Inclusive & differential cross-section measurements of top-quark-pair production with ATLAS and CMS

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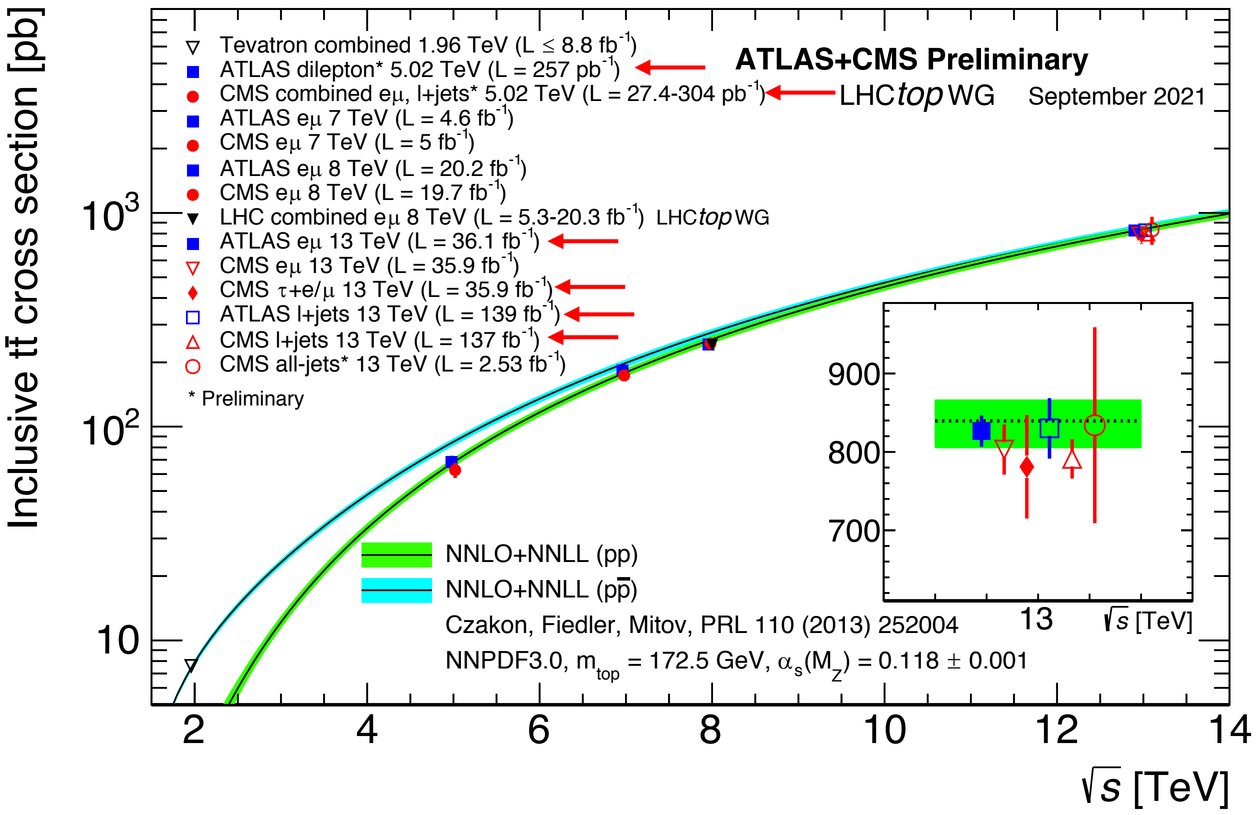
Why $t\bar{t}$ and how?

$t\bar{t}$ measurements can be used to:

- Assess current level of understanding of the SM
- Perform studies to improve MC tuning and systematic uncertainty definitions
- Provide inputs to the gluon PDF
- Extract top mass and α_S
- Set limits on the existence of new physics.



- ➢ **All-hadronic final state**: very challenging
- ➢ **Semi- and di-leptonic final state**: high-precision level can be reached
- ➢ **5, 7, 8, and 13 TeV measurements** were performed*

* = Brief summary of ONLY latest results on 5.02 and 13 TeV LHC data.

Inclusive $\sigma_{t\bar{t}}$ measurements

$\sigma(t\bar{t})$: dilepton @5 TeV – ATLAS

ATLAS EXPERIMENT

5.02 TeV
L = 257 pb^{-1}

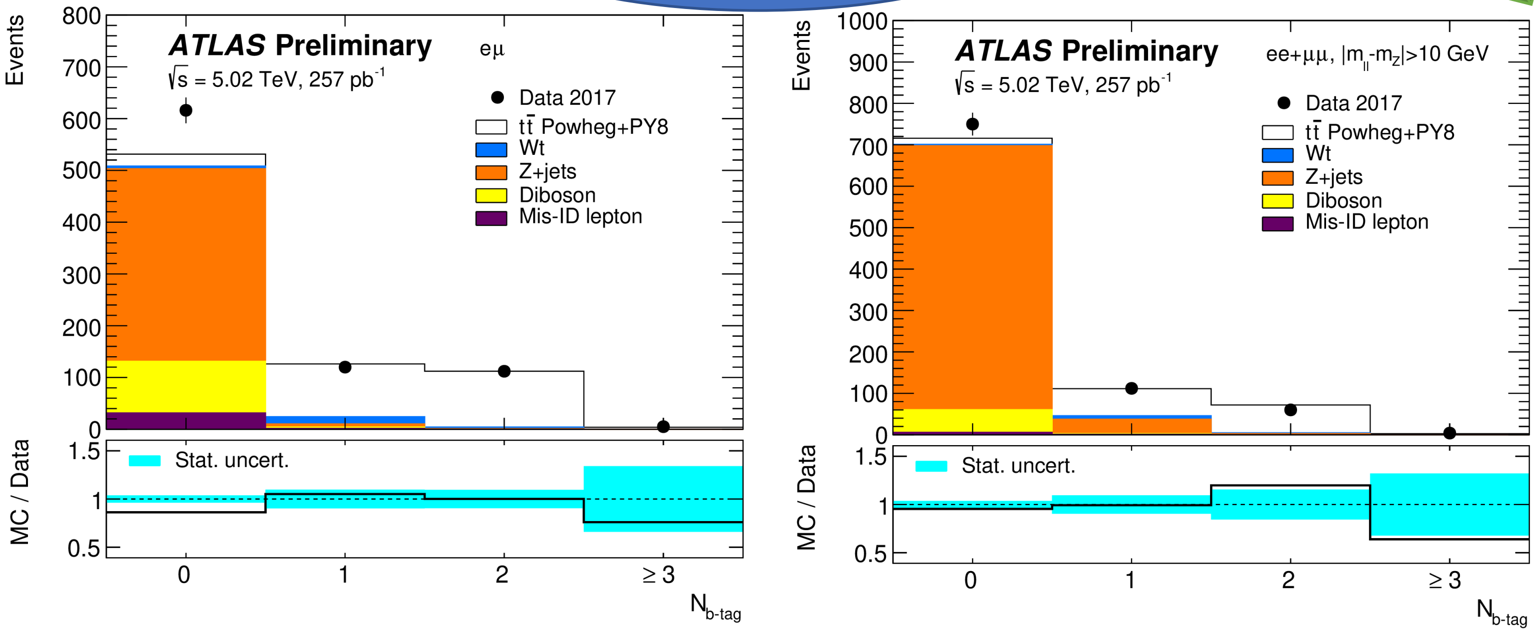
$$\sigma^{NNLO}(5\,TeV) = 68.2 \pm 4.8\,(PDF)\,^{+1.9}_{-2.3}\,(\alpha_S)\,pb$$

ATLAS-CONF-2021-003

Same technique used for 7,8 TeV

NEW

- μμ, ee and eμ channels;
- Counting technique: σ extracted counting the number of b-tags;
- Fit including also m_{ll} information for μμ, ee channels, to constrain also Z+jets background;
- σ extracted at the same time with a parameter sensitive to the b-tagging efficiency to limit the related uncertainty (0.1%);
- No requirements applied on the number of jets ⇒ Very small related uncertainties (0.03%).
- Combination with l+jets channel ongoing



$$\boldsymbol{\sigma = 66.0 \pm 4.5\,(stat) \pm 1.6\,(syst) \pm 1.2\,(lumi) \pm 0.2\,(beam)\,pb}$$

total relative uncertainty of 7.5%

Syst dominated by $t\bar{t}$ and single top modelling

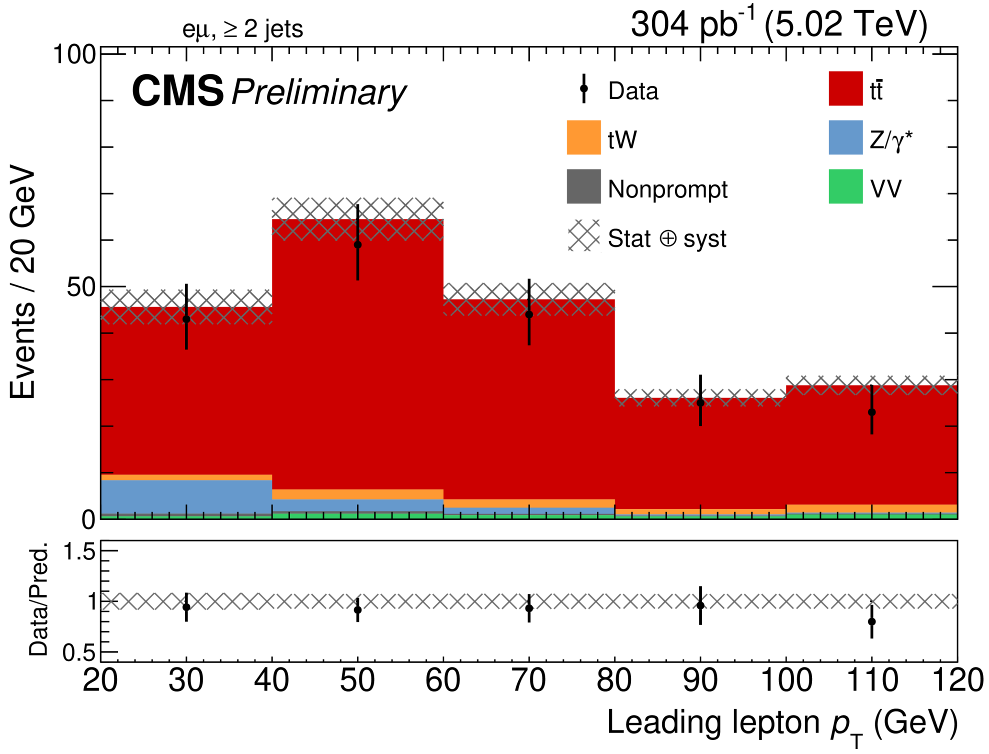
$\sigma(t\bar{t})$: dilepton @5 TeV – CMS

5.02 TeV
L = 304 pb^{-1}

$$\sigma^{NNLO}(5\ TeV) = 68.2 \pm 4.8\ (PDF)\ ^{+1.9}_{-2.3}\ (\alpha_S)\ pb$$

TOP-20-004

NEW



- eμ OS + at least 2 jets
- DY SF obtained (under the Z boson mass) to a better estimation of the background
- Counting experiment $\sigma_{t\bar{t}} = \frac{N - N_{bkg}}{\varepsilon\ A\ BR\ L}$
- Measurement combined together with the l+jets (2015, JHEP 03 (2018) 115) with the BLUE combination.

$\sigma = 60.3 \pm 5.0\ (stat) \pm 2.8\ (syst) \pm 0.9\ (lumi)\ pb$ [only dilepton]

Dominant syst are the JES (2.2%) and DY (1.8%)

$$\boldsymbol{\sigma = 62.6 \pm 4.1\ (stat) \pm 3.0\ (syst + lumi)\ pb}$$

27% for l+jets, 73% for dilepton

total relative uncertainty of 7.9%

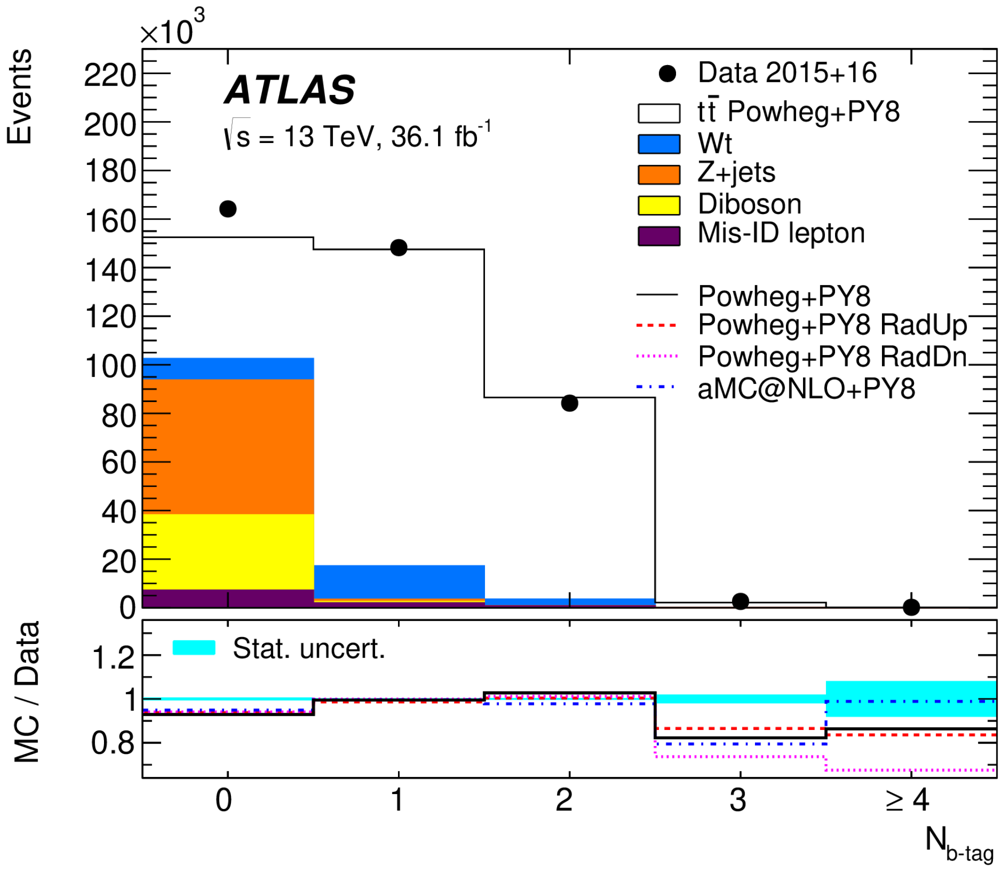
$\sigma(t\bar{t})$: dilepton @13 TeV – ATLAS

13 TeV
L = 36.1 fb^{-1}

$$\sigma^{NNLO}(13\ TeV) = 831.76^{+19.77}_{-29.20}(scale) \pm 35.06\ (PDF + \alpha_S)\ pb$$

Eur. Phys. J. C 80 (2020) 528

- Same technique as for 5.02 TeV measurement
- eμ OS channel
- Counting technique: σ extracted counting the number of b-tags ⇒ same technique used for 5 TeV
- Measurement extremely limited by luminosity
- Small impact of the jet related uncertainties



$$\boldsymbol{\sigma = 826.4 \pm 3.6\ (stat) \pm 11.5\ (syst) \pm 15.7\ (lumi) \pm 1.9\ (beam)\ pb}$$

total relative uncertainty of 2.40%

Dominant syst are $t\bar{t}$ modelling (0.67%) and Wt background (0.52%)

$\sigma(t\bar{t})$: dilepton (with τ) @13 TeV – CMS

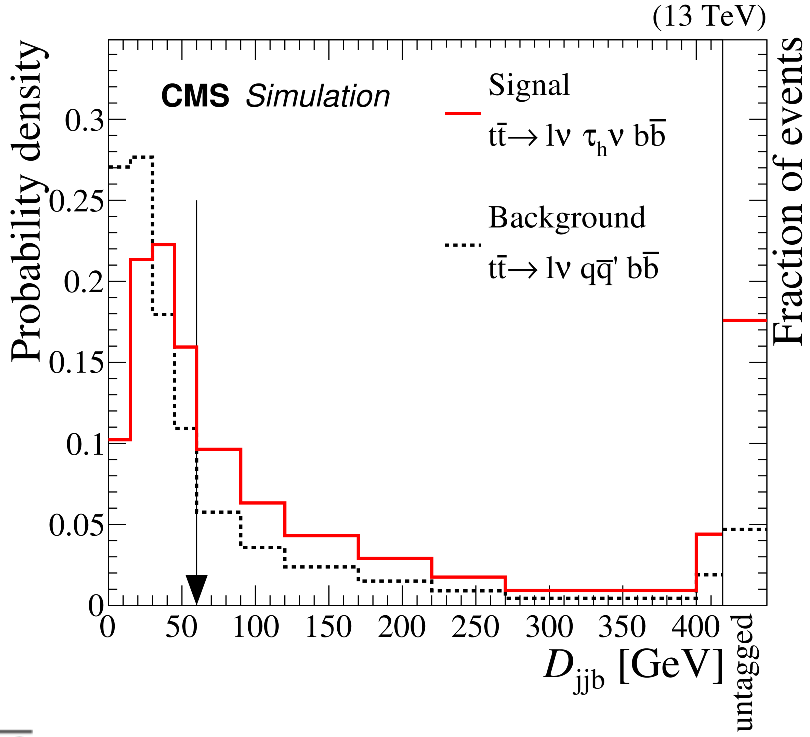
13 TeV
L = 35.9 fb^{-1}

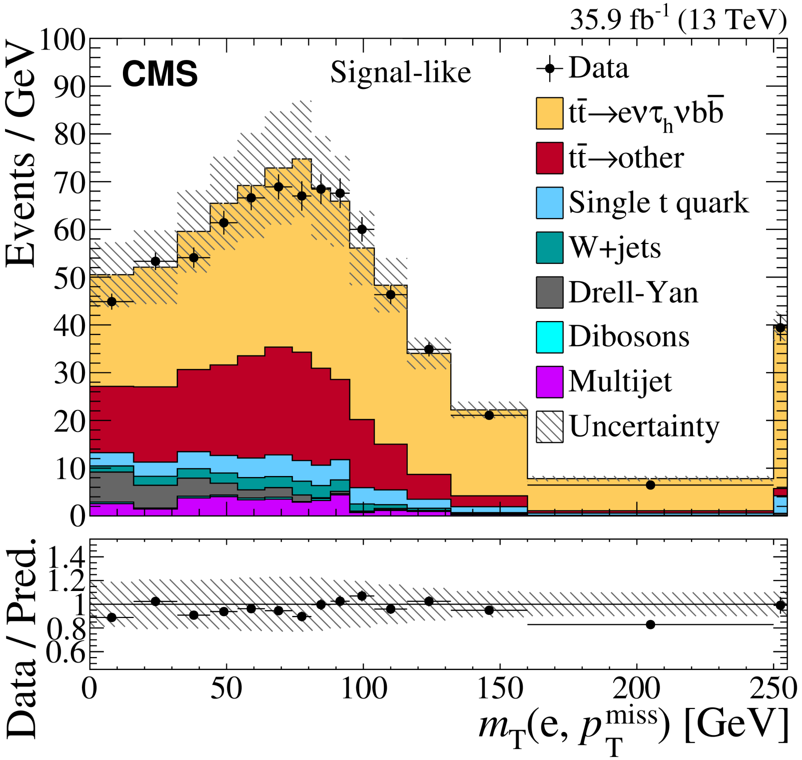
$$\sigma^{NNLO}(13\ TeV) = 831.76^{+19.77}_{-29.20}(scale) \pm 35.06\ (PDF + \alpha_S)\ pb$$

TOP-18-015
JHEP 02 (2020) 191

- First measurement at 13 TeV including τ
- $\mu\tau_h$, $e\tau_h$ channels with τ decaying hadronically
- e/μ + at least 3 jets, of which at least 1 is b-tagged and one identified as hadronic τ
- Invariant mass of the jet triplets used as signal-background discriminator

$$D_{jjb} = \sqrt{(m_W - m_{jj})^2 + (m_t - m_{jjb})^2}$$





- Mis-identified τ_h constrained in the overall fit to the data in the m_T distribution.

$$\boldsymbol{\sigma = 781 \pm 7\ (stat) \pm 62\ (syst) \pm 20\ (lumi)\ pb}$$

total relative uncertainty of 8.4%

Dominant syst are related to the τ identification (4.5%) and mis-identification (2.3%)

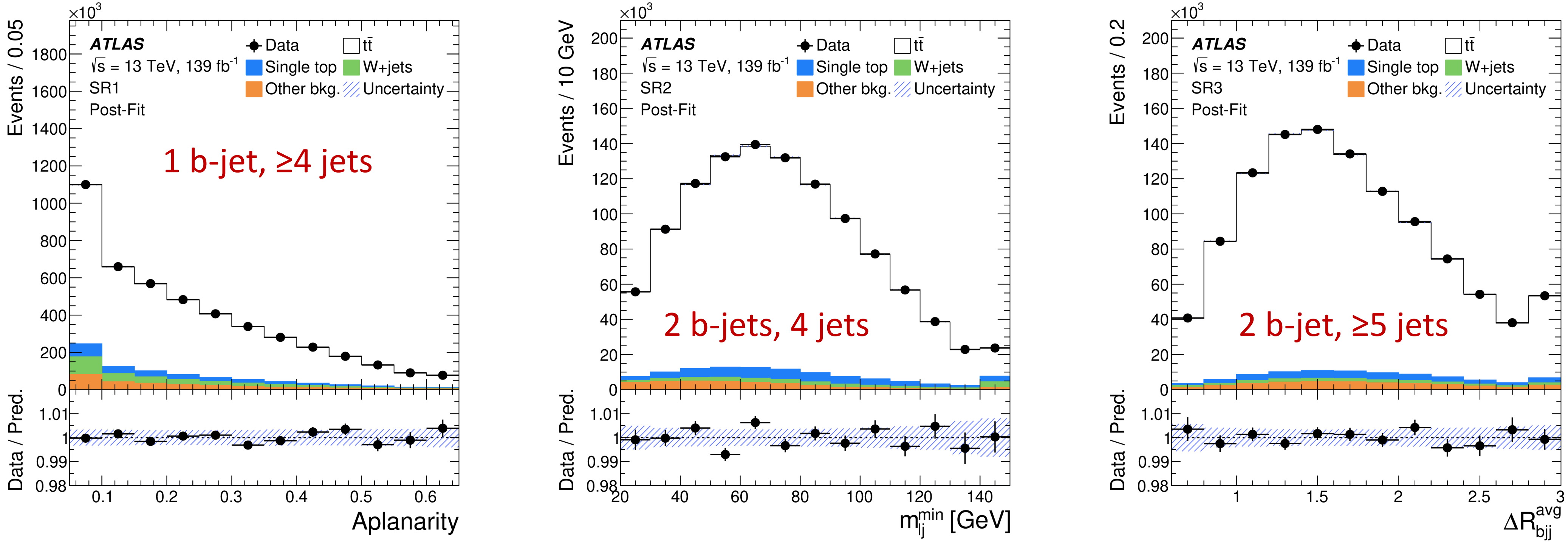
$\sigma(t\bar{t})$: l+jets @13 TeV – ATLAS

13 TeV
L = 139 fb^{-1}

$$\sigma^{NNLO}(13\ TeV) = 831.76^{+19.77}_{-29.20}(scale) \pm 35.06\ (PDF + \alpha_S)\ pb$$

Phys. Lett. B 810 (2020) 135797

- 3 signal region (SR) categorised according to the number of jet/b-jet
- Profile likelihood to fit 3 distributions (one per each SR)



$$\sigma = 830 \pm 0.4\ (stat) \pm 36\ (syst) \pm 14\ (lumi)\ pb$$

total relative uncertainty of 4.6%

Dominant syst are $t\bar{t}$ modelling (2.9%) and Jet reconstruction (2.6%)

Differential $\sigma_{t\bar{t}}$ measurements

$\sigma(t\bar{t})$ differential: dilepton @13 TeV – ATLAS

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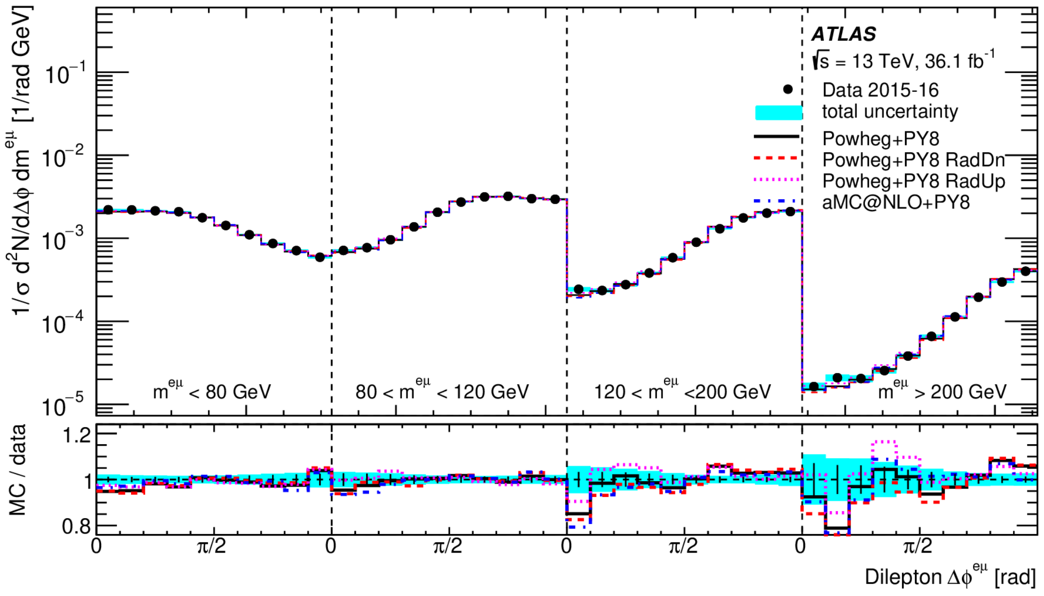
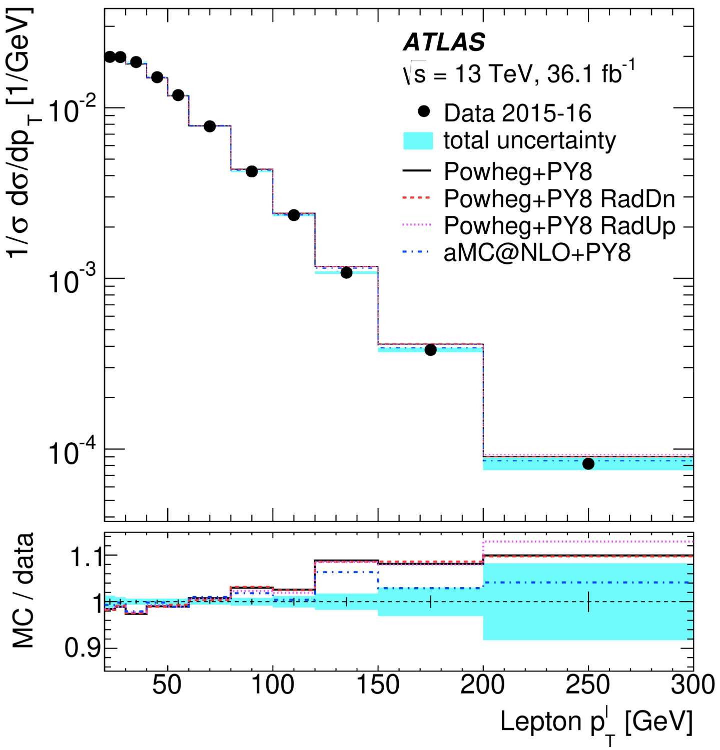
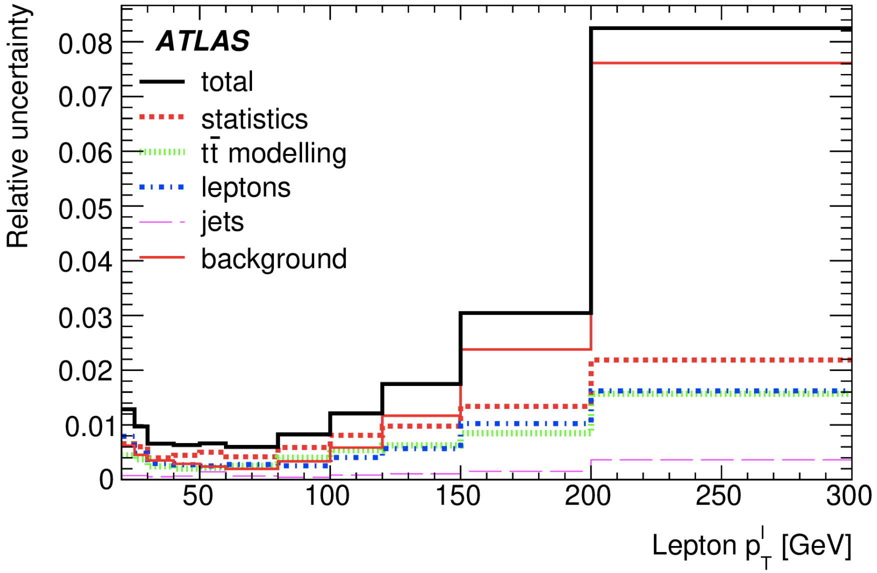
13 TeV
L = 36.1 fb^{-1}

- Same technique as inclusive: counting measurement
- Measurements as a function of several lepton kinematic variables







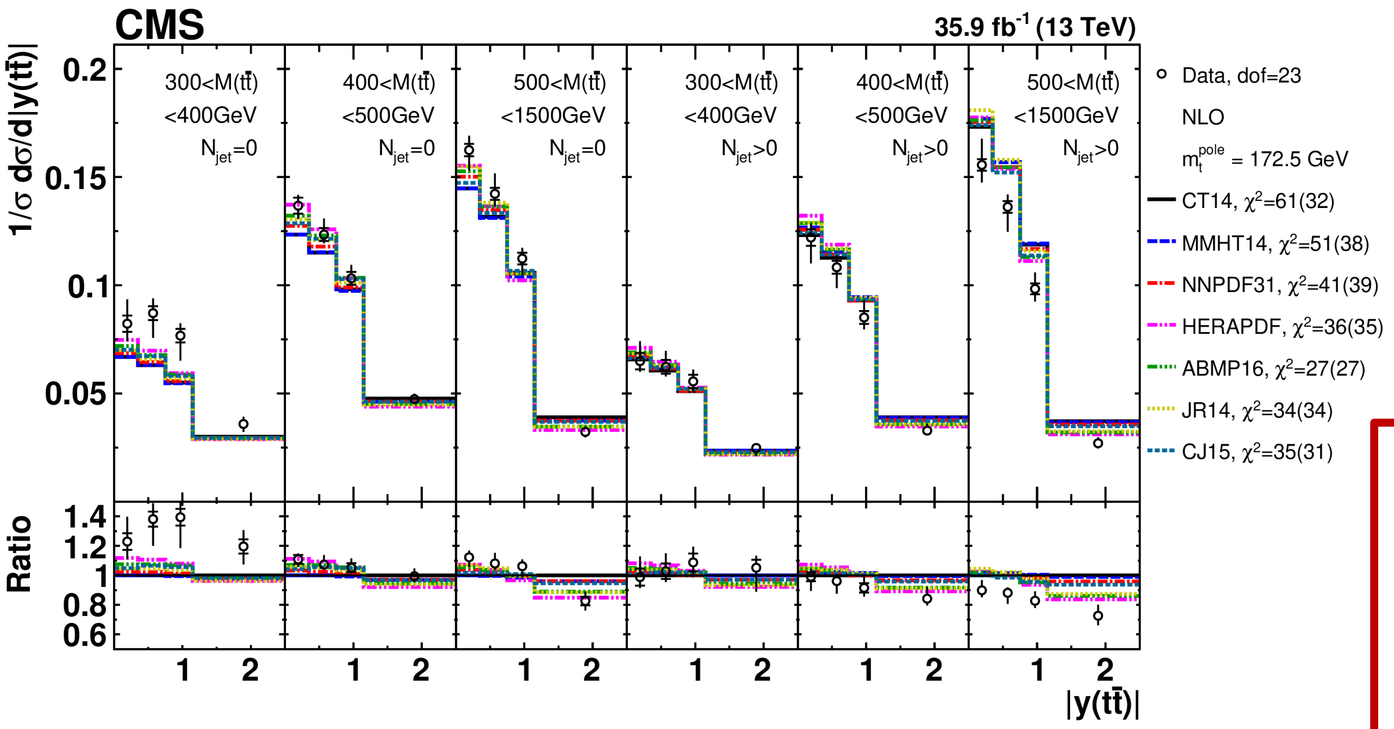
- NLO+PS predictions give a good dscription of several observables
- POWHEG predict a harder spectrum for lepton pT's variables

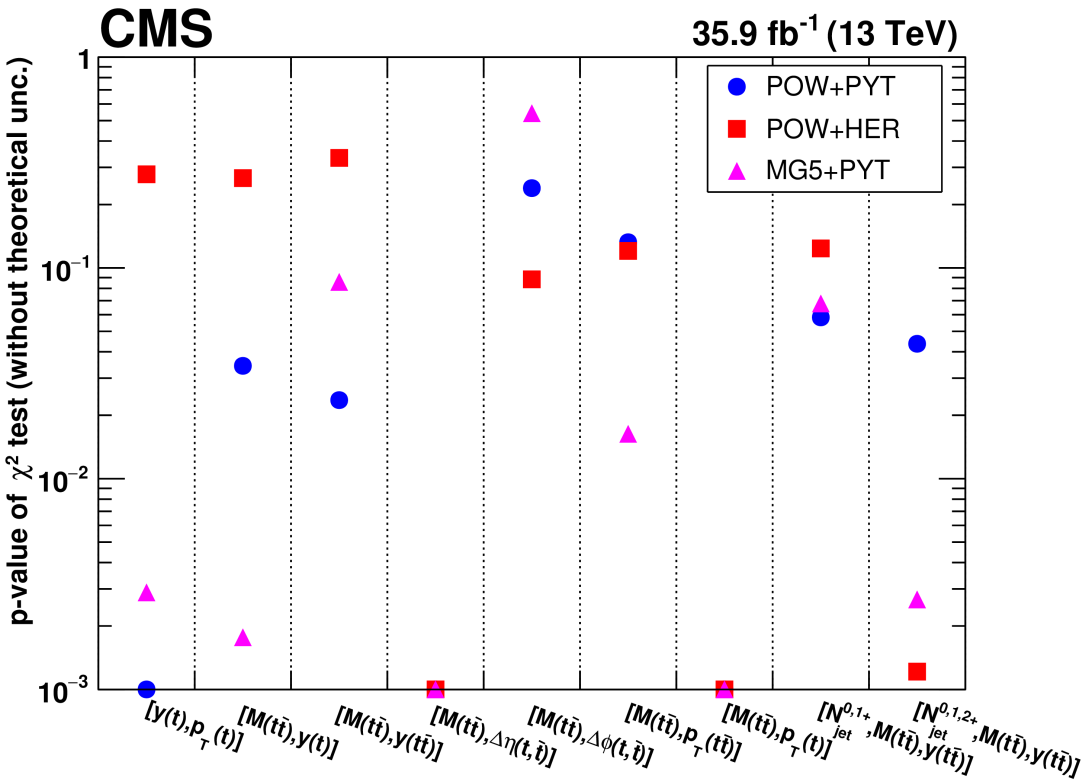
$\sigma(t\bar{t})$ differential: dilepton @13 TeV – CMS

13 TeV
L = 35.9 fb^{-1}

[TOP-18-004](#)
[Eur. Phys. J. C 80 (2020) 658](#)

- μμ, ee and eμ OS channels;
- Double and triple differential measurements
- The total uncertainties are dominated by the systematic uncertainties. Largest systematic uncertainty is associated with the JES.





- best agreement for '*POW+PYT*' and '*POW+HER*', with '*POW+PYT*' better describing the measurements probing Njet and radiation, and '*POW+HER*' better describing the ones involving probes of the p_T distribution.

$\sigma(t\bar{t})$: l+jets @13 TeV – CMS

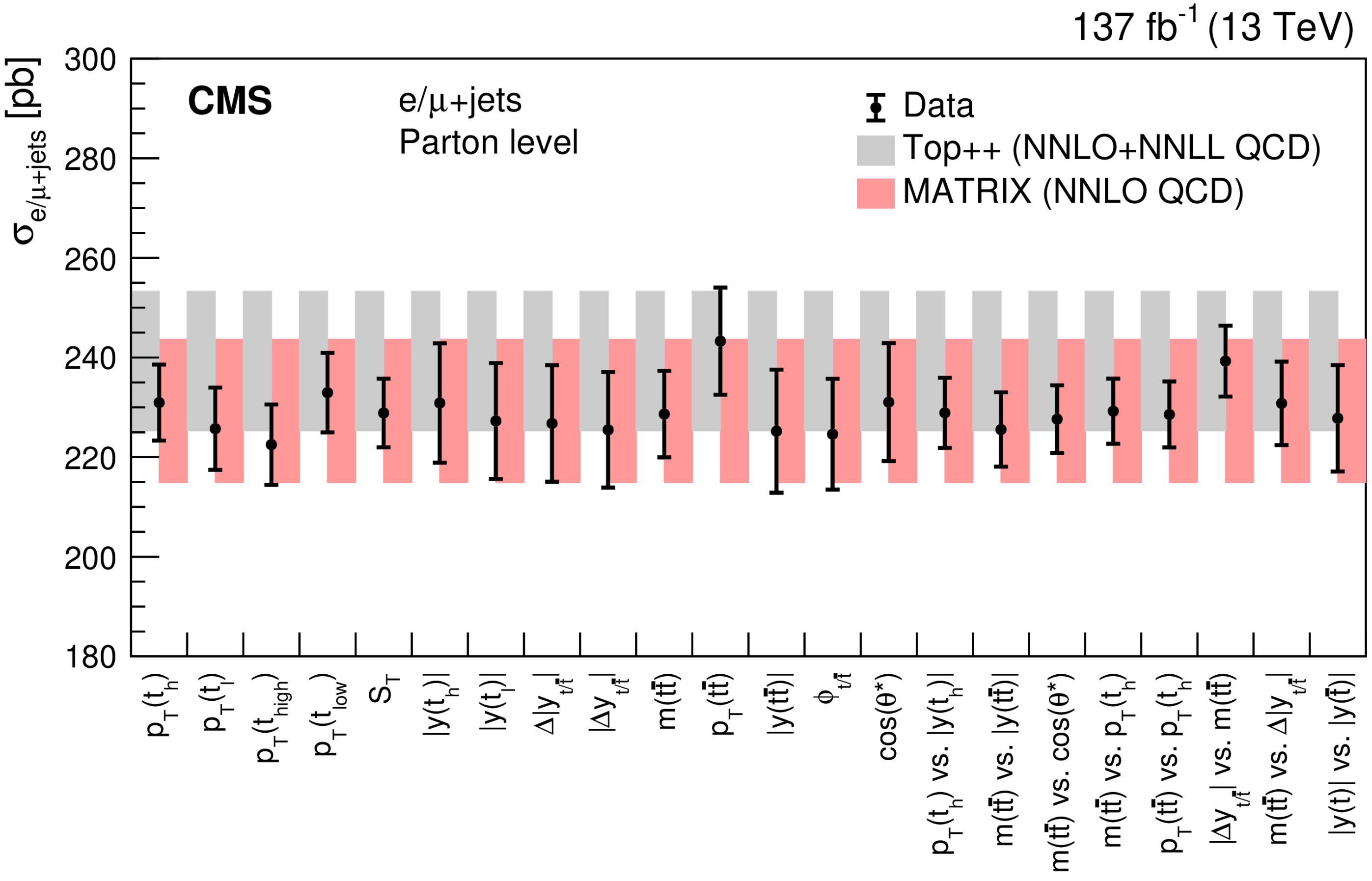
13 TeV
L = 137 fb^{-1}

$$\sigma^{NNLO}(13\ TeV) = 831.76^{+19.77}_{-29.20}(scale) \pm 35.06\ (PDF + \alpha_S)\ pb$$

TOP-20-001
Submitted to PRD

NEW

- 4 regions according to the top p_T (boosted [$p_T \geq 380\ GeV$] and resolved) and the b-tagging score
  - 2t: resolved + 2 tight b-jets
  - 1t1l: resolved + 1 tight and 1 loose b-jet
  - BHRL: 1 boosted and 1 resolved
  - BHBL: 2 top boosted
- Resolved for reconstruction
- Boosted categories ⇒ background subtracted using fit of top tagging discriminant
- χ^2 fit to find the cross-section considering the migration matrices
- Uncertainties are constrained by χ^2 fit
- Inclusive = sum of all bins



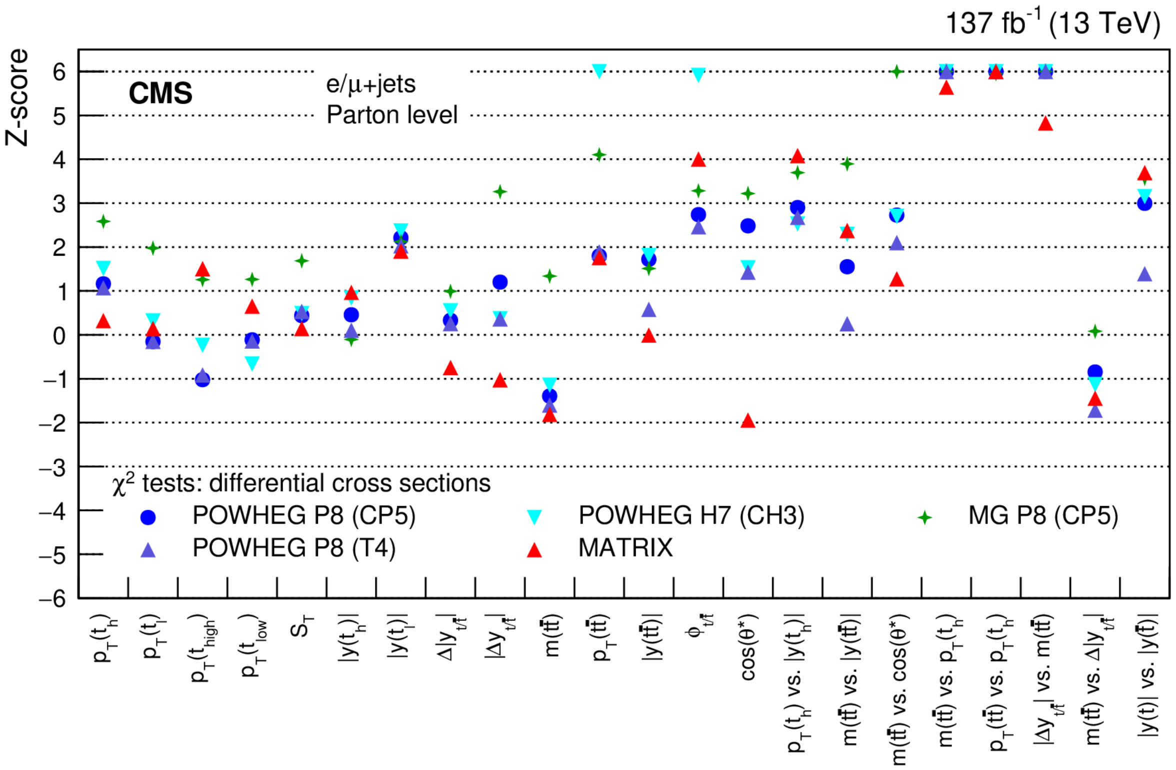
$$\boldsymbol{\sigma = 791 \pm 1\ (stat) \pm 21\ (syst) \pm 14\ (lumi)\ pb}$$

total relative uncertainty of 3.19%

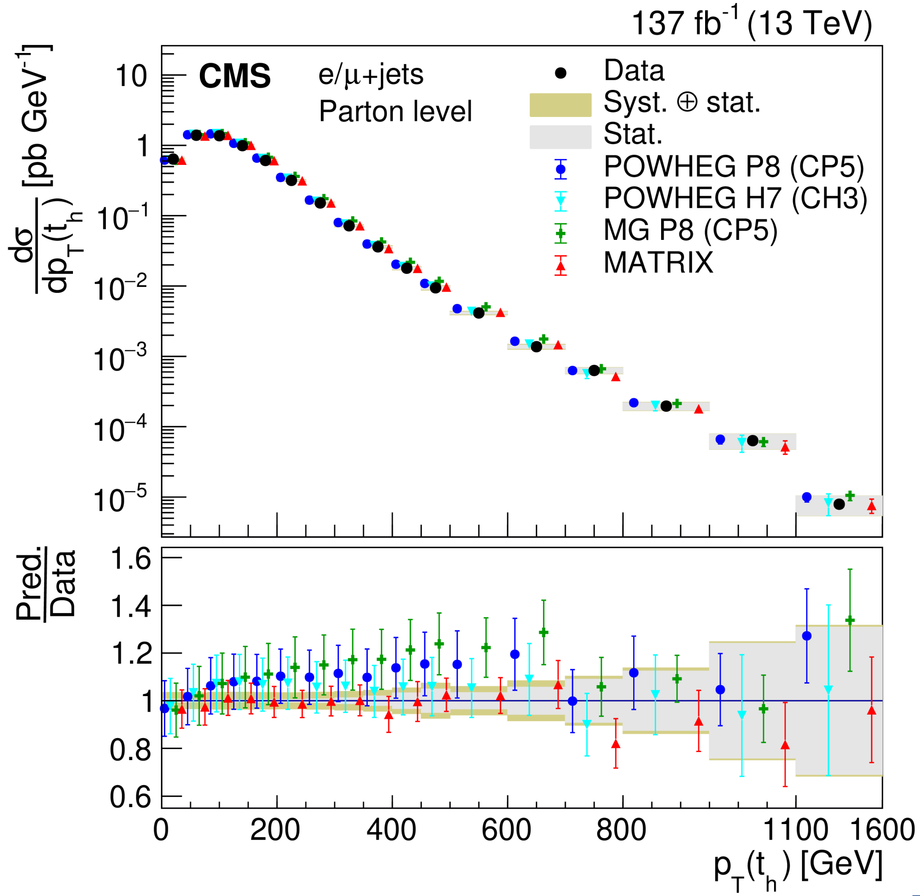
Dominant syst Jet energy (1.38%), BR (1.11%) and lepton unc (0.98%)

$\sigma(t\bar{t})$ differential: l+jets @13 TeV – CMS

13 TeV
L = 137 fb^{-1}



TOP-20-001
Submitted to PRD



- Most differential distributions are compatible with POWHEG+PYTHIA, POWHEG+HERWIG, and MG5 aMC@NLO+PYTHIA predictions
- Softer top p_T (and $m_{t\bar{t}}$) in data wrt MC
- POWHEG+HERWIG and aMC@NLO+PYTHIA predictions are not good to describe jet observables (and jet multiplicites)

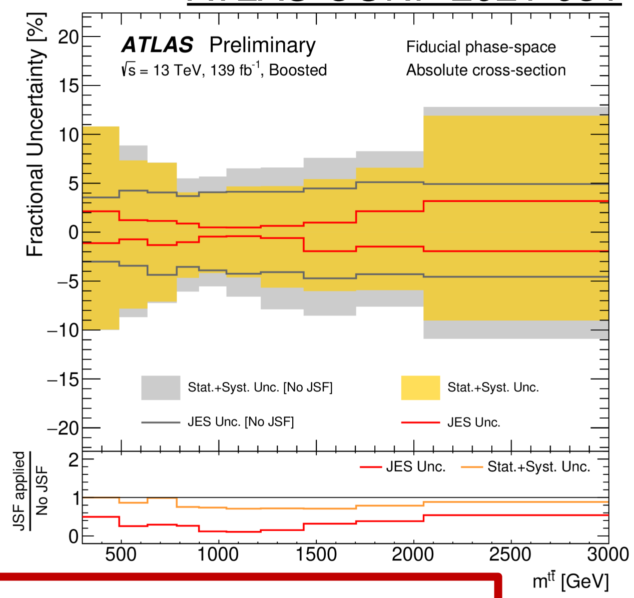
$\sigma(t\bar{t})$ differential: l+jets boosted @13 TeV – ATLAS

13 TeV
L = 139 fb^{-1}

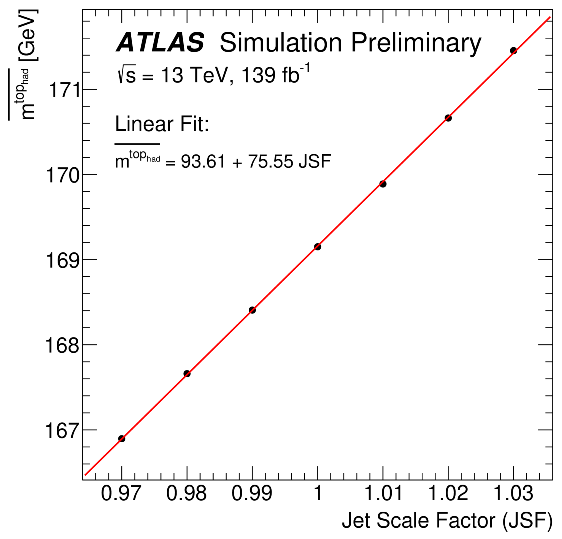
- At least one large-R jet (R = 1.0) with p_T > 355 GeV containing at least one b-tagged jet ⇒ top-jet
- One lepton, 2 b-tagged jets and a top-jet

NEW

ATLAS-CONF-2021-031

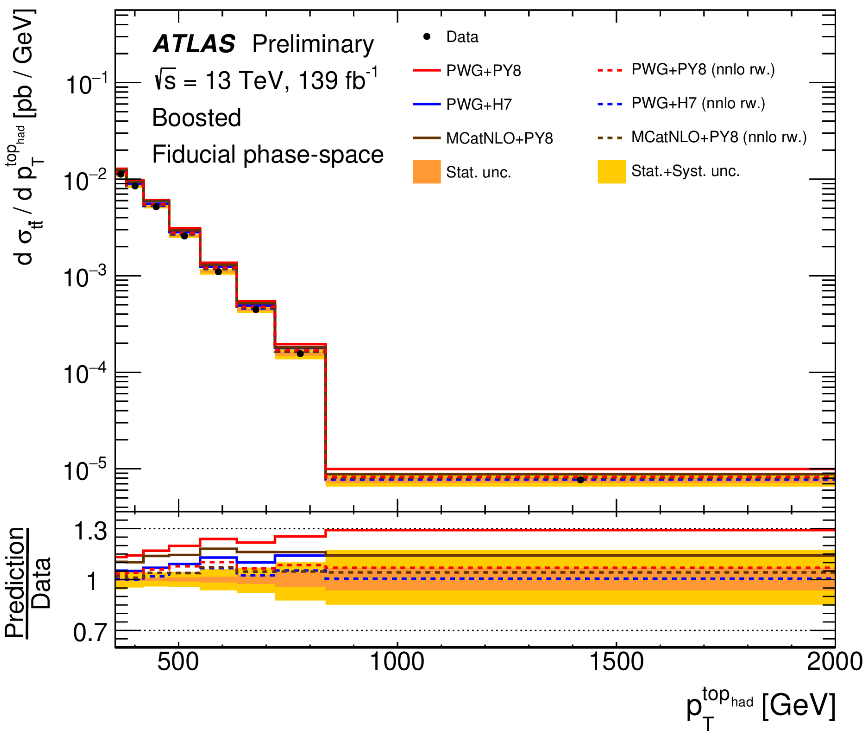


- Employ a parameter sensitive to the top mass to reduce the JET uncertainties (JSF)
- To reduce the impact of jet uncertainties (4.2% ⇒ 0.7%), the m_{top}^{had} is used together m_{top}^{meas}
  - (m_{top}^{had} is fit to find m_{top}^{meas})



Calibration line obtained by shifting JSF and register the effect on jet mass

$JSF = 1.00035 \pm 0.00087$

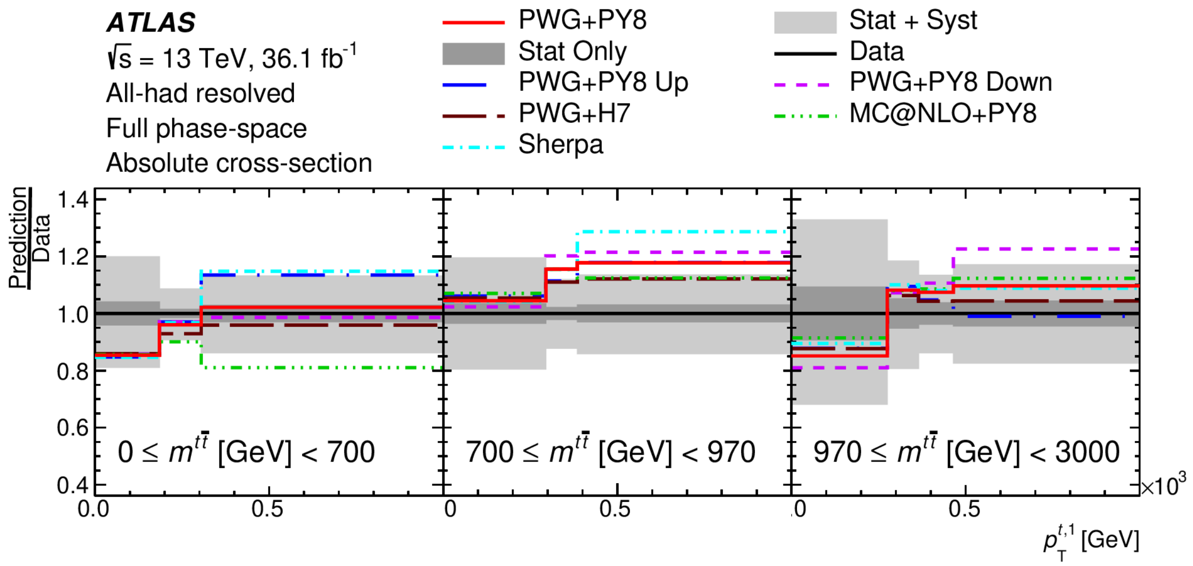


- top p_T softer in data
- Reweighting the MC predictions to the NNLO parton-level improves the agreement
- The modelling of the additional radiation events is not good for all the tested generators (matrix elements with up to one additional jet)
- Good agreement in shape

$\sigma(t\bar{t})$ differential: all-hadronic @13 TeV – ATLAS

JHEP 01 (2021) 033

13 TeV
L = 36.1 fb^{-1}



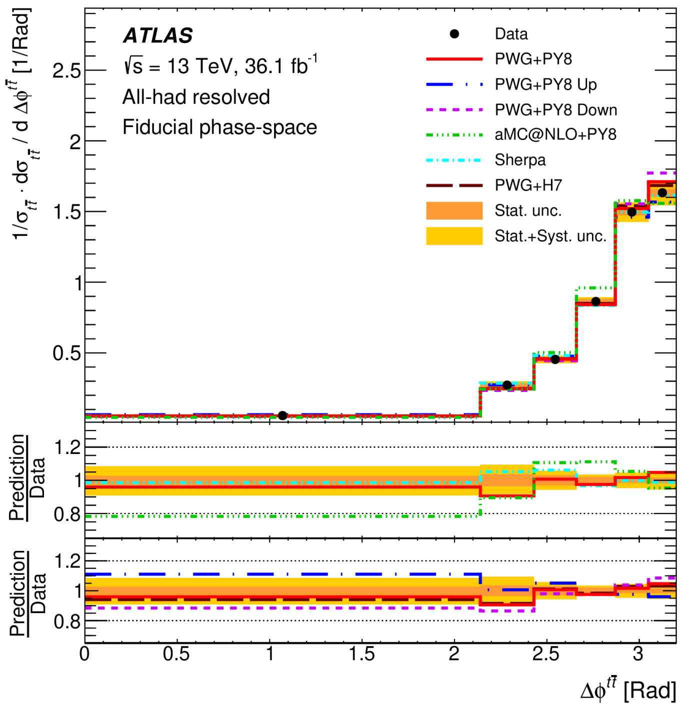
- At least 6 jets (==2 b-jets)
- Veto on the leptons
- Kinematic requirements on system reconstruction

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma_t^2} + \frac{(m_{j_1 j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3 j_4} - m_W)^2}{\sigma_W^2}$$

  - $130 < m_{t,1}, m_{t,2} < 200\ GeV$
  - $\Delta R_{bb} > 2$
  - $\Delta R_{bW} < 2.2$

- Data driven method to estimate multi-jet background

Dominant uncertainties from PS/hadronisation modeling, multijet background estimate and JES/JER.

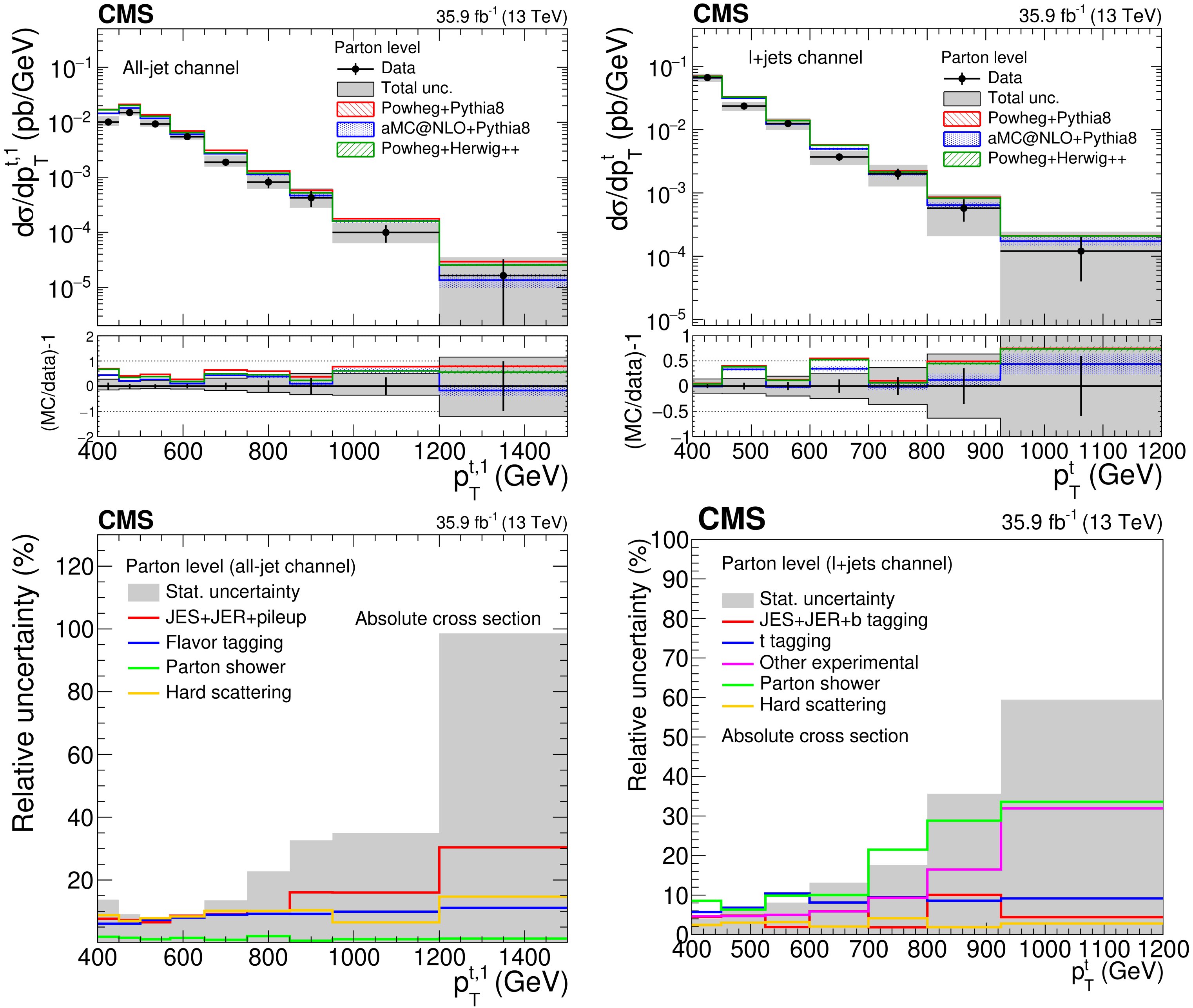


- Very good agreement with NLO+PS generator on angular variables, p_T of the leading top quark and $t\bar{t}$ system.

$\sigma(t\bar{t})$ differential: all-had and l+jets boosted @13 TeV – CMS

13 TeV
L = 35.9 fb^{-1}

- ALL HAD: At least two large-R jet (R = 1.0) with p_T > 400 GeV (with b-tagged jet inside) + NN to discriminate the bkg
- SINGLE LEP: Exactly lepton and large-R jet + MET.



TOP-18-013
PRD 103 (2021) 052008

- In both decay channels the observed absolute cross sections are significantly lower than the predictions from theory, while the normalized differential measurements are well described

Conclusions

- Top quark pair production are measured with high precision at both ATLAS and CMS

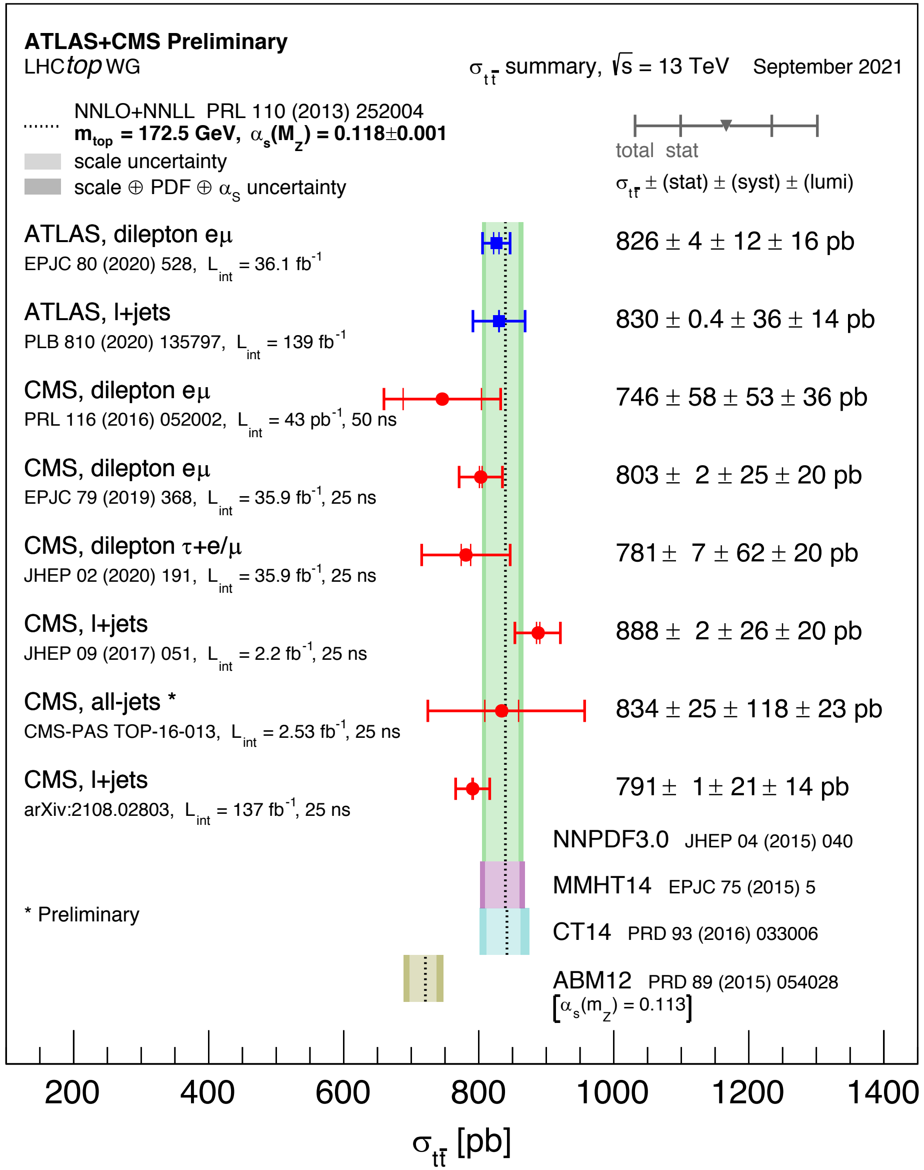
- Presented the results of the **inclusive** cross-section at **5.02 TeV** ⇒ **good agreement** with predictions NNLO
- Presented the results of the **inclusive** cross-section at **13 TeV** ⇒ **good agreement** with predictions NNLO

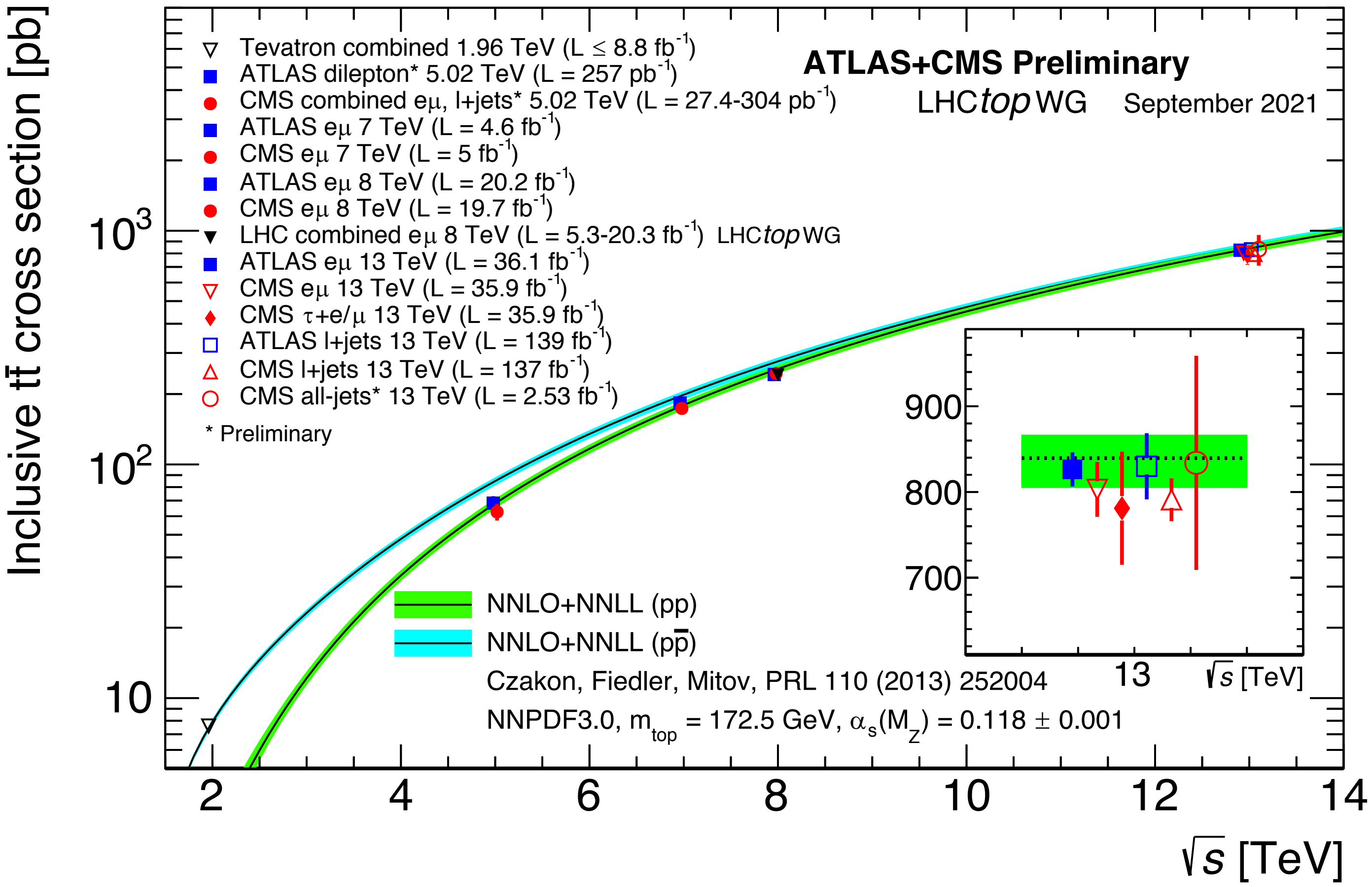
- **Differential measurements** performed at 13 TeV in all channels (dilepton, l+jets and all-hadronic) for resolved and boosted topologies as a function of many observables of $t\bar{t}$, jets and leptons kinematics, including double and triple differential distributions, at particle and parton level.
  - **No significant differences** with the SM have been observed
  - Some tension observed with the NLO predictions, in particular on double-differential distributions and variables related to the top p_T.

Thanks for your attention!

BACKUP

Summary of the $\sigma(t\bar{t})$ measurements at 13 TeV





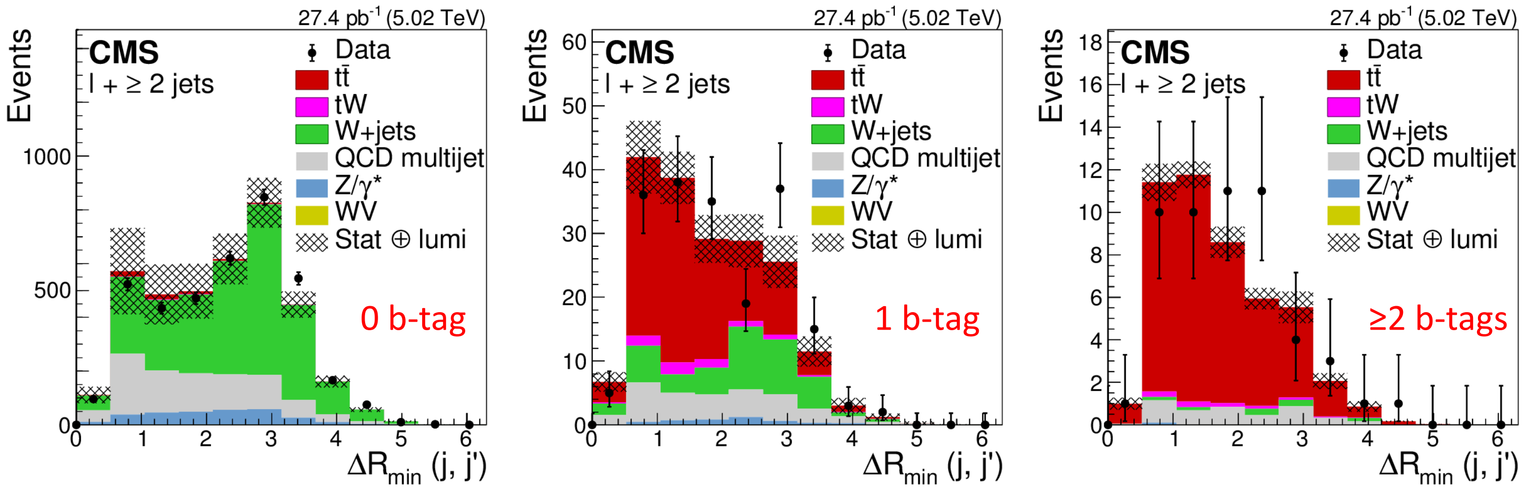
$\sigma(t\bar{t})$: l+jets @5 TeV – CMS

5.02 TeV
L = 27.4 pb⁻¹ (l+jets)
L = 304 pb⁻¹
(dilepton)

$$\sigma^{NNLO}(5\ TeV) = 68.2 \pm 4.8\ (PDF)\ ^{+1.9}_{-2.3}\ (\alpha_S)\ pb$$

TOP-16-023
JHEP 03 (2018) 115

- l+jets and μμ + eμ channels.
- l+jets channel: 6 regions according to lepton flavour and number of b-tags (0, 1, more);
- $\Delta R_{min}(j,j')$ variable is used to extract the $t\bar{t}$ cross section;
- A profile likelihood ratio method is used with a scale factor for the b-tagging included as a parameter of interest.
- Dilepton channel: 2 lepton + 2 jets;
- Counting experiment.
- All channels are combined together with the BLUE combination.



$$\boldsymbol{\sigma = 69.5 \pm 6.1\ (stat) \pm 5.6\ (syst) \pm 1.6\ (lumi)\ pb}$$

total relative uncertainty of 12%

81.8% for l+jets, 13.5% for eμ, and 4.7% for μμ channels.

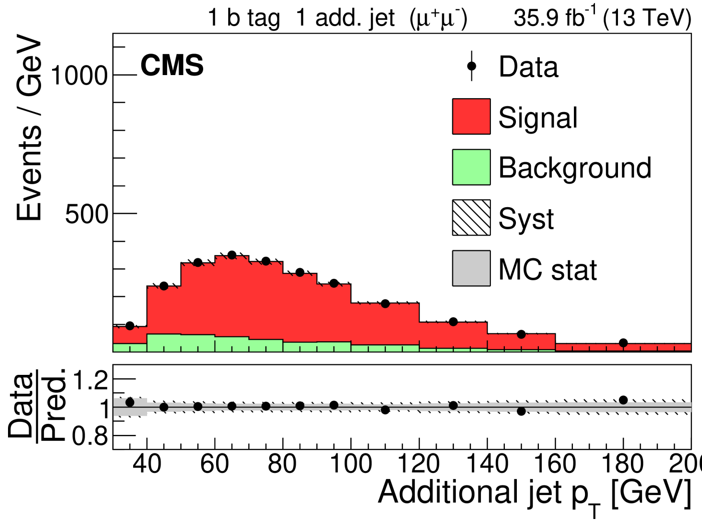
$\sigma(t\bar{t})$: dilepton @13 TeV – CMS

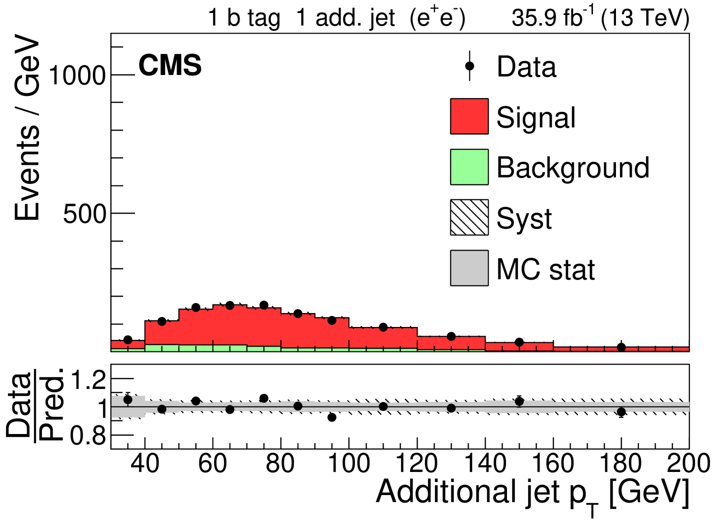
13 TeV
L = 35.9 fb^{-1}

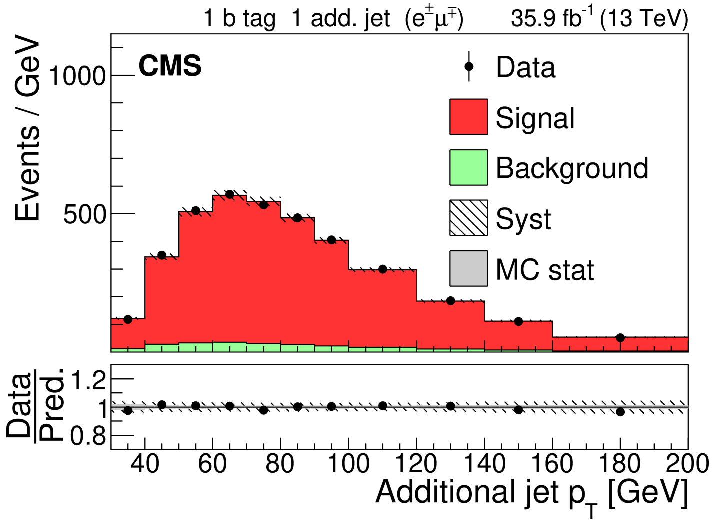
$$\sigma^{NNLO}(13\ TeV) = 831.76^{+19.77}_{-29.20}(scale) \pm 35.06\ (PDF + \alpha_S)\ pb$$

TOP-17-001
Eur. Phys. J. C 79 (2019) 368

- μμ, ee and eμ OS channels;
- Template fit on multidimentional distributions (28 regions);
- 3 regions according to the number of b-tags (1, 2, 0+≥3 only for eμ)
- Additional classification based on the jet multiplicity (0, 1, 2, ≥3)
- Yield and p_T of the softer jet used as input of the fit.







total relative uncertainty of 4.0%

$$\boldsymbol{\sigma = 803 \pm 2\ (stat) \pm 25\ (syst) \pm 20\ (lumi)\ pb}$$

Dominant syst are related lepton (2.0%) and PDF (1.1%) or tW background (1.1%)