Top & $t\bar{t}H$ Measurements at the LHC

The 6th China LHC Physics Workshop (CLHCP2020)

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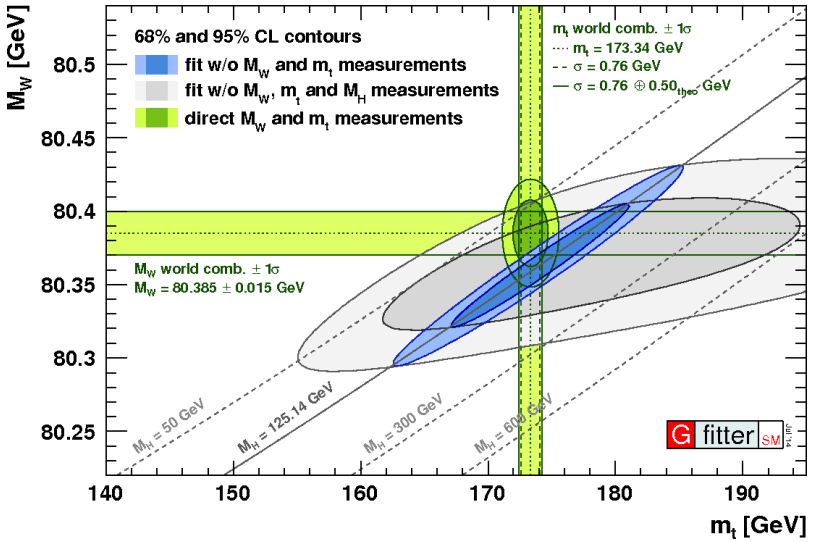
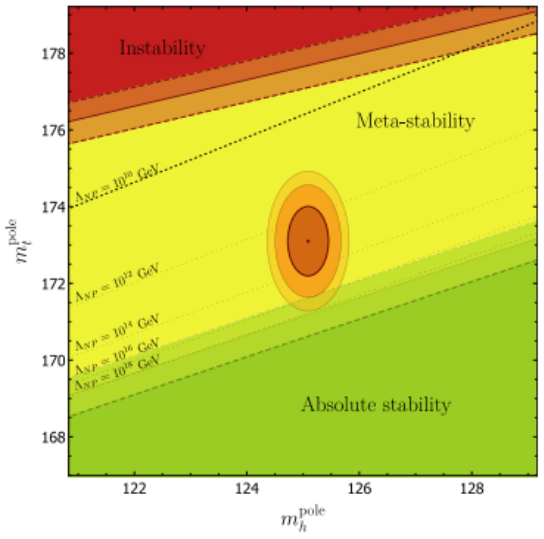
Top Quark: A Unique Particle

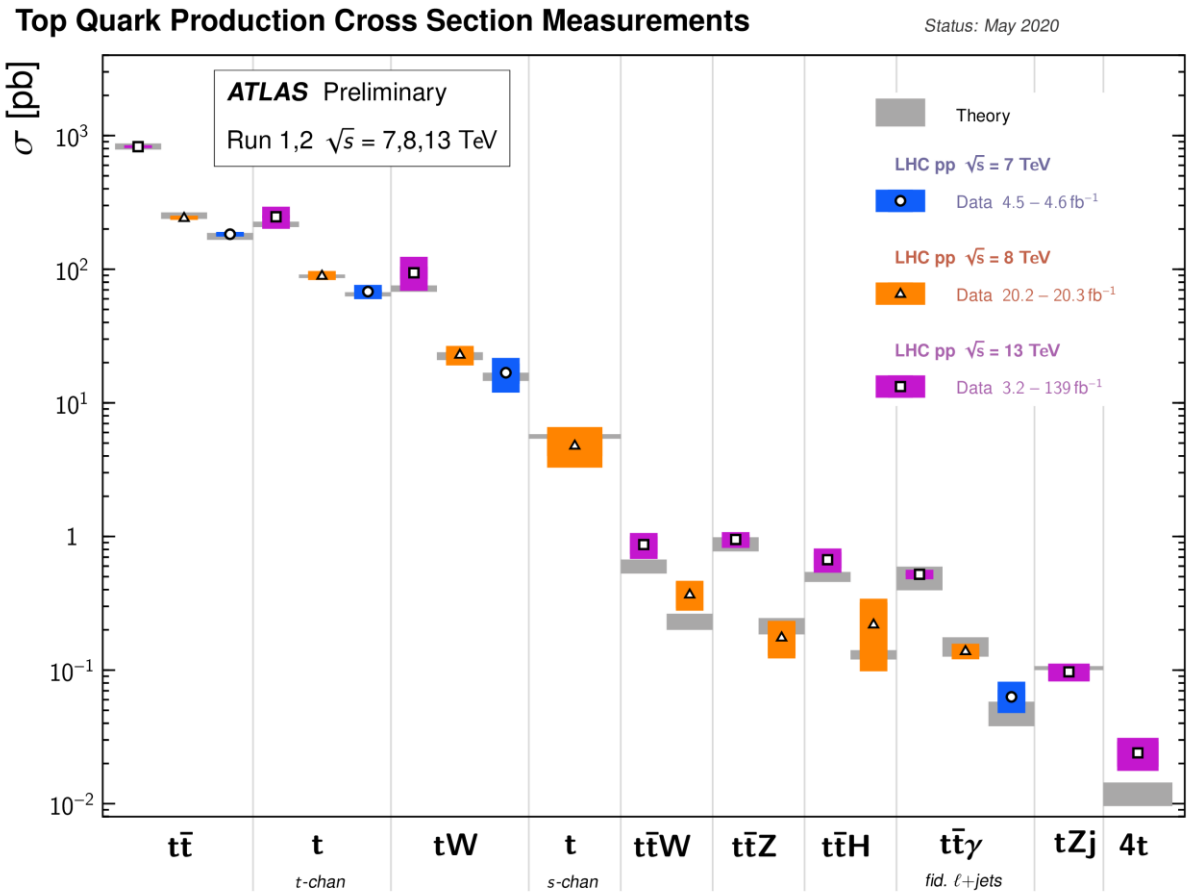
- **Top quark is the heaviest elementary particle: 172.9±0.4 GeV → y_t=0.994±0.002 (near-unity Yukawa)**
- **Decays (τ_t~0.5x10^{-24}s) before hadronizing & spin-decorrelation →** Bare quark properties, maintains spin-correlation in decay products
- Uniqueness of its phenomenology basically comes from its large mass.
- Large corrections to Electroweak observables.
- Dominant contributions in the Higgs potential → e.g. insights to its origin as well as the lifetime of the Universe





A. Andreassen et al., PRD 97, 056006 (2018)

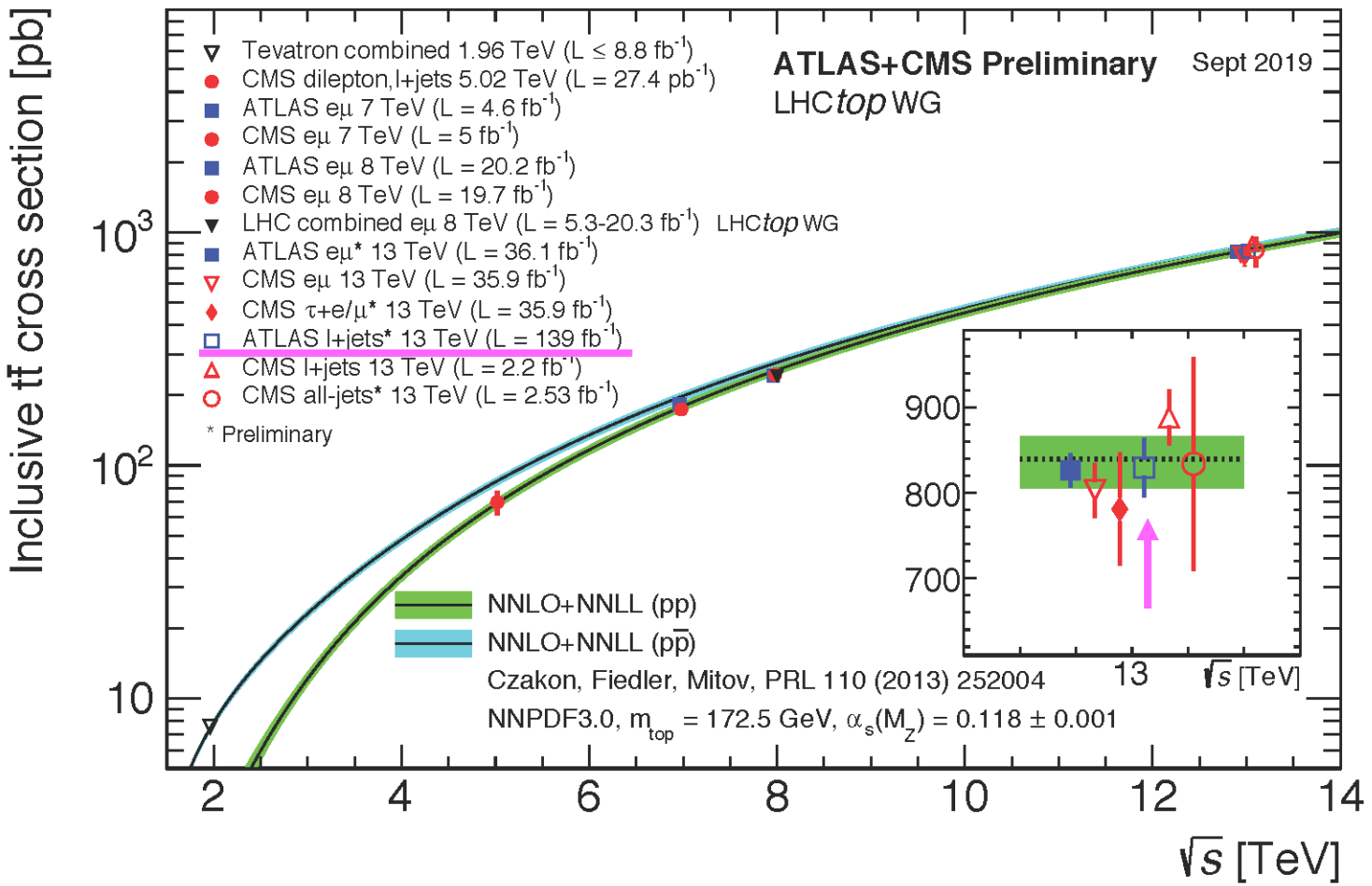
Top Production at LHC



- **LHC is new generation "Top Factory,"** covering O(10^5) range in cross section for top productions.
- ~120M top-pair events produced at CMS & ATLAS respectively.
- LHC Top program:
  - Precise cross sections measurements (inclusive & differential).
  - Searches for rare productions and decays
  - Top quark properties

Cross Section Measurements

Top Inclusive Cross Sections



- Top-pair production cross section is measured at √s=5.02,7,8,13 TeV.
- In good agreement with **NNLO QCD+NNLL resummation** (Top++ v2.0).
- ATLAS 1-lepton channel measured with Full Run-2 data.
- **The most precise measurement from the dilepton channel** (**2.4%** in ATLAS; 1.9% lumi. unc.).

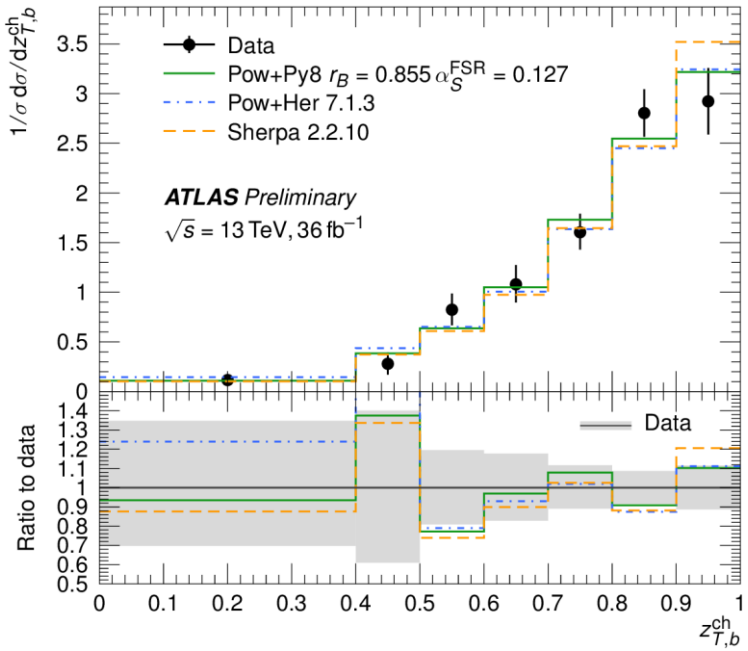
b-Quark Fragmentation NEW!

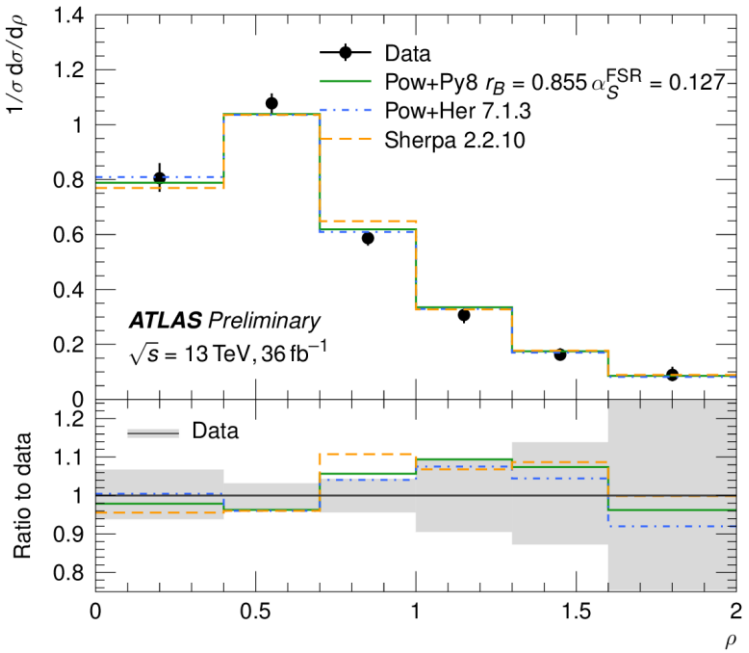
$$z_{\mathrm{T},b}^{\mathrm{ch}} = \frac{p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T,jet}}^{\mathrm{ch}}}$$

$$\rho = \frac{2p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu}}$$

$\vec{p}_{jet}^{ch}$: momentum sum of charged particles in jet

$\vec{p}_{b}^{ch}$: momentum of b-hadron in jet

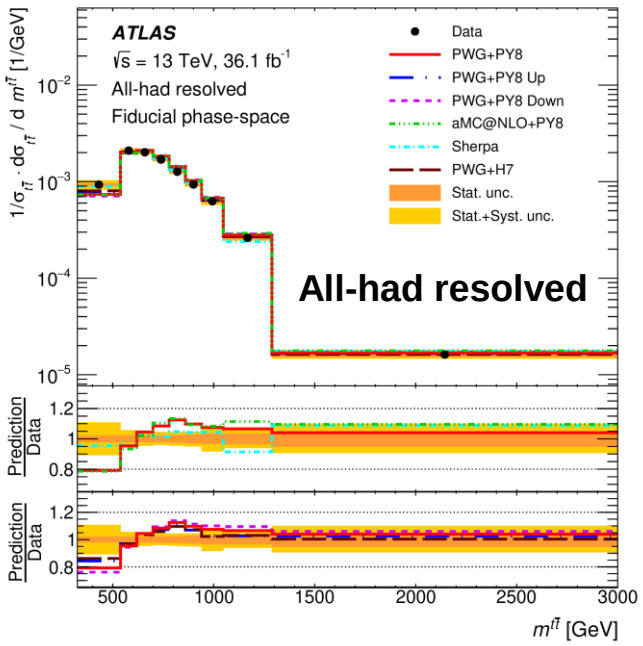


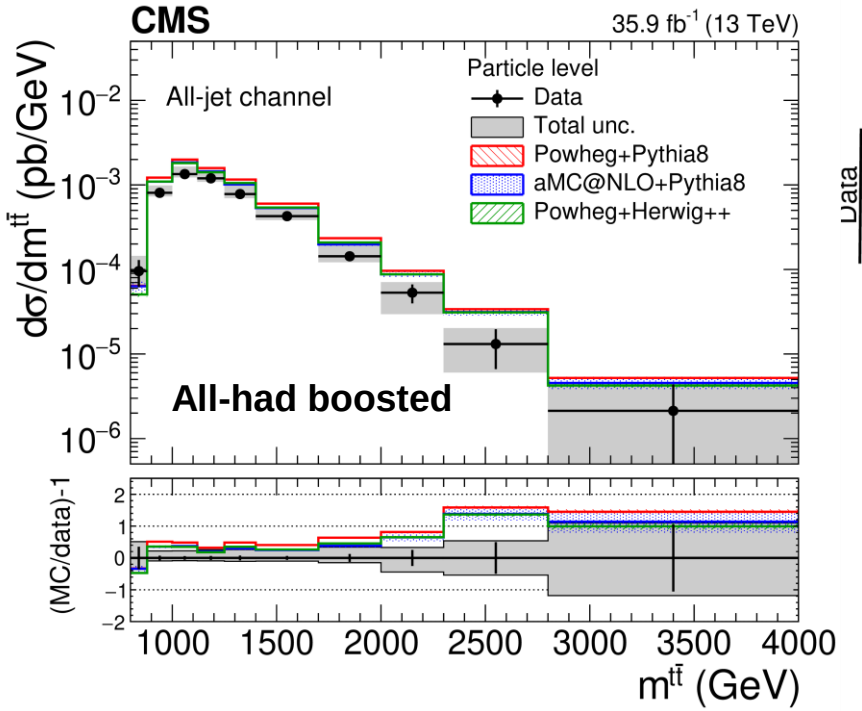


- **Large number of b-jets from $t\bar{t}$ provides complementary measurements of b-quark fragmentation to e^+e^- colliders.** Dilepton channel is used.
- Longitudinal/transverse momentum, soft-lepton, number of b-hadron children distributions are **largely in agreement with the state-of-the-art MC generators**.
- Fragmentation modeling is not yet sufficient for mass measurement → NNLO calculation under way.

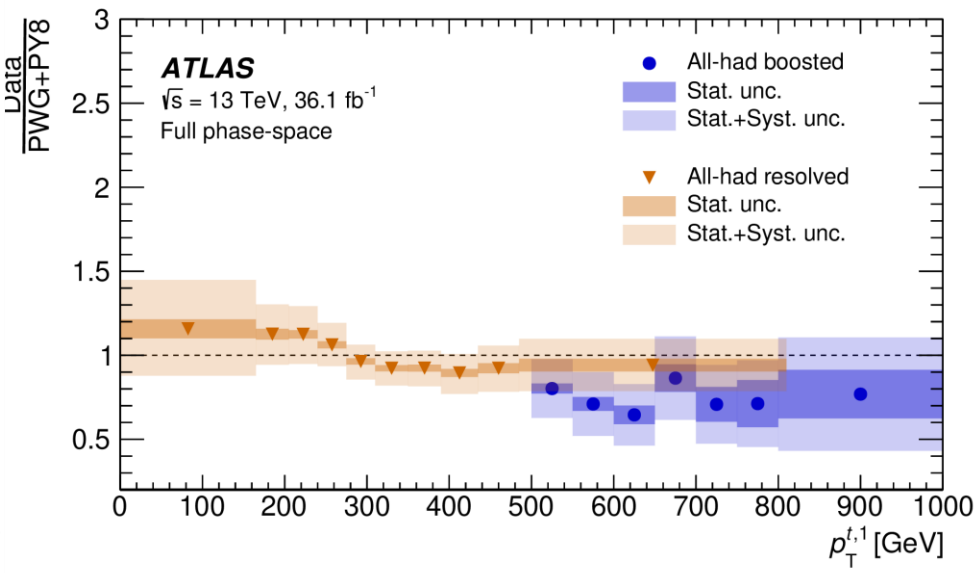
A.Mitov et al.

$t\bar{t}$ Differential Cross Section



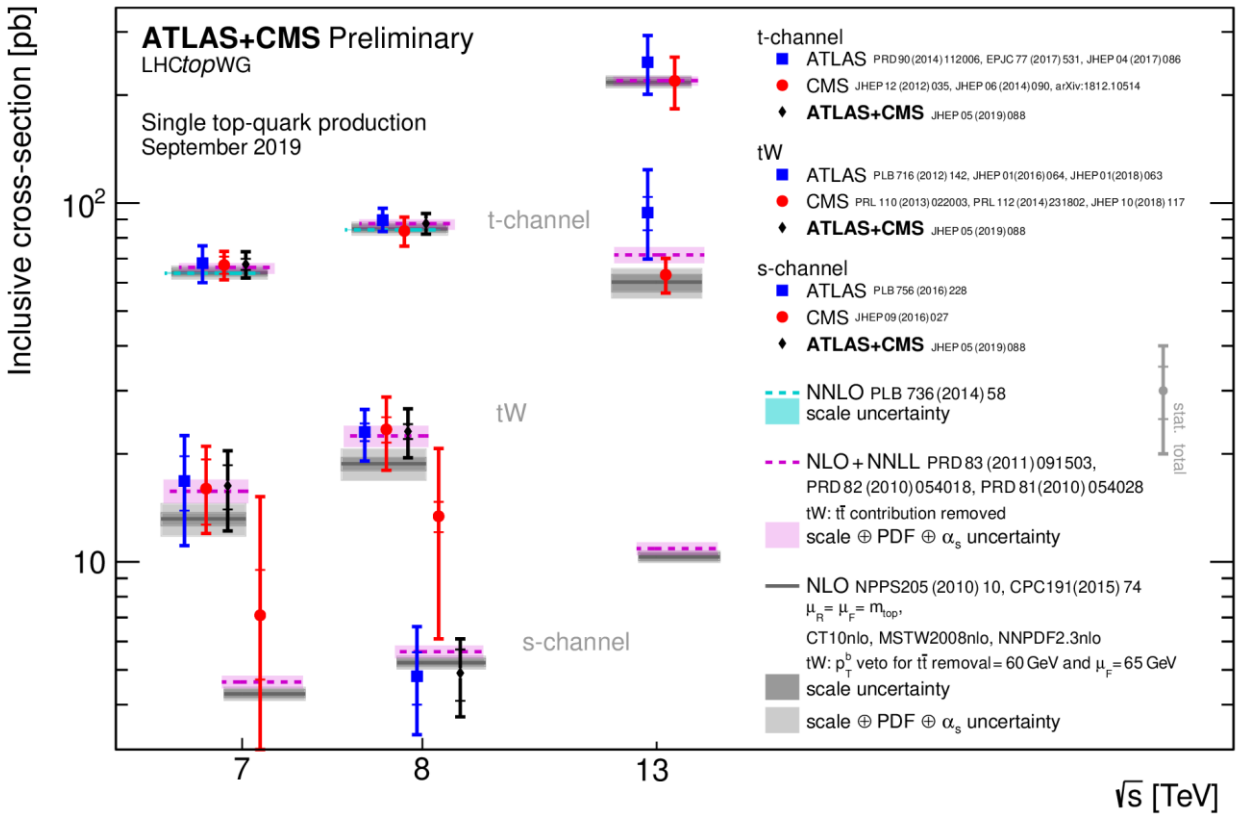


arXiv:2006.09274 (ATLAS), arXiv:2008.07860 (CMS)

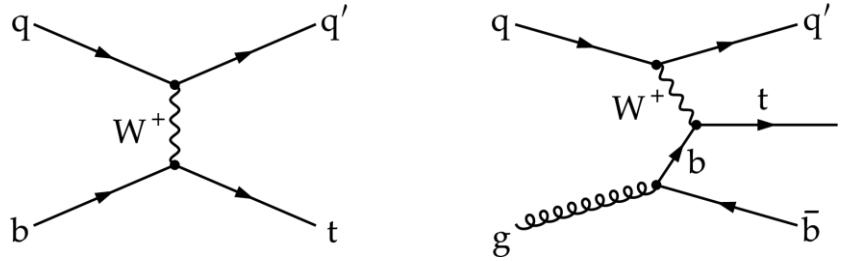


- Similar trends observed in differential cross section measurements for 0,1,2-lep. channels. **Slope seen for top p_T, m_{tt} and other related kinematics.**
- **Shape is well described in the boosted region, but sizable discrepancy in absolute cross section.** ← Likely originating from the slope seen in resolved measurements.

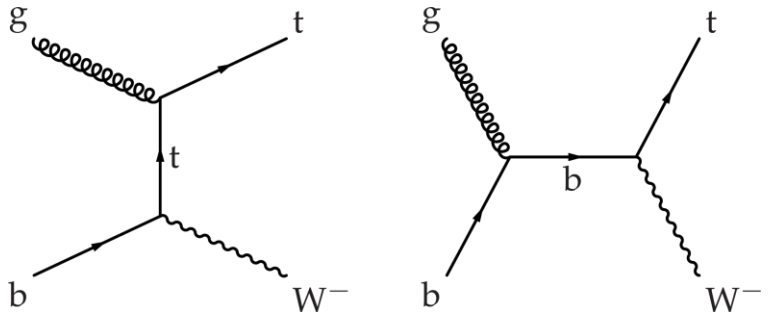
Single Top



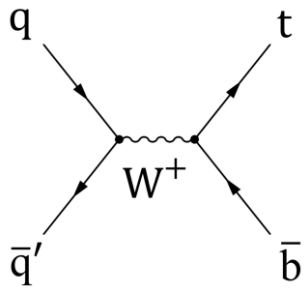
t-Channel



W-association (tW)



s-Channel

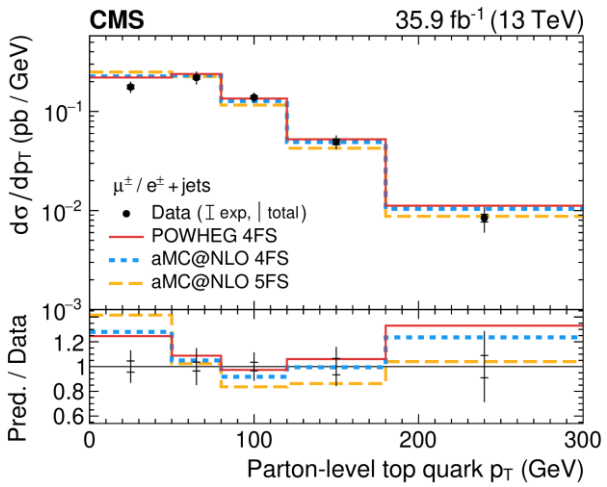


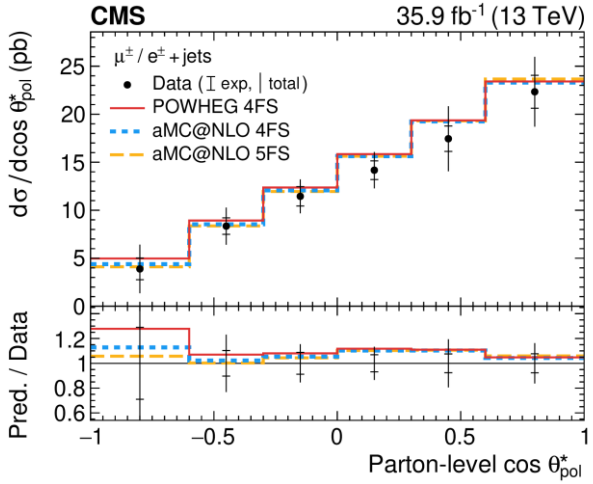
- Inclusive xsec measurements are **in good agreement w/ NLO+NNLL & NNLO prediction.**
- **The very rare Z-association mode was observed in 2018.**

$\sigma^{SM} = 94.2 \pm 3.1$ fb

PRL 122 (2019) 132003, JHEP 07 (2020) 124

Single Top Differential





t-Channel

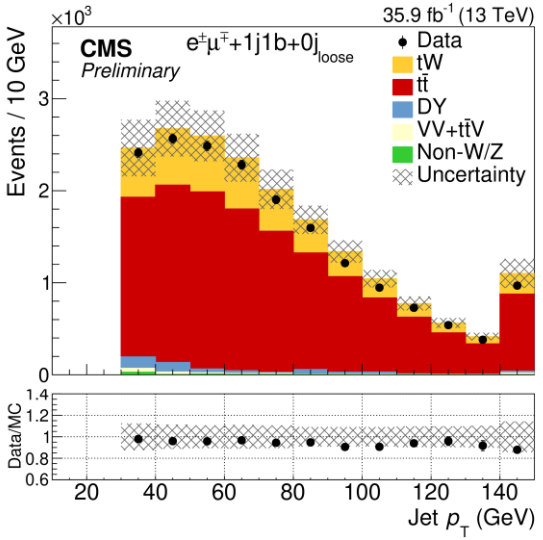
Eur. Phys. J. C 80 (2020) 370

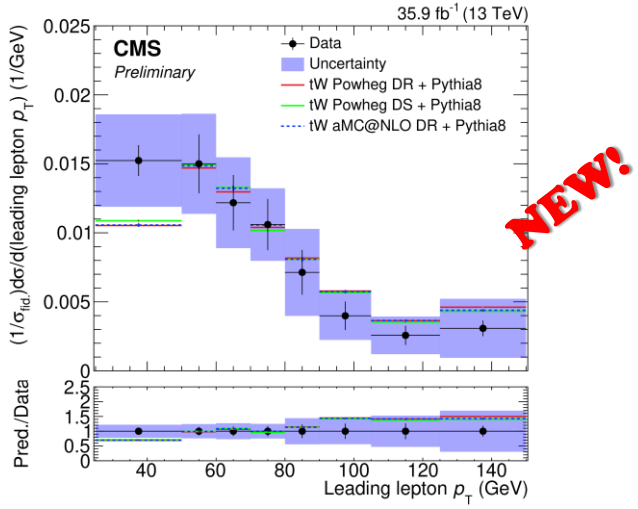
- Differential measurement in 1-lepton channel.
- Good agreement w/ NLO QCD prediction.
- Spin asymmetry is measured from the polarization angle distribution: 0.440 ± 0.070 → consistent with SM

tW

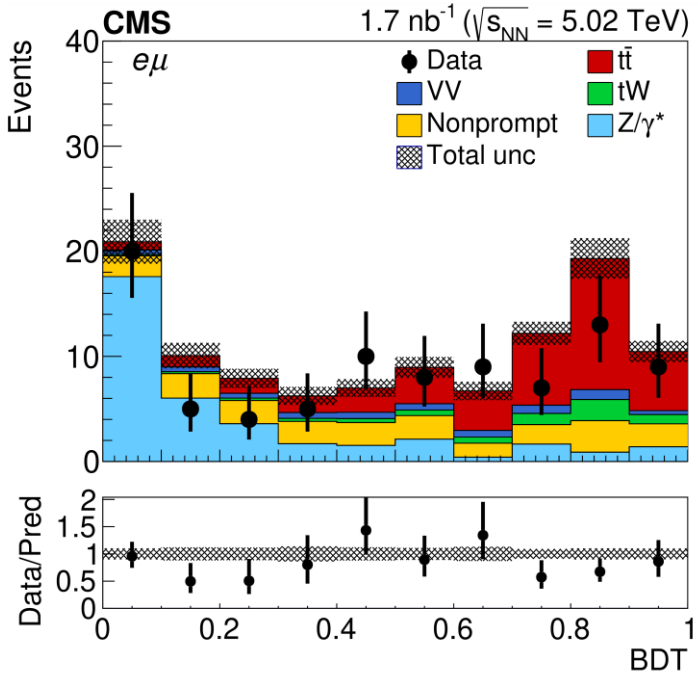
Eur. Phys. J. C 78 (2018) 186 (ATLAS), CMS-PAS-TOP-19-003

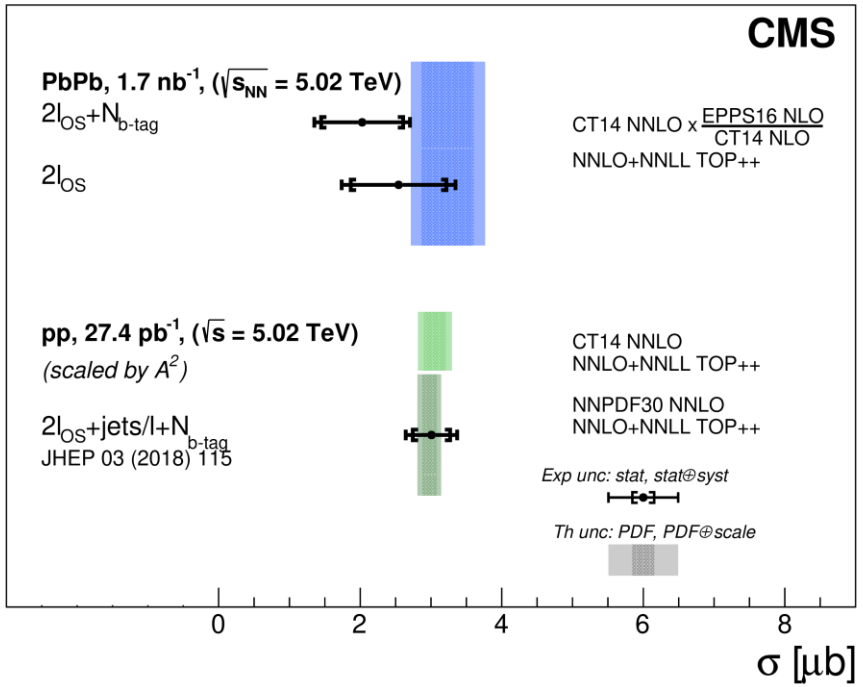
- Differential measurement is **challenging due to the large $t\bar{t}$ background**.
- Good agreement w/ NLO QCD prediction.



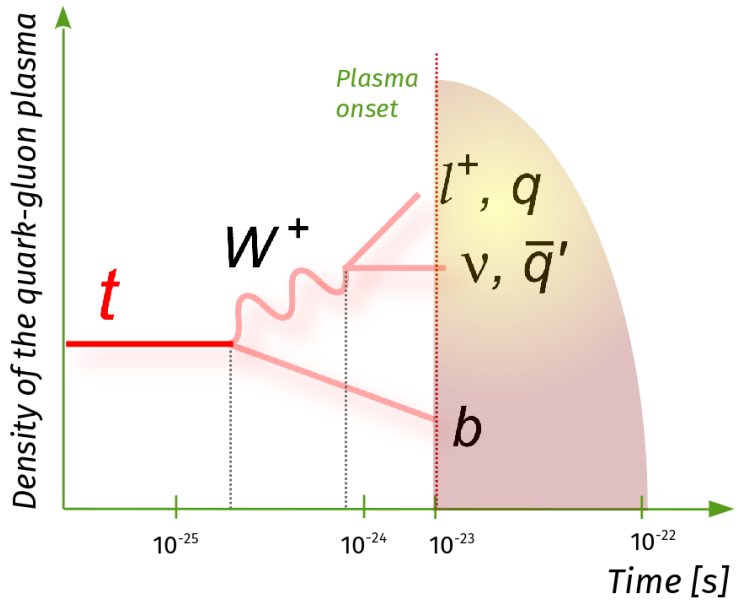


First Evidence of Top in PbPb





arXiv:2006.11110, accepted by PRL



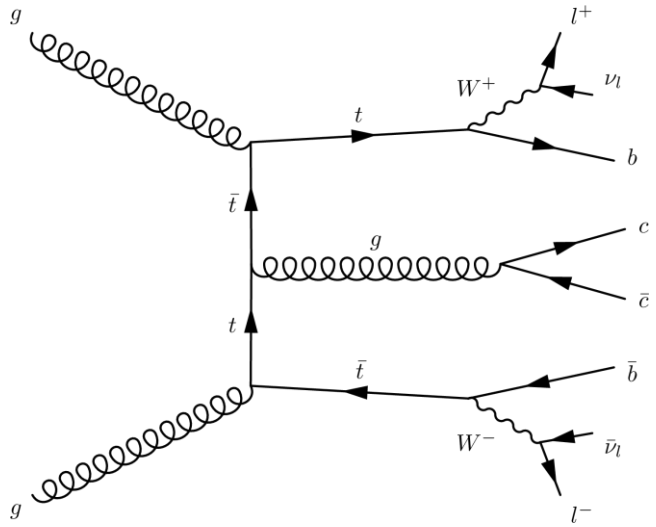
- **First-ever evidence of top-quark production w/ dilepton channel in PbPb!**
- Measured xsec is compatible with the scaled pp xsec & QCD prediction.
- **Will be an interesting new probe for QGP studies in the HL-LHC era.**

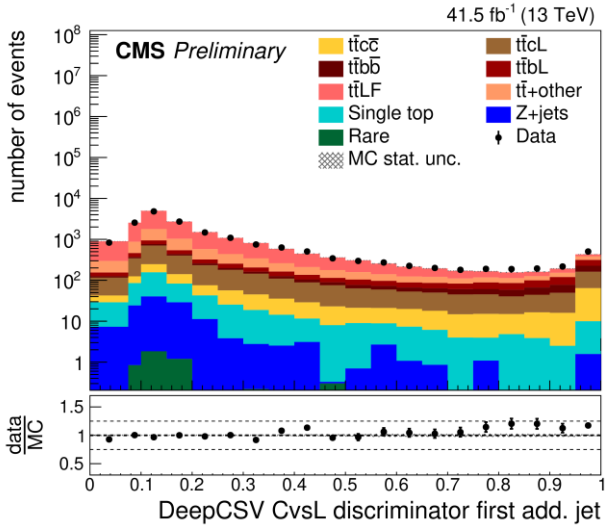
Rare Processes ($t\bar{t}$+X) & Decays

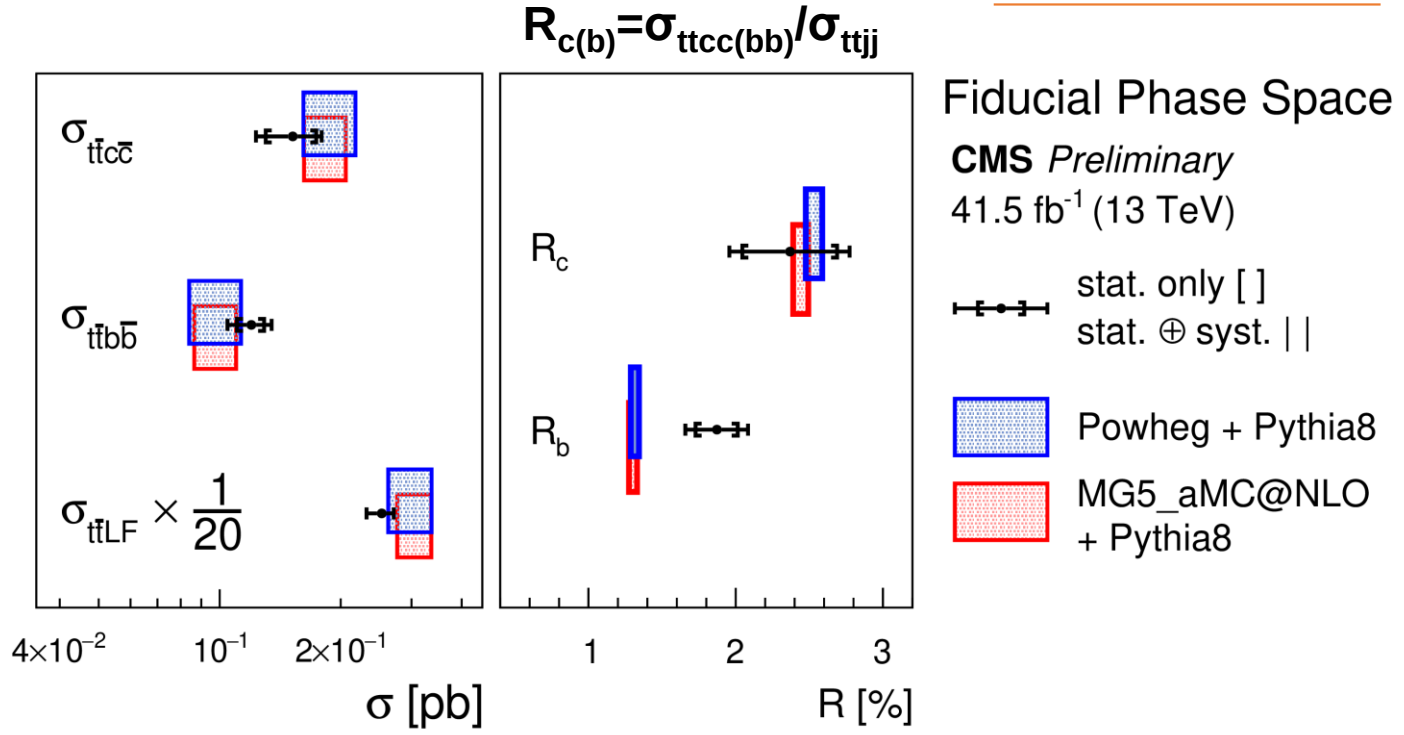
$t\bar{t}$ + $c\bar{c}$ / $b\bar{b}$ / jj

NEW!

CMS-PAS-TOP-20-003

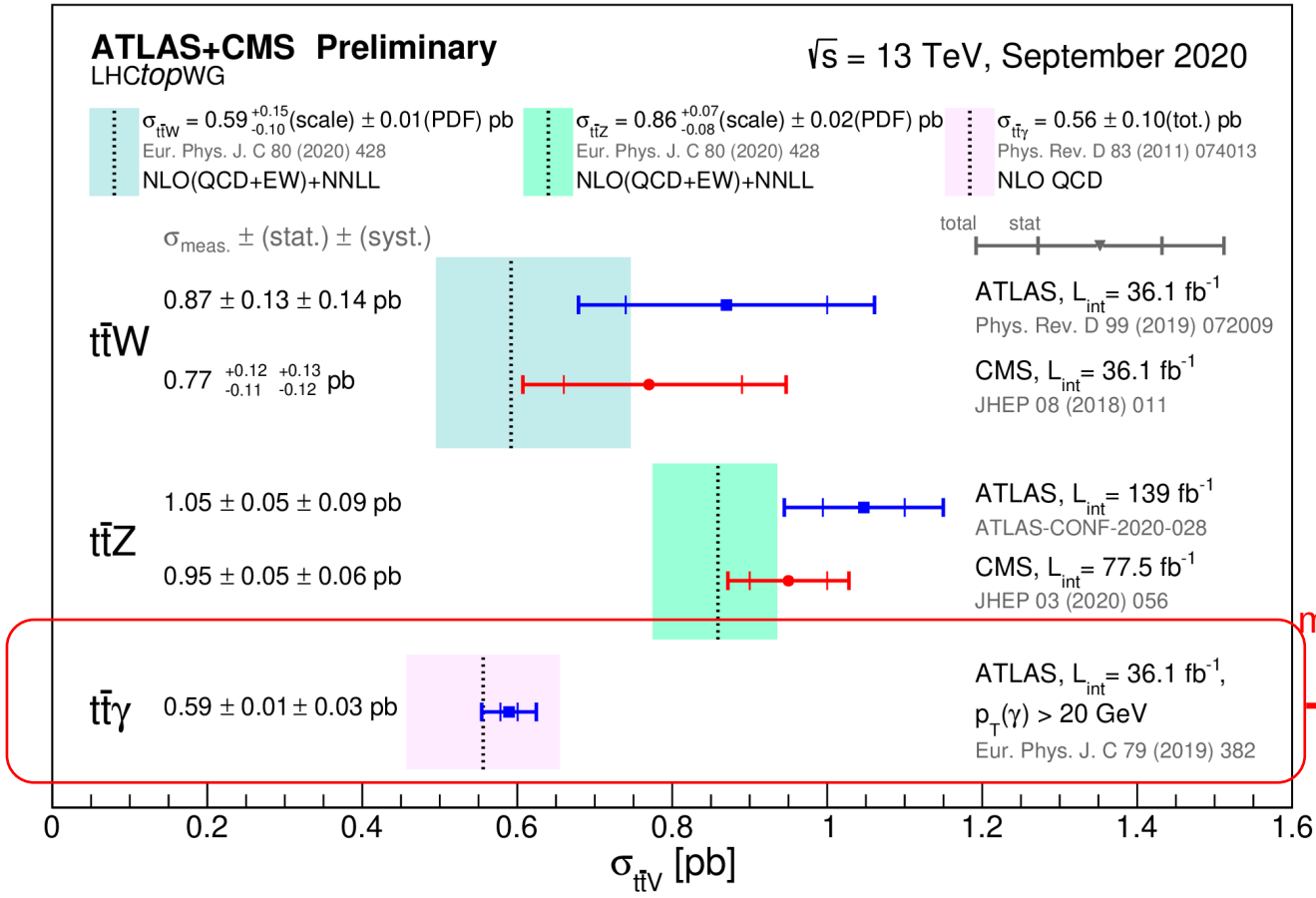






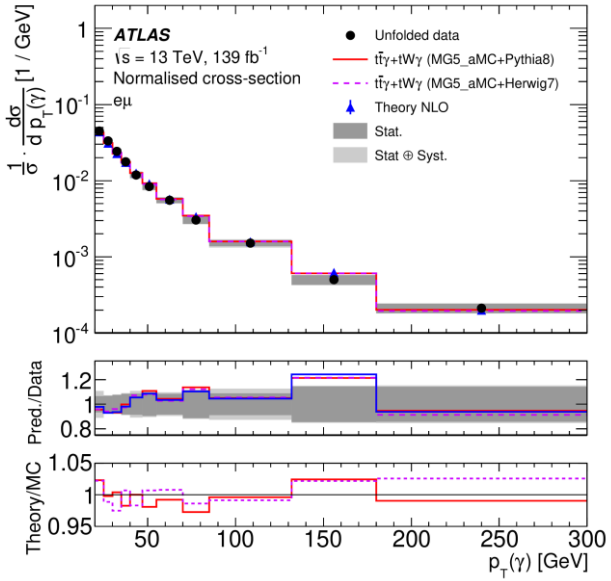
- **Theoretically very challenging** to model $t\bar{t}$+$c\bar{c}$/$b\bar{b}$ due to 2 distinct scales in diagram (top mass & soft gluon splitting).
- **$t\bar{t}$+$c\bar{c}$ measured for the first time** in dilepton chan. **with simultaneous fit to $t\bar{t}$+$b\bar{b}$ & $t\bar{t}$ +LF(jj)** using **c-taggers**.
- Generally in good agreement. 2.5σ deviation in R_b.

$t\bar{t}$+V



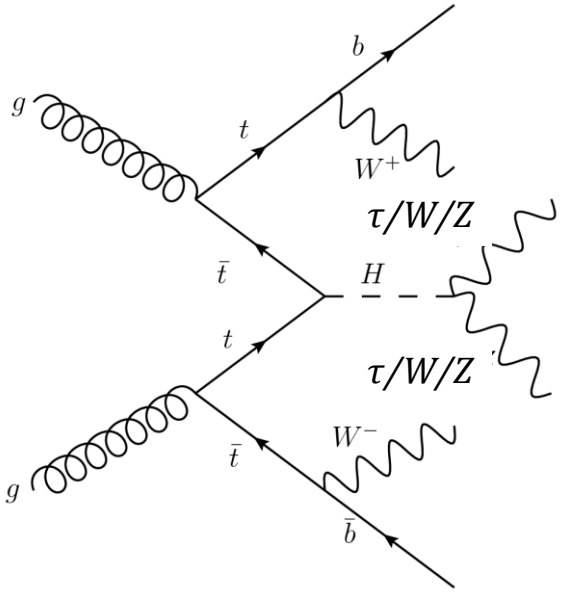
- Direct measurement of top couplings to gauge bosons.
  - Important inputs to EFT
- $t\bar{t}W$ & $t\bar{t}Z$ are dominant irreducible BG for $t\bar{t}H$.

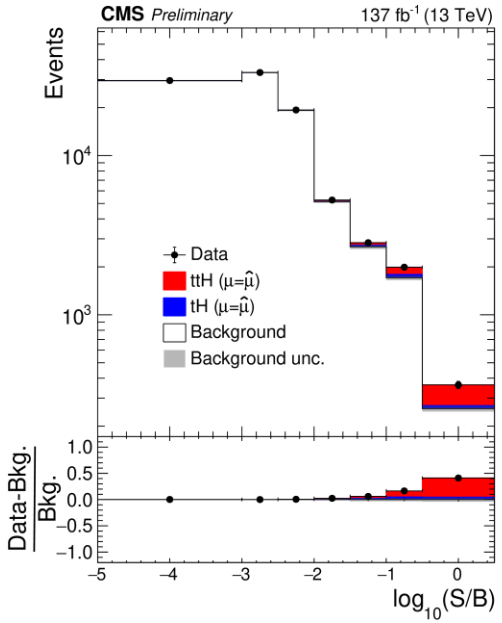
Fiducial & differential measurements available with Full Run 2

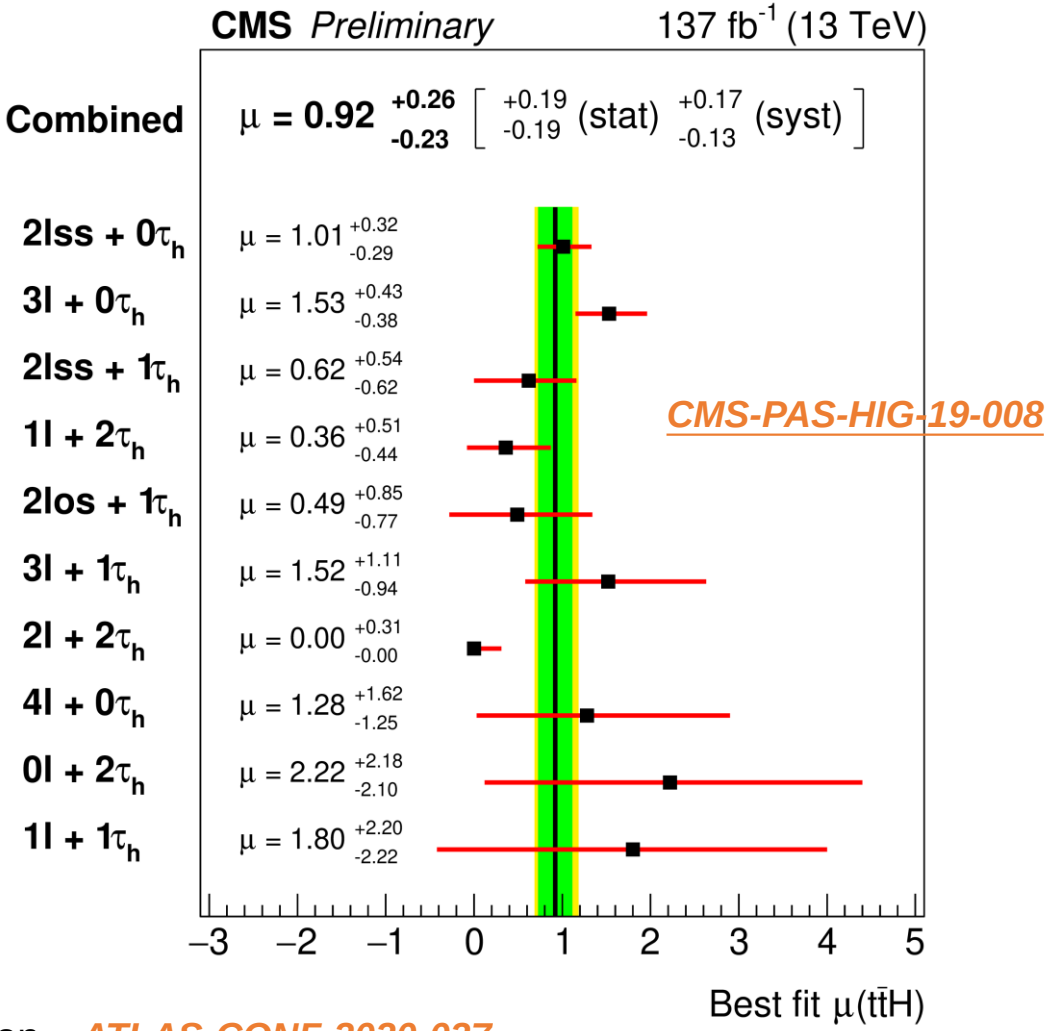


$t\bar{t}H$ Multilepton NEW!

Parallel talk by Huaqiao Zhang







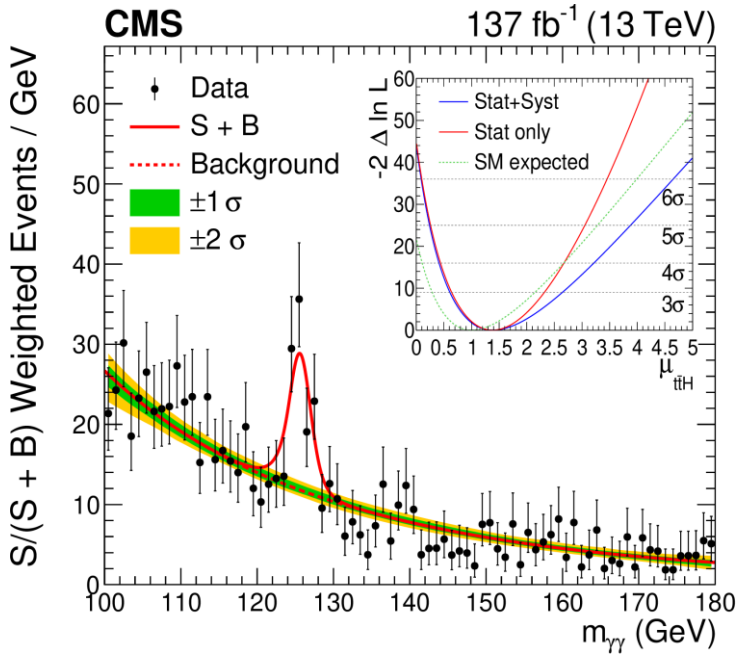
CMS-PAS-HIG-19-008

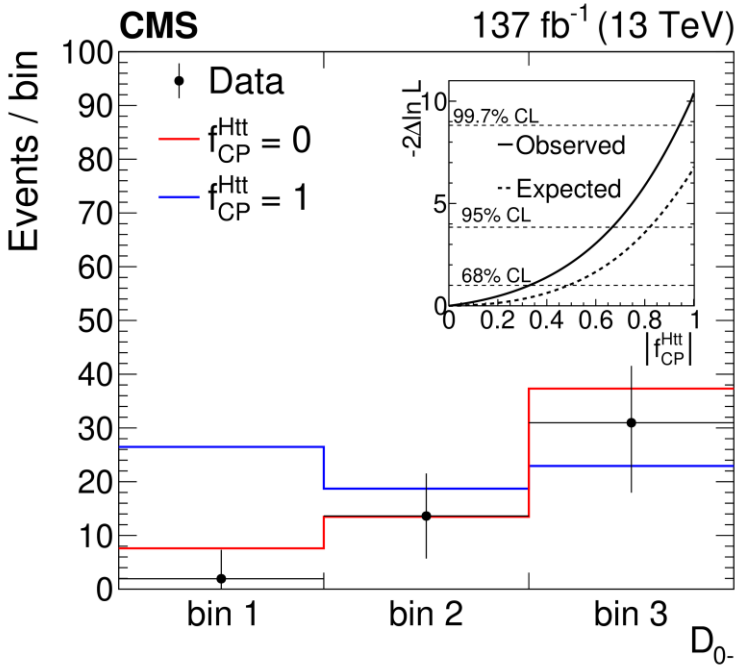
- $t\bar{t}H$ production allows us to directly measure the top Yukawa coupling. tH can determine its sign.
- **$t\bar{t}H$: Obs. (exp.) sig. 4.7σ (5.2σ)**
- **tH : Obs. (exp.) sig. 1.4σ (0.3σ)**
- $-0.9 < y_t < -0.7$ or $0.7 < y_t < 1.1$ @95% CL.
  - Negative value of κ_t is excluded at 2.9σ by ATLAS Higgs combination. ATLAS-CONF-2020-027

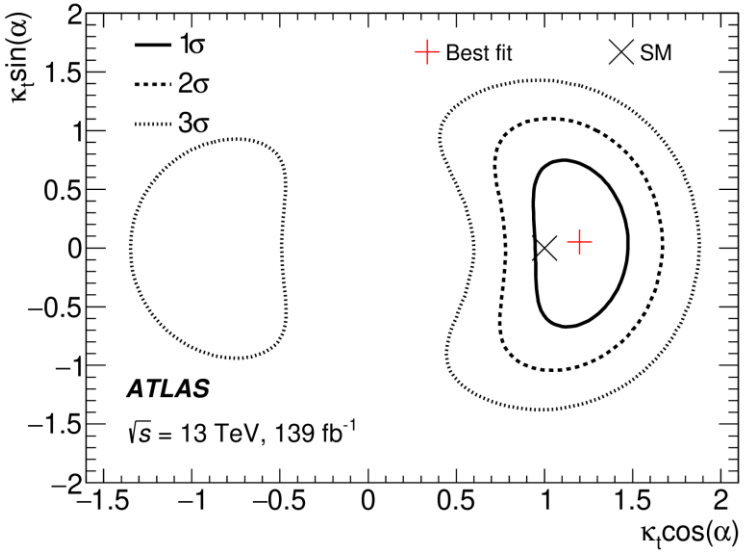
$t\bar{t}H(\rightarrow\gamma\gamma)$ & CP NEW!

Parallel talk by Renqi Pan

PRL 125 (2020) 061801, *PRL 125 (2020) 061802*



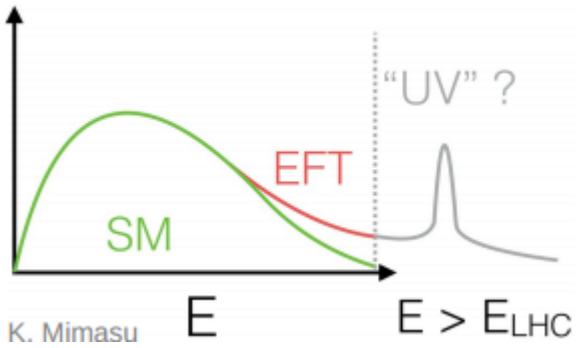




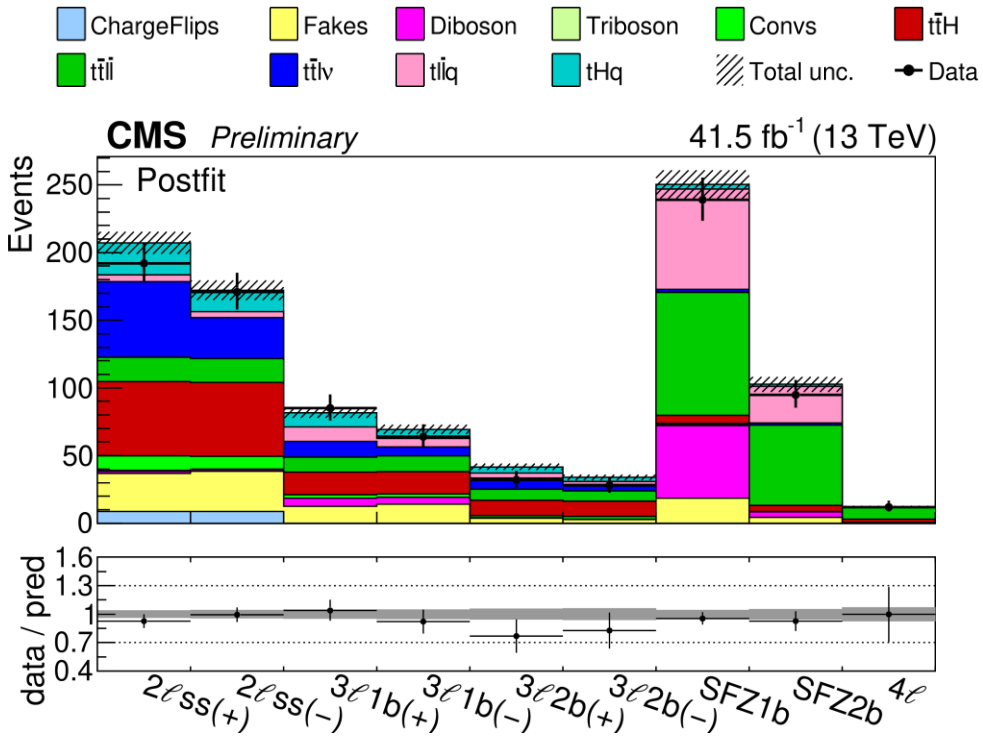
- **First observation of $t\bar{t}H$ by a single channel**.
- CP properties affect the production rate & some kinematic distributions.
- **[CMS] Pure CP-odd top Yukawa excluded at 3.2σ.** $f^{Htt}_{CP} = 0.00 \pm 0.33$.
- [ATLAS] |CP mixing angle| < 43° at 95% CL.

Top EFT w/ $t\bar{t}$+lepton(s)

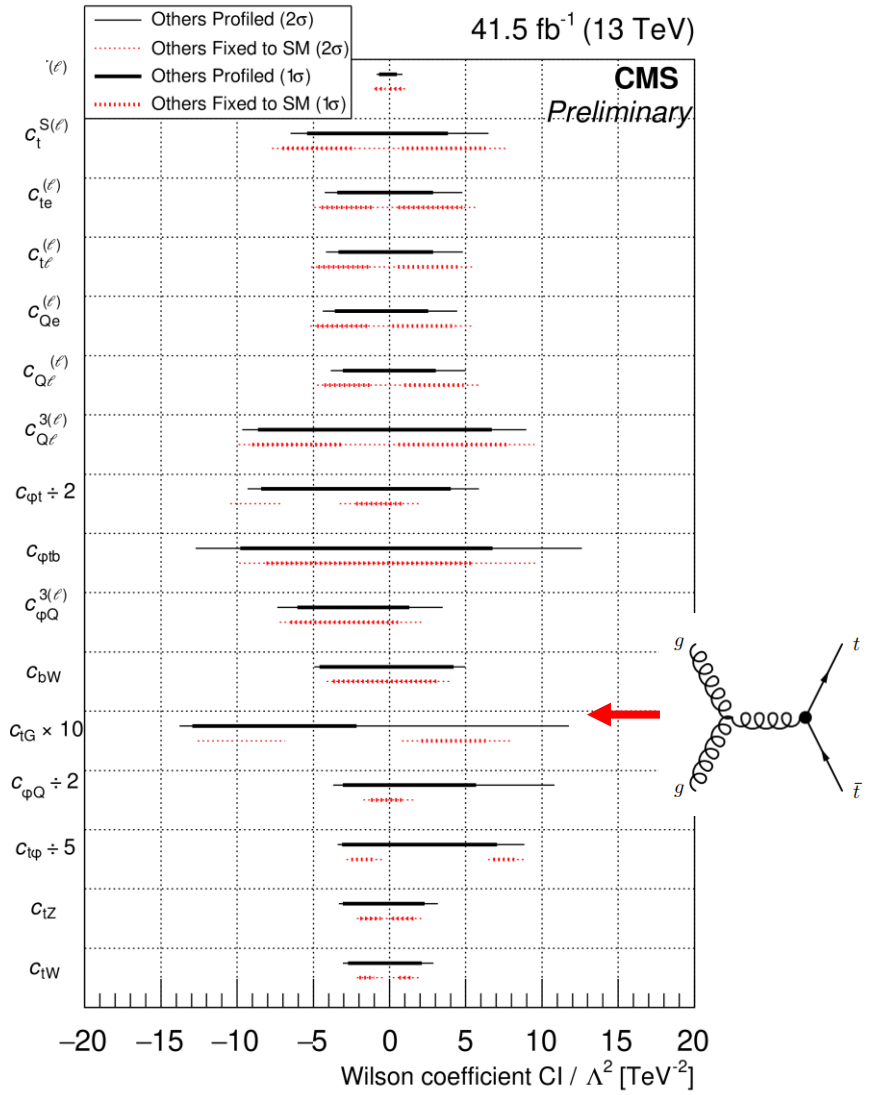
NEW!



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$



CMS-PAS-TOP-19-001



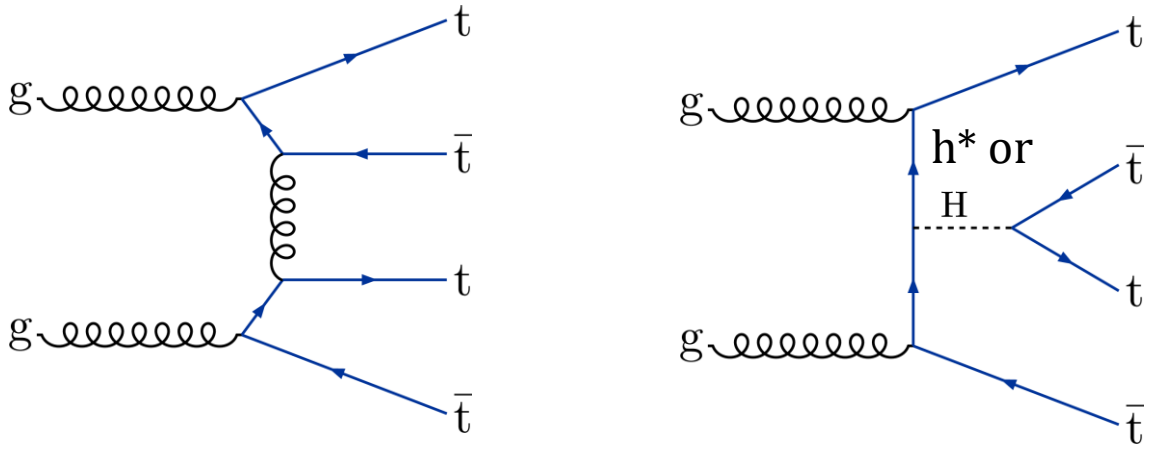
- Inclusively covers $t\bar{t}l\bar{l}$, $t\bar{t}lv$, $tl\bar{l}q$, $t\bar{t}H$, tHq.
- 16 dimension-six operators affect the associated processes.
- 2σ confidence interval consistent with SM.

Evidence of 4-top Production

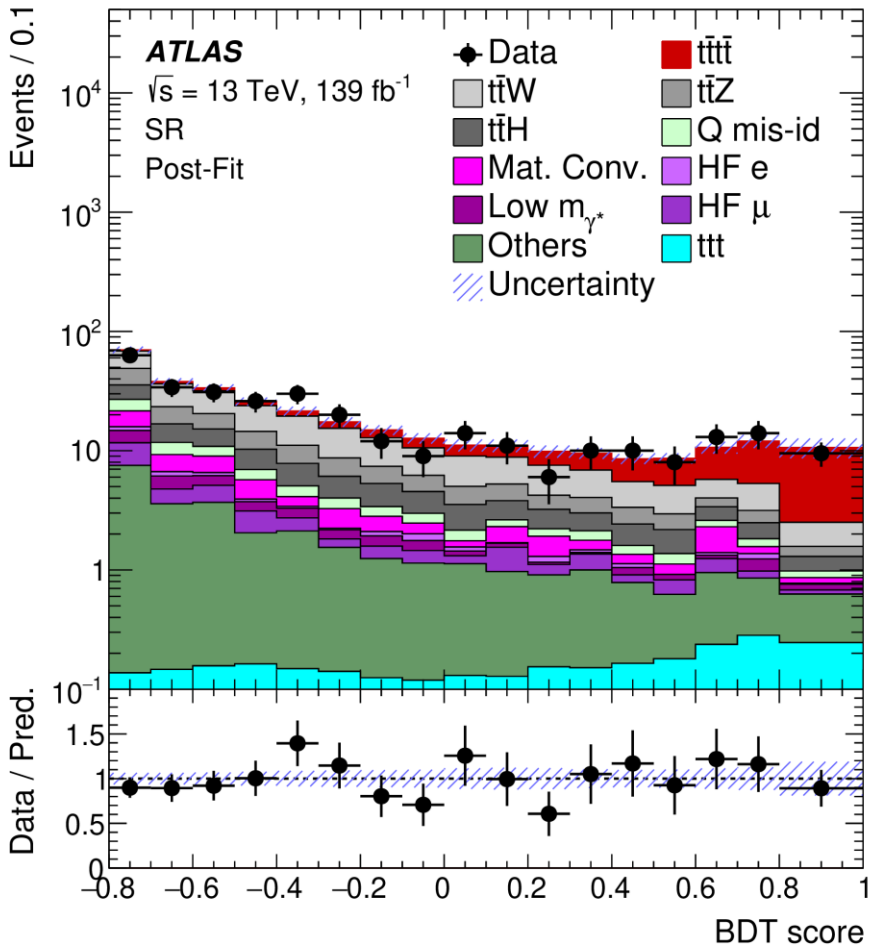
NEW!

arXiv:2007.14858,
Eur. Phys. J. C 80 (2020) 75

The most rare top production currently searched at LHC. $\sigma_{4t}^{SM}=12_{+2.2}^{-2.5}$ fb.



- **Sensitive to off-shell Higgs** (magnitude & CP properties of top Yukawa, oblique parameter) & **BSM**.
- Same-sign/multi-lepton searches are the most sensitive.
- **Significance: 4.3σ (2.4σ) [ATLAS], 2.6σ (2.7σ) [CMS] obs (exp)**
- **CMS: $|y_t/y_t^{SM}|<1.7$@95%CL, oblique parameter $\hat{H}<0.12$**



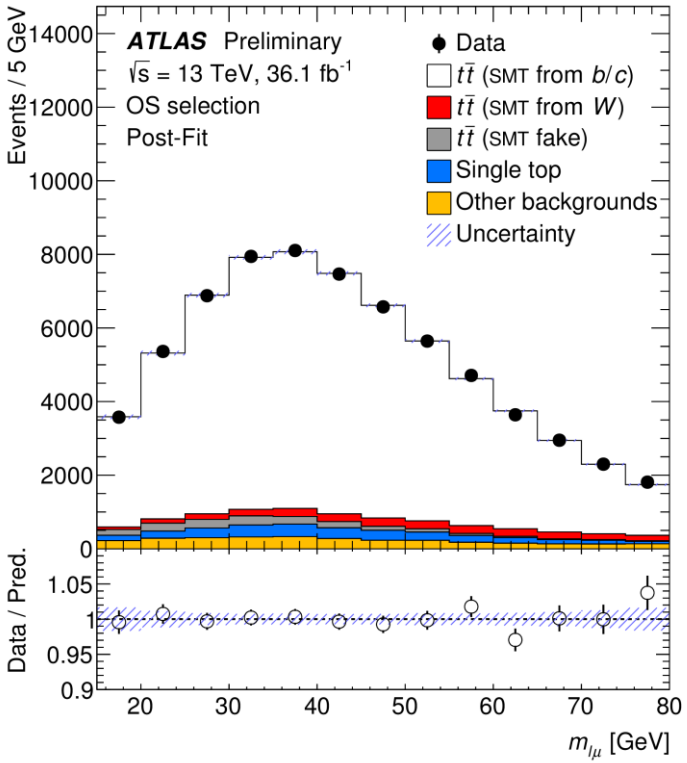
Top Quark Properties

Top Mass (Direct Measurement)

the so-called "MC mass"

- **Determines the top mass parameter defined in MC from kinematic observables.**
- **Most precise measurements: 172.44±0.48 GeV [CMS], 172.69±0.48 GeV [ATLAS]**
- The latest measurements are not yet included in the combination above.

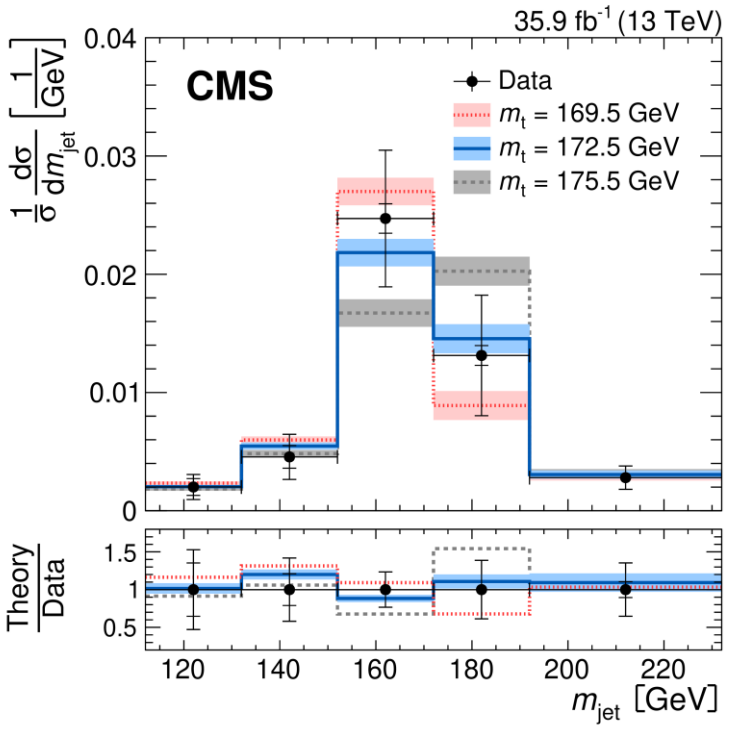
ATLAS-CONF-2019-046



ATLAS using soft-muon tagging: 174.48 ± 0.78 GeV

Visible deviation from the world average indicates **need for higher order calculation of b-fragmentation.**

PRL 124 (2020) 202001

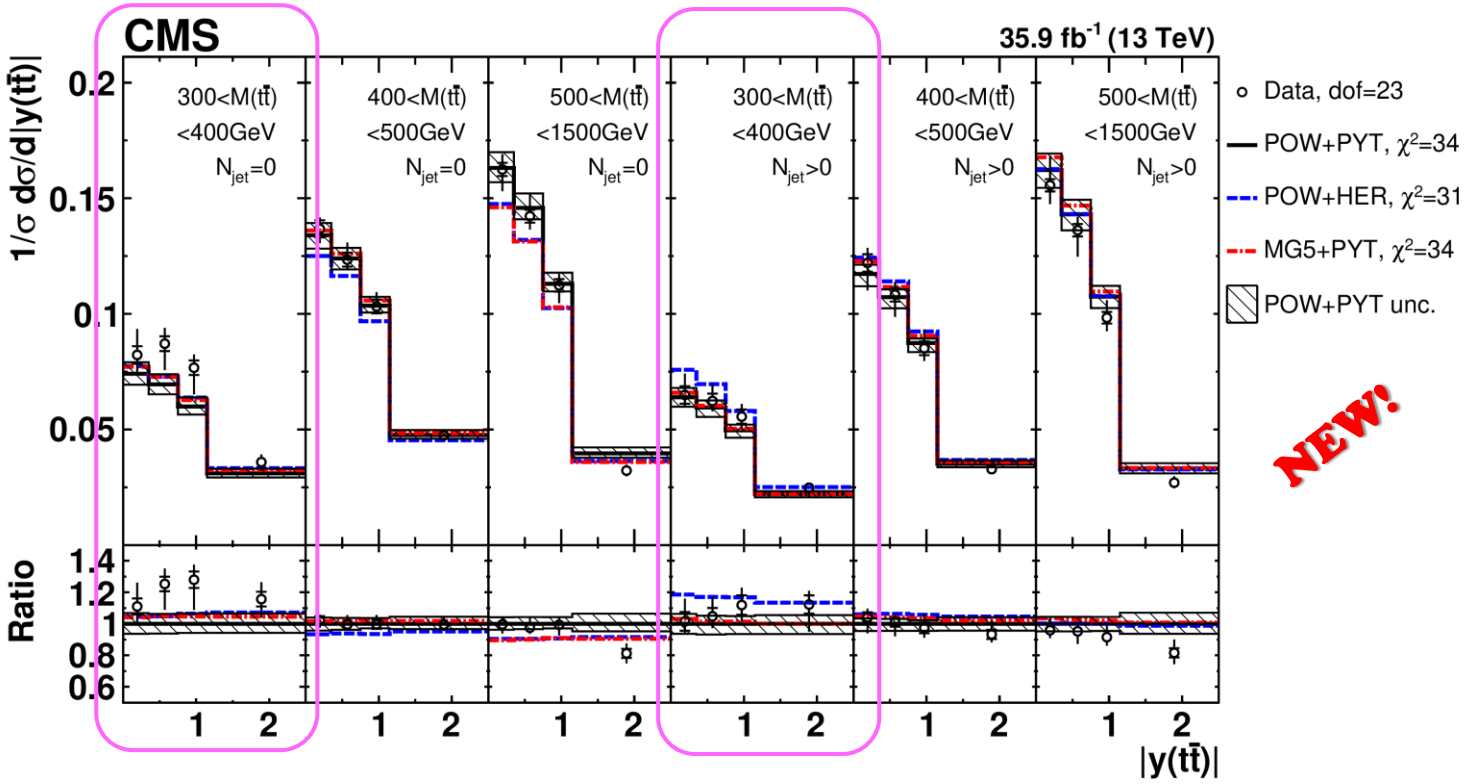


CMS using boosted Top in 1-lep: 172.56 ± 2.47 GeV

1st top mass measurement in boosted regime.
Sensitivity to non-perturbative effects reduced.

Top Mass (Pole Mass)

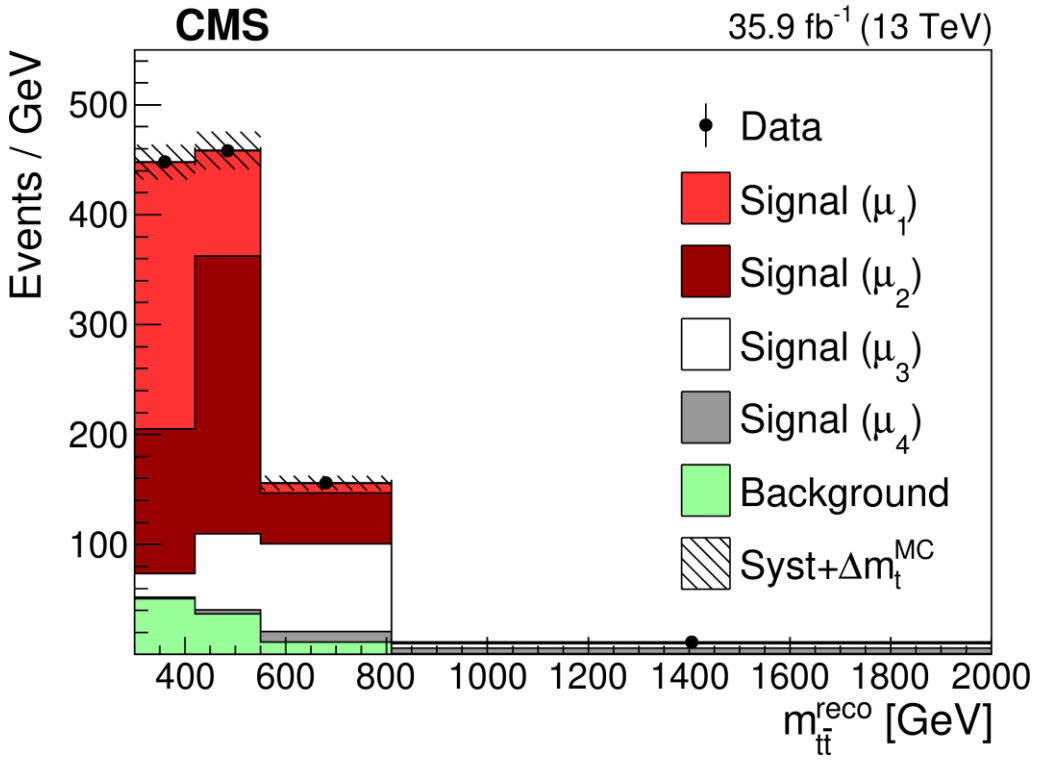
- **Pole mass: mass defined in parton-level scattering amplitudes.** Self-energy corrections are absorbed in this mass.
- Extracted from total or differential cross sections.

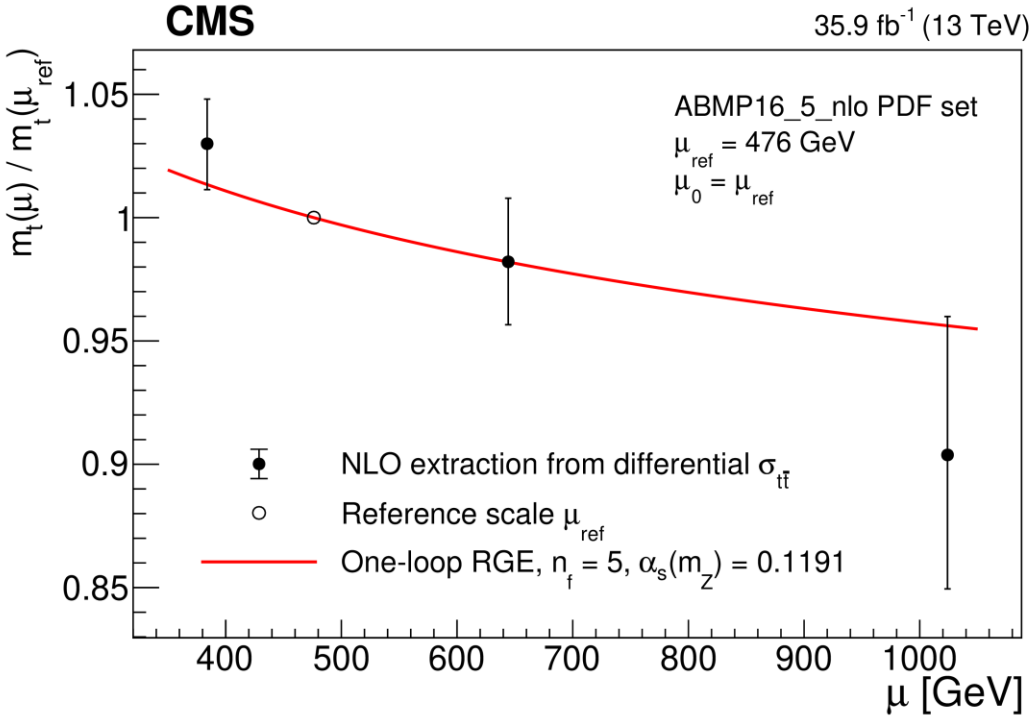


- **Triple differential measurements on N_{jet}, M_{tt}, y_{tt} in dilepton channel.**
- Simultaneous fit on PDF, α_s & m_t at NLO.
- **Most precise measurement of top pole mass: m_t = 170.5±0.8 GeV**
- However, **higher-order effects near the threshold can give as large as 1.4 GeV effect** *(W.-L. Ju et al., JHEP06(2020)158).*

Running of Top Mass

Phys. Lett. B 803 (2020) 135263

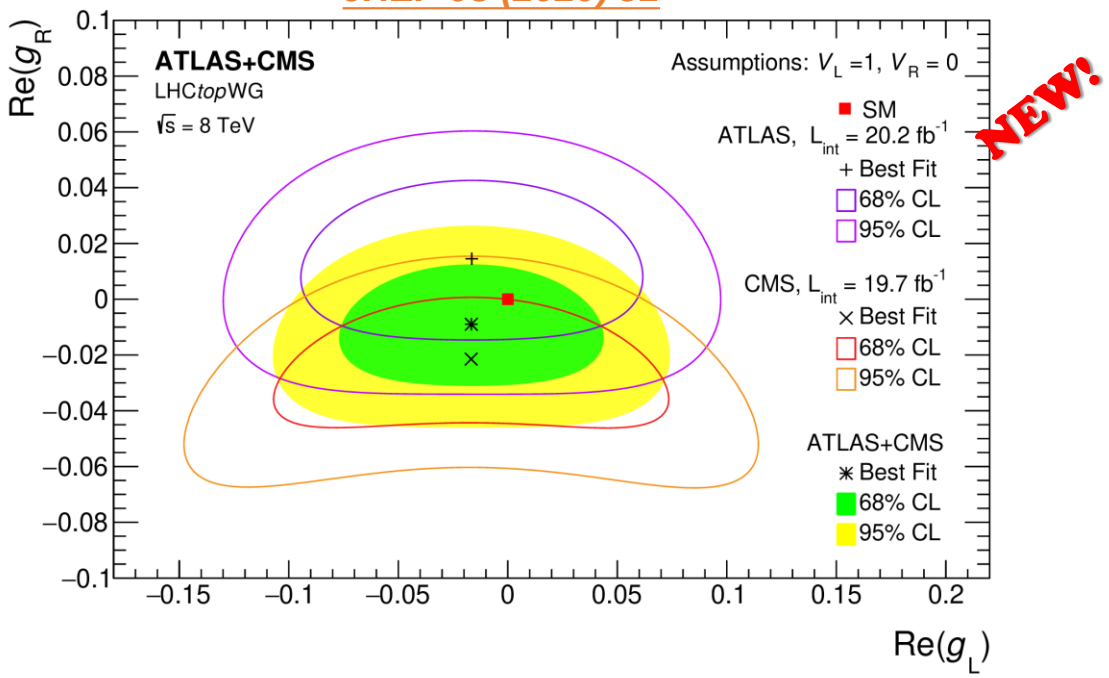




- First investigation on "running" of m_t in $\overline{MS}$ scheme.
- $m_t(\mu)$ is extracted from the m_{tt} distribution in the dilepton channel.

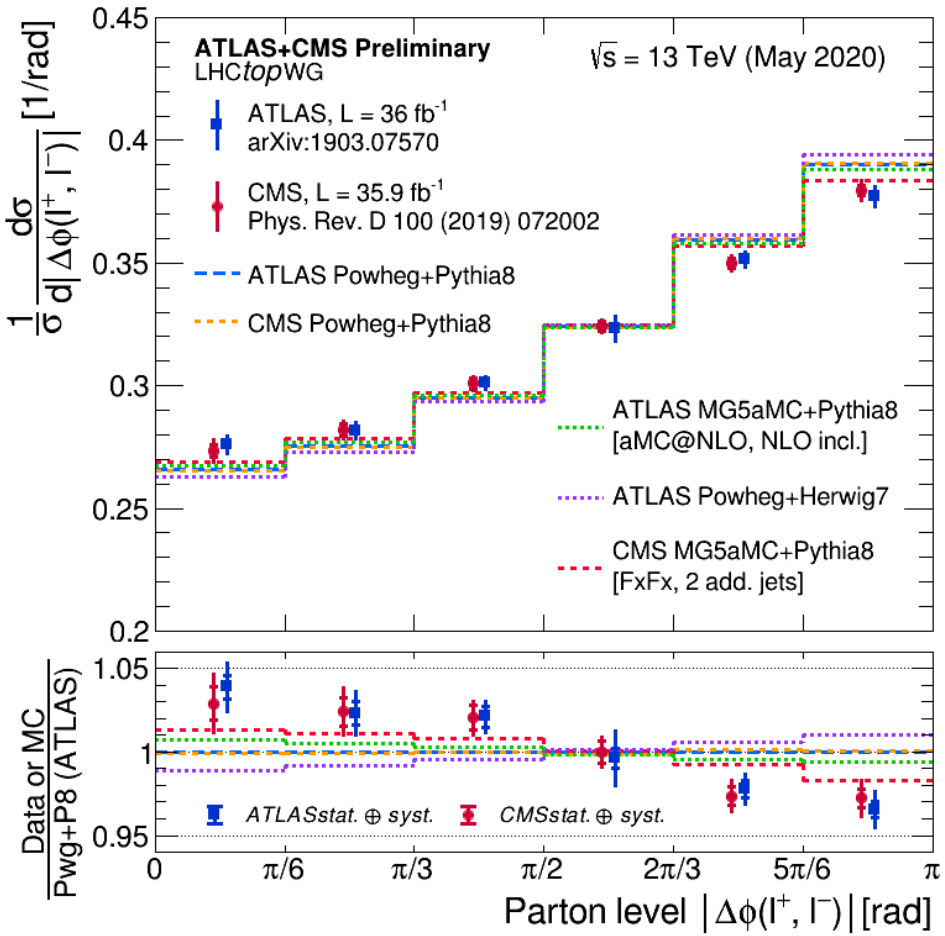
W Polarization & Spin Correlation

JHEP 08 (2020) 51



- ATLAS+CMS combination on W polarization measurement agree well with NNLO QCD.
- **Observed spin correlation** significantly higher than the baseline MC but **can still be described by NLO QCD+EW corr.) w/ large uncertainty**.

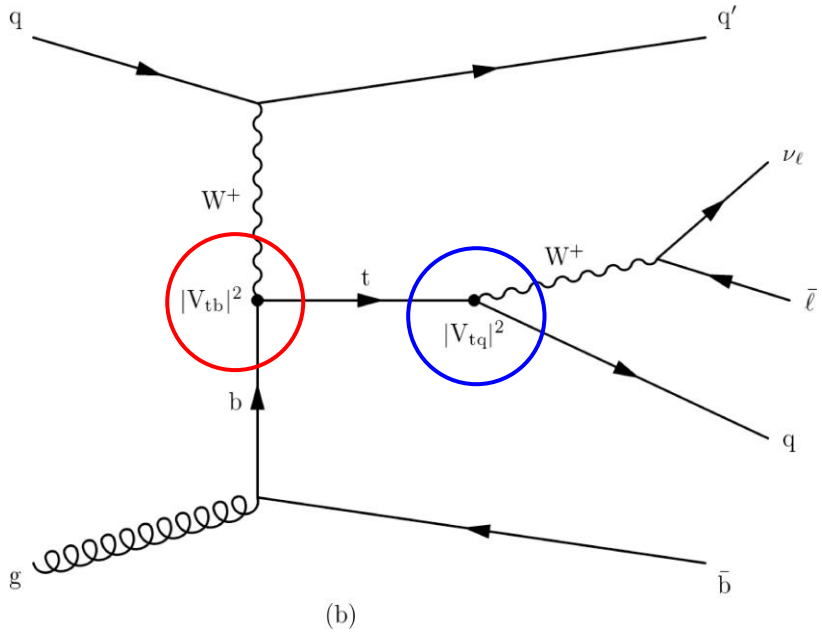
Phys. Rev. D 100 (2019) 072002, Eur. Phys. J. C 80 (2020) 754

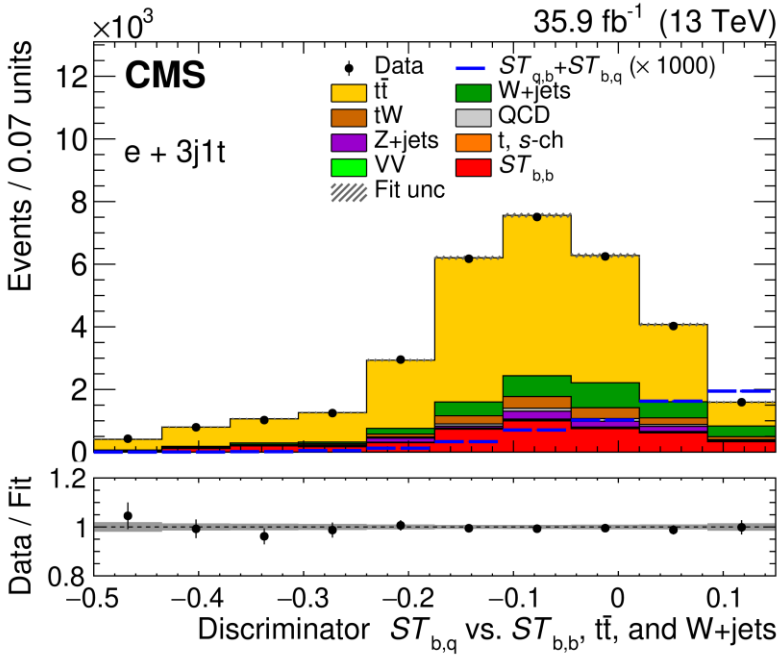


CKM Parameter

NEW!

Phys. Lett. B 808 (2020) 135609



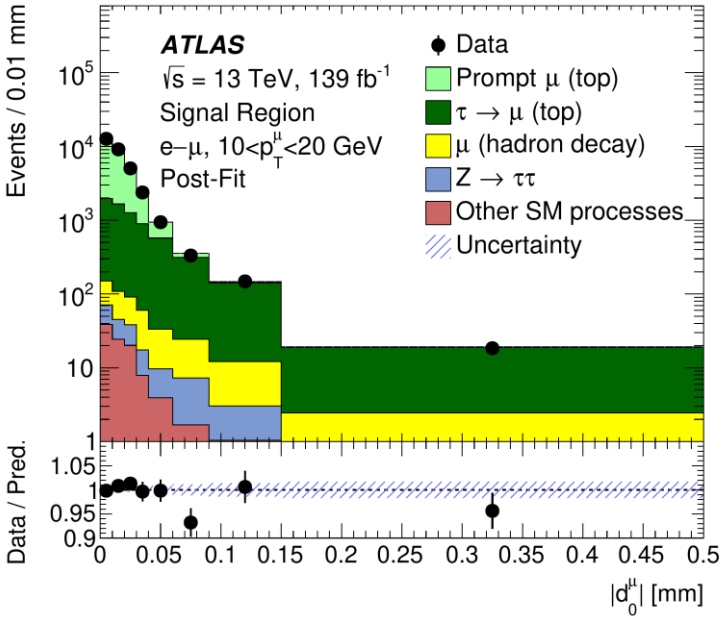


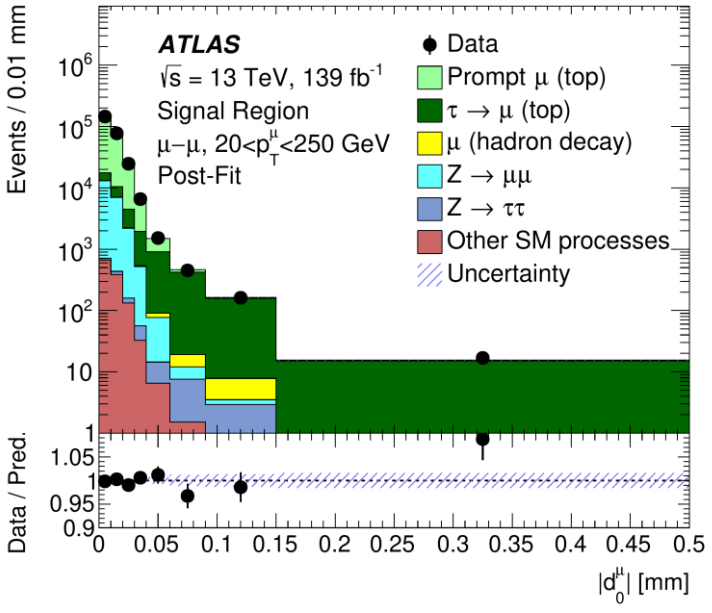
- **First direct, model-independent measurement of CKM matrix elements** using t-channel (tWb,tWq). → i.e. no assumption on unitarity or SM
- **$|V_{tb}|=0.988\pm0.024$, $|V_{td}|^2+|V_{ts}|^2=0.06\pm0.06$.**
  - **Precision on $|V_{tb}|$ improved by 50% from previous CMS measurement**
- In SM hypothesis of CKM unitarity: $|V_{tb}| > 0.970$ at 95%CL.

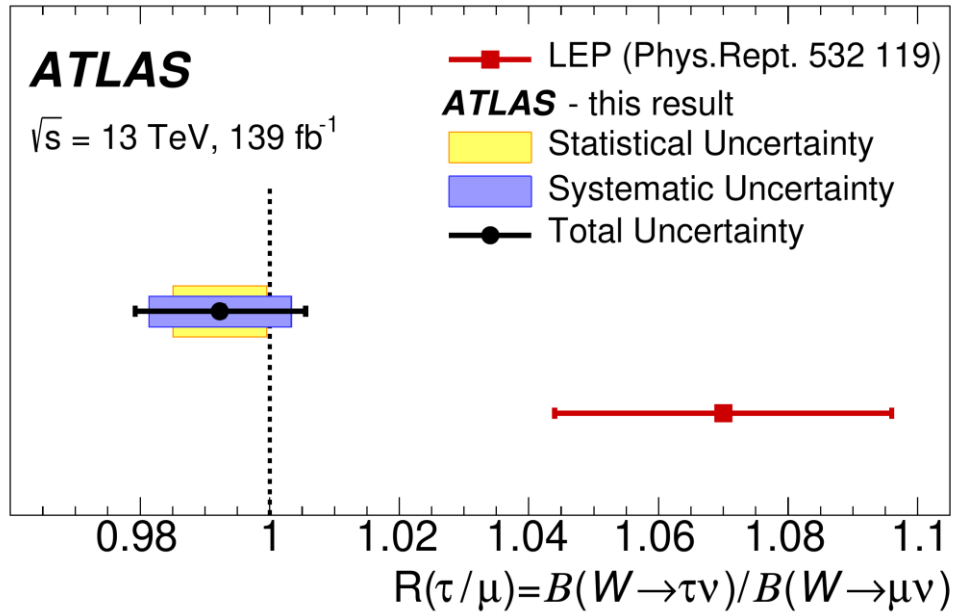
Lepton-Flavor Universality

NEW!

arXiv:2007.14040, submitted to Nature Phys.







- Dilepton $t\bar{t}$ events are used to measure **$B(W\to\tau\nu_\tau)/B(W\to\mu\nu_\mu)$.**
  Previous measurements have been showing some tensions with SM (2.7σ at LEP).
- **τ is identified from its displaced decay to muons.**
- **Measurement is in good agreement with SM prediction.**

Summary

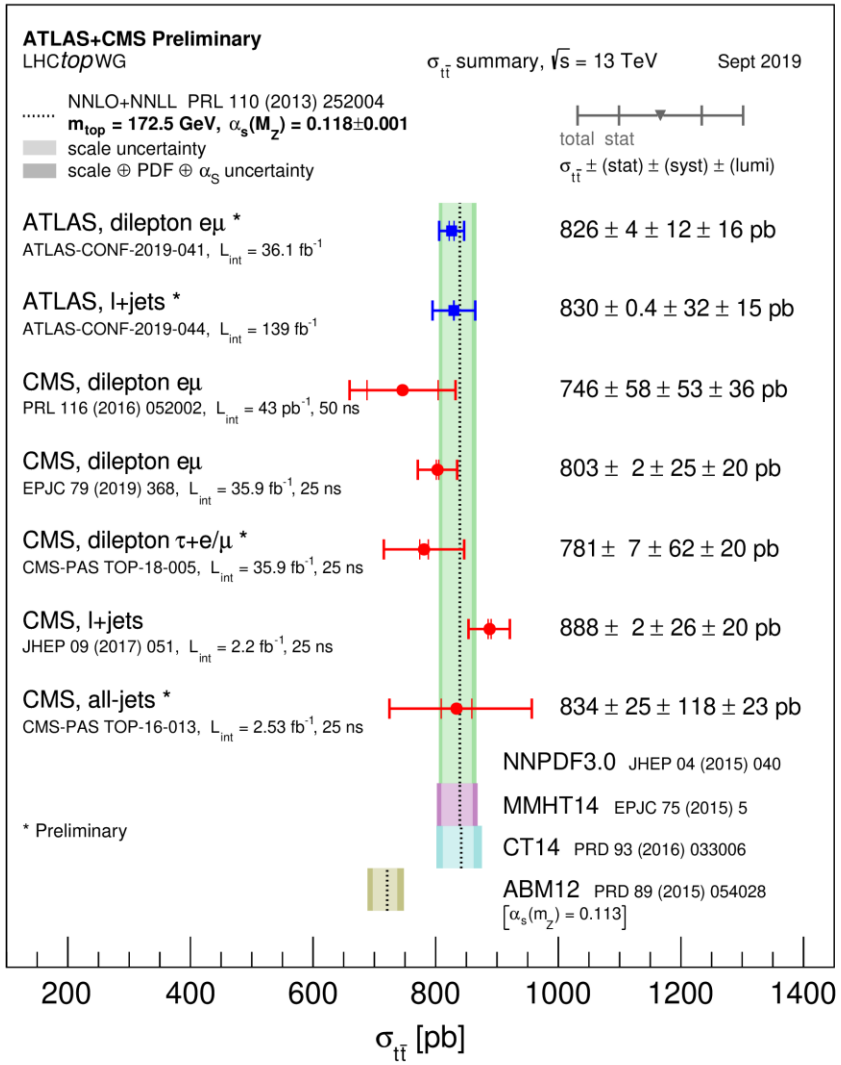
- **CMS & ATLAS started to provide many results with Full Run 2 dataset.**
  - Inclusive & differential cross section measurements with higher precision.
  - First observation of $t\bar{t}H$ by a single channel ($\gamma\gamma$) & exclusion of pure CP-odd top Yukawa; $t\bar{t}H$ multilepton
  - First evidence of 4-top production
  - First evidence of $t\bar{t}$ production in PbPb
  - Test of Lepton Flavor Universality
  - Various BSM searches incl. EFT
- More analyses are under way.

Parallel talks on Top:
- BSM searches in top dilepton, Xuyang Gao
- Top FCNC searches, Boyang Li
- Leptoquark searches in top di-tau, Taozhe Yu
- $t\bar{t}H$ multilepton, Huaqiao Zhang
- $t\bar{t}H$ $\gamma\gamma$ & CP, Renqi Pan

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

Backup

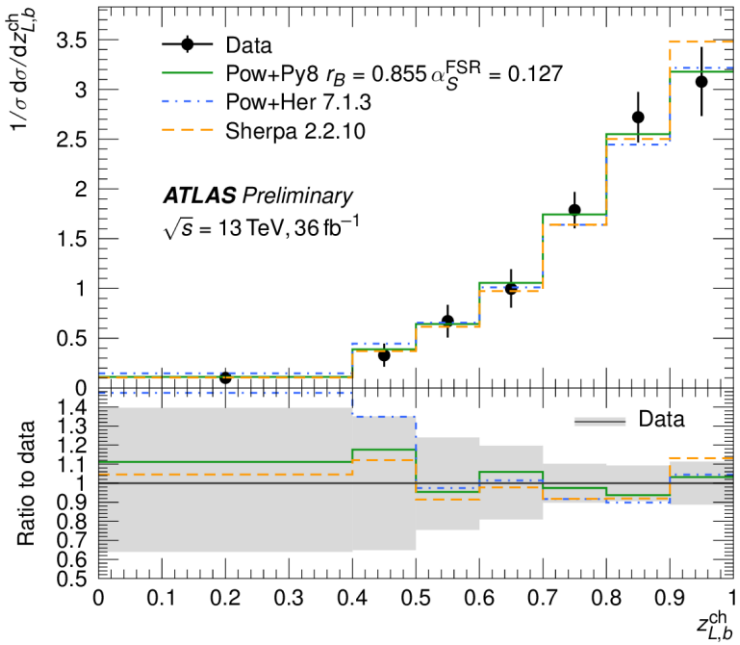
Cross Section Summary

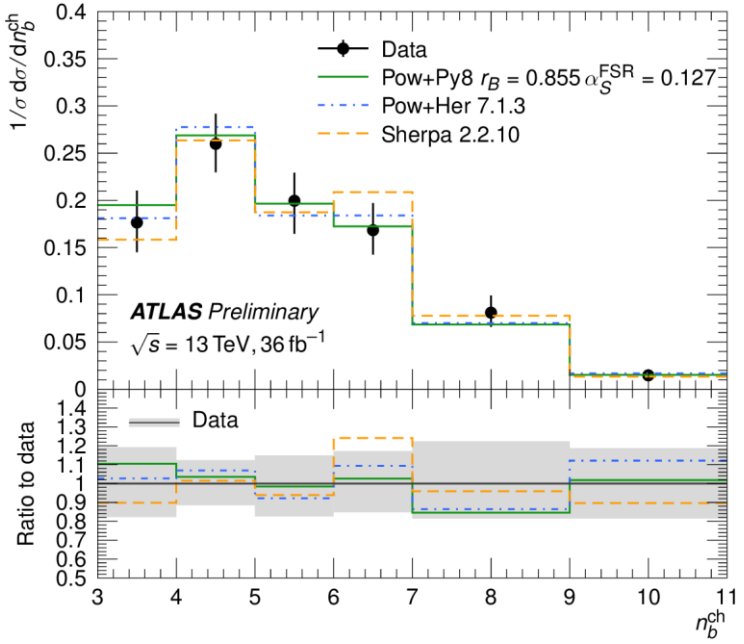


b-Quark Fragmentation NEW!

$$z_{\mathrm{L},b}^{\mathrm{ch}} = \frac{\vec{p}_b^{\,\mathrm{ch}} \cdot \vec{p}_{\mathrm{jet}}^{\,\mathrm{ch}}}{|p_{\mathrm{jet}}^{\mathrm{ch}}|^2}$$

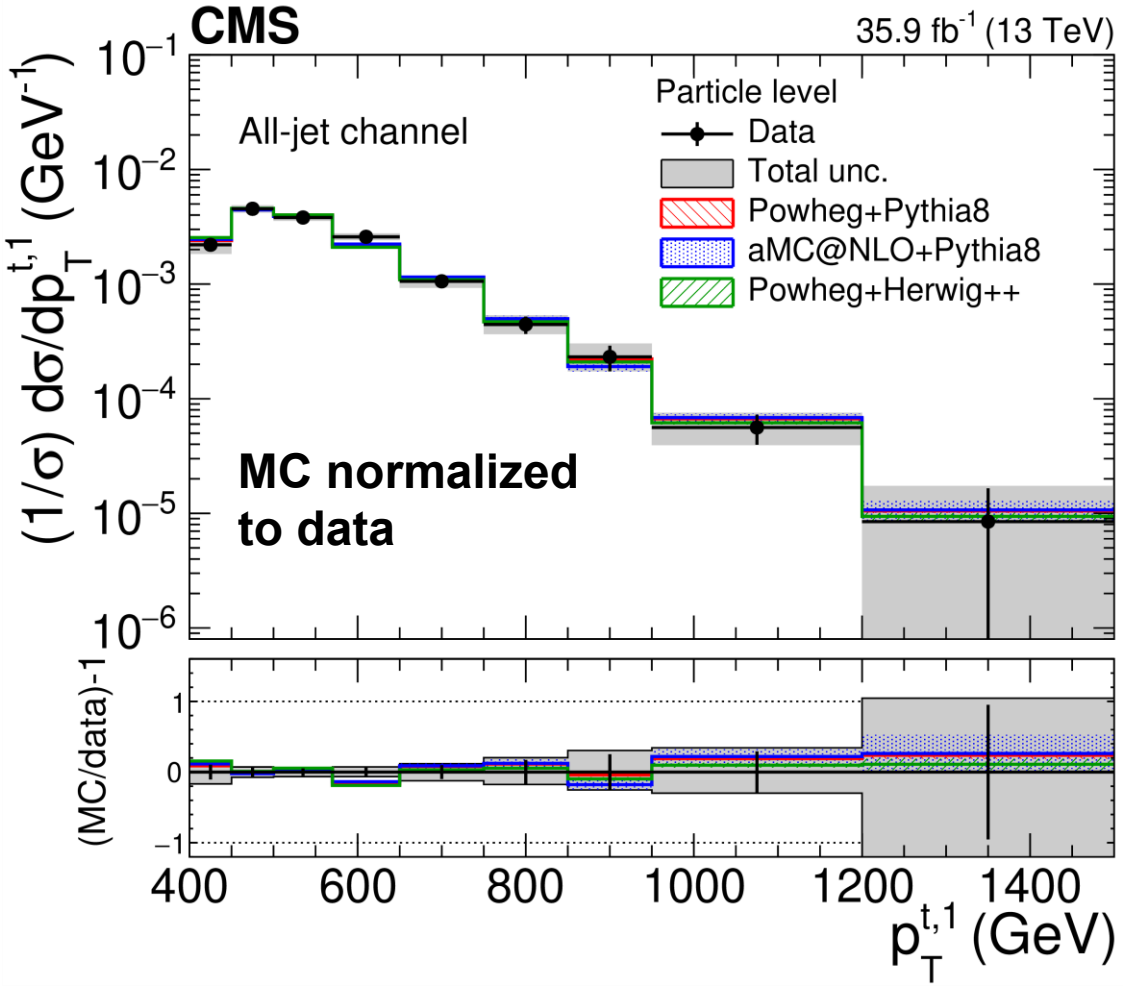
n_b^{ch} = number of fiducial b-hadron children.

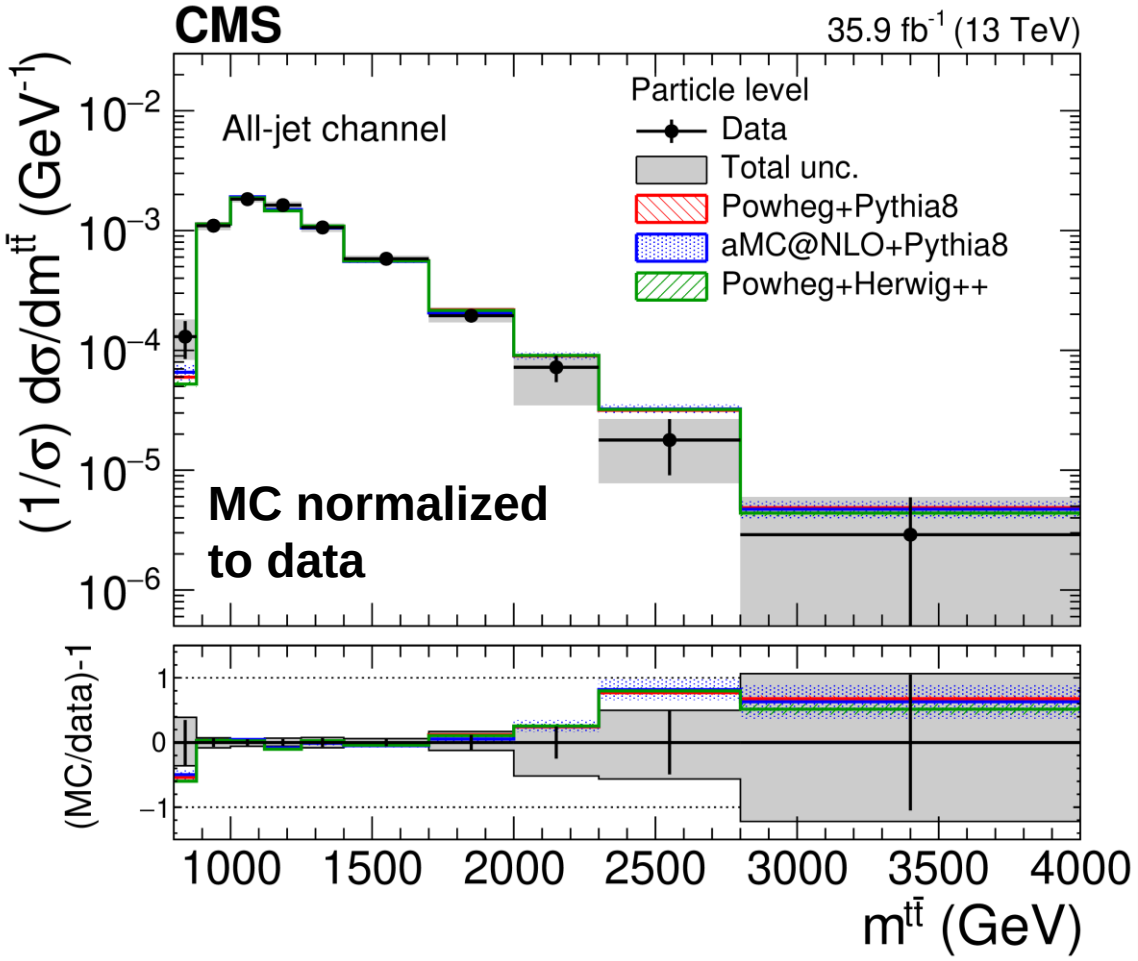




- **Large number of b-jets from $t\bar{t}$ provides complementary measurements of b-quark fragmentation to e^+e^- colliders.** Dilepton channel is used.
- Longitudinal/transverse momentum, soft-lepton, # of b-hadron children distributions are **largely in agreement with the state-of-the-art MC generators**.

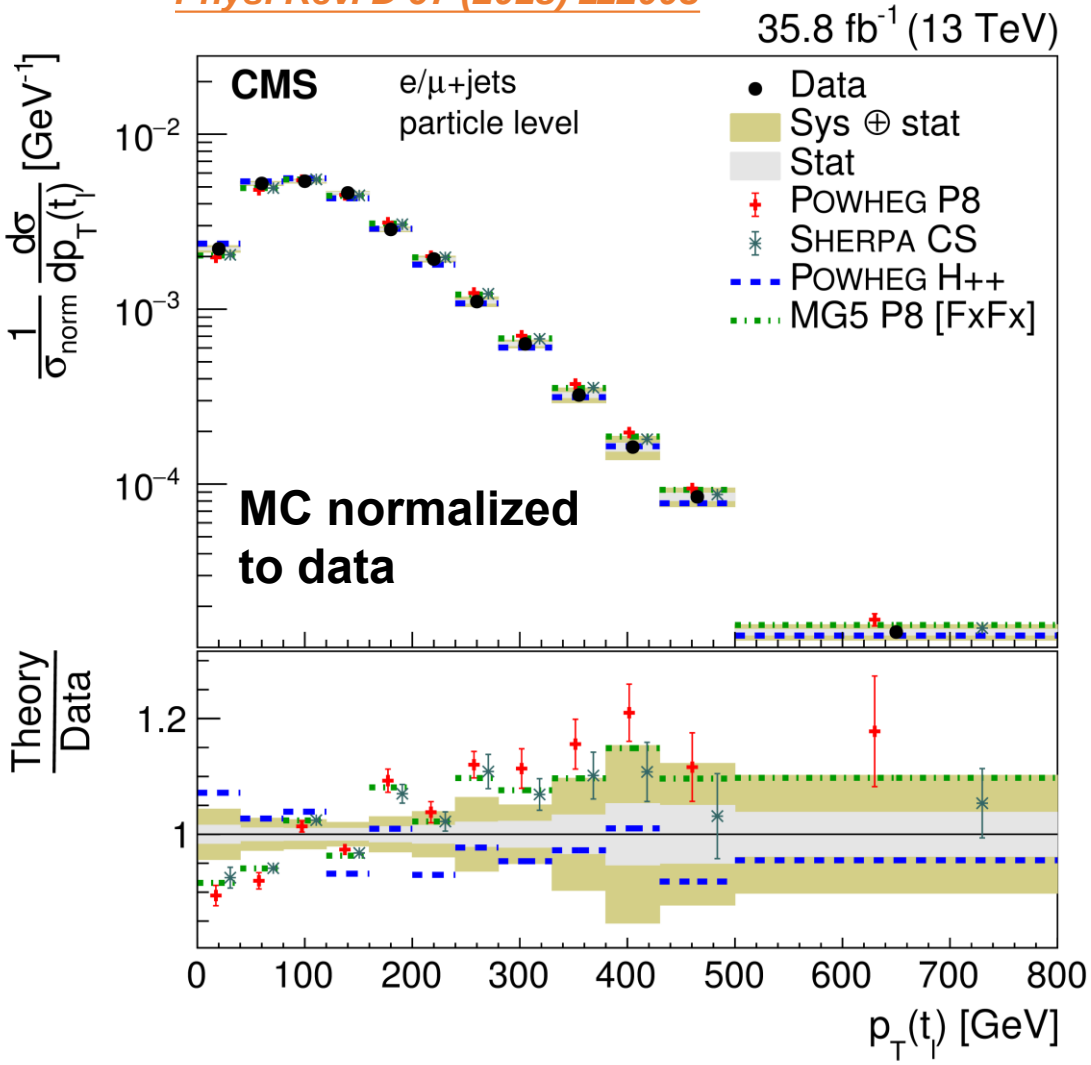
$t\bar{t}$ Differential Cross Section (Boosted)



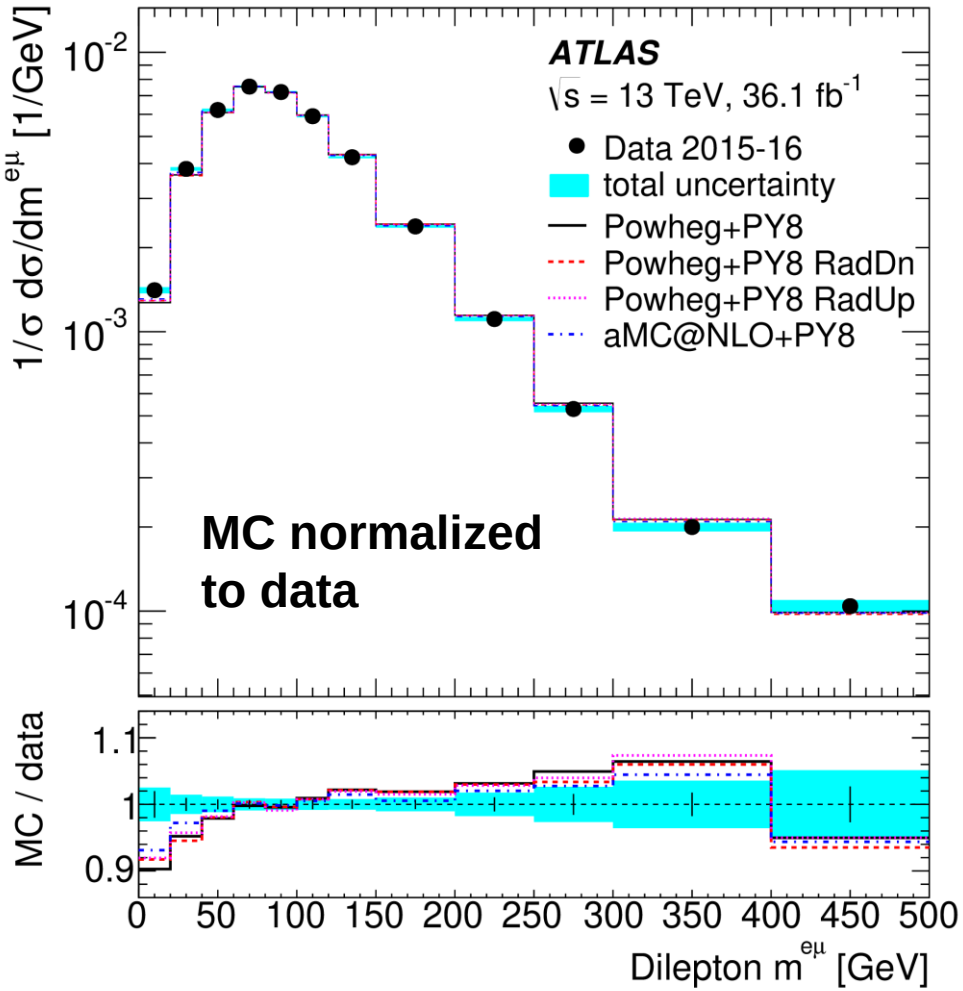


$t\bar{t}$ Differential Cross Section (1,2-Lep.)

Phys. Rev. D 97 (2018) 112003

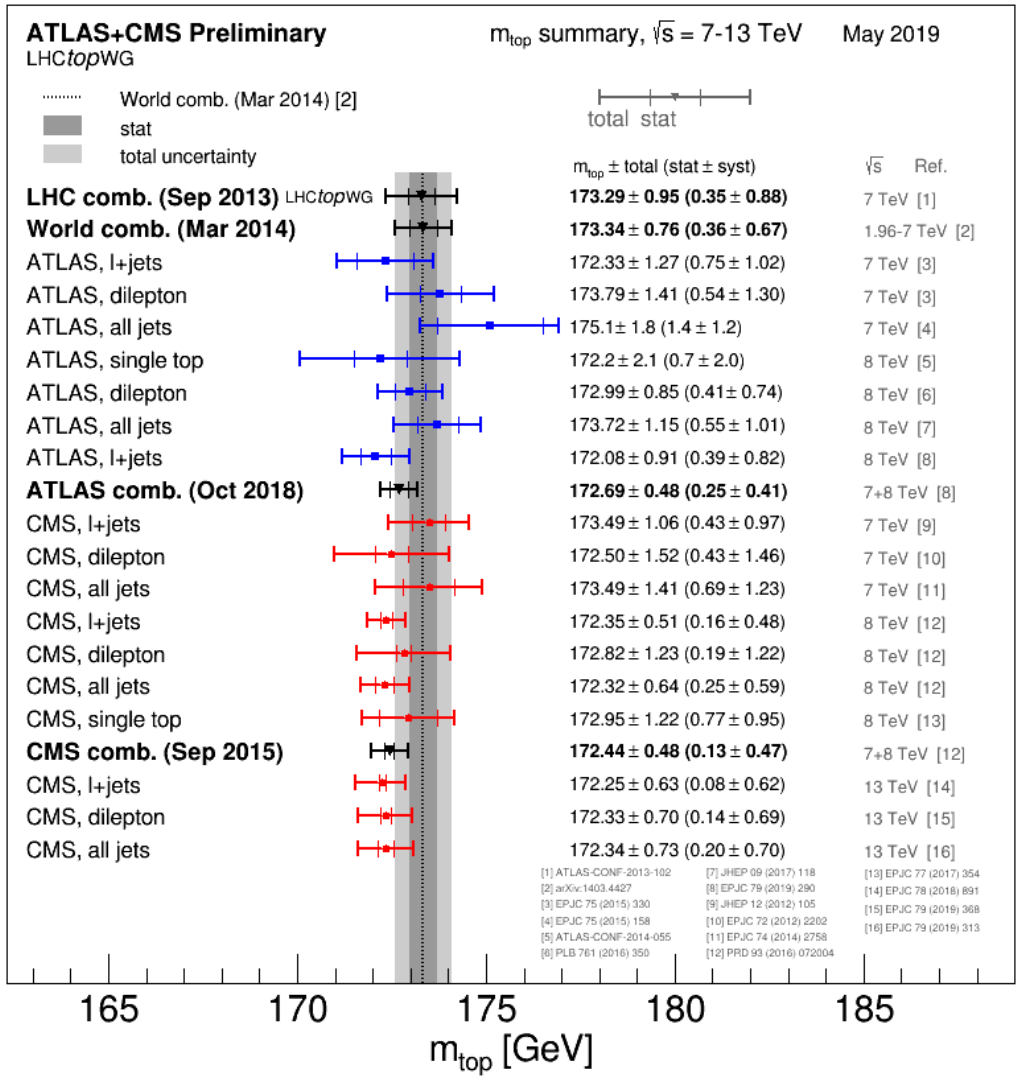


Eur. Phys. J. C 80 (2020) 528

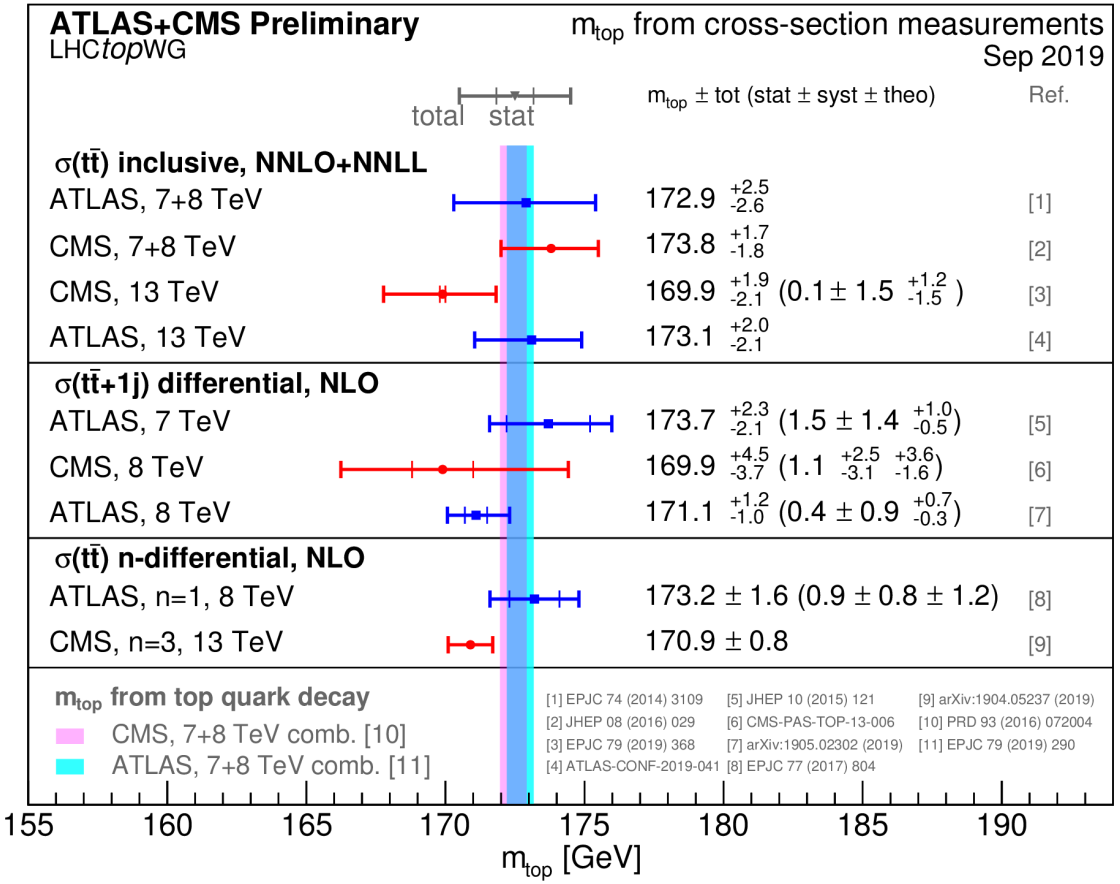


Top Mass

Direct Meas. (MC Mass)

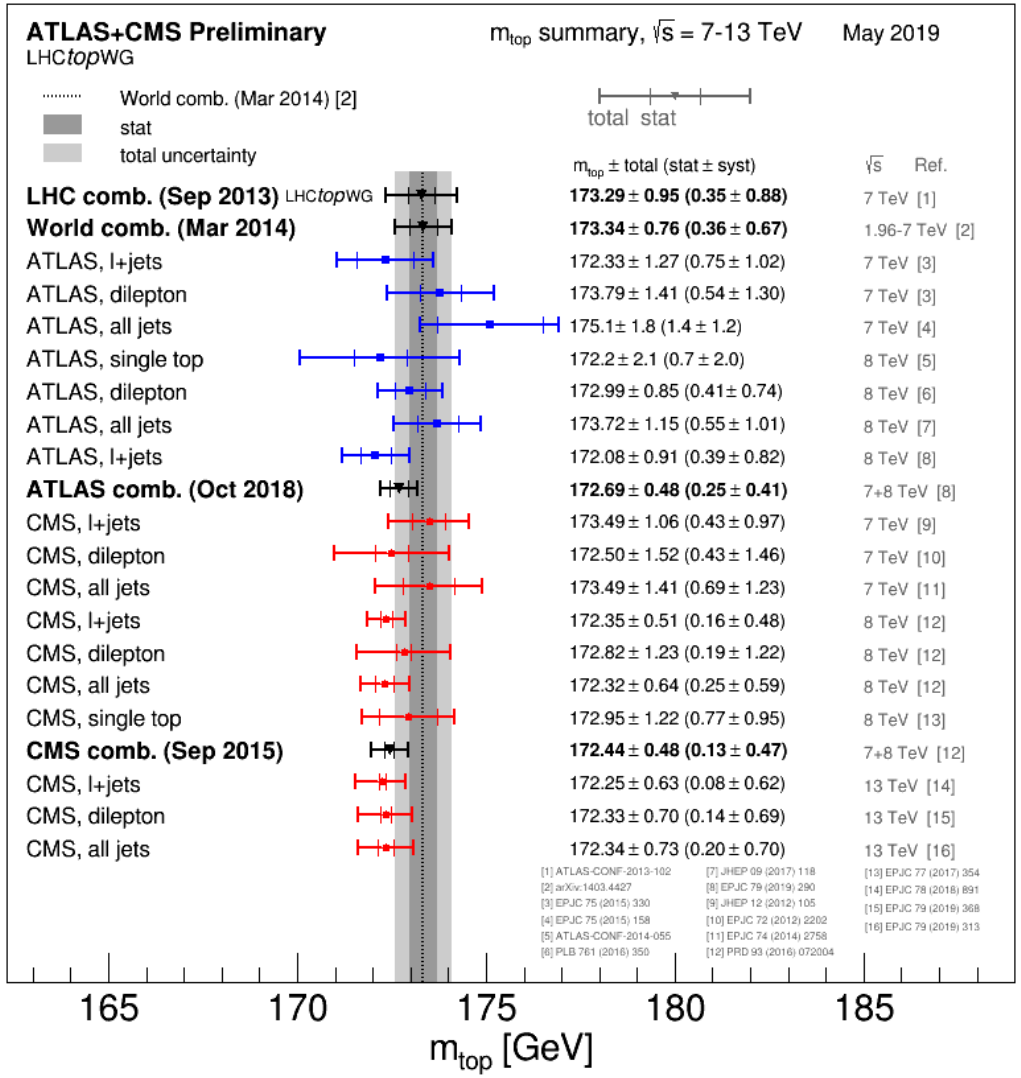


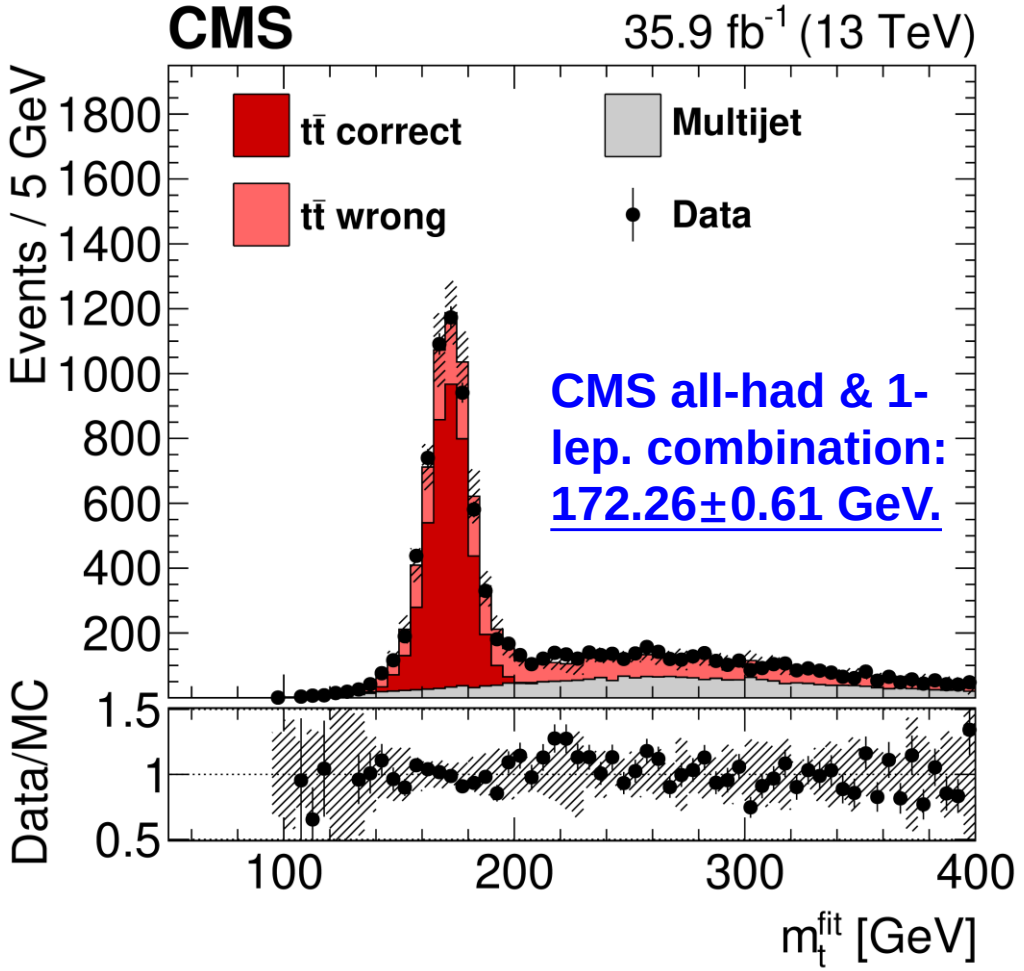
Pole Mass



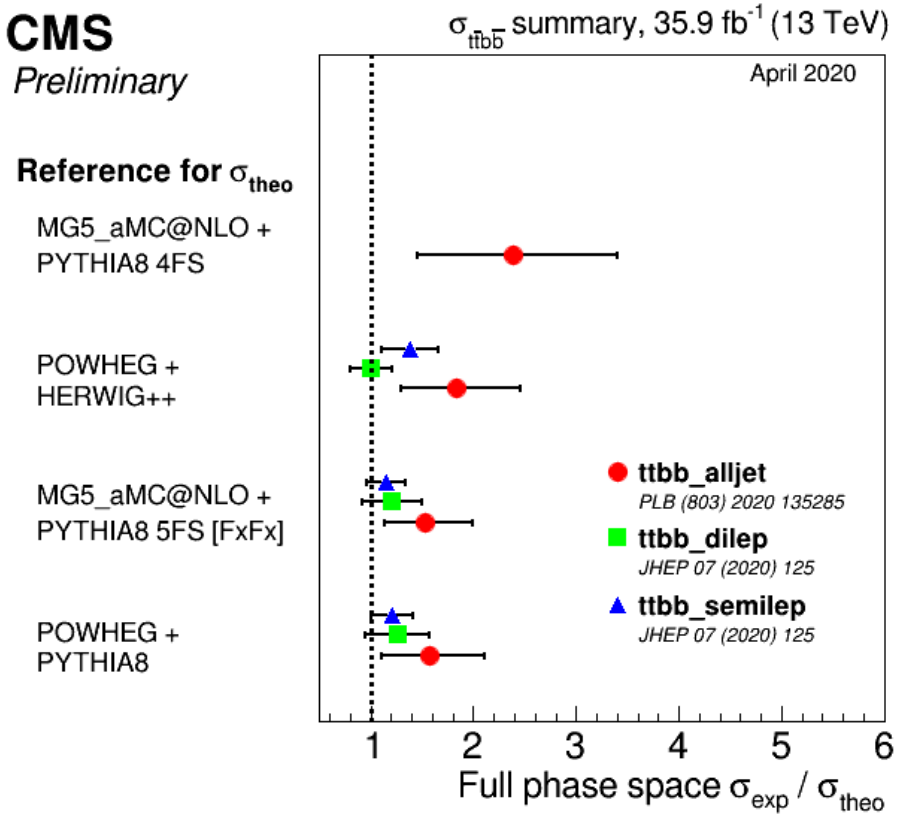
Top Mass

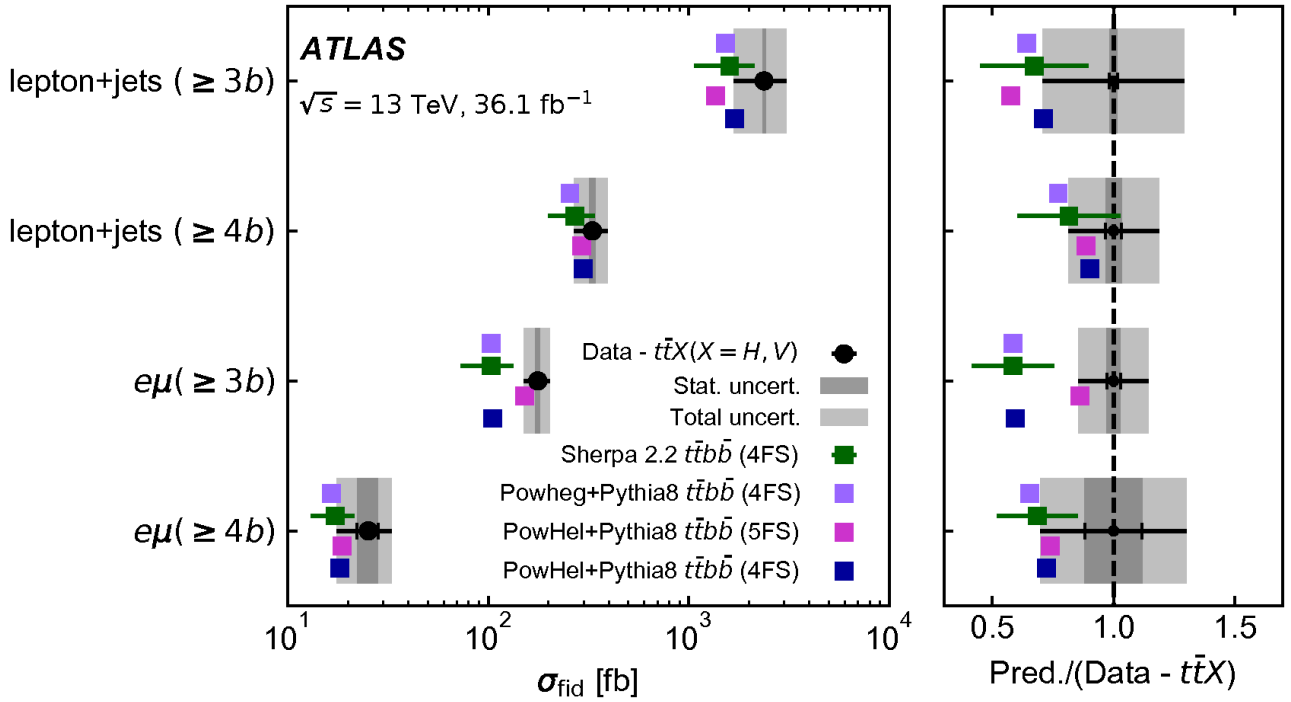
Direct Meas. (MC Mass)



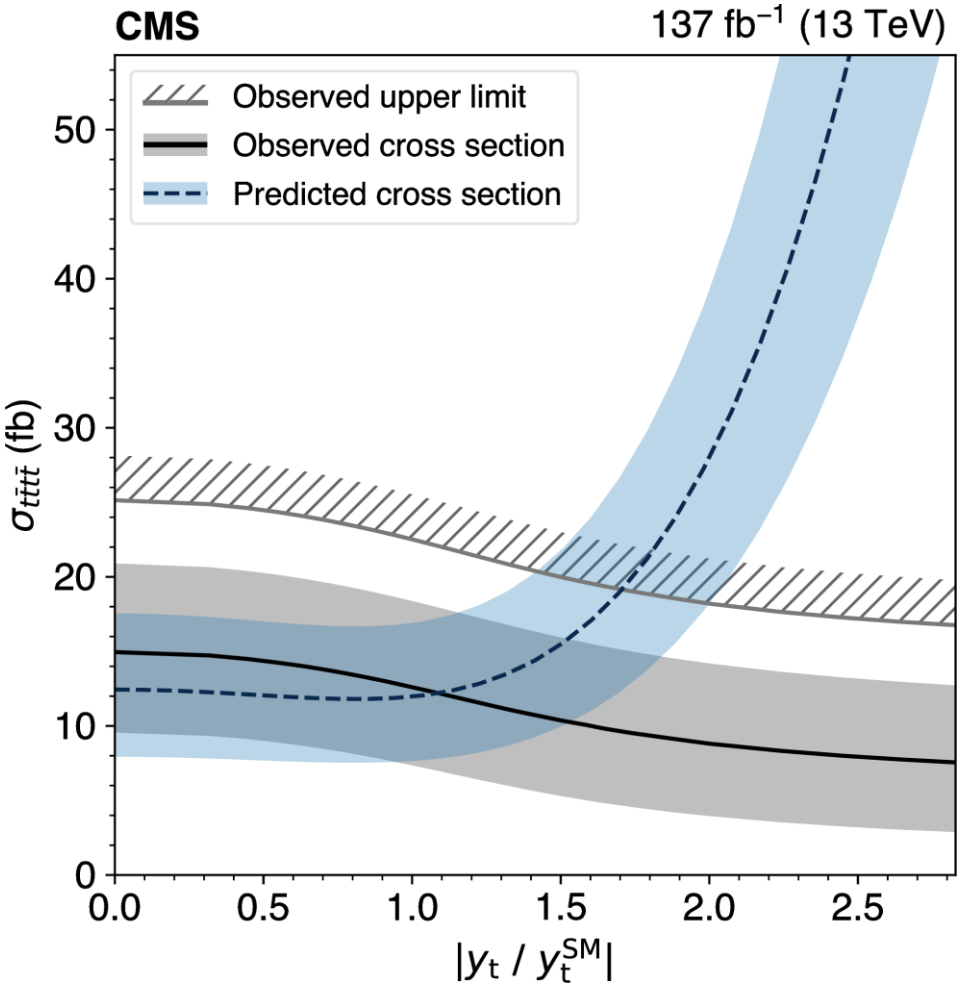


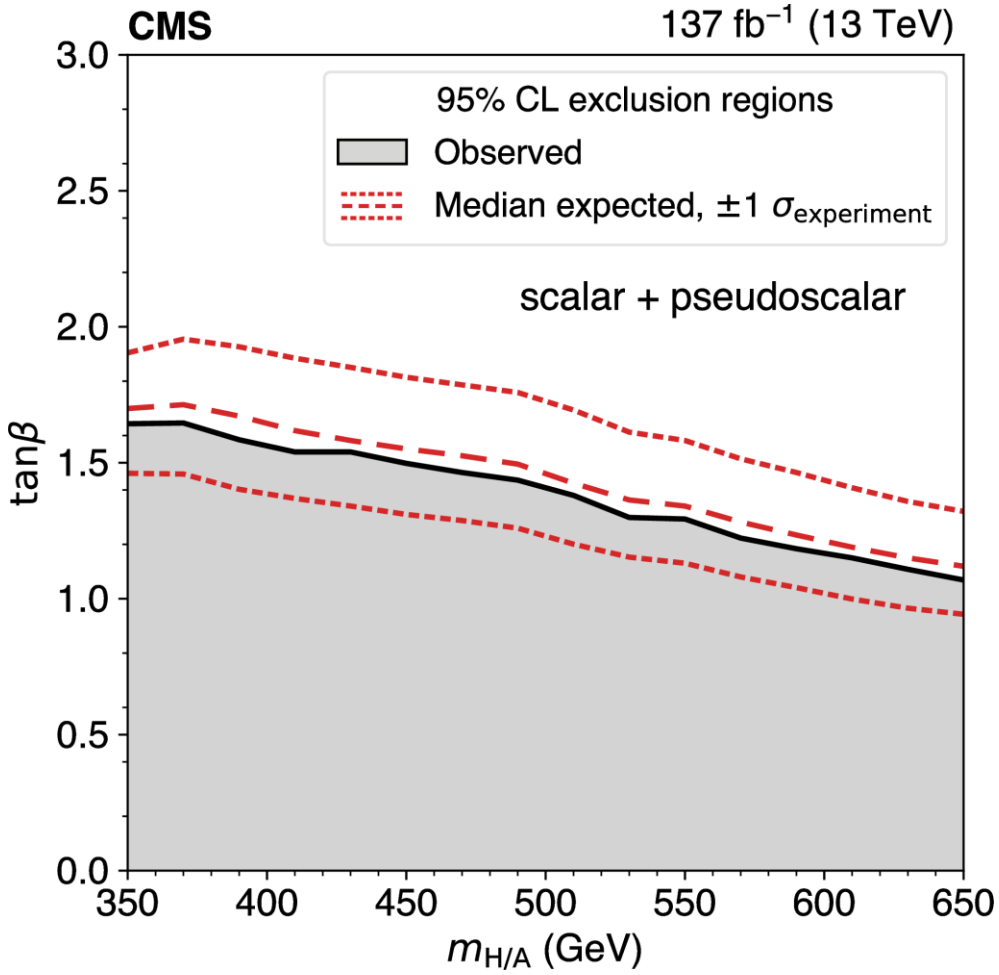
$t\bar{t} + b\bar{b}$


CMS
Preliminary
$\sigma_{t\bar{t}b\bar{b}}$ summary, 35.9 fb^{-1} (13 TeV)
April 2020
Reference for σ_{theo}
MG5_aMC@NLO + PYTHIA8 4FS
POWHEG + HERWIG++
MG5_aMC@NLO + PYTHIA8 5FS [FxFx]
POWHEG + PYTHIA8
ttbb_alljet
PLB (803) 2020 135285
ttbb_dilep
JHEP 07 (2020) 125
ttbb_semilep
JHEP 07 (2020) 125
1
2
3
4
5
6
Full phase space σ_{exp} / σ_{theo}


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
lepton+jets (≥ 3b)
lepton+jets (≥ 4b)
$e\mu$(≥ 3b)
$e\mu$(≥ 4b)
Data - $t\bar{t}X(X = H, V)$
Stat. uncert.
Total uncert.
Sherpa 2.2 $t\bar{t}b\bar{b}$ (4FS)
Powheg+Pythia8 $t\bar{t}b\bar{b}$ (4FS)
PowHel+Pythia8 $t\bar{t}b\bar{b}$ (5FS)
PowHel+Pythia8 $t\bar{t}b\bar{b}$ (4FS)
10^1
10^2
10^3
10^4
σ_{fid} [fb]
0.5
1.0
1.5
Pred./(Data - $t\bar{t}X$)

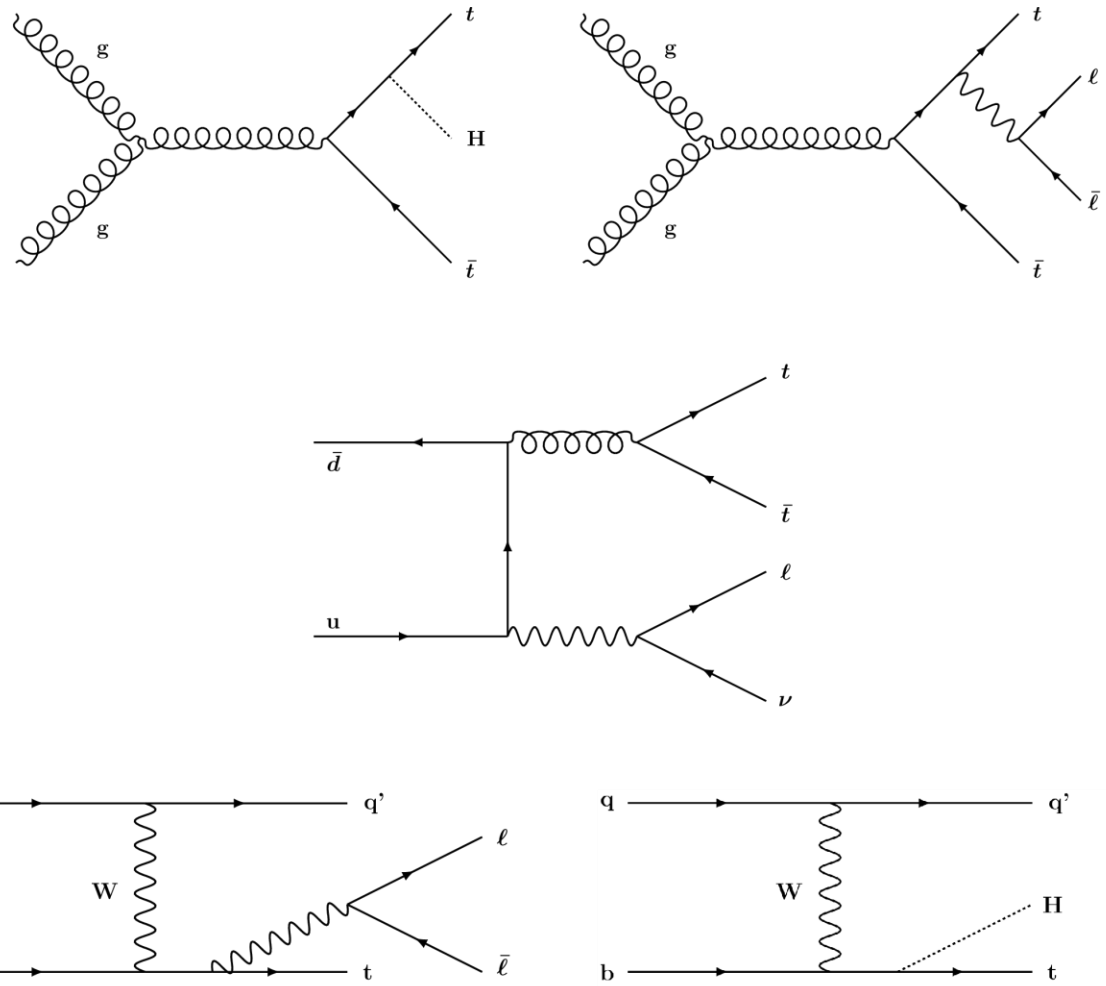
4-top Production





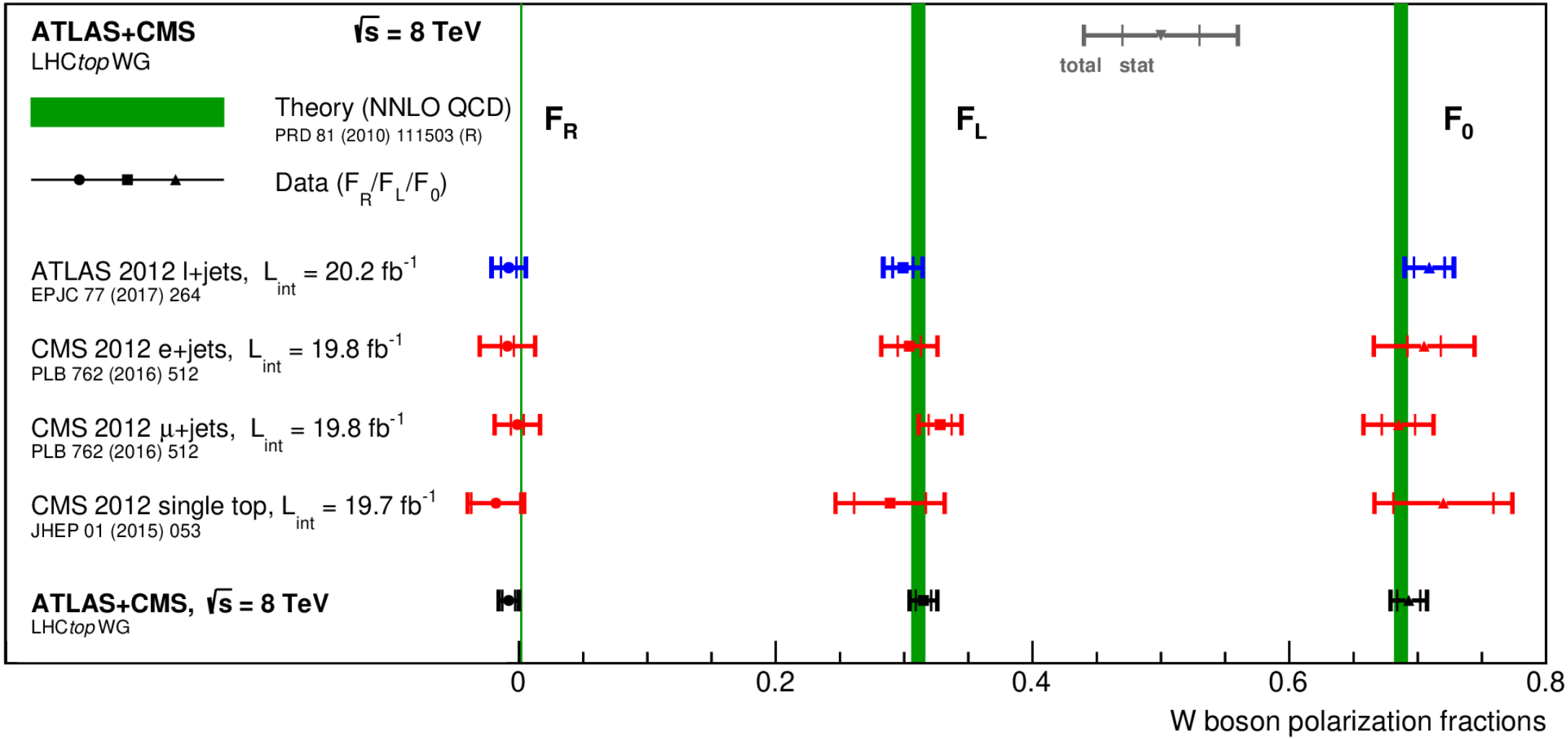
Top EFT w/ $t\bar{t}$+lepton(s) NEW!

CMS-PAS-TOP-19-001

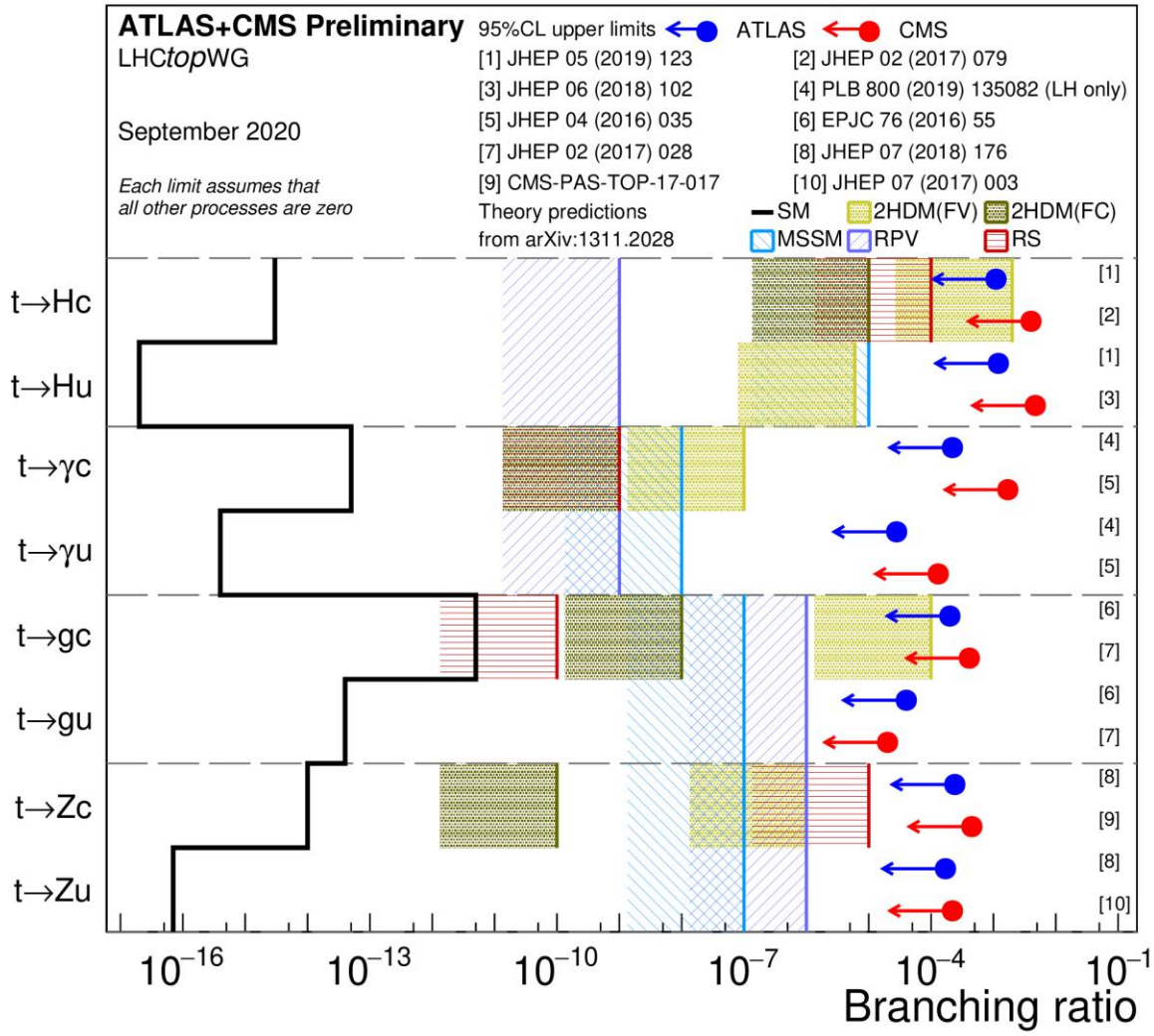


W Helicity

JHEP 08 (2020) 51



Top FCNC


ATLAS+CMS Preliminary
LHCtopWG
September 2020
Each limit assumes that all other processes are zero
95%CL upper limits
ATLAS
CMS
[1] JHEP 05 (2019) 123
[2] JHEP 02 (2017) 079
[3] JHEP 06 (2018) 102
[4] PLB 800 (2019) 135082 (LH only)
[5] JHEP 04 (2016) 035
[6] EPJC 76 (2016) 55
[7] JHEP 02 (2017) 028
[8] JHEP 07 (2018) 176
[9] CMS-PAS-TOP-17-017
[10] JHEP 07 (2017) 003
Theory predictions from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
[1]
[2]
[1]
[3]
[4]
[5]
[4]
[5]
[6]
[7]
[6]
[7]
[8]
[9]
[8]
[10]
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
Branching ratio