At the top of the Large Hadron Collider

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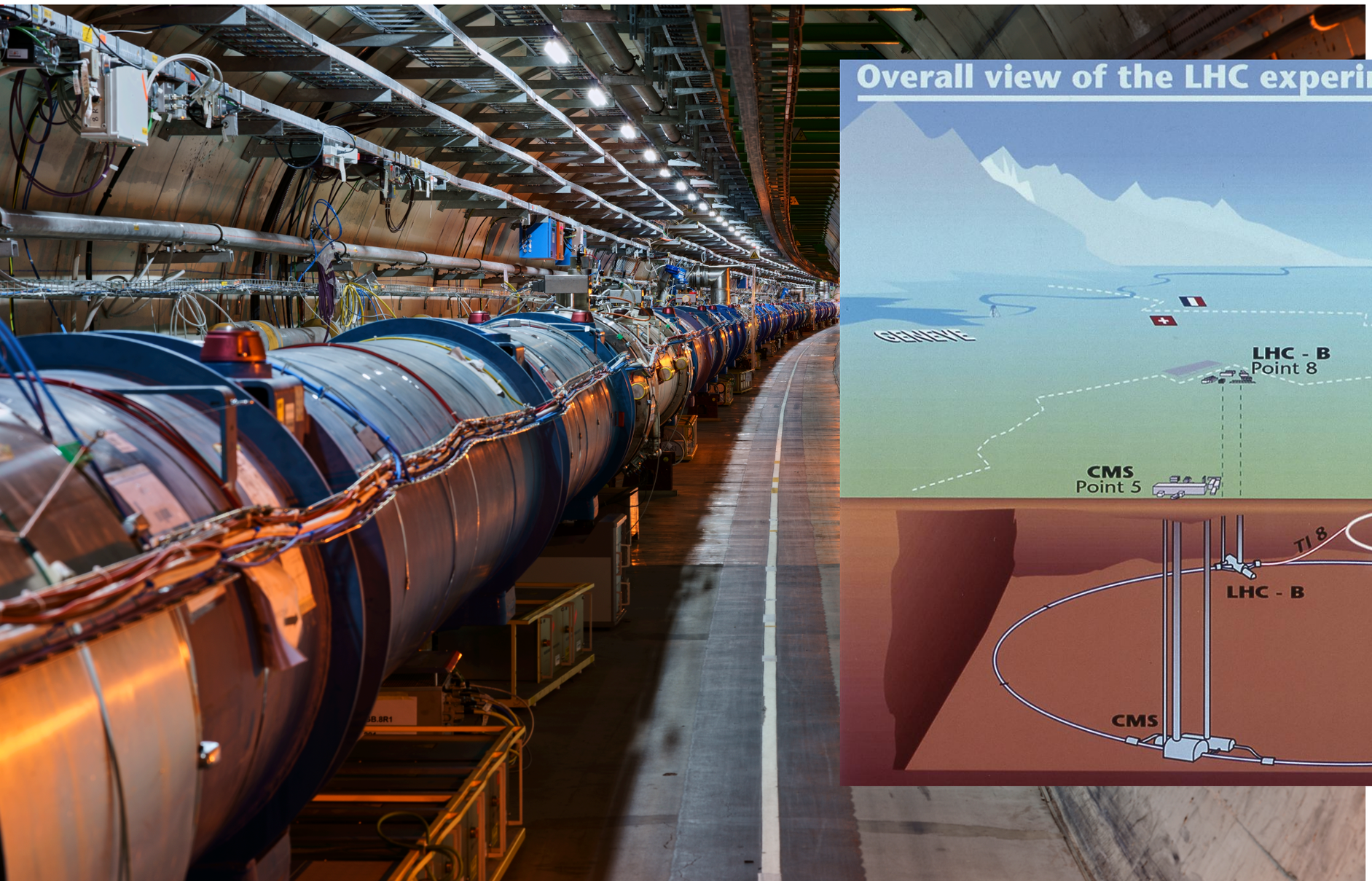
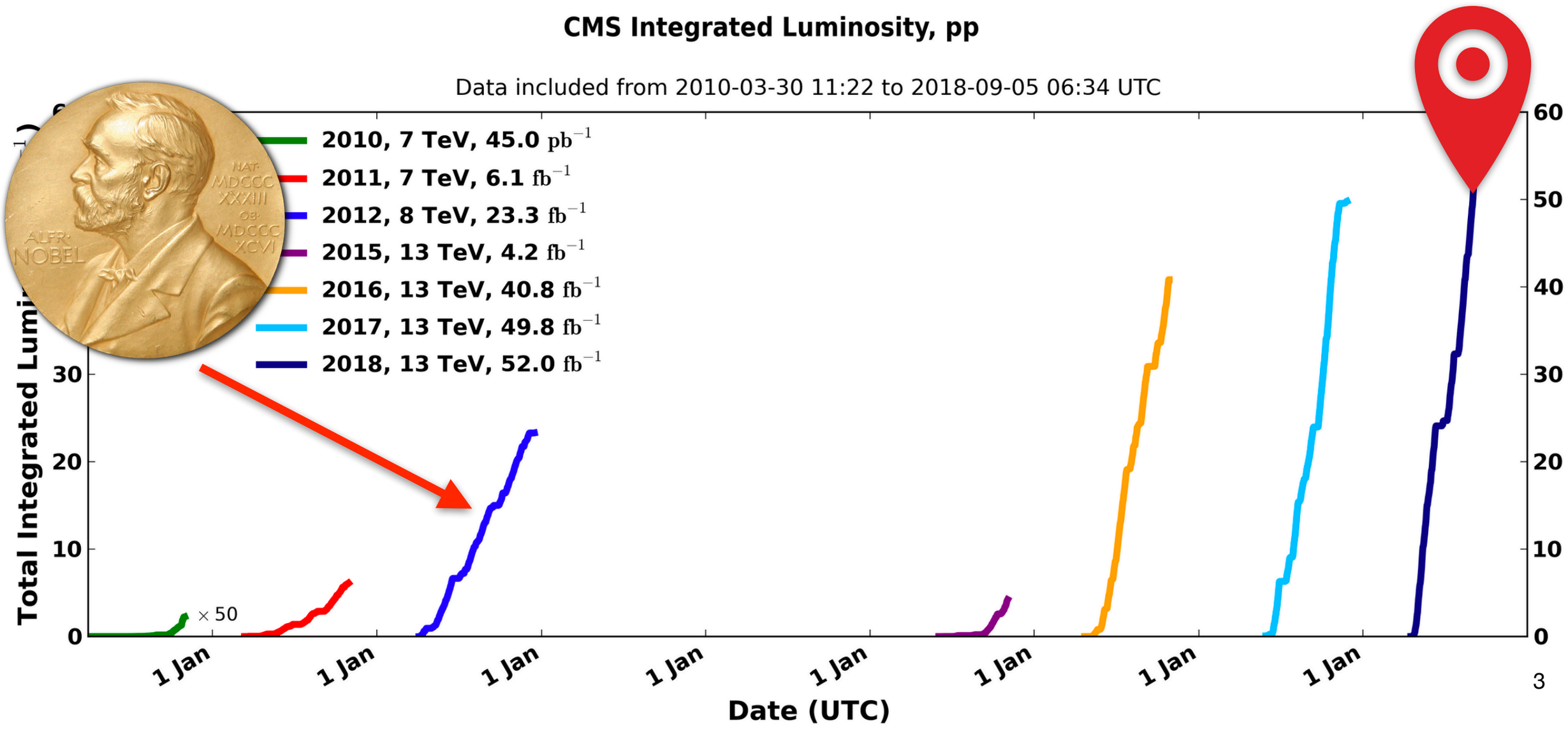
The Large Hadron Collider

- The LHC is the largest and most energetic particle accelerator ever built.
- It collides mostly protons and started operation in 2009.
- It houses 4 big experiments.
  - The largest of them (**ATLAS** and **CMS**) are organized in collaborations of more than 3000 people each and cover the widest possible spectrum of measurements and searches.

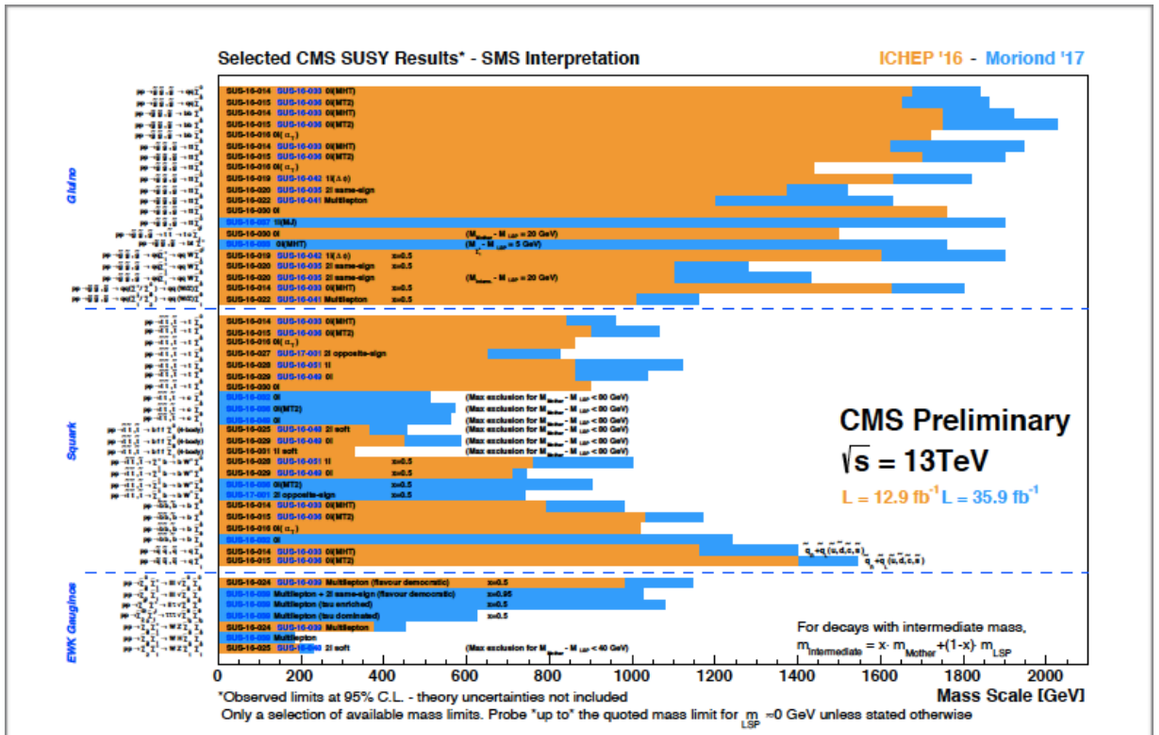


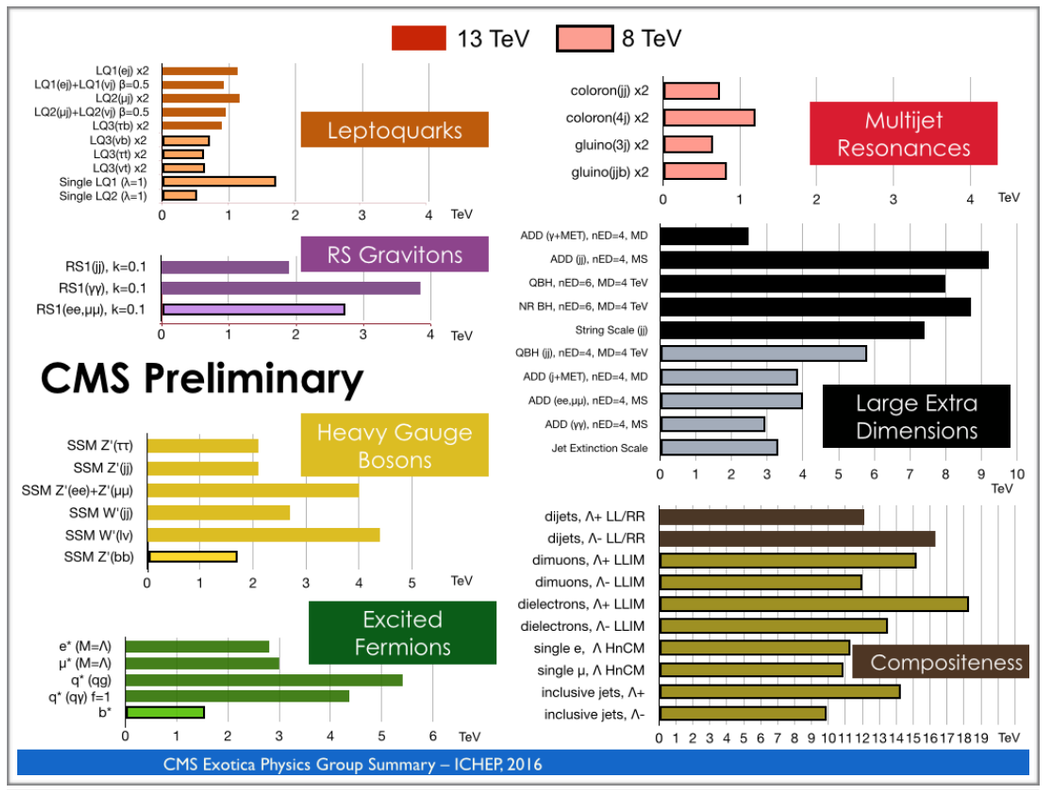
Where do we stand?

- The latest BIG discovery happened 6 years ago:
  - **2012: Higgs boson discovery**
- Since then, the LHC has delivered more than 100fb^{-1} of integrated luminosity, and has increased the collision energy from 7, to 8, and finally to 13TeV



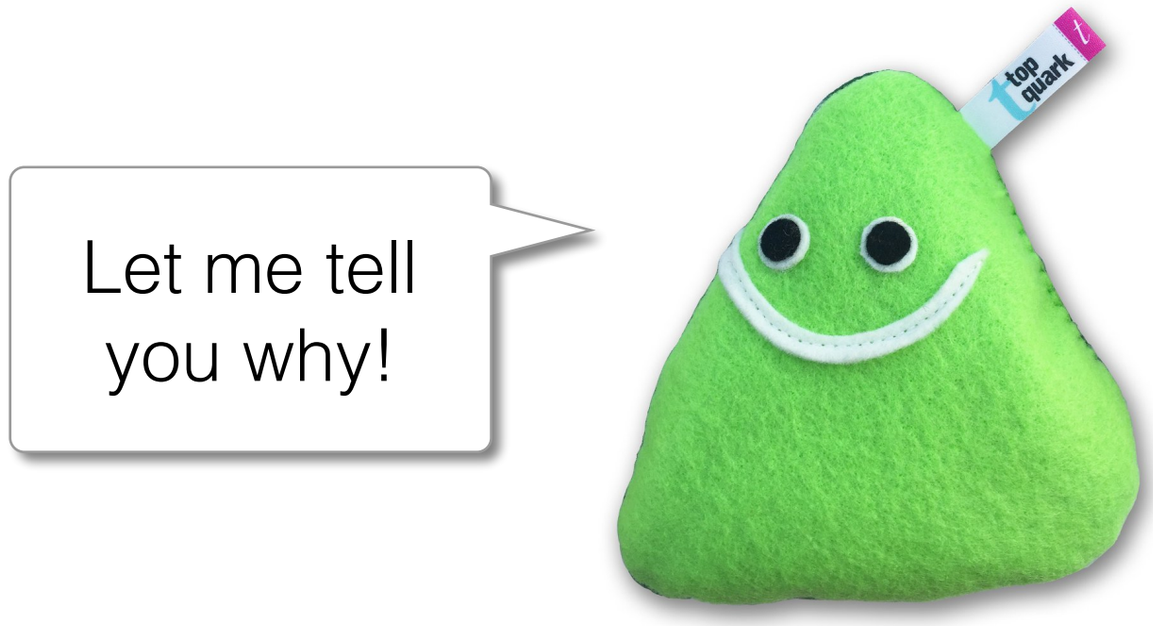
- The hunt for new physics is fully on
  - We want to address the **open questions that the Standard Model (SM) cannot answer yet**
    - *Dark Matter, matter/anti-matter balance in the universe, gravity, neutrino masses… (infinite list)*
- **Considerable effort at the LHC experiments focused on BSM searches**
- But so far: no new particles have been found…





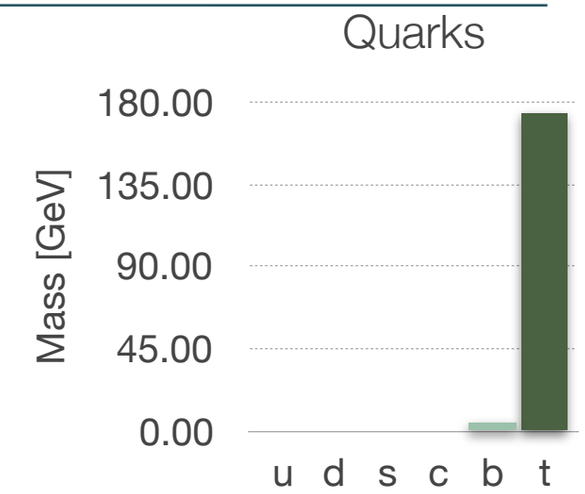
What does this mean?

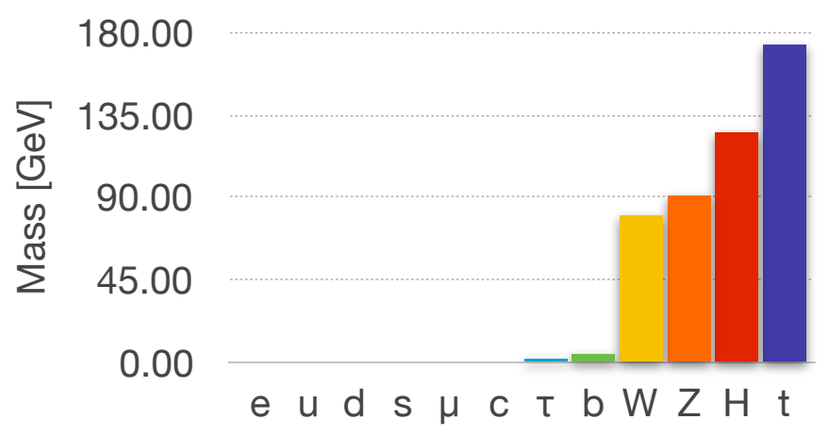
- **New particles may still be out of our reach (or just not exist)**
- **New phenomena could be revealed by precision measurements**
  - Tiny deviations wrt the expectations could open the door to understanding the open questions
- The top quark may be the key to that door
- **Precision measurements on the top quark sector have enormous physics potential, both in SM studies and to constrain BSM effects**

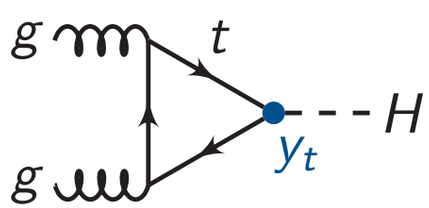


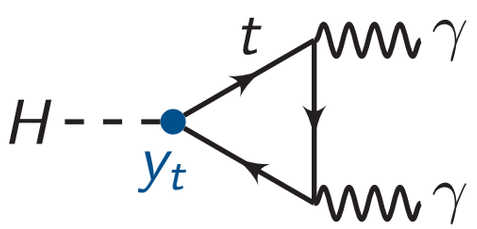
Not like the other quarks

- 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*
  - **Short lived**
    - Decays before it has the time to hadronize
    - Some properties pass directly to the decay products
    - Does not form bound states
      - → *no top mesons, no toponium*
- **Couples strongly to Higgs**
  - Impact on the Higgs sector
  - Deep connection





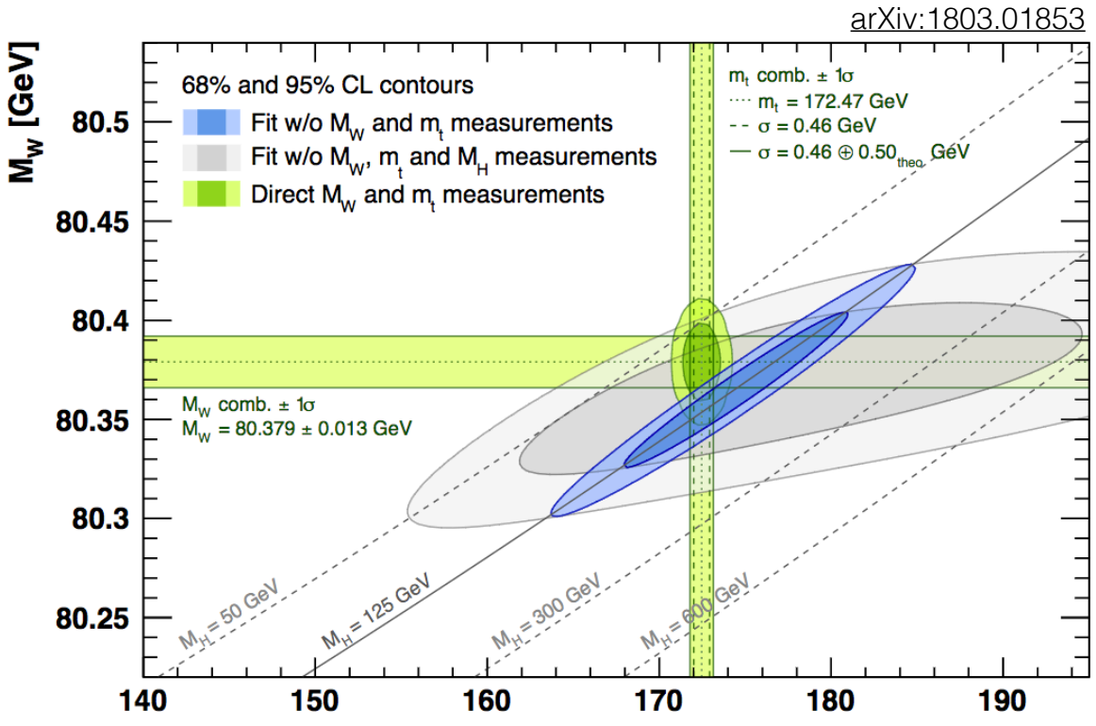


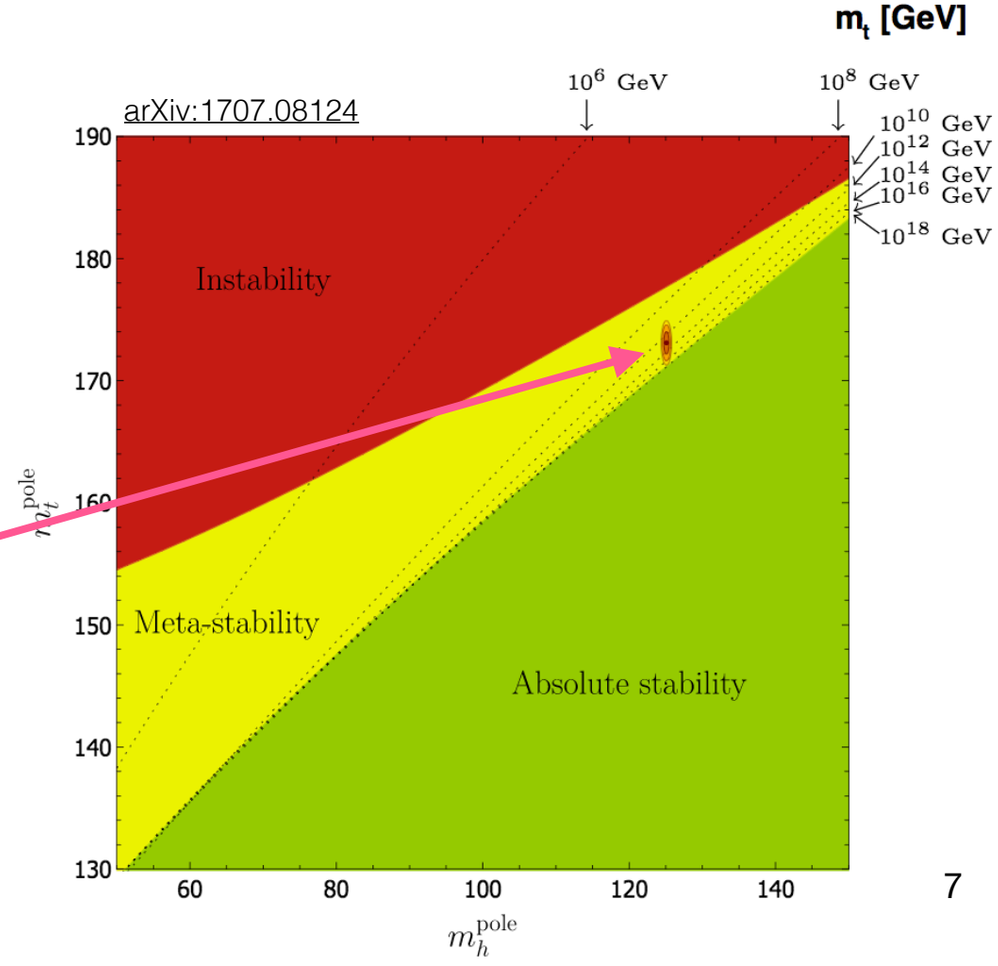


Every (top) precision measurement is a search

- When testing 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**

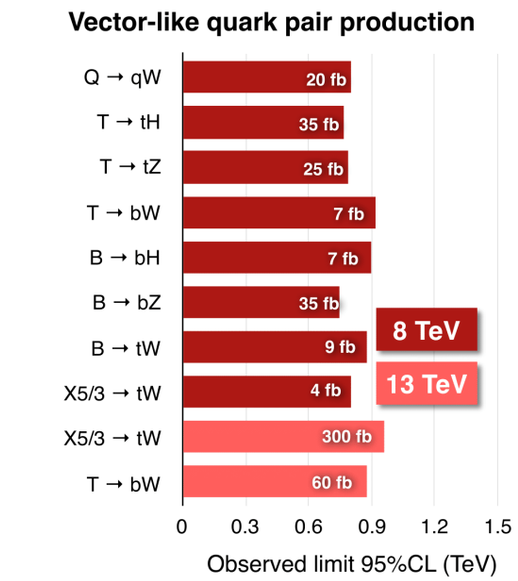
You are here
(current world average)

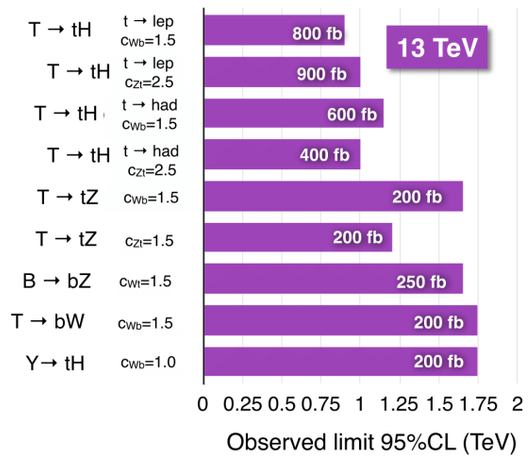


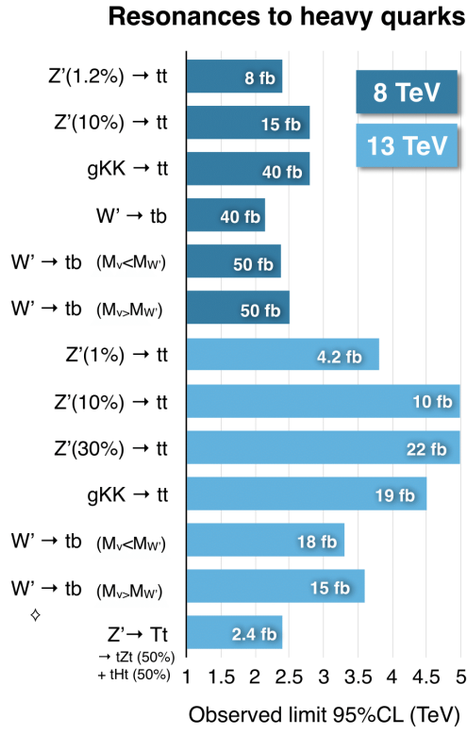


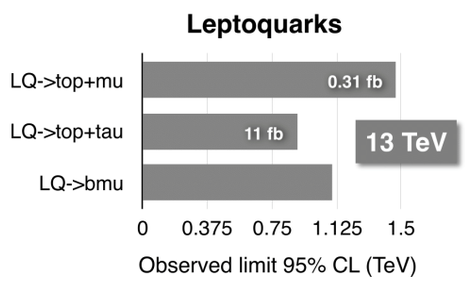
And there are many searches with top

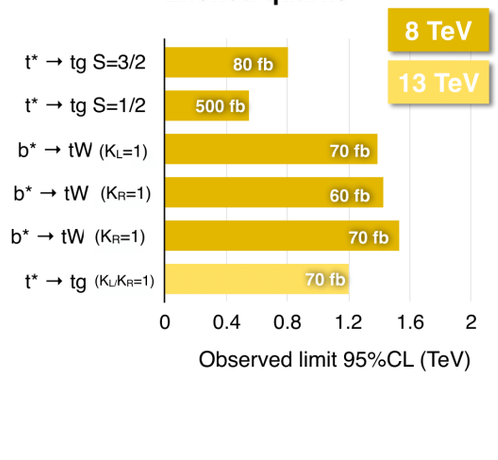
- The top quark is a main ingredient of many **new physics scenarios**
  - Exotic partners, rare decays, heavy new particles decaying to top, new particles produced together with top…

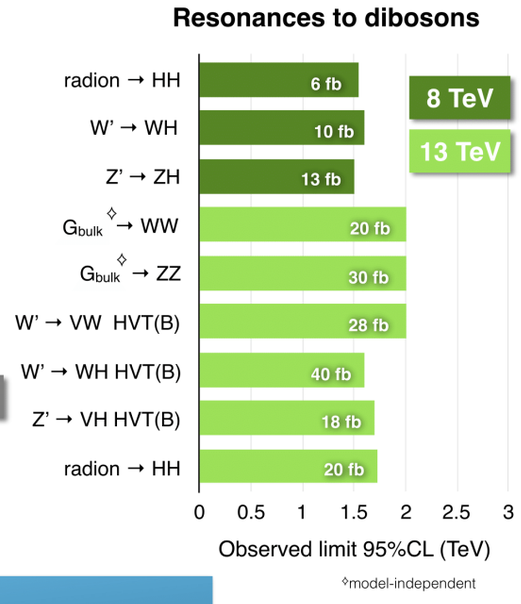










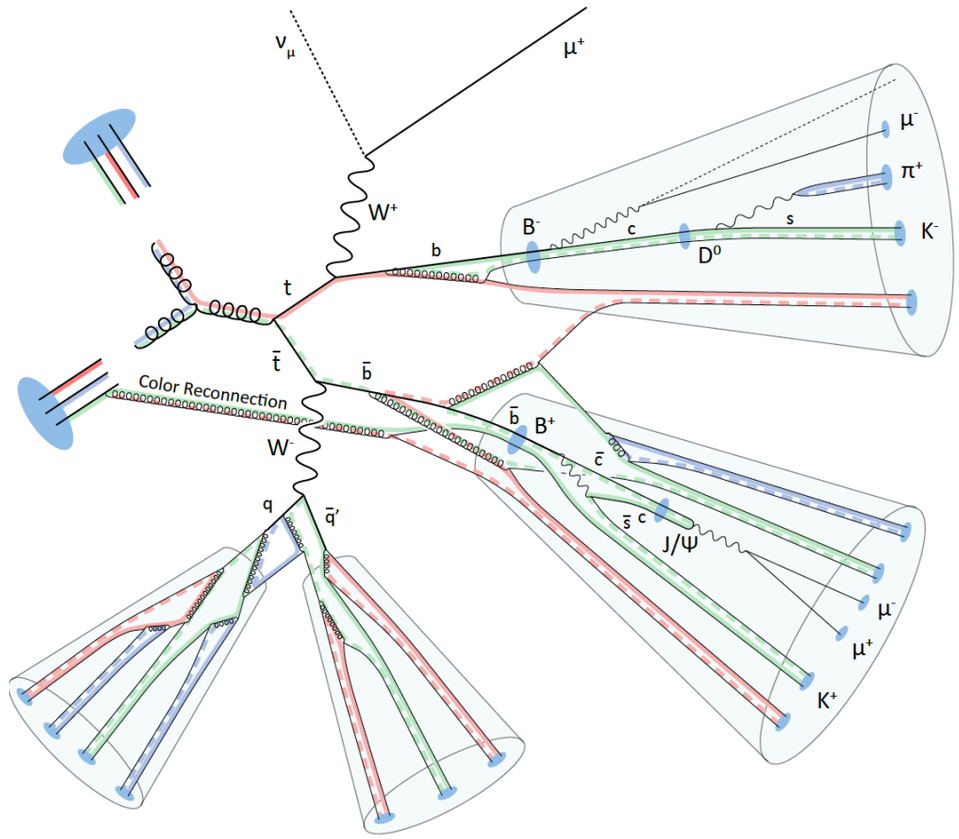


B2G
new physics searches with heavy SM particles

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

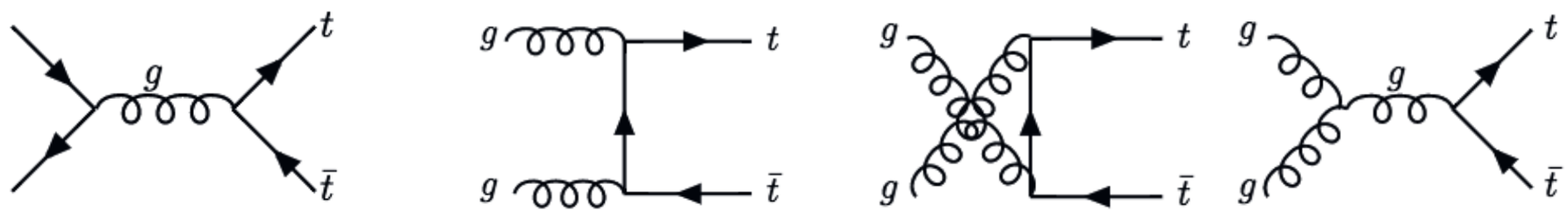


- And either:
  - Isolated leptons
  - Neutrinos → invisible, inferred from missing transverse energy (MET)
  - AND/OR
    - jets coming from lighter quarks

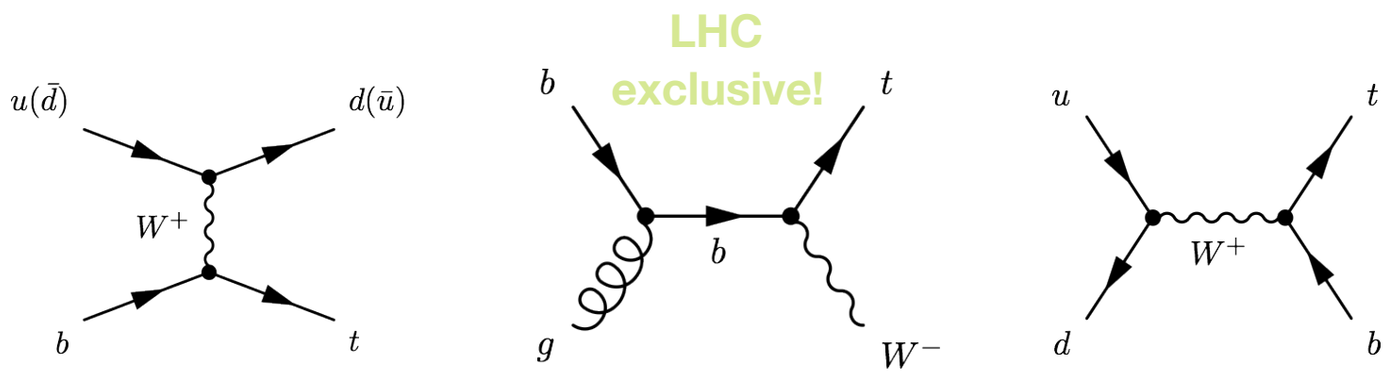
Using the full potential of the LHC experiments

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



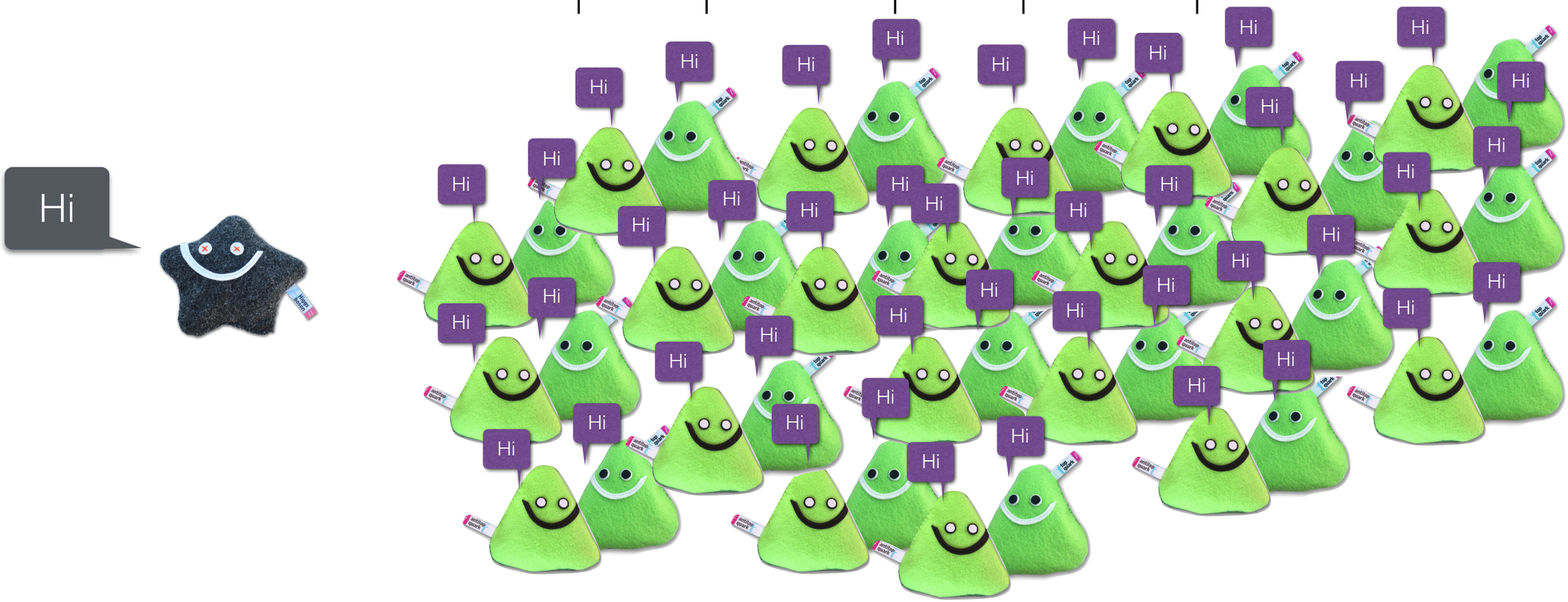
- Then there are **many** other smaller modes of production:
  - (t)t+X (X= W, Z, γ, H, bb, tt, …)

A certified **top quark factory**

- 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

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

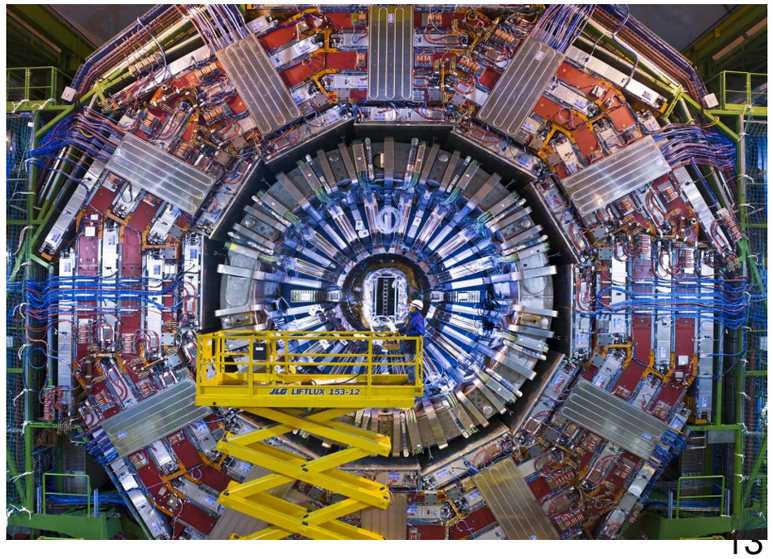


- Top is background of virtually **everything** at the LHC → **we need to know it well!**

Why am I telling you this?

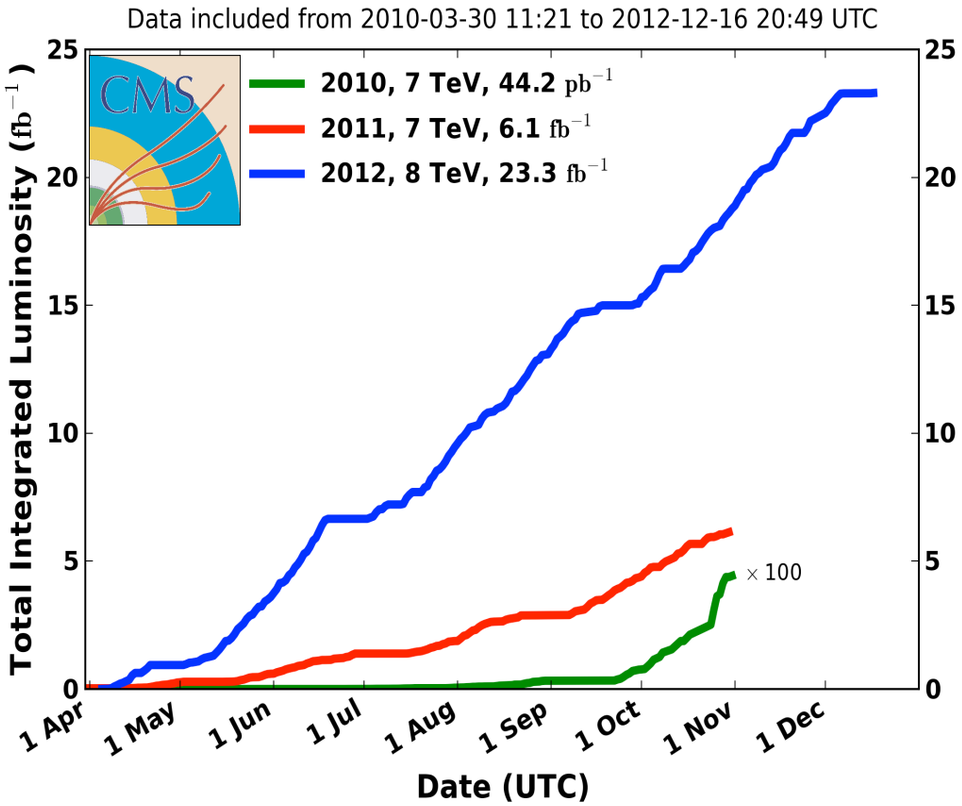
- During the last 2 years I was in charge of the top quark physics group at the CMS Collaboration.
  - I coordinated all physics analyses related to SM top quarks.

- This is why **this talk will be slightly biased towards CMS results**.
  - ATLAS usually has a similar set of results, both experiments complement each other and confirm each other findings very well.



The beginning of times: 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

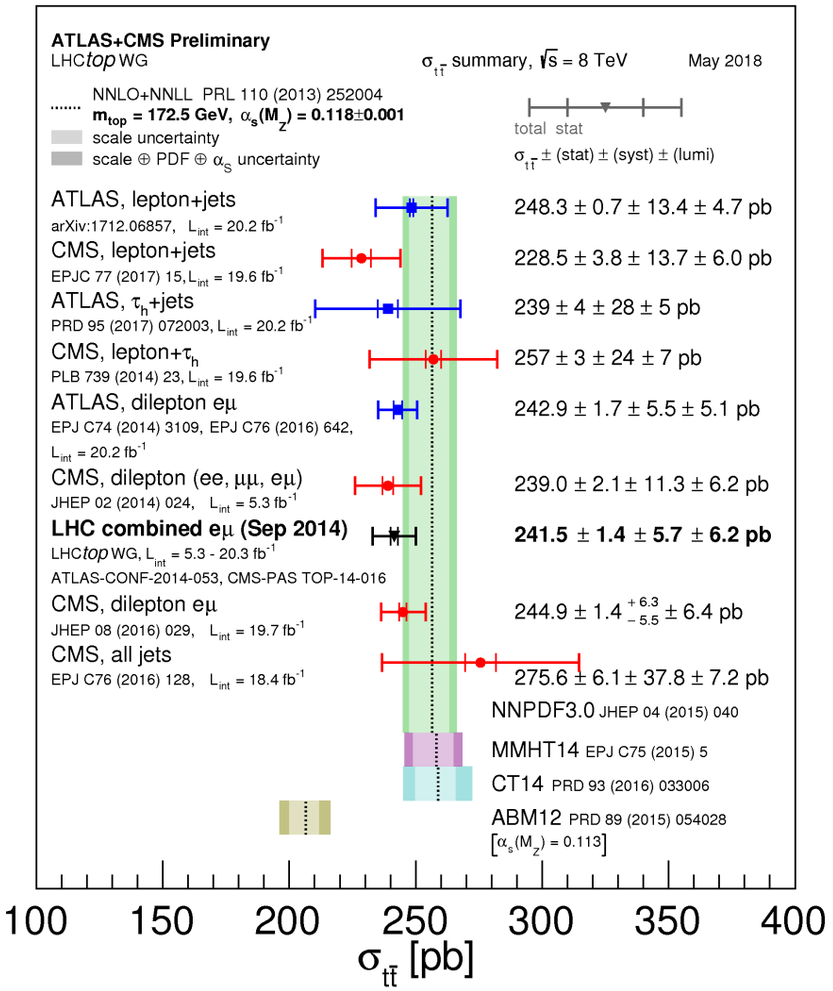
This was enough to establish a **very healthy top Run-1 Legacy**

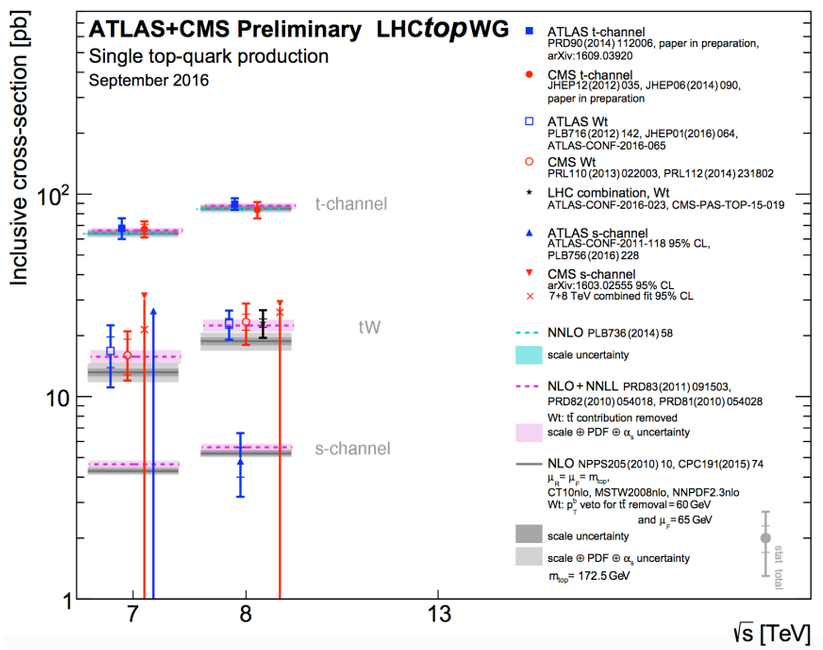
With a good number of ATLAS+CMS combinations (and even a world combination!)

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



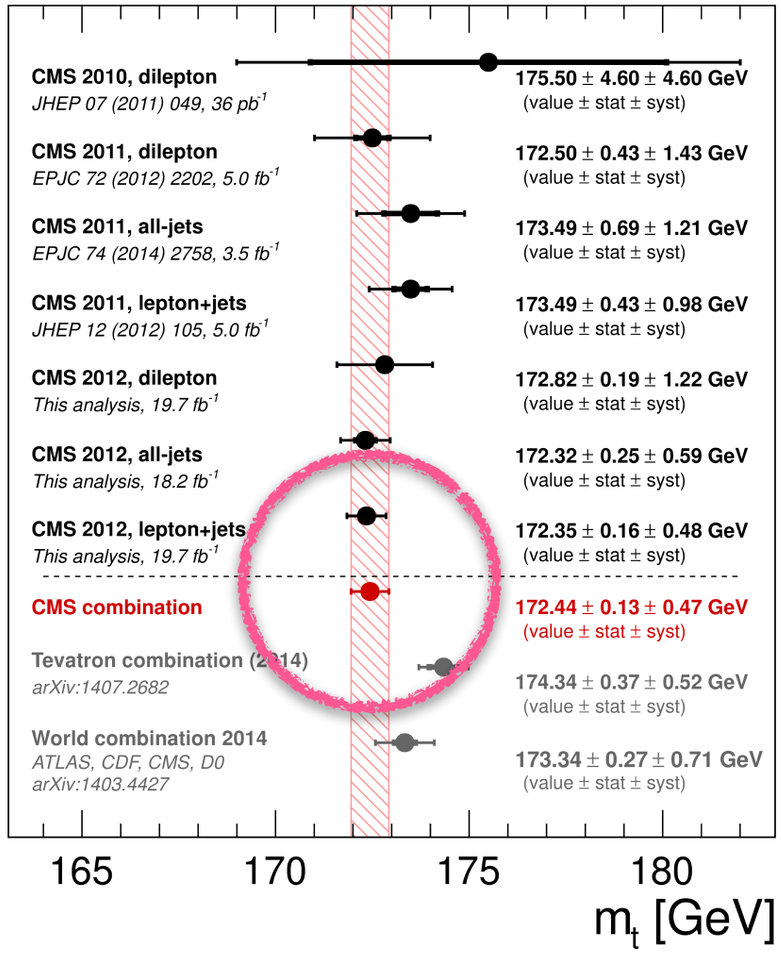


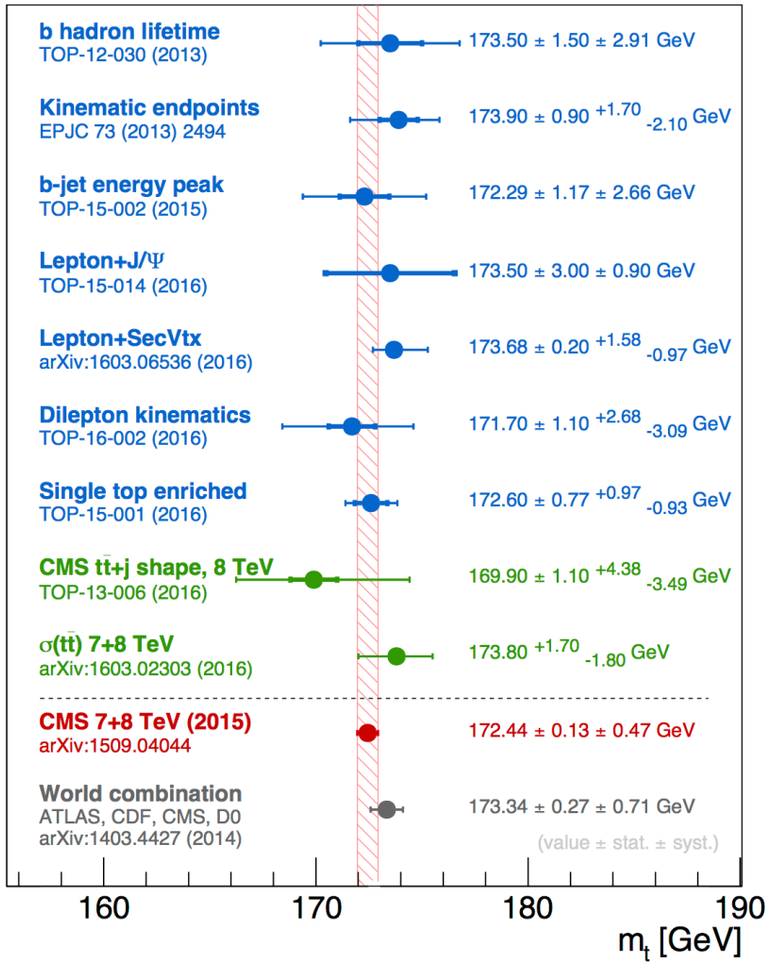
The Run-1 legacy

- **Properties**
  - Very close to the high precision regime
  - Everything consistent with the SM predictions so far
- Top mass: Flagship property!
  - A variety of dedicated measurements
  - Extremely precise ±0.48 GeV (0.3%)

Shopping list:

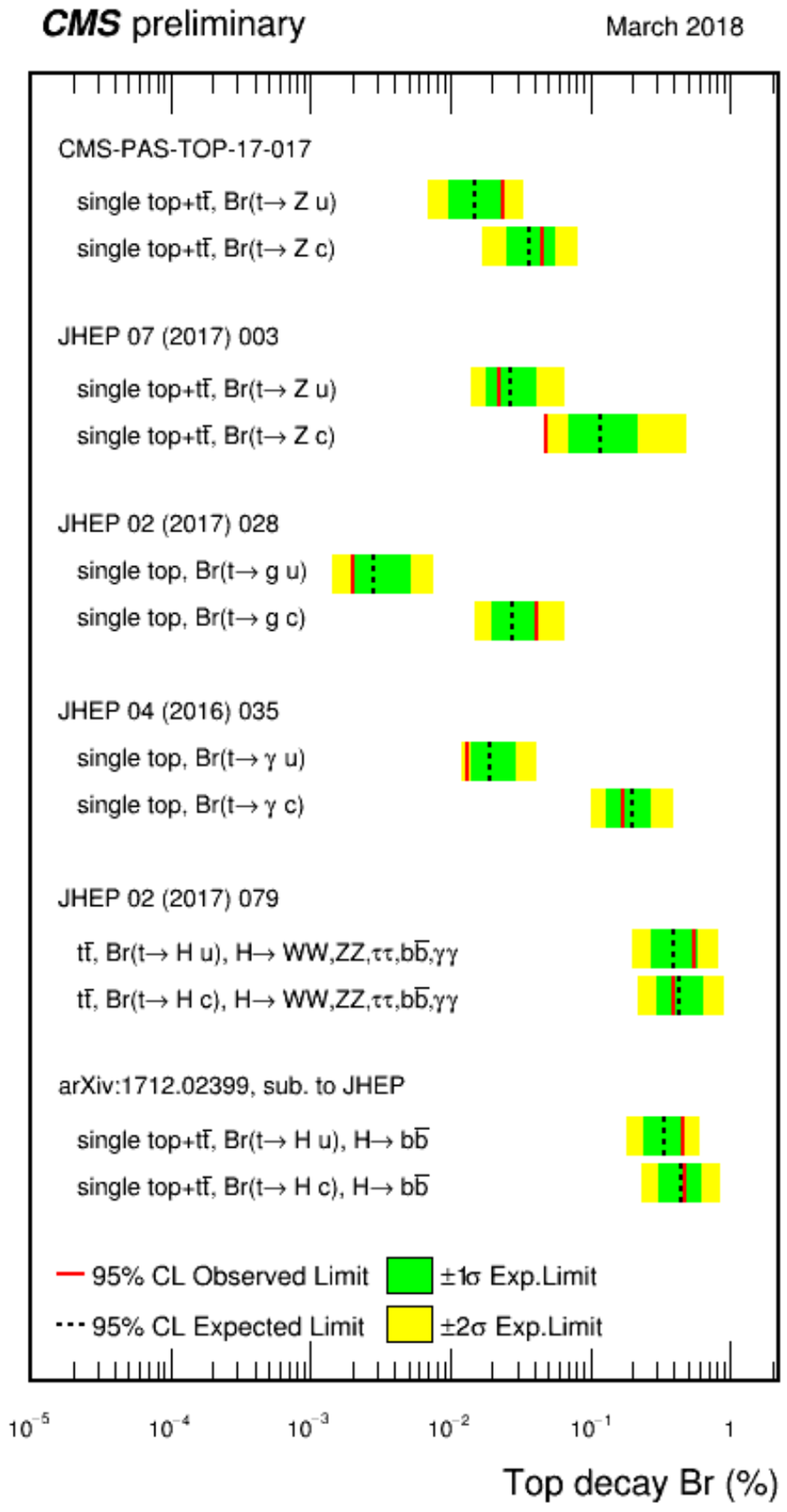
Asymmetries (charge)
W-helicity fractions
Spin correlations
Top polarization
BR (t→Wb)
$|V_{tb}|$ CKM matrix element
Top quark width
CP violation tests





The Run-1 legacy

- We studied top quark pairs produced together with many other particles
  - Insight on top quark couplings
  - Achieved observation of ttV
- New physics searches with top quarks
  - A number of searches in many channels
  - **No signs of new physics**
    - But the possibilities are still unlimited



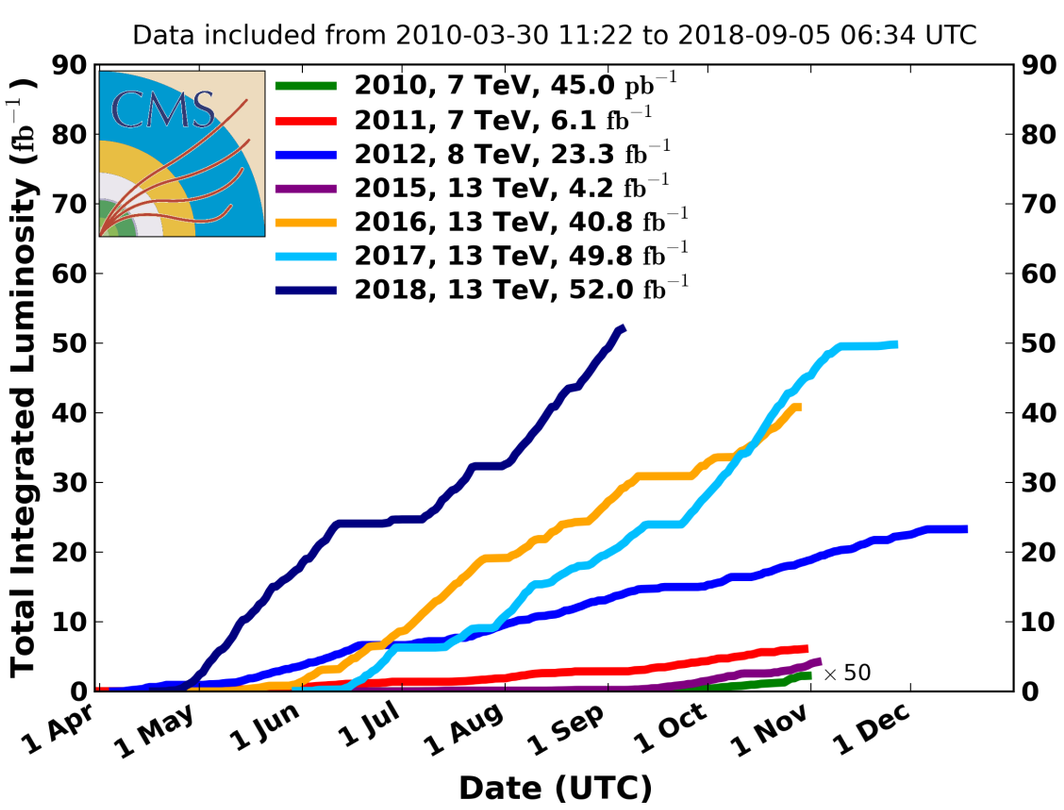
Run-2

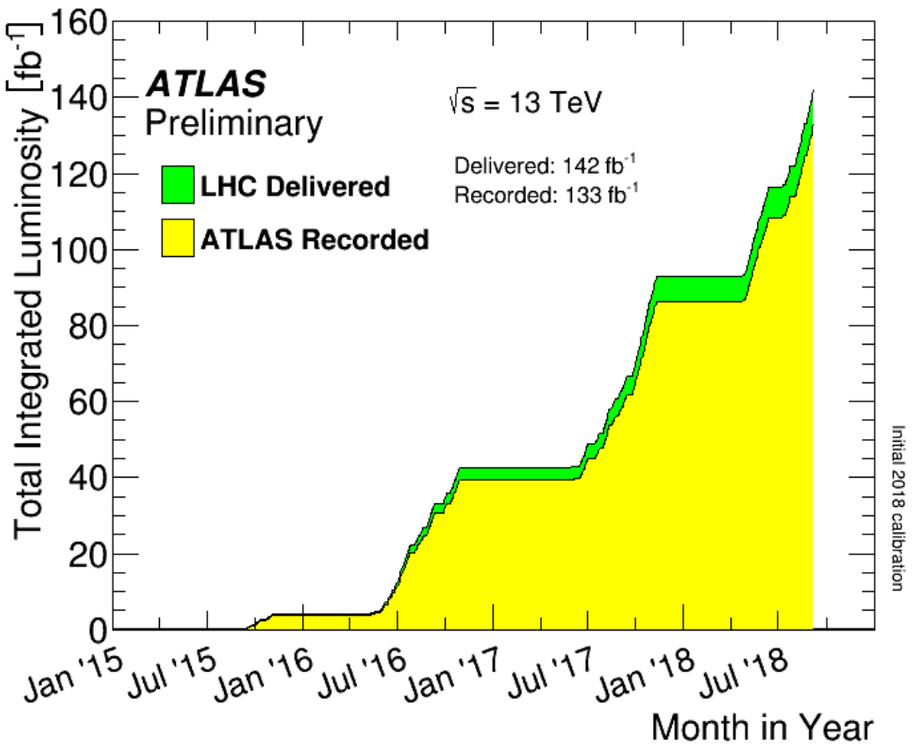
LHC pp data

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

$>130fb^{-1}$ at 13TeV

$100fb^{-1}$ was the goal for Run-2



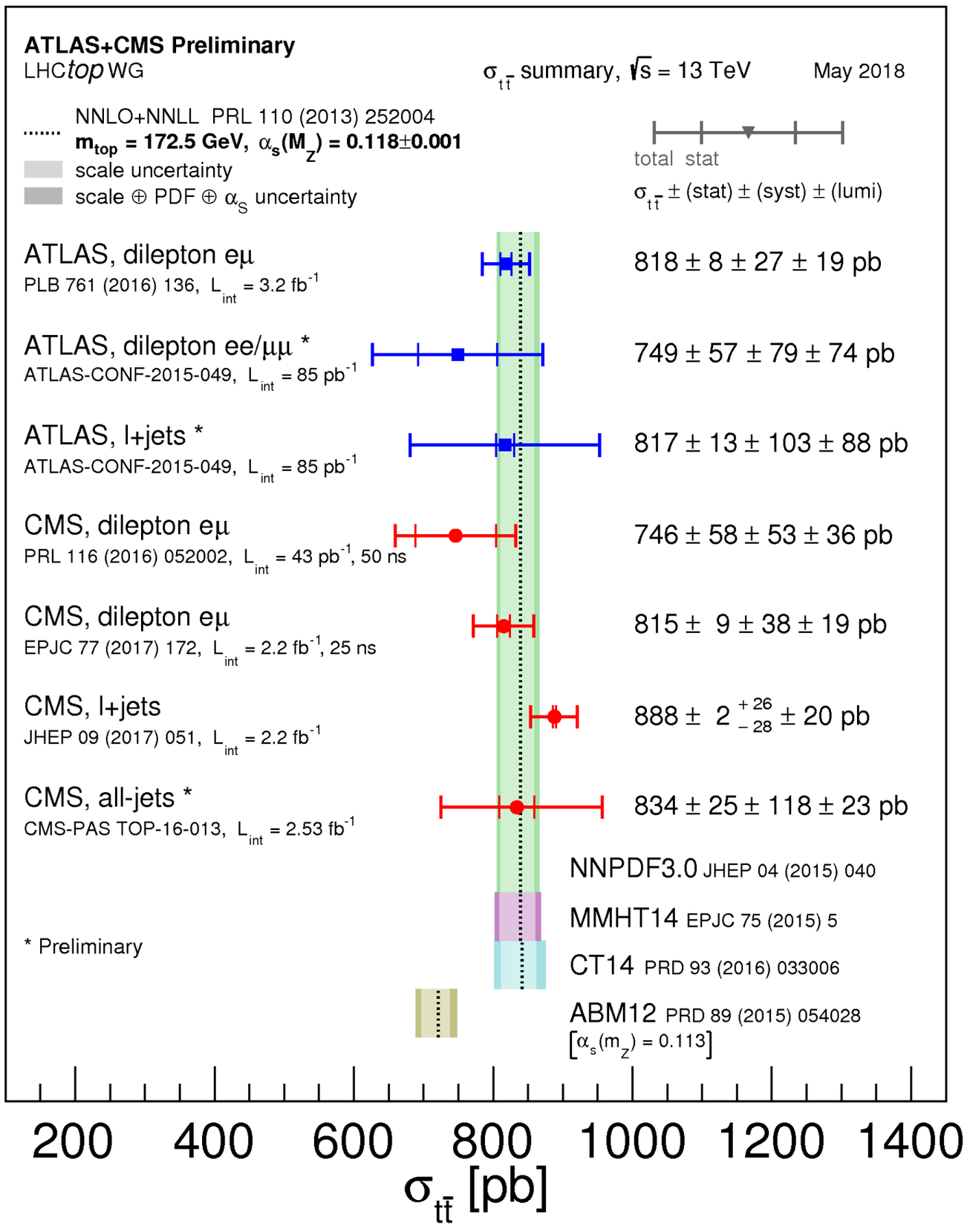


The legacy that is to come will be even better

- 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 physics at the LHC



- Early measurements at any new energy regime
- Deviations from the predictions would be a 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

- The LHC delivered in 2015 **pp collisions at 5.02 TeV**, as a reference run for Heavy Ions

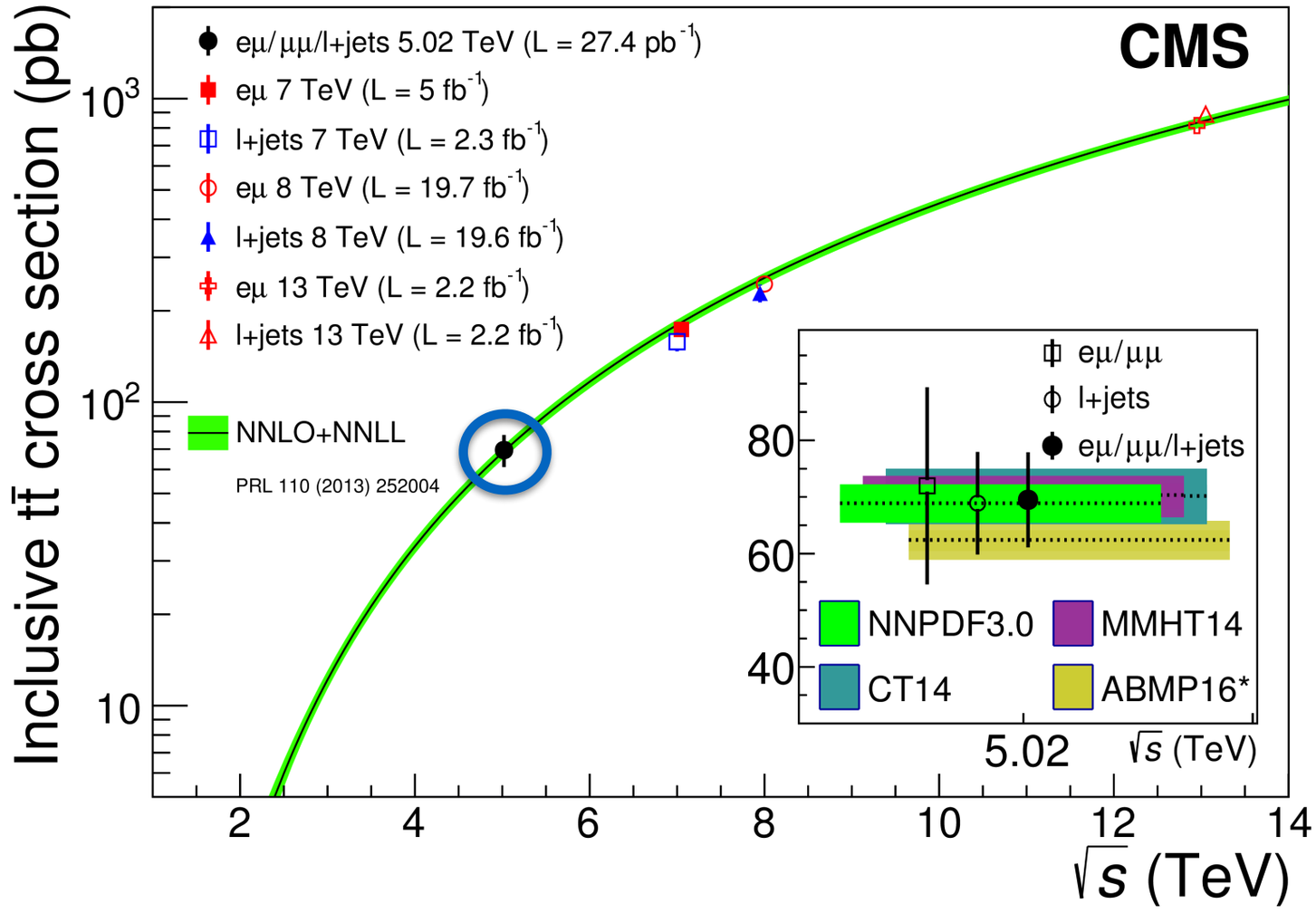
Surprise √s! 5TeV

Reference for nuclear measurements at that energy

1711.03143

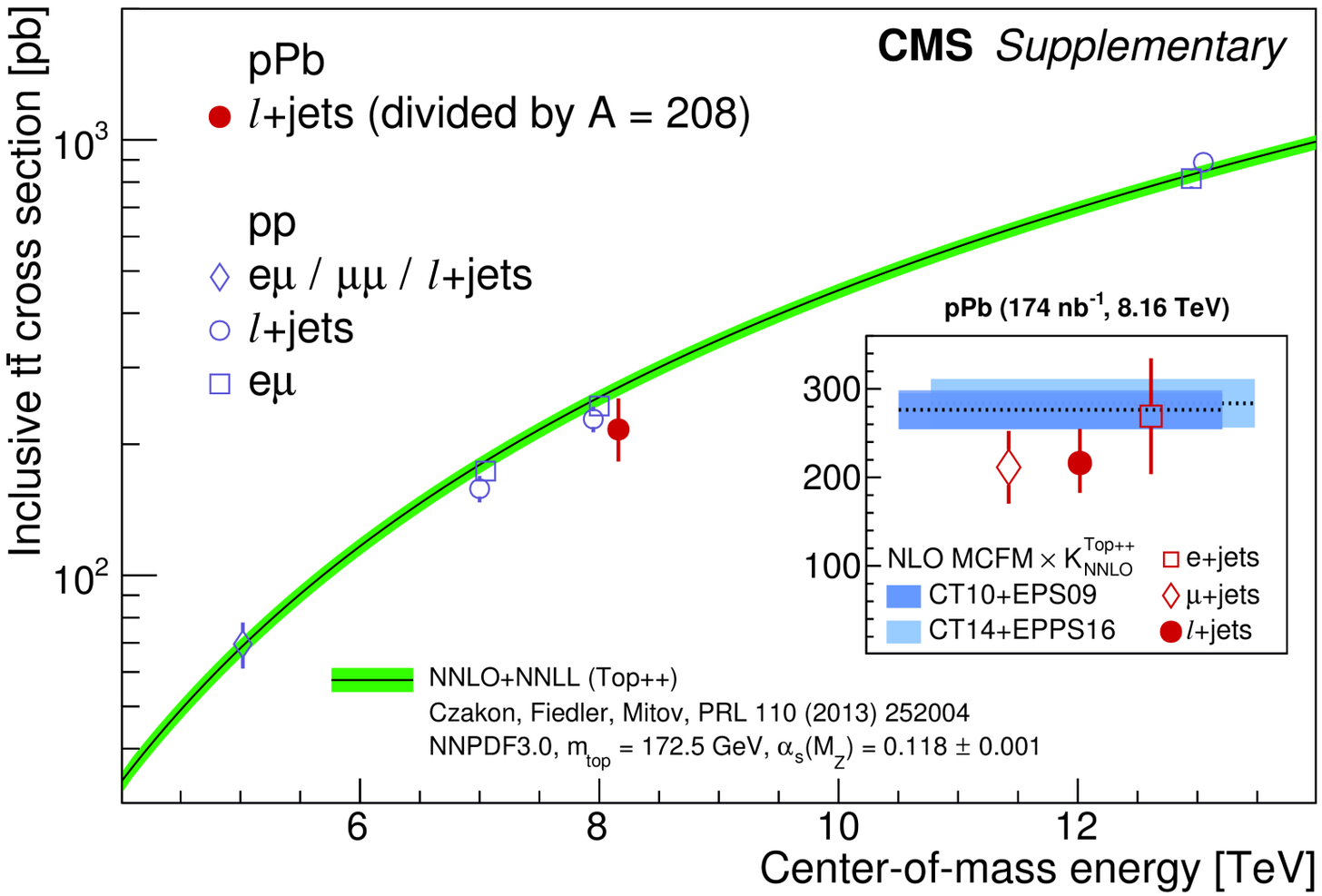
Δσ/σ≈12%

Also useful to constrain PDFs



Inclusive tt cross sections: the oddballs II

- Then we also did measure tt production in **proton-nucleus (pPb) collisions at 8.16TeV**



Surprise collision type! pPb

First observation (> 5σ) of top quarks in heavy ions

1709.07411

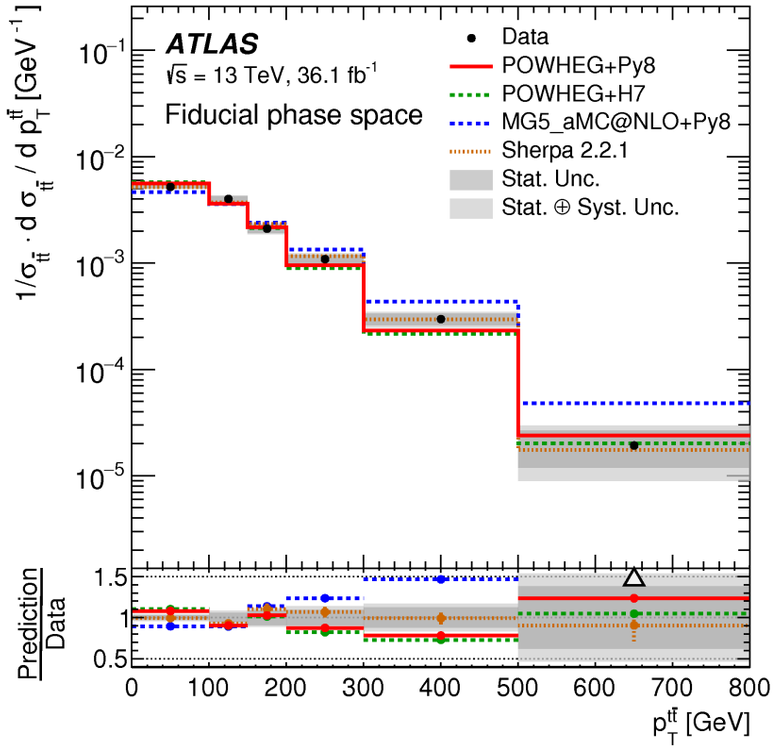
Δσ/σ≈18%

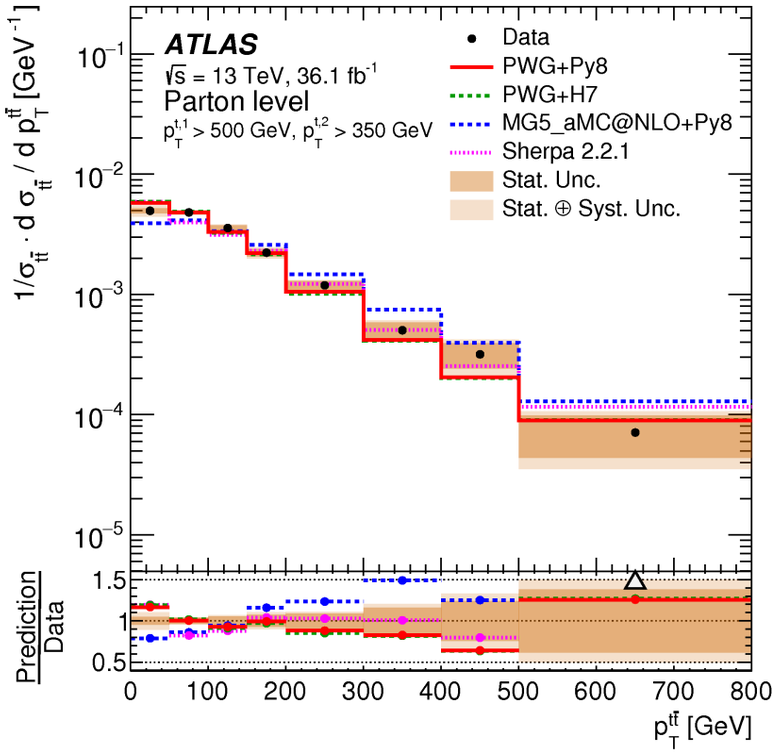
Paves the way for future measurements in Heavy Ions

Differential tt cross sections

Differential tt cross sections

- 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



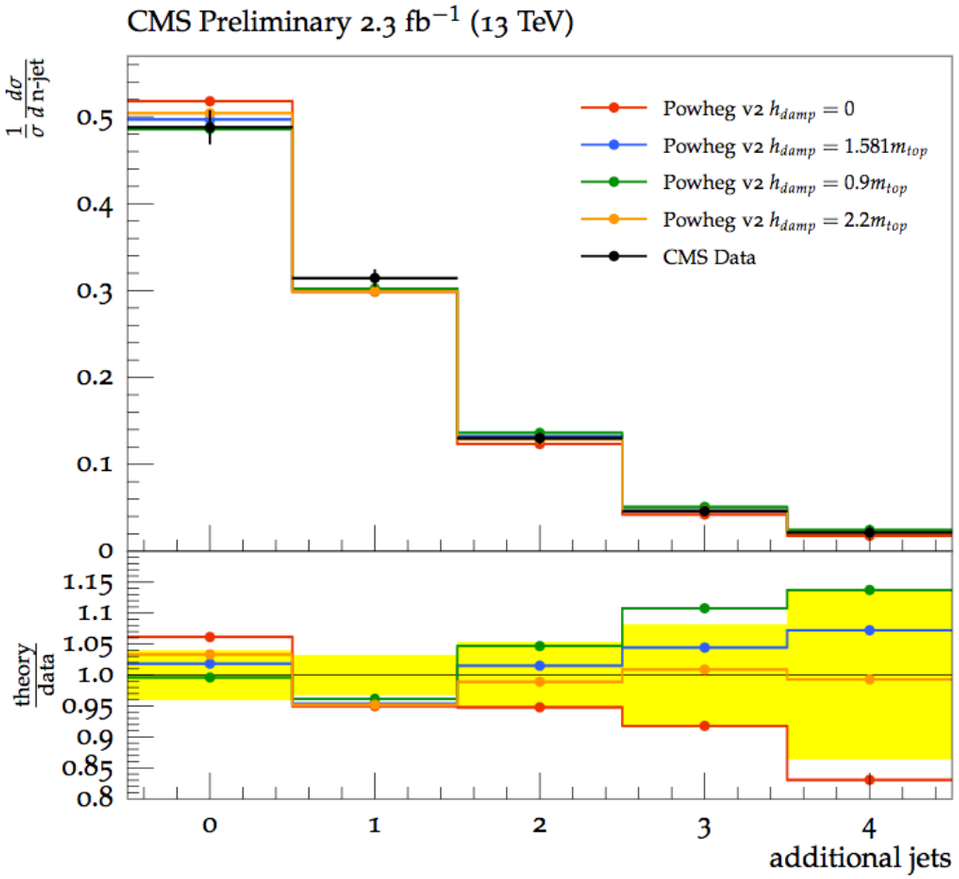


arXiv:1801.02052

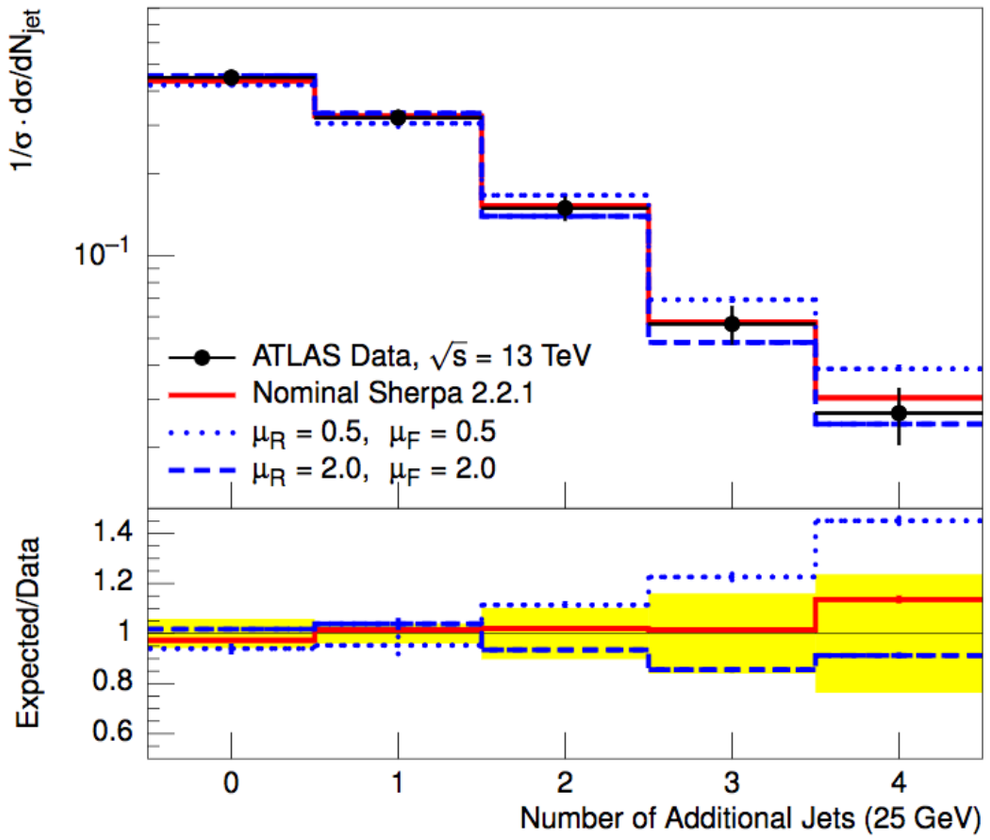
boosted, all-hadronic

Differential tt cross sections

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



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

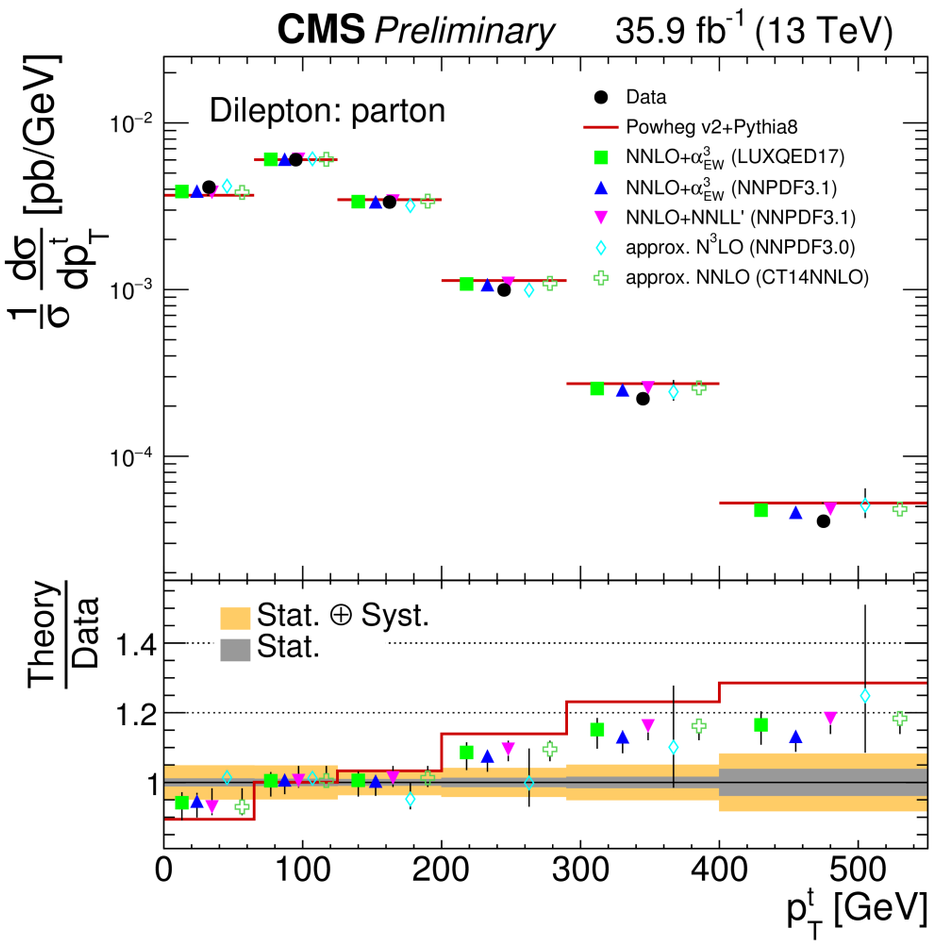


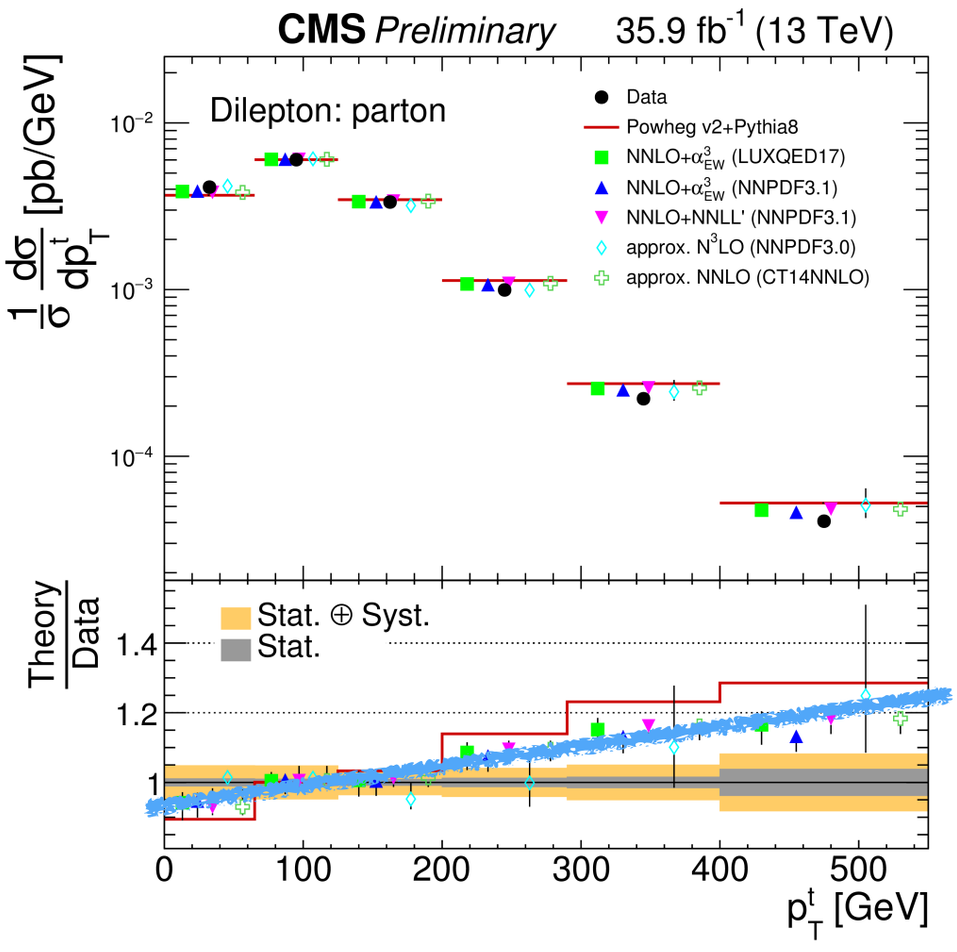
ATL-PHYS-PUB-2017-007
Modelling studies

However…

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





CMS PAS-TOP-17-014

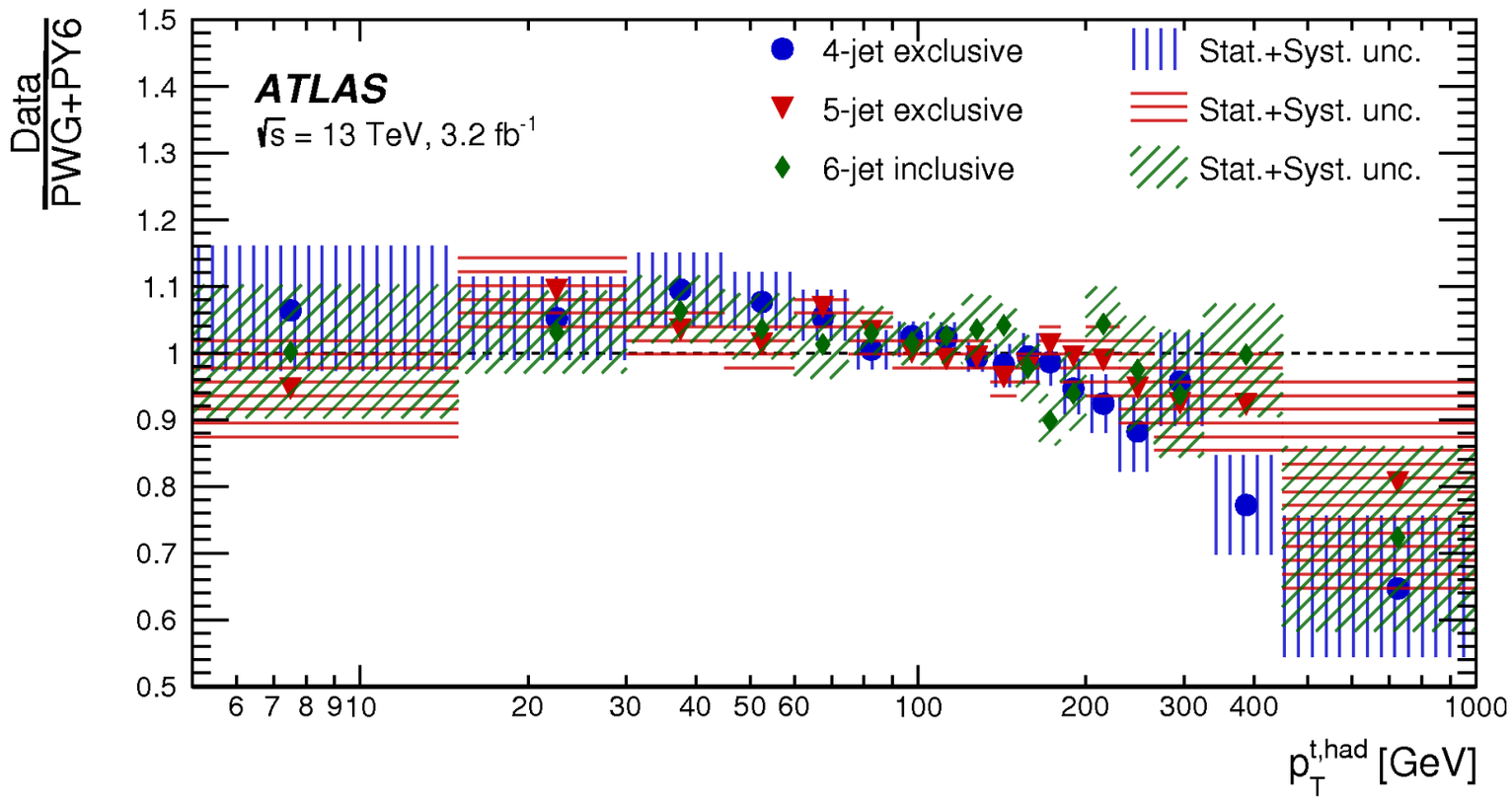
Dilepton

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)



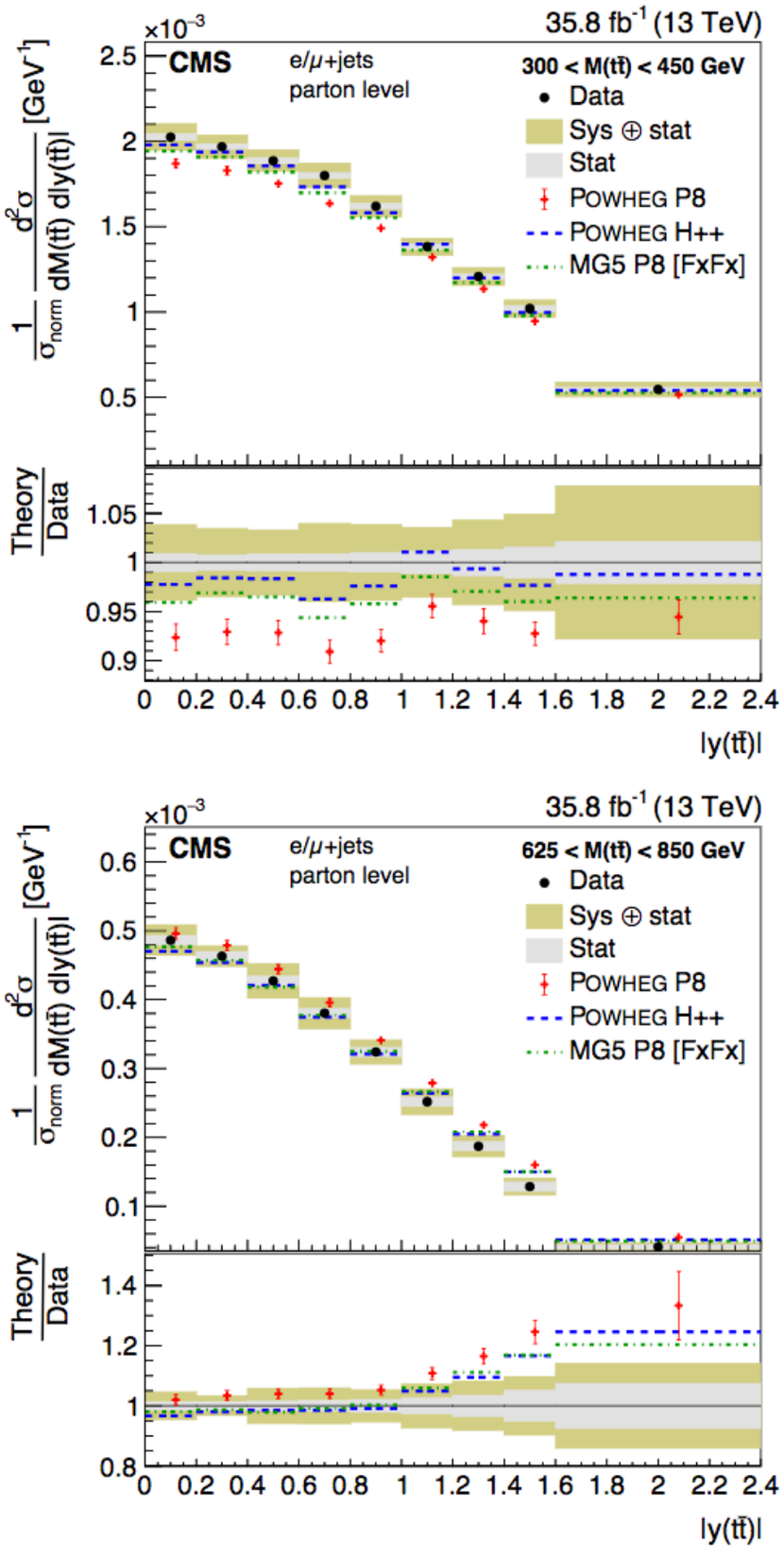
arXiv:1802.06572

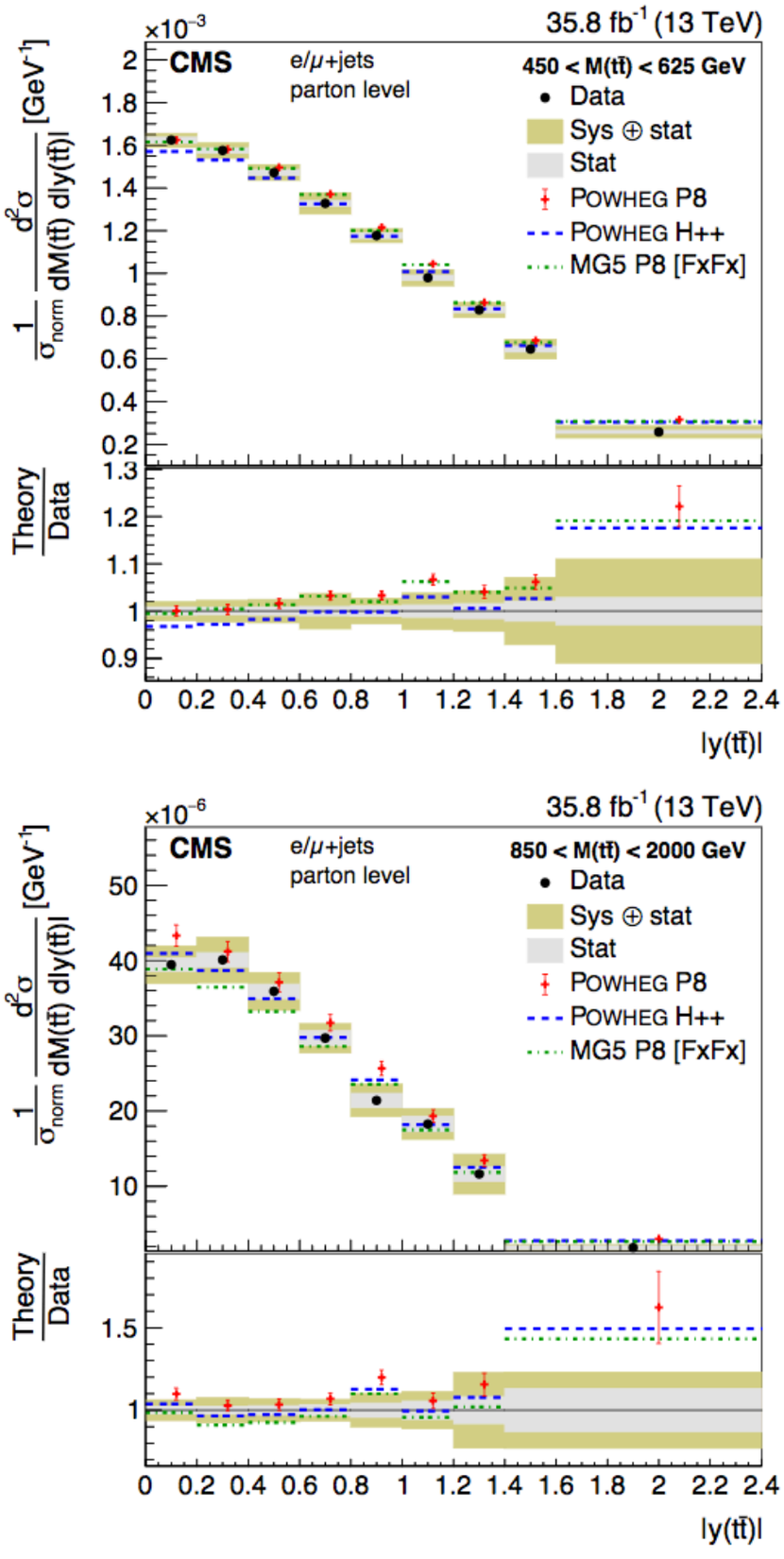
in association with jets

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

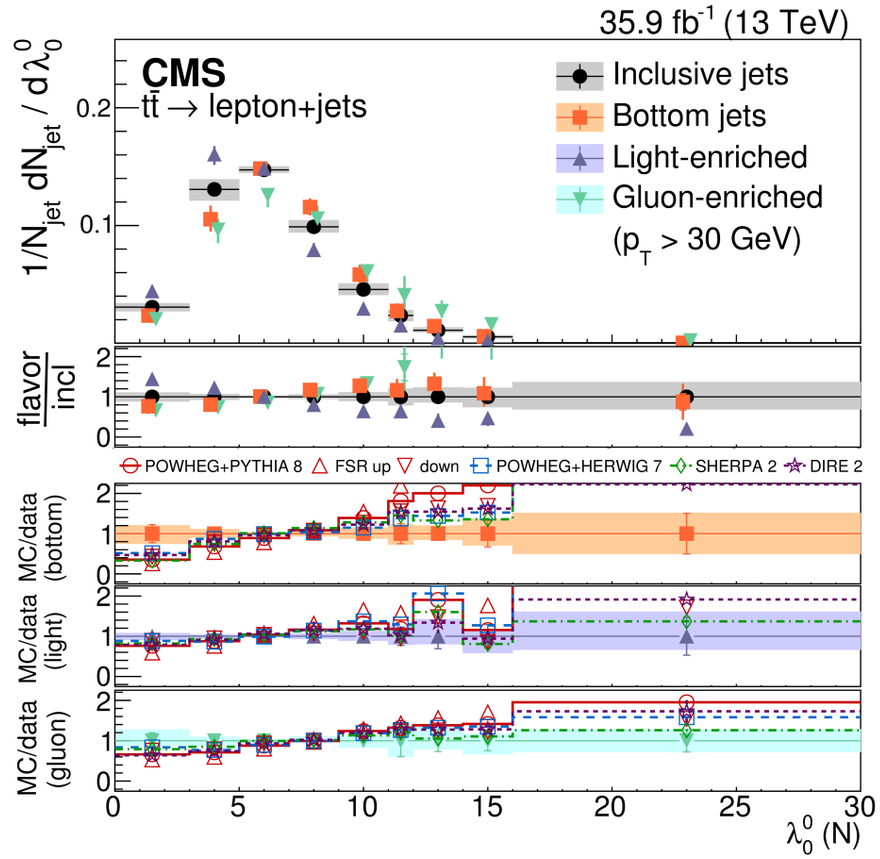




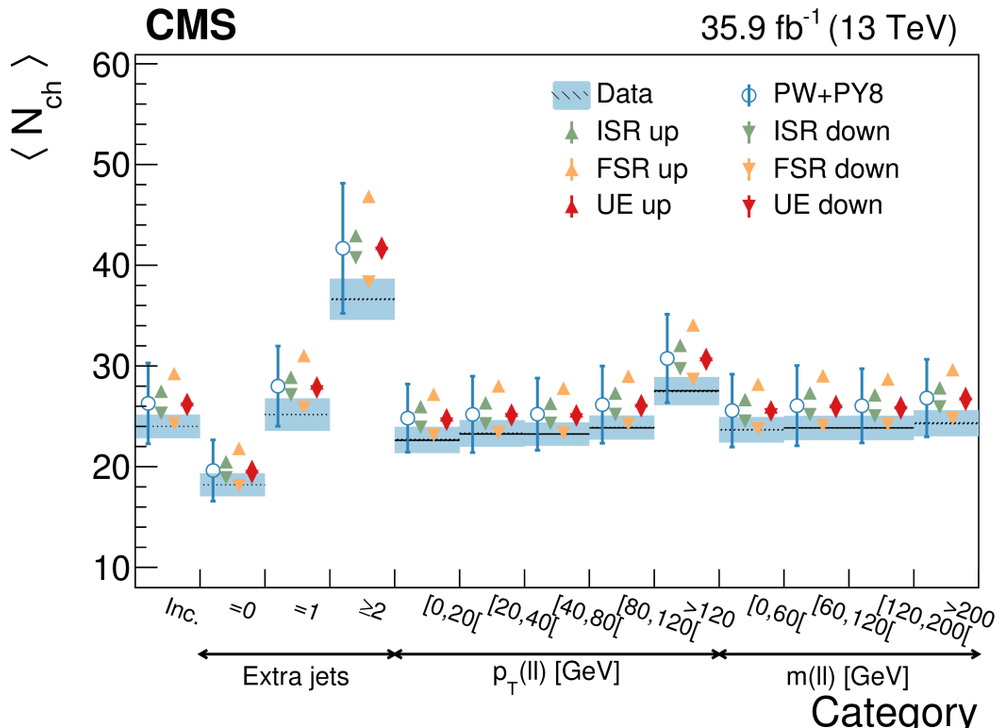
arXiv:1803.08856
l+jets

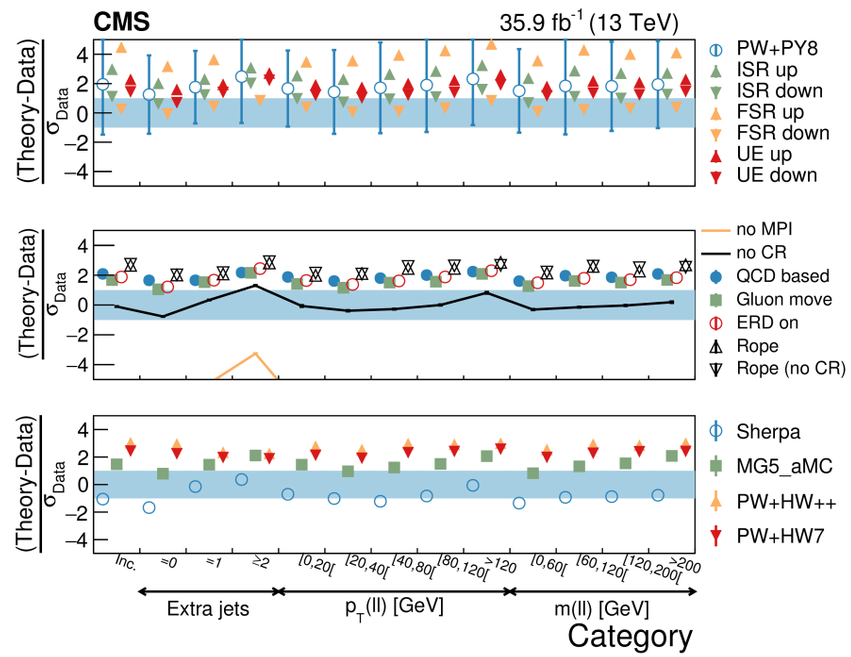
Studies with charged particles (in or outside jets)

- Recent measurements investigating
  - jet constituents/ structure variables
  - multiplicity and kinematic variables of tracks from the underlying event
- Helpful for tuning the simulation
- Sensitive to colour effects, α_S

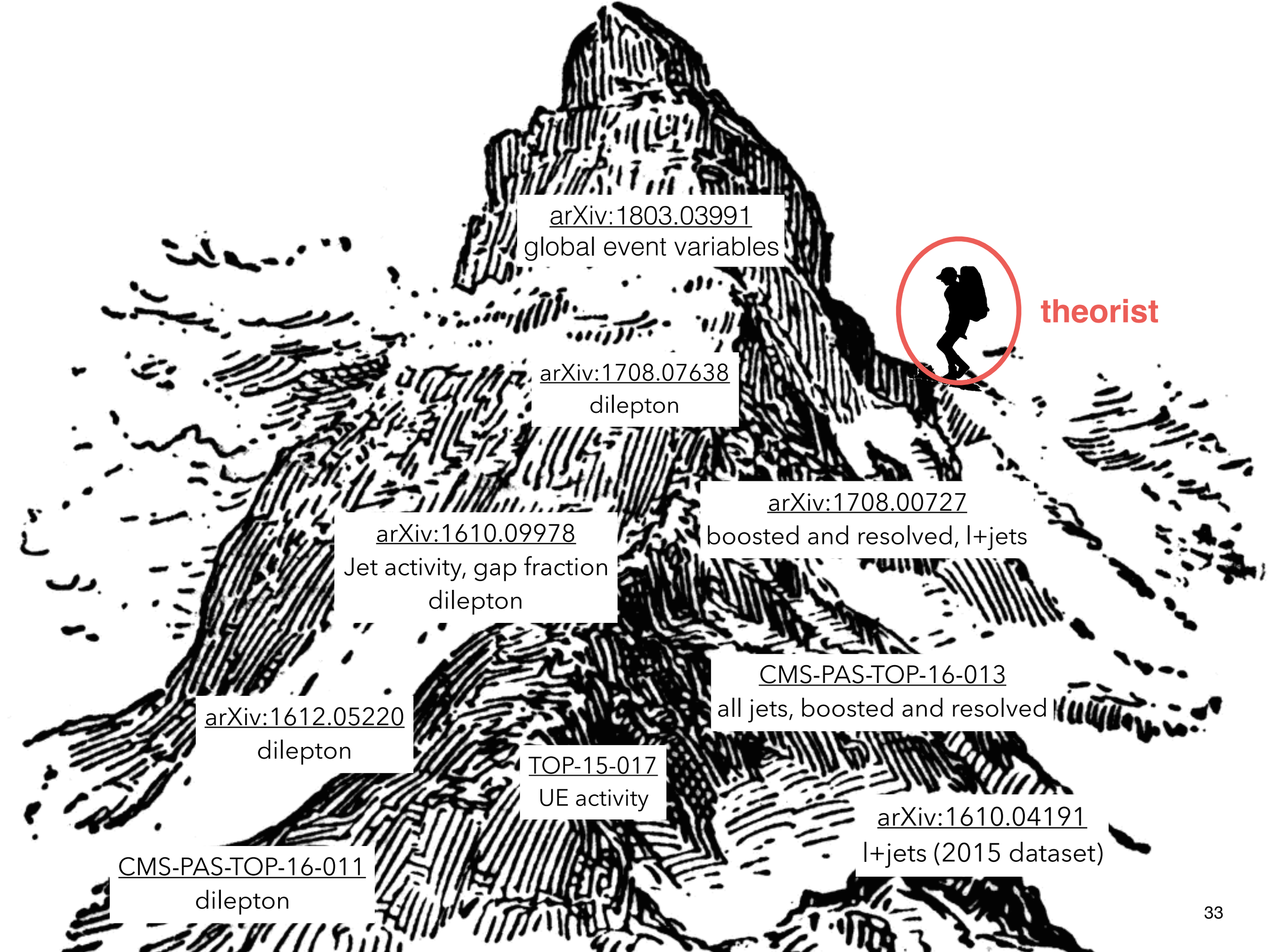


arXiv:1808.07340
jet substructure observables



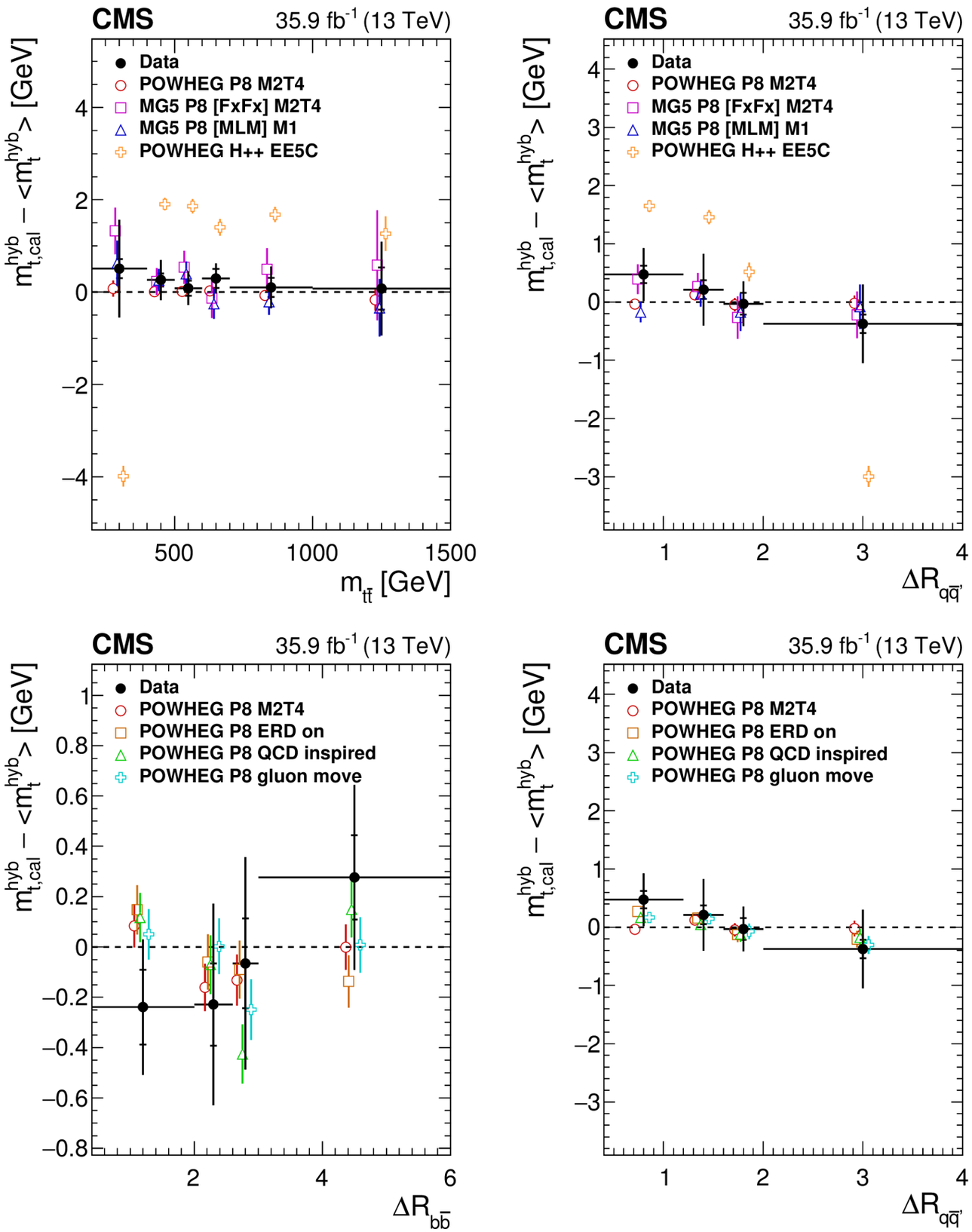


arXiv:1807.02810
underlying event


arXiv:1803.03991
global event variables
arXiv:1708.07638
dilepton
theorist
arXiv:1708.00727
boosted and resolved, l+jets
arXiv:1610.09978
Jet activity, gap fraction
dilepton
CMS-PAS-TOP-16-013
all jets, boosted and resolved
arXiv:1612.05220
dilepton
TOP-15-017
UE activity
arXiv:1610.04191
l+jets (2015 dataset)
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
- Direct measurement of **the top quark mass with 13 TeV data**
  - classic method, l+jets (most precise value in Run-1)
- The result includes **differential** measurements



arXiv:1805.01428

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

($\Delta m_t = 0.36\%$)

Updated treatment of syst. uncertainties

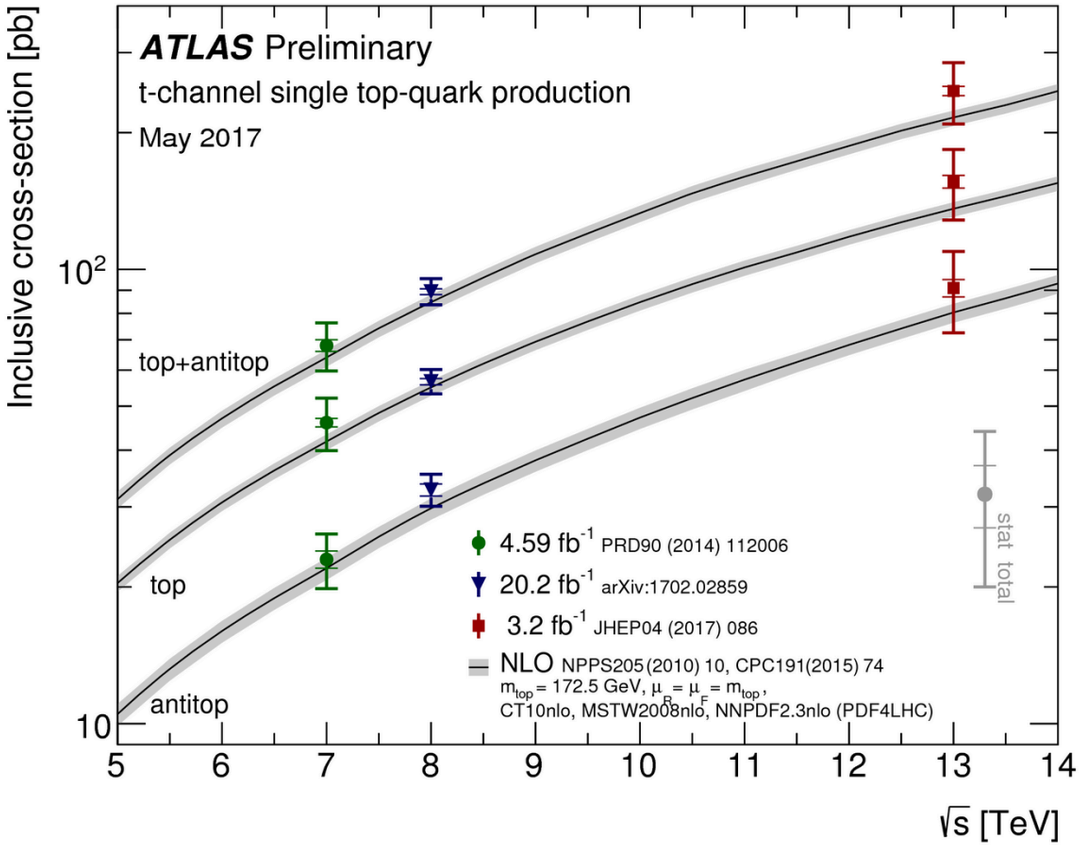
CMS PAS-TOP-17-008

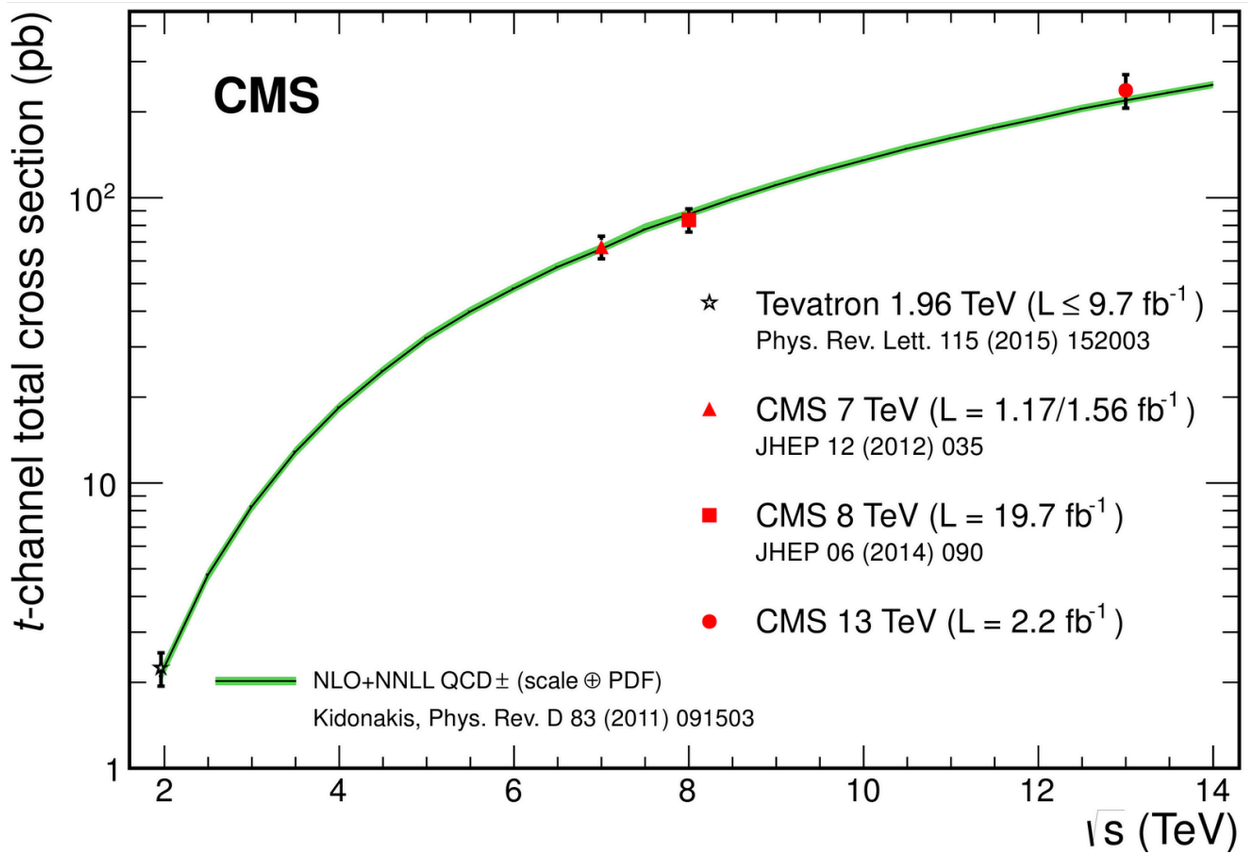
Latest mass measurement (all jets, $\Delta m_t = 0.45\%$)

Single top production

Single top quark production

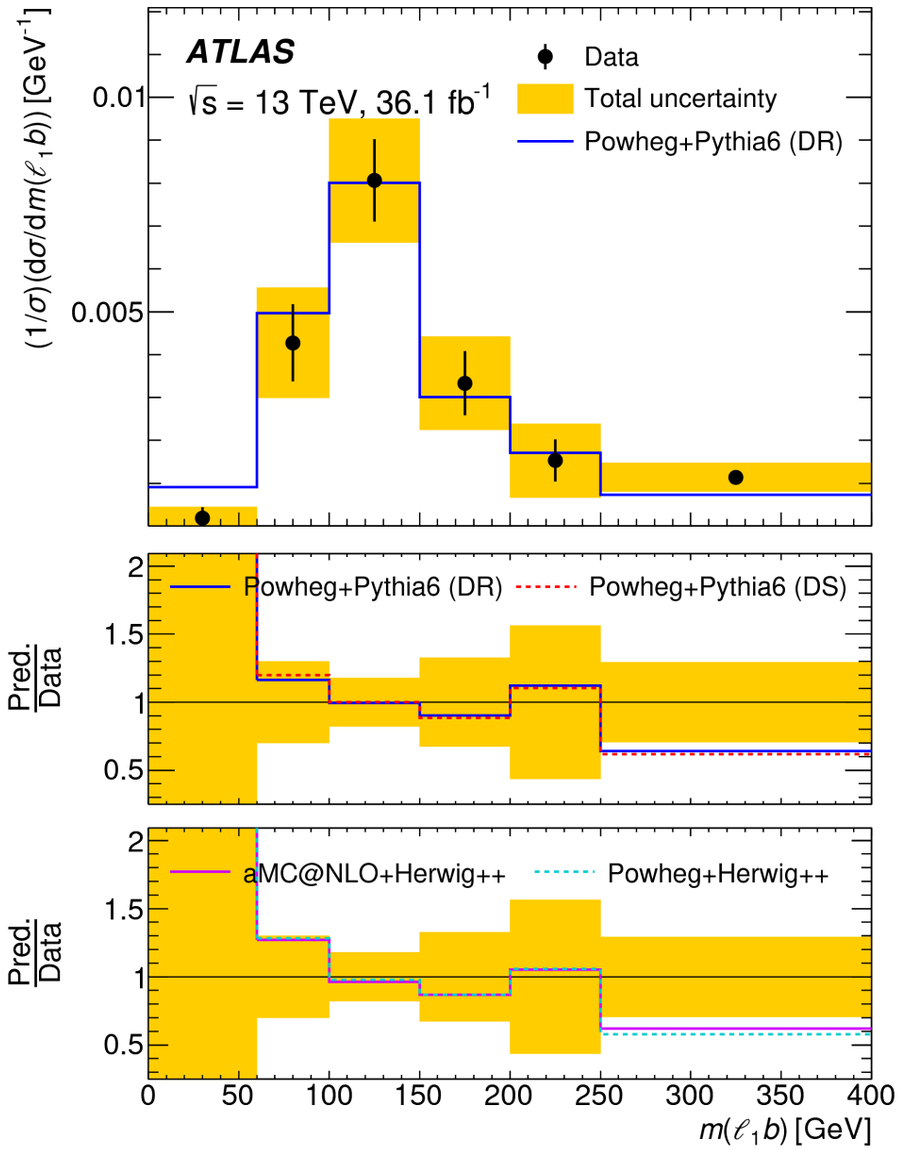
- The study of single top quarks is also well advanced
- **t-channel cross section at 13TeV ~ tt cross section at 8TeV**
  - Early measurements of t-channel (inclusive, differential)
  - Recent update with more luminosity (not pictured) from CMS (CMS PAS TOP-17-011)





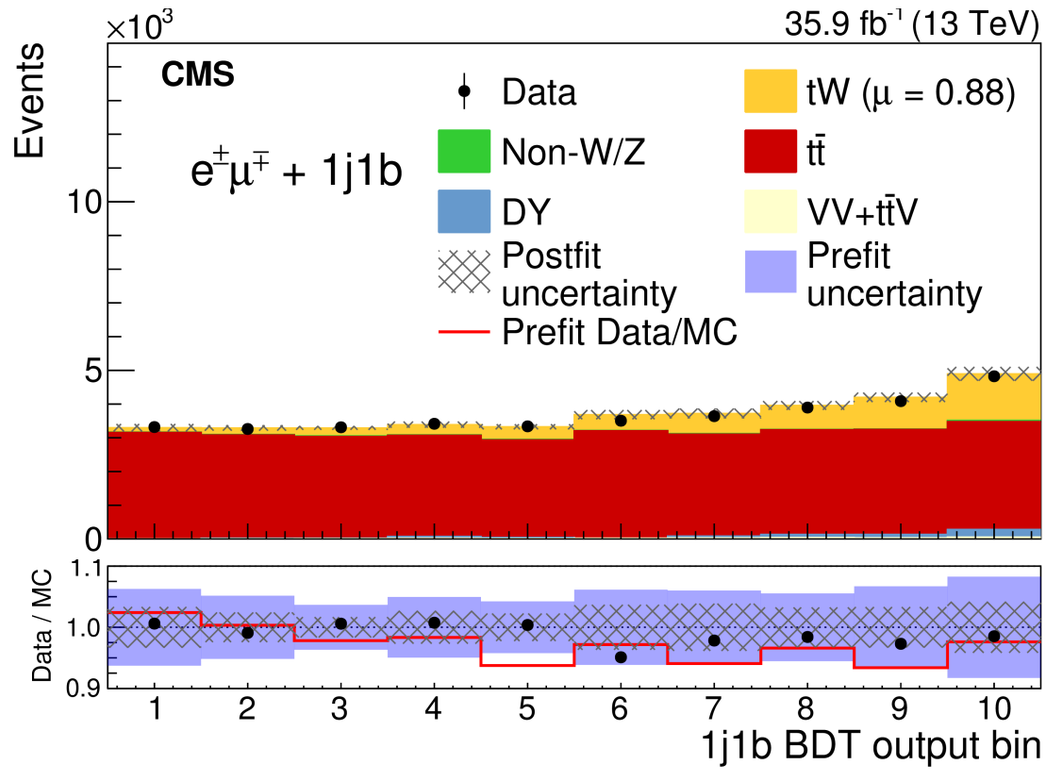
Single top quark production

- **tW 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



arXiv:1805.07399

Inclusive, $\Delta\sigma/\sigma \approx 10\%$

Rare top production

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**

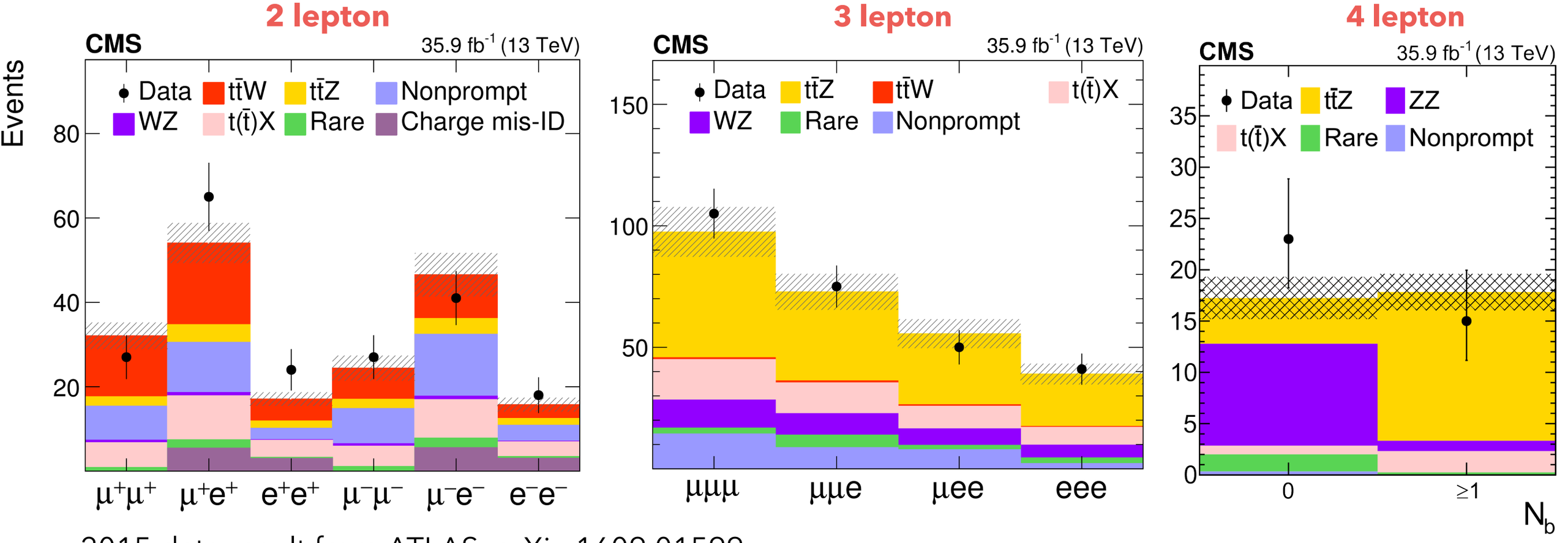
arXiv:1711.02547

$\sigma_{ttZ} = 0.99^{+0.09}_{-0.08}(\text{stat})^{+0.12}_{-0.10}(\text{syst})$ pb **> 5σ**

$\sigma_{ttW} = 0.77^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{syst})$ pb **5.3σ**

σ_{ttZ} = 0.839 (±12%) pb

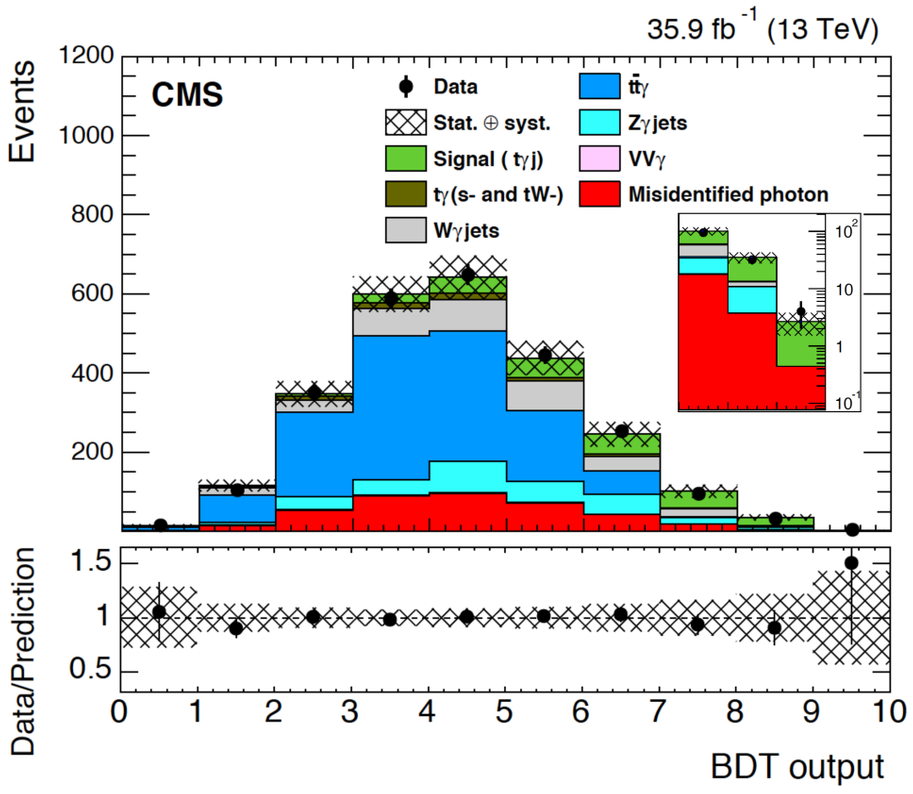
σ_{ttW} = 0.600 (±13%) pb



2015 data result from ATLAS: arXiv:1609.01599

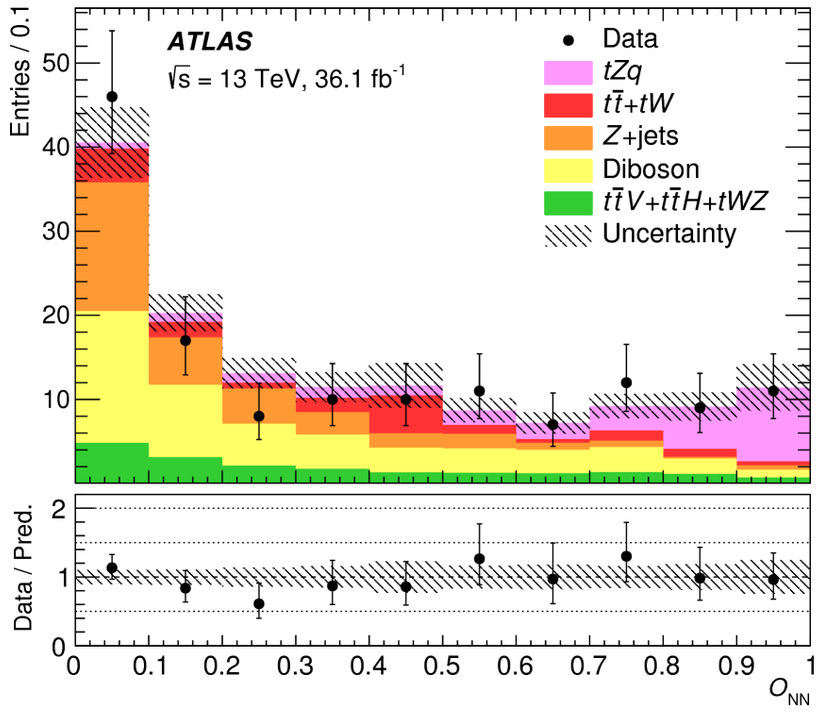
Rare single top is also very close

- Single top tZ is sensitive to the Z coupling and to new physics (FCNC)
- Single top tγ is sensitive to the top quark charge, and to its electric and magnetic dipole moments
  - Both are **very rare**
  - **We have evidence of both**, tZ being close to observation at 13 TeV



arXiv:1808.02913

SM tγ significance **4.4σ** (3.0σ)

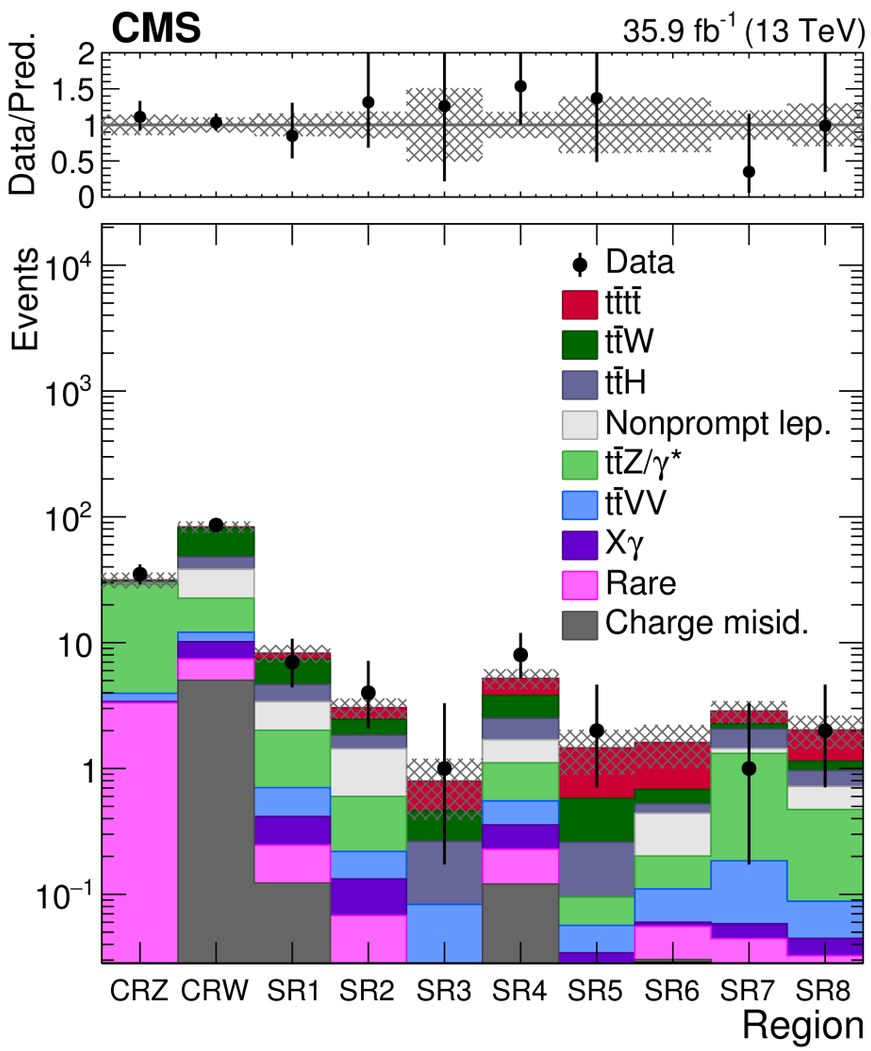


arXiv:1710.03659

SM tZq significance **4.2σ** (5.4σ)

Exciting times ahead

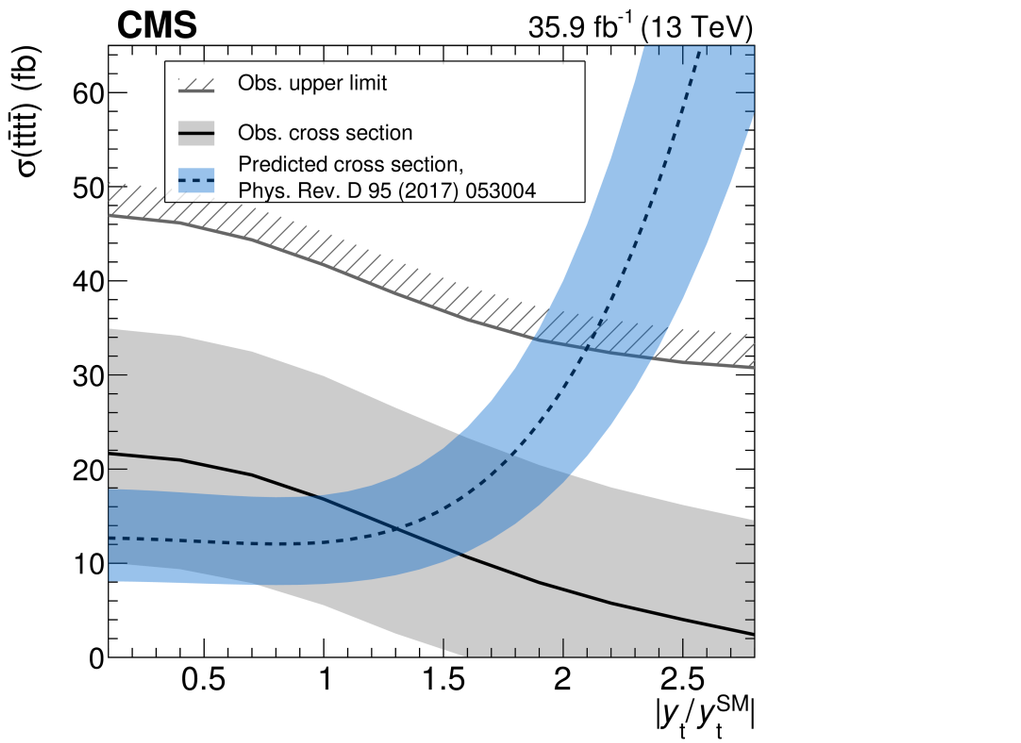
- 4t production is a **VERY** rare production → 5 orders of magnitude less often than tt in the SM
  - Future measurements will be useful tests of analytical higher order calculations
- Before that → **many BSM models predict an increase of the 4t cross section**
  - Particles decaying to top quarks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



arXiv:1710.10614

SM tttt significance **1.6σ**

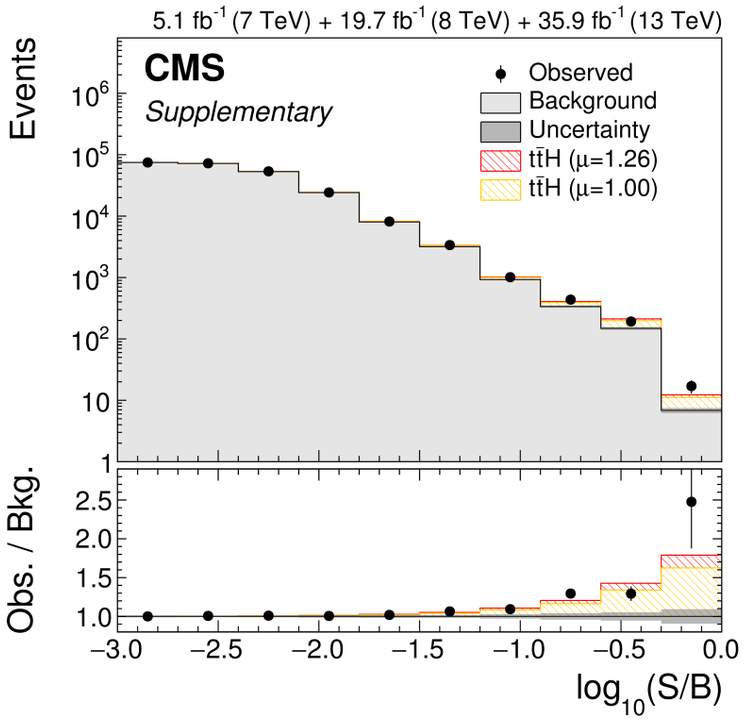
Yukawa coupling < 2.1 xSM at 95%CL



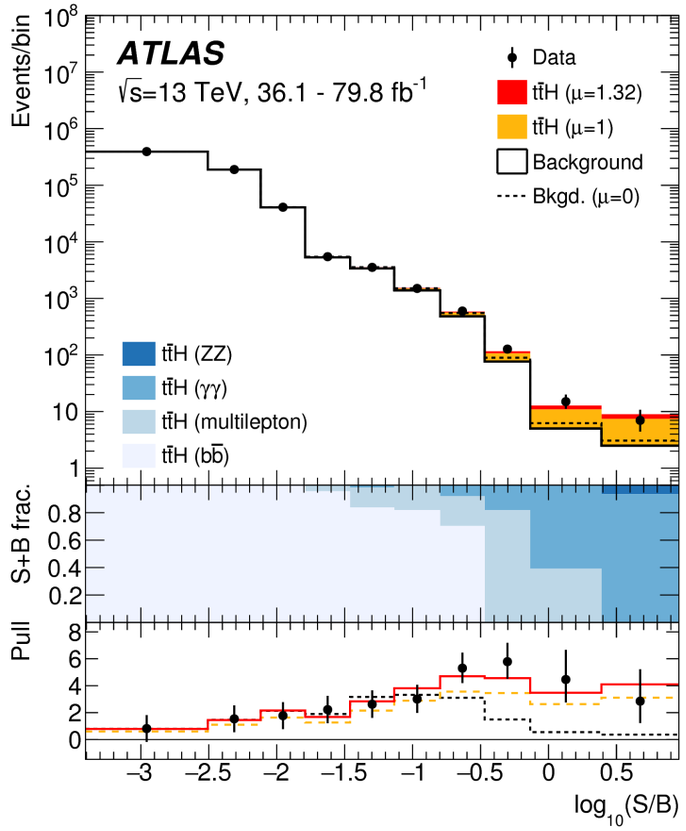
previously at 13TeV arXiv:1702.06164 and ATLAS-CONF-2016-020

Remember slide 6?

- The coupling between the Higgs boson and the top quark is a **main point in the SM Higgs boson check-list**
  - Can be measured in two ways
    - **Indirectly** (in the processes where a Higgs is produced or decays via top loop -ggH, H$\gamma\gamma$)
    - **Directly** when you have top quarks and Higgs boson generated together:
      - Single top + Higgs, and especially ttH



arXiv:1804.02610
Combination of channels
H→ WW, ZZ, $\gamma\gamma$, $\tau\tau$, bb



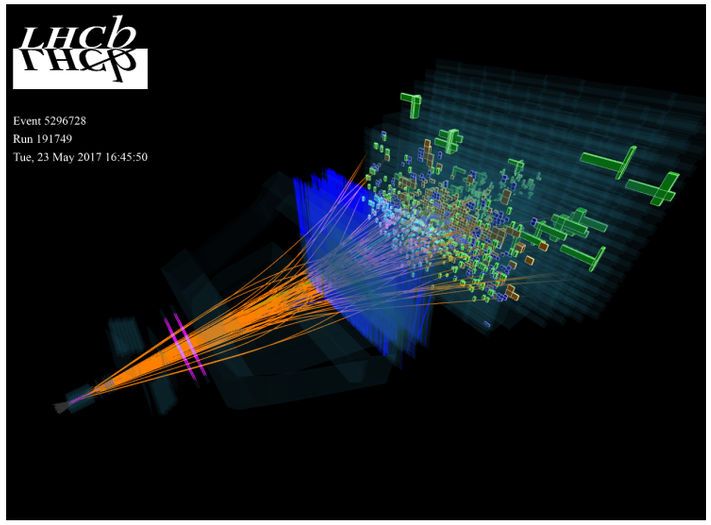
arXiv:1806.00425
Combination of channels
H→ WW, ZZ, $\gamma\gamma$, $\tau\tau$, bb

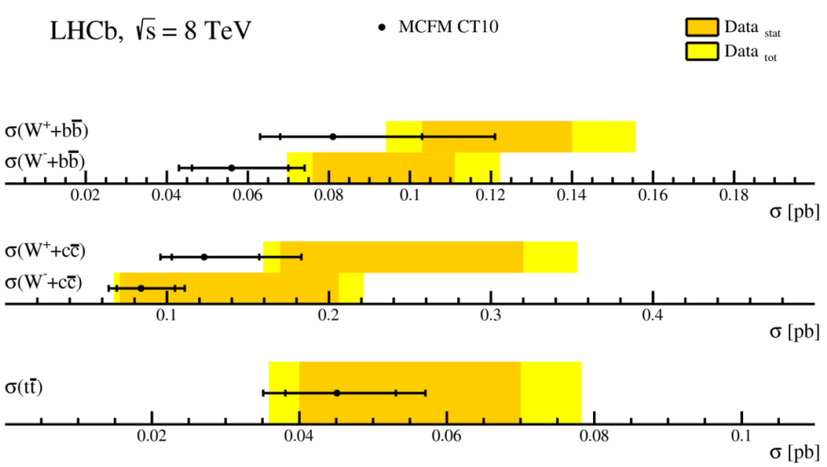
We are finally sensitive to ttH production!
Both ATLAS and CMS, have observed this production -in combination- this year.
Single top + Higgs will follow.
Soon we will tackle the coupling.
Will everything be as the SM predicts?

The ever-growing top sector at the LHC: Forward top production

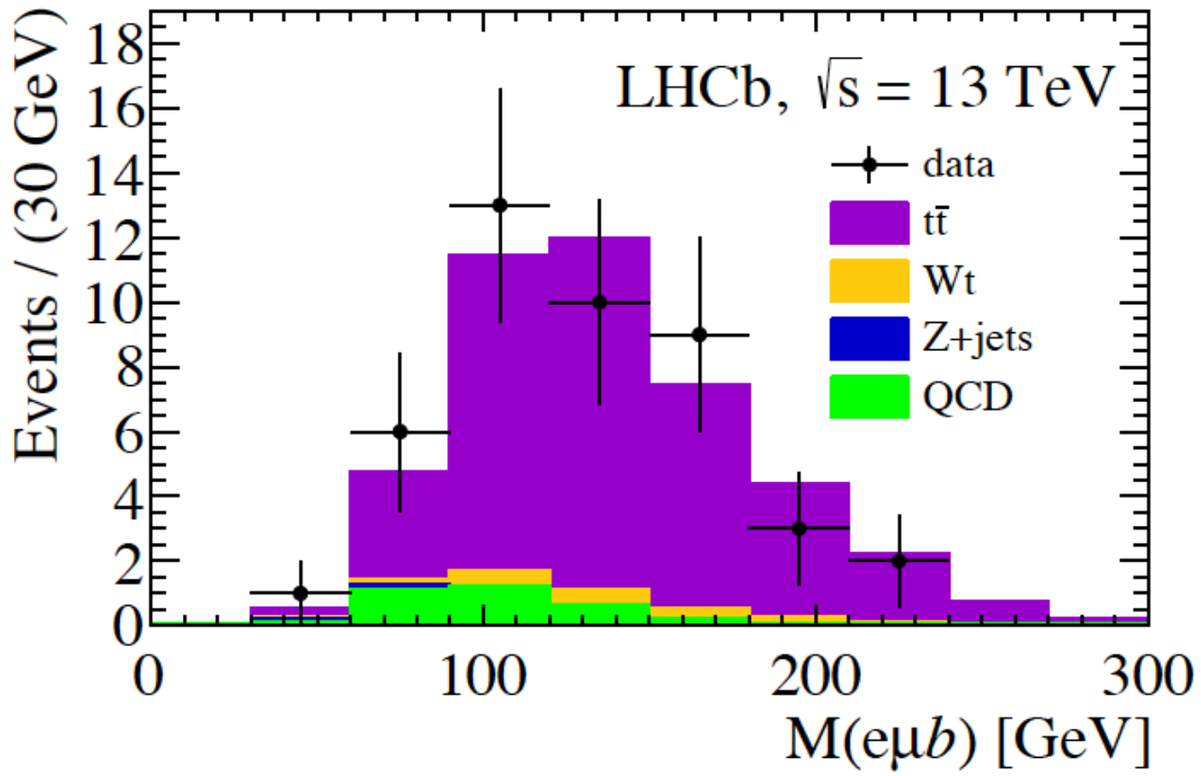
The dawn of a new era

- 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

Summary

- The study of the top quark remains an exciting topic at the LHC
- **Precision measurements** could be the key to answer 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 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