Top quark pair production cross section measurements with the ATLAS detector

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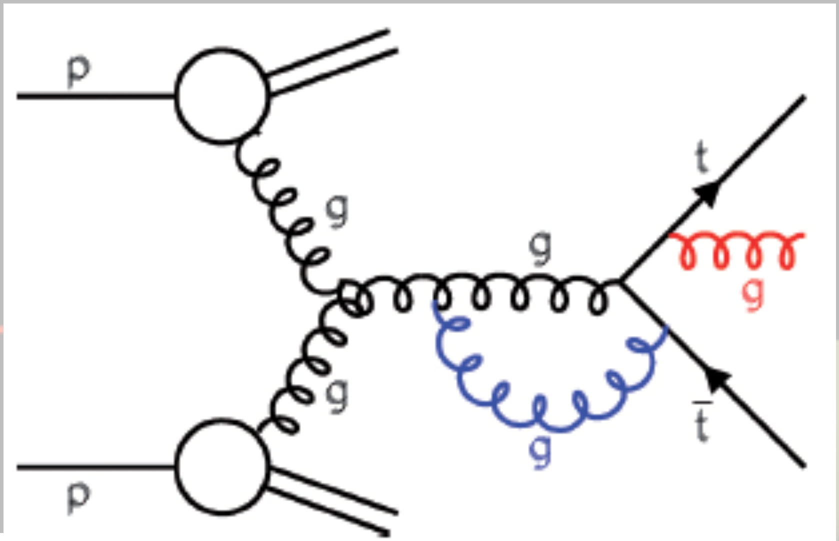
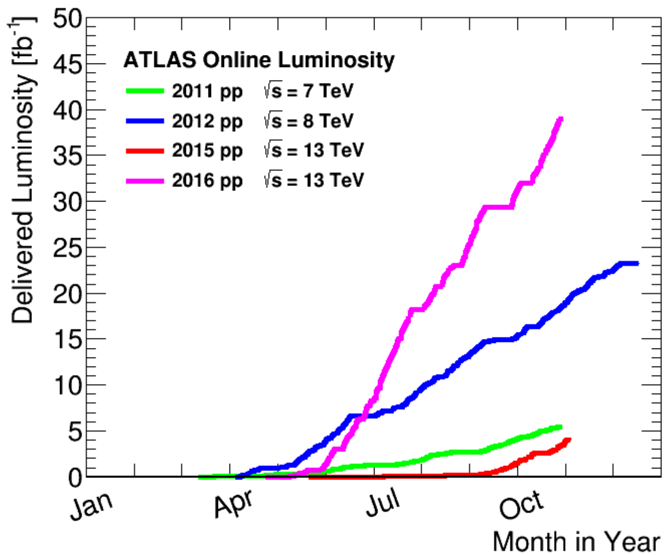
HELMHOLTZ ASSOCIATION

Top pair production at ATLAS

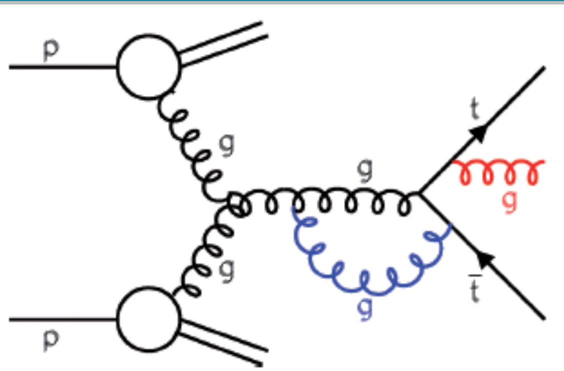




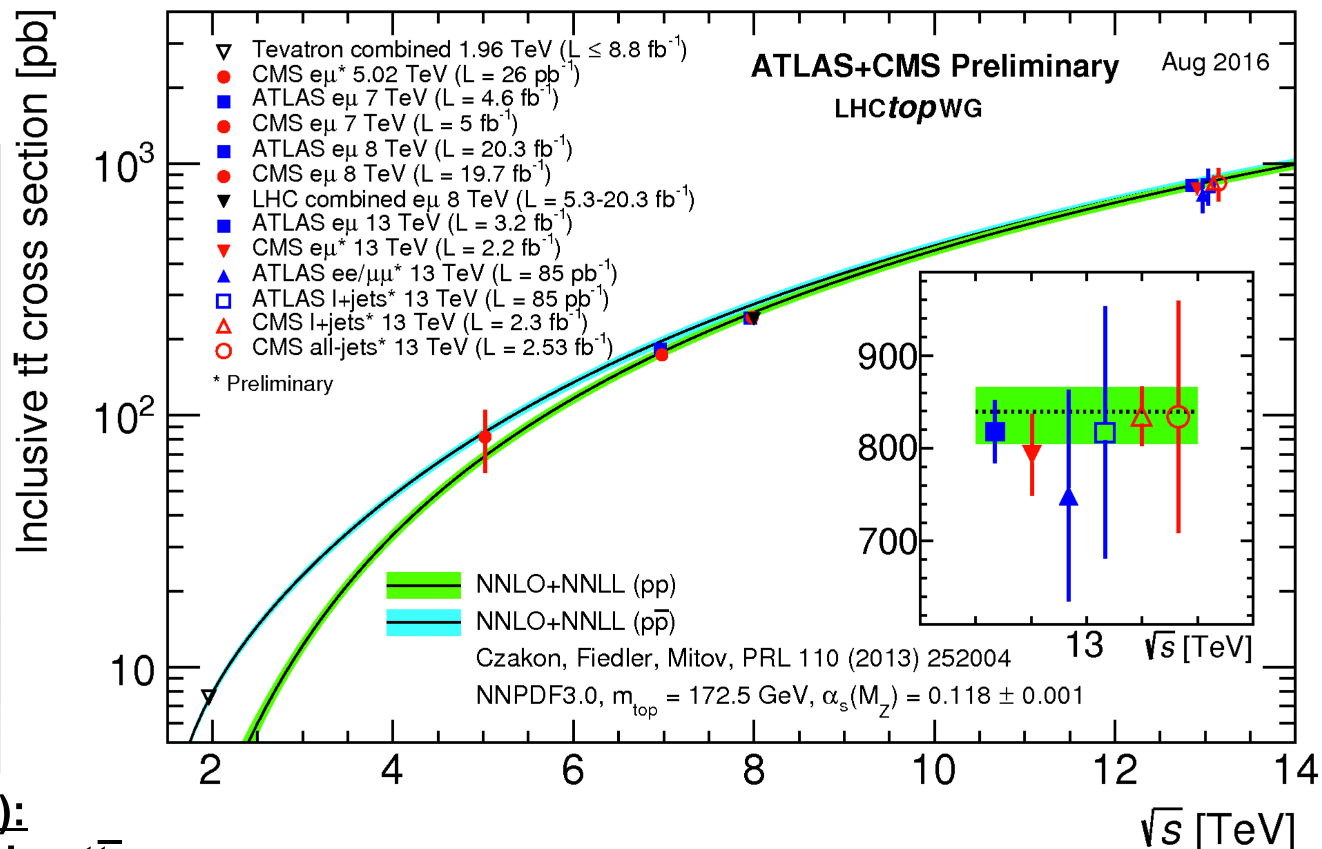
Energy (TeV)	No. of events produced
7	0.8 M @ 4.6 fb^{-1}
8	5.1 M @ 20.3 fb^{-1}
13 (2015)	2.6 M @ 3.2 fb^{-1}
13 (2016)	27 M @ 33 fb^{-1}

- Constrain SM parameters: PDFs, α_s, M_{top}, …
- Test pQCD
- Probe new physics

Top pair production at ATLAS



Precision of inclusive cross section measurement better than theory!



@ √s = 13 TeV (eμ channel):

Uncertainty of ATLAS **inclusive $t\bar{t}$ cross section** measurement : **4.4%**

Theory uncertainty : **5.5%**

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ATLAS 13 TeV data, 3.2 fb^{-1}:

$\sigma_{t\bar{t}}$ = 818 ± 8 (*stat.*) ± 27 (*syst.*) ± 19 (*lumi*) ± 12 (*beam*) pb

$\sigma_{t\bar{t}}$ / σ_Z cross section ratio

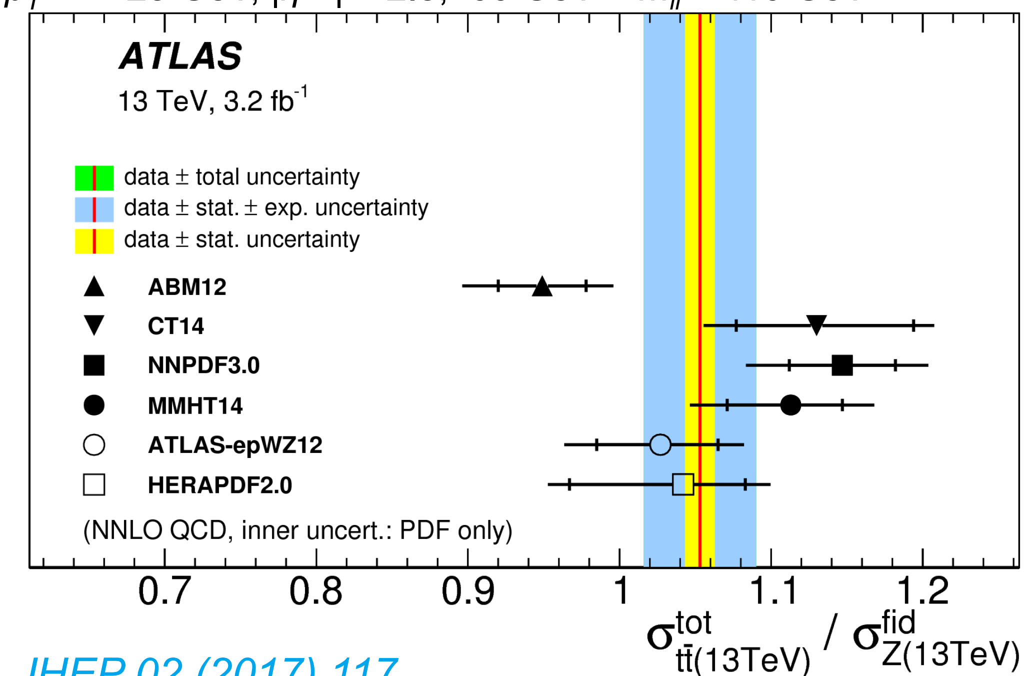
- Sensitive to gluon-to-quark PDFs ratio
- Cancellation of several uncertainties in cross section ratio

Measurements at $\sqrt{s}$ = 7, 8 and 13 TeV

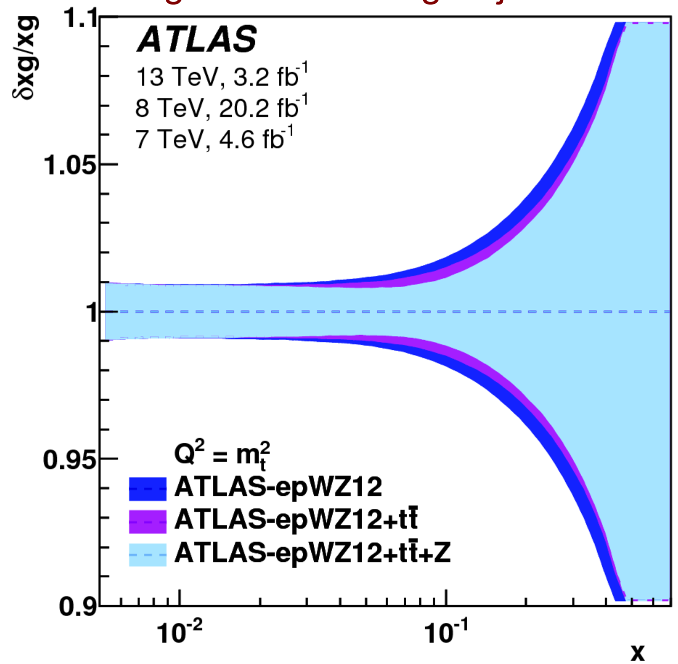
- Data compared to state-of-the-art NNLO calculations using various PDF sets
  - ATLAS measurement precision is better than theory precision
  - theory uncertainties for $\sigma_{t\bar{t}}^{tot}$ / σ_Z^{fid} ratio dominated by PDFs uncertainties, M_{top} and QCD scale choice
  - data agree best with ATLAS-epWZ12 PDF set, and disfavor ABM12 PDF set

fiducial definition for *Z* production:

p_T^{lep} > 25 GeV, $|\eta^{lep}|$ < 2.5, 66 GeV < m_{ll} < 116 GeV



Data have constraining power for gluon PDF at high Bjorken *x*



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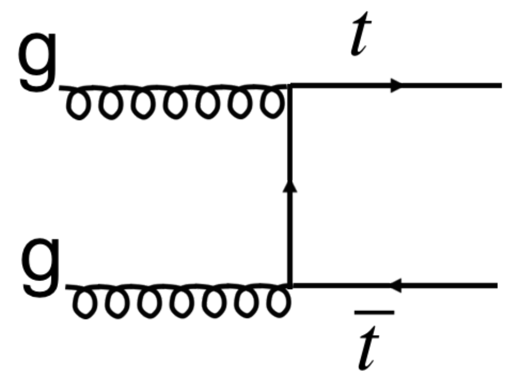
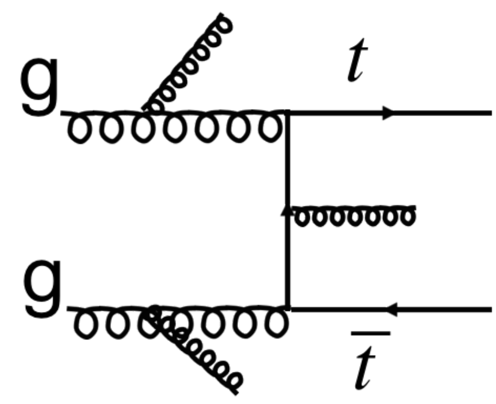
$t\bar{t}$ differential measurements

- Differential measurements provide **stronger tests of pQCD and SM**
  - increase sensitivity to gluon PDF at high momentum fraction, QCD coupling constant α_s, top quark mass, etc.…



- Measurement of QCD radiation jets produced with $t\bar{t}$ is crucial for **tuning MC generator** parameters
  - improve modelling of parton shower and hadronisation in various region of phase space
  - tune matching procedures and merging parameters of matrix element generators
  - improve top kinematic measurements



- $t\bar{t}$ + jets is **interesting background** for rare SM processes (e.g $t\bar{t}H$) and many new physics models
  - differential distributions are more sensitive in probing new physics

Interesting observables measurements at ATLAS

> Quantities which are directly measurable with the detector

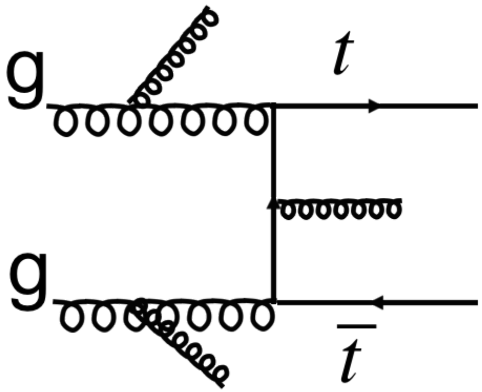
- **no. of jets** : **additional jets produced with $t\bar{t}$ are sensitive to p_T of $t\bar{t}$ system and modeling of I/FSR**
- **jet p_T** : **leading *b*-jet p_T sensitive to top p_T modeling**

  additional jet p_T sensitive to $t\bar{t}$ system modeling
- **top p_T, $m^{t\bar{t}}$** : **NLO QCD modeling and probe new physics**
- **$t\bar{t}$ system $p_T^{t\bar{t}}$, $H_T^{t\bar{t}}$, $\Delta\Phi^{t\bar{t}}$, out-of-plane momentum $|p_{out}^{t\bar{t}}|$** : **sensitive to shower models, I/FSR**
- **top rapidity y, $y^{t\bar{t}}$, longitudinal boost $y_B^{t\bar{t}} = (y^{t,1} + y^{t,2}) / 2$** : **sensitive to PDFs**
- **production angles, in Collin-Soper frame *CosΘ**, and in center of mass frame $\chi^{t\bar{t}} = \exp(|y^{t,1} - y^{t,2}|)$** : **sensitive to new physics at very high p_T**

> Some of these measurements in various channels of top quark decays and in resolved and boosted regimes

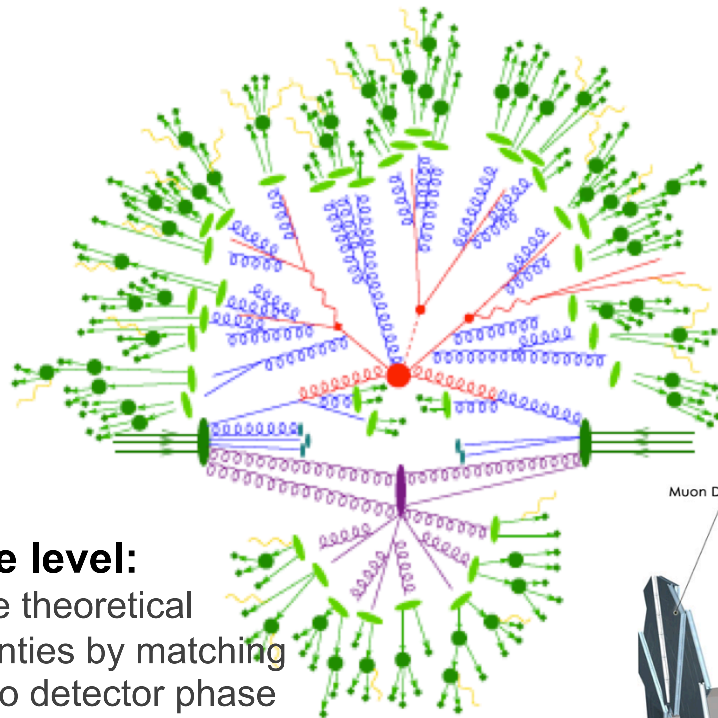
> Check for consistent picture of QCD

Unfolding of detector-level measurements



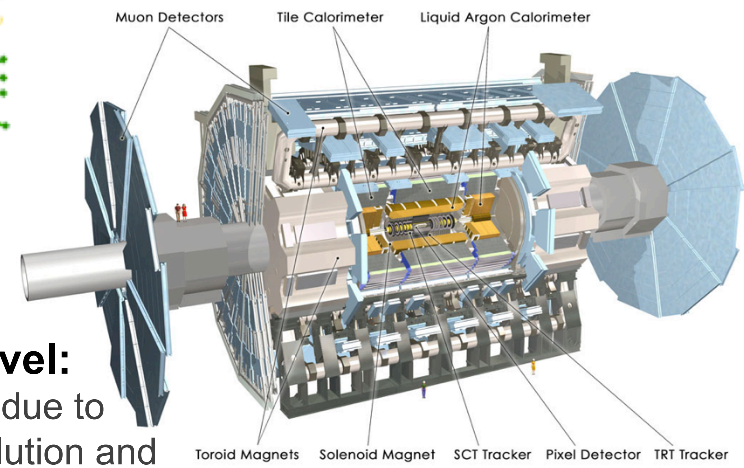
Parton level:
directly probes the ME, PDFs, α_s, M_{top} , etc…

but, large model dependence and hence large uncertainties



Particle level:
minimize theoretical uncertainties by matching closely to detector phase space

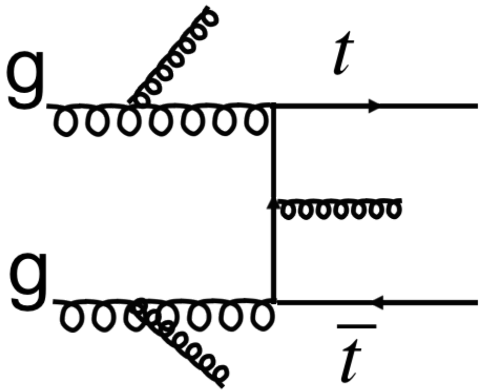
suffers mostly by non-perturbative effects (parton shower, fragmentation, hadronisation, PDFs …)



Detector level:
inefficiencies due to detector resolution and response

detector dependent modeling

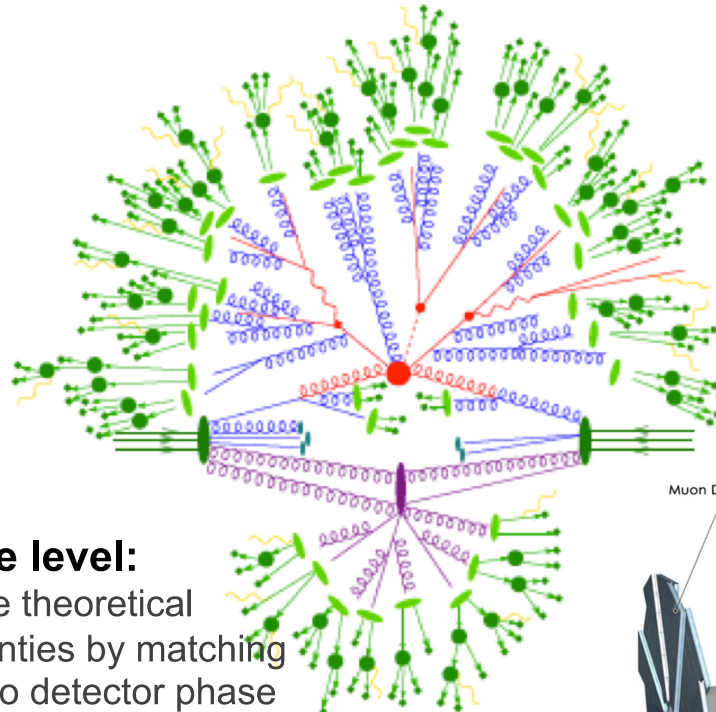
Unfolding of detector-level measurements



Parton level:
directly probes the ME, PDFs, α_s, M_{top} , etc…

but, large model dependence and hence large uncertainties

Parton level ATLAS measurements available at $\sqrt{s}$ = 7, 8 TeV, but **this talk will focus on recent particle-level results**



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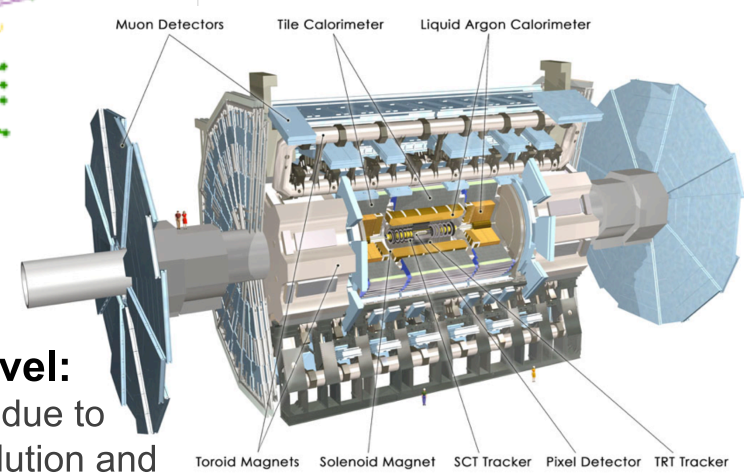


Detector level:
inefficiencies due to detector resolution and response

detector dependent modeling

Jet multiplicity and jet spectra measurements

Event selection :

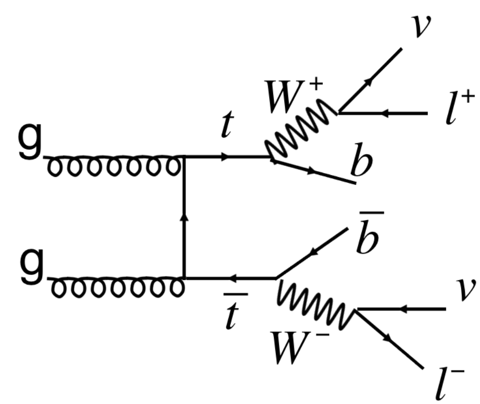
1 oppositely charged *eμ* pair

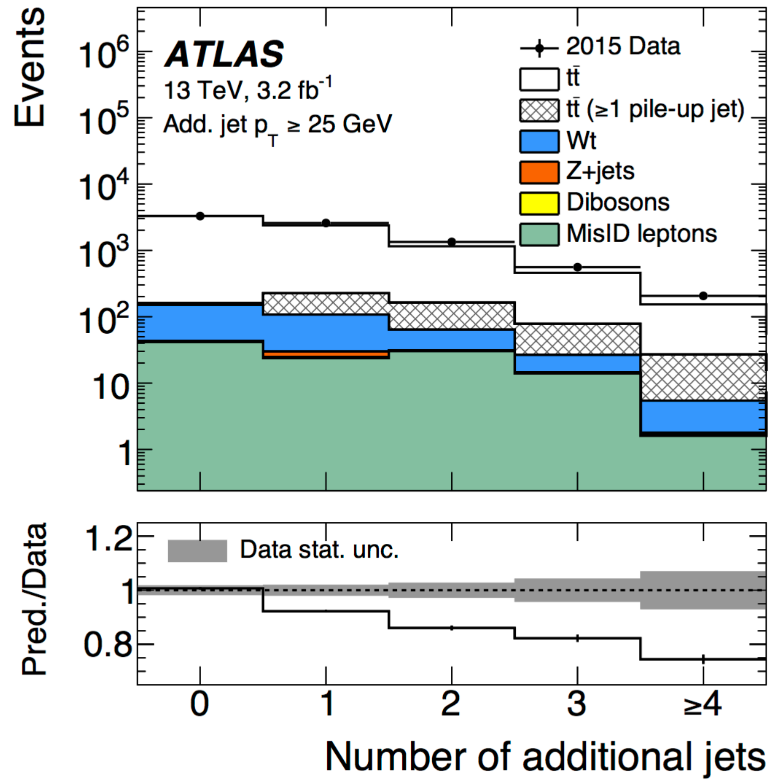
- 1 electron: p_T > 25 GeV, $|\eta|$ < 2.47 (excluding the crack, 1.37 < $|\eta|$ < 1.52)
- 1 muon: p_T > 25 GeV, $|\eta|$ < 2.5

≥ 2 anti-k_T R =0.4 jets (p_T > 25 GeV) and **≥ 2 *b*-tags** (77% efficiency)

No requirement on top reconstruction

< 5% background



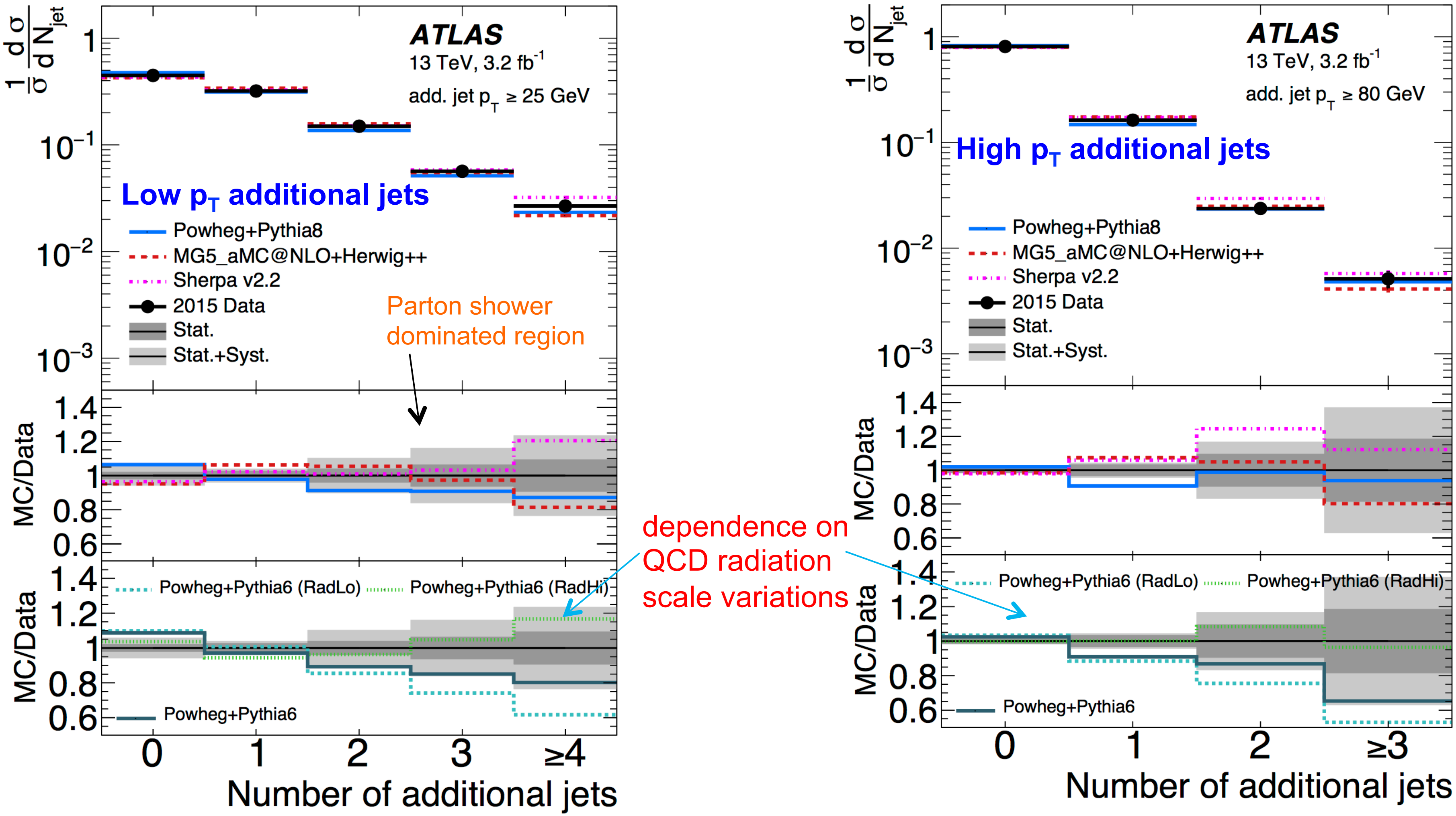


- di-lepton channel has less ambiguity in identification of additional jets
- detector-level distribution from data show discrepancy at higher jet multiplicity bins

TOP-2015-17, CERN-EP-2016-218, arXiv:1610.09978

Jet multiplicity distribution @ particle-level

> **Fiducial phase space:** (1 $e\mu$ pair and ≥ 2 b-jets with p_T > 25 GeV, $|\eta|$ < 2.5, and ΔR (lepton,jet) > 0.4)



Predictions from Powheg+Pythia8, MG5_aMC@NLO+Herwig++ and Sherpa vary within 10%- 20%

reasonable description of data within total uncertainties of measurement

TOP-2015-17, CERN-EP-2016-218, arXiv:1610.09978

Jet spectra @ particle level

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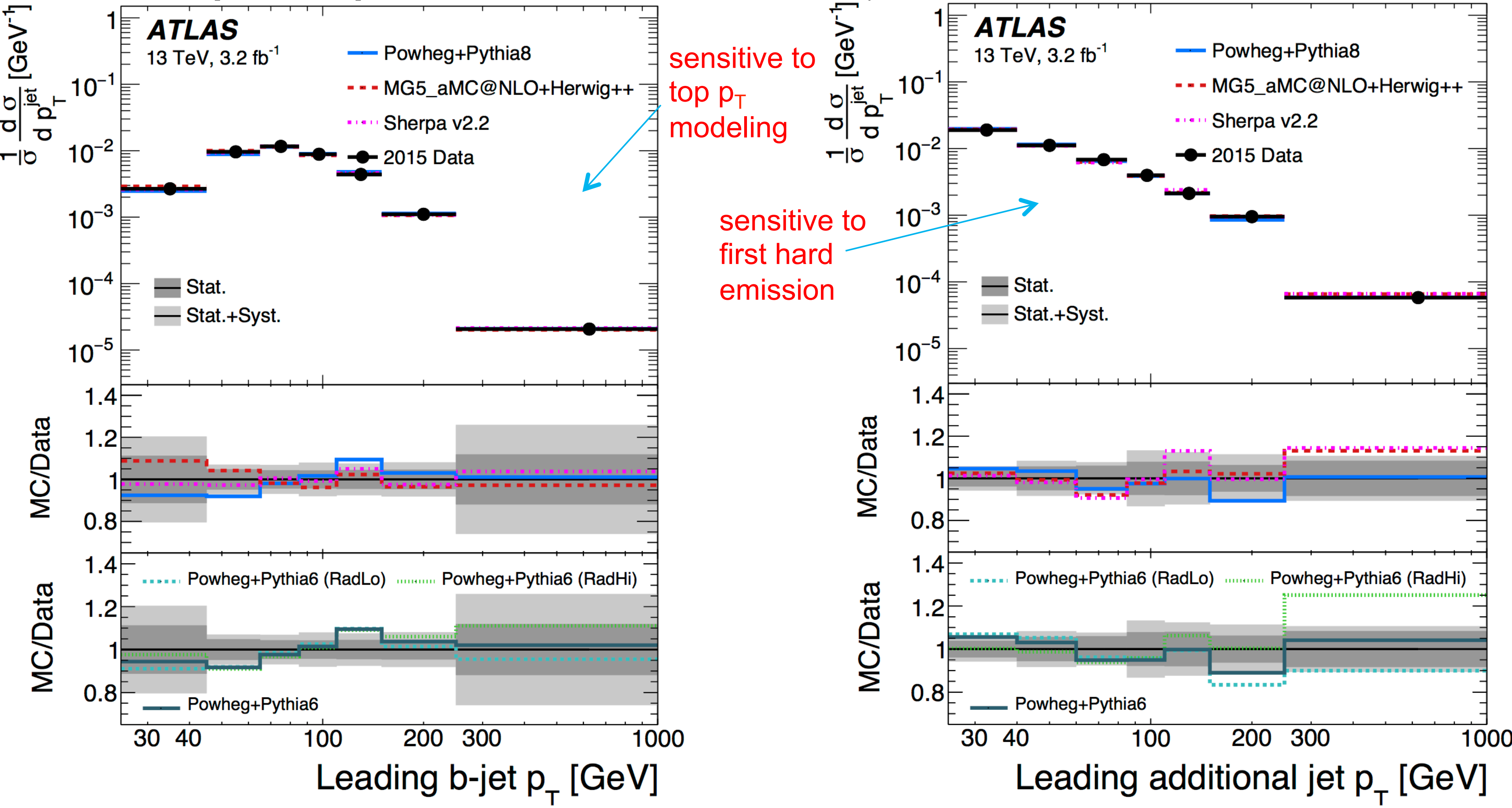

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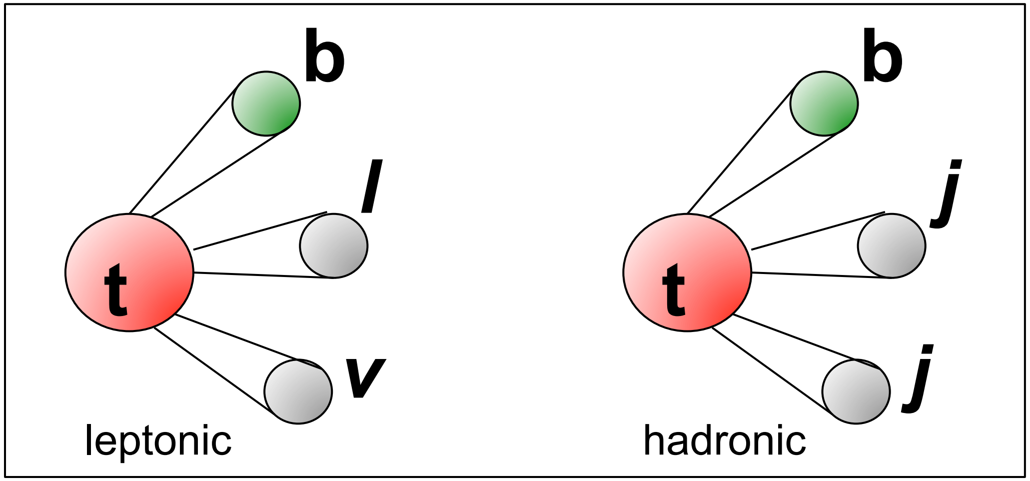
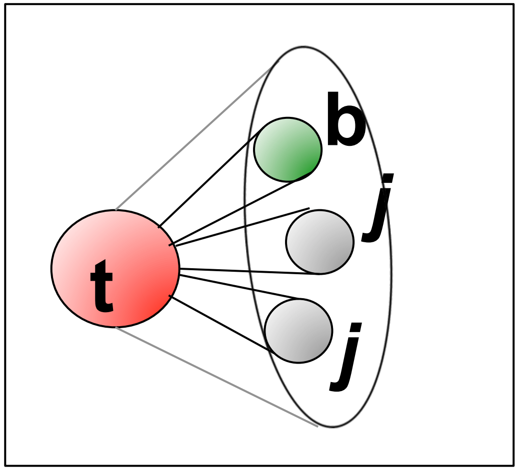
Top reconstruction

Resolved



Boosted: $\Delta R \approx 2\, M_{top}/p_T^t$



Dilepton channel :

TOP-2016-04; arXiv:1612.05220

- two tops reconstruction using neutrino weighting algorithm
- two η solutions for each ν, based on constraints on M_W and M_{top}
- pick solution giving smallest difference in measured and estimated missing E_T

Lepton+jets channel :

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- one *b*-jet associated to closest lepton in ΔR to kinematically reconstruct leptonic top
- **resolved hadronic top**: one *b*-jet combined with other close-by jets to identify hadronic top based on constraints on M_W and M_{top}

All-hadronic channel:

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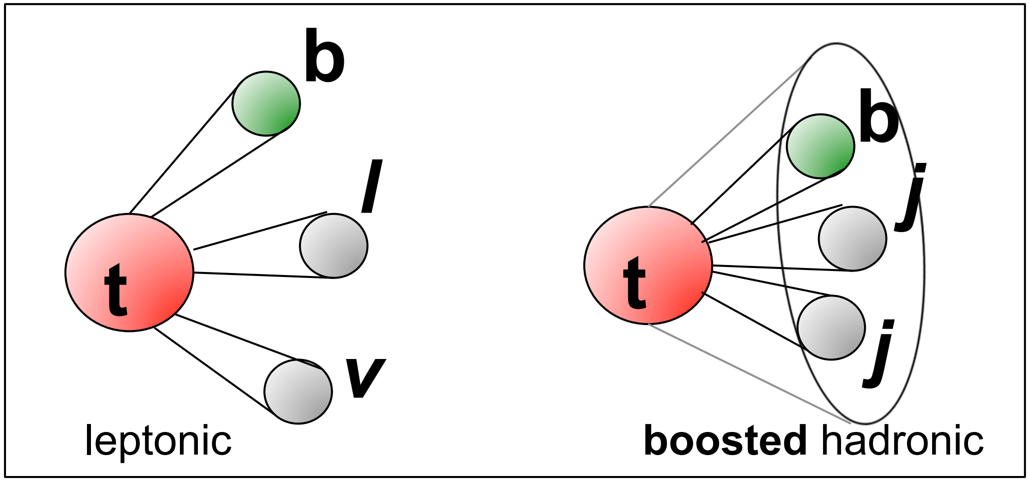
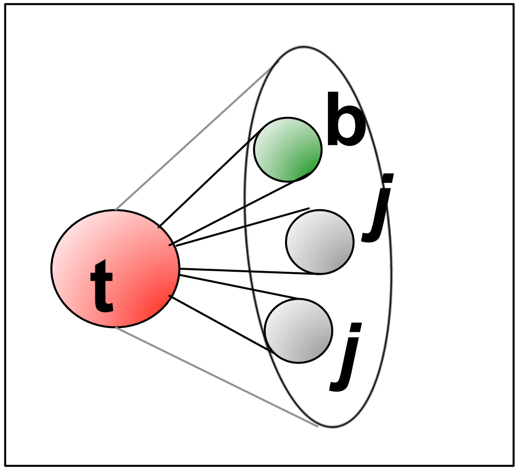
- Top taggers for large radius (R = 1.0) anti-k_T jets using substructure, jet mass and presence of *b*-jet
- two tops reconstruction in **boosted regime**

Top reconstruction

Boosted: $\Delta R \approx 2\, M_{top}/p_T^t$





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- pick solution giving smallest difference in measured and estimated missing E_T

Lepton+jets channel :

JHEP 06 (2015) 100
ATLAS-CONF-2016-040

- one jet associated to closest lepton in ΔR to kinematically reconstruct leptonic top
- **boosted hadronic top**: one large radius (R = 1.0) anti-k_T jet, which is top-tagged using jet substructure and jet mass information

All-hadronic channel:

ATLAS-CONF-2016-100

- Top taggers for large radius (R = 1.0) anti-k_T jets using substructure, jet mass and presence of *b*-jet
- two tops reconstruction in **boosted regime**

Top kinematic measurements in dilepton channel

Event selection :

1 oppositely charged *eμ* pair

- 1 electron: p_T > 25 GeV, $|\eta|$ < 2.47 (excluding the crack, 1.37 < $|\eta|$ < 1.52)
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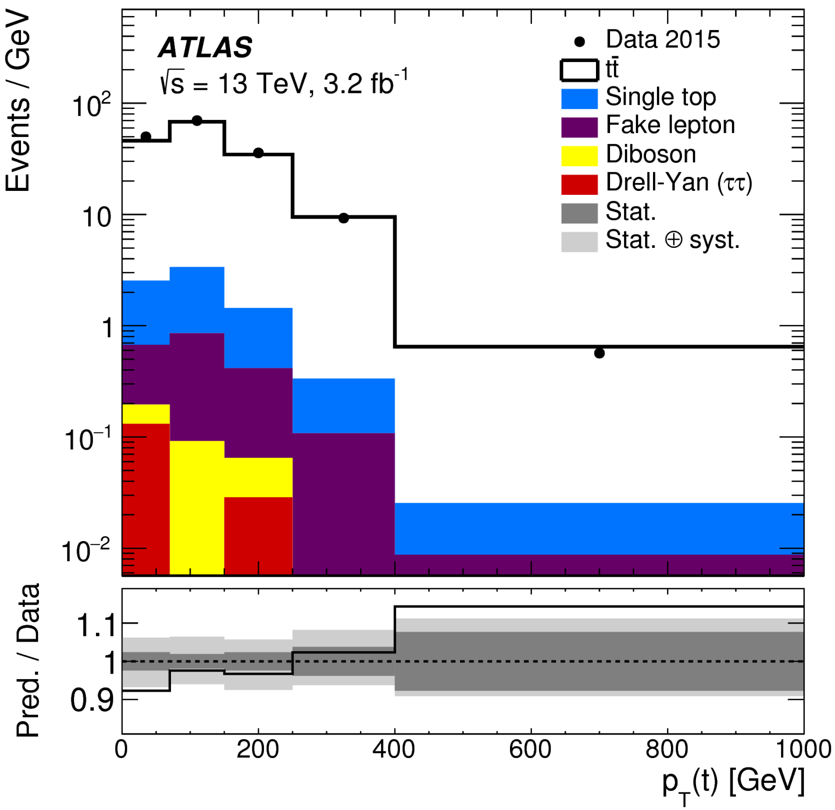
≥ 2 anti-k_T R =0.4 jets (p_T > 25 GeV, $|\eta|$ < 2.5) and **≥ 1 *b*-tag** (77% efficiency)



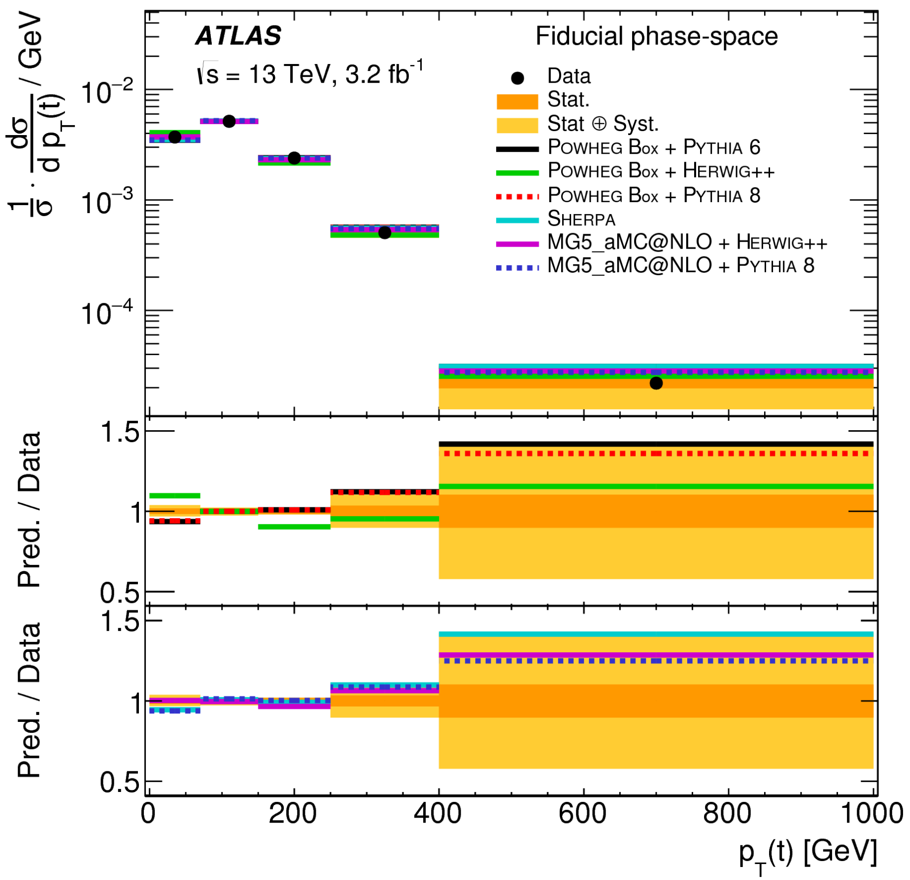
Background ≈ 5% after kinematic reconstruction of top via neutrino weighting (dominated by *Wt* and mis-identified leptons)

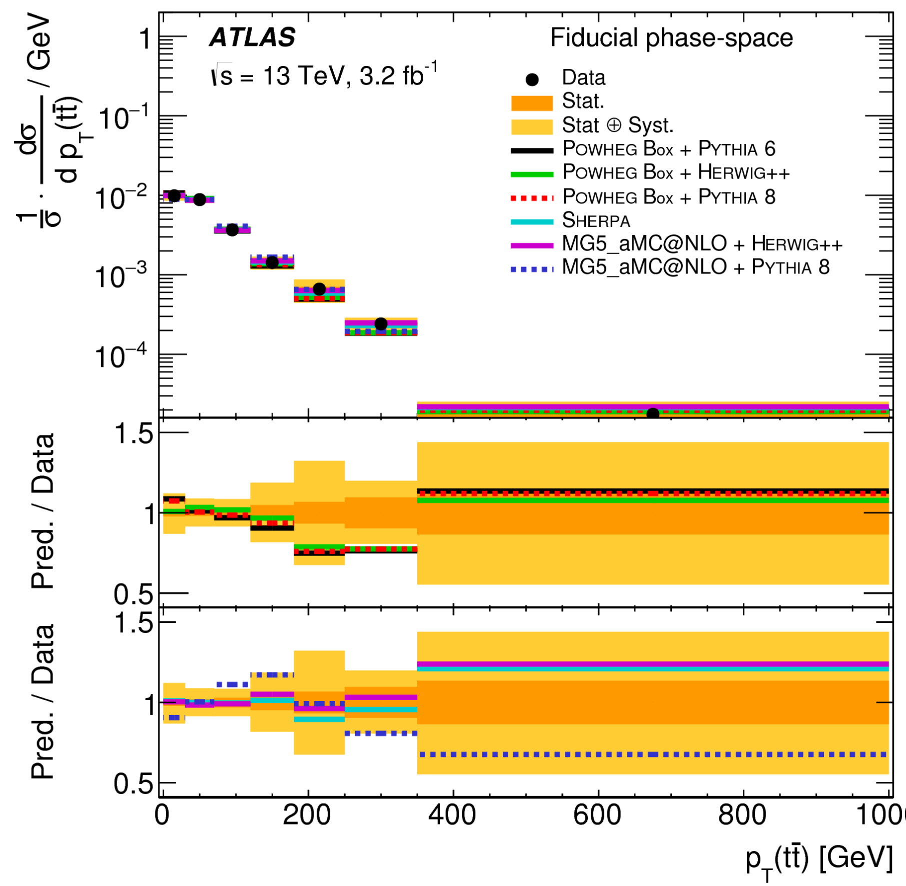
- Trend in detector-level p_T of top showing softer spectra in data compared to nominal prediction

TOP-2016-04, CERN-EP-2016-220, arXiv:1612.05220

Top kinematic measurements in dilepton channel

- **Absolute and normalised distributions in fiducial phase space (**2 semi-leptonic pseudo-top quarks):



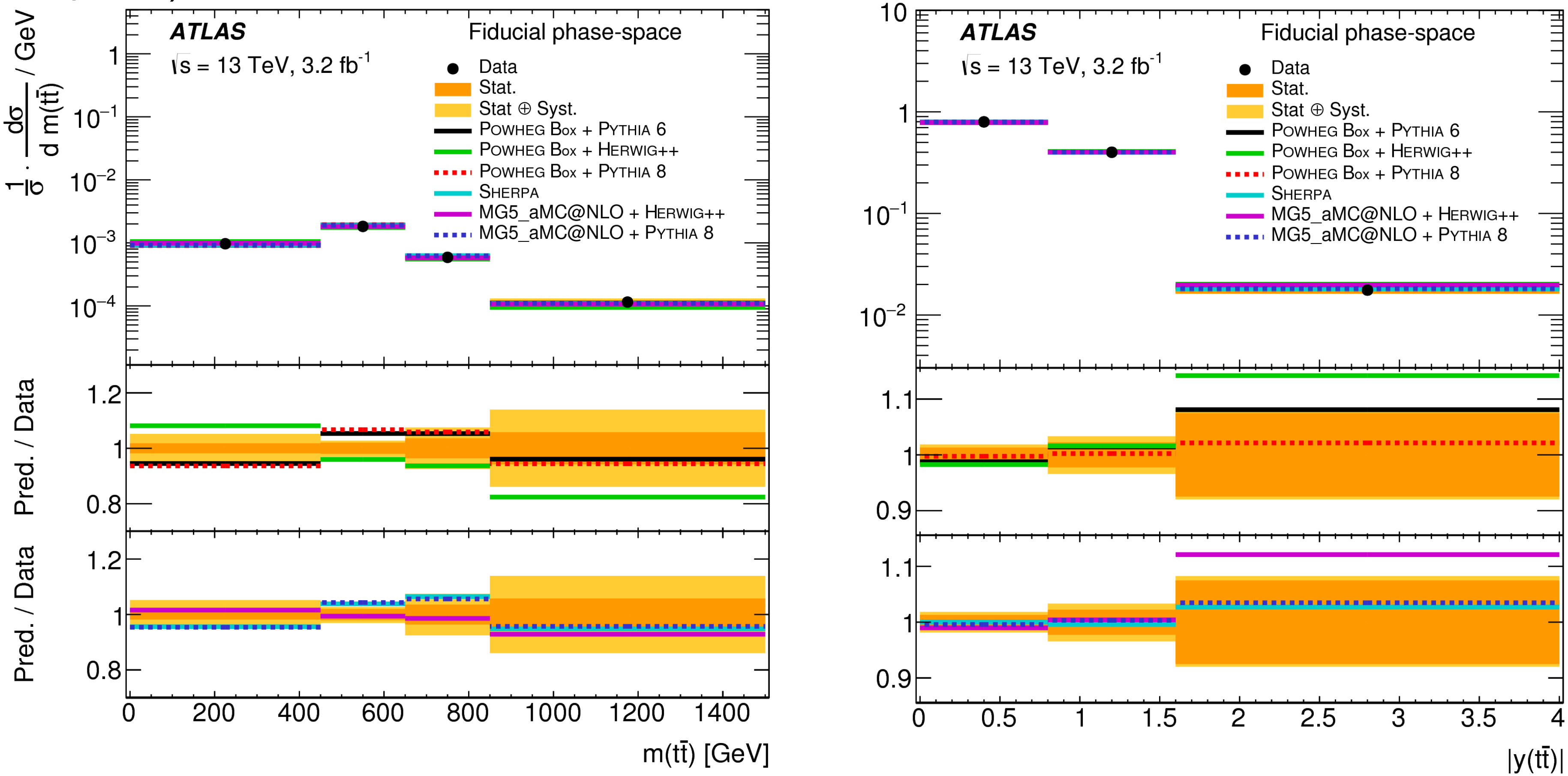


- Measurement uncertainties dominated by JES and signal modelling
  - main uncertainties due to signal modeling arise from PS modeling
- Most predictions agree within large uncertainties (largest difference is seen in Powheg+Herwig++)

TOP-2016-04, CERN-EP-2016-220, arXiv:1612.05220

Top kinematic measurements in dilepton channel

> **Absolute and normalised distributions in fiducial phase space (**2 semi-leptonic pseudo-top quarks):



> Measurement uncertainties dominated by JES and signal modelling

> NLO generators interfaced with Herwig++ show deviation at high $y^{t\bar{t}}$

sensitive to PDFs

$$x = \frac{M(t\bar{t})}{\sqrt{s}} e^{\pm y(t\bar{t})}$$

TOP-2016-04, CERN-EP-2016-220, arXiv:1612.05220

Top kinematic measurements in lepton+jets channel

Event selection :

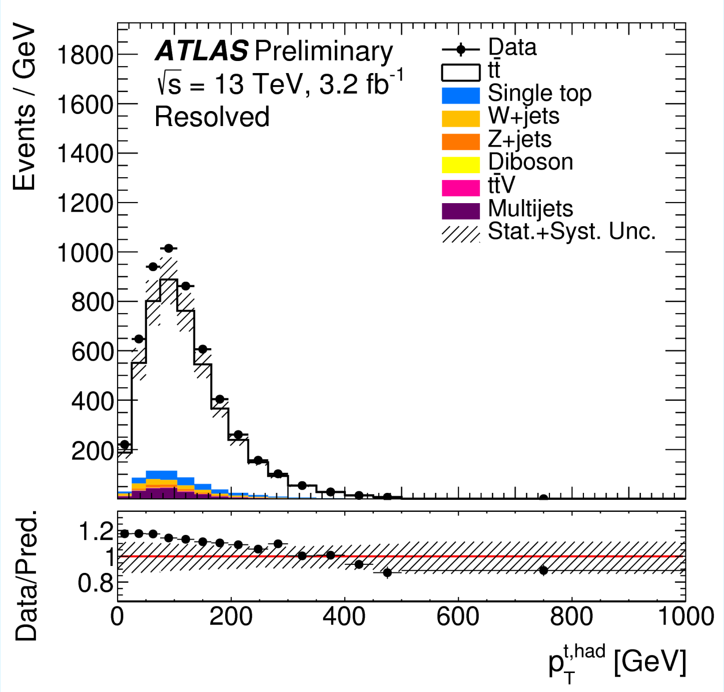
1 electron (p_T > 25 GeV, $|\eta|$ < 2.47 (excluding 1.37 < $|\eta|$ < 1.52)), **or 1 muon** (p_T > 25 GeV, $|\eta|$ < 2.5)

Resolved jet selection:

≥ 4 anti-k_T **small *R* = 0.4** jets (p_T > 25 GeV)

- **≥ 2 *b*-tag** (77% efficiency)

~ 13% background



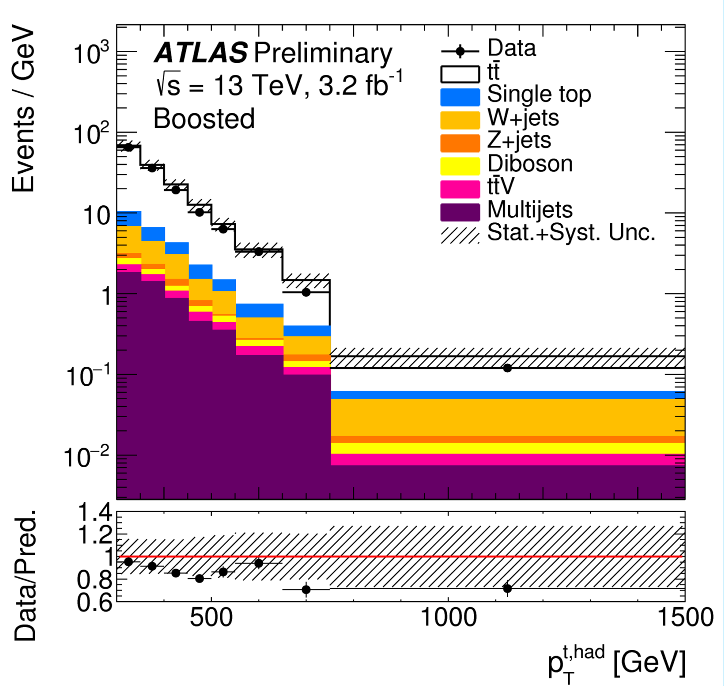
Boosted jet selection:

≥ 1 anti-k_T small *R* = 0.4 jets and ΔR (jet, lep) < 2.0

≥ 1 anti-k_T large *R* = 1.0 jets (p_T > 300 GeV) top-tagged jet @ 80% efficiency (separated in ΔR from small *R* jet and lepton)

≥ 1 *b*-tag anti-k_T *R* = 0.4 jet (closest to lepton or within large *R* jet)

missing E_T > 20 GeV, (M_T^W + missing E_T) > 60 GeV



~ 17% background

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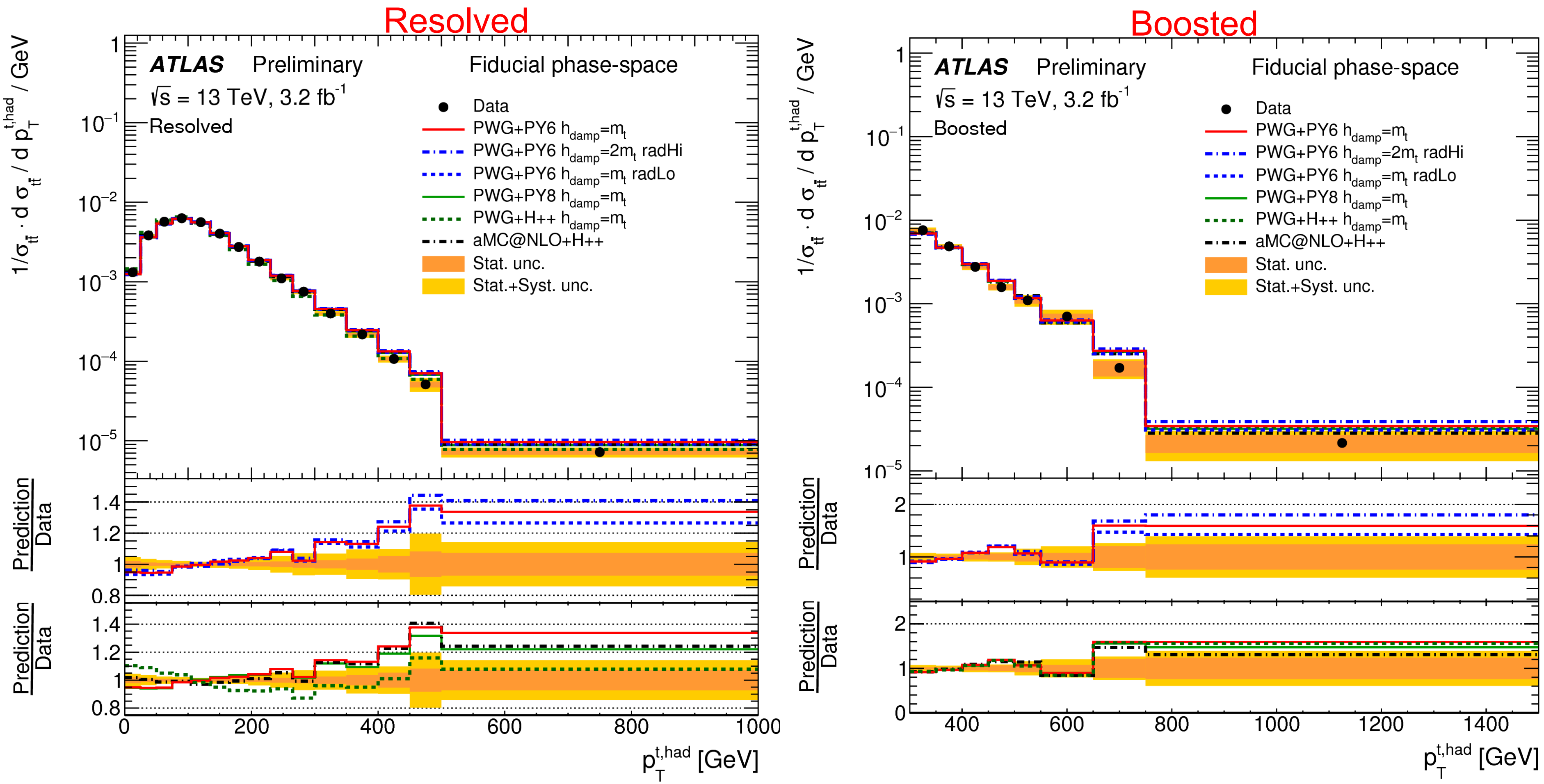
Top kinematic measurements in lepton+jets channel

Absolute and normalised distribution measurement in fiducial phase space

- $p_T^{t,\,had}$ measurements reaching TeV scale with 20% - 40% precision



Data show softer p_T^t than most MC predictions both in resolved and boosted topologies

boosted topology suffers from larger systematic uncertainties

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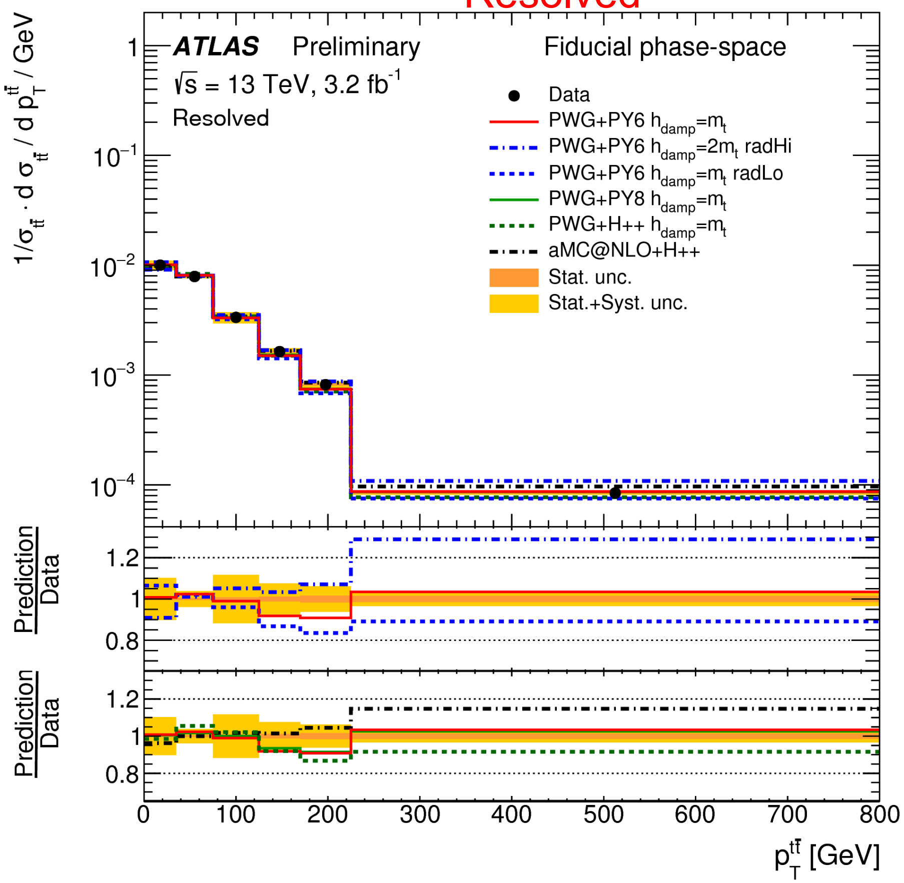
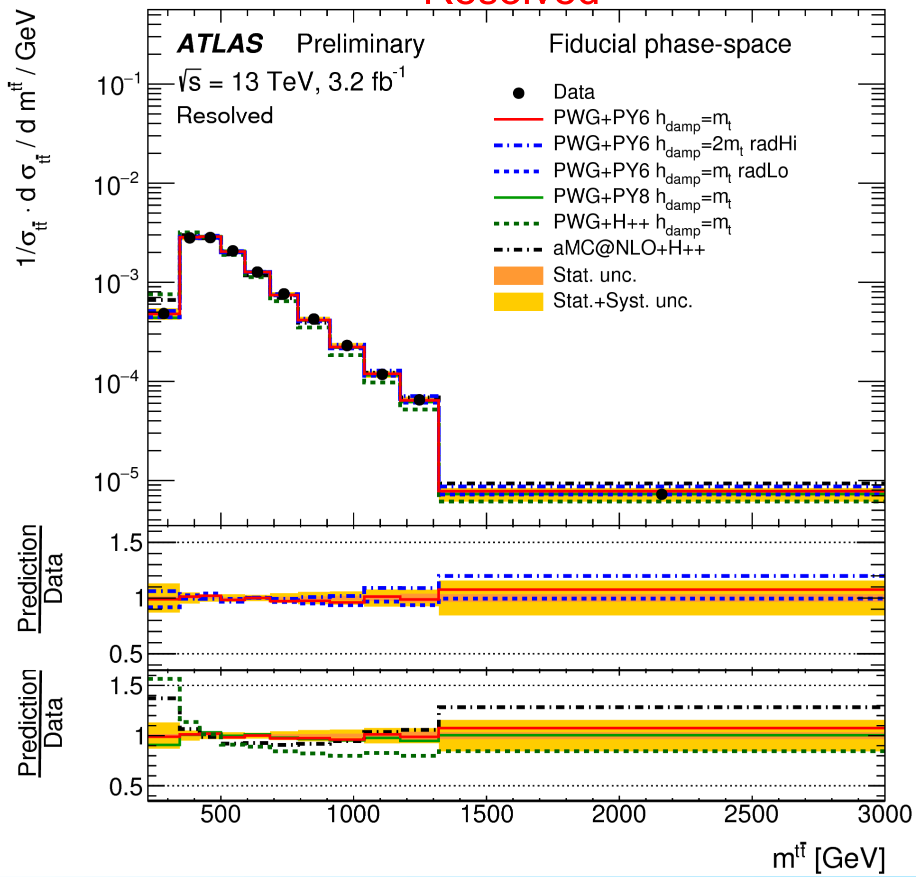
Top kinematic measurements in lepton+jets channel

Absolute and normalised distribution measurement in fiducial phase space

Resolved



Resolved



$p_T^{t\bar{t}}$ show large sensitivity to QCD radiation scale variations

NLO generators interfaced with Herwig++ show notable deviations in $m^{t\bar{t}}$ spectra (modern Herwig7 may have different behaviour)

$y^{t\bar{t}}$ exhibits similar comparison between data & NLO predictions as seen in di-lepton channel

ATLAS-CONF-2016-040

Top kinematic measurements in all-hadronic channel

Event selection (boosted regime):

≥ 2 anti-k_T R = 1.0 jets; lead jet p_T > 500 GeV, 2nd leading jet p_T > 350 GeV and $|\eta|$ < 2.0

- top-tagging @ 50% efficiency (sub-jettiness ratio, 122.5 GeV < M_J < 222.5 GeV)

≥ 2 *b*-tag anti-k_T R = 0.4 jets (p_T > 25 GeV) @ 70% efficiency; each matched to one top-tagged jet

No electron or muon (p_T > 25 GeV)

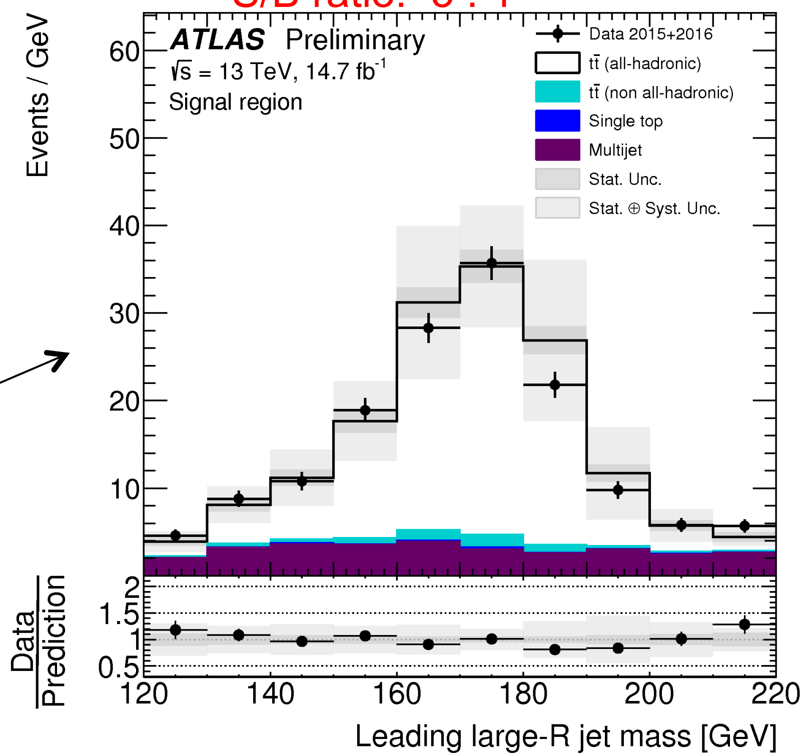
- Dominant background due to multi-jets production is estimated using data from various control regions

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

Multi-jet = ½ (G/A + H/B) x C

Validation region

S/B ratio: 3 : 1



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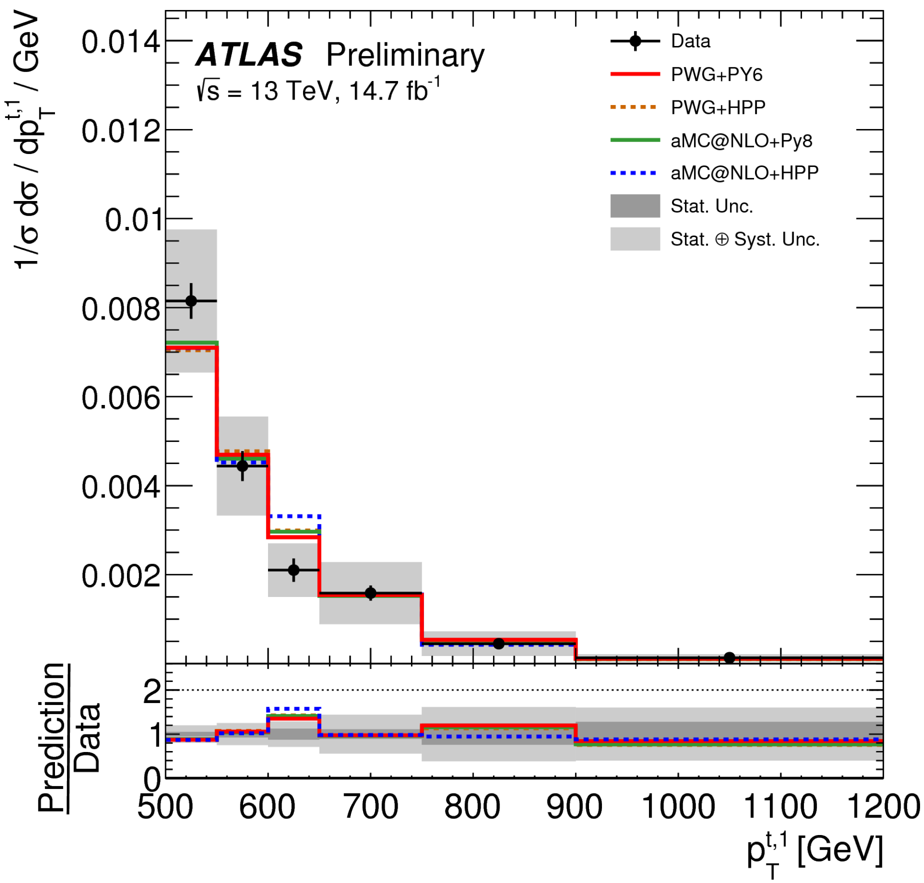
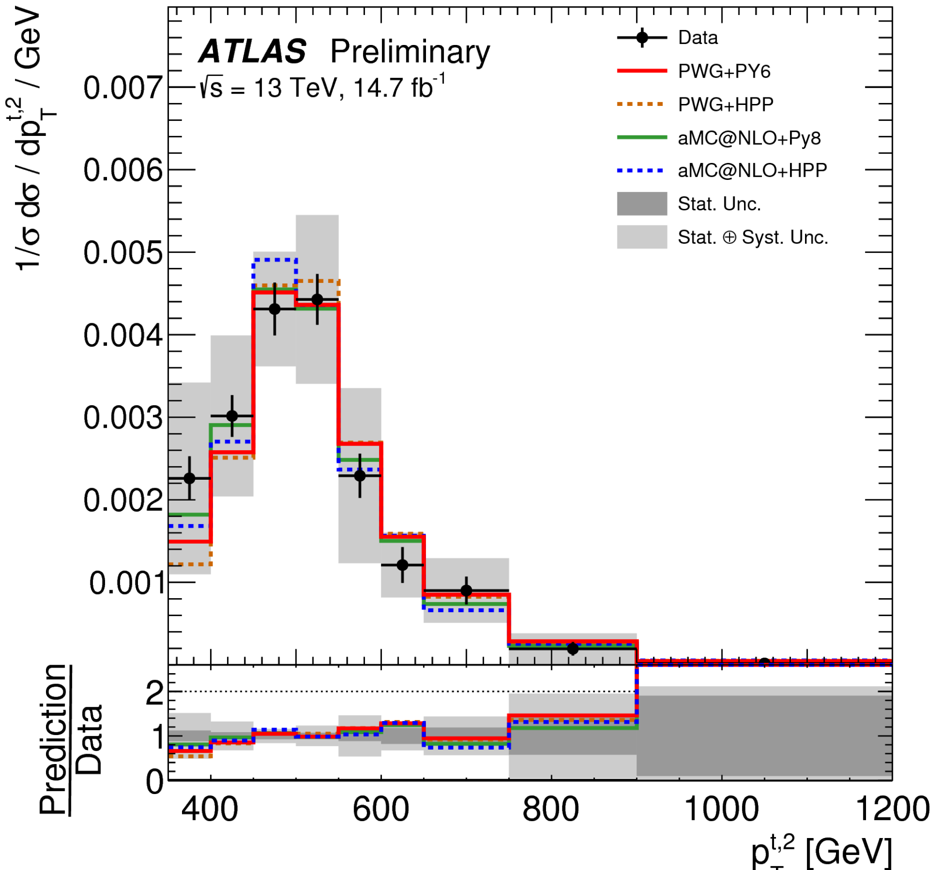
Top jets p_T in all-hadronic channel

Normalised distribution measurements in fiducial phase space:

≥ 2 large R = 0.1 jets: $p_T^{t,1}$ > 500 GeV; $p_T^{t,2}$ > 350 GeV, $|\eta|$ < 2.0, each jet contain b-hadron

$|M_J - M_{top}|$ < 50 GeV; No electron or muon





Data agree with NLO predictions within uncertainties:

- measurement uncertainties dominated by large R jet calibration and signal modelling

ATLAS-CONF-2016-100

$t\bar{t}$ system distributions in all-hadronic channel

Normalised distribution measurements in fiducial phase space:

≥ 2 large R = 0.1 jets: $p_T^{t,1}$ > 500 GeV; $p_T^{t,2}$ > 350 GeV, $|\eta|$ < 2.0, each jet contain b-hadron

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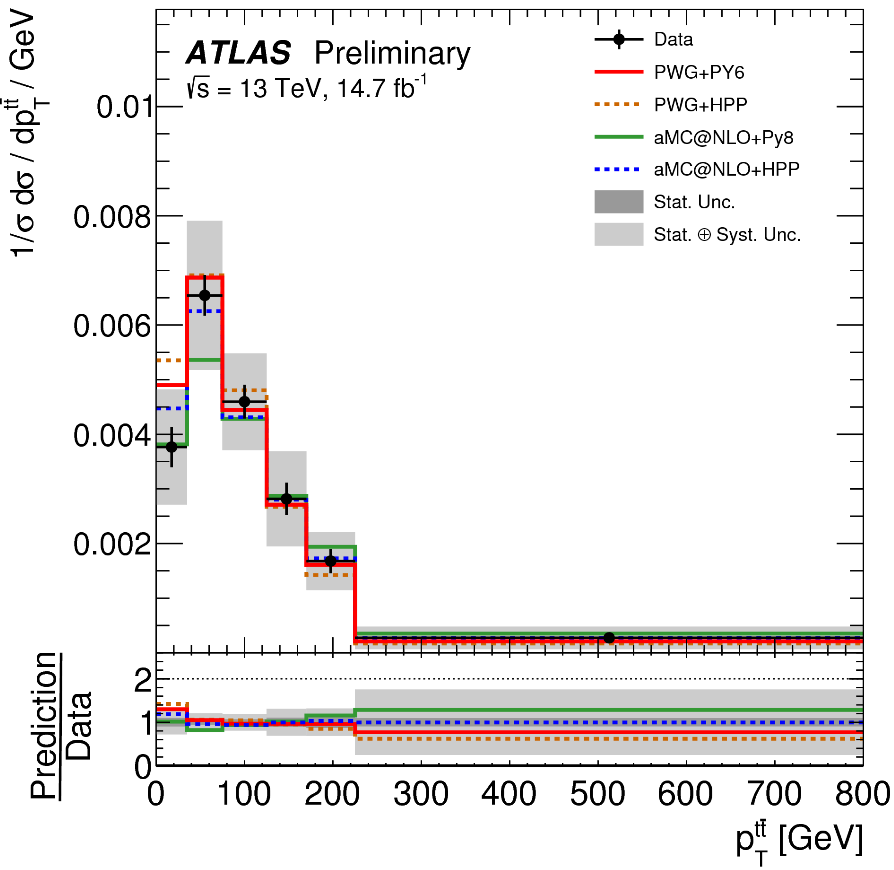

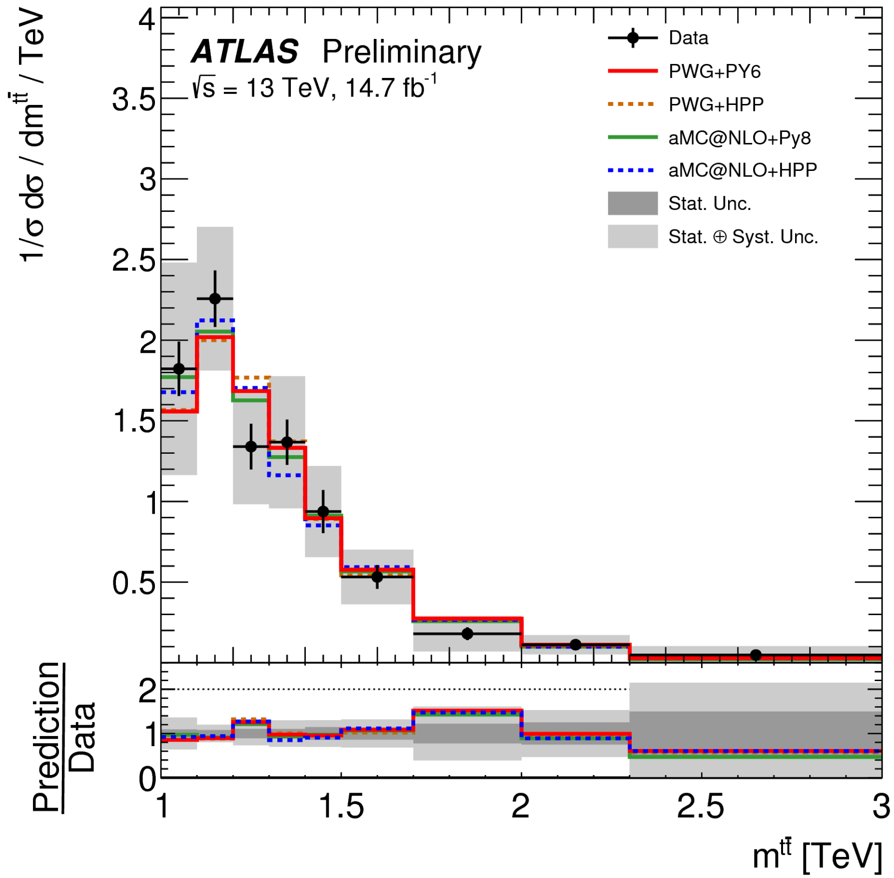

Data agree with NLO predictions within uncertainties for $p_T^{t\bar{t}}$, $m^{t\bar{t}}$ and production angles

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Summary

- Inclusive cross section measurements have reached precisions equivalent or better than theory precision
  - significant constraining power to gluon PDFs at high Bjorken *x ~ 0.1*
- Several differential measurements from ATLAS with $t\bar{t}$ events exploring large phase space which are sensitive to QCD modelling and MC generators tuning
  - measurements probing TeV scale
- Data is in general comparable with NLO predictions within uncertainties
  - small tension between measurement and NLO predictions for some quantities (e.g top p_T)
- Measurements sensitive to QCD radiations already very useful in tuning the MC generators
- Looking forward to exploit full potential of the LHC data

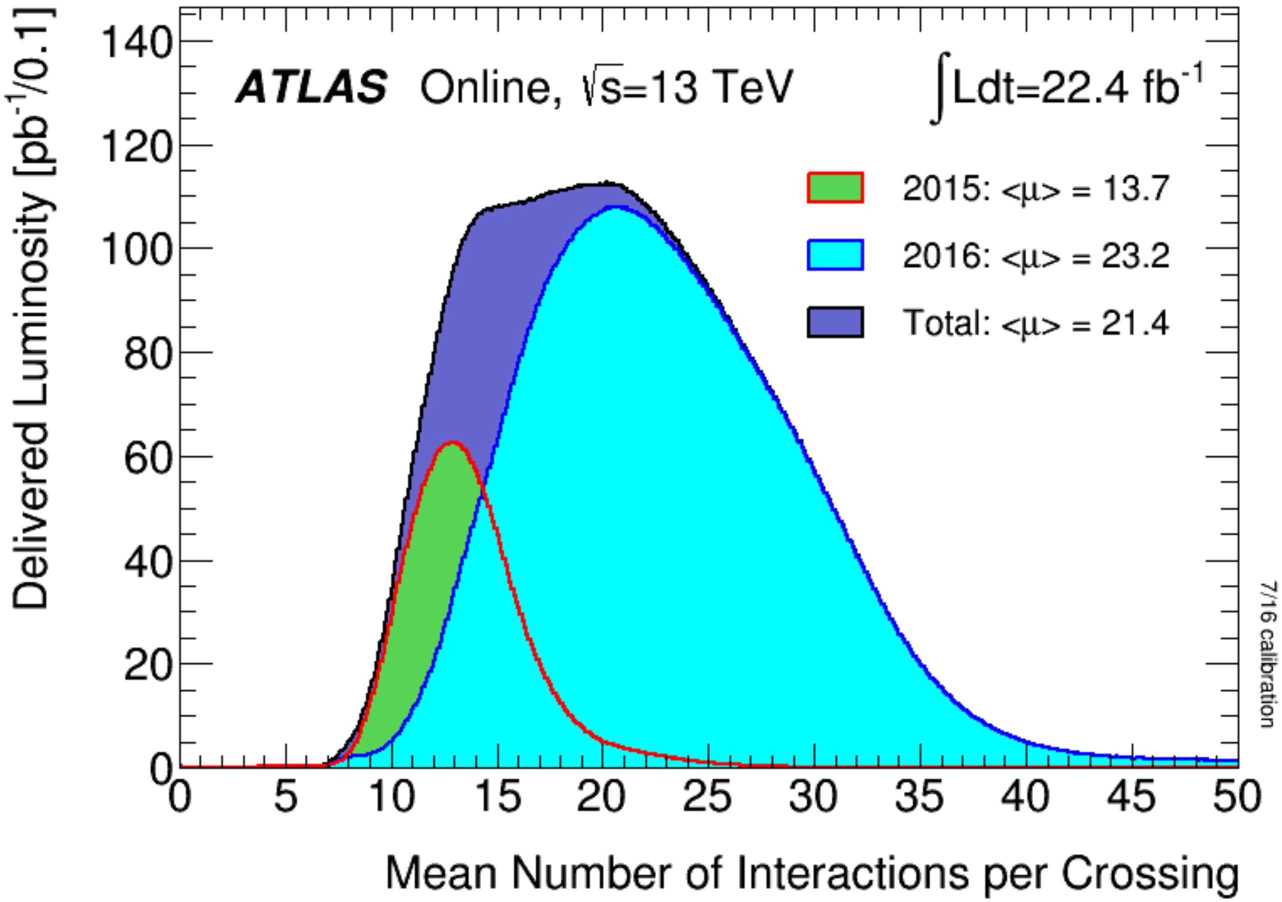
For more results, please see: TopPublicResults

THANKS!

Back-ups

Pile-up

- Mean number of interactions per bunch crossing with 25 ns bunch spacing
- Simulated in the MC by overlaying the number of inelastic interactions from pp collision in the same bunch crossing and in the previous bunch crossing



Particle-level measurement definitions

Particle level LHCTopWG prescription: **(from stable particles (τ > 30 ps))**

> **Electron/muon :**

- prompt (directly from *W*/*Z* or from tau (not originated from hadrons)) and corrected for radiative effect by adding 4-momenta for prompt photon within $\Delta R < 0.1$

> **Missing E_T :**

- event level quantity determined from sum of 4-momenta of neutrinos from *W*/*Z* (including the neutrinos from tau decays), but not from hadrons

> **Jets :**

- clustering of stable particles (excluding the electrons, muons, photons and neutrinos used in selected leptons and missing E_T constructions) using anti-k_T algorithm with $R = 0.4$
- jet is flavored tag as *b*-jet, if a *b*-hadron is ghost matched to jet

> **Overlap removal :**

- events where leptons are within $\Delta R < 0.4$ of jets are discarded

> **Pseudo-top-quark :**

- identified from algorithms based on constraints on ΔR separation, M_W, M_{top} using the selected leptons, jets and missing E_T

LHCTopWG twiki

Unfolding from detector level to particle level

> **Fiducial phase space:**

$$N^i_{\text{unfold}} = \frac{1}{f^i_{\text{eff}}} \cdot \sum_j (M^{-1})^{\text{part},i}_{\text{reco},j} \cdot f^j_{\text{accept}} (N^j_{\text{data}} - N^j_{\text{bg}})$$

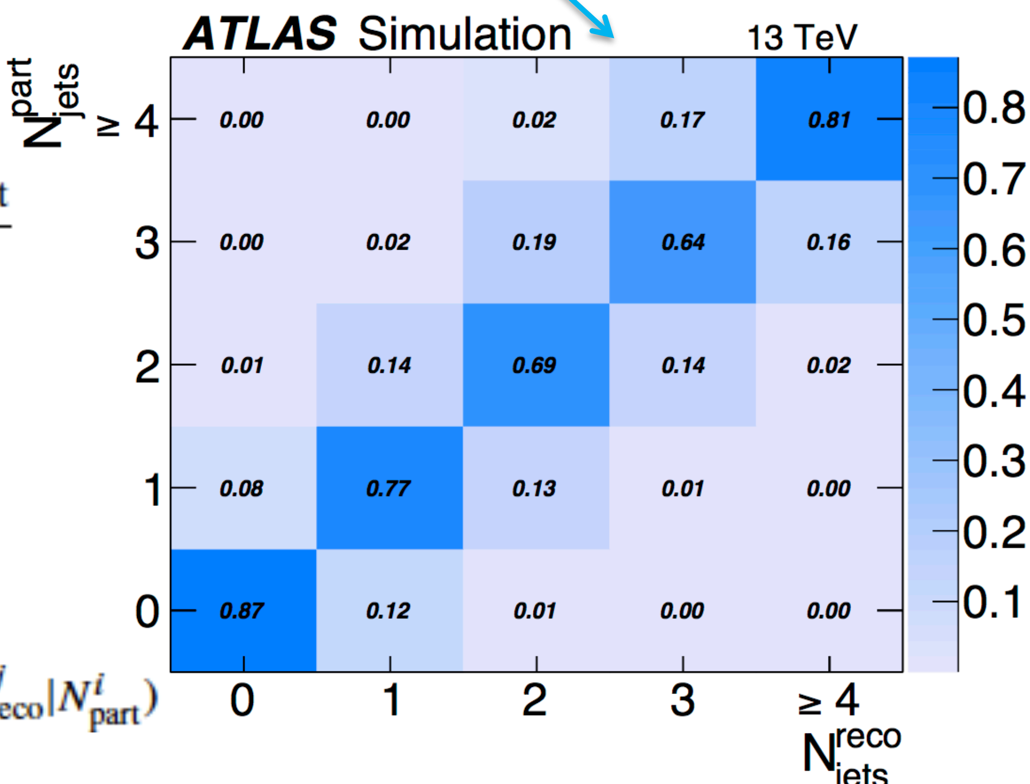
bin-by-bin efficiency correction

migration correction via iterative Bayesian unfolding

bin-by-bin acceptance correction:
(correct for events passing selection at reco-level,
but failing at particle-level)

$$f^i_{\text{eff}} = \frac{N^i_{\text{reco}\wedge\text{part}}}{N^i_{\text{part}}}$$

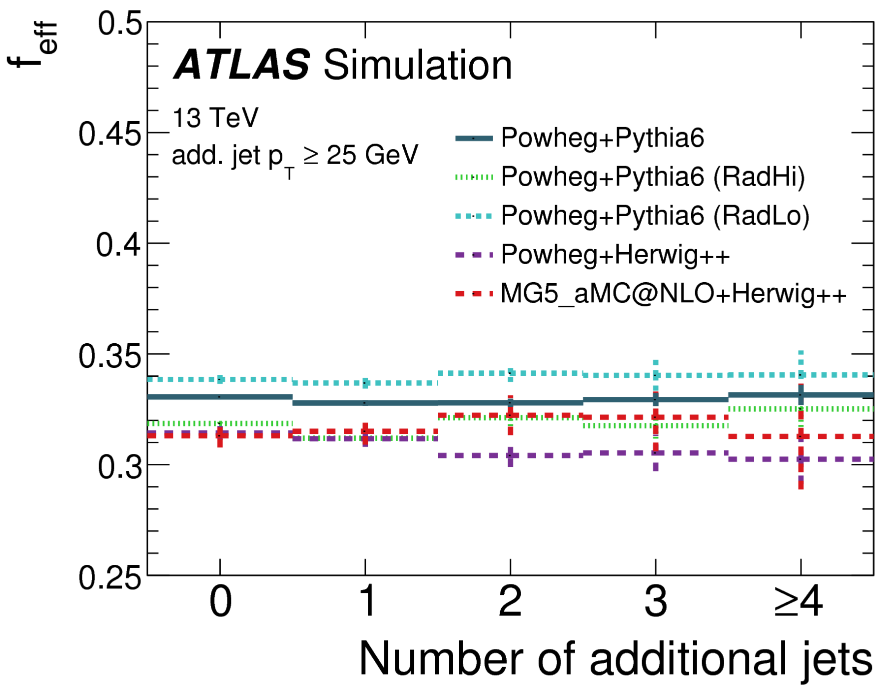
$$P(N^j_{\text{reco}} | N^i_{\text{part}})$$

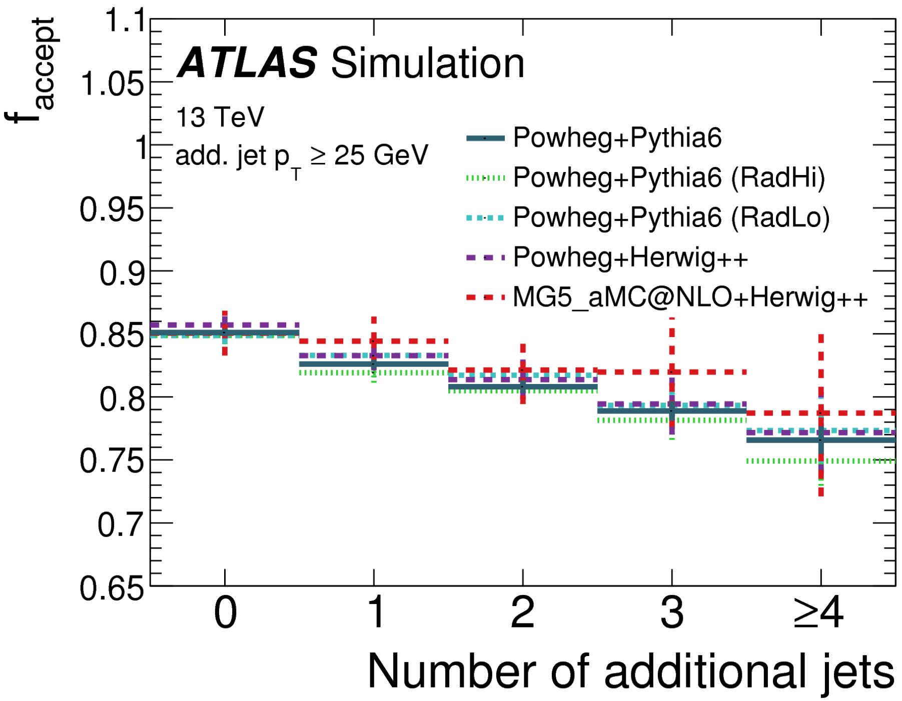


$$f^j_{\text{accept}} = \frac{N^j_{\text{reco}\wedge\text{part}}}{N^j_{\text{reco}}}$$

CERN-EP-2016-218, arXiv:1610.09978

$t\bar{t}$+jets signal efficiency and acceptance corrections



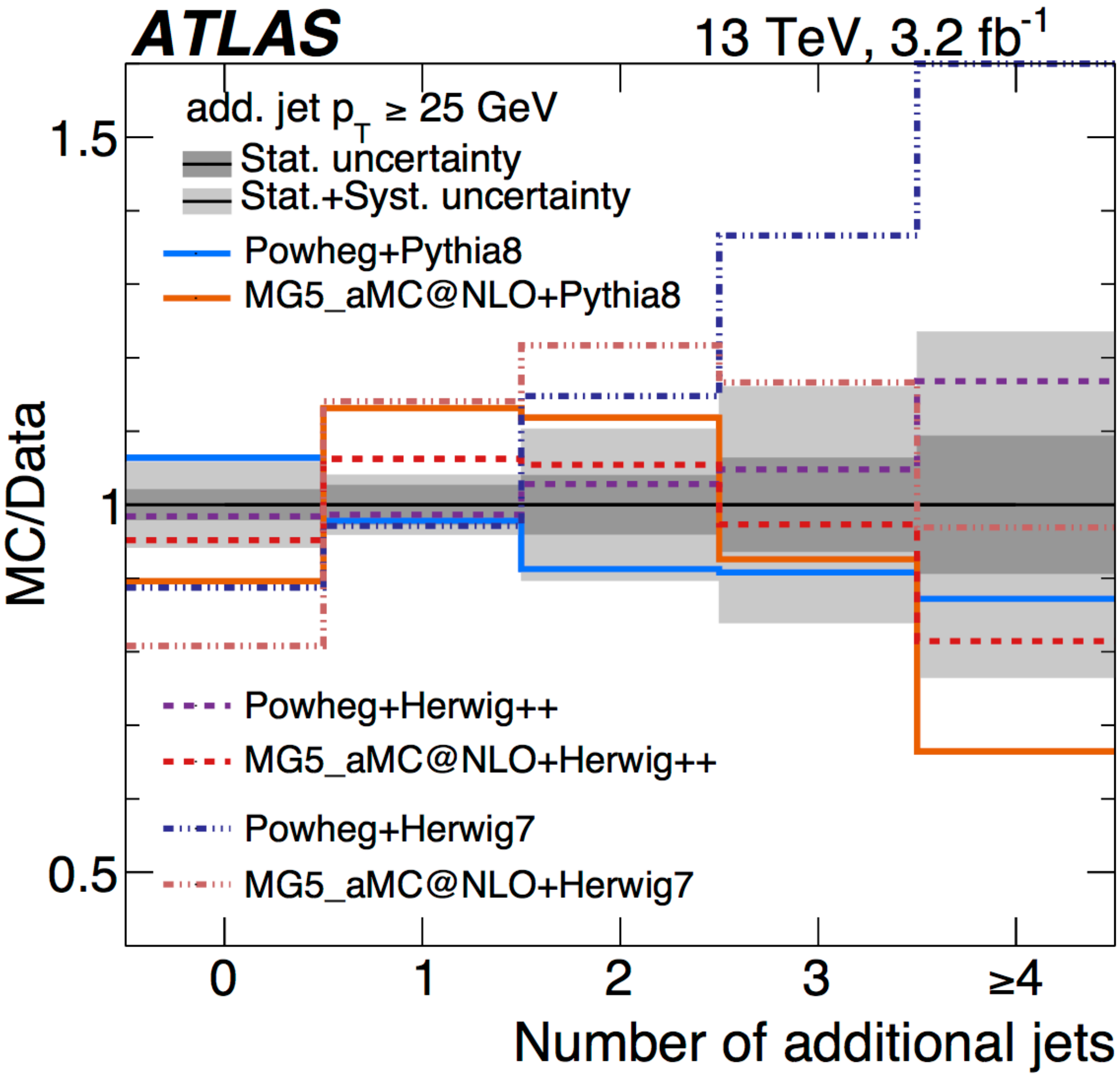


$$f^{i}_{\mathrm{eff}} = \frac{N^{i}_{\mathrm{reco}\wedge\mathrm{part}}}{N^{i}_{\mathrm{part}}}$$

$$f^{j}_{\mathrm{accept}} = \frac{N^{j}_{\mathrm{reco}\wedge\mathrm{part}}}{N^{j}_{\mathrm{reco}}}$$

CERN-EP-2016-218, arXiv:1610.09978

Comparison of data with more ME+PS models



Larger deviations in additional jets activity predictions when using same PS, but different ME
➔ matching between ME and PS plays important role

MG5_aMC@NLO+Pythia8, Powheg+Herwig7, and MG5_aMC@NLO+Herwig7 do not give good descriptions of data

CERN-EP-2016-218, arXiv:1610.09978

Measurement uncertainties of additional jets multiplicity

Relative uncertainty in [%] in additional jets multiplicity					
Sources	0	1	2	3	≥ 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**

Uncertainties dominated by jet energy scale/resolution, signal modeling, and statistics

Larger uncertainties in higher multiplicity bins

High correlations (50% - 70%) in uncertainties in neighboring bins of higher jet multiplicity due to migrations

Important to take into account the correlation across bins in quantitative comparison of measurements with predictions via statistical tests

CERN-EP-2016-218, arXiv:1610.09978

Quantitative comparison of $t\bar{t}$ +jets measurements and predictions

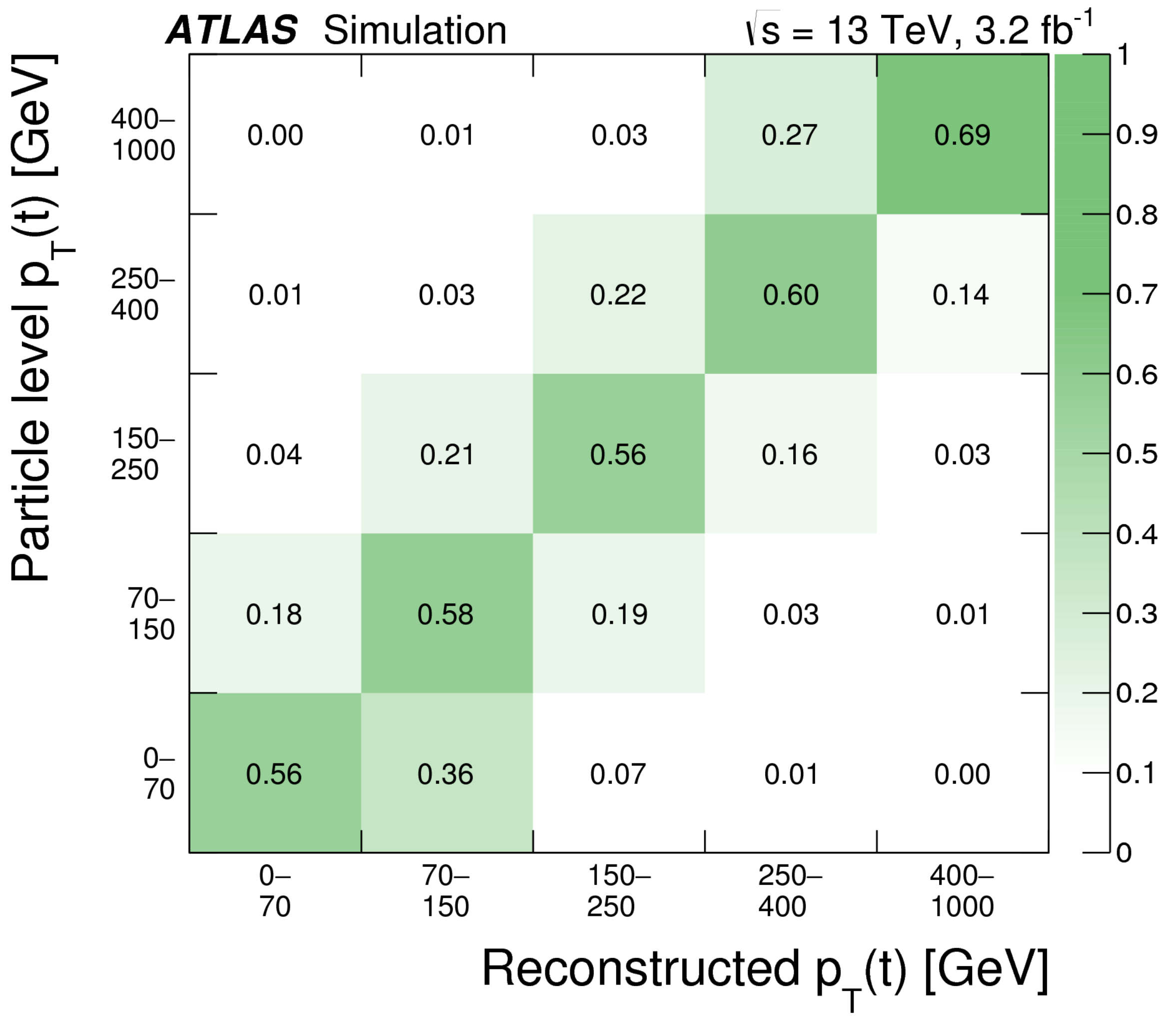
$$\chi^2 = S_{n-1}^{\mathrm{T}} \mathrm{Cov}_{n-1}^{-1} S_{n-1}$$

Generator	$p_{\mathrm{T}} > 25$ GeV		$p_{\mathrm{T}} > 40$ GeV		$p_{\mathrm{T}} > 60$ GeV		$p_{\mathrm{T}} > 80$ 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

CERN-EP-2016-218, arXiv:1610.09978

Unfolding of top kinematic distributions in dilepton channel

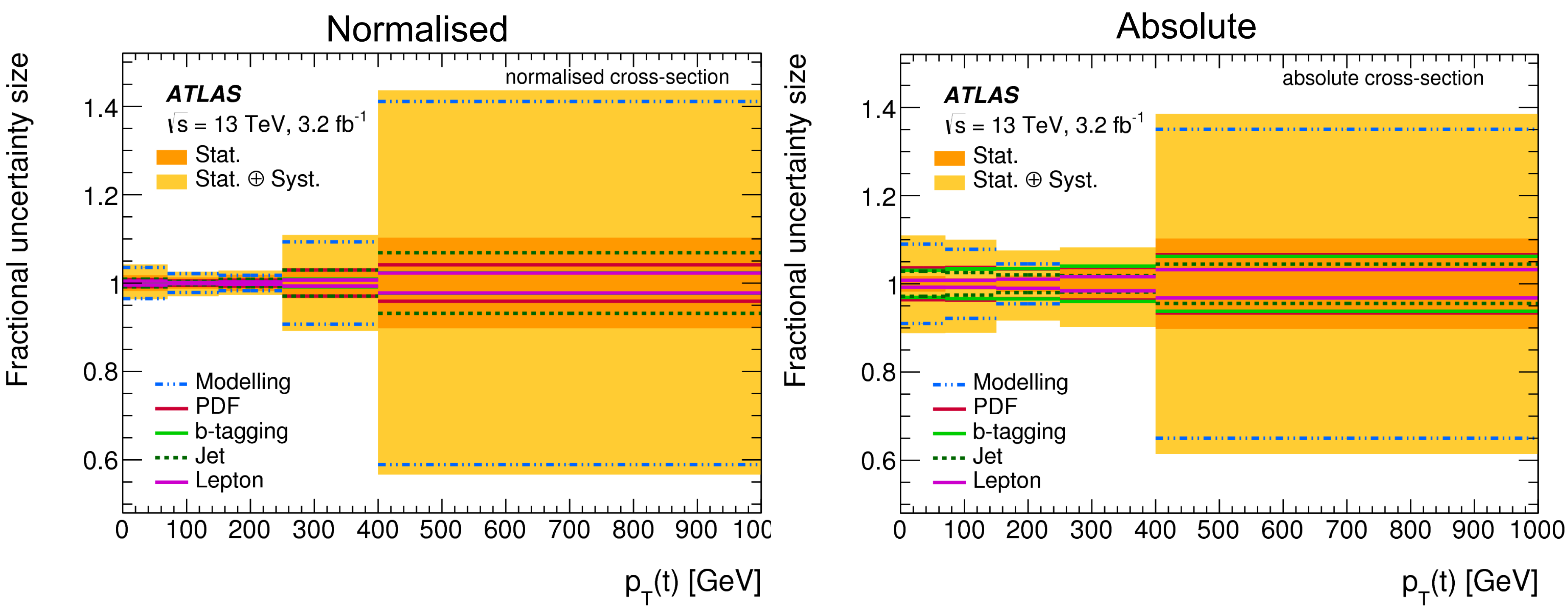
> **Fiducial phase space (**2 semi-leptonic pseudo-top quarks):



TOP-2016-04, CERN-EP-2016-220, arXiv:1612.05220

Uncertainties associated with top kinematic measurements in dilepton channel

> **Fiducial phase space:** (2 semi-leptonic pseudo-top quarks)

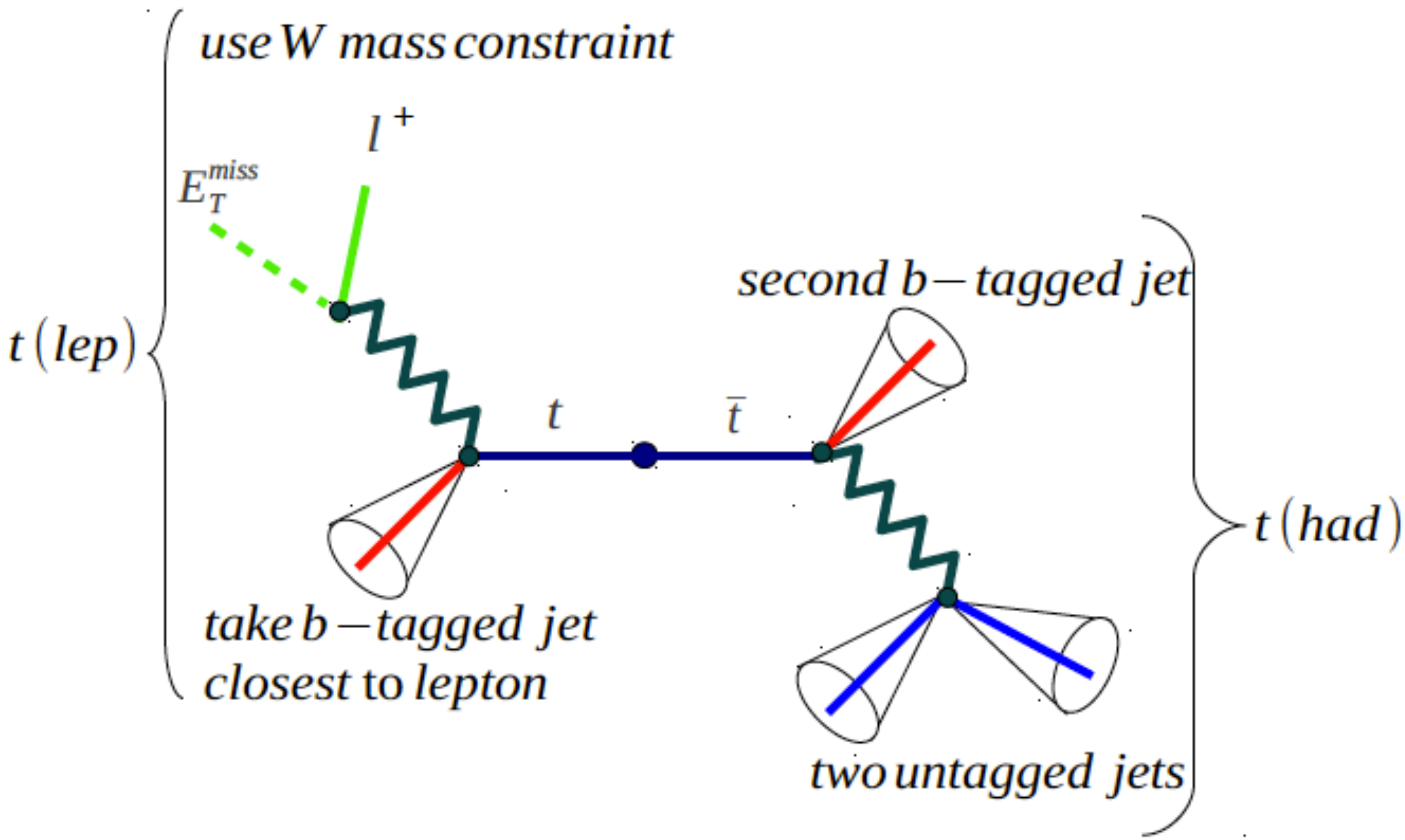


> Measurement uncertainties dominated by JES and signal modeling

TOP-2016-04, CERN-EP-2016-220, arXiv:1612.05220

Pseudo-top

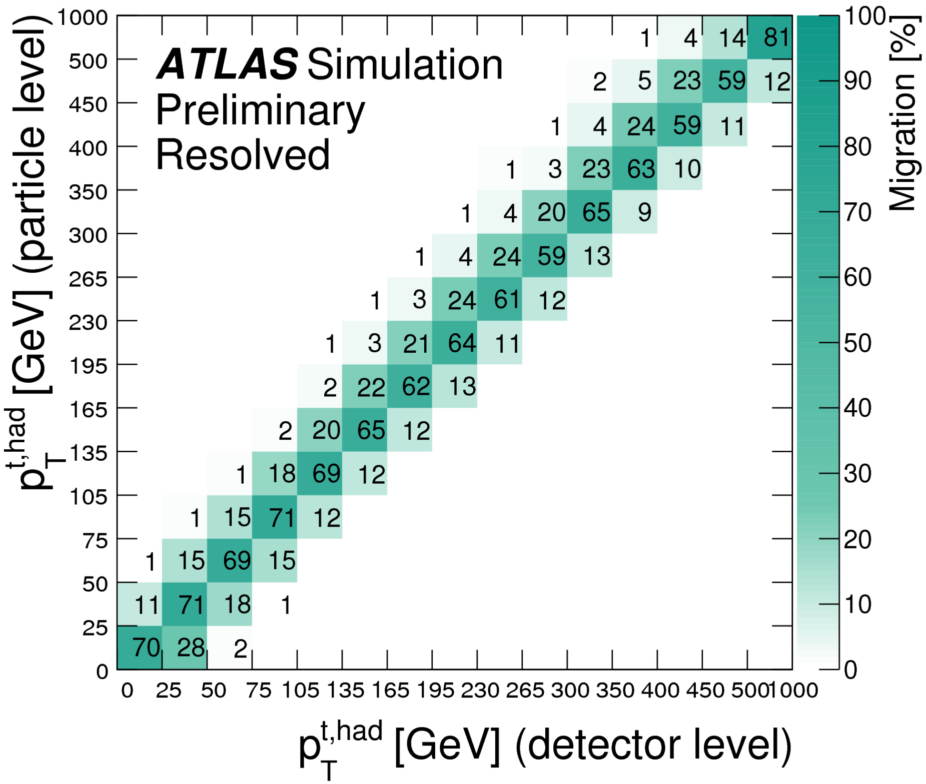
Full event reconstruction with pseudo-top algorithm
Same algorithm for detector-level and particle-level



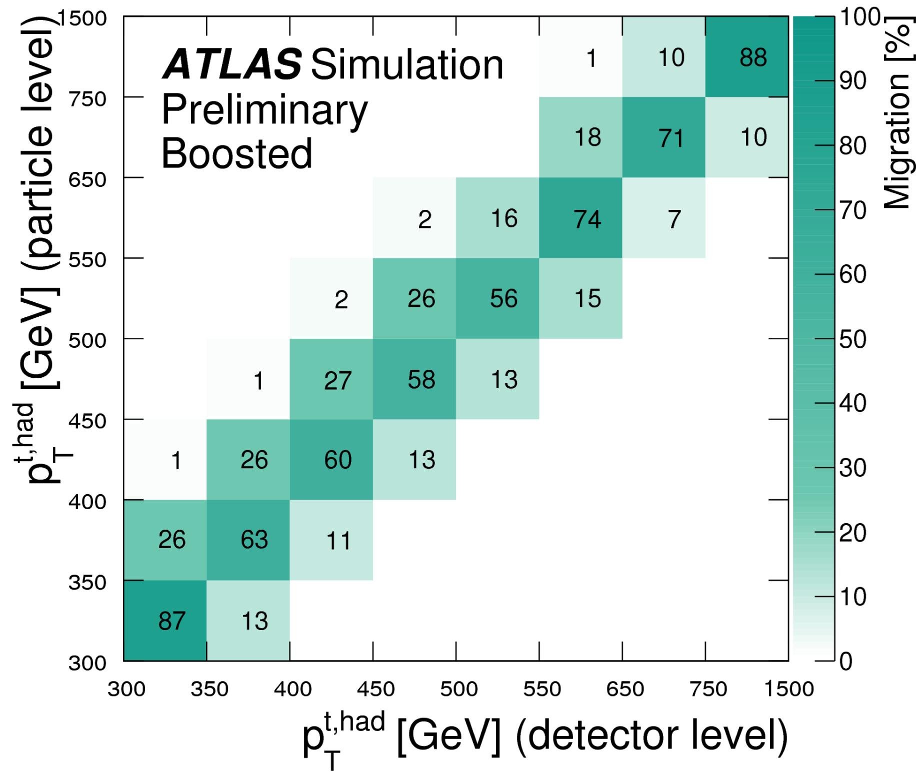
Unfolding of top kinematic distributions in lepton+jet channel

> **Fiducial phase space (**1 semi-leptonic pseudo-top quark, 1 hadronic top):

Resolved



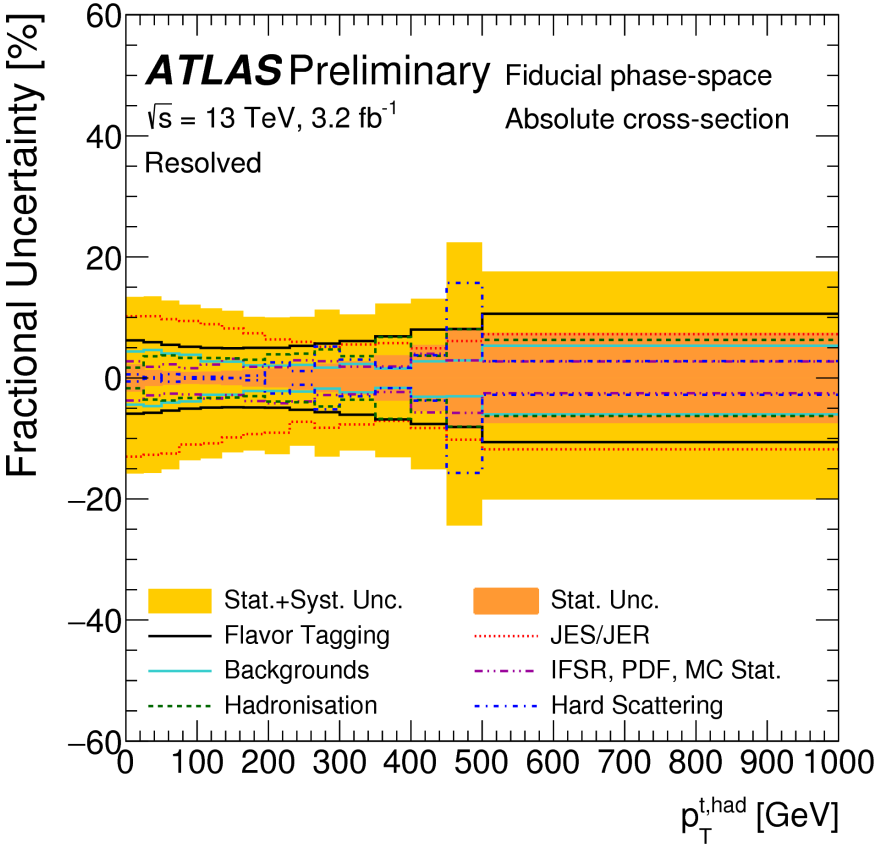
Boosted



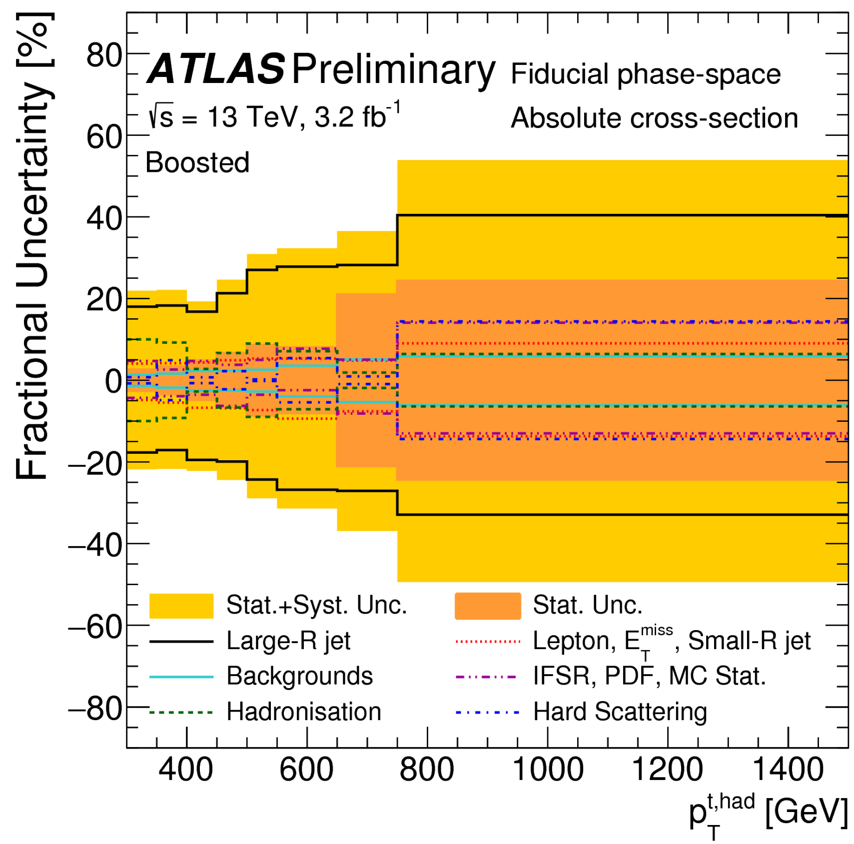
ATLAS-CONF-2016-040

Uncertainties associated with top kinematic measurements in lepton+jets channel

Resolved



Boosted



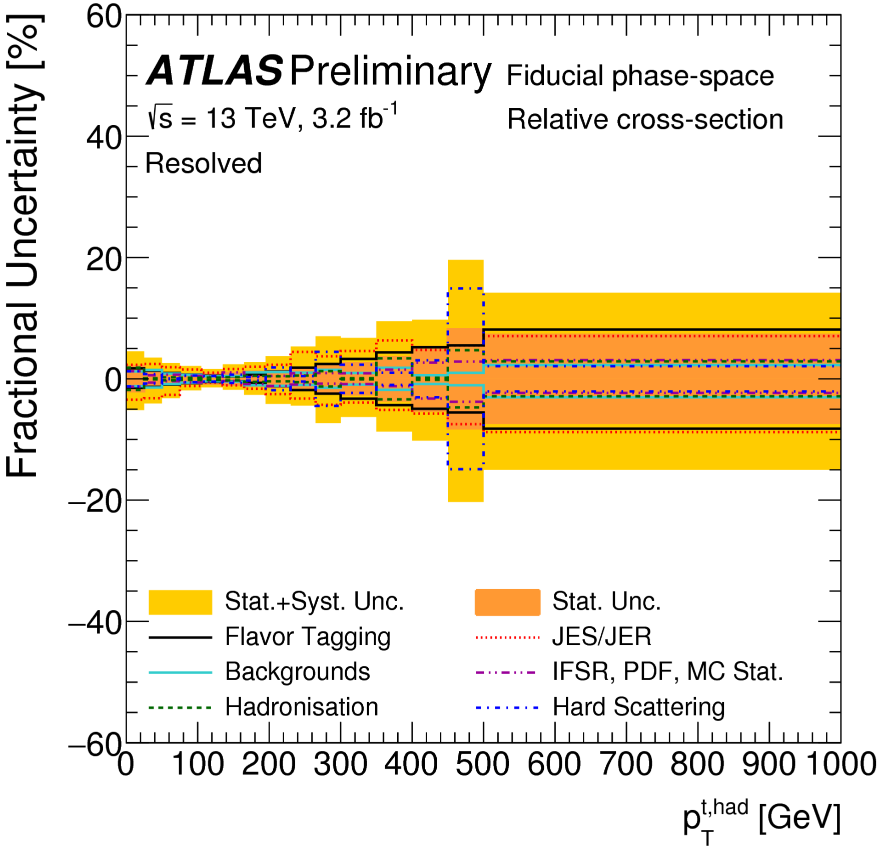
Uncertainties associated with absolute cross section

ATLAS-CONF-2016-040

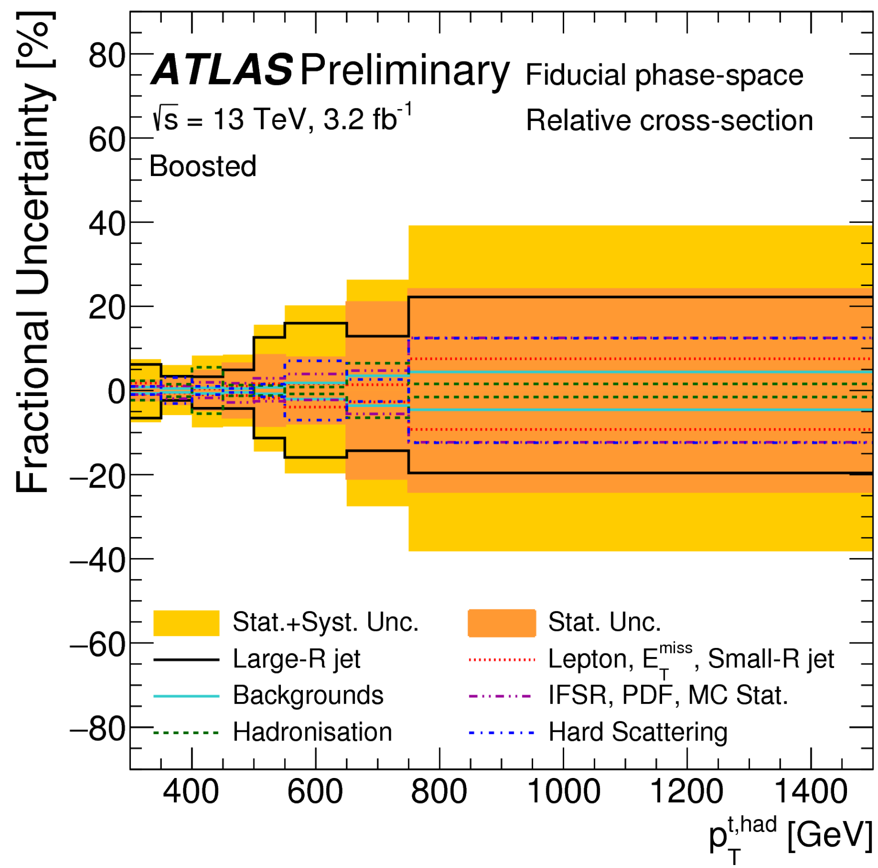
Uncertainties associated with top kinematic measurements in lepton+jets channel

- $p_T^{t,\,had}$ measurements reaching TeV scale with ~ 20% precision

Resolved



Boosted



Uncertainties associated with normalised cross section

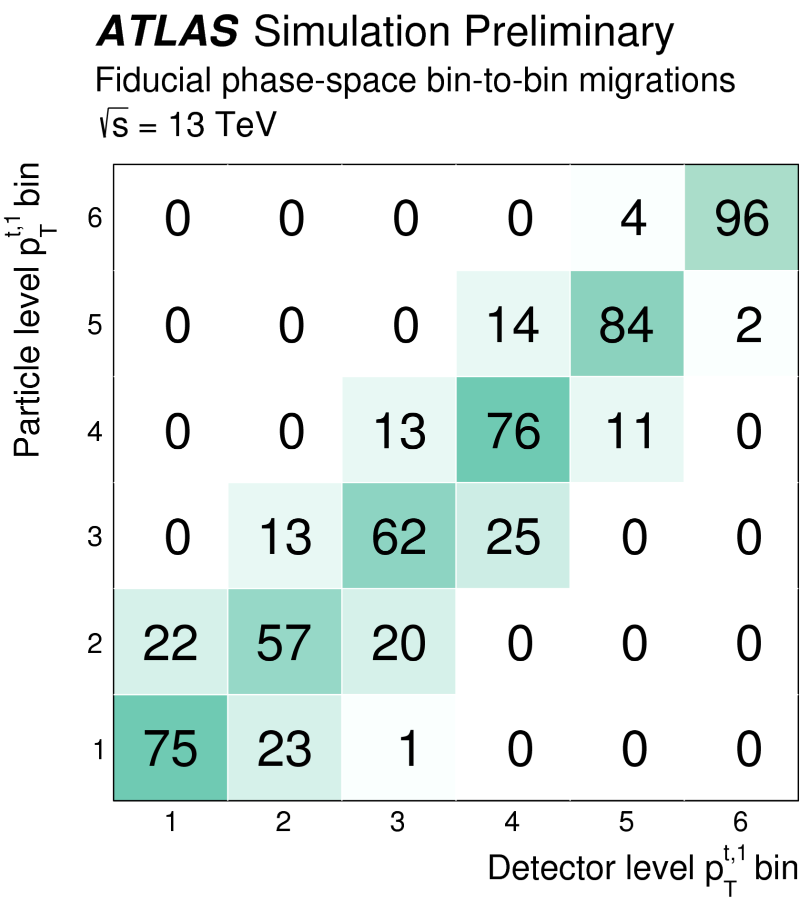
ATLAS-CONF-2016-040

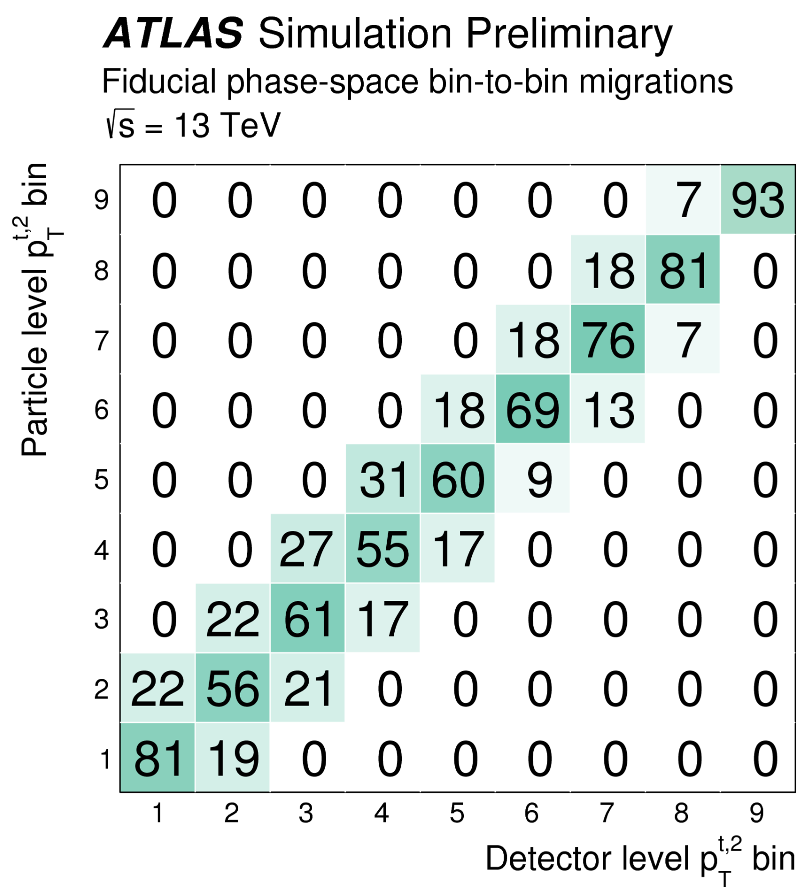
$t\bar{t}$ system distributions in all-hadronic channel

Normalised distribution measurements in fiducial phase space:

≥2 large R=0.1 jets: $p_T^{t,1} > 500$ GeV; $p_T^{t,2} > 350$ GeV, $|\eta| < 2.0$, each jet contain *b*-hadron

$|M_J - M_{top}| < 50$ GeV; No electron or muon





ATLAS-CONF-2016-100

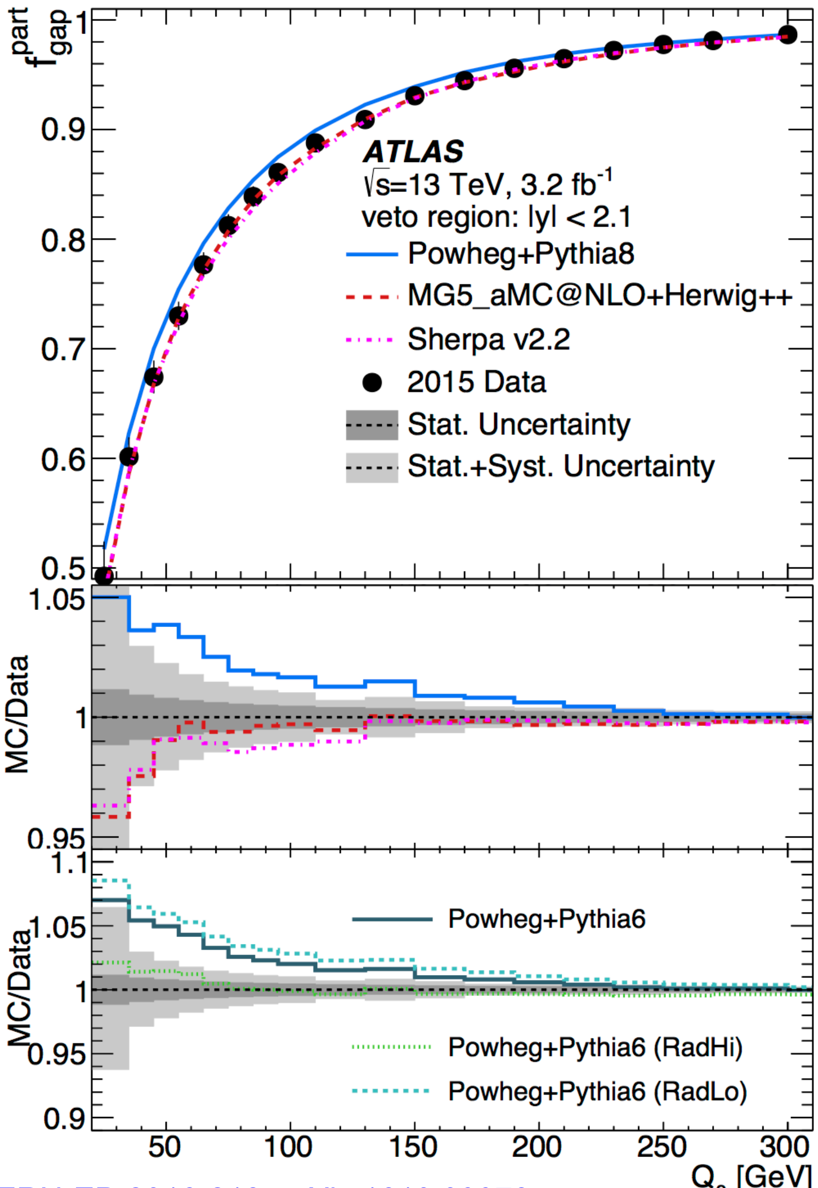
$t\bar{t}$+jets signal Monte Carlo

- Several state-of-the-art calculations available in market
- NLO ME generators
  - Powheg, Madgraph5_aMC@NLO, MEPS@NLO Sherpa
    - Powheg and Madgraph5_aMC@NLO can produce first real emission with LO accuracy
    - Madgraph5_aMC@NLO (FxFx) and Sherpa can produce 1 or 2 additional jets with NLO accuracy, but not yet used commonly due to having some technical limitations
- Parton shower generators
  - Pythia6/8, Herwig++/7, MEPS@NLO matching with Sherpa PS
    - for shower, hadronisation and underlying event modeling

$t\bar{t}$+jets signal Monte Carlo

Sample name	ME generator	PS/UE generator	ME PS/UE PDF	PS tune	Matching (Merging)
Powheg+Pythia6	POWHEG-BOX r2330.3	Pythia6 6.427	CT10 CTEQ6L1	P2012	Powheg ($h_{damp} = m_{top}$)
Powheg+Pythia8	POWHEG-BOX v3026 (v2)	Pythia8 8.210	NNPDF3.0NLO NNPDF2.3LO	A14	Powheg ($h_{damp} = [0.5\ m_{top}, 2.0\ m_{top}]$)
Powheg+Herwig++	POWHEG-BOX r2330.3	Herwig++ 2.7.1	CT10 CTEQ6L1	UE-EE-5	Powheg
Powheg+Herwig7	POWHEG-BOX r2330.3	Herwig7 7.0.1	CT10 MMHT2014lo68cl	H7-UE-MMHT	Powheg
MG5_aMC@NLO+Herwig++	Madgraph5_aMC@NLO 2.2.1	Herwig++ 2.7.1	NNPDF3.0NLO CTEQ6L1	UE-EE-5	MC@NLO
MG5_aMC@NLO+Herwig7	Madgraph5_aMC@NLO 2.2.1	Herwig7 7.0.1	NNPDF3.0NLO MMHT2014lo68cl	H7-UE-MMHT	MC@NLO
MG5_aMC@NLO+Pythia8	Madgraph5_aMC@NLO 2.2.1	Pythia8 8.183	NNPDF3.0NLO NNPDF2.3LO	A14	MC@NLO
MG5_aMC@NLO+Pythia8 (LO)	Madgraph5_aMC@NLO 2.2.1	Pythia8 8.210	NNPDF3.0NLO NNPDF2.3LO	A14	CKKW-L (merging)
MG5_aMC@NLO+Pythia8 (FxFx)	Madgraph5_aMC@NLO 2.3.3	Pythia8 8.210	NNPDF3.0NLO NNPDF2.3LO	A14 (FxFx, $\mu_Q = 70$ GeV)	MC@NLO
Sherpa	Sherpa 2.2	Sherpa	NNPDF3.0NNLO	default	MC@NLO (MEPS@NLO, $Q = 30$ GeV)

Gap fraction measurements for additional jets in $t\bar{t}$+jets event

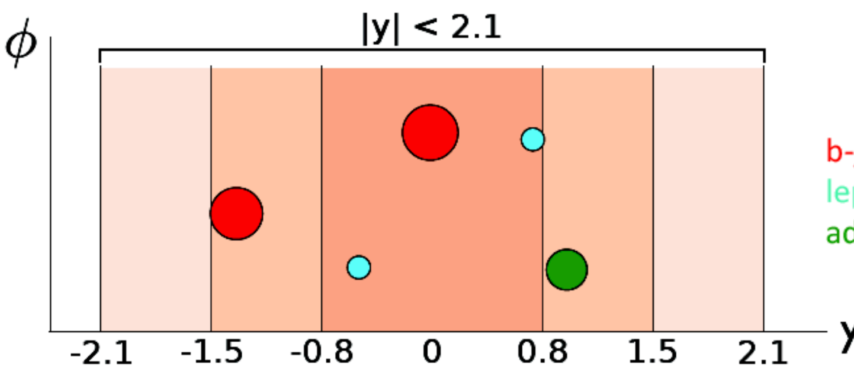


$$f_{gap}(Q_0) = \frac{n(Q_0)}{N_{t\bar{t}}}$$

gap: range in rapidity with no additional jets

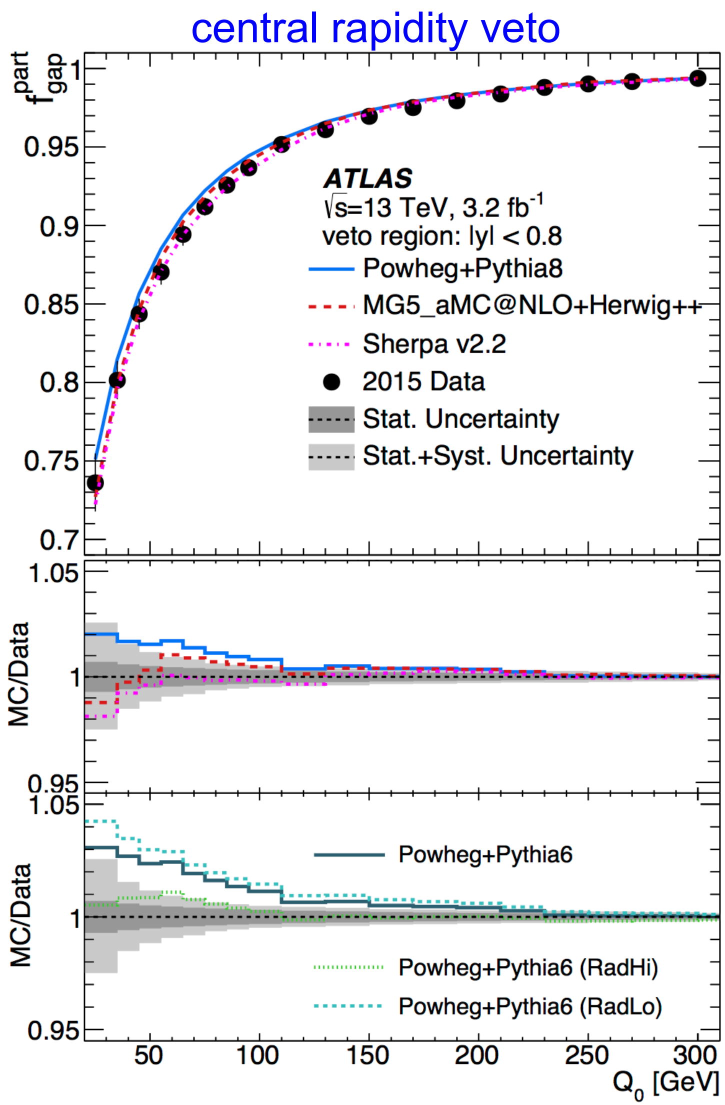
Fraction of events with no additional jet activity above a certain p_T threshold (Q_0) in various rapidity regions

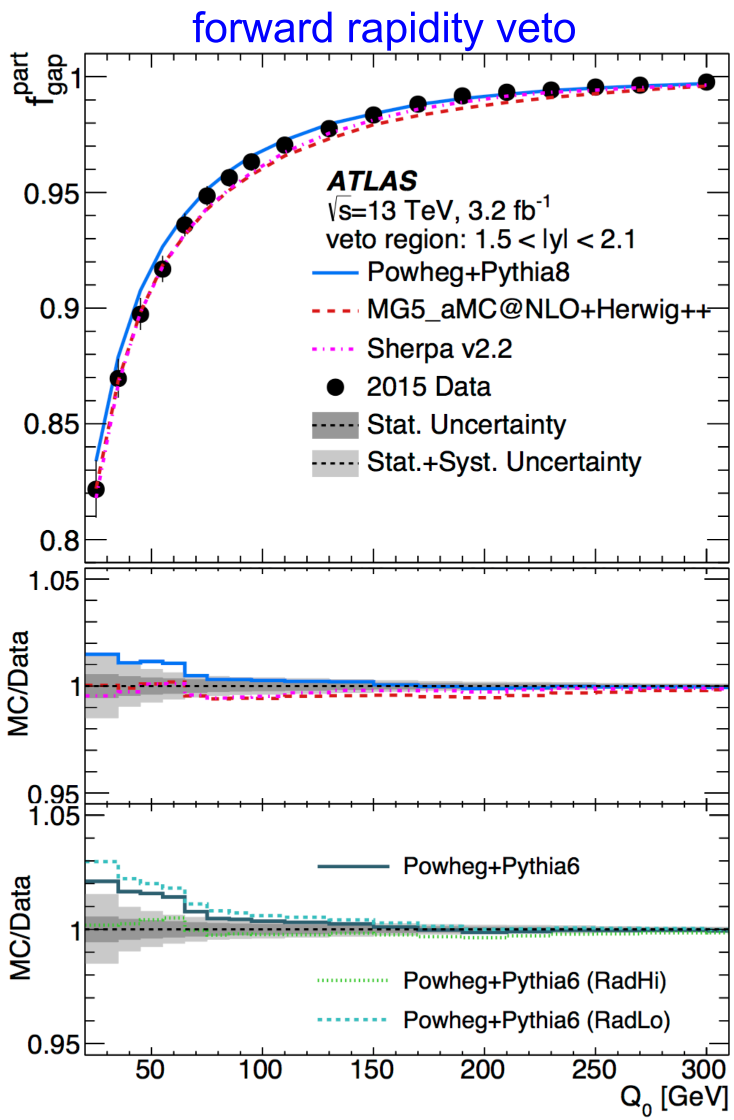
- sensitive to first hard emission modeling
  - hardest emission in a certain rapidity region does not necessarily mean hardest in the entire event
- complementary to jet multiplicity measurement, probe multiple thresholds Q_0 for additional jets



CERN-EP-2016-218, arXiv:1610.09978

Gap fraction measurements for additional jets in $t\bar{t}$+jets event

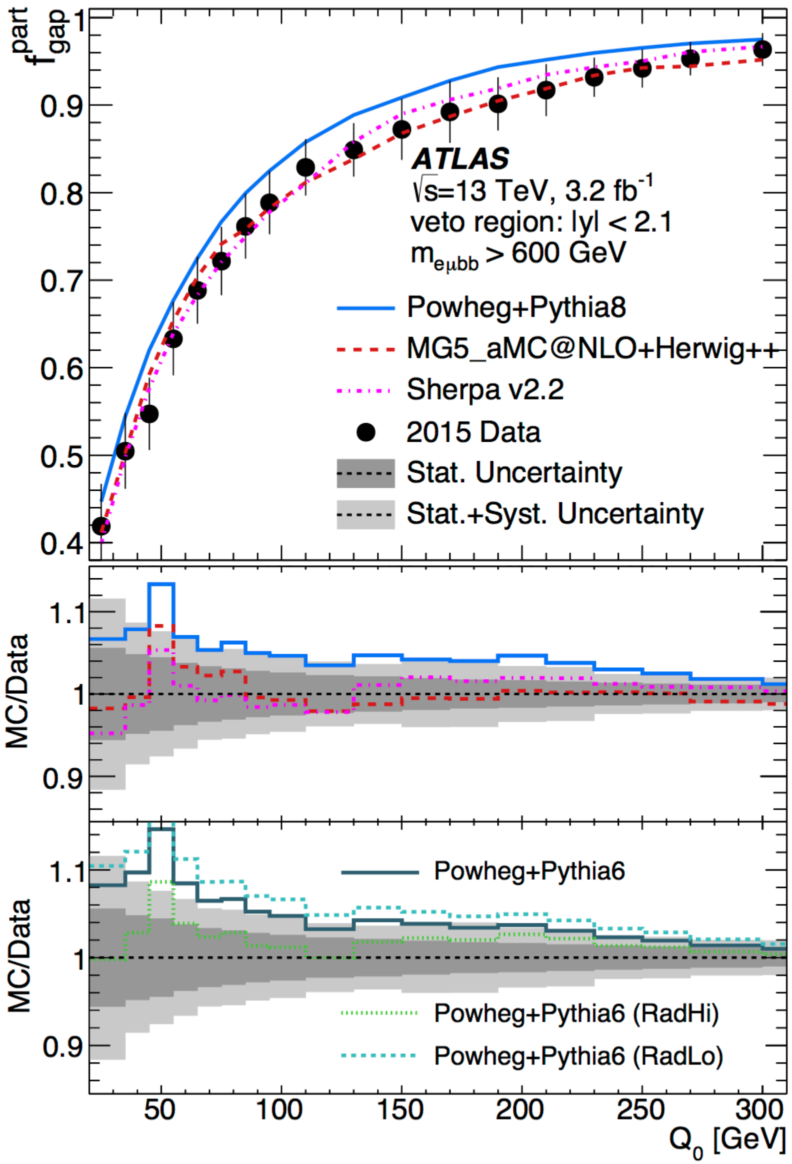


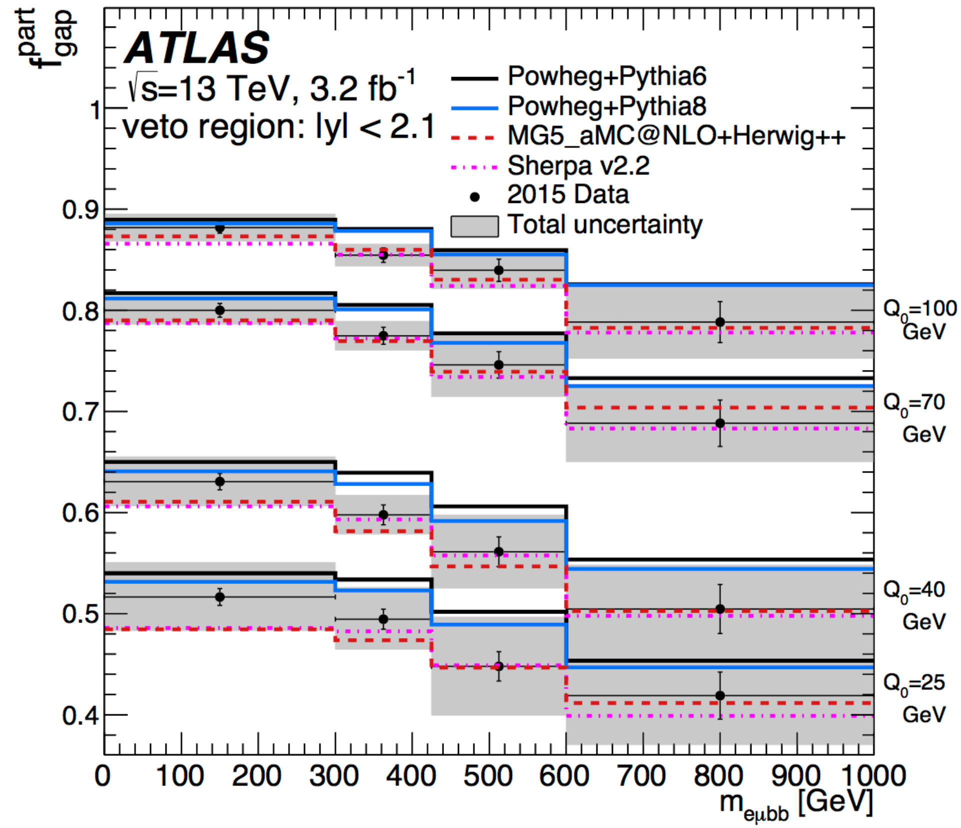


Gap fractions for exclusive rapidity regions do not add up to gap fraction in an inclusive rapidity range

CERN-EP-2016-218, arXiv:1610.09978

Gap fraction measurements for various mass regions in $t\bar{t}$+jets events





- Numbers of additional jets depend on invariant mass of $t\bar{t}$ system
  - Higher mass → more additional jets

CERN-EP-2016-218, arXiv:1610.09978

Top quark production

$m_{top} = 173.34 \pm 0.27\ (\mathit{stat}) \pm 0.71\ (\mathit{syst})$ GeV

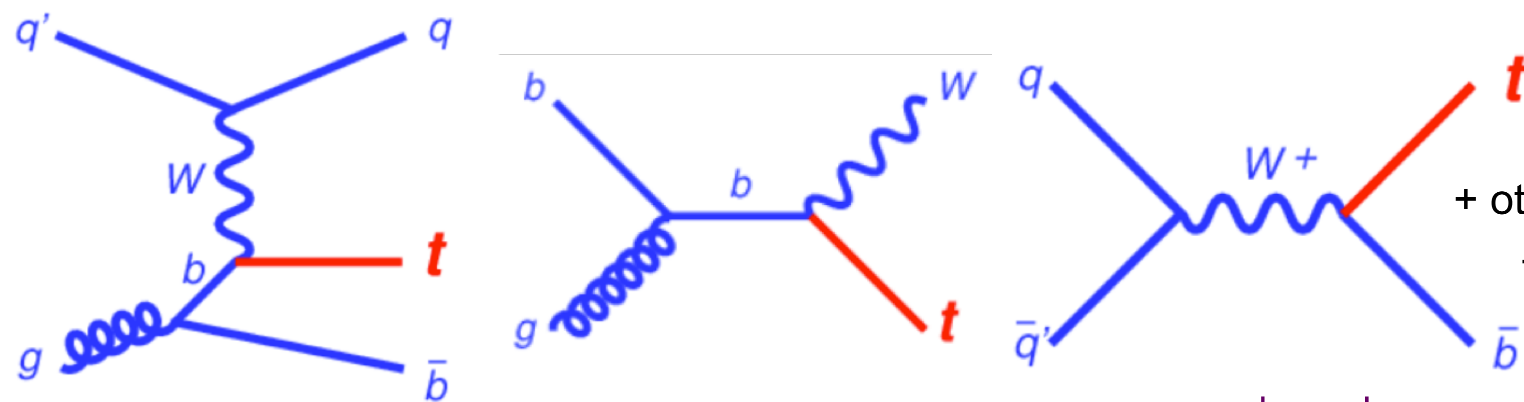
Tevatron + LHC combined 2014
arXiv:1403.4427

Strong production

+ other LO diagrams

+ higher orders ….

Weak production



t-channel

W associated

s-channel

+ other LO diagrams

+ higher orders …