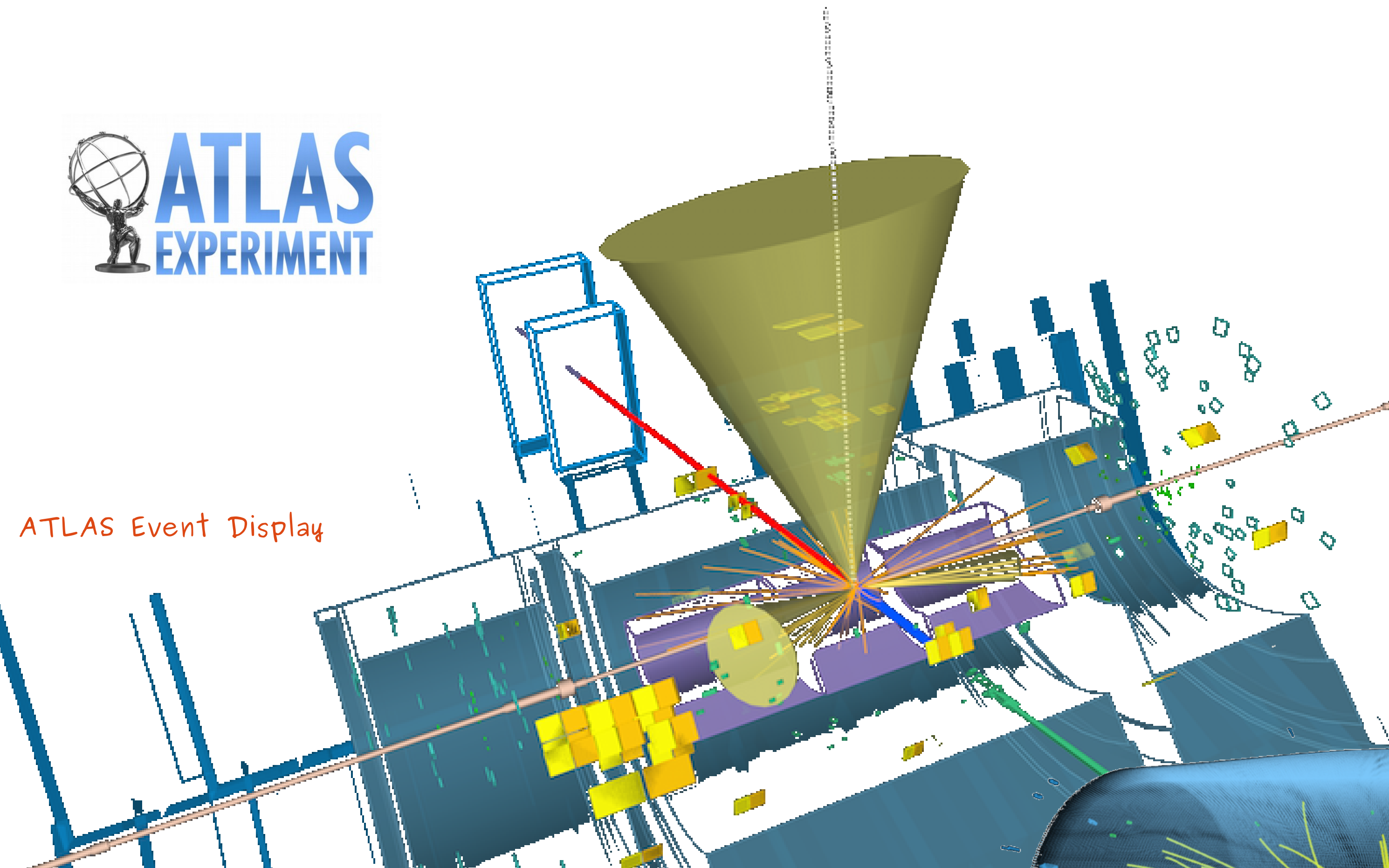
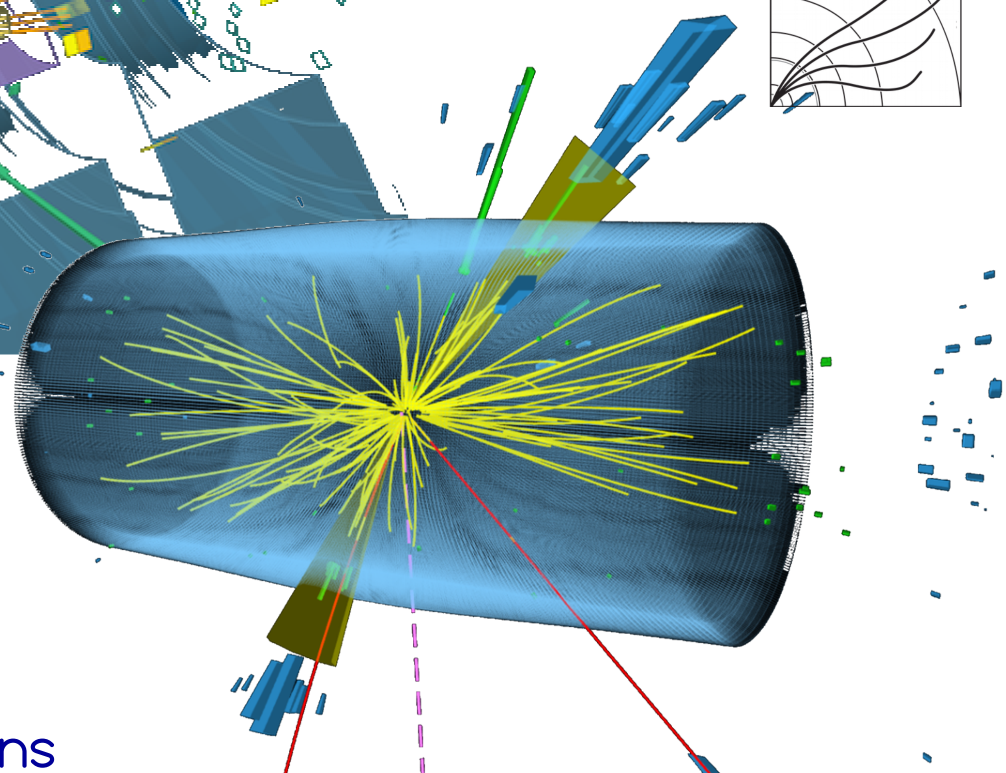
UCL
Université catholique de Louvain

ATLAS EXPERIMENT



ATLAS Event Display

CMS

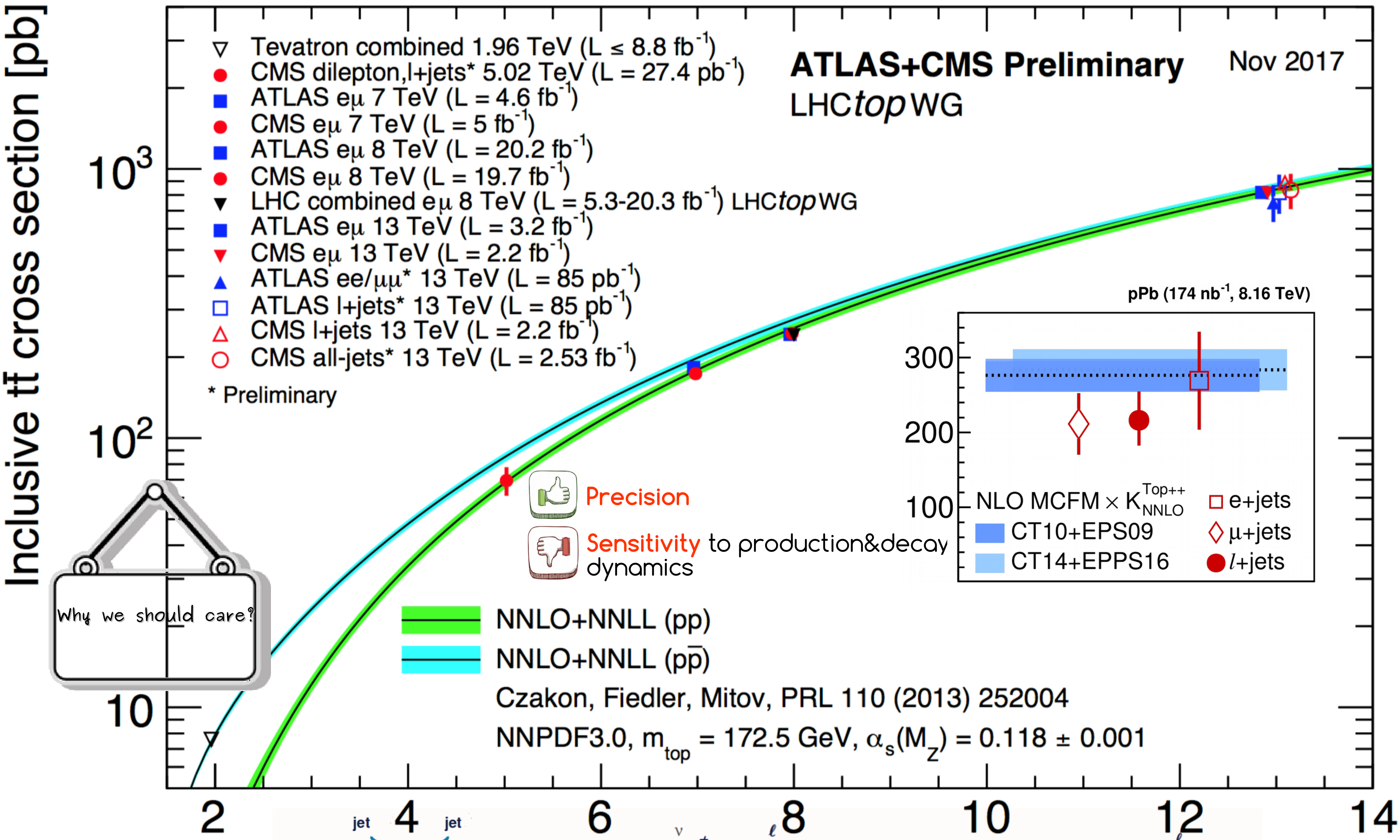


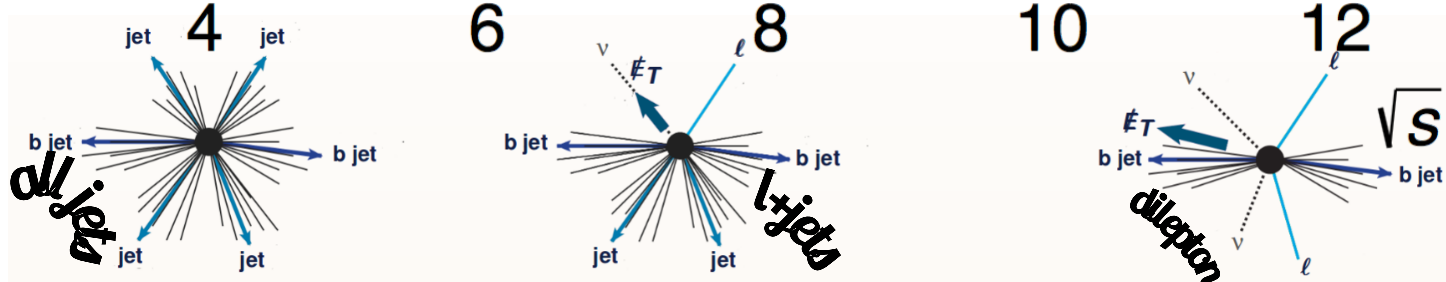
CMS-PHO-EVENTS-2016-009-19

Top quark properties @ LHC

GK Krintiras
on behalf of **ATLAS** and **CMS** Collaborations

Up-to-date compilation: 4 $\sqrt{s_{NN}}$ & 2 systems @ LHC !





A non-exhaustive list of top quark-antiquark properties

	Property	Result (most precise or most recent)	Uncertainty	Journal Link (or Preprint)/ Conf. note
“Intrinsic”	Charge	0.64 e	0.02 (stat) ± 0.08 (syst) e	**JHEP 11 (2013) 031**
	Mass (kinematic extraction)	172.44 GeV	0.13 (stat) ± 0.47 (syst) GeV	**PRD 93 (2016) 072004**
	Mass difference	-0.15 GeV	0.19 (stat) ± 0.09 (syst) GeV	**PLB 770 (2017) 50**
	Width (direct method)	1.76 GeV	0.33 (stat) $^{+0.79}_{-0.68}$ (syst) GeV	**EPJ C 78 (2018) 129**
	Width (indirect method)	1.36 GeV	0.02 (stat) $^{+0.14}_{-0.11}$ (syst) GeV	**PLB 736 (2014) 33**
	Spin (polarization)	Not uniquely defined variables		**JHEP 03 (2017) 113** **PRD 93 (2016) 052007**
“Production”	Spin (correlation fraction)	1.20	0.05 (stat) ± 0.13 (syst)	**PRL 114 (2015) 142001**
	Rapidity cut-independent charge asymmetry	0.0055	0.0023 (stat) ± 0.0025 (syst)	**arXiv:1709.05327**
	Colour flow Underlying event	No “one-fits-all” prediction		**ATLAS-CONF-2017-069** **CMS-PAS-TOP-17-015**
	Gauge and Yukawa couplings	Wilson $\tilde{c}$ compatible with 0 μ_t strength: 1.18	+0.31-0.27 (tot)	**arXiv:1709.05327** **CMS-PAS-HIG-17-031**
“Decay”	W boson helicity fractions	F_0 = 0.709 F_L = 0.299 F_R = -0.008	0.012 (stat) +0.015-0.014 (syst) 0.008 (stat) +0.013-0.012 (syst) 0.006 (stat) ± 0.012 (syst)	**EPJ C 77 (2017) 264**

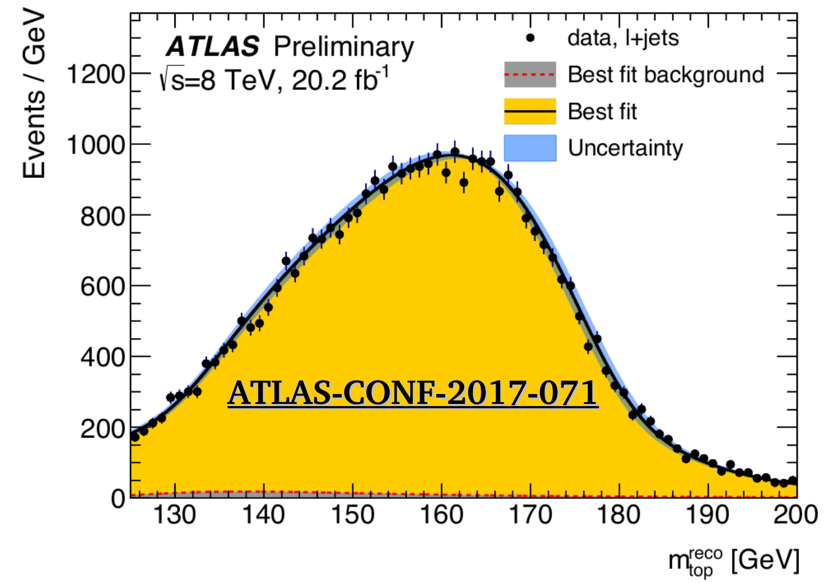
- We know some properties well, but several key properties remain poorly understood
  - modeling uncertainties typically dominant or important source

The most recent measurements at √s = 8 and 13 TeV

Mass

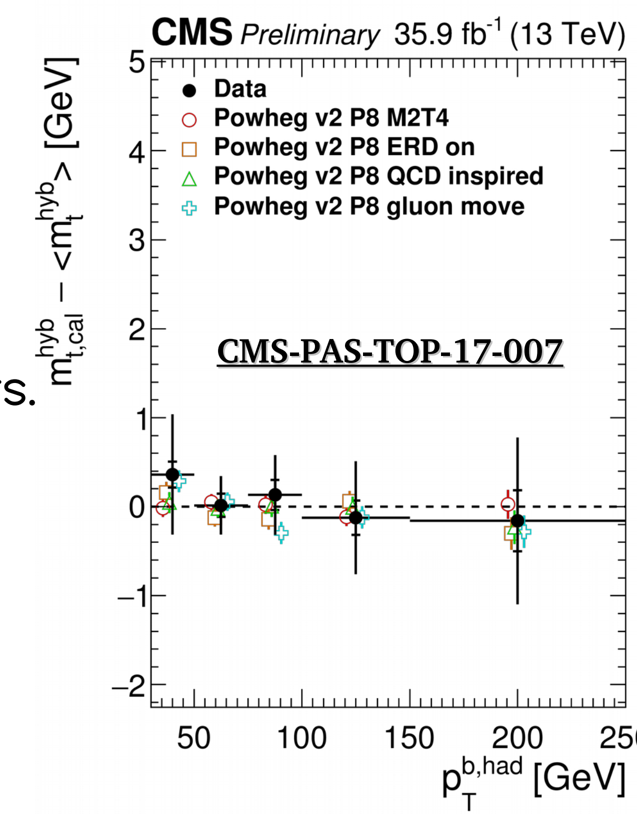
- **3D template** fit method using: $m_{top}^{reco}, m_{W}^{reco}, R_{bq}^{reco}$
- **Kinematic fit** for jet-parton assignment
  - rejects combinatorial background
- m_{top}, JES factor (JSF) & b-to-light-jet JSF (bJSF)
  - simultaneously determined
  - BDT optimisation reduced syst. unc.
  - dominant syst. JES (exp.) and tt modeling (theo.)

172.08 ± 0.39 (stat) ± 0.82 (syst) GeV



- Ideogram method: $(m_{top}^{reco}, m_{W}^{reco})$ 2D fit
- **In situ** JSF extraction **& kinematic fit** for jet-parton assignment
- Measurement as a function of **several** kinematic vars.
  - compared to **different** CR refined models
  - searching for biases
  - dominant syst. JEC (exp.) and tt modeling (theo.)

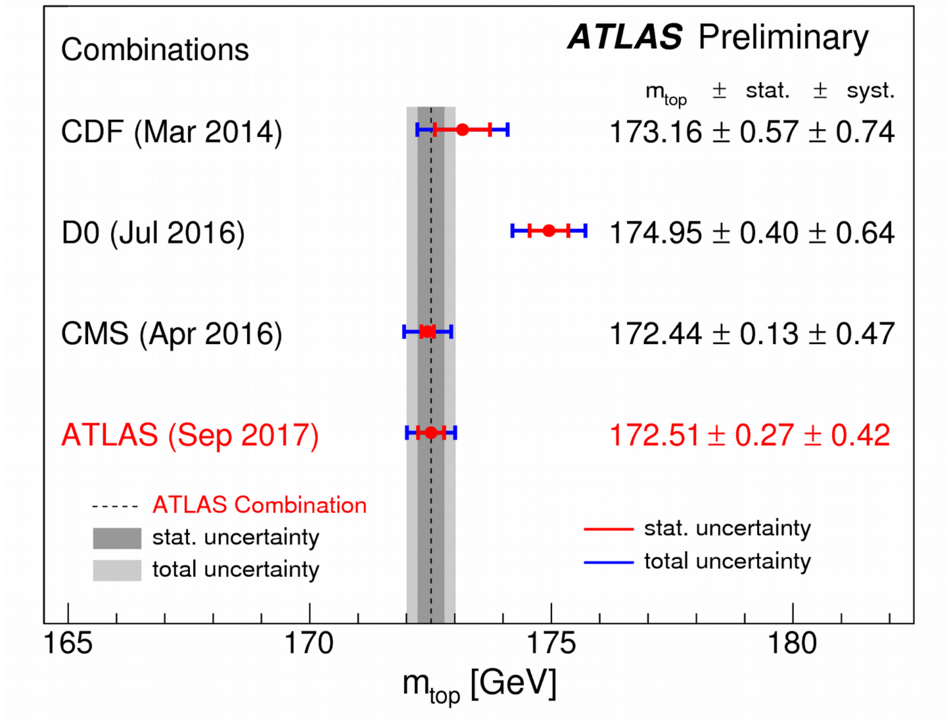
172.25 ± 0.08(stat+JSF) ± 0.62(syst) GeV



Where do we currently stand then ?

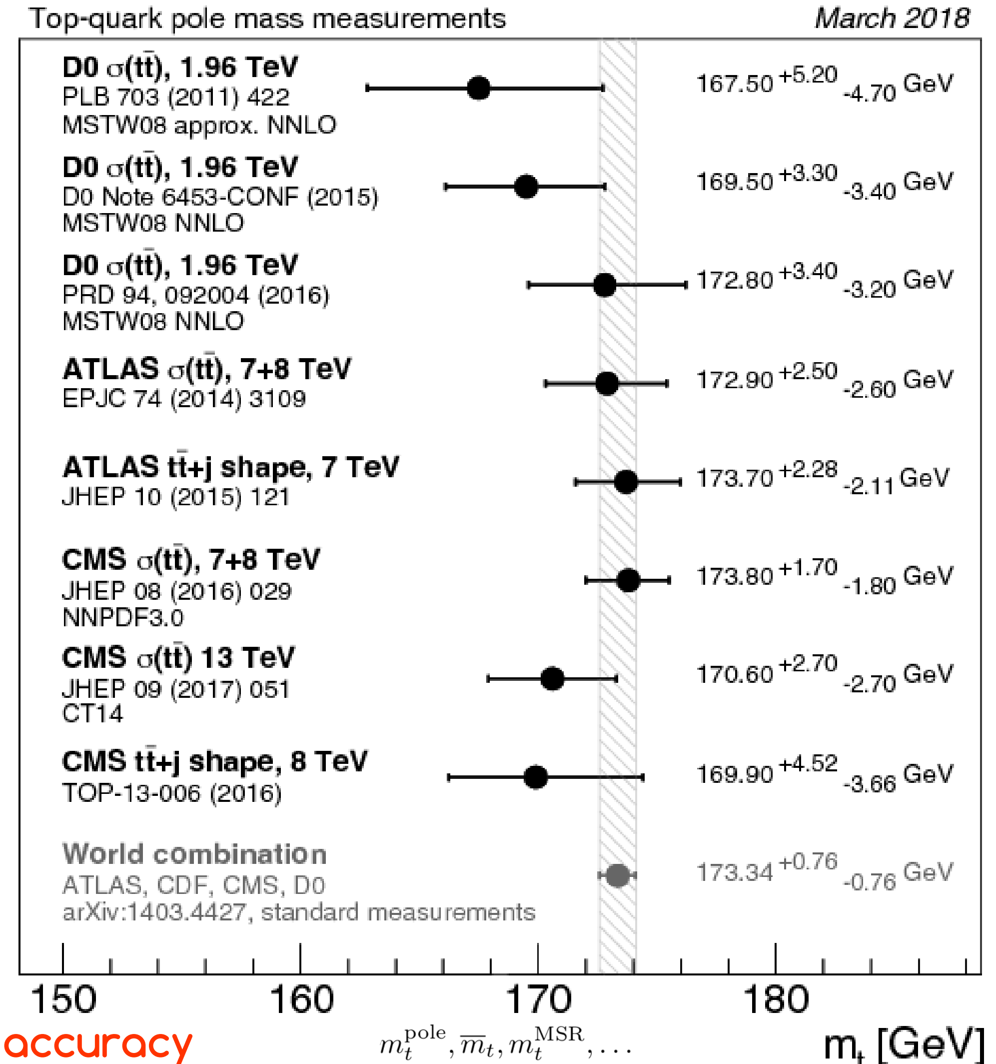
Mass

ATLAS-CONF-2017-071, CMS: PRD 93 (2016) 072004

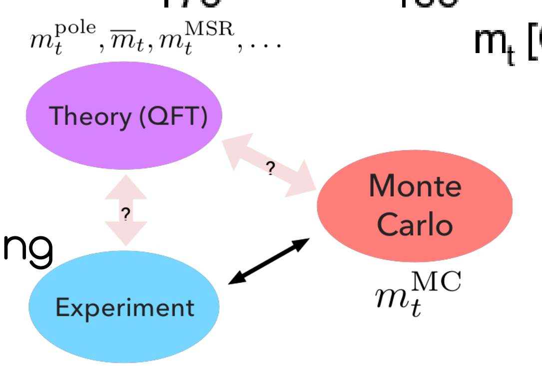


see talk from André

Derived from tt(+jet) x.section (system)



- Kinematic extractions make use of MC
  - measuring a MC top mass parameter
  - translating to a well defined scheme "costs" in accuracy
- Calibration of MC top mass possible
  - at the same time with e.g. x.section but less precise
  - devise analytically calculable observables e.g. soft drop grooming
- Difference to Tevatron legacy not (yet?) understood



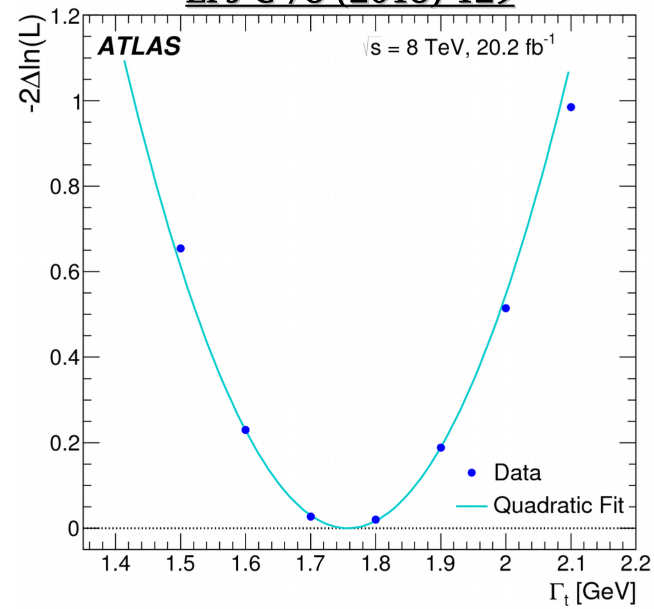
The most recent direct measurements at 8 and 13 TeV

Width

- **Template** method using $m_{bl}, \Delta R_{min}(b,q)$ from bW(lν), bW(qq)
  - Γ_t sensitive observables
- **MC reweighting** for different Γ_t values
- QCD multijet separately estimated from data in e,μ+jets
  - based on low-E_T (lepton isolation) in e (μ) + jets
- Dominated by tt modeling (theo.) and JES&JER (exp.)

1.76 ± 0.33 (stat)$^{+0.79}_{-0.68}$(syst) GeV

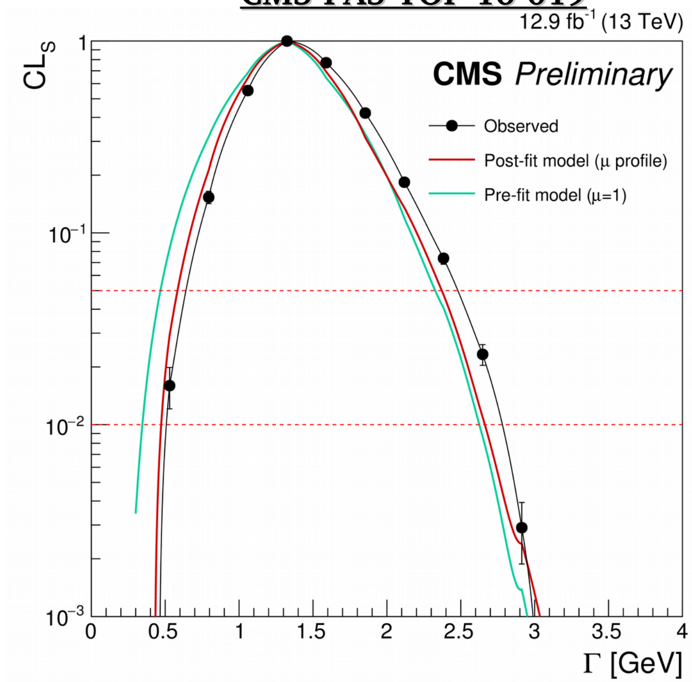
EPJ C 78 (2018) 129



- Similar **template** method using m_{bl} from bW(lν), bW(lν)
- **MC samples** for different Γ_t values
  - NLO (LO) precision in production (decay)
- DY estimated from data in eμ, ee, μμ
  - based on Z pole mass control region
- Dominated by tt and tW modeling (theo.)

$0.6 < \Gamma_t < 2.5$ GeV @ 95% CL

CMS-PAS-TOP-16-019



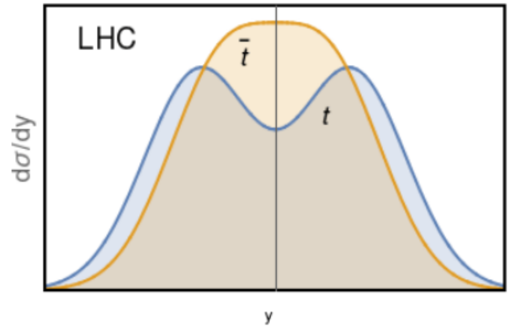
Combined inclusive and differential charge asymmetry

Ac

In pp collisions: asymmetry appears as a central-forward asymmetry

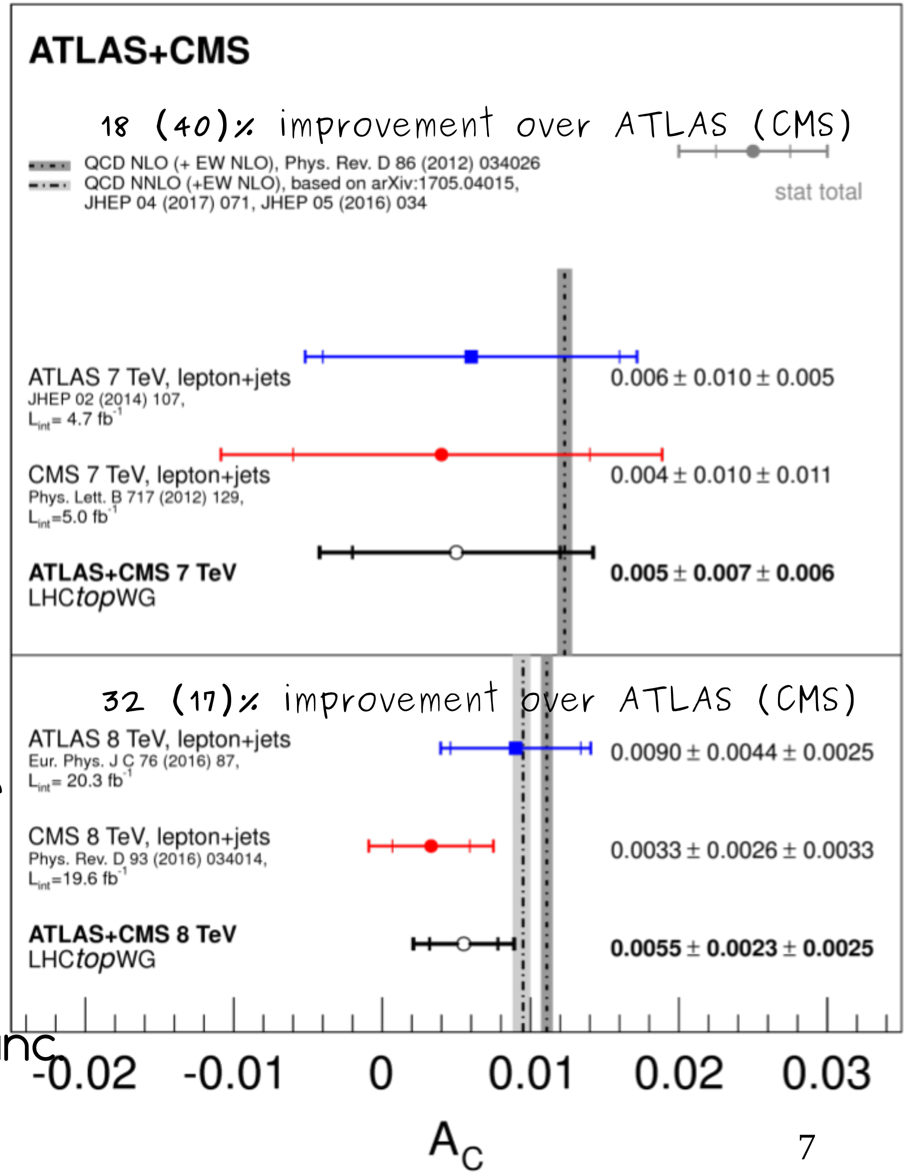
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

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



(figure by G.Rodrigo)

arXiv:1709.05327
(accepted by JHEP)



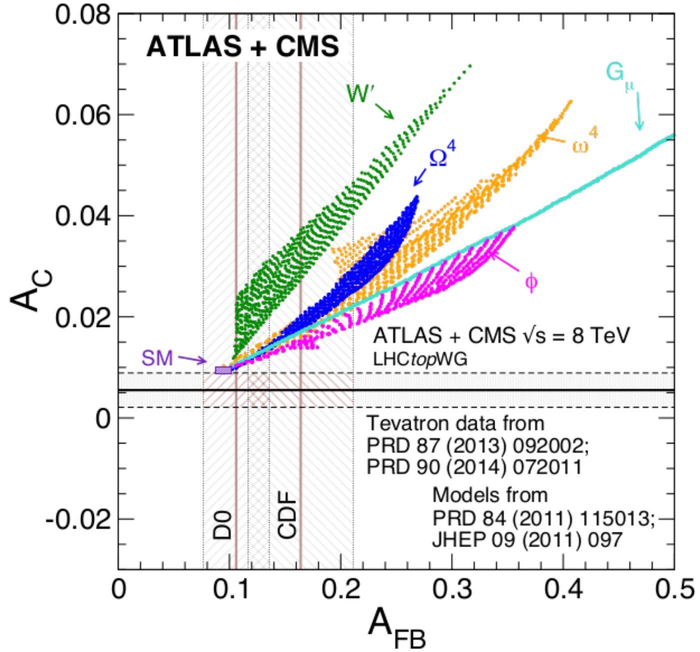
- Inputs extracted from Δ|y| at parton level
  - ATLAS: Fully Bayesian Unfolding
  - CMS: regularised matrix inversion (7 TeV), and template fits to y_{tt}=tanhΔ|y| (8 TeV)
- Combination with Best Linear Unbiased Estimate
  - assumptions must be made on correlations
  - 7 TeV: a 'coarse' model (less available info.)
    - e.g. all detector uncertainties as single unc.
  - 8 TeV: detailed systematic unc. mapping
    - both inclusively and differentially

Combined inclusive and differential charge asymmetry

A_C

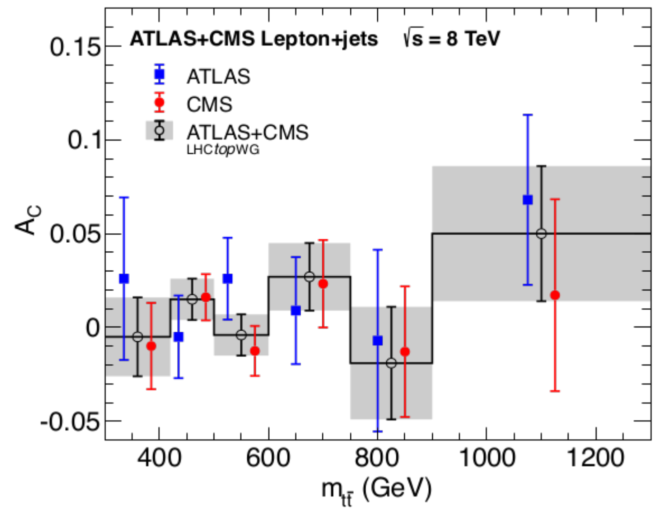
arXiv:1709.05327
(accepted by JHEP)

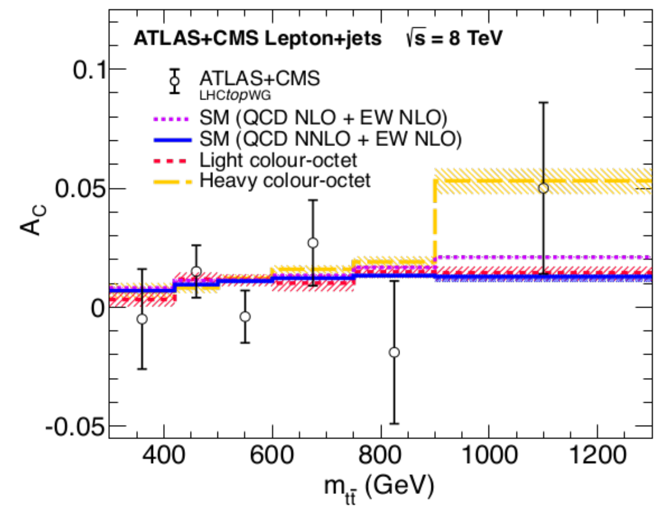
Fig. to be updated with the Tevatron combination
PRL 120 (2018) 042001



Reduce phase space for many models (W', heavy Axigluon, scalar isodoublet, colour triplet scalar, colour sextet scalar)

Dedicated NNLO calculation provided for this analysis





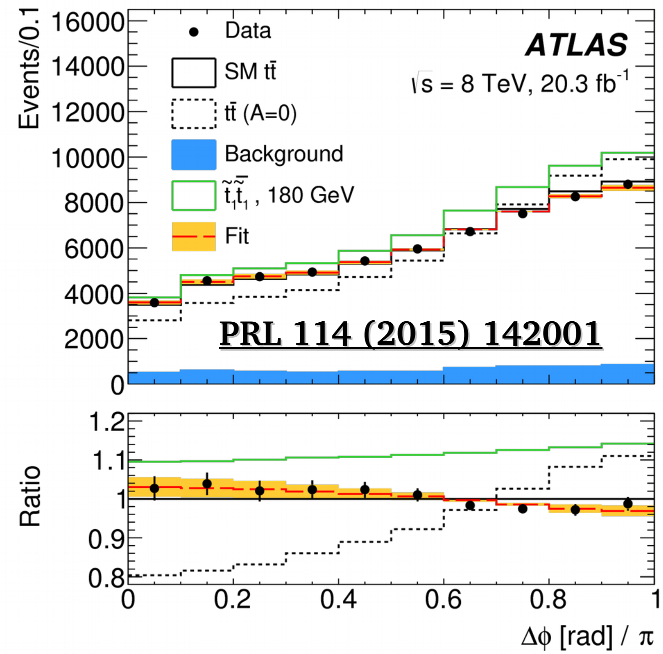
- Charge asymmetry depends on phase space
  - high mass/p_T enhance quark annihilation
- Asymmetry measured against inv. mass of tt system
- Good agreement found between data and SM expectations within uncertainties

Spin information via angular distributions of $t\bar{t}$ decays

Spin corr

- Azimuthal angle between two leptons in the final state
  - no need for full top quark event reconstruction
- Likelihood fit with spin (SM) and w/o spin correlation
  - used to constrain BSM models
- Full spin density matrix in JHEP 03 (2017) 113

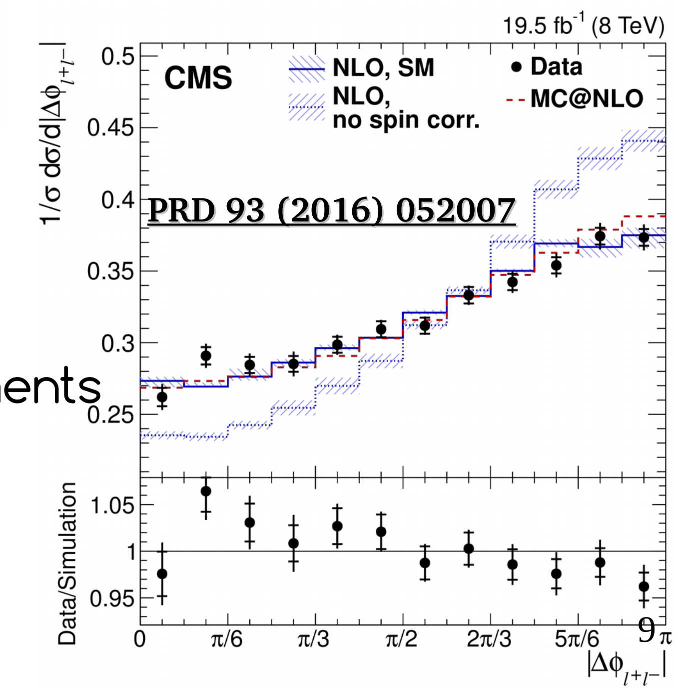
1.20 ± 0.05 (stat) ± 0.13 (syst)



$$f_{SM} = \frac{N^{tt}_{SM}}{N^{tt}_{SM} + N^{tt}_{UnCorr}}$$

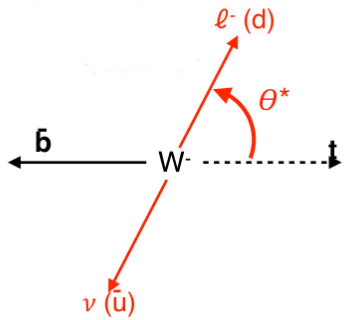
- Similar method with modeling the dominant syst.
  - lepton reco., fake leptons & JES subdominant
- Measurement as a function of several kinematic vars.
  - unfolded to parton level
  - limits on chromo-magnetic and chromo-electric moments
- Competing tot. unc. with l+jets (MEM) in PLB 758 (2016) 321

1.12 ± 0.06 (stat) ± 0.11 (syst)

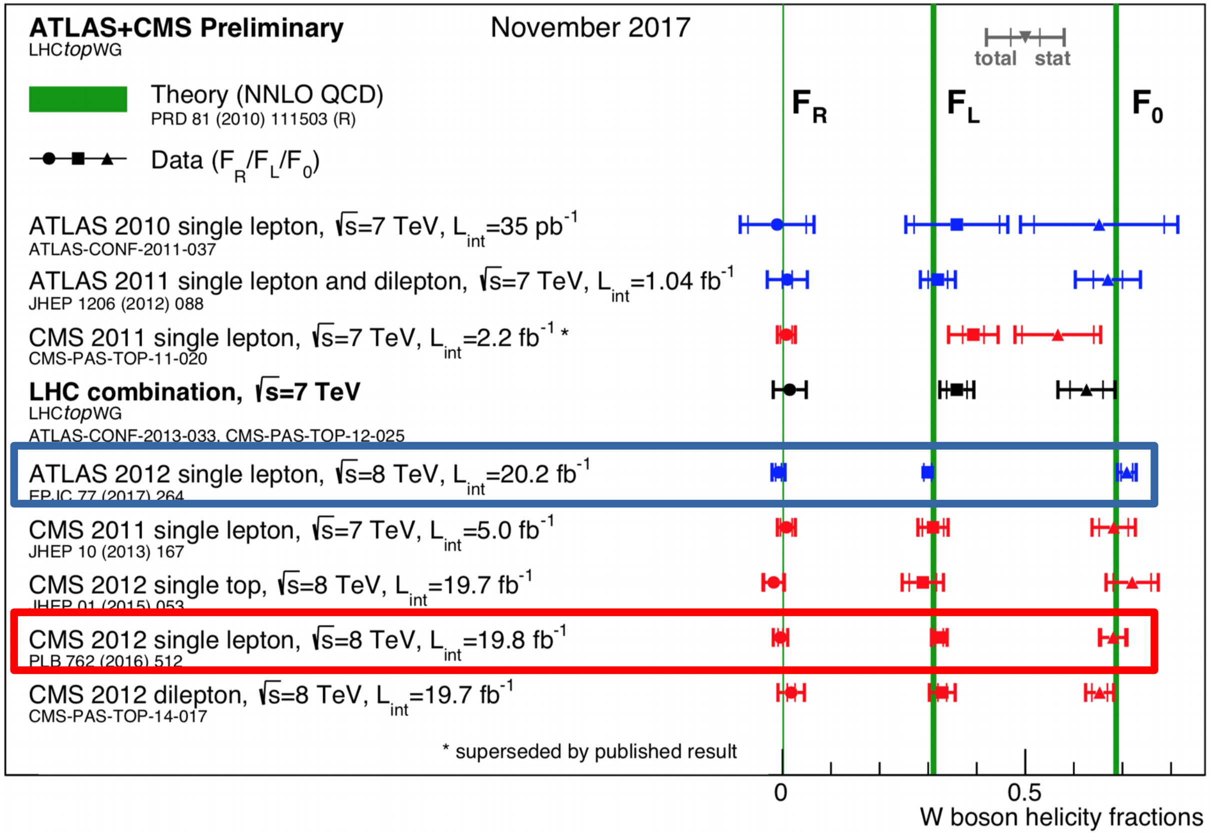


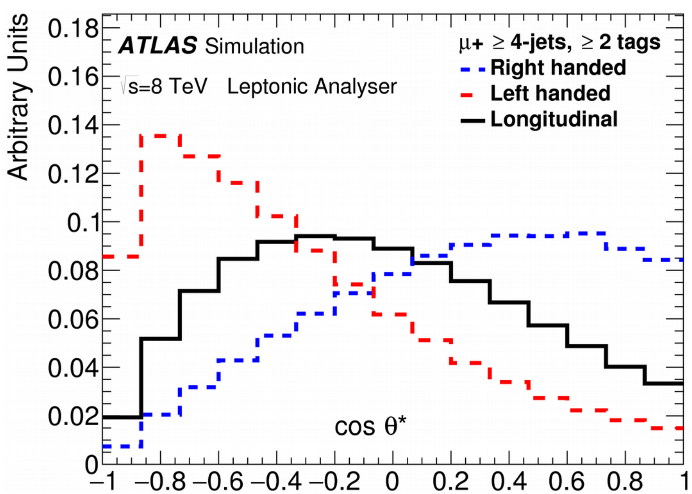
The Wtb vertex in top decays

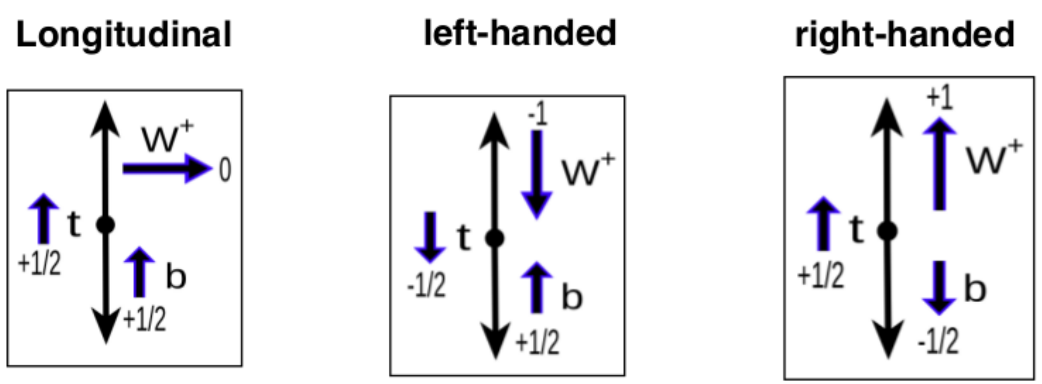
W helicity



- maximize likelihood using the cosθ* expected from the 3 helicities
- hadronic "branch" less precise
  - ATLAS: no improvement in tot. unc.
  - CMS: considered as a x.check







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

$F_0 + F_R + F_L = 1$

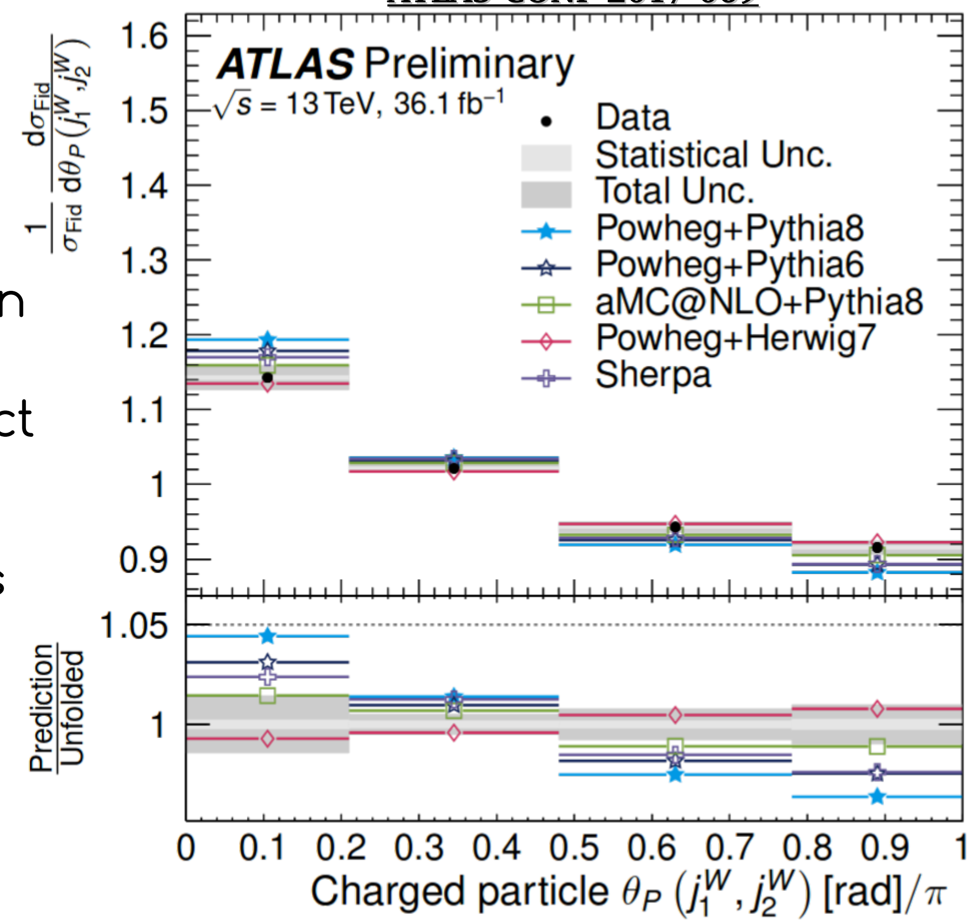
SM (@NNLO, % rel unc.) ~0.687 ~0.311 ~0.0017

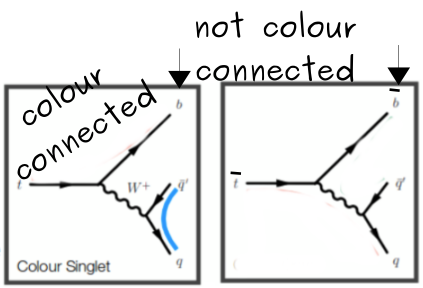
Colour connections between partons and jets

Colour flow

- It affects the energy distribution **within** & **between** jets, quantified through
  - a radial jet-constituent moment ("jet pull")
  - angle between jet pull and $\vec{J}_1 - \vec{J}_2$ direction
- Data disclose
  - a weaker than predicted colour-flow effect
  - larger than predicted values for jet pull
- **Not well modeled** by most ME+PS combinations

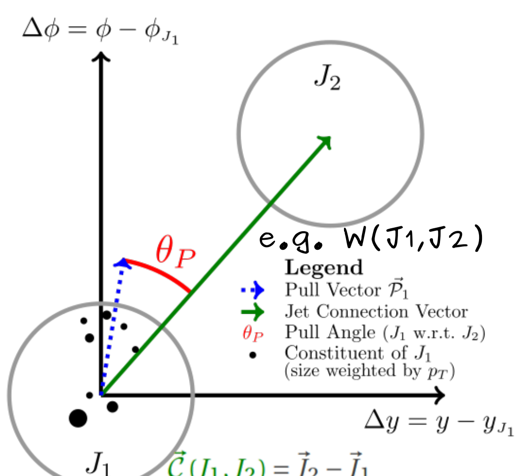
ATLAS-CONF-2017-069





- *Jet pull*: A p_T weighted radial moment of the jet

$$\vec{\mathcal{P}}(J) = \sum_{i \in J} \frac{|\Delta \vec{r}_i| \cdot p_T^i}{p_T^J} \Delta \vec{r}_i$$



$\vec{\mathcal{C}}(J_1, J_2) = \vec{J}_2 - \vec{J}_1$

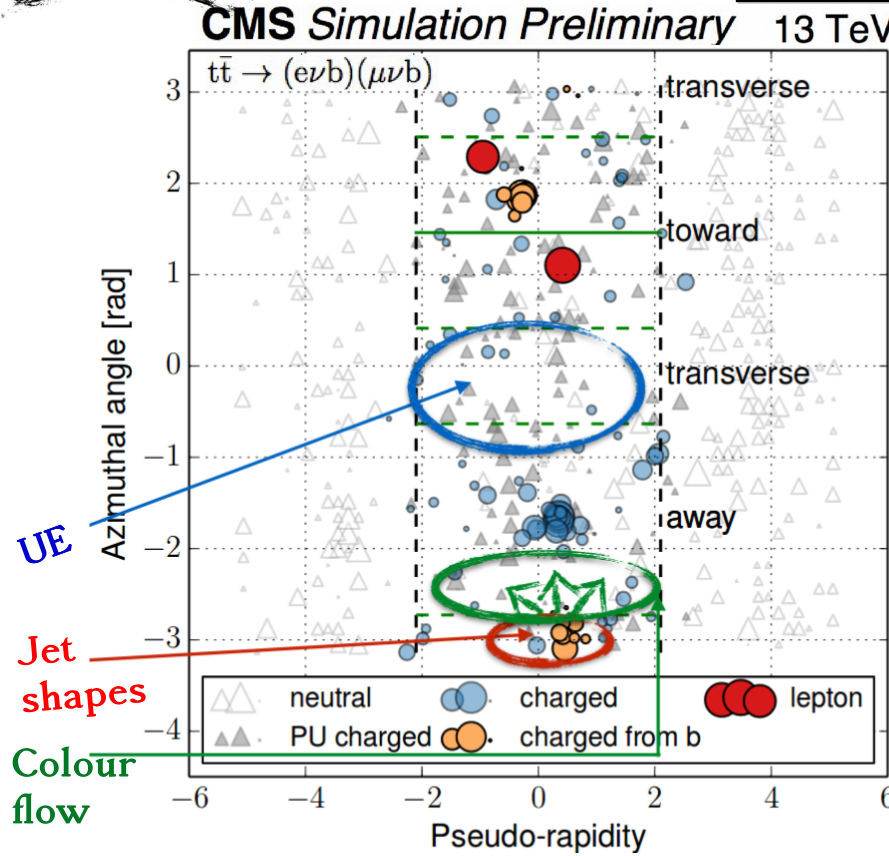
$\theta_{\mathcal{P}}(J_1, J_2) = \sphericalangle\left(\vec{\mathcal{P}}(J_1), \vec{\mathcal{C}}(J_1, J_2)\right)$

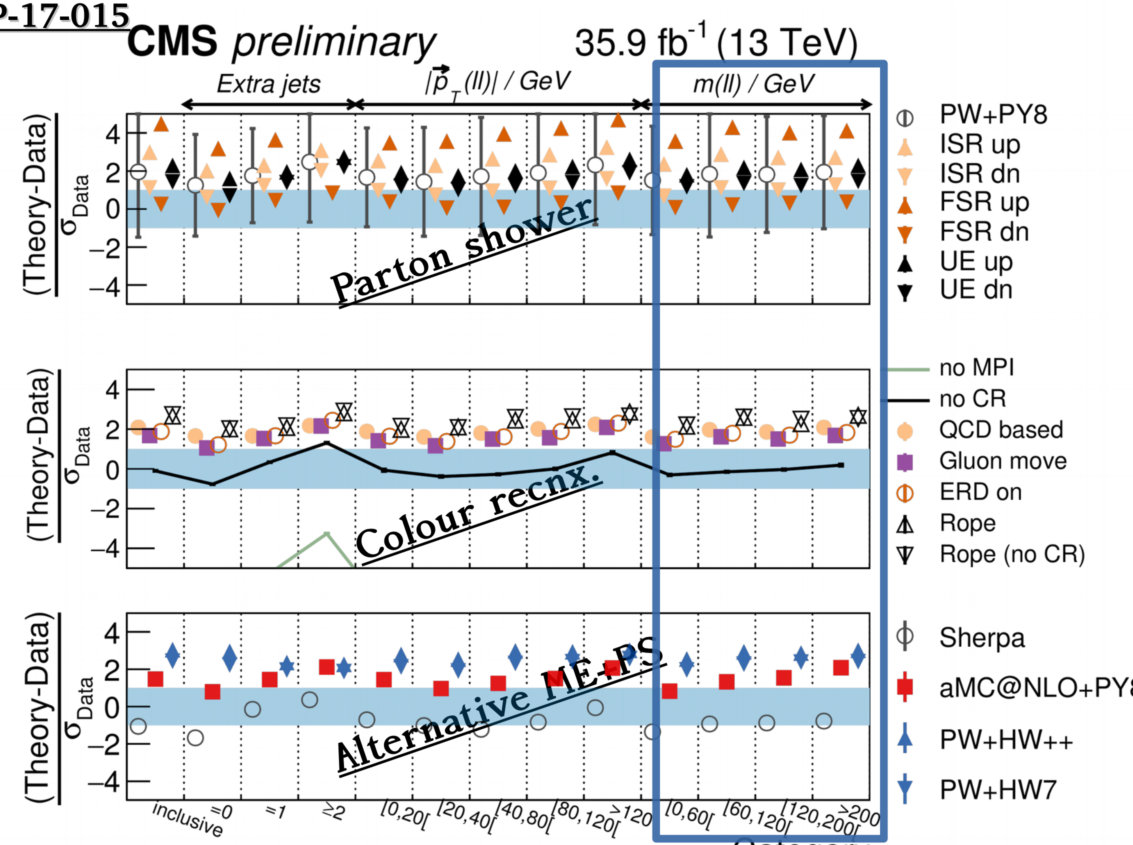
- For colour connected: a peak at small values and a sloped reduction from there on
- For not colour connected: uniformly distributed

Can we improve the modeling of tops?

UE

CMS-PAS-TOP-17-015

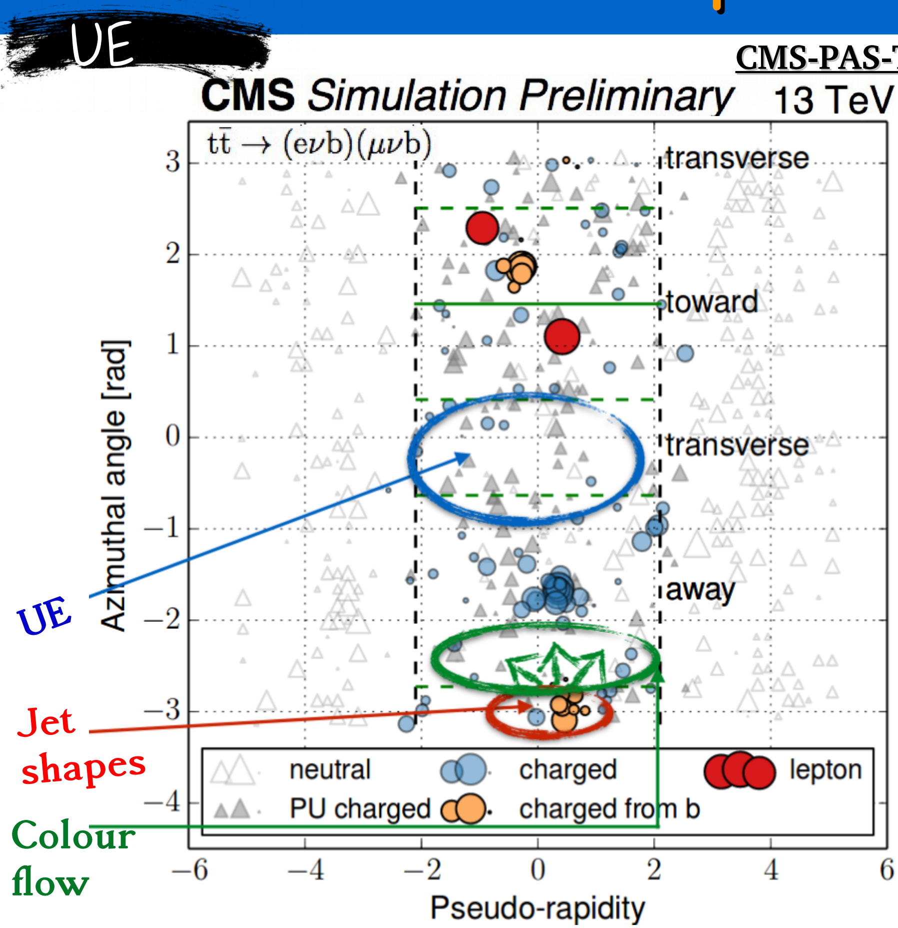




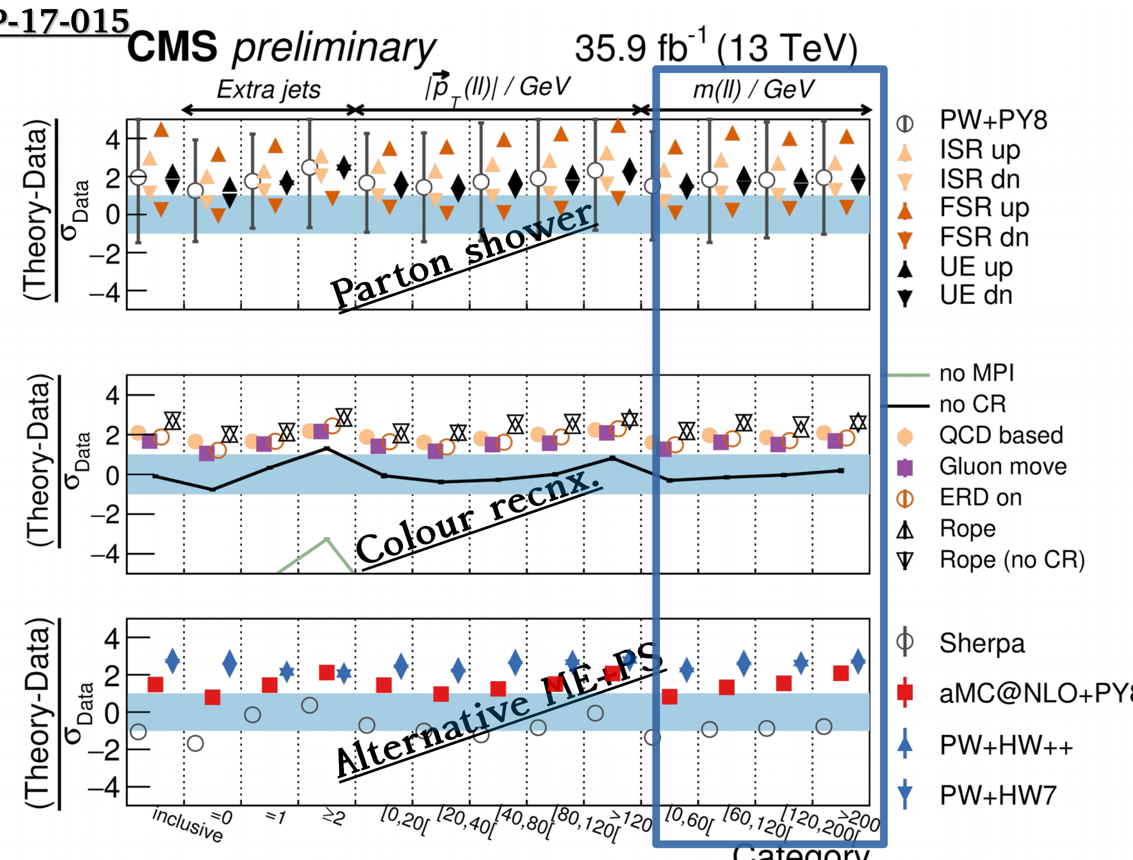
Nch≡every particle in fid. region not associated with the tt decay and the b tagged jets

- Crucial to understand soft QCD reminiscent effects in heavy quark hadroproduction
  - accurate description of the fragmentation and hadronization of the quarks
  - test universality assumption of the underlying event (UE) at scales up to 2×mtop

Can we improve the modeling of tops?



CMS-PAS-TOP-17-015

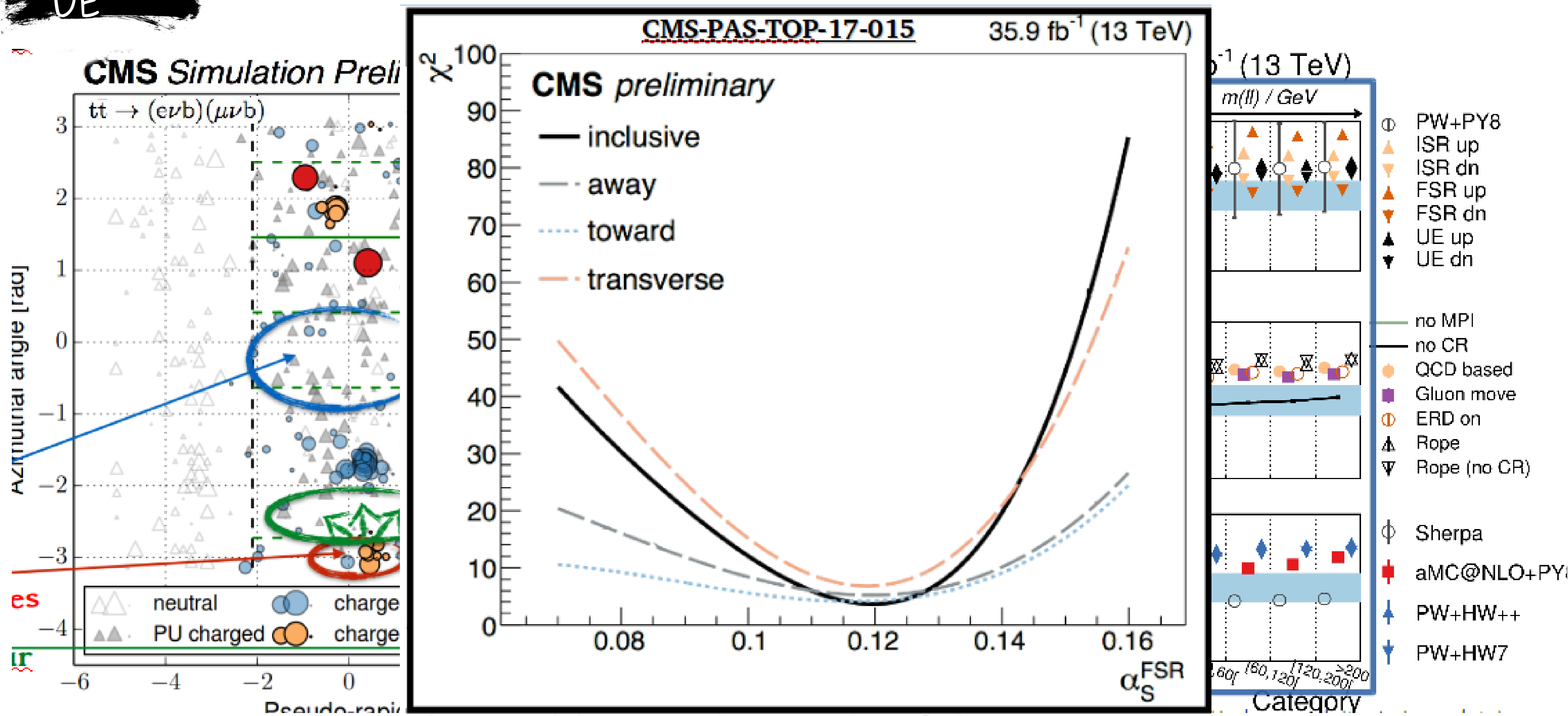


Nch≡every particle in fid. region not associated with the tt decay and the b tagged jets

- Crucial to understand soft QCD reminiscent effects in heavy quark hadroproduction
  - accurate description of the fragmentation and hadronization of the quarks
  - test universality assumption of the underlying event (UE) at scales up to 2×mtop
- A rich set of variables to probe the *tt* recoil, the contribution from MPI and CR
  - multiplicity, momentum flux, and the topology or shape of the event
  - fair agreement with PW/MG5aMC@NLO[FxFx]+P8 (CUETP8M2T4)
  - default settings for HW++, HW7, and Sherpa disfavored

Can we improve the modeling of tops?

UE



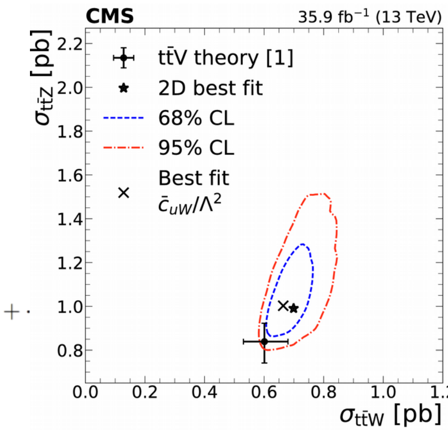
$\|\vec{p}_T(\ell\ell)\|$ region	Inclusive	Away	Toward	Transverse
Best fit α_S^{FSR}	0.120	0.119	0.116	0.119
68% CI	[-0.006,+0.006]	[-0.011,+0.010]	[-0.013,+0.011]	[-0.006,+0.006]
95.45% CI	[-0.013,+0.011]	[-0.022,+0.019]	[-0.030,+0.021]	[-0.013,+0.012]

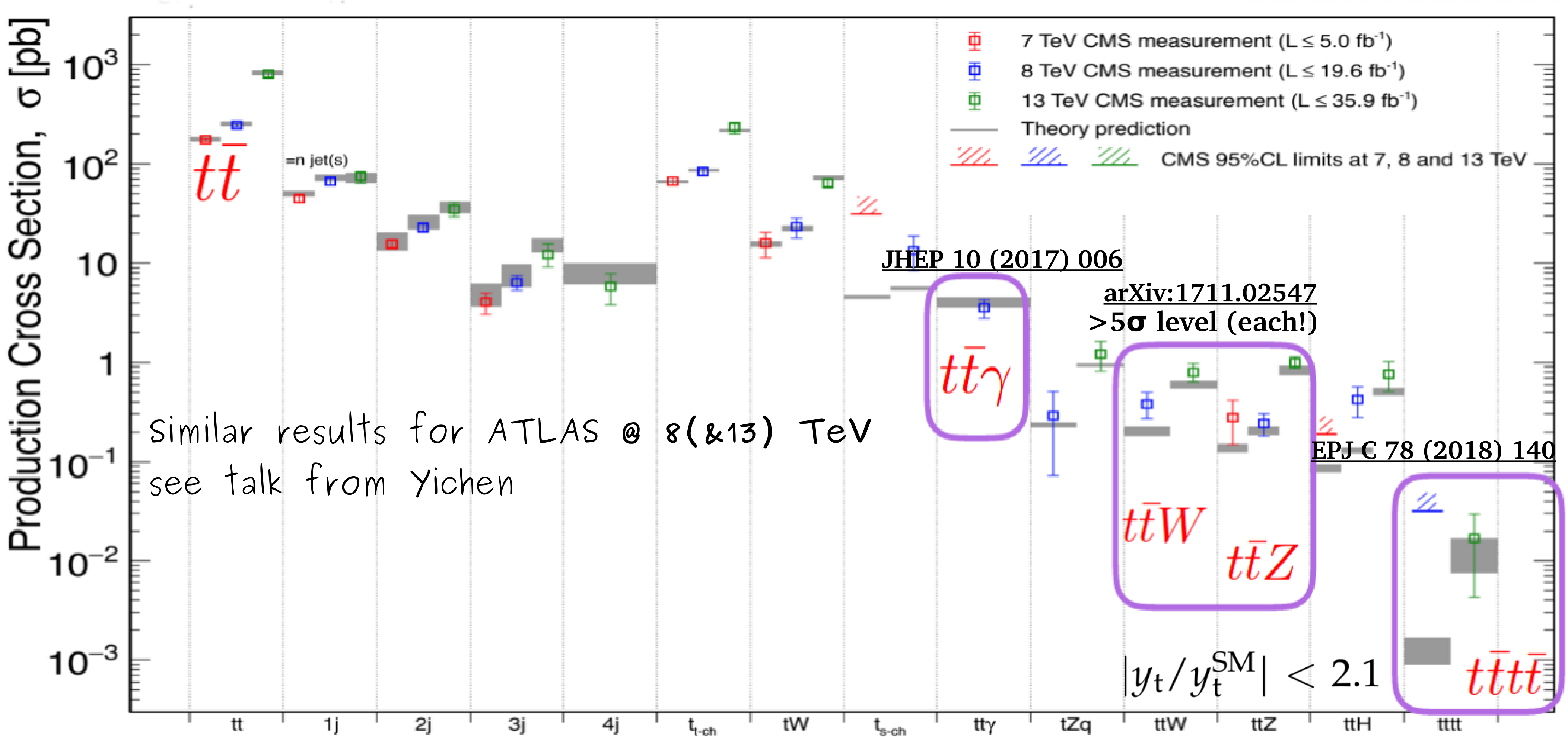
- Data indicate lower effective strong coupling for FSR than the default in PYTHIA8
  - similar trend is seen for jet substructure observables in tt events → see talk from Ece
- Results can be used to improve assessment of systematics in future top measurements

Accessing the top couplings with EW bosons & Higgs

- **Direct** access to the couplings of the top quark
  - important **background** (ttV,γ,bb) for ttH measurements
- These final states can be **affected** by BSM Physics
  - interpretation in terms of e.g. EFT approach $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_i c_i\mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j\mathcal{O}_j + \cdots$

arXiv:1711.02547





Establishing top quark Yukawa coupling

- ttH production crucial for probing tree level coupling of Higgs boson to top quarks
  - rare (~1% of ggH) , but distinct final state with multiple jets, b jets, leptons, and photons
- Both ATLAS and CMS reported evidence for ttH production using Run 2 (2016) data
  - increased sensitivity combining already published measurements with Run 1 data
- Correlations between Run-1 and Run-2 analyses not exactly known
  - signal theory and some background theory uncertainties correlated
  - experimental uncertainties largely uncorrelated
  - detailed investigation of correlation scheme between the two sets of analyses to ensure least possible bias

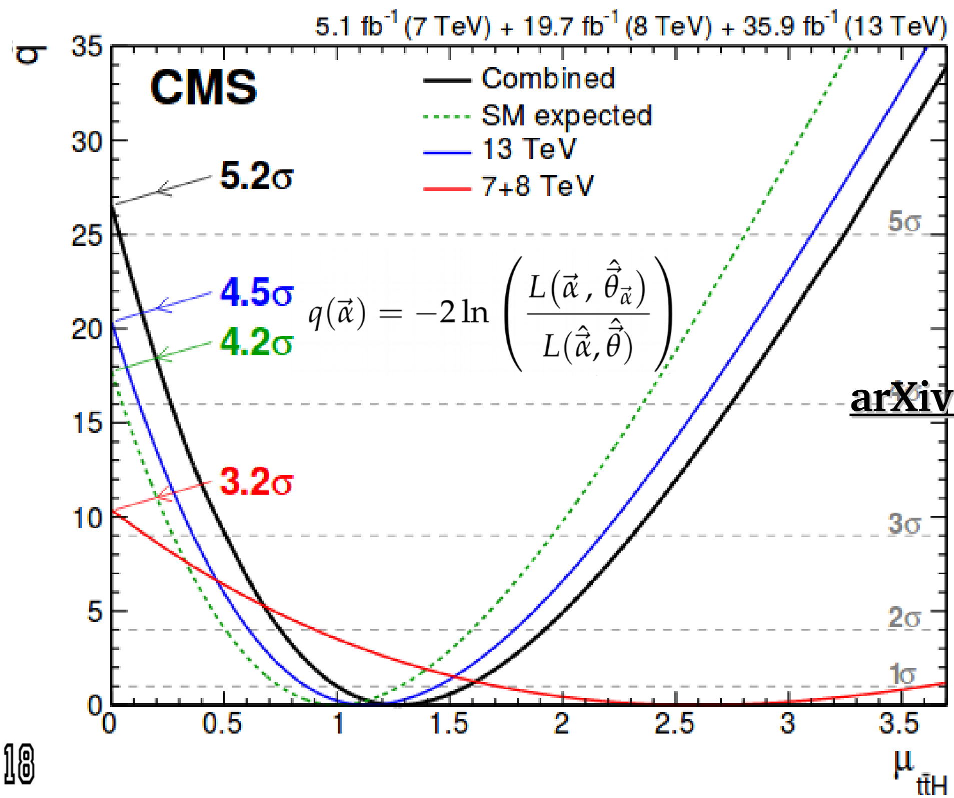
Analysis		Categories	Result (μ_{ttH})
$H \to ZZ \to 4l$	JHEP 11 (2017) 047	3	$0.00^{+1.19}_{-0.00}$
$H \to \gamma\gamma$	arXiv:1804.02716	2	$2.2^{+0.9}_{-0.8}$
$ttH \to WW/ZZ/\tau\tau$	arXiv:1803.05485	19	$1.23^{+0.45}_{-0.43}$ 3.2σ (2.8σ)
$ttH \to bb$ (leptonic)	HIG-17-026 (submitted to JHEP)	21	0.72 ± 0.45 1.6σ (2.2σ)
$ttH \to bb$ (hadronic)	arXiv:1803.06986	6	0.9 ± 1.5
Run 1 (7+8 TeV) $bb/\tau\tau/WW/ZZ/\gamma\gamma$	JHEP 09 (2014) 087	37	2.8 ± 1.0

arXiv: 1804.02610

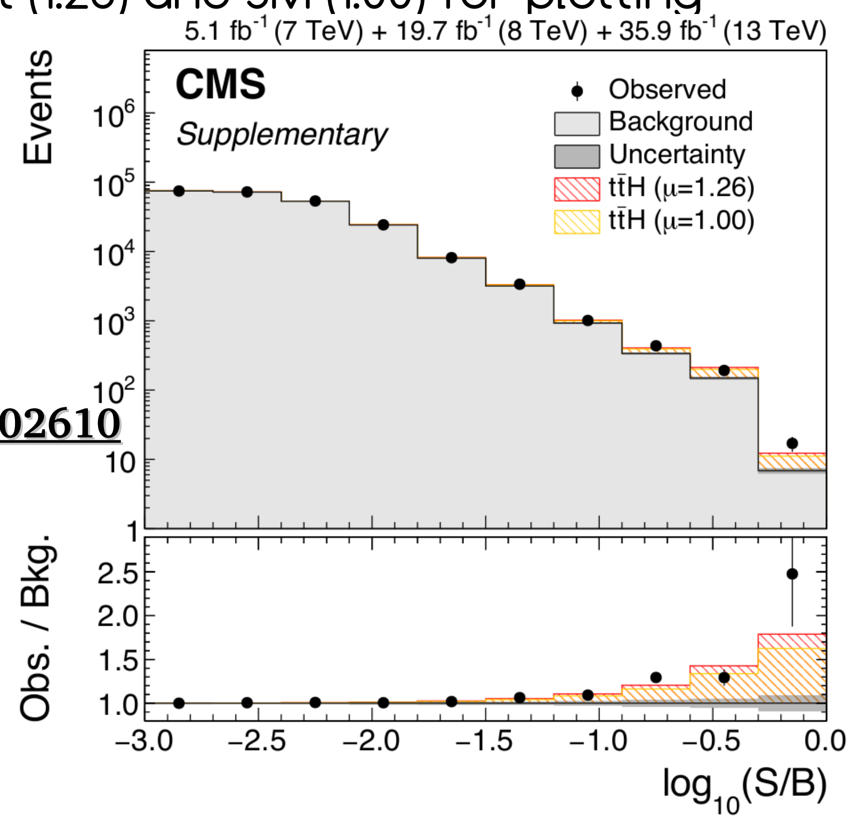
Signal normalisation and uncertainties updated to the latest LHC Higgs XS WG

The first observation of ttH production

- Results calculated using the profile test likelihood (L) ratio q, for which the asymptotic approximation entails
  - q to follow a χ^2 distribution with ndof=set of POIs being tested
  - the tail integral of q (p-value) at μ=0 to quantify the incompatibility level with the null hypothesis
  - the p-value to be converted into an equivalent significance of Z standard deviations for one-tailed Gaussian distribution
  - the estimators for the parameters to equal to their hypothesized values when the likelihood is evaluated with an artificial dataset, a.k.a. the Asimov dataset
- Visualize the excess in terms of a $\log_{10}$(S/B) distribution for each bin in the combination
  - post-fit from S+B fit with μ fixed at best-fit (1.26) and SM (1.00) for plotting

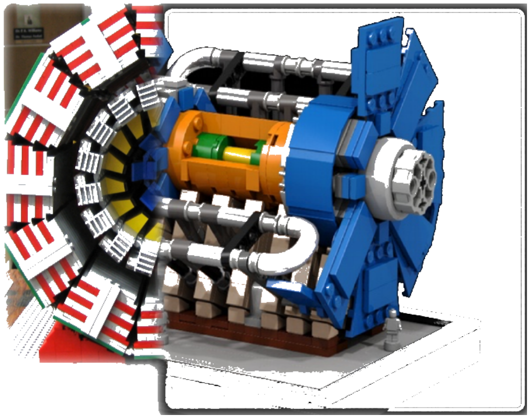


arXiv: 1804.02610



"I like the dreams of the future better than the history of the past"

- Given m_{top} and couplings, the rest of properties can be also inferred from its decay products
- Level of precision reached (<0.3%) in measuring m_{top} impressive but
  - comes with an ambiguity as to what parameter it is actually measured
- SM predictions agree with measurements probing the Wtb vertex
  - degree of W polarisation tested at 2-5%
  - level of tt spin correlations tested at O(10-20)%

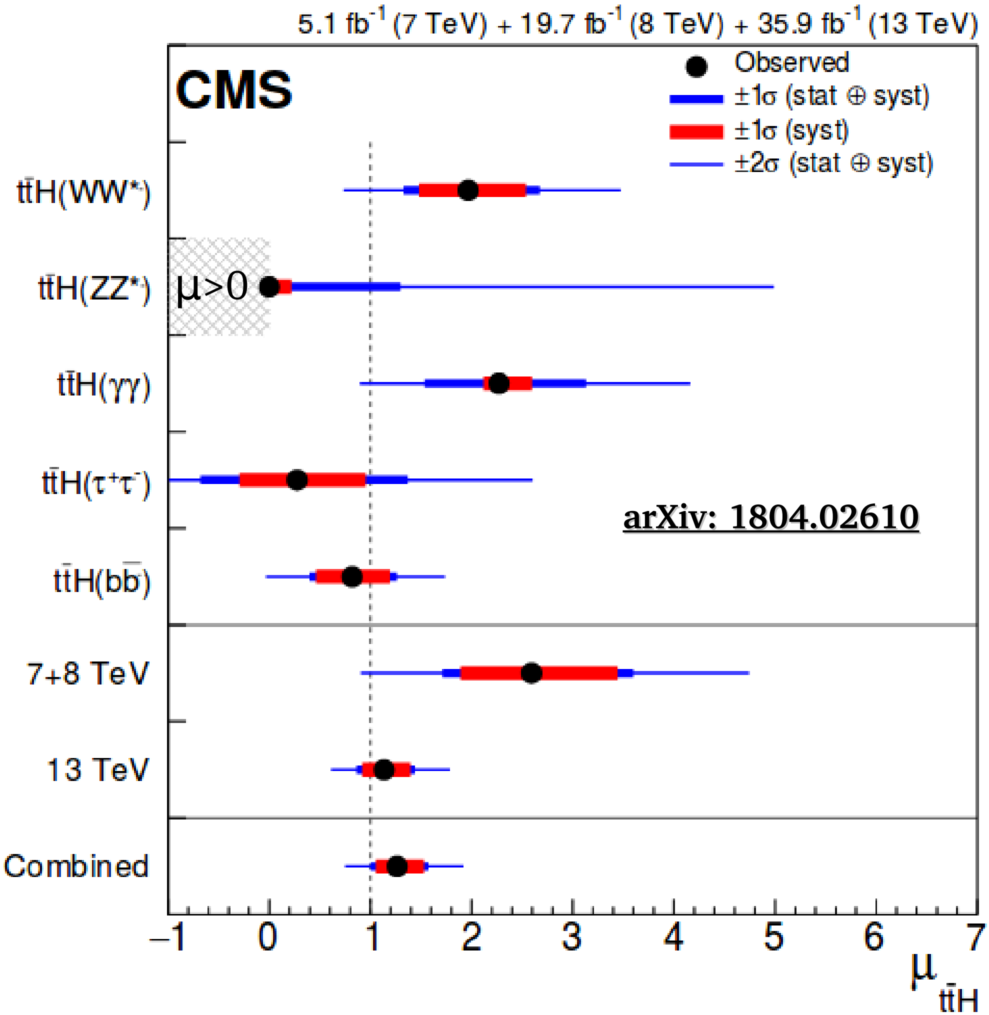


- Top quark width direct measurement achieves <50% relative unc.
  - consistent with the much more precise SM calculation
- Charge asymmetries are consistent with SM predictions
  - effects in production tested at 10^{-3} (inclusively) and at 50% level (differentially, m_{tt})
- Top modeling has a direct impact on extracting its properties
  - several MC predictions show poor modeling of jet pull magnitude and angle
  - crucial to understand soft physics even in something high-Q^2 scale like tt
- On our way to precision tests of the couplings
  - a pivotal step already performed with the ttH observation

S slides

Logistics of the ttH combination

- Measure ttH signal strength, $\mu=\sigma/\sigma_{theo.}$, in combined fit for three configurations
  - per decay channel, CM (7+8 and 13 TeV), and overall (decay channel and CM)
  - branching ratios fixed to SM in all 5 decay channels
- Processes (e.g. t,$\bar{t}$H) are treated as bkg. normalised to SM prediction accounting for their associated theo. unc.



- performed for mH = 125.09 GeV
  - internal consistency with other combination efforts

One μ_{ttH} per decay channel

Expectation from minor ttH decay modes (cc, gg, Zγ) treated as background

One μ_{ttH} per dataset

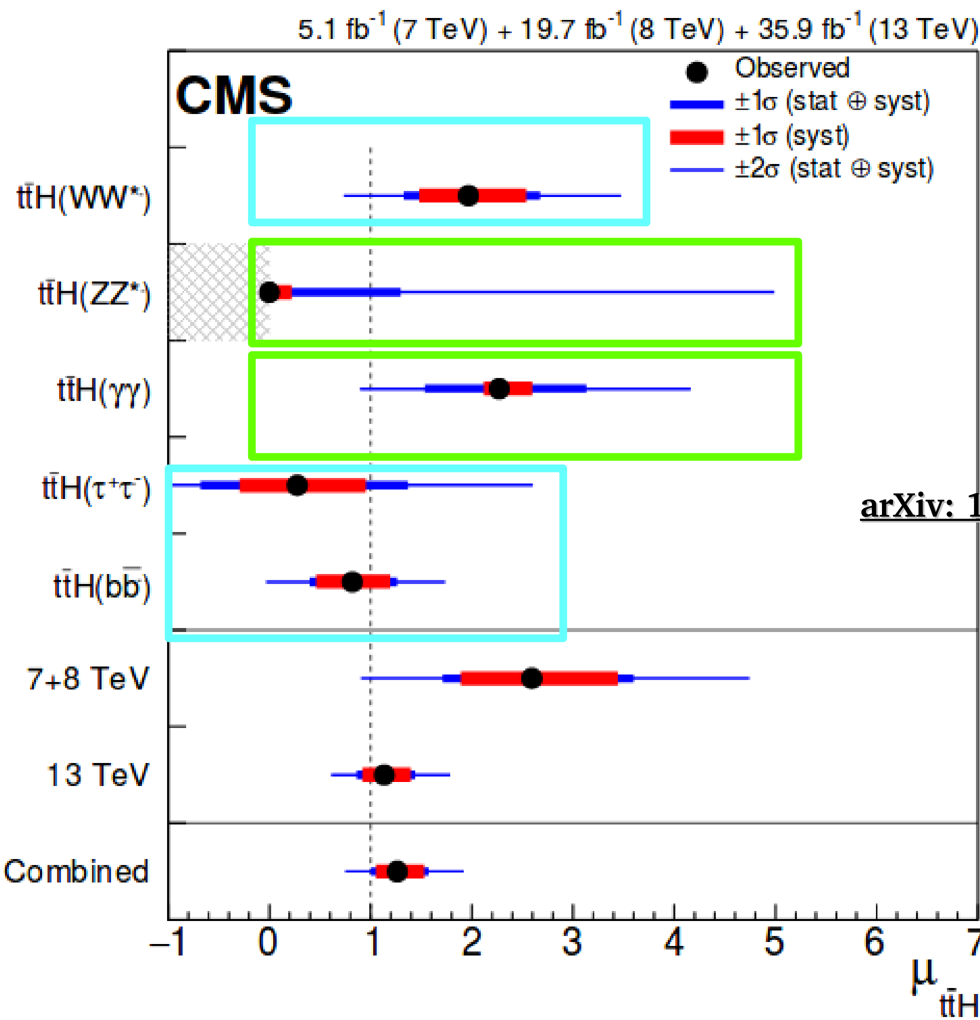
Minor ttH decay modes scale with μ_{ttH} as signal

One overall μ_{ttH}

Minor ttH decay modes scale with μ_{ttH} as signal

The overall result combining all 88 categories

- The individual measurements **consistent** with each other within the uncertainties
  - H(γγ) and H(ZZ) channels still limited by stat.
  - H→multi-leptons and H(bb) dominated by syst.
- **Agreement** with μ=1 (SM) within 1 sigma



arXiv: 1804.02610

Decomposition into statistical, experimental, background theo. and signal theo. components

Parameter	Best fit		Uncertainty: Stat	Uncertainty: Expt	Uncertainty: Thbgd	Uncertainty: Thsig
$\mu_{t\bar{t}H}^{WW^*}$	1.97	$^{+0.71}_{-0.64}$	$^{+0.42}_{-0.41}$	$^{+0.46}_{-0.42}$	$^{+0.21}_{-0.21}$	$^{+0.25}_{-0.12}$
		$\left(^{+0.57}_{-0.54}\right)$	$\left(^{+0.39}_{-0.38}\right)$	$\left(^{+0.36}_{-0.34}\right)$	$\left(^{+0.17}_{-0.17}\right)$	$\left(^{+0.12}_{-0.03}\right)$
$\mu_{t\bar{t}H}^{ZZ^*}$	0.00	$^{+1.30}_{-0.00}$	$^{+1.28}_{-0.00}$	$^{+0.20}_{-0.00}$	$^{+0.04}_{-0.00}$	$^{+0.09}_{-0.00}$
		$\left(^{+2.89}_{-0.99}\right)$	$\left(^{+2.82}_{-0.99}\right)$	$\left(^{+0.51}_{-0.00}\right)$	$\left(^{+0.15}_{-0.00}\right)$	$\left(^{+0.27}_{-0.00}\right)$
$\mu_{t\bar{t}H}^{\gamma\gamma}$	2.27	$^{+0.86}_{-0.74}$	$^{+0.80}_{-0.72}$	$^{+0.15}_{-0.09}$	$^{+0.02}_{-0.01}$	$^{+0.29}_{-0.13}$
		$\left(^{+0.73}_{-0.64}\right)$	$\left(^{+0.71}_{-0.64}\right)$	$\left(^{+0.09}_{-0.04}\right)$	$\left(^{+0.01}_{-0.00}\right)$	$\left(^{+0.13}_{-0.05}\right)$
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	0.28	$^{+1.09}_{-0.96}$	$^{+0.86}_{-0.77}$	$^{+0.64}_{-0.53}$	$^{+0.10}_{-0.09}$	$^{+0.20}_{-0.19}$
		$\left(^{+1.00}_{-0.89}\right)$	$\left(^{+0.83}_{-0.76}\right)$	$\left(^{+0.54}_{-0.47}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.14}_{-0.01}\right)$
$\mu_{t\bar{t}H}^{b\bar{b}}$	0.82	$^{+0.44}_{-0.42}$	$^{+0.23}_{-0.23}$	$^{+0.24}_{-0.23}$	$^{+0.27}_{-0.27}$	$^{+0.11}_{-0.03}$
		$\left(^{+0.44}_{-0.42}\right)$	$\left(^{+0.23}_{-0.22}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.26}_{-0.27}\right)$	$\left(^{+0.11}_{-0.04}\right)$
$\mu_{t\bar{t}H}^{7+8\ \mathrm{TeV}}$	2.59	$^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
		$\left(^{+0.87}_{-0.79}\right)$	$\left(^{+0.51}_{-0.49}\right)$	$\left(^{+0.48}_{-0.44}\right)$	$\left(^{+0.50}_{-0.44}\right)$	$\left(^{+0.14}_{-0.02}\right)$
$\mu_{t\bar{t}H}^{13\ \mathrm{TeV}}$	1.14	$^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
		$\left(^{+0.29}_{-0.26}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	1.26	$^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
		$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.15}_{-0.15}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$

Detailed breakdown of the total uncertainty

- Not unique way to split the identified sources of unc. and of their impact (Δμ)
  - estimated by freezing each group in turn and subtracting from the total unc.
- Stat., expt., thsig. and thbgd. components ~ comparable magnitude
  - thsig: theory mainly from inclusive ttH prediction
  - thbgd.: theory mainly from tt+heavy flavour prediction in ttH(bb)
  - expt: lepton efficiencies, lepton mis-ID, b tagging and MC stats equally important

Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+0.06	−0.06
Other background uncertainties	+0.03	−0.03
Experimental	+0.17	−0.15
b-Tagging efficiency	+0.05	−0.04
Misidentified lepton prediction	+0.06	−0.06
Jet and τ_h energy scale and resolution	+0.04	−0.04
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08	−0.06
Luminosity	+0.04	−0.03
Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
Statistical	+0.16	−0.16
Total	+0.31	−0.26

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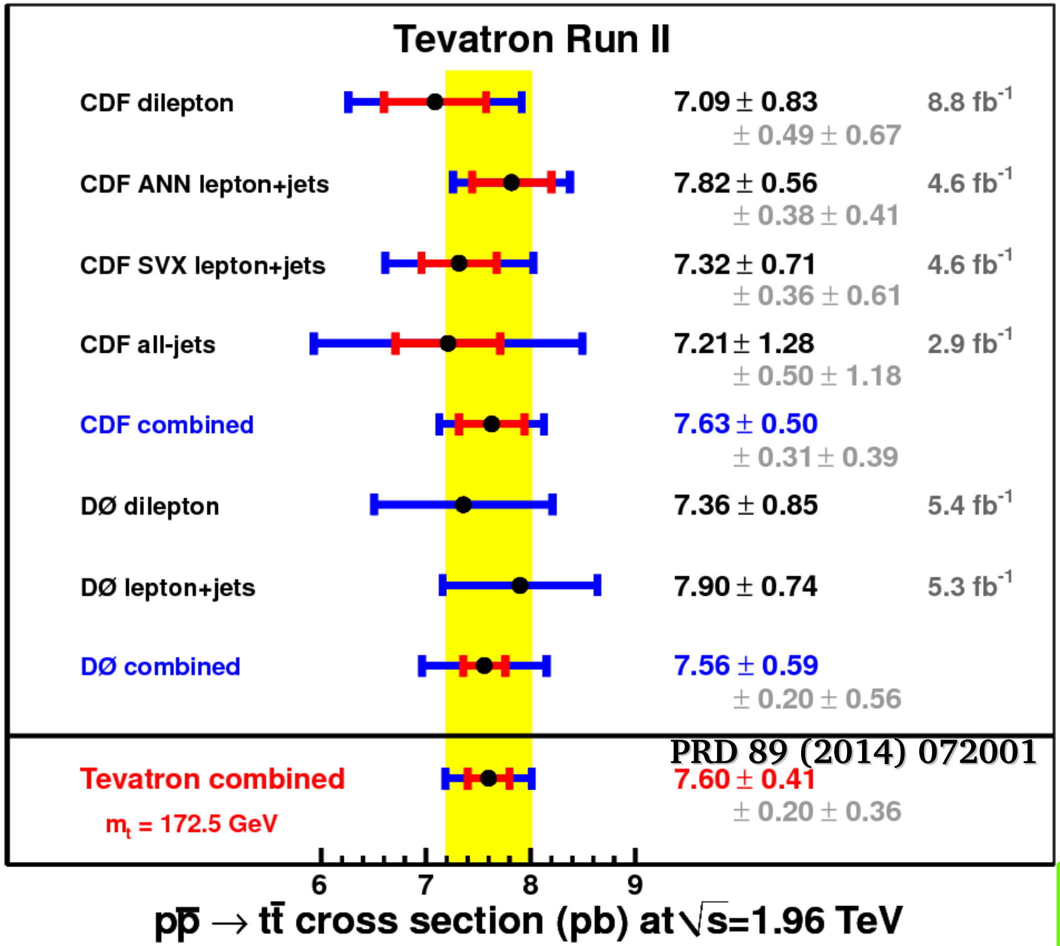
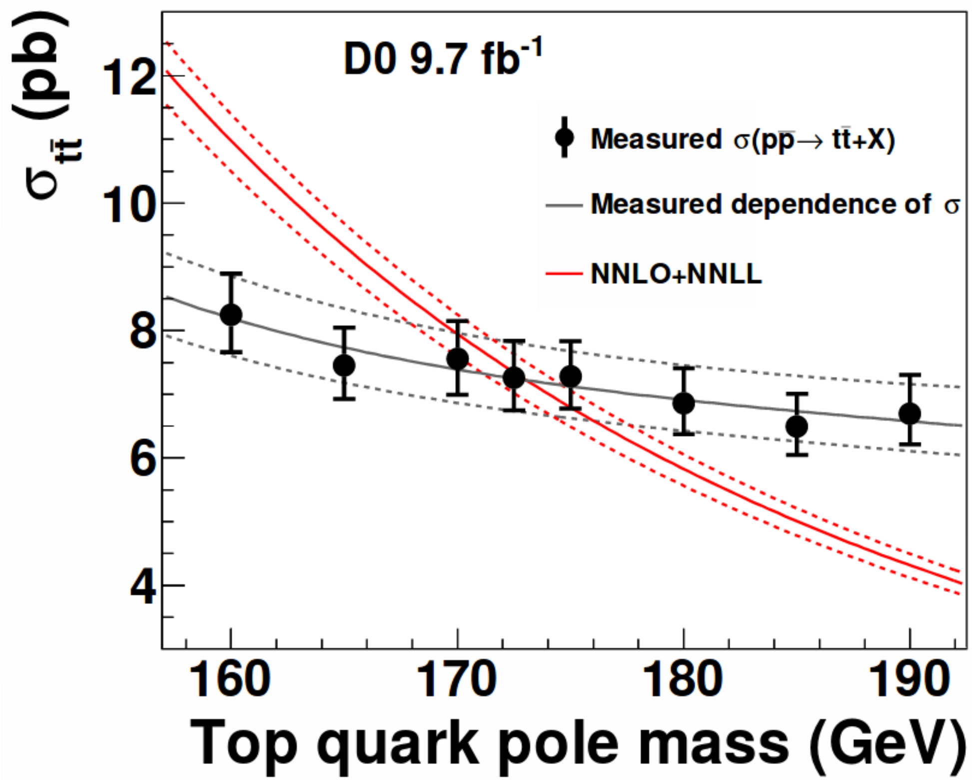
Updated measurement from D0 including 9.7fb-1

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat})^{+0.57}_{-0.50}(\text{syst})\ \text{pb}$$



PRD 89 (2014) 072001

PRD 94 (2016) 092004



$$m_t = 172.8 \pm 1.1(\text{theo})^{+3.3}_{-3.1}(\text{exp})\ \text{GeV}$$