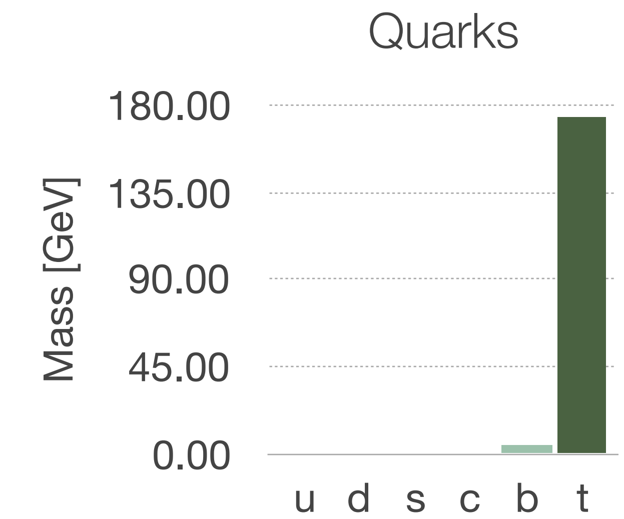
Rebeca Gonzalez Suarez
University Of Nebraska, Lincoln

TOP PHYSICS

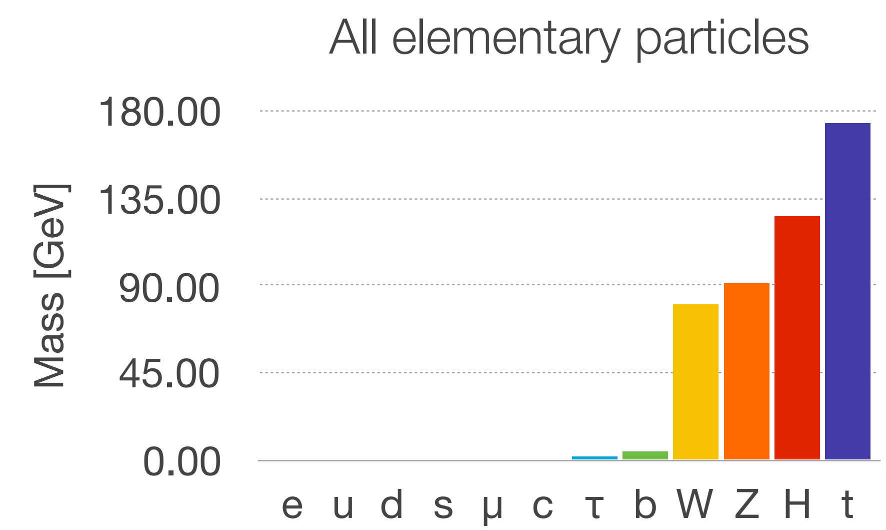
UK HEP Forum: "Into the Unknown with LHC13"

Why top physics?

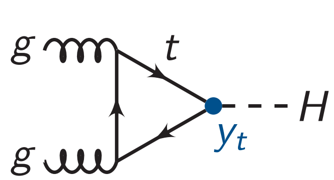
- The top quark is ❄️**special**🦄

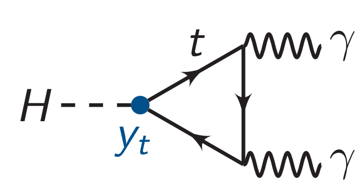


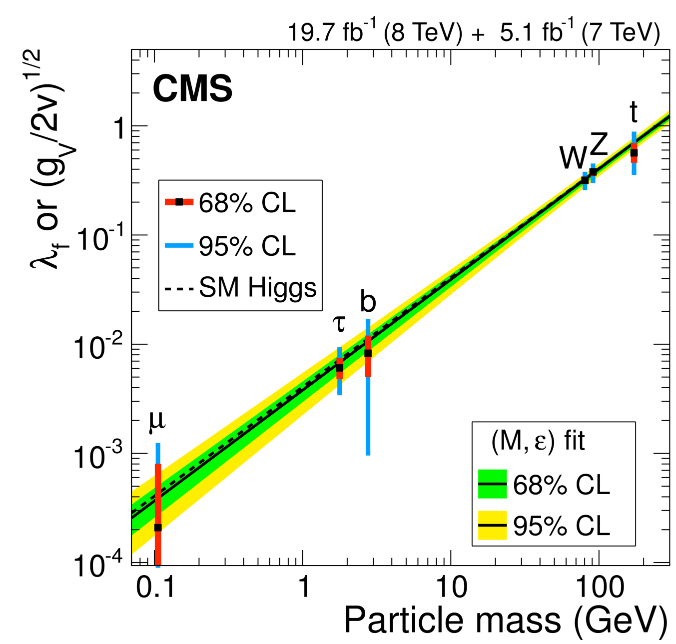
- It is **very heavy** → the most massive quark, the most massive fermion, and the most massive elementary particle known (**so far**)



  - **Short lived**
    - Decays before hadronizing
    - does not form bound states → no toponium
    - we get direct access to its properties via decay products
  - **Couples strongly to Higgs**
    - Impact on the Higgs sector

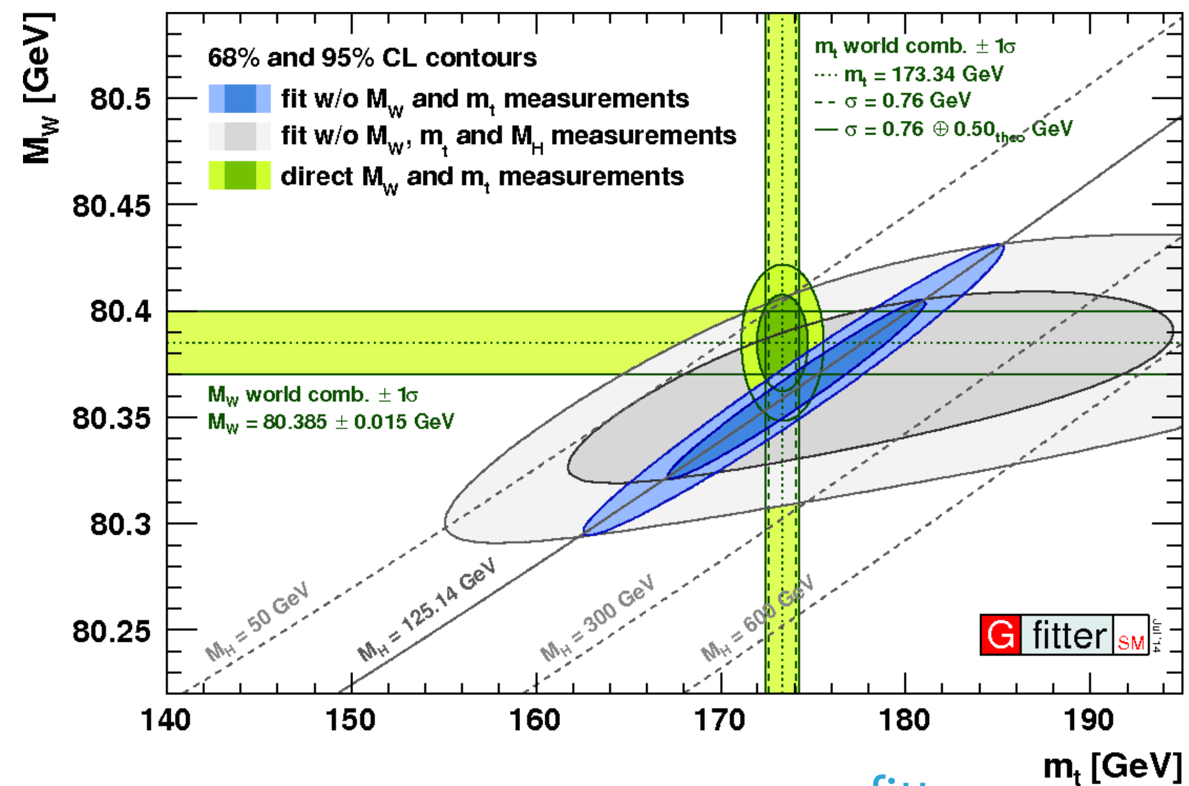




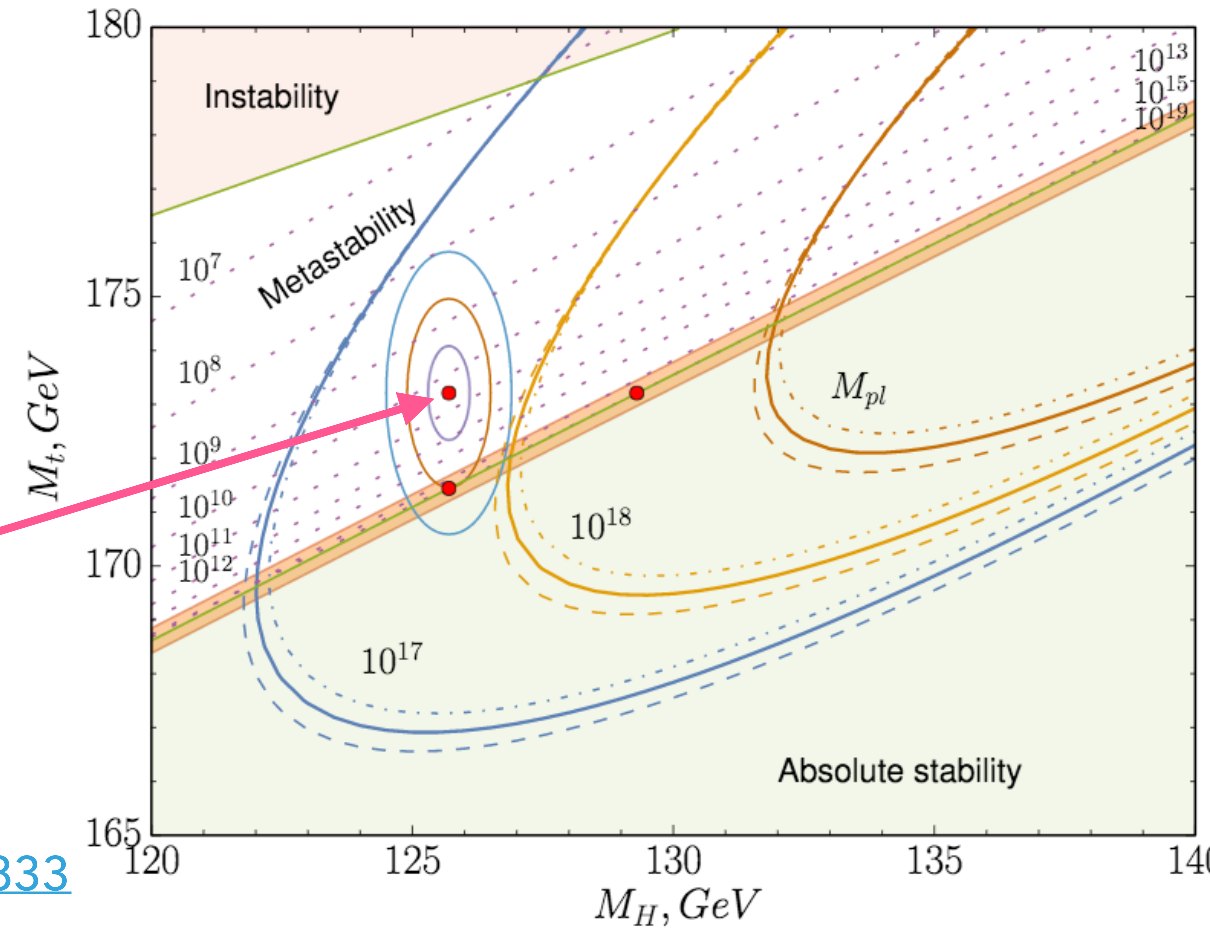


Every precision measurement is a search

- Measurement of top properties → SM test
  - The **top mass** is a **fundamental SM property**
    - It is essential for testing the SM consistency (and constrain new physics models) through precision electroweak fits
    - Plays a role on the stability of the **electroweak vacuum**: top radiative corrections can drive the Higgs self-coupling towards negative values, potentially leading to an unstable vacuum



gfitter



You are here

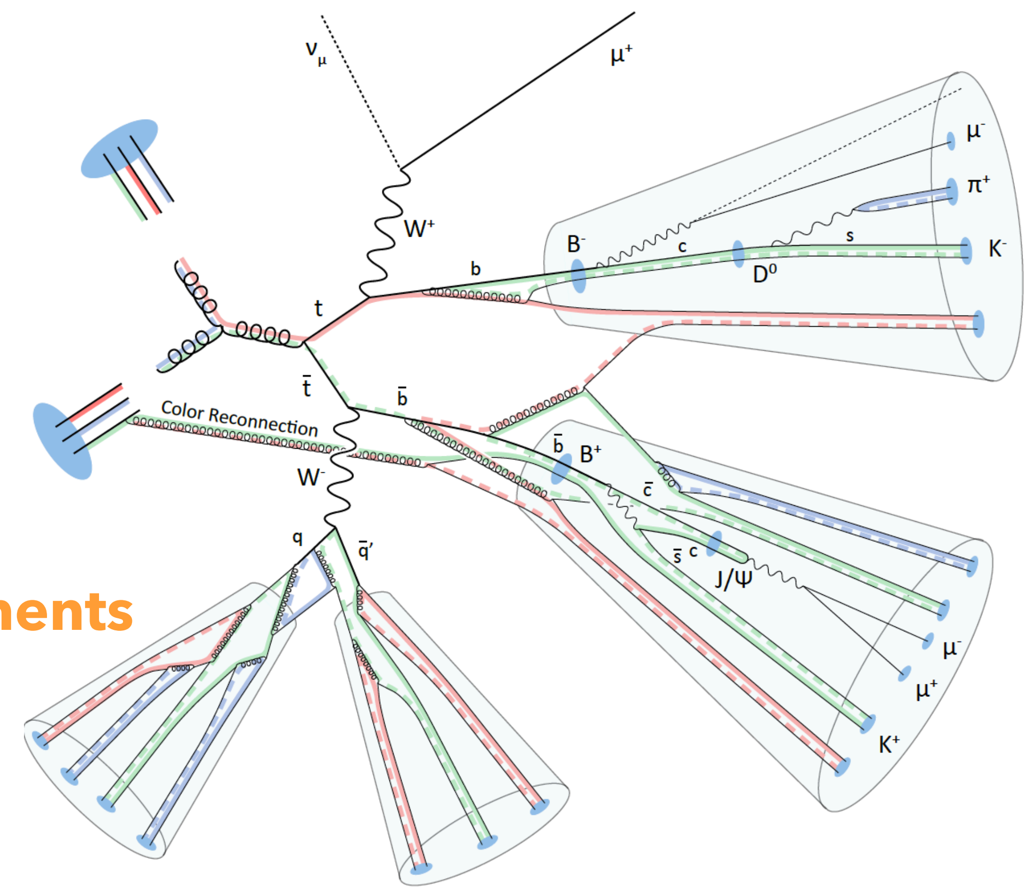
(current world average)

arXiv:1507.08833

If you are not convinced yet

- The top quark is a main ingredient of many **BSM scenarios**
  - Rare decays, heavy resonances decaying to top, new particles produced together with top, exotic partners…

- **top is fun*!** (*experimentally)
  - top decays almost always to Wb
    - Signatures with b-jets in the final state
      - Plus: leptons, neutrinos and/or light quarks
      - **Using the full potential of the LHC experiments**

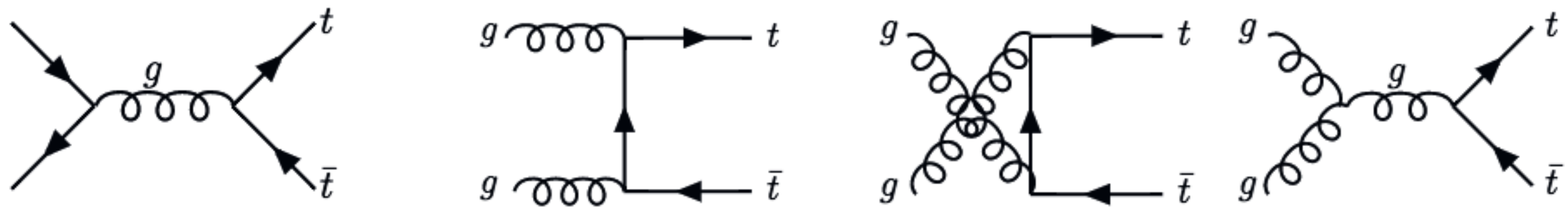


- But no matter if you like it or not: It is **unavoidable** at the LHC
  - Background of virtually **everything** (measurements, searches) → need to know it very well

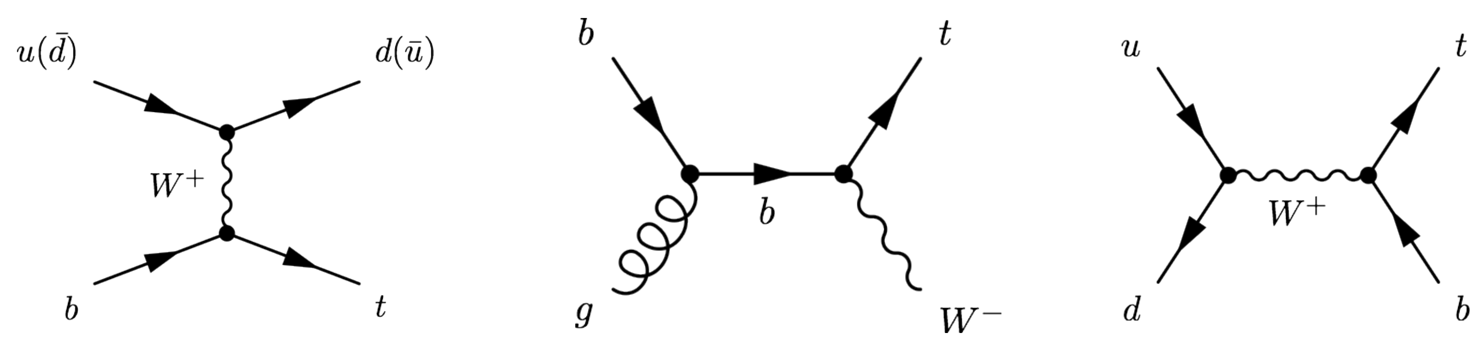
- 21 years since its discovery (1995, Tevatron)
  - We already know it quite well, but we can know it even better!

Producing tops

- Top quarks at the LHC are produced at a very high rate
- Mainly produced in **ttbar pairs** → **strong interaction**



- At a lower rate: **Single top quark production**→ **EWK interaction**
  - Three main modes: t-channel, tW associated production, and s-channel



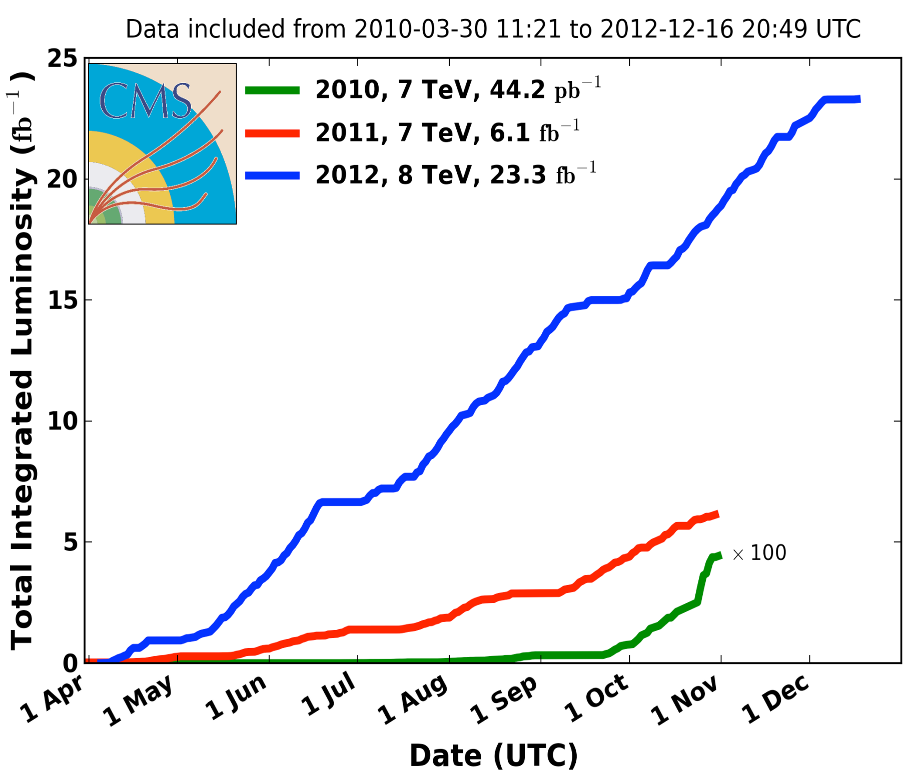
LHC exclusive!

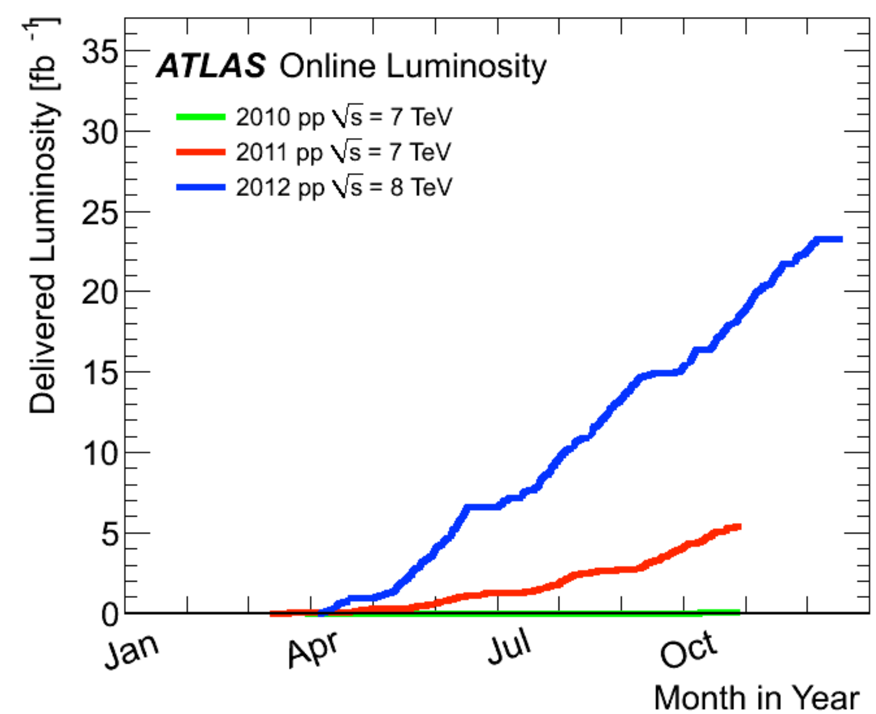
σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.0	2.08	0.22	1.046
LHC @ 7TeV	177.3	63.89	15.74	4.29
LHC @ 8TeV	252.8	84.69	22.2	5.24

Top Factory™

The "top factory" - Run 1

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





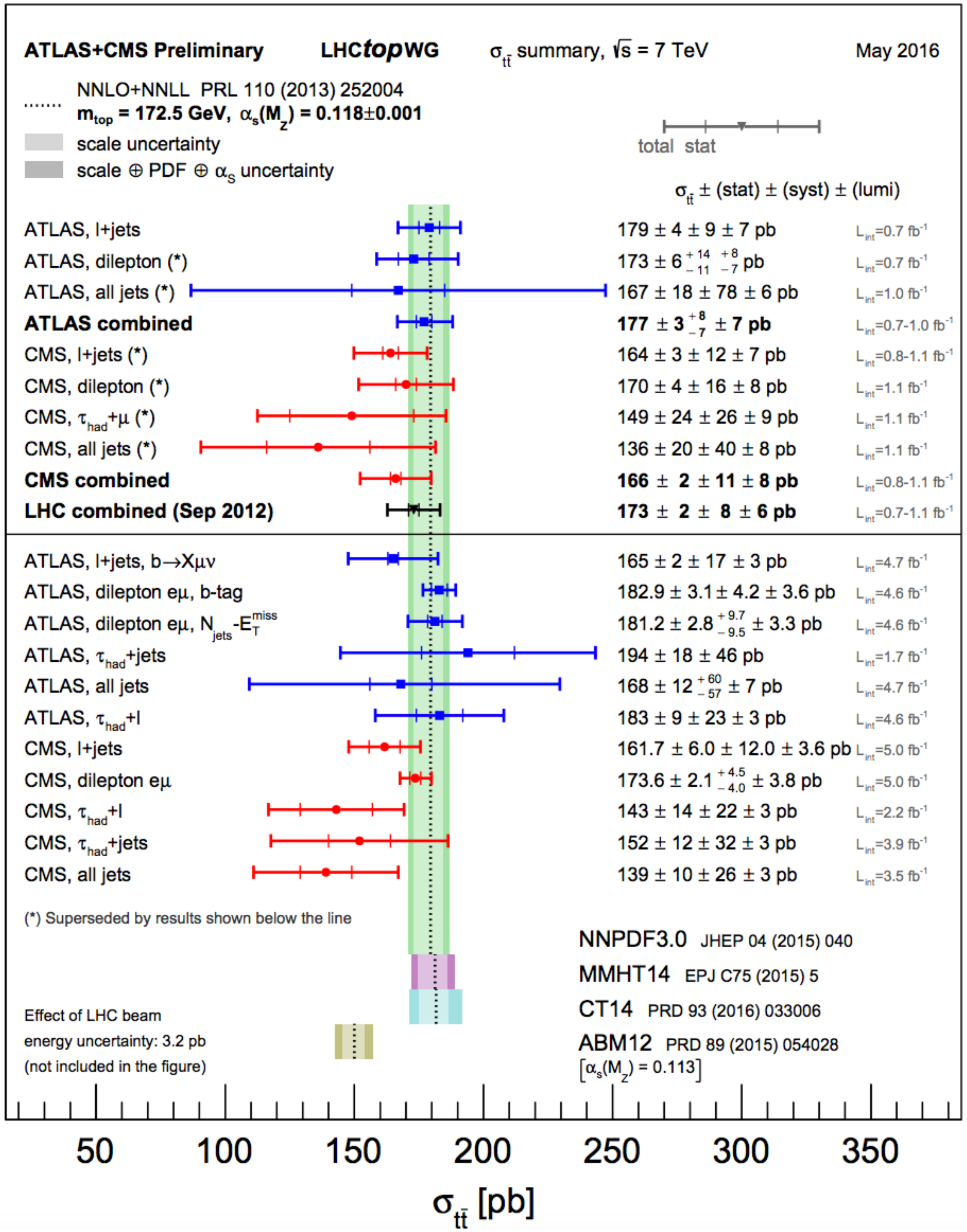
More the 10M ttbar pairs, about 4M single top t-channel events, 1M of tW events, and more than 200K s-channel events

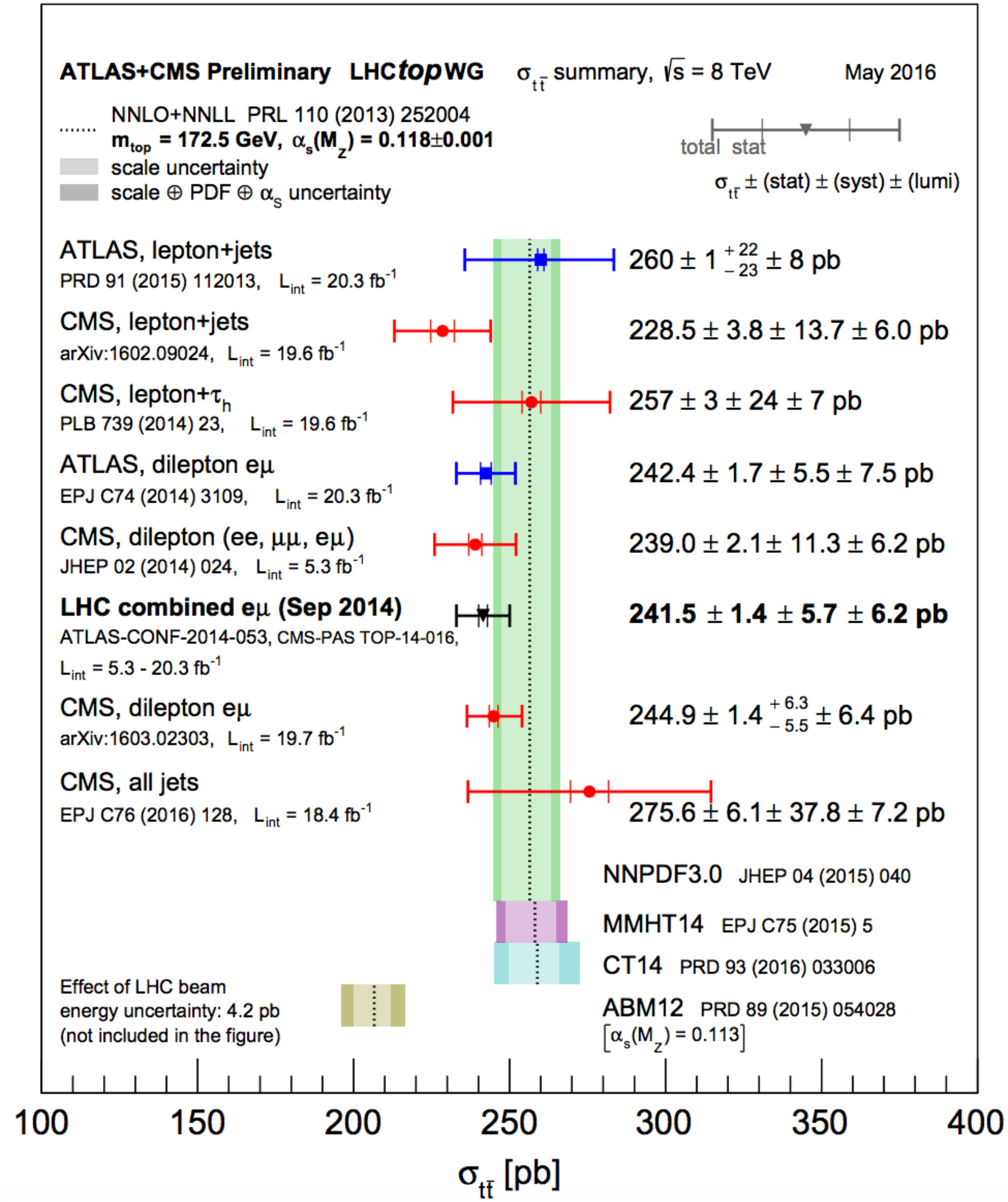
Many top events → Enough to establish a **very healthy top Run-1 Legacy**

Large number of ATLAS+CMS combinations

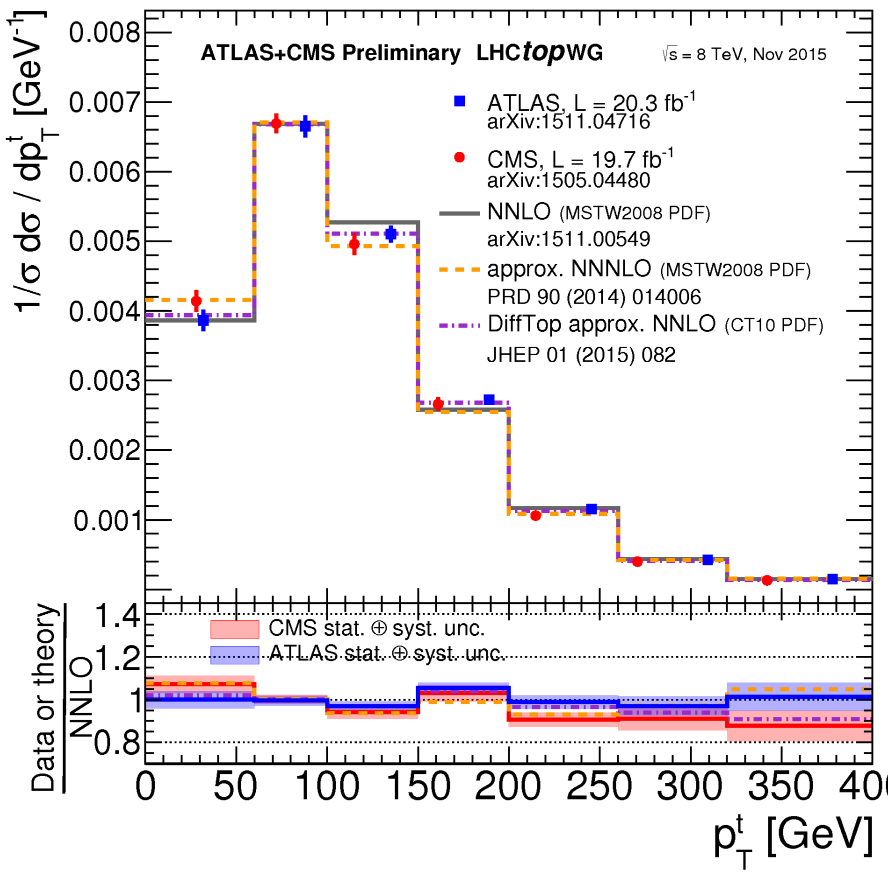
The Run-1 legacy

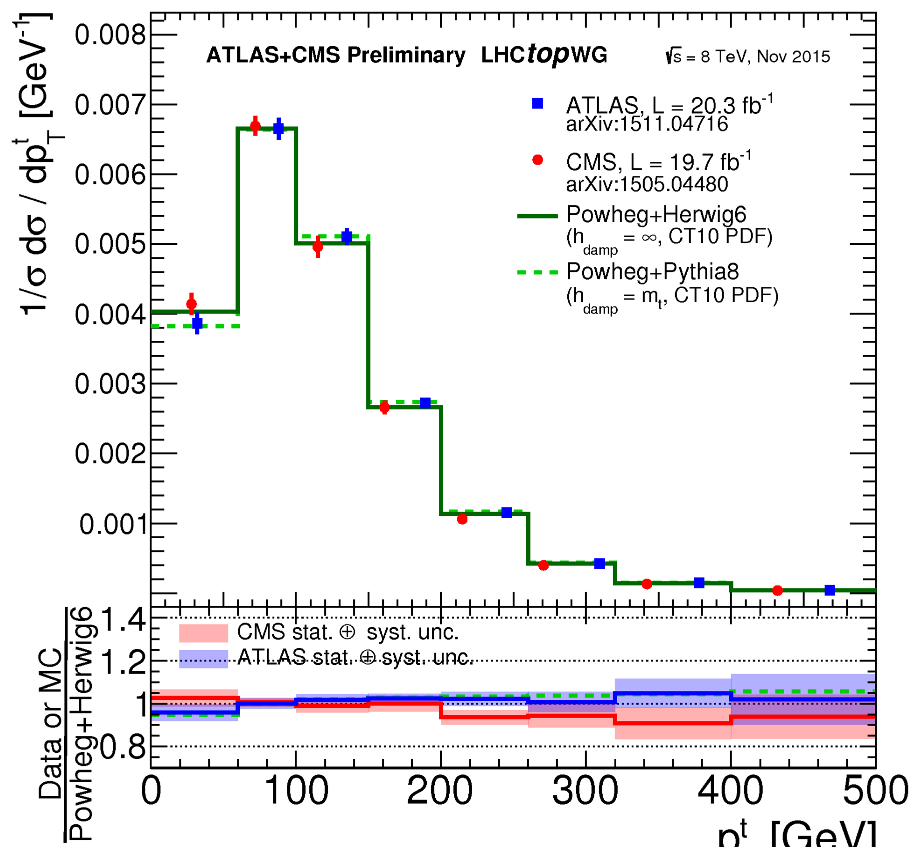
- **Inclusive cross sections:** High precision measurements in many channels, all compatible with NNLO predictions





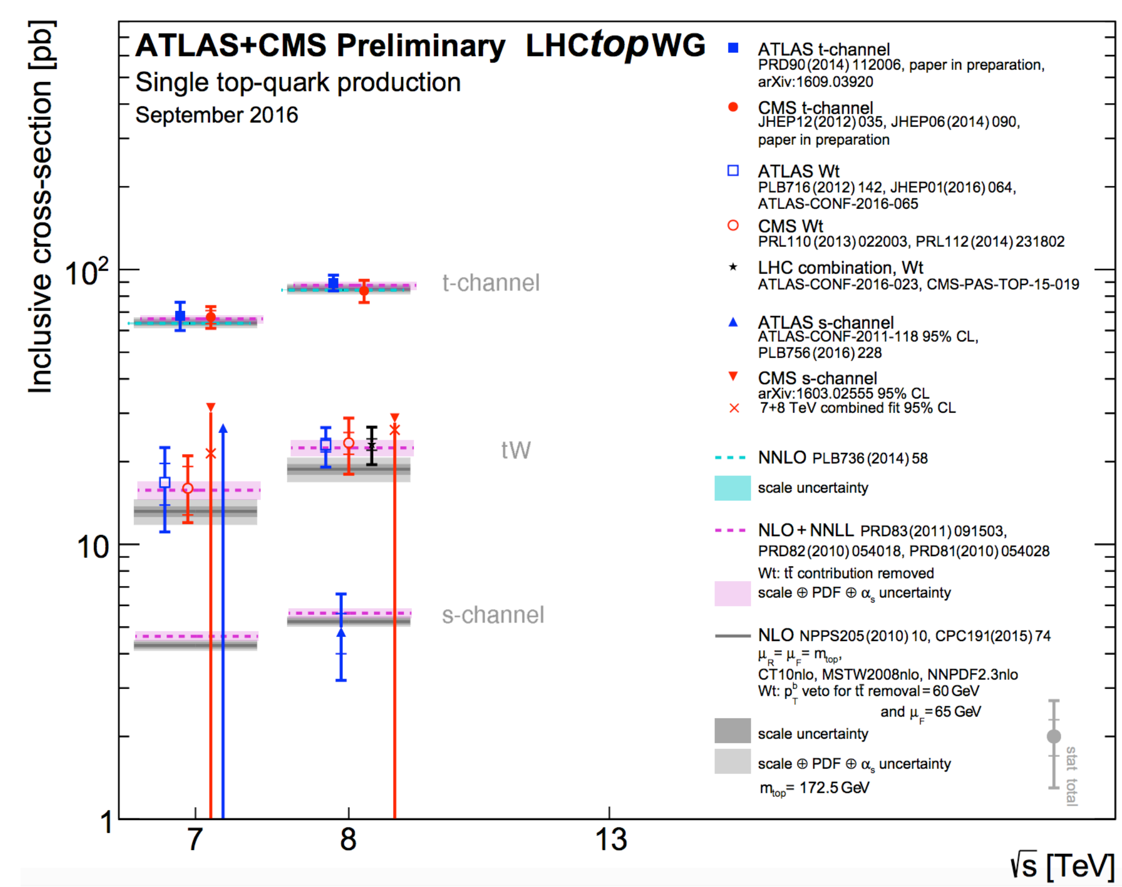
The Run–1 legacy



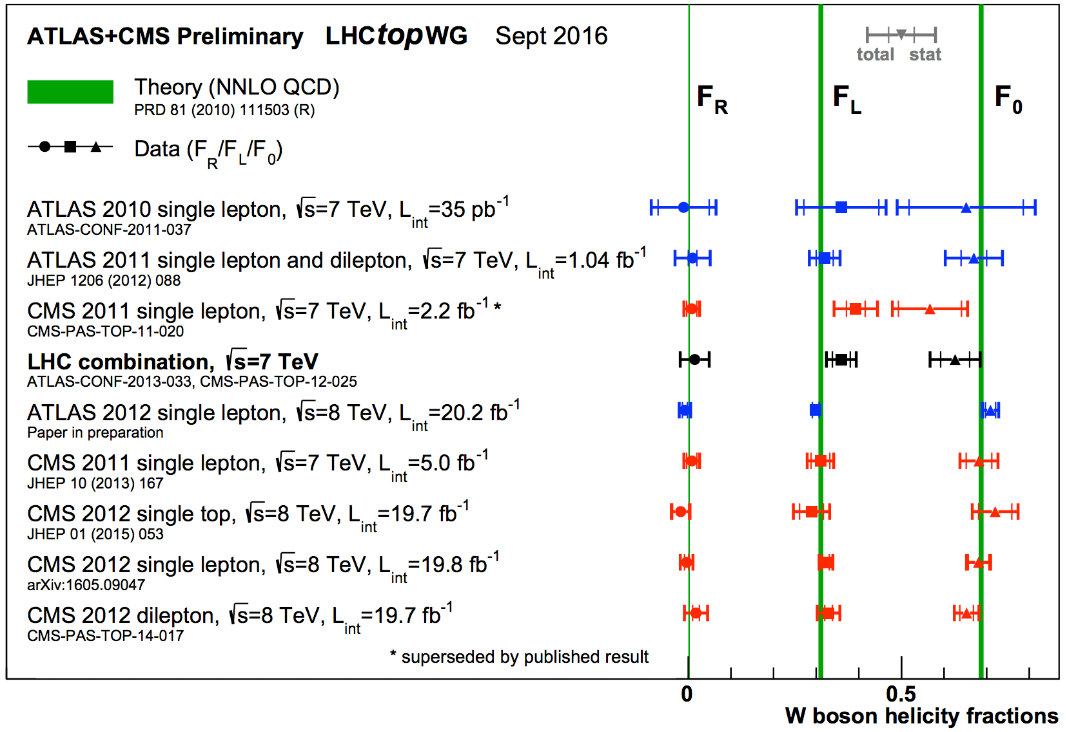


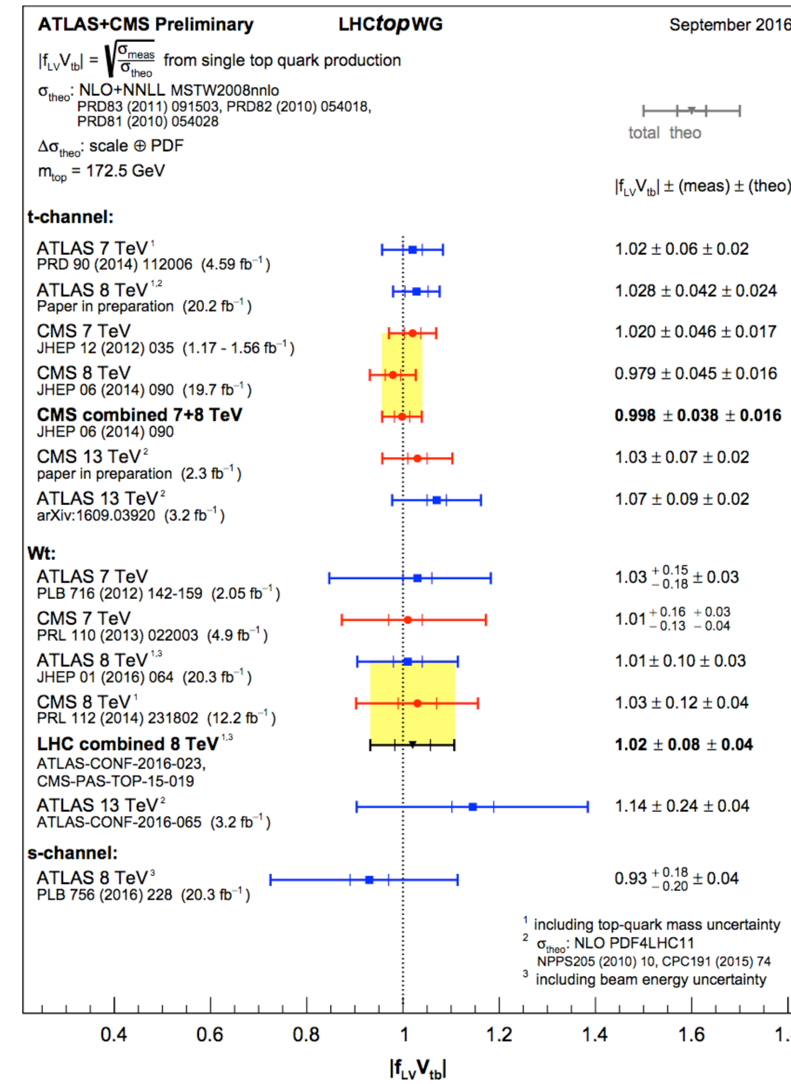
- **Differential cross sections:**
  - probing QCD predictions
  - facilitating the comparison of the data with state-of-the-art generators

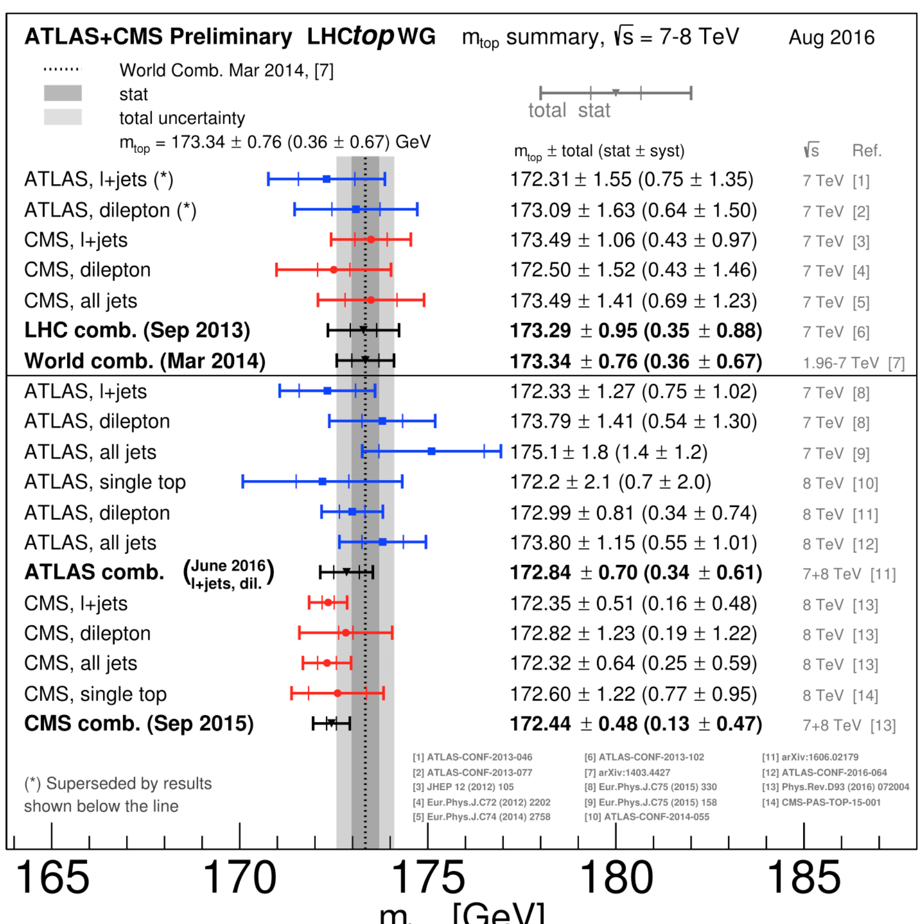
- **Single top:** single top factory!
  - observation of the tW process
  - measurement of properties in t-channel
  - study of s-channel
  - rare SM single top (tZq, tγ)



The Run-1 legacy



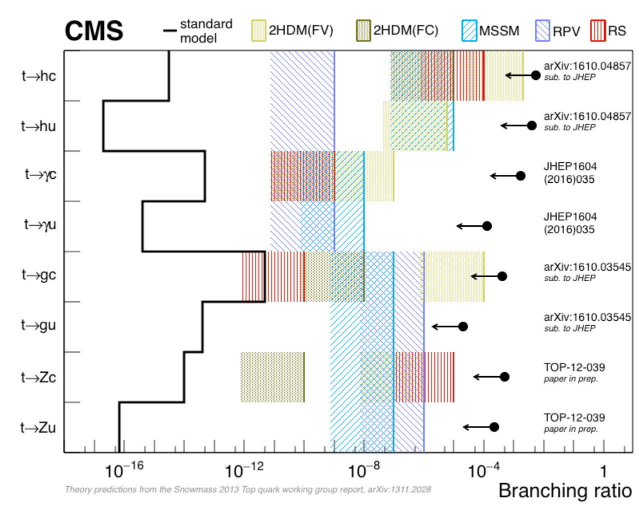


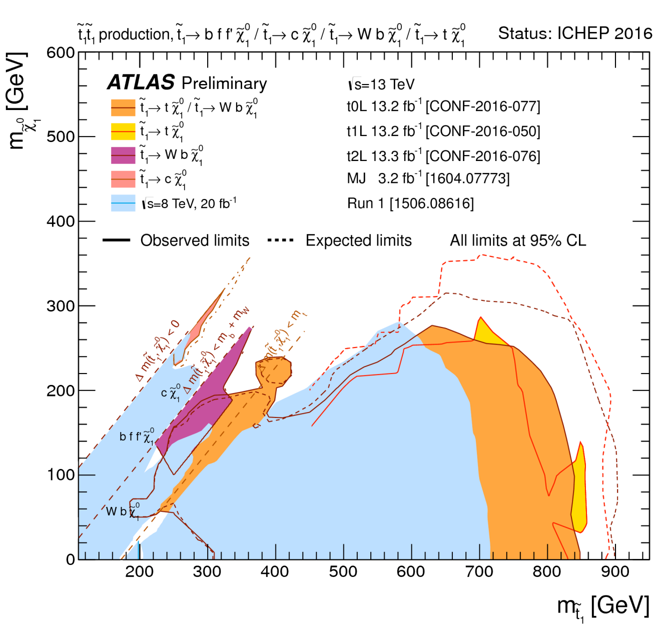


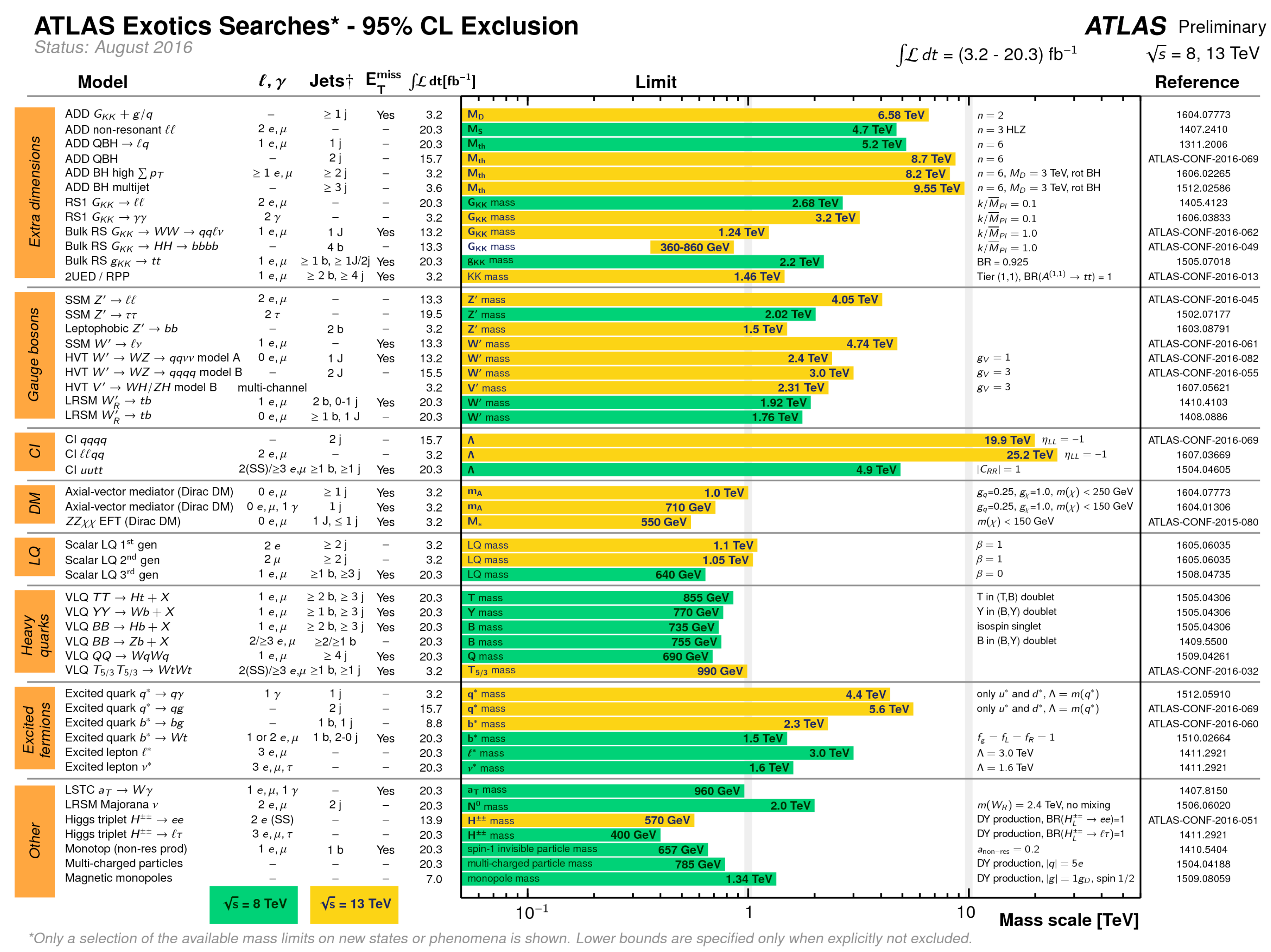
- High precision regime in measurement of **top properties**
- **All consistent with the SM predictions so far**
- Flagship: **top mass**
    - A variety of dedicated measurements
    - Extremely precise ±0.48 GeV (0.3%)
    - Original alternative methods with consistent results

The Run-1 legacy

- **Top pair (and single top quarks) produced together with a Higgs boson or a W/Z/γ**
    - Insight on couplings, low cross section processes
    - Observation of ttV (≥ 5σ) , small ttH excess in H→WW
    - **Single top + Higgs** studied across Higgs decay channels! (arXiv:1509.08159)
- **Catalog of BSM searches** performed during Run-1 in the top quark sector
    - **No signs of new physics yet** → the possibilities are still unlimited







The "top factory" today - Run 2

- The Run-2 of the LHC started in 2015
  - **4fb^{-1}** of pp collisions delivered
- Operation continued in 2016, passing 30fb^{-1} in September,
  - The 2016 pp run ended last week
  - **~40fb^{-1} delivered in total**
- It will go on until the end of 2018 - 100fb^{-1} → The Run-2 legacy will be **exceptional** (not only for top)

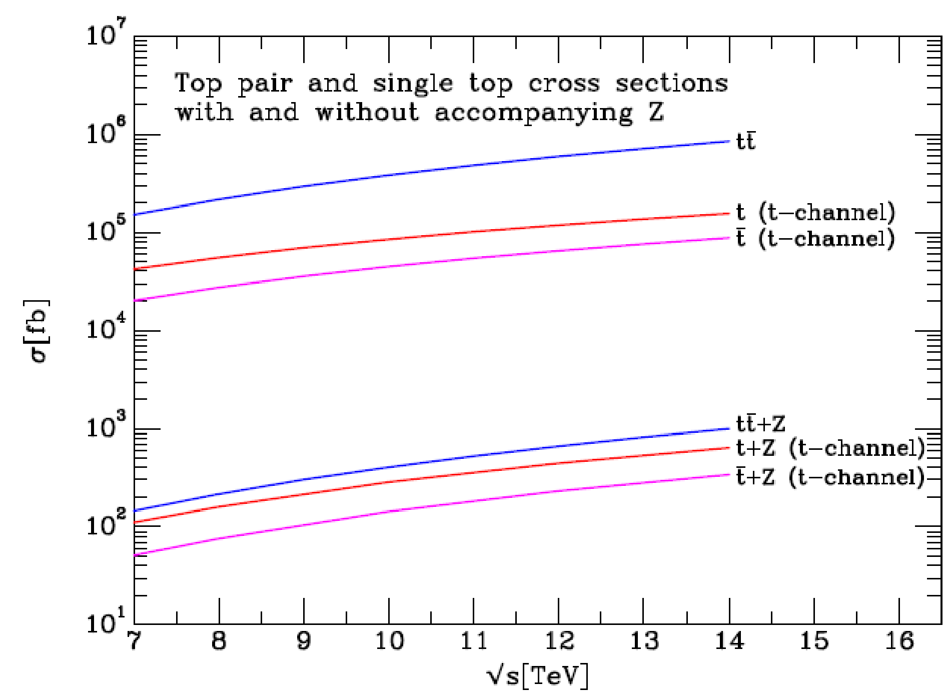
New energy regime to test SM validity: 13TeV

The top cross section continues to grow

Increase of energy: good for Higgs, better for top, perfect for top and Higgs

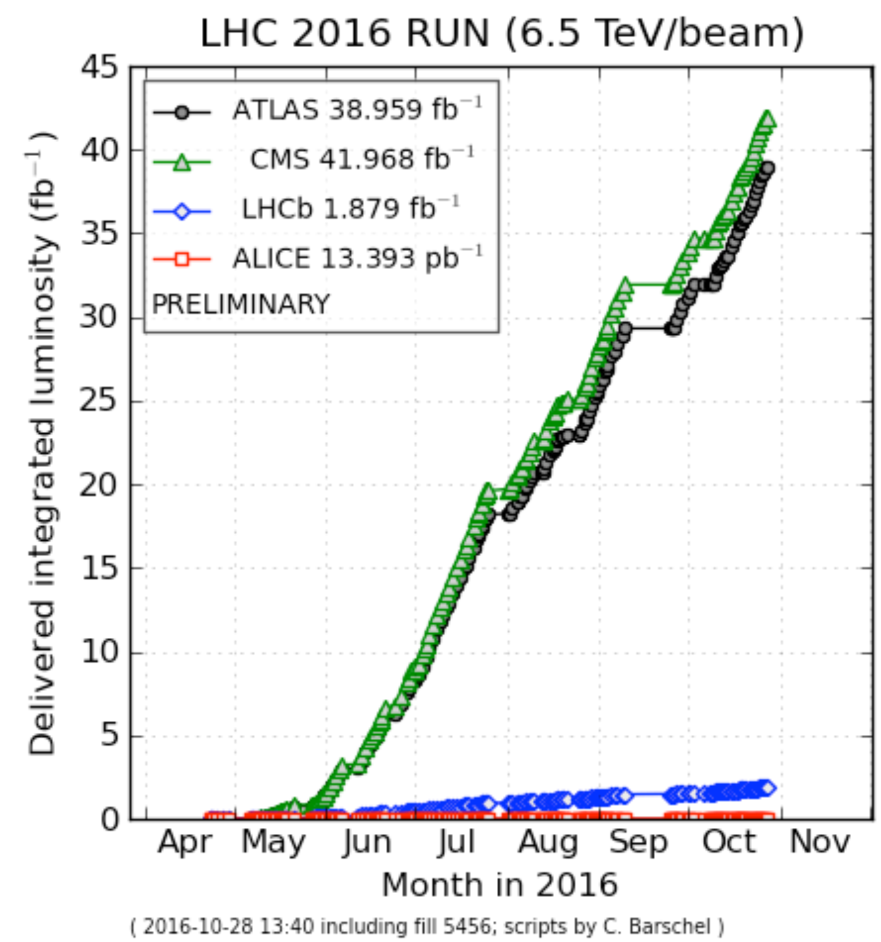
σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.0	2.08	0.22	1.046
LHC @ 7TeV	177.3	63.89	15.74	4.29
LHC @ 8TeV	252.8	84.69	22.2	5.24
LHC @ 13 TeV	831.7	216.99	71.2	10.32
	x 3.3	x 2.6	x 3.2	x 2

	WW	ggH	ttH	tH
13/8 ratio	x 2	x 2.2	x 3.8	x 3.9



What are we doing with the Run-2 data?

- We will need some time to digest the full 2016 dataset
  - **Most of the data is still unexplored!**
  - Stay tuned for next winter and summer conferences!
- Already many results available
  - since very early in 2015
- In fact, they are so many that **I cannot show everything!**
  - Overview of some of the latest Run-2 results



All the publications and preliminary results available here:

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

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

INCLUSIVE CROSS SECTIONS

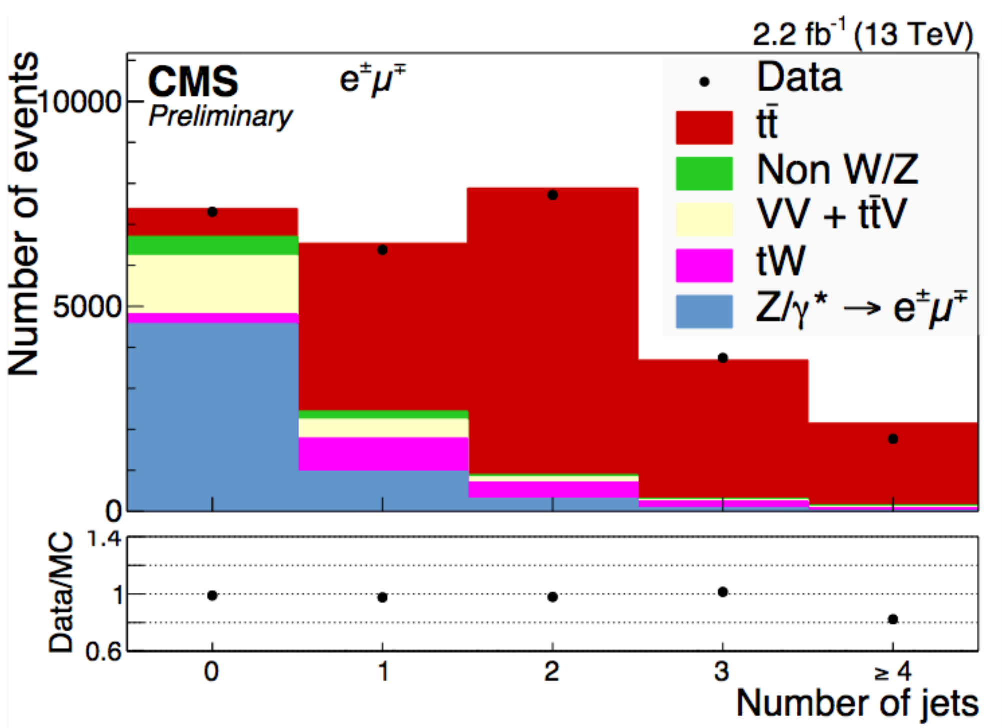
- Early measurements at each new energy regime
  - **June 2015**: Run-2 starts
  - **August 2015**: Measurements of the $t\bar{t}$ inclusive cross section public (arXiv:1510.05302)

Inclusive tt cross sections: dilepton

- Simple and robust approach
  - eμ, at least 1 b-jet ➝ purity > 90%
  - Counting experiment, ATLAS obtains the b-tag efficiency at the same time
  - DY and fake leptons from data (same-sign events or matrix method)
  - Analyses limited by systematic uncertainties, related to the modelling of the top signal

$\sigma_{tt}^{NNLO+NNLL}=832+20-29(scale)\pm35\ (PDF)\ pb$

σ_{tt}=793±8(stat) ±38(syst) ± 21(lumi) pb

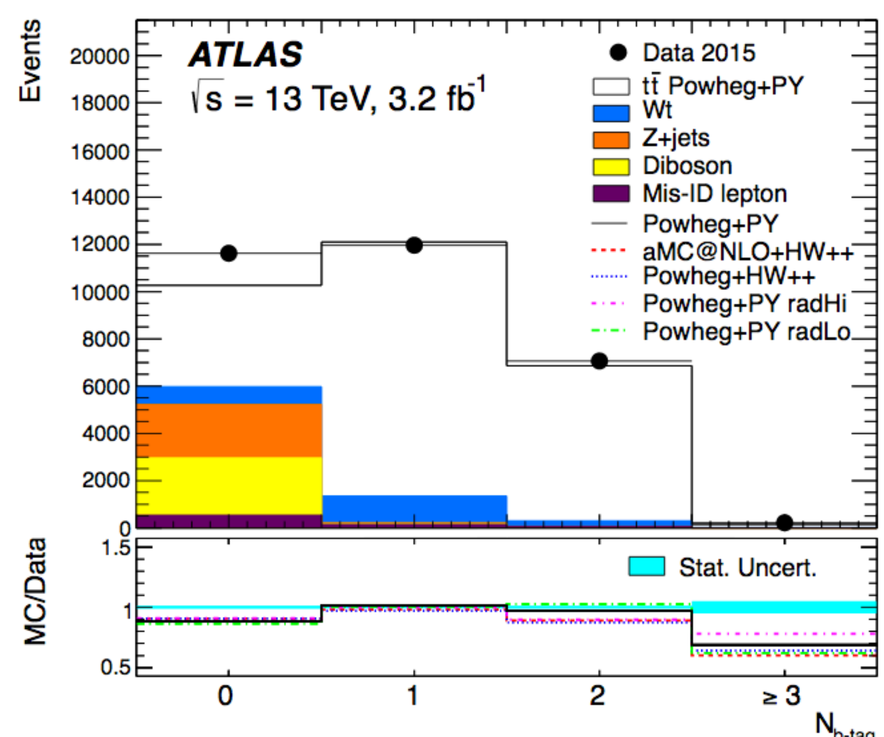


CMS-TOP-16-005

Δσ/σ≈5.6%

(Run-1 legacy precision ≈3.5%)

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



arXiv:1606.02699

Δσ/σ≈4.4%

Includes fiducial measurement (3.9% unc.)

ATLAS-CONF-2015-049

ee/μμ, Δσ/σ≈16%

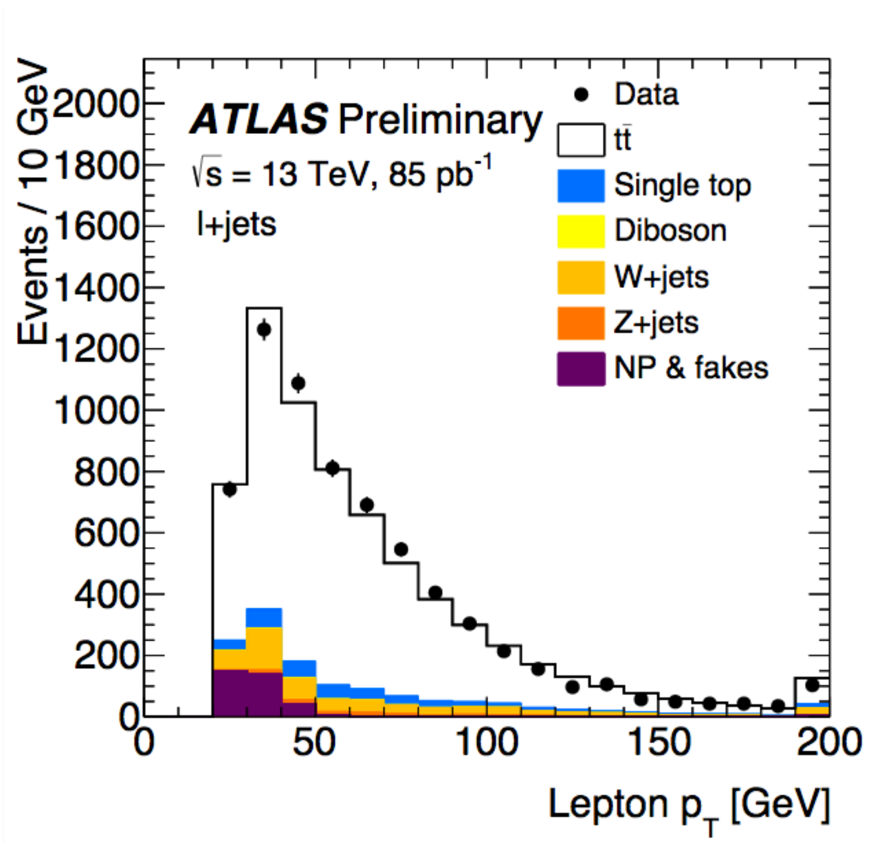
Inclusive $t\bar{t}$ cross sections: lepton+jets

- ATLAS and CMS part ways in the strategy
  - ATLAS: 1e or μ, ≥ 4 jets (≥ 1 b-tagged) → **Very early** analysis, focused on achieving high purity
  - CMS: 1e or μ, ≥ 1 jets → constraining backgrounds and signal in-situ profiting from 27x more data

$\sigma_{tt}^{NNLO+NNLL}$=832+20-29(scale)±35 (PDF) pb

σ_{tt}=817±13(stat) ±103(syst) ± 88(lumi) pb

σ_{tt}=834.6±2.5(stat) ±22.8(syst) ±22.5(lumi) pb

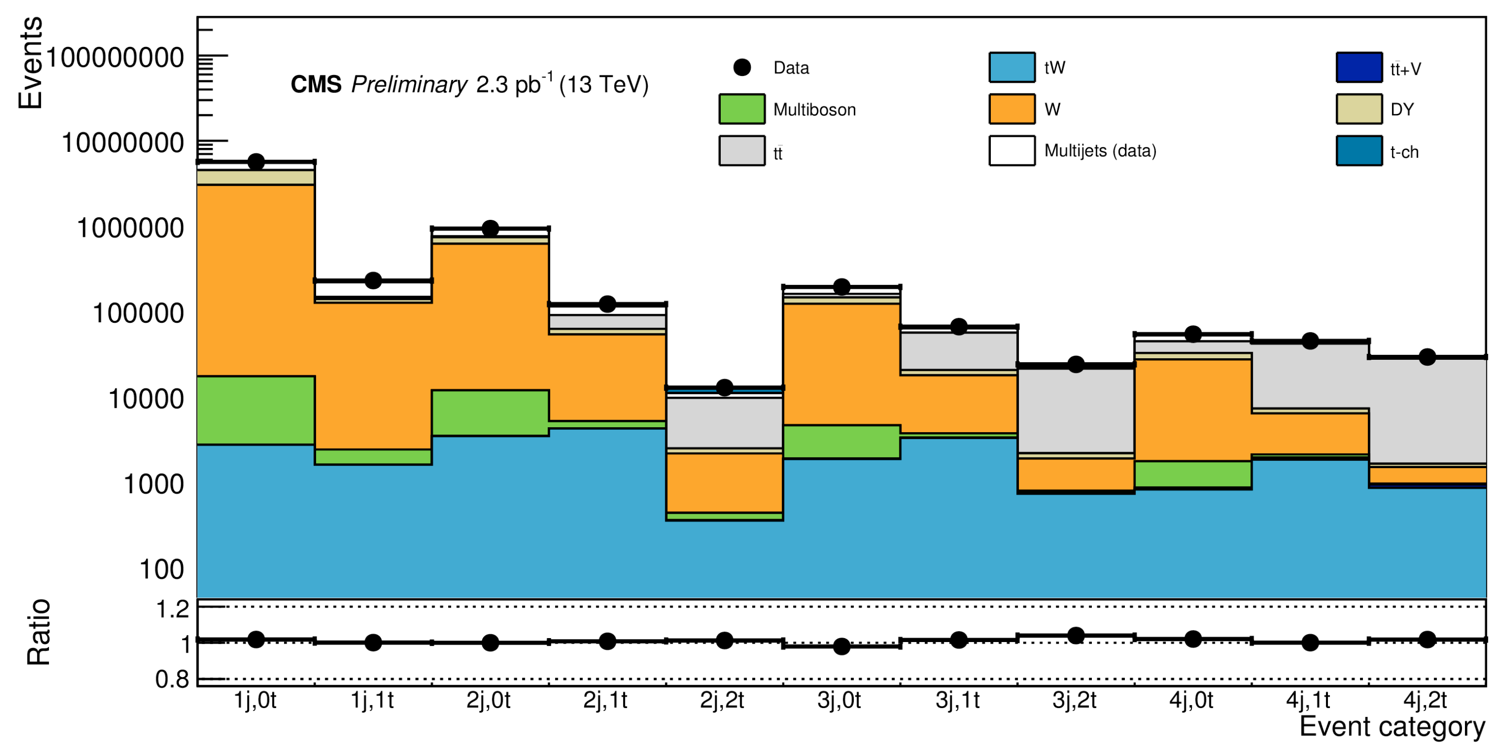


[ATLAS-CONF-2015-049]

Counting experiment

Δσ/σ≈17%

Systematic dominated



[CMS-TOP-16-006]

Simultaneous fit in 44 categories (lepton charge, flavour, number of jets, number of b-tags) to M_{lb}

Constraining JES, b-tag, lepton uncertainties

Main systematic: W+jets bkg. modelling

Δσ/σ≈3.9%

Inclusive tt cross sections: fully hadronic

- Measurement performed in two different regimes:
  - **resolved**: low p_T top quarks
    - jets: anti-kt 0.4
    - ≥ 6 jets, ≥ 2 b-tagged
  - **boosted**: high p_T top quarks
    - jets: anti-kt 0.8
    - ≥ 2jets, both jets should contain one b-tagged sub-jet
- In both cases: fit to the top mass -different requirements and definitions

$\sigma_{tt}^{NNLO+NNLL}$=832+20-29(scale)±35 (PDF) pb

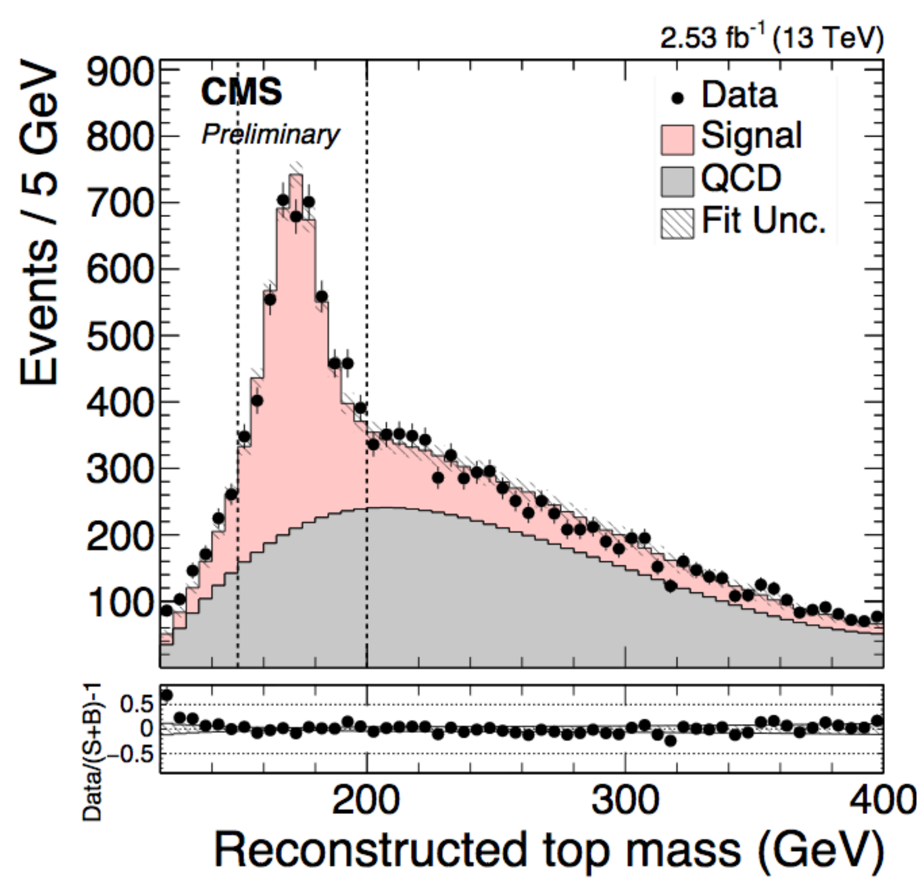
σ_{tt}=834±25(stat) +118-104(syst) ± 23(lumi) pb

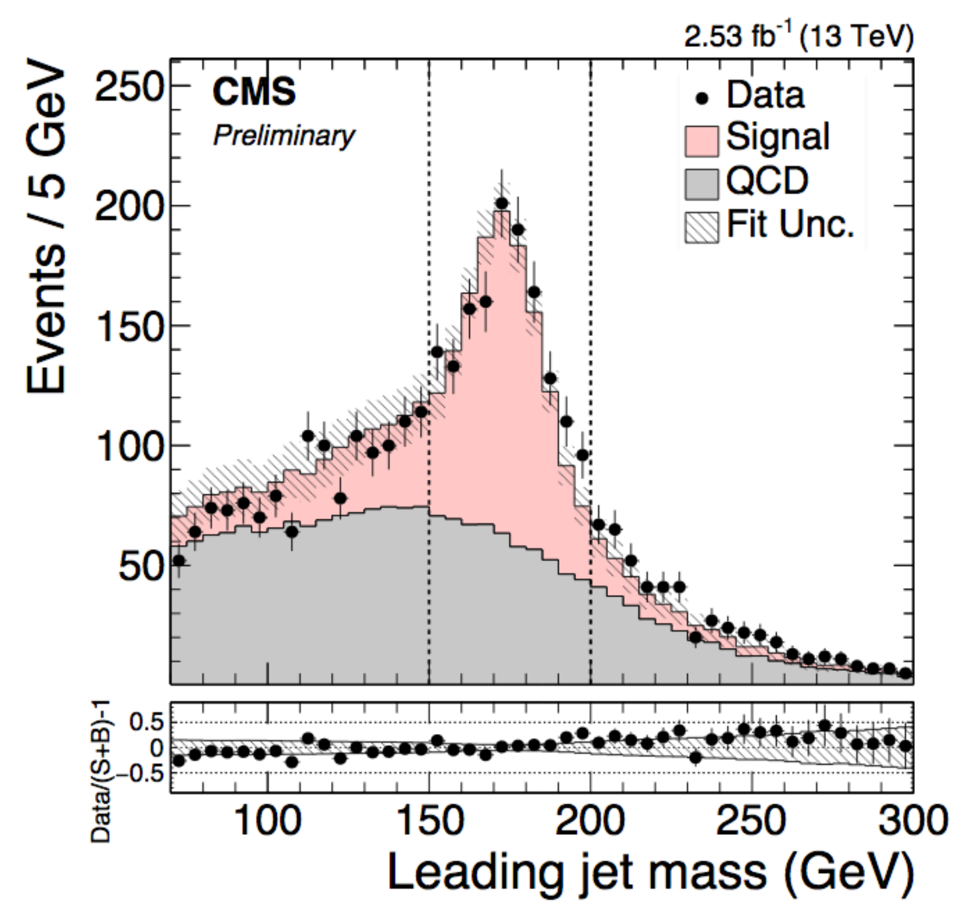
CMS-TOP-16-013

Δσ/σ≈14%

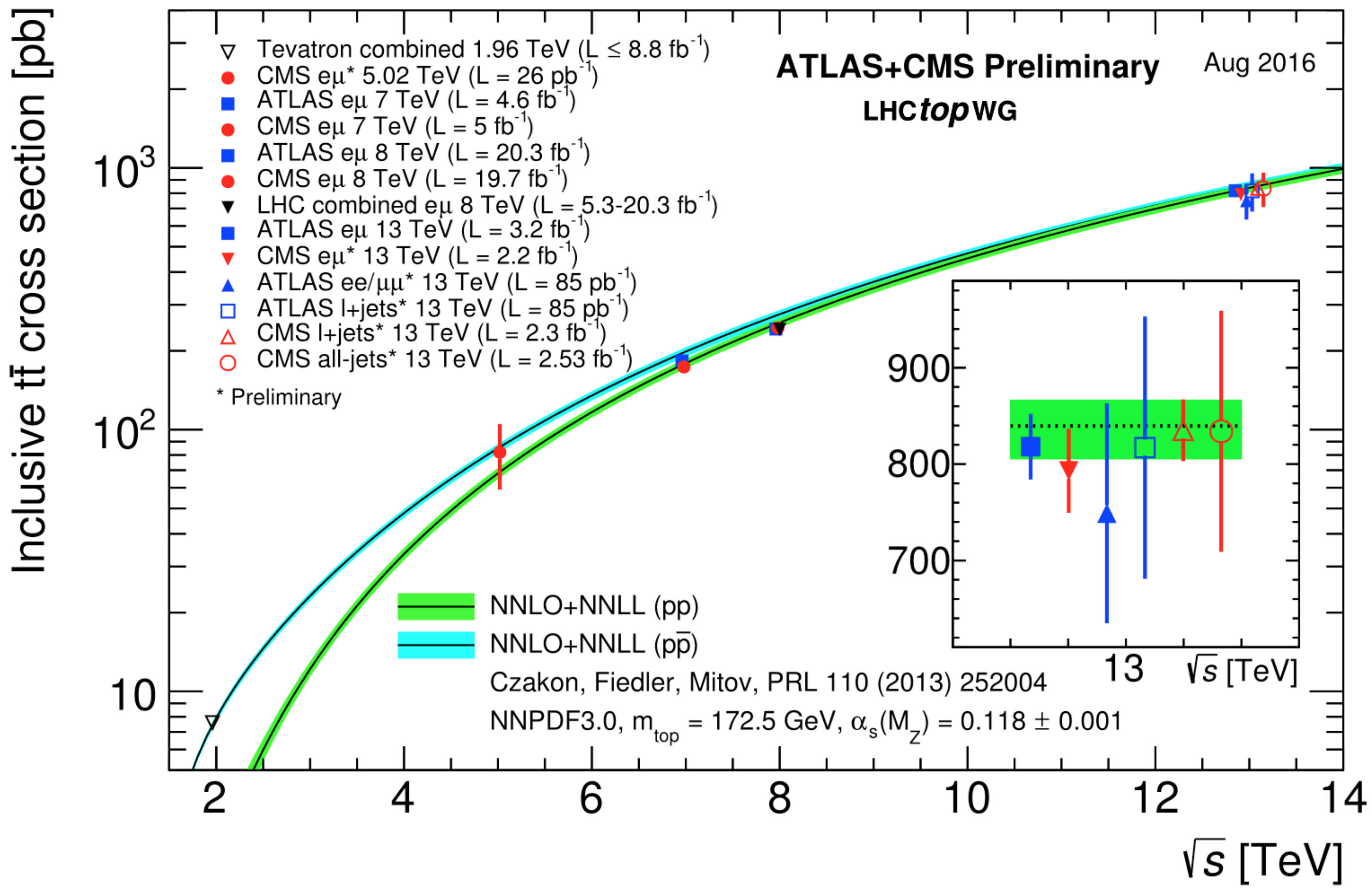
Systematic dominated

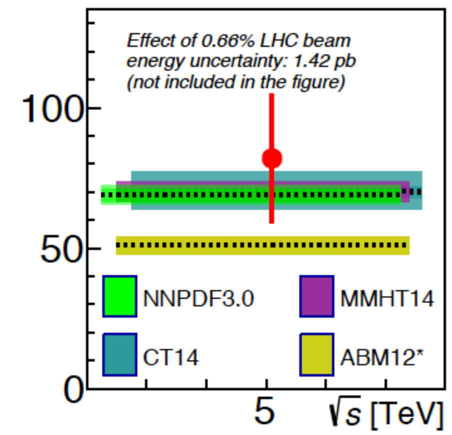
(JES, b-tagging)





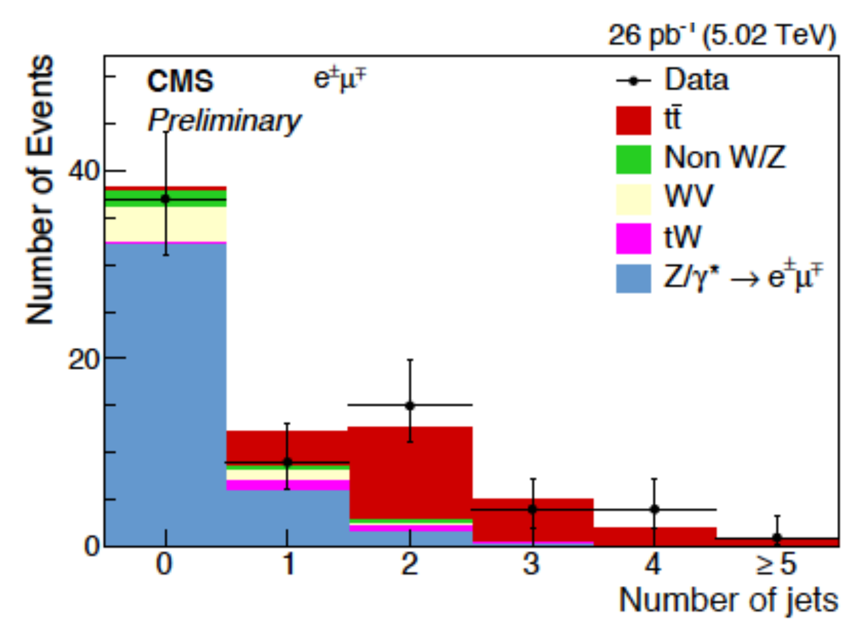
Run-2 tt inclusive cross sections





Surprise √s in cross section summary!

- The LHC delivered 26pb^{-1} of pp collisions at **5.02 TeV** in November 2015 → √s for the Heavy Ions run
- tt cross section measured [CMS-TOP-16-015]
  - Useful reference for HI
- Dilepton (eμ) final state, no b-tag
  - same approach as first 13TeV measurement
- Statistically limited, Δσ/σ≈25%

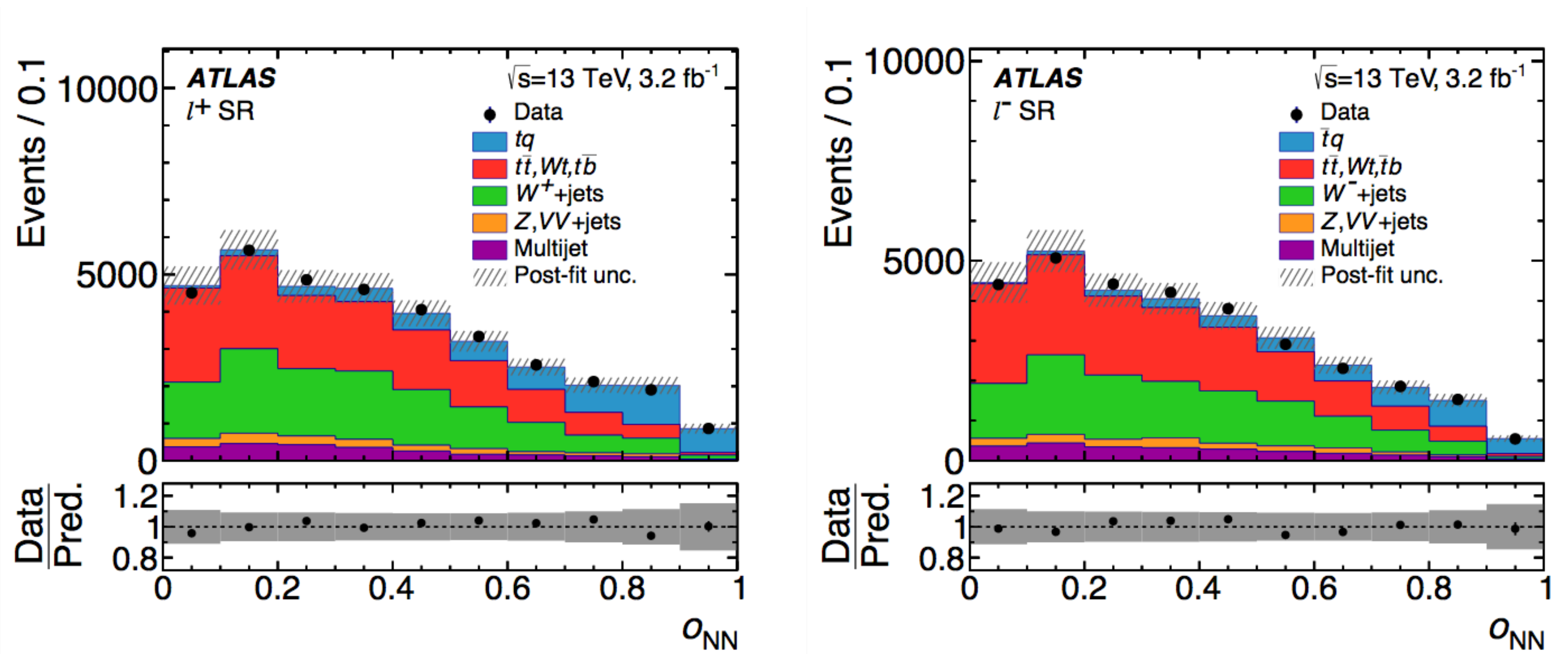


σ_{tt}=82 ±20(stat) ±5(sys) ± 10(lumi) pb

$\sigma_{tt}^{NNLO+NNLL}$=68.9+1.9-2.3(scale)±2.3 (PDF)+1.4-1.0(α_s) pb

Single top inclusive cross section: t-channel

- Among the first results at the start of the Run-2 → Single top t-channel inclusive cross section
  - September 2015
- Fit to multivariate discriminant (NN) using different regions enriched in signal and background
- Separated by charge into top quark and antiquark, ratio -R- → potential to constrain PDFs
- Systematics limited (signal modelling)



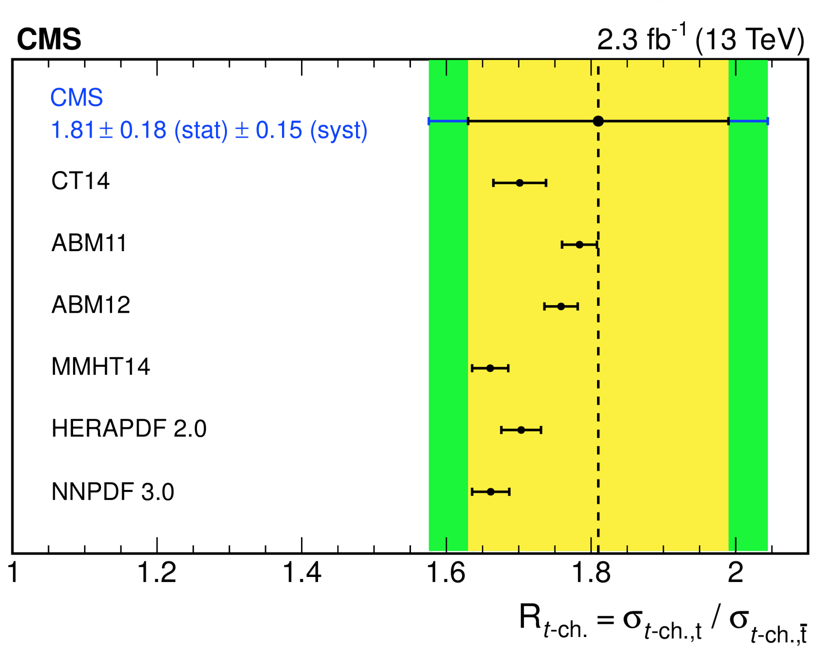
$\sigma_{t\text{-channel}}$*=247 ±6(stat) ±32(sys) ± 4(lumi) pb

arXiv:1609.03920

e and μ

Δσ/σ≈13%

R=1.72±0.09(stat)±0.18(syst)



$\sigma_{t\text{-channel}}$=232 ±13(stat) ±29(sys) ± 6(lumi) pb

arXiv:1610.00678

μ channel only

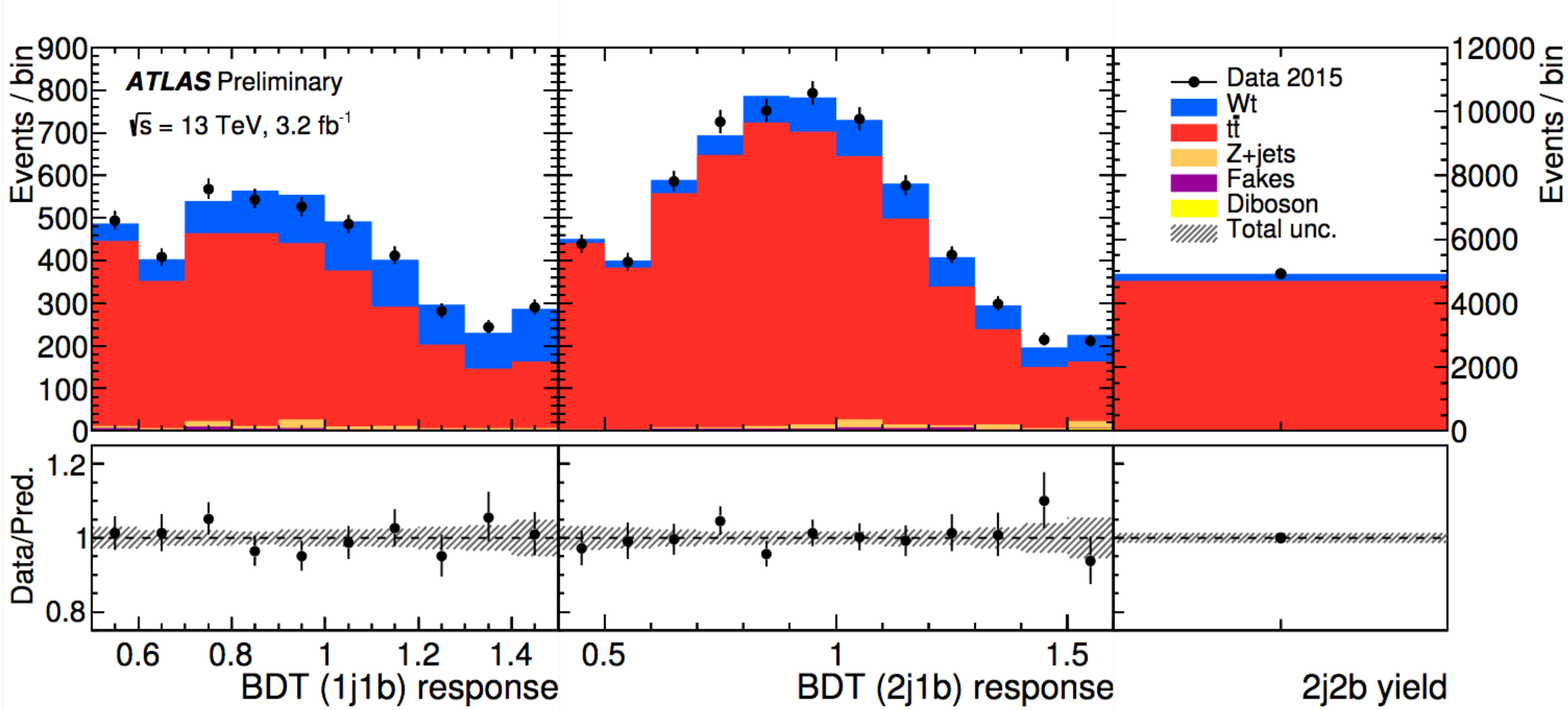
Δσ/σ≈14%

R=1.81±0.18(stat)±0.15(syst)

$\sigma_{t\text{-channel}}^{NLO}$=217 +7-5(scale) ±6(PDF & α_s) pb

Single top inclusive cross section: tW

- tW associated production was **observed for the first time at the LHC** in 2013 (arXiv:1401.2942)
- It is the second single top mode and grows faster than any other single top production at 13TeV
- Main background for tt measurements, Higgs (H→WW), and other searches
- Particular feature: mixes at NLO with ttbar → Process only unambiguously defined at 5FS LO
  - **Explore 4FS definitions at full NLO of WWbb processes → Main goal for Run-2**



ATLAS-CONF-2016-065

First tW result of Run-2, August 2016

BDT in two signal regions + one control region

4.5σ, Δσ/σ≈14%

Syst. dominated (JES, modeling)

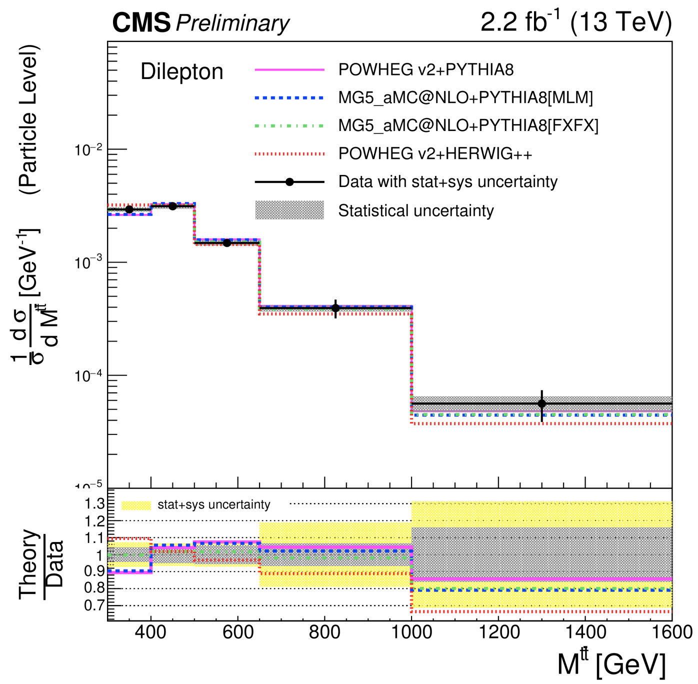
σ_{tW}=92 ±10(stat)+28-23(sys) pb

$\sigma_{tW}^{NLO+NLL}$=71.7±1.8(scale)±3.4 (PDF) pb

DIFFERENTIAL MEASUREMENTS

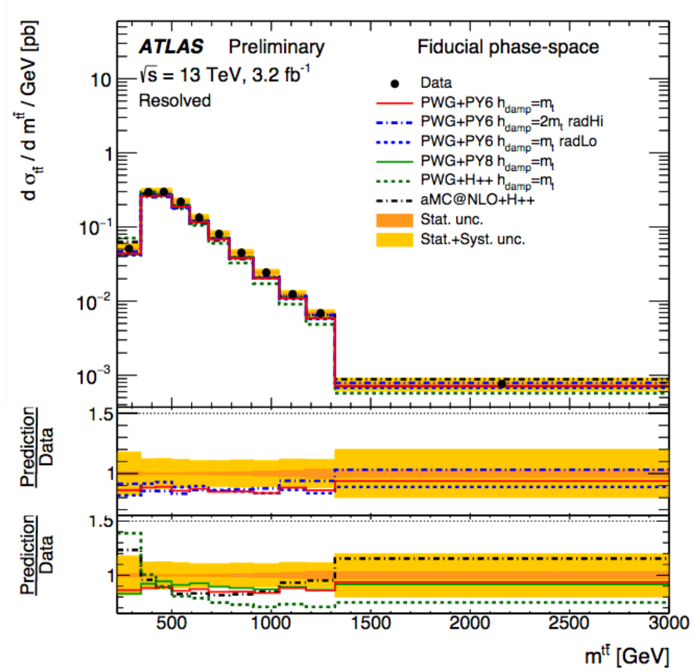
Differential Cross Sections

- Main systematic uncertainty for many top analyses: **top modelling**
  - Differential: Interface between theory calculations, MC generation, and the experiments
- **Several measurements public in Run-2, more to come:**
  - Full/fiducial, boosted/resolved, parton/particle
  - Multiple channels, probing different regimes of the phase space (p_T, jet multiplicity…)
  - Reconstructing the top systems or based on global event variables
- **Comparisons with state-of-the-art predictions**
  - MC generators, high order predictions, matching schemes, variation of scales and tunes, using different PDF sets
  - In general, agreement with NNLO predictions and NLO generators, discriminating power between MC models and tuning parameters (work in progress ATLAS+CMS)



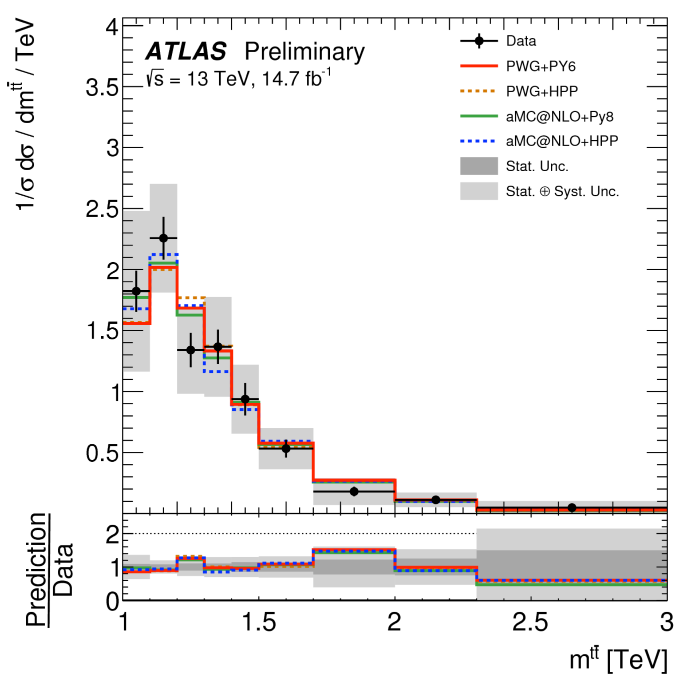
CMS-TOP-16-007

dilepton



ATLAS-CONF-2016-040

l+jets

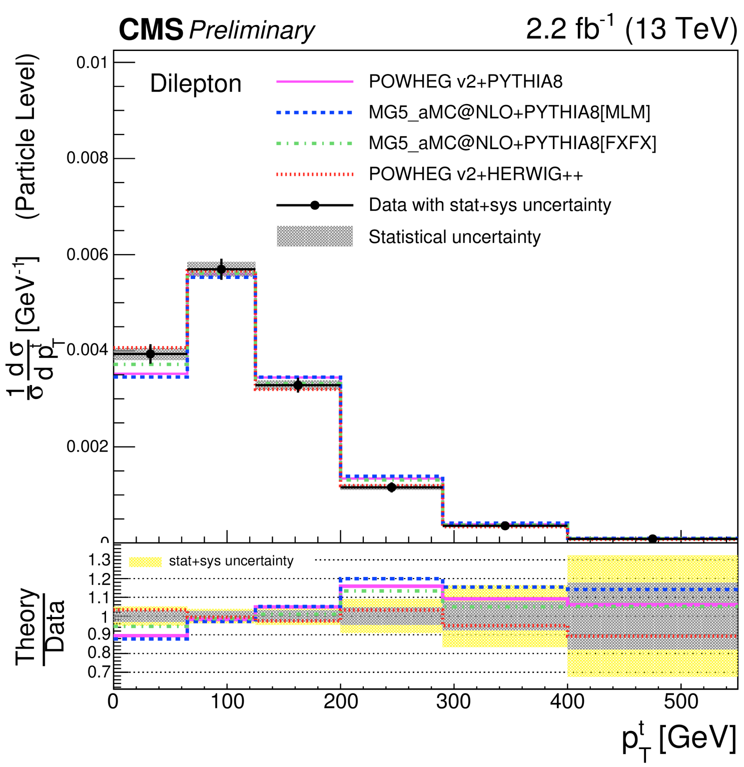


ATLAS-CONF-2016-100

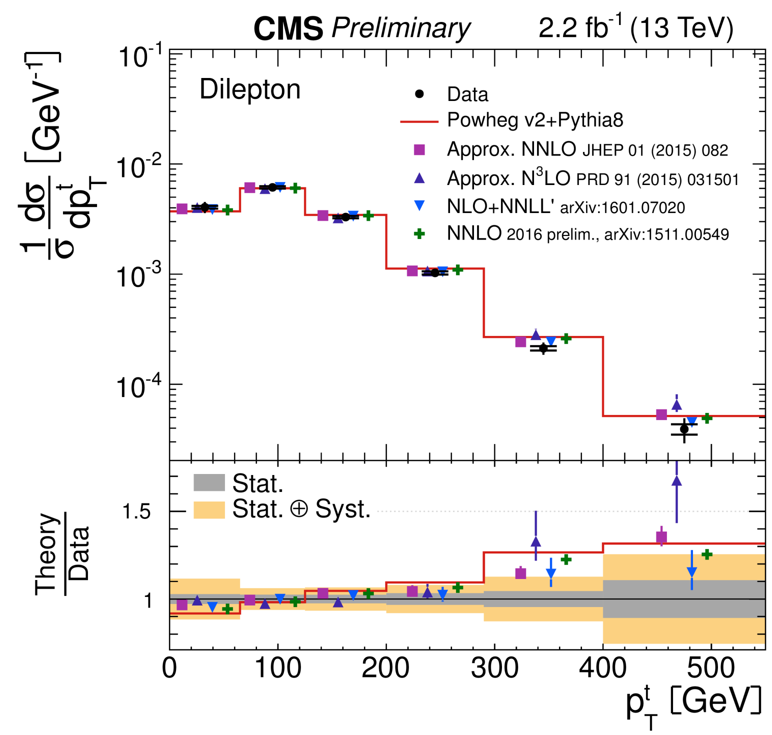
all jets

Differential distributions: top p_T

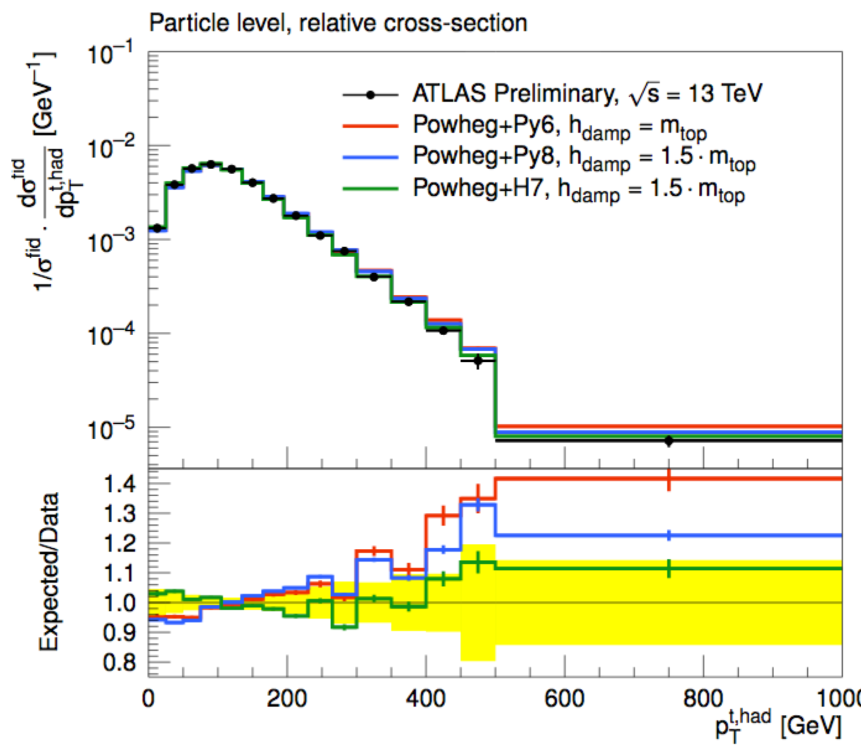
- Effect observed during Run-1, still present in Run-2 in differential measurements:
  - **The top quark p_T spectrum is softer in data than in simulation**



CMS-TOP-16-007

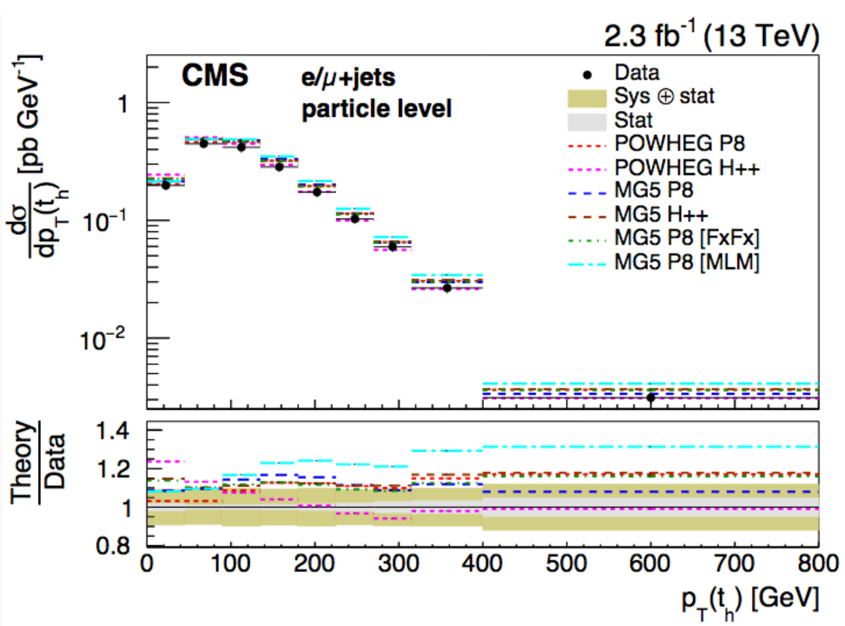


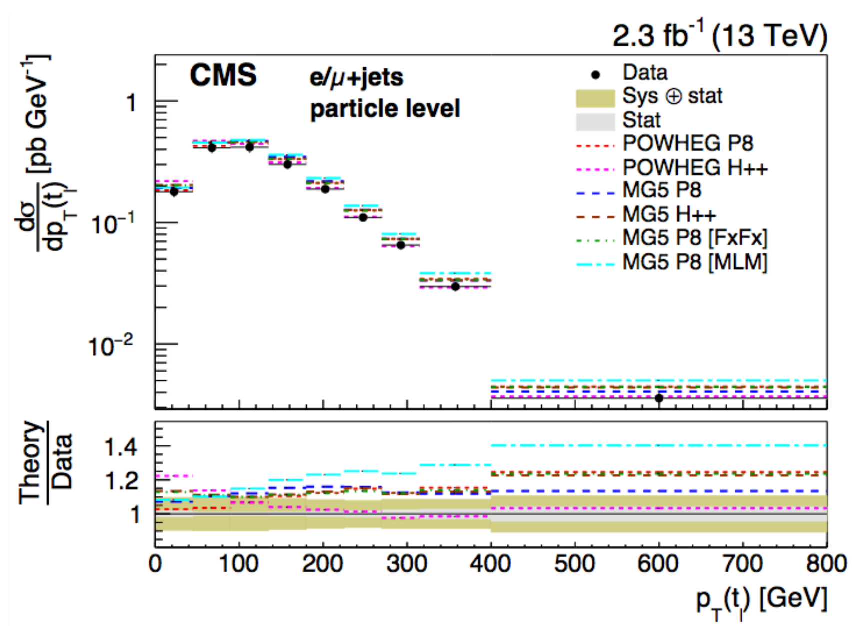
CMS-TOP-16-011



ATL-PHYS-PUB-2016-020

l+jets, several channels



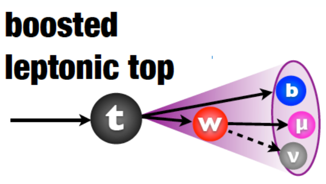


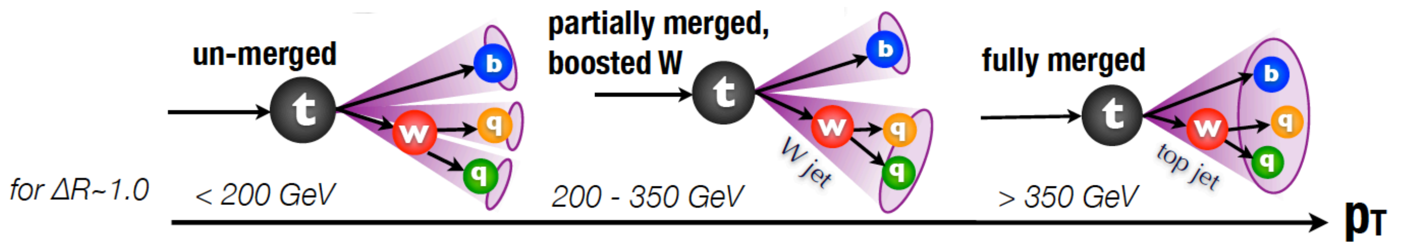
arXiv:1610.04191

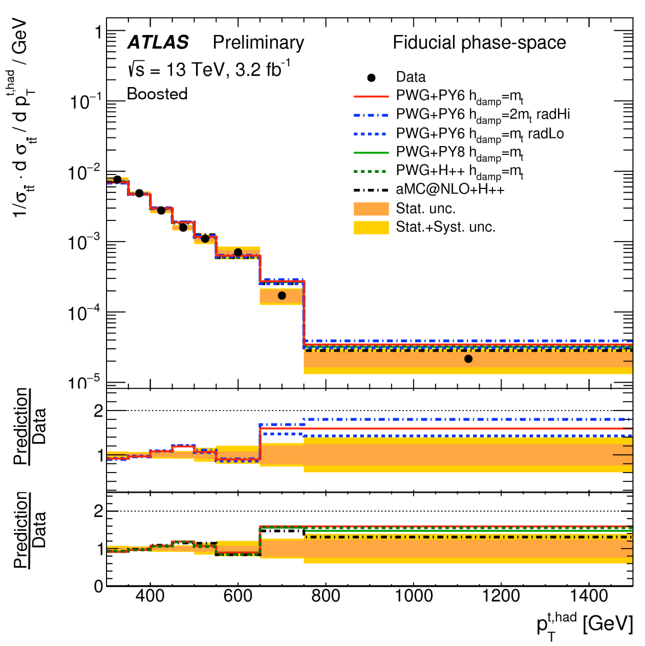
- Improved by NNLO calculations
- less effect when using NLO simulation
- Appears clearly in ATLAS and CMS data
- **To be followed up**

Differential measurements: boosted regime

- The boosted regime is important, especially in the context of **new physics at the LHC**
  - high p_T (boosted) top quarks appear in many new physics scenarios
    - High boost → collimated top decay products
- The **reconstruction of boosted tops is challenging**
  - top vs QCD boosted jets, pileup, leptons within boosted jets, b-tagging

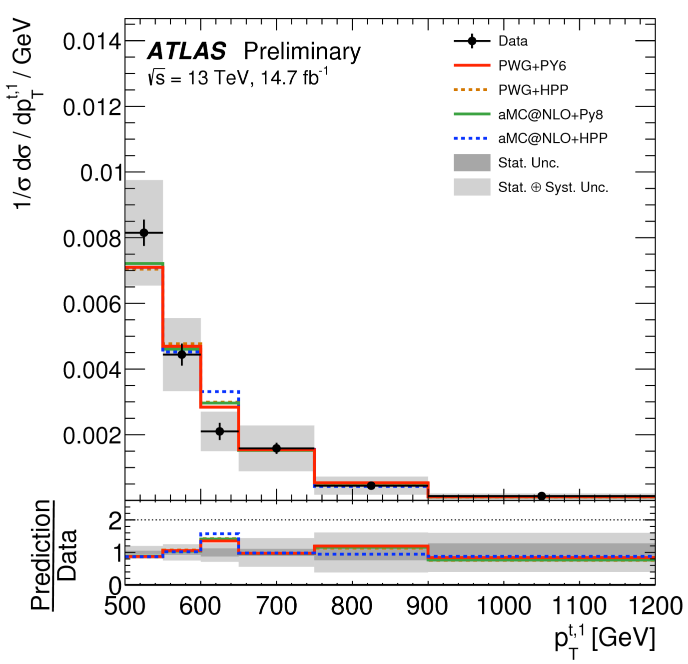






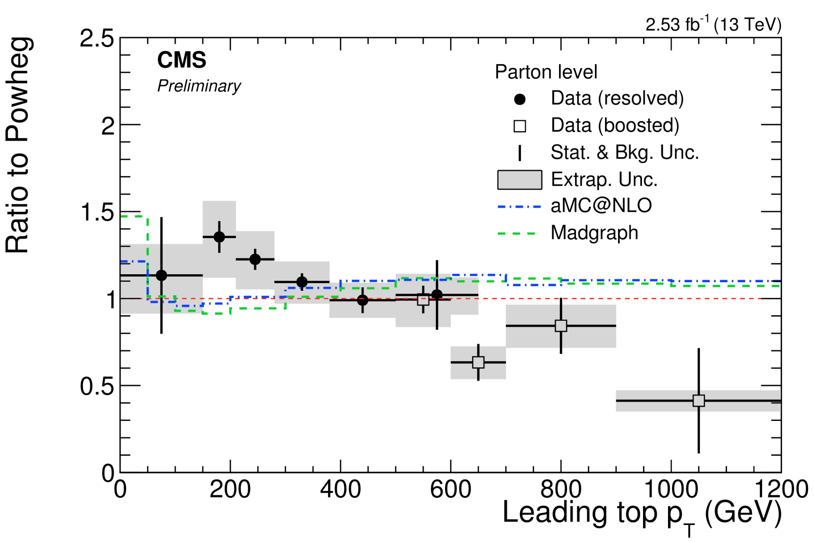
ATLAS-CONF-2016-040

l+jets



ATLAS-CONF-2016-100

all jets



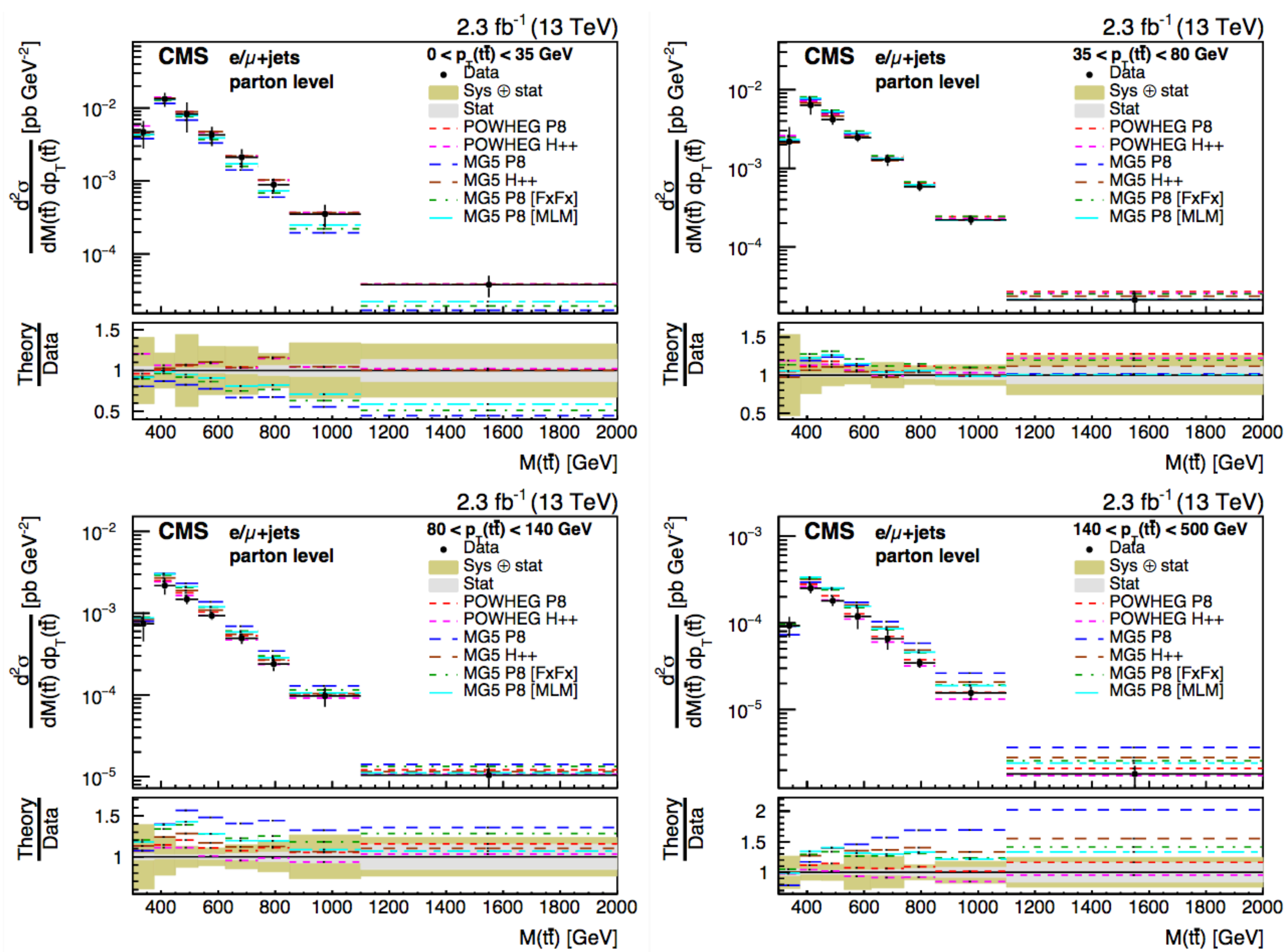
[CMS-TOP-16-013](CMS-TOP-16-013)

all jets

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

Differential measurements: Double differential

- The start of a new differential era: **Double differential** measurements
  - Already explored in Run-1, will bloom in Run-2
- Bin events in pairs of variables:
  - **Better constrains to the MC by disentangling effects**
  - Constraining: PDF, potentially top mass and α_S

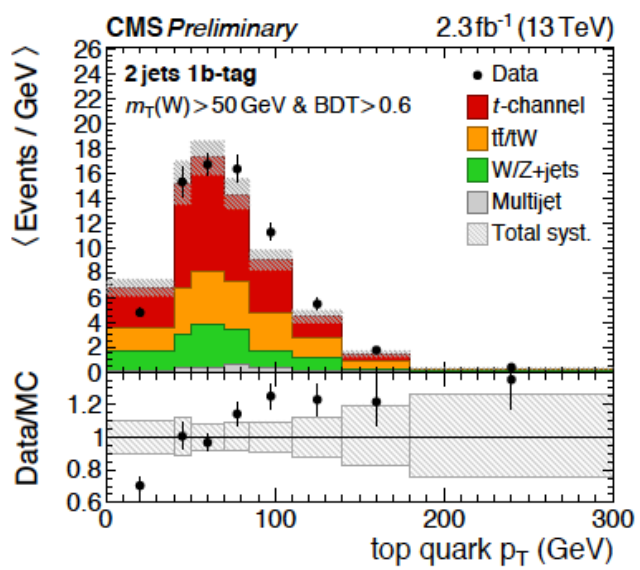


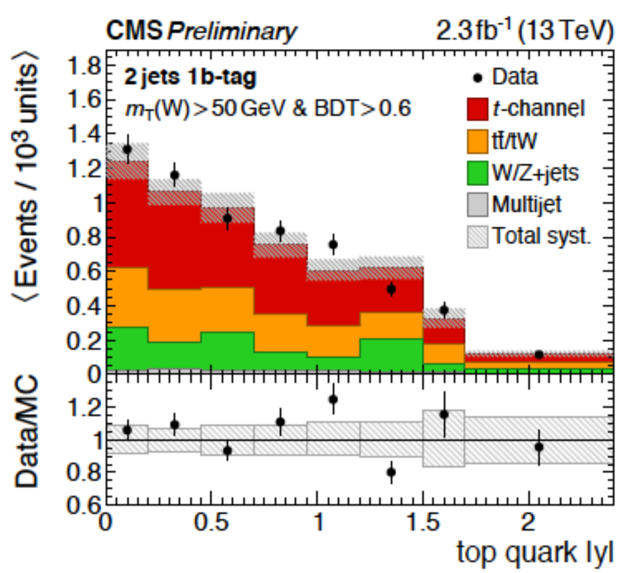
[arXiv:1610.04191](https://arxiv.org/abs/1610.04191)

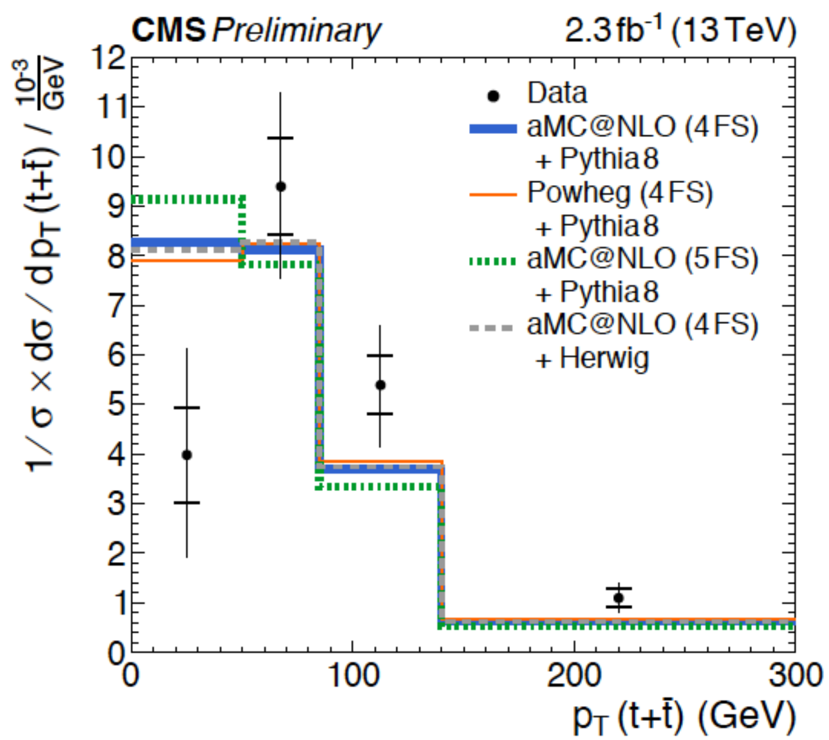
l+jets

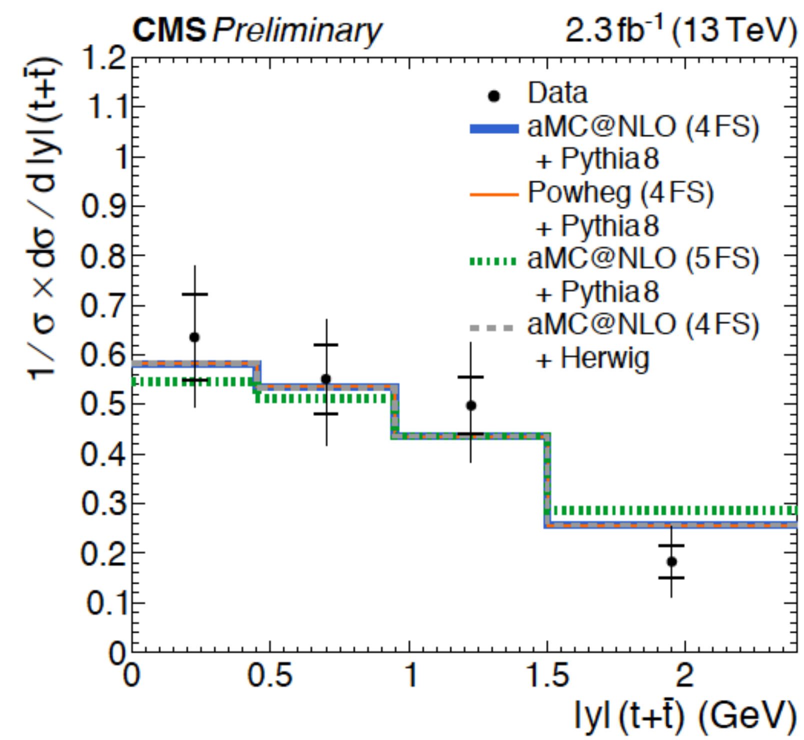
Differential measurements: single top

- Single top t-channel cross sections in Run-2 are as large as tt in Run-1
  - t-channel differential measurement already possible with the 2015 dataset
- **Run-2 will allow us to fully explore single top differential distributions**
  - 2σ effect in top polarization in Run-1 ([arXiv:1511.02138]) to be followed up









[TOP-16-004]

μ channel only

BDT used to isolate a signal-enriched sample

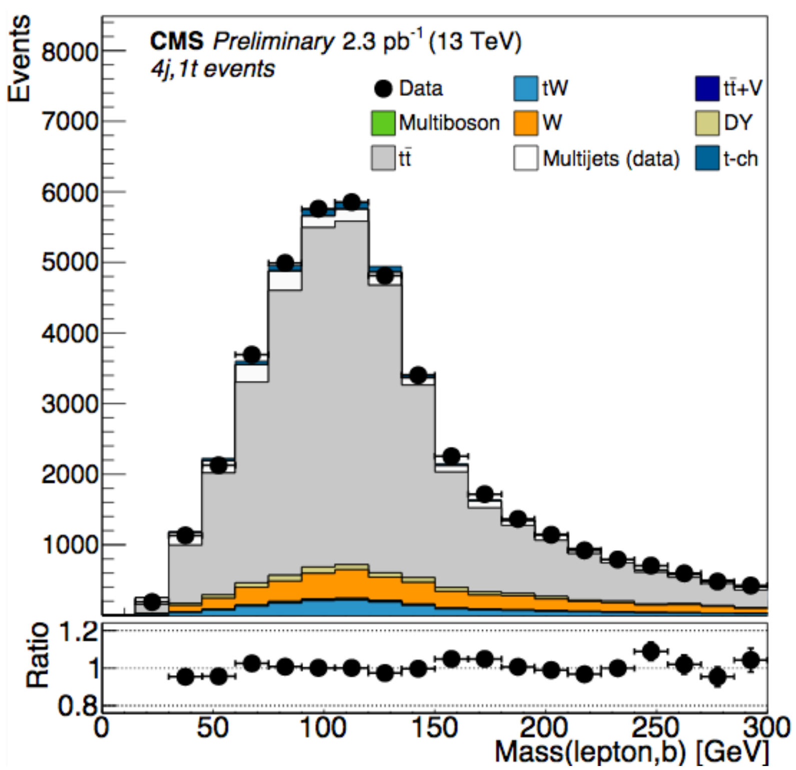
PROPERTIES

Top properties: Early birds

- The time to start performing measurements of top properties in Run-2 is ***NOW***
  - Expect a wave of high precision property measurements arriving in 2017-2018
  - A couple of teasers

Top mass

Indirect measurement→ from tt cross section exploiting the m_t dependance



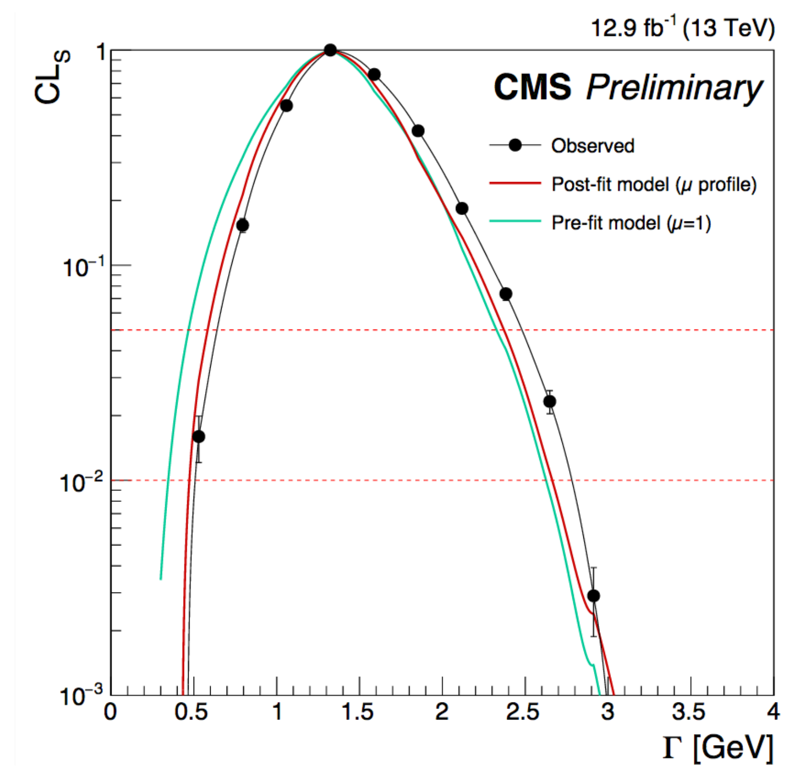
[CMS-TOP-16-006](CMS-TOP-16-006)

l+jets inclusive cross section result re-interpreted to measure the top quark pole mass

m_t = 172.3+2.7-2.3GeV (Δm_t = 1.6%)

Top width

Using kinematic variables at 13TeV, dilepton final state



[CMS-TOP-16-019](CMS-TOP-16-019)

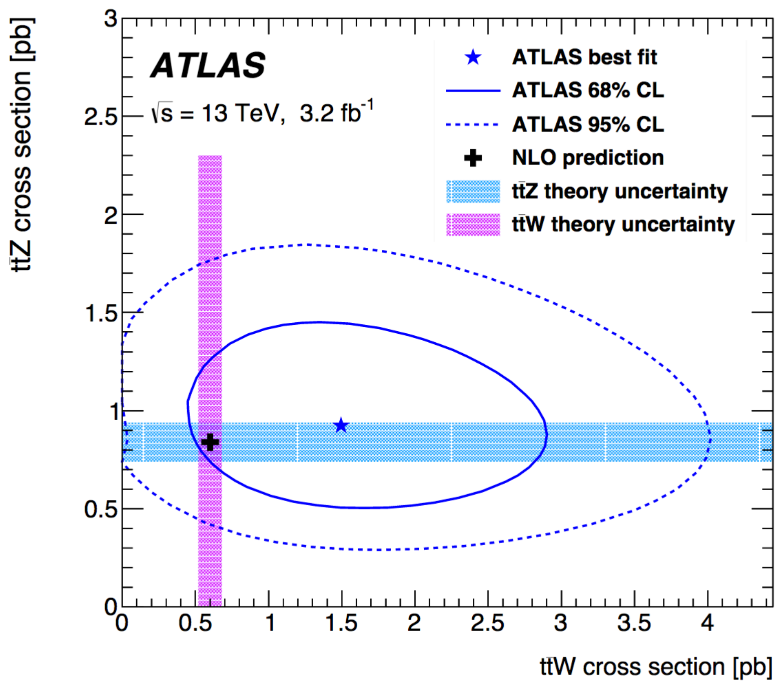
Binary hypothesis tests with different Γ_t values used to bound an SM-like top

$0.6 \leq \Gamma_t \leq 2.5$ GeV (SM_{NLO} =1.35)

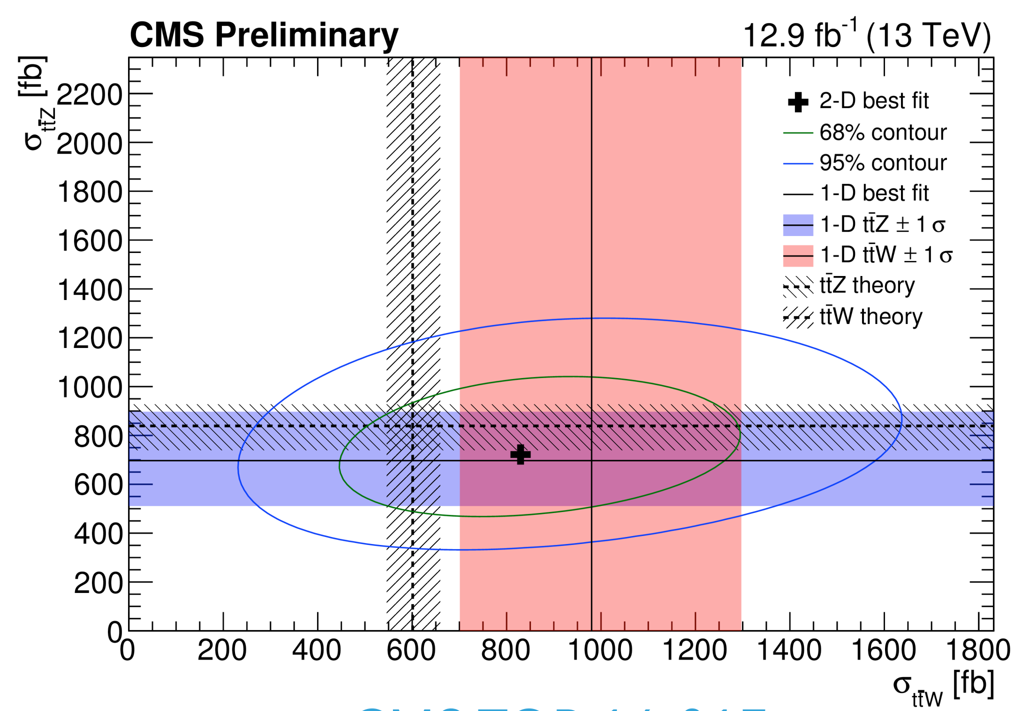
TOP PAIRS+X

top quark pairs produced with vector bosons

- tt+ W/Z/γ: **rare SM processes**, ttZ and ttW already measured in Run-2
- Coupling studies, sensitive to new physics, background of ttH and other BSM searches
  - **ttZ**: directly sensitive to neutral current top coupling
  - **ttW**: source of same-sign leptons, sensitive to new couplings
- Follow up of Run-1 results, still **statistically limited**
  - dilepton same-sign, 3 lepton, 4 lepton, kinematic selections (CMS uses a BDT to select ttW events)
  - simultaneous fit across several signal and control regions



arXiv:1609.01599



CMS-TOP-16-017

σ_{ttZ} =0.92 ± 0.29 (stat) ± 0.10 (syst) pb - 3.9σ

σ_{ttW}=1.50 ± 0.72 (stat) ± 0.33 (syst) pb - 2.2σ

σ_{ttZ} = 0.70 +0.16−0.15 (stat) +0.14−0.12 (syst) pb - 4.6σ

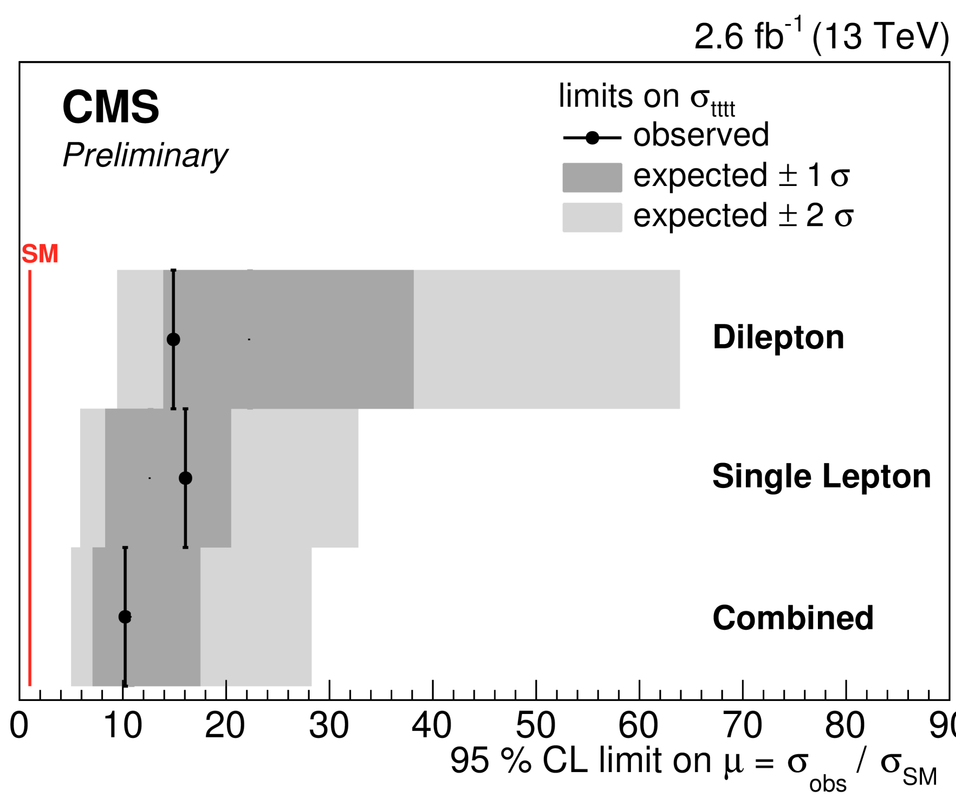
σ_{ttW} = 0.98 +0.23−0.22 (stat) +0.22−0.18 (syst) pb - 3.9σ

σ_{ttZ} = 0.839 (±12%) pb

σ_{ttW} = 0.600 (±13%) pb

top quark pairs produced with top quark pairs (tttt)

- **<u>Very</u>** rare production → SM 4t is produced 5 orders of magnitude less often than tt
  - its measurement will be useful test of analytical higher order QCD 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

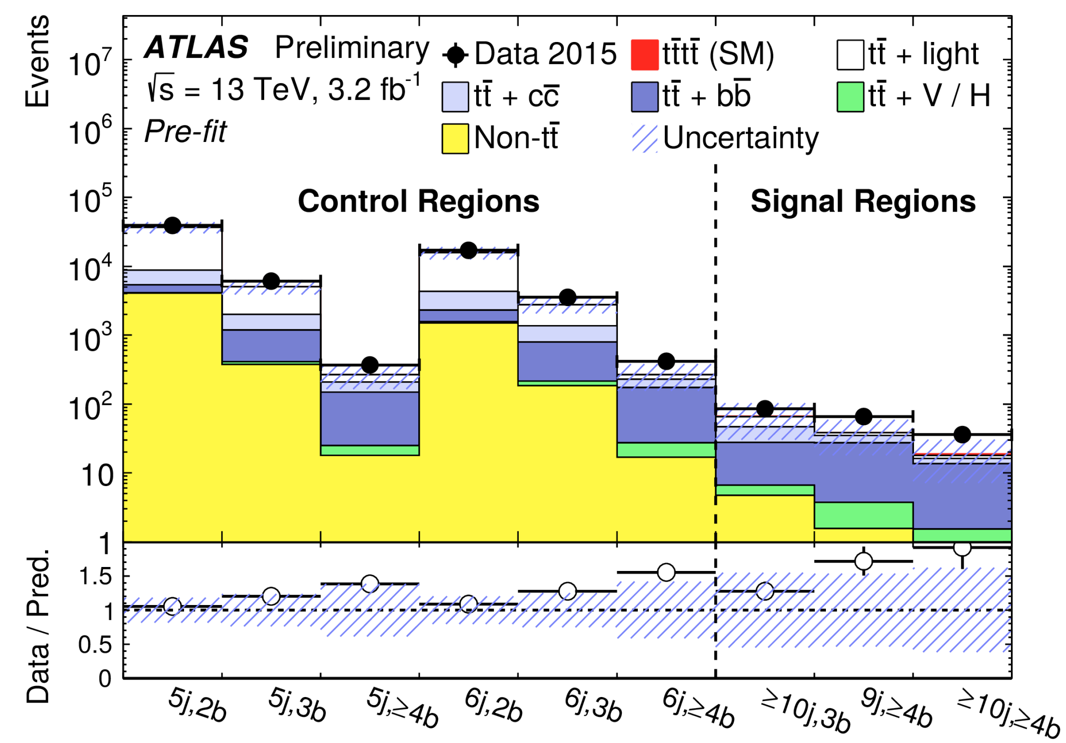


[CMS-TOP-16-016](CMS-TOP-16-016)

l+jets and dilepton final states

Main background tt (also ttV, ttH)

7 BDTs in different regions optimized individually



ATLAS-CONF-2016-020

l+jets final state

several regions (jets, b-tag)

Scalar sum of the jet transverse momenta used as discriminant variable

Summary

- The LHC experiments, ATLAS and CMS, are continuing the legacy from CDF and DØ in top quark physics (also **LHCb**! arXiv:1610.08142)
- **Extremely successful first running period (Run-1) of the LHC**
    - Cross sections: differential, fiducial, and inclusive
    - Top properties: especial focus on top mass (most precise measurement to date!)
    - Single top measurements: all main channels, properties, observation of tW
- **At the very start of the Run-2 in 2015 → A set of top physics results available**
- **Collection of results for this year's TOP conference (this is just the beginning)**
    - Inclusive cross section measurements, differential distributions (tt, t-channel, tW)
    - First hints of properties
    - First results for low cross section processes ttV, tttt (ttH)
- **The dataset of 2016 contains more than 30M of top pairs per experiment**

Ahead: Unlimited potential for high precision measurements, sensitivity for observation of rare processes, catalog of BSM searches in the top sector