Top Quark Pair Differential Cross-Sections with the ATLAS detector, eh?

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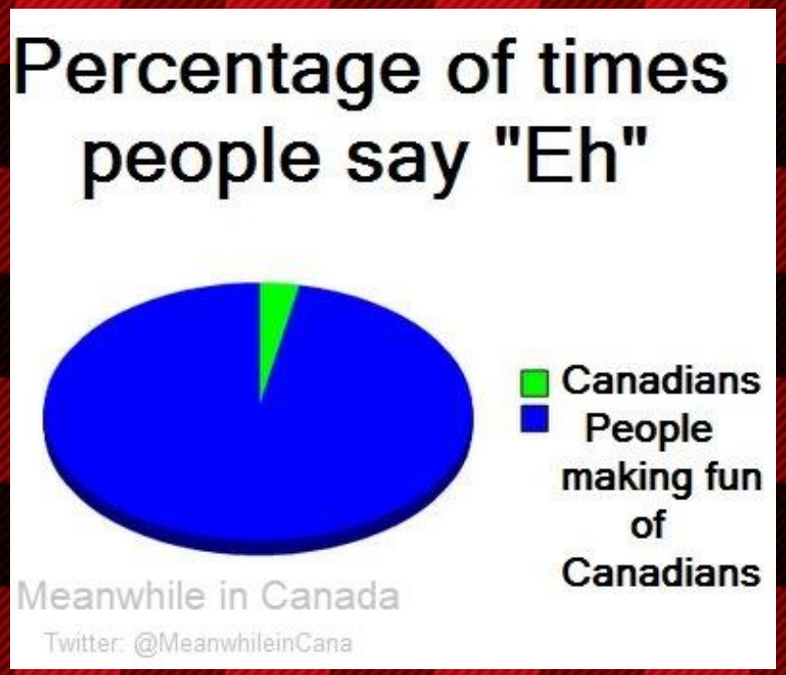


Differential xs analyses

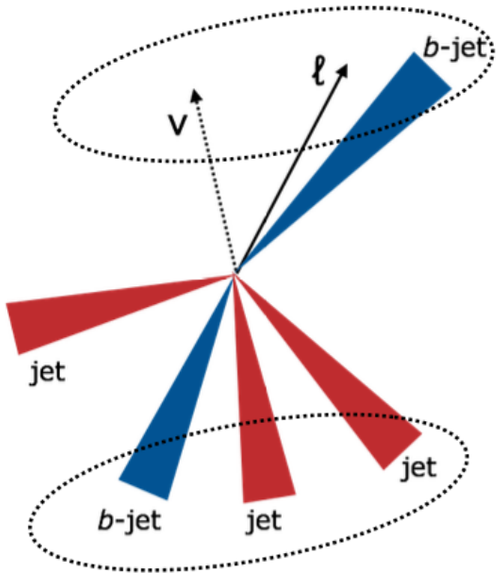
$t\bar{t}$ (ℓ+jets/$\ell\ell$) + γ	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	EPJC 79 (2019) 382
$t\bar{t}$ (ℓ+jets/$\ell\ell$) + H.F.	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	JHEP 04 (2019) 046
$t\bar{t}$ (all-jets) high-pT	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	PRD 98 (2018) 012003
$t\bar{t}$ (ℓ-jets) + jets	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	JHEP 10 (2018) 159
$t\bar{t}$ (ℓ+jets) low-pT	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	JHEP 11 (2017) 191
$t\bar{t}$ (ℓ+jets) high-pT	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	JHEP 11 (2017) 191
$t\bar{t}$ ($\ell\ell$)	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	EPJC 77 (2017) 292
$t\bar{t}$/tW ($\ell\ell$) interference	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	PRL 121 (2018) 152002
PDF fits	$\sqrt{s}$ = 8 TeV	20.2 fb^{-1}	ATL-PHYS-PUB-2018-017
MC tuning Run2	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	ATL-PHYS-PUB-2018-009

Also relevant, but not covered in this talk:

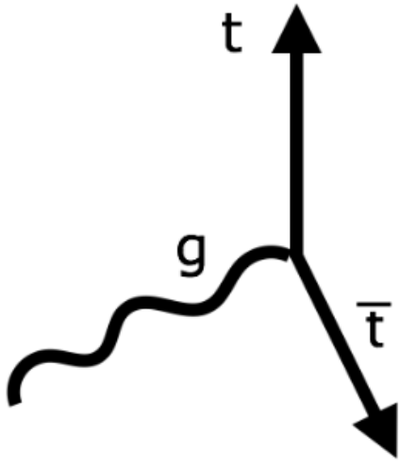
$t\bar{t}$ spin correlations ($\ell\ell$)	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	arXiv:1903.07570
Jet shapes (ℓ+jets boosted)	$\sqrt{s}$ = 13 TeV	36 fb^{-1}	arxiv:1903.02942
Color flow (ℓ-jets)	$\sqrt{s}$ = 13 TeV	3.2 fb^{-1}	EPJC 78 (2018) 847

Comparison with theory

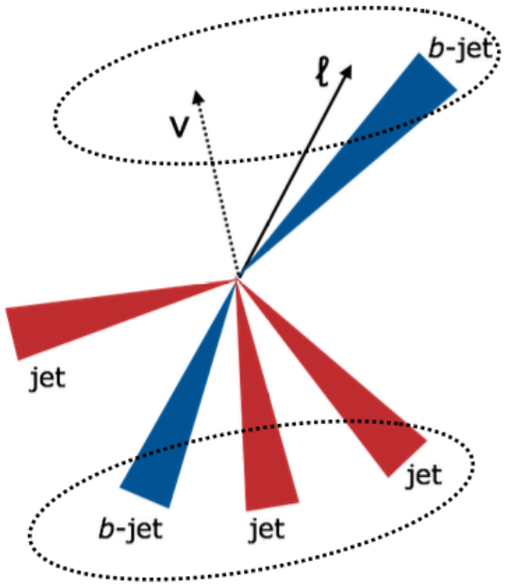
- **Fiducial phase-space**
  - Similar kinematic reconstruction at detector- and particle-level objects
  - Reduce extrapolation uncertainty
  - Valid for all Monte Carlo **event generators**
  - Endpoint of the theoretical prediction



- **Full phase-space**
  - **NNLO+NNLL** accuracy only available by asking to the theorists, slow turnaround
  - Larger **extrapolation** uncertainty to low-p_T, high-η.
  - Observables must be **infrared safe**

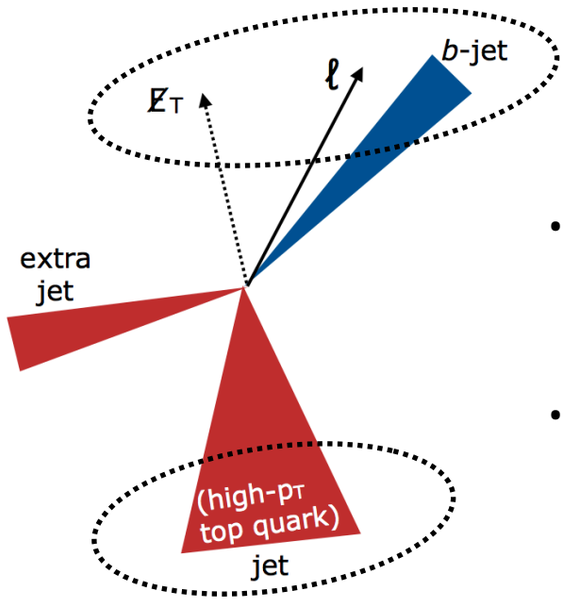


Kinematic reconstruction



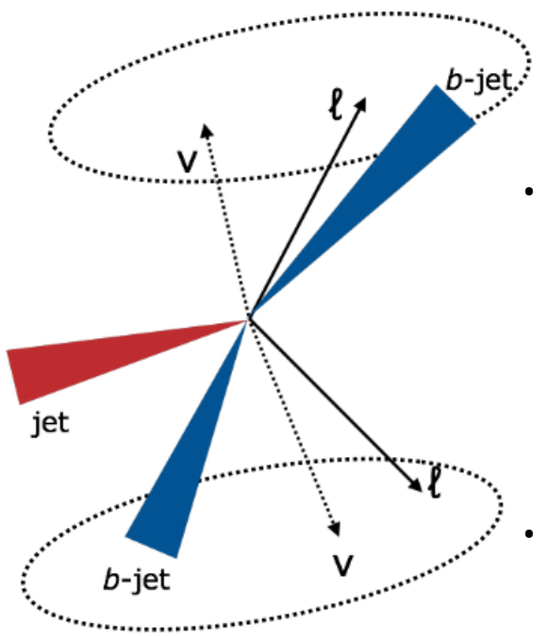
Single lepton resolved - PseudoTop

Mass constrains (m_W, m_t) and b-tagging information to reconstruct decay chain



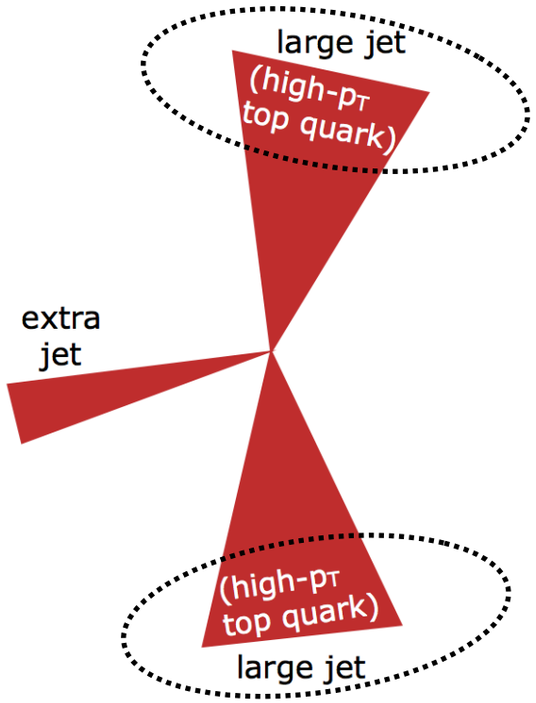
Single lepton boosted

- Kinematic constrains to reconstruct $t \to \ell\nu b$
- Hadronic top = large-*R* trimmed jet



Dilepton Neutrino weighting

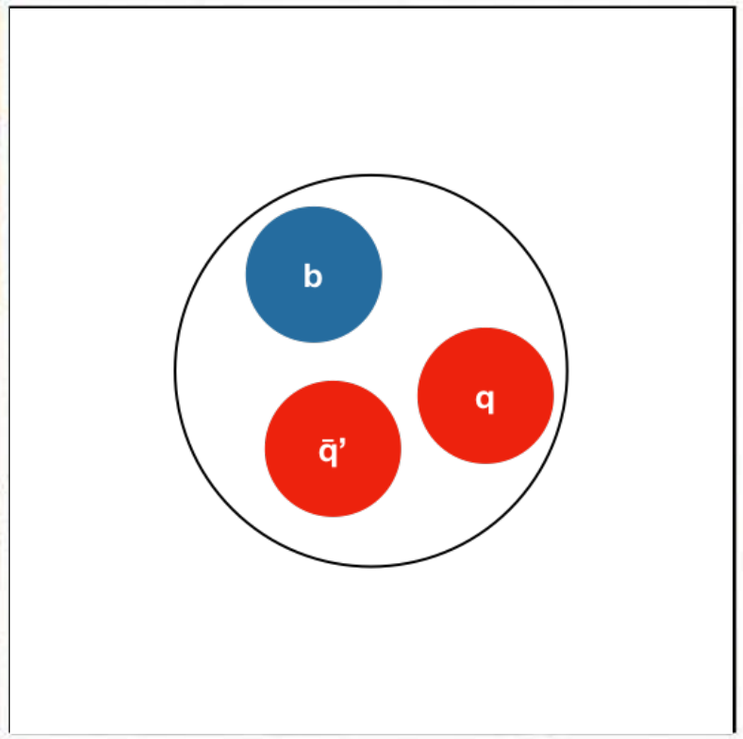
- Kinematic constrains to find optimal longitudinal component of the two neutrinos' momenta [Phys. Lett. B, 752 (2016) 18-26]
- Extra jet may also be photon, $b\bar{b}$ pair

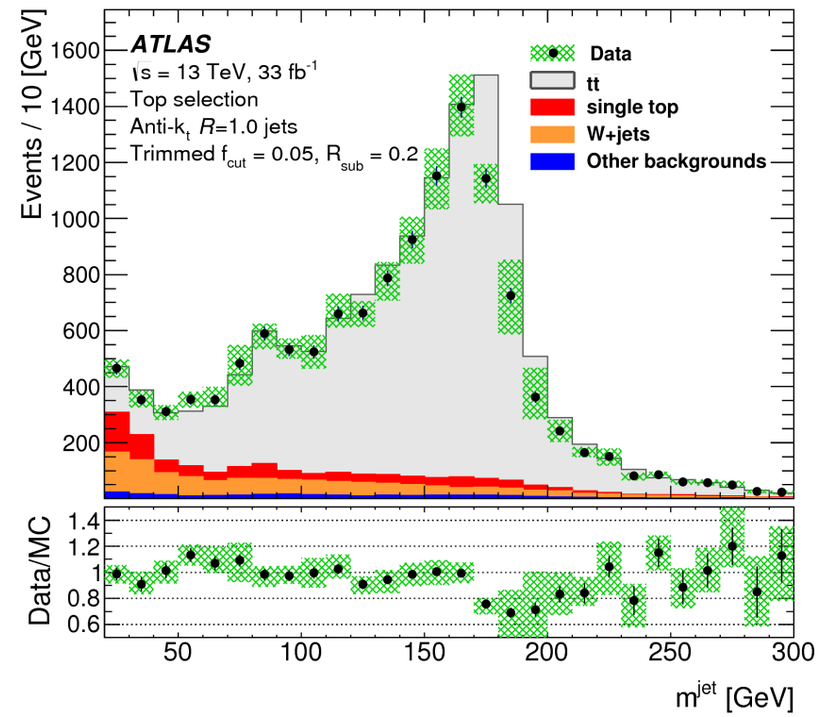


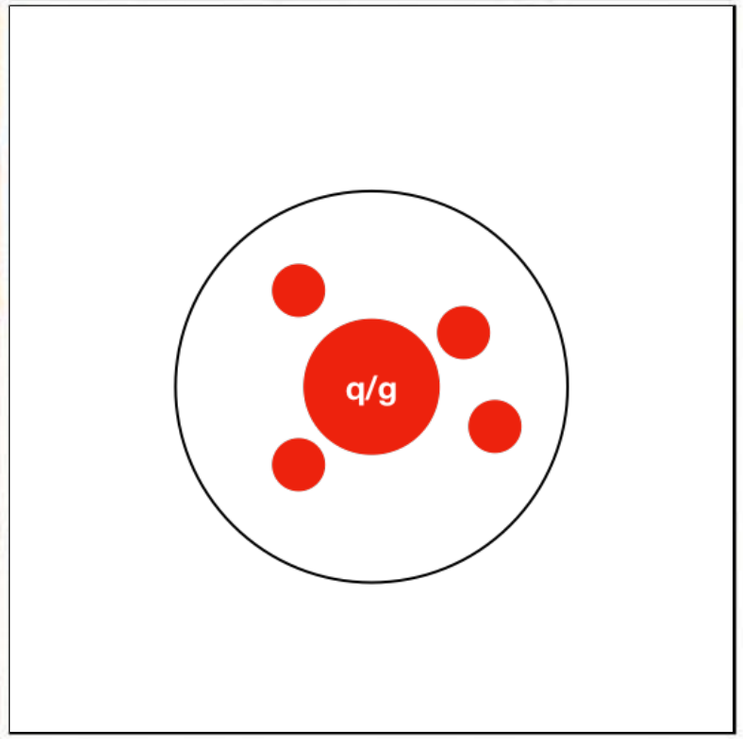
All-hadronic boosted "double double"

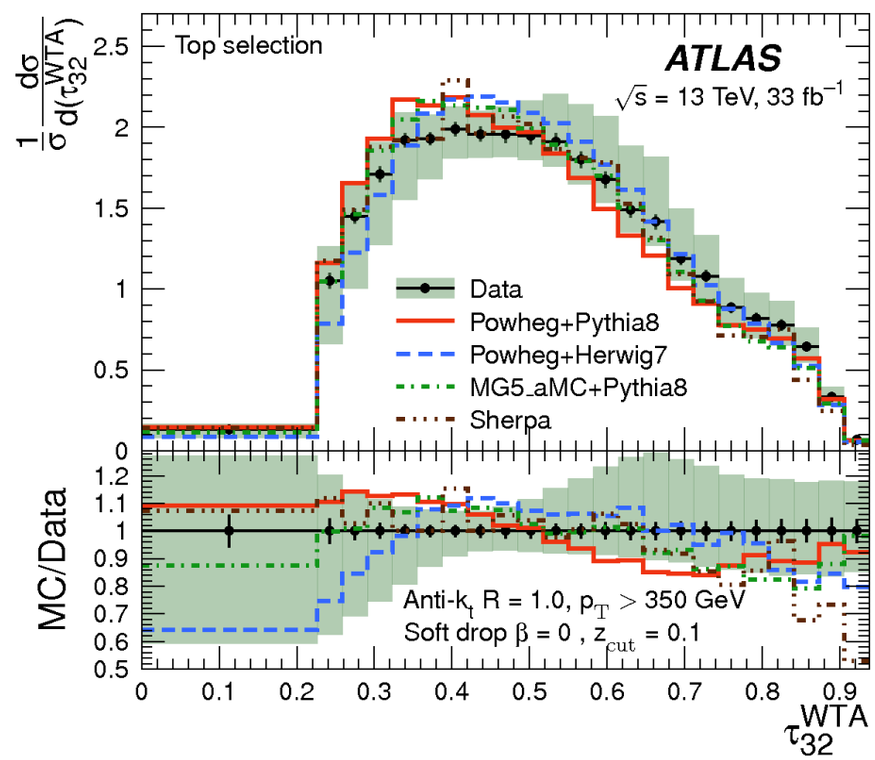
Top quark candidates = 2 leading large-*R* trimmed massive jets (*b*- and *top*-tagged)

Top Tagging in a Nutshell





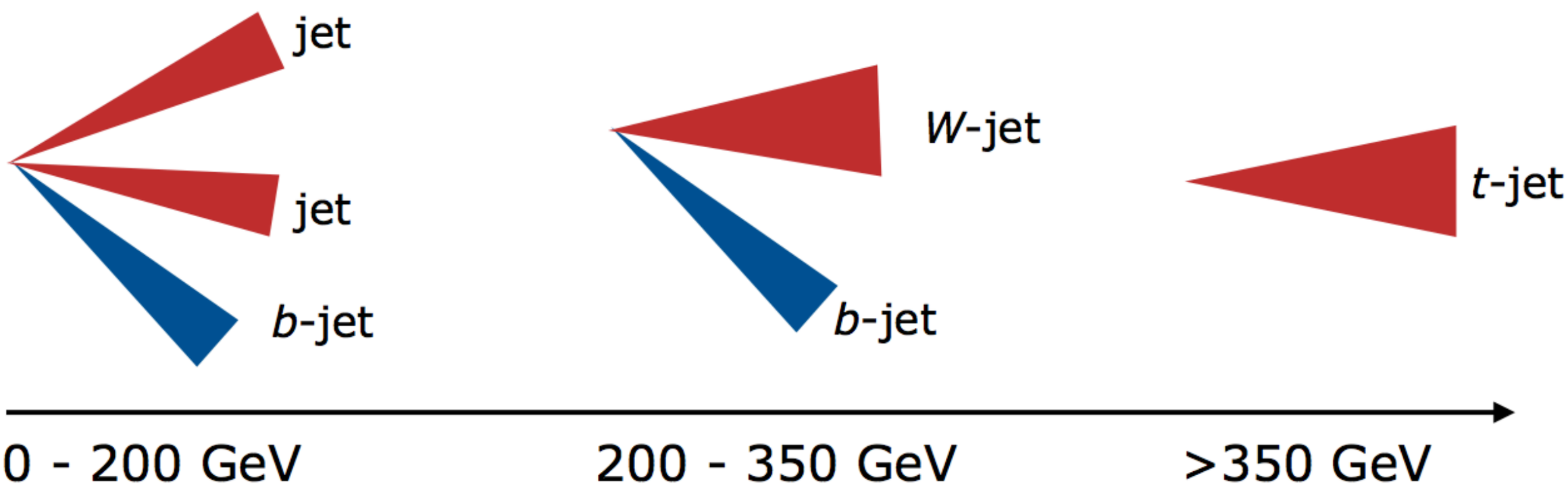




Apply **cut** on **substructure** variable as a function of jet **kinematic** variables (p_T, y, m)

Top quark p_T

- Probably, the most important observable
- Sensitive to **final state radiation**
- Measurement up to ~1 TeV spans different kinematic regimes, requiring different reconstruction methods
- Many sources indicate data/theory **disagreement** with increasing p_T



Top quark p_T

"the devil is in the tails"

Hadronic top
(single lepton channel)

Leptonic top
(dilepton channel)

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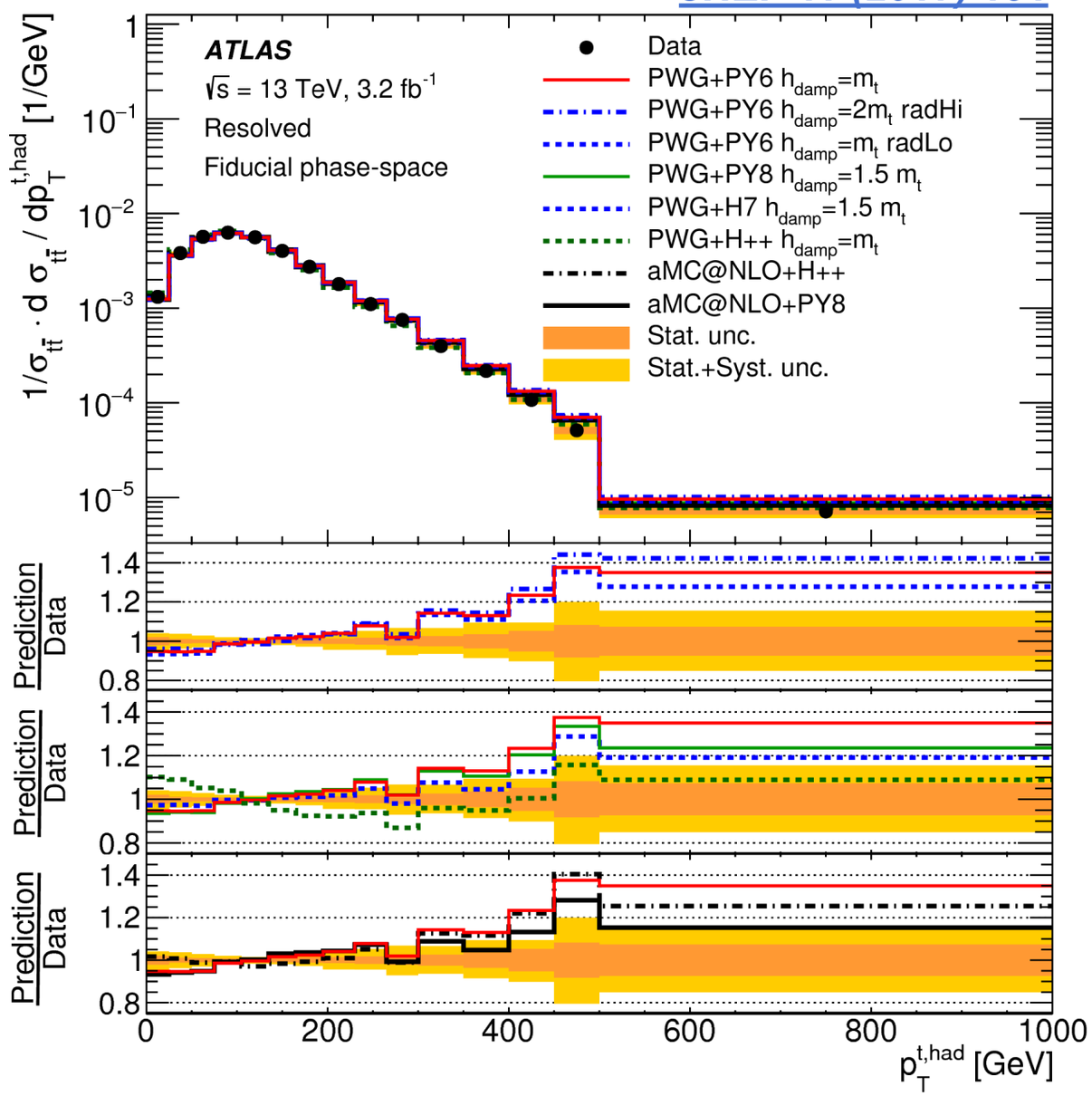

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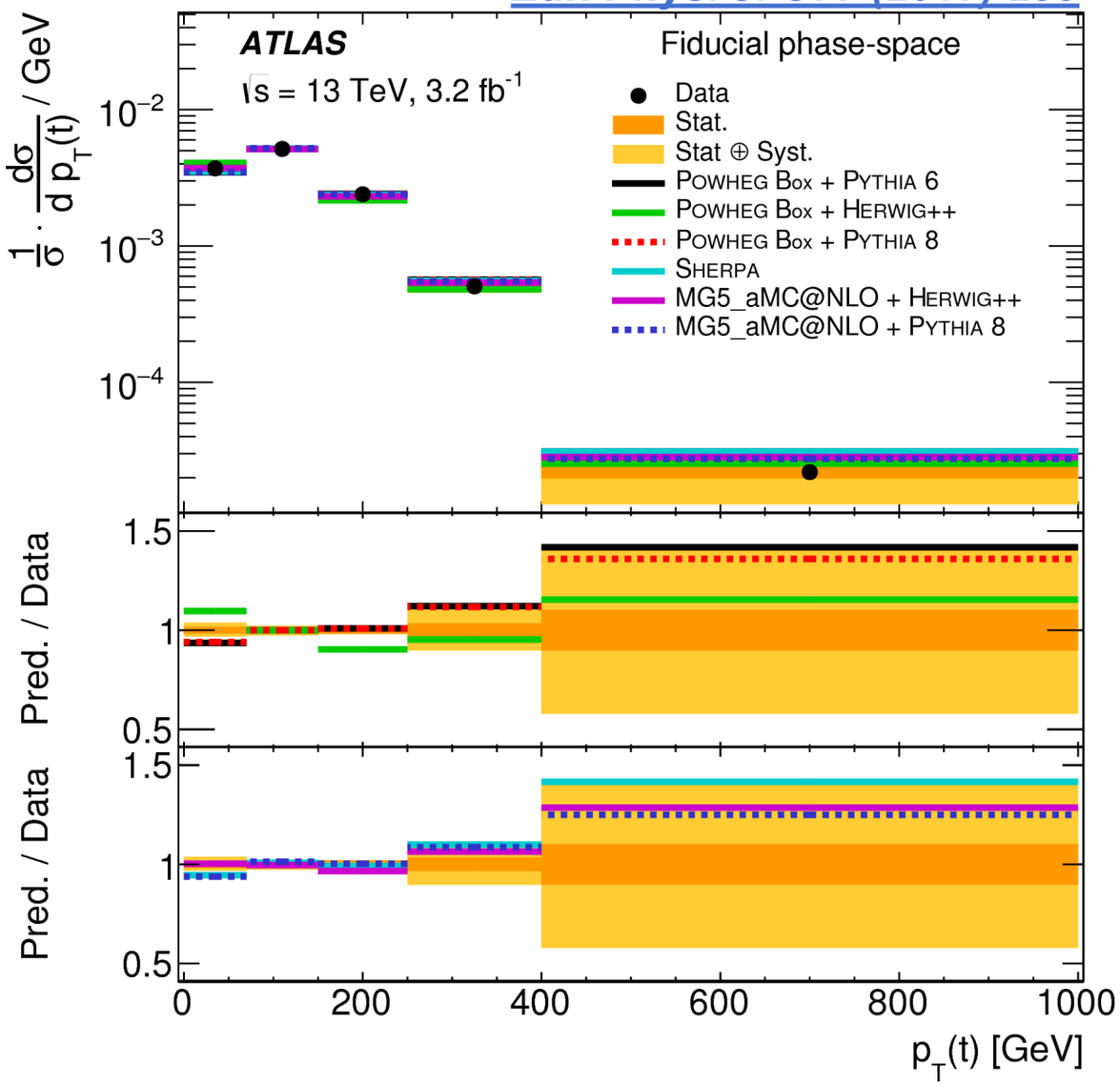

Top quark p_T

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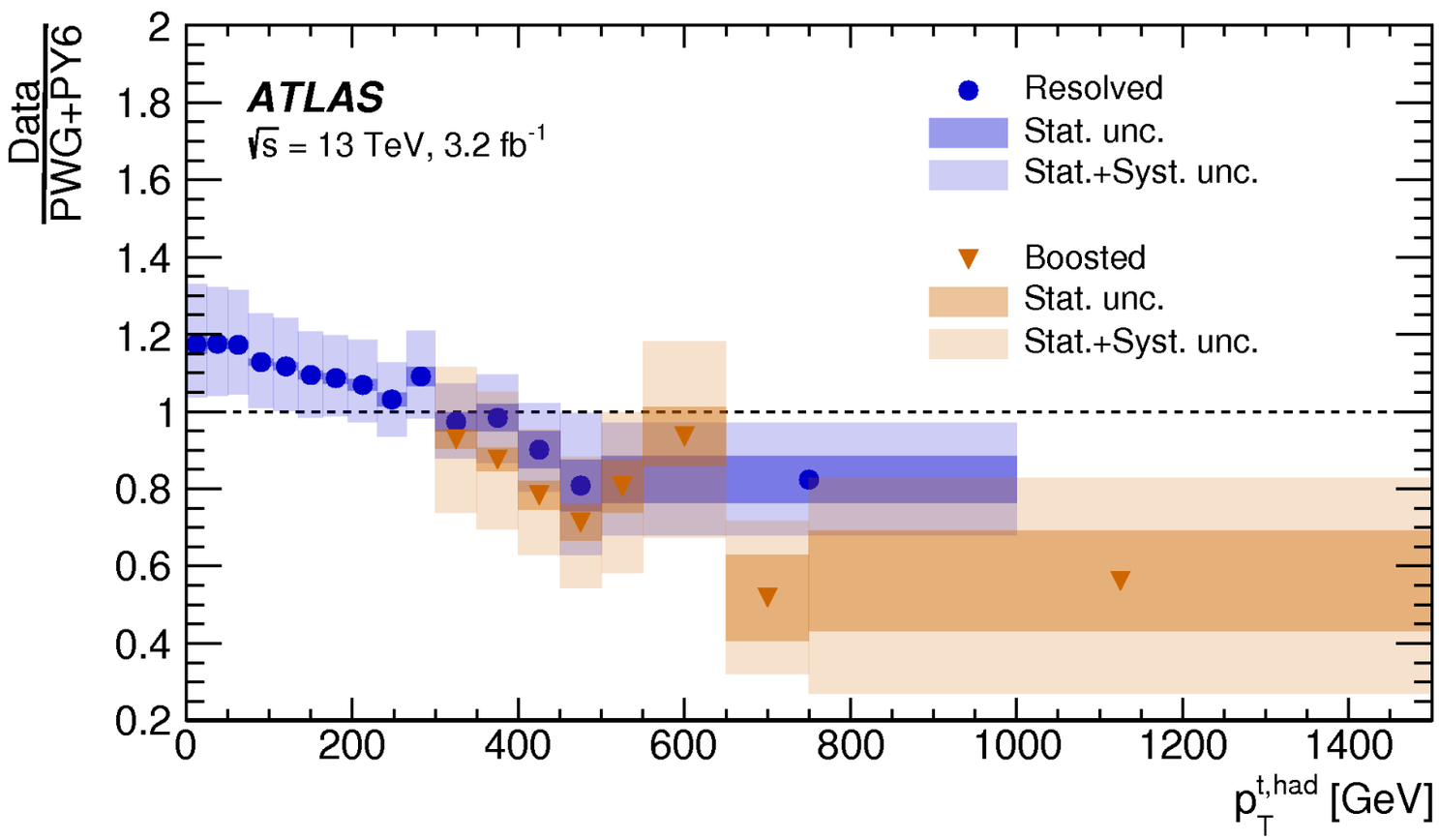
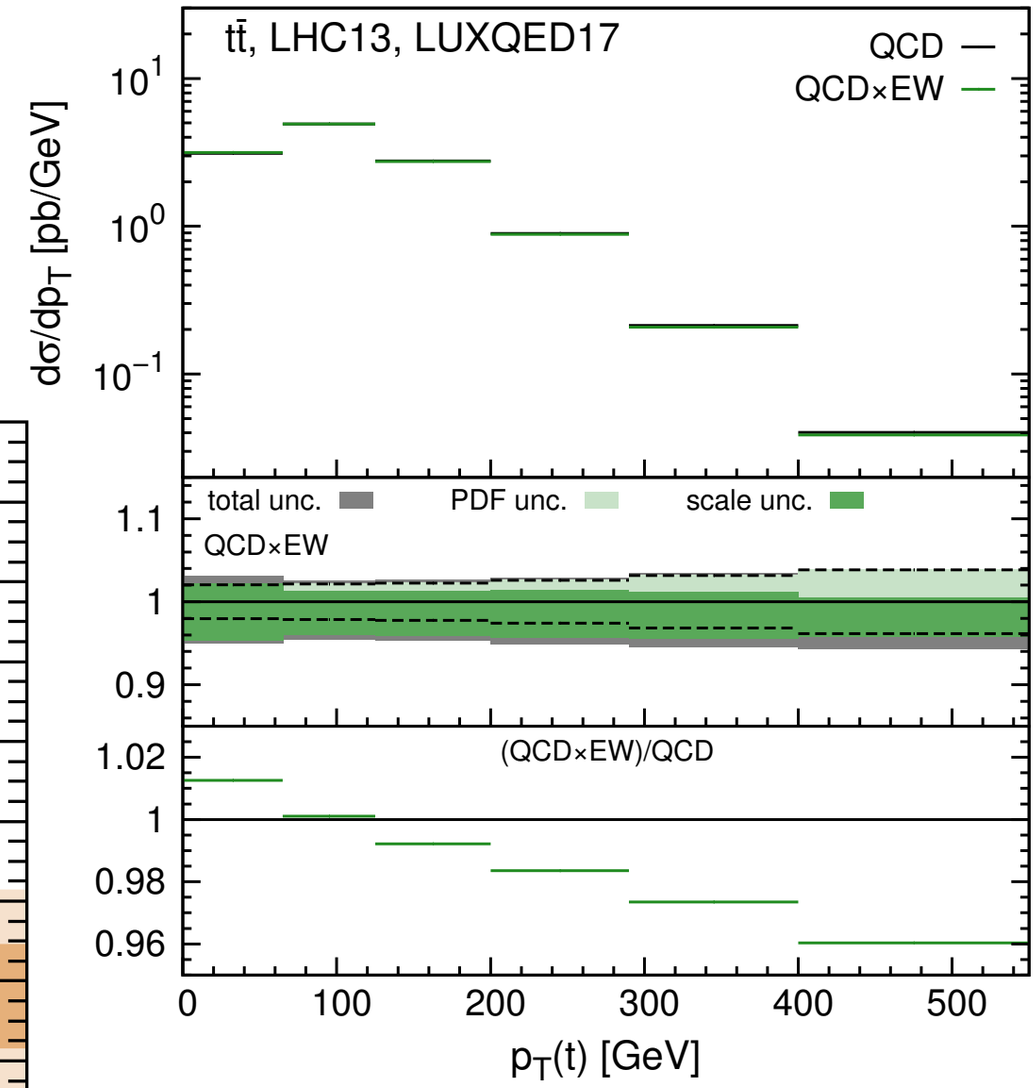
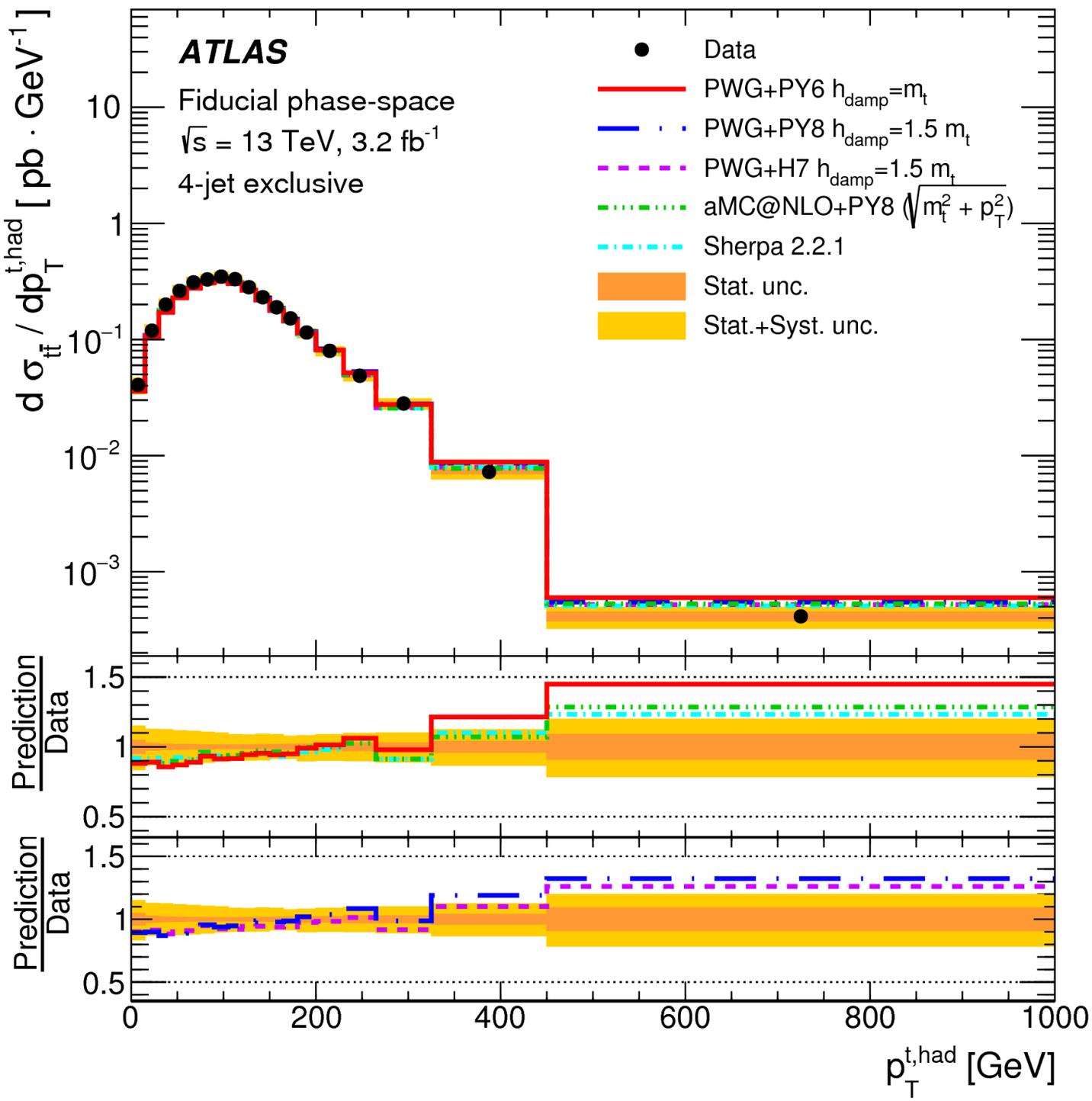
Resolved and boosted channel "overlap" and reinforce the mismodelling

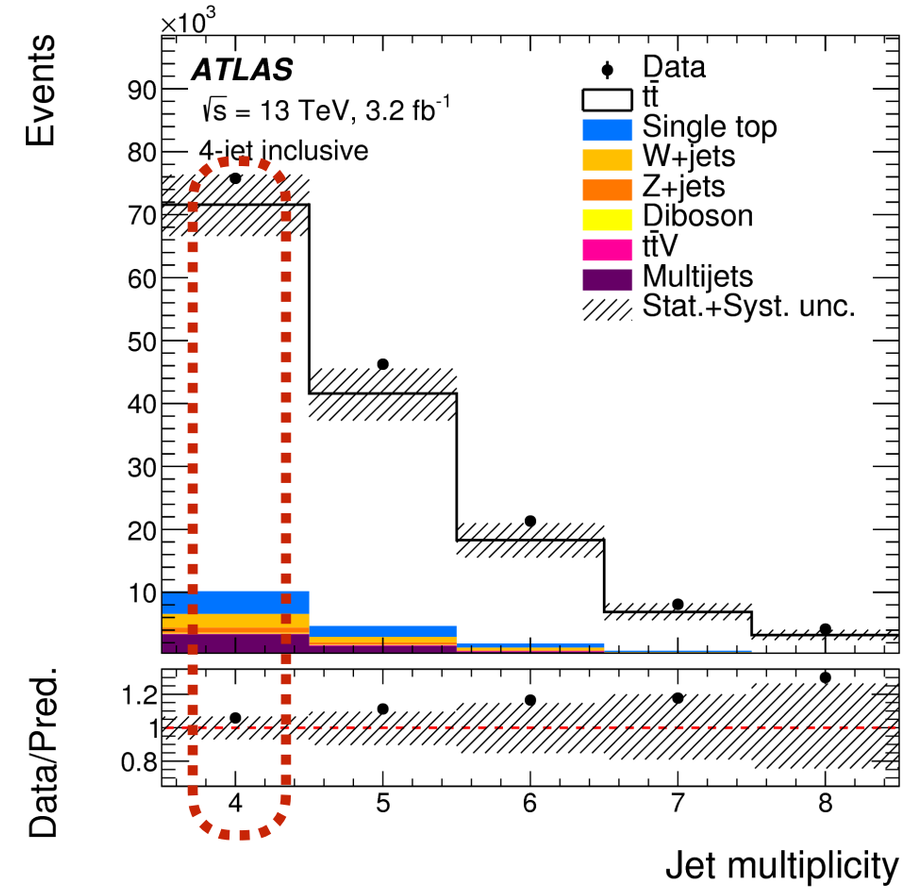




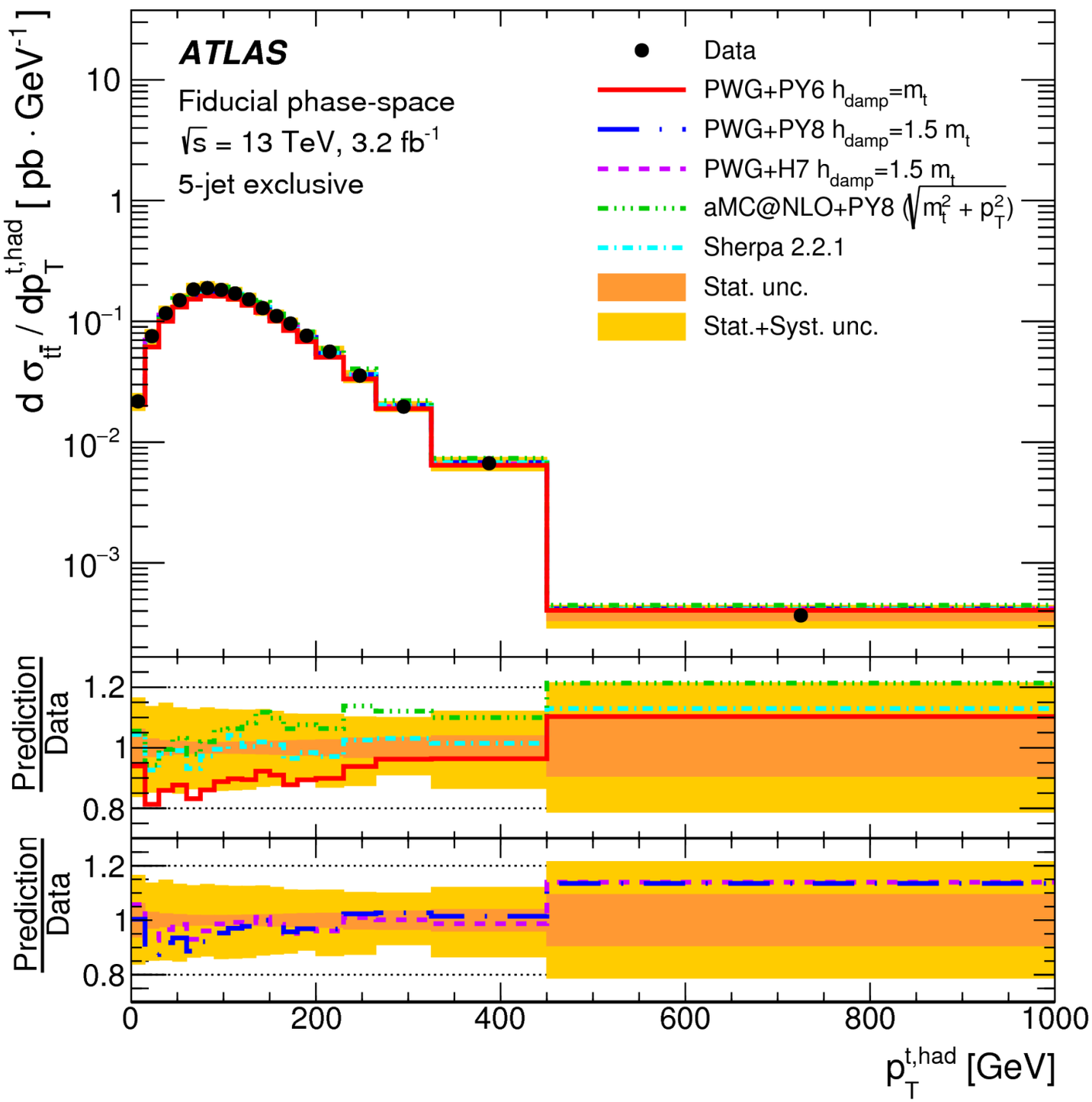
NNLO QCD + NLO EW corrections important
But do not fully explain discrepancy

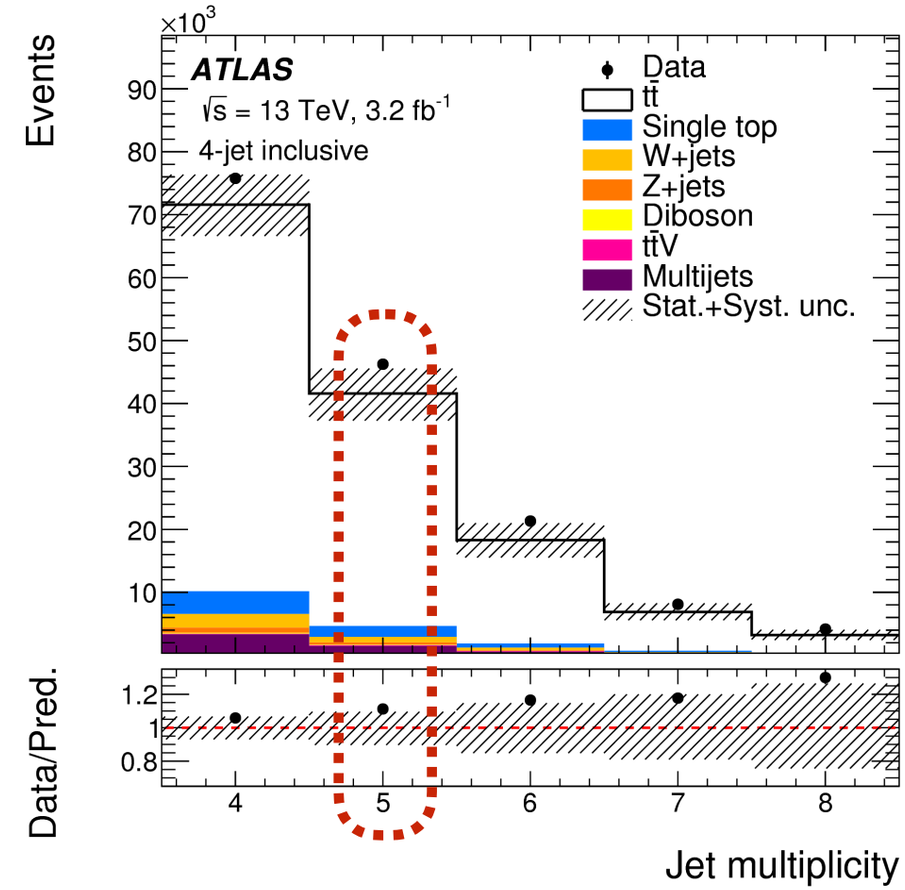
$t\bar{t}$ (ℓv2j2b)+ 0j



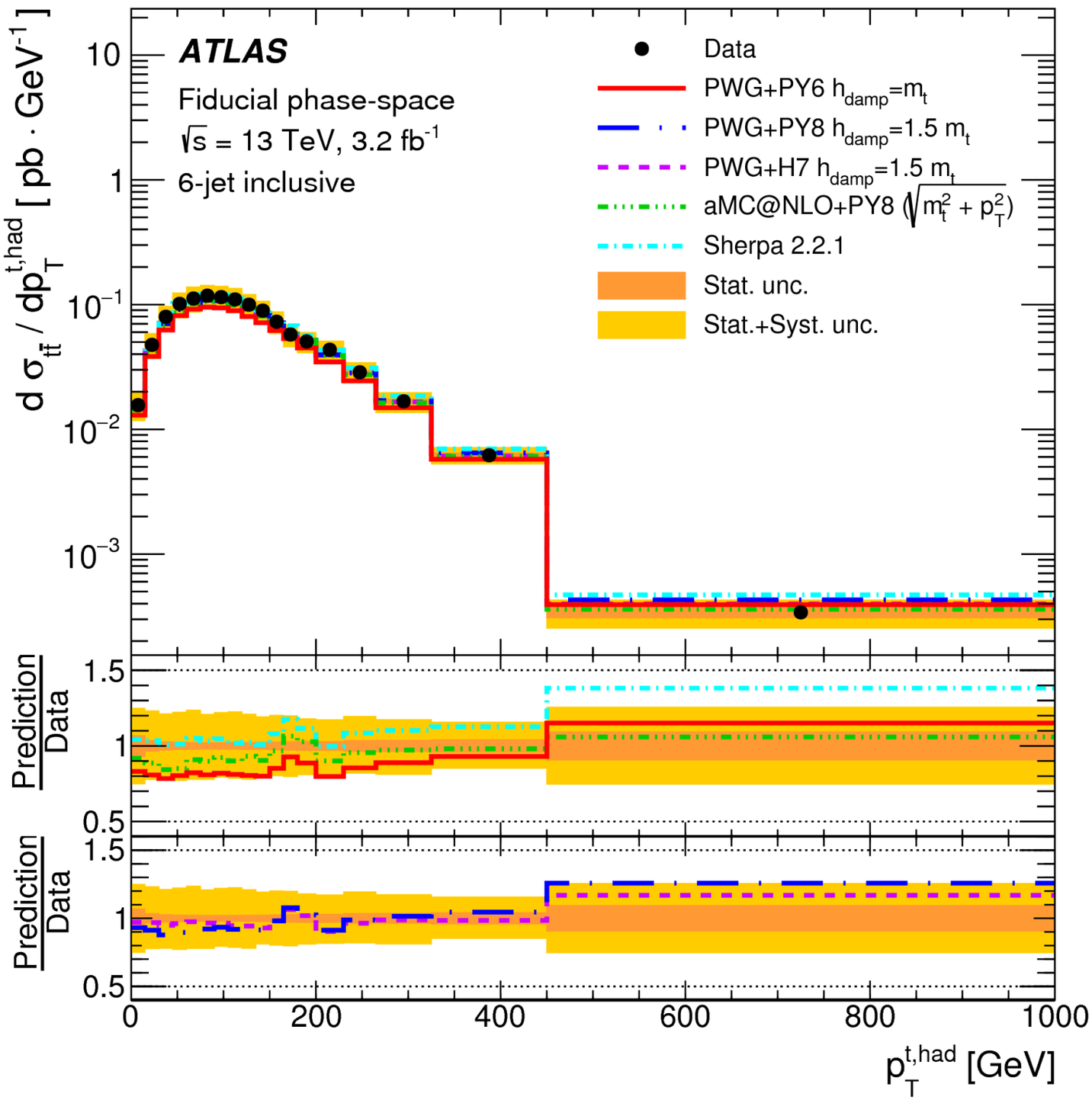


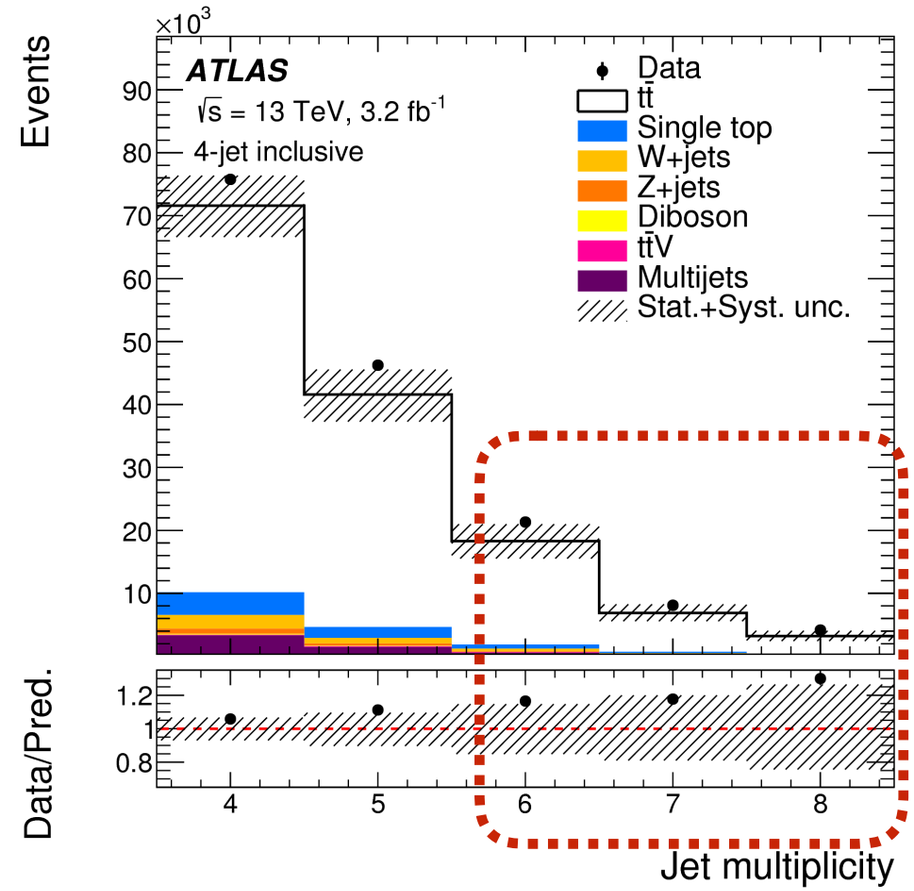
$t\bar{t}(\ell\nu 2j2b) + 1j$

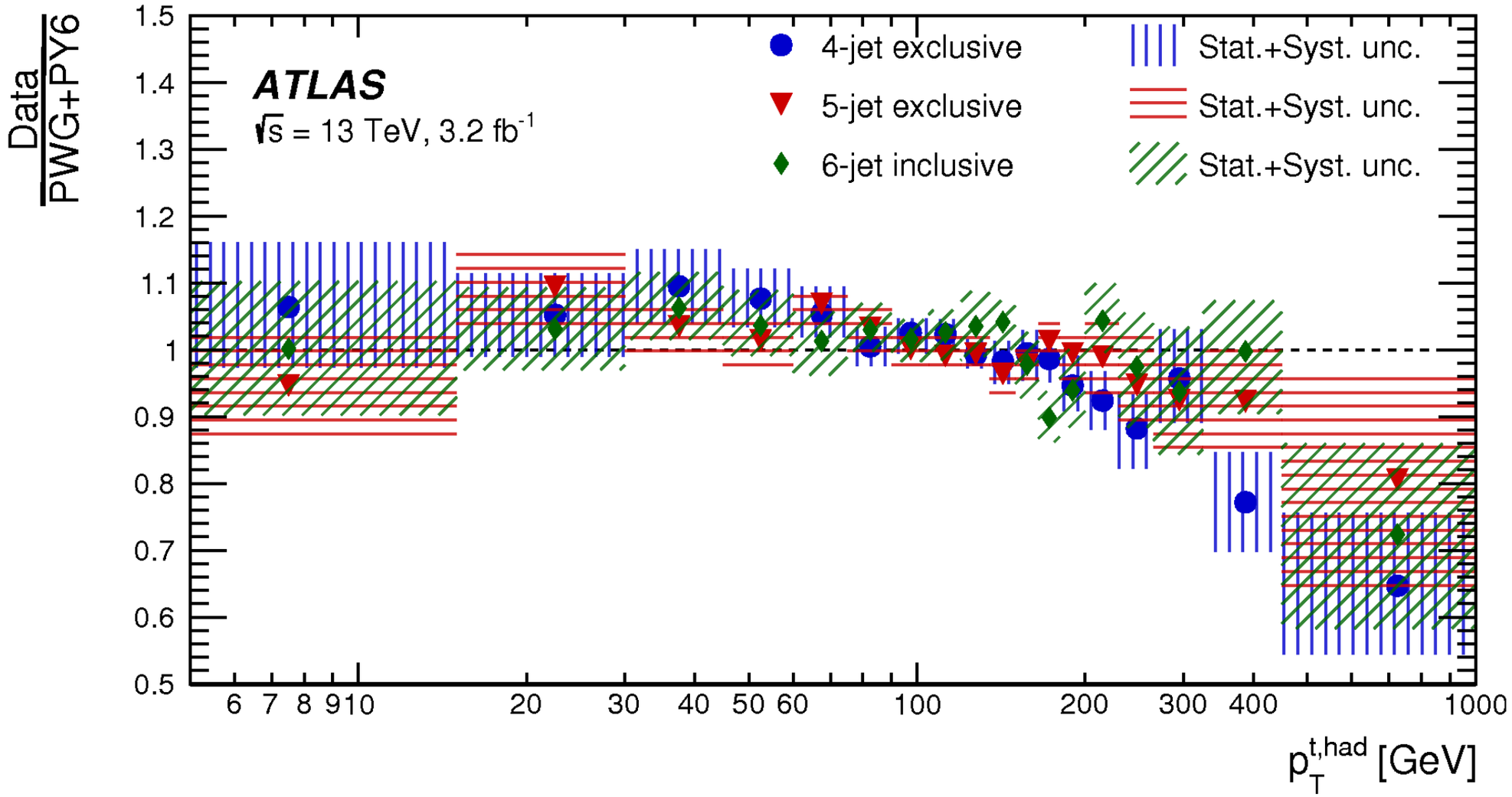




$t\bar{t}$ (ℓv2j2b)+ ≥2j







- Poorest data/PP6 disagreement in $t\bar{t}$ ($\ell\nu$2j2b)+ 0j
- Improved agreement with more additional jets

Top quark p_T (boosted)

Hadronic top
(single lepton channel)

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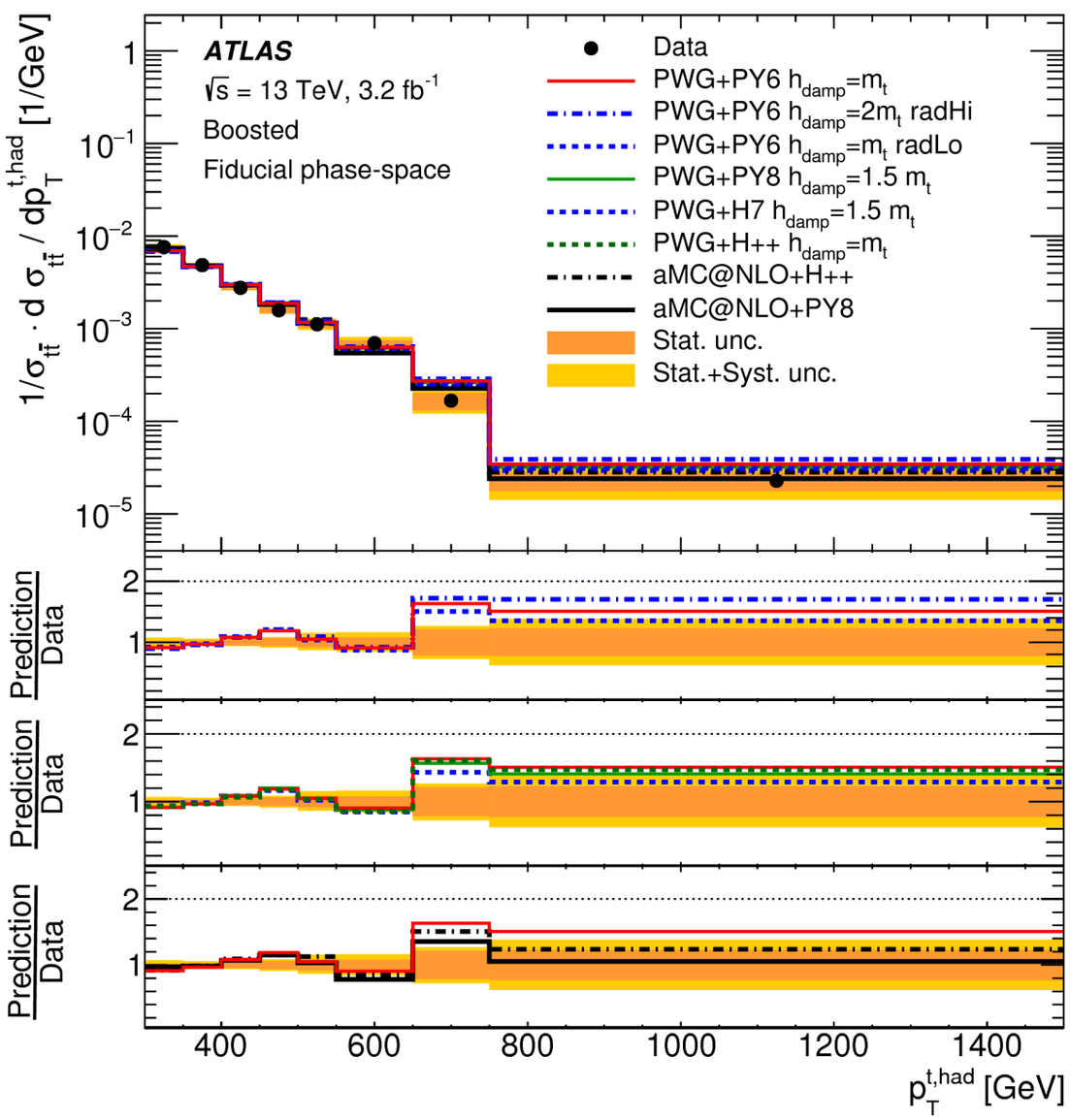

Leading hadronic top
(all-hadronic channel)

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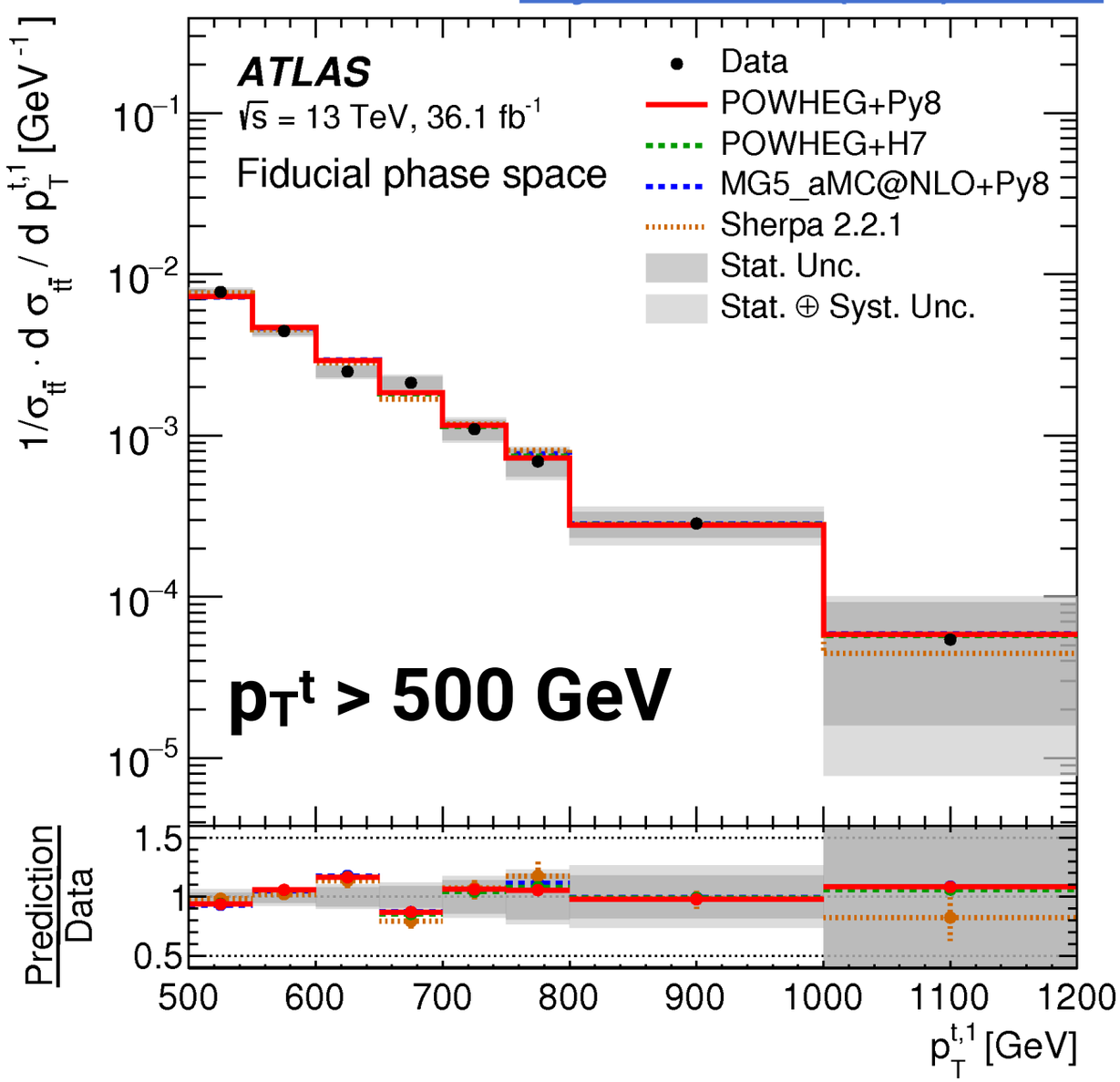

Top quark y (low p_T)

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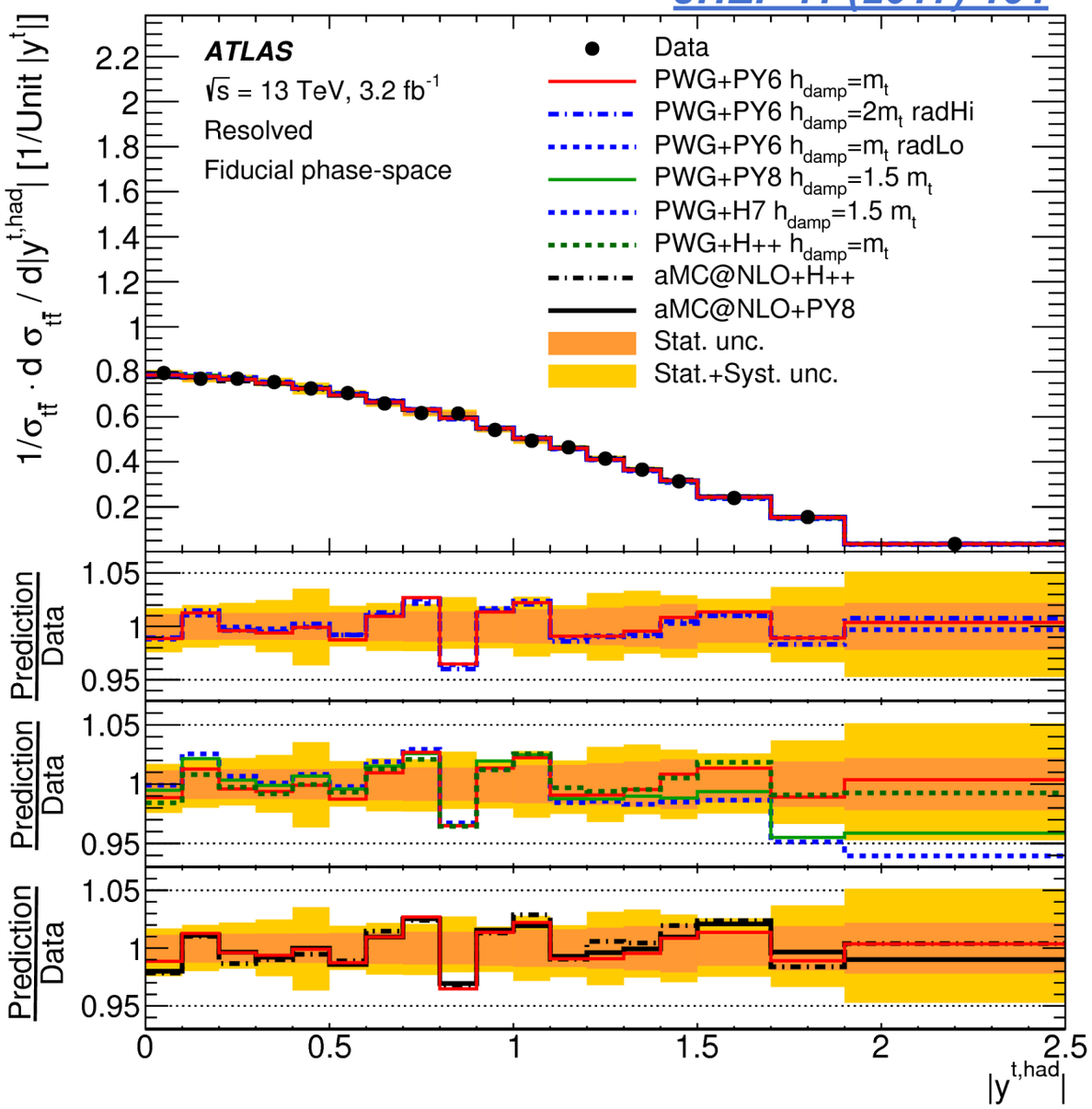

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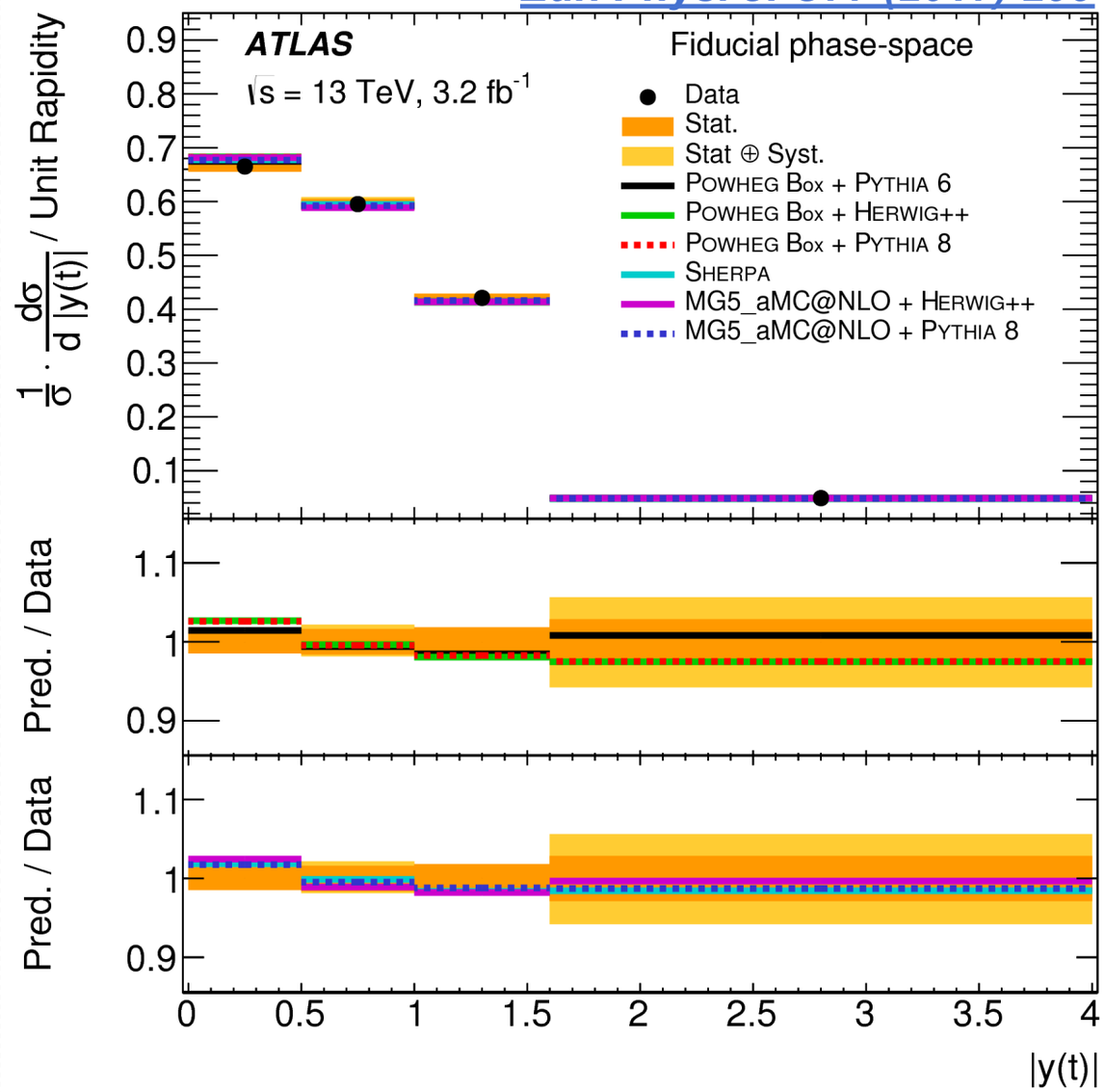

Hadronic top
(single lepton channel)

Leptonic top
(dilepton channel)

Top quark y (high p_T)

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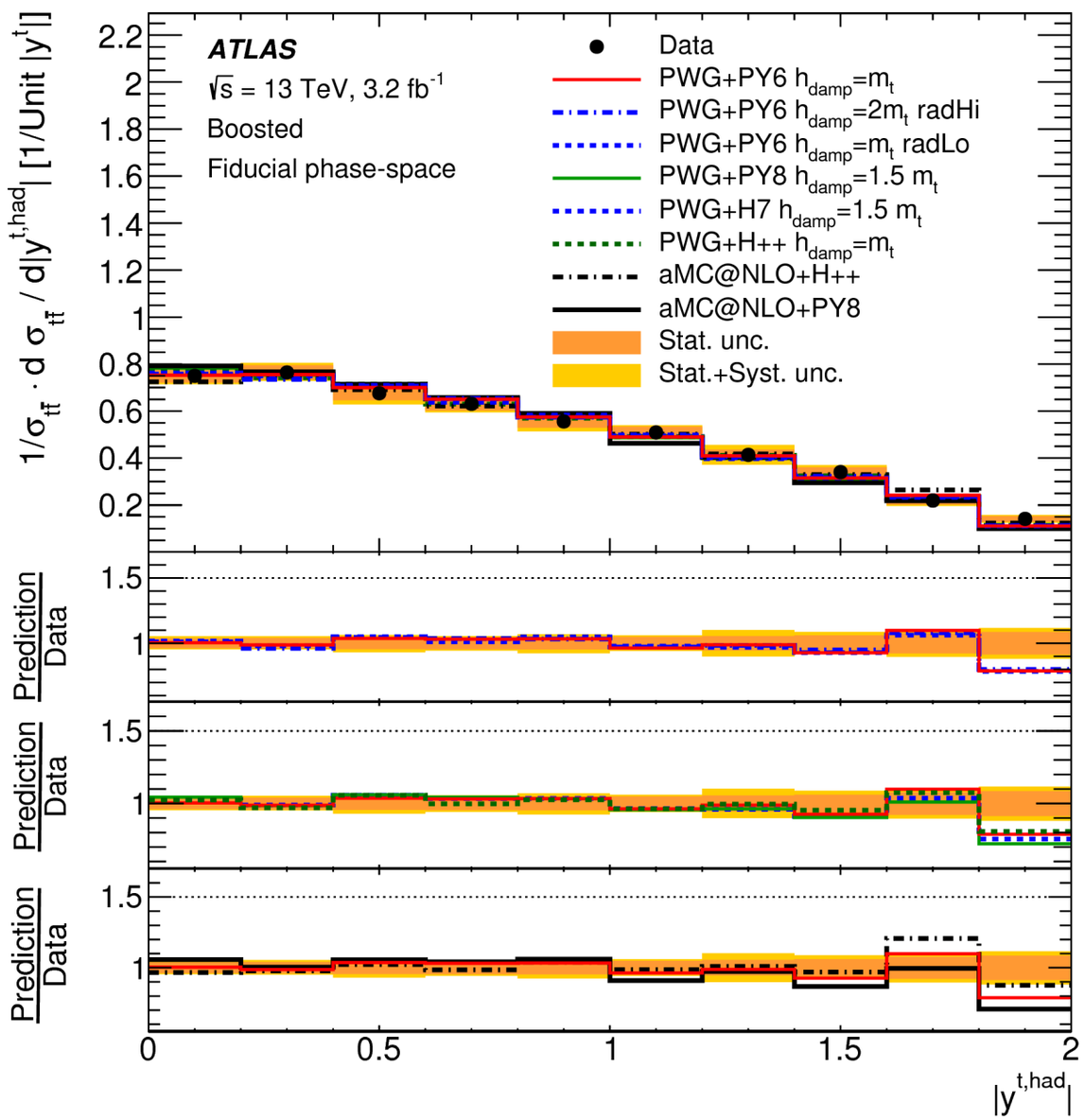

Hadronic top
(single lepton channel)

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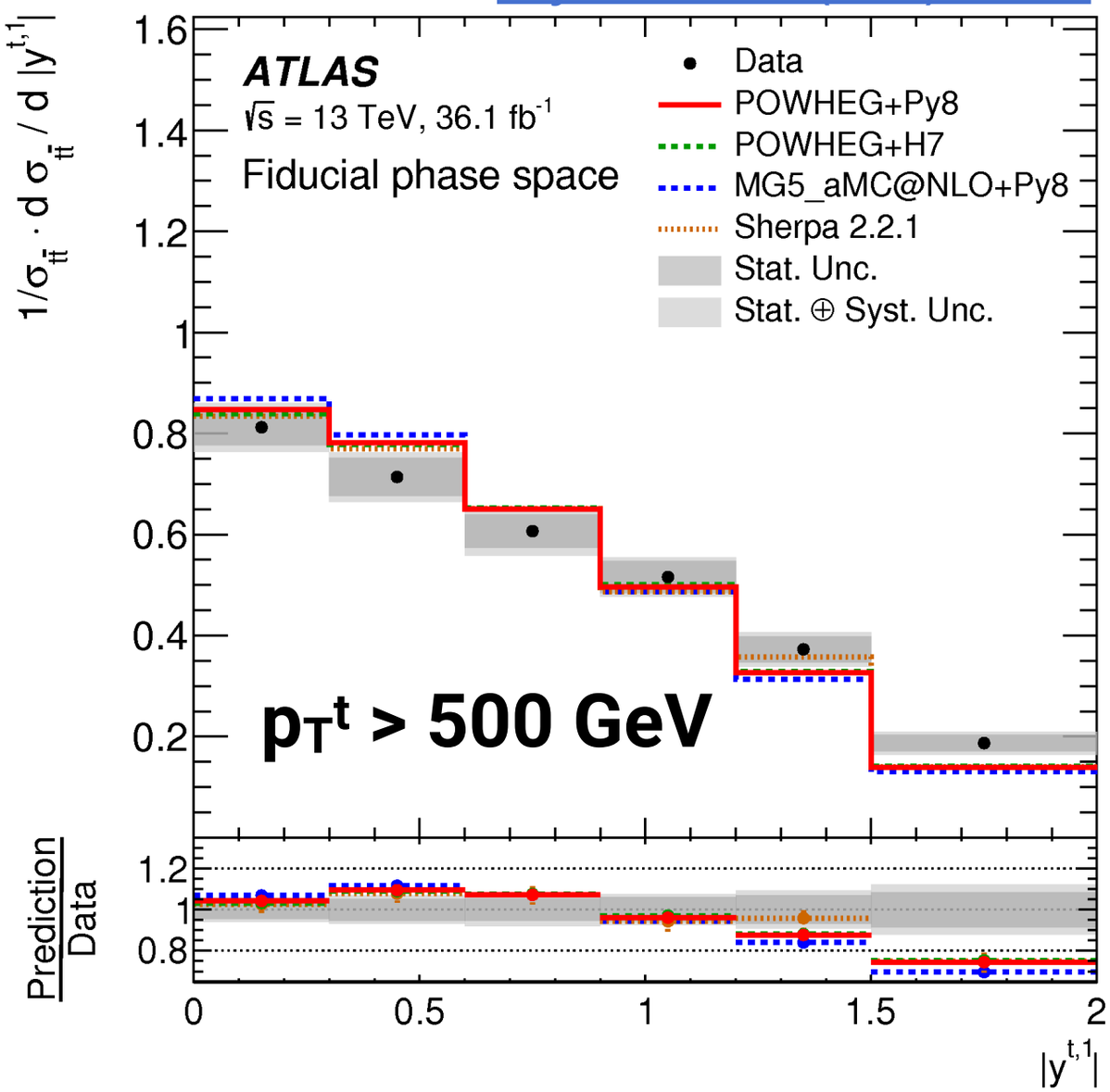
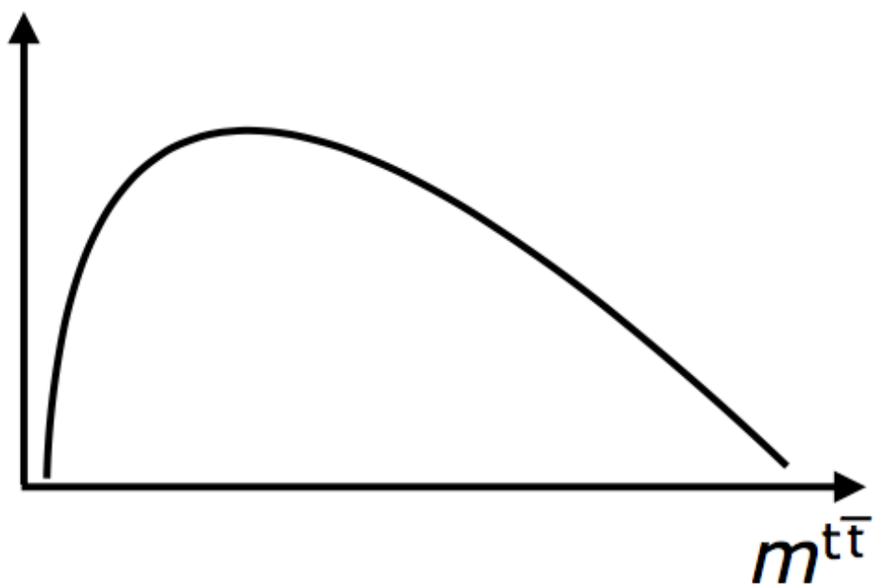
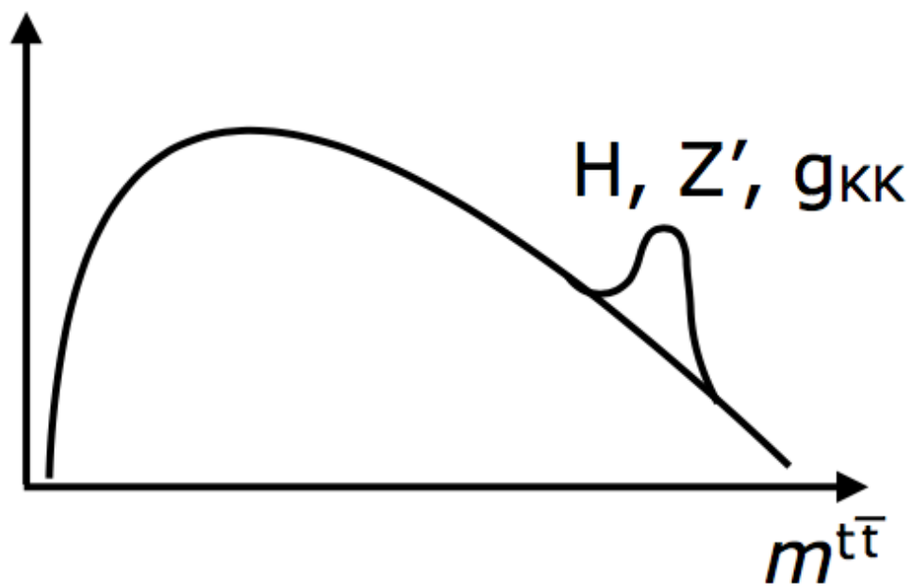


Leading hadronic top
(all-hadronic channel)

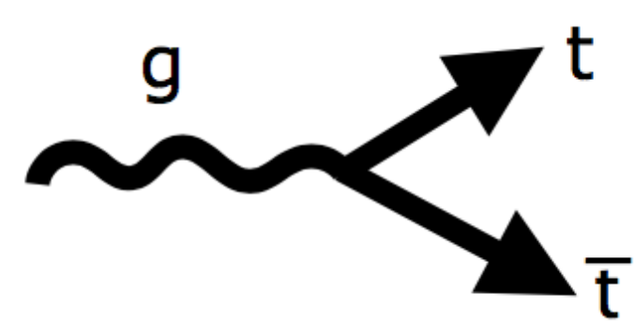
$t\bar{t}$ system m, y, p_T

- Mass the most intriguing observable
- Appearance of bumps/deficits may indicate presence of BSM (resonances, interference)





- Rapidity sensitive to PDF
- p_T^{tt} sensitive to extra radiation



$t\bar{t}$ invariant mass

Single lepton

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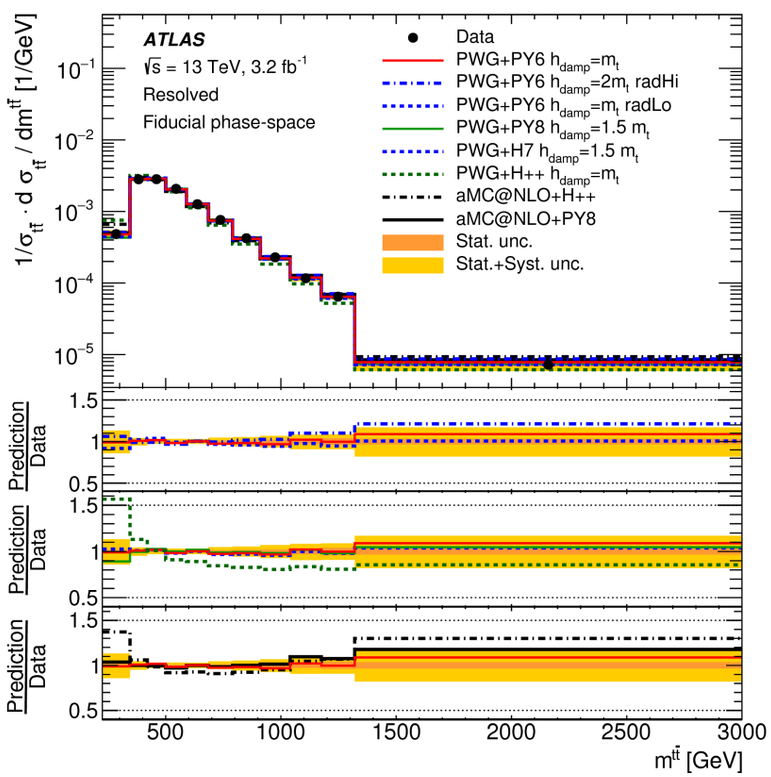

Dilepton

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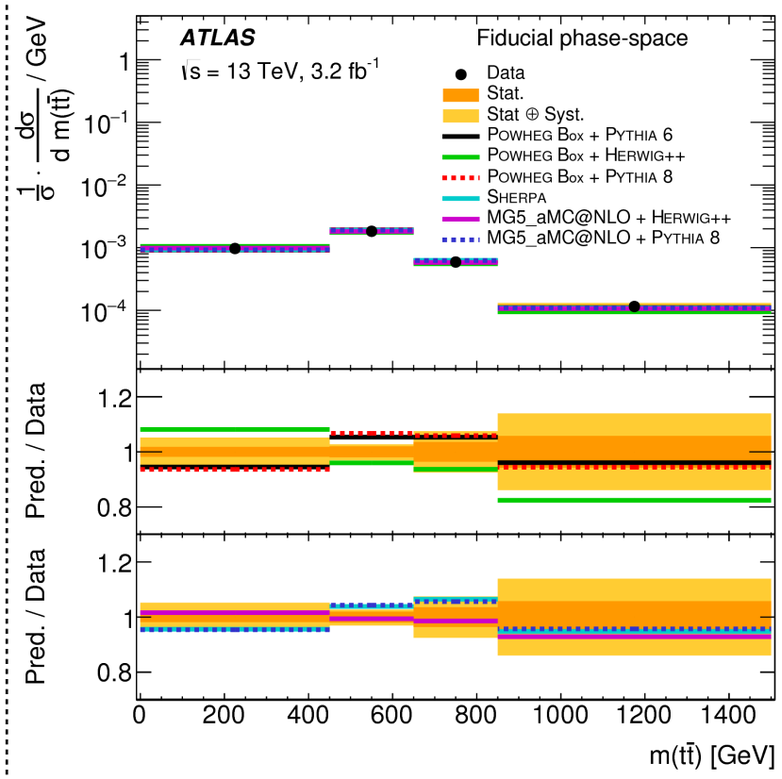

All-hadronic

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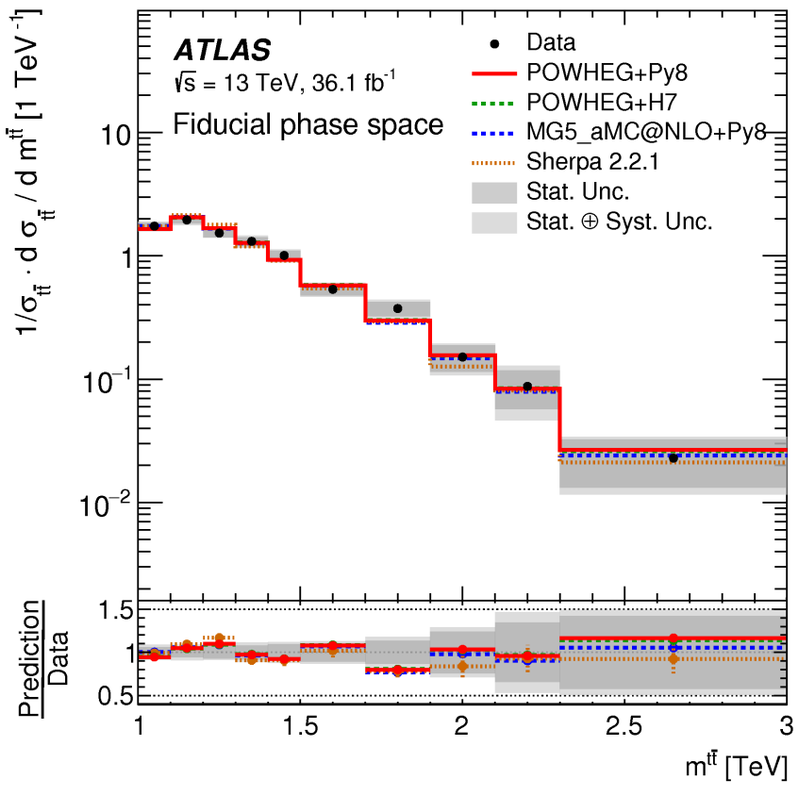

- Generally well modelled, PWG+Herwig++ out-of-the-box disagrees with data
- Low stats or low resolution at high-m^{tt} limiting bump hunting
- All-Hadronic boosted best resolution to this date at very high mass

$t\bar{t}$ rapidity

Single lepton

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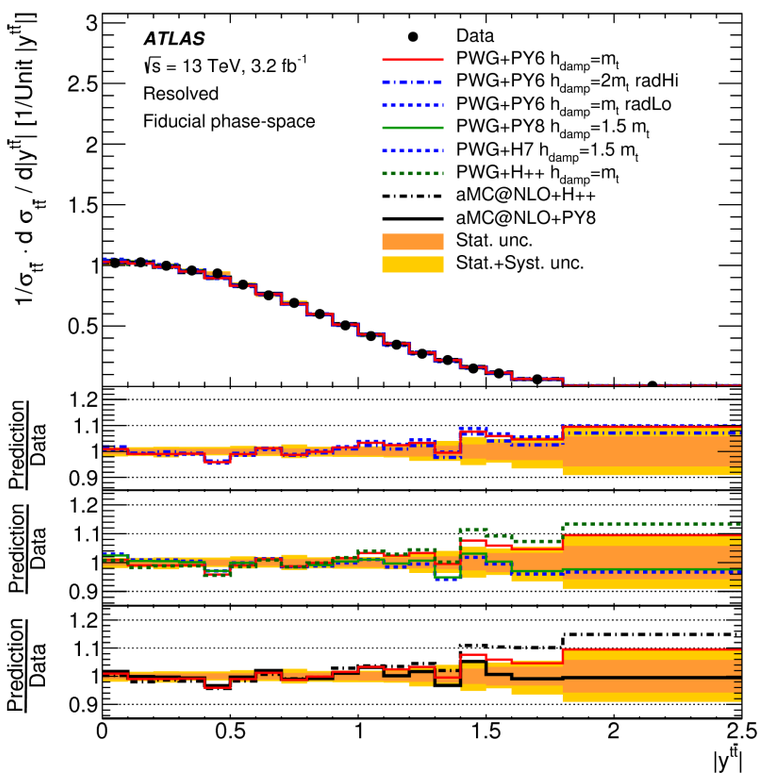
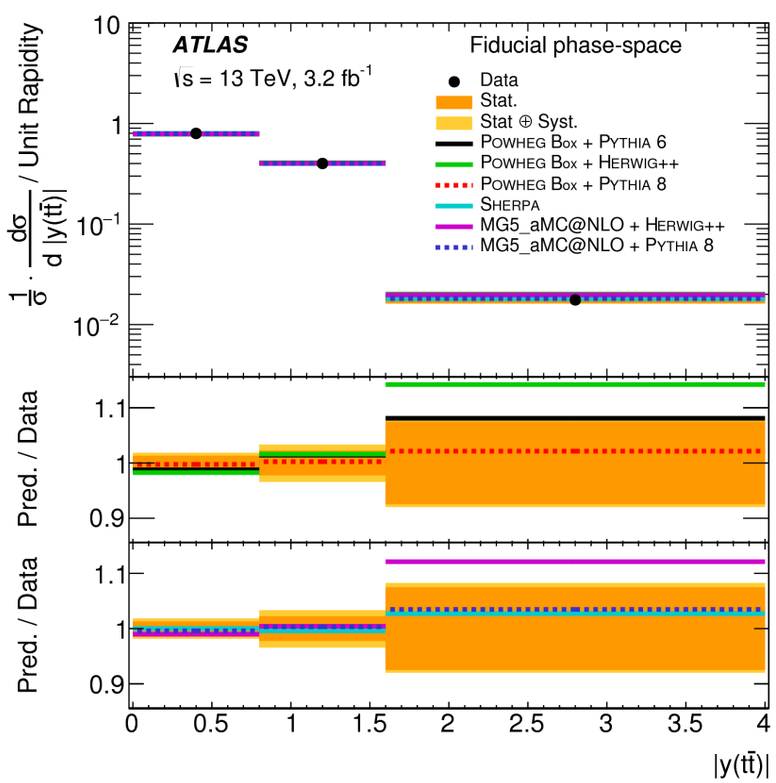


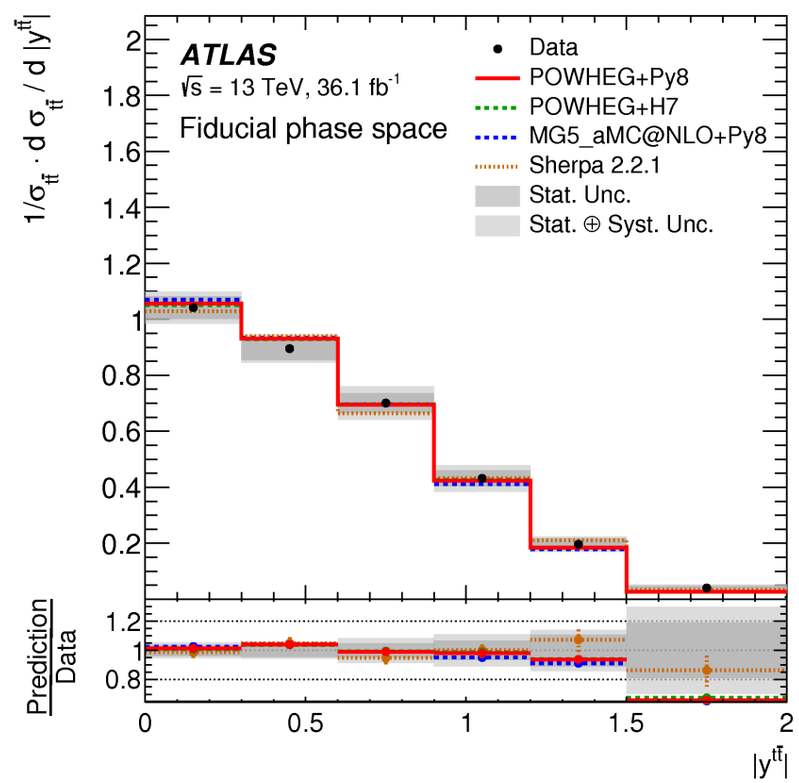
Dilepton

[Eur. Phys. J. C77 (2017) 299](#)



All-hadronic

[Phys. Rev. D 98 (2018) 012003](#)



- Good agreement with PWG+P8
- PWG+Herwig++ too hard/forward

$t\bar{t}$ transverse momentum

Single lepton

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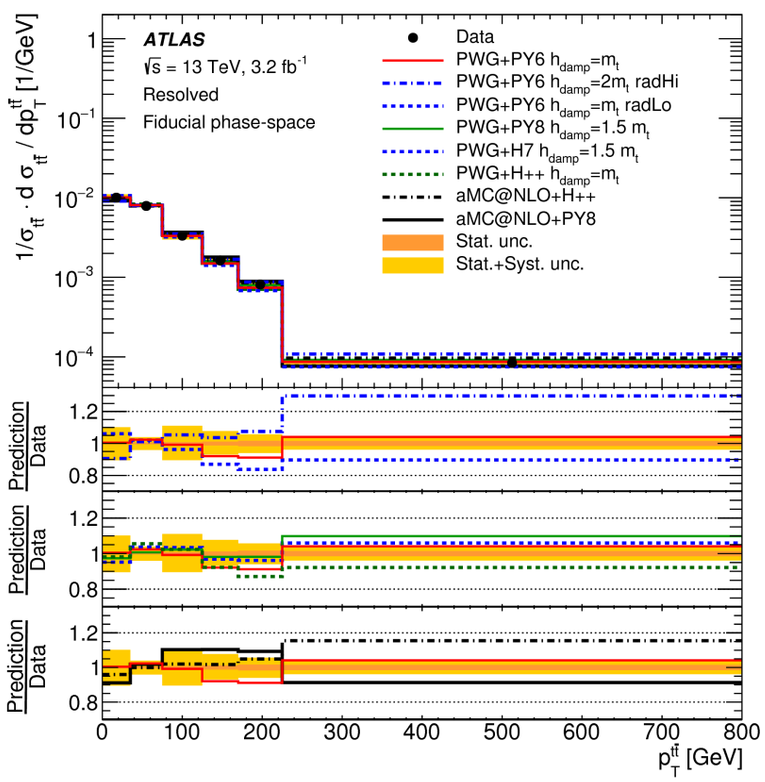

Dilepton

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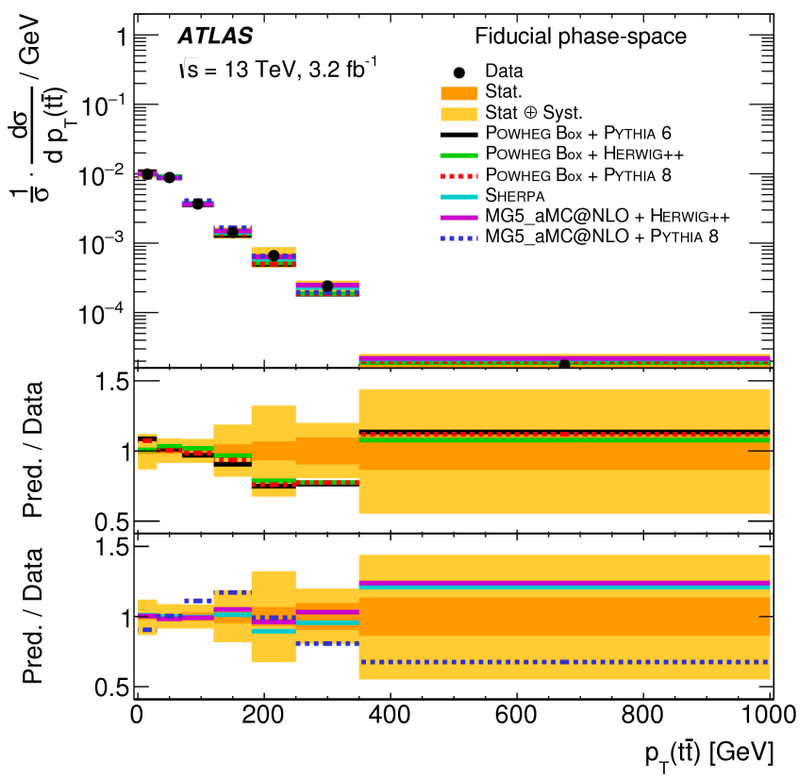
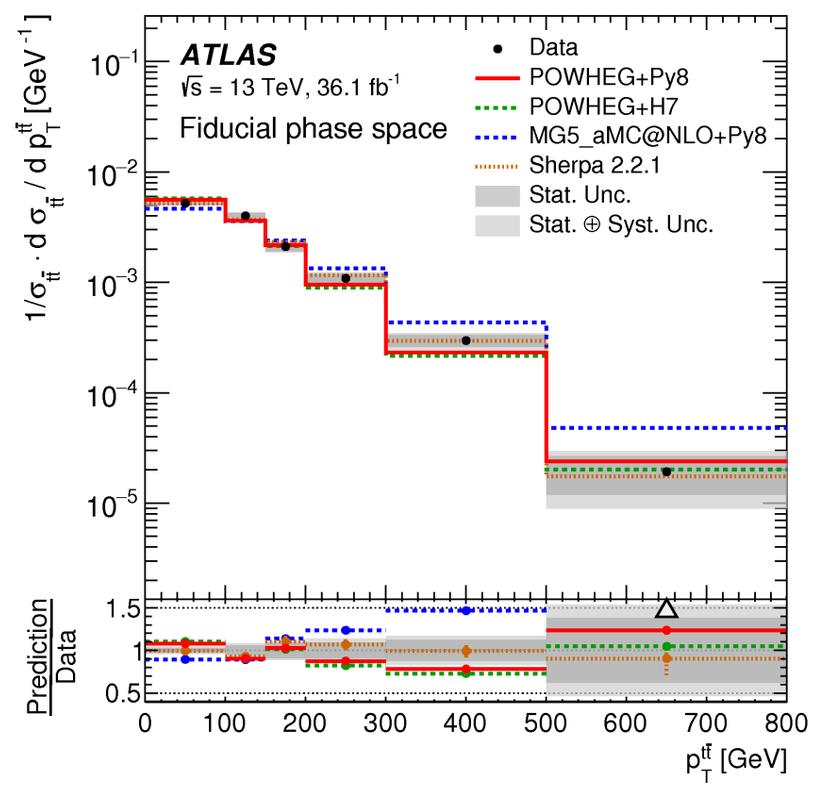


All-hadronic

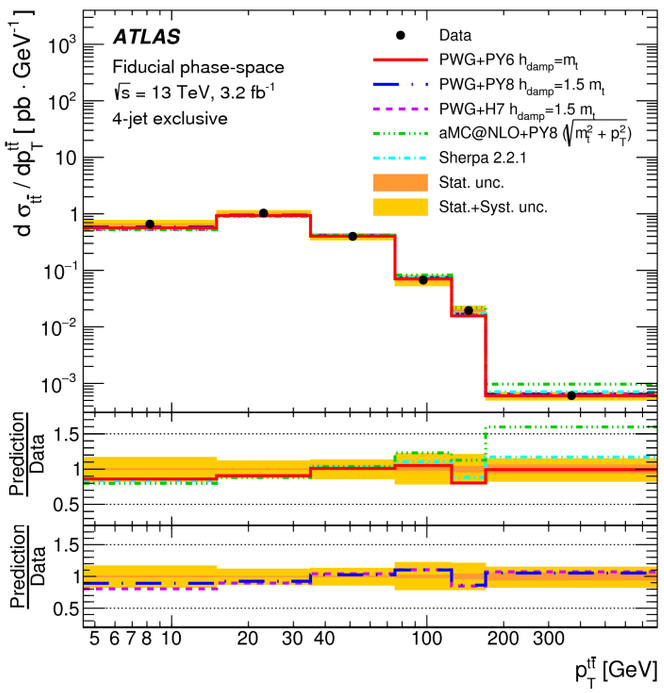
Phys. Rev. D 98 (2018) 012003



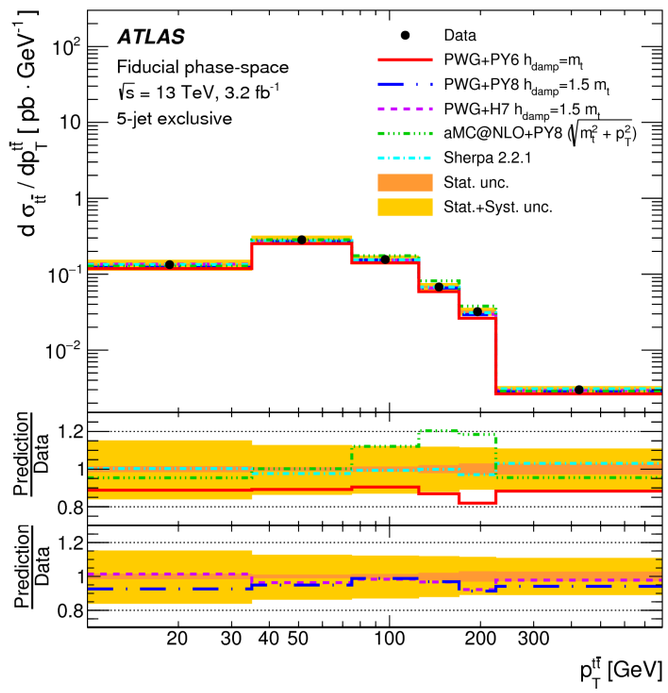
- Good agreement, but low stats and large uncertainties at high-p_T^{tt}
- aMC@NLO+P8 setup needs improvement

$t\bar{t}$ transverse momentum

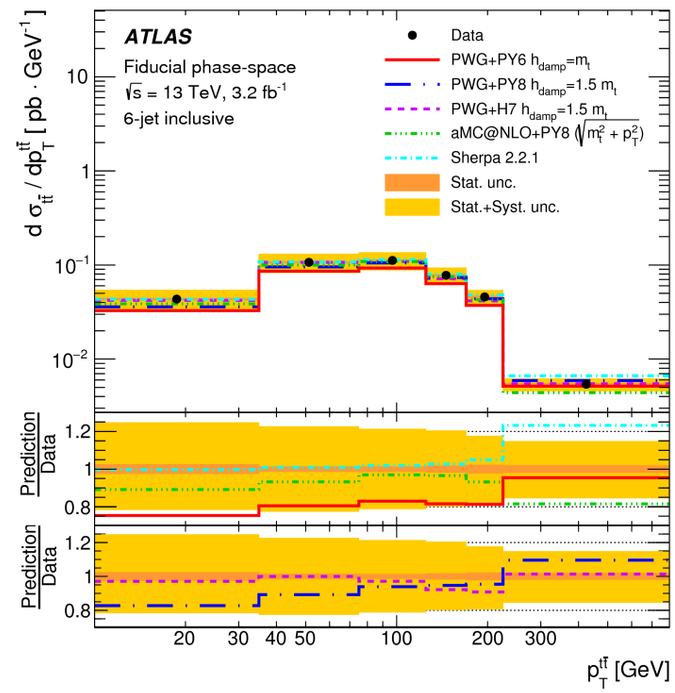
$t\bar{t}$ ($\ell\nu$2j2b)+ 0j



$t\bar{t}$ ($\ell\nu$2j2b)+ 1j



$t\bar{t}$ ($\ell\nu$2j2b)+ ≥2j



- NB: $p_T(t\bar{t})$ up to 300 GeV even in 4j excl bin
- Overall good agreement, ~20% uncertainties

Extra radiation

$t\bar{t}$ (ℓv2j2b)+ 0j

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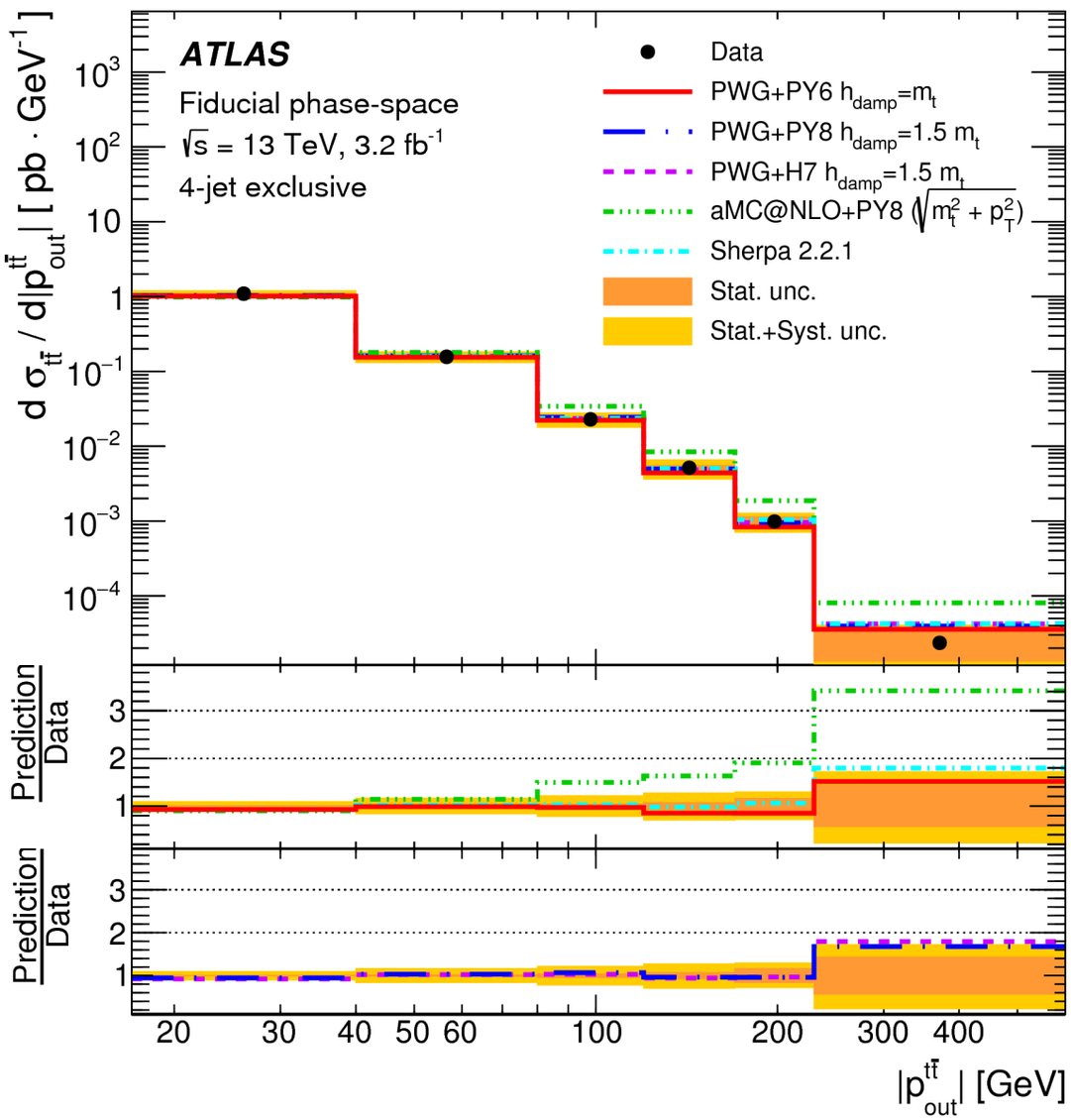

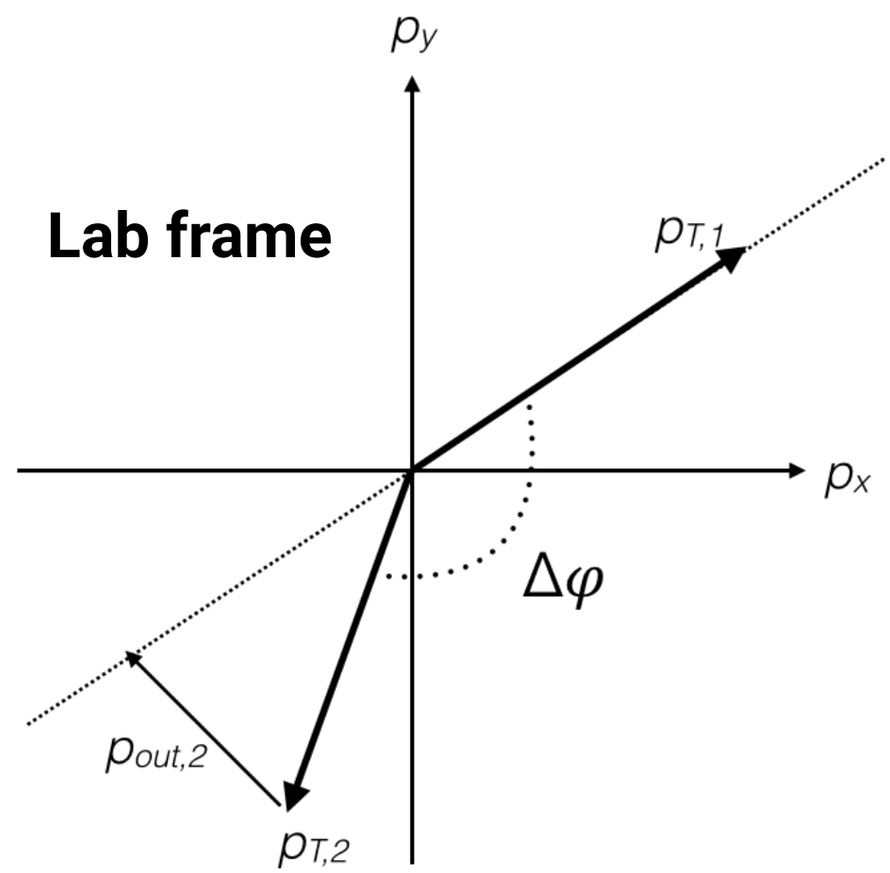

"out-of-plane" momentum
(correlated with p_T^{tt} and $\Delta\varphi^{tt}$)

- Additional radiation (esp ISR) test NLO, NNLO calculations
- Very useful for MC tuning

Extra radiation

$t\bar{t}$ (ℓv2j2b)+ 1j

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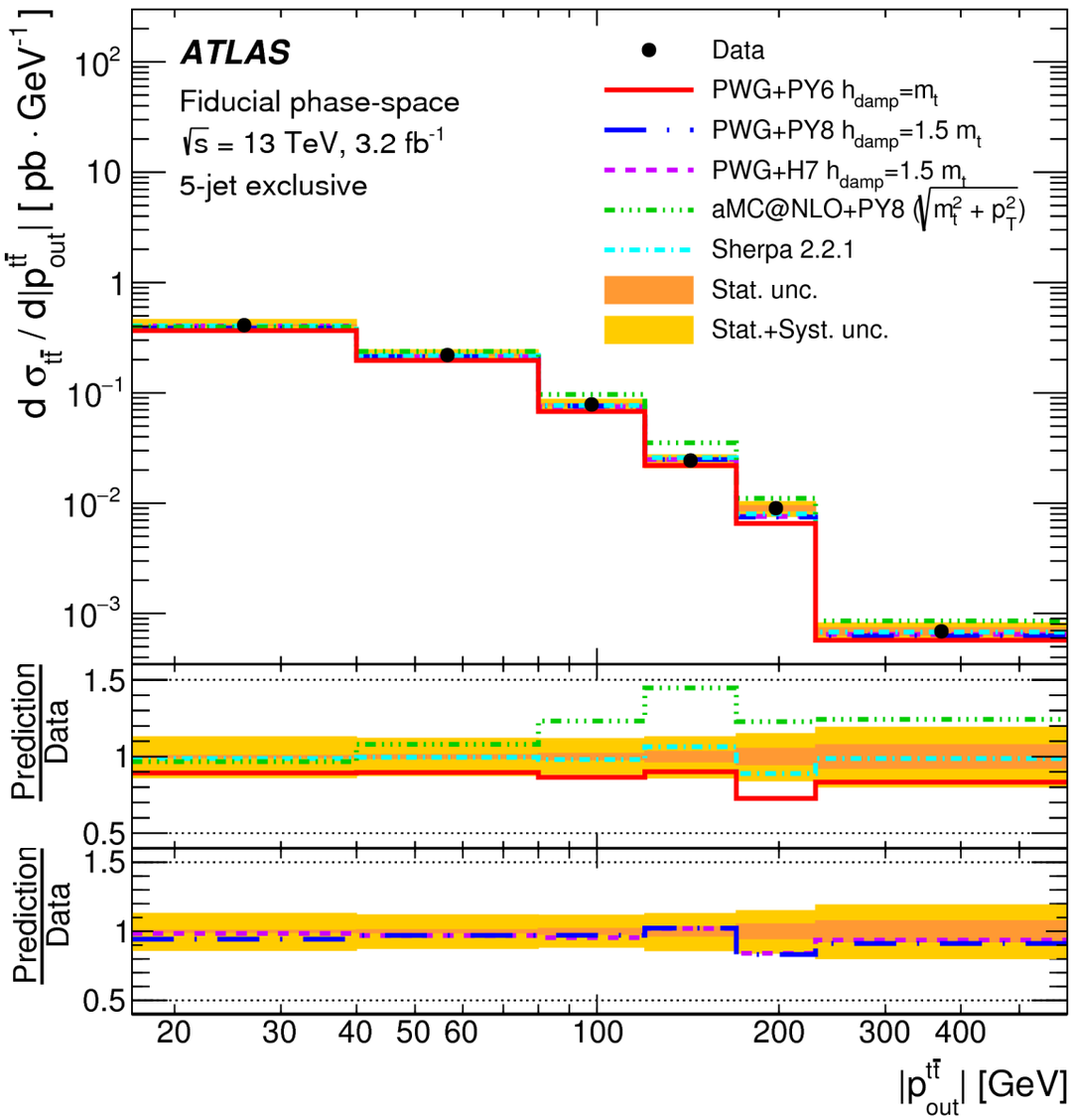

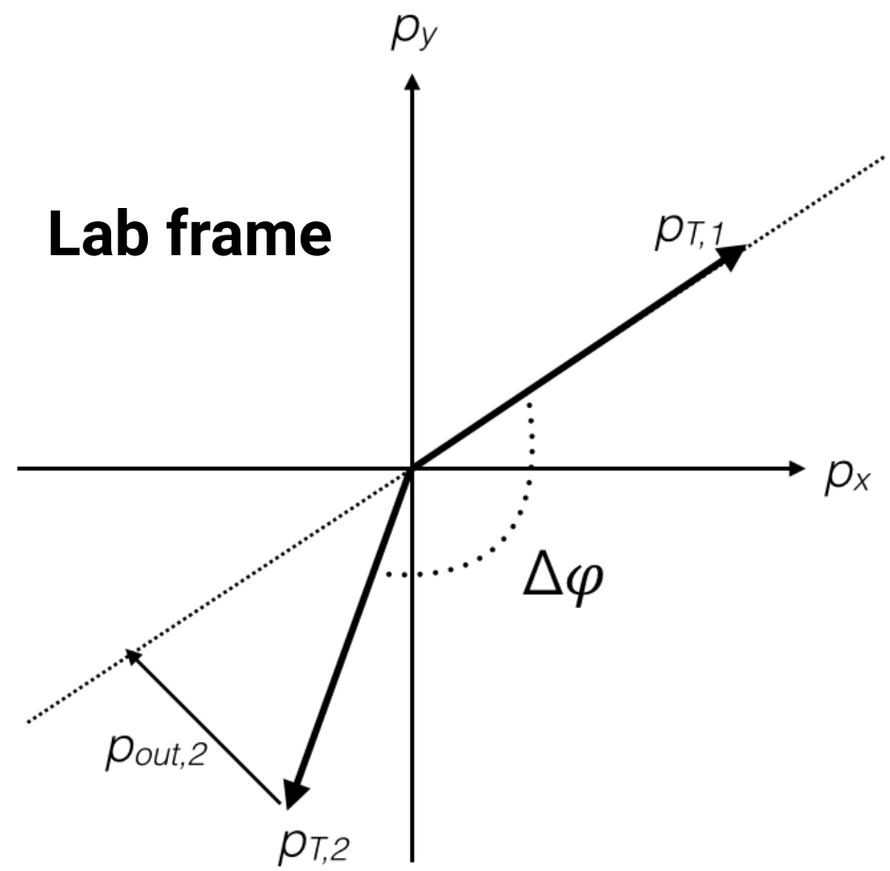

"out-of-plane" momentum
(correlated with p_T^{tt} and $\Delta\varphi^{tt}$)

- Additional radiation (esp ISR) test NLO, NNLO calculations
- Very useful for MC tuning

Extra radiation

$t\bar{t}$ ($\ell\nu$2j2b)+ ≥2j

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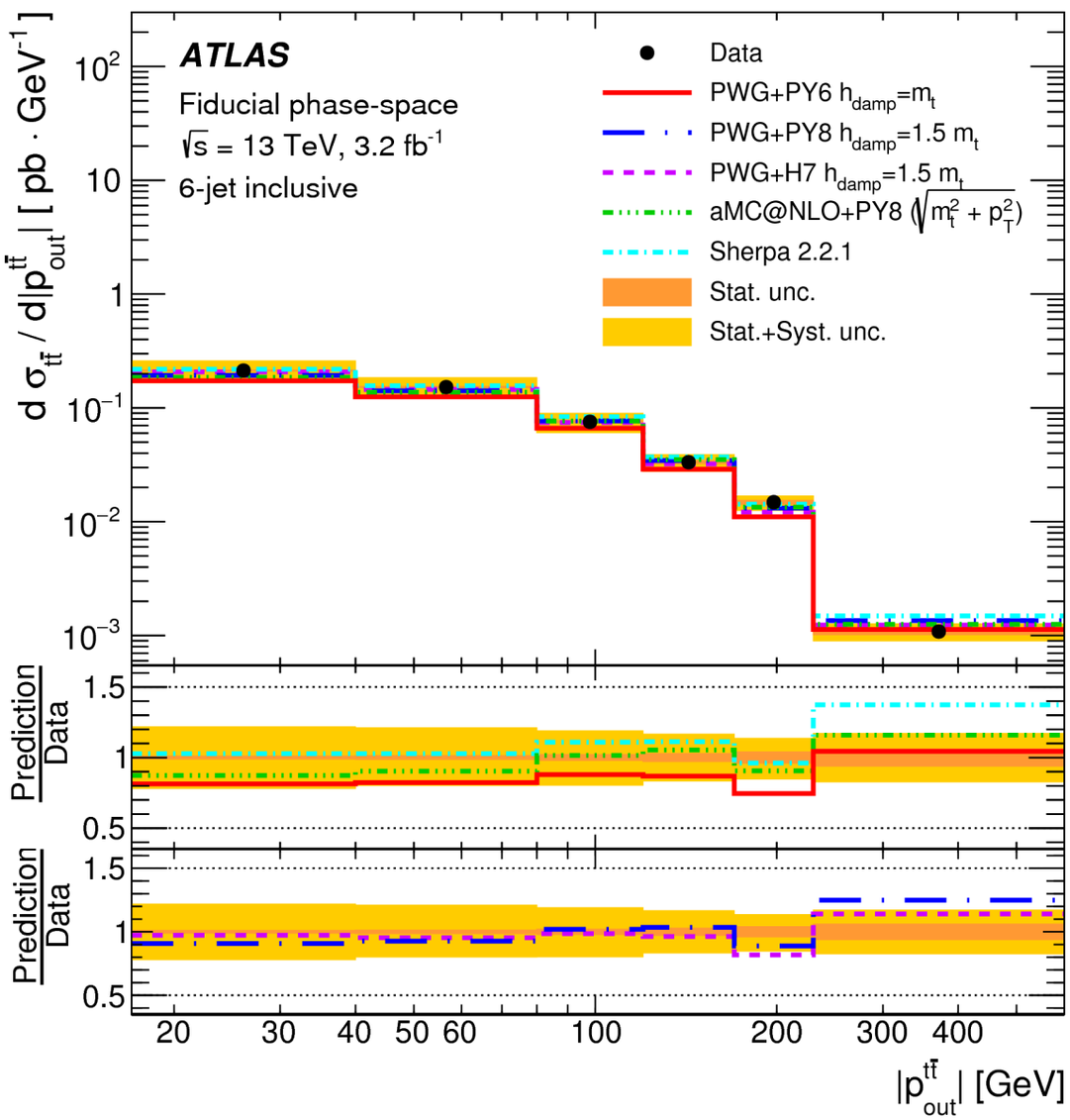

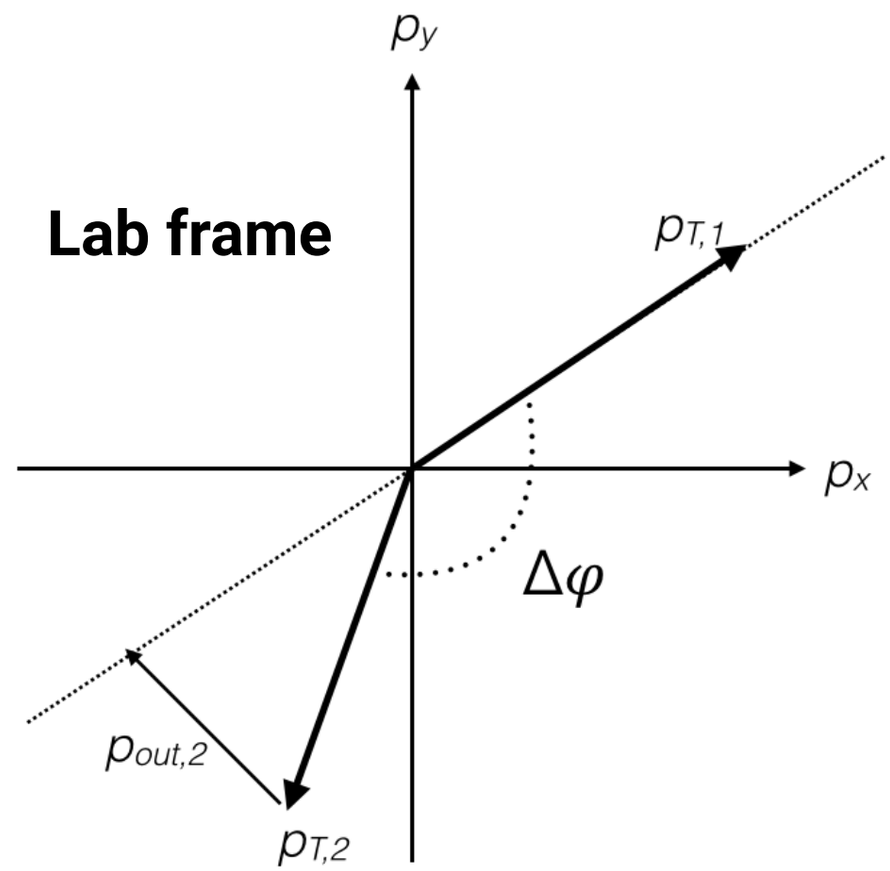

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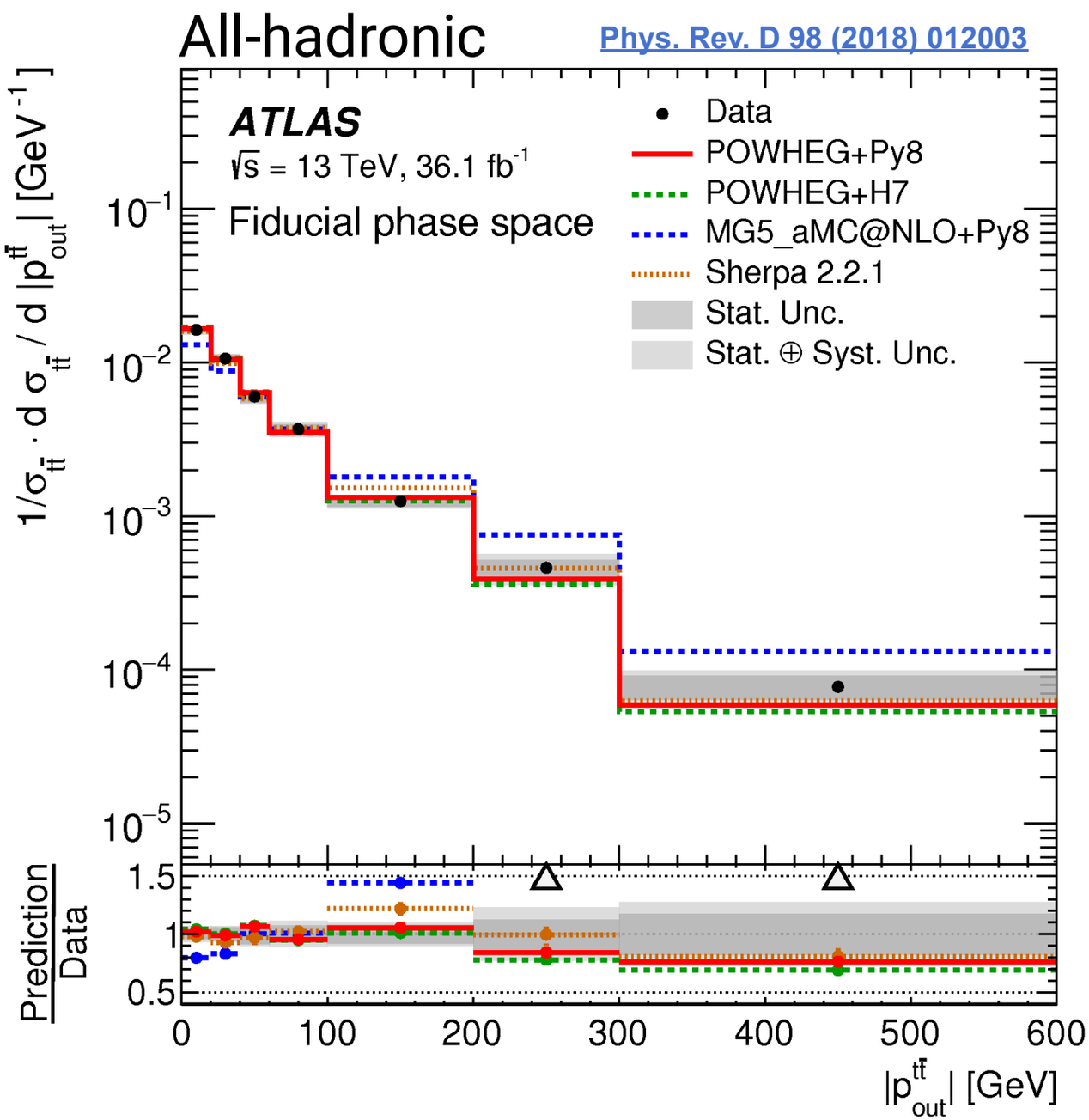

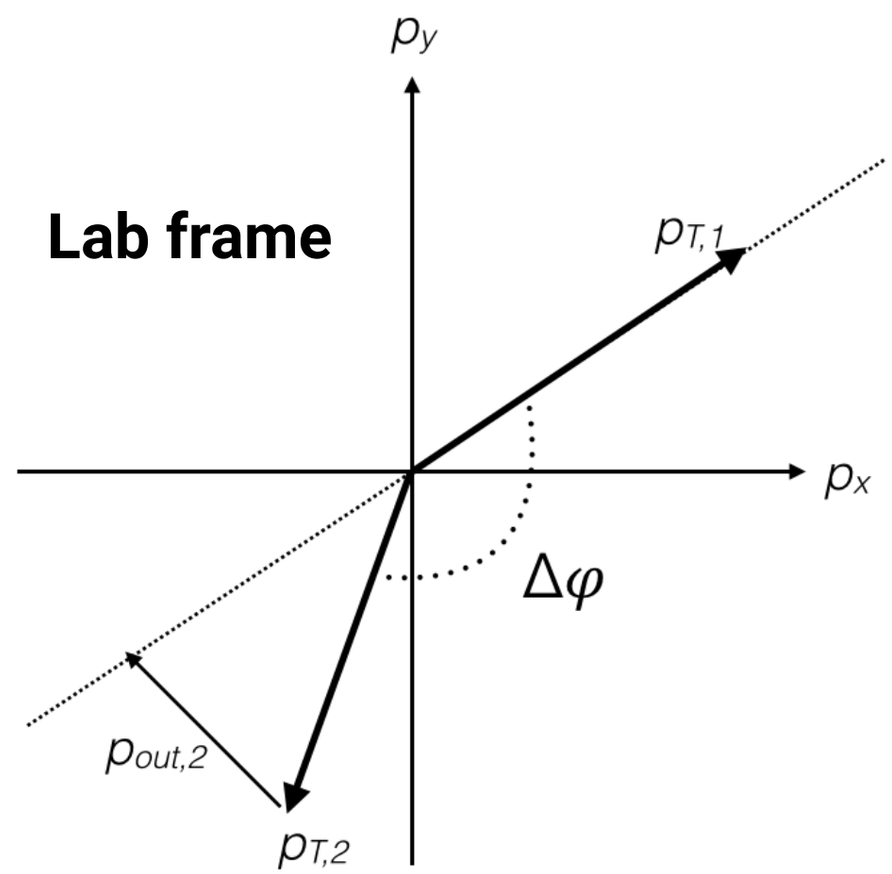

"out-of-plane" momentum
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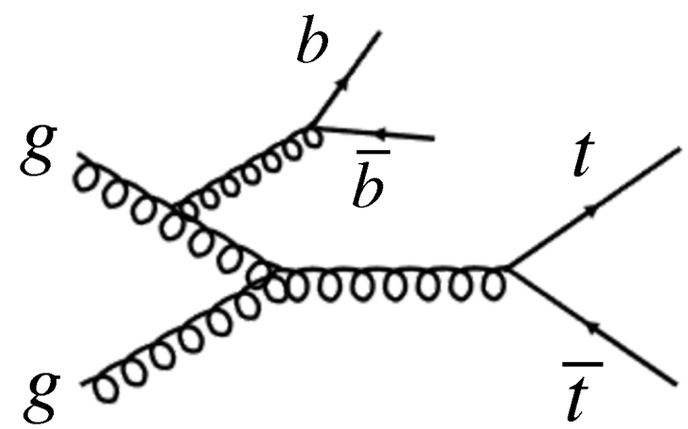
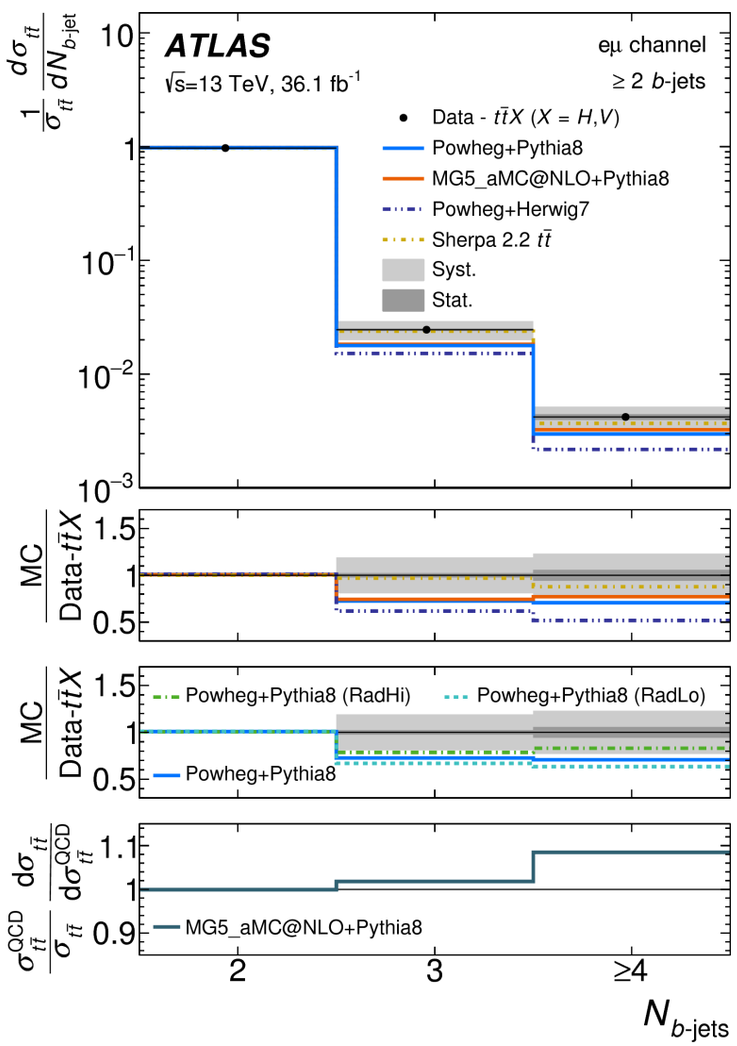
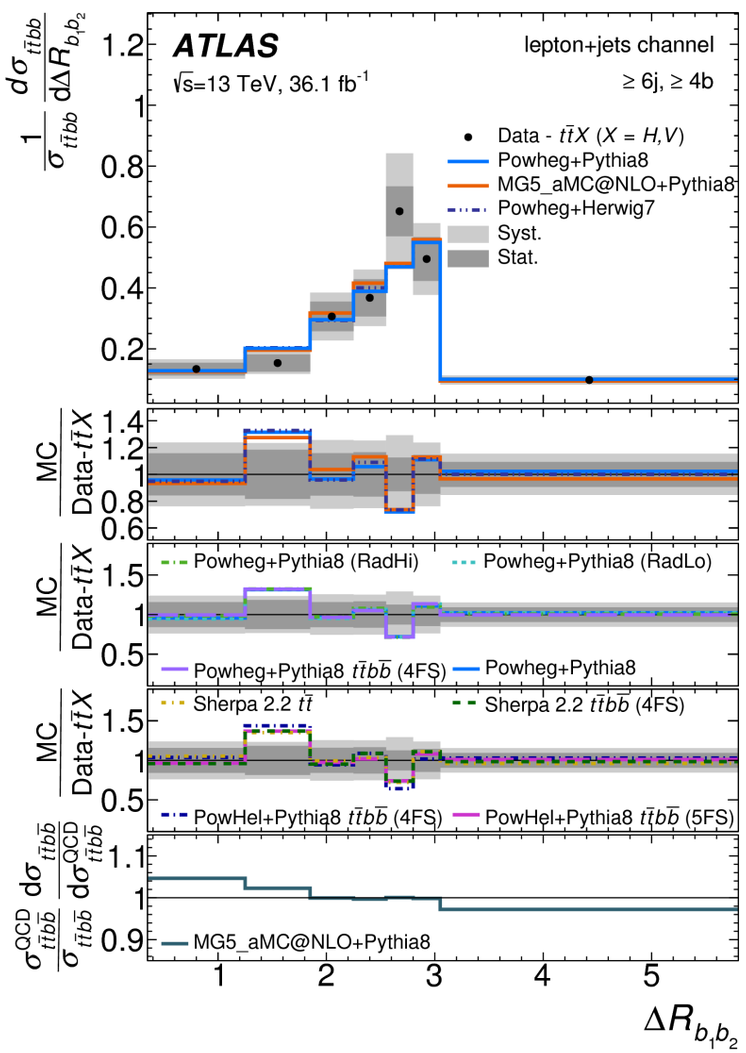
Extra radiation (HF)

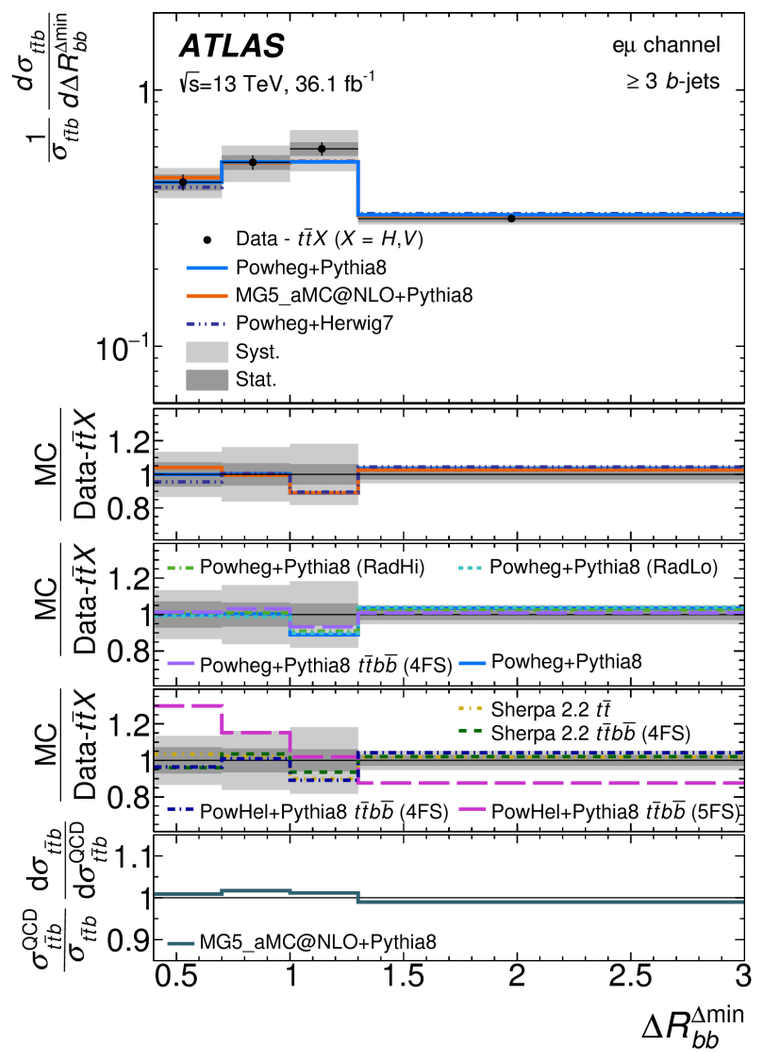
JHEP 04 (2019) 046

- Associated emission of $t\bar{t}$ pair + heavy flavour complicated process!
- No decay chain reco in this measurement
- Smaller uncertainties for eμ+≥3b and ℓ+jets(≥6j,≥4b)
- Total xs higher than predicted after removing ttV and ttH









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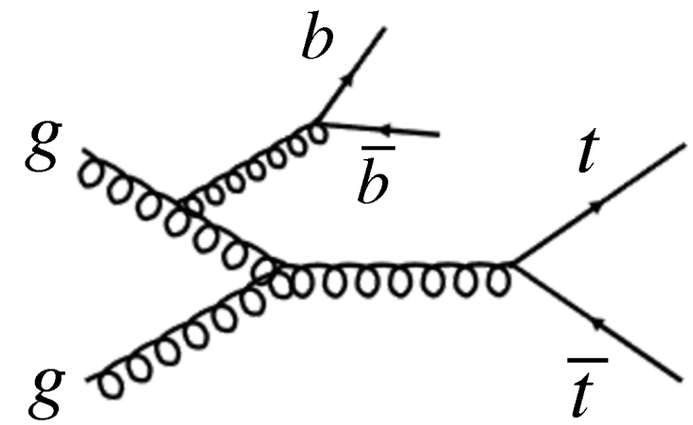
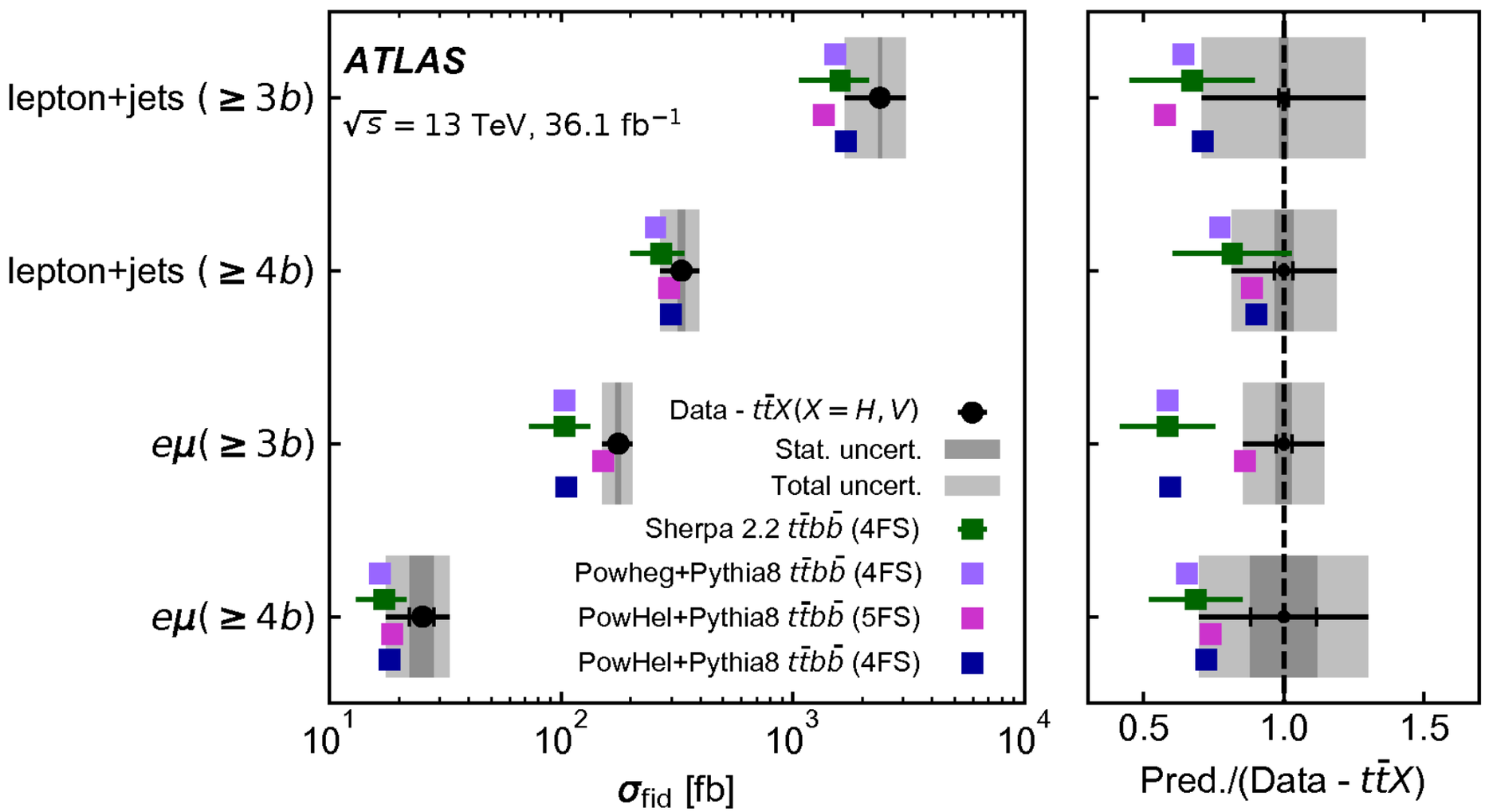
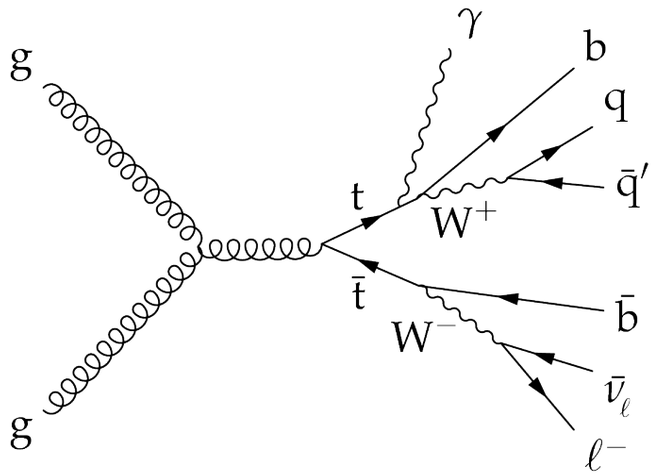
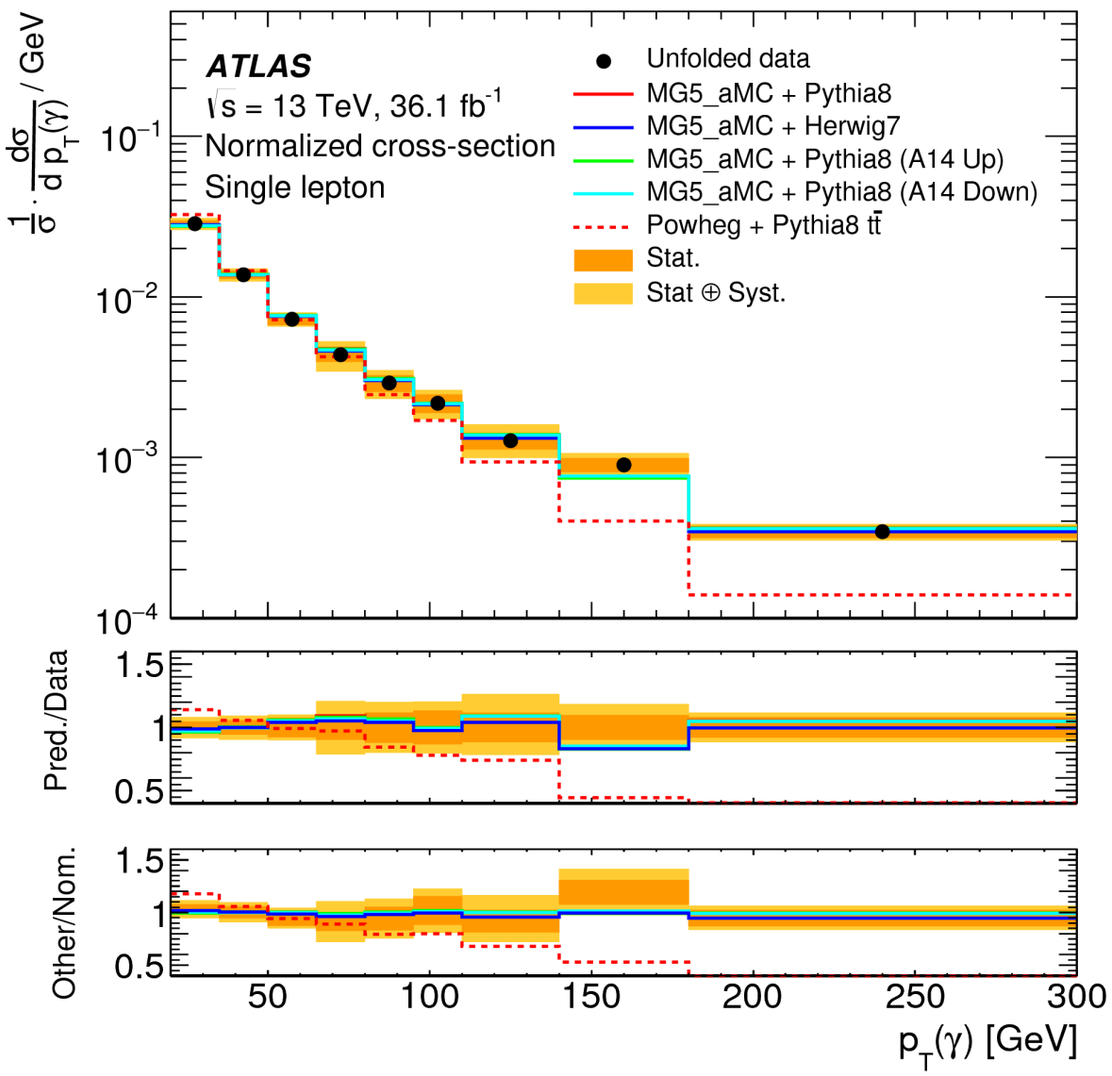


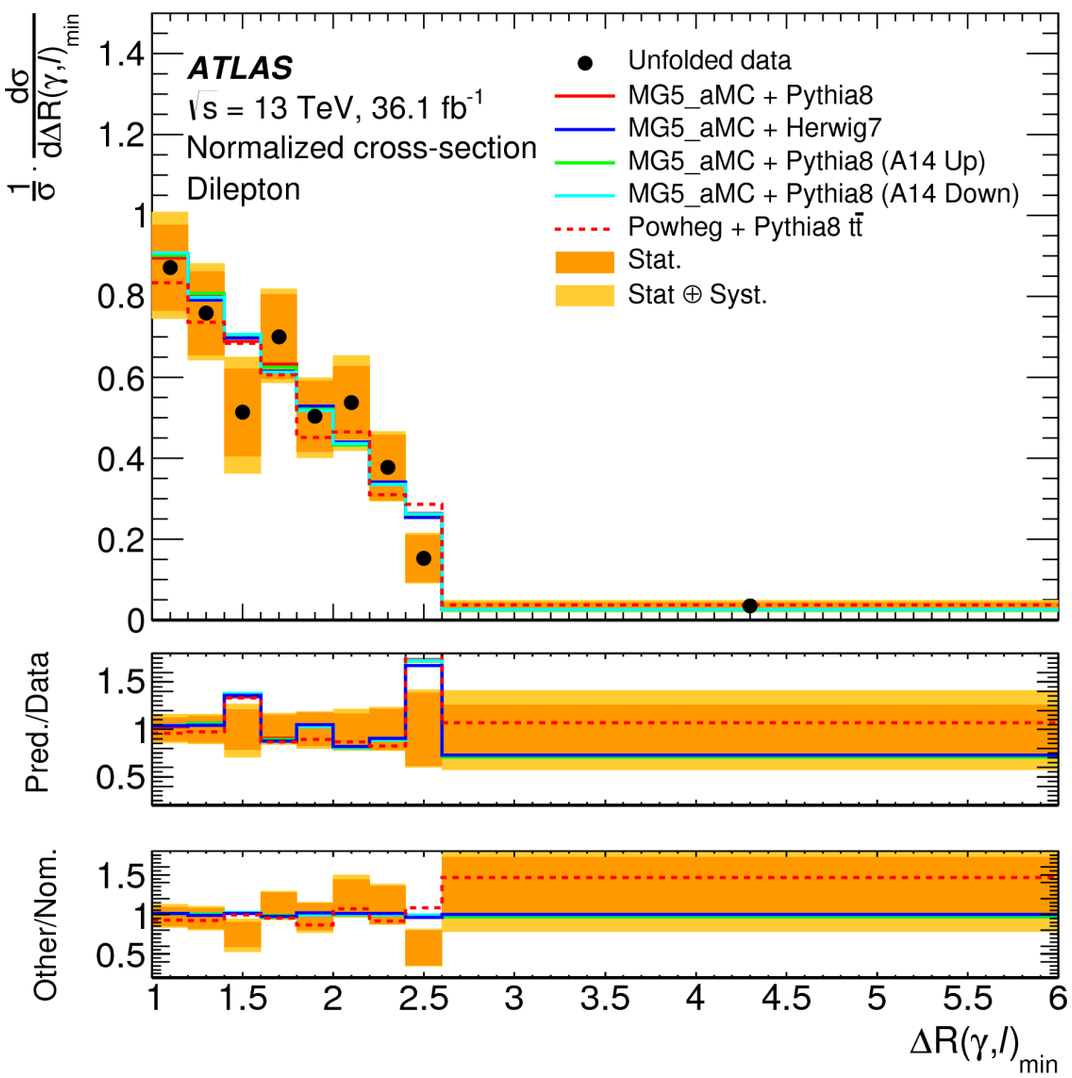


Extra radiation (γ)

- Top quarks have EM charge, emit light!
- But also quarks in the initial state…

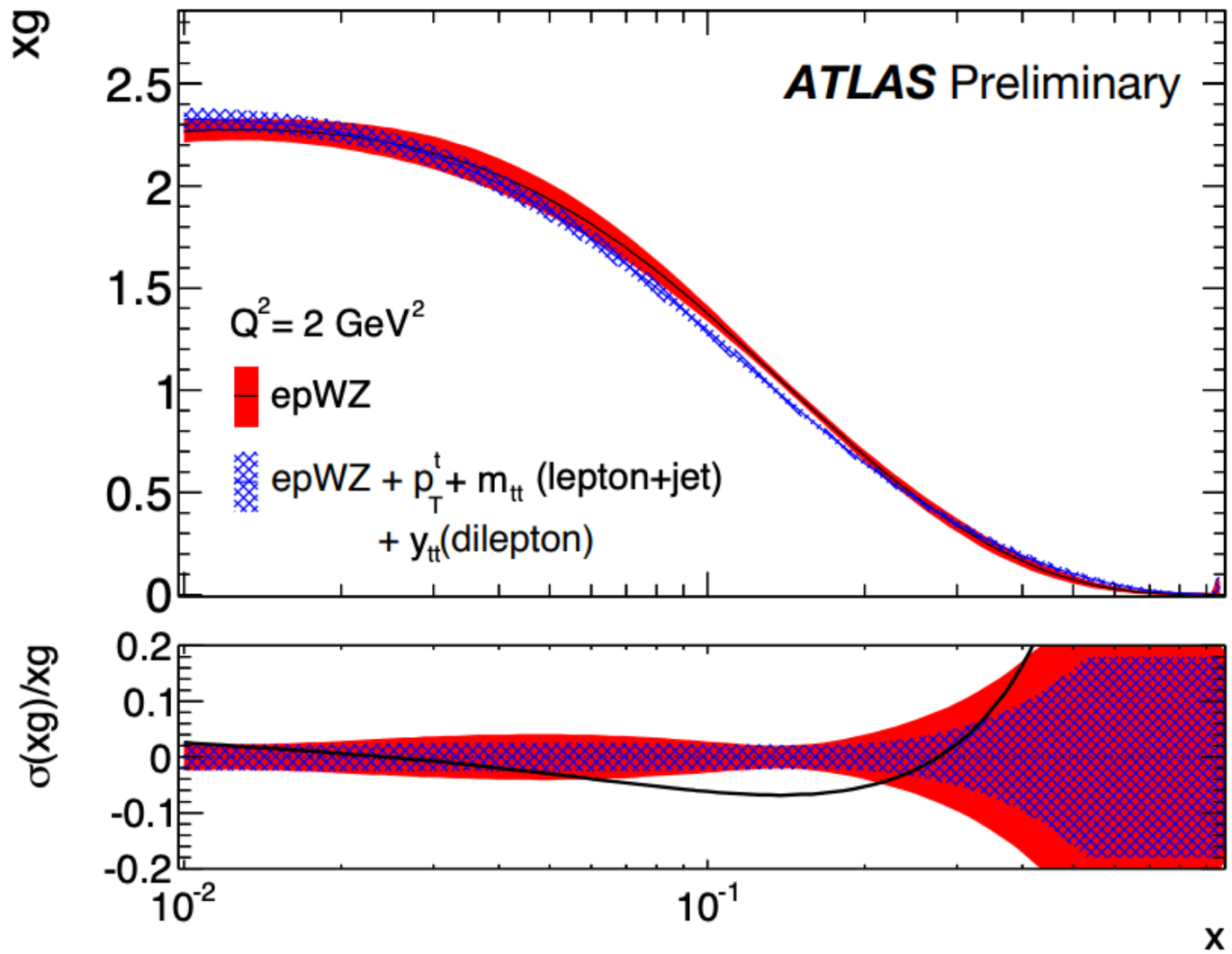






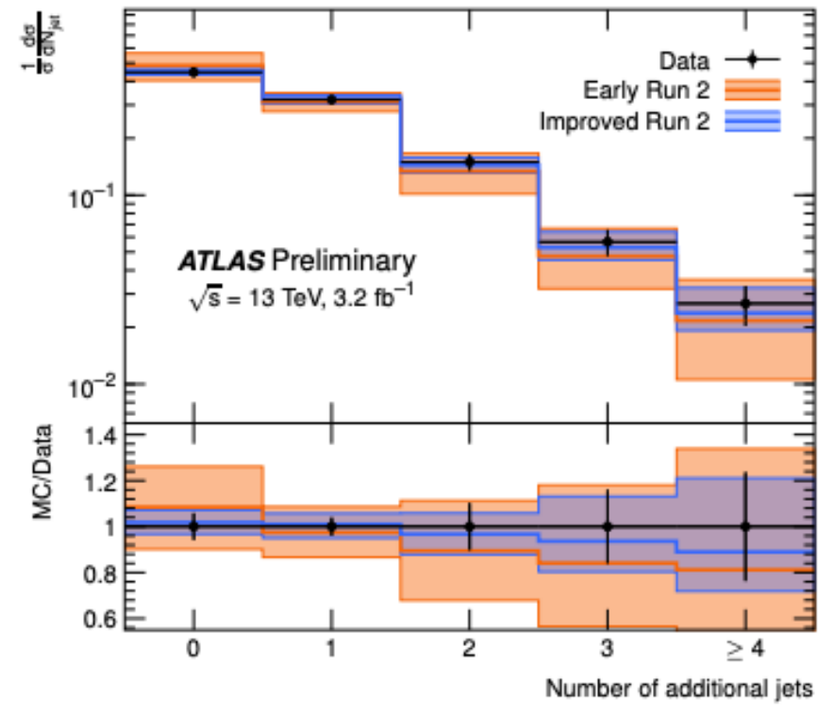
PDF Fit

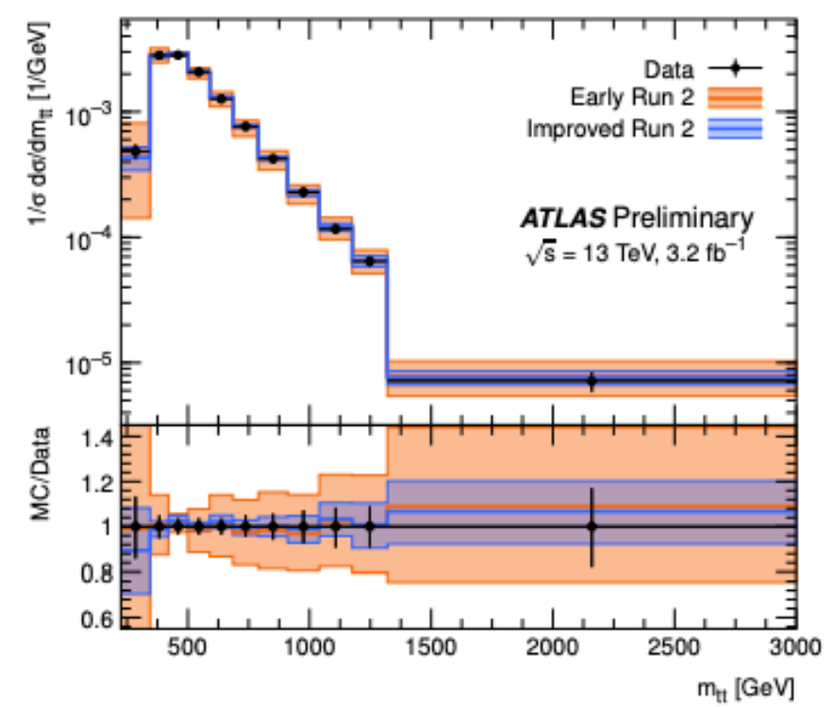
- **ATLASepWZtop18**: NNLO pQCD fit using ATLAS differential cross-sections at 7 TeV (W, Z/γ*) and 8 TeV ($t\bar{t}$ p_T, m_{tt} single lepton, y_{tt} dilepton) + HERA $e^{\pm}p$ data
- Good fit to data when p_T^t and m_{tt} used separately, pull opposite ways >> decorrelation, effect due to **IFSR** modelling systematic. No significant impact on the shape of gluon PDF
- Impact of top diffxs: harder PDF, reduced high-x gluon uncertainty



MC Modeling

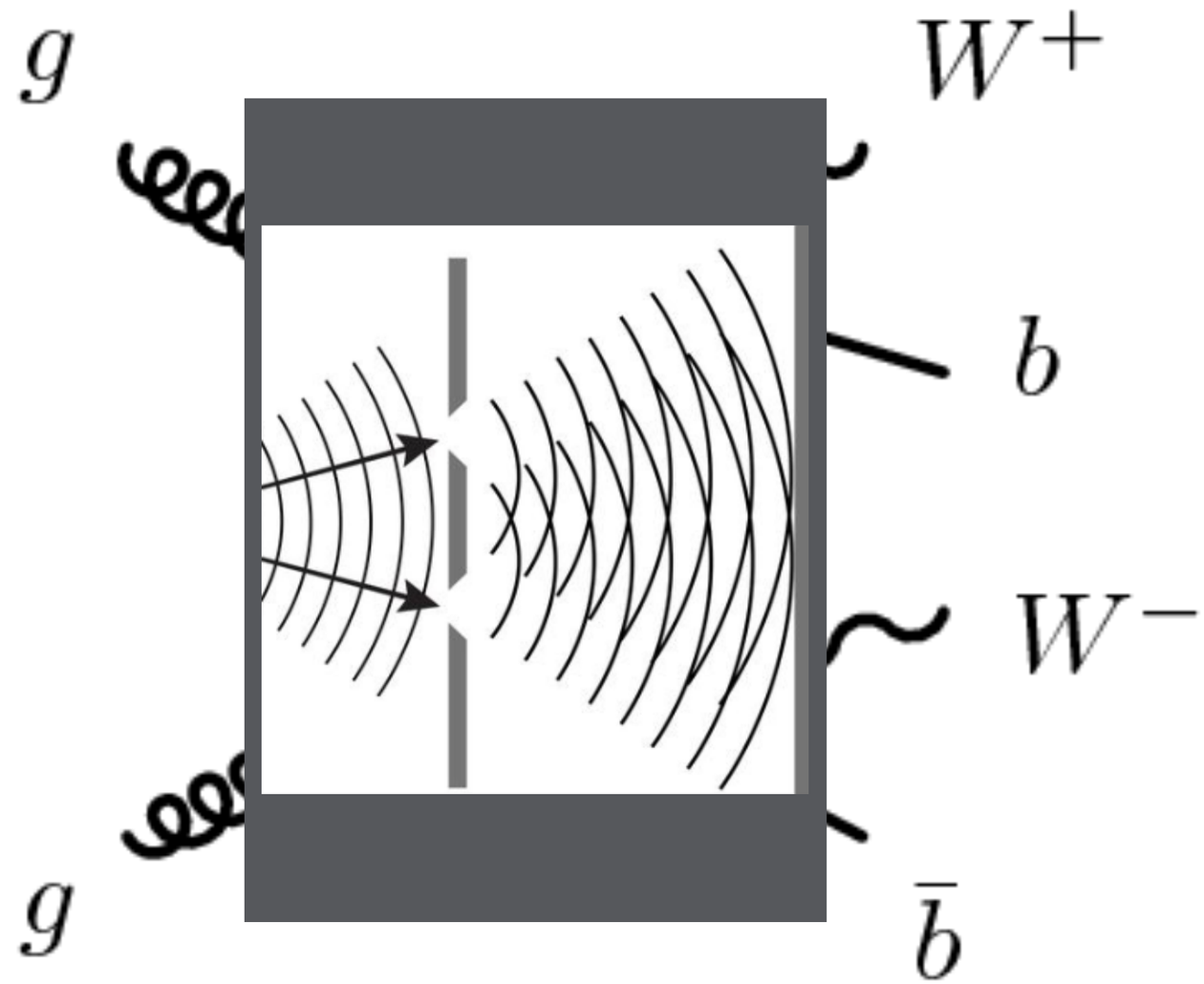
- **Early Run2 measurements**:
  Setup derived from extrapolation of 8 TeV diffxs.
  PWG+P6 workhorse, MC@NLO and H++ systematics, IFSR P2012
- **Baseline Run2 measurements:**
  Iterative process, make use of early Run2 results
  PWG+Pythia8 nominal, MG5_aMC@NLO and Herwig7 systematics, IFSR A14 tune
- Clear reduction of systematic uncertainties





tt/tW interference

- Double slit experiment with top quarks!
- Doubly ($t\bar{t}$) and singly (tWb) resonant productions have similar final states and thus interfere
- Interference "removed" with
  - "Traditional" methods (diagram removal, diagram subtraction)
  - Fully-consistent treatment (POWHEG bb4l)



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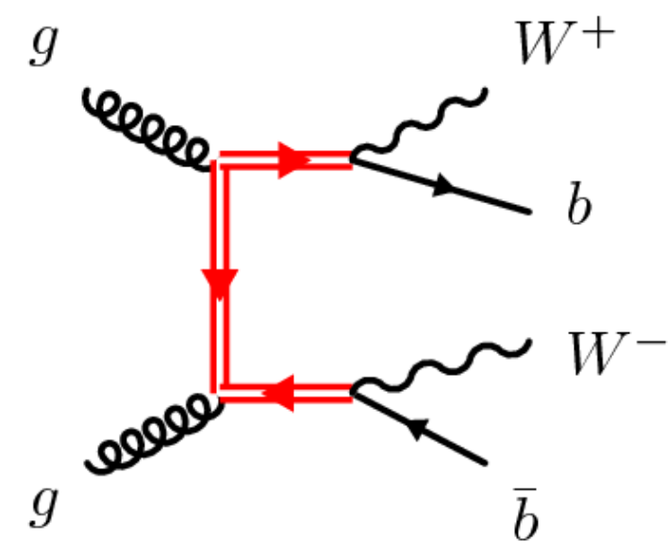
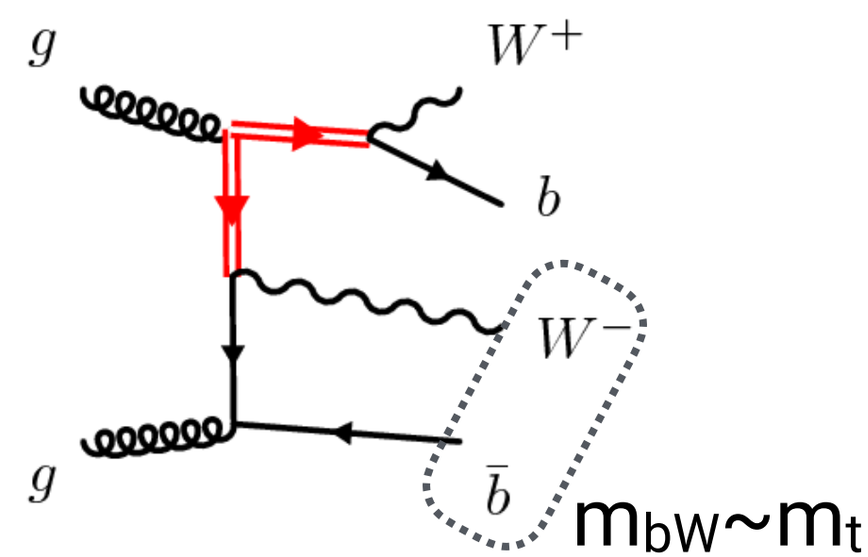
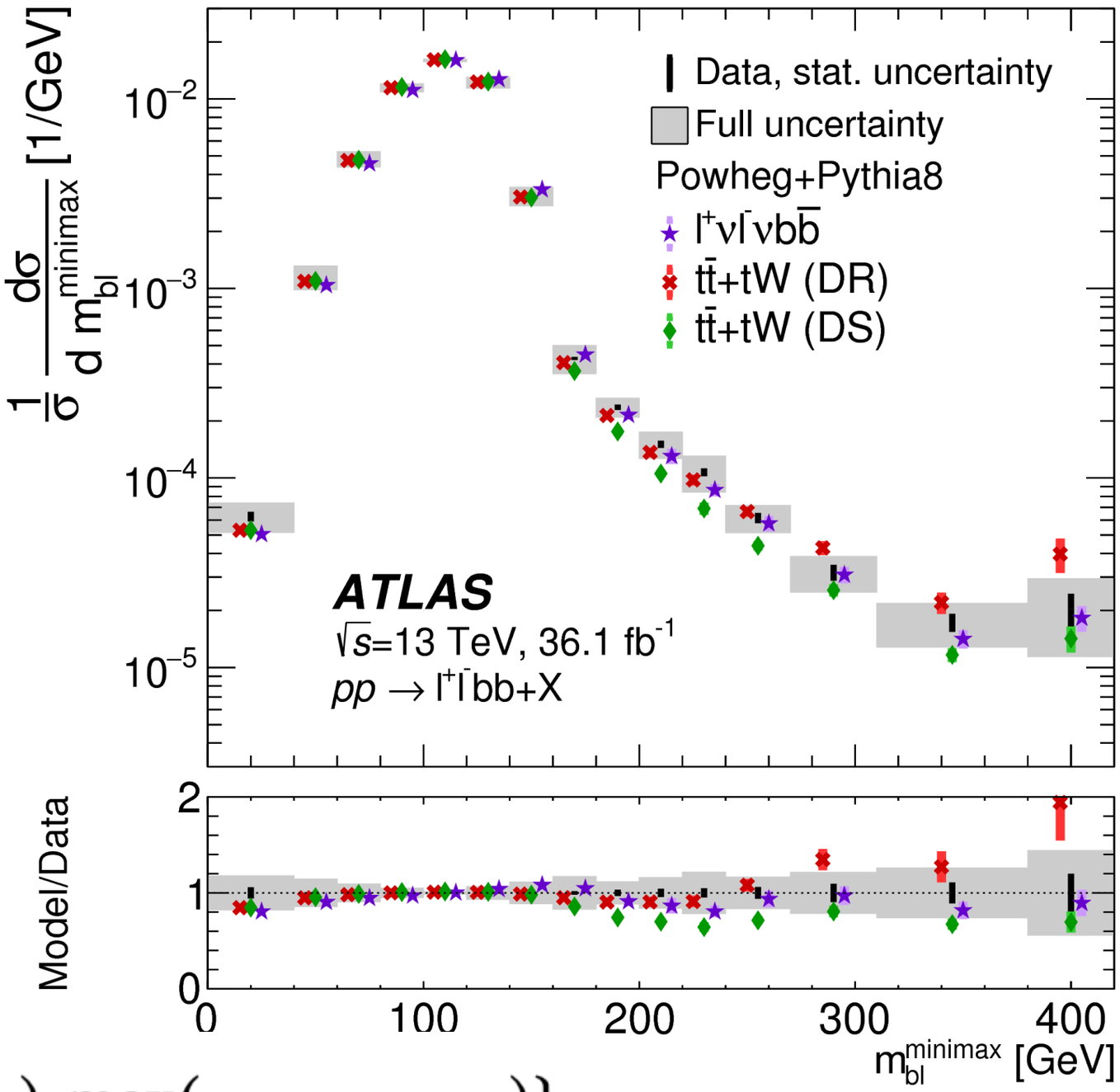




tt/tW interference

- Invariant mass (b,ℓ) characteristic distribution in presence of resonance
- $m_{b\ell}^{minimax}$ sensitive to interference effects in the tail
- Uncertainty small enough to constrain different treatments
  - Resonance-aware treatment in better agreement with data



$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

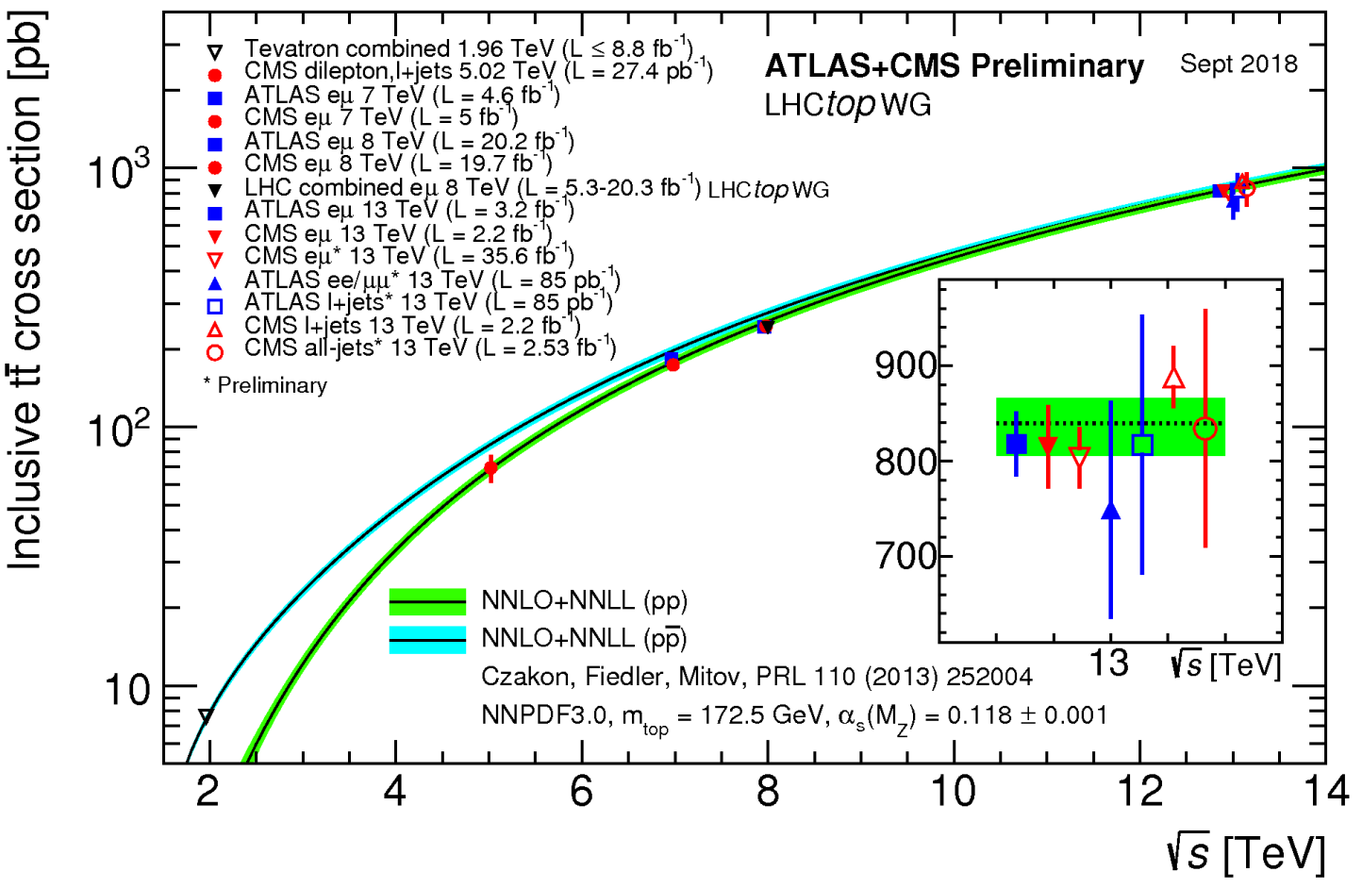
$$m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$$

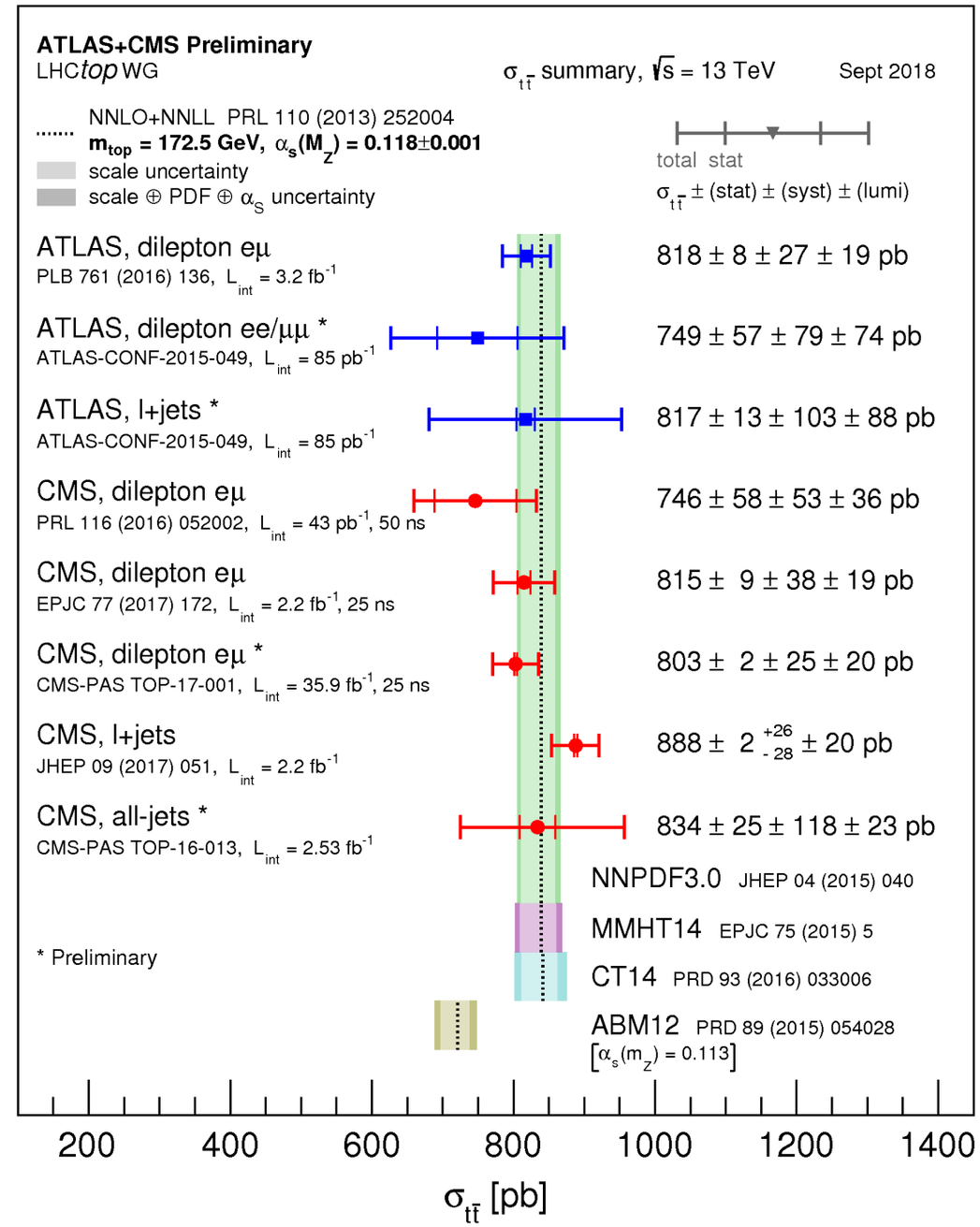
Conclusions

- How well do we understand Standard Model interactions?
- High statistics allows both **precision measurement** and search for **new physics**.
- Most $t\bar{t}$ measurements limited by systematics, affecting other measurements (e.g. ttH)
  - Hard-scattering and parton-shower **modelling** still a big source of **systematic** uncertainty
  - Run1 measurements used to improve PDFs
  - Tick-tock approach to reduce modelling systematics works!
- $t\bar{t}$ complex final state, but **not too complex**, fostering:
  - Theoretical and experimental **advancements**
  - Fine details not yet completely understood: **NNLO** calculations still rather new / not matched to PS, $t\bar{t}$/tW/WbWb **interference** effects, …

Backup

Inclusive xs





Inclusive cross-section in very good agreement with NNLO+NNLL calculations

$\Delta\sigma(\text{exp}) \lesssim \Delta\sigma(\text{th})$

Possible deviations still allowed:

- small corners of the phase-space
- differential cross-sections
- associate production

$t\bar{t}$ + h.f.

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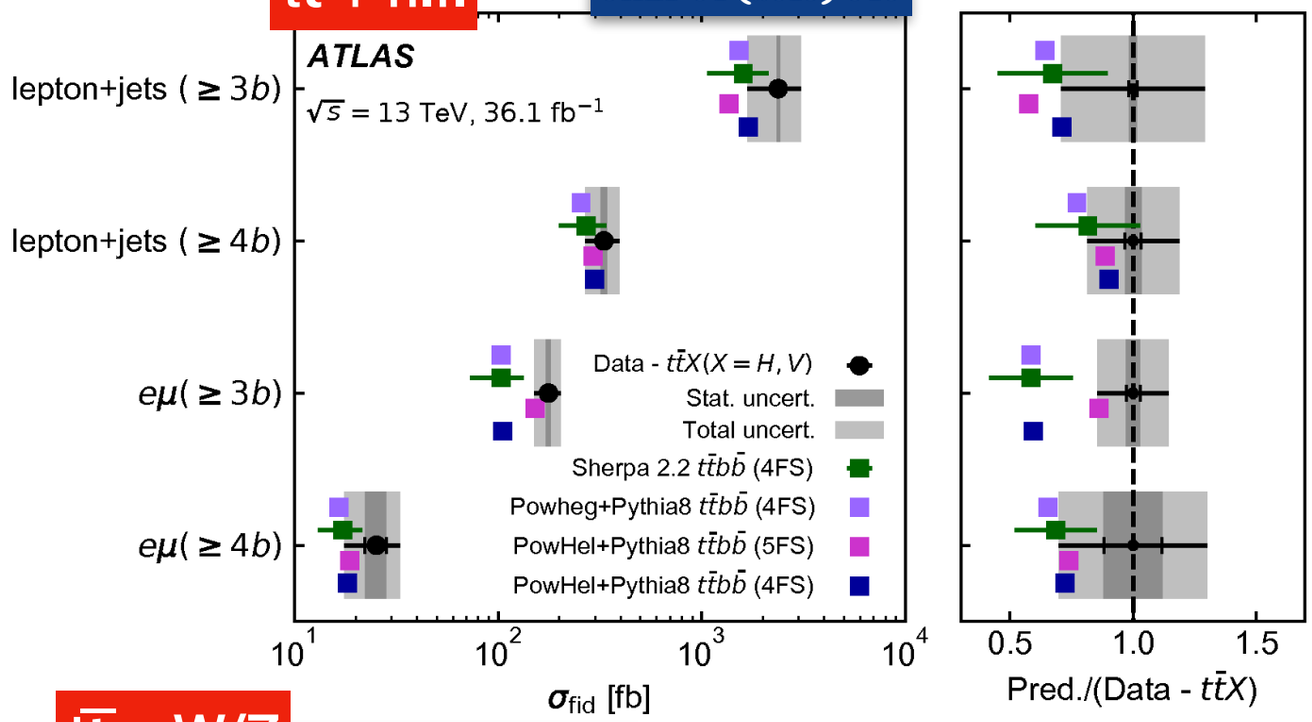
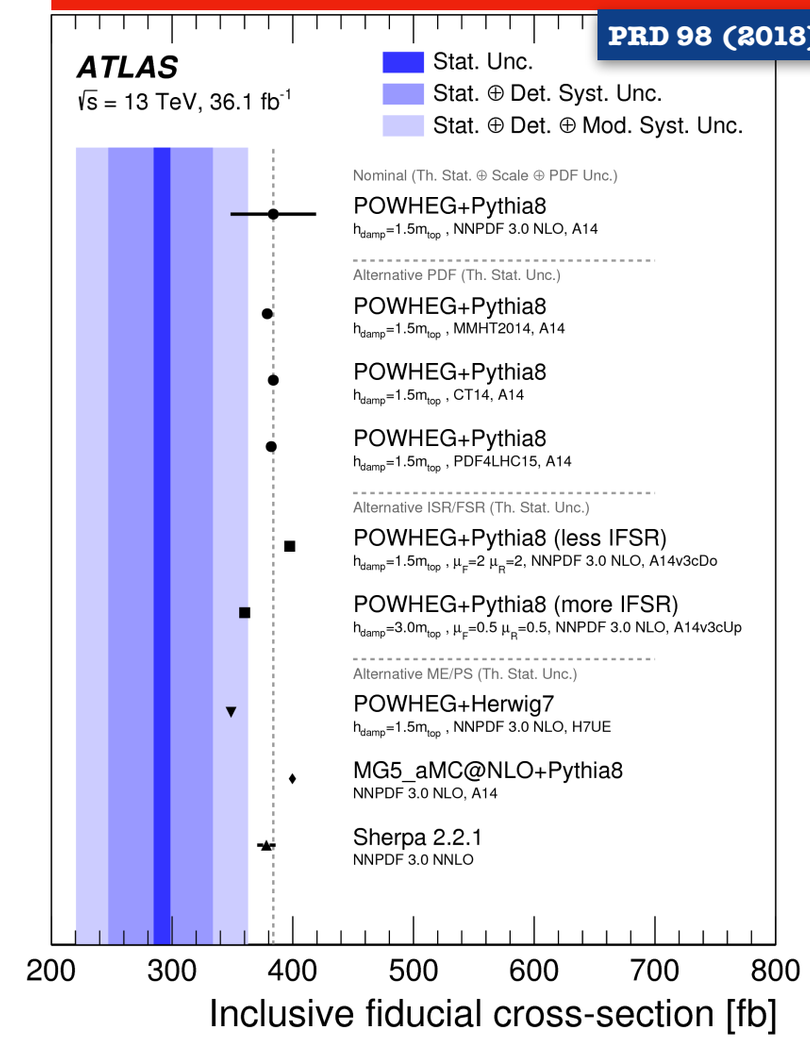


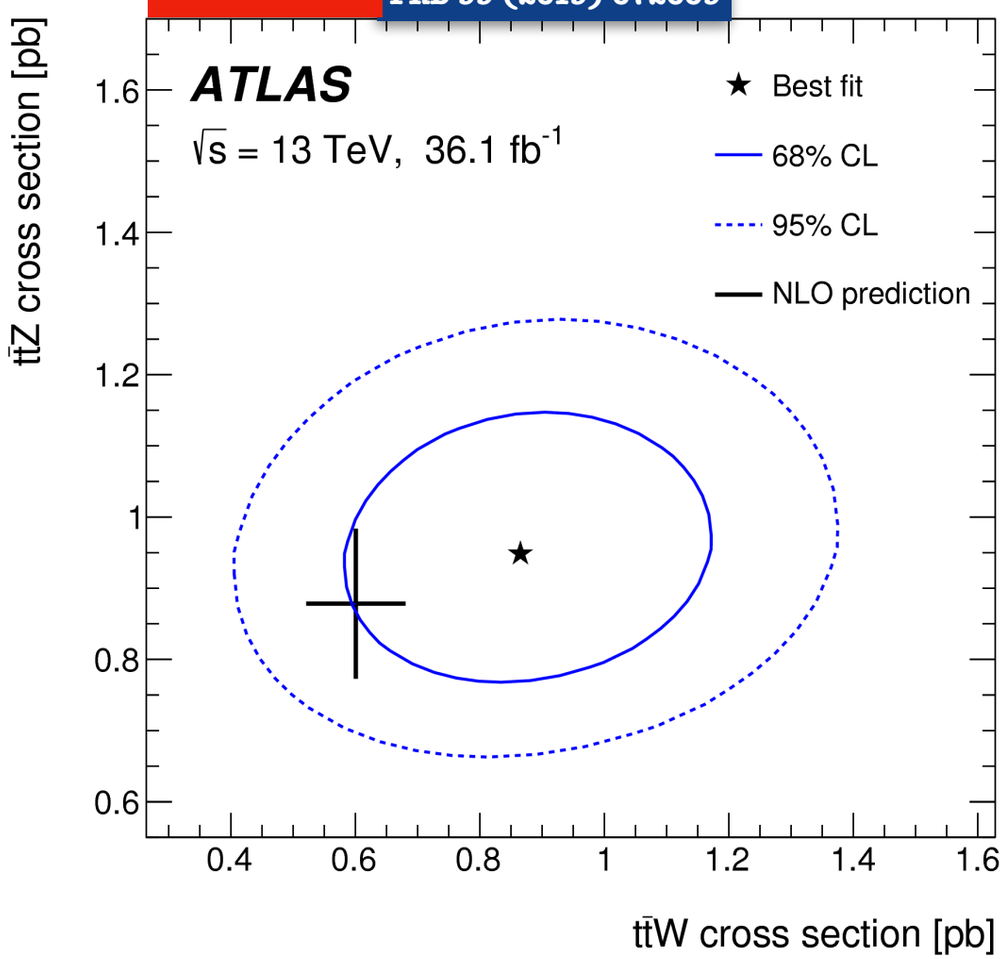
All-hadronic ($p_{T,1}$>500 GeV, $p_{T,2}$>350 GeV)

PRD 98 (2018) 012003



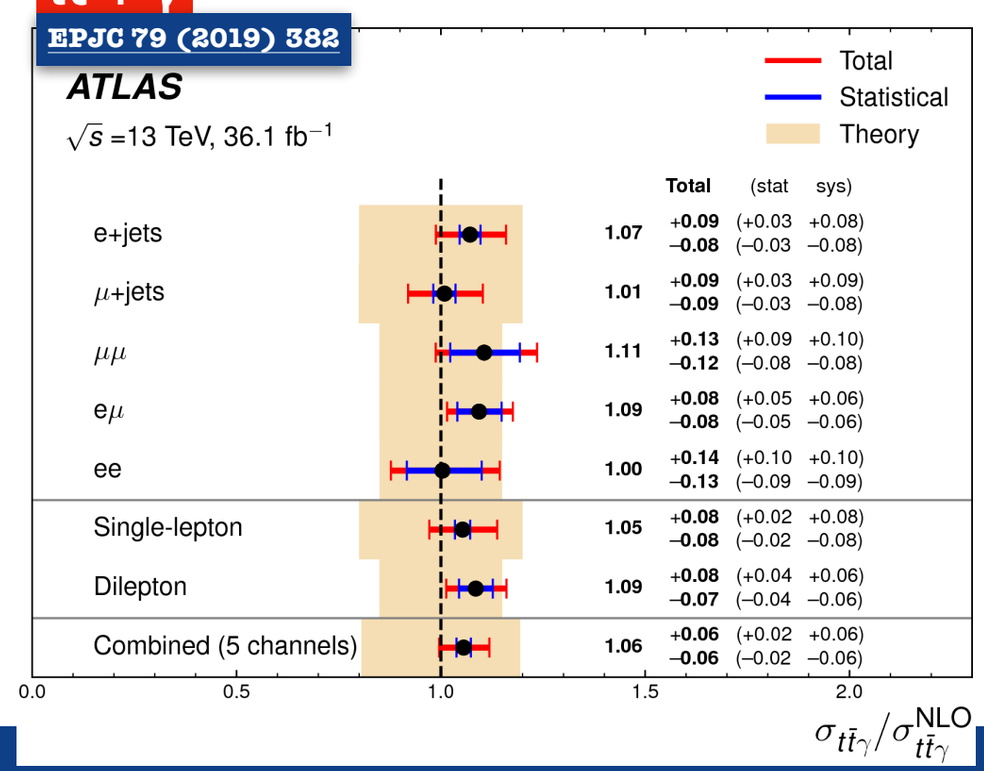
$t\bar{t}$ + W/Z

PRD 99 (2019) 072009

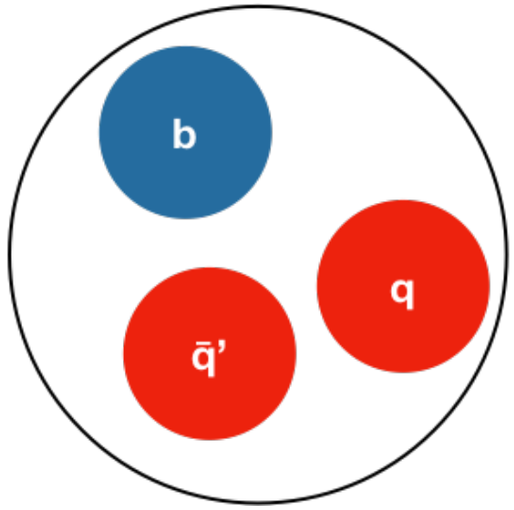


$t\bar{t}$ + γ

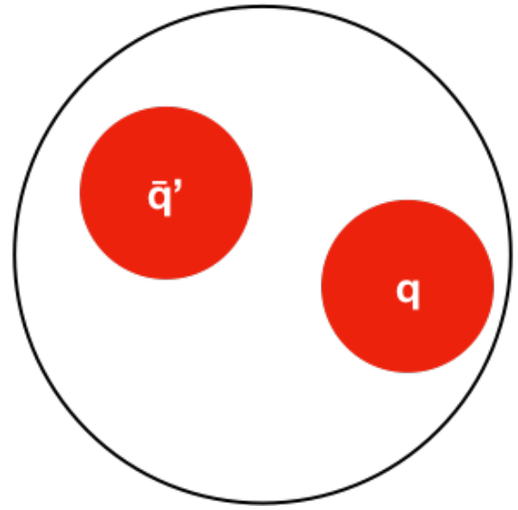
EPJC 79 (2019) 382



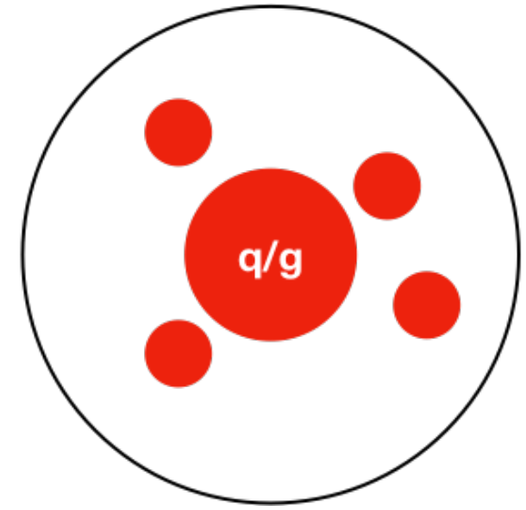
High-pT (Boosted) Tops



Top quark
Three-prong topology



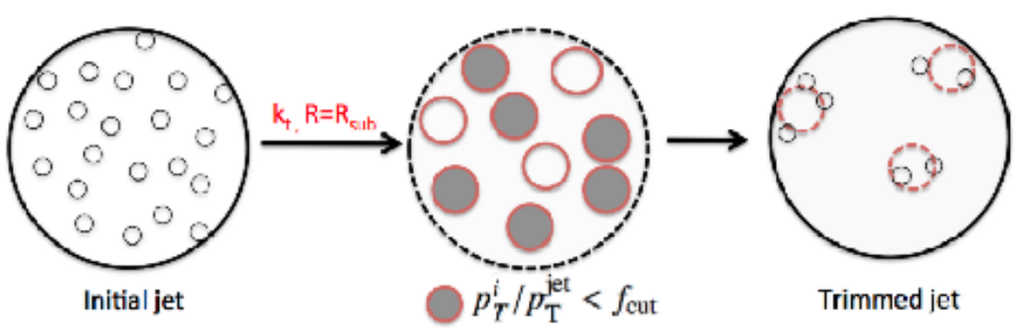
W boson
Two-prong topology

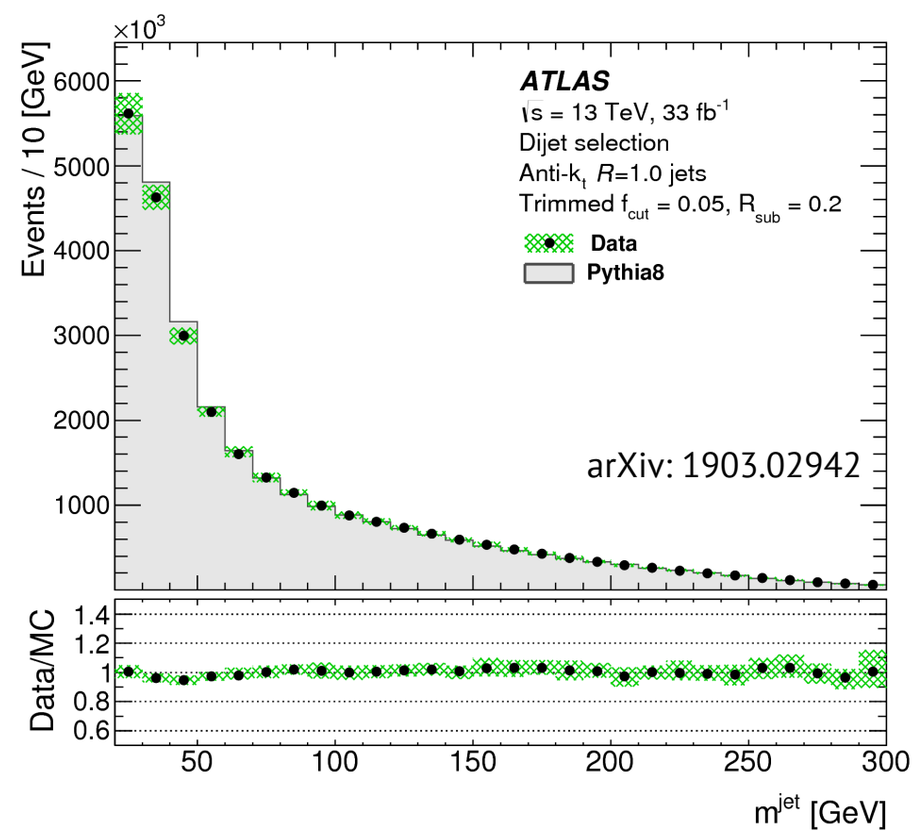


Quark/gluon
Axial topology

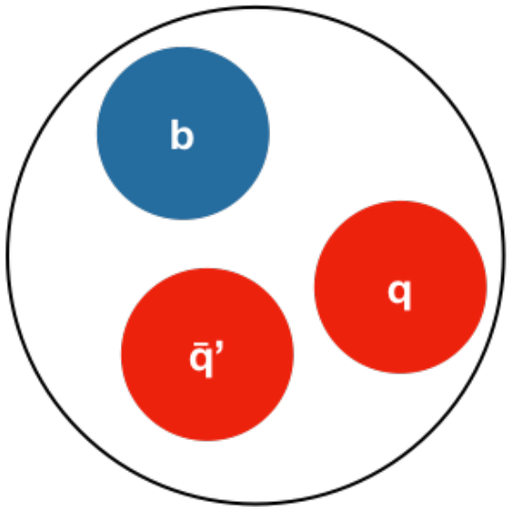
Trimming Thaler et al., JHEP 1002:084,2010

Removes pileup by discarding R=0.2 subjets with pT < 5% pT(J)

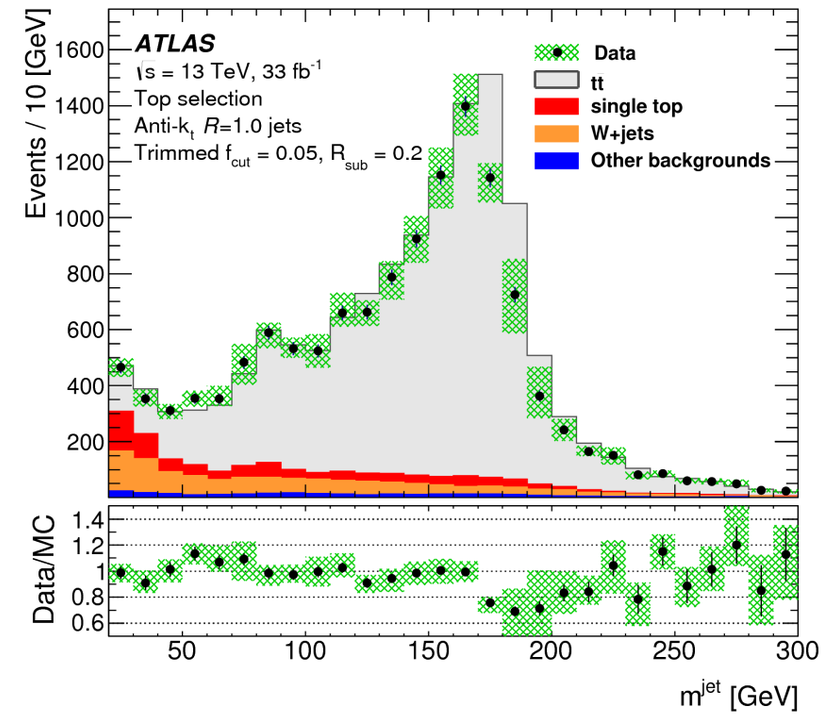




Detecting top quarks



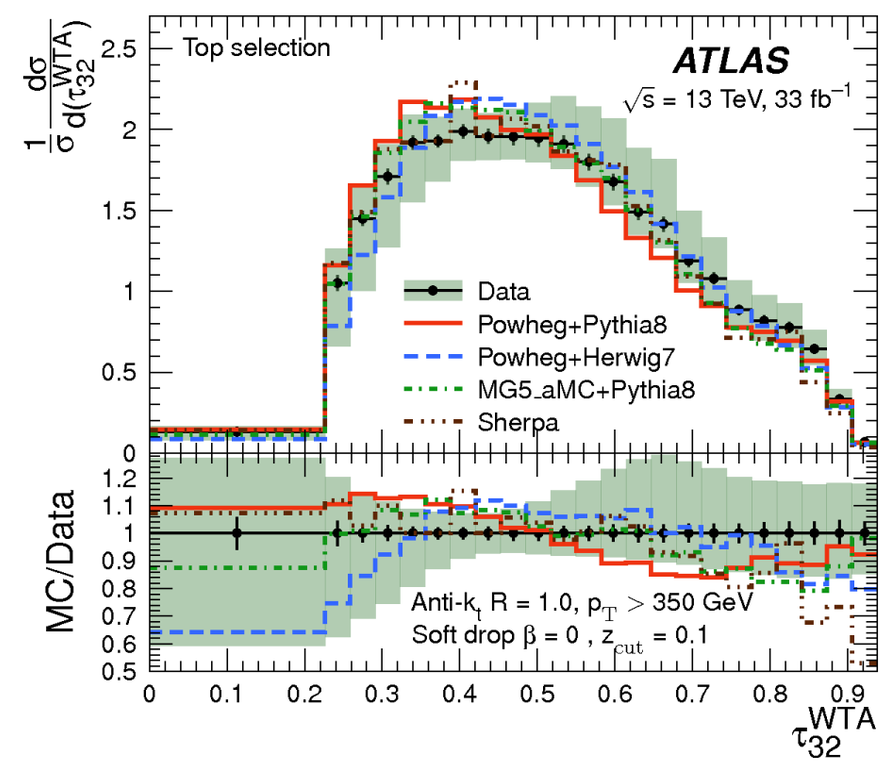
Jet Mass
Expected to peak around resonance mass (t~173 GeV; W~80.4 GeV)



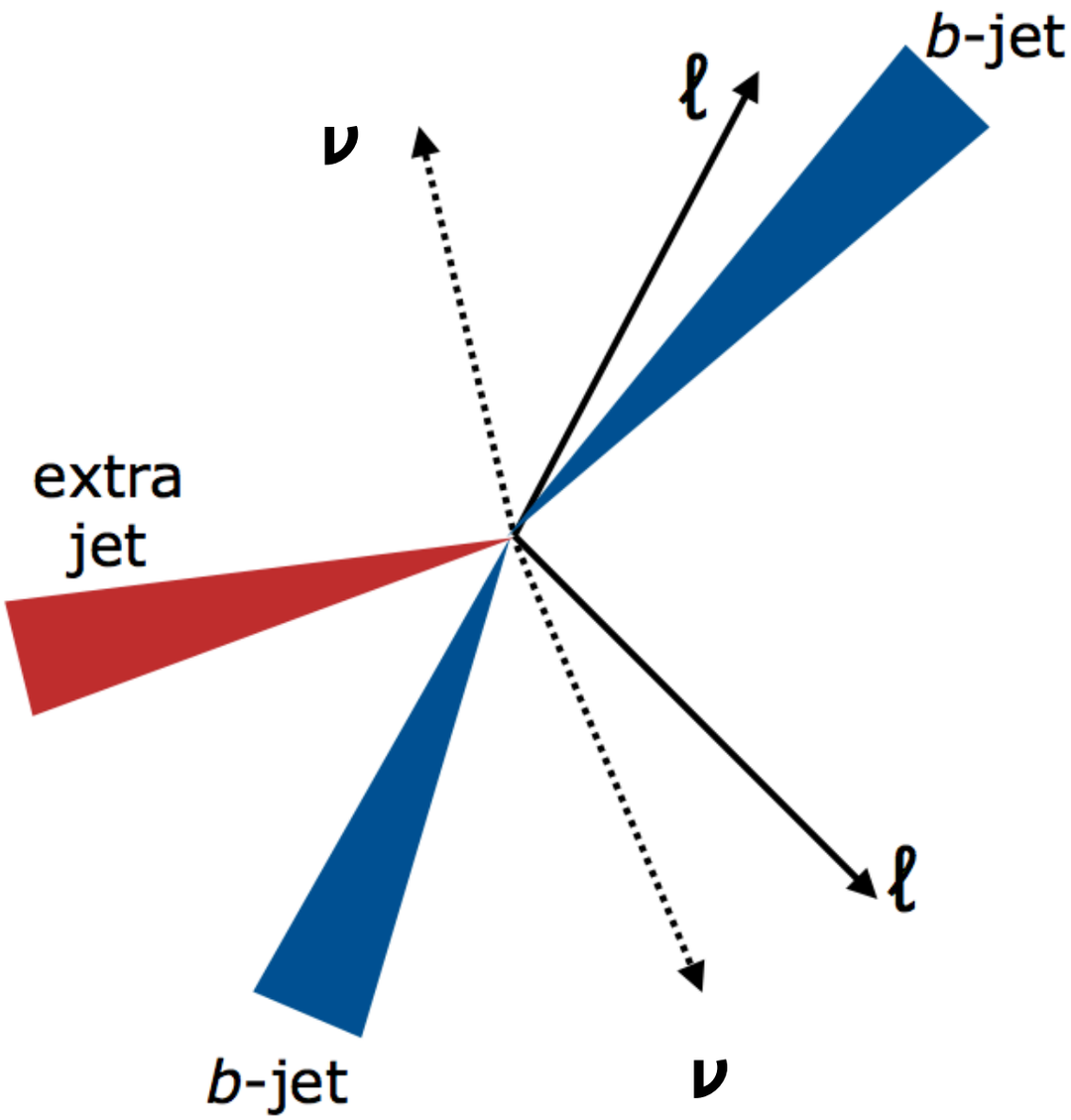
Substructure
Distribution in (η,ϕ,E) of calo clusters reflects underlying top quark decay

- N-subjettiness ratio τ_{32}
- Splitting scale $\sqrt{d_{12}}$
- Soft drop mass, multiplicity n_{SD}
- Les Houches Angularity (LHA)
- Energy correlation functions, $C_2^{(\beta)}$, $D_2^{(\beta)}$

Typical simple tagger:
Apply **cut** on **substructure** variable as a function of jet **kinematic** variables (p_T, y, m)



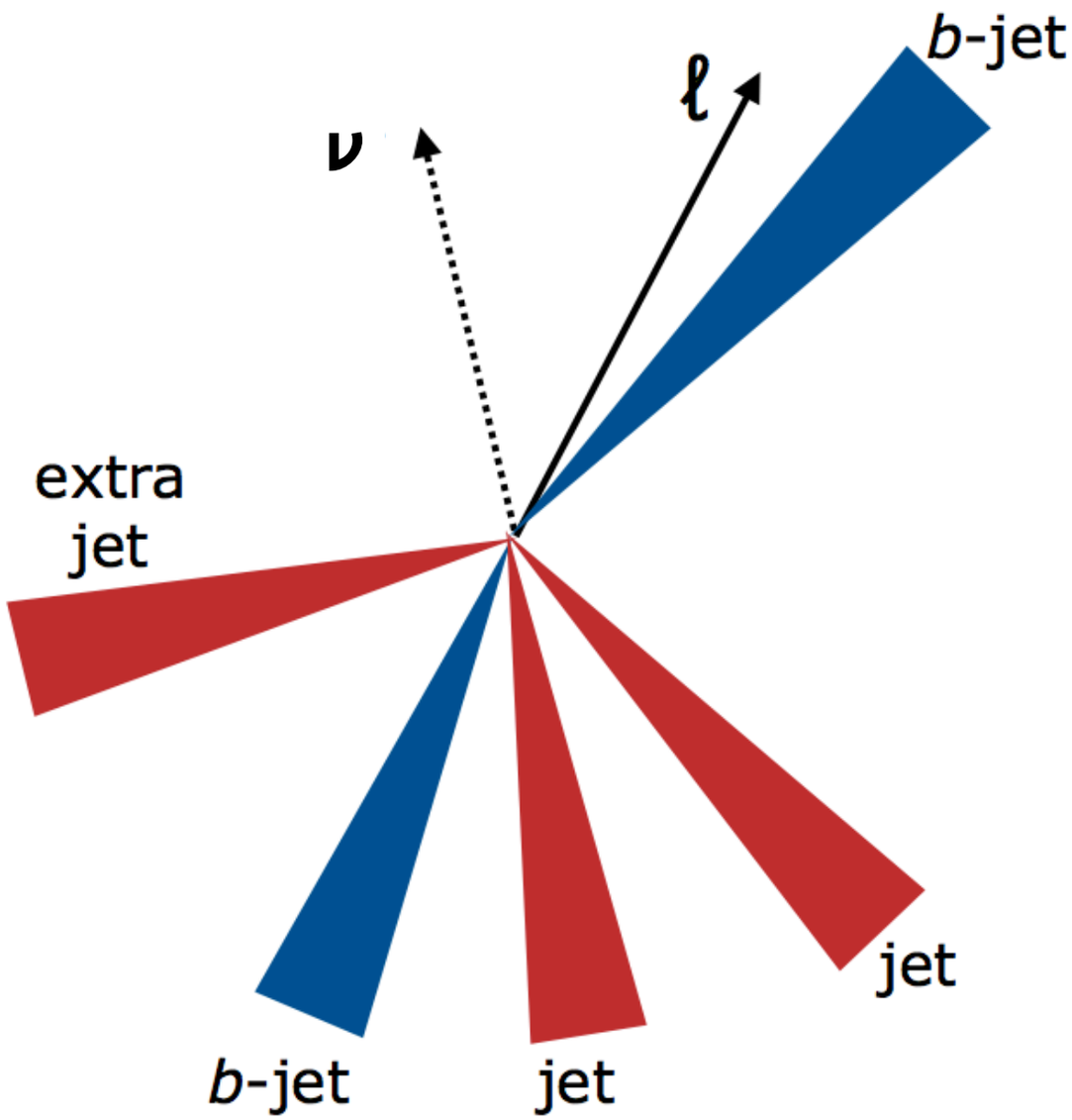
What you see is what you get



di-leptonic

- Isolated *e*/μ lepton(s)
- Anti-k_T R=0.4 (“narrow”) jets
  - MVA b-tagging
- Objects-calibrated E_T^{miss}
- Anti-k_T R=1.0 (“large-R”) jets
  - Trimmed R=0.2 f=0.05
  - Substructure information

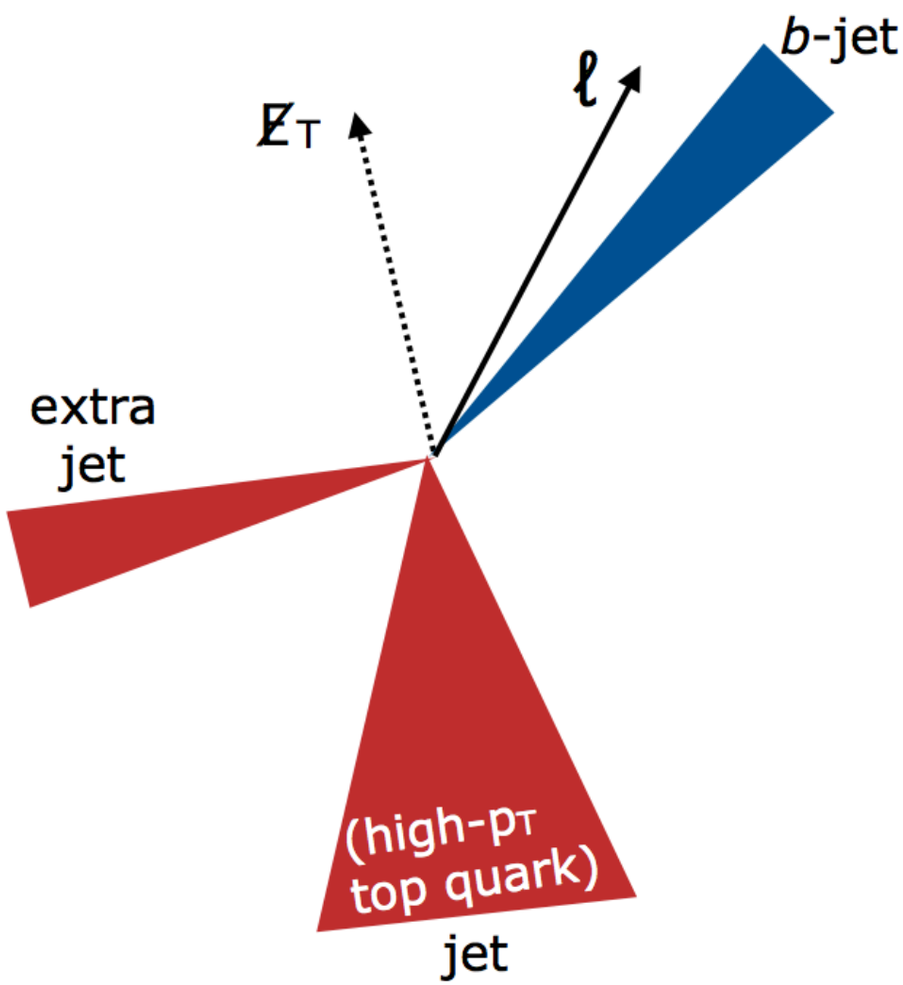
What you see is what you get



Single lepton resolved

- Isolated *e*/μ lepton(s)
- Anti-k_T R=0.4 ("narrow") jets
  - MVA b-tagging
- Objects-calibrated E_T^{miss}
- Anti-k_T R=1.0 ("large-R") jets
  - Trimmed R=0.2 f=0.05
  - Substructure information

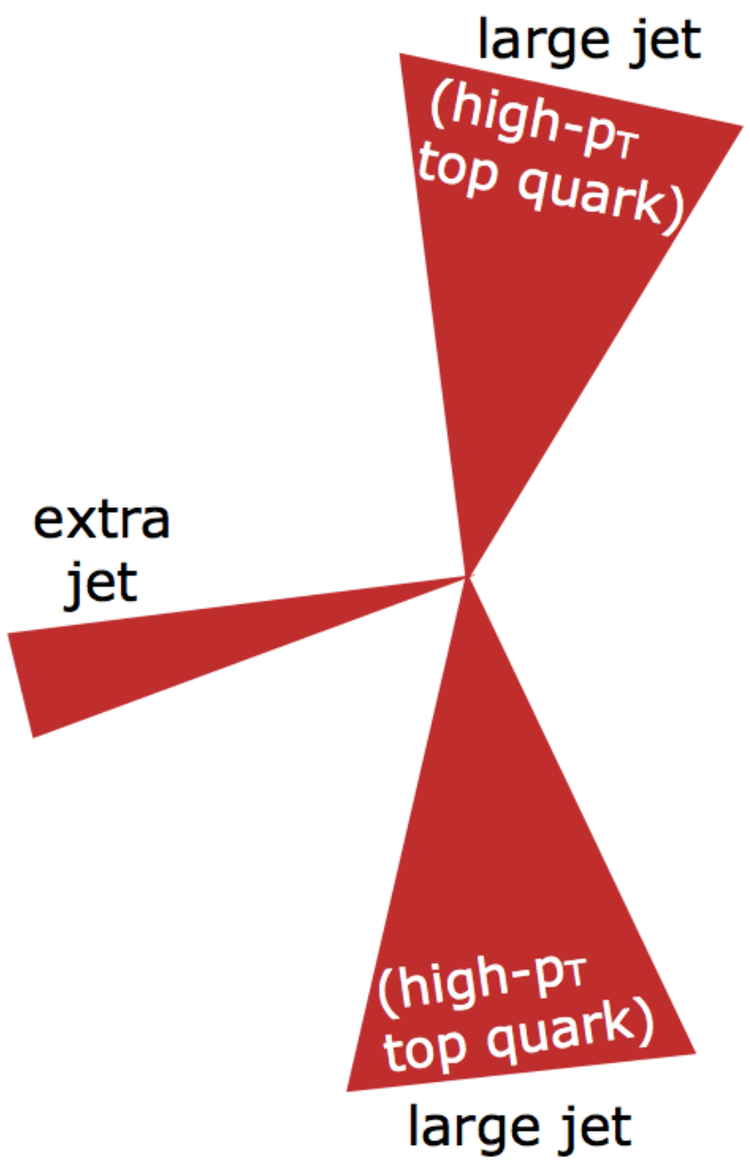
What you see is what you get



Single lepton boosted

- Isolated *e*/μ lepton(s)
- Anti-k_T R=0.4 (“narrow”) jets
  - MVA b-tagging
- Objects-calibrated E_T^{miss}
- Anti-k_T R=1.0 (“large-R”) jets
  - Trimmed R=0.2 f=0.05
  - Substructure information

What you see is what you get

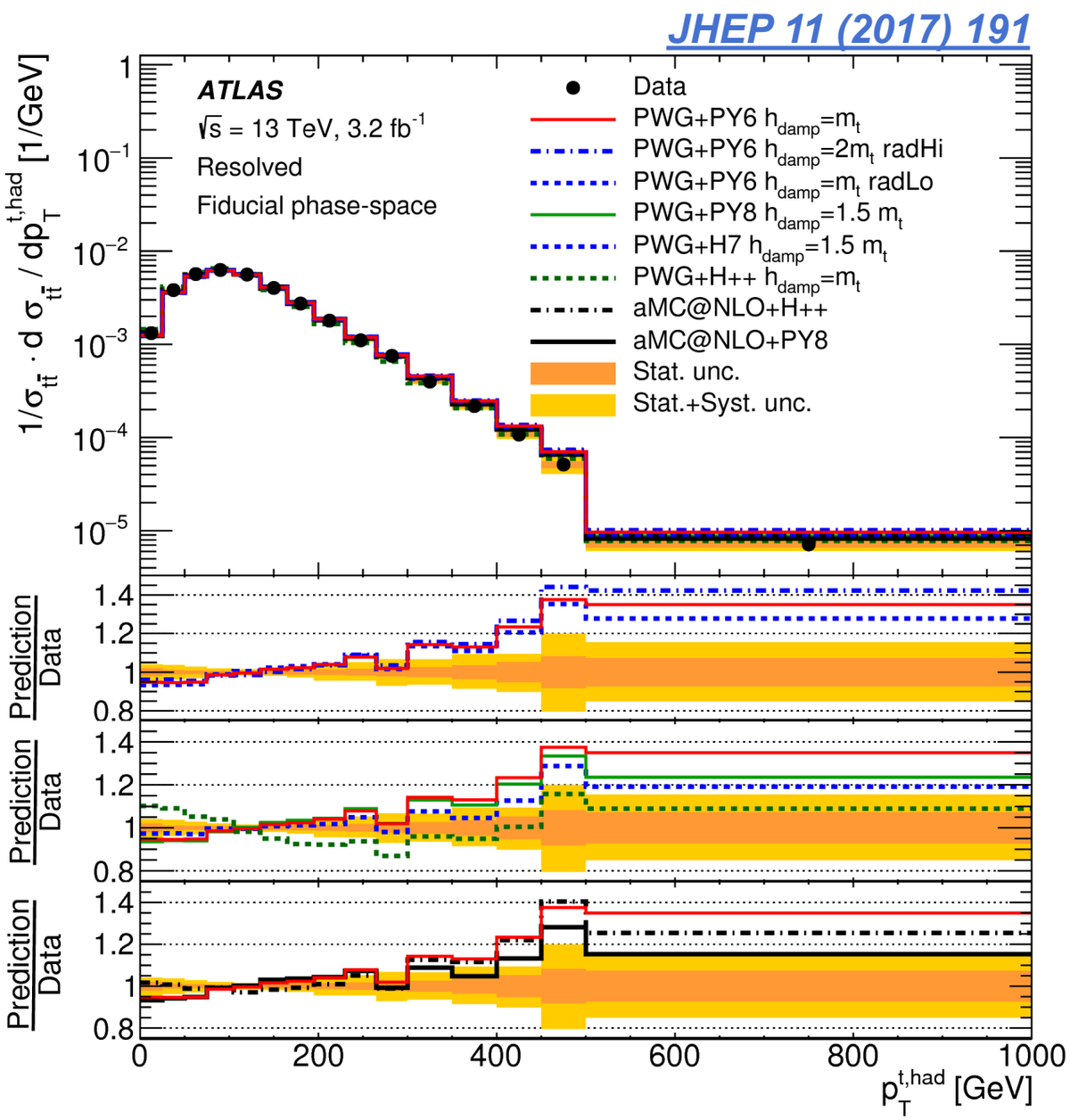


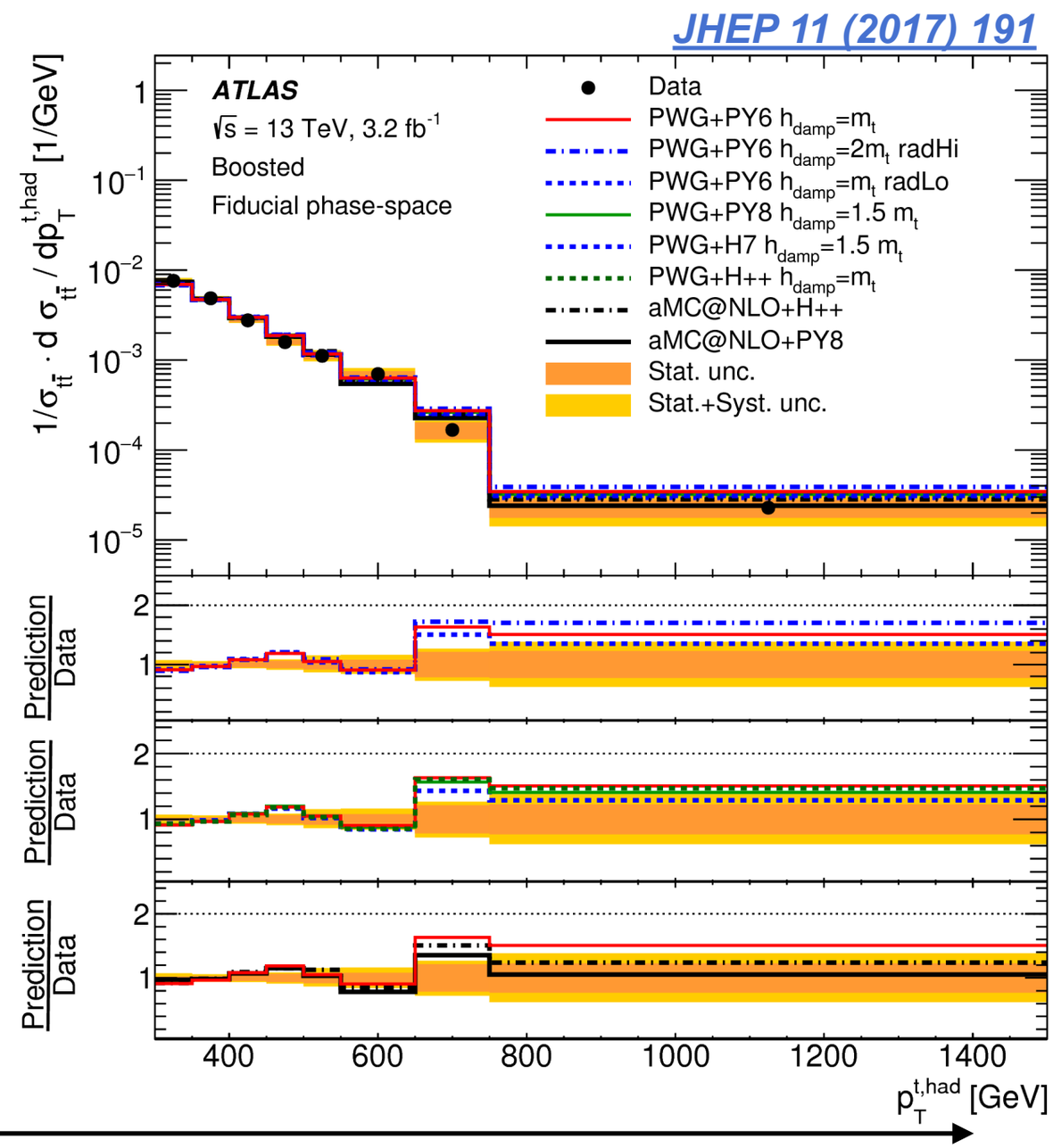
All-hadronic boosted

- Isolated *e*/μ lepton(s) [**veto**]
- Anti-k_T R=0.4 (“narrow”) jets
  - MVA b-tagging
- Objects-calibrated E_T^{miss}
- Anti-k_T R=1.0 (“large-R”) jets
  - Trimmed R=0.2 f=0.05
  - Substructure information

Top quark p_T

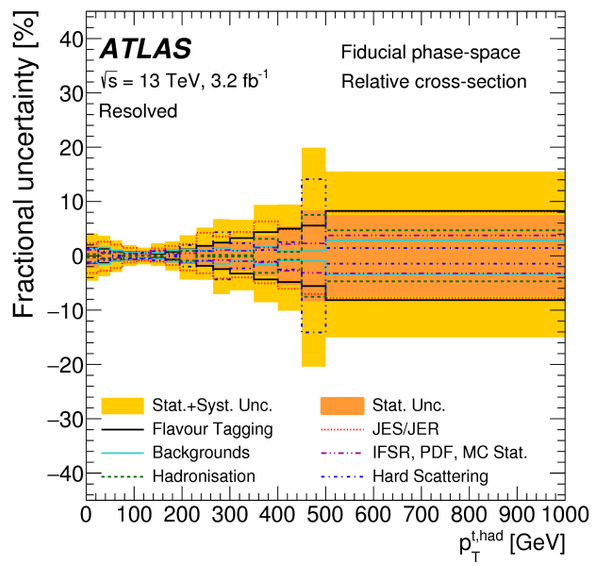
Hadronic top
(single lepton channel)





Resolved → Boosted

Uncertainties: Top quark p_T



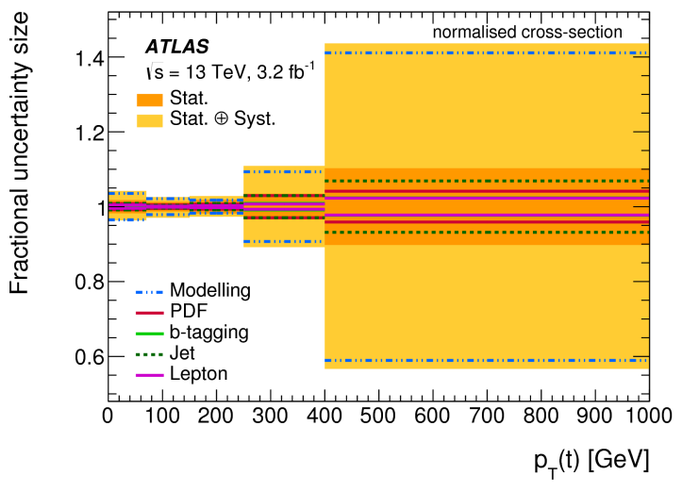
Single lepton

Jet energy scale 5%

b-tagging < 5%

Background modelling (low pT) 2%

→ Signal modelling (high pT) 5%

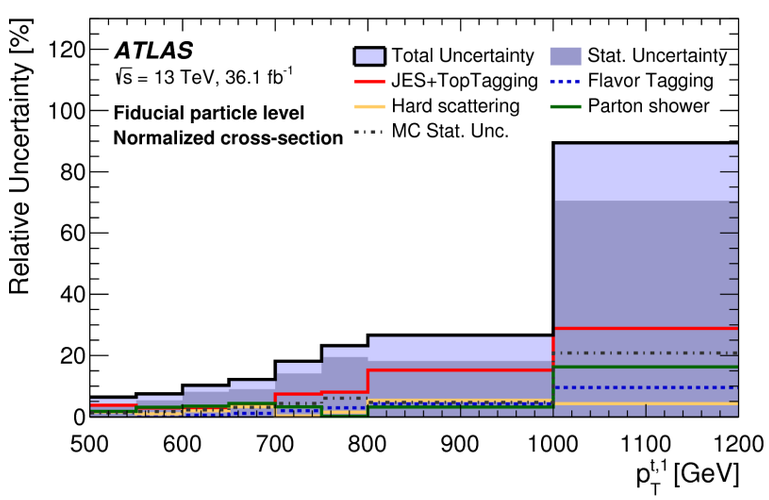


Dilepton

→ Signal modelling >10%

PDF 5%

b-tagging < 5%



All hadronic

Jet energy scale 5%

Top-tagging 10%

b-tagging < 10%

→ Signal modelling (ps/had) 15%

Single lepton

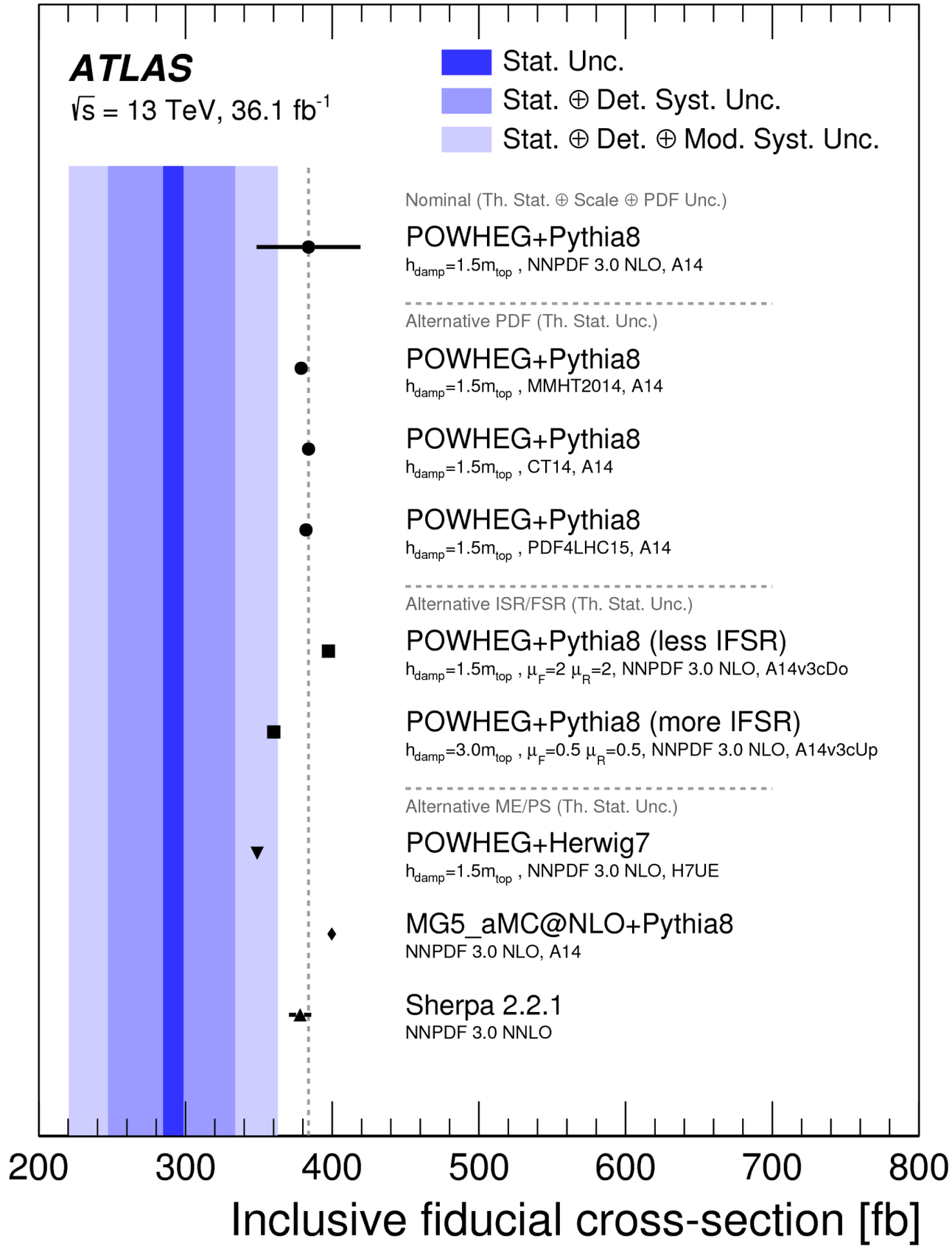
	$p_T^{t,had}$		$\lvert y^{t,had}\rvert$		$m^{t\bar{t}}$		$p_T^{t\bar{t}}$		$\lvert y^{t\bar{t}}\rvert$	
	χ^2/NDF	p-val	χ^2/NDF	p-val	χ^2/NDF	p-val	χ^2/NDF	p-val	χ^2/NDF	p-val
Powheg+Pythia6	19.0/15	0.22	7.8/18	0.98	9.8/11	0.55	14.9/6	0.02	20.0/18	0.33
Powheg+Pythia6 (radHi)	20.9/15	0.14	8.5/18	0.97	8.7/11	0.65	56.1/6	<0.01	17.3/18	0.51
Powheg+Pythia6 (radLo)	20.8/15	0.14	7.4/18	0.99	12.7/11	0.32	22.1/6	<0.01	25.5/18	0.11
MadGraph5_aMC@NLO+Herwig++	23.5/15	0.07	10.7/18	0.91	32.4/11	<0.01	16.4/6	0.01	28.1/18	0.06
Powheg+Herwig++	30.3/15	0.01	7.9/18	0.98	34.8/11	<0.01	28.0/6	<0.01	30.4/18	0.03
MadGraph5_aMC@NLO+Pythia8	19.1/15	0.21	8.4/18	0.97	7.6/11	0.75	19.0/6	<0.01	16.1/18	0.59
Powheg+Pythia8	18.4/15	0.24	10.5/18	0.92	7.7/11	0.74	11.7/6	0.07	12.3/18	0.83
Powheg+Herwig7	13.8/15	0.54	10.9/18	0.90	7.0/11	0.80	11.6/6	0.07	12.8/18	0.80

Dilepton

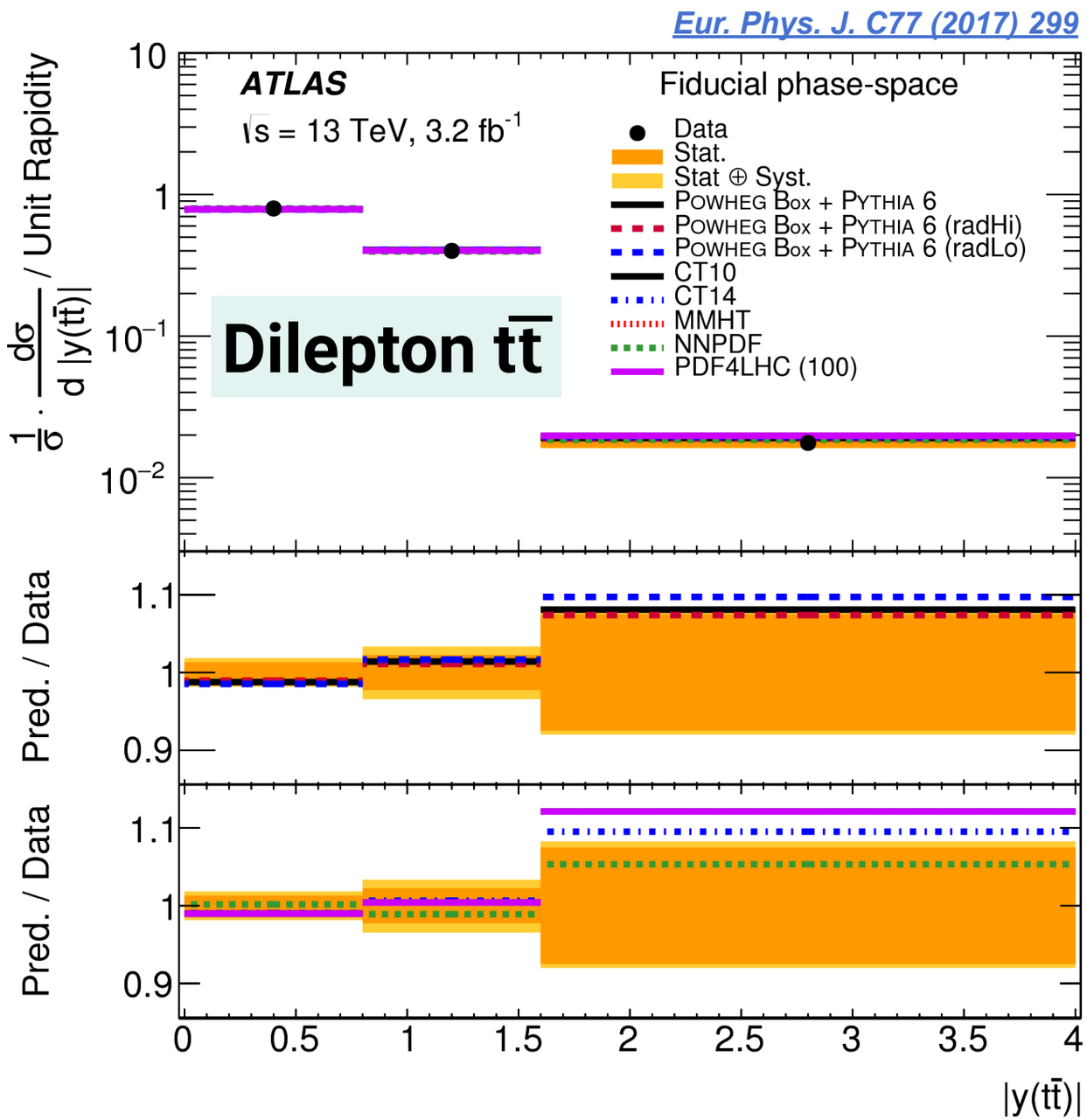
	$p_T(t)$		$\lvert y(t)\rvert$		$p_T(t\bar{t})$		$\lvert y(t\bar{t})\rvert$		$m(t\bar{t})$	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg + Pythia 6	5.2/4	0.27	0.5/3	0.92	5.5/6	0.48	0.6/2	0.74	3.9/4	0.42
Powheg + Pythia 8	4.6/4	0.33	1.3/3	0.73	5.1/6	0.53	0.0/2	1.00	5.7/4	0.22
Powheg + Herwig++	14.6/4	0.01	1.4/3	0.71	4.1/6	0.66	1.0/2	0.61	12.0/4	0.02
MG5_aMC@NLO + Herwig++	2.0/4	0.74	1.3/3	0.73	0.6/6	1.00	0.2/2	0.90	0.9/4	0.92
MG5_aMC@NLO + Pythia 8	3.6/4	0.46	0.6/3	0.90	10.7/6	0.10	0.1/2	0.95	2.7/4	0.61
Sherpa	3.8/4	0.43	0.8/3	0.85	0.7/6	0.99	0.0/2	1.00	2.3/4	0.68
Powheg + Pythia 6 (radHi)	7.8/4	0.10	0.6/3	0.90	0.9/6	0.99	0.4/2	0.82	3.8/4	0.43
Powheg + Pythia 6 (radLow)	5.5/4	0.24	0.8/3	0.85	9.6/6	0.14	0.8/2	0.67	4.5/4	0.34

All-hadronic

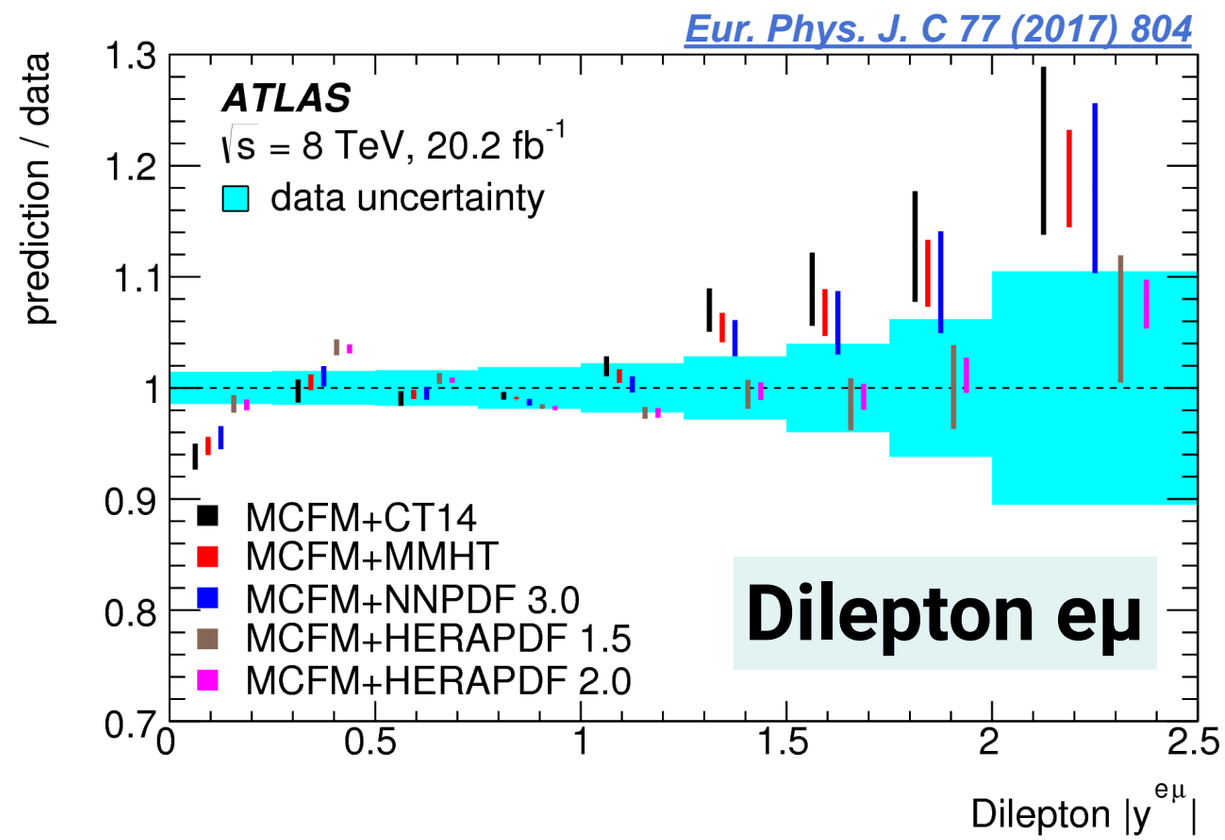
Observable	PWG+PY8		aMC@NLO +PY8		PWG+H7		PWG+PY8 (more IFSR)		PWG+PY8 (less IFSR)		Sherpa 2.2.1	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
$p_T^{t,1}$	7.7/7	0.36	8.2/7	0.32	8.0/7	0.33	9.1/7	0.24	8.7/7	0.27	9.3/7	0.23
$\lvert y^{t,1}\rvert$	7.5/5	0.18	12.2/5	0.03	6.8/5	0.24	8.8/5	0.12	8.1/5	0.15	4.0/5	0.55
$p_T^{t,2}$	8.6/6	0.20	2.6/6	0.86	9.9/6	0.13	12.2/6	0.06	5.0/6	0.54	5.0/6	0.55
$\lvert y^{t,2}\rvert$	3.7/5	0.59	4.6/5	0.46	3.1/5	0.68	3.5/5	0.63	3.2/5	0.67	2.9/5	0.72
$m^{t\bar{t}}$	4.5/9	0.88	4.7/9	0.86	4.0/9	0.91	5.3/9	0.81	5.2/9	0.82	10.0/9	0.35
$p_T^{t\bar{t}}$	7.8/5	0.17	20.9/5	<0.01	12.6/5	0.03	15.0/5	0.01	1.9/5	0.86	1.9/5	0.87
$\lvert y^{t\bar{t}}\rvert$	1.1/5	0.95	2.2/5	0.83	0.9/5	0.97	0.8/5	0.98	1.8/5	0.88	1.7/5	0.89
$\chi^{t\bar{t}}$	14.2/6	0.03	12.7/6	0.05	13.6/6	0.03	16.9/6	<0.01	10.1/6	0.12	18.5/6	<0.01
$y_B^{t\bar{t}}$	2.5/6	0.87	3.3/6	0.77	2.2/6	0.90	2.6/6	0.86	2.8/6	0.84	3.0/6	0.81
$\lvert p_{out}^{t\bar{t}}\rvert$	1.9/6	0.93	53.1/6	<0.01	3.1/6	0.80	4.2/6	0.64	4.8/6	0.57	5.9/6	0.44
$\Delta\phi^{t\bar{t}}$	0.9/3	0.84	16.3/3	<0.01	2.0/3	0.58	3.0/3	0.40	0.6/3	0.89	3.4/3	0.33
$H_T^{t\bar{t}}$	4.8/6	0.57	5.2/6	0.52	4.5/6	0.61	5.0/6	0.54	5.0/6	0.55	3.1/6	0.80
$\cos\theta^\star$	9.9/5	0.08	10.5/5	0.06	9.3/5	0.10	12.8/5	0.03	6.5/5	0.26	18.7/5	<0.01


ATLAS
√s = 13 TeV, 36.1 fb-1
Stat. Unc.
Stat. ⊕ Det. Syst. Unc.
Stat. ⊕ Det. ⊕ Mod. Syst. Unc.
Nominal (Th. Stat. ⊕ Scale ⊕ PDF Unc.)
POWHEG+Pythia8
hdamp=1.5mtop , NNPDF 3.0 NLO, A14
Alternative PDF (Th. Stat. Unc.)
POWHEG+Pythia8
hdamp=1.5mtop , MMHT2014, A14
POWHEG+Pythia8
hdamp=1.5mtop , CT14, A14
POWHEG+Pythia8
hdamp=1.5mtop , PDF4LHC15, A14
Alternative ISR/FSR (Th. Stat. Unc.)
POWHEG+Pythia8 (less IFSR)
hdamp=1.5mtop , μF=2 μR=2, NNPDF 3.0 NLO, A14v3cDo
POWHEG+Pythia8 (more IFSR)
hdamp=3.0mtop , μF=0.5 μR=0.5, NNPDF 3.0 NLO, A14v3cUp
Alternative ME/PS (Th. Stat. Unc.)
POWHEG+Herwig7
hdamp=1.5mtop , NNPDF 3.0 NLO, H7UE
MG5_aMC@NLO+Pythia8
NNPDF 3.0 NLO, A14
Sherpa 2.2.1
NNPDF 3.0 NNLO
200
300
400
500
600
700
800
Inclusive fiducial cross-section [fb]

$t\bar{t}$ rapidity



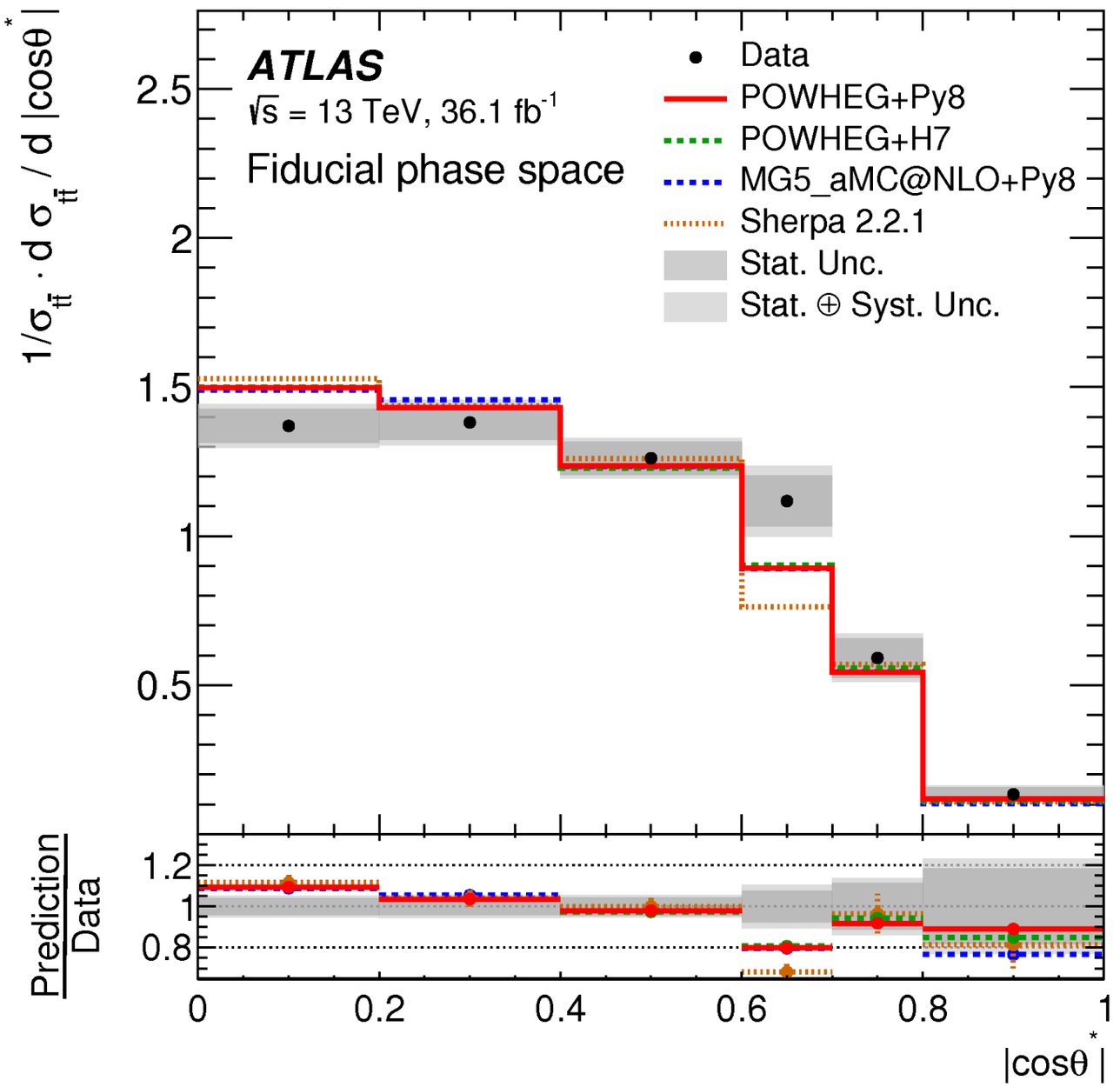
- Forward region sensitive to PDF
- 13 TeV data seems to prefer NNPDF 3.0
- 8 TeV Lepton differential

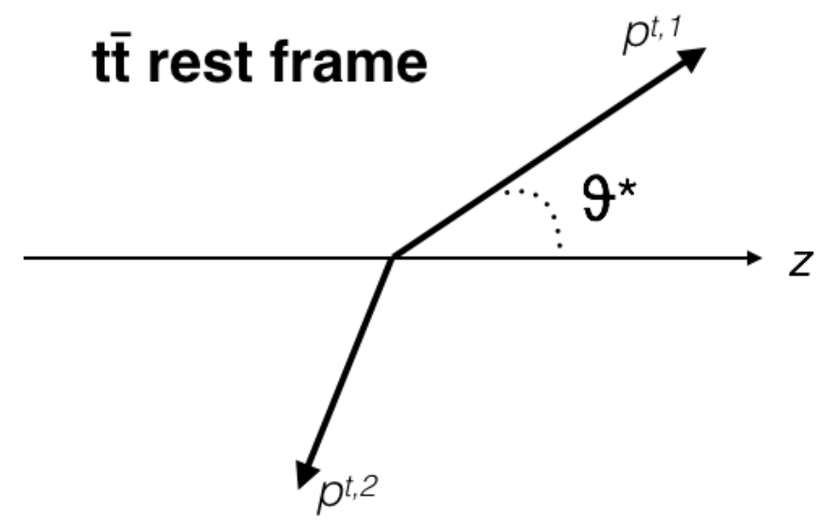


$t\bar{t}$ angle in Rest Frame

All-hadronic

arXiv:1801.02052





- Fair agreement
- Something going on at low cosϑ*

Lepton differential and pole mass 8 TeV

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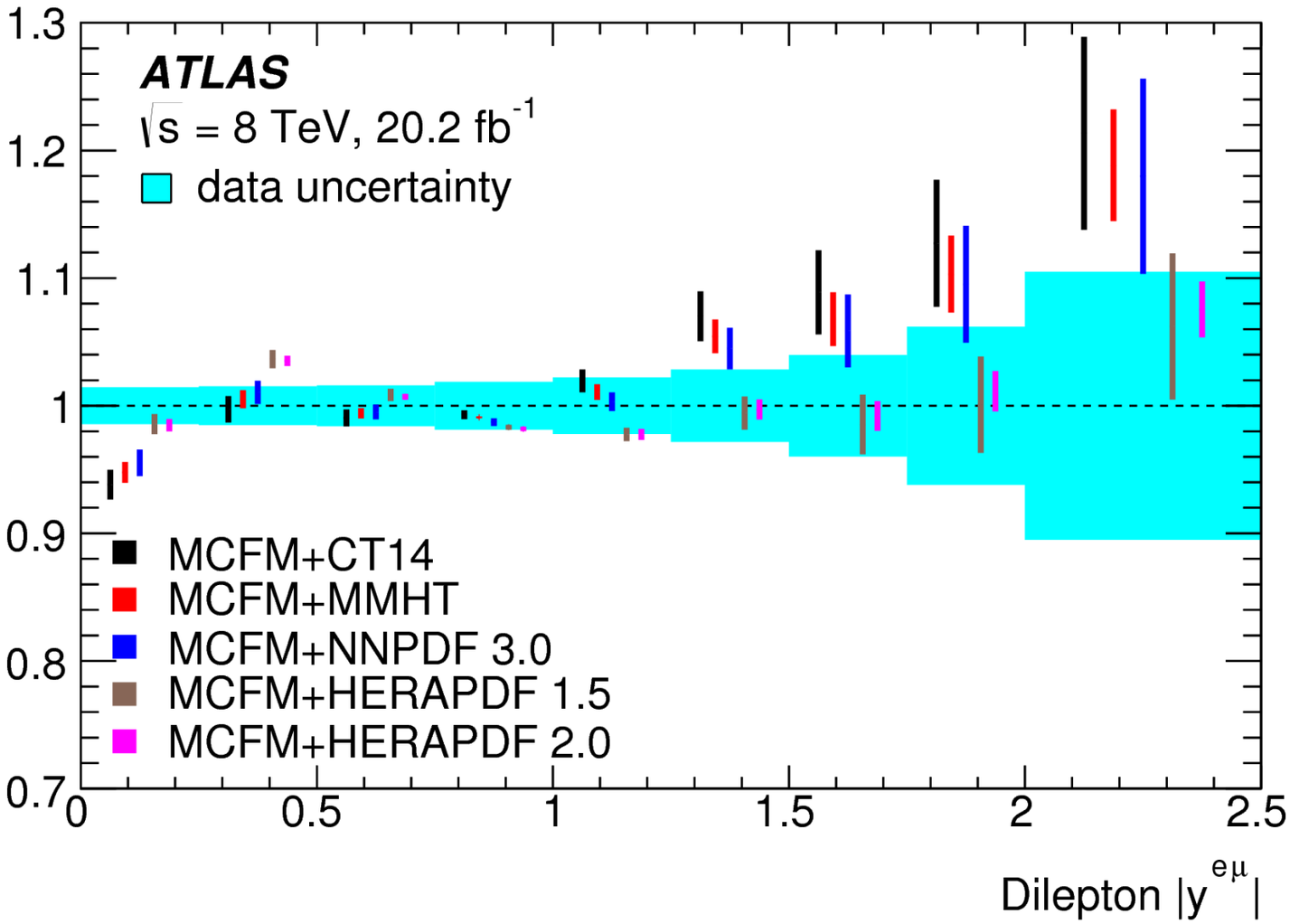

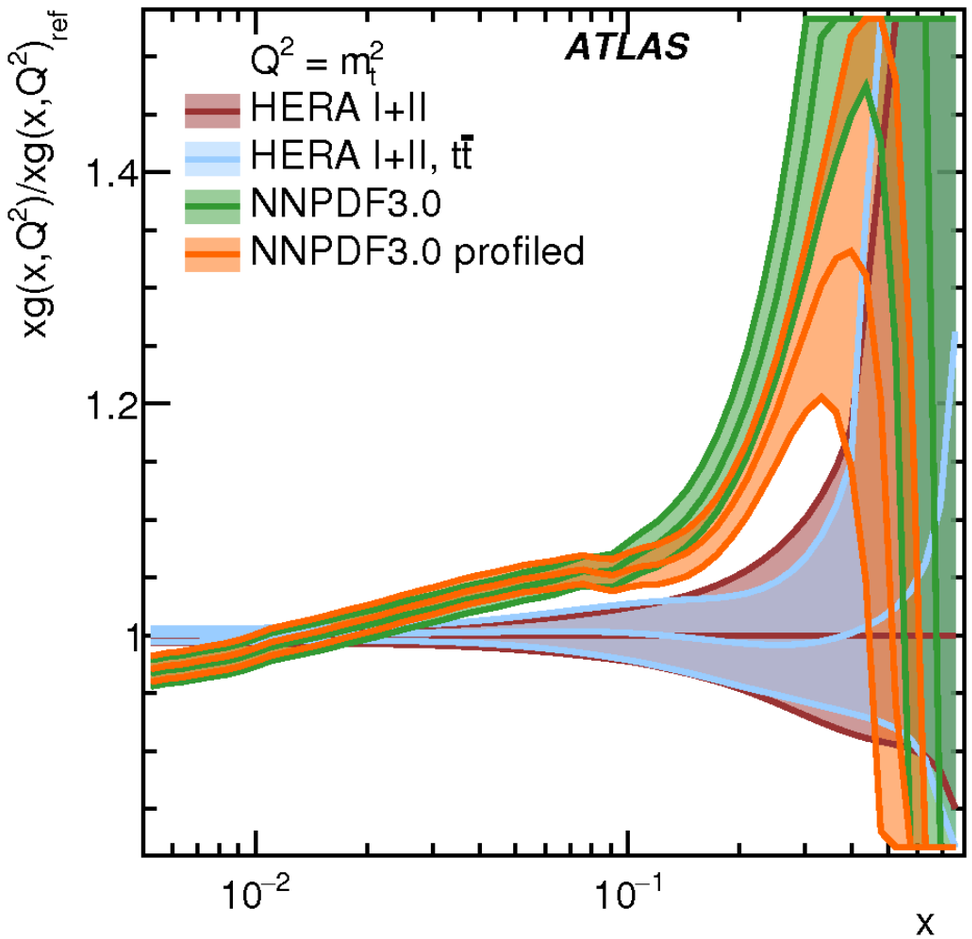

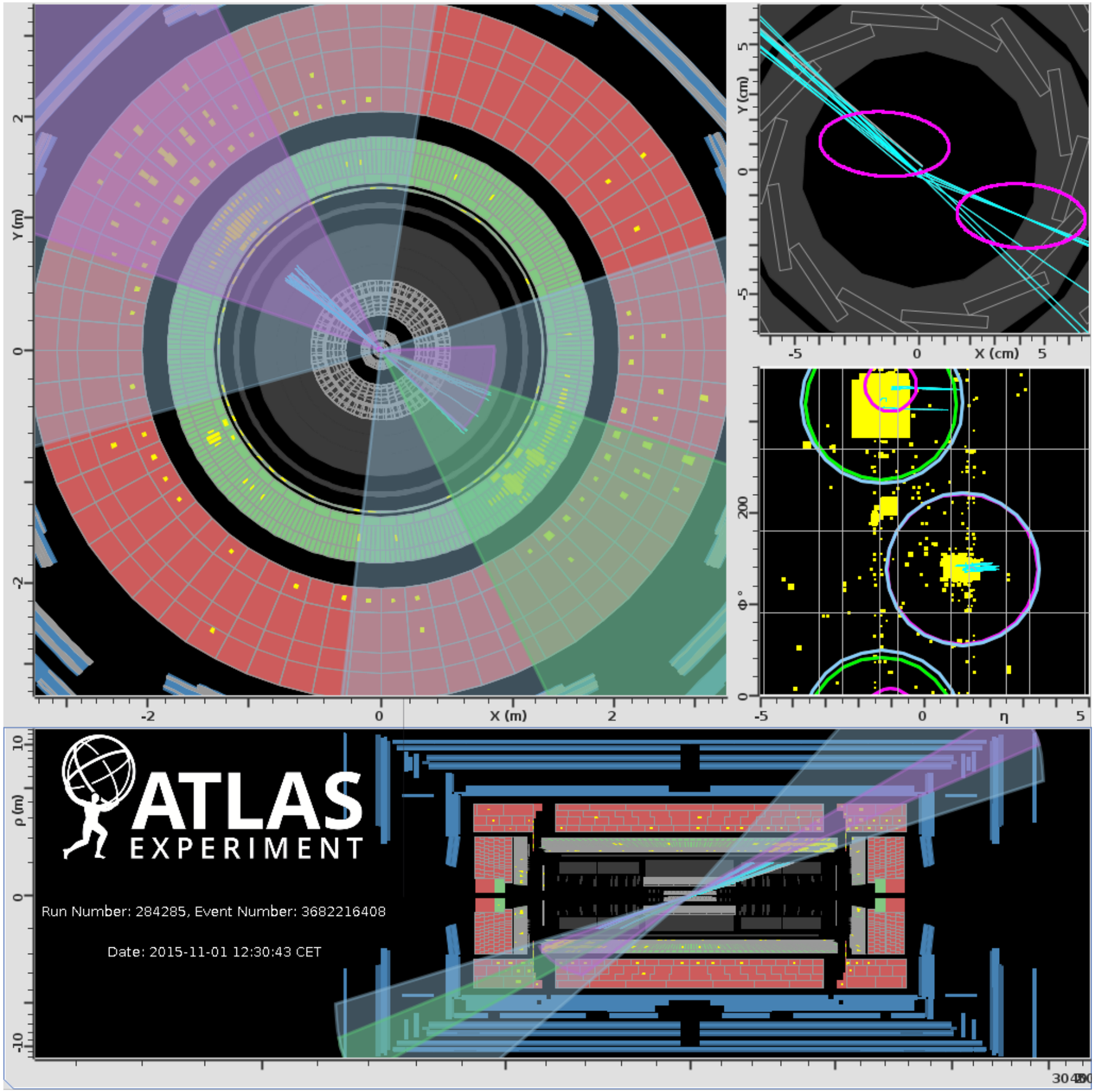

Event display of a $t\bar{t}$ candidate event in the 2015 data. The large-R anti-kt R=1.0 jets are shown in blue while the remaining jets are anti-kt R=0.4 jets. The jets identified as containing b-hadrons are shown in magenta. The centers of magenta ellipses in the top right pad correspond to secondary vertices. The transverse momenta of the leading and second-leading large-R jets are **961 GeV** and **824 GeV**, respectively. The dijet invariant mass of the two large-R jets is **3.33 TeV** while the τ32 values are 0.35 and 0.34 for the leading and second-leading large-R jets, respectively.