LHC results on Top Quark Physics

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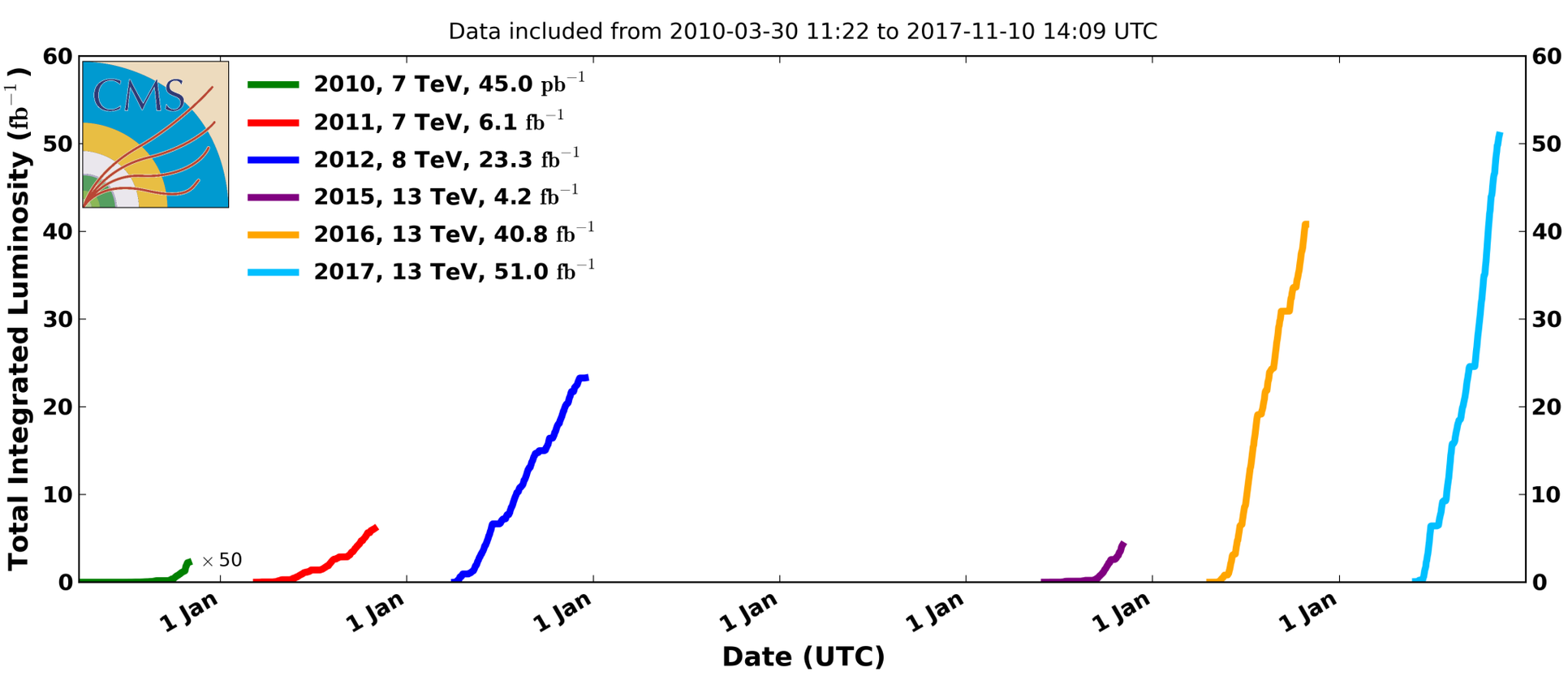
LHC pp data

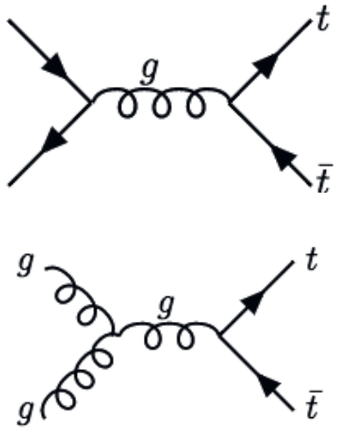
- Since 2010, the LHC has delivered an impressive amount of data to ATLAS and CMS
- We are days before the start of the last period of pp collisions of Run-2, and we have:

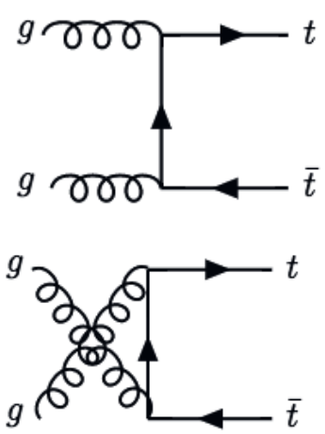
5fb^{-1} at 7TeV, 20fb^{-1} at 8TeV
90fb^{-1} at 13TeV

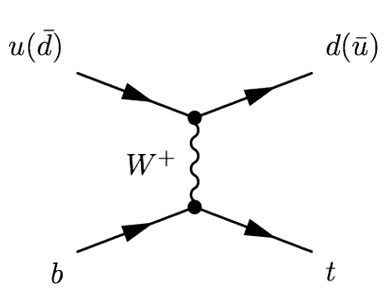
100fb^{-1} was the goal for Run-2, with 2018 still ahead, it will certainly be surpassed

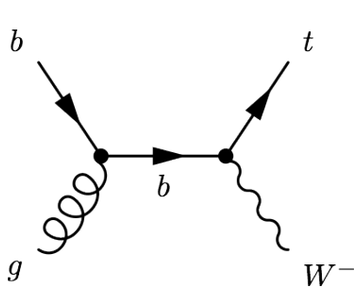


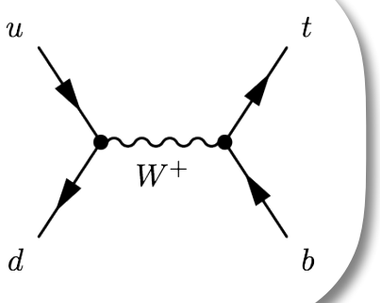
A certified top quark factory

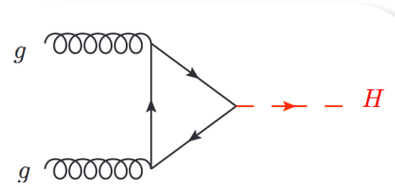












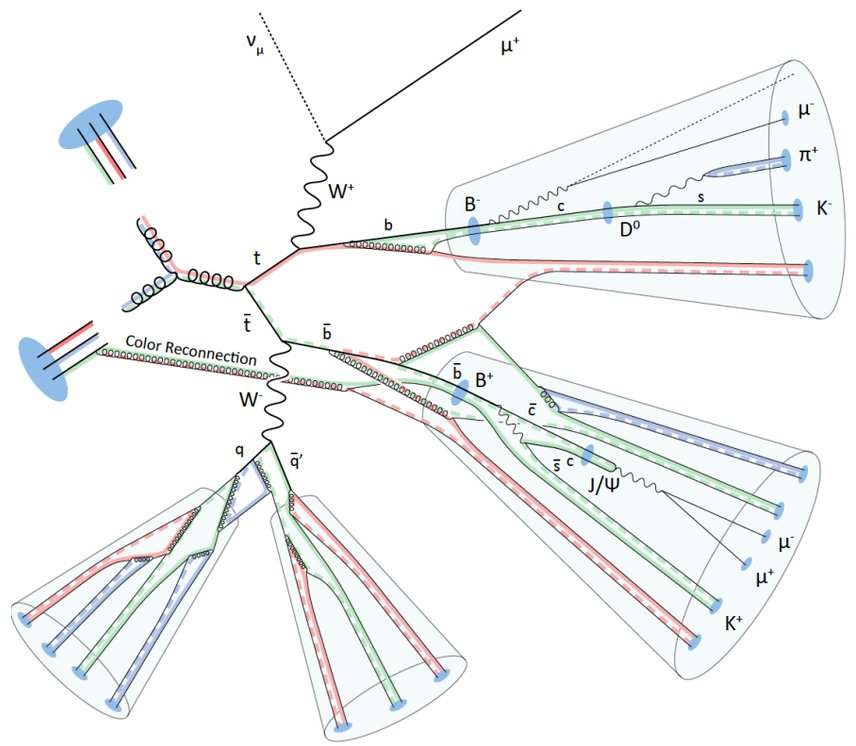
σ [pb]	ttbar	t-channel	tW	s-channel	ggH
Tevatron	7.0	2.08	0.22	1.046	-
LHC @ 7TeV	177.3	63.89	15.74	4.29	15.31
LHC @ 8TeV	252.8	84.69	22.2	5.24	19.47
LHC @ 13 TeV	831.7	216.99	71.2	10.32	44.14

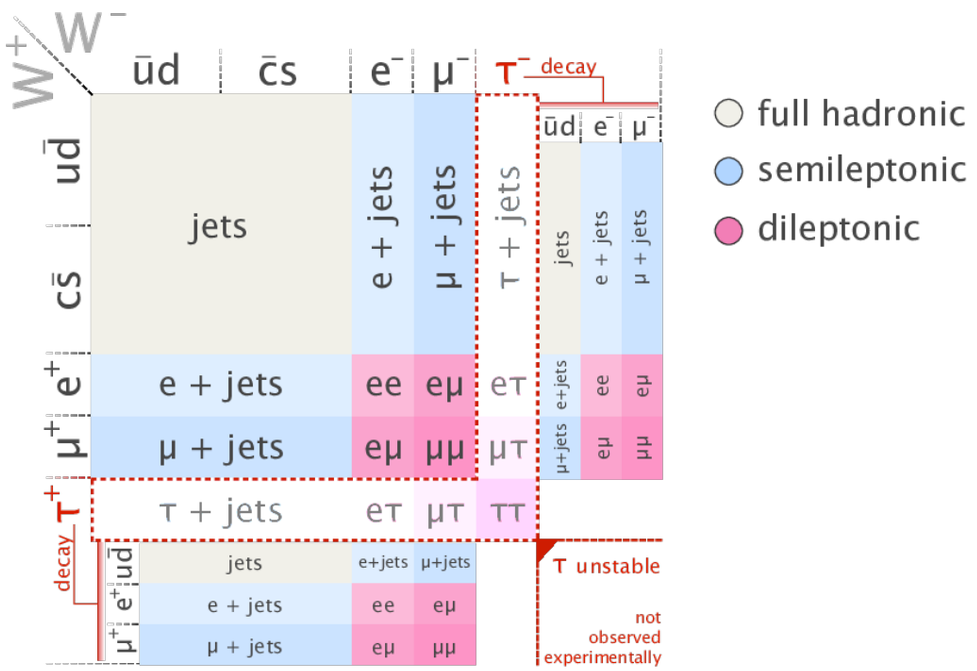
- Top quarks are produced today at the LHC more than 100 times as often as they were produced at the Tevatron
- For every Higgs boson produced in collisions → 22 top quark pairs
- During Run-1 of the LHC more than 6M top quark pairs were produced
  - In the current dataset of **Run-2 we already have > 60M of top quark pairs**

And this is good news because

- **The top quark is as interesting as it gets**
- Heaviest elementary particle ever observed
  - almost as heavy as a gold atom
    - *79 protons, 118 neutrons, and 79 electrons*
  - Short lived:
    - **Decays before hadronizing**
    - Some of its **properties pass directly to the decay products**
    - Does not form bound states
- **Couples strongly to Higgs**
  - Has an impact in Higgs sector

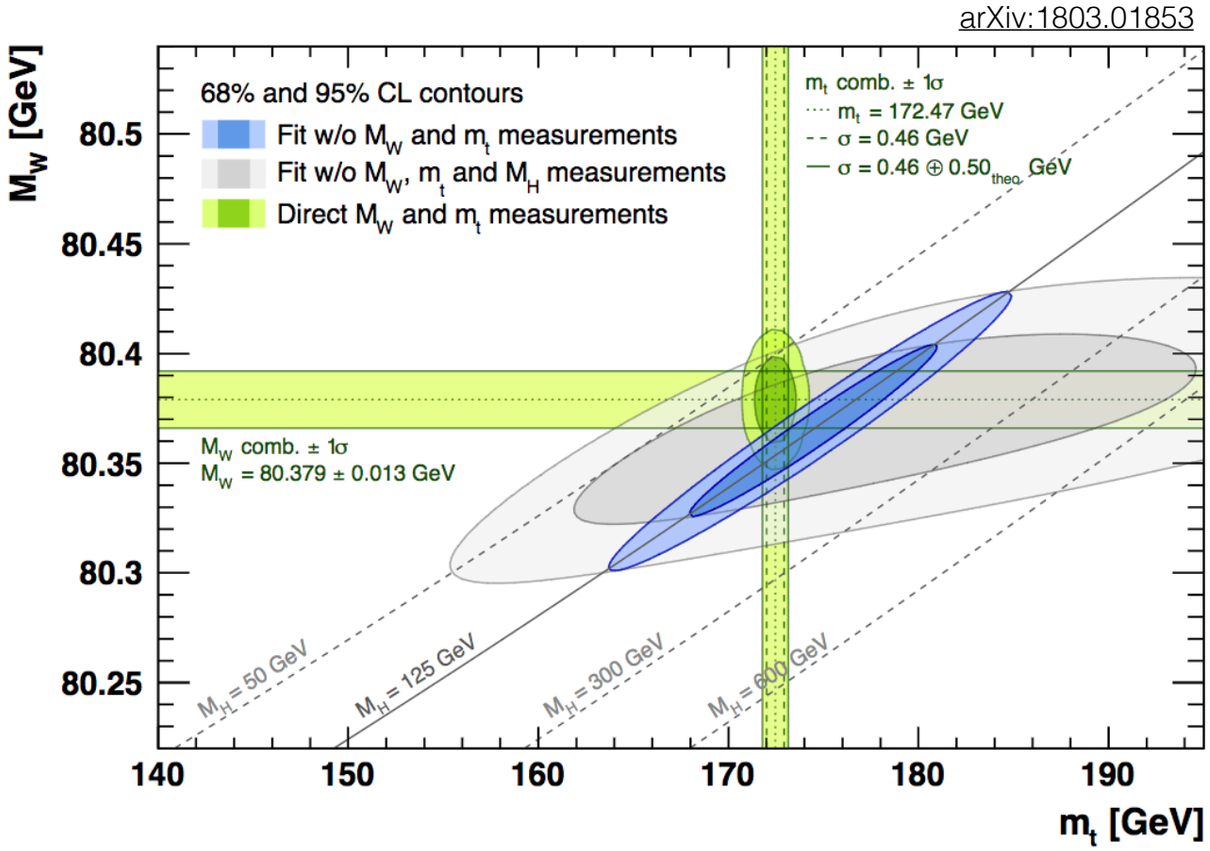
t→Wb ~100% of times

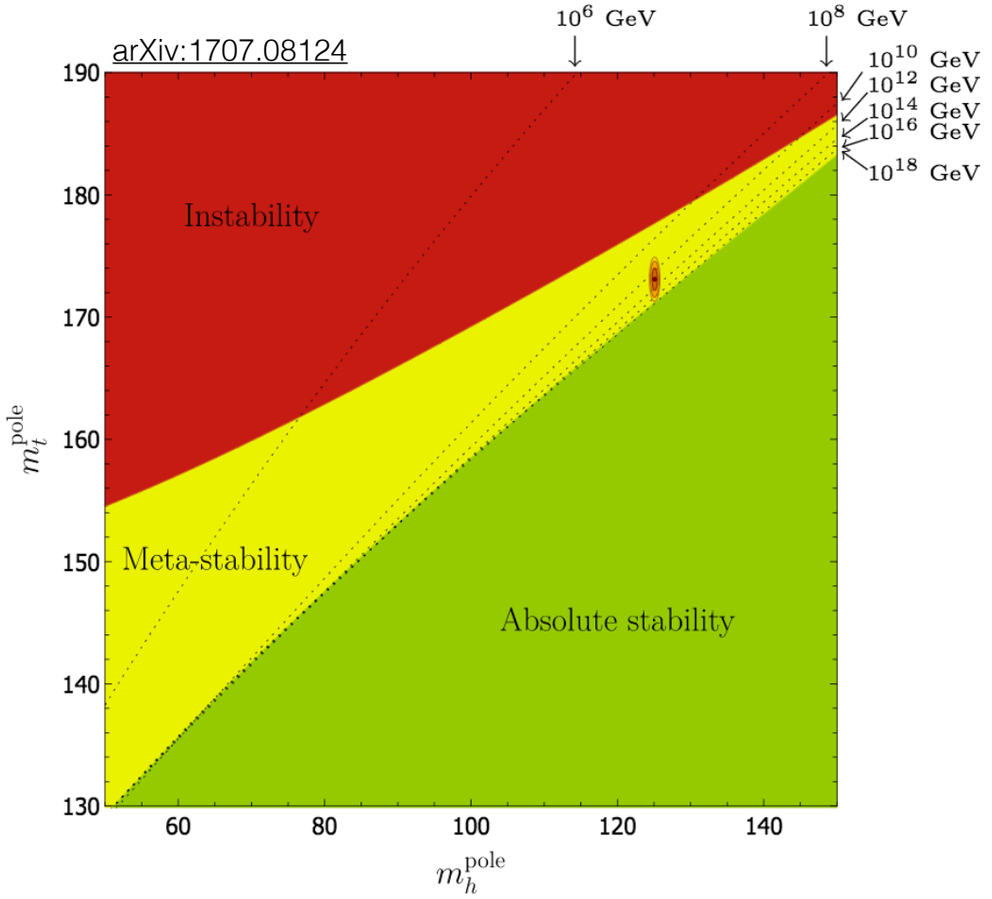




Important implications

- Observed for the first time in 1995, the measurement of its properties is as relevant as ever
- In particular the **top quark mass**
  - Essential for probing the SM consistency
  - Plays a role on the stability of the **electroweak vacuum of the Universe**

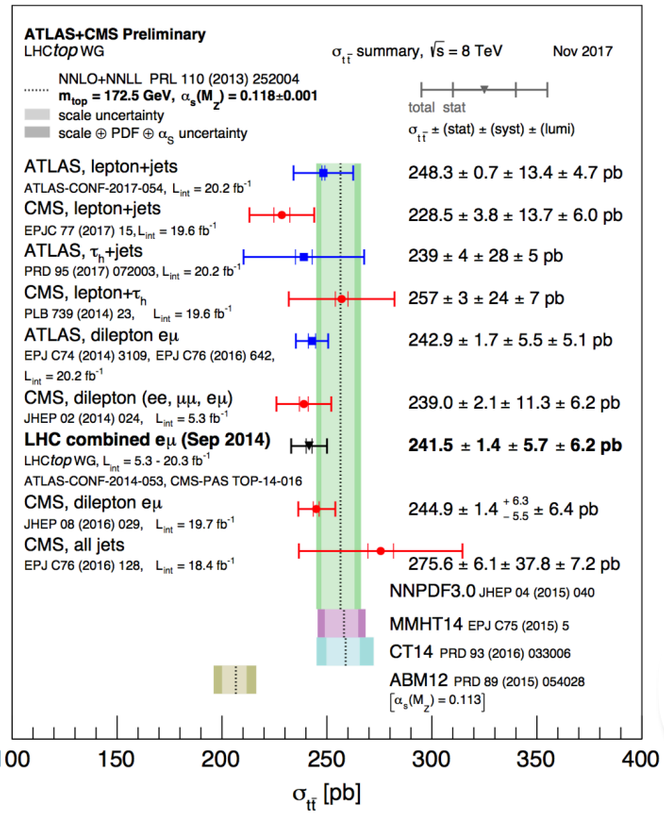


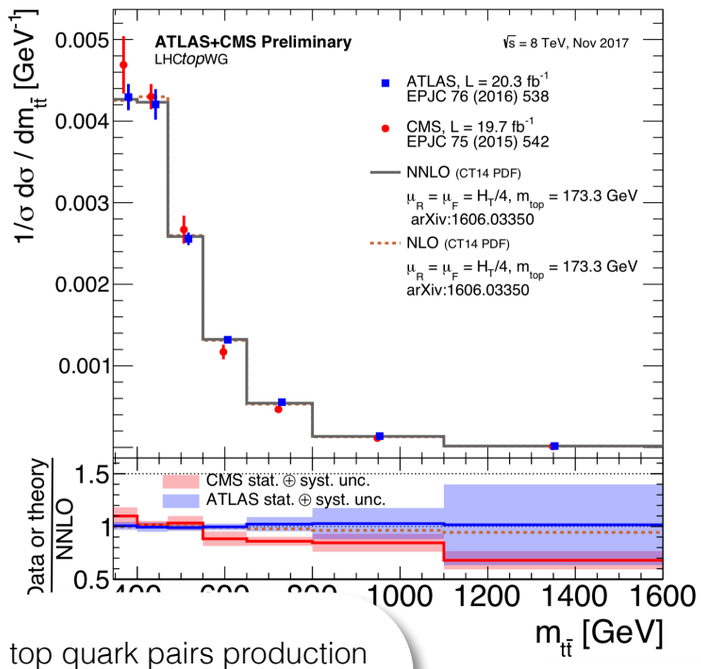


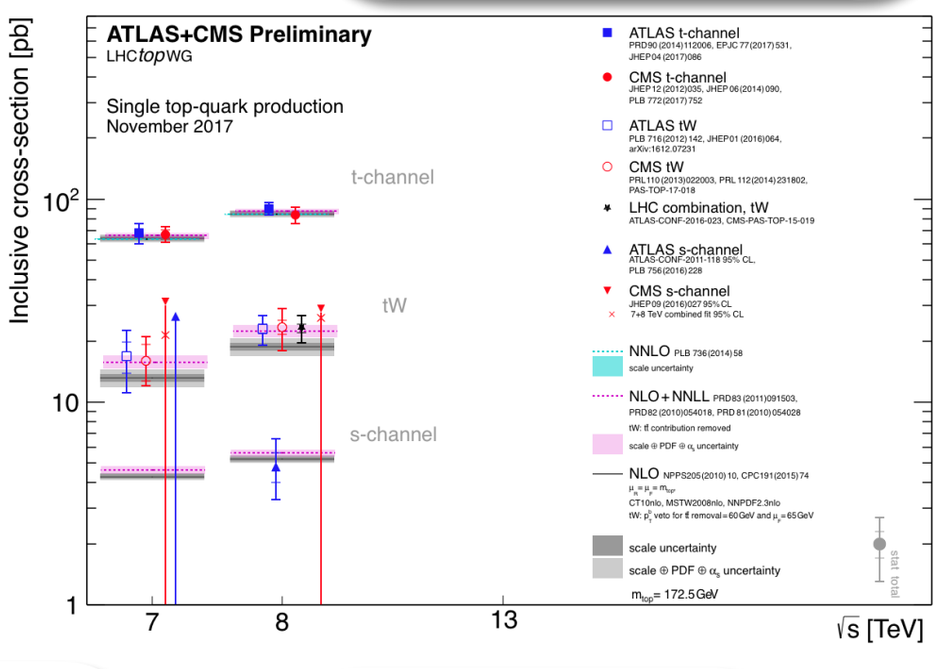
** It is also a main ingredient of BSM searches, but those are out of the scope of this talk*

A healthy Run-1 legacy

Single top production: t-channel (inclusive, differential, properties); tW observation; s-channel; rare single top; FCNC





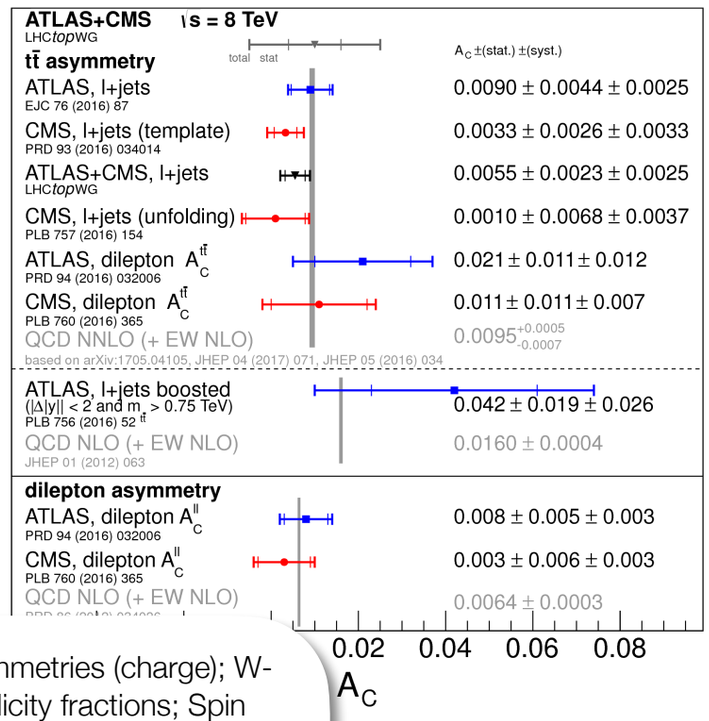


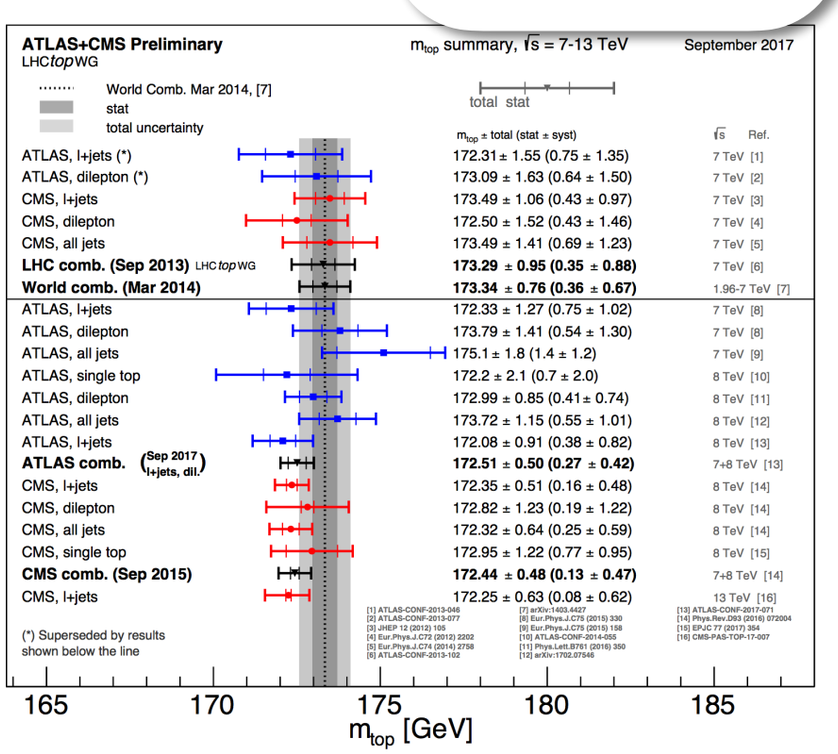
top quark pairs production cross sections (inclusive and differential)

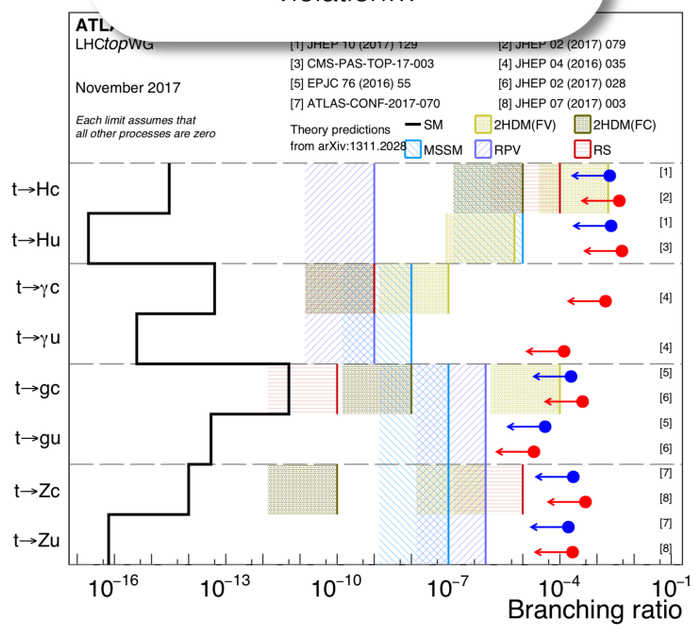
top mass: variety of measurements, extremely precise ±0.48 GeV (0.3%)

top quarks produced together with Higgs, W/Z, γ, tt, bb…: couplings, observation of ttV

Anomalous couplings, FCNC, CP violation…





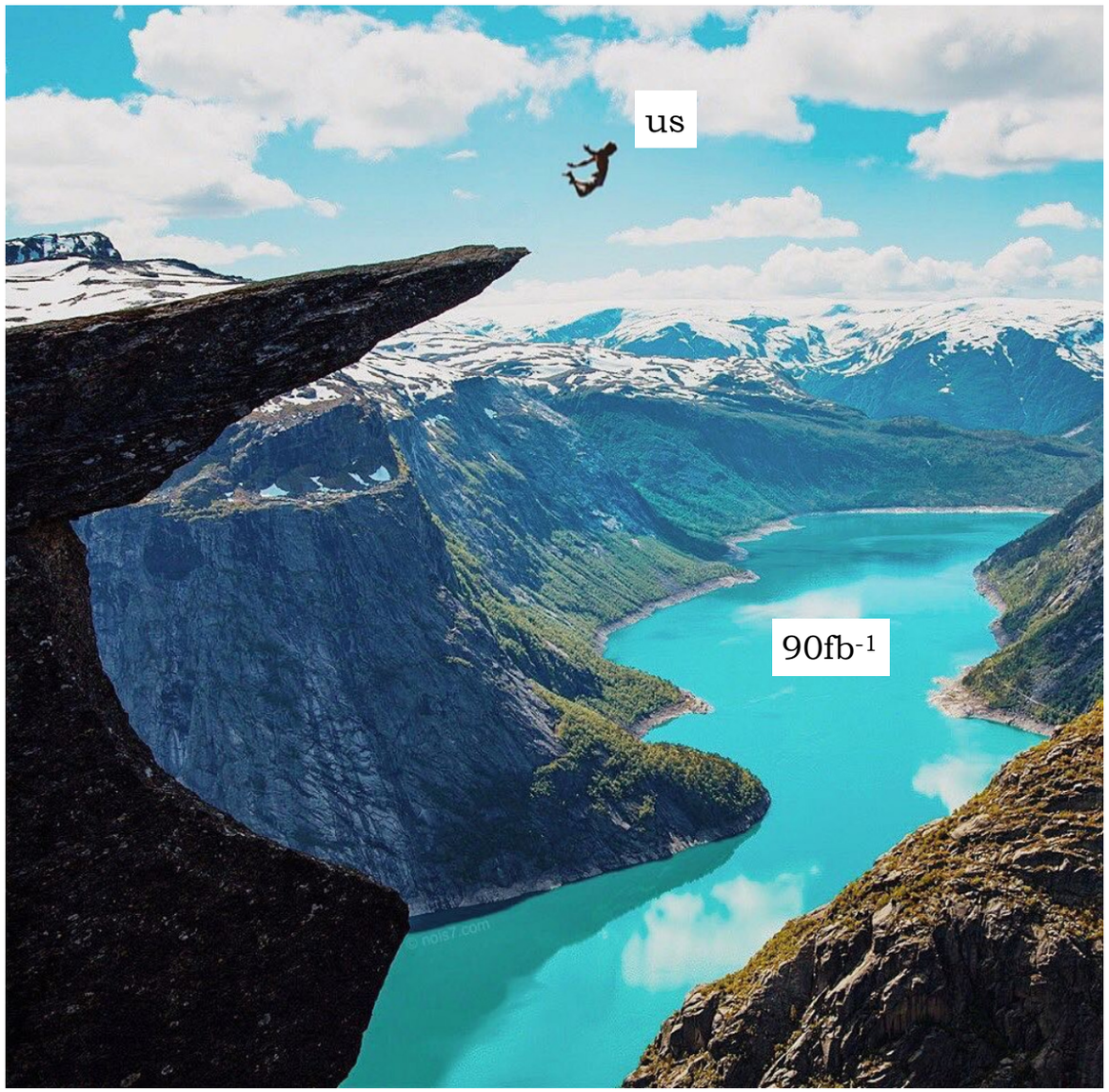


Asymmetries (charge); W-helicity fractions; Spin correlations; Top polarization; BR (t→Wb); $|V_{tb}|$; width

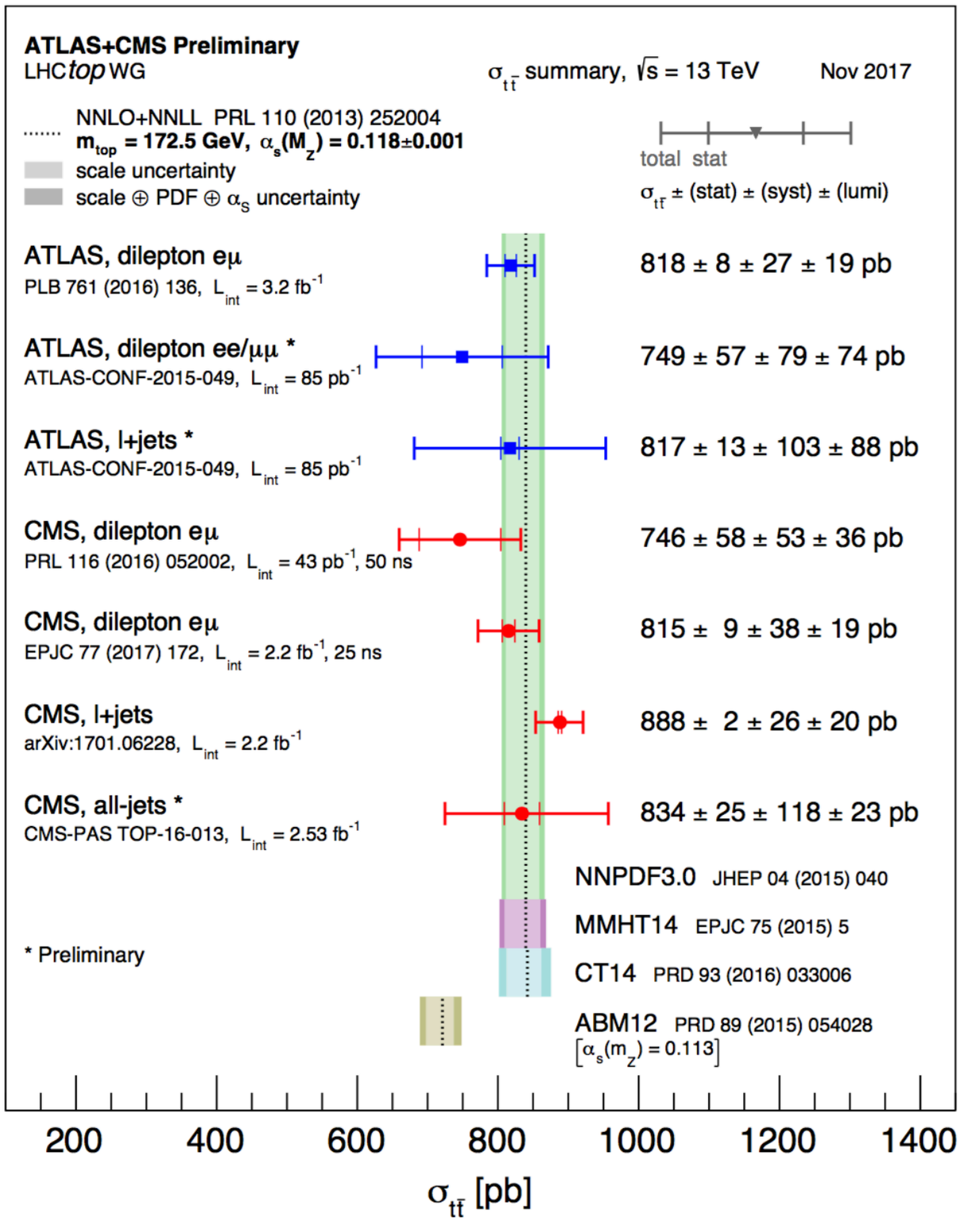
(And it is not over yet)

The legacy that is to come will be even better

- Well into Run-2
  - We have a collection of results (**this talk focuses on the latest among those**)
- But keep in mind:
  - **most of the data collected at 13TeV is not yet explored** (we are about to jump into it!)



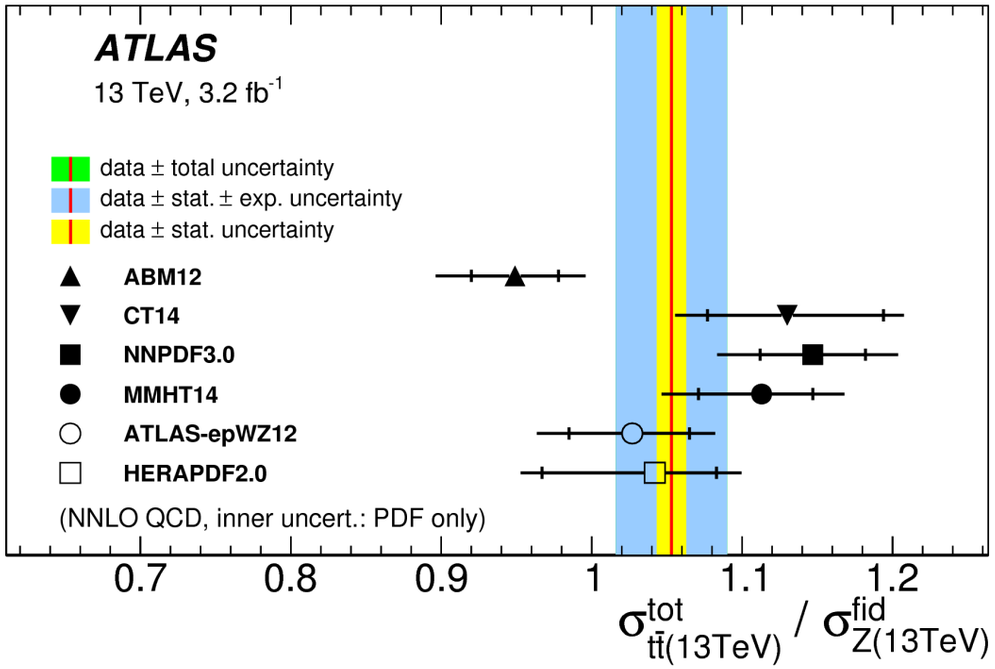
Inclusive tt cross sections



- The **bread and butter of top quark physics at the LHC**
  - early measurements at any new energy regime
  - deviations from the predictions would be a clear flag for new physics but so far they are all consistent with the SM

With a small fraction of the data:
Δσ/σ ≈ 4% and decreasing
(Run-1 legacy precision ≈3.5%)

Inclusive tt cross sections: the oddballs

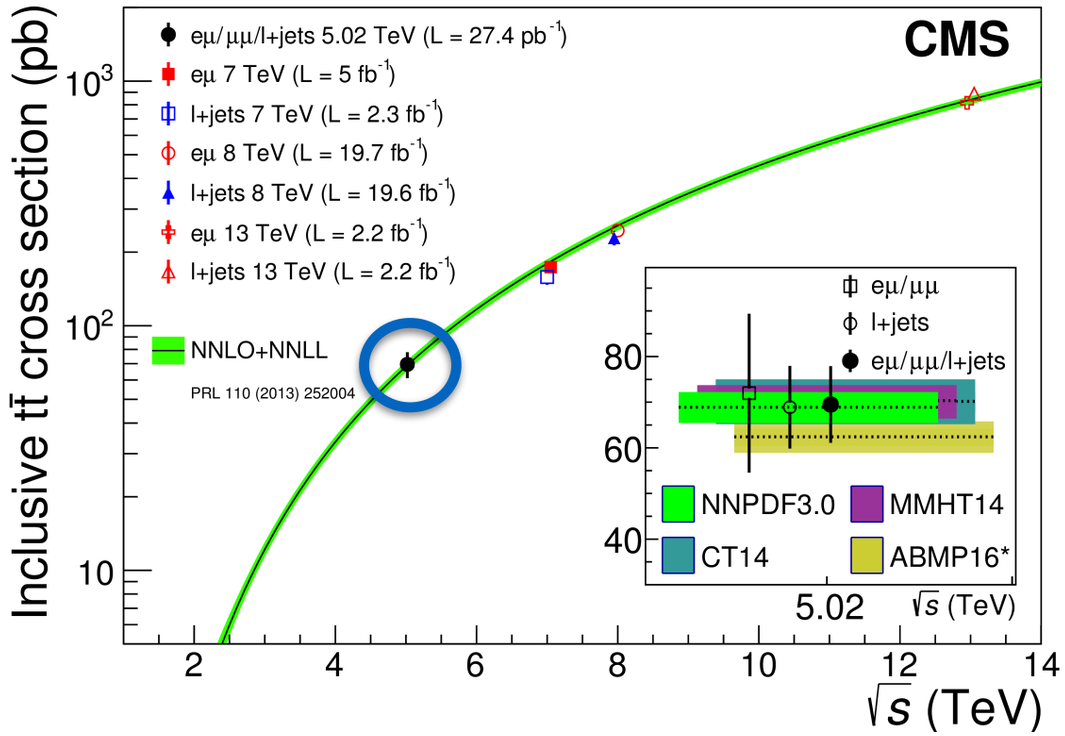


Ratios!

arXiv:1612.03636

tt/Z cross section ratios

power to constrain PDFs

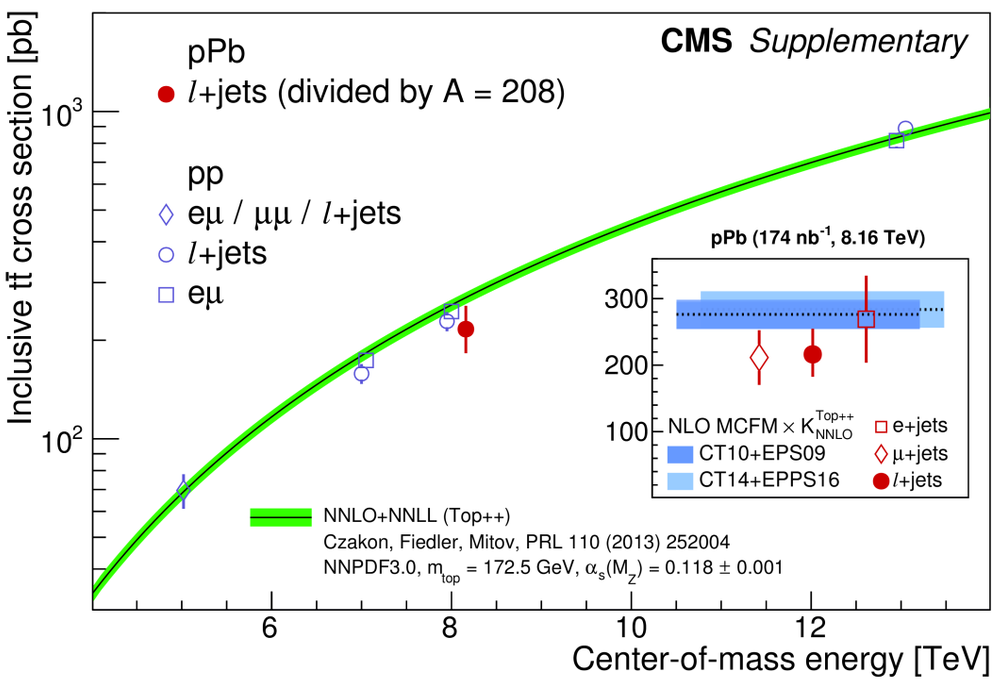


Surprise √s! 5TeV

1711.03143

Δσ/σ≈12%

Also useful to constrain PDFs



Surprise collision type! pPb

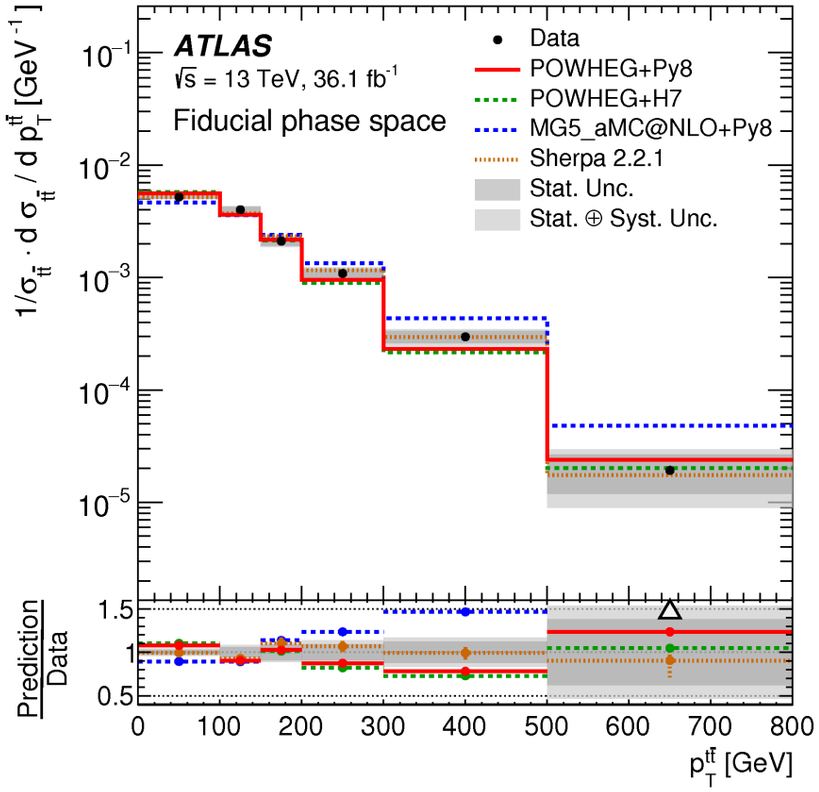
1709.07411

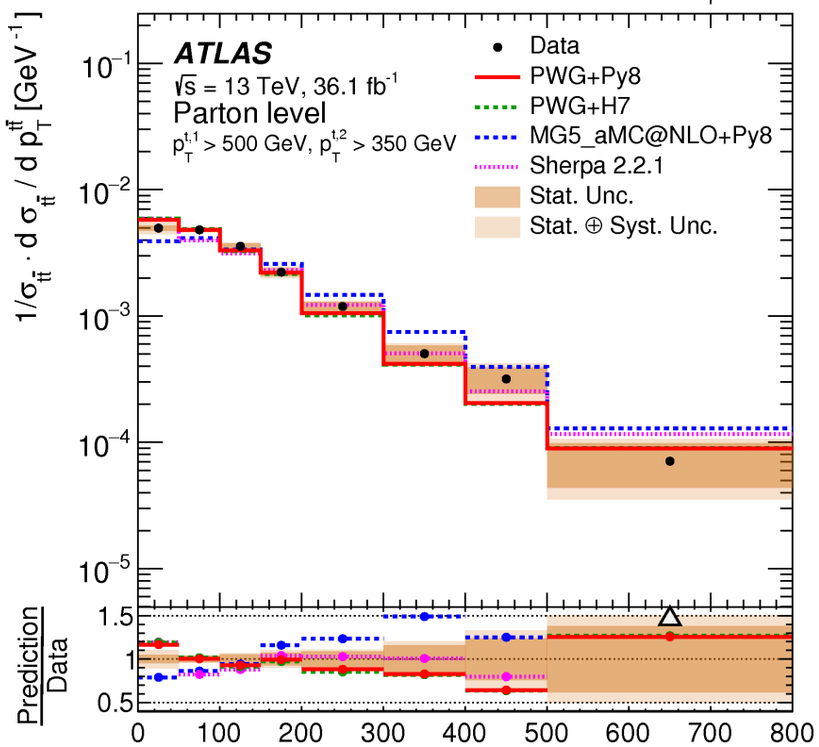
Δσ/σ≈18%

Paves the way for future measurements in Heavy Ions

Differential tt cross sections

- **Interface theory, simulation, and the experiments**
- Allow for comparisons with state-of-the-art predictions
  - MC generators; high order predictions; different matching schemes, scales and tunes
- **Ultimate stress-test of the SM**
  - **Extraction of parameters** (m_t, α_S)
    - Constrains on BSM models, EFT
- Results in every final state, at all levels, covering boosted and resolved regimes
- In general: good agreement with NNLO predictions and NLO generators
  - Discriminating between models and tuning parameters possible



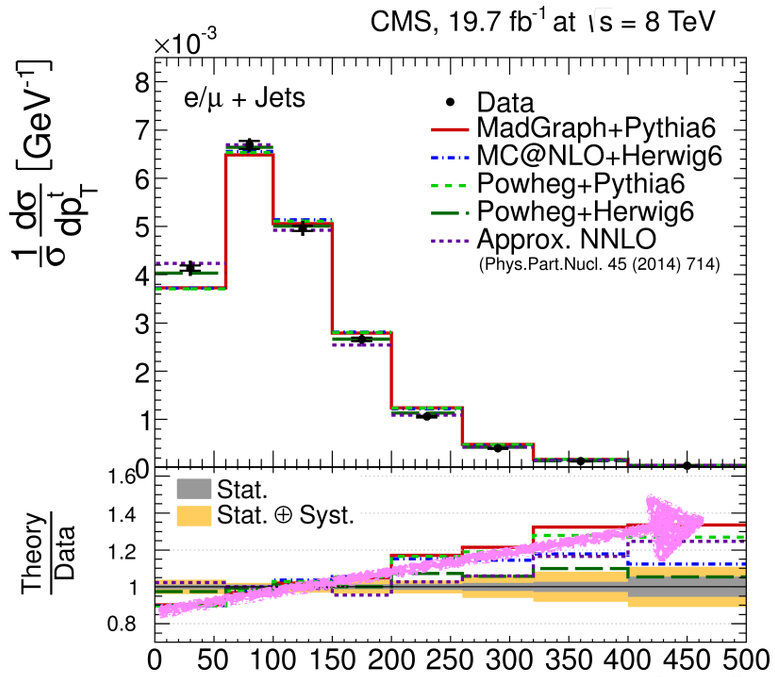


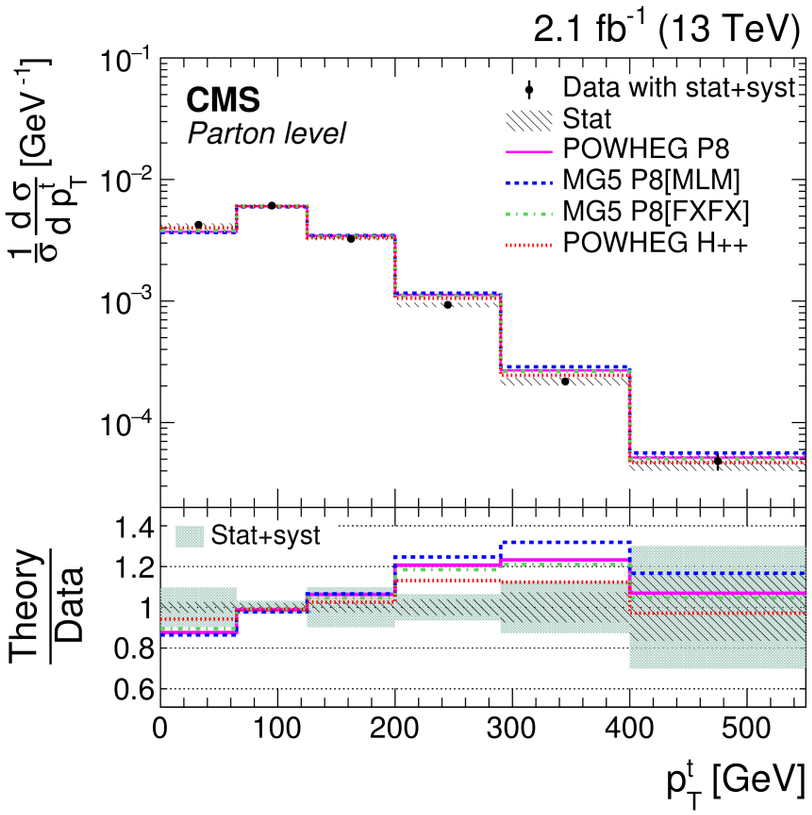
arXiv:1801.02052

boosted, all-hadronic

Differential distributions: top quark p_T

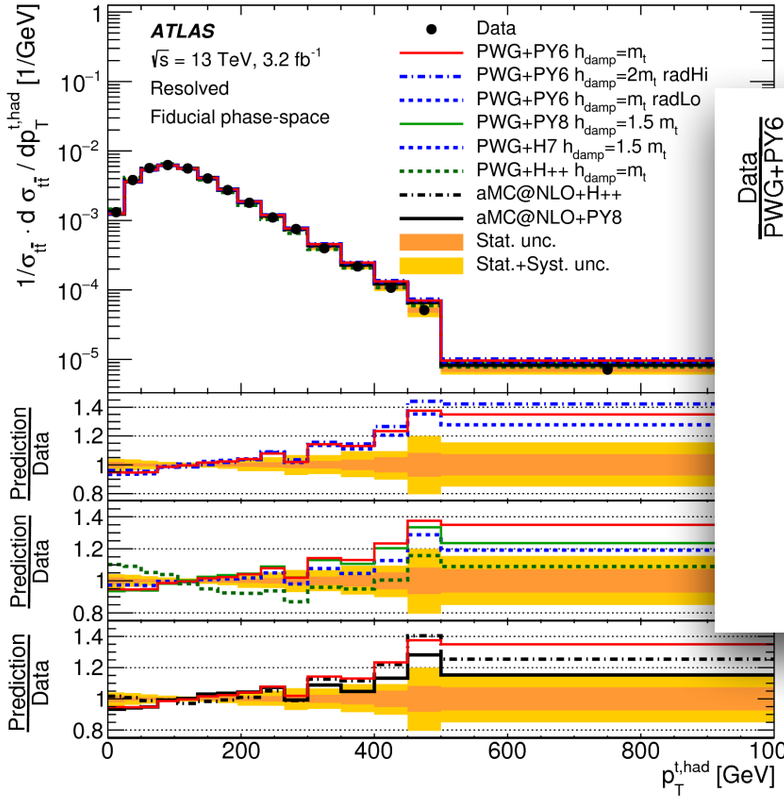
- **The top quark p_T is softer in data than in simulation**
  - Effect observed during Run-1, still present in Run-2
  - Appears clearly in ATLAS and CMS data
- It is improved (not fully fixed!) by higher order (NNLO) calculations
  - *The effect is also smaller in simulation at higher orders (NLO)*





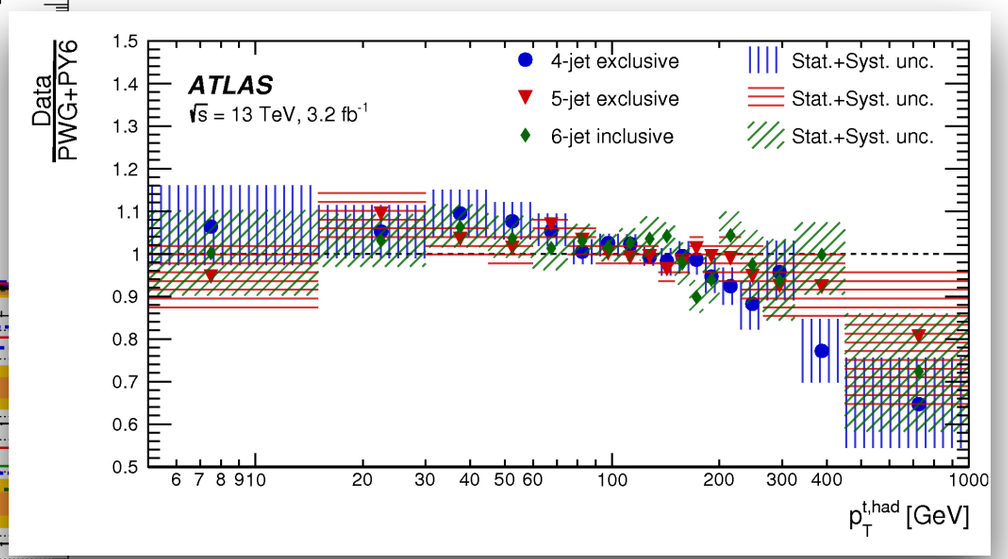
arXiv:1708.07638

dilepton



arXiv:1708.00727

boosted and resolved, l+jets



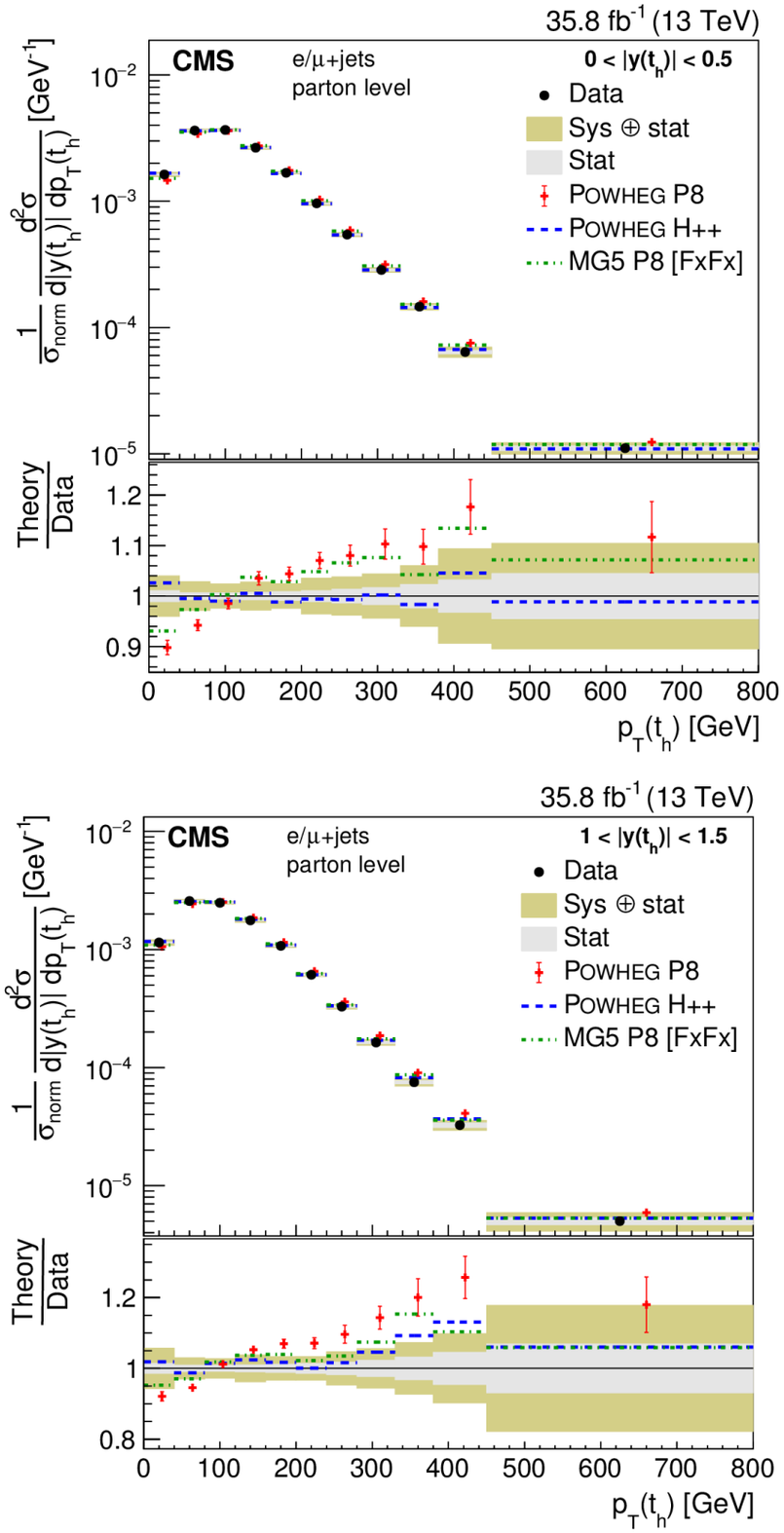
arXiv:1802.06572

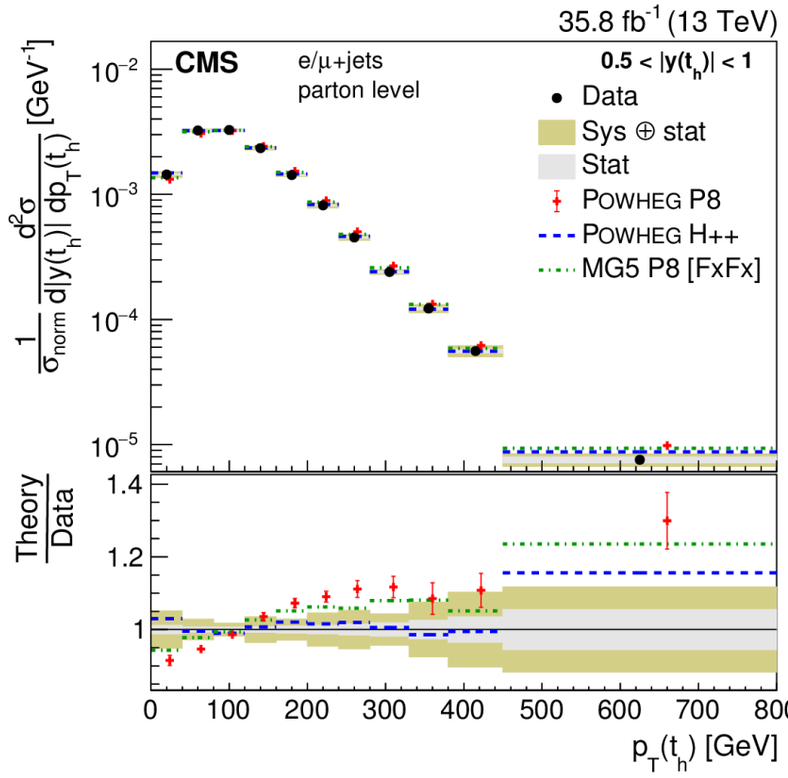
in association with jets

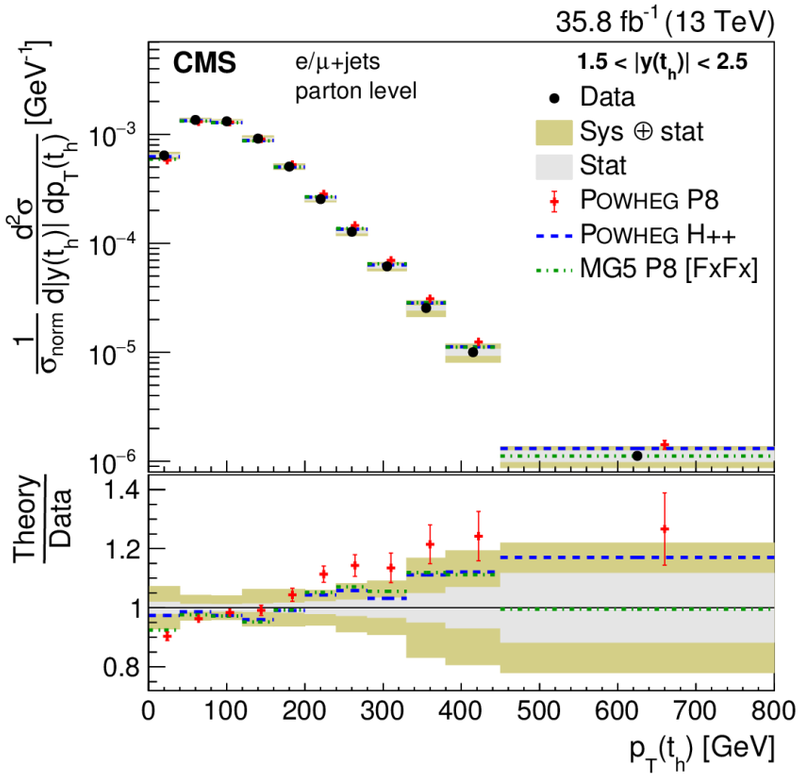
double differential

Multi differential distributions

- Not only to study this effect
- We in fact are in a new differential era
- Bin events not in one variable but in two (or more) variables:
- Better constrains to the MC by disentangling effects
- Better constrains to PDFs



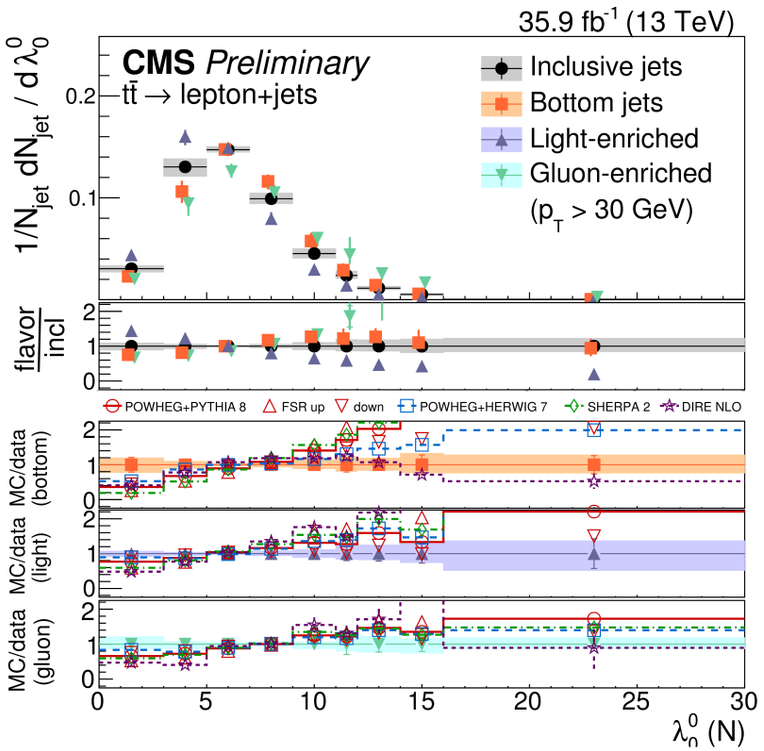


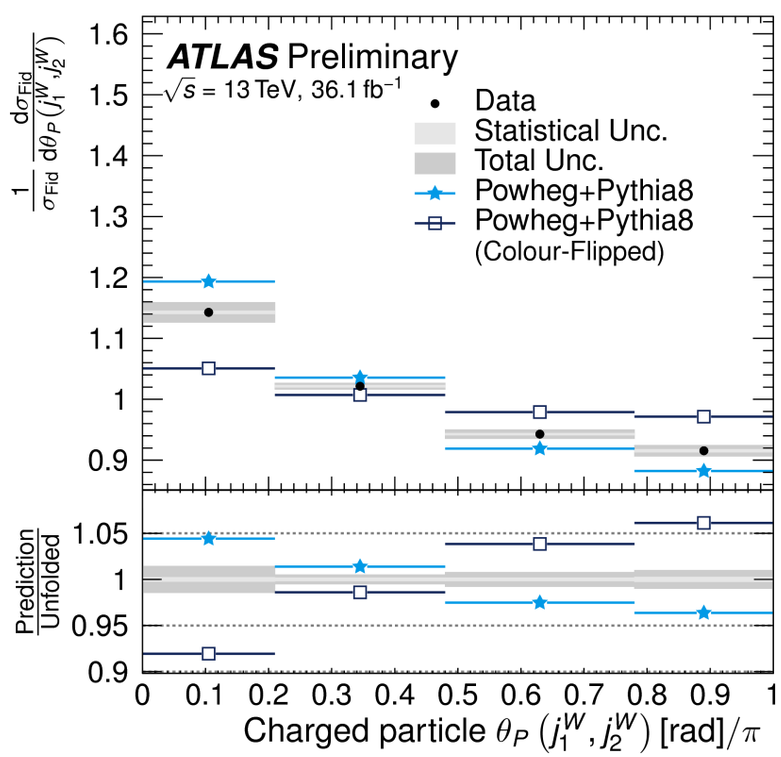


arXiv:1803.08856
l+jets

Studies with charged particles (in or outside jets)

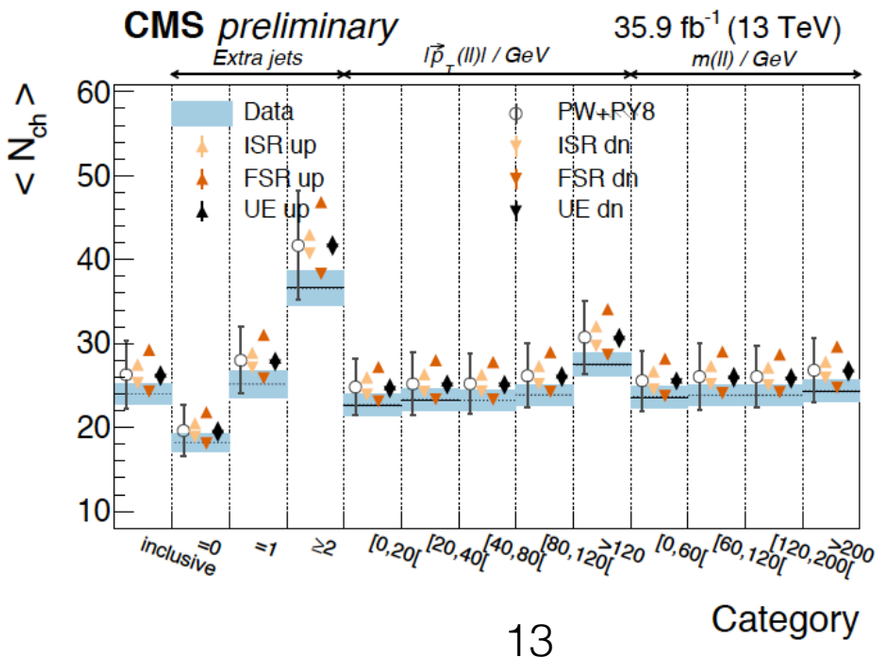
- Recent measurements investigating
  - jet constituents/ **structure variables**
  - multiplicity and kinematic variables of charged-particle tracks from the underlying event
- *tuning of the simulation*
- *sensitive to colour effects, α_S*



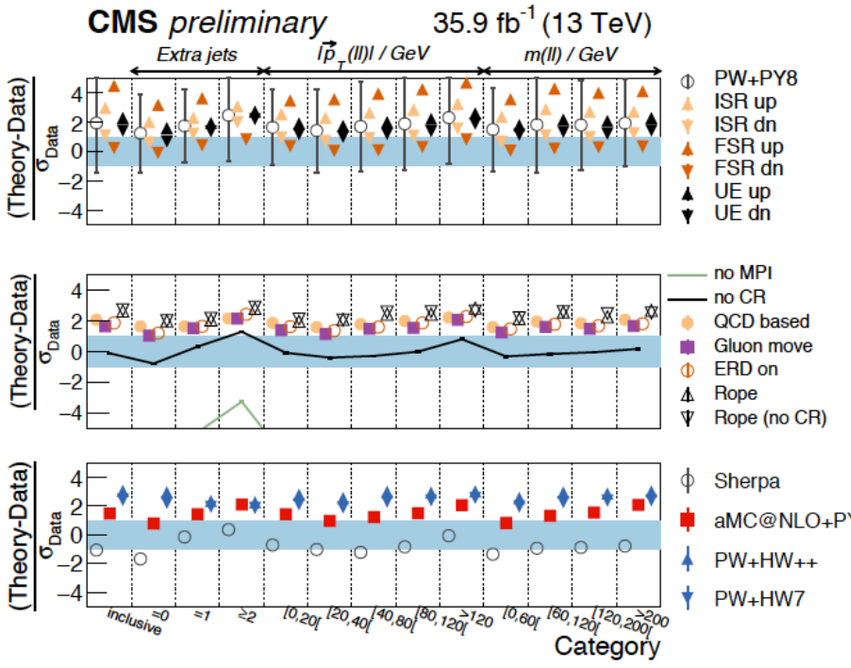


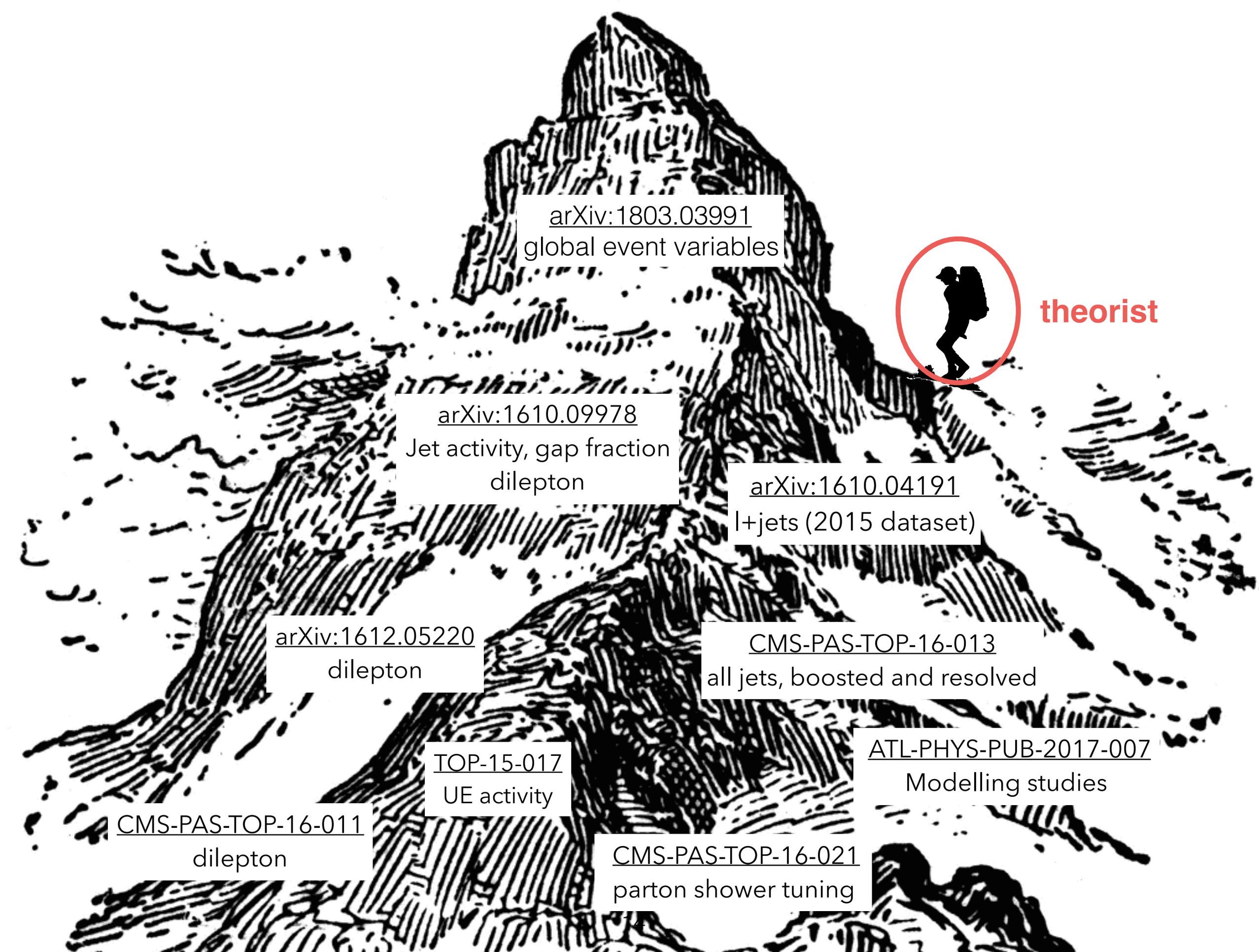
CMS PAS-TOP-17-015
underlying event

CMS PAS-TOP-17-013
jet substructure observables



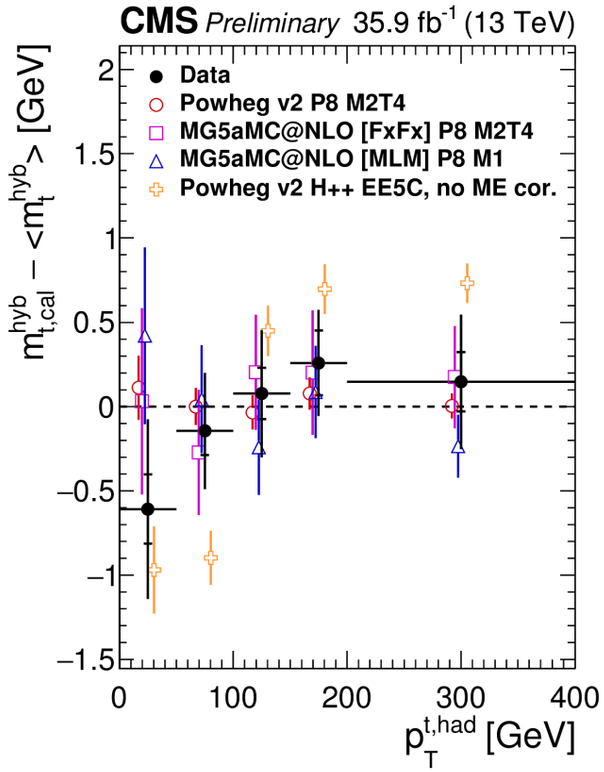
ATLAS-CONF-2017-069
colour flow

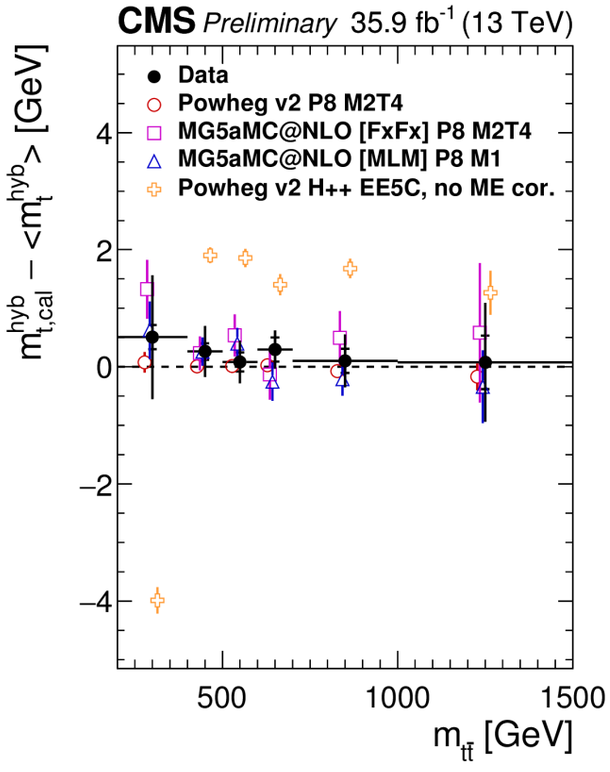


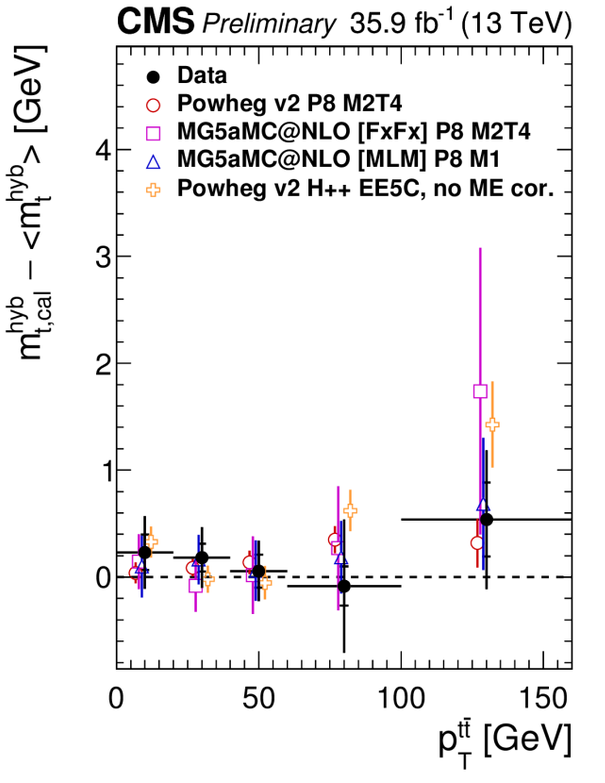

arXiv:1803.03991
global event variables
theorist
arXiv:1610.09978
Jet activity, gap fraction
dilepton
arXiv:1610.04191
l+jets (2015 dataset)
arXiv:1612.05220
dilepton
CMS-PAS-TOP-16-013
all jets, boosted and resolved
TOP-15-017
UE activity
ATL-PHYS-PUB-2017-007
Modelling studies
CMS-PAS-TOP-16-011
dilepton
CMS-PAS-TOP-16-021
parton shower tuning

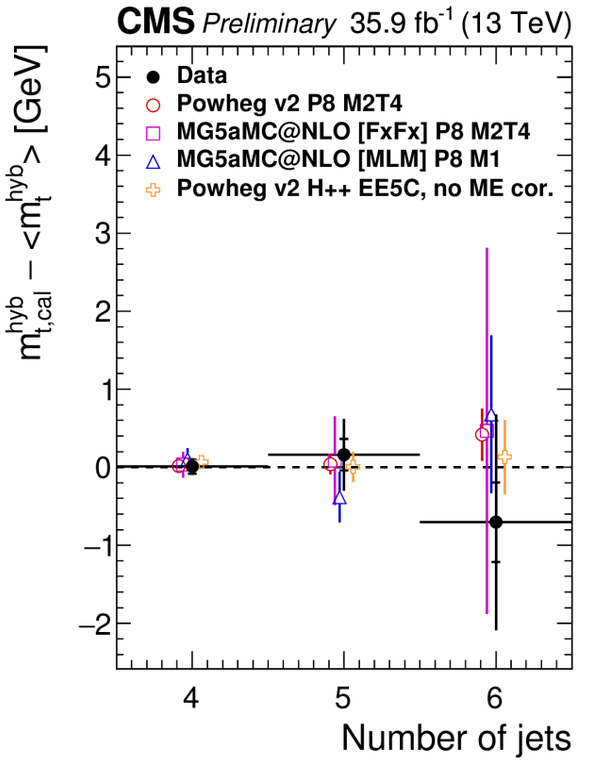
Before you go: differential top quark mass!

- Not many properties results yet, we need to understand the data very well first
  - a first measurement of top width (compatible with the SM)
- Direct measurement of **the top quark mass with 13 TeV data**
  - classic method (most precise value in Run-1)
- The result includes **differential** measurements
- Updated treatment of model uncertainties









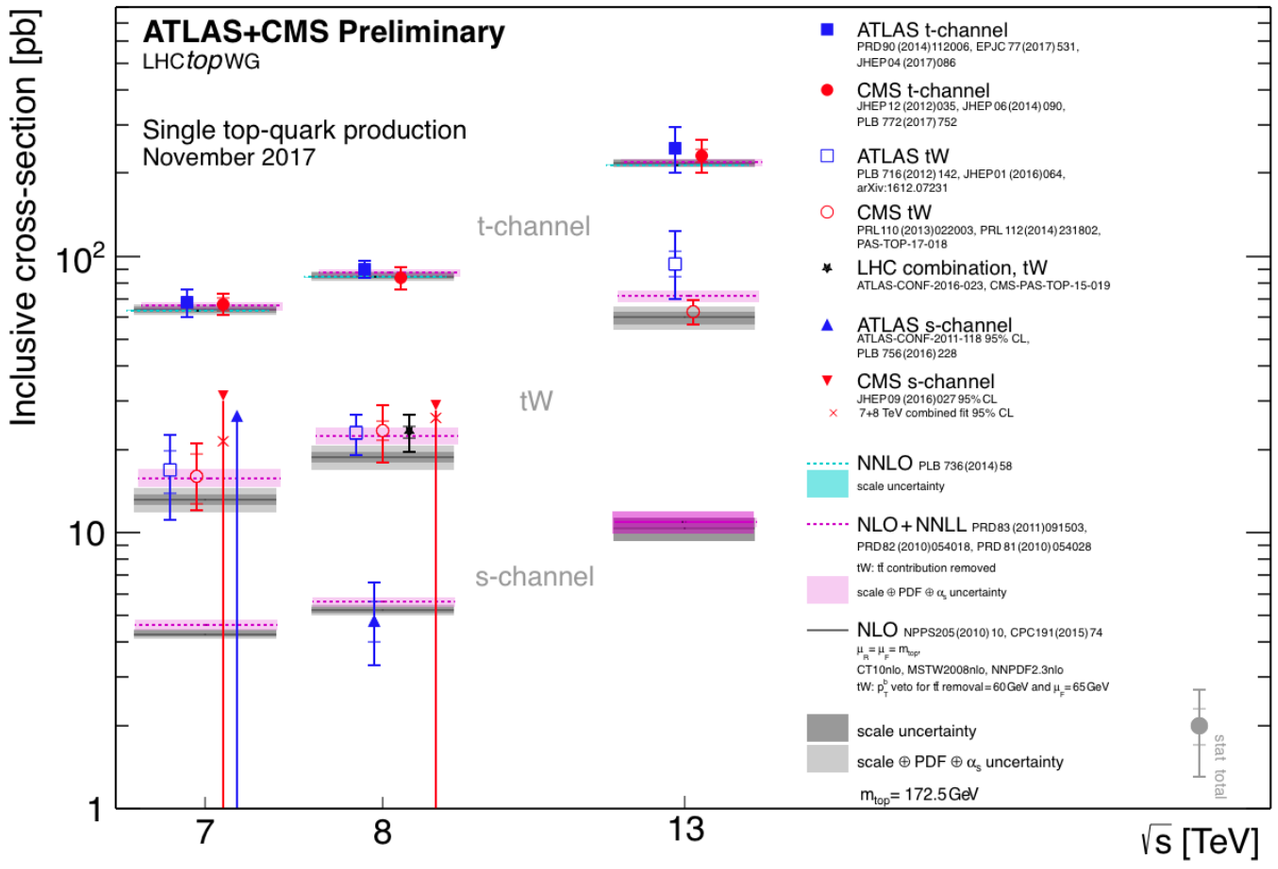
CMS-TOP-17-007

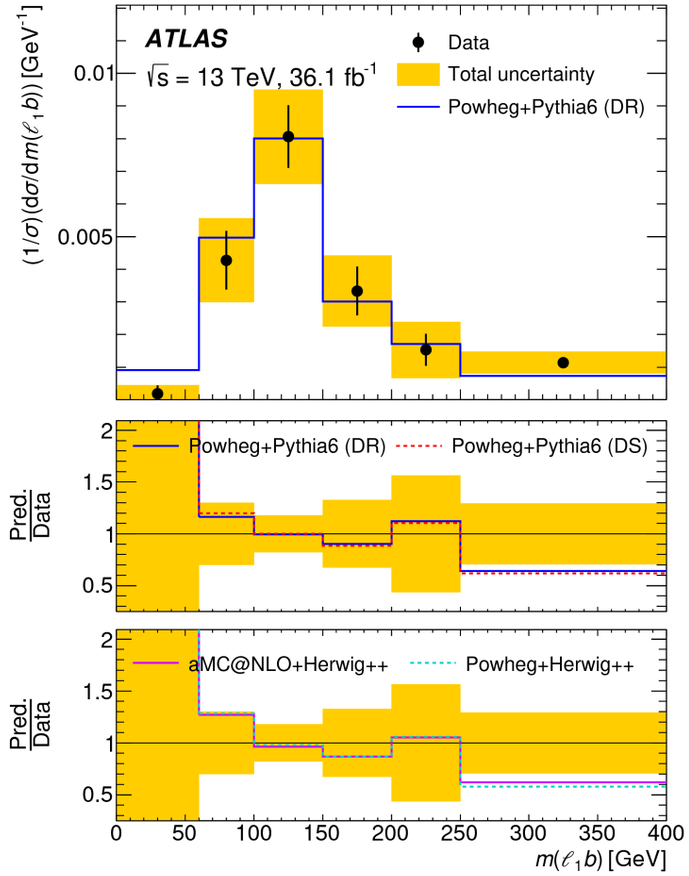
$m_t = 172.25 \pm 0.08\ (stat+JSF) \pm 0.62\ (syst)$ GeV

$(\Delta m_t = 3.6\%)$

Single top quark production

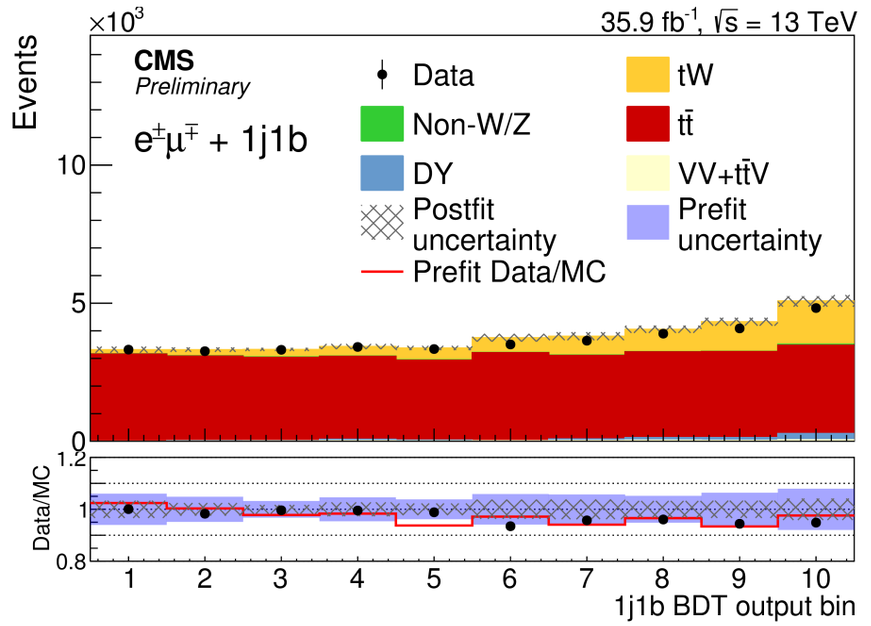
- The study of single top quarks is also well advanced
- t-channel cross section at 13TeV ~ tt cross section at 8TeV
  - Early measurements of t-channel (inclusive, differential)
- **tW entering precision regime** (and the differential world)





arXiv:1712.01602

tW differential



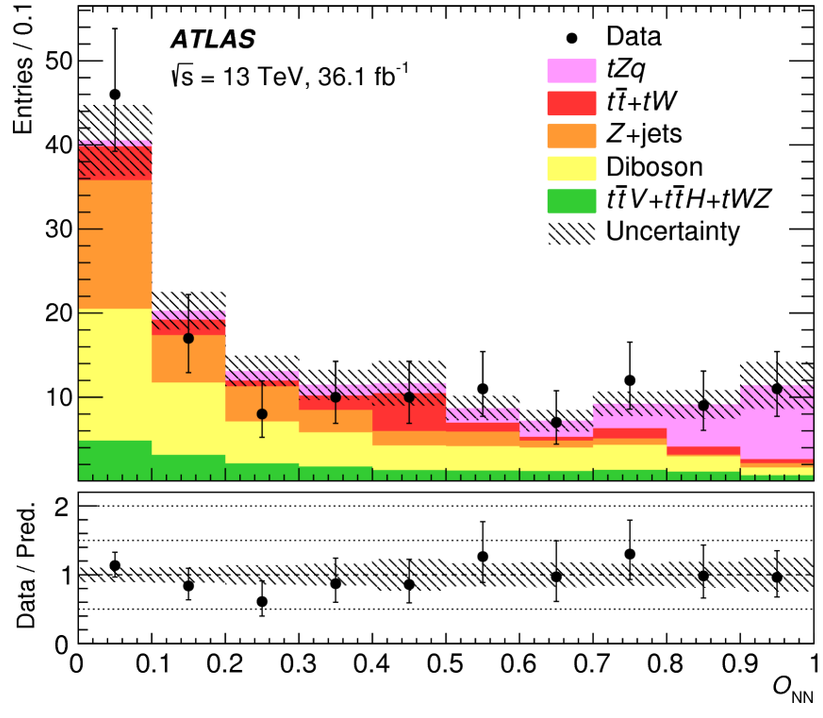
CMS PAS-TOP-17-018

Inclusive, Δσ/σ≈10%

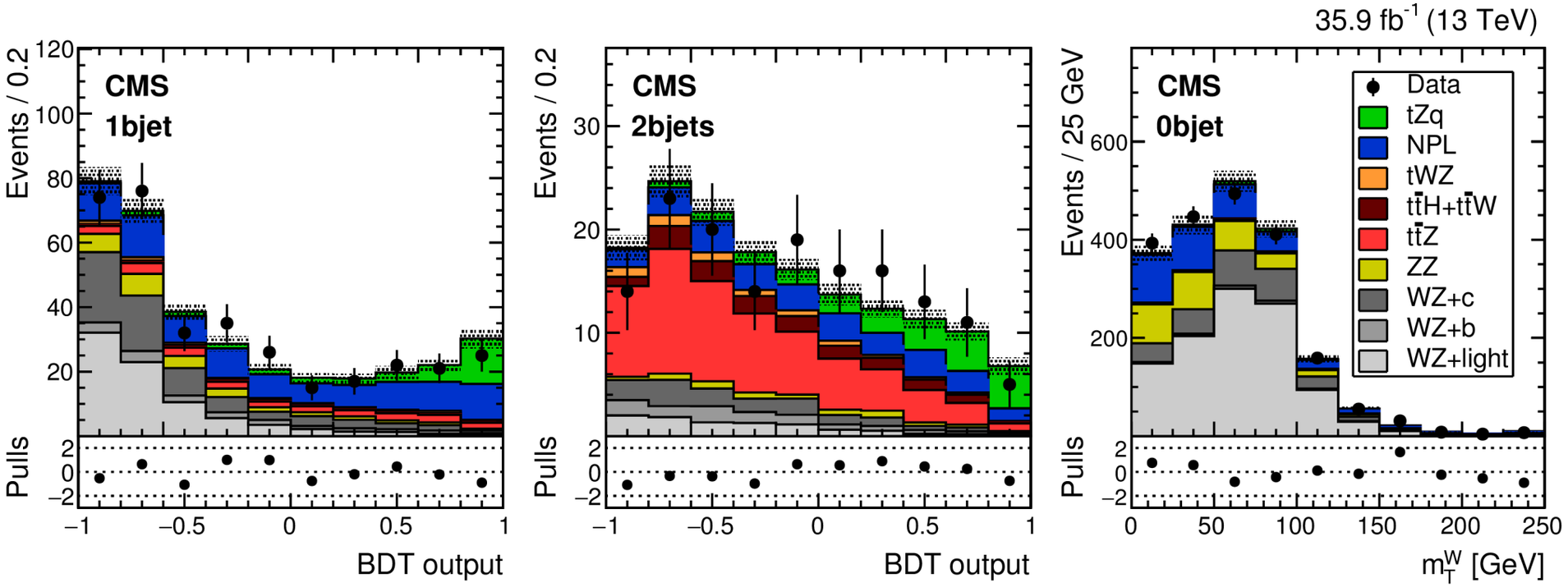
Rare single top at our fingertips

- Single top tZ is a very rare single top process
  - sensitive to the Z coupling and to new physics (FCNC)
- Evidence of the process, close to observation at 13 TeV

arXiv:1710.03659
SM tZq significance **4.2σ** (5.4σ)



arXiv:1712.02825
SM tZq significance **3.7σ** (3.1σ)



tZq FCNC in the same signature: CMS PAS-TOP-17-017, ATLAS-CONF-2017-070
FCNC results in other channels, like: (t→ Hq) arXiv:1712.02399 arXiv:1707.01404

Other rare production processes are becoming mainstream

- tt+V (W/Z), low cross section SM processes, $\sigma_{tt} \sim 10^3\, \sigma_{ttZ}$
  - sensitive to anomalous couplings & BSM effects, ttH background
- Both ttW and ttZ above 5σ each, systematic and statistic uncertainty on the same ballpark
  - **EFT interpretation**

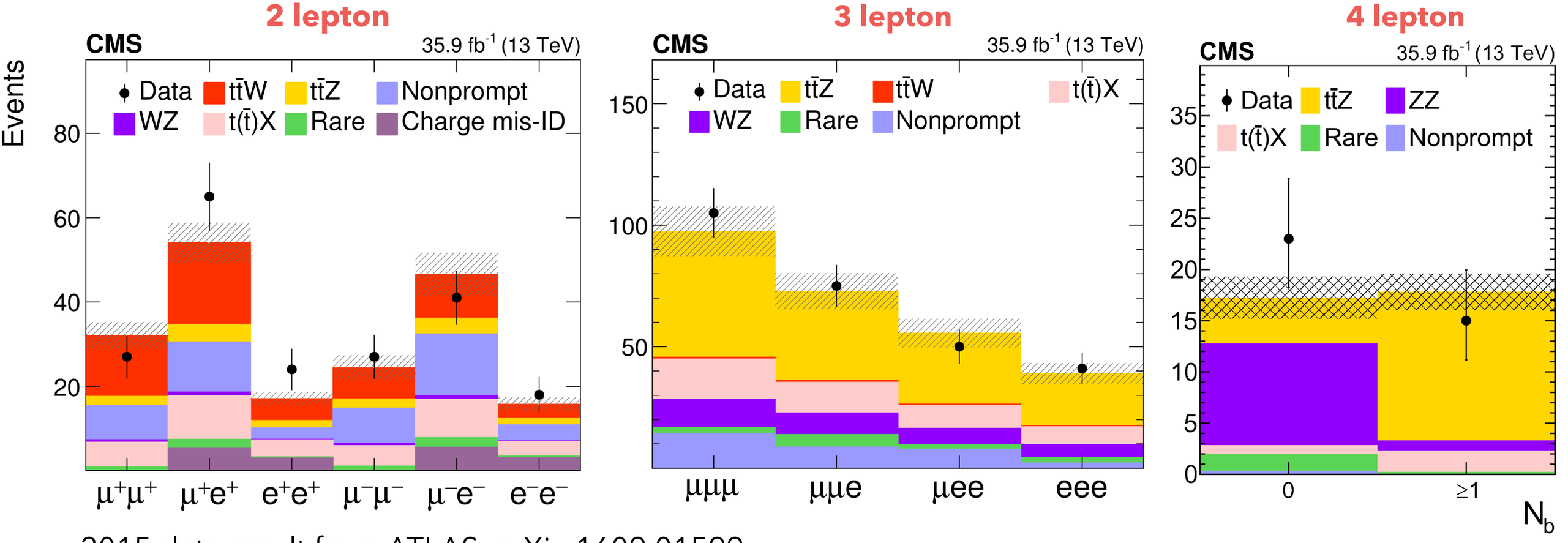
arXiv:1711.02547

σ_{ttZ} = 0.99+0.09-0.08(stat)+0.12-0.10(syst) pb **> 5σ**

σ_{ttW} = 0.77+0.12-0.11(stat)+0.13-0.12(syst) pb **5.3σ**

σ_{ttZ} = 0.839 (±12%) pb

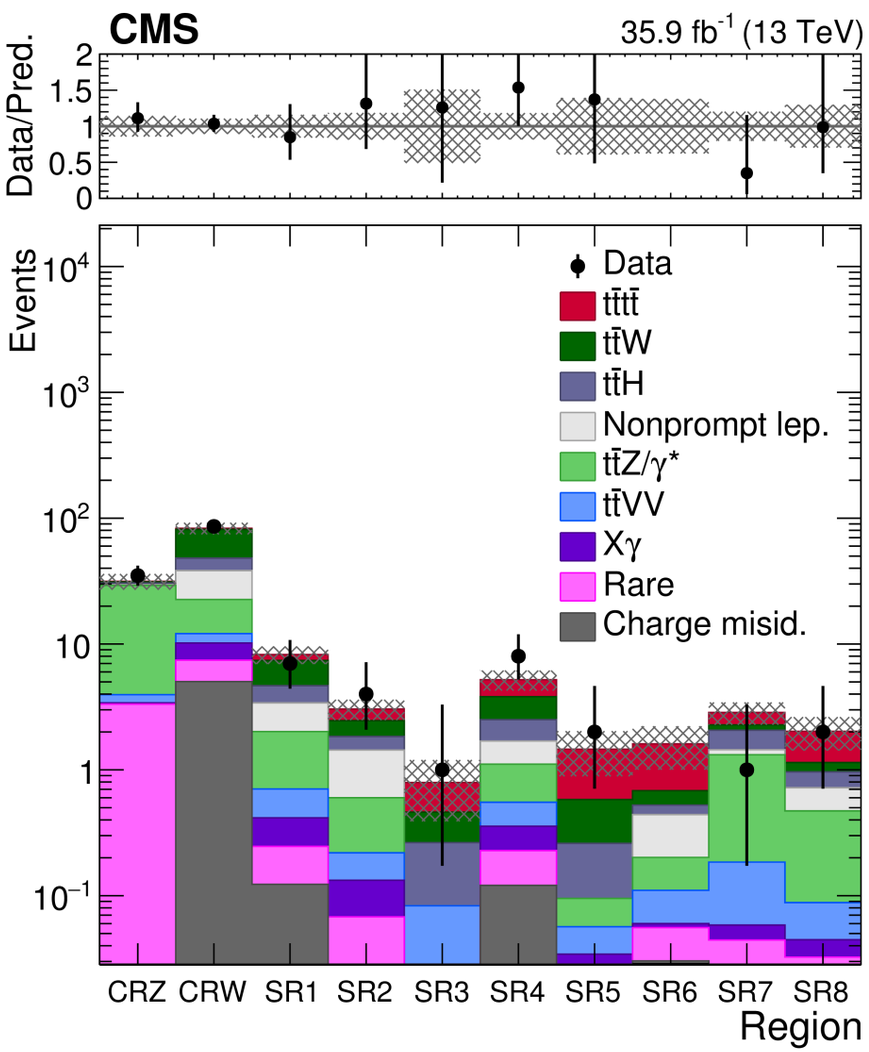
σ_{ttW} = 0.600 (±13%) pb



2015 data result from ATLAS: arXiv:1609.01599

Exciting times ahead

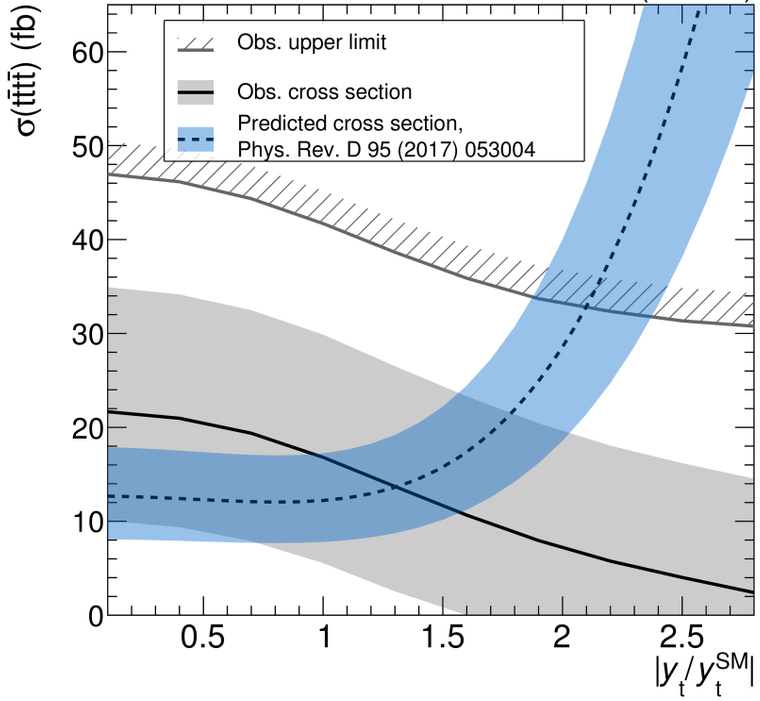
- 4t production is a **VERY** rare production → 5 orders of magnitude less often than tt in the SM
  - Future measurement useful test of analytical higher order calculations
- Before that → **many BSM models predict an increase of the 4t cross section**
  - Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY [...]



arXiv:1710.10614

SM tttt significance **1.6σ**

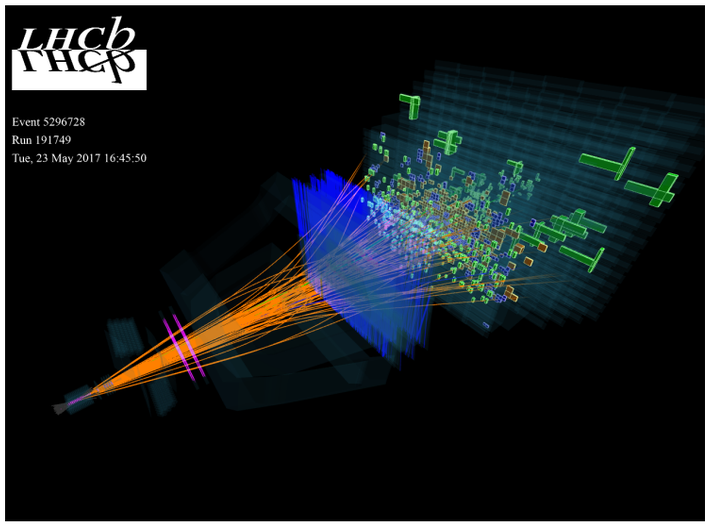
Yukawa coupling < 2.1 xSM at 95%CL

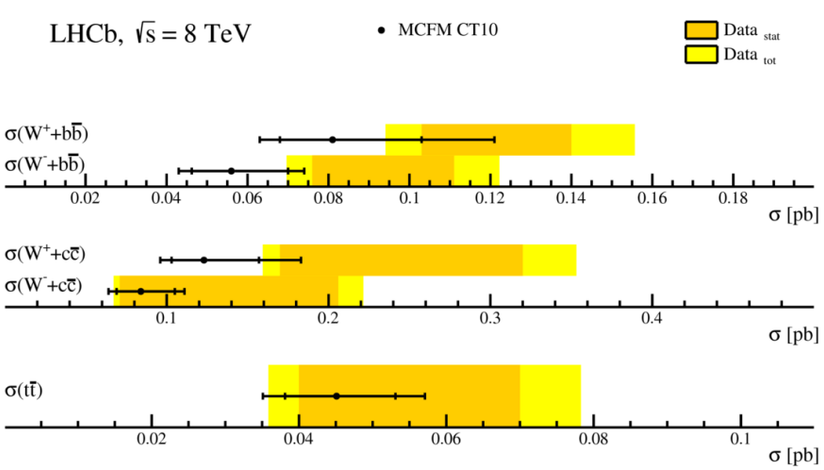


previously at 13TeV arXiv:1702.06164 and ATLAS-CONF-2016-020

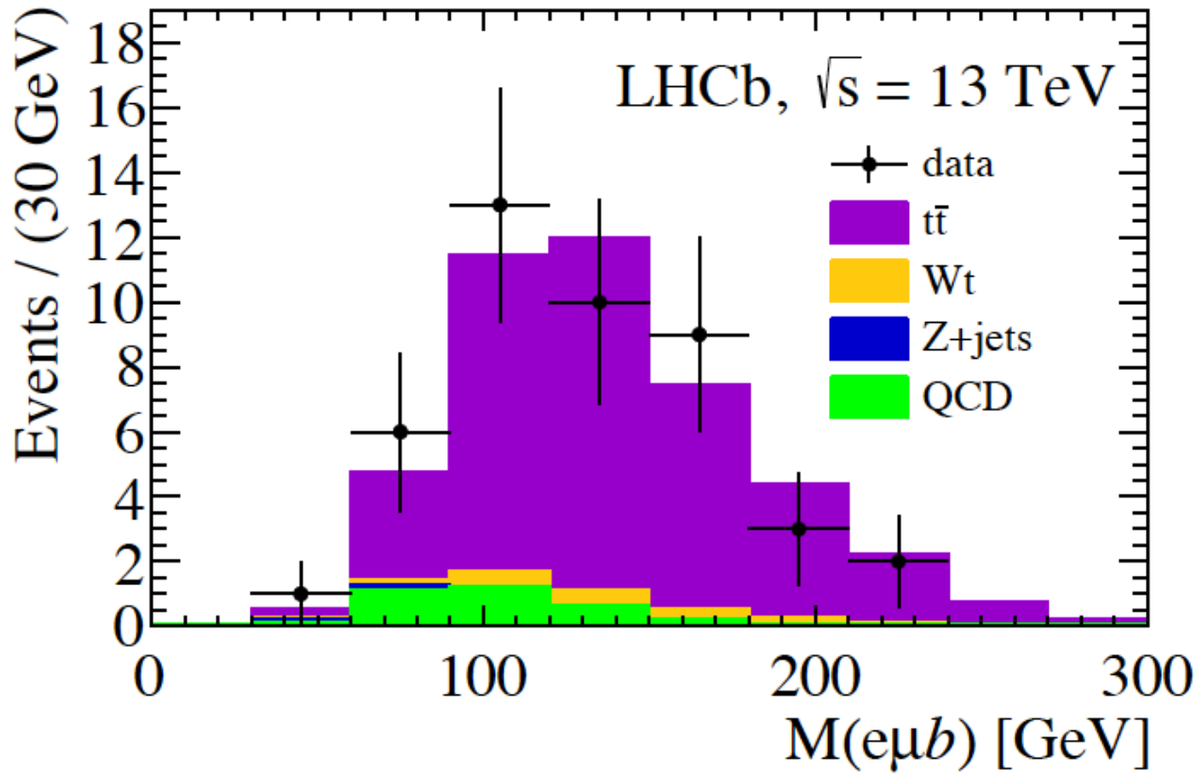
The dawn of a new era

- After a first **observation of top quark production in the forward region in 2015**
  - LHCb has started to seriously **measure** top quark cross sections
  - Very valuable complementary measurements to ATLAS and CMS





arXiv:1610.08142



arXiv:1803.05188

very recent dilepton measurement

$\Delta\sigma/\sigma \approx 20\%$

syst and stat uncertainty on the same order

Summary

- The study of the top quark sector remains an exciting topic at the LHC
- Precision measurements could be the key to unveil the answers to fundamental questions that the SM cannot answer yet
  - The top quark offers a catalogue of those
- After a rich legacy from Run-1, we are about to attack a much larger body of data
  - The Run-2 will be even more prosperous for top quark physics
- Stay tuned to the results from ATLAS, CMS, and now LHCb!
  - You can follow them all at the LHC top working group!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG