Recent measurements of differential $t\bar{t}$ cross sections from CMS

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New differential cross section results since November:

- Measurements of differential cross sections of top quark pair production as a function of kinematic event variables in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ (Submitted to JHEP,arXiv:1803.03991)
- Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} = 13\,\text{TeV}$ (Submitted to PRD,arXiv:1803.08856)

Talk by Pedro tomorrow:

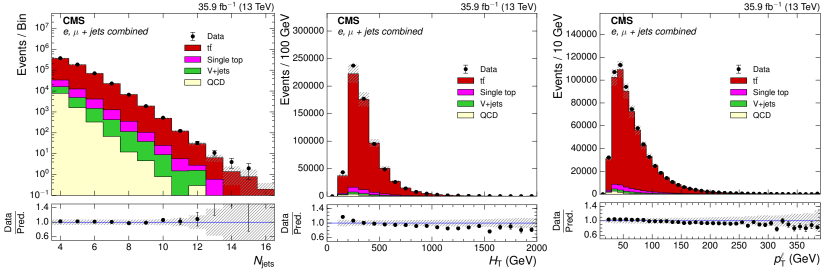
- Measurement of jet substructure observables in $\mathrm{t\bar{t}}$ events from pp collisions at $\sqrt{s} = 13\,\text{TeV}$ (CMS PAS TOP-17-013)
- Study of the underlying event in top quark pair production at $\sqrt{s} = 13\,\text{TeV}$ (CMS PAS TOP-17-015)

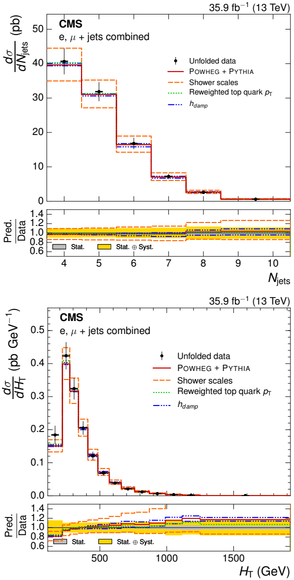
35.9 fb^{-1}, 13 TeV, Sub. to JHEP, arXiv:1801.03991

Measurements of variables that do not need a reconstruction of the 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/μ, at least 4 jets, at least 2 b-tagged jets.



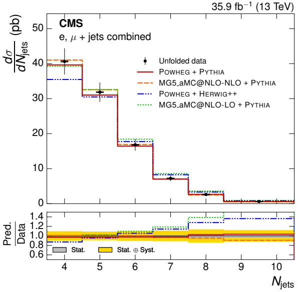


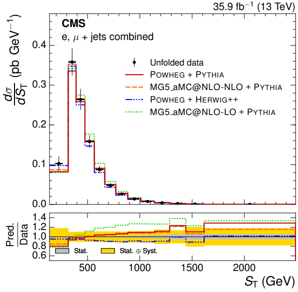
Systematic uncertainties

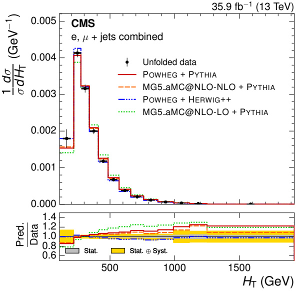
Relative uncertainty source (%)	N_{jets}	H_T
b tagging efficiency	3.2 – 4.1	3.6 – 4.7
Electron efficiency	1.2 – 1.4	1.3 – 1.6
Muon efficiency	1.7 – 1.9	1.6 – 2.2
JER	0.1 – 0.9	0.1 – 1.2
JES	1.8 – 12.6	5.7 – 16.8
QCD bkg cross section	0.1 – 0.5	0.1 – 0.7
QCD bkg shape	<0.1	0.1 – 1.0
Single top quark cross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

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

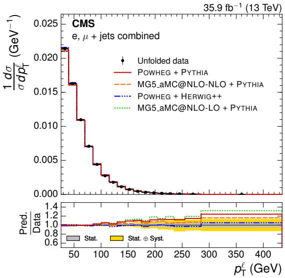


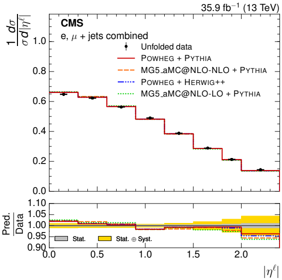


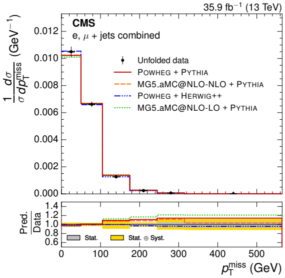


- POWHEG+HERWIG++ and POWHEG/MG5(MLM)+PYTHIA8 predict higher jet multiplicity
- H_T and S_T (p_T sum of all objects) are softer than predicted by most MCs.

  All results are provided as normalized and absolute distributions.







	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

Lepton related variables

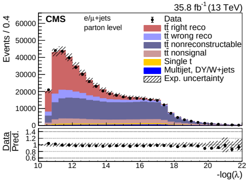
- e/μ p_T softer and η less central.
- also observed for p_T^{miss}.

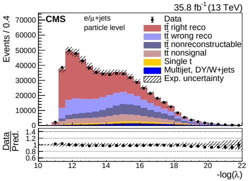
χ^2-tests considering theory uncertainties (POWHEG+PYTHIA8) show compatibility between measurements and expectations.

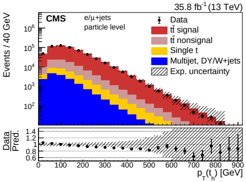
35.8 fb^{-1}, 13 TeV, Sub. to PRD, arXiv:1803.08856

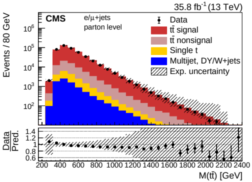
Measurements at parton and particle level

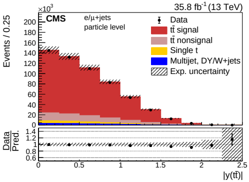
- Selection: exactly 1 e/μ, at least 4 jets, at least 2 b-tagged jets.
- Based on lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$ use mass constraints of M_{t}, M_W on leptonic side to obtain p_z-component of neutrino momentum, and correct b-jet.
- Calculate likelihood λ according to 2D mass distributions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









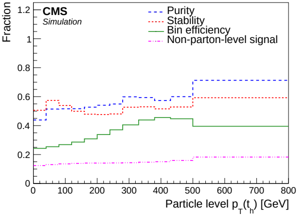


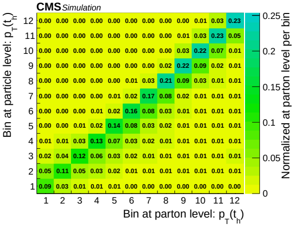
35.8 fb^{-1}, 13 TeV, Sub. to PRD, arXiv:1803.08856

Define proxy of top quark based on measurable objects (leptons, jets) in experimental acceptance:
$\rightarrow$ clean definition of "top quark" observable.
$\rightarrow$ 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:

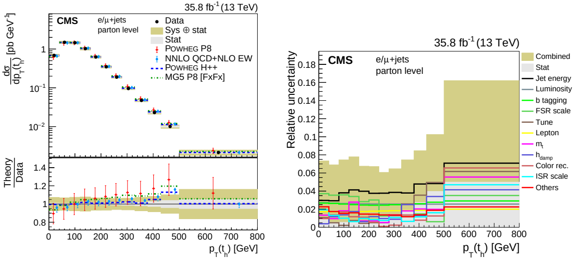
$$K^2 = (M(p_N + p_\ell + p_{b_1}) - m_\mathrm{t})^2 + (M(p_{j_1} + p_{j_2}) - m_\mathrm{W})^2 + (M(p_{j_1} + p_{j_2} + p_{b_2}) - m_\mathrm{t})^2$$



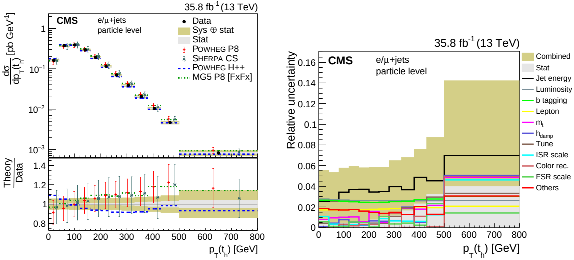


Analysis uses RIVET for particle level level definitions. plugin available I1663958.

Parton level

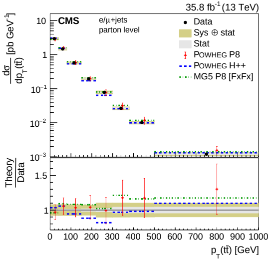


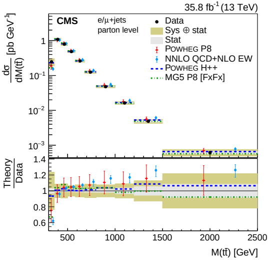
Particle level



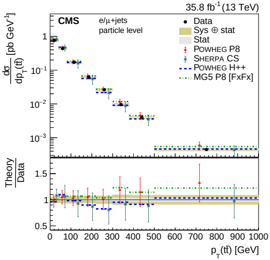
- Softer $p_T(t)$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA.
- Better p_T agreement with NNLO QCD + NLO EW [M. Czakon et al.,2017] calculation (only scale variations in uncertainty)
- POWHEG+HERWIG++: better at parton, but too soft at particle level, general lowest data-MC agreement at particle level.

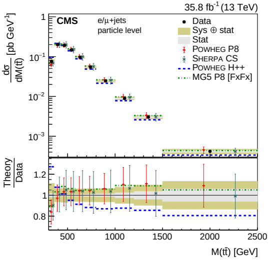
Parton level





Particle level

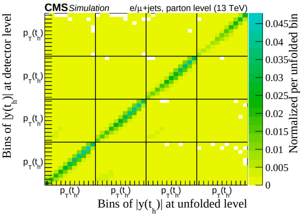




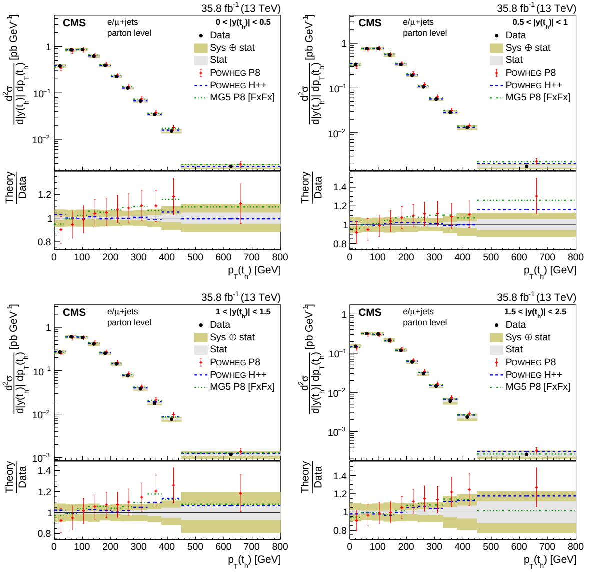
- Softer $M(t\bar{t})$ compared to POWHEG/MG5(FxFx)+PYTHIA8 and SHERPA.
- For $M(t\bar{t})$ again POWHEG+HERWIG++ too soft at particle level.
- In general: χ^2-tests (see backup) considering theory uncertainties (POWHEG+PYTHIA8 and SHERPA) show reasonable compatibility between measurements and SM predictions.

35.8 fb^{-1}, 13 TeV, Sub. to PRD, arXiv:1803.08856

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

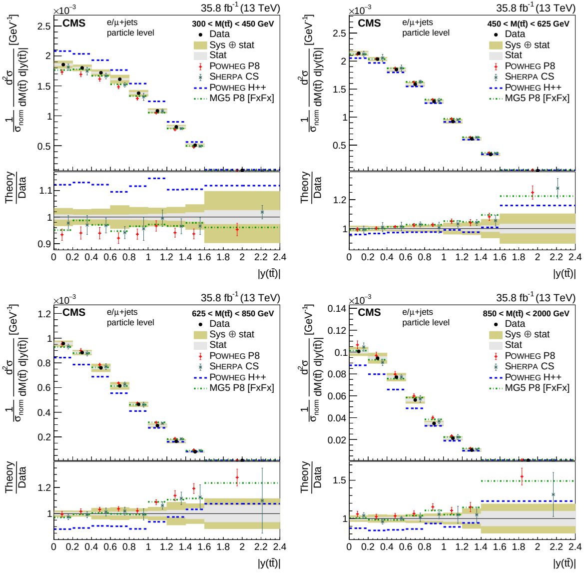


- Provide more details in corners of phase space.
- $p_{\mathrm{T}}(\mathrm{t})$ softer in all rapidity regions.



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

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



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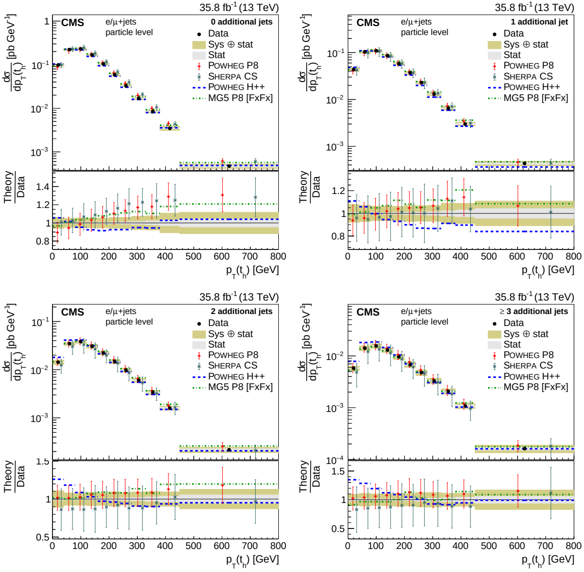
$p_T(t)$ in bins of jet multiplicity ($p_T(\text{jet}) > 30$ GeV)

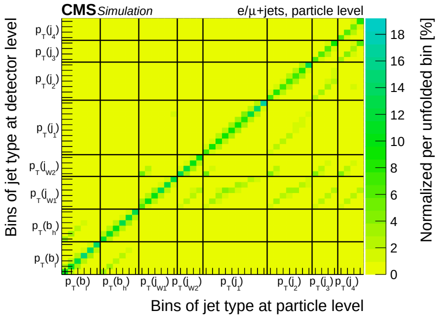


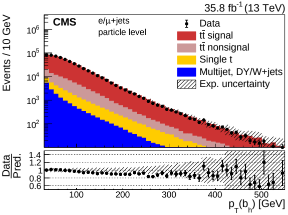
2 dim. unfolding in $p_T(t)$ and number of additional jets.

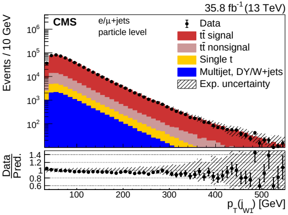
- The slope disappears for events with higher jet multiplicity.
- HERWIG++ does not follow the trend.

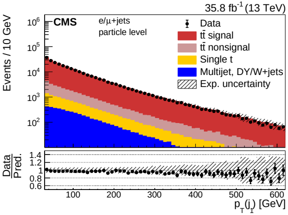
Jet properties

- 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_{T}.
- Correct for effects of resolution and misidentification of jets.

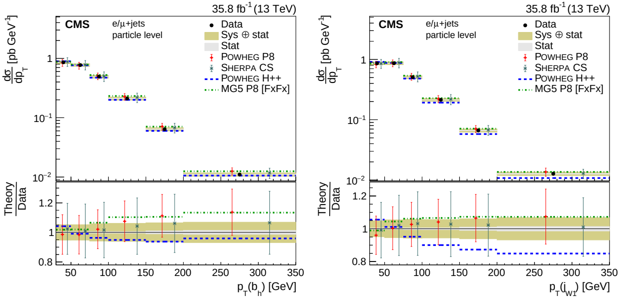




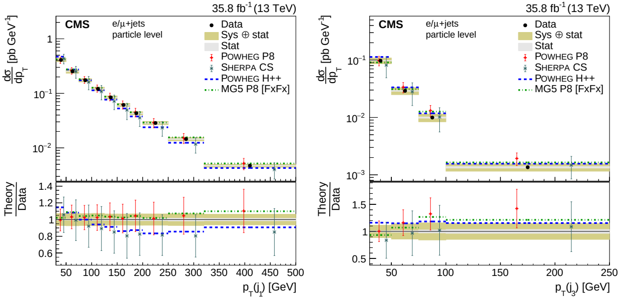




Jets of the $t\bar{t}$ system

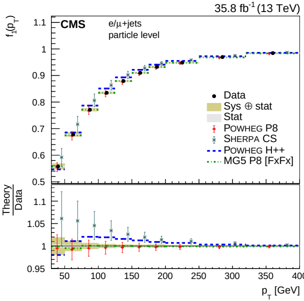


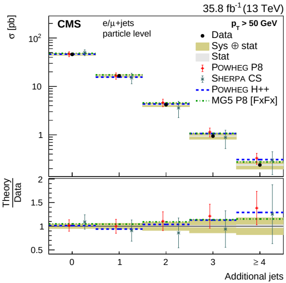
Additional Jets

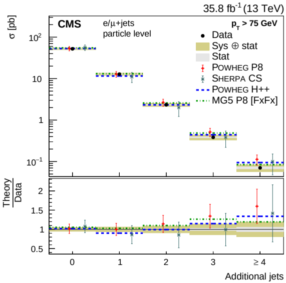


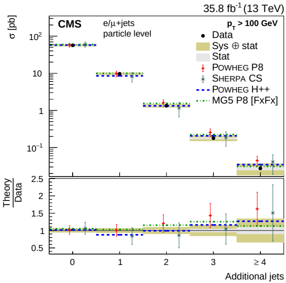
- POWHEG+PYTHIA8: describes data, but > 1 jet from parton shower.
- MG5+PYTHIA8 [FxFx] ($t\bar{t}$ + up to 2 jets NLO): similar to POWHEG+PYTHIA8.
- SHERPA ($t\bar{t}$ + 0,1 jet NLO, up to 4 jets LO): some deviation description of add. jets.
- POWHEG+HERWIG++: jets in $t\bar{t}$ system too soft (related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

- 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.









35.8 fb^{-1}, 13 TeV, Sub. to PRD, arXiv:1803.08856

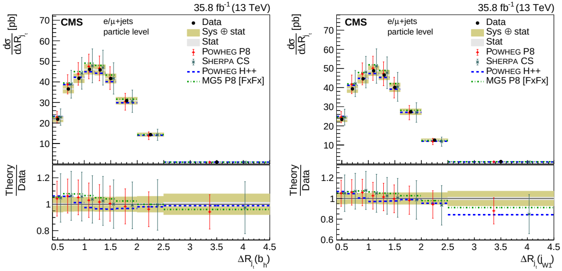
Minimum separation between a jet and the jets in $t\bar{t}$ system

- 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. $\rightarrow$reduced momentum of particle level top quark.

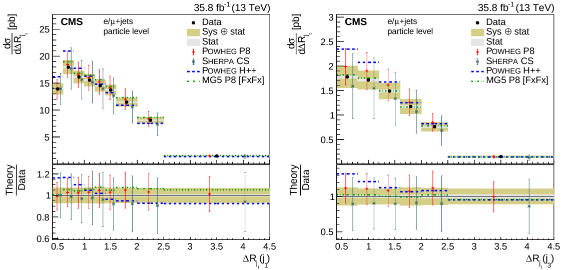
χ^2-tests with full set of th. uncertainties for jet related distributions:

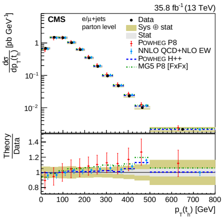
- POWHEG+PYTHIA8: relies on PS tuning shows reasonable agreement
- SHERPA: with default tune and LO at high jet multiplicities shows larger deviations.

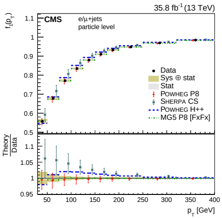
Jets of the $t\bar{t}$ system

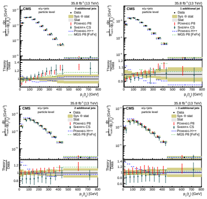


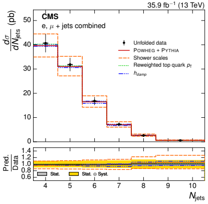
Additional Jets

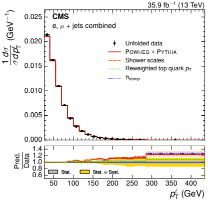












Differential $t\bar{t}$ cross sections:

- 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 →improved understanding of systematics in other measurements, e.g., top mass.
- PDF constraints.
- ...

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
$\lvert\eta(\text{jet})\rvert$	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
$\lvert\eta(\text{jet})\rvert$	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