Top quark physics at the LHC

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for the ATLAS and CMS Collaborations

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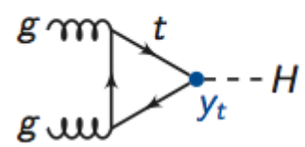
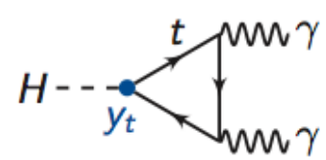
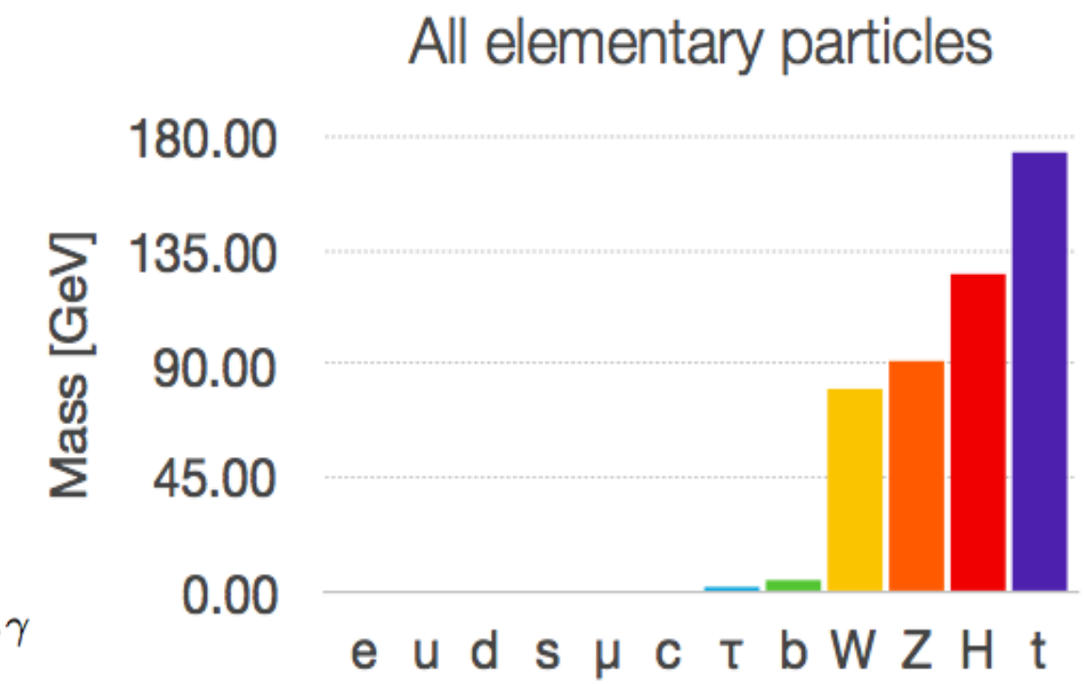
HELMHOLTZ
SPITZENFORSCHUNG FÜR
GROSSE HERAUSFORDERUNGEN

The top quark is special

- **Heaviest elementary particle known to date**
  - Decays before hadronizing: “bare” quark
    - No bound states, spin transferred to decay products
  - **Couples strongly to Higgs**
    - $y_t \sim 1$ => special role in EWSB?





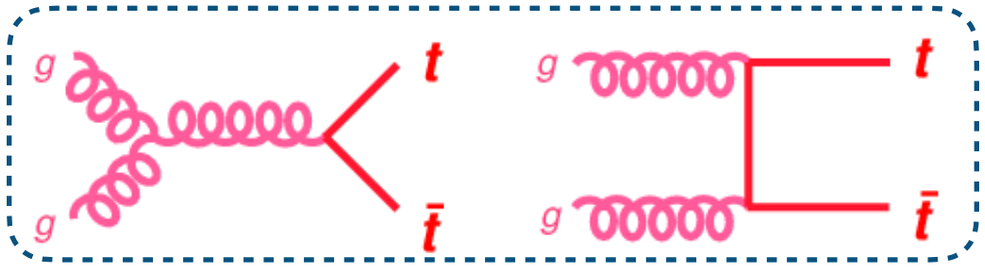


- **Precision measurements of SM parameters**
  - top mass, α_S, couplings
- **Search for physics beyond SM**
  - Precision measurement of top quark properties
  - Window to new physics that couples preferentially to tops

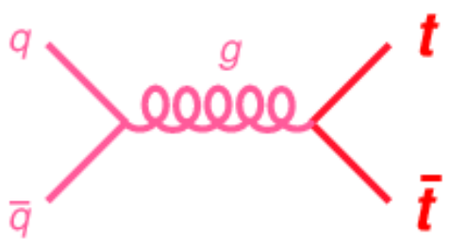
Precise understanding of the top quark is crucial for both SM and BSM physics

Top quark production and decay

- Main: strong **top pair (tt) production**

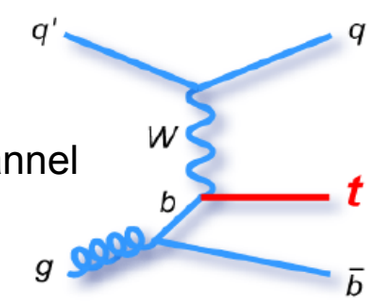


~90%
(13 TeV)

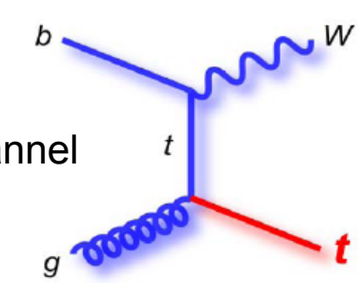


~10%
(13 TeV)

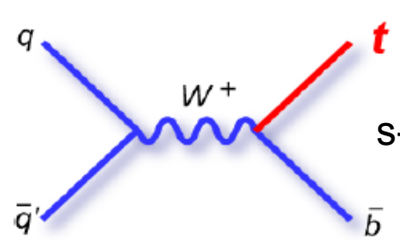
- Electroweak **single top production**



t-channel



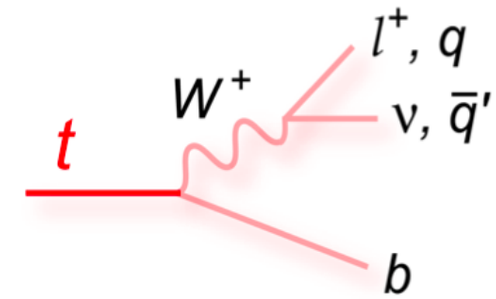
tW-channel

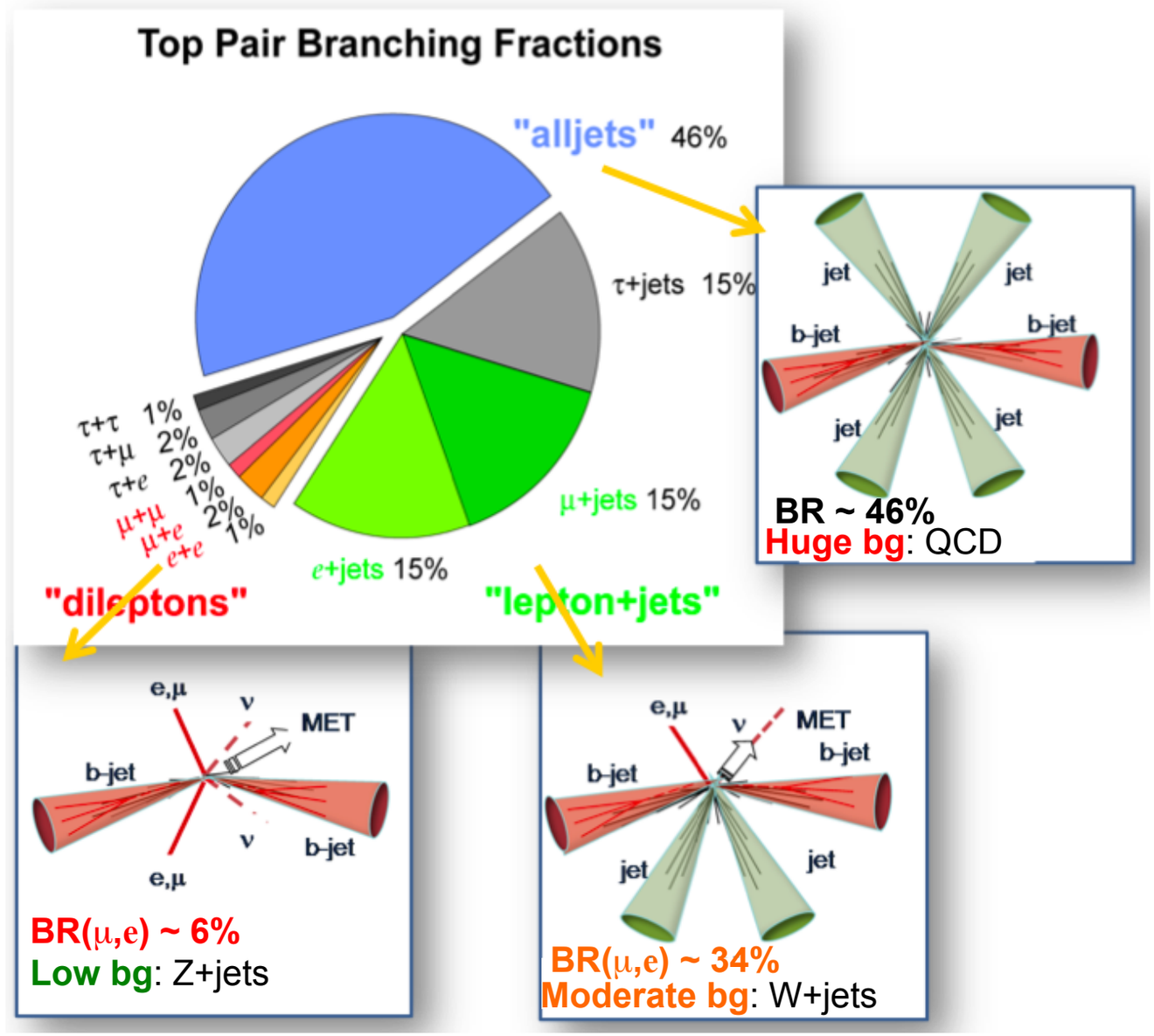


s-channel

- **Top decay:**

In the SM:
~100%

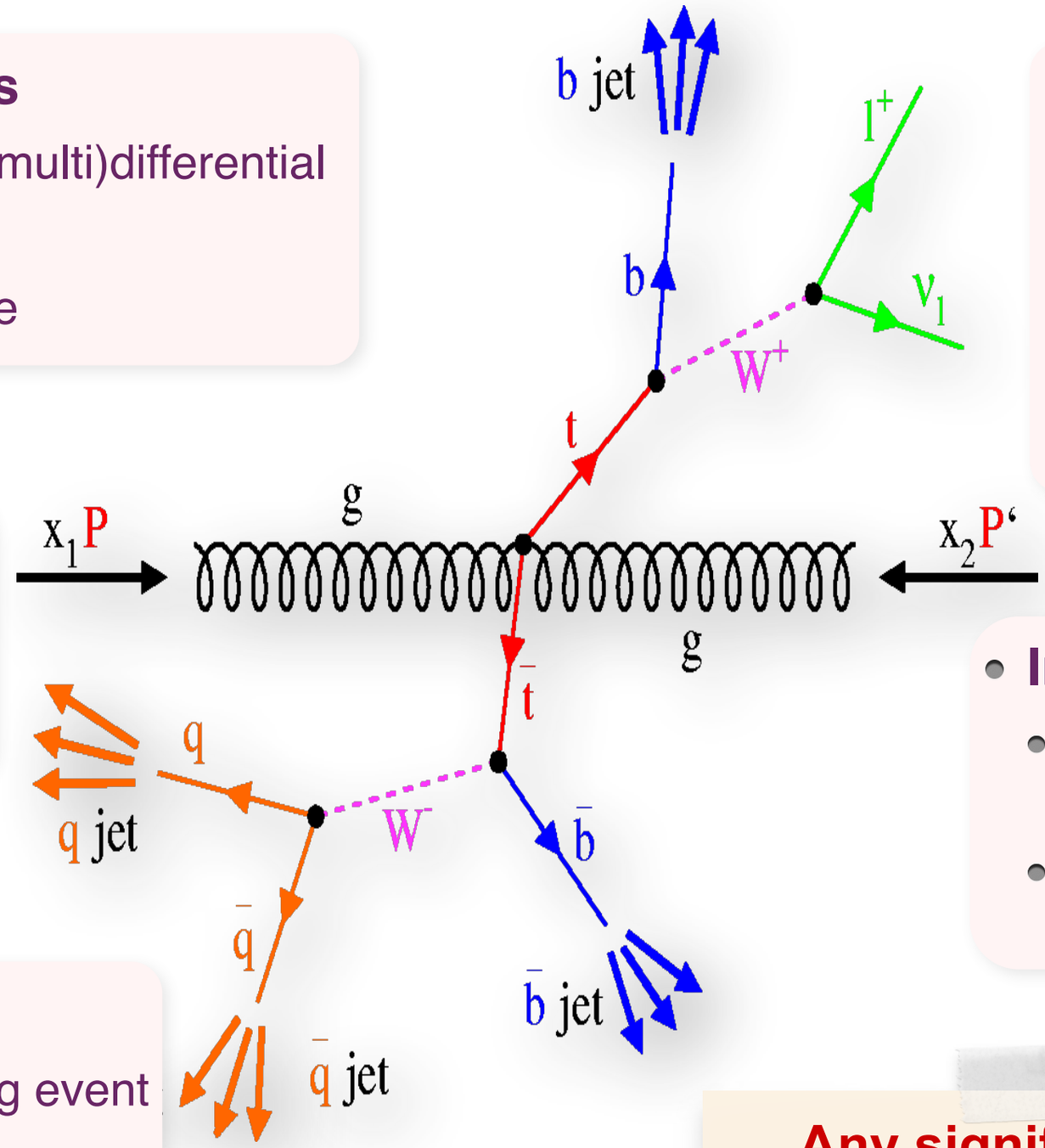




Top quarks: rich experimental programme

- **Cross sections**
  - inclusive and (multi)differential
  - tt, single top
  - boosted regime

- **Mass and properties**
  - mass, width, charge
  - spin correlations
  - asymmetries
  - couplings
  - branching fractions



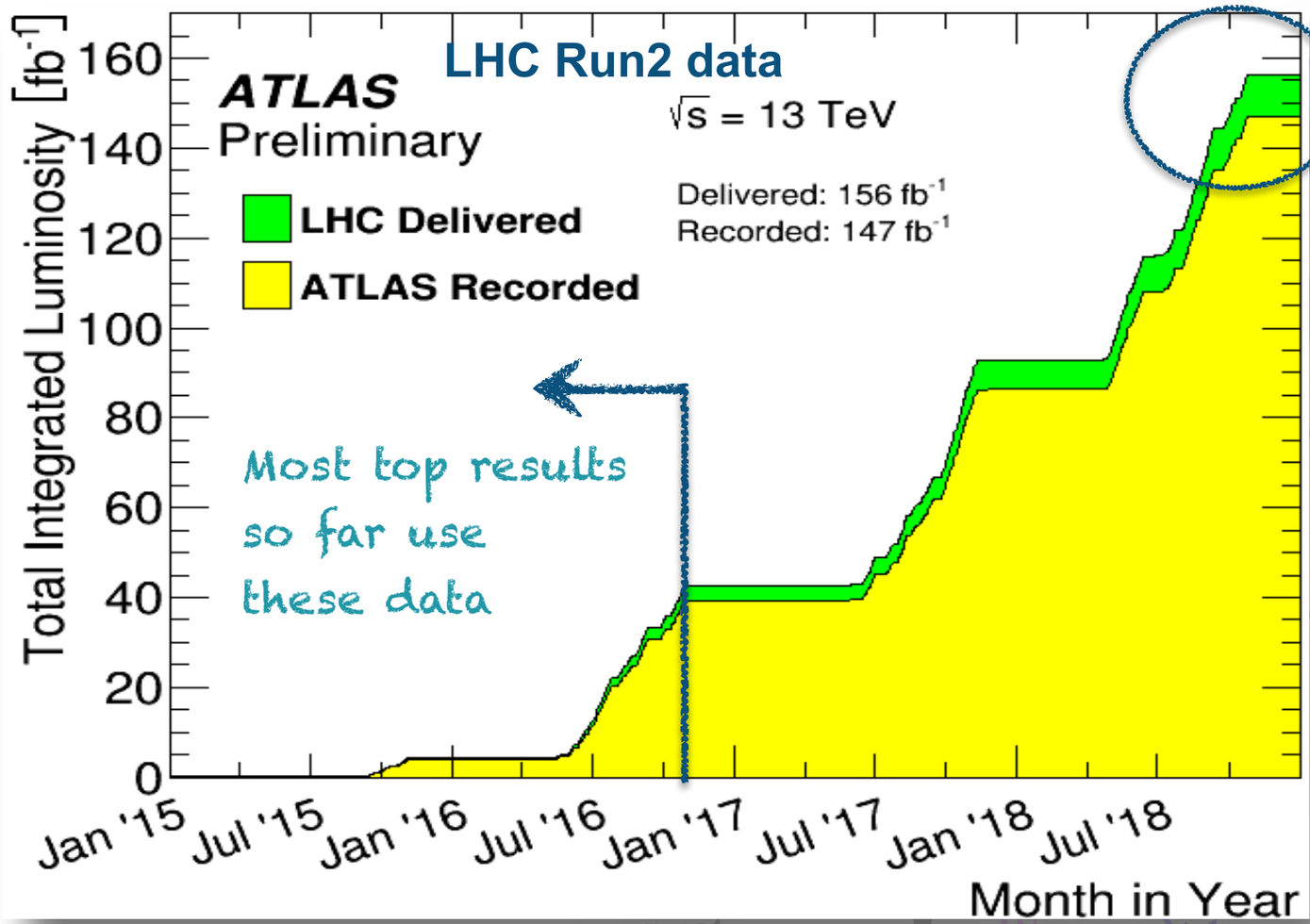
- **Rare production and decays**
  - ttX, tX, tttt
  - FCNC

- **Interpretations**
  - QCD parameters: α_S, mass, PDFs
  - BSM constraints (e.g, EFT)

- **Modelling**
  - tuning of underlying event
  - colour reconnection
  - colour flow

Any significant deviation from the SM is a hint for new physics

Top quarks: rich experimental programme



Similar plot for CMS

For top, this means:

- **~ 120M tt pairs**
- **~ 30M single top**
- **~ 120K ttZ, tZ**

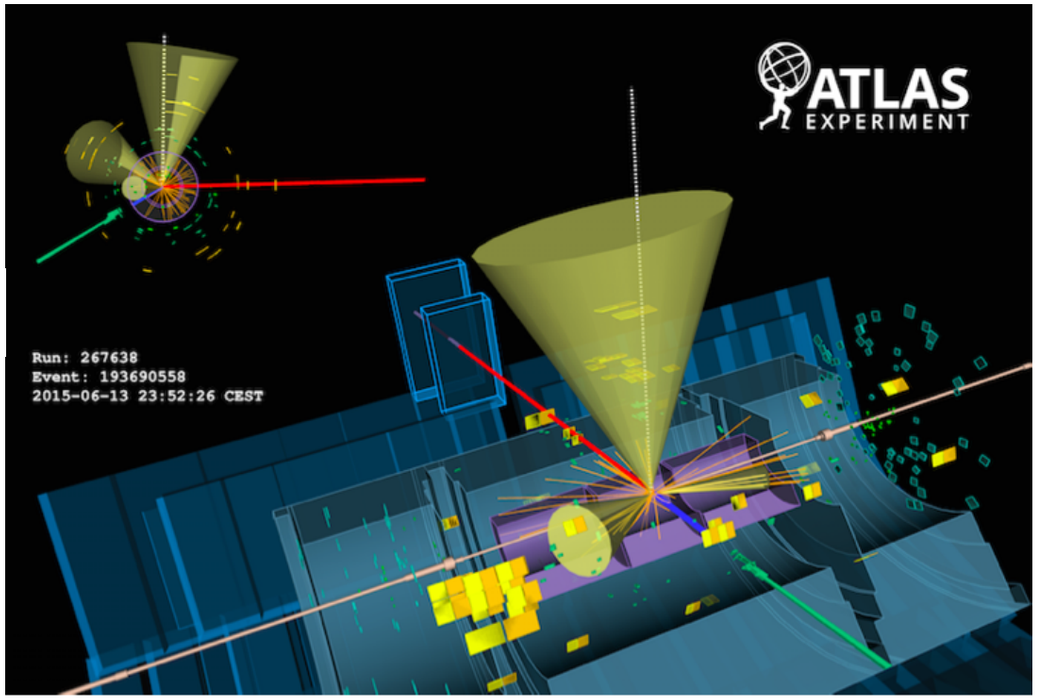
Focus of Run2 top physics (and beyond):

- Ultimate precision measurements
- Properties and couplings (tt and single top)
- Low cross section frontier: tt+X, t+X, tt+tt

Today's talk:
Selection of most recent results from Run2 (13 TeV)

Results for Summer Conferences indicated by New

$e\mu$ + 2 b-tags



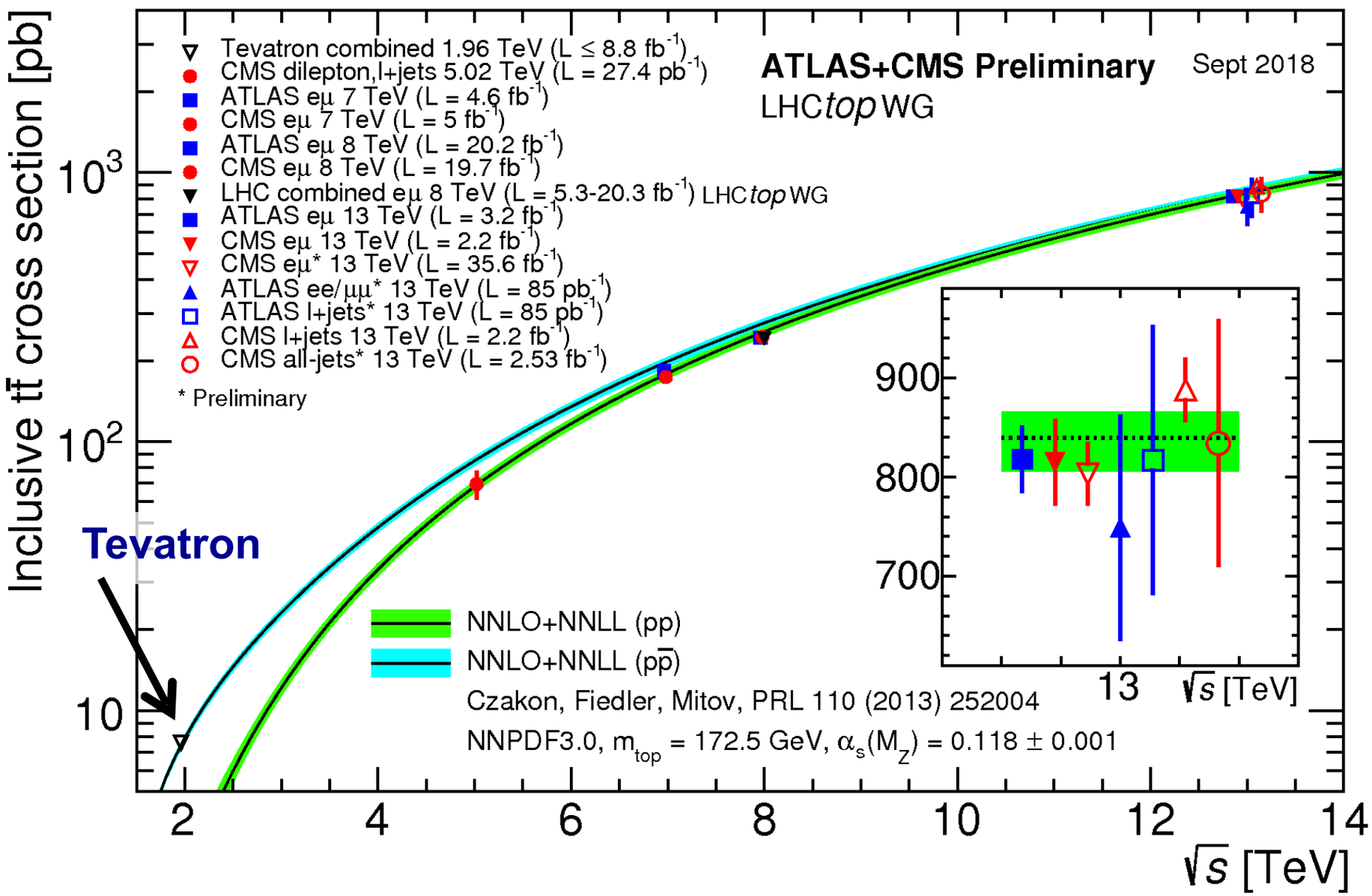
Rates and dynamics of tt production

- First step in understanding top physics
- Test of QCD calculations and search for new physics

→ More in parallel talk by A. Perrotta

Inclusive tt cross sections

Measured at all energies, dependence as a function of √s well understood



- Measure all channels to look for the unexpected
- Good agreement with NNLO+NNLL calculations
- Highest precision: dilepton and l+jets channels ~4%, similar to theory prediction

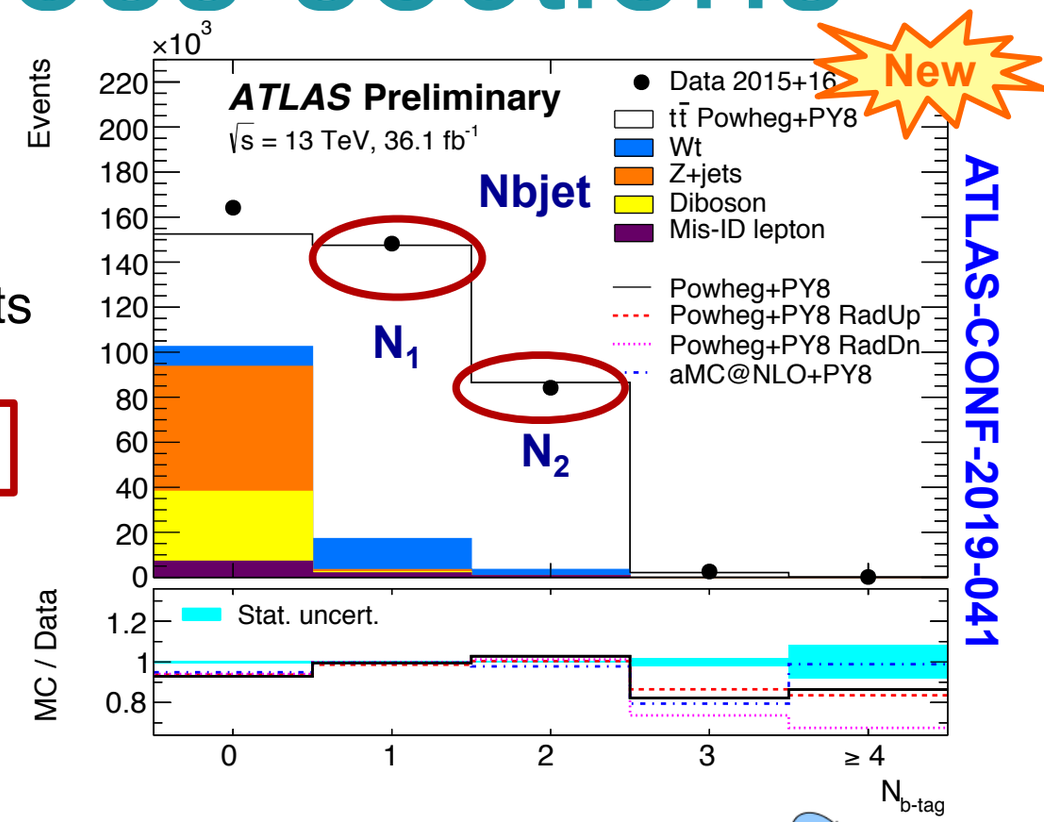
- LHCb catching up! —> complementary measurements to ATLAS and CMS (see backup)
- Top also observed in proton-nucleus (Pb) collisions! (**CMS, PRL 119 (2017) 242001**)

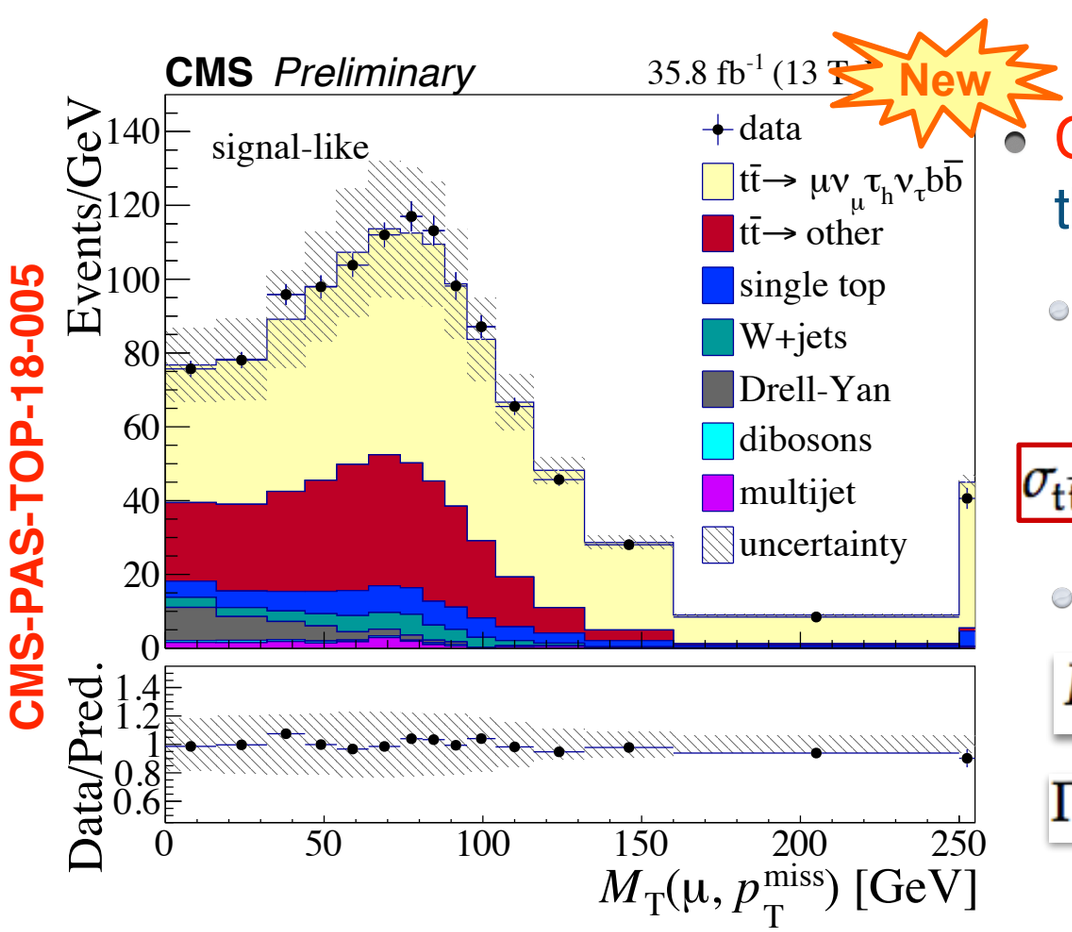
Latest inclusive tt cross sections

- ATLAS: eroding the systematics wall using eμ events
  - Simultaneous extraction of σ_{tt} & efficiency to select, reconstruct and b-tag a jet in events with exactly 1 or 2 b-jets

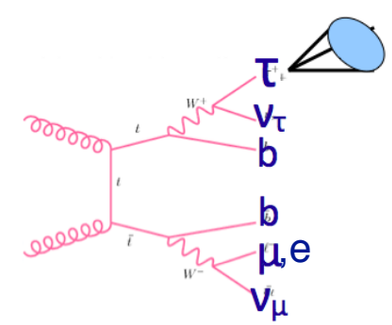
σ_{tt} = 826.4 ± 3.6 (stat) ± 11.5 (syst) ± 15.7 (lumi) ± 1.9 (beam) pb

(2.4% !!)





- CMS: probing lepton universality in the top sector using l+τ events
  - Fit to m_T(lepton, p_T^{miss}) in signal- and background-like regions



$\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7\,(\text{stat}) \pm 62\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb}$ **(8%)**

  - Ratios to σ(tt) in dileptons (CMS, EPJC 79 (2019) 368):

$R_{\ell\tau_h/\ell\ell} = 0.973 \pm 0.009\,(\text{stat}) \pm 0.066\,(\text{syst})$

$\Gamma(t \to \tau\nu_\tau b)/\Gamma_{\text{total}} = 0.1050 \pm 0.0009\,(\text{stat}) \pm 0.0071\,(\text{syst})$

(7%)

Differential tt cross sections

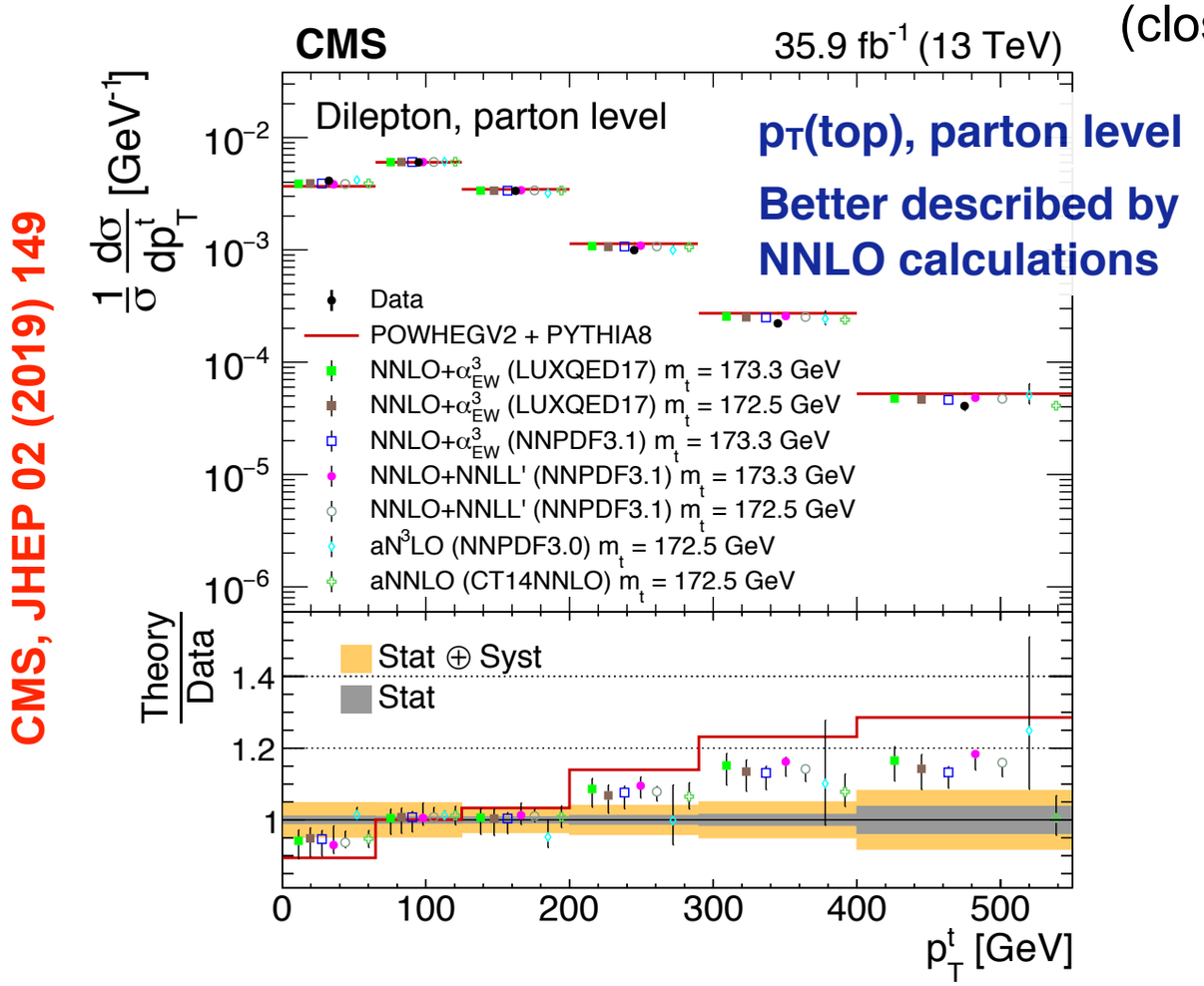
Scrutinize tt production in many channels as a function of many observables

→ Precision tests of pQCD in different regions of phase space, window to BSM physics

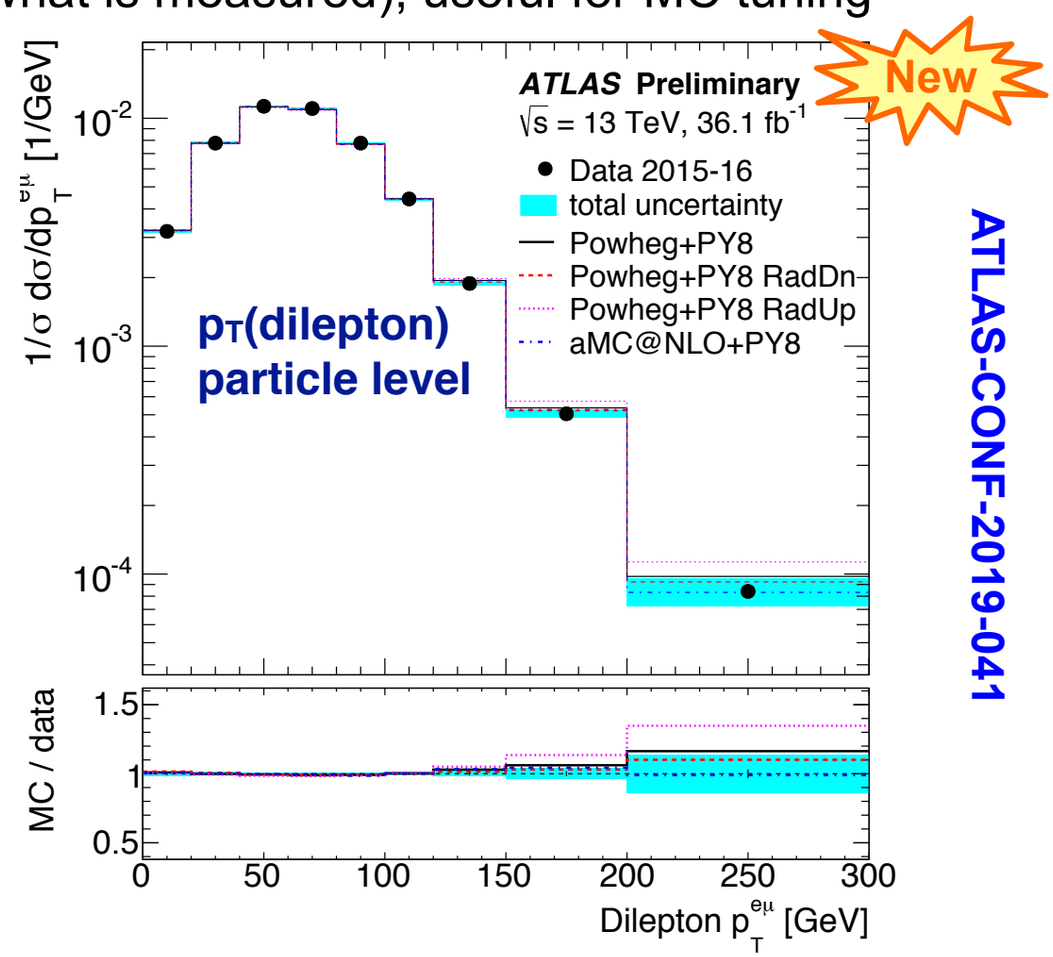
- Use final-state products to reconstruct top quark candidates
- Correct for detector effects & acceptance —> unfolding

Parton level: compare to fixed-order calculations

Particle level: mimic detector-level selection & reconstruction (closer to what is measured); useful for MC tuning



CMS, JHEP 02 (2019) 149

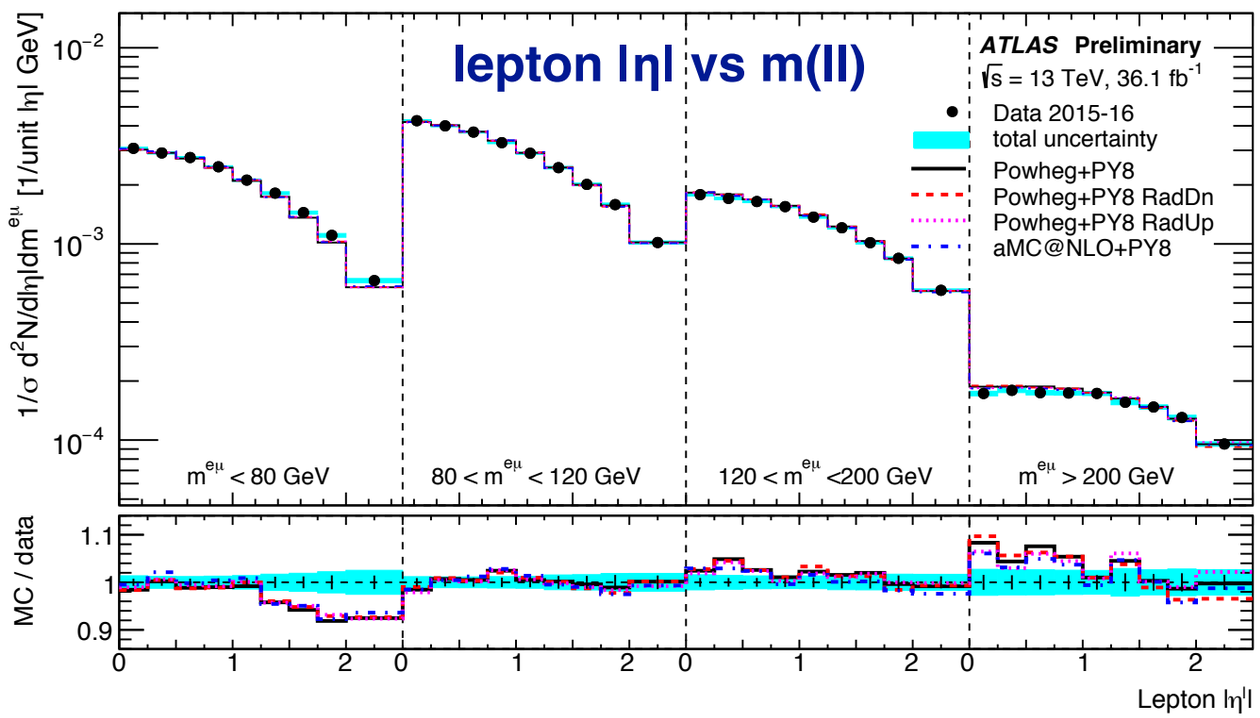


ATLAS-CONF-2019-041

Good agreement with SM, but no single MC simulation describes well all measured distributions

Zooming in: going multidifferential !

Enhance further the sensitivity to QCD parameters, PDFs, and BSM effects



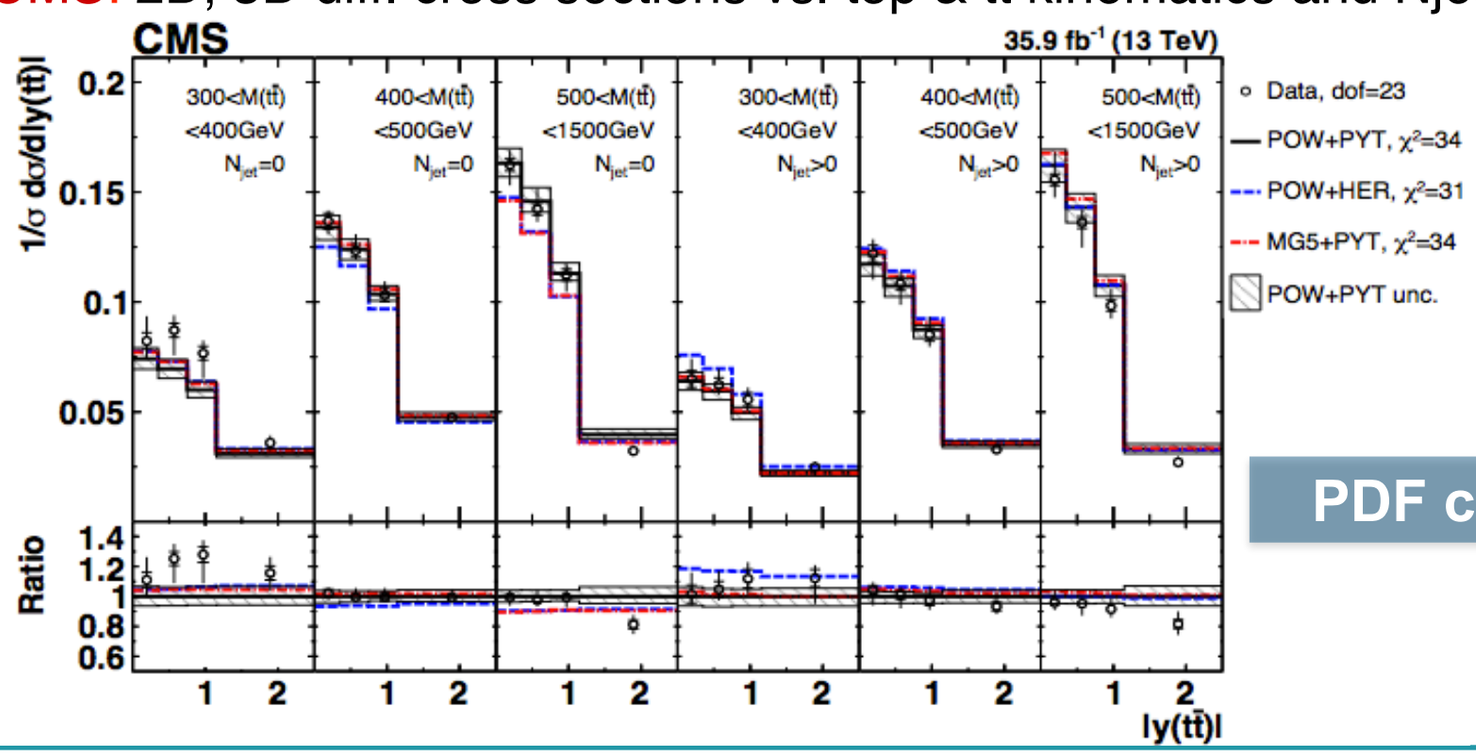
New

ATLAS-CONF-2019-041

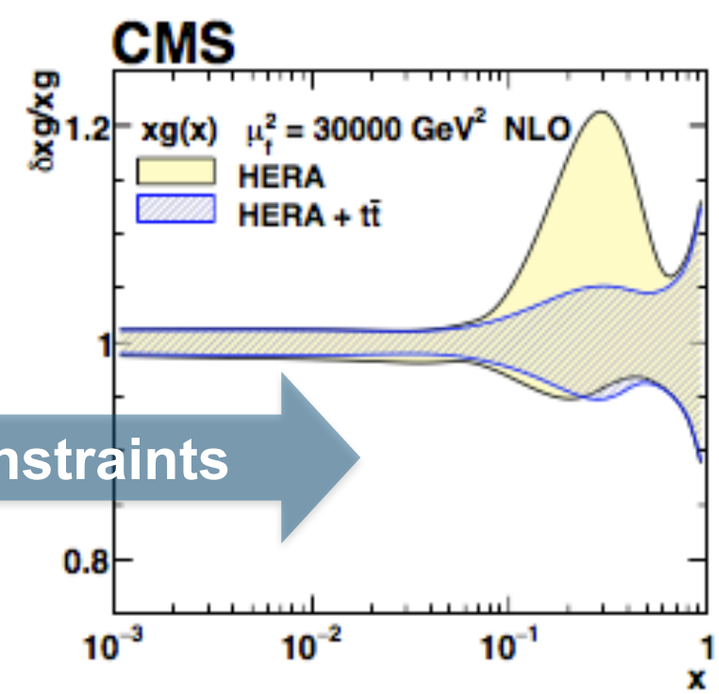
- ATLAS: 2D differential cross sections as a function of lepton and dilepton kinematics
  - General good agreement with different NLO simulations, except at low m(ll)

- CMS: 2D, 3D diff. cross sections vs. top & tt kinematics and Njets, used to extract m_t^{pole}, αs, PDF

CMS, arXiv:1904.05237



PDF constraints

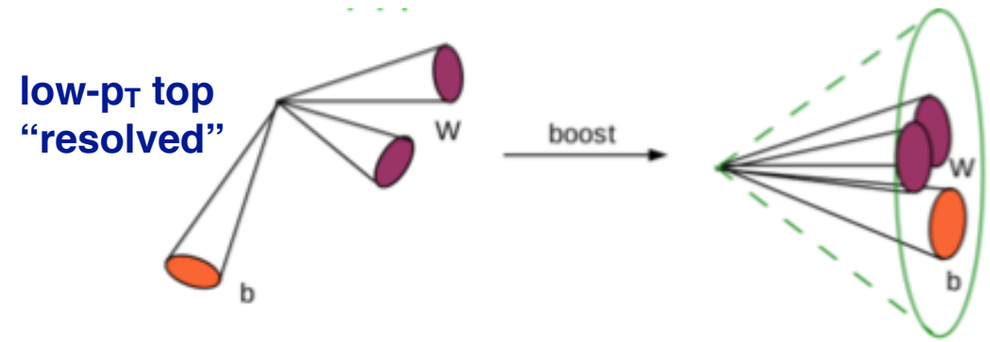


High-p_T tops: exploring the boosted regime

New

Measure tops at high p_T using optimized event selection & reconstruction up to TeV range!

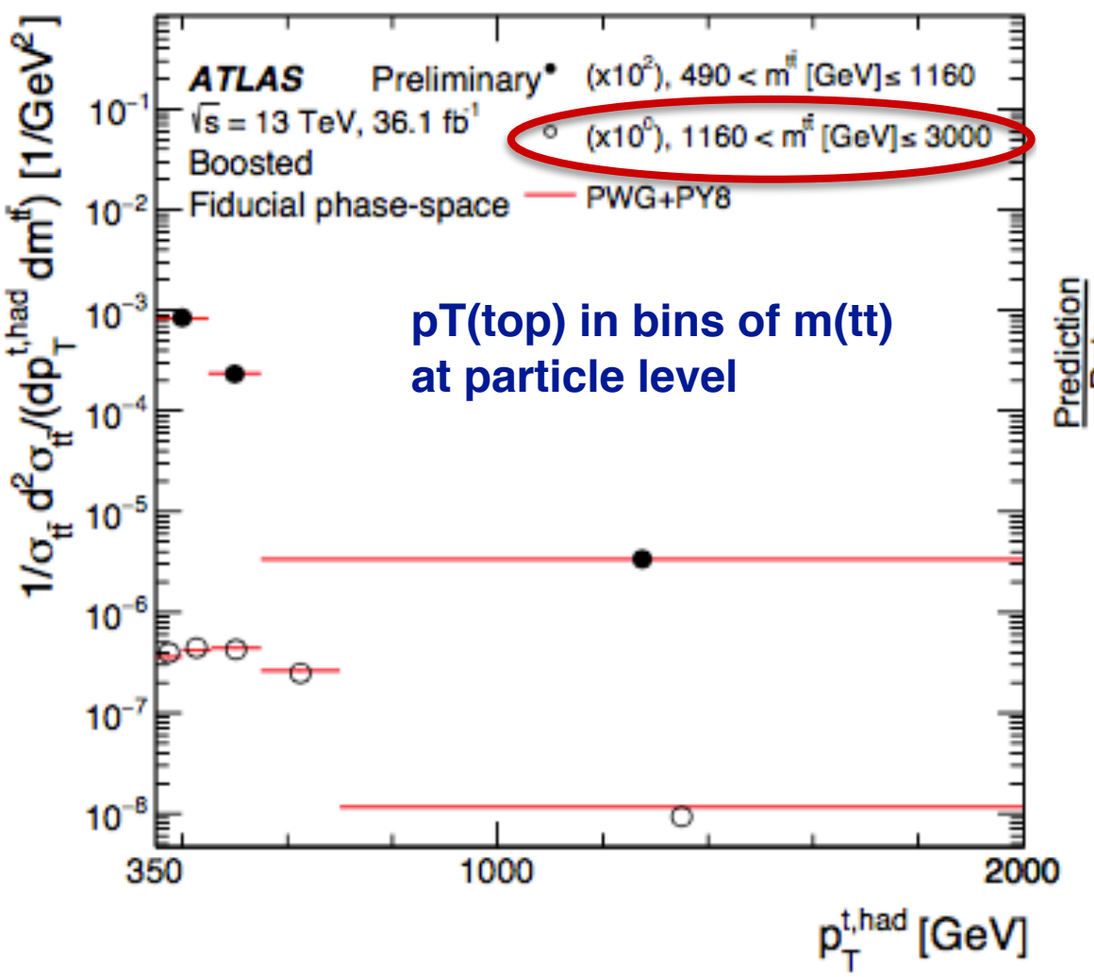
- Particularly sensitive to BSM: high-p_T tops appear in many new physics scenarios



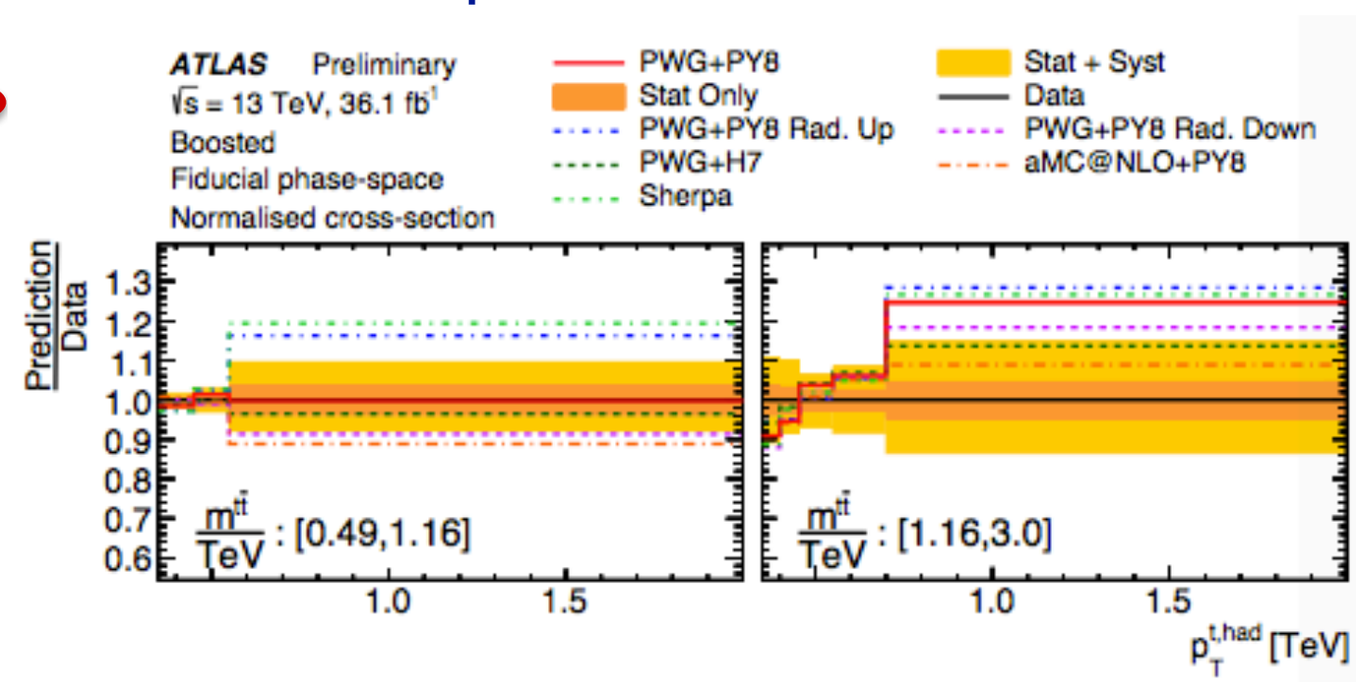
- Re-cluster R = 0.4 jets with anti-kT R = 1
- $120 < m_{jet} < 220$ GeV

- New ATLAS, l+jets: 1D differential cross sections a function of top & tt-system kinematics (and more), and first 2D results!

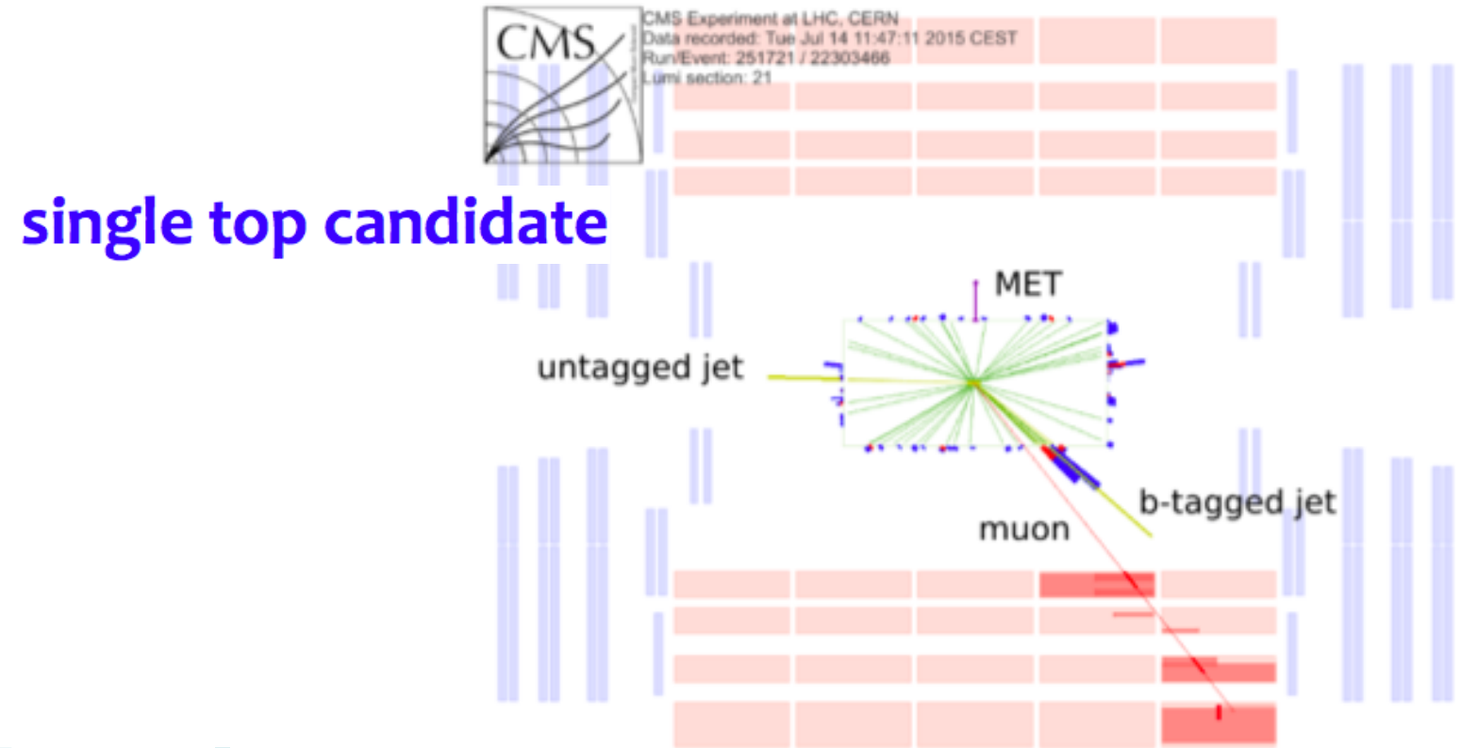
ATL-COM-PHYS-2019-030



Comparison to different MC models



- Larger data/MC discrepancy at high m(tt)
- Data starts to discriminate between models!

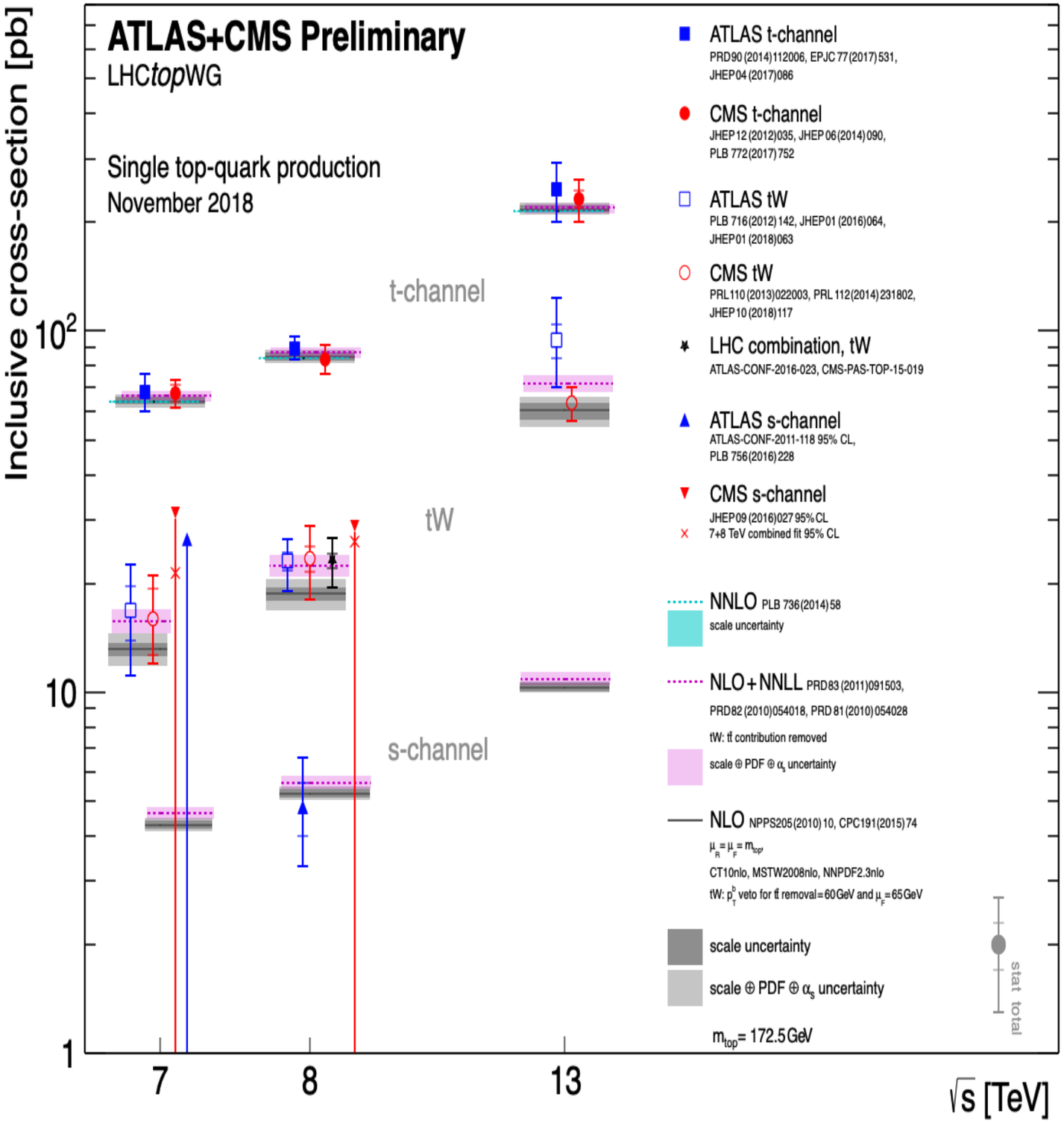


Single top

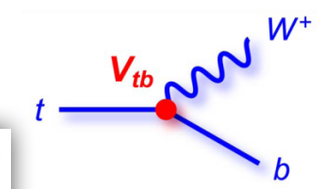
- Probe CKM matrix element $|V_{tb}|$, EWK coupling structure
- Probe alternative production mechanisms (e.g heavy bosons, FCNC)
- Sensitive to b-PDF and u/d-PDFs

→ More in parallel talk by A. Perrotta

Single top production: the big picture



- **Run1** legacy ATLAS+CMS cross sections and V_{tb} combinations **JHEP 05 (2019) 088**
  - Probing the Wtb vertex: best direct V_{tb} determination to date!



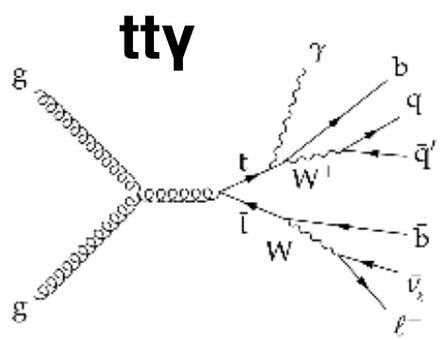
$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}\ (V_{tb} = 1)}}$$

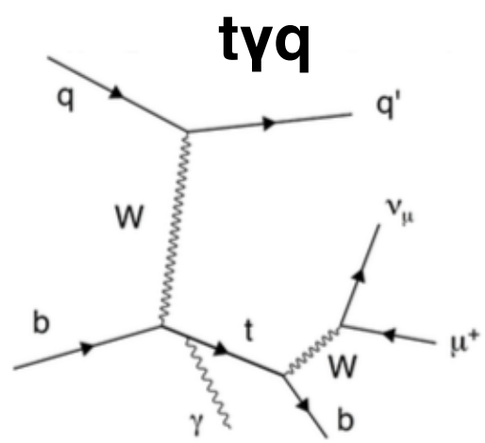
(assume $|V_{ts}|$, $|V_{td}| << |V_{tb}|$) In SM: $f_{LV} = 1$

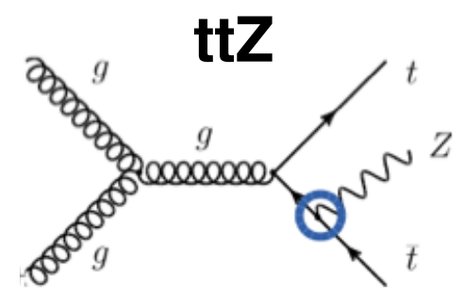
$$|f_{LV} V_{tb}| = 1.02 \pm 0.04\ (meas.) \pm 0.02\ (theo.)$$

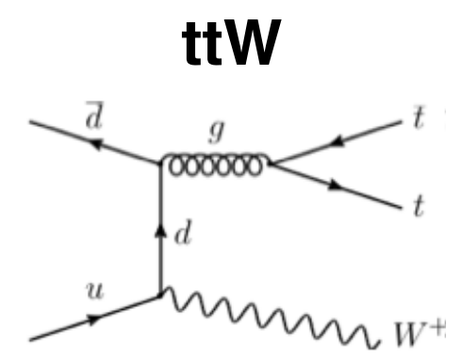
(3.7%)

- **Run2**: ramping up towards new era in precision
  - Differential cross sections
  - Properties



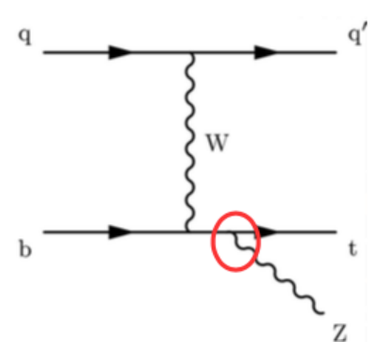


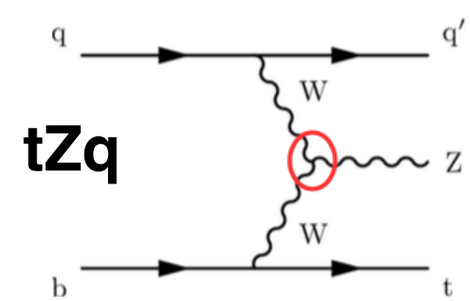


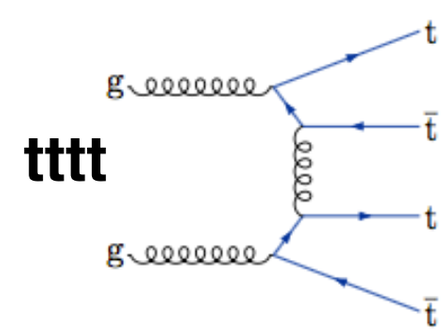


top production + “friends”

- Very low production cross sections O(fb)
- Need multivariate analysis techniques to maximize sensitivity



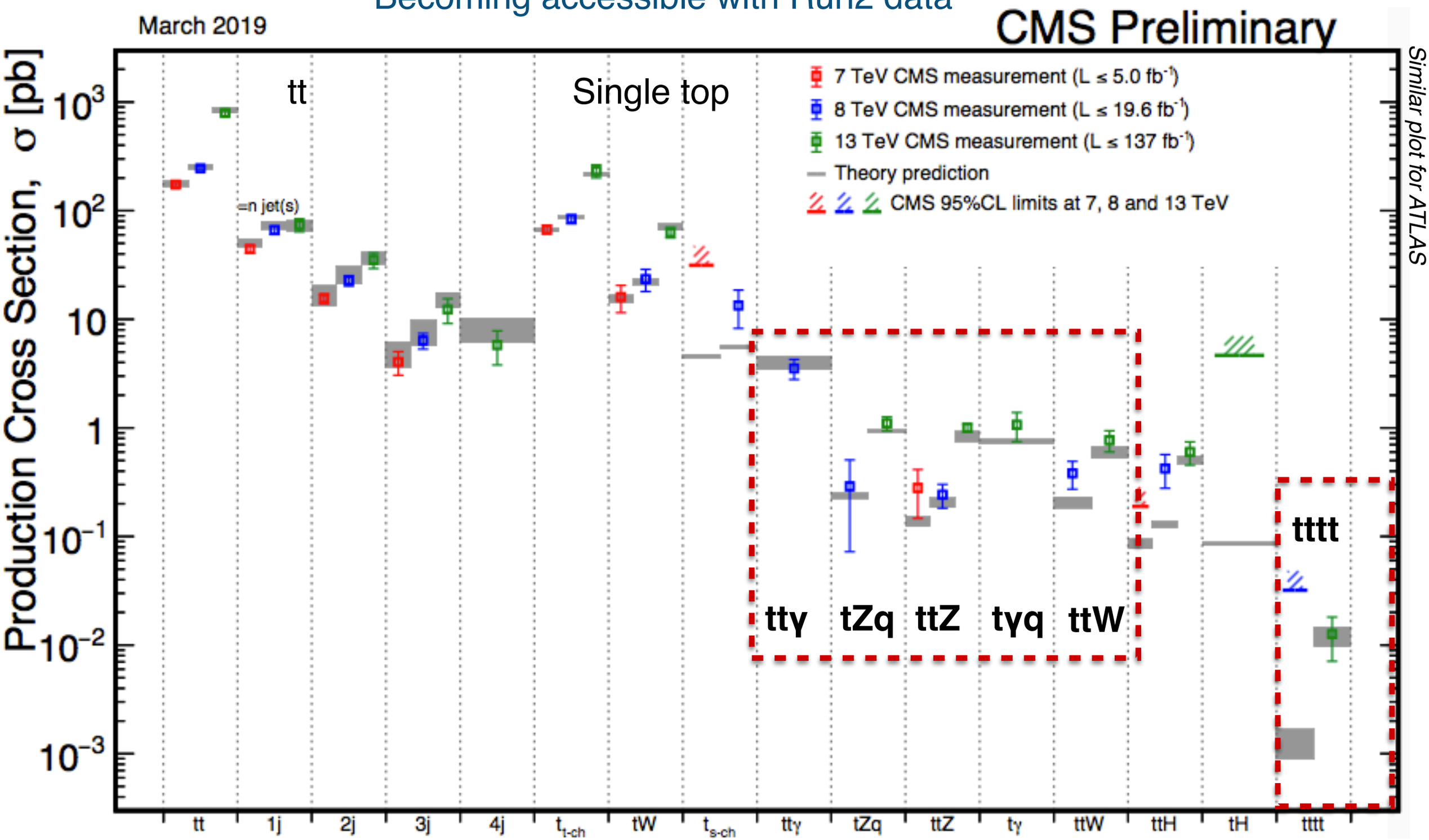




→ More in parallel talk by D. Dobur

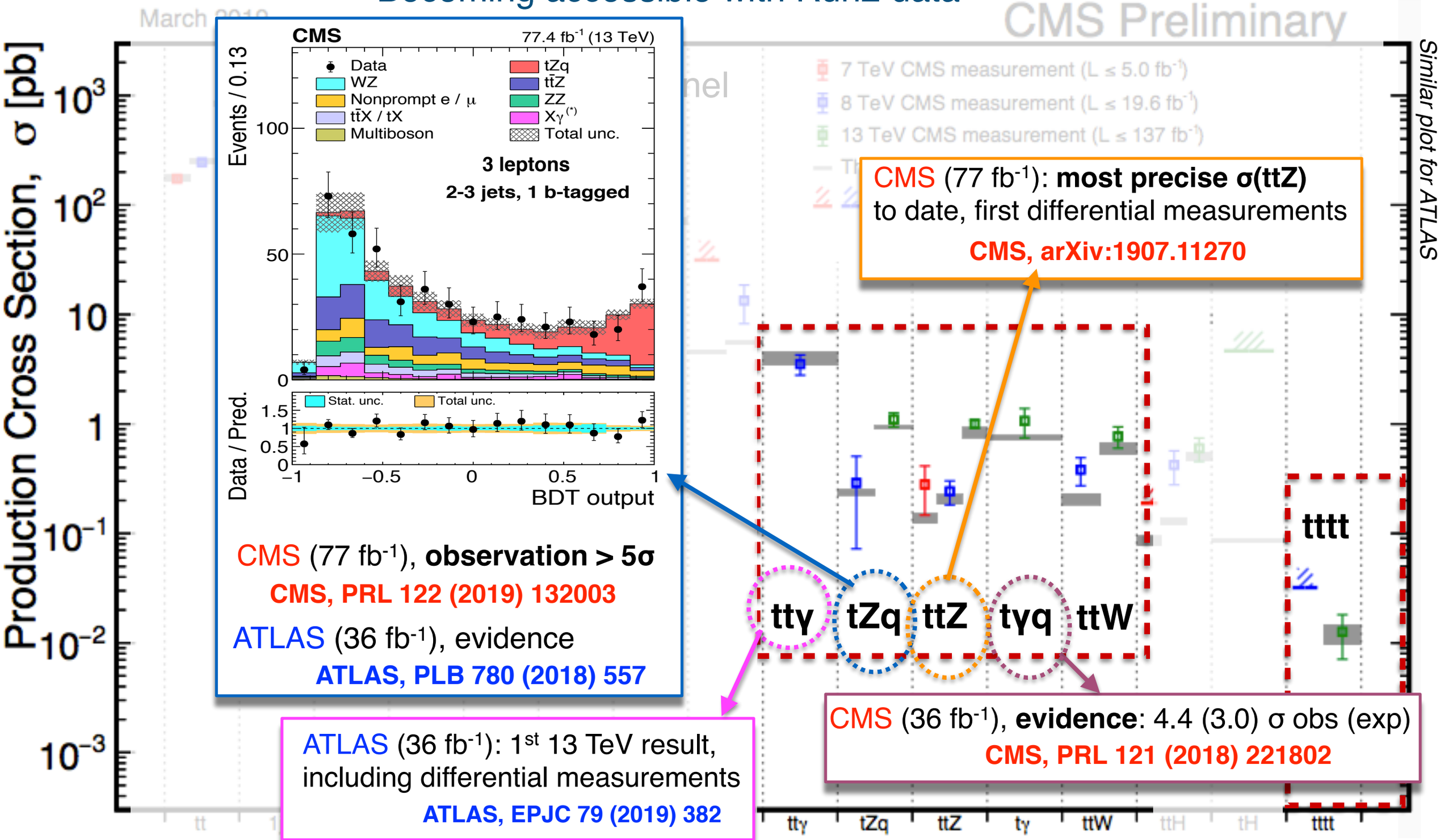
Top+X production in a nutshell

Becoming accessible with Run2 data



Top+X production in a nutshell

Becoming accessible with Run2 data



Top+X production in a nutshell

Very rare, **not yet observed**:
σ(tttt) ~ 12 fb^{-1} (NLO+EW)

Sensitive to BSM, direct access to top-Higgs Yukawa coupling

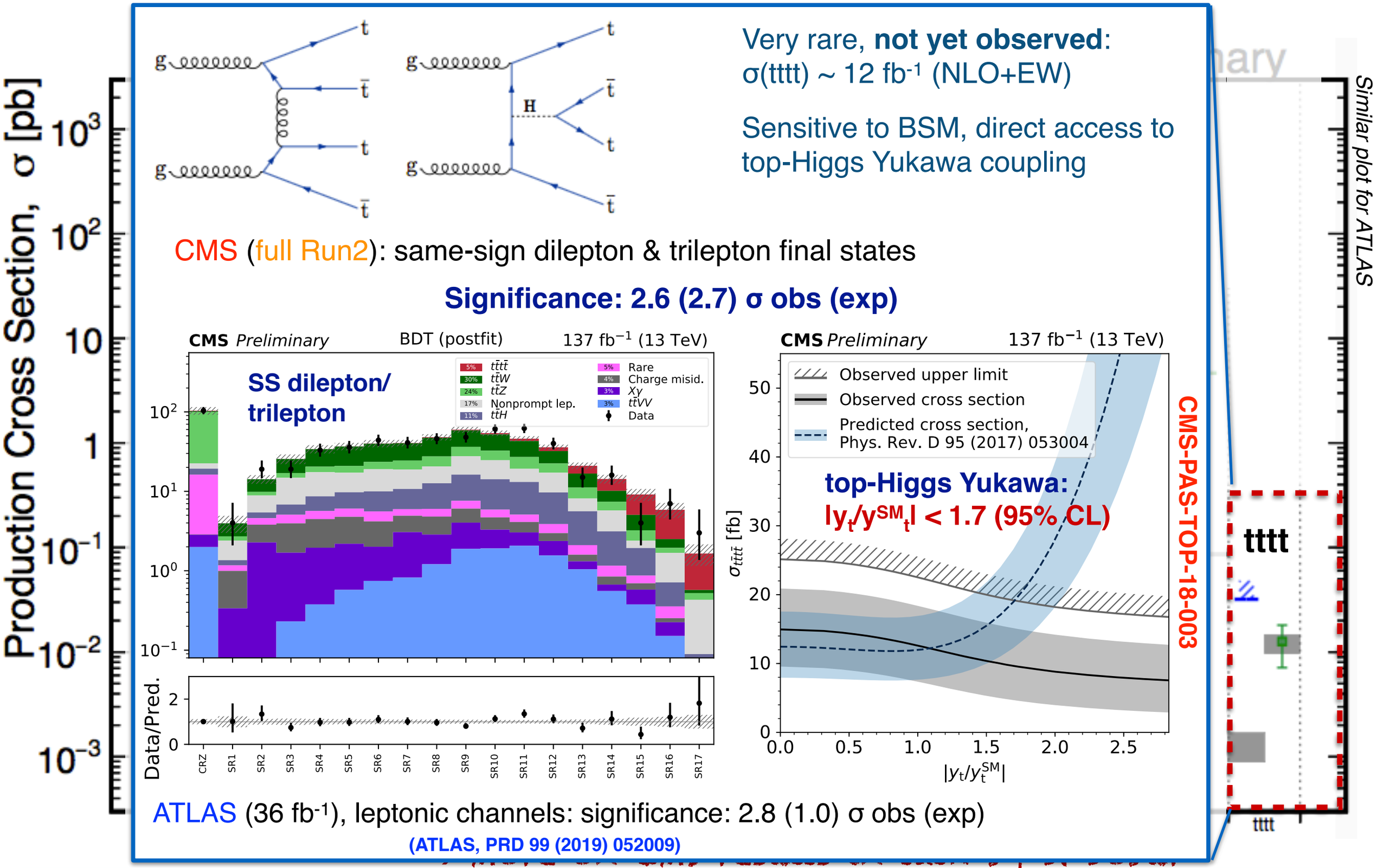
CMS (full Run2): same-sign dilepton & trilepton final states

Significance: 2.6 (2.7) σ obs (exp)

CMS-PAS-TOP-18-003

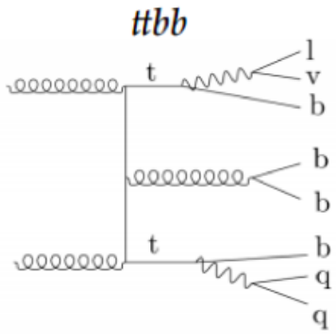
ATLAS (36 fb^{-1}), leptonic channels: significance: 2.8 (1.0) σ obs (exp)

(ATLAS, PRD 99 (2019) 052009)

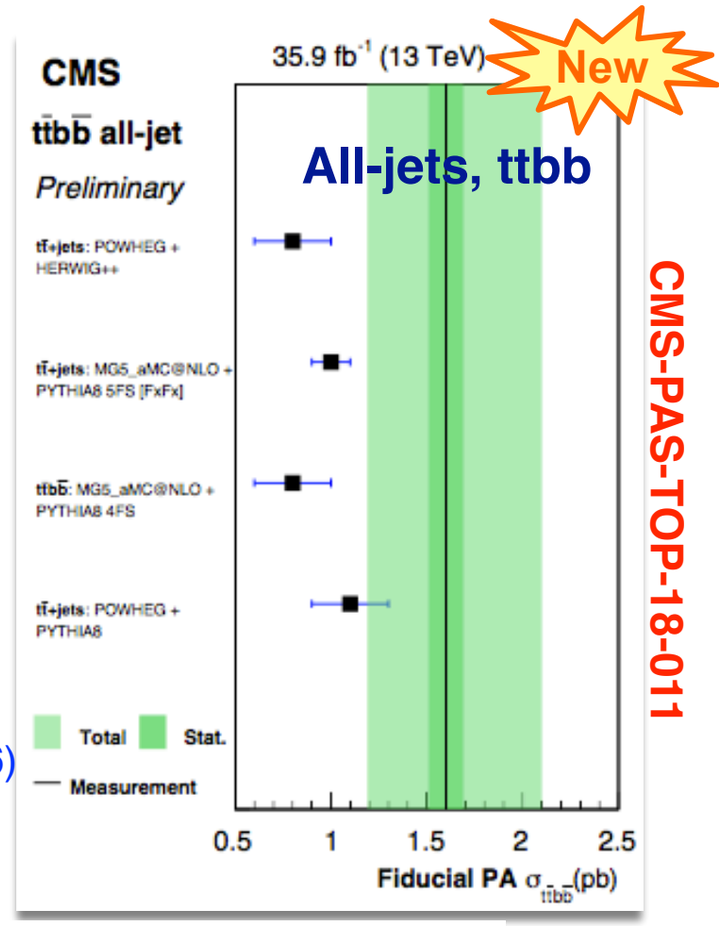


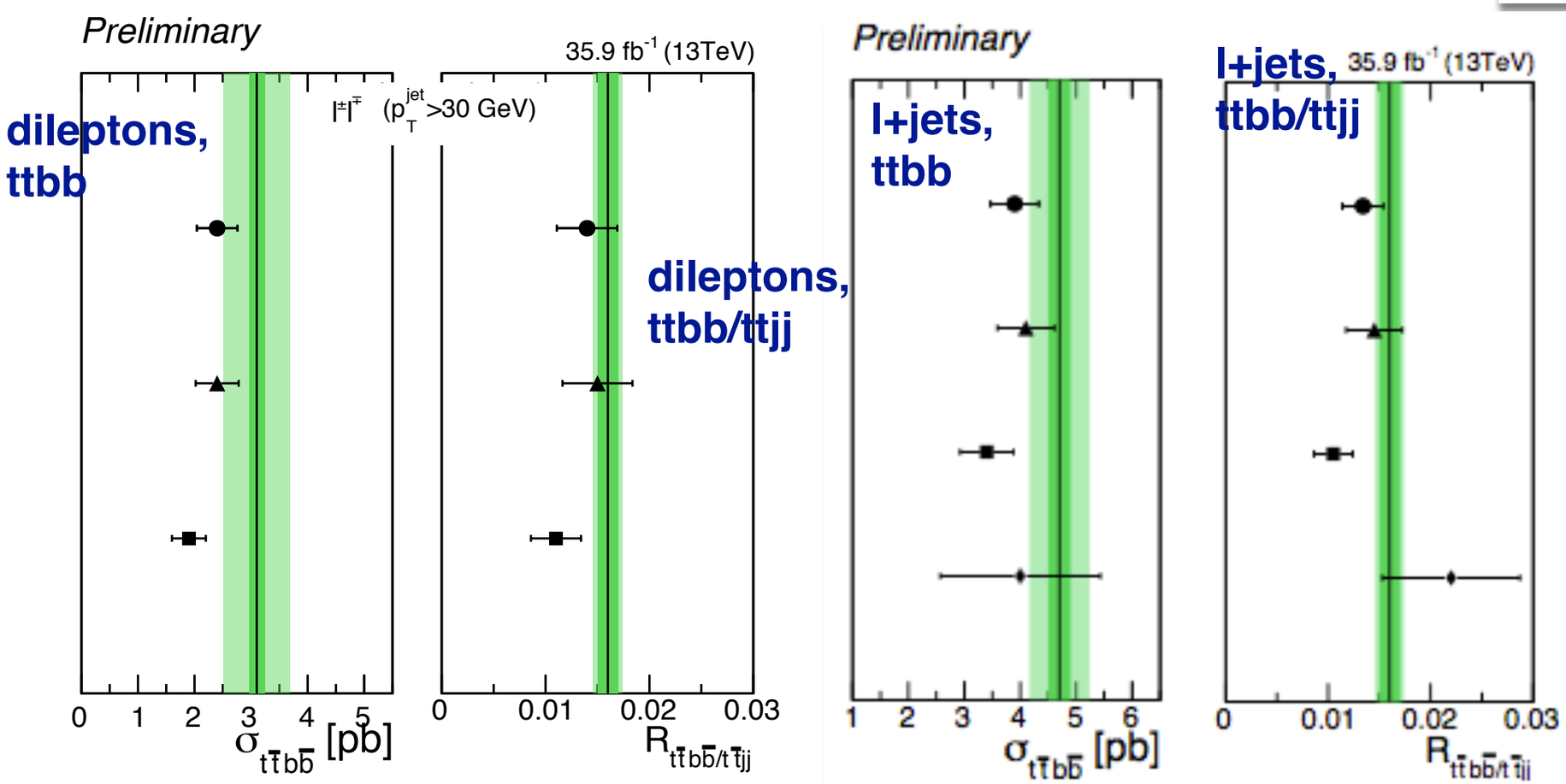
tt+bb production

Major background for tt+H(bb) (irreducible) and tttt

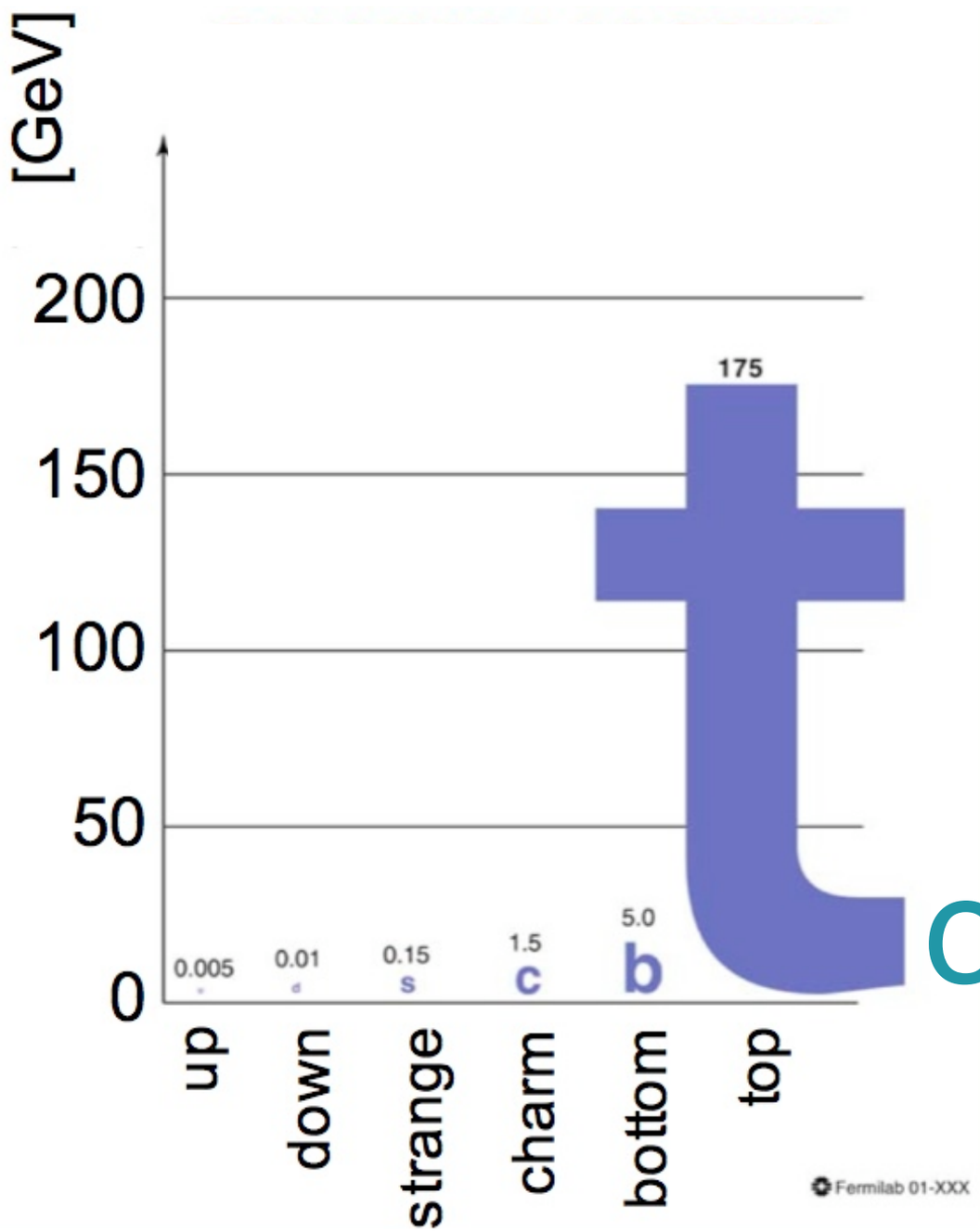


- Challenging to model: complex final state, very different scales (tt, bb)
- CMS: new dilepton & l+jets, all-jets
- Different phase spaces, comparison to NLO MC simulations
- in general, σ(ttbb) slightly higher in data, also for ATLAS (JHEP 04 (2019) 046)
- Improved precision will have an impact on upcoming ttH(bb) results





top properties



Top quark mass

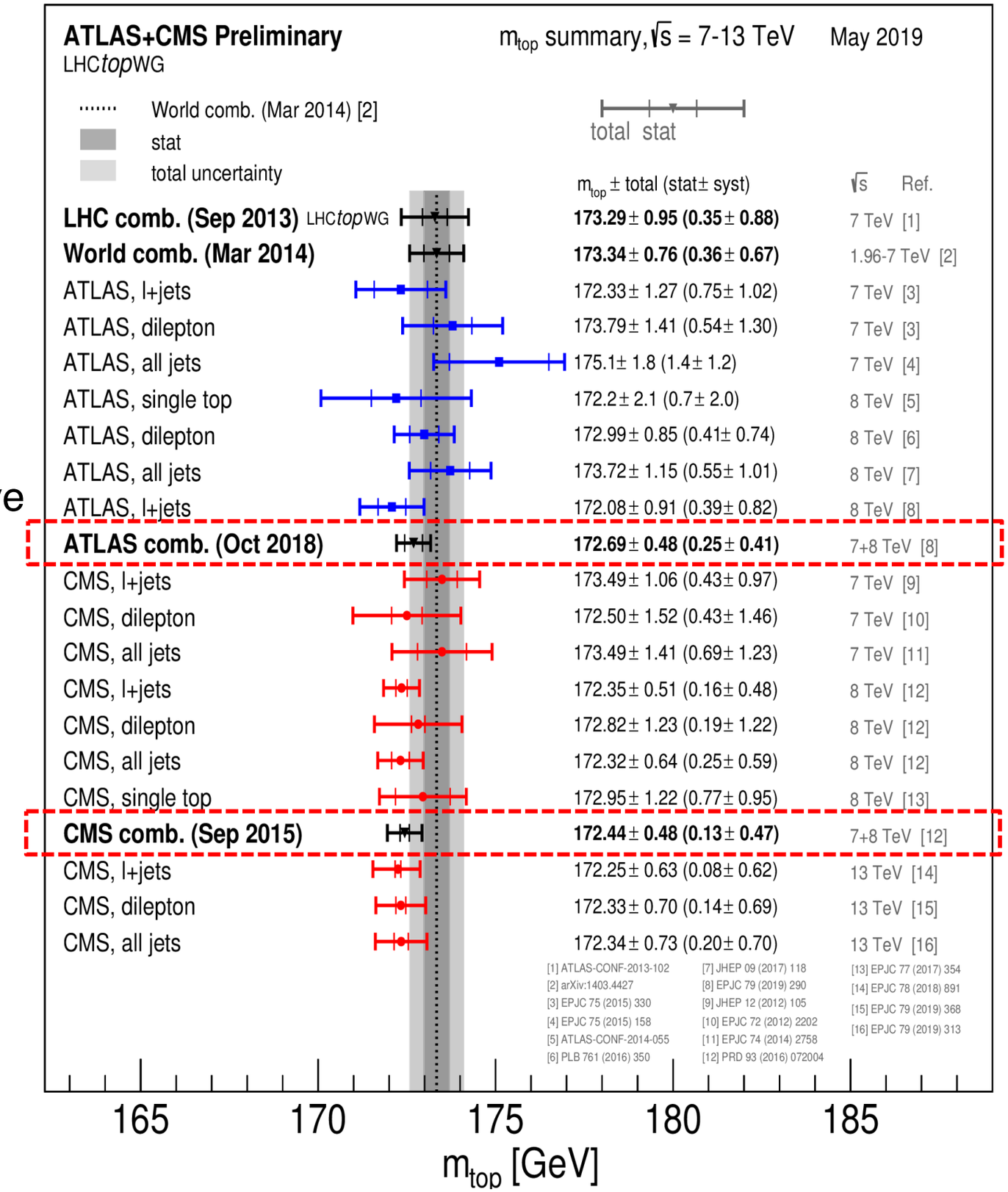
Fundamental parameter in the SM,
not an observable → scheme-dependent

- **"Direct" measurements**: from reconstructed top decay products —> MC mass m_t^{MC} (mass as defined in the MC)
  - Highest sensitivity, reaching **precision below 500 MeV (< 0.3%)**
- **"Indirect" measurements**: from fit to sensitive observable (e.g tt cross section) + theory

  —> top mass in a well-defined scheme (e.g. m_t^{pole}, $m_t(m_t)$)
- Difference between m_t^{MC} and m_t^{pole} estimated to be ~ few hundred MeV to 1 GeV

Need to measure the top mass in all possible ways with the highest possible precision

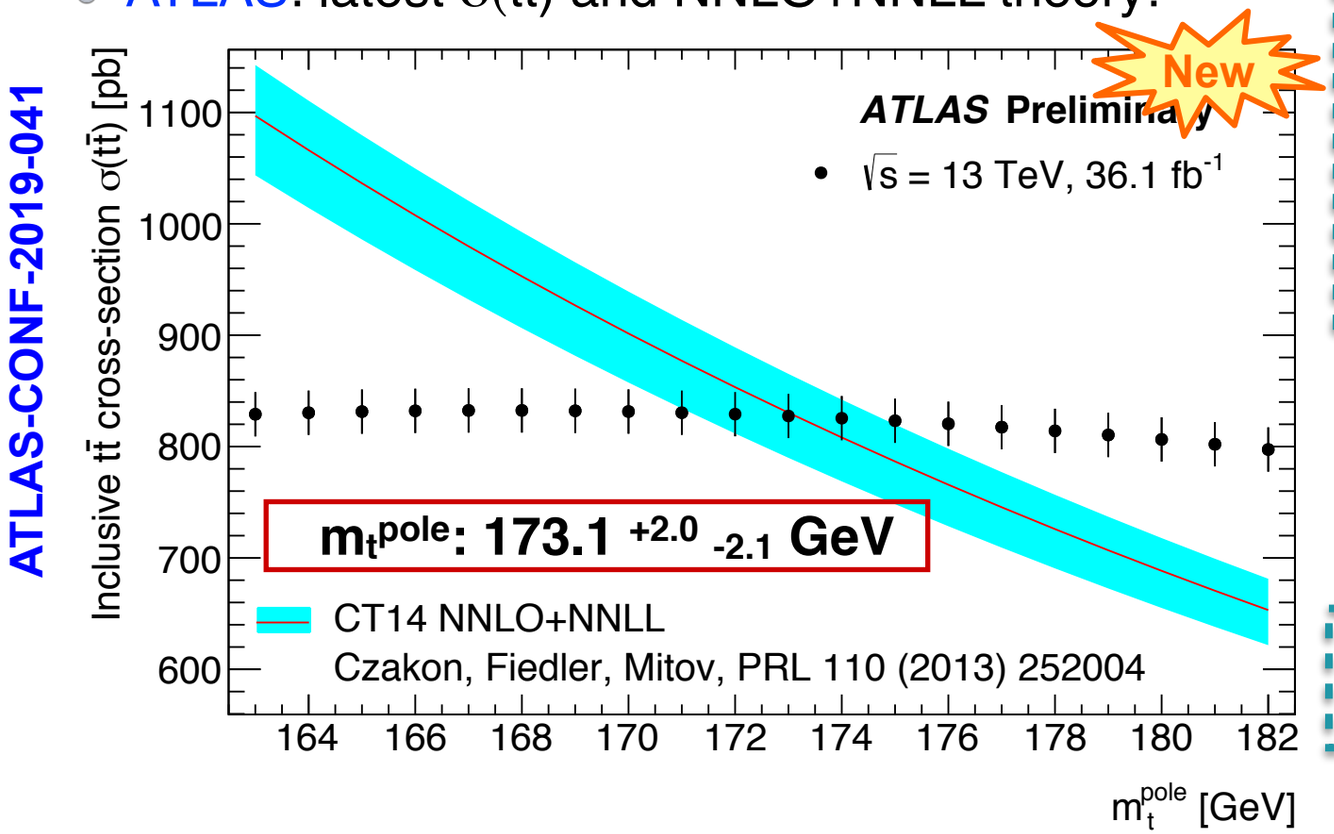
"Direct" measurements



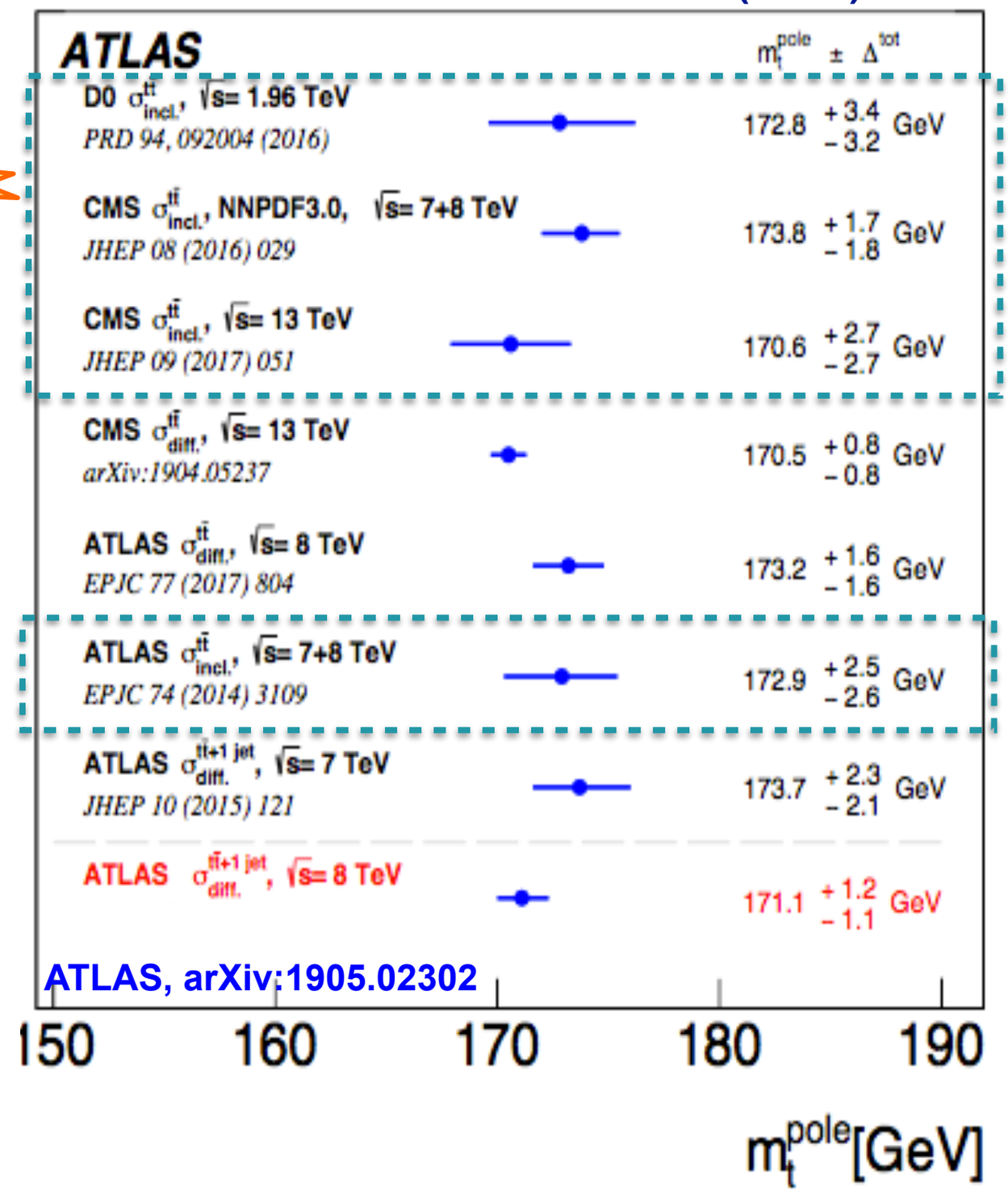
Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining m_t from measured $\sigma(tt)$

- **Inclusive cross sections:**
  - ATLAS: latest $\sigma(tt)$ and NNLO+NNLL theory:



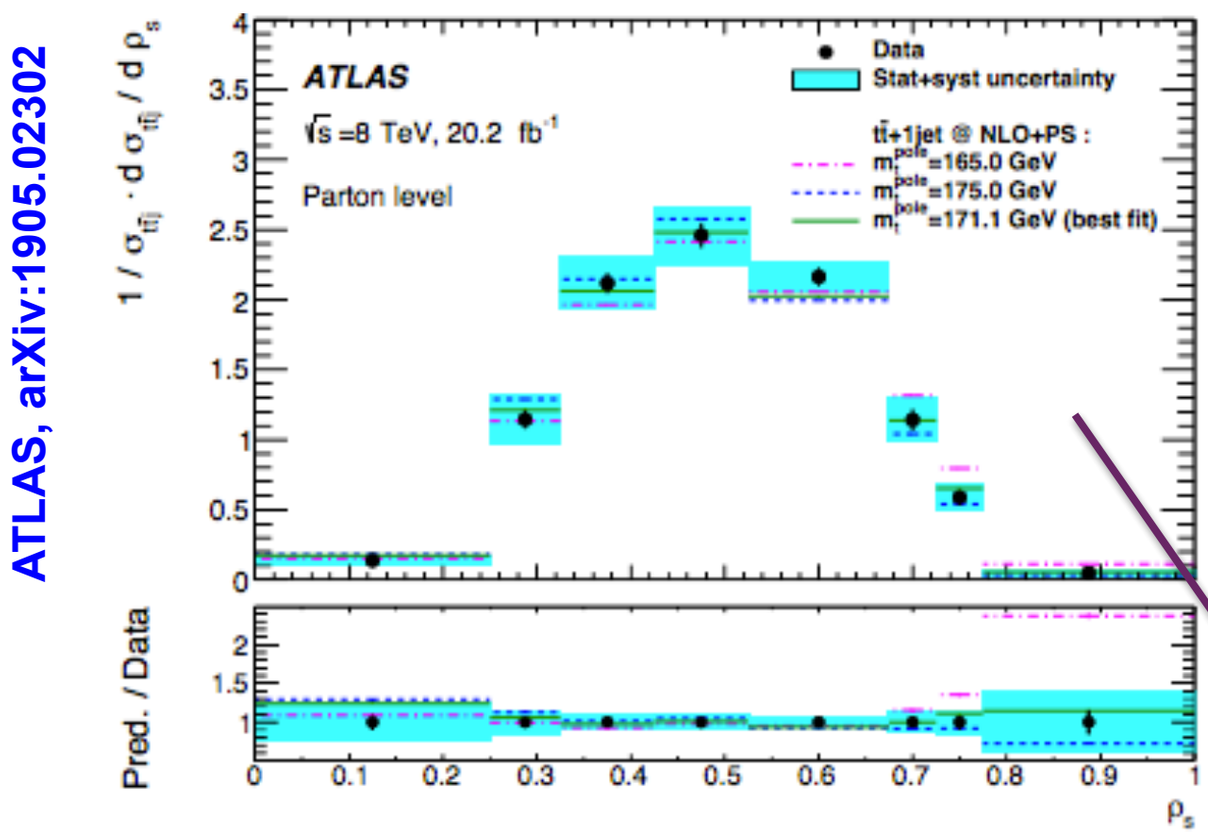
“Indirect” measurements (m_t^{pole})



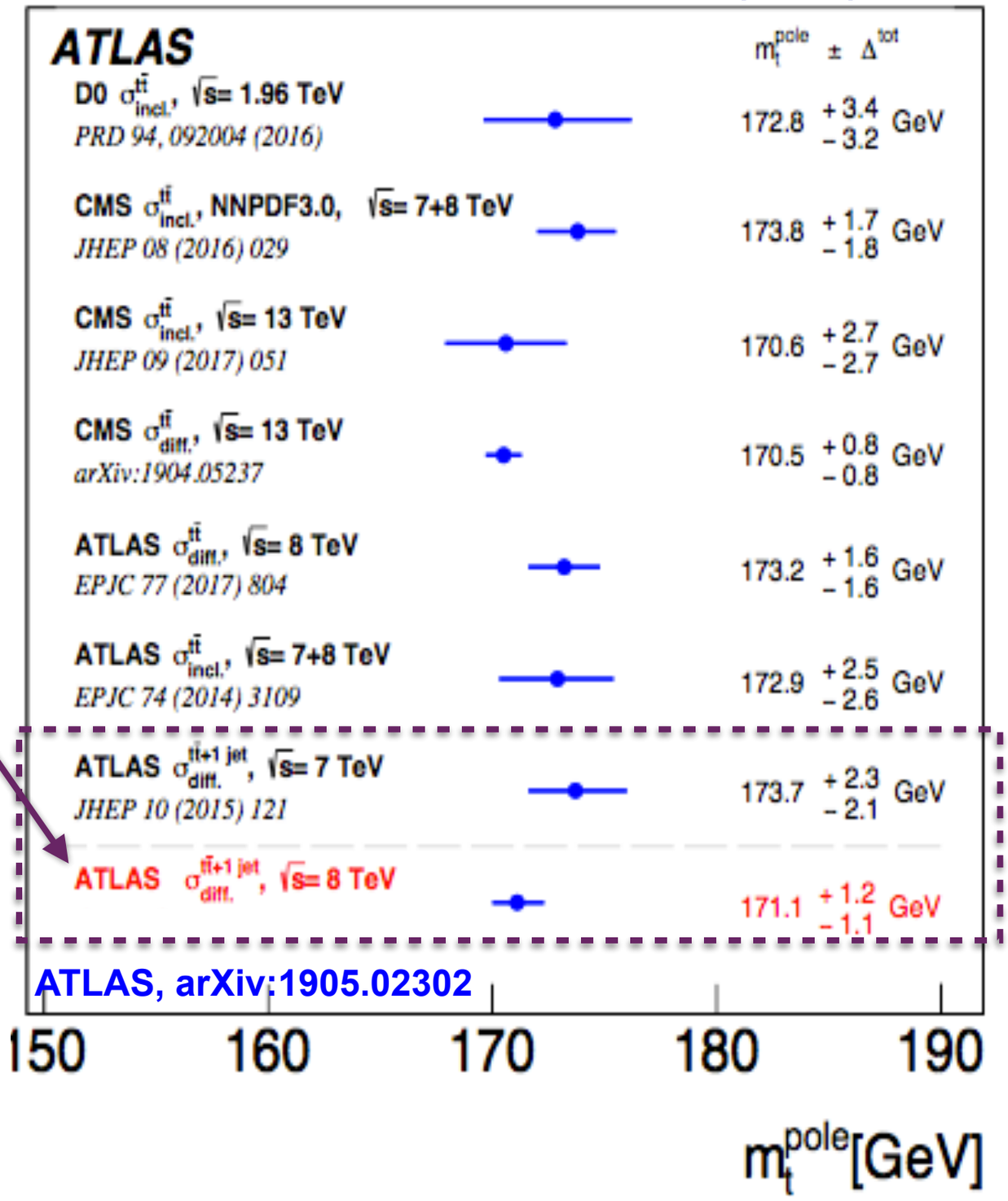
Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining m_t from measured $\sigma(tt)$

- **1D differential cross sections:**
  - ATLAS: Differential σ(tt+1jet) and NLO+PS:



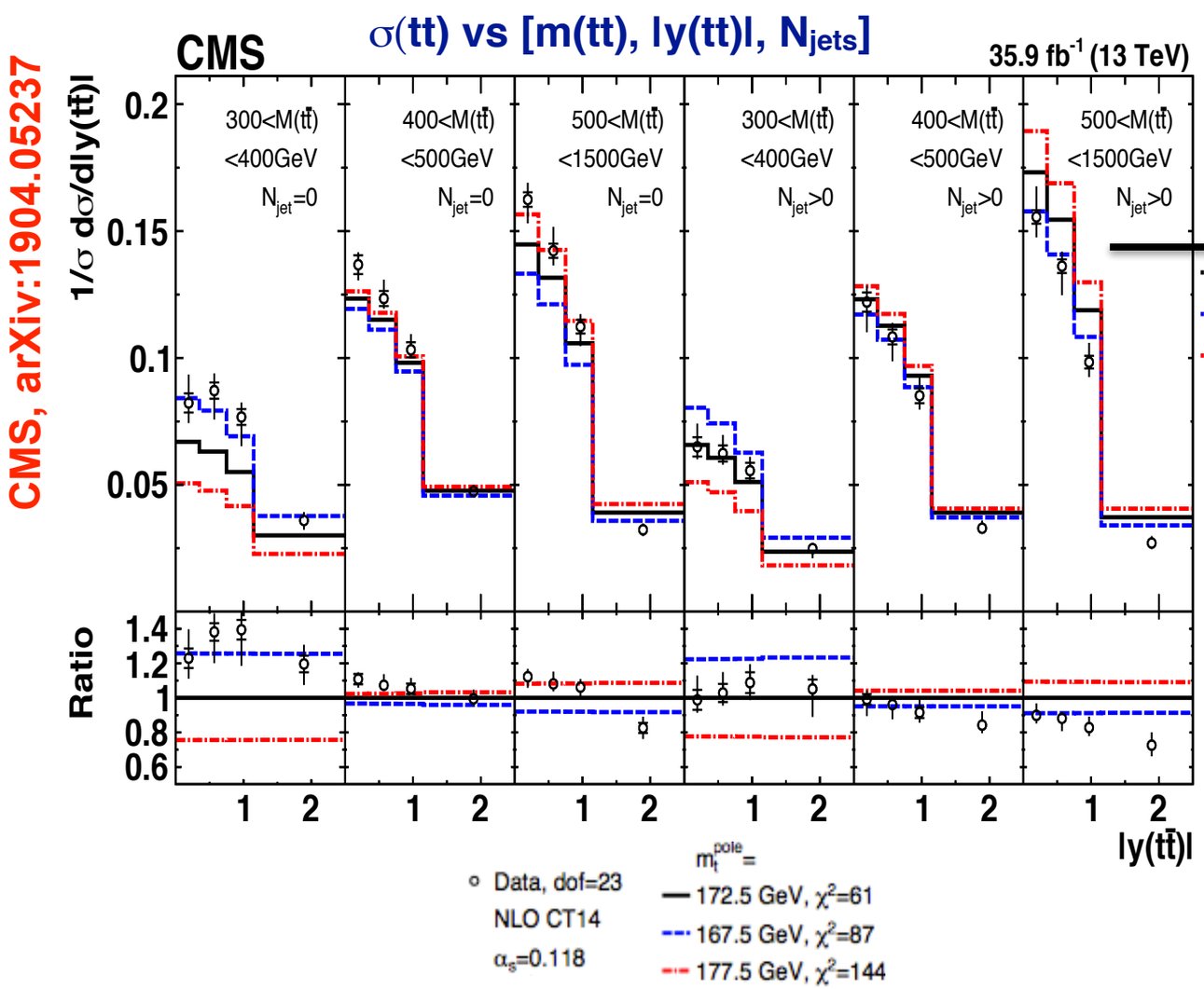
“Indirect” measurements (m_t^{pole})



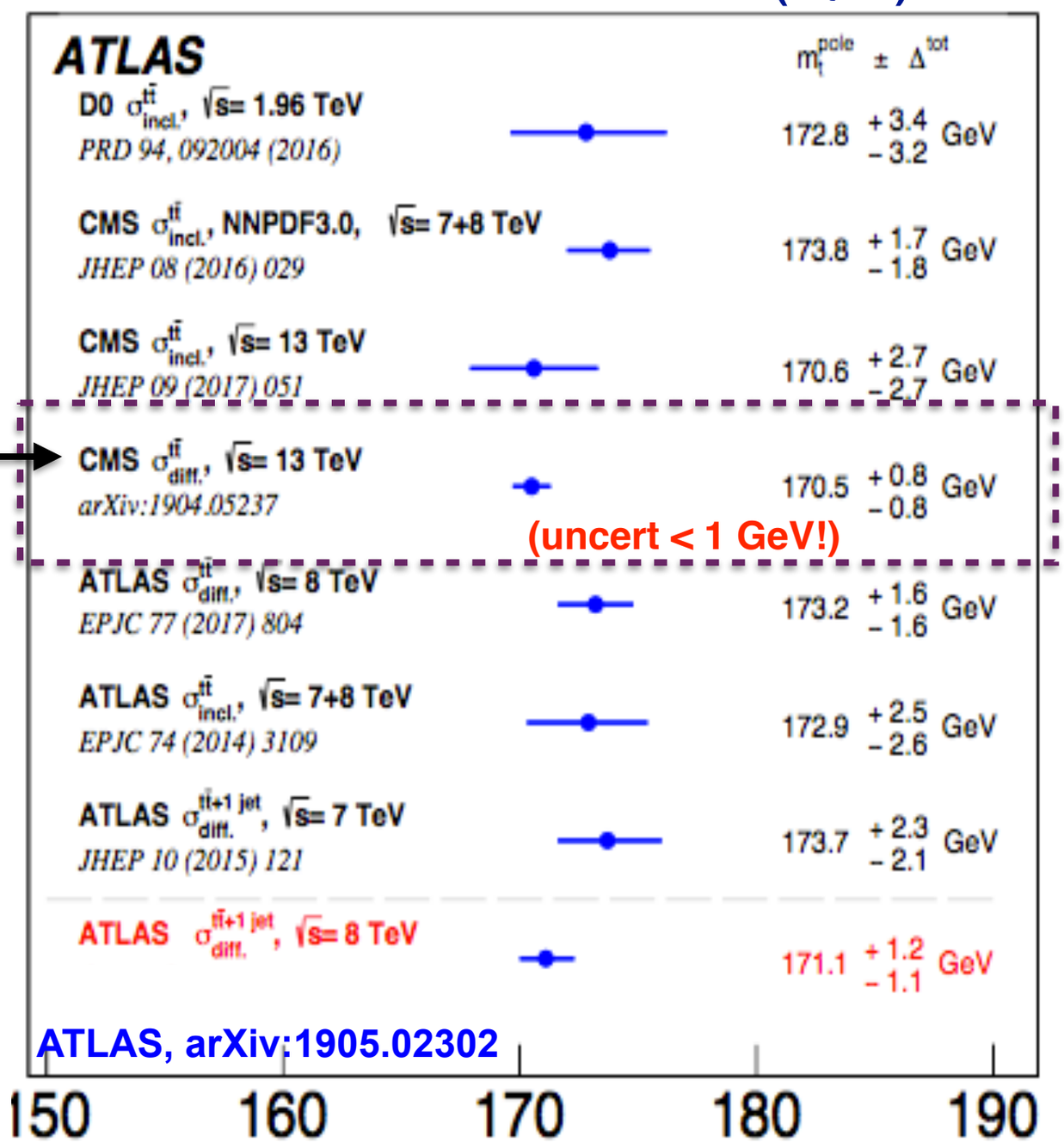
Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining m_t from measured $\sigma(tt)$

- **Multidifferential cross sections:**
  - CMS: Simultaneous fit of m_t^{pole}, α_s, PDF using 3D differential $\sigma(tt)$ and NLO theory:



“Indirect” measurements (m_t^{pole})



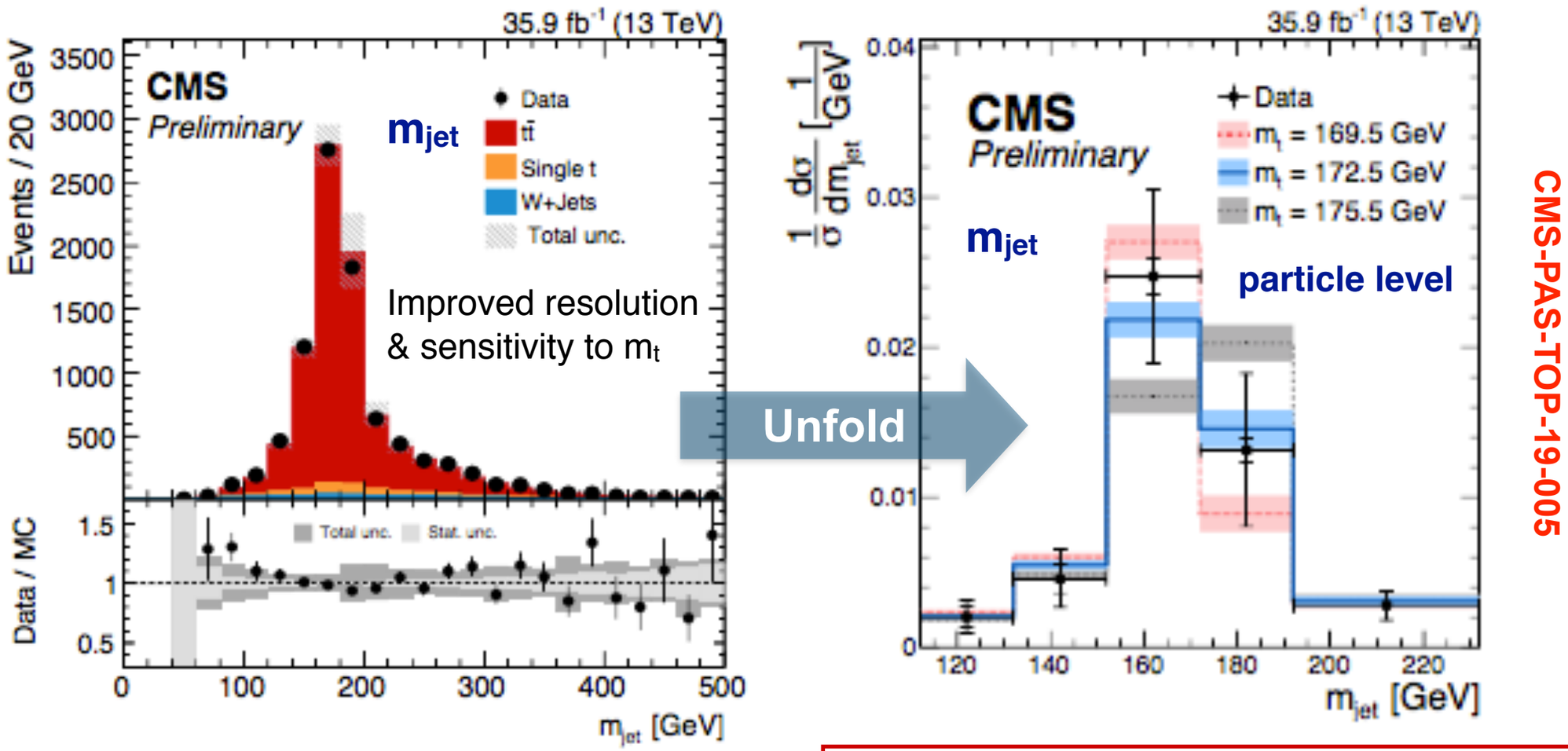
Top pole mass measurements entering the sub-GeV precision!

Top mass from boosted jets

New

Towards understanding better the ambiguities between m_t^{MC} and m_t^{pole}

- Highly boosted top quarks (p_T > 400 GeV) in l+jets events:
  a single jet includes all top decay products: $t \to bW \to bq\bar{q}'$
- CMS: measure m_{top} from boosted jet mass (m_{jet}) observable —> can be calculated analytically
  - Use novel XCone jet algorithm (JHEP 11 (2015) 072): reconstruct large jets and 3 subjets per jet



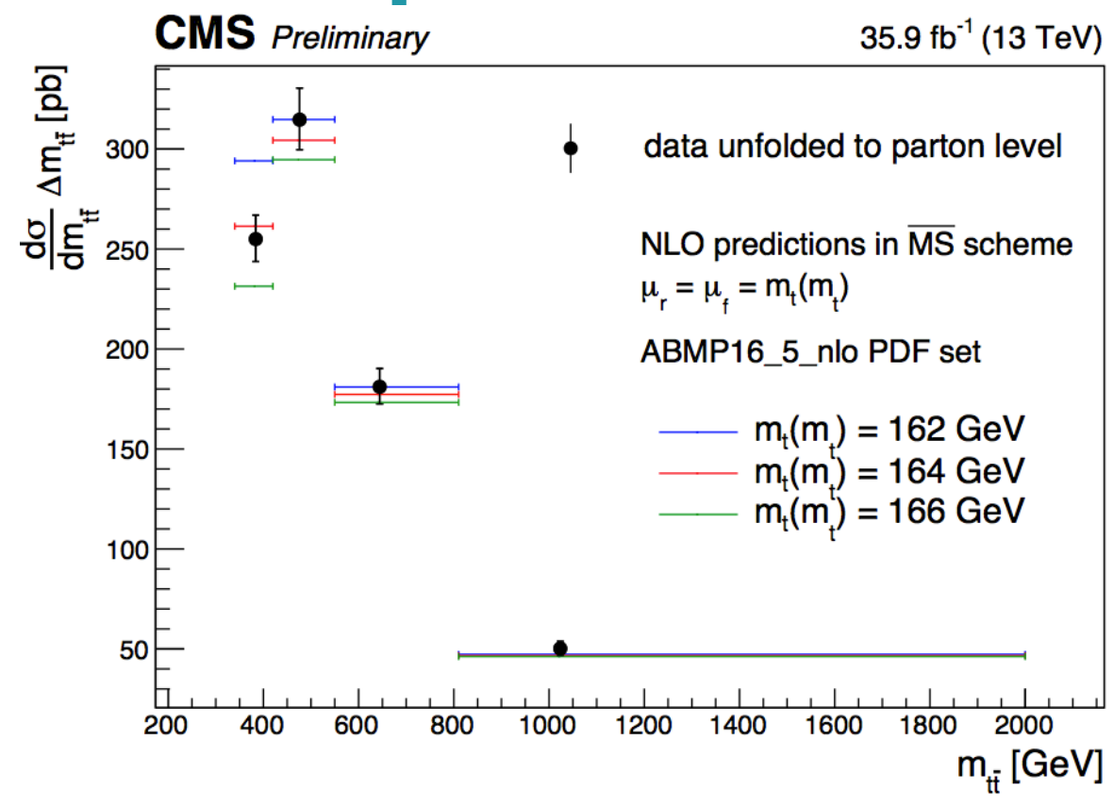
- Top mass from m_{jet} differential cross section: $m_t = 172.56 \pm 0.41\ (stat) \pm 2.44\ (syst)$ GeV **(1.4%)**

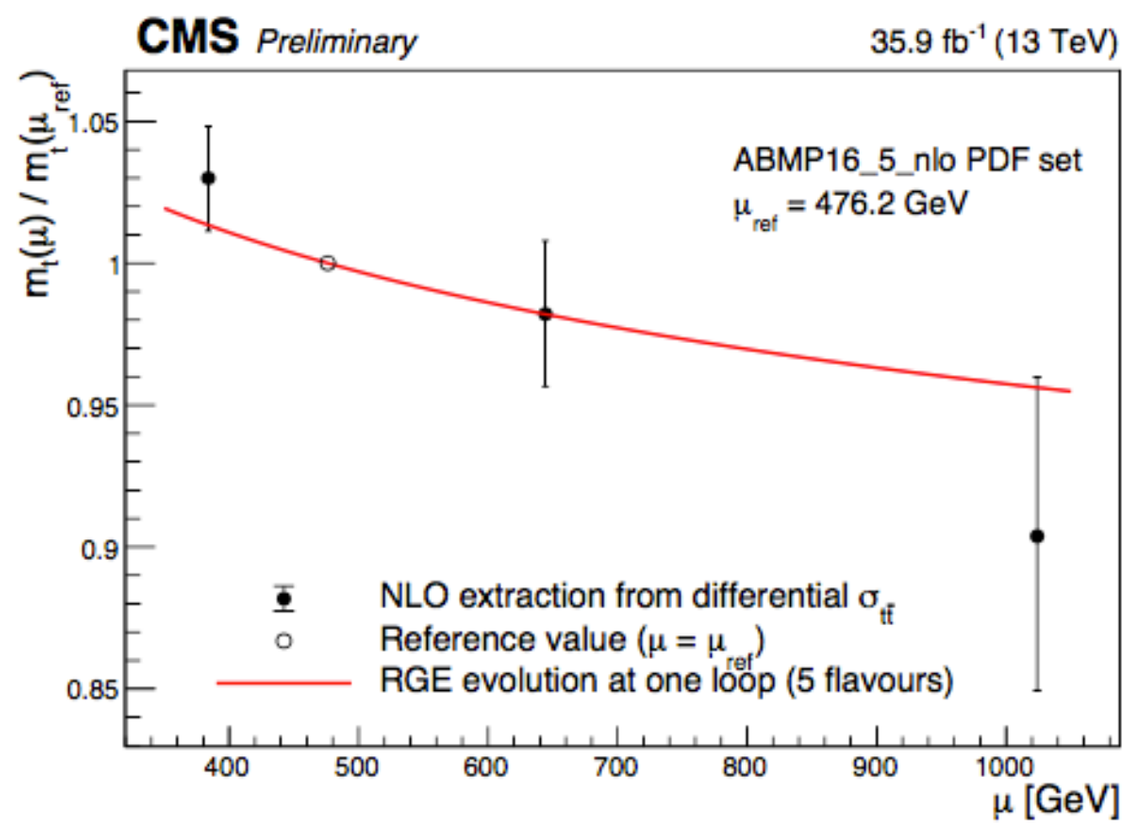
The running of the top mass

New

First measurement of the scale dependence ("running") of the top quark mass in the MSbar scheme

- CMS: extract the running mass $m_t(\mu)$ at NLO from differential σ(tt) as a function of m(tt) using eμ events
  - dσ(tt)/dm(tt): measured at parton level via fit to multidifferential distributions
    - Experimental dependence on m_t^{MC} taken into account in the fit
  - To determine the running of $m_t(\mu)$, the top mass is extracted in bins of m(tt) by comparing to NLO predictions
  - Extracted running compatible with scale dependence predicted by RGE at 1-loop precision within 1.3 s.d.





CMS-PAS-TOP-19-007

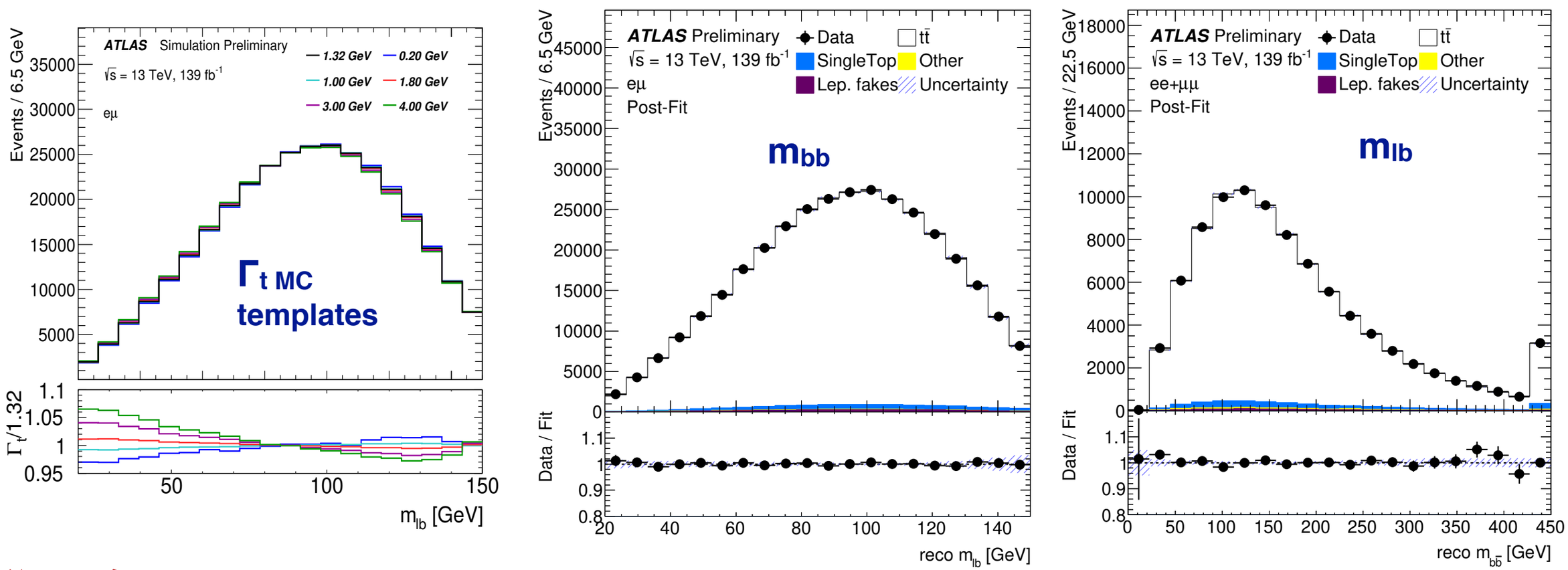
Top decay width

New

Deviations from the expected top decay width can be a sign of non-SM top couplings

- ATLAS (full Run2): Direct measurement of the top decay width Γ_t in dilepton events
- Compare data to MC templates with different Γ_t assumptions
  - Use an observable in $e\mu$ events that partially reconstructs the top kinematics: m_{lb}
  - Constrain main systematics by fitting simultaneously to m_{bb} in ee, $\mu\mu$ events

ATLAS-CONF-2019-038



→ More in parallel talk by T. Dado

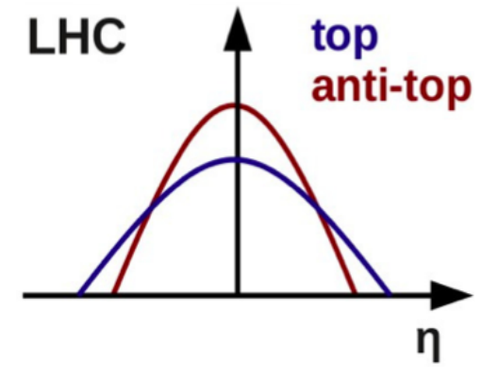
For m_t = 172.5 GeV: $\Gamma_t = 1.9 \pm 0.5$ GeV

NNLO Γ_t = 1.322 GeV, < 1% uncert

tt charge asymmetry

New

Top-pair angular asymmetries may indicate BSM top production interfering with SM



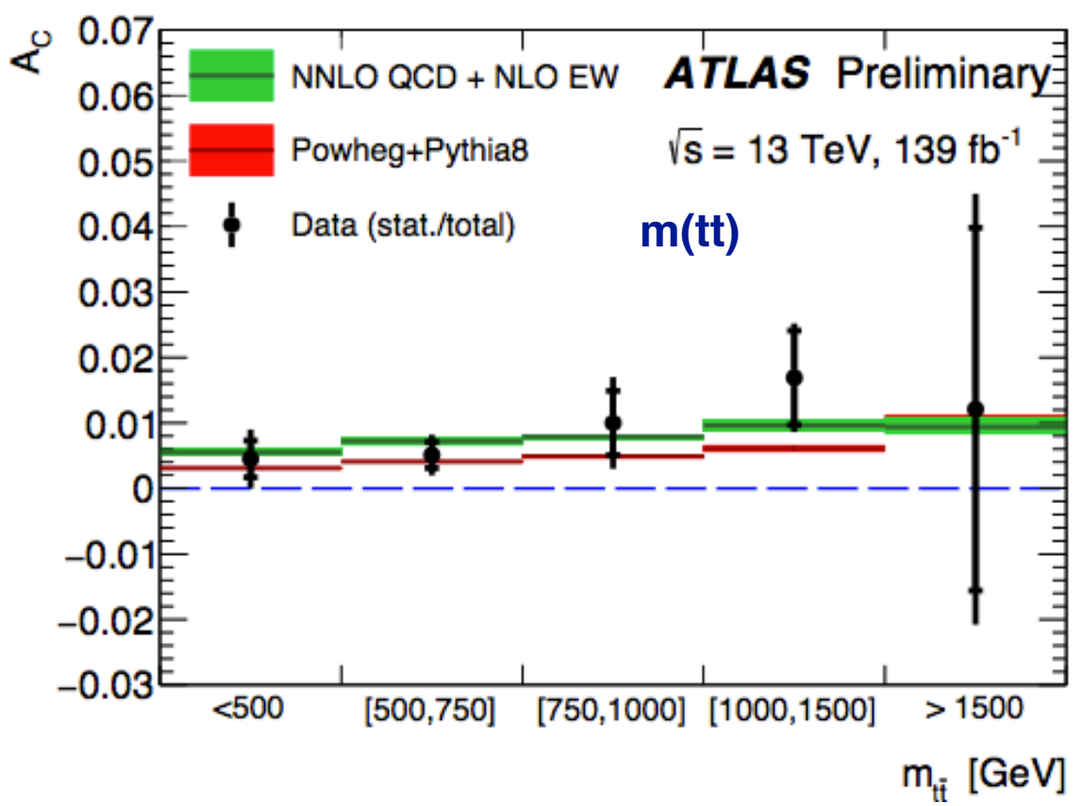
top is more forward than antitop

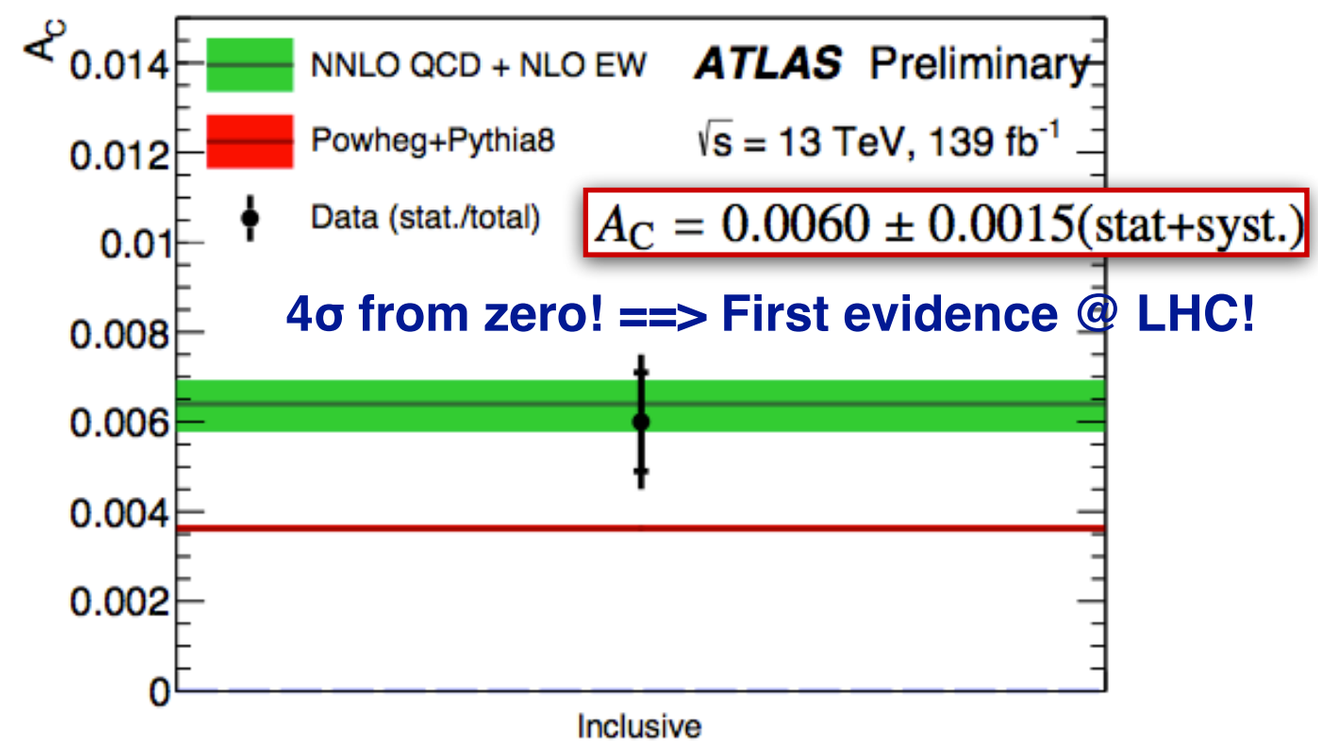
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

- NLO effect originating from interference of qq—>tt diagrams, can be enhanced by BSM physics
- Several results in Run1, in agreement with SM but also compatible with zero
- ATLAS (full Run2) l+jets: inclusively and differentially in regions of phase space where Ac can be enhanced, including the boosted regime

$\Delta|y| = |y_{top}| - |y_{antitop}|$

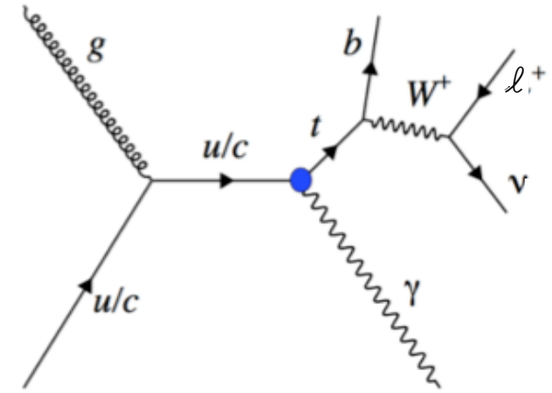
ATLAS-CONF-2019-026





- Good agreement with NNLO (QCD) + NLO (EW) calculations

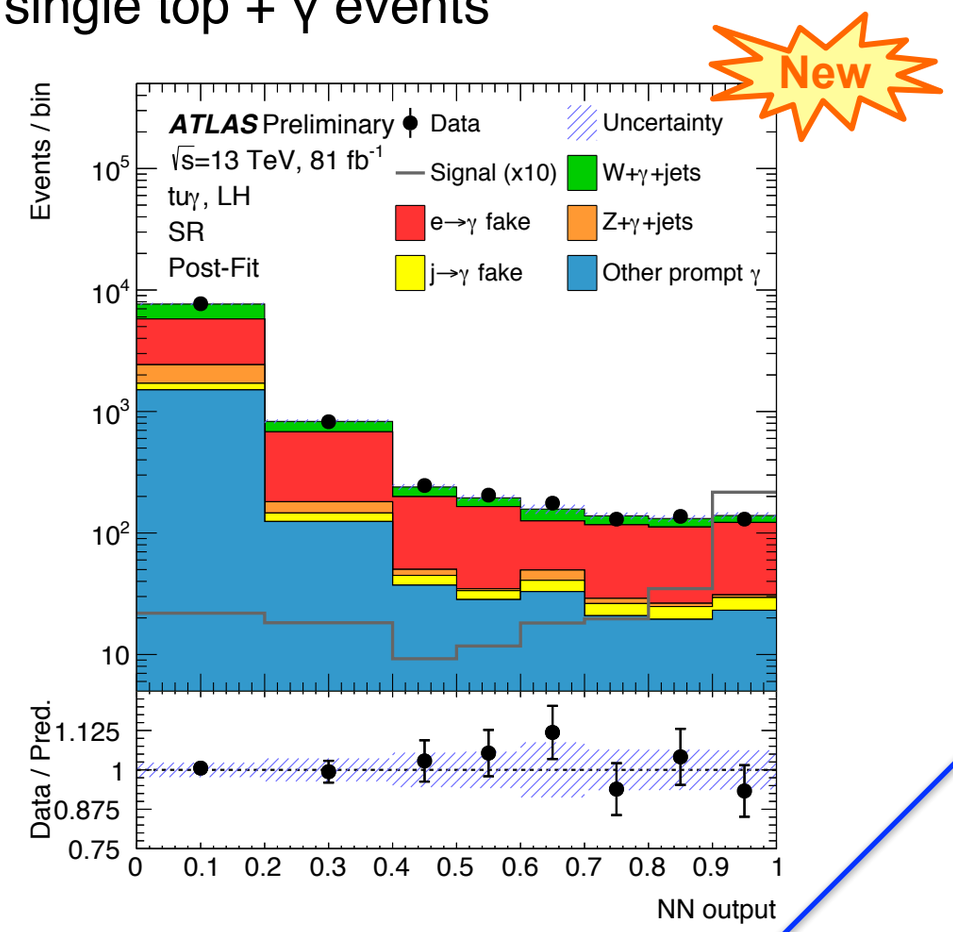
FCNC searches



Flavour Changing Neutral Currents are highly suppressed in SM
—> enhancement is clear sign of BSM physics

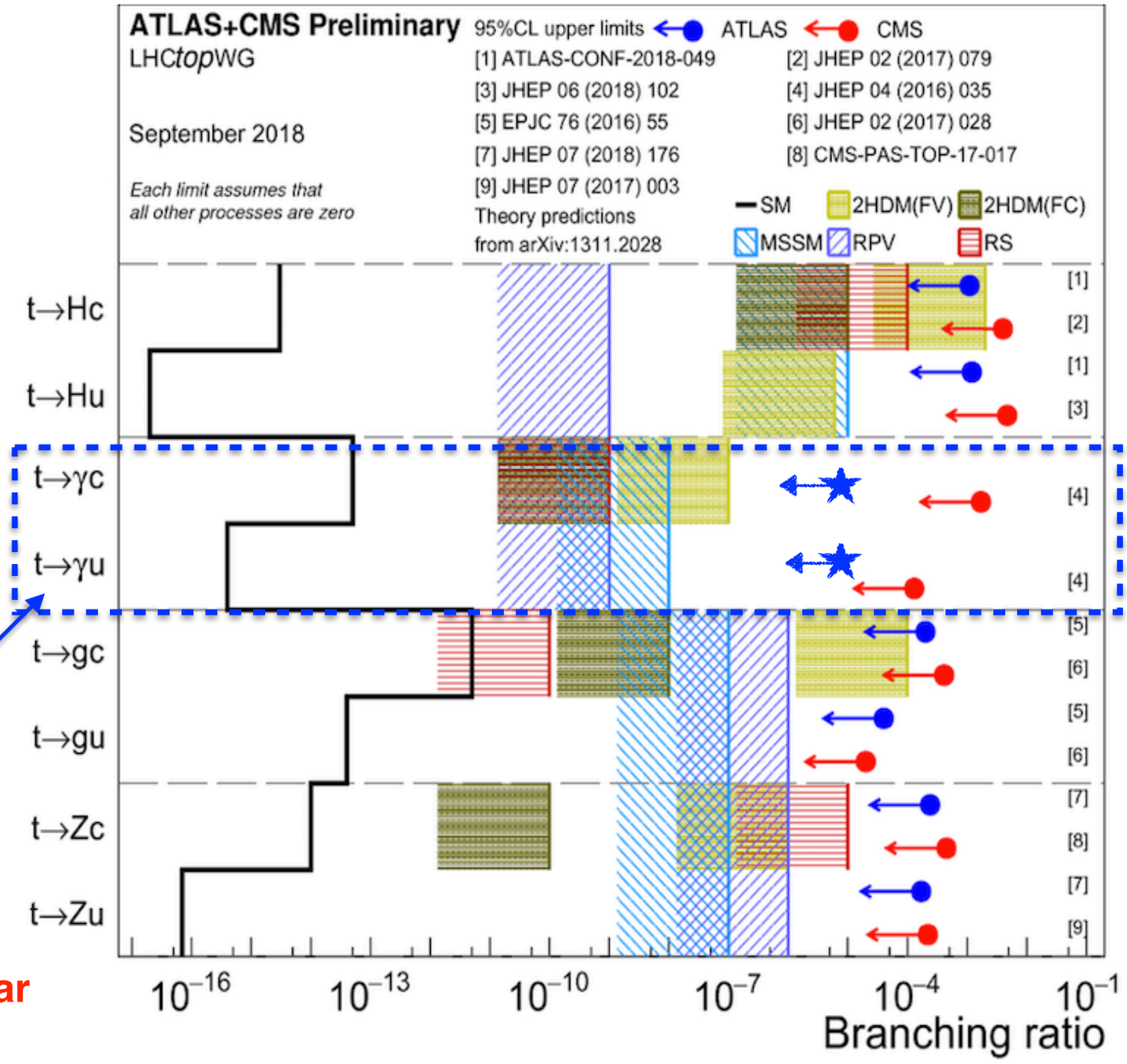
- ATLAS (81 fb^{-1}): Search for tqγ FCNC in single top + γ events

ATLAS, paper in preparation



- **B(t—>γc) < 22 x 10^{-5} obs**
  27 x 10^{-5} exp
- **B(t—>γu) < 2.8 x 10^{-5} obs**
  4.0 x 10^{-5} exp

Most stringent limits so far



Summary & Outlook

- **Top quark physics: key to QCD, electroweak, and BSM physics**
- **Very rich experimental programme at the LHC:**
  - **High precision top cross sections and properties**
  - **Rare processes becoming less rare — some even systematically limited !**
  - **A variety of BSM interpretations (e.g Effective Field Theory) starts to appear** (not covered today)
  - **Started to challenge theory predictions in many respects**

- **Full Run2: ~150 fb^{-1}:**
  ~ 120M tt pairs, ~ 30M single top, ~ 120K ttZ, tZ events
  - **Trade-off statistics for systematics**
  - **Access to new physics in the top environment**
  - **Improvements in MC models and theoretical calculations**

The ultimate potential for top quark physics is ahead of us

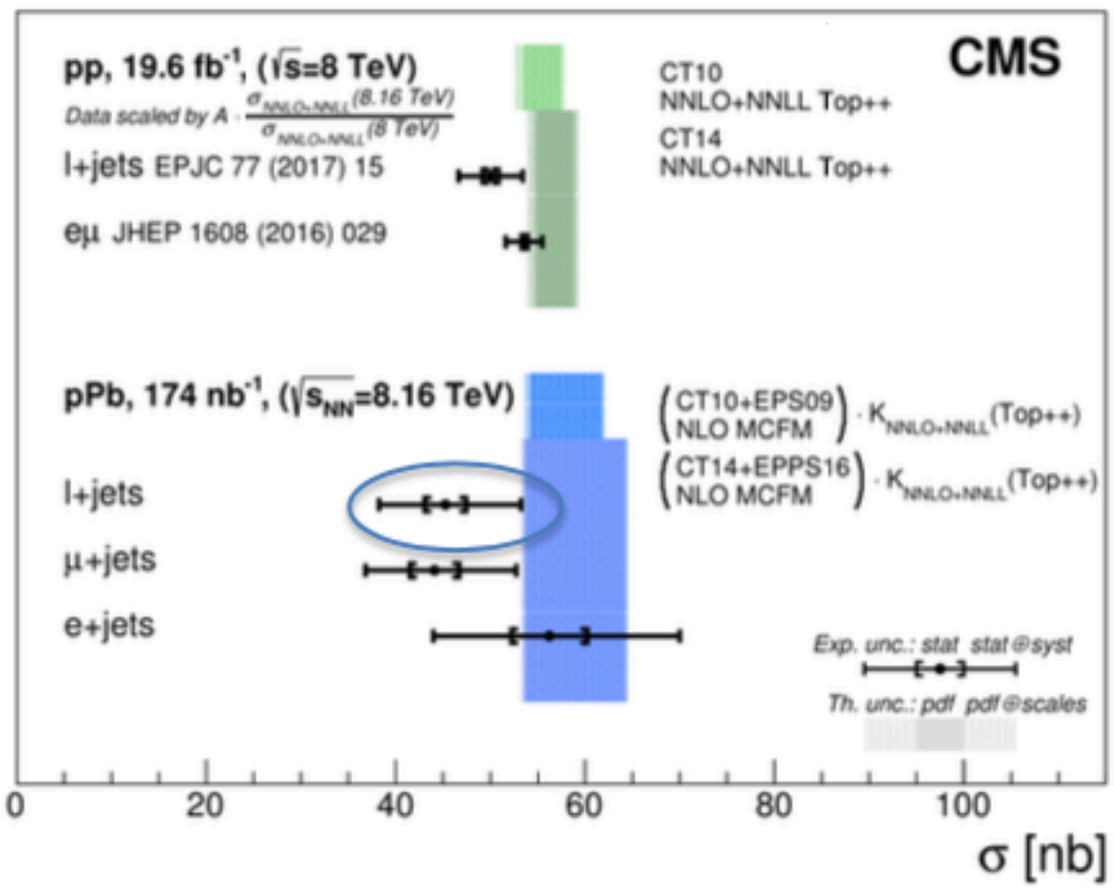
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

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

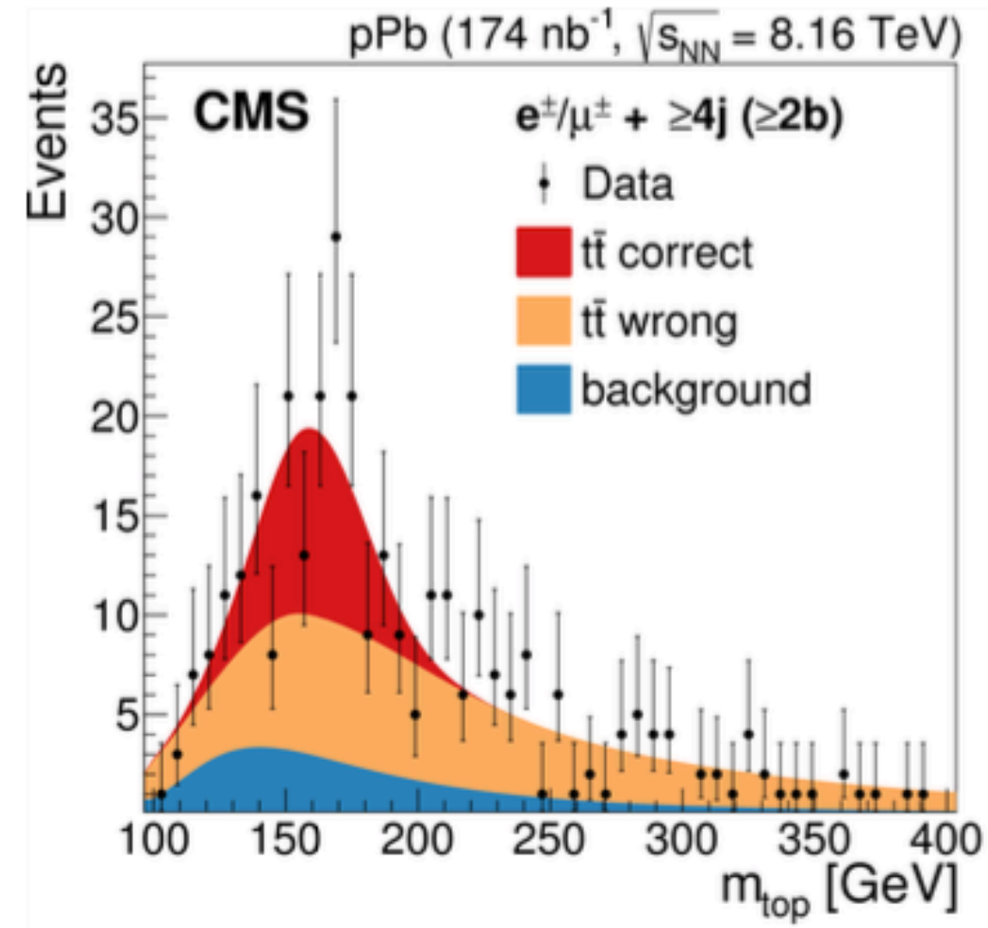
Additional information

tt in proton-nucleus (Pb) collisions

First observation at $\sqrt{s}$=8.16TeV (2016)



Phys. Rev. Lett. 119 (2017) 242001



- Novel and theoretically precise probe of the nuclear gluon density at high virtualities
- Considering different event categories with 0, 1, ≥ 2 b-tagged jets
- $t\bar{t}$ cross section extracted from comb. unbinned max. likelihood fit of $m$jj' (W→ jj')

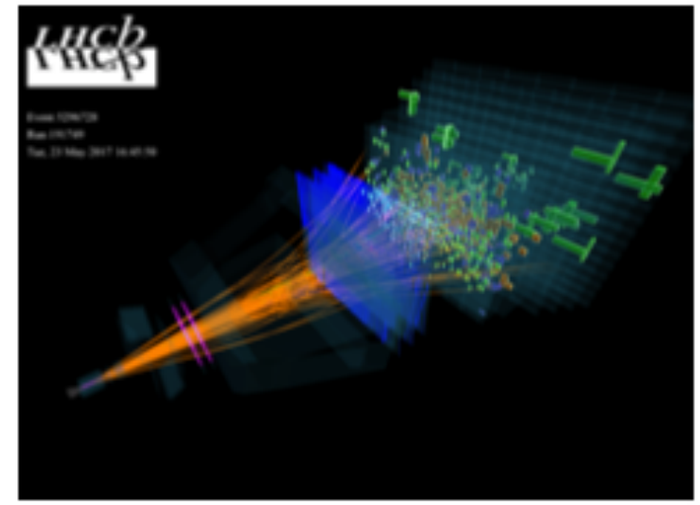
$$\sigma_{t\bar{t}}^{\mu+\text{jets}} = 44 \pm 3\,(\text{stat}) \pm 8\,(\text{syst})\,\text{nb},$$
$$\sigma_{t\bar{t}}^{e+\text{jets}} = 56 \pm 4\,(\text{stat}) \pm 13\,(\text{syst})\,\text{nb},$$

→ $\sigma_{t\bar{t}} = 45 \pm 8\ (total) nb$

J. Fernandez Menendez, LHCP2018

Latest top result from LHCb

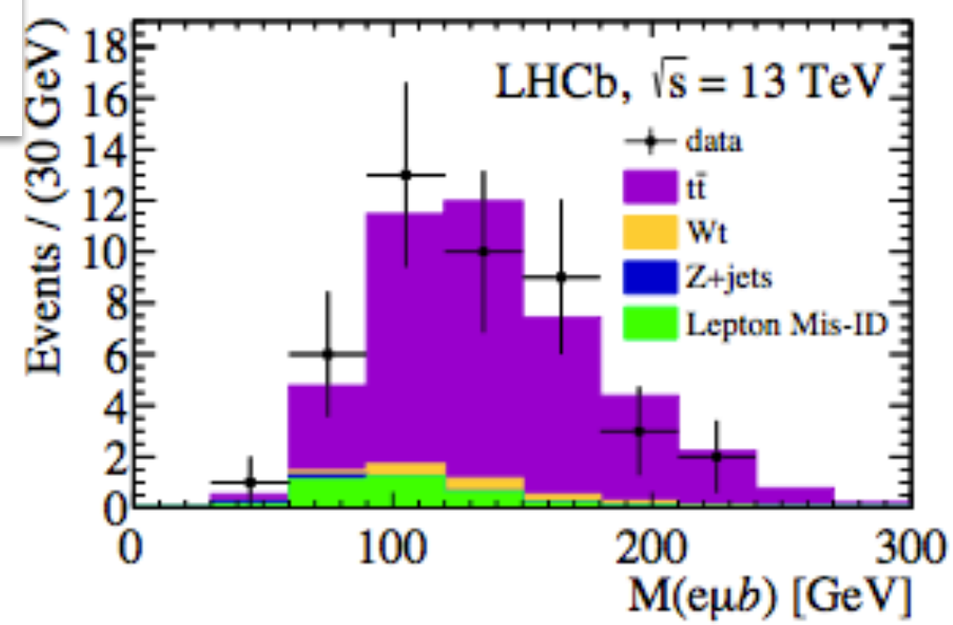
- After a first observation of top quark production in the forward region in 2015
  - LHCb has started to **measure** top quark cross sections
  - Very valuable complementary measurements to ATLAS and CMS



LHCb explores top quark production in the forward region of *pp* collisions

- access larger values of Bjorken *x*
- increased contribution from quark-initiated production relative to central region
- test of perturbative QCD in unexplored region
- can provide unique constraints on gluon PDF at large-*x*

eμb final state, JHEP 08 (2018) 174



ATLAS: σ(tt) in dileptons

Uncerts. cross section

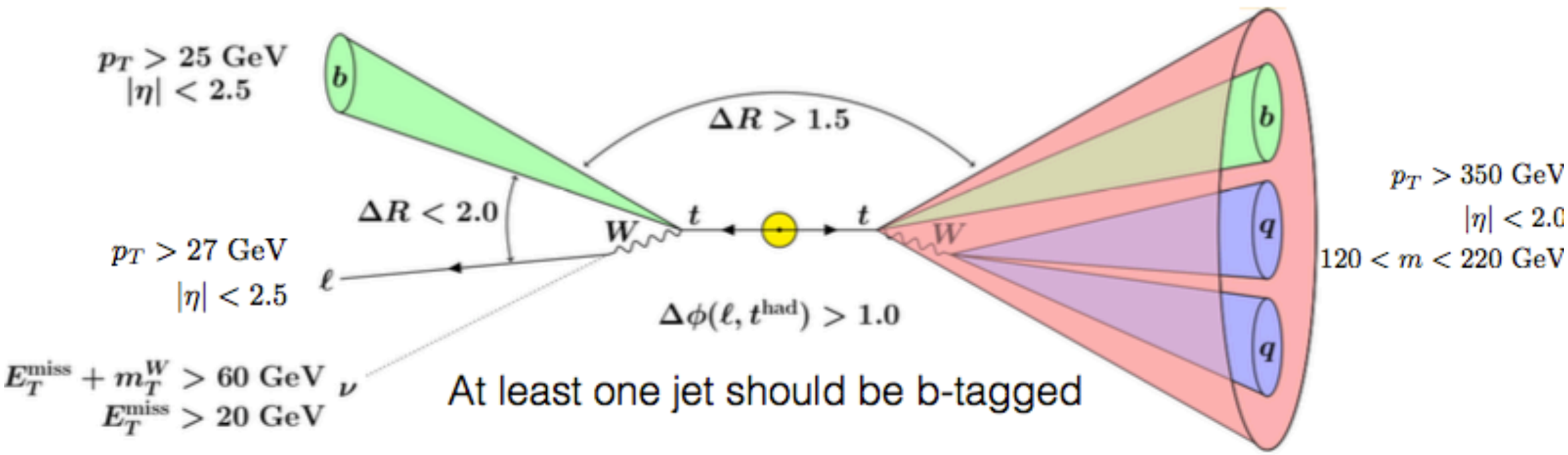
	Uncertainty source	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta G_{e\mu}/G_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ (%)
	Data statistics				0.44	0.44
$t\bar{t}$ mod.	$t\bar{t}$ generator	0.38	0.05	0.05	0.43	0.10
	$t\bar{t}$ hadronisation	0.24	0.42	0.25	0.49	0.67
	Initial/final state radiation	0.30	0.26	0.16	0.45	0.41
	$t\bar{t}$ heavy-flavour production	0.01	0.01	0.26	0.26	0.26
	Parton distribution functions	0.44	0.05	-	0.45	0.07
	Simulation statistics	0.22	0.15	0.17	0.22	0.18
Lept.	Electron energy scale	0.06	0.06	-	0.06	0.06
	Electron energy resolution	0.01	0.01	-	0.01	0.01
	Electron identification	0.34	0.34	-	0.37	0.37
	Electron charge mis-id	0.09	0.09	-	0.10	0.10
	Electron isolation	0.22	0.22	-	0.24	0.24
	Muon momentum scale	0.03	0.03	-	0.03	0.03
	Muon momentum resolution	0.01	0.01	-	0.01	0.01
	Muon identification	0.28	0.28	-	0.30	0.30
	Muon isolation	0.16	0.16	-	0.18	0.18
	Lepton trigger	0.13	0.13	-	0.14	0.14
Jet/b	Jet energy scale	0.02	0.02	0.06	0.03	0.03
	Jet energy resolution	0.01	0.01	0.04	0.01	0.01
	Pileup jet veto	-	-	-	0.02	0.02
	b-tagging efficiency	-	-	0.04	0.20	0.20
	b-tag mistagging	-	-	0.06	0.06	0.06
Bkg.	Single top cross-section	-	-	-	0.52	0.52
	Single-top/$t\bar{t}$ interference	-	-	-	0.15	0.15
	Single top modelling	-	-	-	0.34	0.34
	Z+jets extrapolation	-	-	-	0.09	0.09
	Diboson cross-sections	-	-	-	0.02	0.02
	Diboson modelling	-	-	-	0.03	0.03
	Misidentified leptons	-	-	-	0.43	0.43
	Analysis systematics	0.91	0.75	0.44	1.39	1.31
L/E_b	Integrated luminosity	-	-	-	1.90	1.90
	Beam energy	-	-	-	0.23	0.23
	Total uncertainty	0.91	0.75	0.44	2.40	2.36

Uncerts. mtpole

Uncertainty source	Δm_t^{pole} [GeV]
Experimental	1.0
PDF+α_S	$^{+1.5}_{-1.4}$
QCD scales	$^{+1.0}_{-1.5}$
Total uncertainty	$^{+2.0}_{-2.1}$

ATLAS: boosted tt differential cross sections — 1

- Boosted hadronic top is identified by re-clustering 0.4 jets with anti-k_T R=1 algorithm.
  - Re-clustering allows propagation of small-R JES and a mass cut is sufficient for background rejection.



Note: possible to have events where the leptonic top is at lower p_T.

M. Owen, BOOST2019

ATLAS: boosted tt differential cross sections — 2

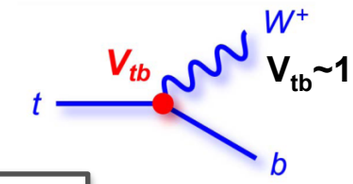
MC Setups

- PWG+PY8: Powheg + Pythia 8.210, NNPDF3.0, ttbar production at NLO, h_{damp}=1.5m_t (tuned to previous ttbar data), A14 tune.
- PWG+PY8 Rad. Up: Powheg + Pythia8, ttbar production at NLO, h_{damp}=3mt, factorisation & renormalisation scales 0.5*nominal, Var 3c up A14 eigentune.
- PWG+PY8 Rad. Down: Powheg + Pythia8, ttbar production at NLO, h_{damp}=1.5mt, factorisation & renormalisation scales 2*nominal, Var 3c down A14 eigentune.
- PWG+H7: Powheg + Herwig 7.01, NNPDF3.0, ttbar production at NLO, H7-UE-MMHT tune.
- Sherpa: Sherpa 2.2.1, NNPDF3.0, ttbar production at NLO for 0 and 1 additional-jets, up-to 4 additional jets at LO, merged with MEPS@NLO, default Sherpa tune.
- aMC@NLO+PY8: MadGraph5_aMC@NLO 2.6.0 + Pythia 8.230, NNPDF3.0, shower starting scale set to HT/2 (tuned to previous ttbar data), A14 tune.

M. Owen, BOOST2019

Single top Run1 combination

- Final word from Run1 ATLAS+CMS combinations on cross sections and V_{tb}



Cross sections

7 TeV combinations

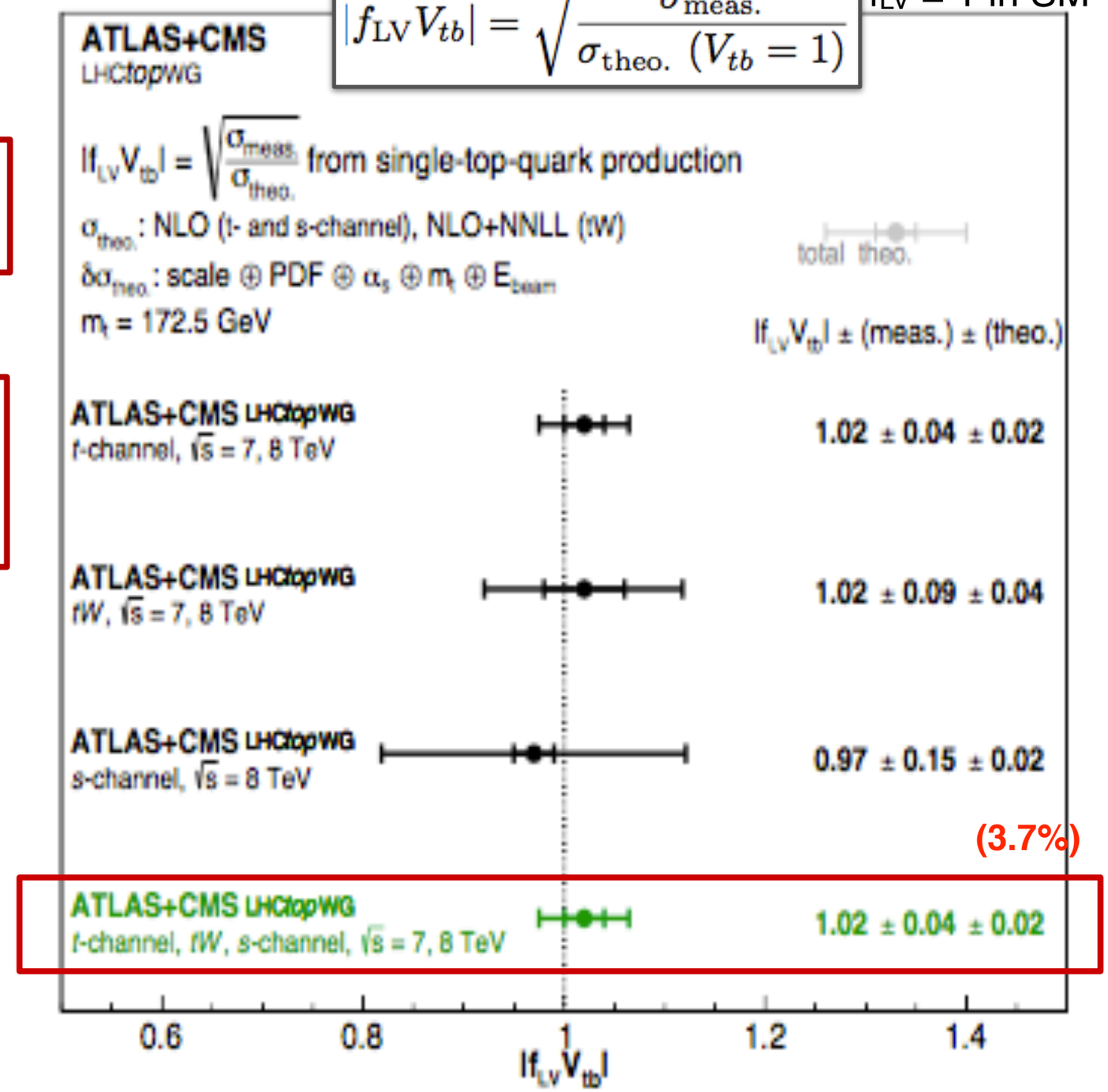
$\sigma_{t\text{-}ch}$ = 67.5 ± 5.7 pb (8.4%) NLO: 4.7%
σ_{tW} = 16.3 ± 4.1 pb (25%) NLO+NNLL: 7.9%

8 TeV combinations

$\sigma_{t\text{-}ch}$ = 87.7 ± 5.8 pb (6.7%) NLO: 4.6%
σ_{tW} = 23.1 ± 3.6 pb (15.6%) NLO+NNLL: 7.0%
$\sigma_{s\text{-}ch}$ = 4.9 ± 1.4 pb (30%) NLO: 4.8%

$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}\ (V_{tb}=1)}}$$

f_{LV} = 1 in SM



JHEP 05 (2019) 088

CMS: Running of the top mass — 1

A well known running: alphaS

running of α_S is described by renormalization group equation (RGE)

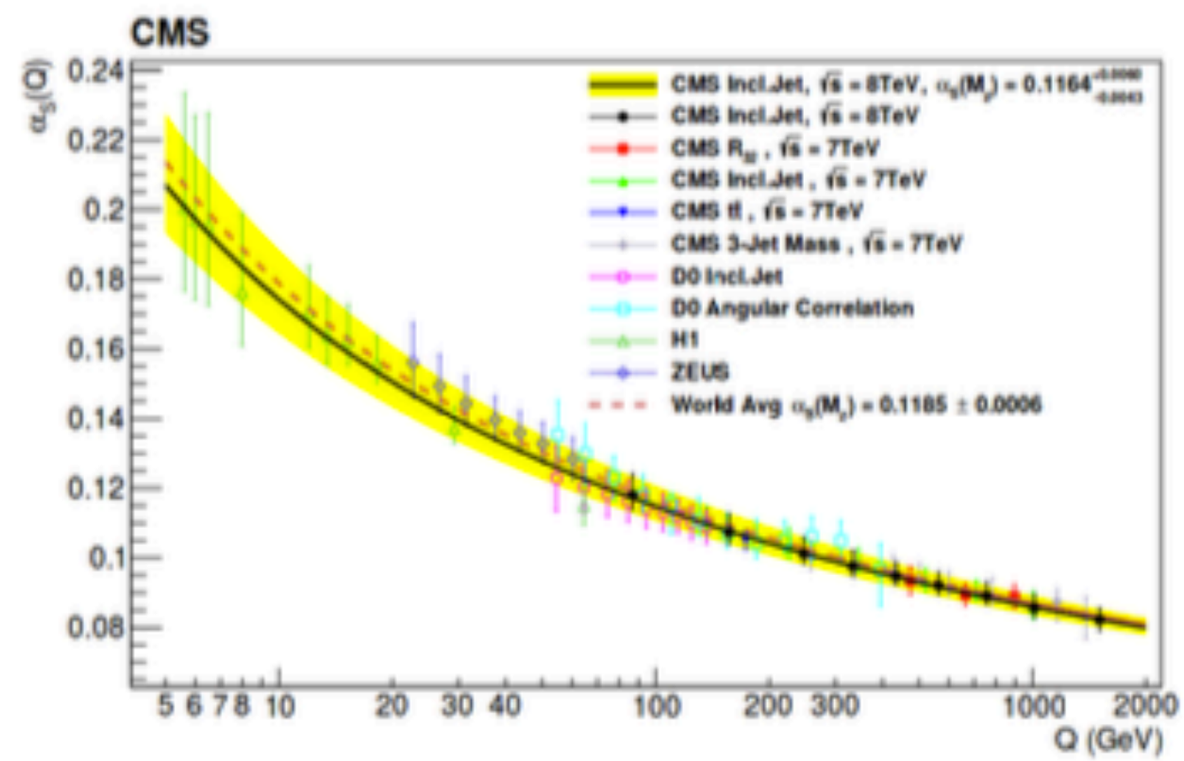
$$\alpha_S(\mu) = \frac{\alpha_S(\mu_0)}{\alpha_S(\mu_0)\frac{11N_c - 2N_f}{12\pi}\ln\frac{\mu^2}{\mu_0^2}} \quad \text{(NLO)}$$

typical procedure to measure α_S running:

- extract $\alpha_S(m_Z)$ from some final state observable in limited scale range (e.g. $\mu =$ jet p_T)
- convert $\alpha_S(m_Z)$ to $\alpha_S(\mu)$ using RGE, w. appropriate choice of μ in each bin

N.B. this is equivalent to extracting $\alpha_S(\mu)$ directly (RGE implicitly assumed)

CMS summary plot



- **well-established procedure**
- experimentally verified on a very wide range of scales, at different experiments

CMS: Running of the top mass — 2

Running of quark masses

- similar procedure can be used to extract running of heavy quark masses

short distance $\overline{\mathrm{MS}}$ mass can be expressed in terms of pole mass

$$m_q(m_q) = m_q^{\mathrm{pole}} \left[1 - \frac{4}{3\pi}\alpha_S(m_q) + \mathcal{O}(\alpha_S^2)\right]$$

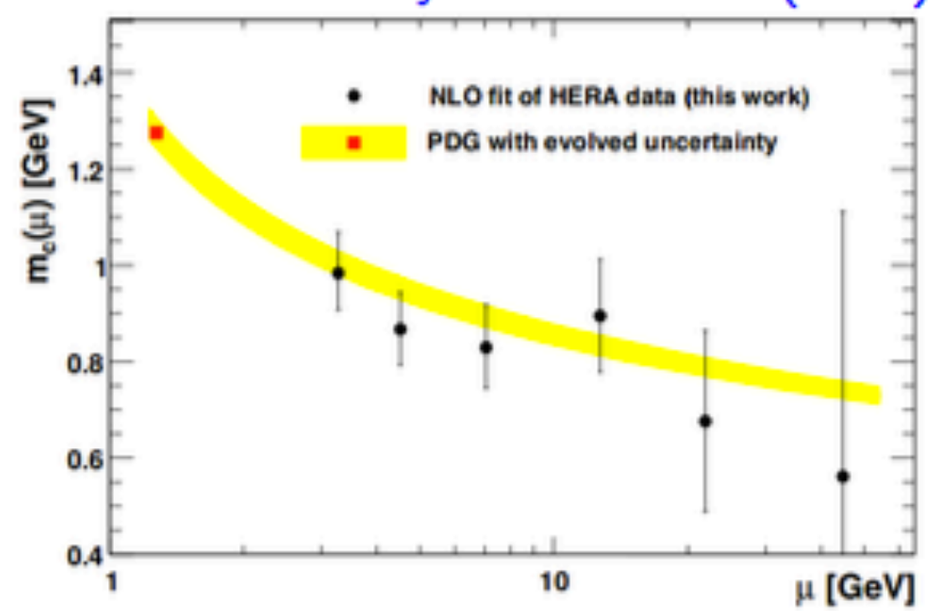
and evolved to an arbitrary scale μ

$$m_q(\mu) = m_q(m_q)\left[1 - \frac{\alpha_S(\mu)}{\pi}\ln\frac{\mu^2}{m_q^2} + \mathcal{O}(\alpha_S^2)\right]$$

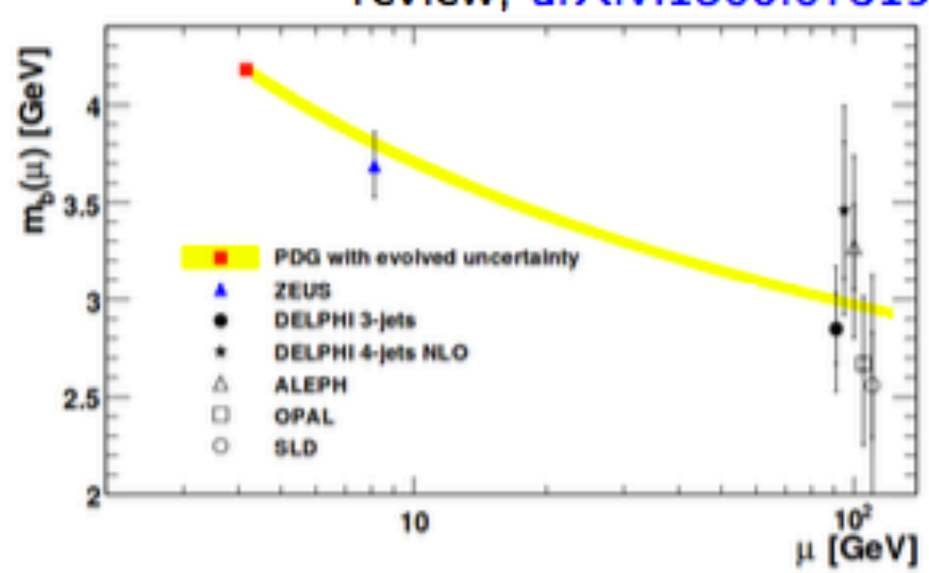
- running of m_c has been experimentally determined at HERA experiments
- running of m_b determined with data from different experiments

→ **goal: determine running of m_t** using LHC data at 13 TeV

Phys. Lett. B775 (2017)



review, arXiv:1506.07519

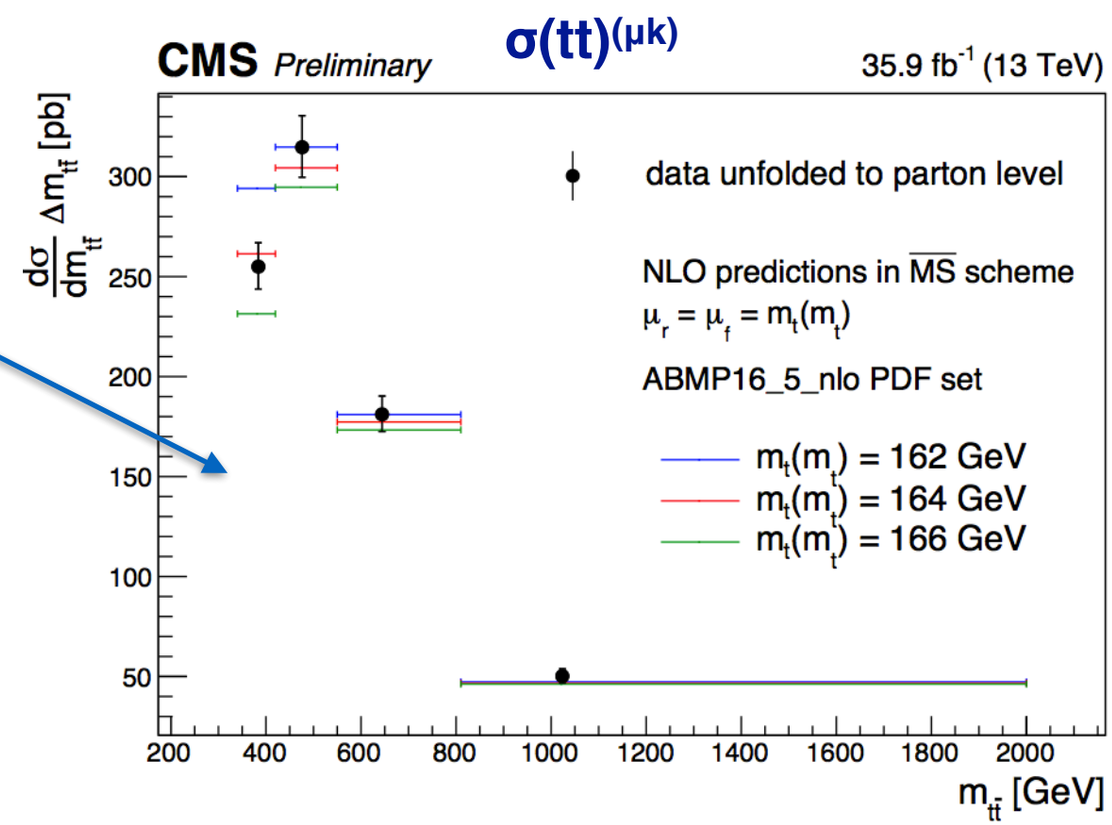


CMS: Running of the top mass — 3

Analysis strategy

- Apply tt selection and kinematic reconstruction —> m(tt)
- Split the tt sample into **4 subsamples** corresponding to **bins of m(tt)** at parton level
- **Each bin** is treated as an independent signal and represents the **tt production at the scale μ_k**, defined as the **centre of gravity in bin k**
- **Measure σ(tt) differentially as a function of m(tt)** via fit to multidifferential distributions
  - Experimental dependence on the m_t^{MC} taken into account
  - Systematics constrained in the visible phase space

bin	$m_{t\bar{t}}$ [GeV]	fraction [%]	μ_k [GeV]
1	340–420	30.1	384.0
2	420–550	39.4	476.2
3	550–810	23.8	644.3
4	810–∞	6.7	1024



CMS: Running of the top mass — 4

Analysis strategy

- The measured $\boldsymbol{\sigma(tt)^{(\mu k)}}$ are used to extract the running of the top MSbar mass at NLO as a function of the scale $\mu = m(tt)$
- The top MSbar mass, $m_t(m_t)$, is determined independently in each bin of m(tt) from a Chi2 fit to a fixed-order NLO calculation in MCFM (the top mass is treated in the MSbar scheme)
- The measured $m_t(m_t)$ are converted to $m_t(\mu_k)$ using RunDec
  - μ_k represents the scale of the process in a given bin of m(tt)
  - Conversion performed with 1-loop precision assuming 5 active flavours
  - This is equivalent to extracting directly $m_t(\mu_k)$ in each bin
- Take ratios of $m_t(\mu_k)/m_t(\mu_{ref})$ to cancel correlated uncerts in the measured $\sigma(tt)^{(\mu k)}$

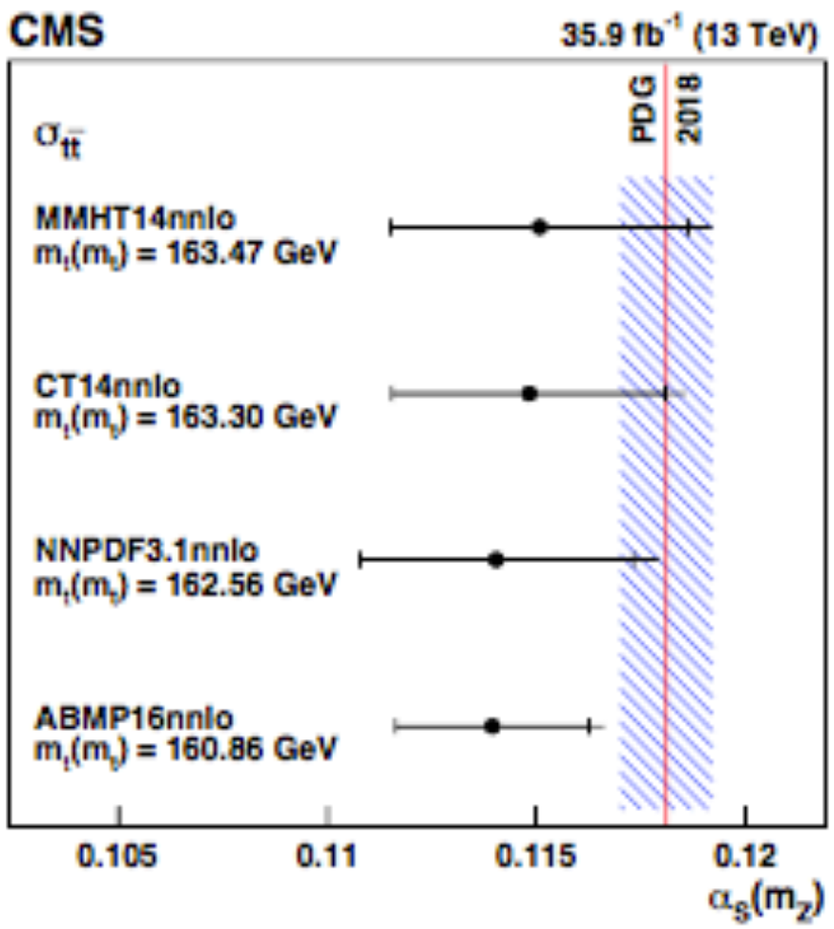
$$r_{12} = m_t(\mu_1)/m_t(\mu_2) = 1.030 \pm 0.018\ (\text{fit})\ ^{+0.003}_{-0.006}\ (\text{PDF} + \alpha_S)\ ^{+0.003}_{-0.002}\ (\text{extr}),$$
$$r_{32} = m_t(\mu_3)/m_t(\mu_2) = 0.982 \pm 0.025\ (\text{fit})\ ^{+0.006}_{-0.005}\ (\text{PDF} + \alpha_S)\ ^{+0.004}_{-0.004}\ (\text{extr}),$$
$$r_{42} = m_t(\mu_4)/m_t(\mu_2) = 0.904 \pm 0.050\ (\text{fit})\ ^{+0.019}_{-0.017}\ (\text{PDF} + \alpha_S)\ ^{+0.017}_{-0.013}\ (\text{extr}).$$

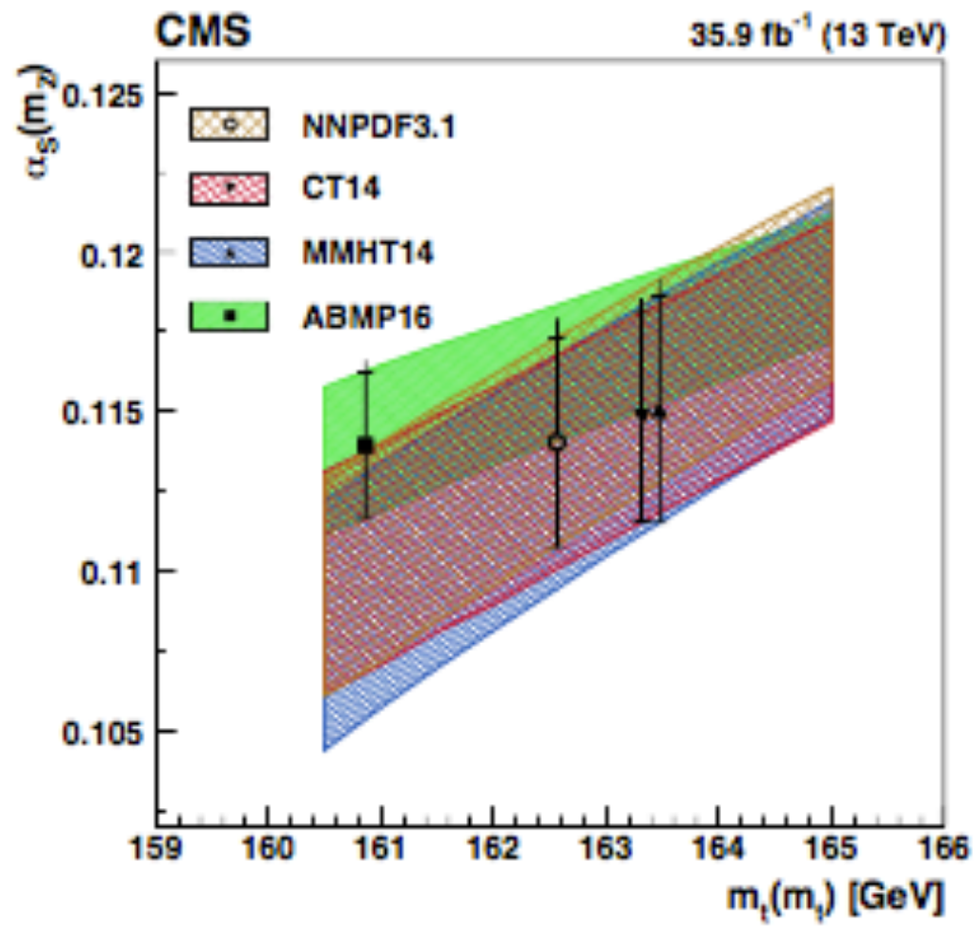
CMS: MSbar top mass in dileptons

Simultaneous extraction of tt cross section and mtMC:

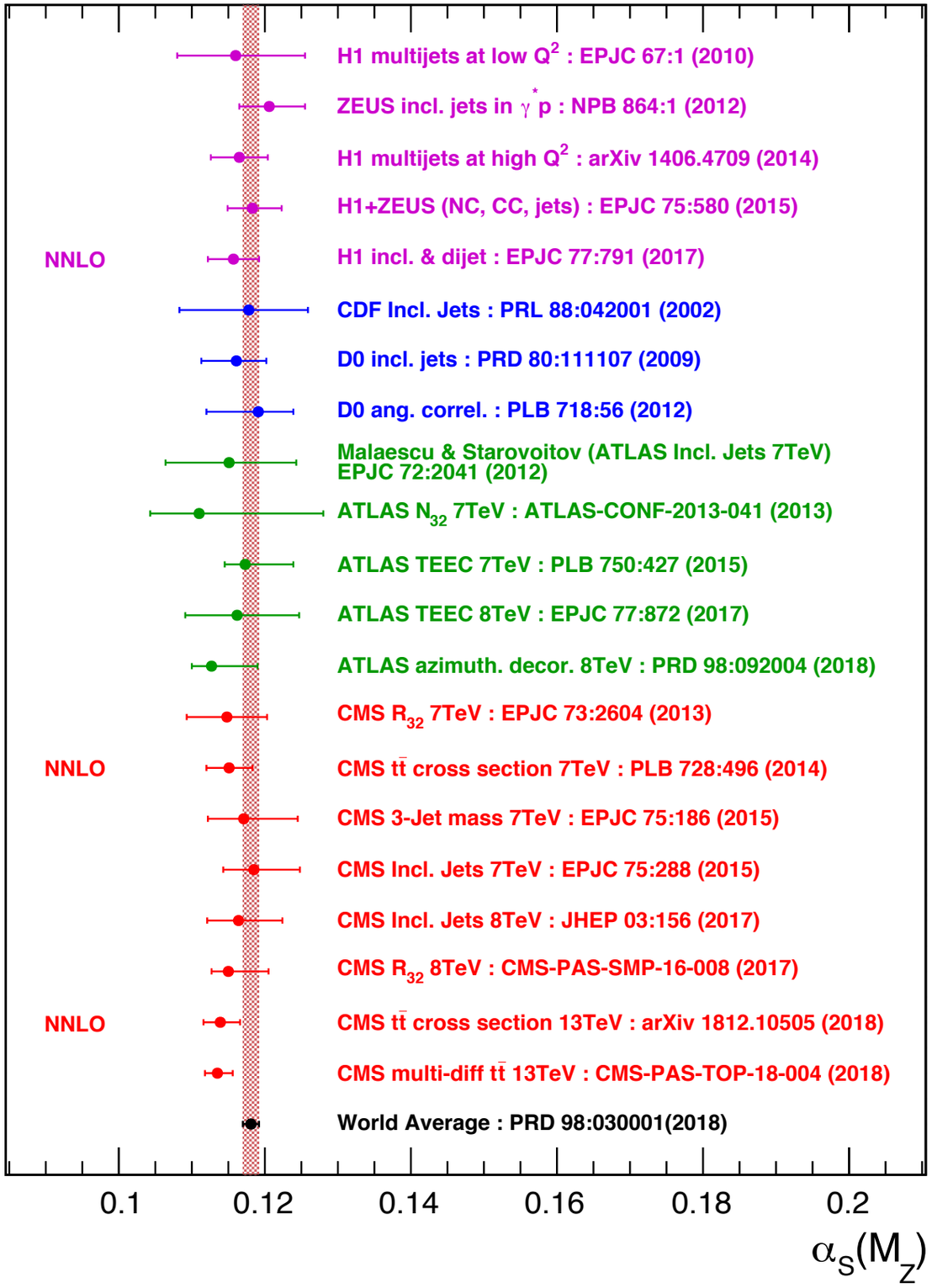
$$\sigma_{t\bar{t}} = 815 \pm 2\,(\text{stat}) \pm 29\,(\text{syst}) \pm 20\,(\text{lumi})\ \text{pb}$$
$$m_t^{\text{MC}} = 172.33 \pm 0.14\,(\text{stat})\ ^{+0.66}_{-0.72}\,(\text{syst})\ \text{GeV}$$

- Residual dependence of the cross section on m_t^{MC}
  $\rightarrow$ indirect $m_t(m_t)$ and α_S determination: Eur. Phys. J. C 79 (2019) 368





alphaS summary plot



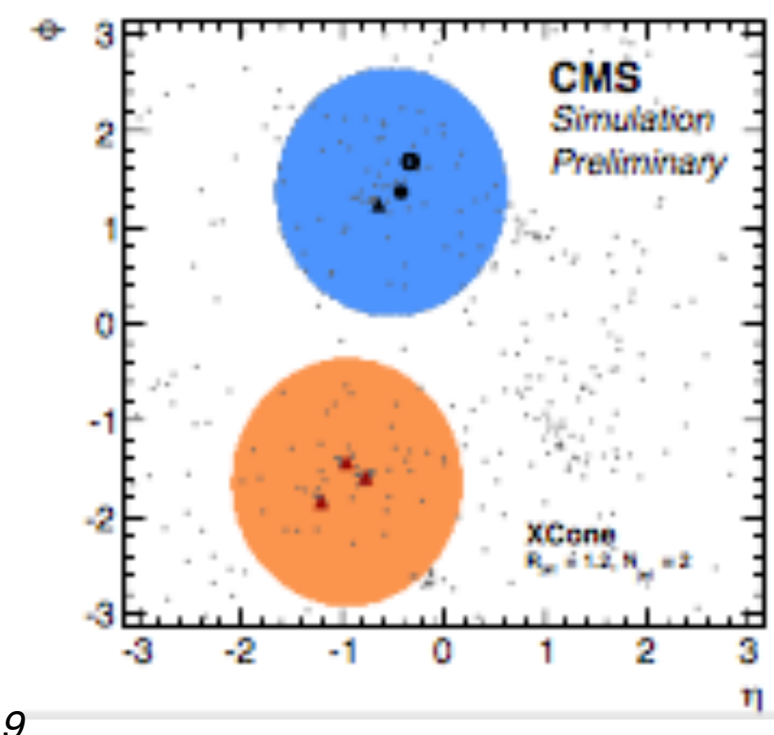
CMS: top mass from boosted jets (TOP-19-005) — 1

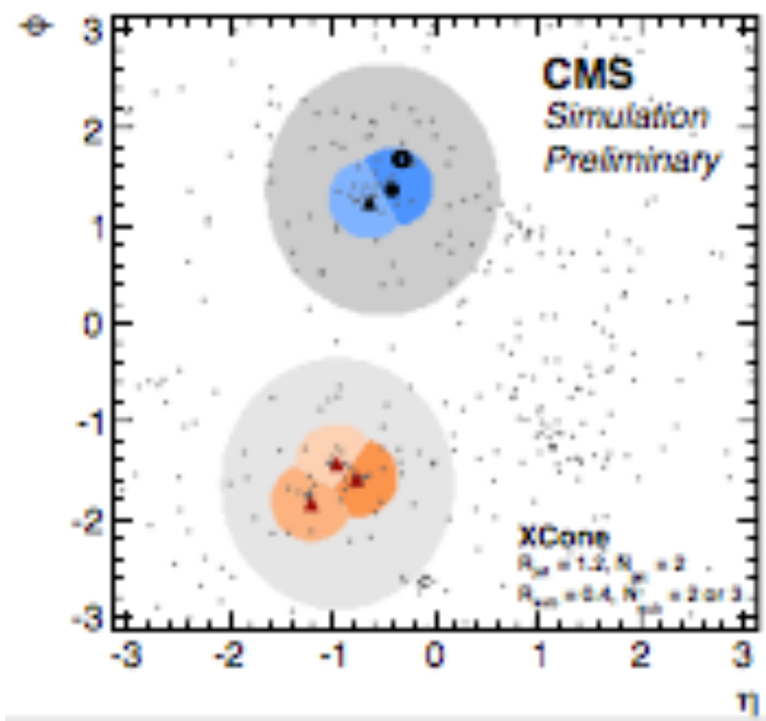
XCone [I. W. Stewart, F. J. Tackmann, J. Thaler, C. K. Vermilion and T. F. Wilkason, JHEP 1511 (2015) 072]

- exclusive jet algorithm → returns exactly N jets
- jet axes found by minimizing N-jettiness
- cluster particles inside R around axes

set-up for lepton+jets $t\bar{t}$ idea from: [J. Thaler and T. F. Wilkason, JHEP 1512 (2015) 051]

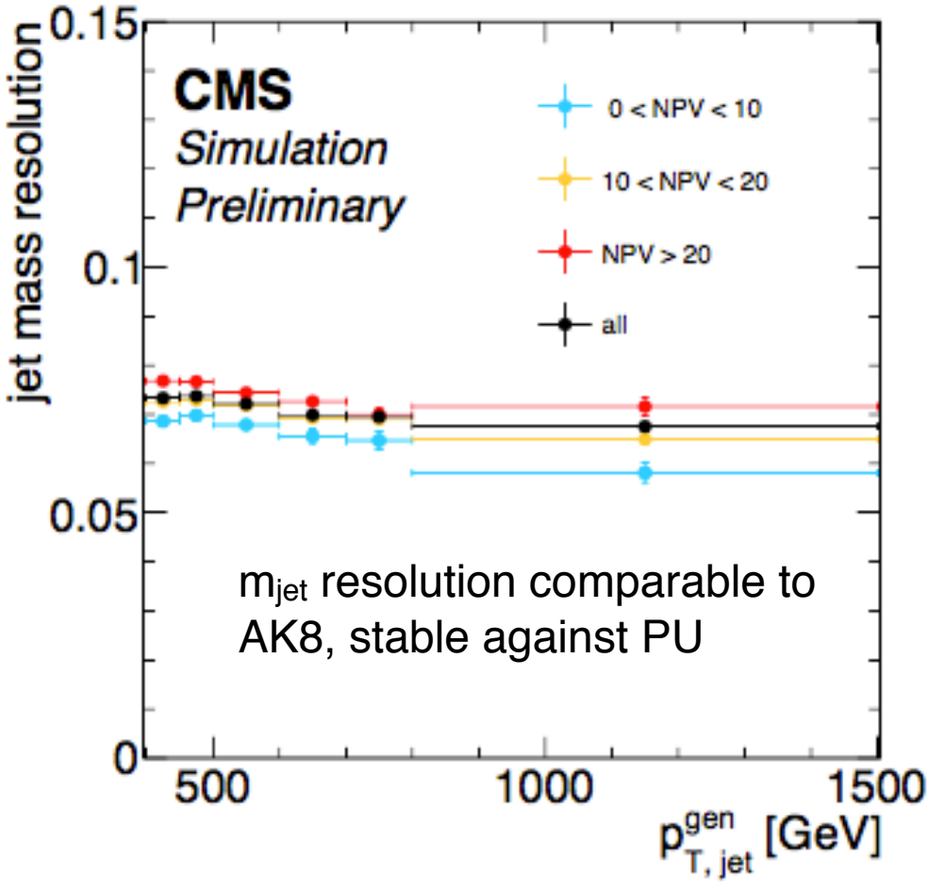
1. find 2 jets with large radius
2. calculate ΔR(lep, jet) for both jets
3. lowest ΔR → leptonic jet; other → hadronic jet
4. find subjets: 3 in hadronic jet, 2 in leptonic jet
5. combine subjets to final jet



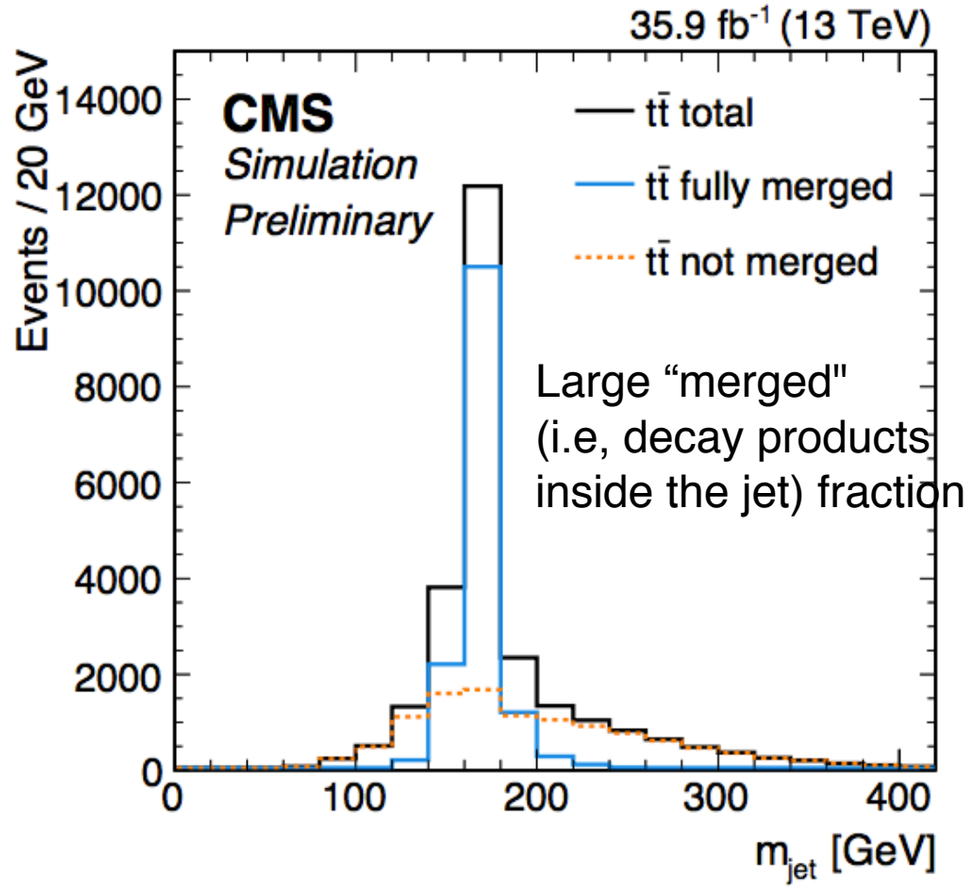


D. Schwarz, BOOST2019

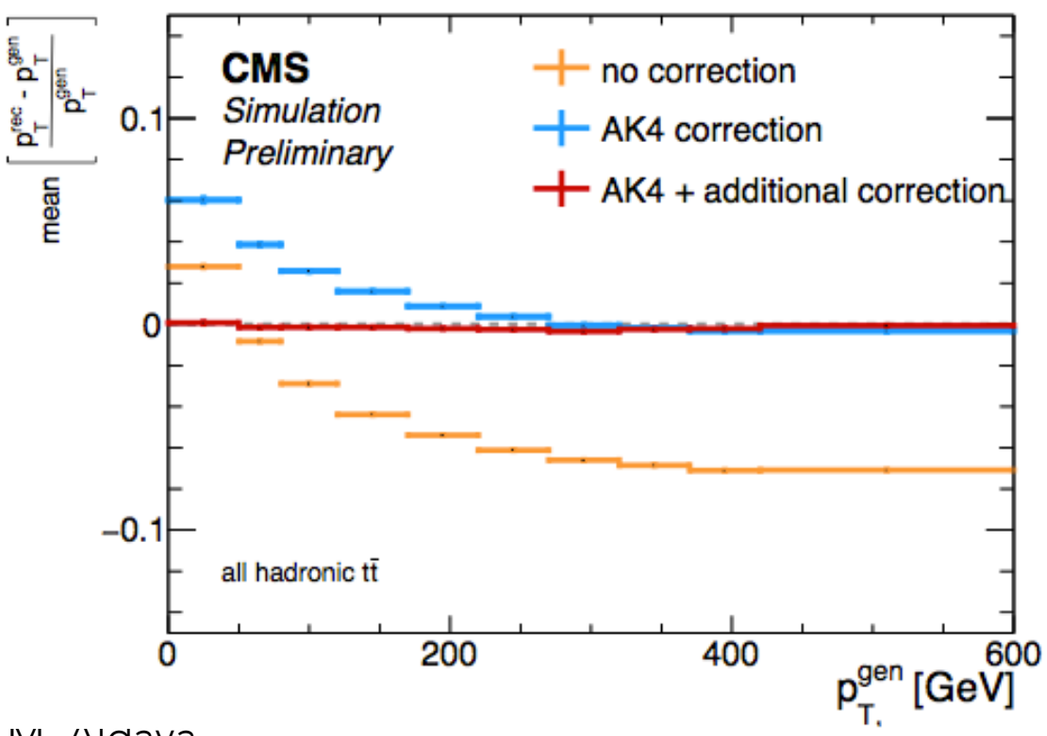
CMS: top mass from boosted jets (TOP-19-005) — 2



m_{jet} resolution comparable to AK8, stable against PU

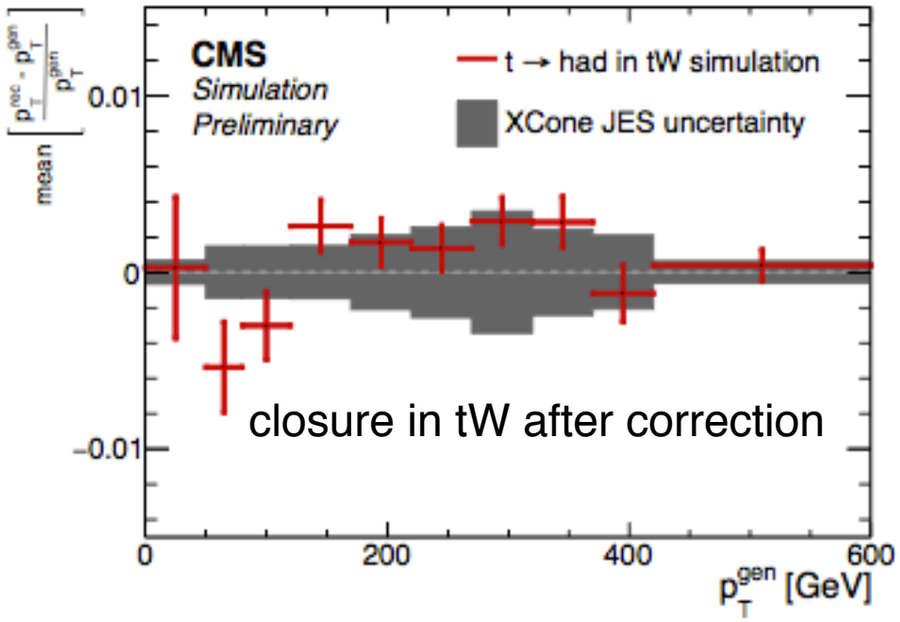


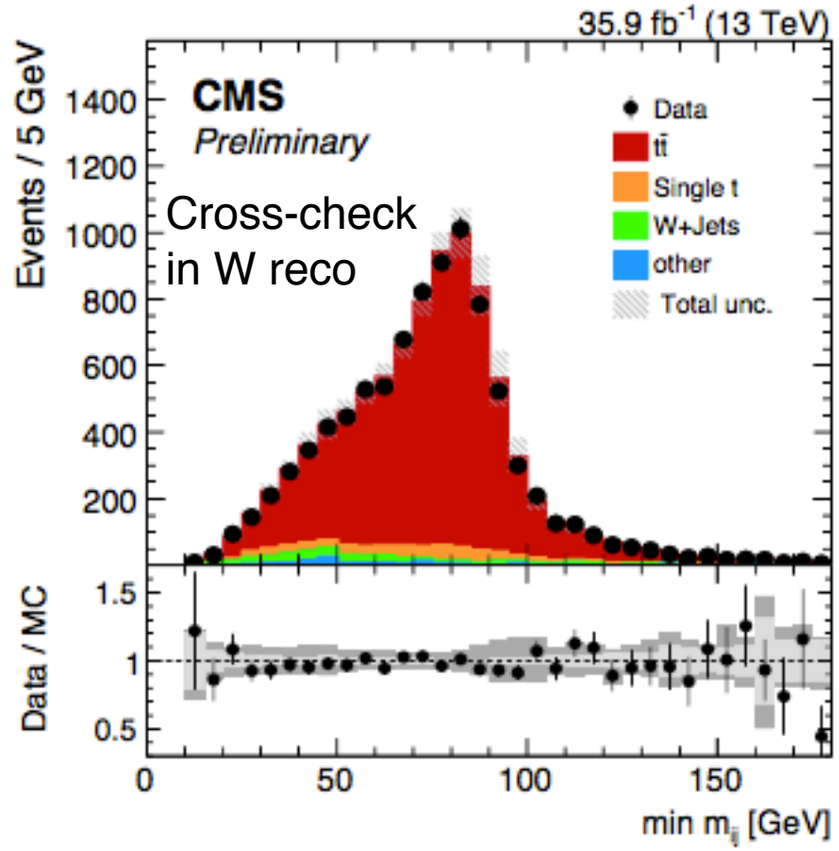
Large "merged" (i.e, decay products inside the jet) fraction

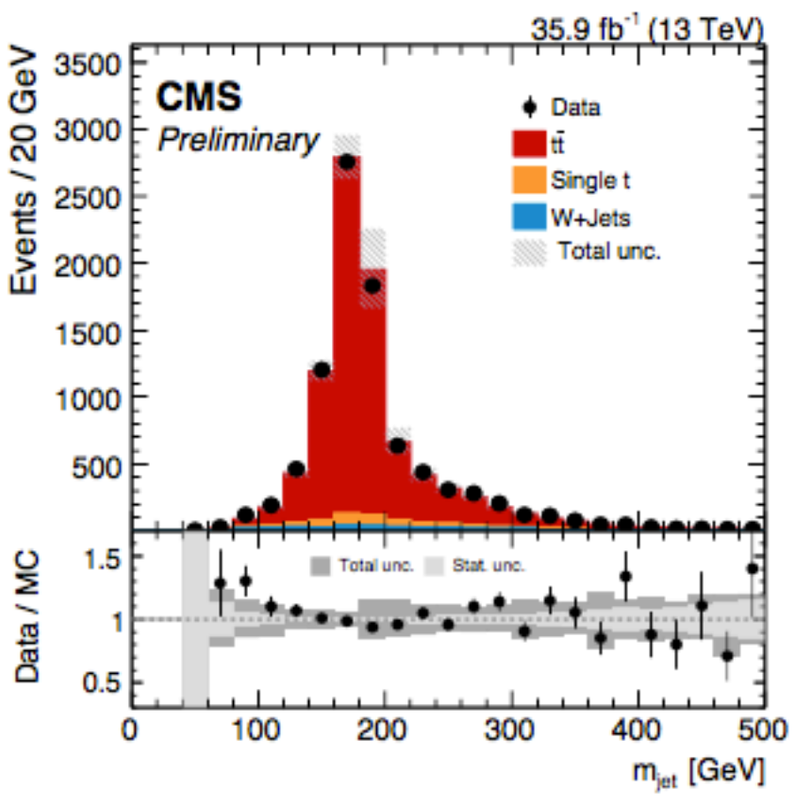


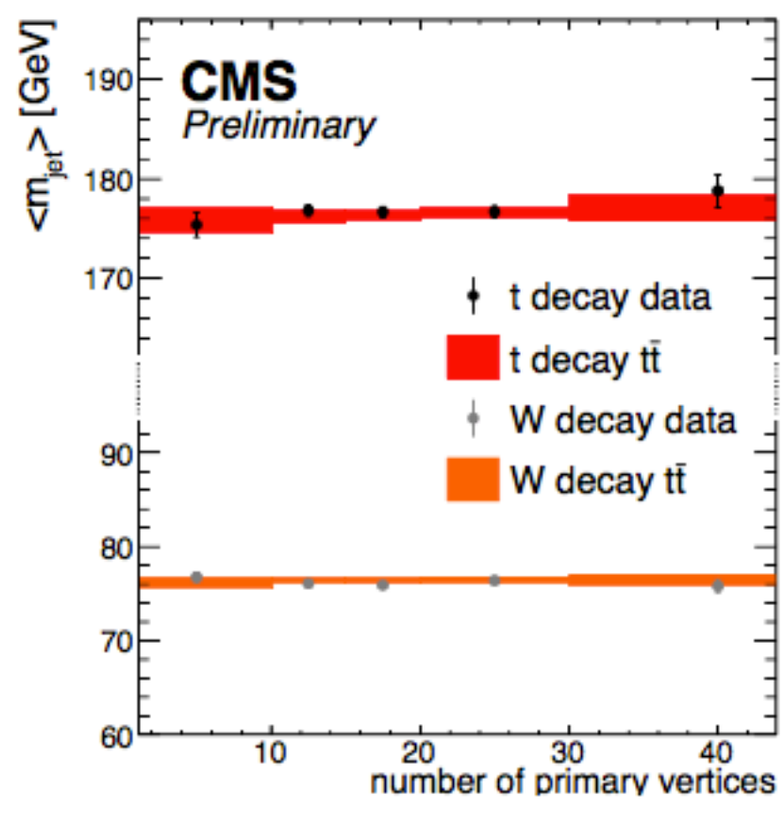
- no jet calibration for XCone so far
- idea: AK4 calibration + additional correction
- correction derived in all hadronic $t\bar{t}$
- correction applied dependent on p_T and η of subjets

CMS: top mass from boosted jets (TOP-19-005) — 3



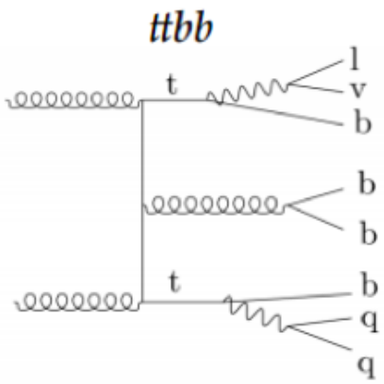






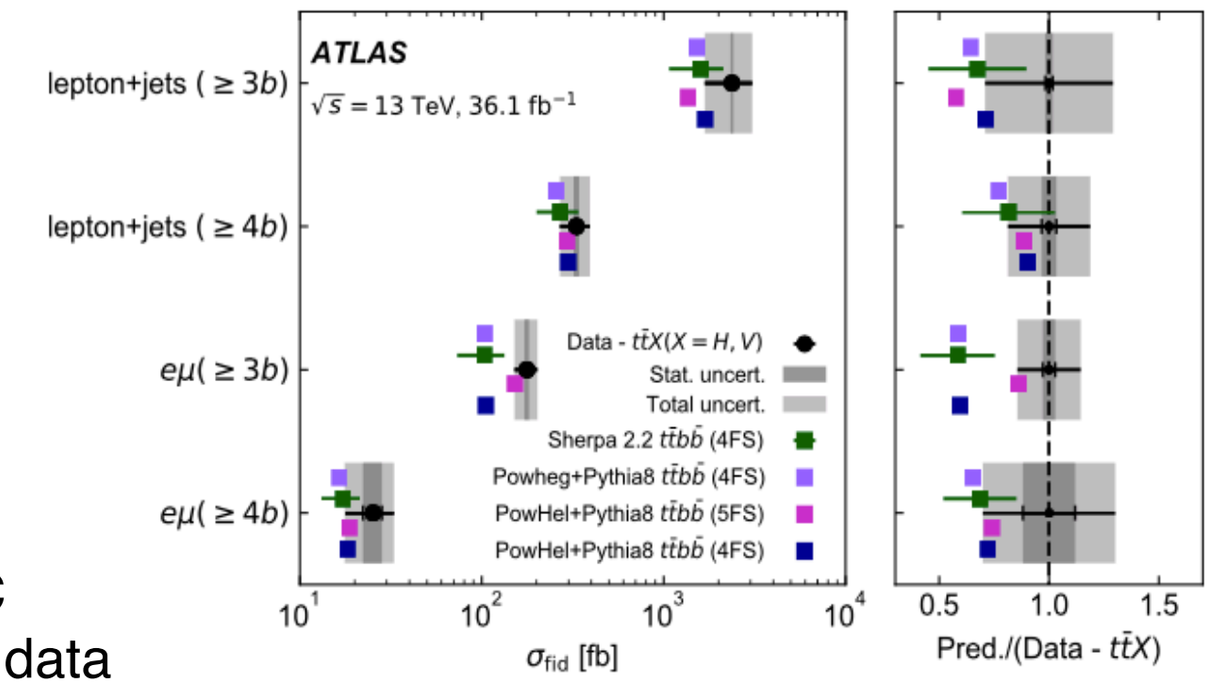
stable against PU

tt+bb production



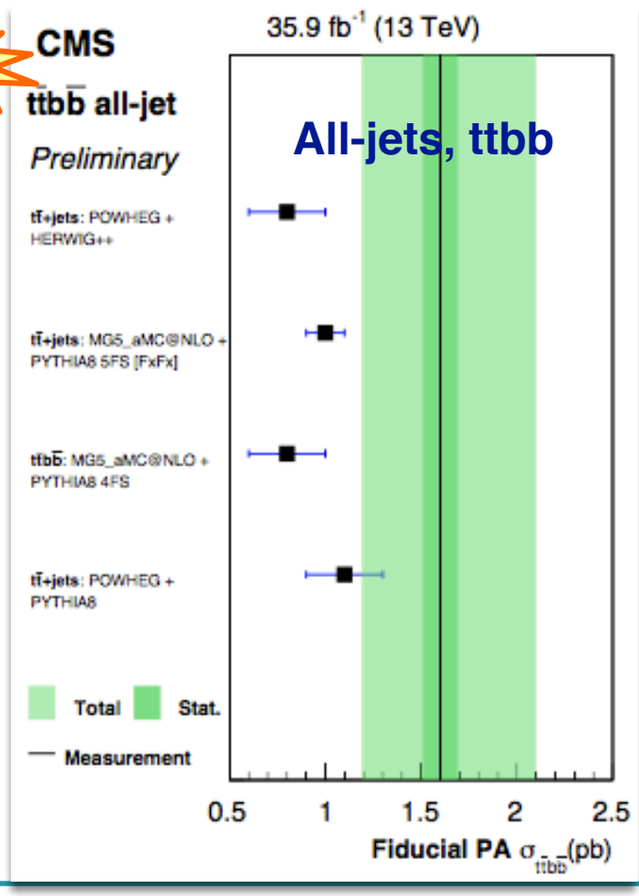
Major background for tt+H(bb) (irreducible) and tttt

- Challenging to model: complex final state, very different scales (tt, bb)
- ATLAS: dilepton & l+jets
  CMS: new dilepton & l+jets, all-jets
- Different phase spaces, comparison to NLO MC simulations: in general, σ(ttbb) slightly higher in data

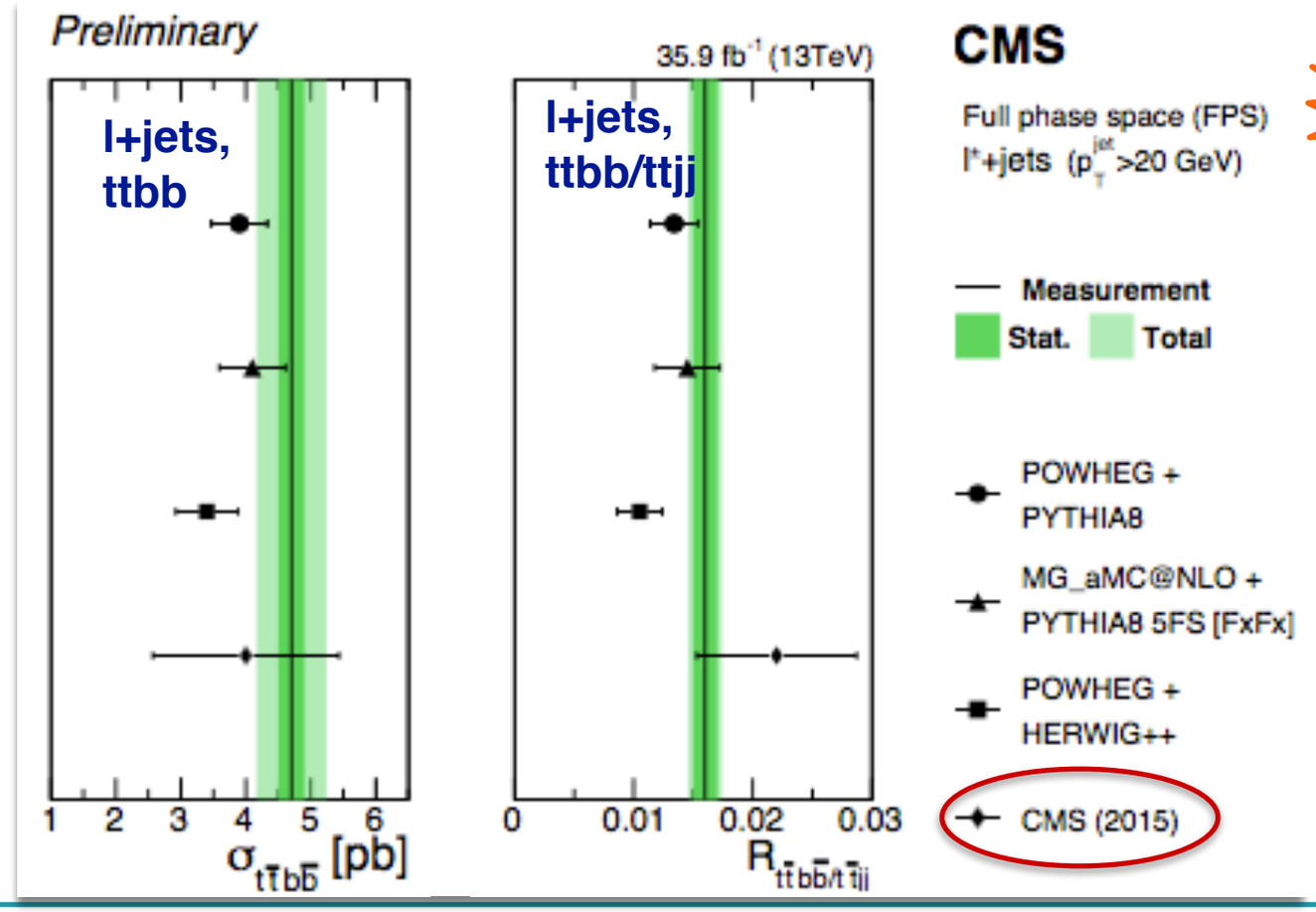


ATLAS, JHEP 04 (2019) 046

New



CMS-PAS-TOP-18-011



New

CMS-PAS-TOP-18-002

ATLAS: top width

Source	Impact on Γ_t [GeV]
Jet reconstruction	±0.24
Signal and bkg. modelling	±0.19
MC statistics	±0.14
Flavour tagging	±0.13
E_T^{miss} reconstruction	±0.09
Pile-up and luminosity	±0.09
Electron reconstruction	±0.07
PDF	±0.04
$t\bar{t}$ normalisation	±0.03
Muon reconstruction	±0.02
Fake-lepton modelling	±0.01

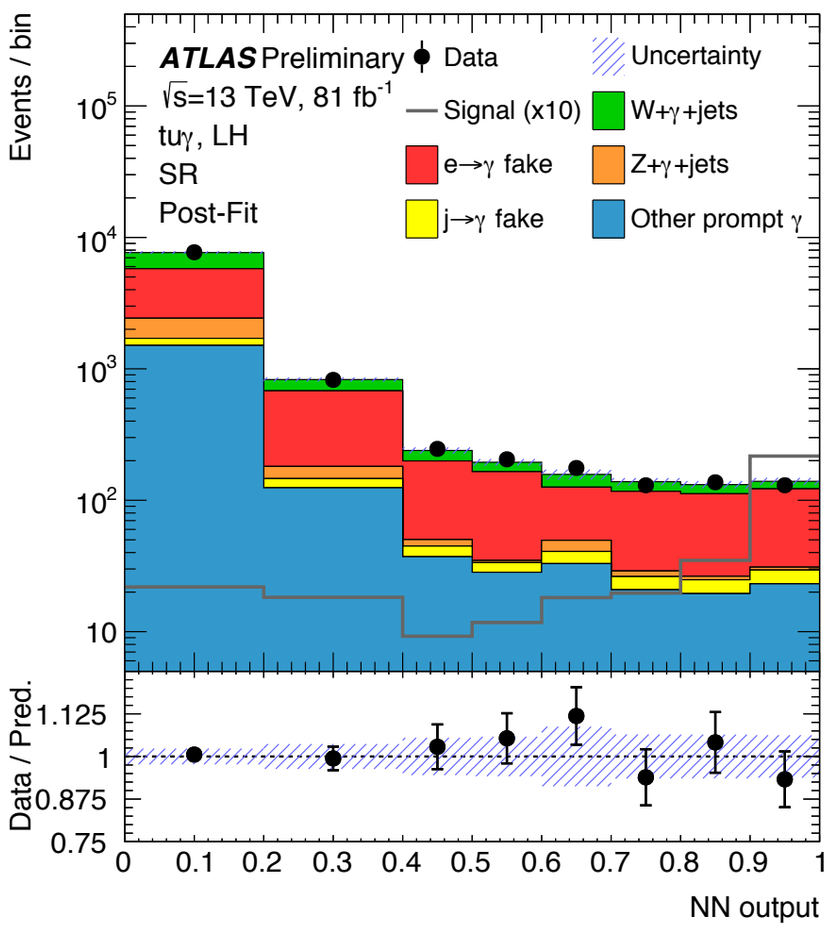
Table 3: Impact on the uncertainty of the Γ_t measurement from different categories of systematic uncertainties. The categories with the highest impact are on the top of the table. The quoted values are obtained by repeating the fit while fixing a set of nuisance parameters from the corresponding category sources, and subtracting in quadrature the resulting total uncertainty of Γ_t from the uncertainty from the full fit.

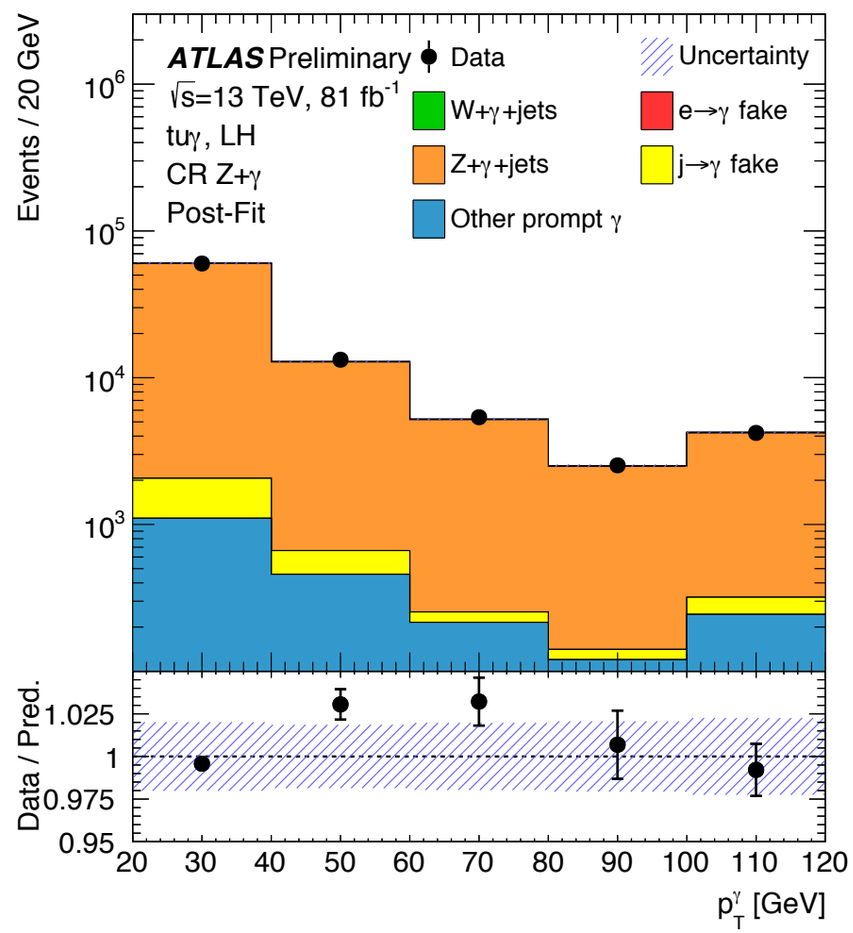
	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	**Unc. [GeV]**	**Mean [GeV]**	**Unc. [GeV]**	**Mean [GeV]**	**Unc. [GeV]**
Measured	2.01	$^{+0.53}_{-0.50}$	1.94	$^{+0.52}_{-0.49}$	1.90	$^{+0.52}_{-0.48}$
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%

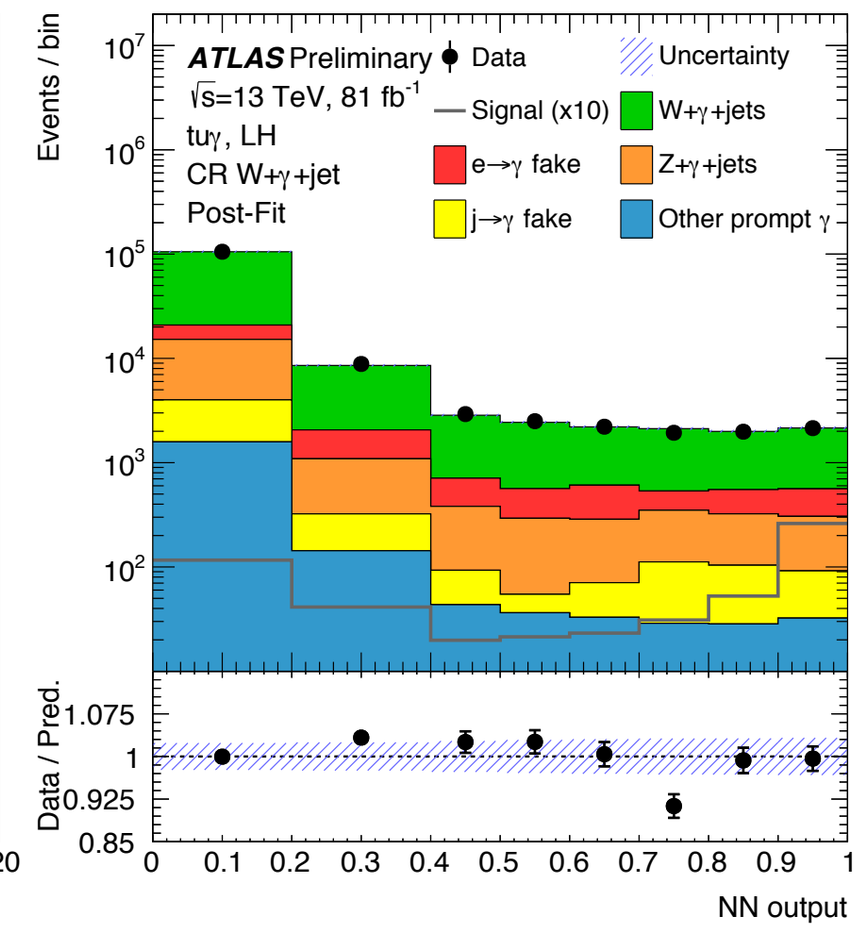
Table 4: Fitted values and their uncertainties under different top-quark mass hypotheses. The theoretical values are extracted from the leading order values that are corrected following Ref. [6].

ATLAS: tqγ FCNC

- ATLAS (81 fb^{-1}): Search for tqγ FCNC in single top + γ events
  - Topology: 1 e/mu, 1 γ, 1 b-jet, MET
- NN to separate signal from background
- Fit to NN output in SR and CR dominated by main bgs from events with prompt γ
  - Contribution from events electrons/hadrons misID as γ estimated from data







ATLAS: tqγ FCNC

- ATLAS (81 fb^{-1}): Search for tqγ FCNC in single top + γ events

- Limits on:
  - strength of effective operators that introduce a left- or right-handed FC tqγ coupling with an up-type q
  - cross sections for pp —> tqγ
  - B(t—>qγ)

ATLAS Preliminary

Observable	Vertex	Coupling	Obs.	Exp.
$\left\lvert C_{\mathrm{uW}}^{(13)*} + C_{\mathrm{uB}}^{(13)*} \right\rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\lvert C_{\mathrm{uW}}^{(31)} + C_{\mathrm{uB}}^{(31)} \right\rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\lvert C_{\mathrm{uW}}^{(23)*} + C_{\mathrm{uB}}^{(23)*} \right\rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\lvert C_{\mathrm{uW}}^{(32)} + C_{\mathrm{uB}}^{(32)} \right\rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}