

Recent Jet Substructure Results from the LHC

APS Division of Particles of Fields

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on behalf of the ATLAS and CMS Collaborations

Tuesday, August 4, 2015



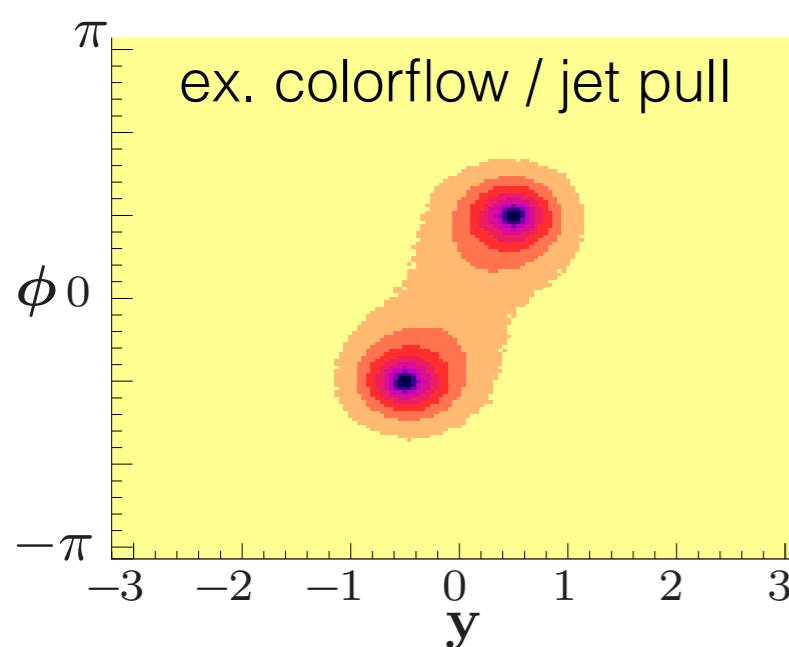
Introduction

The field of **jet substructure** is an active field of research with a fast pipeline from new ideas to experimental results.

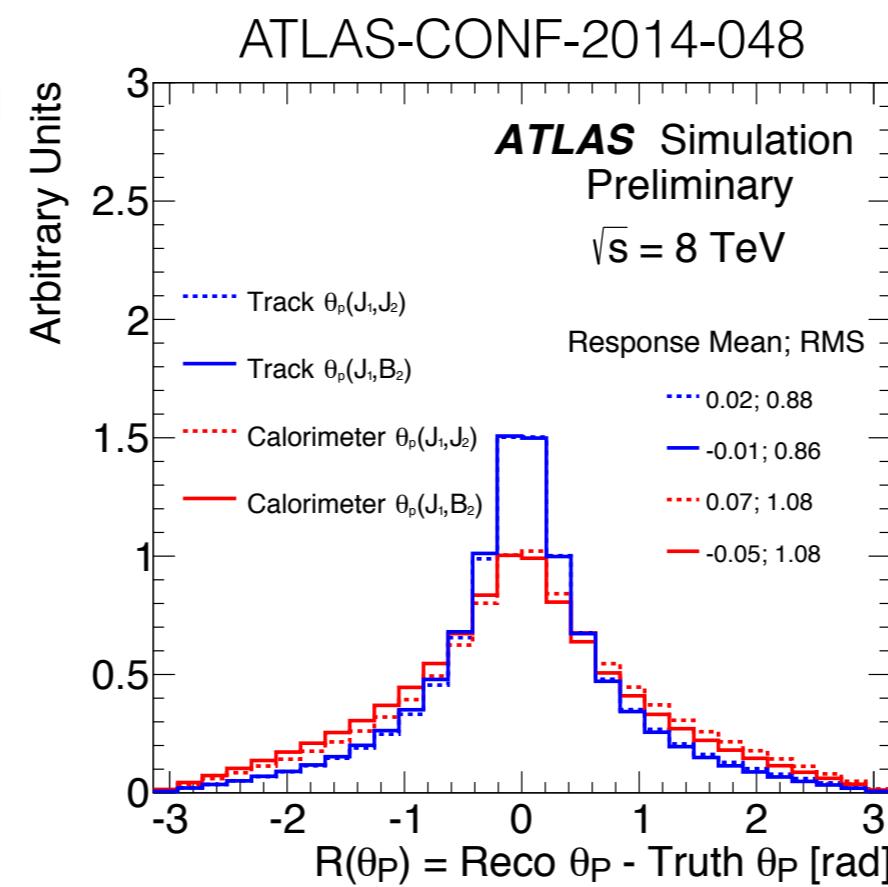
In **Theory** → In **Principle** → In **Practice**

Phenomenology Studies

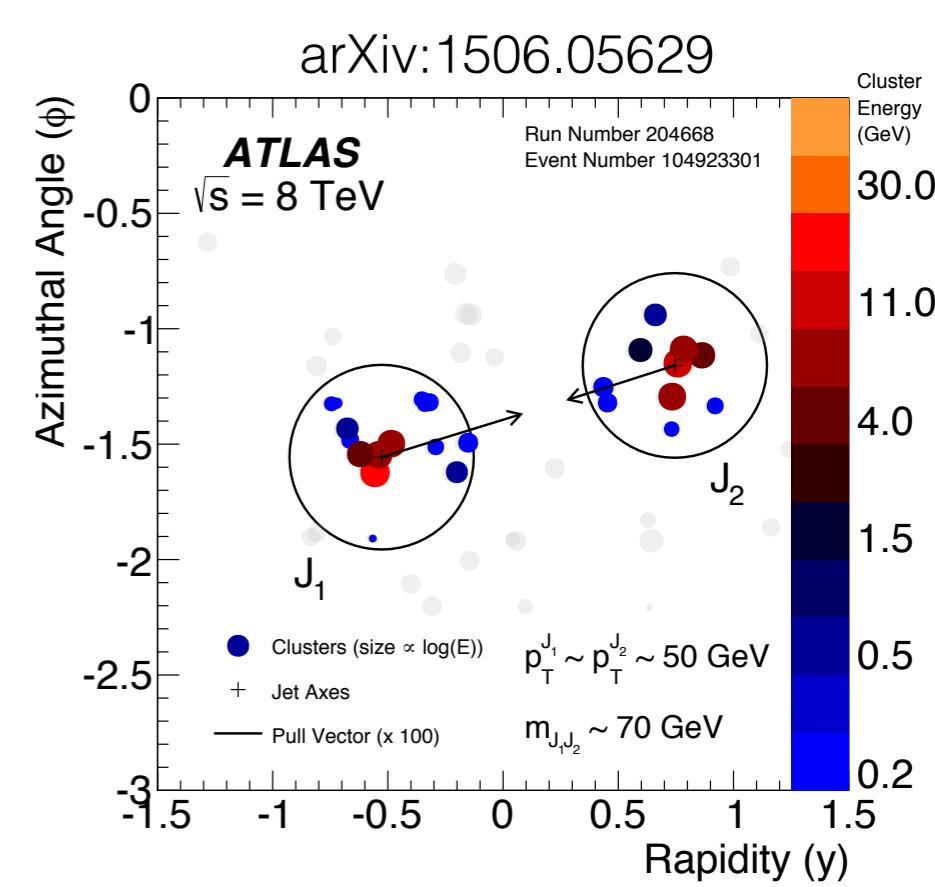
Phys. Rev. Lett. 105 (2010) 022001



New ways of thinking about jet sub/super structure



Understanding the detector response



Constraining models of (B)SM!

Overview

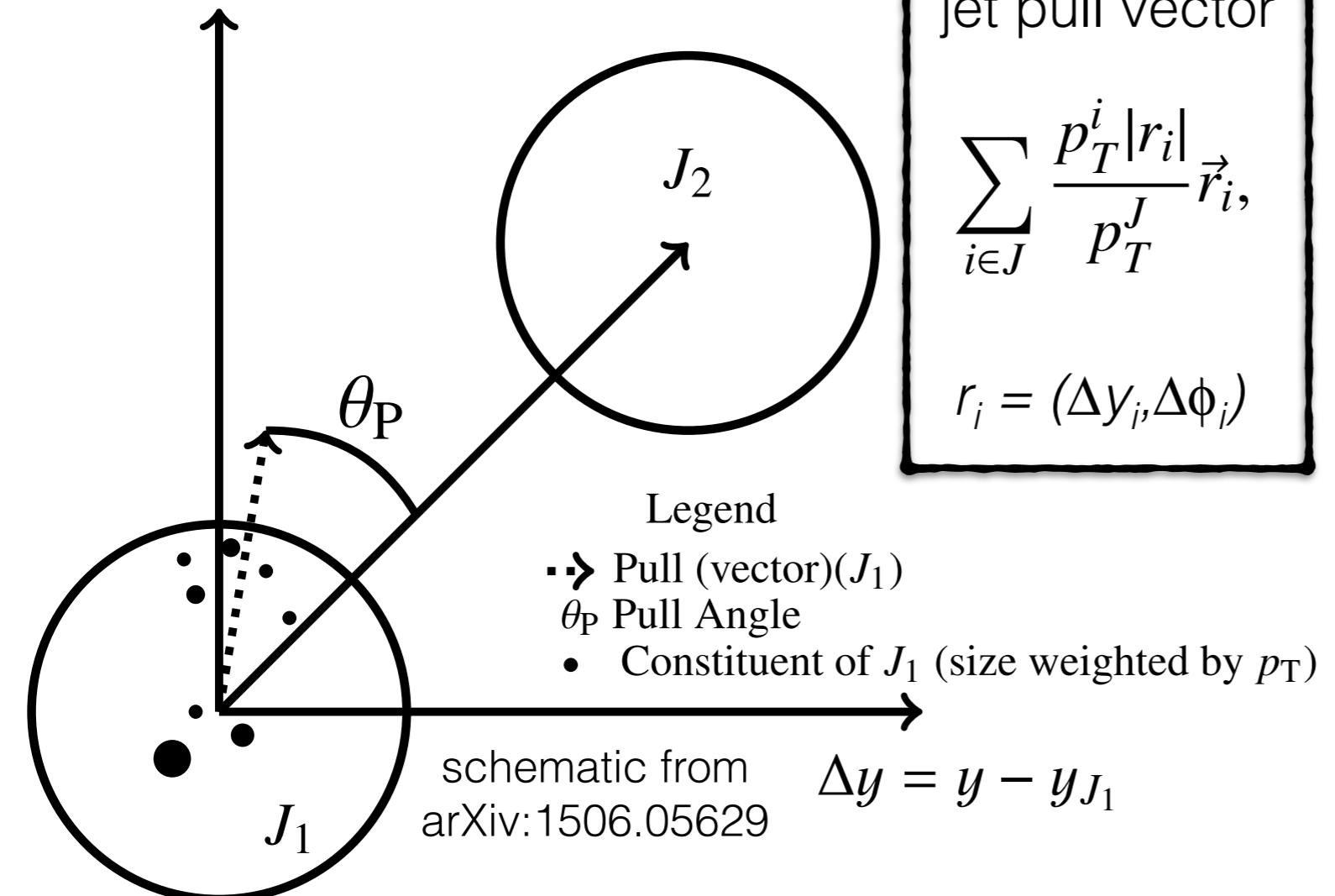
CMS BOTH ATLAS

Property	Substructure Variable(s)	Performance Result	Search Result	Measurement Results
Color(flow)*	Jet Pull	CMS-PAS-JME-14-002 ATLAS-CONF-2014-048	CMS-PAS-EXO-12-055 (and others)	arXiv:1506.05629
Charge*	Jet Charge	arXiv:1410.4227 ATLAS-CONF-2013-086		ATLAS-CONF-2015-025 (and others)
W or Z*	several	ATLAS-PERF-2015-02		
W/Z or QCD	many	arXiv:1410.4227 ATLAS-PUB-2014-004	CMS-PAS-EXO-12-055 arXiv:1506.00962 (and others)	arXiv:1407.0800
top or QCD	many	CMS-PAS-JME-13-007 ATLAS-CONF-2013-084	arXiv:1506.03062 arXiv:1505.07018 (and others)	ATLAS-CONF-2014-057
H or QCD	many	CMS-PAS-BTV-13-001 and update ATLAS-PUB-2014-013	arXiv:1506.01443 arXiv:1506.00285 (and others)	
q or g	many	CMS-PAS-JME-13-002 arXiv:1405.6583	CMS-PAS-EXO-12-055 (and others)	

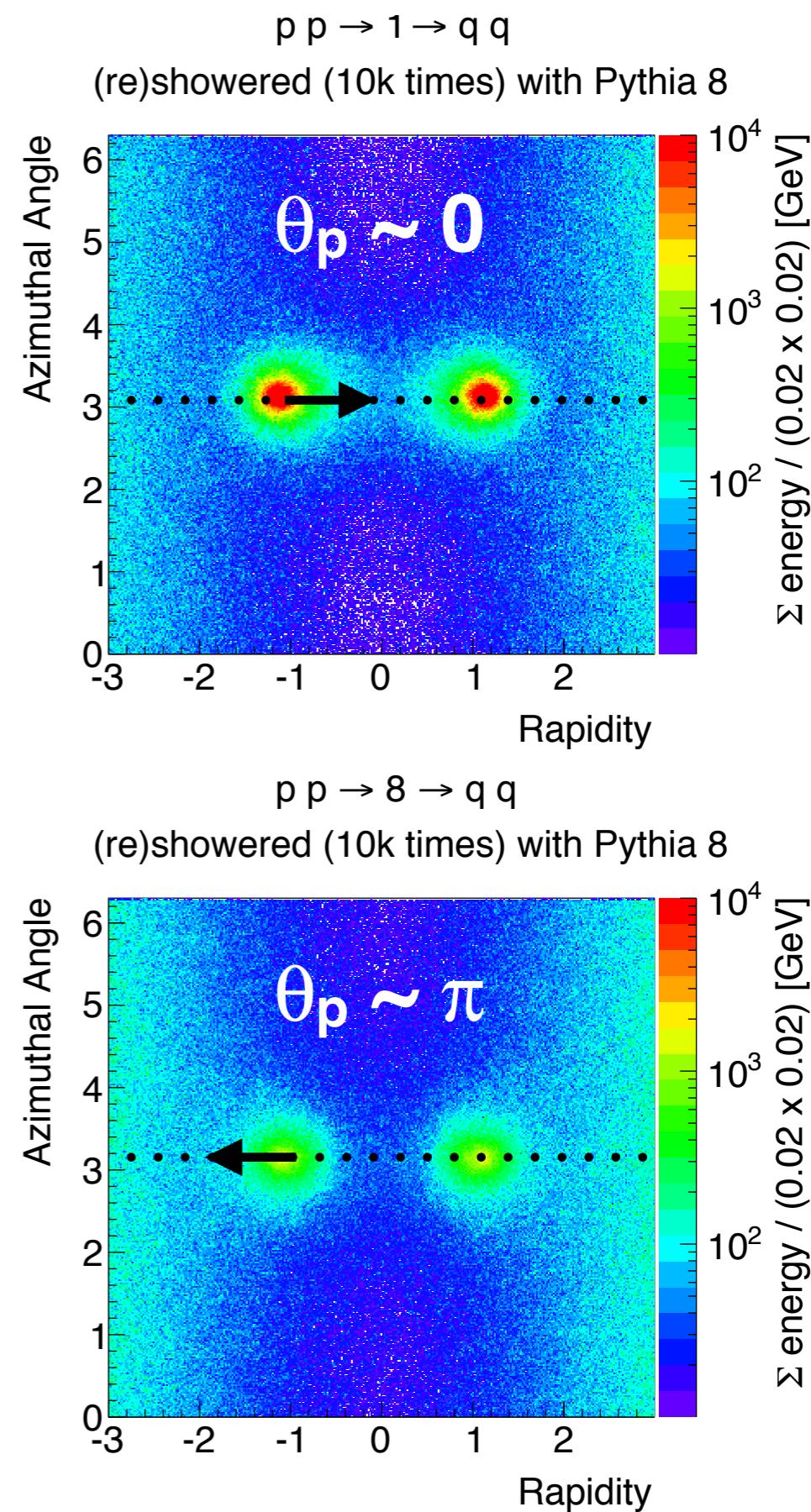
*Focus of this talk - no time to cover everything!

Colorflow with the Jet Pull

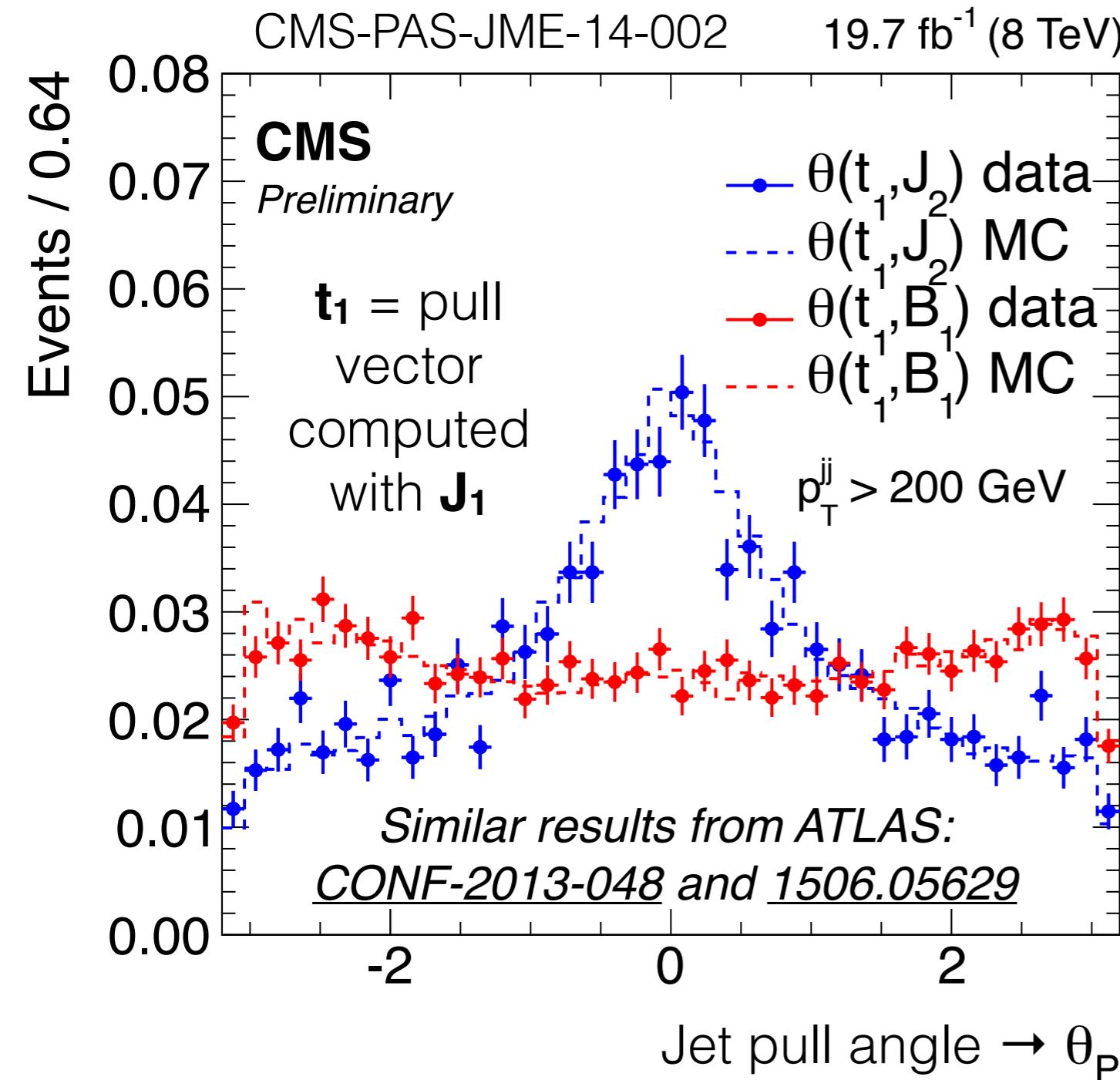
$$\Delta\phi = \phi - \phi_{J_1}$$



Jet Pull Angle (θ_p) =
direction the radiation
from one jet leans
relative to another jet.



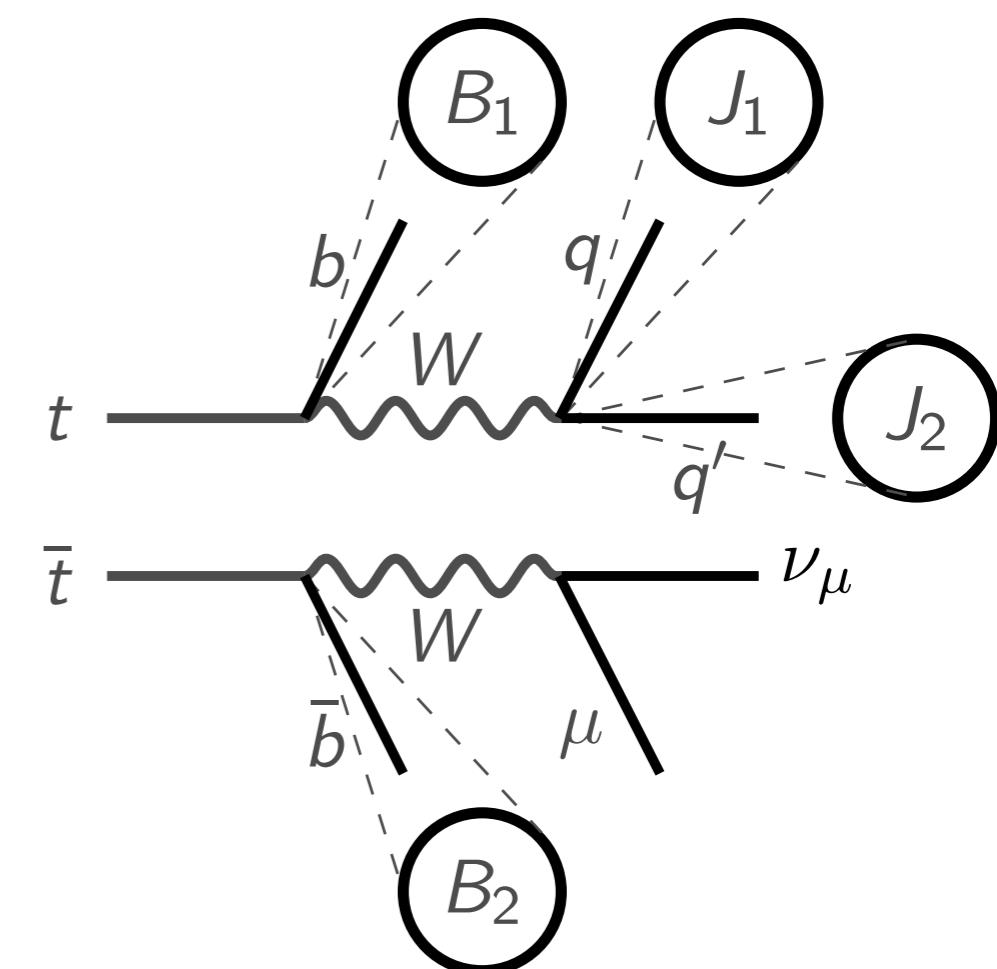
Colorflow Tagging Performance



Tag-and-look

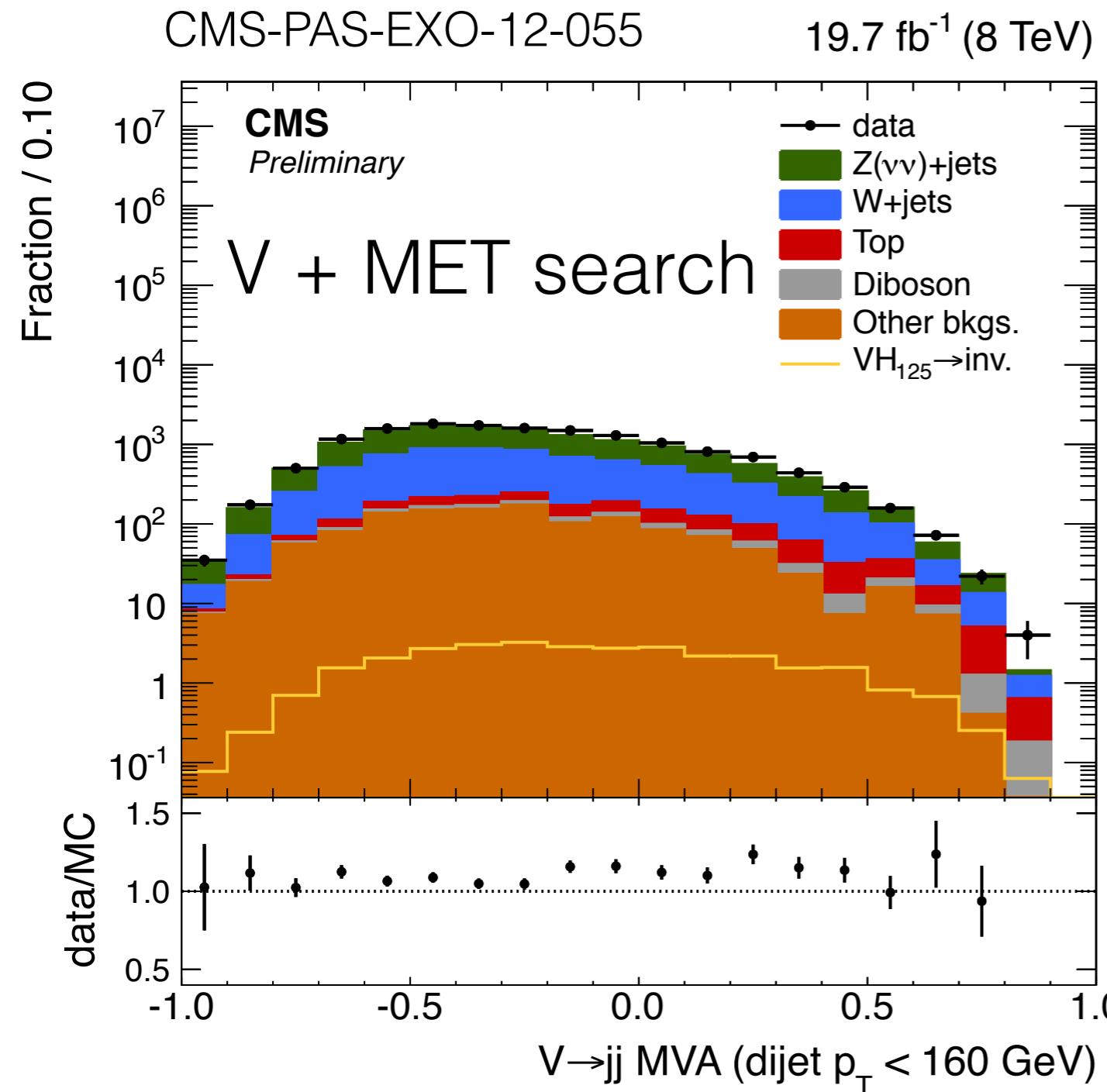
(tag-and-probing will come later!)

Can study the jet pull angle in top quark events where we expect non-trivial shapes for W jets and b-jets.



These shapes seem to be well re-produced by the simulation!

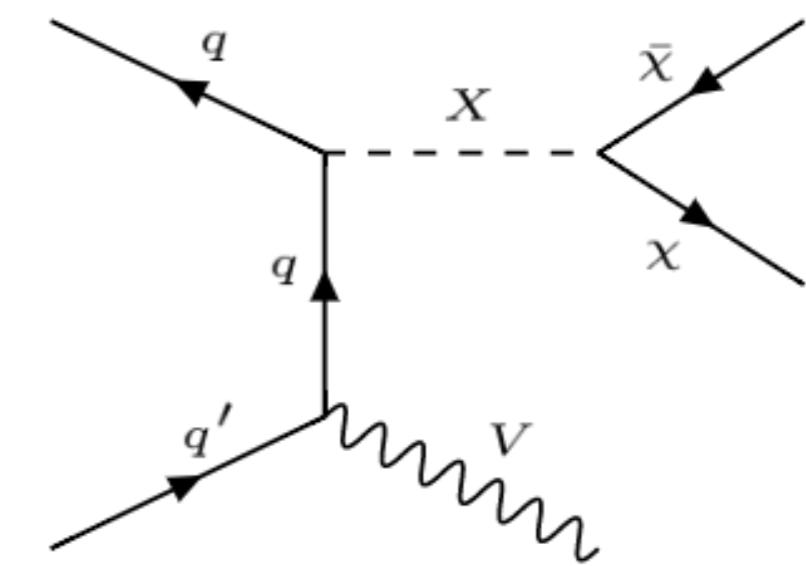
Colorflow Tagging for BSM Searches



Tagger: dijet mass **jet pull angle**
 dijet m/ p_T q/g tags mass drop

Jet pull is used in several **CMS** searches for **boosted bosons** in the high p_T but still **resolved regime**.

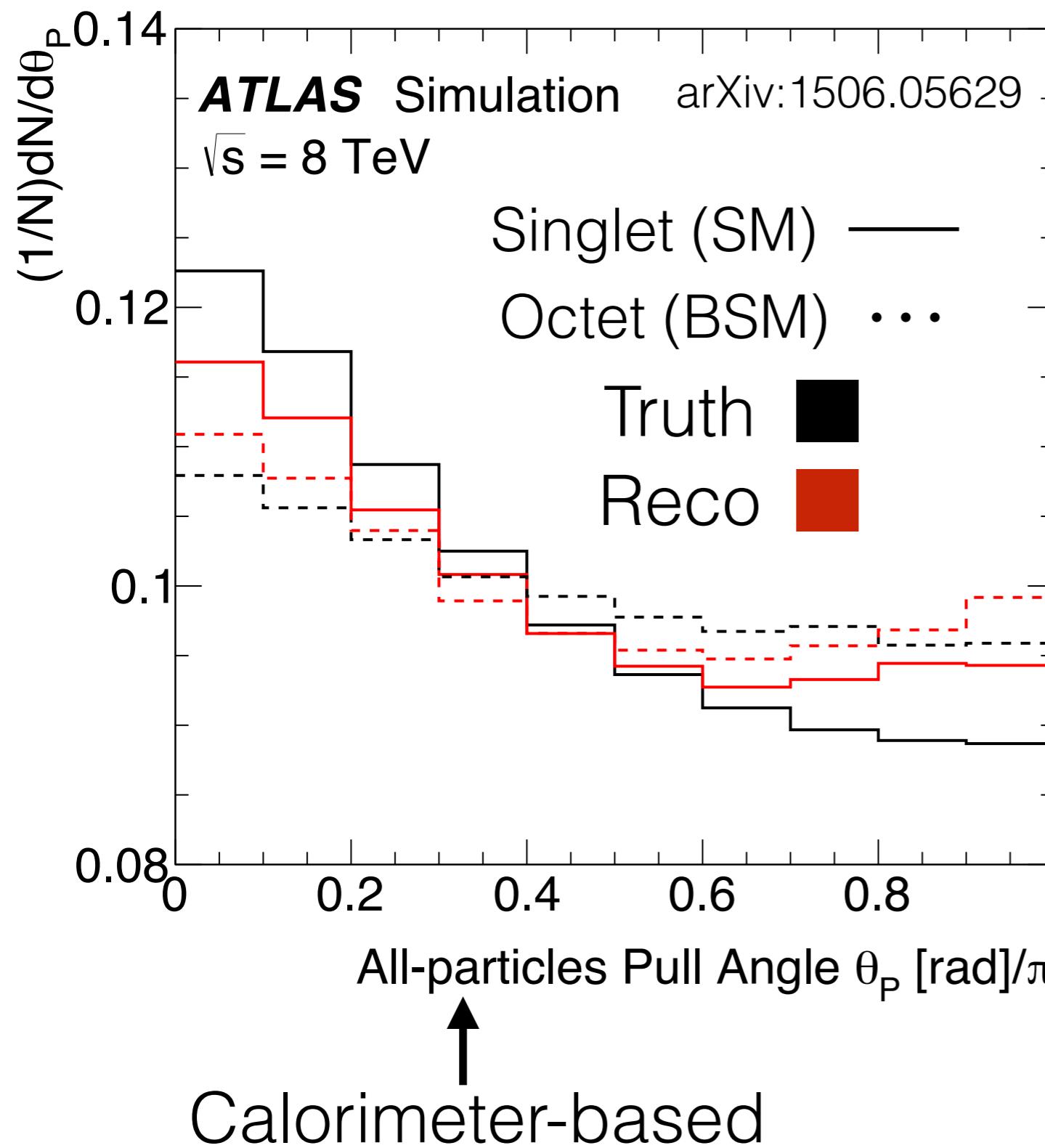
Color flow is **subtle**, so needs to be combined in an **MVA**.



Colorflow Tagging for an SM Measurement

Truth-level = particle-level = before detector simulation

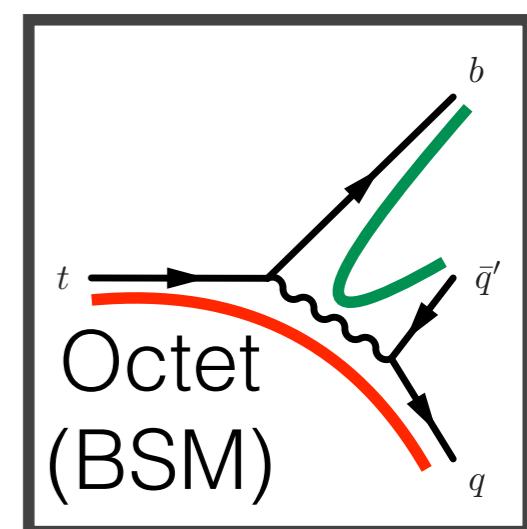
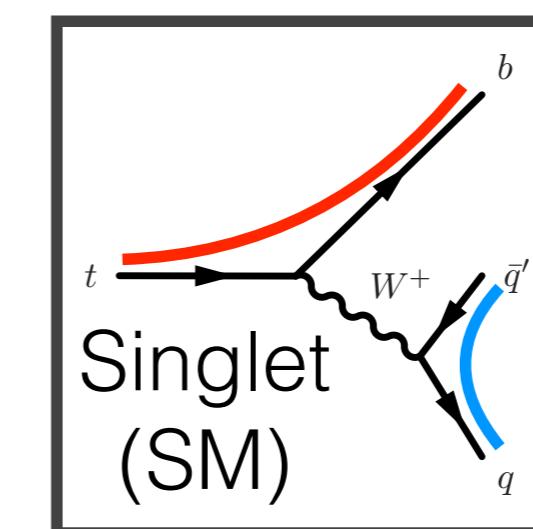
Reco-level = detector-level = after detector simulation



ATLAS has measured the pull angle in top events

Quantified sensitivity of a dijet resonance color representation

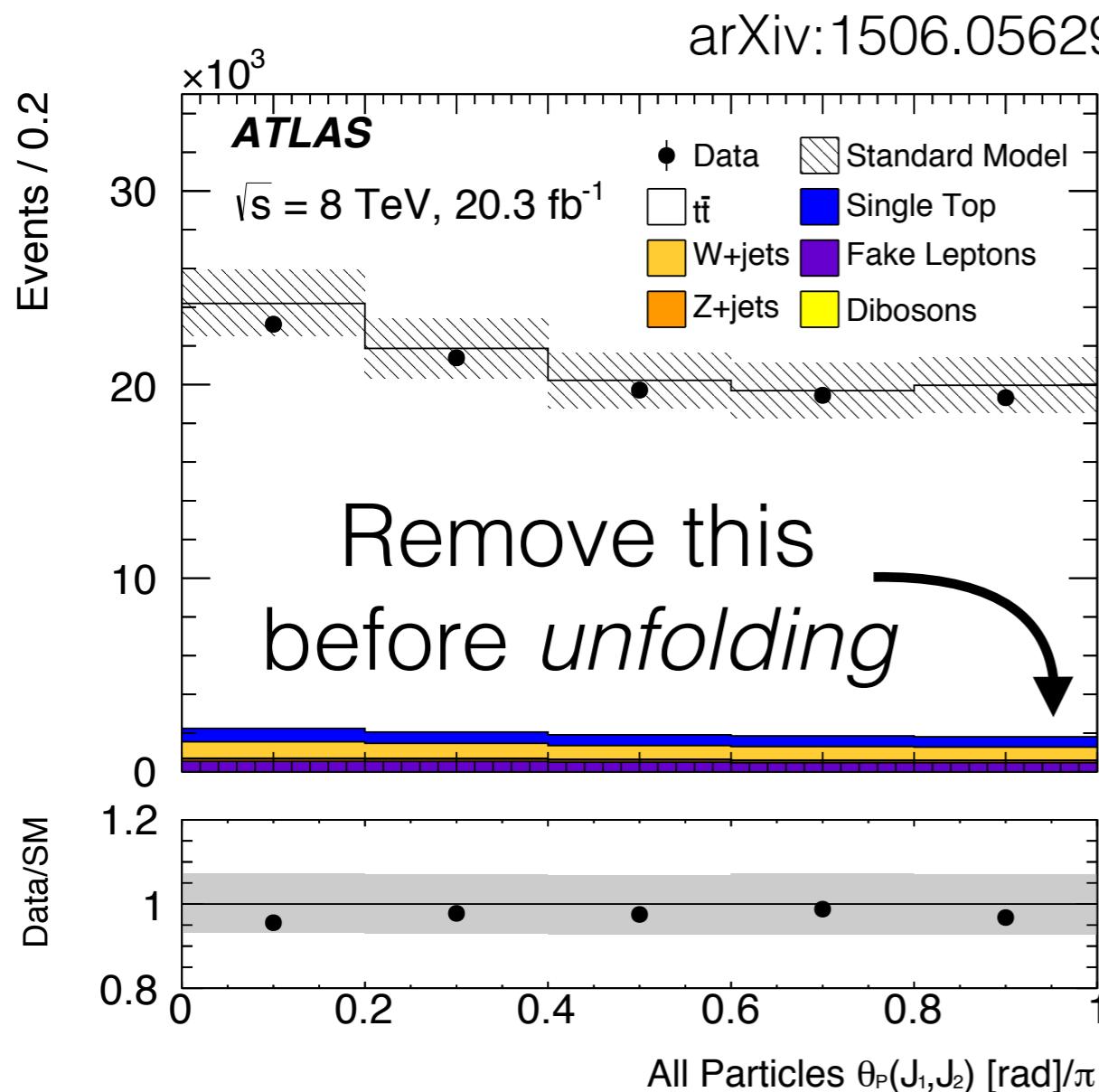
(in this case, a W boson)



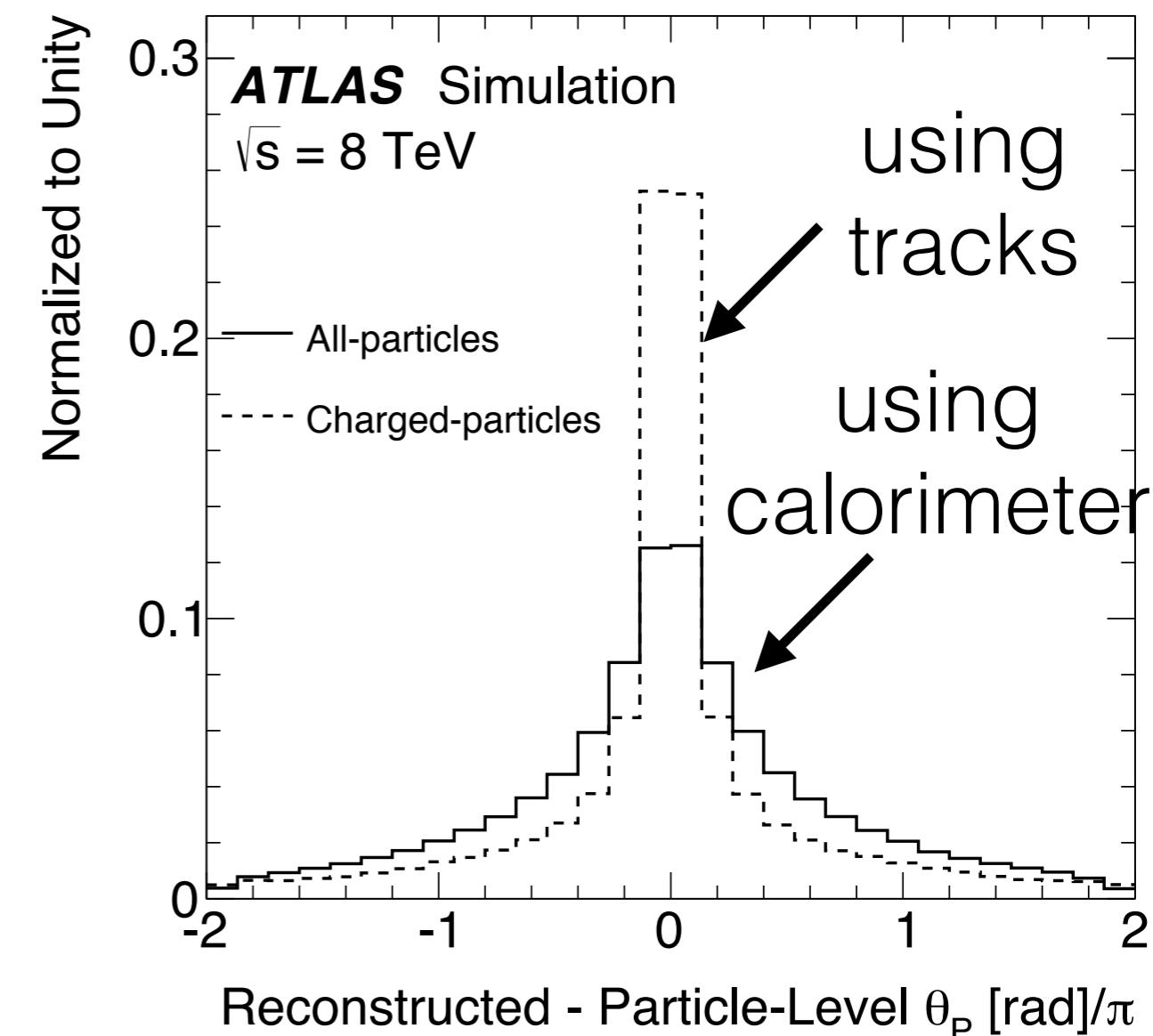
→ ATLAS Colorflow in backup

Colorflow Tagging for an SM Measurement

Two big challenges in this measurement:



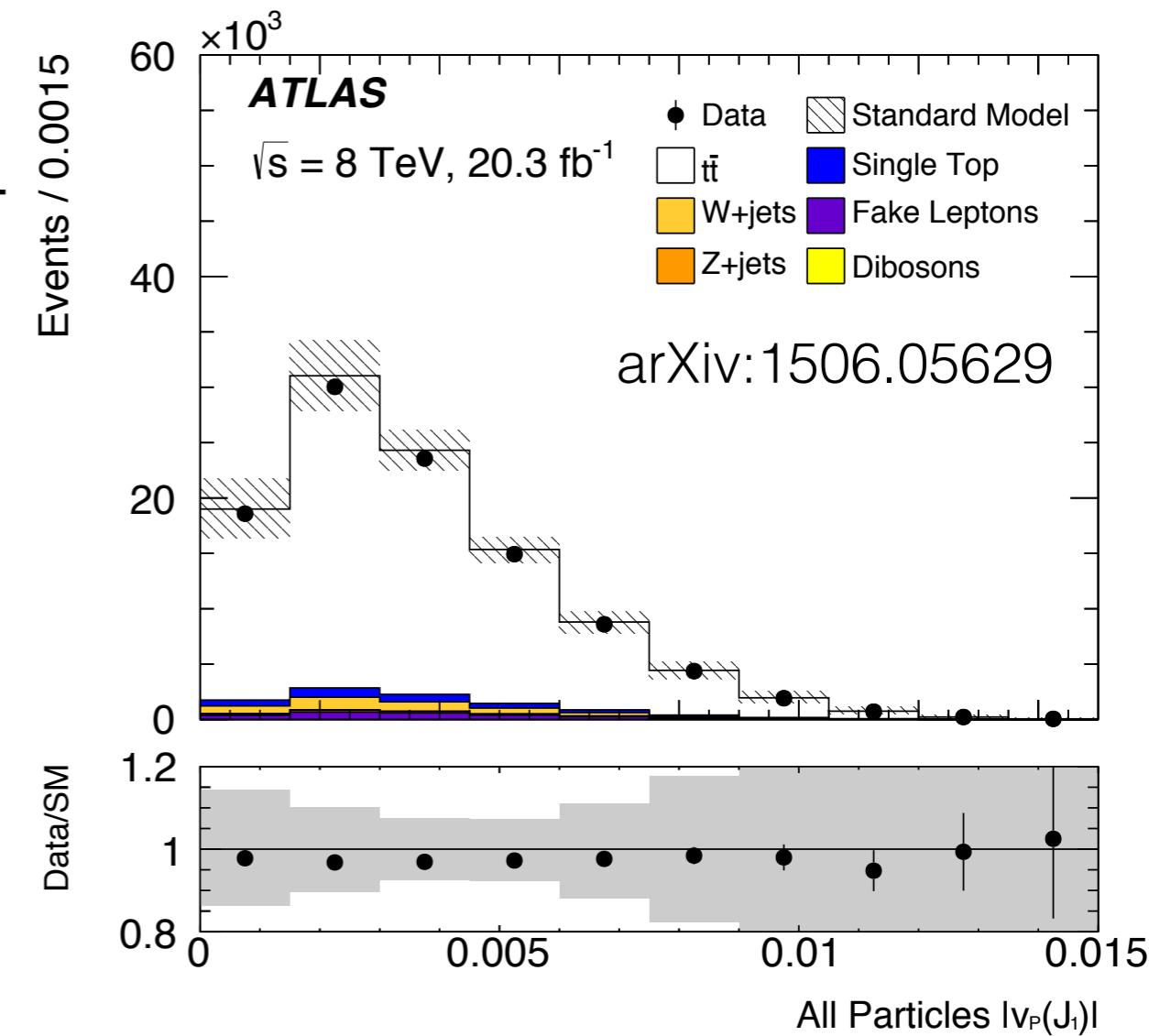
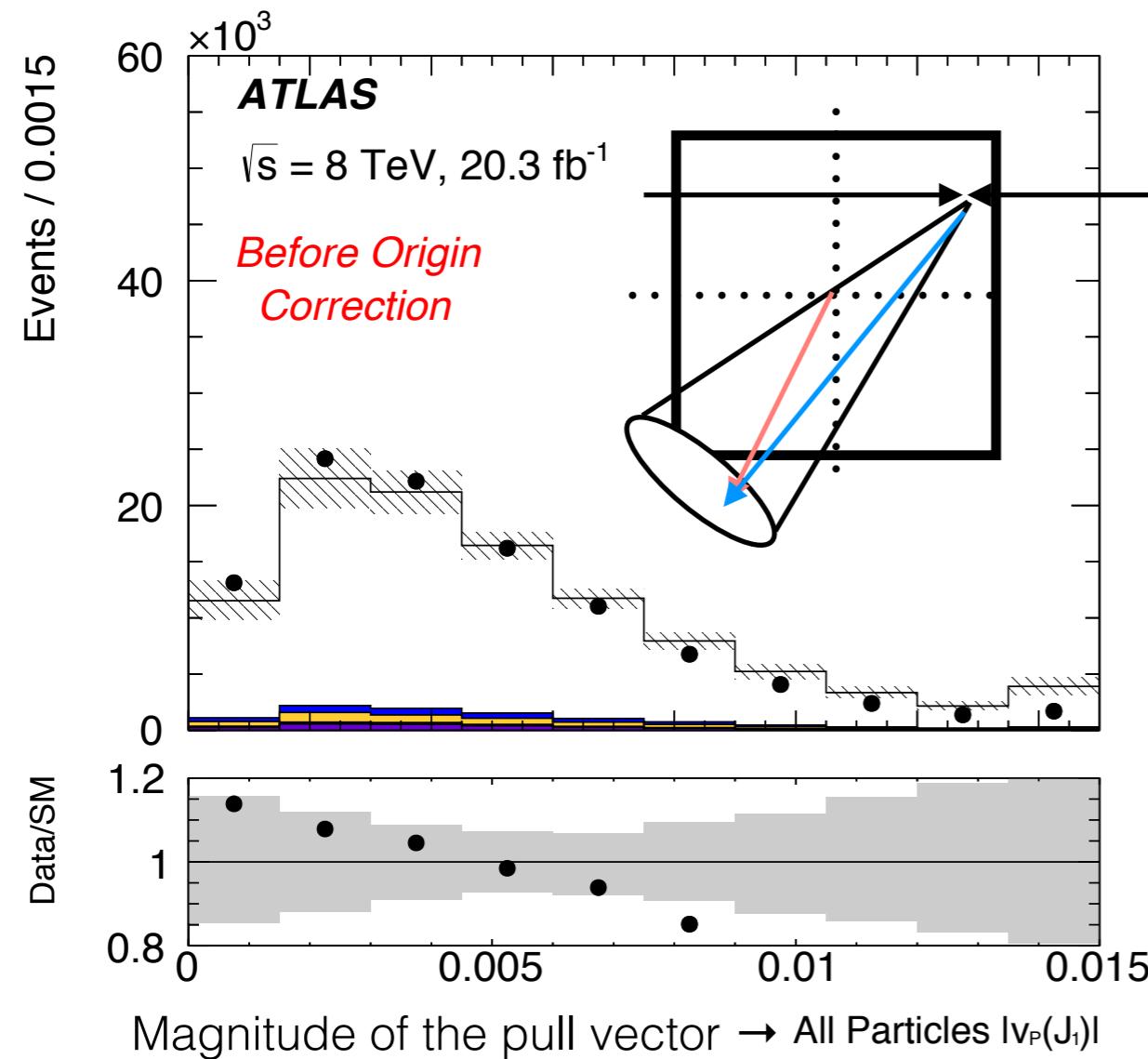
Nearly uniform
 (but backgrounds are small!)



Resolution is comparable
 to the range

Colorflow Tagging for an SM Measurement

There are severe subtleties in the measurement: e.g. what is the jet axis?



Jets are corrected to point to the primary vertex, but it is crucial that their constituents are also corrected!

→ ATLAS Colorflow in backup

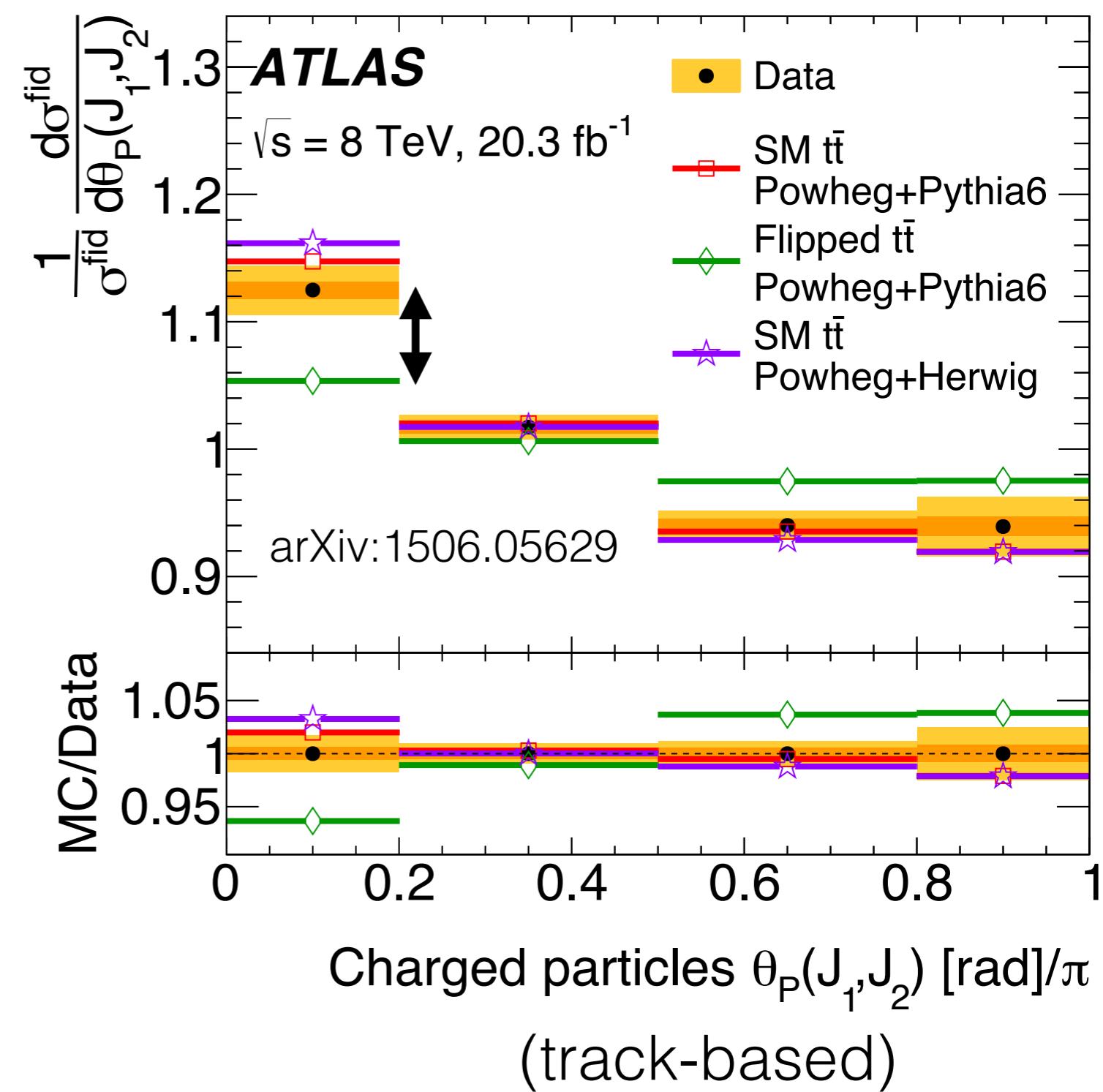
Colorflow Tagging for an SM Measurement

Can **significantly** ($\sim 3\sigma$) distinguish a singlet W from an octet W .

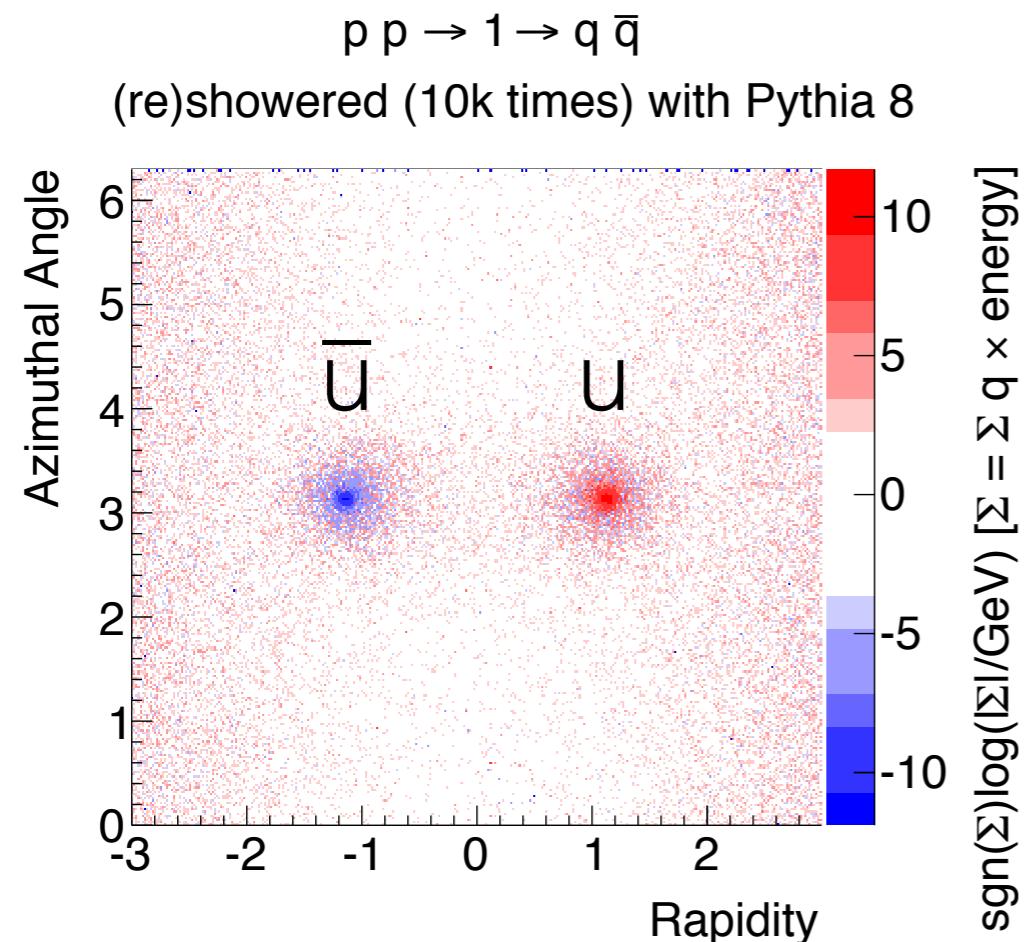
Furthermore the unfolded data are public for future model comparisons.

N.B. **track-based** is more sensitive than **calorimeter-based**.

Measurement Results



Charge Tagging Performance



Tr is the set of tracks associated with the jets

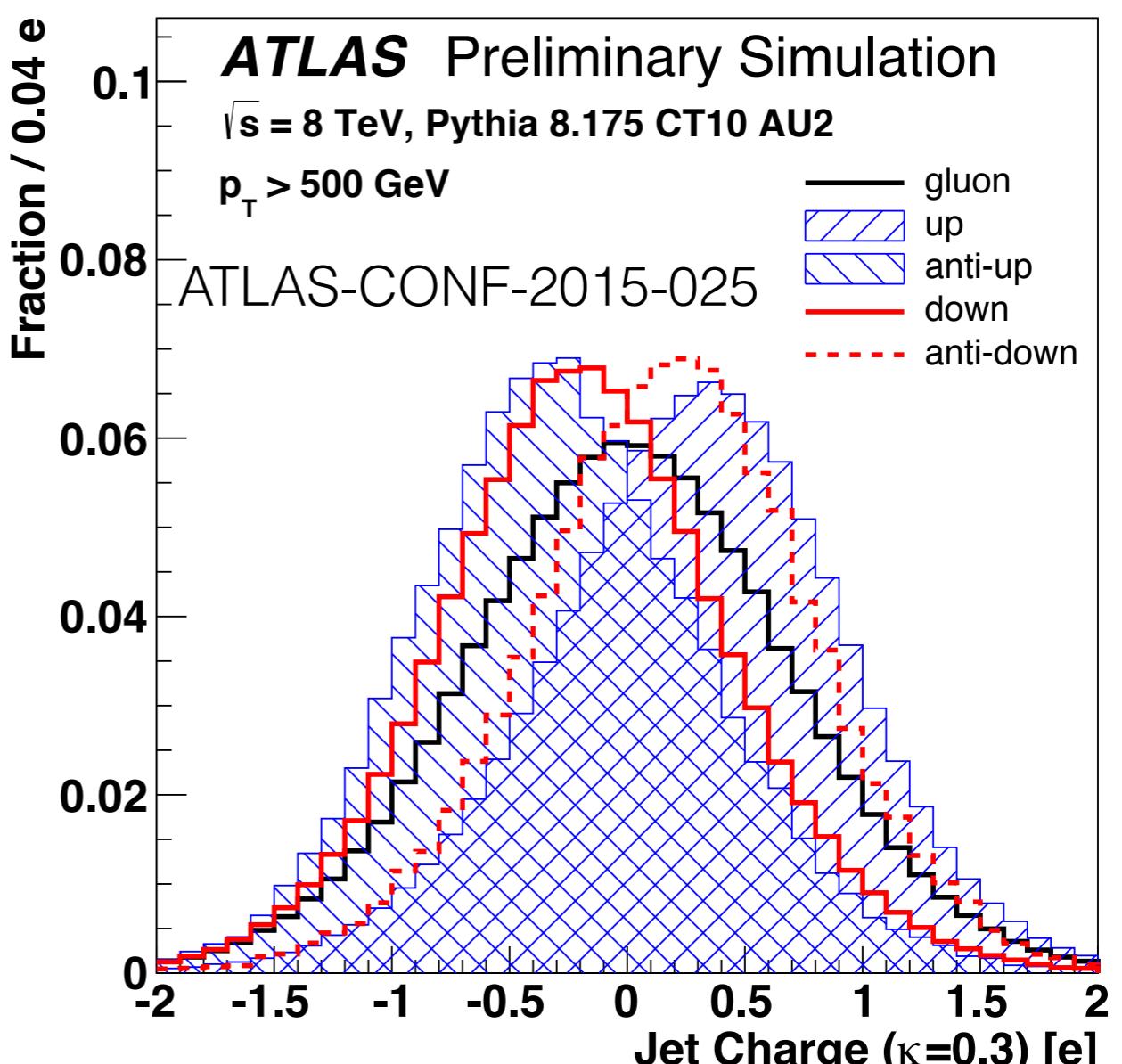
ATLAS: via ghost-association
CMS: charged PF candidates

+ / - / neutral means shifted, but small compared to width!

$$Q_j = \frac{1}{(p_T j)^\kappa} \sum_{i \in \text{Tr}} q_i \times (p_T^i)^\kappa$$

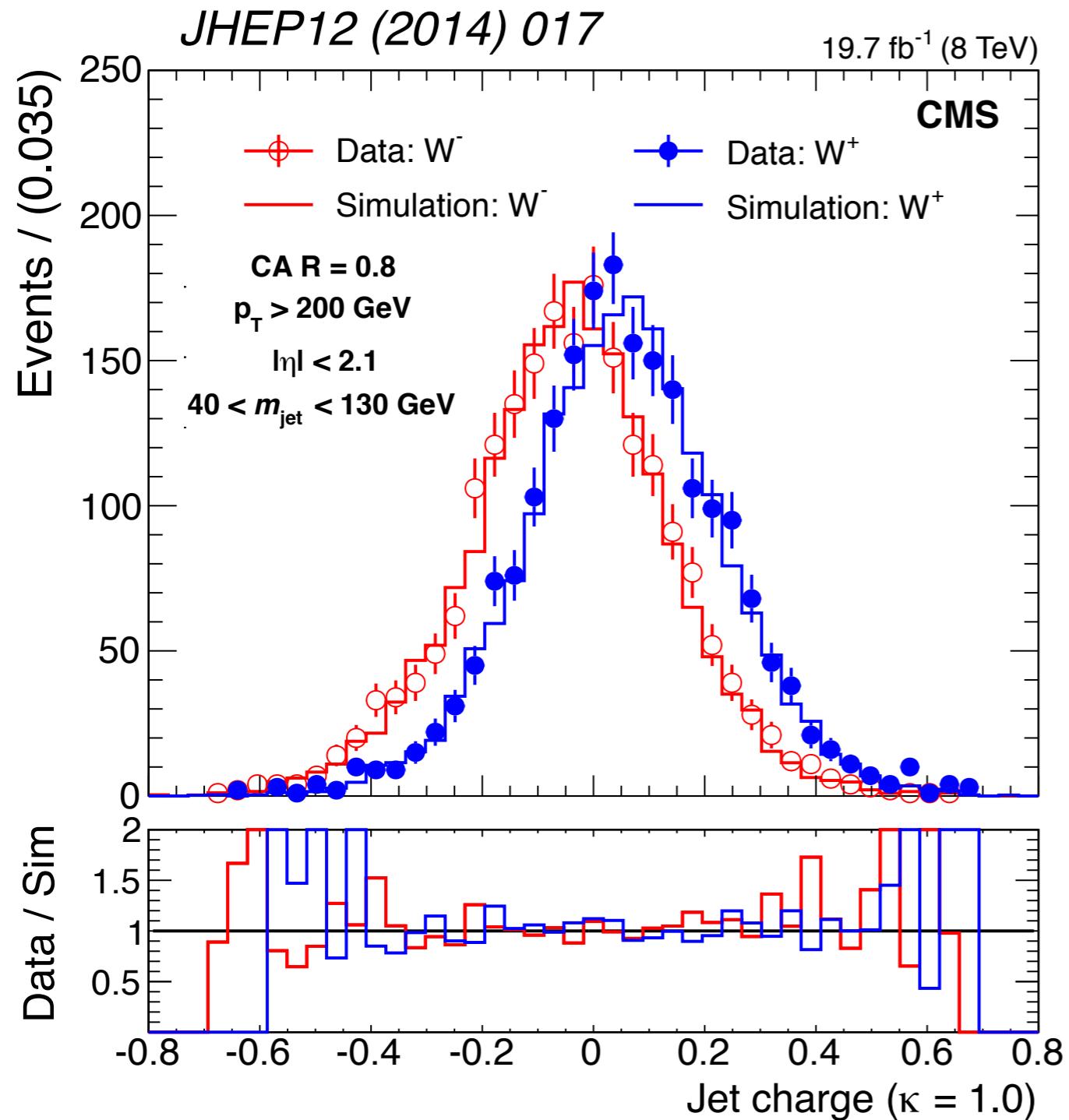
κ is a regularization parameter - controls sensitivity to soft radiation.

κ in
[0.3, 1.0]



In units of the positron charge [e]

Charge Tagging Performance



Similar results from ATLAS:
ATLAS-CONF-2013-086 and
ATLAS-PERF-2014-002

Tag-and-probe

Tag the charge of $W \rightarrow l\nu$
 and then probe the
 charge of $W \rightarrow jj$ in top
 quark pair production.

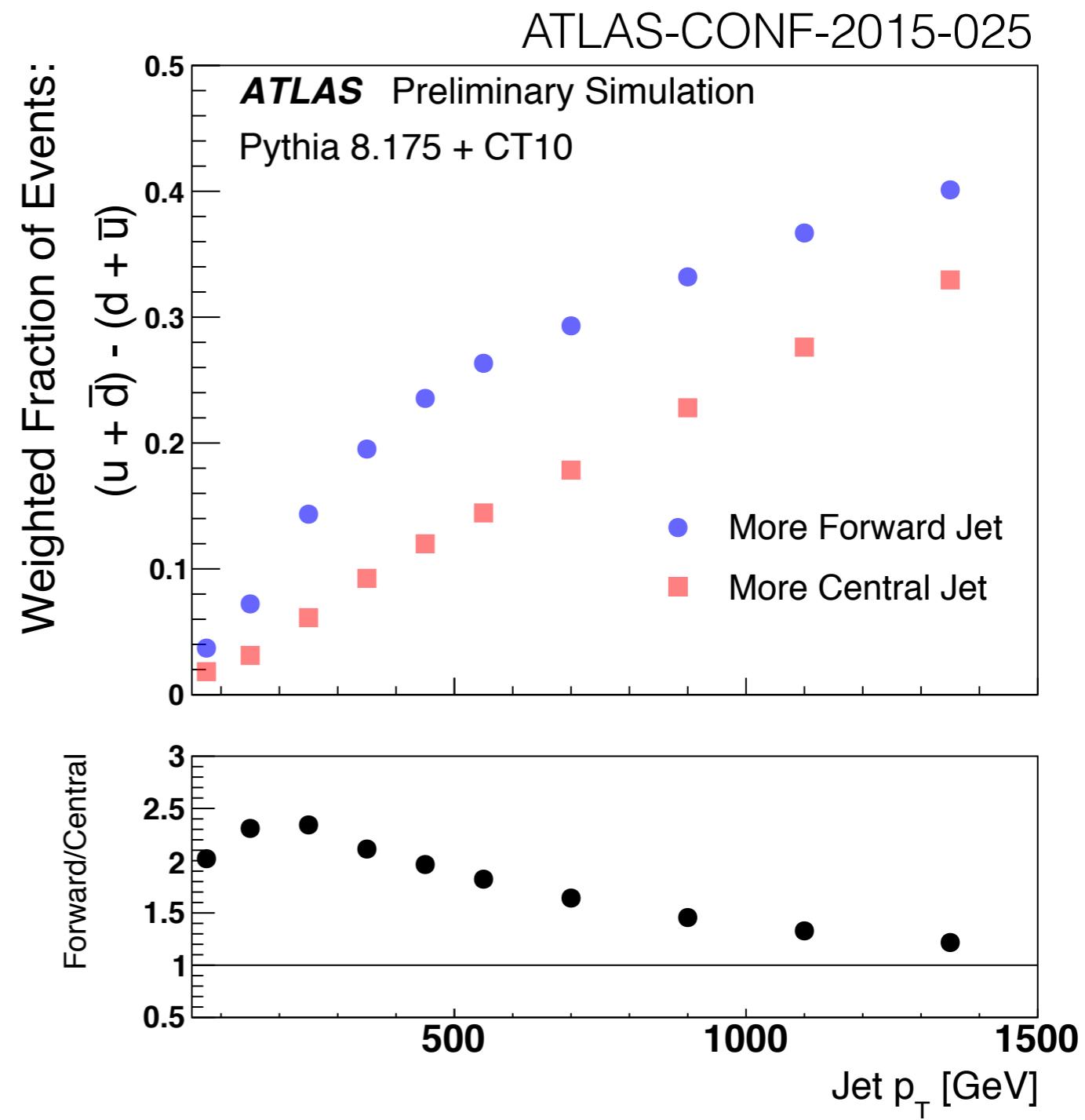
Significant difference
 between W^+ and W^- ,
 though **subtle**; well-
 reproduced by the
 simulation.

Charge Tagging a SM Measurement

ATLAS has measured the jet charge in dijet events.

Non-trivial change in the mean jet charge as a function of p_T because the up-quark jet fraction increases.

Furthermore, there have been recent calculations which we can put to the test!



Charge Tagging a SM Measurement

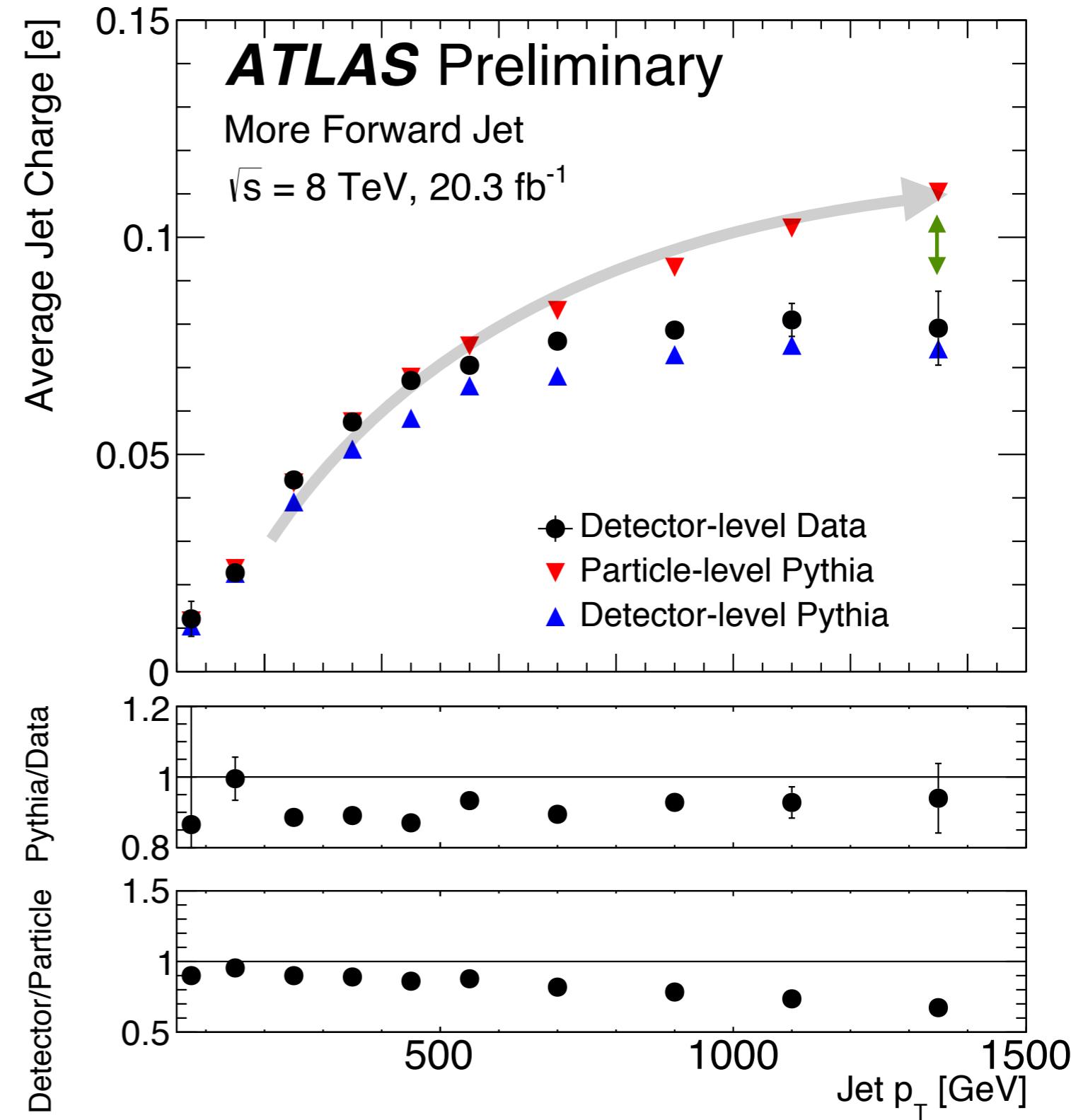
Unfold to facilitate model/calculation comparisons.

Increases due to more up-quark jets

Resolution degrades at high p_T

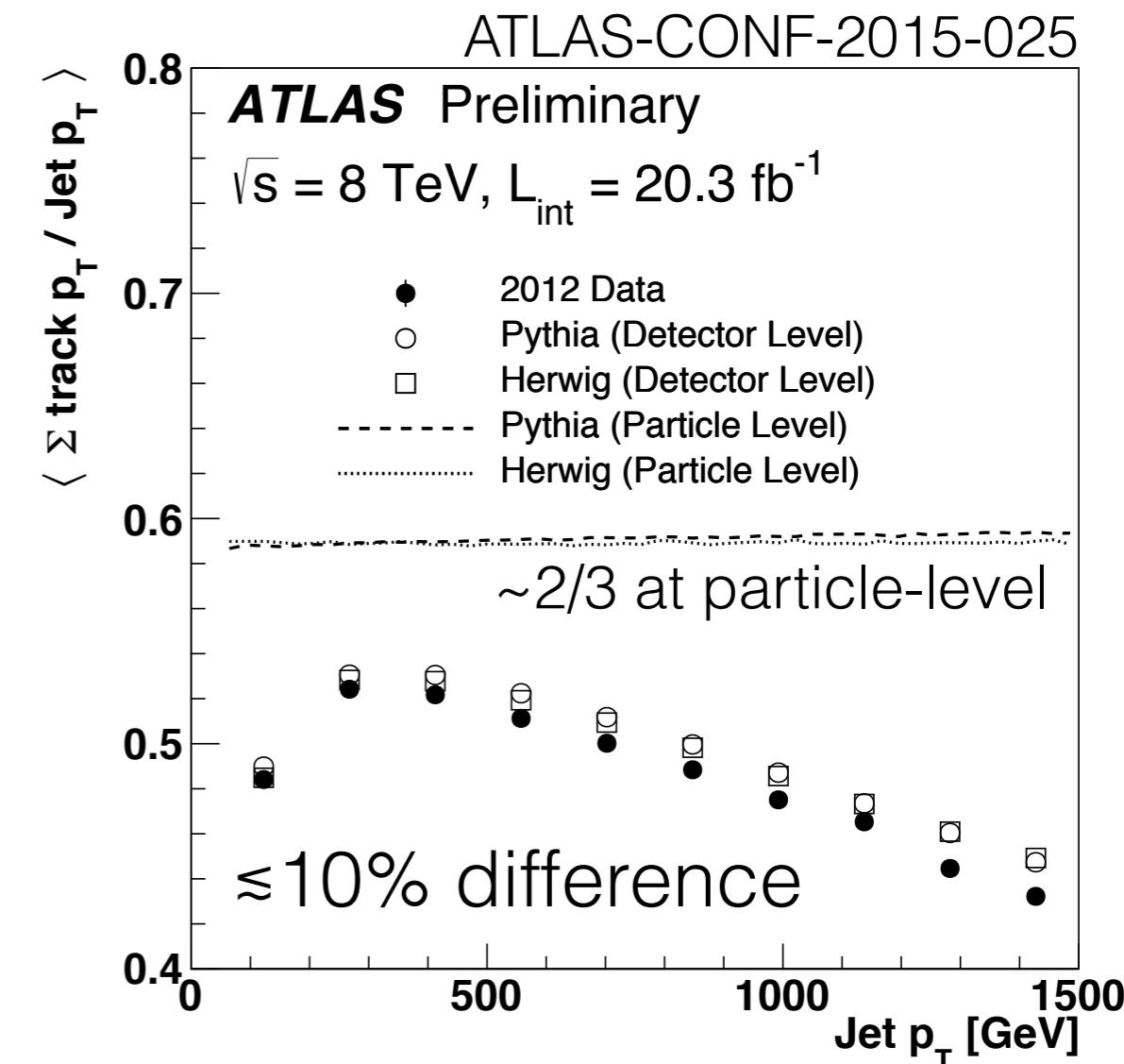
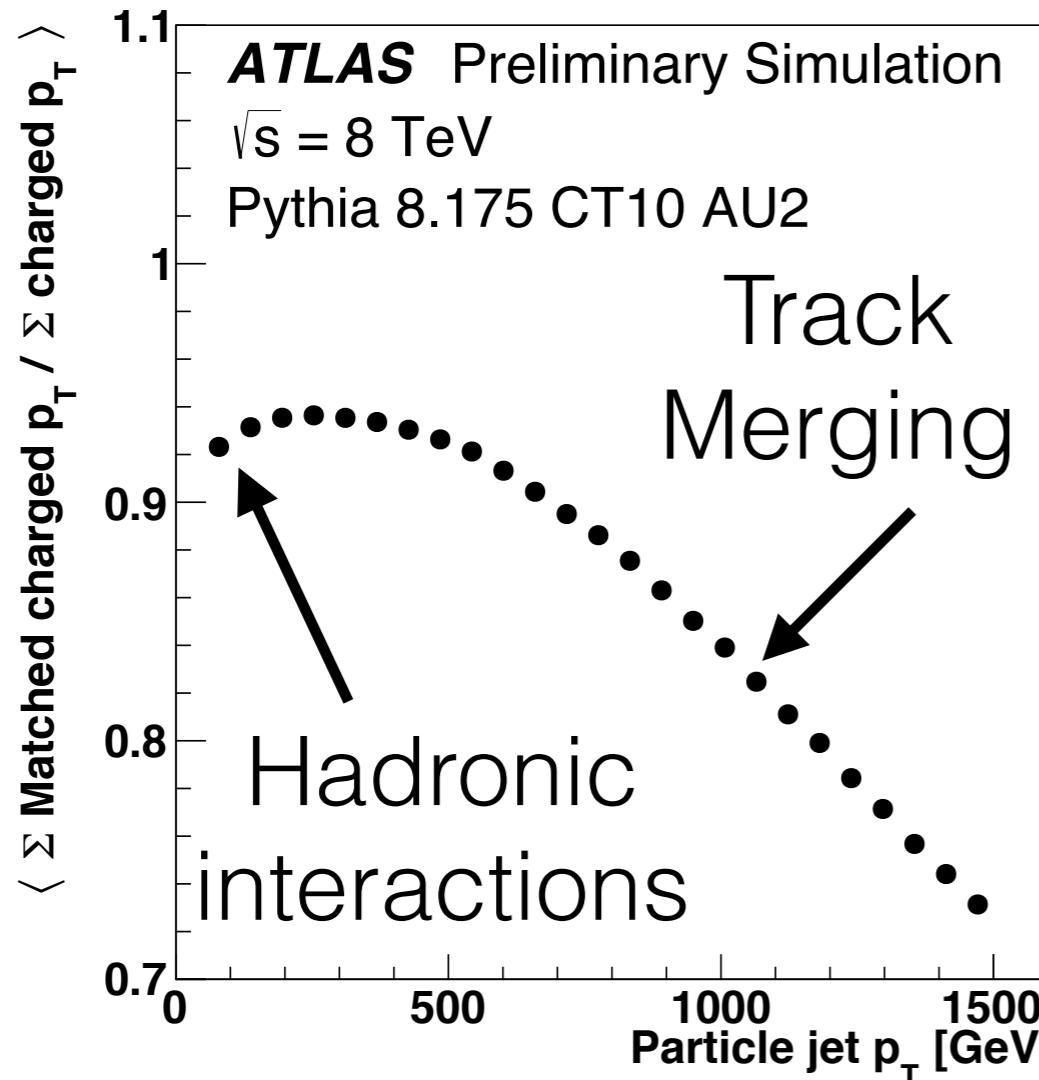
→ ATLAS Jet Charge in backup

ATLAS-CONF-2015-025



Charge Tagging a SM Measurement

Need to understand tracking (inside jets)!



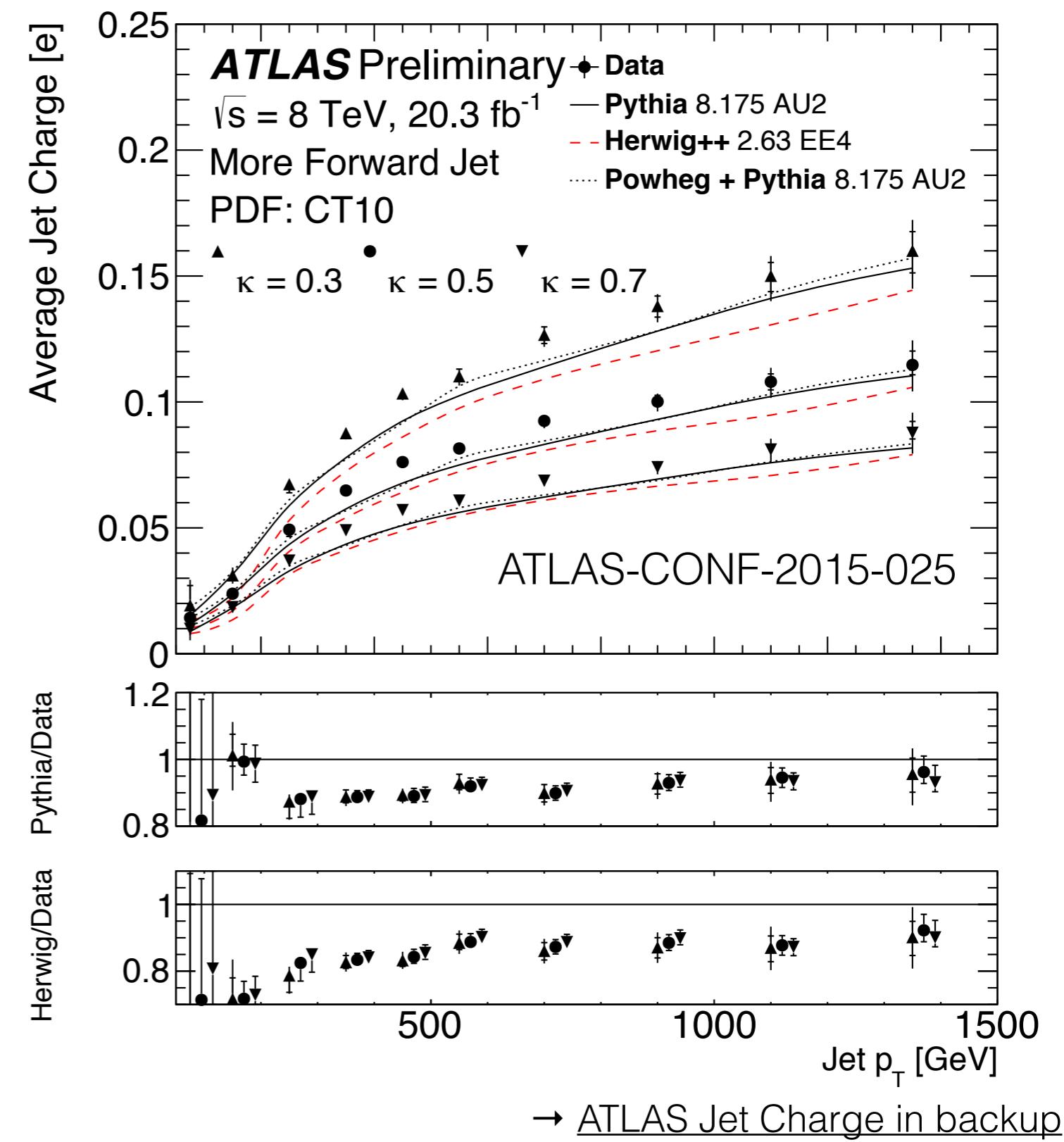
The number of charged particles increases with p_T and their tracks become straighter. One way to study the modeling of the merging is to look at the charged-energy fraction.

Charge Tagging a SM Measurement

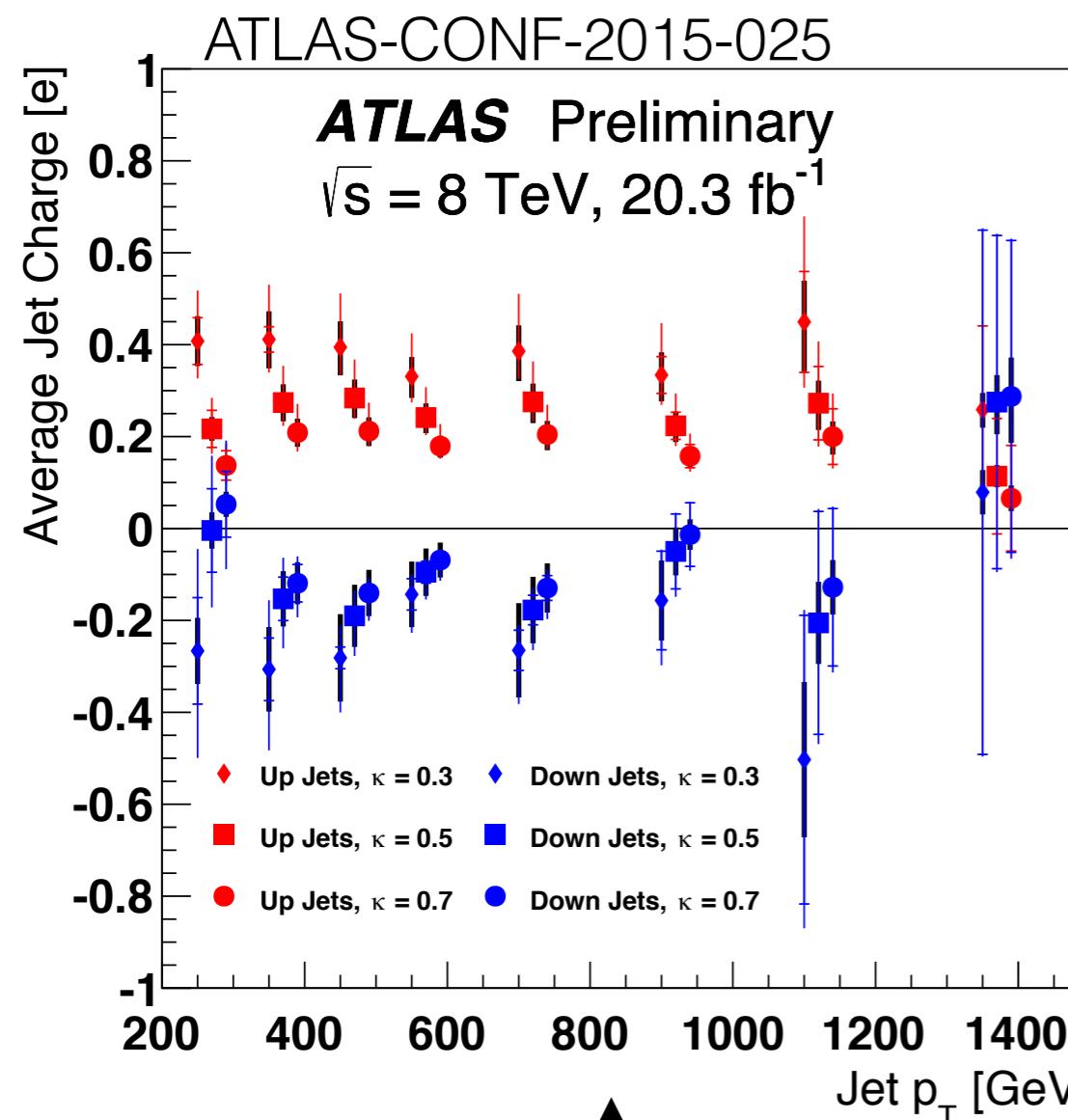
The unfolded data are compared to various models.

- Systematically lower mean in the simulation
- Significant variation with PDF, CTEQ6L1 best description of the data
- Sensitive to amount of radiation in the shower (depends on κ)

Measurement Results



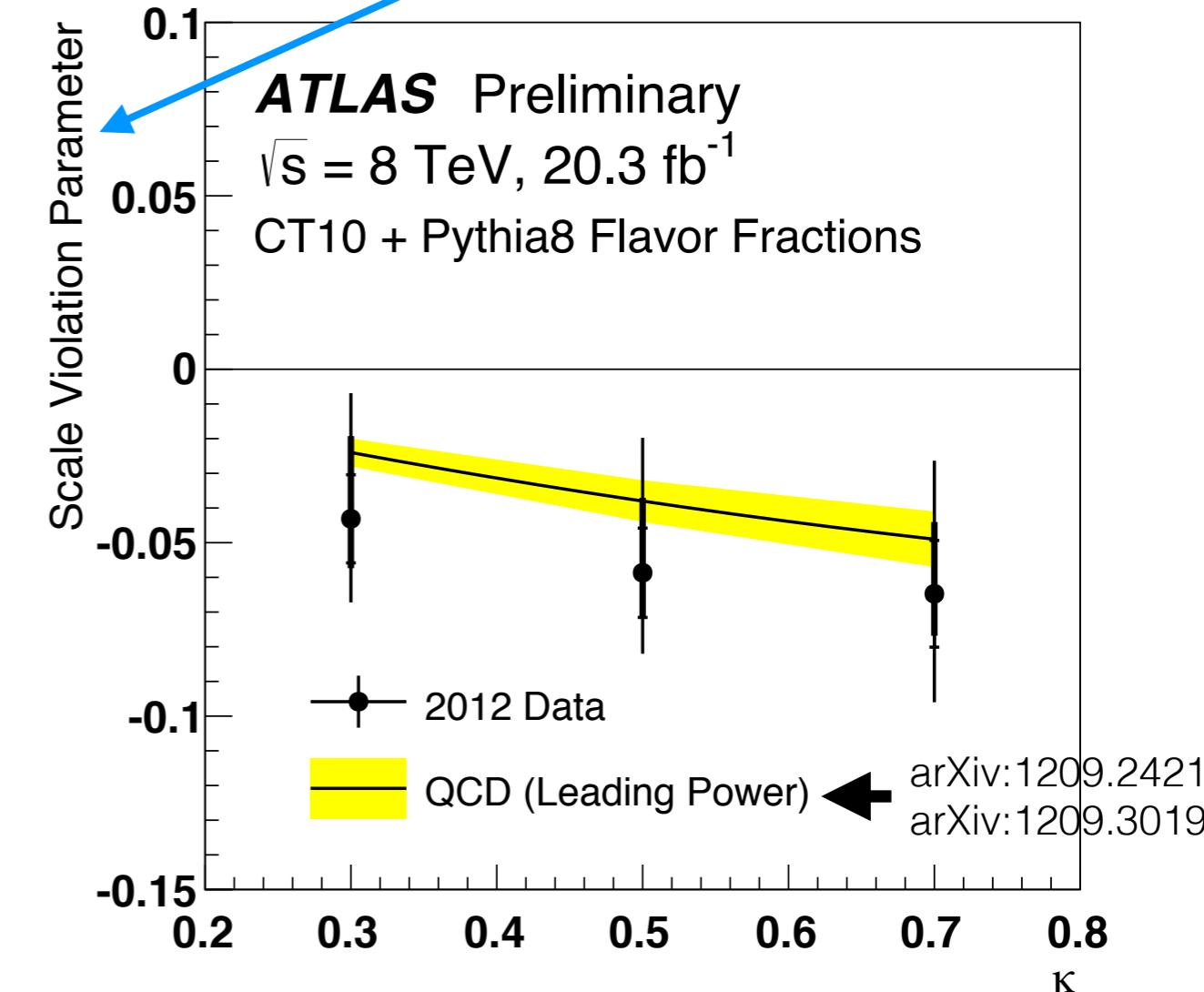
Charge Tagging a SM Measurement



Can exploit the η -dependence of the flavor fractions to extract the up- and down-quark jet charge in each p_T bin.

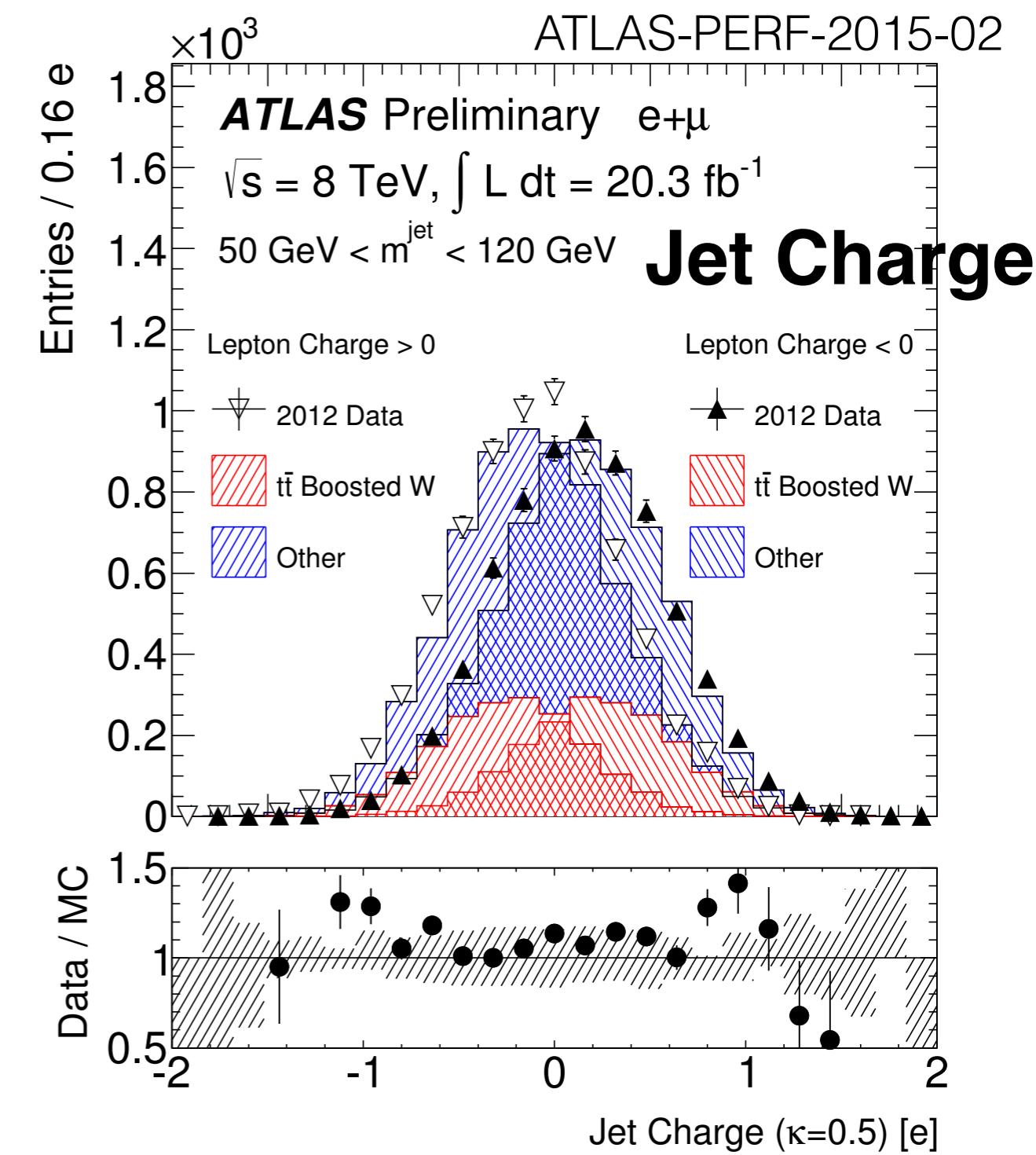
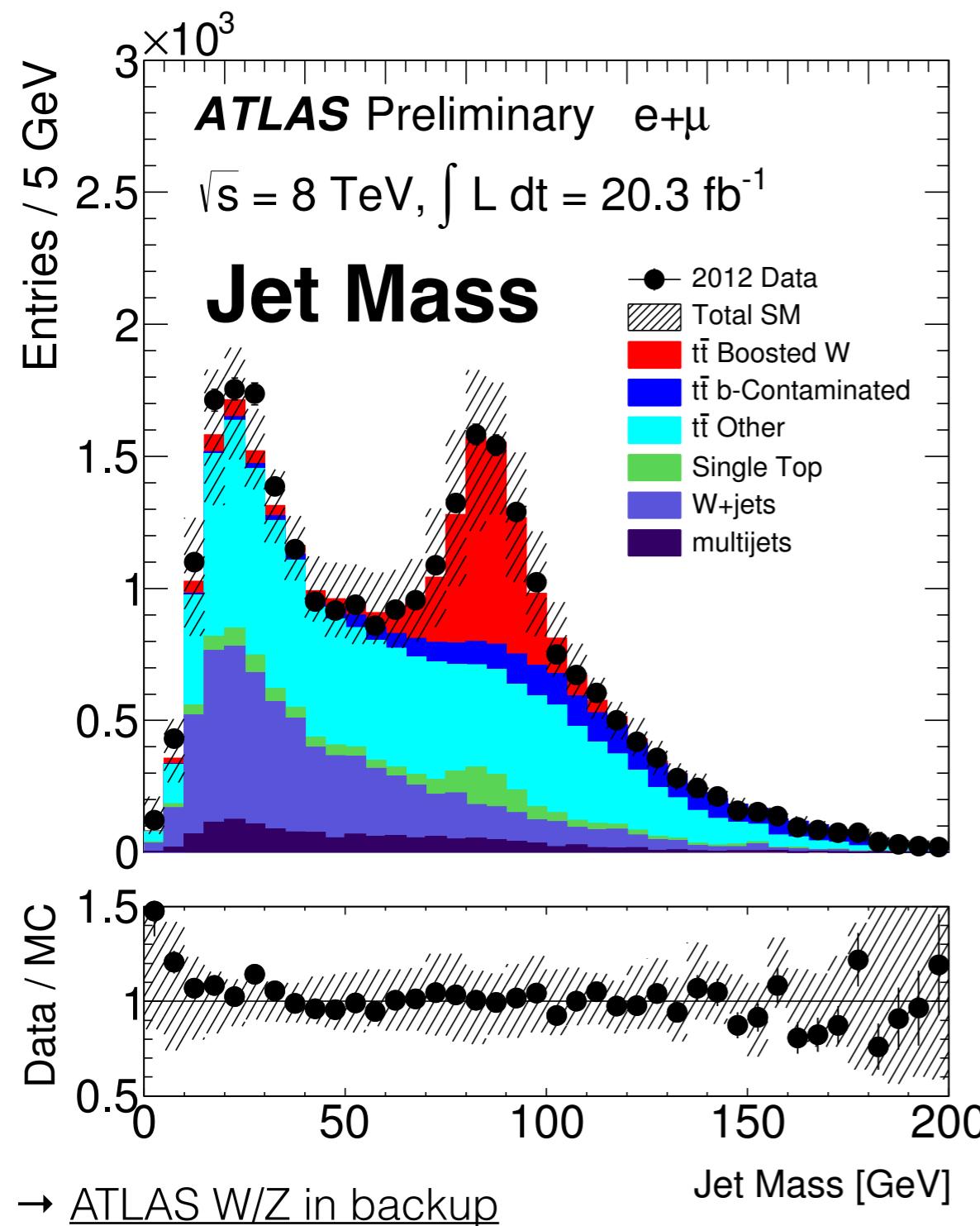
→ ATLAS Jet Charge in backup
 Question: accounting for PDFs, does jet charge depend on p_T ? (recent **theory calculation**: yes!)

$$\langle Q_i \rangle \approx \sum_f \alpha_{f,i} \bar{Q}_f (1 + c_f \log(p_{T,i}/\bar{p}_T))$$



Boson type tagging performance

Another use for jet charge (and jet mass and b-tagging):
 Distinguishing W bosons from Z bosons



Boson type tagging performance

Rejection of ~ 10 at
50% Z efficiency

Potential uses

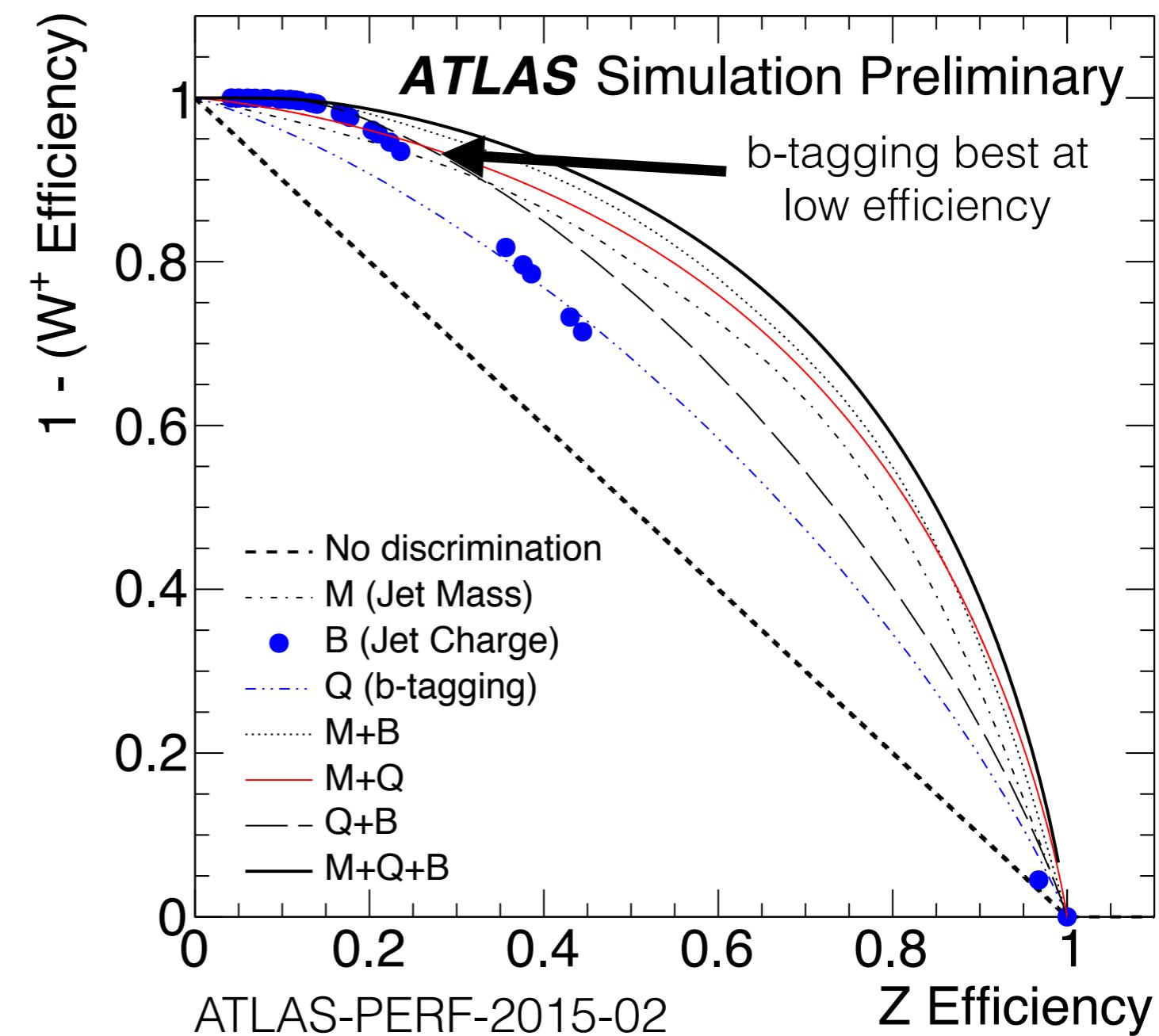
WZ/WW cross
section

Classifying diboson
resonances

Flavor-changing-
neutral currents

\rightarrow ATLAS W/Z in backup

Results: Performance curve

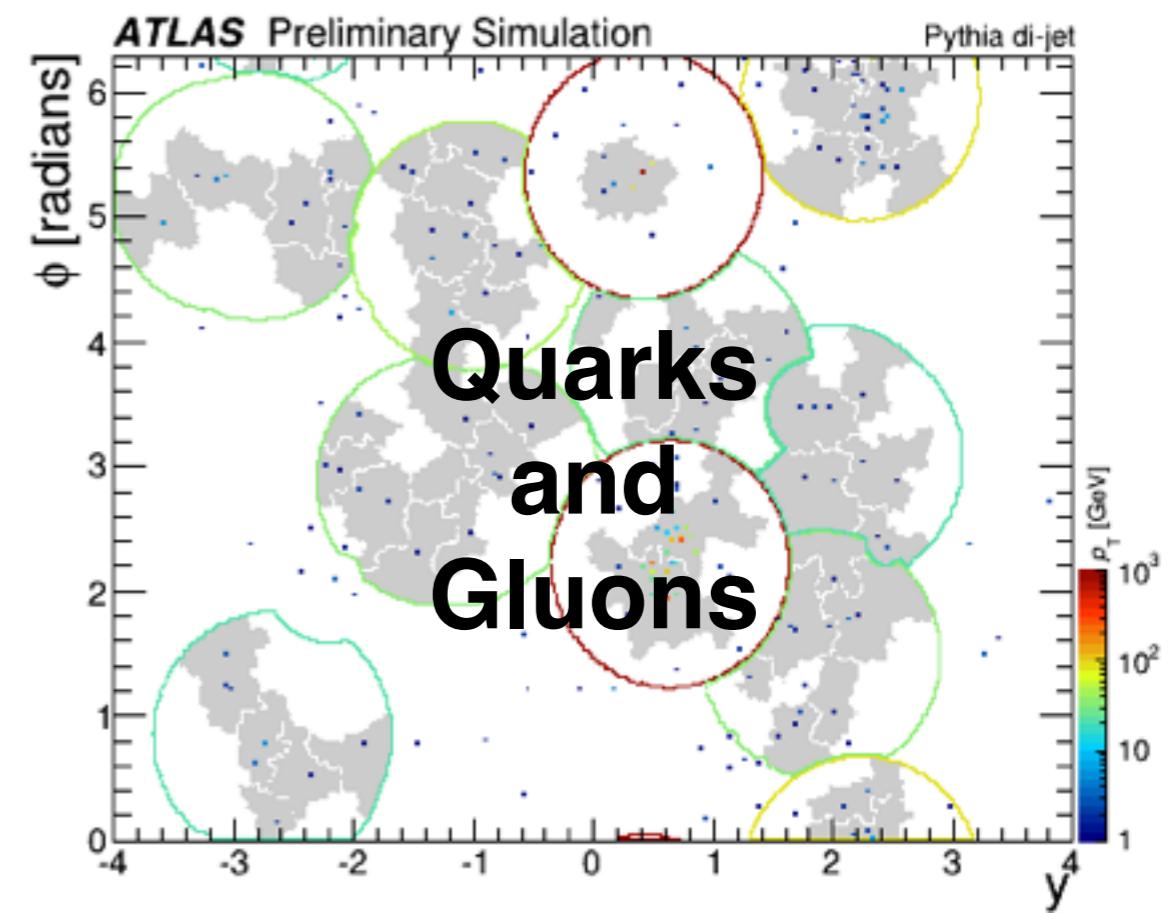
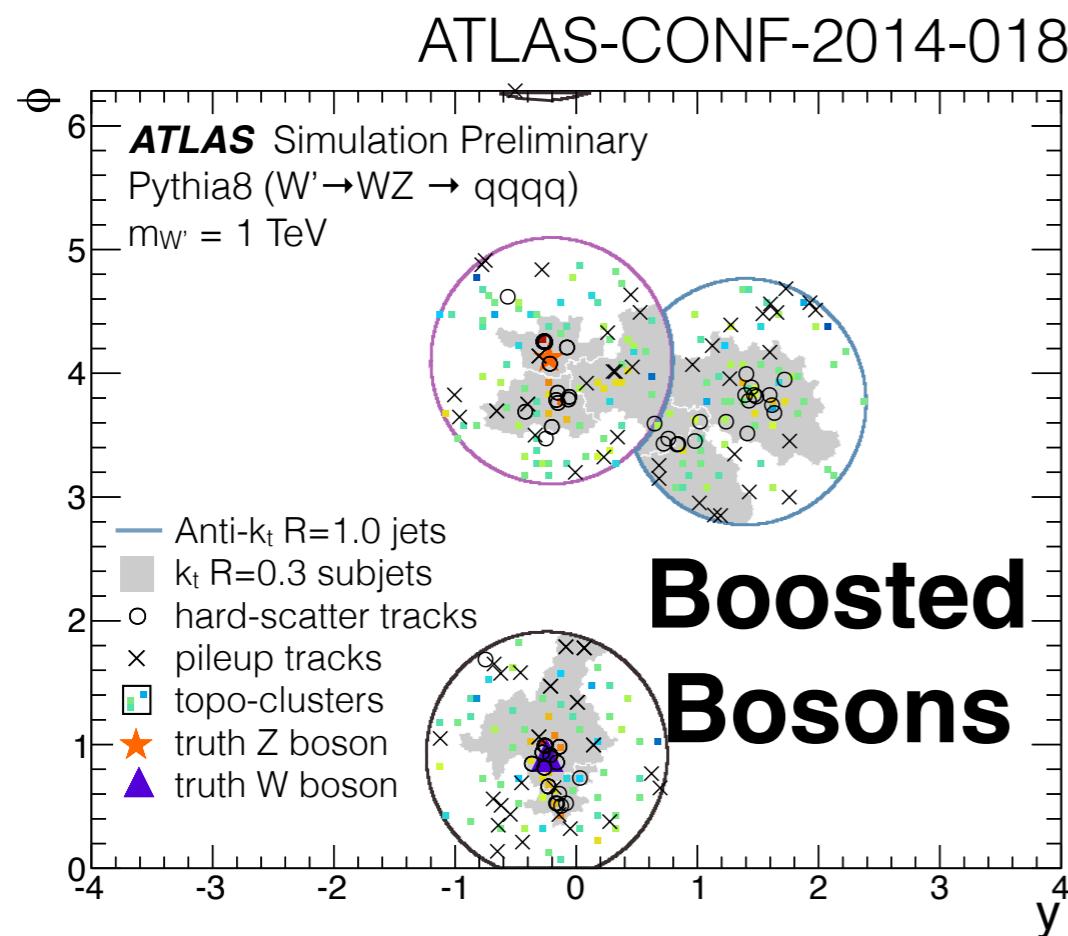


Mass the most powerful variable,
but gain from combining!

Tagging: W/Z/h/t versus quark/gluon jets

So far, focused on discriminating particles of the same type
 (boson versus boson, quark versus quark)

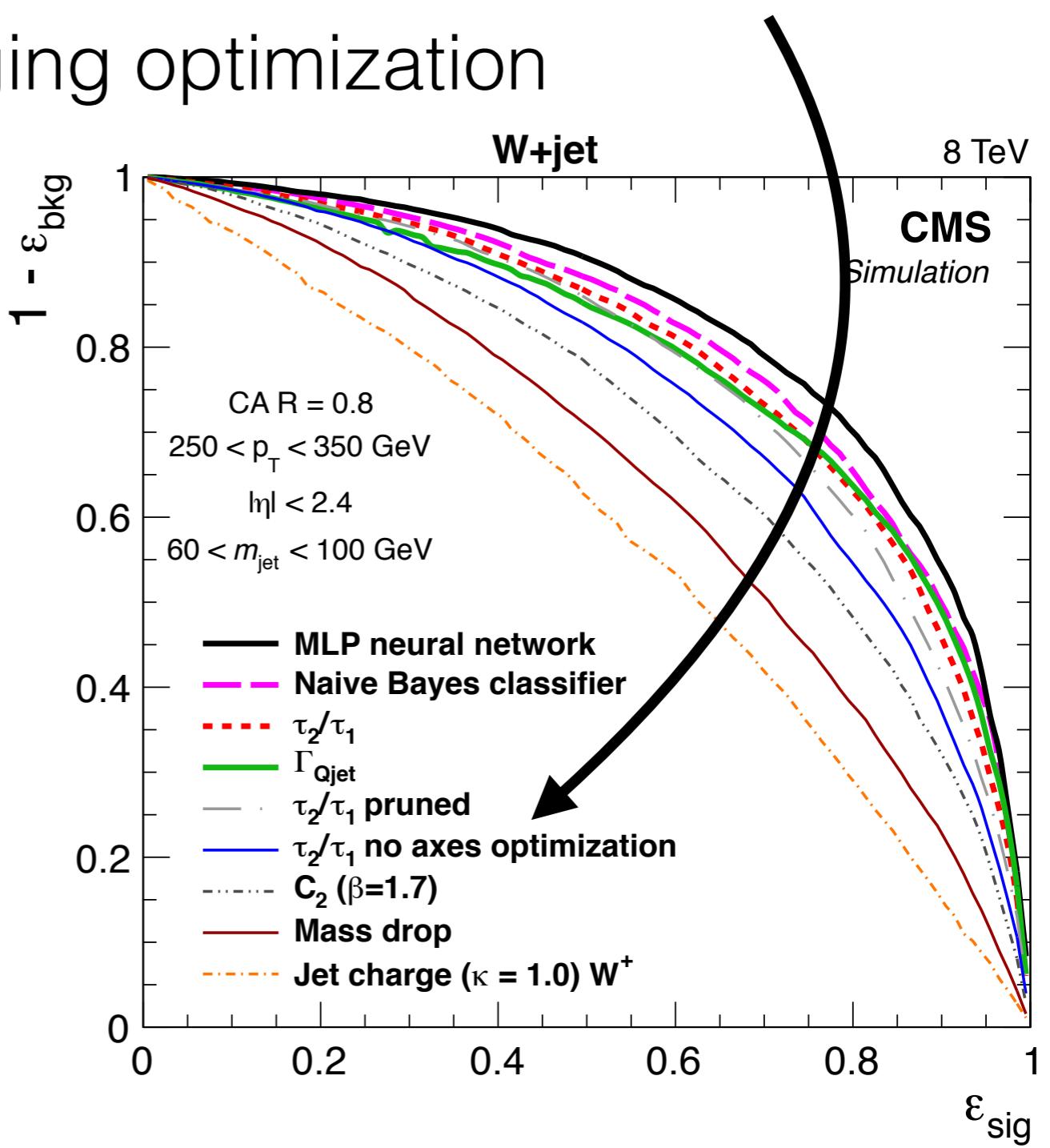
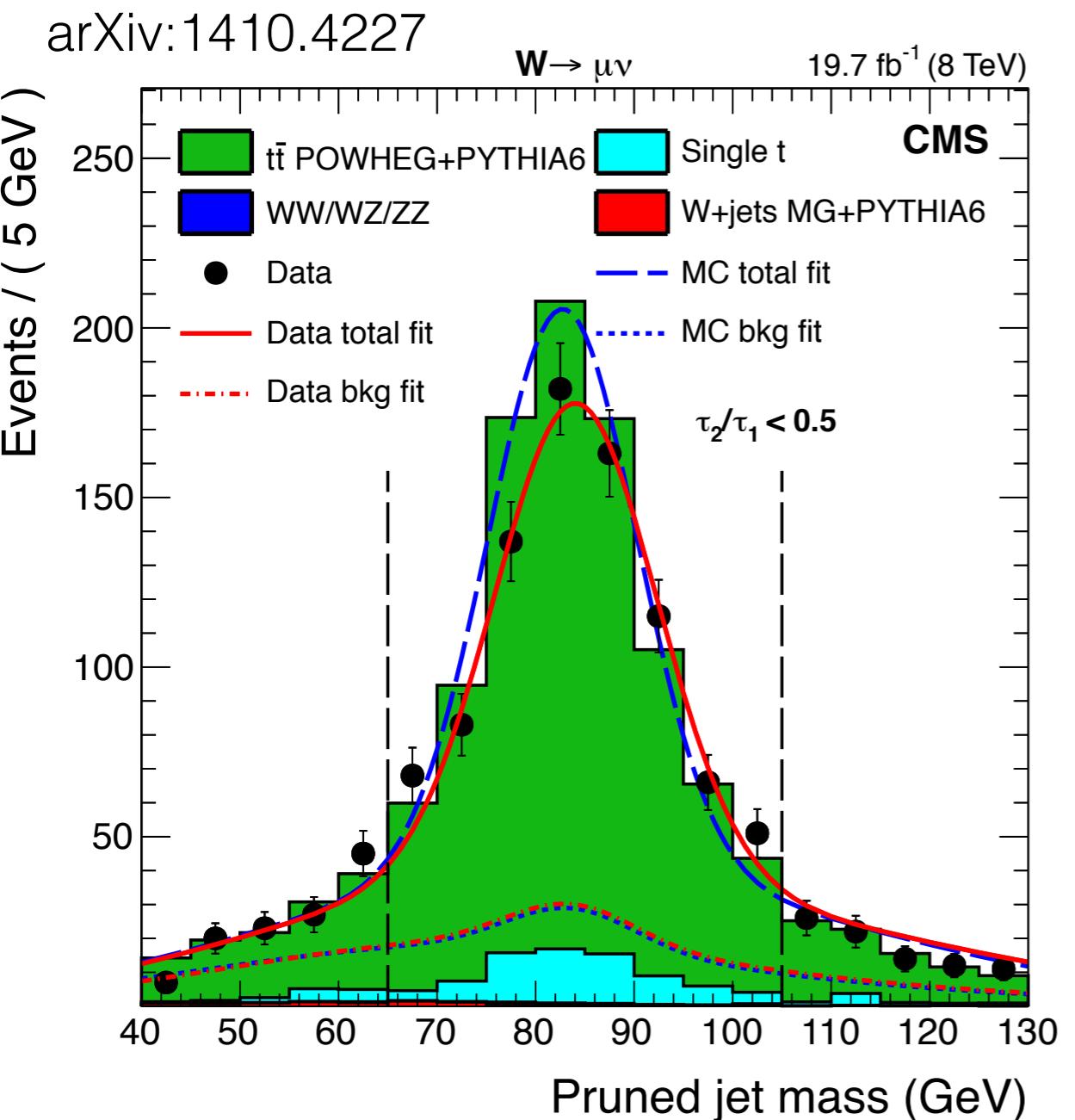
When a heavy particle (W/Z/h/t) is ***boosted***, jet substructure
 can improve over standard ***resolved*** techniques.



A lot of dedicated work to distinguish W/Z/h/t from
 quark/gluon jets. Just enough time to flash results.

W Tagging Performance

Both ATLAS and CMS have conducted extensive studies of W tagging optimization

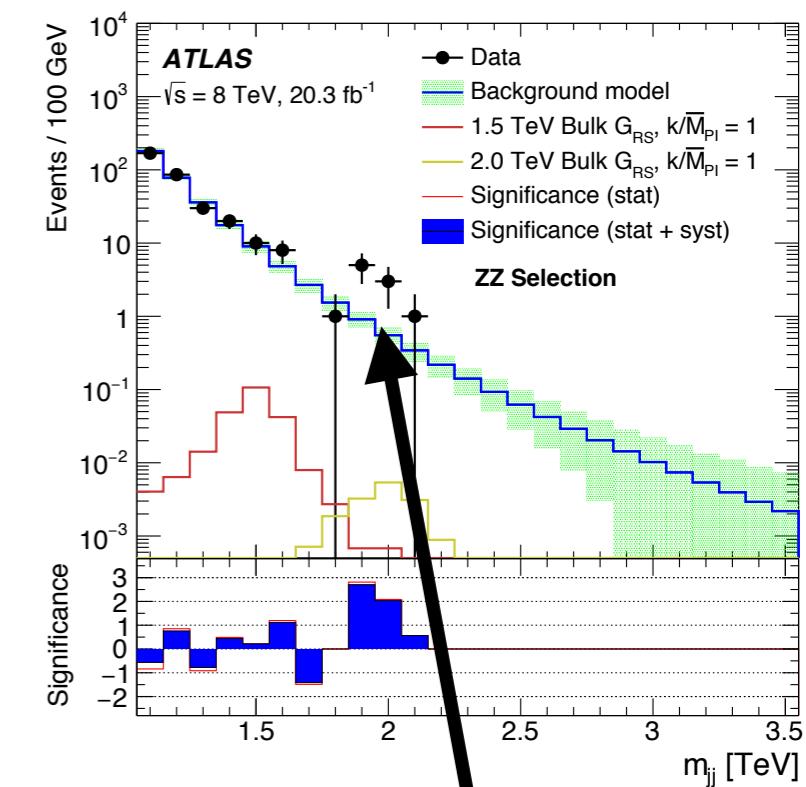
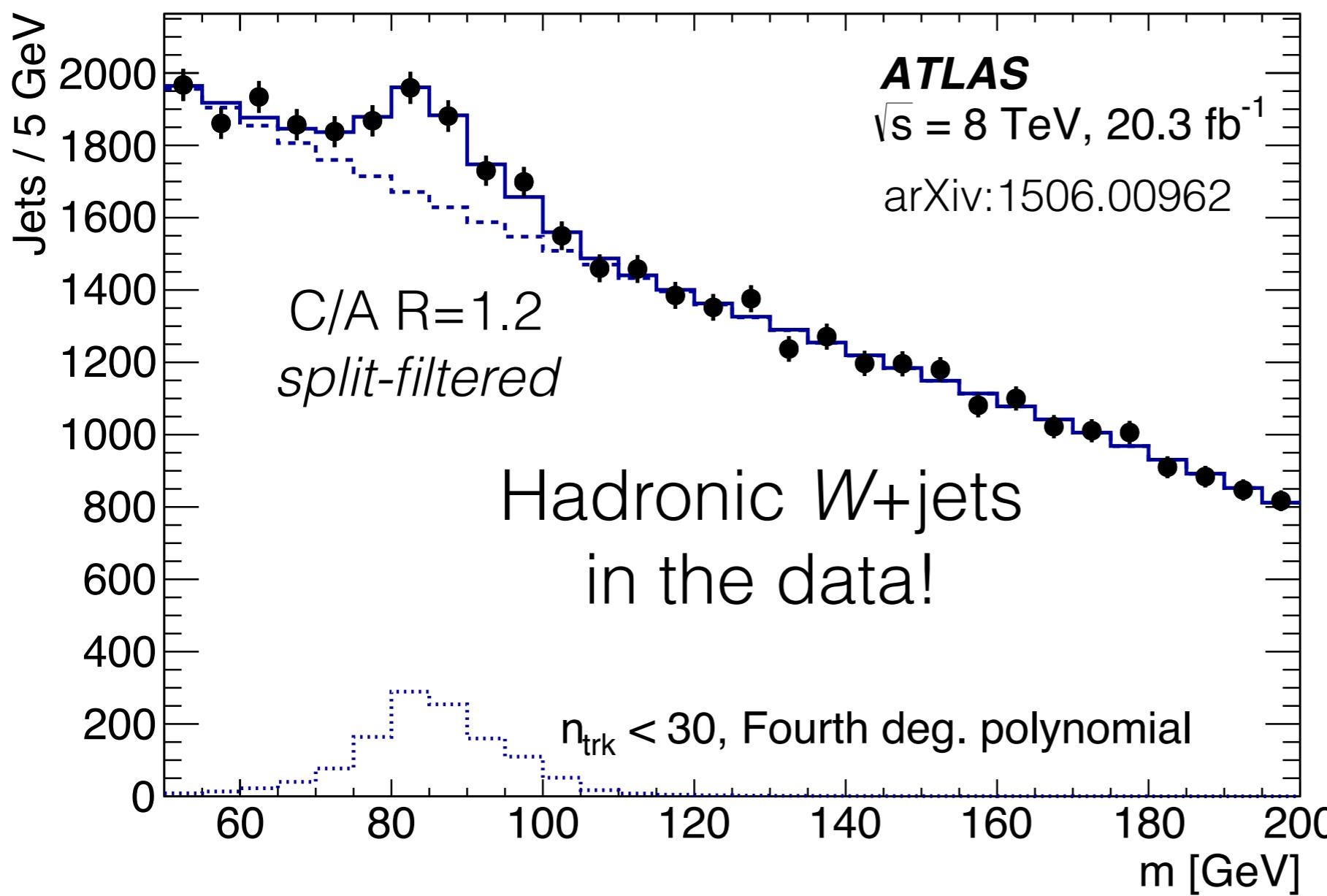


CMS has further measured the tagger efficiency in boosted W bosons from top quark events.

W Tagging in Action

Many uses of tagging boosted bosons for searches; e.g. the

ATLAS diboson resonance search.

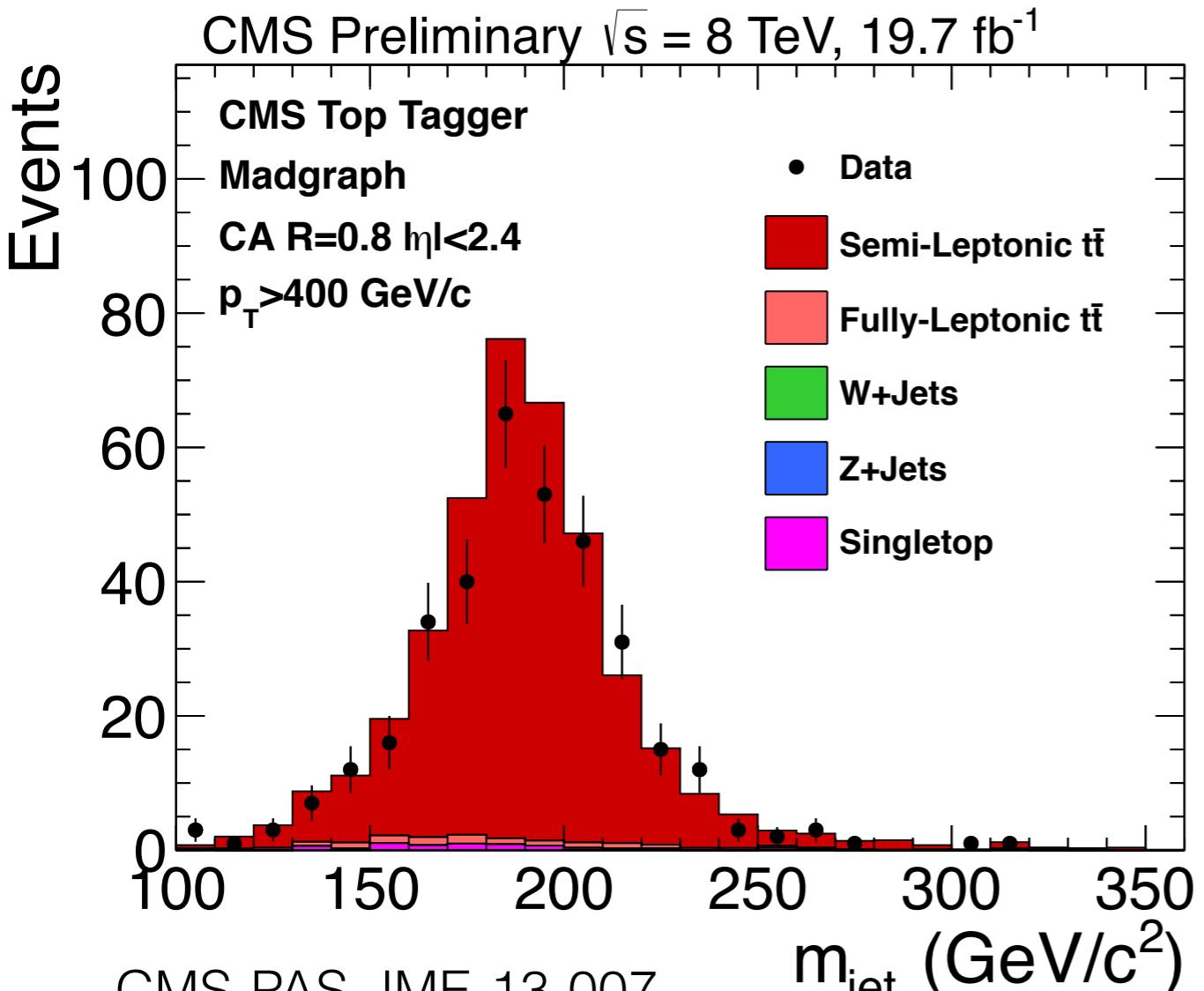


Stay tuned for Run II!

Tagger: subject momentum balance, jet mass, and n_{track}

Top Quark Tagging Performance

There are more handles for top tagging due to its three-prong structure which includes b-quarks (subjet b-tagging!).

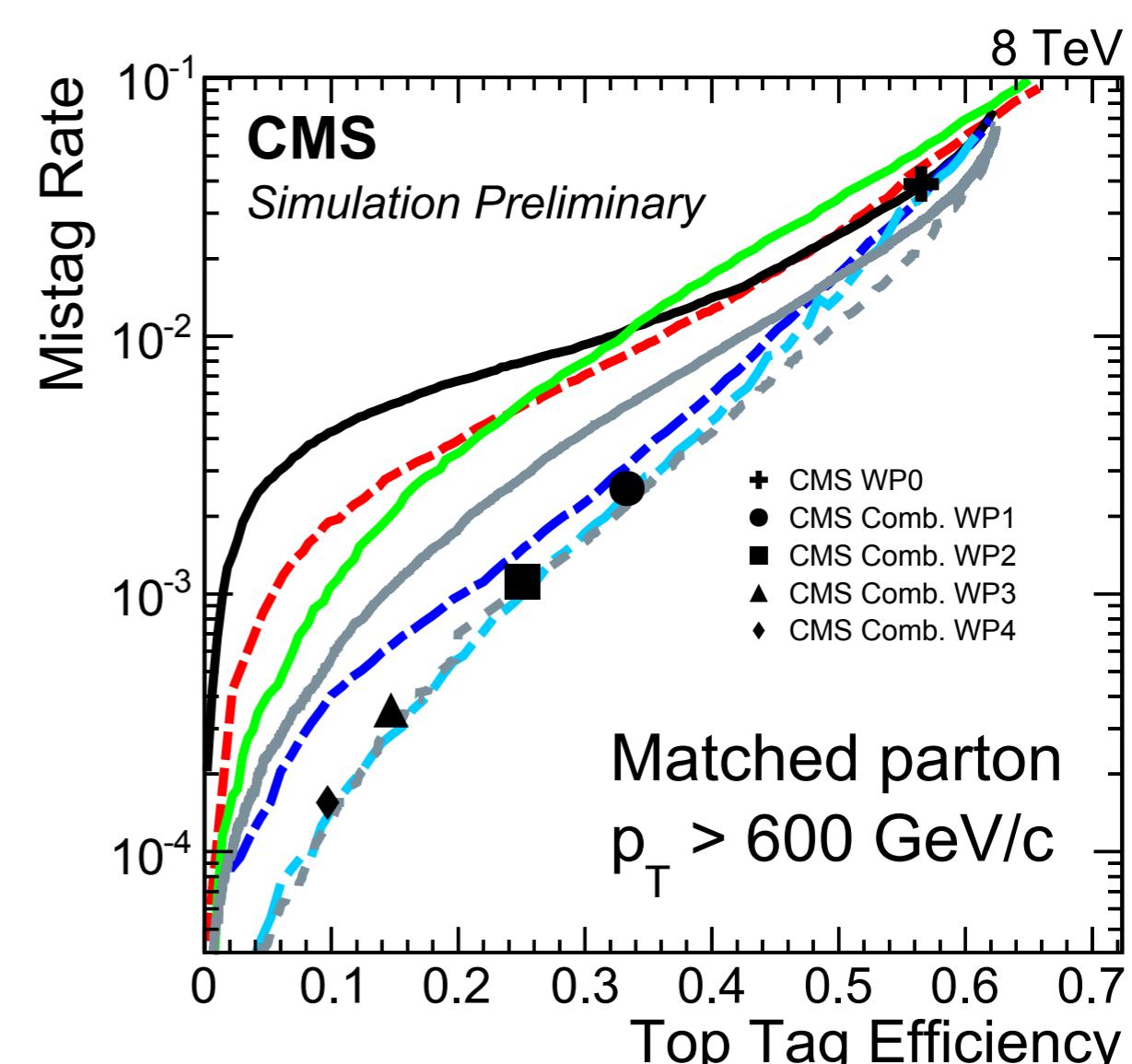


— CMS Top Tagger

- - - subjet b-tag

— N-subjettiness ratio τ_3/τ_2

- - - CMS + subjet b-tag

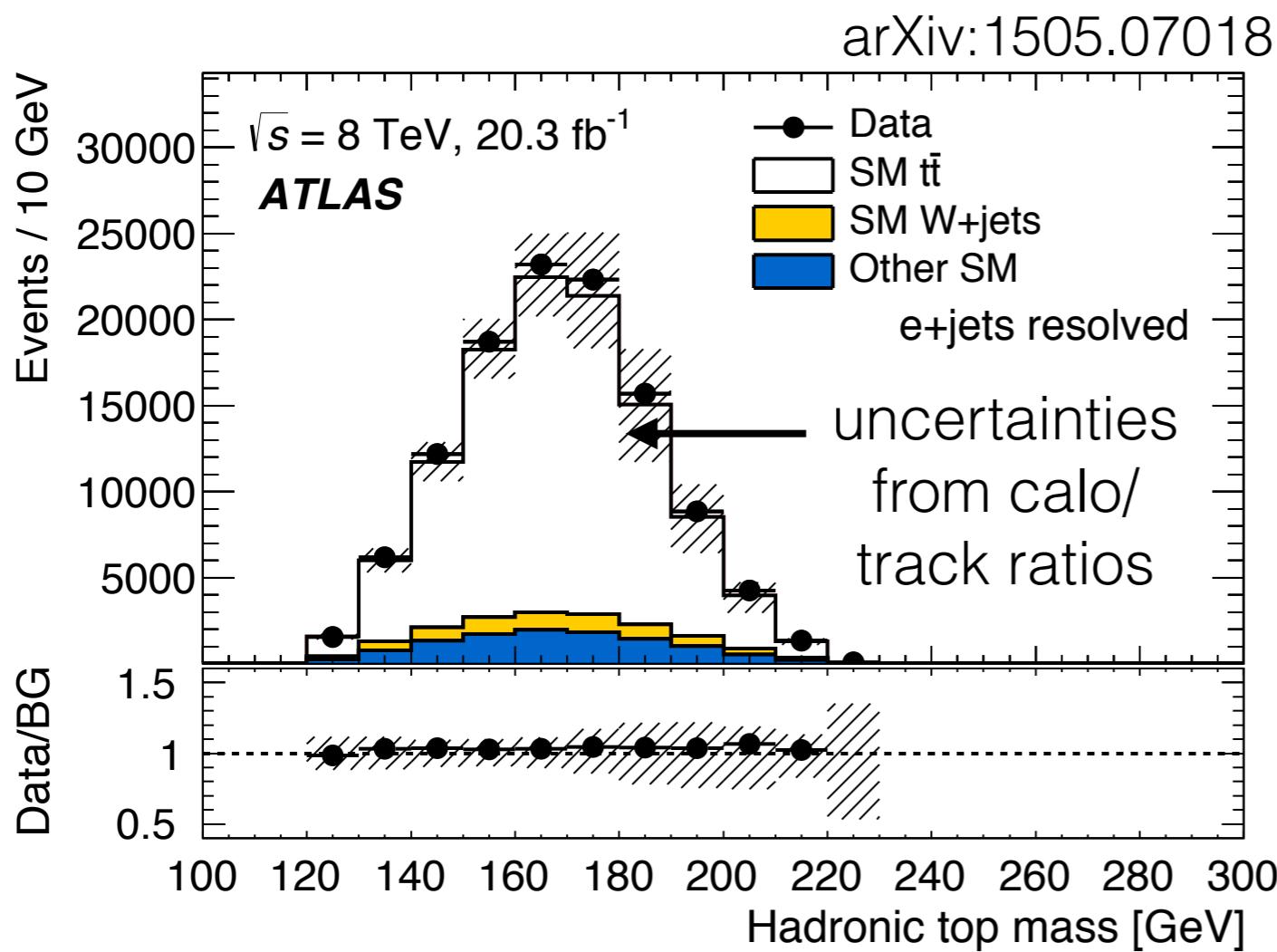


- - - CMS + $\tau_3/\tau_2 +$ subjet b-tag

— Shower deconstruction

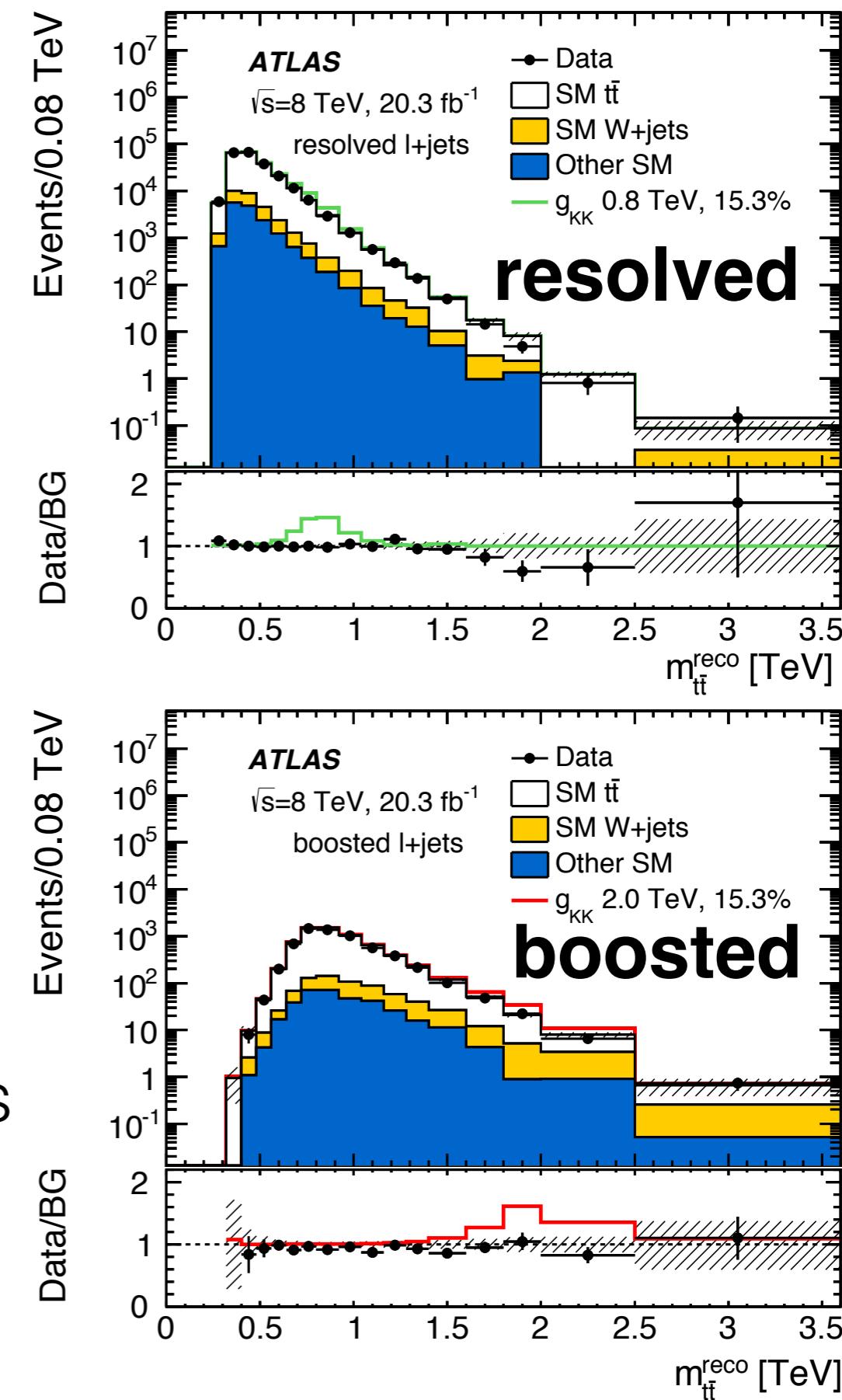
- - - Shower deconstruction + subjet b-tag

Top Quark Tagging in Action



Top quark pair resonance search

Tagger: k_t splitting scale and jet mass
careful treatment of electrons-in-jets!

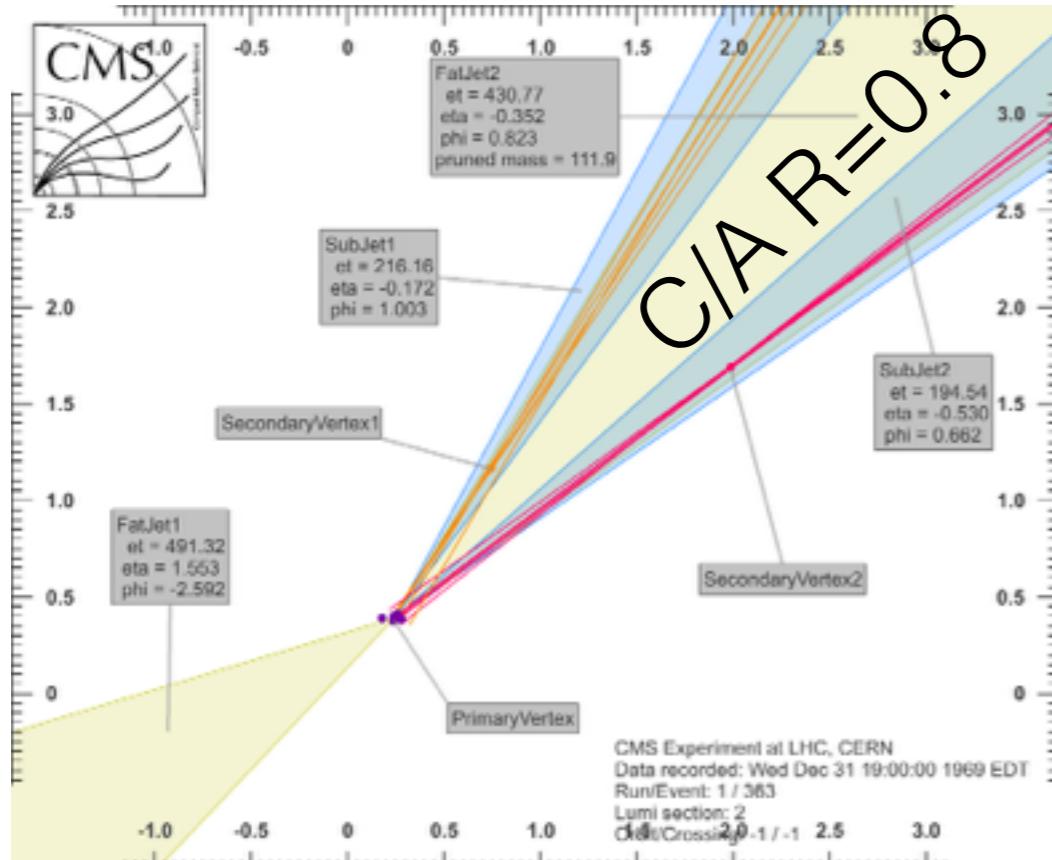


Higgs Tagging Performance

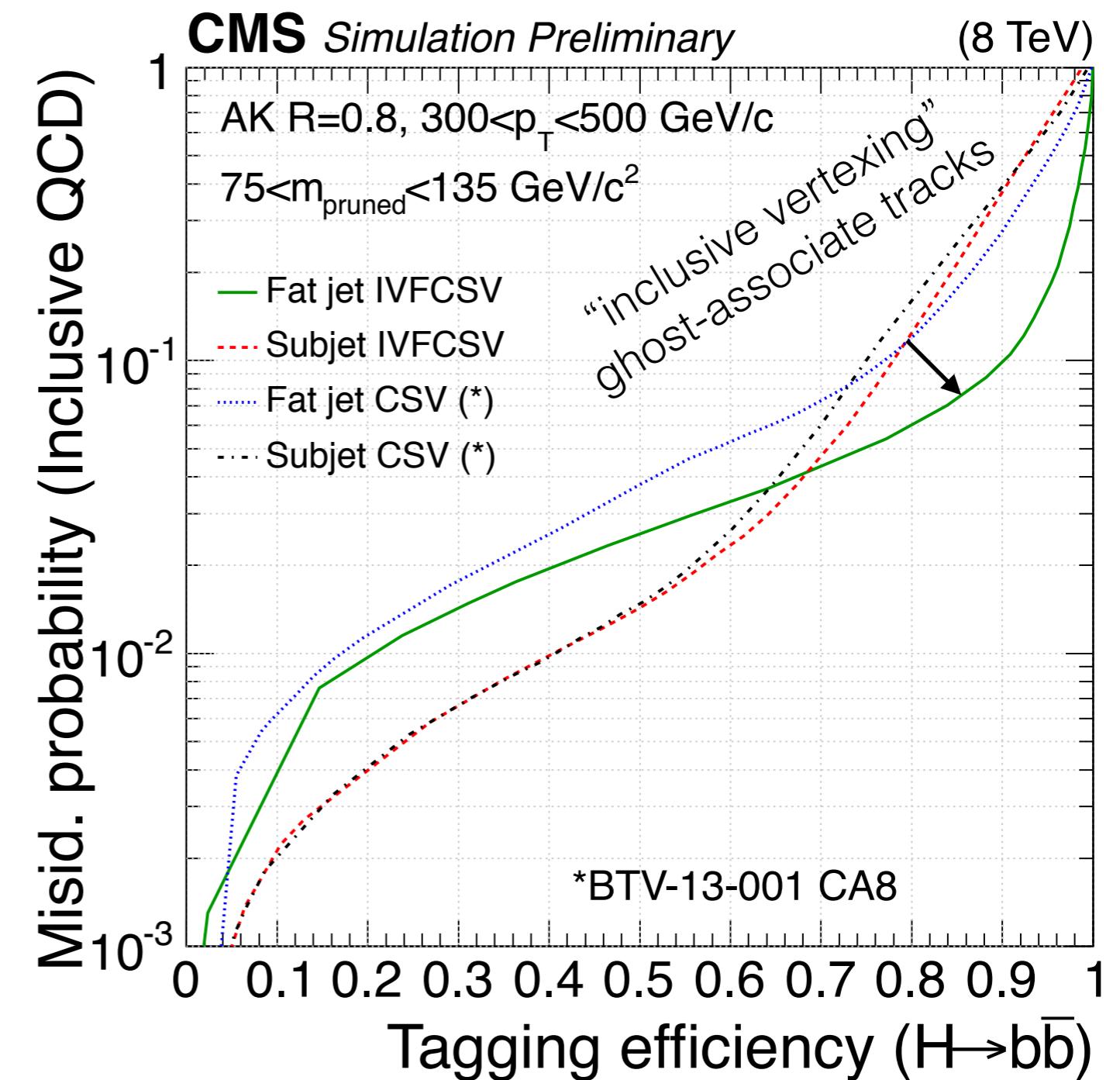
The key is subjet (double) b -tagging

CMS-PAS-BTV-13-001

$\text{HH} \rightarrow b\bar{b}b\bar{b}$

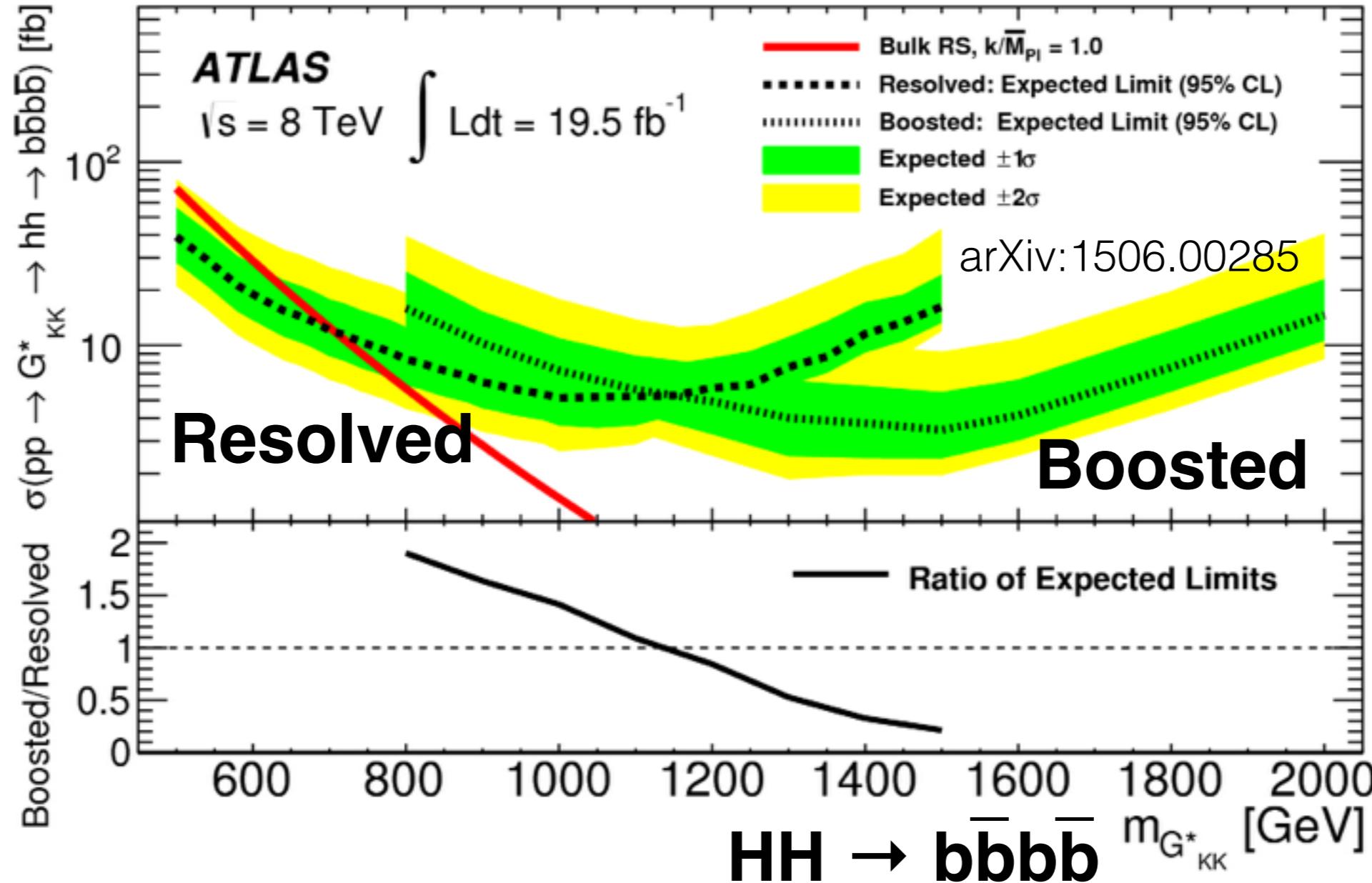


Challenge: select axes correlated with the b -hadron direction - use the last jet clustering step



except for very high eff., subjet b -tagging outperforms fat jet b -tagging

Higgs Tagging in Action



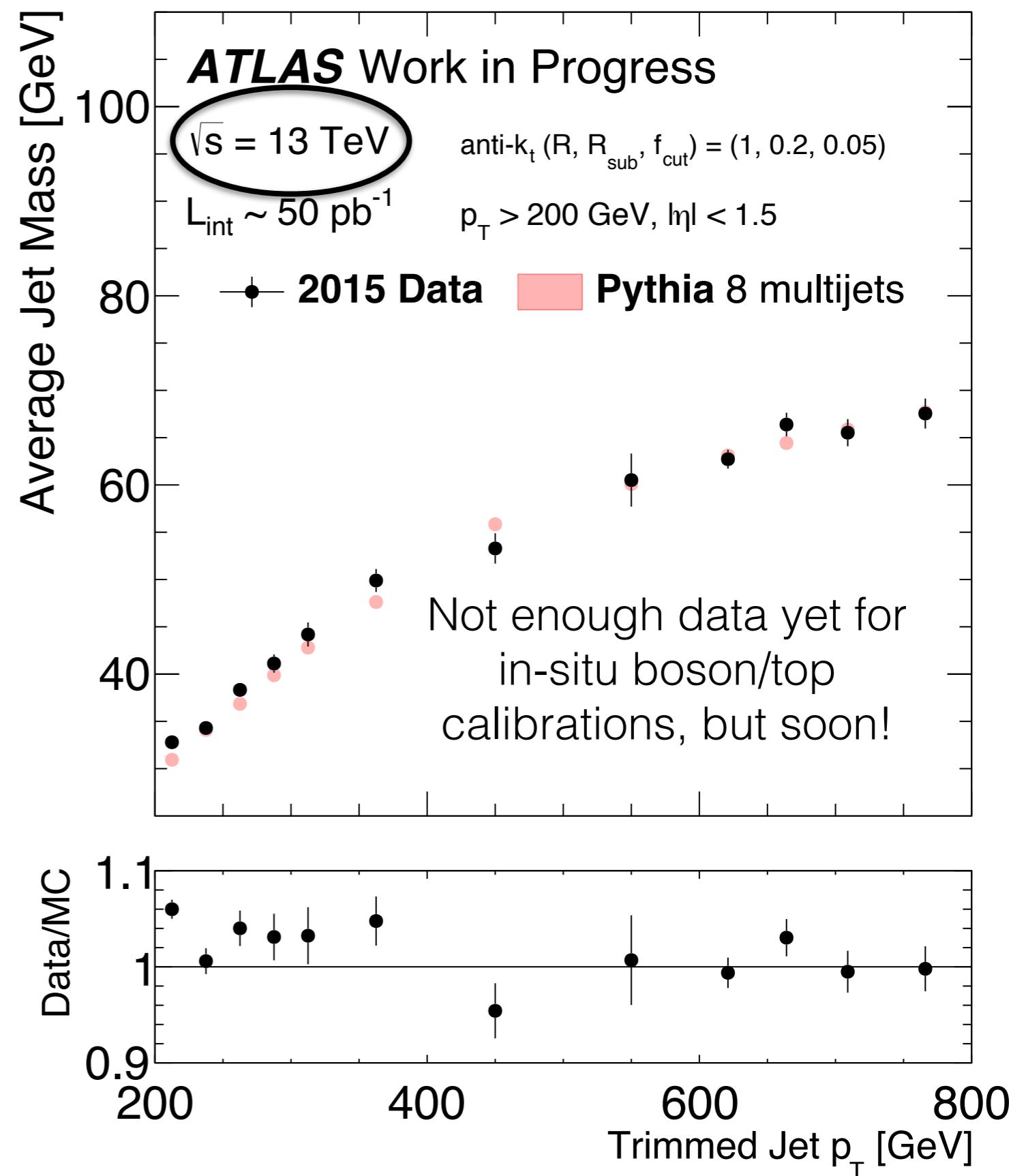
Tagger: trimmed jet mass and ($R=0.3$) track-jet b-tagging

track jets are the ATLAS approach to a calo jet-independent and b-hadron direction correlated algorithm

Outlook

Many sophisticated and powerful techniques already tested and tried in the 8 TeV data.

Gearing up now for boosted object tagging and substructure studies at 13 TeV!

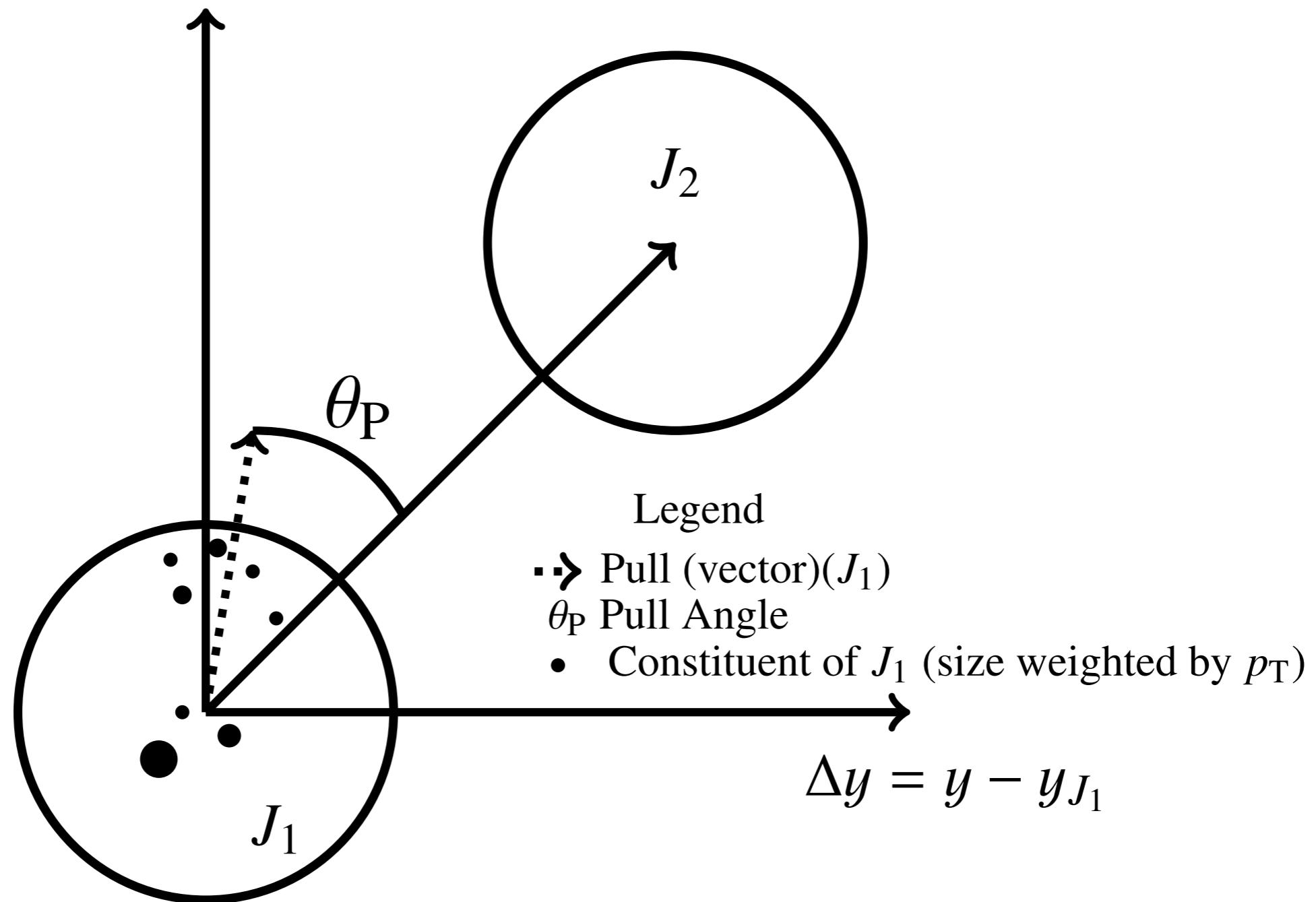


BACKUP

Colorflow Backup

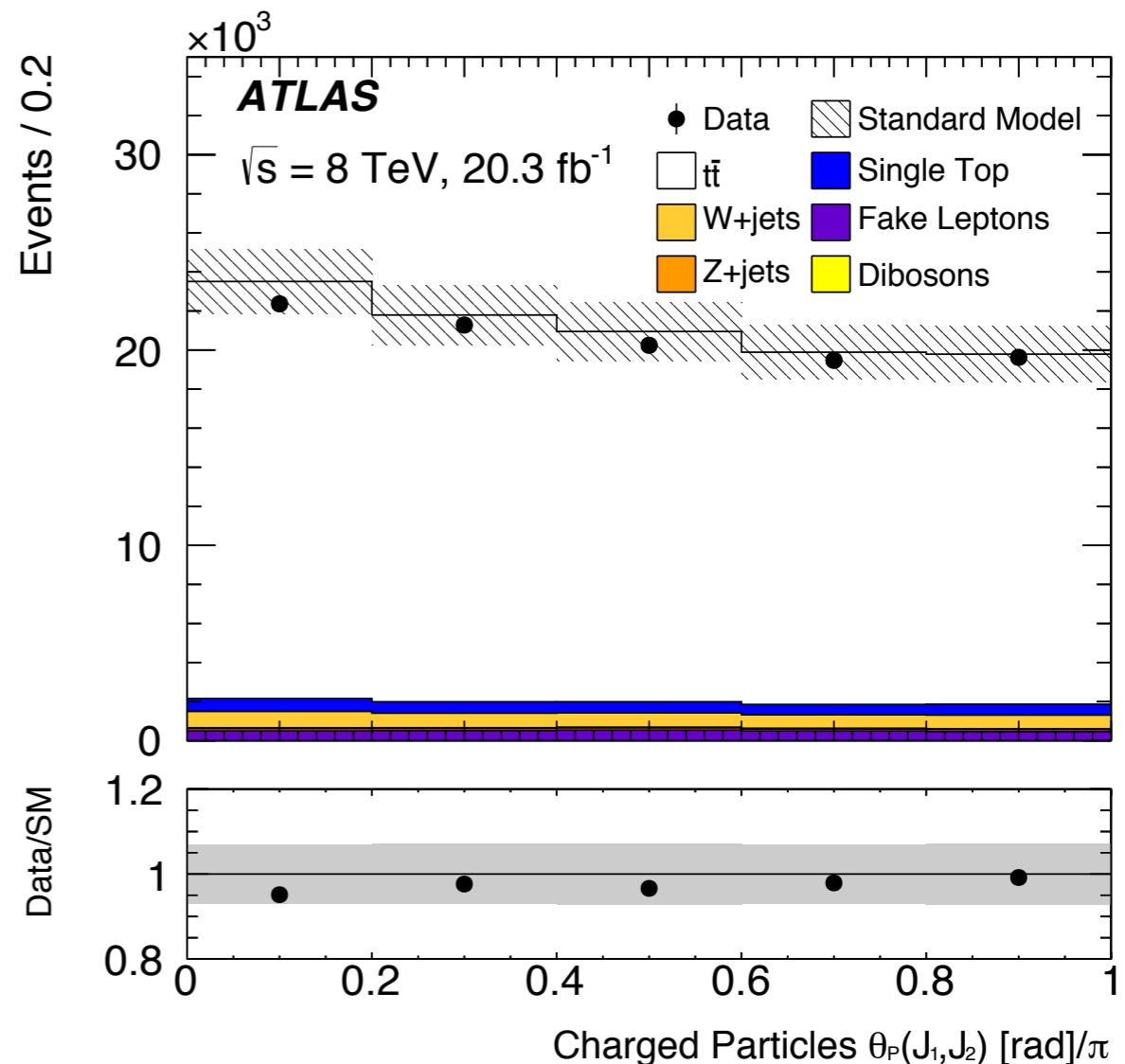
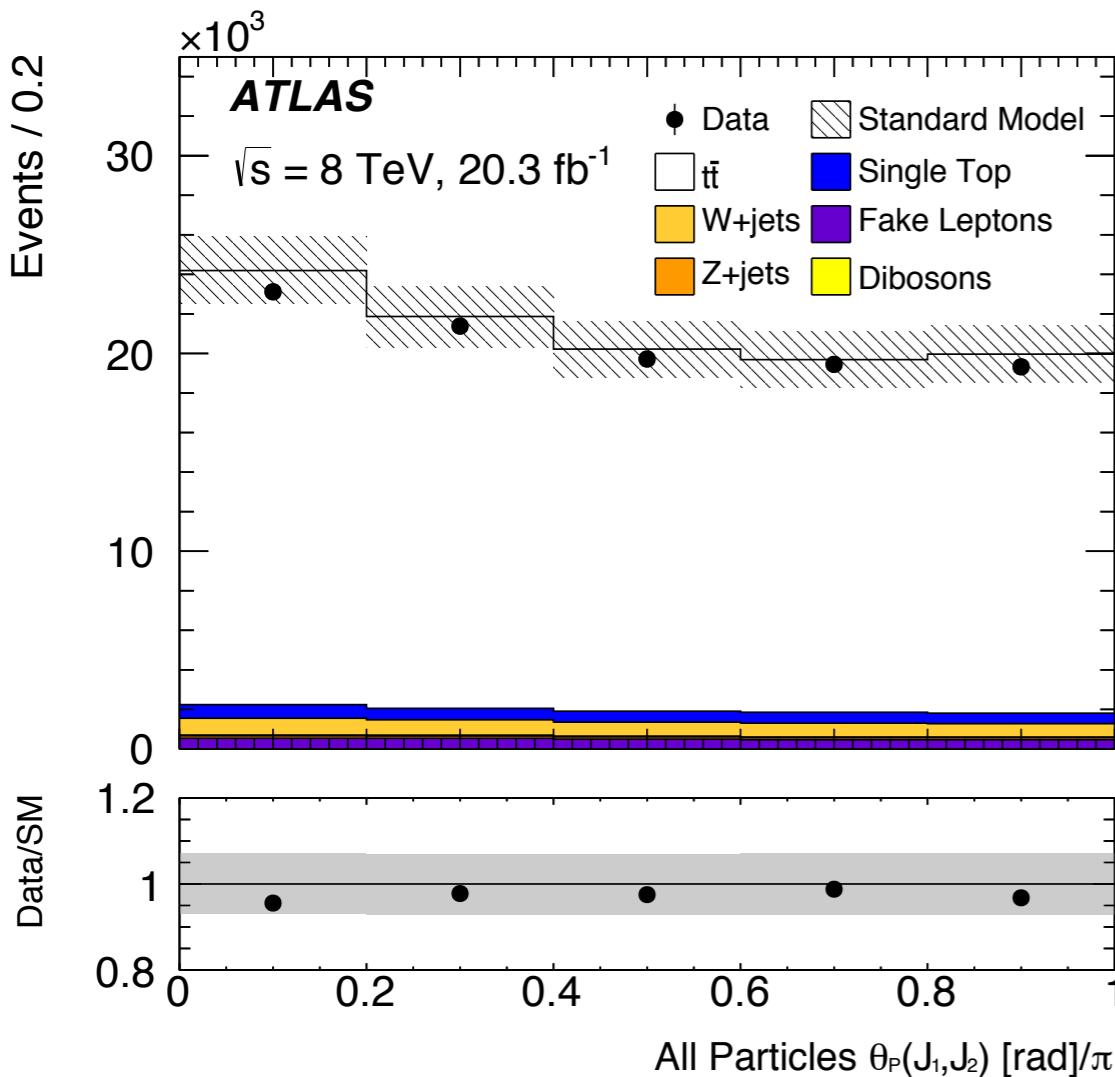
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/>

$$\Delta\phi = \phi - \phi_{J_1}$$



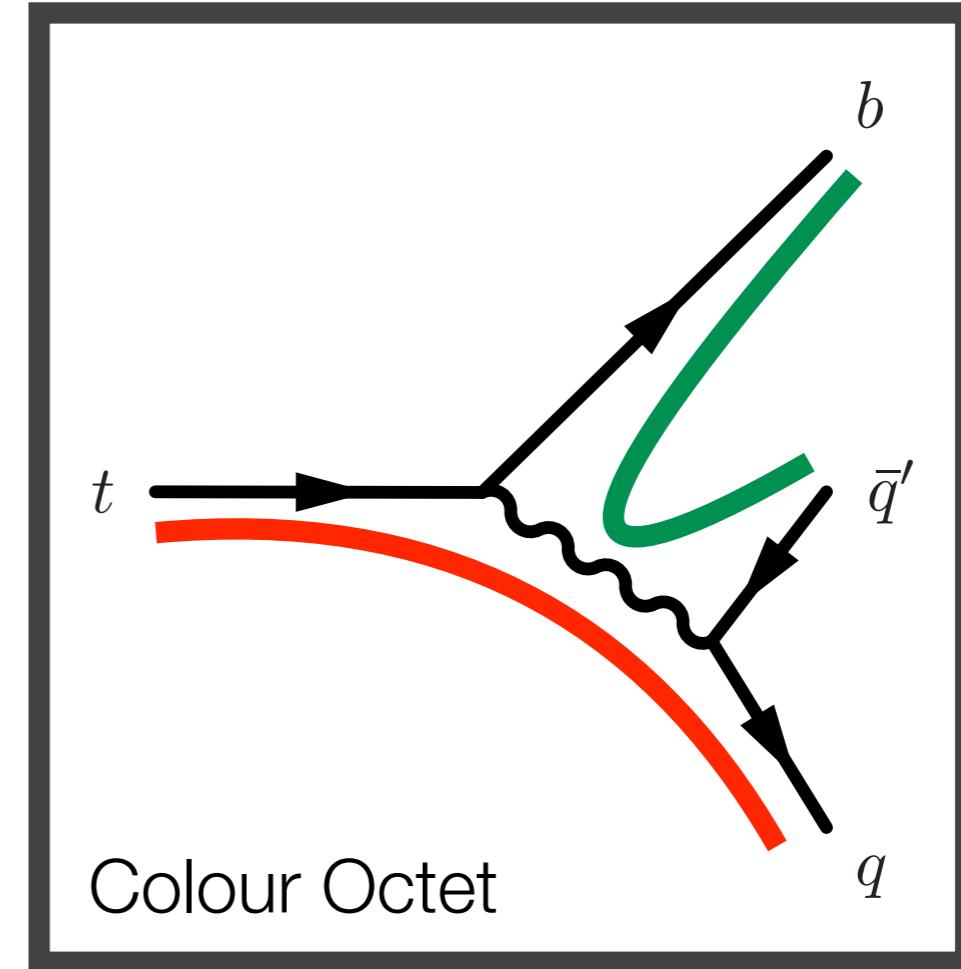
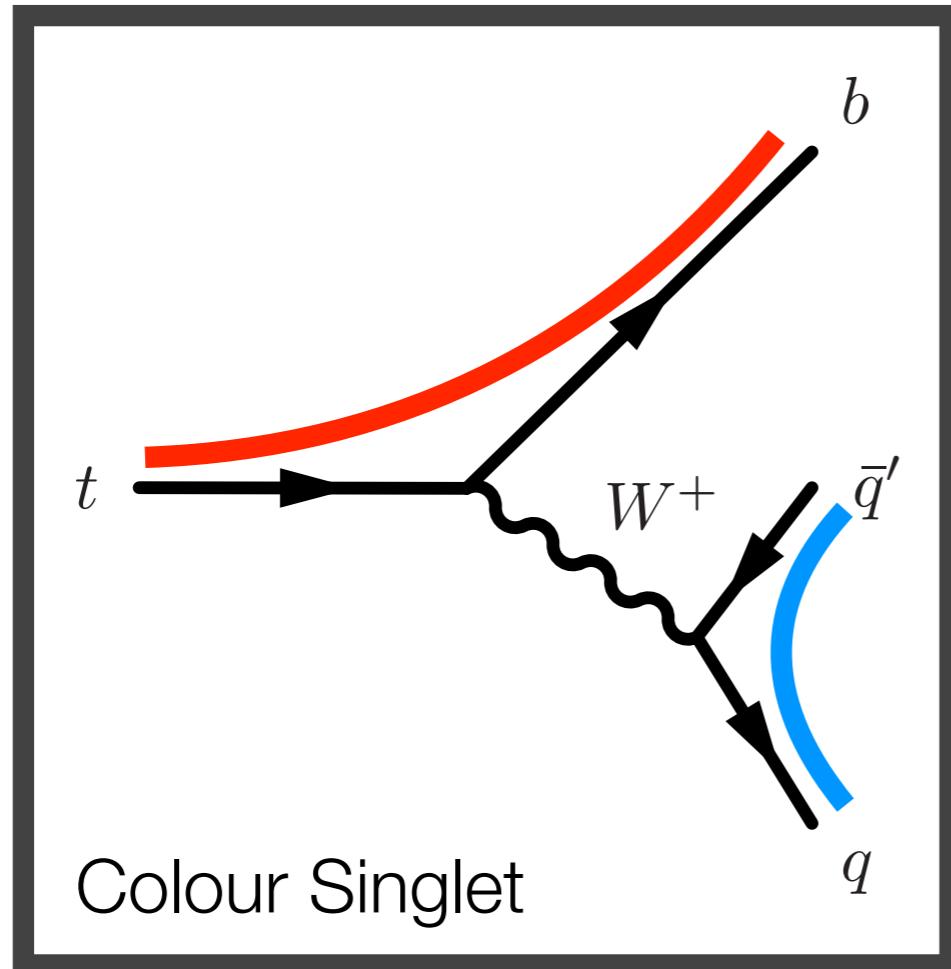
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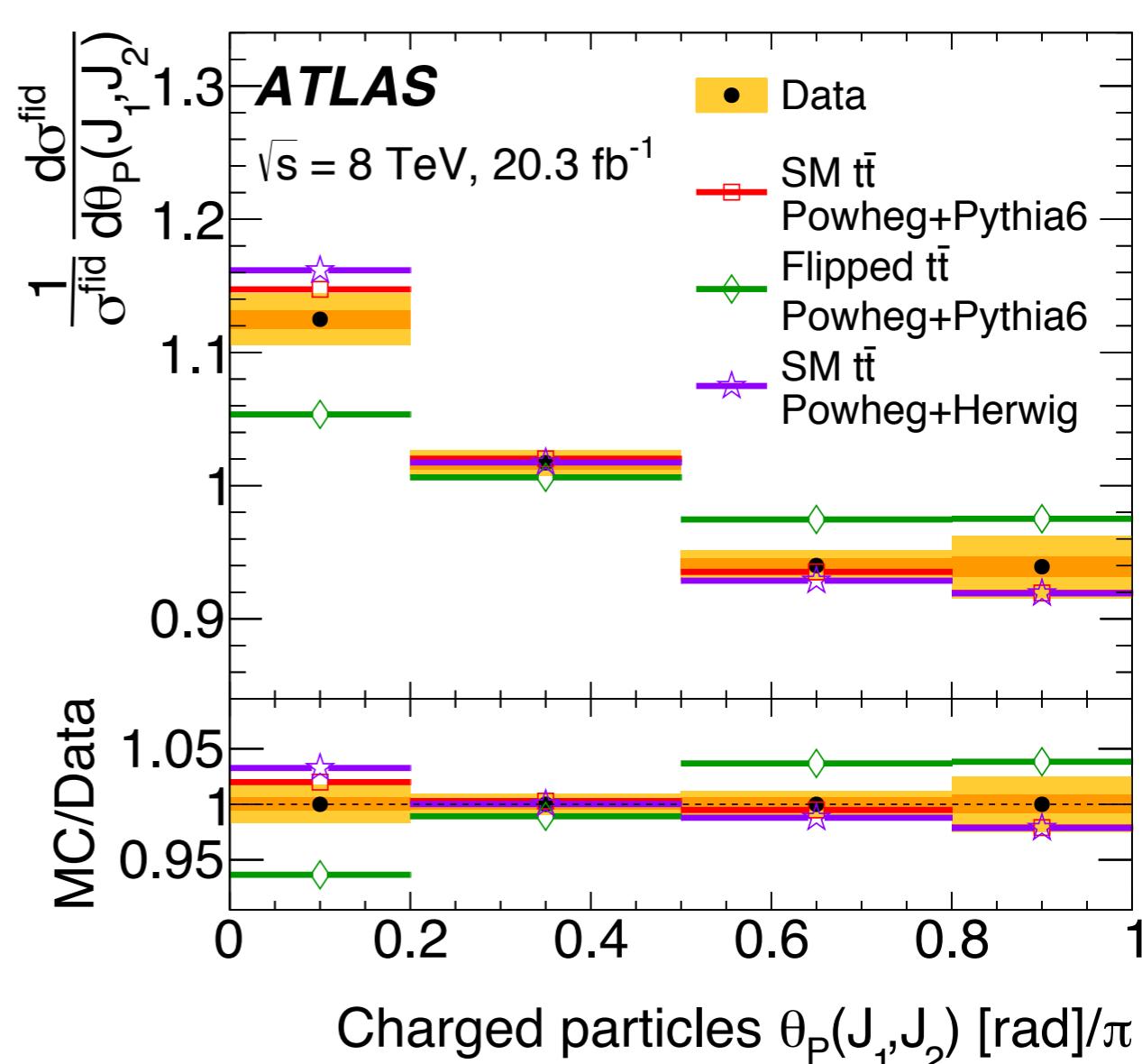
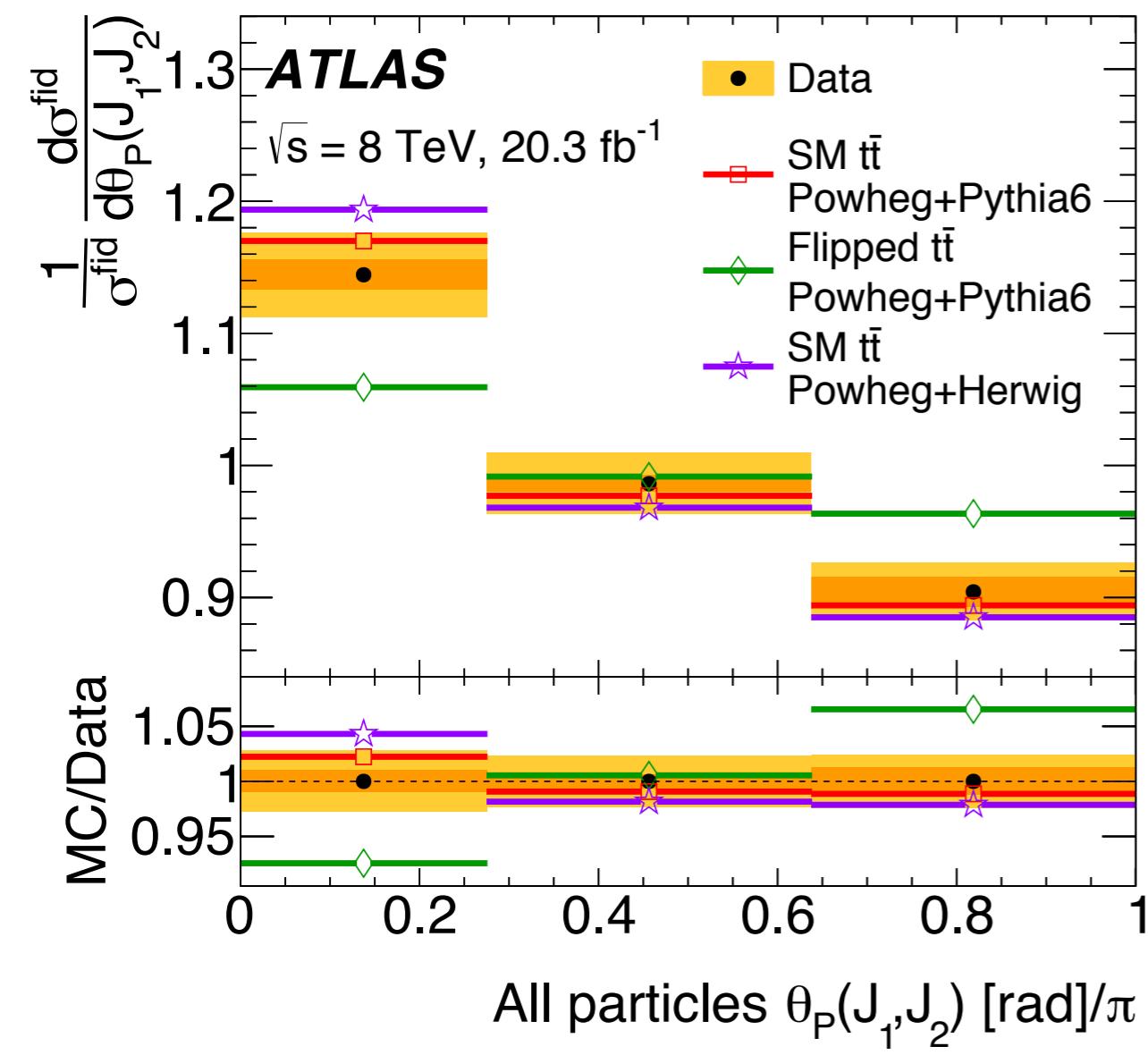
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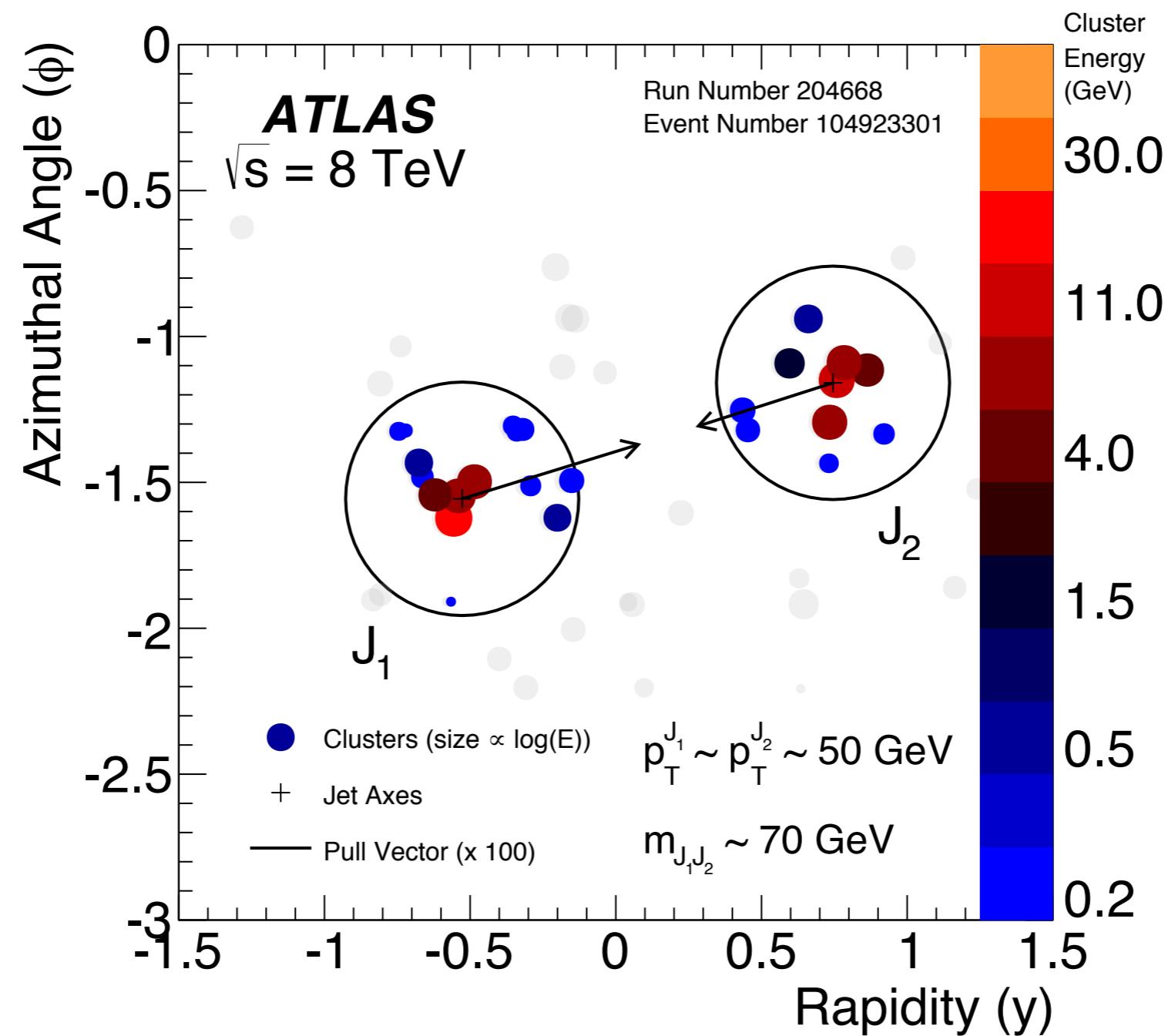
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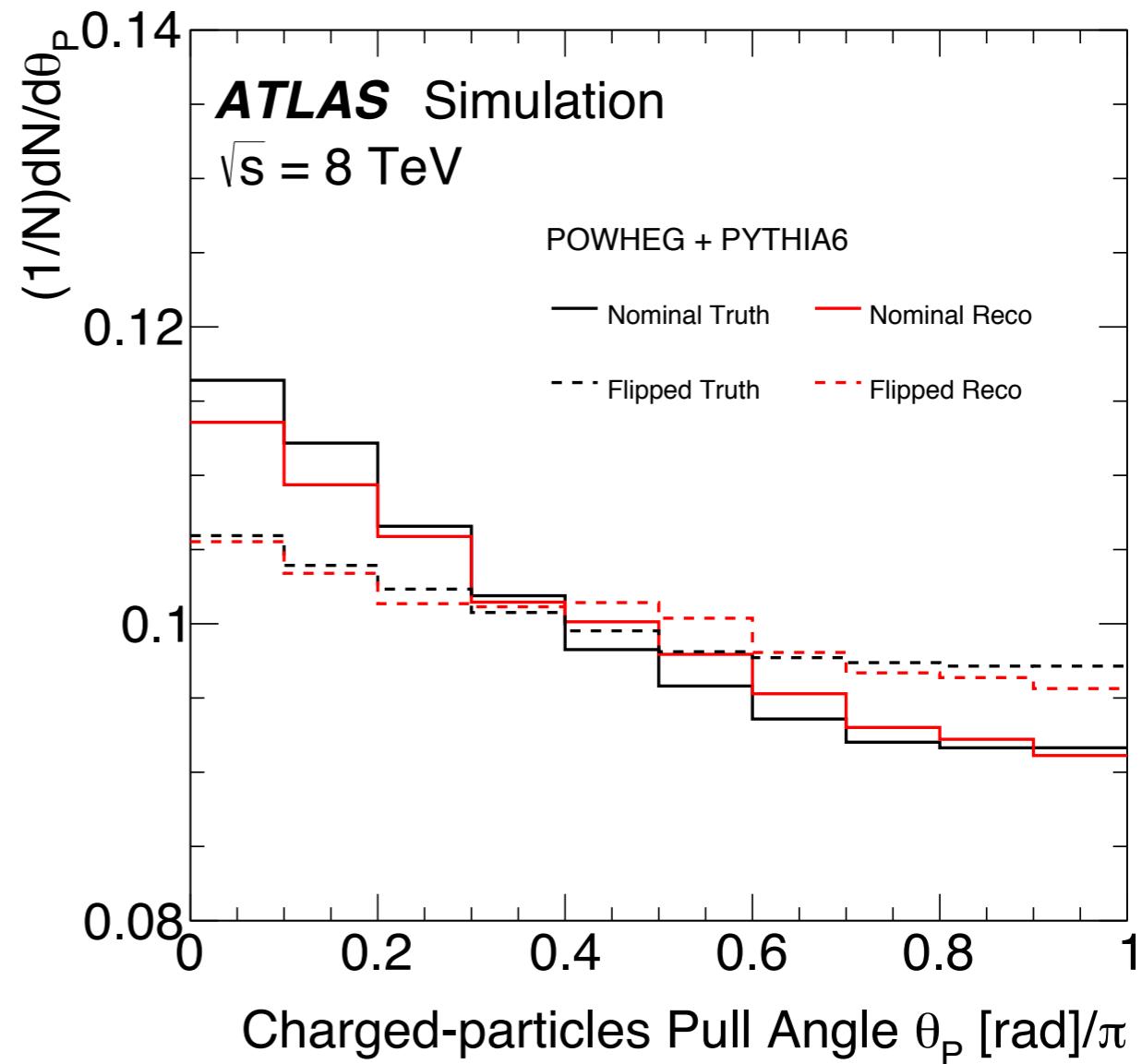
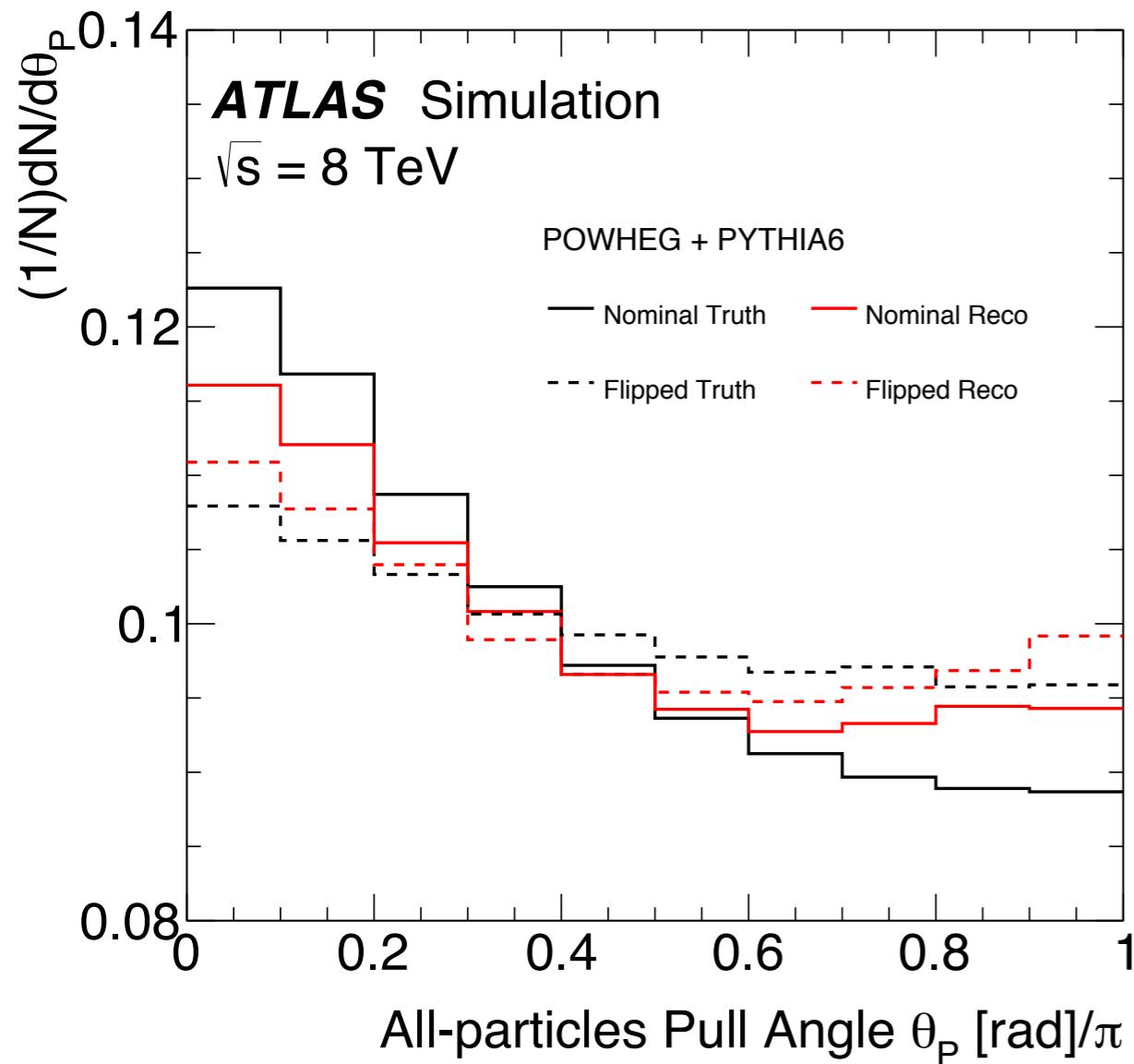
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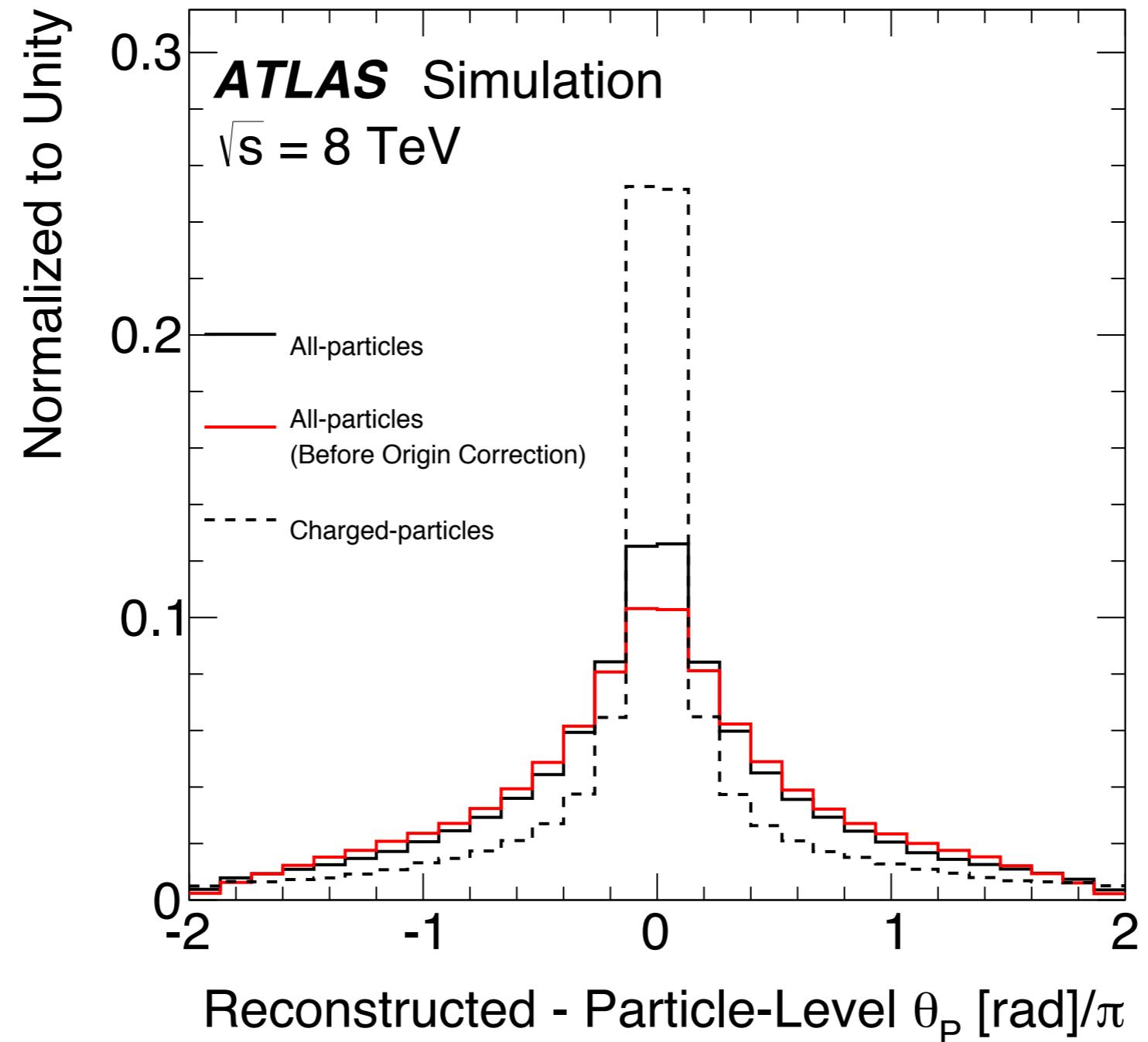
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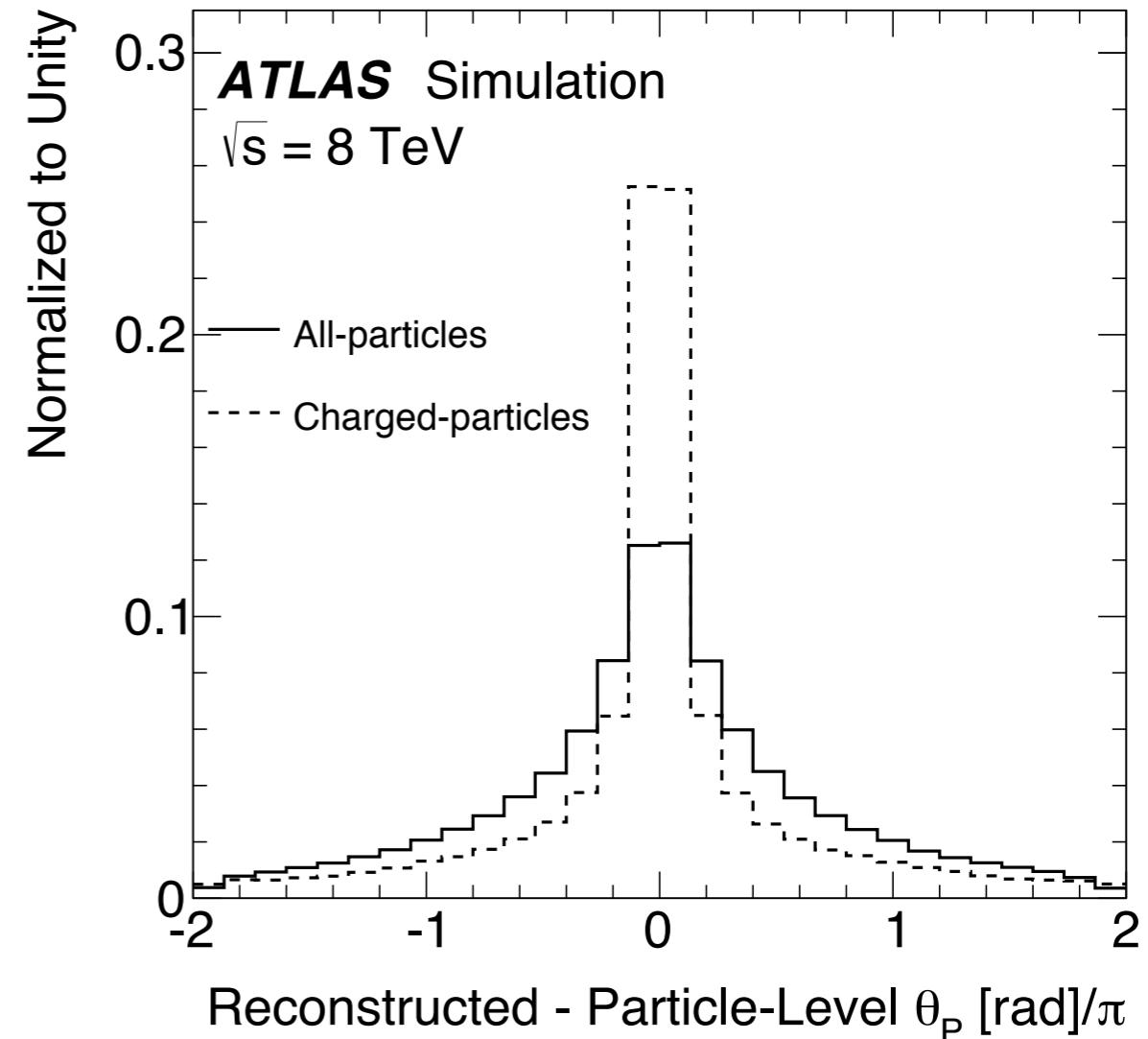
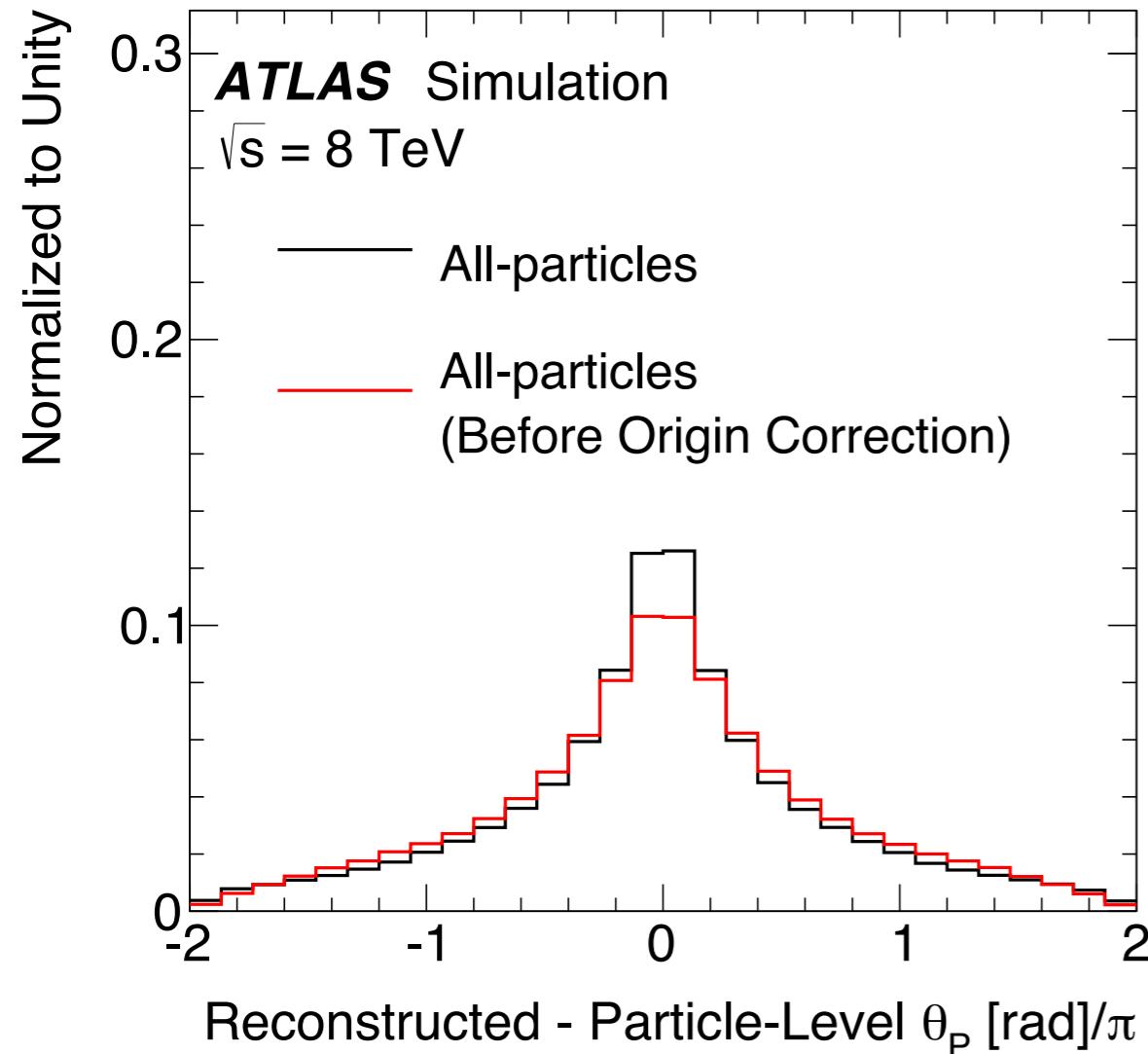
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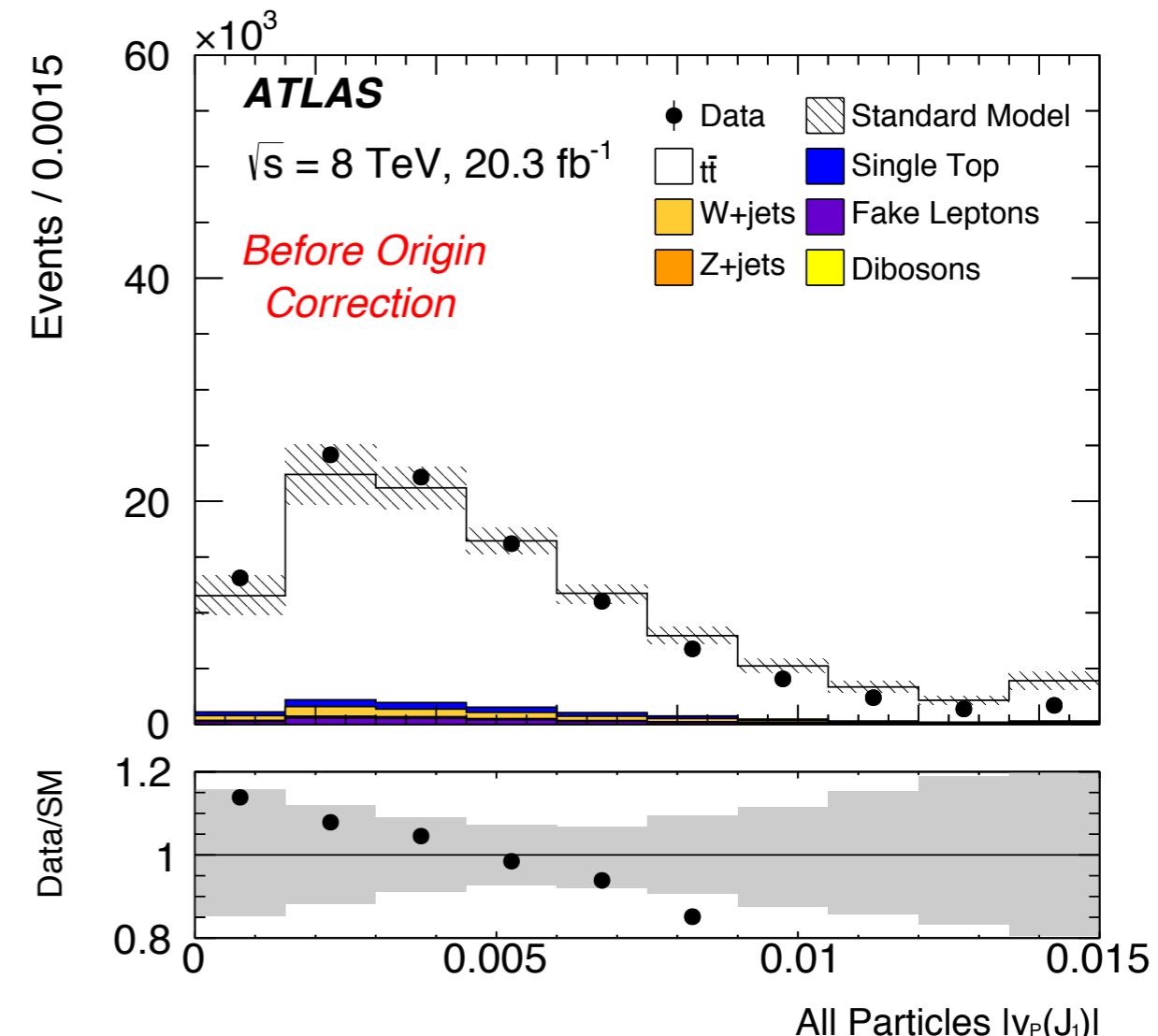
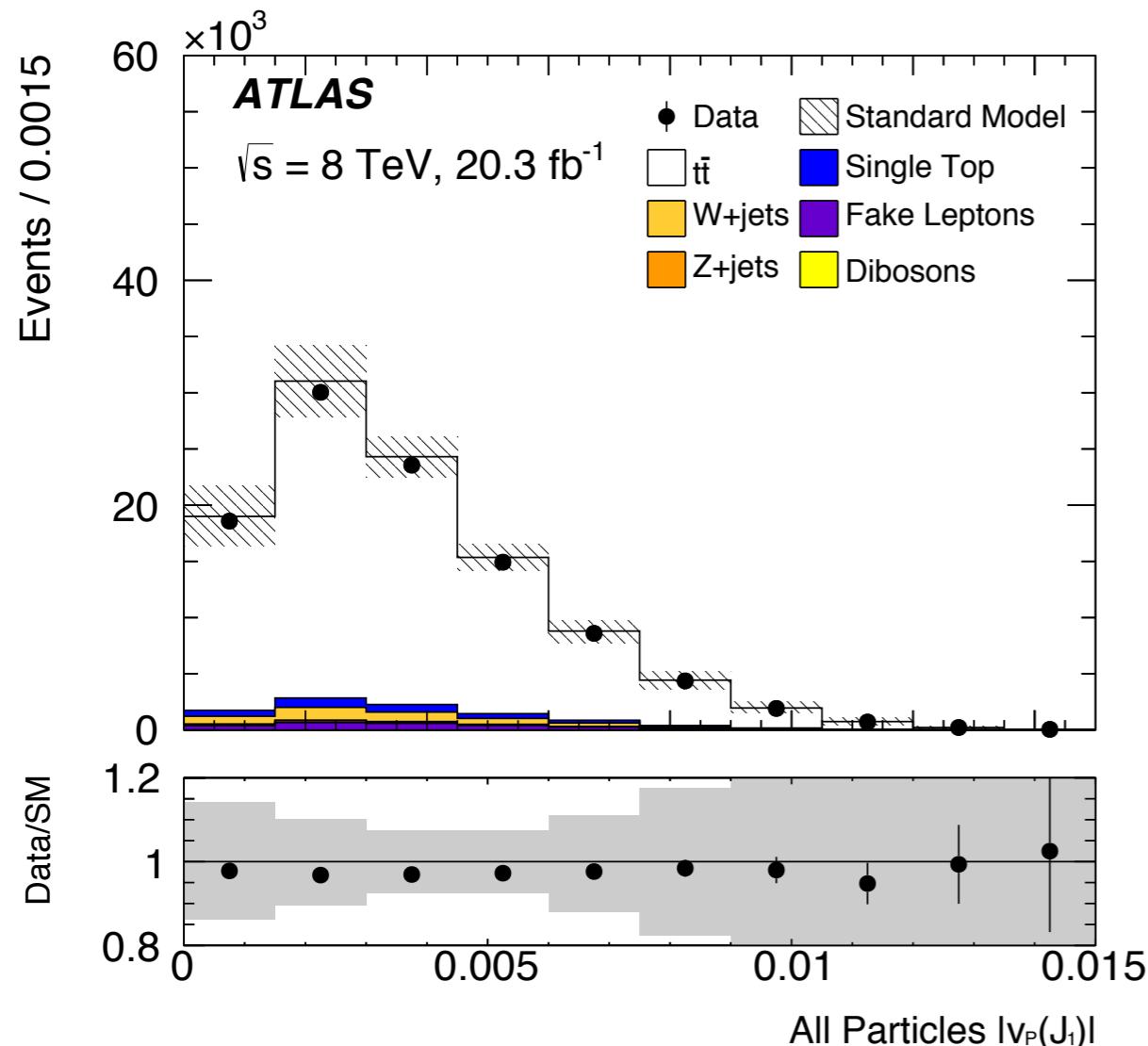
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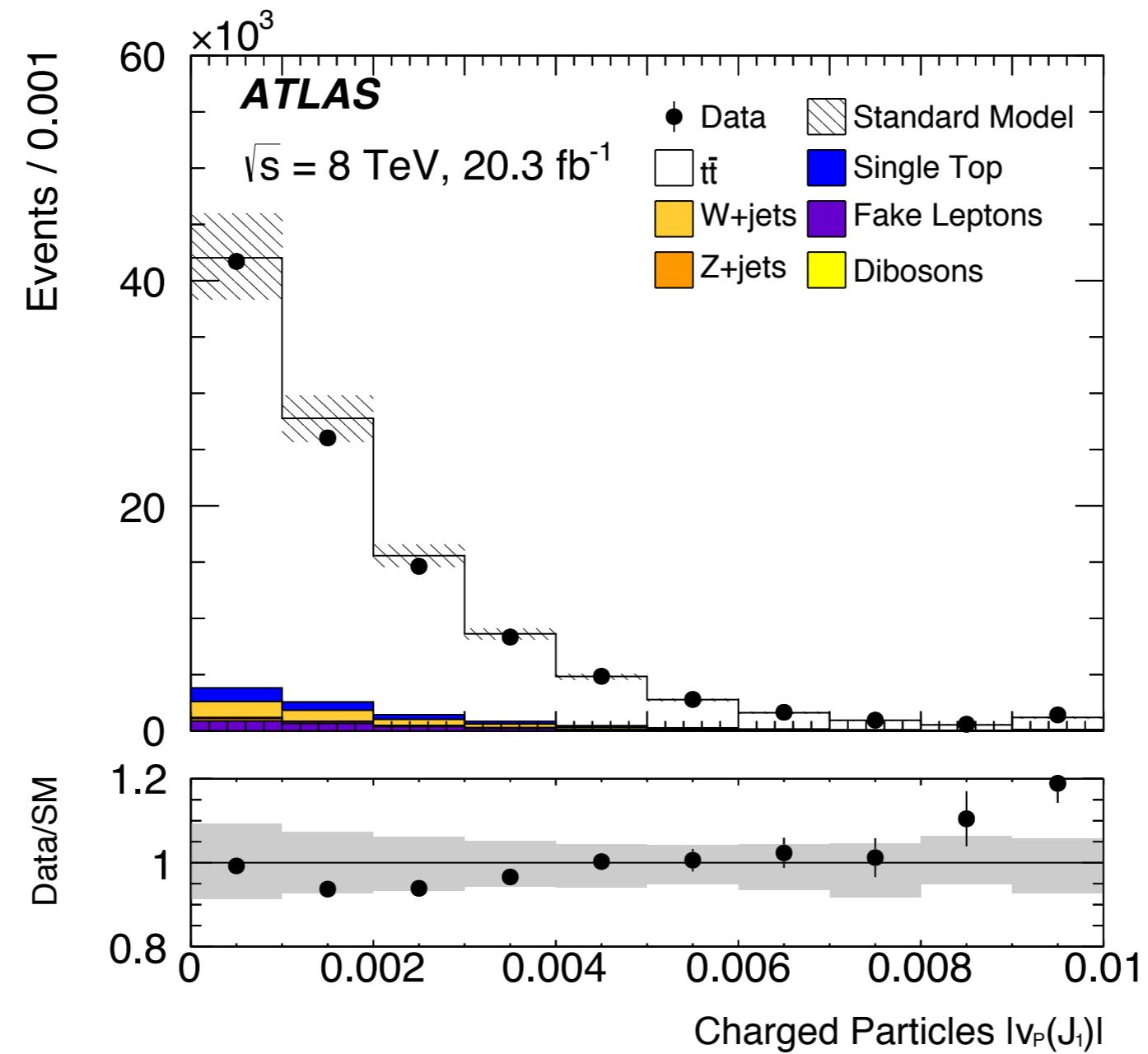
Colorflow Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/>



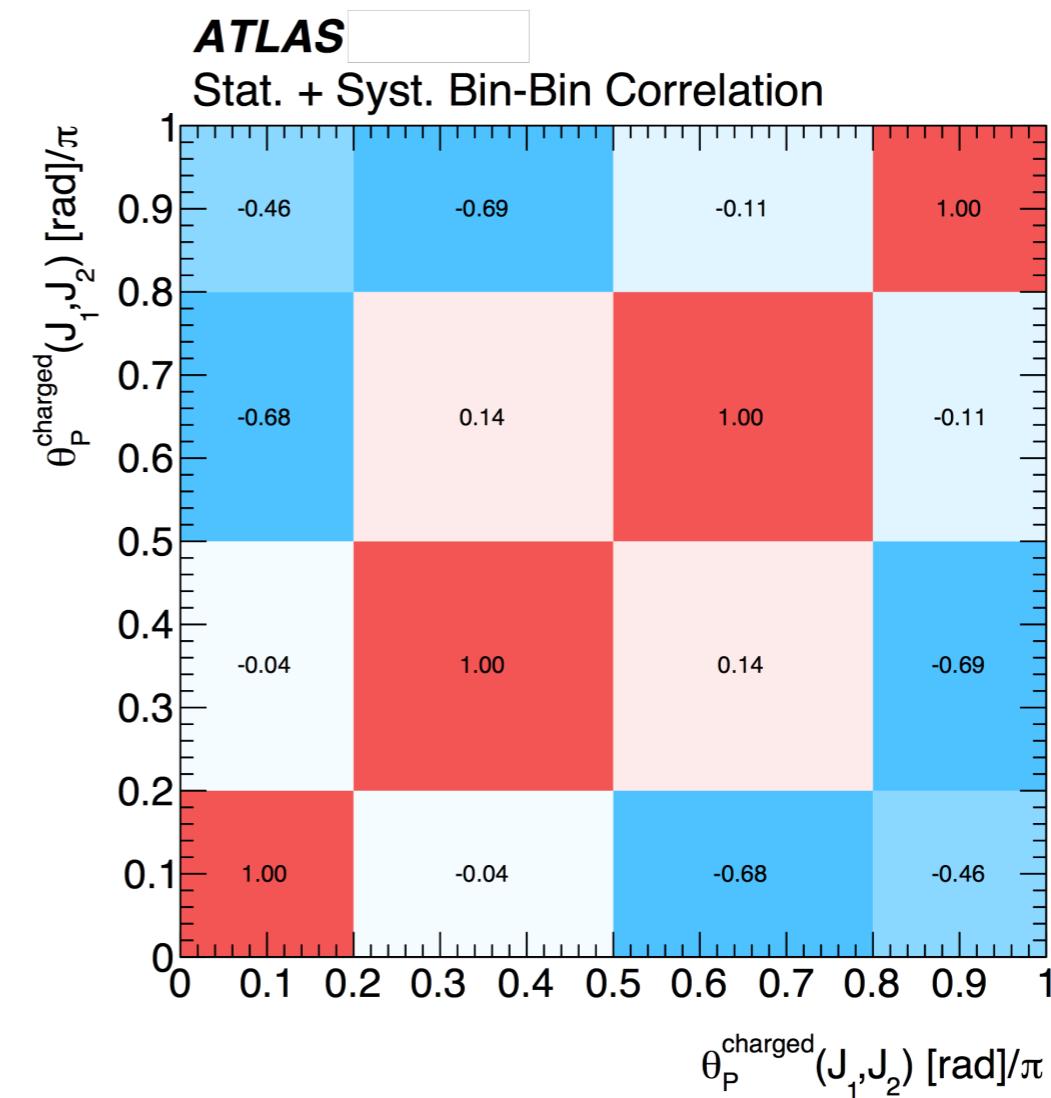
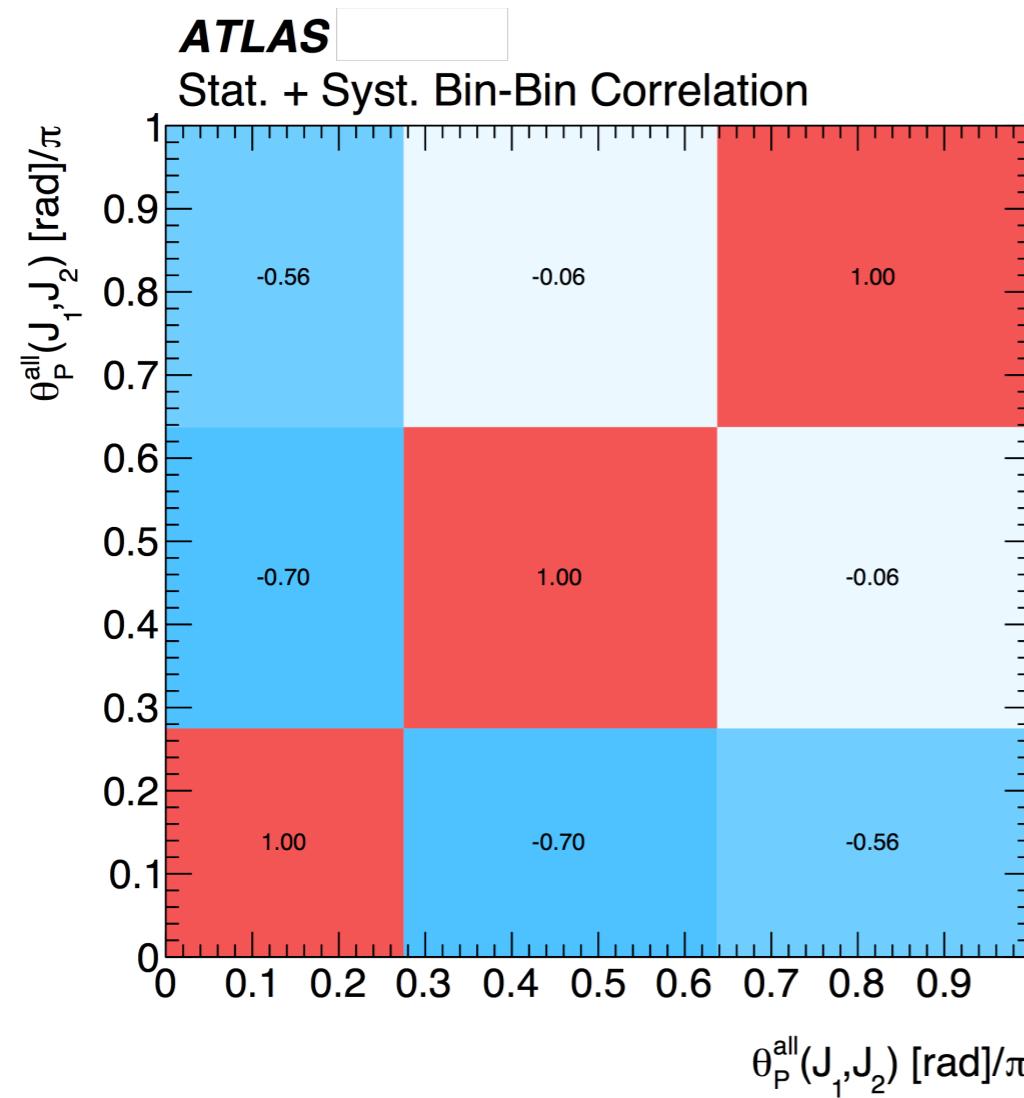
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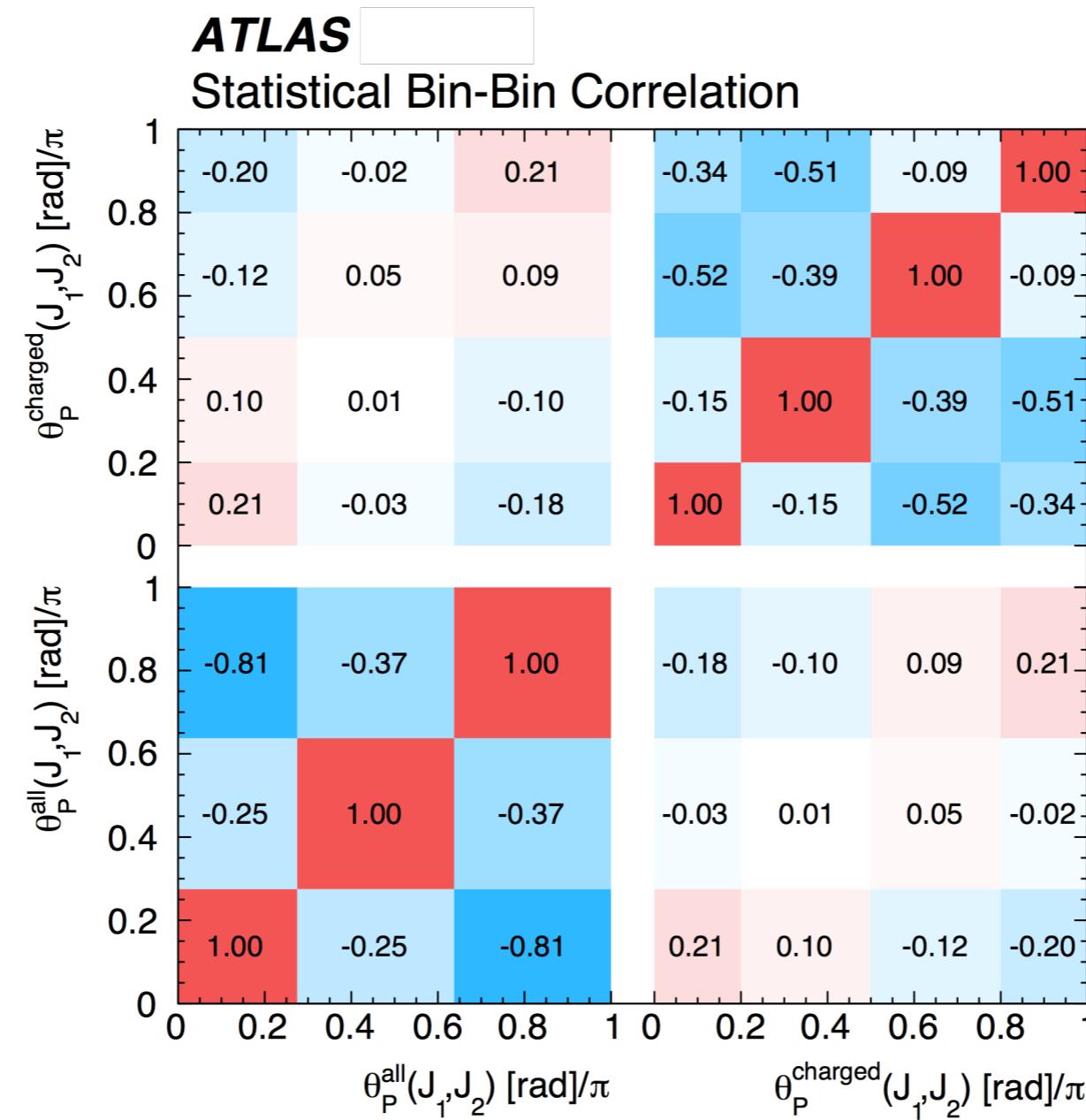
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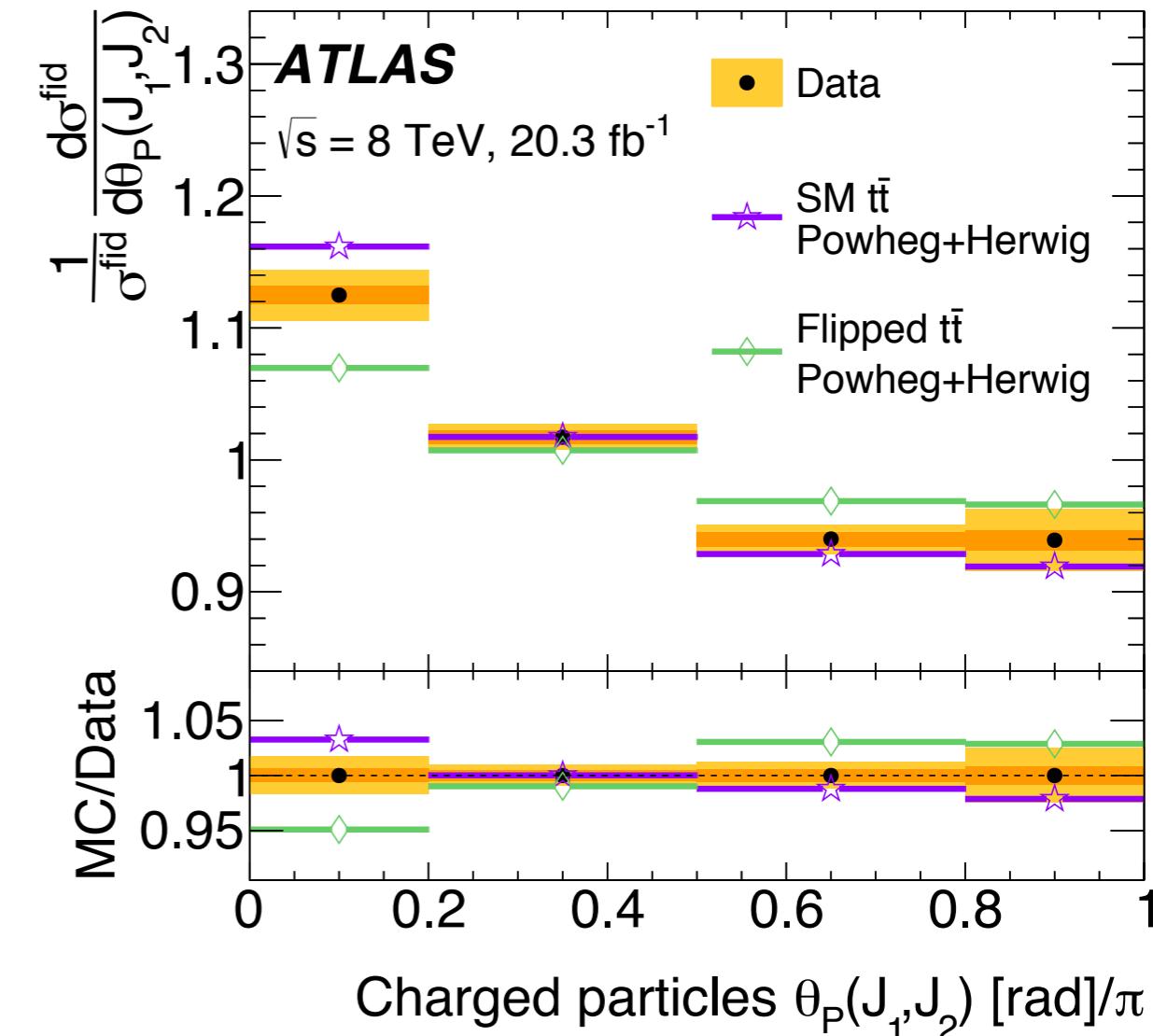
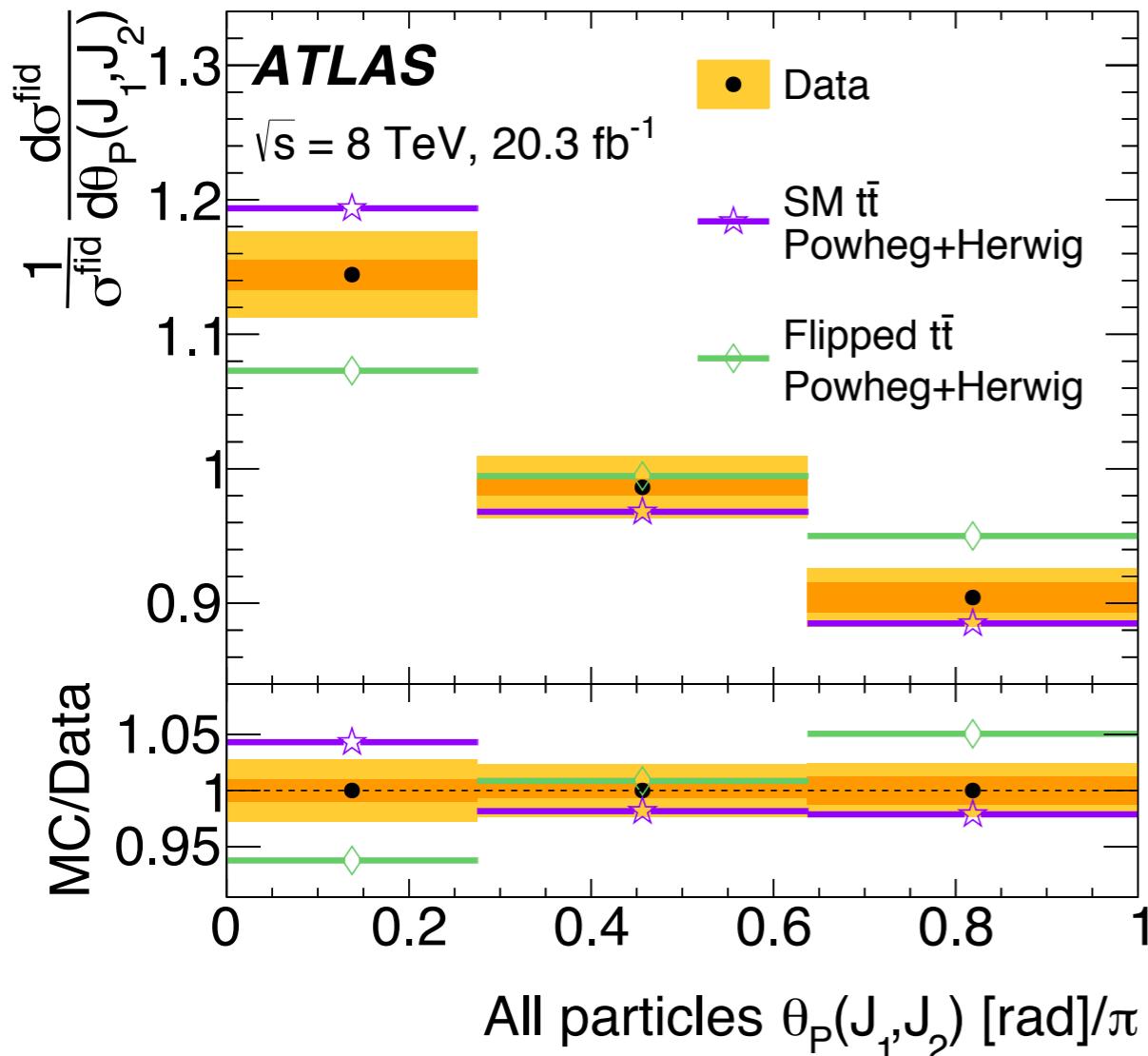
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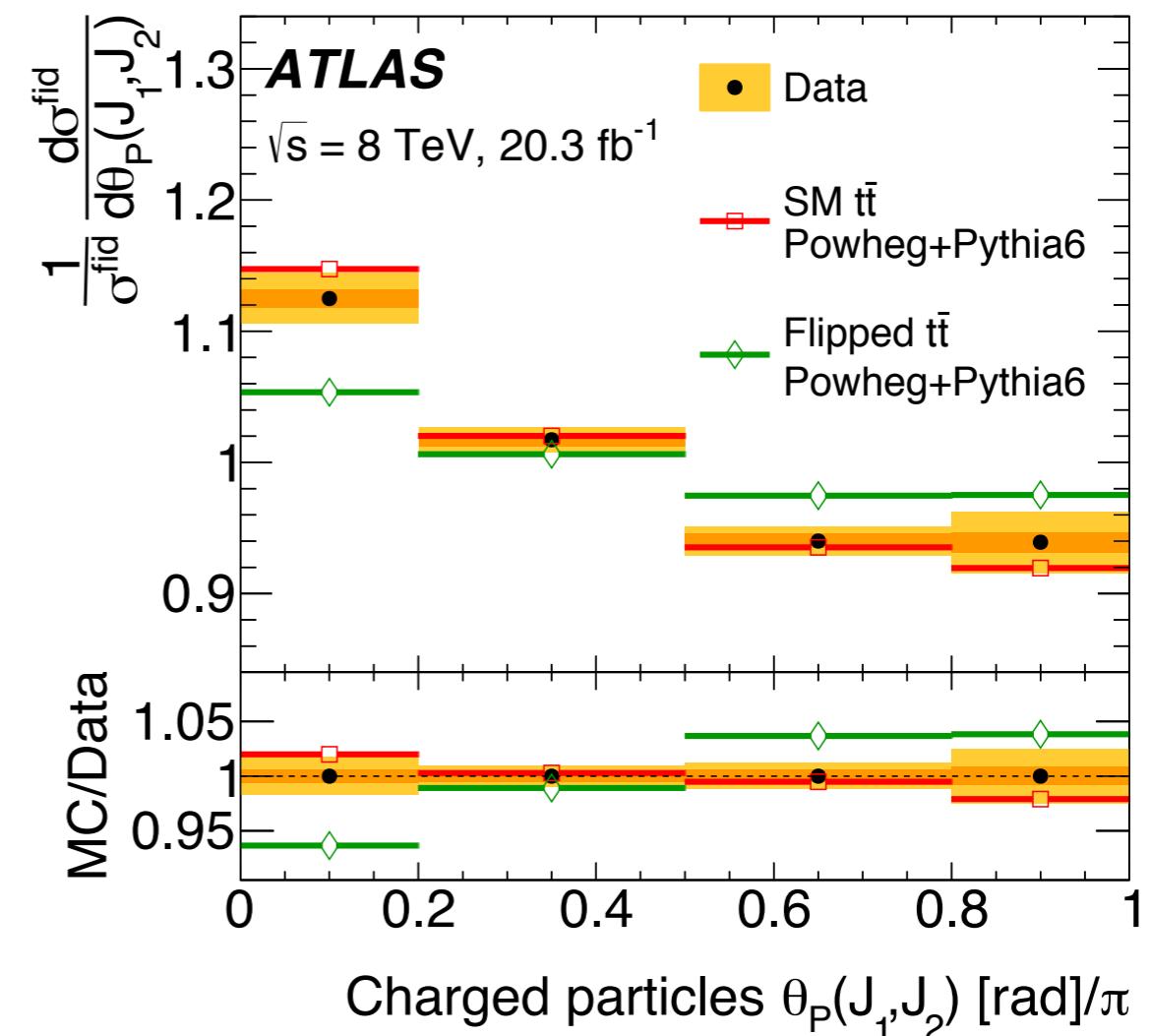
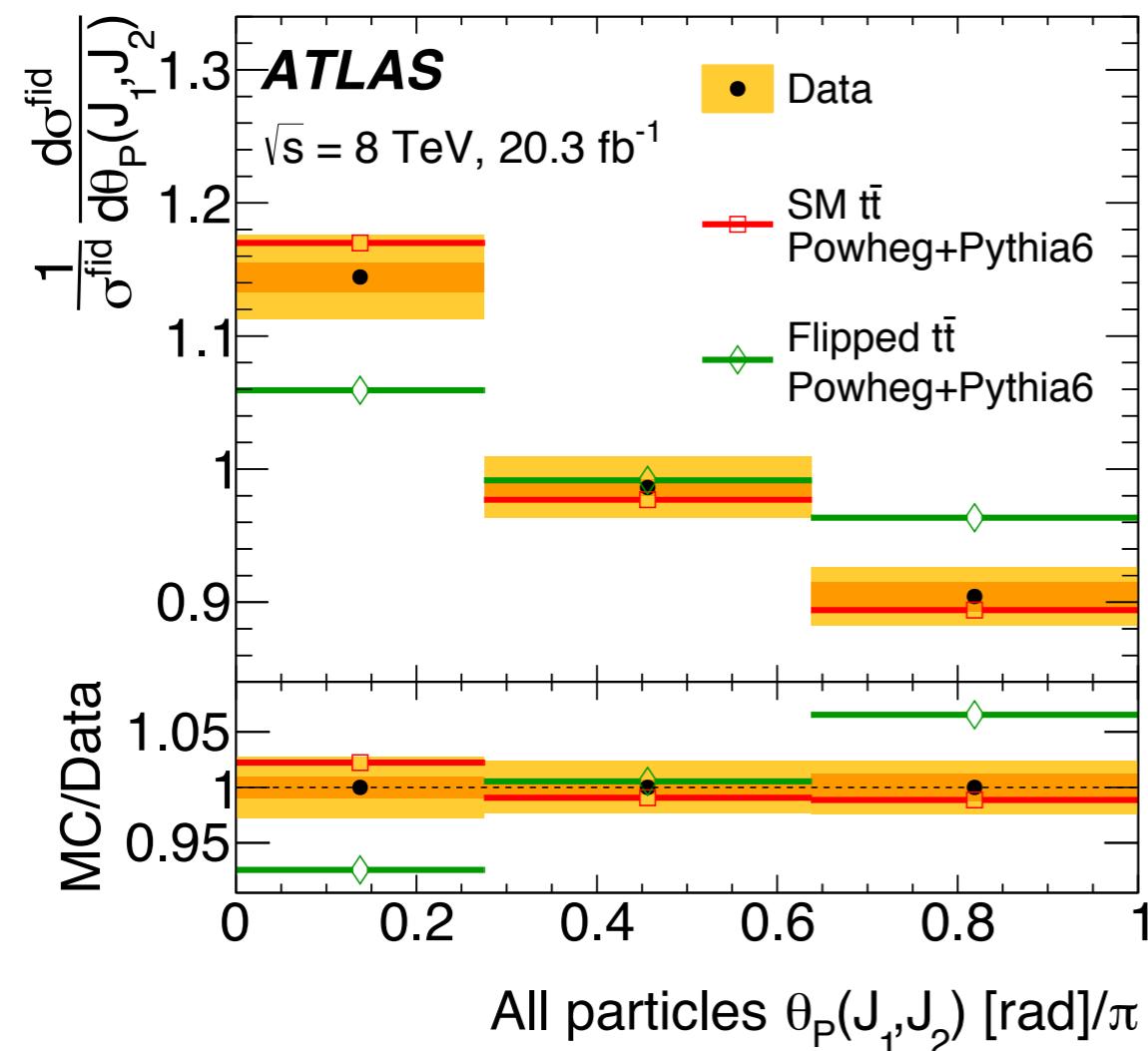
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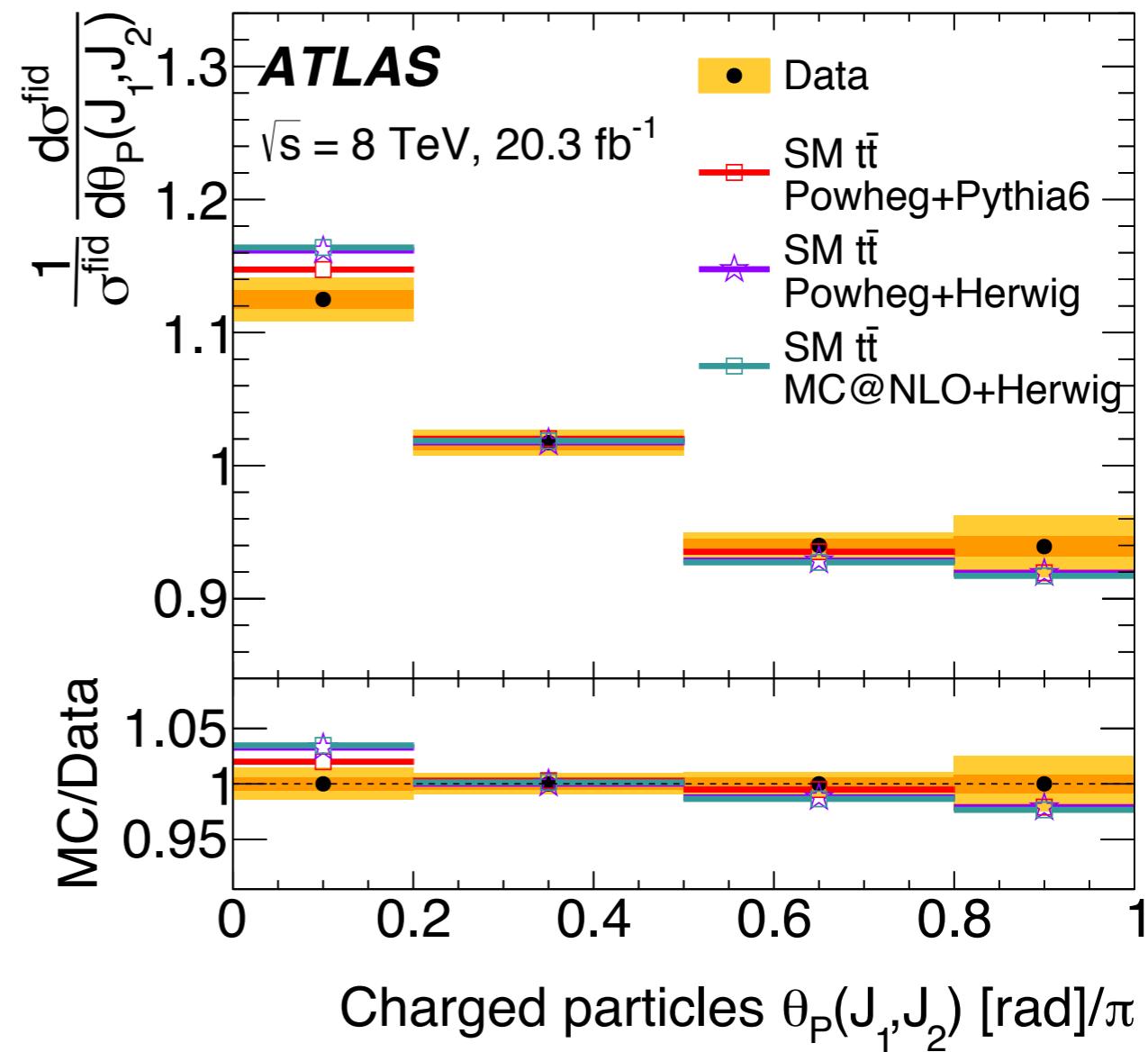
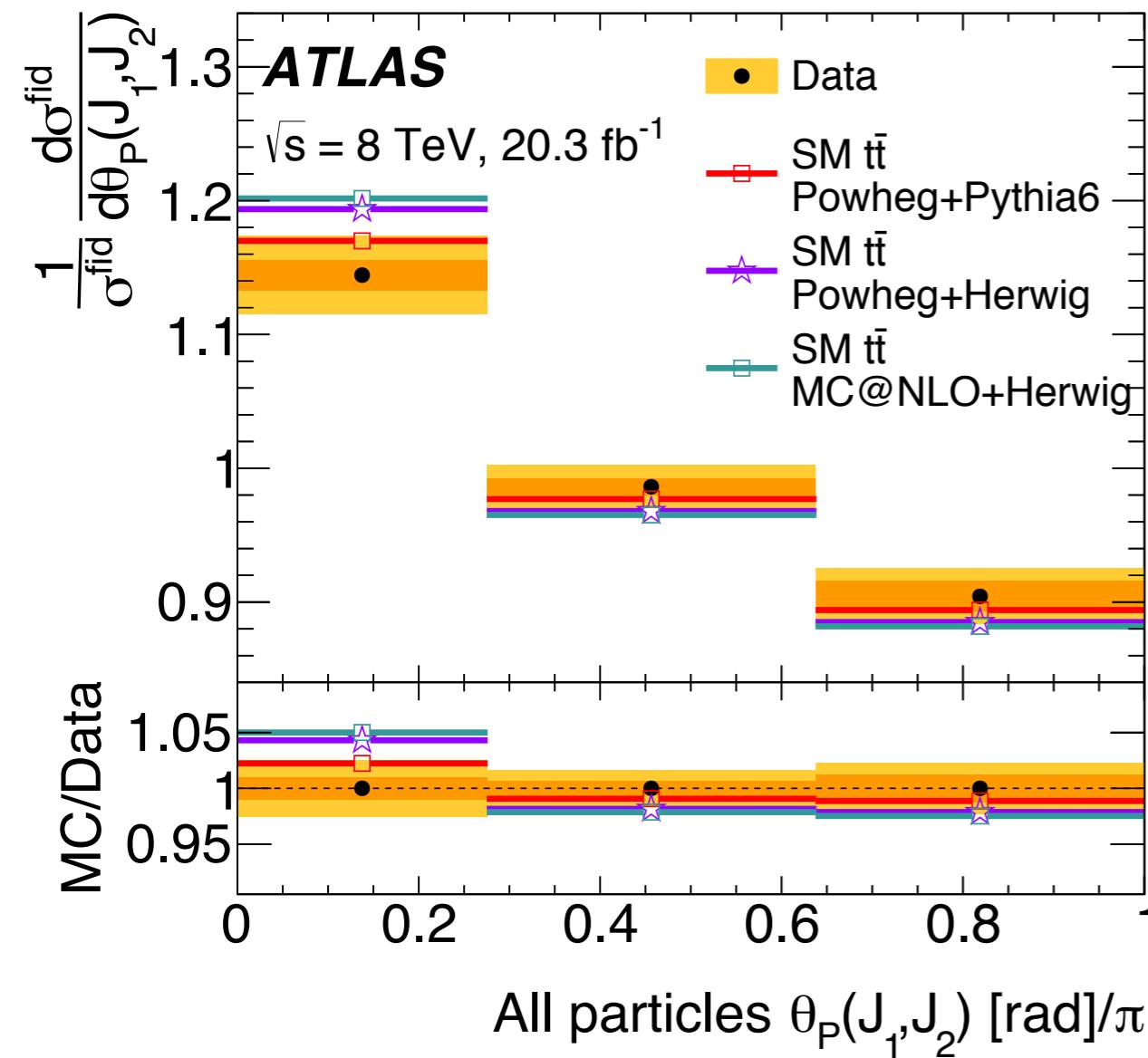
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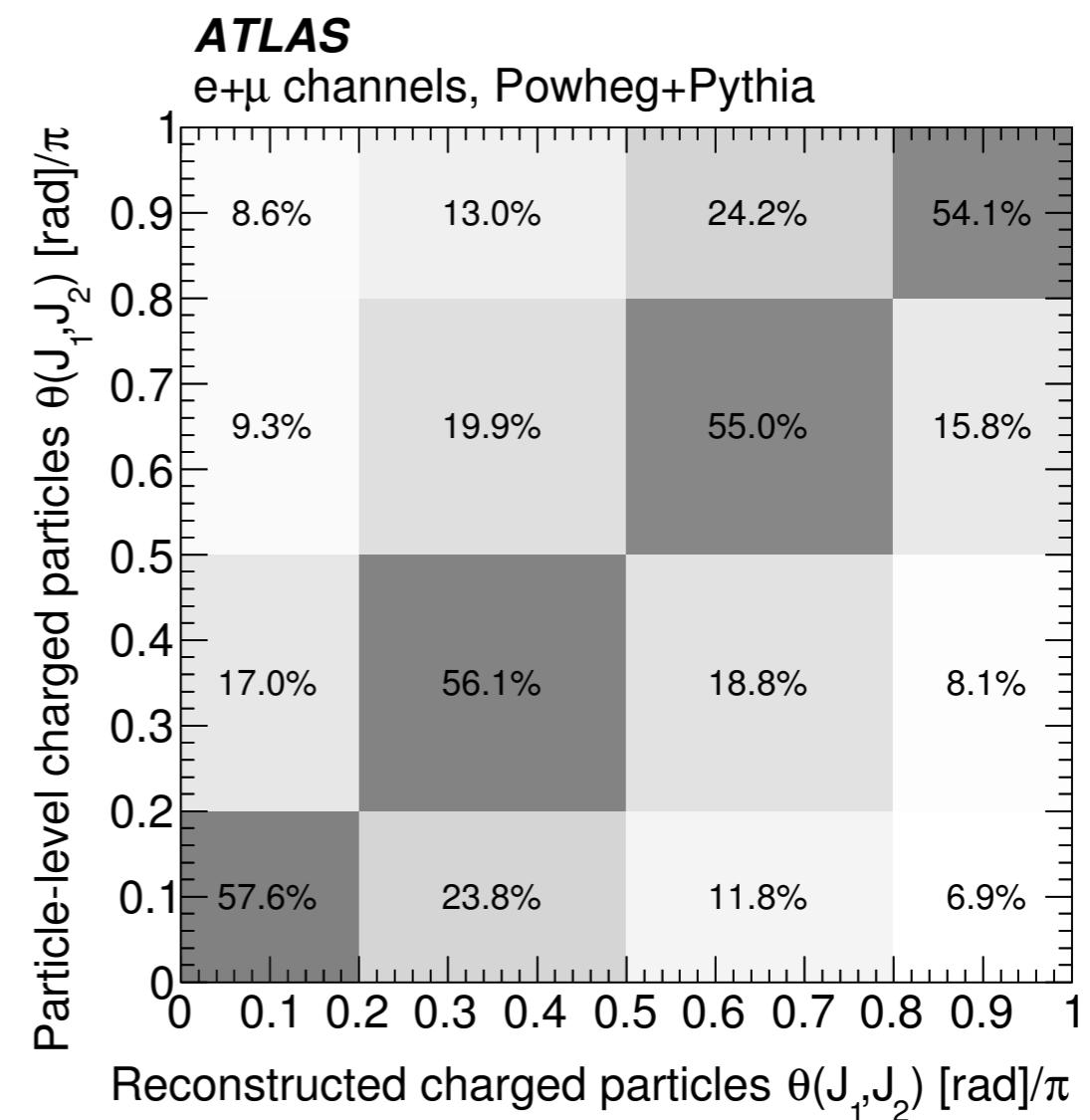
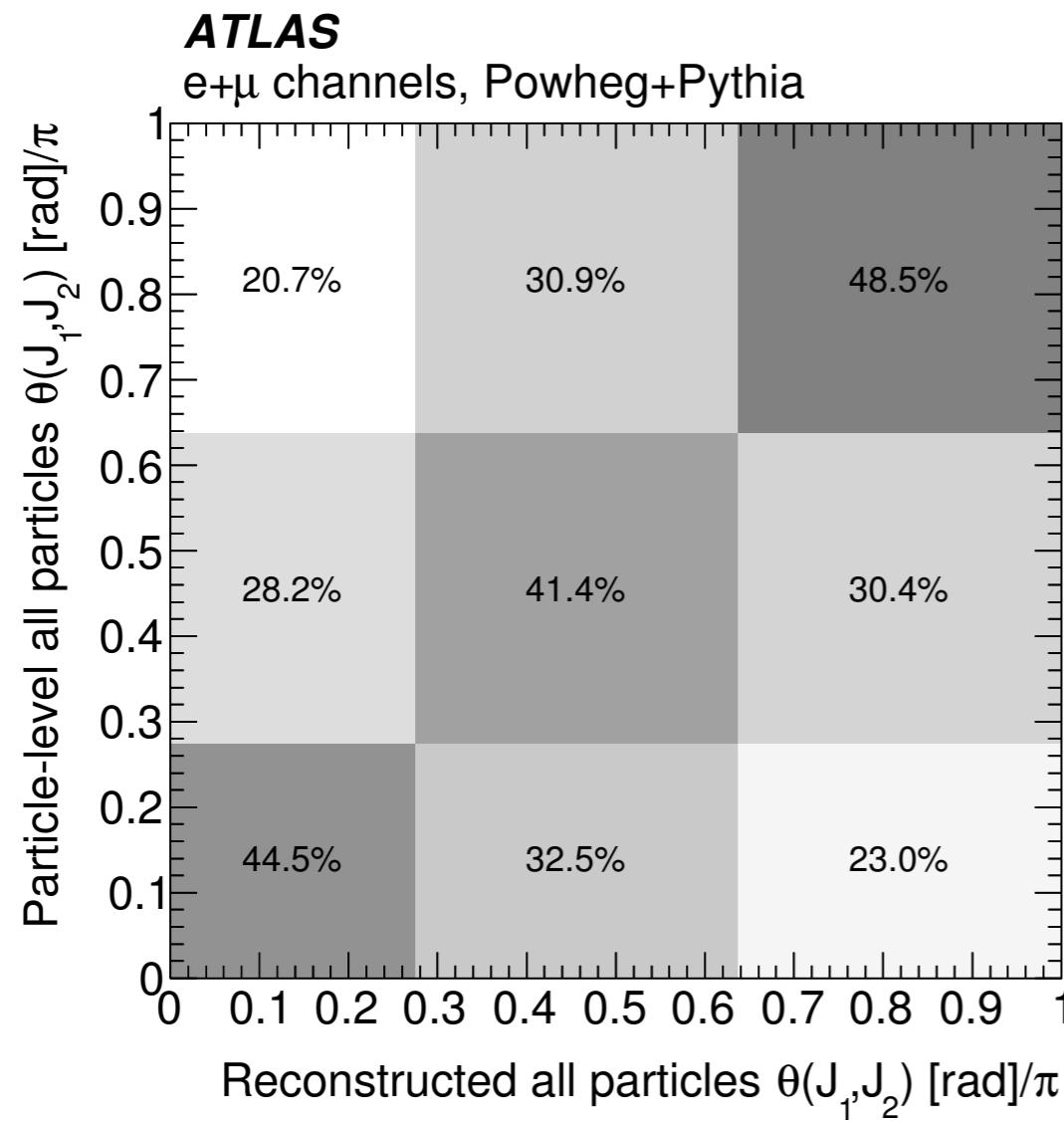
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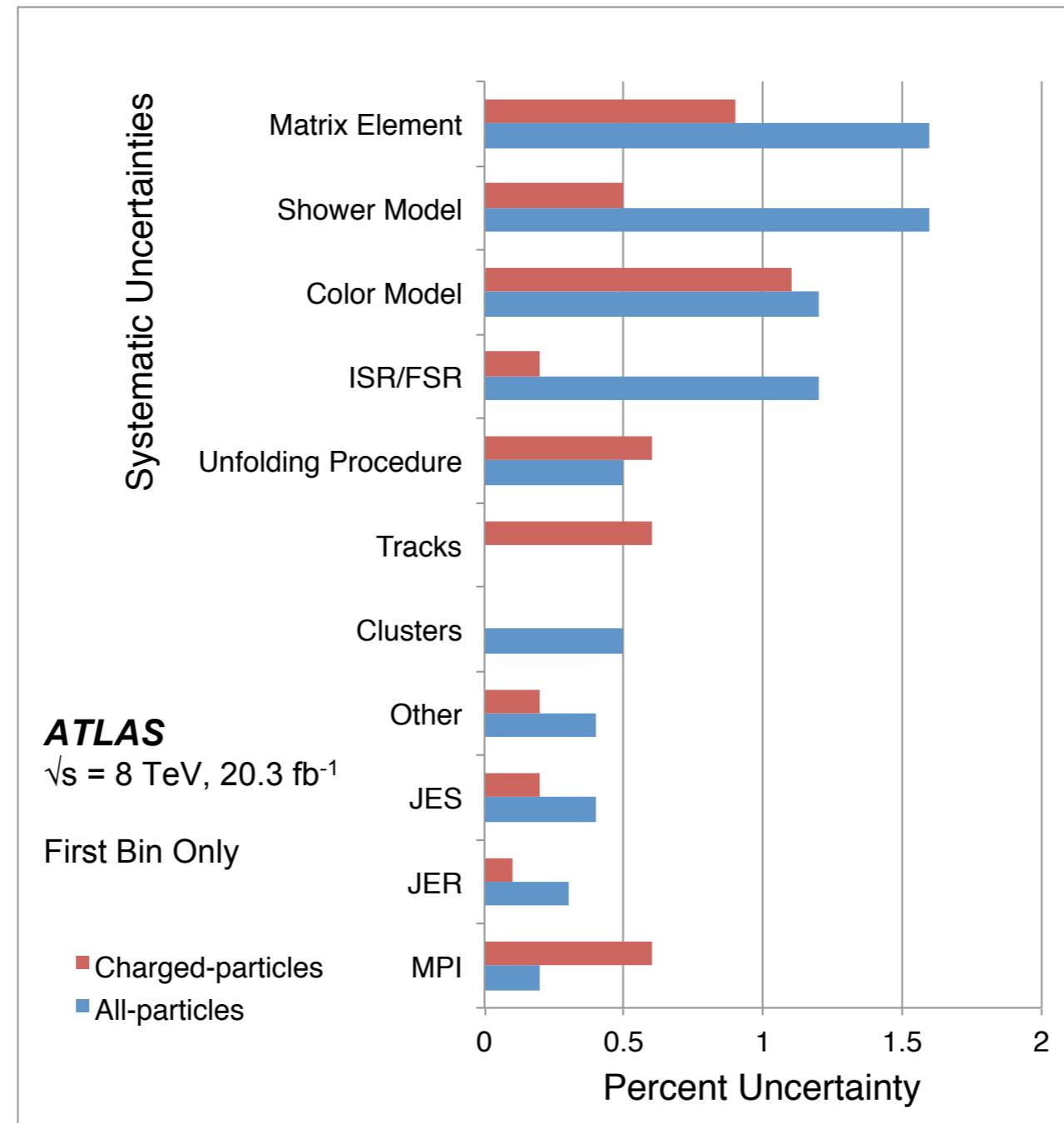
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Colorflow Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/>

Process	Number of Events
$t\bar{t}$	95400 ± 14000
Wt -channel single top	2730 ± 600
s - and t -channel single top	150 ± 10
W +jets	3710 ± 120
Z +jets	560 ± 270
Dibosons	190 ± 40
Multijets	2500 ± 910
Total SM	105000 ± 14000
Data	102987

Process	Generator	Type	Version	PDF	Tune
$t\bar{t}$	POWHEG [17,18,19] +PYTHIA [22]	NLO ME + PS	- 6.426.2	CT10 [20,21] CTEQ6L1 [23]	- PERUGIA2011C [24]
Single top	POWHEG +PYTHIA	NLO ME + PS	6.426.2	CT10(4f) CTEQ6L1	- PERUGIA2011C
WW, WZ, ZZ	SHERPA [25]	LO multi-leg ME + PS	1.4.1	CT10	Default
W/Z +jets	ALPGEN [26] +PYTHIA	LO multi-leg ME + PS	2.1.4 6.426.2	CTEQ6L1 CTEQ6L1	- PERUGIA2011C
$t\bar{t}^\dagger$	POWHEG +HERWIG [27] +JIMMY [29]	NLO ME + PS (MPI)	- 6.520.2 4.31	CT10 CT10	- AUET2 [28]
$t\bar{t}^\dagger$	MC@NLO[30,31] +HERWIG +JIMMY	NLO ME + PS (MPI)	4.06 6.520.2 4.31	CT10 CT10	- AUET2

Colorflow Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/>

$\Delta\theta_p^{\text{all}} [\%]$	$\theta_p^{\text{all}} [\text{rad}]/\pi$		
	0.0 - 0.275	0.275 - 0.6375	0.6375 - 1.0
Shower, fragmentation & hadronisation	1.66	0.91	0.60
$t\bar{t}$ NLO generator	1.48	0.55	0.82
Colour model	1.26	1.68	0.62
ISR/FSR	1.18	0.58	0.50
Non-closure	0.47	0.06	0.38
Clusters	0.46	0.67	0.73
Colour reconnection	0.44	0.42	0.88
JES	0.38	0.19	0.40
Other	0.36	0.10	0.39
JER	0.27	0.02	0.23
MPI	0.11	0.06	0.04
Stats.	1.12	0.63	1.12
Total	3.19	2.32	2.18
m_t	0.28	0.07	0.20

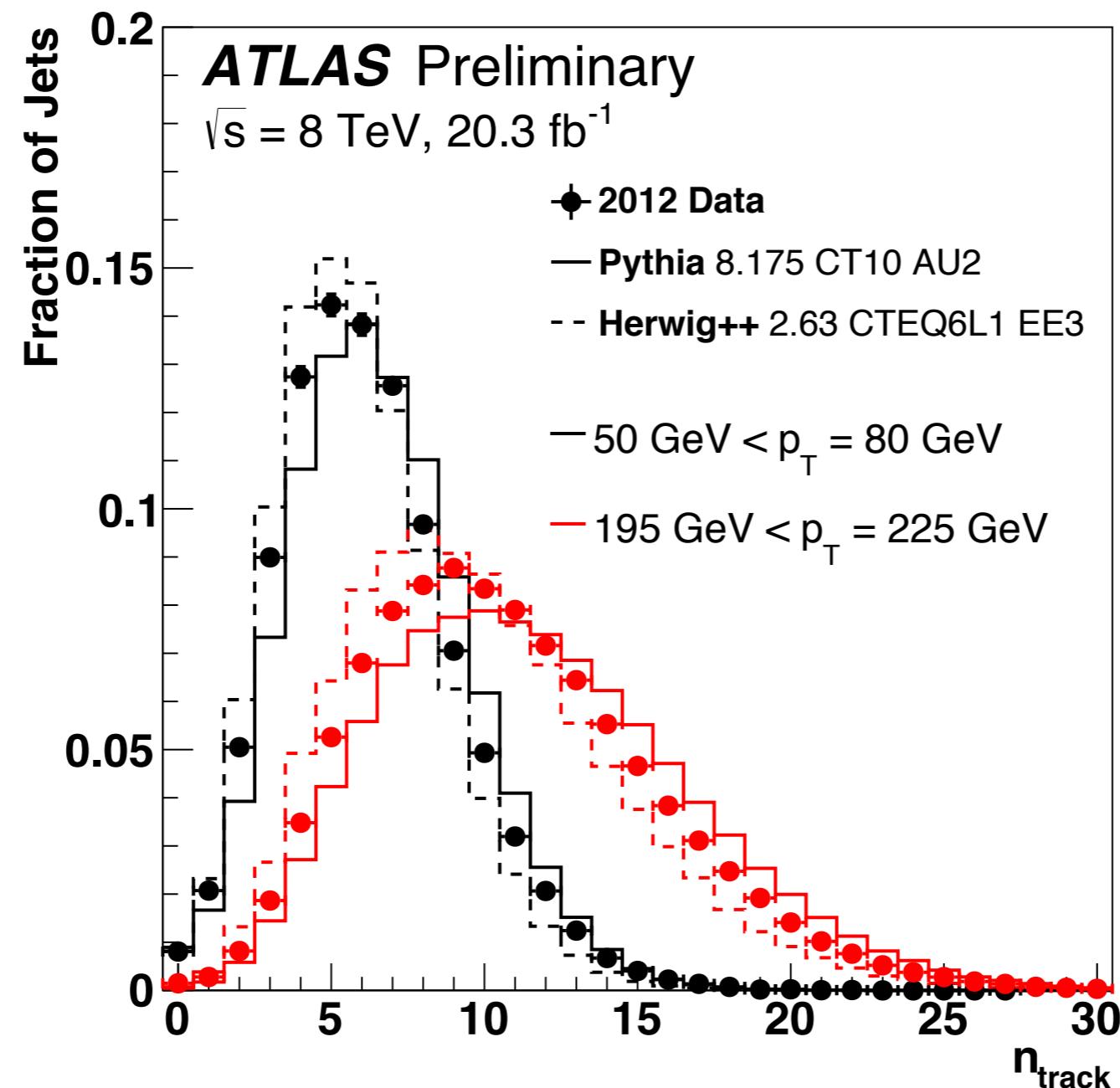
Colorflow Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/>

$\Delta\theta_p^{\text{charged}} [\%]$	$\theta_p^{\text{charged}} [\text{rad}]/\pi$			
	0.0 - 0.2	0.2 - 0.5	0.5 - 0.8	0.8 - 1.0
Colour model	1.04	0.17	0.49	0.24
$t\bar{t}$ NLO generator	0.93	0.21	0.07	1.56
Non-closure	0.61	0.58	0.32	1.19
MPI	0.58	0.24	0.44	0.36
Shower, fragmentation & hadronisation	0.56	0.29	0.55	0.63
Colour reconnection	0.41	0.24	0.22	0.22
ISR/FSR	0.24	0.04	0.01	0.37
JES	0.23	0.14	0.16	0.00
Other	0.19	0.15	0.14	0.00
Tracks	0.16	0.14	0.08	0.00
JER	0.10	0.13	0.13	0.54
Stats.	0.68	0.51	0.54	0.77
Total	1.94	0.97	1.12	2.35
m_t	0.02	0.00	0.15	0.25

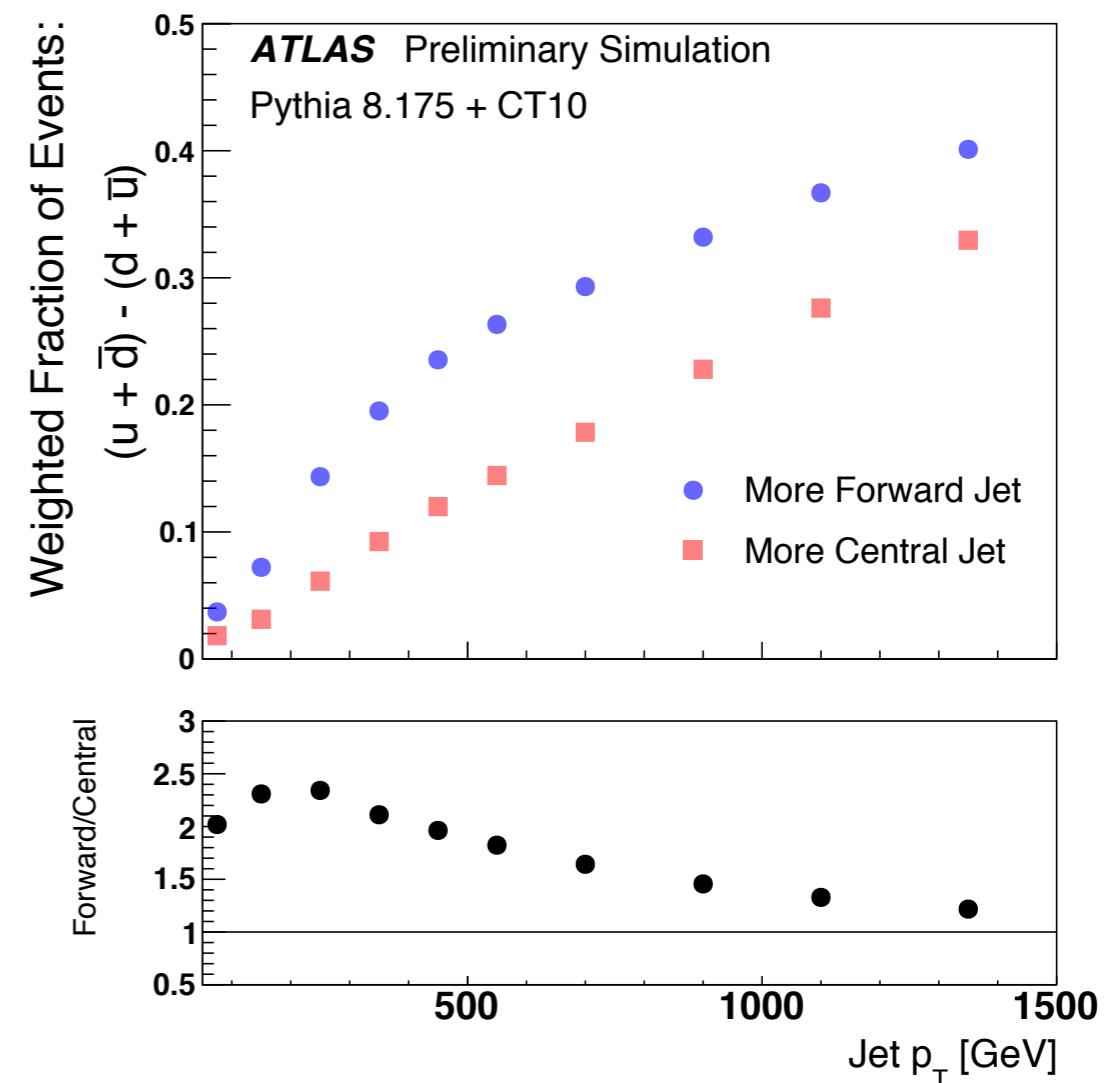
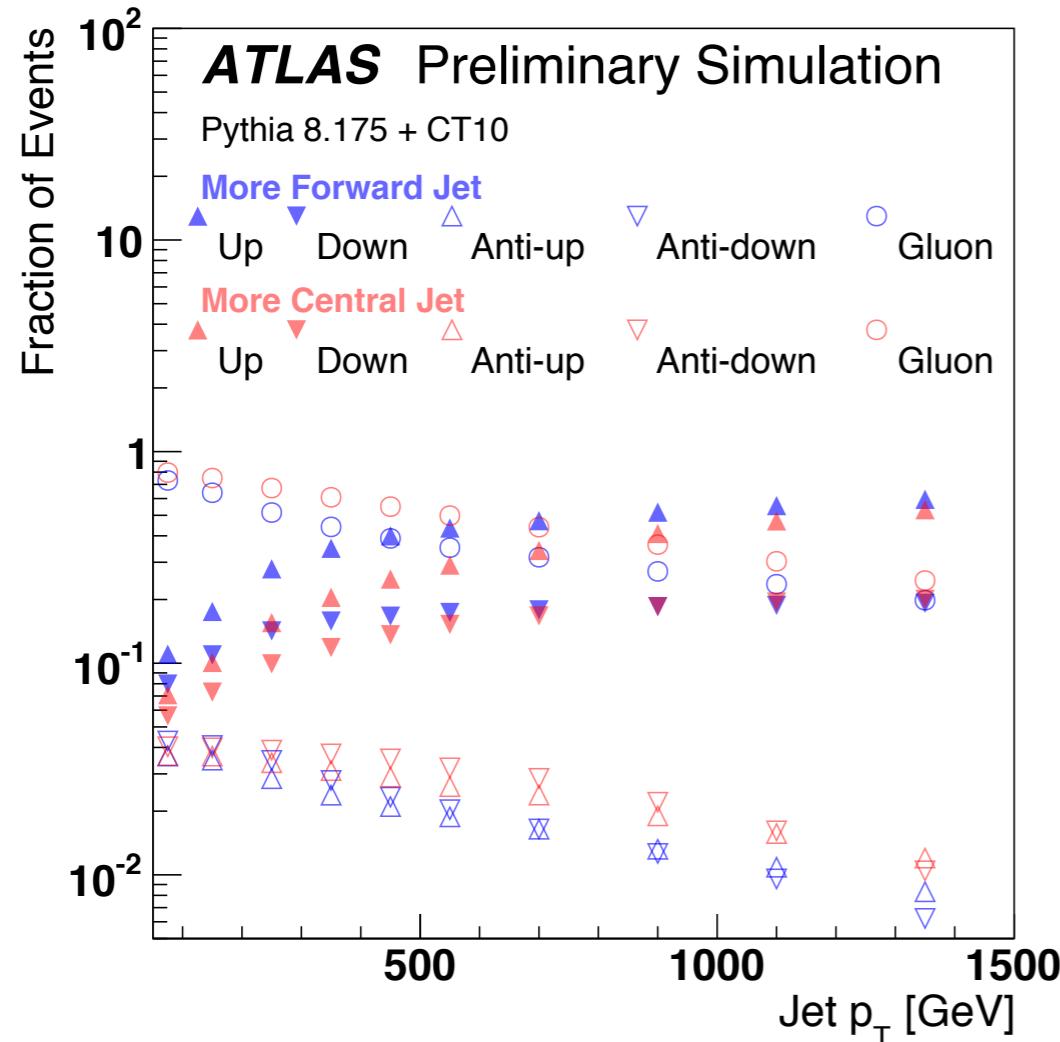
Jet Charge Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-025/>



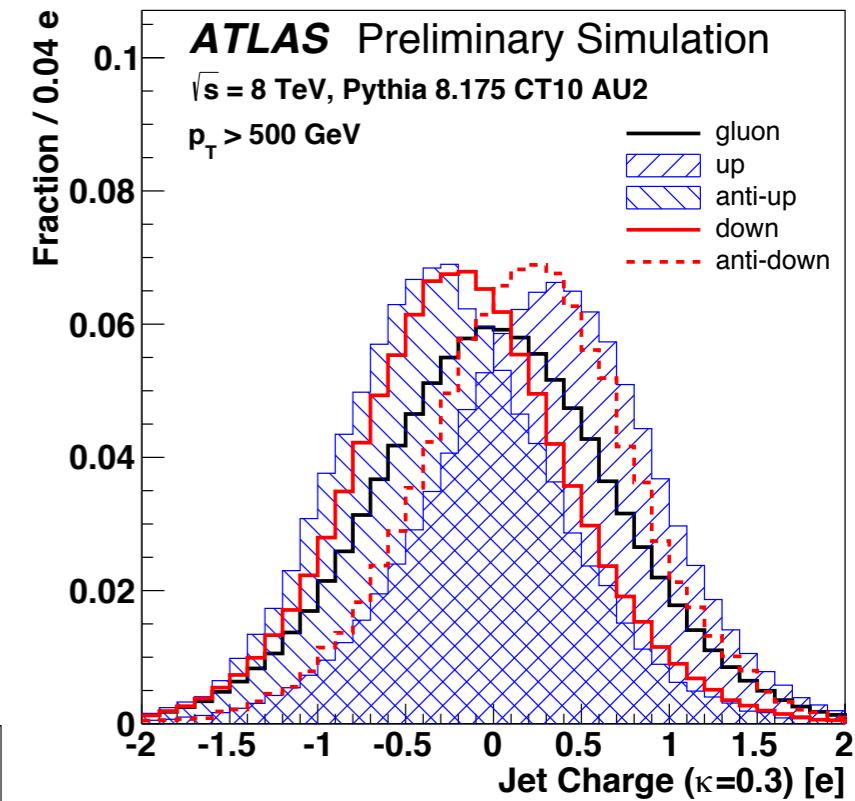
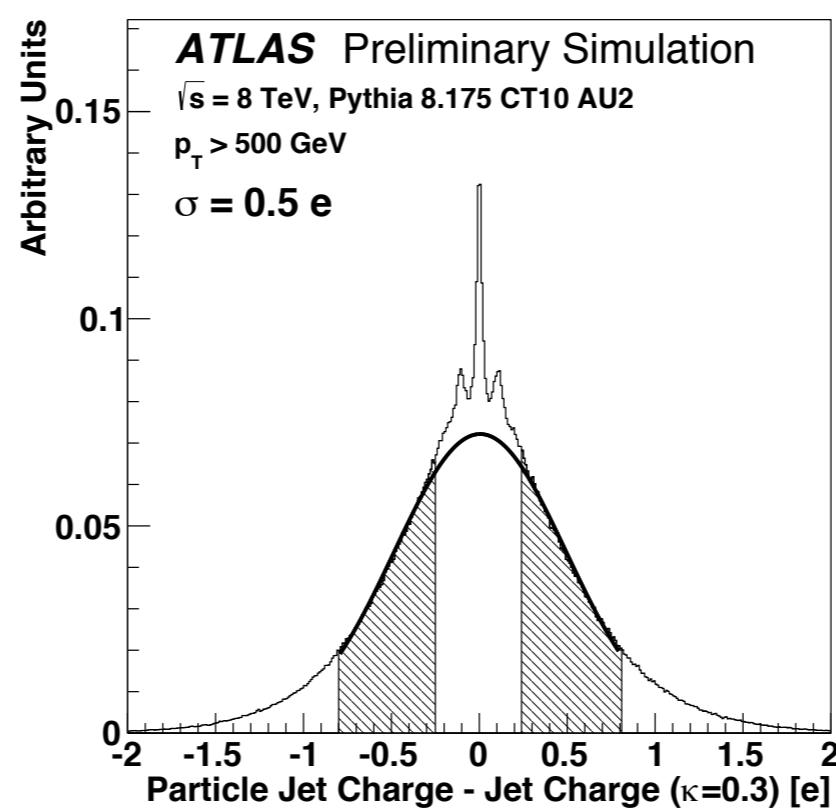
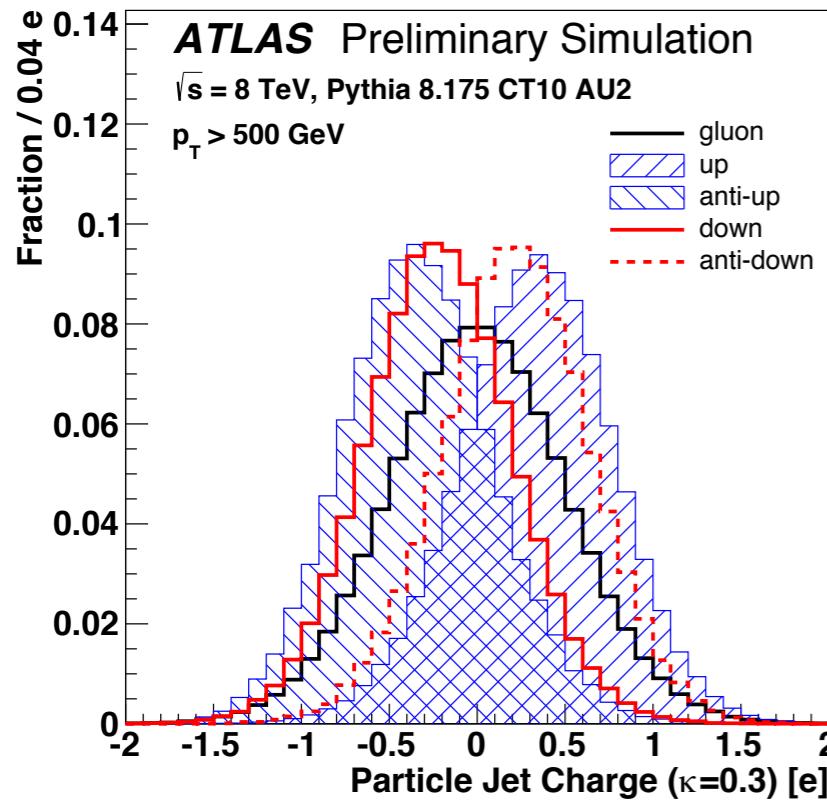
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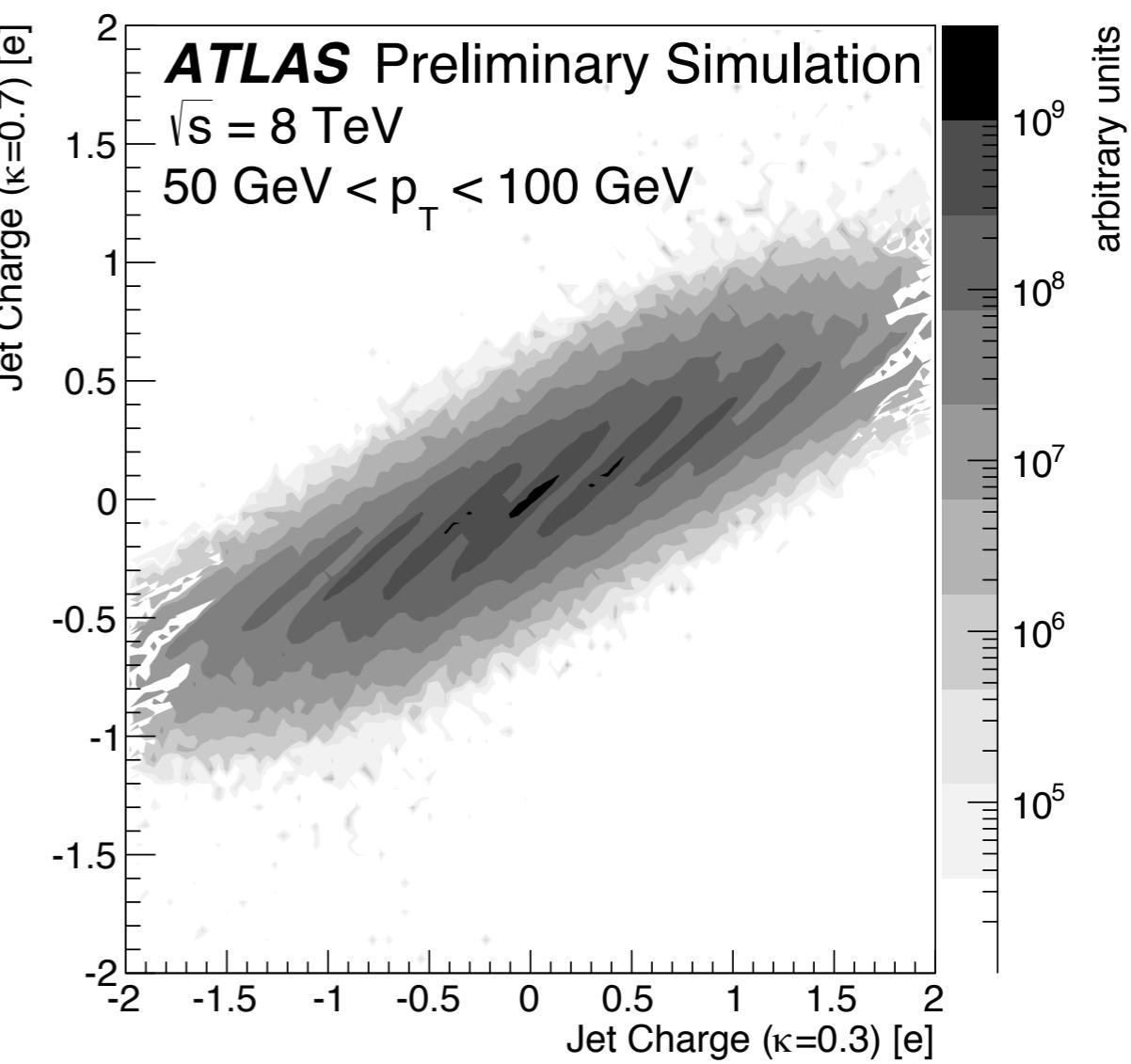
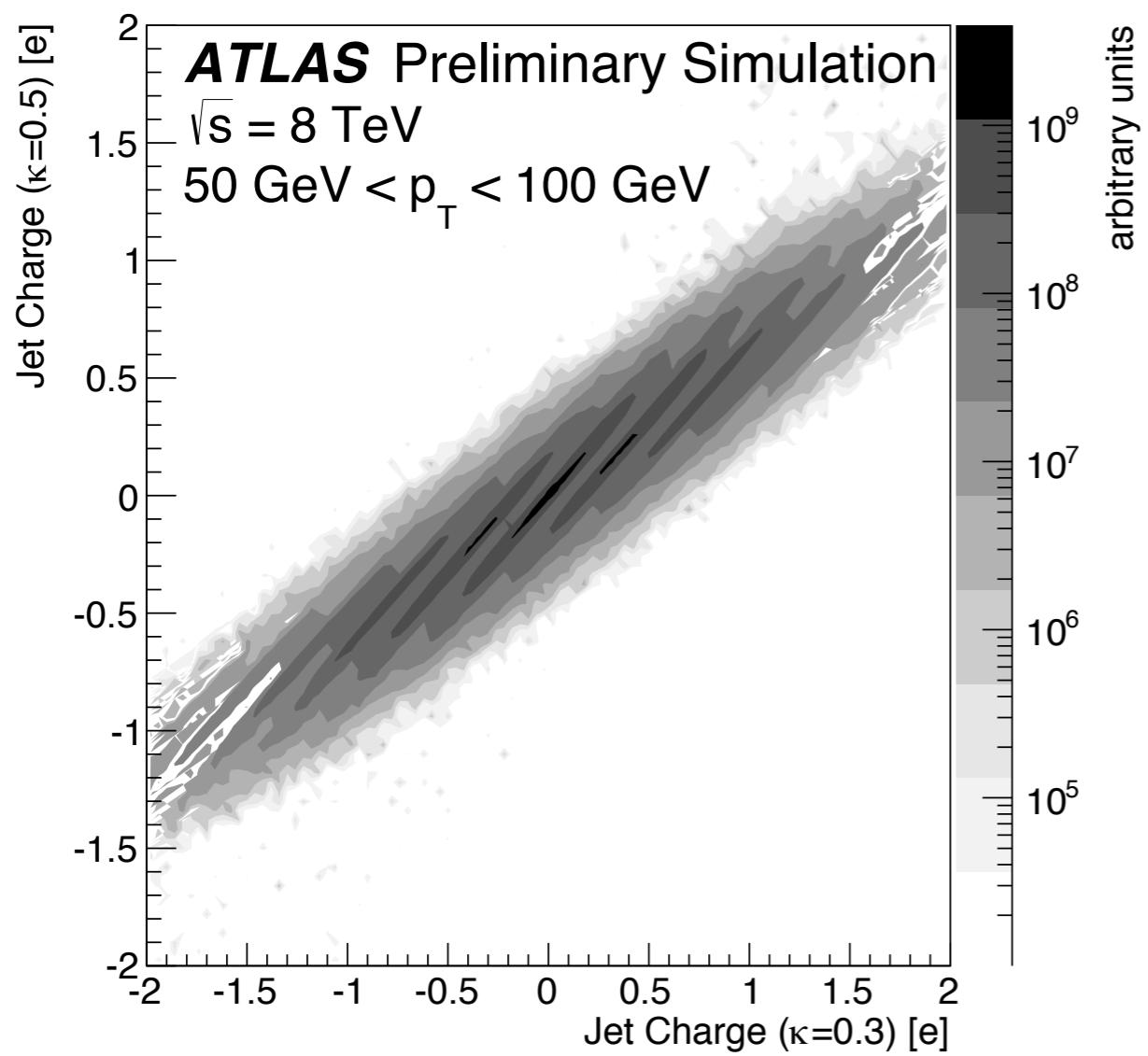
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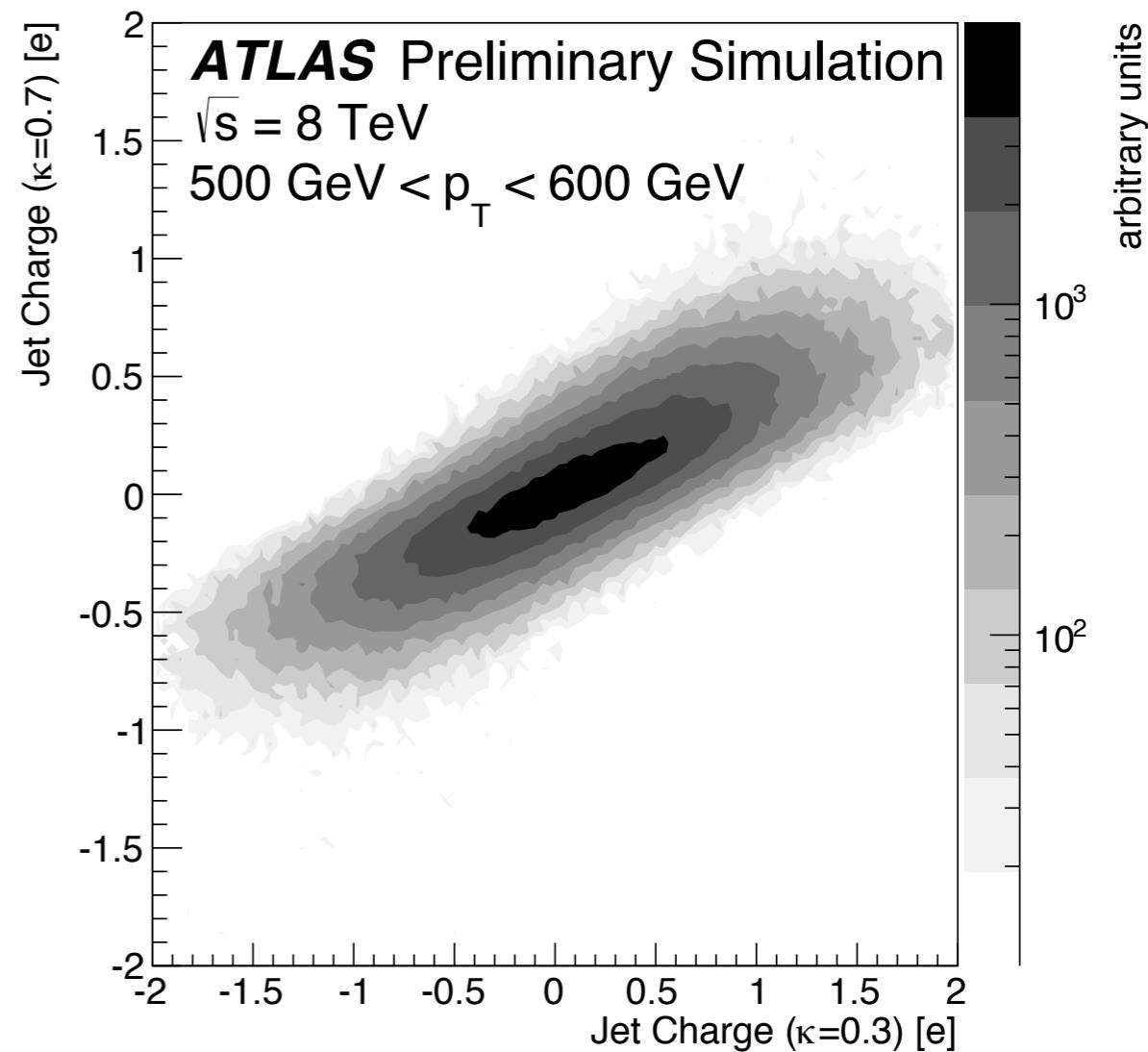
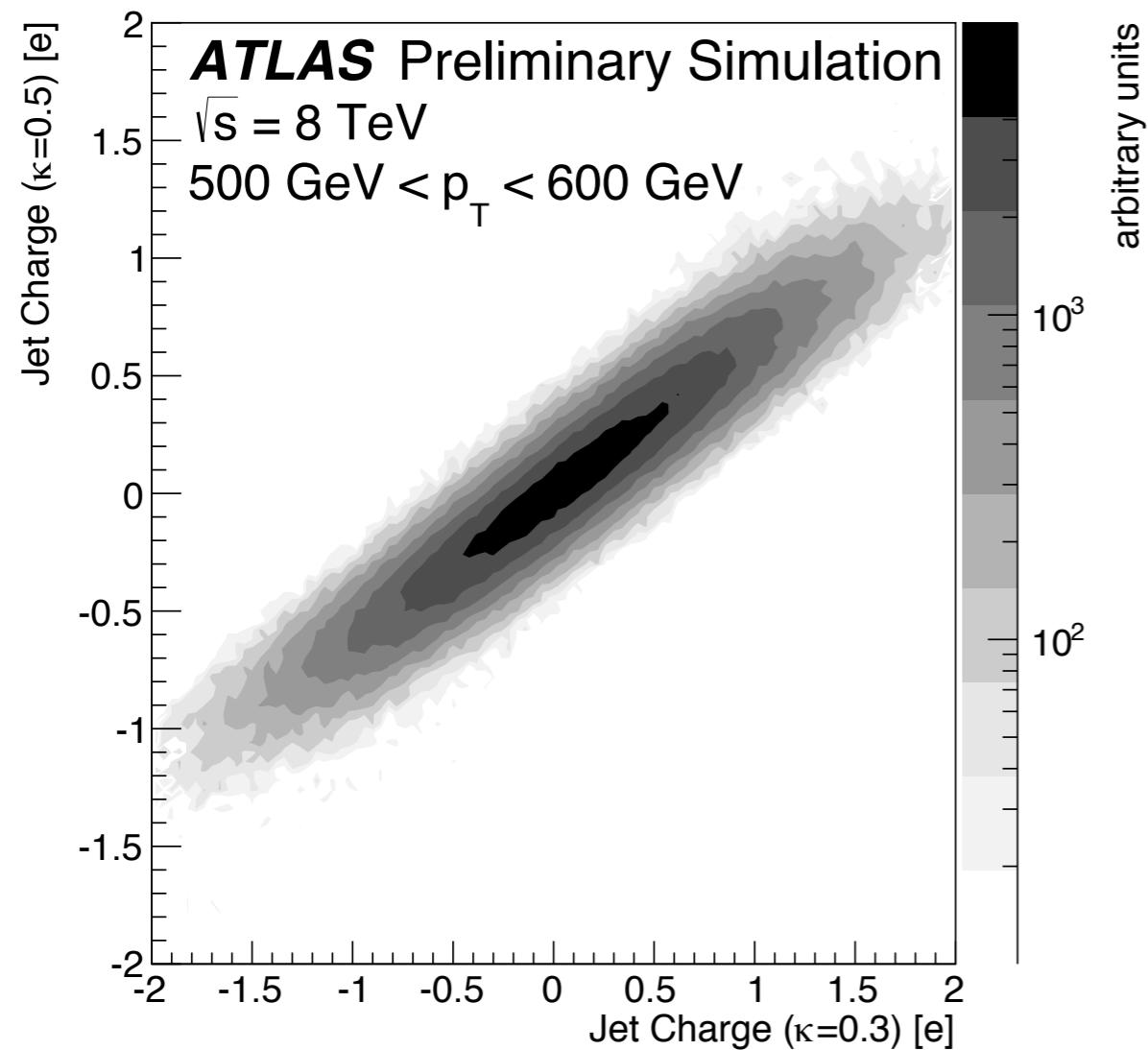
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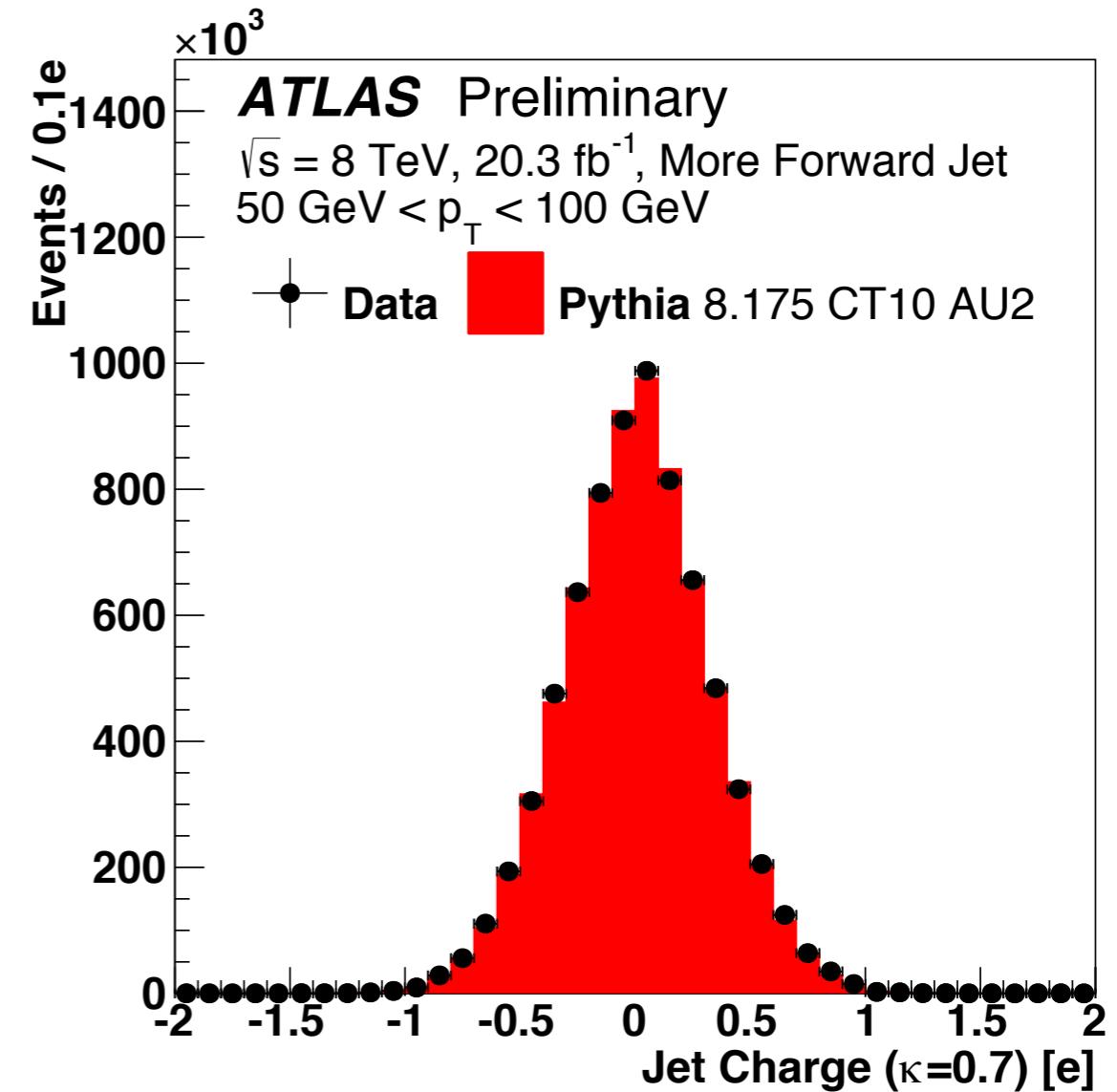
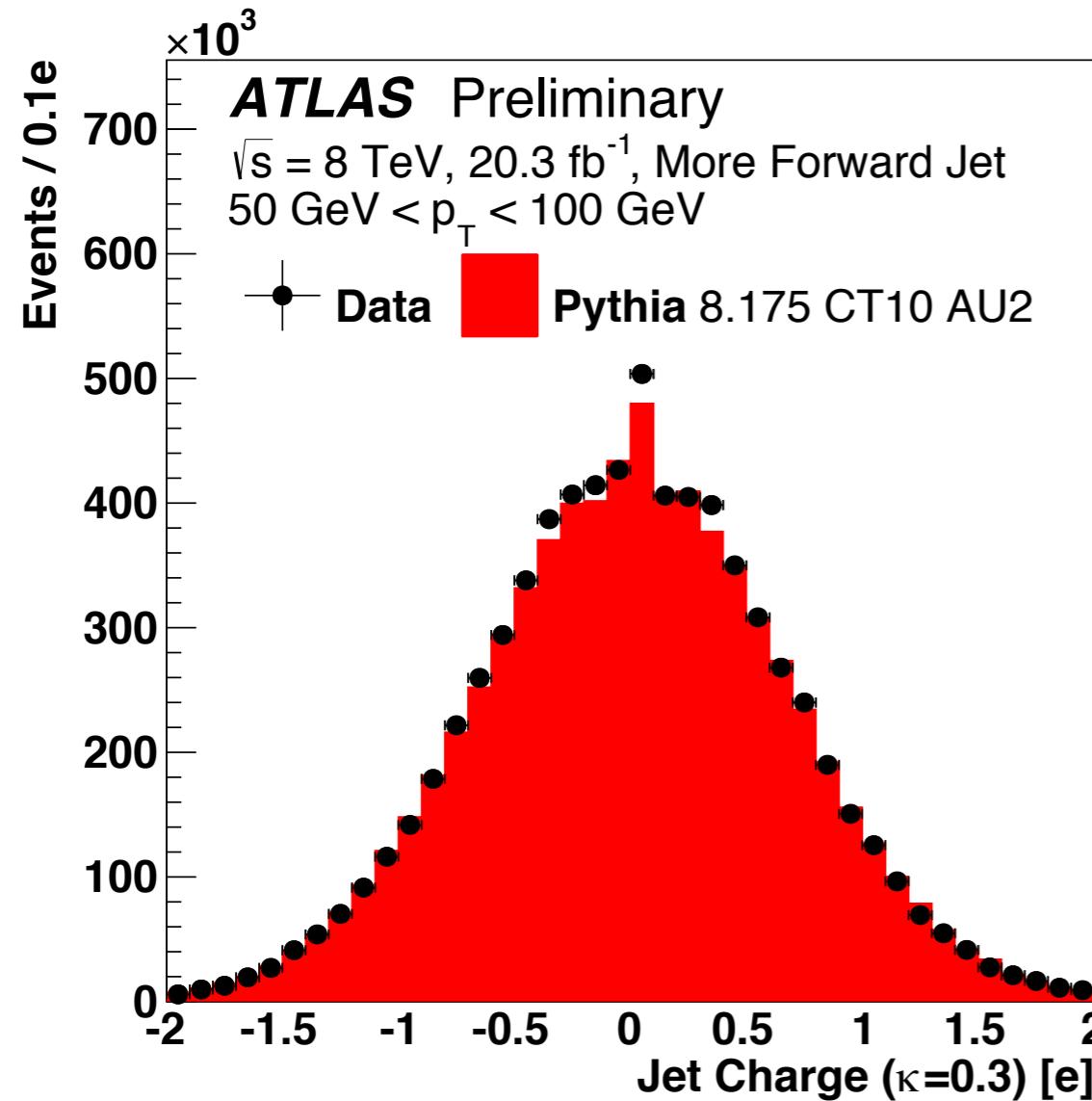
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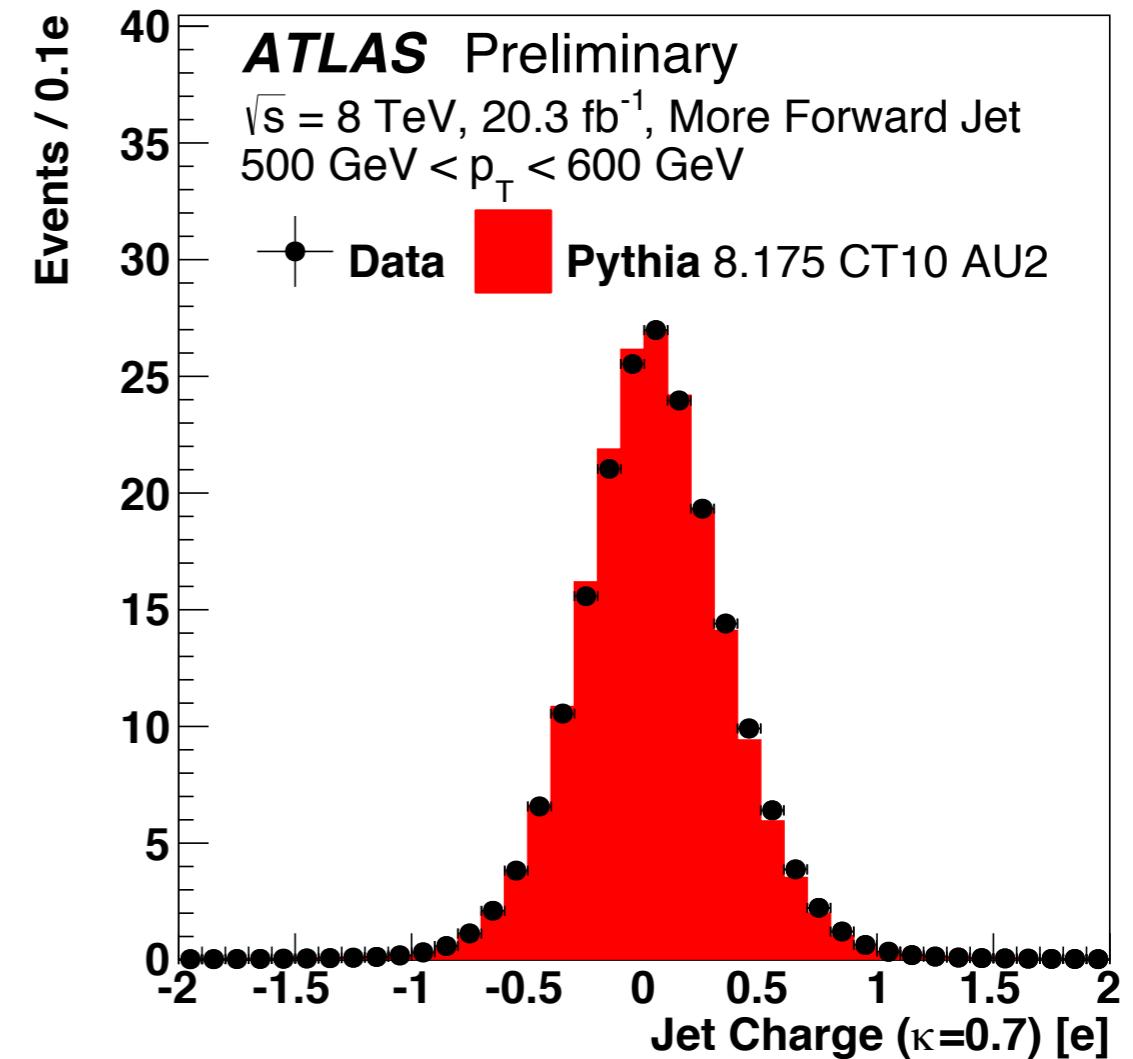
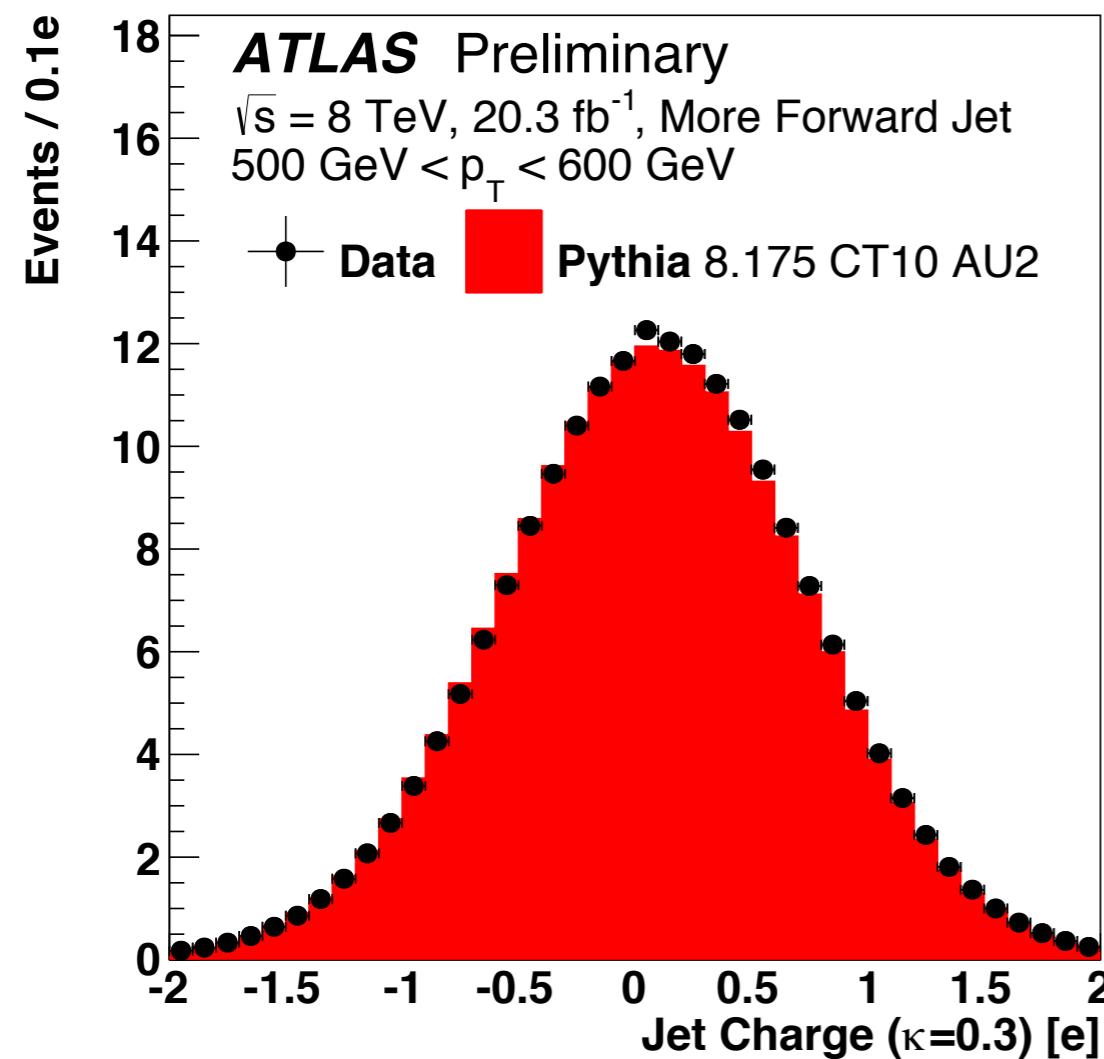
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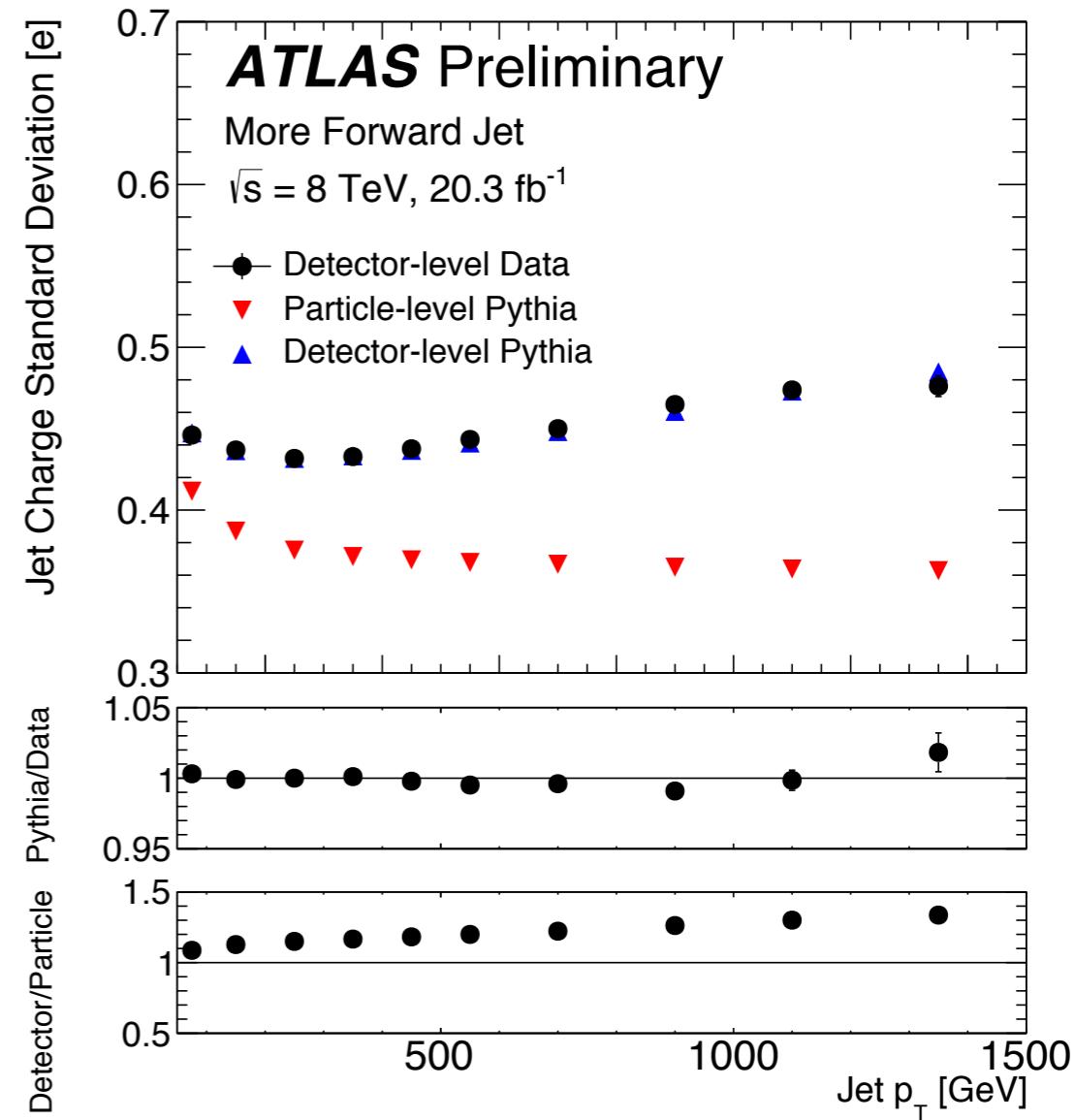
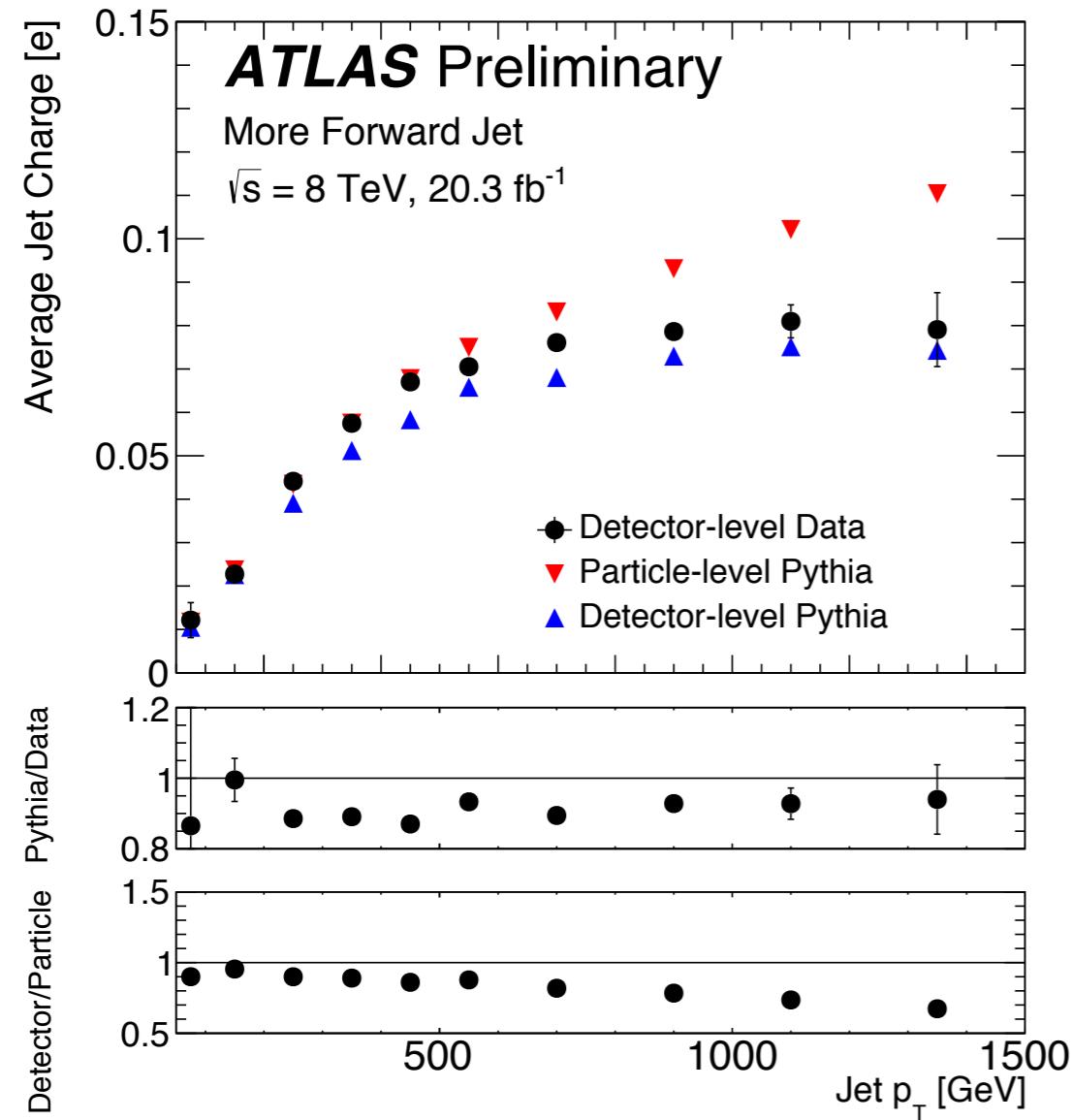
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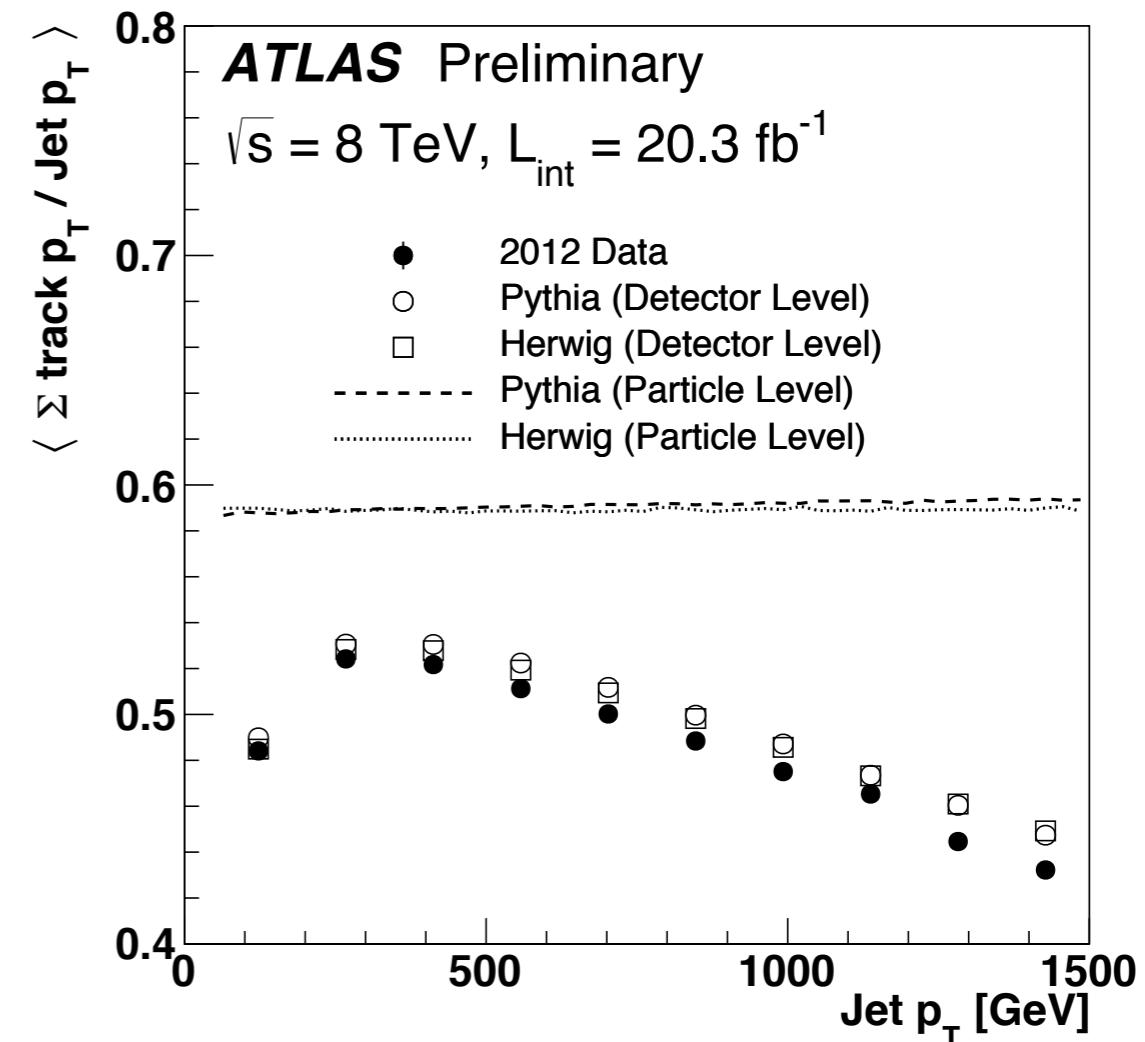
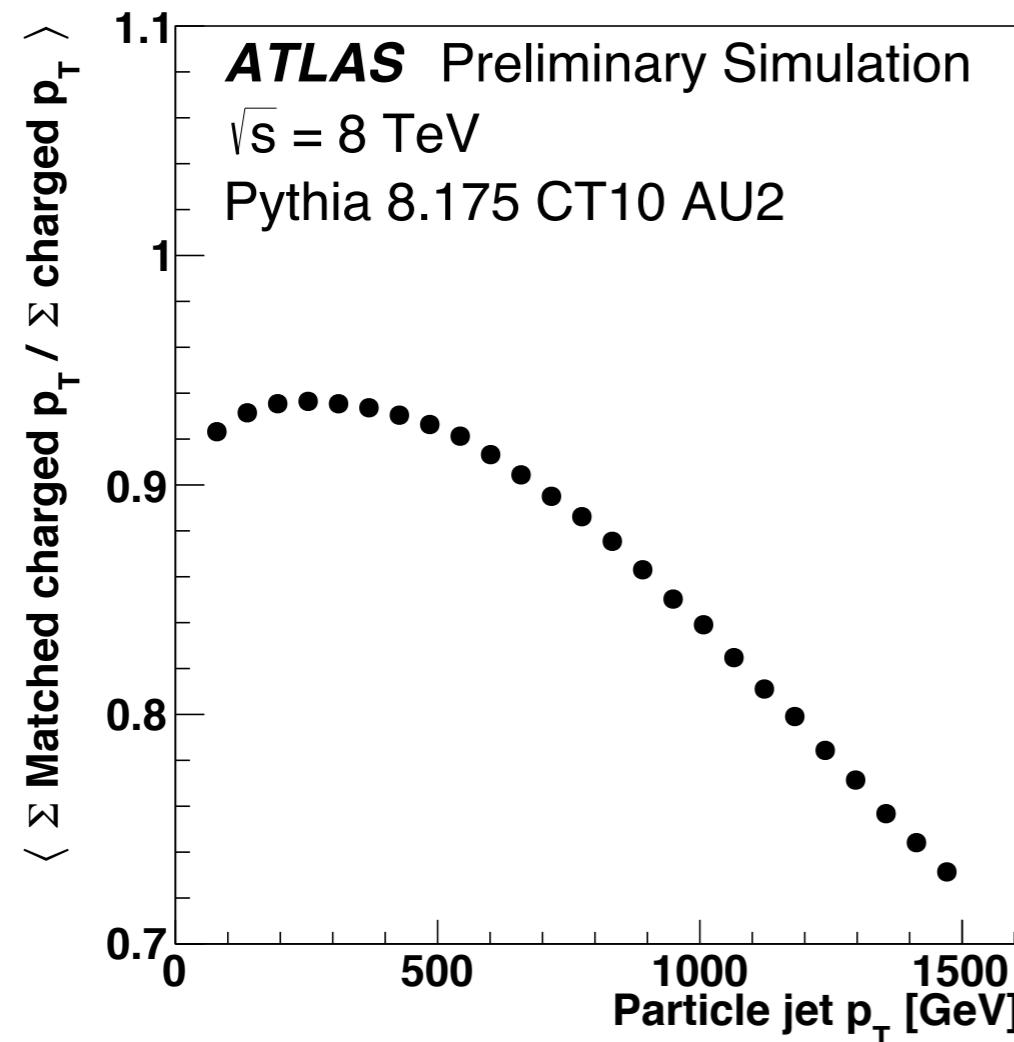
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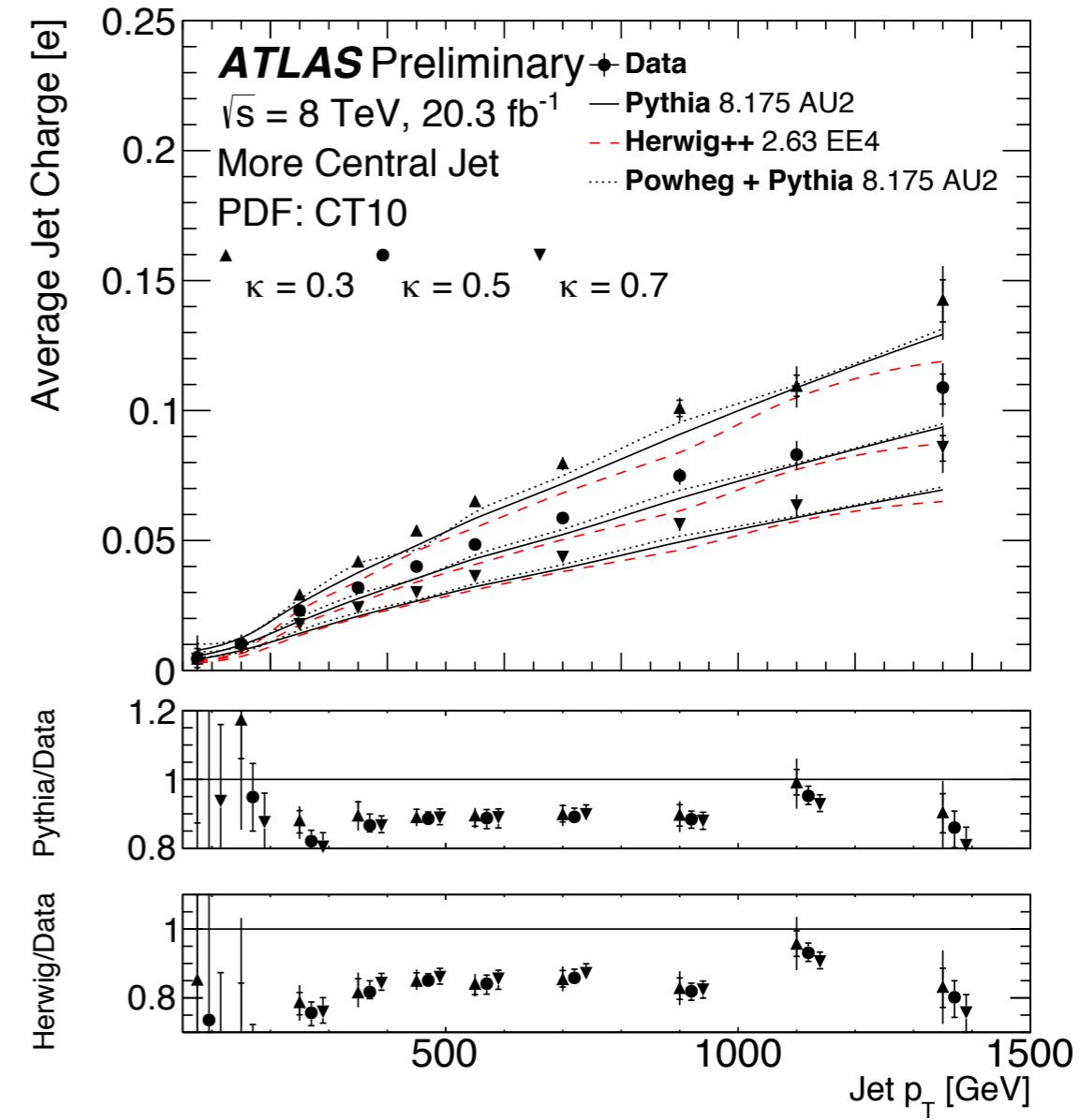
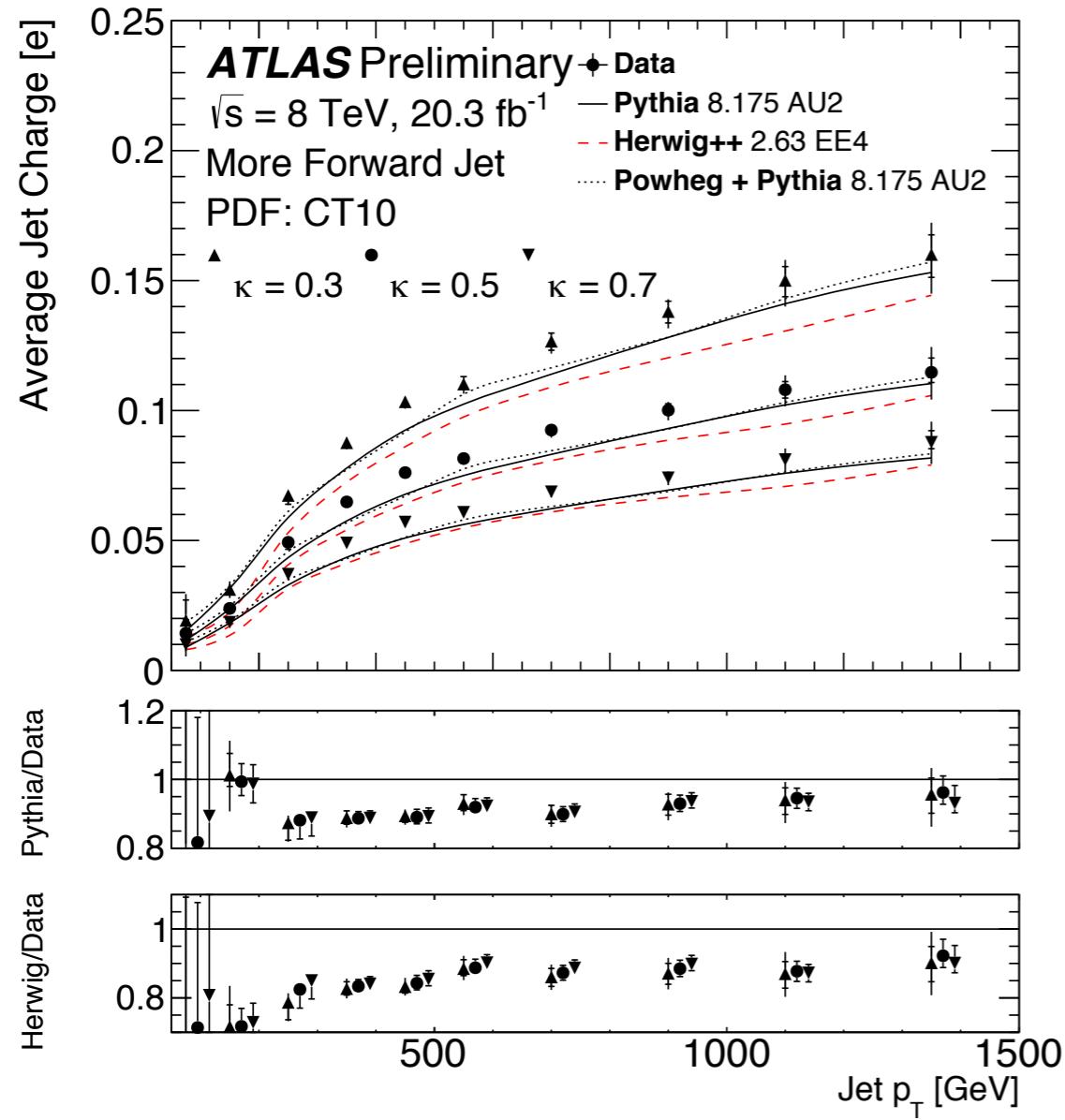
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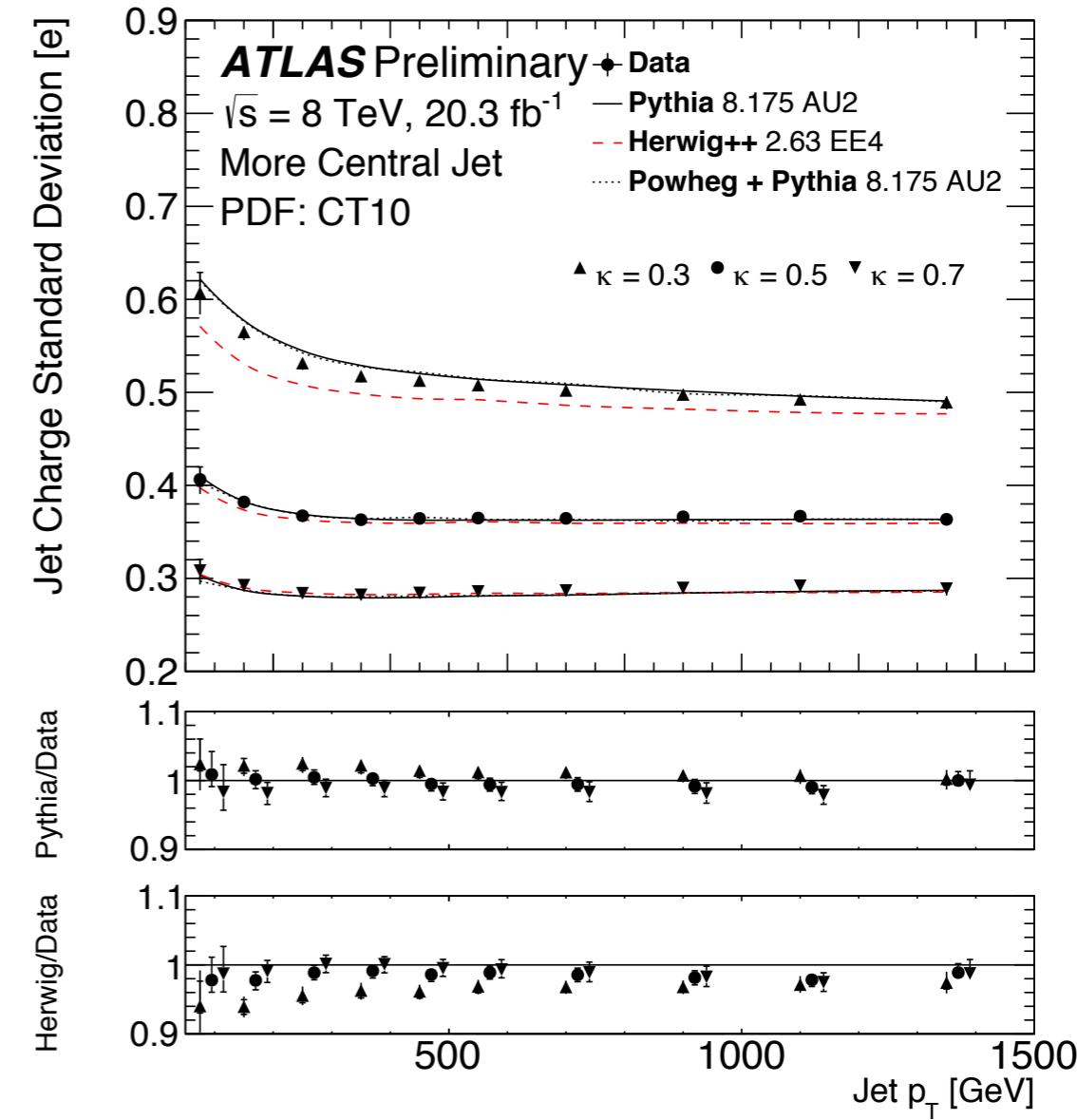
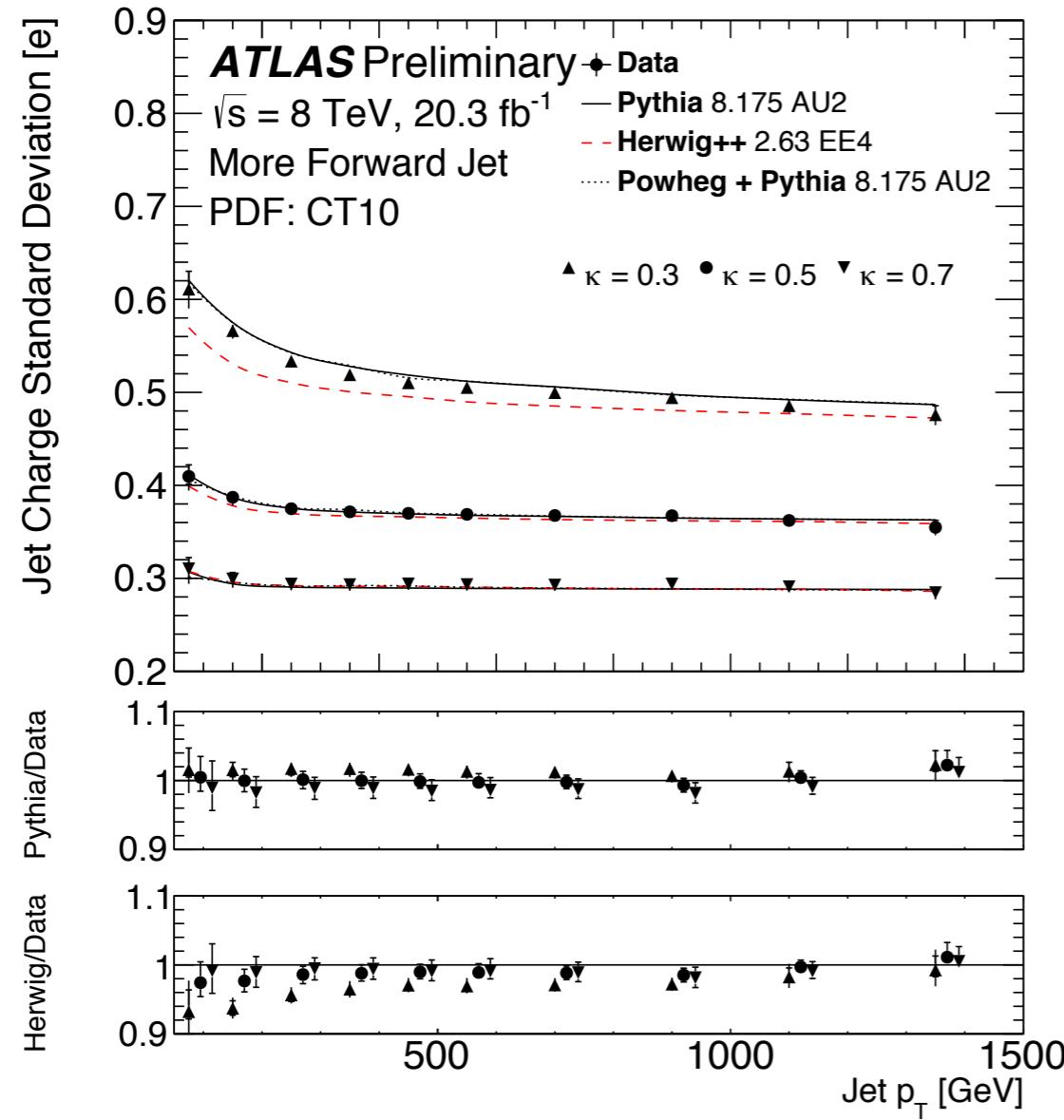
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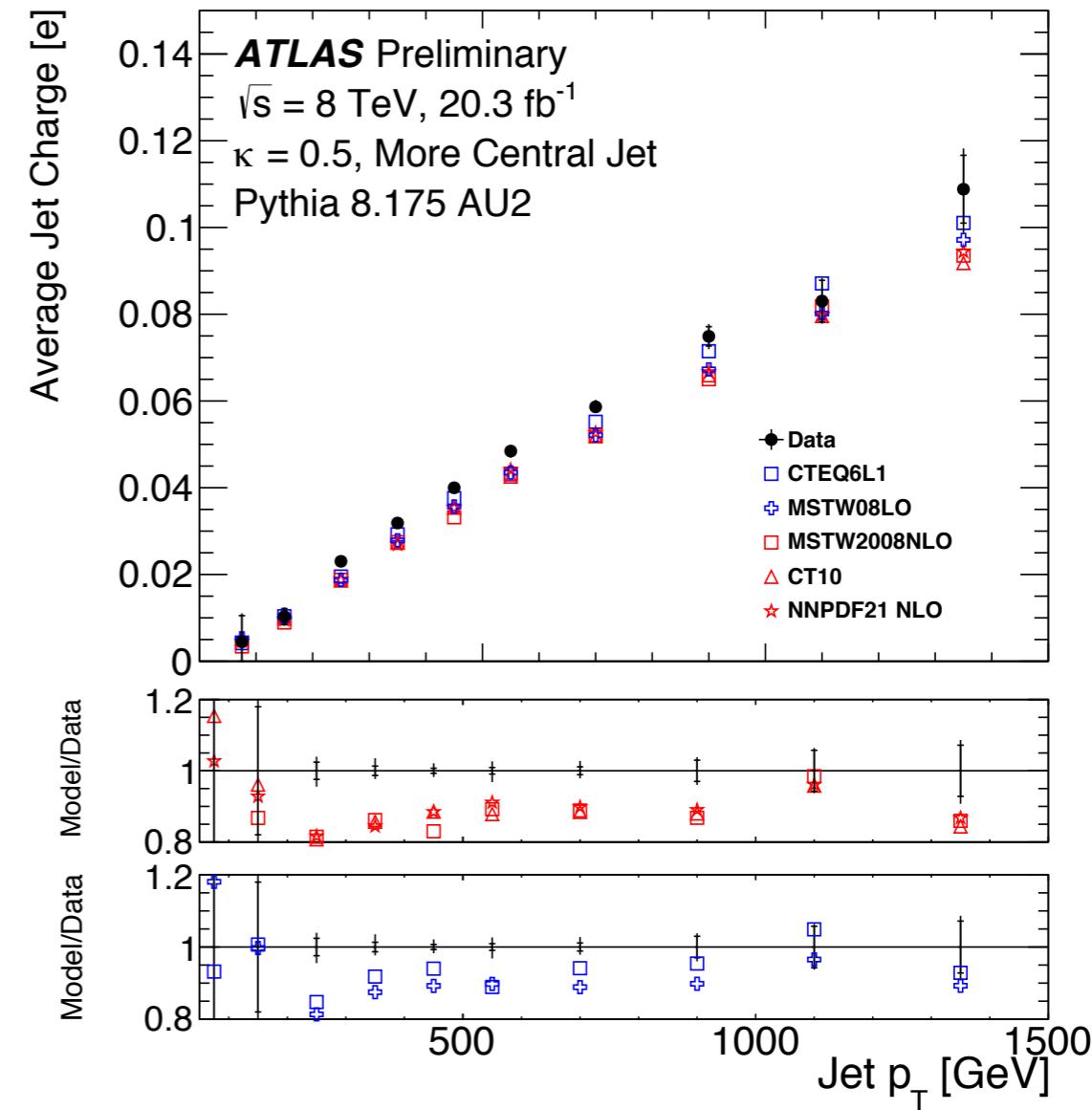
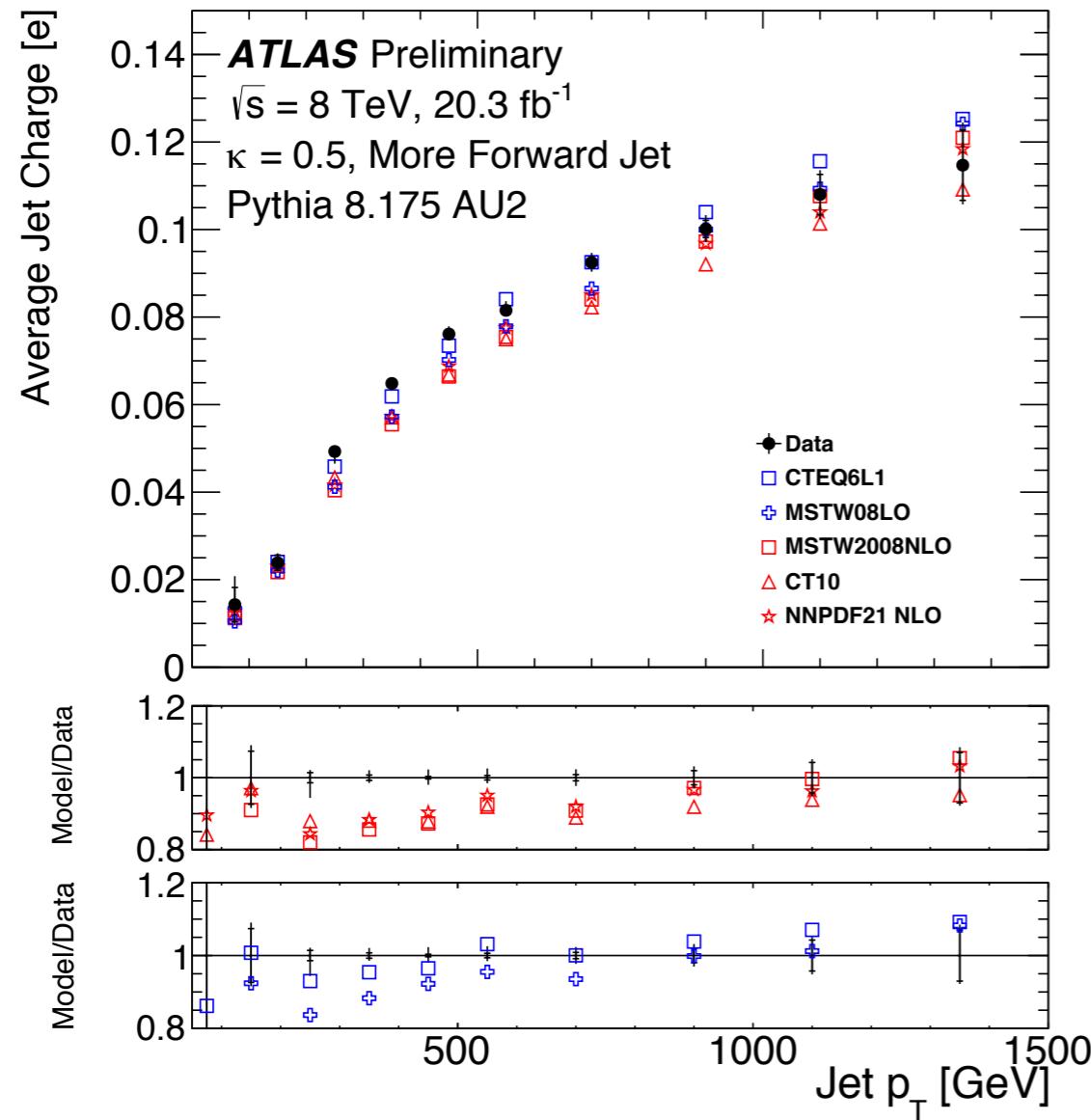
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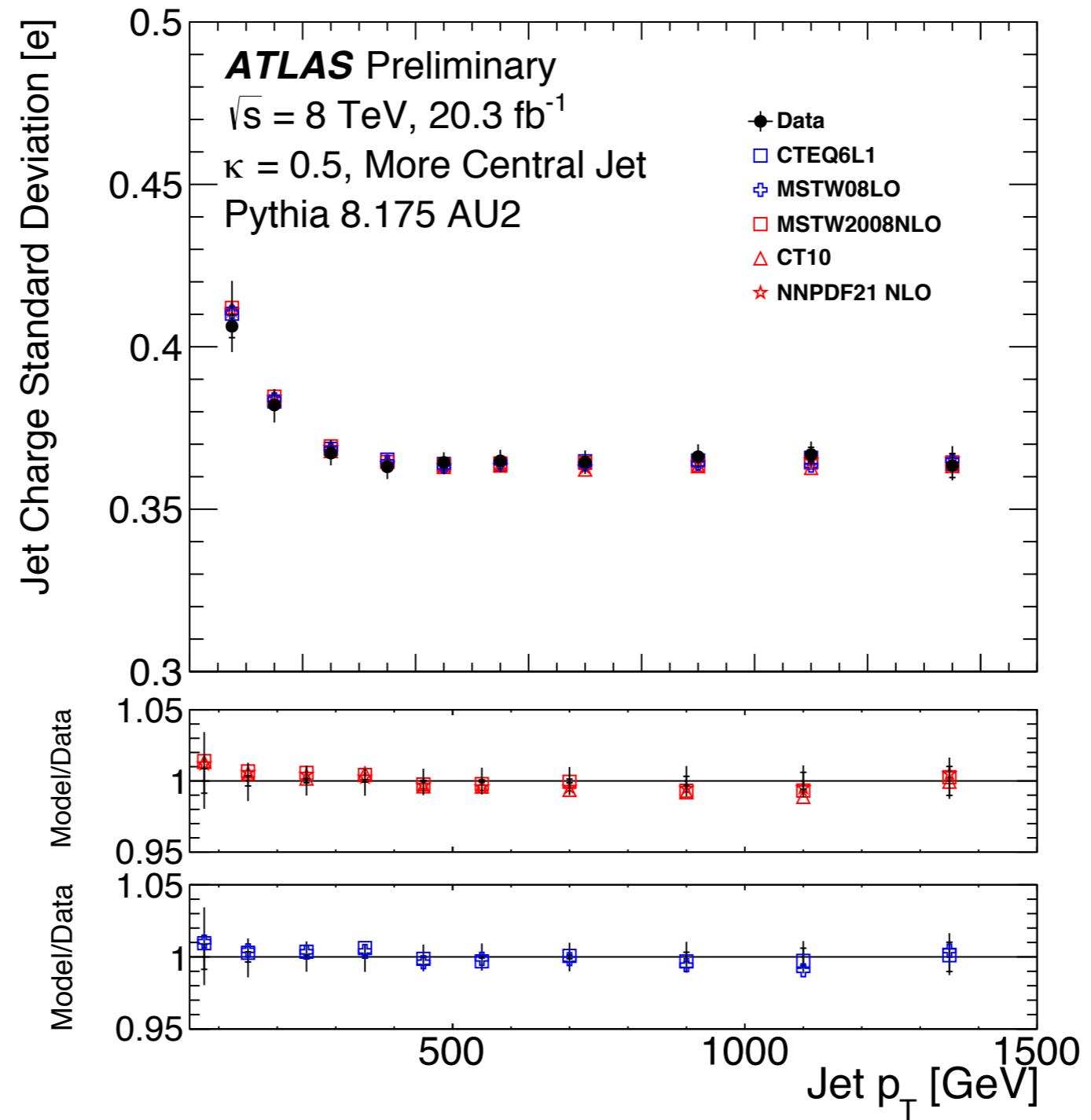
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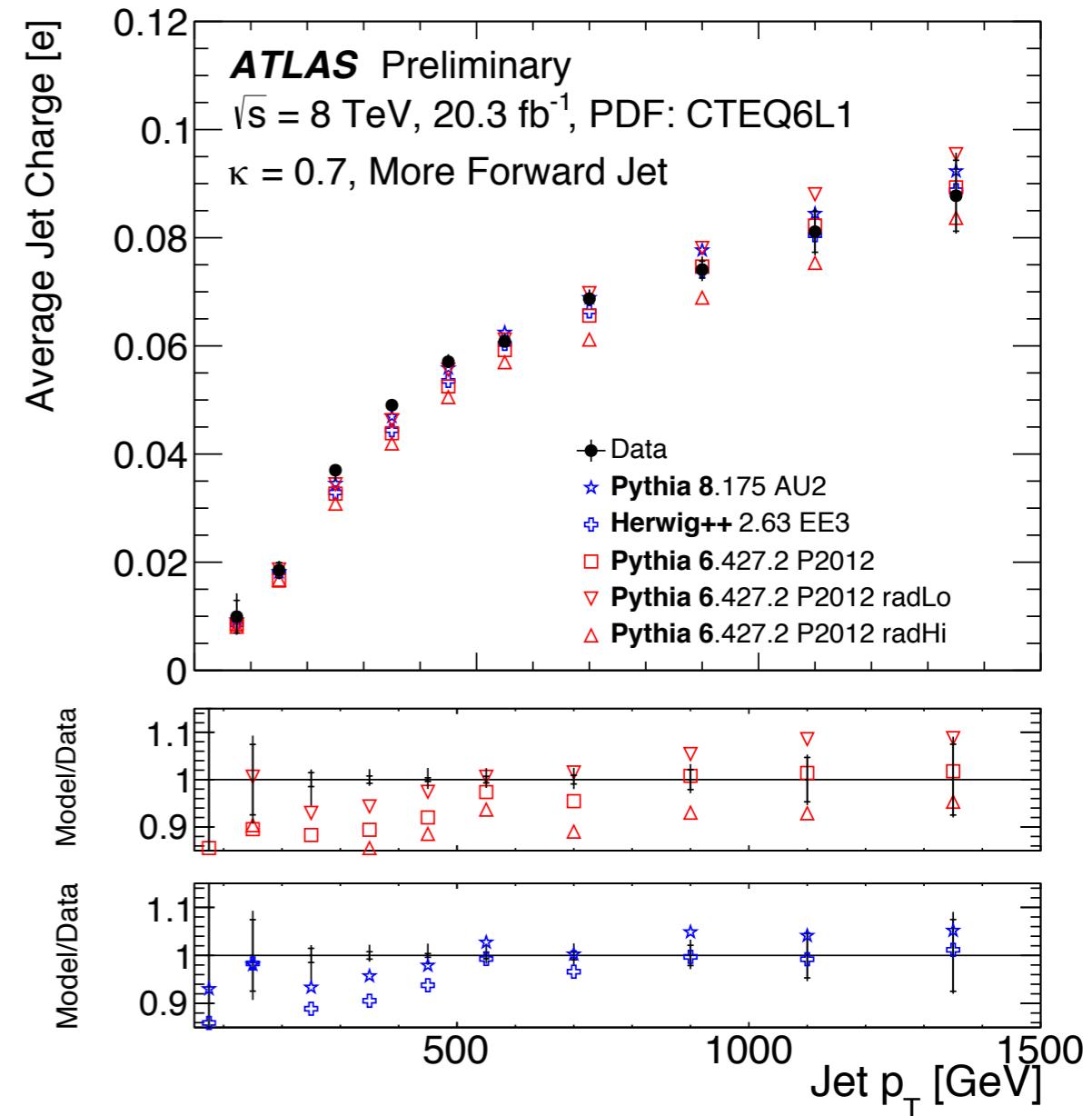
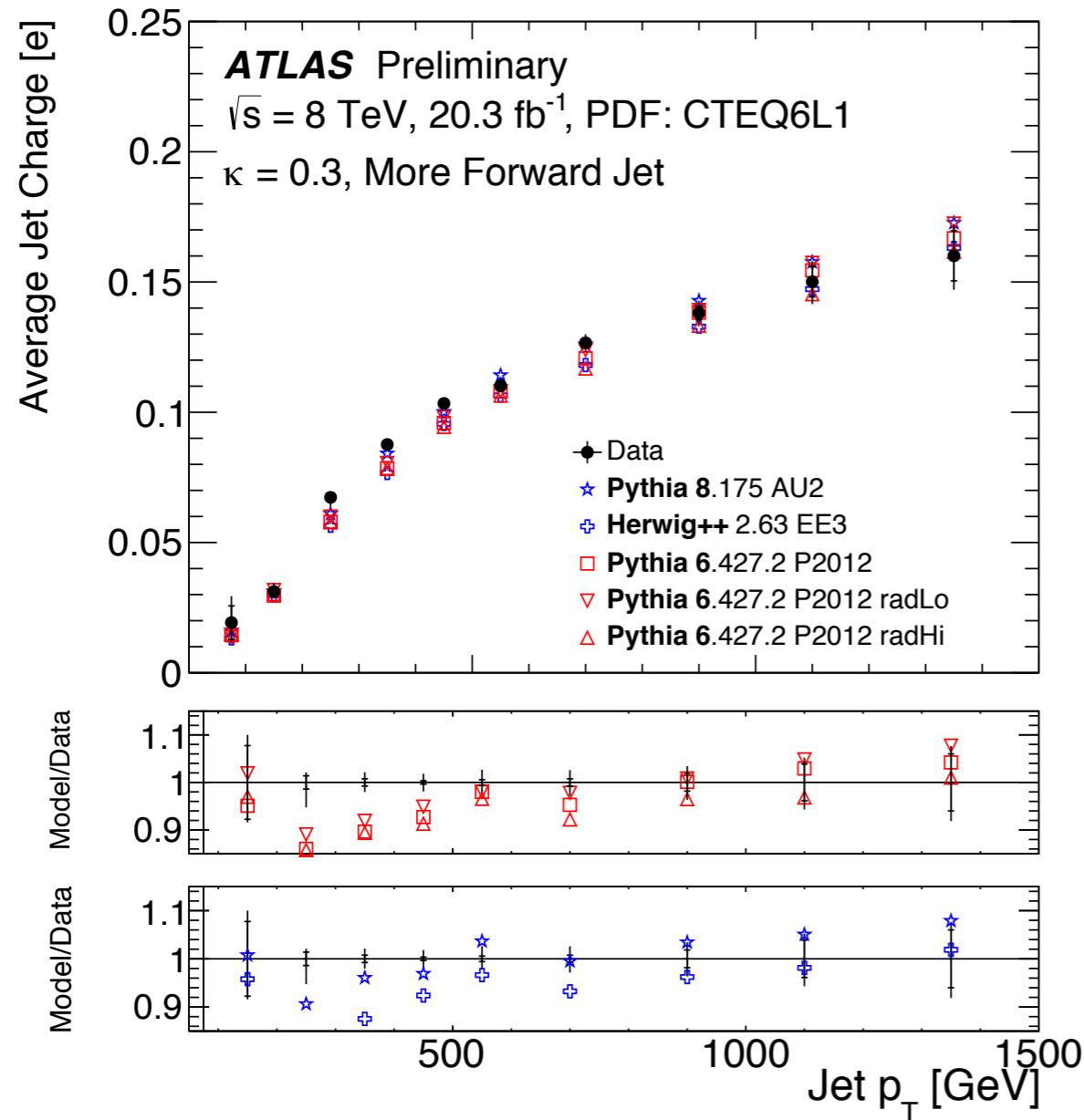
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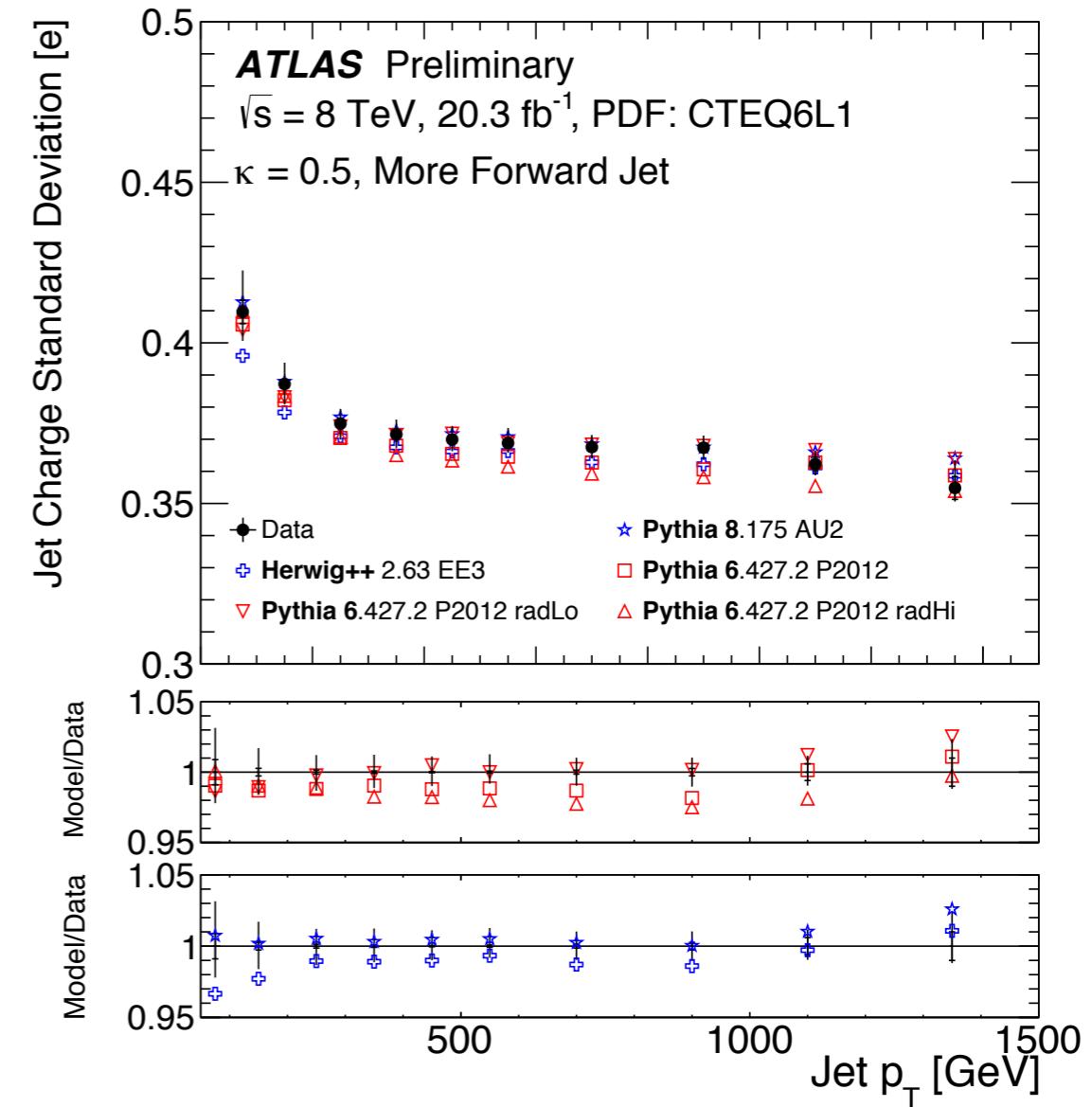
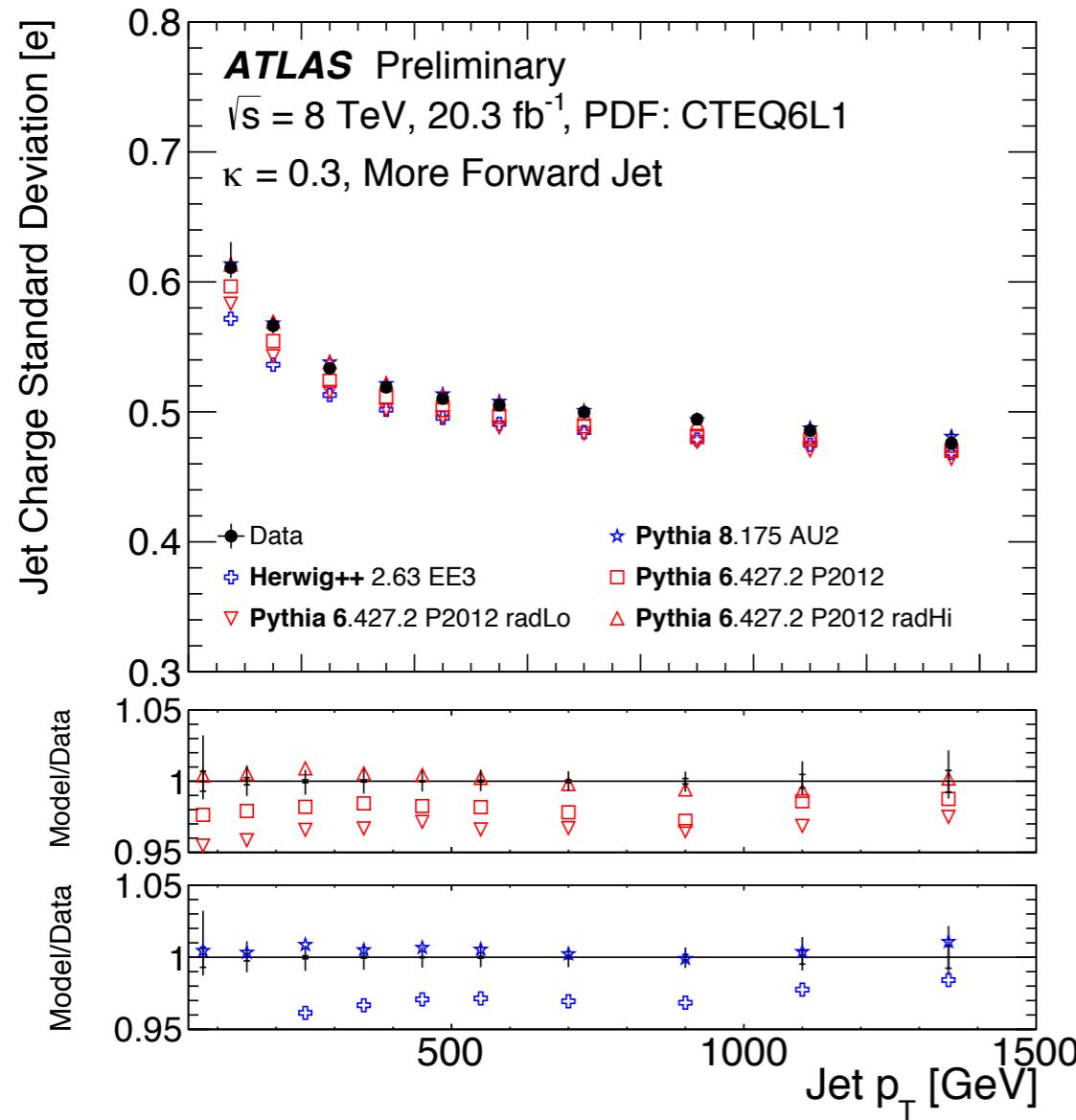
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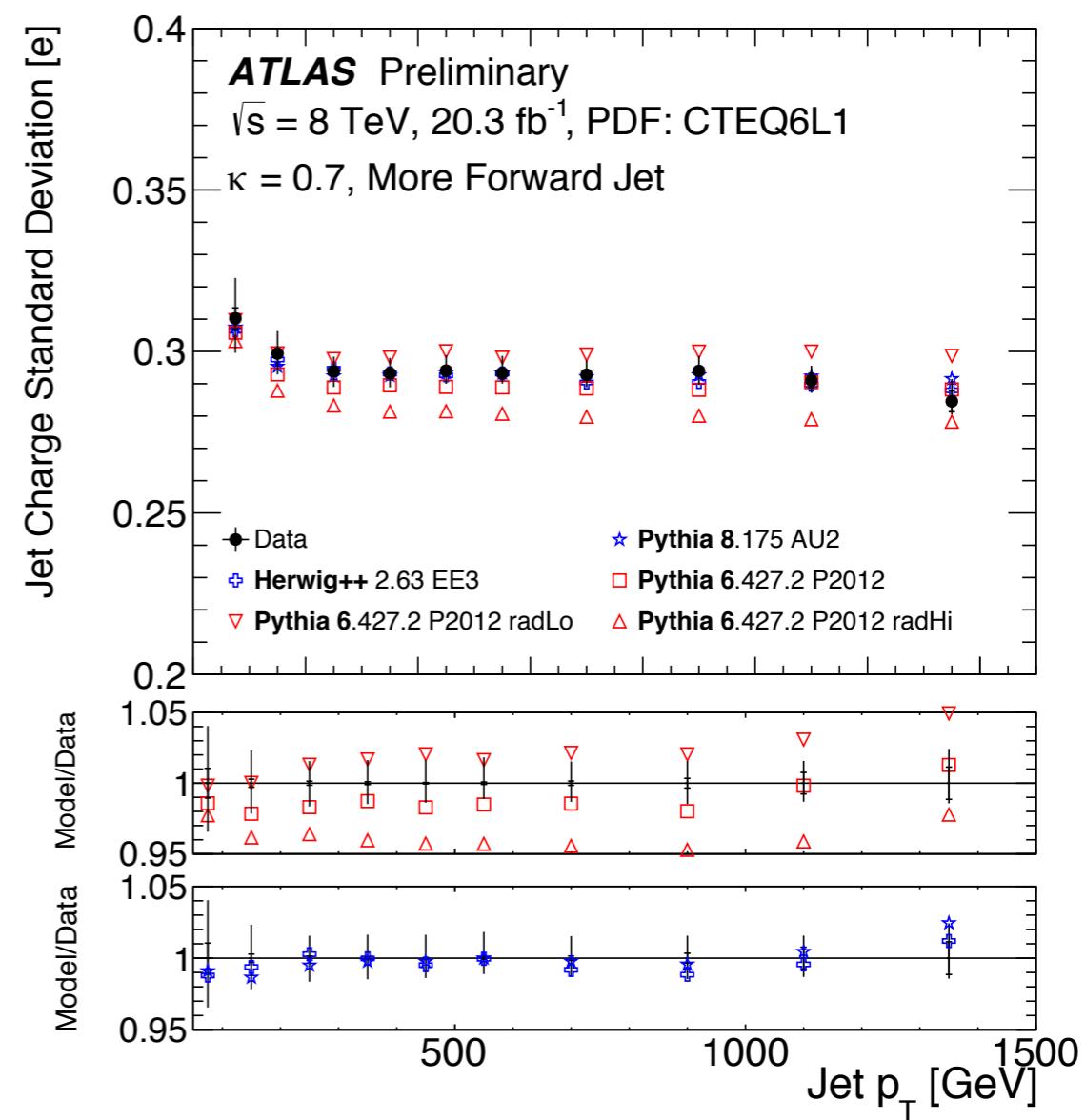
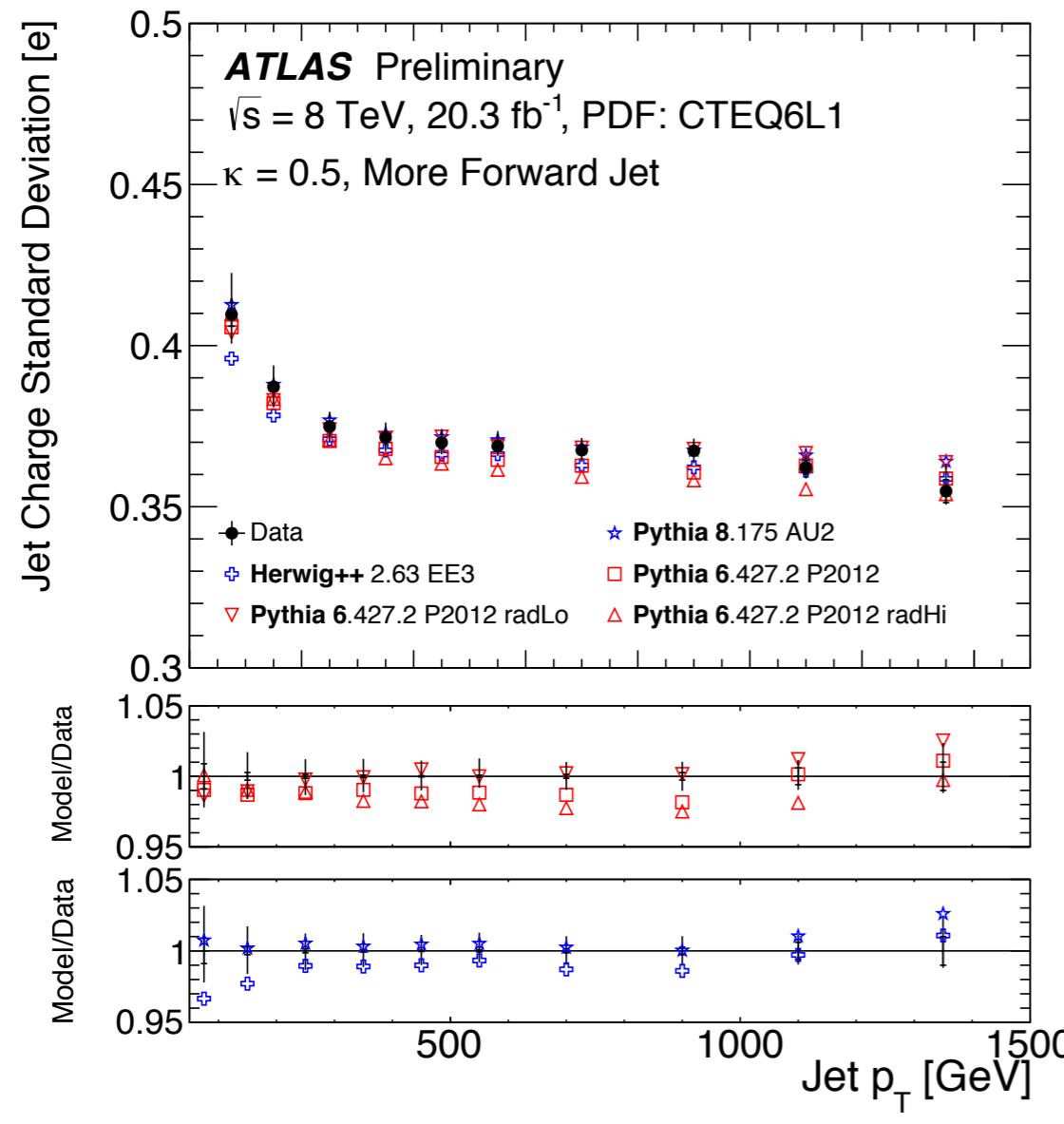
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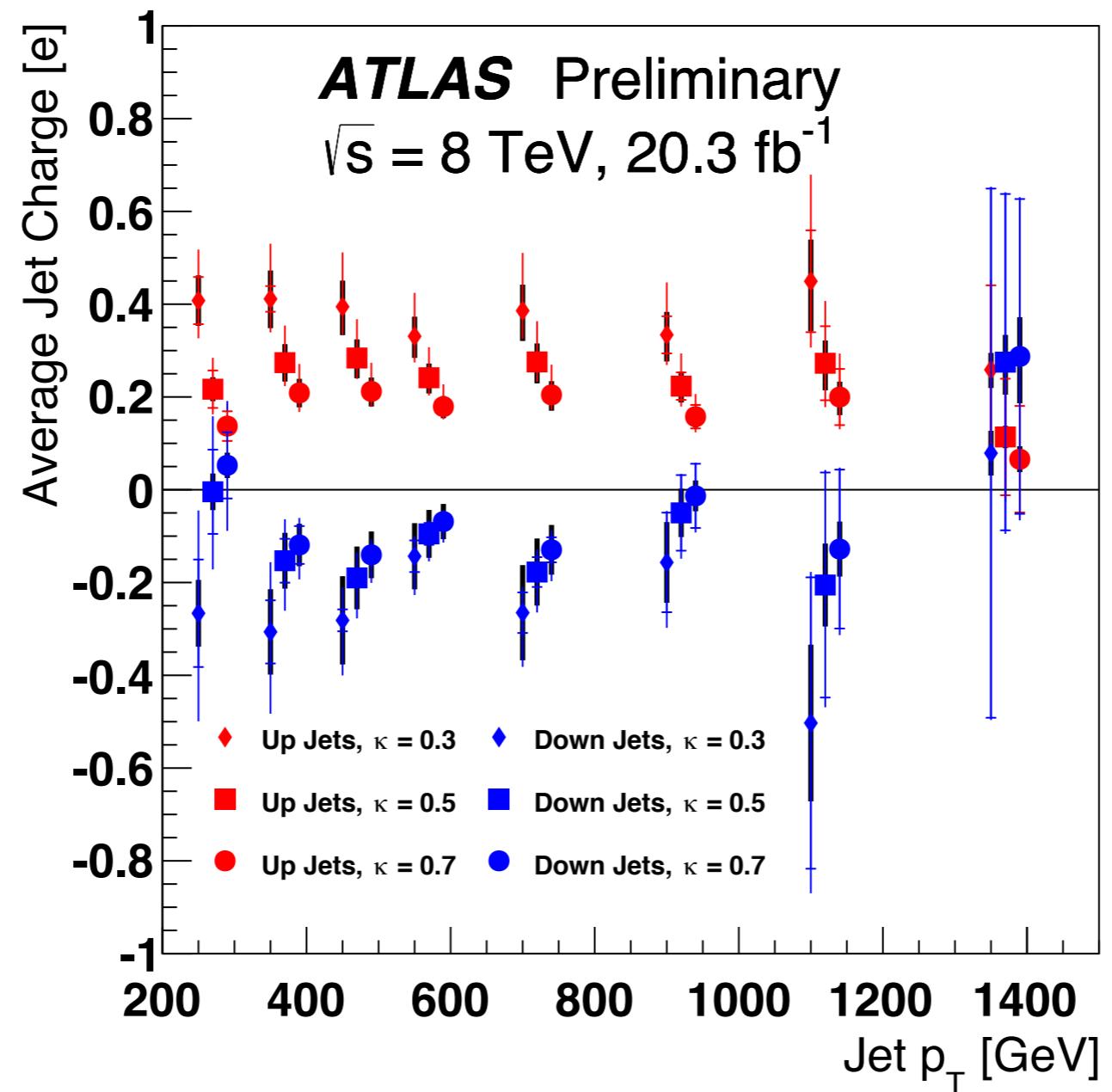
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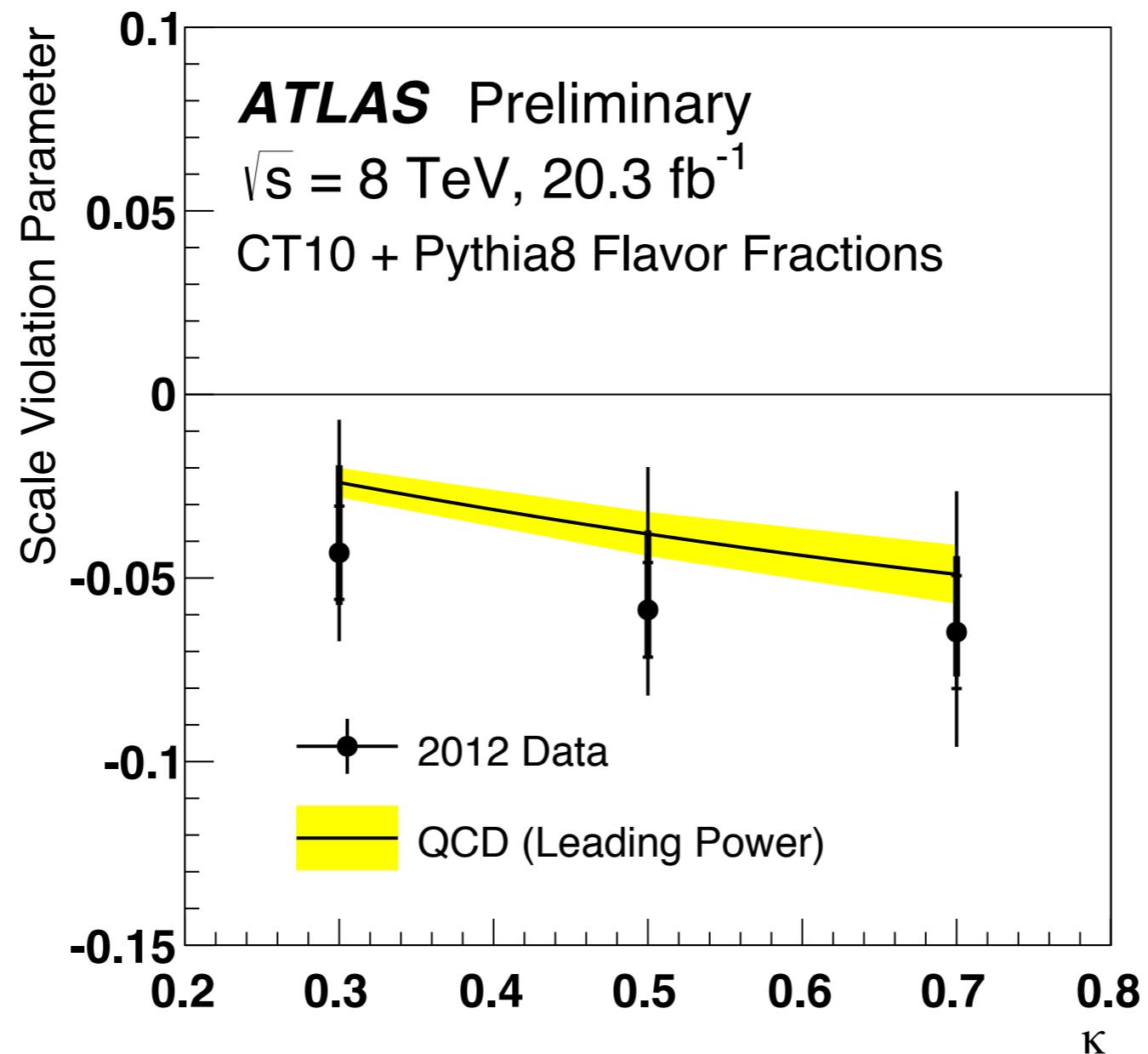
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Jet Charge Backup

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Jet Charge Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-025/>

Trigger threshold [GeV]	Offline Selection [GeV]	Luminosity [fb^{-1}]
25	[50,100]	7.84×10^{-5}
55	[100, 136]	4.42×10^{-4}
80	[136, 190]	2.32×10^{-3}
110	[190, 200]	9.81×10^{-3}
145	[200, 225]	3.63×10^{-2}
180	[225, 250]	7.88×10^{-2}
220	[250, 300]	2.61×10^{-1}
280	[300, 400]	1.16
360	≥ 400	20.3

Jet Charge Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-025/>

Average Jet Charge Systematic Uncertainty [%]	Jet p_T Range [100 GeV]									
	[0.5,1]	[1,2]	[2,3]	[3,4]	[4,5]	[5,6]	[6,8]	[8,10]	[10,12]	[12,15]
Correction Factors	23	0.9	0.8	1.0	0.3	0.6	0.1	0.3	0.2	0.1
Total JES	8.8	3.8	0.9	0.8	1.1	1.1	0.7	0.7	0.4	0.9
JER	6.8	2.3	0.7	0.7	0.3	0.3	0.1	0.1	0.1	0.3
Charged Energy Loss	0.0	0.0	0.0	0.0	1.7	1.5	1.5	1.5	1.6	3.6
Track Multiplicity	1.5	0.1	0.6	1.1	0.8	0.6	1.2	1.4	2.1	2.9
Other Tracking	3.6	0.4	0.9	0.7	0.6	1.5	1.2	1.6	1.7	1.9
Unfolding Procedure	28	2.4	0.3	0.2	0.2	0.3	1.1	1.0	1.6	0.6
Total Systematic	38	5.1	1.8	2.0	2.4	2.6	2.6	2.9	3.6	5.1
Data Statistics	28	7.4	1.4	0.7	0.3	0.6	0.9	2.0	4.2	7.0

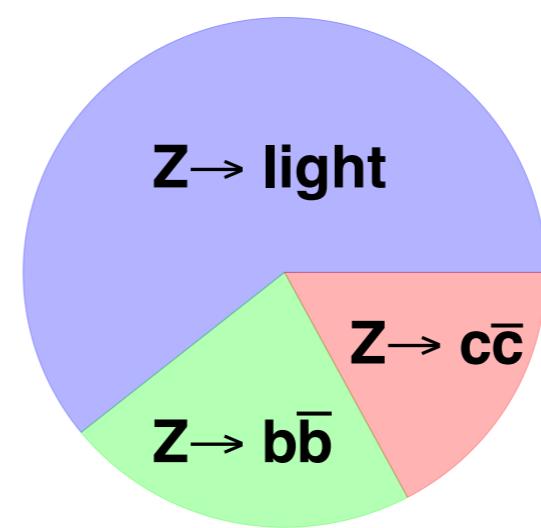
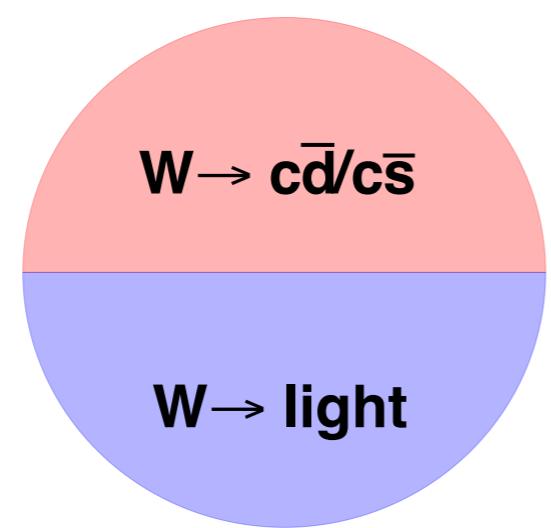
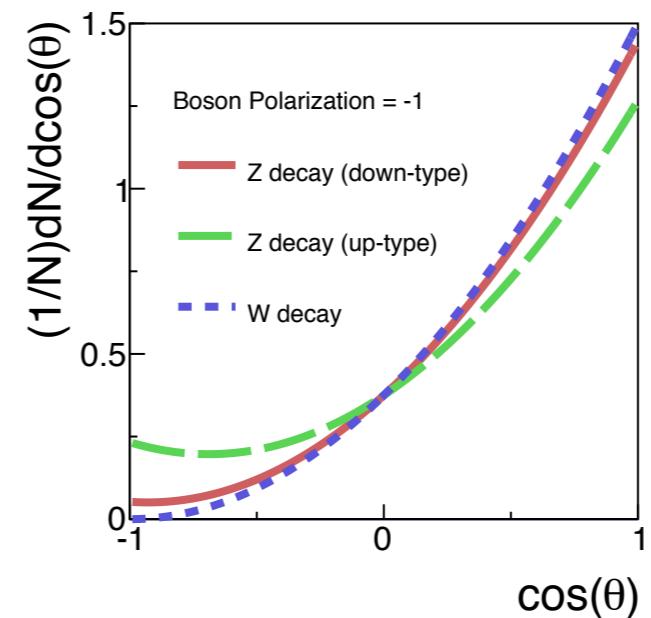
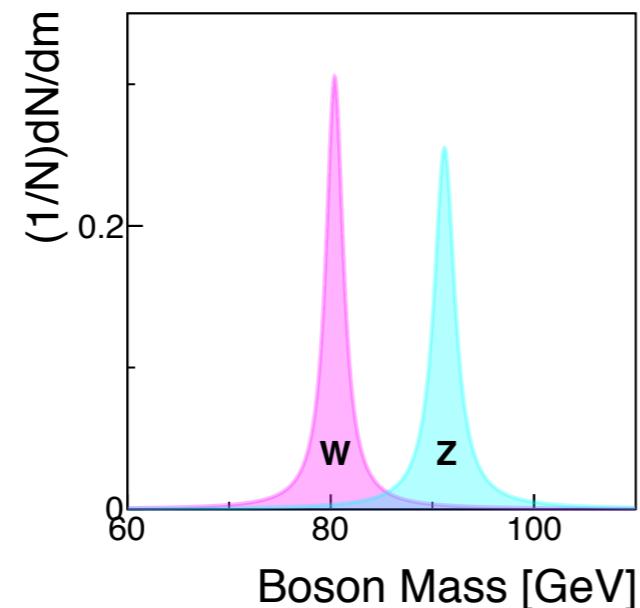
Jet Charge Backup

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-025/>

Standard Deviation	Jet p_T Range [100 GeV]										
	Systematic Uncertainty [%]	[0.5,1]	[1,2]	[2,3]	[3,4]	[4,5]	[5,6]	[6,8]	[8,10]	[10,12]	[12,15]
Correction Factors	0.9	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Total JES	1.9	1.5	1.1	1.1	0.9	1.0	0.8	0.7	0.5	0.5	0.5
JER	1.3	0.3	0.1	0.2	0.3	0.4	0.2	0.2	0.2	0.2	0.2
Charged Energy Loss	0.0	0.0	0.0	0.0	0.2	0.3	0.3	0.3	0.4	1.1	
Track Multiplicity	0.2	0.3	0.2	0.1	0.0	0.1	0.2	0.2	0.3	0.2	
Other Tracking	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.6	
Unfolding Procedure	1.9	0.4	0.0	0.1	0.2	0.0	0.1	0.3	0.4	1.7	
Total Systematic	3.1	1.6	1.2	1.2	1.2	1.3	1.1	1.1	1.0	2.1	
Data Statistics	0.9	0.3	0.1	0.1	0.0	0.1	0.1	0.3	0.6	1.0	

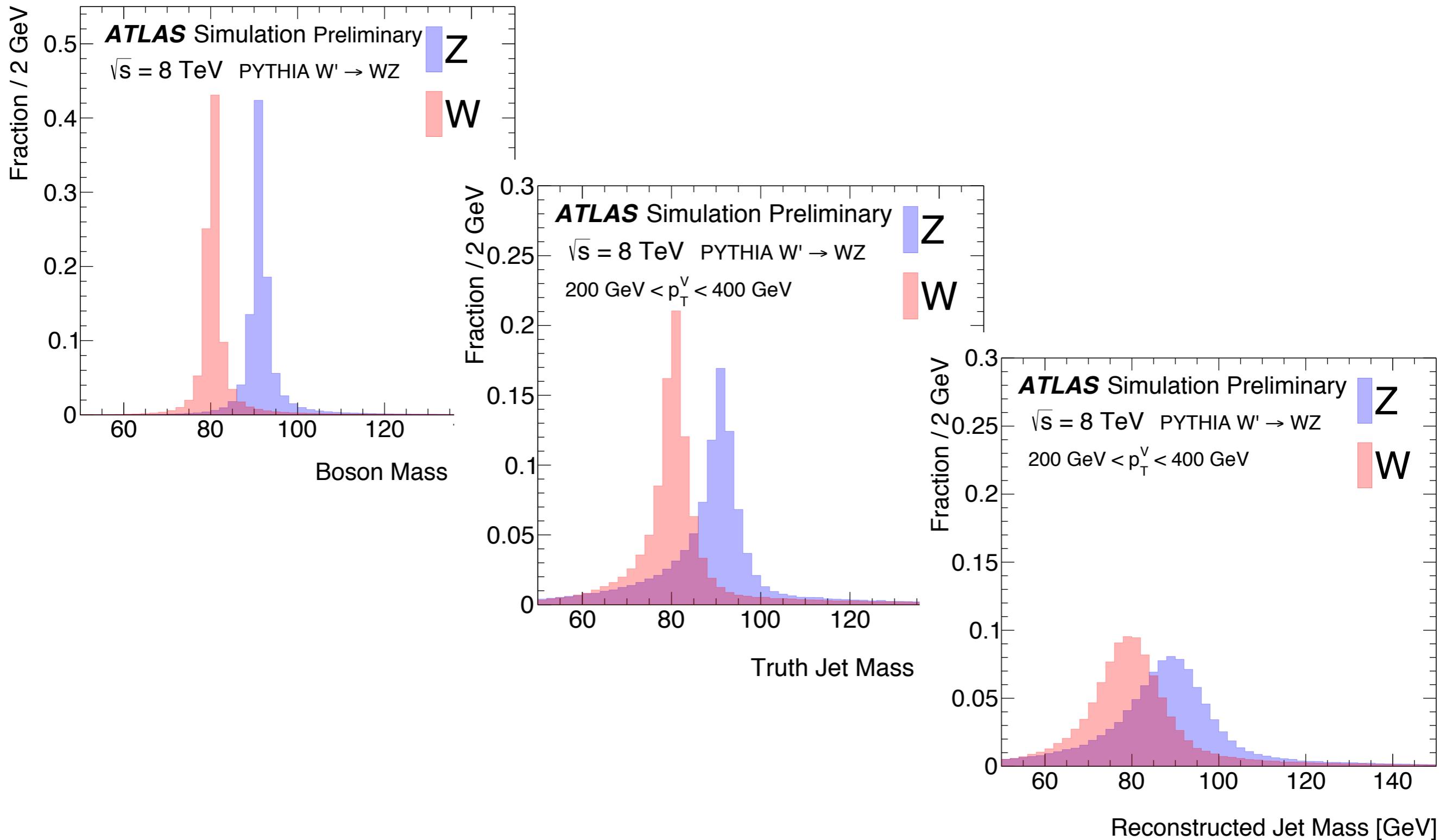
W/Z Tagger Backup

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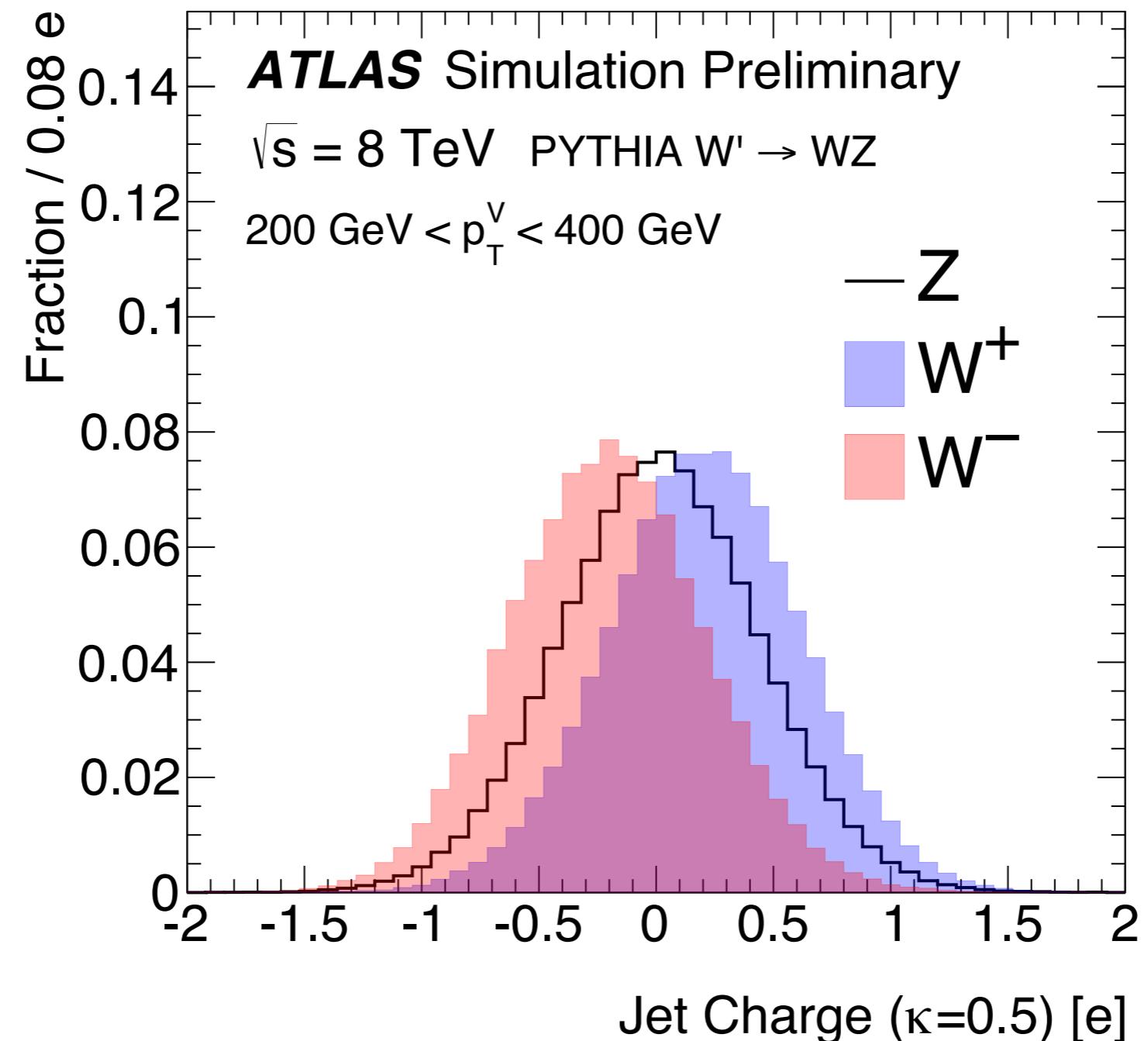
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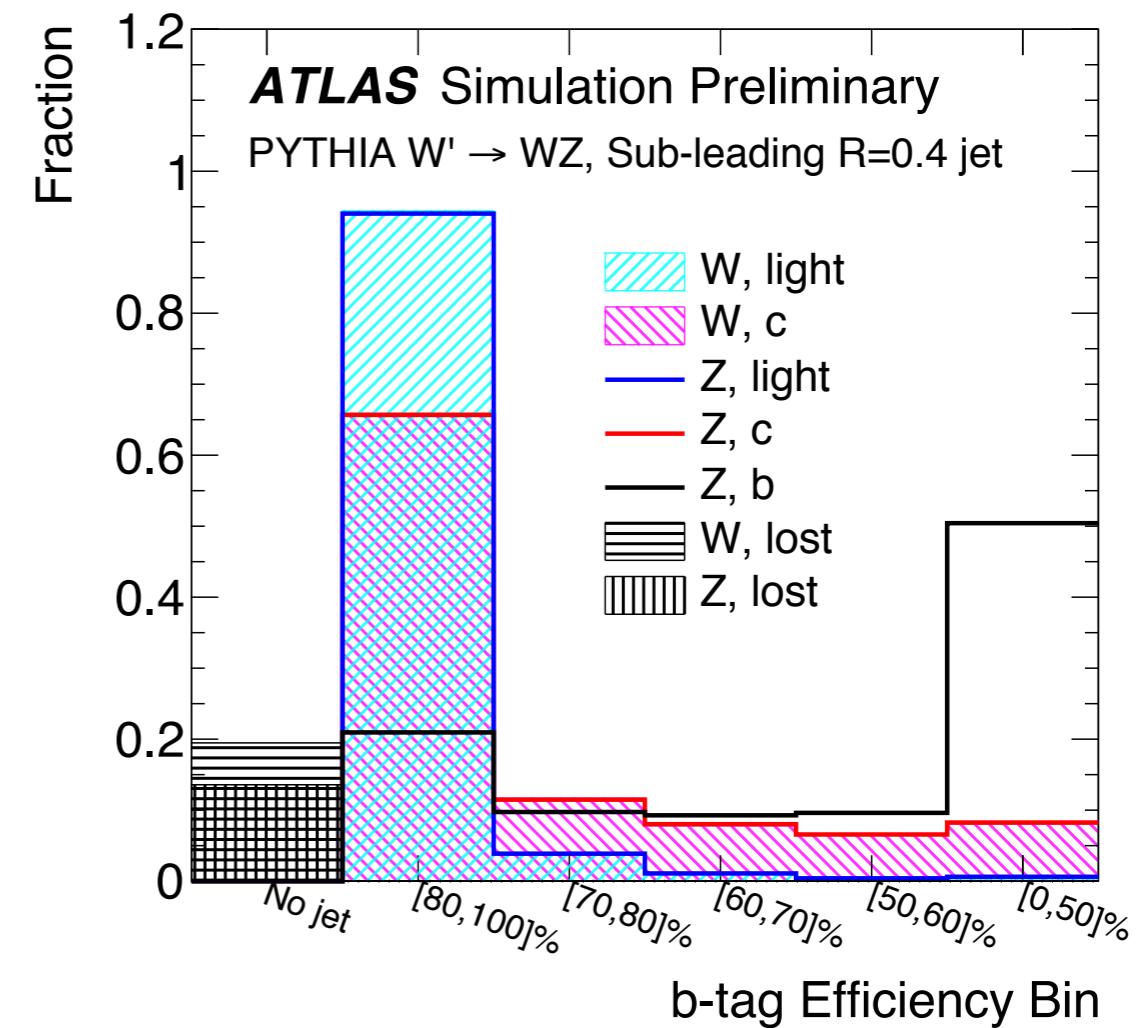
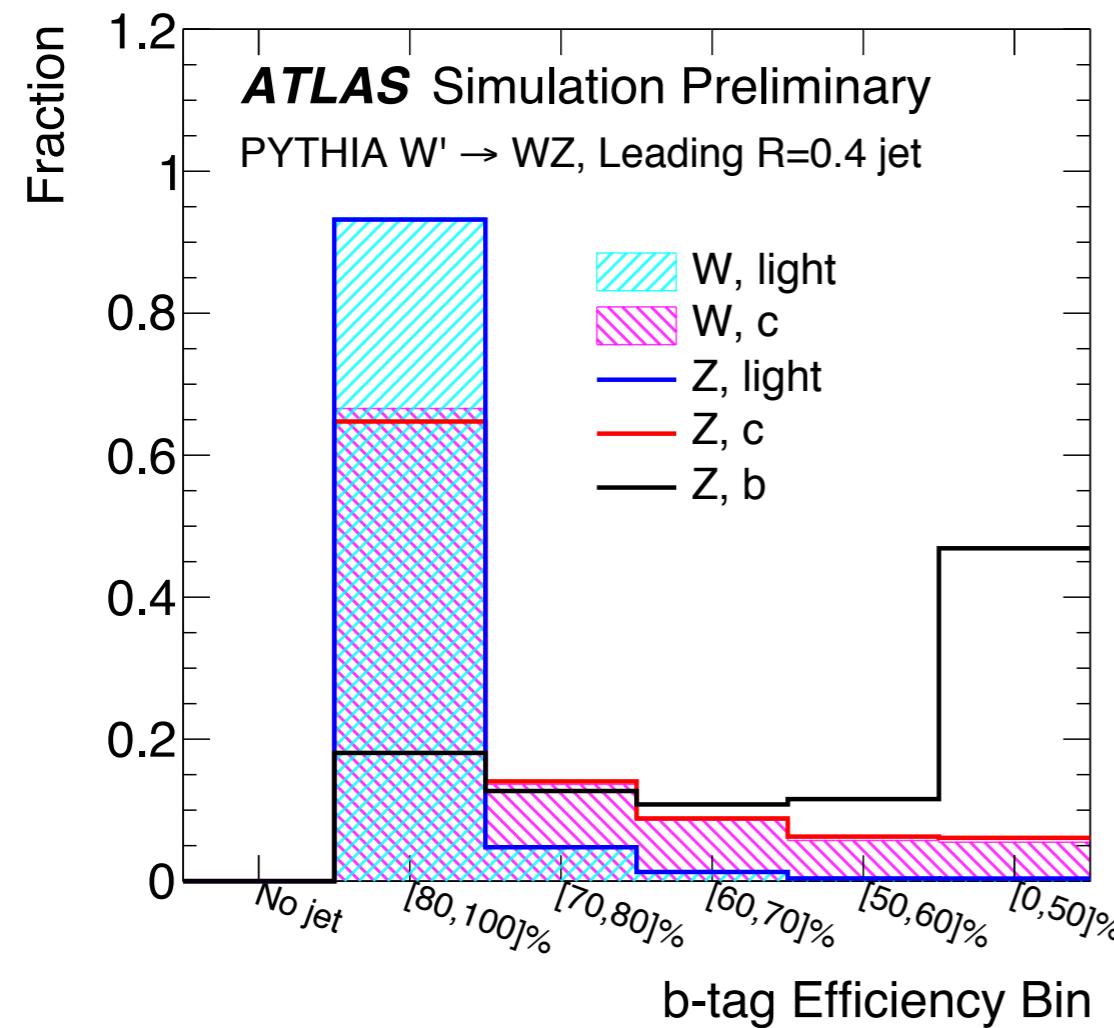
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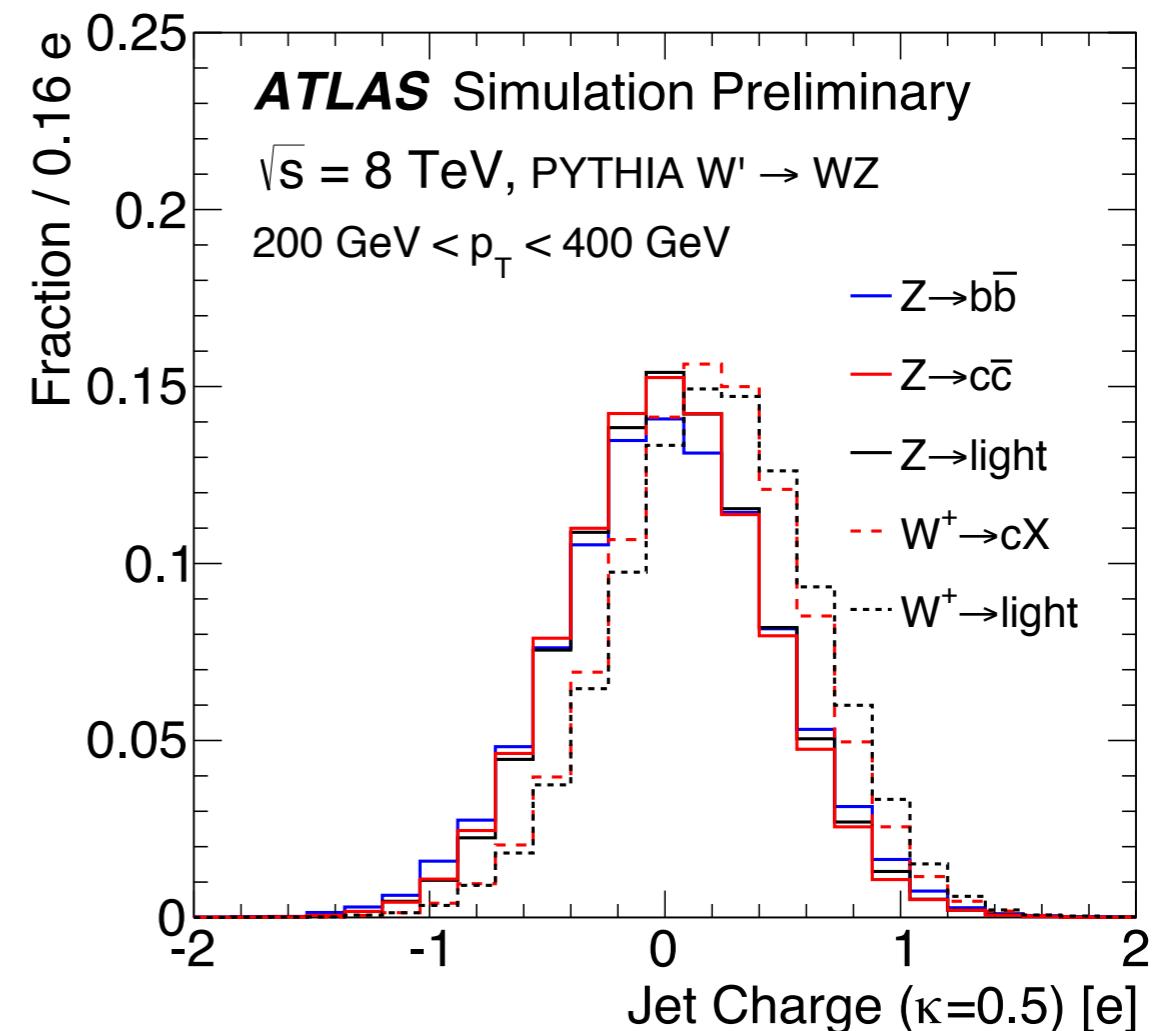
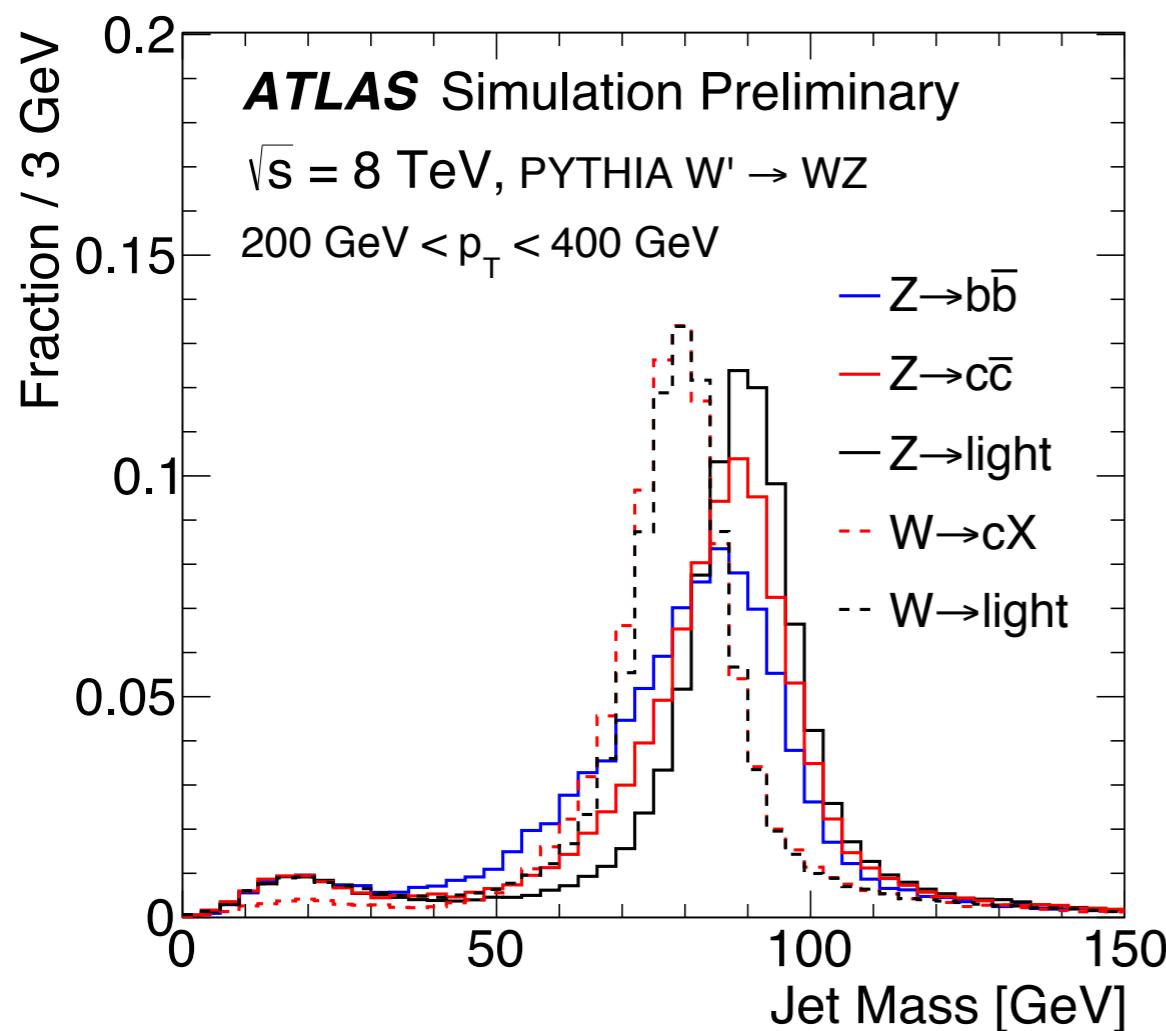
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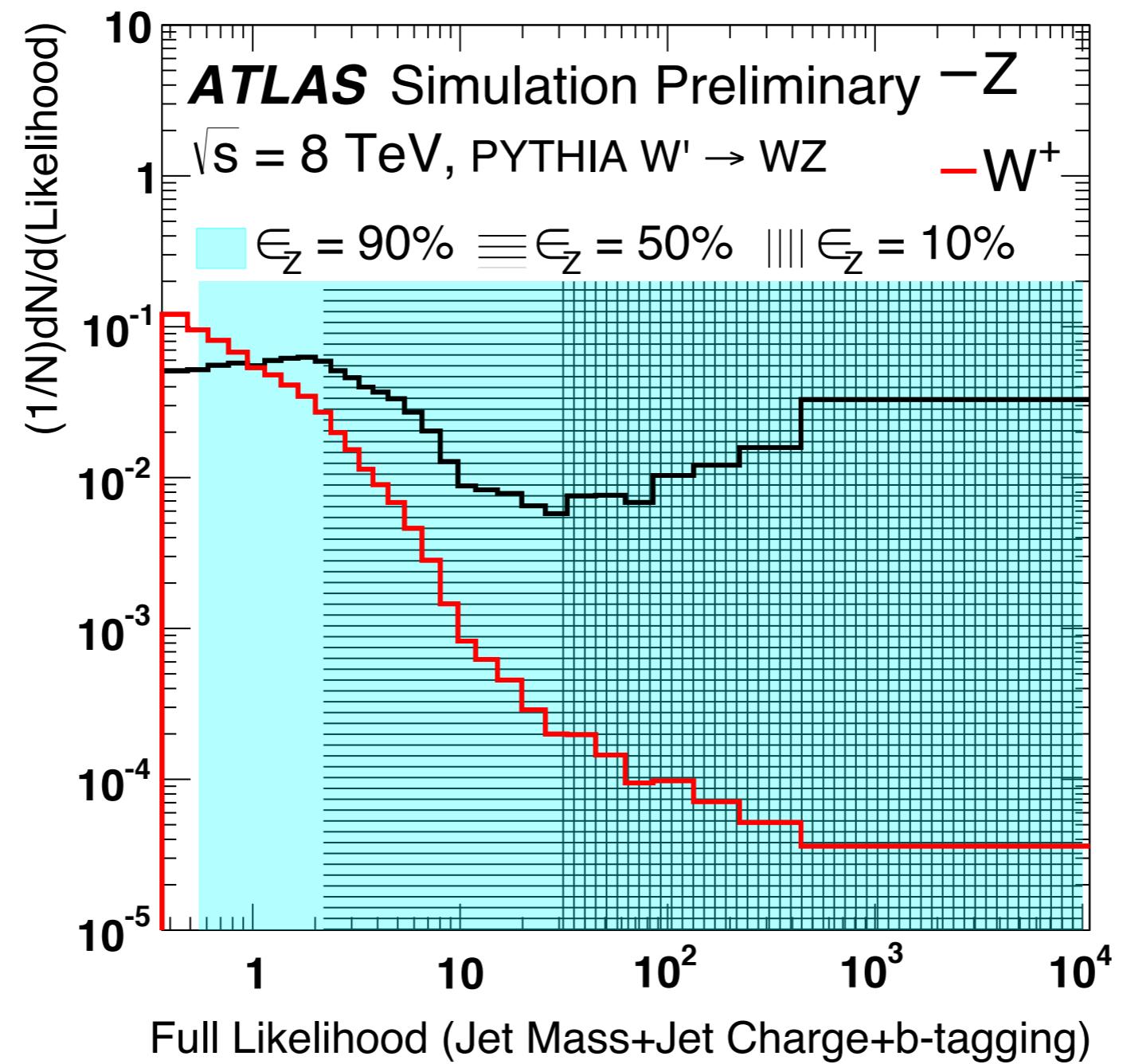
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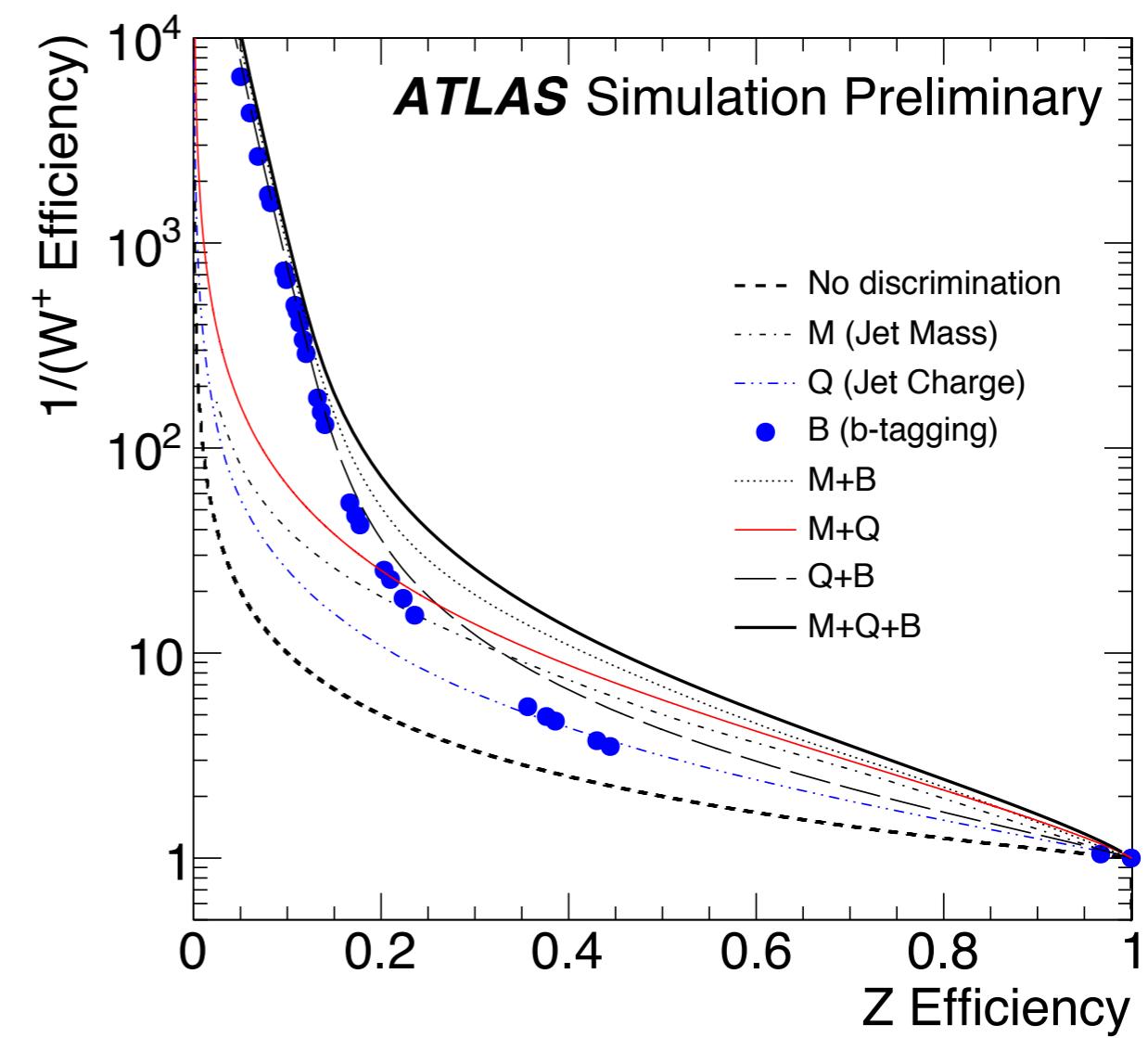
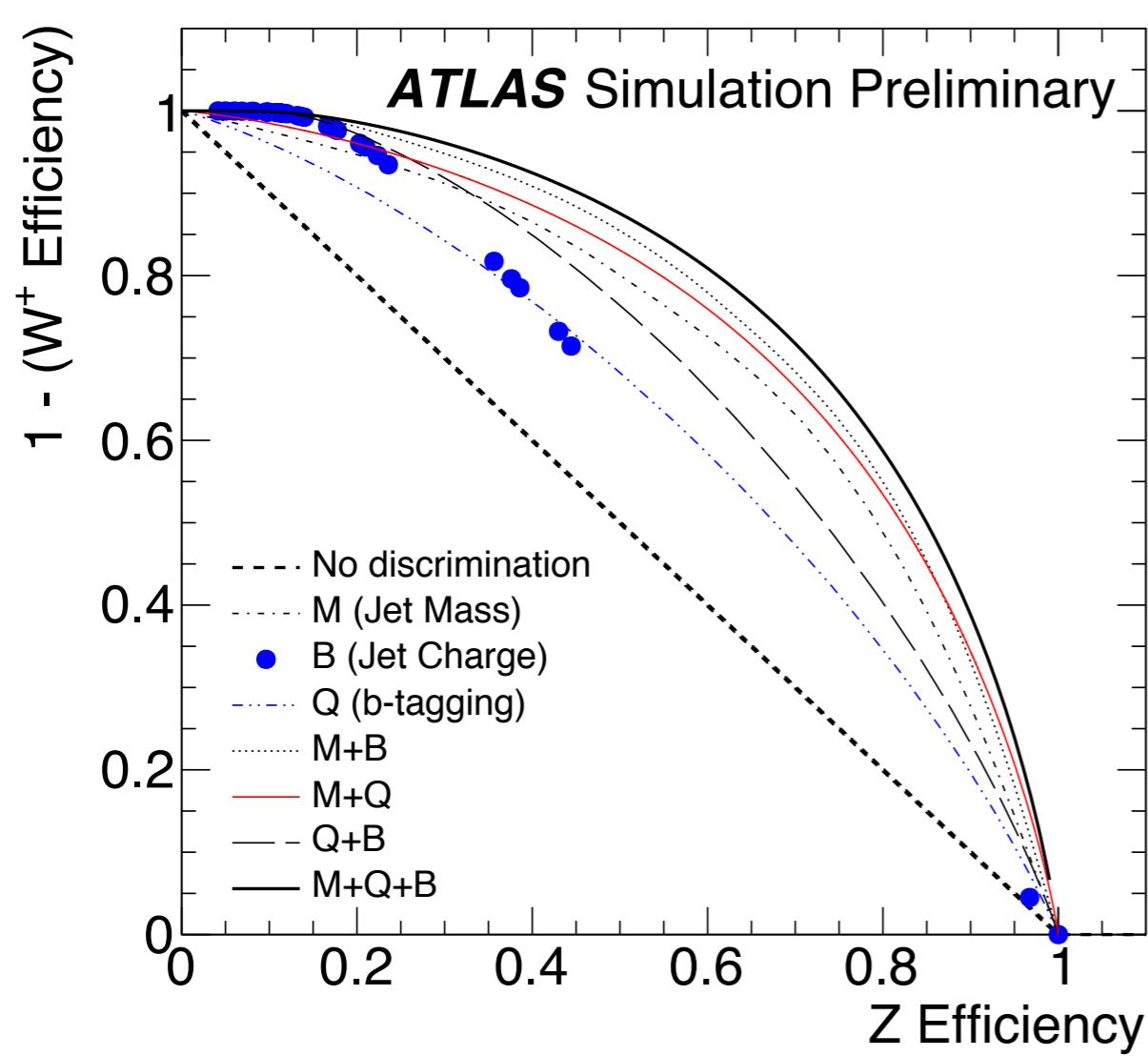
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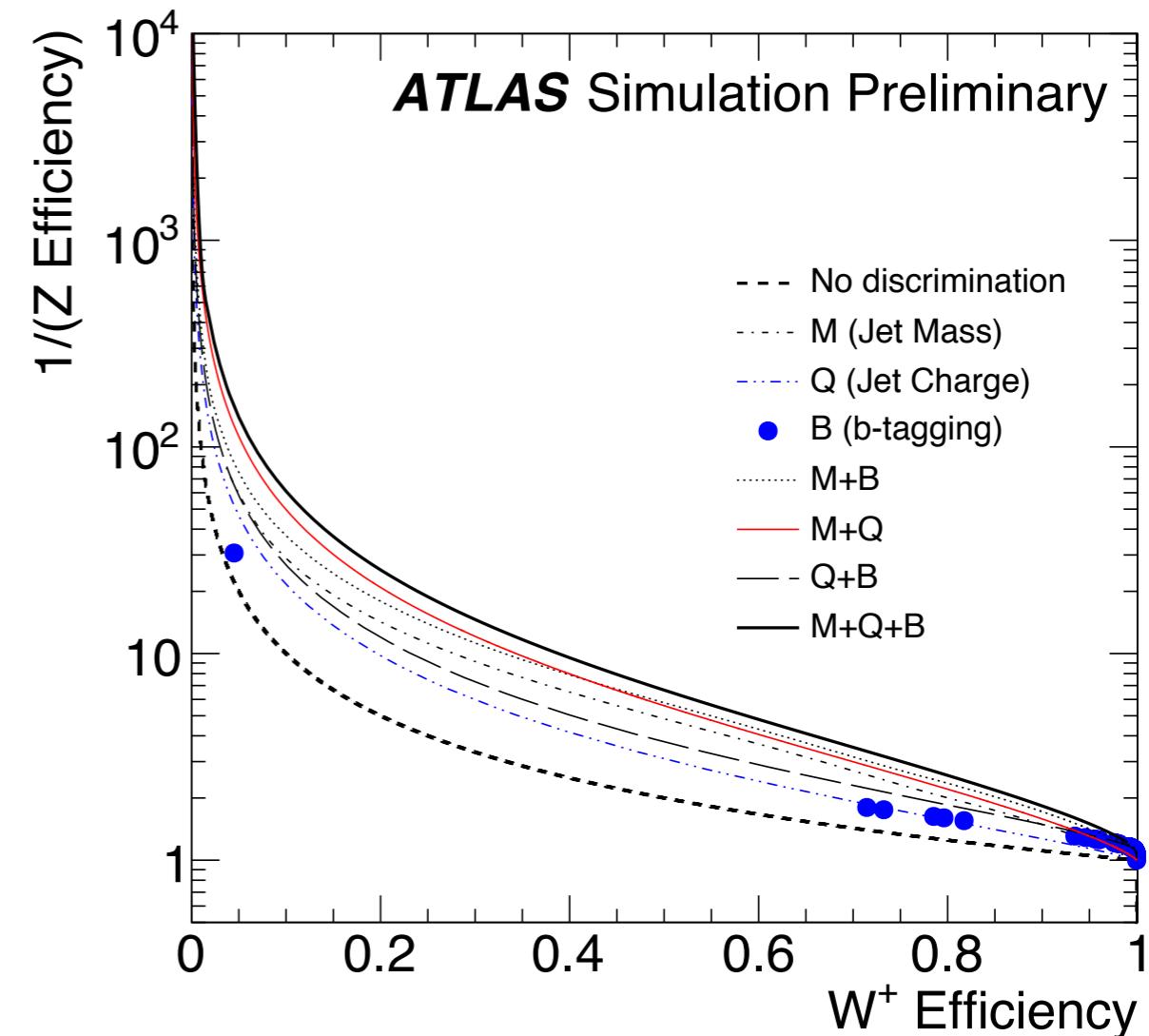
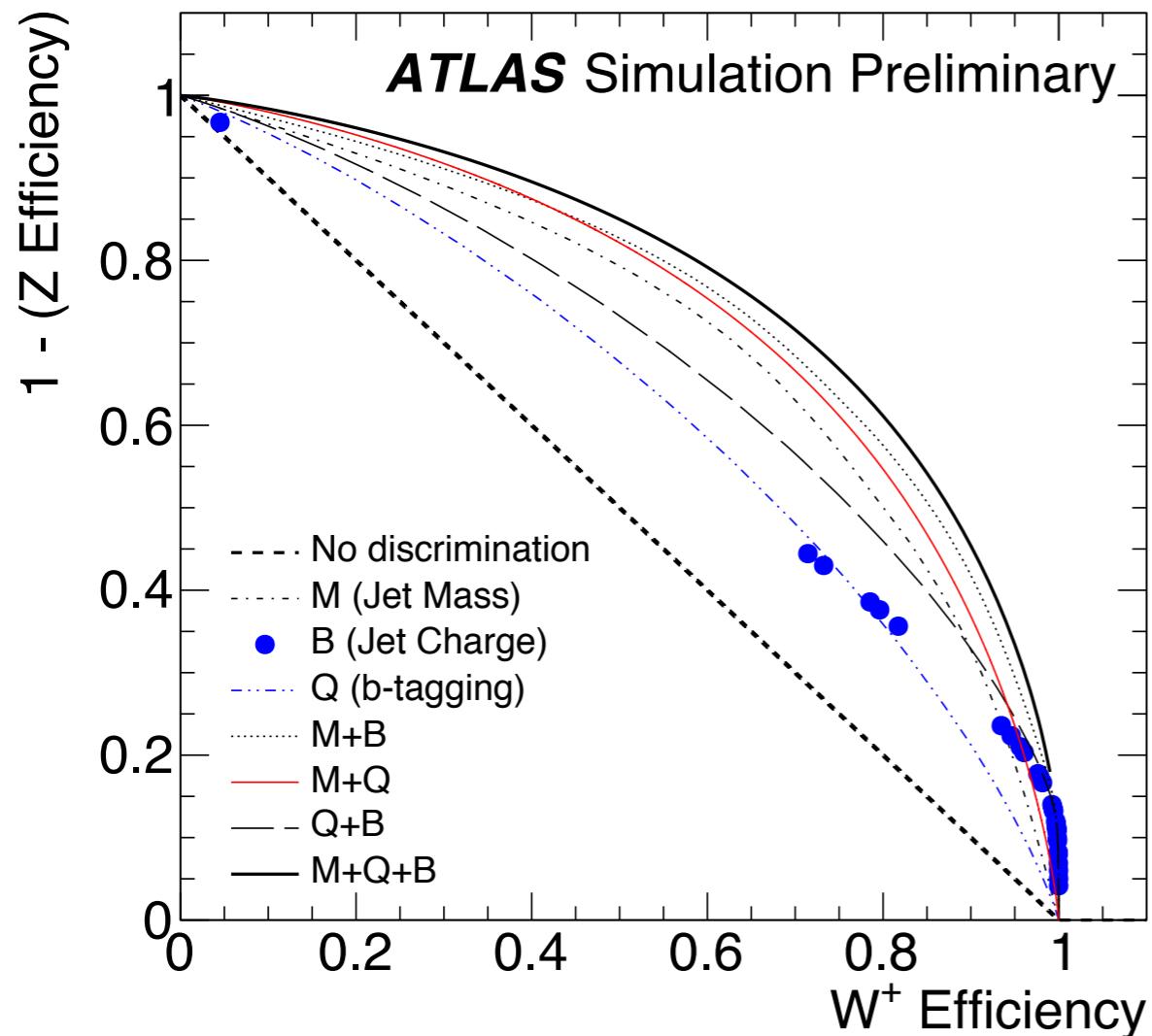
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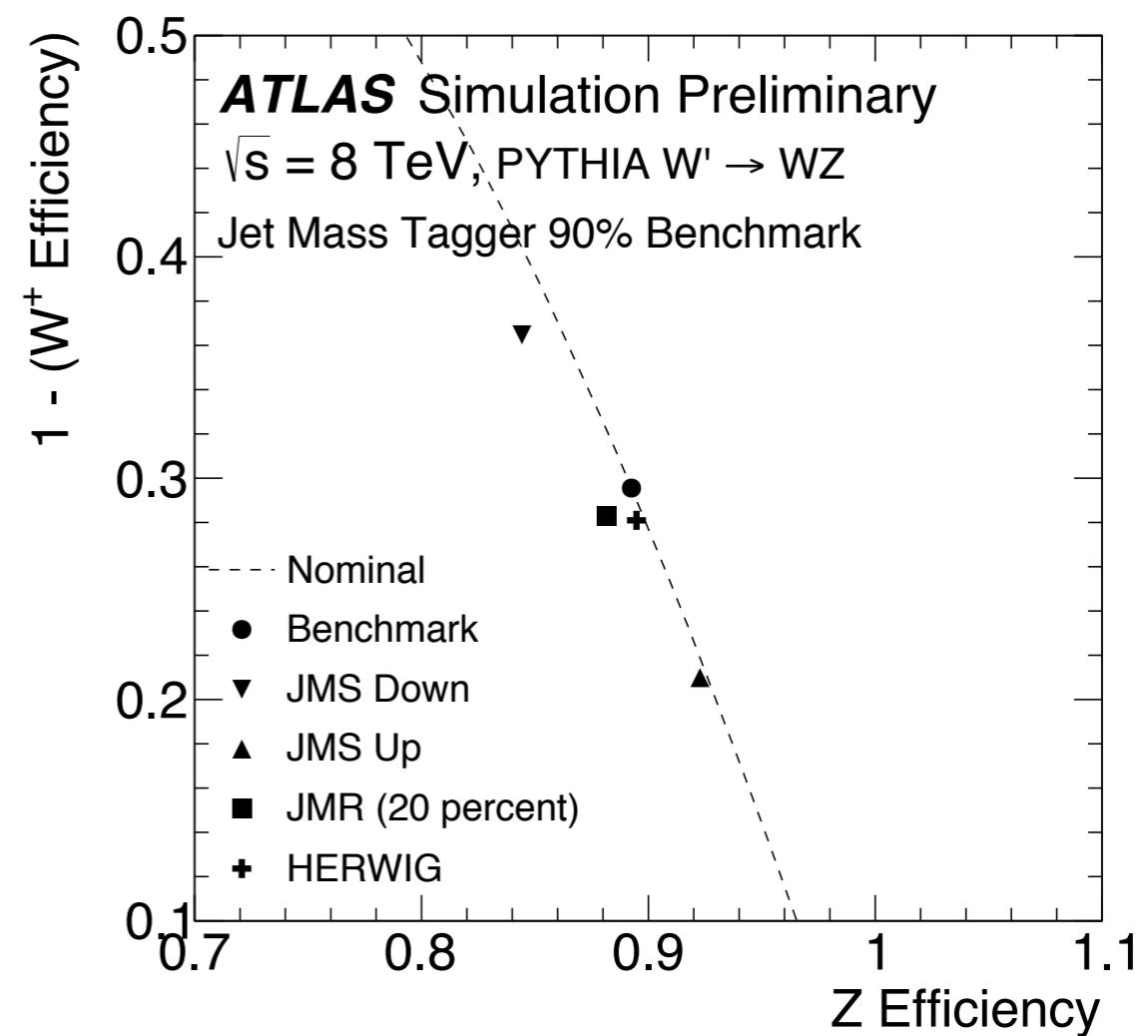
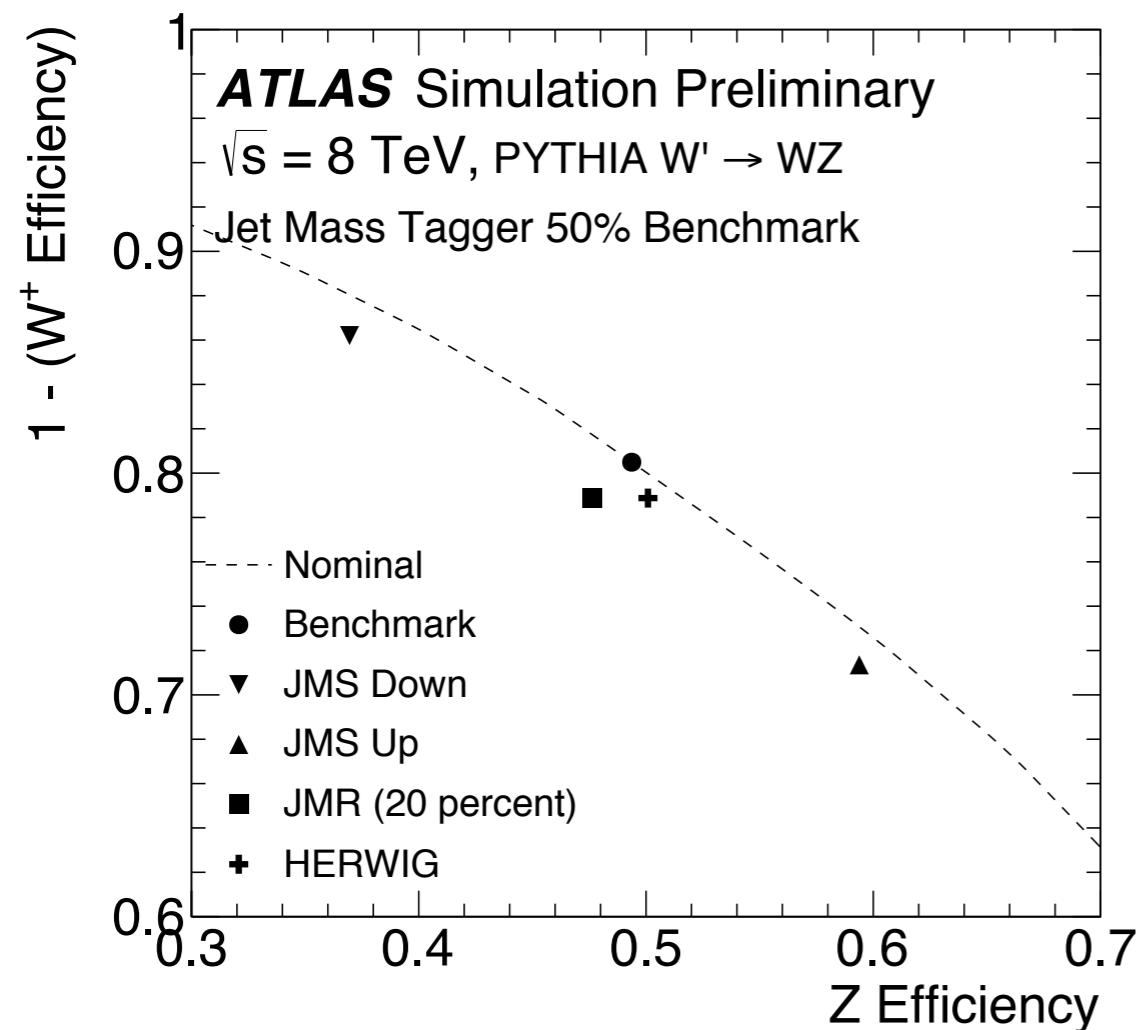
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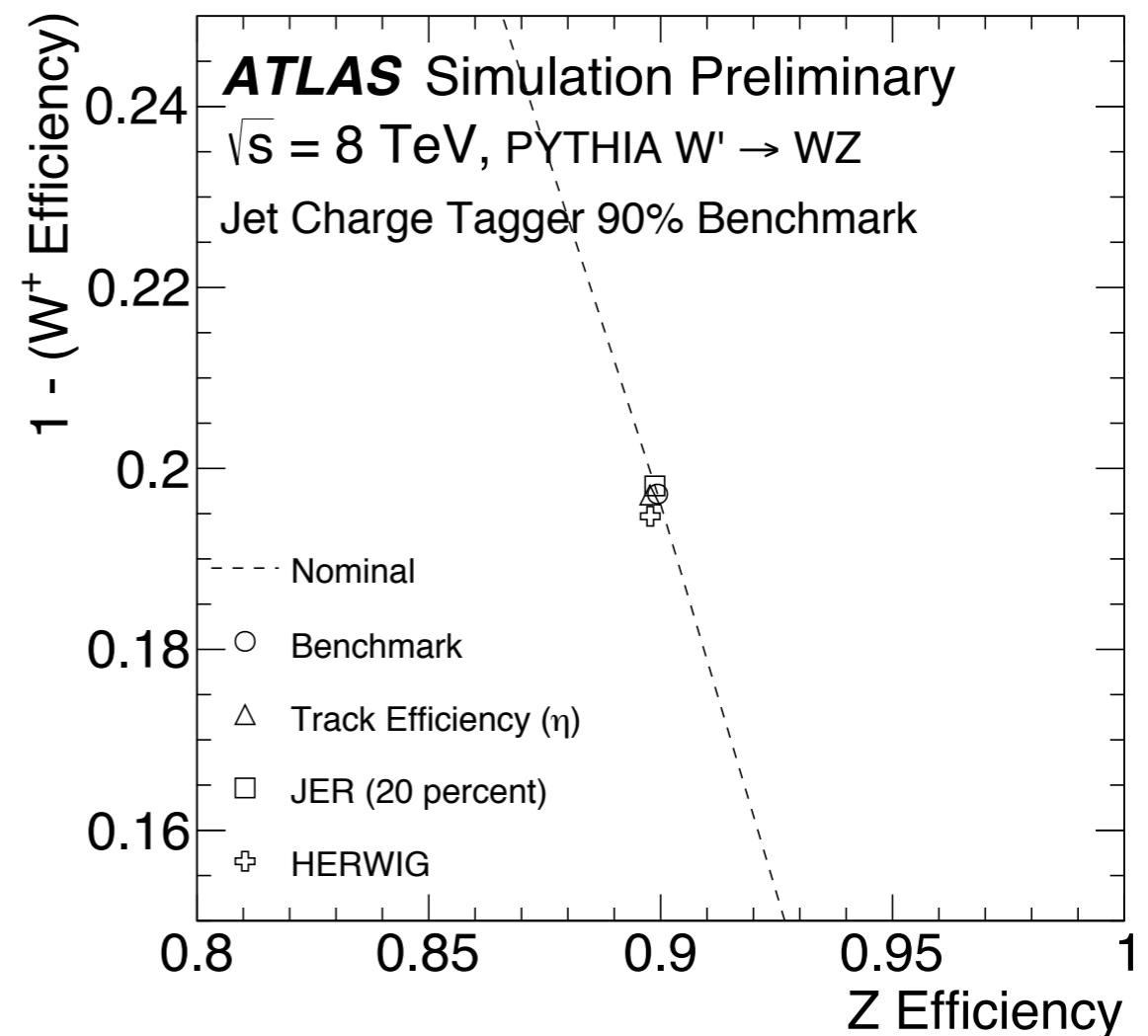
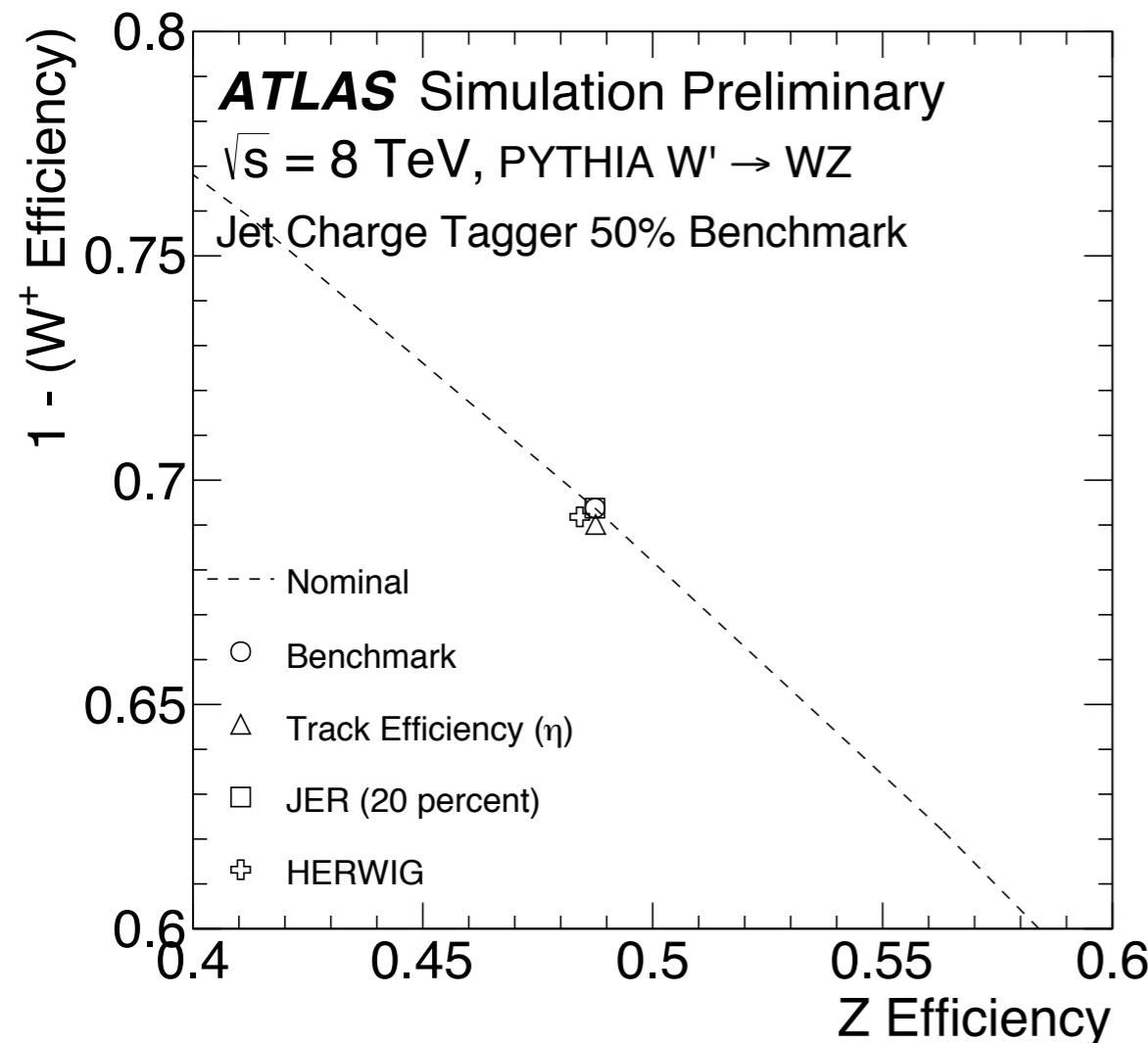
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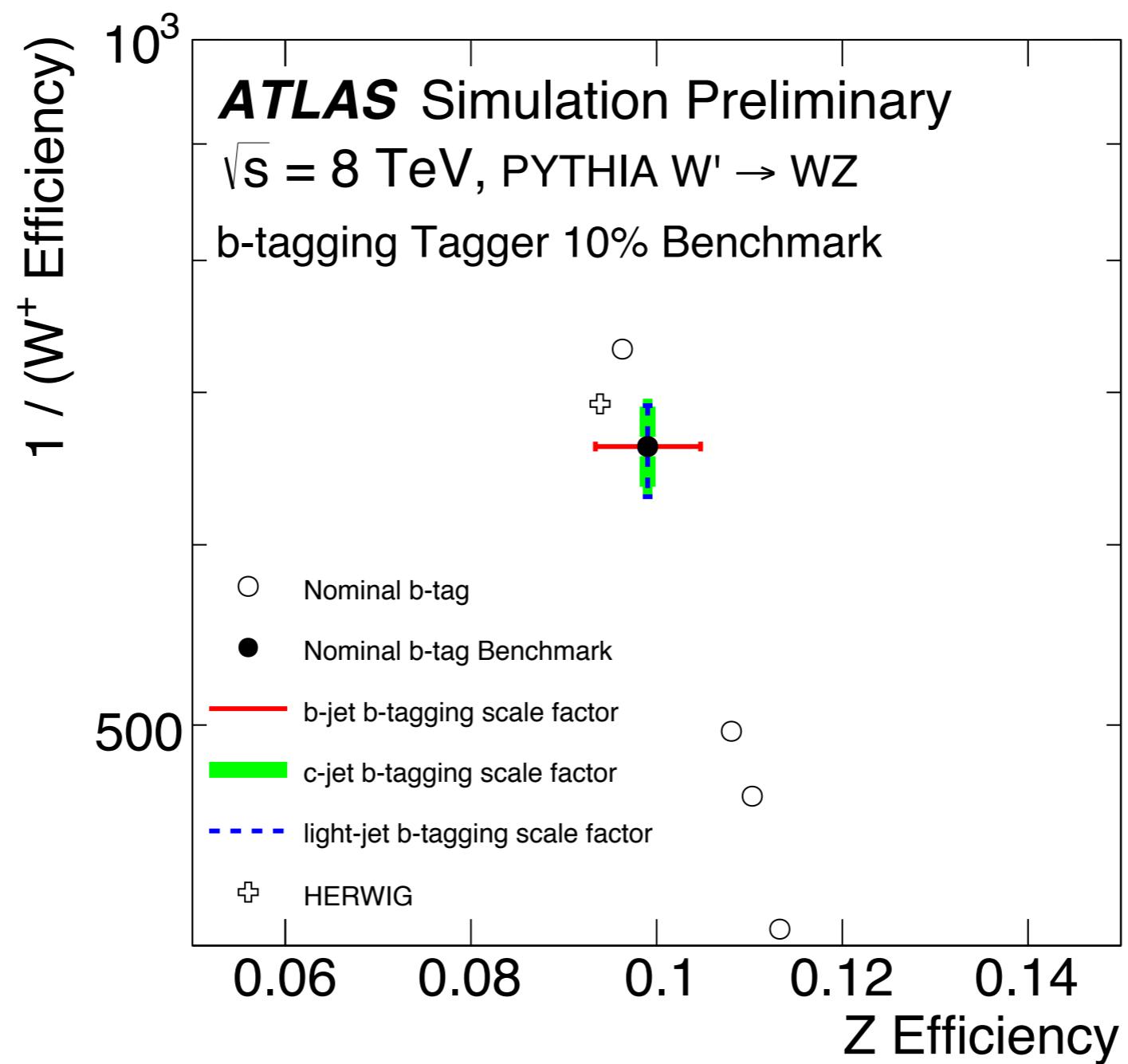
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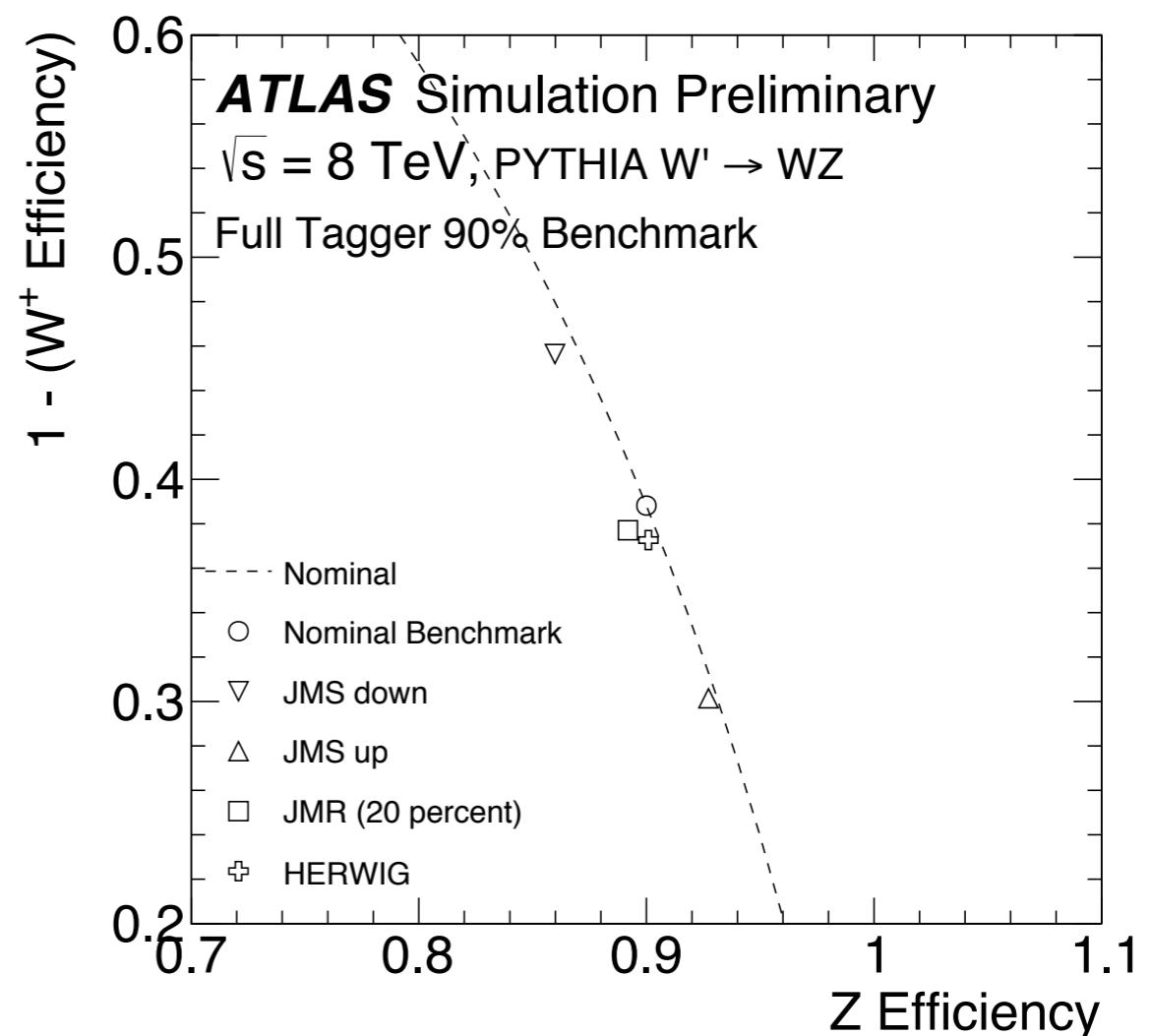
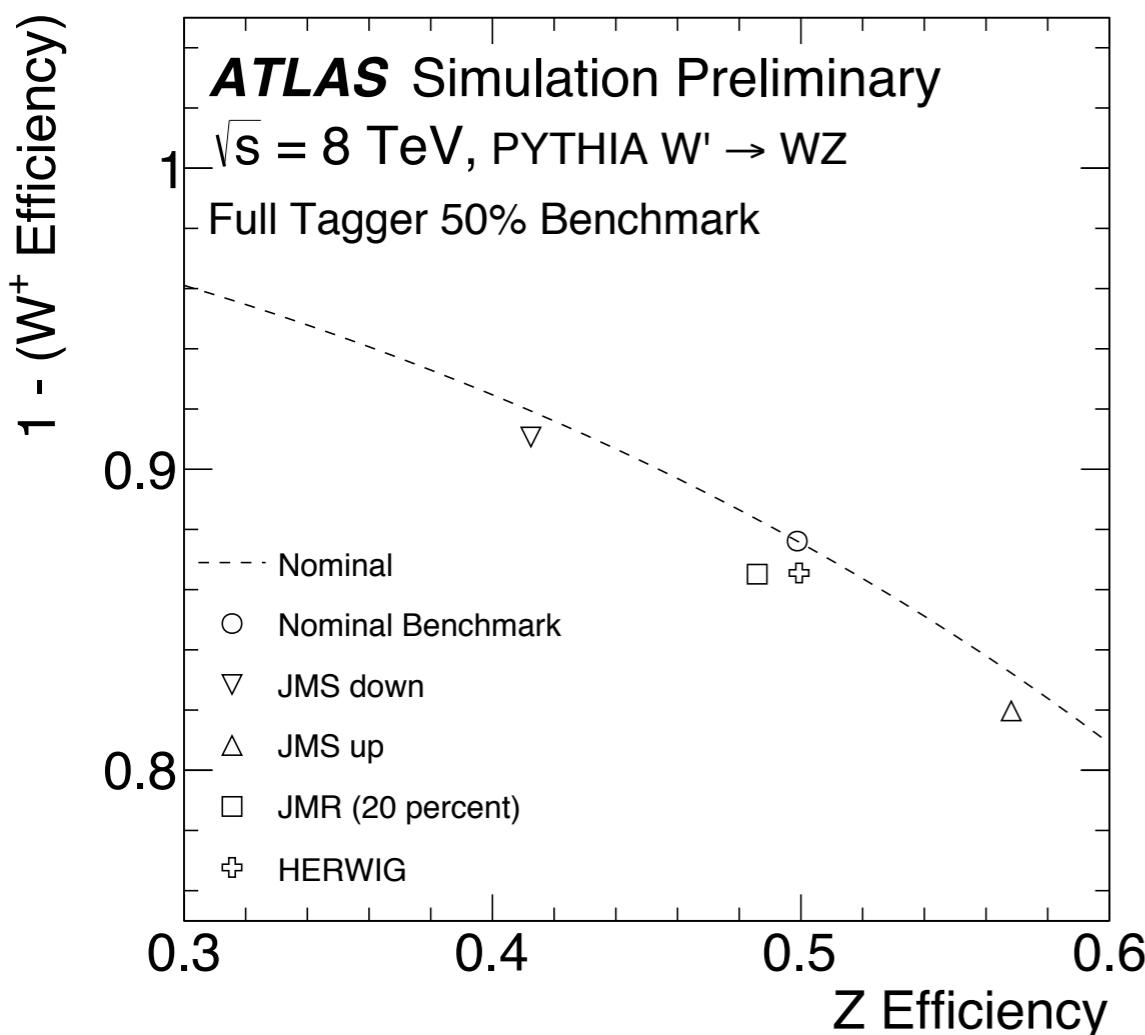
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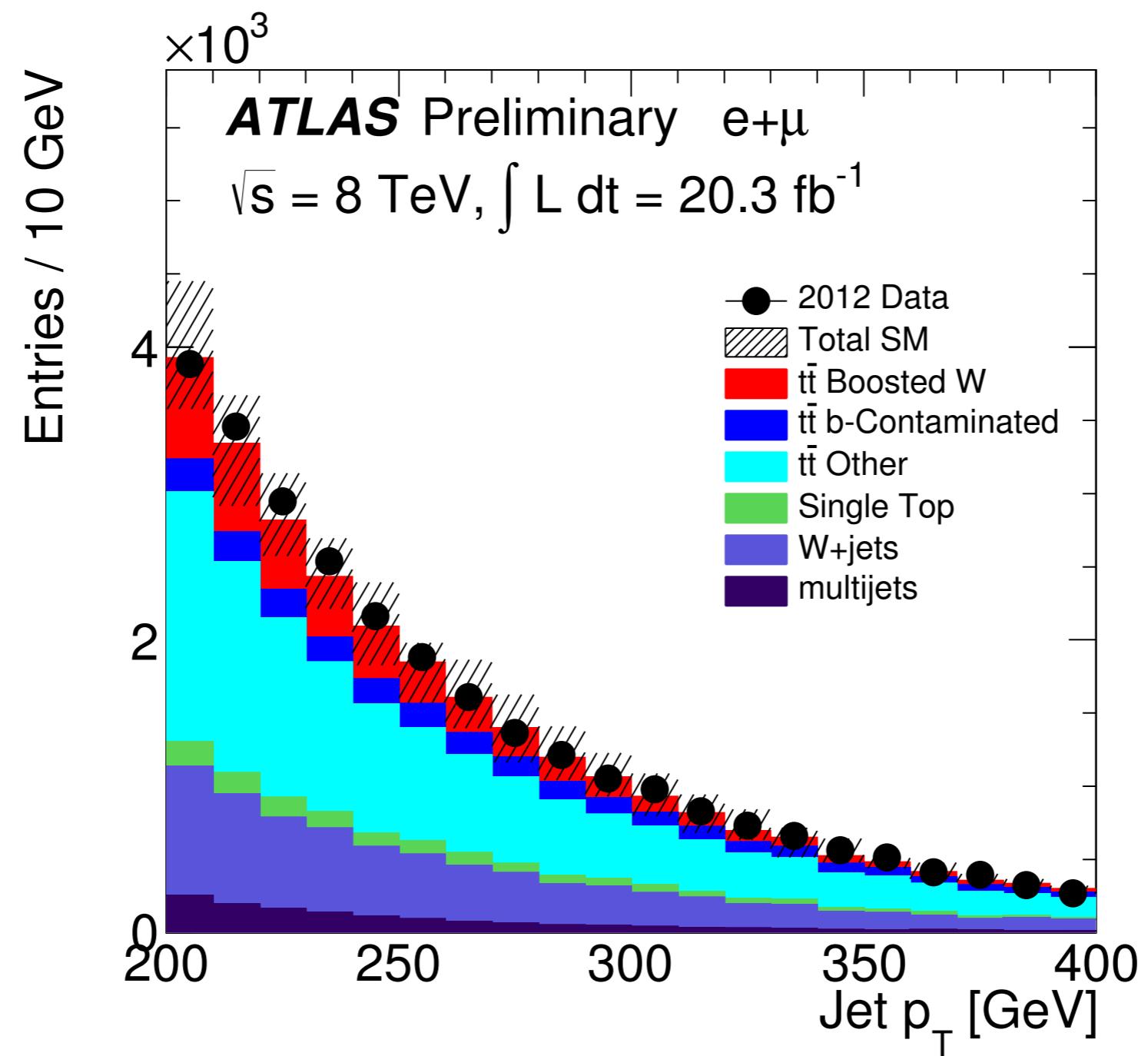
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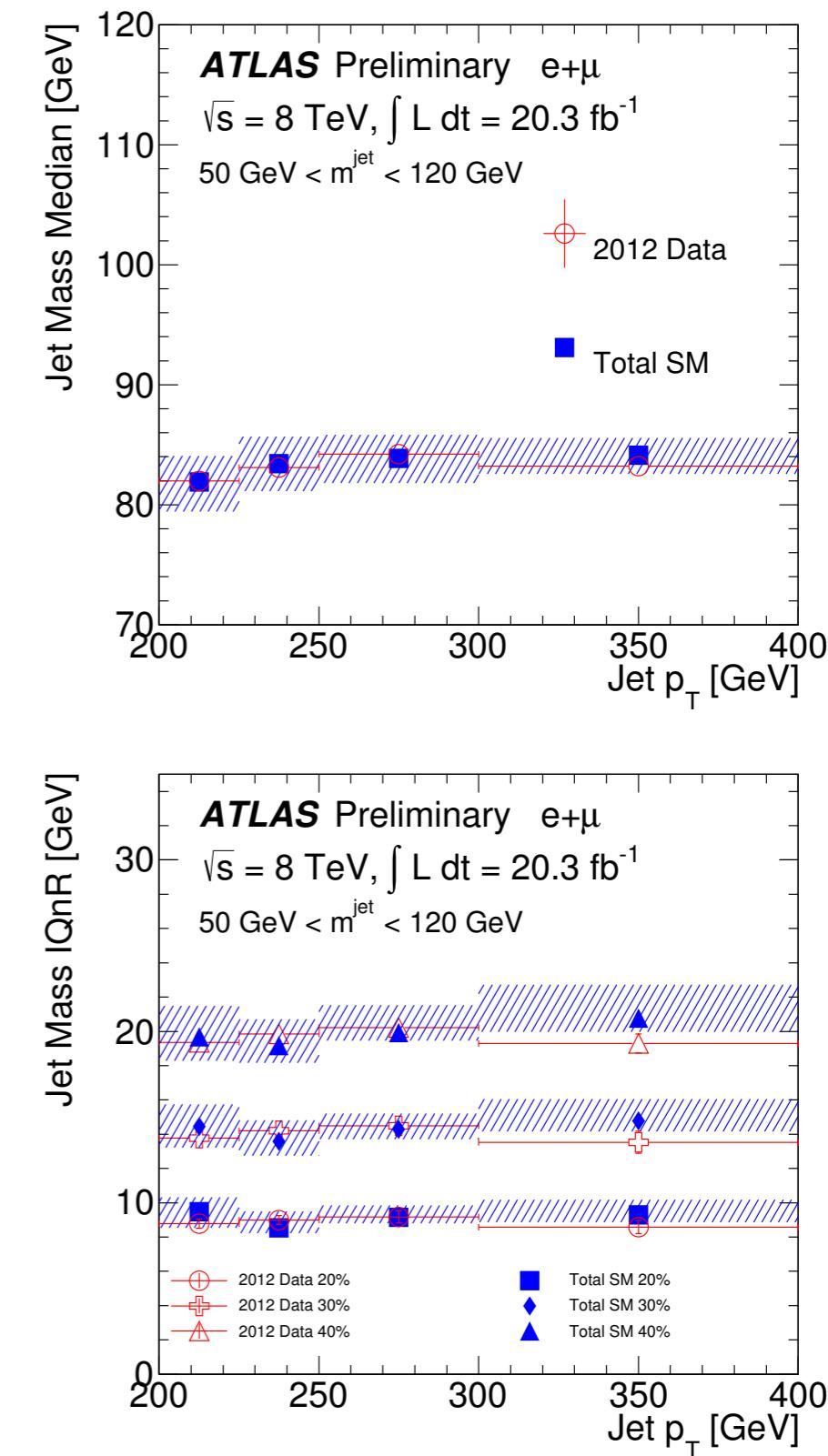
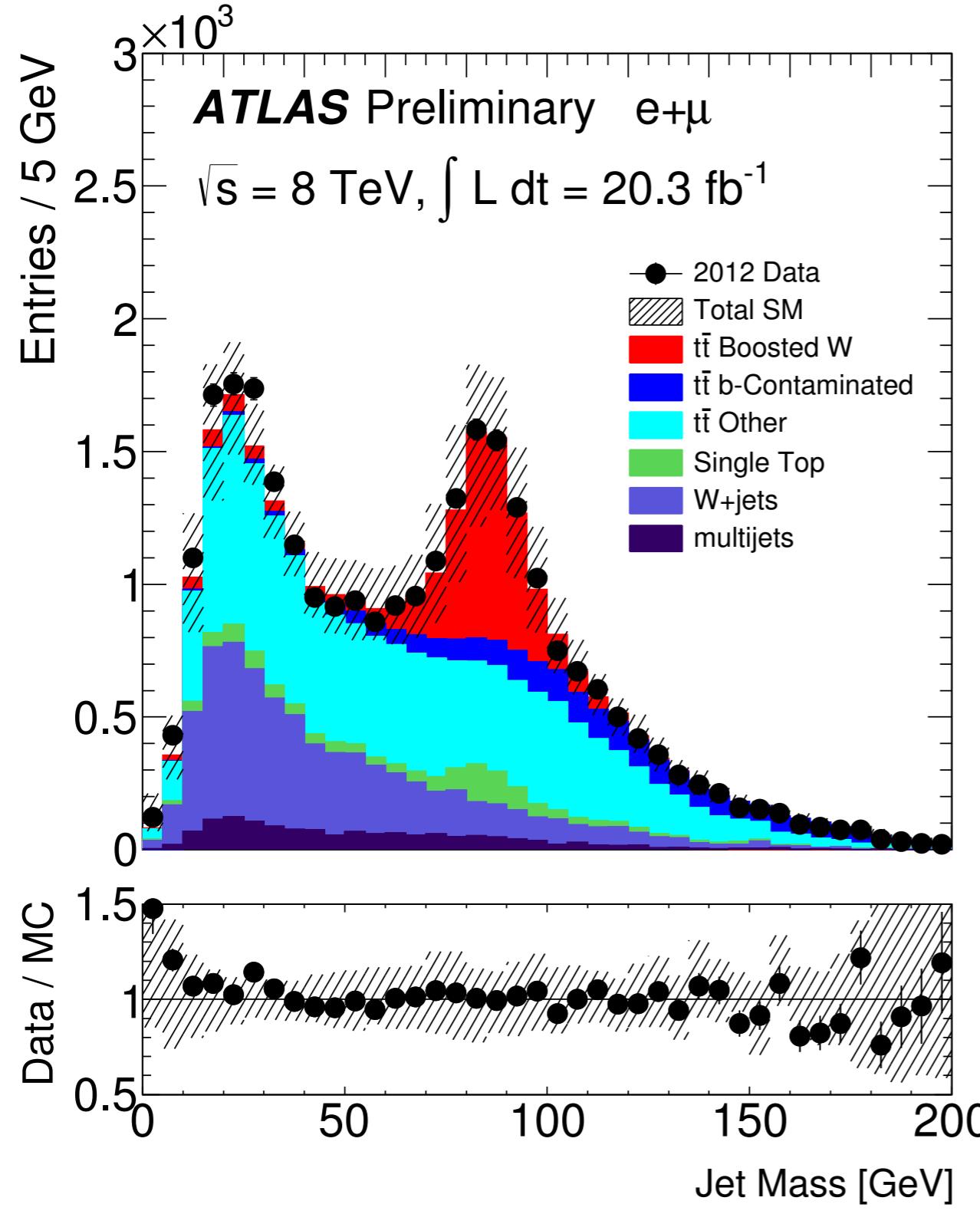
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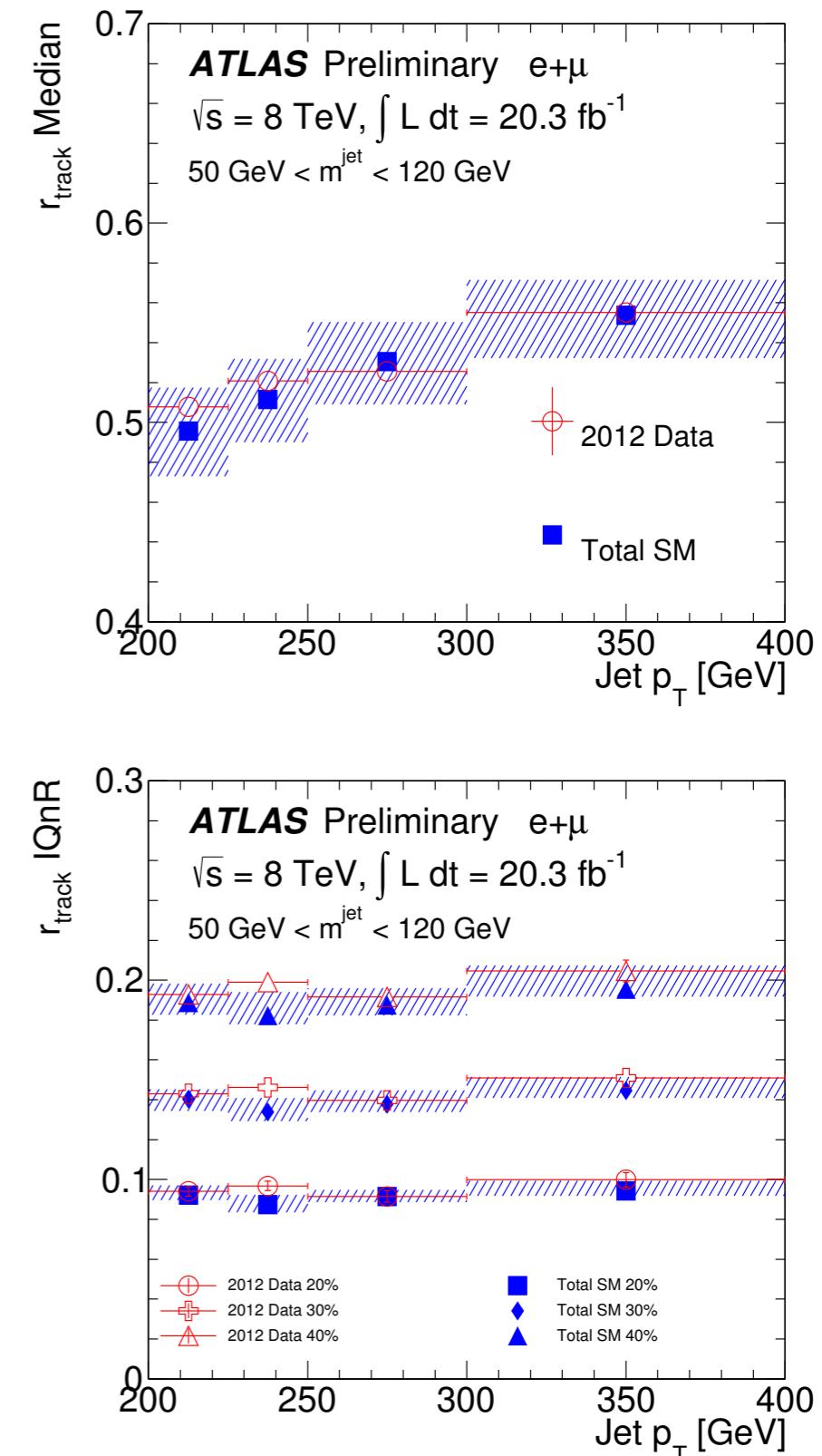
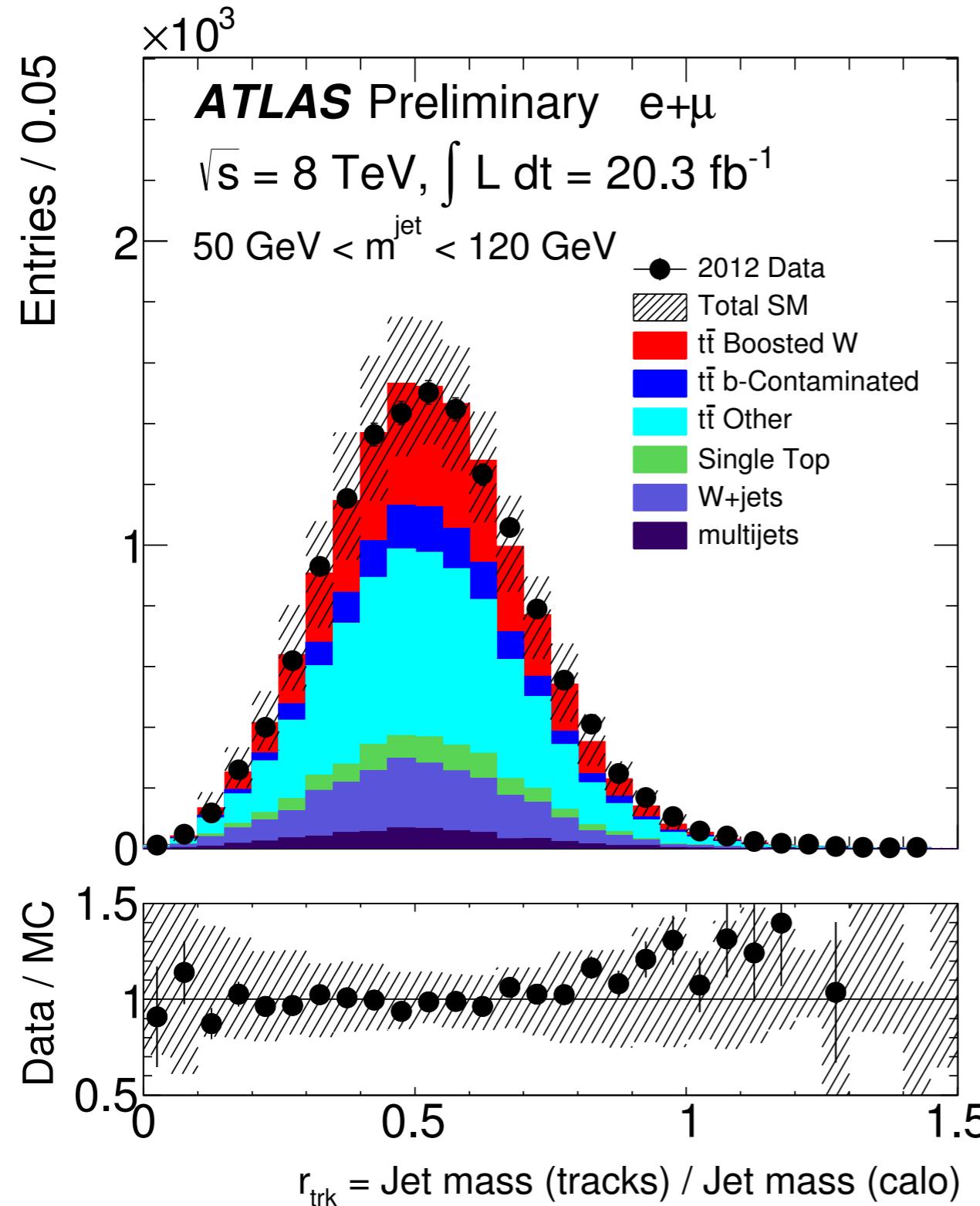
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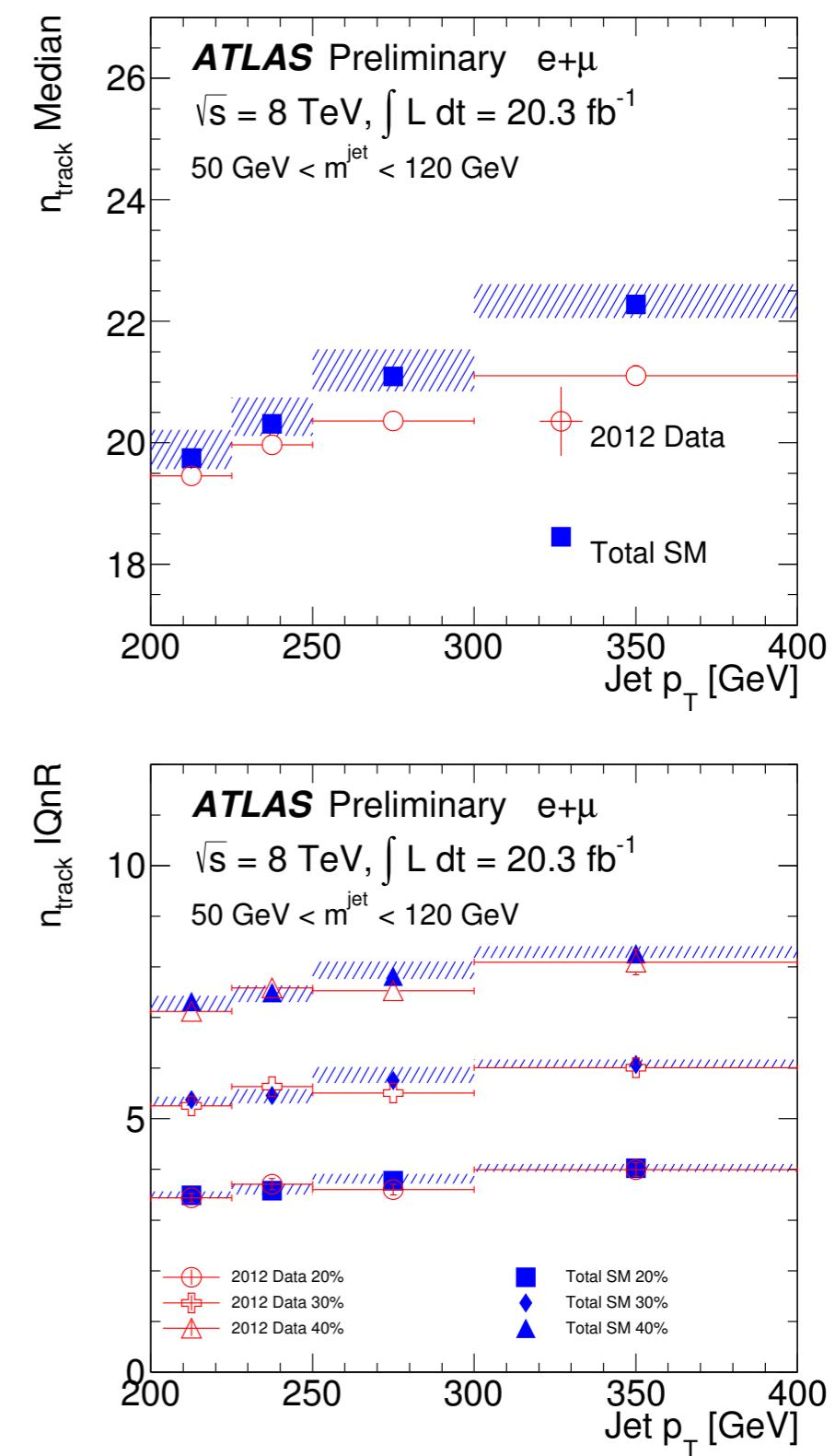
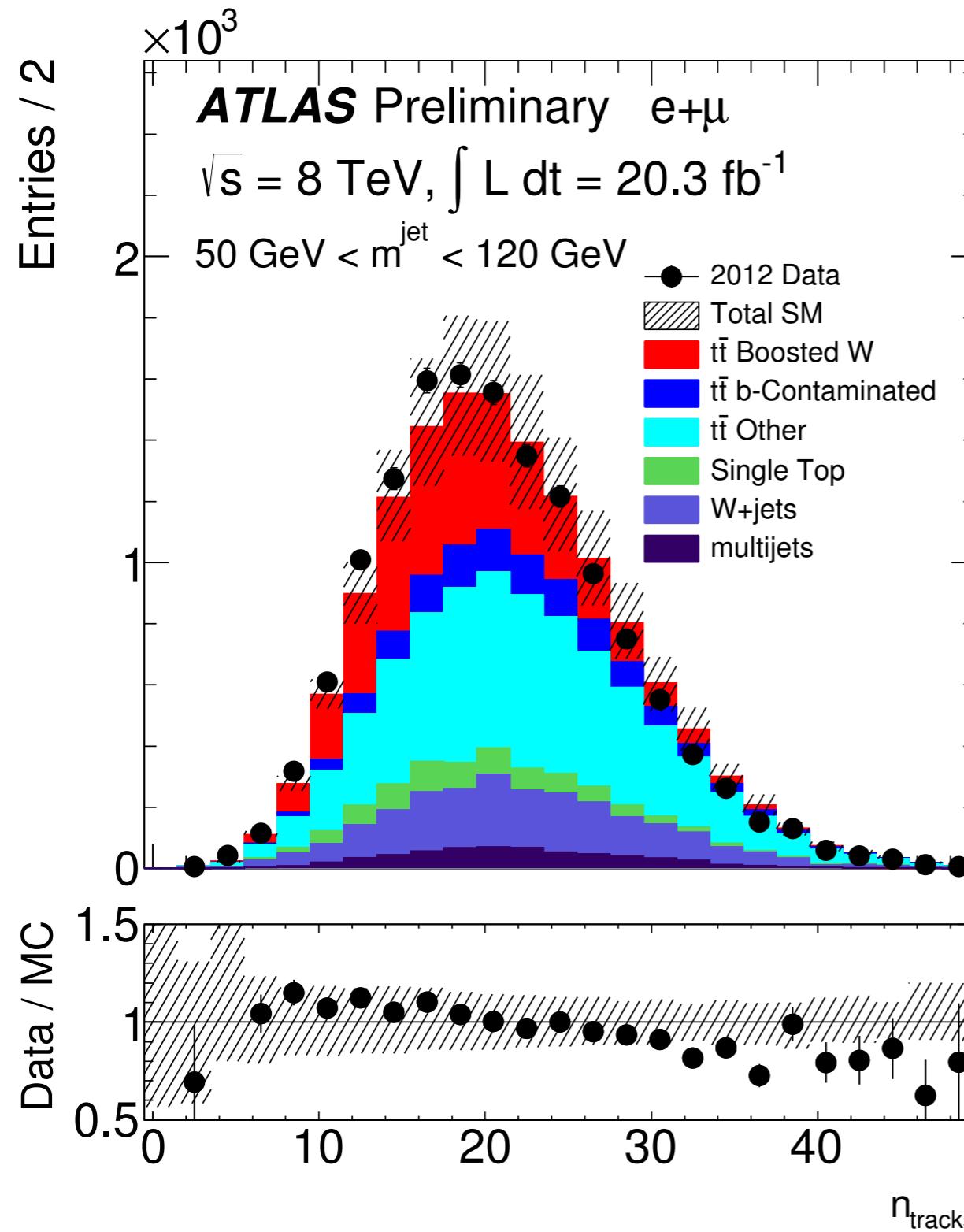
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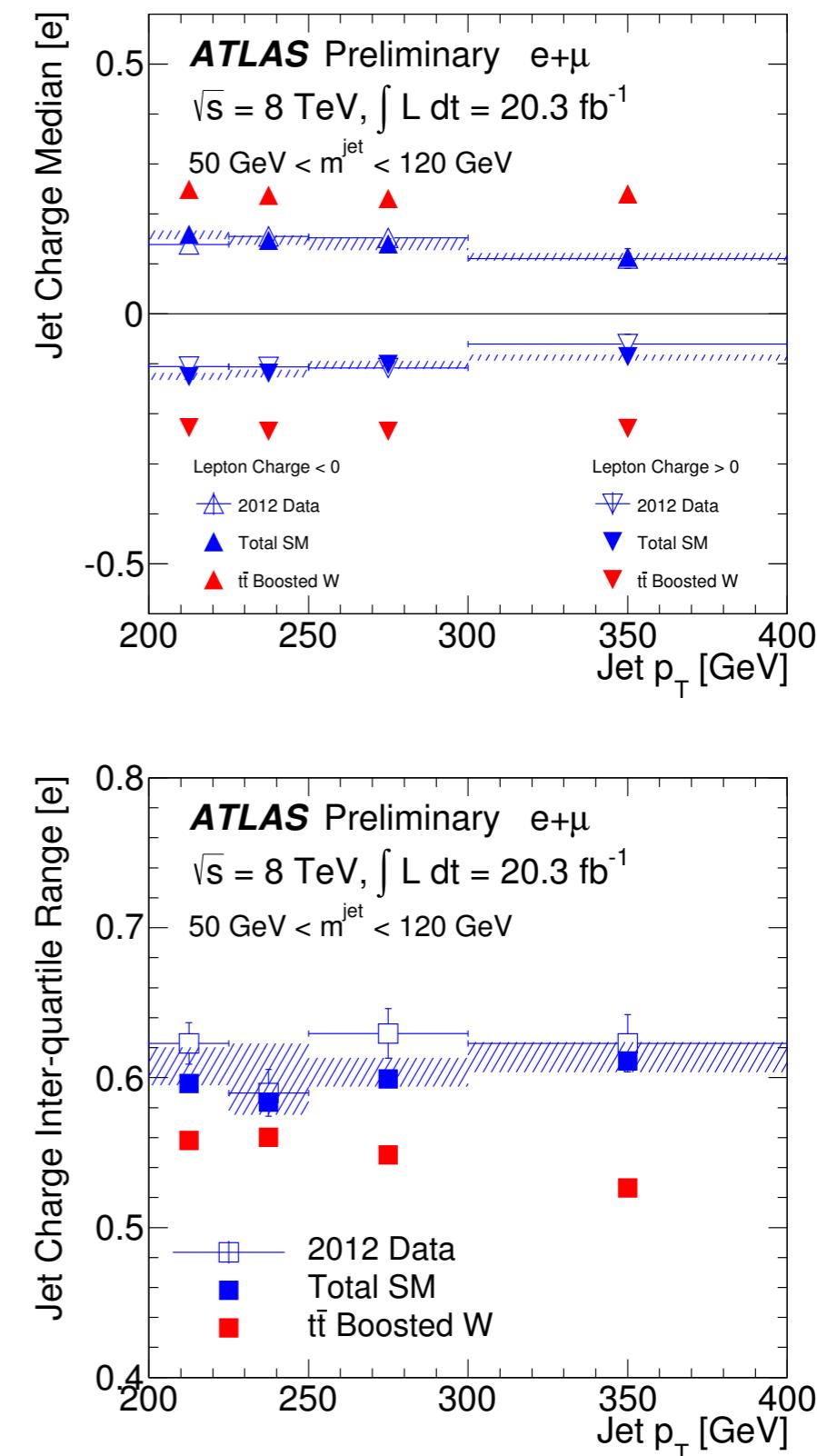
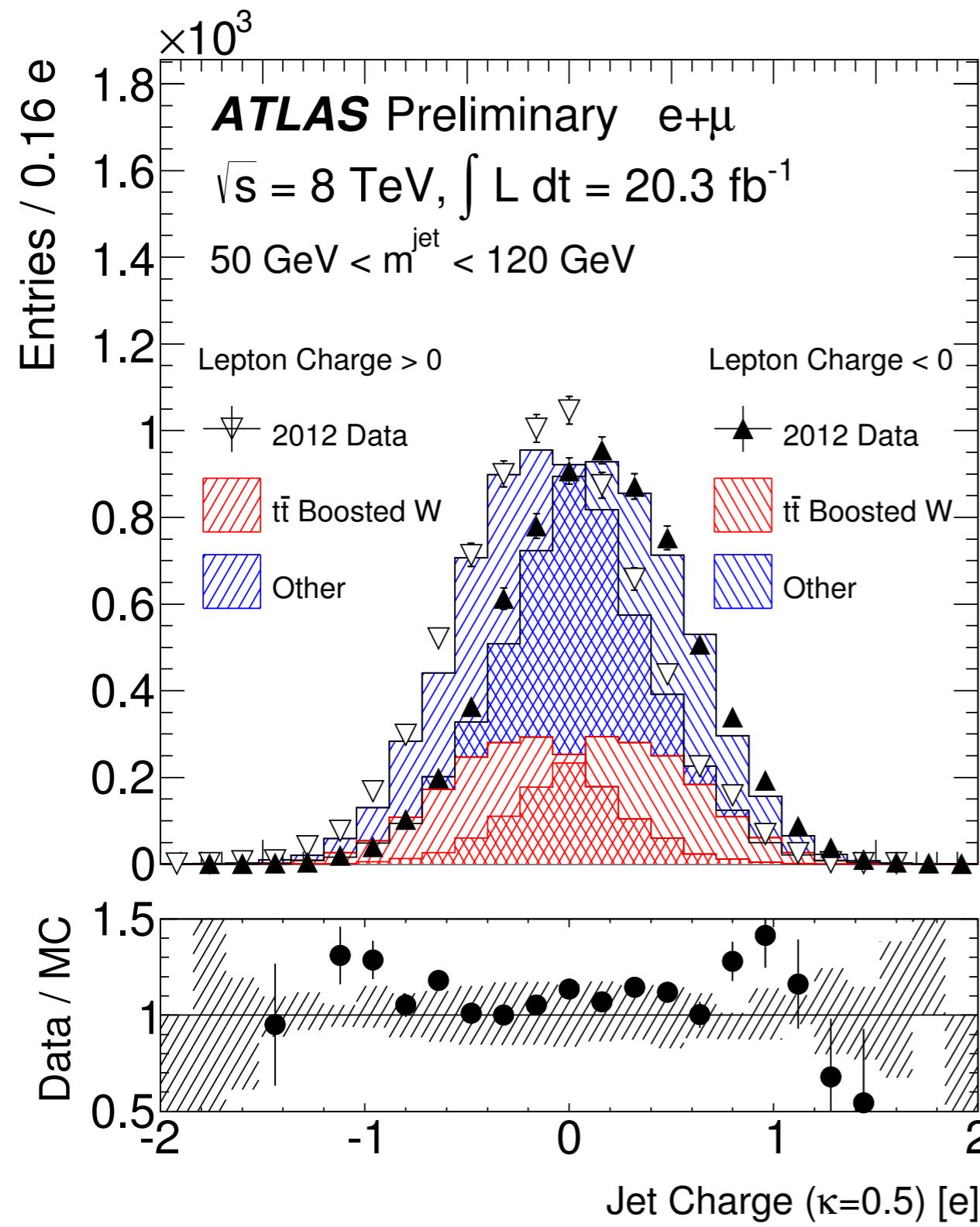
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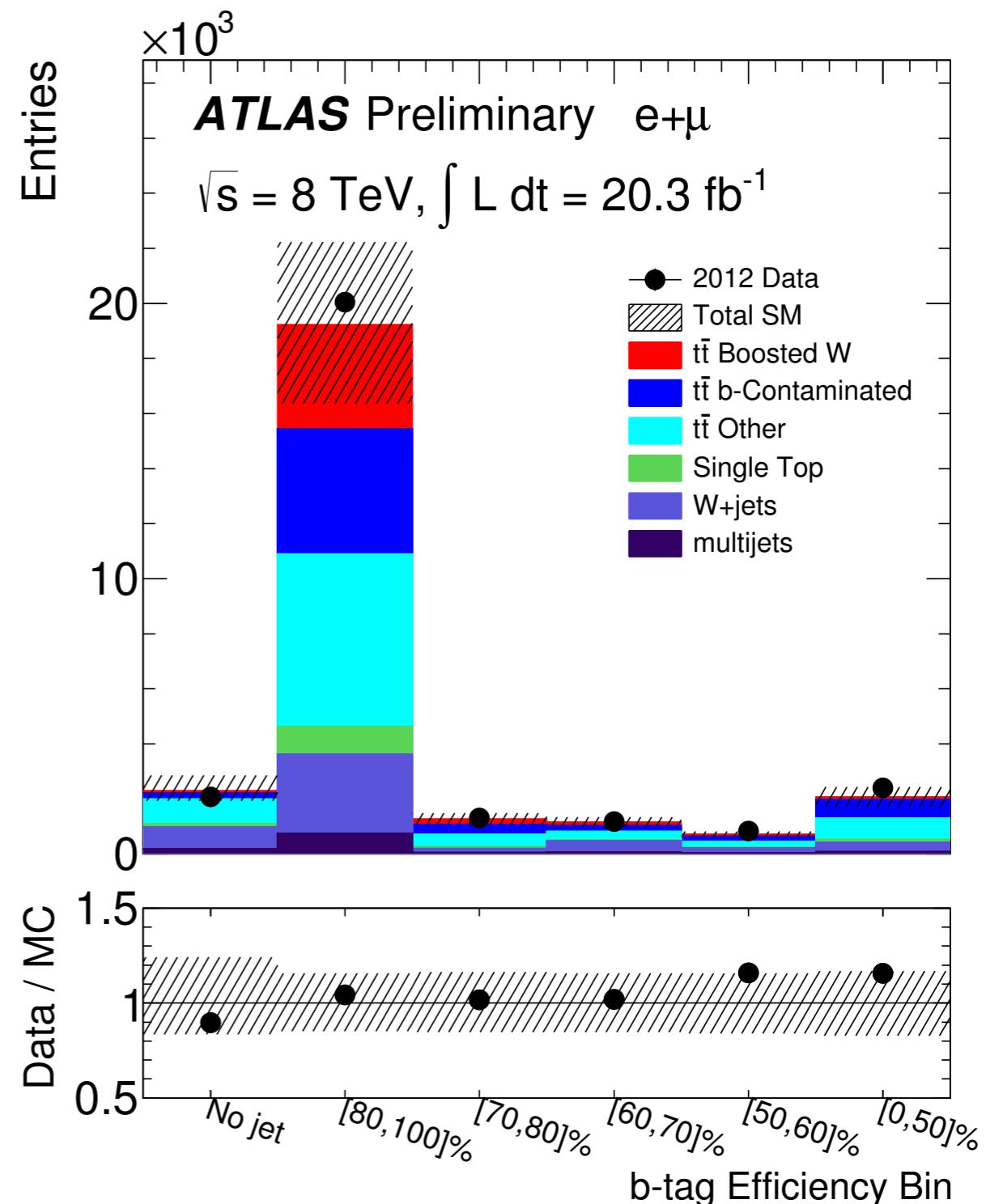
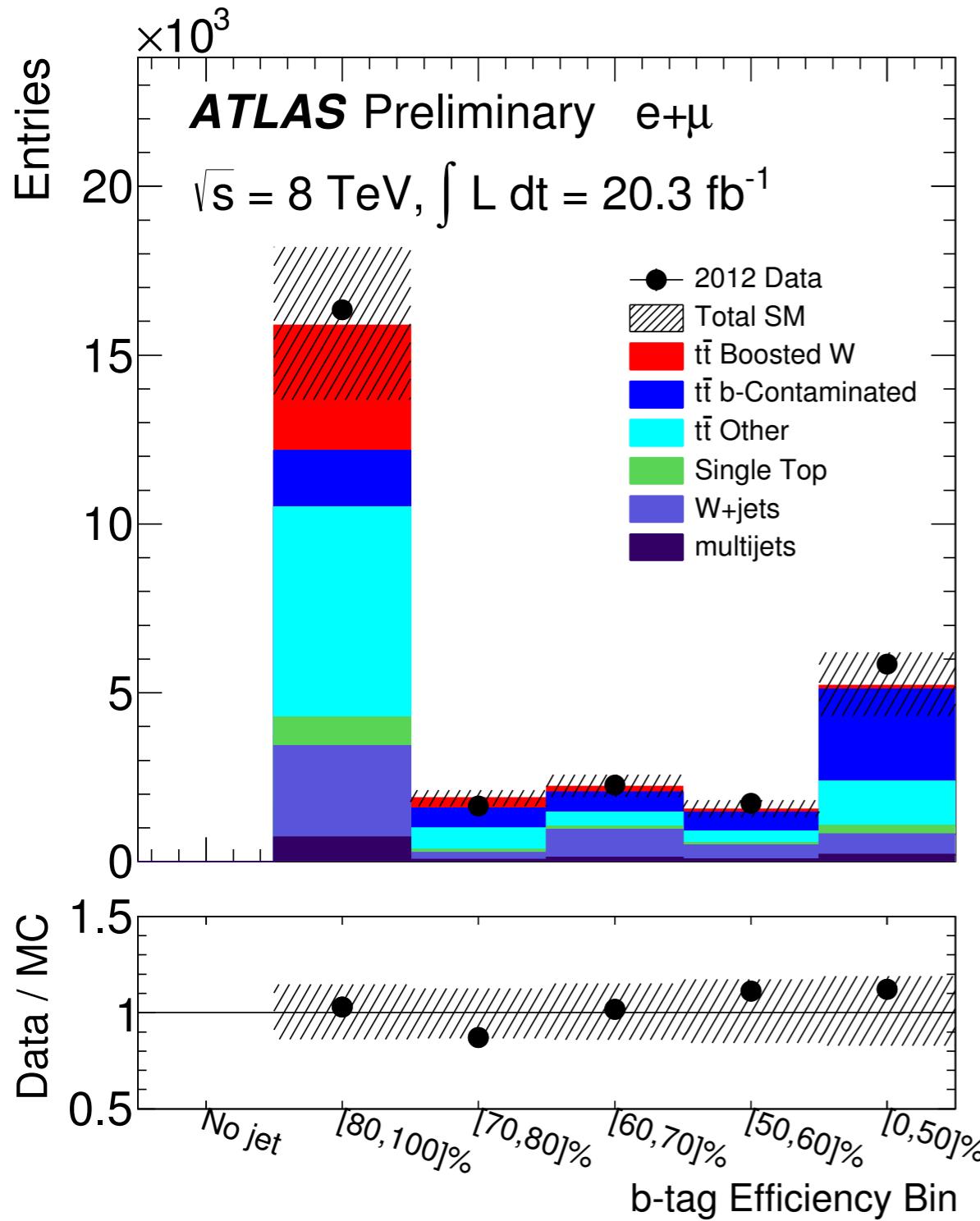
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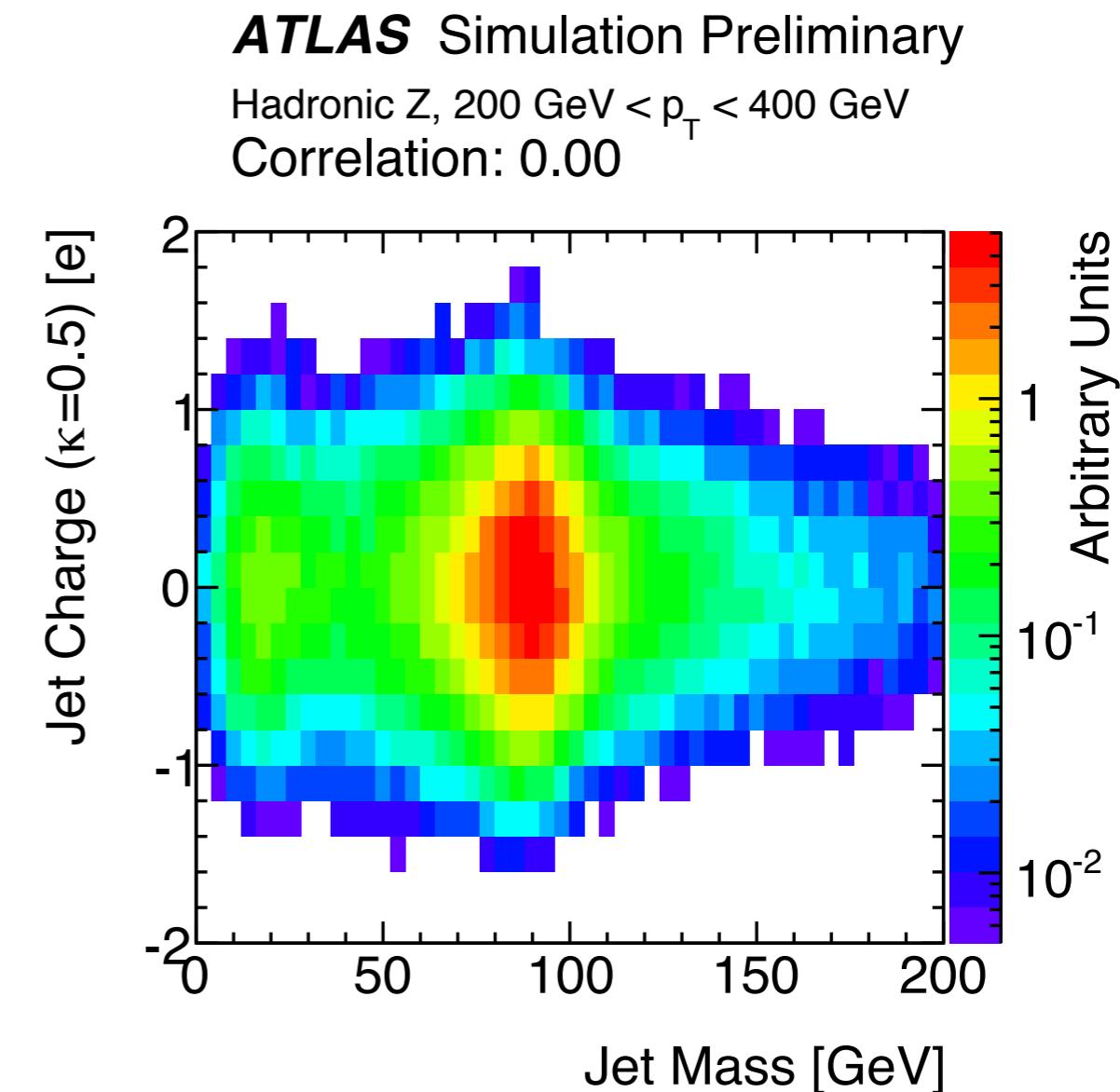
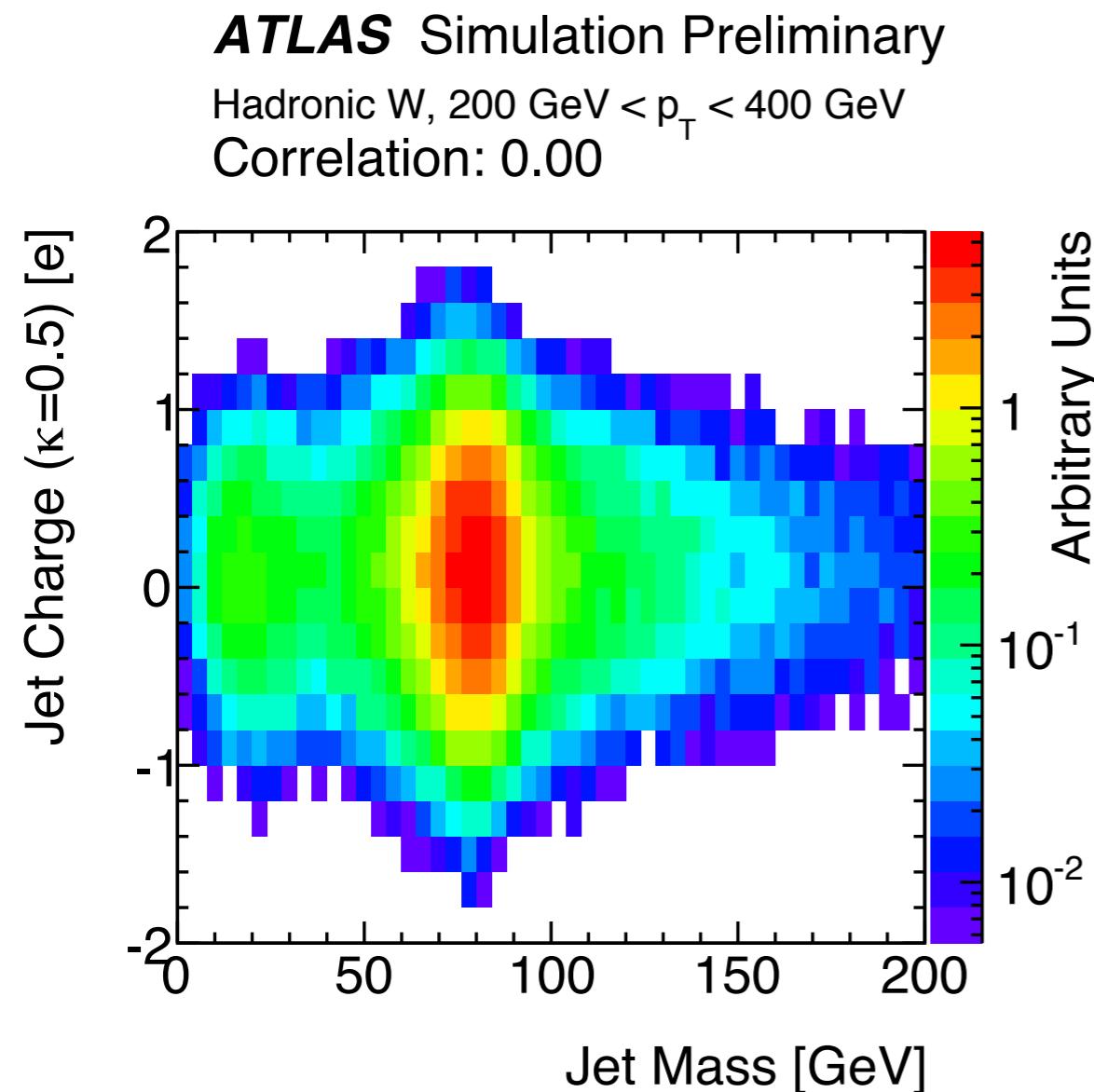
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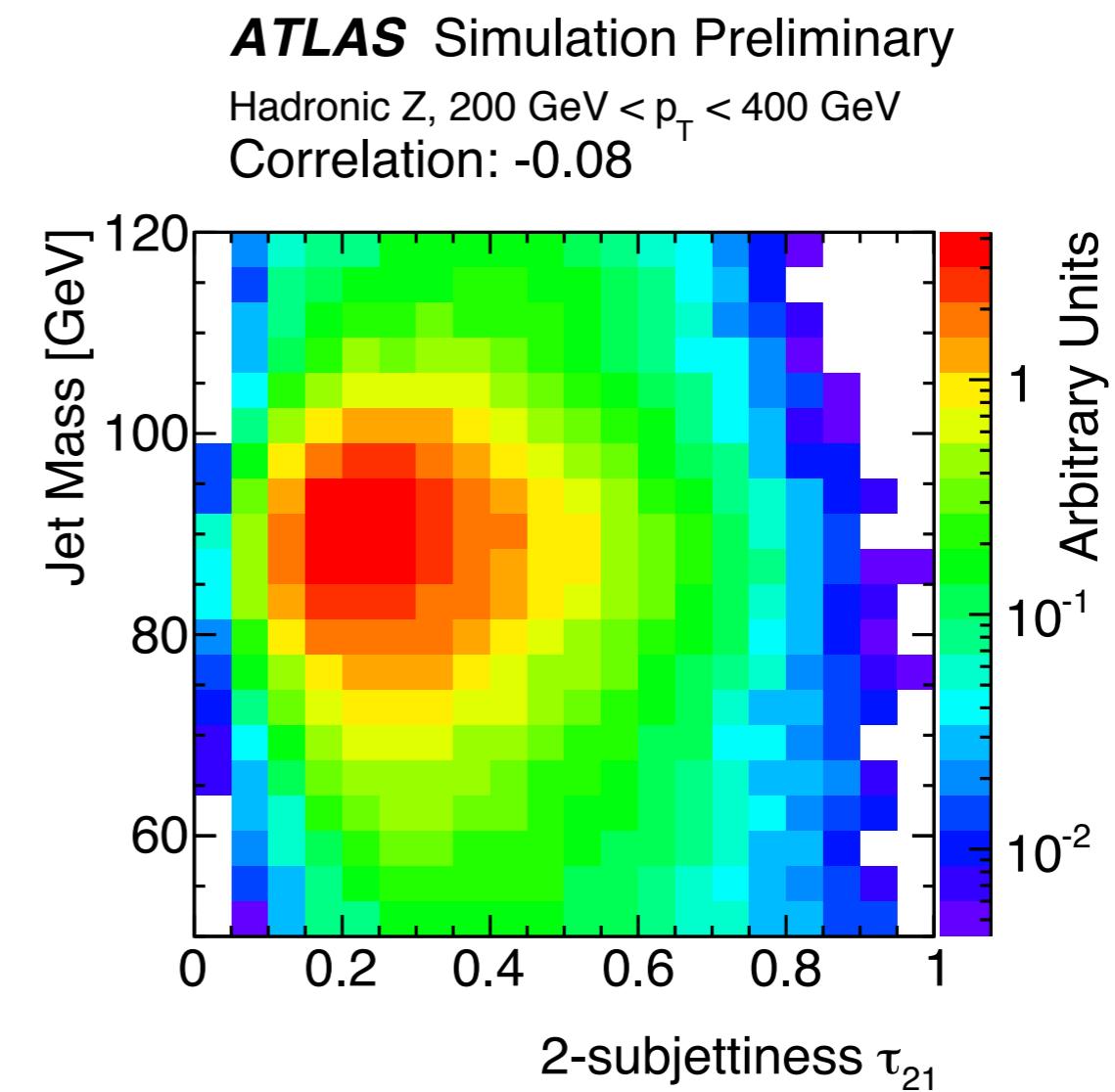
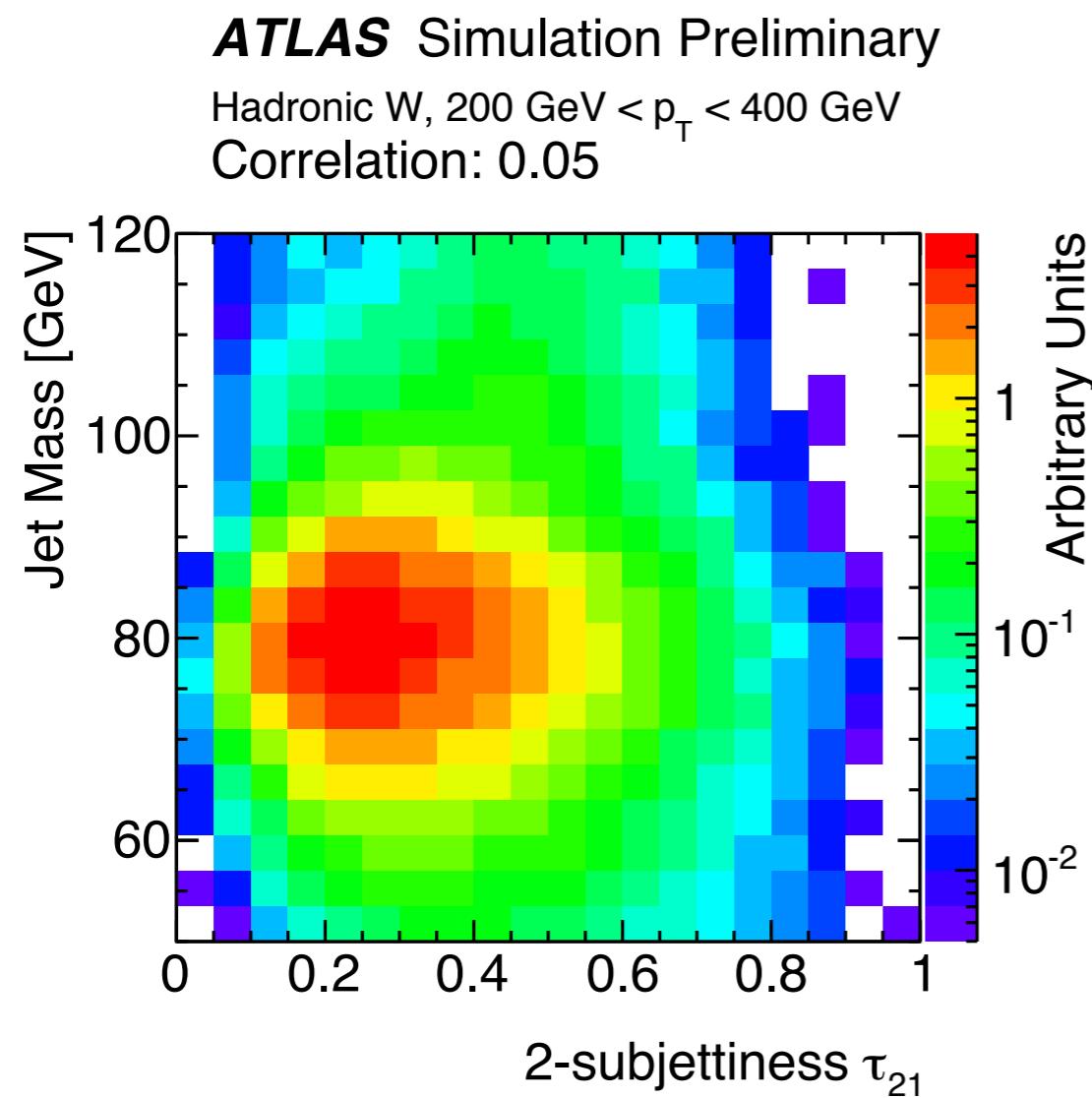
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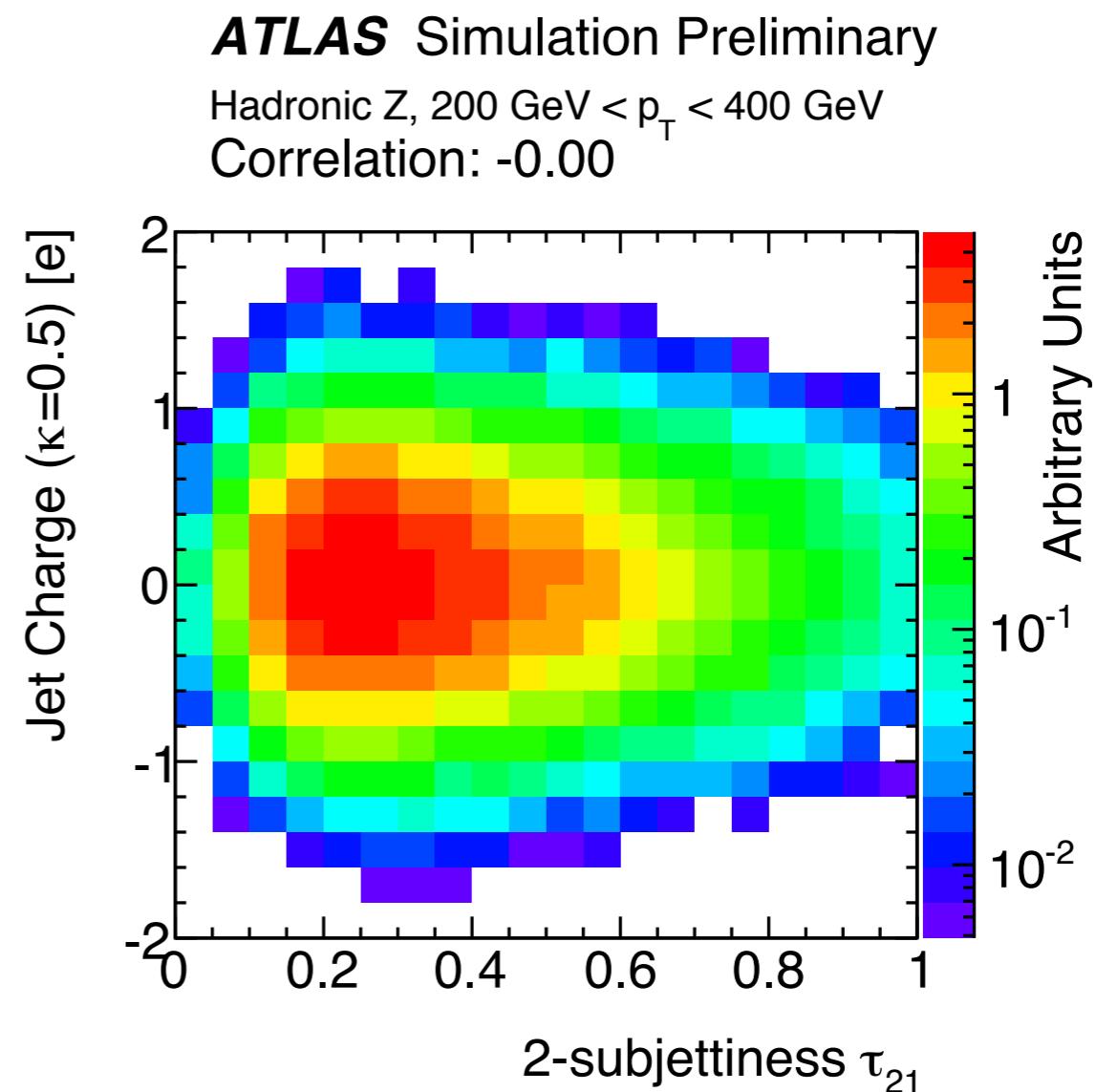
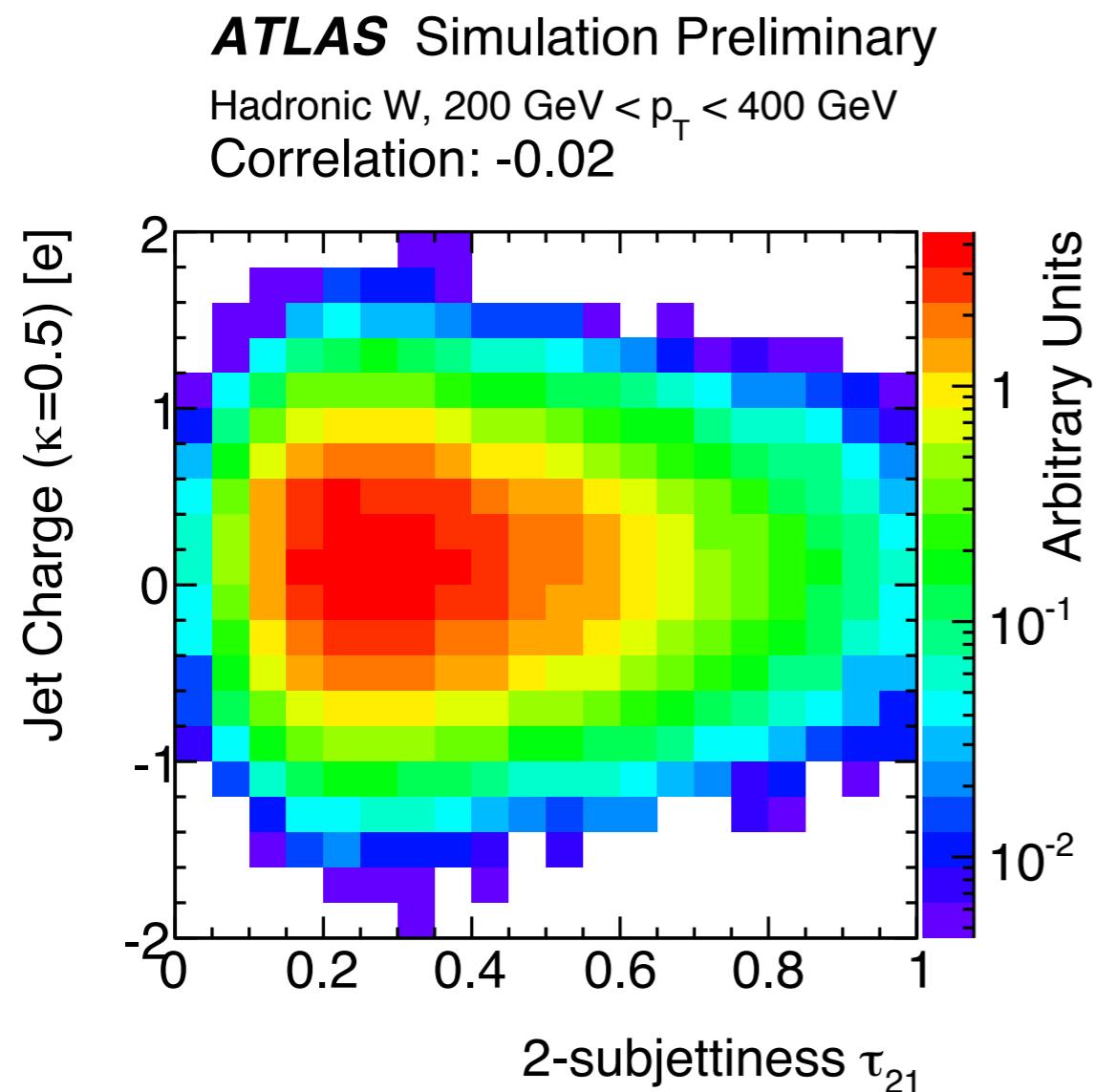
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