Measurements of $t\bar{t}$ production cross sections and reinterpretations at the LHC

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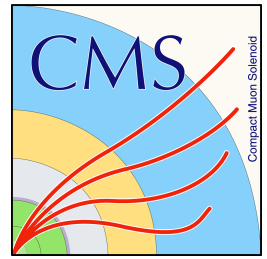
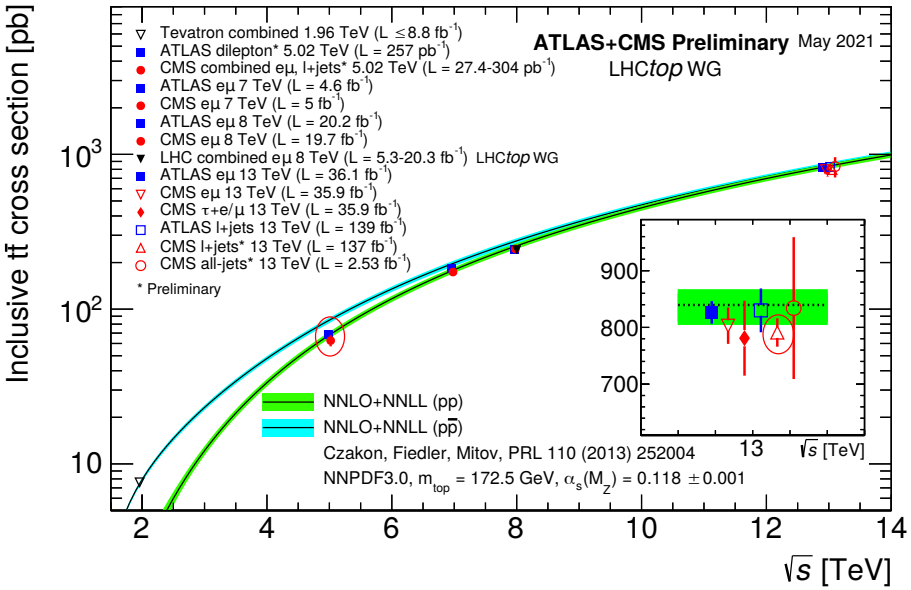


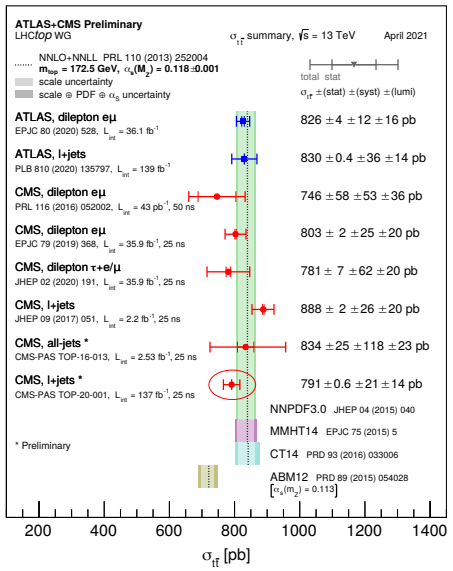
PANIC 2021

08.09.2021

Inclusive $\mathrm{t\bar{t}}$ production cross sections

A huge variety of measurements at different collision energies and in various decay channels have been performed at the LHC:





Differential $\mathrm{t\bar{t}}$ cross sections:

- have been measured in dilepton, e/μ+jets, and all-hadronic events
- in resolved and boosted regimes

These measurements provide:

- precision tests of standard model top quark pair production
- measurements used for: EFT interpretations, PDF constraints, extractions of m_{t}, α_{S} ...
- usually full covariance matrices of uncertainties provided $\rightarrow$facilitates quantitative comparisons to theory predictions and reinterpretations

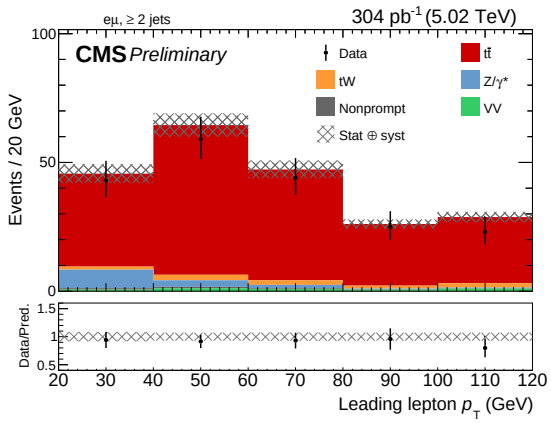
Will concentrate on recent and most precise results

New: inclusive $t\bar{t}$ cross sections at 5 TeV

CMS

304 pb^{-1}, 5.02,TeV, *TOP-20-004 (2021)* *new*

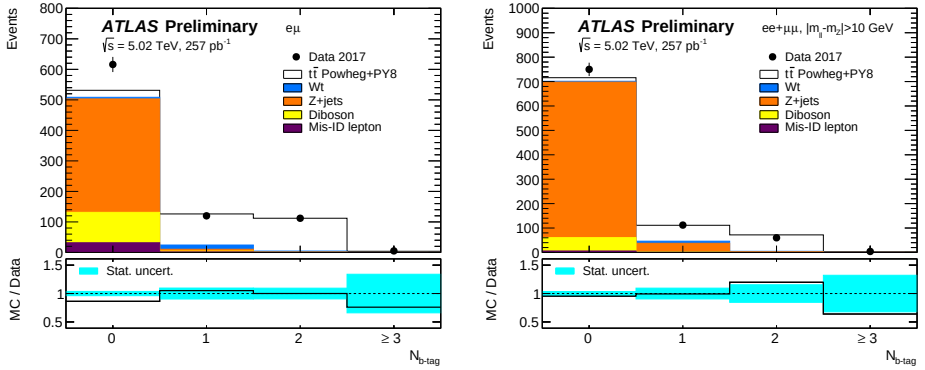
- perform high purity $t\bar{t}$ selection with eμ + 2 b-jets
- dominant DY background (via leptonic τ) estimated from data using same flavor as sideband



ATLAS

257 pb^{-1}, 5.02 TeV, *ATLAS-CONF-2021-003 (2021)* *new*

- eμ, ee, $\mu\mu$ events selected
- use categories of 1 and 2 b-jets (for ee and $\mu\mu$ also m(ll)-bins) for extraction of cross section and background constraints



$\sigma_{t\bar{t}} = 60.3 \pm 5.5(\text{stat}) \pm 2.8(\text{sys}) \pm 0.9(\text{lumi})$ pb

combined using BLUE with e/μ+jets results [*JHEP 03 (2018) 115*]:

$\sigma_{t\bar{t}} = 62.6 \pm 5.0$ pb

$\sigma_{t\bar{t}} = 66.0 \pm 4.5(\text{stat}) \pm 1.6(\text{sys}) \pm 1.2(\text{lumi}) \pm 0.2(\text{beam})$ pb

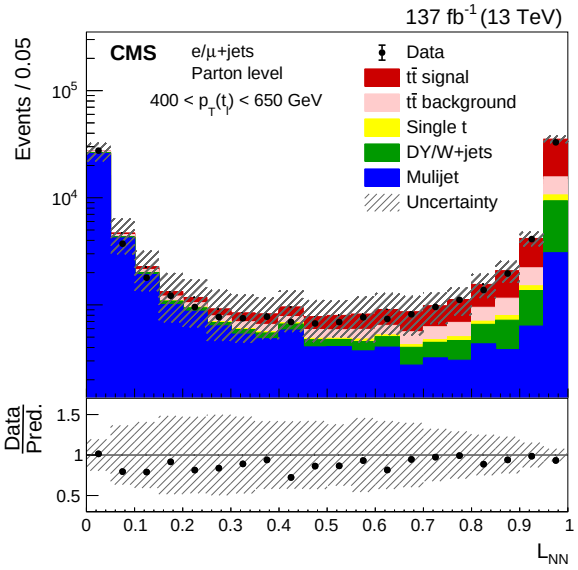
Measurements in good agreement with standard model $68^{+5.2}_{-5.3}$ pb (NNLO+NNLL).

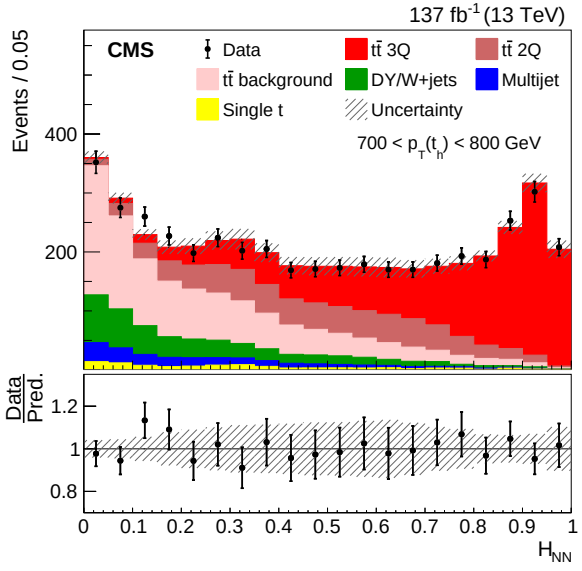
Full spectrum differential $t\bar{t}$ cross sections measurements in e/μ+jets events

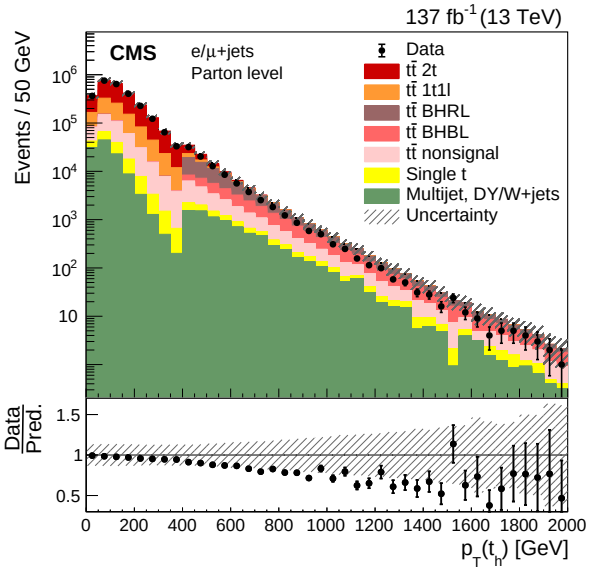
137 fb^{-1}, 13 TeV, CMS: *TOP-20-001 sub. to PRD new*

Analysis uses combination of resolved and boosted reconstructions:

- resolved: 1 isolated e/μ and at least 4 jets (2 categories with tight and relaxed b-tagging requirement)
- boosted t_l: 1 non-isolated lepton within $\Delta R < 0.6$ of a b-jet. Selection using NN based on isolation and kinematic variables (selection $L_{NN} > 0.7$).
- boosted t_h: 1 anti-k_T (size=0.8) jet with $p_T > 400$ GeV. Identified using deep neural networks with information based on subjets (H_{NN} fitted for background subtraction).

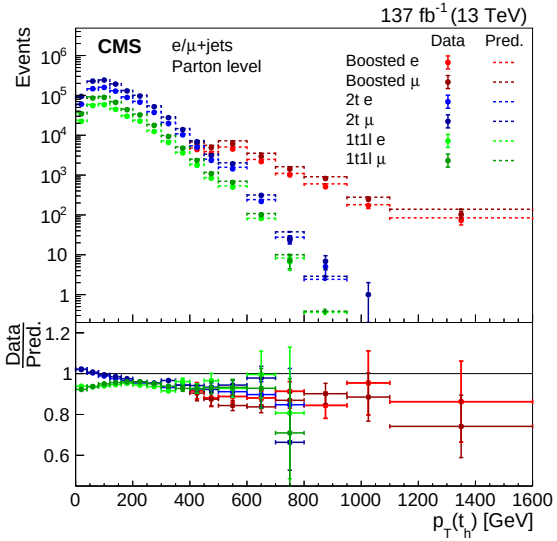


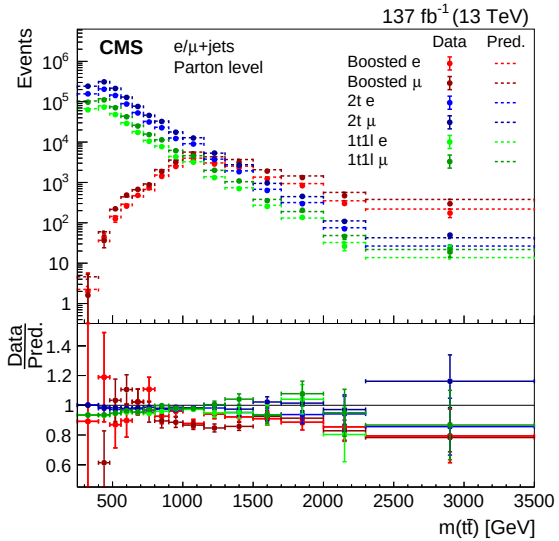


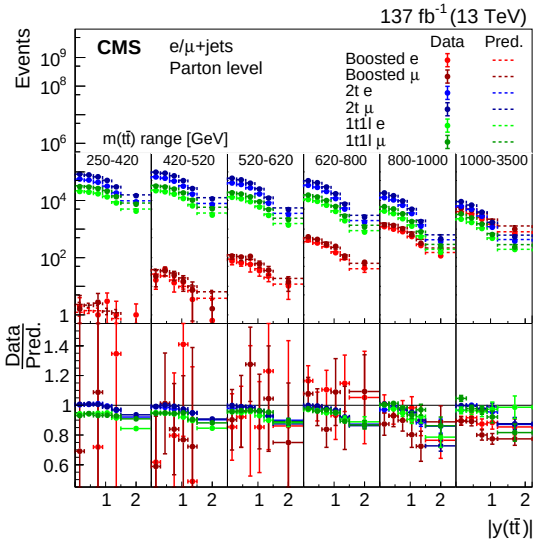


BHRL: boosted t_h, resolved t_l; BHBL: boosted t_h and t_l

Perform χ^2-fit to extract the cross sections:





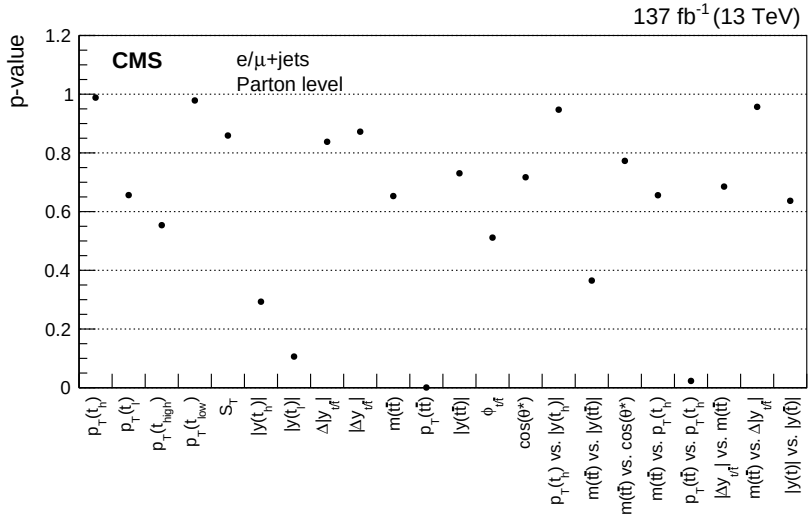


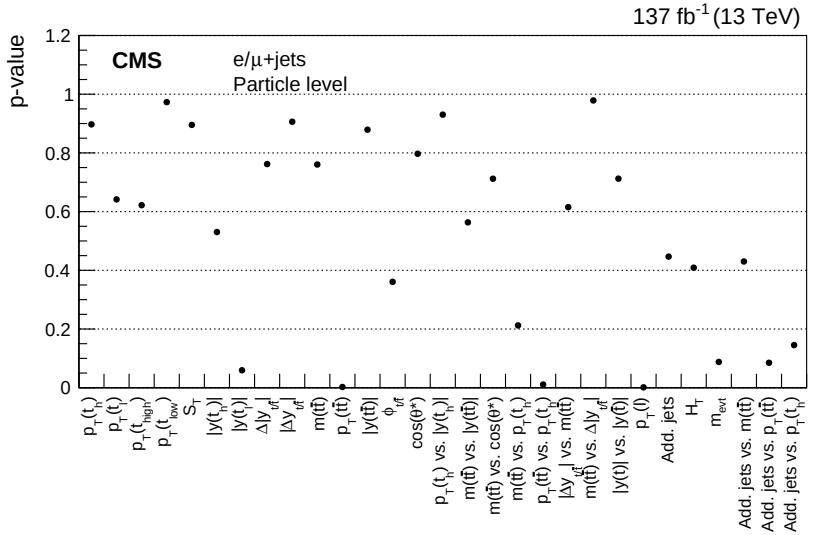
$$\chi^2 = \sum_{\ell} \sum_{y} \sum_{r} (\mathbf{m}_{yr\ell} - \mathbf{b}_{yr\ell}(\nu_\alpha) - M_{yr\ell}(\nu_\alpha)\boldsymbol{\sigma})^T C^{-1}_{yr\ell} (\mathbf{m}_{yr\ell} - \mathbf{b}_{yr\ell}(\nu_\alpha) - M_{yr\ell}(\nu_\alpha)\boldsymbol{\sigma}) + \kappa(\nu_\alpha)$$

- **m** measured distribution of events with the covariance matrix C; per year y, reconstruction r method (res. 1t1l, res. 2t, boosted), and lepton channels ℓ (18 categories)
- $\boldsymbol{\sigma}$ vector of cross sections (free parameters of interest).
- ν_α nuisances representing the uncertainties. These are constrained in $\kappa(\nu_\alpha)$ taking into account year-by-year correlations.
- $M(\nu_\alpha)$ response matrices that map $\boldsymbol{\sigma}$ to the $\mathrm{t\bar{t}}$ event yields at detector level.
- $\mathbf{b}(\nu_\alpha)$ non $\mathrm{t\bar{t}}$ background.

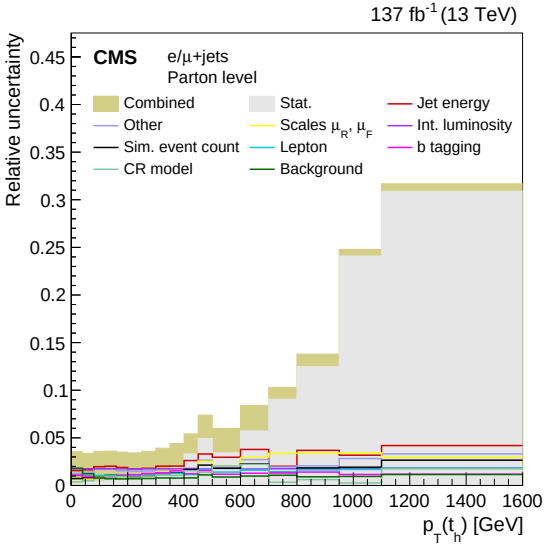
– No regularization condition is used

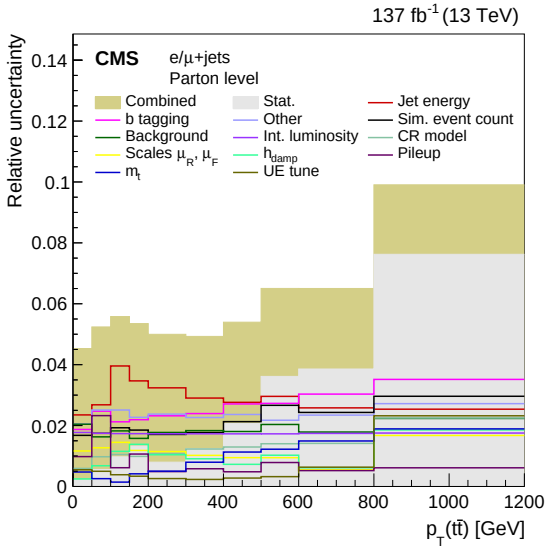
Goodness of fits

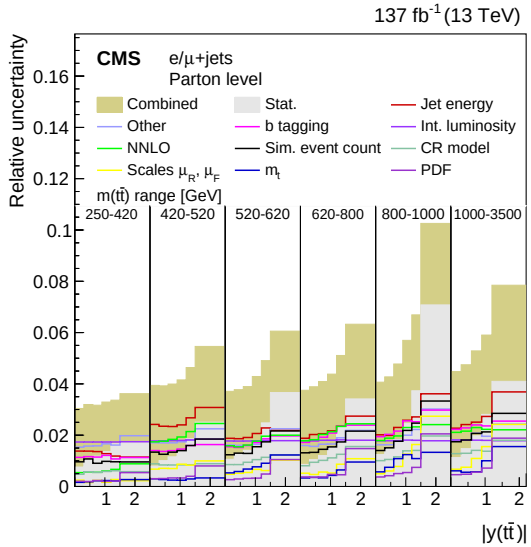




Uncertainties

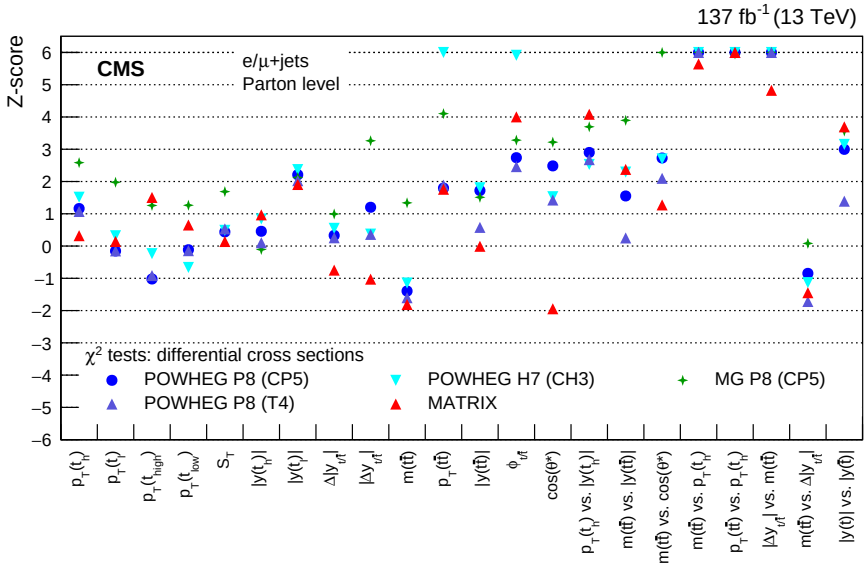


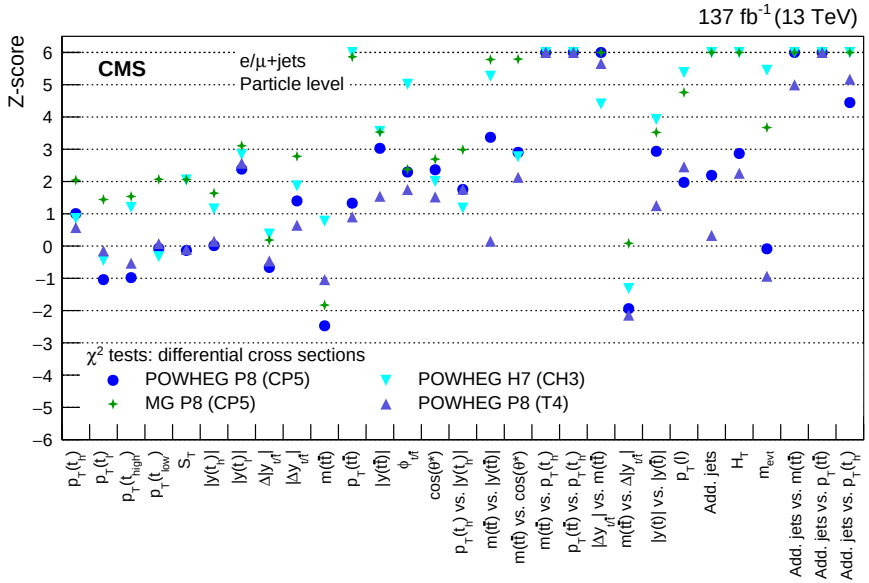




- Depending on the phase space region the precision is limited by systematics or statistics.
- Systematic (dominated by jet energy calibration and b-tagging) uncertainties reduced by up to 50% using combination of categories.

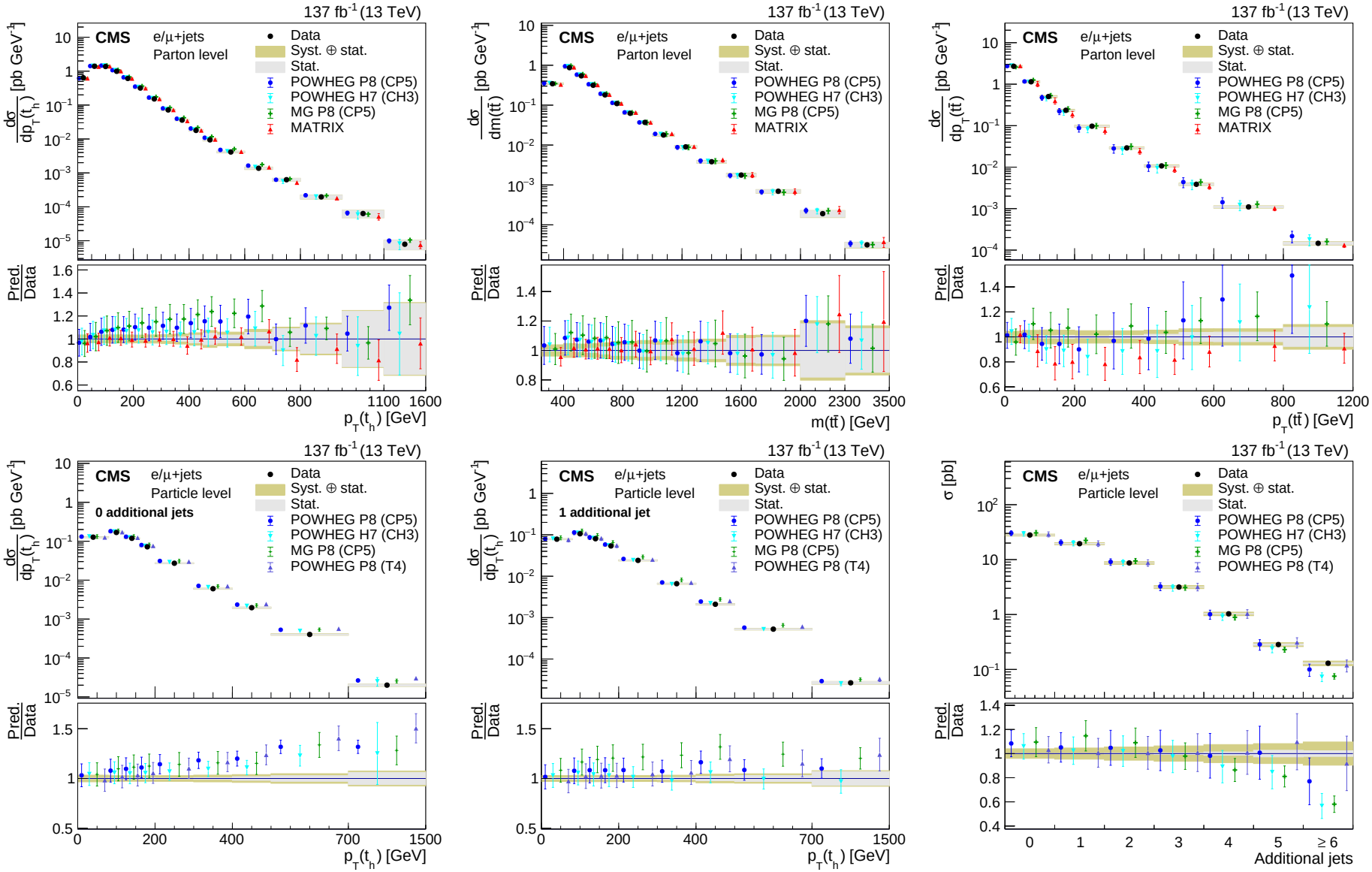
Comparison of measurements to various predictions using χ^2-tests.
– uncertainties in measurements and predictions are included.





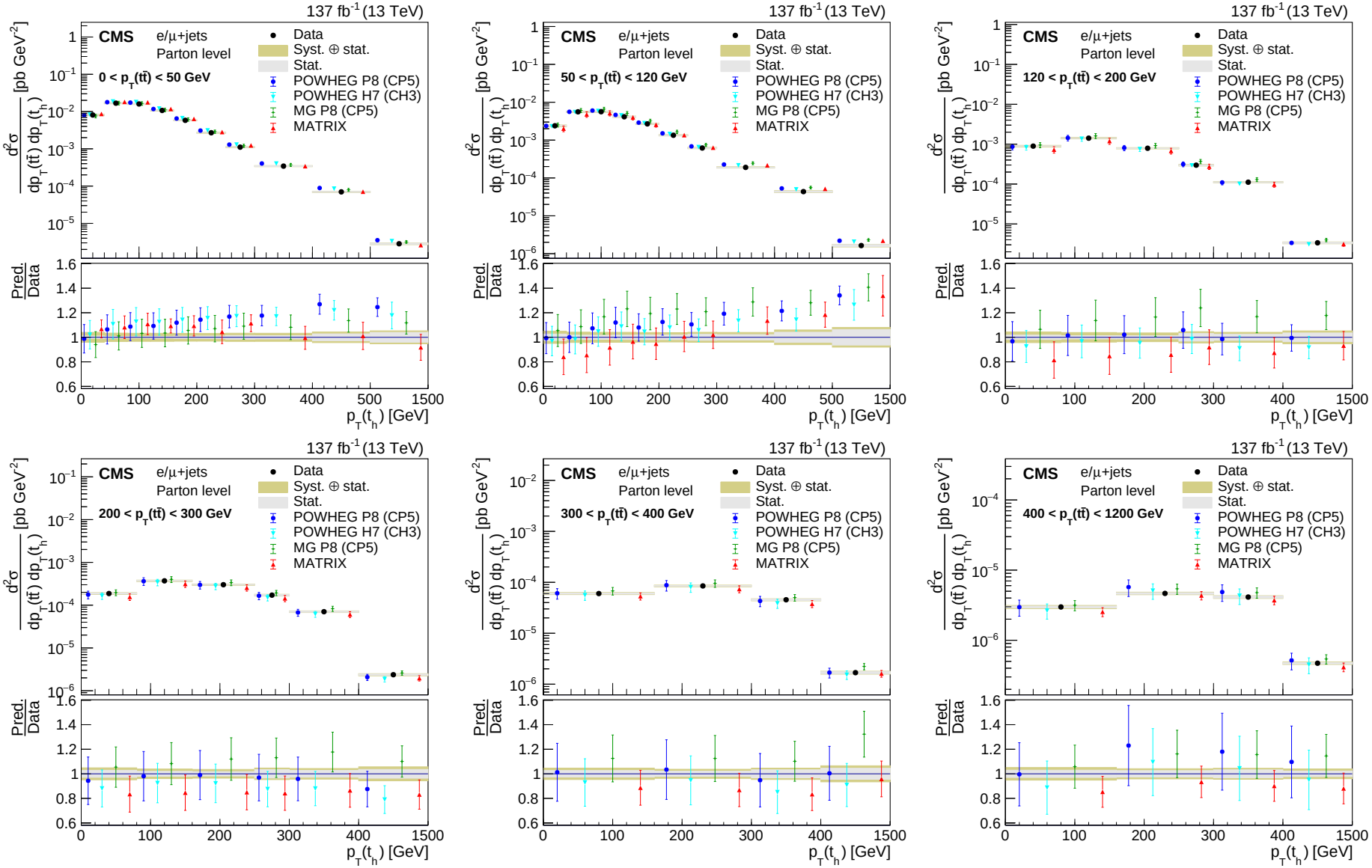
Most of the predictions are in good agreement with the measurement—with a few exceptions:

- $m(\mathrm{t\bar{t}})$ vs. $p_{\mathrm{T}}(\mathrm{t_h})$ and $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ vs. $p_{\mathrm{T}}(\mathrm{t_h})$ shows largest disagreements.
- At particle level add. jets vs. kinematic observable are difficult to describe.



– p_{T} well described by NNLO calculation.
– trend of harder spectrum in NLO calculations disappears above 600 GeV
– worst description of p_{T} in events without additional jet.

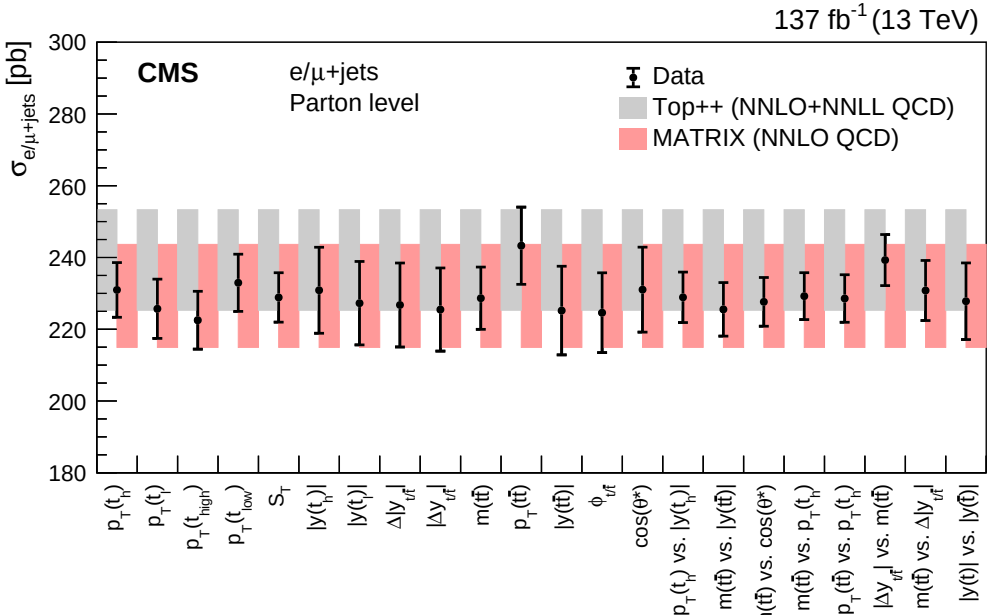
Double-differential measurement of $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ vs. $p_{\mathrm{T}}(\mathrm{t_h})$



- $p_{\mathrm{T}}(\mathrm{t_h})$ prediction too hard in low $p_{\mathrm{T}}(\mathrm{t\bar{t}})$-bin. Agreement better at high $p_{\mathrm{T}}(\mathrm{t\bar{t}})$.

Inclusive Cross Section

Obtain inclusive cross section from integration of differential distributions:



- Result of best expected measurement ($m(\mathrm{t\bar{t}})$ vs. $\cos(\theta^*)$), also best observed:

$$\sigma_{e/\mu+\mathrm{jets}} = 227.6 \pm 6.8\,\mathrm{pb}.$$

- With a branching fraction of $28.77 \pm 0.32\%$ to e/μ+jets:

$$\sigma_{\mathrm{t\bar{t}}} = 791 \pm 25\,\mathrm{pb}\ (\pm 1(\mathrm{stat}) \pm 21(\mathrm{sys}) \pm 14(\mathrm{lumi})\,\mathrm{pb})$$

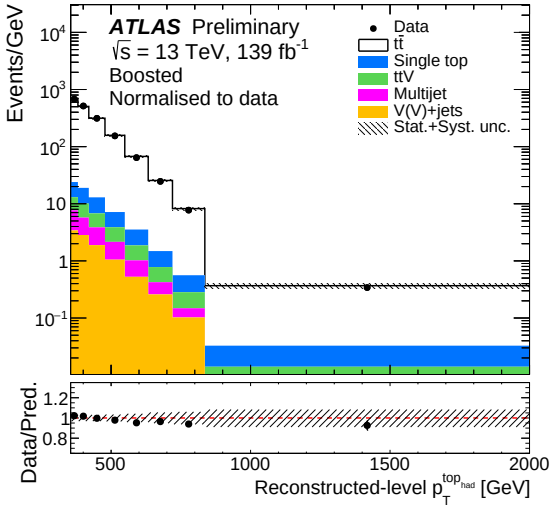
With 3.2% uncertainty, one of the most precise $\mathrm{t\bar{t}}$ cross section measurements.
Dominant uncertainties: jet energy, lepton identification, NNLO reweighting of NLO MC

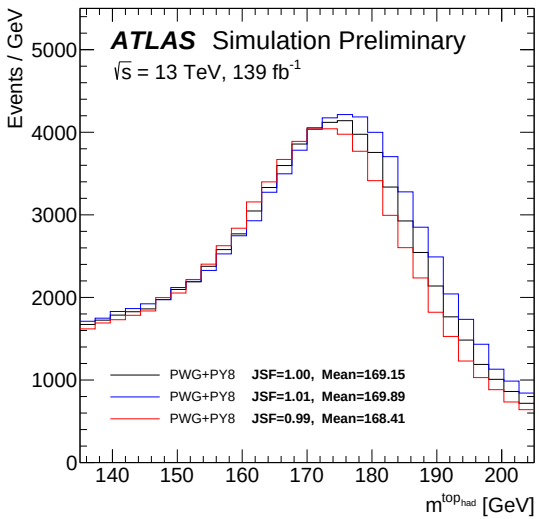
Differential cross section in e/μ+jets boosted

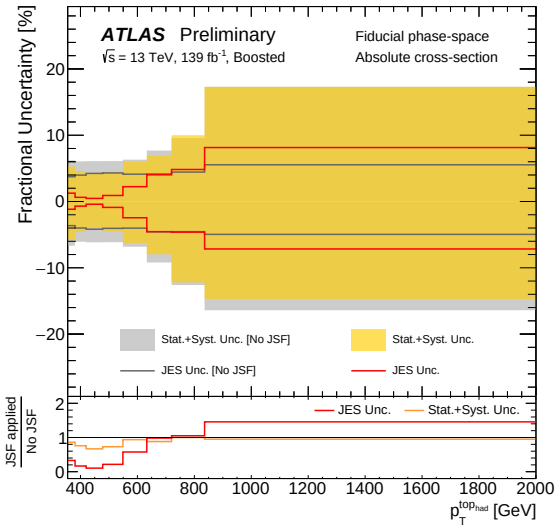
139 fb^{-1}, 13 TeV, ATLAS: *ATLAS-CONF-2021-031* *new*

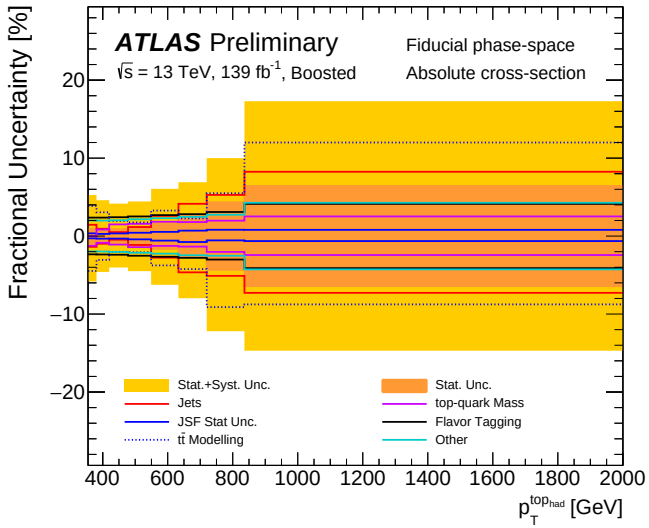
Selection

- t_h: 1 anti-k_T jet (size=1), $p_T > 355$ GeV, clustered from anti-k_T (s=0.4) jets; contains 1 b-jet; $120 < m_{jet} < 220$ GeV.
- t_l: 1 e/μ, 1 b-jet, $E_T^{miss} > 20$ *GeV*
- Jet energy calibrated using m_t $\rightarrow$reduces uncertainty
- Iterative Bayesian unfolding

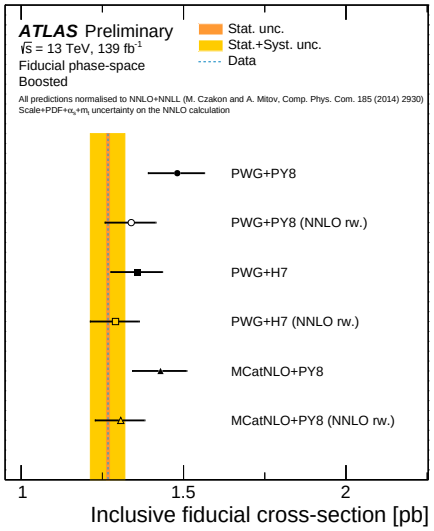


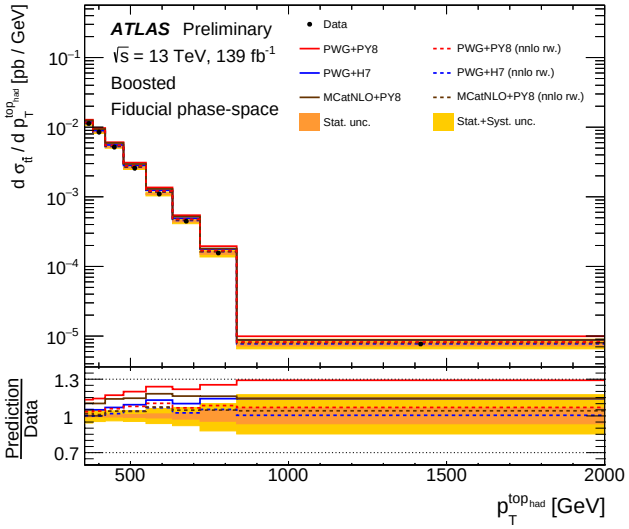


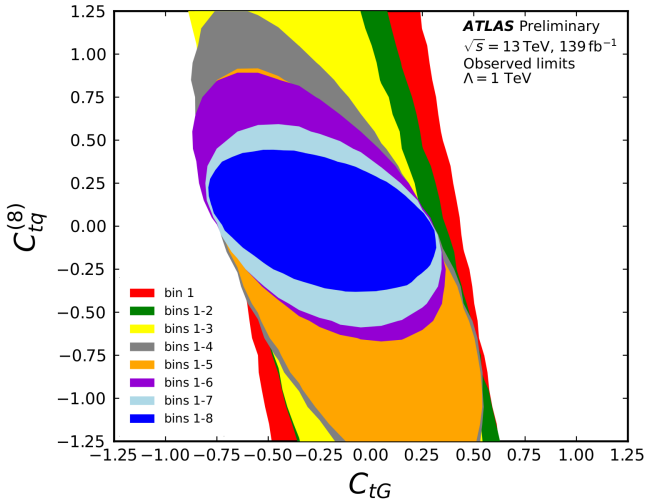




Results and interpretation





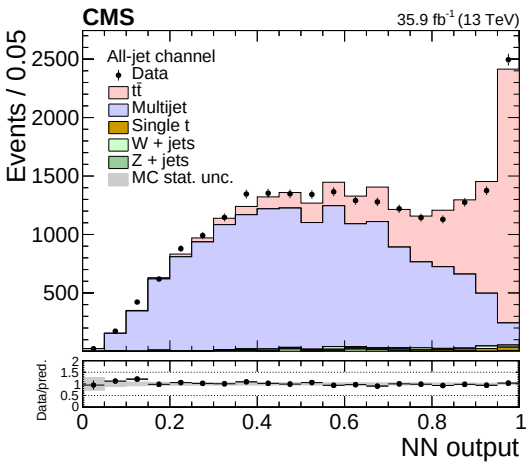


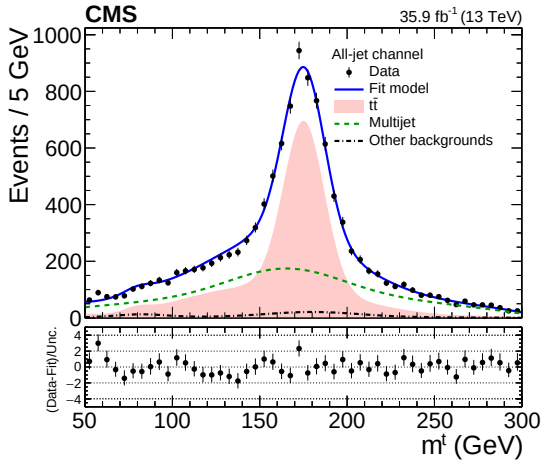
- Overall normalization overestimated by NLO calculations (NNLO better)
- Shapes are modeled reasonably taking into account uncertainties (also in predictions)
- EFT limits on anomalous ttg C_{tG} and ttqq $C_{\mathrm{tq}}^{(8)}$ couplings calculated limits are shown using different bin-ranges of $p_{\mathrm{T}}(\mathrm{t_h})$.

Differential $t\bar{t}$ cross sections in all-hadronic events: boosted

36 fb^{-1}, 13 TeV, *PRD 103 (2021) 052008*

- 2 jets (size: 0.8) $p_T > 400$ GeV, soft-drop mass: 120 – 220 GeV, b-tagged
- neural network based on n-subjettiness used to define signal and control region:

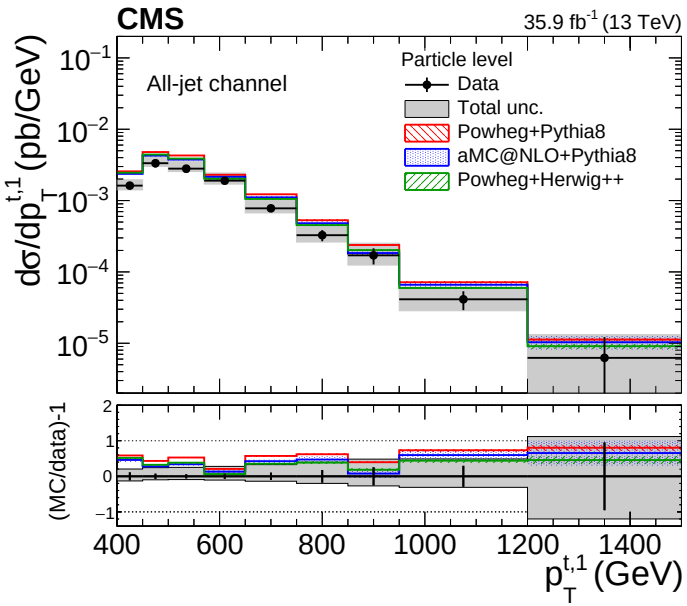


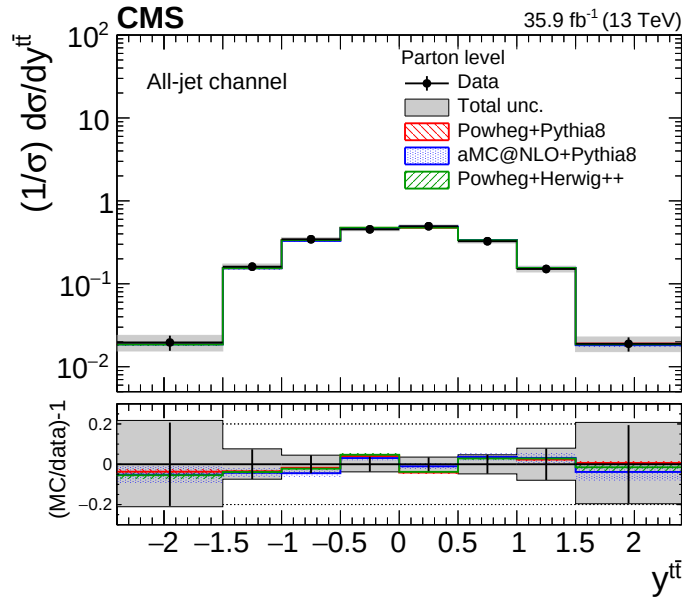


CR: $NN < 0.8$ normalized using m_t-fit

Unregularized unfolding (matrix inversion)

- good agreements of shapes between predictions and measurements in boosted regime
- normalization of cross sections about 20% lower than predicted by NLO MCs.





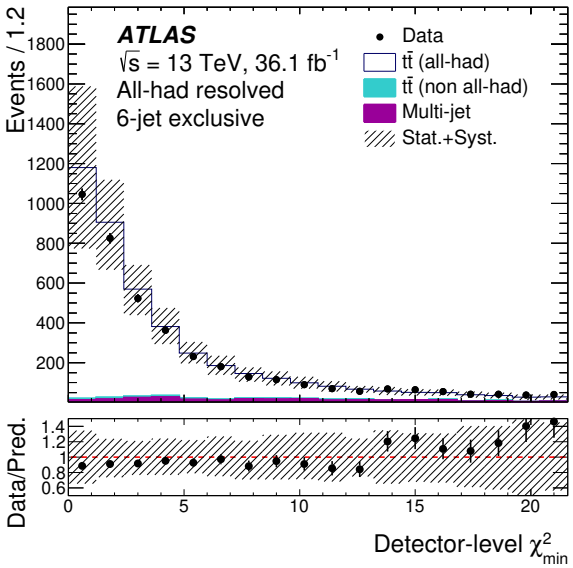
Differential $t\bar{t}$ cross sections in all-hadronic events: resolved

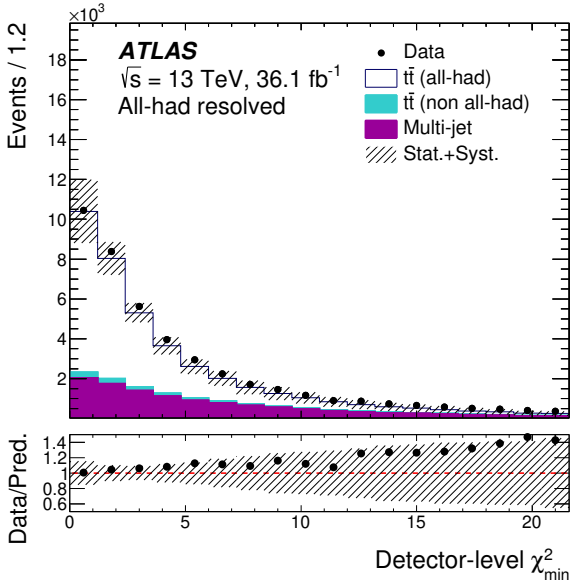
36 fb^{-1}, 13 TeV, ATLAS: *JHEP 01 (2021) 033* *new*

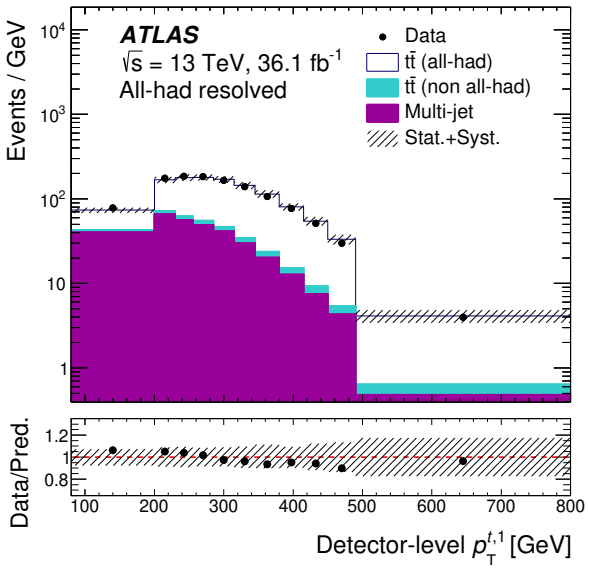
- 6 jets $p_{\mathrm{T}} > 55$ GeV, exactly 2 b-tagged
- reconstruction:

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

60% of 6 jets events correctly reconstructed. $130 < m_{\mathrm{t}} < 200$ GeV

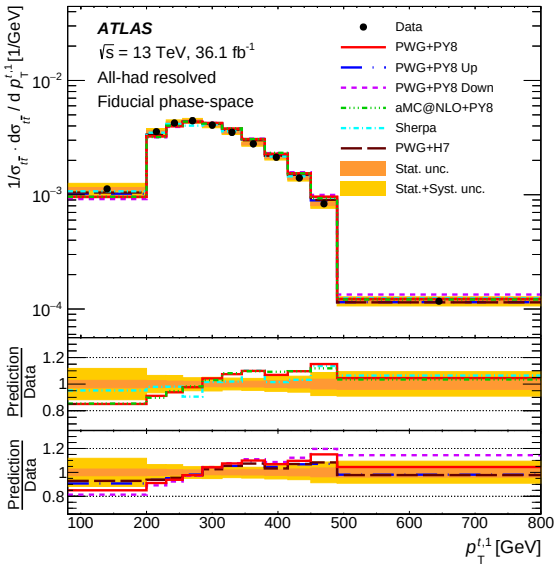




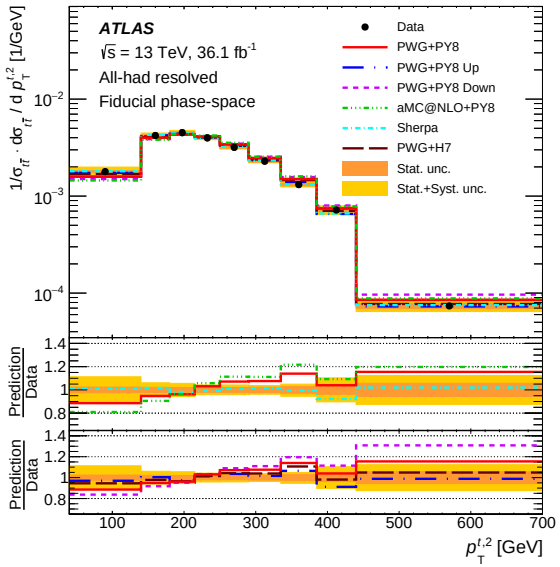


High purity in 6 jet bin.

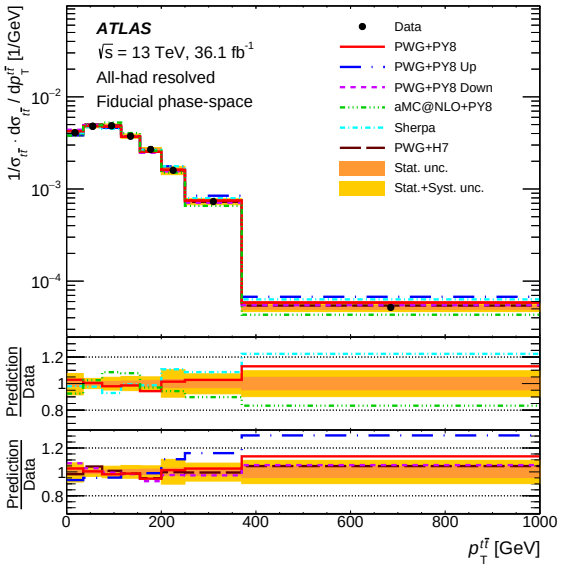
- confirmation of softer p_{T} spectrum in all-hadronic channel
- but there are other deviations, also observed in e/μ+jets and dilepton:
  - modulation in $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ (deficit in data for very low and high $p_{\mathrm{T}}(\mathrm{t\bar{t}})$) but depends on MCs.
  - excess at the $m(\mathrm{t\bar{t}})$ production threshold: due to off-shell production or bound-state effects?



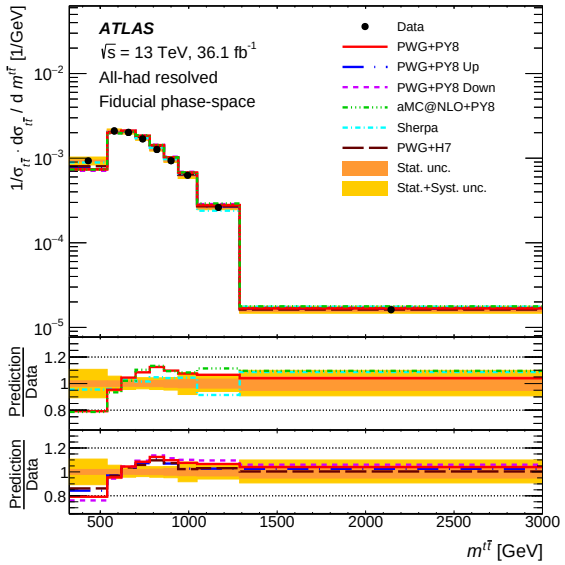
$0.01 < \text{p-val} < 0.33$



$0.01 < \text{p-val} < 0.97$



$0.01 < \text{p-val} < 0.67$

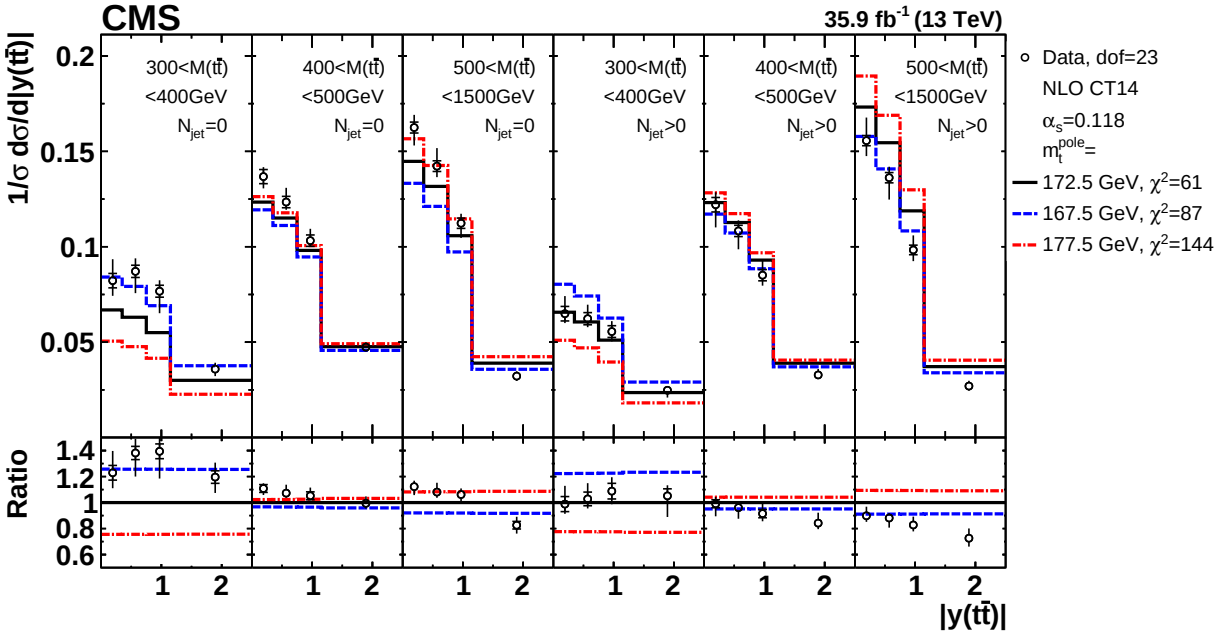


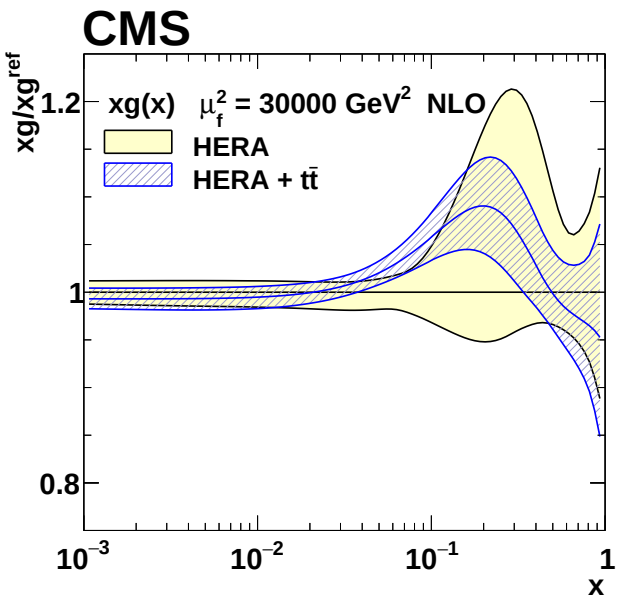
$0.02 < \text{p-val} < 0.58$

Interpretations of multi-differential $t\bar{t}$ cross sections in dilepton events

36 fb^{-1}, 13 TeV, CMS: *EPJC 80 (2020) 658*

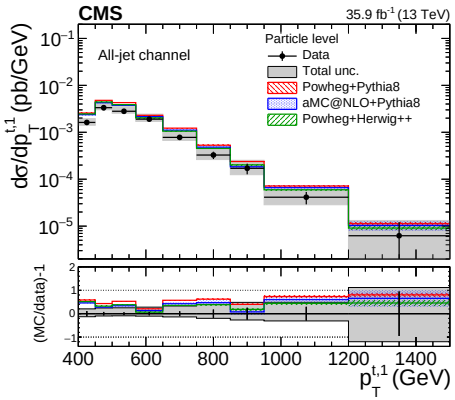
- Selection: ee, $e\mu$, $\mu\mu$ at least 2 jets, at least 1 b jet.
- The kinematics of the $t\bar{t}$ system (not of the individual top quarks) are reconstructed without using m_t to avoid a reconstruction bias: $p_z(\nu\bar{\nu}) = p_z(\ell^+\ell^-)$

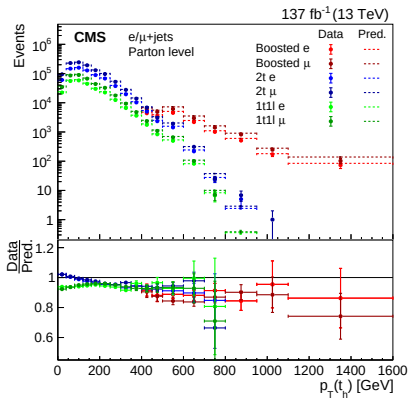


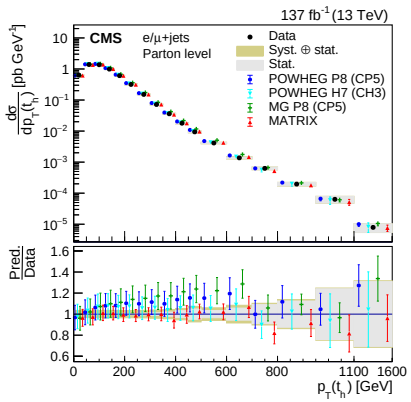


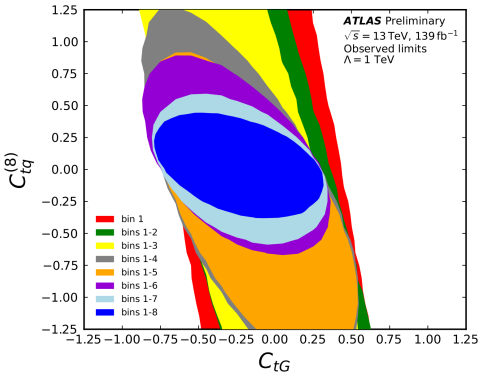
- PDF parameterization similar to HERAPDF2.0 using xFitter
- m_t and α_s are free parameters
- comparisons with NLO cross section taking into account scale and PDF uncertainties
- combined fit with HERA DIS data, most significant improvement of gluon PDF
- extracted: $m_t^{\text{pole}} = 170.5 \pm 0.8\,\text{GeV}$ $\alpha_s(m_Z) = 0.1135^{+0.0021}_{-0.0017}$

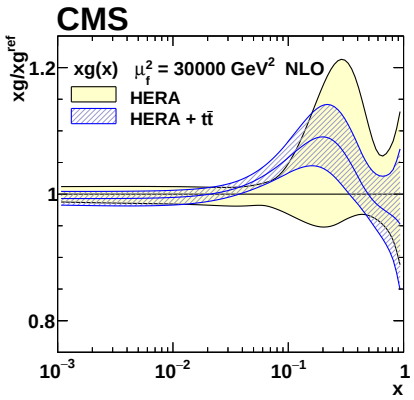
Conclusion

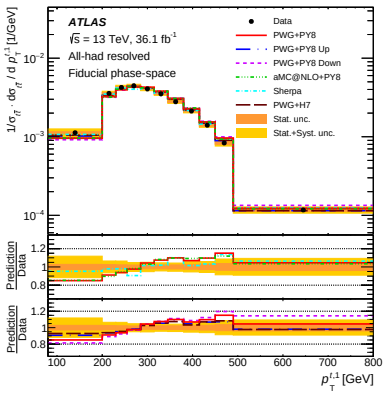












Knowledge of (differential) $t\bar{t}$ production cross section improved significantly:

- inclusive cross section at new collision energy (5 TeV)
- new analysis techniques constraining systematic uncertainties
- increased statistics to explorer the boosted regime.

- Results for different channels/experiments are consistent
- Most of the measurements are well described by standard model predictions
  —but some mismodeling of double-differential distributions
- Cross sections are used for limits on EFT couplings or to extract PDFs and standard model parameters (m_t^{pole}, α_s)

Backup