Jet Charge and Jet Pull in ***ATLAS***

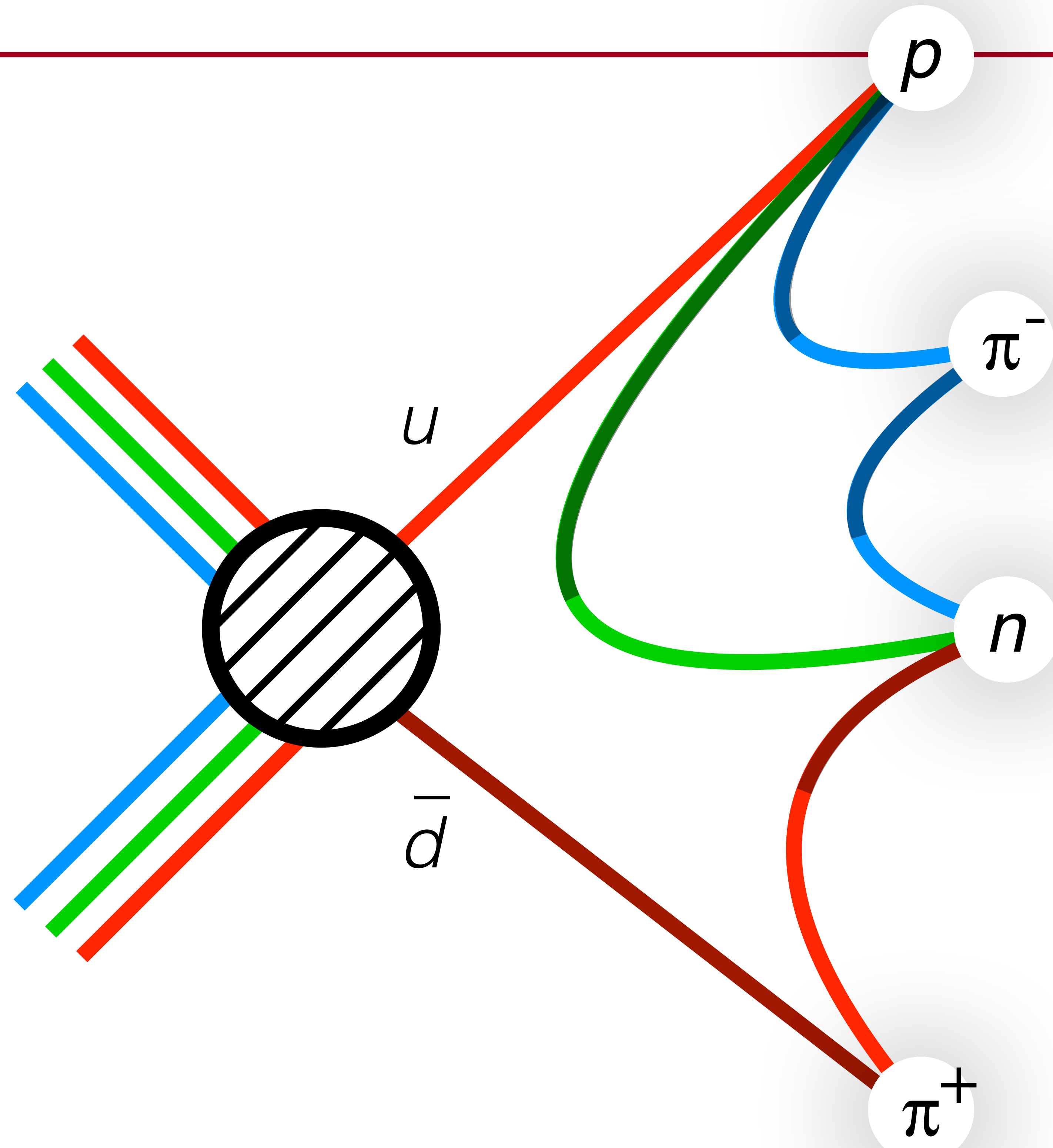
Benjamin Nachman

SLAC, Stanford University

Day, August 10, 2015

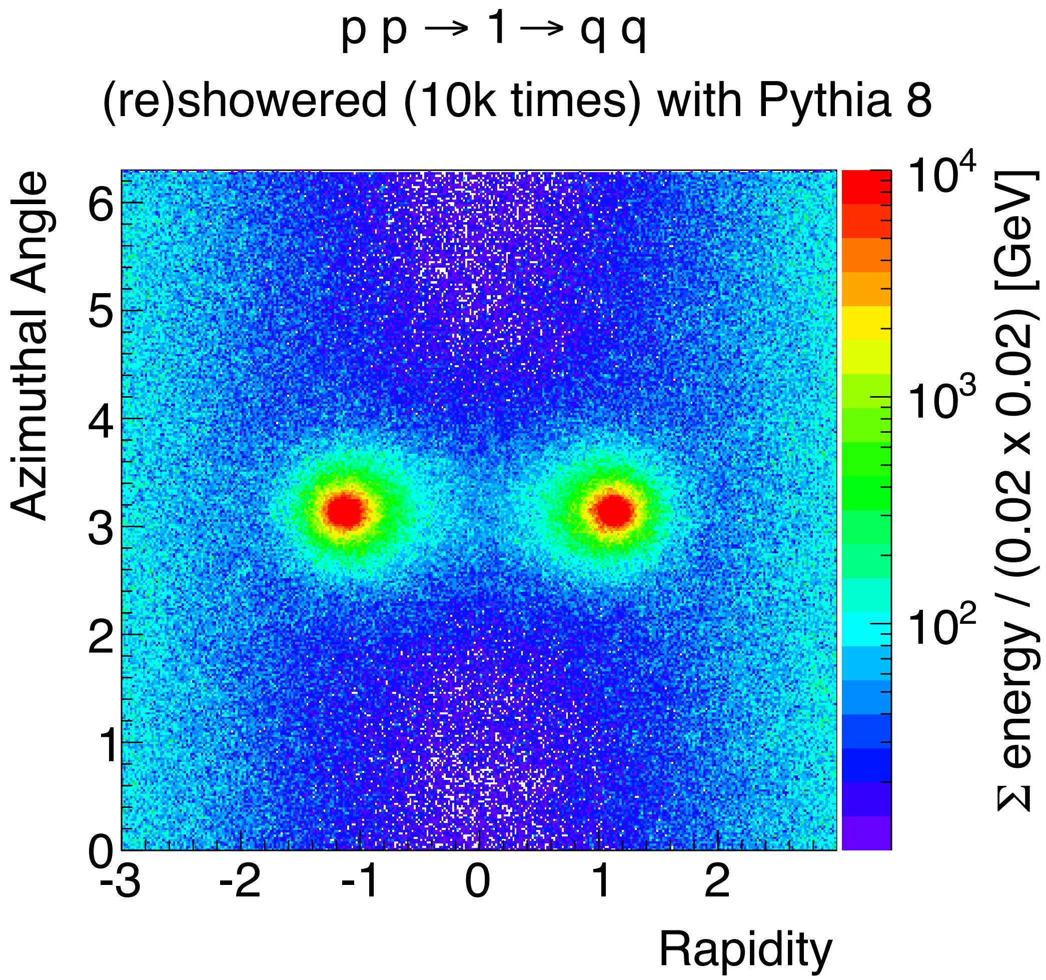
BOOST 2015

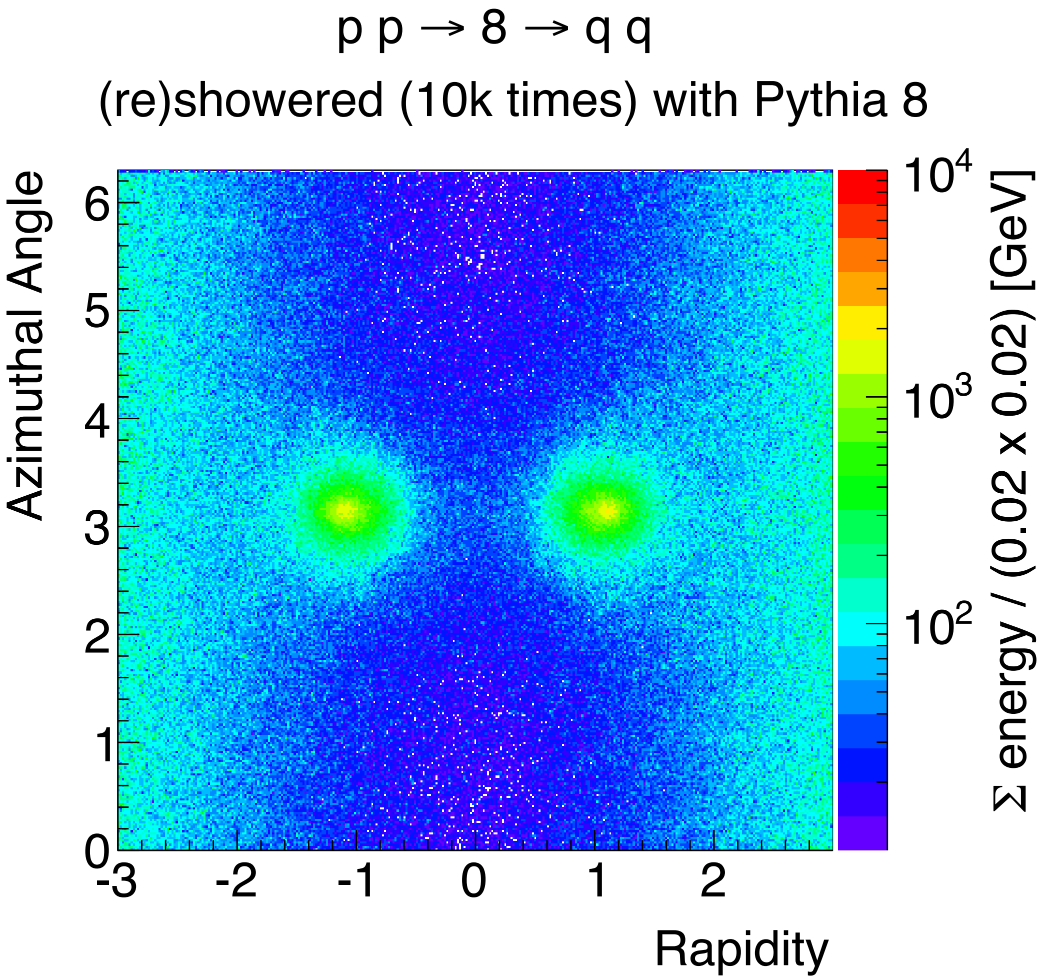
Chicago, USA



Quarks are the most interesting elementary particle: nontrivial transformation under all SM gauge groups!

…but due to confinement, we can't observe any of the conserved charges directly…





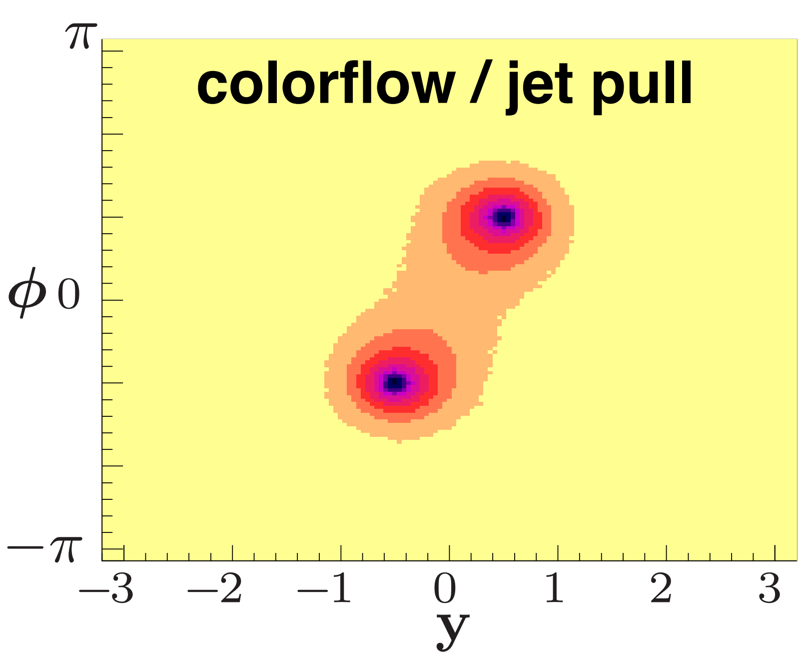
However: Information from the quarks is imparted on the observable final state: jets and their sub- and super-structure.

Our 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**

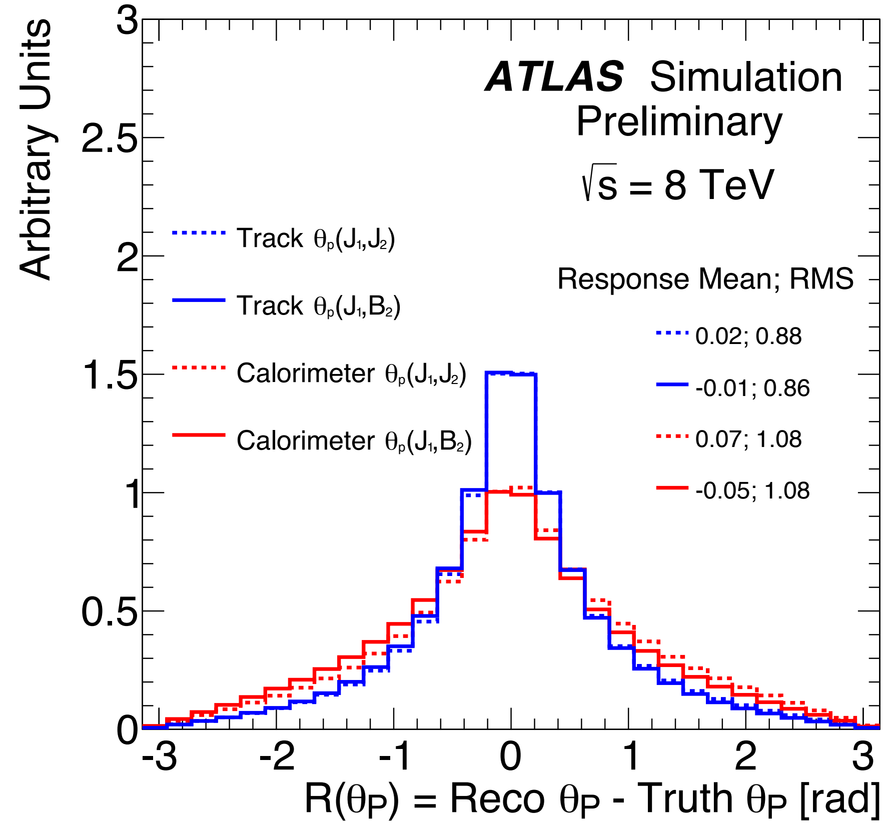
Phenomenology Studies | *Performance Studies* | *BSM Searches SM Measurements*

Phys. Rev. Lett. 105 (2010) 022001



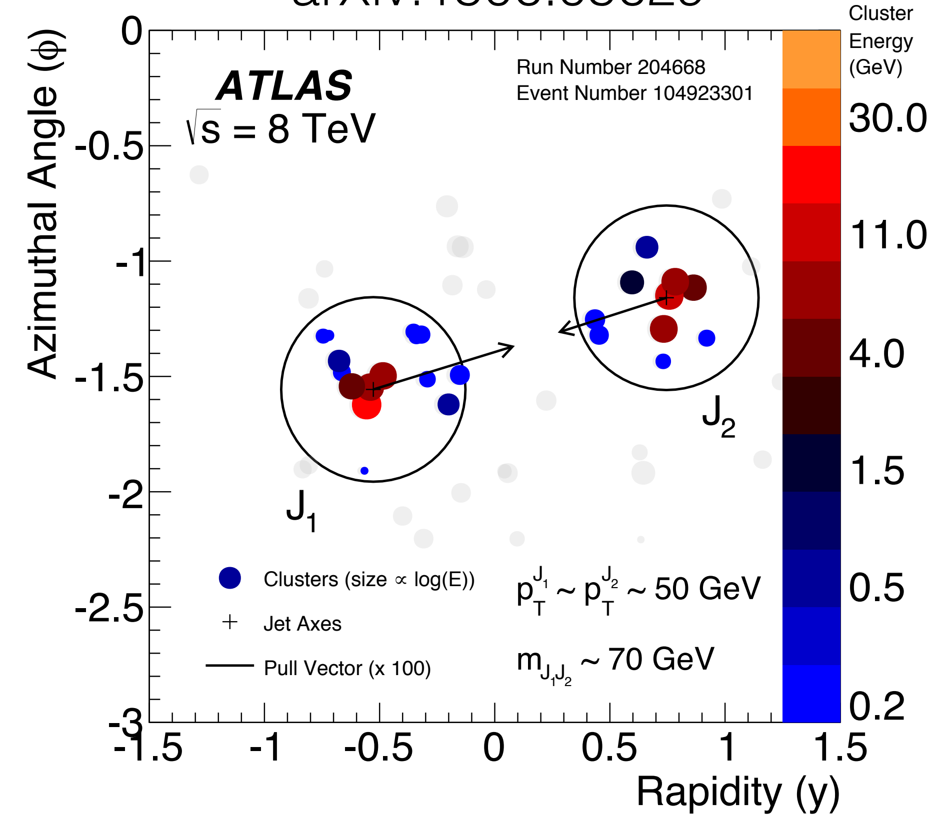
New ways of thinking about jet sub/super structure

ATLAS-CONF-2014-048



Understanding the detector response

arXiv:1506.05629



Constraining models of (B)SM!

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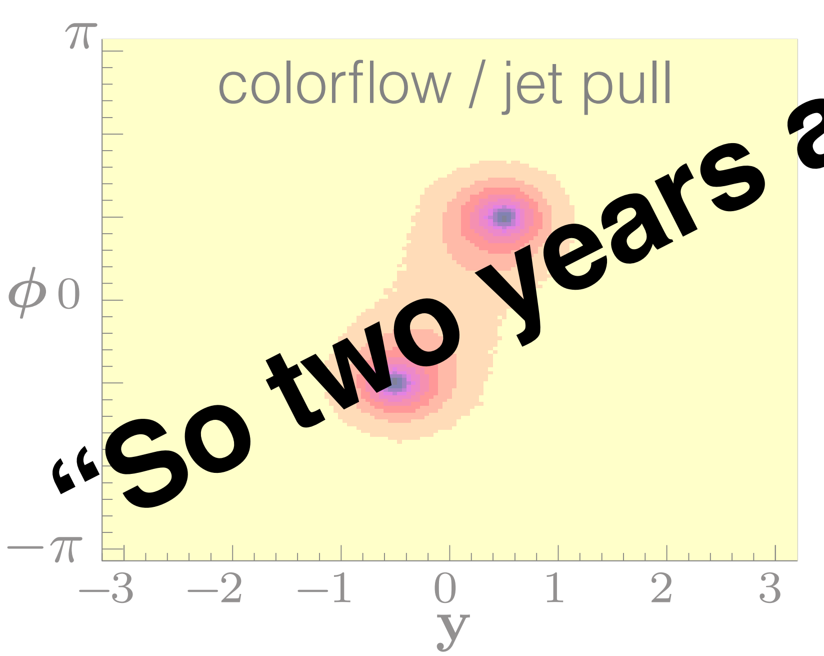

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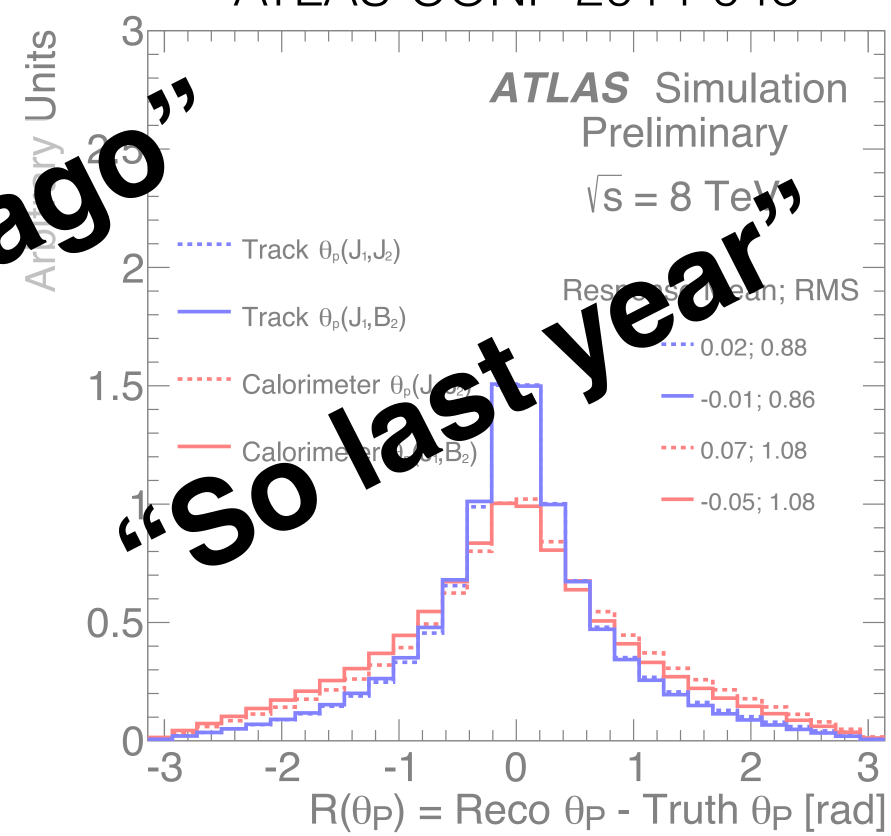

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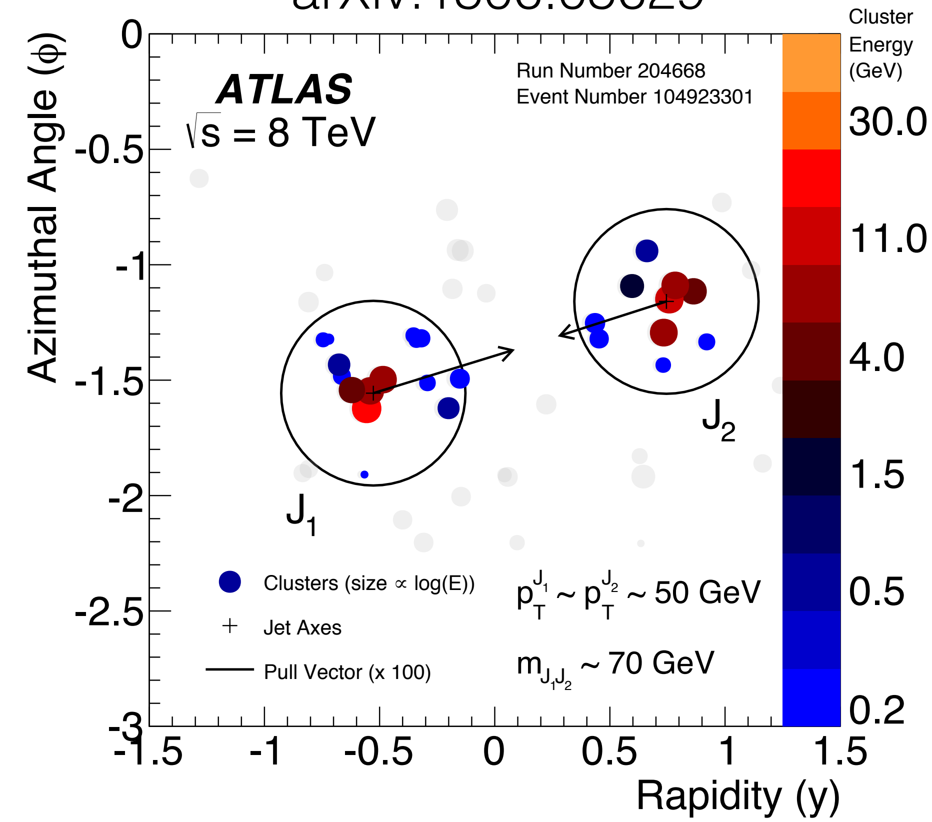
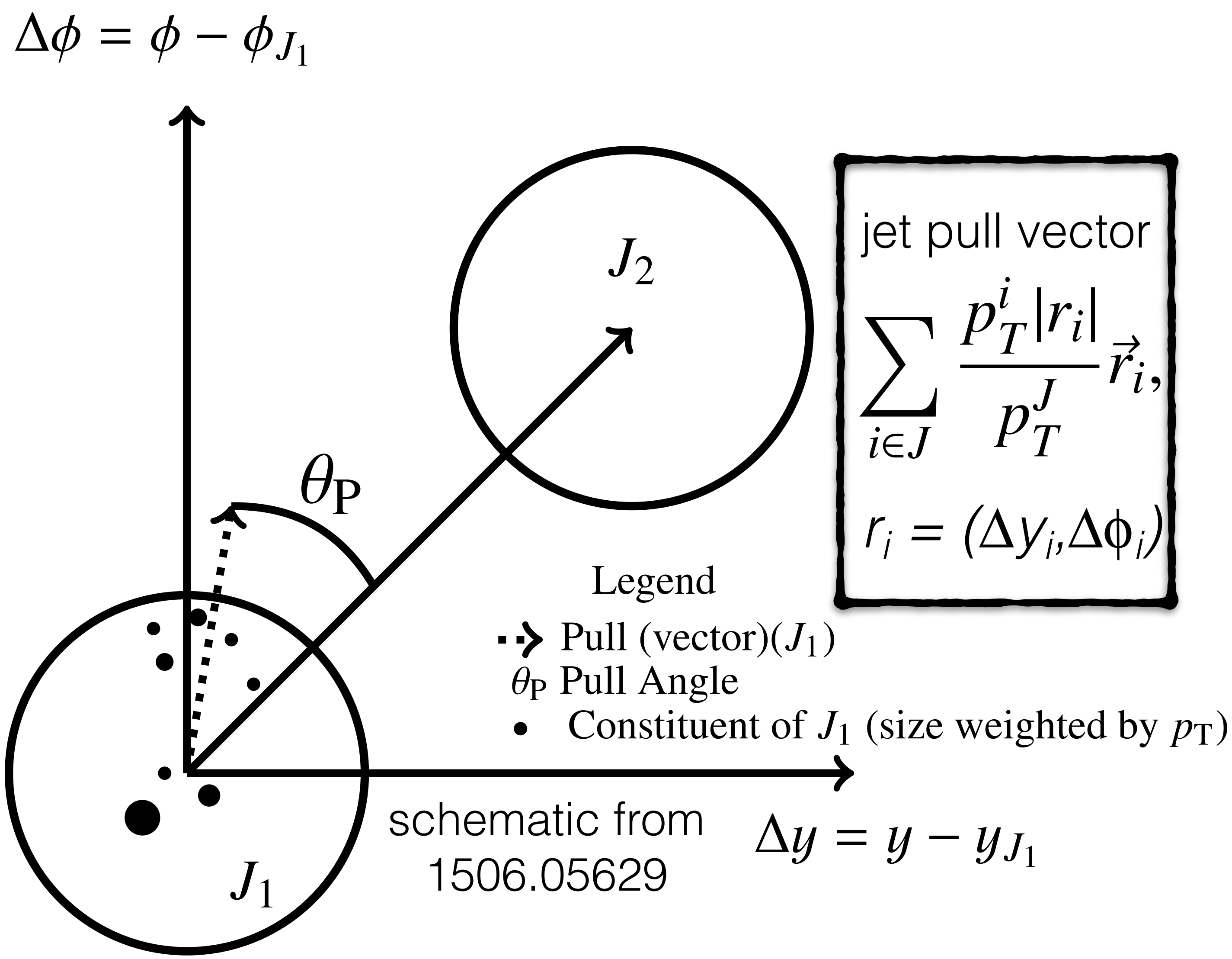


Constraining models of (B)SM!

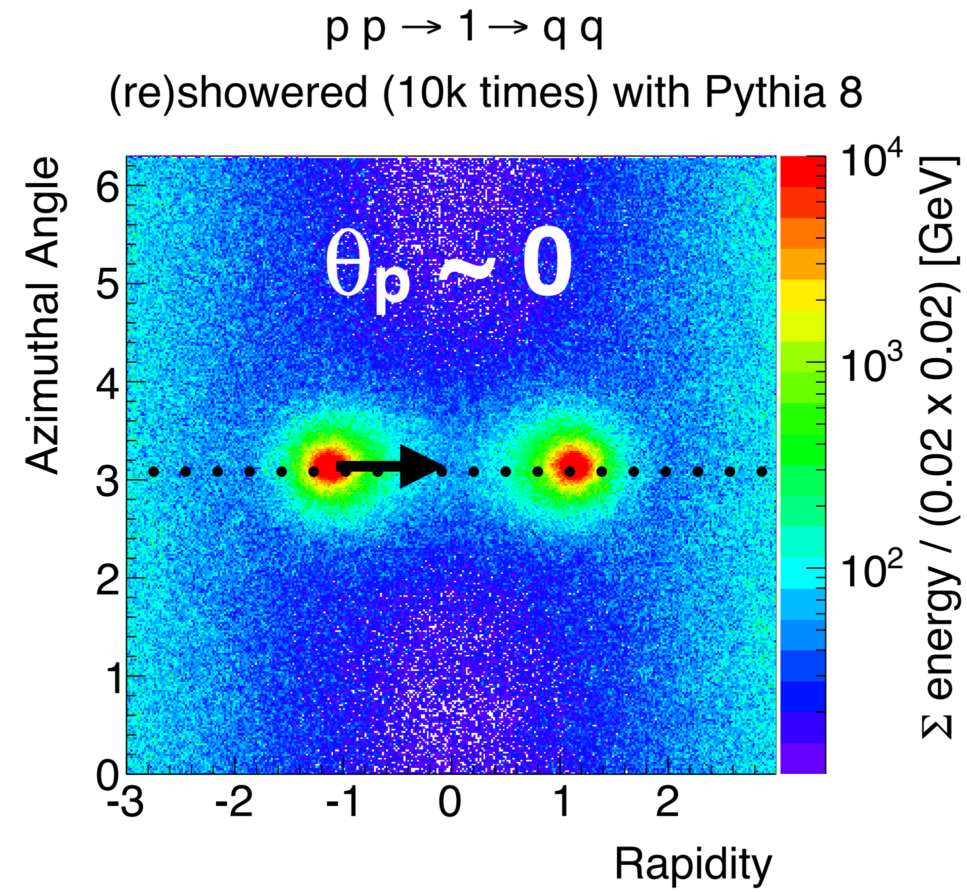
Colorflow with the Jet Pull

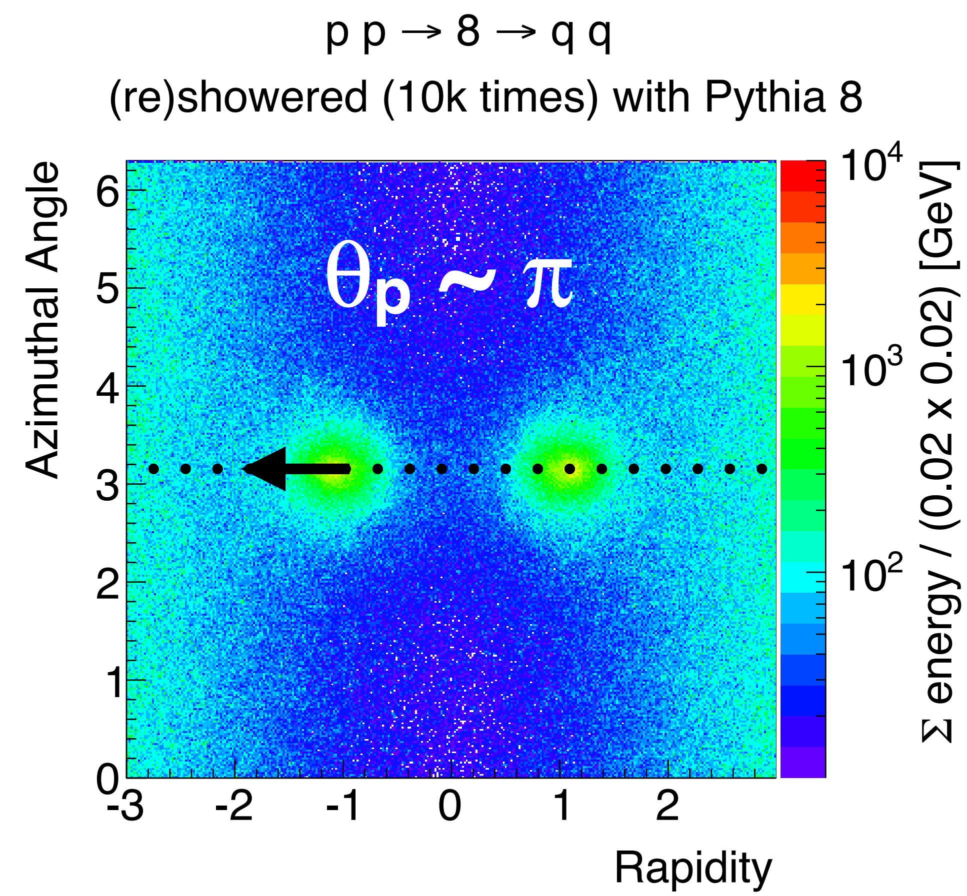


jet pull vector

$$\sum_{i\in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i,$$

$$r_i = (\Delta y_i, \Delta\phi_i)$$





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

Jet Pull in ATLAS

Two (~independent) jet inputs:

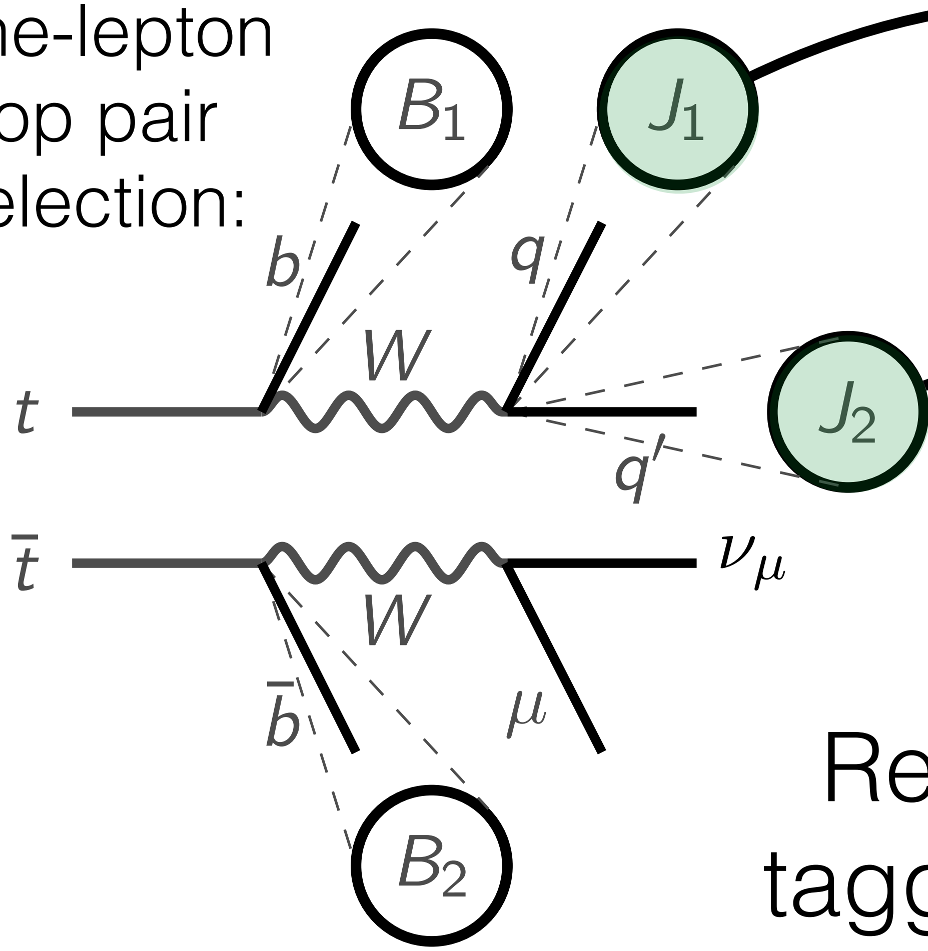
Calibrated calorimeter clusters

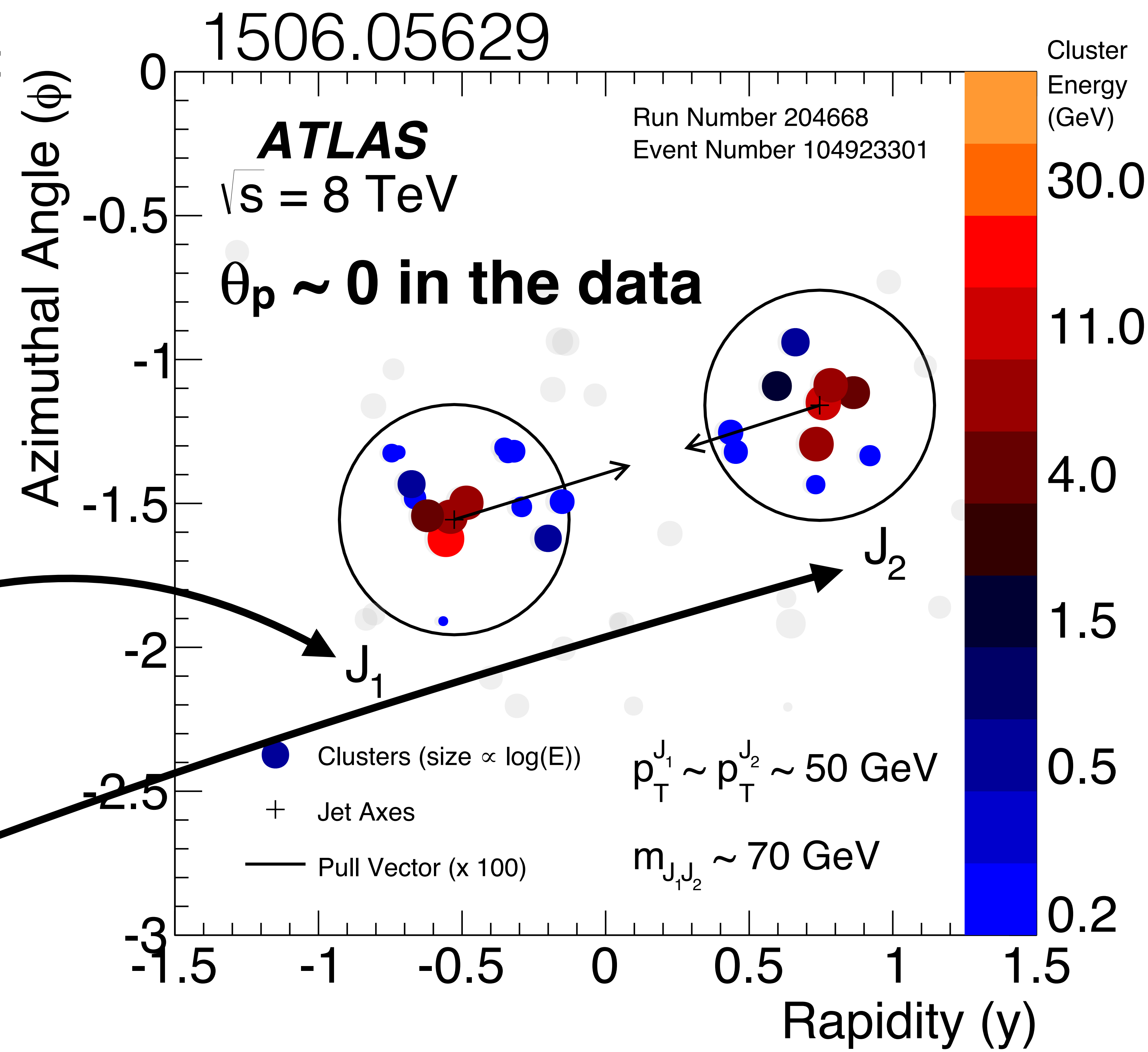
used in jet formation

Tracks

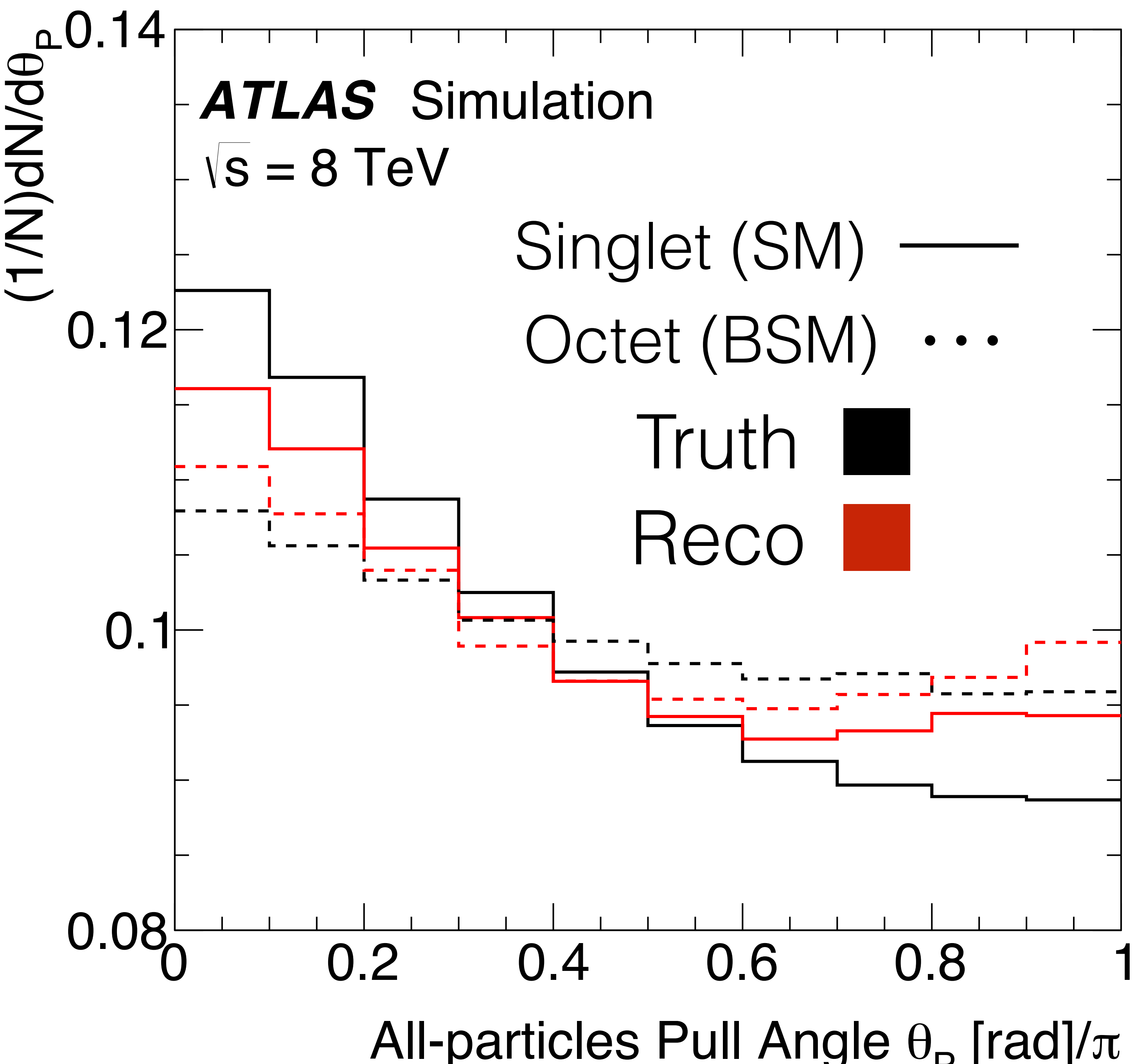
ghost associated

One-lepton top pair selection:





Require two *b*-tagged and two non-*b*-tagged (J_1 and J_2) jets with $p_T > 25$ GeV.



↑

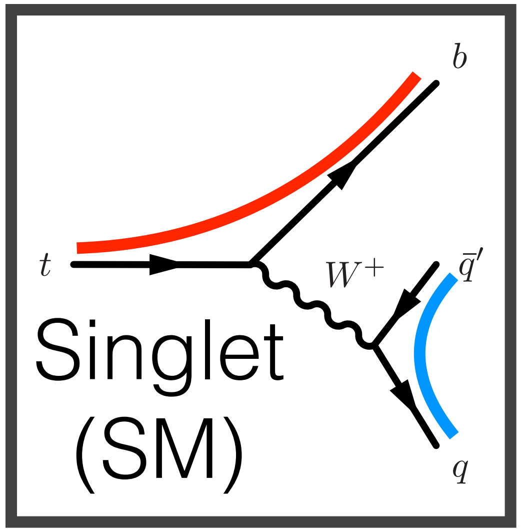
Calorimeter-based

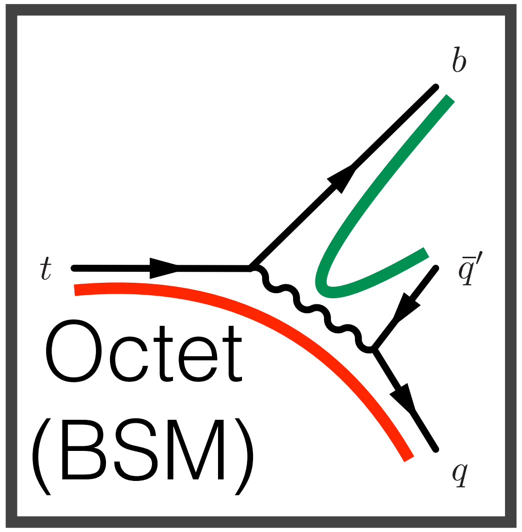
Goals:

-Present a measurement of a **colorflow-sensitive** observable in top events

-Quantify sensitivity to the **color** representation of a dijet resonance

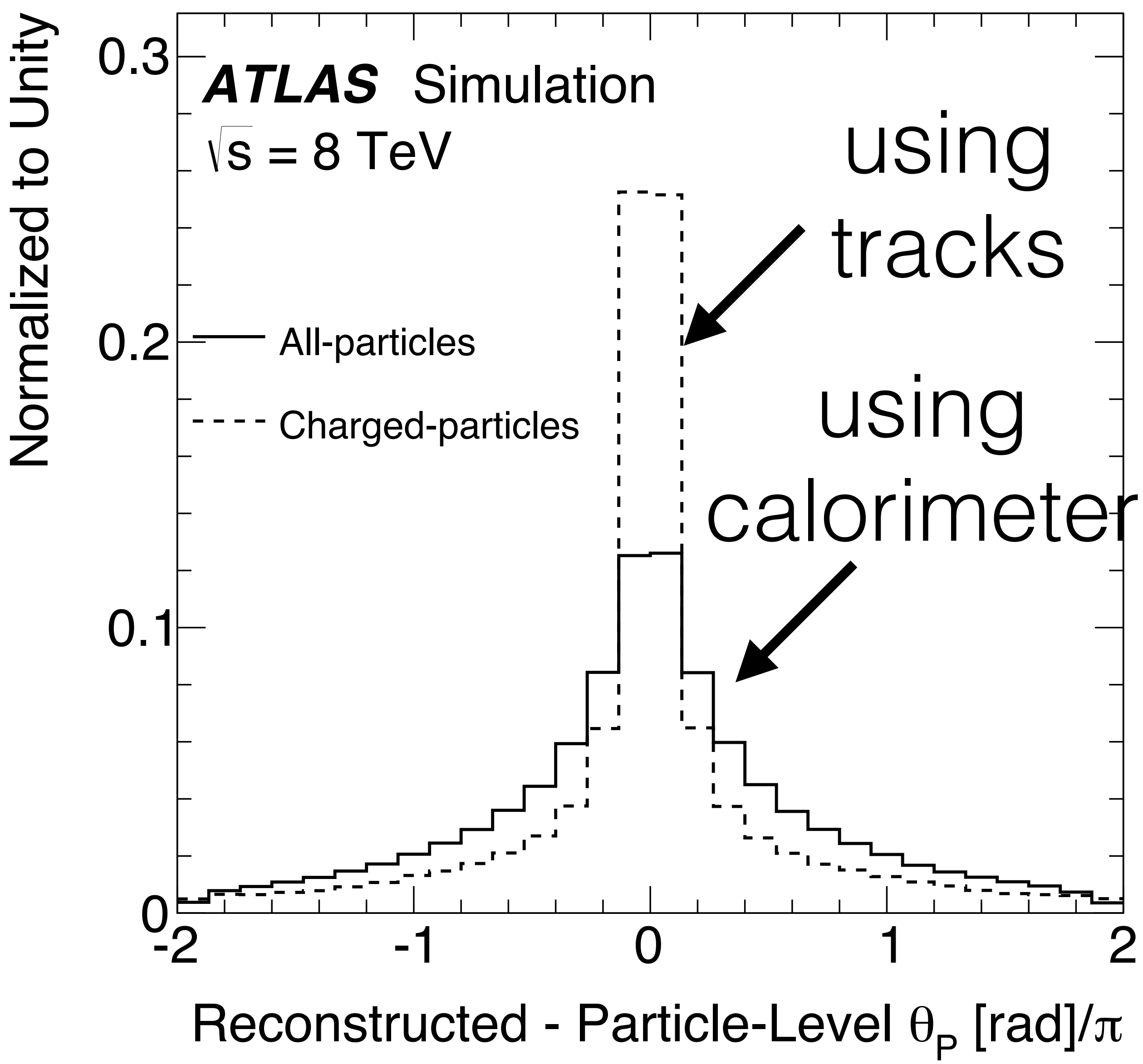
(in this case, a *W* boson)



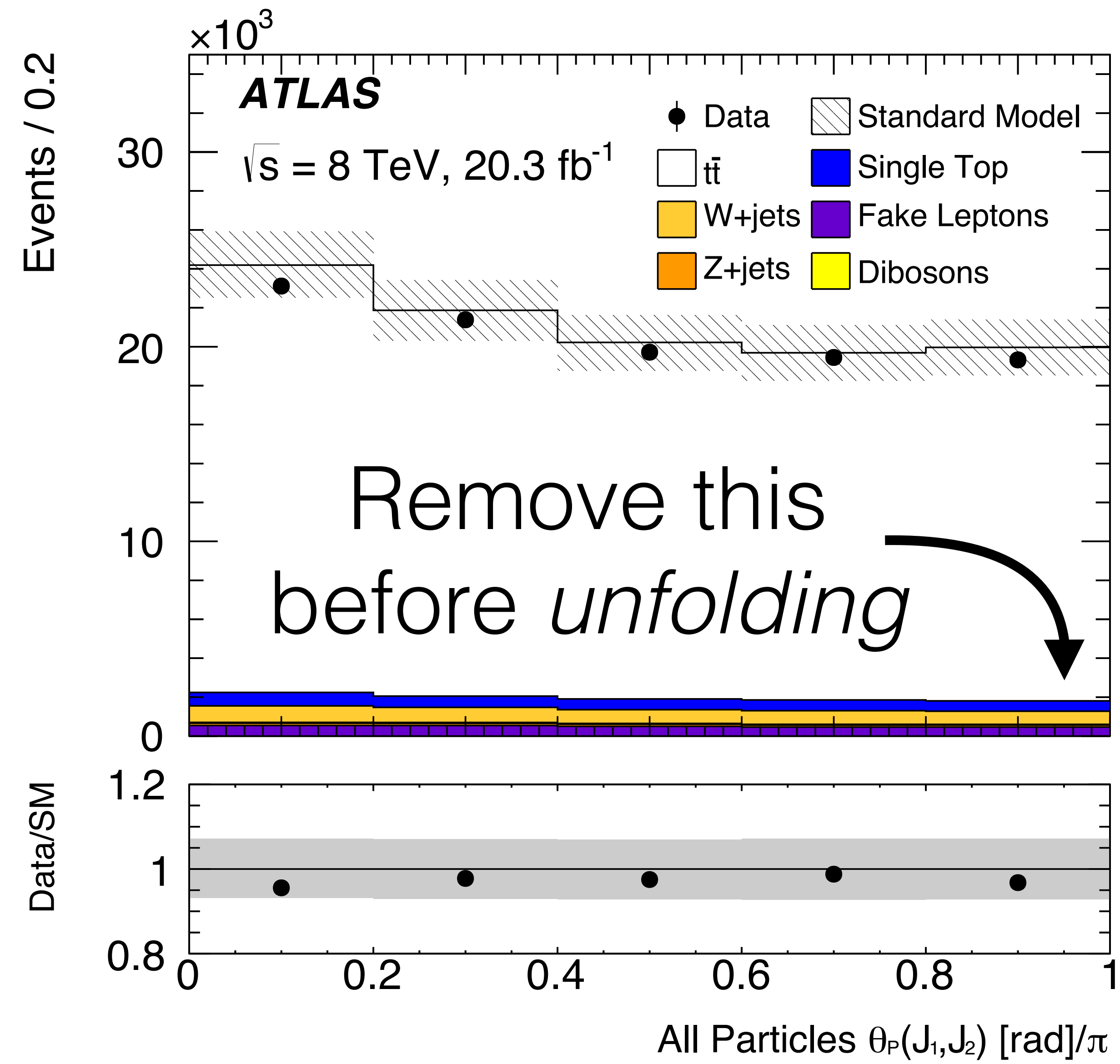


→ ATLAS Colorflow in backup

Two big challenges in this measurement:



Resolution is comparable to the range

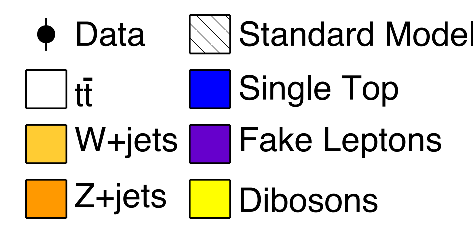


Nearly uniform (but backgrounds are small!)

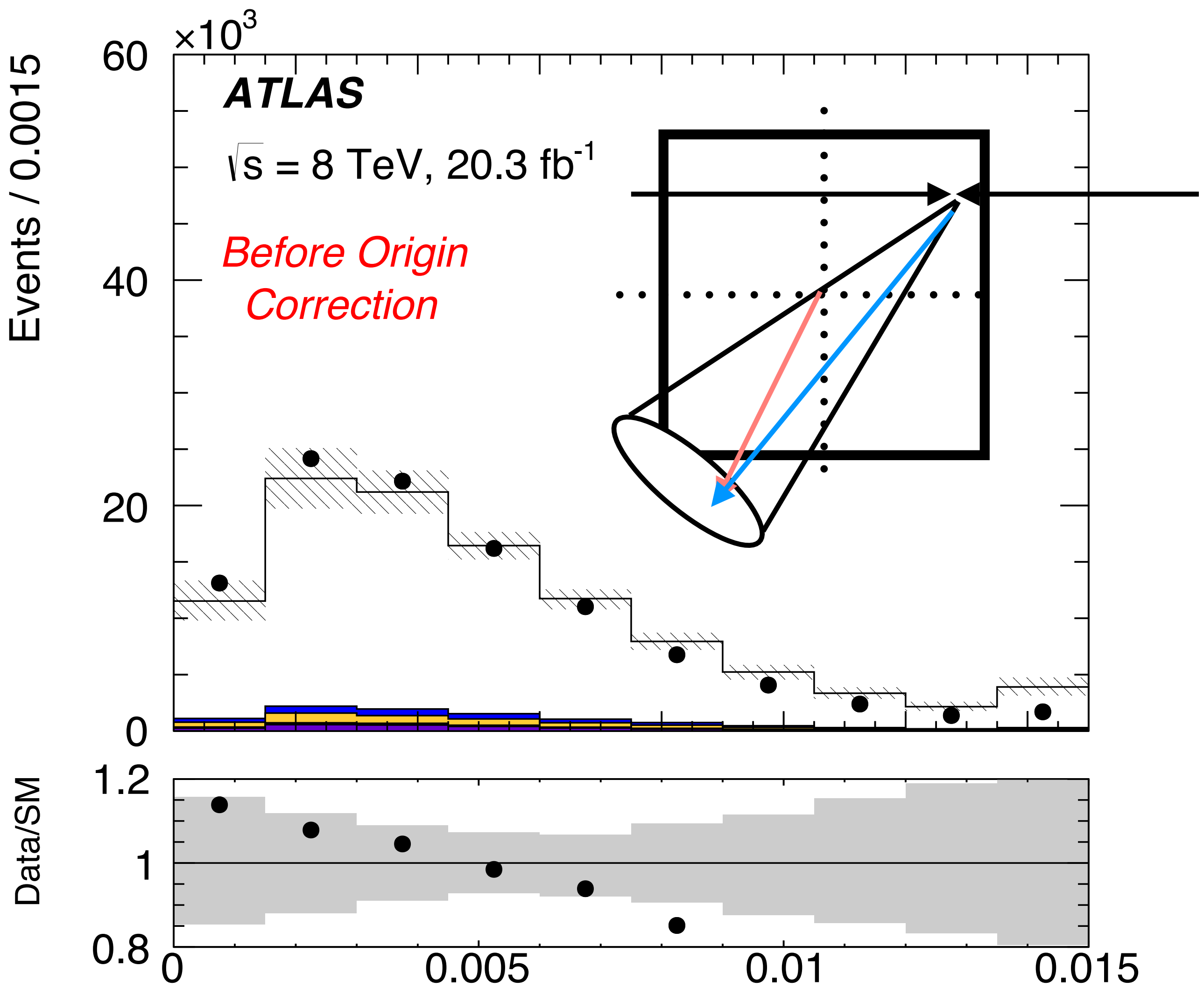
→ ATLAS Colorflow in backup

Colorflow Tagging Measurement Subtleties

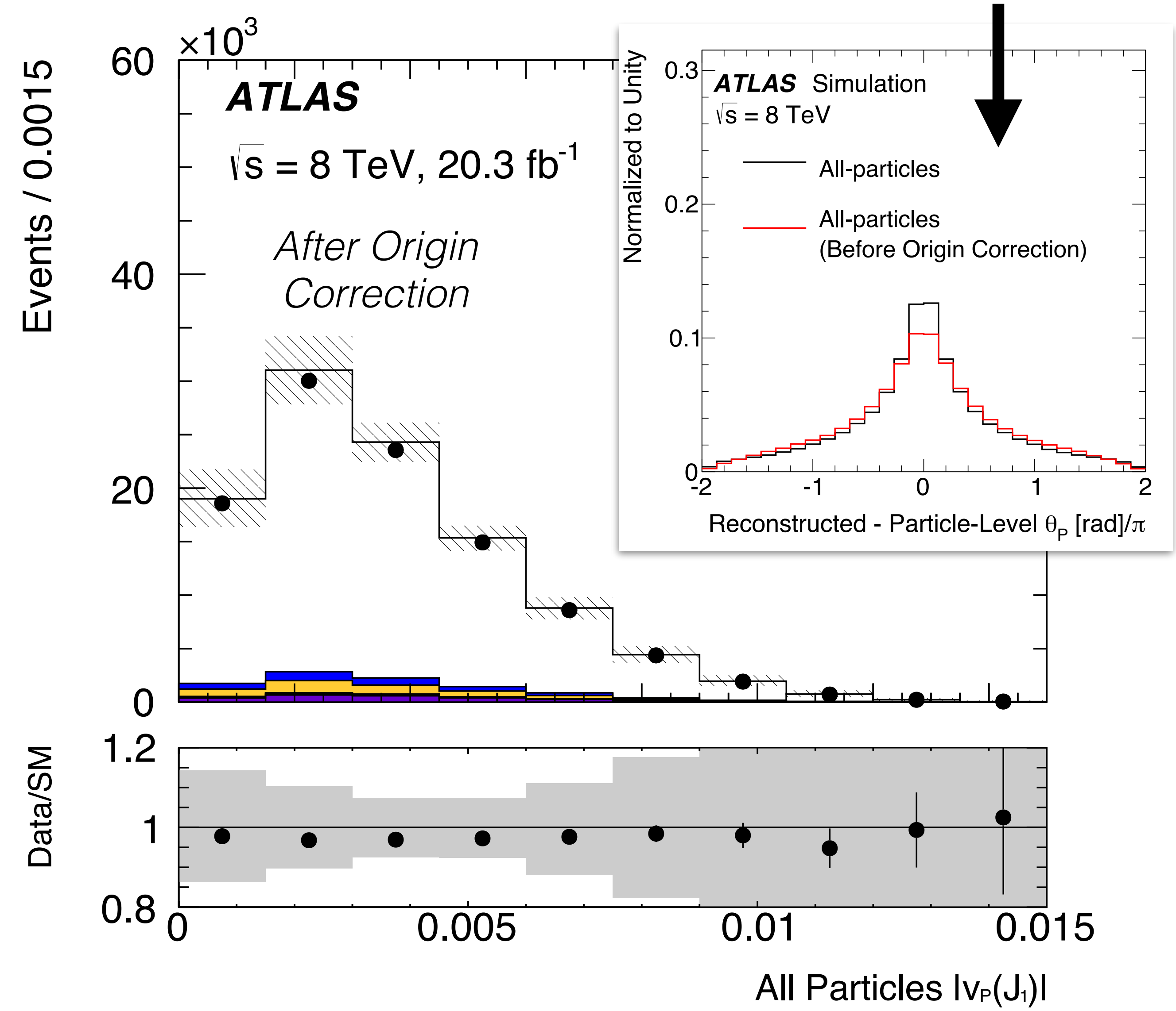
There are severe subtleties in the measurement: e.g. what is the jet axis?



Resolution also improved



Magnitude of the pull vector → All Particles $|v_P(J_1)|$



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

→ ATLAS Colorflow in backup

Colorflow Measurement Results

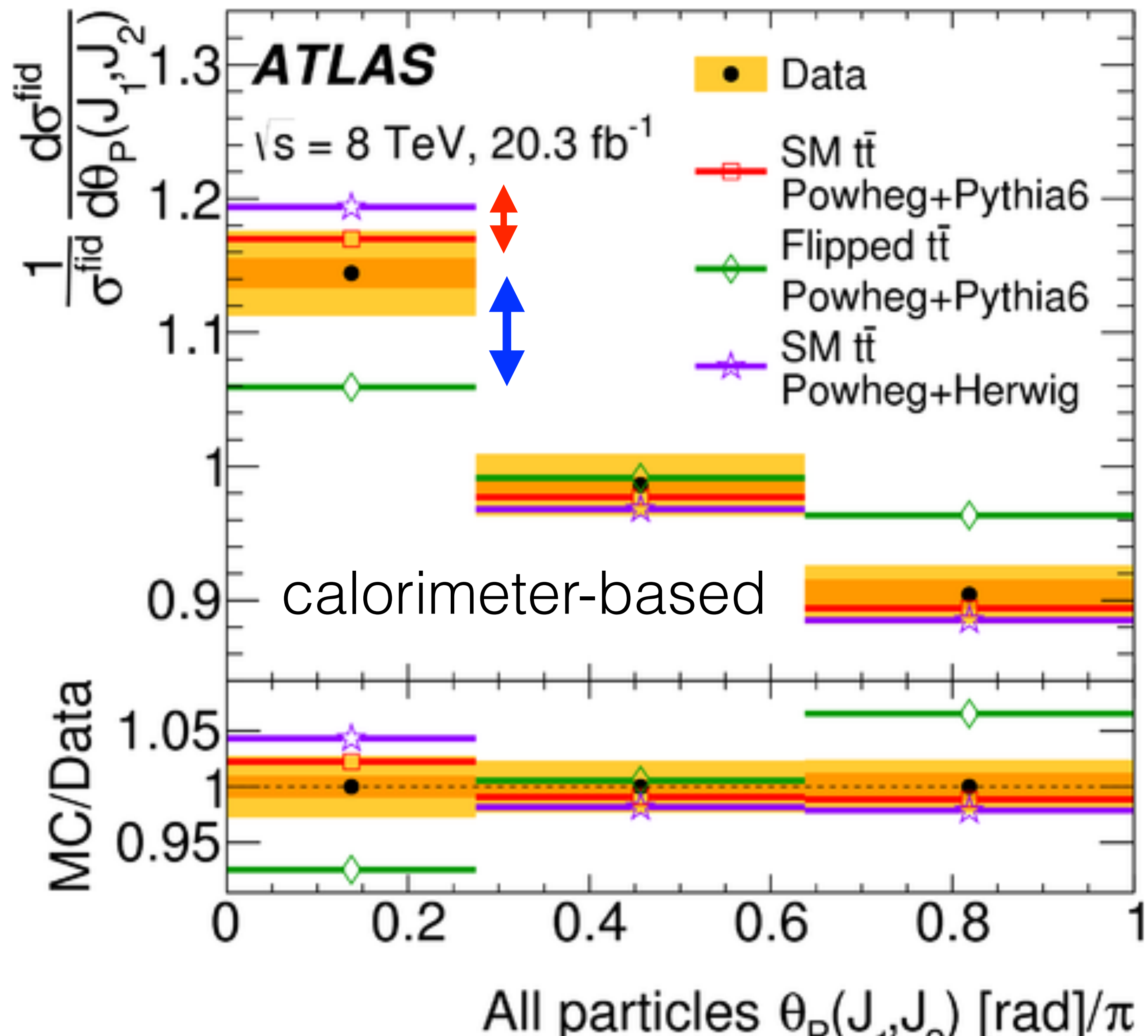
→ ATLAS Colorflow in backup

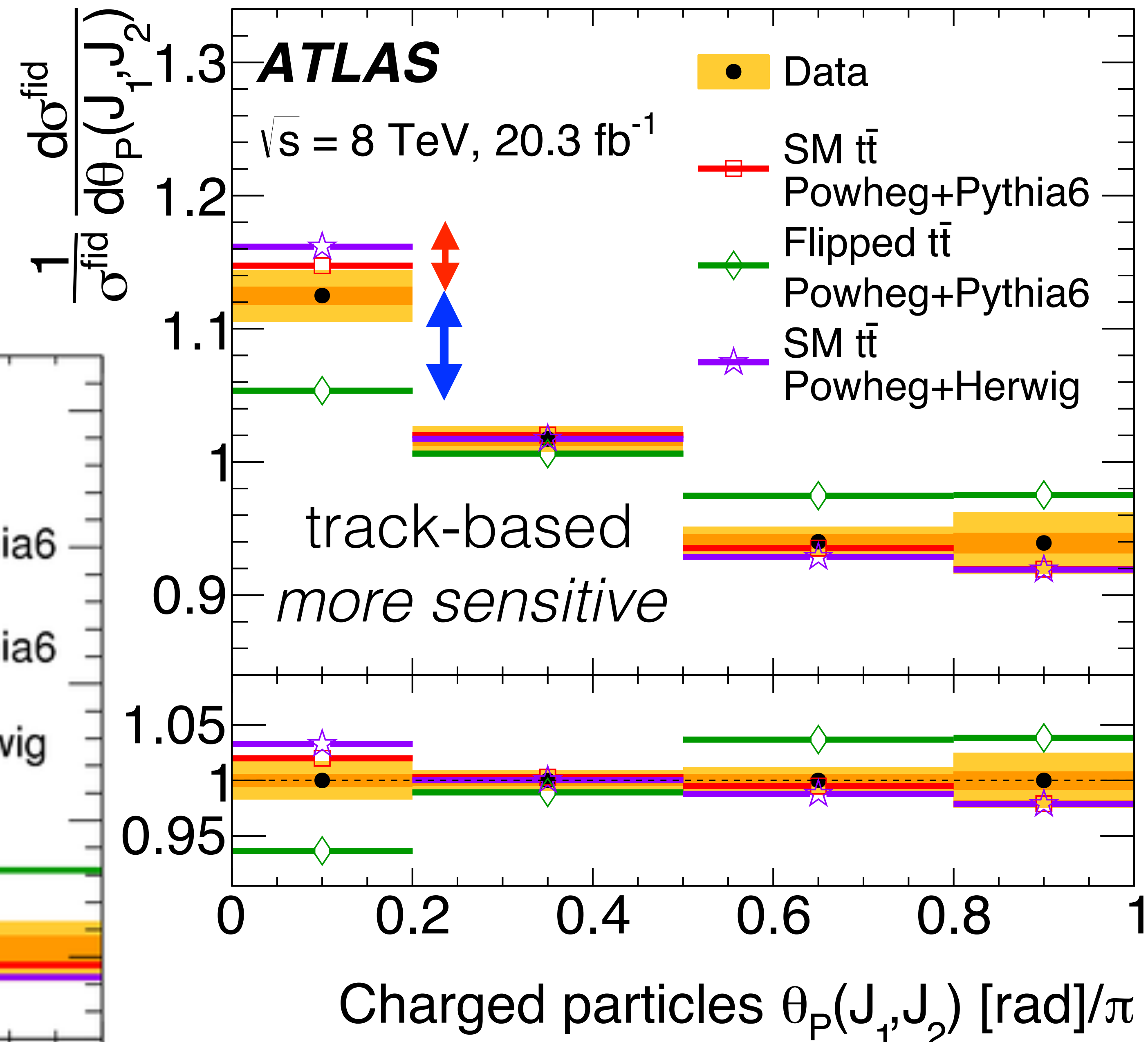
Significantly

(~3σ) distinguish

singlet from octet

Legend
stat
stat ⊕ syst





Unfolded data are public for **model comparisons** and tuning

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

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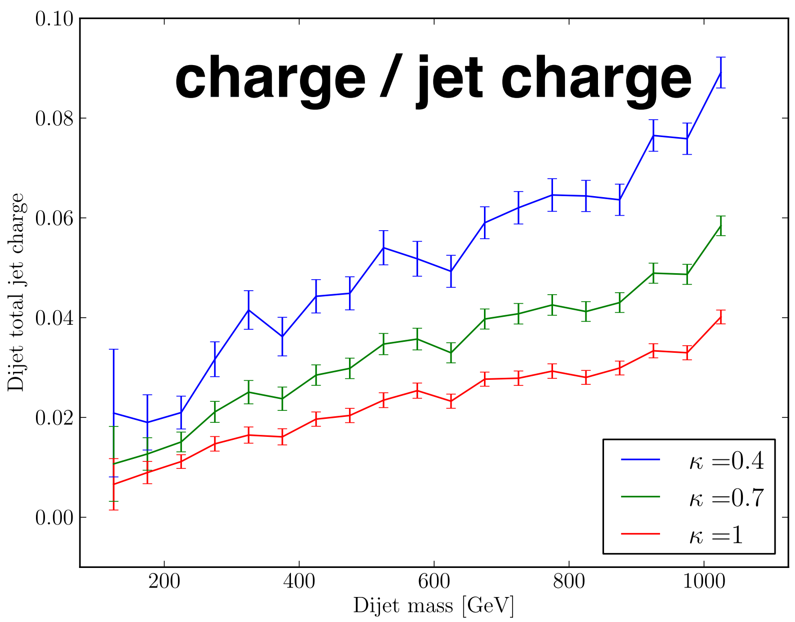
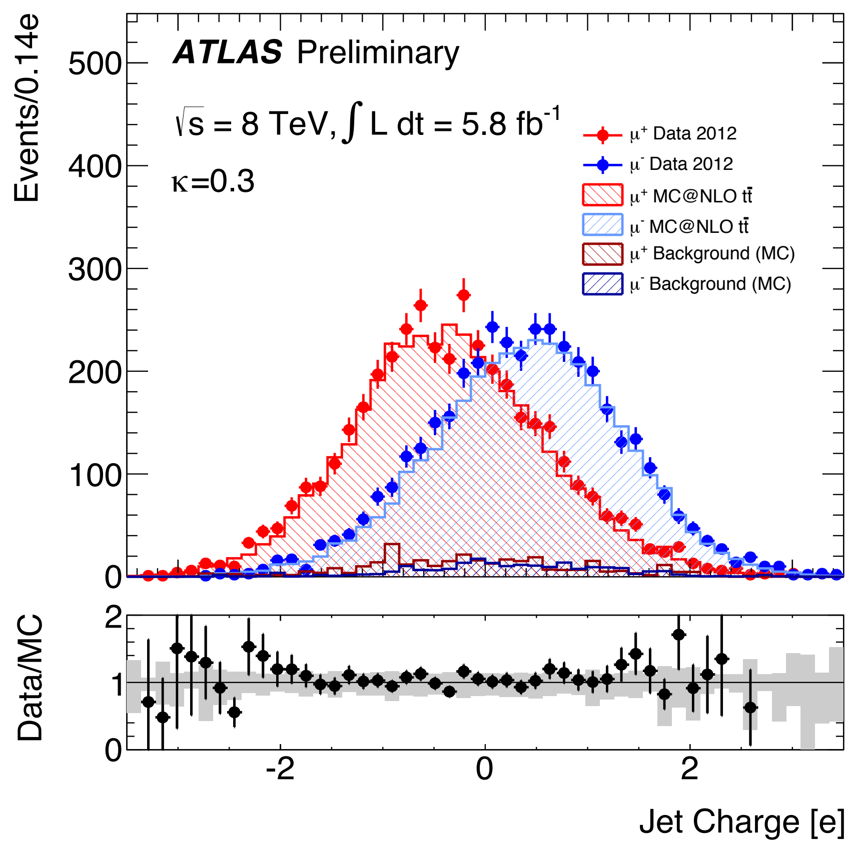
Phys. Rev. Lett. 110 (2013) 212001



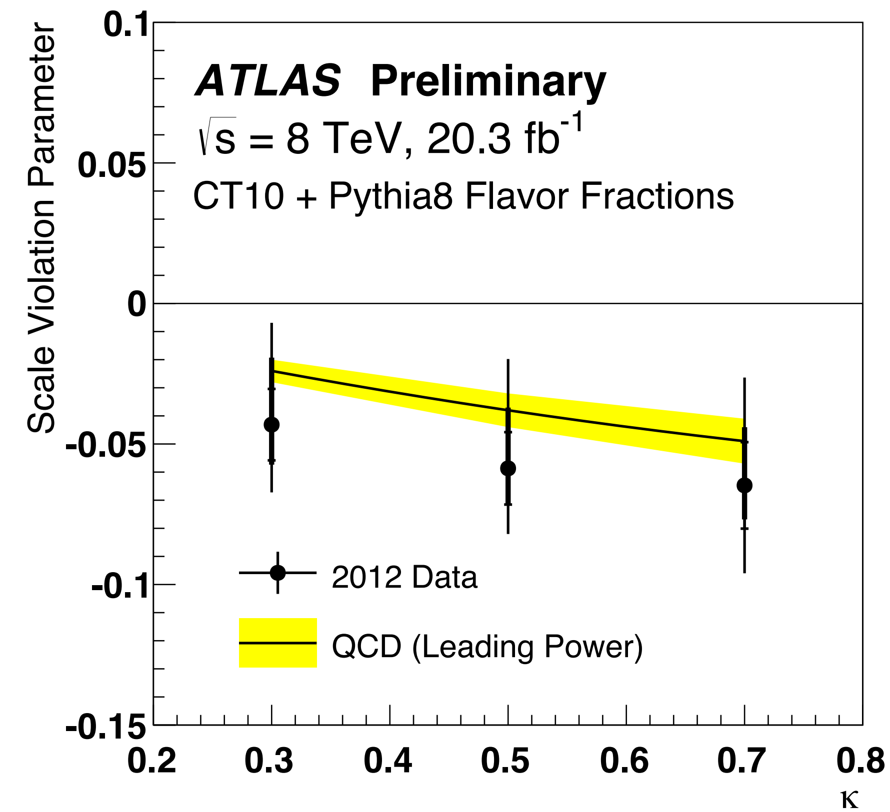
New ways of thinking about jet sub/super structure

ATLAS-CONF-2013-086



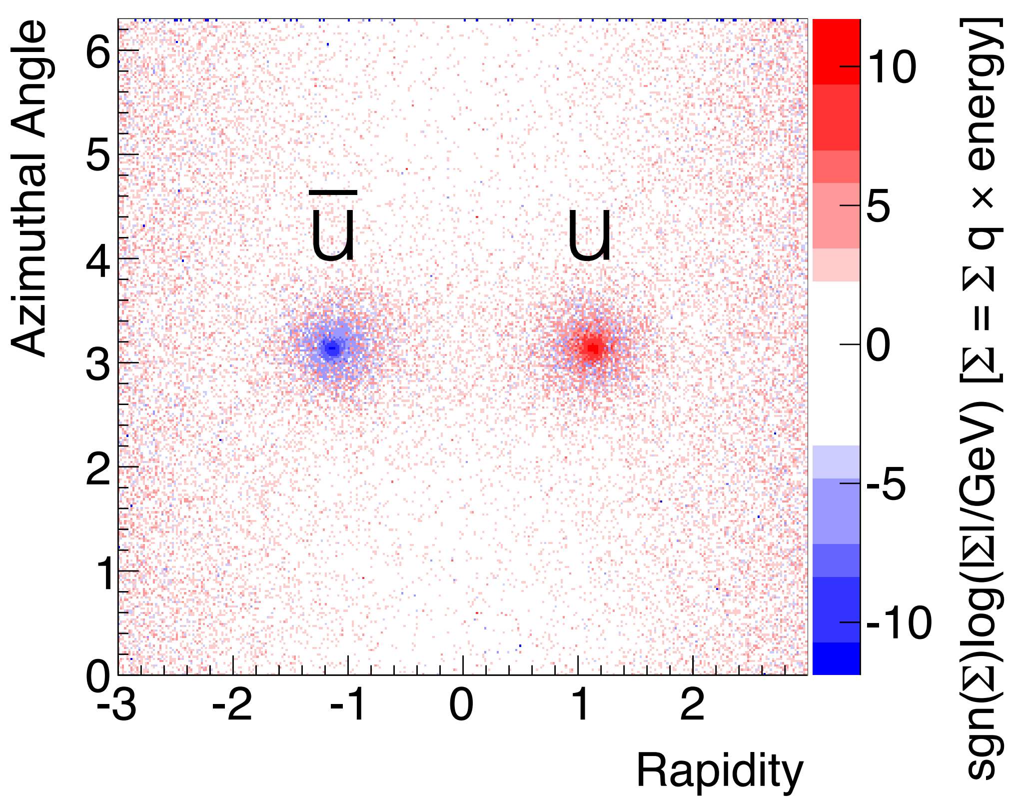
Understanding the detector response

ATLAS-CONF-2015-025



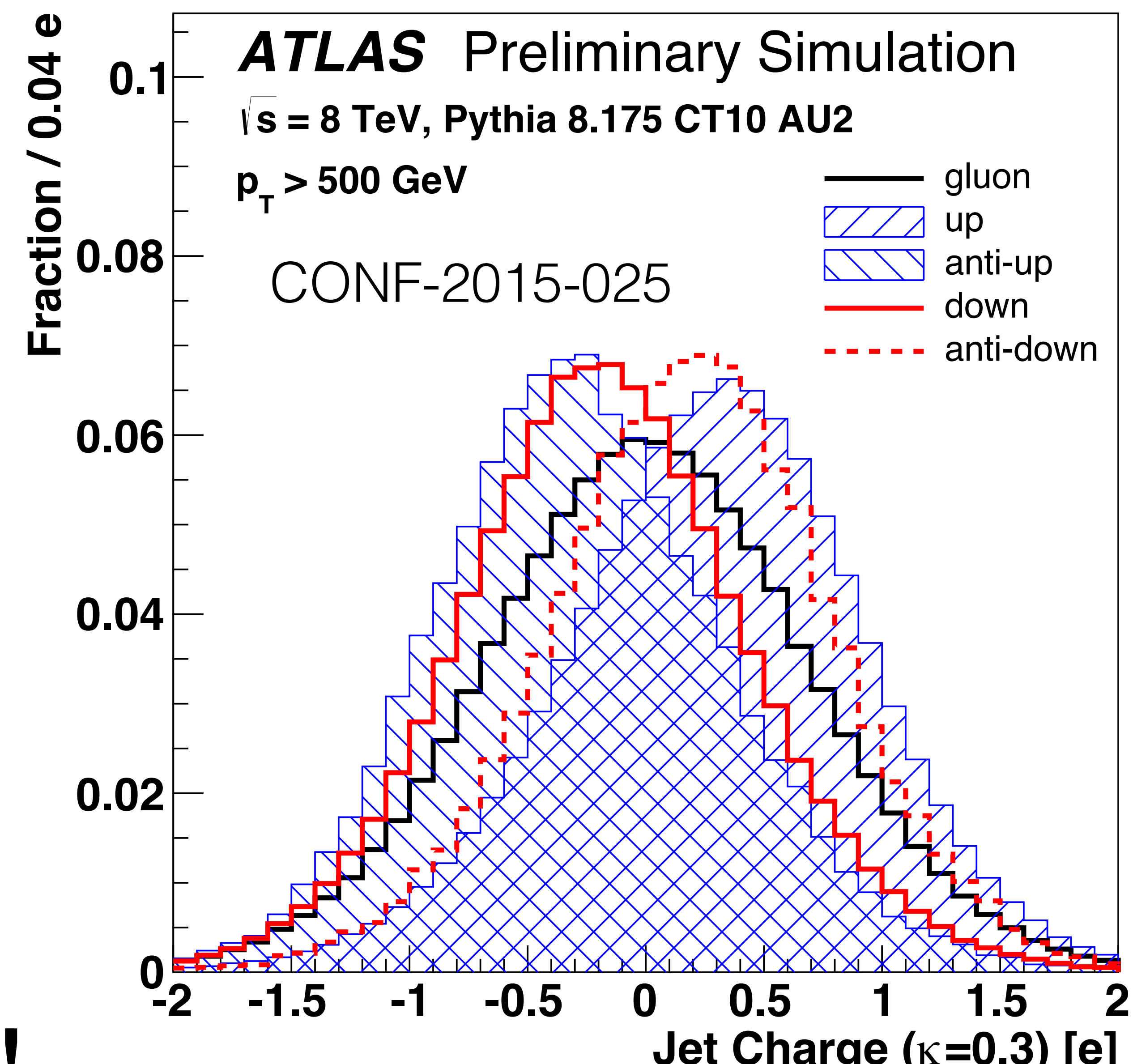
Constraining models of (B)SM!

Charge Tagging



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

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



In units of the positron charge [e]

Tr is the set of tracks associated with the jets

ATLAS: via ghost-association
CMS: charged PF candidates

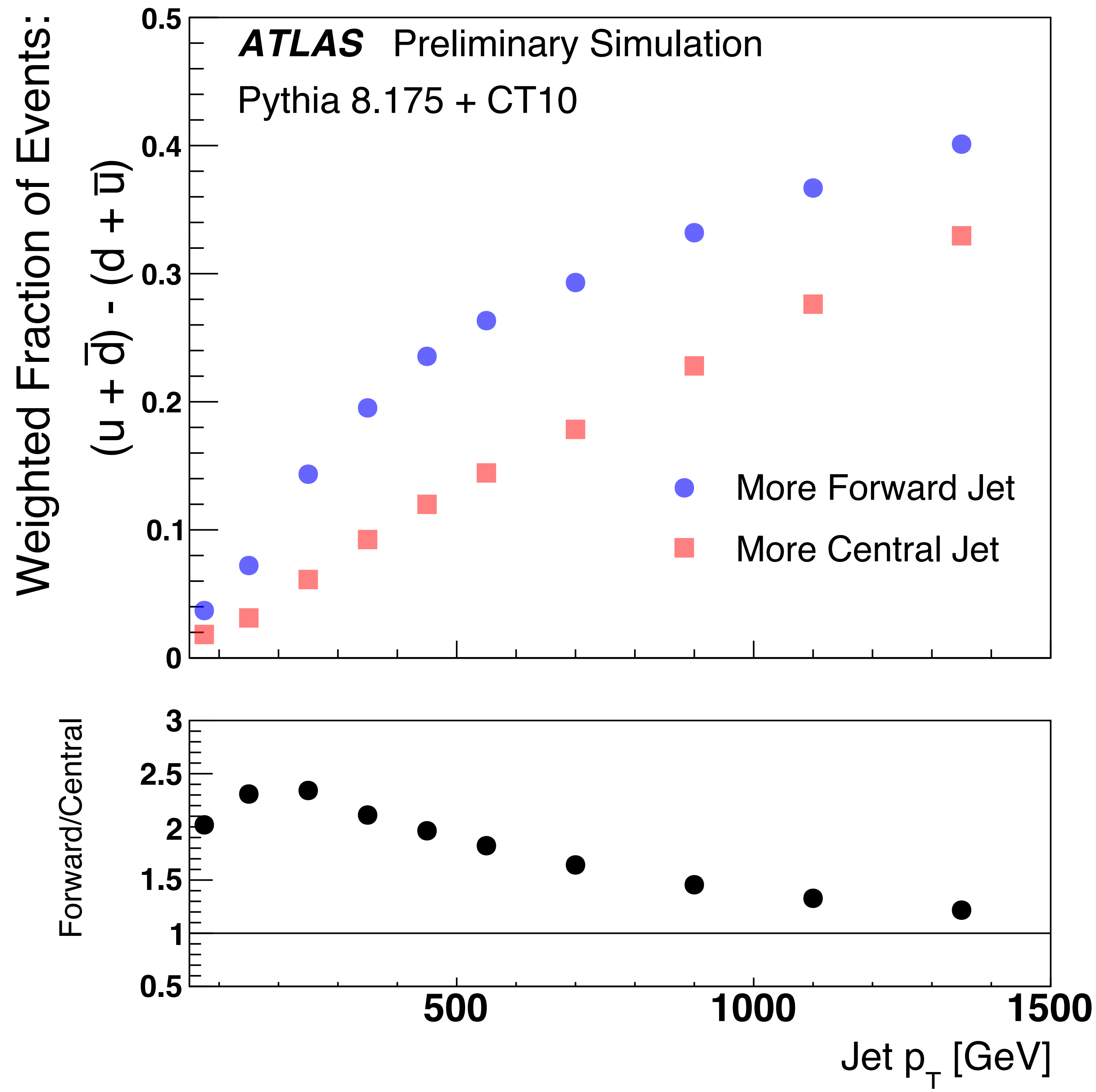
+ / - / neutral means shifted, but small compared to width!

We have 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.

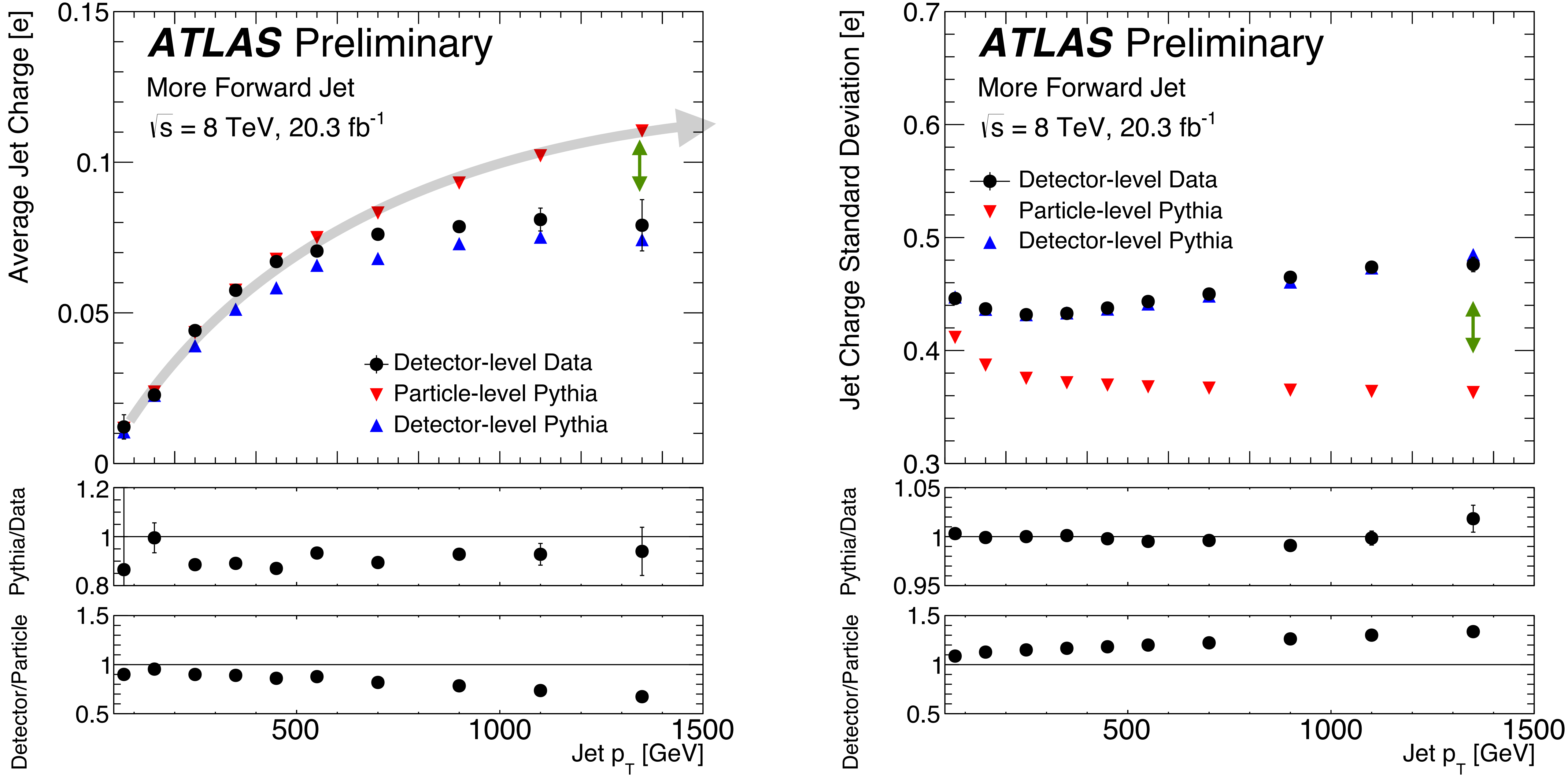
Furthermore, there have been recent calculations which we can put to the test!

CONF-2015-025



→ ATLAS Jet Charge in backup

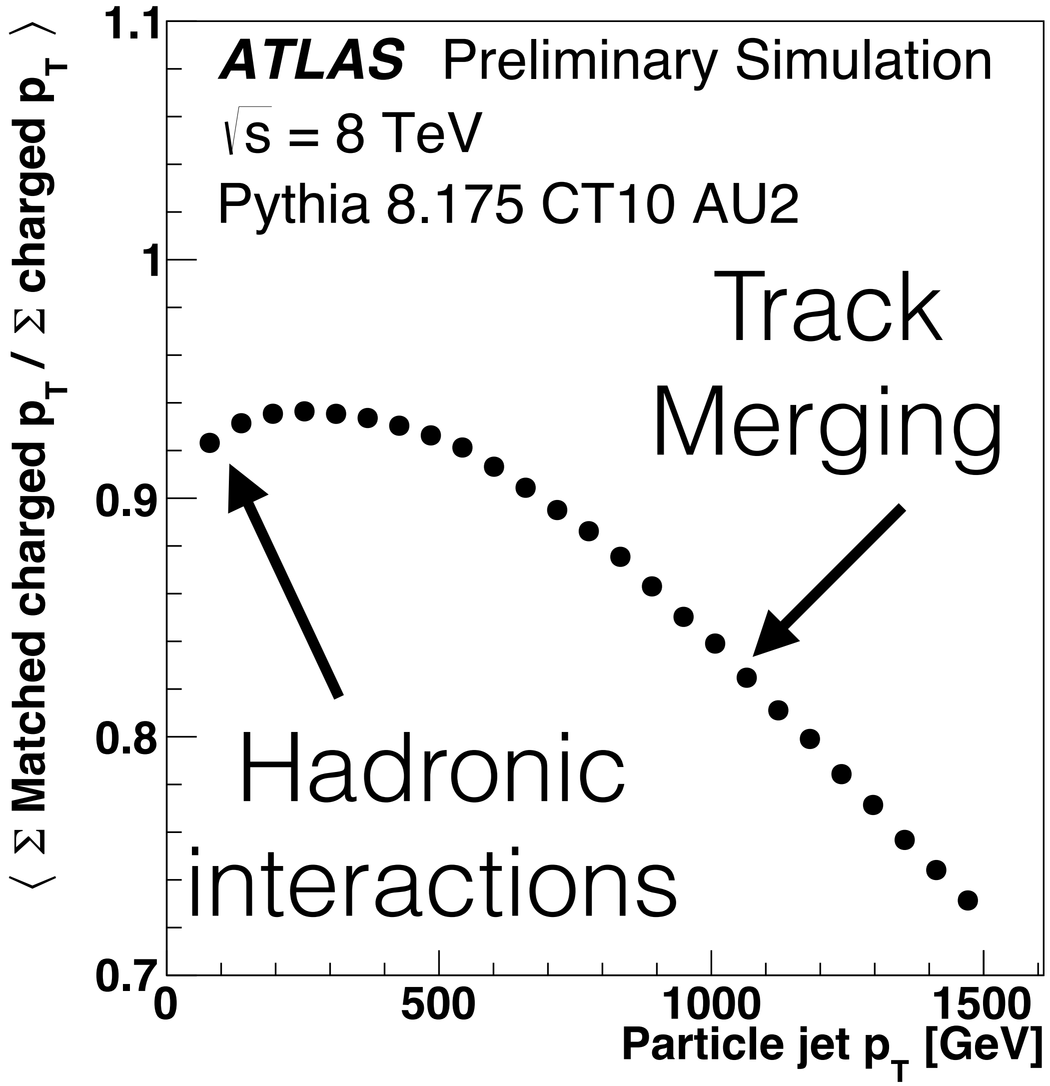
Unfold to facilitate model/calculation comparisons.

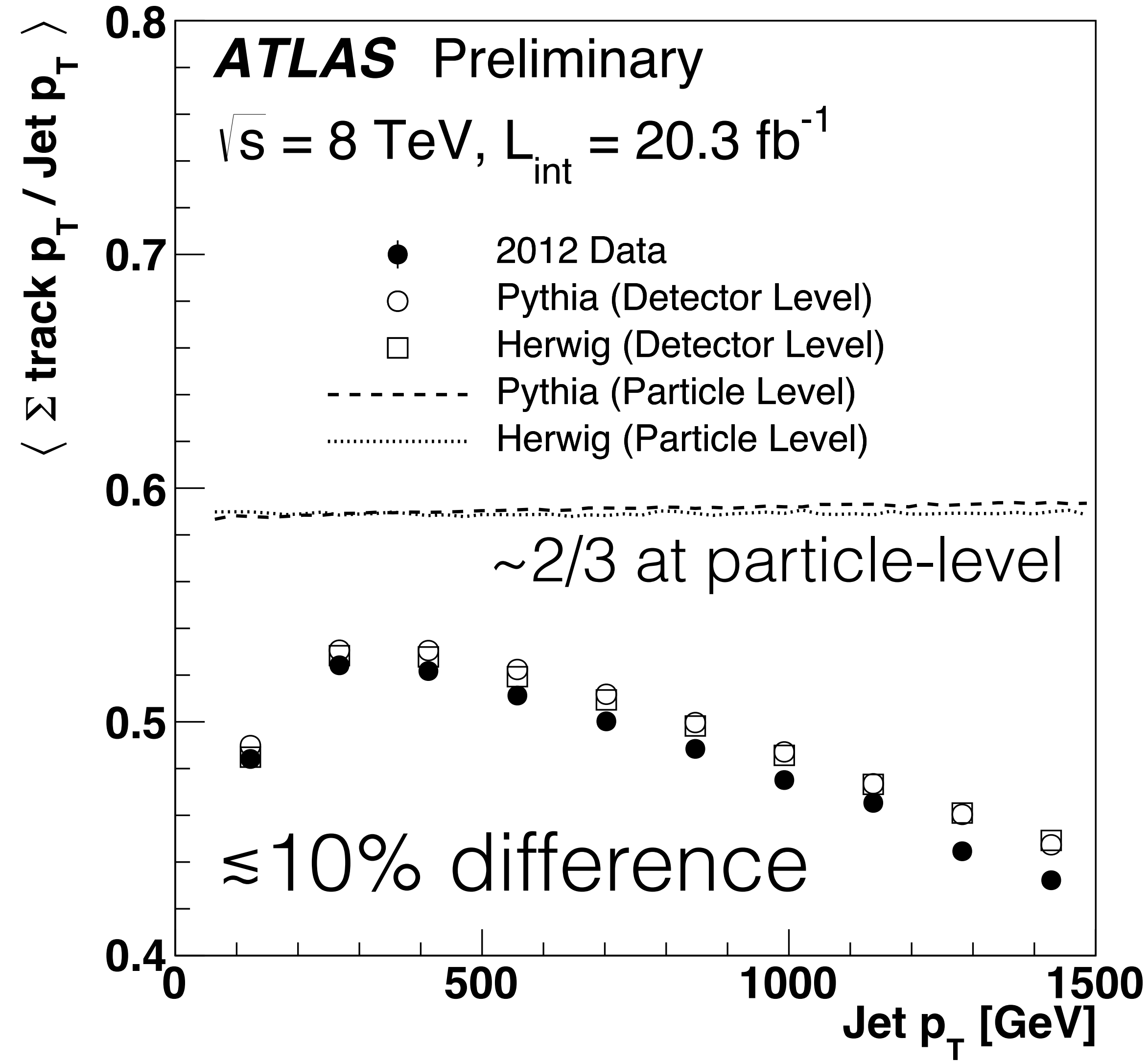


Increases due to more up-quark jets

Increases at reco, decreases at truth-level

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.

Jet Charge Measurement Uncertainty

un-prescaled trigger

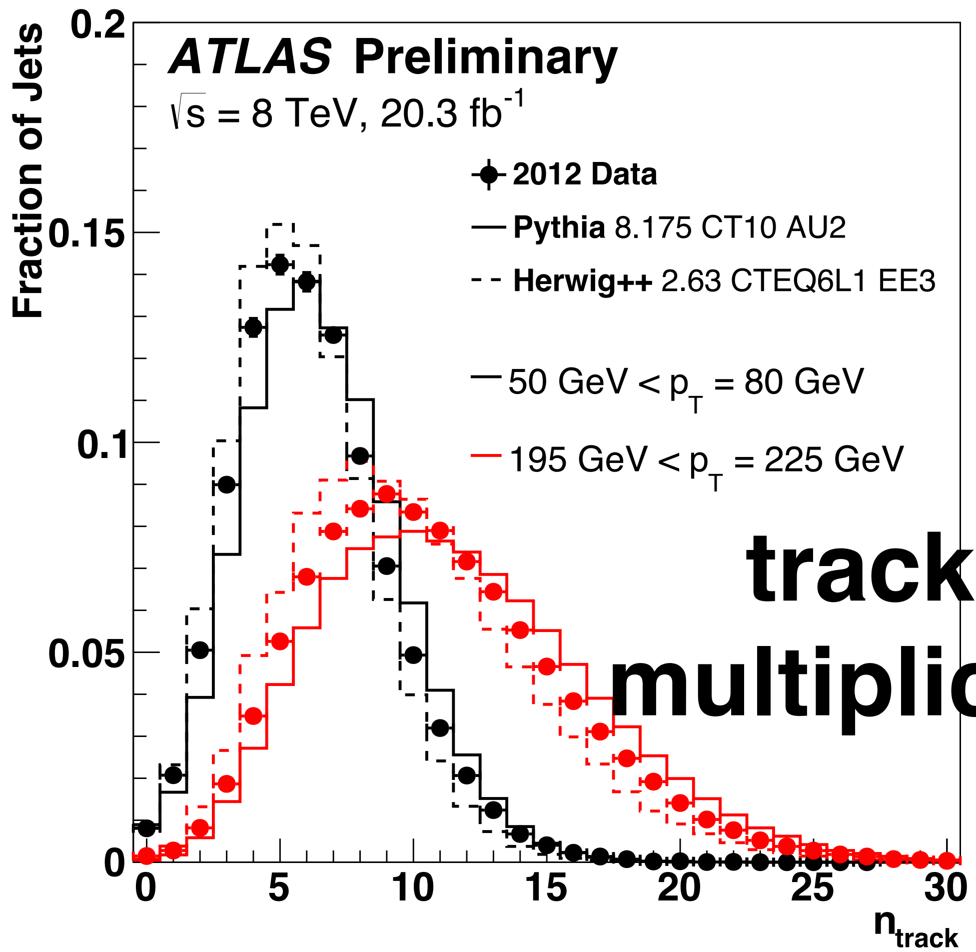
Average Jet Charge Systematic Uncertainty [%]	Jet p_T Range [100 GeV] [0.5,1]	[1,2]	[2,3]	[3,4]	[4,5]	[5,6]	[6,8]	[8,10]	[10,12]	[12,15]
Correction Factors	23	0.9	0.8	1.0	0.3	0.6	0.1	0.3	0.2	0.1
Total JES	8.8	3.8	0.9	0.8	1.1	1.1	0.7	0.7	0.4	0.9
JER	6.8	2.3	0.7	0.7	0.3	0.3	0.1	0.1	0.1	0.3
Charged Energy 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

average is ~0, so fractional uncertainty is large

Modeling of track merging

Modeling of charged particle multiplicity (resolution depends on this!)

Reconstruction efficiency, resolution, charge mis-ID, fake tracks



track multiplicity

Jet Charge Measurement Results

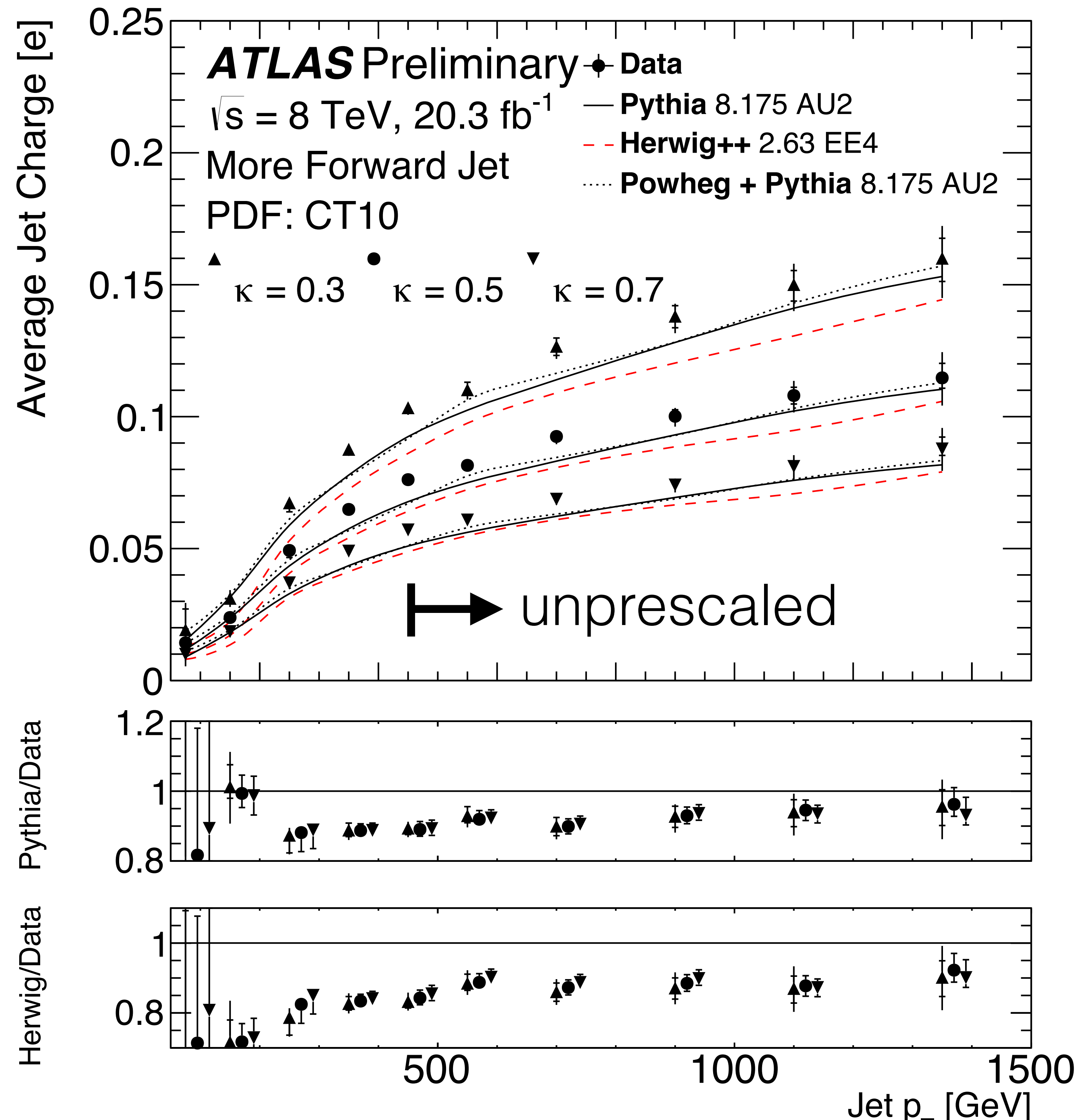
The unfolded data are compared to various models.

-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



→ ATLAS Jet Charge in backup

What happens when we 'remove' the PDF?
Does the jet charge for jets of a particular flavor depend on p_T?

$$\langle Q_J \rangle = [1 + \mathcal{O}(\alpha_s)] \sum_h Q_h \widetilde{D}_q^h(\kappa, E \times R)$$

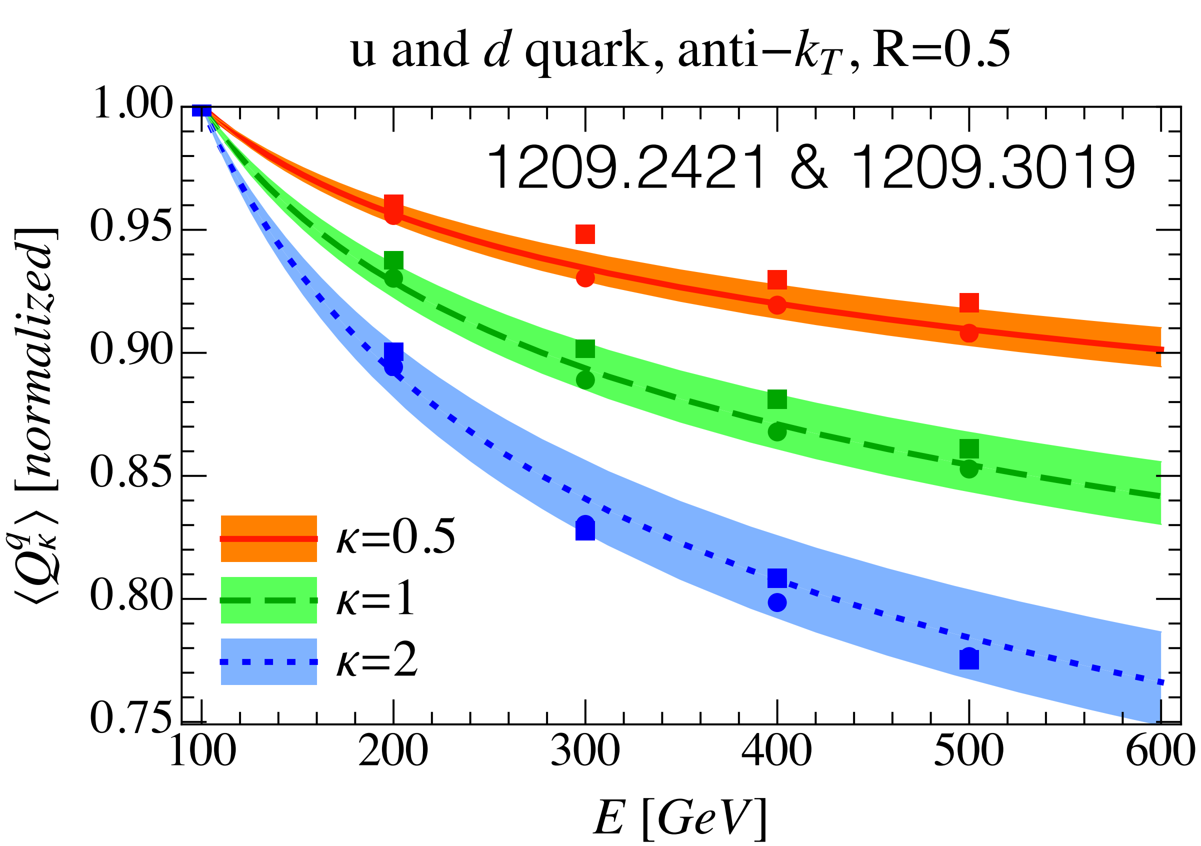
(scale violation)

h = hadron

Moment of a **fragmentation function**

Prediction:

$c < 0$ and $dc/d\kappa < 0$



non-perturbative…but we know how it evolves with scale!

$$\frac{p_T}{\langle Q_\kappa \rangle} \frac{d}{dp_T} \langle Q_\kappa \rangle = \frac{\alpha_s}{\pi} \widetilde{P}_{qq}(\kappa) \equiv c(\kappa)$$

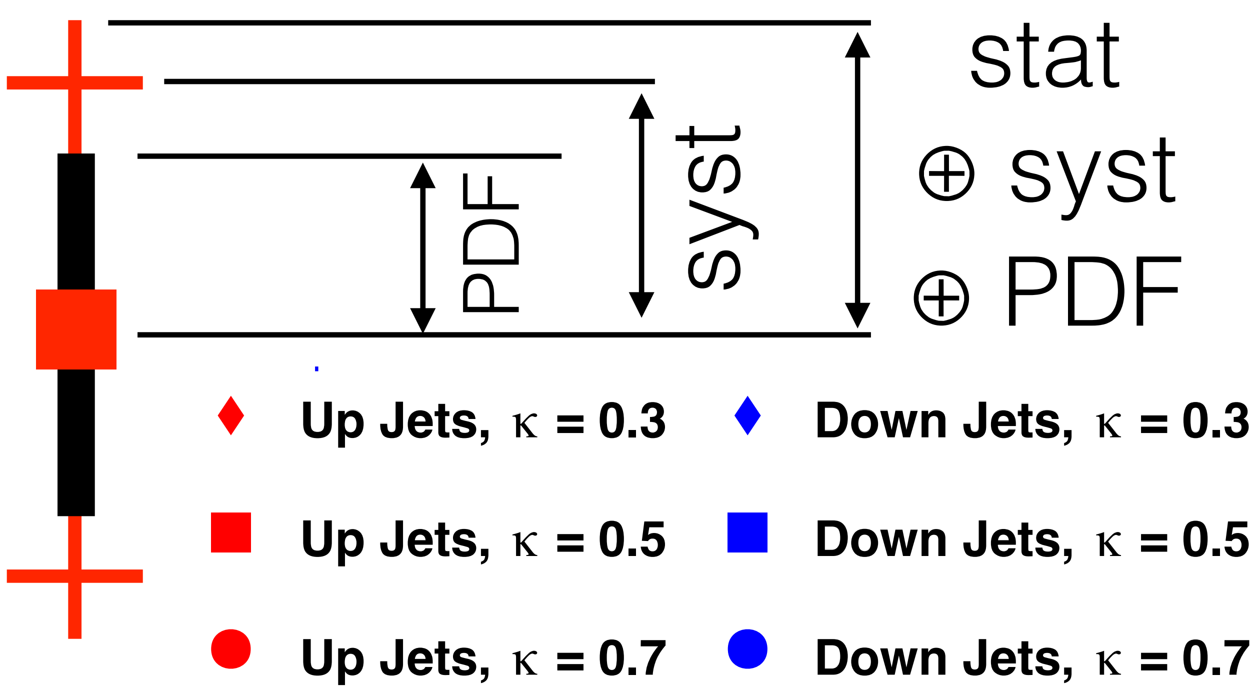
Moment of a **splitting function**

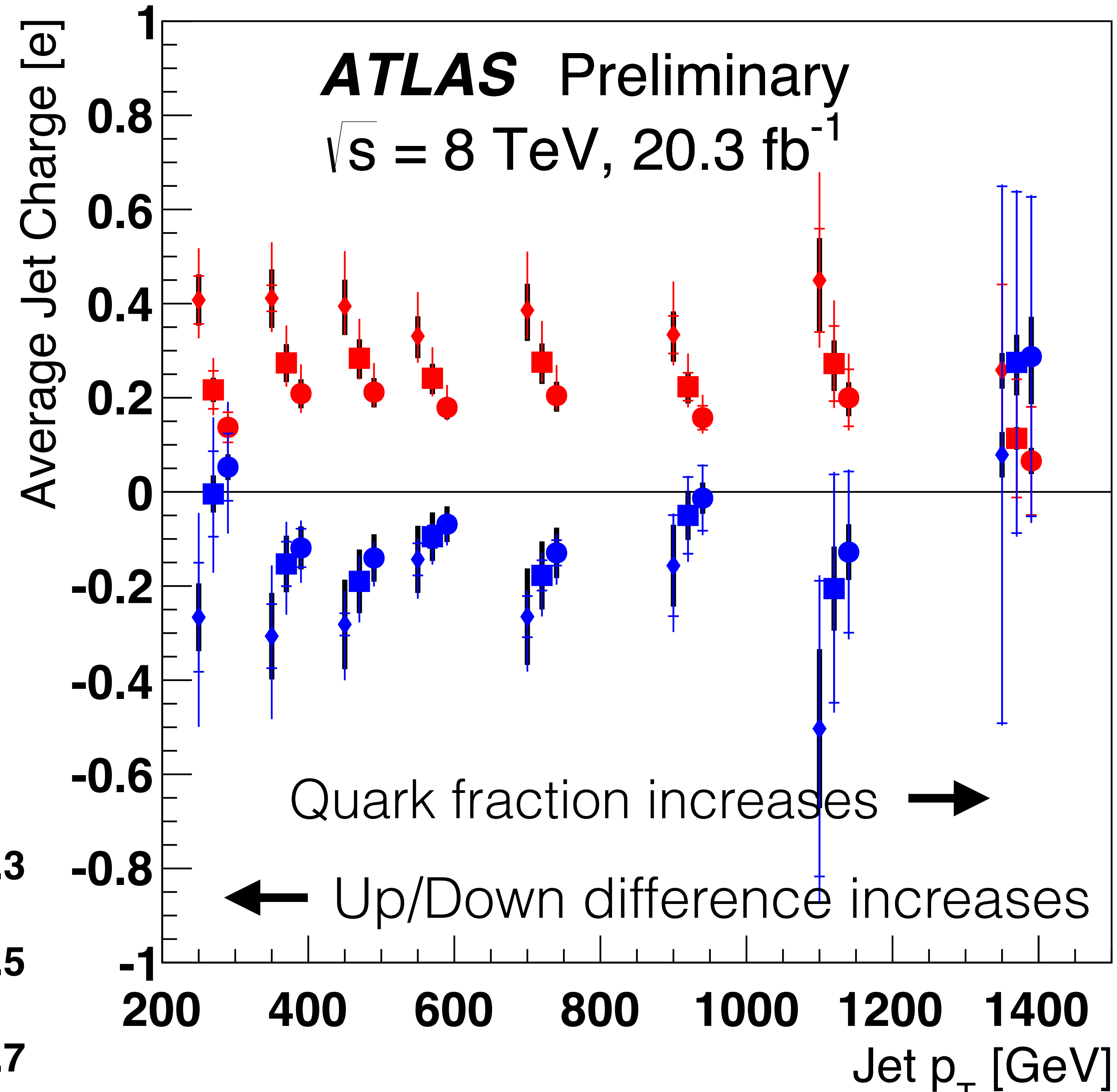
Jet charge per flavor: extraction

$$\langle Q_i^{\text{forward}} \rangle = \left(f_{\text{up,i}}^{\text{forward}} - f_{\text{anti-up,i}}^{\text{forward}} \right) Q_i^{\text{up}} + \left(f_{\text{down,i}}^{\text{forward}} - f_{\text{anti-down,i}}^{\text{forward}} \right) Q_i^{\text{down}}$$

$$\langle Q_i^{\text{central}} \rangle = \left(f_{\text{up,i}}^{\text{central}} - f_{\text{anti-up,i}}^{\text{central}} \right) Q_i^{\text{up}} + \left(f_{\text{down,i}}^{\text{central}} - f_{\text{anti-down,i}}^{\text{central}} \right) Q_i^{\text{down}}$$

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



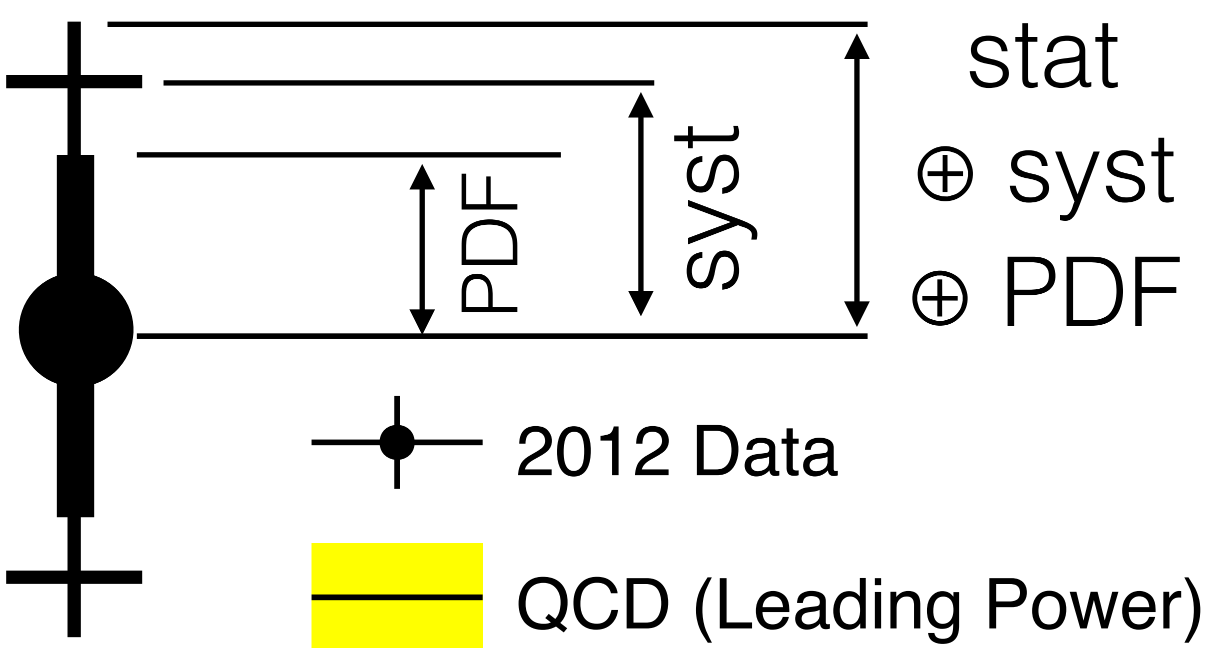


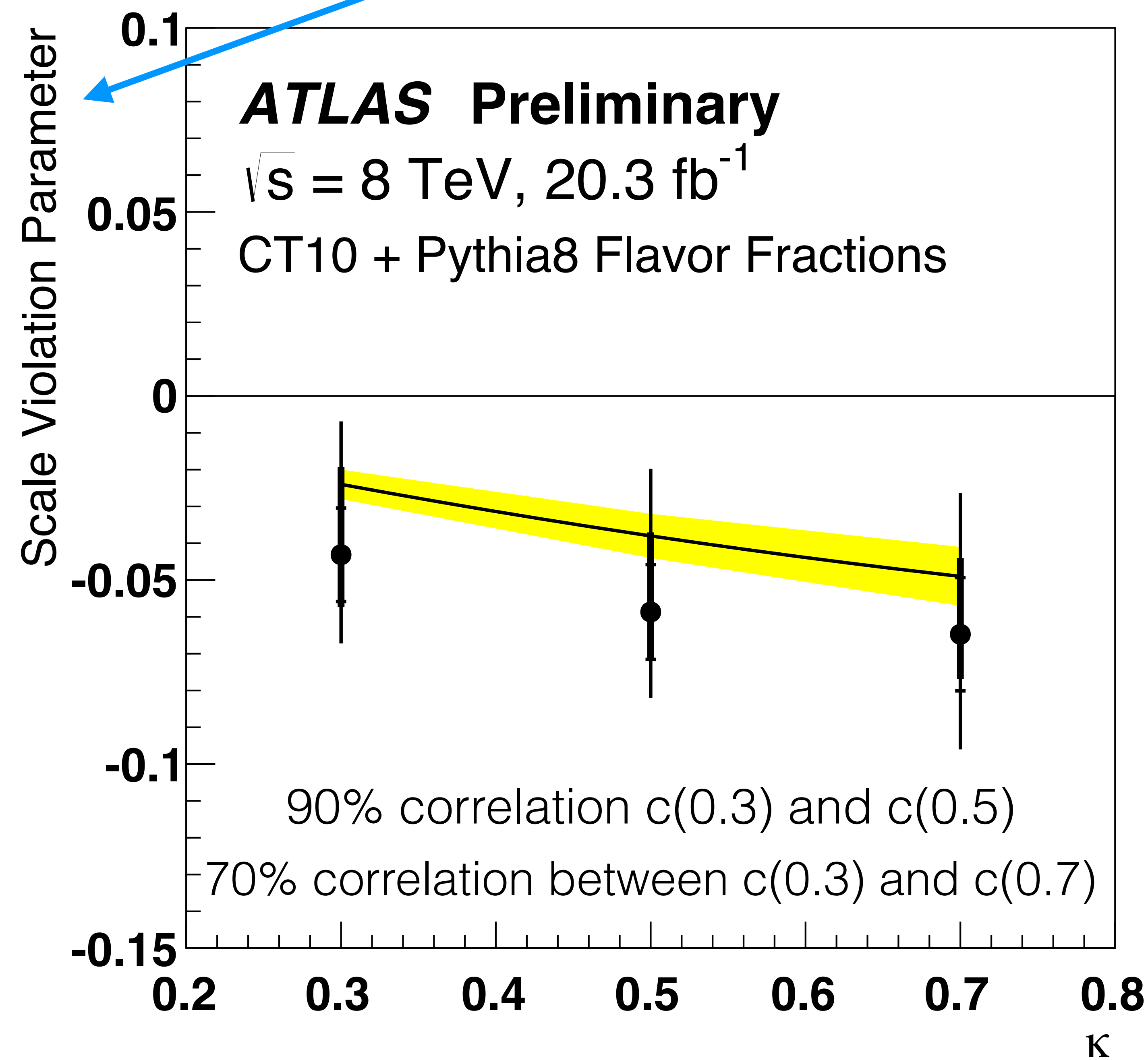
Jet charge per flavor: p_T dependence

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

Question: accounting for PDFs, does jet charge depend on p_T?

Data and theory agree: Yes!

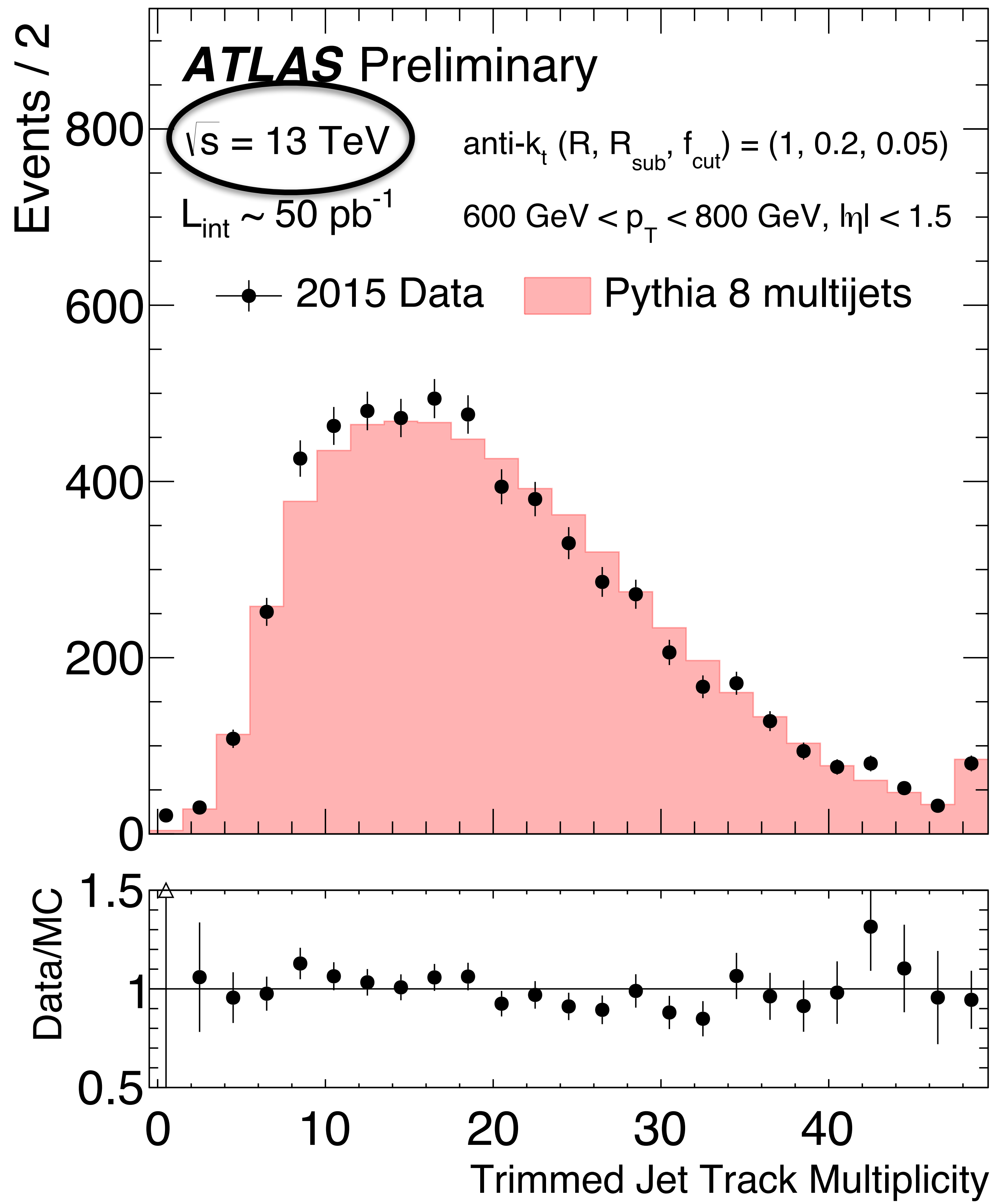




[1209.2421 & 1209.3019]

Many sophisticated and powerful substructure techniques used in searches and in **measurements** in the 8 TeV data.

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

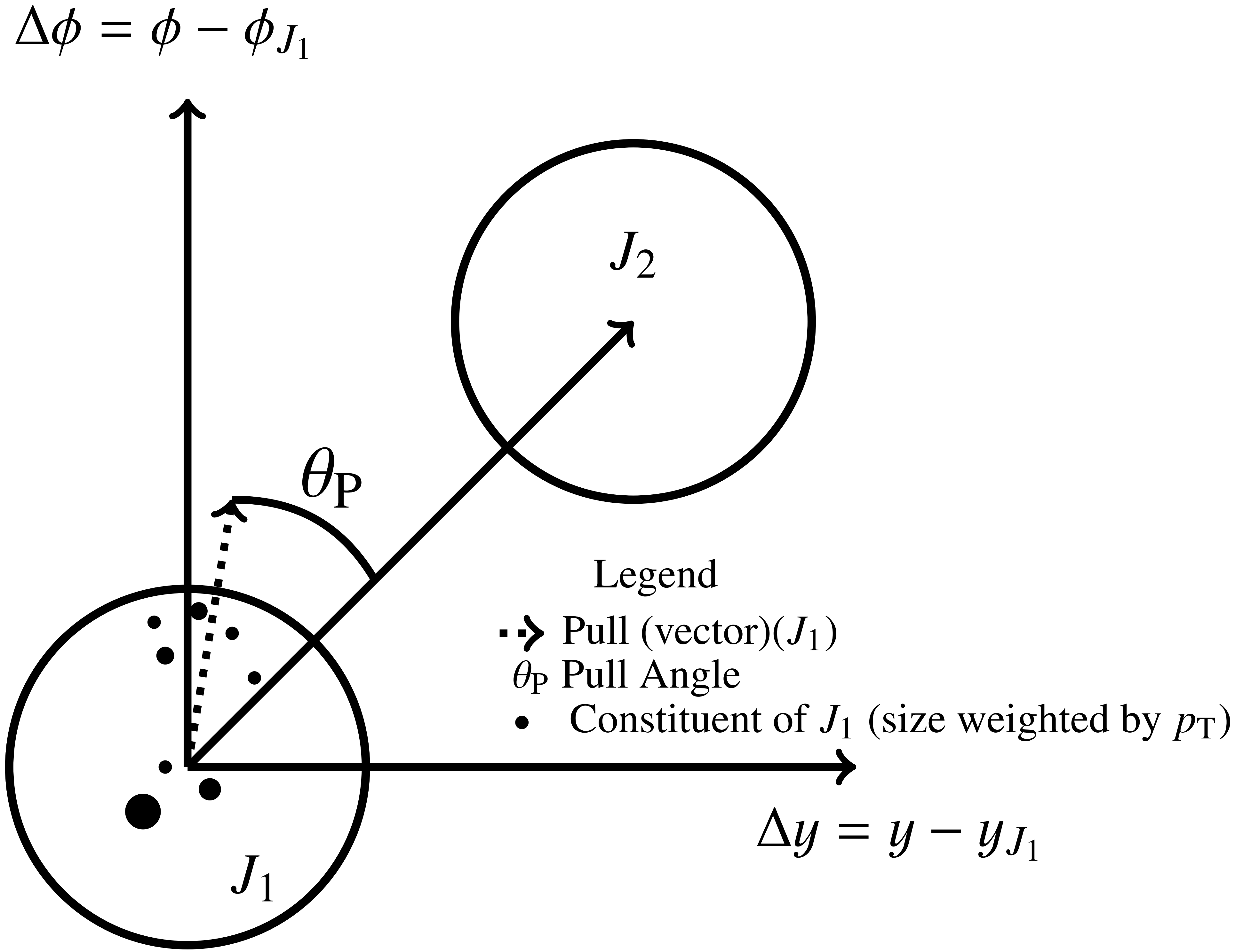


BACKUP

Plots from Colorflow

Colorflow Backup

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



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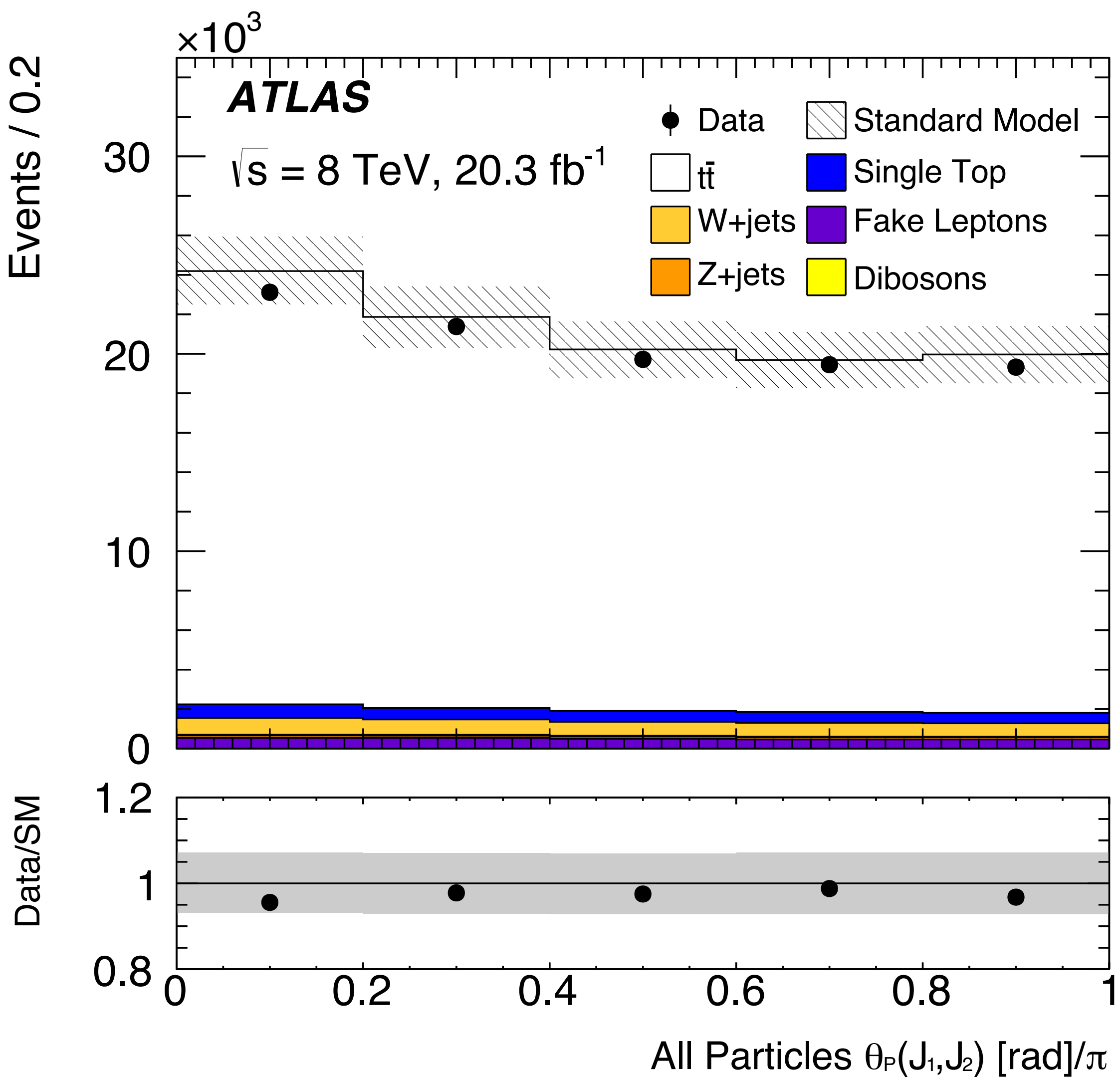

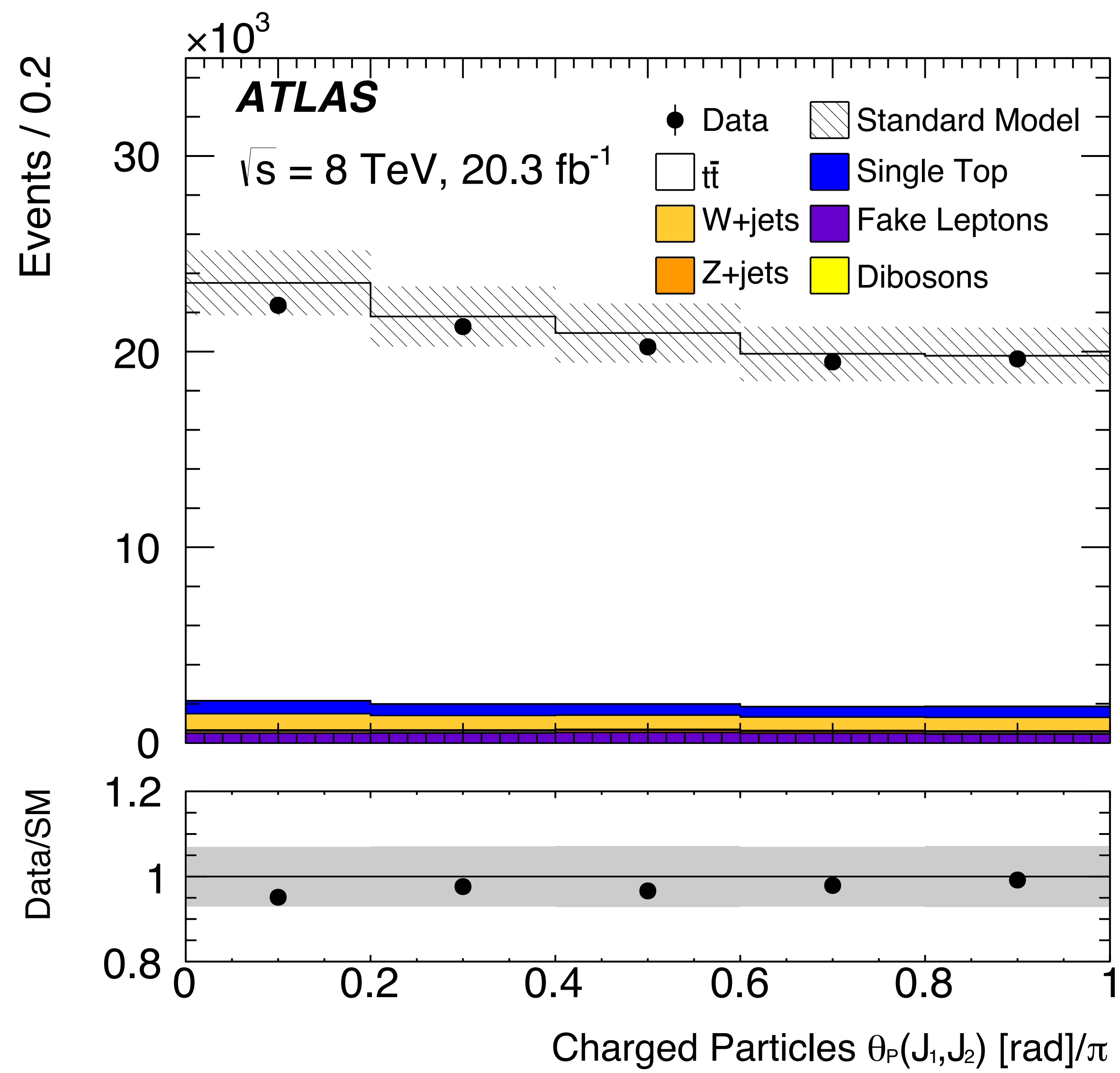

Colorflow Backup

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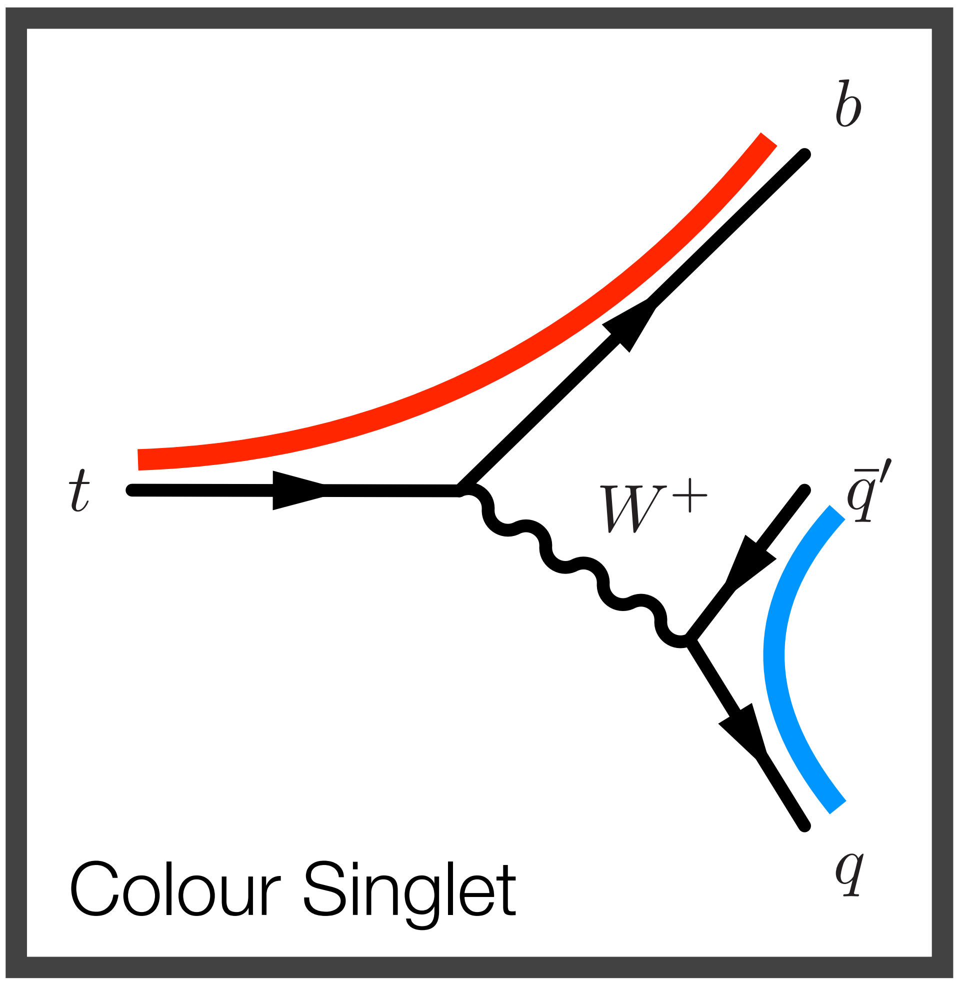

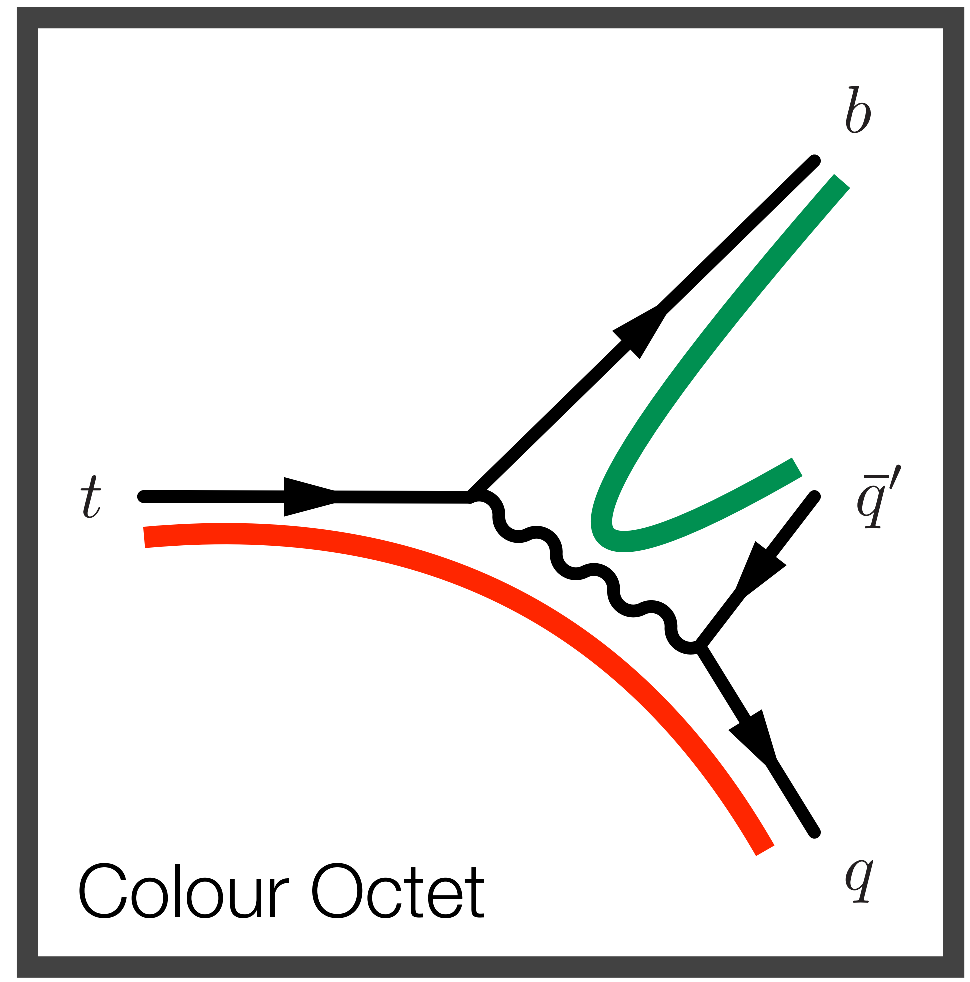

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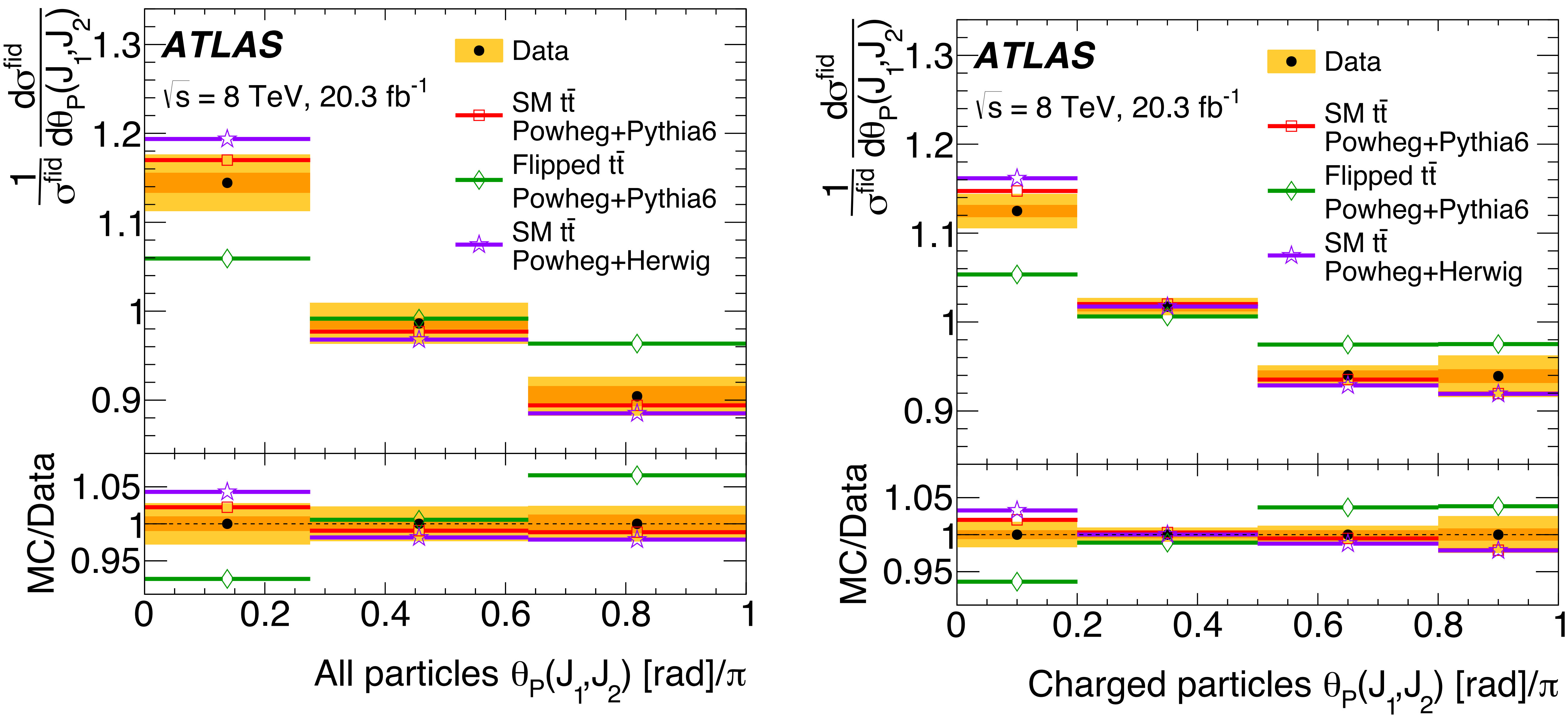

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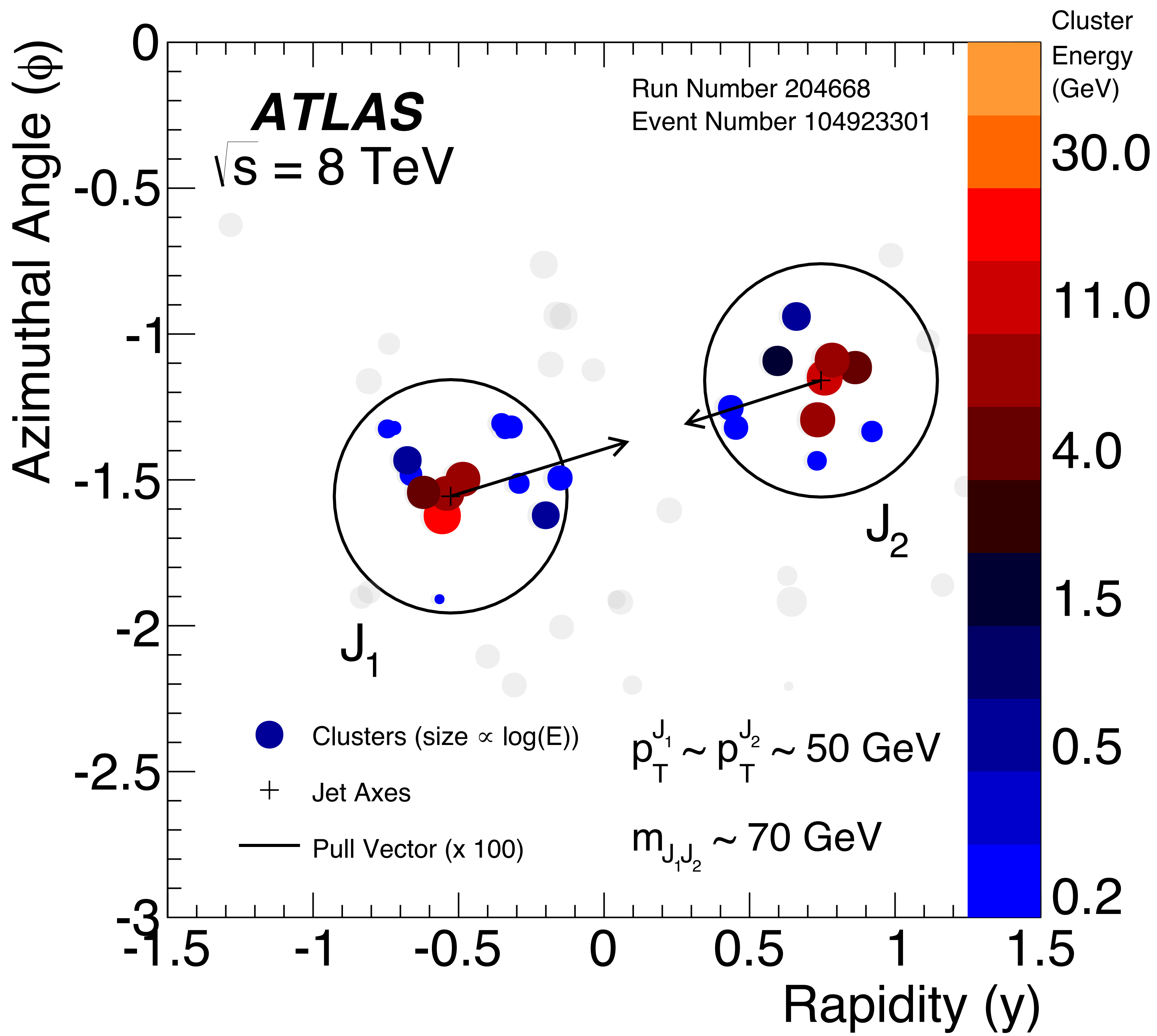

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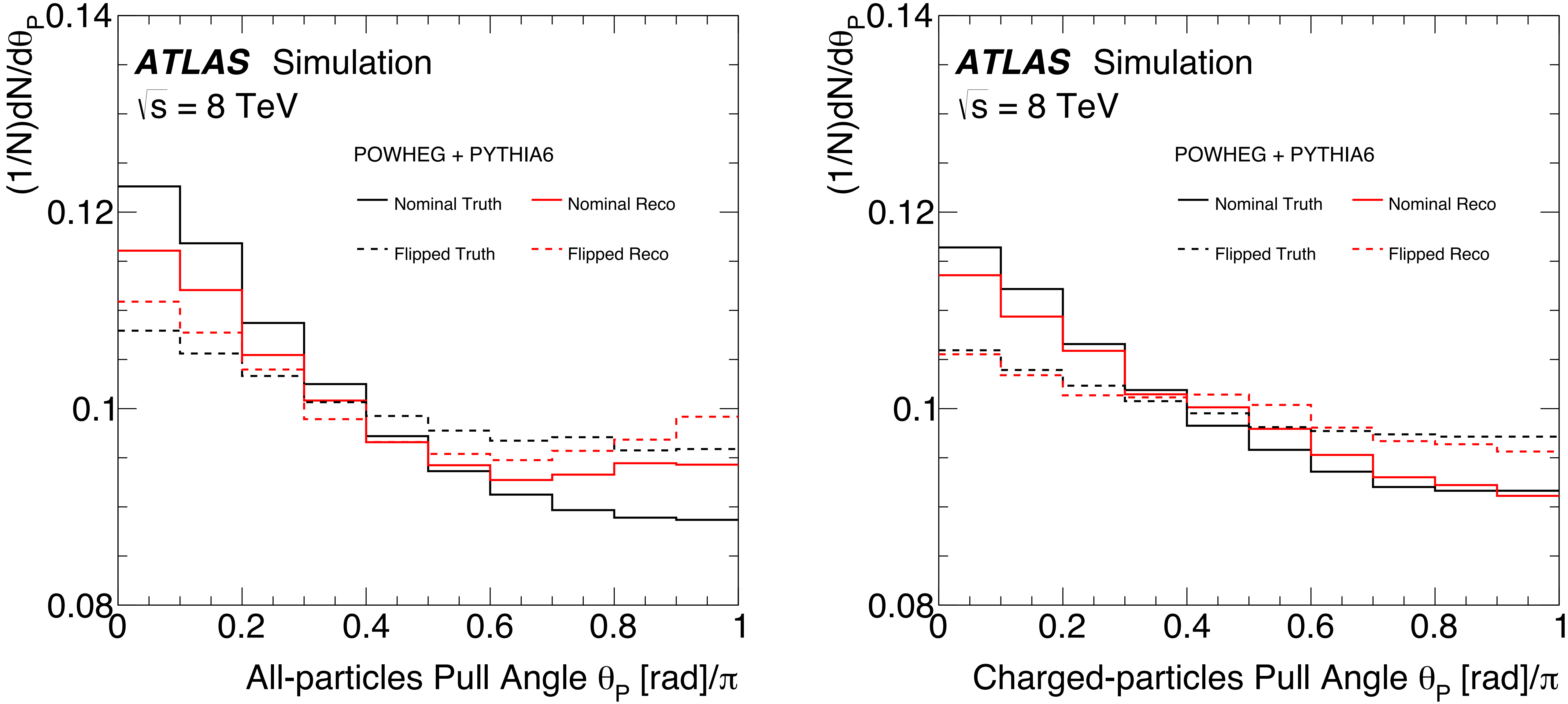

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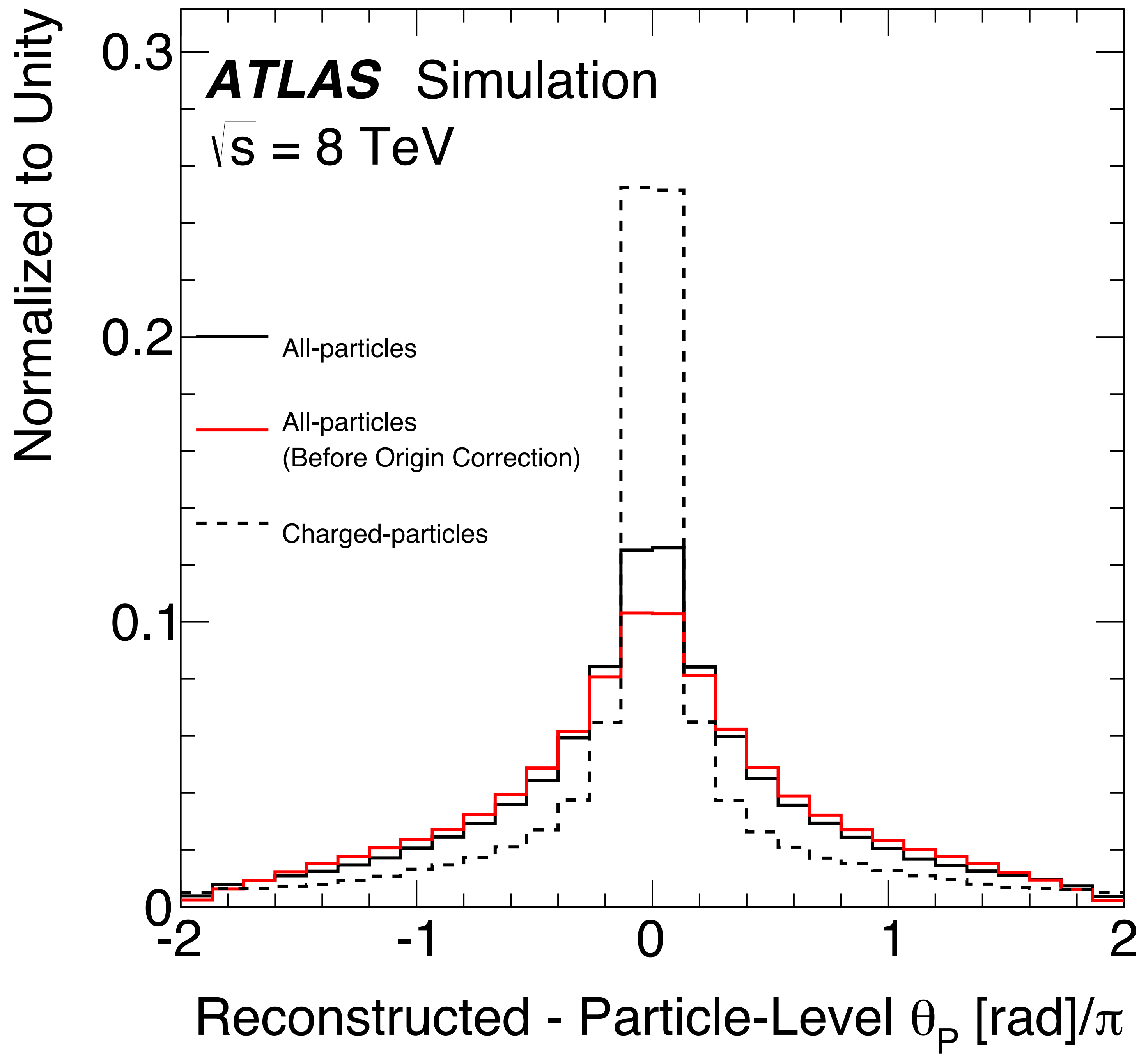

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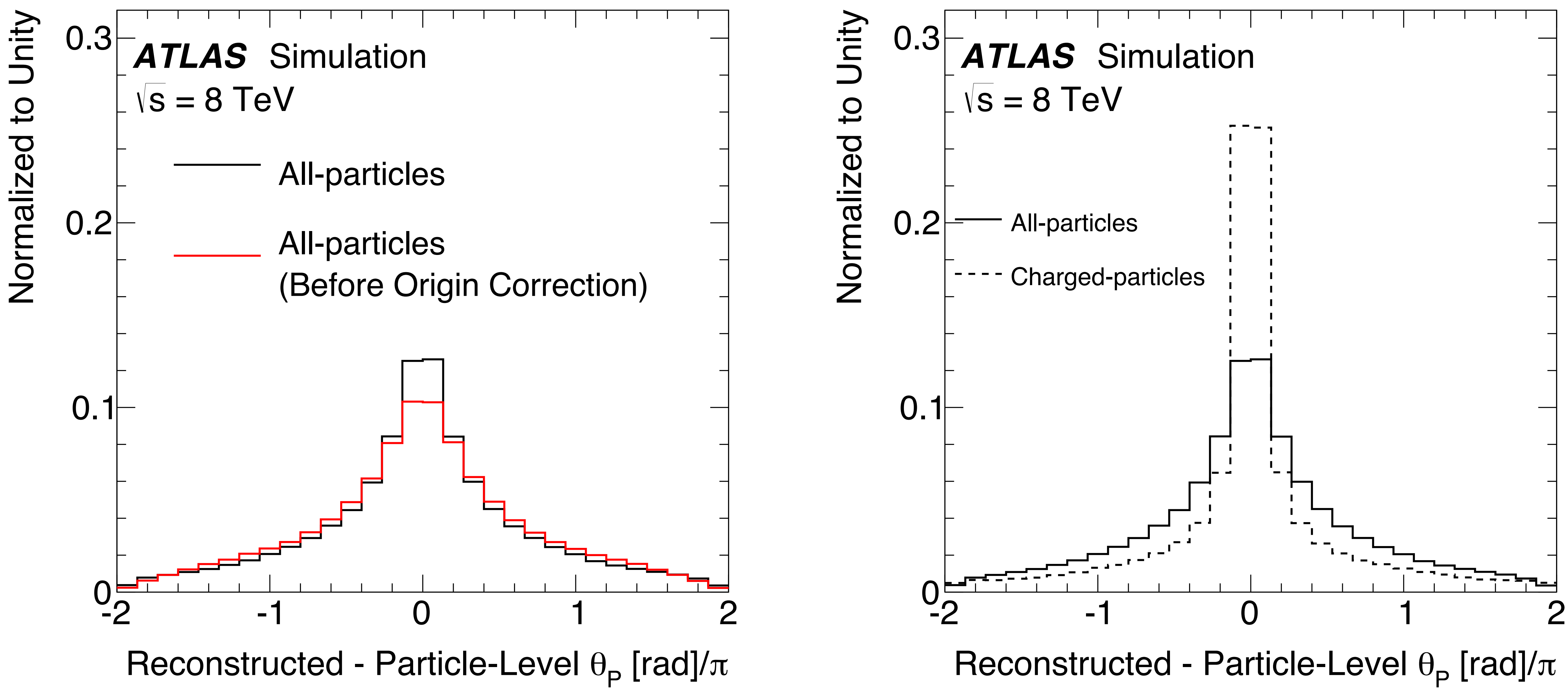

Colorflow Backup

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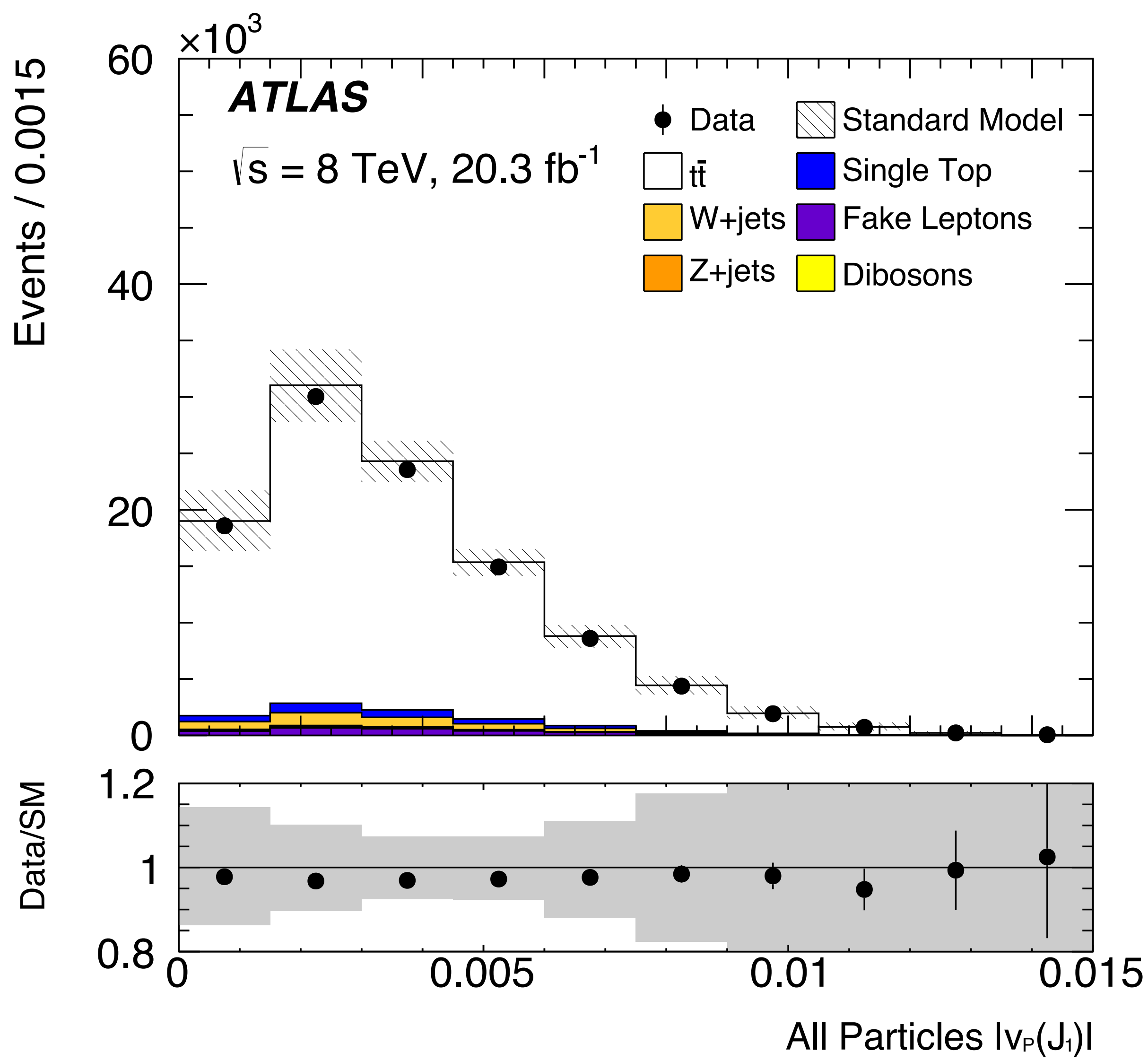

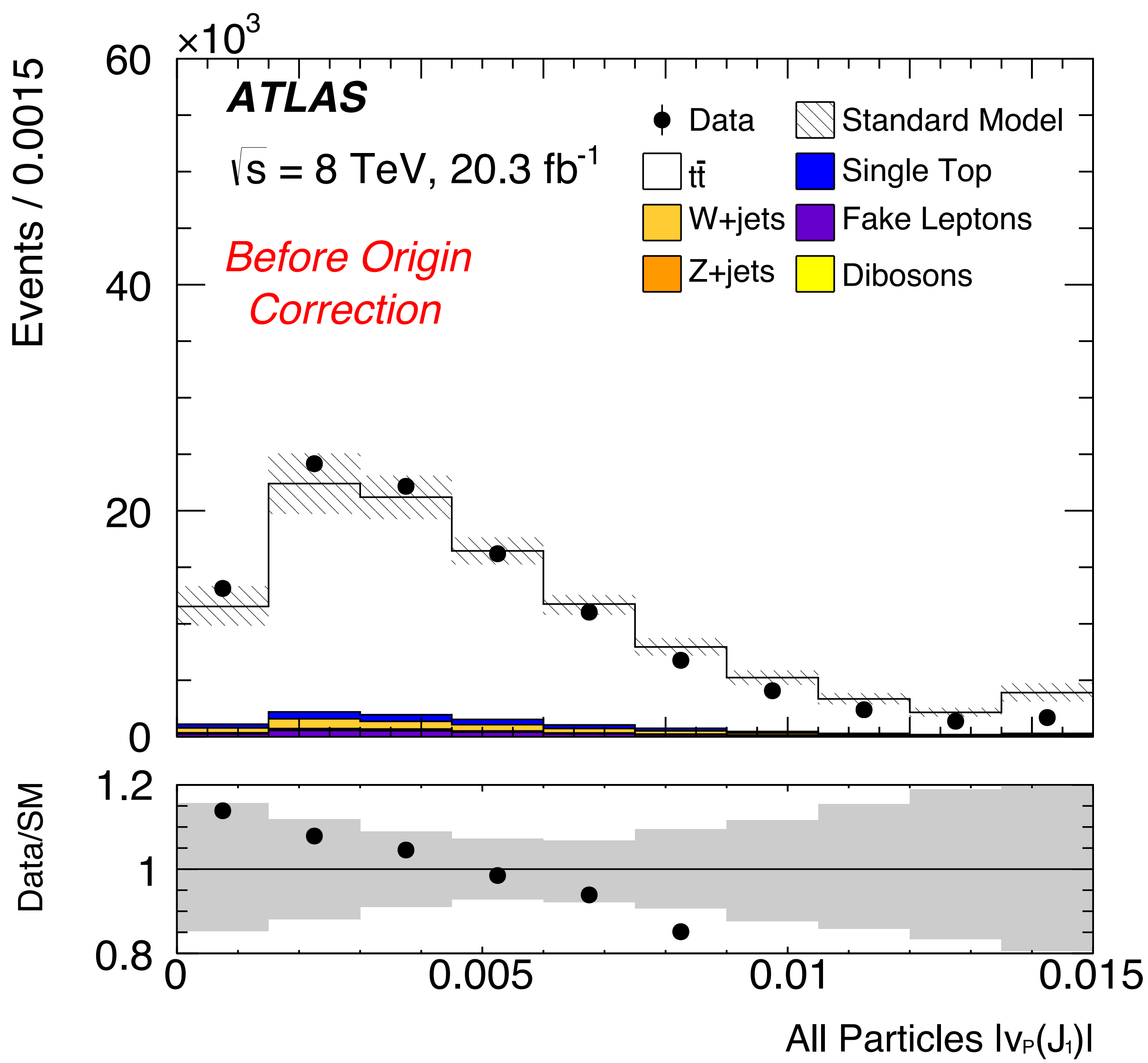

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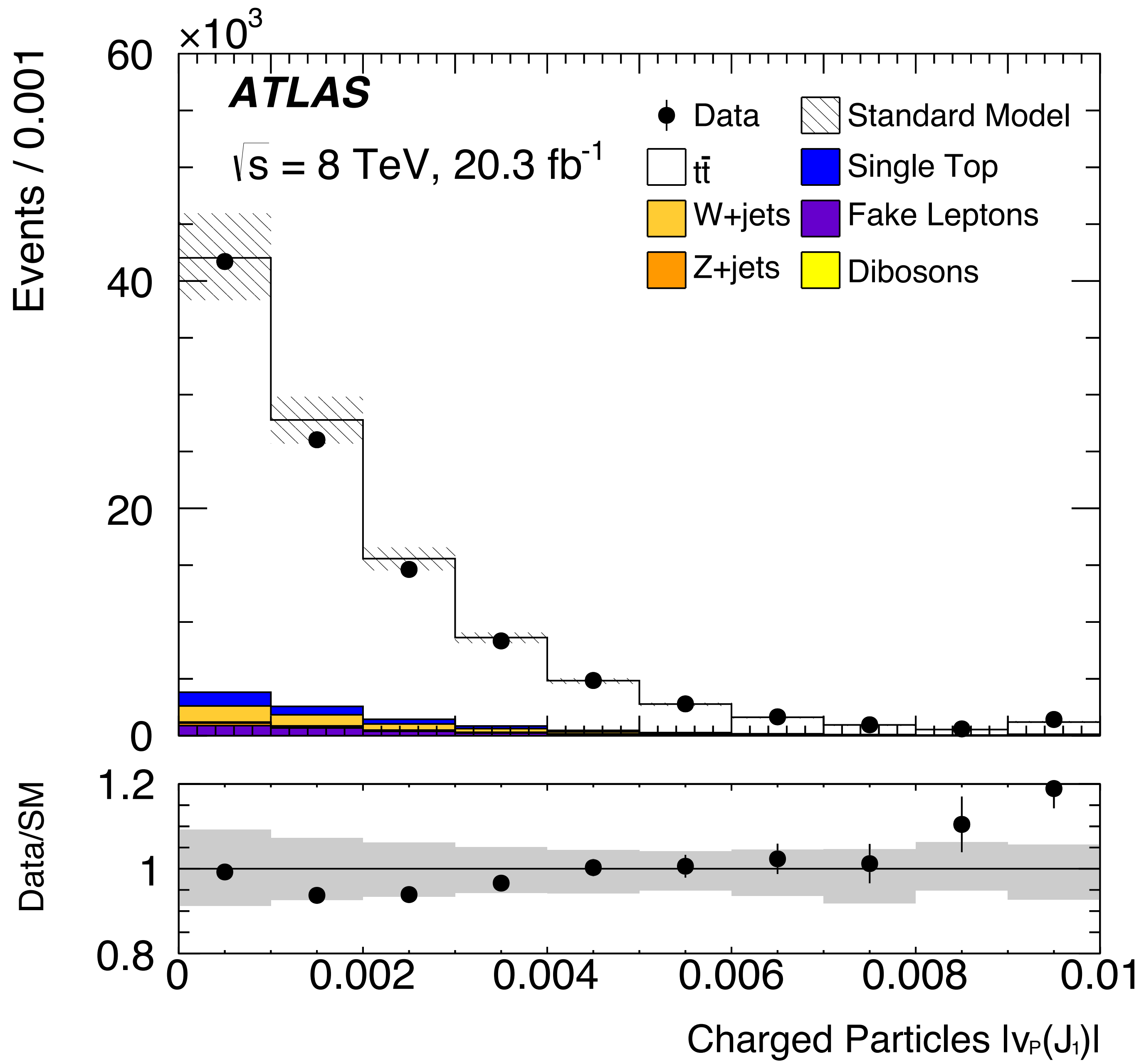

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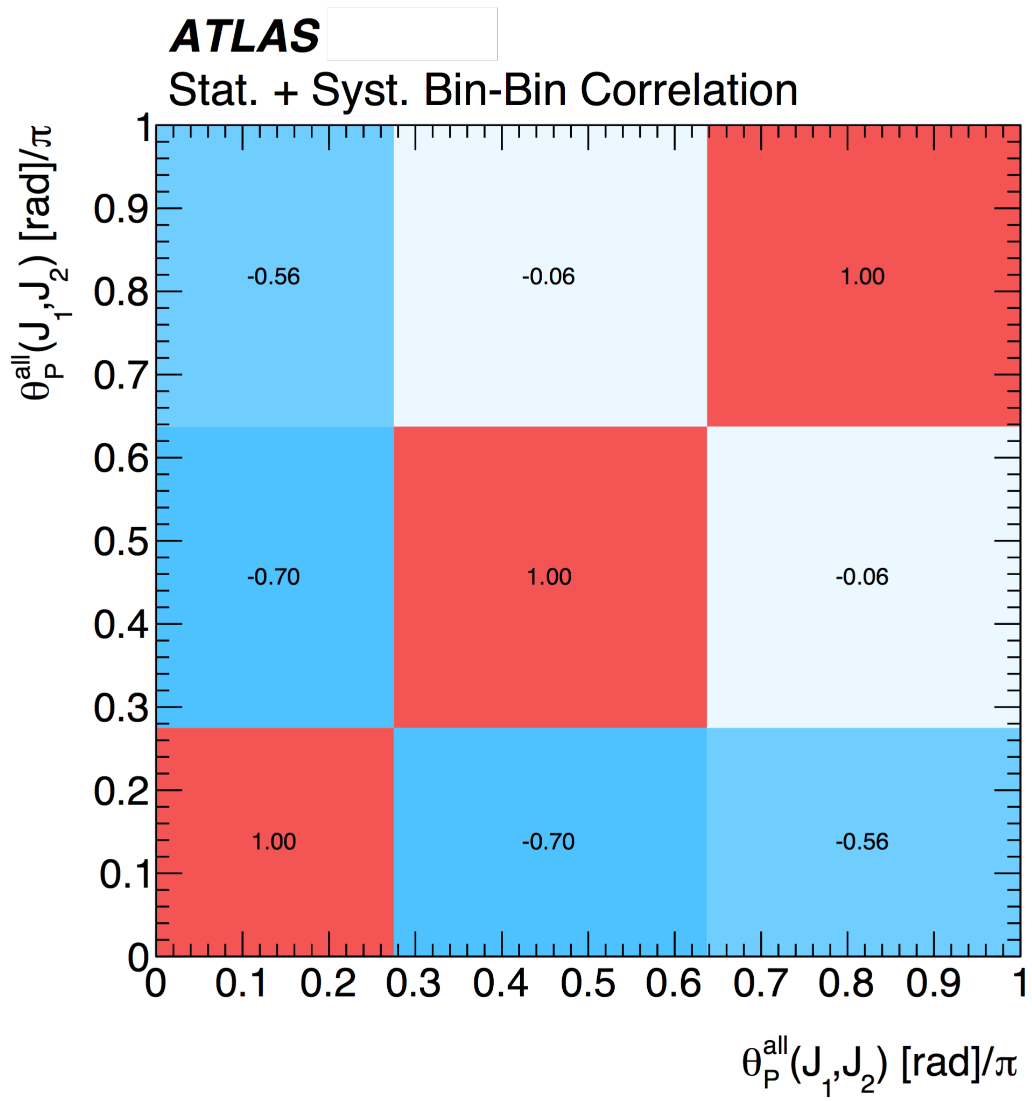

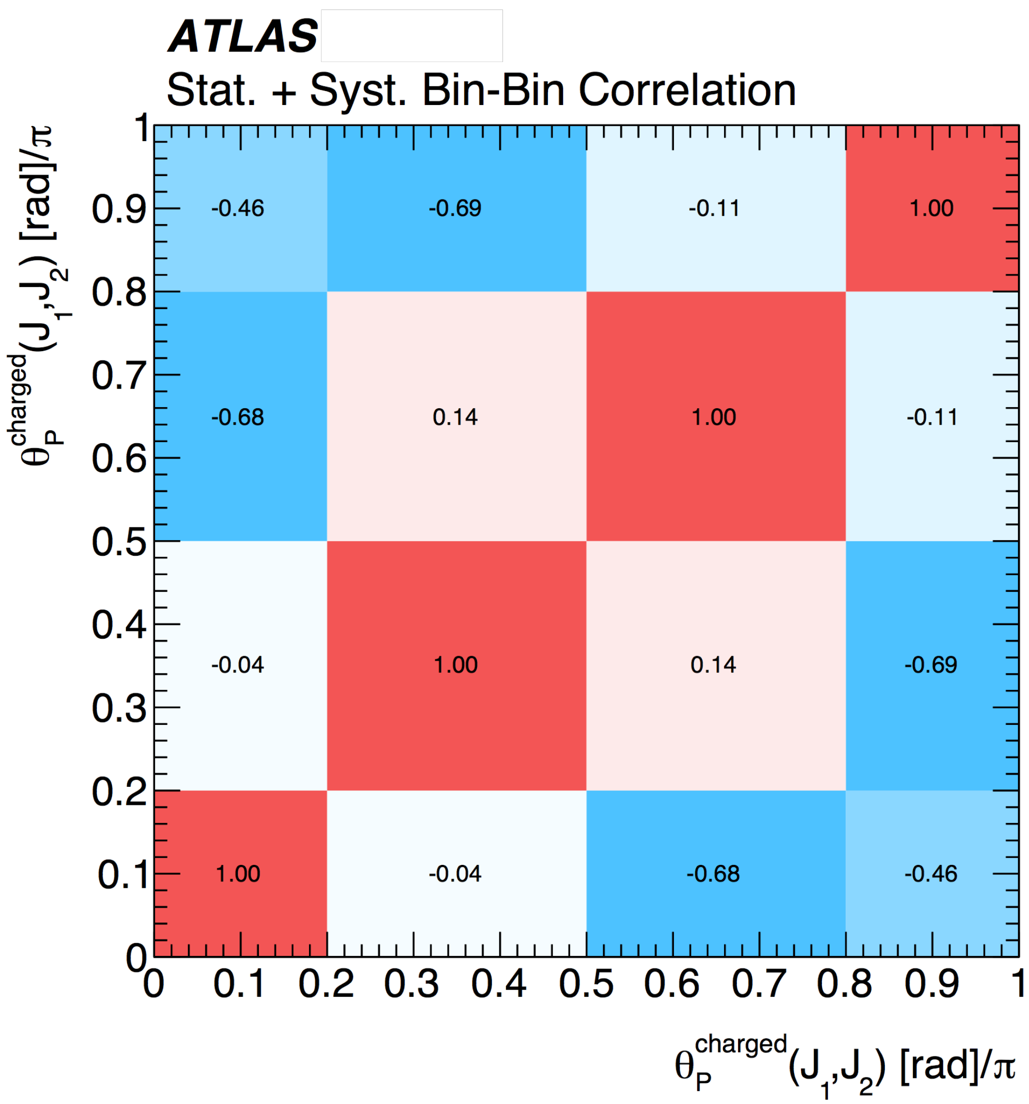

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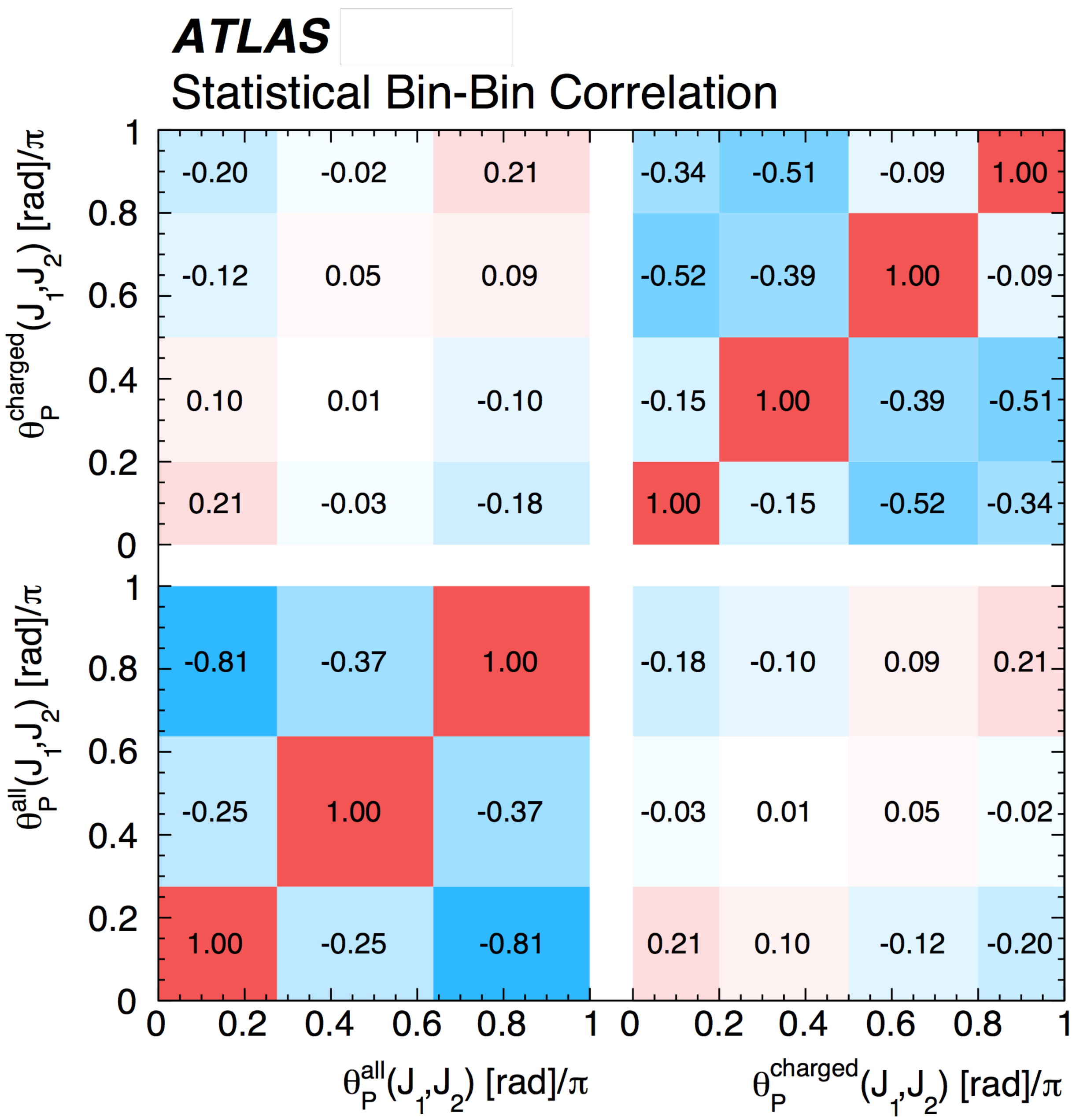

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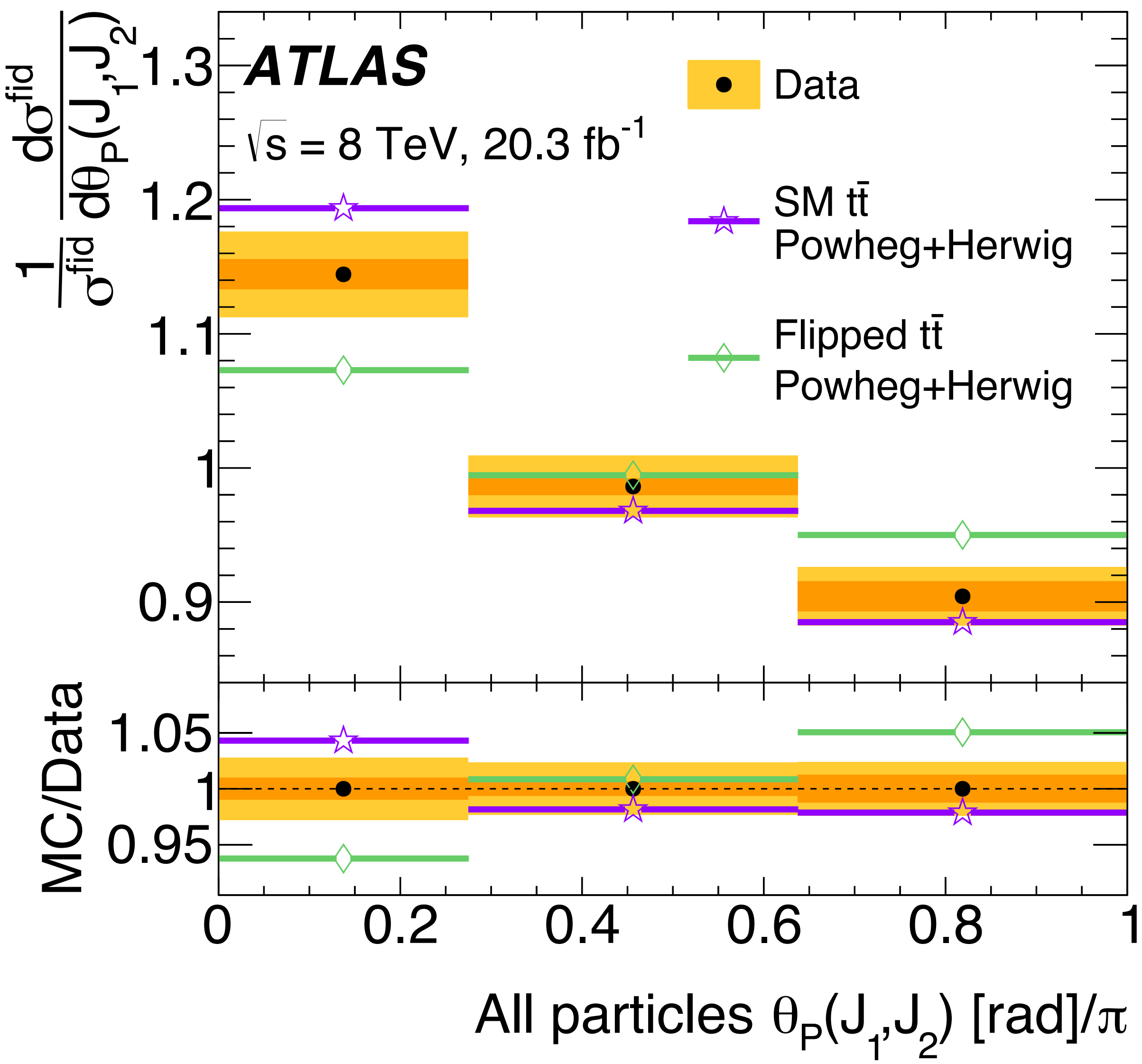

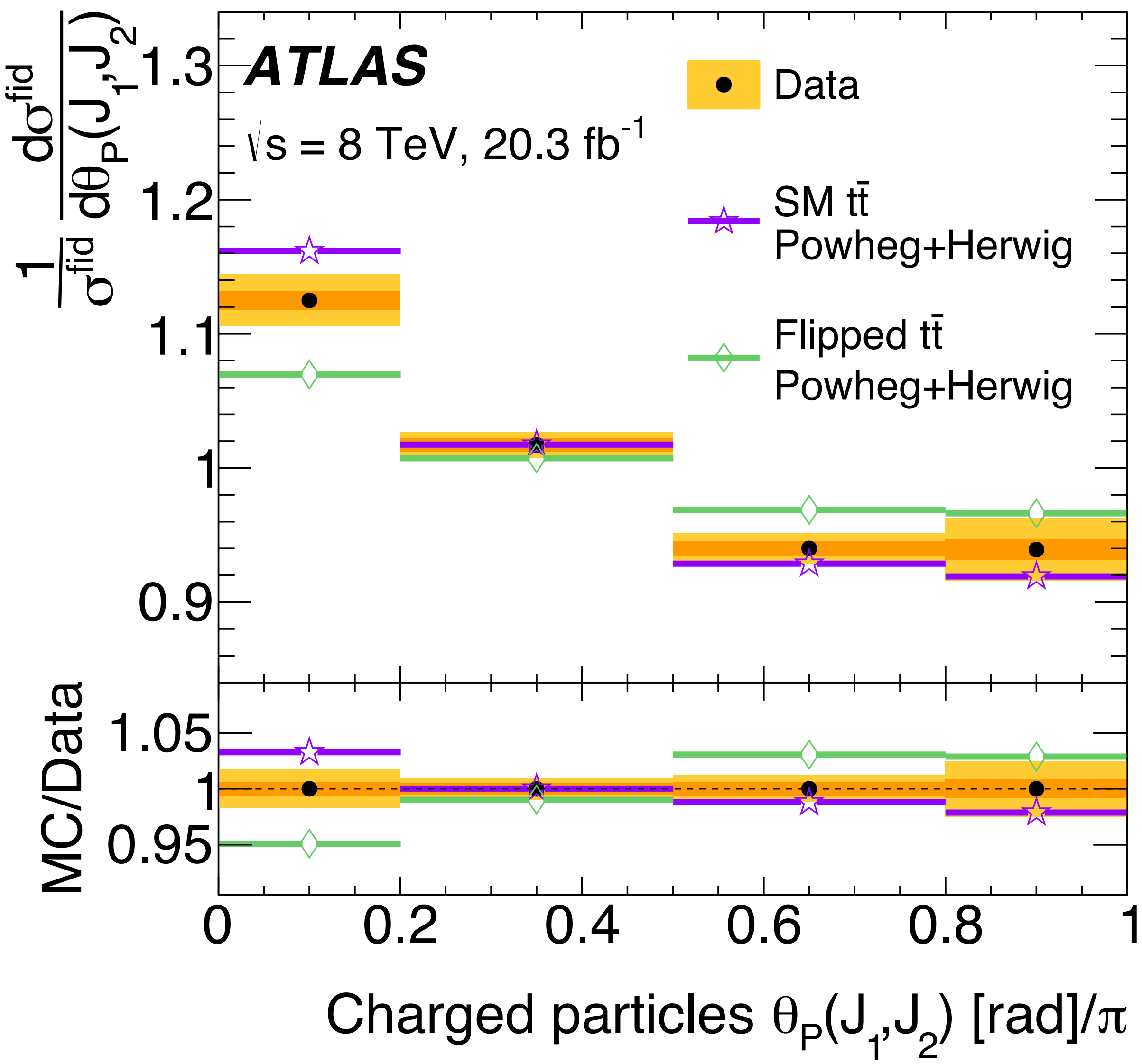

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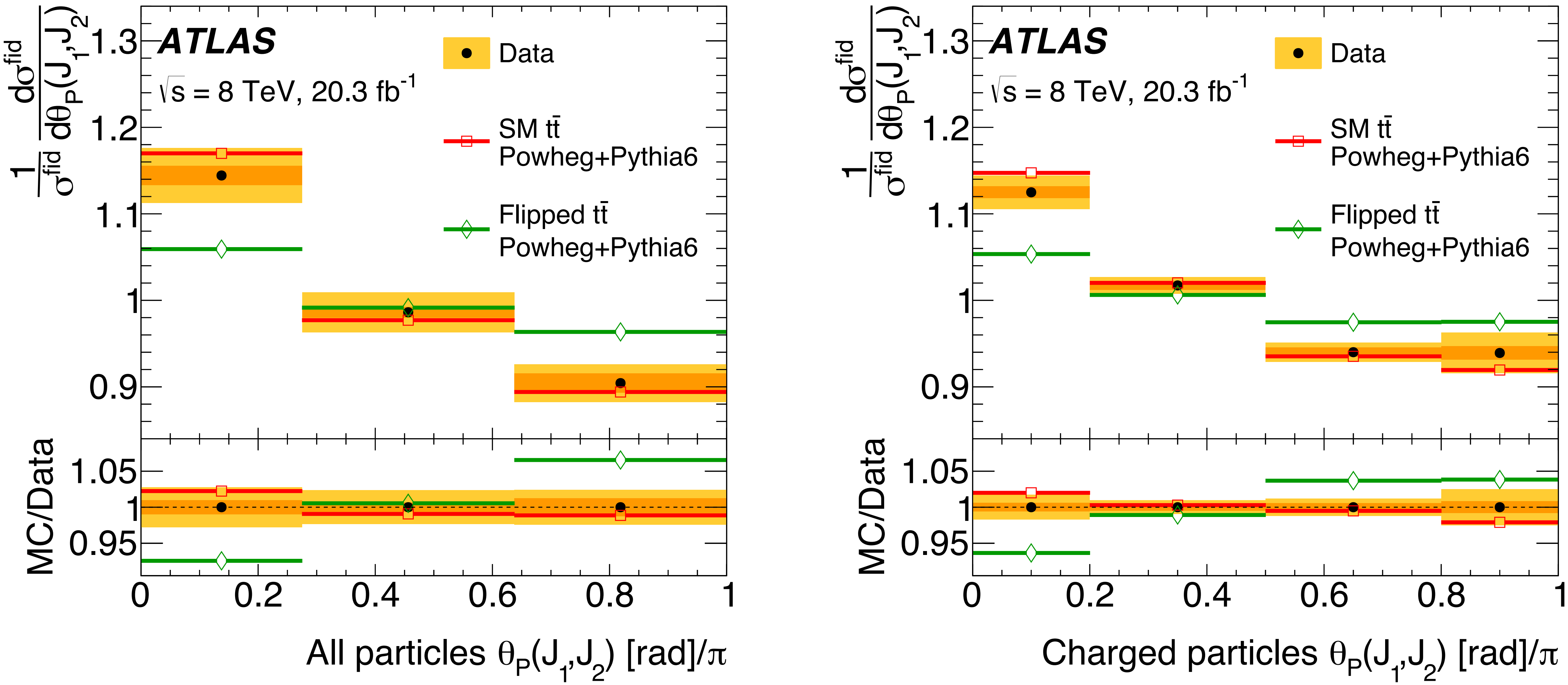

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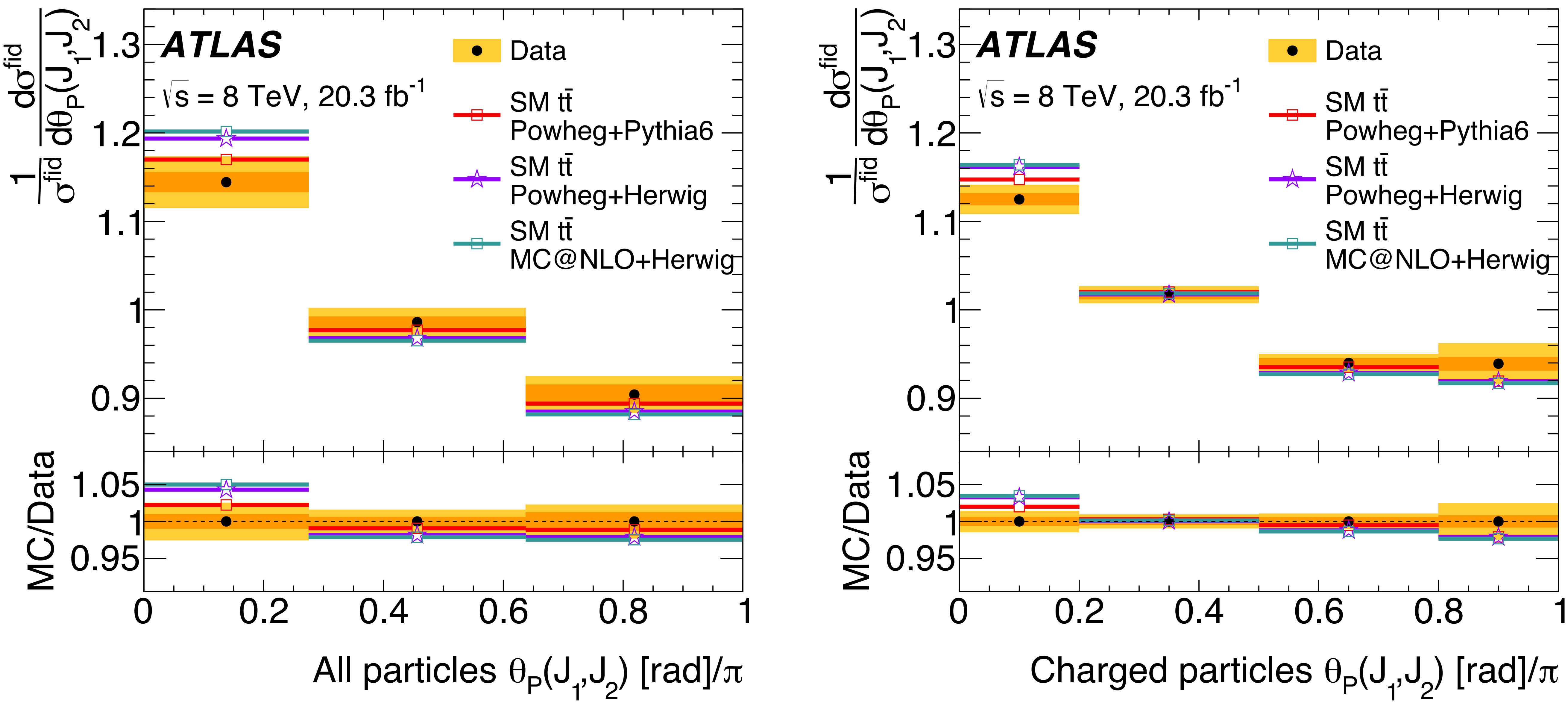

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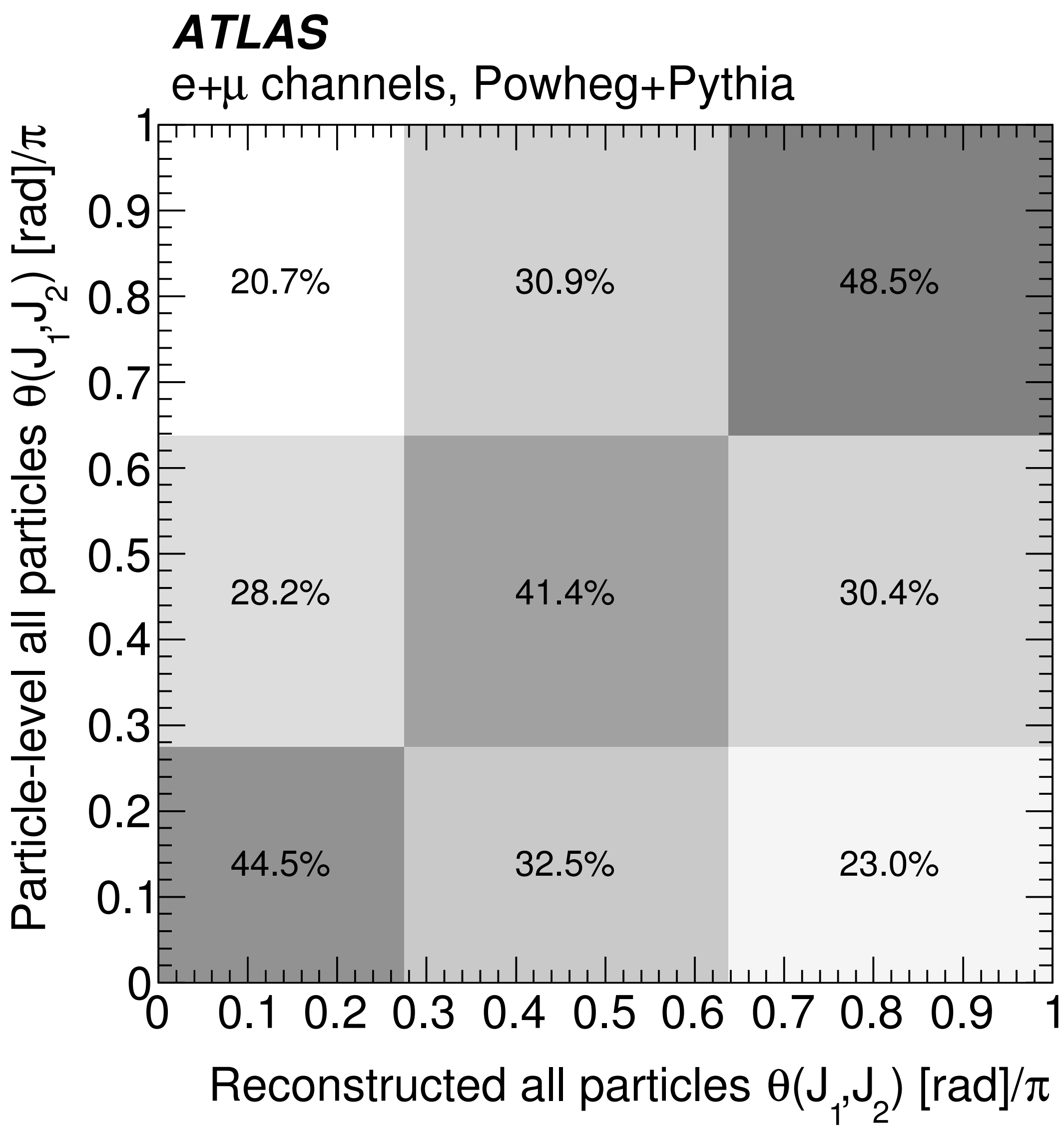

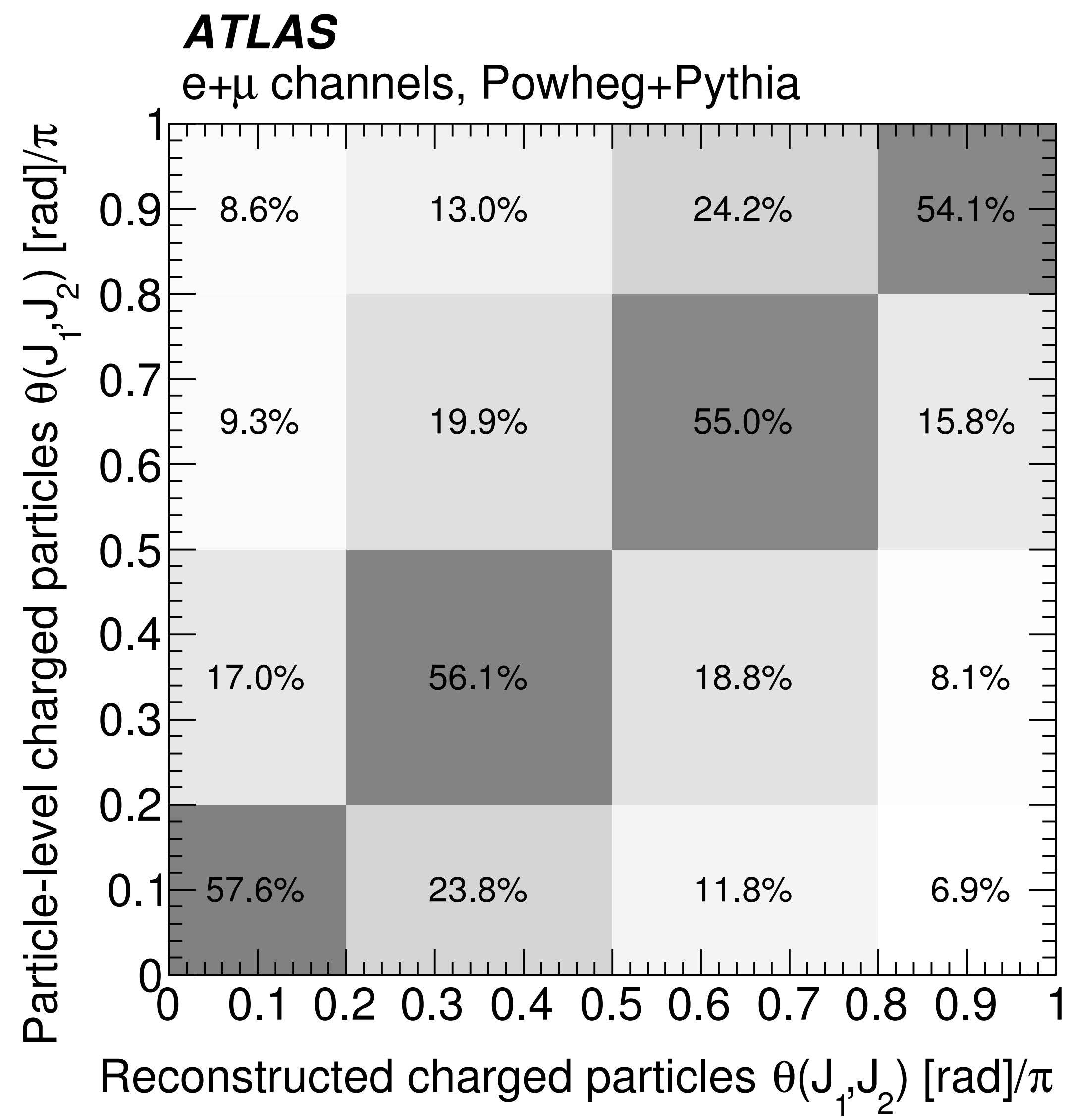

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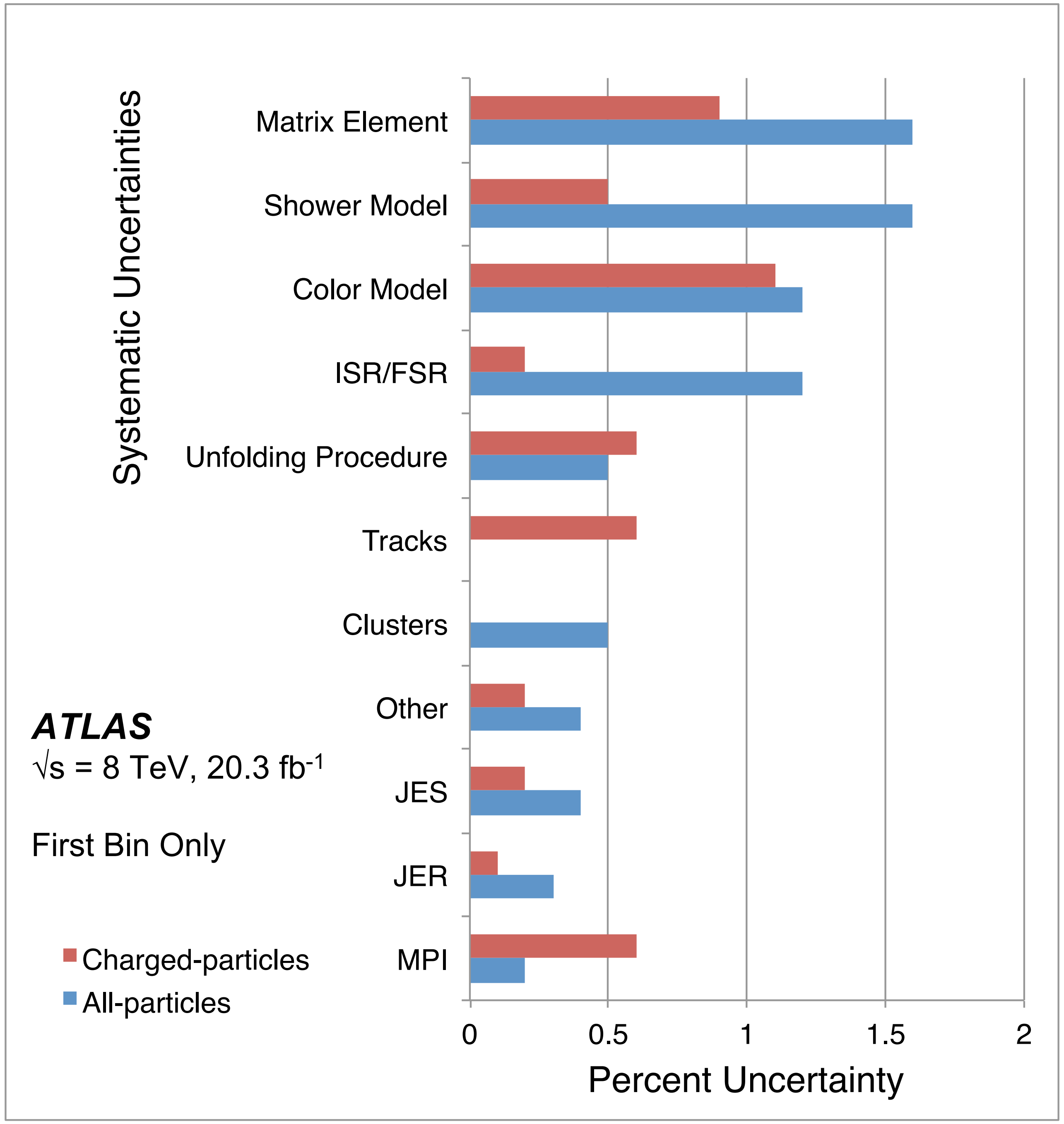


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/

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
$t\bar{t}$ †	Powheg +Herwig [27] +Jimmy [29]	NLO ME + PS (MPI)	- 6.520.2 4.31	CT10 CT10 -	- AUET2 [28] -
$t\bar{t}$ †	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/

$\Delta\theta_p^{\mathrm{all}}[\%]$	θ_p^{all} [rad]/π		
	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

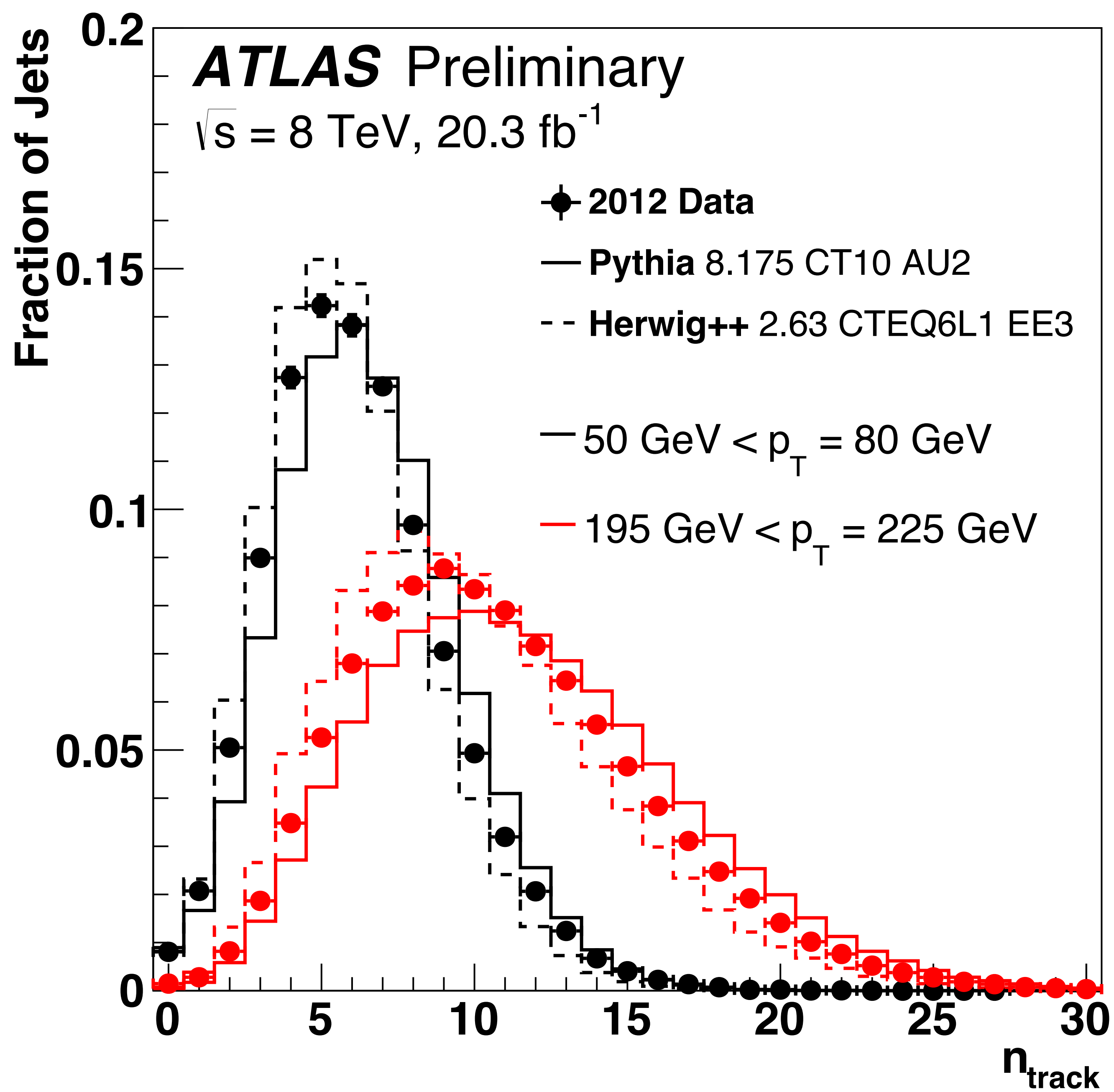
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-09/

$\Delta\theta_p^{\text{charged}}$[%]	$\theta_p^{\text{charged}}$ [rad]/π			
	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

Plots from Jet Charge

Jet Charge Backup

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



Jet Charge Backup

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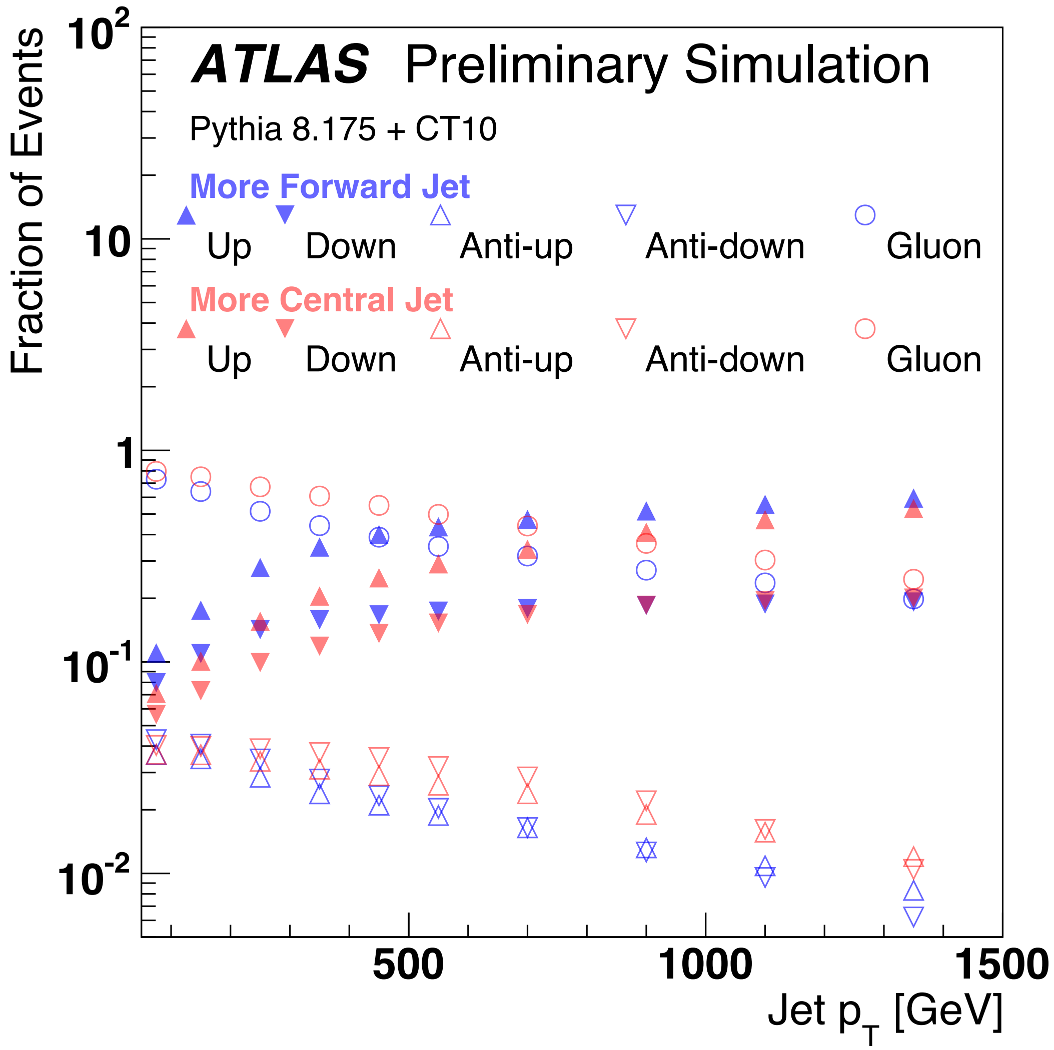

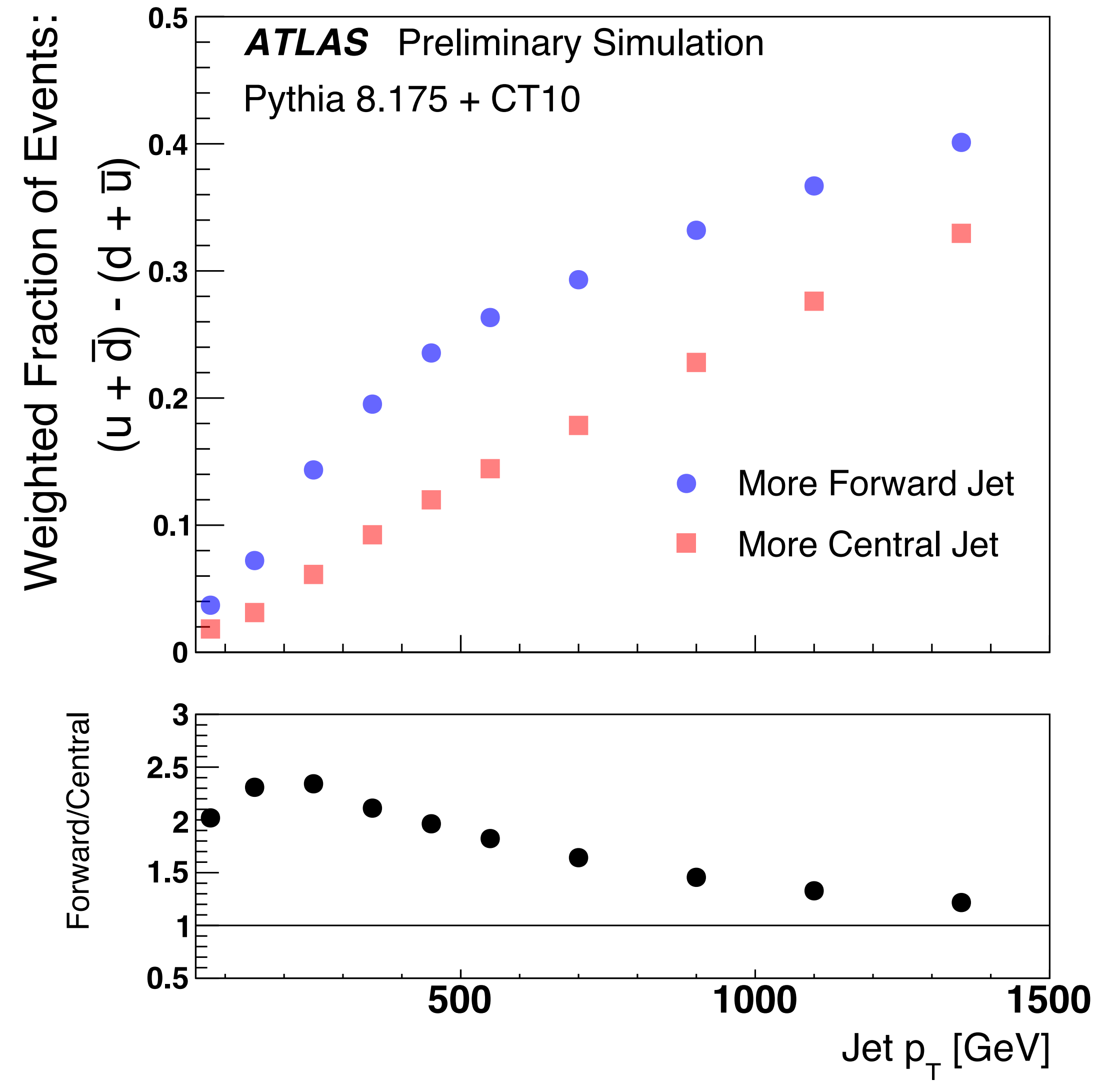

Jet Charge Backup

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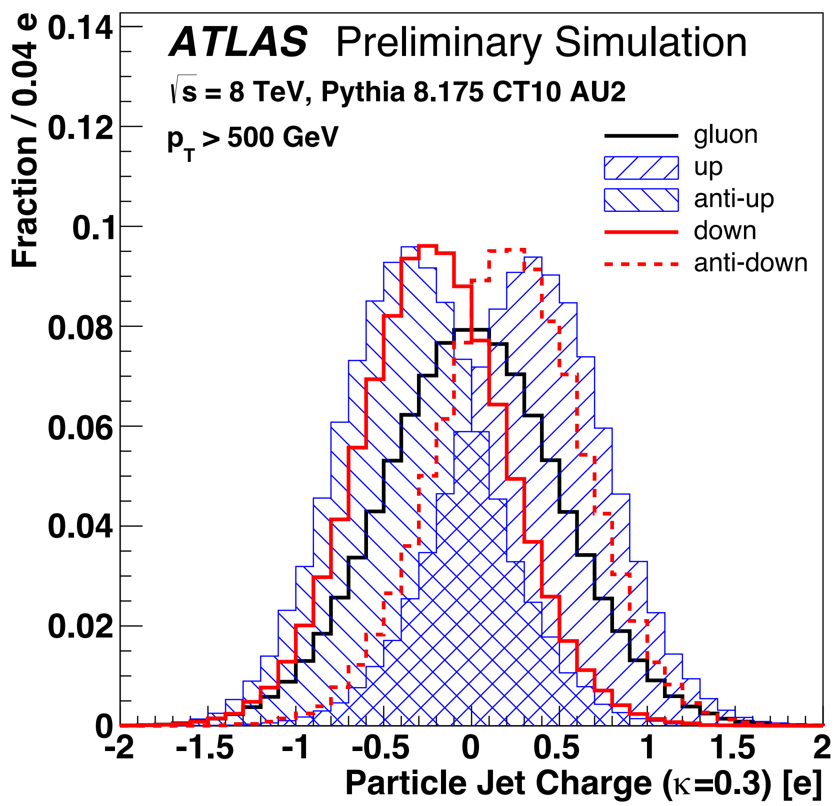

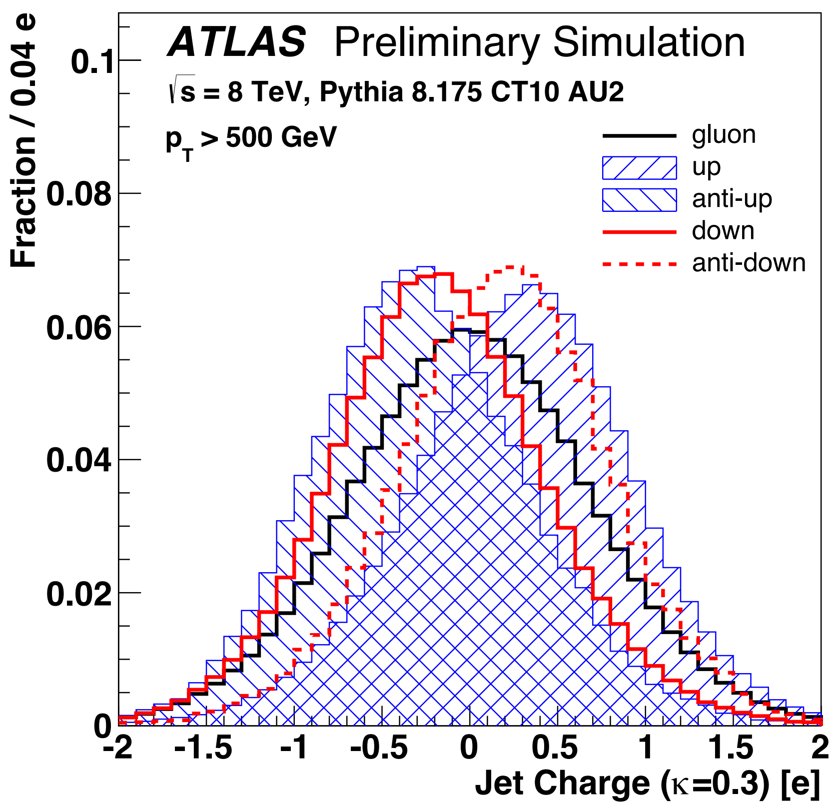

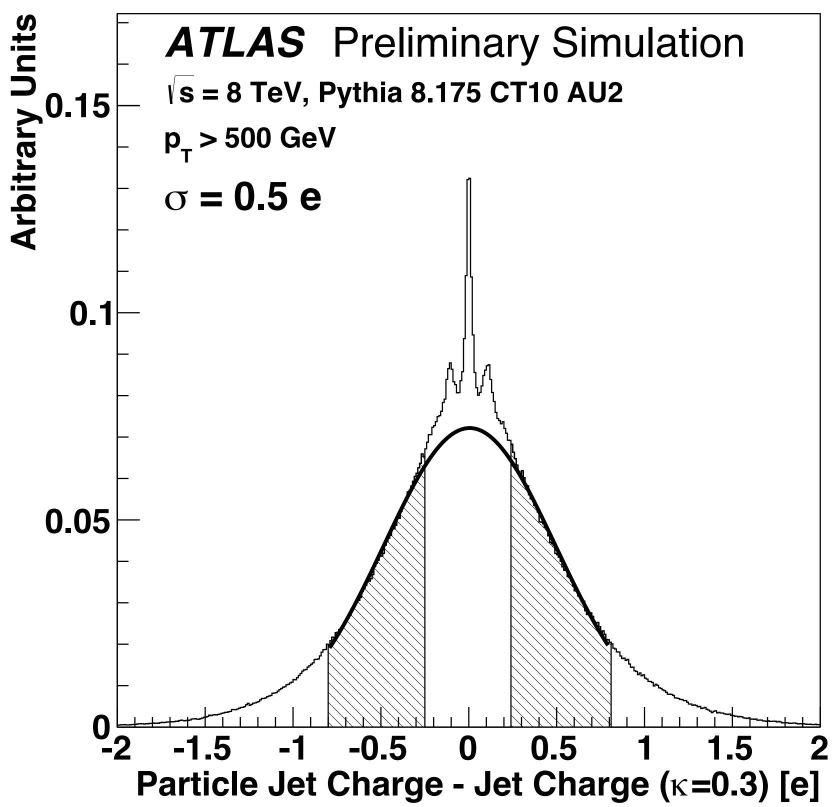

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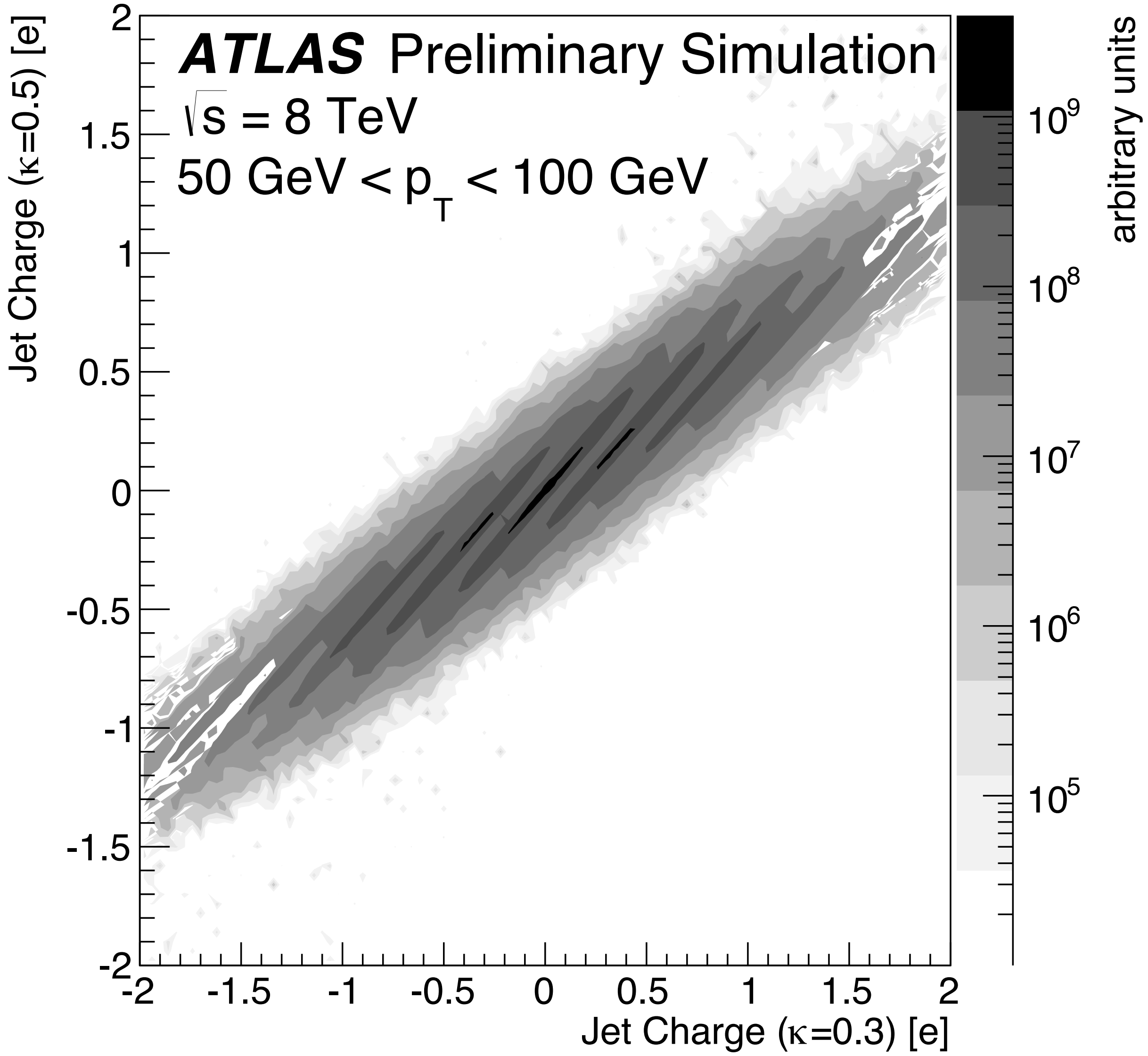

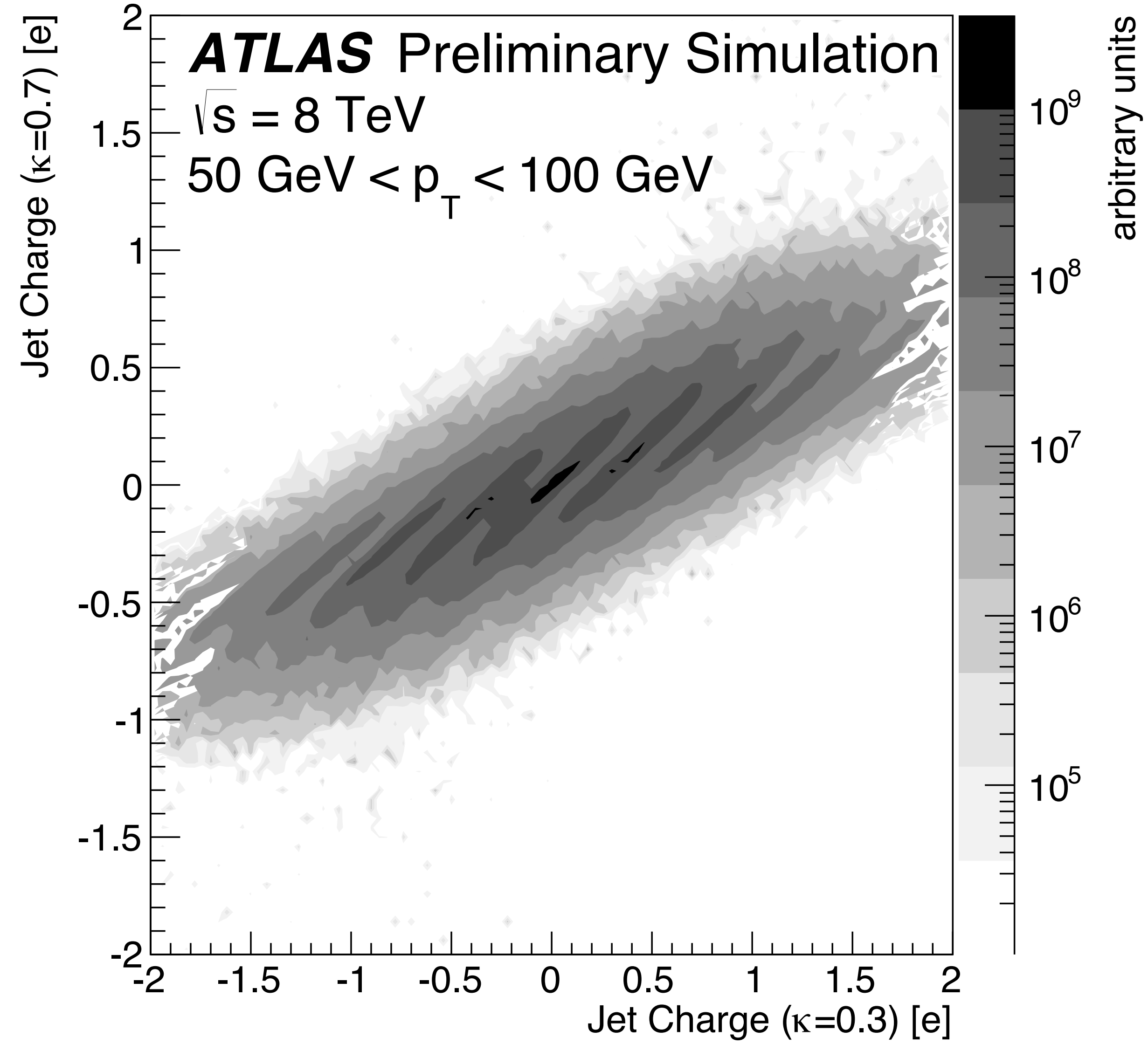

Jet Charge Backup

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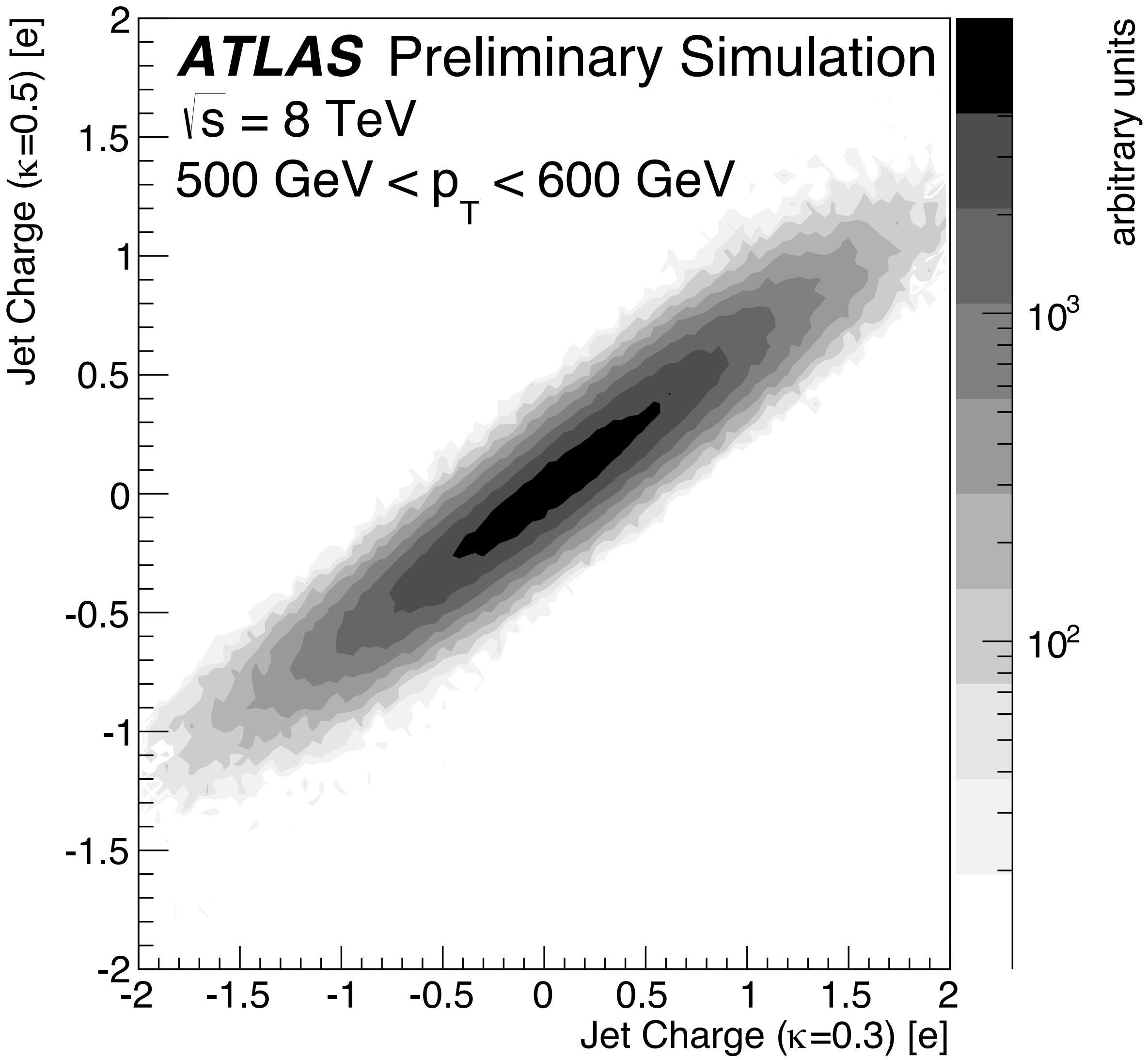

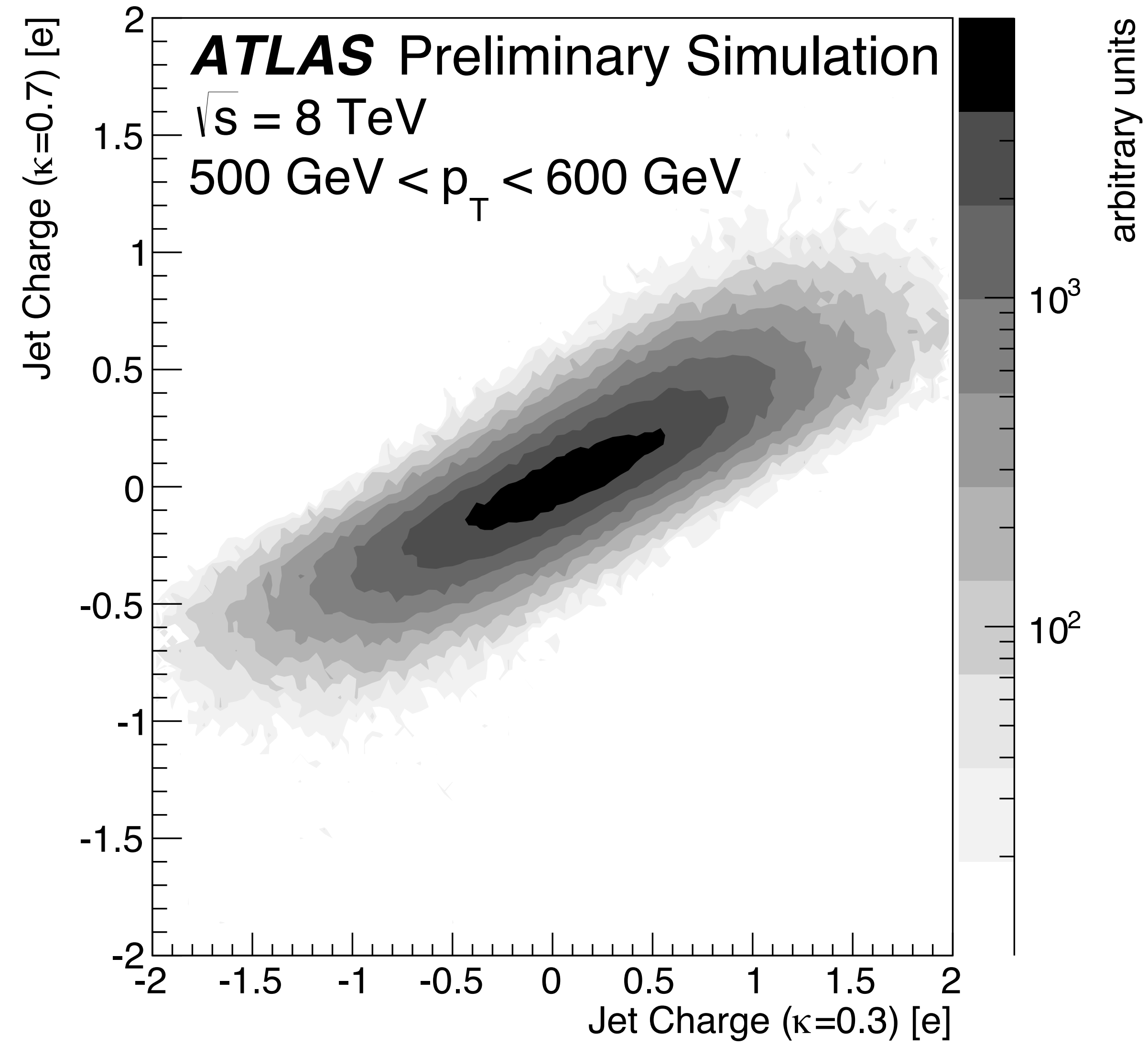

Jet Charge Backup

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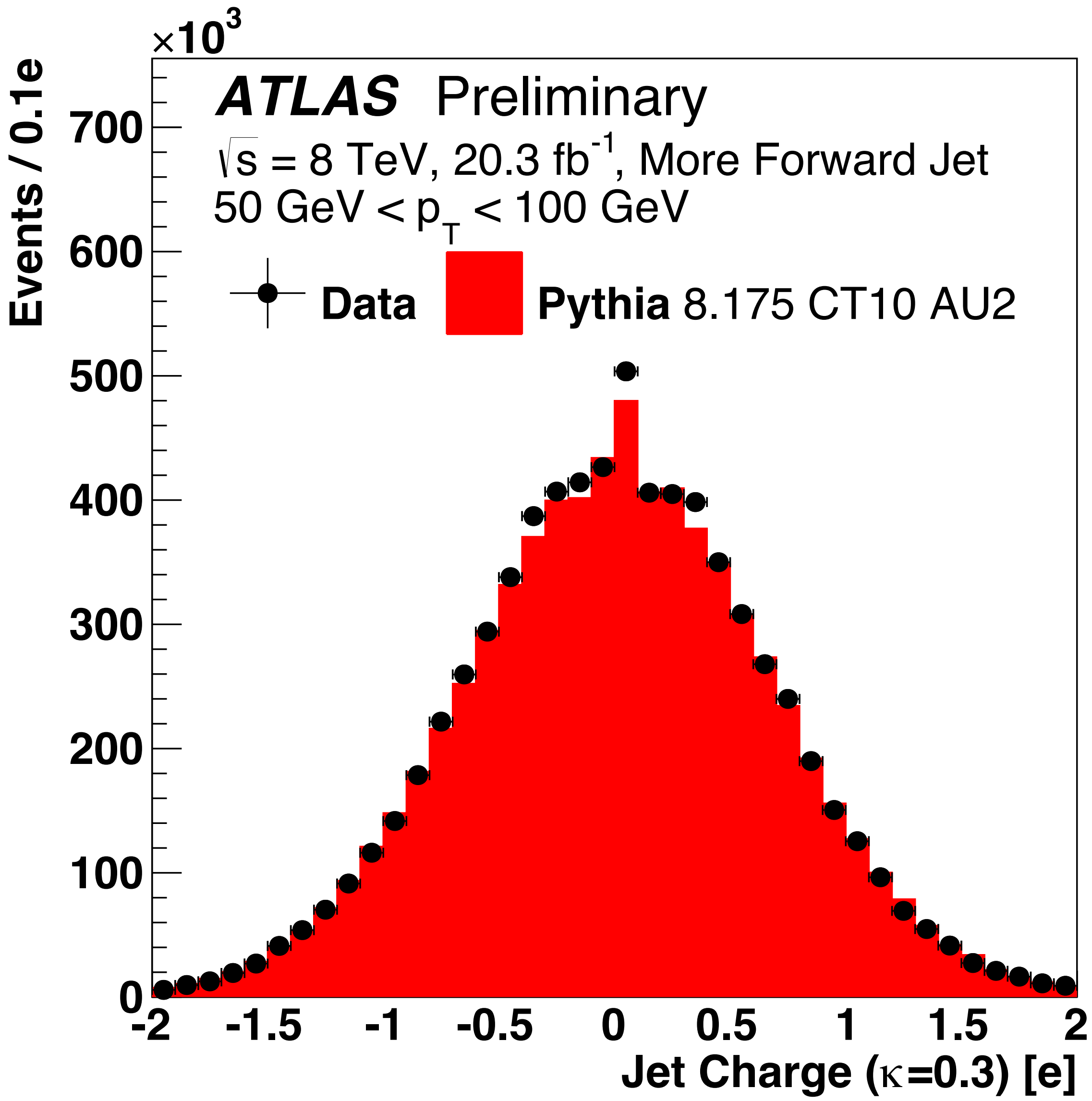

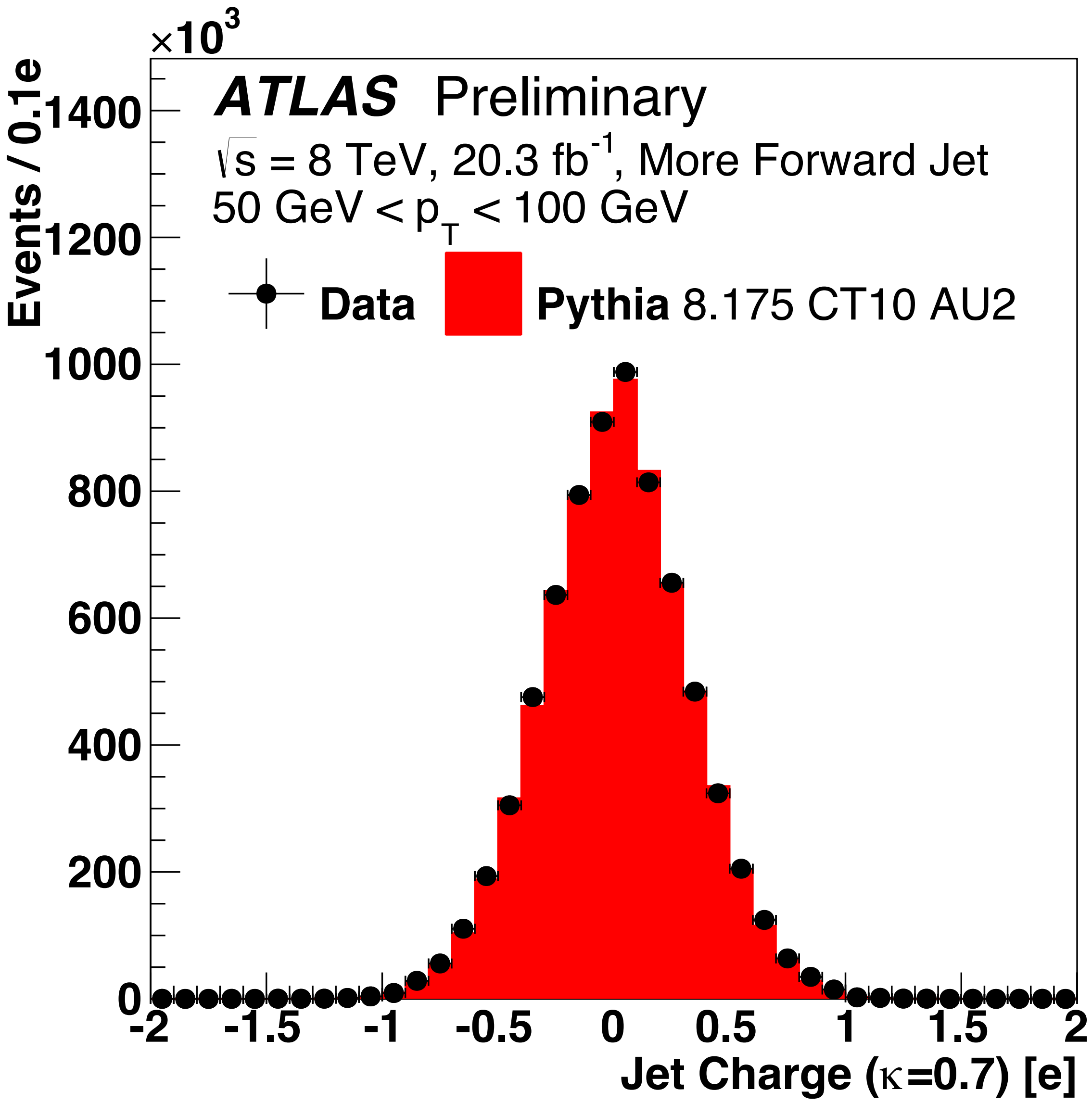

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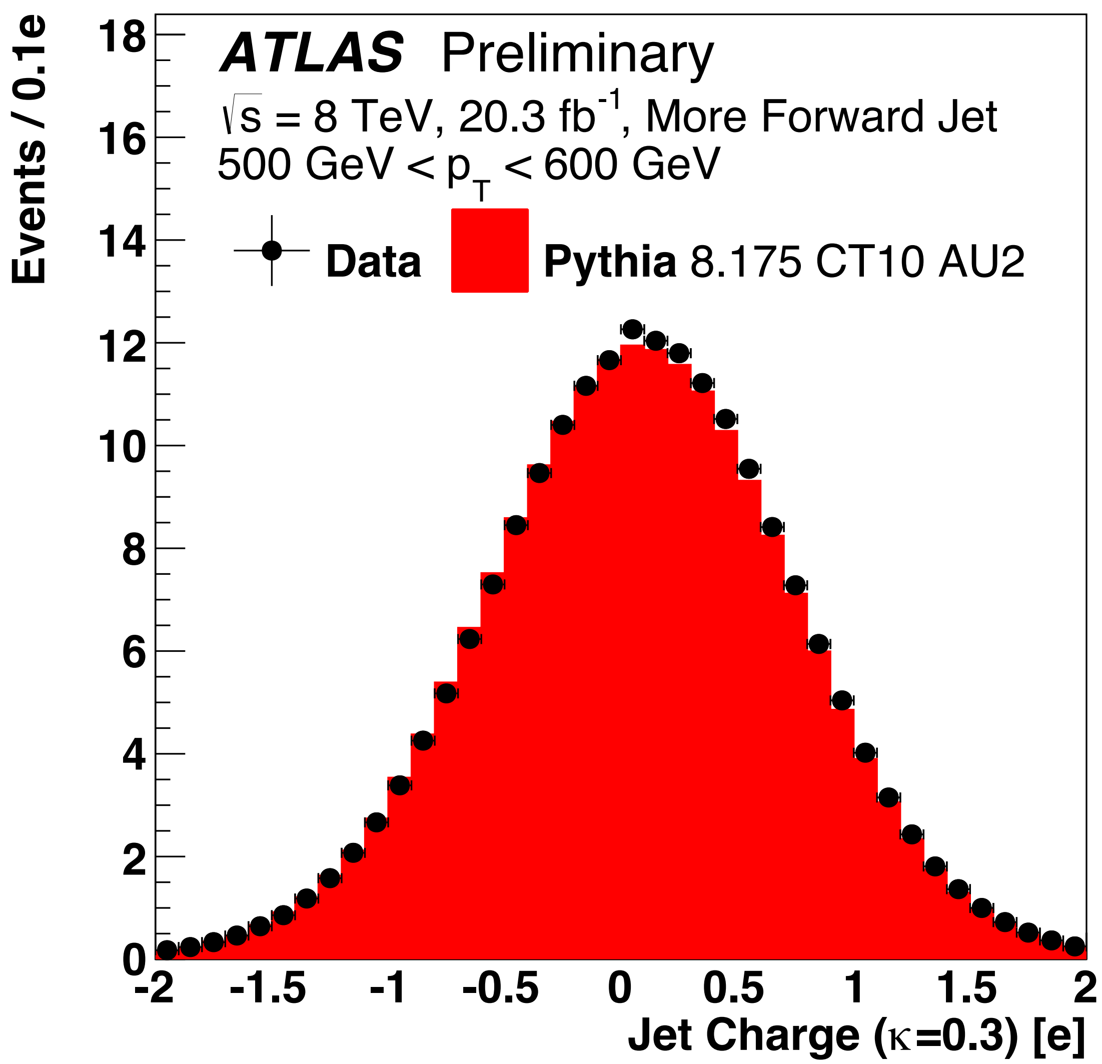

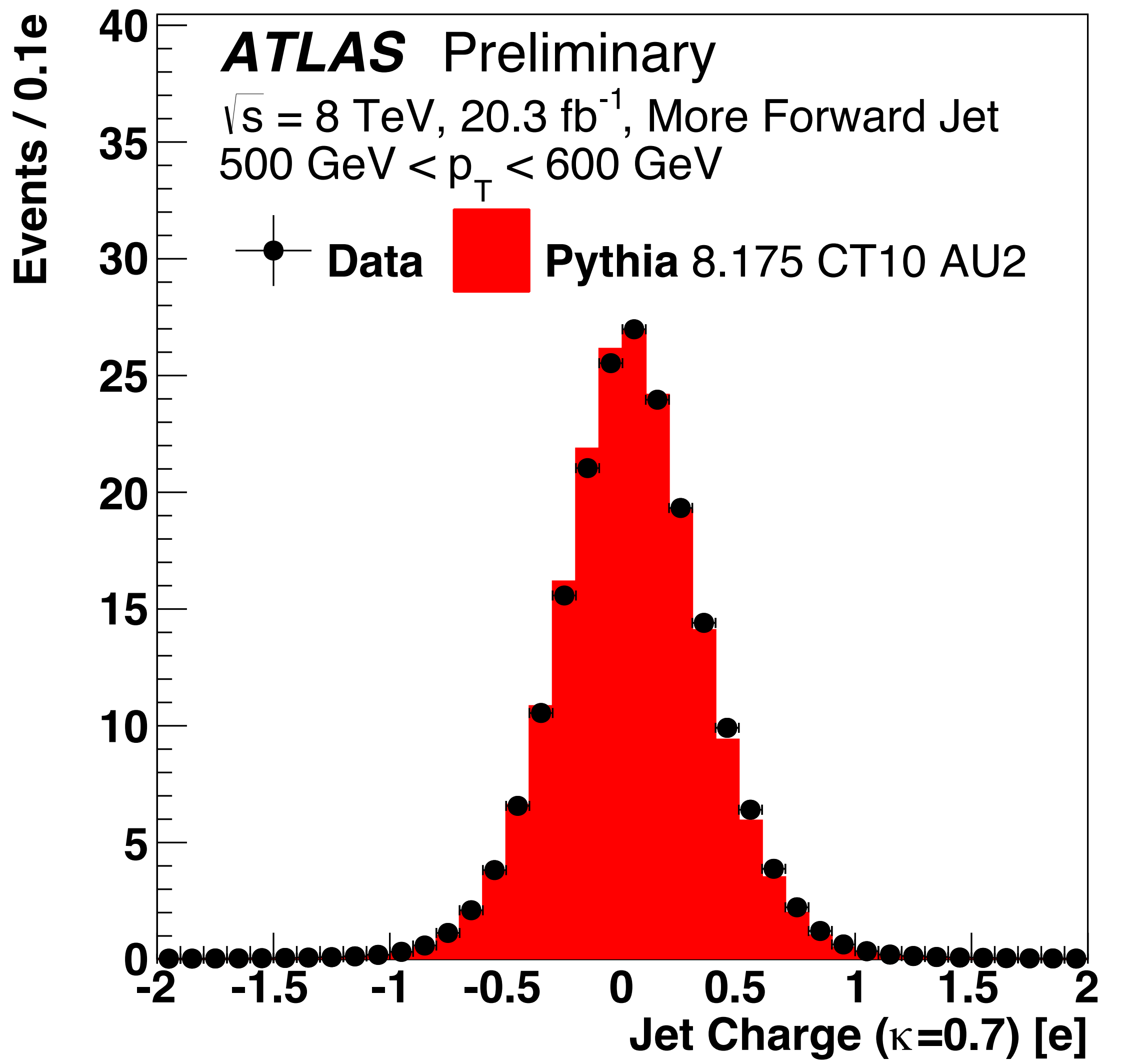

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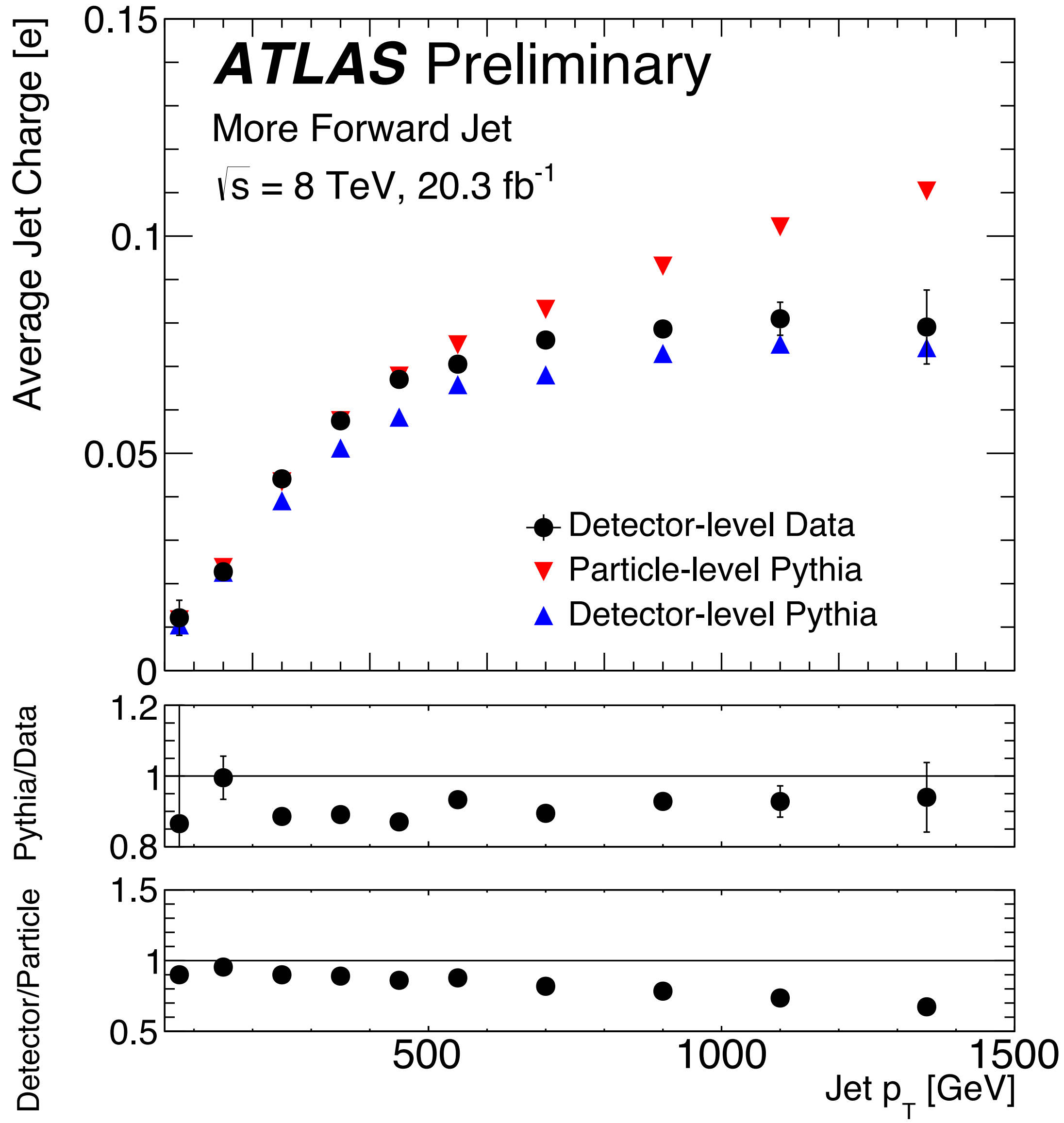

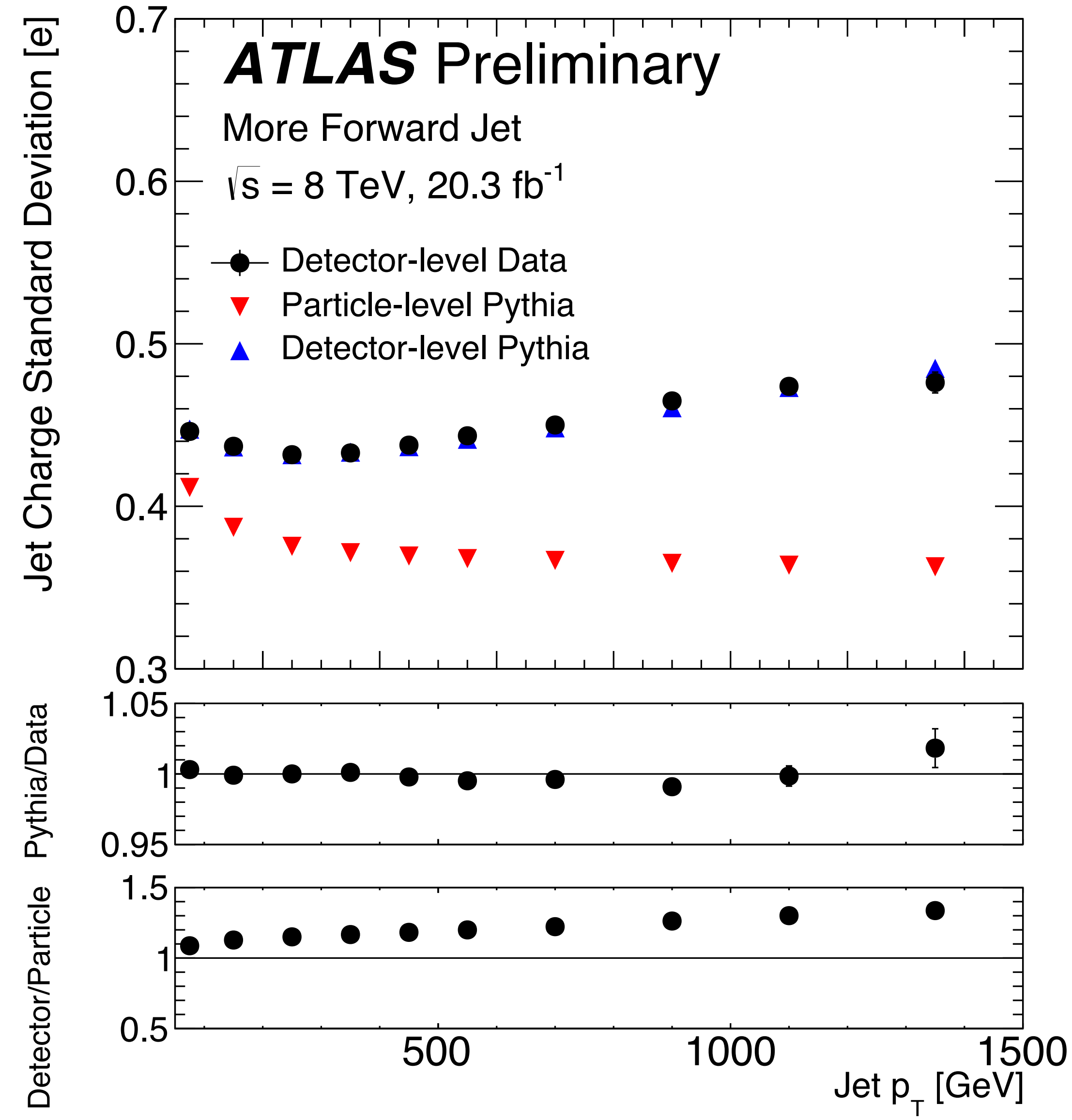

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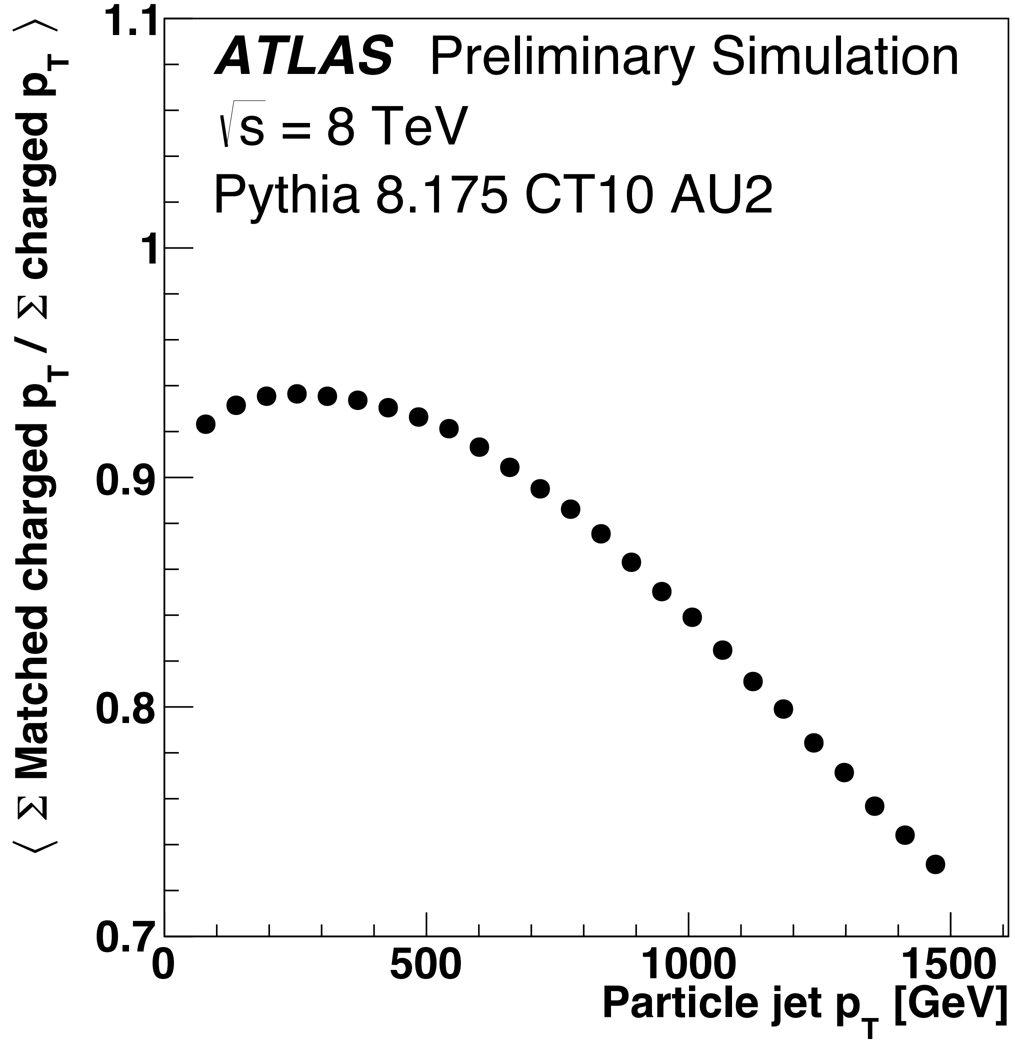

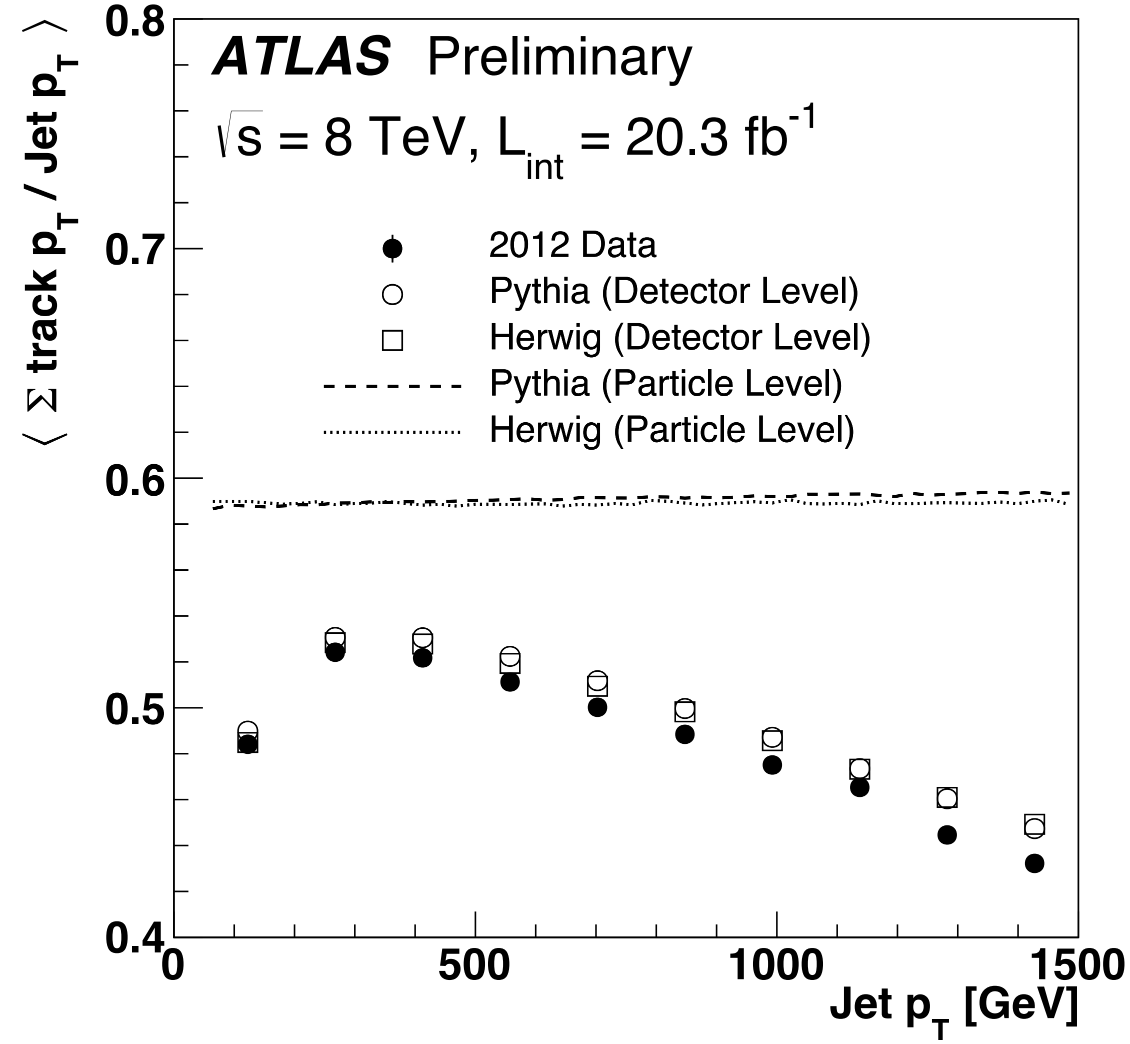

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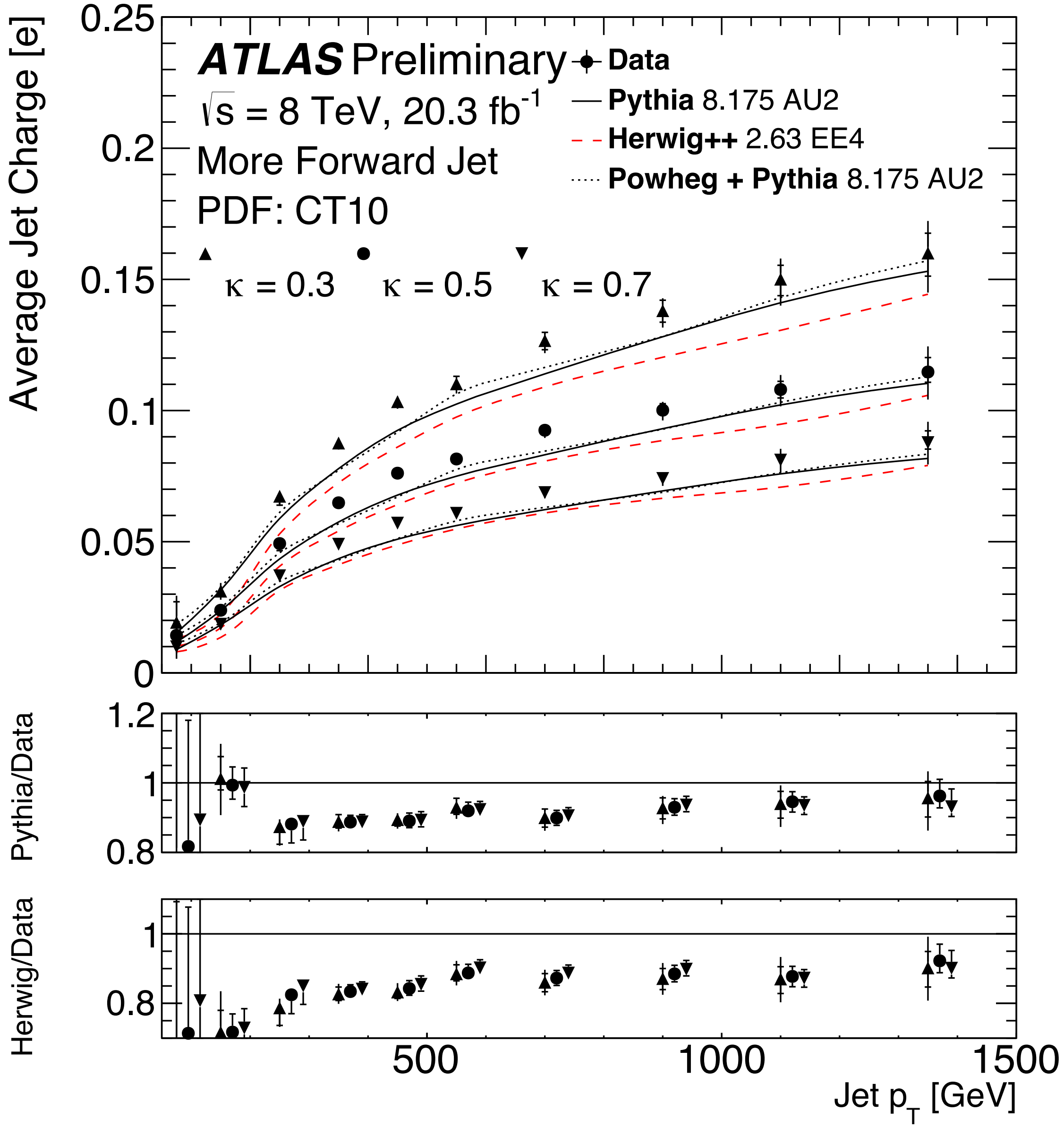

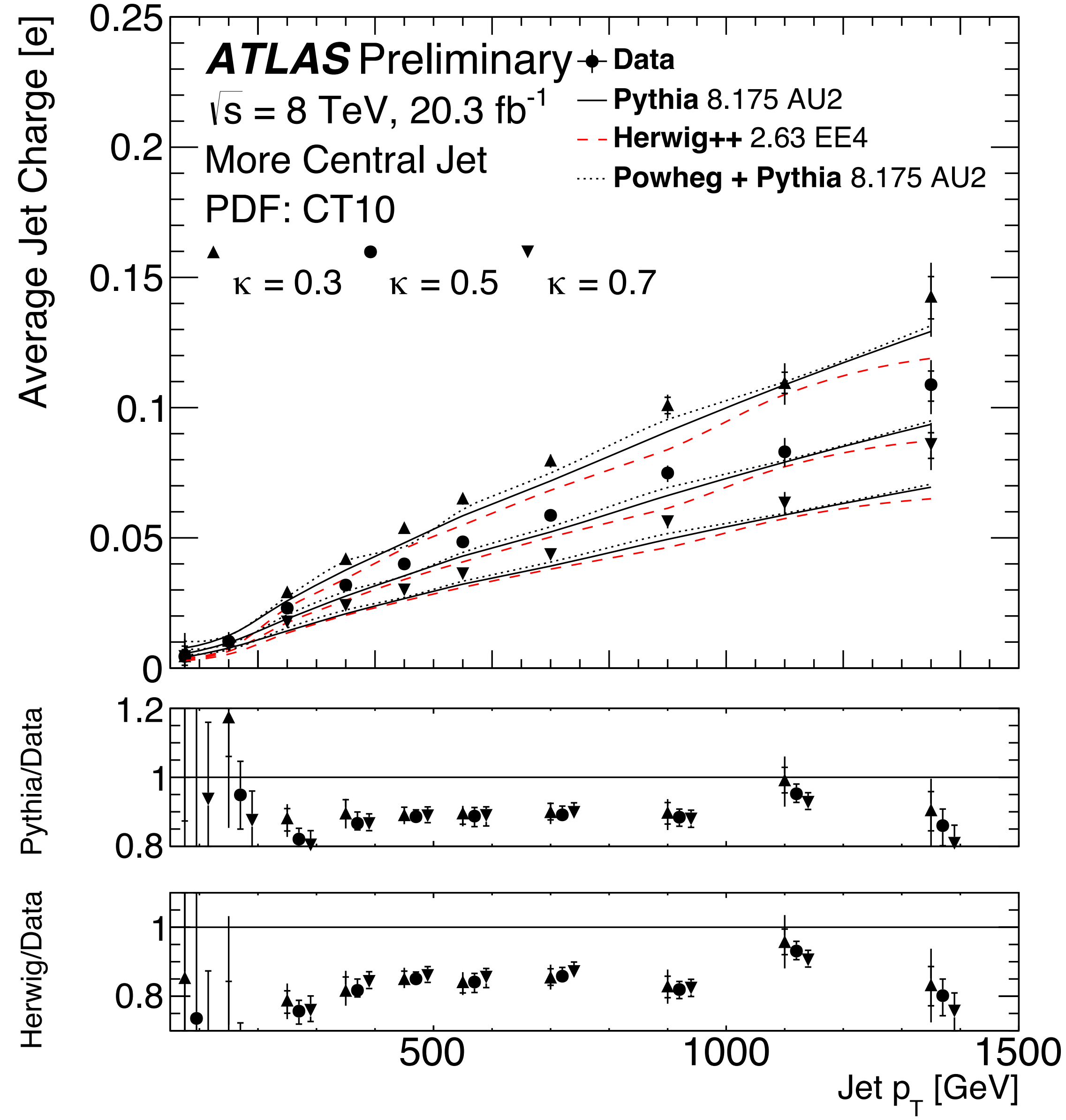

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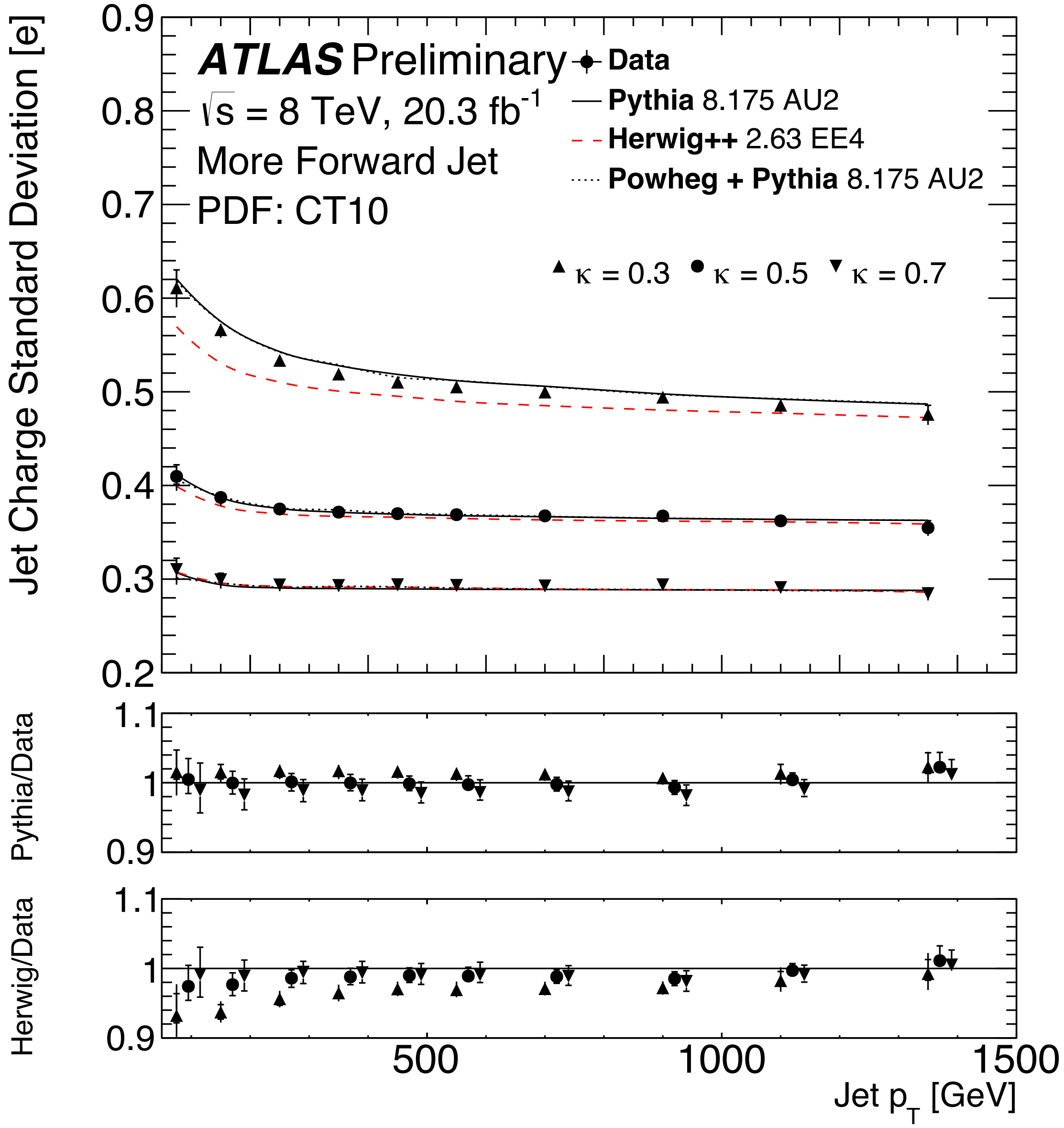

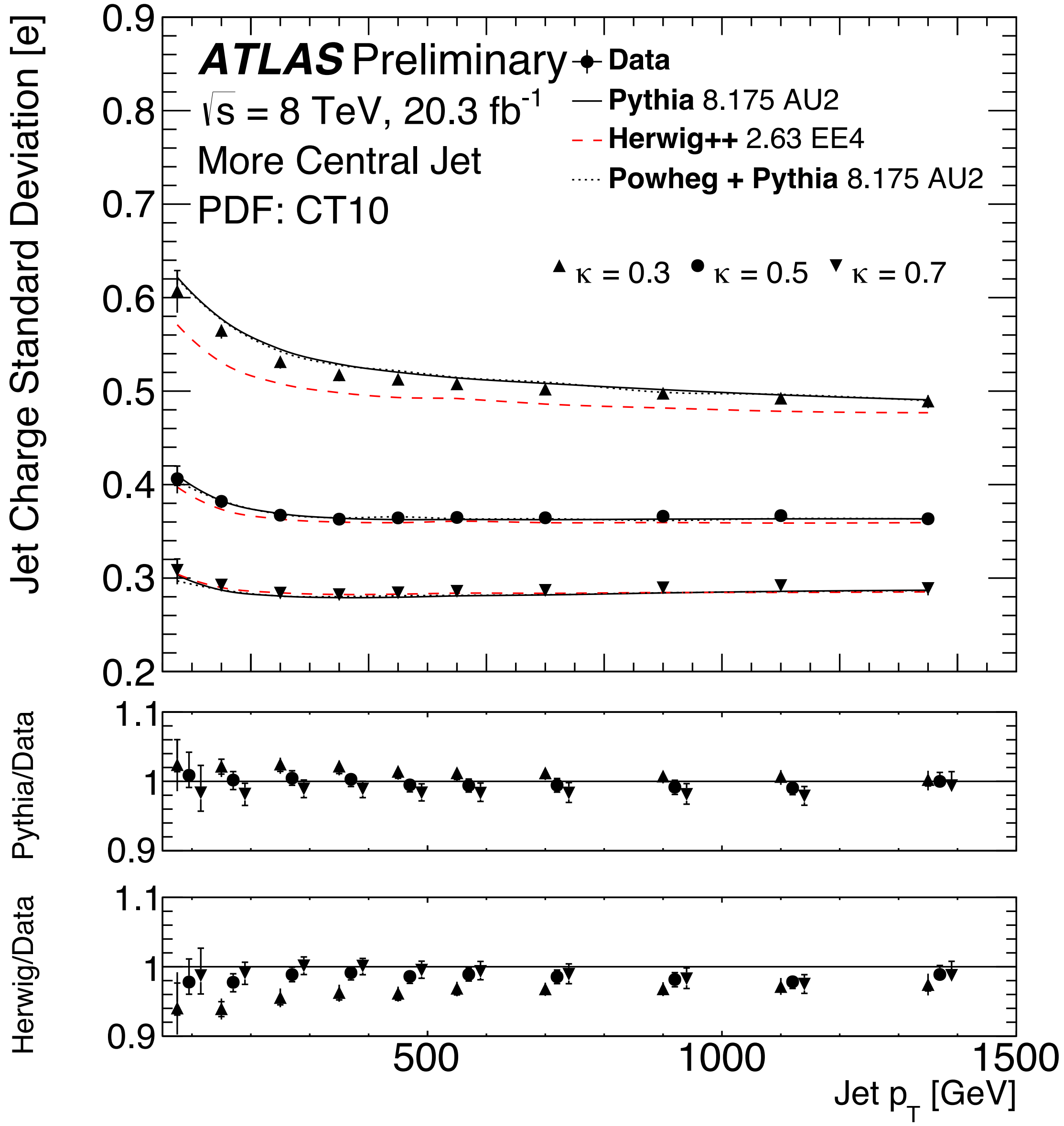

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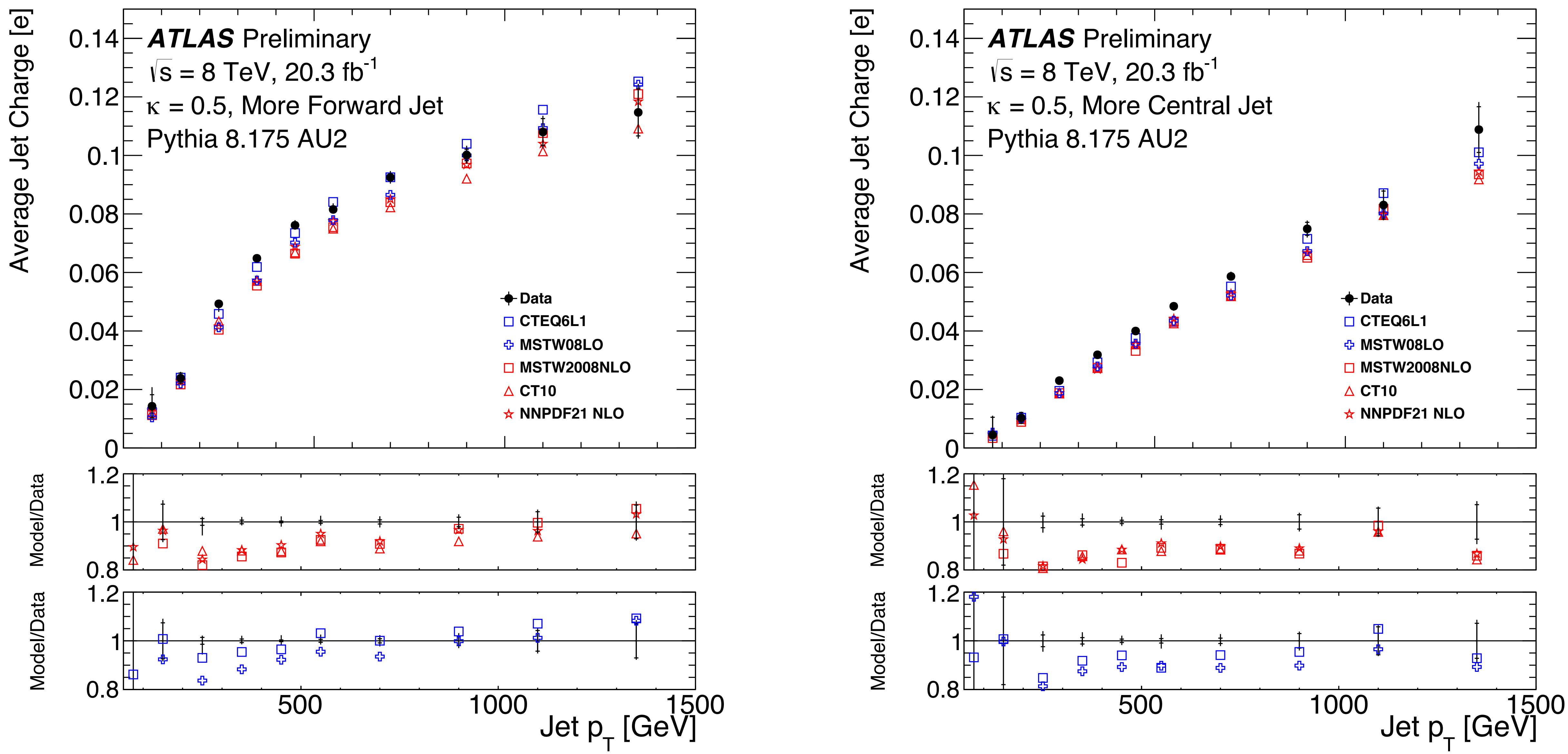

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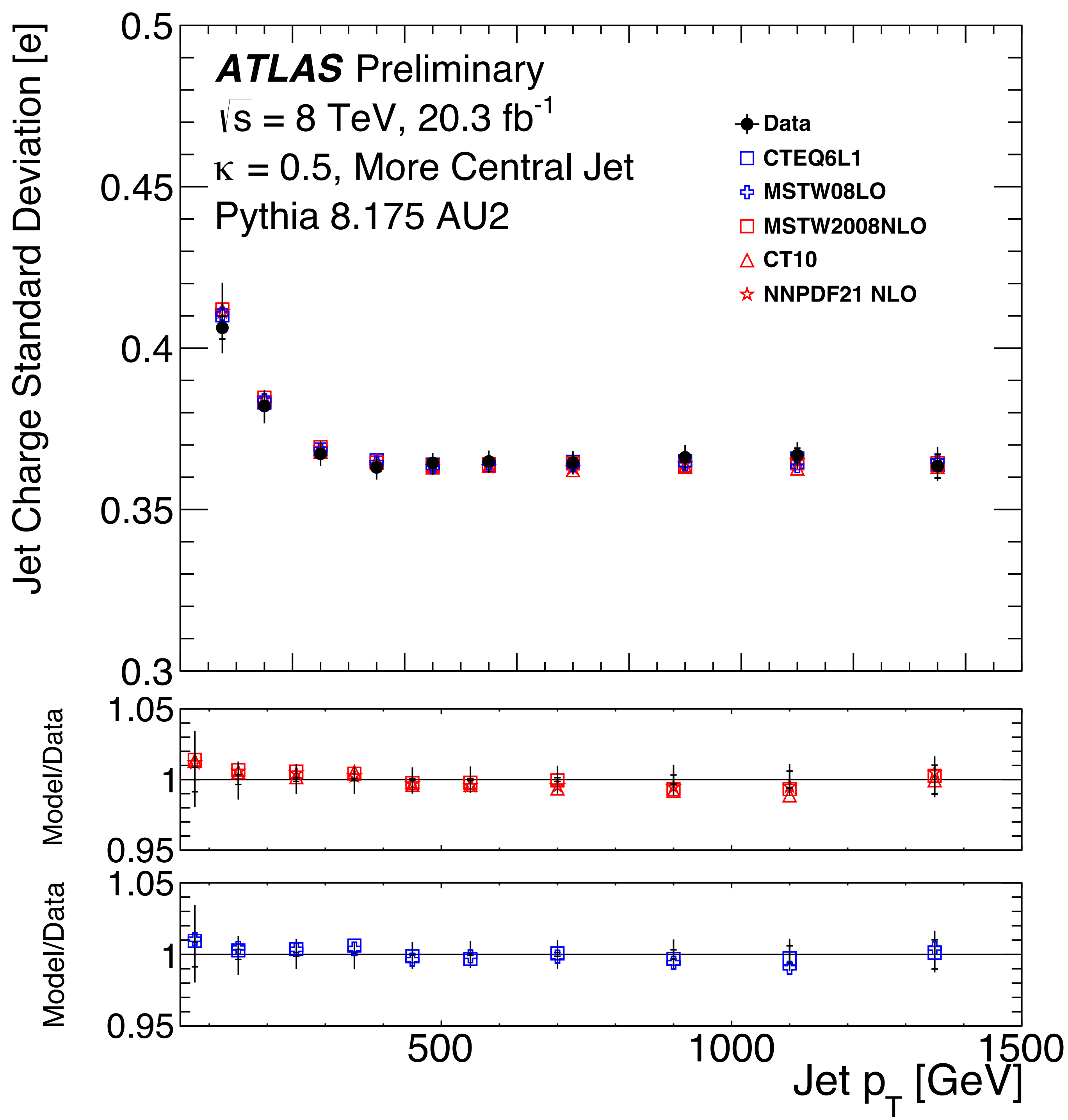

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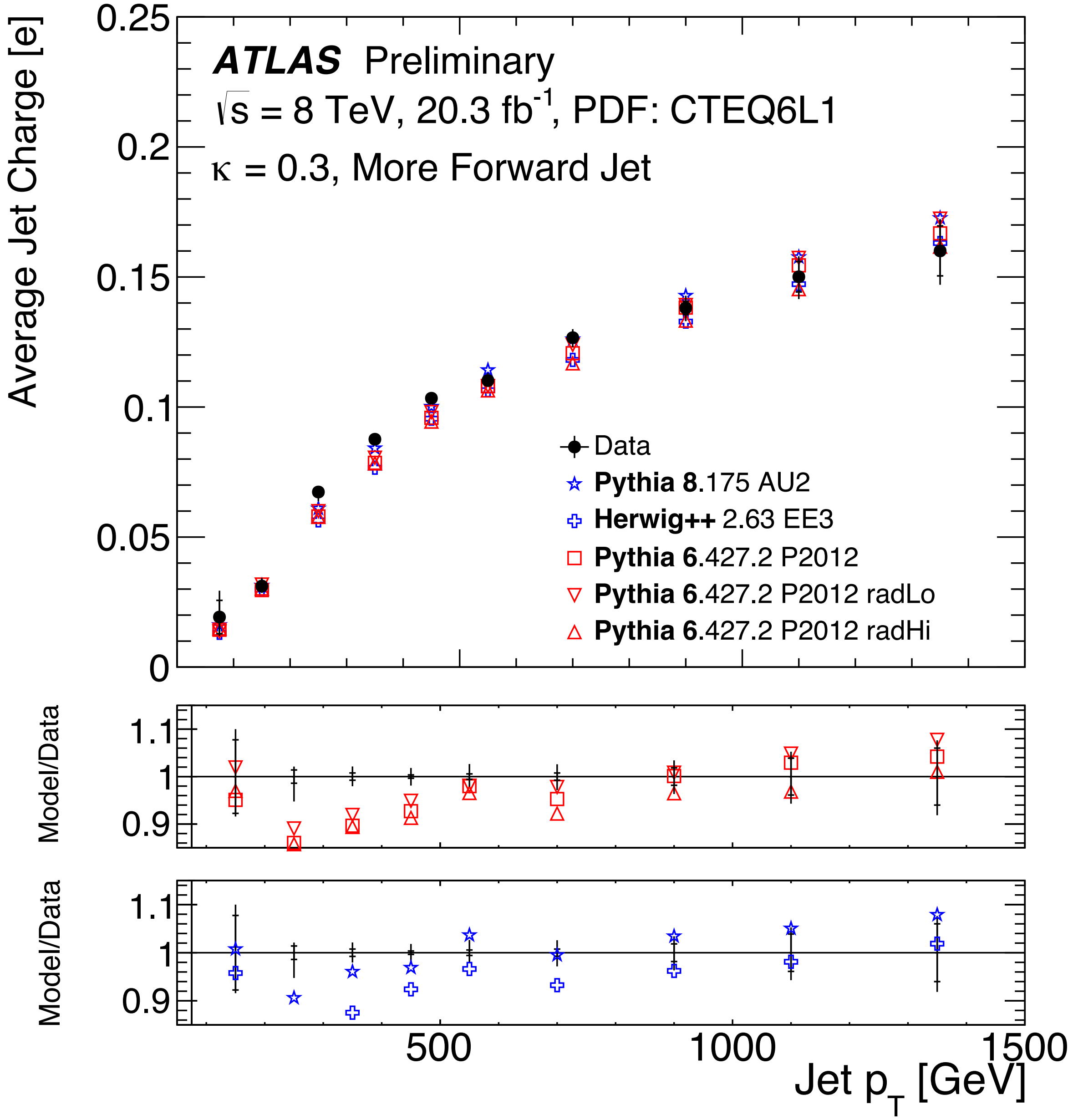

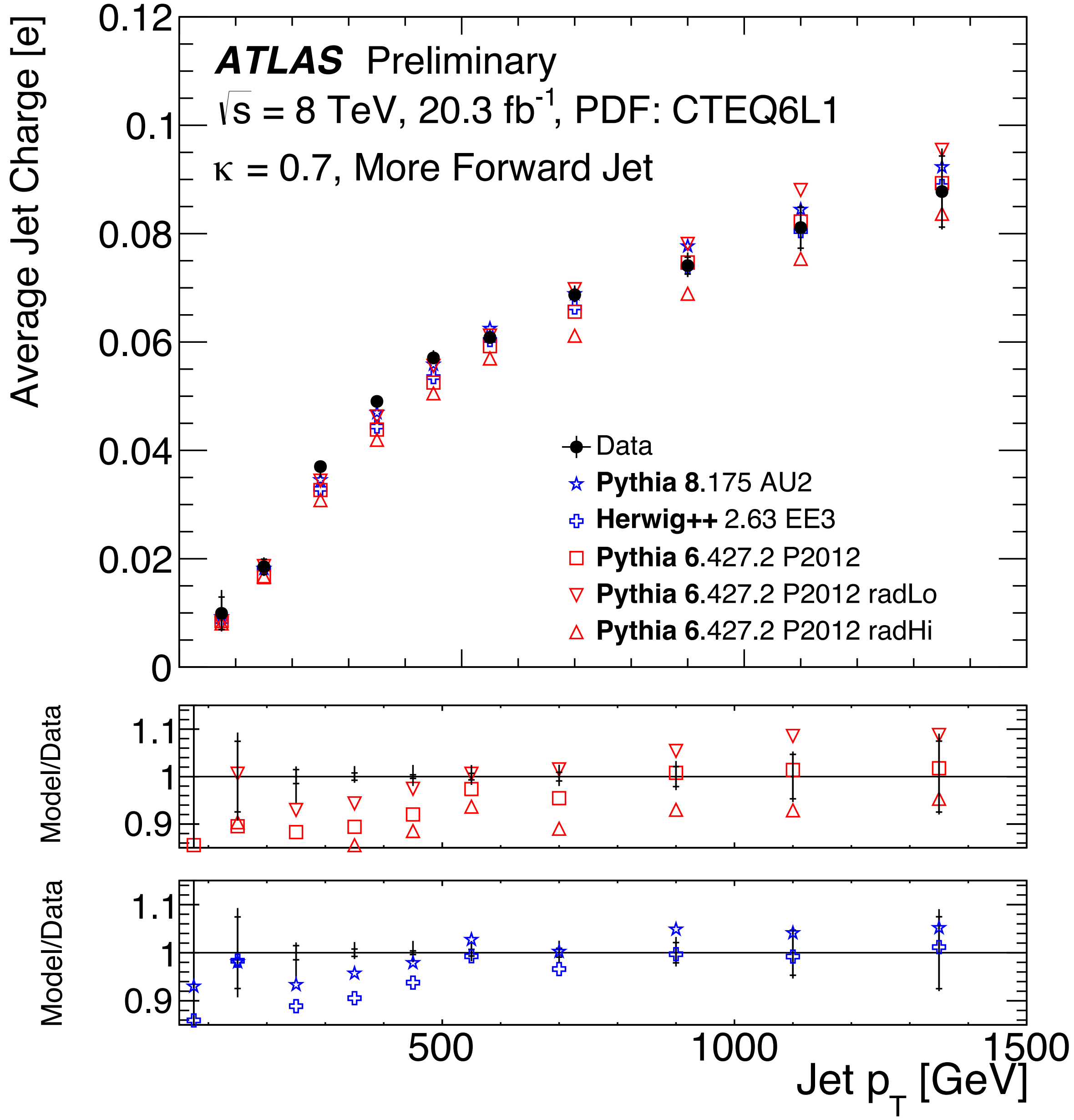

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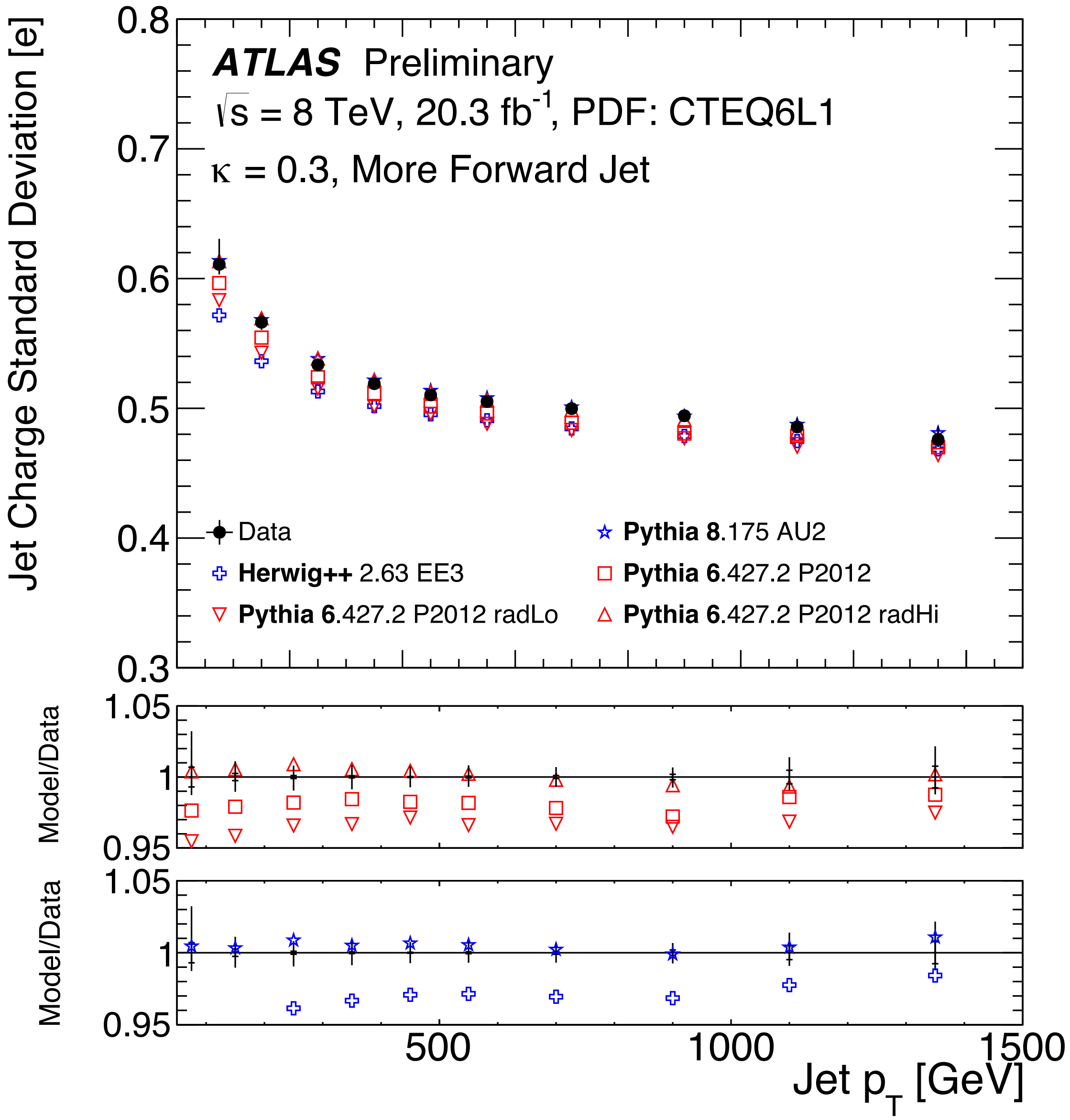

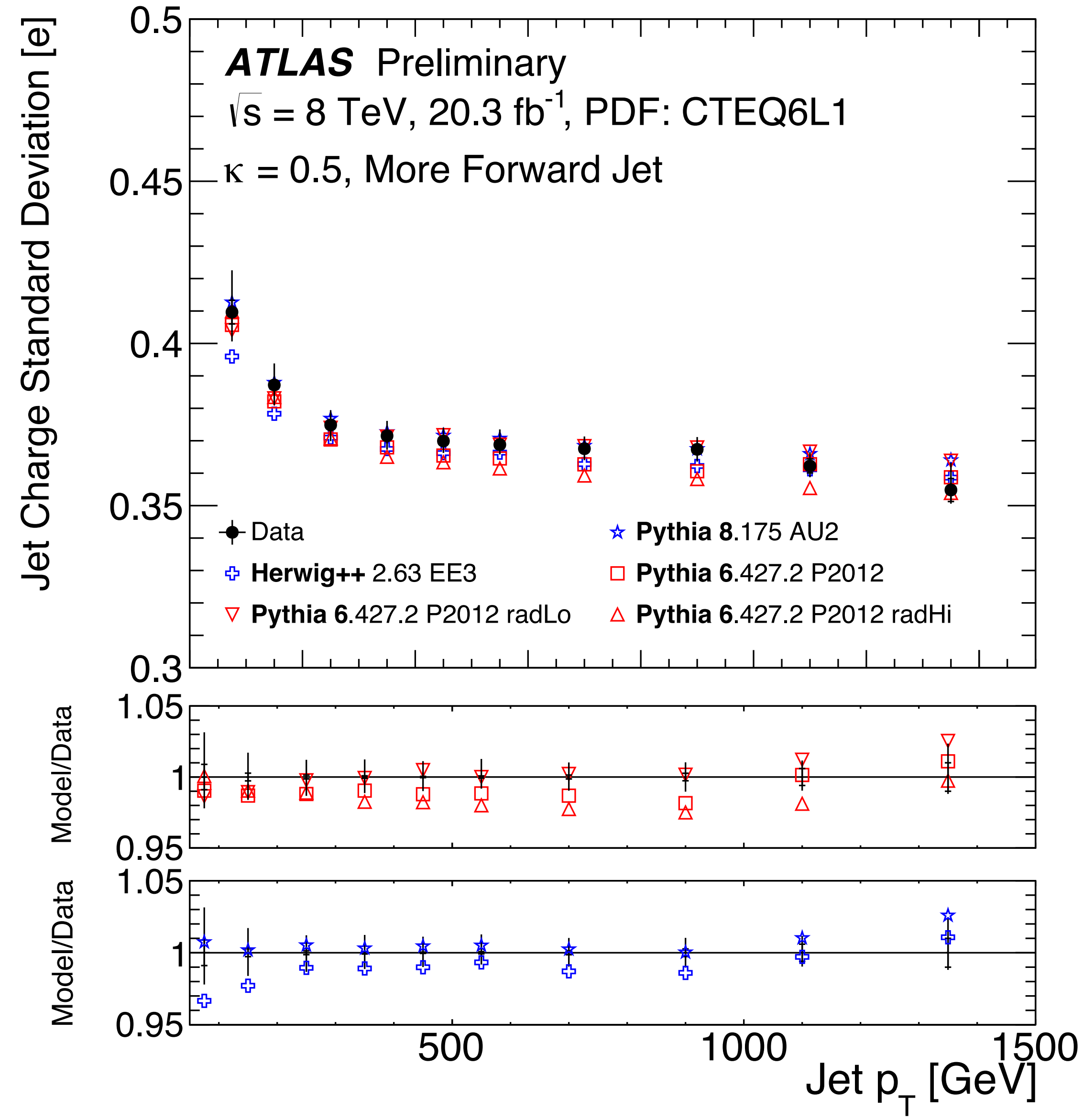

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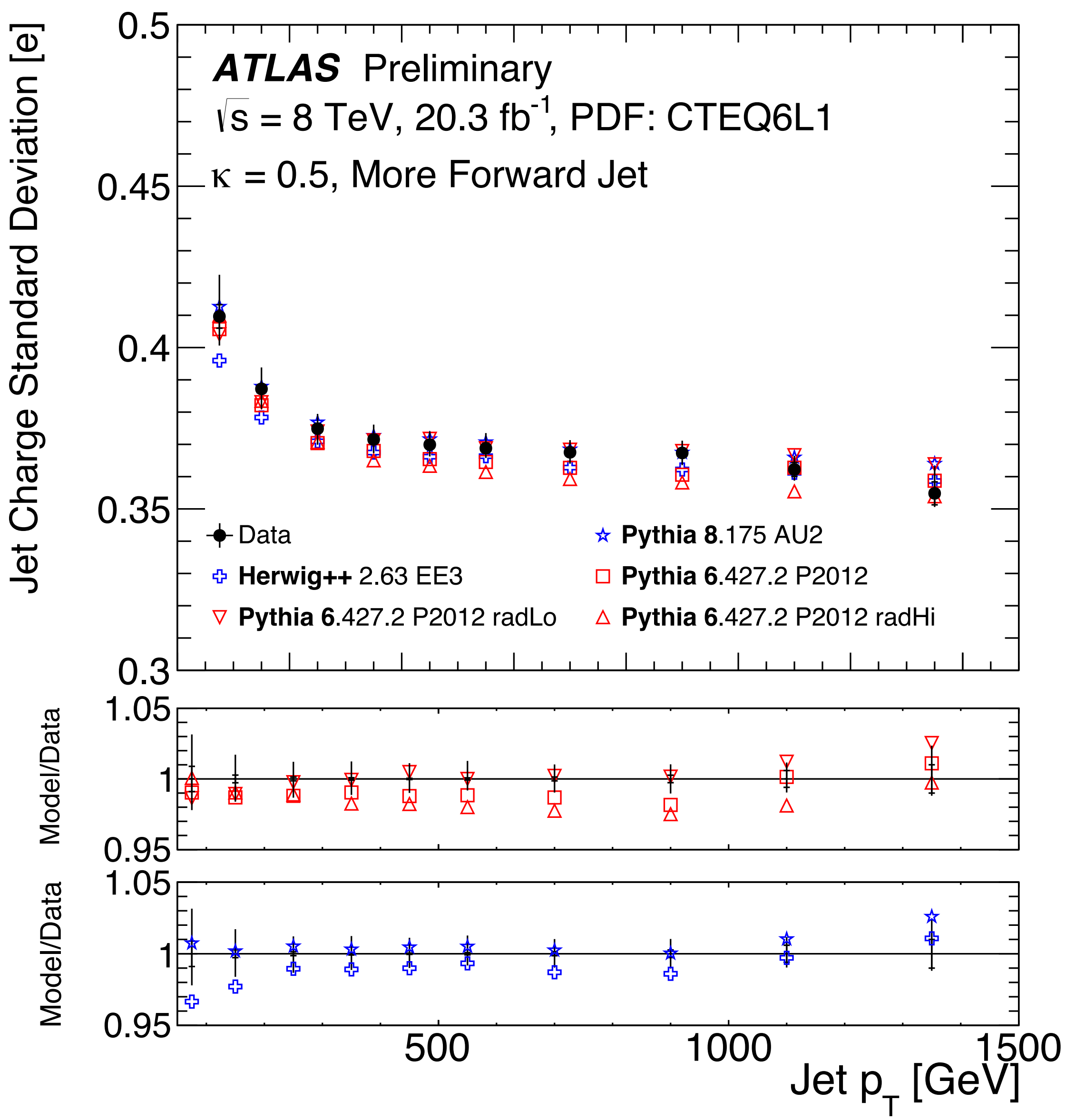

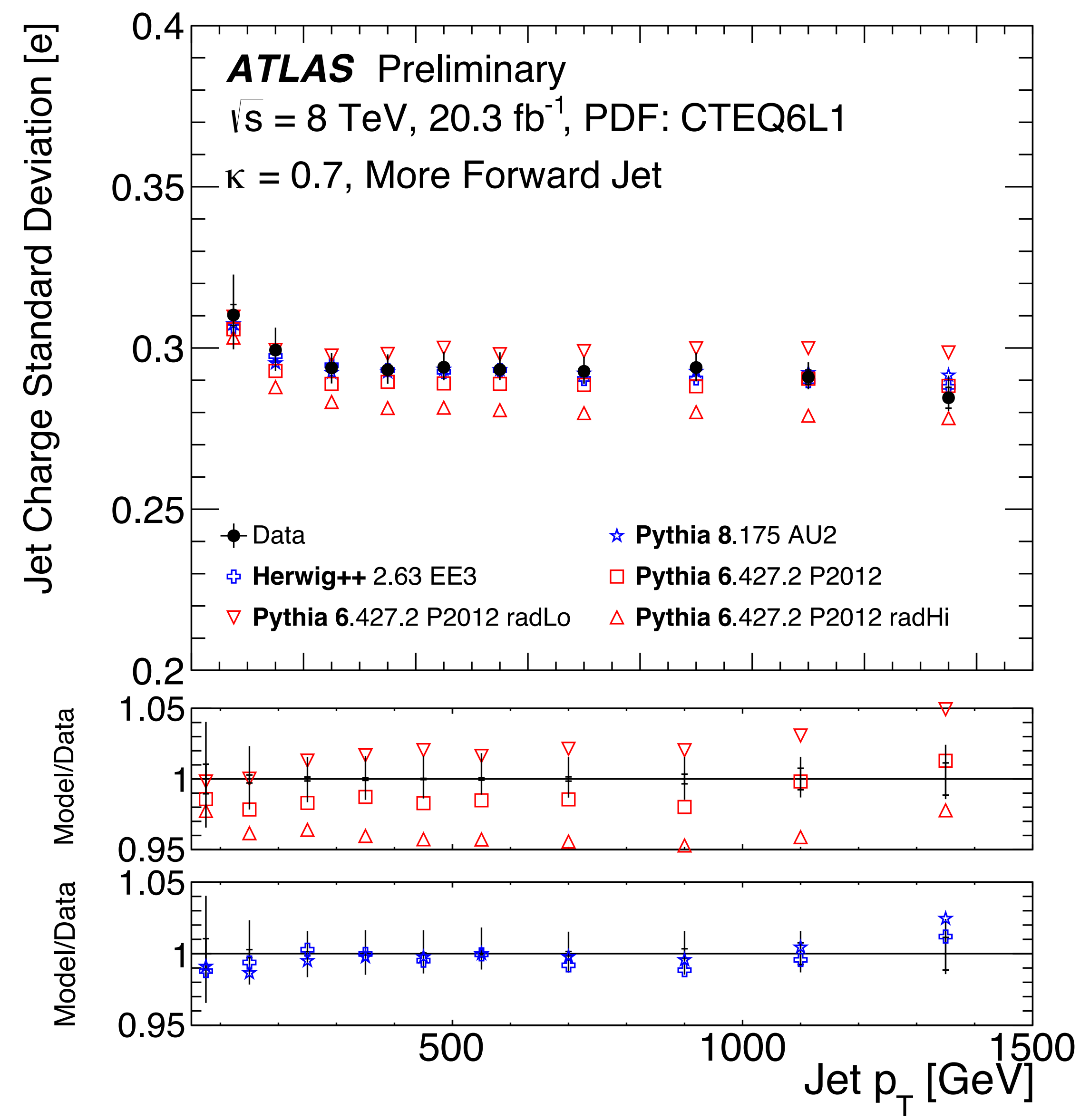

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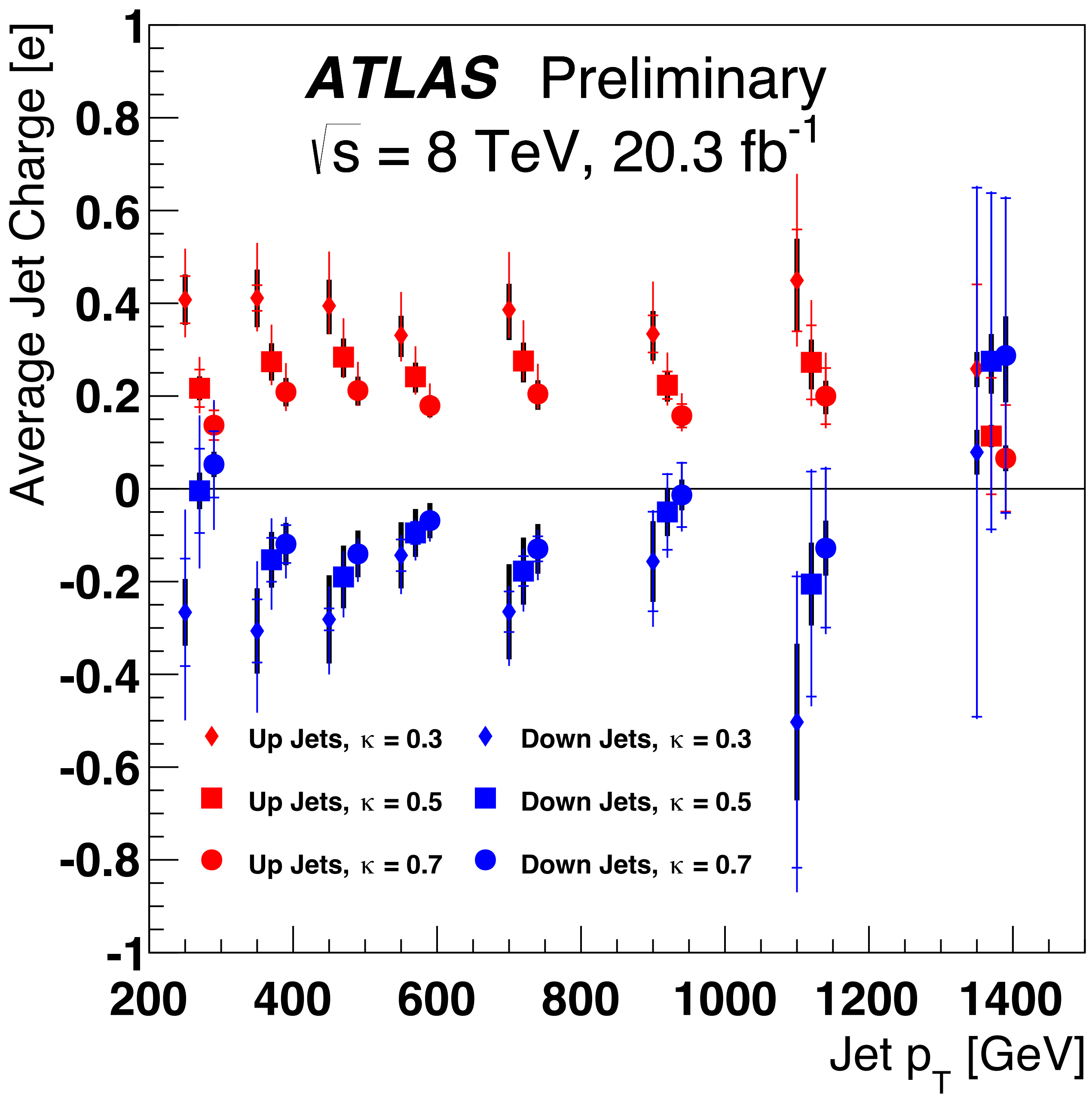

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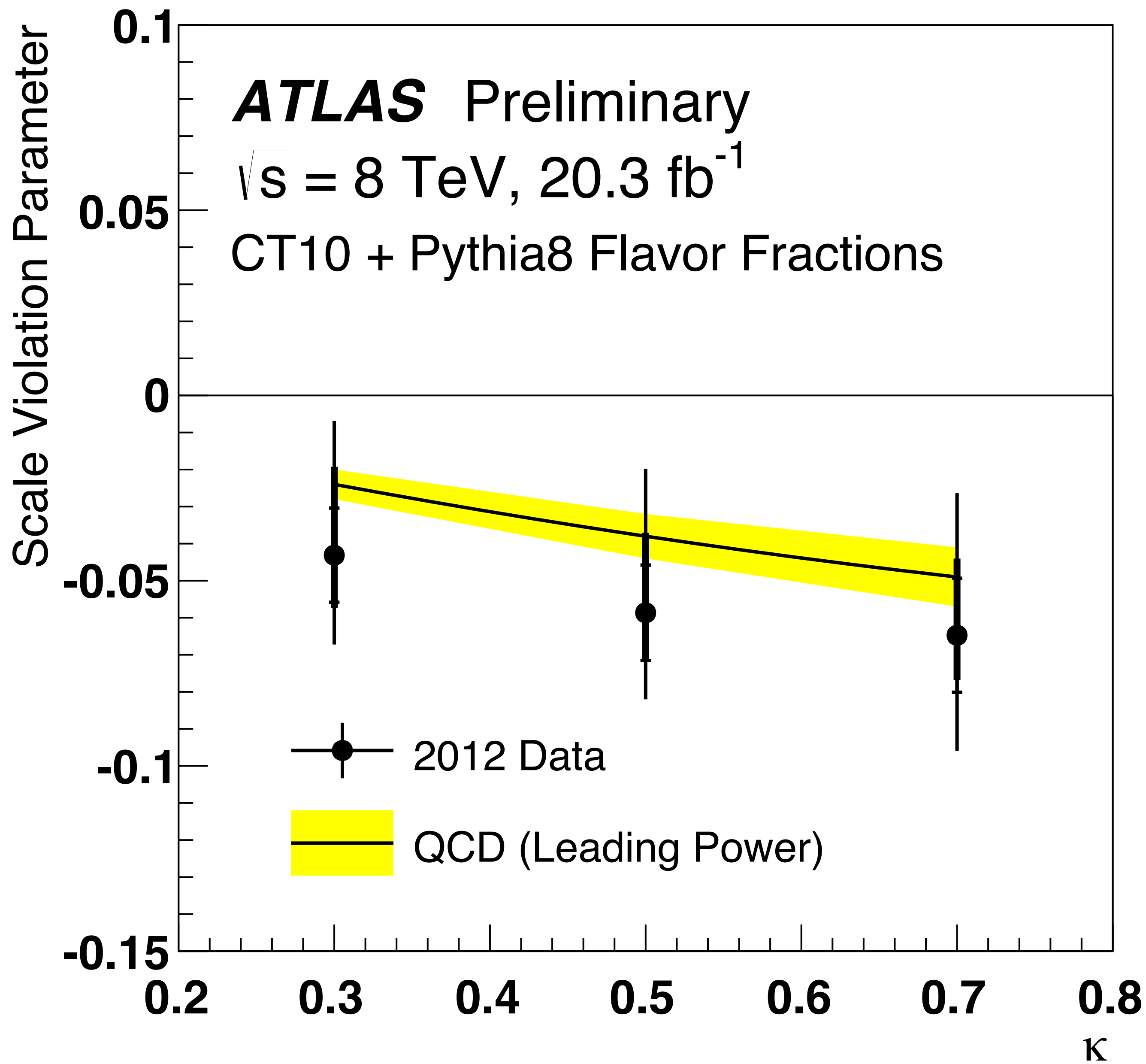

Jet Charge Backup

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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
Total JES	1.9	1.5	1.1	1.1	0.9	1.0	0.8	0.7	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
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