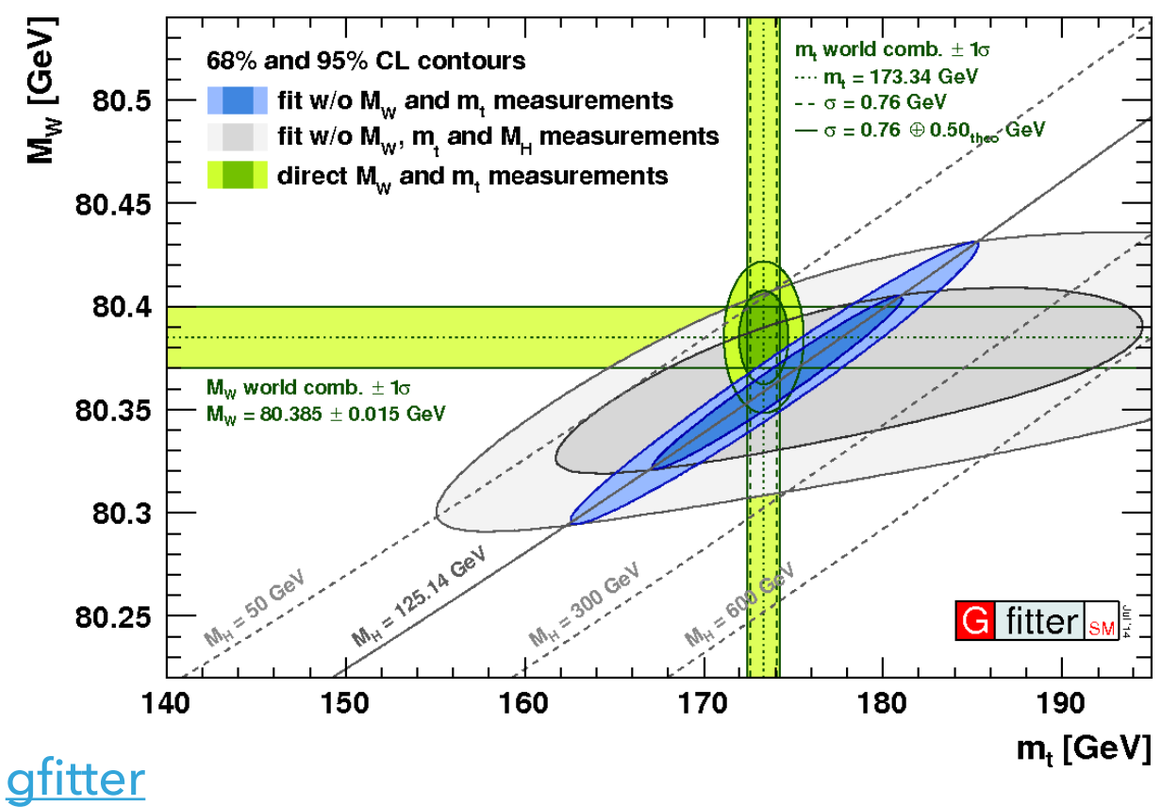
Rebeca Gonzalez Suarez

RECENT LHC RESULTS

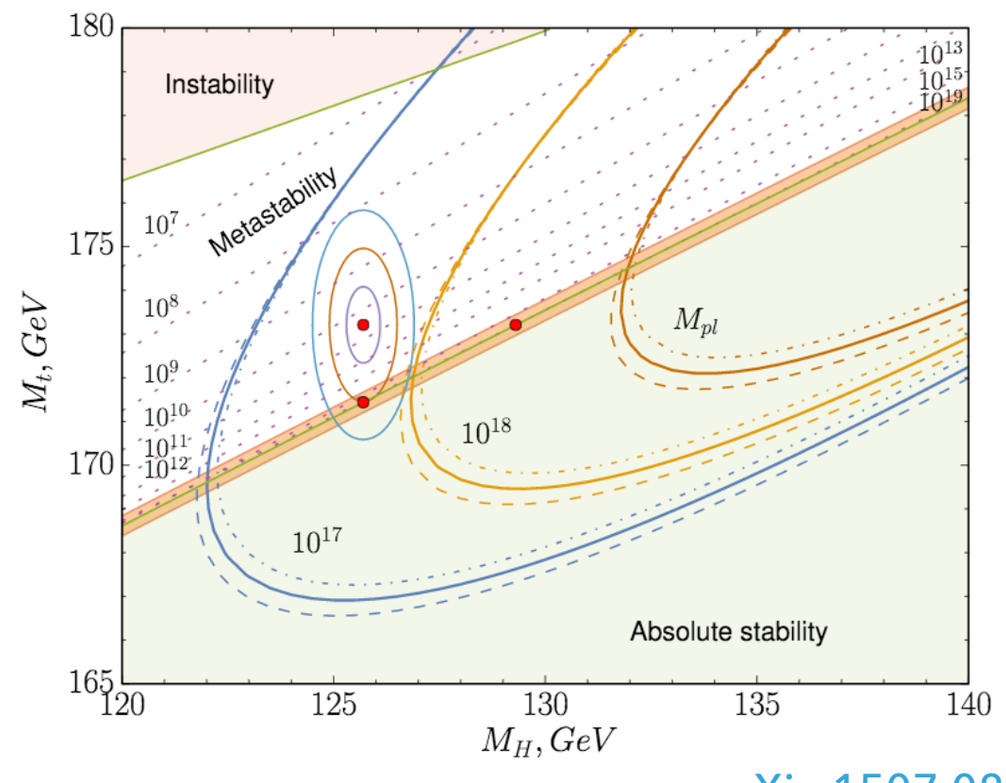
Workshop on top physics at the LC 2017
7-9 June 2017, CERN

I probably do not need to motivate top physics in this talk

- You already know that the top quark is 🌈❄️**special**🦄🌈
- The **heaviest elementary particle** found **so far**
  - **Special properties**
  - Important implications for the SM



gfitter



arXiv:1507.08833

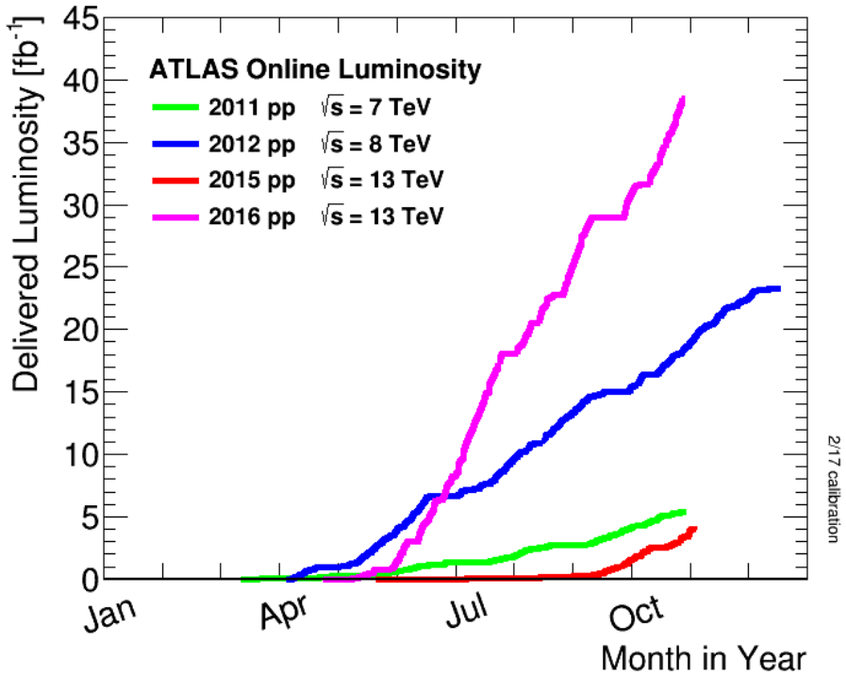
Much less the power of the LHC for top physics

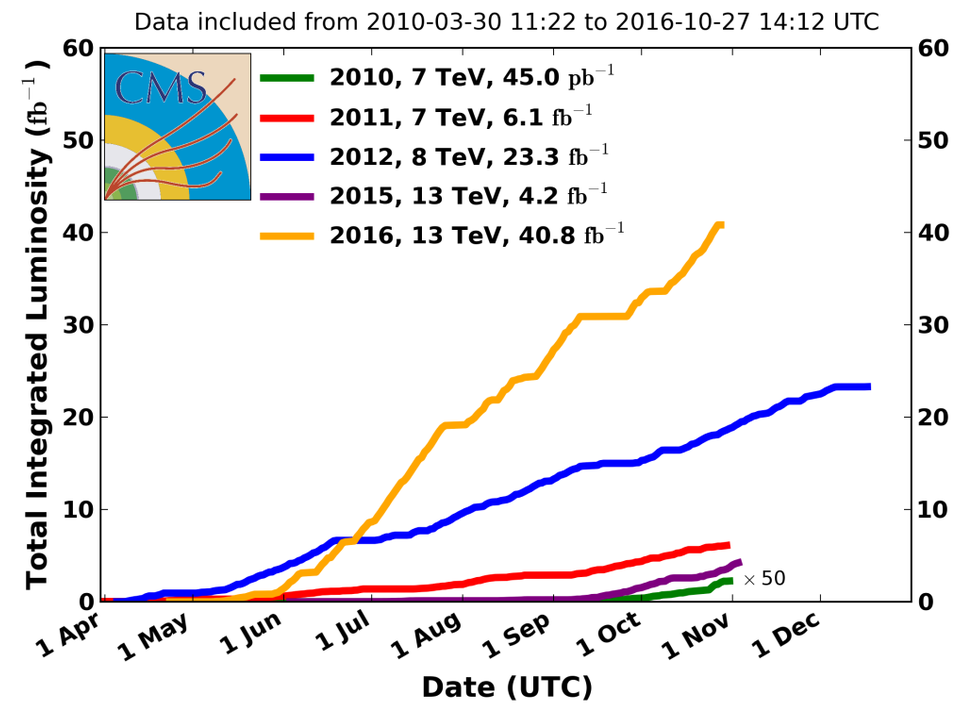
Factory	Quark	Cross Section (nb)	Luminosity ($cm^{-2}s^{-1}$)
B (KEKb)	Bottom	1.15 (Y(4S))	2.11×10^{34}
LHC	Top	0.82 (incl t-t)	1.51×10^{34}

Top pair production at 13 TeV CM energy is mainly (80%) produced by gluons, providing important information on the gluon distribution at relatively high x_F, up to ~0.25

15/05/17 J. Butler, CMS Status, LHCP 12

The factory in numbers



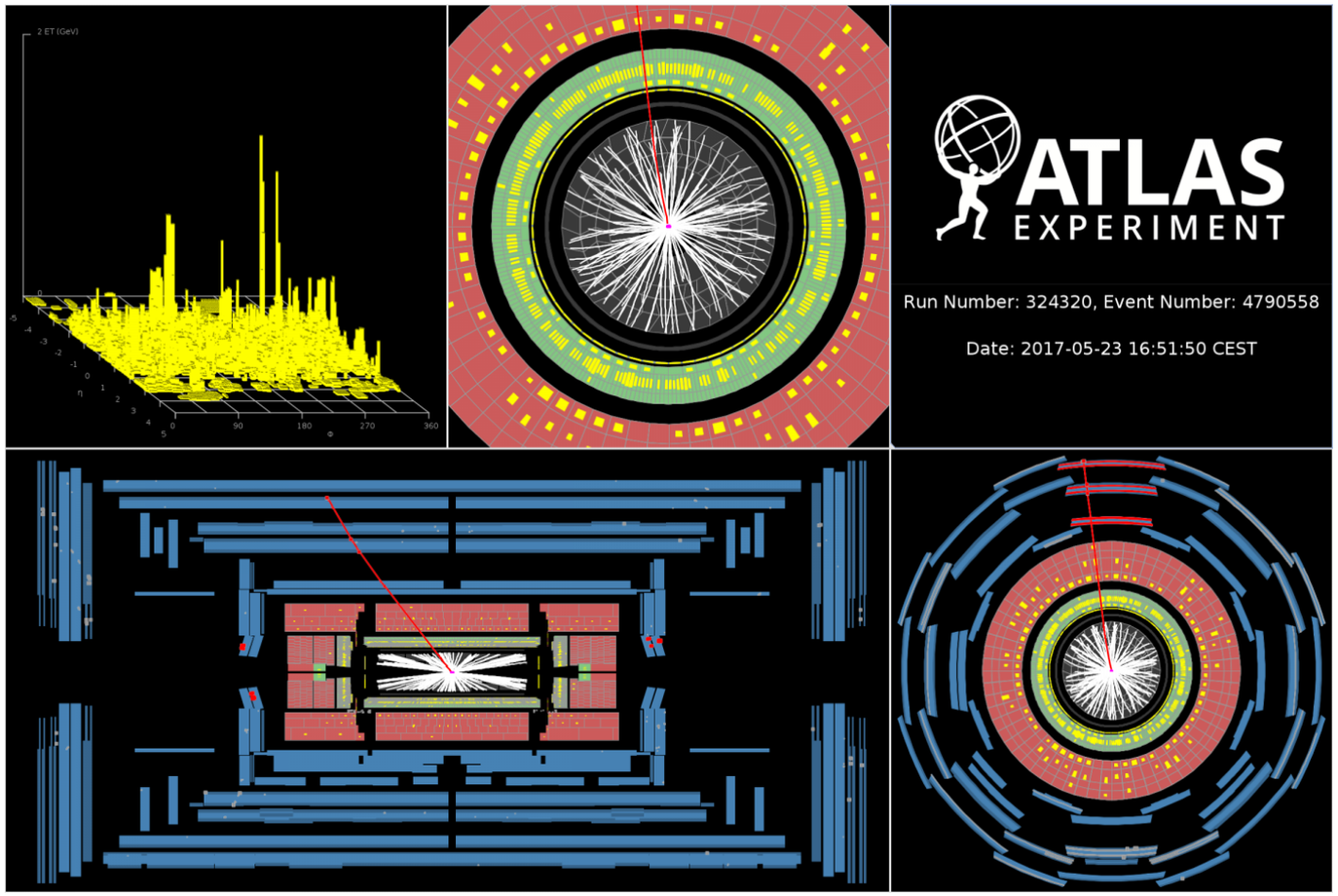


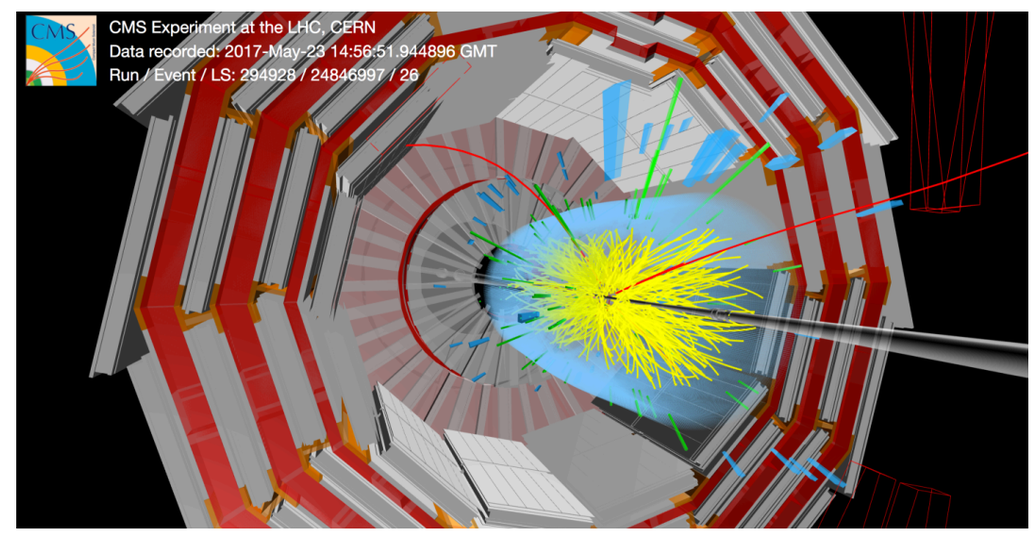
σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.0	2.08	0.22	1.046
LHC @ 7TeV	177.3	63.89	15.74	4.29
LHC @ 8TeV	252.8	84.69	22.2	5.24
LHC @ 13 TeV	831.7	216.99	71.2	10.32

- **Run-1:** More than 5M ttbar pairs, 2M single top t-channel events per experiment
  - 0.5M of Higgs events
- Strong top Run-1 legacy: cross sections, properties, searches for new physics
  - **Still yielding results!**

Currently at the LHC

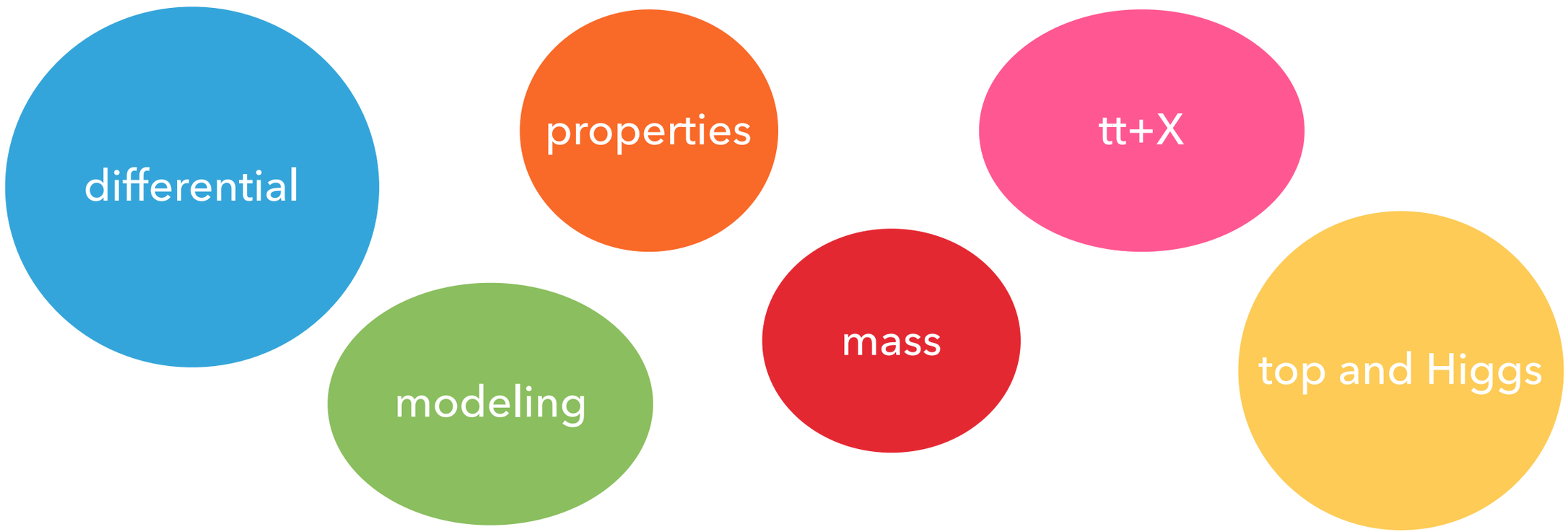
- LHC is waking up from its Winter slumber
  - First collisions May 23, 2017





- We are in the middle of Run-2
  - Started in June 2015
  - Already **delivered more than 40fb^{-1} at 13TeV,**
    - 100fb^{-1} is the final target → **80M tt pairs** expected in ATLAS and CMS

This talk will focus on a small set of recent results from **Run-2** (only)

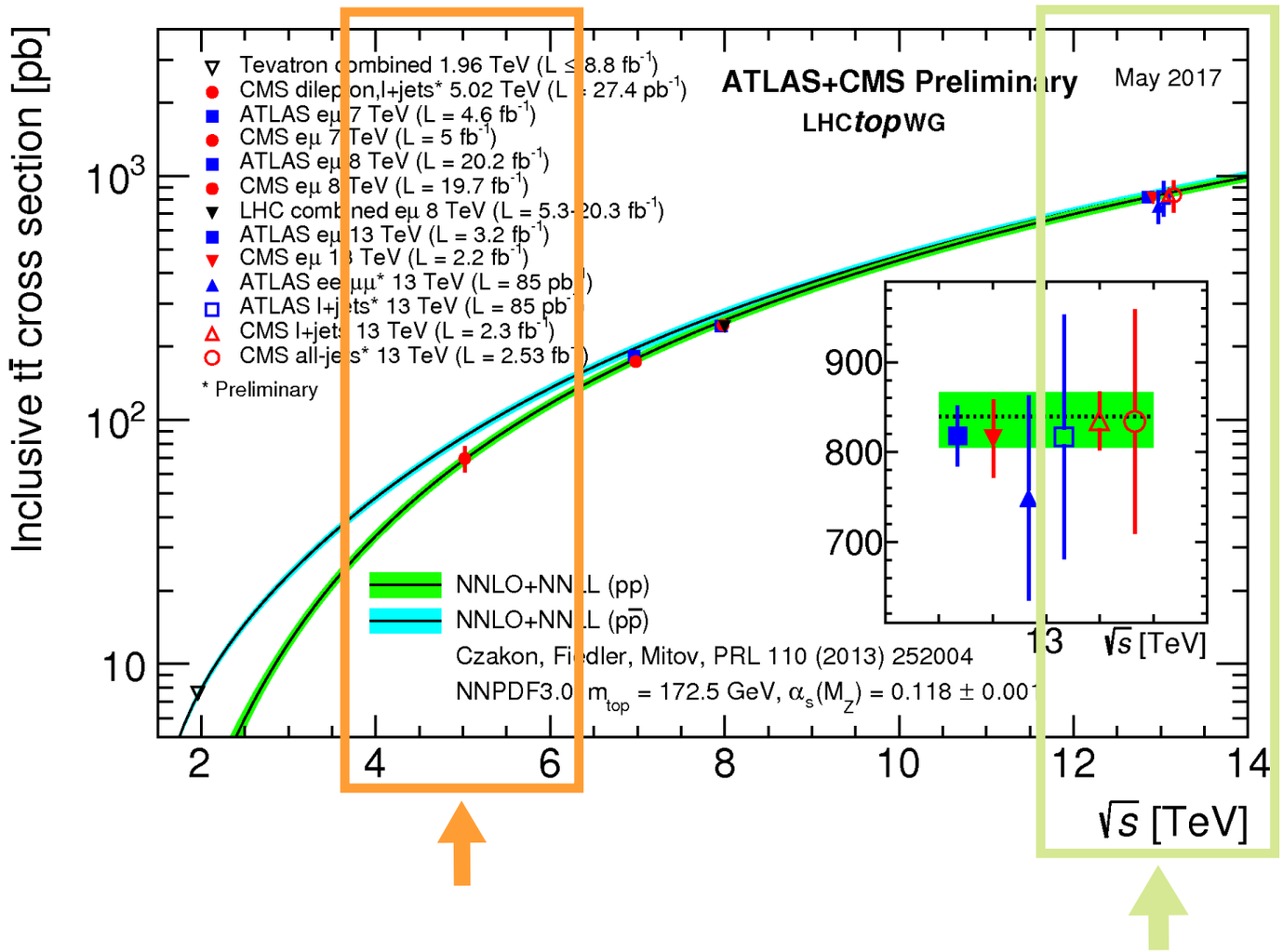


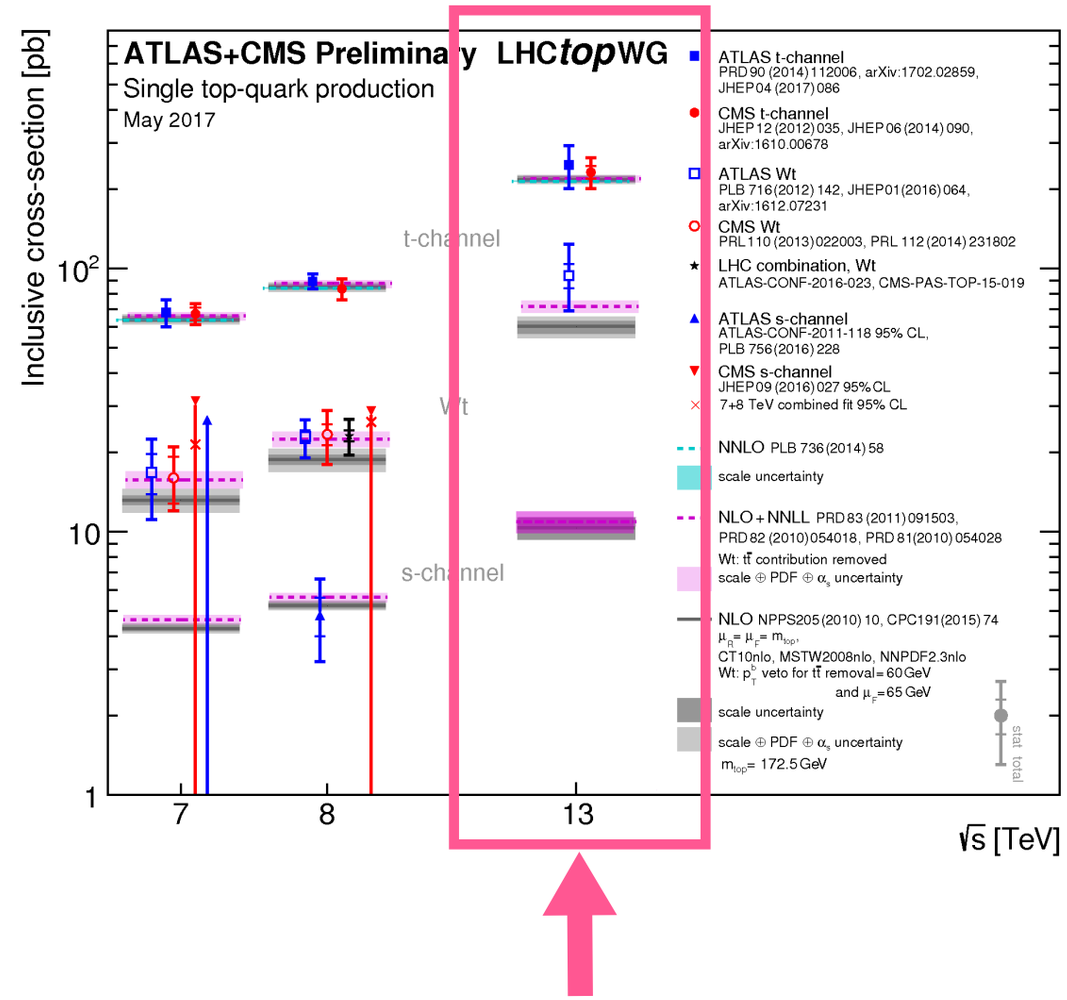
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

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

The 1st (s)top: Inclusive cross sections

- **Early analyses at 13TeV:** First Run-2 inclusive cross sections two months after first collisions

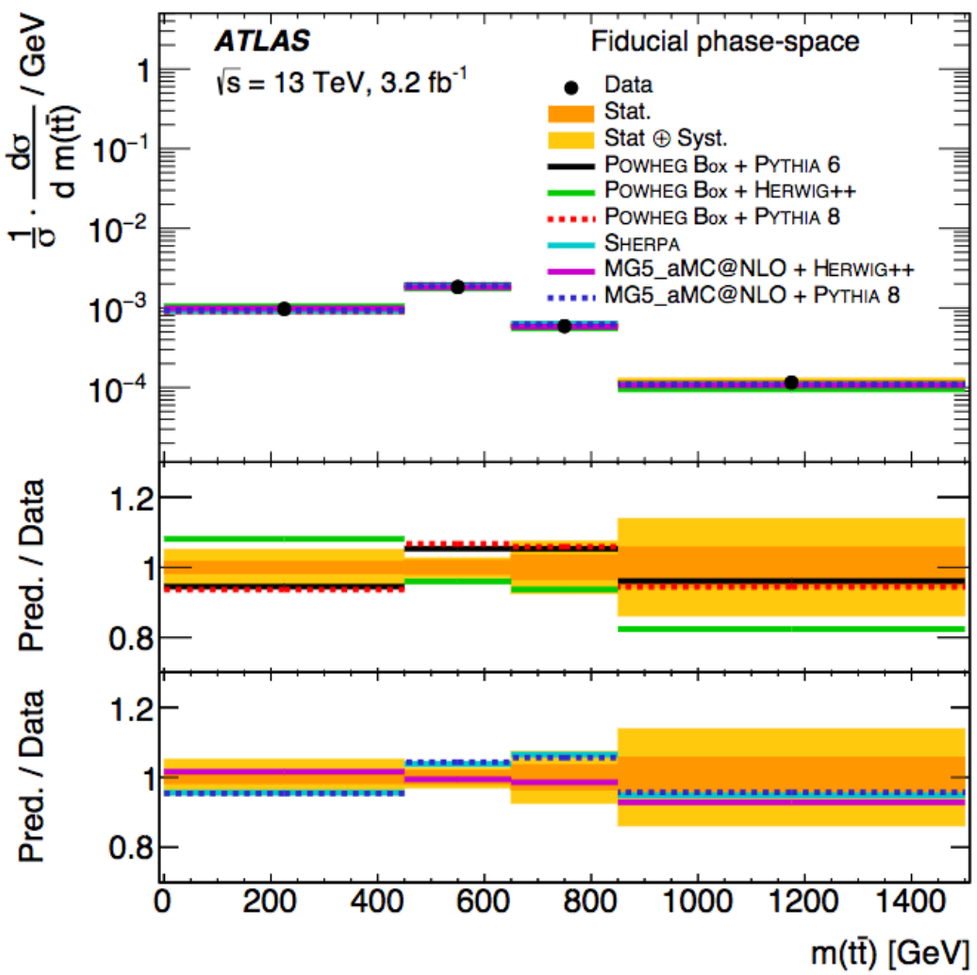




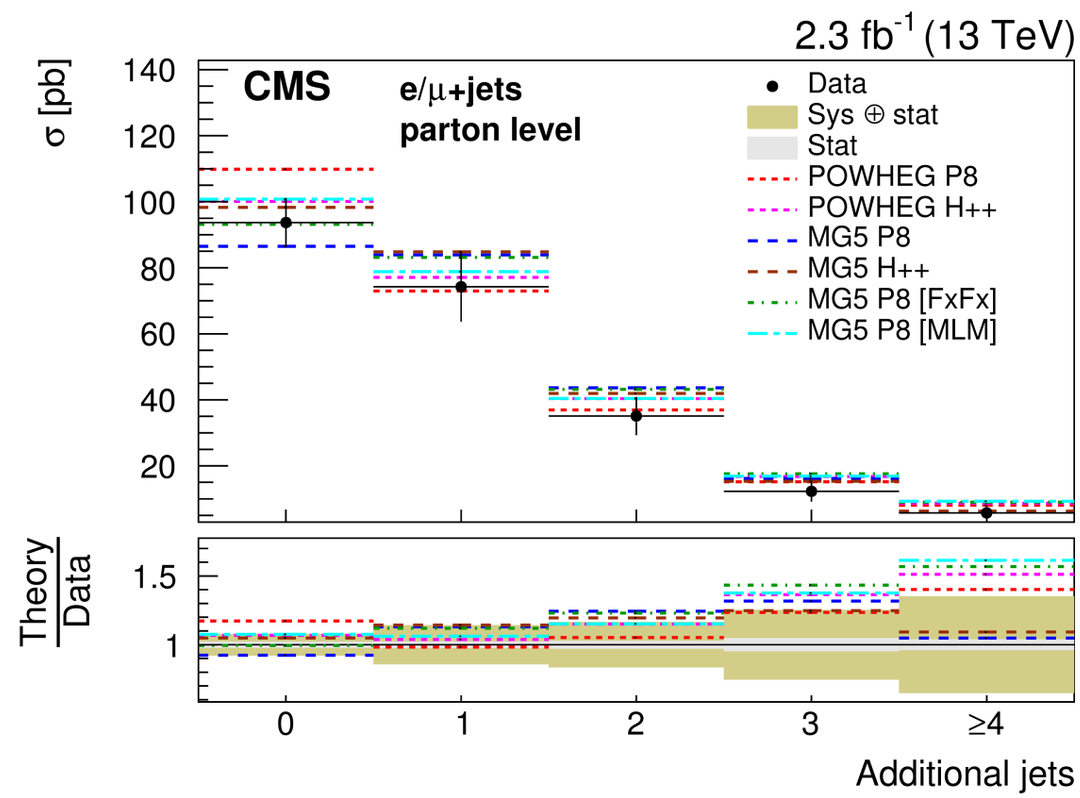
- In agreement with NNLO+NNLL predictions over all energy range
  - Can be used to measure/constrain gluon PDFs, α_s, and the top quark pole mass

Differential regime

- Interface between theory, simulation, and the experiments
- **Comparisons with state-of-the-art predictions**
  - MC generators; high order predictions; different matching schemes, scales and tunes



ATLAS: dilepton (eμ)
Eur. Phys. J. C77 (2017) 299

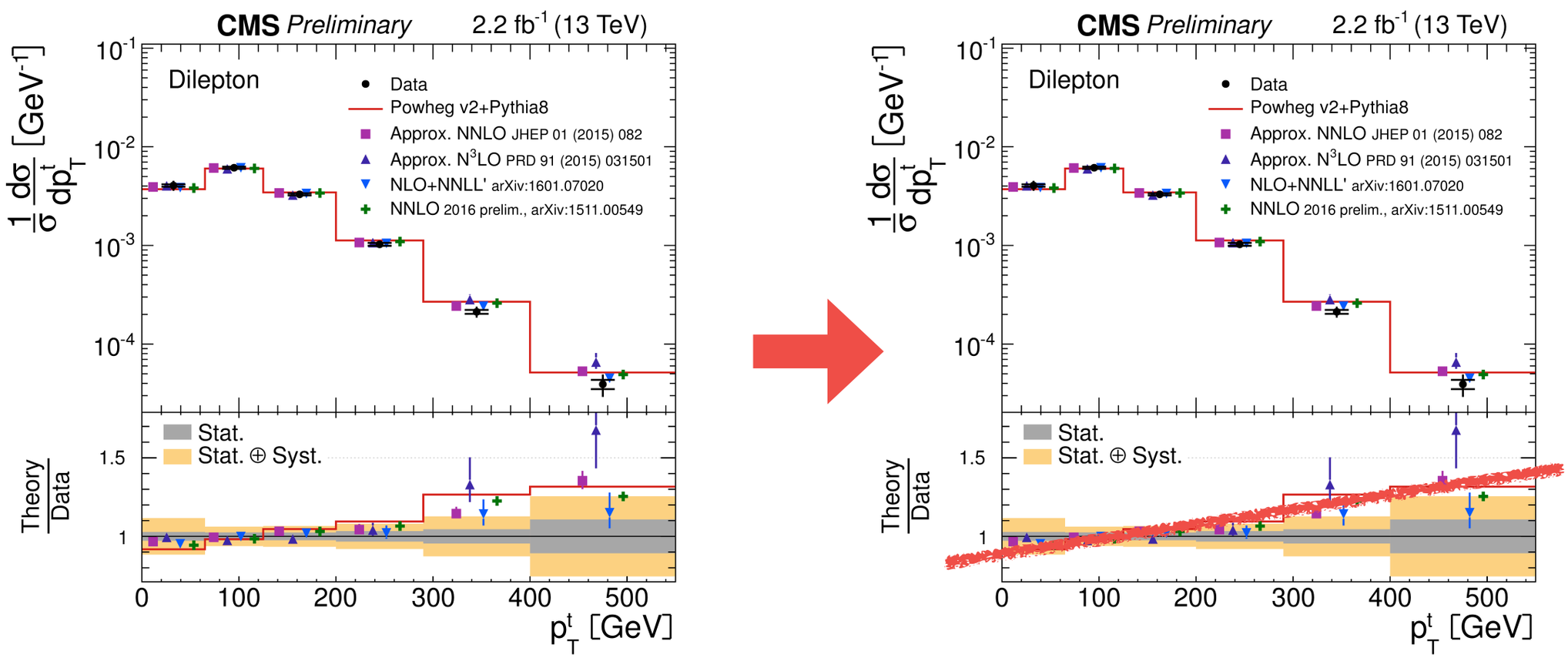


CMS: l+jets
Phys. Rev. D 95, 092001 (2017)

ATLAS: l+jets ATLAS-CONF-2016-040
CMS: eμ, ee, μμ PAS TOP-16-007, PAS TOP-16-011
CMS: all jets CMS-TOP-16-013

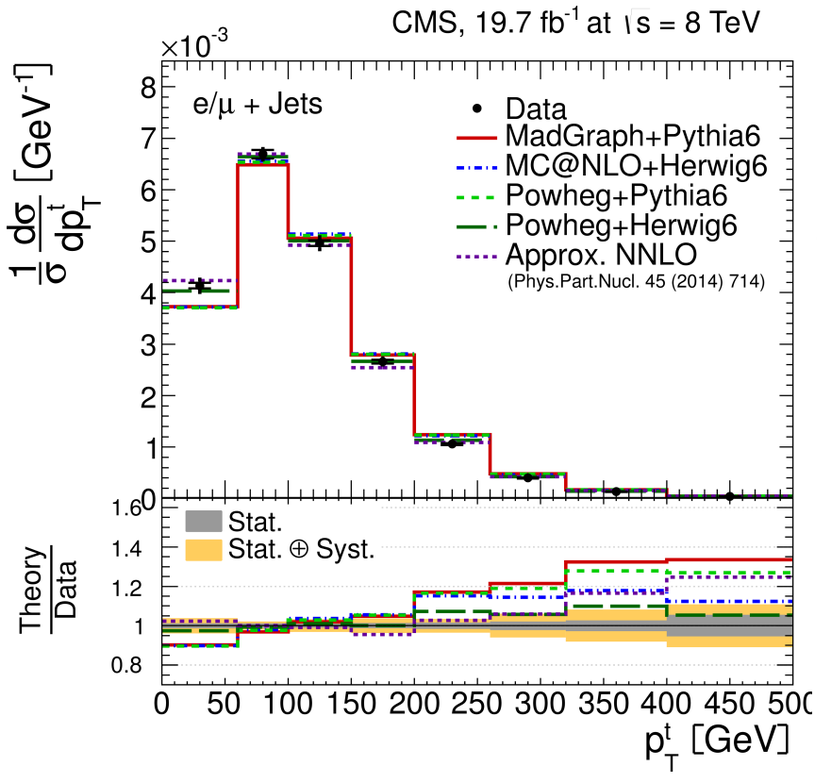
Top p_T, an unexpected feature

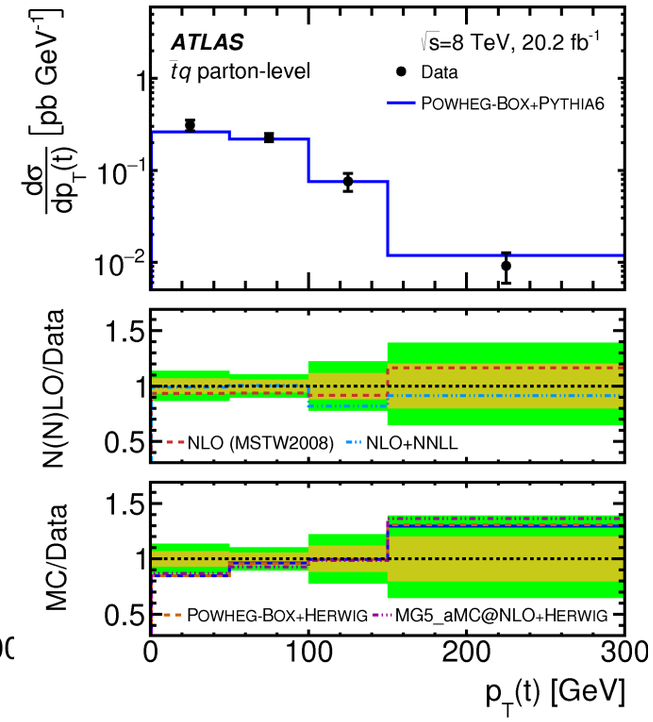
- In general: good agreement with NNLO predictions and NLO generators
  - **Exception:** The top quark p_T spectrum is found to be softer in data than in simulation
    - Effect observed during Run-1, still present in Run-2

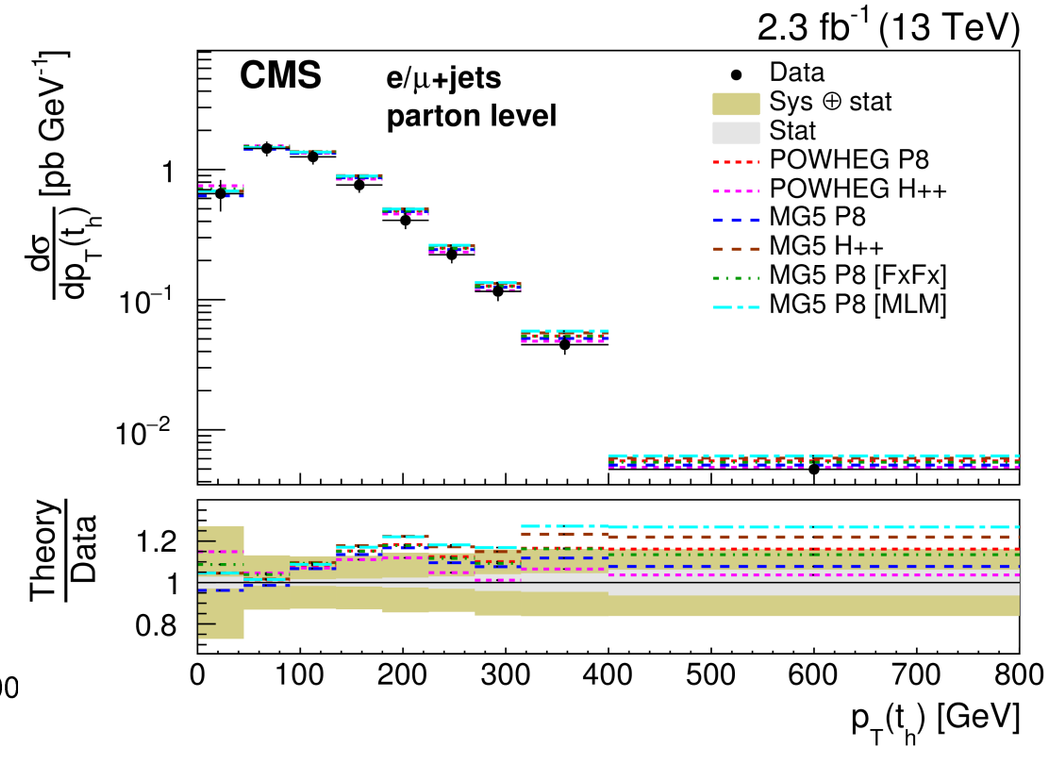


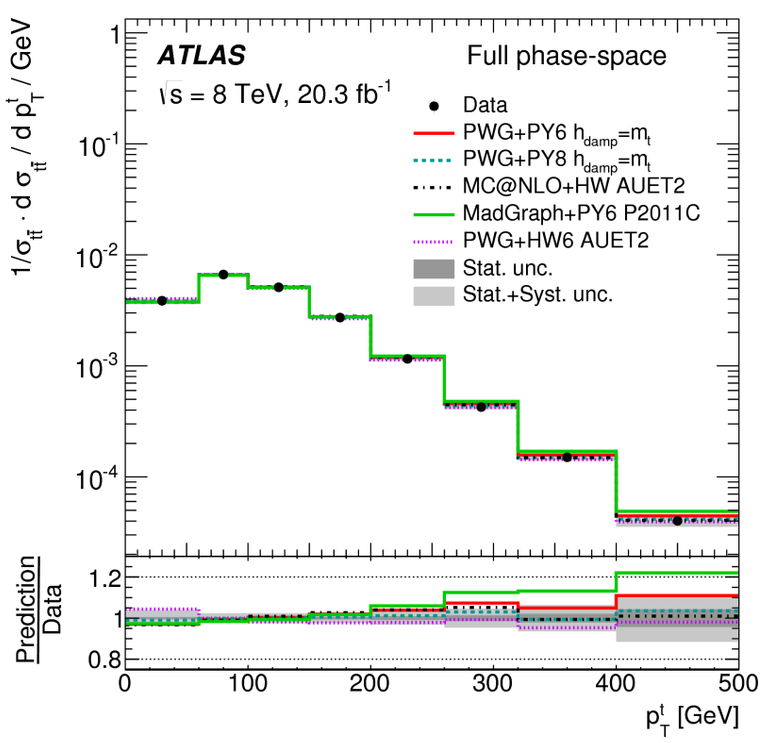
- Improved by higher order (NNLO) calculations and simulation at higher orders (NLO)

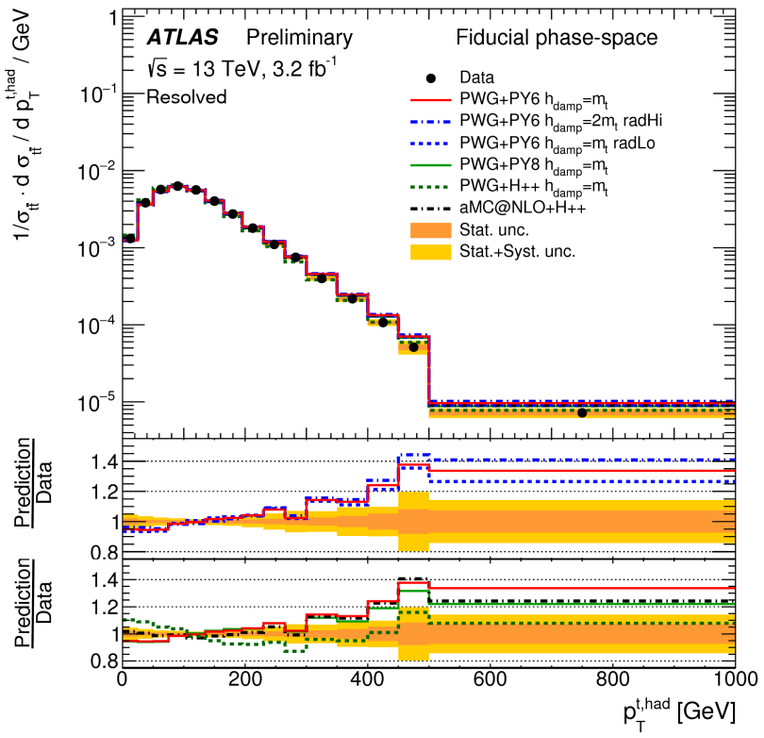
Visible everywhere

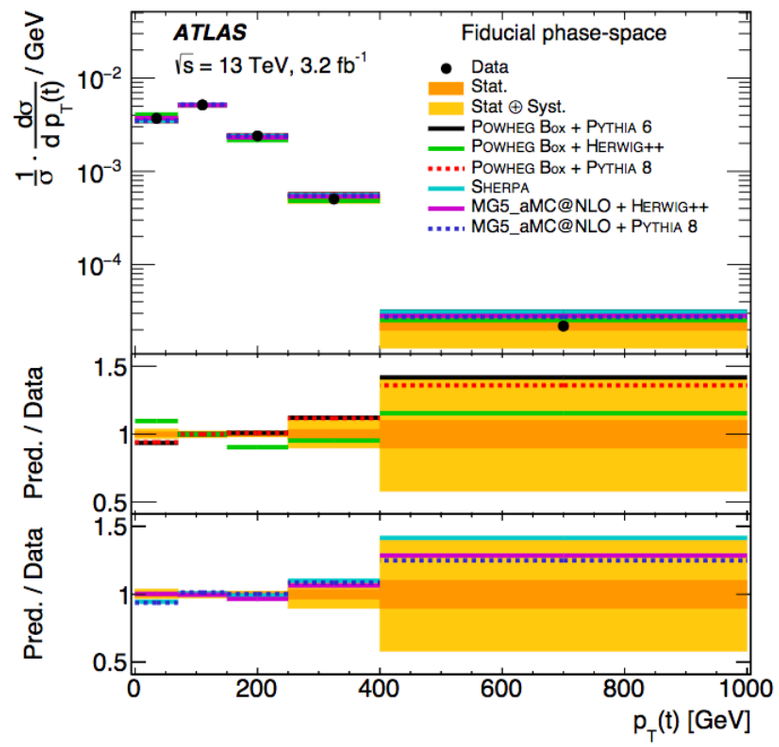




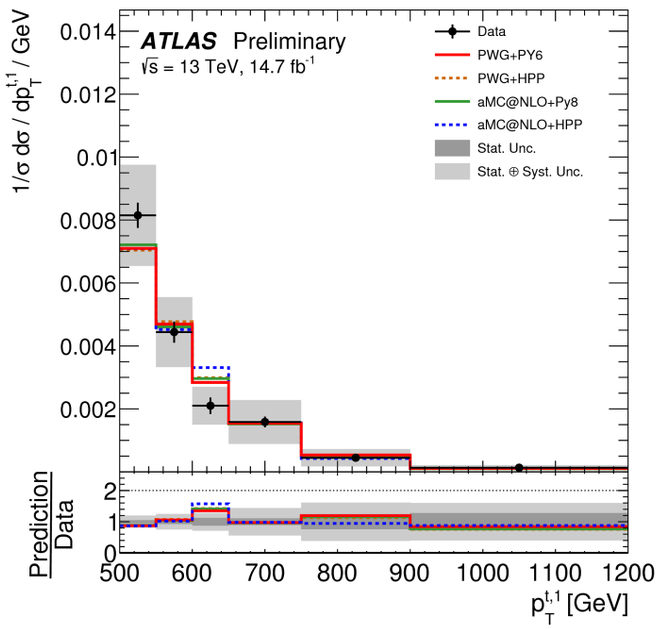


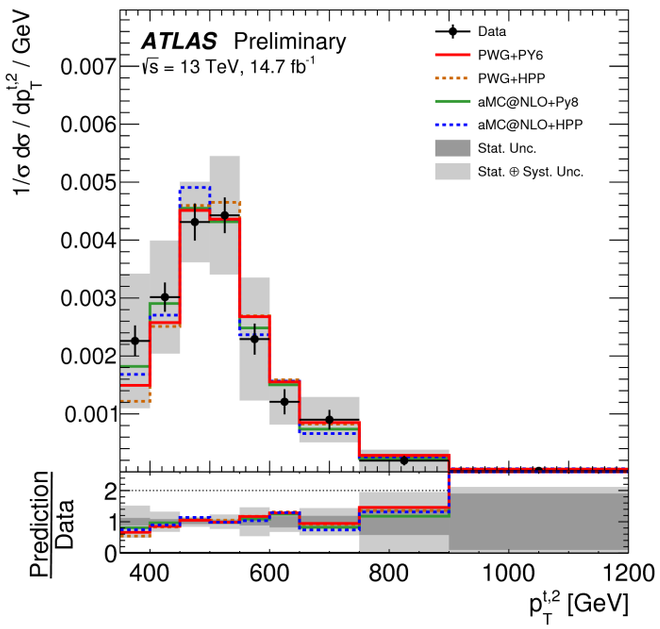


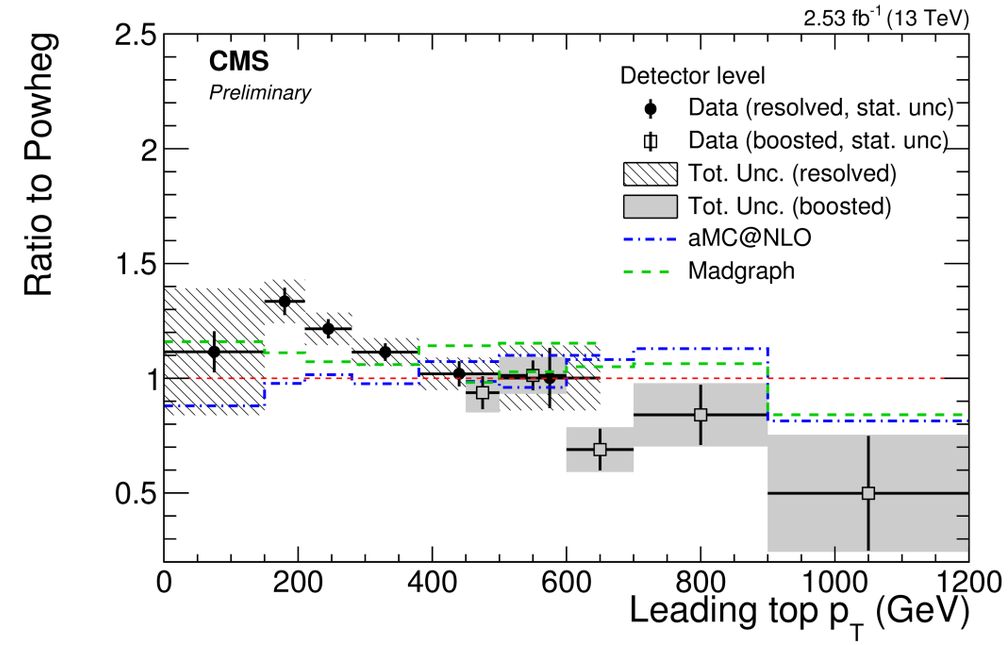




Boosted regime



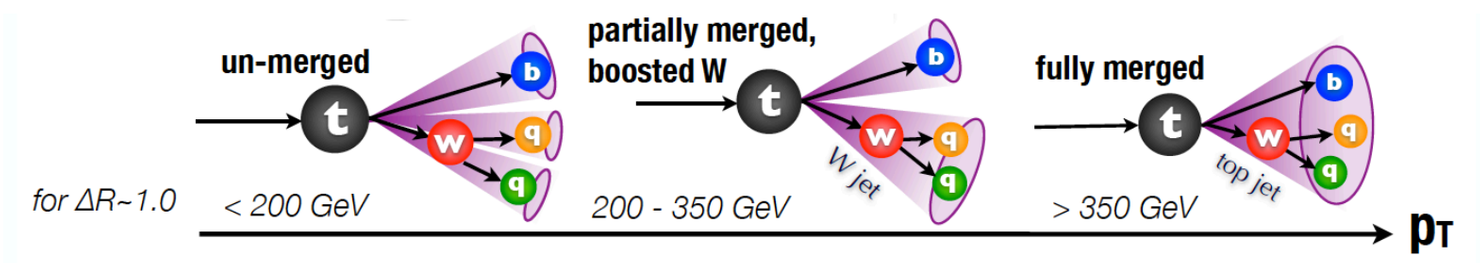


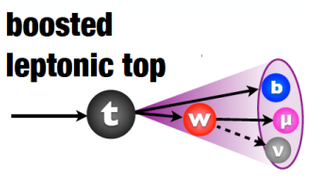


CMS: all jets CMS-TOP-16-013
ATLAS: l+jets ATLAS-CONF-2016-040
ATLAS: all jets ATLAS-CONF-2016-100

The top p_T spectrum is measured beyond the TeV scale, same effect as for non-boosted tops

- 10X boosted signatures at 13 than at 8TeV
  - high p_T top quarks appear in many new physics scenarios
- Challenging reconstruction

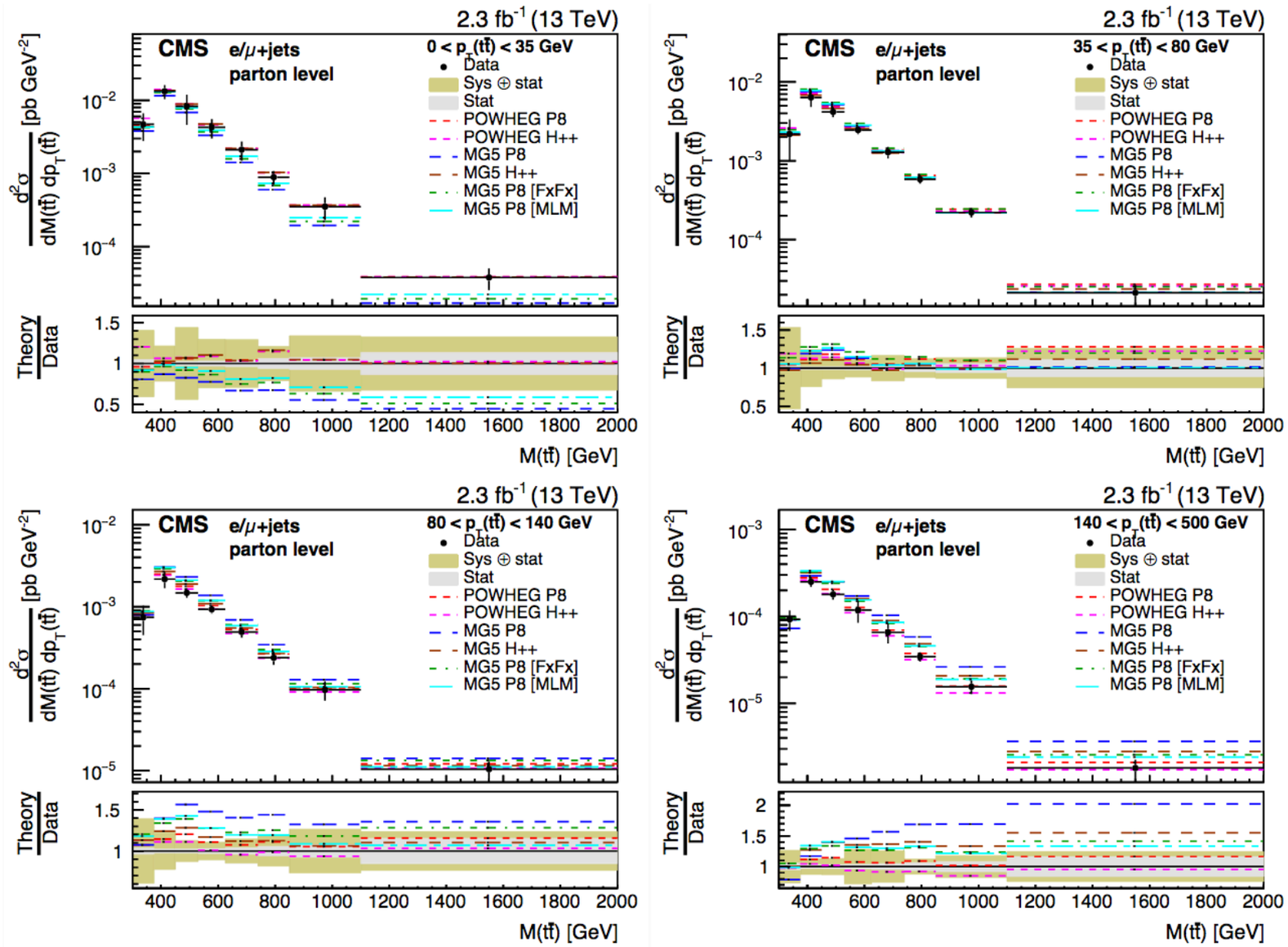


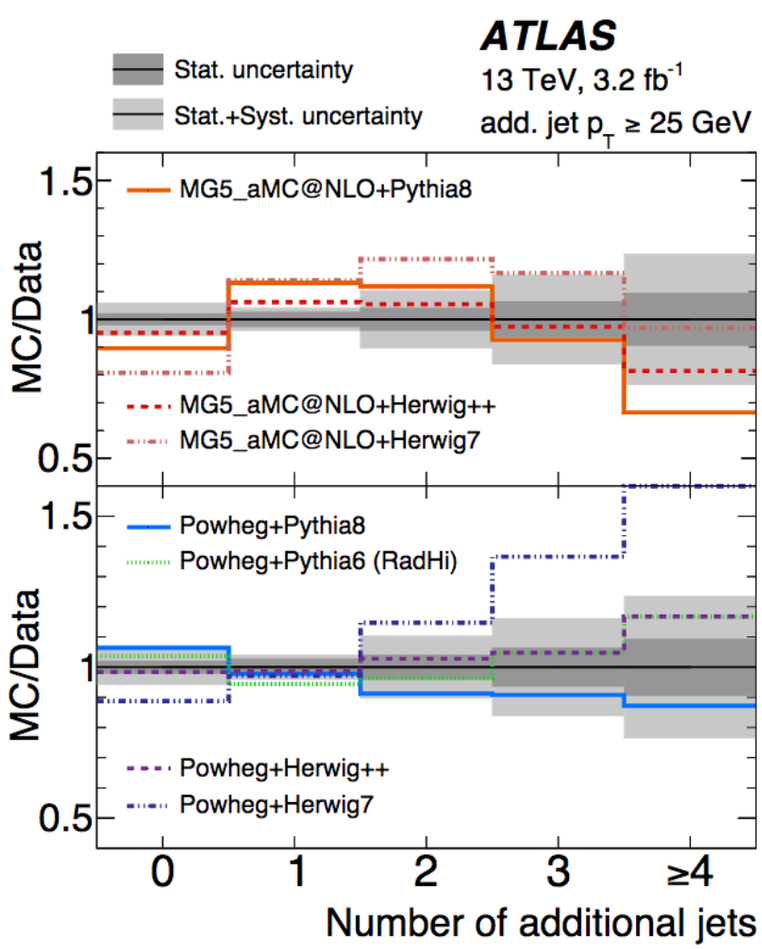


Double differential, gap fraction

- **Double differential**
  - Bin events in pairs of variables
  - Better constrains to the MC by disentangling effects, PDFs

Phys. Rev. D 95, 092001 (2017)



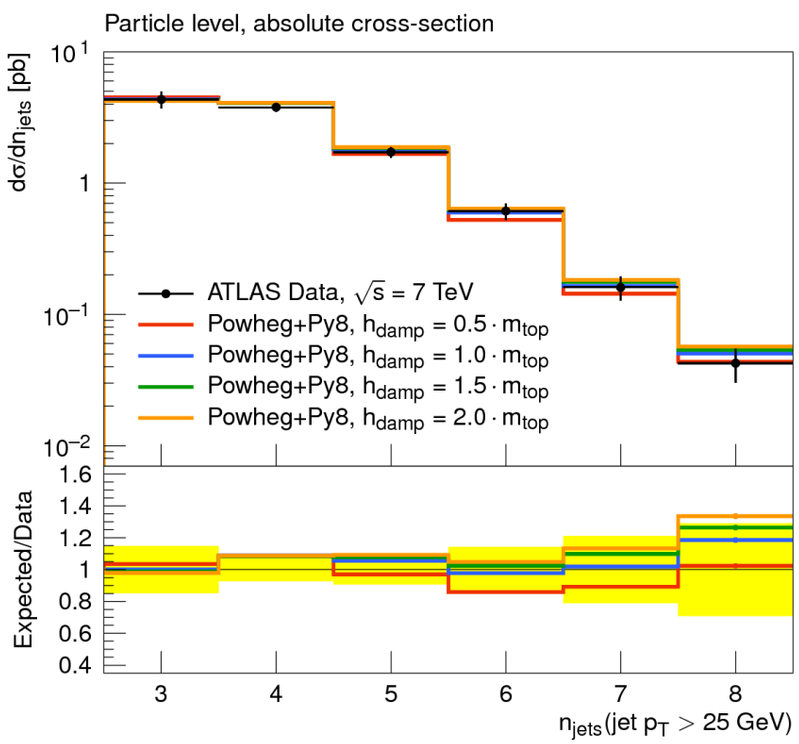


- Measurement of **additional jet activity** important for tuning MC generator parameters
  - Parton shower and hadronization

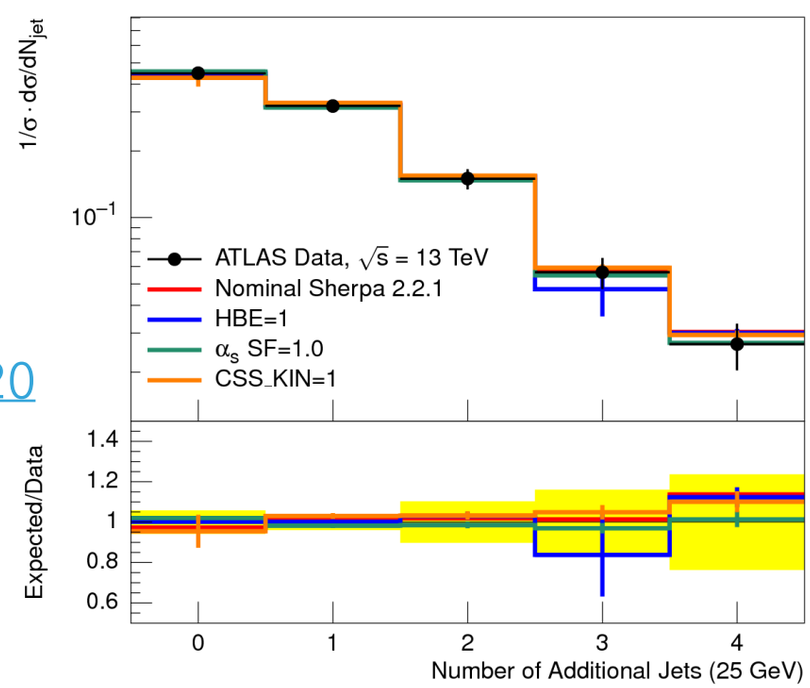
Eur. Phys. J. C77 (2017) 220

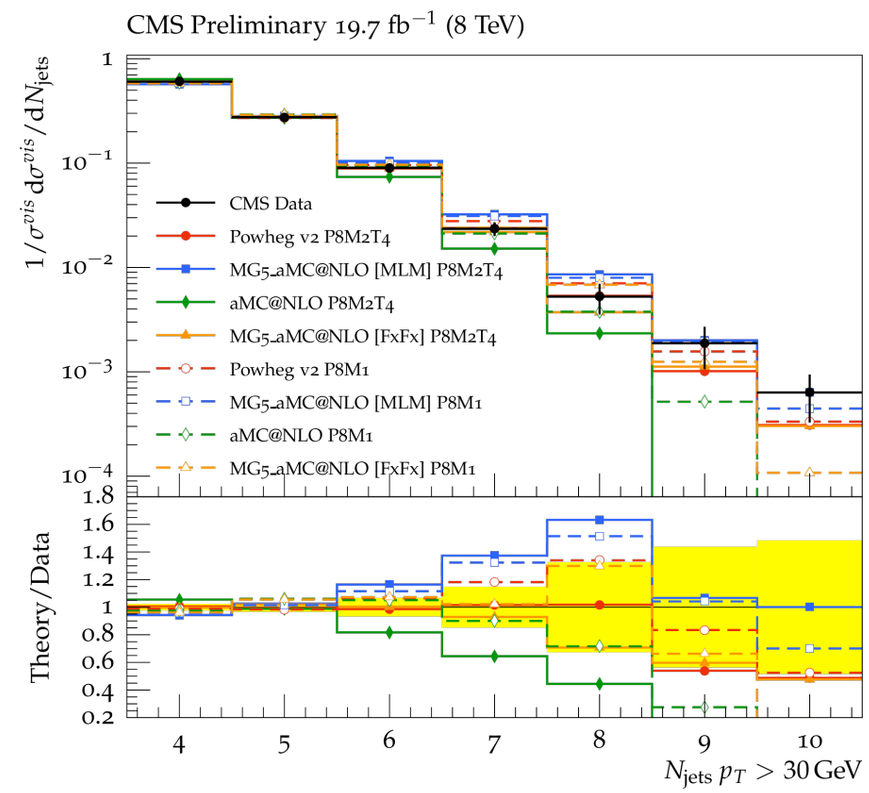
Tuning of the simulation

- Discriminating power between models and tuning parameters already at hand
  - **(delicate) work in progress**
  - Use of available tools (RIVET) crucial



ATLAS: ATL-PHYS-PUB-2016-020





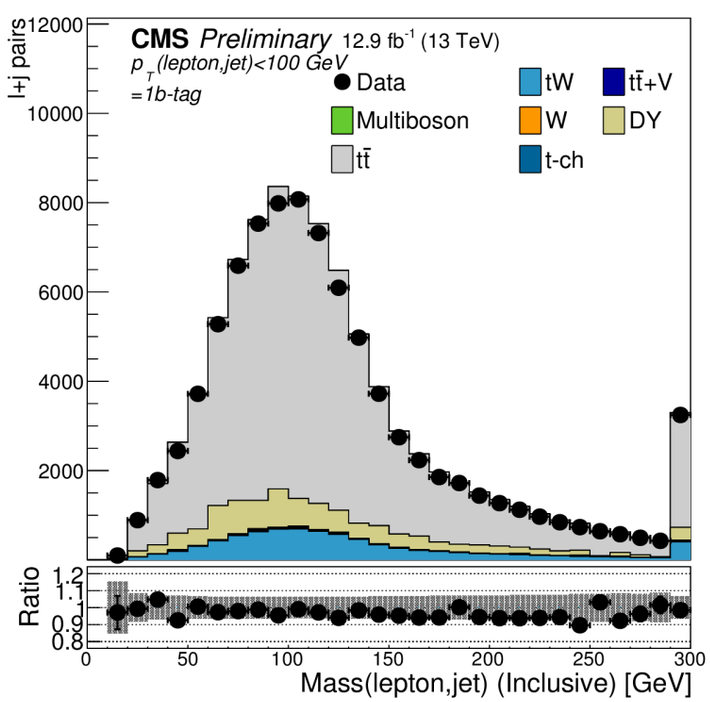
CMS: TOP-16-021

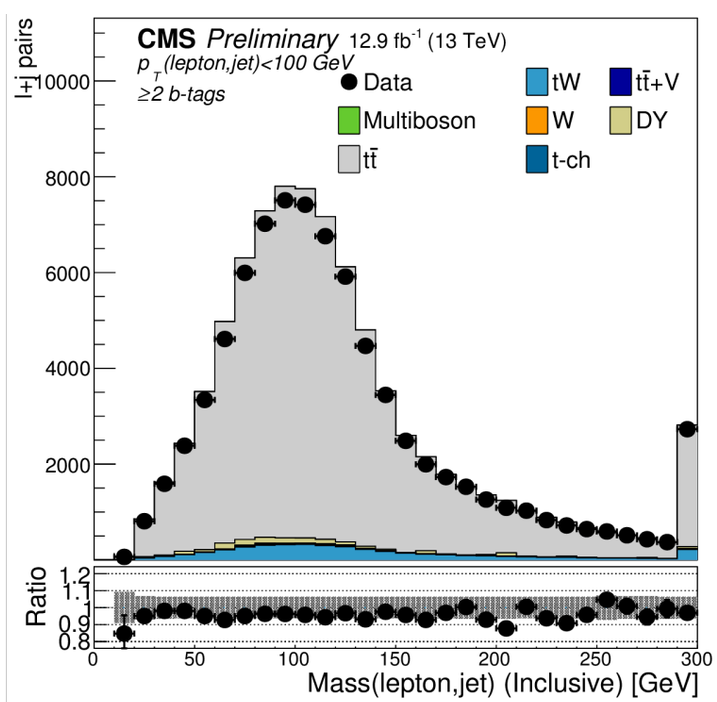
ATLAS: ATL-PHYS-PUB-2017-007

First top properties at 13TeV

- The precision measurement of top properties requires large sets of well-understood data
  - The season of top properties at 13TeV is about to start, teasers

- **Top quark width**
  - We test the SM prediction with **binary hypothesis tests**
    - comparing data with different Γ_t assumptions
  - Using an observable that partially reconstructs the top quark kinematics: $M_{lepton,jet}$





CMS: CMS-TOP-16-019

$0.6 \leq \Gamma_t \leq 2.5$ GeV

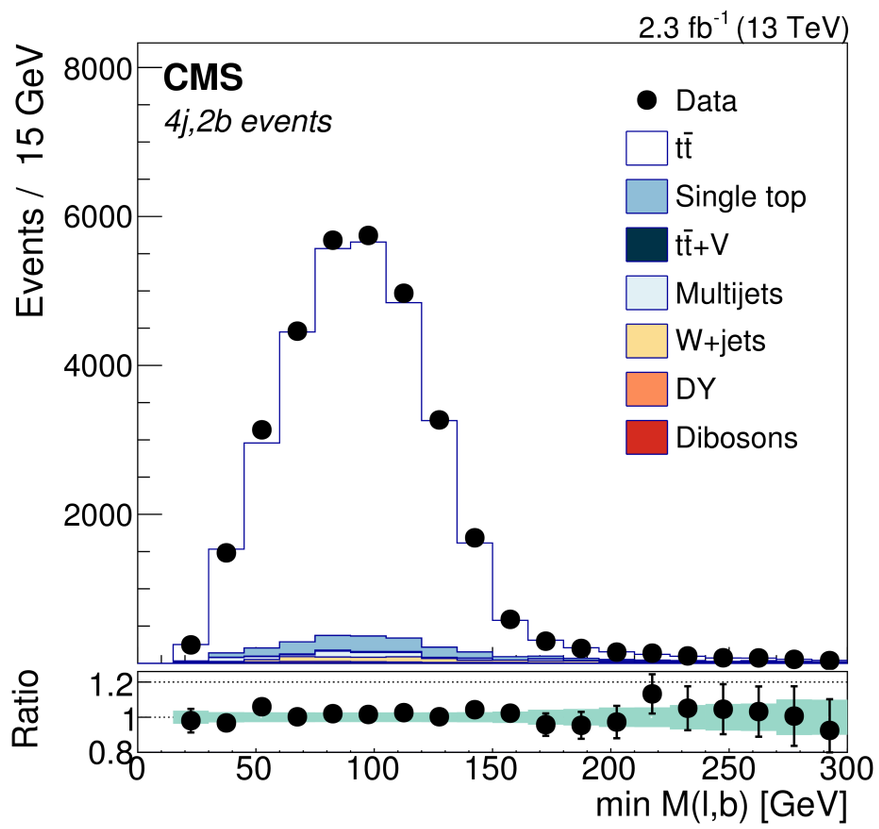
(SM_{NLO} =1.35)

dilepton final state

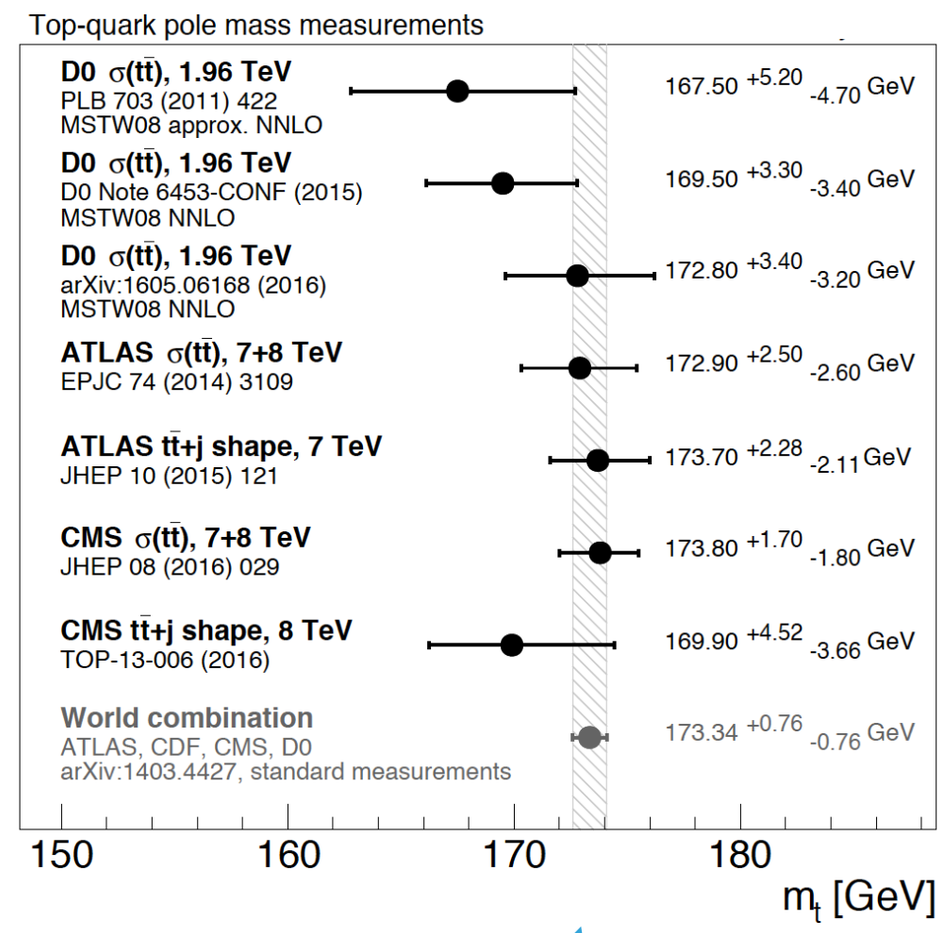
Can be constrasted with the indirect measurement of the width which has 10% unc. Phys. Lett. B 736 (2014) 33

Top "pole" mass at 13TeV

- The top quark **production rate depends directly on the pole mass**
- Any tt inclusive cross section result can be reinterpreted to measure the top pole mass
  - Theoretical input/tools are needed to parametrize the dependency
  - First example at 13 TeV



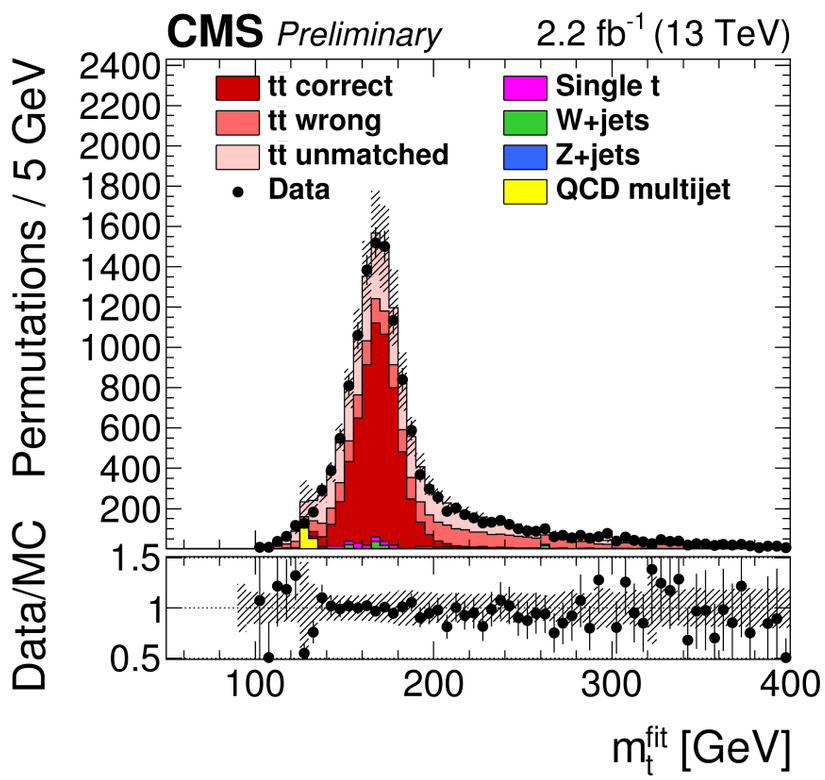
m_t = 172.7+2.4−2.7 (Δm_t = 1.6%)



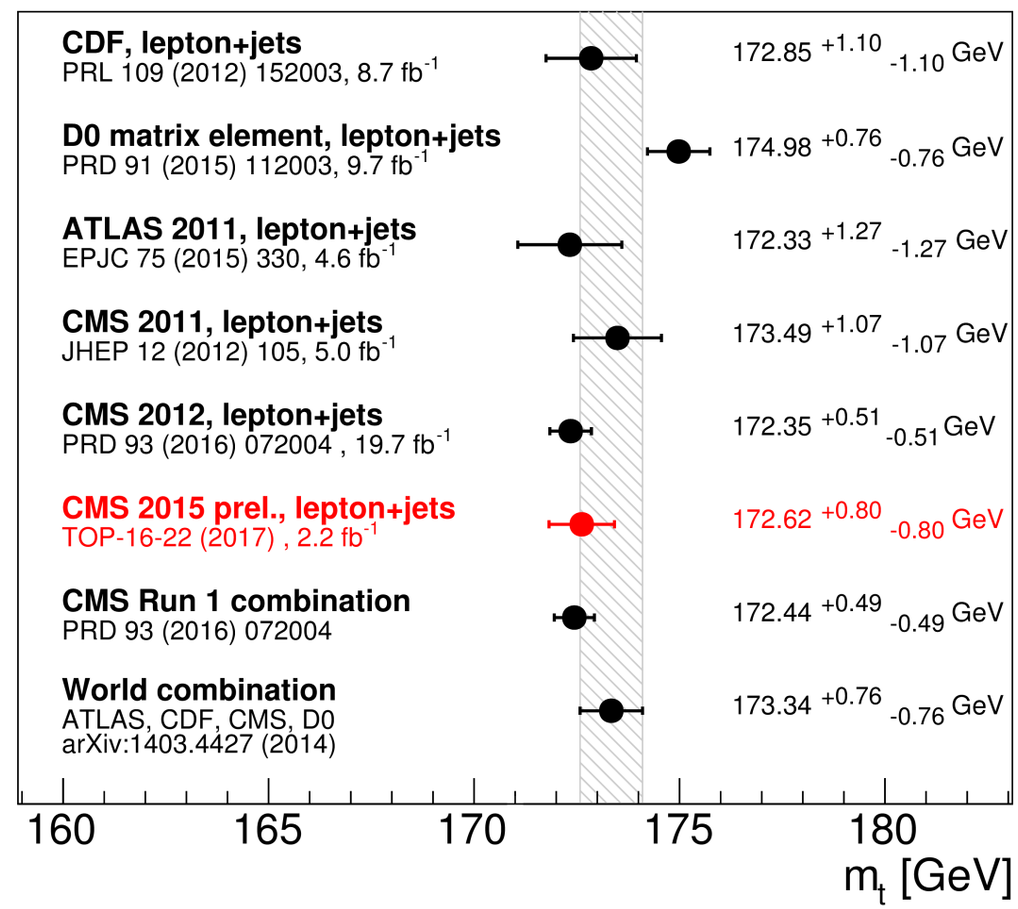
CMS:
l+jets inclusive cross section
Sub. to JHEP

Top mass at 13TeV

- First, preliminary measurement of the top mass at 13TeV
- **Kinematic fit** using decay products
  - simultaneous determination of jet energy scale factor (JSF)
    - constrained by the mass of the W boson in qq decays
- Consistent with Run-1 measurements, reference for improved measurements with Run-2 data



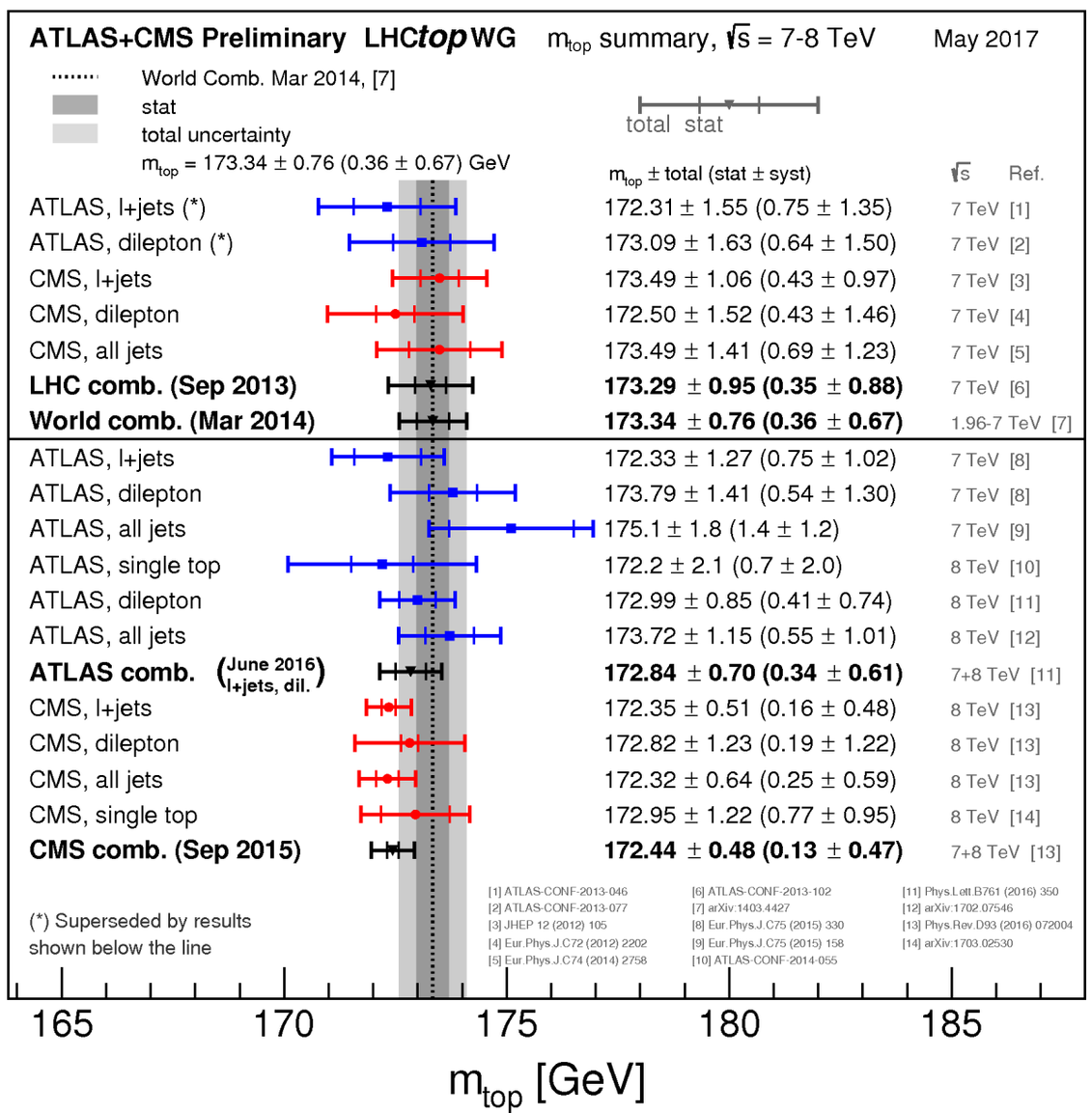
m_{top} =172.62±0.38 (stat.+JSF)±0.70 (syst.) GeV

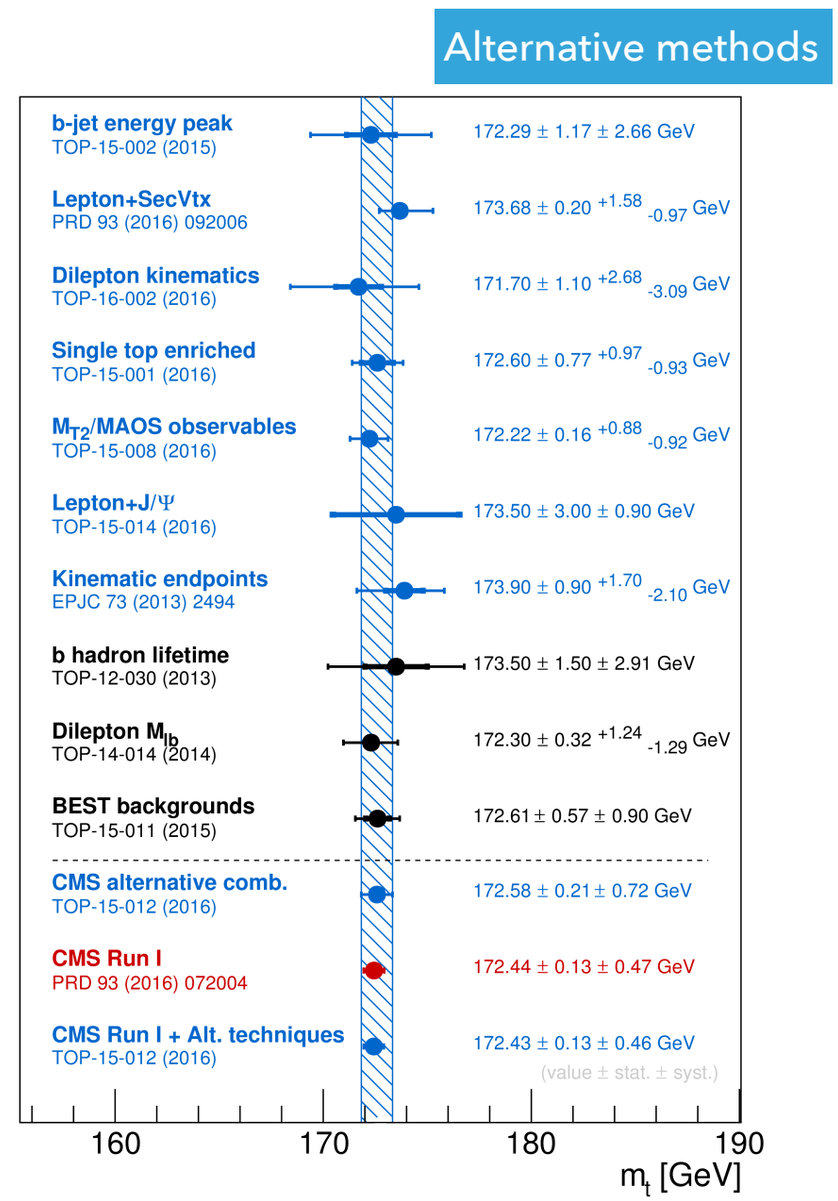


CMS: l+jets final state TOP-16-022

The road ahead for top mass

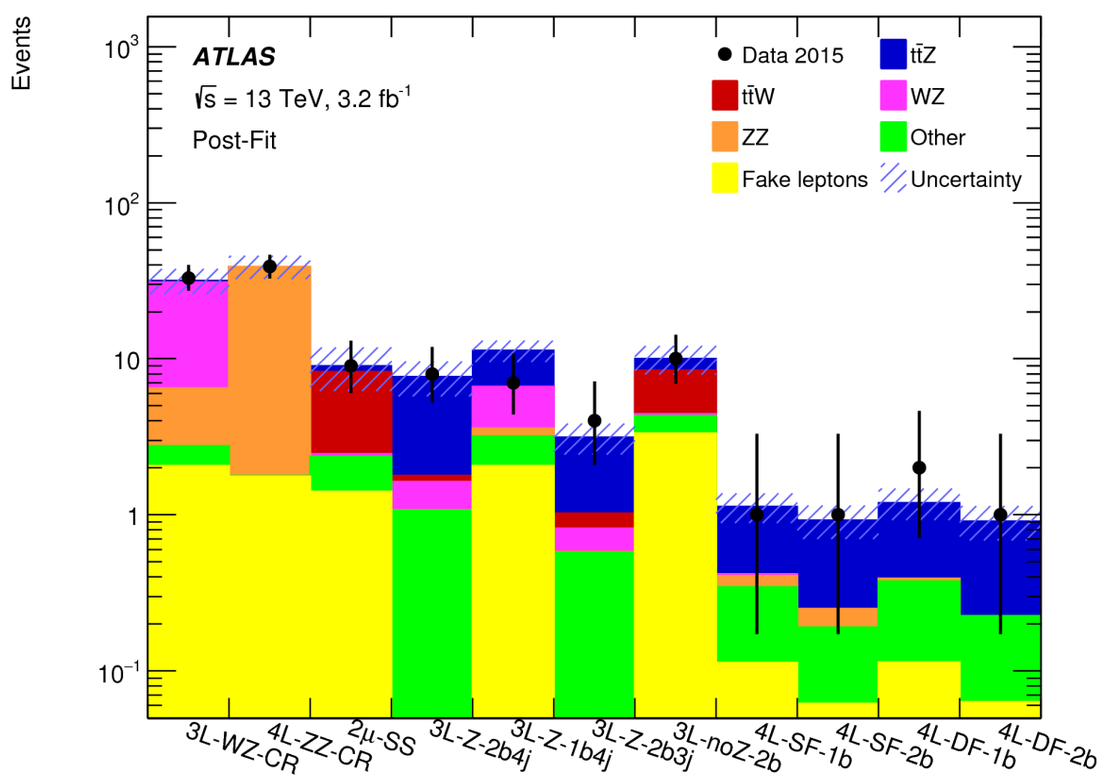
- **Extremely precise measurements**: CMS Run-1 combination 0.3%, ATLAS dilepton only 0.5%
- Systematic uncertainties are the next frontier: JES, MC modelling
  - **Hadronization** (b-fragmentation), underlying event, matching between the tree-level ME generator and the parton showering (PS)



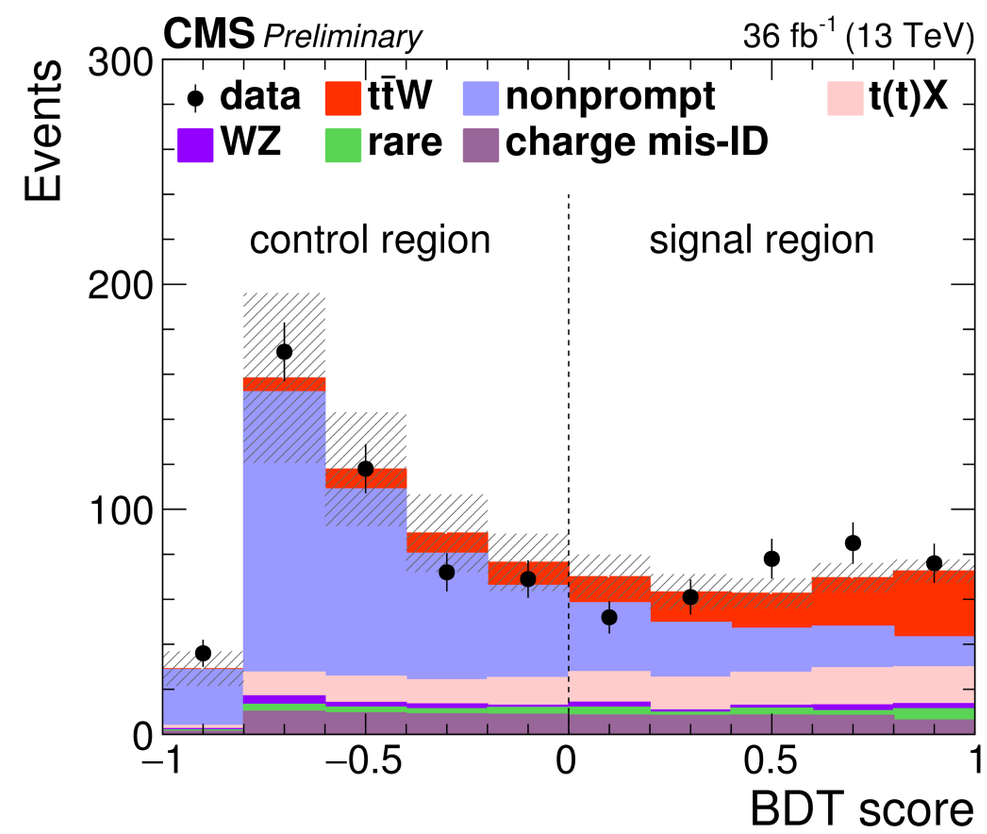


tt+X: insight on top quark couplings

- With large luminosity and centre of mass energies, rare top quark production can be studied
  - **tt+V:** tt+W/Z observed for the first time in the Run-1, ttγ studied
    - Sensitive to **BSM** effects, anomalous **couplings**, leading **EFT operators**
- At 13 TeV, similar approach as in Run-1, 3 channels: dilepton same-sign, 3 lepton, 4 lepton
    - Simultaneous fit across several regions
    - Event counts and BDT



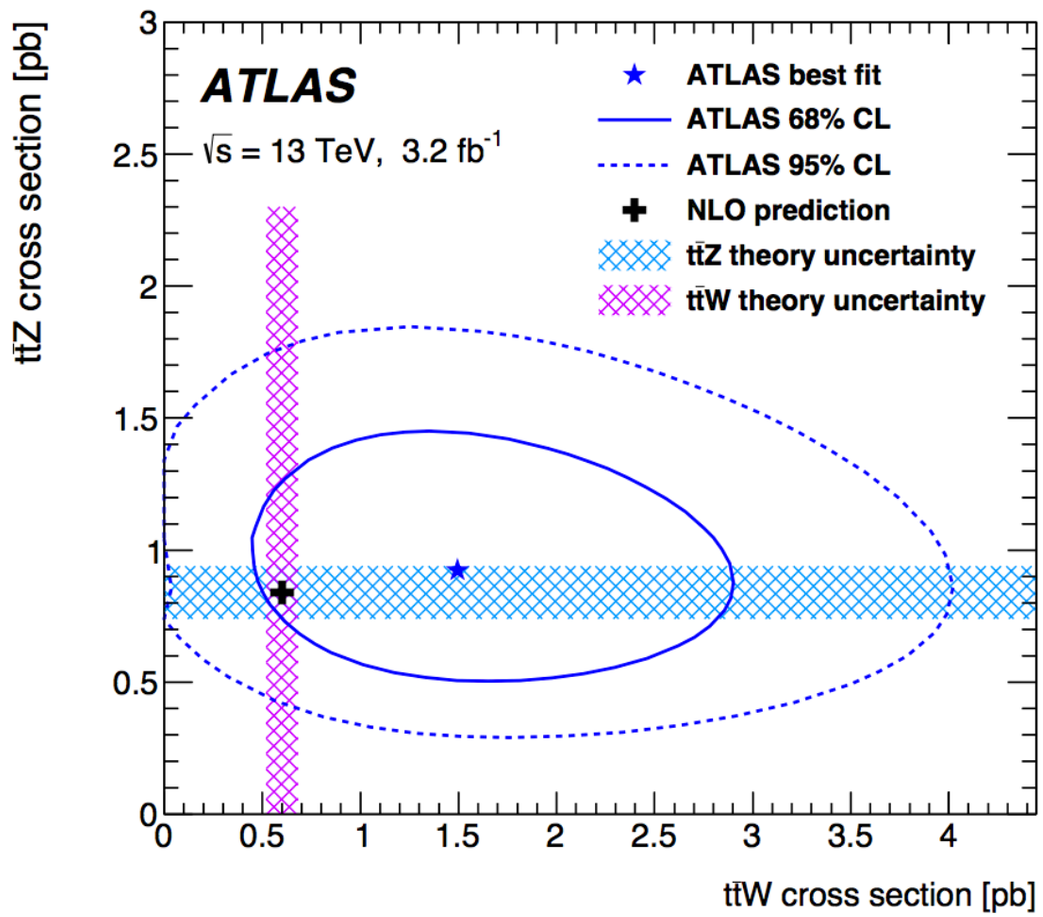
ATLAS: Eur. Phys. J. C (2017) 77:40

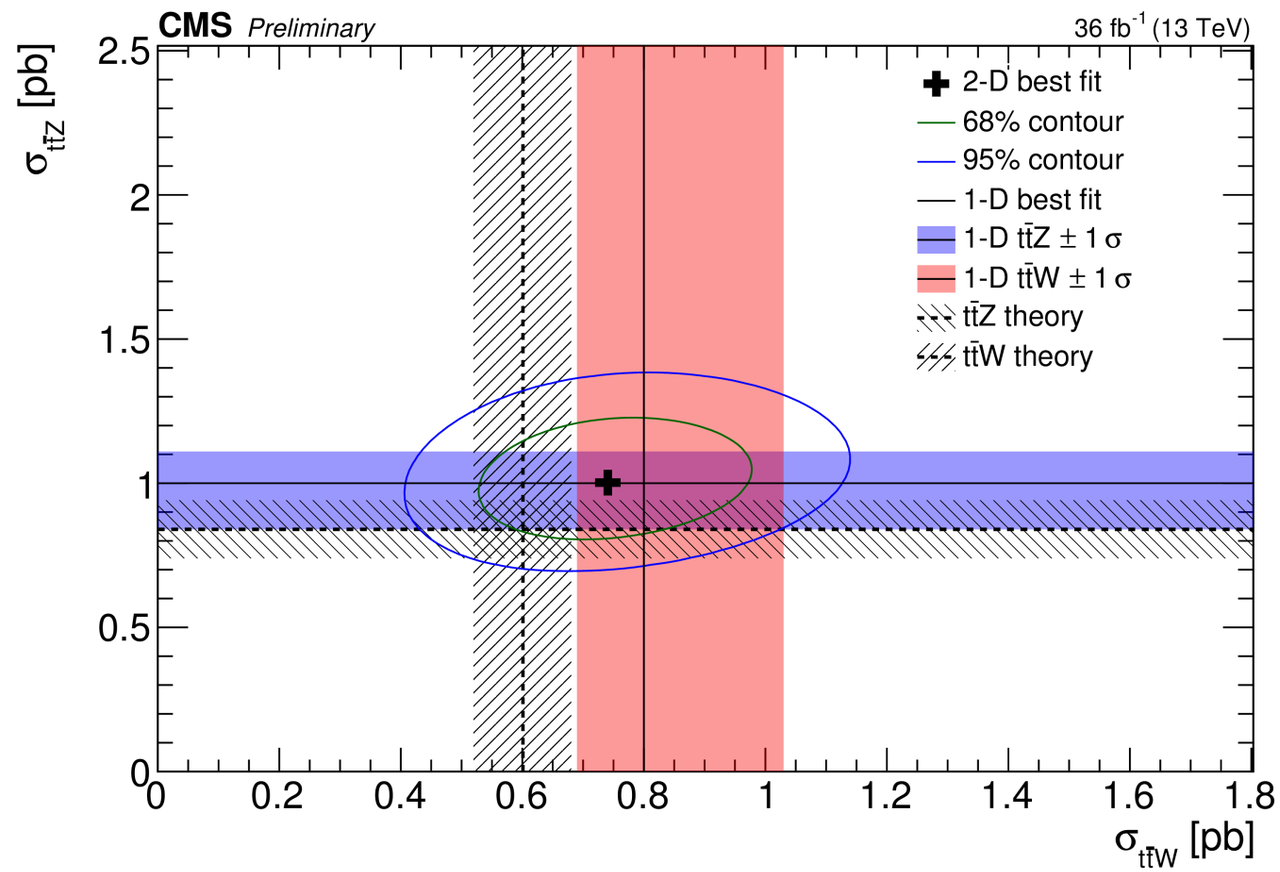


CMS: TOP-17-005

ttW/Z

σ_{ttZ}^{SM} = 0.839 (±12%) pb
σ_{ttW}^{SM} = 0.600 (±13%) pb





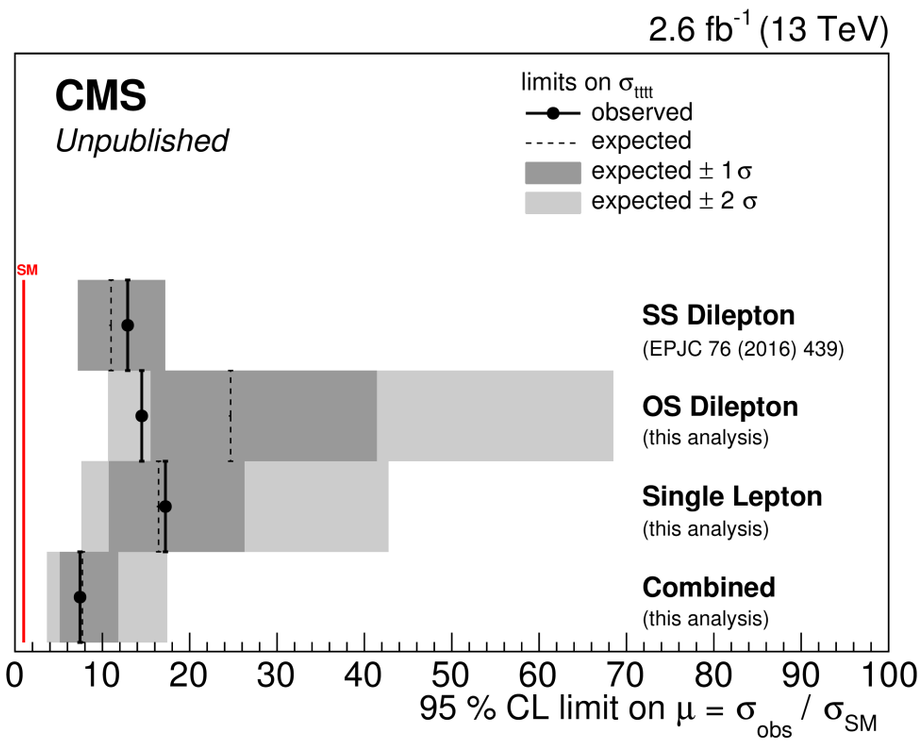
σ_{ttZ} = 0.9 ± 0.3 pb → **3.9σ (3.4)**
σ_{ttW} = 1.5 ± 0.8 pb → **2.2σ (1.0)**

σ_{ttZ} = 1.0 +0.9-0.8 (stat) +0.12-0.10 (sys) → **9.9σ (9.5)**
σ_{ttW} = 0.80 +0.12-0.11 (stat) +0.13-0.12 (sys) → **5.5σ (4.6)**

- **Single top production with a Z or γ** (tZq, tγ) it is also interesting on its own:
  - Enhancement may be a sign of FCNC in the top sector
  - Studied in Run-1, not yet available with Run-2 data

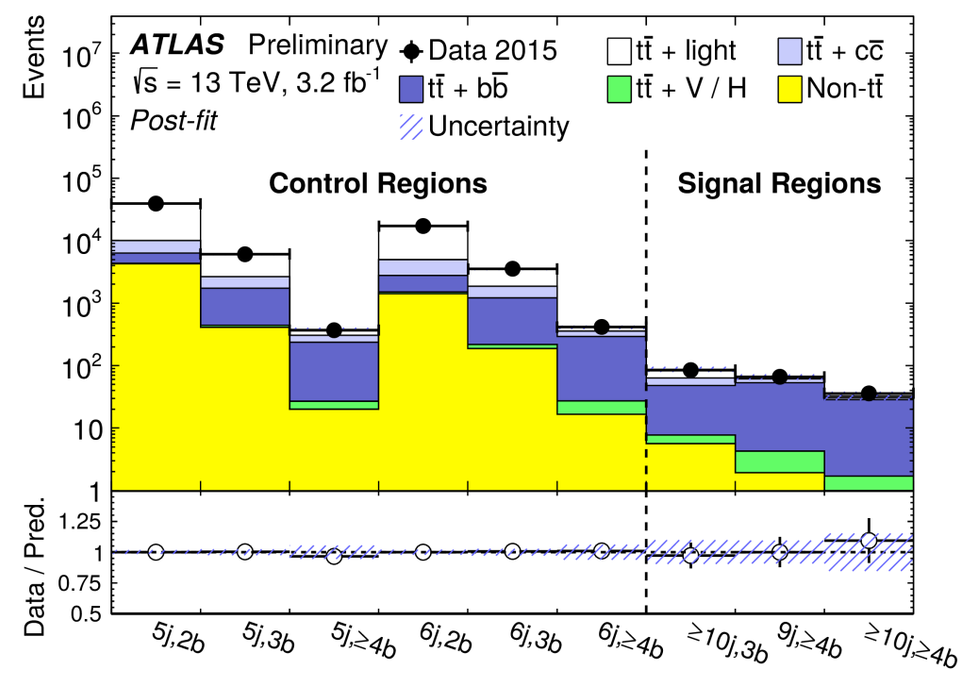
tt+tt: 4 top production

- **VERY** rare production → SM 4top is produced 5 orders of magnitude less often than tt
  - 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 […]



CMS: l+jets and dilepton

Sub. to PLB



ATLAS: l+jets

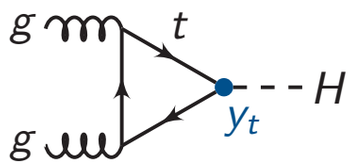
ATLAS-CONF-2016-020

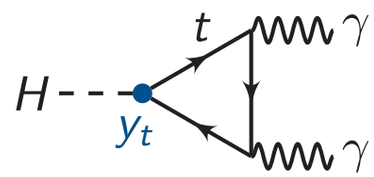
Getting close!

CMS: SUSY SS (Sub. to EPJC) with 35.9fb^{-1} observed (expected) limit 4.6 (2.9 +1.4-0.9) σ_{SM} tttt

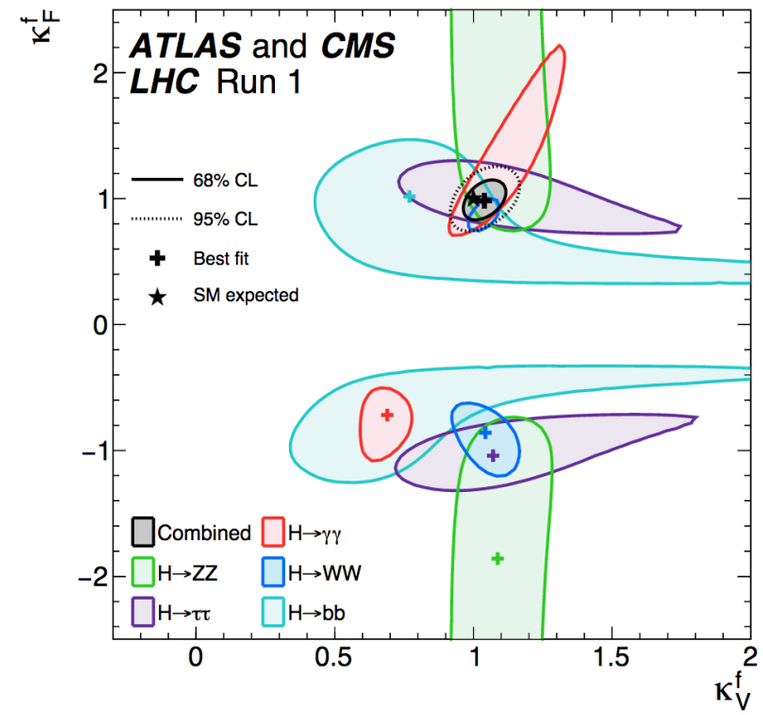
Top – Higgs

- The Higgs boson and the top quark have a special relationship
  - Strong couple in the SM (~1)

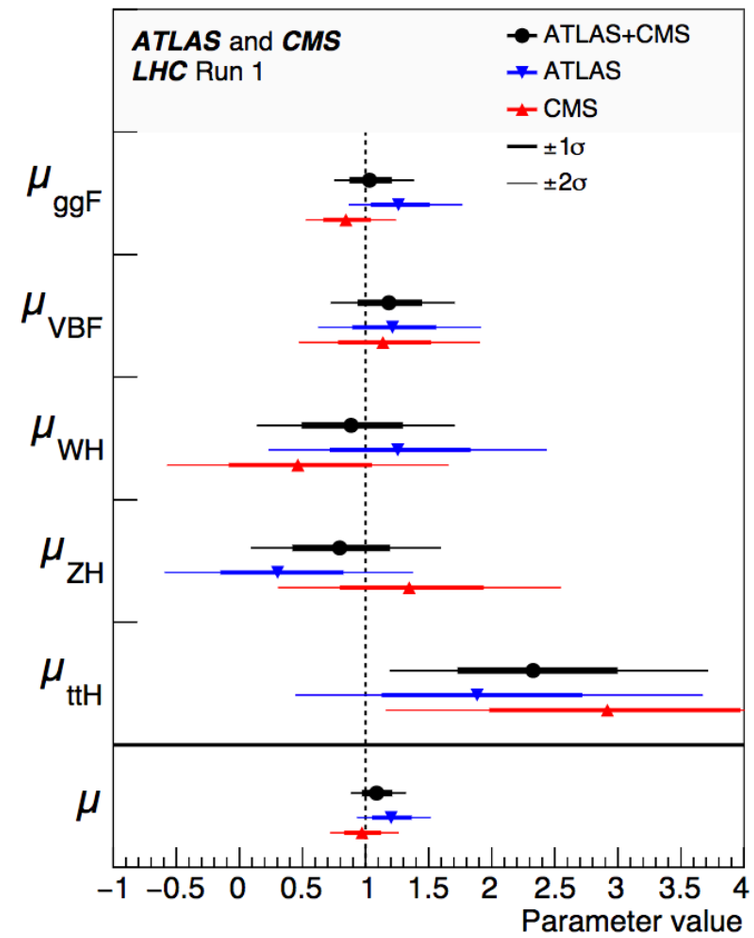




- From ggH and Hγγ → **Indirect constraints**

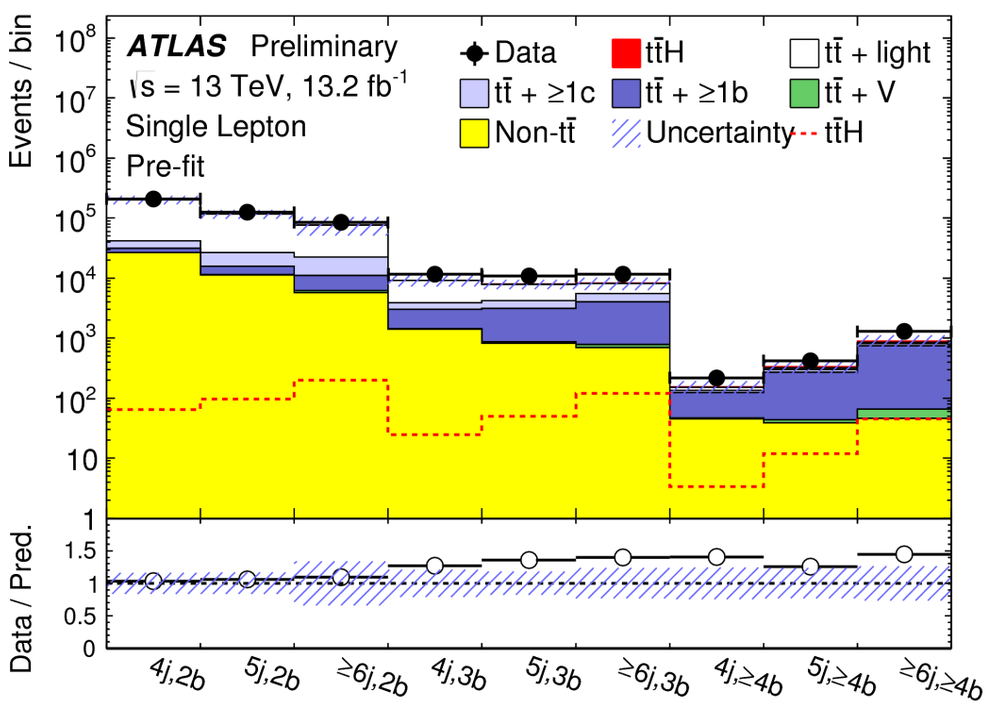


- To perform a **direct measurement of the coupling** → processes where top and Higgs are produced together
  - **ttH** sensitive to the magnitude, tH to the sign
  - Limited by statistics in Run-1
    - Small excess (still compatible with the SM)
  - One of the physics targets for Run-2
    - Good cross section increase
    - Understanding and modelling of tt+X is crucial

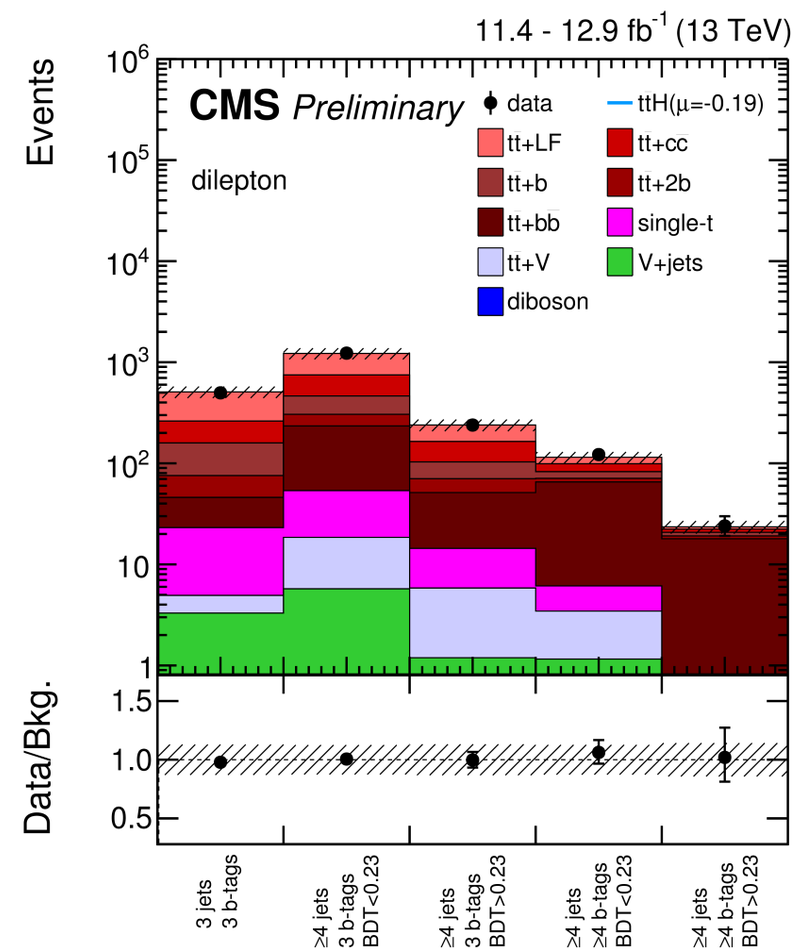


ttH, Hbb

- At 13 TeV: ttH results in different decay modes
- **ttH, H→bb**
  - Understanding tt+bb is a main challenge of the analysis
- Basic ttbar selection (with 1 or 2 leptons) plus additional jets (b-jets)
  - Set of categories based on number of (b) jets with different signal and background composition
  - MVA techniques in signal enriched regions (BDT, ME)



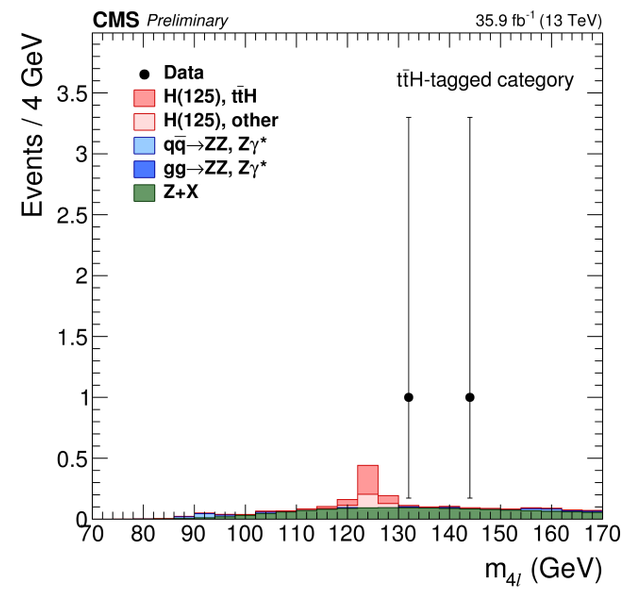
ATLAS: ATLAS-CONF-2016-080



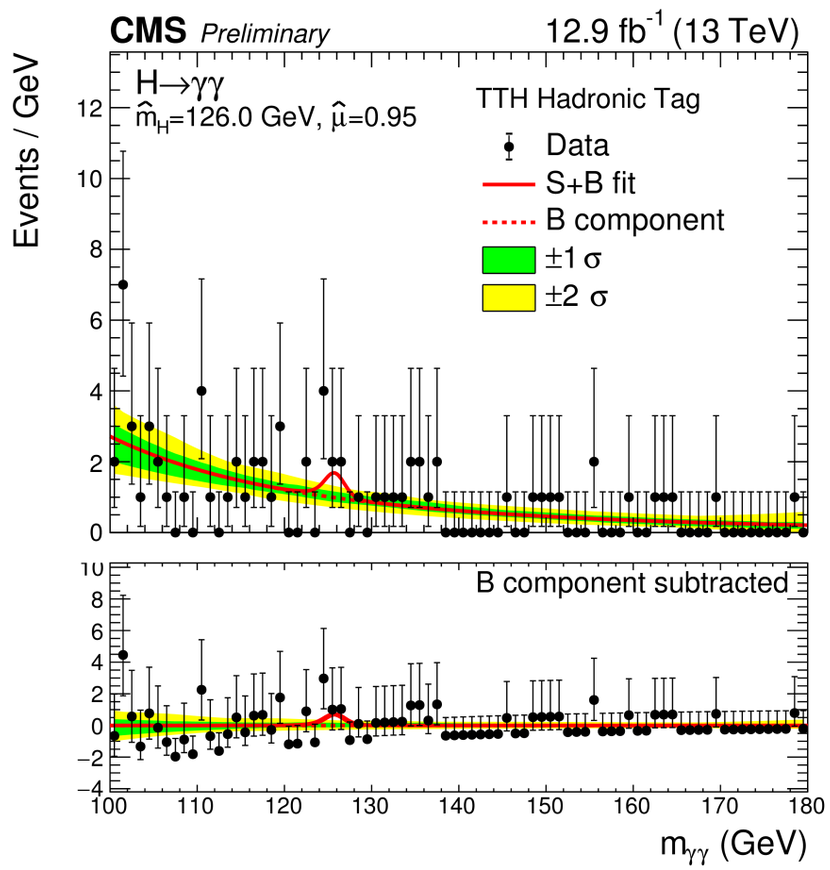
CMS: HIG-16-038

ttH, in high resolution channels

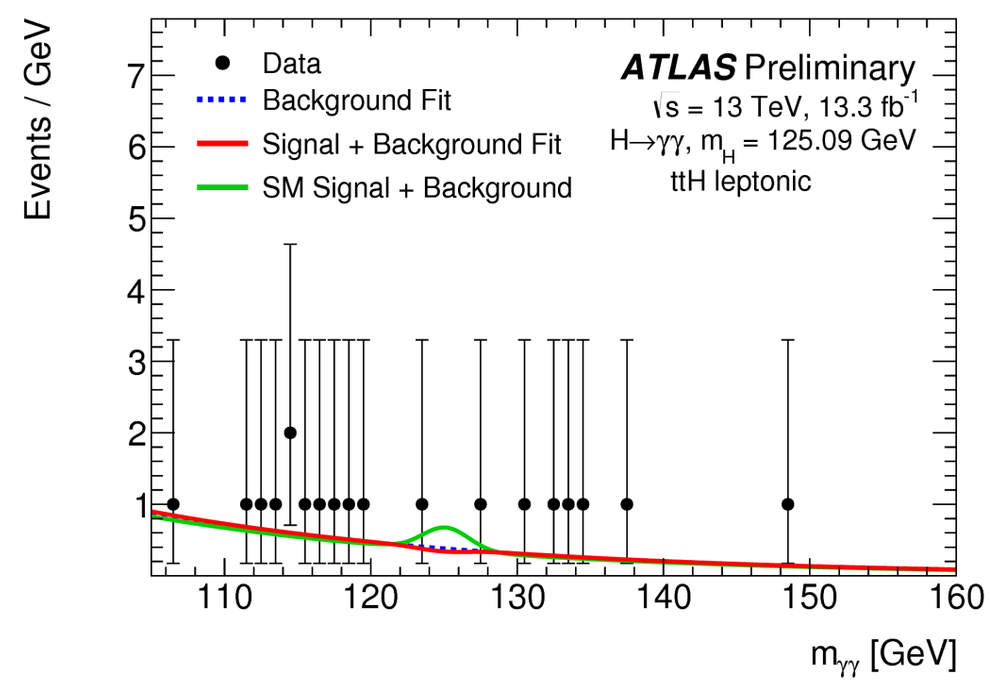
- **H→γγ and H→ZZ→4l** narrow Higgs mass peak over a smooth background
  - Small branching fraction, combined with the low production rate of ttH
    - Low yield signals, statistically limited
- **ttH, H→γγ (ZZ) a part of the main H→γγ (ZZ) analyses**
  - H→γγ leptonic and hadronic tags
  - H→ZZ non overlap with multilepton (next slide)



CMS: H→ZZ→4l HIG-16-041



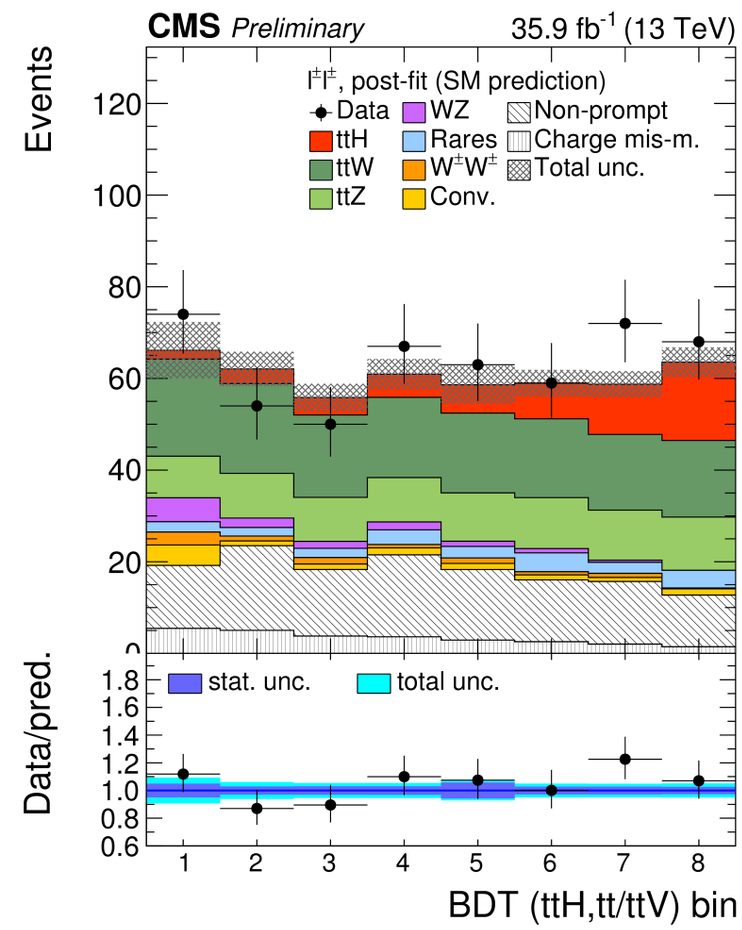
CMS: H→γγ HIG-16-020



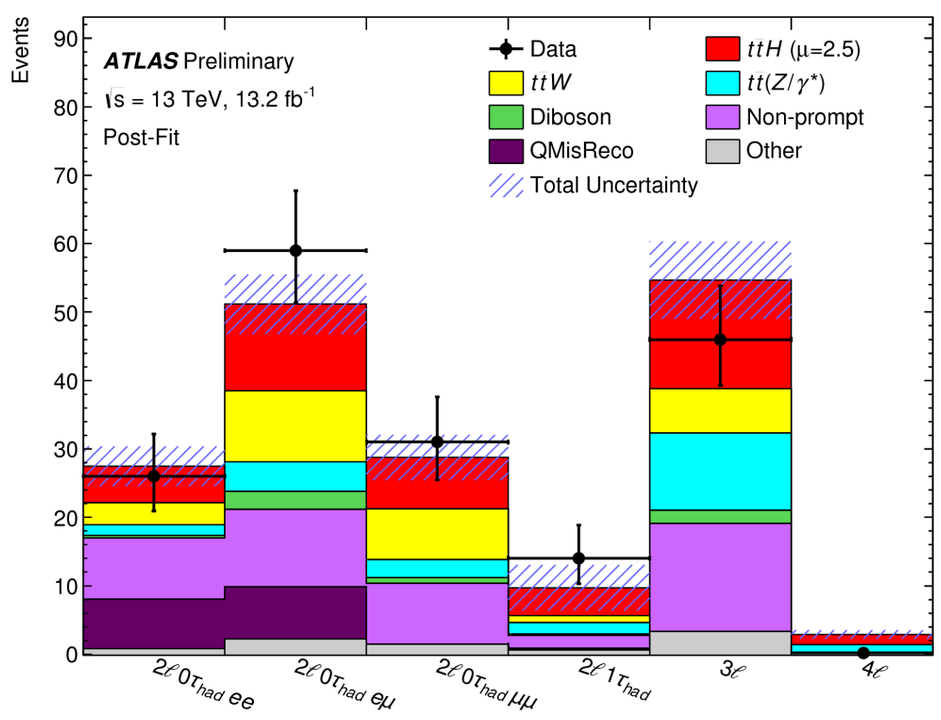
ATLAS: H→γγ ATLAS-CONF-2016-067

ttH in multilepton final states

- Final states with same-sign dileptons, 3 and 4 leptons
  - **sensitivity to ttH,H→WW,**
    - also, to a lesser extent: H→ZZ and H→ττ
  - ttV background very important
- Analysis split into different categories:
  - number of leptons, τ_h , lepton flavor, charge, number of (b) jets
- Using event counts / sophisticated MVA techniques



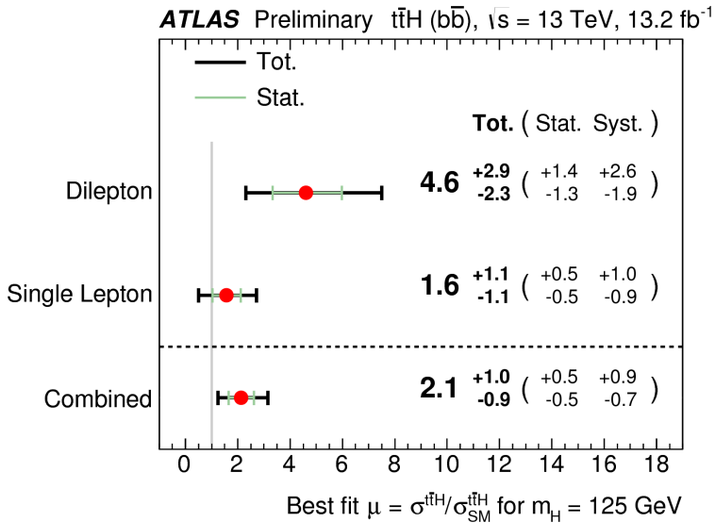
CMS: HIG-17-004
Additional dedicated H→ττ analysis HIG-17-003

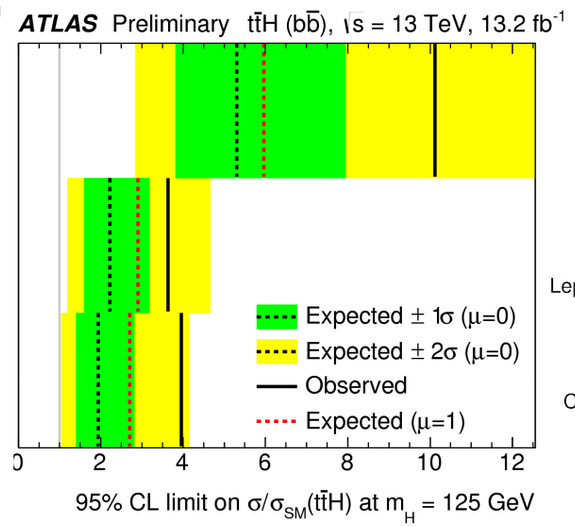


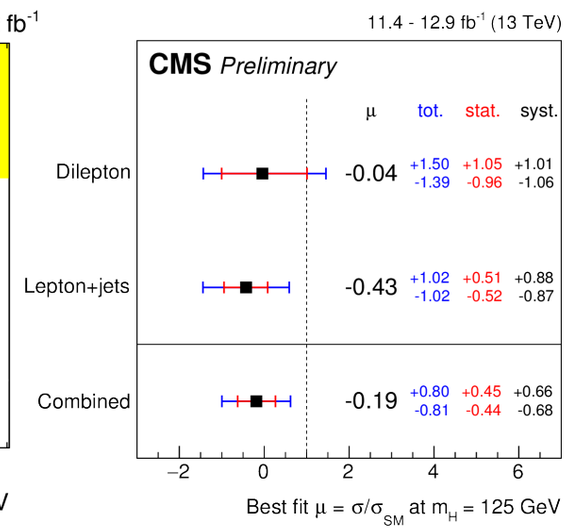
ATLAS: ATLAS-CONF-2016-058

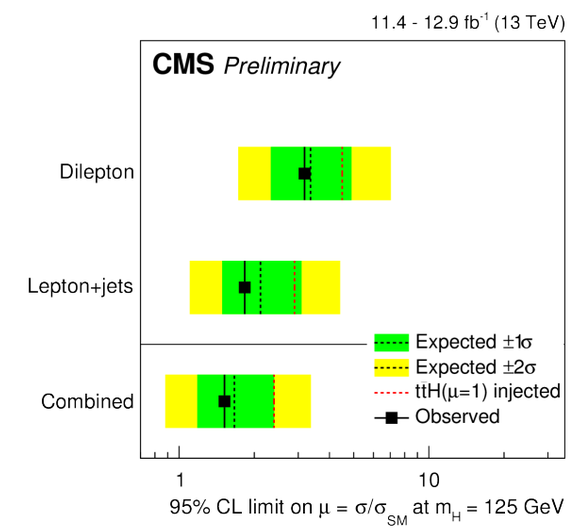
The ttH multilepton is **at the moment** the most sensitive decay for ttH, with 35.9 fb^{-1} CMS without the τ_h analysis has **evidence of ttH production with a significance of 3.3σ (2.5 expected)**

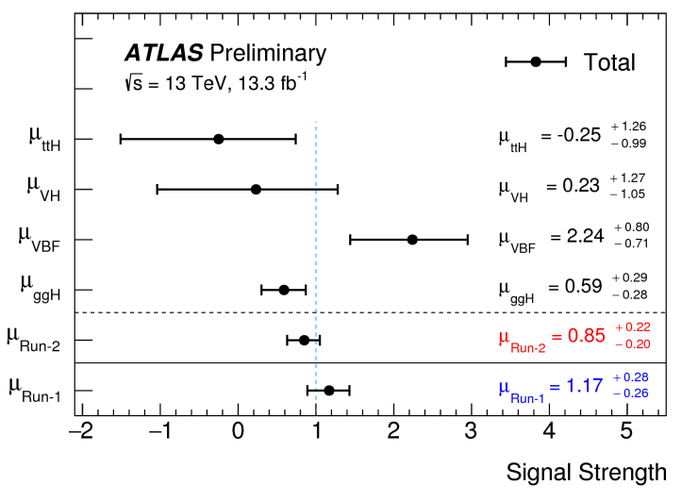
The hunt is on!

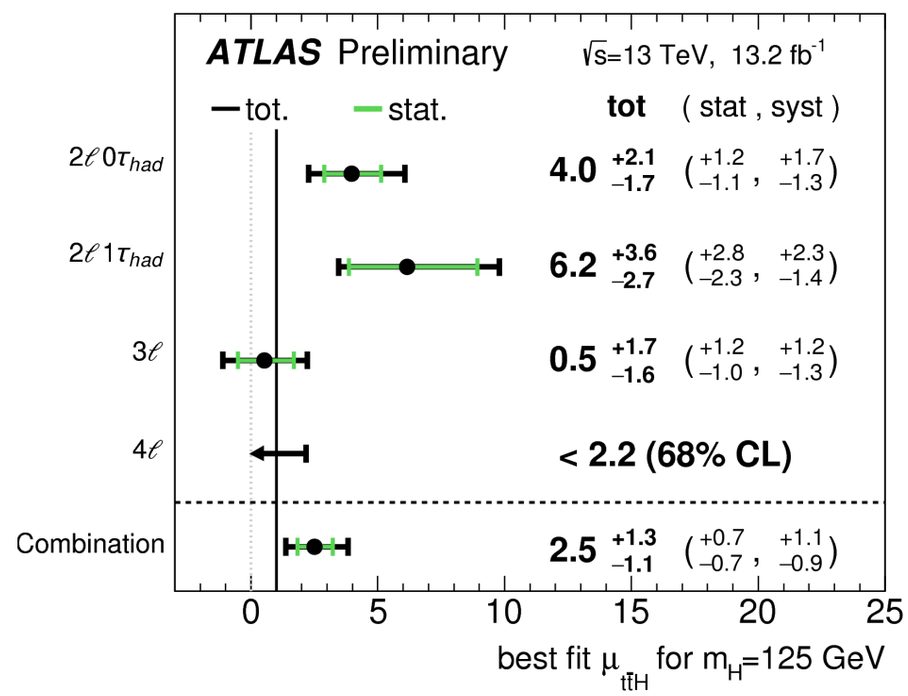


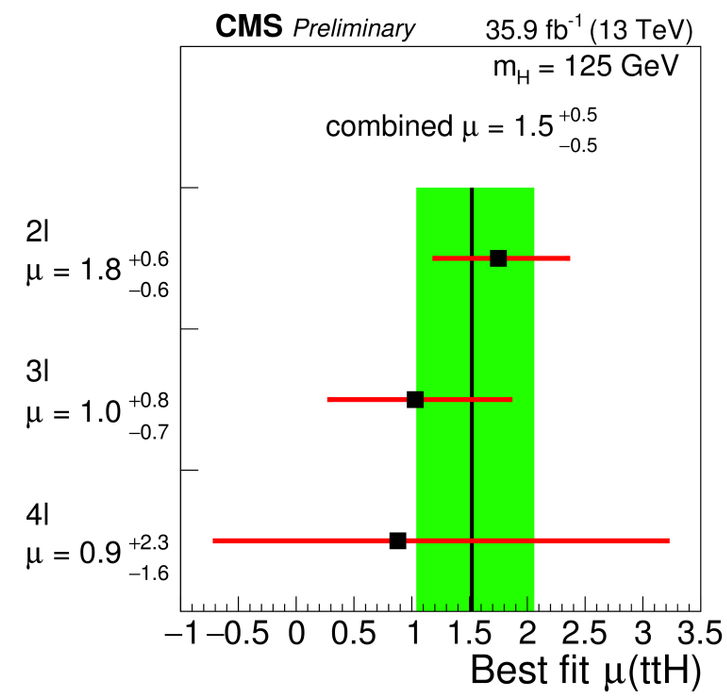


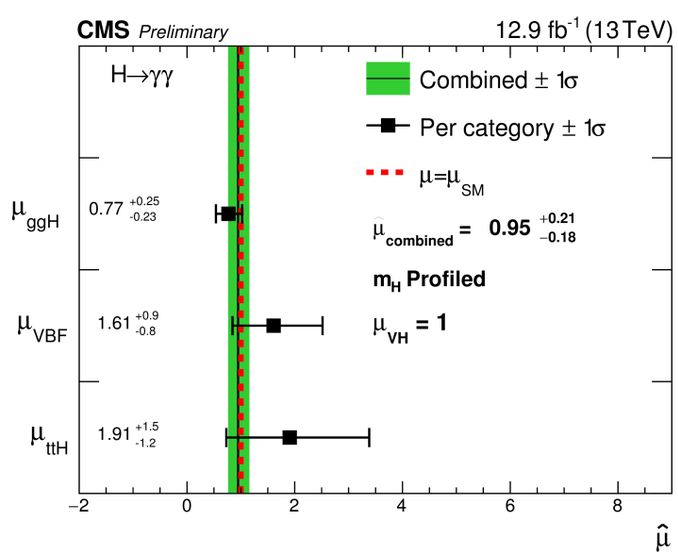










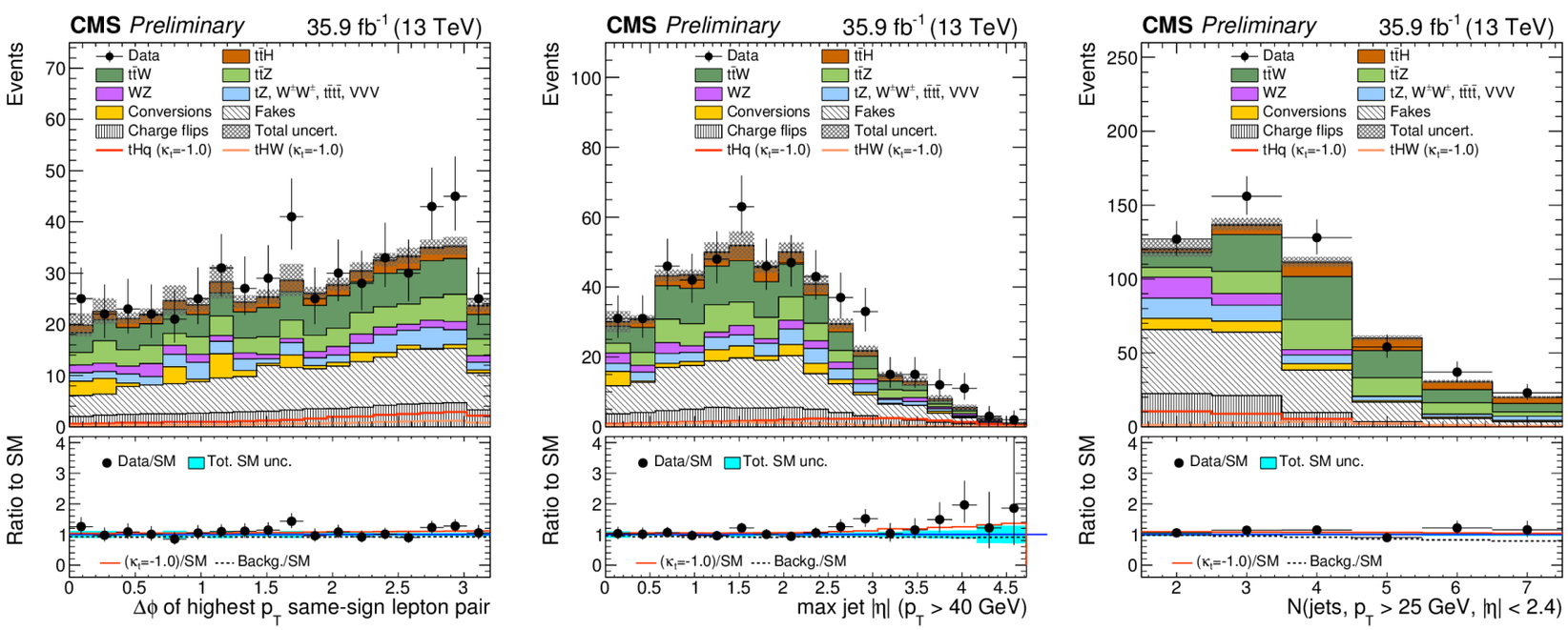


Halfway Run-2 we already have an extensive collection of results, ttH is being thoroughly scrutinized, stay tuned!

Still a slightly larger signal strength than the expected, but more data is needed to understand if it is physical.

Also singly!

- Single top plus Higgs is very **suppressed in the SM**, still grows substantially at 13TeV
- Preliminary results covering single top plus Higgs with Run-2 data, **similar approach to ttH**
  - With less b jets and hadronic activity in general
  - With one additional, forward light jet (characteristic single top t-channel handle)
- Explicitly targeting different **κ_t-κ_V coupling scenarios**, benchmark: $\kappa_t = -1.0$ and $\kappa_V = 1.0$
    - An opposite sign of the coupling would enhance the tH production significantly



Values of κ_t outside the range of -1.25 to +1.60 are excluded at 95% C.L. assuming $\kappa_V = 1.0$.

CMS: tH,H multilepton (2 lepton same-sign, and 3 leptons) HIG-17-005

CMS: Hbb HIG-16-019

Upcoming precision measurements and searches

- Run-2 data is taking a central stage in SM top studies
  - Single top quark and tt inclusive cross sections
  - Differential measurements
  - Rare processes (ttV, 4top), couplings (ttH)
  - **Coming up Next**
    - **Precision measurements of properties and top mass at 13TeV**

- BSM searches with top quarks ongoing in a multitude of channels
  - **Coming up Next**
    - **FCNC, anomalous couplings, EFT with 13 TeV data**

What will the future hold?

Yukawa coupling

Snowmass: arXiv:1311.2028

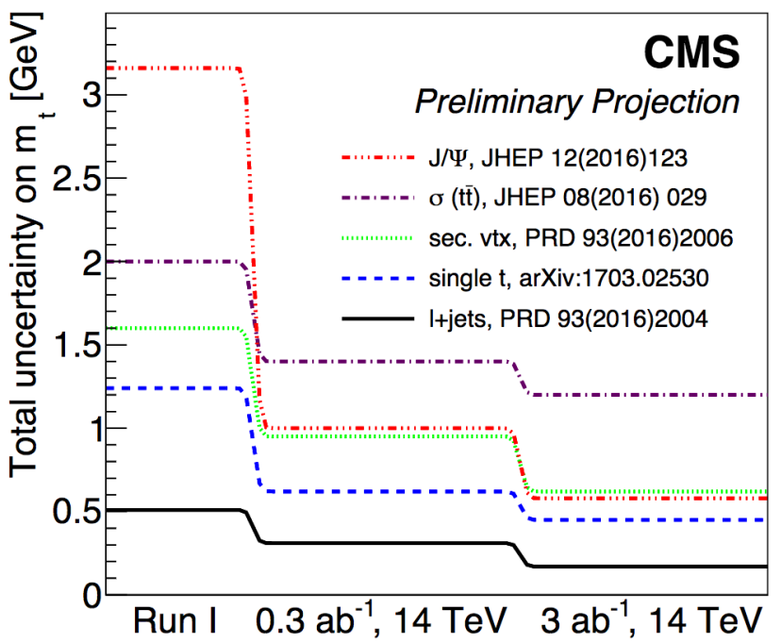
Prospects for full LHC programme:

Kt → 14-15% (300/fb)

Kt → 7-10% (3000/fb)

mass

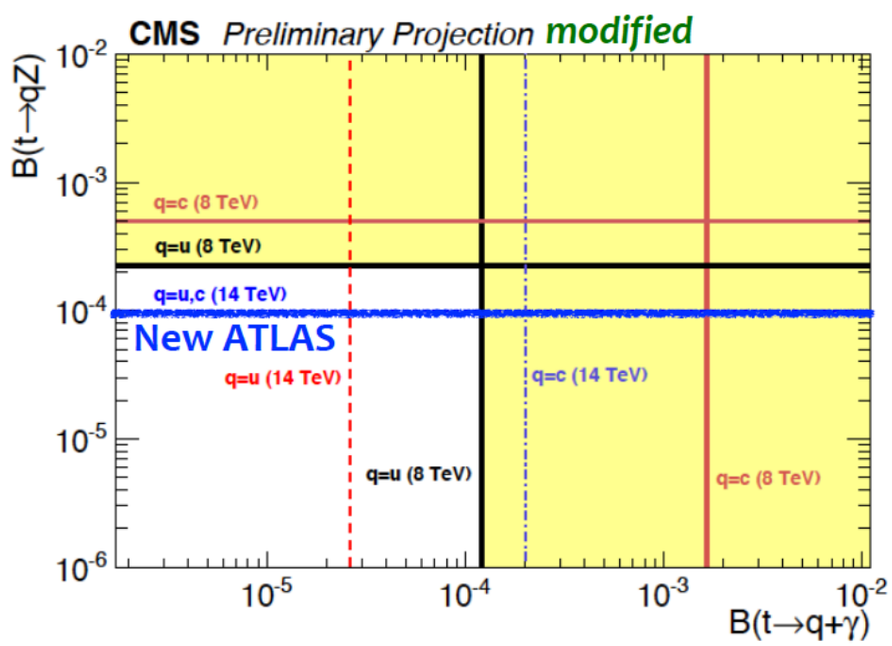
CMS: FTR-16-006

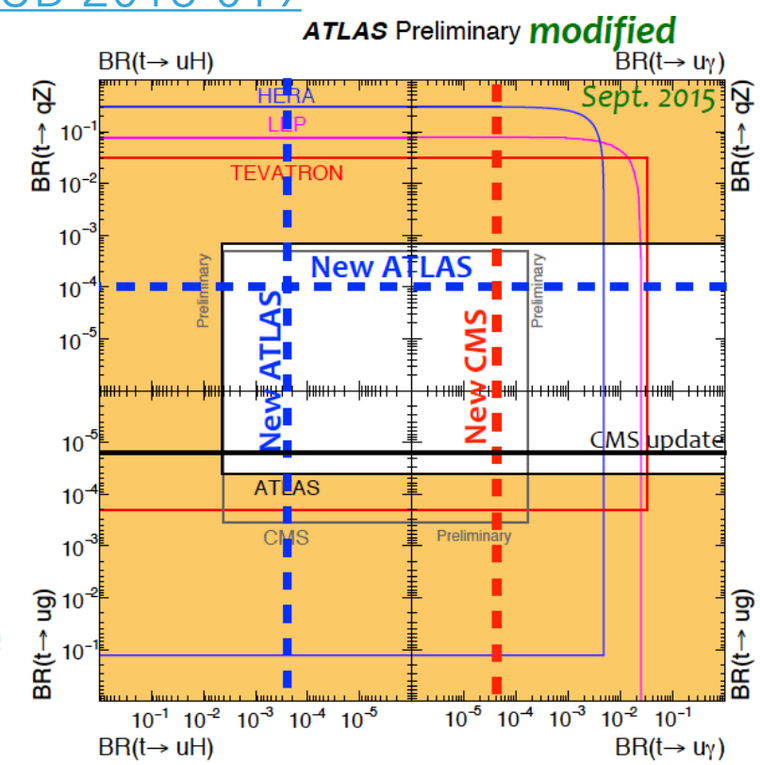


Though the precision already reached seems like a "ceiling", during the LHC's lifetime we still can aim to go as low as ~200MeV

FCNC

ATLAS: ATL-PHYS-PUB-2016-019

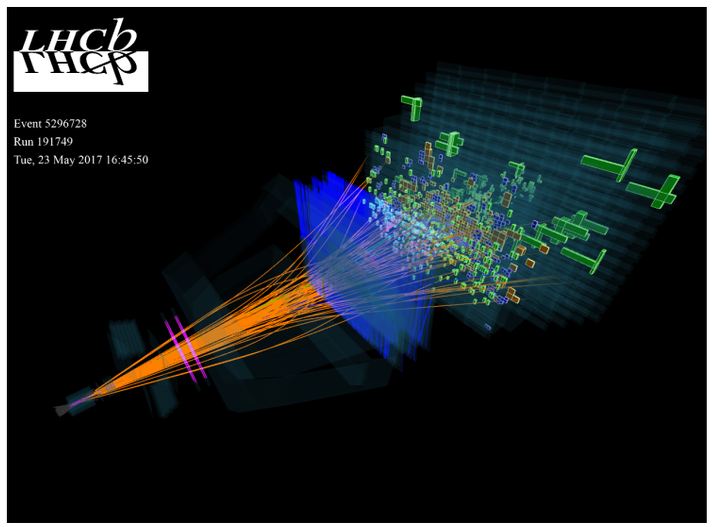


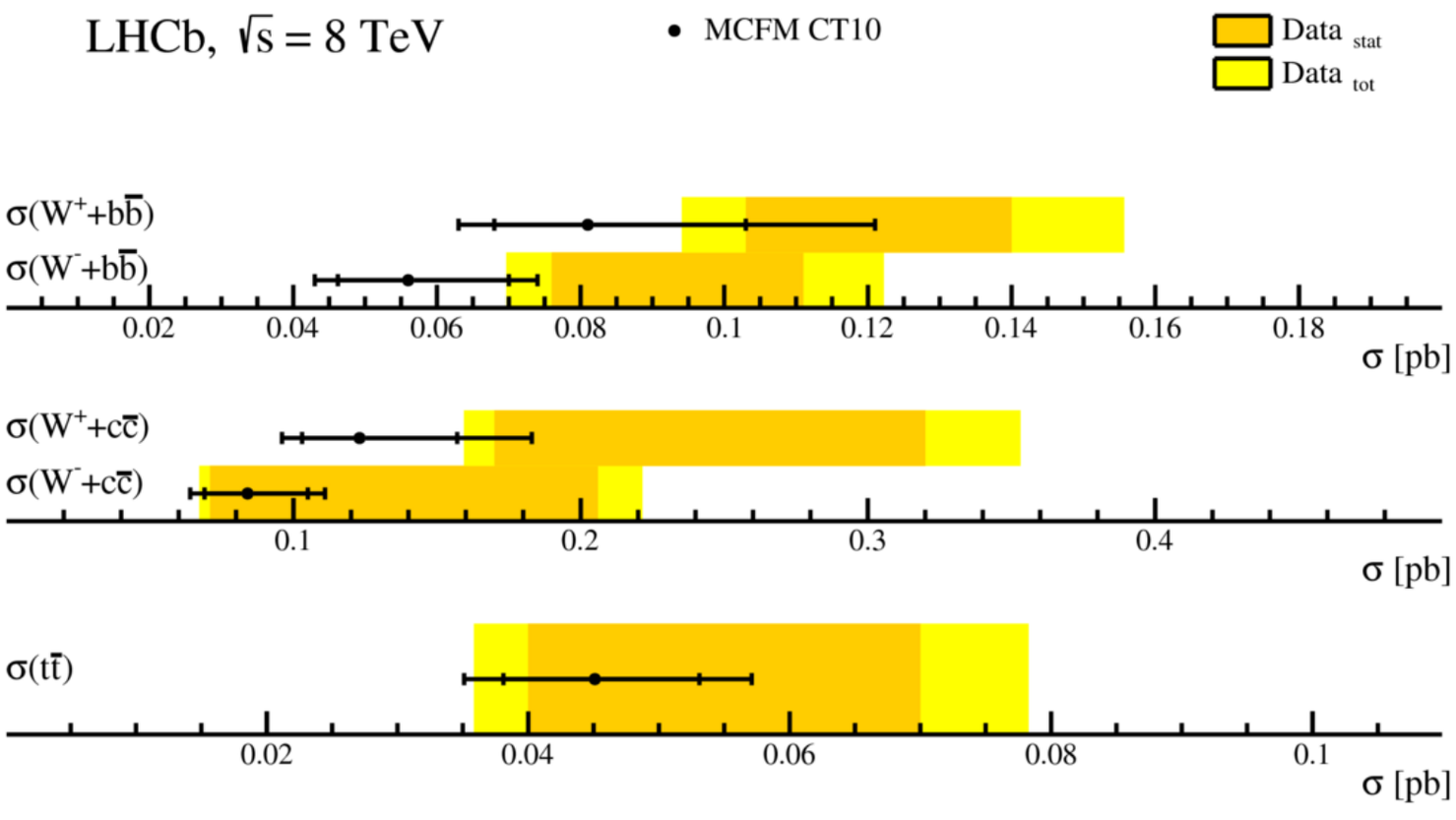


In the next months ATLAS and CMS will substantially enlarge the reach of the searches, beyond the LHC it can go even further

Wait! LHCb is also catching up!

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

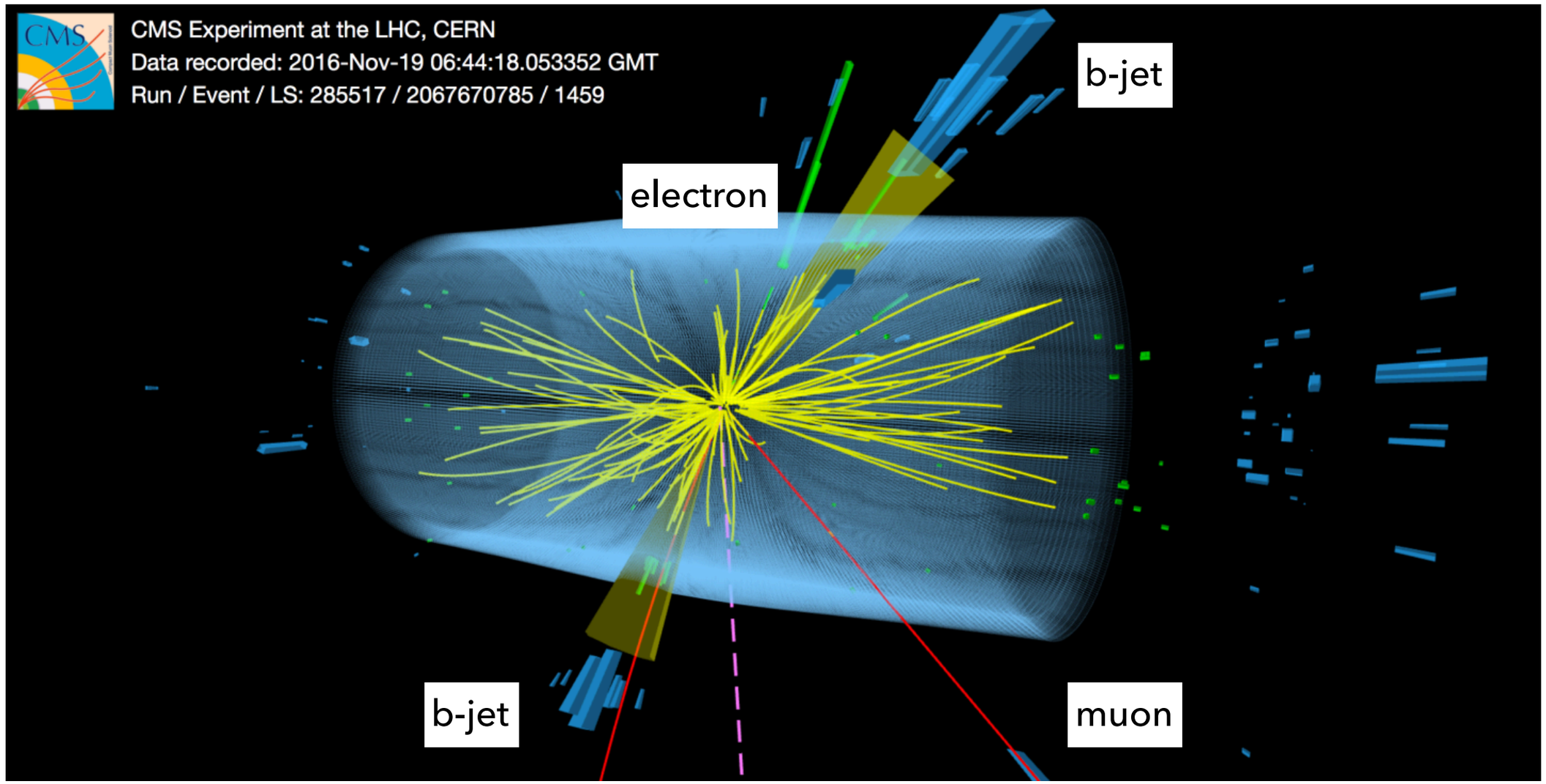




LHCb: Phys. Lett. B767 (2017) 110

How about Heavy Ions?

- We should keep a eye on that!



Candidate tt event produced during the **proton-lead collision run of 2016**

The LHC experiments are in a privileged position to study the top quark with outstanding precision

Run-1 legacy established, many results public from Run-2, but most of the work is ongoing - stay tuned!