TOP 2019

Differential tt cross-section measurements

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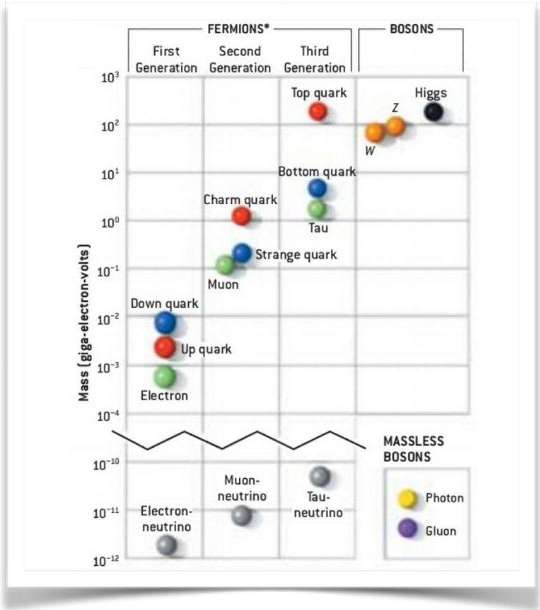
ATLAS EXPERIMENT

CMS

Going differential!

- LHC is a top quark factory: at 13 TeV about 2 tops every second!
  - plenty of statistics to make precision measurements
  - with 2015/16 dataset: 1.1M tt events and 45k tt events with a boosted top! (ATLAS l+jets)
- Studying top production is crucial to the LHC programme:
  - Detailed measurements of QCD, EWK
  - Probe couplings to Higgs, W, Z, γ
  - 3rd generation models within BSM
  - Significant background to searches and Higgs
- Looking at differential distributions of tt production also allows to…
  - be sensitive to new physics that would not modify the inclusive tt cross-section
    - including in a model-independent way with Effective Field Theory
  - stringent test of NNLO QCD calculations
  - improves the simulation to tt production: PDF, MC tuning, etc.



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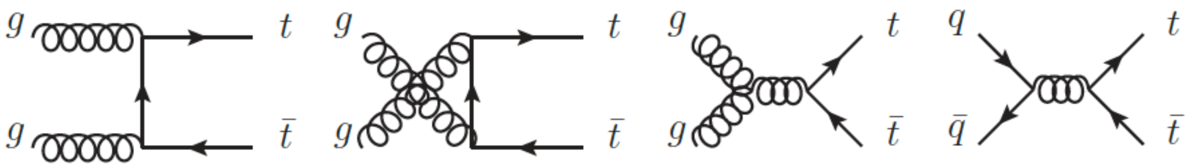
Top production and decay

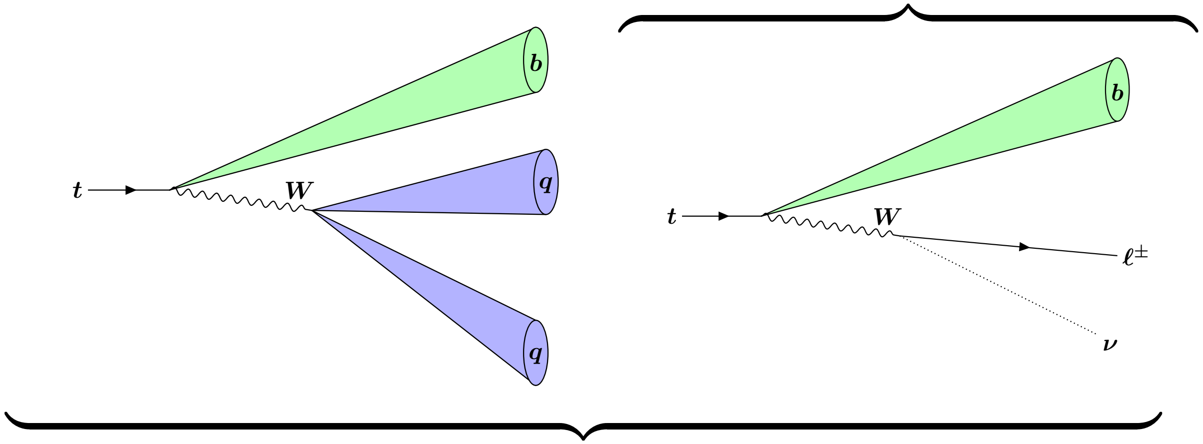
Physics

Production:



Decay:

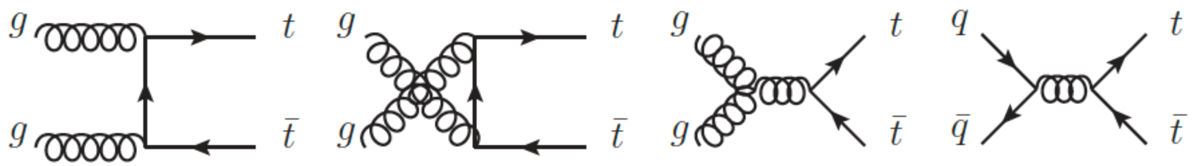
Dilepton: 2 of these



Lepton+Jets Resolved

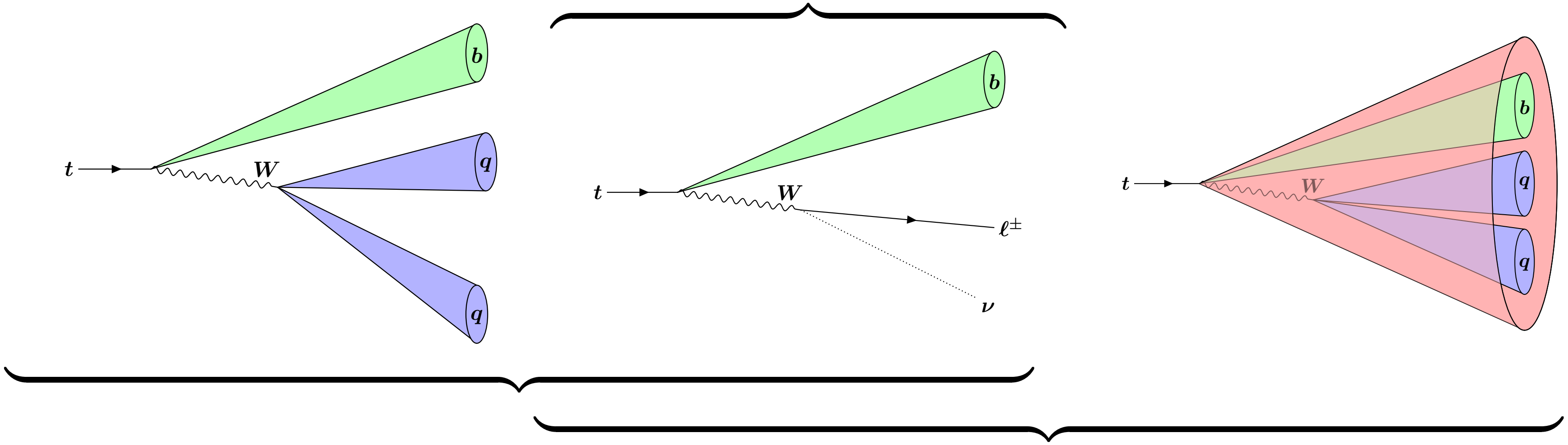
Top production and decay

Production:



Decay:

Dilepton: 2 of these



Lepton+Jets Resolved

Lepton+Jets Boosted

Long history of top differential measurements

Physics

13 TeV											
ATLAS papers	**Channel**	**Int Lumi (ifb)**	**Particle Unf**	**Parton Unf**	**Normalised**	**Asbolute**	**Top reco**	**Boosted**	**Double diff**	**Other meas.**
jet activity: EPJC 77 (2017) 220	emu	3.2	✓		✓					gap fractions
dil: EPJC 77 (2017) 292	emu	3.2	✓		✓	✓	✓			
l+jets: JHEP 11 (2017) 191	l+jets	3.2	✓	✓	✓	✓	✓	✓		
all-had boosted: PRD 98 (2018) 012003	all-had	36	✓	✓	✓	✓	✓	✓		
tt+njets: JHEP 10 (2018) 159	l+jets	3.2	✓		✓	✓	✓			
ttbb: JHEP 04 (2019) 046	l+jets + emu	36	✓		✓					Fiducial Incl xs
l+jets: 1908.07305, sub to EPJC	l+jets	36	✓	✓	✓	✓	✓	✓	✓	
DIL: ATLAS-CONF-2019-041	emu	36	✓		✓	✓			✓	Incl xs, pole mass, ratios of xs
CMS papers										
l+jets: PRD 95 (2017) 092001	l+jets	2.3	✓	✓		✓	✓		✓	extra jets
dil: JHEP 04 (2018) 060	dil	2.1	✓	✓	✓		✓			
l+jets event kinematics: JHEP 06 (2018) 002	l+jets	36	✓		✓	✓				
l+jets: PRD 97 (2018) 112003	l+jets	36	✓	✓	✓	✓	✓		✓	extra jets
underlying event: EPJC 79 (2019) 123	dil	36	✓		✓					UE observables
jet substructure	l+jets	36	✓		✓			✓		jet substructure observables
dil: JHEP 02 (2019) 149	emu	36	✓	✓	✓	✓	✓			chromo dipole moment, asymmetries
TOP-18-004 (dil): sub to EPJC	emu	36		✓	✓		✓		✓	alphas, pole mass, PDF
TOP-18-006 (dil Pol): accepted by PRD	dil	36		✓	✓		✓			polarization, spin correlation

- Outline
  - Unfolding
  - Event selection & reconstruction
  - Extracting the differential cross-section measurements
  - Systematic Uncertainties
  - Results & interpretation

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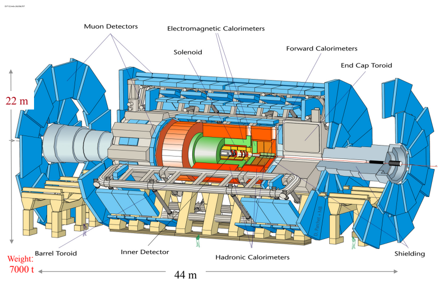
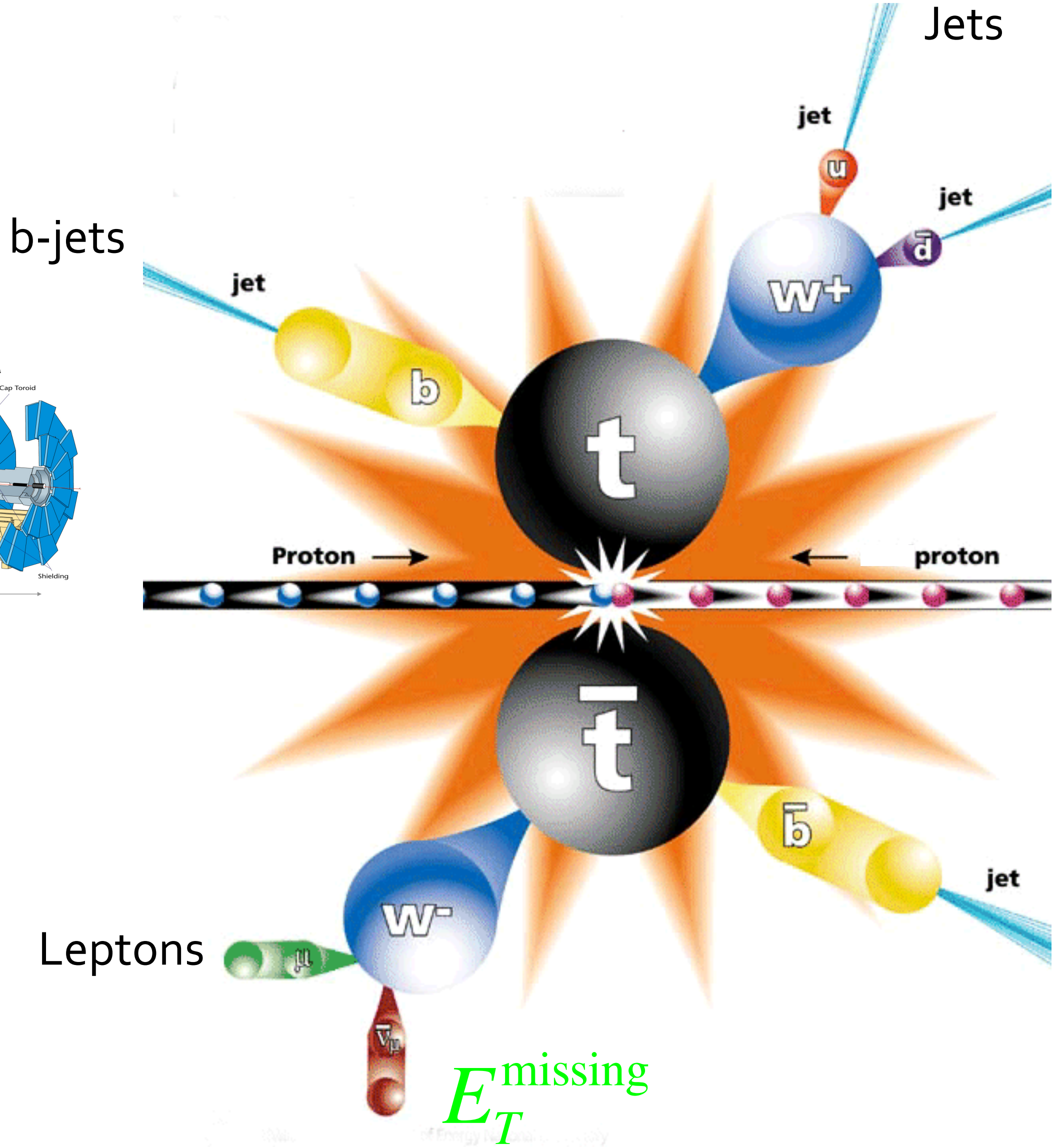
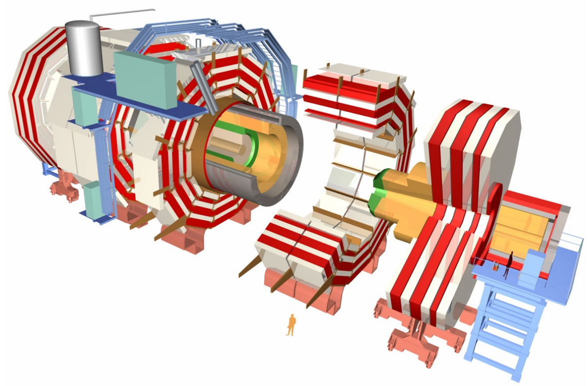
Unfolding from experiment…

Physics

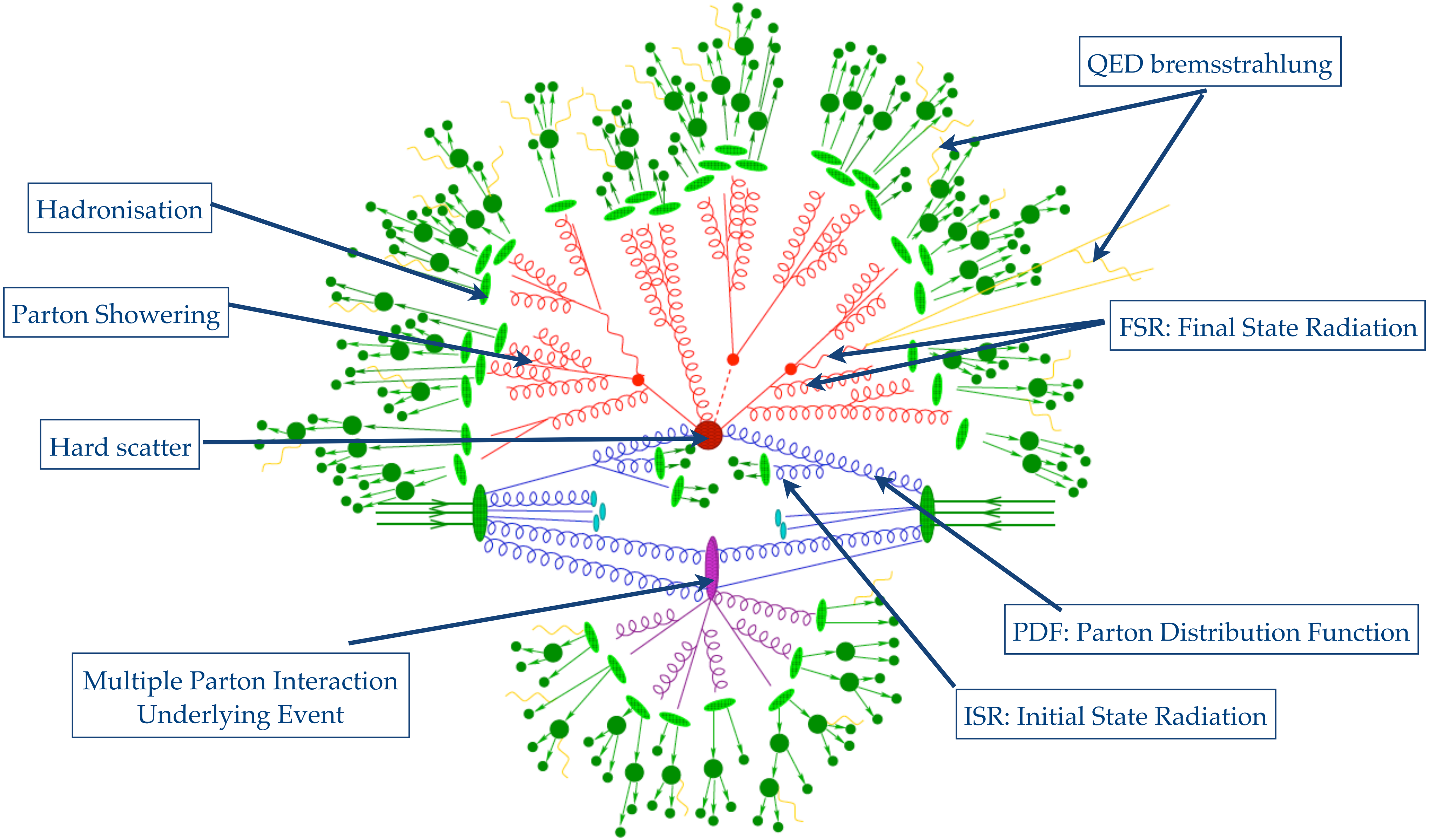






... to theory...

Physics



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… connecting the two:

Physics

detector to parton unfolding

Theory

parton-level
full phase space

Experiment

detector-level
fiducial phase space

parton to particle

detector to particle unfolding

Monte Carlo

particle-level
HepData

Theorists can use data with new models
Ensures longevity and proper exchange of results
Rivet routines

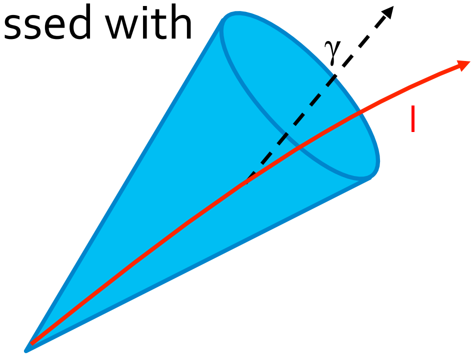
Fiducial measurements reduce uncertainties due to extrapolations

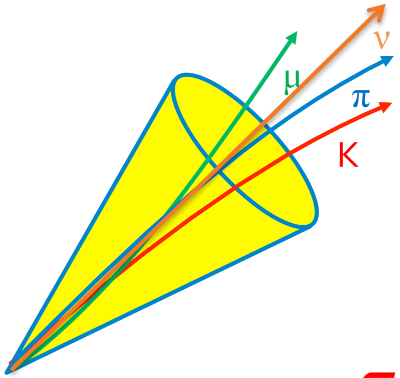
Particle-level objects

Physics

ATLAS and CMS differ in detailed definitions

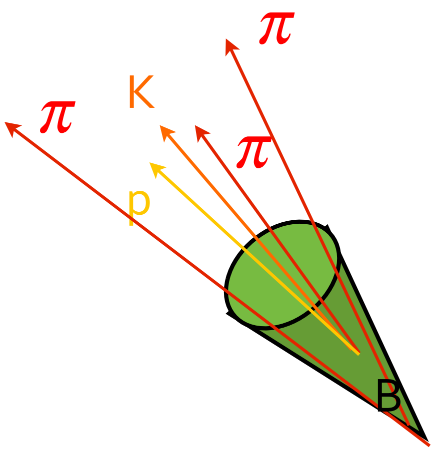
Charged leptons (not from hadrons) are dressed with the energy from nearby photons





Jets are clustered from stable MC particles using anti-kt algorithm

P_TMiss calculated from the sum of all neutrinos



b-jets defined by a jet containing a b-quark hadron

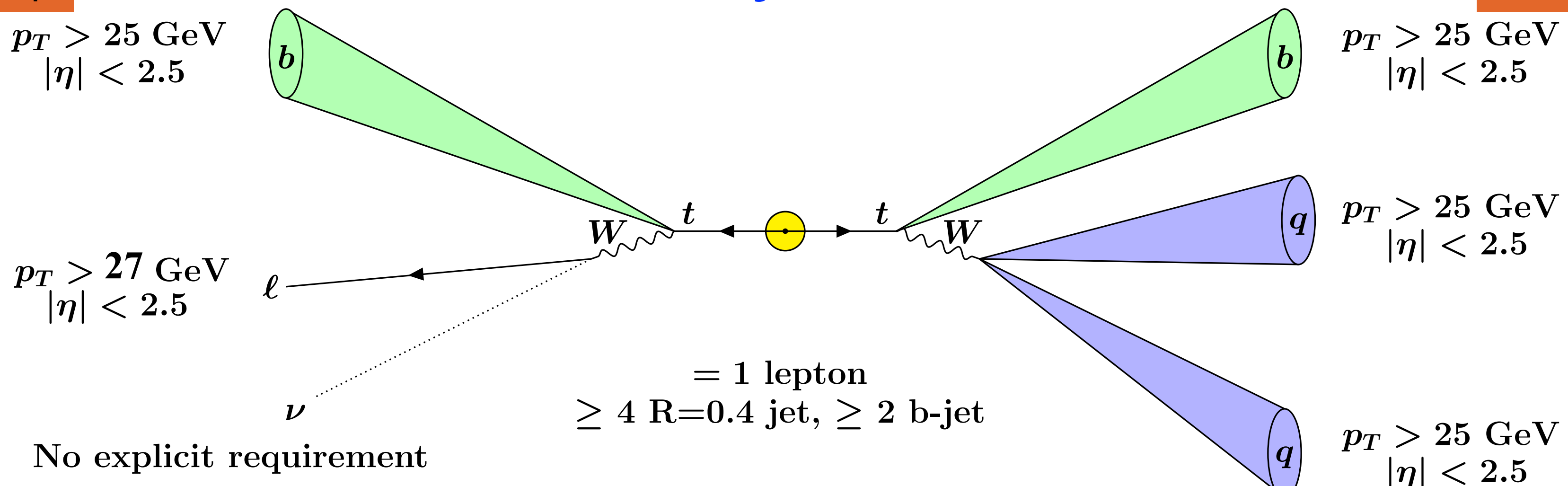
Event Selection & Reconstruction

Physics

Leptonic top

ATLAS l+jets resolved

Hadronic top



Particle: Pseudo-Top reconstruction

b-tagged jets: 2 highest p_T ones

Neutrino p_Z from M_W constraint

Leptonic top: closest leptonic W and b-jet

Find 2 non-b-tagged jets closest to M_W

Hadronic top: hadronic W and other b-jet

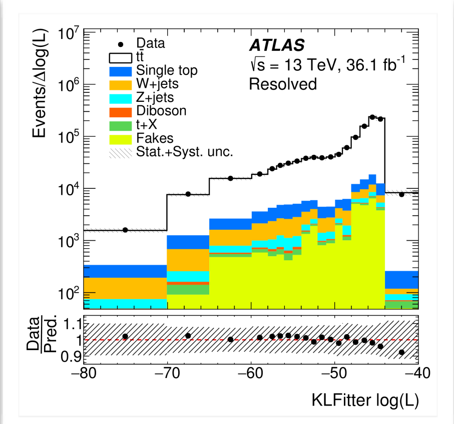
Parton: Kinematic Likelihood Fitter reconstruction

BW distributions and transfer functions

best 4 out of 5 jet permutations

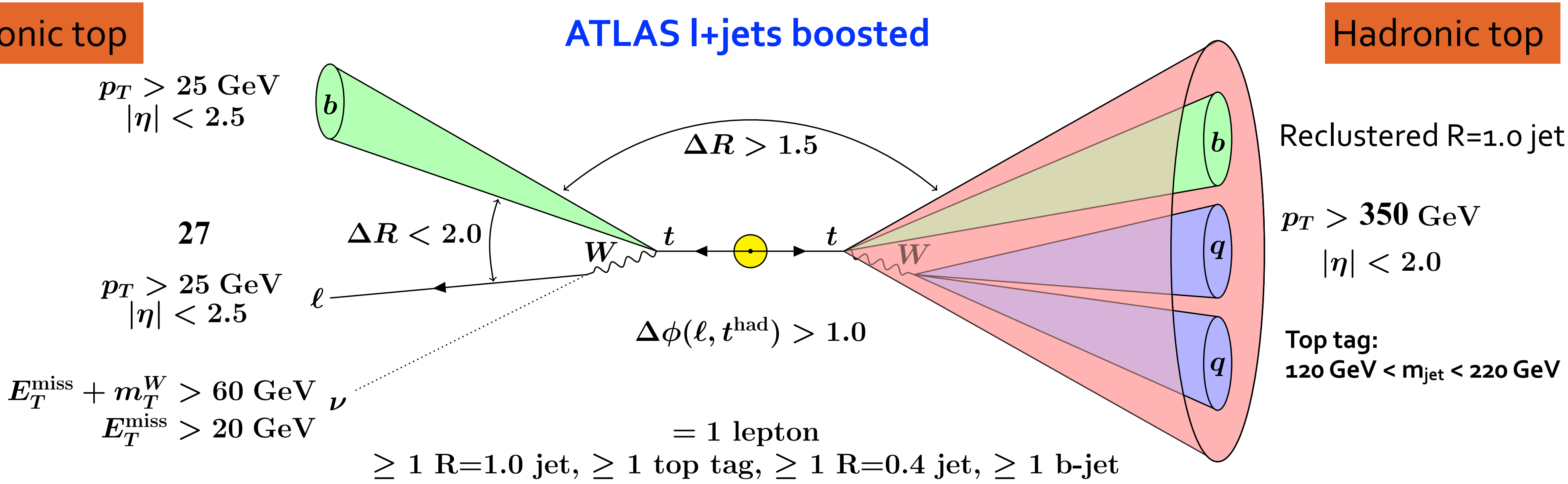
Log L > -52

Events must not satisfy boosted selection

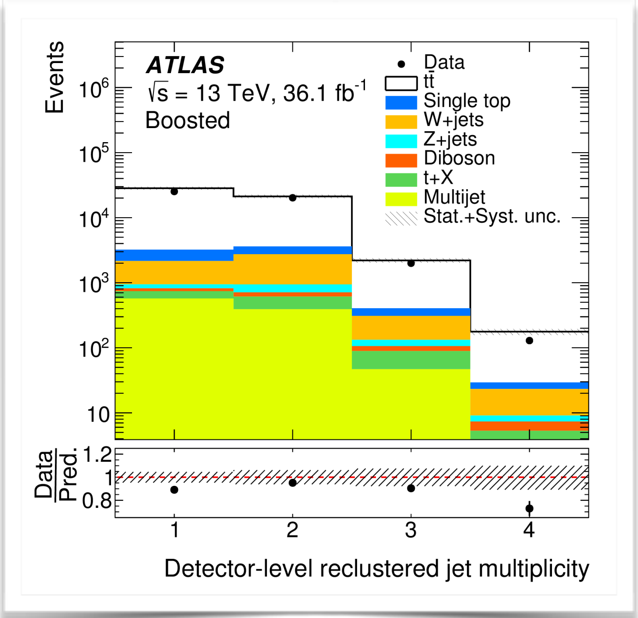


Event Selection & Reconstruction

Physics



from either the leptonic top or within reclustered R=1.0 jet



Parton unfolding into fiducial phase-space: one of the top quark has p_T > 350 GeV
< 2% of full phase-space

Trimming: remove small-R jets with p_T < 5% of reclustered R=1.0 jet

Top-tagging: 60% efficiency

Event Selection & Reconstruction

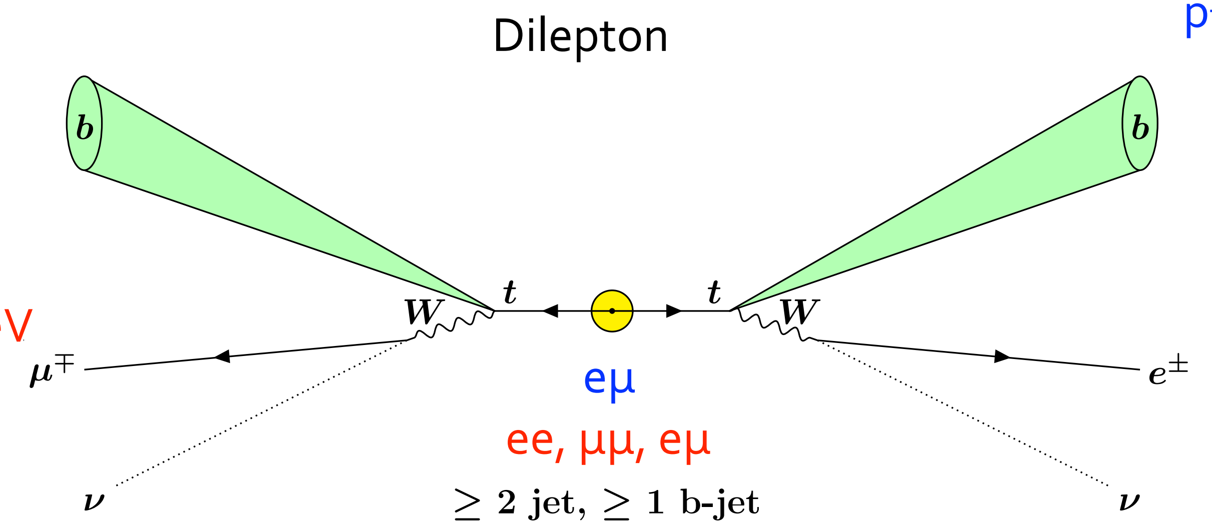
p_T>25 GeV 30 GeV

|η|<2.5 2.4

70% 80-90%

p_T>20 GeV 25 (20) GeV

|η|<2.5 2.4



p_T>25 GeV 30 GeV

|η|<2.5 2.4

70% 80-90%

p_T>20 GeV 25 (20) GeV

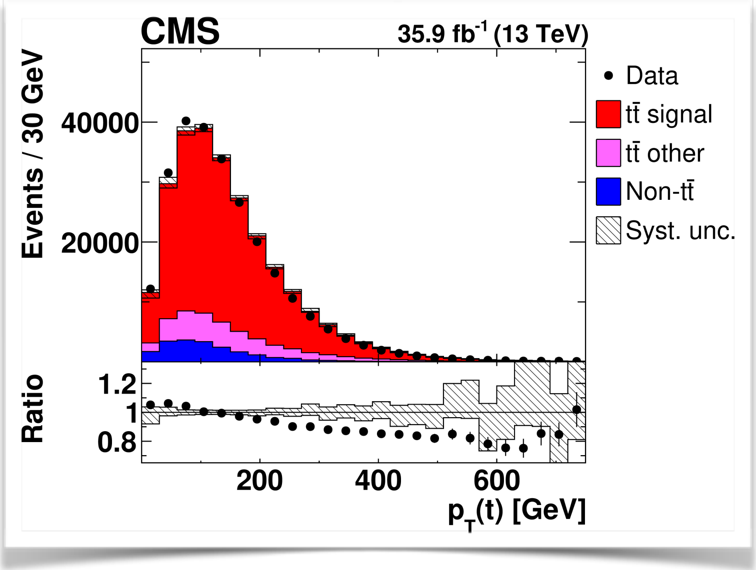
|η|<2.5 2.4

ATLAS:

$$N_1^i = L\sigma_{t\bar{t}}^i \, G_{e\mu}^i 2\epsilon_b^i(1 - C_b^i\epsilon_b^i) + N_1^{i,\mathrm{bkg}},$$
$$N_2^i = L\sigma_{t\bar{t}}^i \, G_{e\mu}^i C_b^i(\epsilon_b^i)^2 + N_2^{i,\mathrm{bkg}},$$

CMS:
m(ll)> 20 GeV
|m_Z-m(ll)| > 15 GeV
$p_T$miss > 40 GeV

Reconstruction:
2 neutrinos: solution with smallest m($t\bar{t}$)
kinematic smearing done and solutions ranked based on presence of b-jets
90% kinematic reconstruction eff
Fot $t\bar{t}$ system: "loose reco"

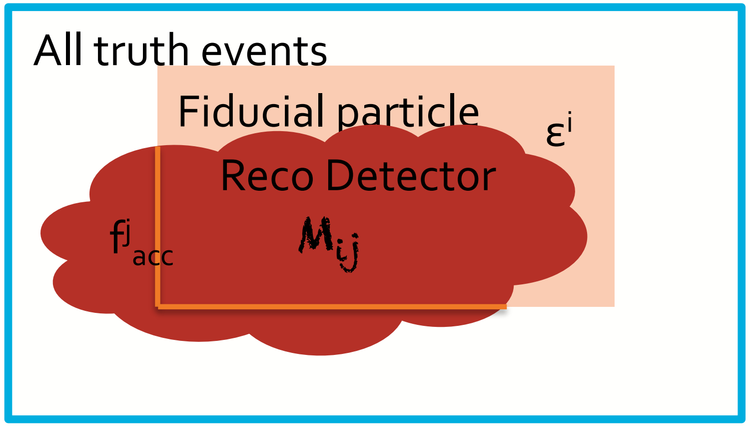


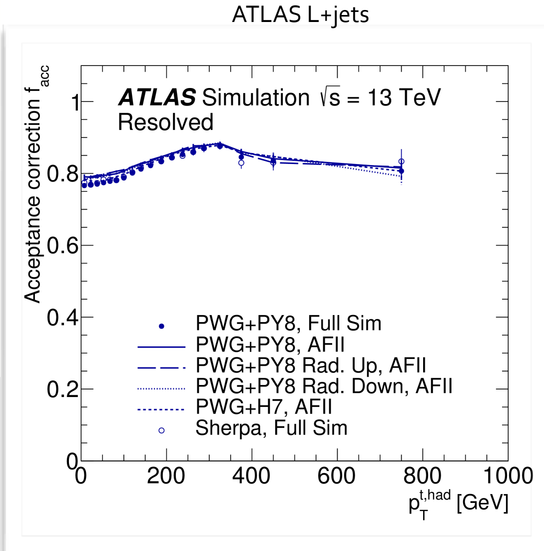
Measuring differential cross-section

Physics

$$\frac{d\sigma}{dX_i} \equiv \frac{1}{\mathcal{L} \cdot \Delta X_i} \cdot N_i^{\text{unf}}$$

$$\frac{d^2\sigma}{dX_i dY_j} \equiv \frac{1}{\mathcal{L} \cdot \Delta X_i \Delta Y_j} \cdot N_{ij}^{\text{unf}}$$

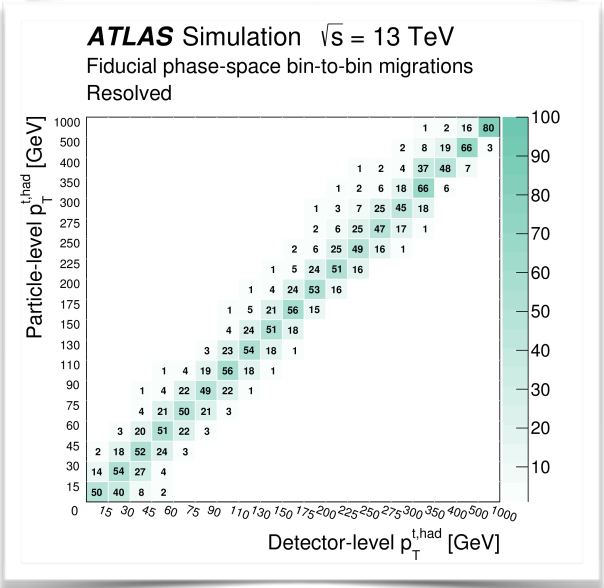




$$N_i^{\text{unf}} \equiv \frac{1}{\varepsilon^i} \cdot \sum_j \mathcal{M}_{ij}^{-1} \cdot f^j_{\text{match}} \cdot f^j_{\text{acc}} \cdot \left(N^j_{\text{detector}} - N^j_{\text{bkg}}\right)$$

Poster by P Baron

- ATLAS DIL: bin-by-bin correction factor
- ATLAS L+jets: Iterative Bayesian from RooUnfold (Expectation Maximization from D'Agostini)
- CMS DIL TOP-2018-004 : TUnfold and Tickonov regularisation
- CMS DIL TOP-2018-006: TUnfold (incl. regularisation)



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Physics

Systematic Uncertainties

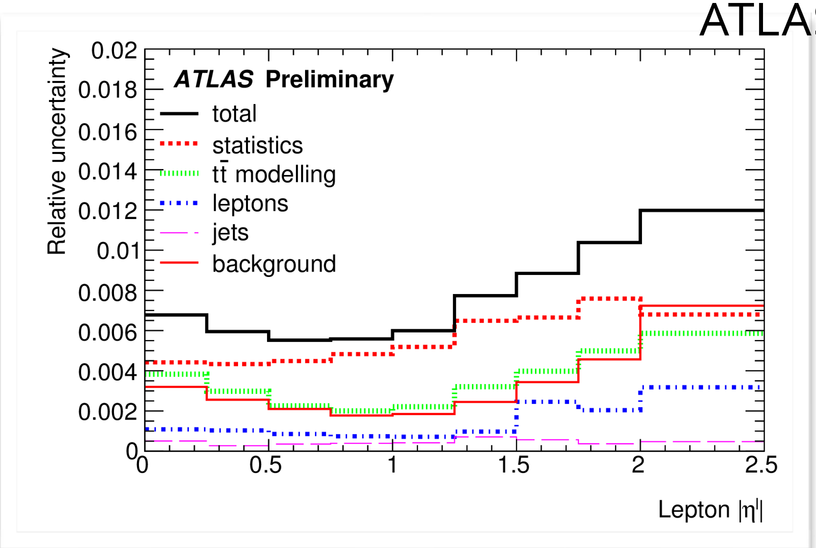
- Systematic uncertainties include:
  - Detector uncertainties:
    - leptons, jets, b-jets
  - Background uncertainties
    - ex: single top diagram removal vs diagram subtraction approaches
  - Signal modelling
    - ATLAS:
      - generator: Powheg+Pythia8 vs aMC@NLO+Pythia8 (DIL) or Sherpa 2.2.1 (L+jets)
      - hadronisation: Powheg+Pythia8 vs Powheg + Herwig7
      - I/F State Radiation: Powheg+Pythia8 with more or less radiation (including hdamp variation)
      - PDF
      - Heavy Flavour variation (DIL)

- Signal modelling
  - CMS:
    - generator: renormalization/factorization scales varied by 2
    - ME to PS matching: hdamp variation
    - I/F State Radiation: scales in parton shower simulation: factor 2 for Initial and sqrt(2) for Final
    - PDF
    - Colour reconnection, underlying event
    - b-quark fragmentation

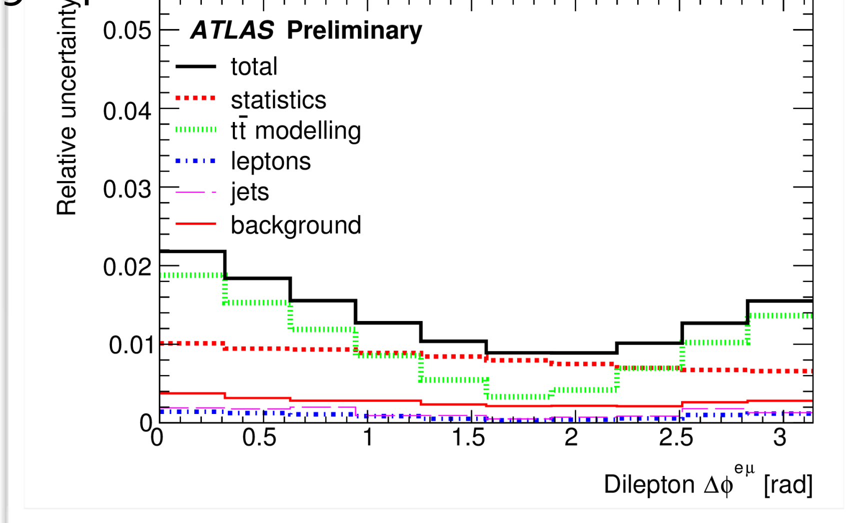
Systematic Uncertainties

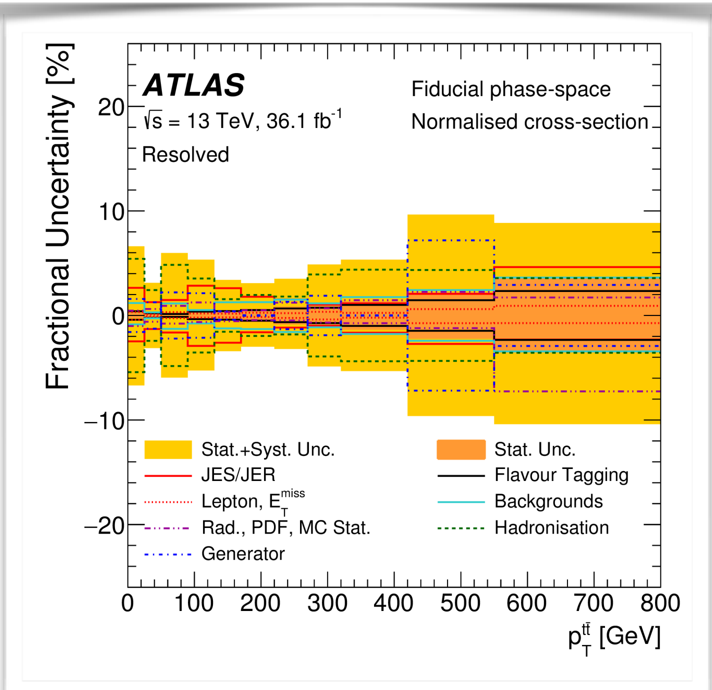
Physics

ATLAS-CONF-2019-041



DIL





L+jets

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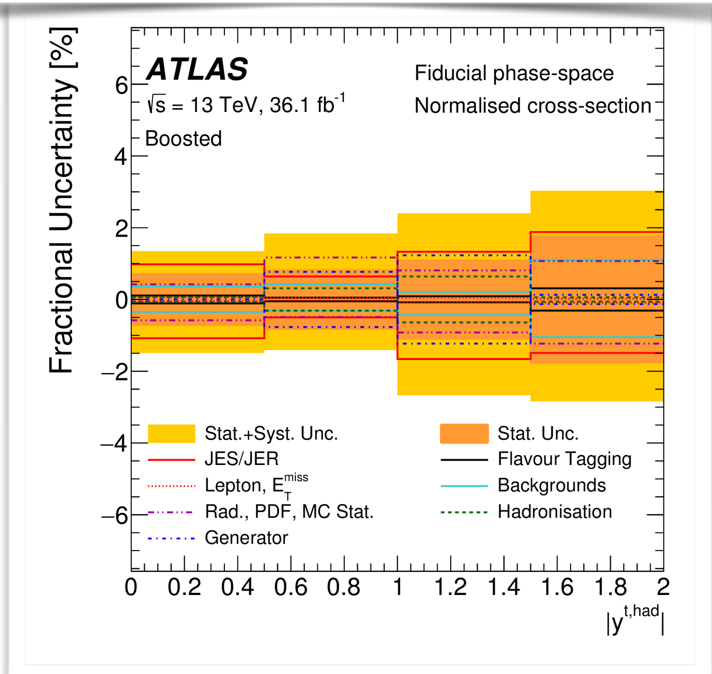
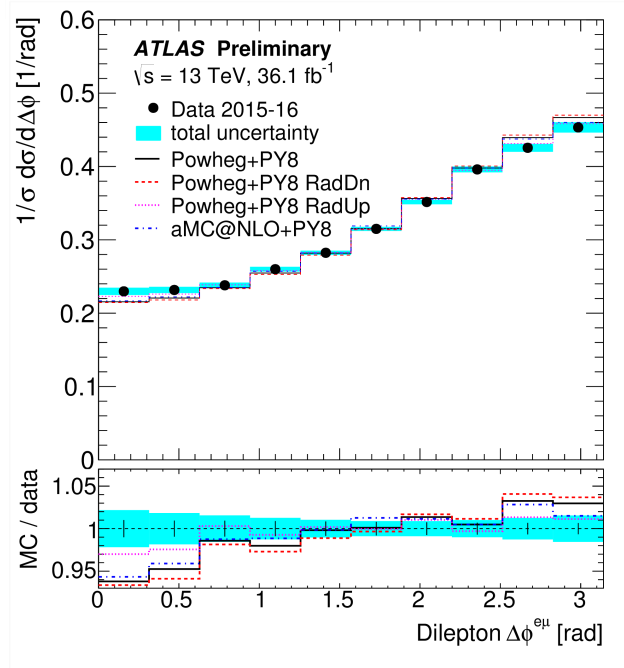


Results and Interpretation
(χ^2 tables in backup)

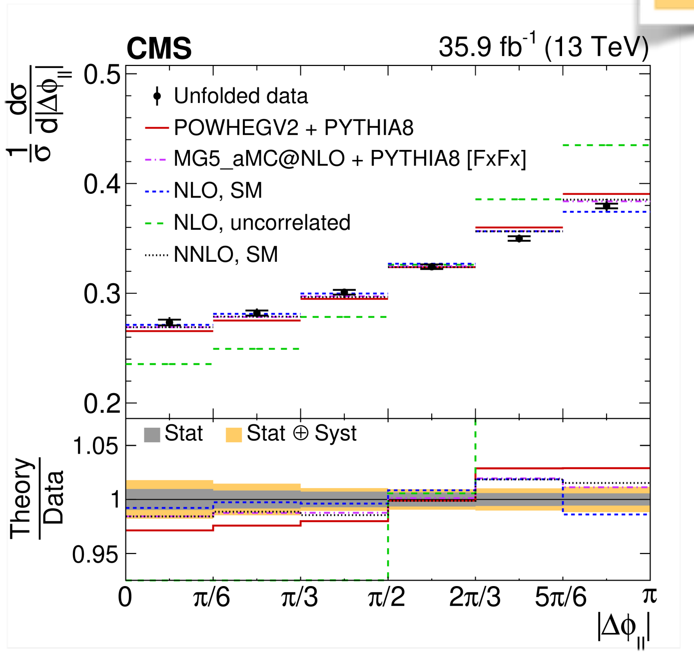
Lepton distributions

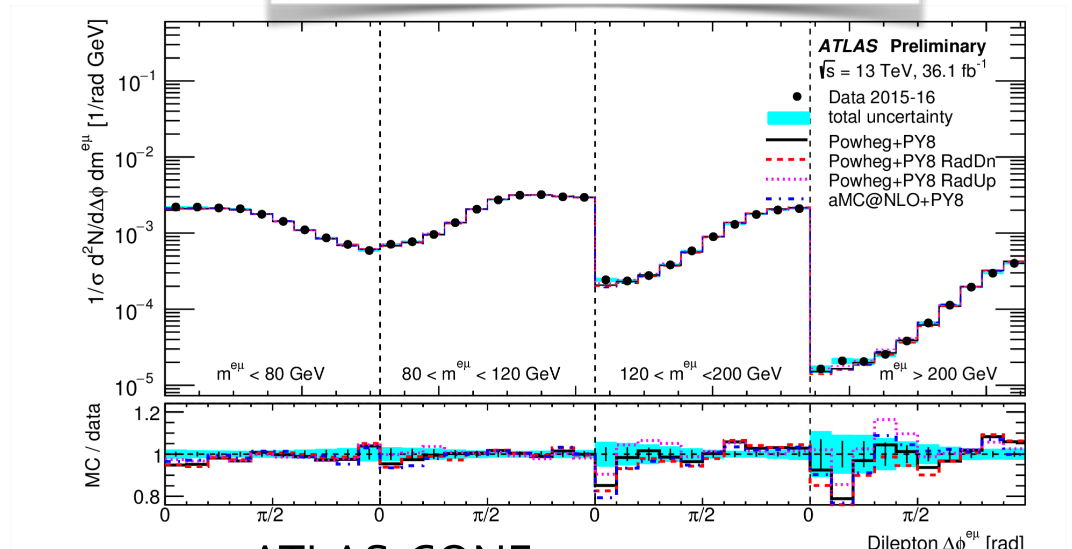
- ATLAS DIL:
  - 1D: $p_T^\ell, |\eta^\ell|, p_T^{e\mu}, m^{e\mu}, |y^{e\,u}|, \Delta\phi^{e\mu}, p_T^e + p_T^\mu, E^e + E^\mu$
  - 2D: $|\eta^\ell|$ vs $m^{e\mu}$, $|y^{e\,u}|$ vs $m^{e\mu}$, $\Delta\phi^{e\mu}$ vs $m^{e\mu}$
  - $\Delta\phi^{e\mu}$: Powheg+Py8 Rad Up best (and reduced QCD scales and top pt rewt)
- CMS DIL Pol:
  - 19 polarization and spin correlation related observables and
  - $\cos\phi$ ($\cos\phi_{\text{lab}}$): dot product of the two leptons in the top rest frames (lab frame) and $|\Delta\phi_{\ell\ell}|$
  - $|\Delta\phi_{\ell\ell}|$: aMC@NLO best. NNLO good



Poster by A Jung

TOP-18-006



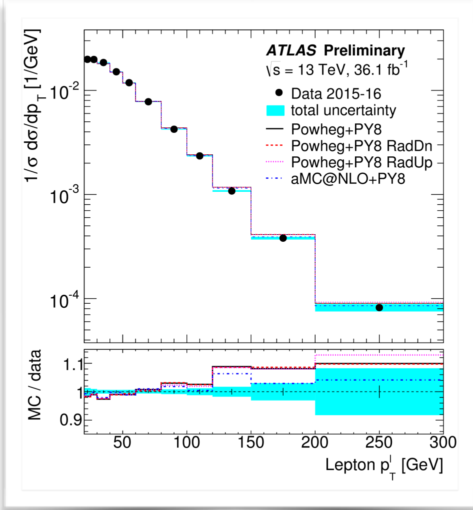


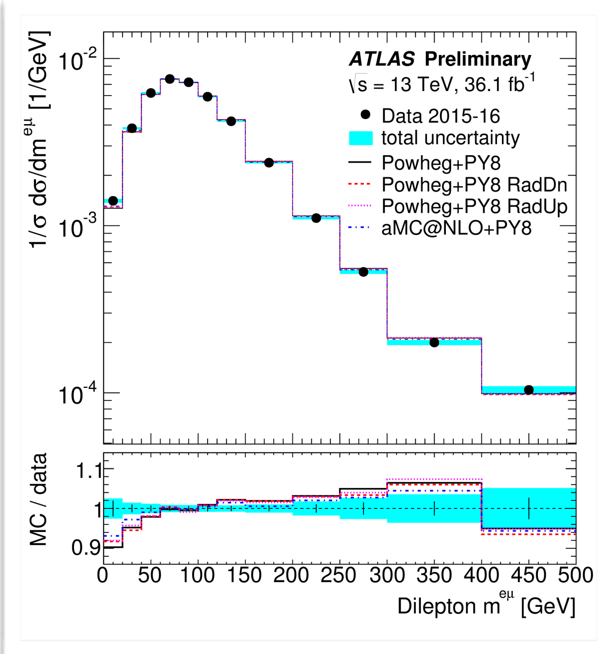
ATLAS-CONF-2019-041

Lepton distributions

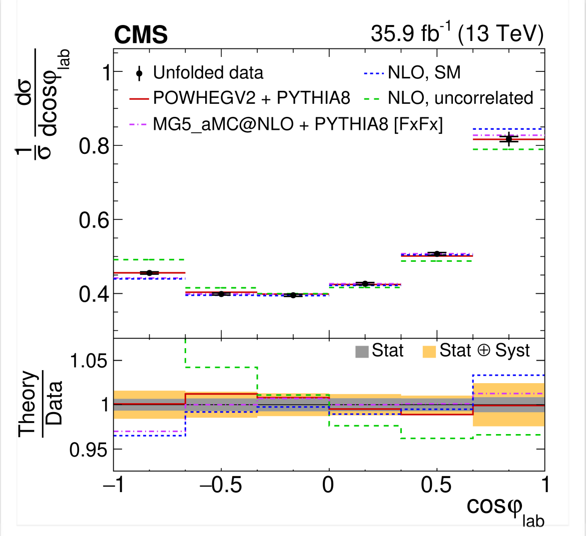
- p_T^{ℓ}: Powheg-based predictions are harder than data
- $m^{e\mu}$: None of the predictions describe well the low mass
- $\cos\phi_{\text{lab}}$: Powheg+Py8 best

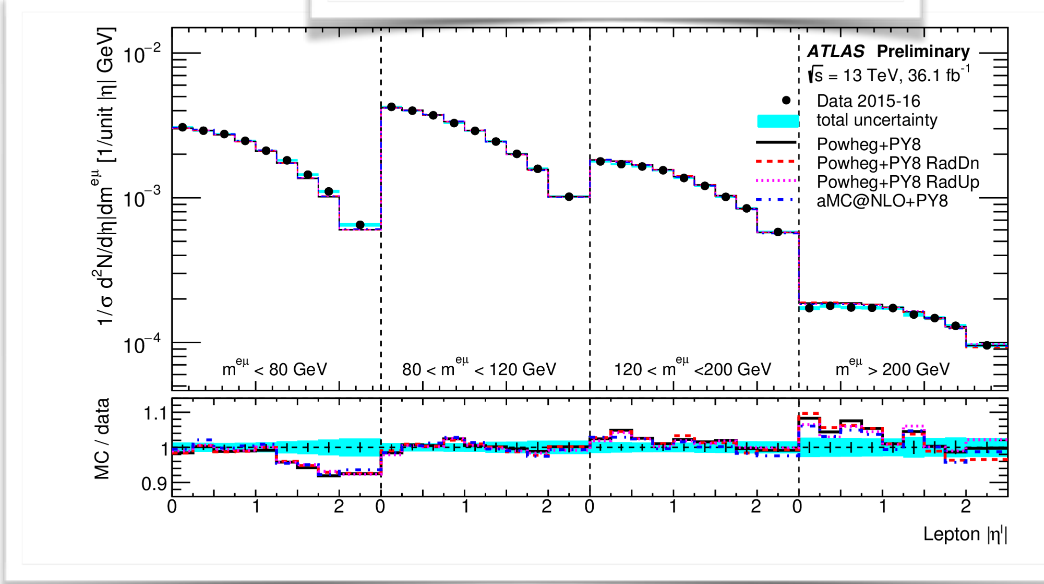
ATLAS-CONF-2019-041





TOP-18-006





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Measured observables

Physics

ATLAS L+jets 1908.07305

Resolved

Particle

1D observables	2D combinations
$m^{t\bar{t}}$	in bins of: $\lvert y^{t\bar{t}}\rvert$ and $N^{\text{extrajets}}$
$p_{\mathrm{T}}^{t\bar{t}}$	in bins of: $m^{t\bar{t}}$, $\lvert y^{t\bar{t}}\rvert$ and $N^{\text{extrajets}}$
$\lvert y^{t\bar{t}}\rvert$	in bins of: $N^{\text{extrajets}}$
$p_{\mathrm{T}}^{t,\text{had}}$	in bins of: $m^{t\bar{t}}$, $p_{\mathrm{T}}^{t\bar{t}}$, $\lvert y^{t,\text{had}}\rvert$ and $N^{\text{extrajets}}$
$\lvert y^{t,\text{had}}\rvert$	in bins of: $N^{\text{extrajets}}$
$p_{\mathrm{T}}^{t,1}$	
$p_{\mathrm{T}}^{t,2}$	
$\chi^{t\bar{t}}$	in bins of: $N^{\text{extrajets}}$
$\lvert y_{\text{boost}}^{t\bar{t}}\rvert$	
$\lvert\Delta\phi(t,\bar{t})\rvert$	in bins of: $N^{\text{extrajets}}$
$H_{\mathrm{T}}^{t\bar{t}}$	in bins of: $N^{\text{extrajets}}$
$\lvert p_{\text{out}}^{t,\text{had}}\rvert$	in bins of: $N^{\text{extrajets}}$
$N^{\text{extrajets}}$	

Parton

1D observables	2D combinations
$m^{t\bar{t}}$	in bins of: $\lvert y^{t\bar{t}}\rvert$
$p_{\mathrm{T}}^{t\bar{t}}$	in bins of: $m^{t\bar{t}}$ and $\lvert y^{t\bar{t}}\rvert$
$\lvert y^{t\bar{t}}\rvert$	
$p_{\mathrm{T}}^{t,\text{had}}$	in bins of: $m^{t\bar{t}}$, $p_{\mathrm{T}}^{t\bar{t}}$ and $\lvert y^{t,\text{had}}\rvert$
$\lvert y^{t,\text{had}}\rvert$	
$\chi^{t\bar{t}}$	
$\lvert y_{\text{boost}}^{t\bar{t}}\rvert$	
$H_{\mathrm{T}}^{t\bar{t}}$	

Poster by J Kvita

Boosted

Particle

1D observables	2D combinations
$m^{t\bar{t}}$	in bins of: $H_{\mathrm{T}}^{t\bar{t}}$, $\lvert y^{t\bar{t}}\rvert$, $p_{\mathrm{T}}^{t\bar{t}}$ and $N^{\text{extrajets}}$
$p_{\mathrm{T}}^{t\bar{t}}$	in bins of: $N^{\text{extrajets}}$
$\lvert y^{t\bar{t}}\rvert$	
$p_{\mathrm{T}}^{t,\text{had}}$	in bins of: $m^{t\bar{t}}$, $p_{\mathrm{T}}^{t\bar{t}}$, $\lvert y^{t,\text{had}}\rvert$, $\lvert y^{t\bar{t}}\rvert$ and $N^{\text{extrajets}}$
$\lvert y^{t,\text{had}}\rvert$	
$p_{\mathrm{T}}^{t,1}$	
$p_{\mathrm{T}}^{t,2}$	
$\chi^{t\bar{t}}$	
$H_{\mathrm{T}}^{t\bar{t}}$	
$\lvert p_{\text{out}}^{t,\text{lep}}\rvert$	
$N^{\text{extrajets}}$	
N^{subjets}	

Parton

1D observables	2D combinations
$m^{t\bar{t}}$	in bins of: $p_{\mathrm{T}}^{t,\text{had}}$
$p_{\mathrm{T}}^{t,\text{had}}$	

CMS DIL Parton TOP-18-004

2D: in bins of $|y^t|$: p_T^t

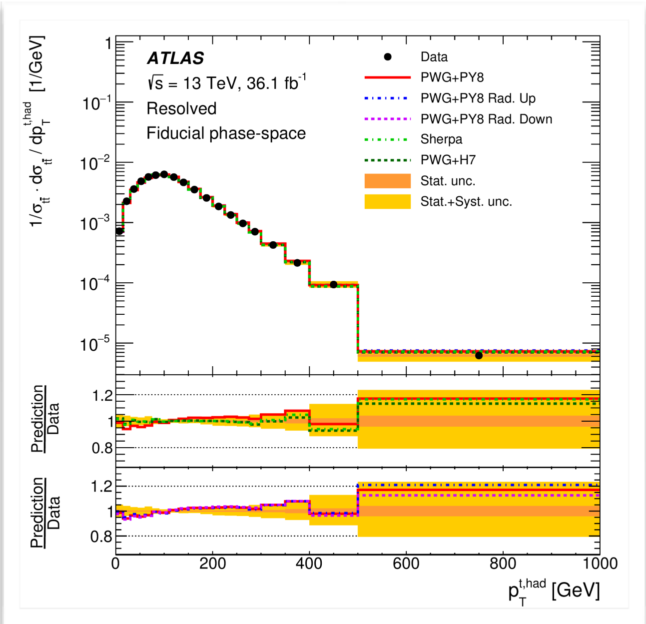
in bins of $m_{t\bar{t}}$: $|y^t|, |y^{t\bar{t}}|, \Delta\eta^{t\bar{t}}, \Delta\phi^{t\bar{t}}, p_T^{t\bar{t}}, p_T^t$

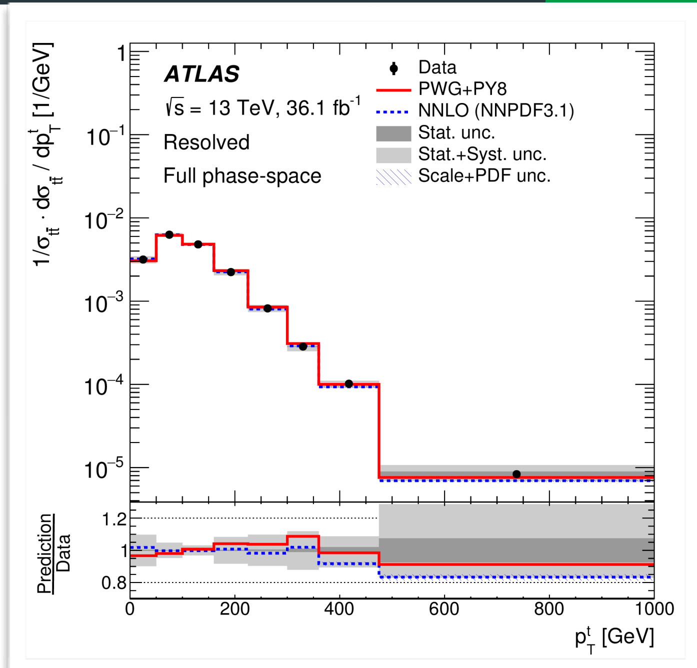
3D: $\left[N_{\text{jet}}^{0,1+}, m^{t\bar{t}}, y^{t\bar{t}}\right]$ and $\left[N_{\text{jet}}^{0,1,2+}, m^{t\bar{t}}, y^{t\bar{t}}\right]$

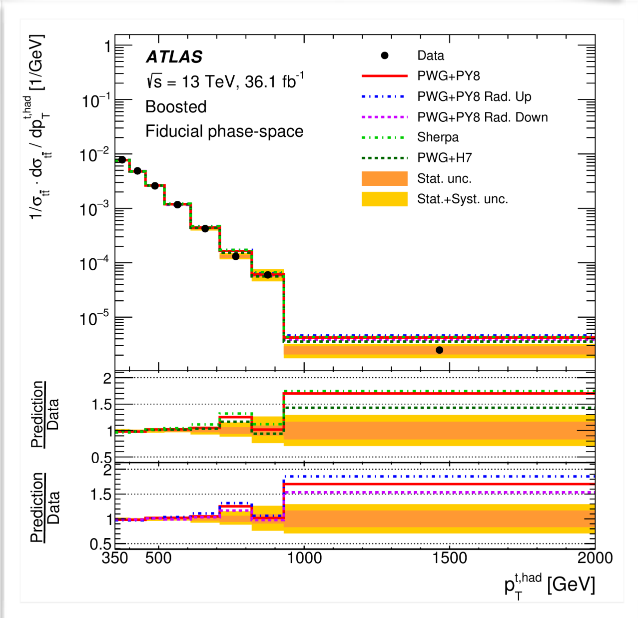
Top quark kinematics

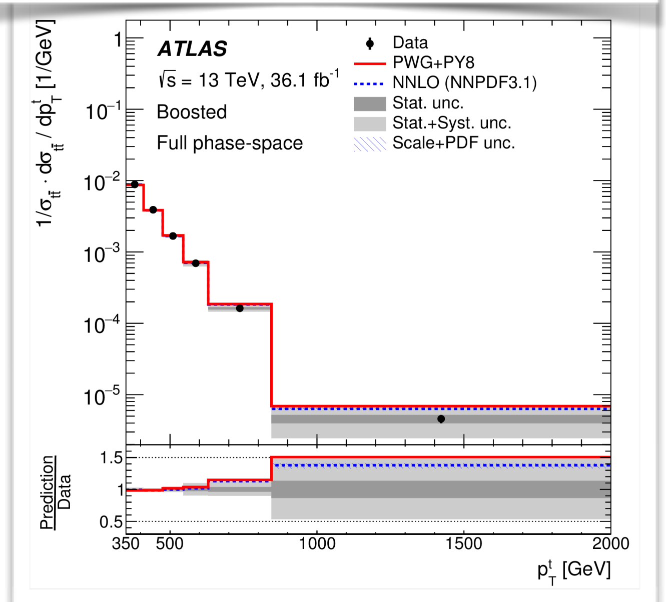
1908.07305

- p_T^t:
  - Powheg+Py8 best, as good agreement as NNLO prediction at parton level









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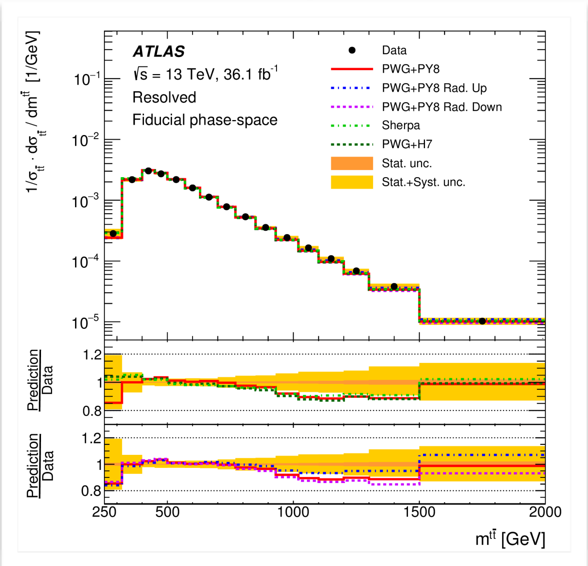
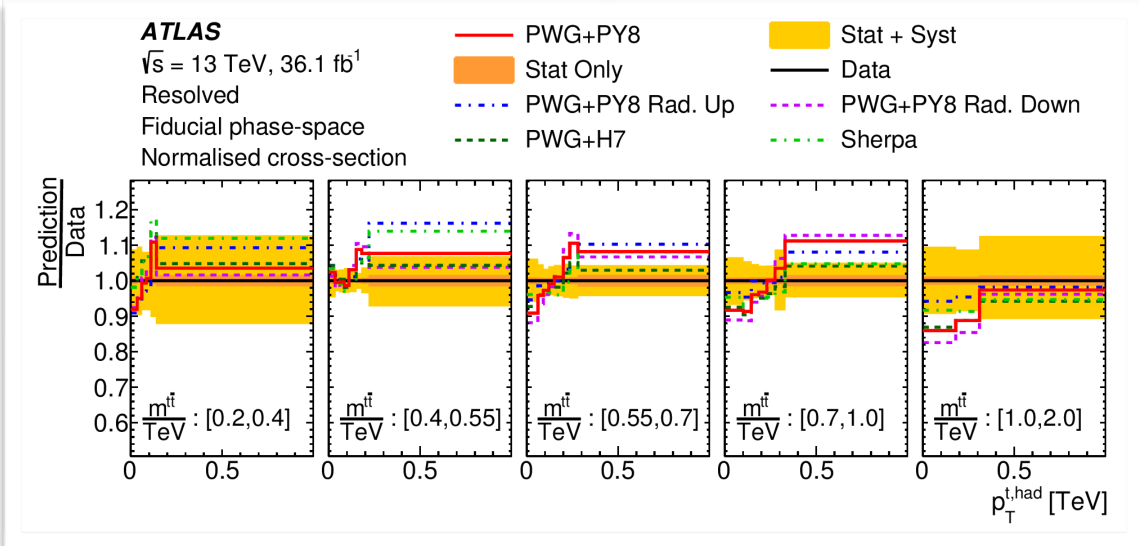
Top quark kinematics

Physics

- Power of double differential: single differentials ok, but not double…

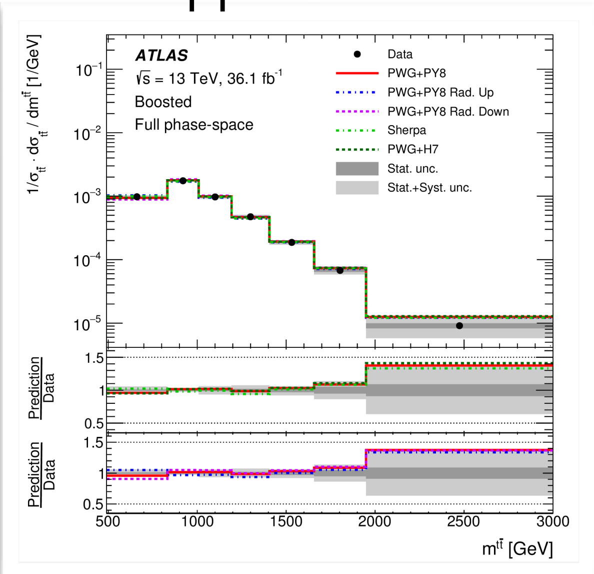
1908.07305

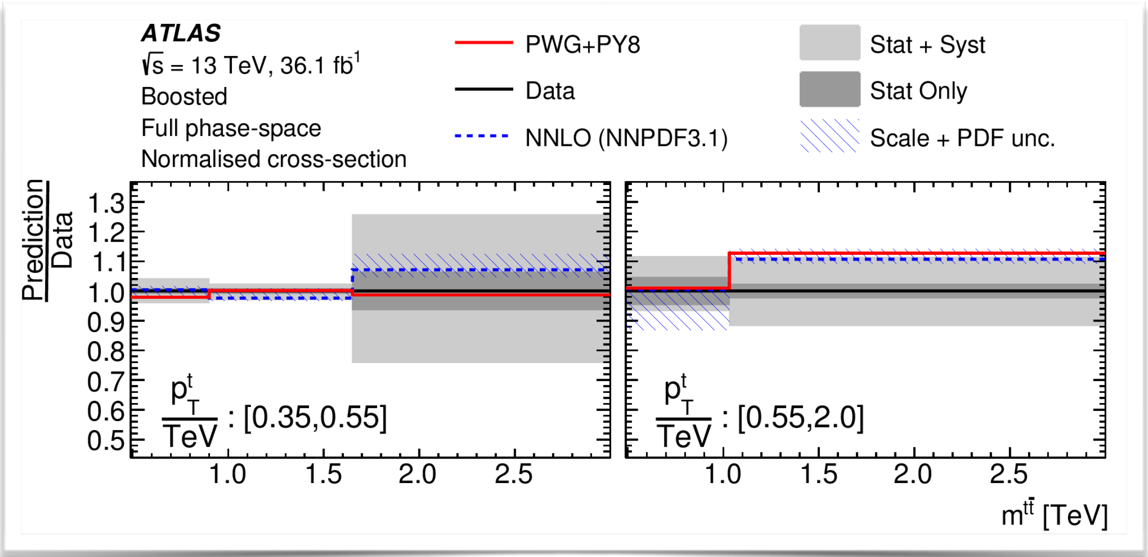




- … or the opposite:

First 2D for boosted!

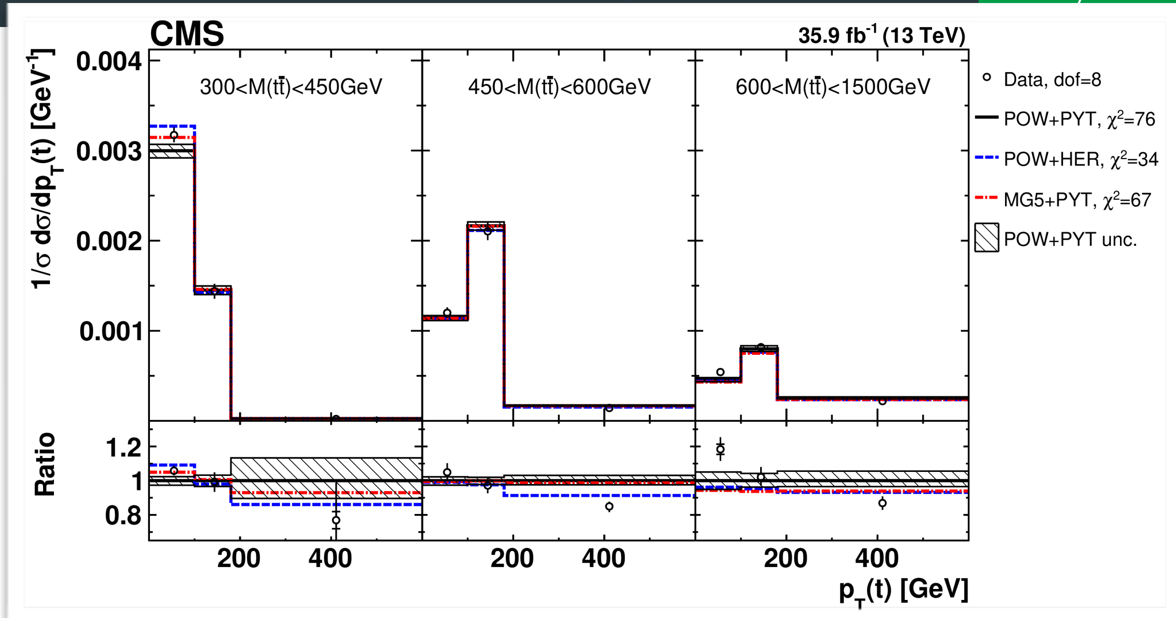




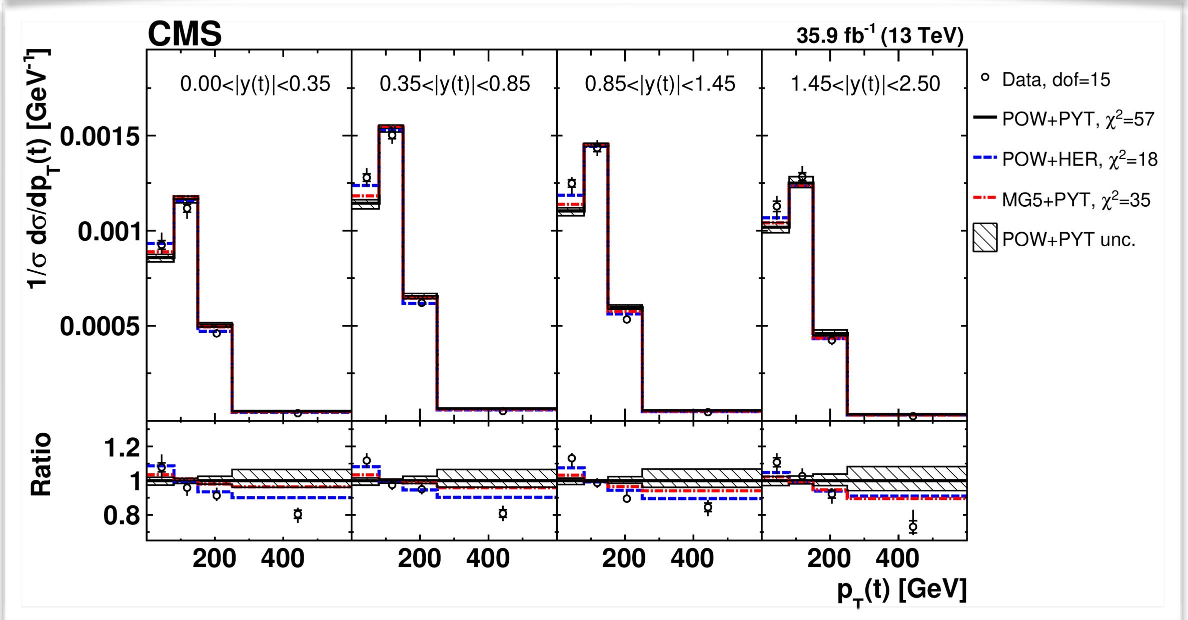
Top quark kinematics

TOP-18-004

- p_T^t vs $m_{t\bar{t}}$: strongest disagreement from Powheg+Pyhia, Powheg+Herwig bit better except in last bin



- p_T^t vs $|y^t|$: Powheg+Herwig best



tt system kinematics

Physics

- Sensitivity to extra radiation
- best agreement with Powheg+Pythia Rad Down

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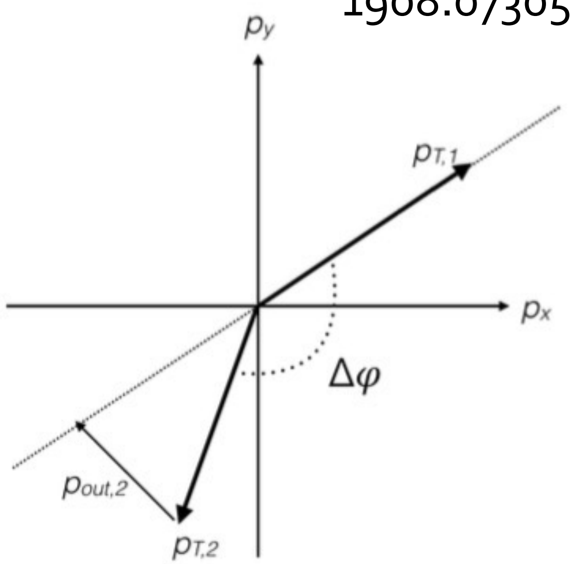
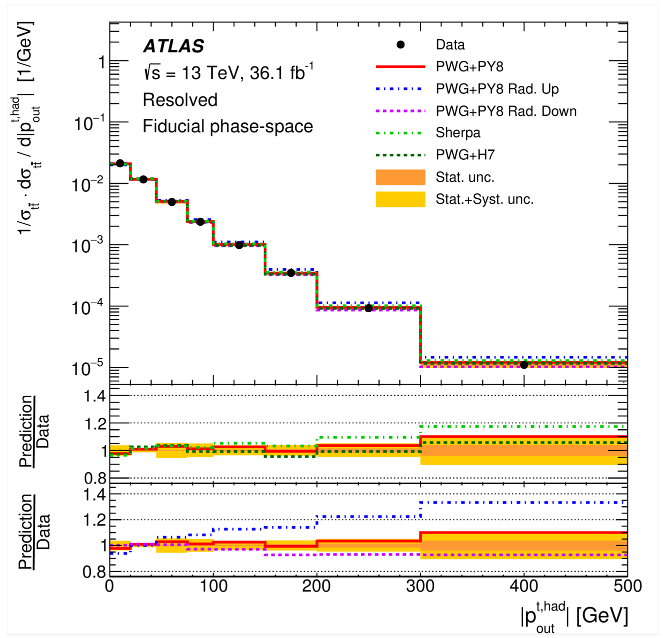
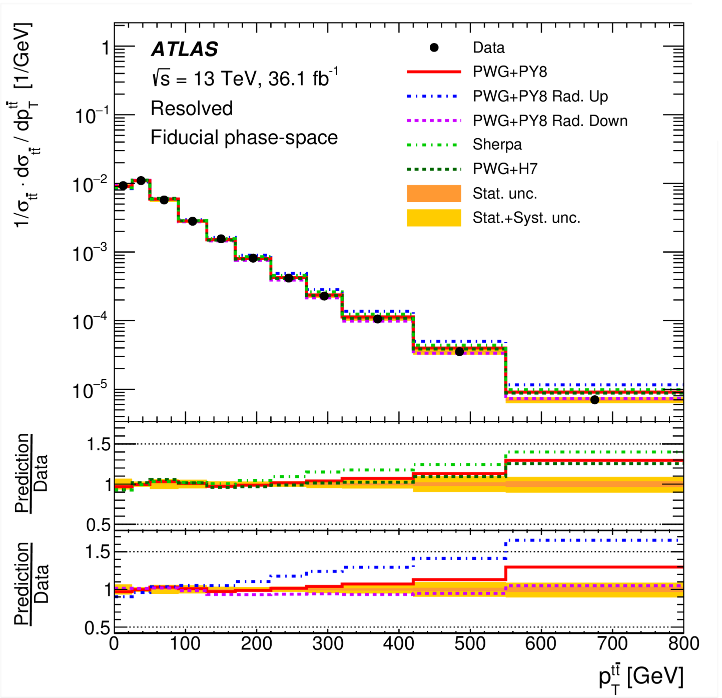
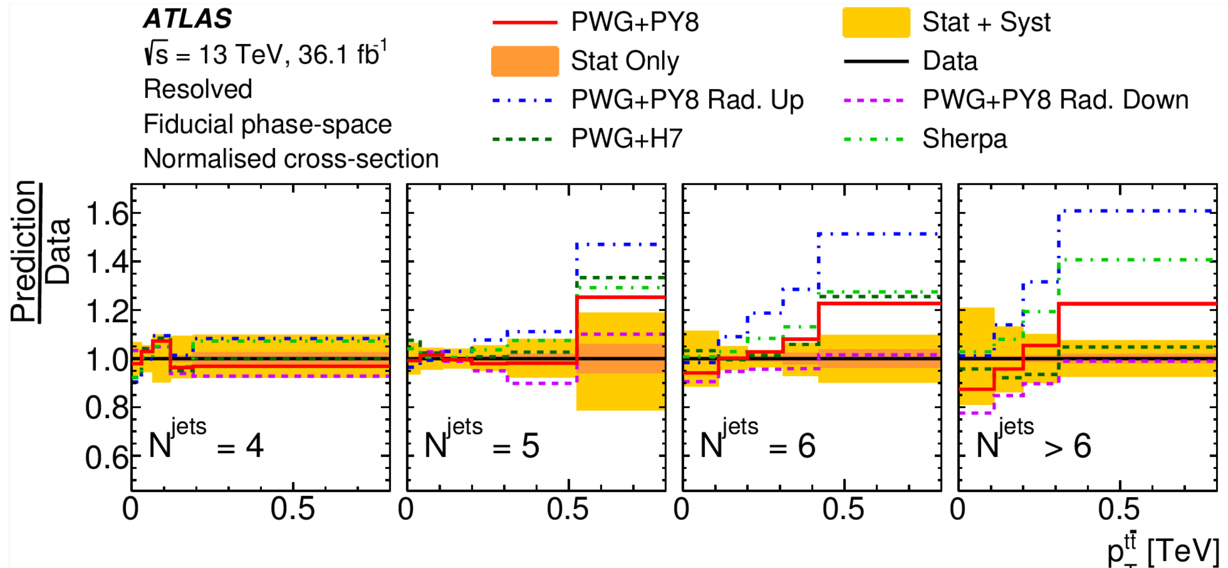






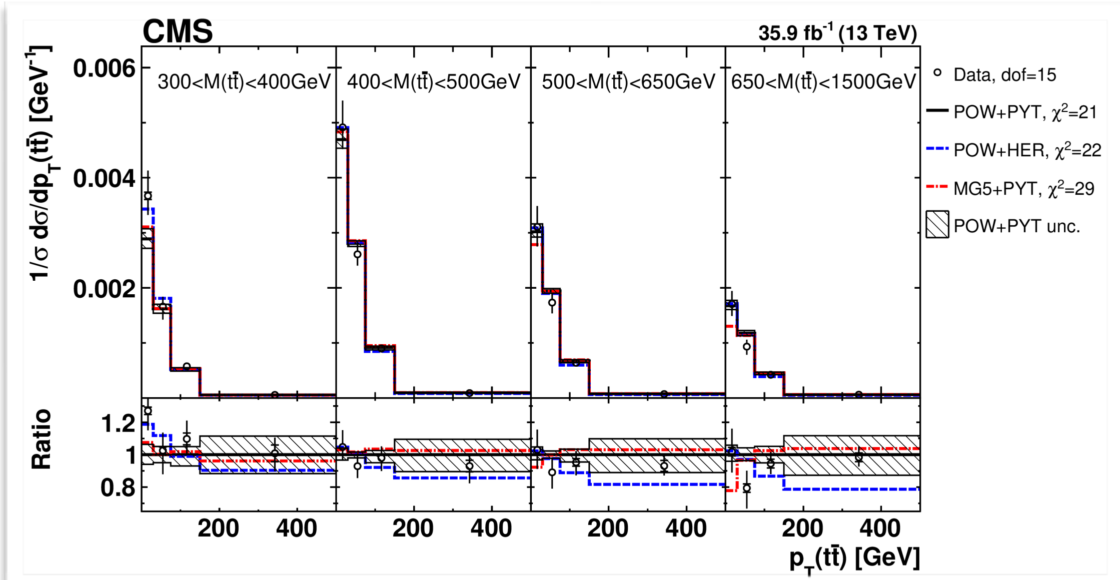


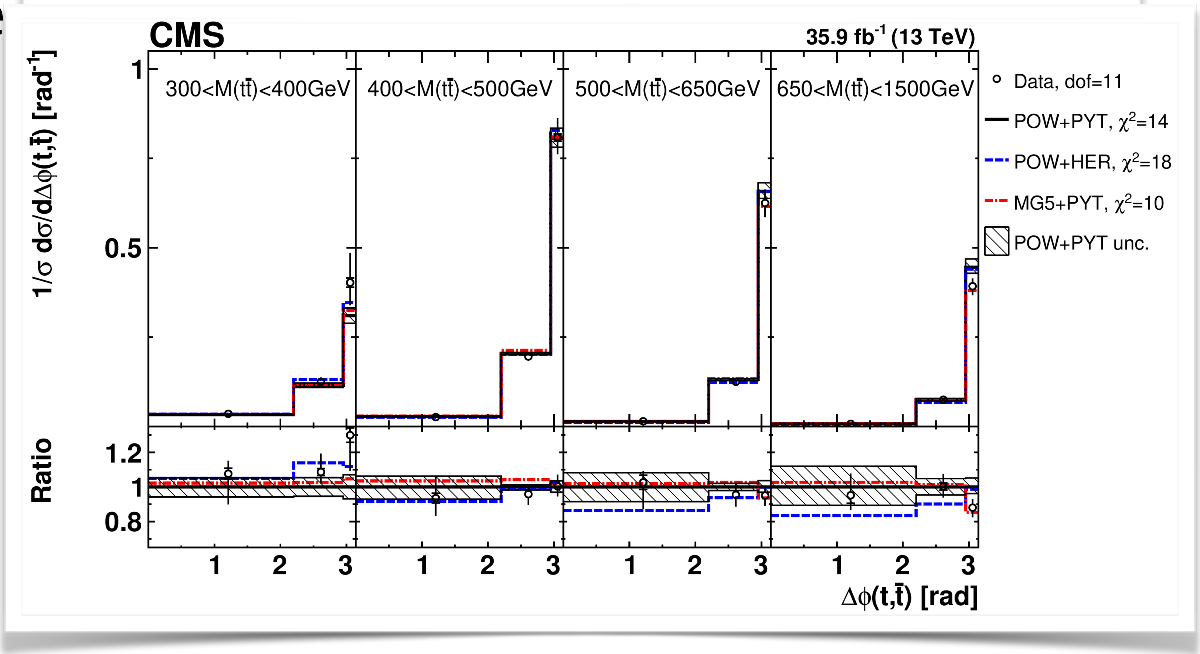
tt system kinematics

Physics

TOP-18-004

- Sensitive to radiation
- Madgraph5+Pythia worse for $p_T(t\bar{t})$





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Physics

p-values

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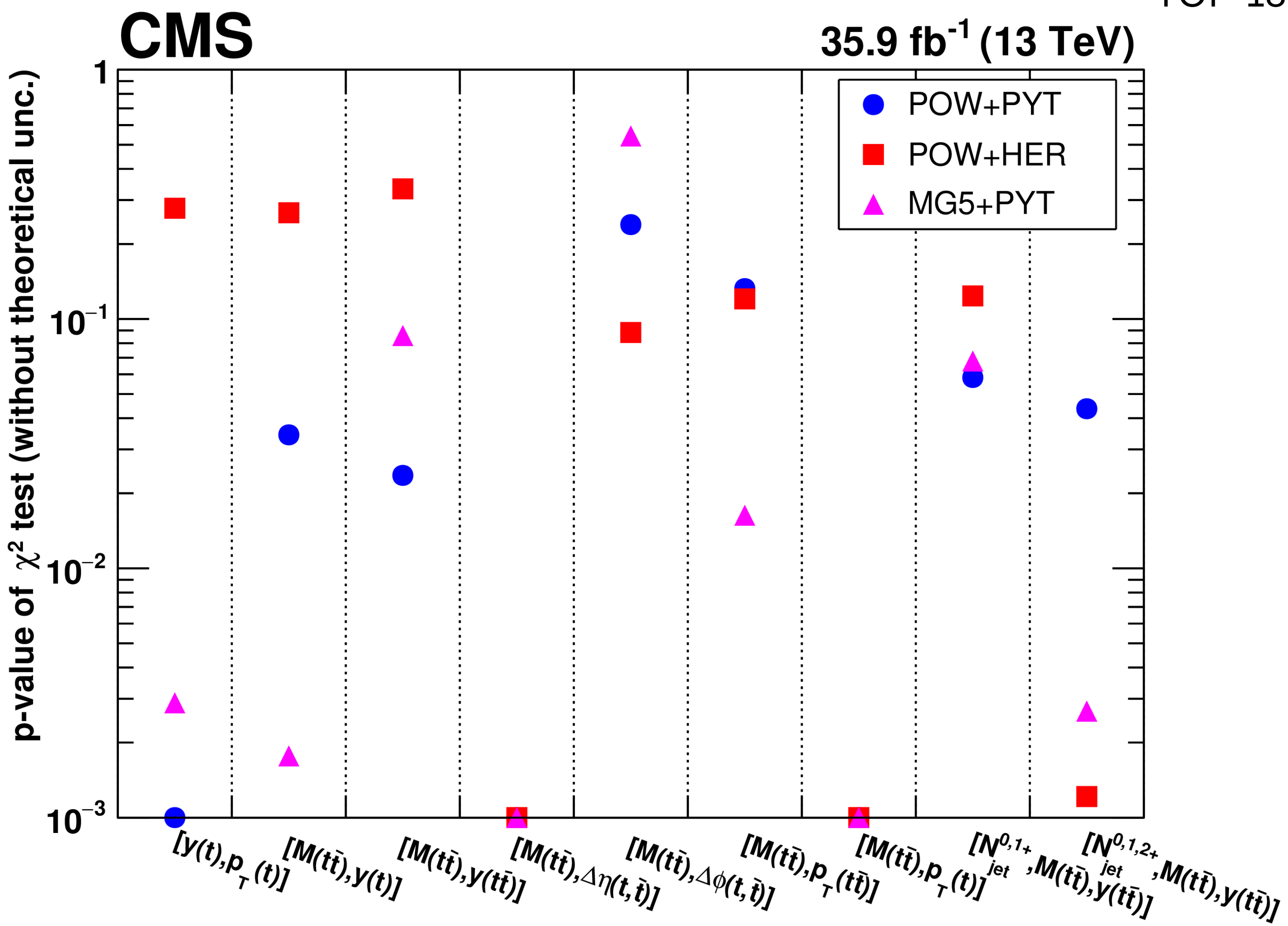
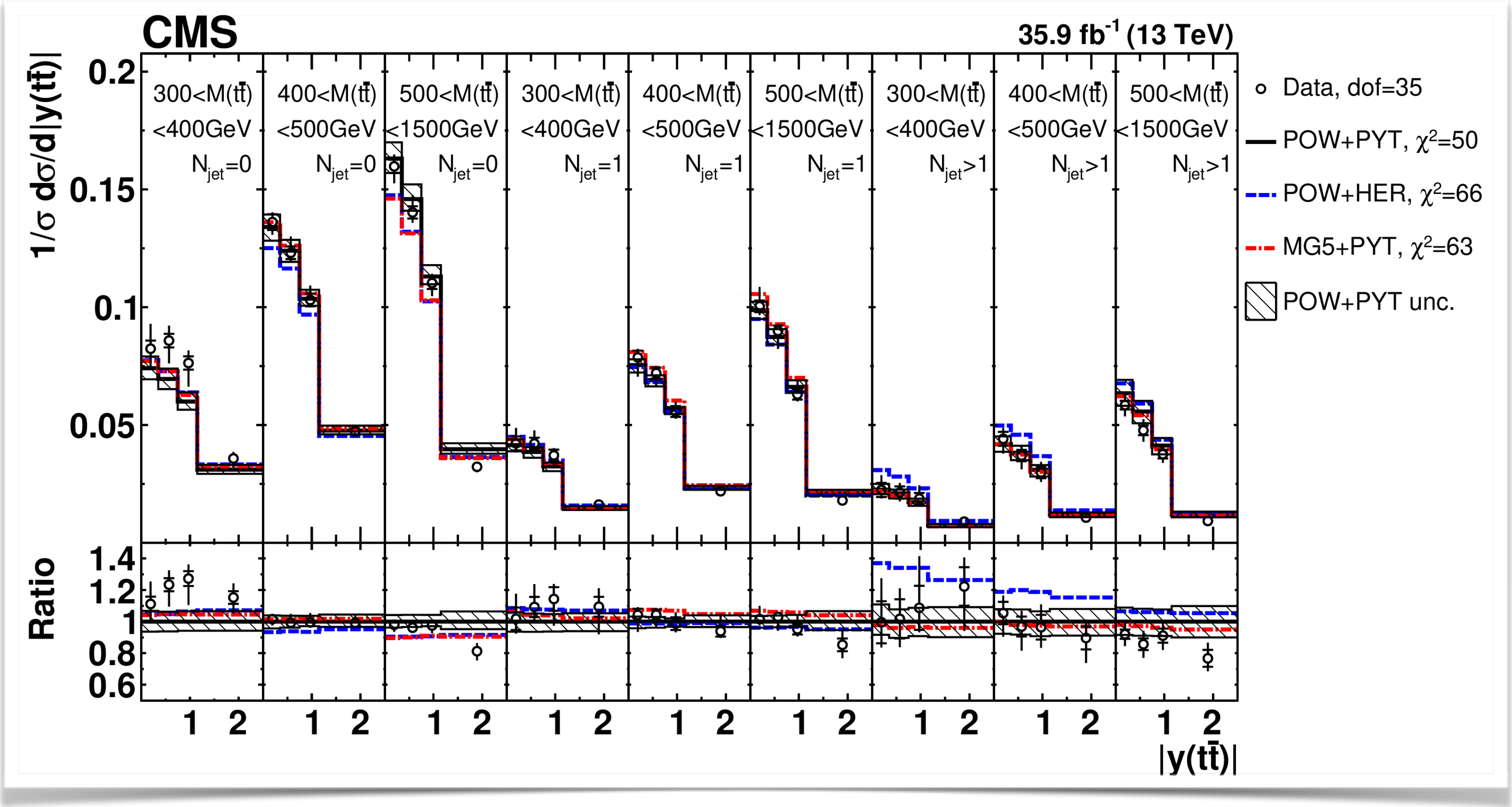


Triple differential

Physics

- First triple differential! TOP-18-004
- $\left[N_{\text{jet}}^{0,1+}, m^{t\bar{t}}, y^{t\bar{t}}\right]$: all ~ ok

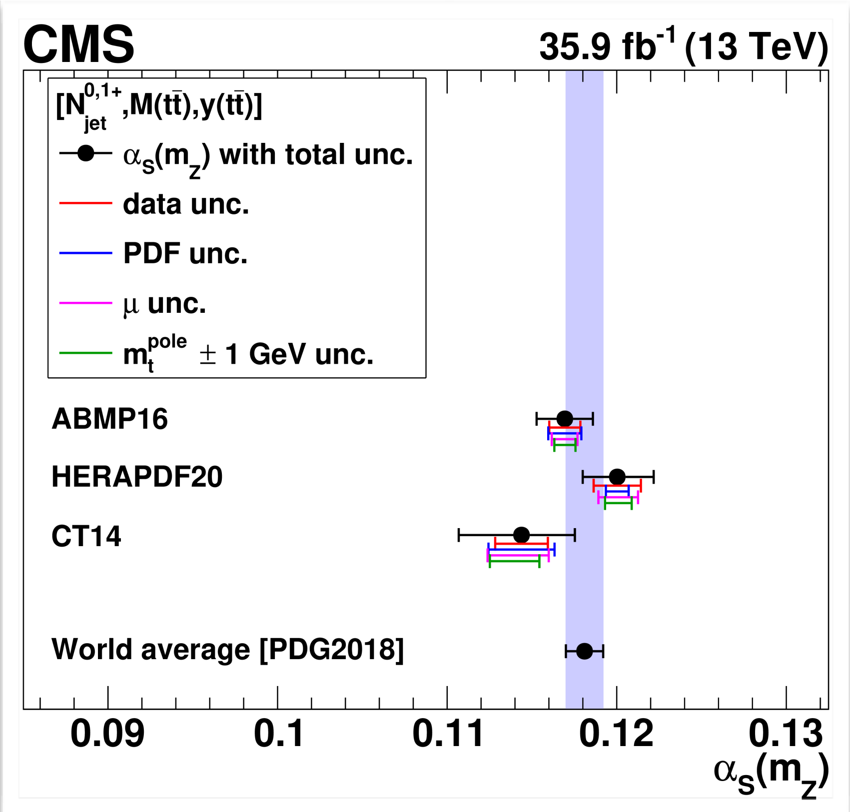
  best pole mass and α_s measurement!
- $\left[N_{\text{jet}}^{0,1,2+}, m^{t\bar{t}}, y^{t\bar{t}}\right]$: Powheg+Pythia best

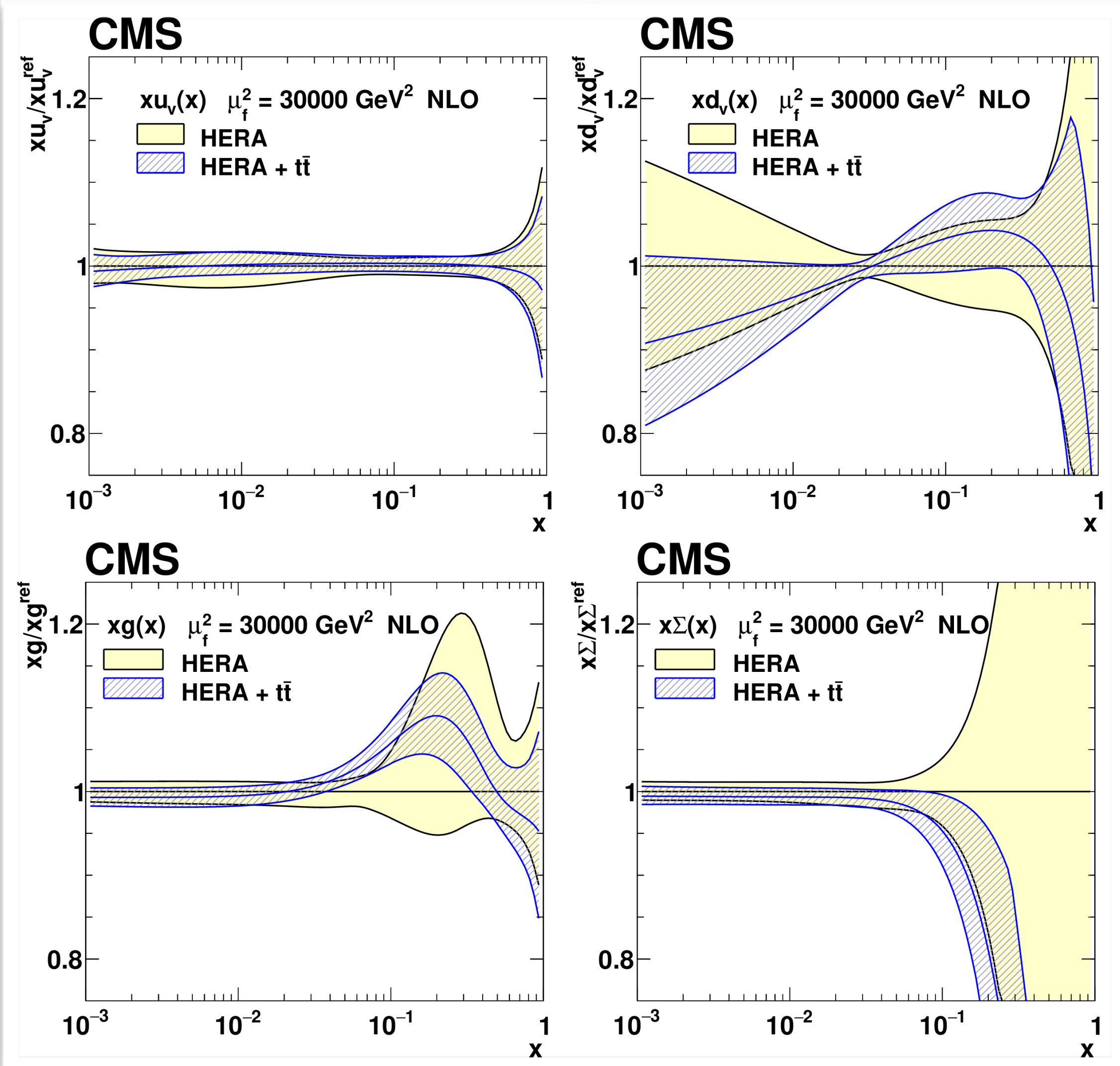


Measuring α_s and PDF improvement

Physics

TOP-18-004





Results are normalised to the PDFs obtained using the HERA DIS data only

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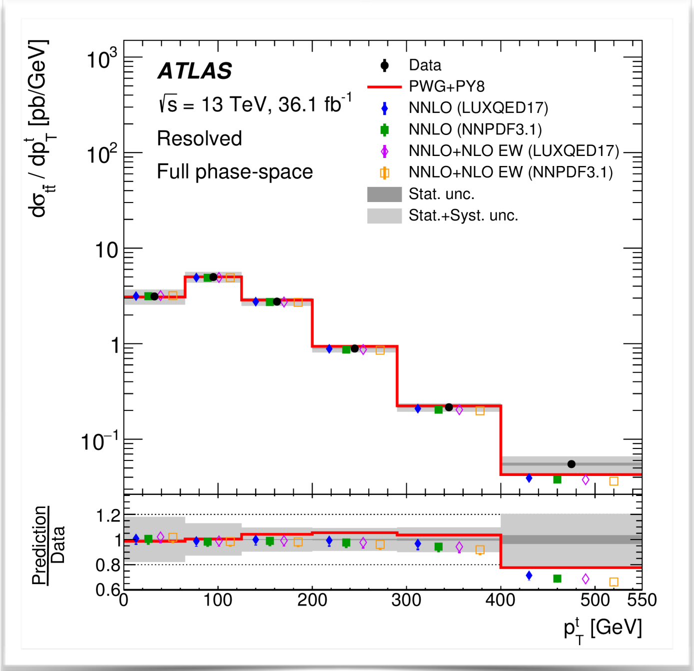
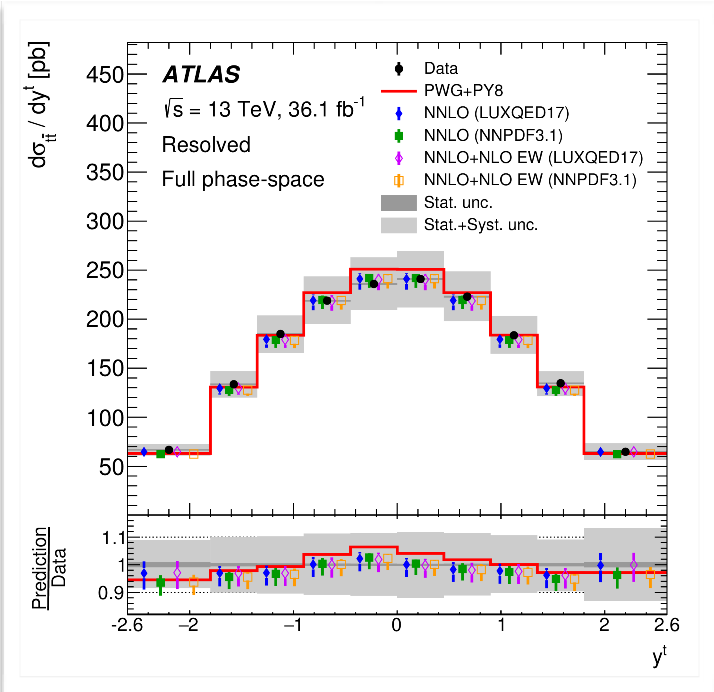
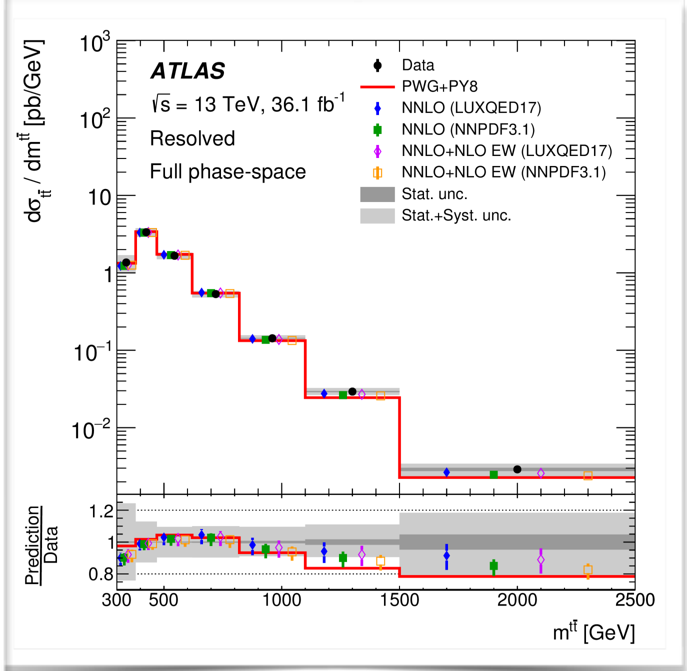
NNLO EWK corrections

Physics

- parton level, coarser binning, same as CMS (will help combination), to test impact of EWK corrections in NNLO pQCD predictions
- because of limited p_T range, no quantitative assessment yet, need more data







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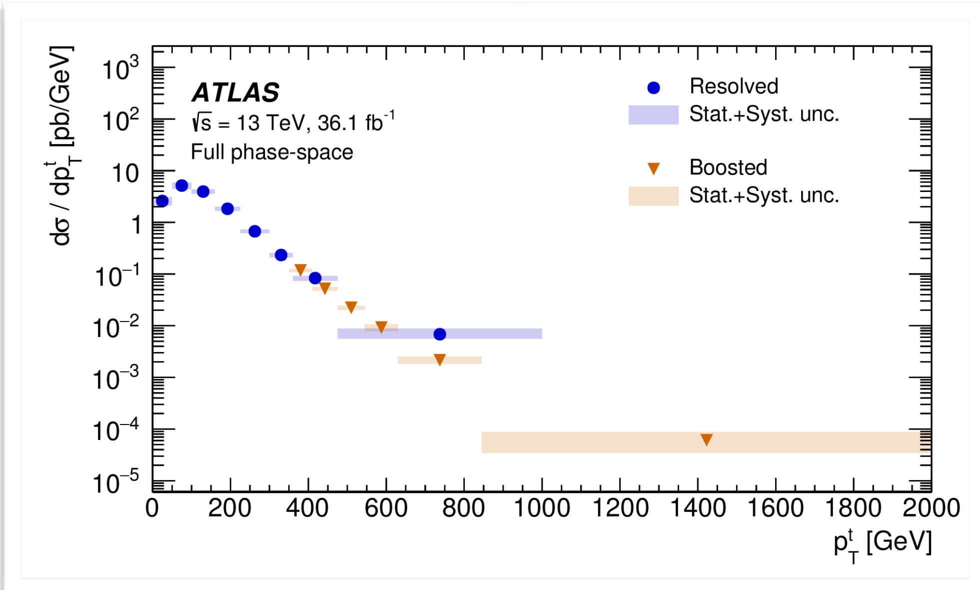
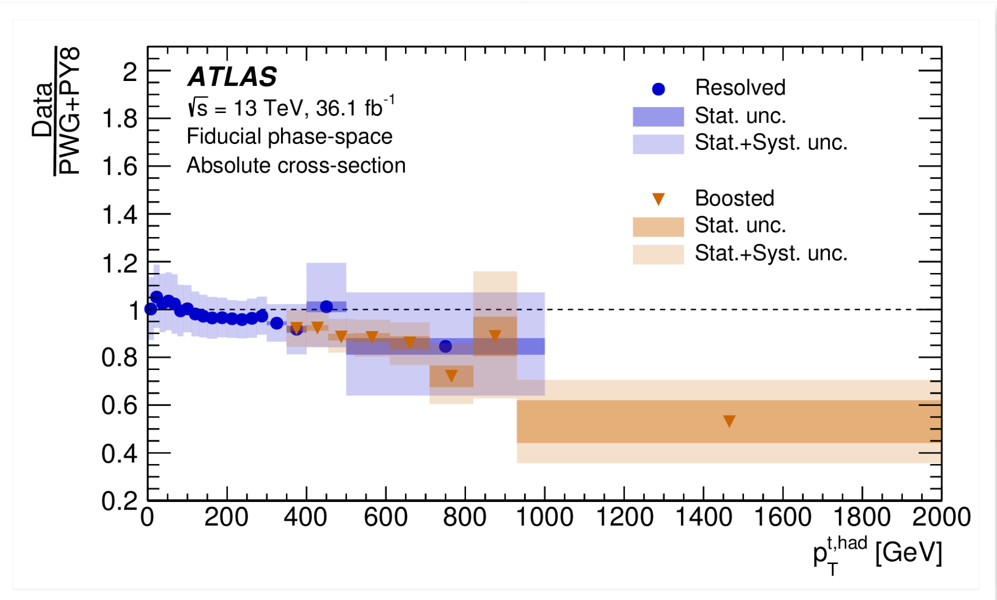
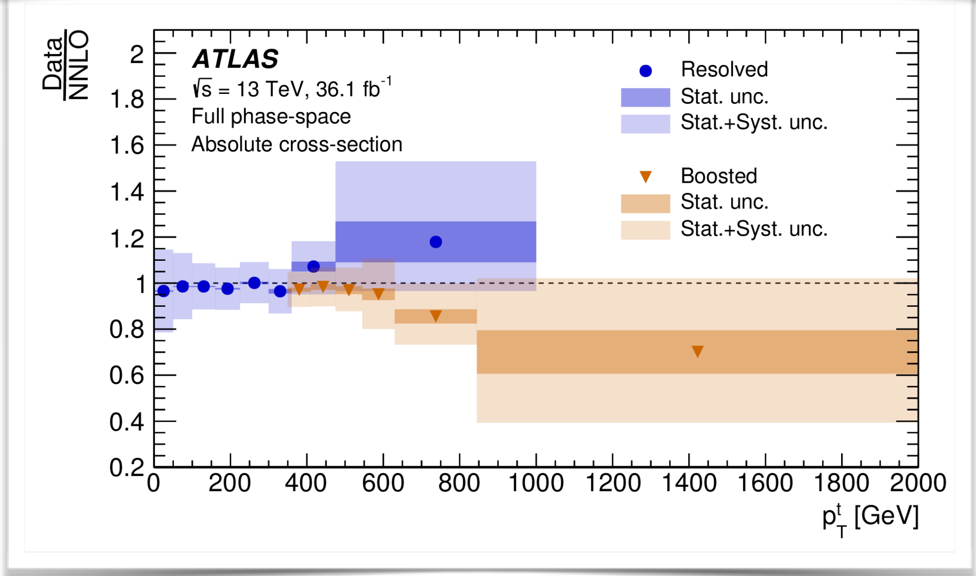
Overlap of resolved and boosted

Physics

- Overlap of Resolved vs Boosted: good
- For Particle level: definitions of particle is different, so direct cross-section comparison not possible, compare data/MC agreement







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Conclusions

Physics

- Differential measurements are used for MC tuning within ATLAS and CMS —> improve signal modelling of future results
- As seen yesterday and today differential measurements are also used to measure important top properties (mass, spin correlation, etc.) as well as measure α_s and help with PDF improvements
- Most analyses dominated by systematic uncertainties (mostly signal modelling)
- First triple differential and first double differential for boosted!
- Particle Level:
  - Overall most predictions are mainly ok for 1D, but not so much for 2D
  - For boosted, normalisation discrepancy between measurement and prediction
  - Overall, Powheg+Pythia8 for resolved and Powheg+Herwig7 for boosted give good predictions for largest fraction of observables
- Parton Level:
  - NNLO predictions provide a general improvement relative to the NLO+PS MC generators

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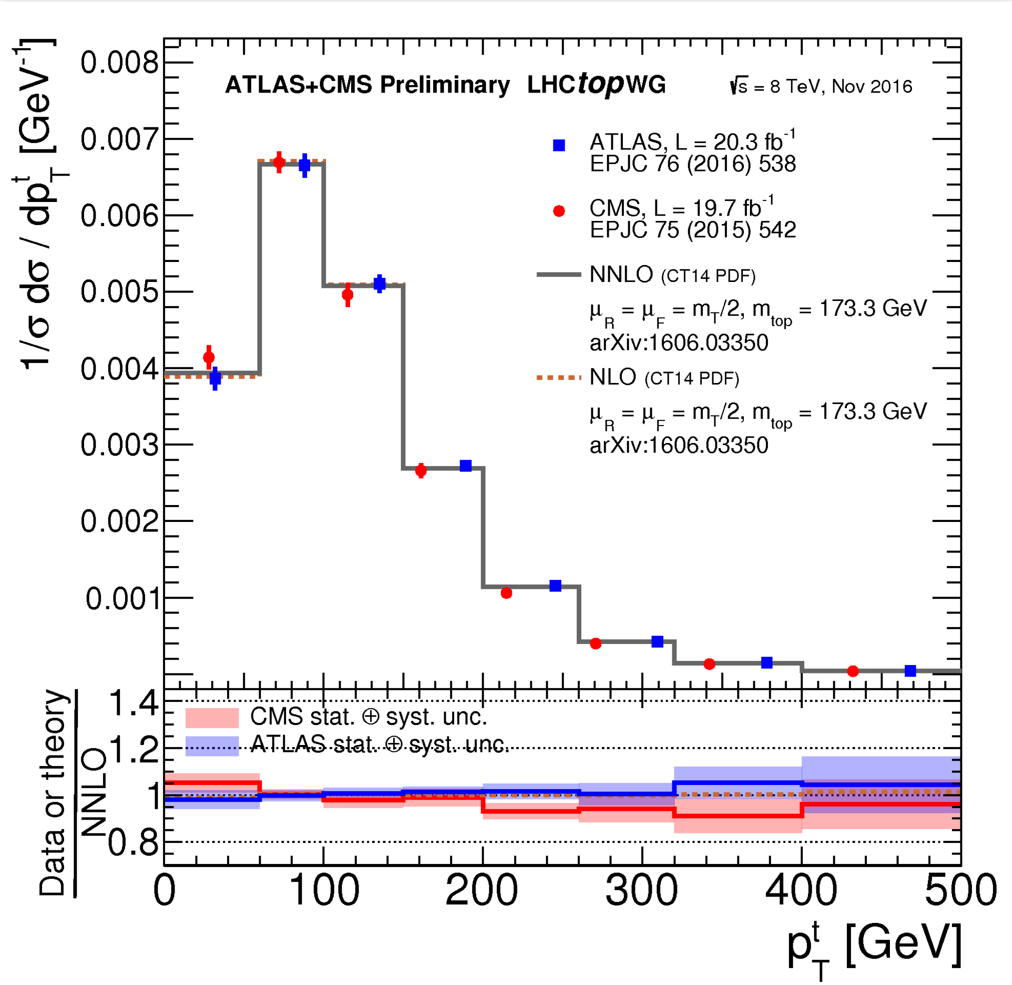
Physics

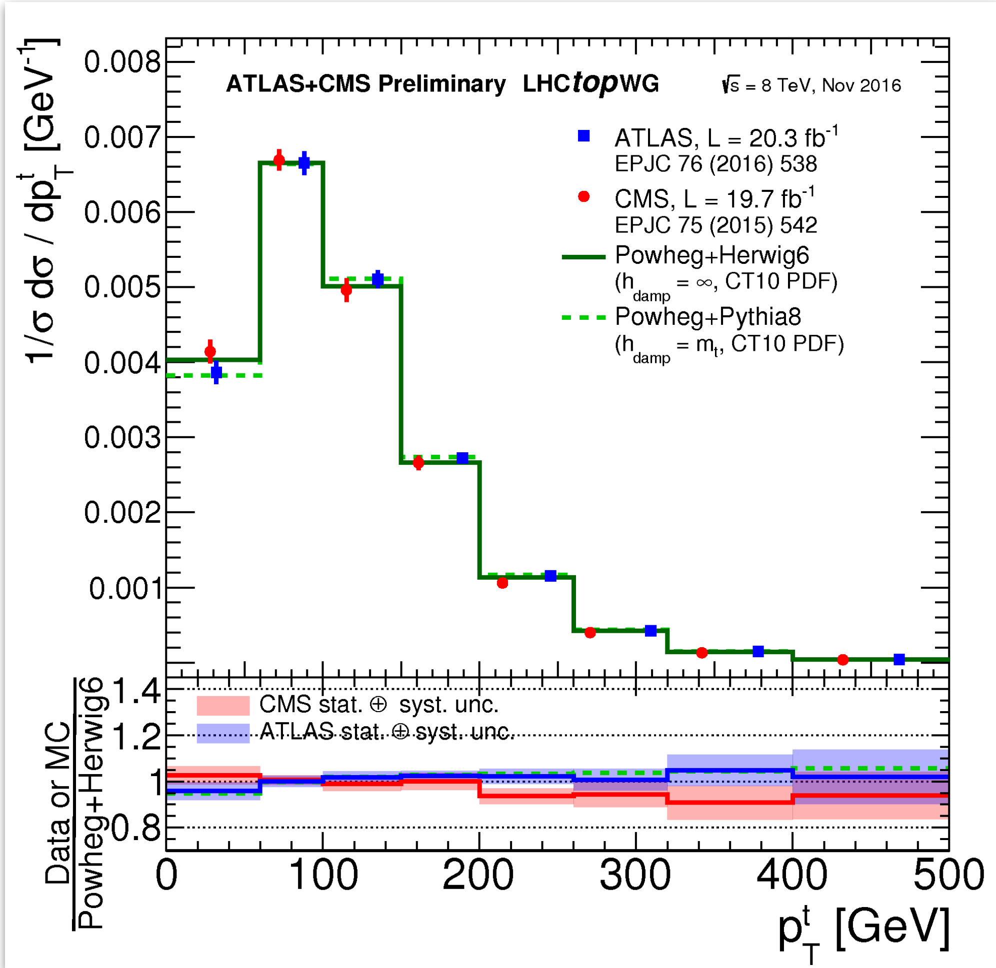
Thank you!

backups

Differential tt cross section at 8 TeV

Physics

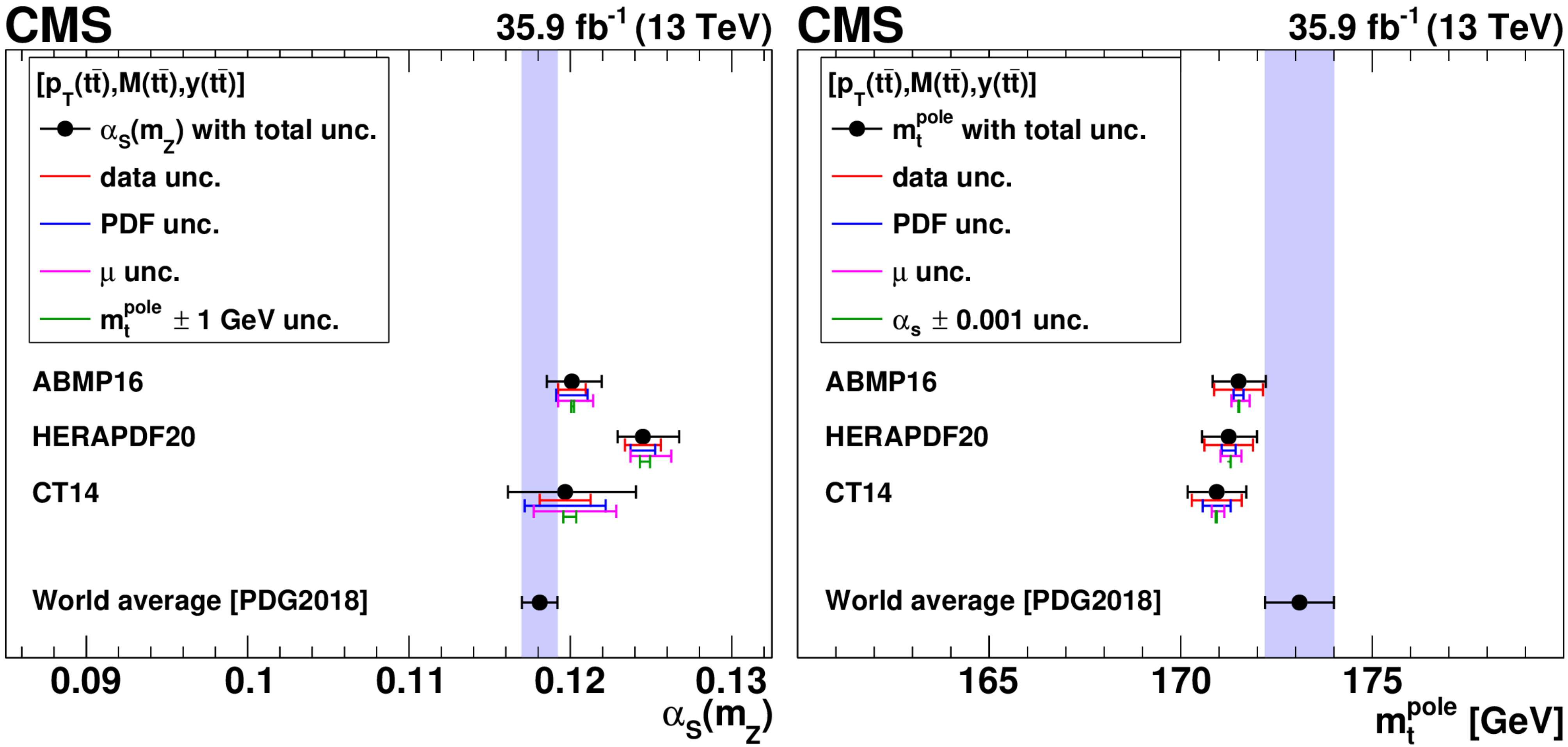




Improvements seen: use NNLO calculations or use Herwig 6

Alpha_s measurement from TOP-2018-004

Physics



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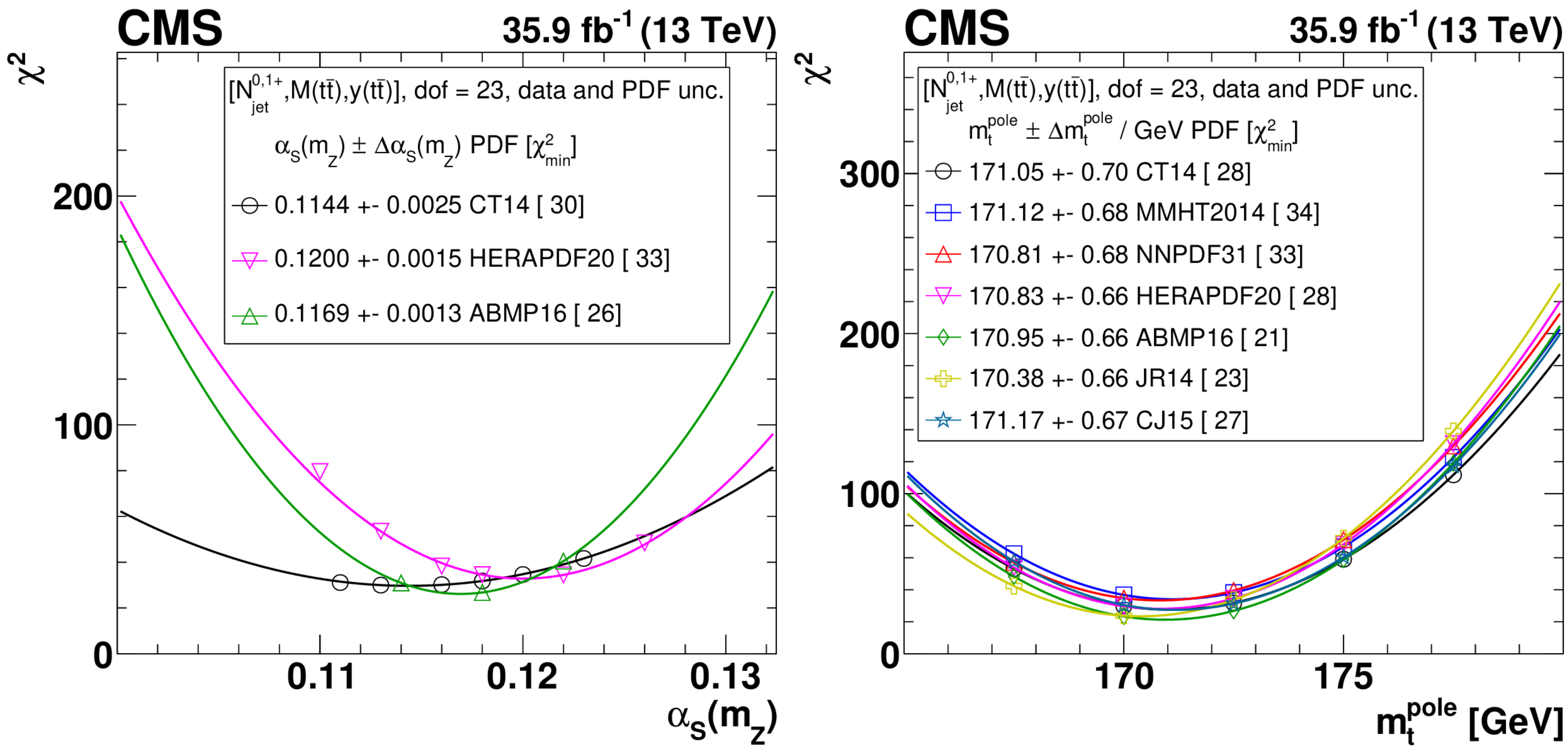
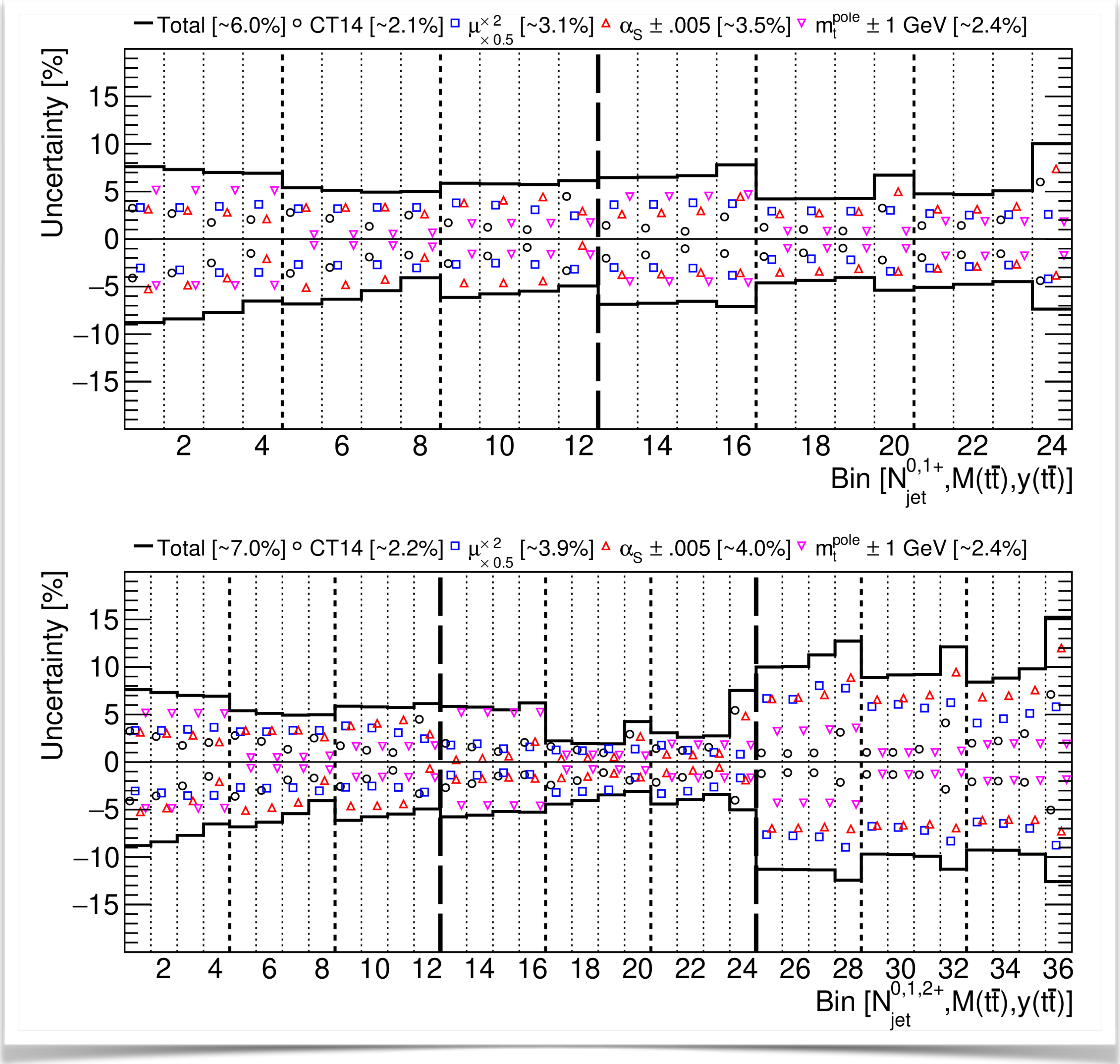
Measuring alphas/mtop

Physics



Theoretical uncertainties

Physics



TOP-18-004

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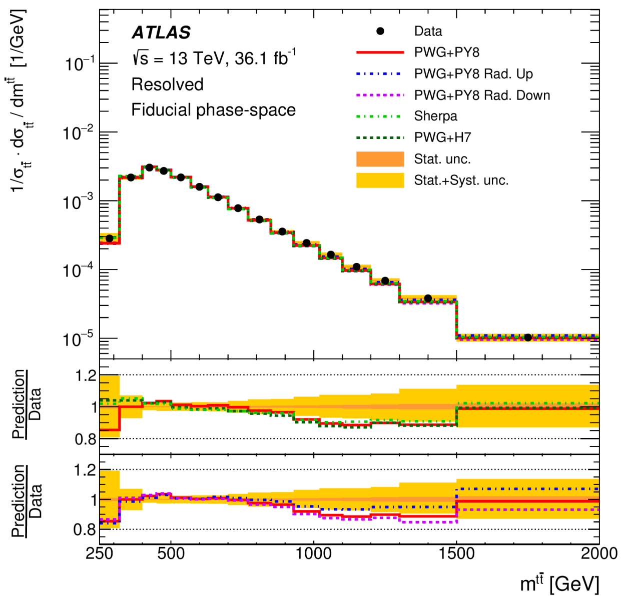
CHi2 tables for TOP-2018-006

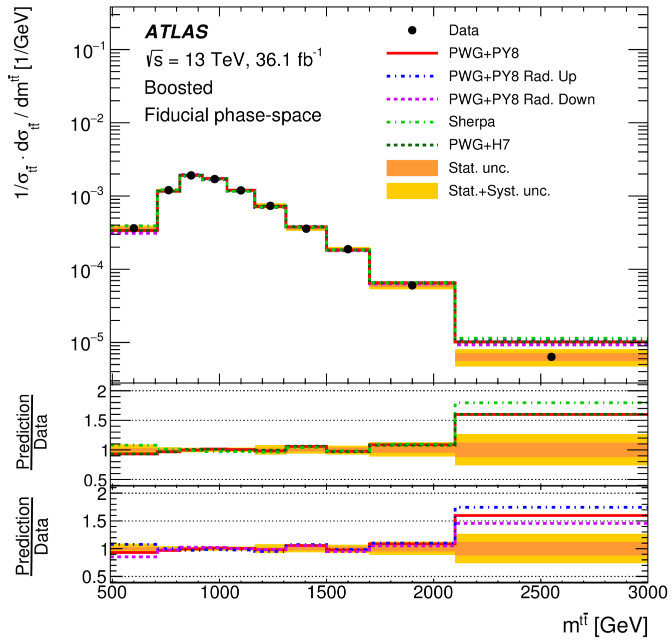
Physics

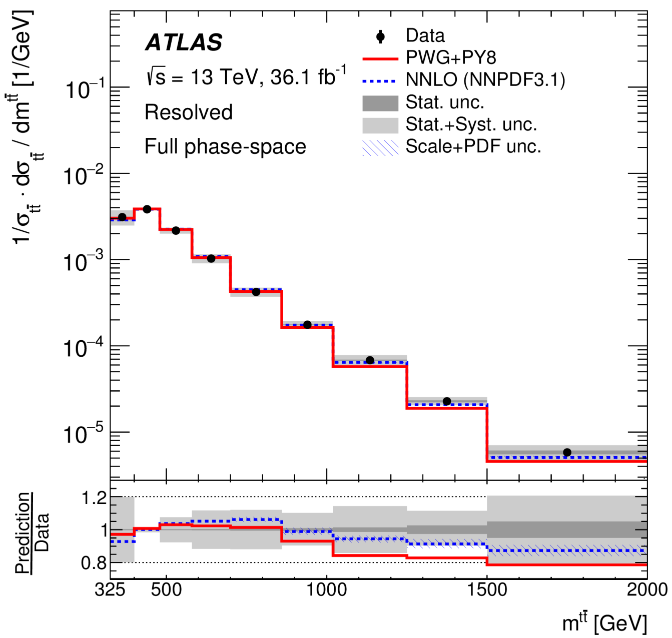
Observable	χ^2 between data and prediction (dof = 5)			
	POWHEG v2	MG5_aMC@NLO	NLO calculation	No SC/pol
$\cos\theta_1^k$	1.1	1.0	1.1	1.1
$\cos\theta_2^k$	5.2	5.0	5.2	5.2
$\cos\theta_1^r$	4.3	4.4	4.2	3.9
$\cos\theta_2^r$	0.7	0.5	0.6	0.5
$\cos\theta_1^n$	1.9	1.8	1.8	1.9
$\cos\theta_2^n$	3.2	3.1	2.1	3.1
$\cos\theta_1^{k*}$	1.3	1.3	1.4	1.3
$\cos\theta_2^{k*}$	1.8	1.6	1.7	1.8
$\cos\theta_1^{r*}$	1.5	1.5	1.6	1.6
$\cos\theta_2^{r*}$	0.5	0.6	0.6	0.6
$\cos\theta_1^k \cos\theta_2^k$	3.1	3.2	3.5	66.7
$\cos\theta_1^r \cos\theta_2^r$	2.0	1.7	1.1	7.4
$\cos\theta_1^n \cos\theta_2^n$	0.6	0.3	0.3	267.0
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	1.5	1.6	1.7	12.3
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	3.6	3.1	3.6	3.6
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	1.7	1.7	1.8	1.8
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	1.8	1.9	1.9	1.9
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	3.8	4.0	4.0	3.9
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	2.3	2.4	2.2	2.2
$\cos\varphi$	1.5	0.7	1.4	496.2
$\cos\varphi_{\mathrm{lab}}$	3.9	7.6	7.0	66.5
$\|\Delta\phi_{\ell\ell}\|$	10.8	4.0	9.2	190.4
All (dof = 110)	88.4	89.7	88.6	2119.8

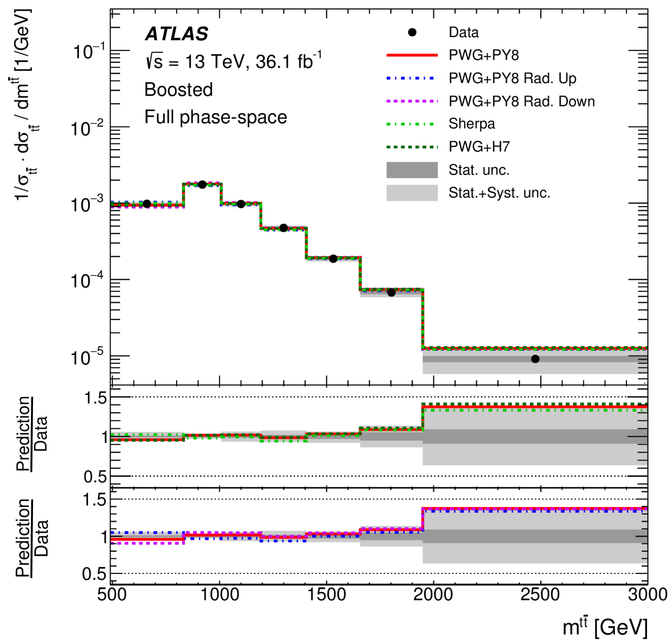
ATLAS L+jets: m(tt)

Physics









Chi2 tables for 1908.07305

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2018-15/#tables

Selection for 1908.07305

Physics

Selection	Detector level		Particle level
	$e + \text{jets}$	$\mu + \text{jets}$	
Leptons	One electron, no muons $\lvert d_0 \text{sign.}\rvert < 5$ $\lvert\Delta z_0 \sin\theta\rvert < 0.5\,\text{mm}$ Track and calorimeter isolation $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$ $E_{\text{T}} > 27\,GeV$	One muon, no electrons $\lvert d_0 \text{sign.}\rvert < 3$ $\lvert\Delta z_0 \sin\theta\rvert < 0.5\,\text{mm}$ and calorimeter isolation $\lvert\eta\rvert < 2.5$ $p_{\text{T}} > 27\,GeV$	One lepton (e/μ) $\lvert\eta\rvert < 2.5$ $p_{\text{T}} > 27\,GeV$
Anti-k_t $R = 0.4$ jets	$N^{\text{jets}} \geq 4$ $\lvert\eta\rvert < 2.5$ $p_{\text{T}} > 25\,GeV$ JVT cut (if $p_{\text{T}} < 60\,GeV$ and $\lvert\eta\rvert < 2.4$) b-tagging: ≥ 2 jets with MV2c10 at 70%		$N^{\text{jets}} \geq 4$ $\lvert\eta\rvert < 2.5$ $p_{\text{T}} > 25\,GeV$ b-tagging: Ghost-matched b-hadron
Overlap removal	If an electron shares a track with a muon: electron removed If $\Delta R(e, \text{jet}_{R=0.4}) < 0.2$: jet removed then If $\Delta R(e, \text{jet}_{R=0.4}) < 0.4$: e removed If $\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$ and $n^{\text{jet}}_{\text{tracks}} \geq 3$: μ removed If $\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$ and $n^{\text{jet}}_{\text{tracks}} < 3$: jet is removed		If $\Delta R(e, \text{jet}_{R=0.4}) < 0.4$: e removed If $\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$: μ removed
Top reconstruction quality	Remove events passing boosted selection. Parton level measurement: $\log L > -52$ for the best permutation from the kinematic fit		

Selection for 1908.07305

<table>
<tr><td>Selection</td><td colspan="2">Detector level</td><td>Particle level</td></tr>
<tr><td></td><td>$e+$jets</td><td>$\mu+$jets</td><td></td></tr>
<tr><td>Leptons</td><td>One electron, no muons
$|d_0\text{sign.}| < 5$
$|\Delta z_0 \sin\theta| < 0.5\,\text{mm}$
Track and calorimeter isolation
$|\eta| <1.37$ or $1.52 < |\eta| < 2.47$
$E_\text{T} > 27\,GeV$</td><td>One muon, no electrons
$|d_0\text{sign.}| < 3$
$|\Delta z_0 \sin\theta| < 0.5\,\text{mm}$ and calorimeter isolation
$|\eta| < 2.5$
$p_\text{T} > 27\,GeV$</td><td>One lepton
(e/μ)
$|\eta| < 2.5$
$p_\text{T} > 27\,GeV$</td></tr>
<tr><td>Reclustered $R{=}1.0$ jet</td><td colspan="3">$p_\text{T} > 350\,GeV$, $|\eta| < 2.0$</td></tr>
<tr><td>Anti-k_t $R = 0.4$ jets</td><td colspan="2">≥ 1 jet
$p_\text{T} > 25\,GeV$
$|\eta| < 2.5$
JVT cut (if $p_\text{T} < 60\,GeV$ and $|\eta| < 2.4$)
b-tagging: ≥ 1 jets with MV2c10 at 70%</td><td>≥ 1 jet
$|\eta| < 2.5$,
$p_\text{T} > 25\,GeV$
b-tagging:
Ghost-matched
b-hadron</td></tr>
<tr><td>Overlap removal</td><td colspan="2">If an electron shares a track with a muon: electron removed
If $\Delta R(e, \text{jet}_{R=0.4}) < 0.2$: jet removed
then
If $\Delta R(e, \text{jet}_{R=0.4}) < 0.4$: e removed
If $\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$ and $n^\text{jet}_\text{tracks} \geq 3$: μ removed
If $\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$ and $n^\text{jet}_\text{tracks} < 3$: jet is removed</td><td>If
$\Delta R(e, \text{jet}_{R=0.4}) < 0.4$:
e removed
If
$\Delta R(\mu, \text{jet}_{R=0.4}) < 0.4$:
μ removed</td></tr>
<tr><td>E_T^miss, m_T^W</td><td colspan="3">$E_\text{T}^\text{miss} > 20\,GeV$, $E_\text{T}^\text{miss} + m_\text{T}^W > 60\,GeV$</td></tr>
<tr><td>Hadronic top</td><td colspan="3">Top-tagging on the leading reclustered jet: $120\,\text{GeV} < m_\text{jet} < 220\,\text{GeV}$,
$|\Delta\phi(\ell, \text{jet}_{R=1.0})| > 1.0$</td></tr>
<tr><td>Leptonic top</td><td colspan="3">At least one anti-k_t $R = 0.4$ jet with $\Delta R(\ell, \text{jet}_{R=0.4}) < 2.0$,
$\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) > 1.5$</td></tr>
<tr><td>b-jets</td><td colspan="3">At least one of:
1. one of the anti-k_t $R = 0.4$ jet with $\Delta R(\ell, \text{jet}_{R=0.4}) < 2.0$ and $\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) > 1.5$ is b-tagged;
2. one of the anti-k_t $R = 0.4$ jet, component of the top-tagged reclustered jet, is b-tagged.</td></tr>
</table>

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Yields for 1908.07305

Physics

Process	Yield					
	Resolved			Boosted		
$t\bar{t}$	1 120 000	$\pm$	90 000	44 700	$\pm$	1900
Single top	54 000		${}^{+10\,000}_{-11\,000}$	2000	$\pm$	900
Multijet	34 000	$\pm$	16 000	1000	$\pm$	400
W+jets	34 000	$\pm$	20 000	3200	$\pm$	1500
Z+jets	12 000	$\pm$	6000	380	$\pm$	210
$t + X$	3800	$\pm$	500	440	$\pm$	60
Diboson	1680		${}^{+220}_{-190}$	194		${}^{+19}_{-21}$
Total prediction	1 260 000	$\pm$	100 000	52 000	$\pm$	2900
Data	1 252 692			47 600		
Data/Prediction	0.99	$\pm$	0.08	0.92	$\pm$	0.05

Observables in 1908.07305

Physics

- The out-of-plane momentum, i.e. the projection of the top-quark three-momentum onto the direction perpendicular to the plane defined by the other top quark and the beam axis (z) in the laboratory frame [107]:

$$p_{\text{out}}^{t,\text{had}} = \vec{p}^{\,t,\text{had}} \cdot \frac{\vec{p}^{\,t,\text{lep}} \times \vec{e}_z}{\left|\vec{p}^{\,t,\text{lep}} \times \vec{e}_z\right|},$$

$$p_{\text{out}}^{t,\text{lep}} = \vec{p}^{\,t,\text{lep}} \cdot \frac{\vec{p}^{\,t,\text{had}} \times \vec{e}_z}{\left|\vec{p}^{\,t,\text{had}} \times \vec{e}_z\right|}$$

  In particular, $|p_{\text{out}}^{t,\text{had}}|$, introduced in Ref. [11], is used in the resolved topology, while in the boosted topology, where an asymmetry between $p^{t,\text{had}}$ and $p^{t,\text{lep}}$ exists by construction, the variable $|p_{\text{out}}^{t,\text{lep}}|$ is measured. This reduces the correlation between p_{out} and $p^{t,\text{had}}$, biased toward high values by construction, while keeping the sensitivity to the momentum imbalance.

- The longitudinal boost of the $t\bar{t}$ system in the laboratory frame ($y_{\text{boost}}^{t\bar{t}}$) [108].
- $\chi^{t\bar{t}} = \mathrm{e}^{2|y^*|}$ [108], closely related to the production polar angle.
- The scalar sum of the transverse momenta of the hadronic and leptonic top quarks ($H_{\text{T}}^{t\bar{t}} = p_{\text{T}}^{t,\text{had}} + p_{\text{T}}^{t,\text{lep}}$) [109, 110].

ATLAS DIL

Physics

Component	2015 OS $1b$	2015 SS $1b$	2015 OS $2b$	2015 SS $2b$	2016 OS $1b$	2016 SS $1b$	2016 OS $2b$	2016 SS $2b$
$t \to e \to \gamma$ conversion e	59 ± 5	41 ± 4	33 ± 3	21 ± 3	594 ± 15	360 ± 11	336 ± 11	191 ± 9
Background conversion e	53 ± 6	35 ± 4	19 ± 3	15 ± 2	424 ± 15	227 ± 36	185 ± 8	116 ± 6
Heavy-flavour e	27 ± 3	26 ± 3	3 ± 1	2 ± 1	208 ± 8	188 ± 8	20 ± 3	11 ± 2
Other e	2 ± 2	0 ± 0	1 ± 1	0 ± 0	48 ± 9	5 ± 1	19 ± 3	2 ± 1
Heavy-flavour μ	50 ± 5	46 ± 5	8 ± 2	2 ± 1	434 ± 14	335 ± 12	79 ± 6	27 ± 4
Other μ	11 ± 2	2 ± 1	4 ± 1	0 ± 0	54 ± 29	151 ± 126	46 ± 4	11 ± 2
Total misidentified	201 ± 10	149 ± 8	69 ± 5	40 ± 4	1761 ± 41	1266 ± 132	684 ± 16	358 ± 12
Wrong-sign prompt	-	24 ± 3	-	12 ± 2	-	224 ± 9	-	113 ± 6
Right-sign prompt	-	21 ± 1	-	9 ± 0	-	195 ± 4	-	88 ± 1
Total	-	194 ± 9	-	61 ± 4	-	1685 ± 132	-	560 ± 13
Data	-	167	-	55	-	1655	-	551

breakdown of misidentified leptons

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Chi2 tables for ATLAS DIL

Physics

Generator	p_T^ℓ	$\lvert\eta^\ell\rvert$	$p_T^{e\mu}$	$m^{e\mu}$	$\lvert y^{e\mu}\rvert$	$\Delta\phi^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
N_{dof}	10	8	8	11	8	9	7	9
Powheg + PY8	43.7	19.5	8.6	44.3	11.4	14.4	32.5	18.4
Powheg + PY6 CT10	36.1	7.9	9.3	33.0	16.2	16.2	21.9	30.5
Powheg + HW7	34.8	15.9	11.5	62.7	9.4	17.3	23.0	14.7
Powheg + PY8 p_T rew.	20.2	14.7	2.3	38.3	8.4	12.7	9.4	14.0
Powheg + PY8 RadDn	40.0	24.2	6.1	44.3	9.2	16.3	29.0	20.1
Powheg + PY8 RadUp	33.0	16.3	21.9	35.3	12.3	6.4	26.7	16.5
Powheg + PY8 $\mu_{F,R} \times 2$	46.5	21.6	6.2	42.6	8.5	16.5	28.9	17.1
Powheg + PY8 $\mu_{F,R} \times 0.5$	39.8	17.3	11.4	38.0	10.7	10.9	27.6	14.2
Powheg + PY8 PDF4LHC15	43.4	14.6	7.4	39.0	6.2	13.5	28.0	15.9
Powheg + PY8 CT14	44.1	9.3	7.6	37.0	8.2	13.5	28.5	18.2
Powheg + PY8 MMHT	41.2	17.7	6.9	39.0	6.3	13.2	26.3	14.3
aMC@NLO + PY8	26.2	25.7	11.4	19.7	16.7	13.2	12.5	14.0
aMC@NLO + PY8 CT10	24.9	11.7	10.6	16.9	10.0	13.4	12.0	19.0
aMC@NLO + PY8 HERA2	17.1	96.6	6.9	26.0	68.5	12.5	6.1	38.4
Powheg + PY8	$4 \cdot 10^{-6}$	0.012	0.37	$6 \cdot 10^{-6}$	0.18	0.11	$3 \cdot 10^{-5}$	0.030
Powheg + PY6 CT10	$8 \cdot 10^{-5}$	0.45	0.32	$5 \cdot 10^{-4}$	0.039	0.062	$3 \cdot 10^{-3}$	$4 \cdot 10^{-4}$
Powheg + HW7	$1 \cdot 10^{-4}$	0.043	0.18	$3 \cdot 10^{-9}$	0.31	0.045	$2 \cdot 10^{-3}$	0.098
Powheg + PY8 p_T rew.	0.028	0.065	0.97	$7 \cdot 10^{-5}$	0.39	0.18	0.23	0.12
Powheg + PY8 RadDn	$2 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	0.64	$6 \cdot 10^{-6}$	0.32	0.060	$1 \cdot 10^{-4}$	0.017
Powheg + PY8 RadUp	$3 \cdot 10^{-4}$	0.038	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	0.14	0.70	$4 \cdot 10^{-4}$	0.057
Powheg + PY8 $\mu_{F,R} \times 2$	$1 \cdot 10^{-6}$	$6 \cdot 10^{-3}$	0.62	$1 \cdot 10^{-5}$	0.39	0.056	$1 \cdot 10^{-4}$	0.048
Powheg + PY8 $\mu_{F,R} \times 0.5$	$2 \cdot 10^{-5}$	0.027	0.18	$8 \cdot 10^{-5}$	0.22	0.28	$3 \cdot 10^{-4}$	0.12
Powheg + PY8 PDF4LHC15	$4 \cdot 10^{-6}$	0.067	0.49	$5 \cdot 10^{-5}$	0.62	0.14	$2 \cdot 10^{-4}$	0.068
Powheg + PY8 CT14	$3 \cdot 10^{-6}$	0.32	0.47	$1 \cdot 10^{-4}$	0.42	0.14	$2 \cdot 10^{-4}$	0.033
Powheg + PY8 MMHT	$1 \cdot 10^{-5}$	0.024	0.55	$5 \cdot 10^{-5}$	0.62	0.15	$5 \cdot 10^{-4}$	0.11
aMC@NLO + PY8	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	0.18	0.049	0.034	0.15	0.086	0.12
aMC@NLO + PY8 CT10	$5 \cdot 10^{-3}$	0.16	0.23	0.11	0.27	0.15	0.10	0.025
aMC@NLO + PY8 HERA2	0.073	0	0.54	$6 \cdot 10^{-3}$	0	0.19	0.53	$1 \cdot 10^{-5}$

Chi2 tables for ATLAS DIL

Generator	$\lvert\eta^{\ell}\rvert \times m^{e\mu}$	$\lvert y^{e\mu}\rvert \times m^{e\mu}$	$\lvert\Delta\phi^{\ell}\rvert \times m^{e\mu}$
N_{dof}	35	19	39
Powheg + PY8	53.1	72.3	65.4
Powheg + PY6 CT10	45.9	92.9	79.5
Powheg + HW7	49.3	67.4	63.7
Powheg + PY8 p_{T} rew.	47.1	56.1	51.4
Powheg + PY8 RadDn	57.1	74.2	69.9
Powheg + PY8 RadUp	50.6	62.5	51.7
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 2$	60.7	68.4	71.1
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 0.5$	50.3	60.0	52.0
Powheg + PY8 PDF4LHC15	51.5	61.5	59.7
Powheg + PY8 CT14	50.6	67.3	60.0
Powheg + PY8 MMHT	53.7	57.9	58.7
aMC@NLO + PY8	55.0	45.9	58.2
aMC@NLO + PY8 CT10	43.7	50.6	59.5
aMC@NLO + PY8 HERA2	130.3	97.6	58.0
Powheg + PY8	0.026	$4 \cdot 10^{-8}$	$5 \cdot 10^{-3}$
Powheg + PY6 CT10	0.10	0	$1 \cdot 10^{-4}$
Powheg + HW7	0.055	$2 \cdot 10^{-7}$	$8 \cdot 10^{-3}$
Powheg + PY8 p_{T} rew.	0.084	$2 \cdot 10^{-5}$	0.088
Powheg + PY8 RadDn	0.011	$2 \cdot 10^{-8}$	$2 \cdot 10^{-3}$
Powheg + PY8 RadUp	0.042	$2 \cdot 10^{-6}$	0.083
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 2$	$5 \cdot 10^{-3}$	$2 \cdot 10^{-7}$	$1 \cdot 10^{-3}$
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 0.5$	0.045	$4 \cdot 10^{-6}$	0.079
Powheg + PY8 PDF4LHC15	0.036	$2 \cdot 10^{-6}$	0.018
Powheg + PY8 CT14	0.042	$3 \cdot 10^{-7}$	0.017
Powheg + PY8 MMHT	0.023	$8 \cdot 10^{-6}$	0.022
aMC@NLO + PY8	0.017	$5 \cdot 10^{-4}$	0.024
aMC@NLO + PY8 CT10	0.15	$1 \cdot 10^{-4}$	0.019
aMC@NLO + PY8 HERA2	0	0	0.026

Chi2 tables for ATLAS DIL

Generator	p_{T}^{ℓ}, $p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}$	$p_{\mathrm{T}}^{e\mu}$, $m^{e\mu}$, $p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}$	$\lvert\eta^{\ell}\rvert$, $\lvert y^{e\mu}\rvert$	$\lvert\eta^{\ell}\rvert$, $\lvert y^{e\mu}\rvert$, $E^{e}+E^{\mu}$	All 8 dists.
N_{dof}	17	26	16	25	70
Powheg + PY8	52.2	92.8	31.2	51.5	176.5
Powheg + PY6 CT10	42.9	87.9	31.0	58.0	176.6
Powheg + HW7	42.5	97.4	25.7	41.6	169.8
Powheg + PY8 p_{T} rew.	27.5	57.4	25.4	36.5	137.6
Powheg + PY8 RadDn	49.7	110.8	37.8	58.3	193.9
Powheg + PY8 RadUp	42.9	71.8	25.5	44.2	151.8
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 2$	54.5	111.1	35.6	54.4	195.0
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 0.5$	50.5	71.3	26.3	42.8	160.4
Powheg + PY8 PDF4LHC15	52.2	89.7	26.7	44.1	167.1
Powheg + PY8 CT14	52.9	91.5	26.6	44.8	170.2
Powheg + PY8 MMHT	49.9	89.4	28.7	44.8	167.6
aMC@NLO + PY8	33.2	46.3	37.1	49.6	131.9
aMC@NLO + PY8 CT10	31.6	46.7	26.2	43.0	122.9
aMC@NLO + PY8 HERA2	23.1	51.5	119.0	132.8	229.8

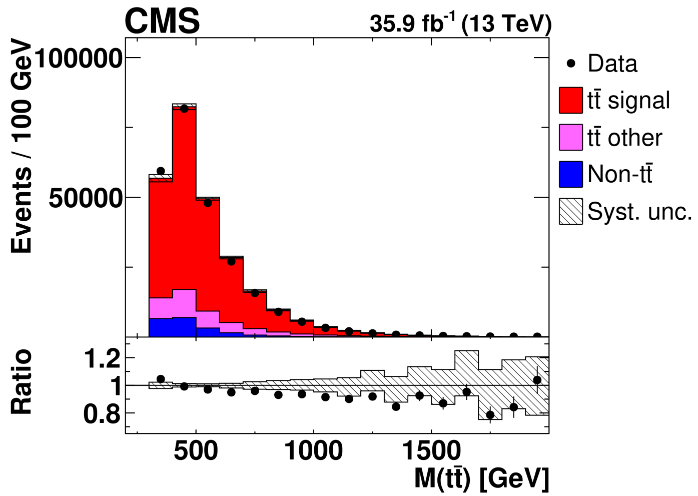
Generator	p_{T}^{ℓ}, $p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}$	$p_{\mathrm{T}}^{e\mu}$, $m^{e\mu}$, $p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}$	$\lvert\eta^{\ell}\rvert$, $\lvert y^{e\mu}\rvert$	$\lvert\eta^{\ell}\rvert$, $\lvert y^{e\mu}\rvert$, $E^{e}+E^{\mu}$	All 8 dists.
Powheg + PY8	$2\cdot10^{-5}$	$2\cdot10^{-9}$	0.013	$1\cdot10^{-3}$	0
Powheg + PY6 CT10	$5\cdot10^{-4}$	$1\cdot10^{-8}$	0.014	$2\cdot10^{-4}$	0
Powheg + HW7	$6\cdot10^{-4}$	$3\cdot10^{-10}$	0.058	0.020	$3\cdot10^{-10}$
Powheg + PY8 p_{T} rew.	0.052	$4\cdot10^{-4}$	0.062	0.064	$3\cdot10^{-6}$
Powheg + PY8 RadDn	$5\cdot10^{-5}$	0	$2\cdot10^{-3}$	$2\cdot10^{-4}$	0
Powheg + PY8 RadUp	$5\cdot10^{-4}$	$4\cdot10^{-6}$	0.062	0.010	$6\cdot10^{-8}$
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 2$	$8\cdot10^{-6}$	0	$3\cdot10^{-3}$	$6\cdot10^{-4}$	0
Powheg + PY8 $\mu_{\mathrm{F,R}} \times 0.5$	$4\cdot10^{-5}$	$4\cdot10^{-6}$	0.049	0.015	$5\cdot10^{-9}$
Powheg + PY8 PDF4LHC15	$2\cdot10^{-5}$	$6\cdot10^{-9}$	0.045	0.011	$7\cdot10^{-10}$
Powheg + PY8 CT14	$2\cdot10^{-5}$	$3\cdot10^{-9}$	0.046	$9\cdot10^{-3}$	$3\cdot10^{-10}$
Powheg + PY8 MMHT	$4\cdot10^{-5}$	$7\cdot10^{-9}$	0.026	$9\cdot10^{-3}$	$6\cdot10^{-10}$
aMC@NLO + PY8	0.011	$9\cdot10^{-3}$	$2\cdot10^{-3}$	$2\cdot10^{-3}$	$1\cdot10^{-5}$
aMC@NLO + PY8 CT10	0.017	$8\cdot10^{-3}$	0.051	0.014	$1\cdot10^{-4}$
aMC@NLO + PY8 HERA2	0.14	$2\cdot10^{-3}$	0	0	0

Loose kinematic reconstruction

Physics

The $M(\mathrm{t\bar{t}})$ value obtained using the full kinematic reconstruction described above is highly sensitive to the value of the top quark mass used as a kinematic constraint. Since one of the objectives of this analysis is to extract the top quark mass from the differential $\mathrm{t\bar{t}}$ measurements, exploiting the $M(\mathrm{t\bar{t}})$ distribution in particular, an alternative algorithm is employed, which reconstructs the $\mathrm{t\bar{t}}$ kinematic variables without using the top quark mass constraint. This algorithm is referred to as the “loose kinematic reconstruction”. In this algorithm, the $\nu\bar{\nu}$ system is reconstructed rather than the ν and $\bar{\nu}$ separately. Consequently, it can only be used to reconstruct the total $\mathrm{t\bar{t}}$ system but not the top quark and antiquark separately. As in the full kinematic reconstruction, all possible lepton-jet combinations in the event that satisfy the requirement on the invariant mass of the lepton and jet $M_{\ell\mathrm{b}} < 180\,\mathrm{GeV}$ are considered. Combinations are ranked based on the presence of b-tagged jets in the assignments, but among combinations with equal number of b-tagged jets, the ones with the highest-p_T jets are chosen. The kinematic variables of the $\nu\bar{\nu}$ system are derived as follows: its $\vec{p}_\mathrm{T}$ is set equal to $\vec{p}_\mathrm{T}^{\,\mathrm{miss}}$, while its unknown longitudinal momentum and energy are set equal to the longitudinal momentum and energy of the lepton pair. Additional constraints are applied on the invariant mass of the neutrino pair, $M(\nu\bar{\nu}) \geq 0$, and on the invariant mass of the W bosons, $M(\mathrm{W^+W^-}) \geq 2M_\mathrm{W}$, which have only minor effects on the performance of the reconstruction. The method yields similar $\mathrm{t\bar{t}}$ kinematic resolutions and reconstruction efficiency as for the full kinematic reconstruction. In this analysis, the loose kinematic reconstruction is exclusively used to measure triple-differential cross sections as a function of $M(\mathrm{t\bar{t}})$, $y(\mathrm{t\bar{t}})$, and extra jet multiplicity, which are exploited to determine QCD parameters, as well as the distributions used to cross-check the results. Figure 2 shows the distributions of the reconstructed $\mathrm{t\bar{t}}$ invariant mass and rapidity using the loose kinematic reconstruction. These distributions are similar to the ones obtained using the full kinematic reconstruction (as shown in Fig. 1).

Default kinematic reconstruction



Loose kinematic reconstruction