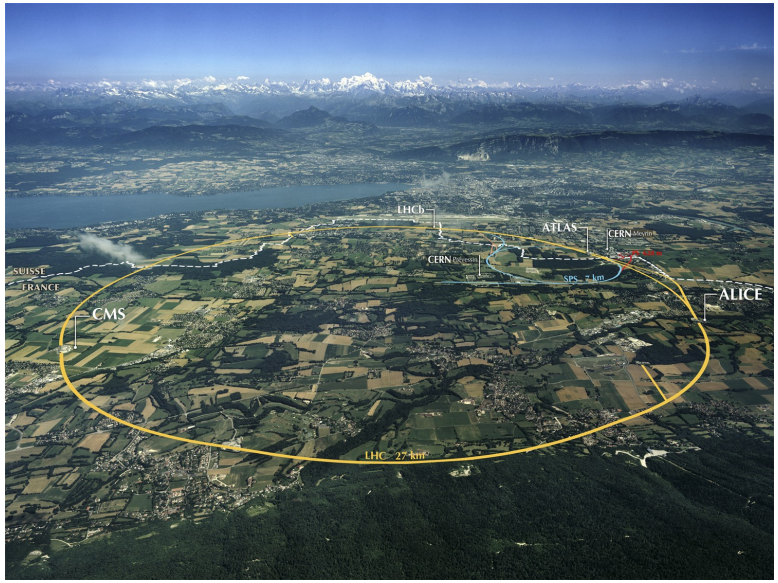
The precision frontier

aka: Top quark properties and electroweak measurements



(Introduction)
→ W, Z production
→ top quark production
→ Indications for BSM physics ?
→ Conclusions & Outlook

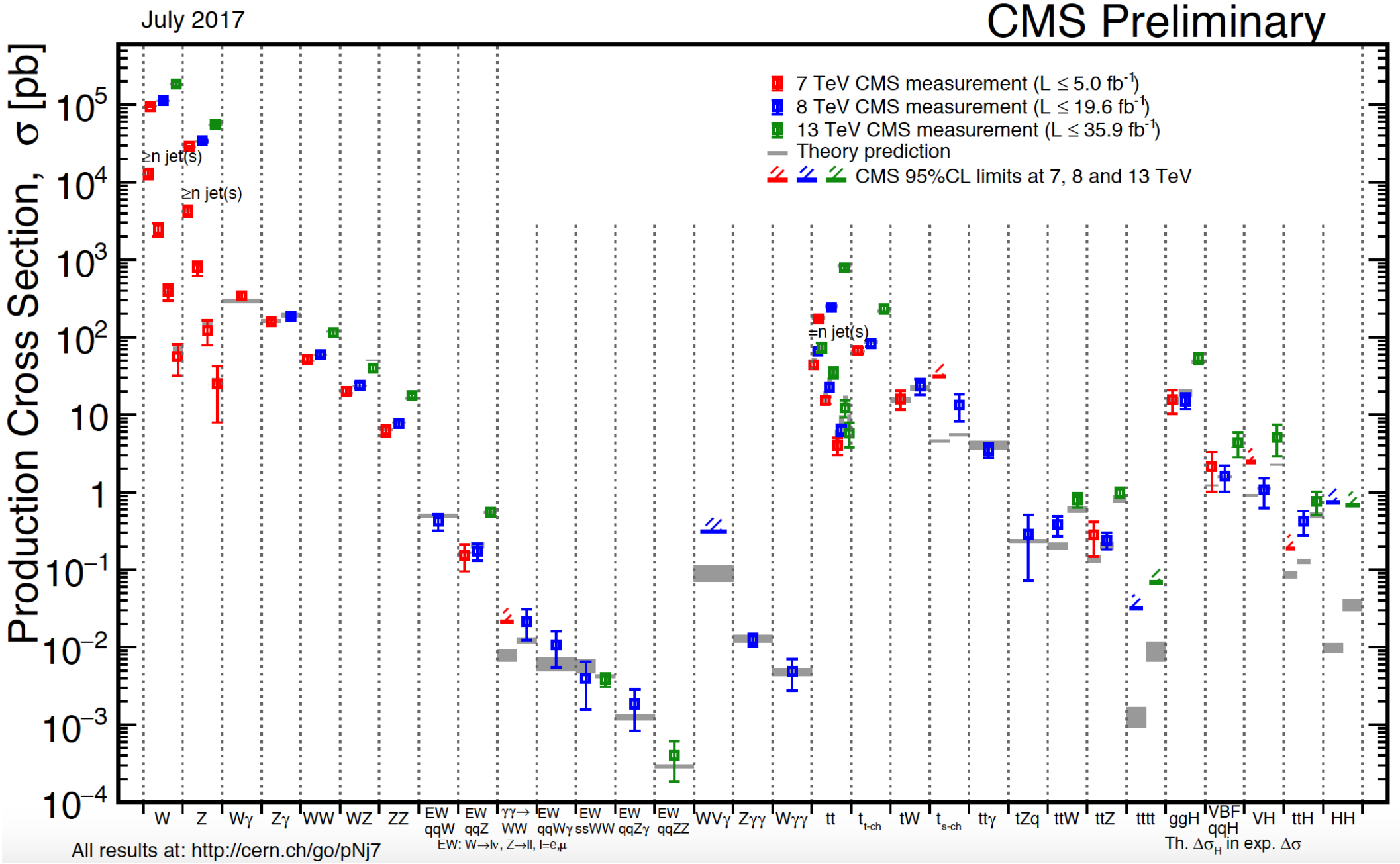
Andreas Jung for the ATLAS & CMS collaboration

PURDUE UNIVERSITY

American Physical Society – Division of Particle & Fields

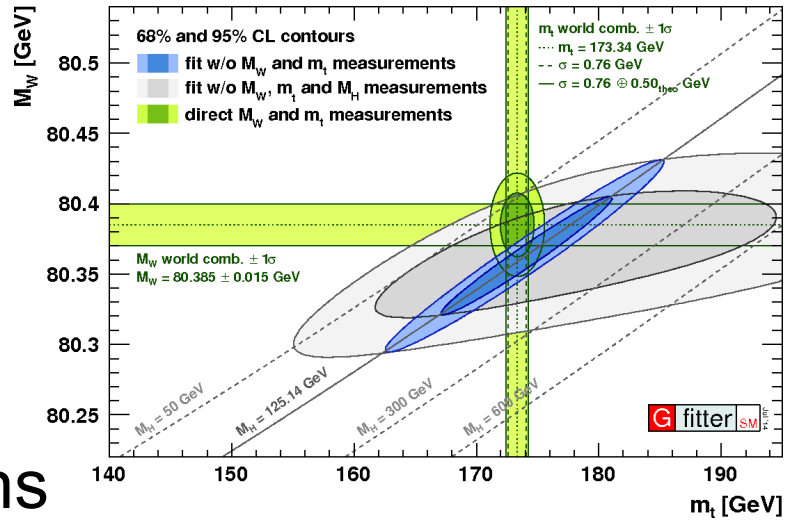
August 2nd, 2017

The precision frontier



The precision frontier

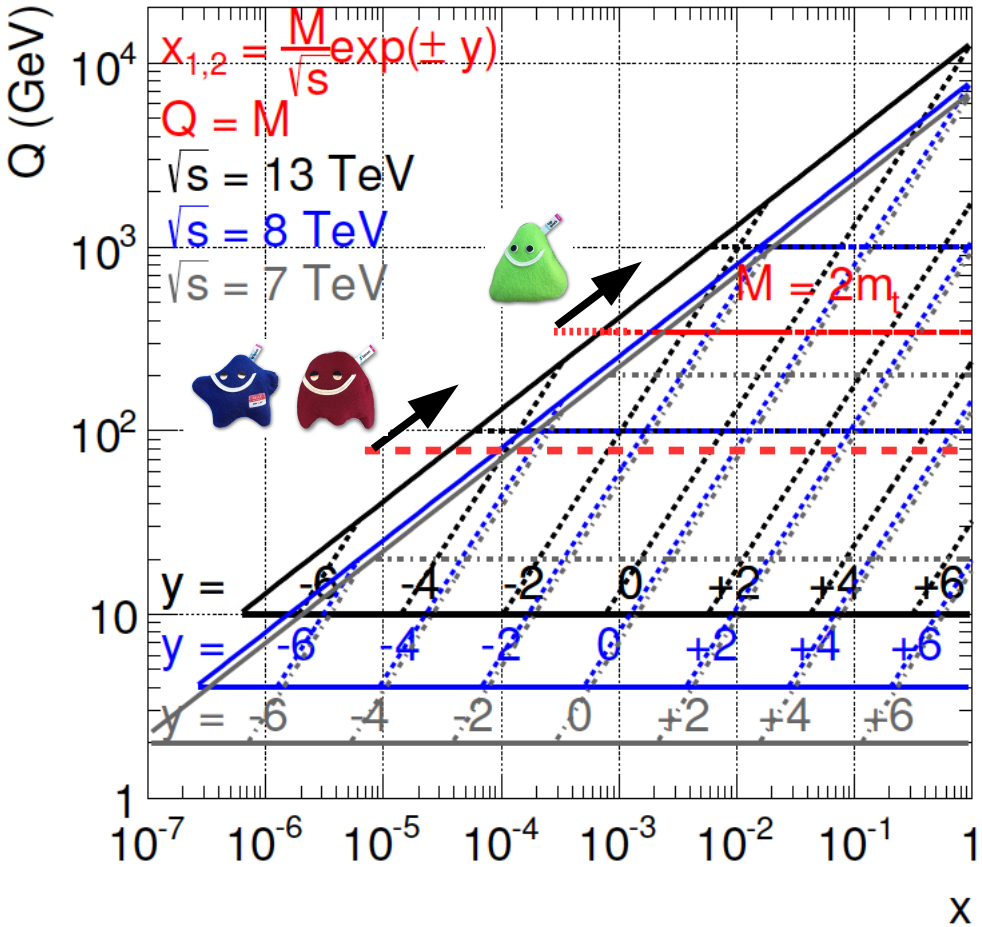
- Self-consistency check of the standard model using precision measurements of the t and W mass

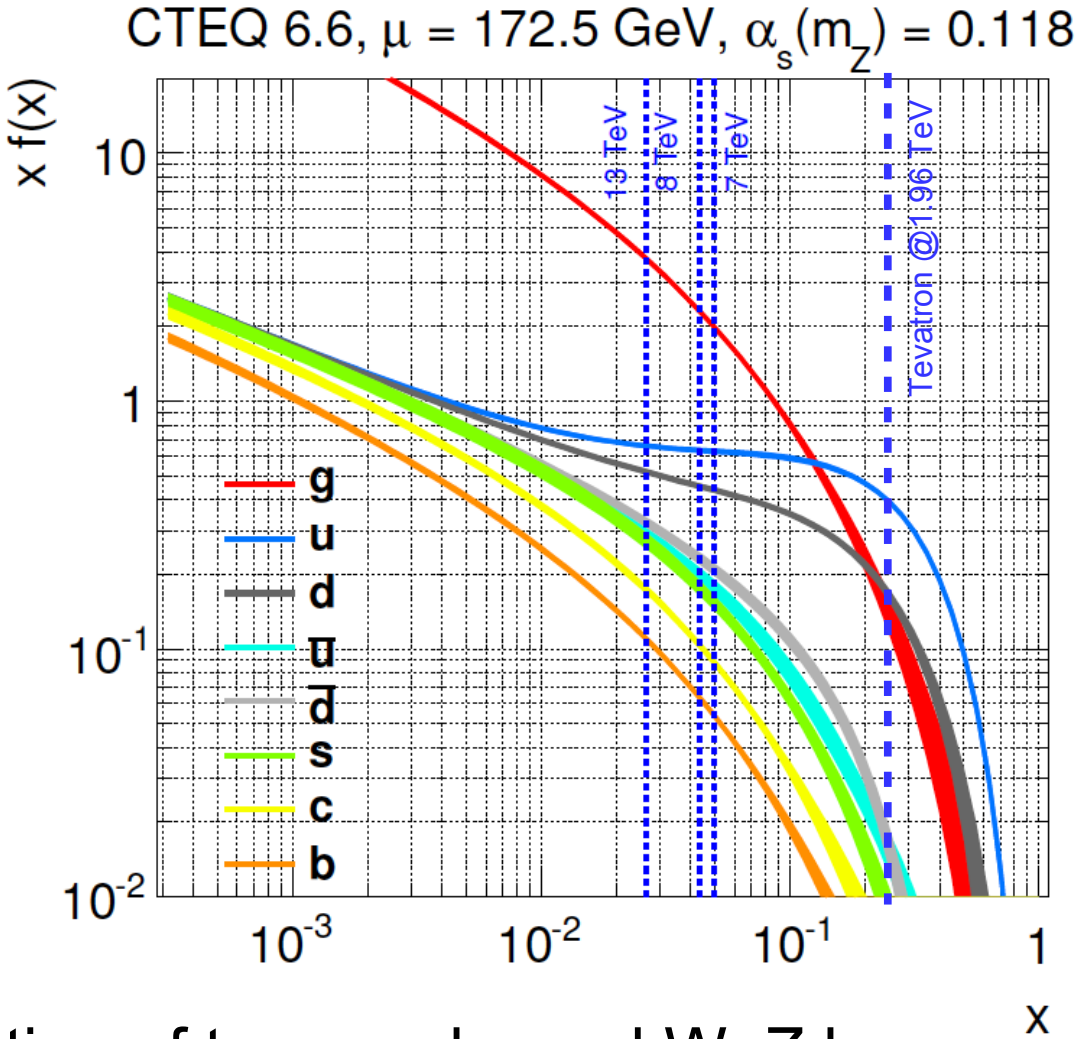


- Constrain new physics via virtual corrections
  - Anomalous triple & quartic gauge couplings
  - Flavor Changing Neutral Currents

- Challenge the SM at the precision level
  - Plethora of final states, inclusive & differential
  - Various properties of top, W, Z

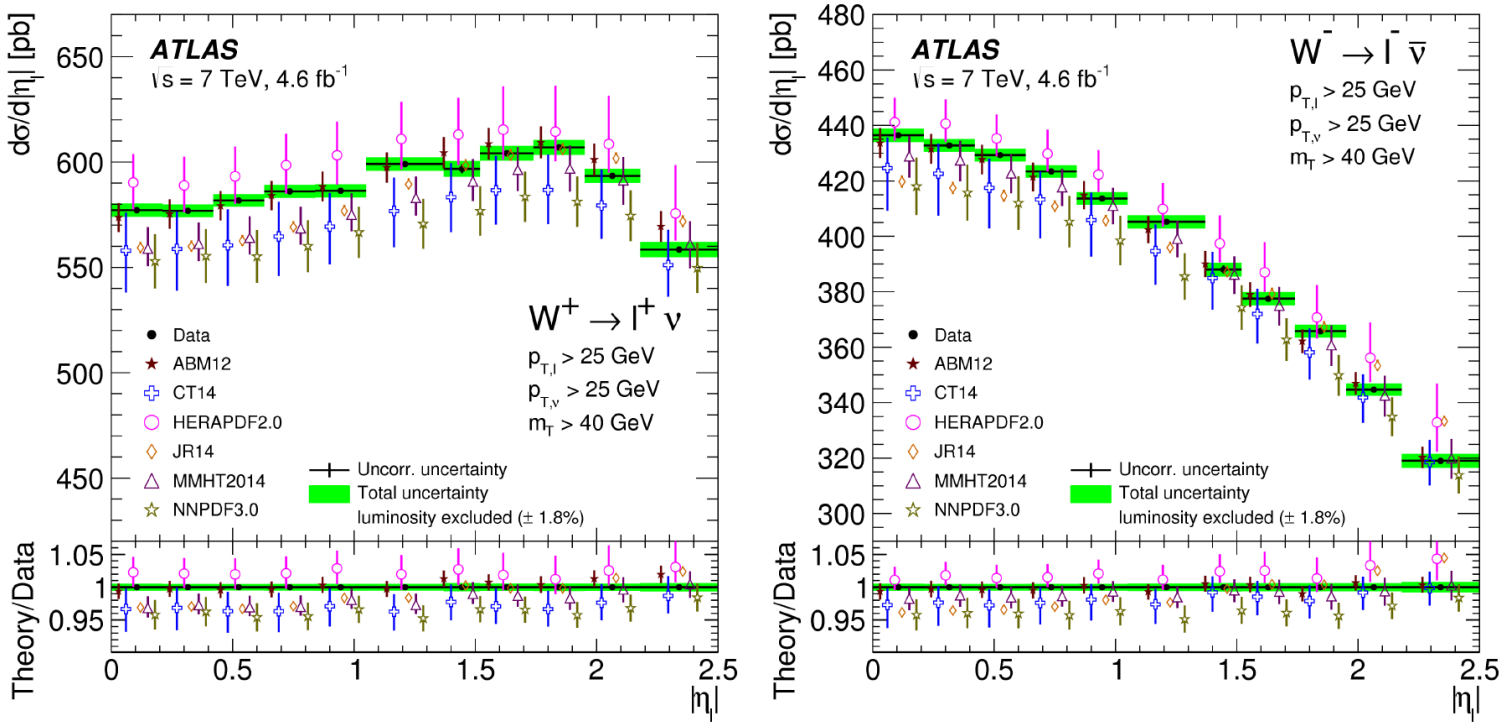
The precision frontier: EW



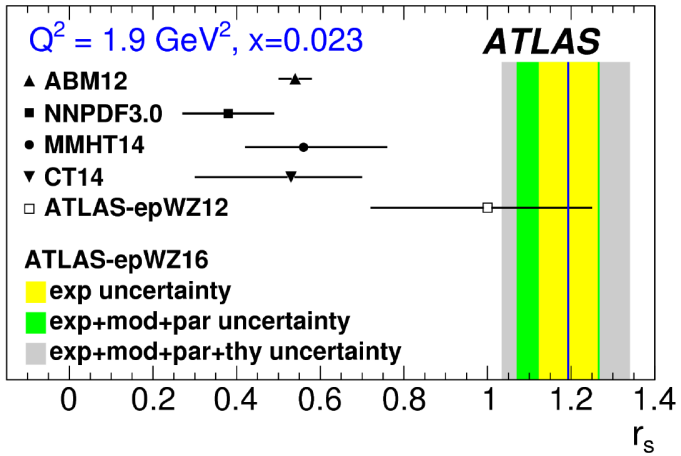


- Kinematic plane, Q vs. x, for production of top quarks and W, Z bosons
  - Horizontal lines indicate production thresholds
- Measurements of t, W, Z constrain α_s and proton structure (PDFs)

W boson production



- Production rate calculated at NNLO and sensitive to PDFs
- Asymmetry in W+ and W- production sensitive to u- and d-quark PDF
- Rate constrains strange quark content, supported by W+c production



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Z boson production

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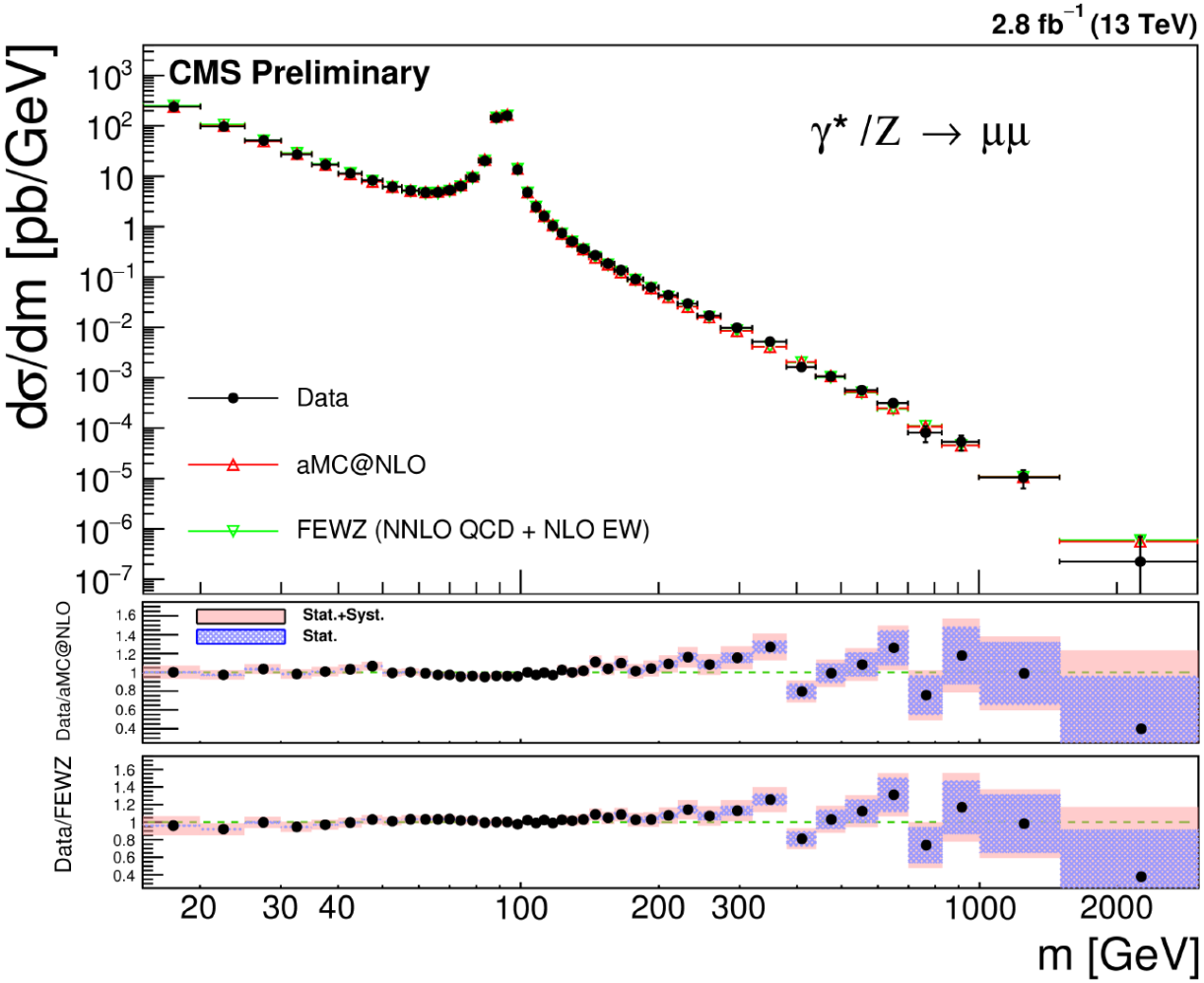
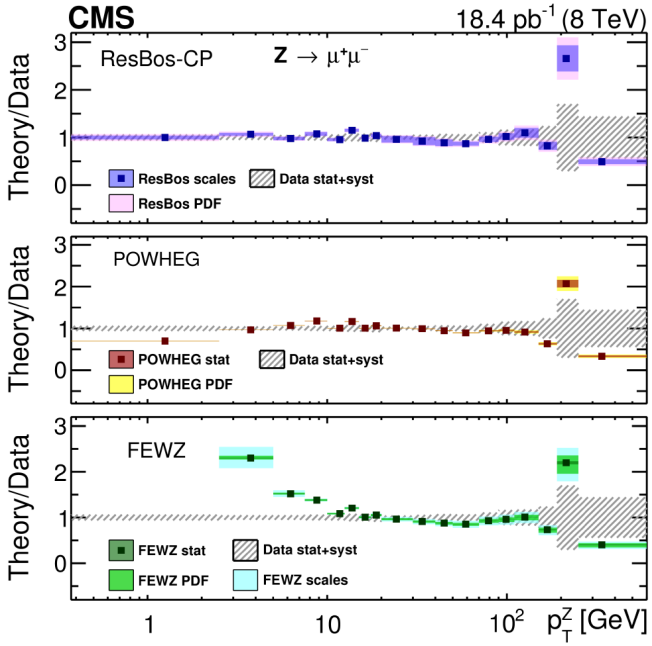
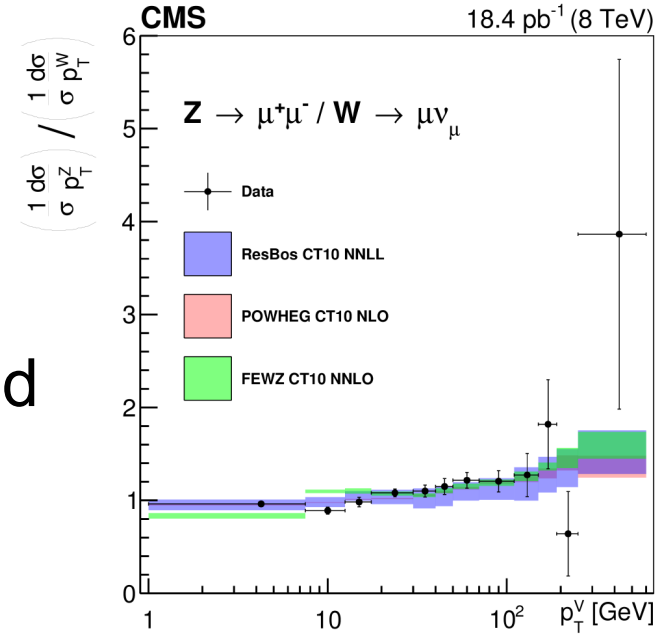


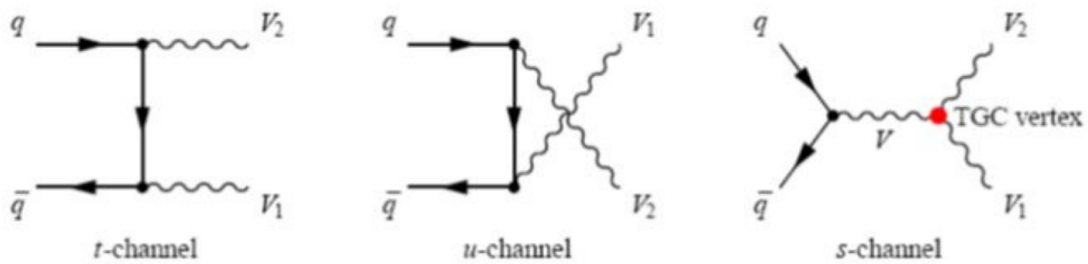


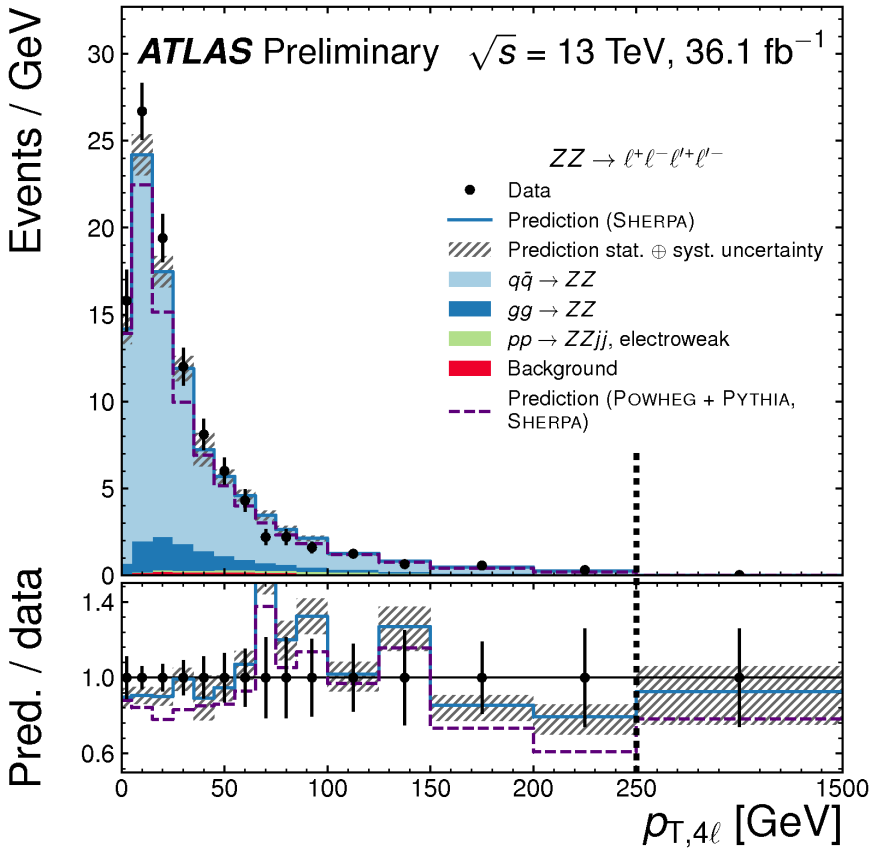


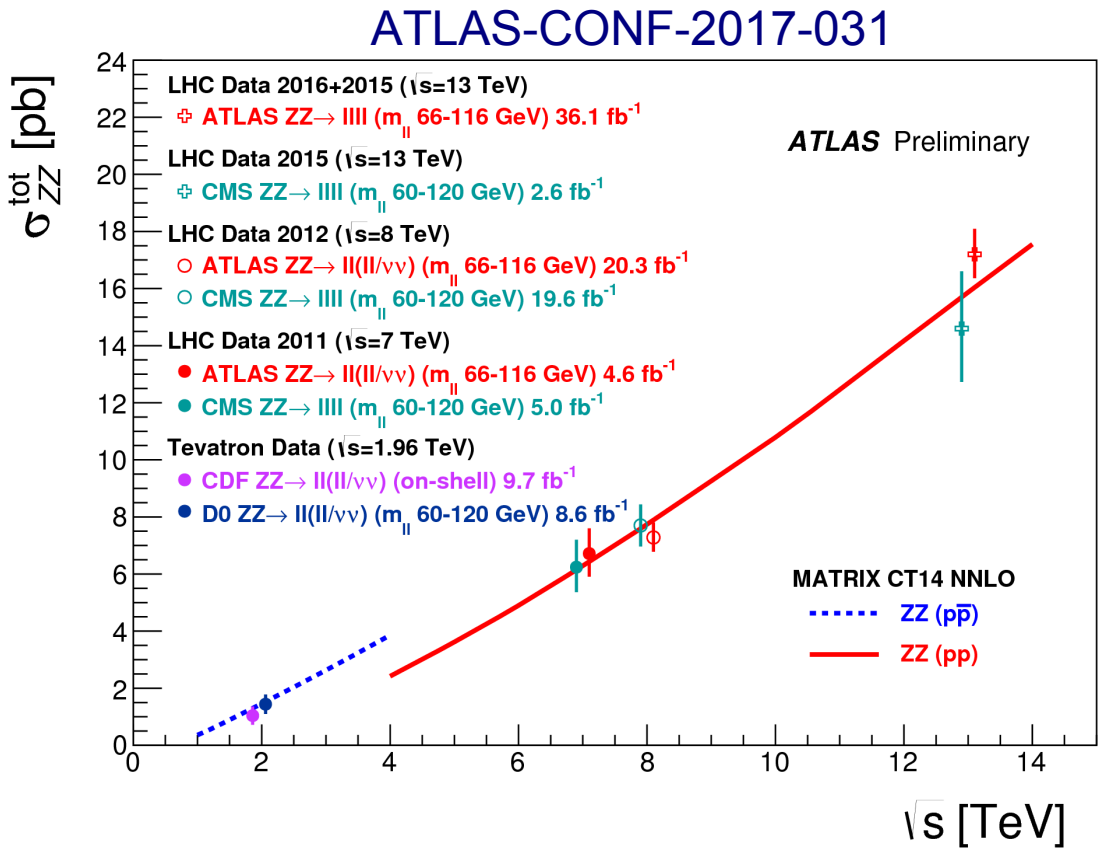
- Drell-Yan cross section described well by NLO and NNLO over entire mass range
- High precision pT Z measurement critical input to W mass measurement

Diboson production

- Large amount of measurements
  variety of final states
- Sensitive to BSM contributions
- Good agreement with the SM







Diboson production

- Large amount of measurements, variety of final states
- Sensitive to BSM contributions
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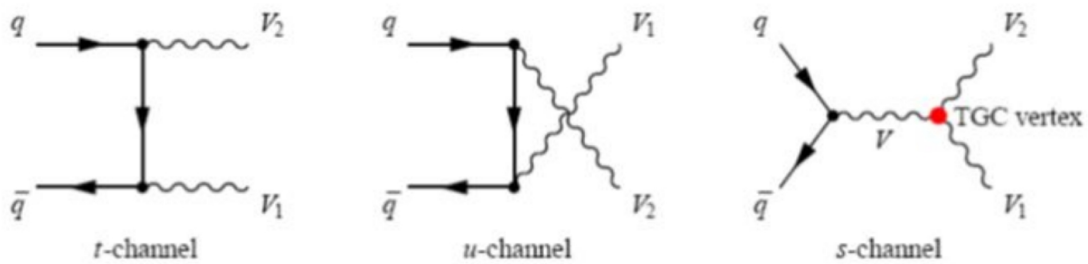
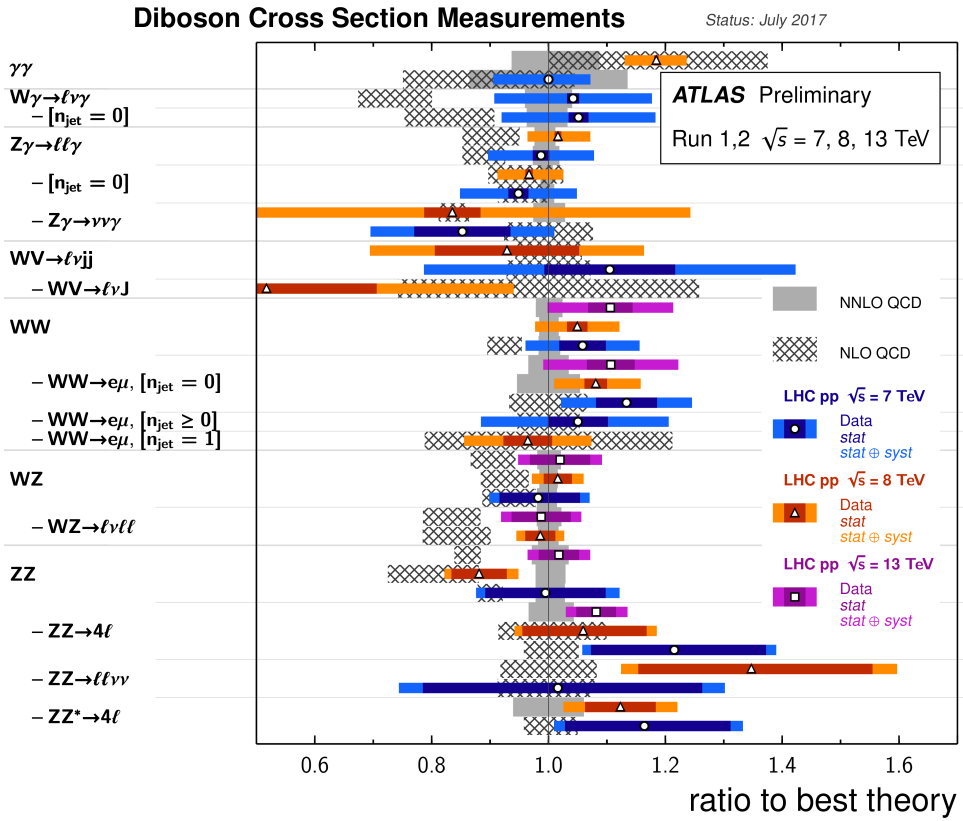
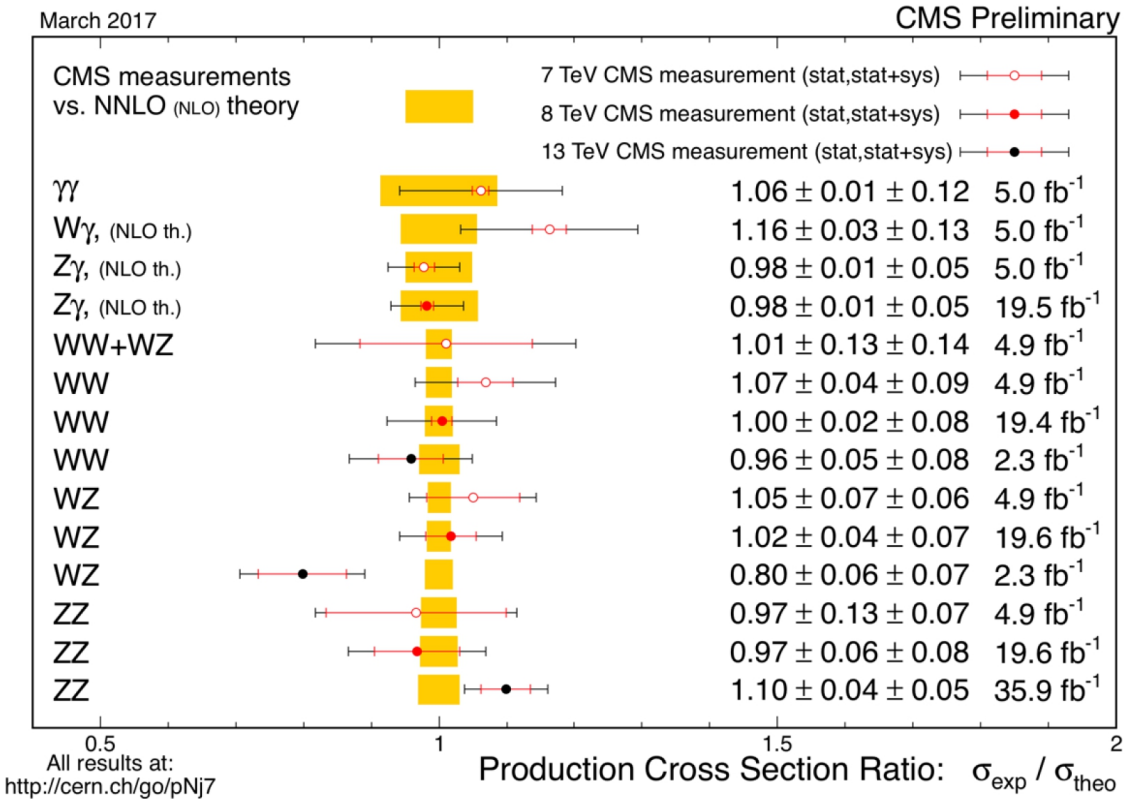
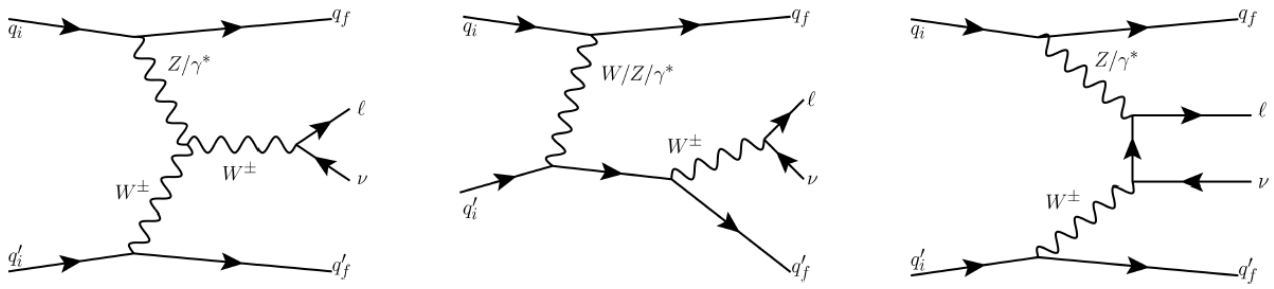
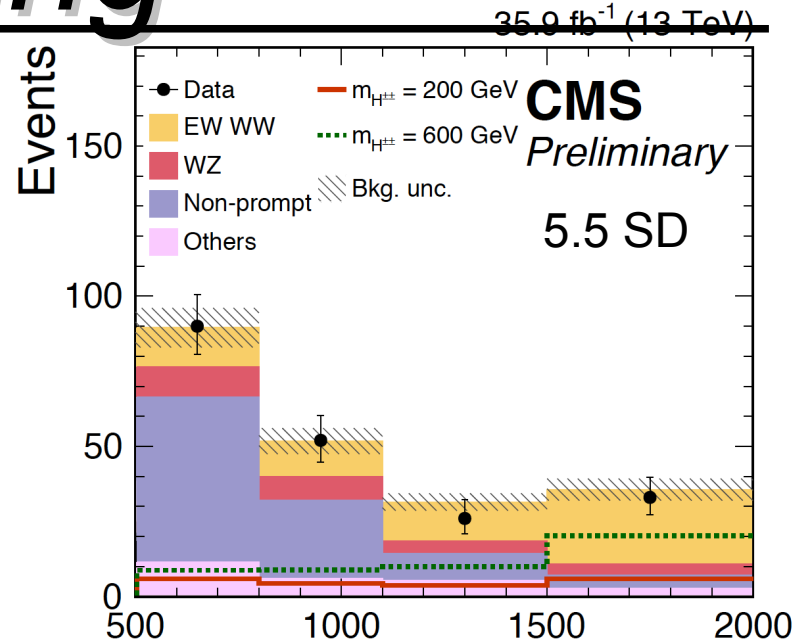






EW boson scattering

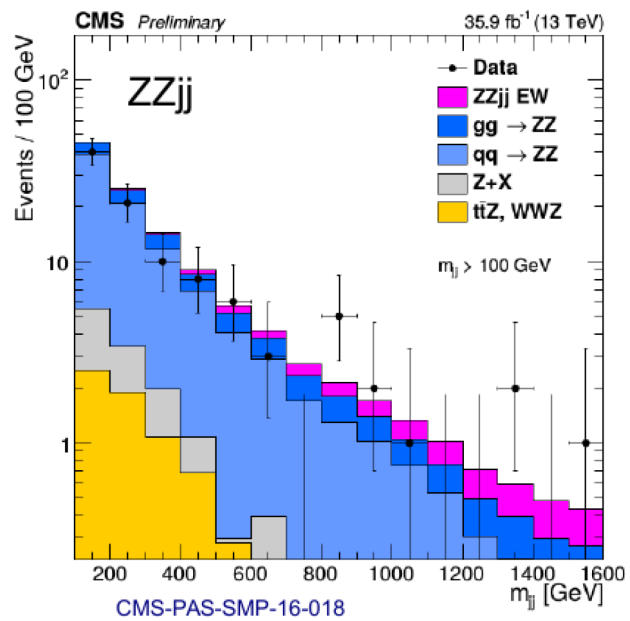




Observation of Vector Boson Scattering provides new window to the EW sector

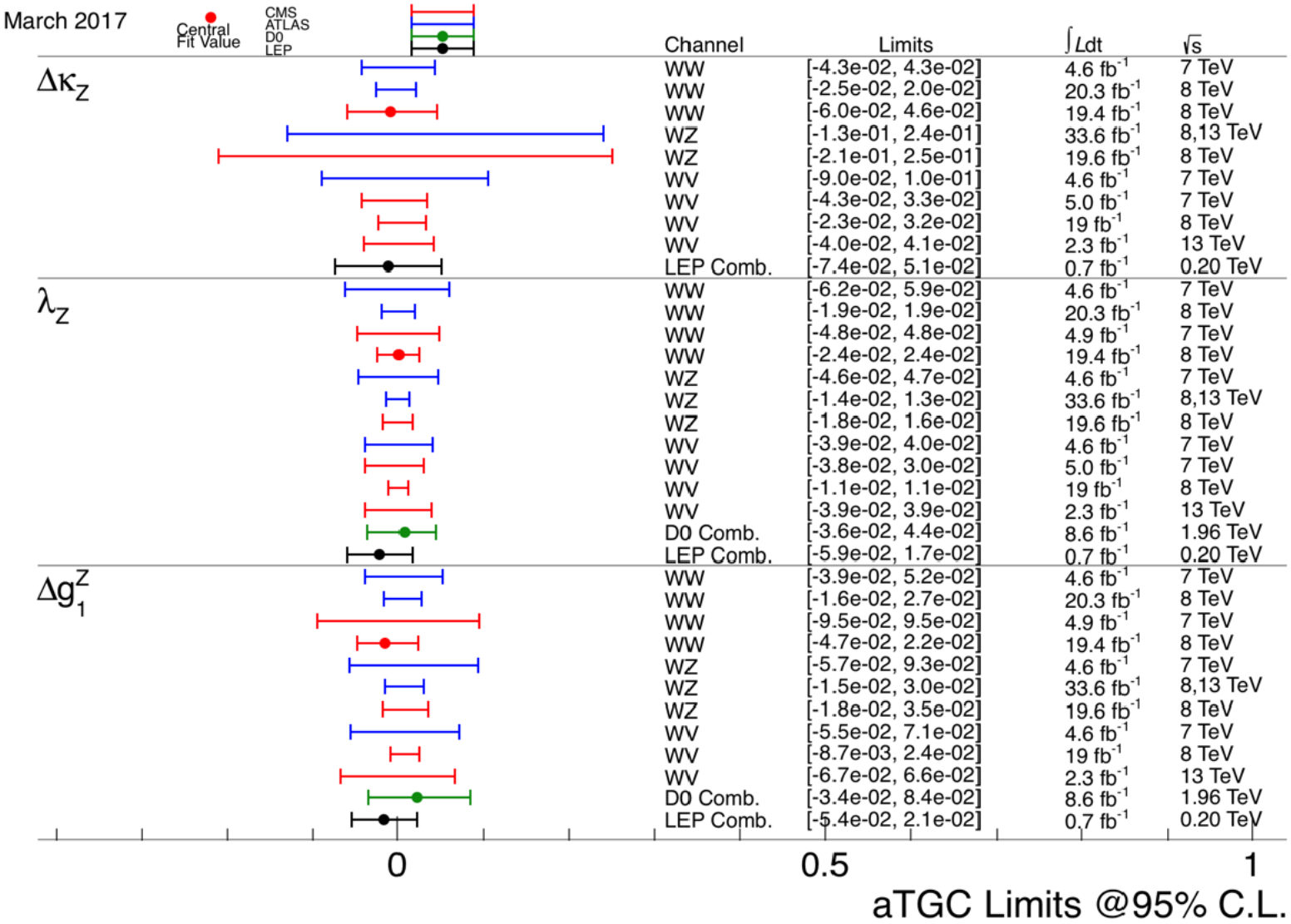
→ Discriminate with di-jet mass against bg and reach 5.5 SD significance

→ Rich precision measurement program with larger data set



BSM physics in EW sector ?

→ aTGC from VV production: WWZ vertex



See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC for additional results

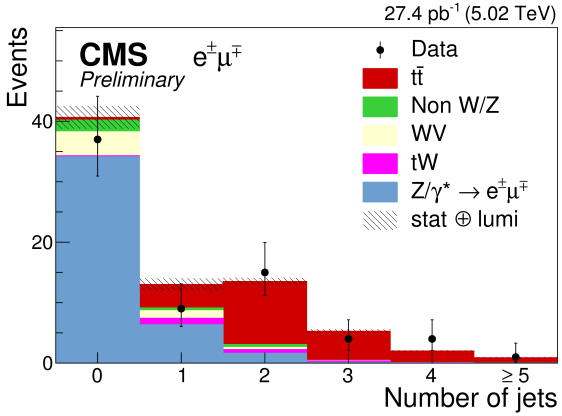
The precision frontier: top

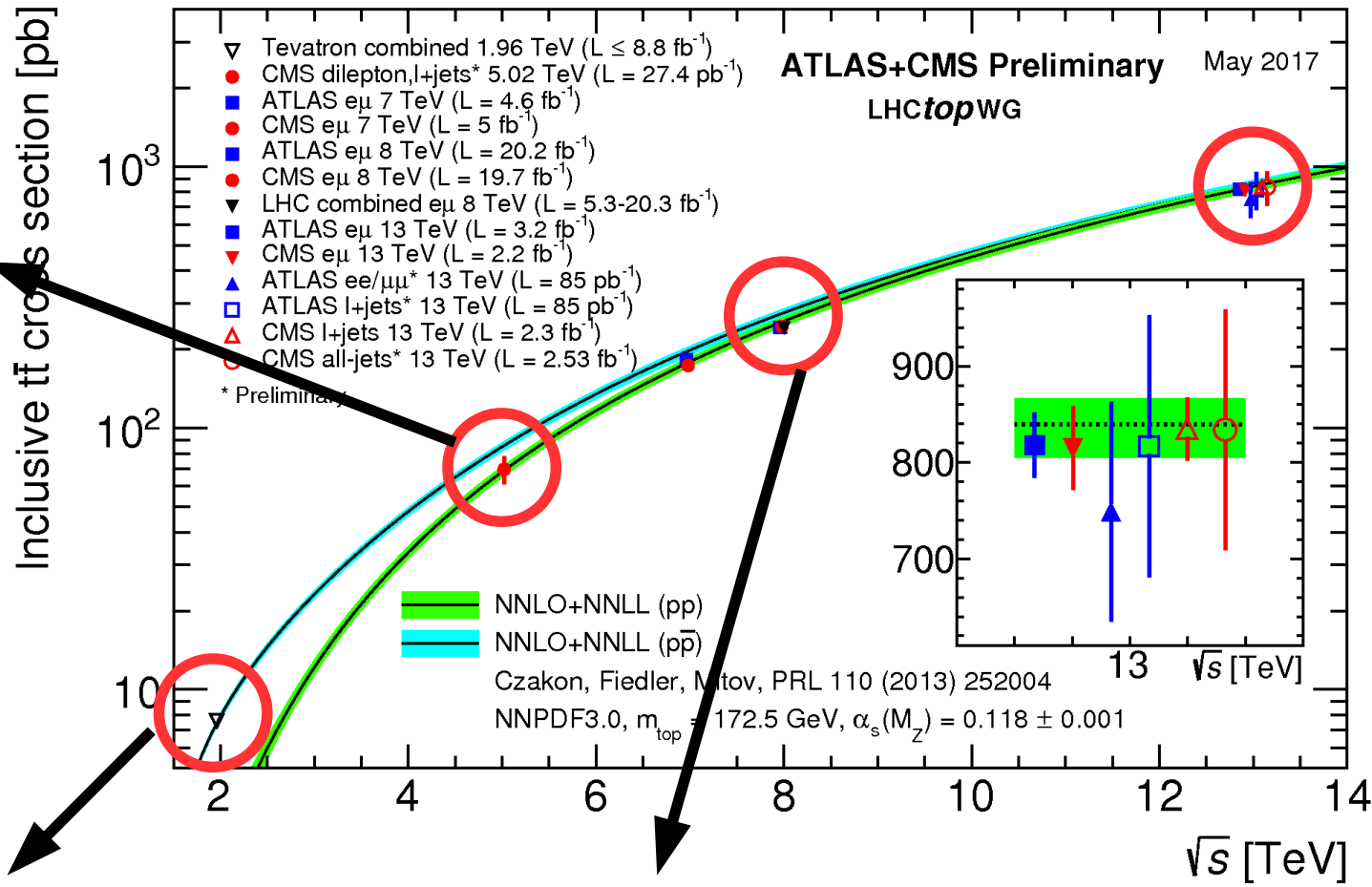
- New measurements at 2, 5, 8 and 13 TeV – agreement with the SM

CMS 2nd cross section
Relative precision: $\delta\sigma/\sigma$ = 13%

σ = 68.9 ± 6.5 (stat.) ± 6.1 (syst.) ± 1.6 (lumi.) pb

CMS-PAS-TOP-16-015





- Profile log-LH fit by D0:
  - Reduced uncertainties

σ = 7.26 ± 0.13 (stat.) ± 0.57/0.50 (syst.) pb

$\delta\sigma/\sigma$ = 7.6%

Phys. Rev. D 94 092004 (2016)

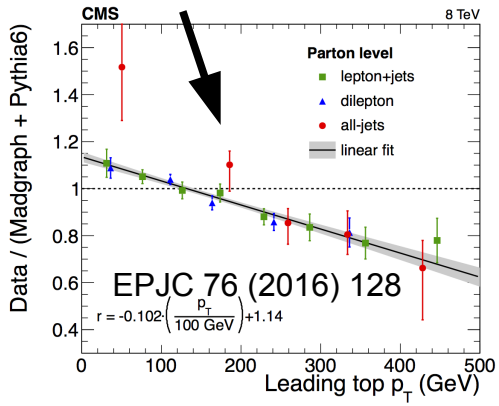
ATLAS cross section at 8 TeV in l+jets channel
Relative precision: $\delta\sigma/\sigma$ = 5.7%

σ = 248.3 ± 0.7 (stat.) ± 13.4 (syst.) ± 4.7 (lumi.) pb

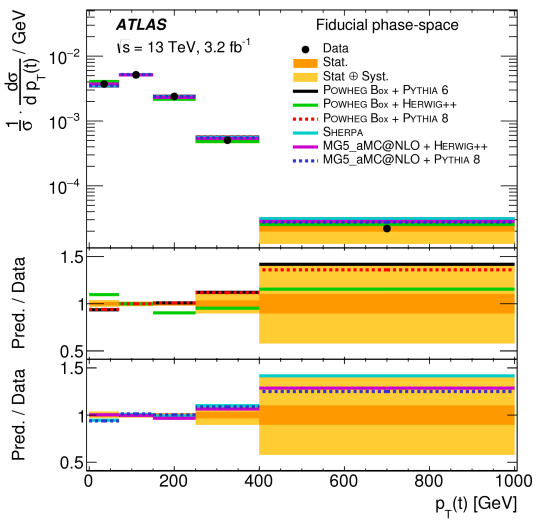
ATLAS-CONF-2017-054

Differential cross sections

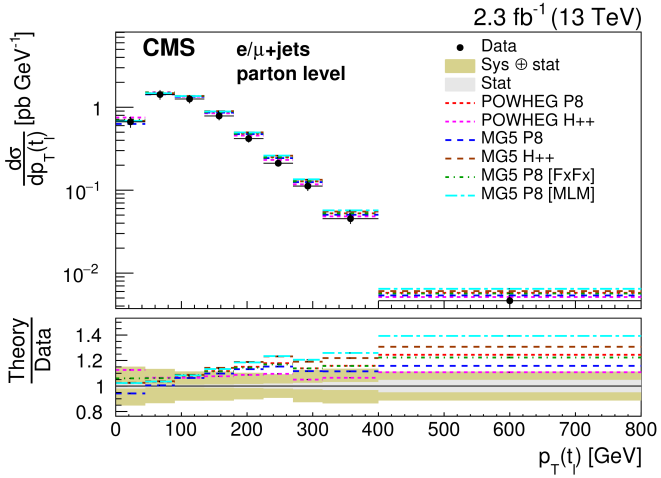
- Results in ATLAS+CMS agree with NNLO predictions and NLO generators
  - BUT **top pT** measurements **not described** by NLO and most MCs, it is softer in data than in simulation
- New measurements at 13 TeV by ATLAS and CMS
  → 1st indications of a slope wrt NLO MCs in 13 TeV data, starting to be significant



EPJC 77 (2017) 299



PRD 95, 092001 (2017)



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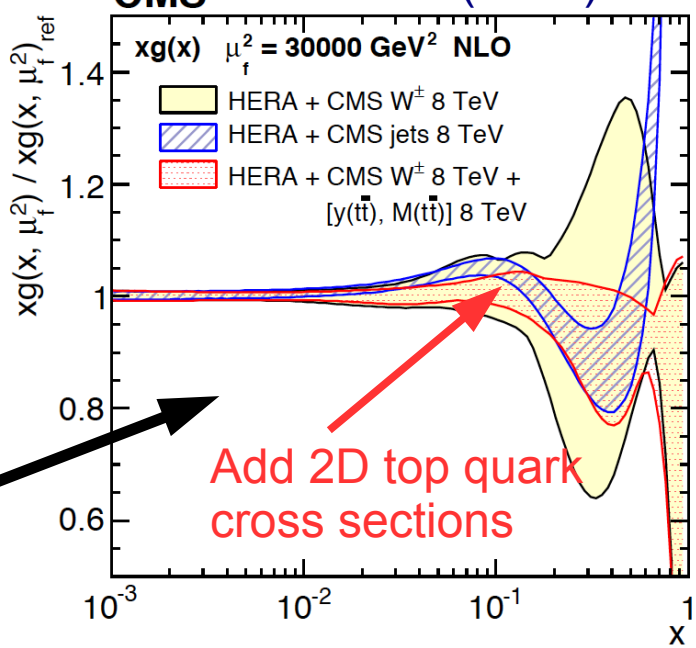
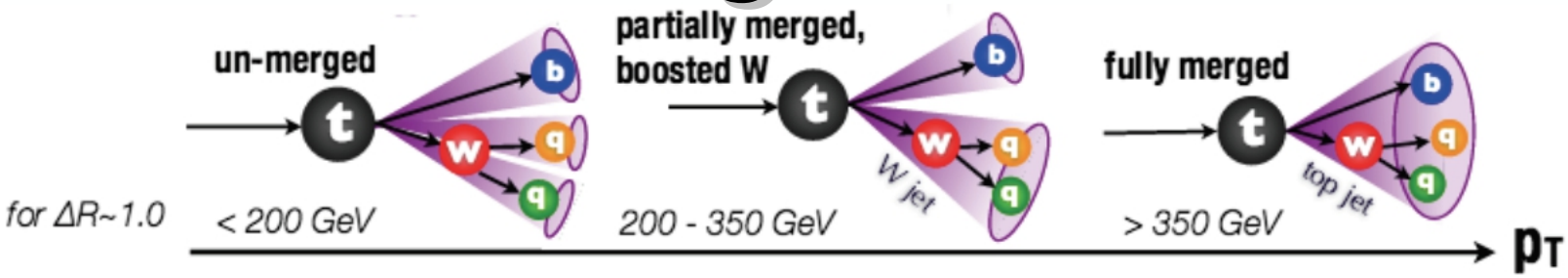
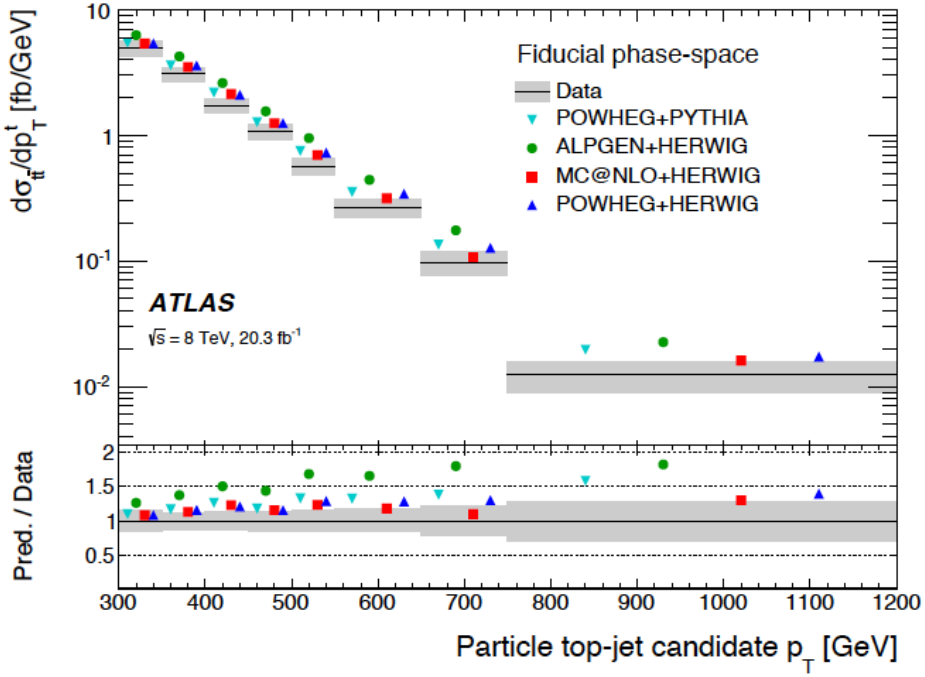


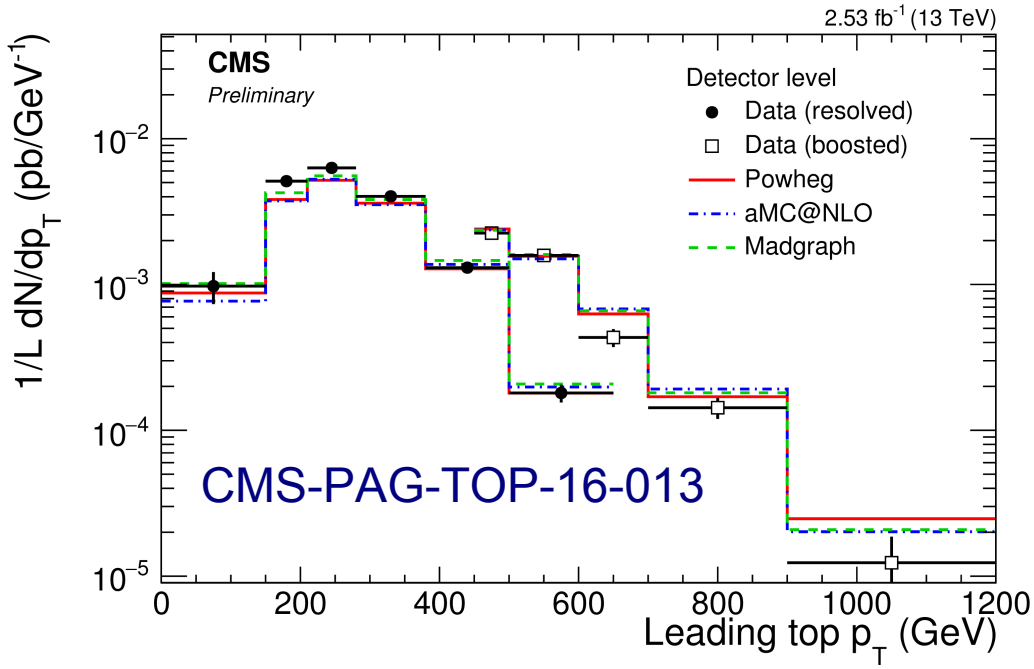
- First 2D cross section measurement of this type at the LHC
  - Dilepton eμ channel – very good S/B
  - 2D cross sections more sensitive to large x PDFs
  - Constrain PDFs at large x

Boosted regime



PRD 93, 032009 (2016)

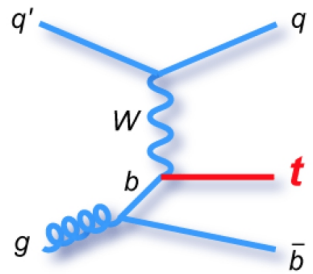


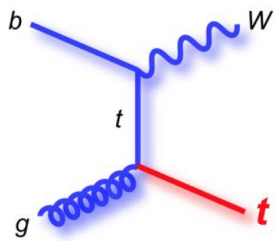


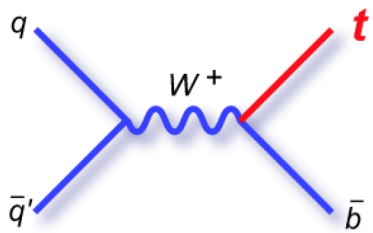
- ATLAS boosted regime: pT > 300, trimmed large-R 1.0
- Consistent picture in boosted and resolved phase space
- Parton level results receive larger systematic uncertainties
- CMS 13 TeV <u>all-hadronic combined resolved and boosted analysis</u>

Single top quark production

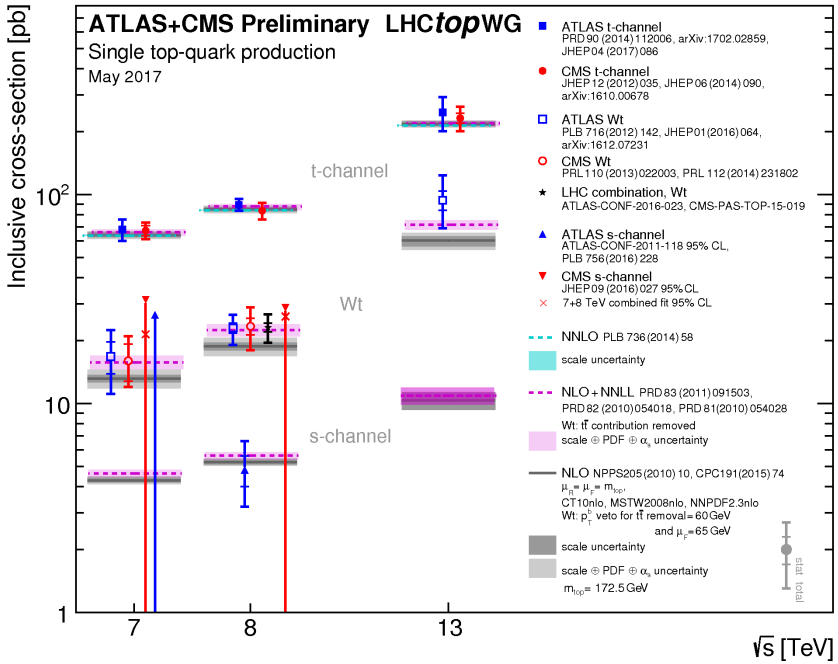
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**
- Single top production: Test of EW interactions







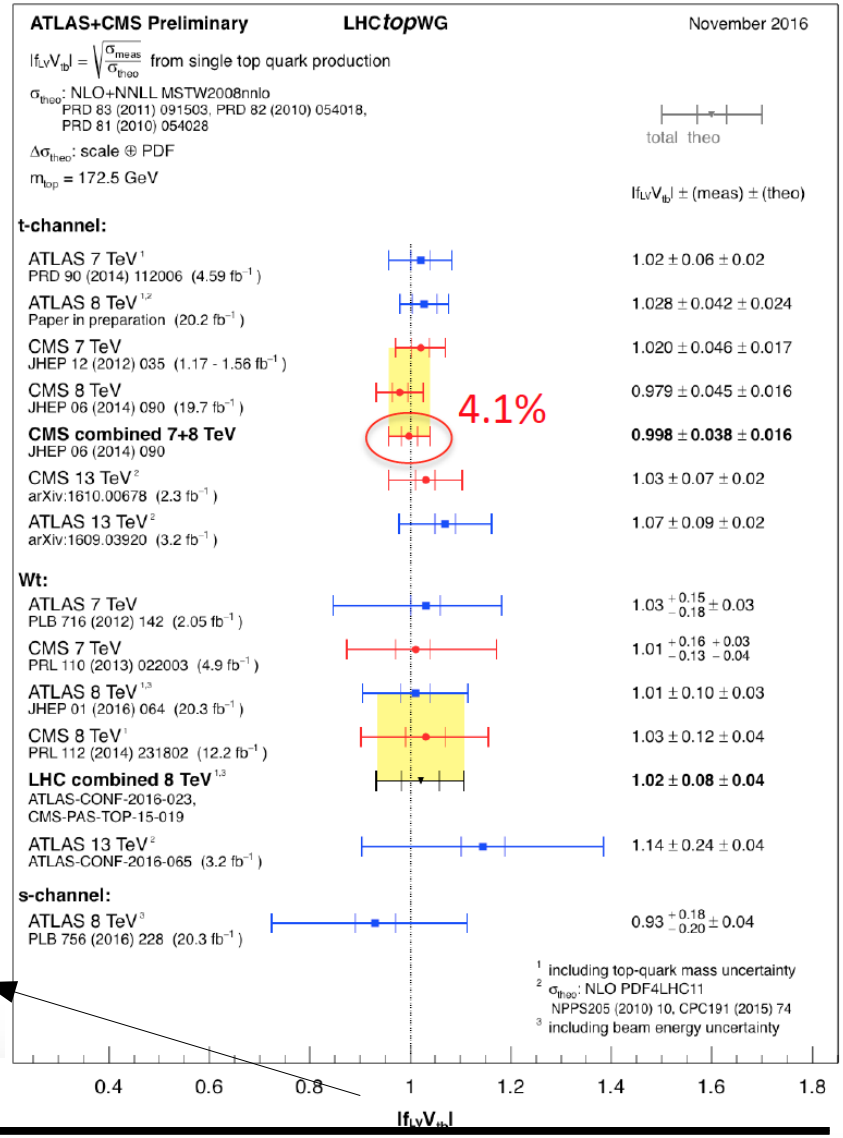
- Summary (May 2017):



$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs}}{\sigma^{theory}}$$

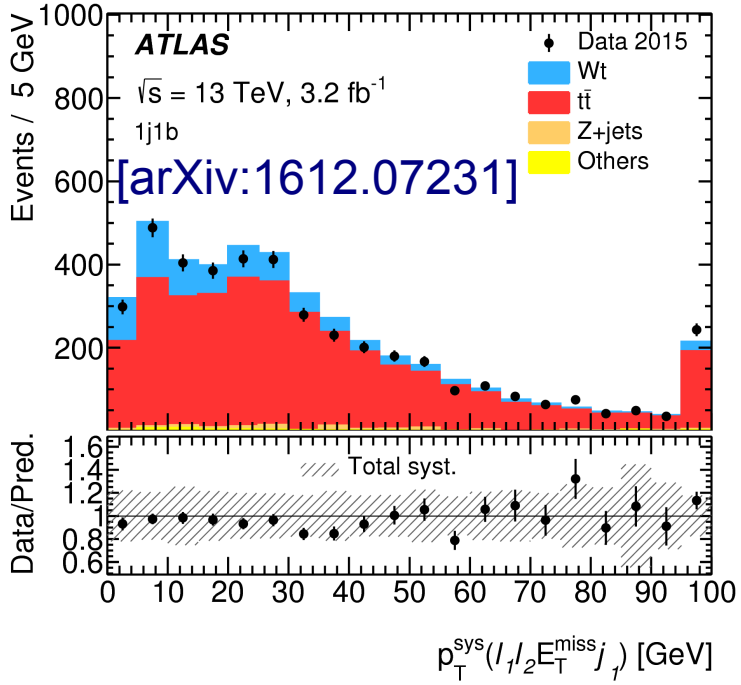
f_{LV}: BSM form factor

Consistent with $f_{LV} \cdot V_{tb} = 1$

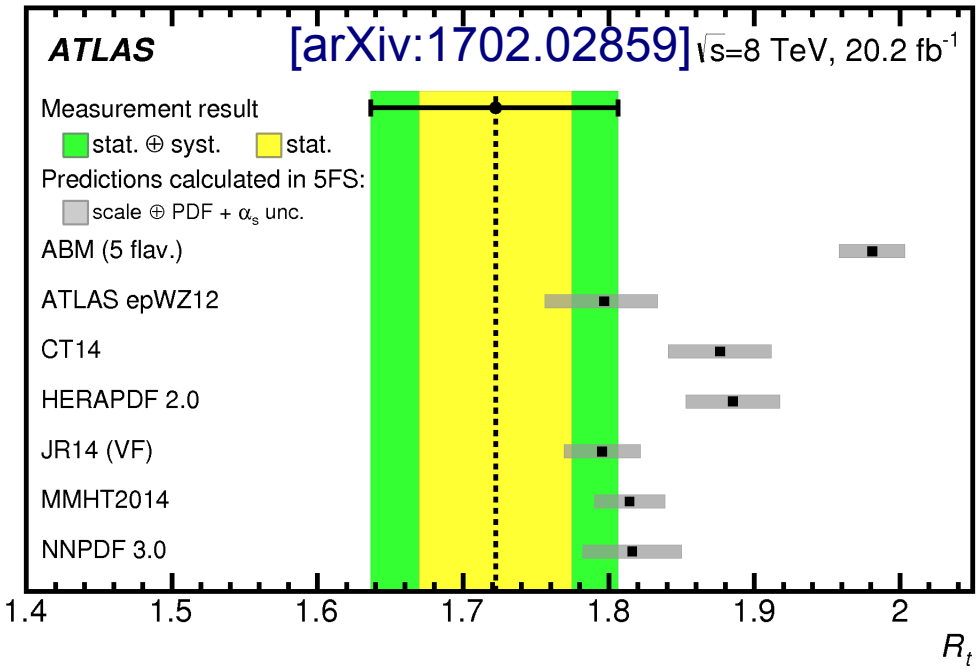


Single top quark production

- **Latest updates...**
- ATLAS measurement of **Wt single top** production @13 TeV
  - Single-most powerful BDT input variable

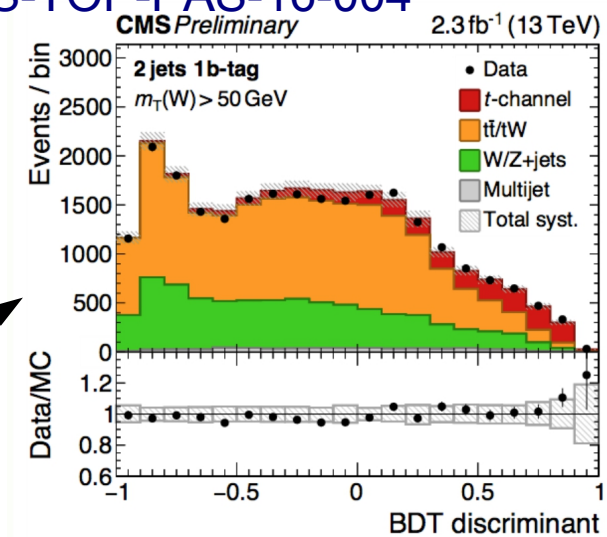


- Single top t-channel production
  - T/tbar sensitive to PDFs
  - Most PDFs agree at 1SD level
    (ABM is 2.5 SD, driven through flavor scheme and alphaS)



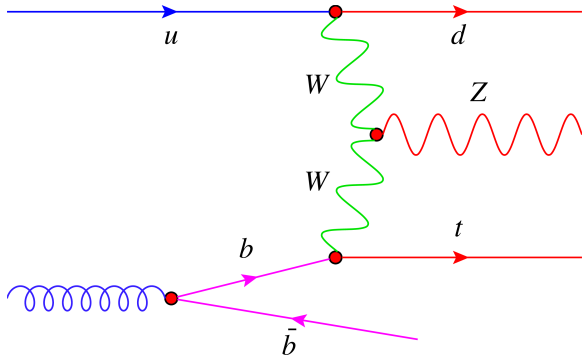
CMS-TOP-PAS-16-004

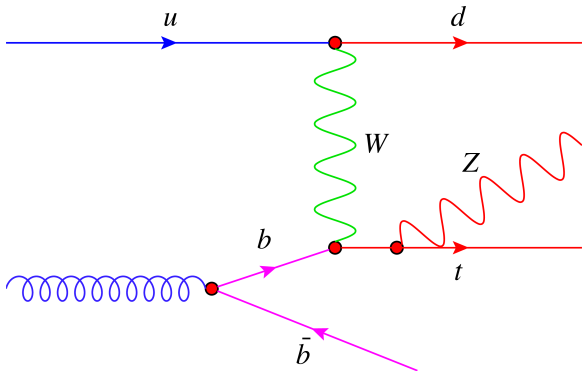
- Differential measurement of **t-channel top** production
  - Muon-channel only employing a BDT discriminator and maximum likelihood fit



Single top quark production

- **ATLAS (13 TeV) & CMS (8 TeV) measurements on tZq**
- Rely on NN and BDT to enrich signal
- Dominant SM production @leading order:





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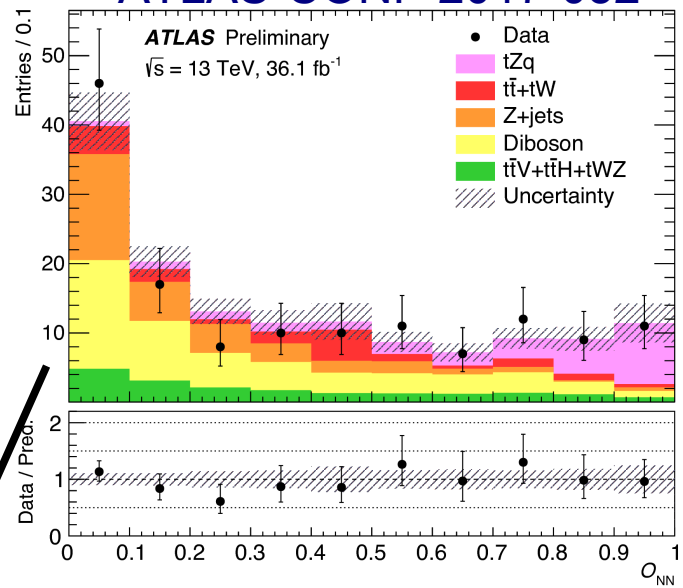
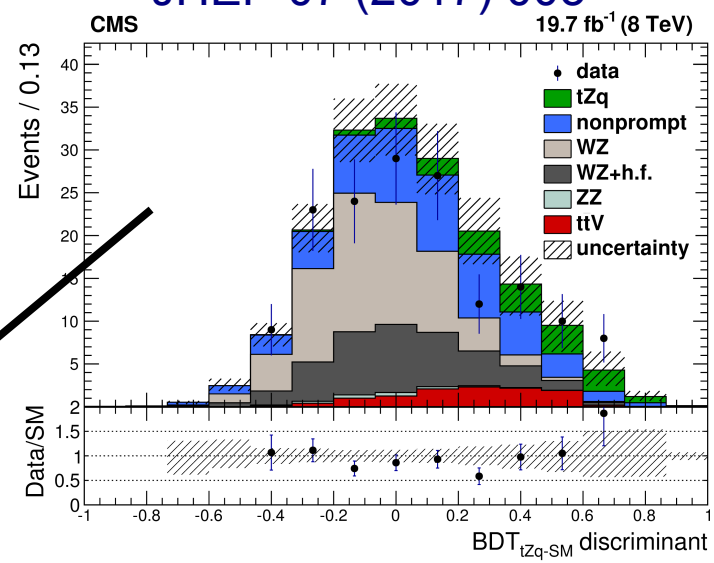


σ = 600 ± 170 (stat.) ± 140 (syst.) fb
(Expected is 5.4 SD, observed 4.2 SD)
13 TeV

JHEP 07 (2017) 003

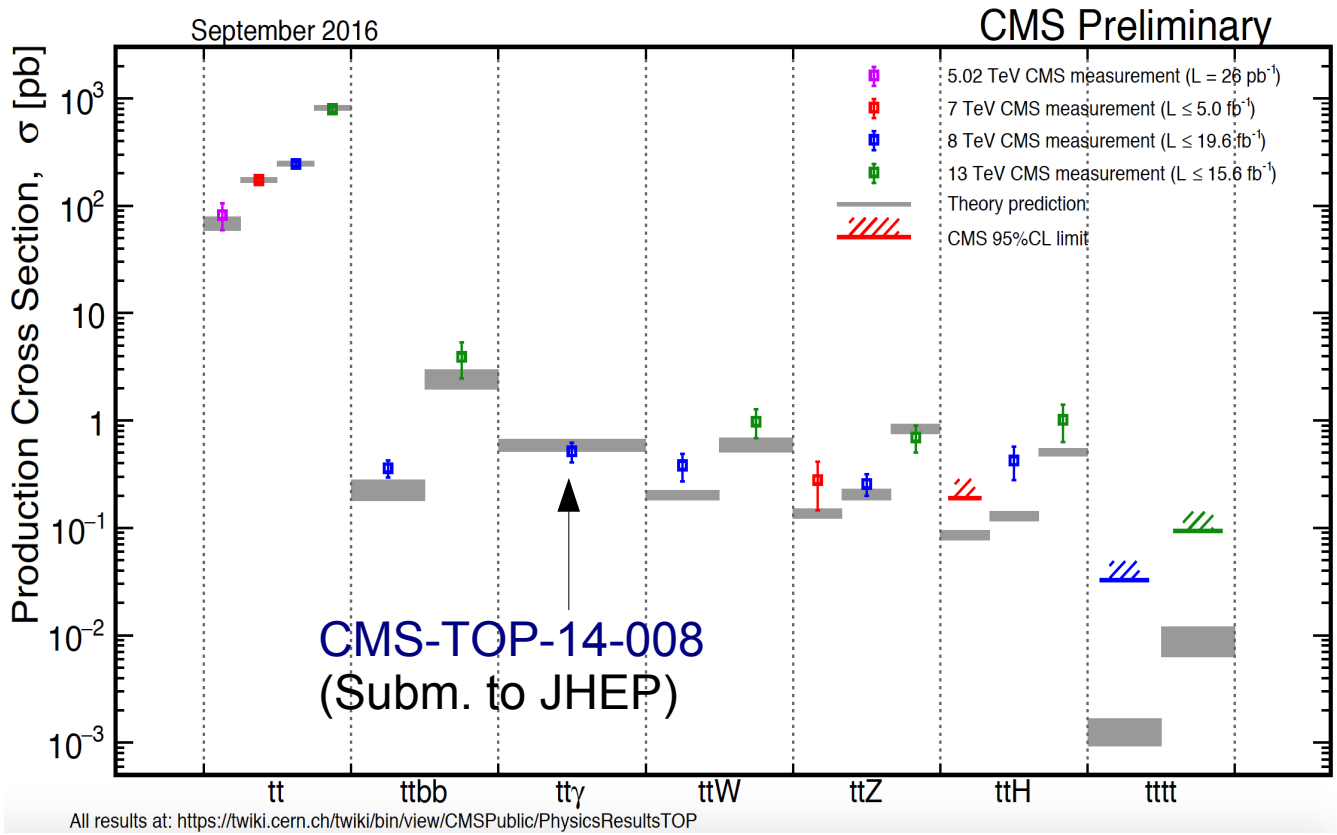


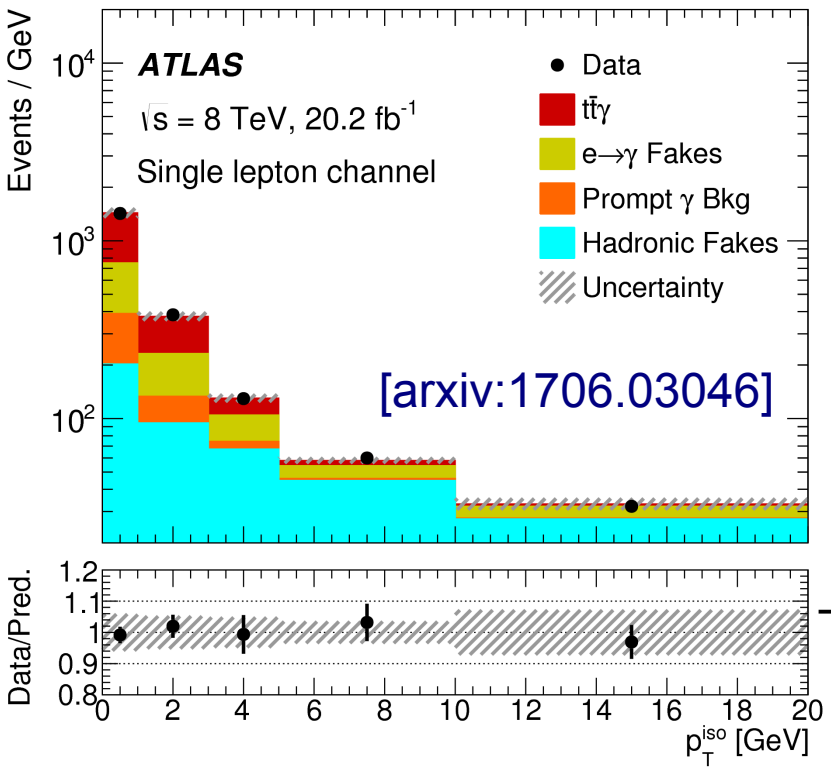
σ = 10 ± 8/7 (tot.) fb
(Observed 2.4 SD)
8 TeV

The precision frontier: top

- CMS measurement in l+jets channel @8 TeV
  - Photon requirement is pT > 25 GeV

→ σ = 127 ± 27 (tot) fb
(Prediction at NLO: 151 ± 24 fb)





- Measurement in the l+jets channel @8TeV
  - Photon requirement of pT > 15 GeV

→ σ = 139 ± 7 (stat.) ± 17 (syst.) fb
(Prediction at NLO: 151 ± 24 fb)
ATLAS

Ttbar + X: HF

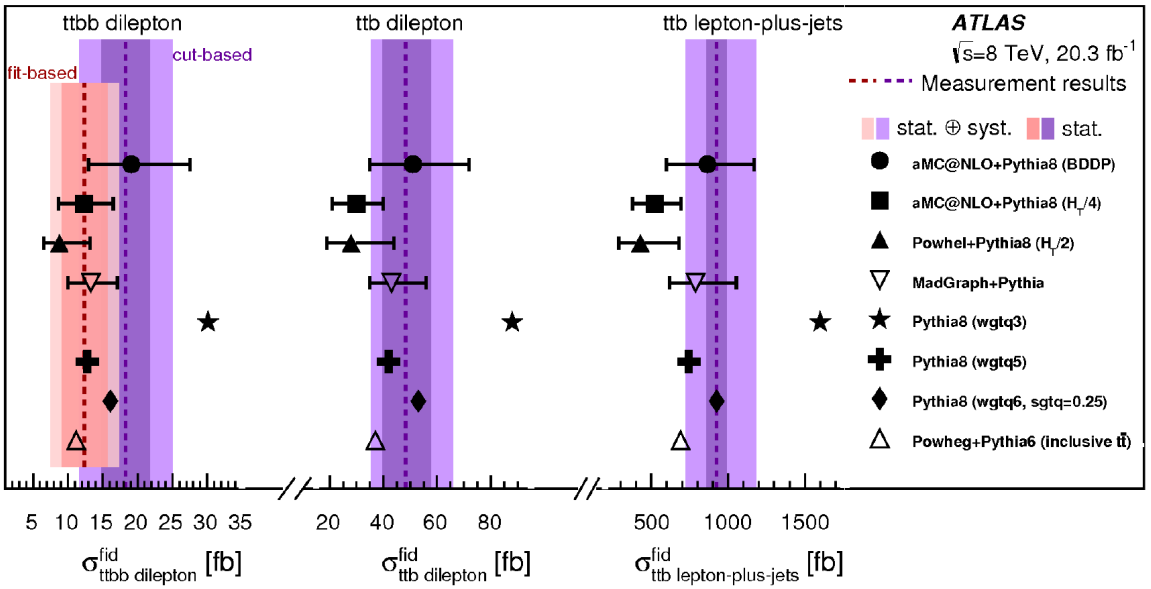
CMS-TOP-16-010
(Subm. to PLB)

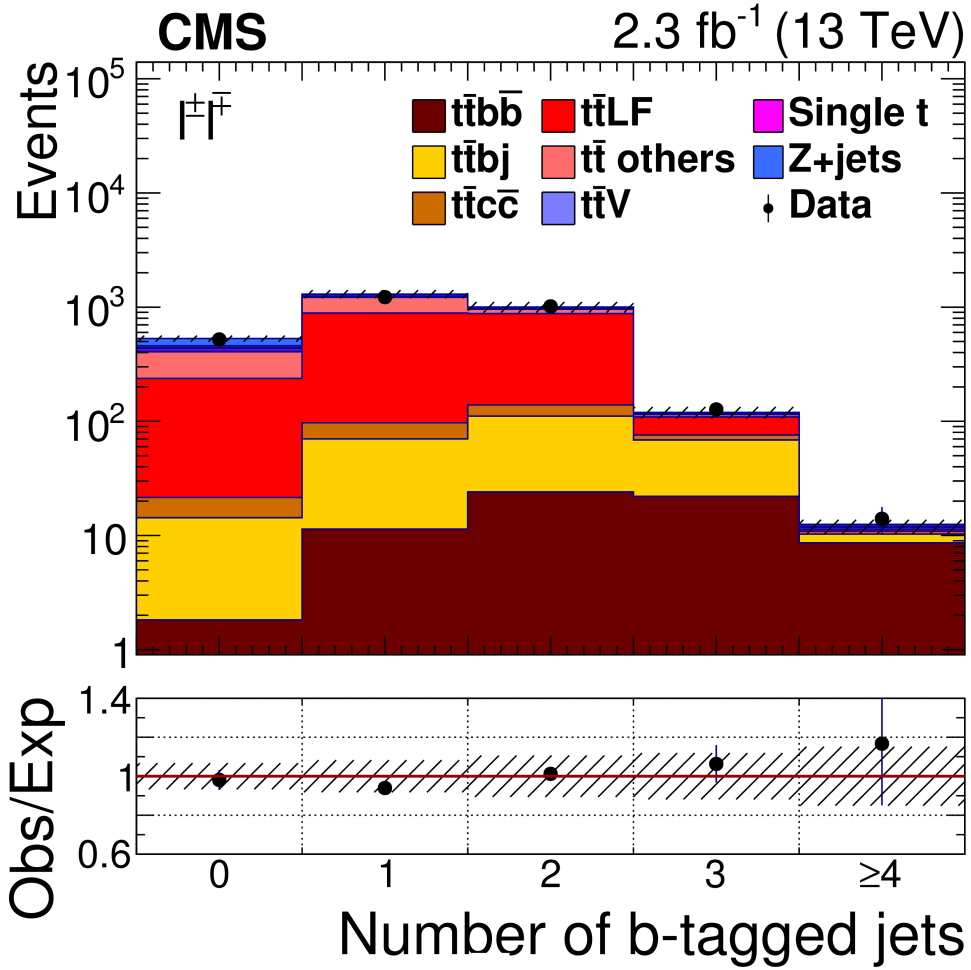
Observation of tt+H a major goal for ATLAS & CMS:

→ Correct modeling of associated HF production is crucial

→ Theoretical and experimental challenge

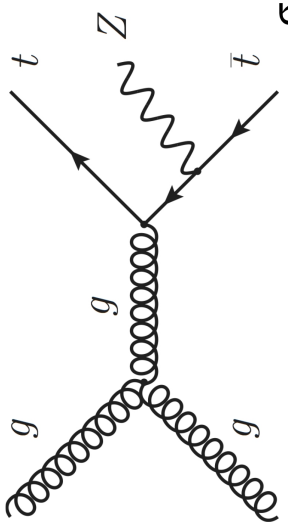
Measurements at 8 TeV (ATLAS & CMS) and 13 TeV (CMS)

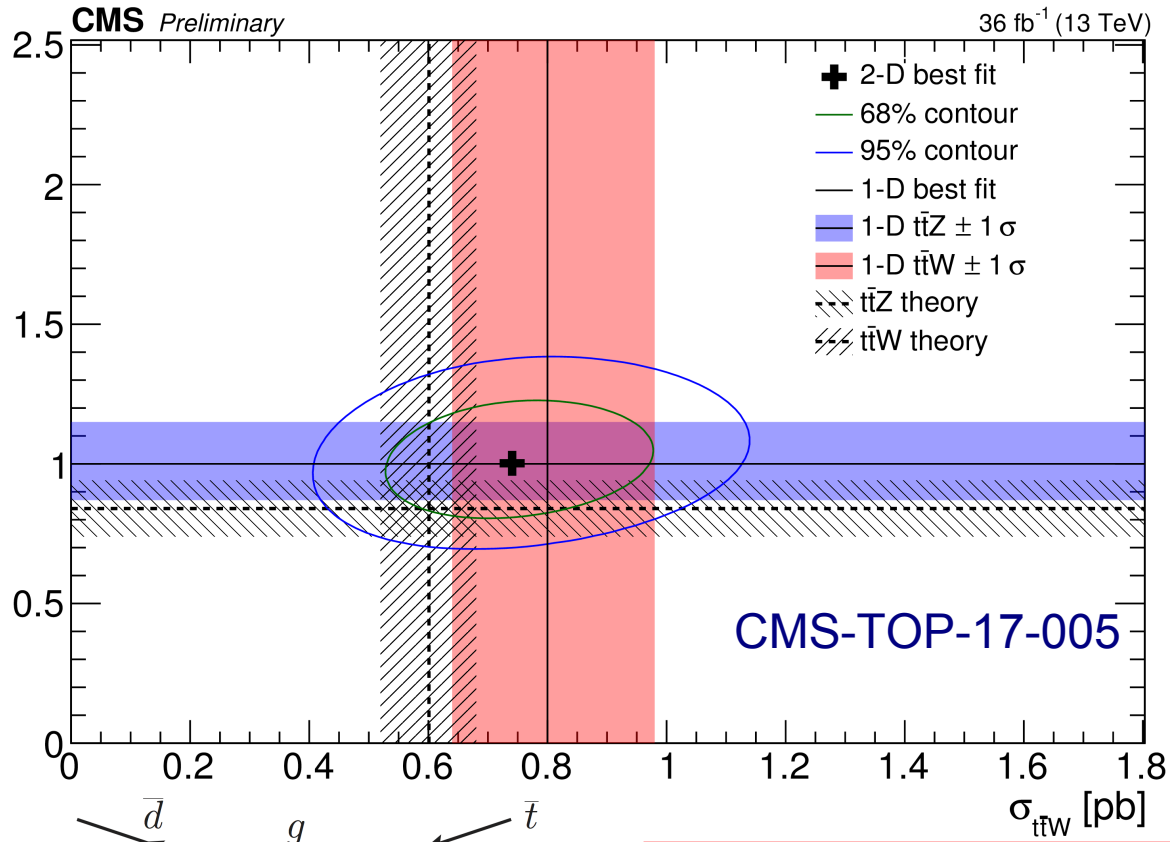


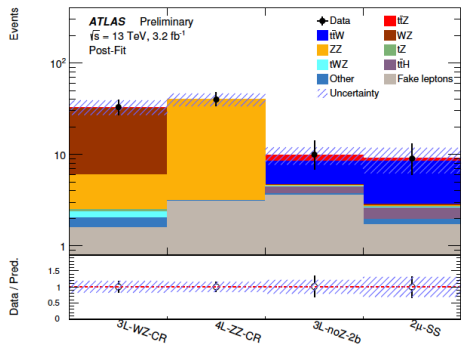


Ttbar + X: W, Z

→ Sensitive to FCNC couplings (ttZ) and BSM (ttW and ttZ)
→ Results consistent with the SM (NLO prediction)







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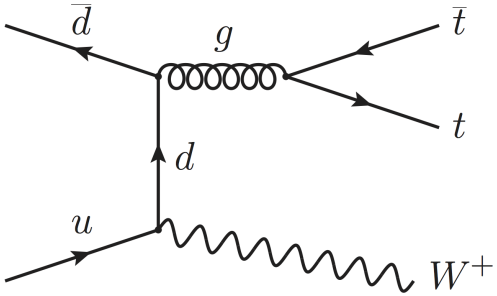


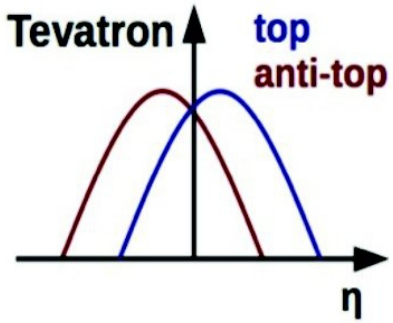
SM (NLO)
$\sigma(t\bar{t}Z)$ = 839 ± 93 fb
$\sigma(t\bar{t}W)$ = 601 ± 55 fb

→ $\sigma(t\bar{t}Z)$ = 1.00 ± 0.09/0.08(stat.) ± 0.12/0.10(syst.) pb
Expected (observed) significance of 4.6 (9.9)

$\sigma(t\bar{t}W)$= 0.80 ± 0.12/0.11(stat.) ± 0.13/0.12(syst.) pb
Expected (observed) significance of 4.6 (5.5)

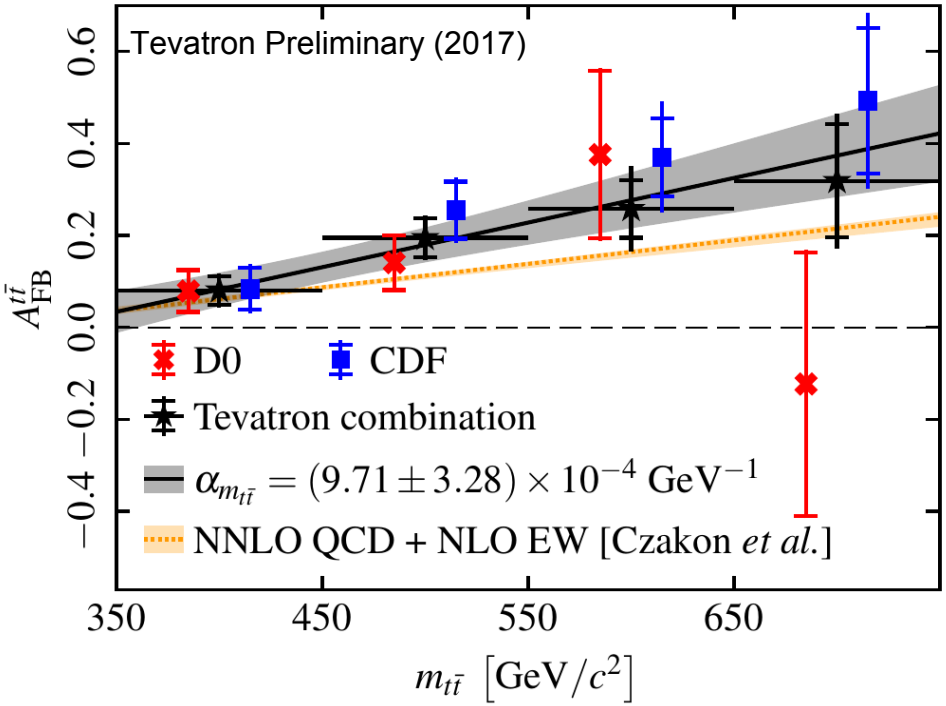
Top quark asymmetries

- Production asymmetry due to NLO interferences

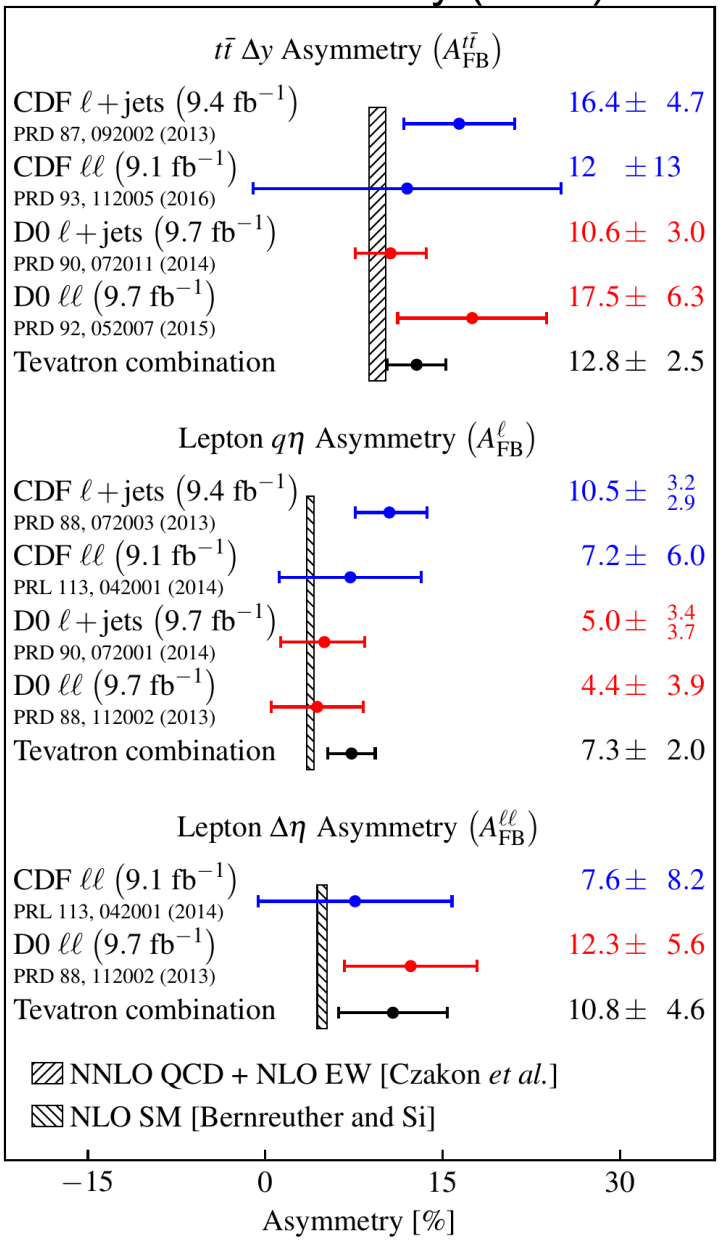


- Inclusive combinations via BLUE
- Differential combinations employing full covariance matrices

→ Final Tevatron combination agrees with SM

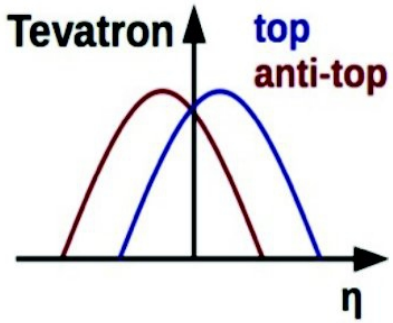


Tevatron Preliminary (2017)

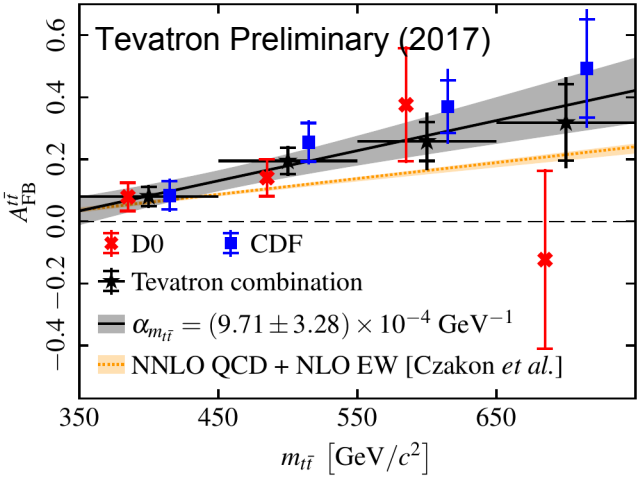


Top quark asymmetries

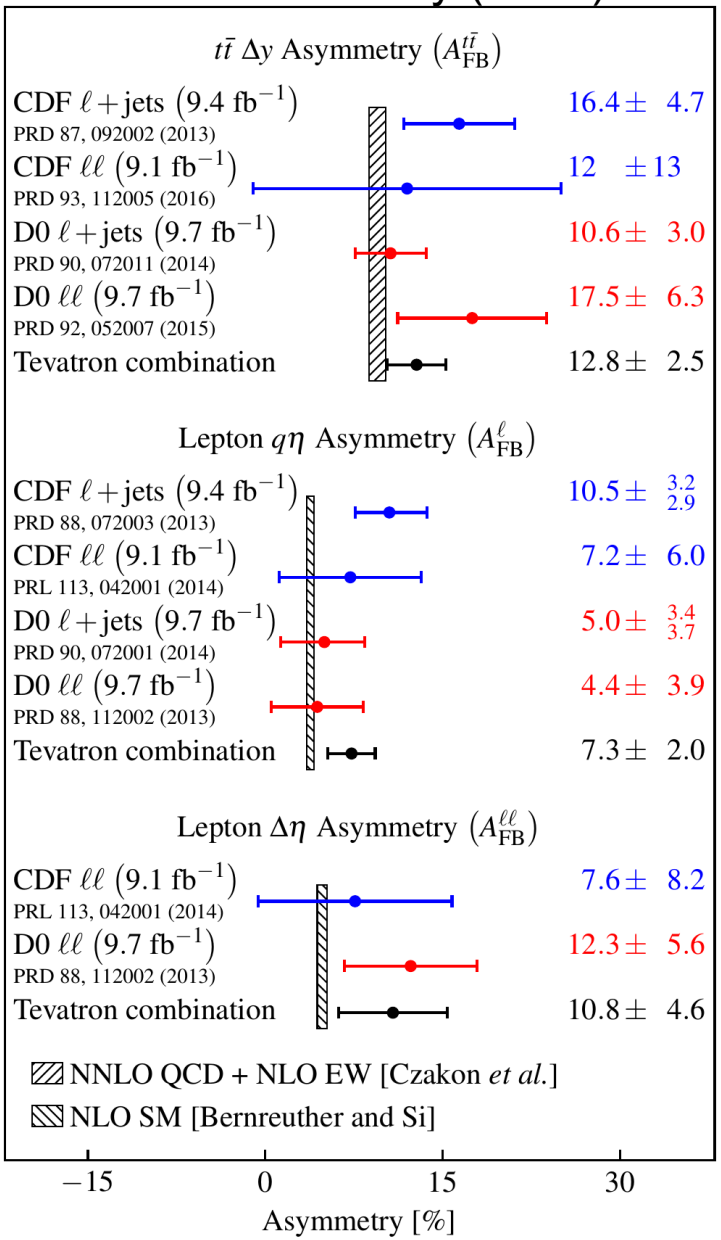
- Production asymmetry due to NLO interferences

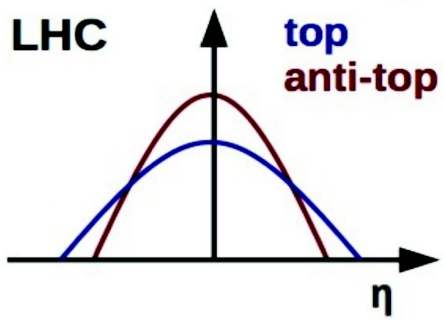


→ Final Tevatron combination agrees with SM



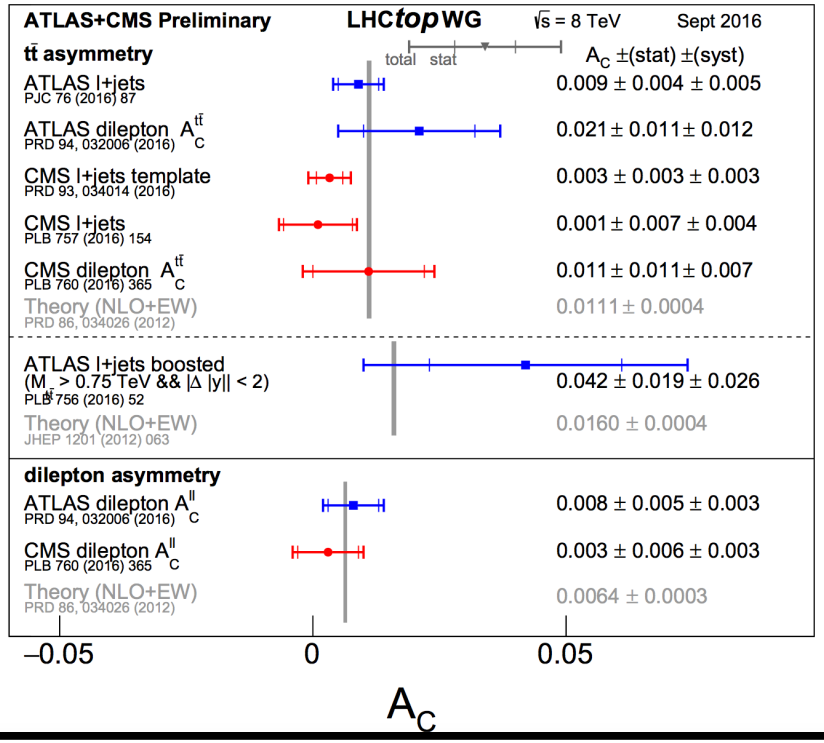
Tevatron Preliminary (2017)



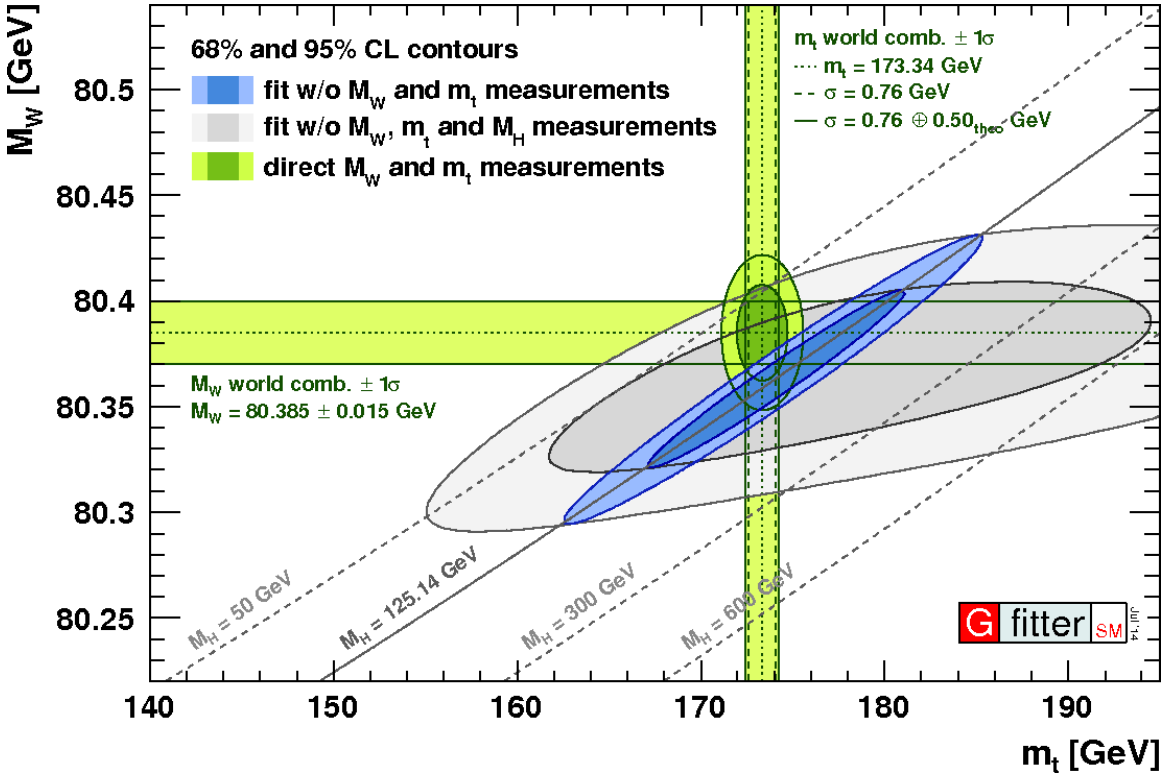


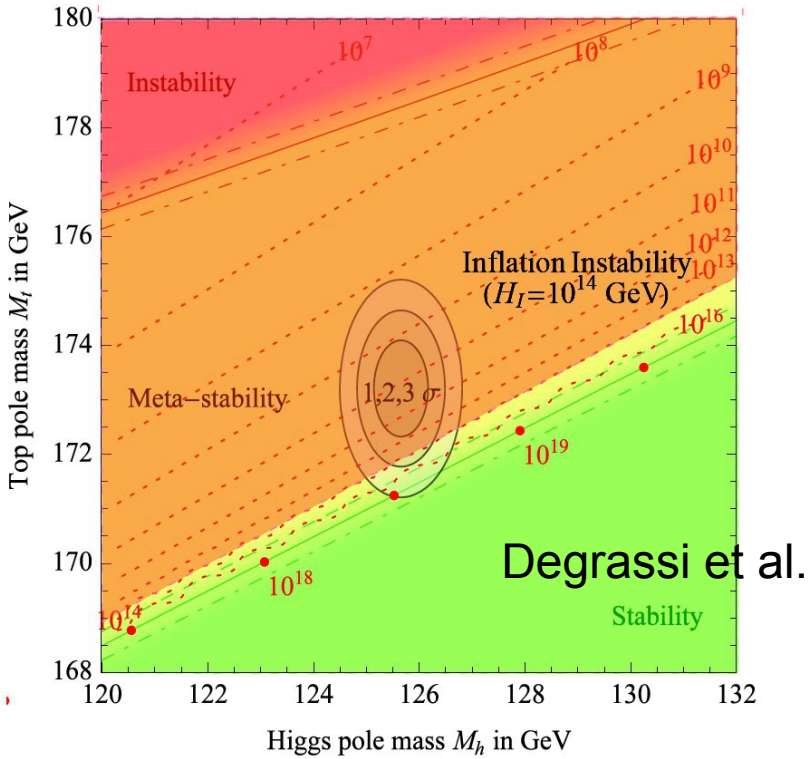
Measurements at the LHC much harder

LHC results agree with SM (but not yet significant)



Latest weighing...





More on EW stability: K. Mukaida

- Self-consistency test of the SM & stability of the EW vacuum both rely/use pole mass – what we measure depends on the method
  - Indirect extraction from e.g. cross section, end point, J/psi method → top quark pole mass
  - Direct methods e.g. template, matrix element, likelihood, ideogram → “MC” mass, close to pole mass

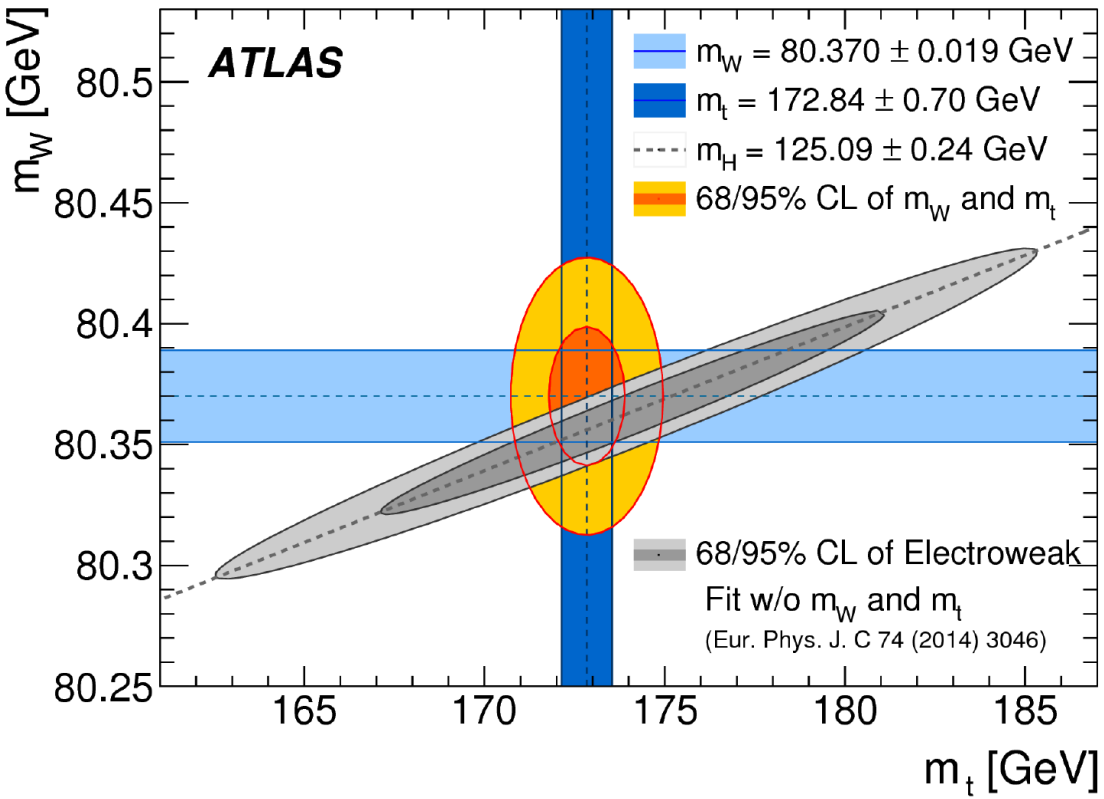
W mass: 1st LHC measurement

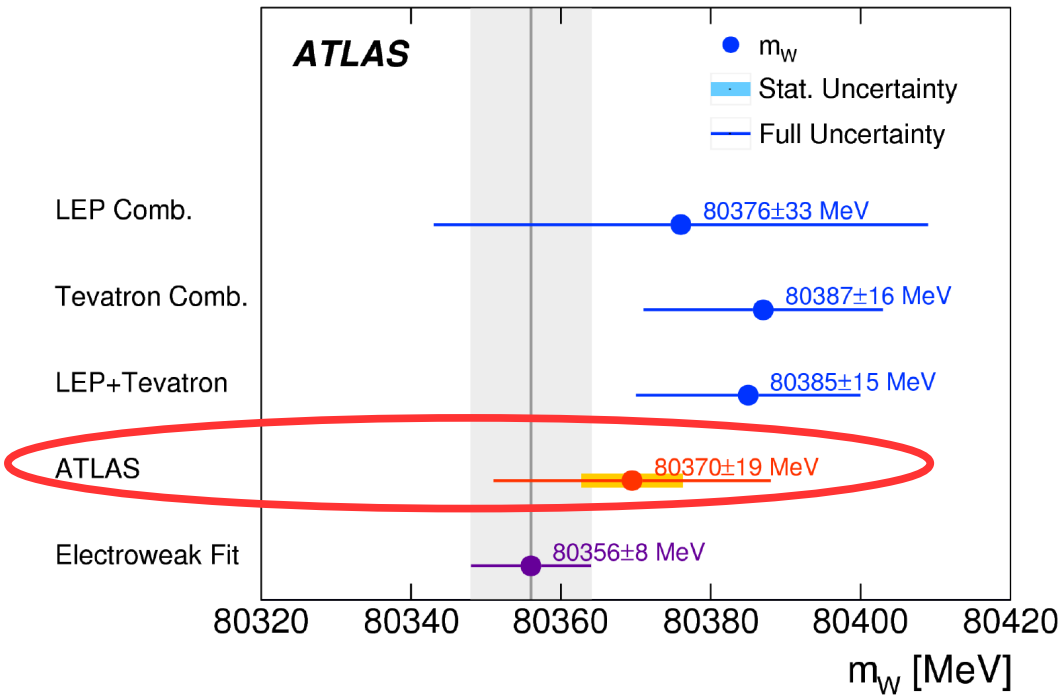
[arXiv:1701.07240]

- Employ the 7 TeV data: **low pile up environment**
  - Huge effort to control systematic uncertainties
  - Higher pile-up at 8 and 13 TeV **challenging**

→ m_W = 80370 ± 7 (stat) ± 11 (exp. syst.) ± 14 (modeling syst.) MeV

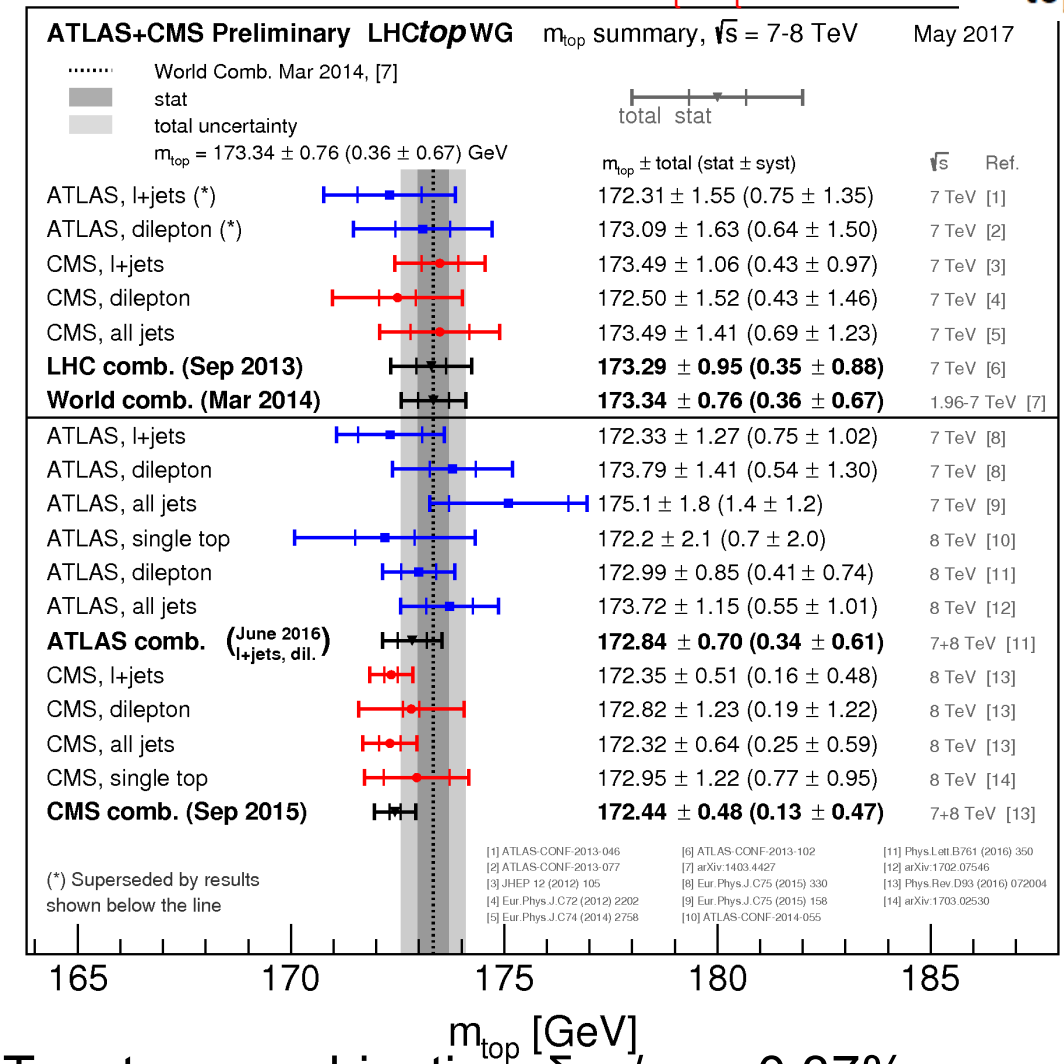
$\delta m_W/m_W$ = 0.024%





Top quark mass: direct

- Direct measurements combined using BLUE – consistent among methods/channels
  - Latest CMS combination, $\delta m_t/m_t = 0.28\%$ $m_{top} = 172.44 \pm 0.48$ GeV CMS-PAS-TOP-15-012

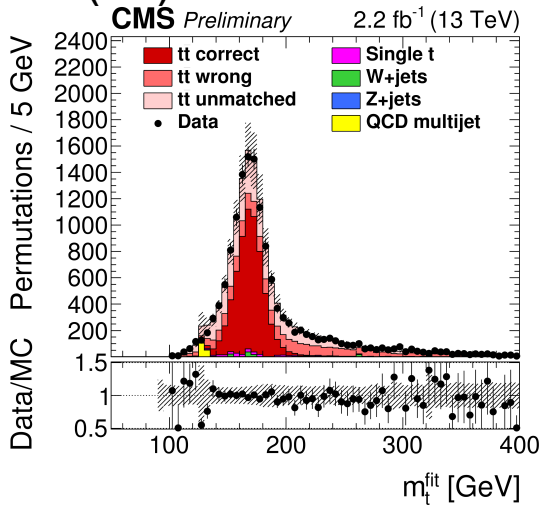


Recent results at 13 TeV:

→ CMS μ+jets: 2D fit of m(t) vs. JSF

$m_{top} = 172.62 \pm 0.80$ (tot) GeV

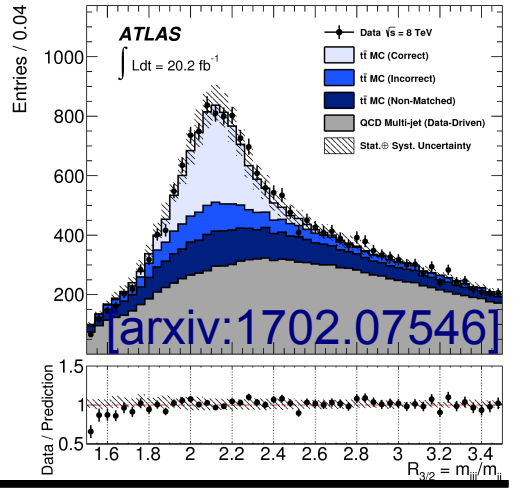
CMS-TOP-16-022



→ ATLAS all-hadronic:

$m_{top} = 173.72$

± 1.15 (tot) GeV



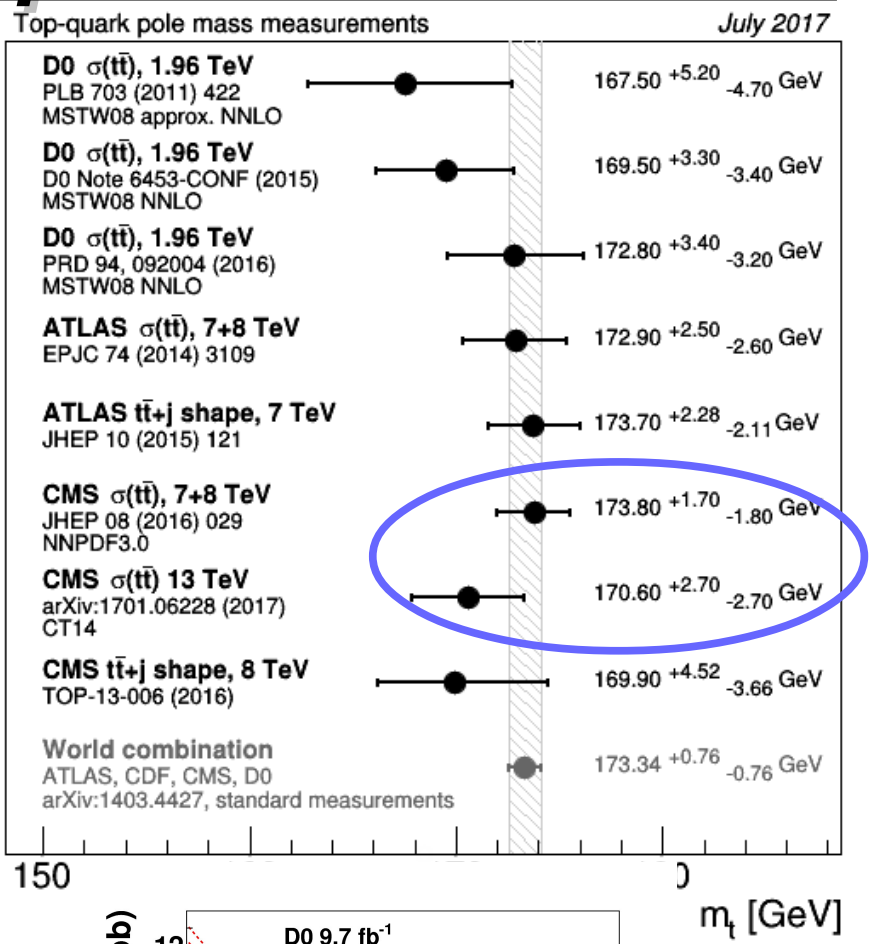
- Tevatron combination, $\delta m_t/m_t = 0.37\%$

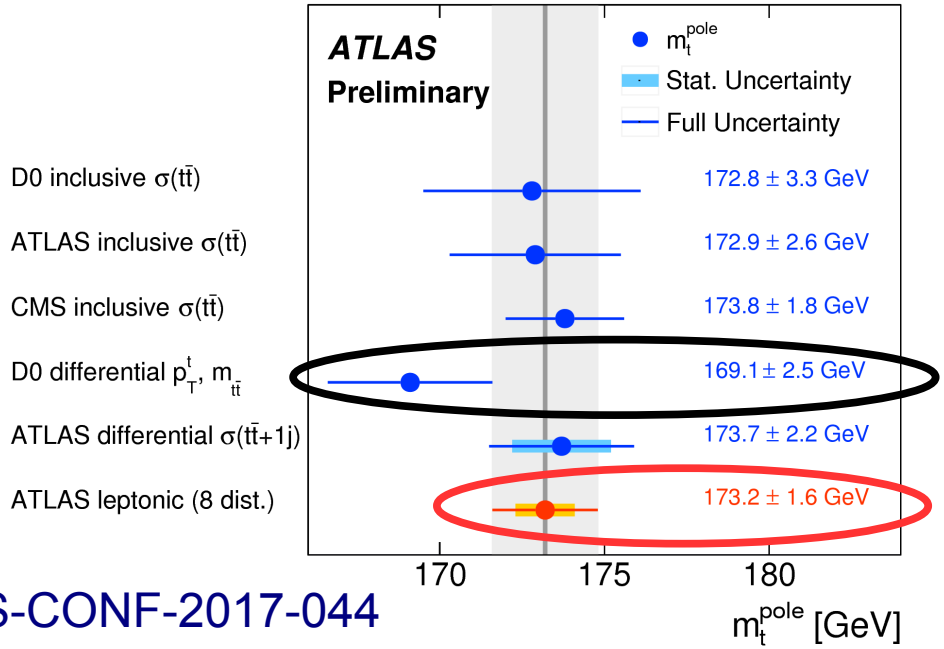
  $m_{top} = 174.30 \pm 0.65$ GeV [arxiv:1608.01881]

Top quark mass: pole

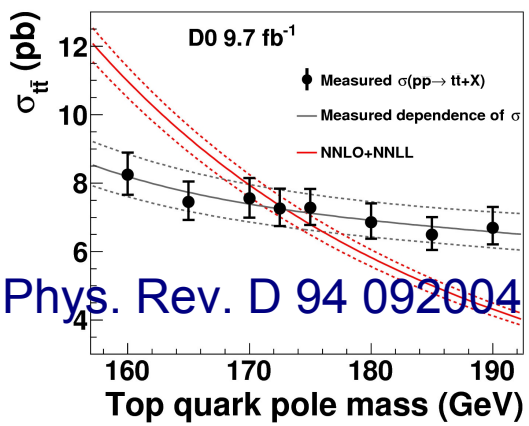
CMS [arXiv:1603.02303]
CMS-TOP-16-006

- Extraction from production cross section not (yet) competitive with direct measurements – but getting closer
- ATLAS: 0.9%; CMS precision at 1%
  - **D0** precision (best at Tevatron): ~ 1.5% D0 6473
- With ~5% theory uncertainty and ~2% exp → <u>can reach 0.5% on pole mass</u>





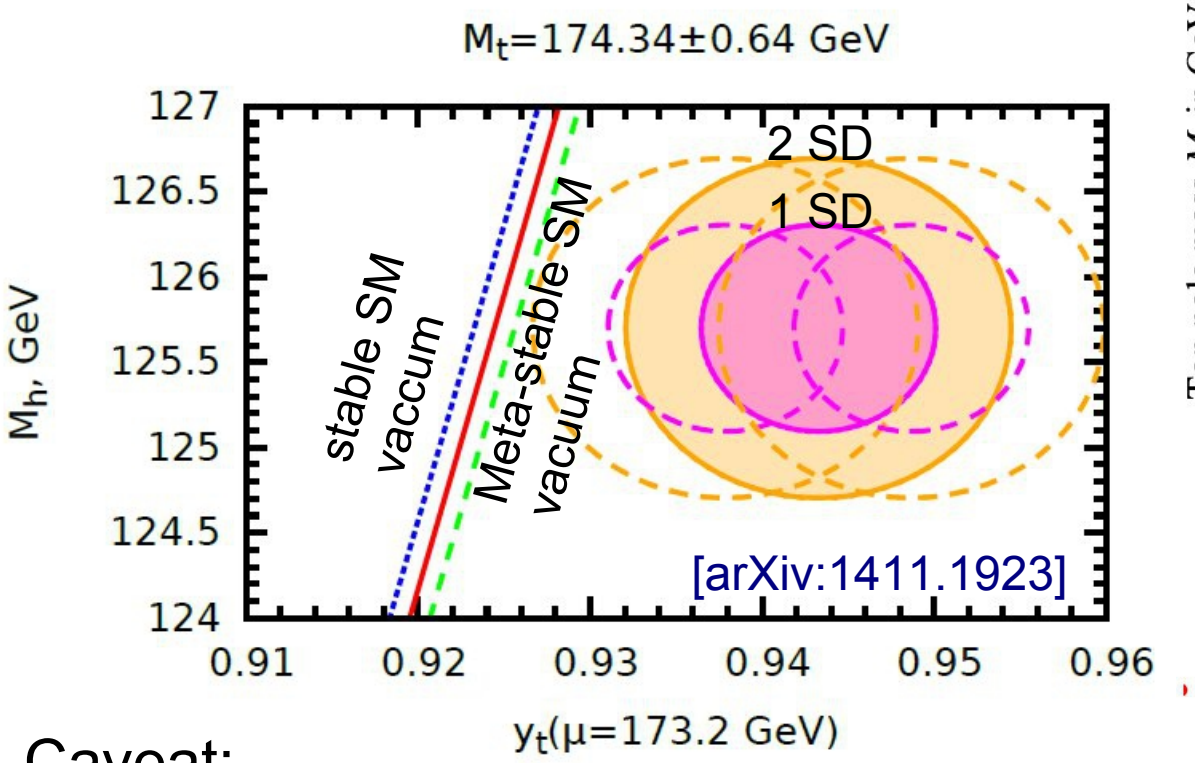
ATLAS-CONF-2017-044

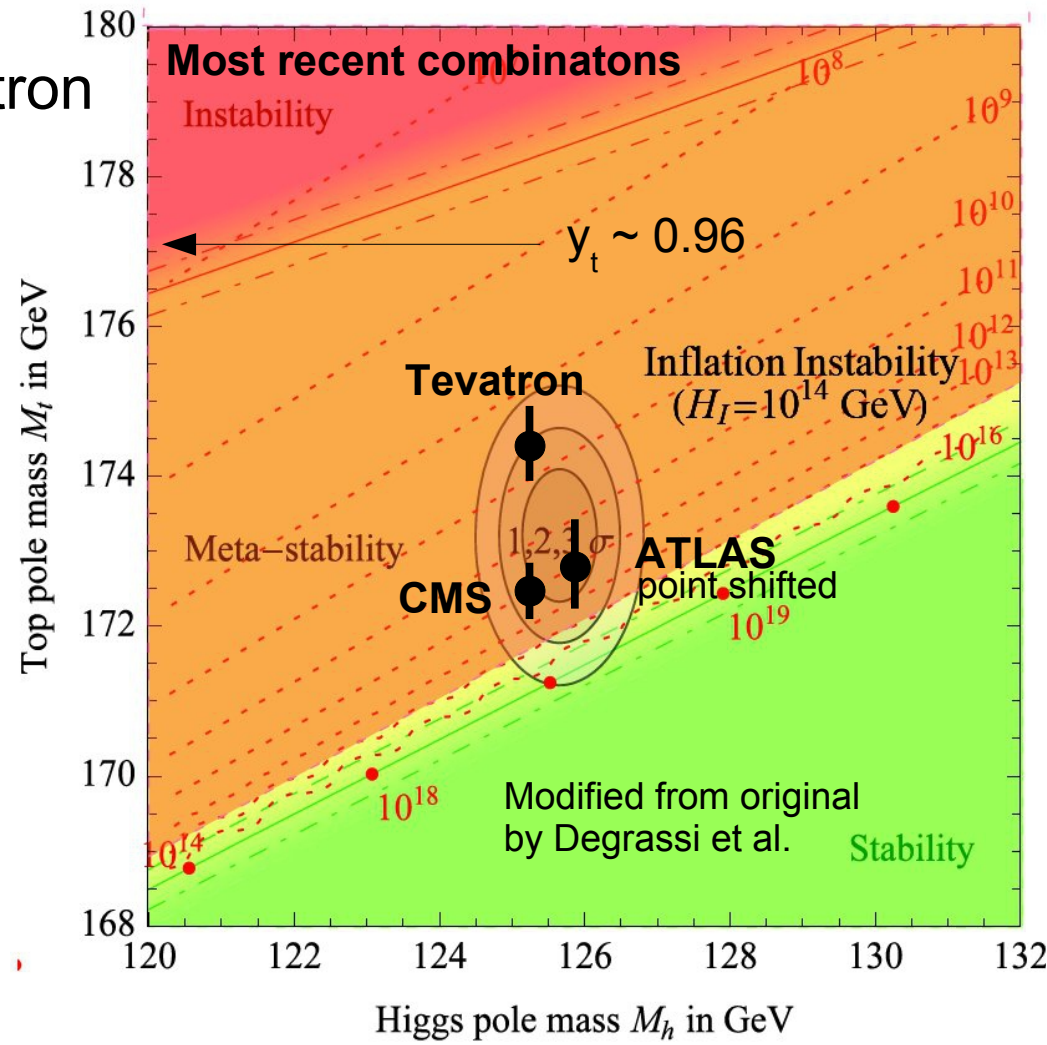


Phys. Rev. D 94 092004 (2016)

EW vacuum stability

- Very subjective but illustrative, combined latest results from ATLAS, CMS, Tevatron
  - Some tension...
- Assumes SM to be true

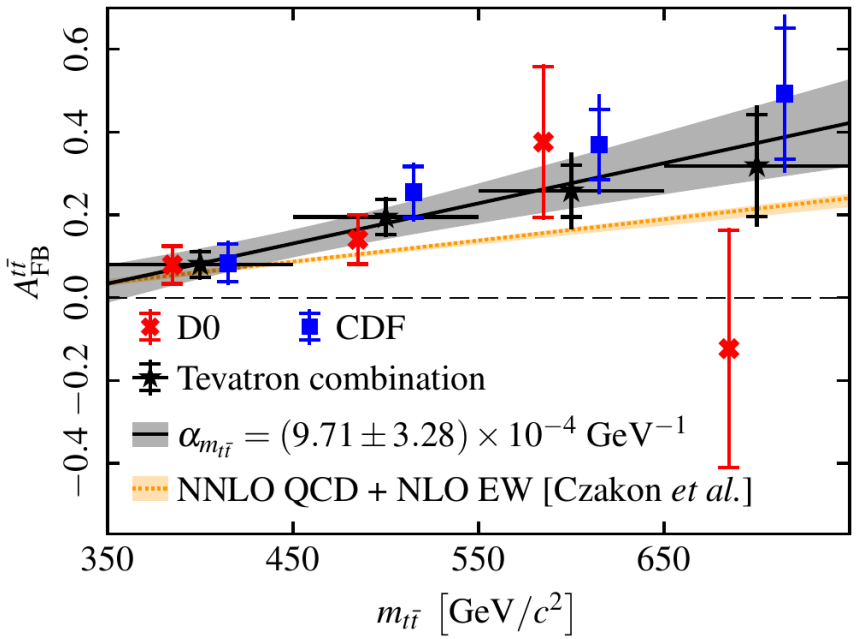




Caveat:

- Direct methods e.g. template, matrix element, likelihood, ideogram measure the "MC" mass, lots of effort to "calibrate" the "MC" mass
- Estimates: O(0.5 GeV) difference to pole mass PRL 117, 232001 (2016)

BSM physics in top sector ?



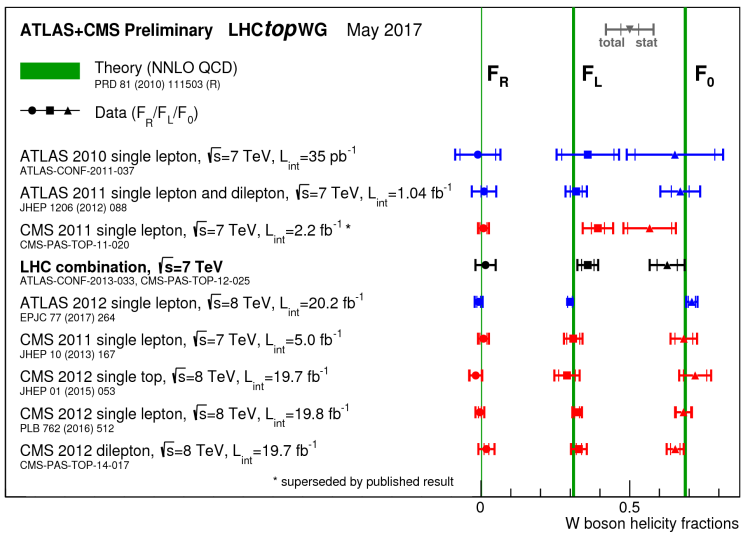
→ Forward-backward asymmetry **agrees** with SM at the 1.3-1.6 SD level

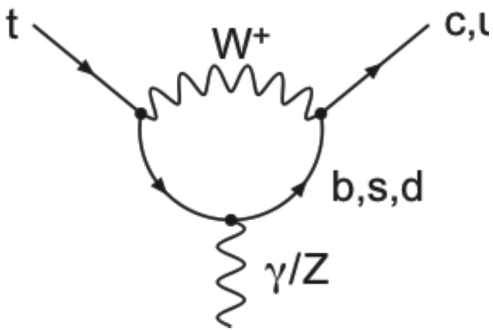
→ W helicity & other results **agree** with SM

→ Vtb enters in production and decay:

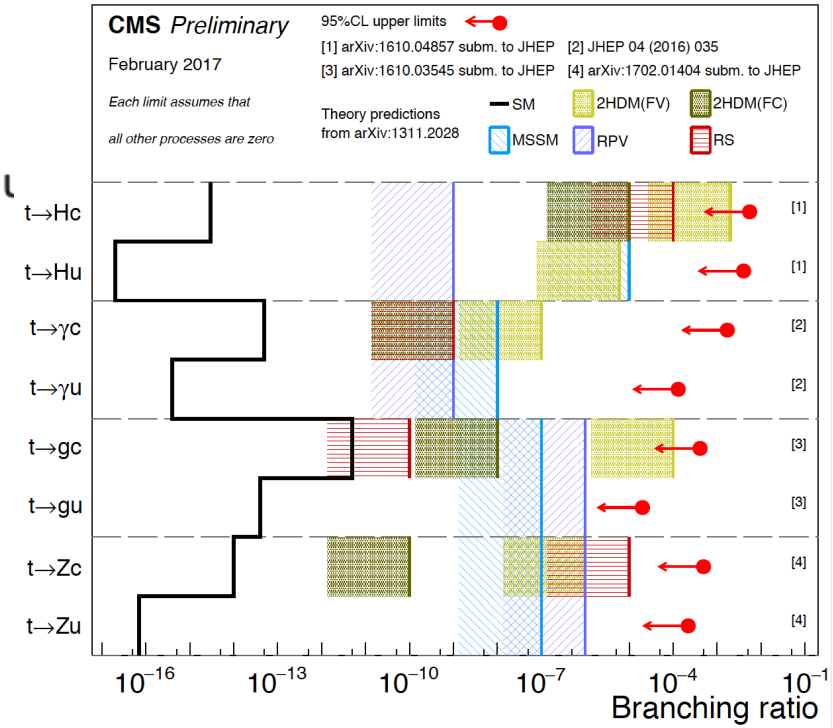
$\sigma \sim |Vtb|^2$, FCNCs highly suppressed but limits start to reach relevant BSM Brs

no BSM signal yet





CMS-TOP-PAS-16-004

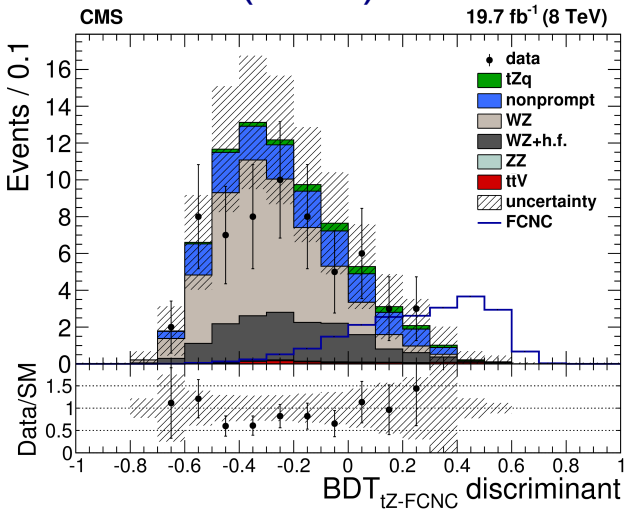


BSM physics in top sector ?

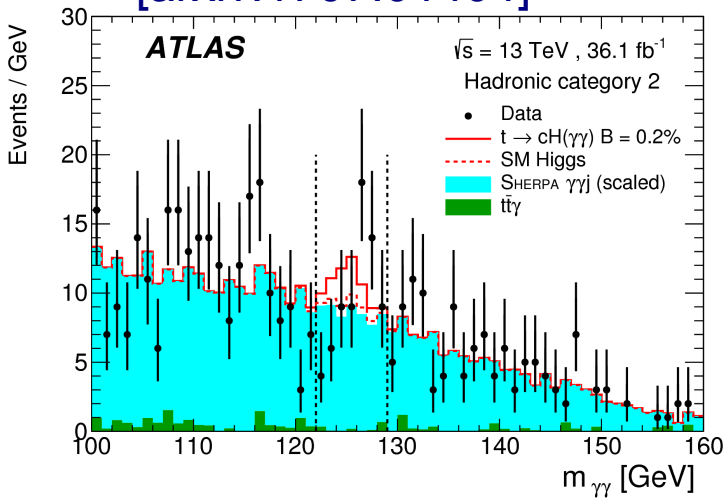
→ Detailed study of the Wtb vertext to identify any BSM contributions
→ Use triple-differential angular decay rates in single t-channel production

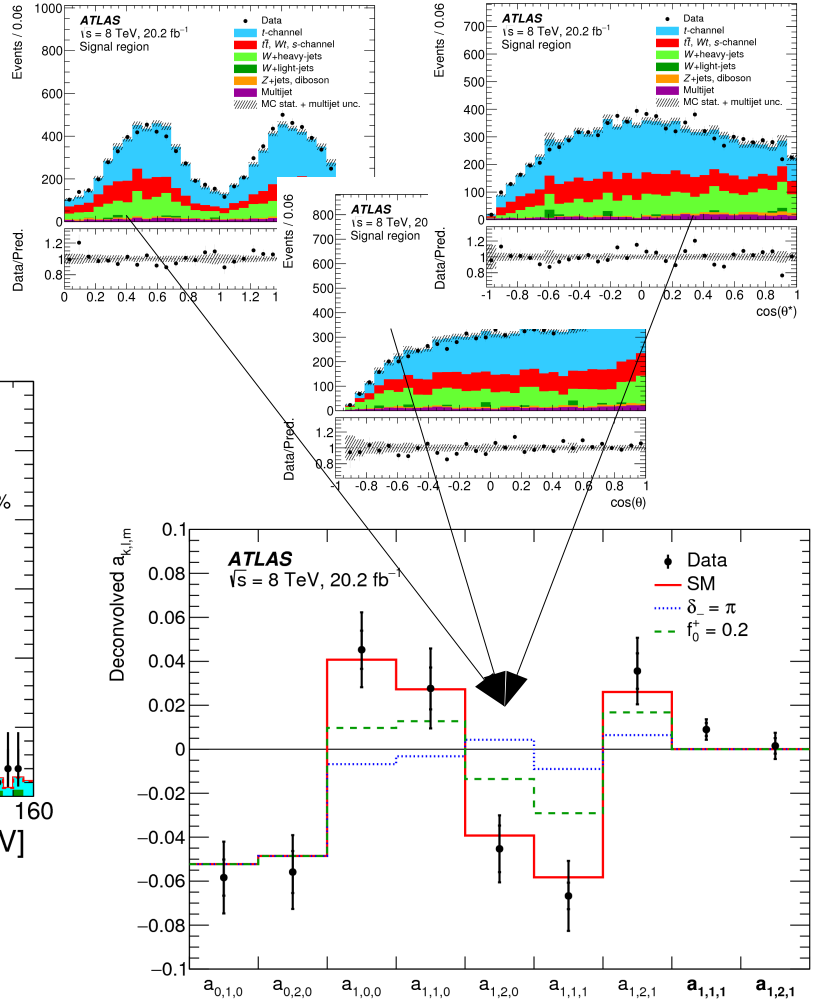
→ FCNCs in tZ (ATLAS & CMS) and t →cH (ATLAS) – **no BSM signal yet**

JHEP 07 (2017) 003



[arxiv:1707.01404]





→ Data agrees with SM
no BSM signal yet

Conclusions

- Large data sets on W,Z and top quarks allow to constrain PDFs
- High precision top quark property measurements, also accessible now in **single top quark production** (*t*-channel)
- Plethora of W and Z boson final state measurements:
  → **Evidence** for associated production of *W, Z*
  → **Observation** of diboson scattering

→ No significant deviations seen from SM expectations at LHC Run I or early Run II results

Only small limited selection of results shown

Thank you!

Outlook

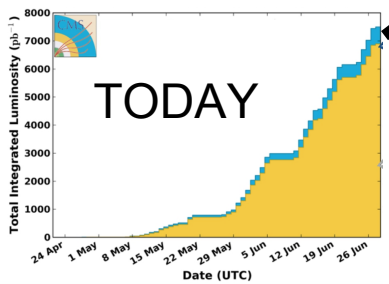
Run II just started!

→ We will get about 80 million $t\bar{t}$ events

→ Allows for multi-dimensional & simultaneous measurements of σ, α_s, PDFs and properties as well – ultra precision results via measurements @ parton level & fiducial particle level

→ FCNCs and other statistically limited processes will significantly improve!

3000/fb



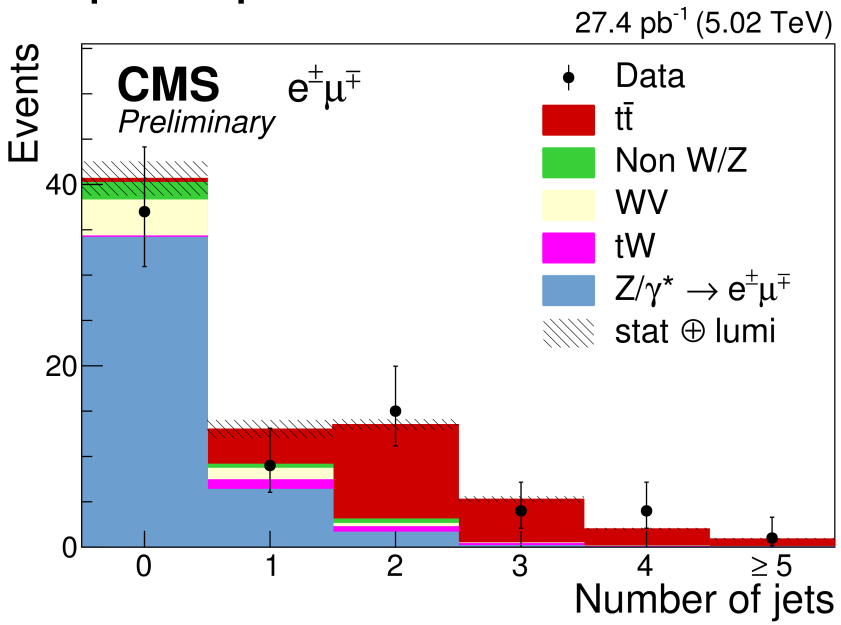
Backup

Top quark production

- CMS 2nd cross section measurement at 5 TeV in eμ dilepton CMS-TOP-16-023
  - Event counting in dilepton & fit in l+jet channel
  - Relative precision: $\delta\sigma/\sigma$ = 13%

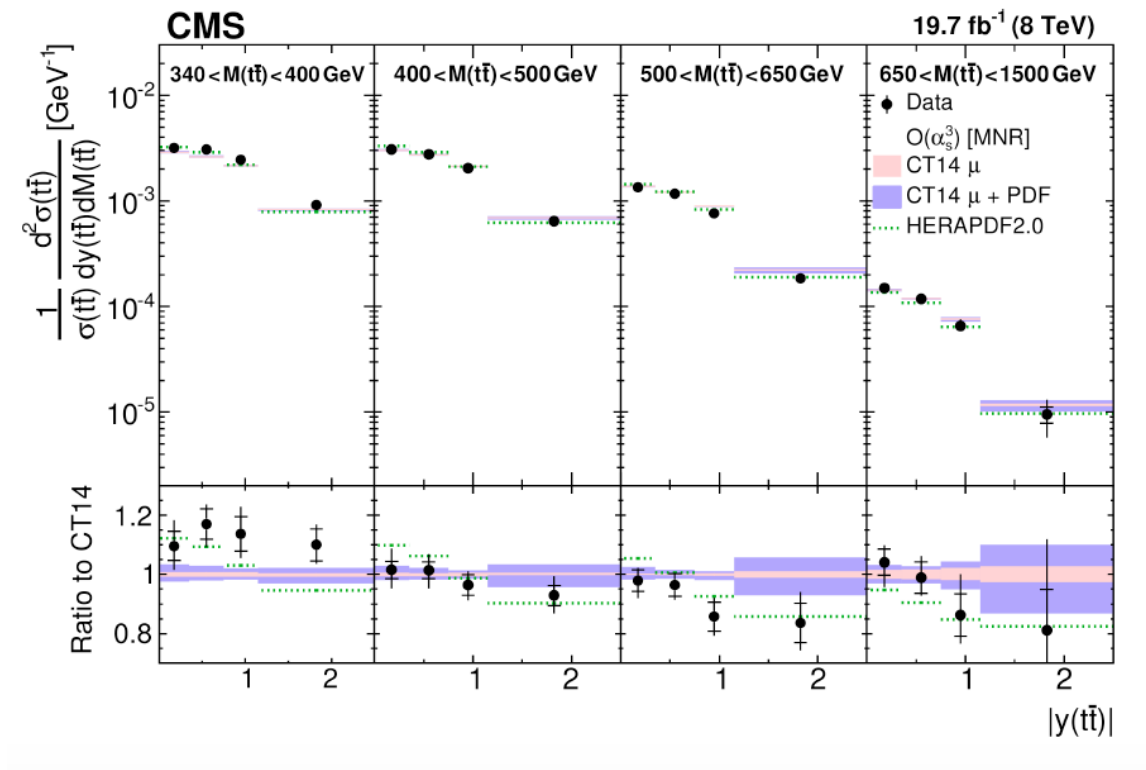
→ σ = 68.9 ± 6.5 (stat.) ± 6.1 (syst.) ± 1.6 (lumi.) pb

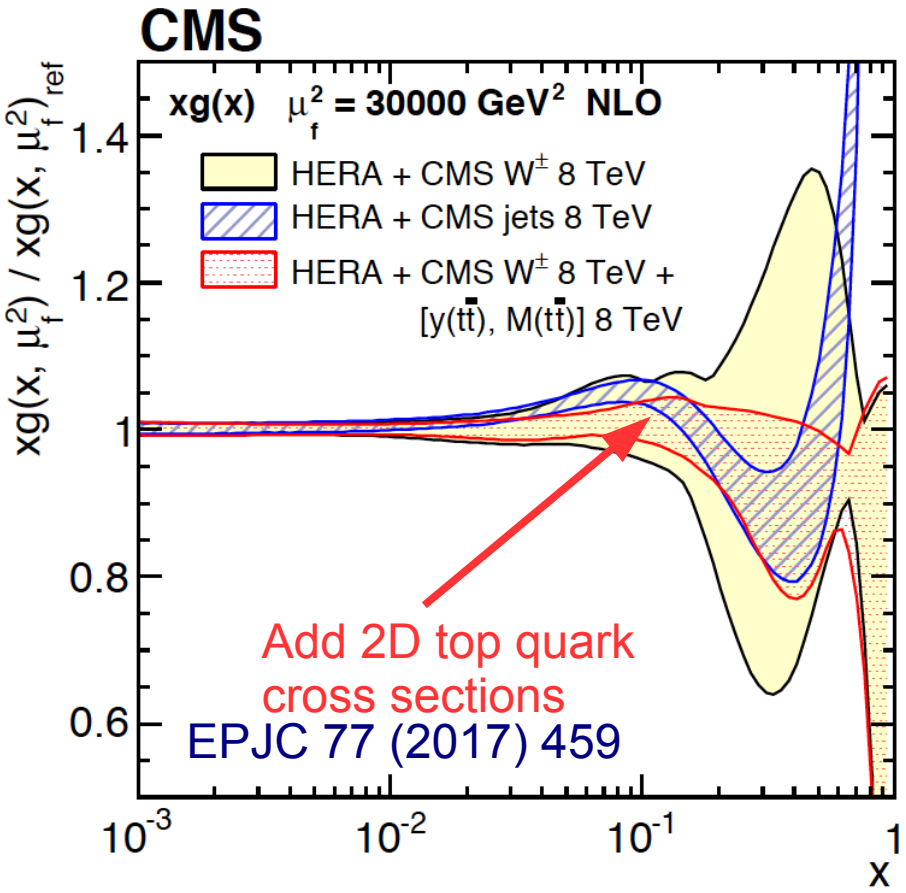
Agrees well with 1st measurement @5.02 TeV, in dilepton channel only: CMS-PAS-TOP-16-015



Differential cross sections

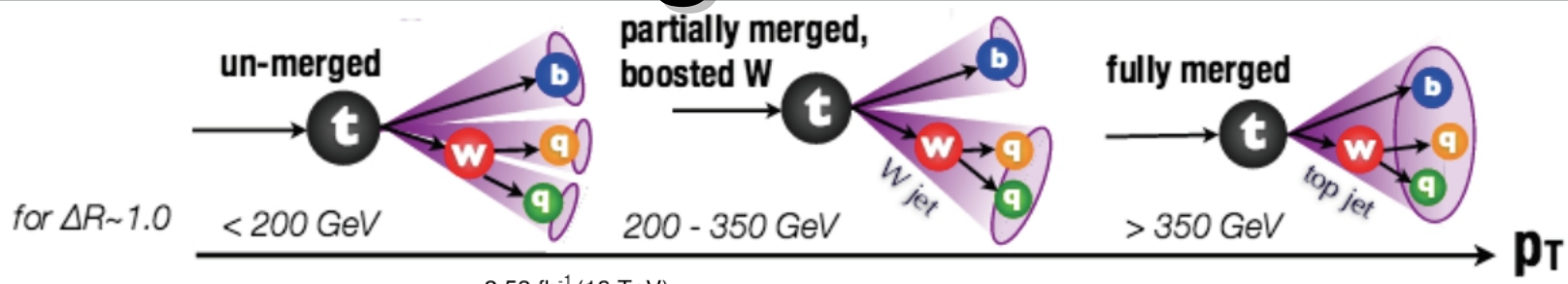
- First 2D cross section measurement of this type at the LHC
- Dilepton eμ channel – very good S/B
- Provide 1D & 2D differential cross sections
  - 2D cross sections more sensitive to large x PDFs
  - Constrain PDFs at large x

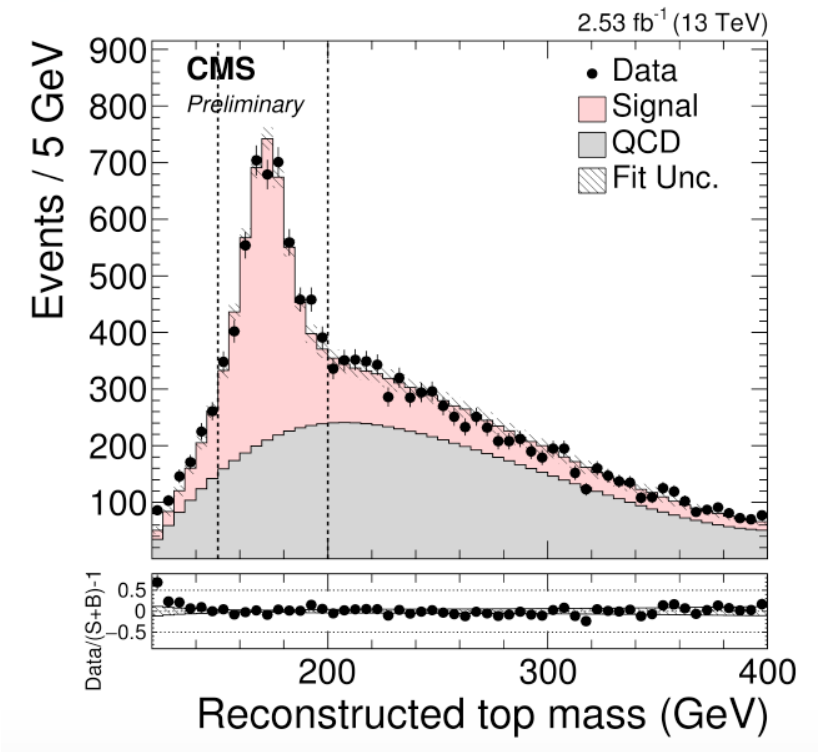


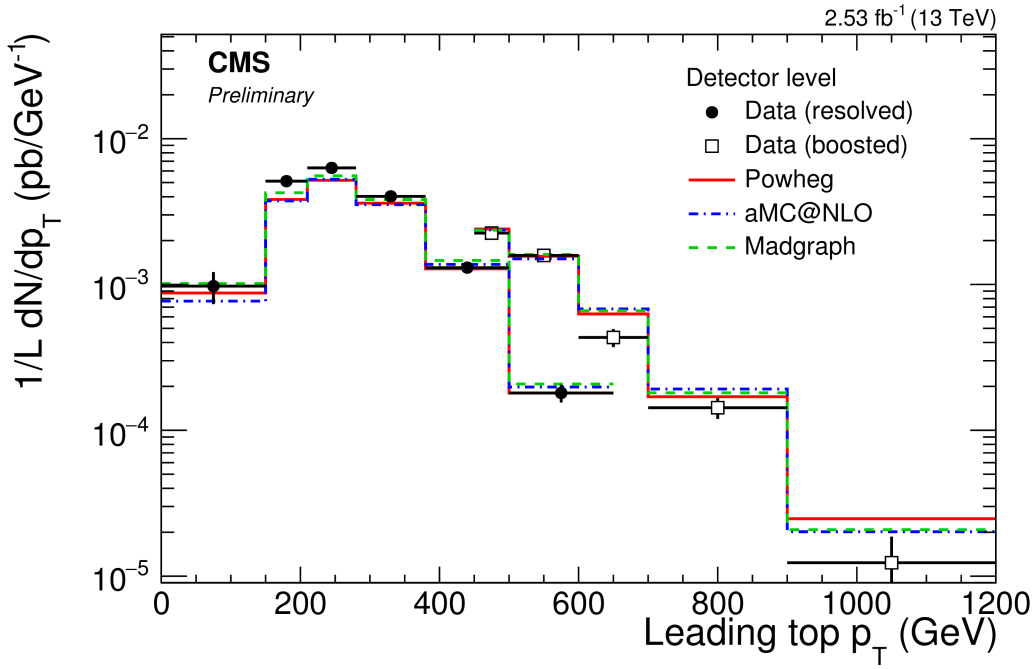


Boosted regime

CMS-PAG-TOP-16-013



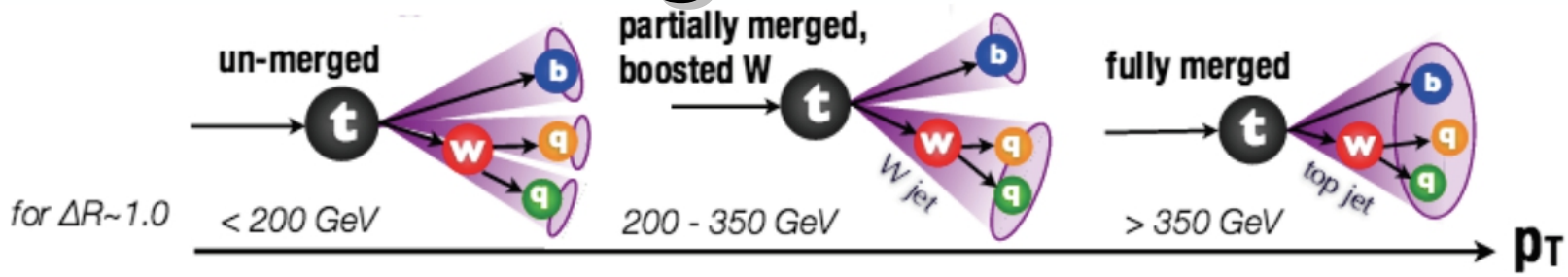


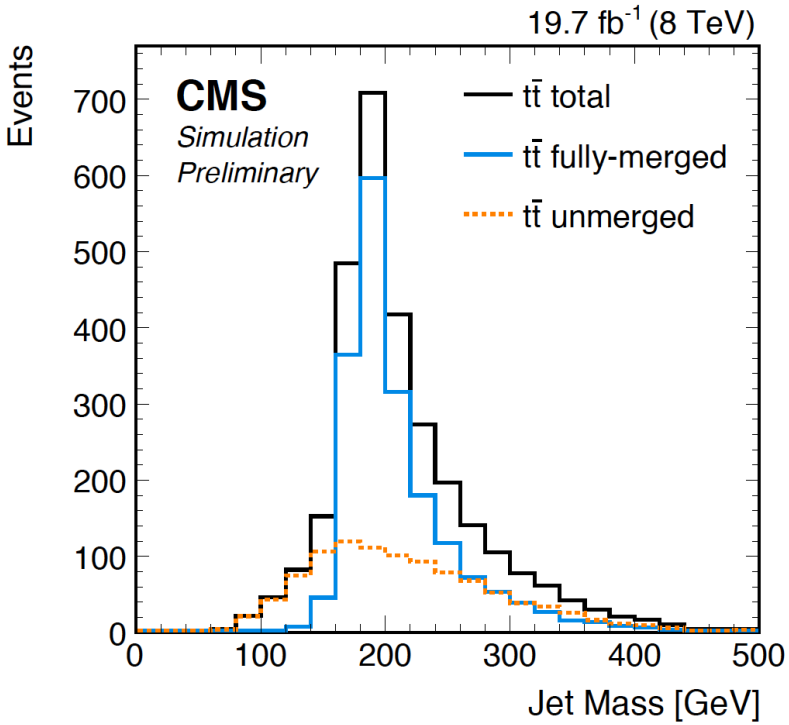


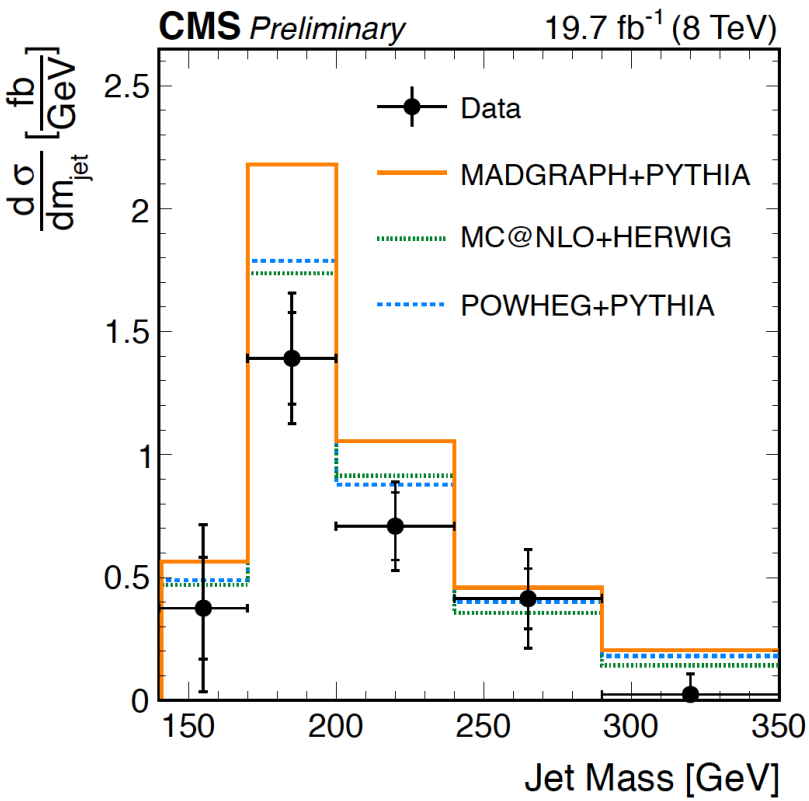
- All-hadronic channel: Use reconstructed top mass to derive bg norm+shape
- Consistent picture in boosted and resolved phase space
- Parton level results receive larger systematic uncertainties
- CMS 13 TeV <u>all-hadronic combined resolved and boosted analysis</u>

Boosted regime

CMS-PAS-TOP-15-015







- Hadronic decay products reconstructed with single jet R = 1.2
- Peak position of m_{jet} sensitive to m_t

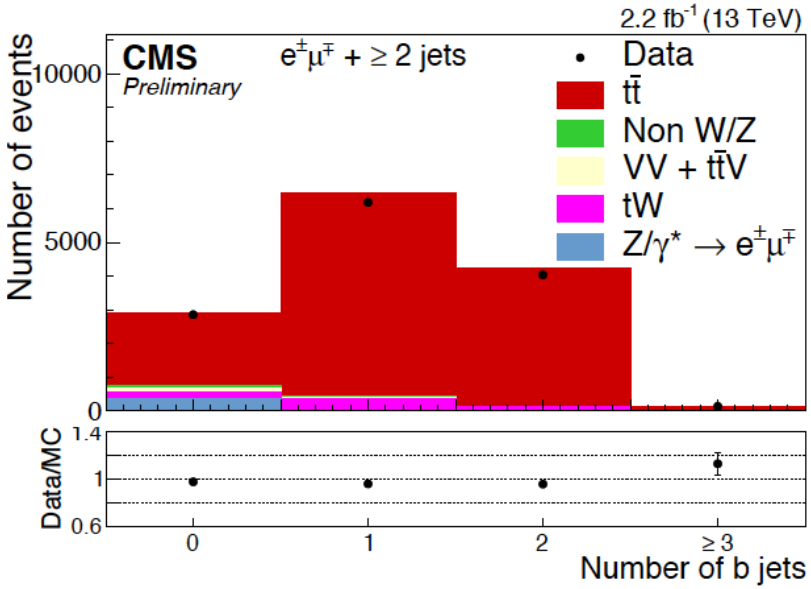
→ M_{top} = 171.8 ± 9.5 (tot) GeV

- Detailed understanding of jet substructure observable crucial for boosted topologies

Top quark production

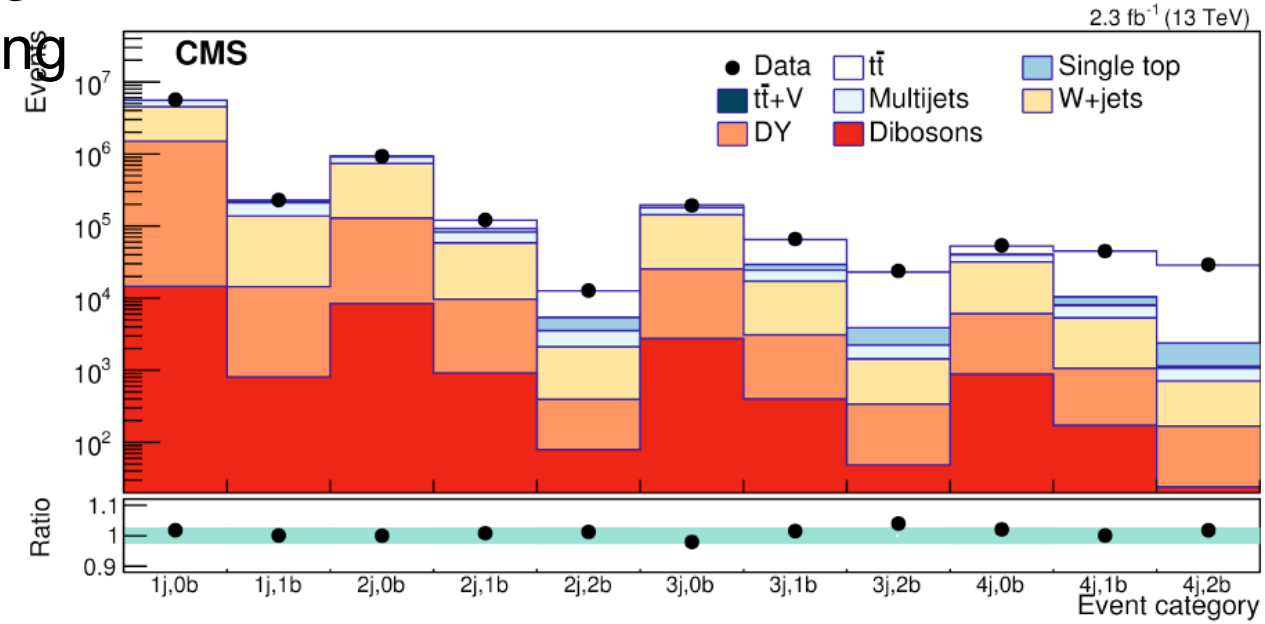
- CMS cross section measurement in the dilepton channel @13TeV, $\delta\sigma/\sigma$ = 5.6%
- Dominated by Hadronisation, JES

→ σ = 793 ± 8 (stat.) ± 38 (syst.) ± 21 (lumi.) pb



- Most precise measurement at 13 TeV
- In-situ constrains on systematics
- Fit jet and *b*-jet categories starting 1 jet to reduce systematics
- <u>Relative precision:</u> $\delta\sigma/\sigma$ = 3.9%
- l+jets decay channel

→ σ = 835 ± 3 (stat.) ± 23 (syst.) ± 23 (lumi.) pb

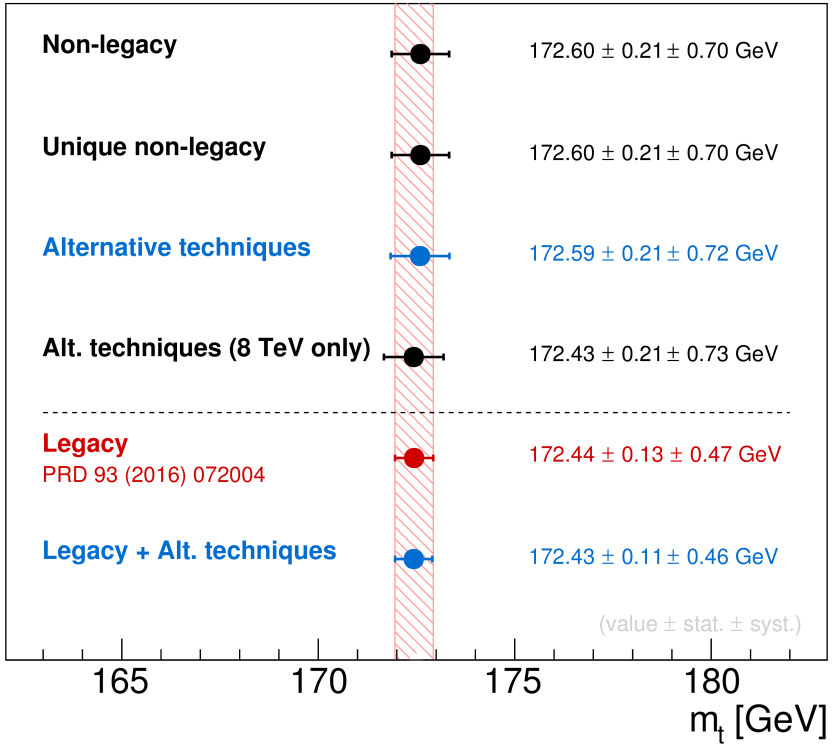


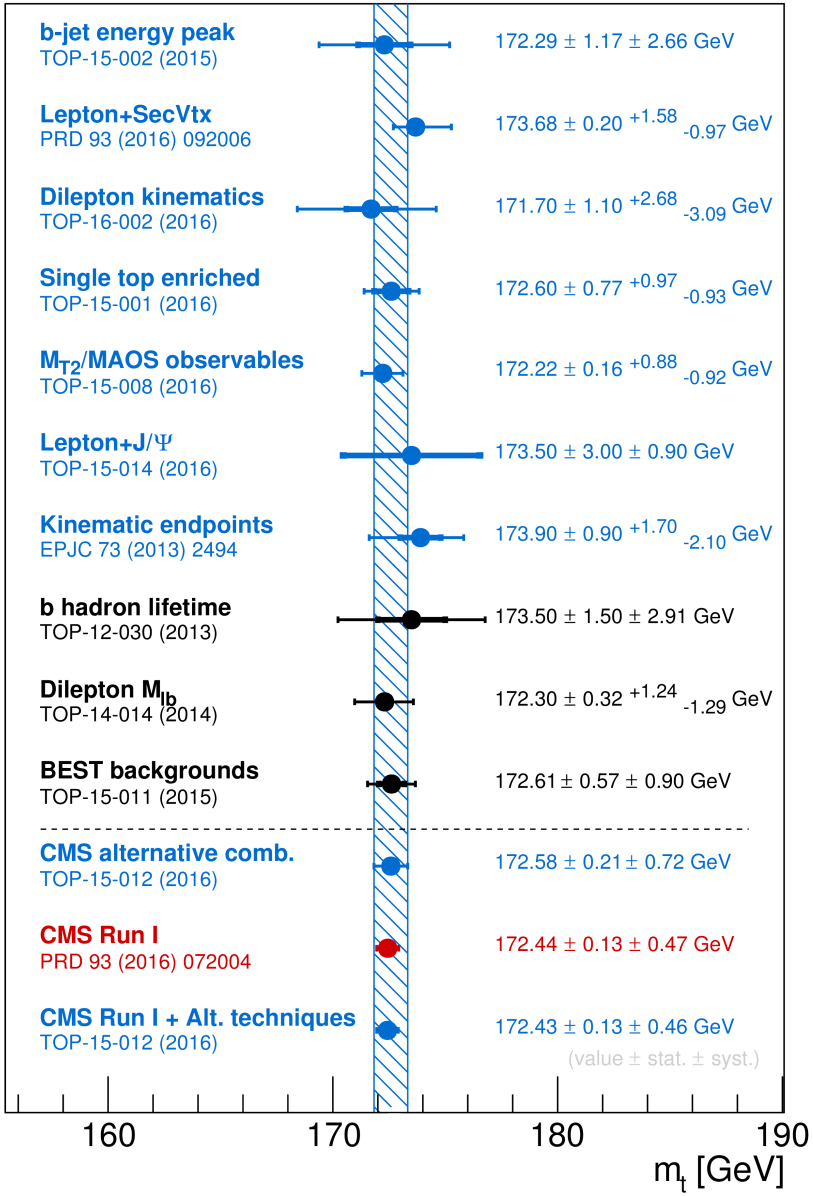
Top quark mass: direct

CMS-PAS-TOP-15-012

- Direct measurements combined using BLUE – consistent among methods/channels
- Latest CMS combination, $\delta m_t/m_t = 0.28\%$

  $m_{top} = 172.44 \pm 0.48$ GeV





- World combination, $\delta m_t/m_t = 0.44\%$

  $m_{top} = 174.34 \pm 0.76$ GeV

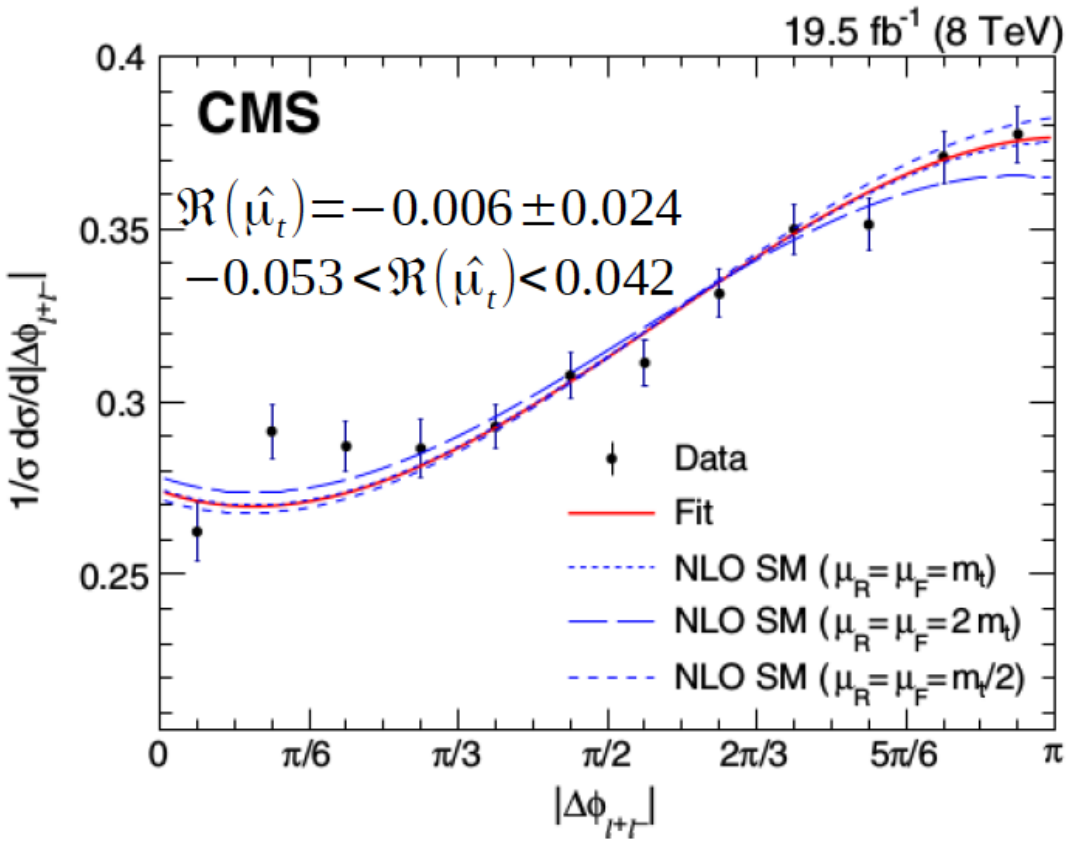
- Final D0 combination, $\delta m_t/m_t = 0.43\%$

  $m_{top} = 174.95 \pm 0.75$ GeV [arXiv:1703.06994]

Top quark spin correlations

- Top quark spins expected to be correlated in SM
- Reconstruction based on leptons → Dilepton decay channel, ≥ 2 jets
- Inclusive and differential measurements @ parton level by reg. Unfolding
- Dominated by: Unfolding & top p_T reweighting

→ Results agree with NLO QCD: Spins correlated!



•Search for top chromomagnetic anomalous couplings using differential cross section distribution

PRD 93, 052007 (2016)

CP-conserving dipole moment CP-violating dipole moment

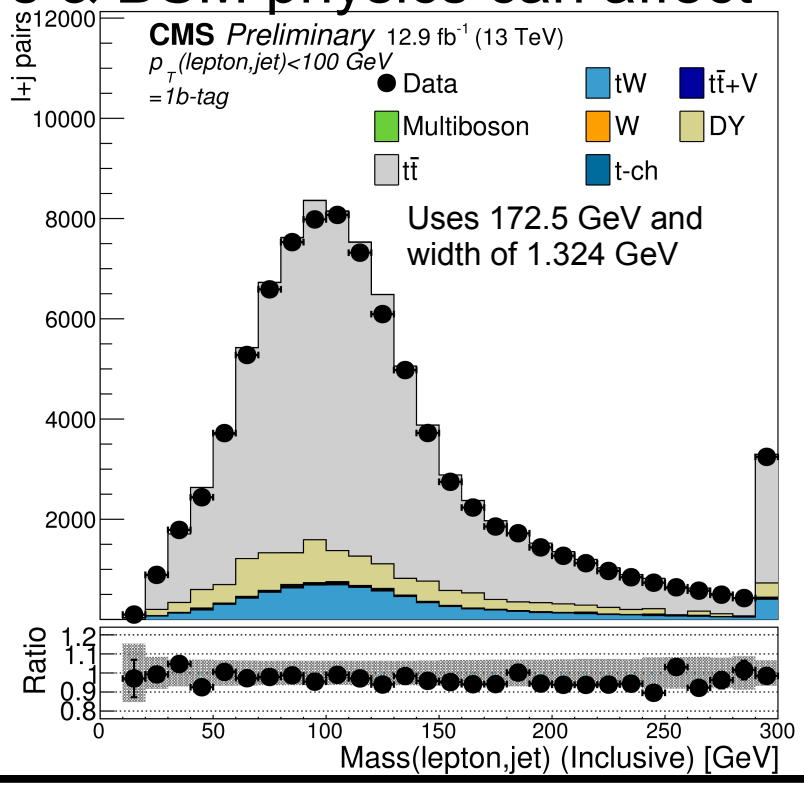
$$\mathcal{L}_{\text{eff}} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

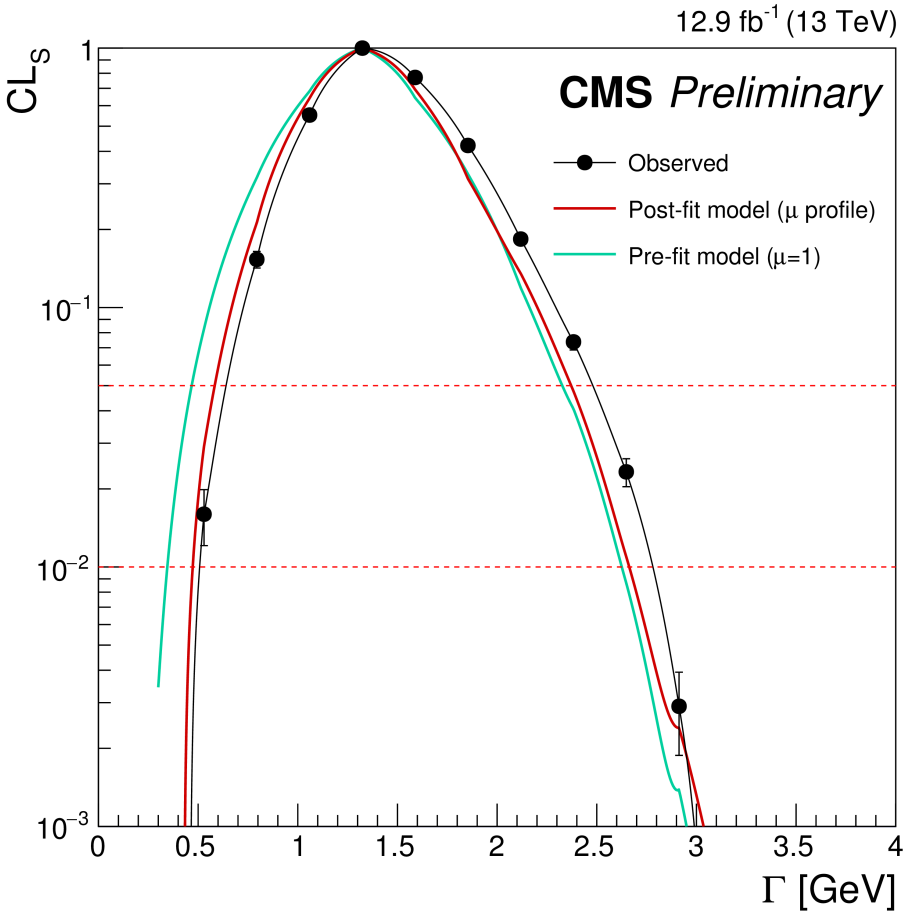
$Re(\mu_t) = -0.006 \pm 0.024$ (tot.)
– $0.053 < Re(\mu_t) < 0.042$ at 95% CL
– $0.068 < Re(\int_t) < 0.067$ at 95% CL

Top quark width

CMS-PAS-TOP-16-019

- Requires 2 leptons (e,μ) and at least 2 jets (> 0 identified as b-jet)
- Direct bound on top quark decay width
- Likelihood approach using simulated MCs for different decay widths
- MC's accurate to NLO in production and LO in decay
- Missing orders & BSM physics can affect the extraction



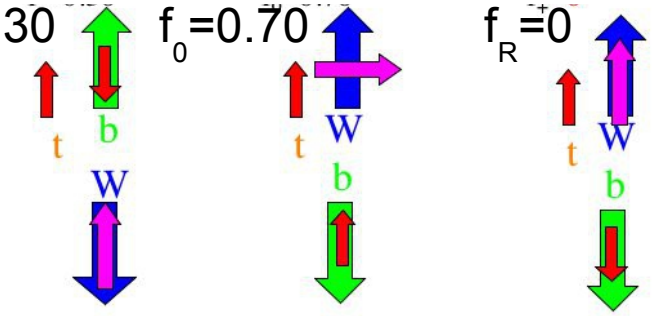


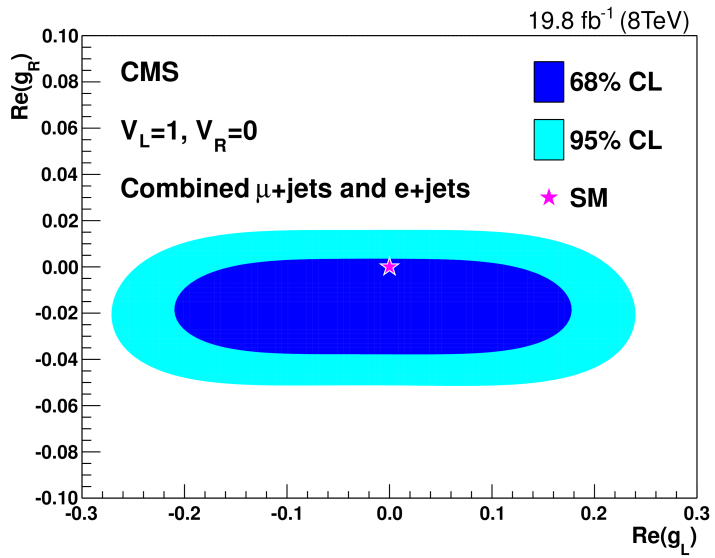
→ $0.6 < \Gamma < 2.5$ GeV @95% CL
(expected $0.6 < \Gamma < 2.4$ GeV)

W helicity

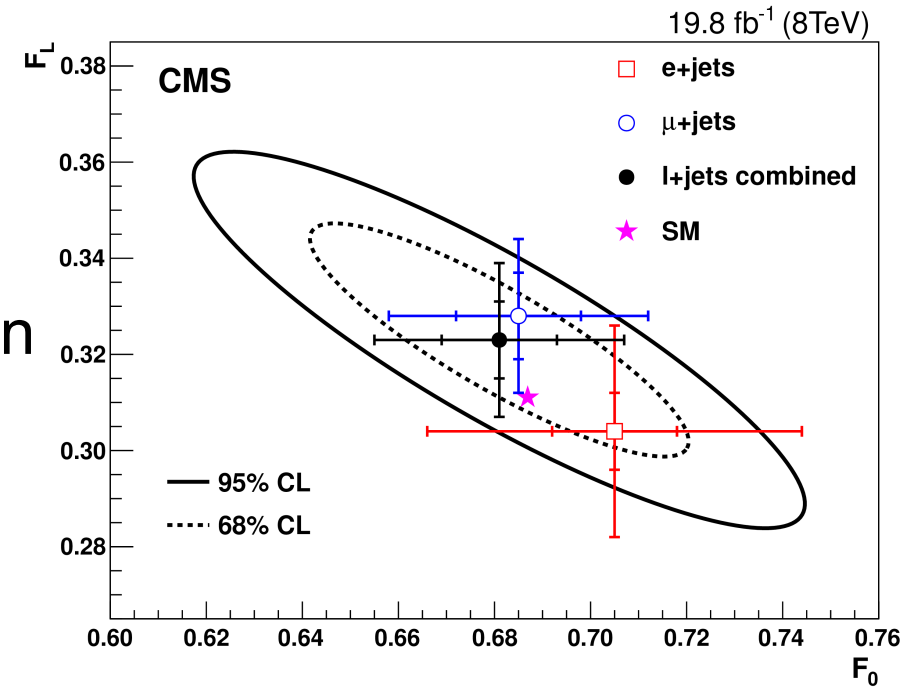
PLB 762 (2016) 512

- W helicity in SM: f_L=0.30 f_0=0.70 f_R=0





- W helicity in top pair l+jets channel
- CMS also measured W helicity in single top events
  - Similar precision but <u>orthogonal</u> systematic uncertainties in single top channels
  - Signal model & template statistics



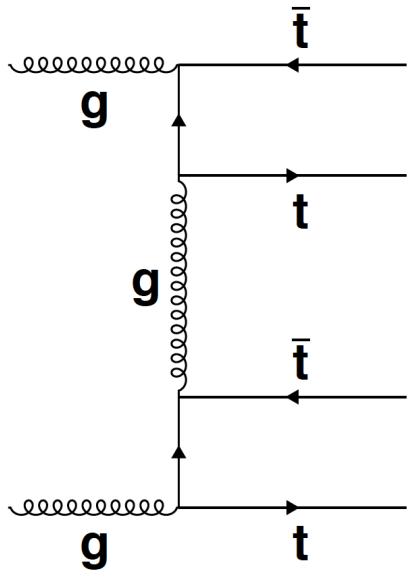
Most accurate experimental determination

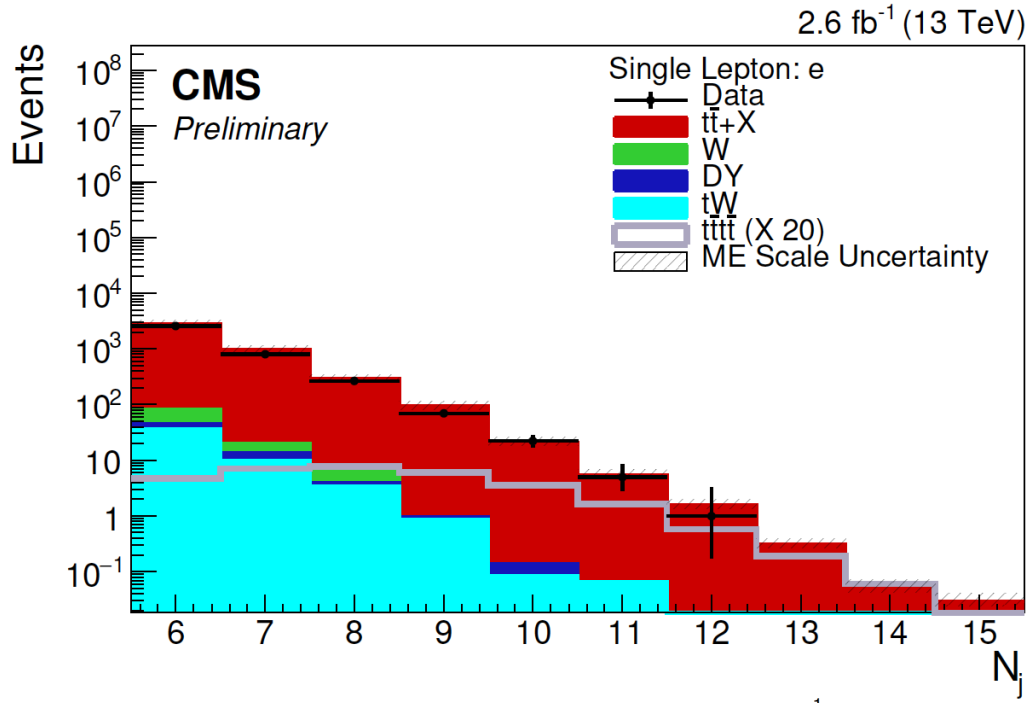
$$F_0 = 0.681 \pm 0.012 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$$
$$F_L = 0.323 \pm 0.008 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$
$$F_R = 0.004 \pm 0.005 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$

Ttbar + Ttbar

CMS-TOP-PAG-16-016

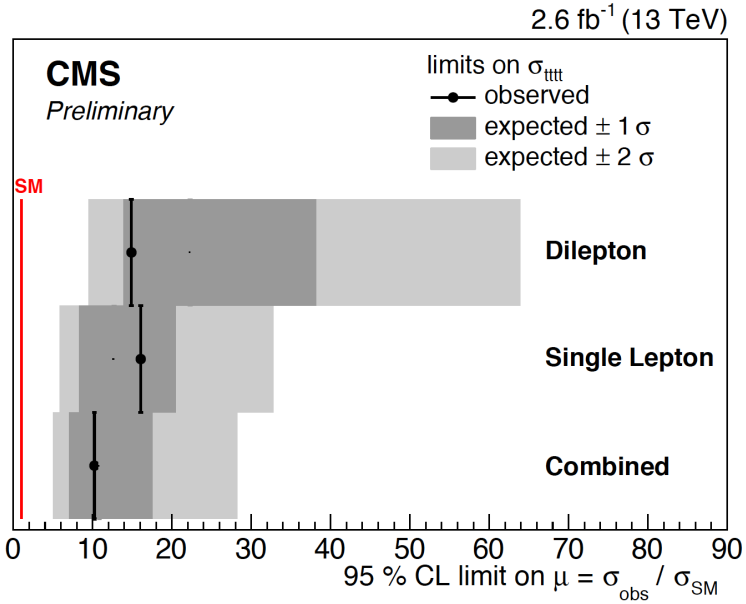
SM (NLO): $\sigma(tt+tt) = 9$ fb





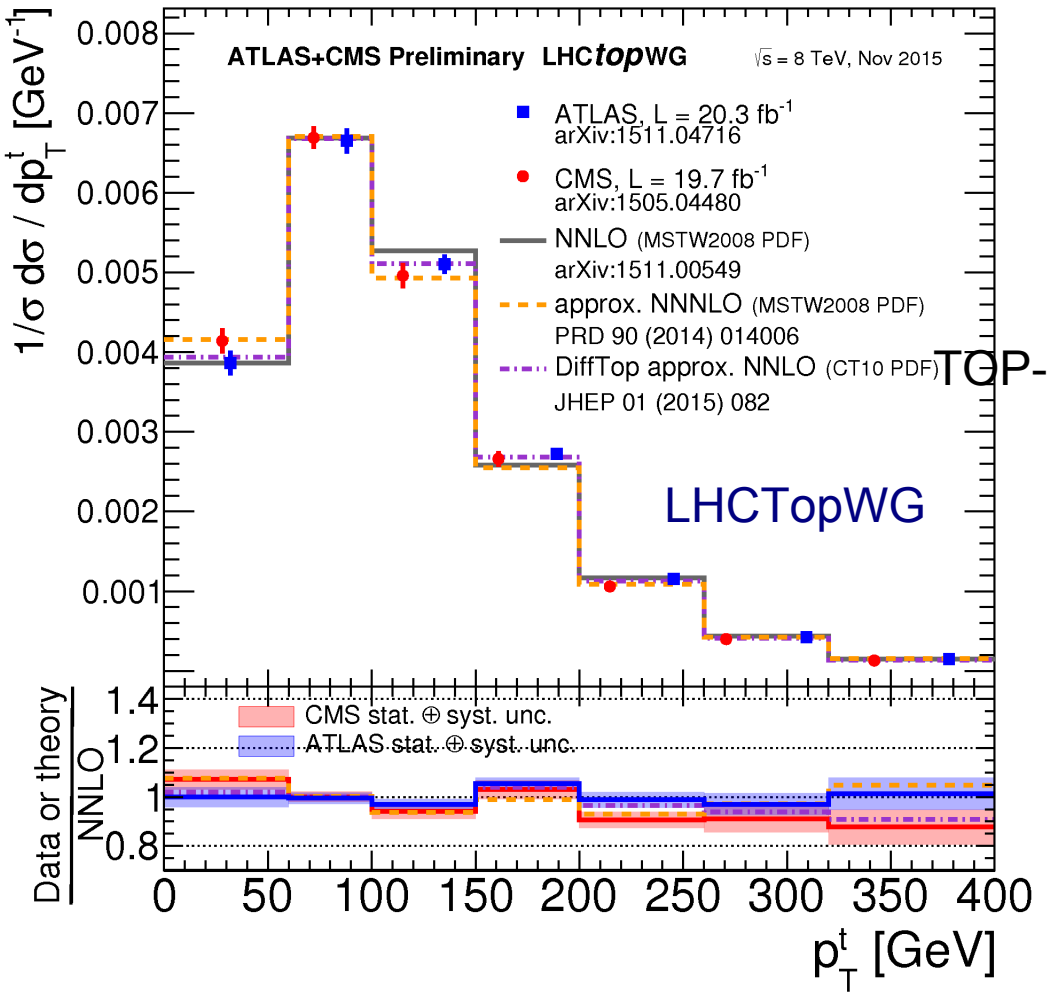
- Dilepton & l+jets channels, at least 2 b-jets
- Use boosted decision tree to enhance signal

Upper limit for Ttbar+Ttbar @95% CL:
– Observed 10.2 x σ(SM, tt+tt)
– Observed 10.8 +6.7-3.8 x σ(SM, tt+tt)

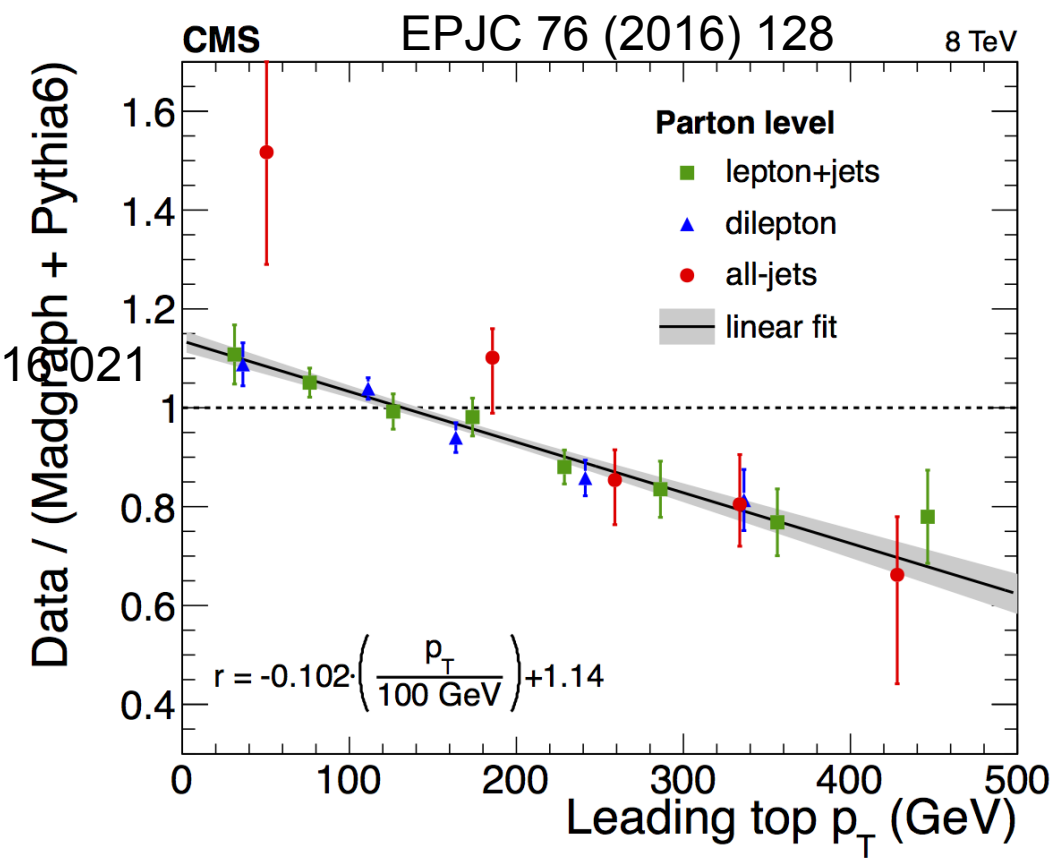


Differential cross sections

- Run I & Run II **top pT** measurements at ATLAS/CMS **not described** by NLO and most MCs
- Data is more soft: consistently seen in all decay channels

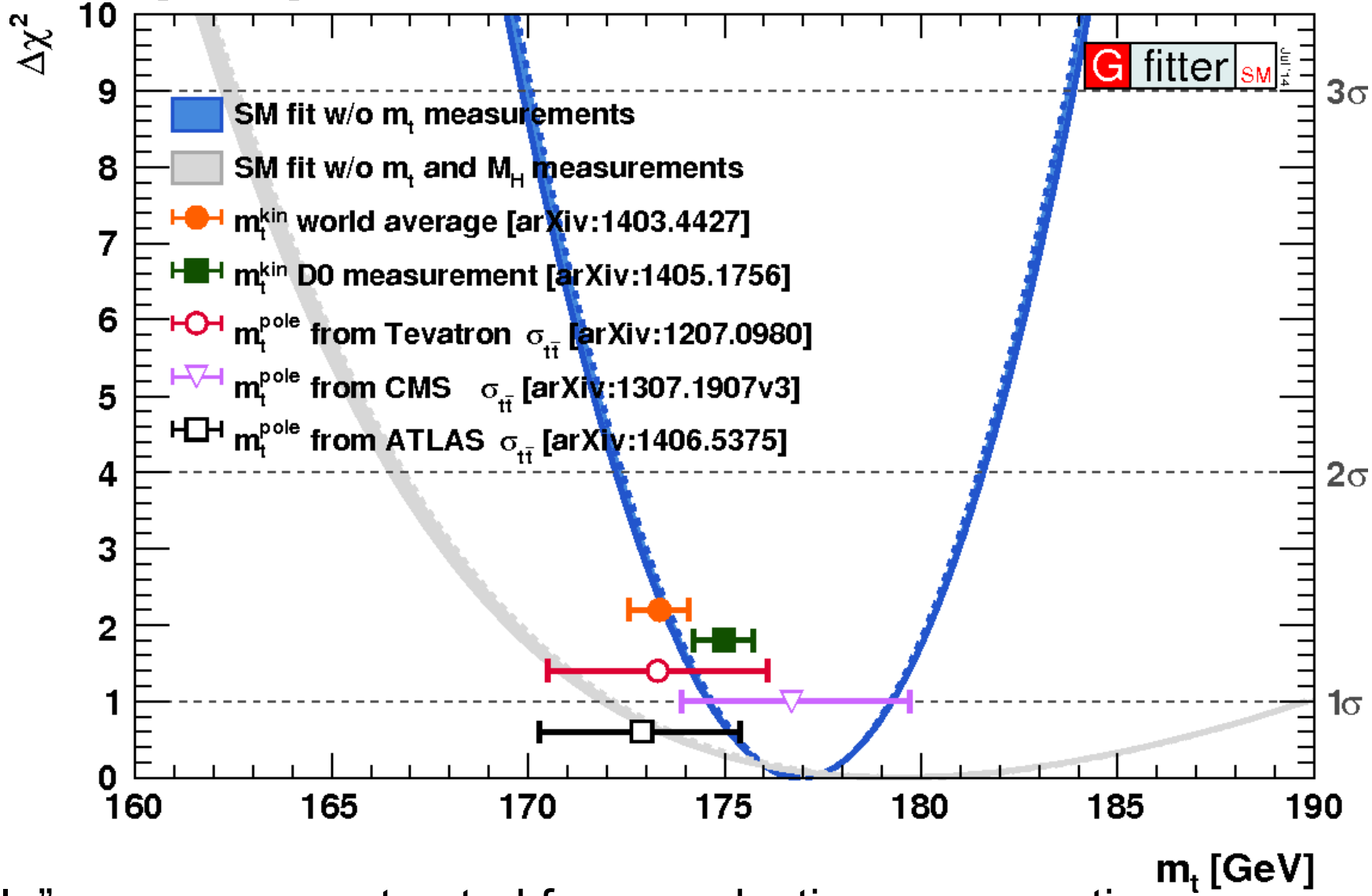


TOP-16-021



Spectra are described by NNLO+NNLL calculations

Top quark mass



→ "pole" means extracted from production cross sections

→ "kin" means direct measurements, e.g. matrix element method

Top quark polarization

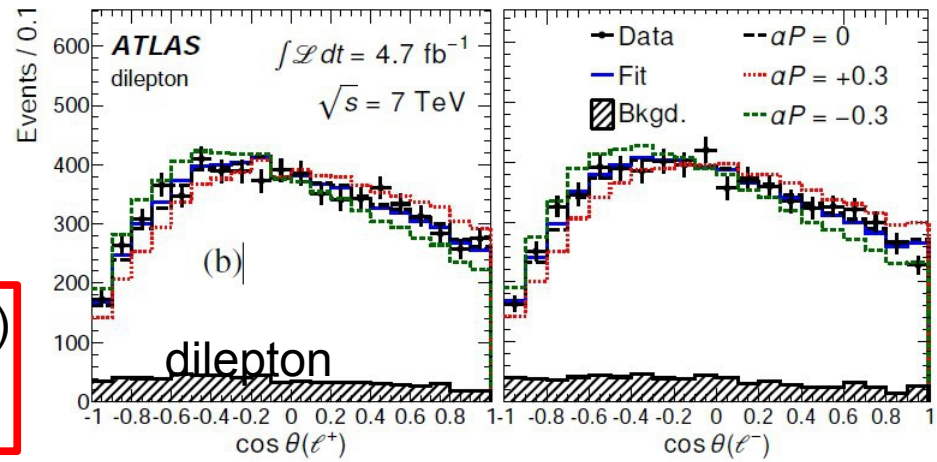
- In $t\bar{t}$ production: New physics polarizes top quarks
- Polarization introduced by CP conserving or violating process:

$$\in P_{CPC} = -0.035 \pm 0.014 \text{ (stat.)} \pm 0.037 \text{ (syst.)}$$

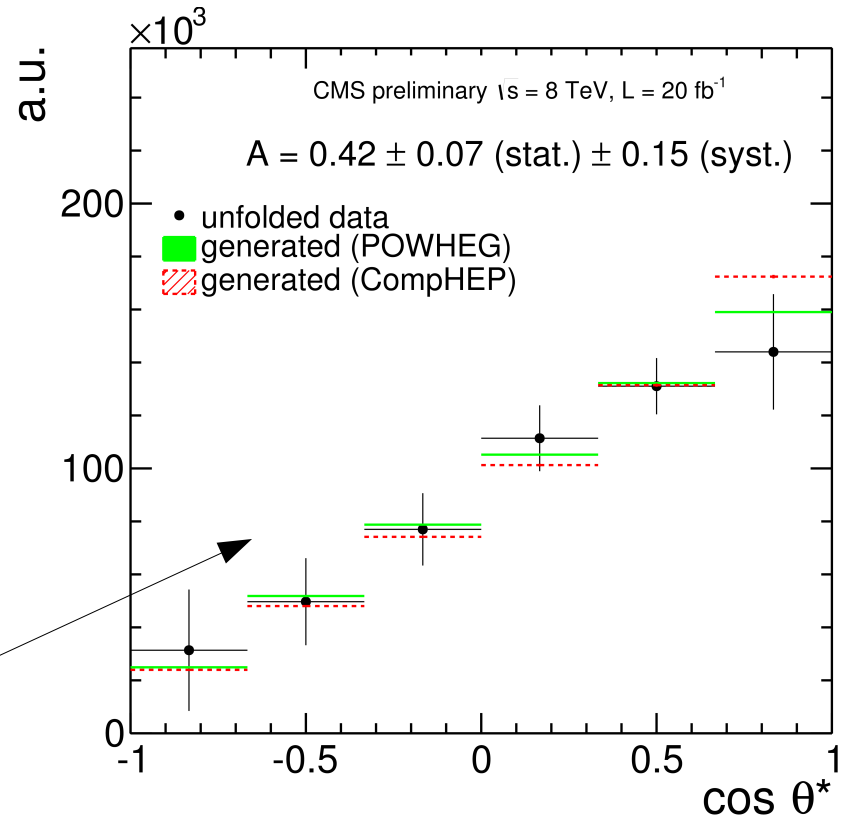
$$\in P_{CPV} = 0.020 \pm 0.016 \text{ (stat.)} \pm {}^{0.013}_{0.017} \text{ (syst.)}$$

$\in$: Spin analyzing power, P_{CPX}: top quark polarization

PRL 111, 232002 (2013)



- Good agreement with SM (negligible polarization), also seen by: → CMS: PRL 112 (2014) 182001
  → D0: PRD 87, 011103(R) (2013)



- In single top production, measure polarized top quarks as expected

$$P_t = 0.82 \pm 0.12 \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

CMS-PAS-TOP-13-001

W helicity in single top production

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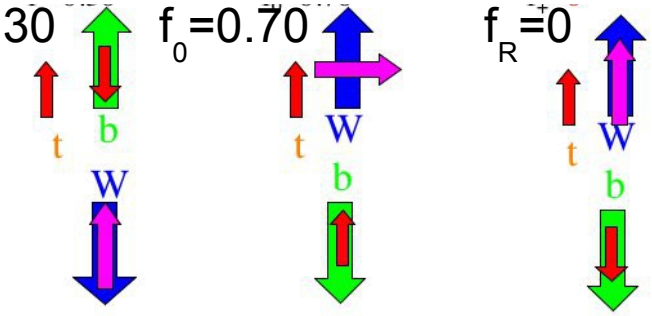
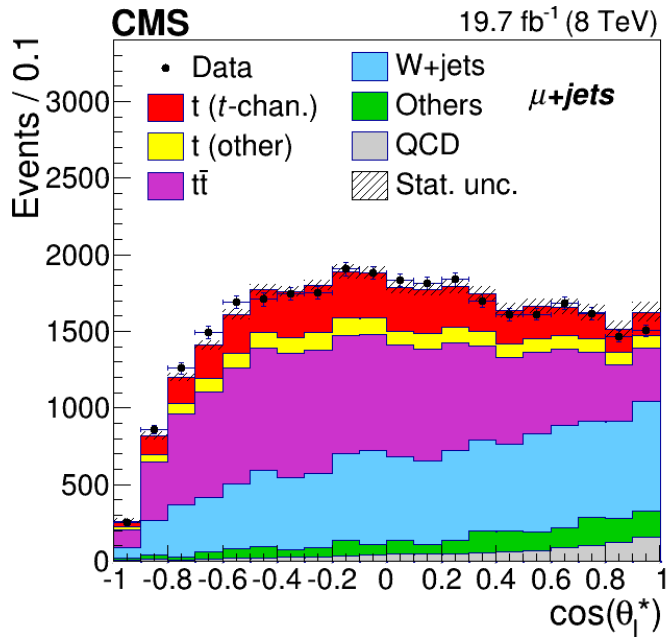
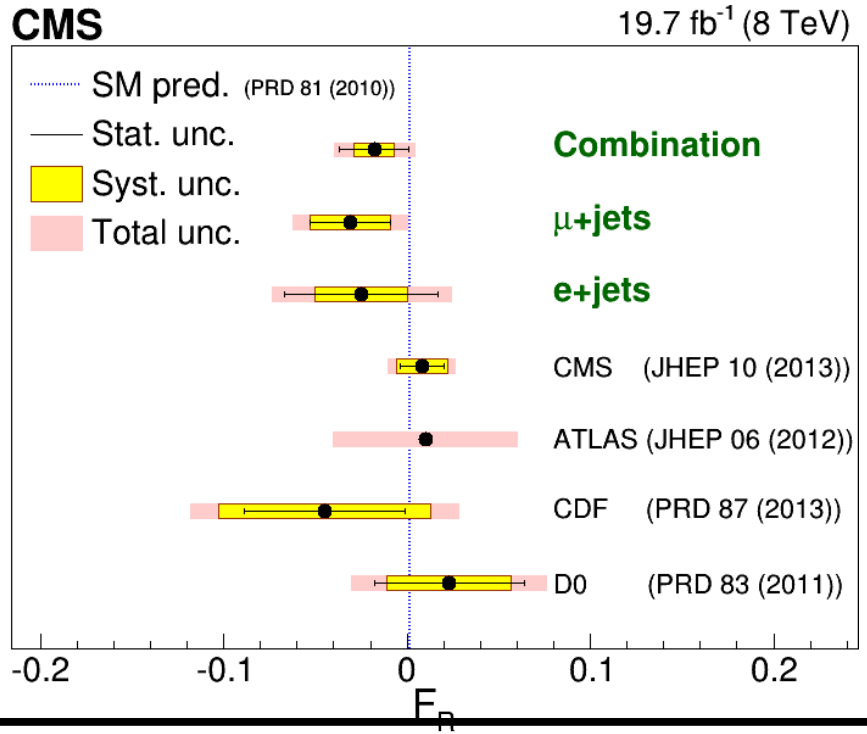
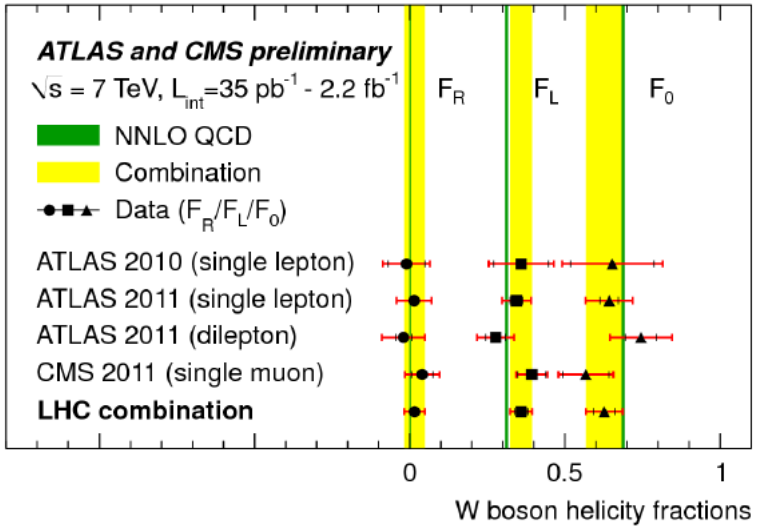
- W helicity in SM: f_L=0.30 f_0=0.70 f_R=0





- Complements results in pair production
- Similar precision but <u>orthogonal</u> systematic uncertainties in single top channels
  - Signal model & template statistics





SM vacuum stability

- With the Higgs discovery the SM can be extrapolated to Planck scale energies
- "Test" the stability of the electroweak vacuum, under assumption of no new physics:

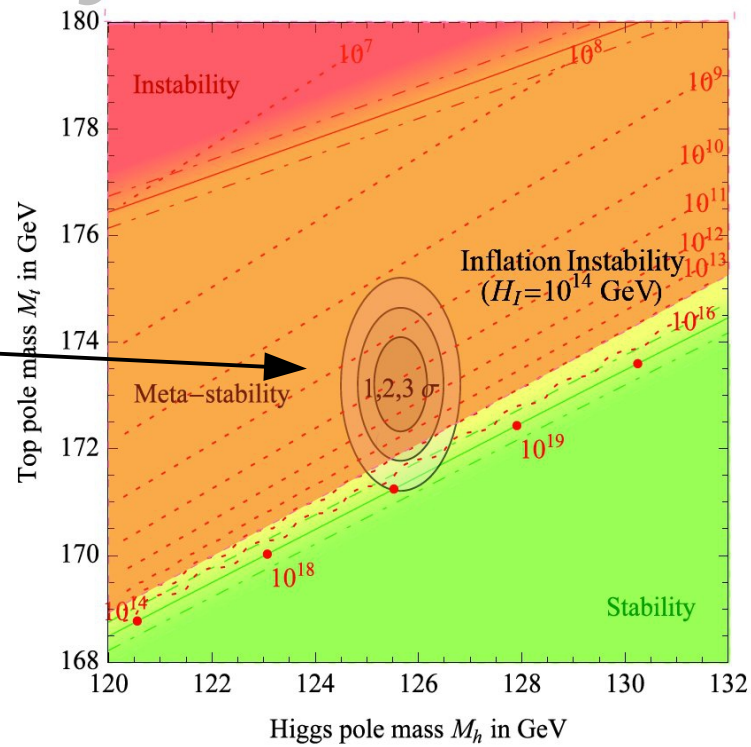
→ meta-stable, life time > O(10^{80}) $t_{universe}$

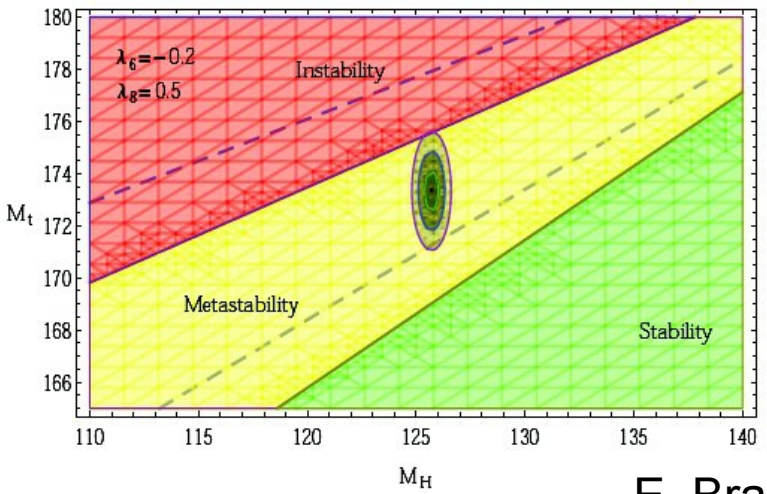
→ **but new physics can change that dramatically**

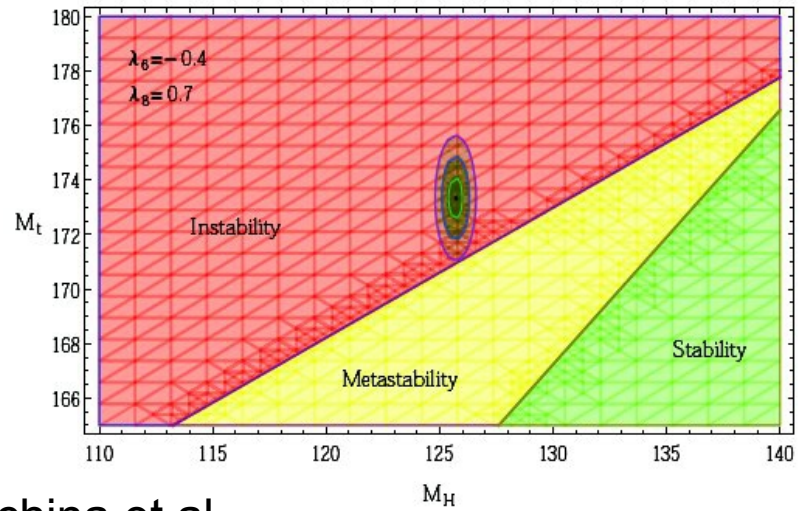
$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

SM Higgs potential

dim 6 & 8 BSM modifications







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