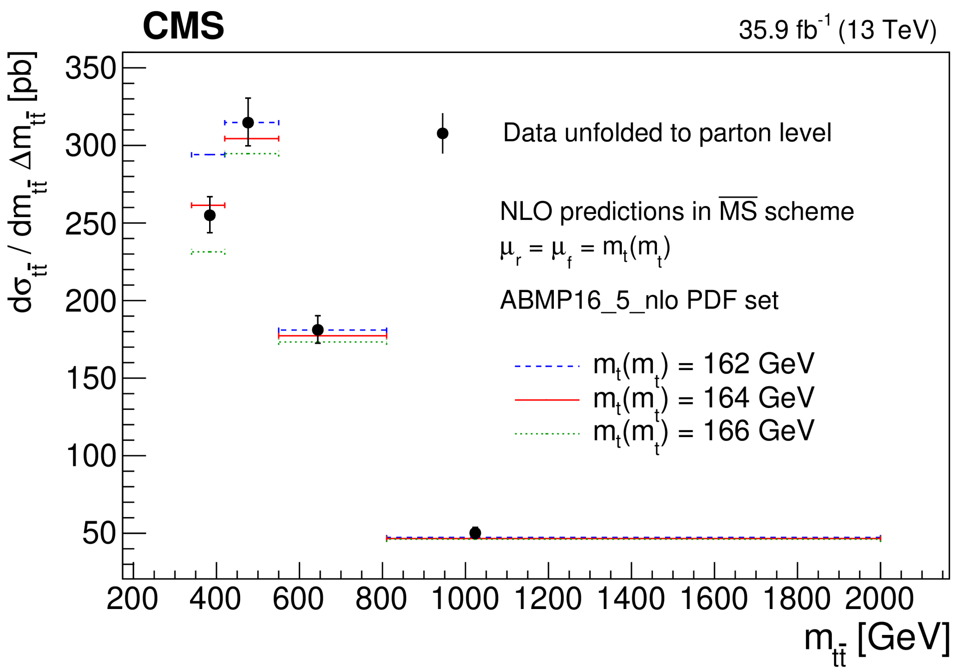
mt = 172.56 ± 2.47 GeV

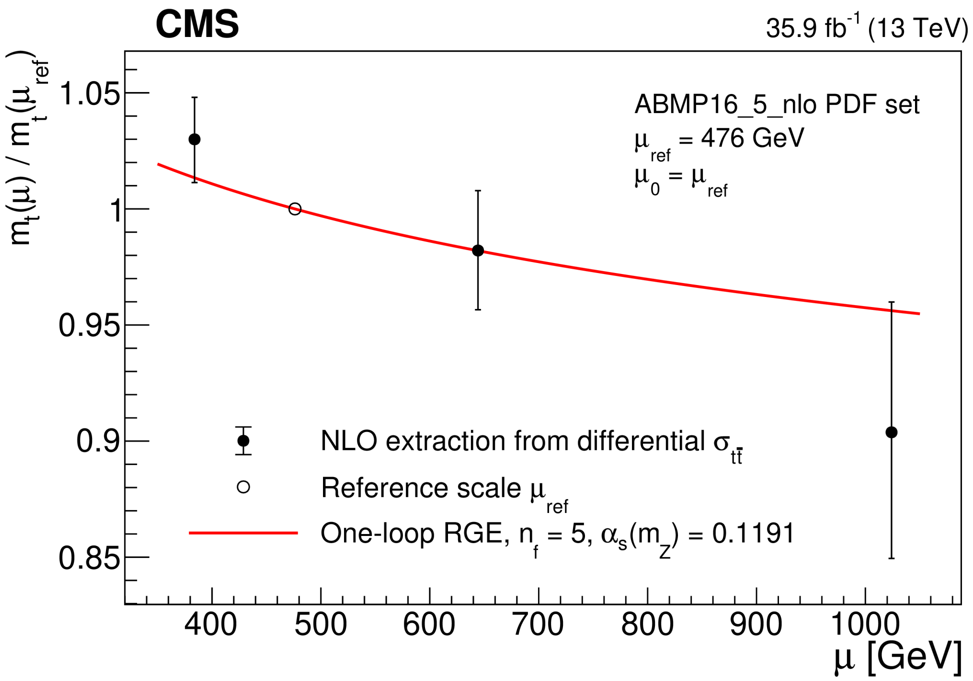
Using XCone jet algorithm (JHEP 11 (2015) 072)

Running Top Mass

CMS-TOP-19-007

- First measurement of running of top quark mass in the MSbar scheme
- Measure cross sections (predicted with certain top mass with MSbar scheme in NLO) in different m_{tt} bins

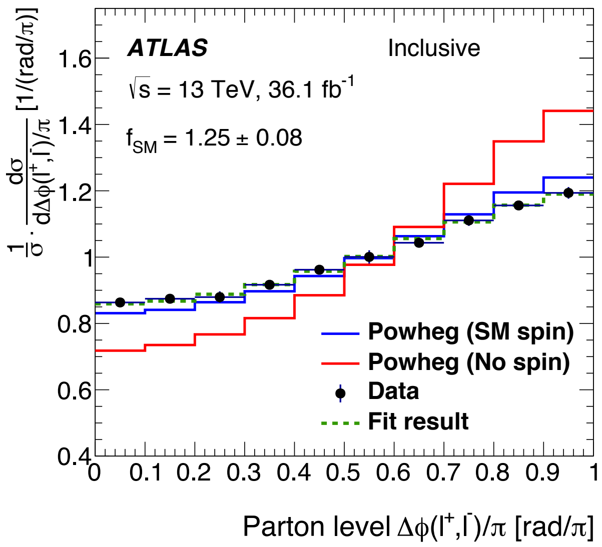


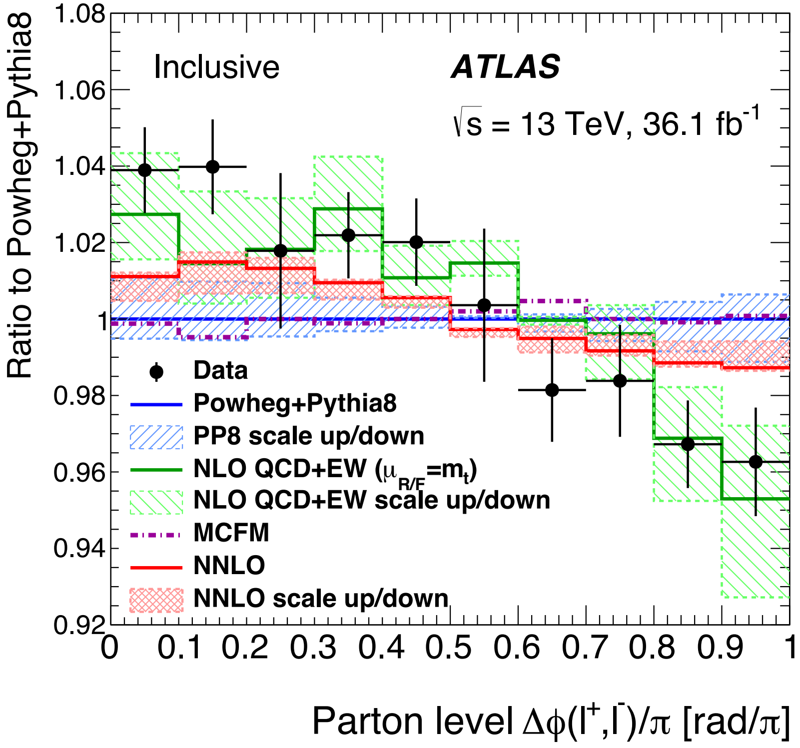


Renormalization Group Equation

Spin Correlation

arXiv: 1903.07570

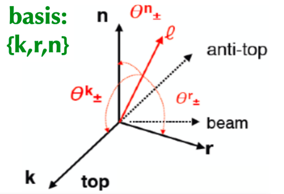




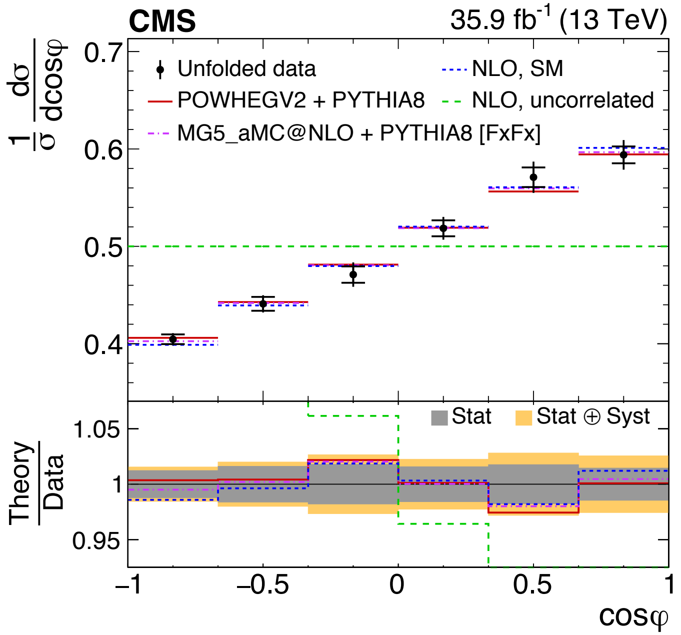
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i\cos\theta_1^i\right),$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}\left(1 + B_2^i\cos\theta_2^i\right),$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\cos\theta_2^j} = \frac{1}{2}\left(1 - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)\ln\left(\frac{1}{|\cos\theta_1^i\cos\theta_2^j|}\right)$$



CMS is using the method from: W. Bernreuther, D. Heisler, and Z.-G. Si, JHEP 12 (2015) 026

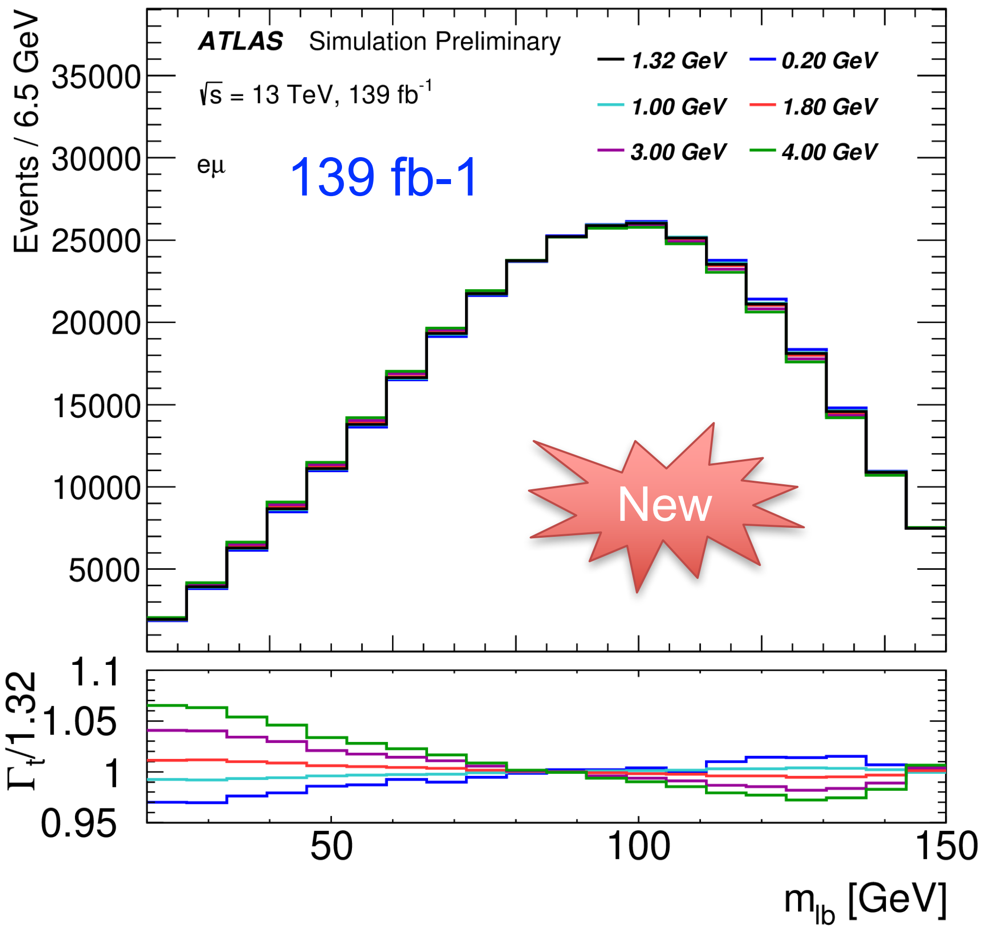


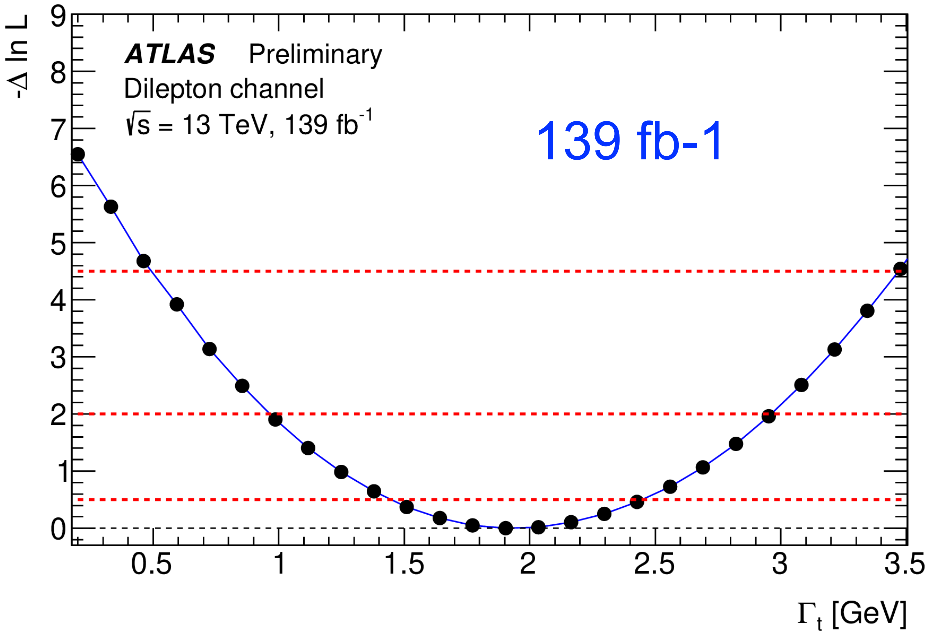
- 3σ deviation from ATLAS measurement
- NNLO-QCD closer to data
- NLO-QCD+EW agrees with data with large uncertainties
- CMS is using Bernreuther&Si method and observation is consistent with SM prediction

Top Width

- Measurement of the top quark width in the dilepton channel
- Top width is obtained by profile likelihood template fit for m_{lb}

ATLAS-CONF-2019-038



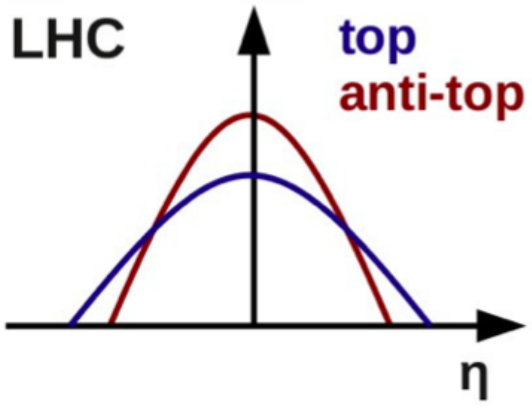


$\Gamma_t = 1.94{+0.52}{-0.49}$ GeV

NNLO $\Gamma_t = 1.322$ GeV, uncertainty < 1%

ttbar Charge Asymmetry

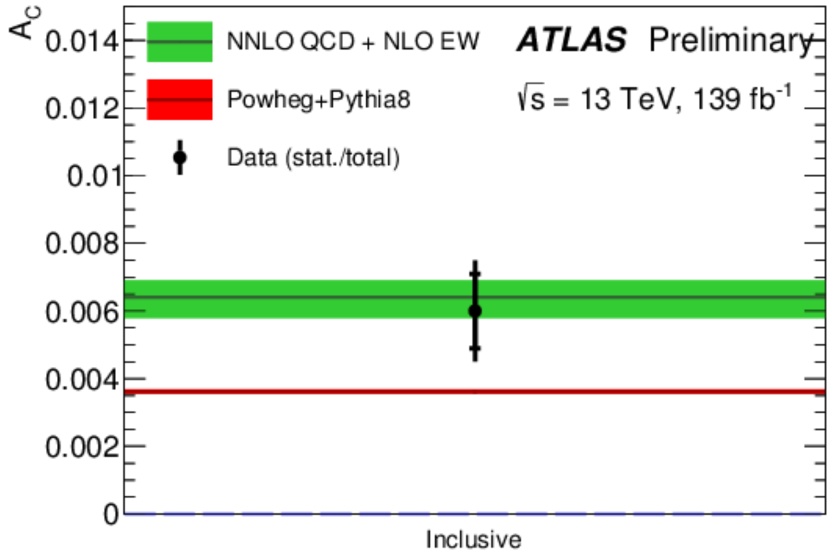
- Use l+jets channel
- More top events in forward region than anti-top

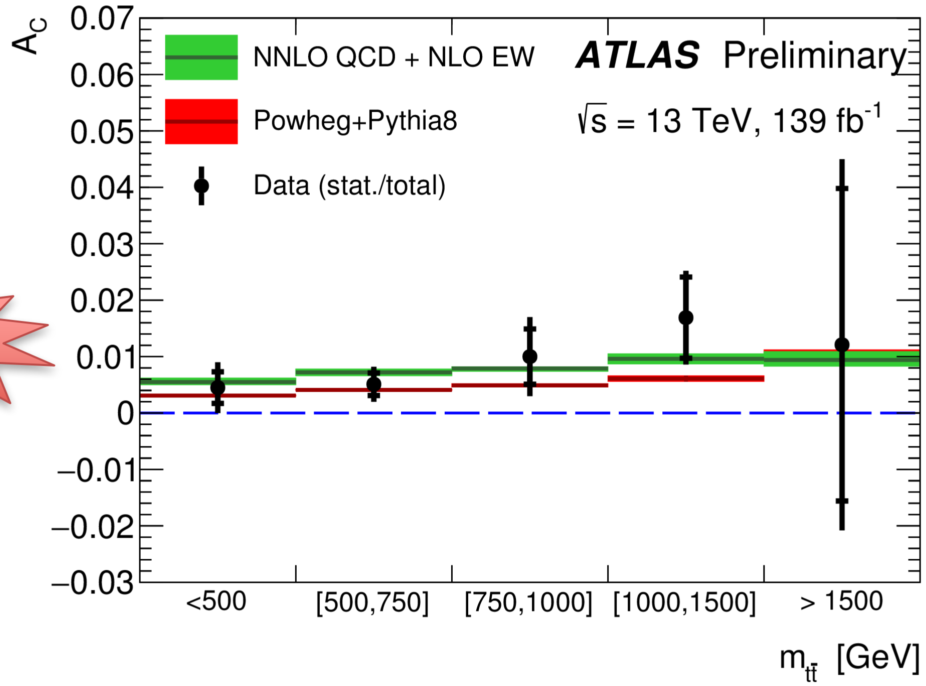


$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| > 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

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

ATLAS-CONF-2019-026





4σ

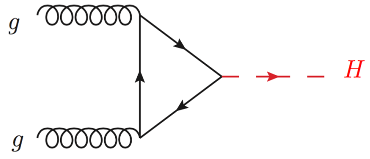
First evidence at LHC

Consistent with SM prediction at NNLO QCD + NLO QED

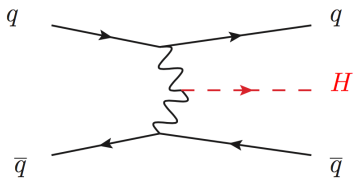
Top Quarks + Higgs (ttH)

ttH

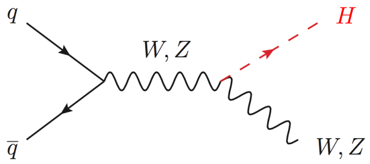
Higgs boson production at LHC



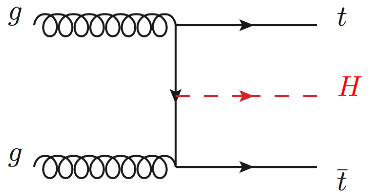
σ: ~49 pb



σ: ~3.8 pb



σ(WH/ZH): ~1.4-0.9 pb



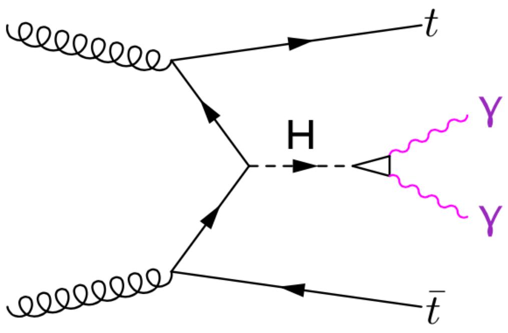
σ: ~0.5 pb → Measure top-Higgs Yukawa coupling directly

Higgs boson dacay

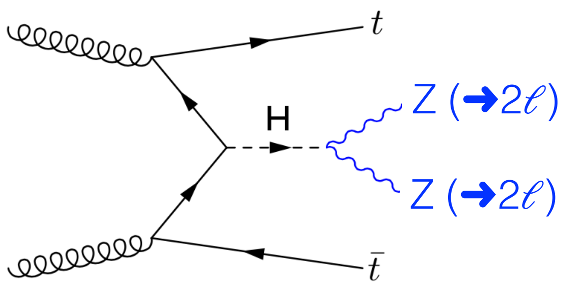
Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

ttH: Channels

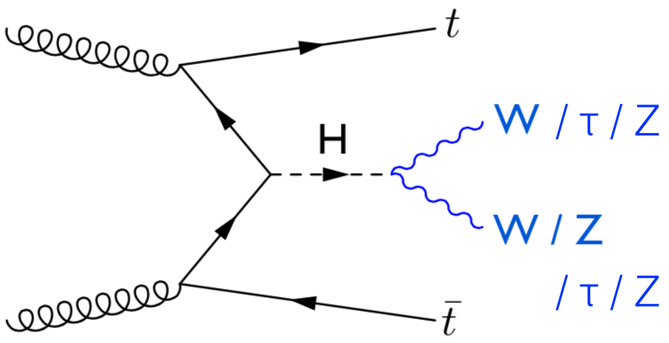
1. ttH, H->$\gamma\gamma$



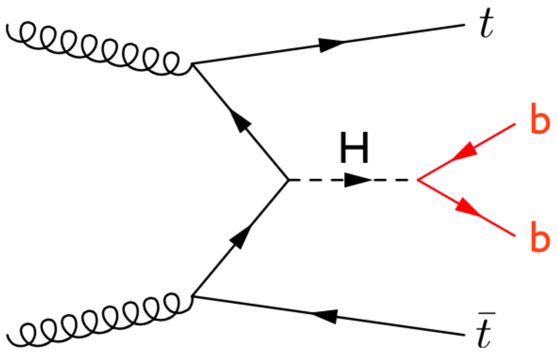
2. ttH, H->ZZ->4l



3. ttH, H->mulitlepton (WW, ZZ (llvv, llqq), $\tau\tau$)

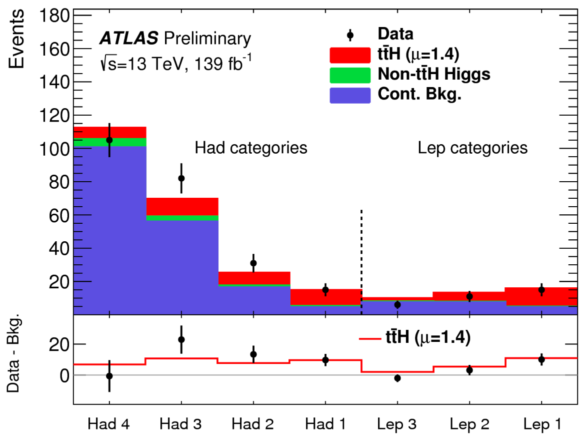


4. ttH, H->bb



ttH, H->$\gamma\gamma$

- Use BDT to define several categories
- Cut on BDT to select SR sample
- Fit to $m\gamma\gamma$ to extract signal strength



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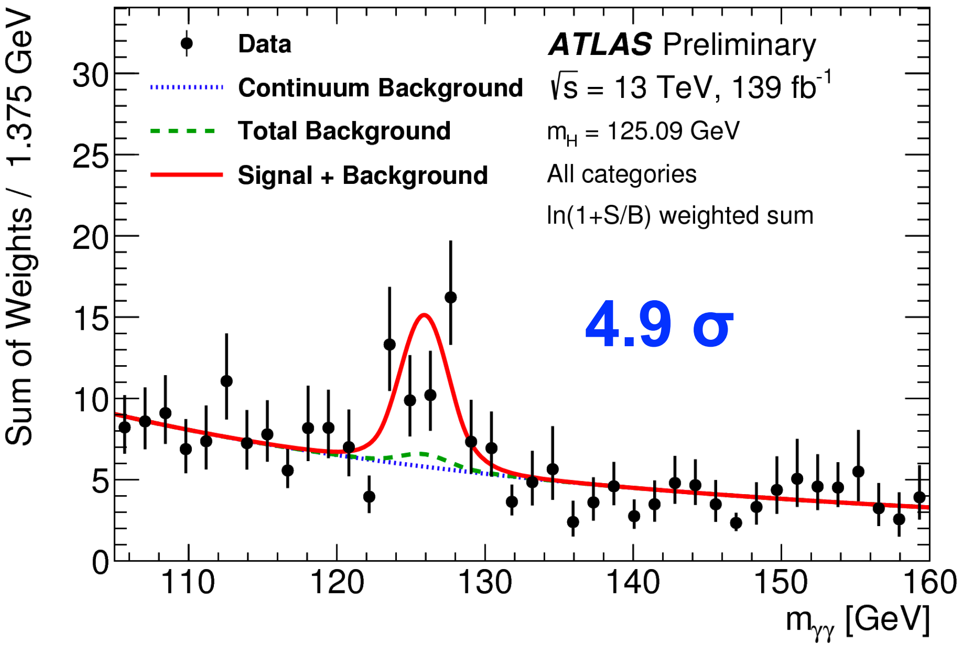
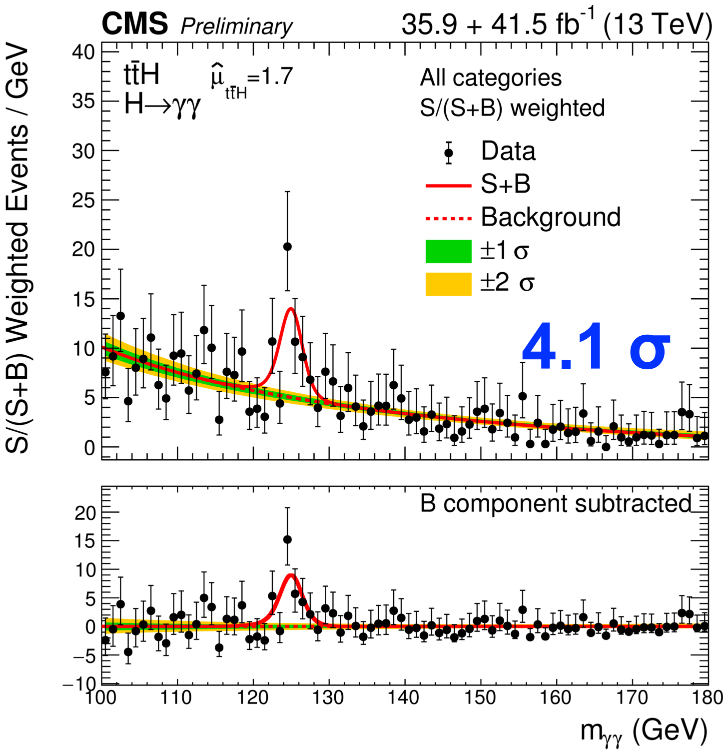
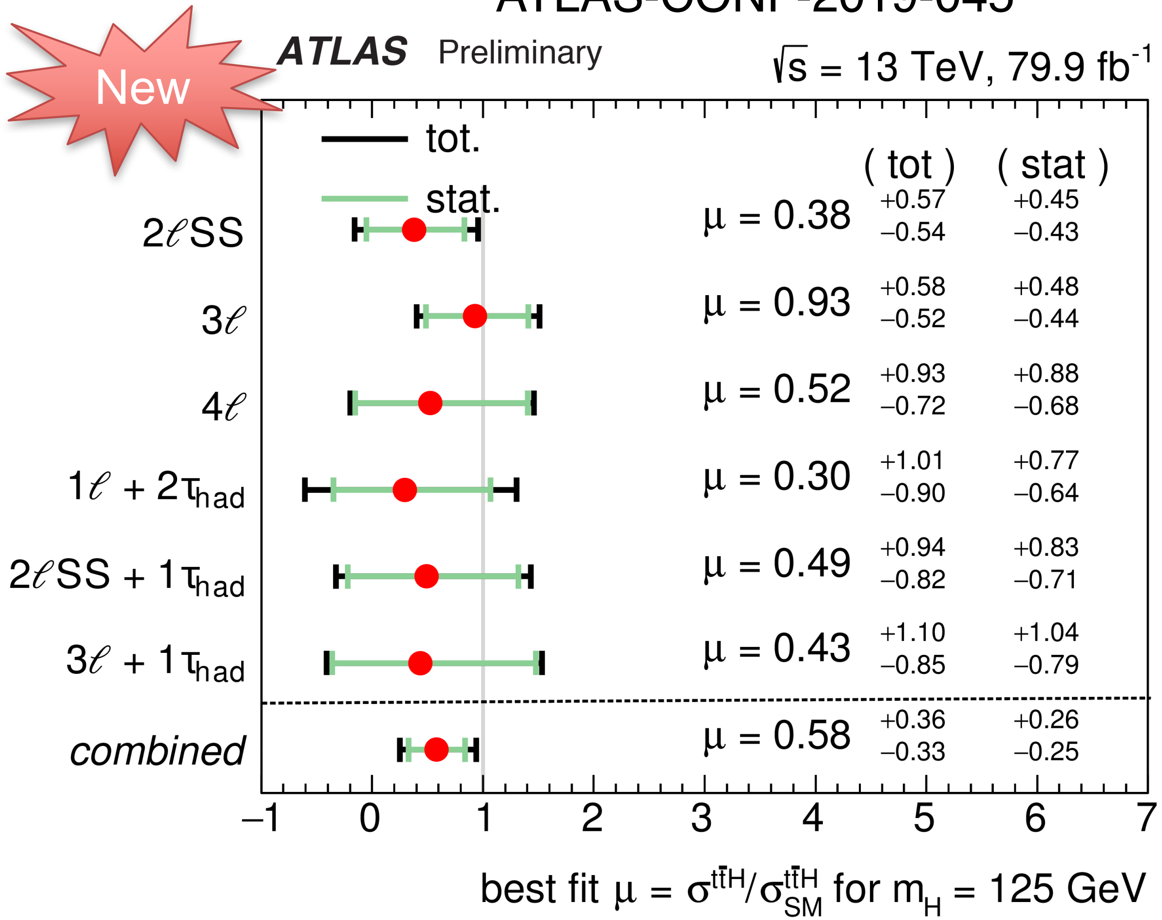


CMS-PAS-HIG-18-018



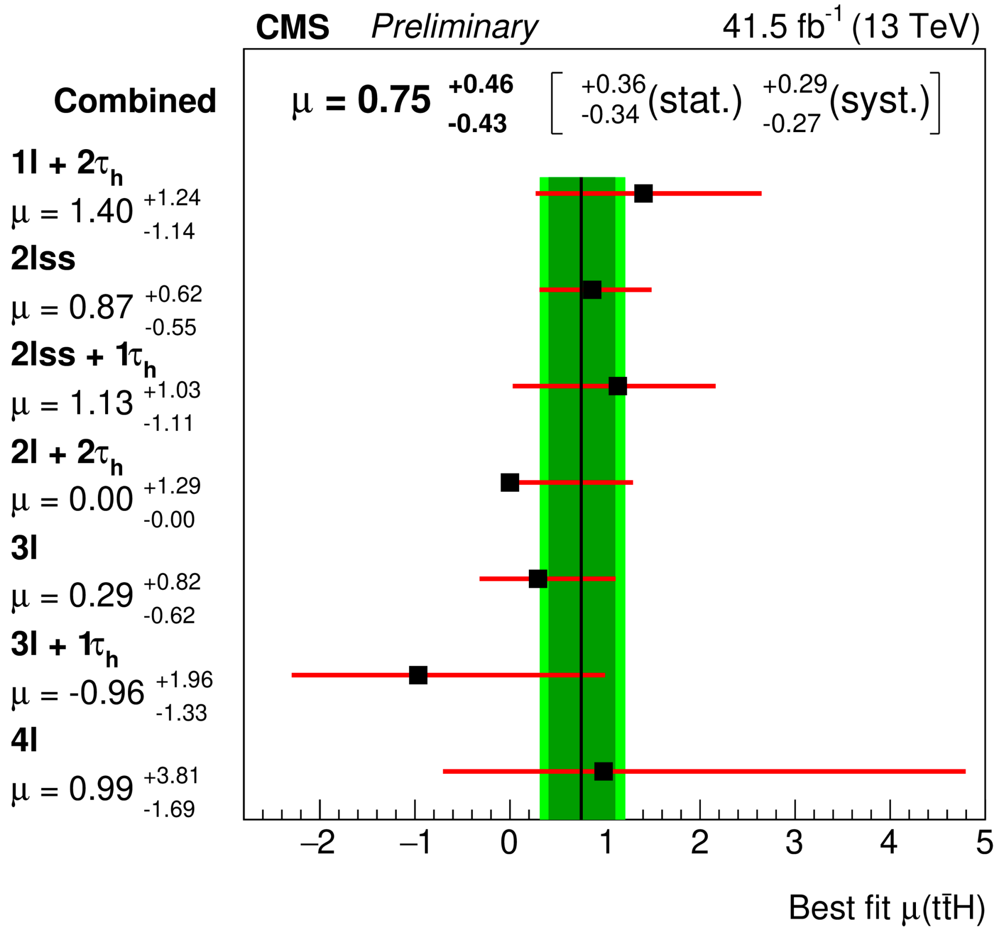
ttH, H->mulitlepton

ATLAS-CONF-2019-045



Obs. (exp.): 1.8 (3.1σ)

CMS-PAS-HIG-18-019



Obs. (exp.): 3.2 (4.0σ)

ttH, H->bb

Main background: ttbar + heavy flavor production

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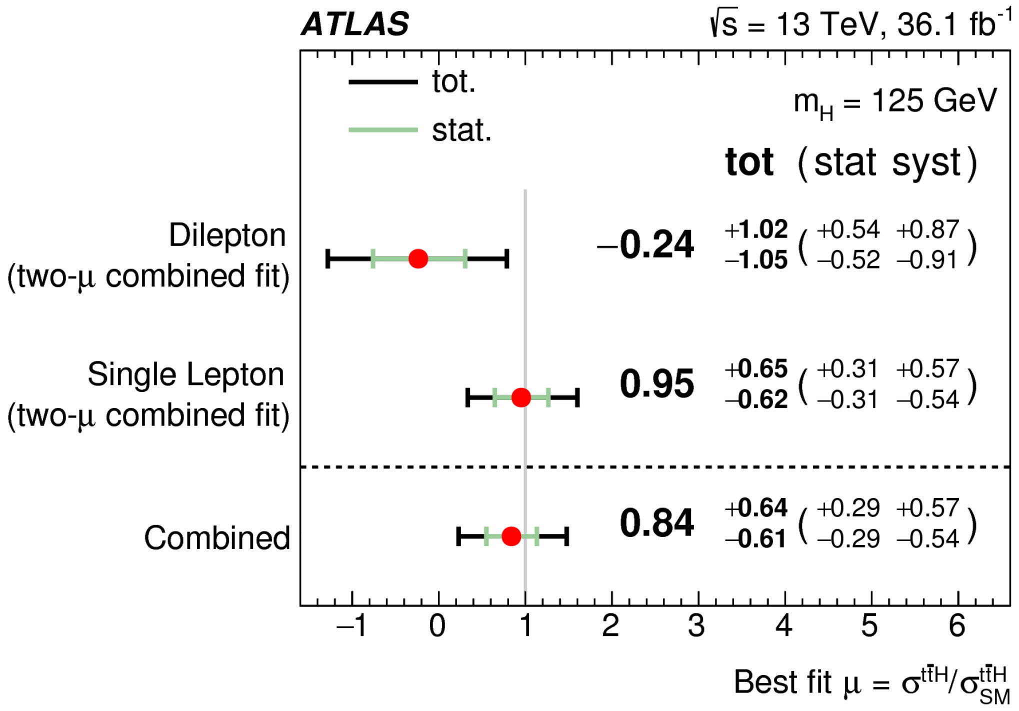
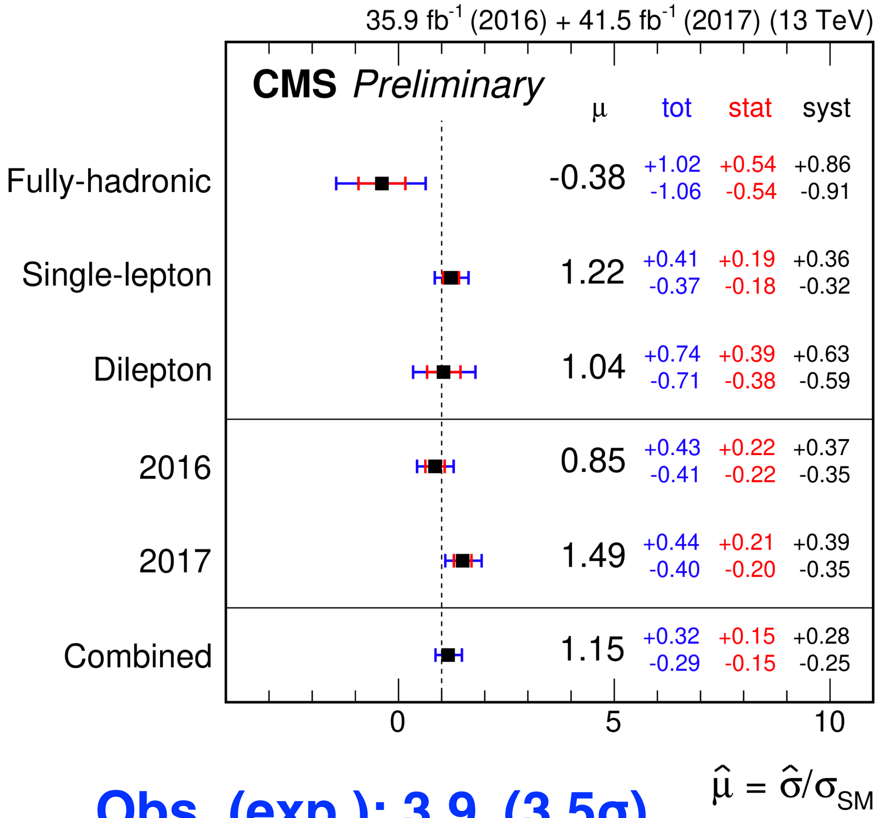


Obs. (exp.): 1.4 (1.6σ)

Evidence of ttH, H->bb from CMS

CMS-PAS-HIG-18-030



Obs. (exp.): 3.9 (3.5σ)

ttH Combination

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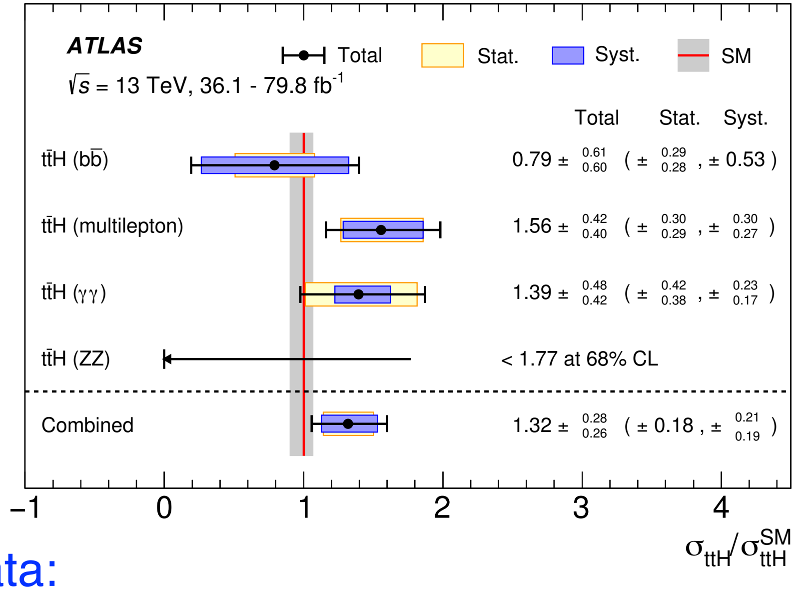
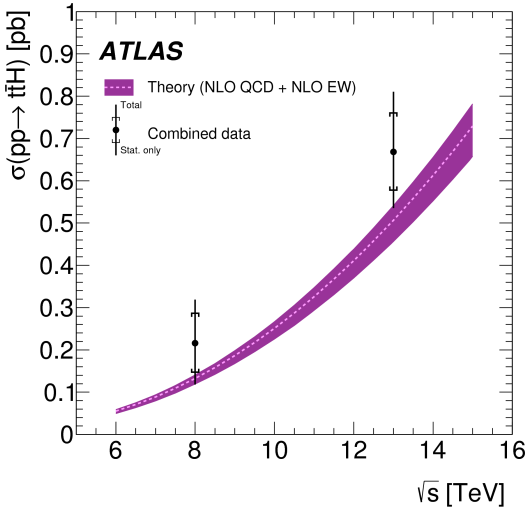


13 TeV data:
5.8 σ (4.9 σ)

7 TeV + 8 TeV + 13 TeV data:
6.3 σ (5.1 σ)

About 1 σ from NLO prediction



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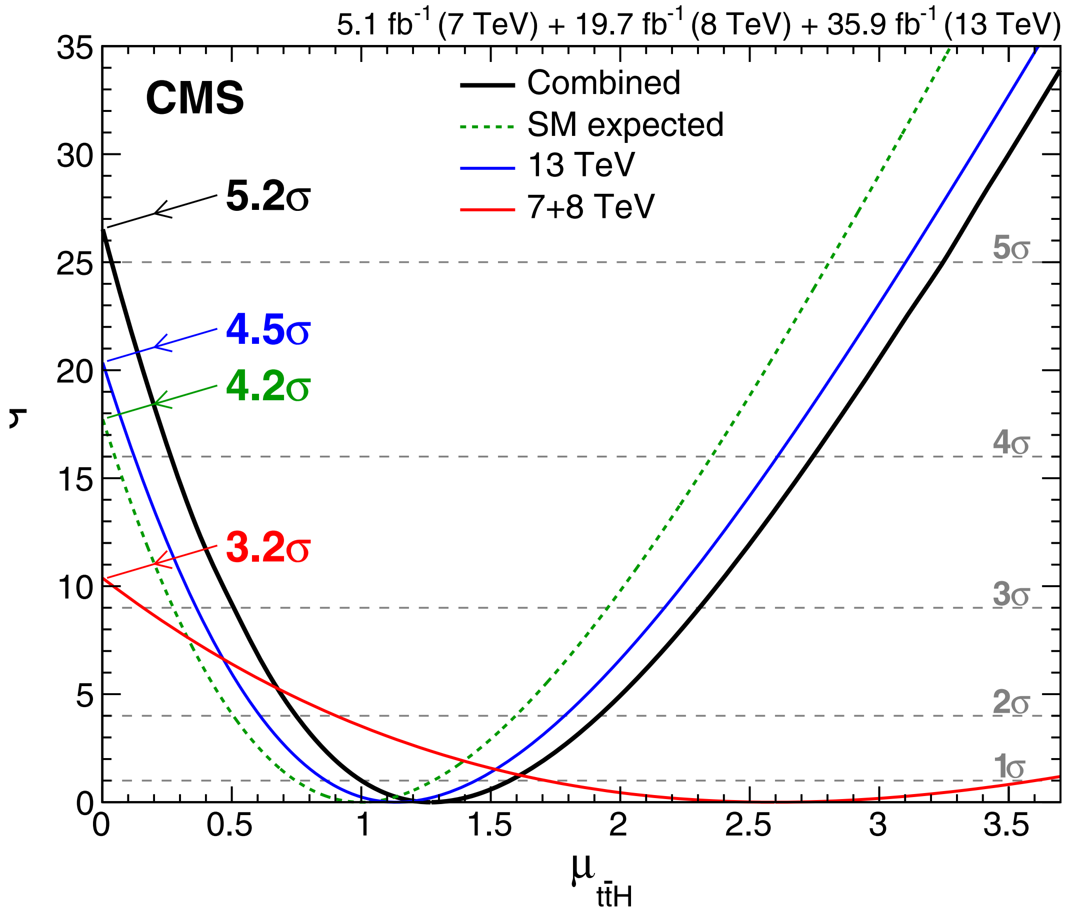

5.2 σ (4.2 σ)

Summary

- ATLAS and CMS experiments continue to produce large amount of top quark physics results with LHC Run2 data
  - Top cross sections and properties measurement with higher precision
  - Keep looking for rare process in top physics (4-top etc.)
  - Observation of ttH; observation of tZq; evidence of ttbar charge asymmetry
- With full Run2 data (115M ttbar), top physics will be very exciting

Top ttH talks in parallel session

- ttH multilepton at CMS, Chaochen Yuan
- ttH multilepton at ATLAS, Xuan Yang
- Single top at ATLAS, Khuram Tariq
- Single top with V at CMS, Duncan Leggat
- tqH at ATLAS, Boyang Li
- Four top search at ATLAS, Shuyang Hu

ATLAS Top Results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS Top Results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Thank you