Top quark physics summary

Rebeca Gonzalez Suarez
University of Nebraska, Lincoln

A long time ago in a collider far,

far away....

Episode IX

THE LAST QUARK

Having achived evidence for a heavy quark at a mass of 174±10+13−12 GeV/c2, the CDF and D0 collaborations have the top quark at the top of their fingertips.

1995

- The discovery of the top quark was announced during a seminar at Fermilab on March 2

- The CDF and DØ collaborations at the Tevatron had submitted their papers reporting the discovery on February 24:
  - arXiv:9503002, arXiv:9503003

20 years

- It had taken 20 years to find the top quark, following the quark model development in the 1970s

Year	Collider(s)	Coll. particles	Limit on m_t
1984	PETRA (DESY)	e^+e^-	$>$ 23.3 GeV
1990	TRISTAN (KEK)	e^+e^-	$>$ 30.2 GeV
1990	SLC (SLAC), LEP (CERN)	e^+e^-	$>$ 45.8 GeV
1988	Sp$\bar{p}$S (CERN)	$p\bar{p}$	$>$ 45 GeV
1990	Sp$\bar{p}$S (CERN)	$p\bar{p}$	$>$ 69 GeV
1991	Tevatron (Fermilab)	$p\bar{p}$	$>$ 91 GeV
1994	Tevatron (Fermilab)	$p\bar{p}$	$>$ 131 GeV

- The top quark completed the list of fundamental constituents of matter in the SM
- The Tevatron allowed for the study of the top quark to a very large extent
  - D0 Results, CDF results
  - and eventually **shut down in 2011** (though they continued producing results after)
- The LHC started running in 2009, and by 2010 it had achieved pp collisions at 7TeV

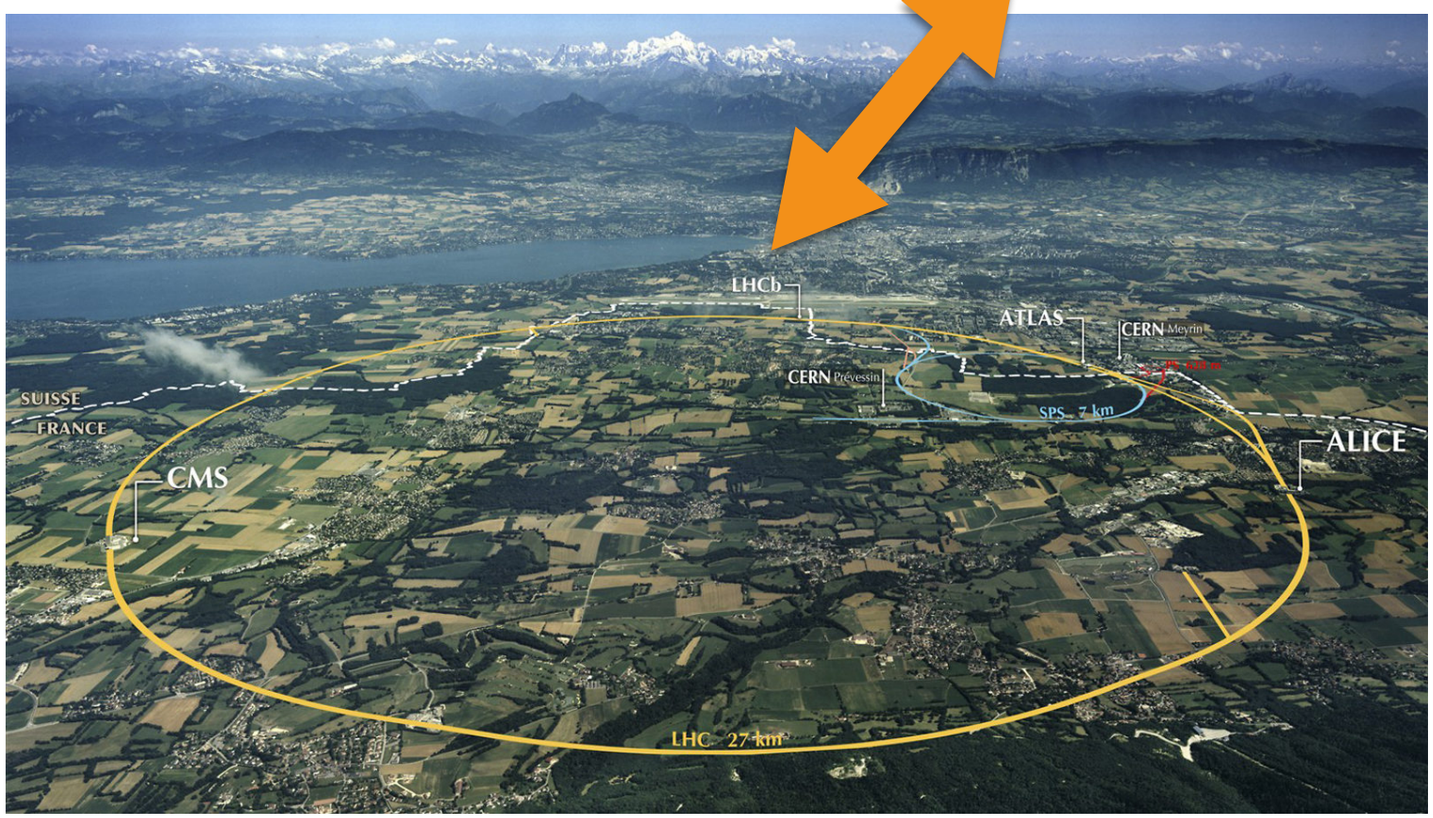
2012

- The 4th of July 2012 in a similar seminar at CERN, the LHC experiments announced the discovery of the Higgs boson: arXiv:1207.7235, arXiv:1207.7214

- Two discoveries with many things in common (such as many authors for example)
- Two particles that are deeply connected, but that is a story for another time
  - and you have heard it already

So, does this mean that…

… the top quark era ended with the Tevatron and the Higgs boson is **the** LHC particle?

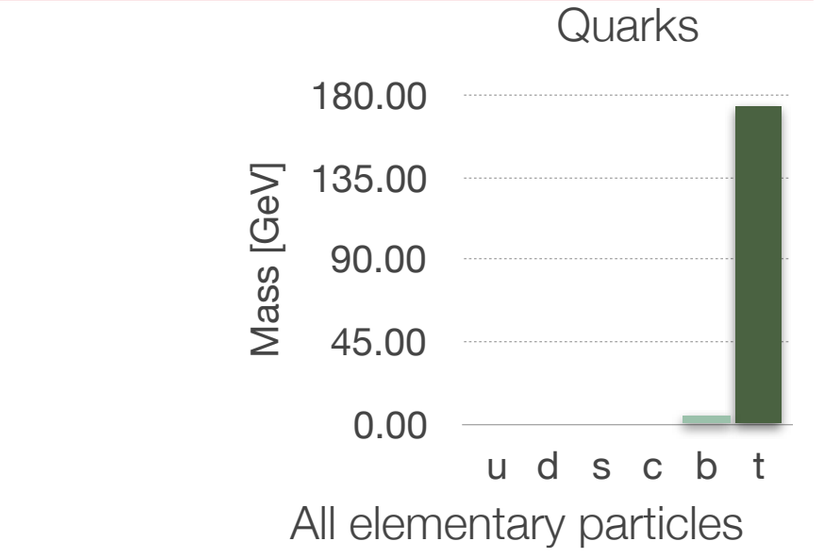


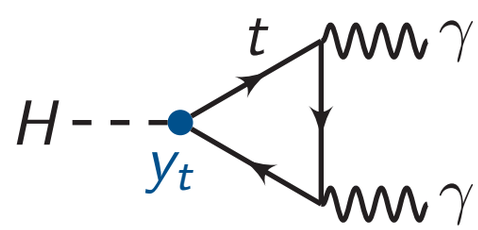
In way yes, but

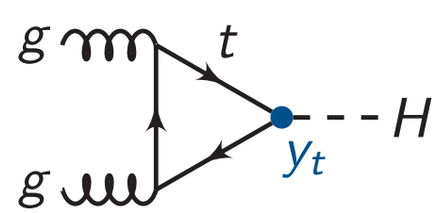
I’m not going anywhere

Not your average quark

- The top quark is ❄️**special**🦄🌈
- It is **very heavy** → heaviest elementary particle found **so far**
  - almost as heavy as a gold atom
    - *79 protons, 118 neutrons, and 79 electrons*
- and because of that
  - it is **short lived**
    - Decays before it has the time to hadronize
    - Does not form bound states → no toponium
    - Some properties pass directly to the decay products
  - **Couples strongly to Higgs**
    - Impact on the Higgs sector

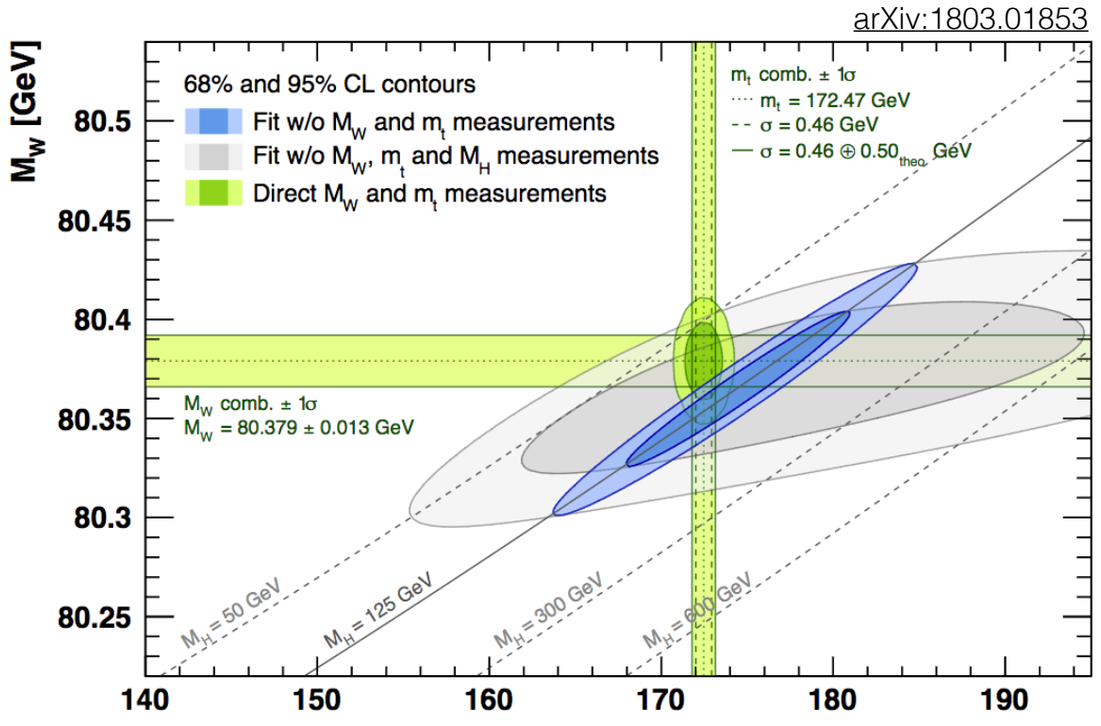




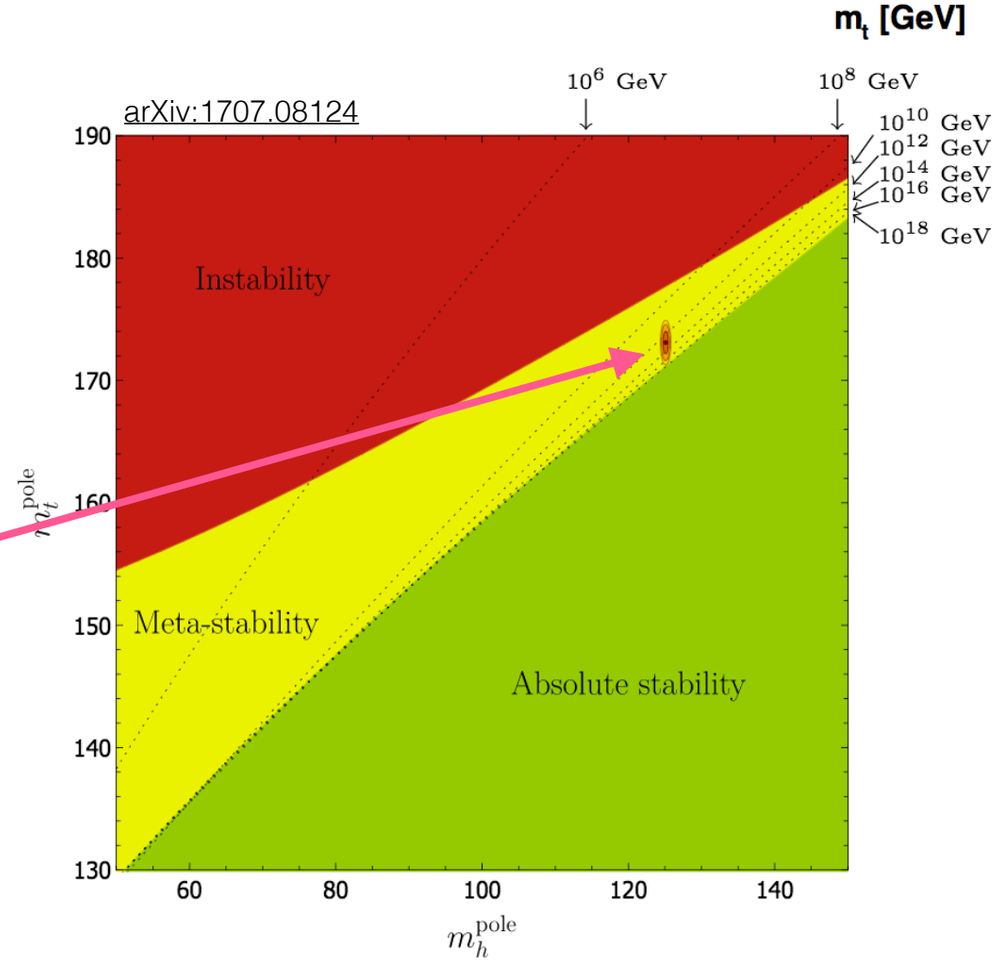


Every (top) precision measurement is a search

- The measurement of top properties is a test of the SM
  - The **top mass** is a **fundamental property**
    - Essential for probing the SM consistency via precision electroweak fits



- Plays a role on the stability of the **electroweak vacuum of the Universe**

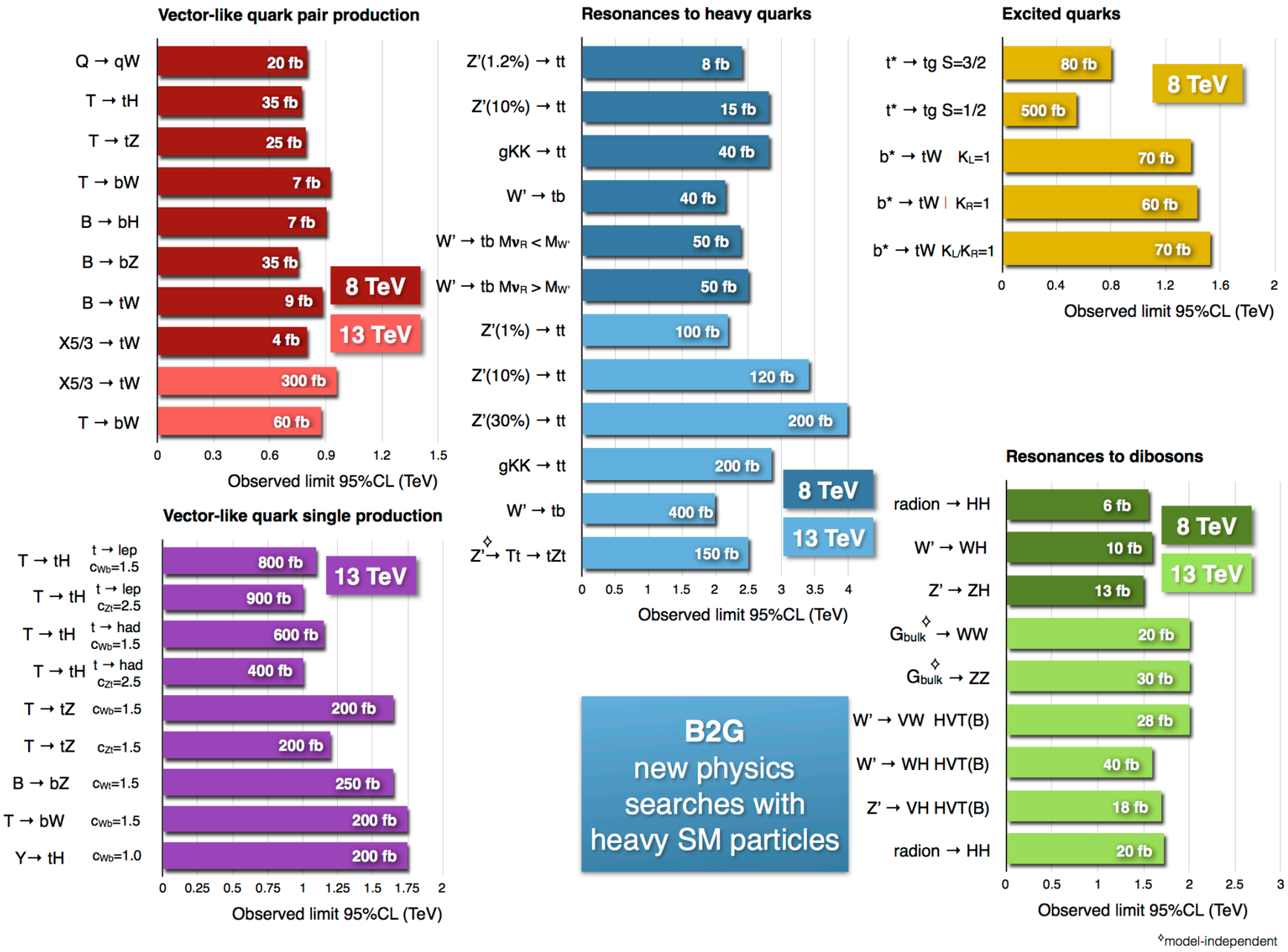


You are here

(current world average)

And there are many searches with top

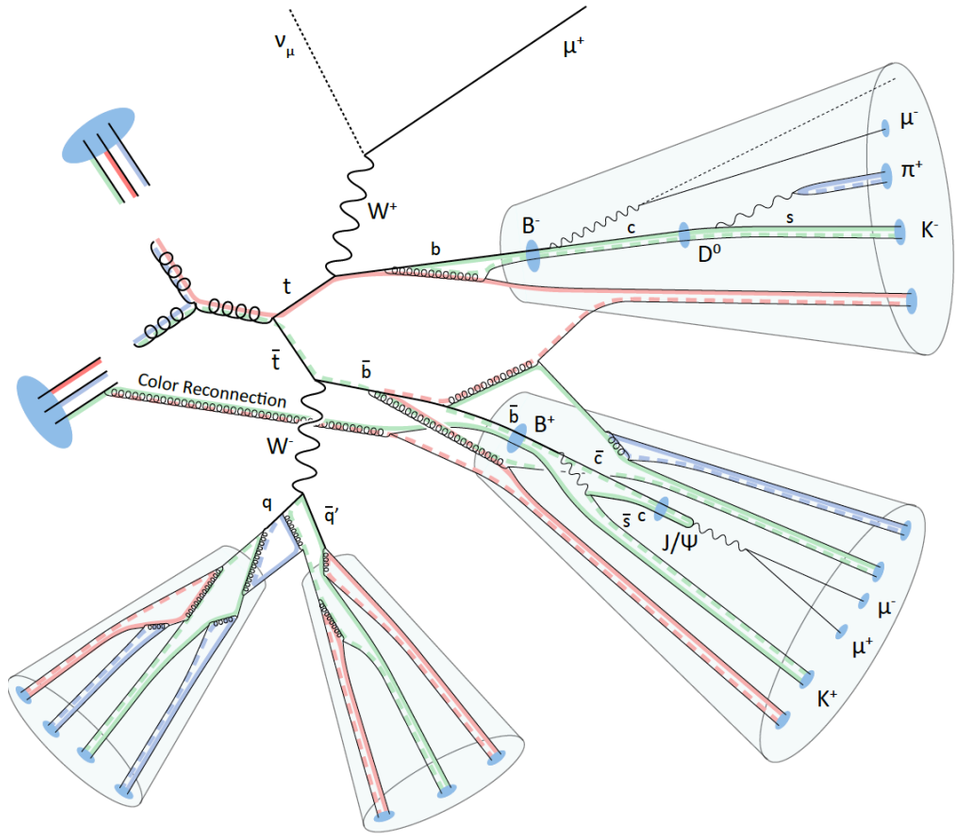
- The top quark is a main ingredient of many **new physics scenarios**
  - Exotic partners, rare decays, heavy new particles decaying to top, new particles produced together with top…



Top signatures are rich

- The top quark is 🎊fun*!💃 (*experimentally)
  - top decays as t→Wb, almost 100% of the times
    - W then decays either to lν or qq

- Whenever a top quark is produced, we'll have
  - Jets coming from b-decays that we need to "tag"
    - **b-tagging**: very important for top
      - Room for creativity: several algorithms

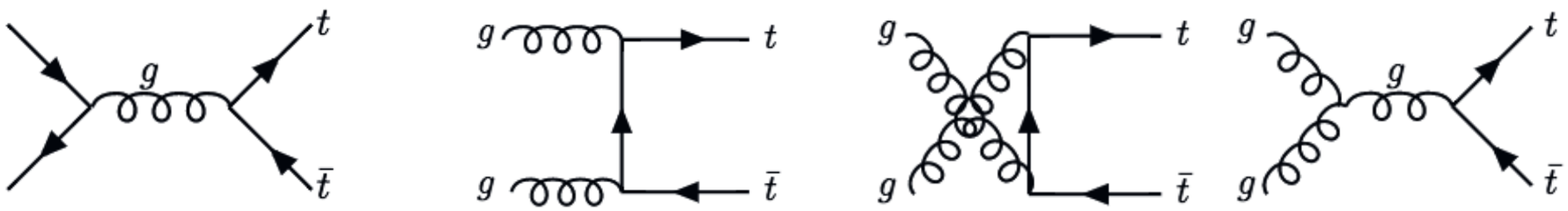


- And either:
  - Isolated leptons
  - Neutrinos → invisible, inferred from missing transverse energy (MET)
- AND/OR
  - jets coming from lighter quarks

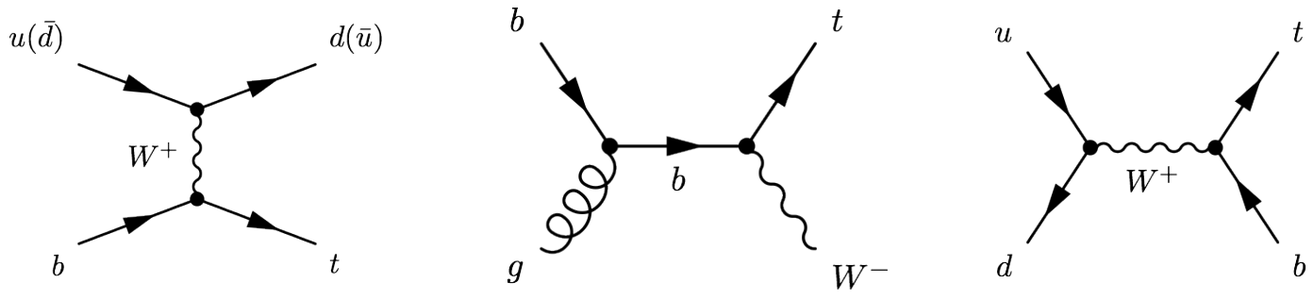
Using the full potential of the LHC experiments

Top is EVERYWHERE

- But no matter if you like it or not: It is **unavoidable** at the LHC
  - Produced at a very high rate, mainly **via strong interaction** in **ttbar pairs**



  - and at a lower rate via **EWK interaction: single top quark** production
    - Three main modes: t-channel, tW associated production, and s-channel

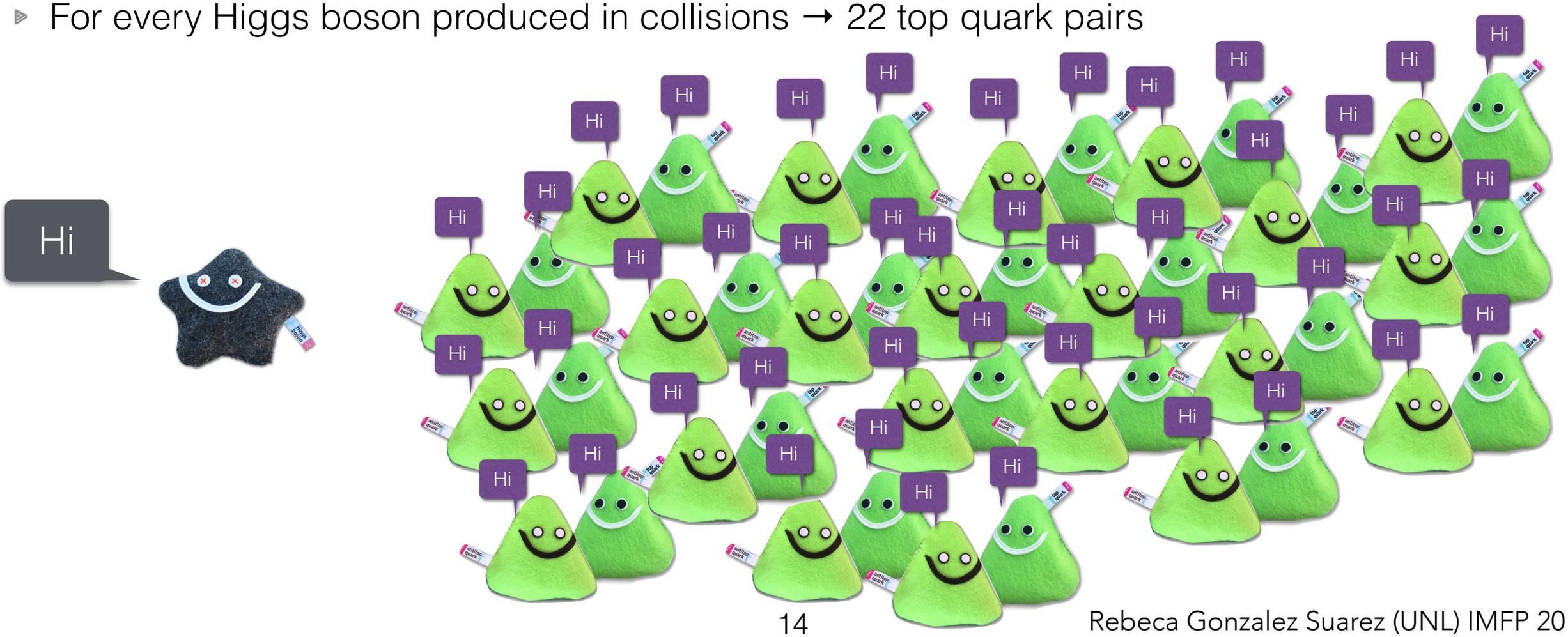


- Then there are many other modes of production:
  - (t)t+X (X= W, Z, γ, H, bb, tt, …)
- **Top is background of virtually everything at the LHC → we need to know it well!**

A certified top quark factory

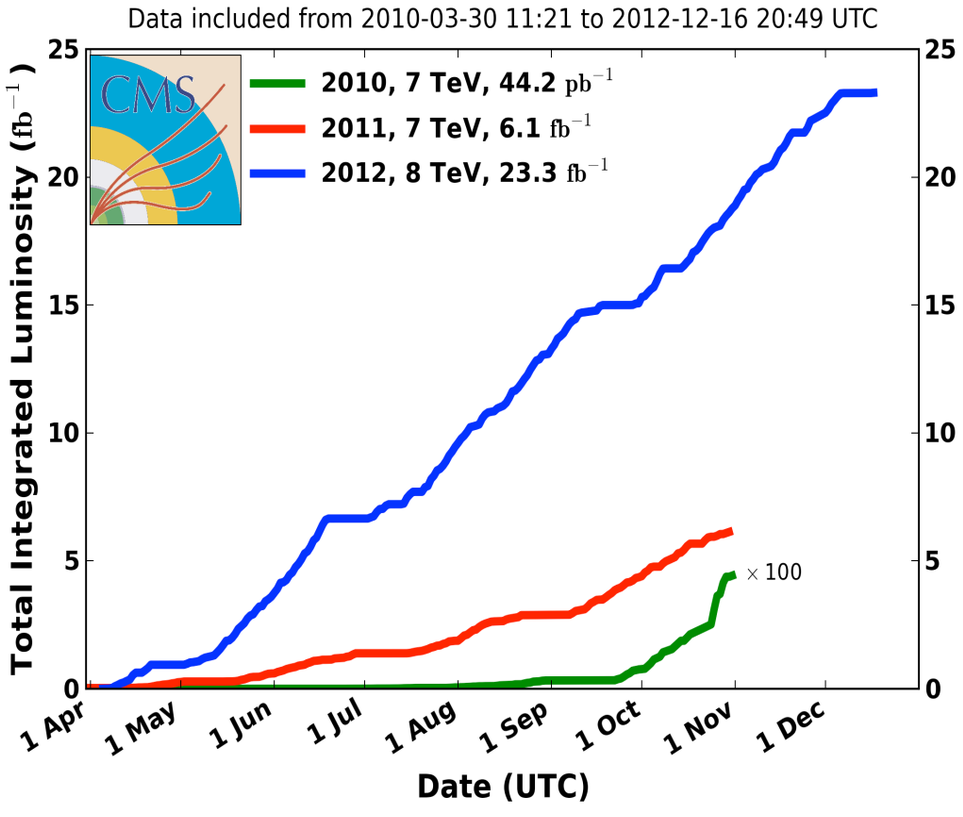
σ [pb]	ttbar	t-channel	tW	s-channel	ggH
Tevatron	7.0	2.08	0.22	1.046	-
LHC @ 7TeV	177.3	63.89	15.74	4.29	15.31
LHC @ 8TeV	252.8	84.69	22.2	5.24	19.47
LHC @ 13 TeV	831.7	216.99	71.2	10.32	44.14

- 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



LHC Run-1

- During the **Run-1** (2010-2012) the LHC delivered **~5fb^{-1}** of pp collisions at 7TeV and **~20fb^{-1}** of pp collisions at 8TeV



- More the 5M ttbar pairs
- About 2M single top t-channel events
- 0.5M of tW events
- more than 100K s-channel events
- *To compare with ~0.5M of Higgs events*

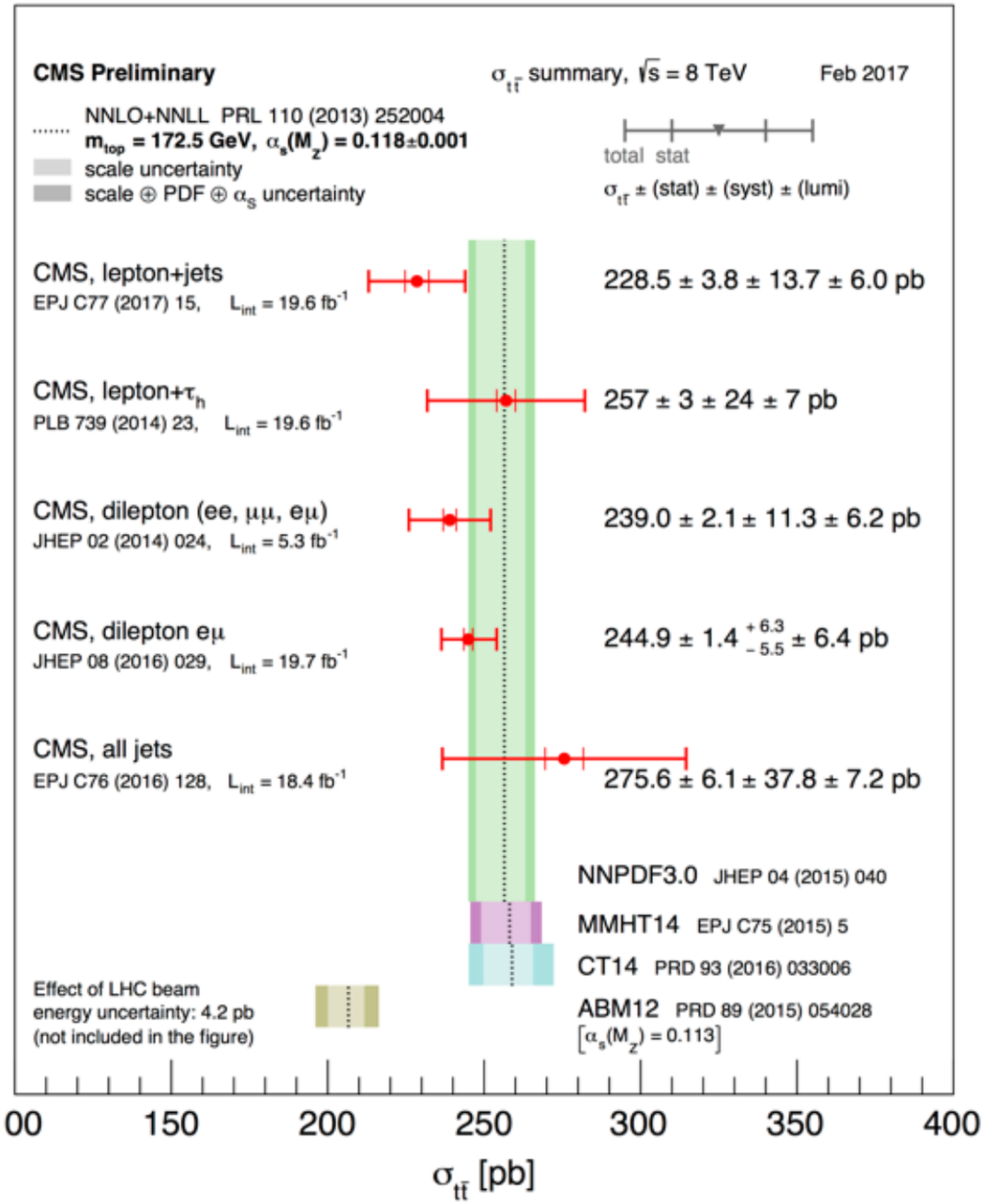
Enough to establish a **very healthy top Run-1 Legacy**

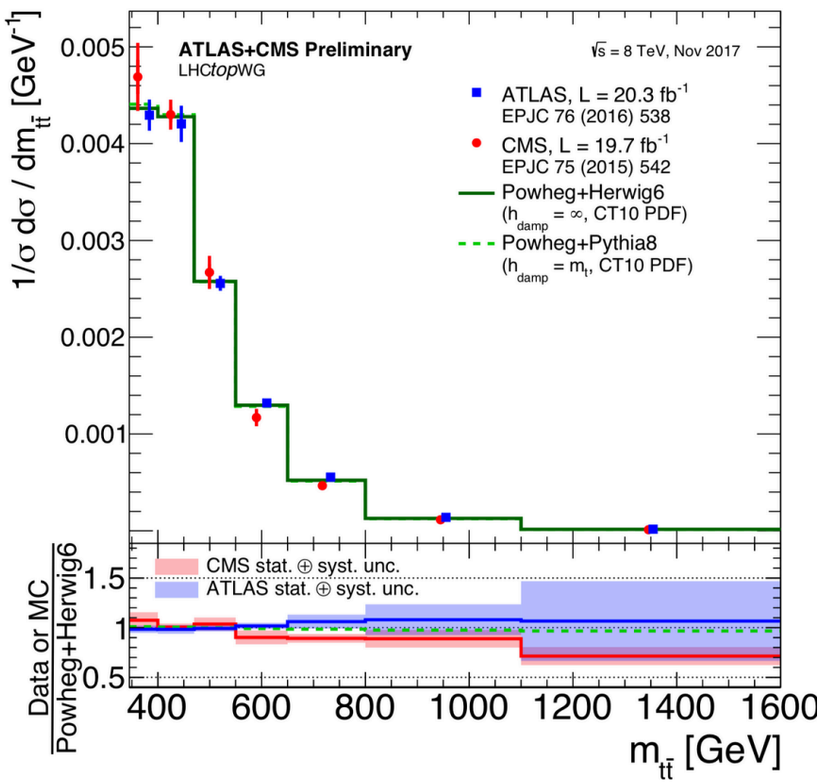
With a good number of ATLAS+CMS combinations (and even a world combination!)

The Run-1 Legacy (so far)

The Run-1 legacy

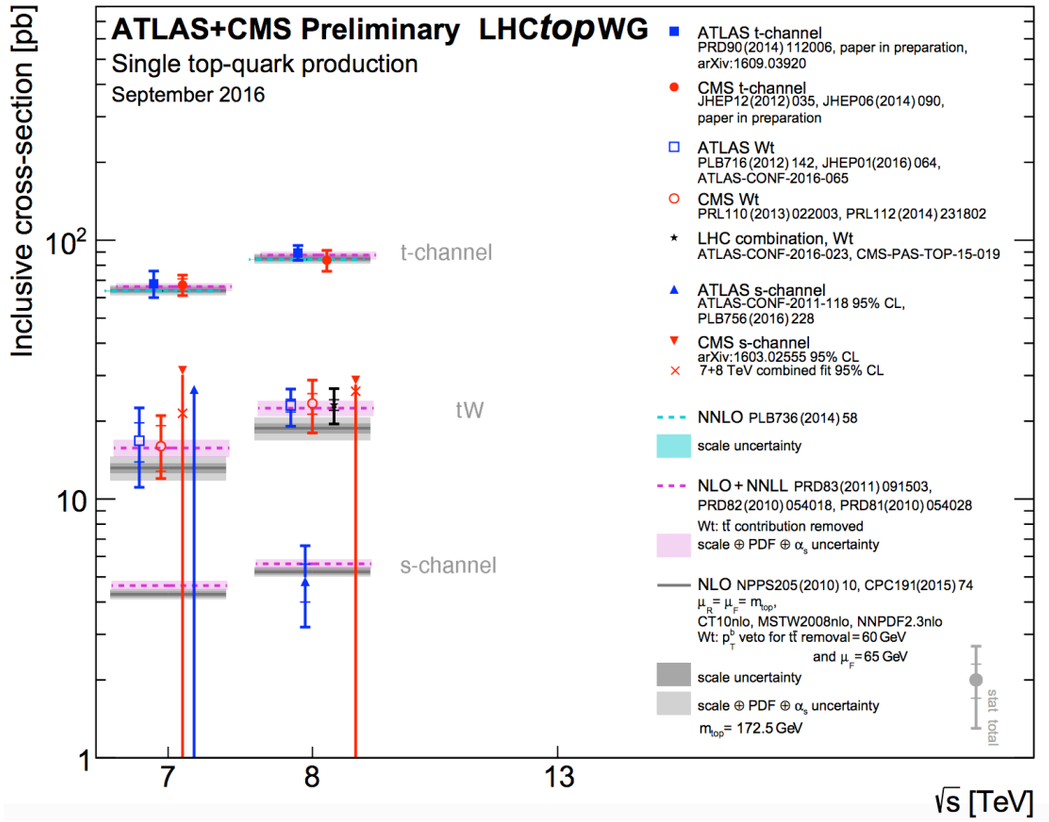
- **Production** rate of **top quark pairs**
  - **Inclusive:**
    - All channels, very high precision (≈3.5%)
    - all compatible with theory predictions at high orders (NNLO)
  - **Differential:** as a function of specific variables
    - all channels, at different levels, in different regimes of the phase space

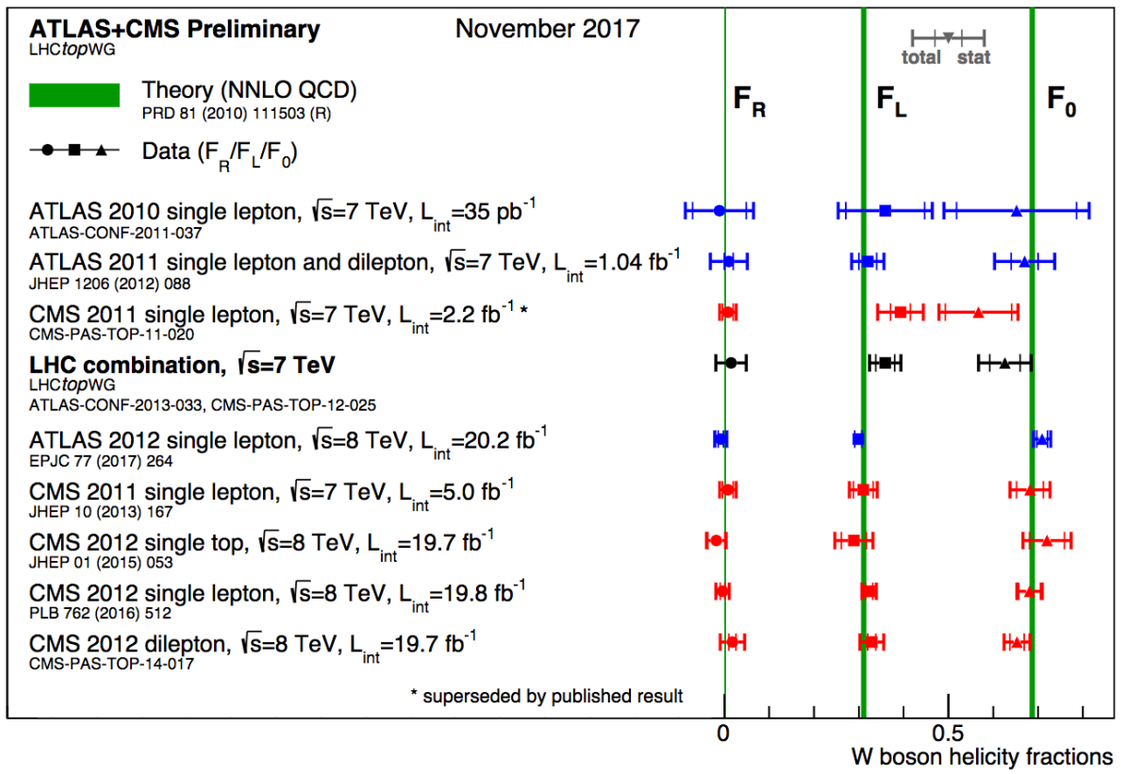


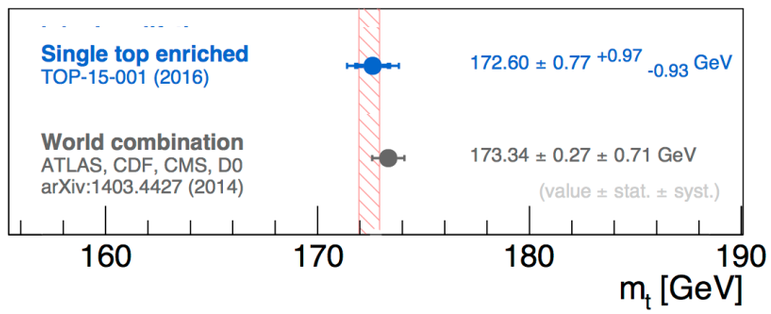


The Run-1 legacy

- **Single top quark** production
  - Main mode, t-channel, measured at high precision (inclusive, differential)
  - First observation of the tW process
  - Study of s-channel and rare single top modes
  - top properties measured in t-channel signatures

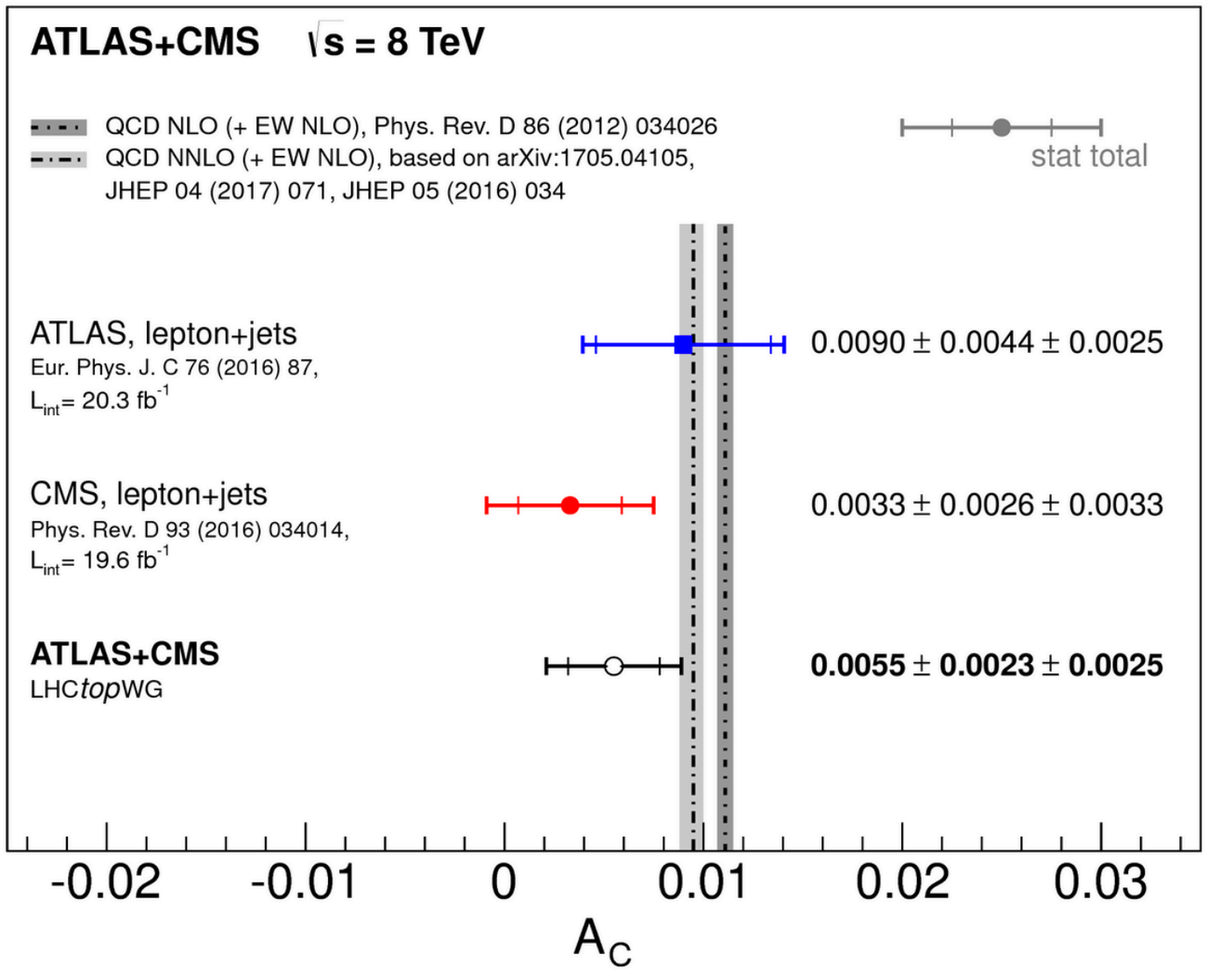






The Run-1 legacy

- **Properties**
  - Very close to the high precision regime
  - Everything is consistent with the SM predictions so far
  - First combined LHC publication in the top group!



Asymmetries (charge)

W-helicity fractions

Spin correlations

Top polarization

BR (t→Wb)

$|V_{tb}|$ CKM matrix element

Top quark width

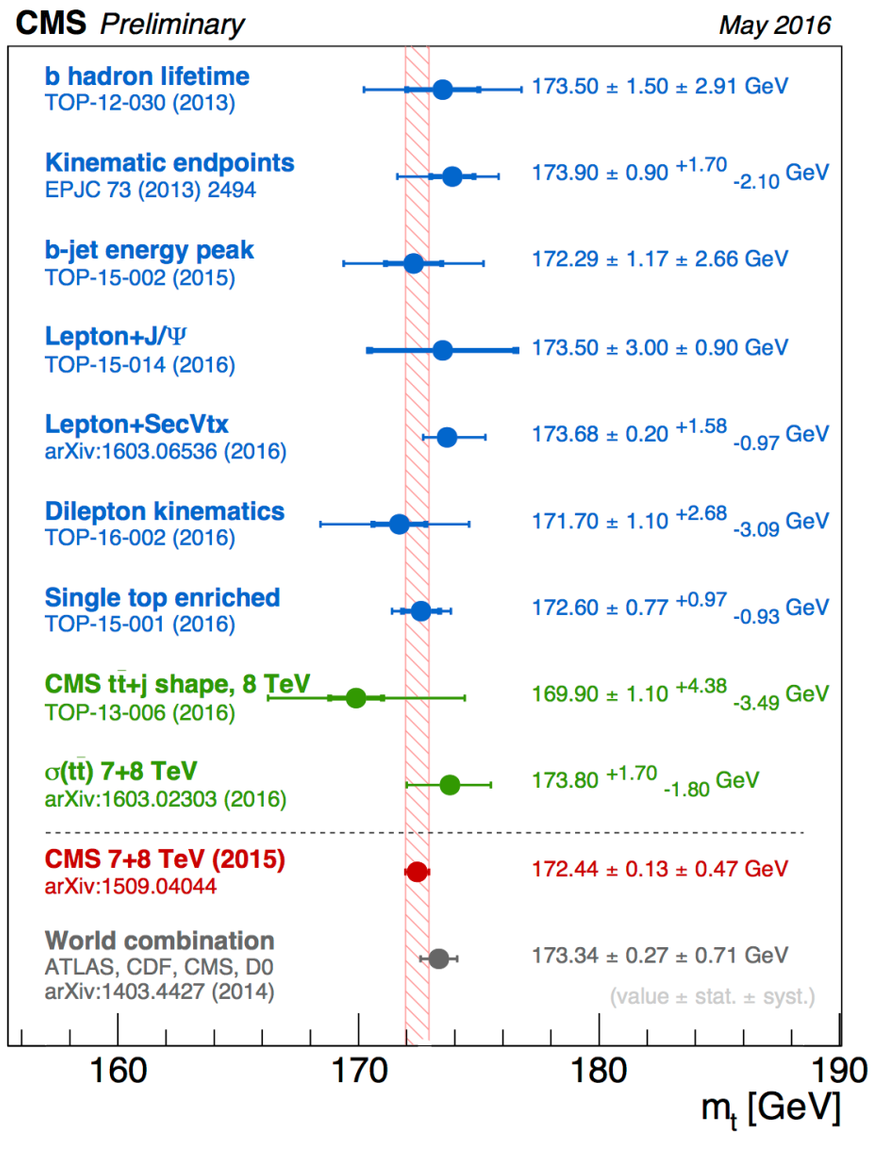
CP violation tests

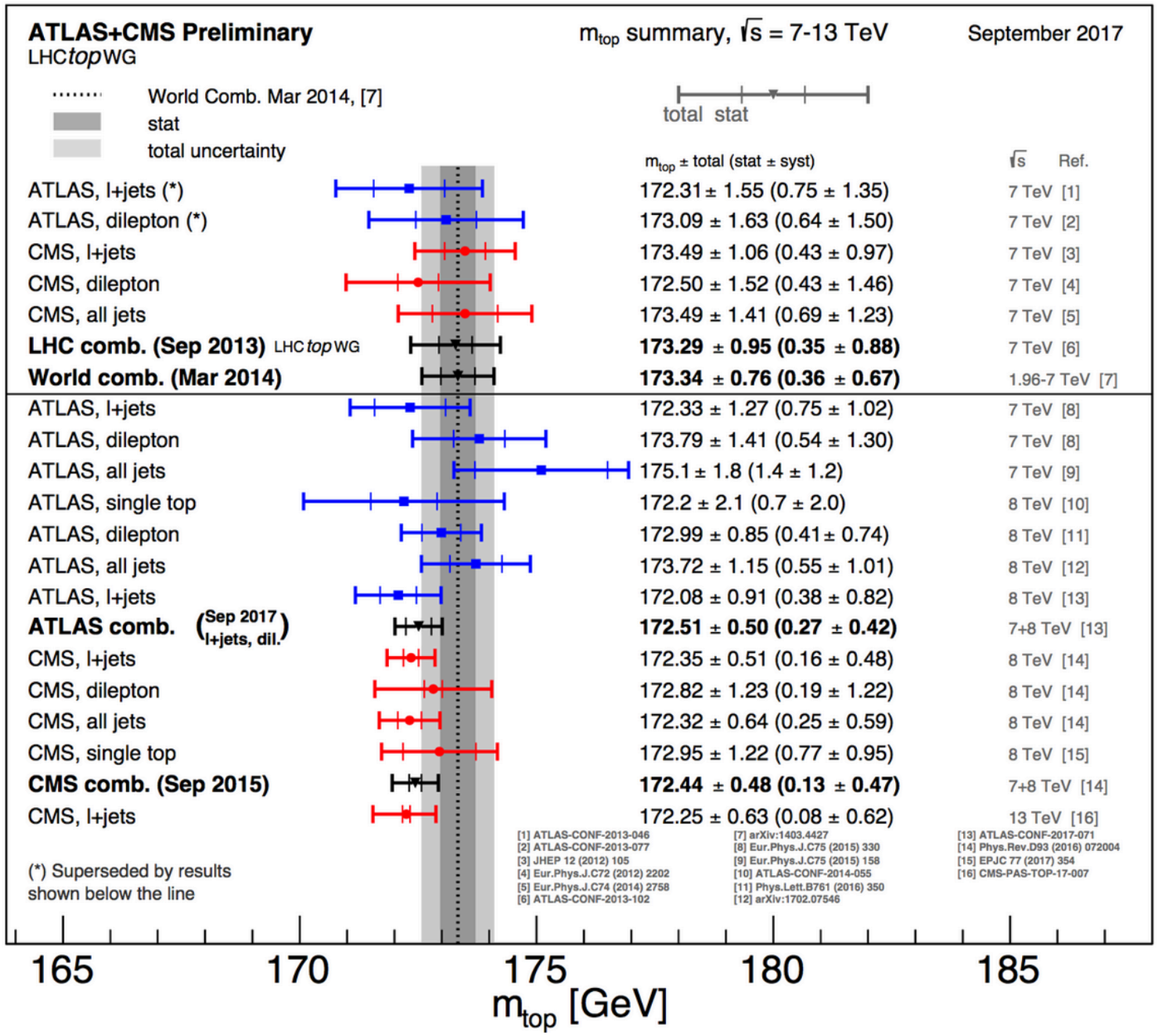
arXiv:1709.05327

Charge asymmetry combination

The Run-1 legacy

- **Top mass:** Flagship property!
  - A variety of dedicated measurements (classic and alternative)
  - Extremely precise ±0.48 GeV (0.34%)



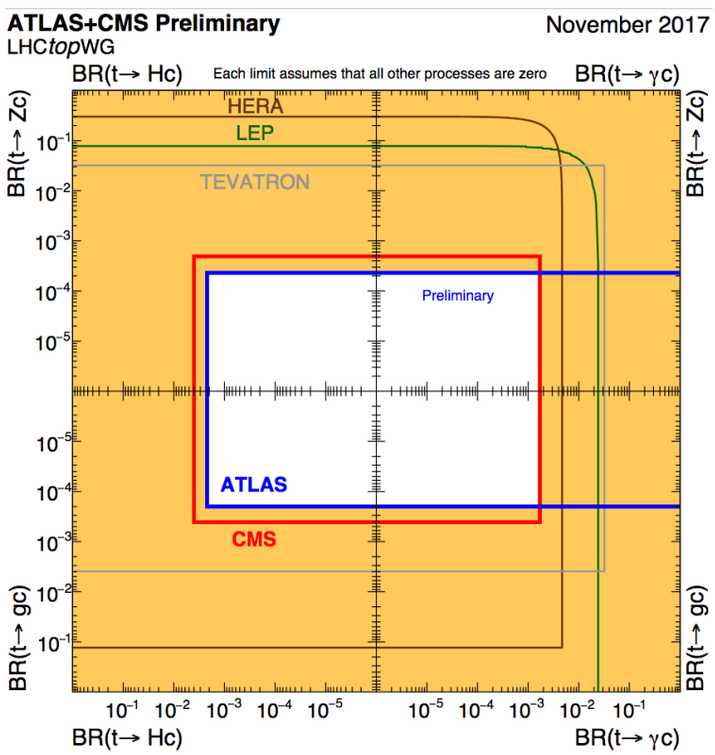


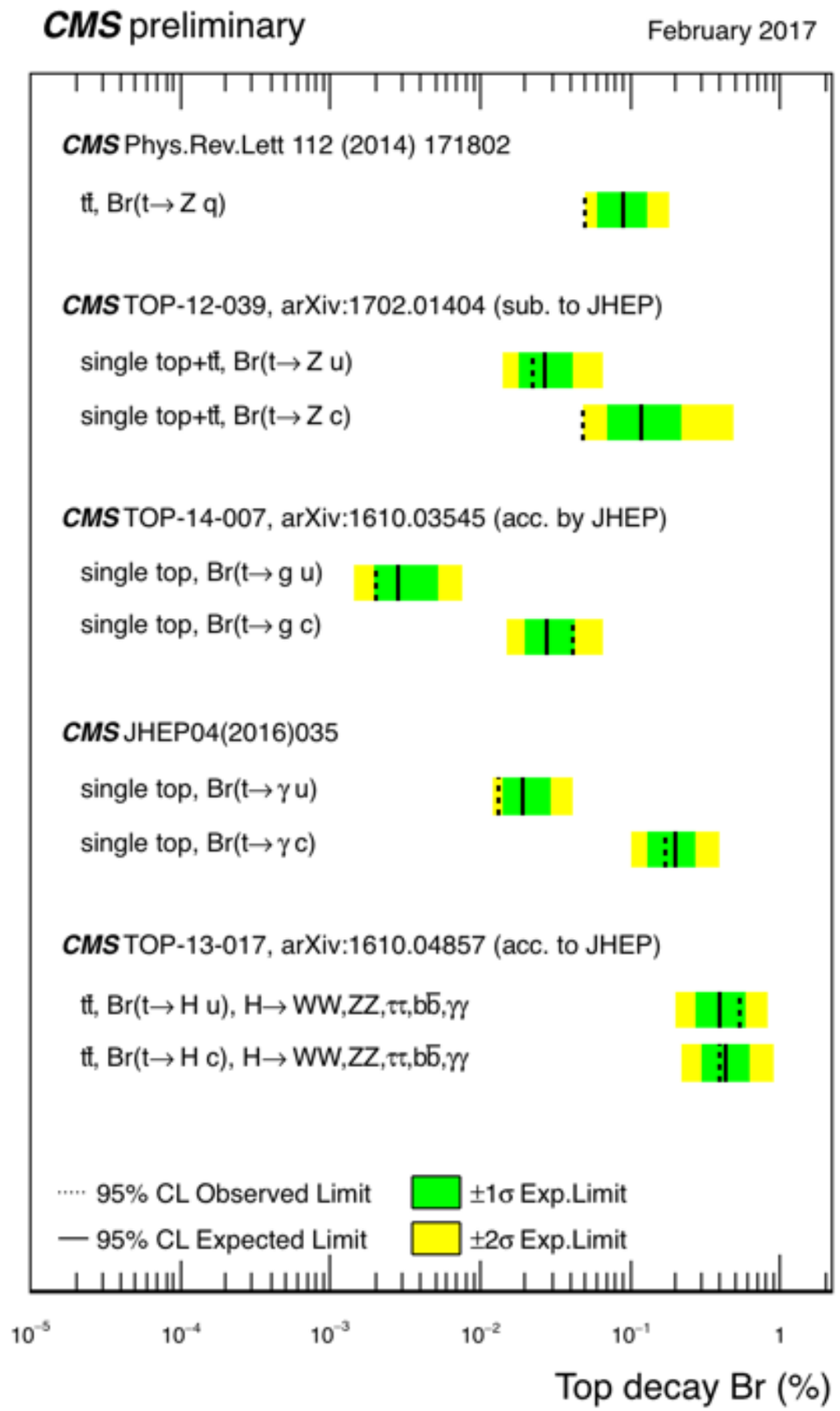
The Run-1 legacy

- Top pairs produced together with other particles
  - Higgs, W/Z, γ, tt…
  - Achieved observation of ttV

- A number of new physics searches with top quarks
  - From FCNC in top, to SUSY scenarios, T' …
  - **No signs of new physics yet**

- But the possibilities are still unlimited





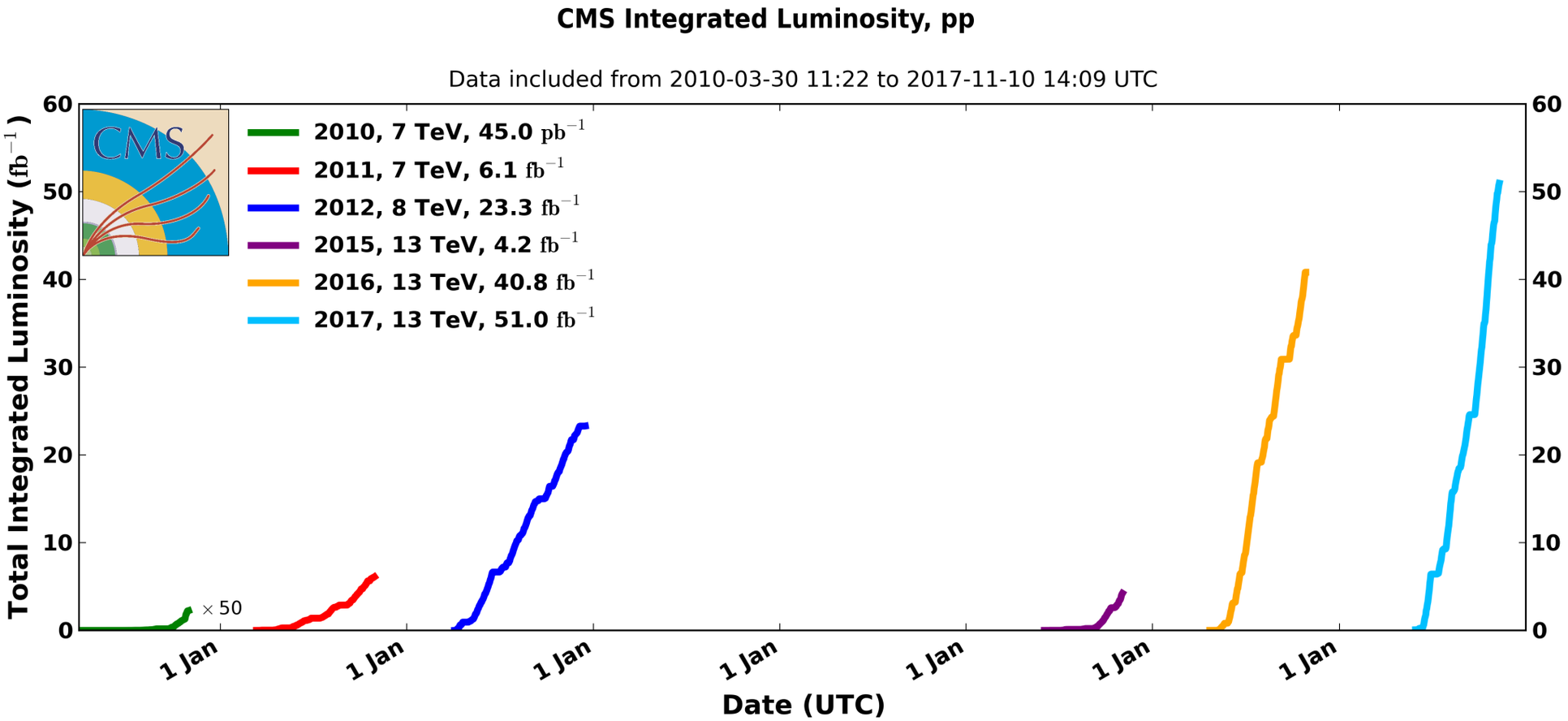
Run-2

LHC pp data

- We are days before the start of the last period of pp collisions of Run-2, and we have:

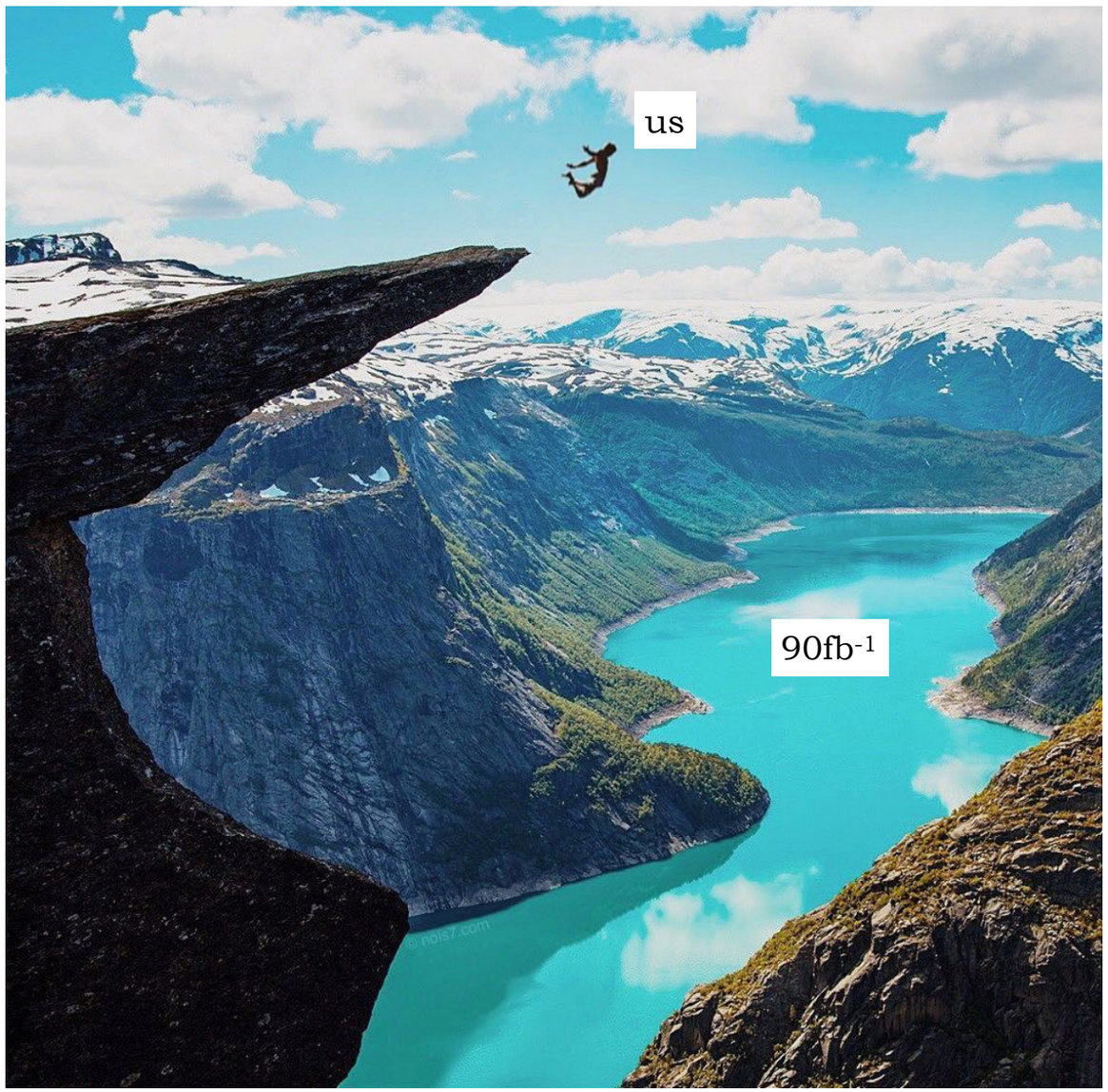
90fb^{-1} at 13TeV

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



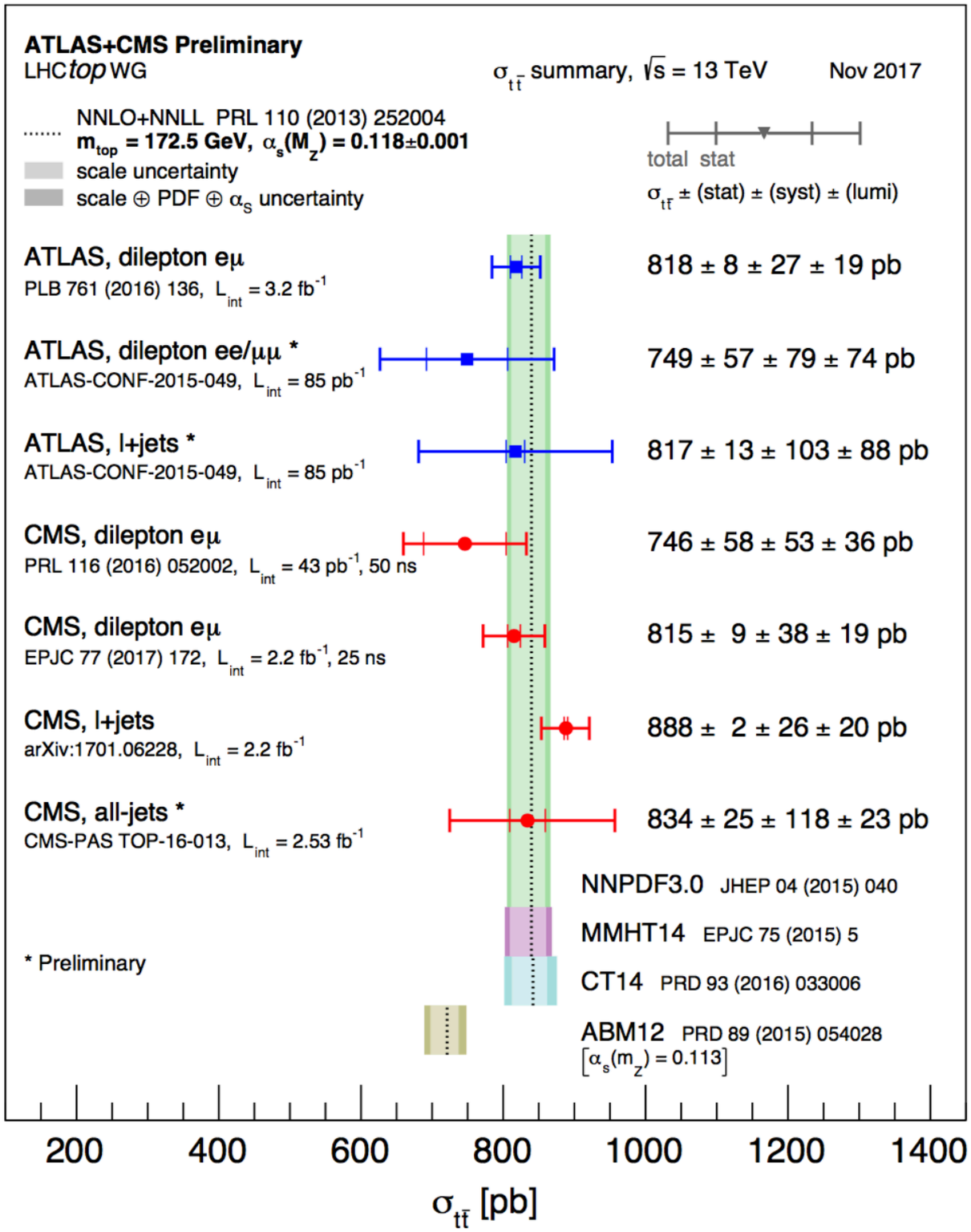
The legacy that is to come will be even better

- Well into Run-2
  - We have a collection of results (**I will discuss 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 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%)

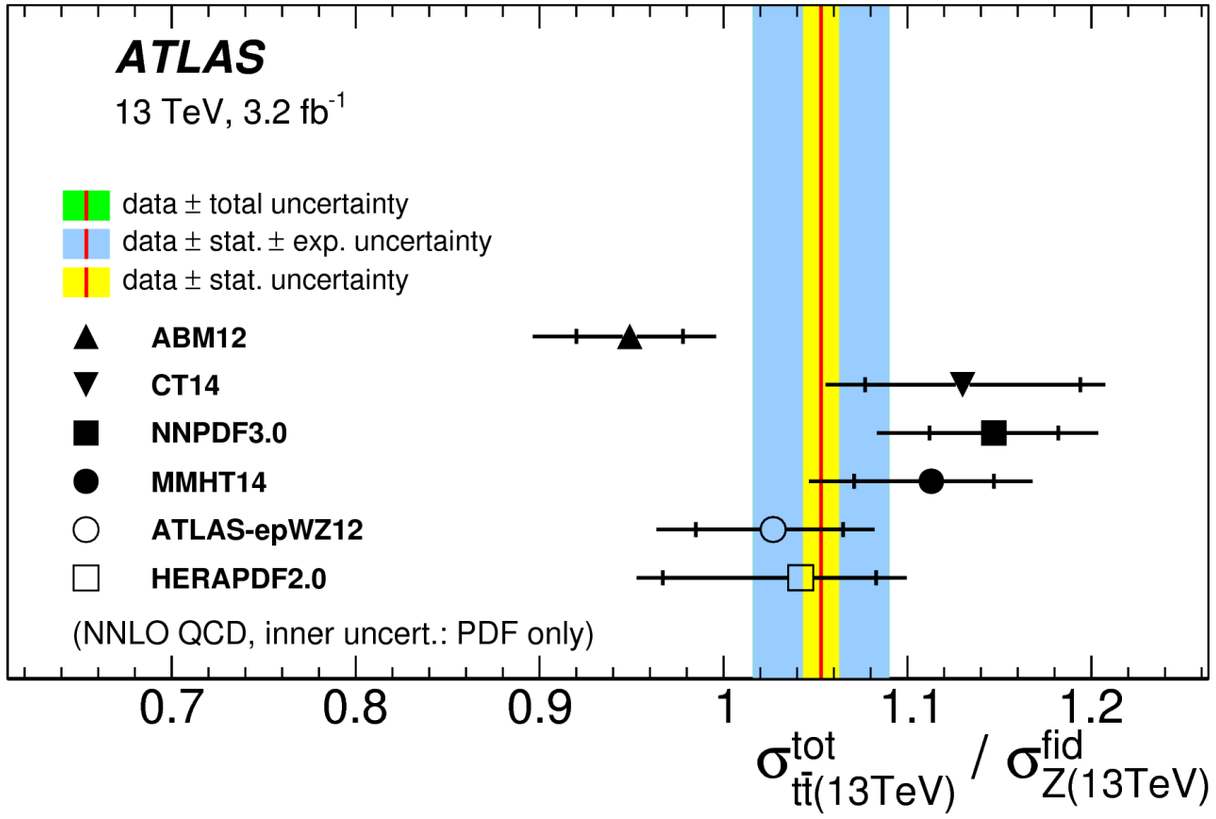
Inclusive tt cross sections: the oddballs

- Even in the most straightforward measurements, **there is always space for creativity**
- The two most precise cross section measurements at 13TeV so far are:

σ_{tt}= 818 ± 8 (stat) ± 27 (syst) ± **19 (lumi)** pb (ATLAS dilepton)

σ_{tt}= 888 ± 2 (stat) +26-28 (syst) ± **20 (lumi)** pb (CMS l+jets)

- while the systematic associated to the luminosity does not limit our measurements now, it will likely do so in the future



Cross section ratios

arXiv:1612.03636

tt/Z cross section ratios

systematics cancel in the ratio

power to constrain PDFs

Inclusive tt cross sections: the oddballs

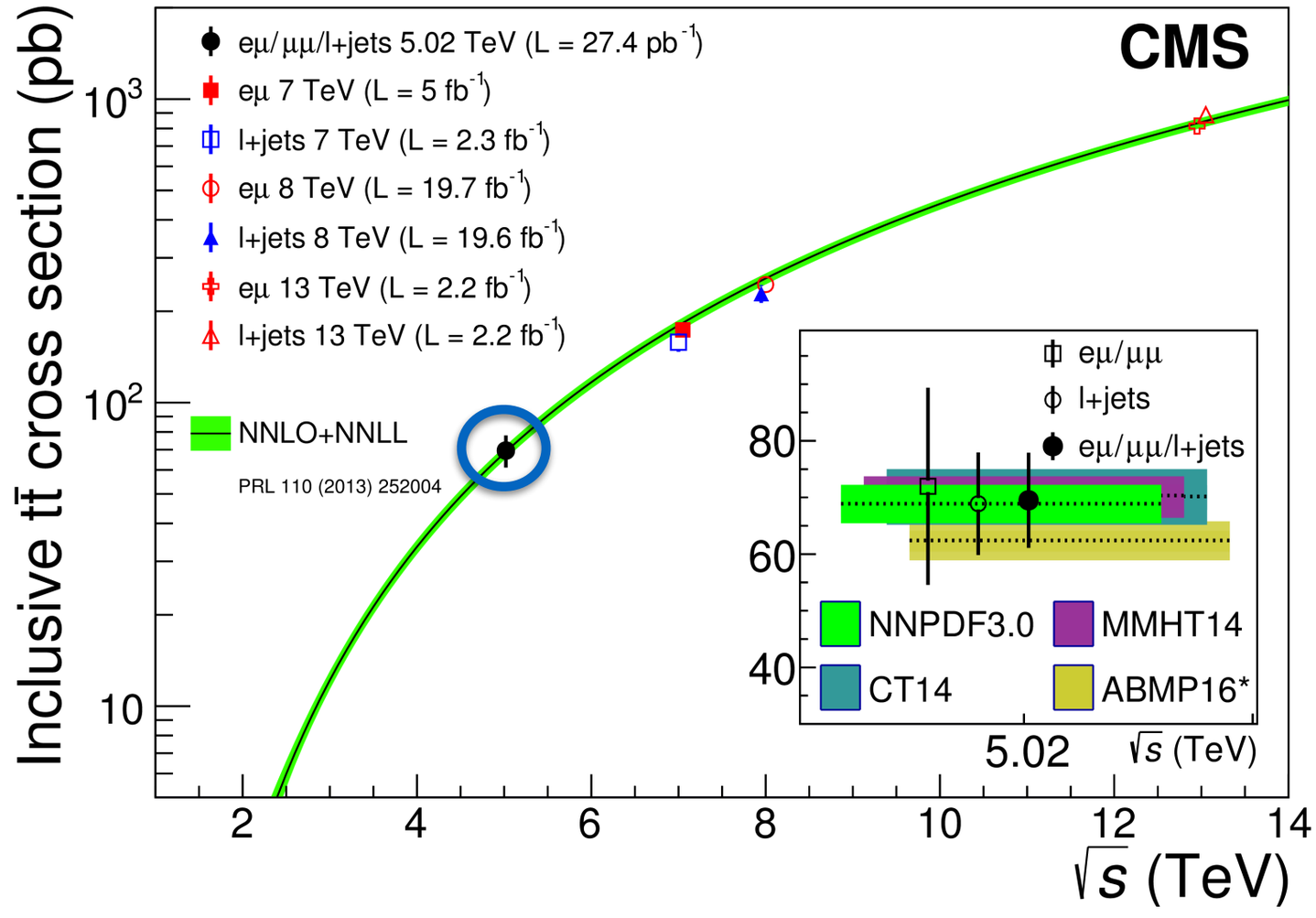
- In November 2015, the LHC delivered **pp collisions at 5.02 TeV**
  - Reference run for Heavy Ions collisions at that energy
- Measuring the inclusive tt cross section provides a **reference** for future measurements tt in nuclear collisions at that nucleon-nucleon collision energy
  - without the need to extrapolate from measurements at different √s

Surprise √s: 5TeV

1711.03143

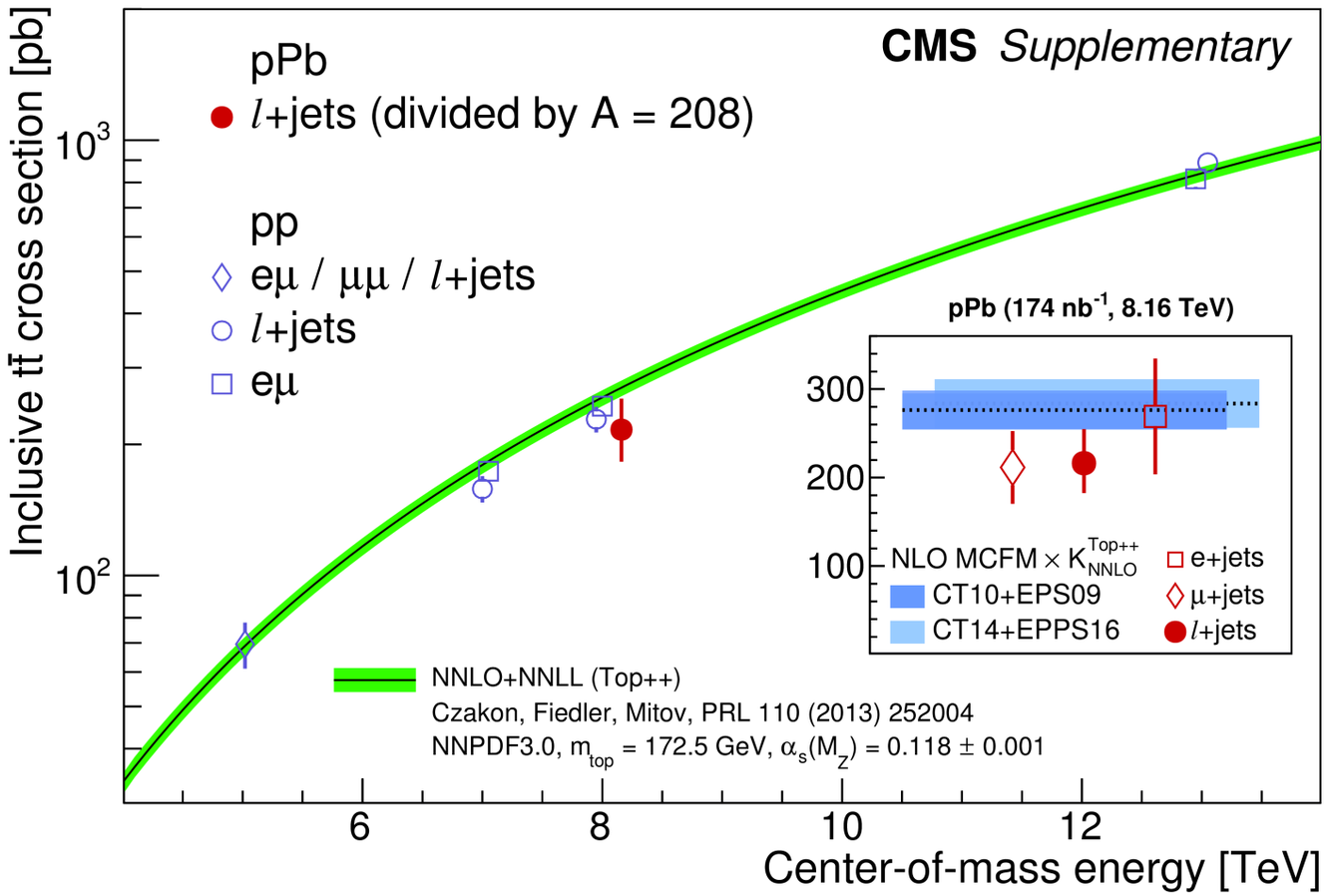
Δσ/σ≈12%

Also useful to constrain PDFs



Inclusive tt cross sections: the oddballs

- Later, we did measure **tt production in actual Heavy Ions collisions**
  - proton-nucleus collisions, pPb data
  - center of mass energy of 8.16TeV
- **First observation** of the tt process using proton-nucleus collisions with > 5σ significance



Surprise collision type: pPb

1709.07411

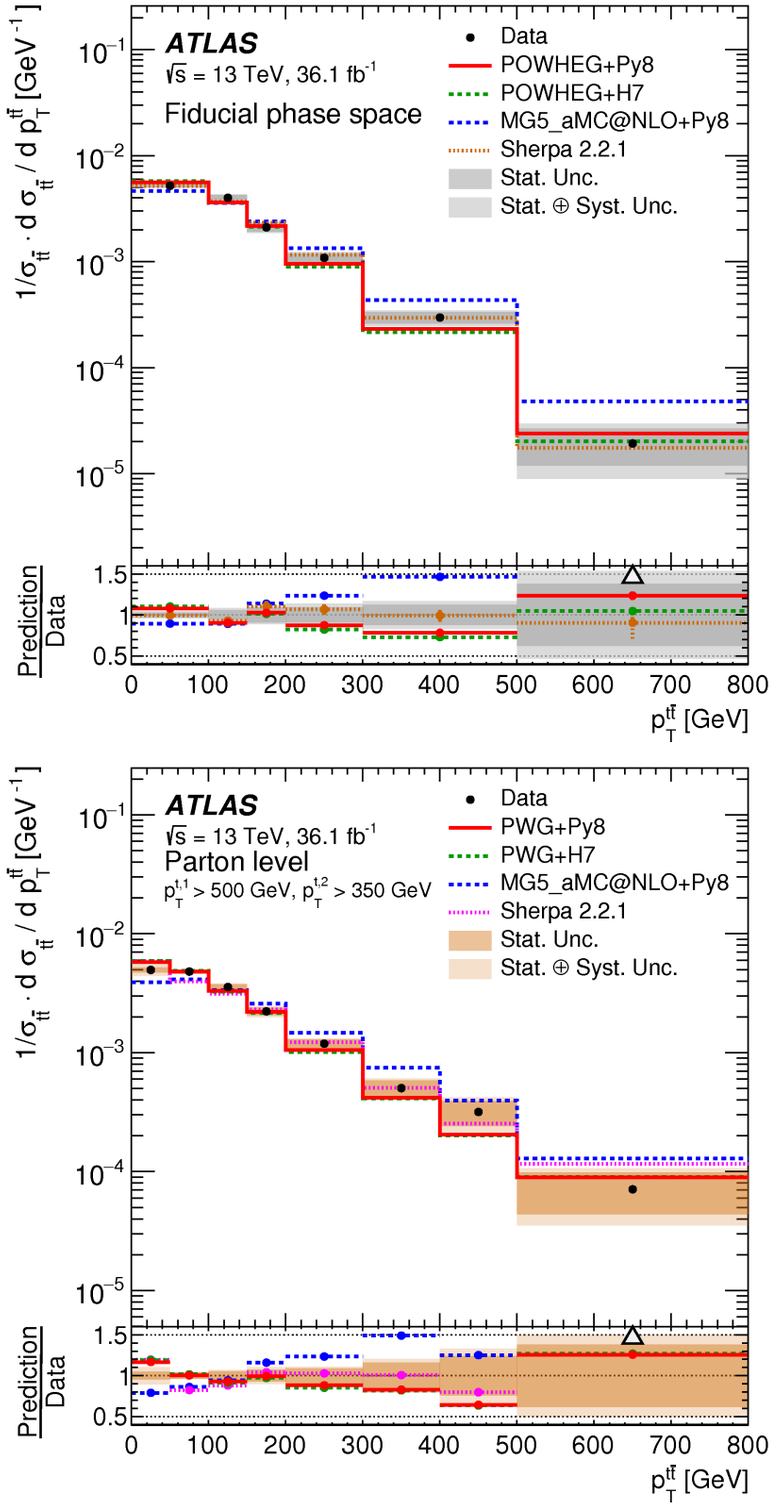
Δσ/σ≈18%

Paves the way for future measurements in Heavy Ions

Differential tt cross sections

Differential tt cross sections

- Modelling uncertainties becoming very important
  - For top quark physics and for every analysis that has top quark background
- Differential measurements
  - **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
  - While at the same time, provide
    - the **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

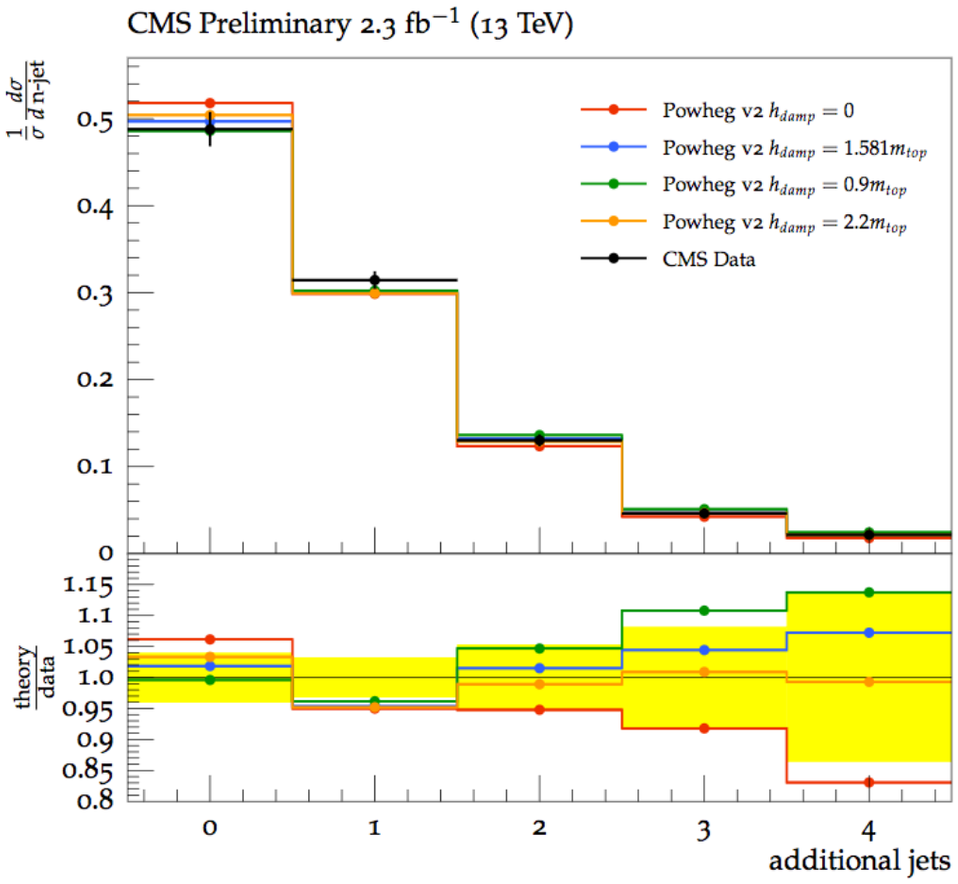


arXiv:1801.02052

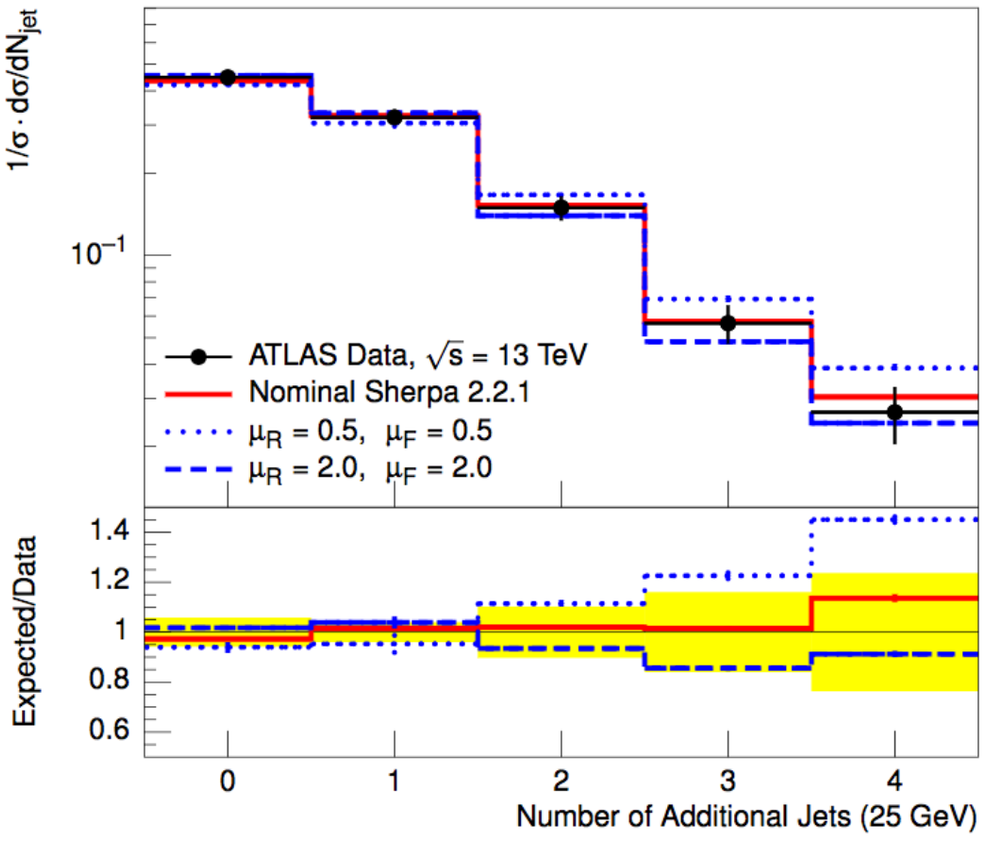
boosted, all-hadronic

Differential tt cross sections

- In general: good agreement with NNLO predictions and NLO generators
  - Discriminating between models and tuning parameters already possible



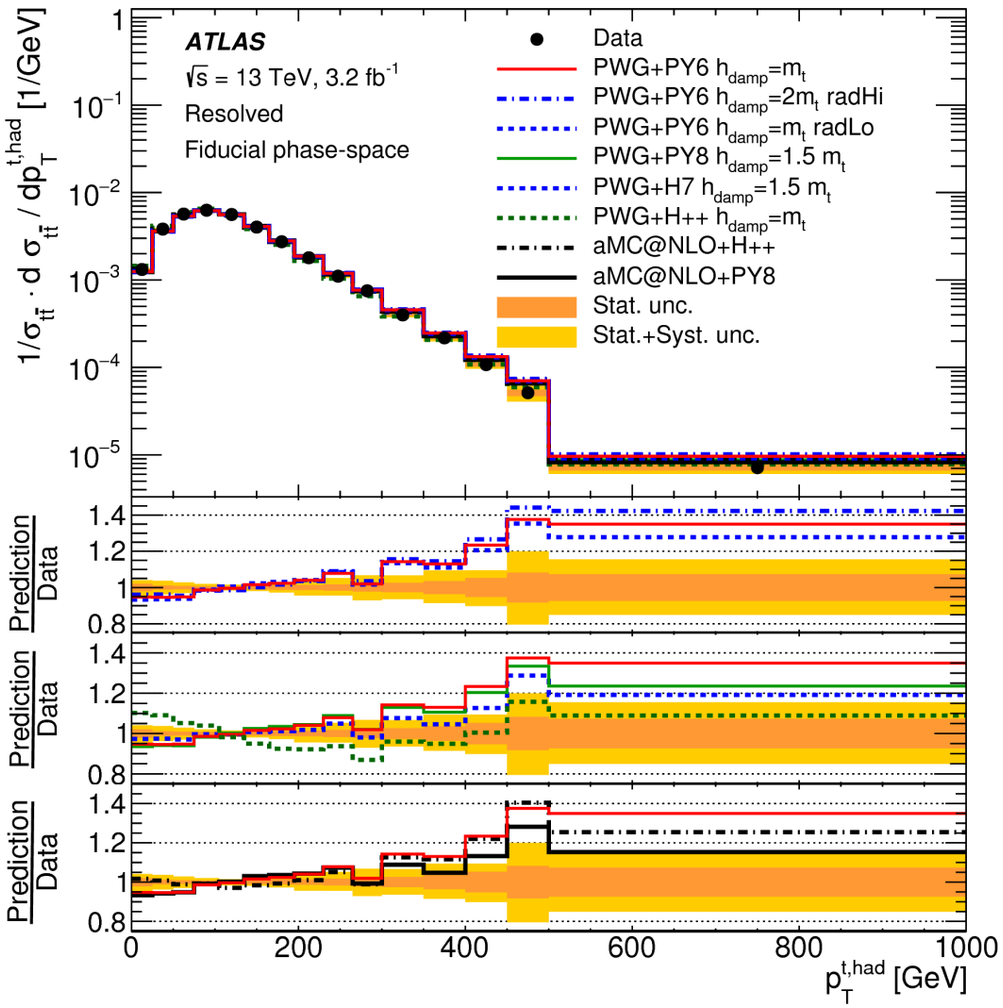
CMS-PAS-TOP-16-021
parton shower tuning

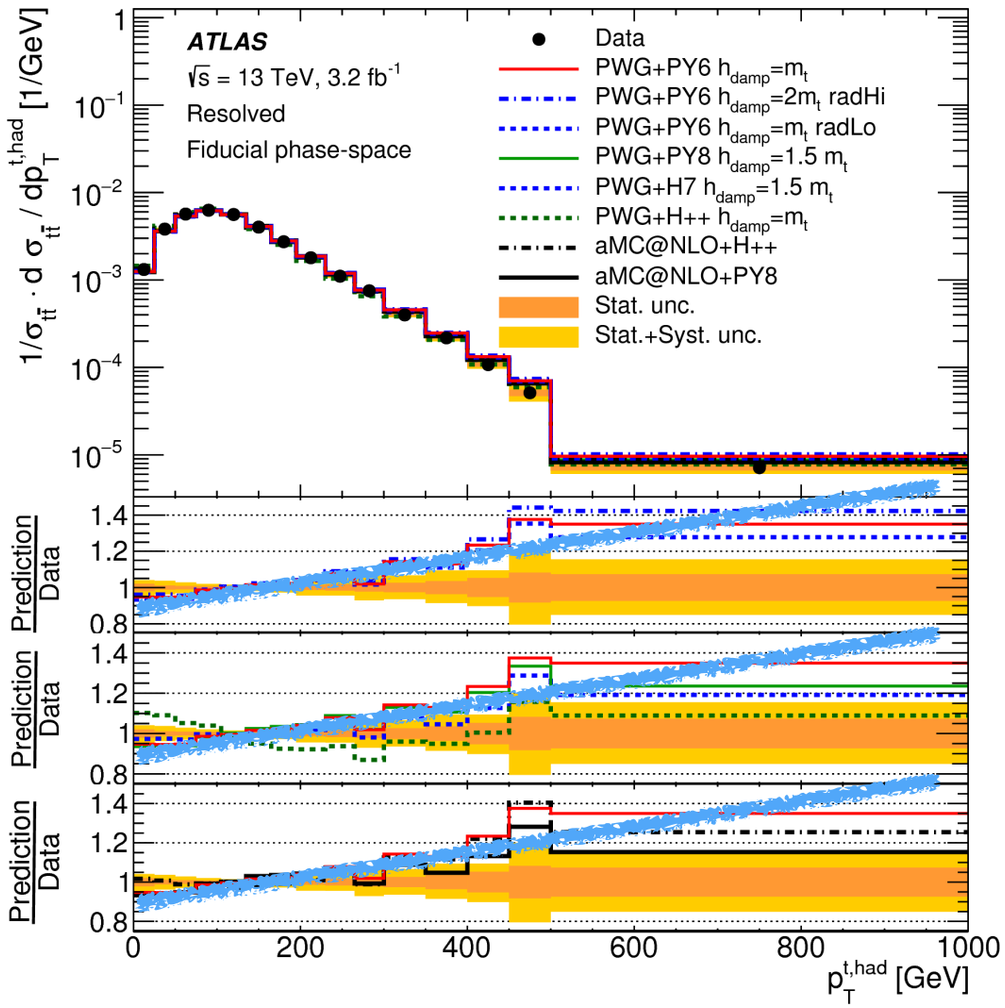


ATL-PHYS-PUB-2017-007
Modelling studies

Top quark p_T: an unexpected feature

- **The top quark p_T is softer in data than in simulation**
  - Effect observed during Run-1, still present in Run-2



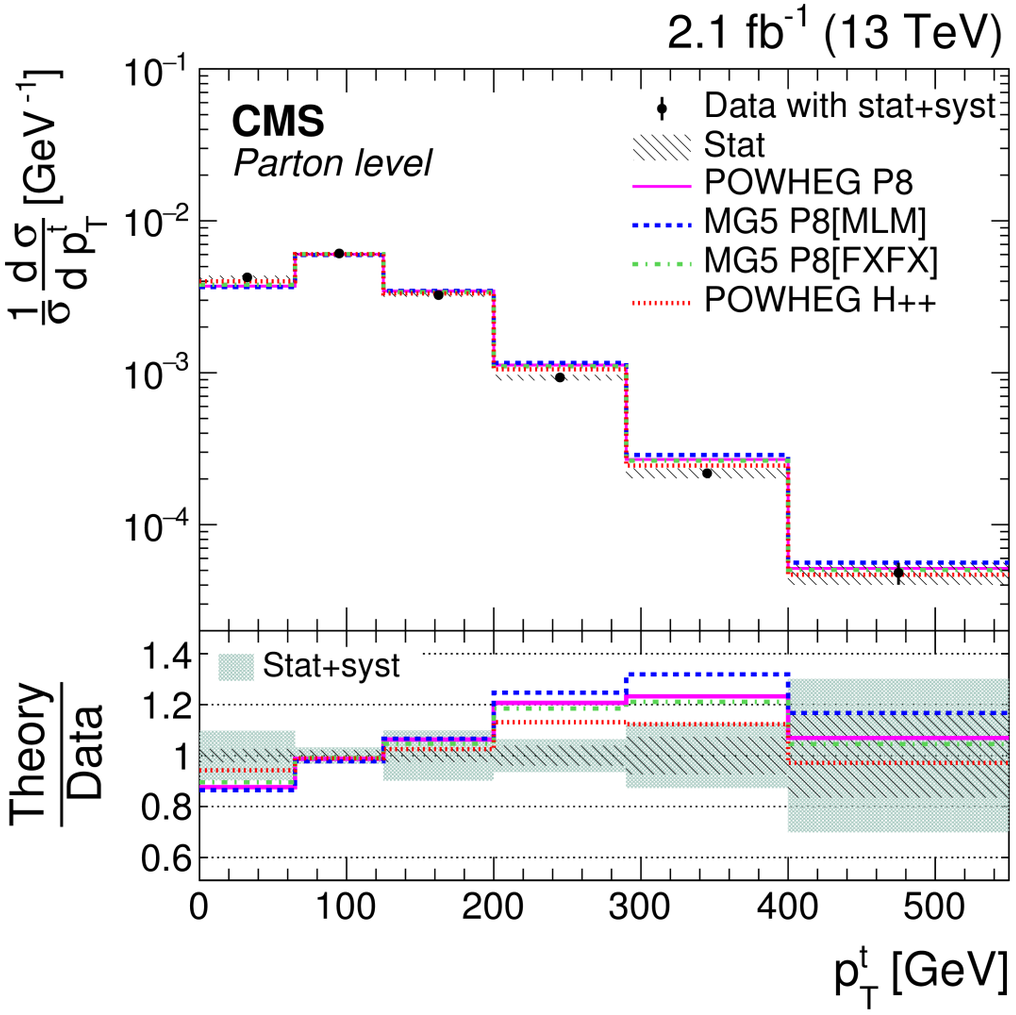


arXiv:1708.00727

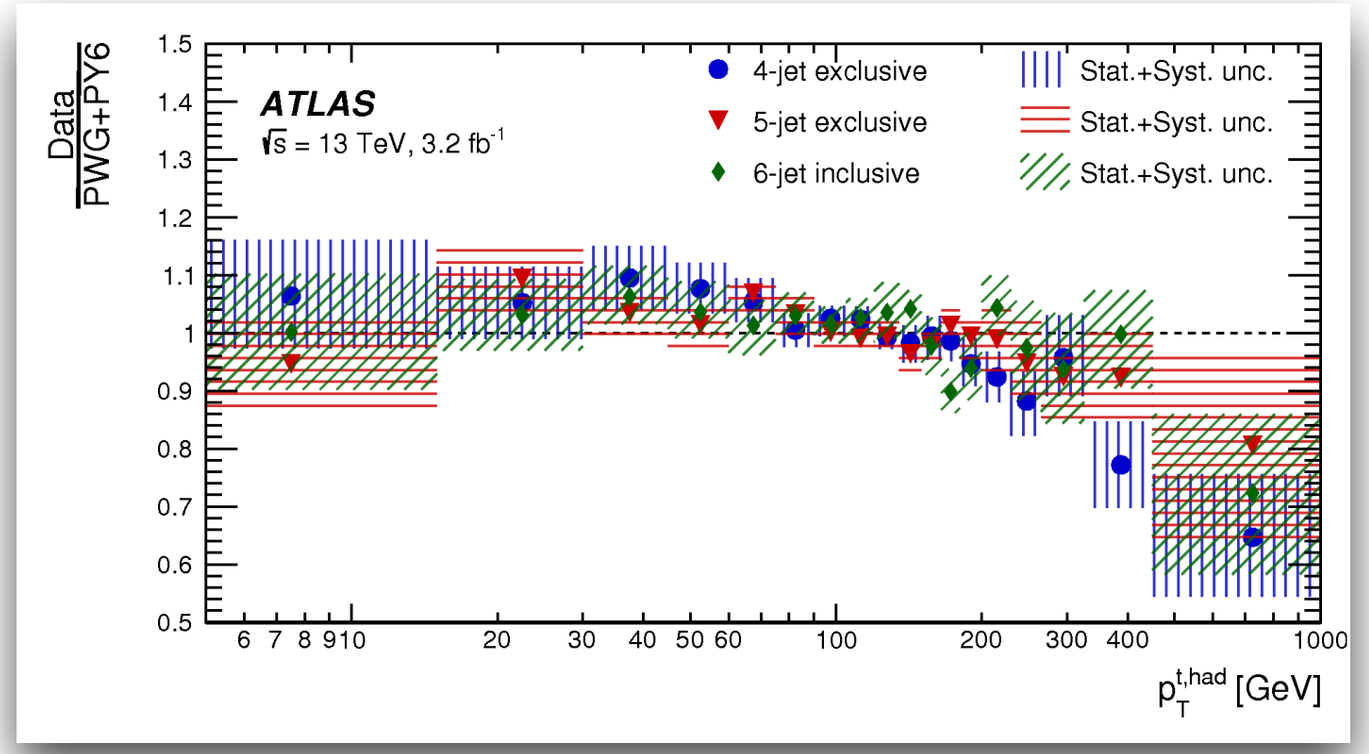
boosted and resolved, l+jets

Visible everywhere

- 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)*



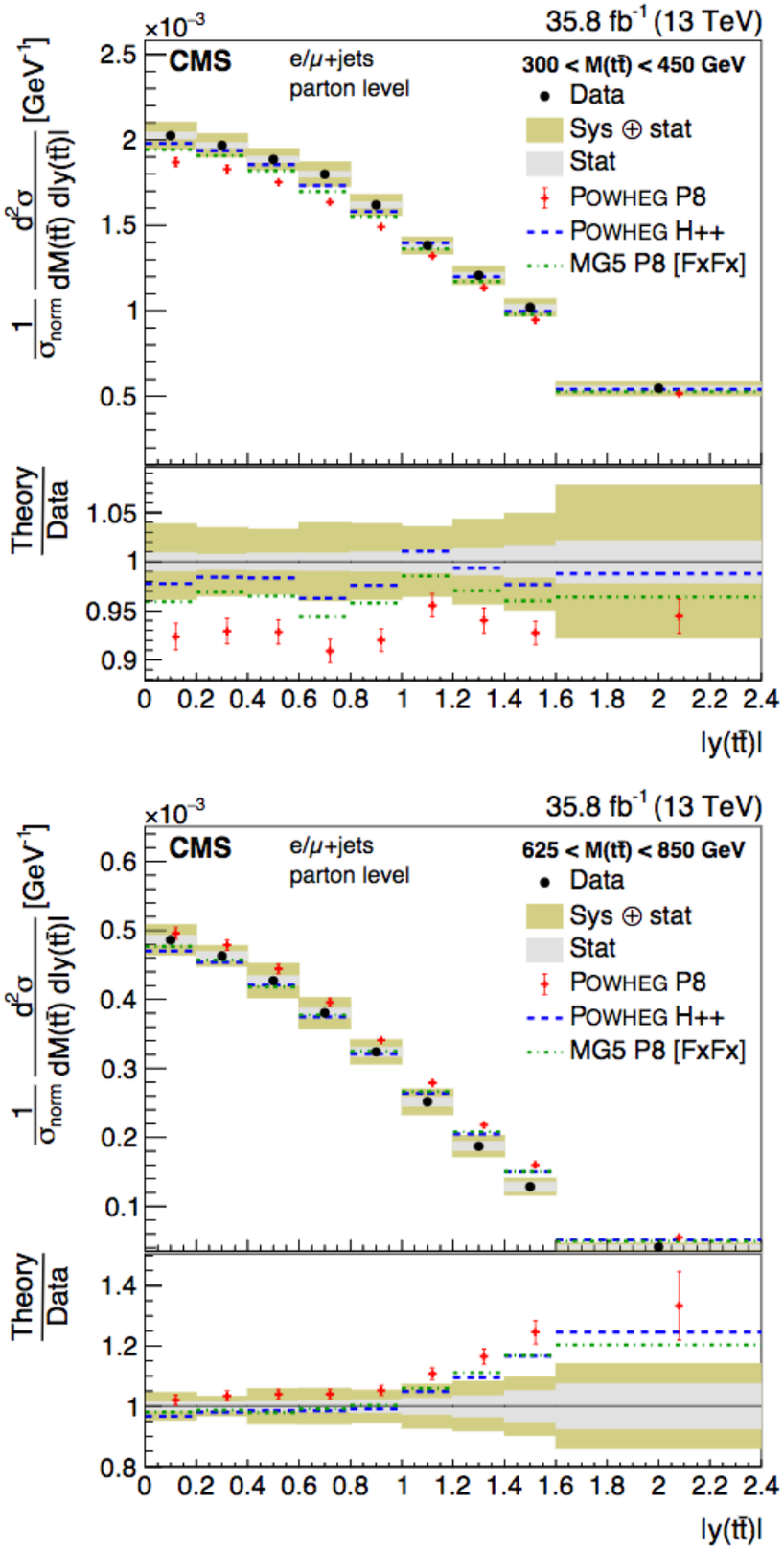
arXiv:1708.07638
dilepton

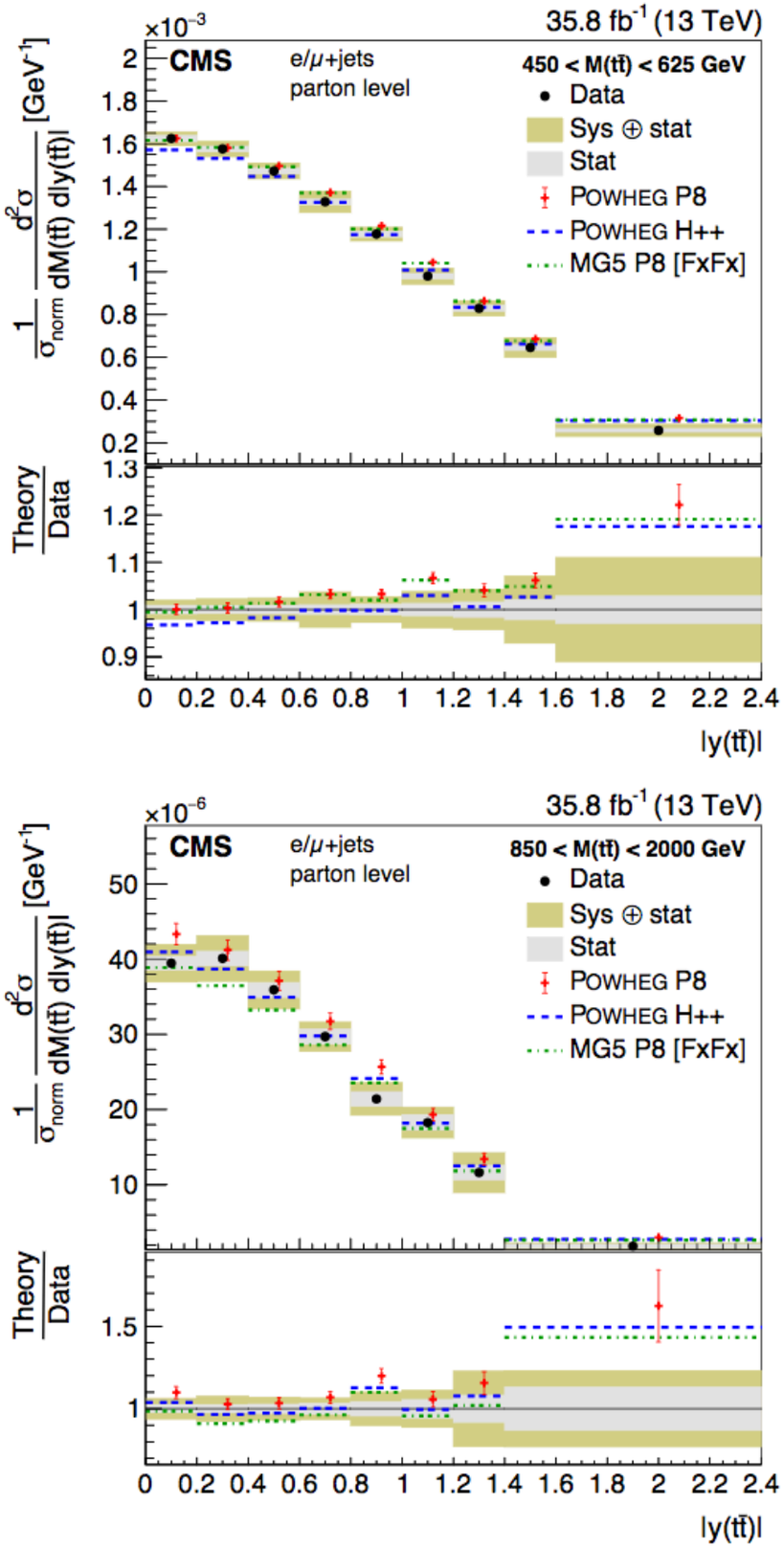


arXiv:1802.06572
in association with jets
double differential

Multi differential distributions

- 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



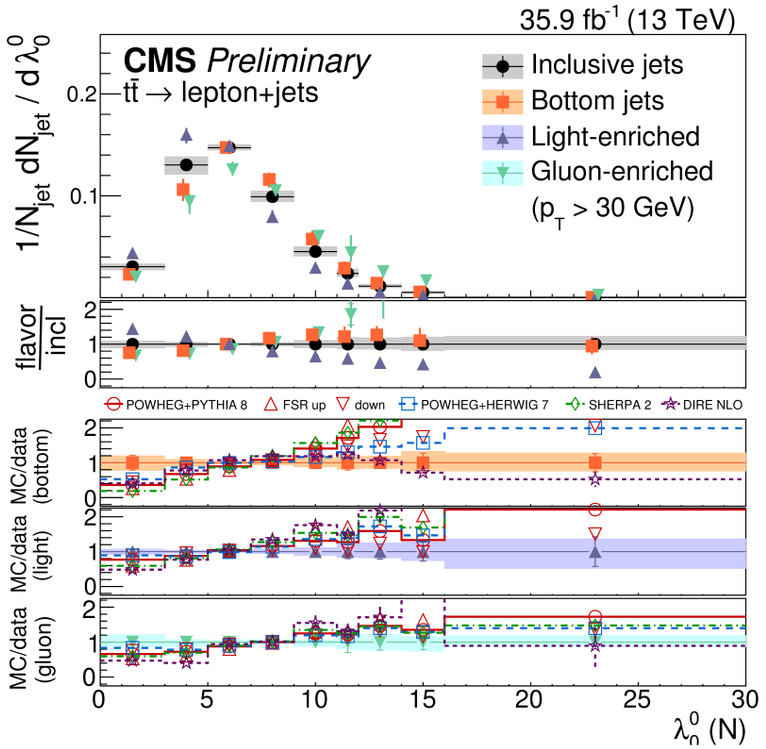


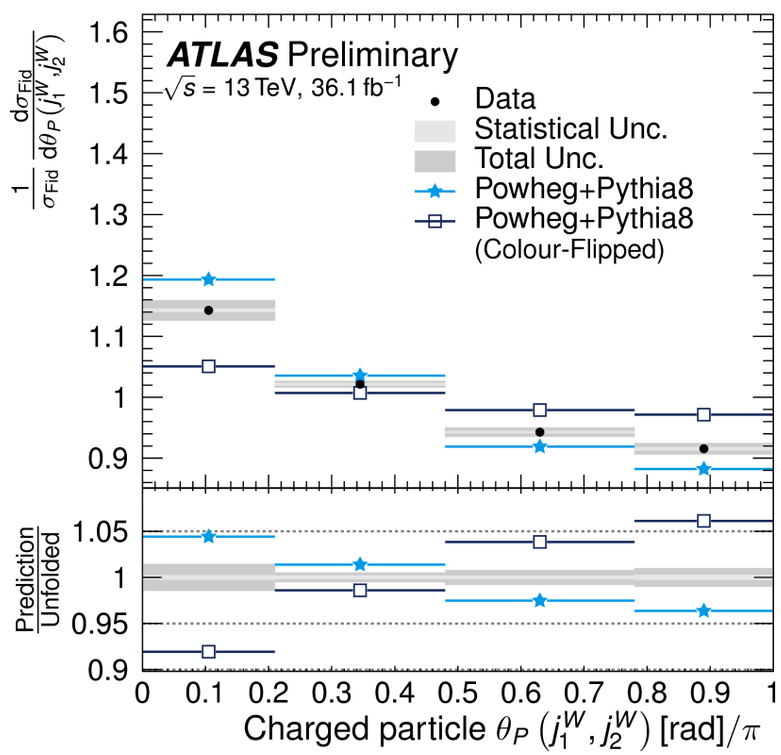
arXiv:1803.08856

l+jets

Studies with charged particles (in or outside jets)

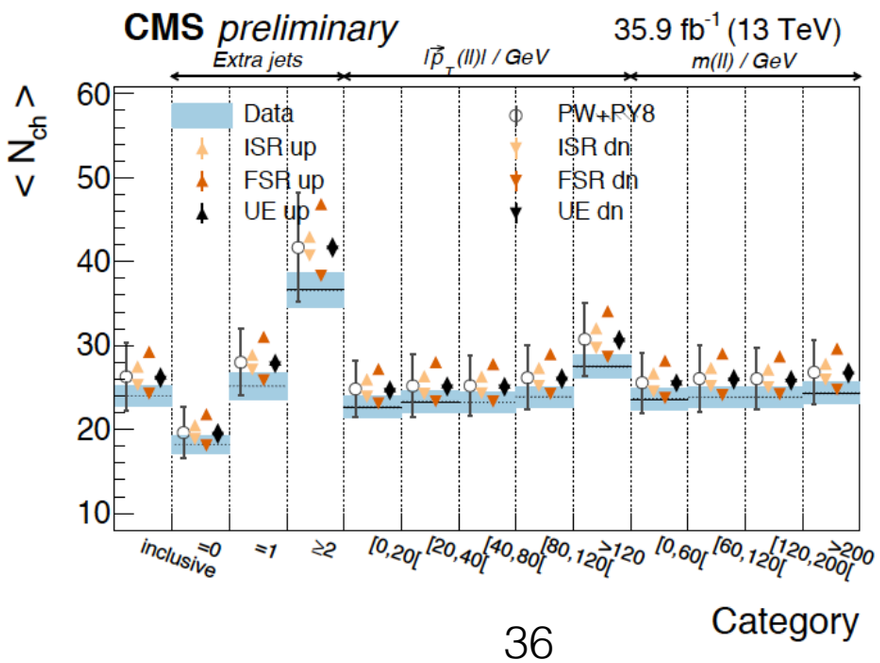
- Recent measurements investigating:
  - **jet constituents/ structure variables**
  - multiplicity and kinematic variables of charged-particle tracks from the **underlying event**
- *tuning of the simulation*
- *sensitive to colour effects, α_s*



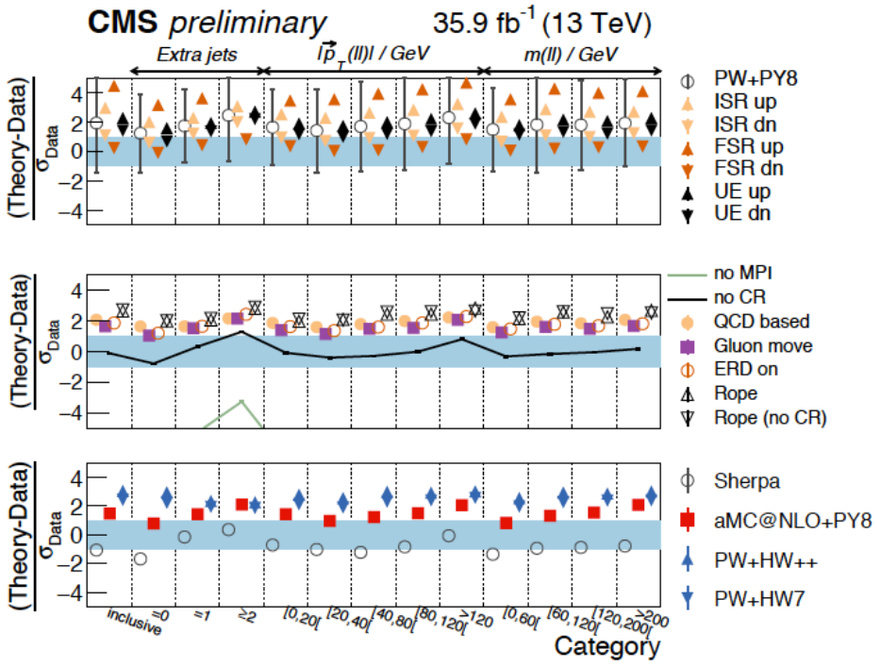


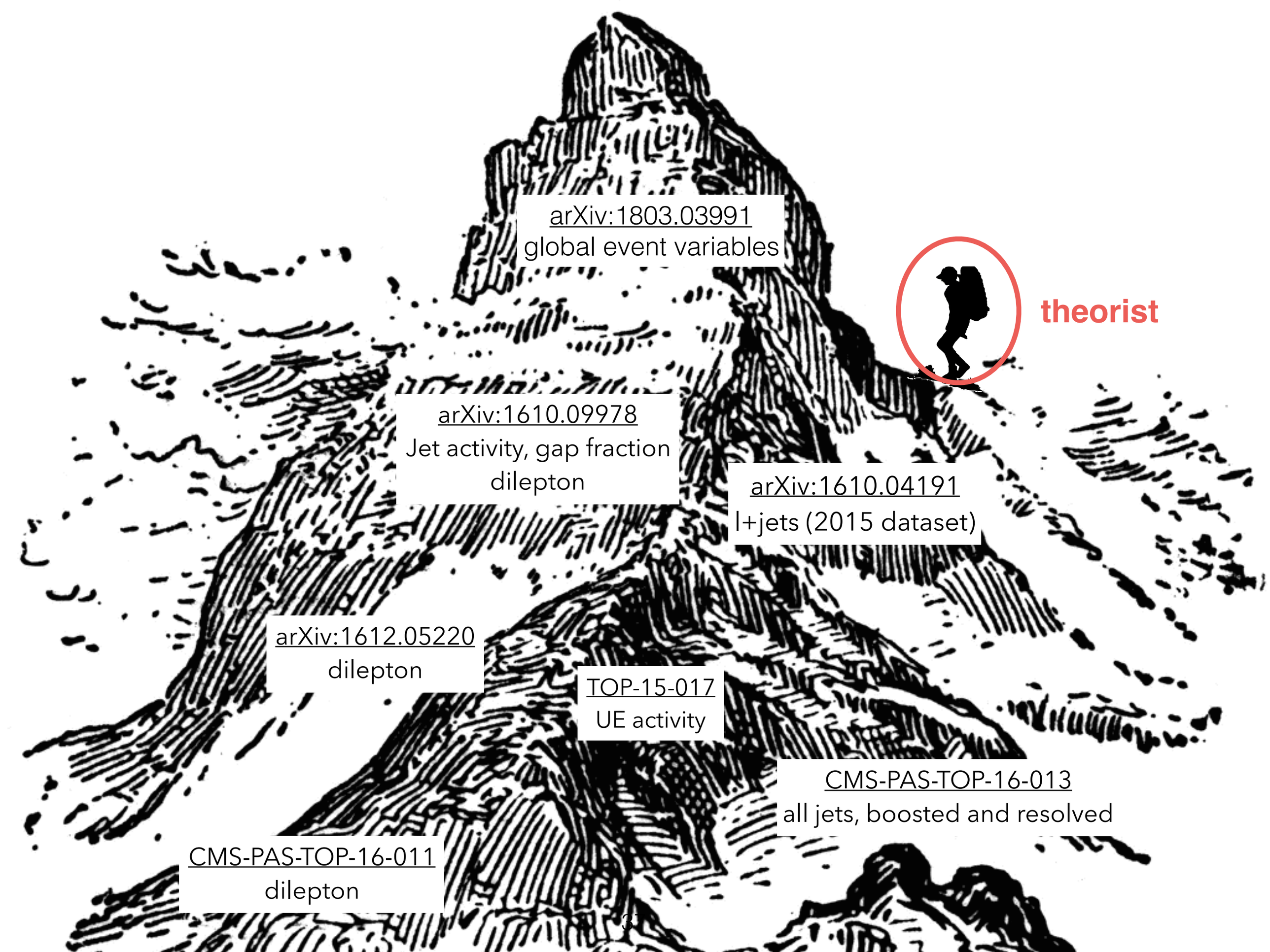
CMS PAS-TOP-17-015
underlying event

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
TOP-15-017
UE activity
CMS-PAS-TOP-16-013
all jets, boosted and resolved
CMS-PAS-TOP-16-011
dilepton

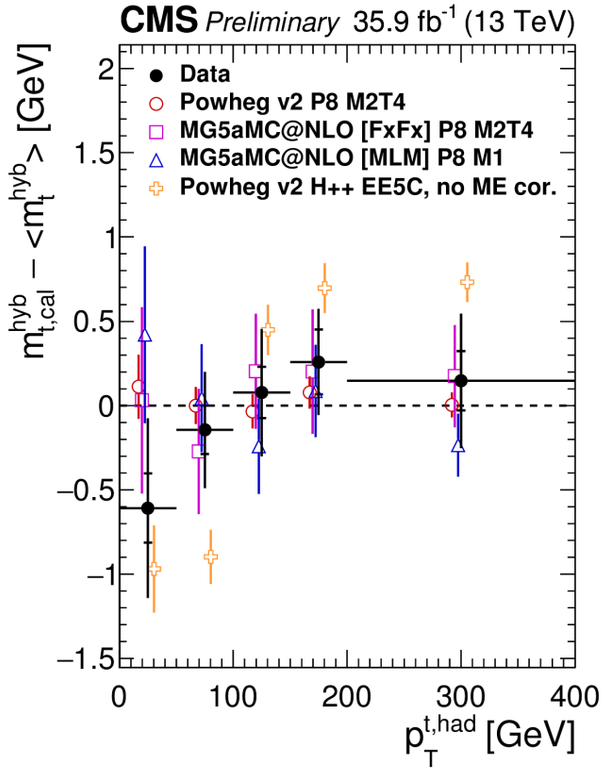
Before you go: differential top quark mass!

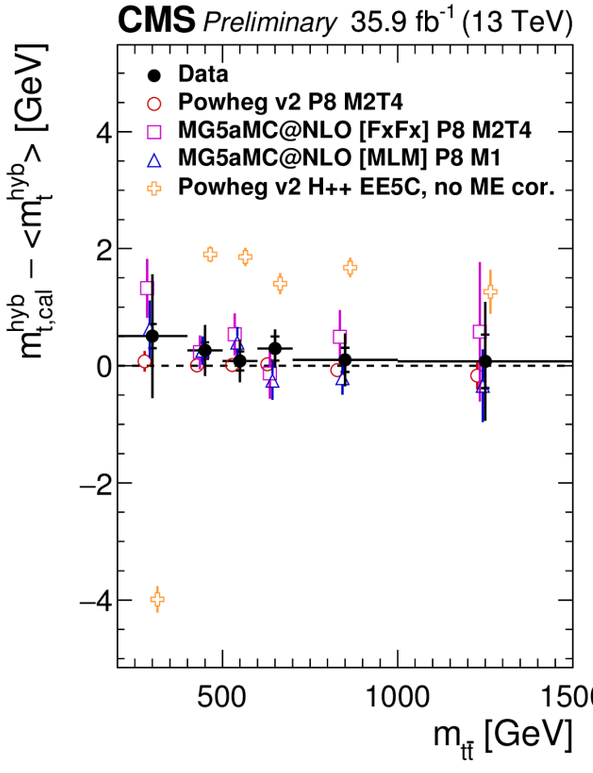
- Not many properties results yet, we need to understand the data very well first
  - a first measurement of top width (compatible with the SM)
- Direct measurement of **the top quark mass with 13 TeV data**
  - classic method (most precise value in Run-1)
  - Updated treatment of model uncertainties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

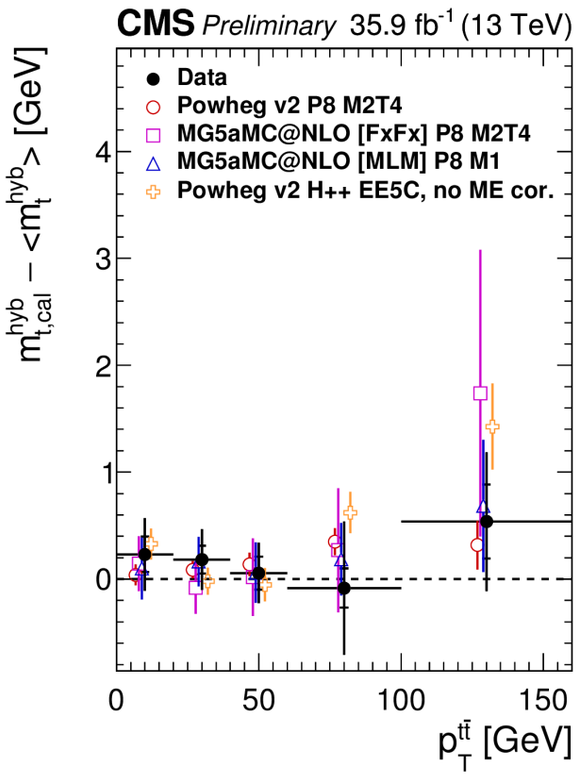
CMS-TOP-17-007

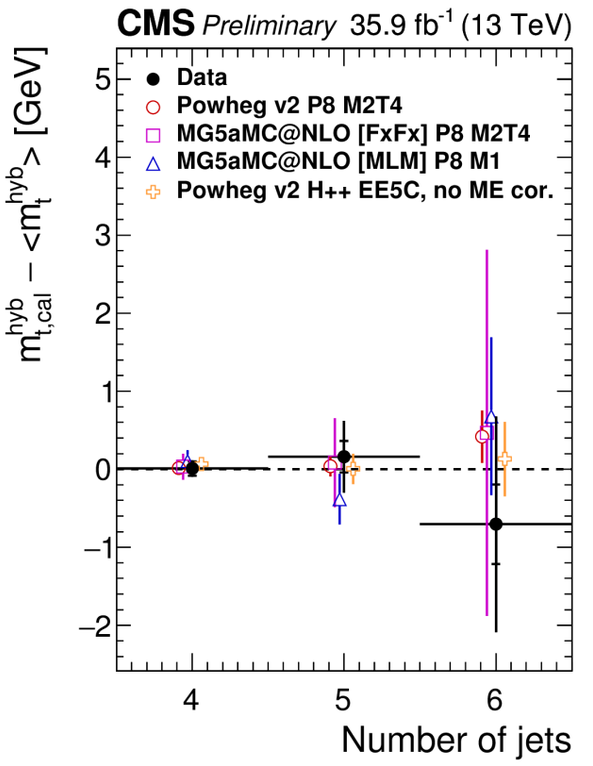
$m_t = 172.25 \pm 0.08\ (\text{stat+JSF}) \pm 0.62\ (\text{syst})$ GeV

$(\Delta m_t = 0.36\%)$





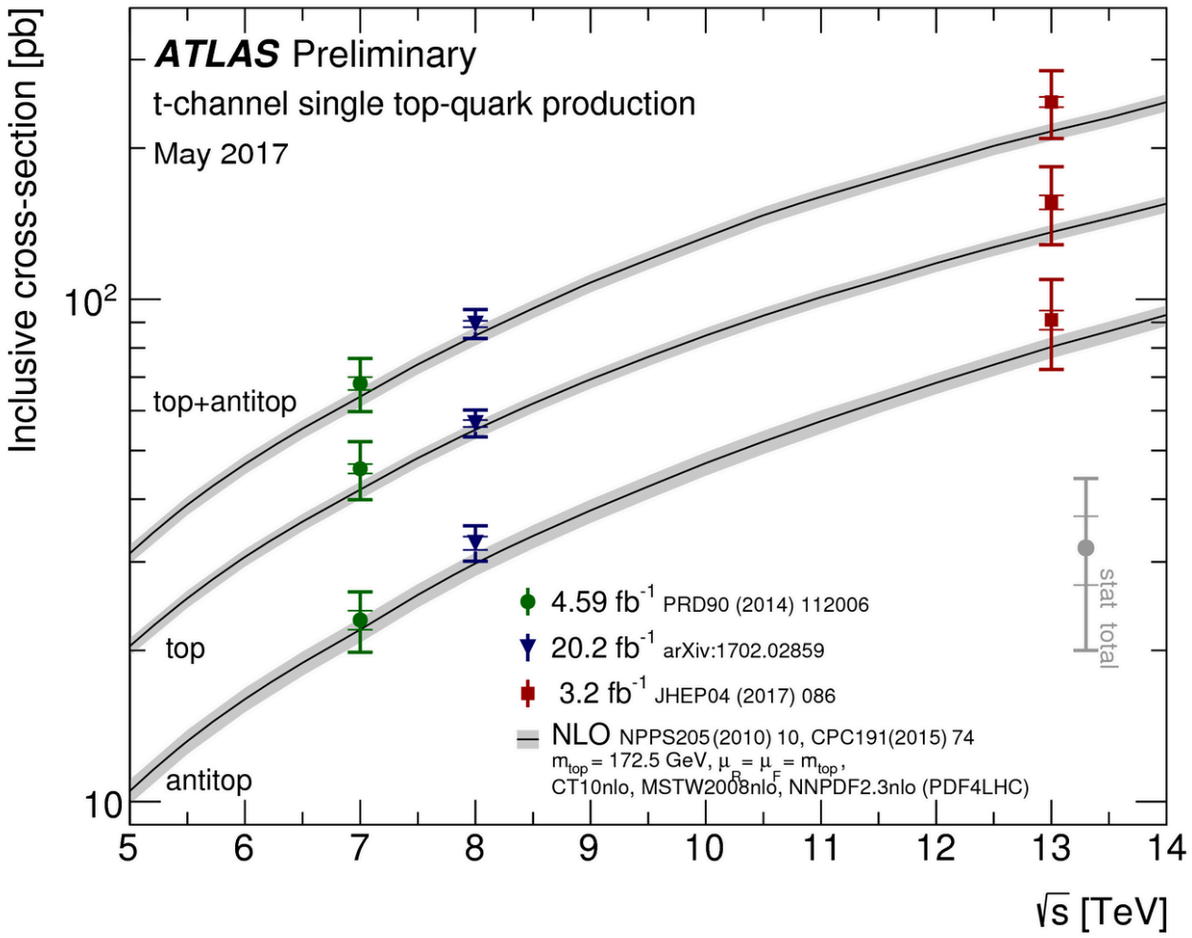


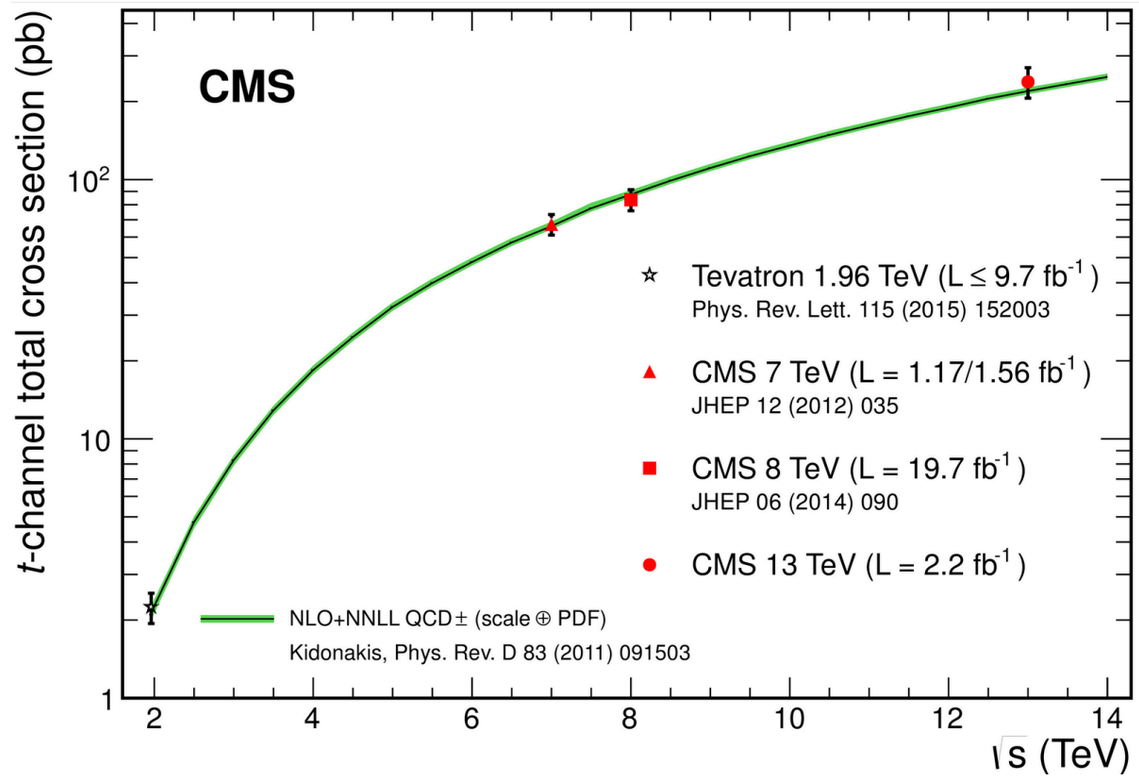


Single top production

Single top quark production

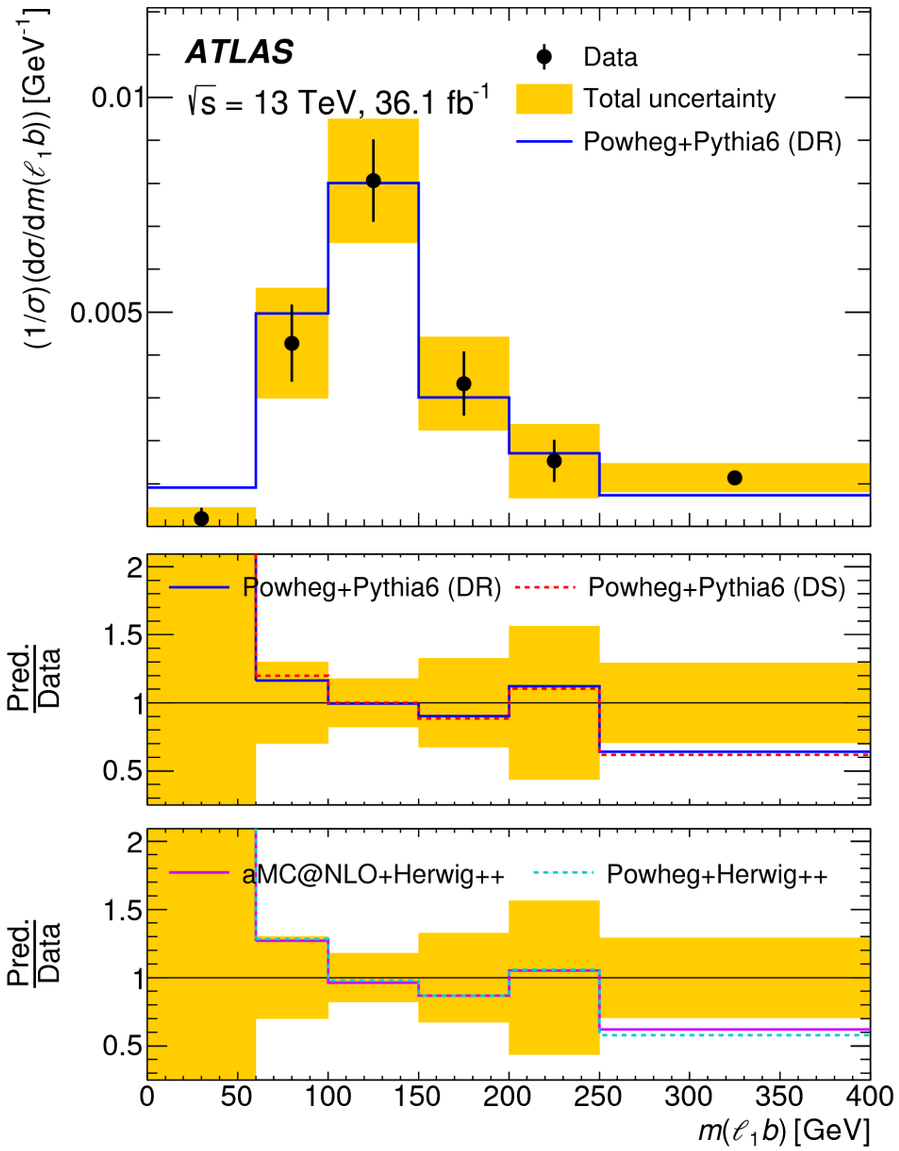
- The study of single top quarks is also well advanced in Run-2
- **t-channel cross section at 13TeV ~ tt cross section at 8TeV**
  - Early measurements of t-channel (inclusive, differential)





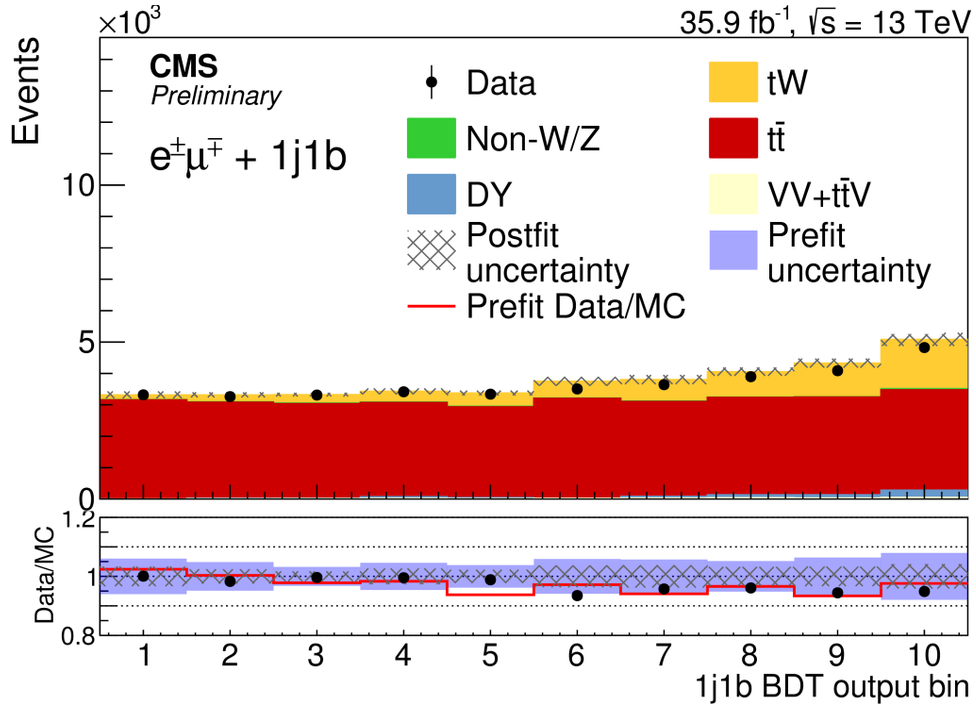
tW, no more a new process

- **tW is entering precision regime** and the differential world
  - Remarkable for a process observed for the first time at the LHC in Run-1 (with 8TeV data)



arXiv:1712.01602

tW differential



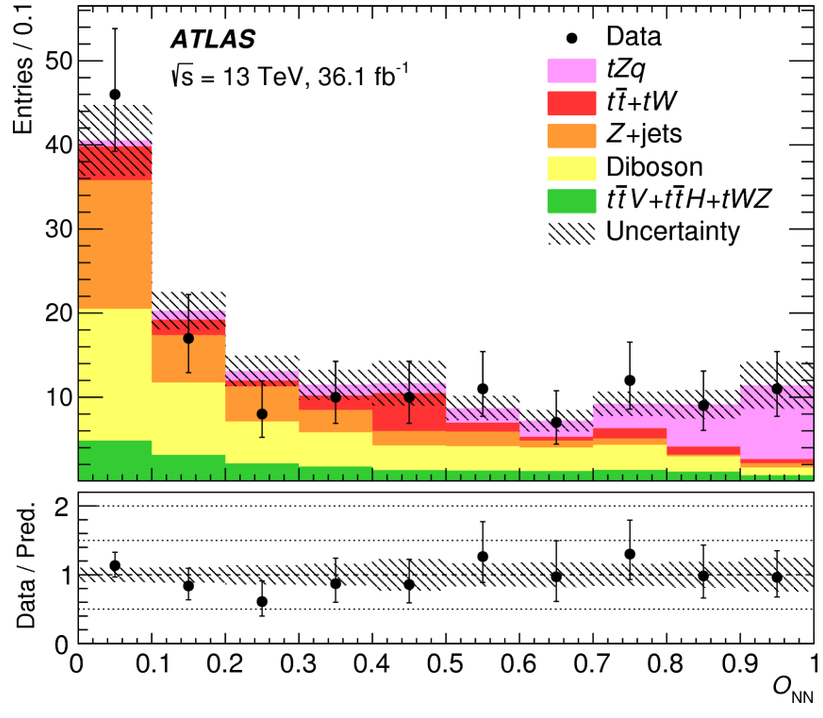
CMS PAS-TOP-17-018

Inclusive, Δσ/σ≈10%

Rare top production

tZq

- 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

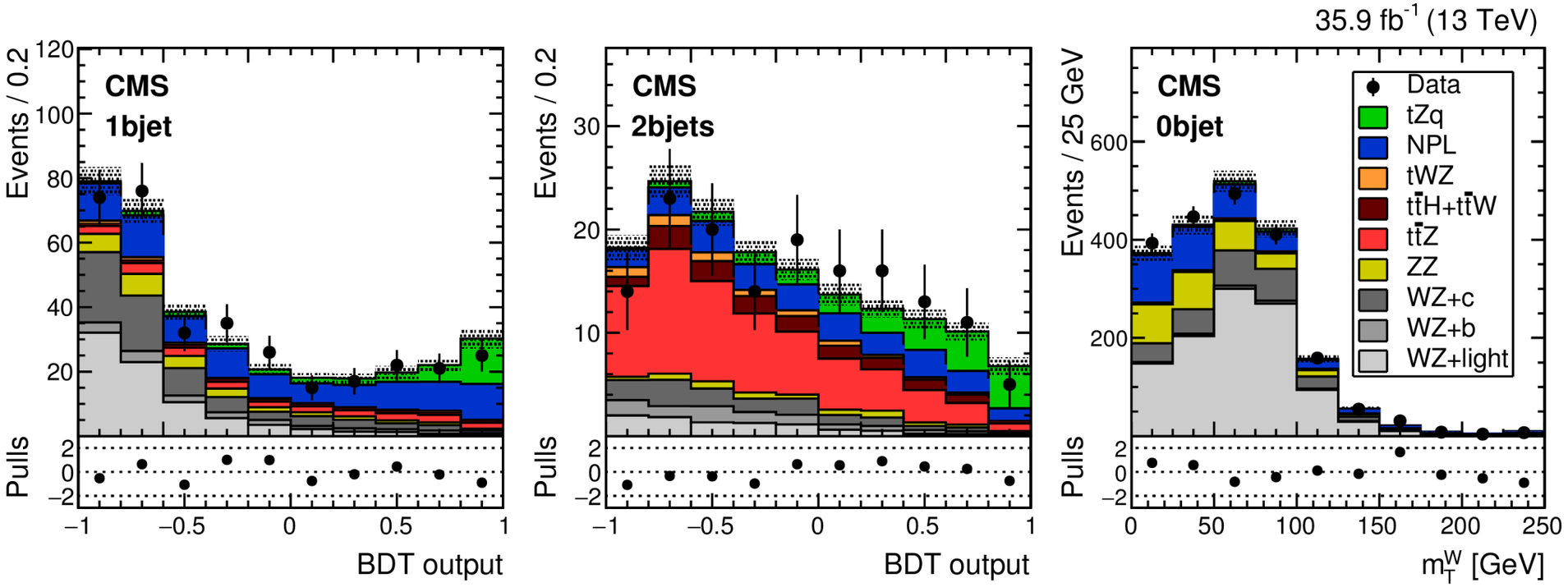


arXiv:1712.02825

SM tZq significance **3.7σ** (3.1σ)

arXiv:1710.03659

SM tZq significance **4.2σ** (5.4σ)



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

Rare production processes 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**

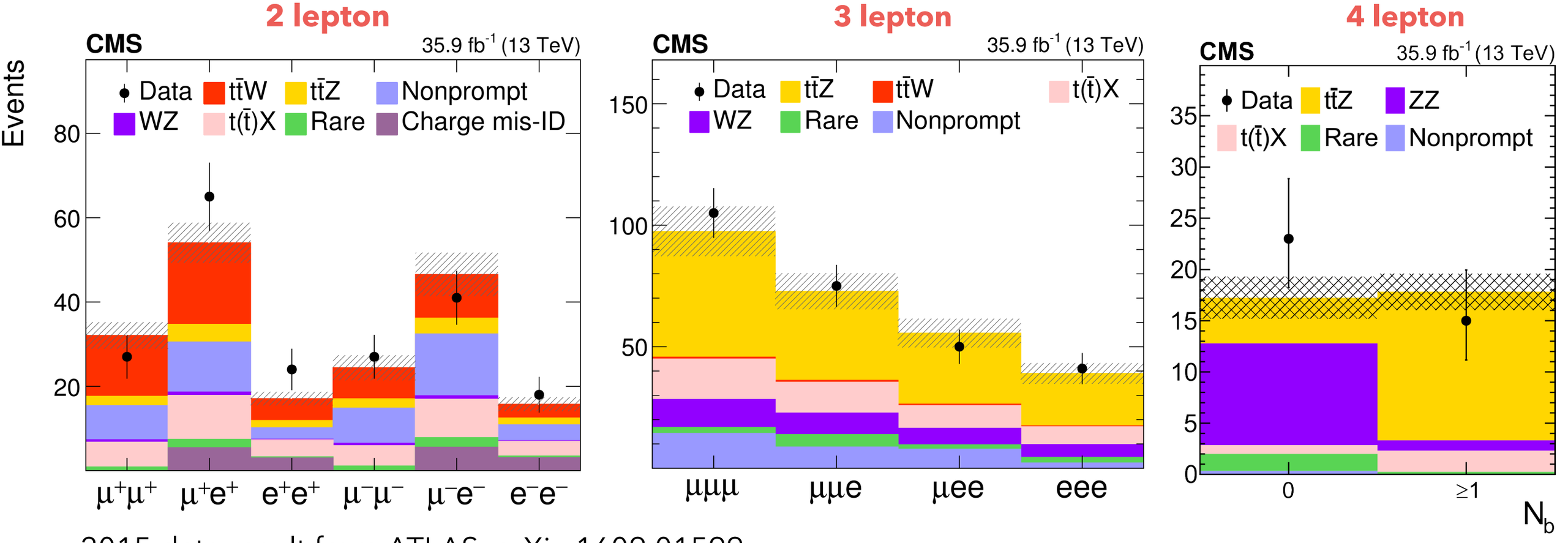
arXiv:1711.02547

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

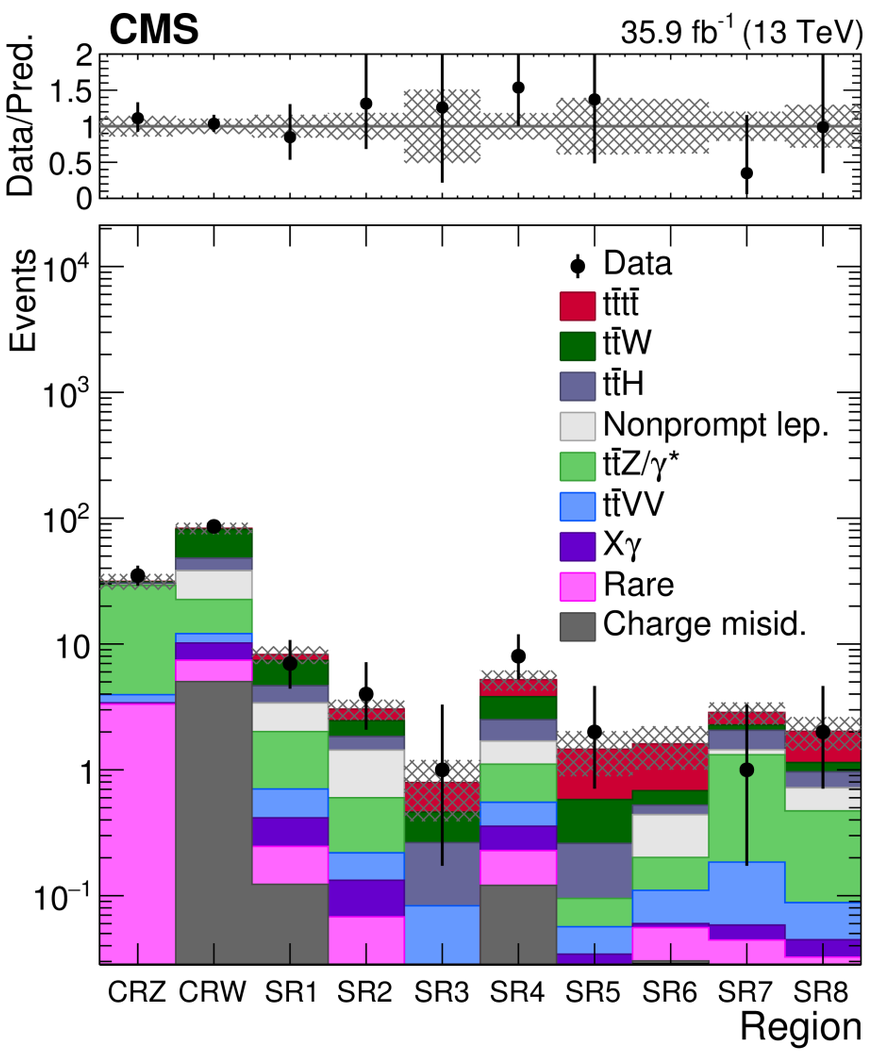
σ_{ttW} = 0.600 (±13%) pb



2015 data result from ATLAS: arXiv:1609.01599

Exciting times ahead

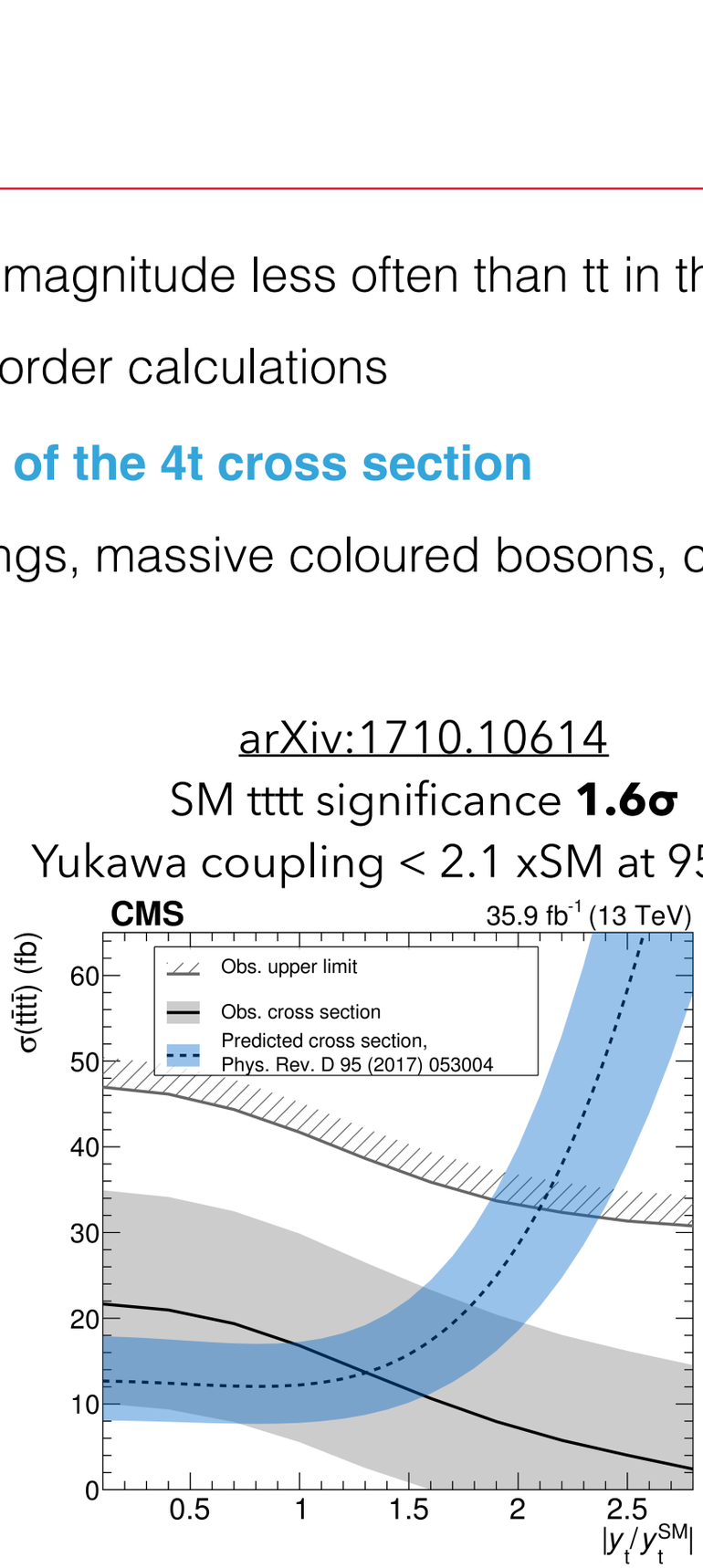
- 4t production is a **VERY** rare production → 5 orders of magnitude less often than tt in the SM
  - Future measurement useful test of analytical higher order calculations
- Before that → **many BSM models predict an increase of the 4t cross section**
  - Particles decaying to top quarks or modified 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

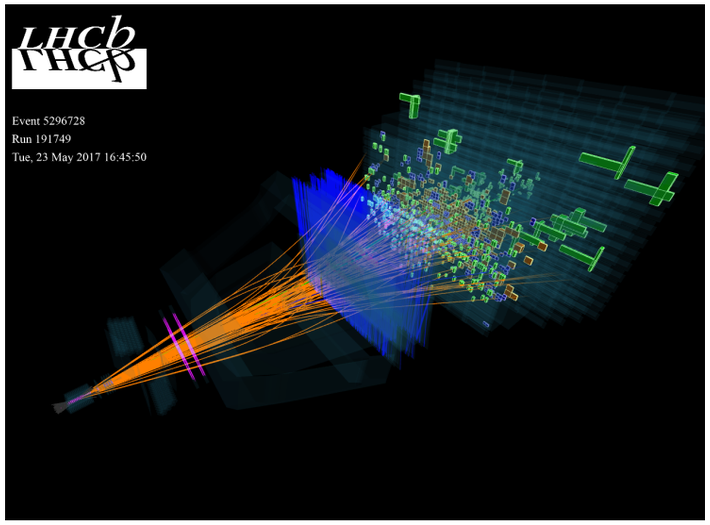


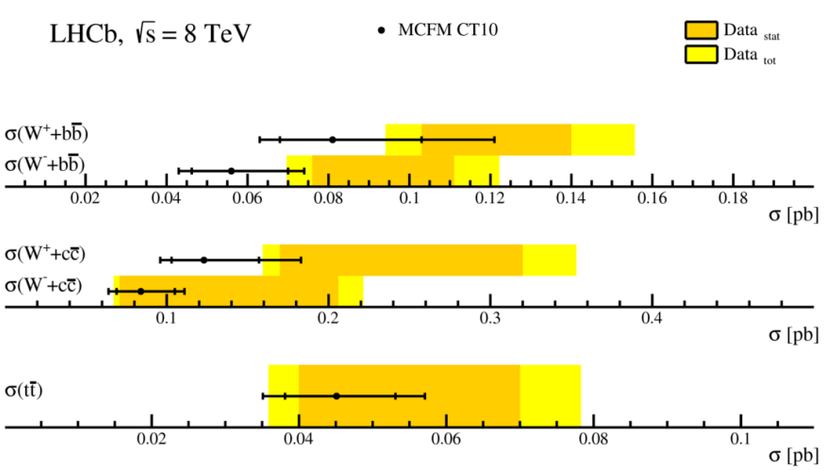
previously at 13TeV arXiv:1702.06164 and ATLAS-CONF-2016-020

Forward top production

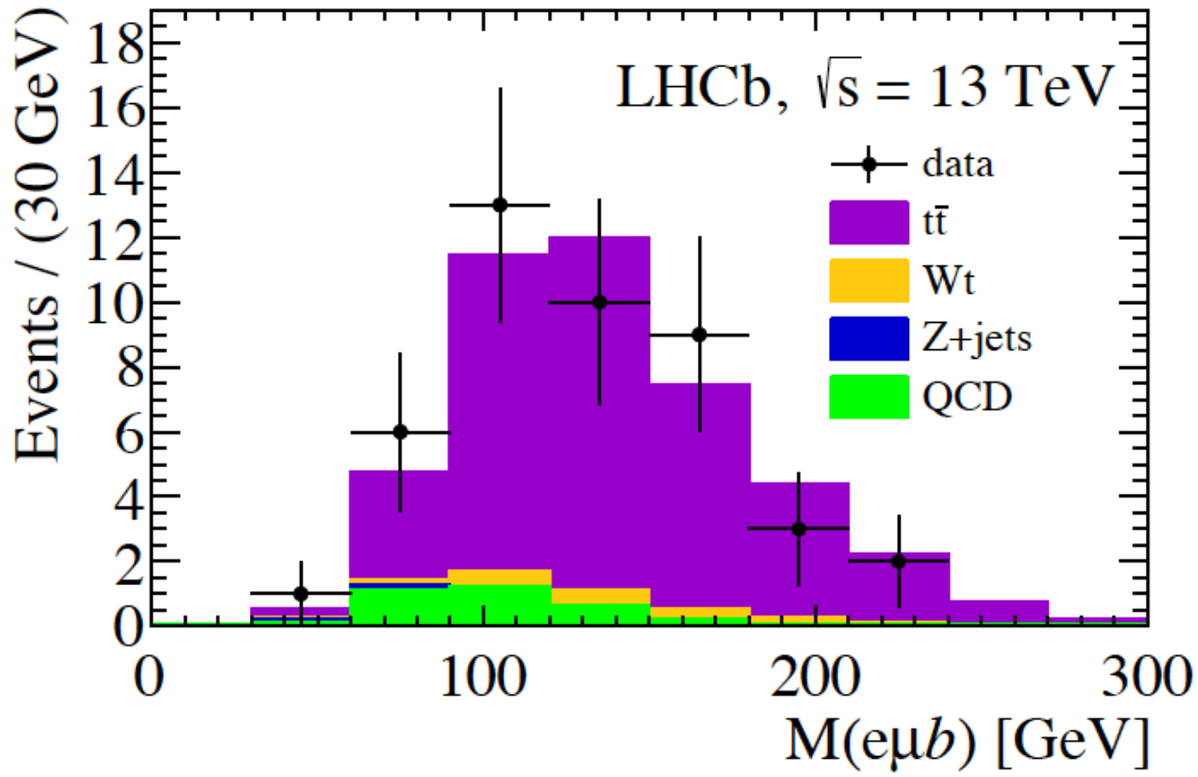
The dawn of a new era

- 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

What will the future hold?

Appetizers

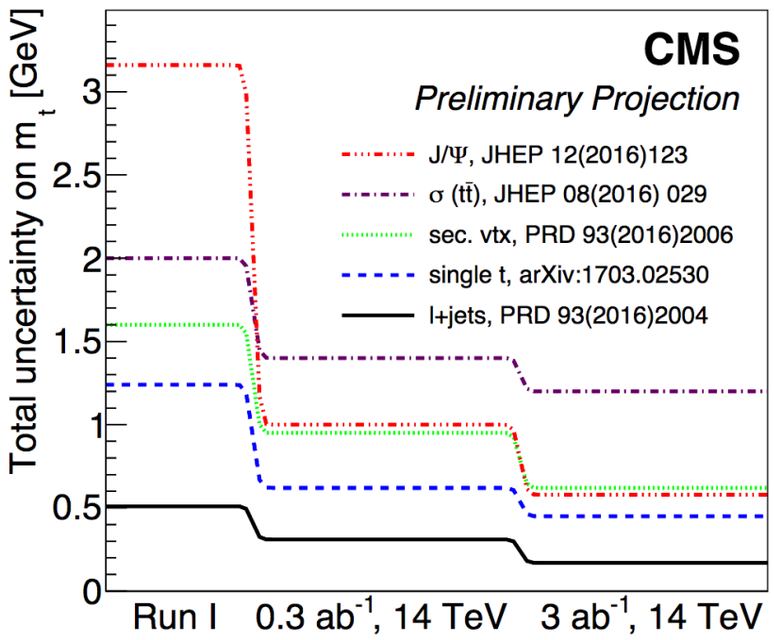
Yukawa coupling

Snowmass: arXiv:1311.2028

Prospects for full LHC programme: Kt → 14-15% (300/fb) / 7-10% (3000/fb)

mass

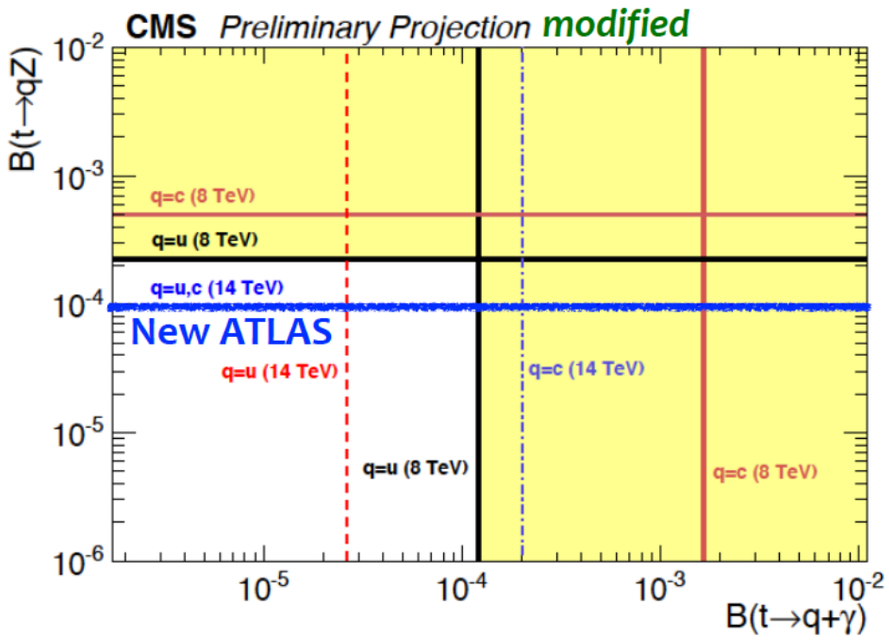
CMS: FTR-16-006

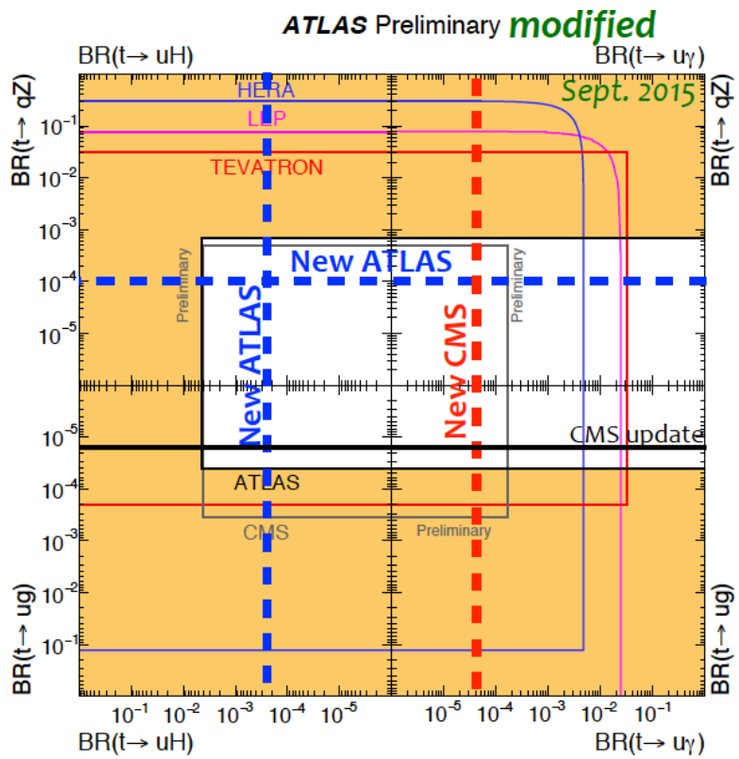


Though the precision already reached seems like a "ceiling", during the LHC's lifetime we still can aim to go as low as ~200MeV

FCNC

ATLAS: ATL-PHYS-PUB-2016-019





In the next months ATLAS and CMS will substantially enlarge the reach of the searches, beyond the LHC it can go even further

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**
  - Run-2 promises to be even better 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