Measurements of differential $t\bar{t}$ and single top quark cross sections at CMS

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Differential $t\bar{t}$/single top quark cross sections:

- Event variables (without top quark reconstruction)
- 1D, 2D differential cross sections of top quarks and $t\bar{t}$ pair
- differential cross sections of single top quark production and their charge ratio

These measurements provide:

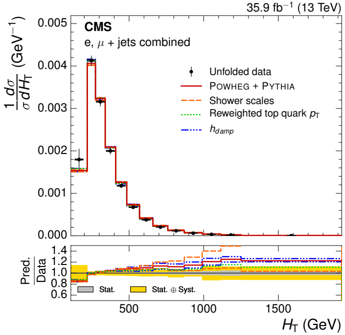
- Precision tests of the standard model top quark production. Different mechanisms for $t\bar{t}$ (QCD) and single top (EW)
- Tests of parton shower models
  $\rightarrow$improved understanding of systematics in other measurements, e.g., top mass.
- PDF constraints, extractions of m_t and α_s.
- Improved understanding of $t\bar{t}$ background for BSM searches.
- ...

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

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

Observables defined using "stable" particles (>30 ns) within experimental acceptance
$\rightarrow$ avoid theory based extrapolations.
Objects use RIVET definitions see CERN-CMS-NOTE-2017-004. plugin available I1662081

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



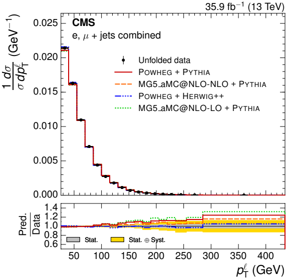
- Shower scales have large impact on predictions. They also contribute as a dominant uncertainty in the measurement.

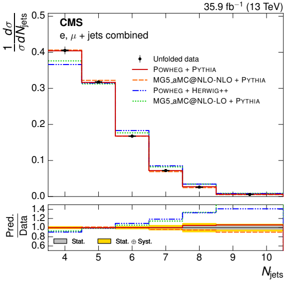
Systematic uncertainties

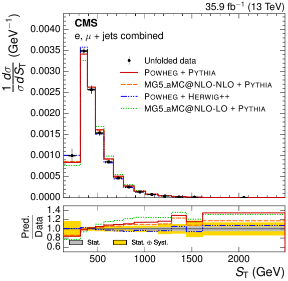
Relative uncertainty source (%)	N_{jets}	H_T
b tagging efficiency	3.2 – 4.1	3.6 – 4.7
Electron efficiency	1.2 – 1.4	1.3 – 1.6
Muon efficiency	1.7 – 1.9	1.6 – 2.2
JER	0.1 – 0.9	0.1 – 1.2
JES	1.8 – 12.6	5.7 – 16.8
QCD bkg cross section	0.1 – 0.5	0.1 – 0.7
QCD bkg shape	<0.1	0.1 – 1.0
Single top quark cross 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_{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.

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







	χ^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^ℓ	14 / 17	0.68
$\lvert\eta^\ell\rvert$	15 / 8	0.06

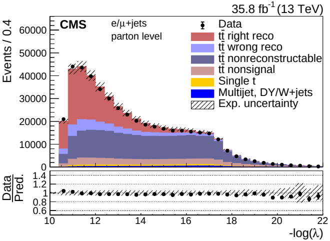
- e/μ p_T and S_T (p_T sum of all objects) are softer than predicted by most MCs.
- POWHEG+HERWIG++ and POWHEG/MG5(MLM)+PYTHIA8 predict higher jet multiplicity.

χ^2-tests taking into account theoretical uncertainties (POWHEG+PYTHIA8) show compatibility between measurements and expectations.

e/μ+jets channel

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

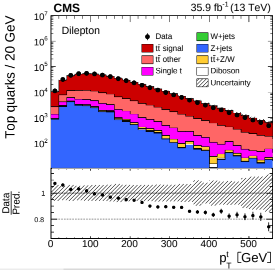
- Selection: exactly 1 e/μ, at least 4 jets, at least 2 b jets.
- Based on lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$ use mass constraints of m_{t}, m_W on leptonic side to obtain p_z-component of neutrino momentum, and correct b jet.
- Calculate likelihood λ according to 2D mass distributions of reconstructed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



dilepton channel

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

- Selection: ee, $e\mu$, $\mu\mu$ at least 2 jets, at least 1 b jet.
- In same flavor channels exclude Z-Peak and require $p_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$
- – Neutrino momenta calculated using m_{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

Parton level

Extract properties of top quarks before their decays.

– available at NNLO QCD + NLO EW precision.

– in general not a well defined observable (WWbb production ...)

Particle level

Define proxy of top quark based on leptons, jets ... within experimental acceptance:

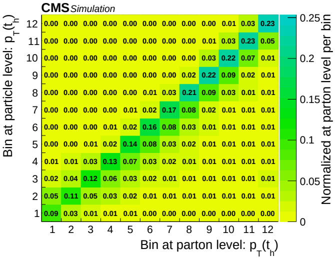
→ clean definition of "top quark" observable.

→ avoids theoretical extrapolations.

Events with exactly 1 isolated electron/muon, at least 4 jets (2 b jets)

Sum momenta of all neutrinos p_N and find permutation of jets that minimizes:

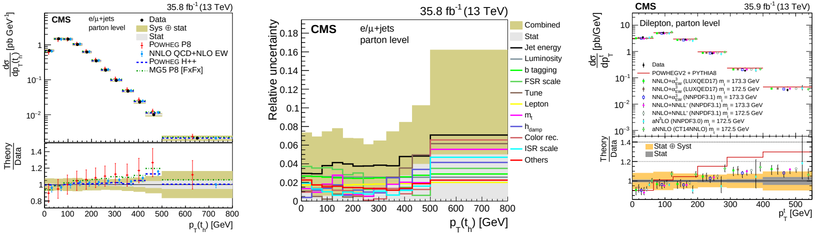
$$K^2 = (M(p_N + p_\ell + p_{b_1}) - m_\mathrm{t})^2 + (M(p_{j_1} + p_{j_2}) - m_\mathrm{W})^2 + (M(p_{j_1} + p_{j_2} + p_{b_2}) - m_\mathrm{t})^2$$



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

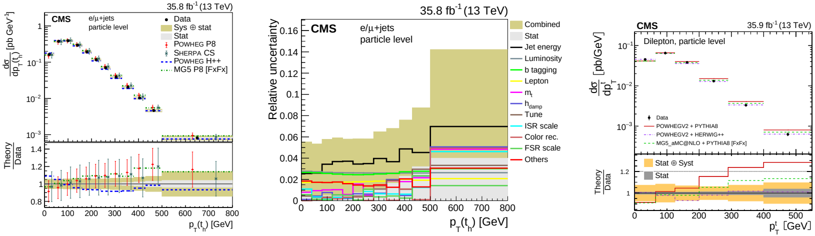
36 fb^{-1}, 13 TeV, PRD97 (2018) 112003, JHEP02 (2019) 149

Parton level



– Better $p_{\mathrm{T}}(\mathrm{t})$ agreement with NNLO QCD + NLO EW [JHEP10 (2017) 186] calculation

Particle level

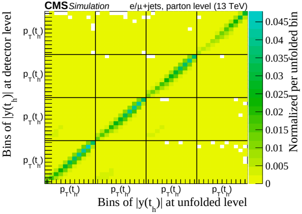


– Softer $p_{\mathrm{T}}(\mathrm{t})$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA at parton and particle levels.

– Reduced theoretical uncertainties at particle level.

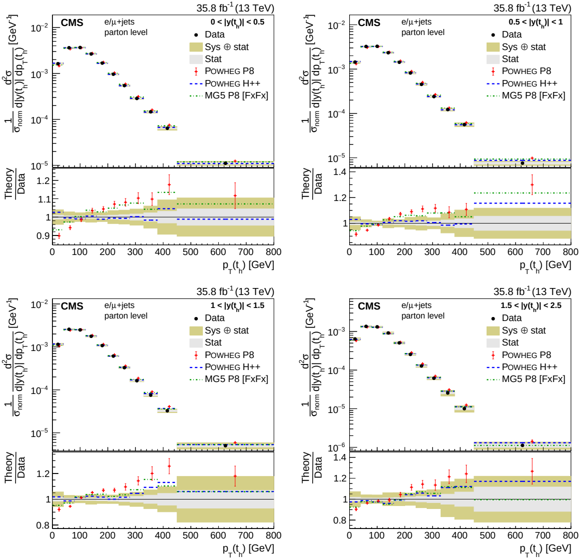
$36\,\mathrm{fb}^{-1}$, 13 TeV, PRD97 (2018) 112003

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

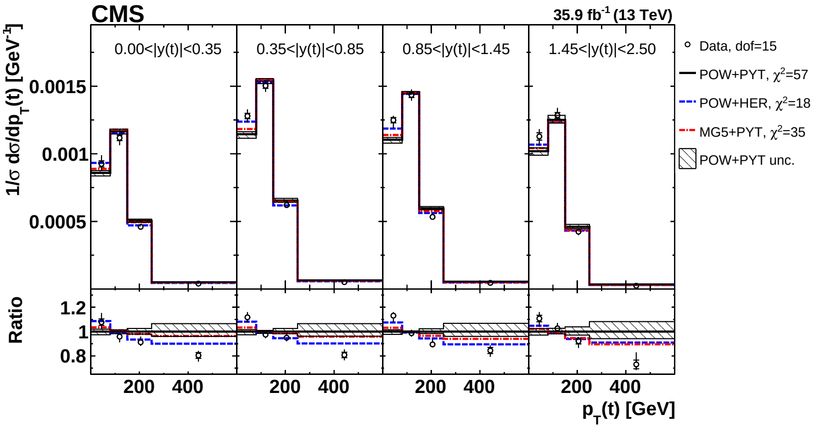


- Provide more details in corners of phase space
- $p_{\mathrm{T}}(\mathrm{t})$ softer in all rapidity regions

In general: χ^2-tests (see backup) taking into account theoretical uncertainties show reasonable compatibility between measurements and standard model.



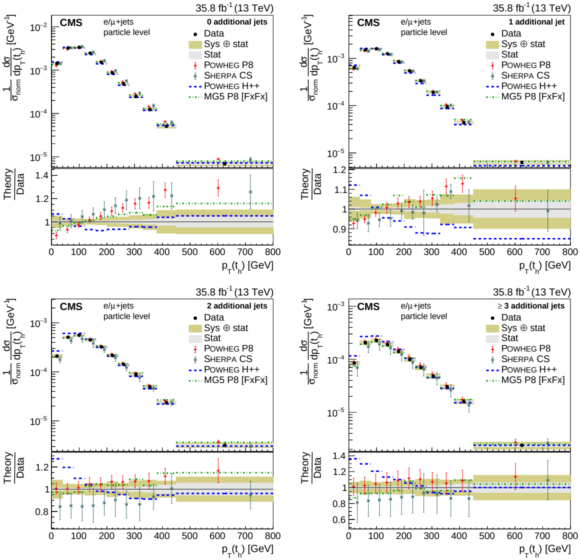
36 fb^{-1}, 13 TeV, arXiv:1904.05237 sub. EPJC



- Uses same reconstruction as single differential measurement in dilepton channel.
- Results show similar behavior as in e/μ+jets: $p_{\mathrm{T}}(\mathrm{t})$ softer in all rapidity regions

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

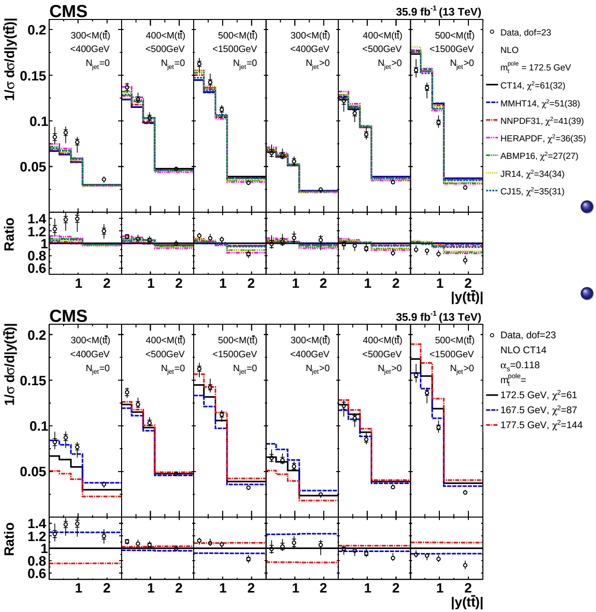
$p_{\mathrm{T}}(\mathrm{t})$ in bins of jet multiplicity ($p_{\mathrm{T}}(\mathrm{jet}) > 30$ GeV)



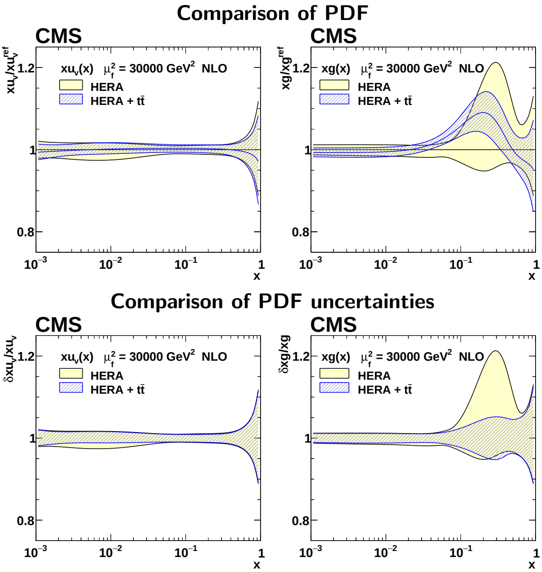
2 dim. unfolding in $p_{\mathrm{T}}(\mathrm{t})$ and number of additional jets.

- The slope disappears for events with higher jet multiplicity.
- HERWIG++ does not follow the trend of POWHEG+PYTHIA8, MG5(FxFx)+PYTHIA8, and SHERPA.

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



- $M(\mathrm{t\bar{t}})$ vs $y(\mathrm{t\bar{t}})$ in bins of jet multiplicity is sensitive to PDFs, $m_{\mathrm{t}}^{\mathrm{pole}}$, and α_{s}
- The kinematics of the $\mathrm{t\bar{t}}$ system (not of the individual top quarks) are reconstructed without using m_{t} to avoid a reconstruction bias: $p_{\mathrm{z}}(\nu\bar{\nu}) = p_{\mathrm{z}}(\ell^+\ell^-)$



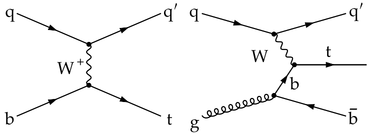
PDF constraints

- $m_{\rm t}$ and $\alpha_{\rm s}$ are free parameters
- PDF parameterization as in HERAPDF2.0 using xFitter
- comparisons with fixed order NLO cross section taking into account scale and PDF uncertainties.
- combined fit with HERA DIS data
- extracted:
  $m_{\rm t}^{\rm pole} = 170.5 \pm 0.8\,\text{GeV}$
  $\alpha_{\rm s}(m_{\rm Z}) = 0.1135^{+0.0021}_{-0.0017}$

more about $m_{\rm t}^{\rm pole}$ and $\alpha_{\rm s}$ measurements in talk of Agostino De Iorio "Recent top quark properties in CMS"

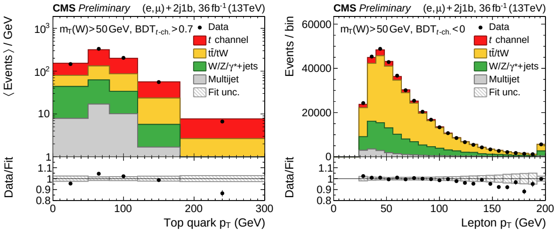
36 fb^{-1}, 13 TeV, CMS-PAS-TOP-17-023

t-channel single top production $\sigma_\mathrm{t} = 136\,\mathrm{pb}$, $\sigma_{\bar{\mathrm{t}}} = 81\,\mathrm{pb}$

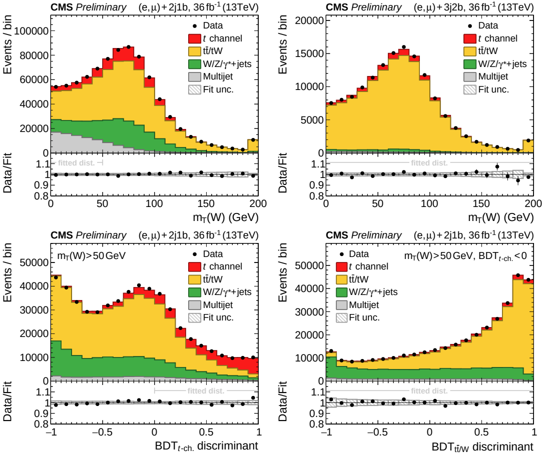


Selection and reconstruction

- 1 isolated electron/muon + 2 jets, 1 b jet (signal region)
- Top reconstructed as momentum sum of b jet, e/μ, and neutrino (calculated from $p_\mathrm{T}^\mathrm{miss}$ and e/μ using W mass constraint)

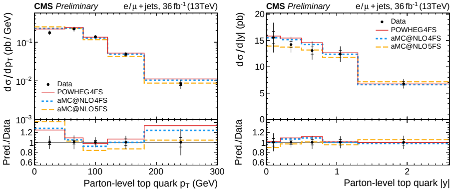


Signal extraction

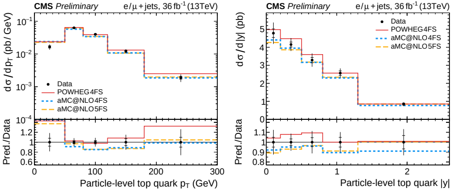


- ML fit of four distributions: $M_{\mathrm{T}}(W)$ in 2j1b and 3j2b categories, two BDTs based on kinematic variables)
- $\mathrm{BDT}_{\mathrm{t-ch}}$ signal vs background
- $\mathrm{BDT}_{\mathrm{t\bar{t}/W}}$ discrimination between $\mathrm{t\bar{t}}$ and W backgrounds
- Uncertainties profiled in fit.
- The total log-likelihood is the sum over all bins of the differential measurement.

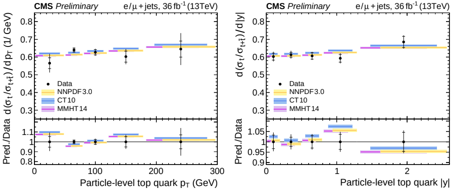
Parton level



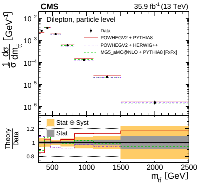
Particle level

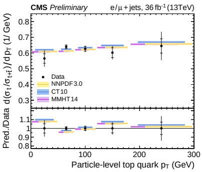


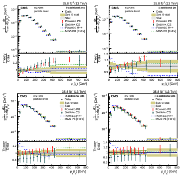
Charge ratio

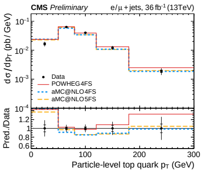


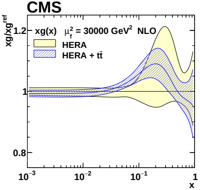
- Extracted event yields are unfolded to parton and particle level
- The various predictions show reasonable agreement with the data: POWHEG 4FS, MADGRAPH 4FS/5FS.
- Charge ratios in agreement with expectations →test of proton composition.

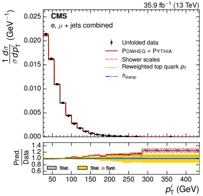












Differential $t\bar{t}$ cross sections:

- All measurements are consistent with standard model expectations.
- A softer $p_{\mathrm{T}}(\mathrm{t})$ spectrum is observed in all channels, but more precise calculations seem to improve the description.
- Different performances of parton shower models (PYTHIA8 and HERWIG++) for various measurements
- Significant reduction of uncertainties in gluon PDF at higher x

Differential single top quark cross sections:

- Well described by NLO MCs.
- Charge ratios in agreement with expectations

Backup

Parton level

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^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

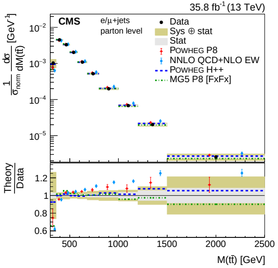
Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
$p_T(t_h)$	15.9/12	0.197	7.21/12	0.844	29.5/12	<0.01
$\|y(t_h)\|$	1.96/11	0.999	1.48/11	1.000	2.23/11	0.997
$p_T(t_\ell)$	27.0/12	<0.01	22.3/12	0.034	80.2/12	<0.01
$\|y(t_\ell)\|$	4.55/11	0.951	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

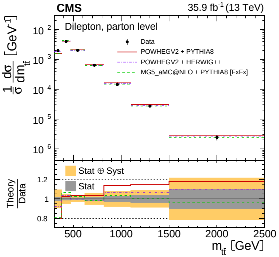
With additional jets

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^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
ΔR_{j_t}	60.9/66	0.655	215/66	<0.01	168/66	<0.01
ΔR_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
ΔR_{j_t}	334/66	<0.01	959/66	<0.01	67.0/66	0.441
ΔR_t	316/62	<0.01	483/62	<0.01	78.9/62	0.073

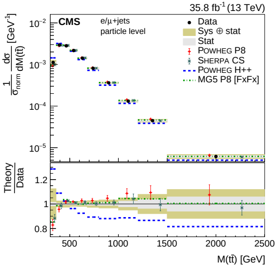
$36\,\mathrm{fb}^{-1}$, 13 TeV, PRD97 (2018) 112003, JHEP02 (2019) 149

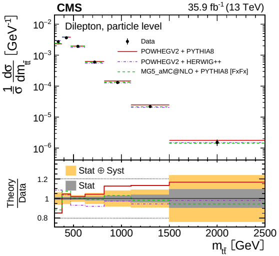
Parton level





Particle level





- e/μ+jets and dilepton channels show similar deviations from predictions
- Softer $M(t\bar{t})$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA.
- POWHEG+HERWIG++ too soft at particle level, while better at parton level.
- In general: χ^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.