Top-antitop pair-production and single top production cross-section at the LHC

XV International Conference on Heavy Quarks and Leptons

September 13-17, 2021, Warwick, United Kingdom

PROLAY MAL

NATIONAL INSTITUTE OF SCIENCE EDUCATION & RESEARCH

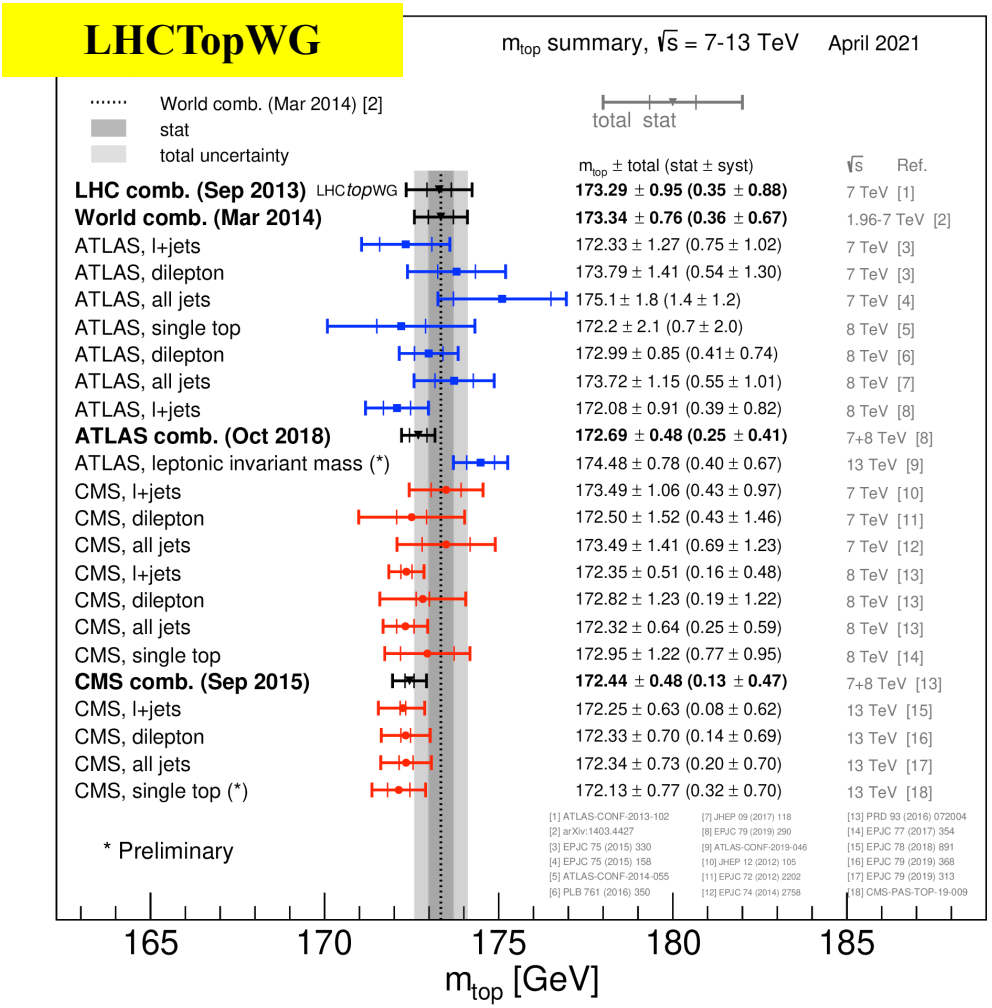
BHUBANESWAR, INDIA

ATLAS EXPERIMENT

CMS

The Top Quark

- The unique quark that decays before the hadronization [lifetime ~ 0.5×10^{-24} sec]
  - Scope of studying the bare quark through its decay products
- Heaviest known elementary particle
  - $m_{top} = 172.76 \pm 0.3$ GeV/c^2 [PDG 2020]
- Known properties within the SM:
  - Electric charge +2/3 e
  - Strong & electroweak production
  - Isospin partner of bottom quark
  - Large coupling to the Higgs boson
    - Special role in EWSB
  - Br($t \rightarrow W^+b$)≈100%

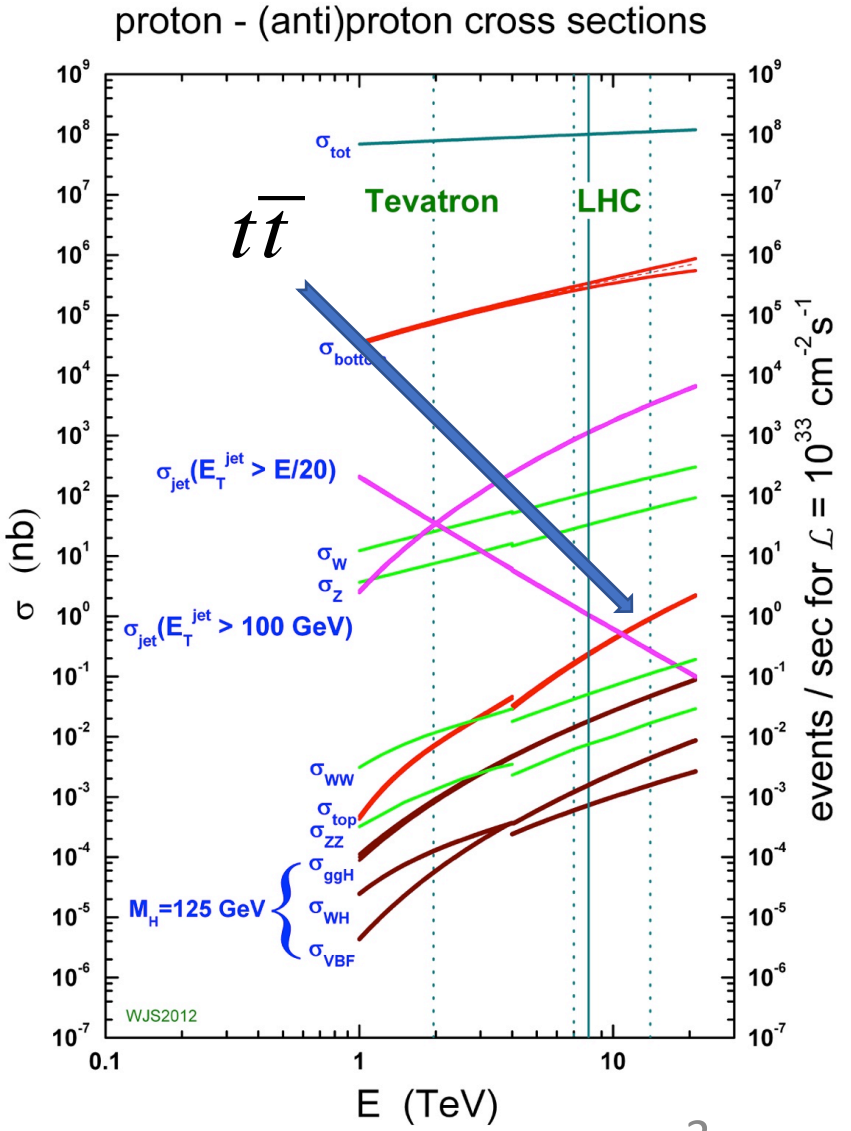


Why Top cross-section?

- The total cross-section for any physics process at the hadron collider is convolution of parton-level cross-section and the Parton Distribution Functions (PDF):

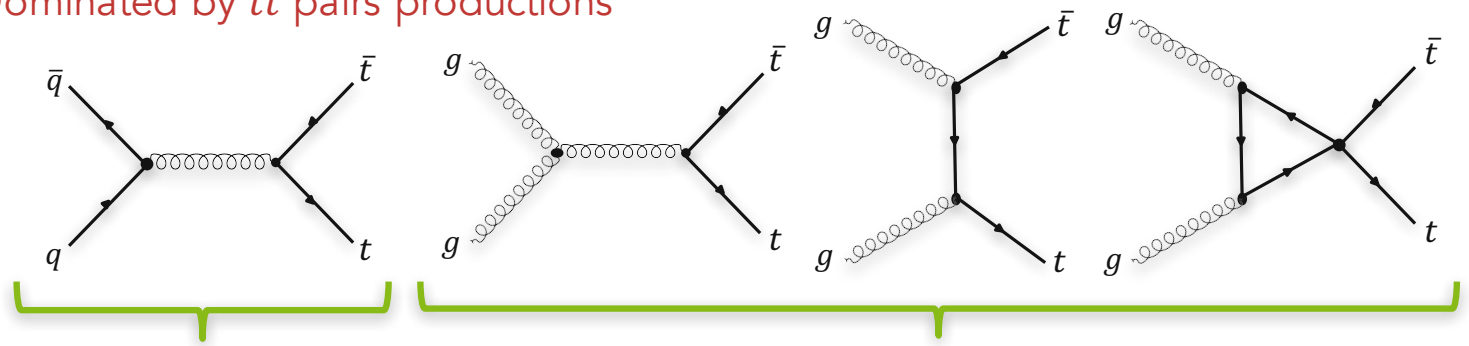
$$\sigma(pp \to A + X) = \sum_{i,j} \int f_{q_i}(x_i, Q^2) f_{q_j}(x_j, Q^2) \sigma(q_i q_j \to A) dx_i dx_j$$

- Inclusive and differential measurements can be the crucial probes for SM & BSM physics
  - Test for the perturbative QCD at NNLO precision
  - Constraints on the PDFs further
  - Differential measurements are sensitive to top mass and polarization, α_S, PDF, etc.; furthermore, it can scrutinize different phase space regions
  - Determination of the SM parameters and measurement of the rare processes (tt+W/Z/γ, t+Z, etc.)
  - Constrain New physics: Anomalous couplings, direct searches (tt resonances, W'→tb, stop decays…)



Top quark production modes at LHC

Dominated by $t\bar{t}$ pairs productions

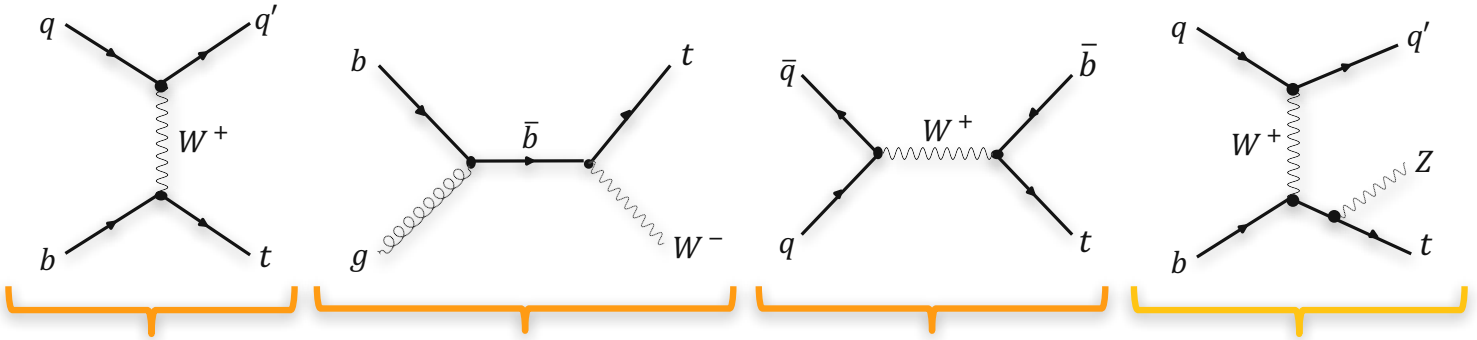


quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Covered in this talk

Single top-quark productions



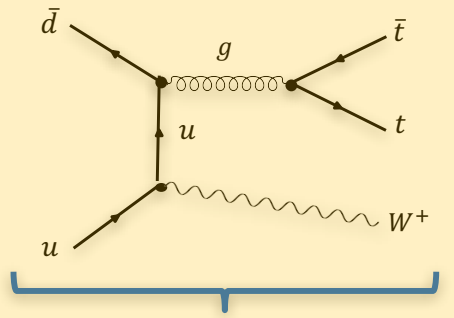
t-channel (~73%)

tW associated production (~24%)

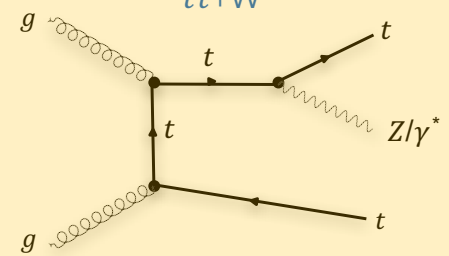
s-channel (~3%)

tZ production (<1%)

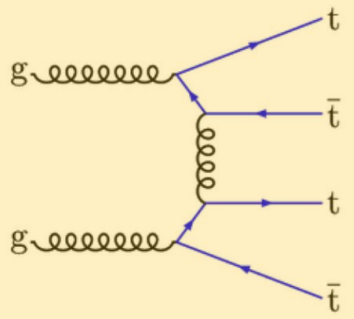
Other productions



$t\bar{t}$+W



$t\bar{t}$+Z/γ*

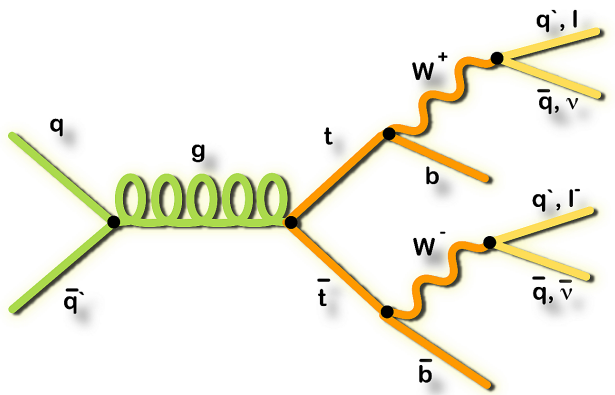


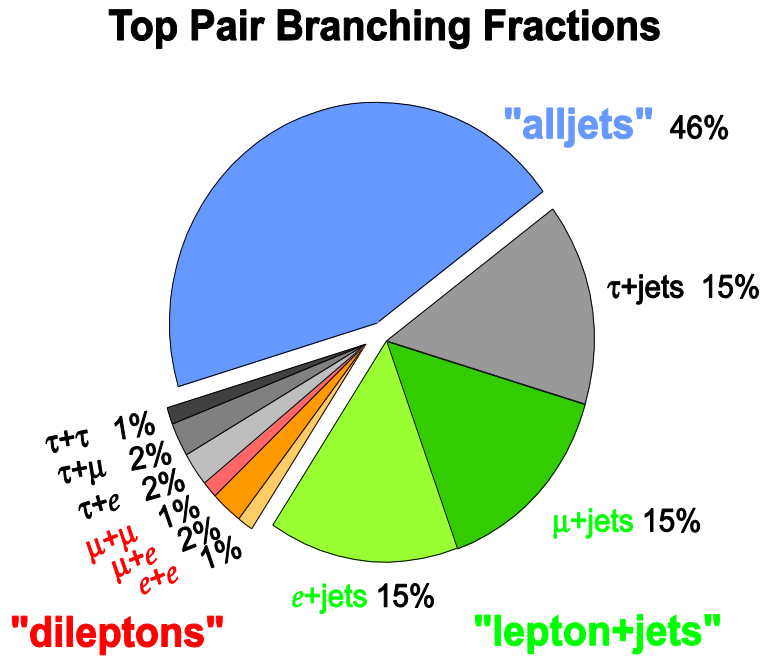
4-tops

See the talk by Mathis Kolb

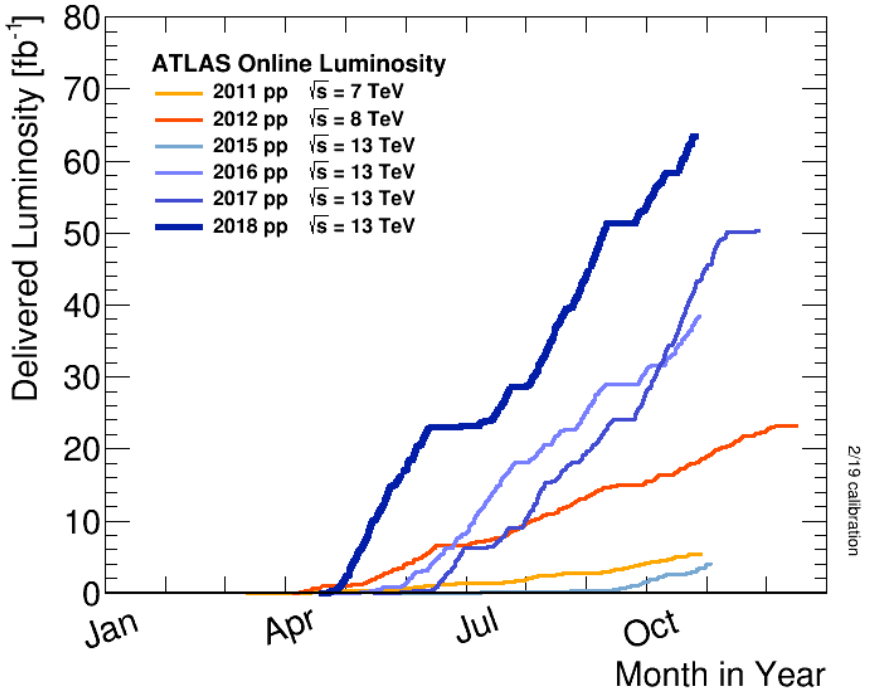
Decay of Top quark

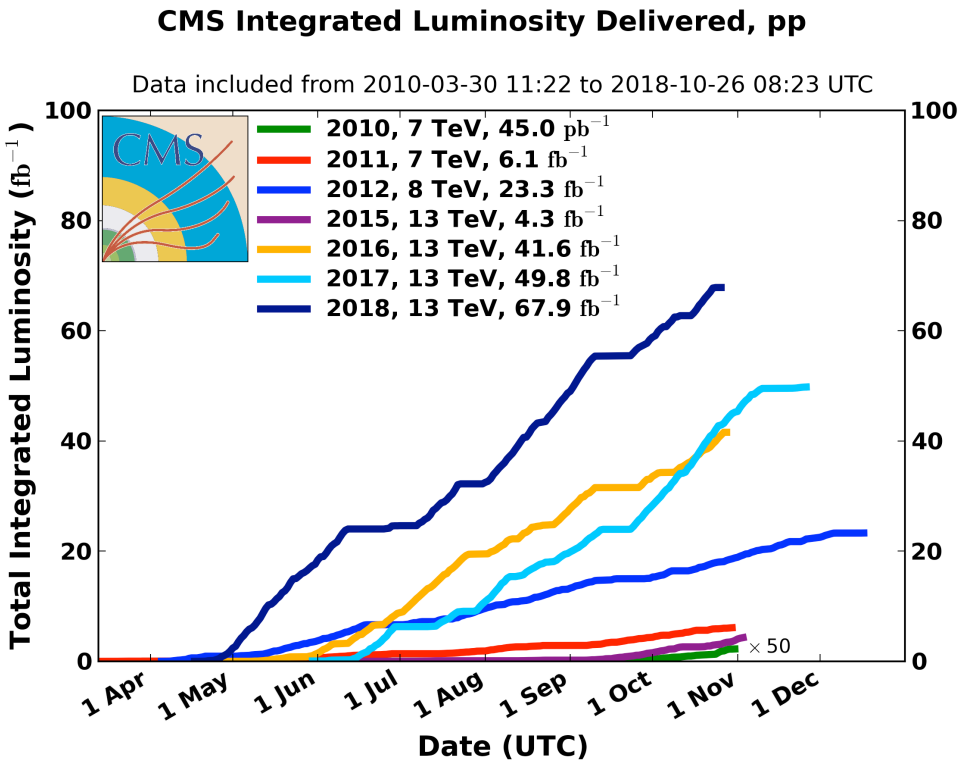
- SM Br(t→W⁺b)=100%
- Final states determined through the decay of W± bosons from top and antitop quarks.
  - All jets: $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}q\bar{q}'q\bar{q}'$
    - High branching ratio but large QCD background
    - ≥ 6 jets, 2 b-jets
  - **lepton+jets:** $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}q\bar{q}'l^-\bar{\nu}$
    - Moderately high branching ratio but relatively low background
  - dilepton: $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}l^+\nu l^-\bar{\nu}$
    - Low branching ratio but clean signal
- Similarly different final states for single top/electroweak top production
  - Dilepton: $tW^- \rightarrow bW^+W^- \rightarrow bl^+\nu l^-\bar{\nu}$
  - Semileptonic s-channel: $t\bar{b} \rightarrow bW^+\bar{b} \rightarrow b\bar{b}l^+\nu$





LHC Performance



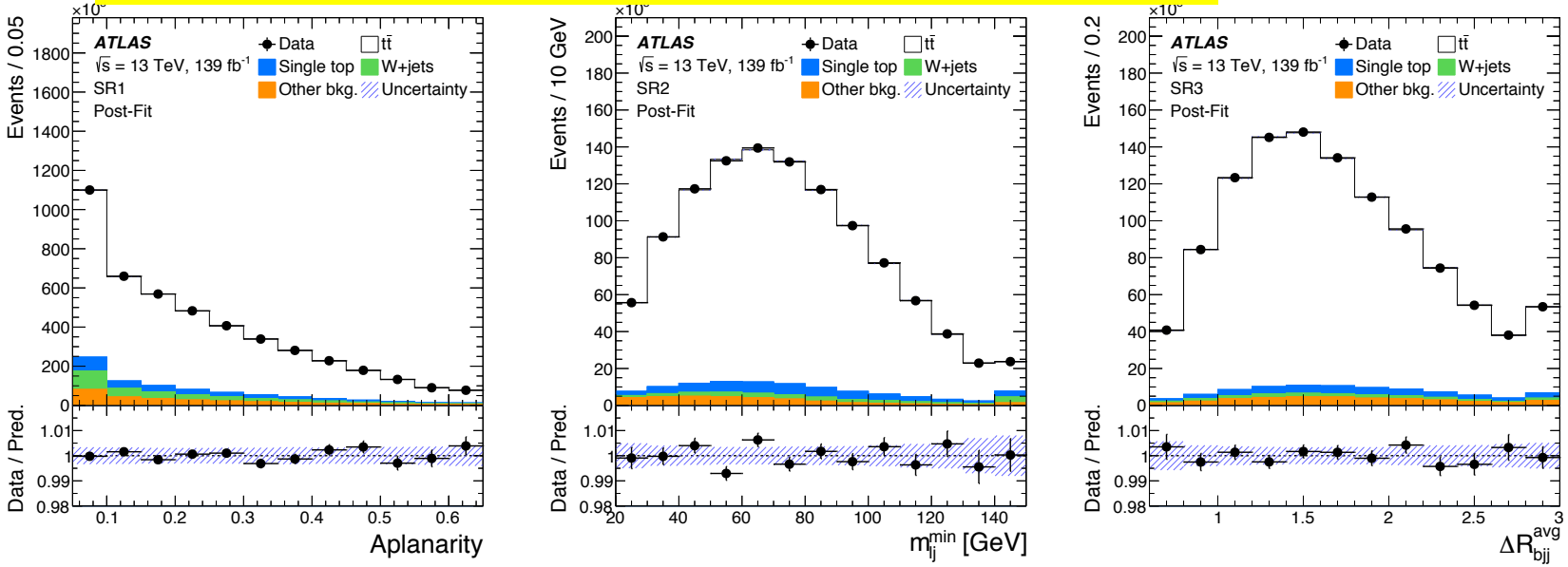


- **After the glorious Run I, LHC have been operated at √s=13 TeV during 2015-18**
- **Both ATLAS and CMS have completed Inner detector upgrades during the Extended Year-End Technical Stop (EYETS) at the end of 2016 operation; average pileup events increased during 2017 and 2018 operations**
- **LHC performed exceedingly well during Run II and both the detectors have recorded ~150 fb^{-1} of pp collision datasets at √s=13 TeV**

Top pair Production Cross-section

Inclusive $t\bar{t}$ production cross-section

Phys. Lett. B 810 (2020), 135797; arXiv: 2006.13076 [hep-ex]



- **Lepton+jets channel analysis based on the full Run 2 dataset**
  - **Electron/muon + missing E_T, m_T^W, ≥ 4 jets, ≥ 1 b-jet**
  - **3 different signal regions (SR) based on # of jets and b-jets**
  - **W+jets, single top and multijet QCD are the dominant background**
- **Profile likelihood fits (in separate signal regions) to extract the inclusive and fiducial cross-sections:**

$$\sigma_{\text{inc}} = 830 \pm 0.4\ (\text{stat.}) \pm 36\ (\text{syst.}) \pm 14\ (\text{lumi.})\ \text{pb} = 830 \pm 38\ \text{pb}.$$

$$\sigma_{\text{fid}} = 110.7 \pm 0.05\ (\text{stat.})\ ^{+4.5}_{-4.3}\ (\text{syst.}) \pm 1.9\ (\text{lumi.})\ \text{pb} = 110.7 \pm 4.8\ \text{pb}.$$

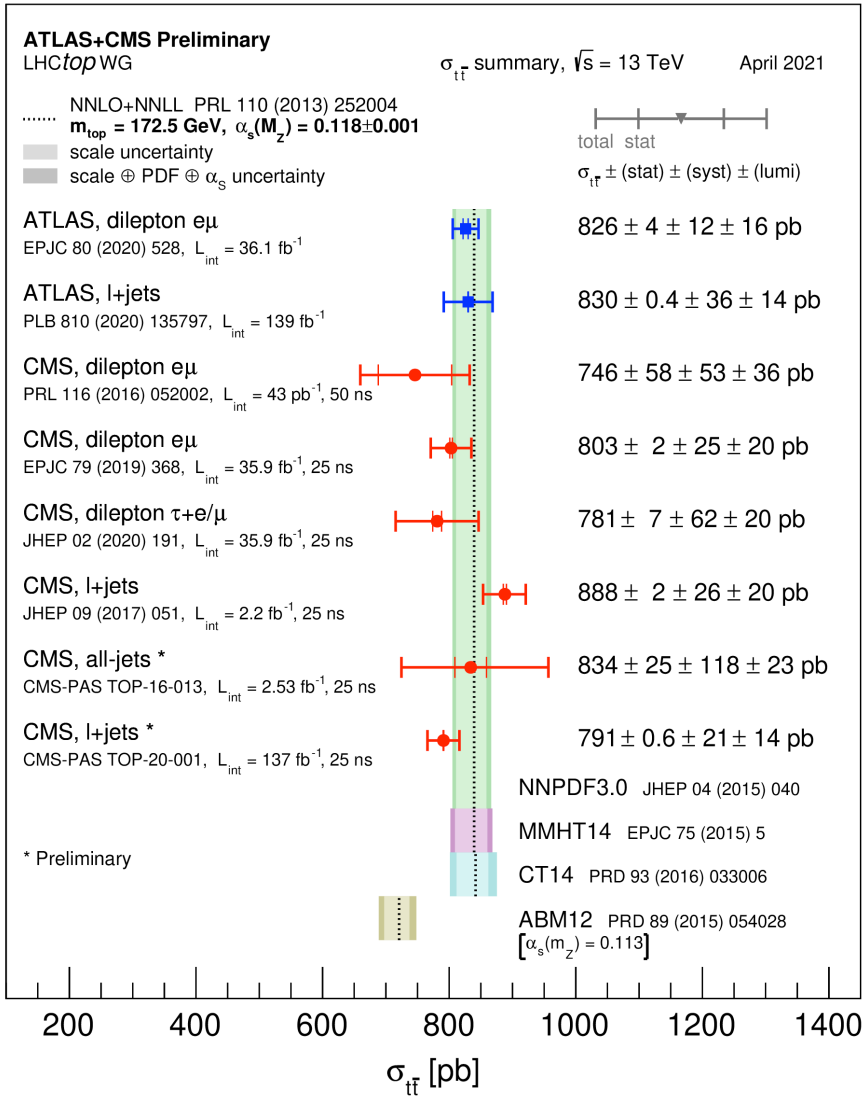
Dominant systematics

Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_T NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
E_T^{miss} + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05
Total uncertainty	±4.3	±4.6

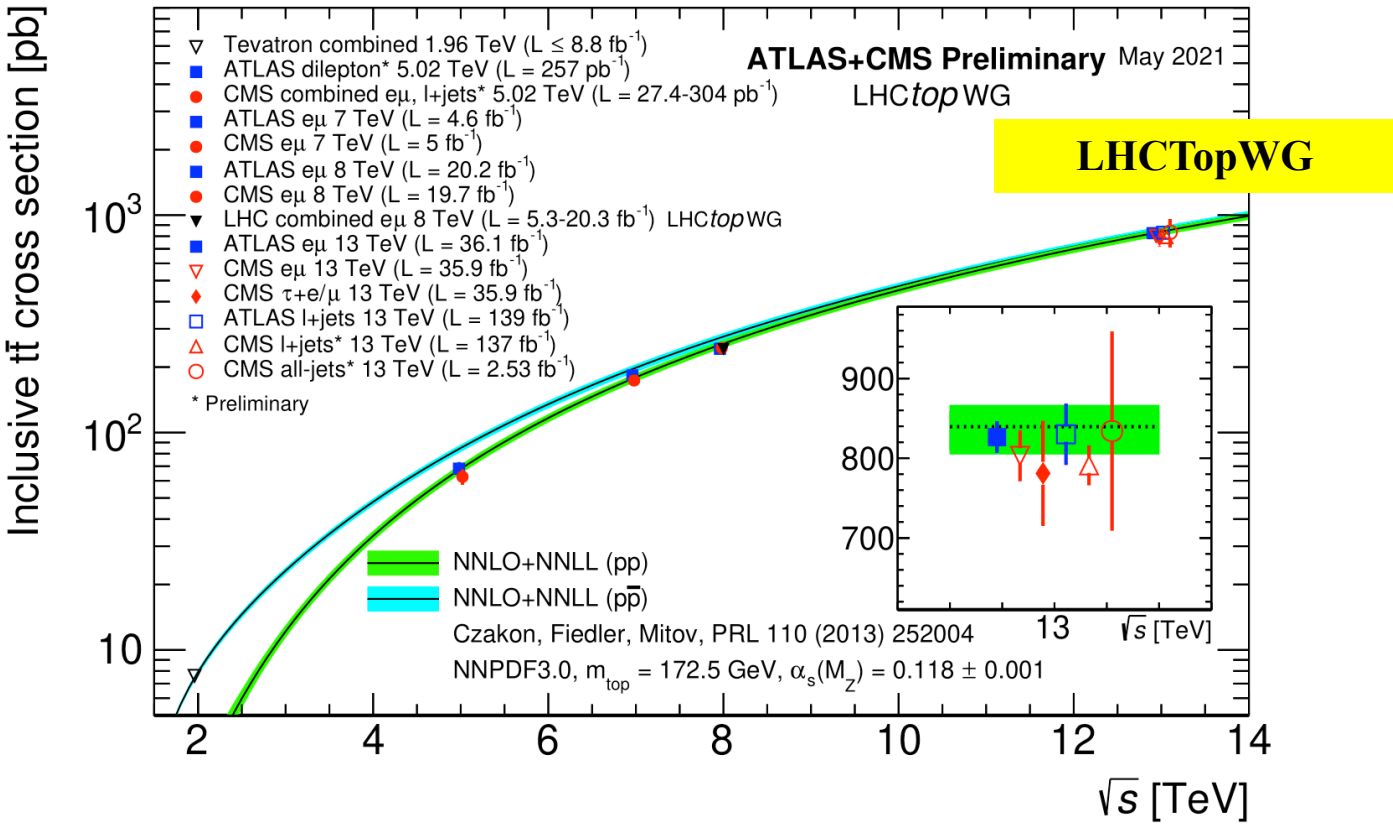
Inclusive $t\bar{t}$ production cross-section

$$\sigma\left(t\bar{t}\right) = \frac{N_{events} - N_{bkg}}{\varepsilon \bullet A \bullet L}$$

LHCTopWG



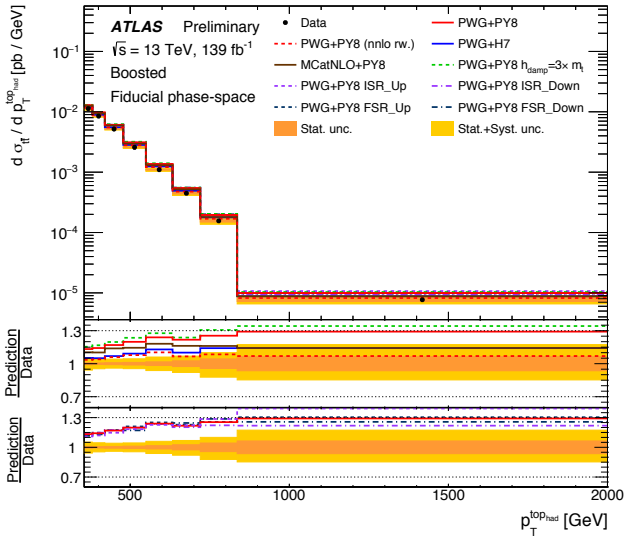
LHCTopWG

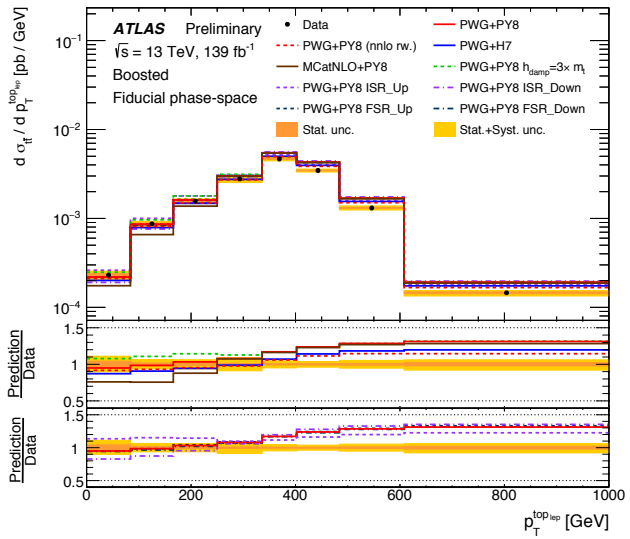


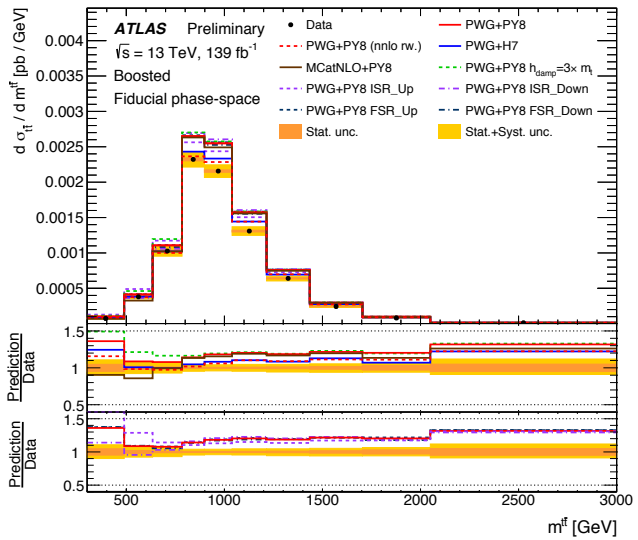
- **Precise cross-section measurements are quite crucial**
  - **Scrutinizes the QCD predictions**
  - **Possibility to extract several SM parameters e.g., α_s, m_{top}…**
- **All inclusive cross-section measurements are consistent with the SM**

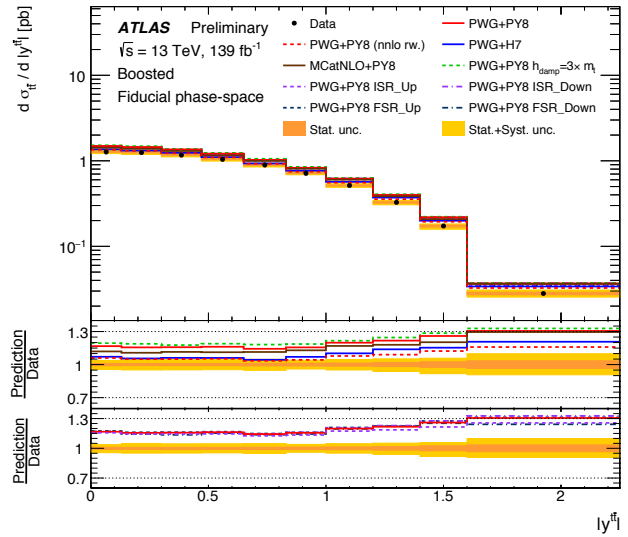
Differential σ ($t\bar{t}$) using boosted top quarks

ATLAS-CONF-2021-031





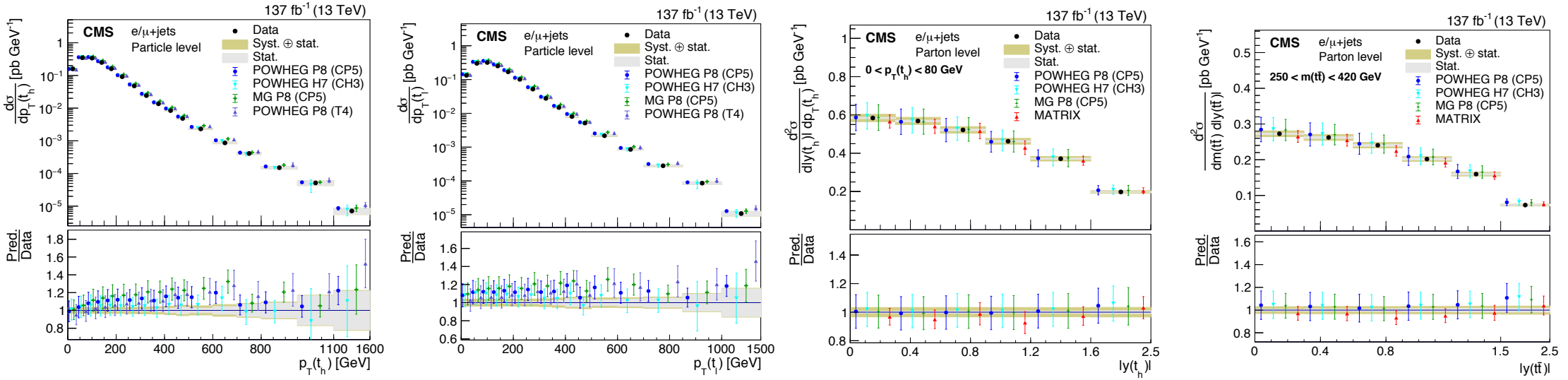




- Lepton+jets channel analysis based on the full Run 2 dataset (139 fb^{-1}) using boosted objects
  - Isolated electron/muon
  - Large-R (ΔR=1.0) hadronic top reconstruction with p_T (hadronic top) > 355 GeV & |η|<2.0
  - ≥2 b-tagged jets
  - In-situ JES correction to reduce the JES uncertainty
- Measured Fiducial cross-section:
  - σ^{Fid} = 1.267 ± 0.0005 (stat) ± 0.053 (syst) pb
  - In agreement with the SM expectations
  - Relative precision of 4.2%
- Differential cross-section
  - Measured as functions of the observables in fiducial regions
- Limited by the systematics
  - Leading ones stem from tt-modelling, b-tagging, luminosity

Inclusive & Differential σ ($t\bar{t}$) in full kinematic range

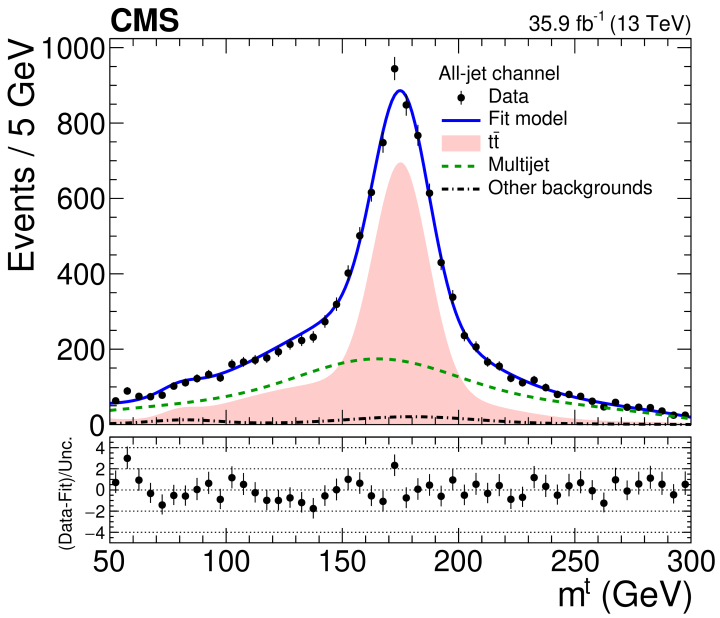
arXiv:2108.02803 [hep-ex]

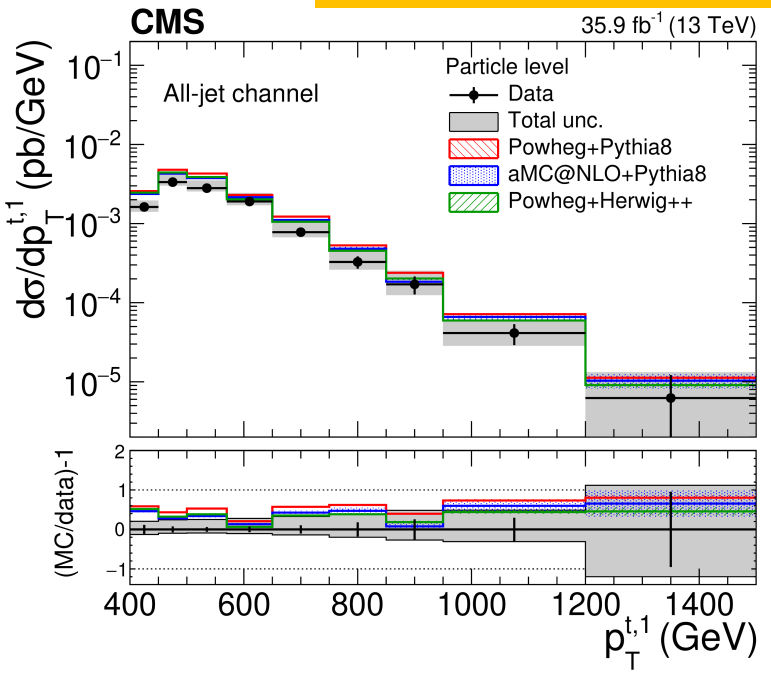


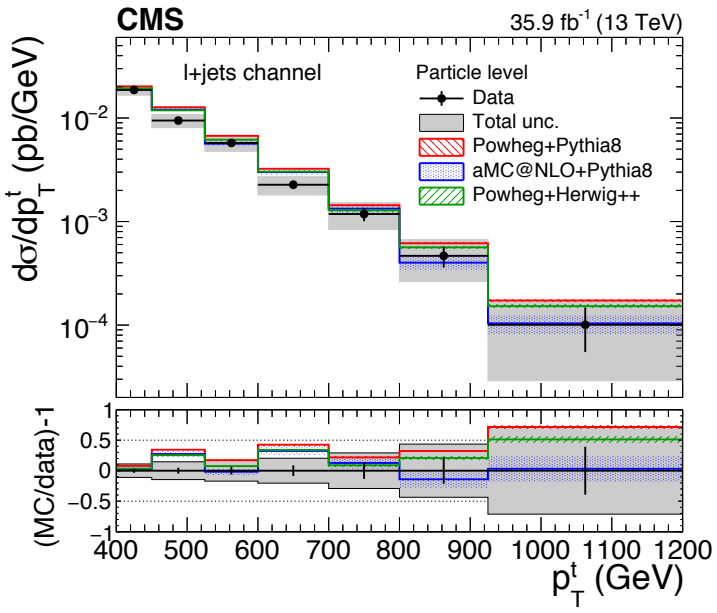
- **Measurements of differential and double-differential cross-section on the l+jets events using full Run 2 dataset (137 fb^{-1}) – both boosted and resolved categories are included**
- **Boosted leptonic (t_l) and hadronic (t_h) tops are defined using the cone of ΔR = 0.4 and 0.8 respectively**
  - **In addition, the invariant mass requirement for t_l (120-240) and hadronic t_h (>120)**
  - **NN discrimination separately for t_l and t_h against the respective backgrounds in different p_T ranges**
- **18 categories of events are fitted together to extract the unfolded cross-sections (represented at the particle and parton levels)**
  - **Differential σ as functions several parton-level observables viz., top (leptonic/hadronic) pT, rapidity (y) , angular separation (Δϕ) between top and antitop, etc.**
  - **Double differential cross-sections as functions of combinations of the above variables**
  - **Inclusive cross-section : $\sigma_{t\bar{t}} = 791 \pm 25\,\mathrm{pb}$**

Differential σ ($t\bar{t}$) using boosted top quarks

Phys. Rev. D 103 (2021) 052008, arXiv:2008.07860 [hep-ex]





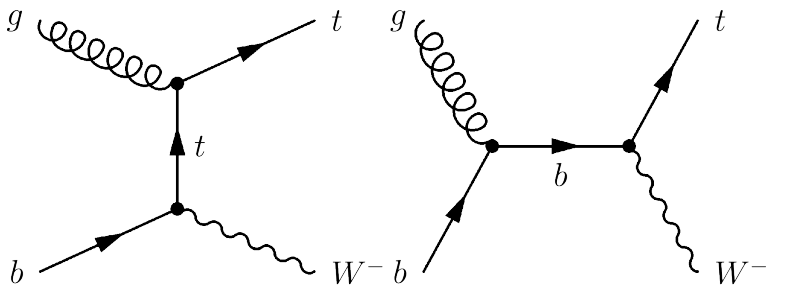


- **Measurements performed on the all-hadronic and l+jets events using 35.9 fb^{-1} 2016 dataset**
  - **Using 1/2 large-R jets (pT>400 GeV), b-tagging**
- **Dedicated fit in the side-band regions**
  - **All hadronic channel: to extract the QCD normalization after NN separation**
  - **L+jets: to extract background normalization**
- **Good agreement on normalized spectra; unfolded σ extracted at particle and parton level**
- **Dominant systematics: JES and b-tagging (All hadronic); PS, FSR (l+jets)**

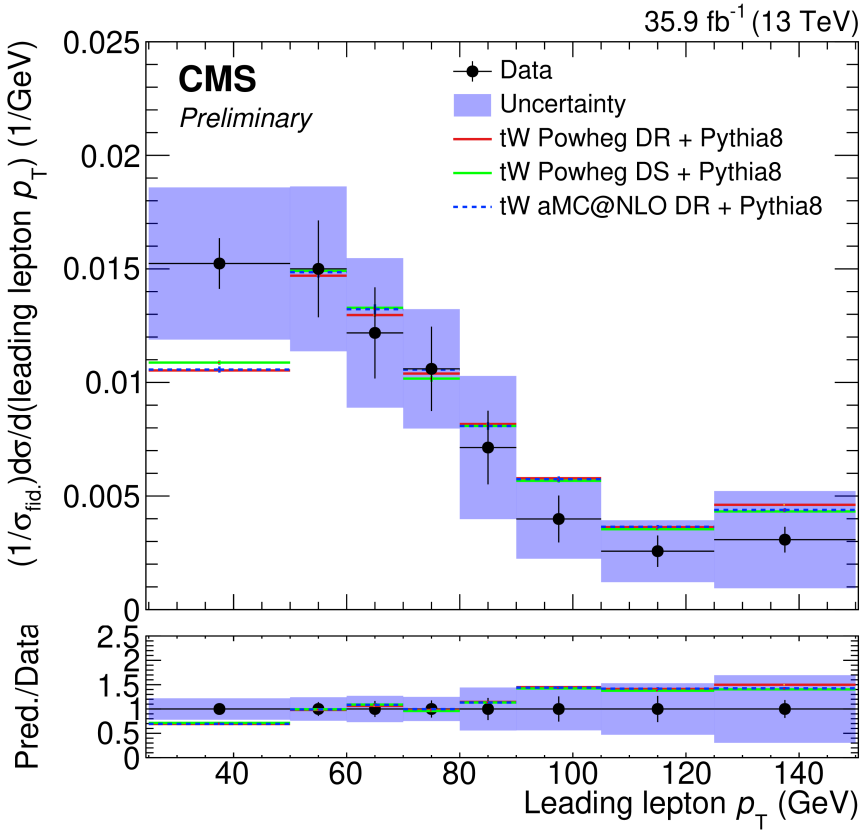
Single Top Cross-section Measurements

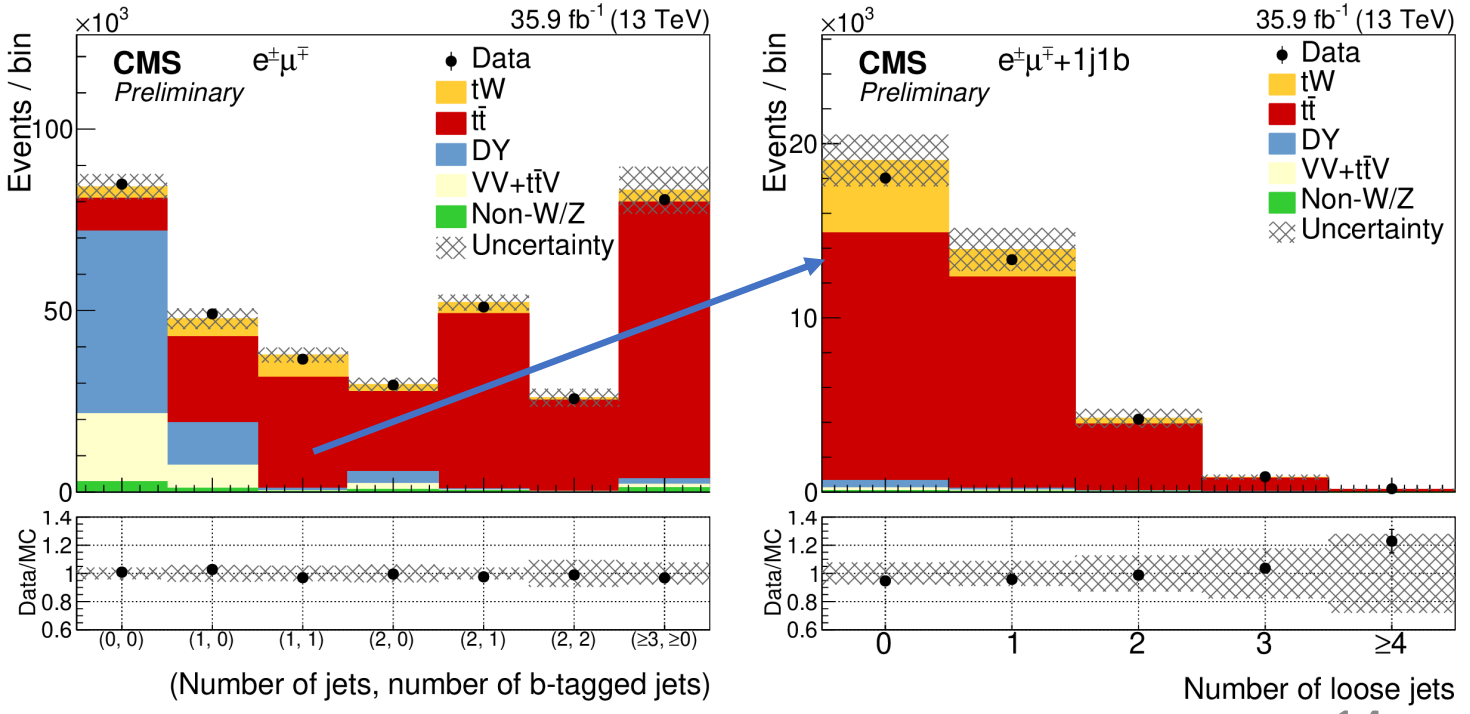
Differential tW Measurements (dilepton)

CMS-PAS-TOP-19-003



- Differential Measurements in dilepton events
  - e, μ, 1 jet and 1 b-jet, no loose jets to enhance S/B ratio
- Background MC estimated and subtracted
- σ^{tW} is measured at the particle-level
- Dominant uncertainty from JES and JER

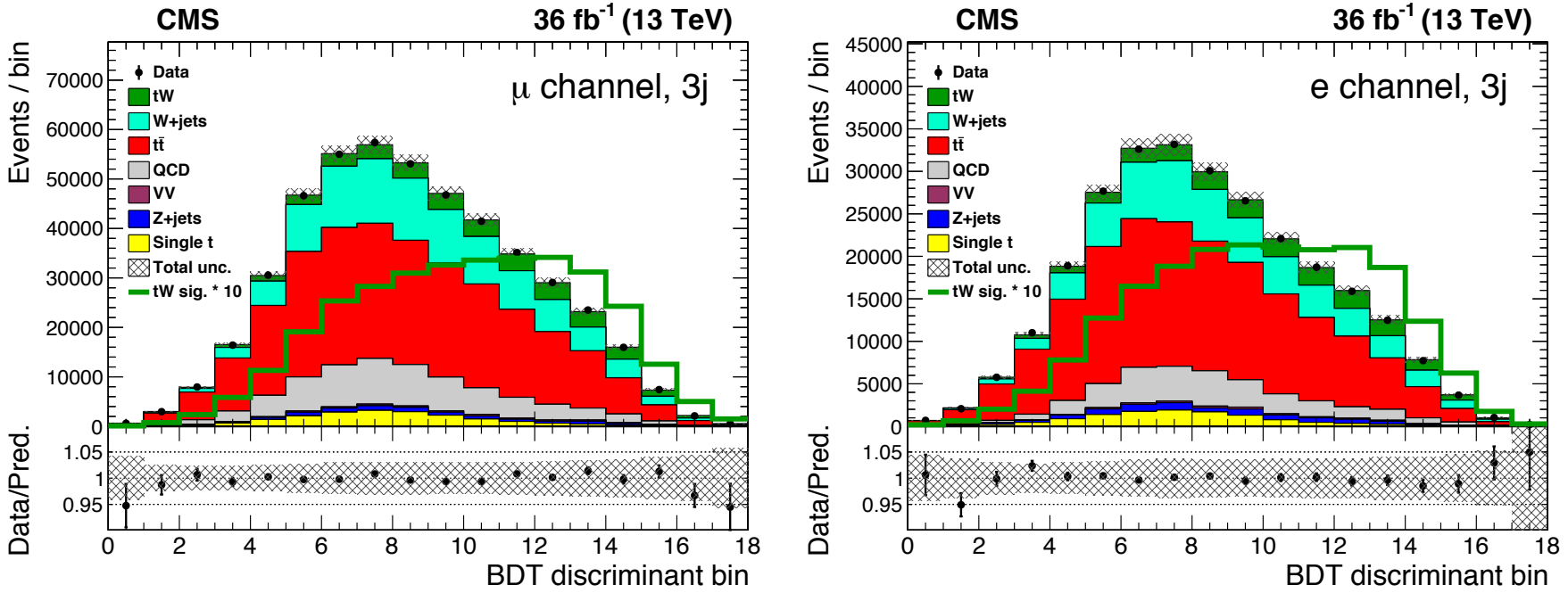




Observation of tW (e/μ+jets)

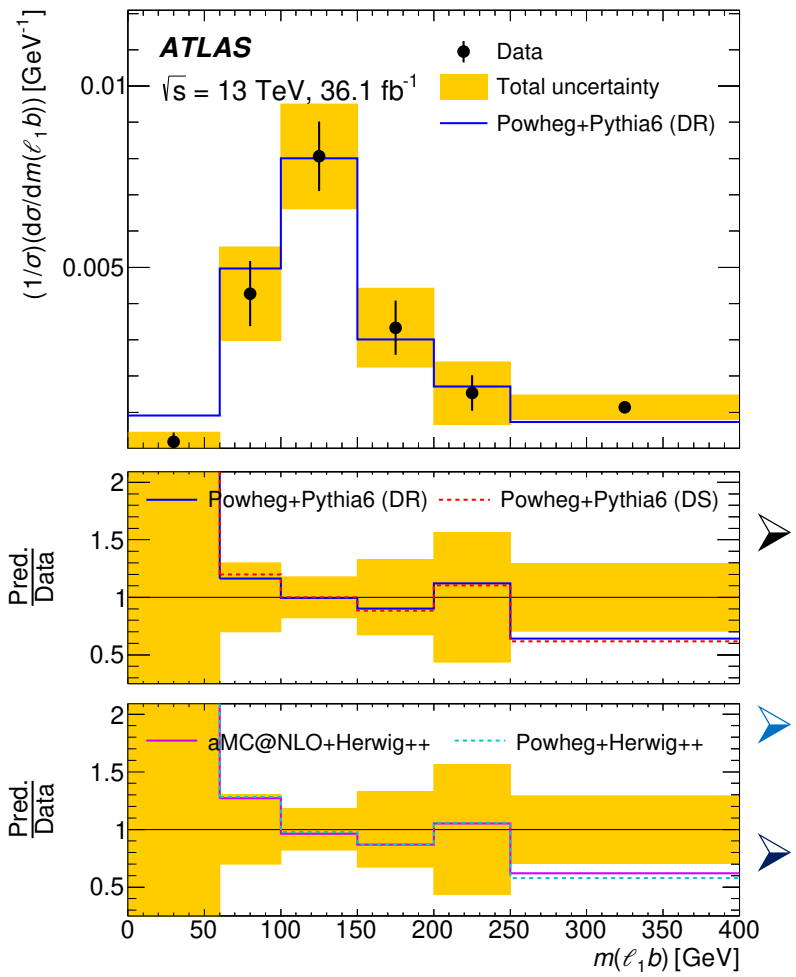
JHEP (submitted in Sept'21); axXiv:2109.01706[hep-ex]

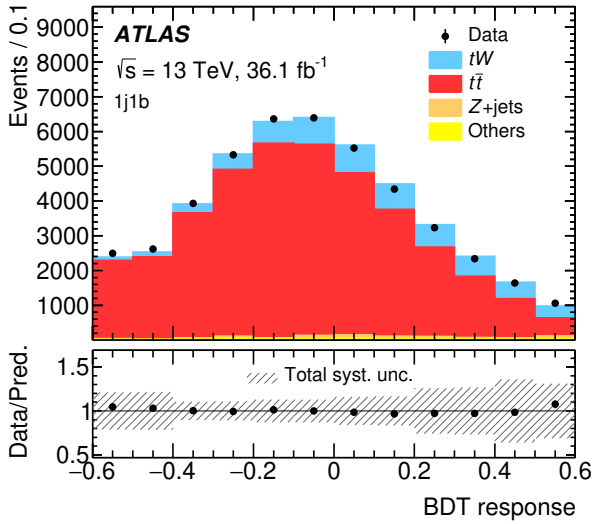
- Differential Measurements in lepton+jets events using 36 fb^{-1} 2016 dataset
  - e/μ, 3 jets and ≥1 b-jet; event categorization based on # of jets
- Usage of boosted decision trees to separate from the tt background and binned likelihood fit of the BDT output distribution to extract the production cross-section
- **First observation of tW process (in e/μ+jets) with significance >5 standard deviation**
  - **σ^{tW} = 89 ± 4 (stat) ± 12 (syst) pb consistent with the SM**
- Dominant uncertainty from JES, QCD multijet and W+jets normalization

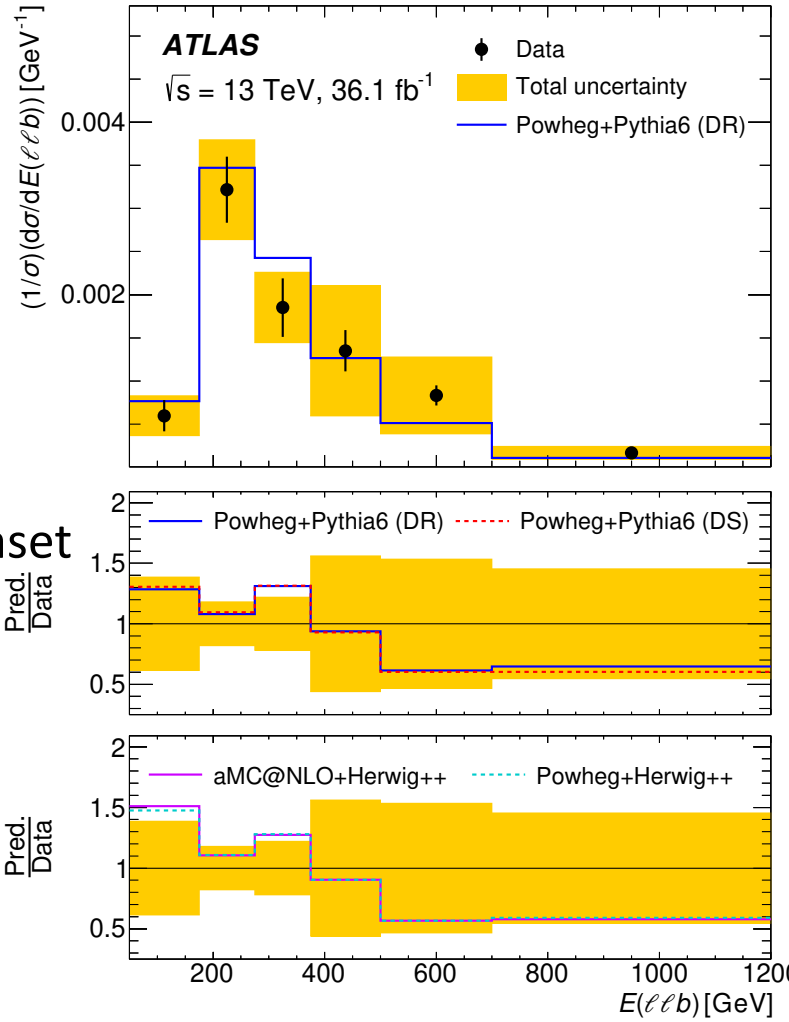


Differential tW cross-section measurements

Eur. Phys J. C 78 (2018) 186; arXiv: 1712.01602 [hep-ex]

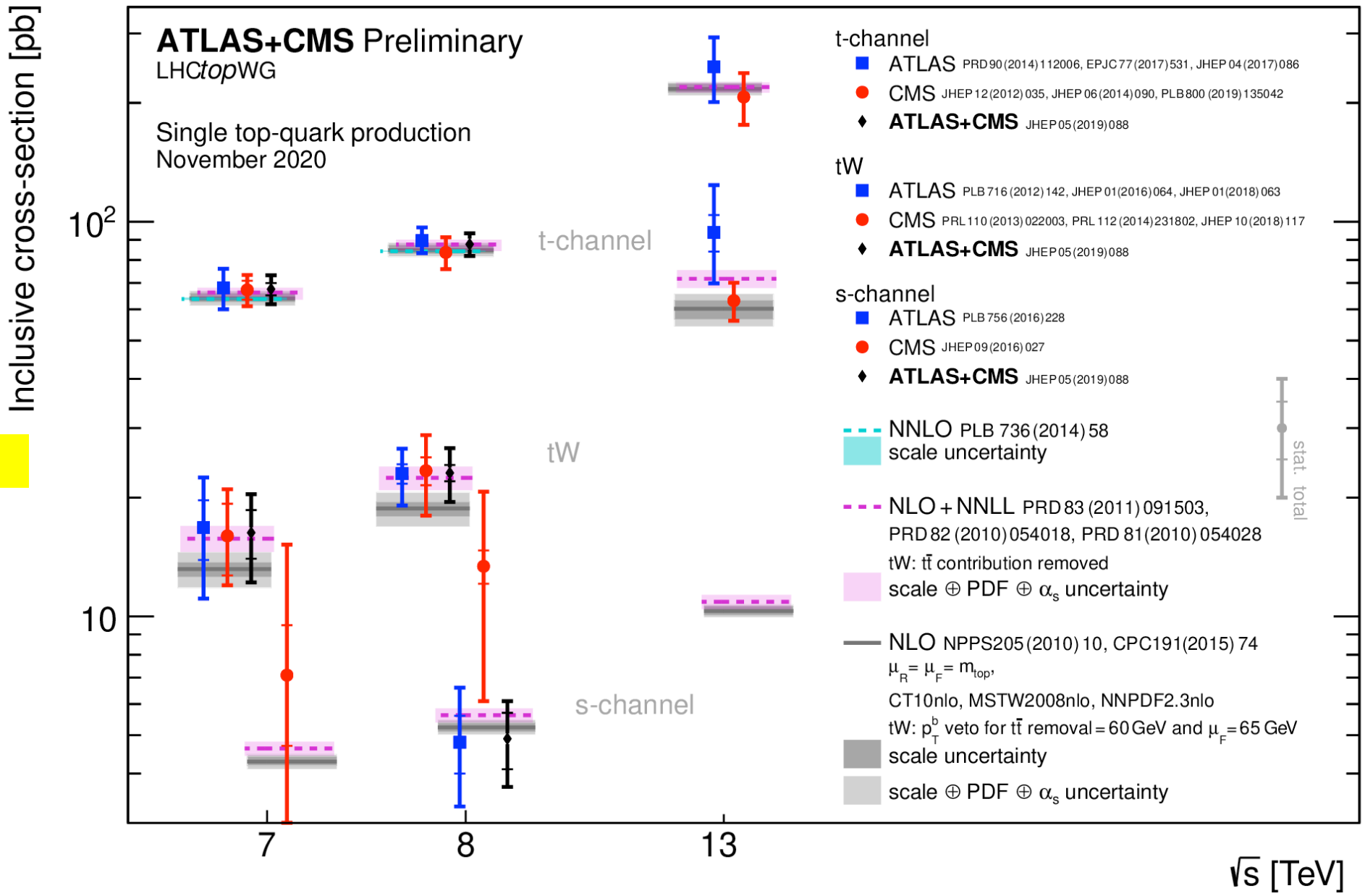






- In dilepton events using 36 fb^{-1} 2016 dataset
  - Fiducial space defined with 2 OS leptons and exactly one 1 b-jet
- Usage of boosted decision trees (BDT) to separate tW from the tt background
- **Differential measurement performed as functions of several observables at particle-level, normalized to the fiducial cross-section**

Summary of Single Top cross-section at LHC

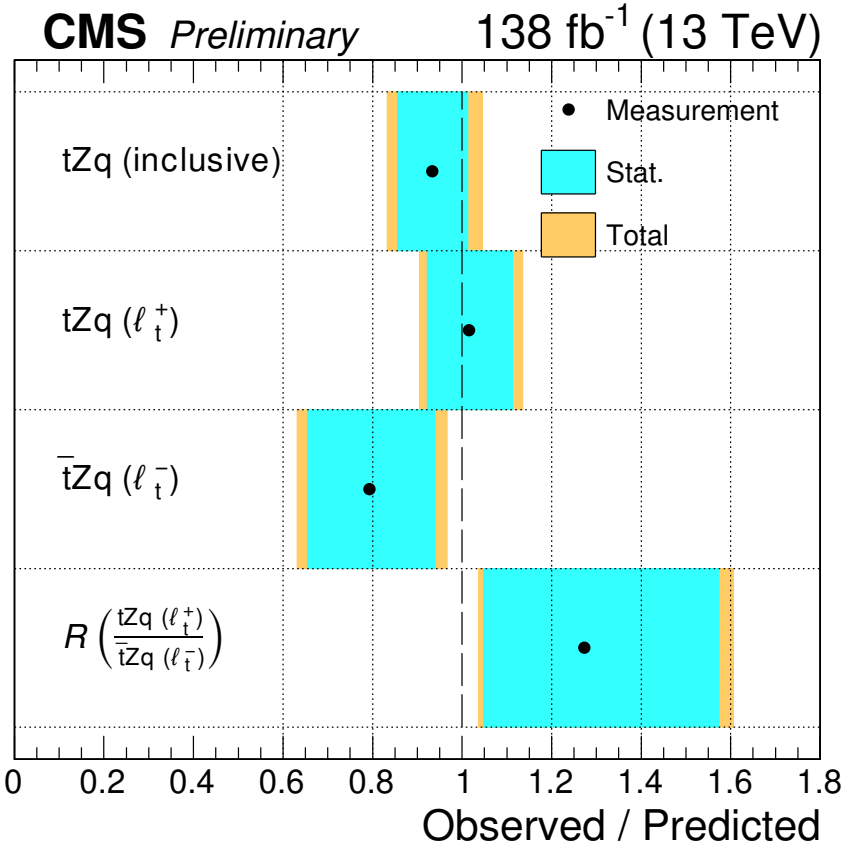


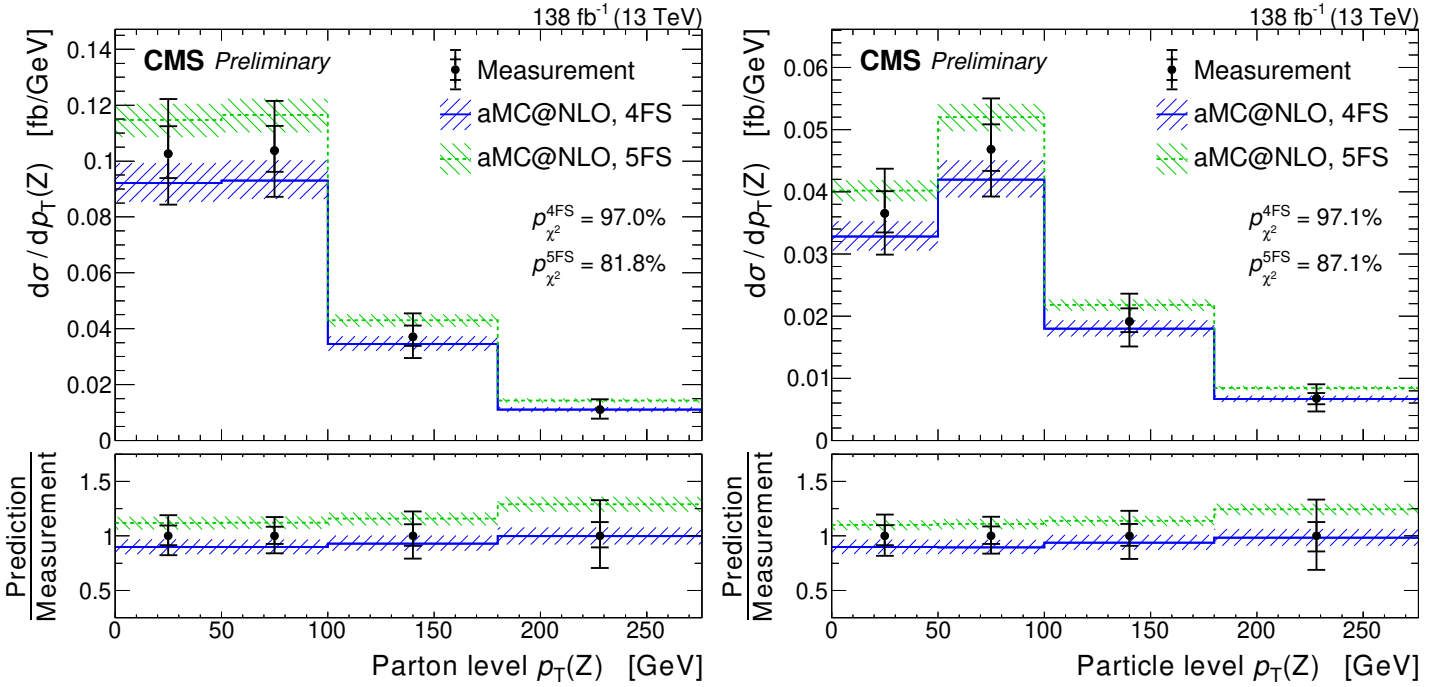
LHCTopWG

Inclusive and Differential tZq cross-section measurements

CMS-PAS-TOP-20-010

- Measurement in tri-lepton channel using the full Run 2 dataset (138 fb^{-1})





$$\sigma_{\mathrm{tZq}} = 87.9\ ^{+7.5}_{-7.3}\ (\mathrm{stat})\ ^{+7.3}_{-6.0}\ (\mathrm{syst})\ \mathrm{fb}\ .$$

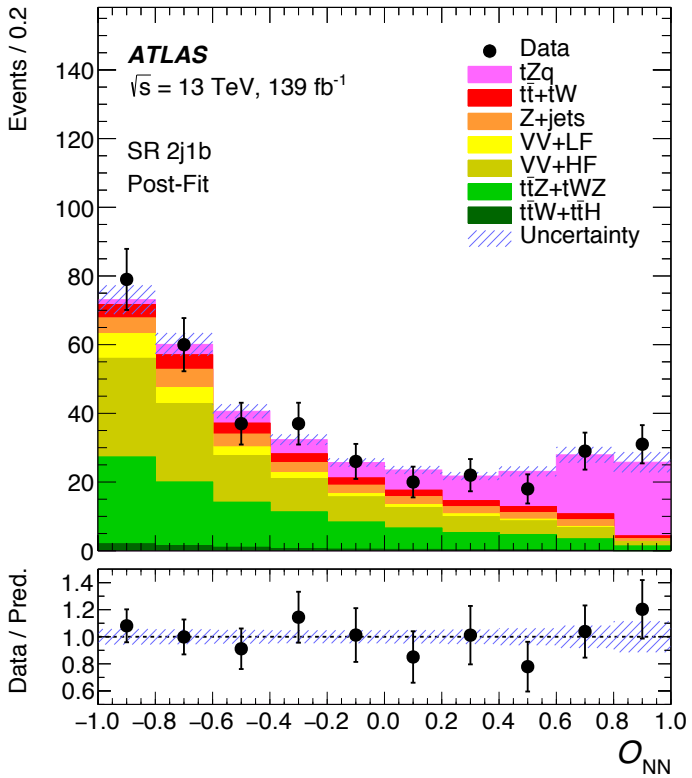
$$R = 2.37\ ^{+0.56}_{-0.42}\ (\mathrm{stat})\ ^{+0.27}_{-0.13}\ (\mathrm{syst})$$

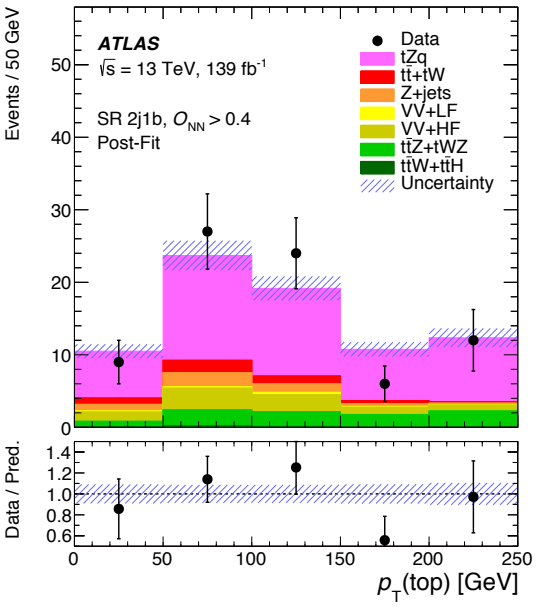
- **Differential σ_{tZq} is measured for both at particle-level and at parton-level using ML-based unfolding**
  - **Results are in good agreement with the SM**

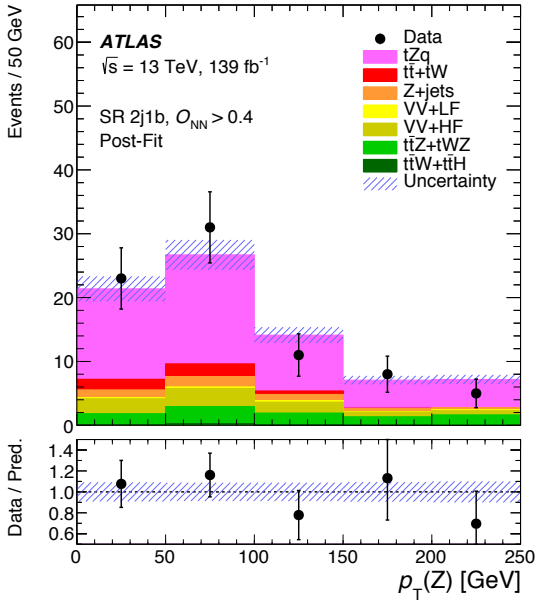
Observation of tZq process at √s=13 TeV

JHEP 07 (2020) 124; arXiv: 2002.07546 [hep-ex]

- Measurement in tri-lepton channel using the full Run 2 dataset (138 fb^{-1})
- Events with 3 isolated leptons, 2-3 jets with ≥1 b-tagged jet
- tZq signal strength extracted by ML fit for the NN discriminant output







- Measured $\sigma_{tZ(\to ll)\,q}$ = 97 ± 13 (stat) ± 7 (syst) fb
  → consistent with the SM prediction of 102^{+5}_{-2} fb

Summary & Conclusions

- ✧During the LHC era, the statistics of top quark events in data has reached to a new level leading to the ATLAS/CMS measurements at an unprecedented precision
  - ✧Many new measurements have already been performed/completed with the full/partial Run 2 dataset
- ✧Inclusive and differential Cross-section presented here involving strong and electroweak production of top quark(s)
  - ✧ All the measurements are consistent with the SM predictions
- ✧ With the enhanced LHC Run 2 statistics, rare SM processes like tW and tZq have been observed now by ATLAS and CMS
  - ✧More refined measurements would probe the BSM physics further
- ✧ Better understanding of detector effects and physics modelling would improve the systematics related to the top quark measurements

References

- LHCTopWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP