# Measurements of differential $t\bar{t}$ cross sections at CMS

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**On behalf of the CMS collaboration**

University of Rochester

**Top Quark Physics at the Precision Frontier**
**Fermilab**

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

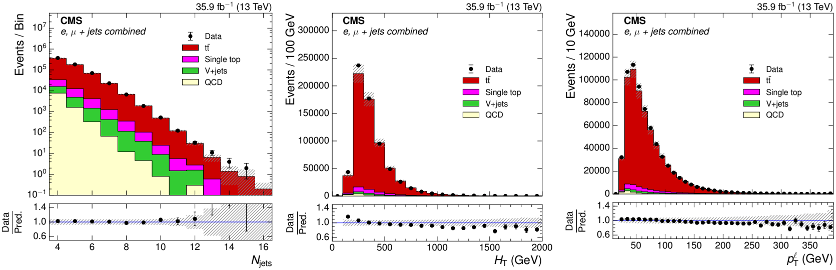
- as a function of kinematic event variables (JHEP06 (2018) 002)
- differential measurements at parton and particle level in dilepton (JHEP02 (2019) 149) and $e/\mu$+jets (PRD97 (2018) 112003) channels
- multi-differential measurements in dilepton (arXiv:1904.05237 sub. EPJC) and $e/\mu$+jets
- multiplicities and properties of jets in $t\bar{t}$ events (PRD97 (2018) 112003)
- with boosted reconstruction in all-jets final state (TOP-16-013)

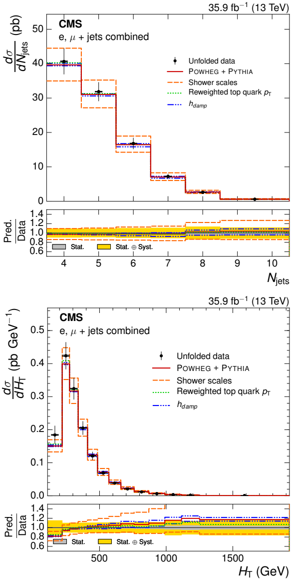
36 fb$^{-1}$, 13 TeV, Sub. to JHEP, arXiv:1801.03991

**Measurements of variables that do not need reconstruction of top quarks.**

Measurement based on "stable" particles (>30 ns) within experimental acceptance
→ avoid theory extrapolations.
Objects use RIVET definitions see CERN-CMS-NOTE-2017-004. plugin available I1662081

- Selection: exactly 1 $e/\mu$, at least 4 jets, at least 2 b-tagged jets.





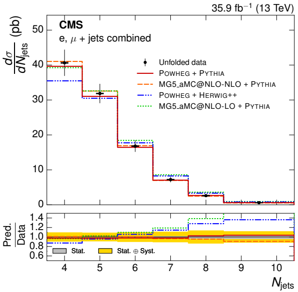

## Systematic uncertainties

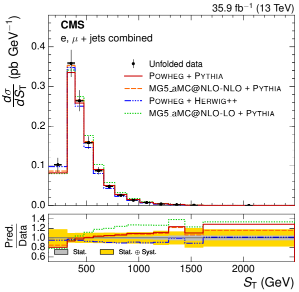
| Relative uncertainty source (%) | $N_{\text{jets}}$ | $H_T$ |
|---|---|---|
| b tagging efficiency | 3.2 – 4.1 | 3.6 – 4.7 |
| Electron efficiency | 1.2 – 1.4 | 1.3 – 1.6 |
| Muon efficiency | 1.7 – 1.9 | 1.6 – 2.2 |
| JER | 0.1 – 0.9 | 0.1 – 1.2 |
| JES | 1.8 – 12.6 | 5.7 – 16.8 |
| QCD bkg cross section | 0.1 – 0.5 | 0.1 – 0.7 |
| QCD bkg shape | <0.1 | 0.1 – 1.0 |
| Single top quark cross section | 1.1 – 1.7 | 1.1 – 3.5 |
| V+jets cross section | 0.7 – 1.1 | 0.6 – 3.4 |
| PDF | 0.2 – 1.0 | 0.1 – 0.8 |
| Color reconnection (Gluon move) | 0.1 – 2.9 | 0.1 – 4.1 |
| Color reconnection (QCD-based) | 0.1 – 2.3 | 0.1 – 4.4 |
| Color reconnection (Early resonance decays) | 0.3 – 3.9 | 0.1 – 7.1 |
| Fragmentation | 0.1 – 2.8 | 0.6 – 3.1 |
| $h_{\text{damp}}$ | 0.8 – 4.9 | 0.3 – 4.1 |
| Top quark mass | 0.7 – 2.8 | 0.4 – 4.9 |
| Peterson fragmentation model | 0.3 – 3.9 | 1.6 – 3.9 |
| Shower scales | 3.1 – 8.0 | 3.6 – 8.3 |
| B hadron decay semileptonic branching fraction | 0.2 – 0.9 | 0.2 – 1.2 |
| Top quark $p_T$ | 0.8 – 1.6 | 0.1 – 1.4 |
| Underlying event tune | 0.8 – 3.9 | 0.3 – 7.0 |
| Simulated sample size | 0.1 – 1.6 | 0.1 – 1.6 |
| Additional interactions | 0.1 – 0.4 | 0.1 – 0.8 |
| Integrated luminosity | 2.5 – 2.5 | 2.5 – 2.5 |
| Total | 10.8 – 16.5 | 11.2 – 19.4 |

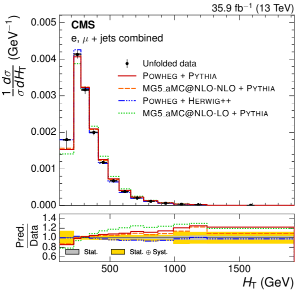
Modeling uncertainties represent baseline for all recent CMS top quark measurements.

- Shower scales have large impact on predictions. They also contribute as a dominant uncertainty in the measurement.

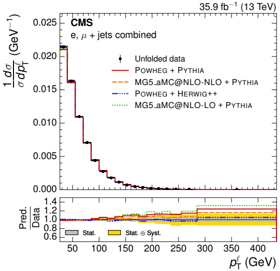
$36\,\mathrm{fb}^{-1}$, 13 TeV, JHEP06 (2018) 002

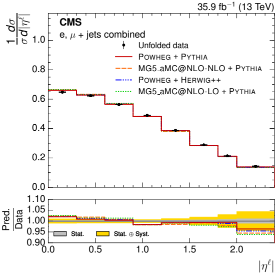


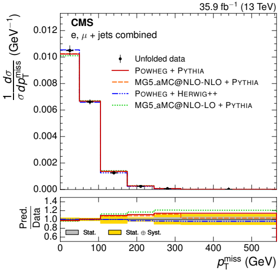




- POWHEG+HERWIG++ and POWHEG/MG5(MLM)+PYTHIA8 predict higher jet multiplicity
- $H_T$ and $S_T$ ($p_T$ sum of all objects) are softer than predicted by most MCs.




| | $\chi^2$/ndf | $p$-value |
|---|---|---|
| $N_{jets}$ | 1.7 / 6 | 0.95 |
| $H_T$ | 4.3 / 13 | 0.99 |
| $S_T$ | 4.7 / 13 | 0.98 |
| $p_T^{miss}$ | 3.1 / 6 | 0.80 |
| $p_T^W$ | 2.7 / 7 | 0.91 |
| $p_T^\ell$ | 14 / 17 | 0.68 |
| $\lvert\eta^\ell\rvert$ | 15 / 8 | 0.06 |

**Lepton related variables**

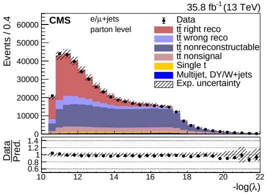
- $e/\mu$ $p_T$ softer and $\eta$ less central.
- also observed for $p_T^{miss}$.

$\chi^2$-tests considering theory uncertainties (POWHEG+PYTHIA8) show compatibility between measurements and expectations.

**$e/\mu$+jets**

36 fb$^{-1}$, 13 TeV, PRD97 (2018) 112003

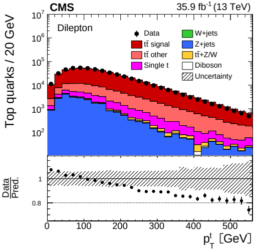
- Selection: exactly 1 $e/\mu$, at least 4 jets, at least 2 b-tagged.
- Based on lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$ use mass constraints of $m_{\mathrm{t}}$, $m_W$ on leptonic side to obtain $p_z$-component of neutrino momentum, and correct b-jet.
- Calculate likelihood $\lambda$ according to 2D mass distributions of reconstructed $m_{\mathrm{t}}$–$m_W$ on hadronic side and compatibility of b-jet on leptonic side.




**dilepton**

36 fb$^{-1}$, 13 TeV, JHEP02 (2019) 149

- Selection: $ee$, $e\mu$, $\mu\mu$ at least 2 jets, at least 1 b-tagged.
- In same flavor channels exclude Z-Peak and require $p_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
- – Neutrino momenta calculated using $m_{\mathrm{t}}$, $m_W$ based on leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$ testing all permutation of jets (b jets preferred). Solution with lowest $\mathrm{M}(t\bar{t})$ selected.
  – Object momenta smeared according to resolution. 100 smeared events summed weighted according to expected $M(\ell\ell bb)$.

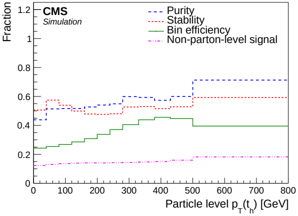


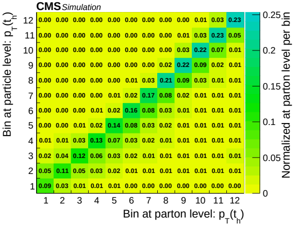
36 fb$^{-1}$, 13 TeV, PRD97 (2018) 112003

Define proxy of top quark based on measurable objects (leptons, jets) in experimental acceptance:
→ clean definition of "top quark" observable.
→ avoid theoretical extrapolations.

**Definition of particle-level top quarks** (CERN-CMS-NOTE-2017-004)
Events with exactly 1 electron/muon, 2 b jets, in total at least 4 jets
Sum momenta of all neutrinos $p_N$ and find the permutation of jets that minimizes:

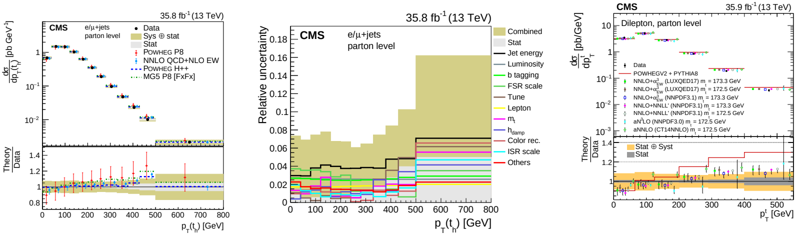
$$K^2 = (M(p_N + p_\ell + p_{b_1}) - m_\mathrm{t})^2 + (M(p_{j_1} + p_{j_2}) - m_\mathrm{W})^2 + (M(p_{j_1} + p_{j_2} + p_{b_2}) - m_\mathrm{t})^2$$



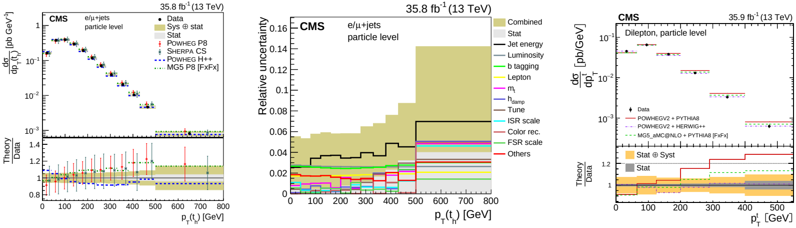




Analysis uses RIVET for particle level level definitions. plugin available I1663958.

## Parton level



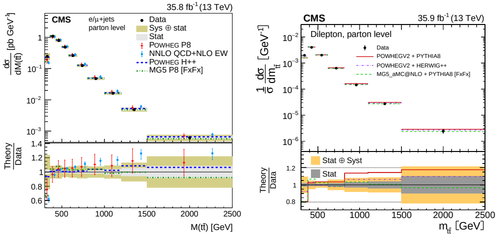

## Particle level



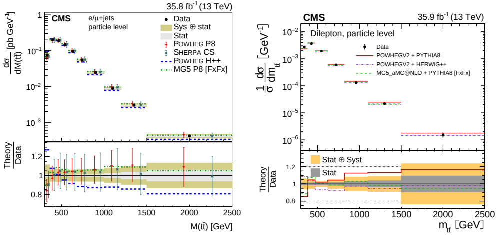

- Softer $p_{\mathrm{T}}(\mathrm{t})$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA.
- Better $p_{\mathrm{T}}(\mathrm{t})$ agreement with NNLO QCD + NLO EW [JHEP10 (2017) 186] calculation

$36\,\mathrm{fb}^{-1}$, 13 TeV, PRD97 (2018) 112003, JHEP02 (2019) 149

## Parton level




## Particle level

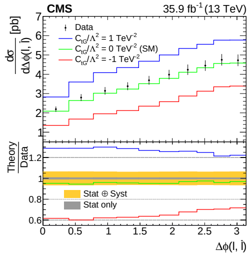


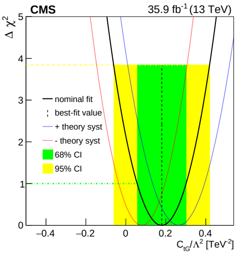

- $e/\mu$+jets and dilepton channels show similar deviations from predictions
- Softer $M(\mathrm{t\bar{t}})$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA.
- POWHEG+HERWIG++ too soft at particle level, while better at parton level.
- In general: $\chi^2$-tests (see backup) considering theory uncertainties (POWHEG+PYTHIA8 and SHERPA) show reasonable compatibility between measurements and SM predictions.

Normalized and absolute cross sections for all distributions available.

36 fb$^{-1}$, 13 TeV, PRD97 (2018) 112003, JHEP02 (2019) 149

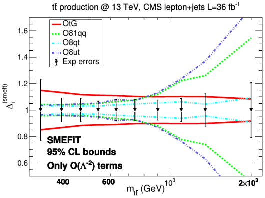
## Chromomagnetic dipole moment

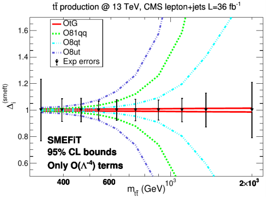



- anomalous CMDM introduced by EFT operator ($O_{Gt}$) introducing a $gg\mathrm{t}\bar{\mathrm{t}}$ vertex
- experimentally mostly visible in angle between leptons.

## Global EFT interpretations (JHEP04 (2019) 100)

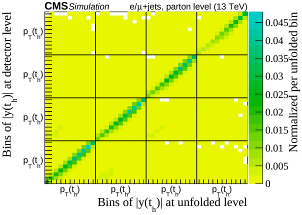


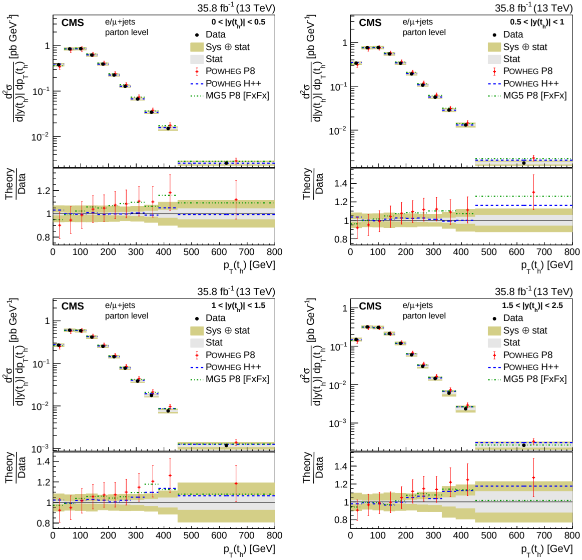

- high $M(\mathrm{t}\bar{\mathrm{t}})$ makes important contribution to the combined EFT interpretations of all top quark production related measurements at the LHC

36 $fb^{-1}$, 13 TeV, PRD97 (2018) 112003

**Results unfolded in 2 dim.**
→correction for migrations among all bins.

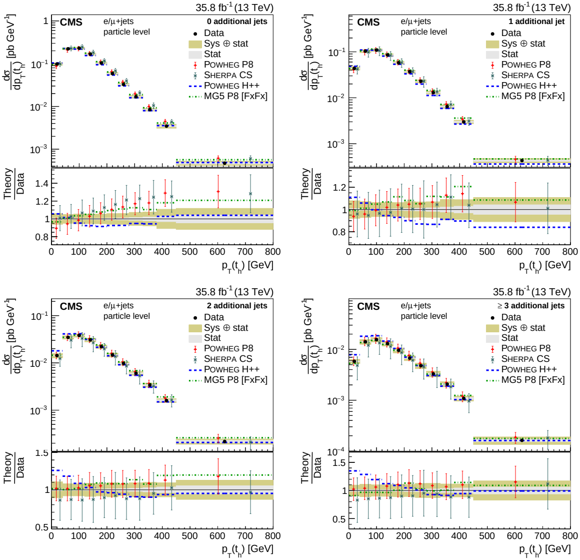



- Provide more details in corners of phase space.
- $p_T(t)$ softer in all rapidity regions.



$36\,\mathrm{fb}^{-1}$, 13 TeV,PRD97 (2018) 112003

# $p_T(\mathrm{t})$ in bins of jet multiplicity ($p_T(\mathrm{jet}) > 30$ GeV)

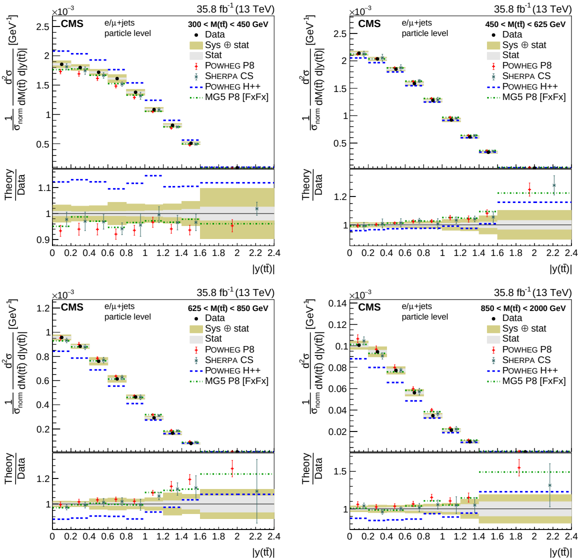



2 dim. unfolding in $p_T(\mathrm{t})$ and number of additional jets.

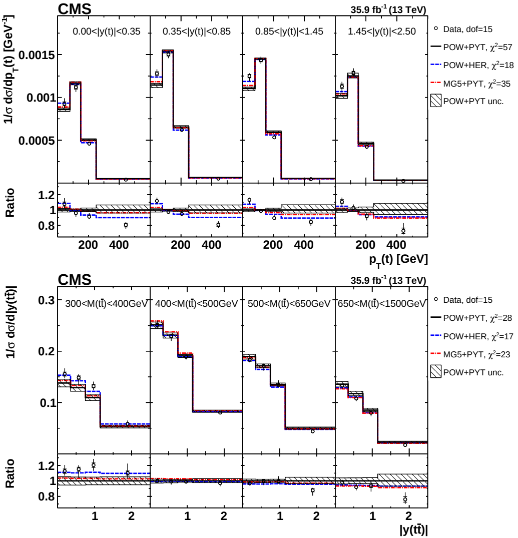
- The slope disappears for events with higher jet multiplicity.
- HERWIG++ does not follow the trend.

## $y(t\bar{t})$ in different $M(t\bar{t})$ regions

- Here at particle level, but all distributions not including additional jets also available at parton level.
- Some tendency to overestimate the cross section at higher $M(t\bar{t})$ and $|y(t\bar{t})|$



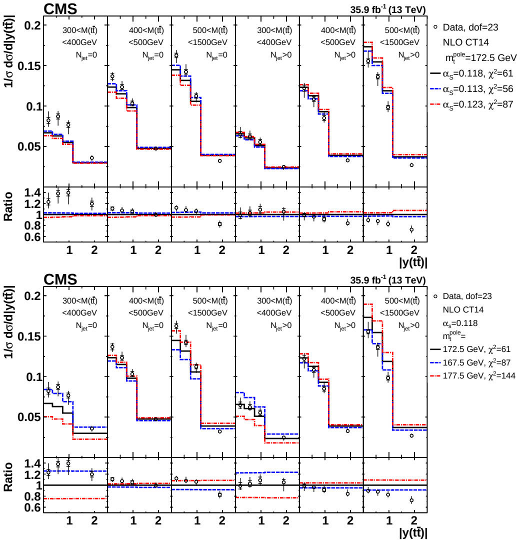
36 $\text{fb}^{-1}$, 13 TeV, arXiv:1904.05237 sub. EPJC




- Uses same reconstruction as single differential measurement in dilepton channel.
- Results show similar behavior as in $e/\mu$+jets.

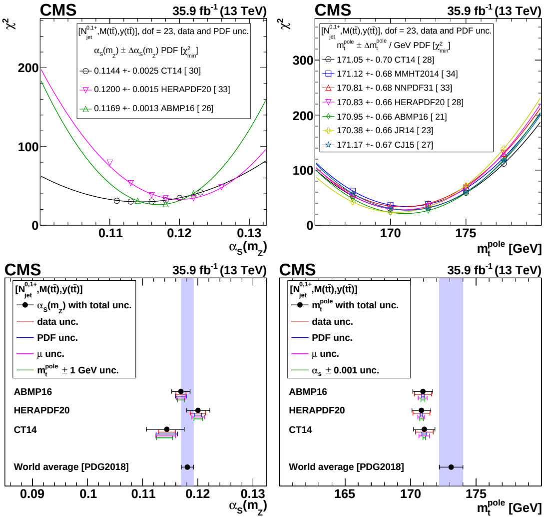
# Interpretations of multi-Differential $t\bar{t}$ cross sections

36 $\text{fb}^{-1}$, 13 TeV, arXiv:1904.05237 sub. EPJC




- $M(t\bar{t})$ vs $y(t\bar{t})$ in bins of jet multiplicity is sensitive to $m_t^{\text{pole}}$ and $\alpha_s$
- 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: $p_z(\nu\bar{\nu}) = p_z(\ell^+\ell^-)$

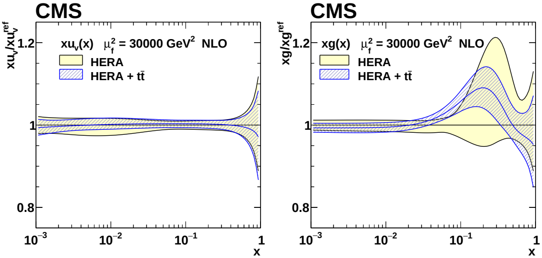
36 fb$^{-1}$, 13 TeV, arXiv:1904.05237 sub. EPJC



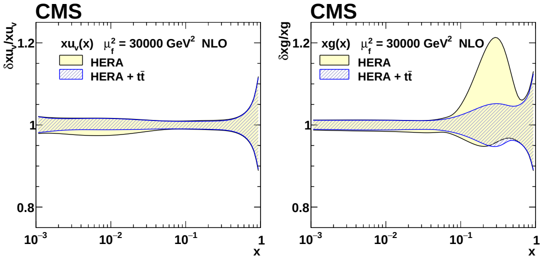

- $m_t^{\text{pole}}$ and $\alpha_s$ are extracted from comparisons with fixed order NLO cross section.
- taking into account scale and PDF uncertainties in the theoretical prediction.

$36\,\mathrm{fb}^{-1}$, 13 TeV, arXiv:1904.05237 sub. EPJC

**Comparison of PDF**




**Comparison of PDF uncertainties**



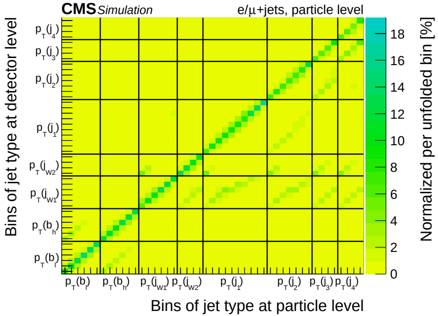

## PDF constraints

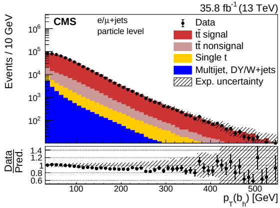
- $m_t$ and $\alpha_s$ are free parameters
- PDF parameterization as in HERAPDF2.0
- combined fit with HERA DIS data
- extracted:
  $m_t^{pole} = 170.5 \pm 0.8\,\mathrm{GeV}$
  $\alpha_s(m_Z) = 0.1135^{+0.0021}_{-0.0017}$

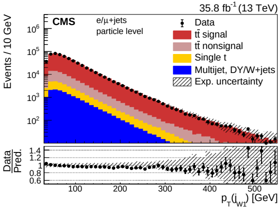
36 fb$^{-1}$, 13 TeV,PRD97 (2018) 112003

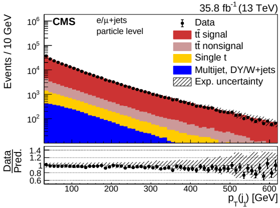
## Jet properties

- Measurement of kinematic properties of jets in $t\bar{t}$ system ($b_l$, $b_h$, $j_{W_1}$, $j_{W_2}$) and up to four additional jets ($j_1$ … $j_4$) ordered by $p_{\mathrm{T}}$.
- Correct for effects of resolution and mis-identification of jets.

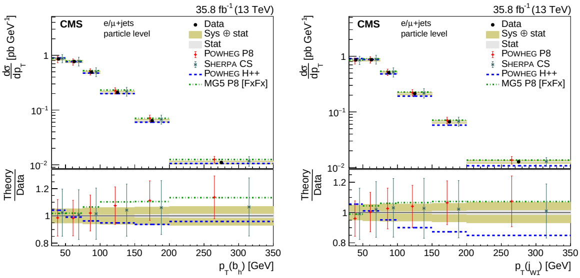


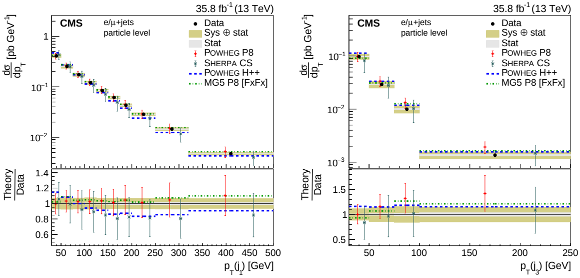



## Jets of the $t\bar{t}$ system



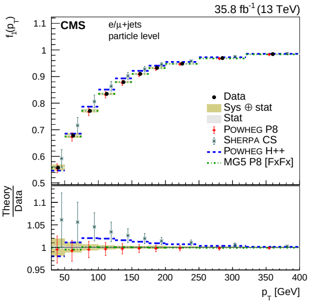

## Additional Jets

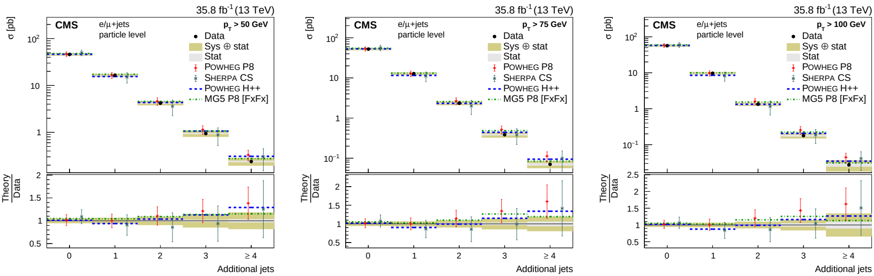



- POWHEG+PYTHIA8: describes data, but $> 1$ jet from parton shower.
- MG5+PYTHIA8 [FxFx] ($t\bar{t}$ + up to 2 jets NLO): similar to POWHEG+PYTHIA8.
- SHERPA ($t\bar{t}$ + 0,1 jet NLO, up to 4 jets LO): some deviation description of add. jets.
- POWHEG+HERWIG++: jets in $t\bar{t}$ system too soft (related to soft $p_T$ at particle level).

$36\,\mathrm{fb}^{-1}$, 13 TeV, PRD97 (2018) 112003

- Gap fraction (fraction of events without a jet above a given $p_T$ threshold) well described by POWHEG/MG5+PYTHIA8.
- SHERPA and POWHEG+HERWIG++ show both differences.
- Jet multiplicities for various $p_T$ thresholds show reasonable agreement.



$36\,\text{fb}^{-1}$, 13 TeV, PRD97 (2018) 112003

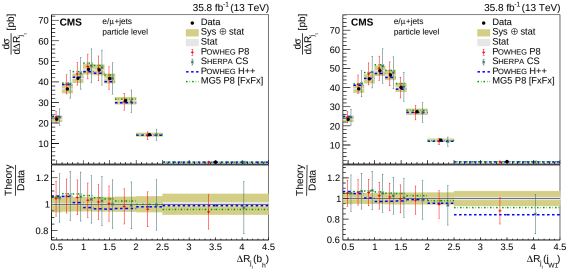
**Minimum separation between a jet and the jets in $t\bar{t}$ system**

- Sensitive to final state PS.
- Jets of $t\bar{t}$ decay closer due to higher top $p_T$ in Simulation.
- POWHEG+HERWIG++ predicts too many jets close to $t\bar{t}$ jets. →reduced momentum of particle level top quark.

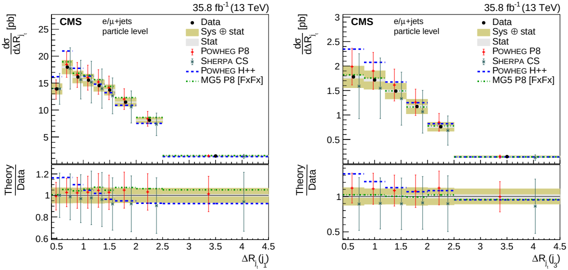
**$\chi^2$-tests with full set of th. uncertainties for jet related distributions:**

- POWHEG+PYTHIA8: relies on PS tuning shows reasonable agreement
- SHERPA: with default tune and LO at high jet multiplicities shows larger deviations.

## Jets of the $t\bar{t}$ system




## Additional Jets



2.5 $\mathrm{fb}^{-1}$, 13 TeV, CMS-TOP-16-013

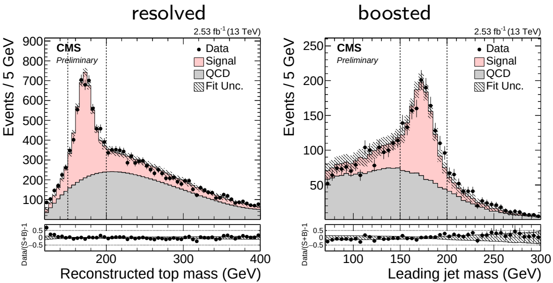
**Resolved**

- Selection: at least 6 jets, 2 b tagged.
- Perform kinematic fit for $t\bar{t}$ reconstruction (based on W and top mass constrains)
- Accept events with $150 < m_t^{\mathrm{fit}} < 200$ GeV, and fit probability greater than 0.02.

**Boosted**

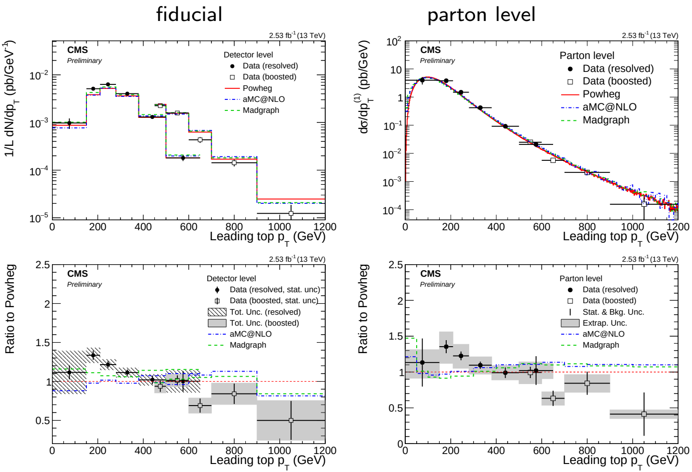
- 1 jet $p_T > 200$ GeV and 1 jet $p_T > 450$ GeV
- each jet: softdrop mass $> 50$ GeV, b tagged subjet, n-jettiness requirements.

Template Fit: Signal template from MC, background template from data by inverting b tagging.



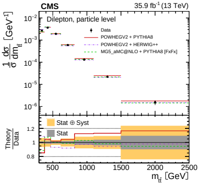

$$\sigma_{t\bar{t}} = 834 \pm 25(stat)^{+118}_{-104}(syst) \pm 23(lumi)\ \mathrm{pb}$$

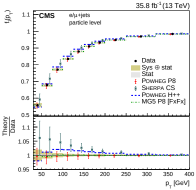
2.5 $\mathrm{fb}^{-1}$, 13 TeV, CMS-TOP-16-013,

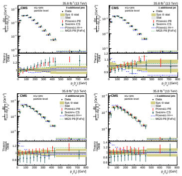


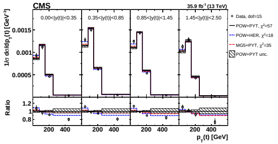

Soft $p_{\mathrm{T}}(\mathrm{t})$ confirmed in all-jets channel and persisting in boosted regime.

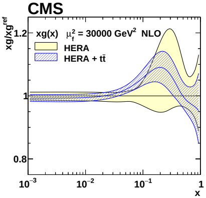
# Conclusion

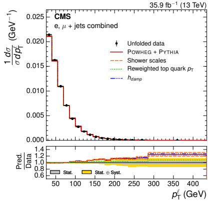





**Differential $t\bar{t}$ cross sections:**

- Event variables.
- 1D, 2D differential cross sections of the top quarks.
- Differential distributions of jets in $t\bar{t}$ events.

**These measurements provide:**

- Precision test of the SM top quark production.
- Tests of parton shower models
  $\rightarrow$improved understanding of systematics in other measurements, e.g., top mass.
- PDF constraints, extractions of $m_t$ and $\alpha_s$.
- Constraints on BSM effective theories
- ...

# Backup

## Parton level

| Distribution | $\chi^2$/dof | $p$-value | $\chi^2$/dof | $p$-value | $\chi^2$/dof | $p$-value |
|---|---|---|---|---|---|---|
| | POWHEG+P8 with unc. | | POWHEG+P8 | | NNLO QCD+NLO EW | |
| $p_T(t_{high})$ | 16.4/12 | 0.173 | 27.4/12 | <0.01 | | |
| $p_T(t_{low})$ | 22.4/12 | 0.033 | 42.7/12 | <0.01 | | |
| $p_T(t_h)$ | 16.4/12 | 0.175 | 24.0/12 | 0.020 | 5.13/12 | 0.953 |
| $\lvert y(t_h)\rvert$ | 1.28/11 | 1.000 | 1.41/11 | 1.000 | 2.27/11 | 0.997 |
| $p_T(t_\ell)$ | 22.2/12 | 0.035 | 38.3/12 | <0.01 | 9.56/12 | 0.654 |
| $\lvert y(t_\ell)\rvert$ | 2.04/11 | 0.998 | 2.42/11 | 0.996 | 8.14/11 | 0.700 |
| $M(t\bar{t})$ | 7.67/10 | 0.661 | 11.6/10 | 0.314 | 24.7/10 | <0.01 |
| $p_T(t\bar{t})$ | 5.38/8 | 0.717 | 46.5/8 | <0.01 | | |
| $\lvert y(t\bar{t})\rvert$ | 3.98/10 | 0.948 | 5.66/10 | 0.843 | 9.26/10 | 0.507 |
| $\lvert y(t_h)\rvert$ vs. $p_T(t_h)$ | 23.6/44 | 0.995 | 41.6/44 | 0.577 | | |
| $M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$ | 20.6/35 | 0.975 | 35.0/35 | 0.469 | | |
| $p_T(t_h)$ vs. $M(t\bar{t})$ | 38.9/32 | 0.188 | 59.3/32 | <0.01 | | |
| | POWHEG+H++ | | MG5_aMC@NLO+P8 FxFx | | — | |
| $p_T(t_{high})$ | 6.60/12 | 0.883 | 16.3/12 | 0.180 | | |
| $p_T(t_{low})$ | 28.5/12 | <0.01 | 15.3/12 | 0.225 | | |
| $p_T(t_h)$ | 5.09/12 | 0.955 | 11.0/12 | 0.530 | | |
| $\lvert y(t_h)\rvert$ | 2.39/11 | 0.997 | 2.21/11 | 0.998 | | |
| $p_T(t_\ell)$ | 6.55/12 | 0.886 | 17.4/12 | 0.136 | | |
| $\lvert y(t_\ell)\rvert$ | 2.54/11 | 0.995 | 3.99/11 | 0.970 | | |
| $M(t\bar{t})$ | 4.16/10 | 0.940 | 12.1/10 | 0.275 | | |
| $p_T(t\bar{t})$ | 55.0/8 | <0.01 | 26.8/8 | <0.01 | | |
| $\lvert y(t\bar{t})\rvert$ | 11.9/10 | 0.292 | 8.92/10 | 0.540 | | |
| $\lvert y(t_h)\rvert$ vs. $p_T(t_h)$ | 57.9/44 | 0.077 | 40.2/44 | 0.634 | | |
| $M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$ | 40.8/35 | 0.229 | 58.7/35 | <0.01 | | |
| $p_T(t_h)$ vs. $M(t\bar{t})$ | 93.0/32 | <0.01 | 166/32 | <0.01 | | |

## Particle level

| Distribution | $\chi^2/\text{dof}$ | $p$-value | $\chi^2/\text{dof}$ | $p$-value | $\chi^2/\text{dof}$ | $p$-value |
|---|---|---|---|---|---|---|
| | POWHEG+P8 with unc. | | SHERPA with unc. | | POWHEG+P8 | |
| $p_T(t_h)$ | 15.9/12 | 0.197 | 7.21/12 | 0.844 | 29.5/12 | <0.01 |
| $\|y(t_h)\|$ | 1.96/11 | 0.999 | 1.48/11 | 1.000 | 2.23/11 | 0.997 |
| $p_T(t_\ell)$ | 27.0/12 | <0.01 | 22.3/12 | 0.034 | 80.2/12 | <0.01 |
| $\|y(t_\ell)\|$ | 4.55/11 | 0.951 | 5.07/11 | 0.928 | 4.99/11 | 0.932 |
| $M(t\bar{t})$ | 5.83/10 | 0.829 | 2.40/10 | 0.992 | 9.07/10 | 0.525 |
| $p_T(t\bar{t})$ | 4.96/8 | 0.761 | 28.9/8 | <0.01 | 41.2/8 | <0.01 |
| $\|y(t\bar{t})\|$ | 5.93/10 | 0.821 | 6.63/10 | 0.760 | 8.61/10 | 0.570 |
| $\|y(t_h)\|$ vs. $p_T(t_h)$ | 35.7/44 | 0.810 | 29.6/44 | 0.953 | 64.1/44 | 0.025 |
| $M(t\bar{t})$ vs. $\|y(t\bar{t})\|$ | 25.9/35 | 0.867 | 24.2/35 | 0.914 | 56.2/35 | 0.013 |
| $p_T(t_h)$ vs. $M(t\bar{t})$ | 47.4/32 | 0.039 | 57.2/32 | <0.01 | 73.2/32 | <0.01 |
| | SHERPA | | POWHEG+H++ | | MG5_aMC@NLO+P8 FxFx | |
| $p_T(t_h)$ | 13.5/12 | 0.335 | 32.1/12 | <0.01 | 17.4/12 | 0.137 |
| $\|y(t_h)\|$ | 2.32/11 | 0.997 | 4.89/11 | 0.936 | 3.16/11 | 0.988 |
| $p_T(t_\ell)$ | 39.4/12 | <0.01 | 21.8/12 | 0.040 | 47.7/12 | <0.01 |
| $\|y(t_\ell)\|$ | 5.54/11 | 0.902 | 4.04/11 | 0.969 | 7.22/11 | 0.781 |
| $M(t\bar{t})$ | 2.86/10 | 0.985 | 52.8/10 | <0.01 | 5.45/10 | 0.859 |
| $p_T(t\bar{t})$ | 68.7/8 | <0.01 | 46.8/8 | <0.01 | 21.3/8 | <0.01 |
| $\|y(t\bar{t})\|$ | 12.1/10 | 0.276 | 18.6/10 | 0.046 | 8.13/10 | 0.616 |
| $\|y(t_h)\|$ vs. $p_T(t_h)$ | 48.3/44 | 0.305 | 116/44 | <0.01 | 44.9/44 | 0.434 |
| $M(t\bar{t})$ vs. $\|y(t\bar{t})\|$ | 41.5/35 | 0.208 | 219/35 | <0.01 | 55.7/35 | 0.014 |
| $p_T(t_h)$ vs. $M(t\bar{t})$ | 66.5/32 | <0.01 | 152/32 | <0.01 | 48.9/32 | 0.028 |

## With additional jets

| Distribution | $\chi^2$/dof | $p$-value | $\chi^2$/dof | $p$-value | $\chi^2$/dof | $p$-value |
|---|---|---|---|---|---|---|
| | POWHEG+P8 with unc. | | SHERPA with unc. | | POWHEG+P8 | |
| Additional jets | 1.52/6 | 0.958 | 27.3/6 | <0.01 | 10.1/6 | 0.121 |
| Additional jets *vs.* $p_T(t_h)$ | 35.1/44 | 0.830 | 64.6/44 | 0.023 | 71.6/44 | <0.01 |
| Additional jets *vs.* $M(t\bar{t})$ | 27.5/36 | 0.845 | 68.9/36 | <0.01 | 38.8/36 | 0.345 |
| Additional jets *vs.* $p_T(t\bar{t})$ | 64.6/29 | <0.01 | 181/29 | <0.01 | 175/29 | <0.01 |
| $p_T$(jet) | 70.2/47 | 0.016 | 374/47 | <0.01 | 133/47 | <0.01 |
| $\|\eta(\text{jet})\|$ | 120/70 | <0.01 | 174/70 | <0.01 | 171/70 | <0.01 |
| $\Delta R_{j_t}$ | 60.9/66 | 0.655 | 215/66 | <0.01 | 168/66 | <0.01 |
| $\Delta R_t$ | 64.0/62 | 0.405 | 229/62 | <0.01 | 121/62 | <0.01 |
| | SHERPA | | POWHEG+H++ | | MG5_aMC@NLO+P8 FxFx | |
| Additional jets | 63.0/6 | <0.01 | 34.1/6 | <0.01 | 11.1/6 | 0.086 |
| Additional jets *vs.* $p_T(t_h)$ | 88.5/44 | <0.01 | 230/44 | <0.01 | 53.4/44 | 0.156 |
| Additional jets *vs.* $M(t\bar{t})$ | 112/36 | <0.01 | 300/36 | <0.01 | 55.1/36 | 0.022 |
| Additional jets *vs.* $p_T(t\bar{t})$ | 285/29 | <0.01 | 223/29 | <0.01 | 122/29 | <0.01 |
| $p_T$(jet) | 768/47 | <0.01 | 624/47 | <0.01 | 111/47 | <0.01 |
| $\|\eta(\text{jet})\|$ | 214/70 | <0.01 | 259/70 | <0.01 | 133/70 | <0.01 |
| $\Delta R_{j_t}$ | 334/66 | <0.01 | 959/66 | <0.01 | 67.0/66 | 0.441 |
| $\Delta R_t$ | 316/62 | <0.01 | 483/62 | <0.01 | 78.9/62 | 0.073 |