Founders building
of Royal Holloway University of London

Chateau de Chambord

Differential tt cross-section measurements on ATLAS

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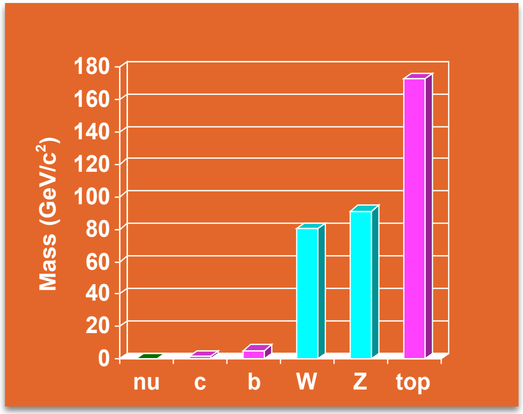
ATLAS EXPERIMENT

Rencontres de Blois 2017

Going differential!

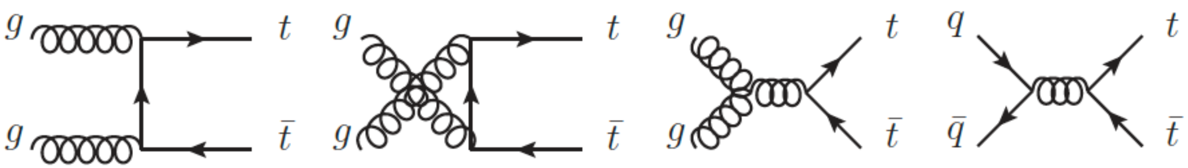
- LHC is a top quark factory: at 13 TeV about 2 tops every second!
  - plenty of statistics to make precision measurements
- Studying top production is crucial to the LHC programme:
  - Detailed measurements of QCD, EWK
  - Probe couplings to Higgs, W, Z, γ
  - 3rd generation models within BSM
  - Significant background to searches and Higgs



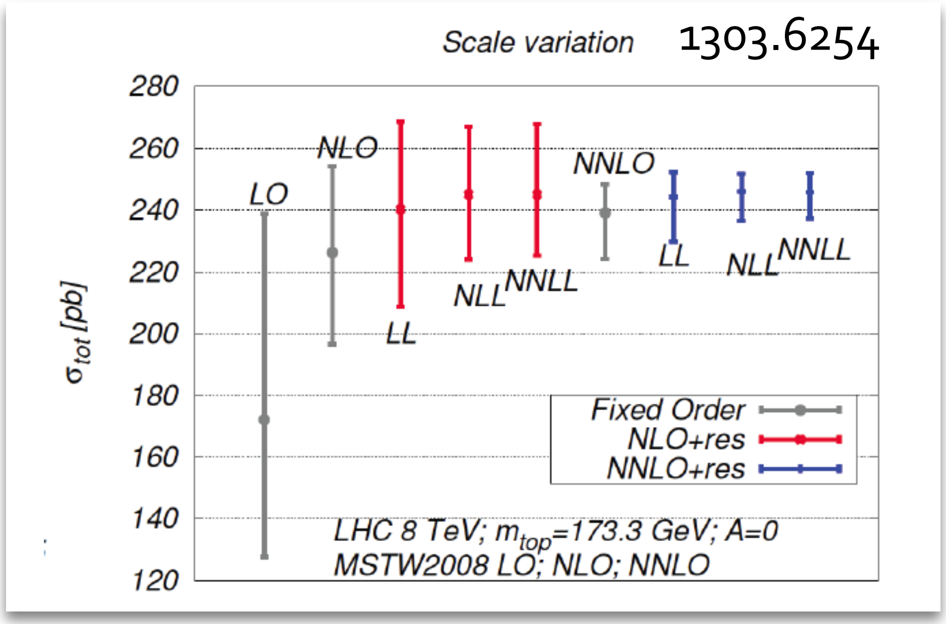
- Looking at differential distributions of tt production also allows to…
  - be sensitive to new physics that would not modify the inclusive tt cross-section
    - including in a model-independent way with Effective Field Theory
  - stringent test of NNLO QCD calculations
  - improves the simulation to tt production: PDF, MC tuning, etc.

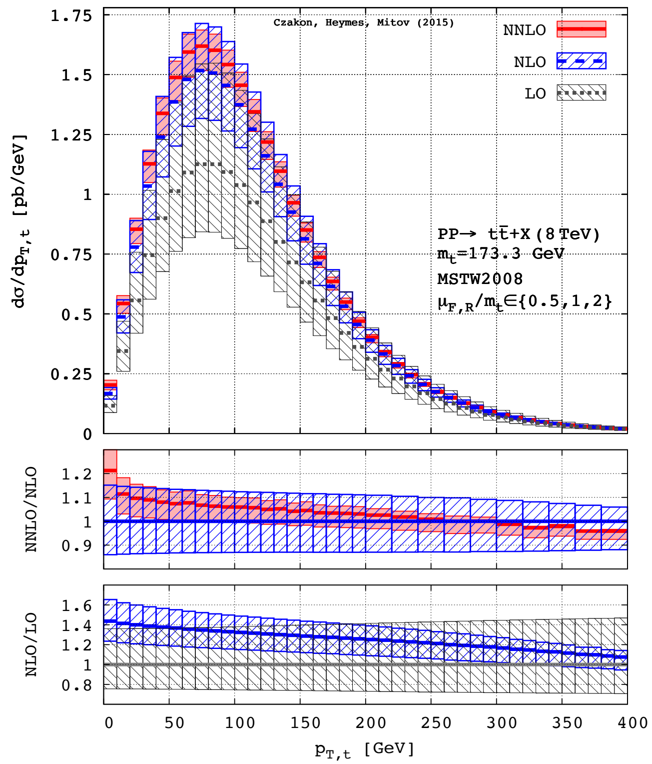
Top anti-top quark production

Physics



M. Czakon, D. Heymes and A. Mitov, *High-precision differential predictions for top-quark pairs at the LHC*, Phys. Rev. Lett. **116** (2016) 082003, arXiv: 1511.00549 [hep-ph].



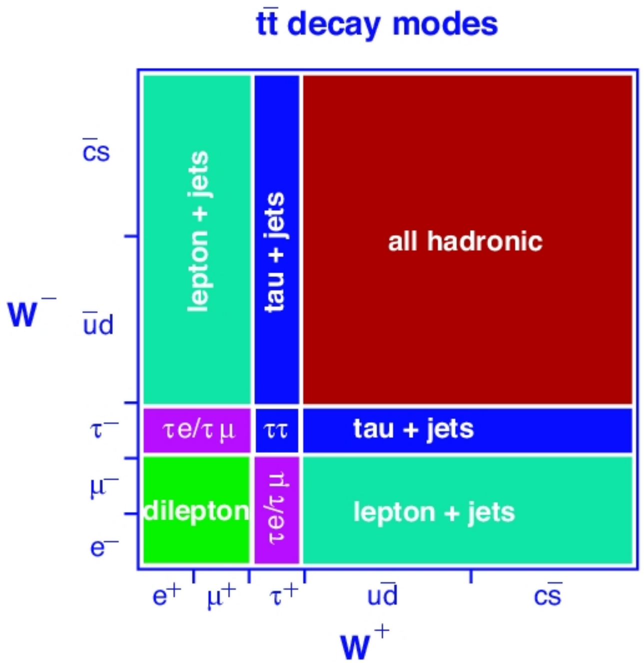


NNLO+NNLL 1303.6254

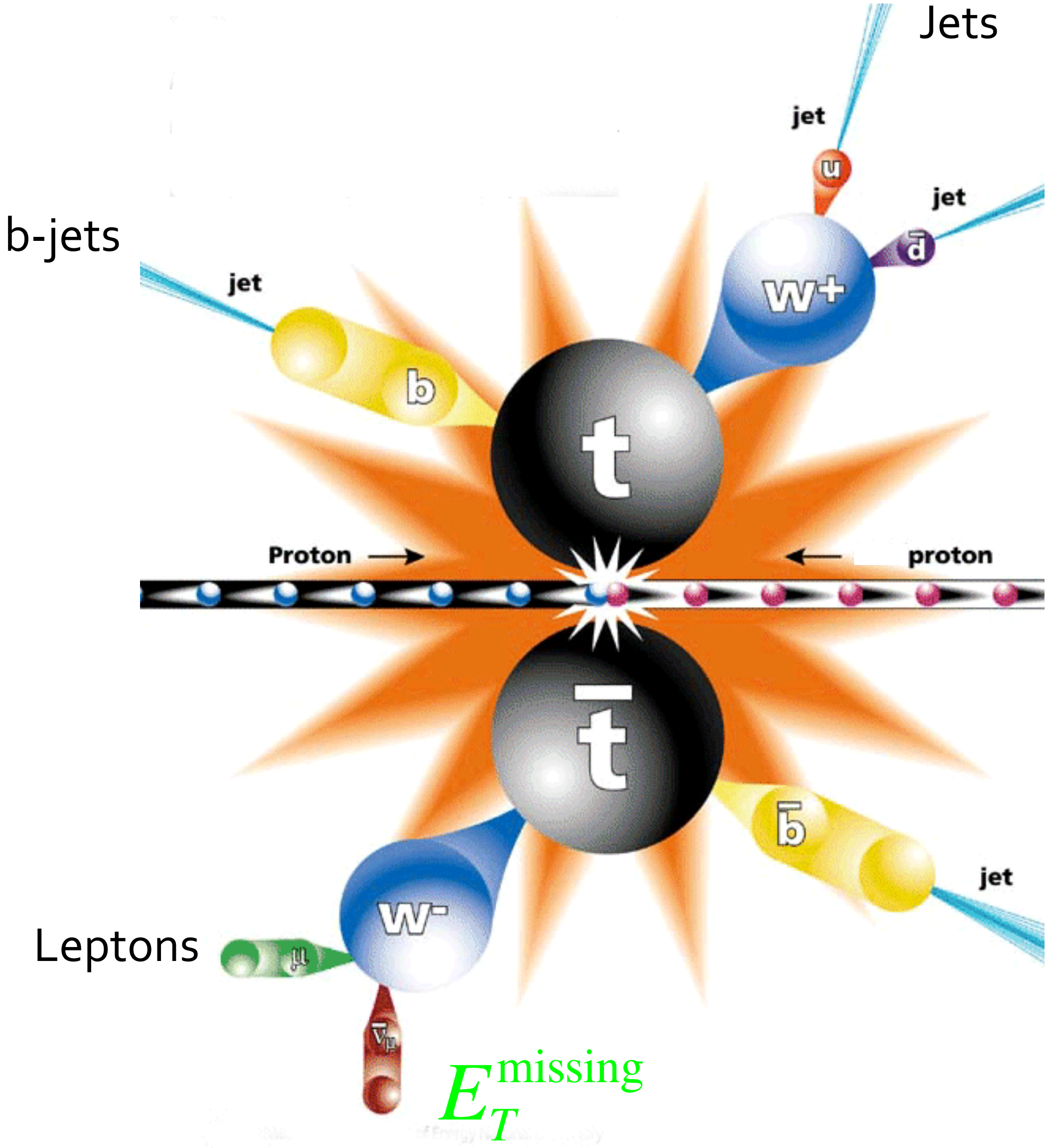
	x	qq vs gg	cross section	± scales	± pdf
Tev 1.96 TeV	0.18	90% vs 10%	7.164 pb	~2%	~2%
LHC 7 TeV	0.048	15% vs 85%	172.0 pb	~3%	~3%
LHC 8 TeV	0.043	12% vs 88%	245.8 pb	~3%	~2.5%
LHC 14 TeV	0.025	10% vs 90%	953.6 pb	~3%	~2%

m_t=173.3 GeV, MSTW2008nnlo68cl

How the top quark decays



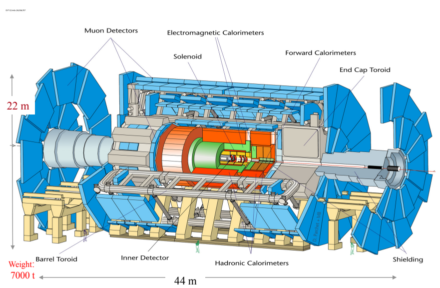
(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

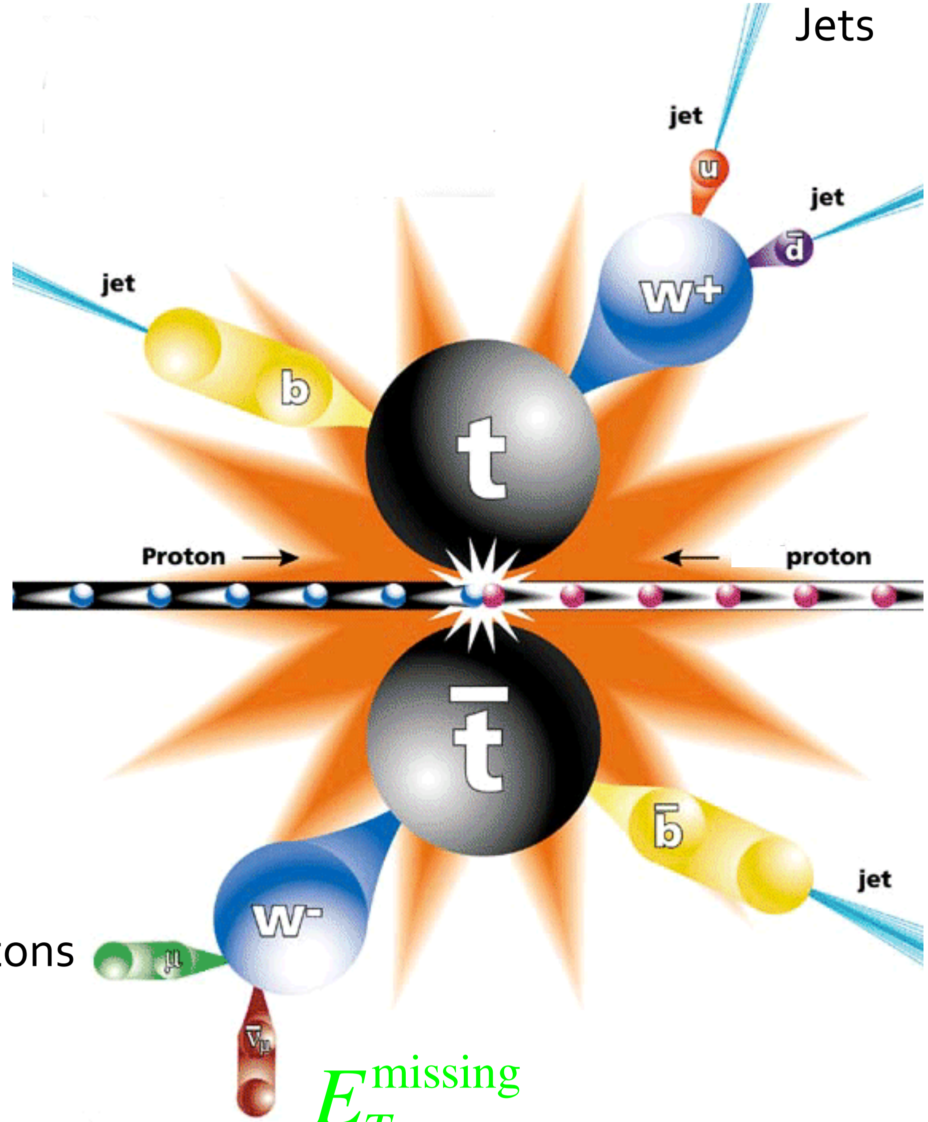


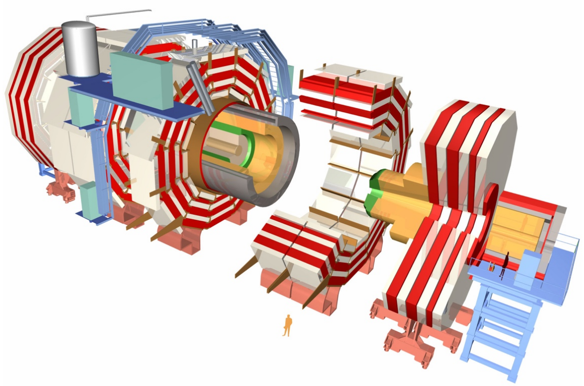
From experiment…

Jets

b-jets



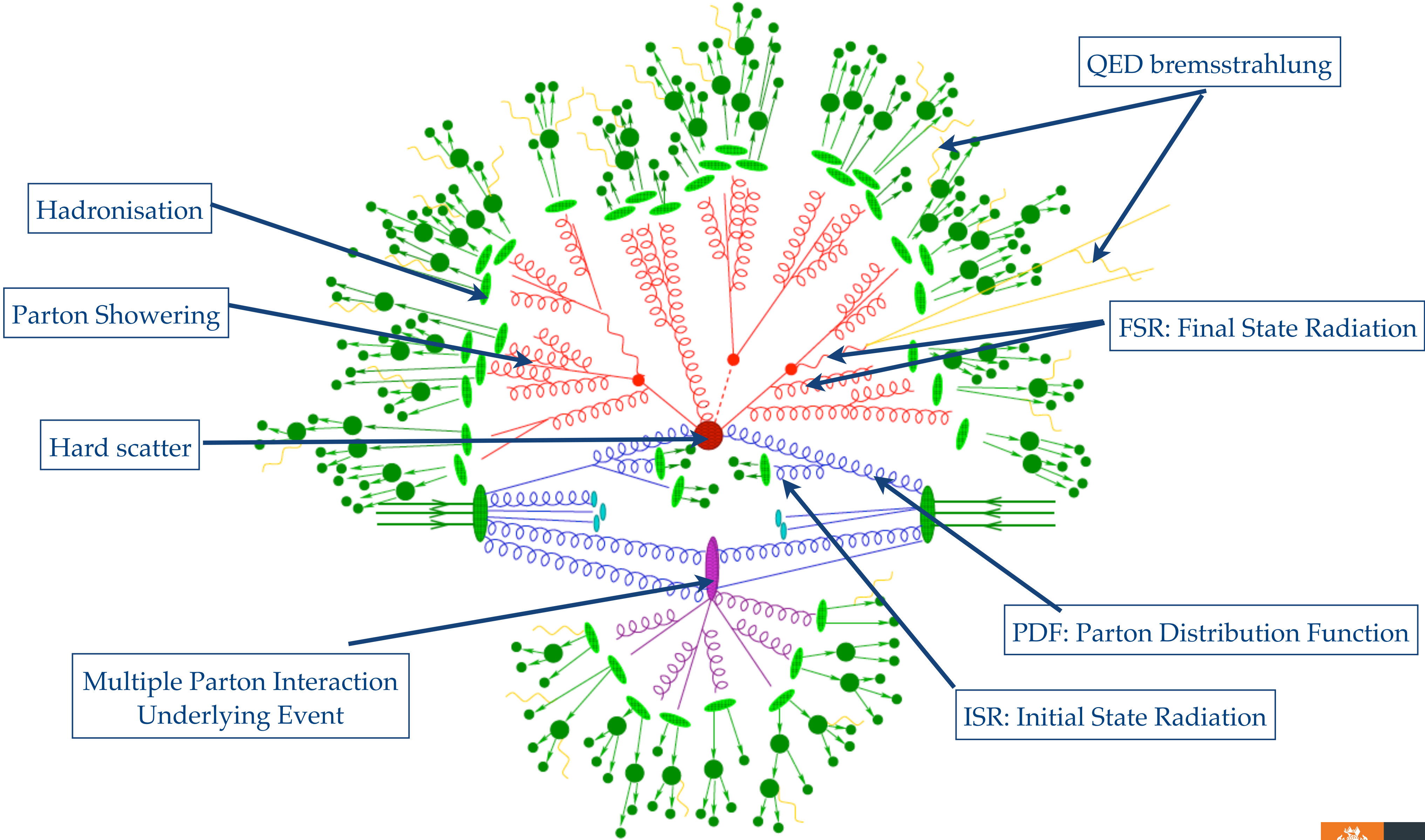




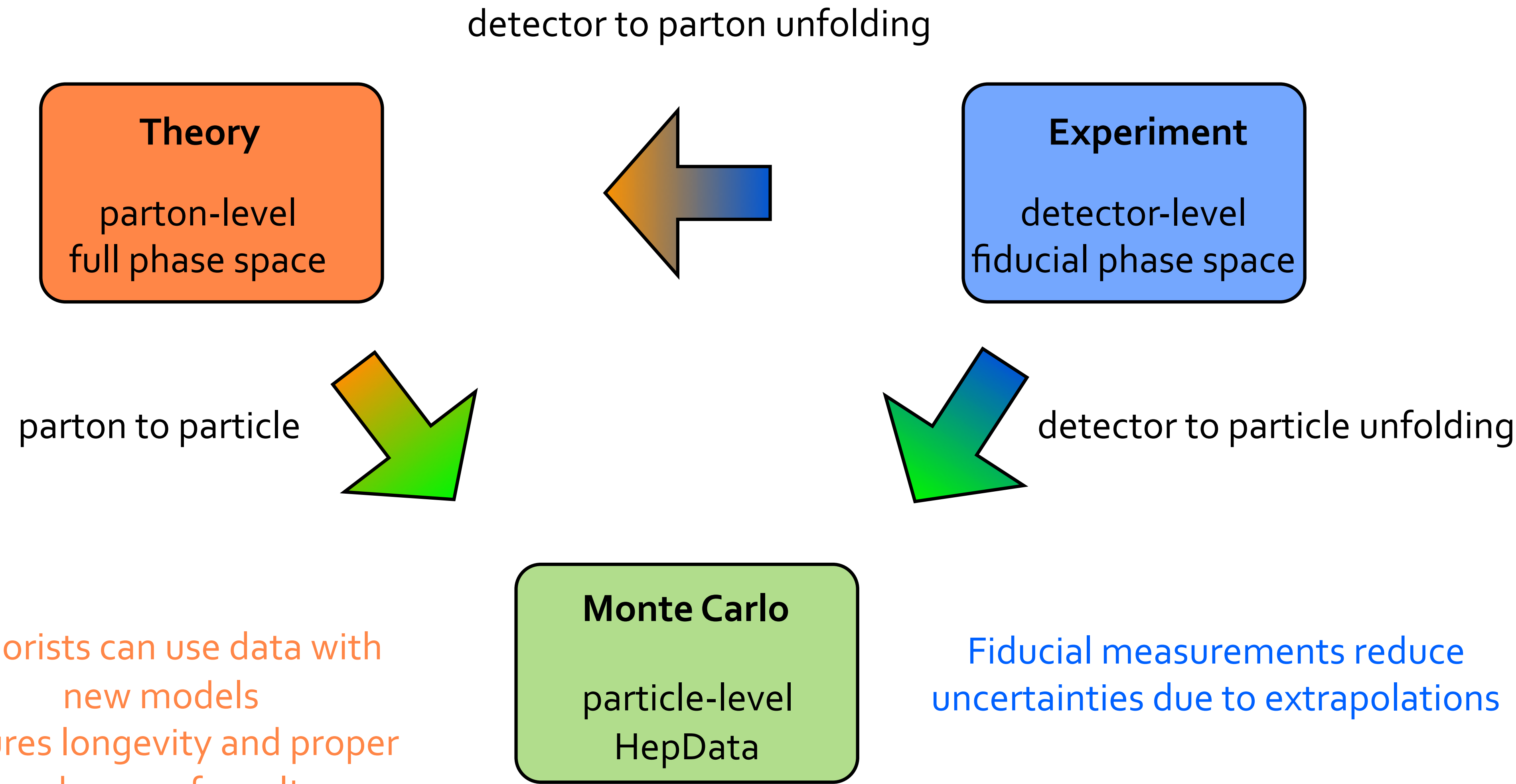
Leptons

E_T^{missing}

... to theory...


QED bremsstrahlung
Hadronisation
Parton Showering
FSR: Final State Radiation
Hard scatter
PDF: Parton Distribution Function
Multiple Parton Interaction
Underlying Event
ISR: Initial State Radiation

… connecting the two:



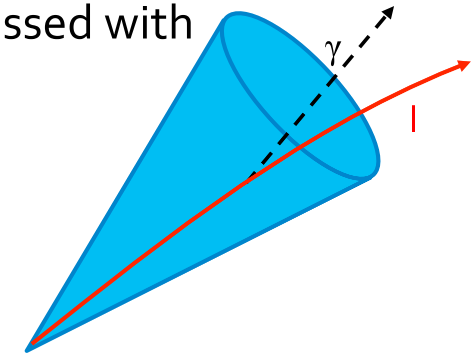
Theorists can use data with new models
Ensures longevity and proper exchange of results
Rivet routines

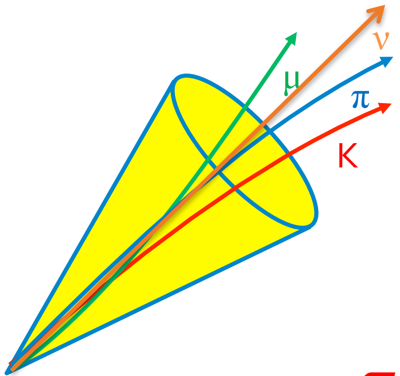
Fiducial measurements reduce uncertainties due to extrapolations

Particle-level objects

ATLAS and CMS differ in detailed definitions

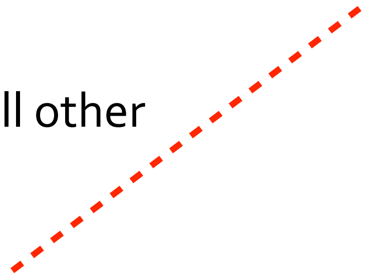
Charged leptons (not from hadrons) are dressed with the energy from nearby photons

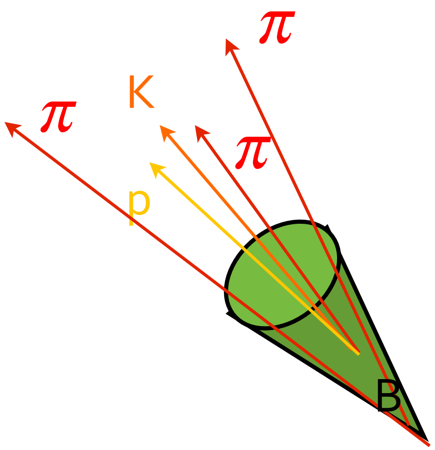




Jets are clustered from stable MC particles using anti-kt algorithm

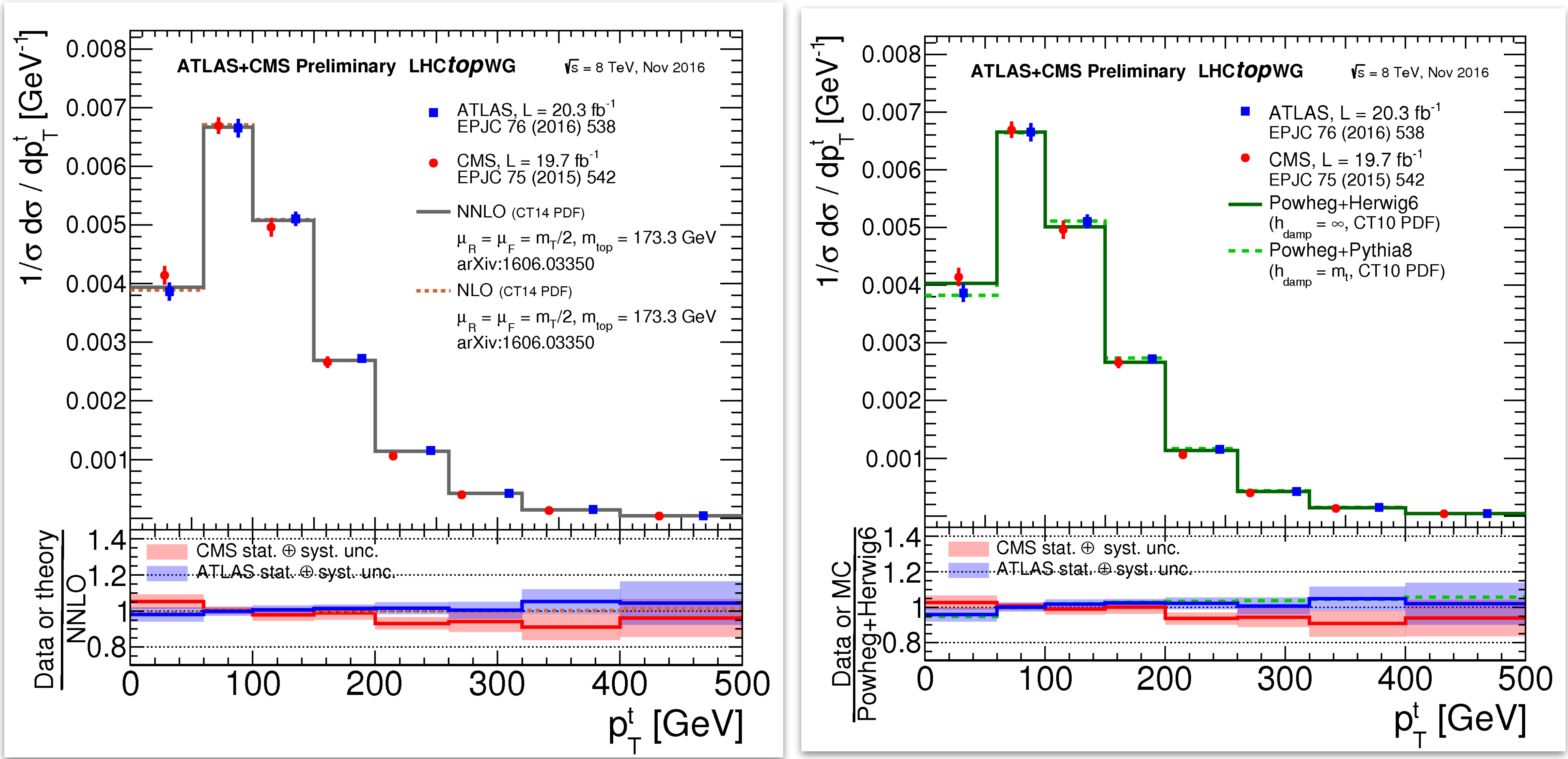
ETMiss calculated from the sum of all other neutrinos





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

Differential tt cross section at 8 TeV



Improvements seen: use NNLO calculations or use Herwig 6

Differential tt σ at 13 TeV: dilepton channel

Physics

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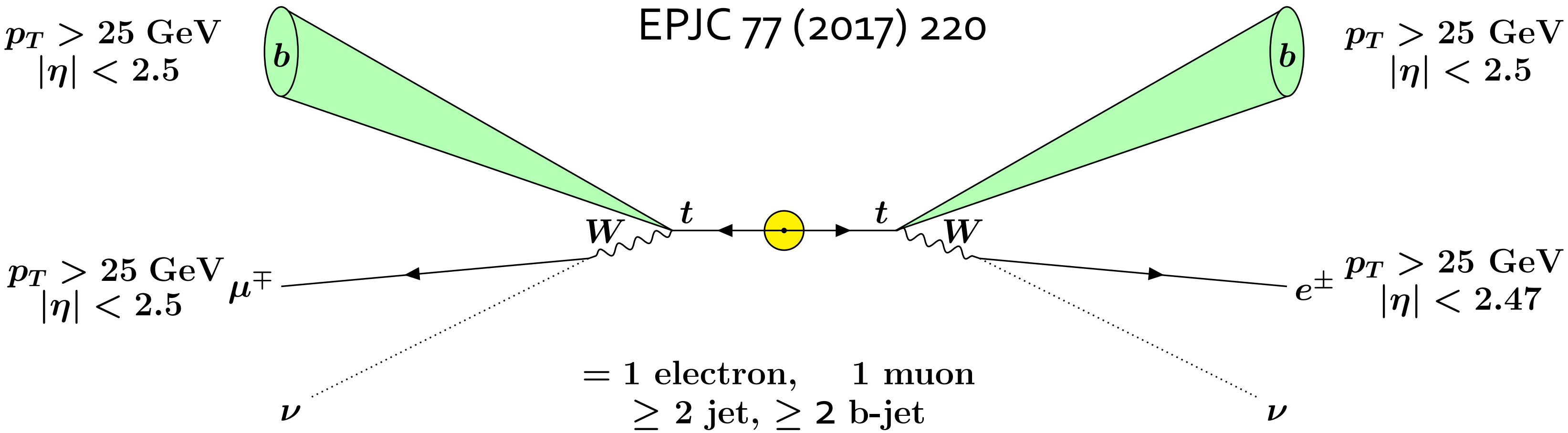

No Top reconstruction
unfolding done to particle-level in a fiducial volume

Process	Yield
Single top (Wt)	236 ±2 (stat.) ±46 (syst.)
Fake leptons	117 ±22 (stat.) ±120 (syst.)
Z+jets	6 ±3 (stat.) ±1 (syst.)
Dibosons	3.1 ±0.4 (stat.) ±1.5 (syst.)
Total background	362 ±22 (stat.) ±130 (syst.)
tt ($\geq$ 1 pile-up jet	310 ±2 (stat.) ±88 (syst.)
tt (no pile-up jets)	6850 ±11 (stat.) ±940 (syst.)
Expected	7520 ±25 (stat.) ±950 (syst.)
Observed	8050

Relative uncertainty in [%] in additional jets multiplicity					
Sources	0	1	2	3	$\geq$ 4
Data statistics	2.1	2.7	4.0	6.0	9.0
JES/JER	5.0	1.8	7.0	12.0	16.0
b-tagging	0.5	0.2	0.7	1.4	2.0
ISR/FSR modelling	0.4	0.5	2.2	3.8	6.0
Signal modelling	1.9	2.0	5.6	6.0	11.0
Other	1.4	0.9	2.5	3.3	5.0
Total	6.0	4.0	10.0	16.0	24.0

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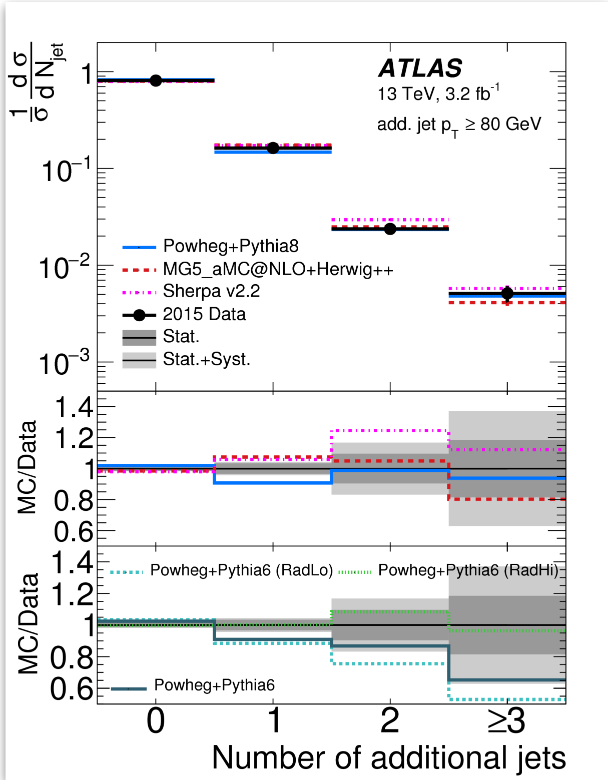
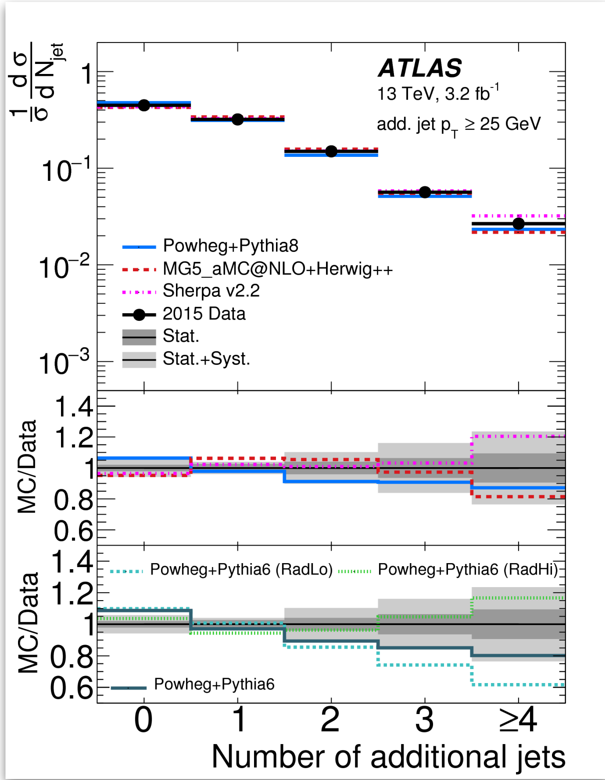
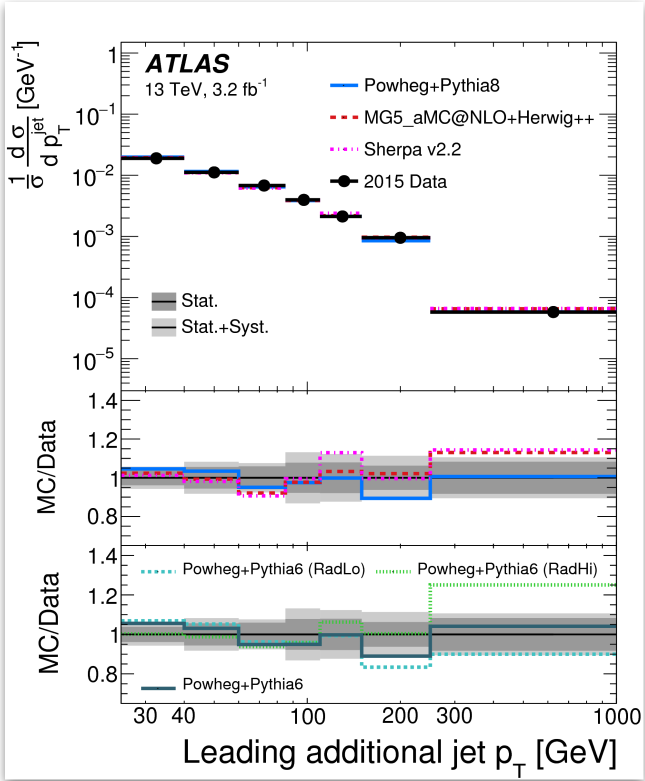
Differential tt σ at 13 TeV: dilepton channel

Physics







Generator	$p_T > 25$ GeV		$p_T > 40$ GeV		$p_T > 60$ GeV		$p_T > 80$ GeV	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia6	0.82/4	0.94	0.83/3	0.84	1.01/3	0.80	1.82/3	0.61
Powheg+Pythia8	0.43/4	0.98	0.90/3	0.83	0.64/3	0.89	1.09/3	0.78
Powheg+Herwig++	0.51/4	0.97	0.88/3	0.83	1.46/3	0.69	2.58/3	0.46
Powheg+Herwig7 ❌	8.62/4	0.07	4.87/3	0.18	3.17/3	0.37	2.57/3	0.46
MG5_aMC@NLO+Pythia8 ❌	5.51/4	0.24	3.10/3	0.38	2.25/3	0.52	2.20/3	0.53
MG5_aMC@NLO+Herwig++ ✅	1.28/4	0.86	0.49/3	0.92	0.34/3	0.95	0.40/3	0.94
MG5_aMC@NLO+Herwig7 ❌	3.14/4	0.54	4.31/3	0.23	3.57/3	0.31	2.87/3	0.41
Sherpa v2.2 ✅	0.43/4	0.98	0.85/3	0.84	0.74/3	0.86	0.79/3	0.85
Powheg+Pythia6 (RadHi) ✅	1.20/4	0.88	1.06/3	0.79	0.22/3	0.97	0.22/3	0.97
Powheg+Pythia6 (RadLo) ❌	4.15/4	0.39	2.05/3	0.56	2.08/3	0.56	2.87/3	0.41

Matching between parton shower and matrix element calculation is important

Differential tt σ at 13 TeV: dilepton channel

Physics

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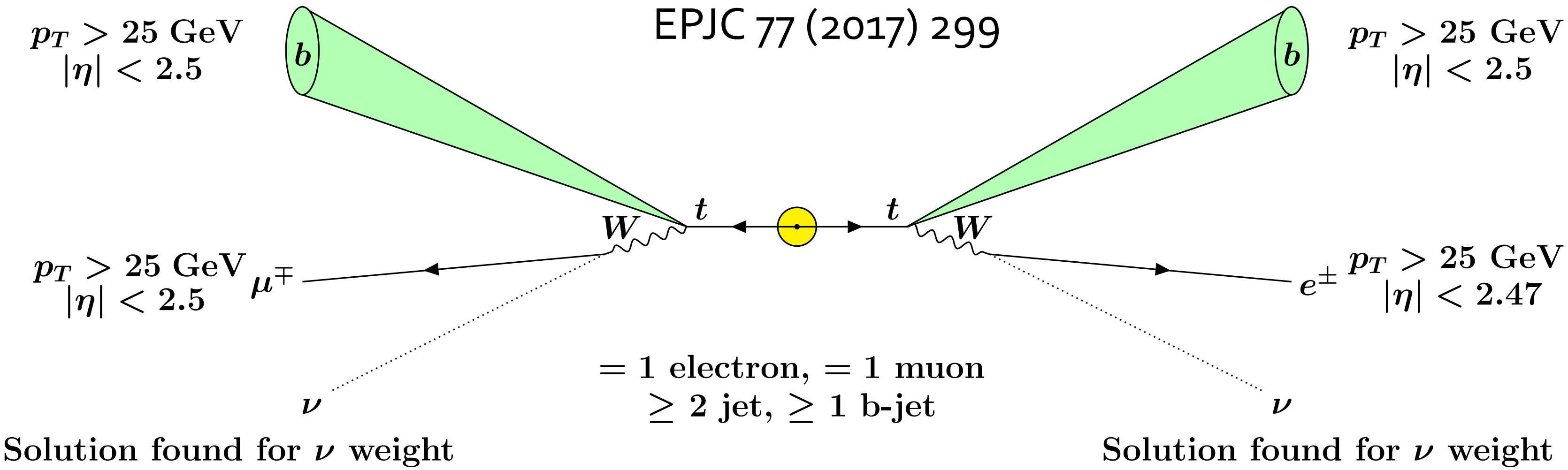
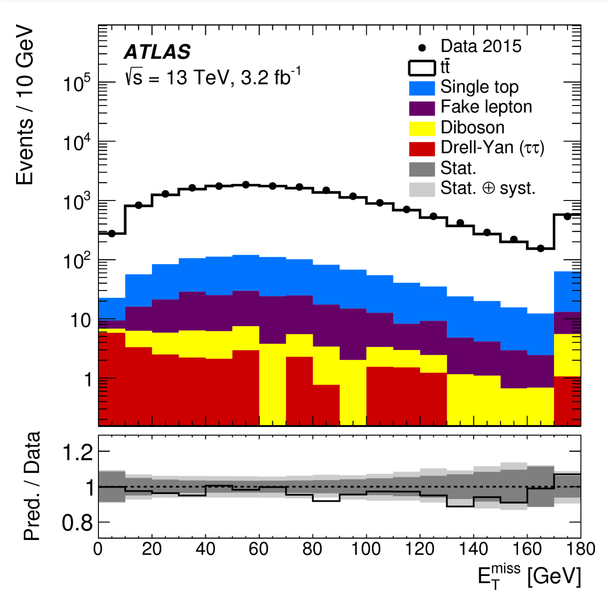
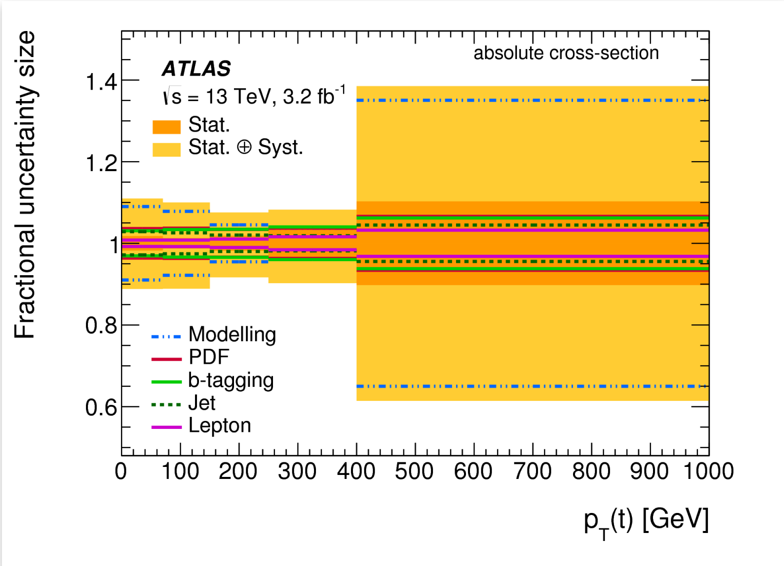


Top reconstruction using neutrino weighting technique

unfolding done to particle-level in a fiducial volume





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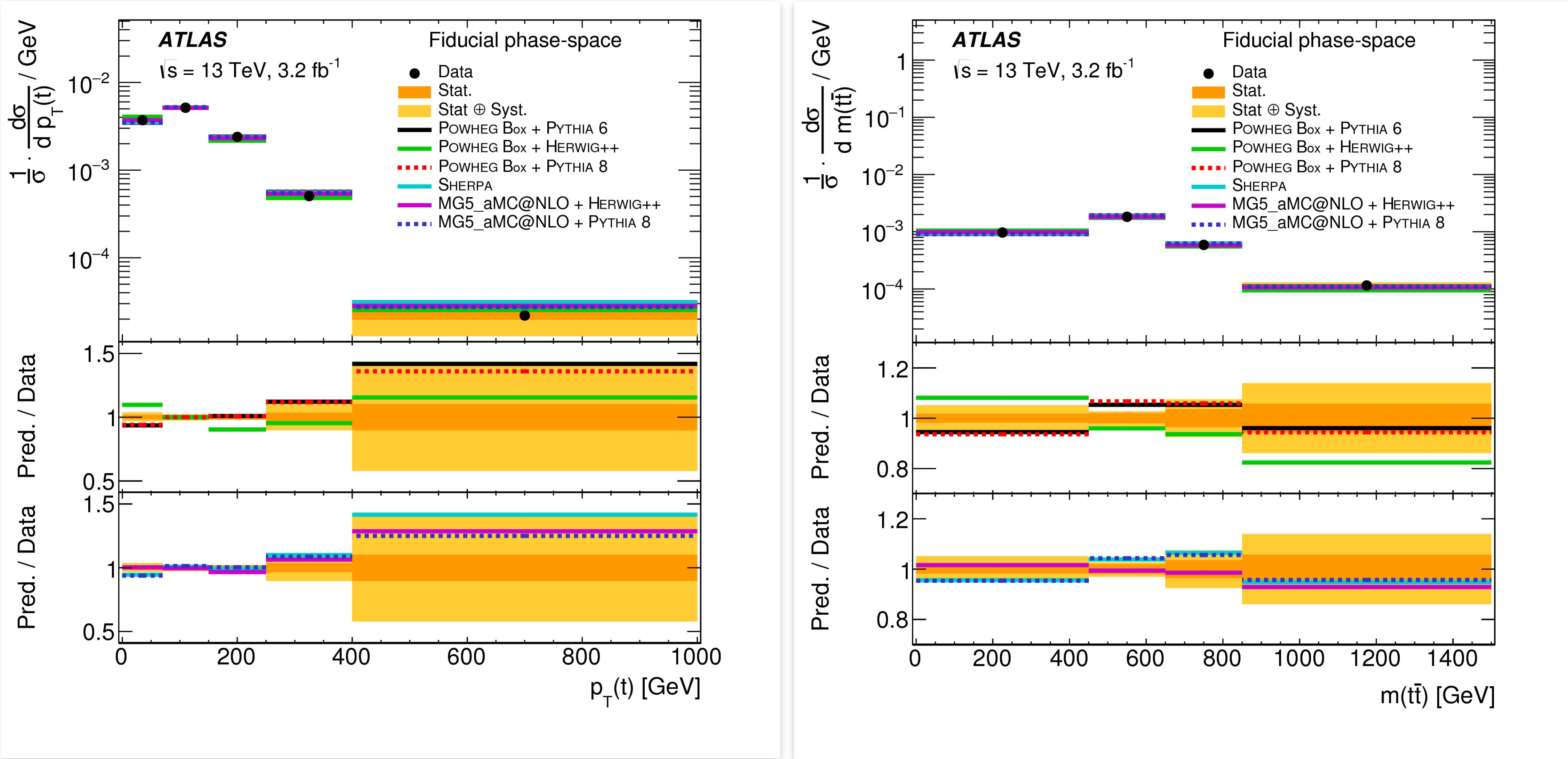
Differential tt σ at 13 TeV: dilepton channel



Data are consistent with NLO generators matched to Parton Shower simulations
Powheg-Box + Herwig++ deviates from data in top quark p_T and tt invariant mass

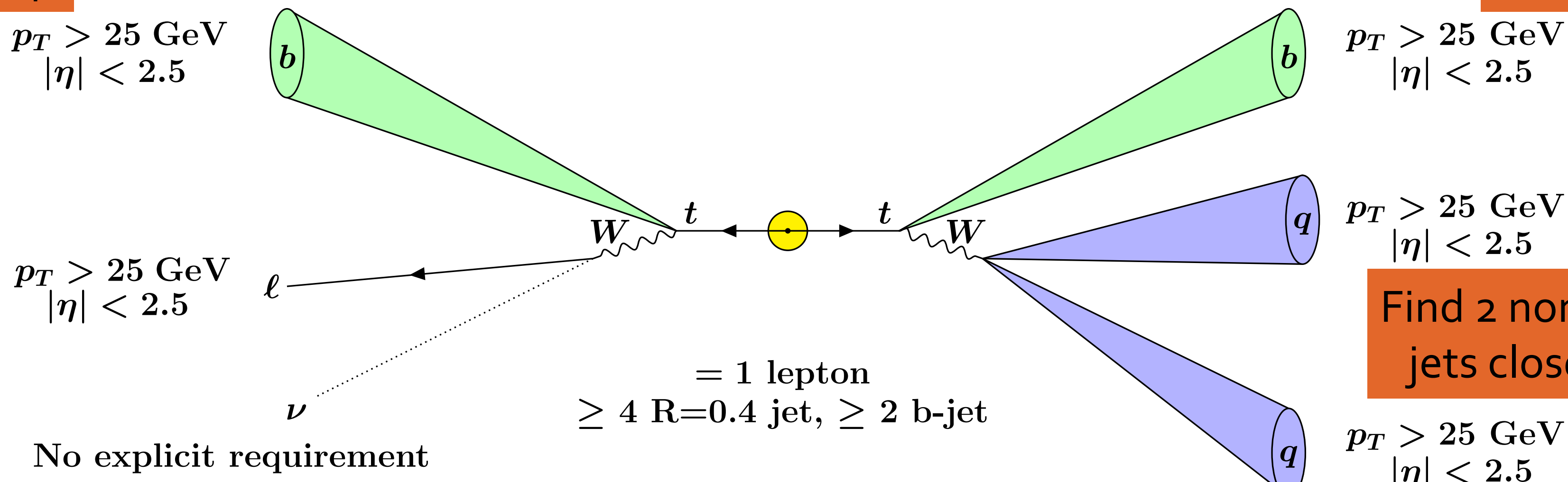
Differential tt σ at 13 TeV: l+jets channel

Physics

Leptonic top

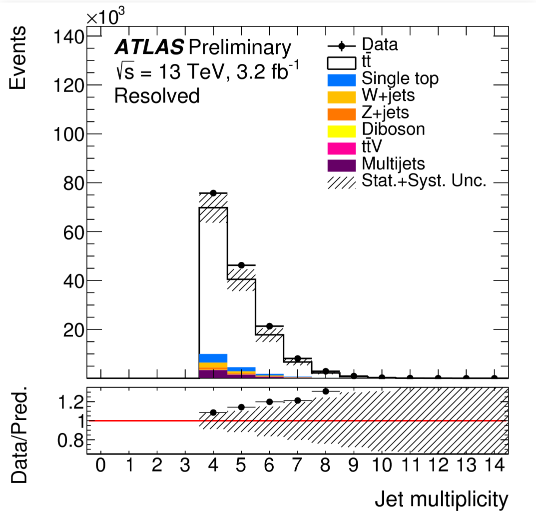
ATLAS-CONF-2016-040

Hadronic top



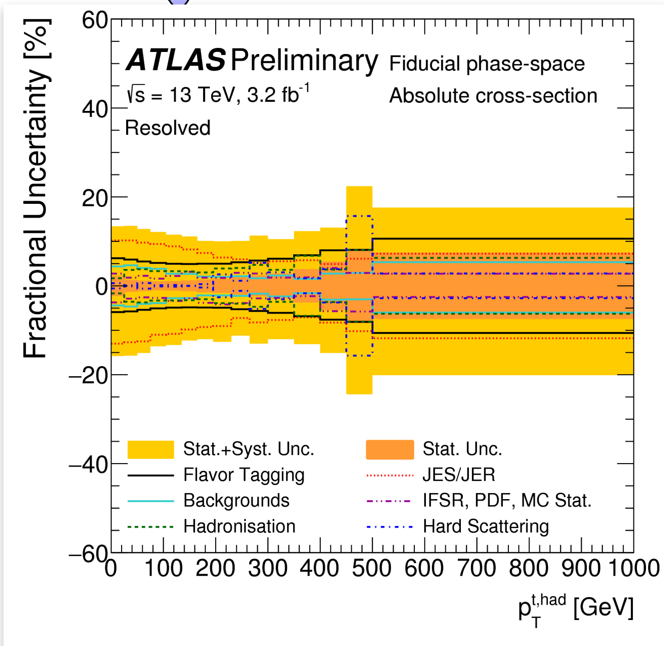
Find 2 non-b-tagged jets closest to M_W

Neutrino p_Z from M_W constraint

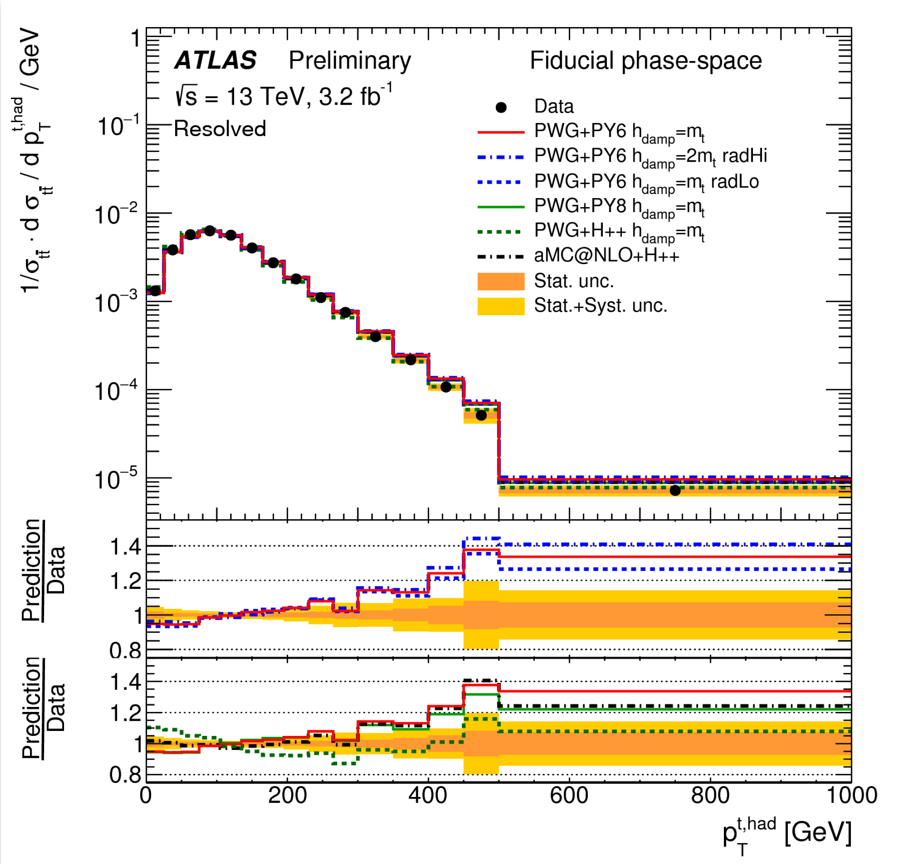


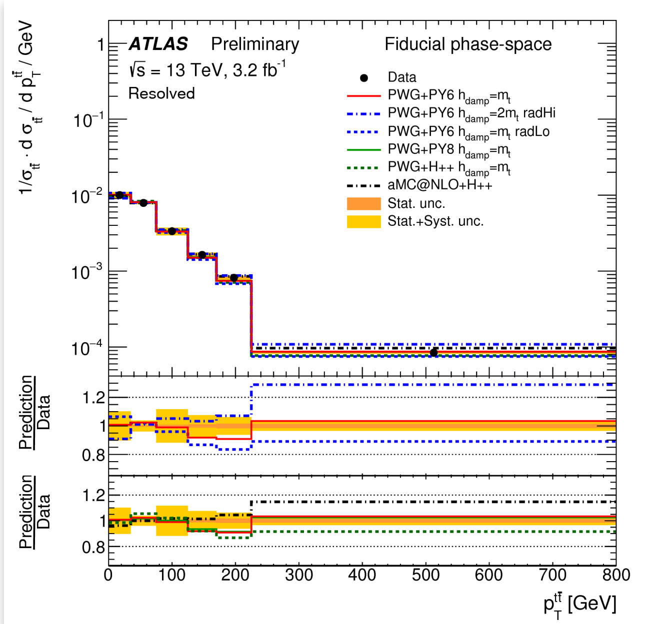
Pseudo-Top reconstruction

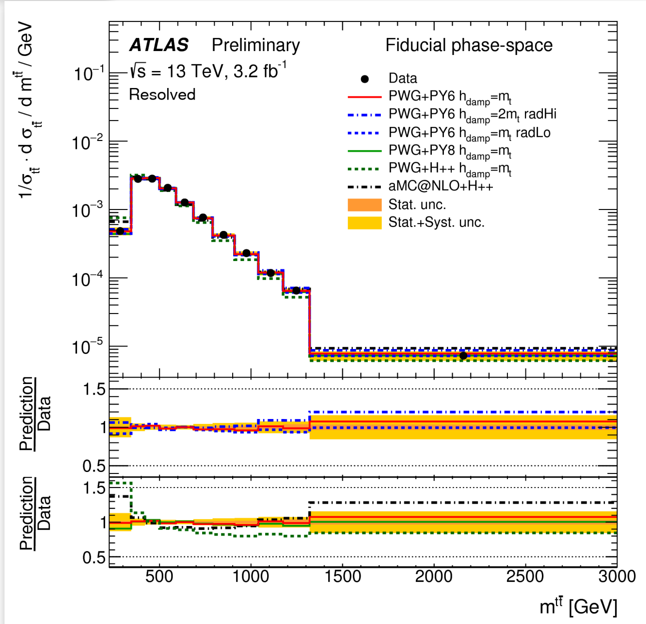
unfolding done to particle-level in a fiducial volume



Differential tt σ at 13 TeV: l+jets channel

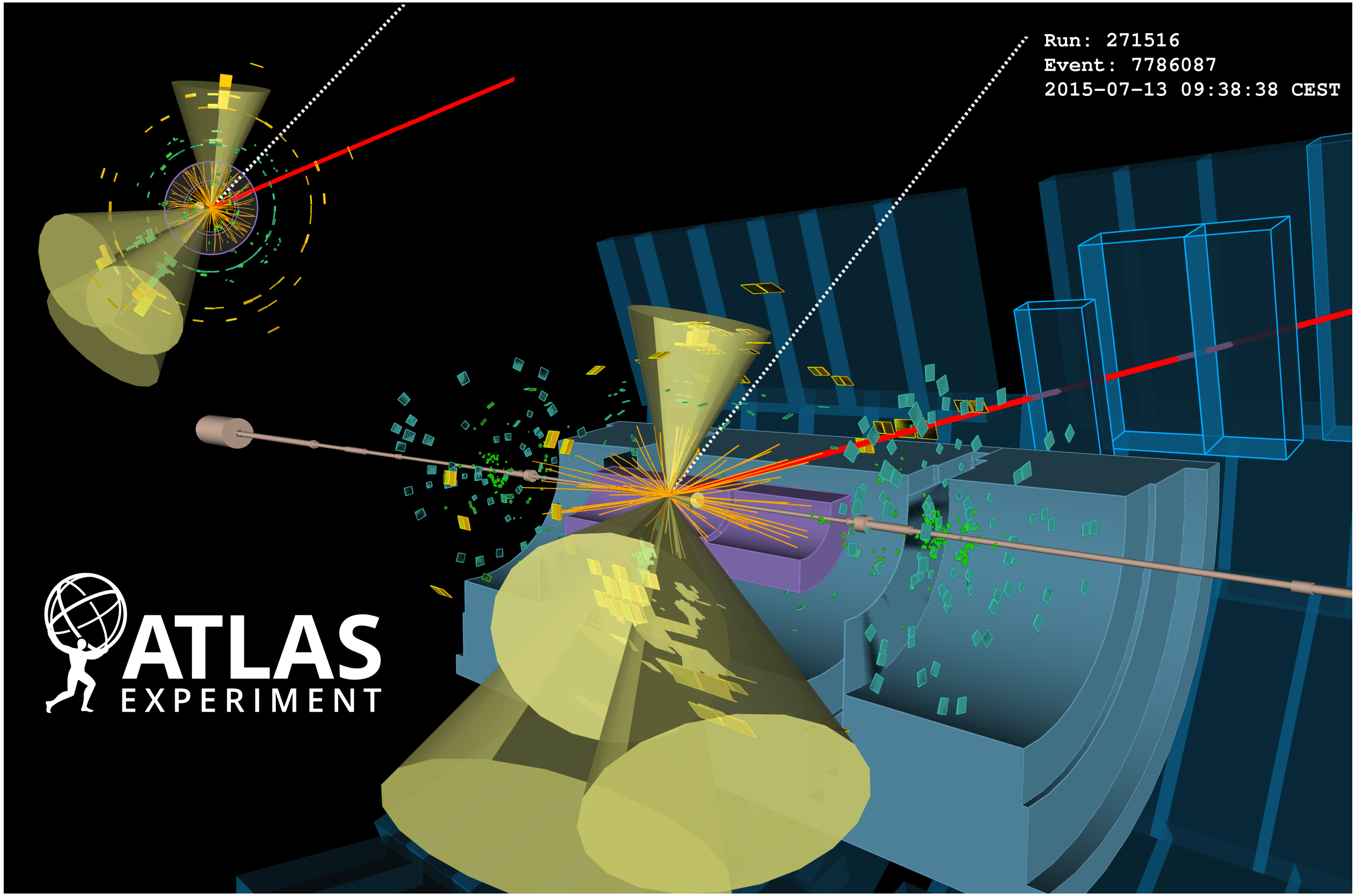






- None of the predictions is able to correctly describe all of the distributions
- hadronic p_T: tension with data for all predictions
- tt p_T: aMC@NLO+Herwig++ doesn't show good agreement with data
- m(tt): Powheg+Pythia7/8 show good agreement with data

Boosted top quarks!

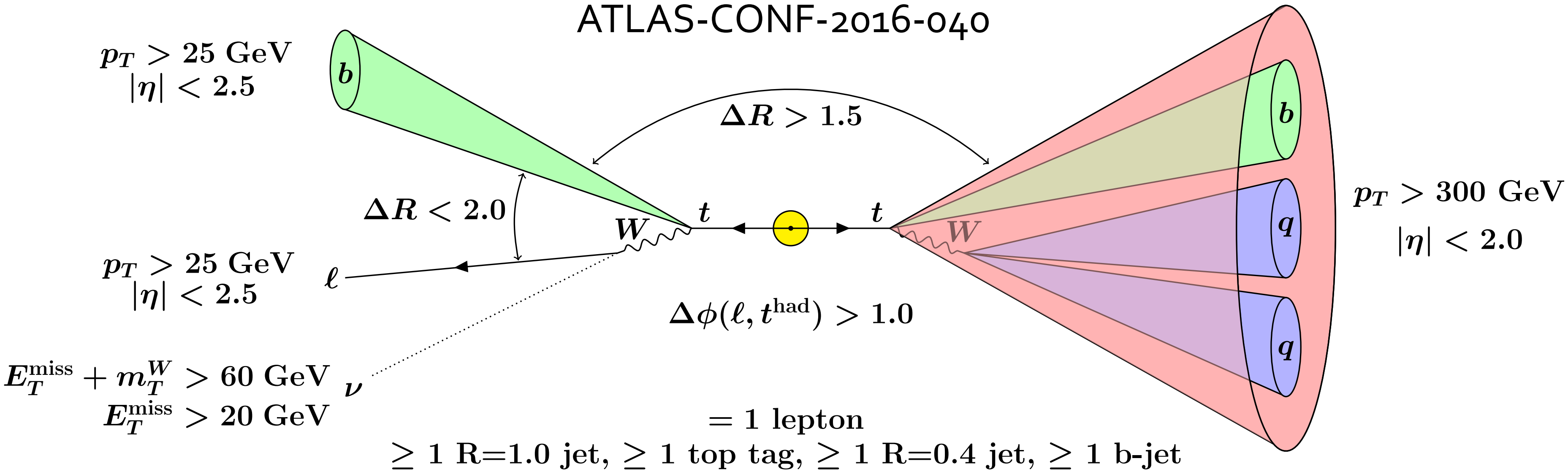


Large R (1.0) jet containing 3 small R (0.4) jets, p_T = 600 GeV, m = 180 GeV

Differential tt σ at 13 TeV: boosted l+jets

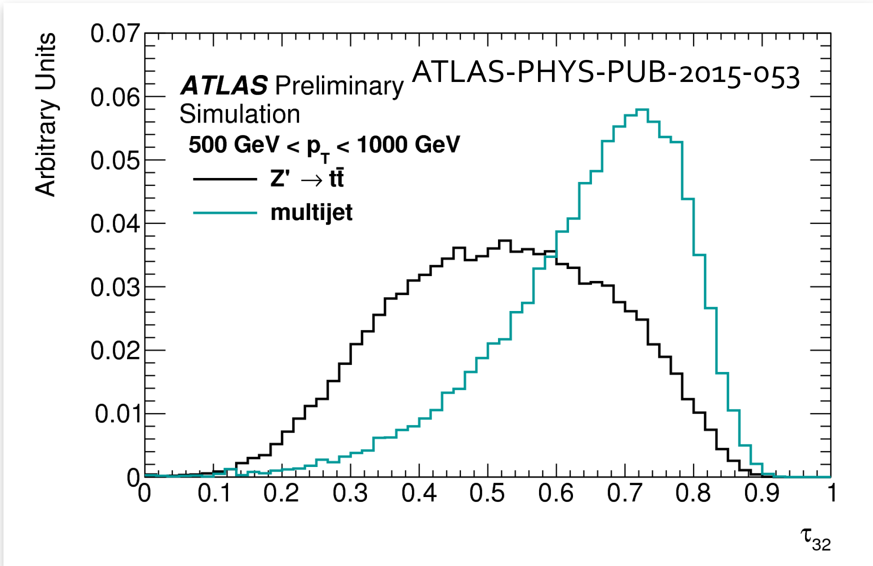
Physics

ATLAS-CONF-2016-040



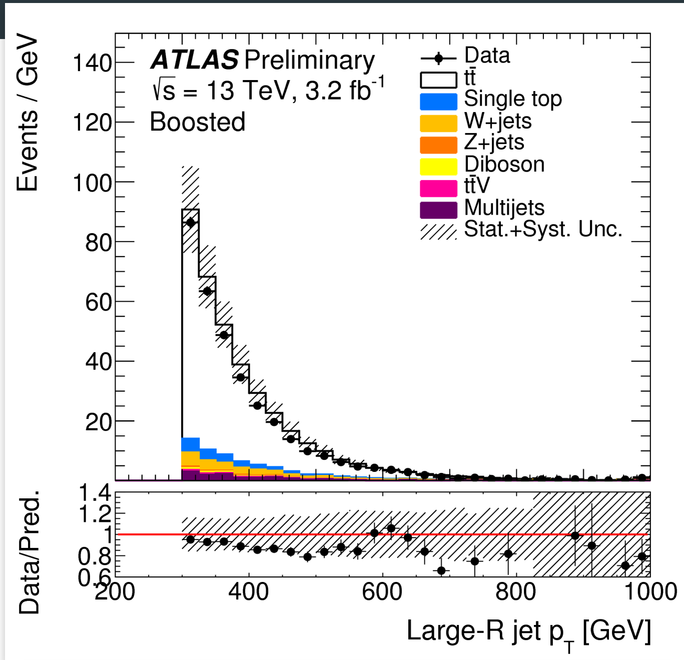
Large R jet: trimming used
Top Tagging (ε = 80%): N-subjettiness shape variable used

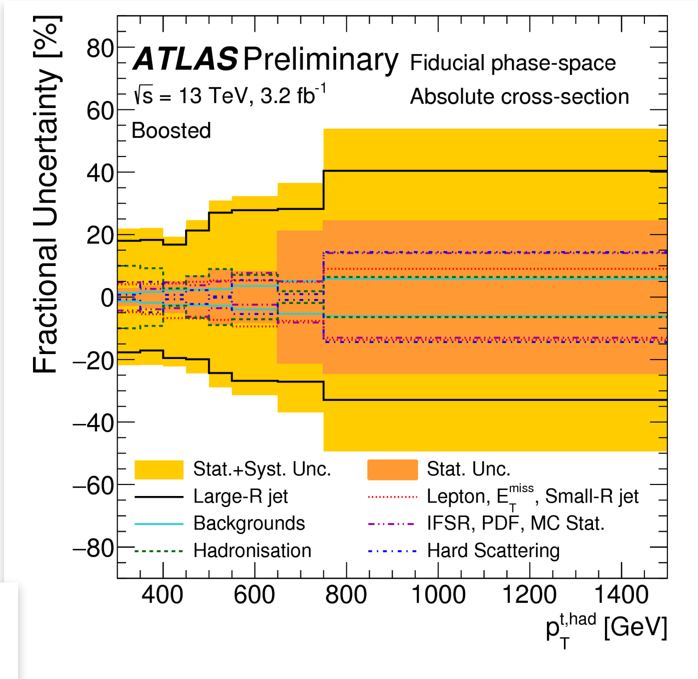
unfolding done to particle-level in a fiducial volume

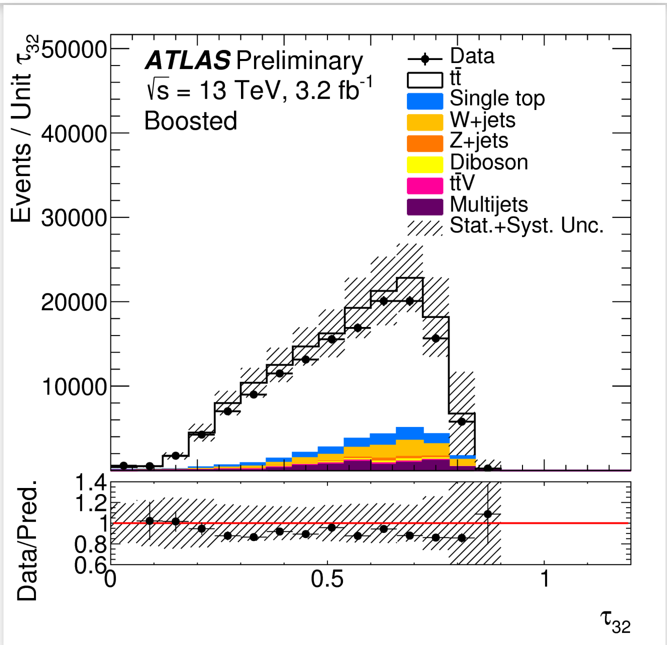


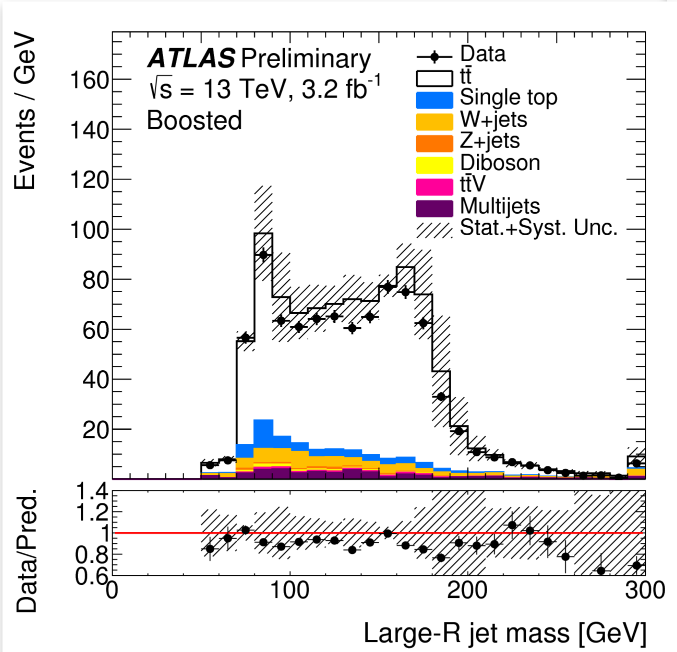
Differential tt σ at 13 TeV: boosted l+jets

Physics



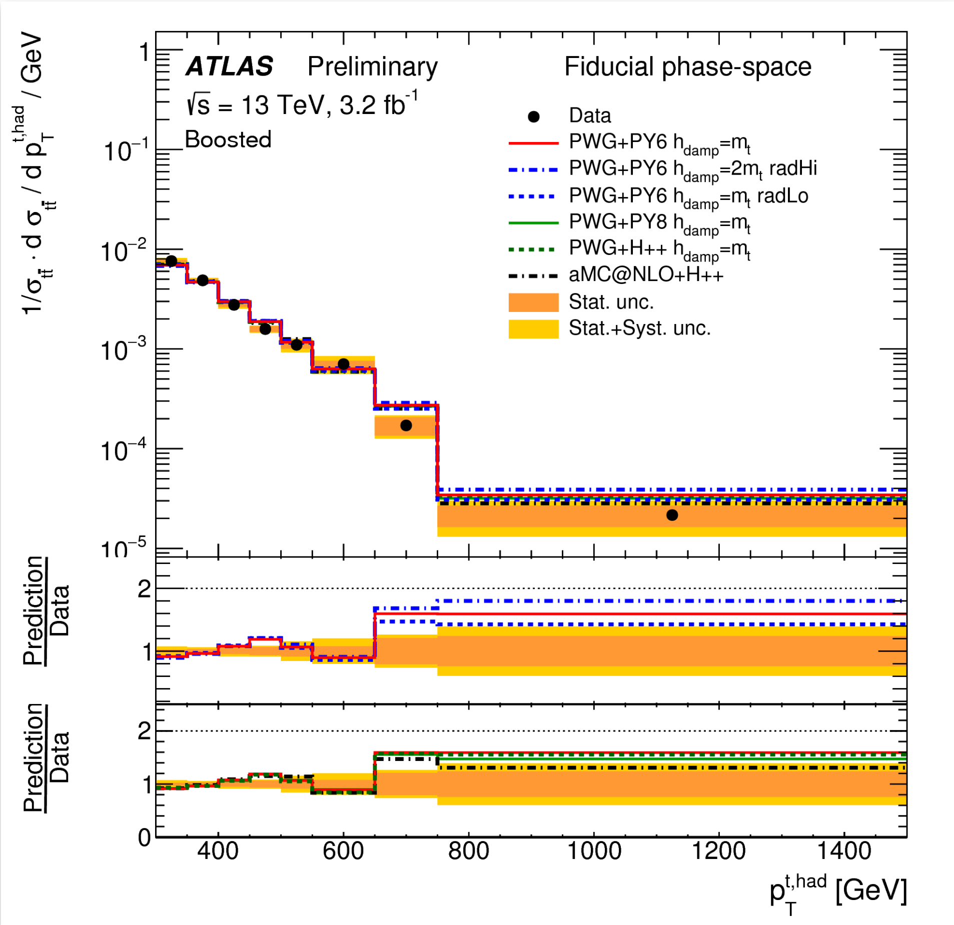


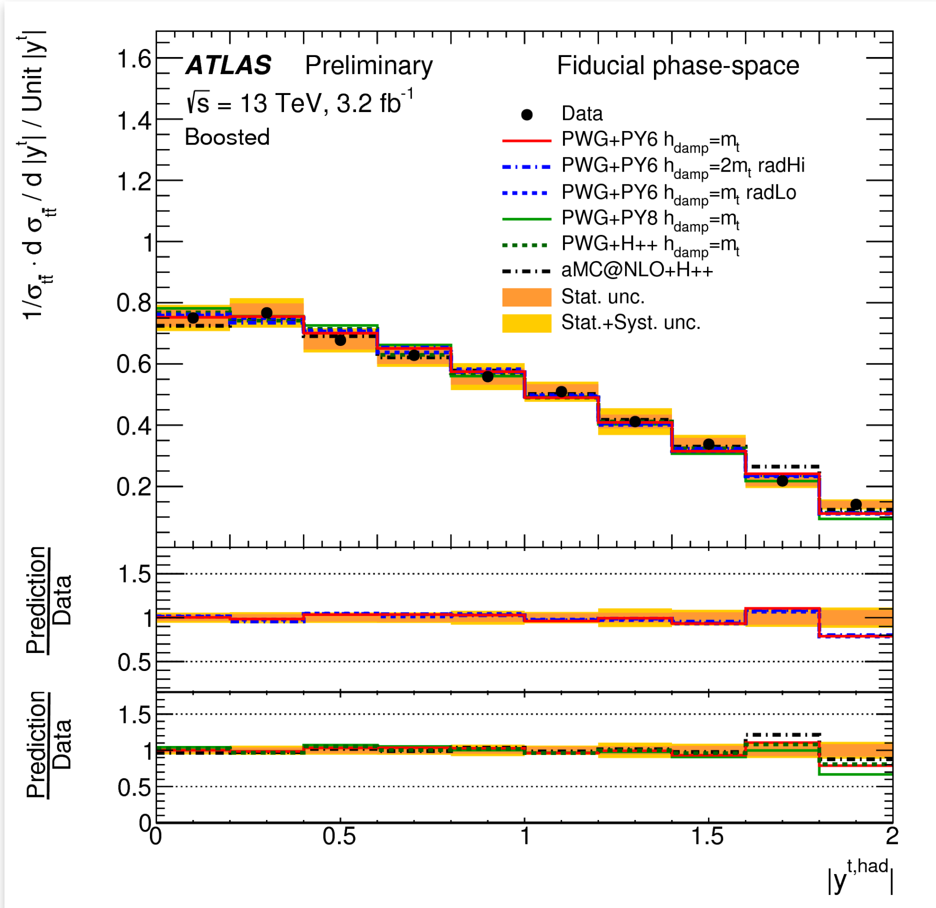




Differential tt σ at 13 TeV: boosted l+jets

Physics



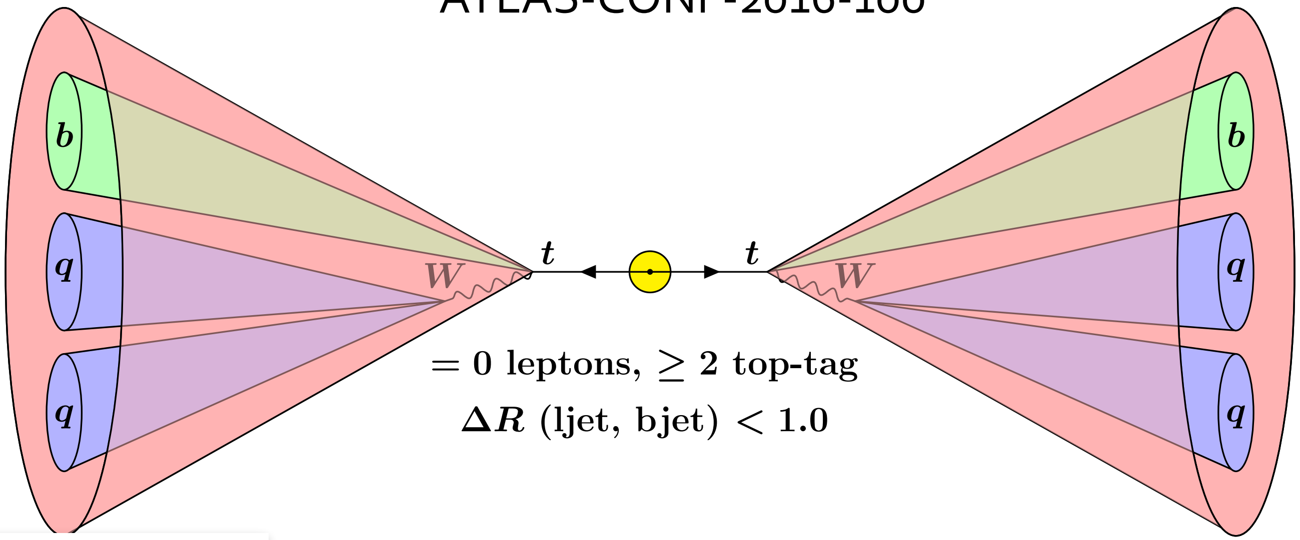


Similar conclusions from resolved topology: at high hadronic top pT some tension between predictions and data

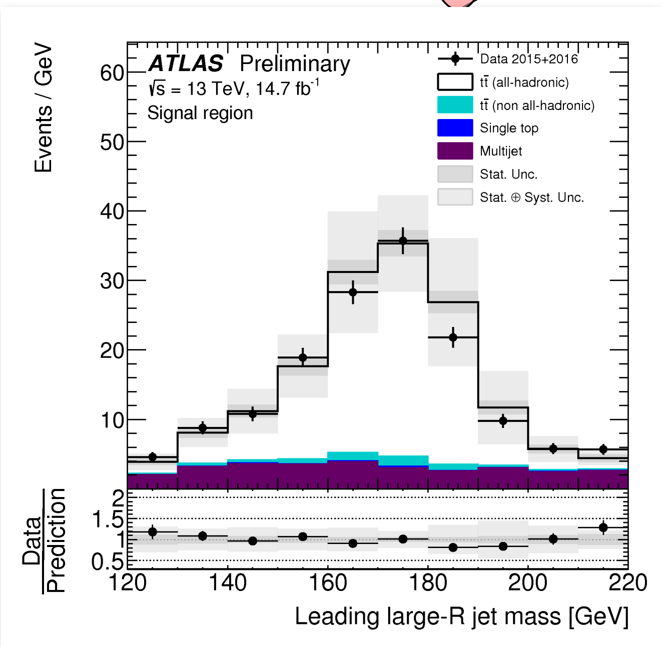
Differential tt σ at 13 TeV: boosted all had

ATLAS-CONF-2016-100

$p_T > 500$ GeV
$|\eta| < 2.0$
$m = 172.5 \pm 50$ GeV



$p_T > 350$ GeV
$|\eta| < 2.0$
$m = 172.5 \pm 50$ GeV

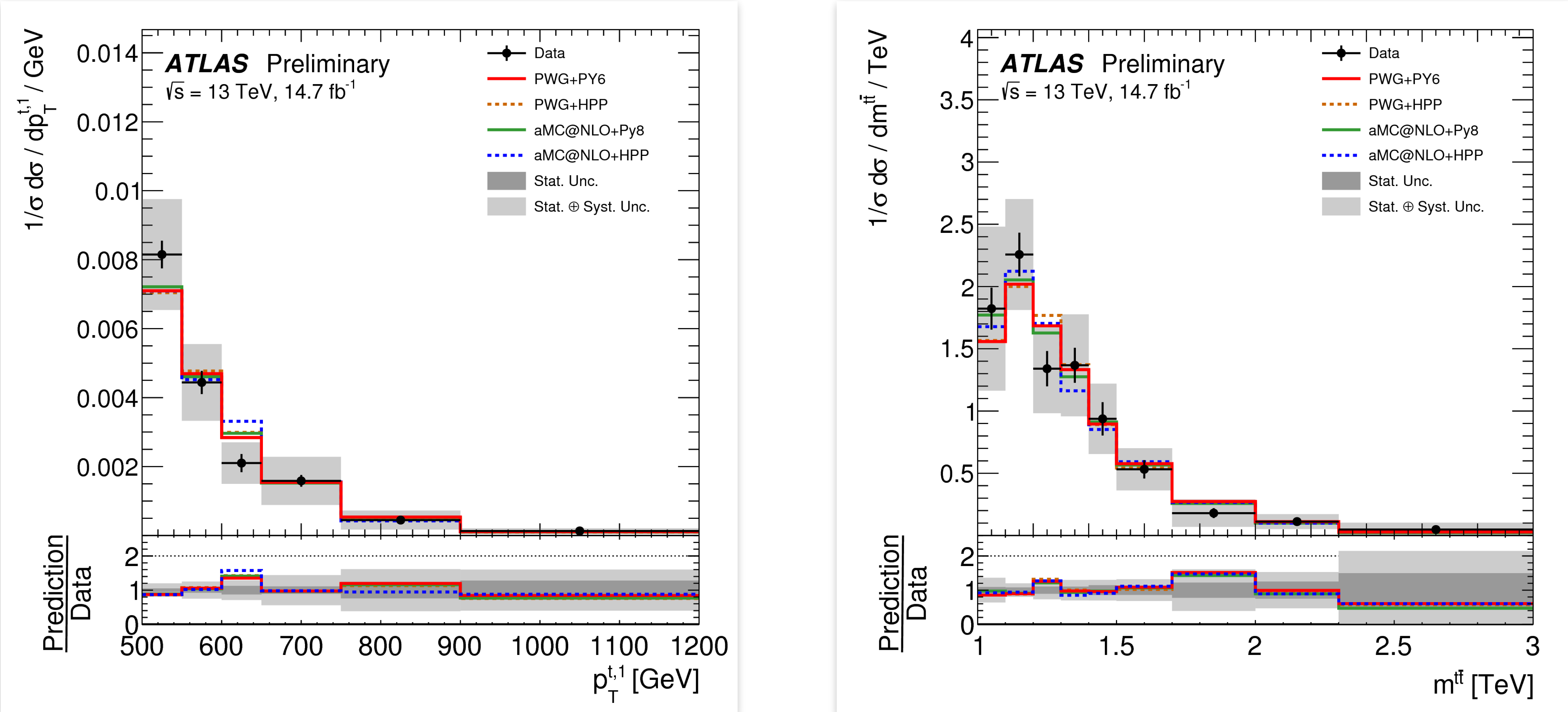


Large R jet: trimming used
Top Tagging (ε = 50%): N-subjettiness shape variable used
Multijet backgrounds estimated from data-driven method
unfolding done to particle-level in a fiducial volume

	0 t	1 t	2 t
0 b	A	D	G
1 b	B	E	H
2 b	C	F	S

Large-R jets	+18 / -15
Monte Carlo signal modelling	±17
b-tagging	+13 / -12
Pileup	±2.9
Luminosity	±2.9
Small-R jets	±1.0
Total Systematic Uncertainty	+29 / -24

Differential tt σ at 13 TeV: boosted all had

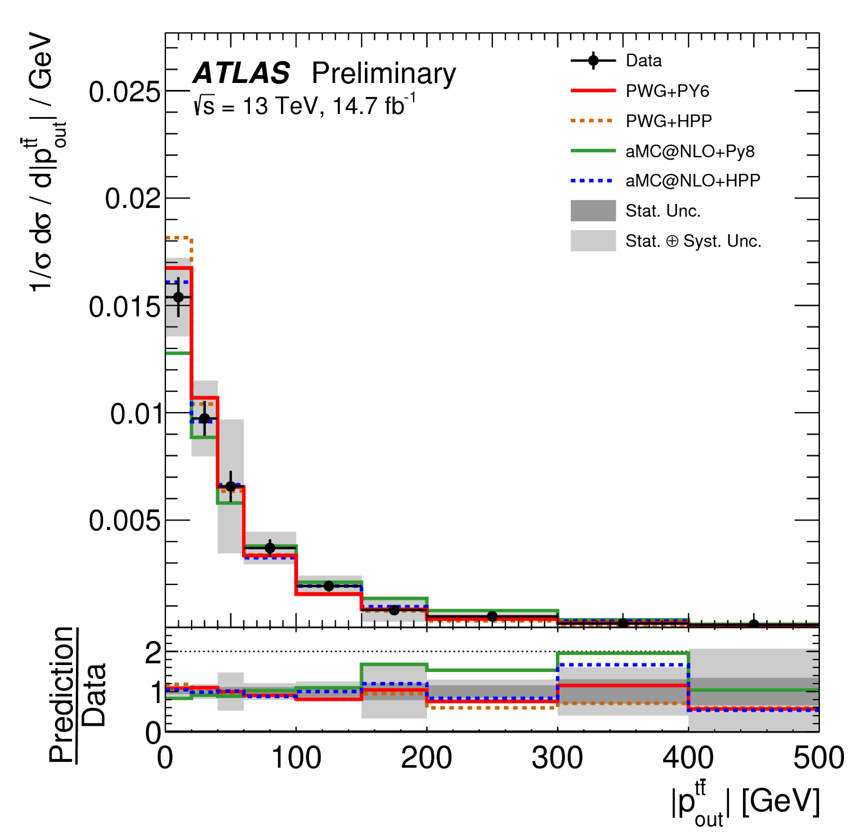


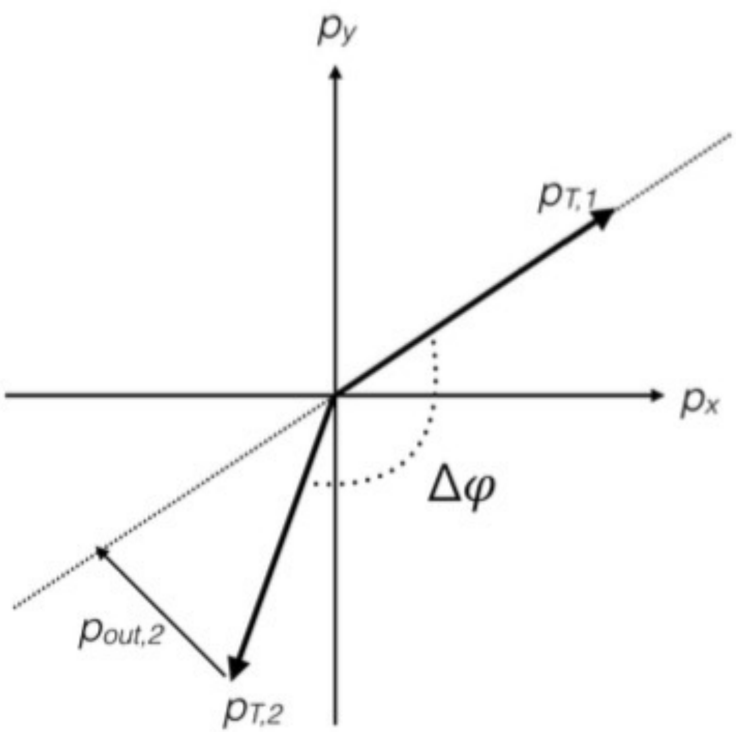
$$\sigma_{\text{fid}} = 374 \pm 13\ (\text{stat})^{+111}_{-92}\ (\text{syst})\ \text{fb}$$

vs 392 fb from Powheg+Pythia 6 (inclusive xs has been renormalized to the NNLO +NNLL prediction)

Good agreement between predictions and data

Differential tt σ at 13 TeV: boosted all had





The boosted all hadronic top quarks topology is similar to dijet measurements done at high transverse momentum

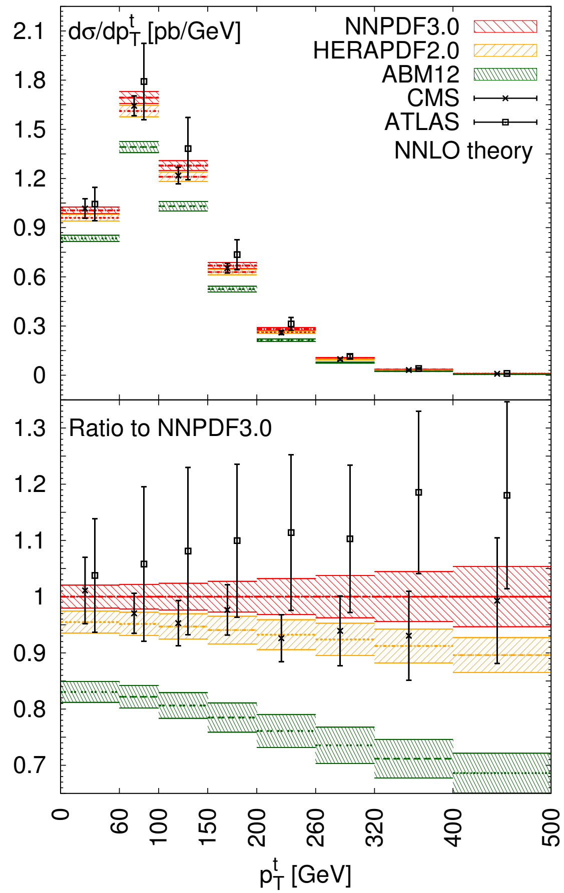
Observables sensitive to the extra radiation present alongside the tt system are obtained and show good agreement between predictions and data

Conclusions

Physics

- 8 TeV Differential measurements were used for MC tuning within ATLAS and are currently being used for PDF fitting and EFT interpretation
- 13 TeV results shown all unfolded to particle-level in a fiducial phase-space
- Results are dominated by systematic uncertainties, especially signal modelling ones
  - importance of those results for tuning MC!
- First measurement of all hadronic boosted top quark pairs
  - Uncertainties are close to offering discrimination of predictions
- Effort currently underway to use full 2015+2016 dataset and unfold to parton level

JHEP04 (2017) 044



backups

Differential variables

the central scattering region. The angle between the two top quarks quarks has been found to be sensitive to non-resonant contributions due to hypothetical new particles exchanged in the t-channel [7]. The rapidities of the two top quarks produced in the hard scattering process in the pp center of mass frame are denoted by $y_{t,1}$ and $y_{t,2}$, while their rapidities in the $t\bar{t}$ center of mass frame are $y^\star = \frac{1}{2}(y_{t,1} - y_{t,2})$ and $-y^\star$. The longitudinal motion of the $t\bar{t}$ system in the pp frame is described by the rapidity boost $y^{t\bar{t}}_{\text{boost}} = \frac{1}{2}[y_{t,1} + y_{t,2}]$ and the scattering angle $\chi_{t\bar{t}} = e^{2|y^\star|}$. In particular, many signals due to processes not included in the Standard Model are predicted to peak at low values of $\chi_{t\bar{t}}$[7].

The following observables have been measured:

- The absolute value of the azimuthal angle between the two top quarks ($\Delta\phi_{t\bar{t}}$);
- the absolute value of the out-of-plane momentum ($|p^{t\bar{t}}_{\text{out}}|$), *i.e.* the projection of top-quark three-momentum onto the direction perpendicular to a plane defined by the other top quark and the beam axis (z) in the laboratory frame

$$\left|p^{t\bar{t}}_{\text{out}}\right| = \left|\vec{p}_{t,\text{had}} \cdot \frac{\vec{p}_{t,\text{lep}} \times \hat{z}}{|\vec{p}_{t,\text{lep}} \times \hat{z}|}\right| ; \tag{3}$$

- the scalar sum ($H^{t\bar{t}}_{\text{T}}$) of the transverse momenta of the two top quarks

$$H^{t\bar{t}}_{\text{T}} = p^{t,\text{had}}_{\text{T}} + p^{t,\text{lep}}_{\text{T}} ; \tag{4}$$

- the longitudinal boost of the $t\bar{t}$ system with respect to the center-of-mass of the colliding protons ($y^{t\bar{t}}_{\text{boost}}$) ;
- the scattering angle between the two top quarks ($\chi_{t\bar{t}}$);
- and the ratio of the transverse momenta of the hadronic W boson and the top quark from which it originates (R_{Wt})

$$R_{Wt} = p^{W}_{\text{T}} / p^{t,\text{had}}_{\text{T}} . \tag{5}$$