TOP-QUARK PHYSICS: A SELECTION OF RESULTS BY CMS

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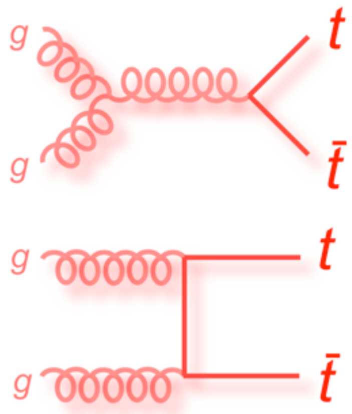
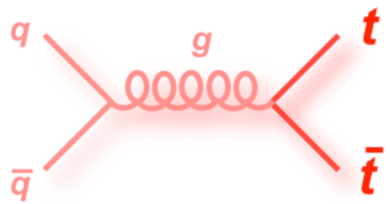
Introduction and motivations

- The top quark plays a special role in the SM
  - The heaviest elementary particle known to date!
  - It decays before hadronizing: BR(t->Wb)~1, $\tau \sim < 10^{-25}$s
  - Unique opportunity to measure bare quark properties!
  - The Higgs boson couples preferentially to the top
  - Several NP scenarios foresee a preferred coupling to the top sector
- CMS has a very rich program of measurements of/with the top quark
  - In this talk, <u>only a selection </u>of results by CMS is reported

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Top-quark production at the LHC





tt pairs

$t\bar{t}$ pairs: dominant production mechanism (QCD)

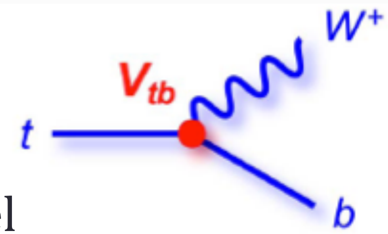
The LHC is a **top factory**!

Cross sections at 13 TeV:

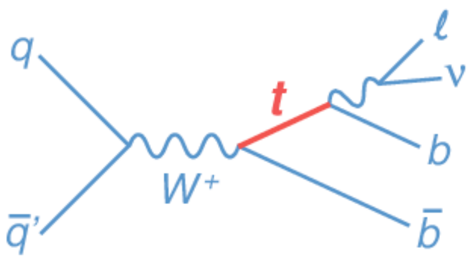
≈830 pb for $t\bar{t}$;

≈220 pb for single top t-channel

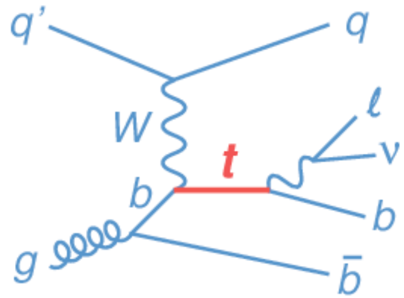
120M $t\bar{t}$ pairs and 30 M single top quarks!



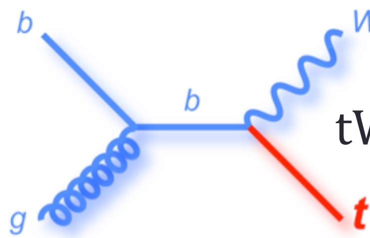
EWK production: single top



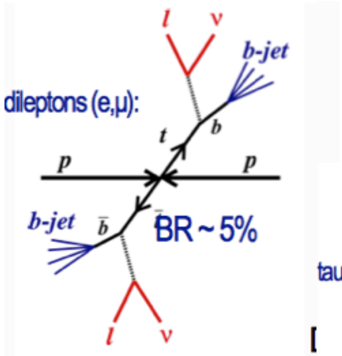
s channel

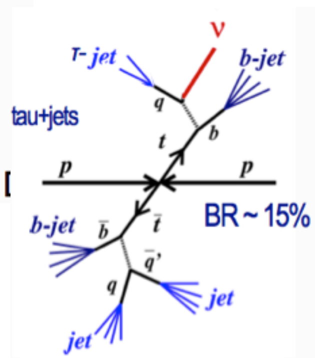


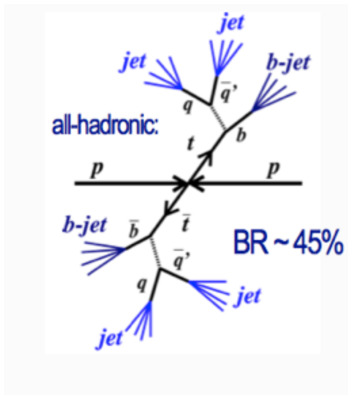
t channel

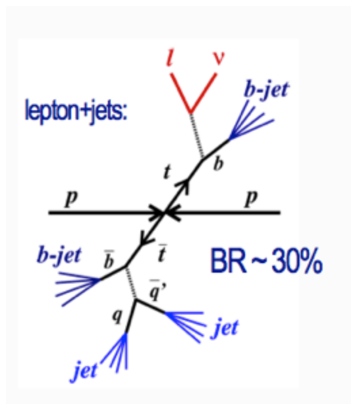


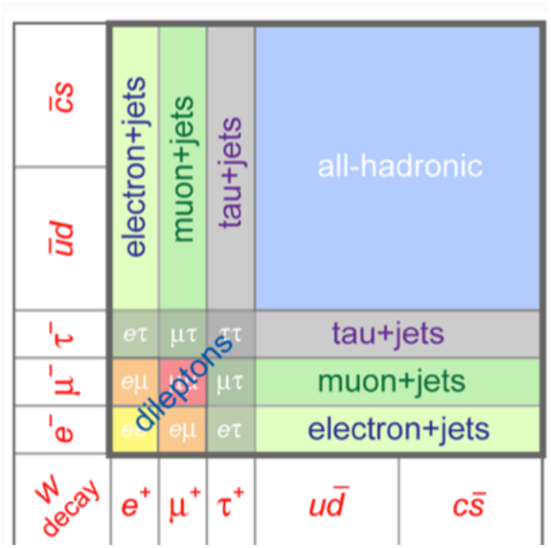
tW channel





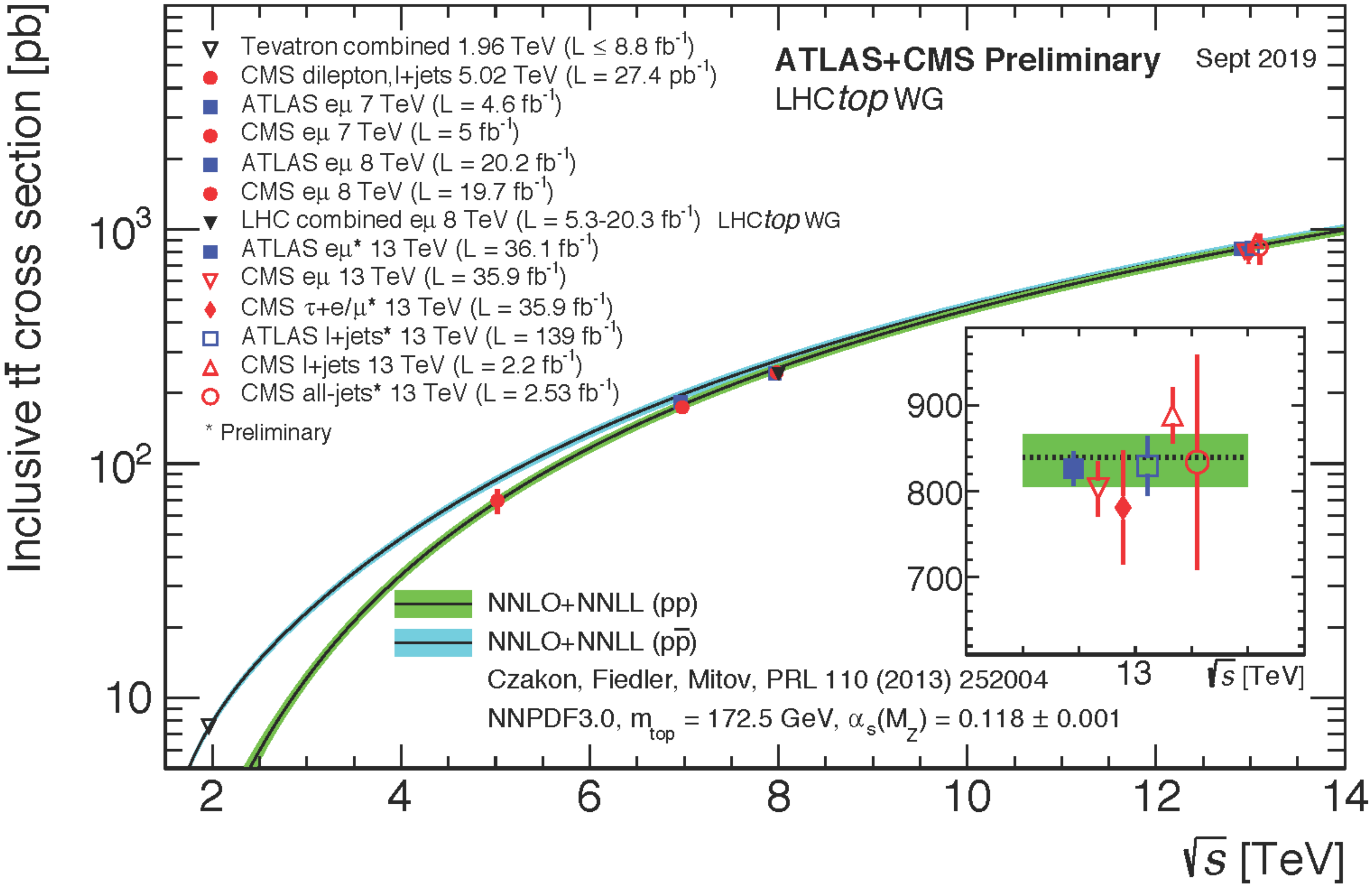




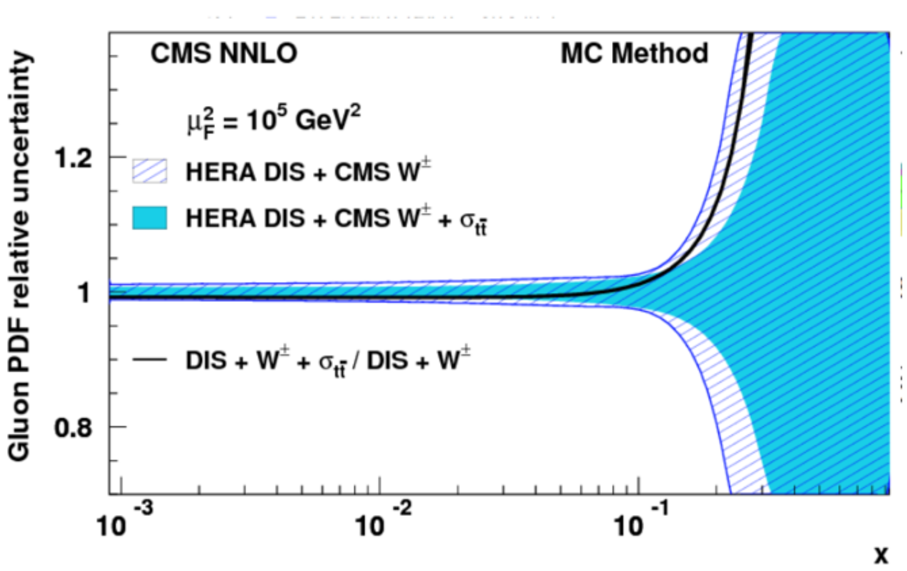


$t\bar{t}$ inclusive cross section

LHC TOP WG



Great improvement on the precisions (single measurements at the level of 3.5%). Precisions comparable to theory



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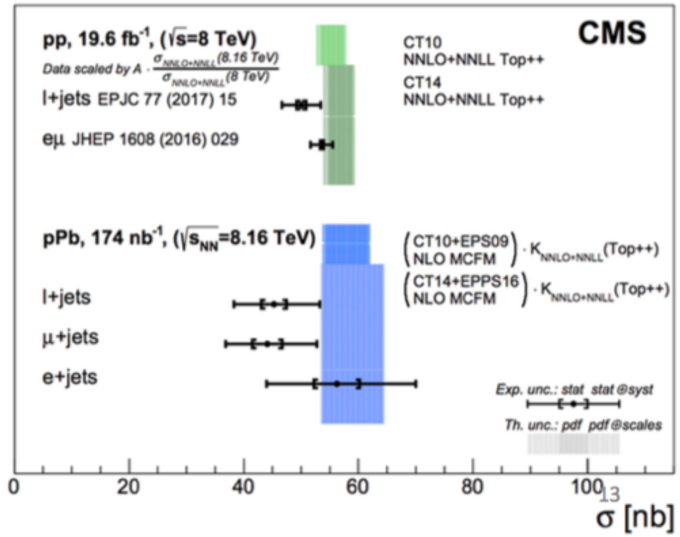
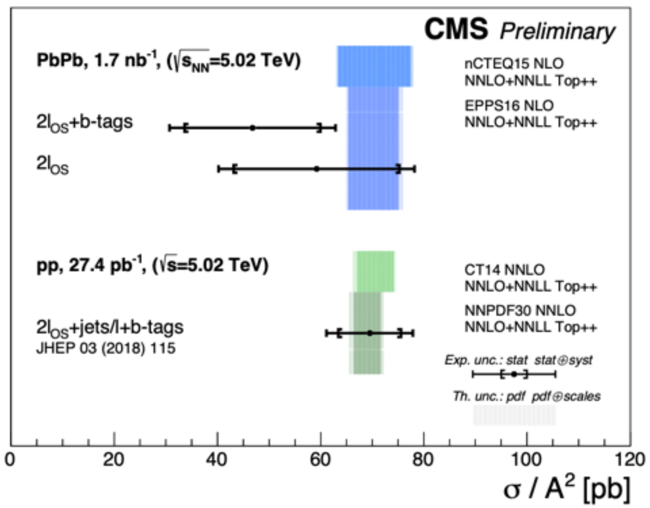
- σ(tt) at 5.02 TeV.
- Can constrain gluon PDF at large momentum fraction.
- Moderate improvement on the uncertainty at large x



PRL 119, 242001 (2017)

- σ(tt) in pPb collisions.
- Consistent with perturbative QCD.
- Probe of nuclear gluon density in the high Bjorken-x region ($x>2m_t/\sqrt{s}\approx0.05$)
- No evidence of nuclear modifications

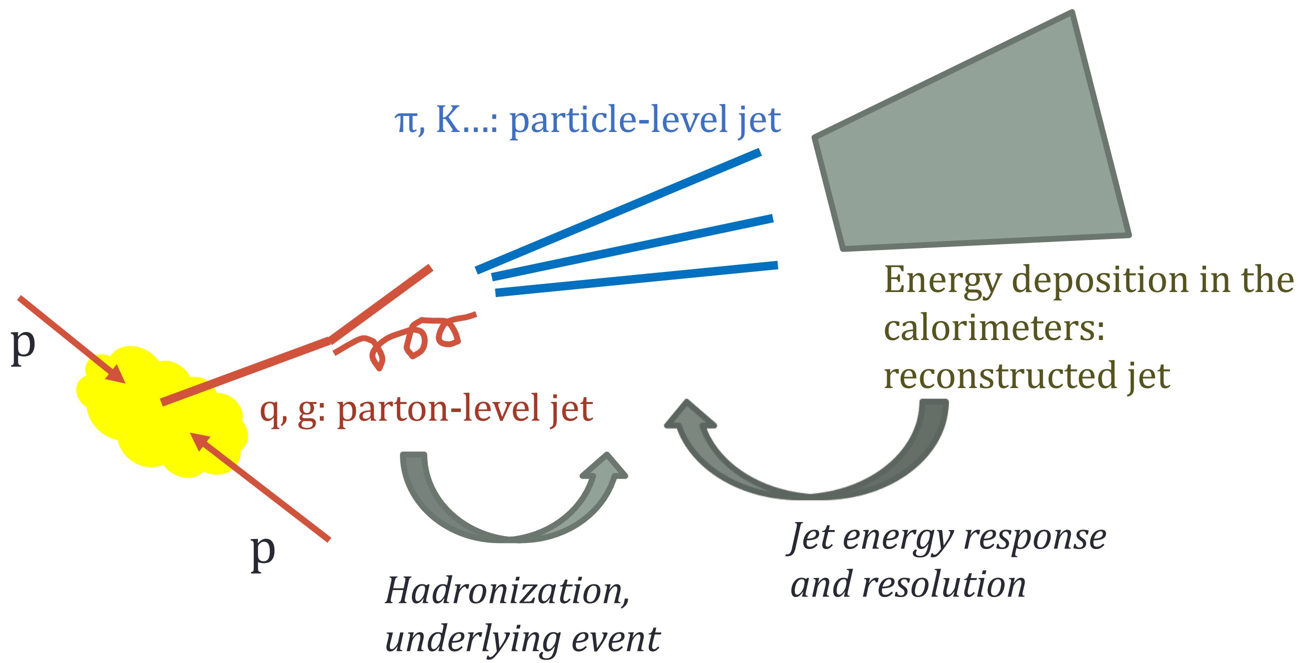


CMS-PAS-HIN-19-001, submitted to Nature-Physics

- σ(tt) in PbPb collisions.
- Probe of the nuclear gluon density in the poorly explored high Bjorken-*x* region.
- Analysis performed both without and with requesting b-jet reconstruction: study of medium-induced parton energy loss.

$t\bar{t}$ differential cross sections

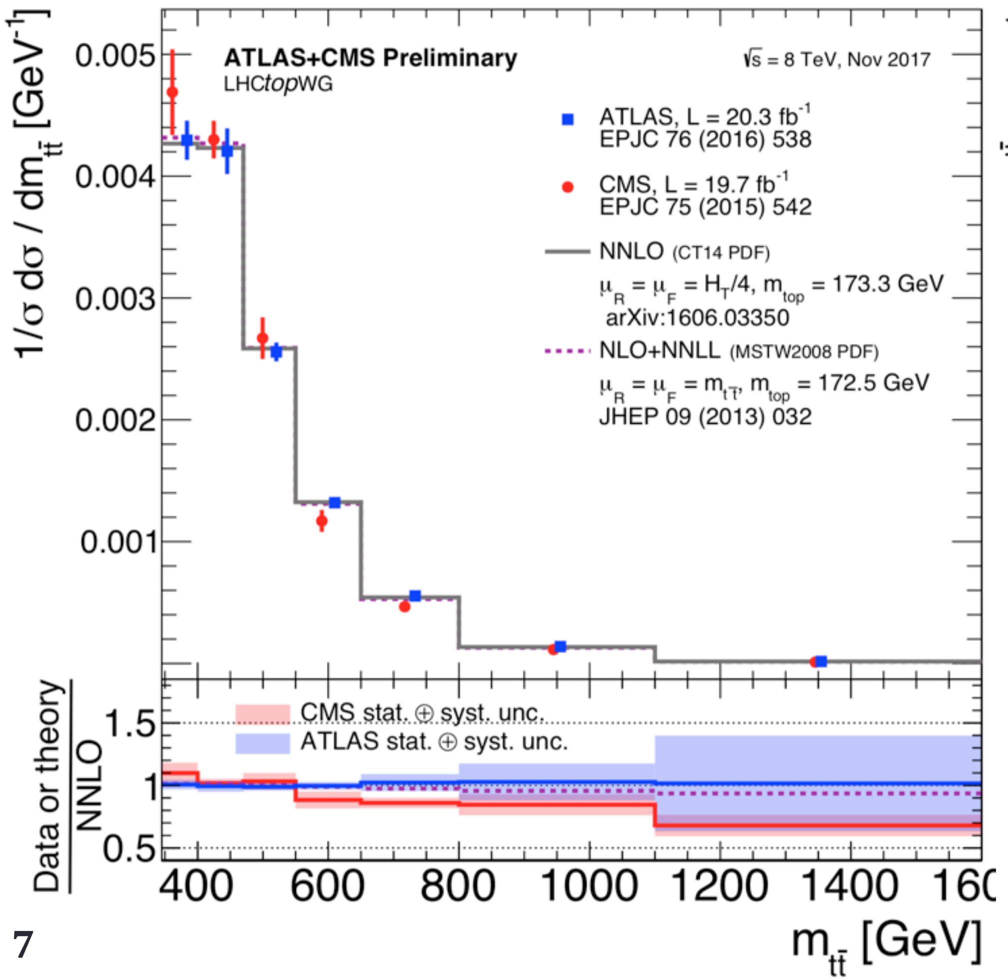
- Measurement of the cross section as a function of various quantities, at either particle or parton level.
  - Parton level: extrapolation to the full phase space; comparison with fixed-order calculations
  - Particle level: reduced model dependence because no extrapolation to the full phase space.
- Comparison with theory and MC predictions (feedback to improve MC descriptions).
- Search for New Physics in corners of the phase space.

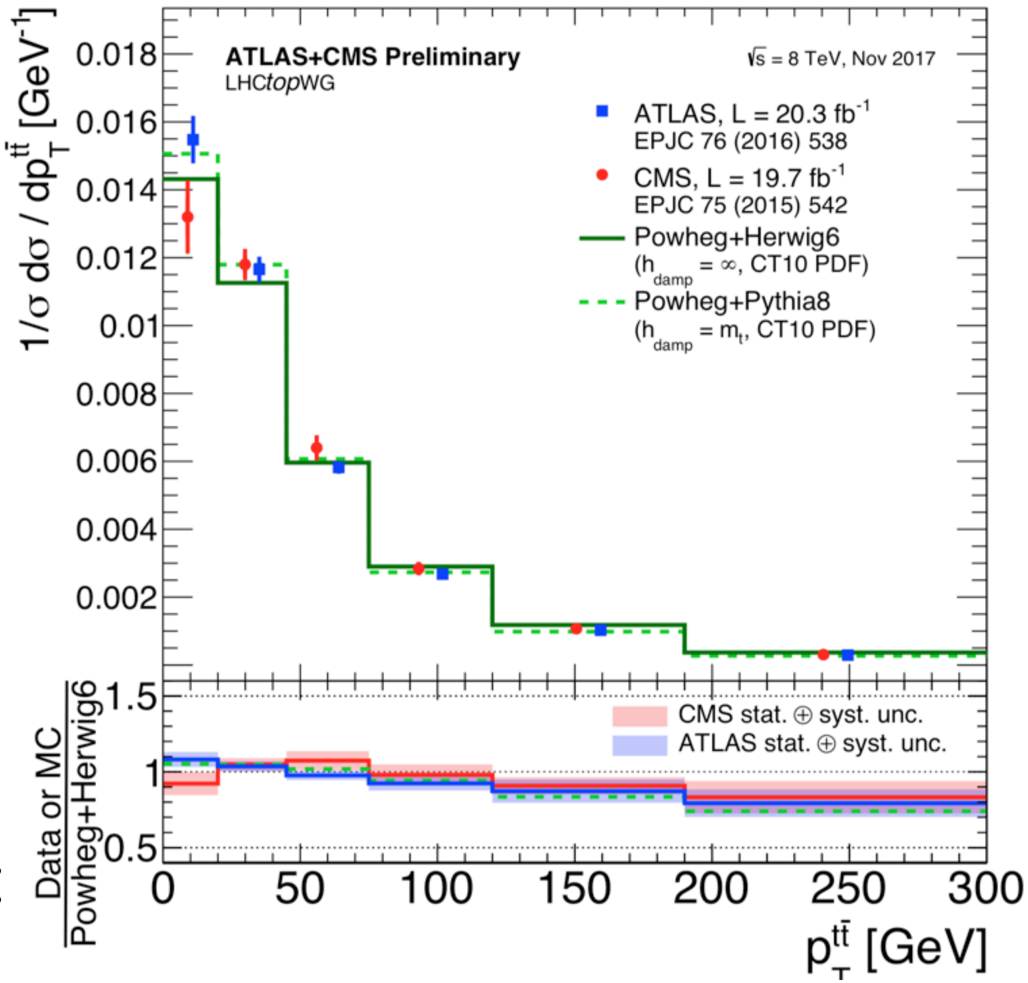


$t\bar{t}$ differential cross sections

LHC TOP WG

- Detailed analysis of the cross section as a function of various variables. Precise test of pQCD. In general, good agreement with predictions

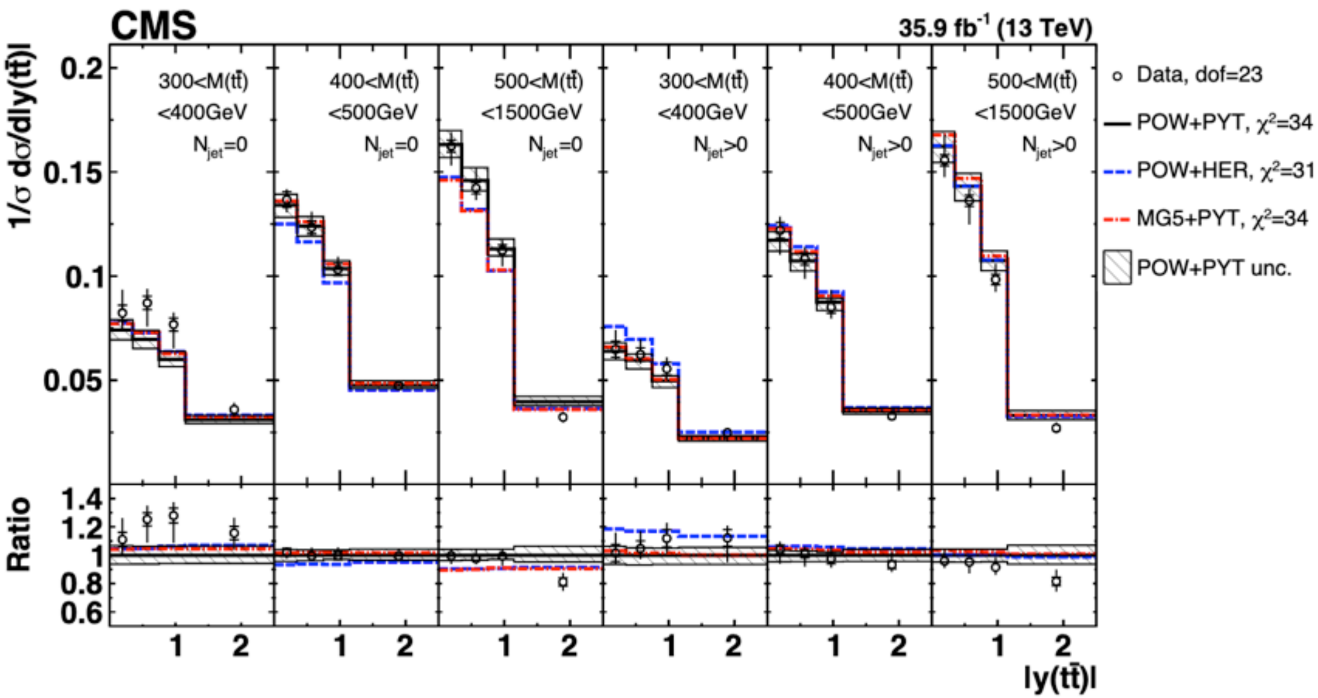




$t\bar{t}$ differential cross sections

arXiv:1904.05237, submitted to EPJC

- Dilepton channel, 35.9 fb^{-1} at 13 TeV. 2D and also 3D diff. X-sections versus various variables of the top, of the $t\bar{t}$ pair or of the number of jets

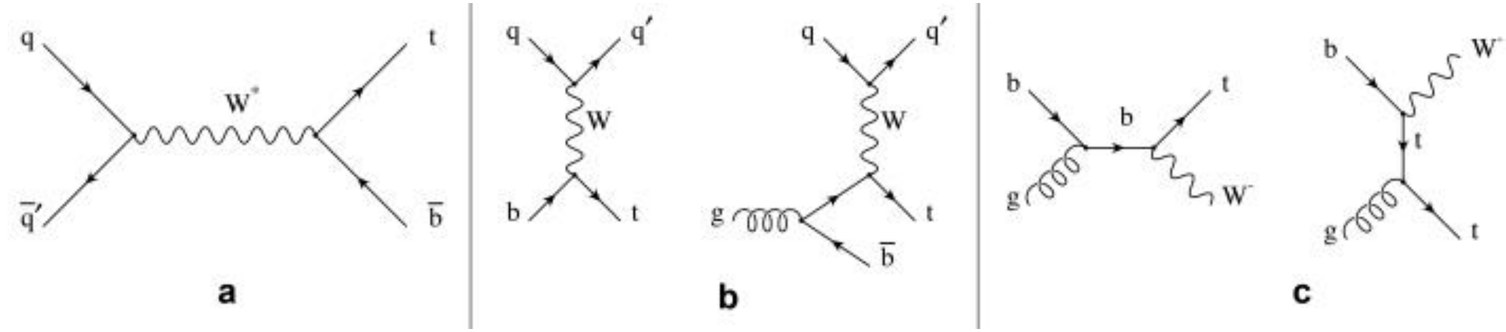


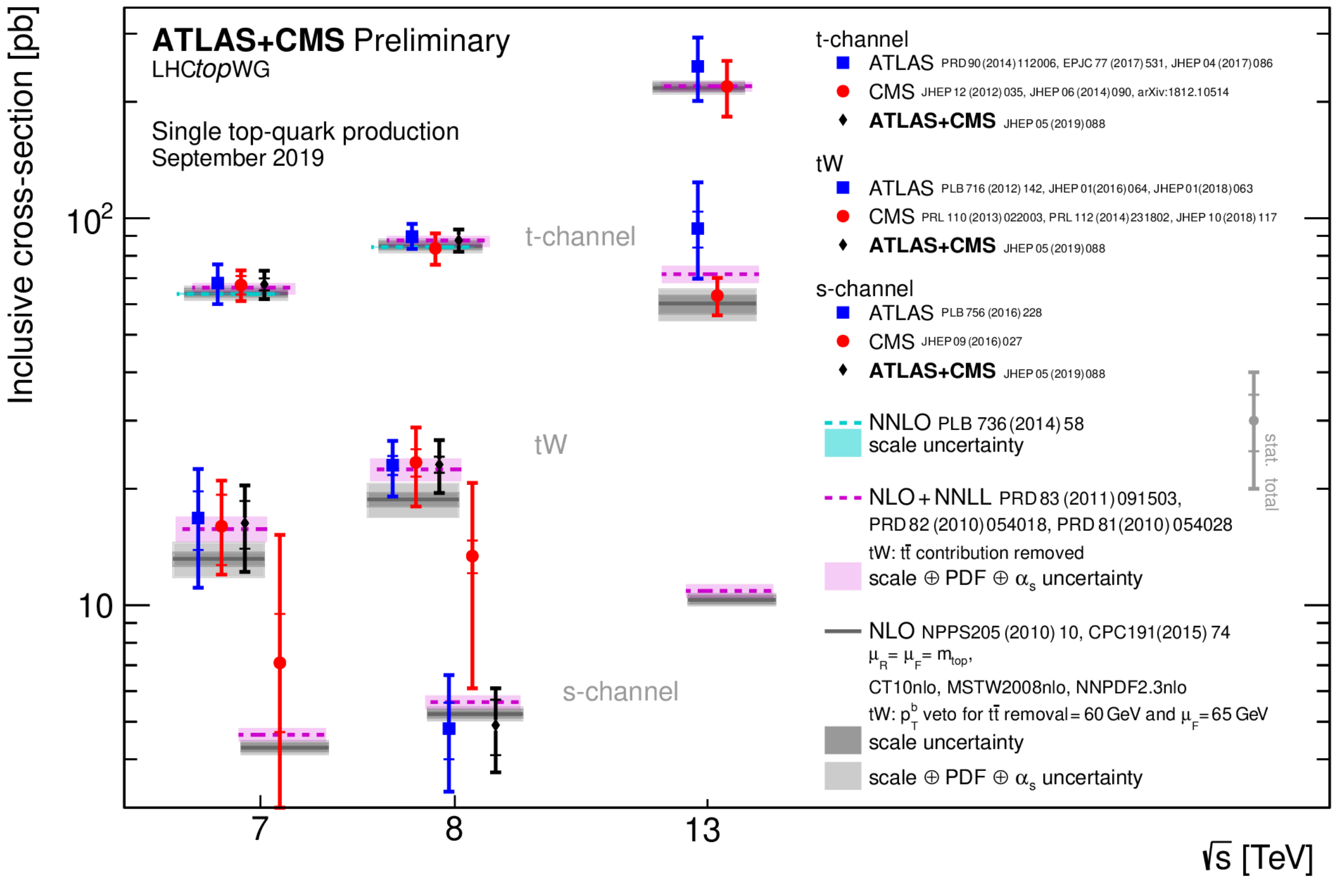
No single MC generator is capable to describe well all the measured distributions

- The measured 3D cross sections have been incorporated into two specific fits of QCD parameters at NLO order, together with the inclusive deep inelastic scattering data from HERA.
- In a simultaneous fit of α_s, m^t_{pole}, and PDFs, the inclusion of the new multi-differential $t\bar{t}$ measurements has a significant impact on the extracted gluon PDF at large x.

Electroweak production

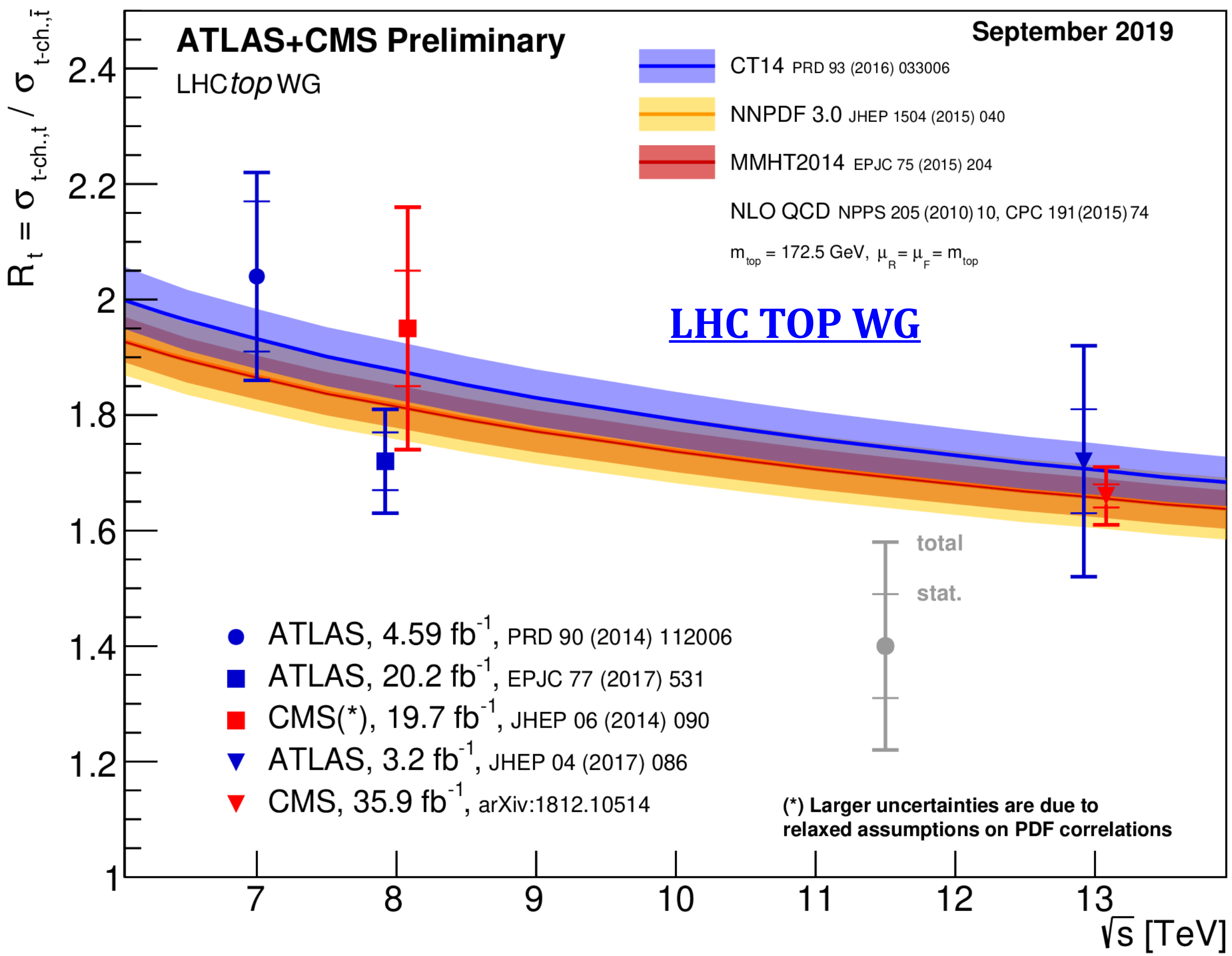
s channel | t channel | tW channel



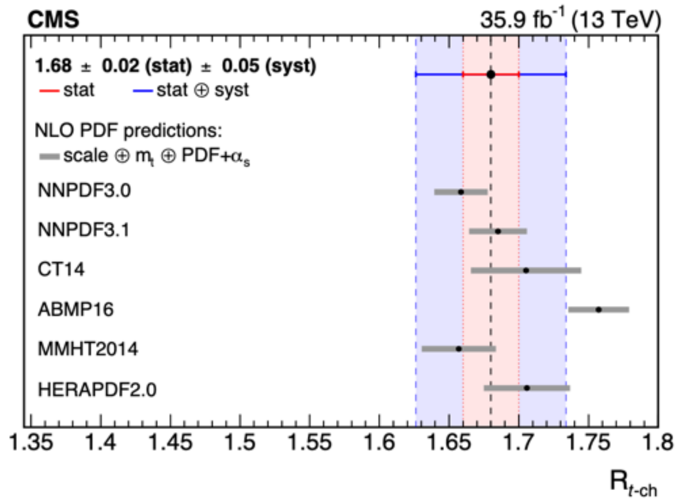


[LHC TOP WG]

Ratio of single top to single antitop

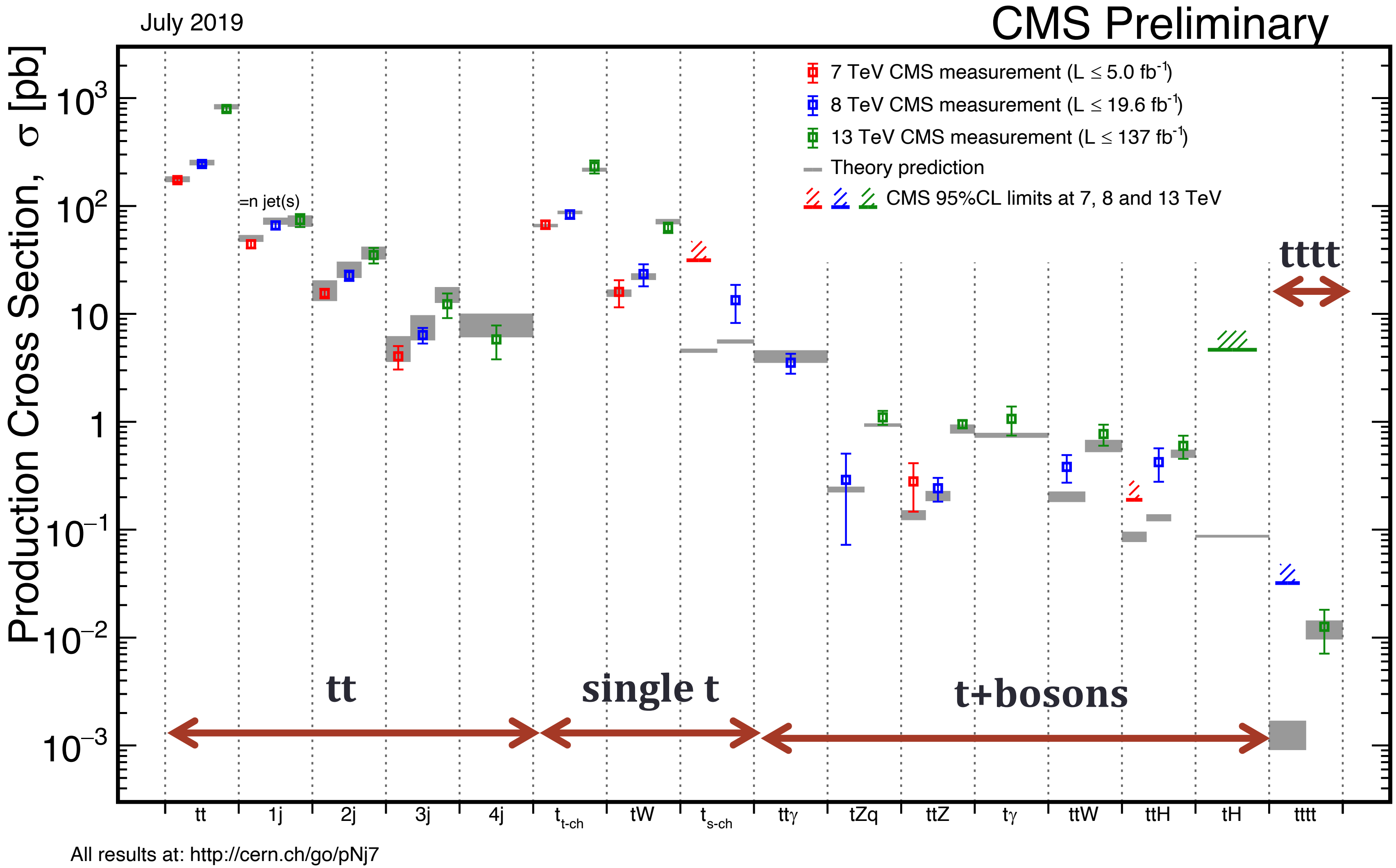


PLB 800 (2019) 135042



The ratio can be used to test the predictions from different PDF sets for their compatibility with data. Also **differential x-sec measurements** using t-channel and tW channel (**CMS-TOP-PAS-19-003, EPJC 80 (2020) 370**)

Top + X

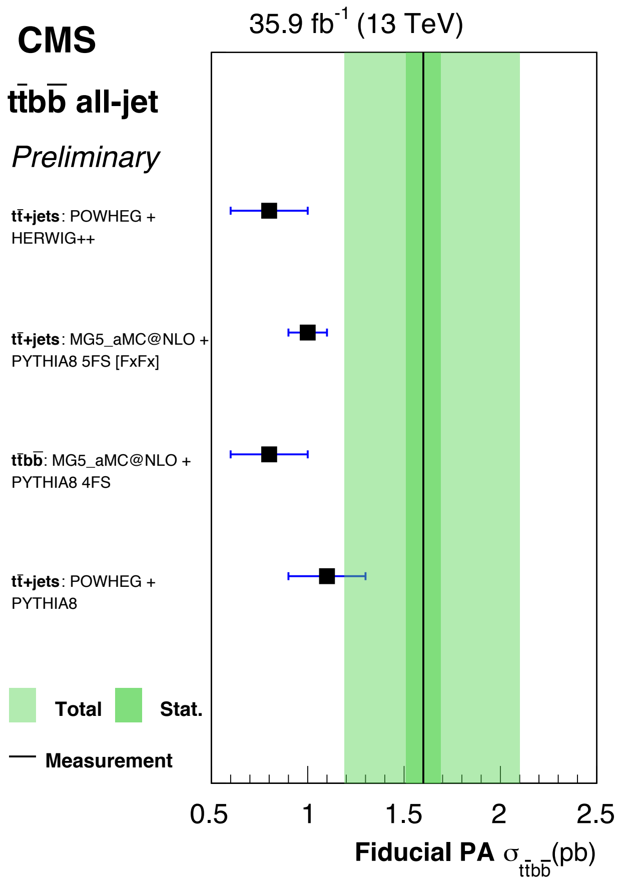


Run2 data allow rare processes to start becoming accessible! Direct tests of top couplings and windows to NP

Inclusive $t\bar{t} + b\bar{b}$ and $t\bar{t} + jj$

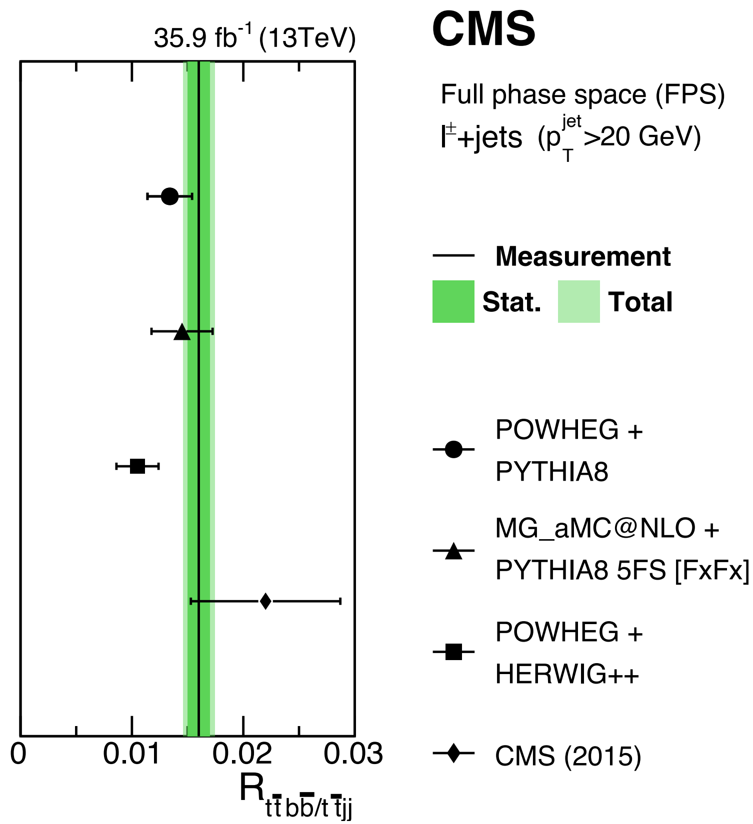
$t\bar{t}b\bar{b}$: tests of higher order calculations. Important background for $t\bar{t}H$ and $t\bar{t}t\bar{t}$

Not easy to model nor separate the signals of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$



All hadronic channel

PLB 803 (2020) 135285



Semileptonic and dileptonic channels

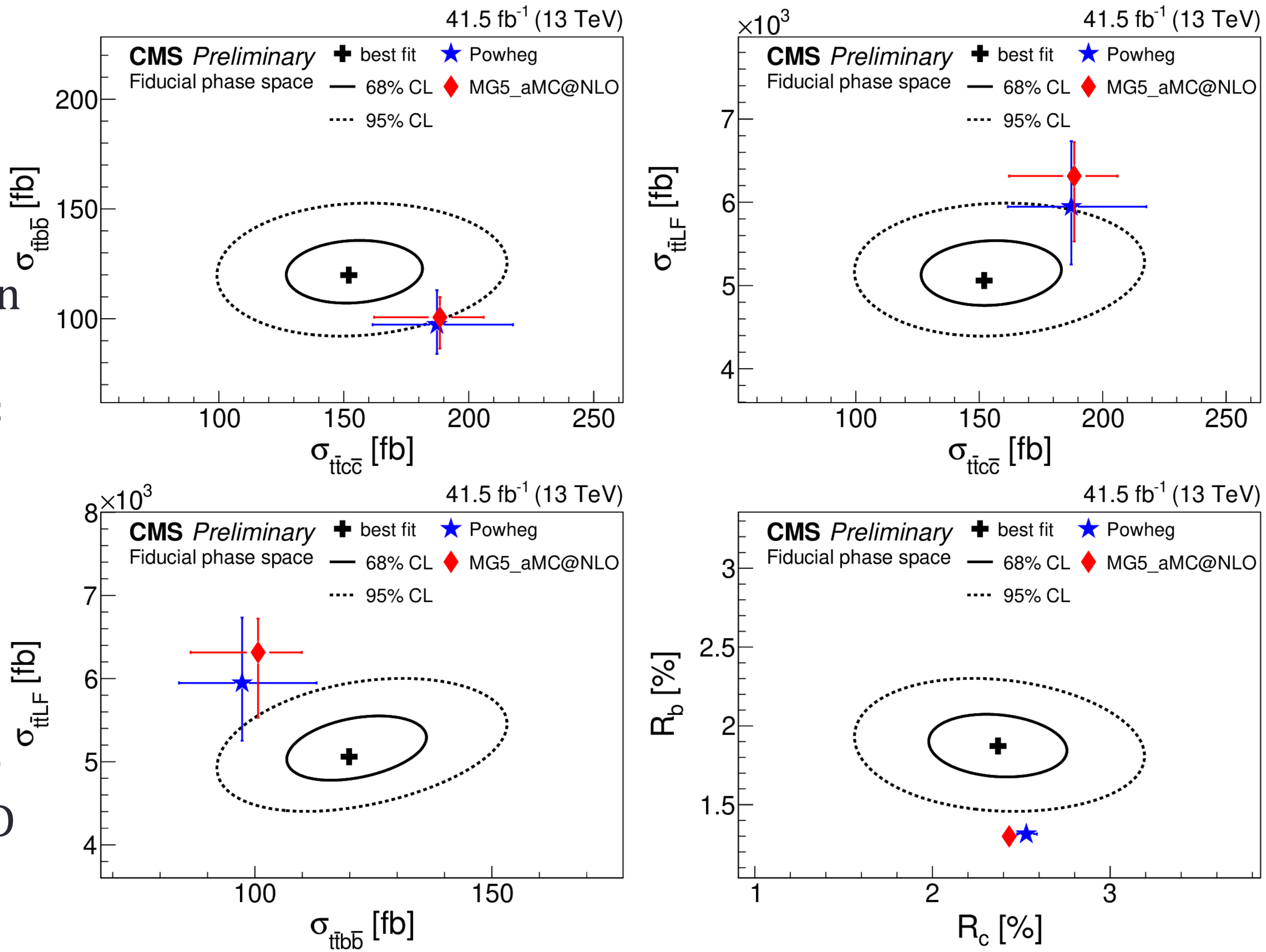
JHEP 2007 (2020) 125

Inclusive $t\bar{t} + c\bar{c}$

CMS-TOP-PAS-20-003

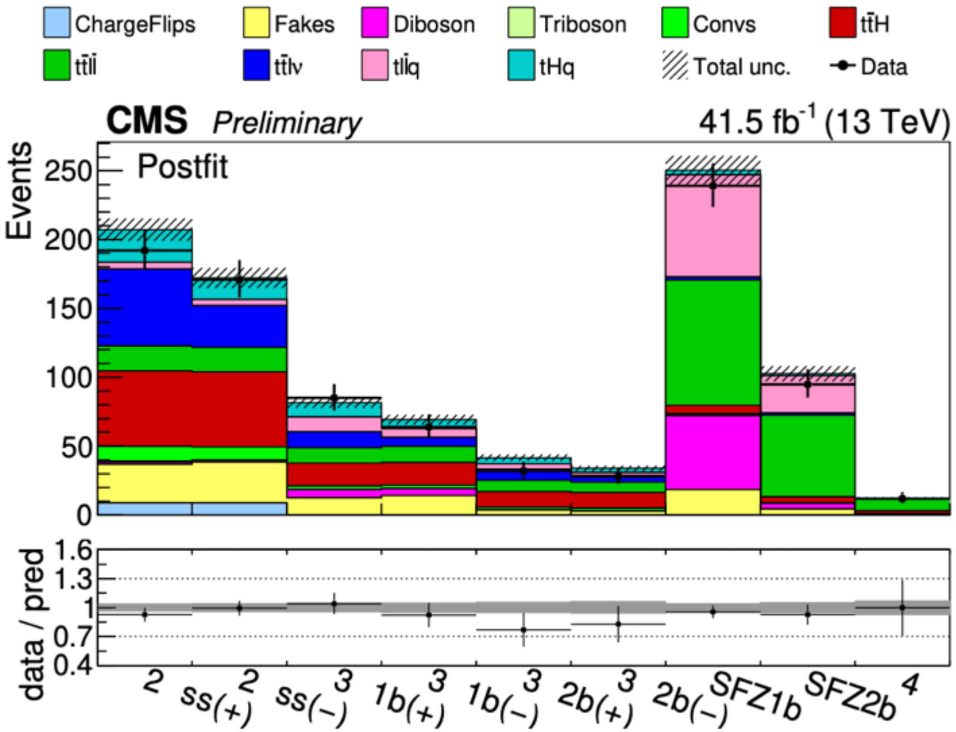
- First measurement of $t\bar{t}+c\bar{c}$! Imporant background for $t\bar{t}$+H

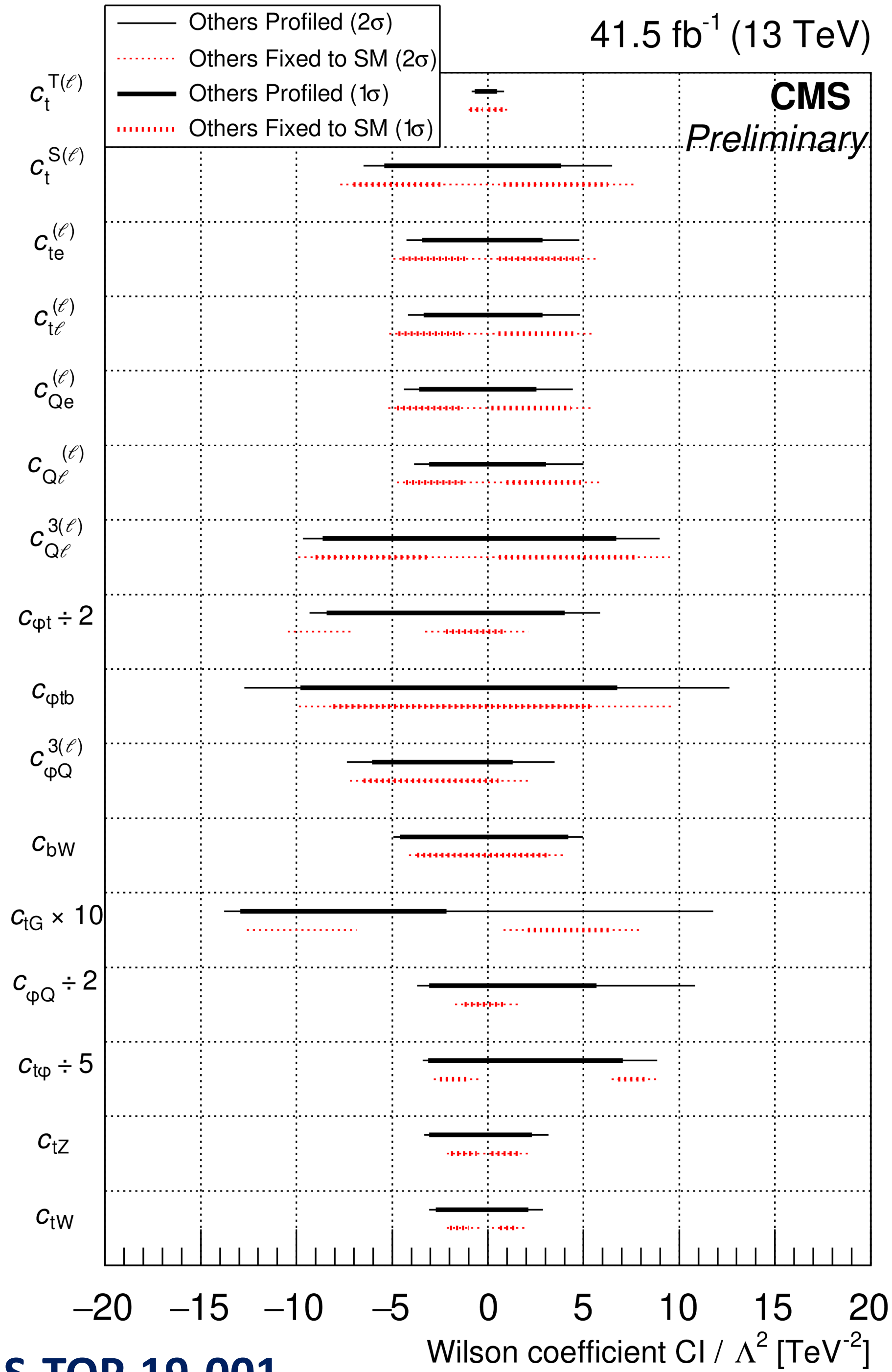
  - Neural network trained to distinguish between ttcc, ttbb and tt+light-flavour jets (ttLF).
  - Tagger algorithm: deep combined secondary vertex. Efficiency in b-jet ID 70%, c-jet misID 12%, light-jet misID 1%



Search for New Physics with EFT

- Study of the associated production of top quark production with a H, W or Z boson -> 16 6D operators simultaneously studied
- Observables at detector-level to enhance sensitivity to all operators





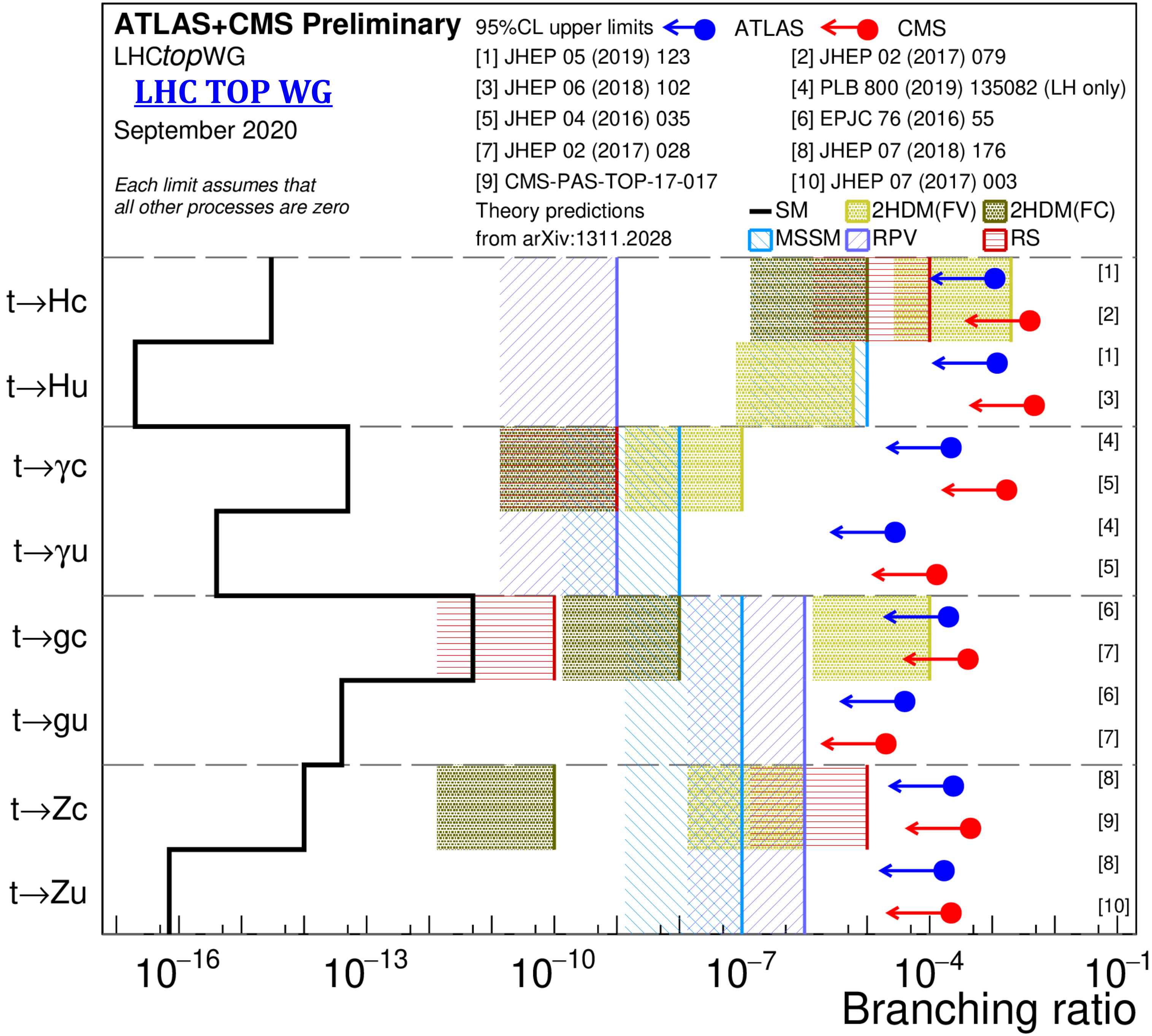
CMS-PAS-TOP-19-001

FCNC

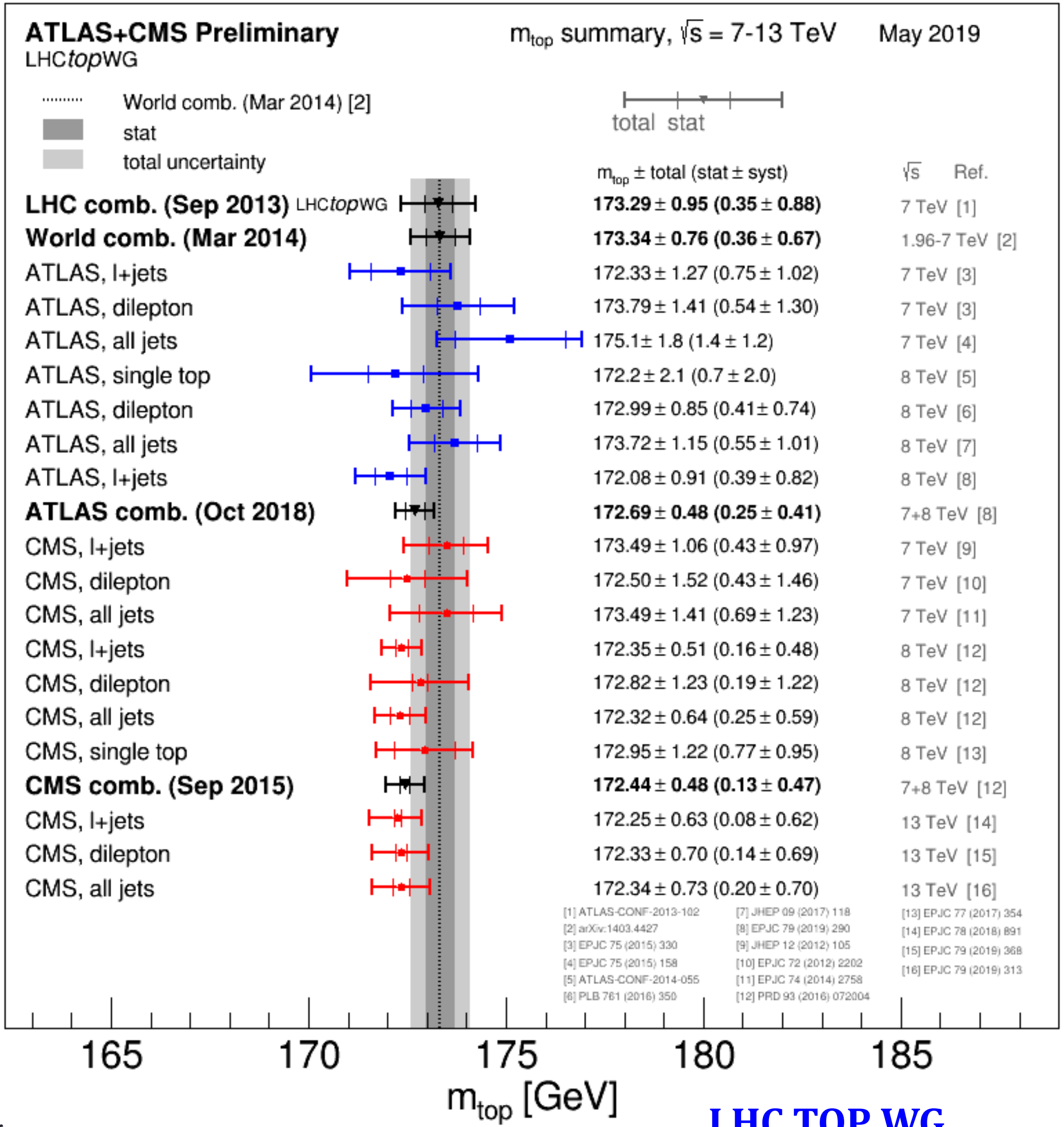
Forbidden at tree level in the SM

Only possible via higher order diagrams, strongly suppressed ($< 10^{-11}$)

Can be enhanced in several NP models (up to $\sim 10^{-4}$)

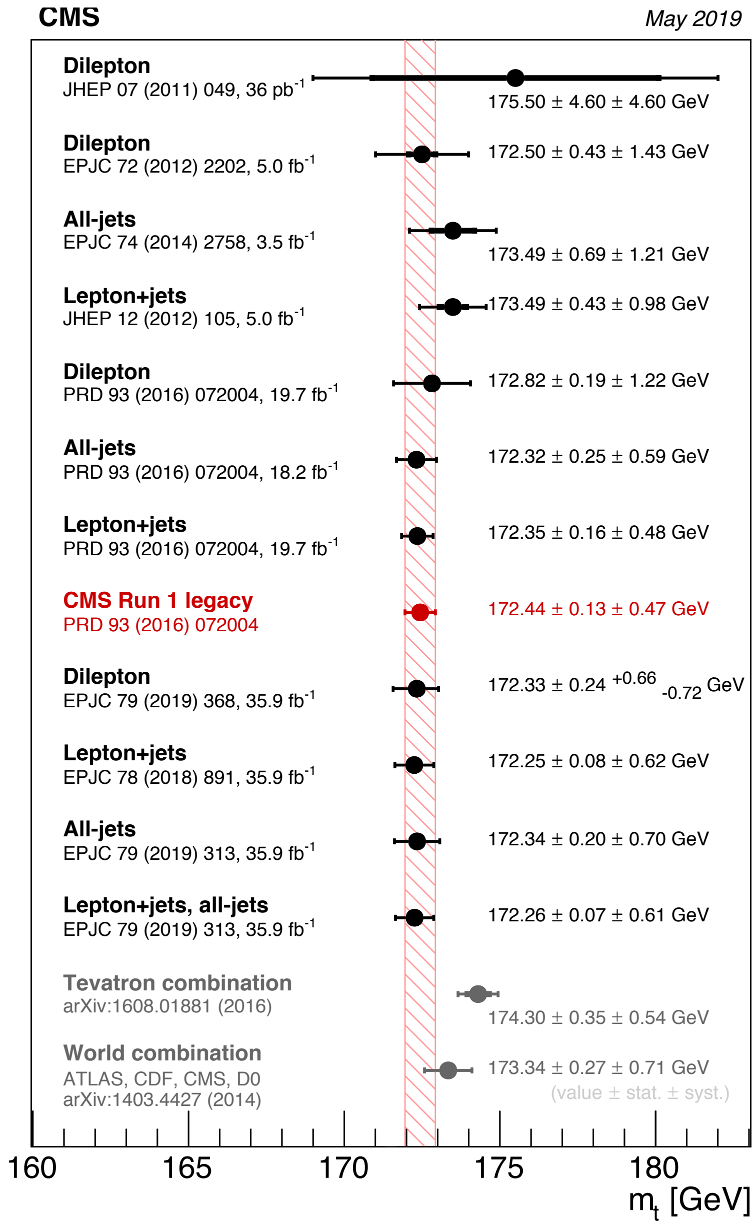


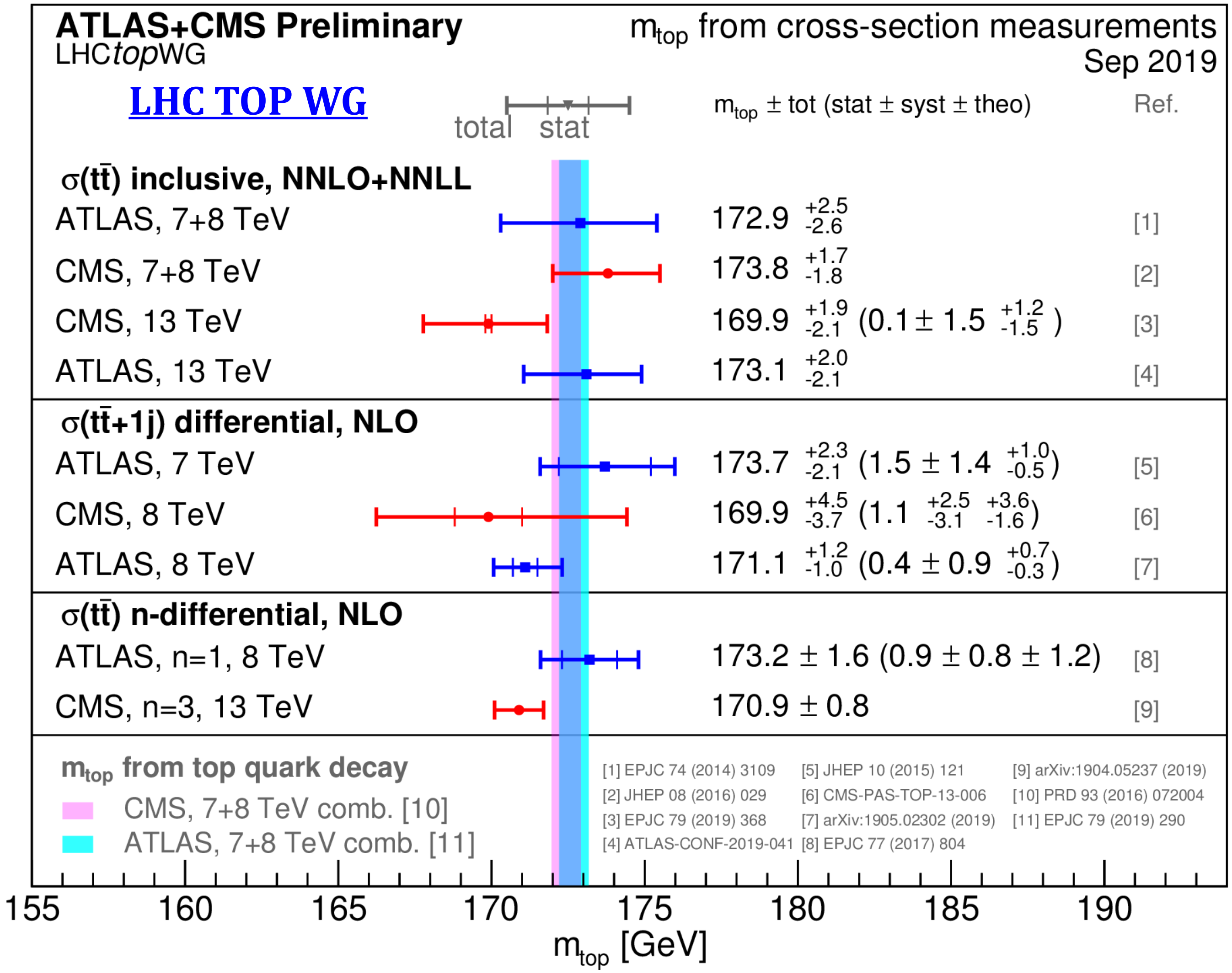
Top quark mass



[LHC TOP WG]

Direct measurements





Indirect measurements. Extraction of the top mass from fits to various sensitive observables (e.g. the top pole mass from cross section measurements), including theory info.

First measurement of the **running of the top quark mass**

- The running of $m_t(\mu)$ is extracted at NLO as a function of the invariant mass of the $t\bar{t}$ system from a measurement of the differential $t\bar{t}$ cross section
  - Measurement at the parton level using a maximum-likelihood fit to multi-differential distributions of final state observables.
    - -> constraining the nuisance parameters simultaneously with the differential cross section -> significantly improved precision compared to conventional procedures in which the unfolding is performed as a separate step.
- The $\overline{MS}$ mass of the top quark is determined independently in each $m(t\bar{t})$ bin via a χ^2 fit to theory predictions at NLO.
  - The extracted masses are then evolved to the representative scale of the process in each bin.
  - The observed evolution of $m_t(\mu)$ is found to be in agreement with the prediction from the renormalization group equation at one-loop precision, within 1.3 standard deviations

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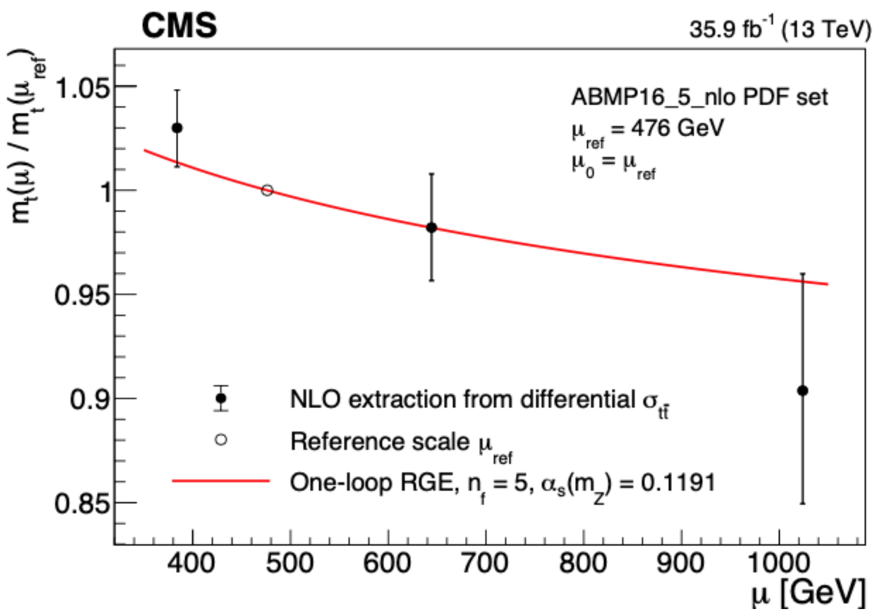
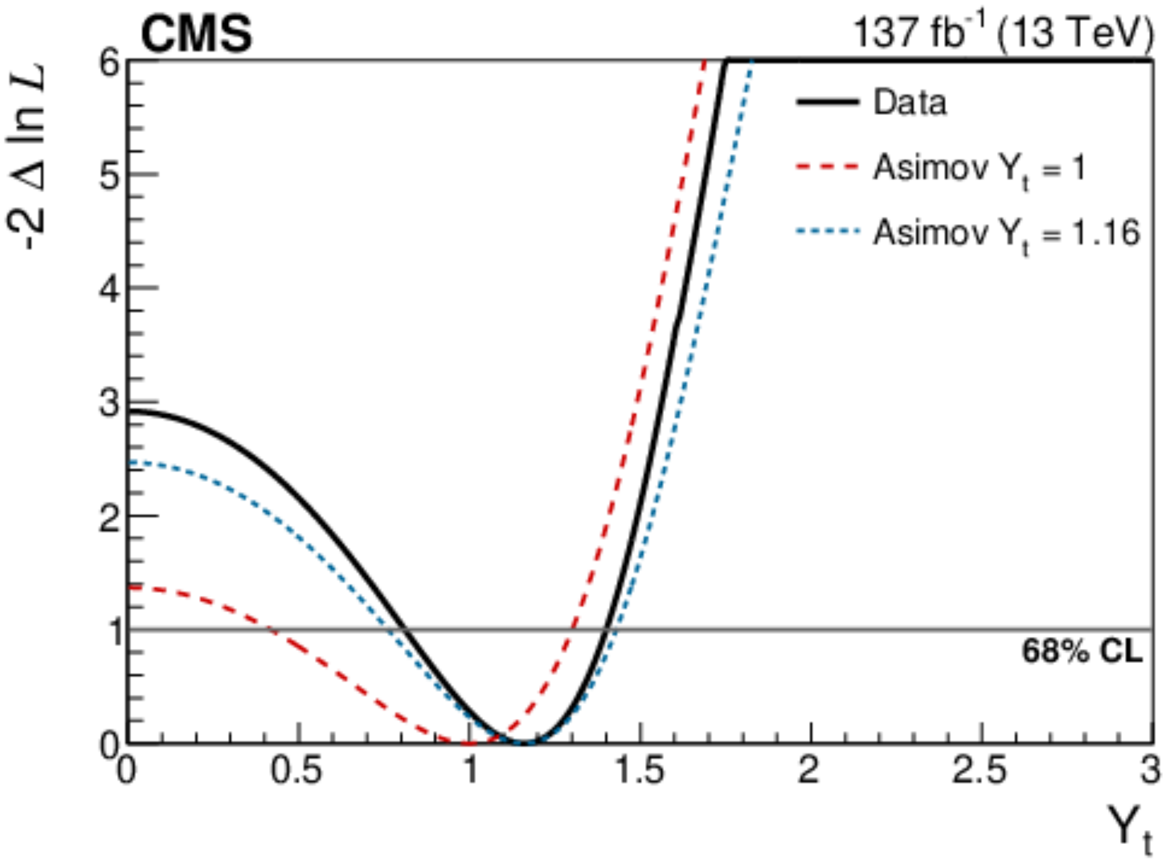


- **The significance of the observed running is found to be 2.6 standard deviations with respect to the no-running hypothesis**.

Top-quark Yukawa coupling

EWK mediated corrections are about O($\alpha^2\ \alpha_{weak}$) : they do not affect the cross sections, but can alter kinematic distributions.
Dileptonic channel. No full kinematic reconstruction due to the presence of 2 neutrinos: usage of proxy variables M_{lbbl} = M(b+l+b+l) and $|\Delta y|_{lbbl}$=|y(b+l)+y(b+l)|

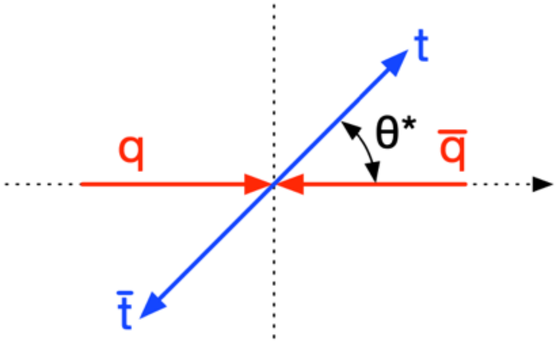


$$Y_t = 1.16^{+0.24}_{-0.35}$$

arXiv:2009.07123, submitted to PRD

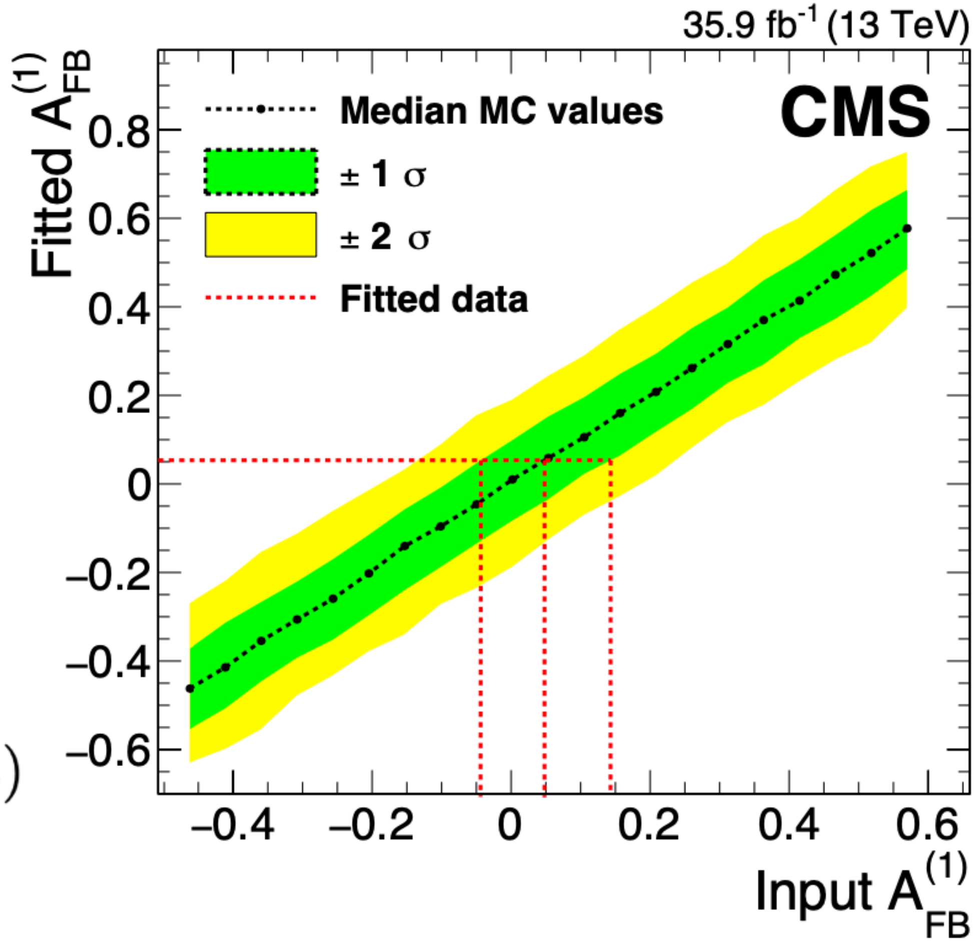
Forward-backward asymmetry

Search for anomalies in the angular distribution of produced $t\bar{t}$ pairs. They can be caused by modifications of the $t\bar{t}g$ vertex or by the presence of heavy states coupled to top quarks. Impact on cos(θ*)



$$A_{\mathrm{FB}} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

$$A_{\mathrm{FB}}^{(1)} = 0.048^{+0.095}_{-0.087}(\mathrm{stat})^{+0.020}_{-0.029}(\mathrm{syst})$$



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CP violation

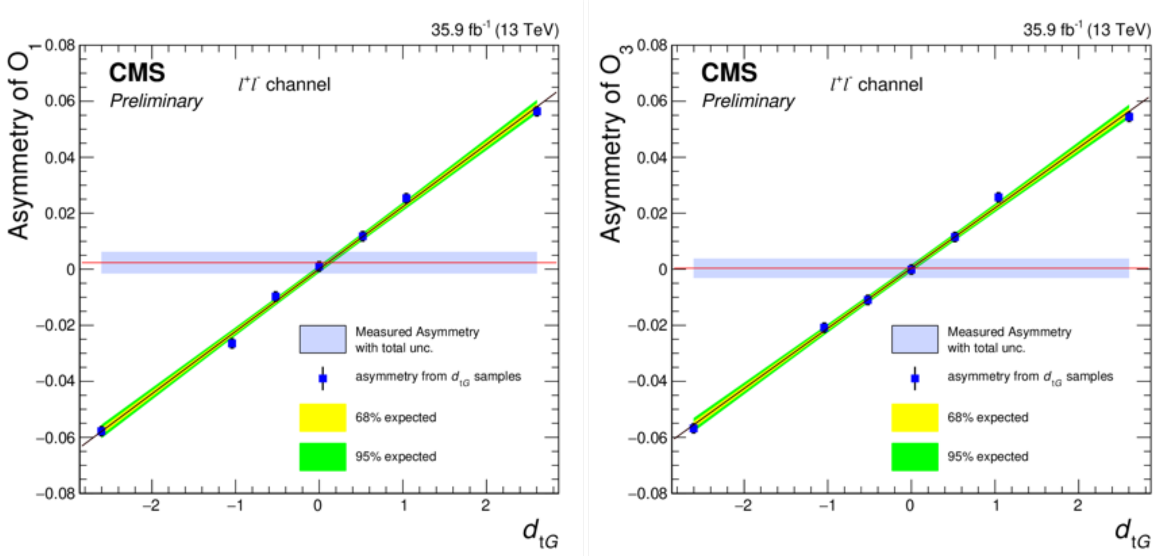
- Very small in the SM. Sought for by effects induced in anomalous couplings (here an interaction through a chromoelectric dipole moment(CEDM) of the top quark, d_{tG})
- Construct 2 CP-odd observables O_i.

$$\mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-}) = \begin{vmatrix} E_t & p_{t_x} & p_{t_y} & p_{t_z} \\ E_{\bar{t}} & p_{\bar{t}_x} & p_{\bar{t}_y} & p_{\bar{t}_z} \\ E_{\ell^+} & p_{\ell^+_x} & p_{\ell^+_y} & p_{\ell^+_z} \\ E_{\ell^-} & p_{\ell^-_x} & p_{\ell^-_y} & p_{\ell^-_z} \end{vmatrix}$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}$$

$$\mathcal{O}_3 = \epsilon(p_b, p_{\bar{b}}, p_{\ell^+}, p_{\ell^-}) = \begin{vmatrix} E_b & p_{b_x} & p_{b_y} & p_{b_z} \\ E_{\bar{b}} & p_{\bar{b}_x} & p_{\bar{b}_y} & p_{\bar{b}_z} \\ E_{\ell^+} & p_{\ell^+_x} & p_{\ell^+_y} & p_{\ell^+_z} \\ E_{\ell^-} & p_{\ell^-_x} & p_{\ell^-_y} & p_{\ell^-_z} \end{vmatrix}$$

CMS-TOP-PAS-18-007



Conclusions

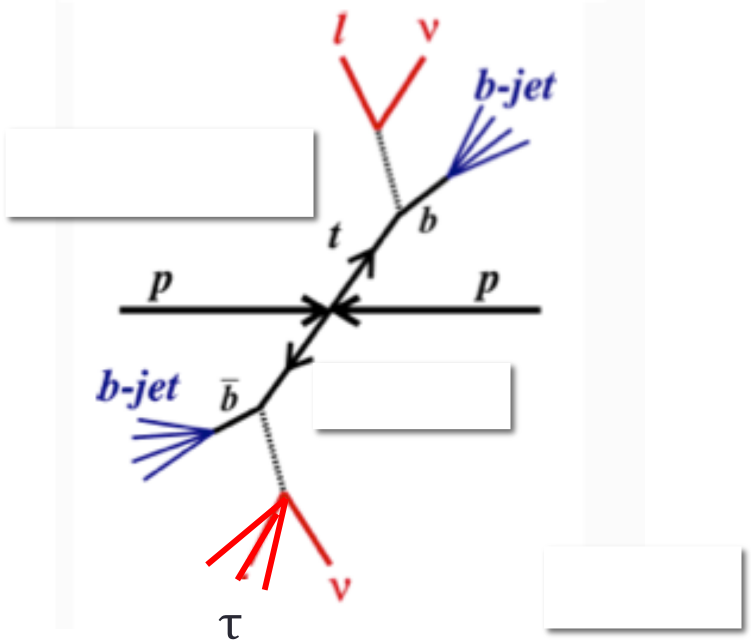
- Many results from pp collisions at 7, 8 and 13 TeV (and not only!)
  - It is impossibile to collect all measurements in a single talk! Several results left out due to lack of time: please see **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP**
- CMS was very prompt to analyse 13 TeV data and excellent results have been collected
  - Inclusive and differential xsec for both $t\bar{t}$ and single top
  - Measurements of top properties
- Many improvements are possible with more data and new tools
  - Improve both on statistics and systematics (theory, objects....)
  - Stay tuned for more results!

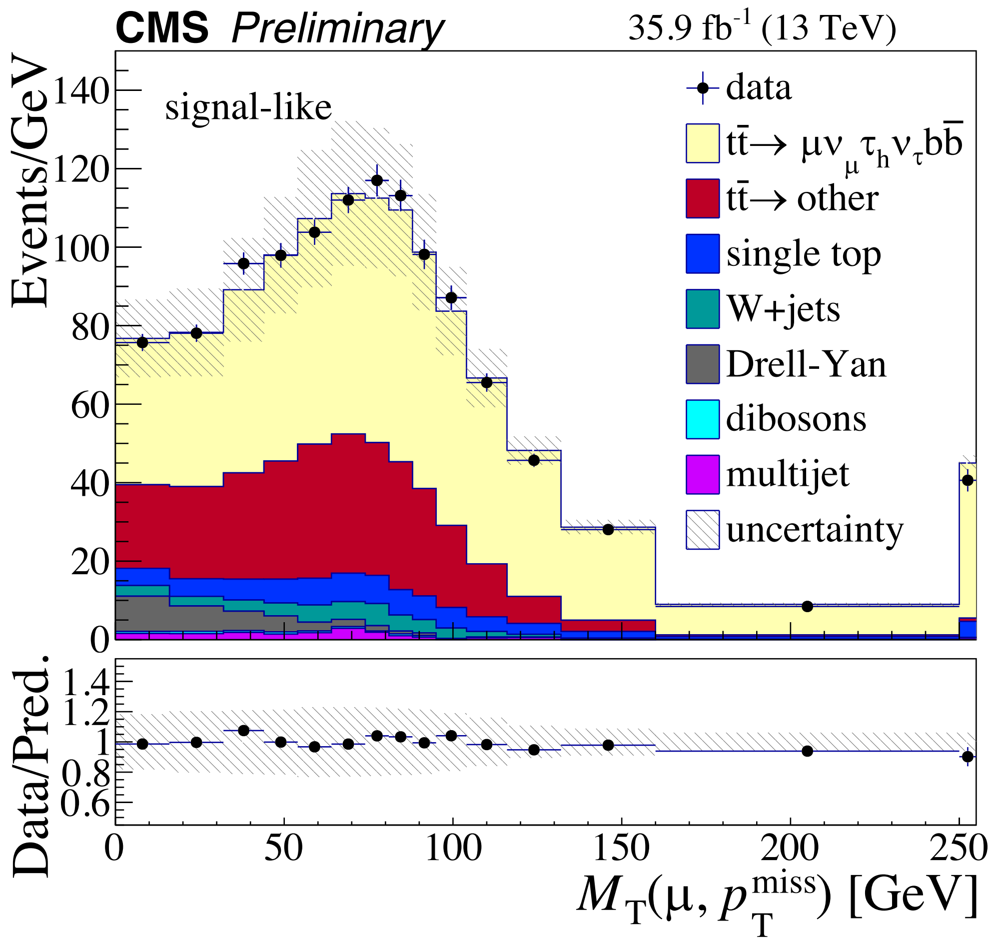
BACKUP

CMS-TOP-PAS-18-005

NEW! The most recent inclusive cross section measurement by CMS: dilepton channel including a tau.

Fit to m_T(lepton, p_T^{miss}) in signal-like and background-like regions

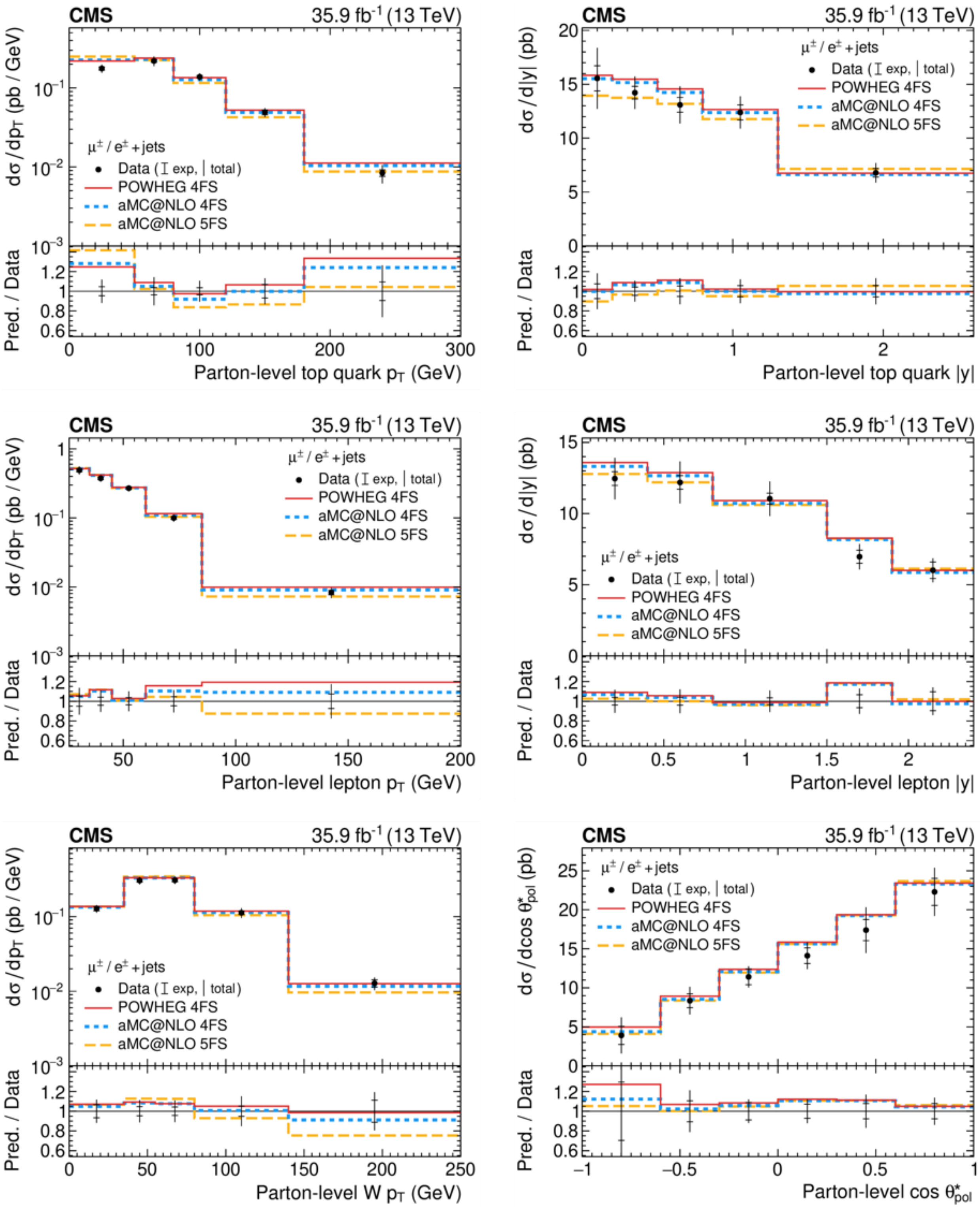




$\sigma_{t\bar{t}}$ **= 781 ± 7 (stat) ± 62 (syst) ± 20 (lum) pb**

CMS is also probing lepton universality in the top sector using l+τ events (see Eur. Phys. J. C (2019) **79**: 368): $\mathbf{R_{l\tau/ll}}$ **= 0.973 ± 0.009 (stat) ± 0.066 (syst)** *t-channel, 36 fb^{-1} at 13 TeV*

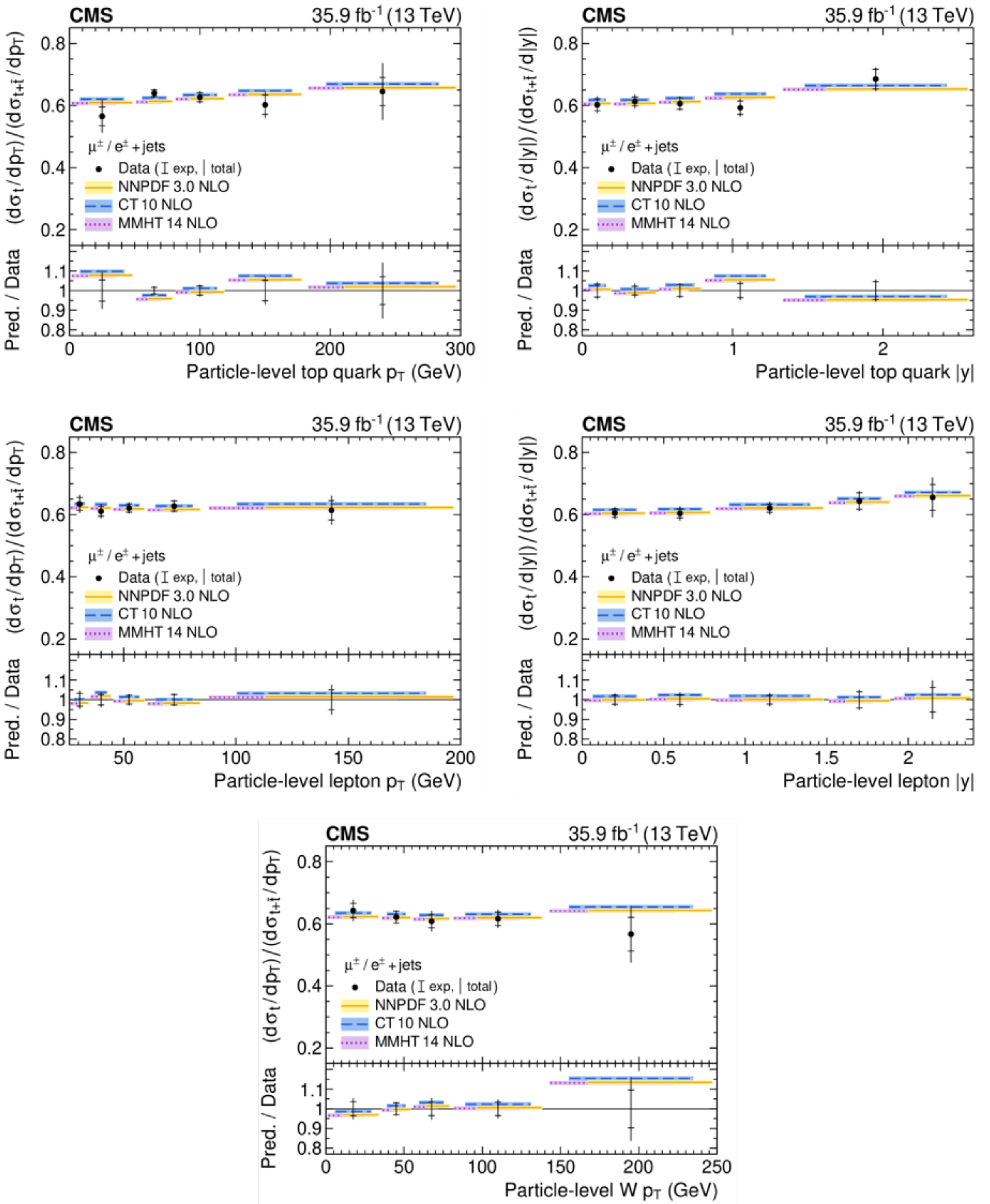
Differential cross sections in single top t-channel



Also measured the spin asymmetry, sensitive to the top quark polarisation, from the differential distribution of the polarisation angle at parton level: 0.439 ± 0.062, in agreement with SM

CMS-TOP-PAS-17-023, accepted by EPJC

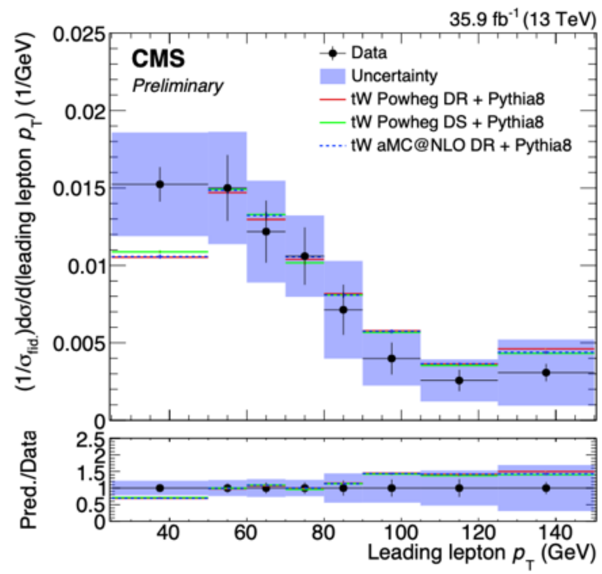
Differential cross sections in single top t-channel

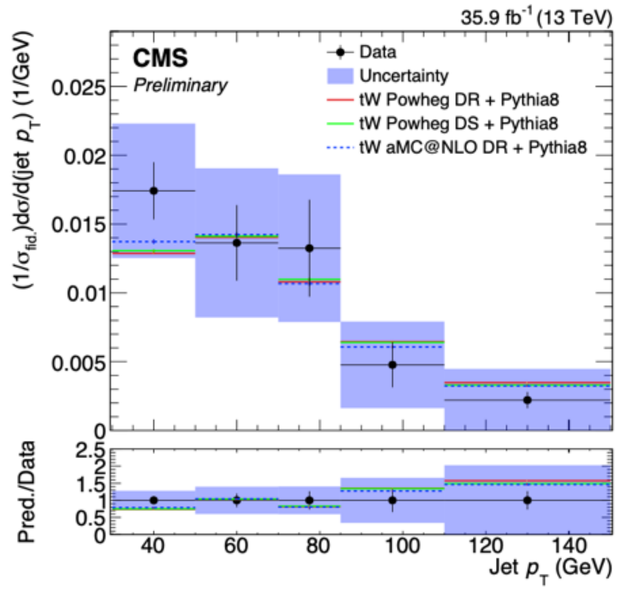


Measurement of top over top-antitop cross sections: sensitive to the ratio of the up to down quark content of the proton. Consistent with varius PDF sets.

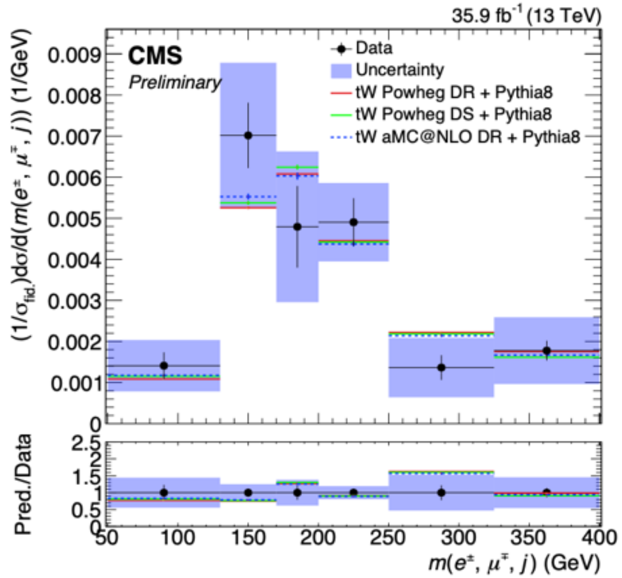
CMS-TOP-PAS-17-023, accepted by EPJC

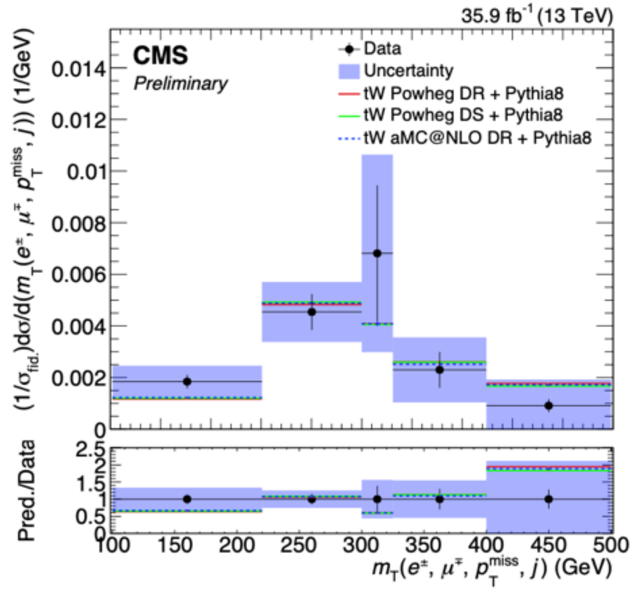
Differential cross sections in single top tW-channel





CMS-TOP-PAS-19-003

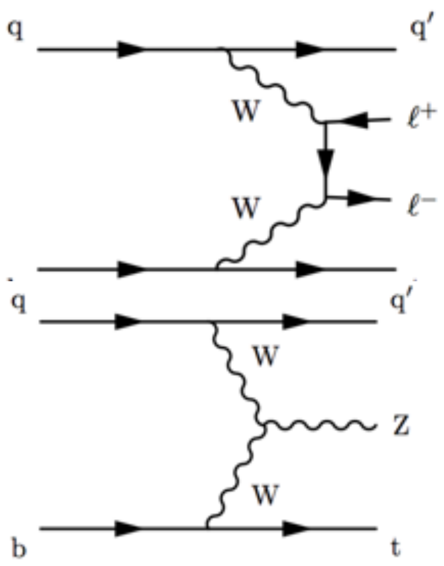


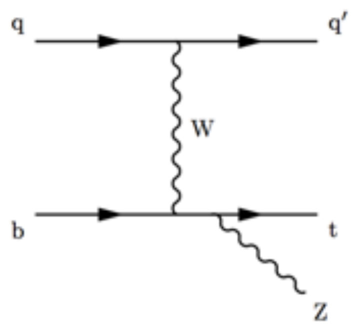


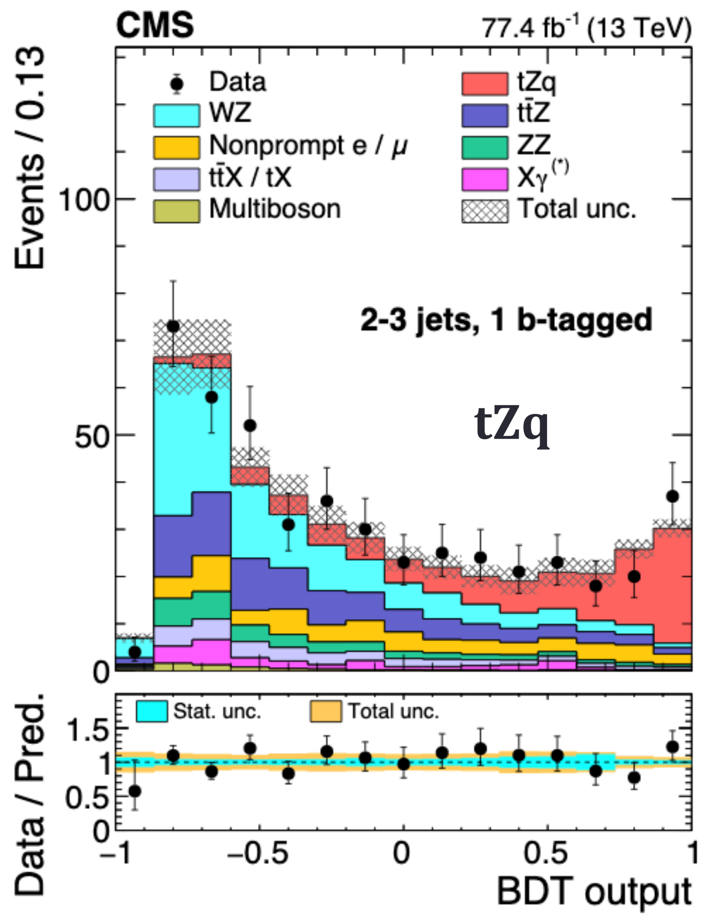
Good agreement with theoretical expectations

Top + bosons

- **ttZ** (arXiv:1907.11270)**:** first differential cross section measurement! Limits on anomalous couplings**.**
- **ttH (**PRL 120, 231801 (2018)): 5.2 sigma observation combining several decay modes, using 7, 8 and 13 TeV data
- **tγq** (PRL 121 (2018) 221802)**:** 4.4 sigma evidence. sensitive to triple gauge couplings and to NP (FCNC, EFT)
- **tZq** (PRL 122 (2019) 132003) 5 sigma observation by CMS





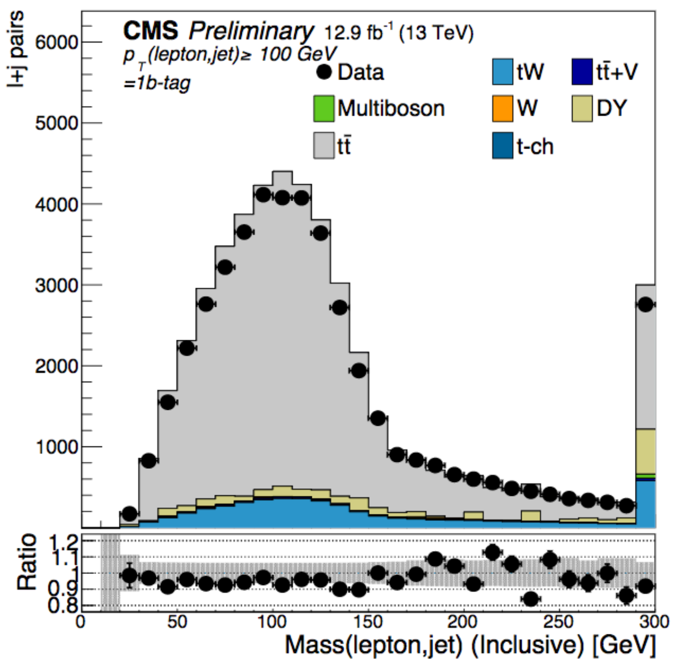


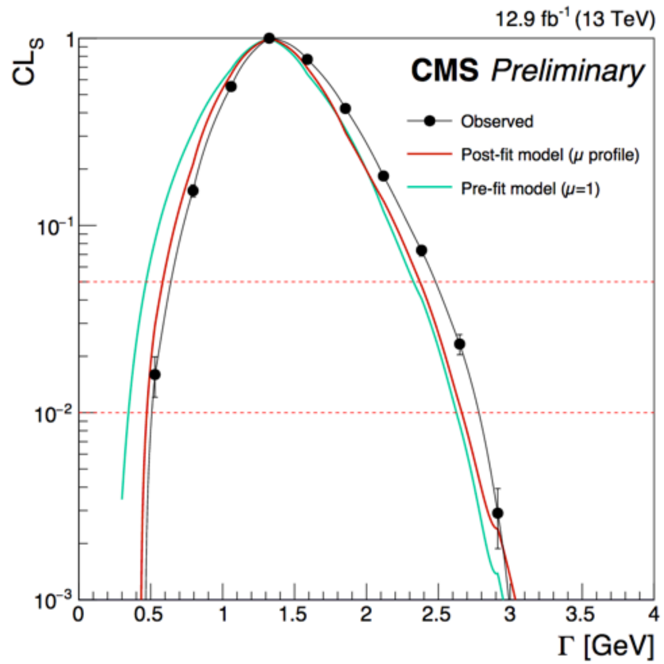
Bounding Top-quark width

CMS-PAS-TOP-16-019

- Indirect measurements of top width by D0 ($2.00^{+0.47}_{-0.43}$ GeV) and CMS, direct measurement by CDF (<6.38 GeV)
  - In agreement with NLO prediction, but much worse precision compared to m(top)
  - CMS attempts a direct measurement using partially reconstructed top quarks withat least 2 charged leptons and 2 jets (one b tagged)

M(lb) fit for deviations of the width wrt SM



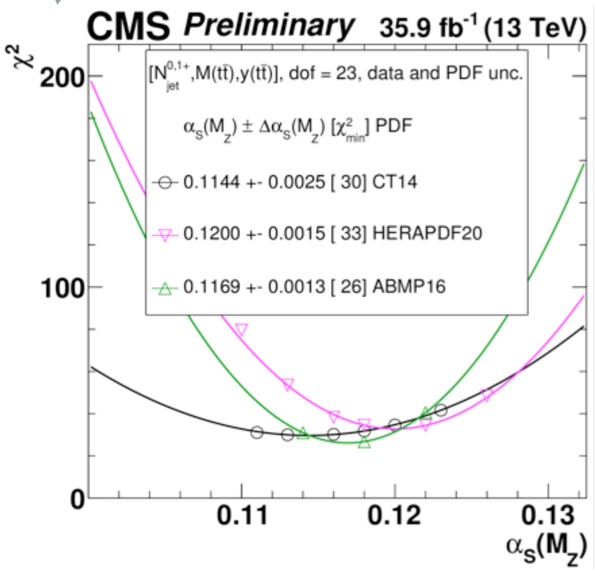


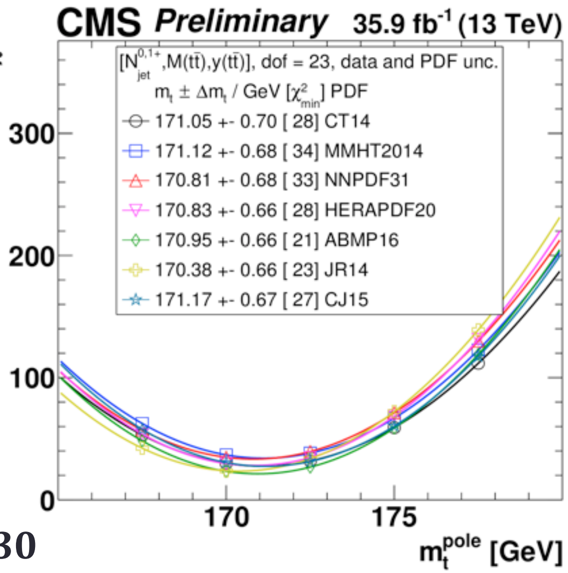
CMS: 95% CL limits: $0.6 \leq \Gamma \leq 2.5$ GeV

Recent **ATLAS** measurment: $\Gamma_t = 1.94^{+0.52}_{-0.49}$ GeV

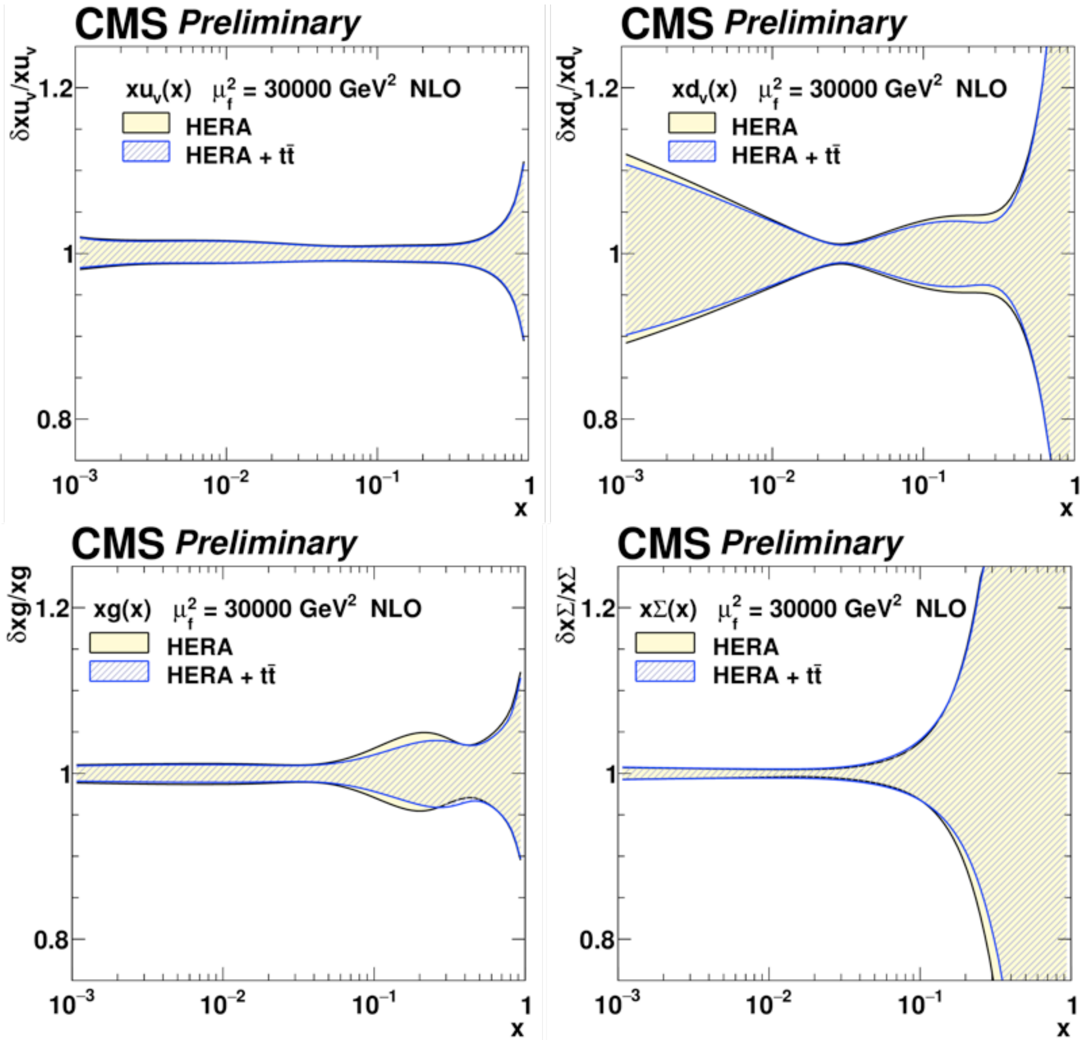
New result: **CMS-PAS-TOP-18-004**

α_S and m_t^{pole} extraction at NLO from the measured $[N_{0,1+jet}, M(t\bar{t}), y(t\bar{t})]$ cross sections using different PDF sets.
A dependence on the PDFs is observed





Relative total PDF uncertainties

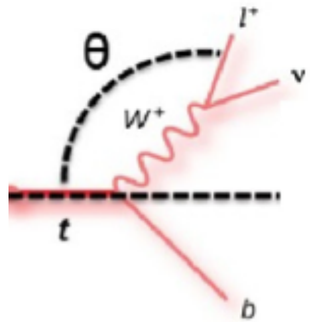


In a **simultaneous fit of α_s and m_t^{pole} and PDFs** the inclusion of the new **multi-differential $t\bar{t}$ measurements** has a significant impact on the gluon PDF at large values of x and also allows to accurately determine α_s and m_t^{pole} !

$$\alpha_s(M_Z) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

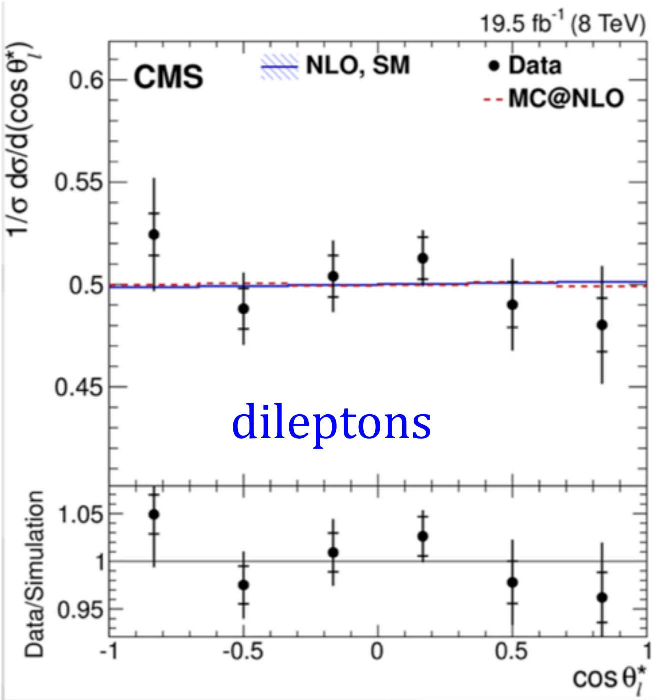
$$m_t^{pole} = 170.5 \pm 0.8 \text{ GeV}$$

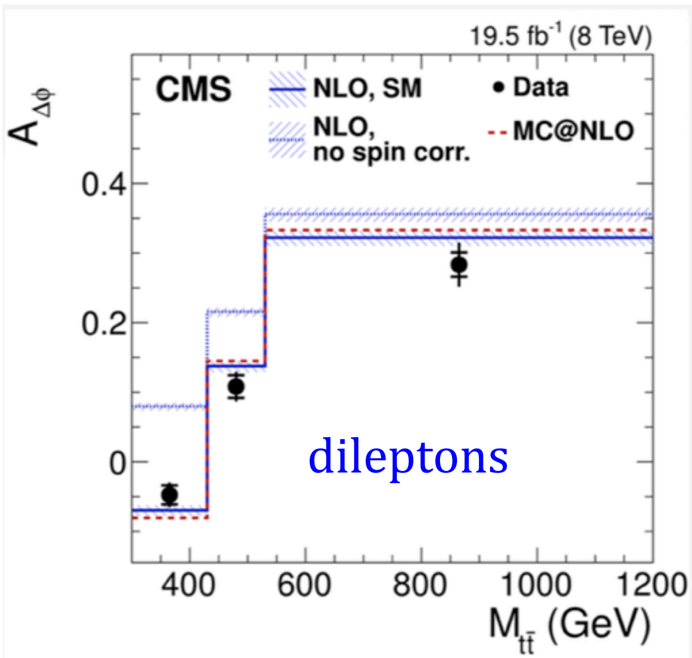
Spin correlations and polarization

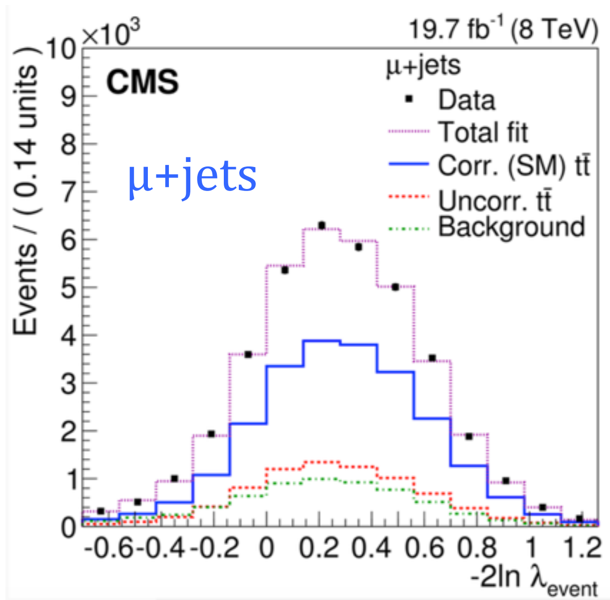


- In the SM, top pair production yields unpolarized tops but the spins of the $\bar{t}$ and t are correlated
  - Top lifetime is much shorter than spin decorrelation time: angular distribution of top decay products give info on top spin

$$A_{\Delta\phi} = \frac{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) - N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) + N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}$$



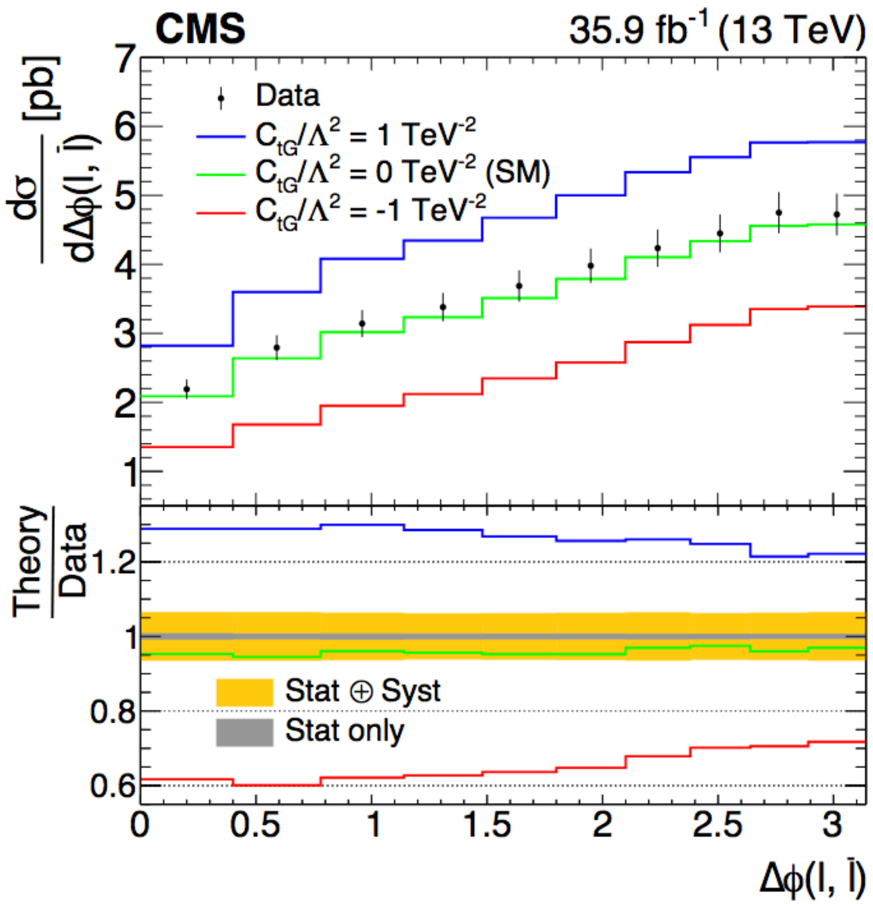


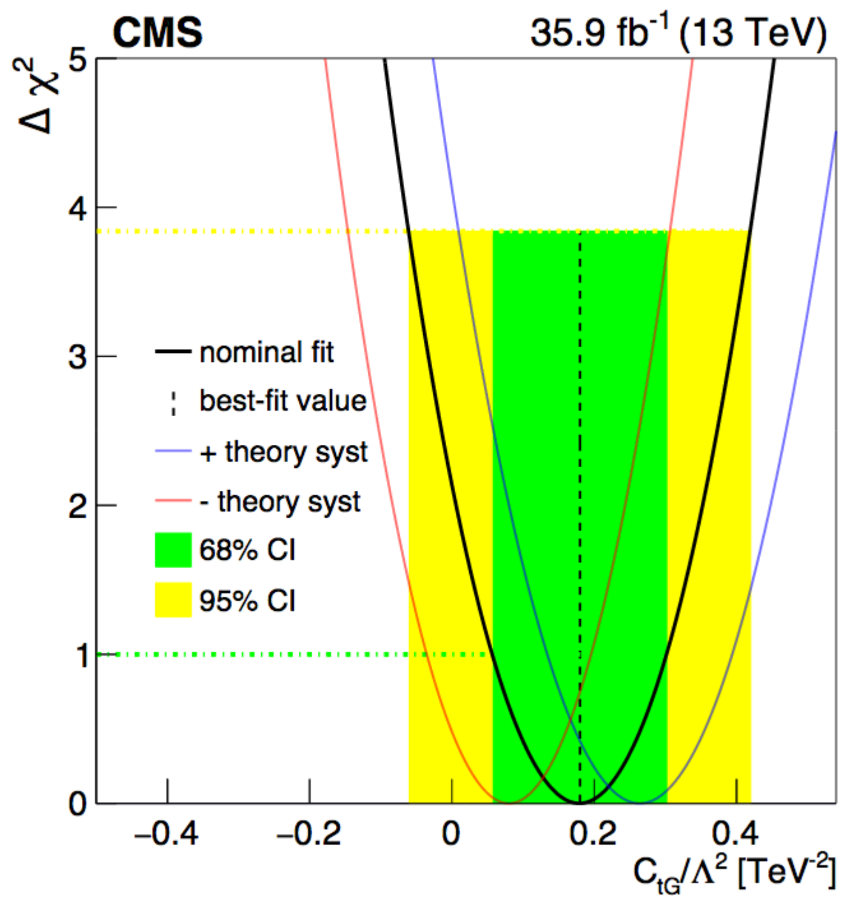


PRD 93 (2016) 052007

PLB 758 (2016) 321

- BSM theories often include anomalous top chromo-magnetic dipole moments (CMDM).
  - New calculations at NLO have become available: modifications to rates and spin correlation can occur.
- Differential xsec in $\Delta\Phi(ll)$ used to constraint CMDM





CMS-PAS-TOP-17-014

Top Branching Fractions and V_{tb}

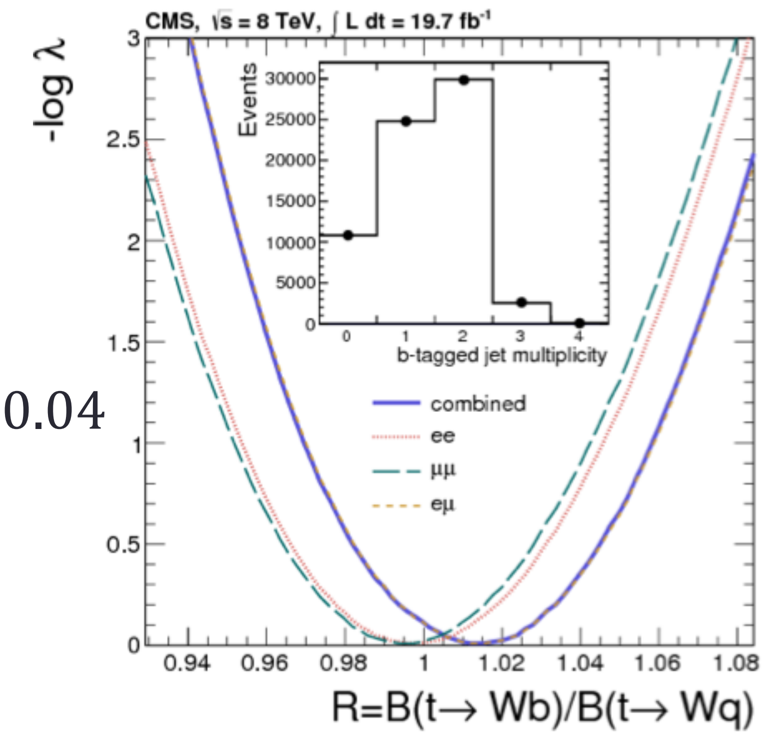
- R=BR(t->Wb)/BR(t->Wq)~1 in the SM
  - Related to V_{tb} and Γ(top)

    $|V_{tb}|^2$=R (assuming 3 generations),

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

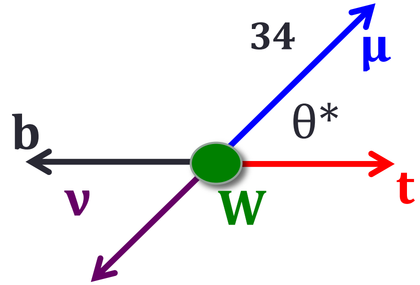
  - D0 had reported some tension: R=0.86±0.04±0.04 (PRL107, 121802)

- Best fit: R=1.014±0.003±0.032
- This translates into a constraint on V_{tb} and Γ:
  - $|V_{tb}|$> 0.975 at 95% CL
  - Using the measured cross section: $\Gamma(\text{top}) = 1.36 \pm 0.02^{+0.14}_{-0.11}$ GeV



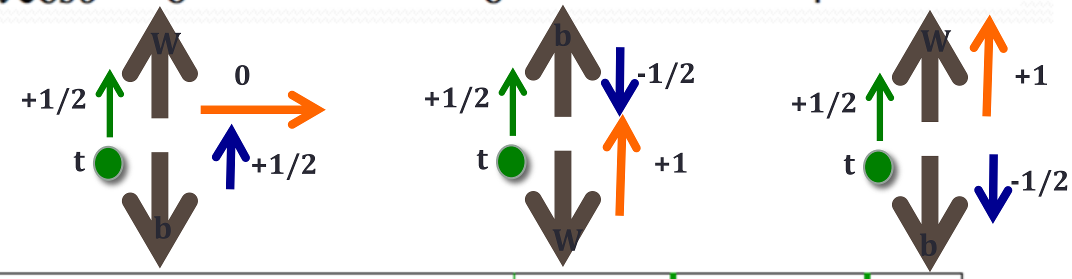
PLB 06 (2014) 076

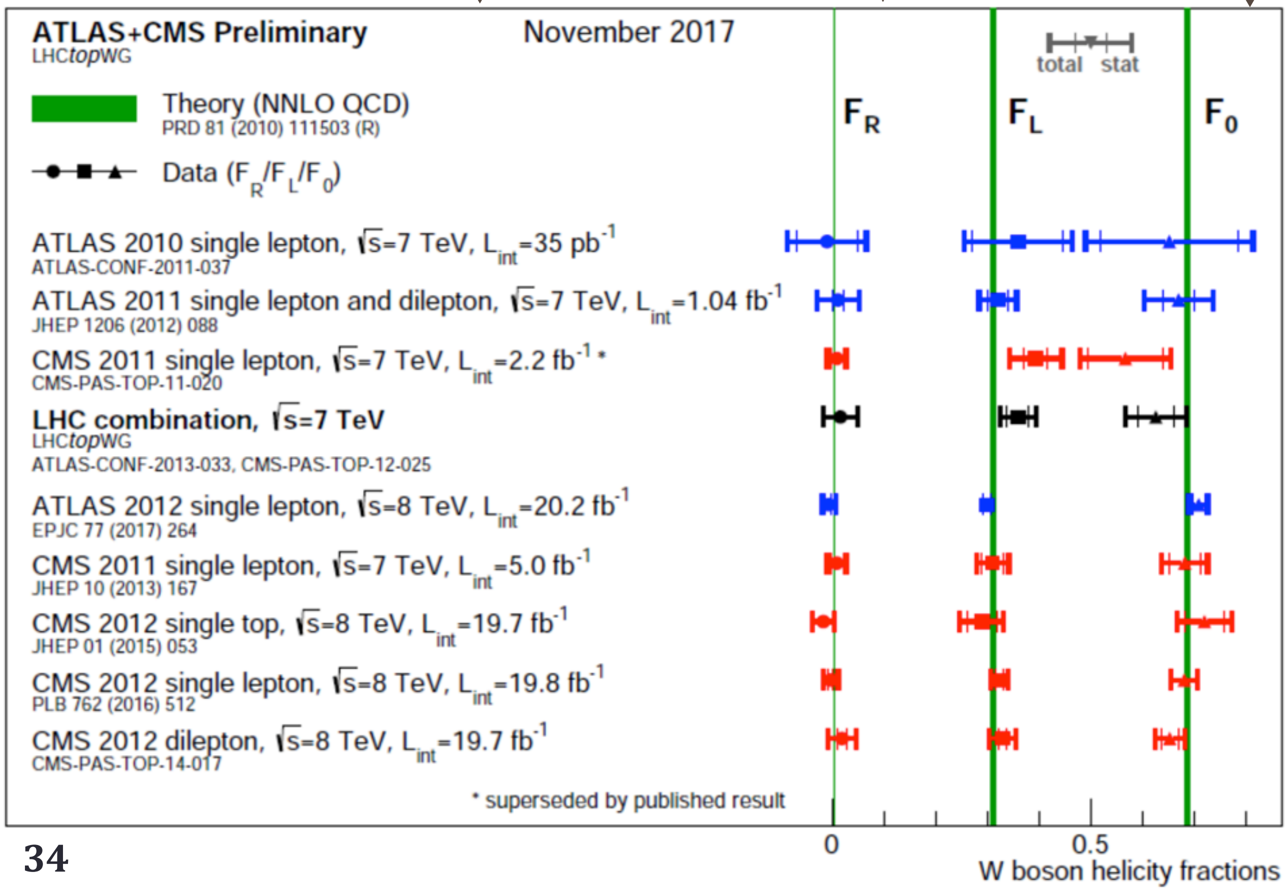
W helicity in top decays



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0$$

$$F_L + F_R + F_0 = 1 \qquad F_X \equiv \frac{\Gamma_X}{\Gamma}$$





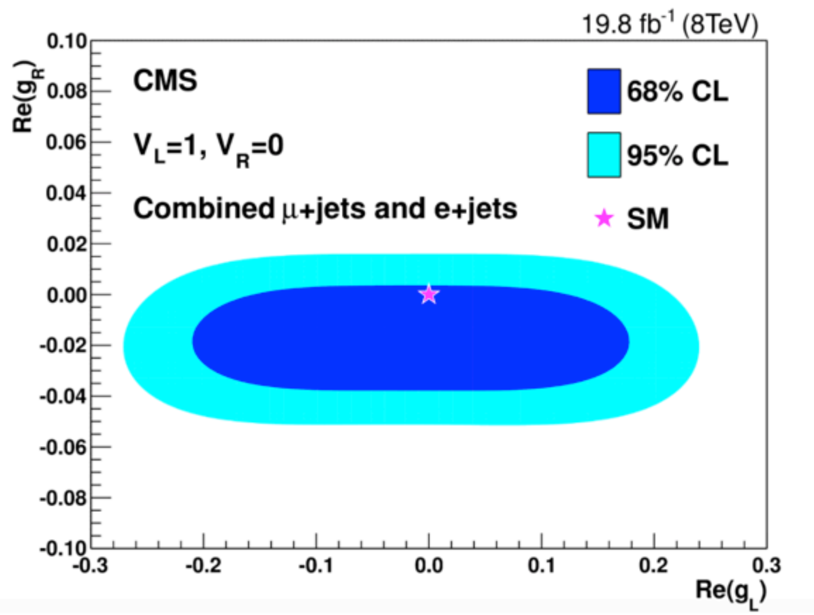
PLB 762 (2016) 512 (tt)
JHEP01 053 (2015) (single t)

The structure of the **Wtb vertex** can be expressed as:

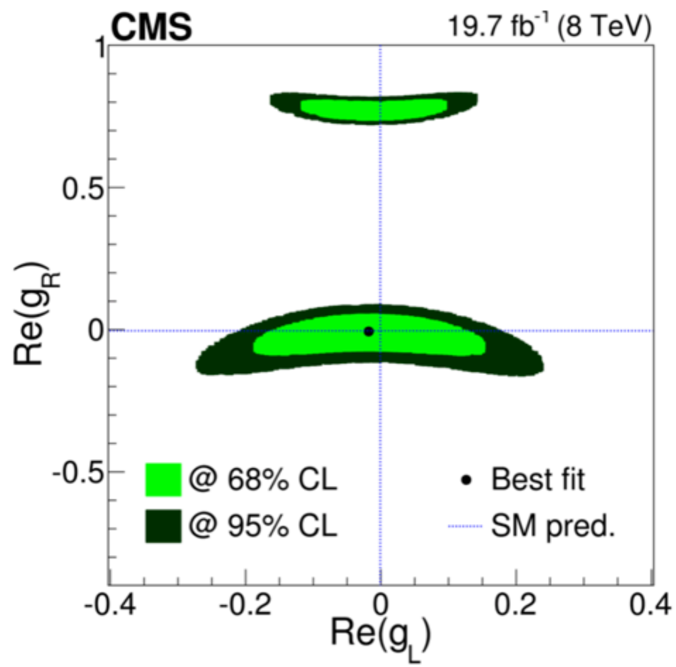
$$\mathcal{L}_{\mathrm{Wtb}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,t\,W_{\mu}^{-} + \mathrm{h.c.}$$

One can set **limits on anomalous tensor couplings** (fixing V_L=1 and V_R=0 as in the SM)

$t\bar{t}$: lepton+jets



single top:
1 lepton+2jets



Anomalous couplings

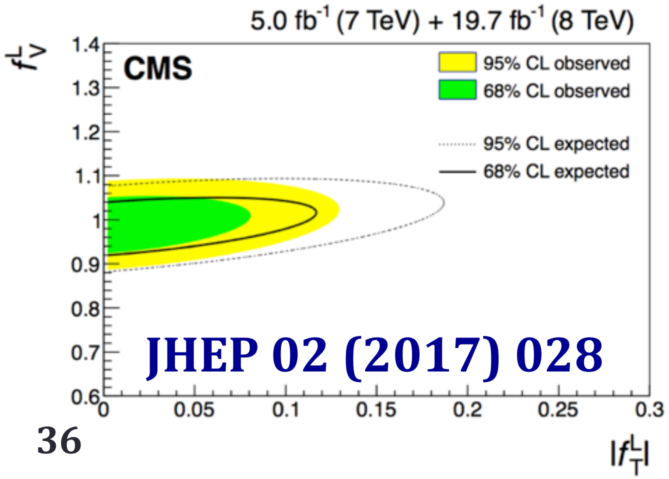
- In the SM, the Wtb vertex has a V-A structure
- FCNC are absent at LO and suppressed by GIM mechanism at higher order.
  - NP can enhance their effect: single-top events very sensitive to this
- Most general, CP-conserving, lowest-order lagrangian for the Wtb vertex:

$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

$$P_{L,R} = \frac{1\mp\gamma_5}{2}, \sigma_{\mu\nu} = \frac{i}{2}(\gamma_{\mu}\gamma_{\nu} - \gamma_{\nu}\gamma_{\mu})$$

f_L^V (f_R^V)left (right) vector coupling;
f_L^T (f_R^T)left (right) tensor coupling;

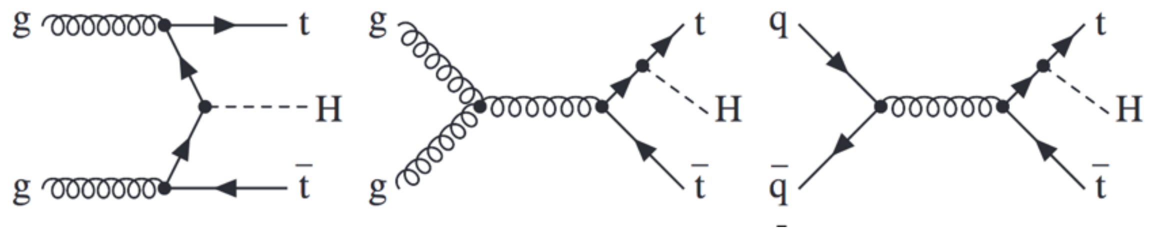
SM: $f_L^V = V_{tb}$; $f_R^V = f_L^T = f_R^T = 0$



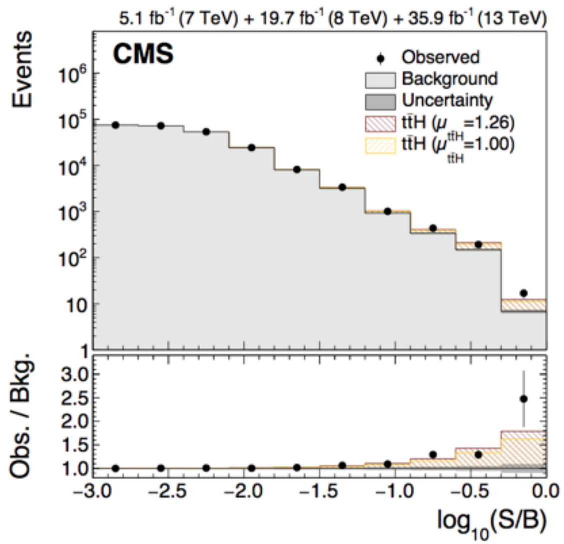
FCNC interactions **tcg** and **tug:** observed (expected) 95% CL upper limits on couplings and BR (combination of 7 and 8 TeV data)

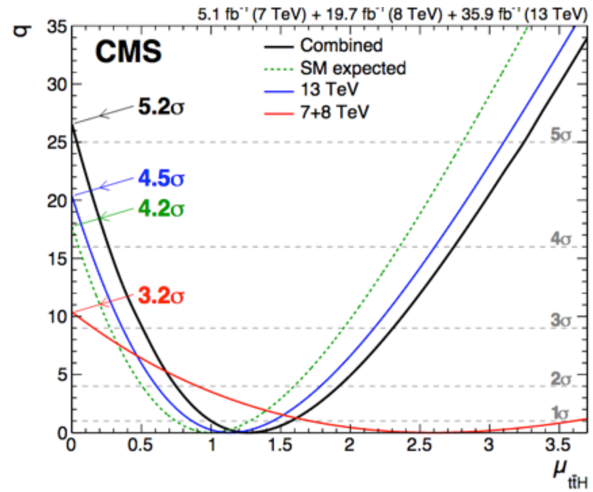
$\lvert k_{tug}\rvert/\Lambda$	BR(t -> ug)	$\lvert k_{tcg}\rvert/\Lambda$	BR(t -> cg)
4.1 (4.8) x 10^{-3}	2.0 (2.8) x 10^{-5}	1.8 (1.5) x 10^{-2}	4.1 (2.8) x 10^{-4}

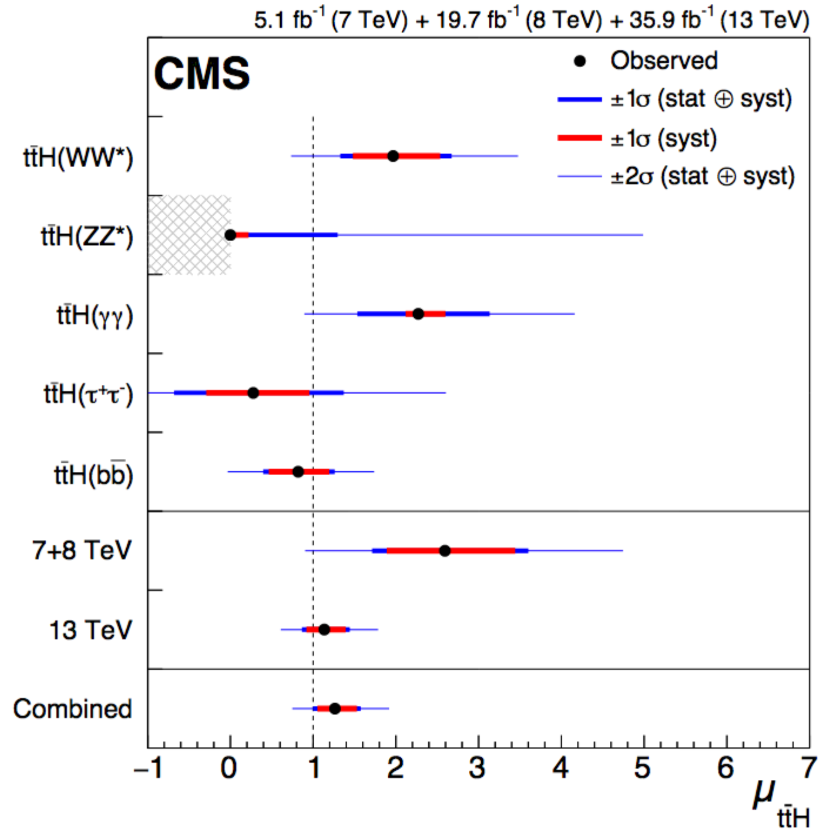
$t\bar{t}H$



- Several combinations studied (many possible final states!)
- Combining 7, 8 and 13 TeV data: **5.2 σ observation**!







Phys. Rev. Lett. 120, 231801 (2018)