Precision measurements in $t\bar{t}$ final states

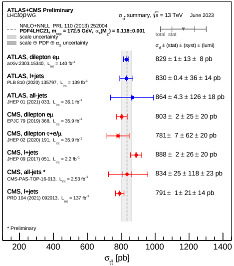
O. Hindrichs
On behalf of the CMS collaboration

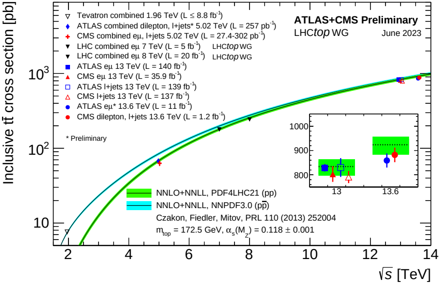
University of Rochester

SM@LHC 2023

July 10, 2023

Cross sections of 830 pb (920 pb) at 13 TeV (13.6 TeV) → about 100M $\mathrm{t\bar{t}}$ pairs in Run 2





(Differential) cross section measurements:

- in all decay channels; at parton and particle level; including high p_{T} (boosted) top quarks
- used to extract m_{t}, charge asymmetry, PDFs ...
- provides interface to theory: test against new SM or BSM calculations
- but relies on unfolding

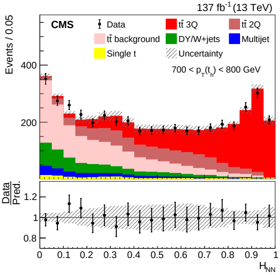
Direct extraction of parameters from data distribution:

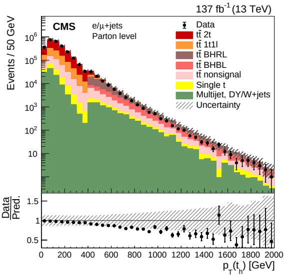
- m_{t}, top quark Yukawa coupling ...
- avoids unfolding, easier to constrain uncertainties from control regions.
- but depends directly on theory predictions

137 fb^{-1}, 13 TeV, CMS: *Phys. Rev. D 104, 092013*

Analysis uses combination of resolved and boosted reconstructions:

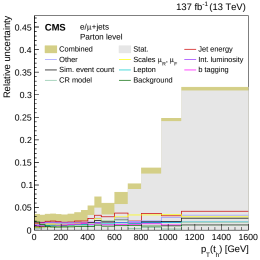
- resolved: 1 isolated e/μ and at least 4 jets (2 categories with tight and relaxed b-tagging requirement)
- boosted t_l: 1 non-isolated lepton within $\Delta R < 0.6$ of a b jet. Selection using neural network (NN) based on isolation and kinematic variables.
- boosted t_h: 1 anti-k_T (size=0.8) jet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

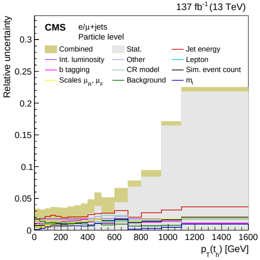




BHRL: boosted t_h, resolved t_l; BHBL: boosted t_h and t_l

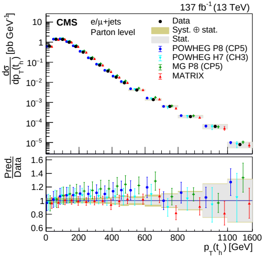
Uncertainties

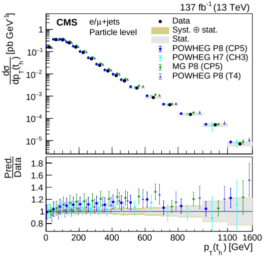




- depending on the phase space region the precision is limited by systematic or statistical uncertainty.
- systematic dominated by experimental uncertainties like jet energy calibration and b-tagging.
- particle-level measurements reduce dependency on theoretical predictions (avoids extrapolation to full phase space)

Results

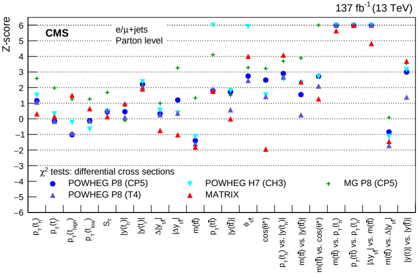


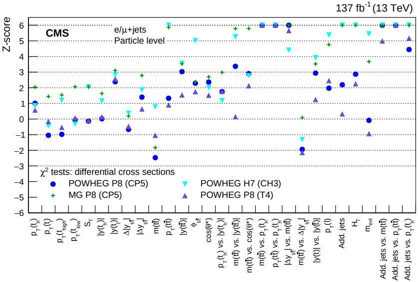


- p_T well described by NNLO calculation.
- trend of harder spectrum in NLO calculations disappears above 600 GeV

Comparison of measurements to various predictions using χ^2-tests

uncertainties in measurements and predictions are take into account.





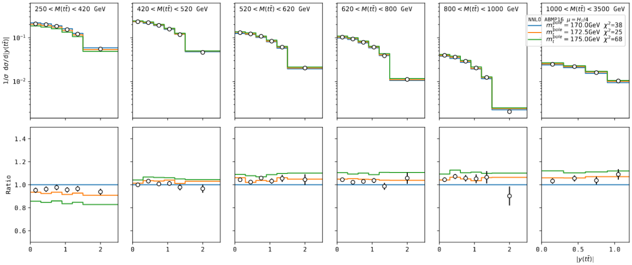
Most of the predictions are in good agreement with the measurement—with a few exceptions:

- $m(\mathrm{t\bar{t}})$ 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.
  but theory uncertainties might be underestimated using fully correlated scale variations
- at particle level additional jets vs. kinematic observable are not well described.
  depends strongly on PS tuning

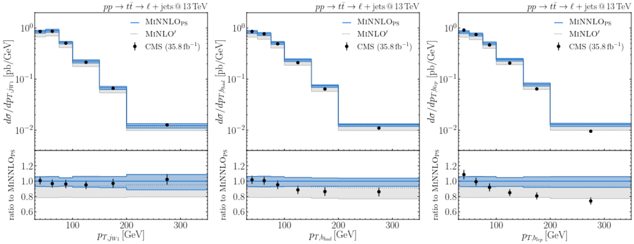
Use cases

[M.V. Garzelli, S.-O. Moch, S. Zenaiev]

Measurements compared to NNLO calculations (MATRIX) to extract m_t or PDFs:



JHEP 04 (2022) 079: calculation of $\mathrm{t\bar{t}}$ NNLO+PS with POWHEG MINNLO$_\mathrm{PS}$ (direct comparison of particle level measurements to NNLO calcualtion)

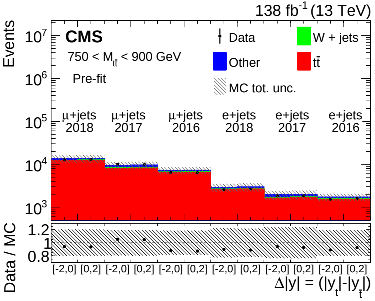


138 fb^{-1}, 13 TeV, *Acc. by Phys. Lett. B*

Asymmetry only expected for $q\bar{q}$ induced $t\bar{t}$ production. At high $m(t\bar{t}) > 750$ GeV the contribution of valence quarks increases. Better sensitivity to BSM contributions expected.

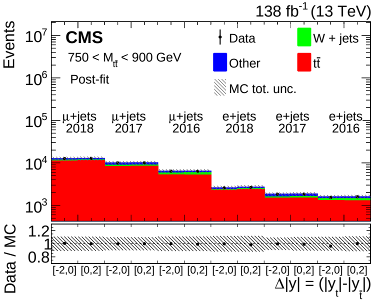
Select e/μ+jets with high p_T top quarks

- t_h: one jet (size 0.8) containing all top decay products, one jet (0.4) + a jet (0.8) with W boson decay products, or fully resolved
- t_l: non-isolated lepton ($p_T(\mu) > 55$, $p_T(e) > 80$ GeV) + jet with $\Delta R(lj) < 0.4$ or p_T relative to jet > 25 GeV



Unfold to full and fiducial phase space:
(migration matrix A, unfolded cross sections μ):

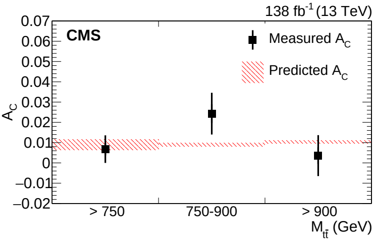
$$\mathcal{L}_k = \prod_{j=1}^{N_{\text{reco}}} P\left(n_j; \sum_{i=1}^{N_{\text{gen}}} A_{ji}(\vec{\delta}_u)\mu_i + b_j\right) N(\vec{\delta}_u)$$



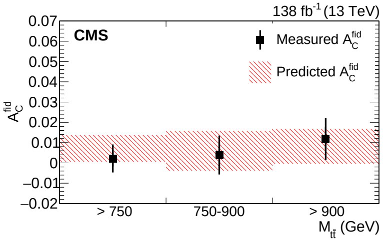
Obtain asymmetry:

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

full



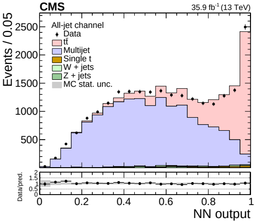
fiducial

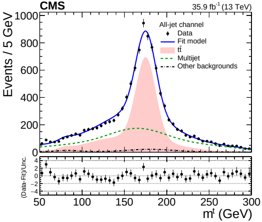


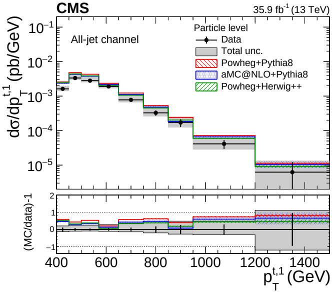
Results are compatible with SM expectation

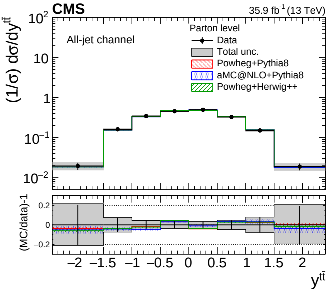
36 fb^{-1}, 13 TeV, *PRD 103 (2021) 052008*

- 2 jets (size: 0.8) $p_{\mathrm{T}} > 400$ GeV, soft-drop mass: 120 – 220 GeV, b-tagged
- NN based on n-subjettiness used to define signal and control region:









CR: $NN < 0.8$ normalized using m_{t}-fit

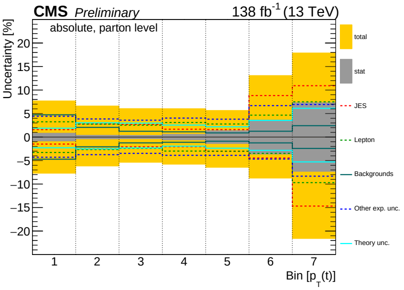
Unregularized unfolding (matrix inversion)

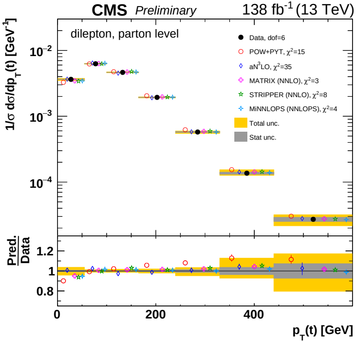
- good agreements of shapes between predictions and measurements in boosted regime

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

138 fb^{-1}, 13 TeV, CMS: *CMS-TOP-20-006*

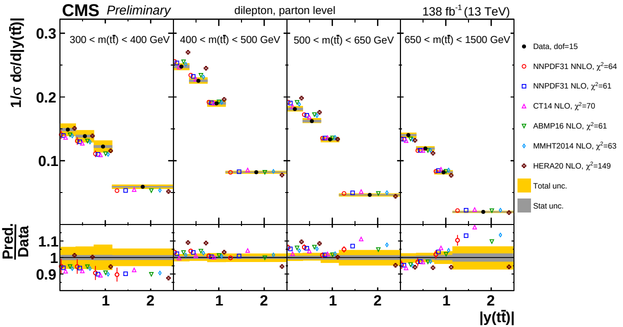
- selection: ee, $e\mu$, $\mu\mu$ at least 2 jets, at least 1 b jet.
- find analytic solutions for neutrino momenta; use solution with lowest $m(t\bar{t})$. Repeat procedure 100 times varying objects within their resolutions.



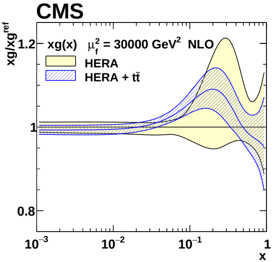


- uncertainty dominated by experimental uncertainties
- NNLO calculation improves description of p_T spectrum

Interpretation of double-differential $t\bar{t}$ measurements



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



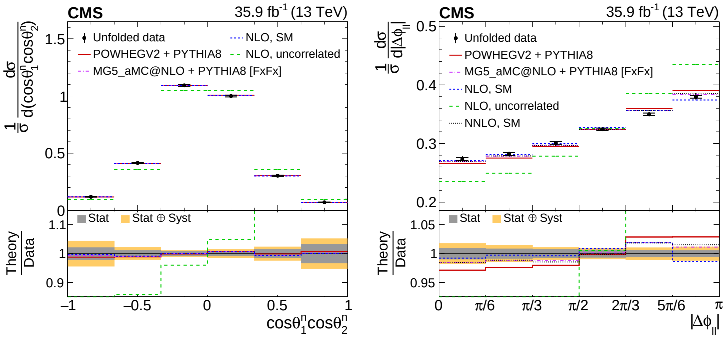
- $m(t\bar{t})$ vs $|y(t\bar{t})|$ shown to be sensitive to high x-gluon PDFs.
- these measurements are/will be included in new PDF fits.

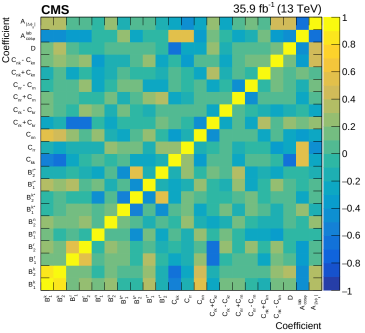
36 fb^{-1}, 13 TeV, *Phys. Rev. D 100 (2019) 072002*

- in helicity-frame the differential cross section of particles from $t\bar{t}$ decay can be parameterized by the polarization vector B and spin correlation matrix C:

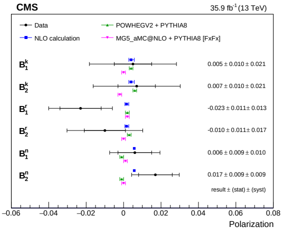
$$\frac{d^4\sigma}{d\Omega d\bar{\Omega}} \propto 1 + \kappa\vec{B}\cdot\Omega + \bar{\kappa}\vec{\bar{B}}\cdot\bar{\Omega} + \kappa\bar{\kappa}\Omega\cdot C\cdot\bar{\Omega}$$

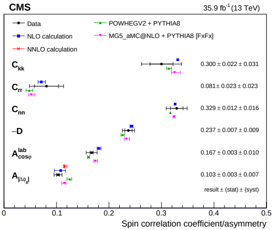
- use dilepton events with same reconstruction as in differential cross section measurement.

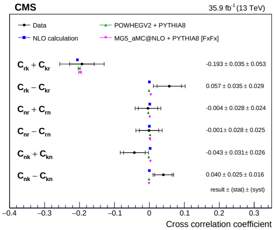




- from a set of unfolded distributions extract all parameters of B and C
- measured polarization and spin correlation in agreement with SM expectations

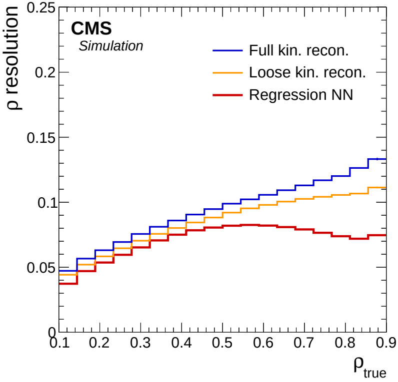


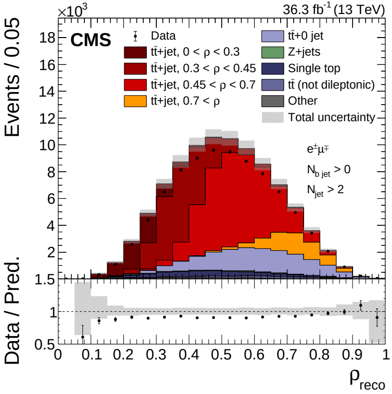


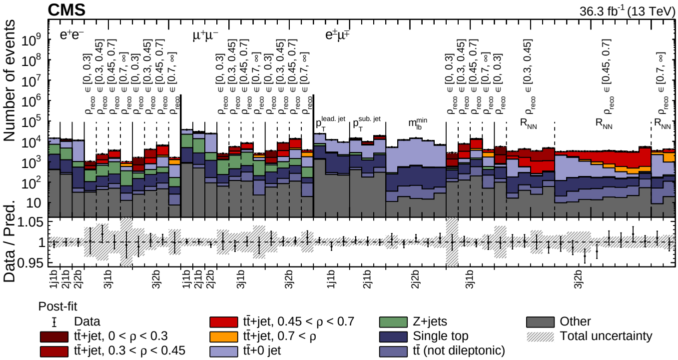


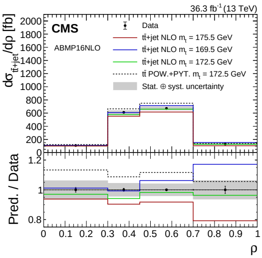
36 fb^{-1}, 13 TeV, *CMS-TOP-21-008 acc. JHEP*

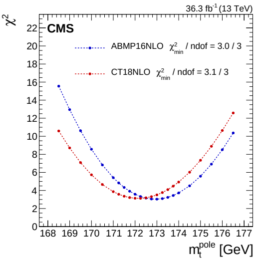
- dilepton events use same reconstruction as in differential cross section measurement.
- sensitive variable $\rho = 2m_0/m_{t\bar{t}+jet}$
  presence of additional jet increases sensitivity on m_t^{pole}
- resolution improved based on regression using NN (input 10 kinematic parameters mostly direct calculations of ρ and invariant object masses)









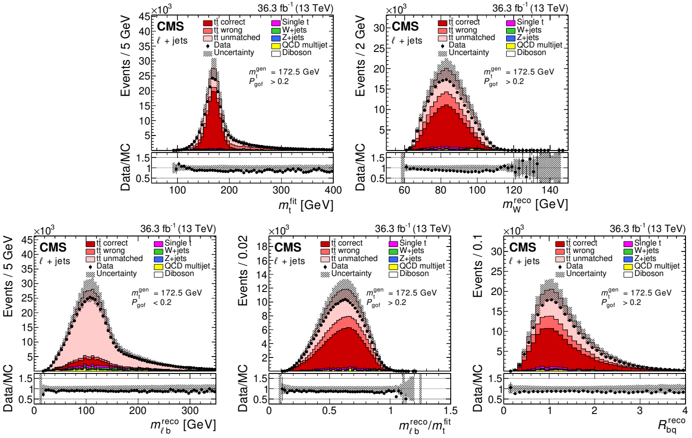


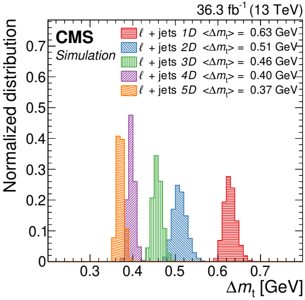
- differential cross section $d\sigma/d\rho$ fitted/unfolded using multiple categories of jet multiplicities and background discriminating NN R_{NN}
- last bin of ρ strong effect of m_t^{pole}. Unc in cross section : 2.9% exp., 1.2% theory, 6.2% total
- best fit result: $m_t^{\mathrm{pole}} = 172.94 \pm 1.37\,\mathrm{GeV}$ (ABMP16NLO)

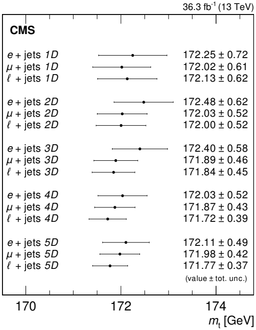
Direct measurement of m_t (MC parameter) in e/μ+jets events

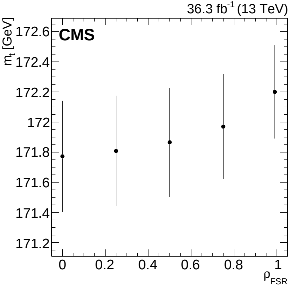
36 fb^{-1}, 13 TeV, *CMS-TOP-20-008 Sub. to Eur. Phys. J. C*

- select events with e/μ and >= 4jets
- perform kinematic fitting with constraints of two equal top quark masses and W mass
- goodness of fit also used to determine best parton-jet assignment
- up to 5 distributions used to extract m_t



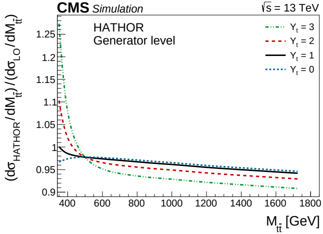


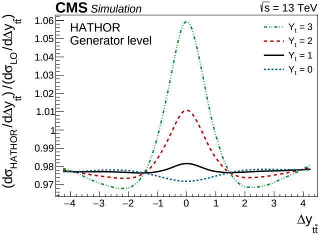




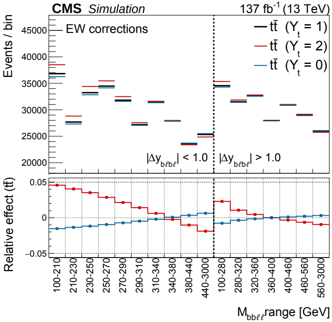
- best fitted value $m_\mathrm{t} = 171.77 \pm 0.37\,\mathrm{GeV}$
- leading uncertainty is final-state PS scales 0.21 GeV
  in contrast to previous measurements uncorrelated scales for different splittings used
- modelling very important for this measurement

137 fb^{-1}, 13 TeV, *Phys. Rev. D 102 (2020) 092013*



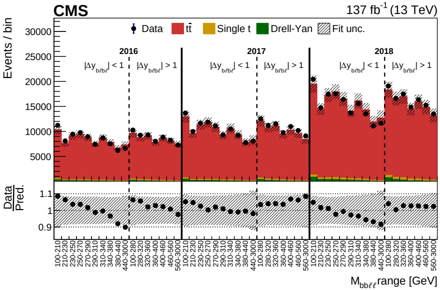


Calculations of EW corrections to $m(\mathrm{t\bar{t}})$ and $|\Delta y_{\mathrm{t\bar{t}}}|$ show significant dependency on the Y_{t}

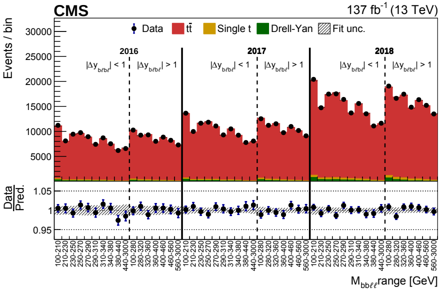


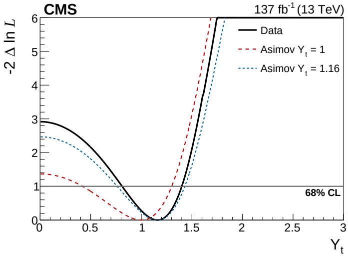
- select events with ee, $\mu\mu$, eμ plus 2 b jets
- to avoid systematic unc. in $p_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction, m_{blbl} and Δy_{bl} are used

prefit

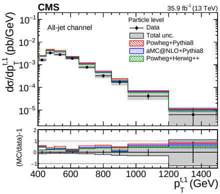


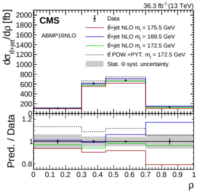
postfit

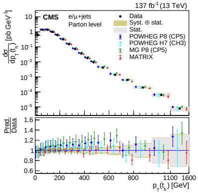


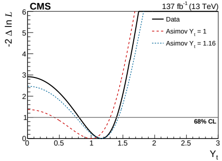


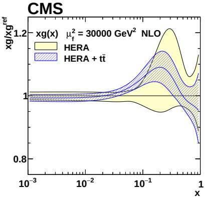
- best fitted value $Y_t = 1.16^{+0.24}_{-0.35}$
- leading uncertainties
  - – jet energy corrections
  - – uncertainty in EW correction (in particular combination NLO(NNLO) QCD + EW)
  - – parton shower modelling

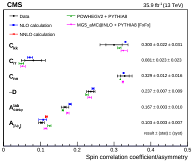












Measurement of differential cross sections:

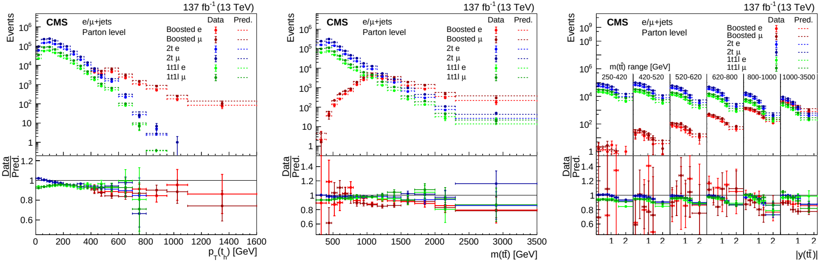
- performed in all channels
- even in low populated phase space regions
- reaches great precision: uncertainties mostly dominated by experimental sources
- to some degree dealing with theory uncertainties can be postponed (in particular for fiducial measurements)
- further used to extract important parameters: m_{t}, $\mathrm{t\bar{t}}$ spin correlations, charge asymmetry, PDFs

Direct extractions of parameters:

- can provide very precise measurements m_{t}, Y_{t} if experimental and theoretical uncertainties can be constrained
- depends on precise understanding of theory and its uncertainties.

Backup

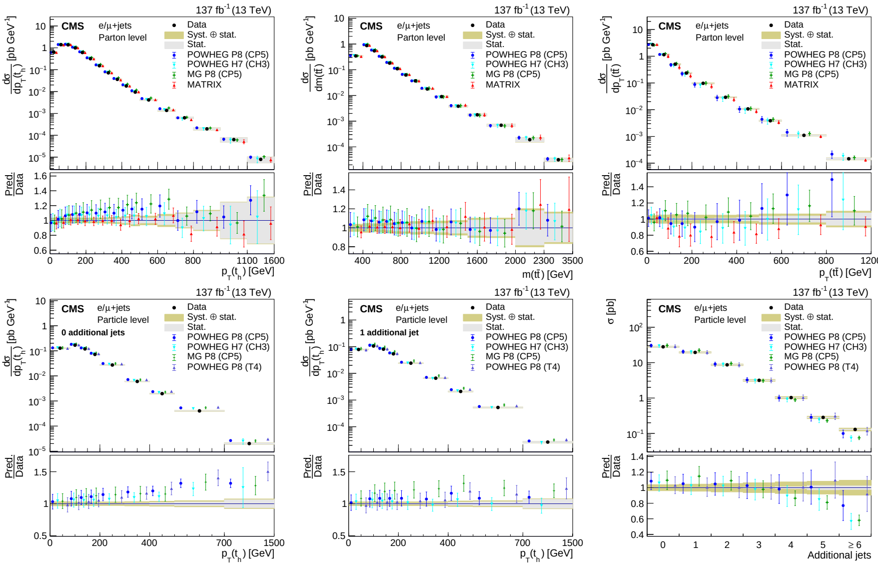
Perform χ^2-fit to extract the cross sections:



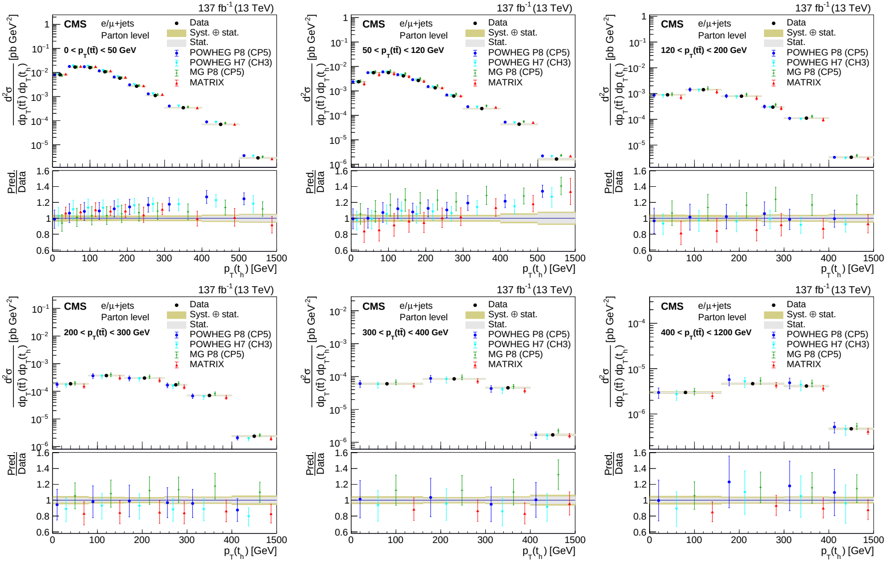
$$\chi^2 = \sum_{\ell} \sum_{y} \sum_{r} (\mathbf{m}_{yr\ell} - \mathbf{b}_{yr\ell}(\nu_\alpha) - M_{yr\ell}(\nu_\alpha)\boldsymbol{\sigma})^T C^{-1}_{yr\ell} (\mathbf{m}_{yr\ell} - \mathbf{b}_{yr\ell}(\nu_\alpha) - M_{yr\ell}(\nu_\alpha)\boldsymbol{\sigma}) + \kappa(\nu_\alpha)$$

- **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 $t\bar{t}$ event yields at detector level.
- $\mathbf{b}(\nu_\alpha)$ non $t\bar{t}$ background.

– No regularization condition is used

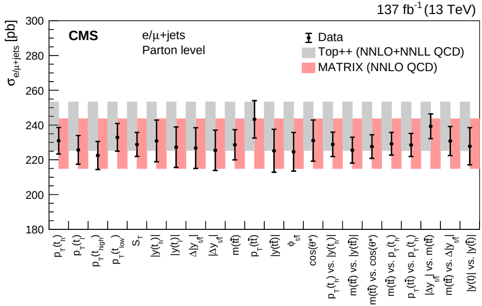


– worst description of p_{T} in events without additional jet.



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

Obtain inclusive cross section from integration of differential distributions:



- Result of best expected measurement ($m(\mathrm{t\bar{t}})\mathrm{vs}\cos(\theta^*)$), 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 $e/\mu+\mathrm{jets}$:

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

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