Measurements of underlying-event properties with the ATLAS detector

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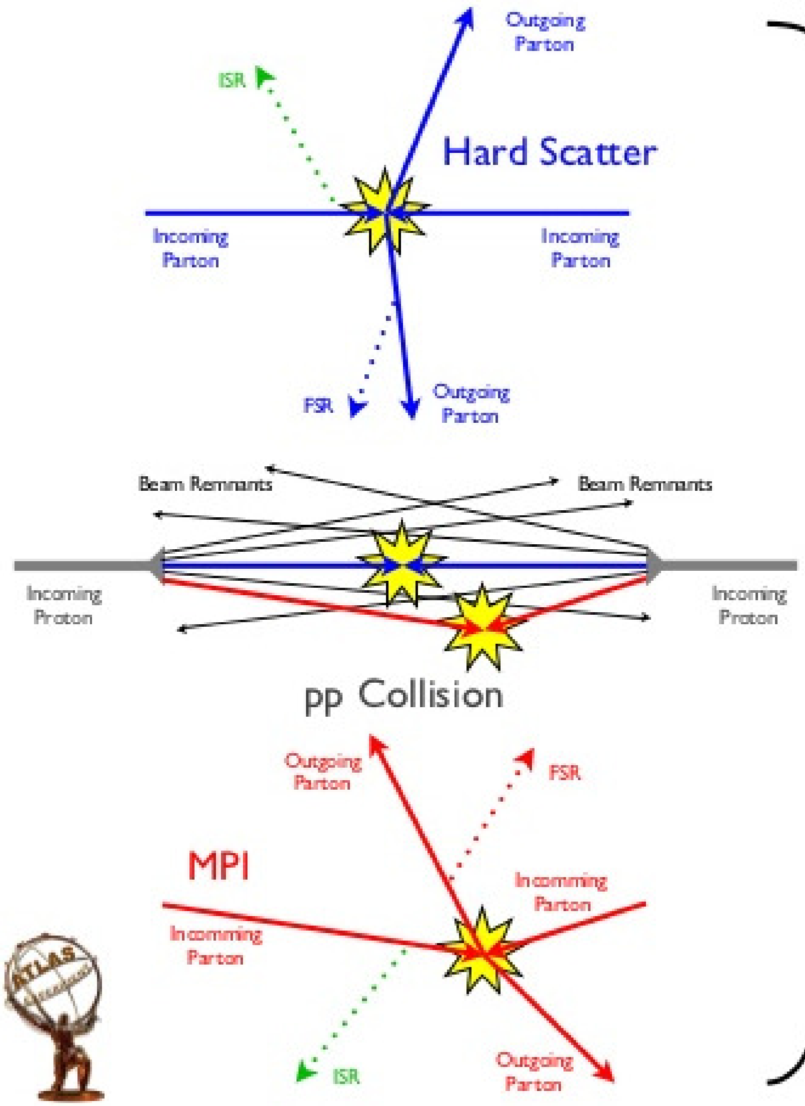
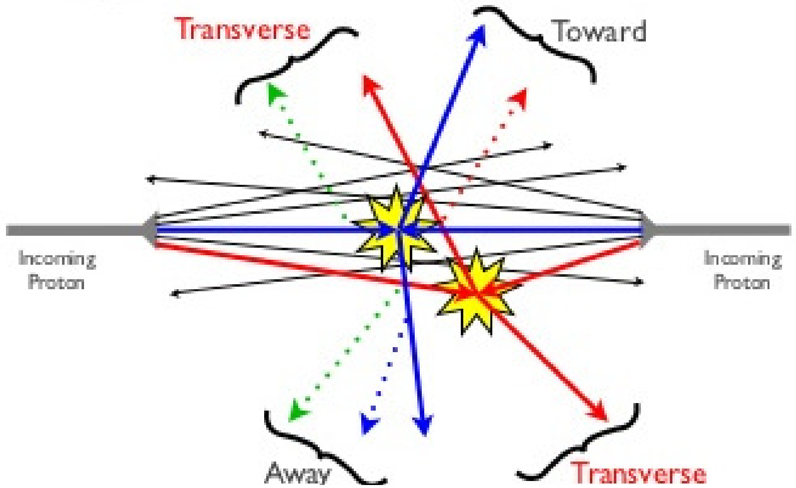
Underlying Event



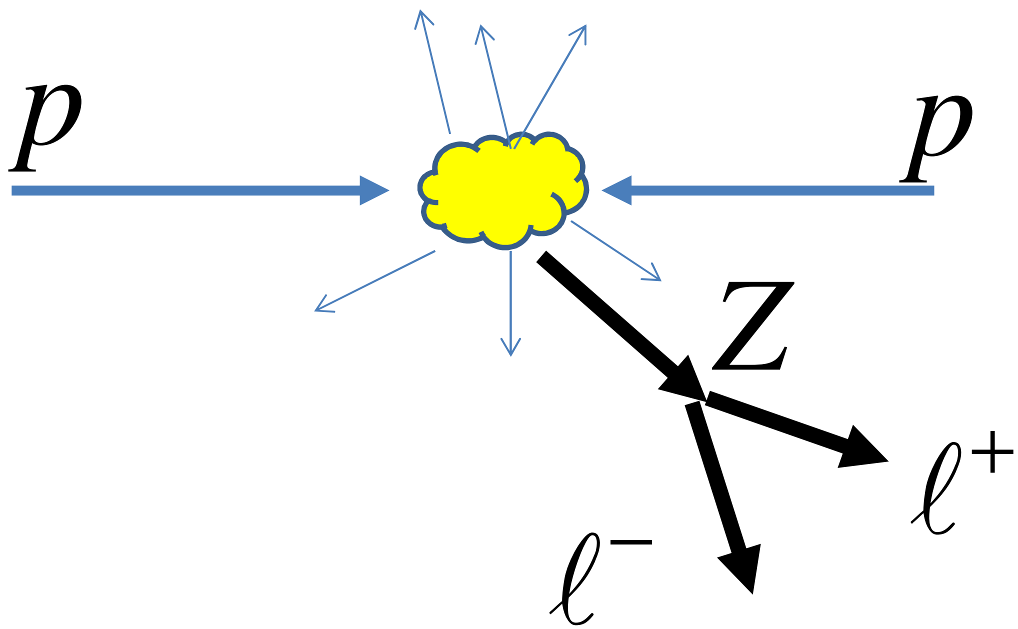


Underling event = everything that does not originate from the hard scatter partons.

Model dependent parts:

- Beam-beam remnants
- Multiple parton interactions
- Initital state radiation
- Final state radiation

Underlying event in Drell-Yan events



No colour charge on Z $\Rightarrow$ event properties with Z-decay products removed sensitive to UE.

Arxiv: 1602.08980 (hep-ex)

UE in Drell-Yan events

- $\sqrt{s} = 7$ TeV (2011)
- Luminosity = 1.1 fb^{-1}

  Mean pp collisions per BC ~ 5
- Dilepton events : e^+e^- , $\mu^+\mu^-$

  : $m_{\ell^+\ell^-} \in [66,116]$ GeV, p$_{T,\ell} > 20$ GeV, $|\eta_\ell| < 2.4$
- Track selection: $p_T > 0.5$ GeV, $|\eta|$<2.5 + quality cuts.

- Pile-up correction
- Correction for multi-jet bg

Event shape observables

Distributions for observable O : $f_O = \frac{1}{N_{ev}} \bullet \frac{dN}{dO}$

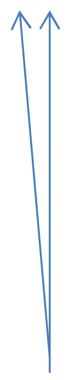
- Charged particle multiplicity N_{ch}
- Scalar sum of charged particles p_T : $\sum p_T$
- Beam thrust : $B = \sum p_T e^{-|\eta|}$
- Transverse thrust : $T = \max_{\vec{n}_T} \frac{\sum |\vec{p}_T \bullet \vec{n}_T|}{\sum p_T}$; $\vec{n}_T =$ thrust axis
- Spherocity : $S = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)^T} \left(\frac{\sum |\vec{p}_T \times \vec{n}|}{\sum p_T} \right)^2$
- F-parameter : $\frac{\lambda_1}{\lambda_2}$ = Ratio of smaller and larger eigenvalues

of $M^{lin} = \sum_i \frac{1}{p_{T,i}} \begin{pmatrix} p_{x,i}^2 & p_{x,i} p_{y,i} \\ p_{x,i} p_{y,i} & p_{x,i}^2 \end{pmatrix}$

Z decay products removed before calculating O

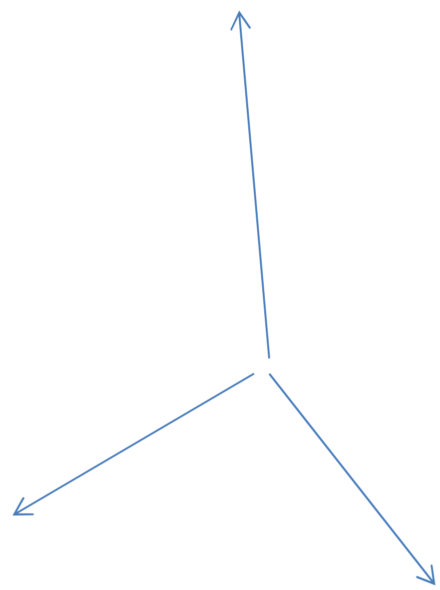
Corrected distributions after Bayesian unfolding.

Event shape observables



"Pencil-like" events

$S \sim 0, T \sim 1, F \sim 0$

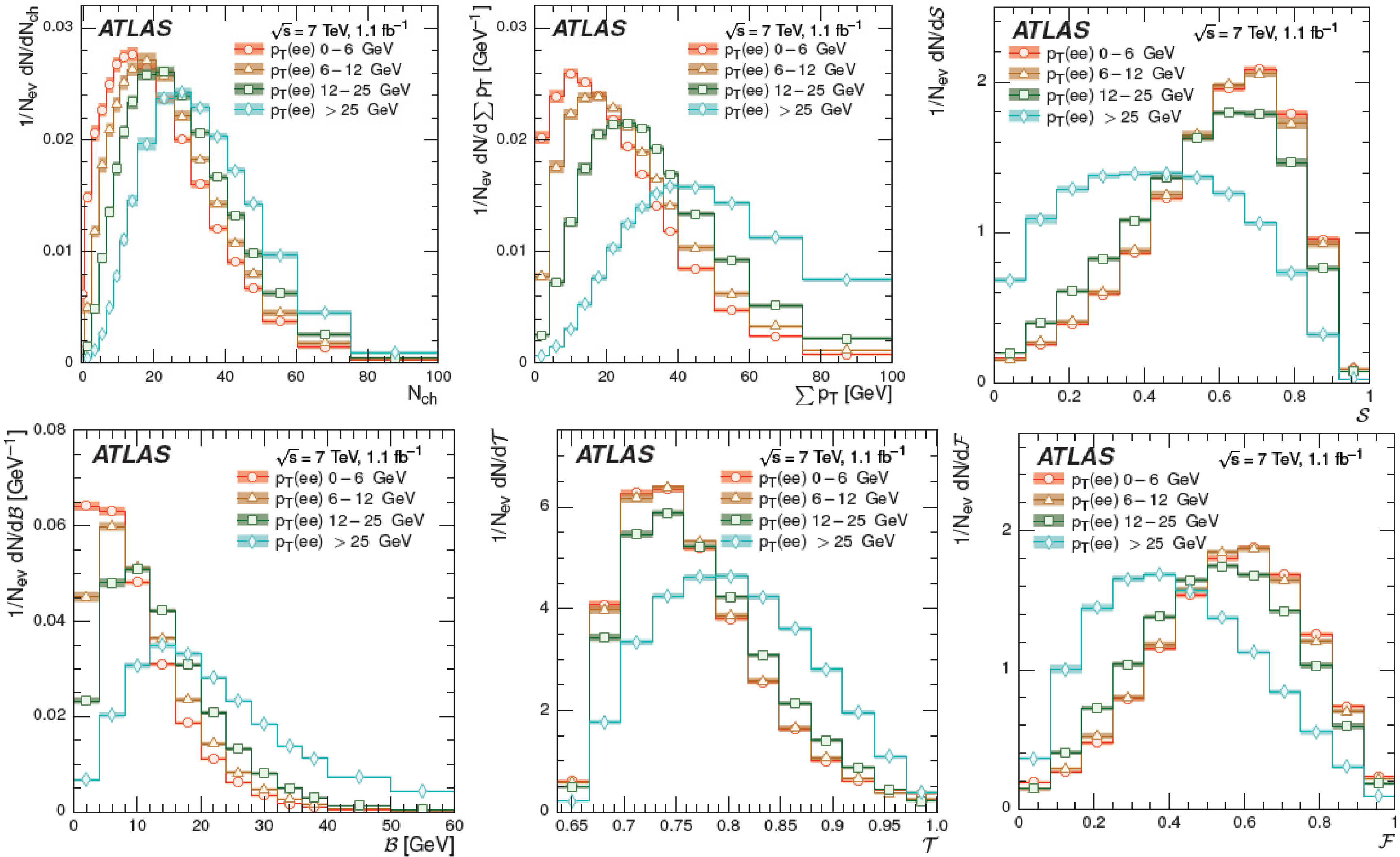


"Spherical" events

$S \sim 1, T \sim \dfrac{2}{\pi}, F \sim 1$

S, T, F correlated amongst themselves but weakly correlated with $N_{ch}, \sum p_T$ and B

Event shape distributions: $Z \to e^{+} + e^{-}$



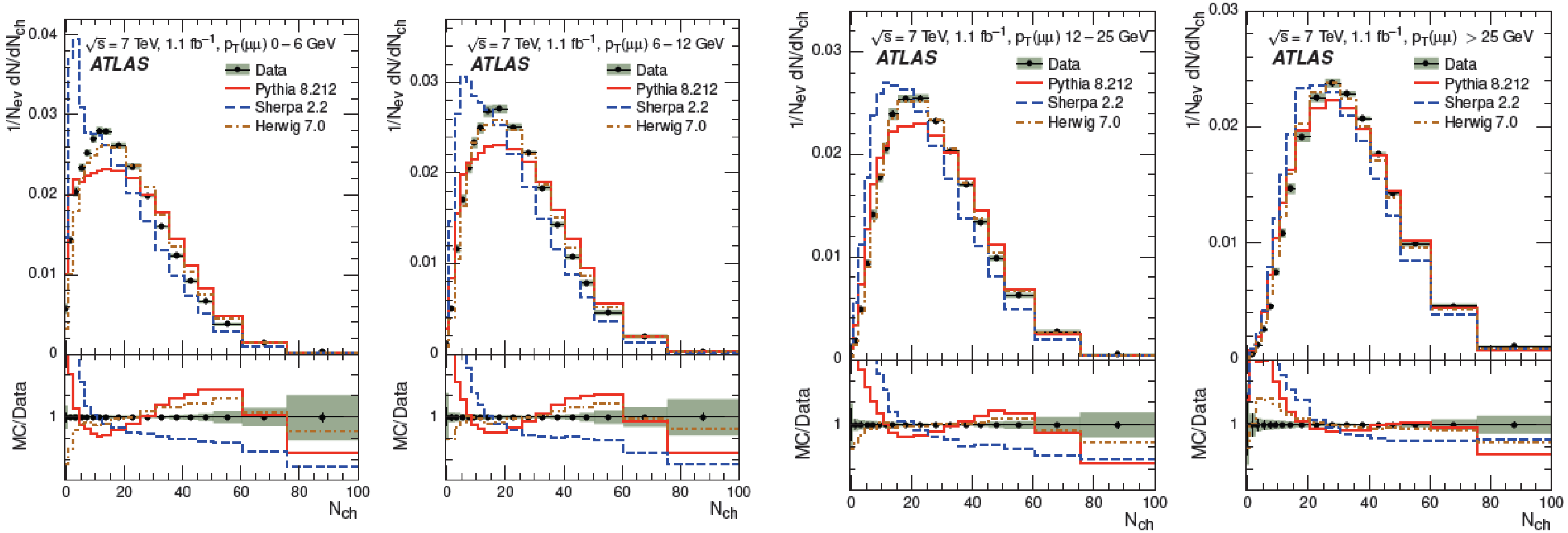
Higher $p_T\left(e^{+}e^{-}\right) \Rightarrow$ recoiling jets emerging

$\Rightarrow$ $N_{ch}, \sum p_T$, B , T increase, S decreases

Monte Carlo models

Generator	Tune/setting	PDF
Pythia 8	Monash	NNPDF2.3LO
Sherpa 2.2.0	Default	NNPDF 3.0 NNLO
Herwig7	Default	MMHT2014

$$\frac{1}{N_{ev}} \bullet \frac{dN}{dN_{ch}} \quad \text{vs} \quad N_{ch} \; ; \quad Z \rightarrow \mu^{+} + \mu^{-}$$



Low jet activity

High jet activity

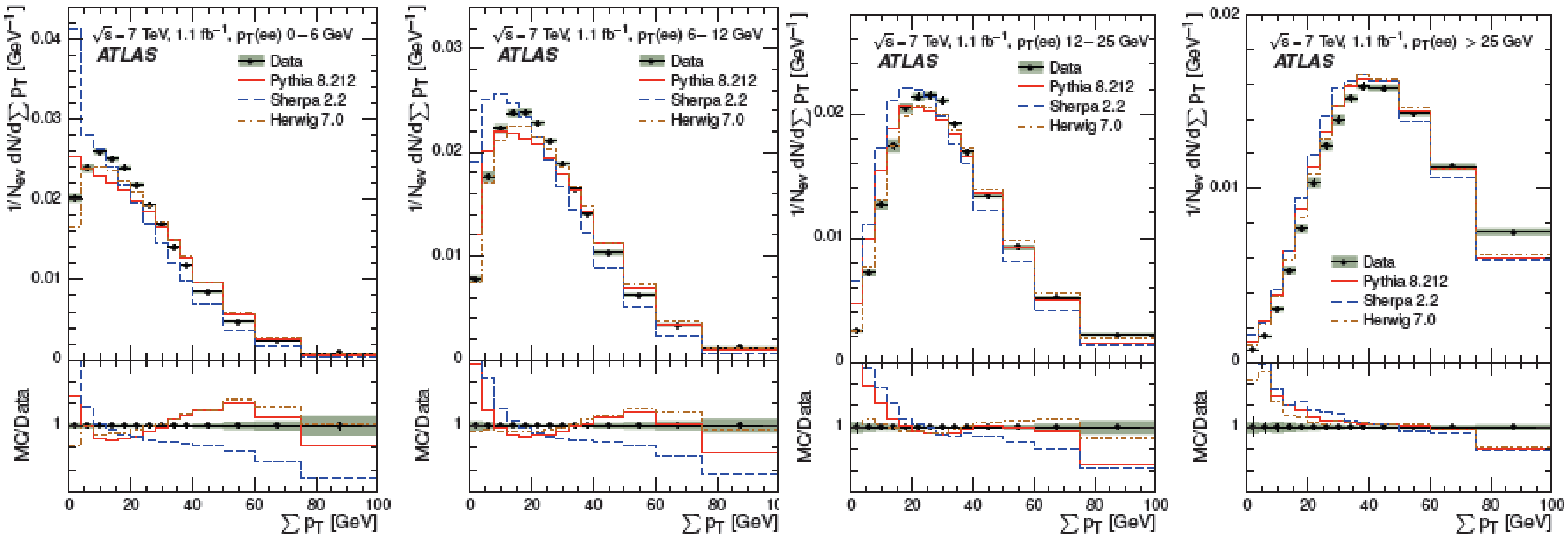
$p_T\left(\mu^{+}\mu^{-}\right)$

Best agreement for Pythia,Herwig and Sherpa as $p_T\left(\mu^{+}\mu^{-}\right)$ and N_{ch} increase.

Difficult to achieve agreement at low N_{ch} - Herwig 7 is closest.

Larger deviations with Sherpa.

$$\frac{1}{N_{ev}} \bullet \frac{dN}{d\sum p_T} \quad \text{vs} \quad \sum p_T \;;\; Z \to e^+ + e^-$$



Low jet activity

High jet activity

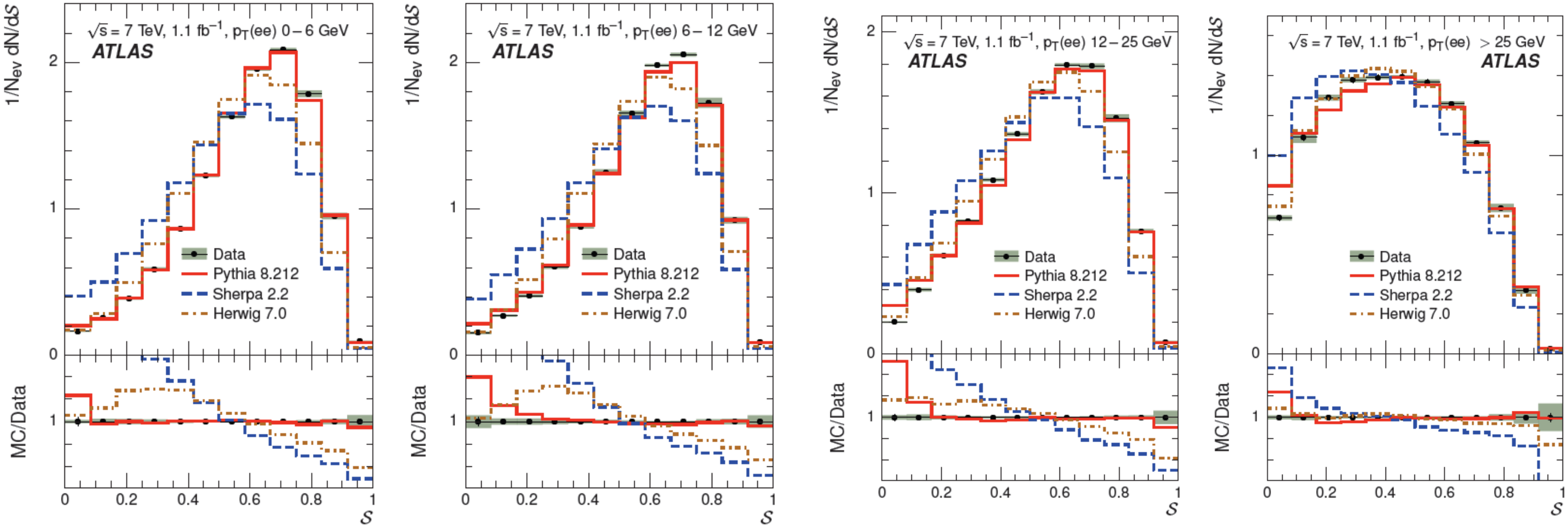
$p_T\left(e^+e^-\right)$

Best agreement for Pythia,Herwig and Sherpa as $p_T\left(e^+e^-\right)$ and $\sum p_T$ increase.

Difficult to achieve agreement at low $\sum p_T$ - Herwig 7 is closest.

Larger deviations with Sherpa.

$$\frac{1}{N_{ev}} \cdot \frac{dN}{dS} \quad \text{vs} \quad S \;;\; Z \to e^{+} + e^{-}$$



Low jet activity → High jet activity

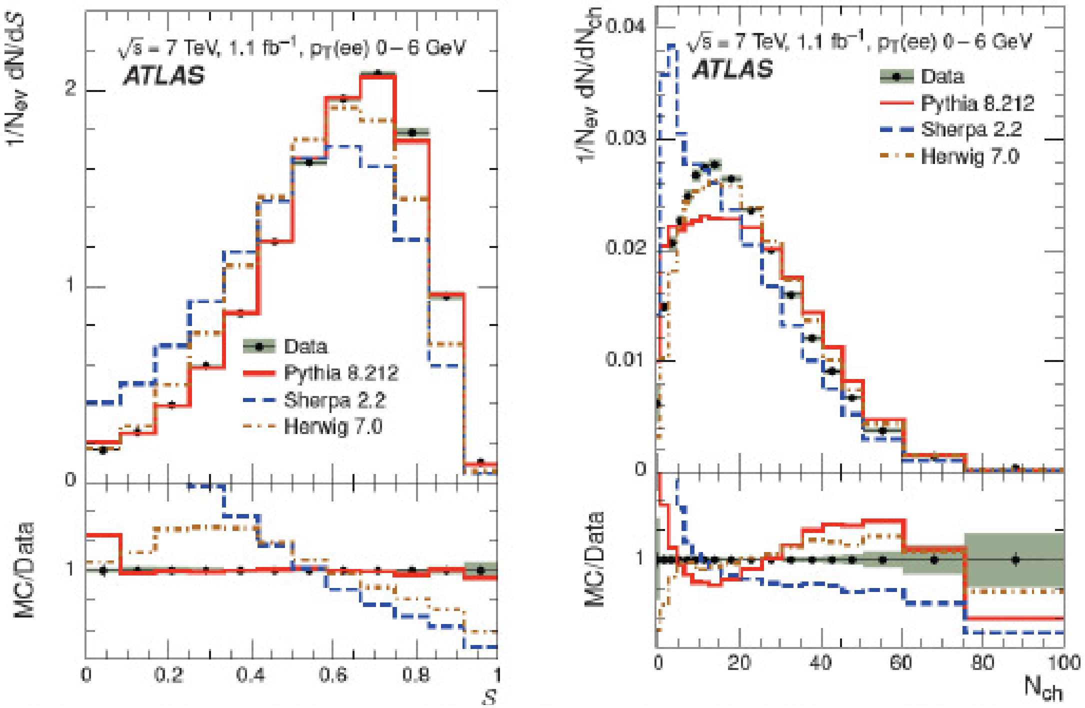
$p_T\left(e^{+}e^{-}\right)$

Best agreement for Pythia,Herwig and Sherpa as $p_T\left(e^{+}e^{-}\right)$ and S increase.

Pythia generally closest to the data.

Larger deviations with Sherpa.

Model performance at low p_T: 0-6 GeV



Less chance of a hard process jet at low p_T $\Rightarrow$ UE sensitivity.

Observables which are not very sensitive to number of tracks (T, S, F):

Best description by Pythia

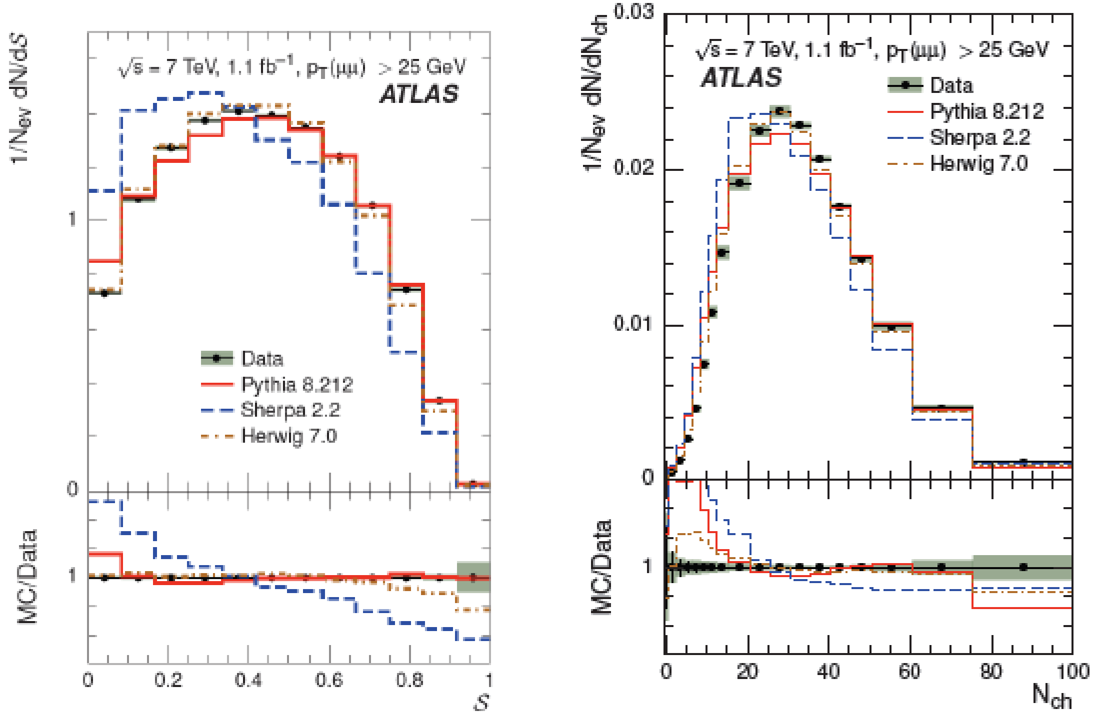
Observables which are very sensitive to number of tracks $(N_{ch}, \sum p_T, B)$:

Best description by Herwig

Largest deviations with Sherpa.

Similar observations for p_T : 6-12 GeV , 12-25 GeV.

Model performance for $p_T > 25$ GeV



p_T >25 GeV $\Rightarrow$ at least one high p_T jet recoiling against the Z.

Better agreement of data-models than for low p_T

Best descriptions by Pythia8 and Herwig7 and largest deviations with Sherpa.

Systematic uncertainties

$6 < p_T\left(\ell^+\ell^-\right) < 12$ GeV

Observable	Channel	δ_O^{stat} [%]	δ_O^{Lepton} [%]	$\delta_O^{\text{Tracking}}$ [%]	$\delta_O^{\text{Non-Prim.}}$ [%]	δ_O^{PU} [%]	$\delta_O^{\text{Multijet}}$ [%]	δ_O^{Unfold} [%]
N_{ch}	(e^+e^-)	1–10	0.1–2.2	0.2–10	0.2–6.6	0.1–24	< 0.1–0.2	< 0.1–10
	$(\mu^+\mu^-)$	0.8–8.4	0.1–1.8	< 0.1–11.4	0.1–4.5	0.6–21	< 0.1–0.4	0.7–7.7
$\sum p_{\text{T}}$	(e^+e^-)	1–2.3	0.1–0.5	0.1–5.3	< 0.1–1.9	0.4–2.9	< 0.1–0.3	< 0.1–1.8
	$(\mu^+\mu^-)$	0.8–1.8	0.1–0.6	< 0.1–4.9	< 0.1–1.4	0.1–3.2	< 0.1–0.3	0.1–1.7
$\mathcal{B}$	(e^+e^-)	0.7–8.8	0.1–1.5	0.2–4.3	0.1–1.5	< 0.1–19	< 0.1–1	< 0.1–2.4
	$(\mu^+\mu^-)$	0.6–6.7	0.1–1	0.3–3.9	< 0.1–1.9	0.1–10	< 0.1–0.6	0.1–2.4
$\mathcal{T}$	(e^+e^-)	0.6–4.7	0.1–0.5	0.2–2.2	0.1–1.5	0.1–2.9	0.1–0.5	0.1–2.5
	$(\mu^+\mu^-)$	0.5–3.7	0.1–1	0.2–2.8	0.1–1	0.1–4.4	< 0.1	0.2–2.7
$\mathcal{S}$	(e^+e^-)	0.6–3.6	0.1–0.3	0.2–2.4	0.1–1.6	0.1–5.0	0.1–0.4	0.2–3.4
	$(\mu^+\mu^-)$	0.5–2.9	0.2–0.7	0.2–2.2	0.1–1.1	0.1–4.4	< 0.1	0.1–3.1
$\mathcal{F}$	(e^+e^-)	0.6–3.8	0.1–0.4	0.1–2.0	0.1–0.9	0.1–7.4	0.1–0.4	0.2–2.7
	$(\mu^+\mu^-)$	0.5–3.0	0.1–0.6	0.1–2.4	0.1–1.3	0.1–1.6	< 0.1	0.1–3.2

Uncertainties from tracking efficiency, lepton reconstruction/ID, non-primary bg, pile-up correction, multijet bg, and unfolding.

Total systematic uncertainties: ~$5\text{-}10\%$ $\left(N_{ch}, \sum p_T, B\right)$

: ~2-5% $(S,\ F,\ T)$

Leading track UE studies at 13 TeV

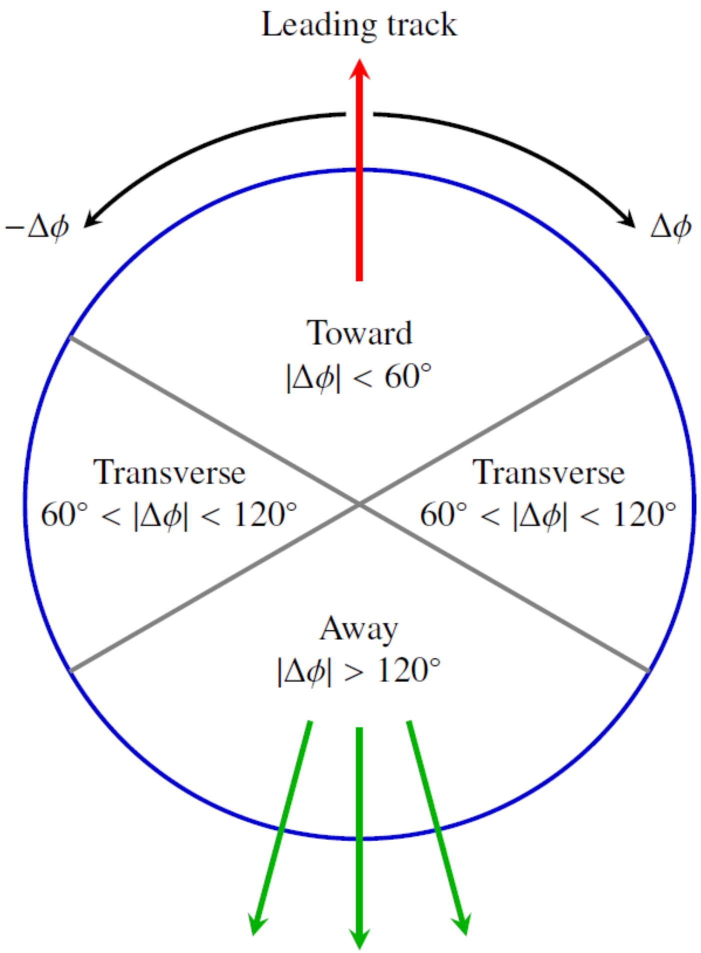
- ATL-PHYS-PUB-2015-019
- 13 TeV
- Luminosity = 170 μb^{-1}
- At least one minimum bias counter above threshold
- Leading track $p_T > 1$ GeV
- Primary vertex
- No extra vertex with >3 tracks.

Non-colliding beam bg < 0.01%

Tracks from additional interactions < 0.01%

Track selection: $p_T > 0.5$ GeV, $|\eta|$<2.5 + quality cuts.

Kinematic regions and observables



Detector level observables

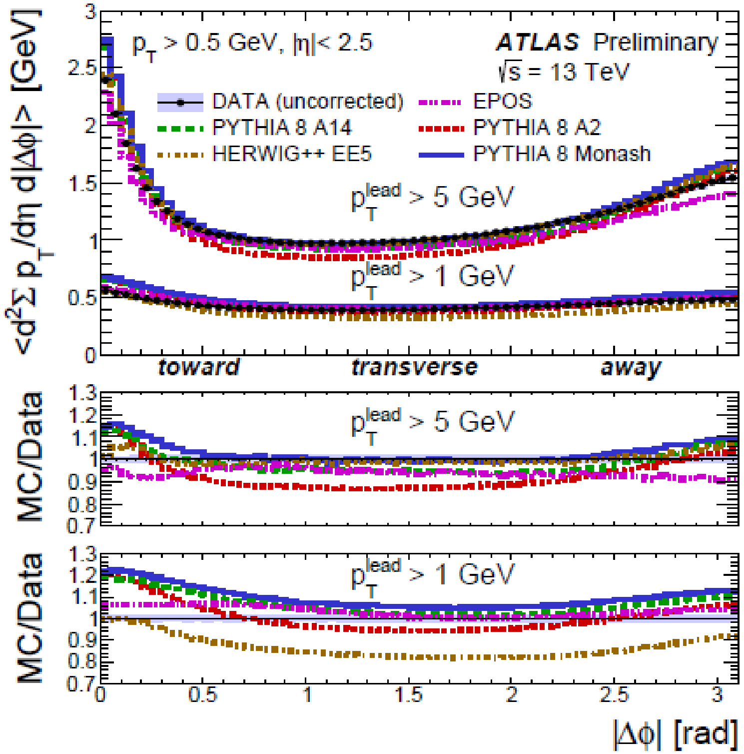
Observable	Definition
$\langle d^2N_{ch}/d\eta\, d\phi\rangle$	Number of tracks per unit η–ϕ
$\langle d^2\sum p_T/d\eta\, d\phi\rangle$	Scalar sum of track p_T per unit η–ϕ

Monte Carlo models

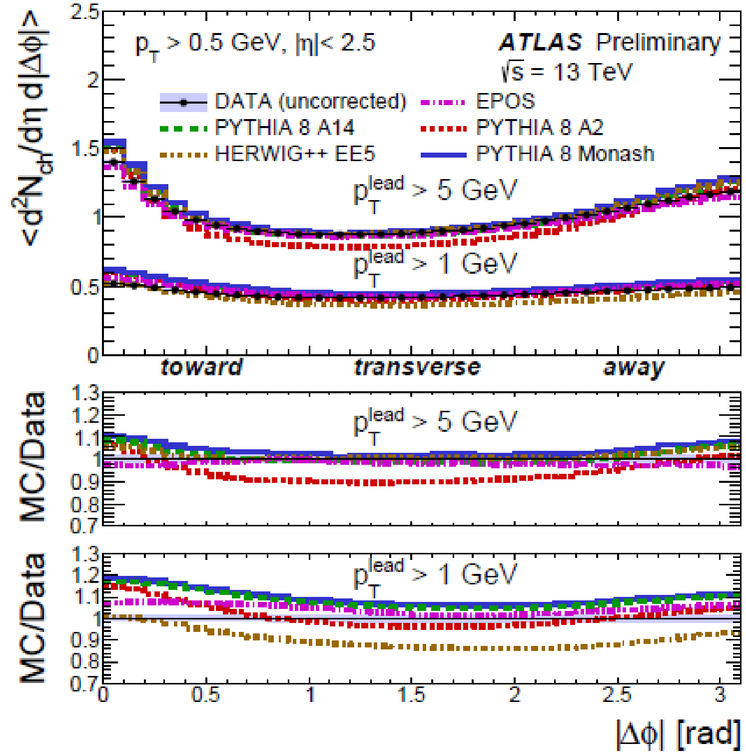
Generator	Tune	PDF	Focus
Pythia 8	A2	MSTW2008LO	MB
Pythia 8	Monash	NNPDF2.3LO	MB/UE
Pythia 8	A14	NNPD2.3LO	UE/Shower
Herwig++ 2.7.1	UEEE5	CTEQ6L1	UE
EPOS	LHC		MB

Tunes use data from different experimental processes

$$\left\langle \frac{d^2 \sum p_T}{d\eta d|\Delta\phi|} \right\rangle \text{ vs } |\Delta\phi|$$



$$\left\langle \frac{d^2 N_{ch}}{d\eta d|\Delta\phi|} \right\rangle \text{ vs } |\Delta\phi|$$

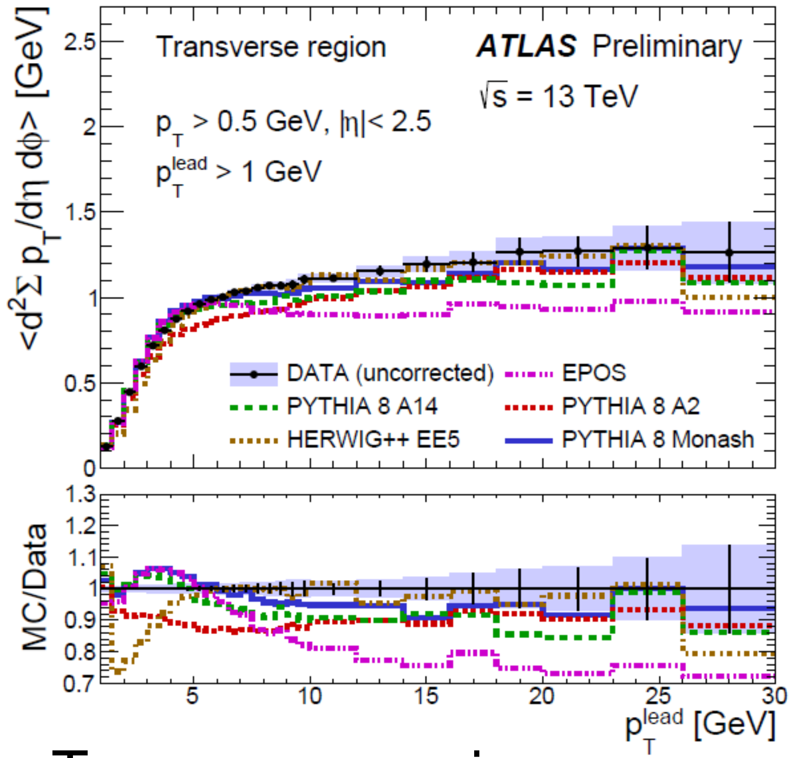


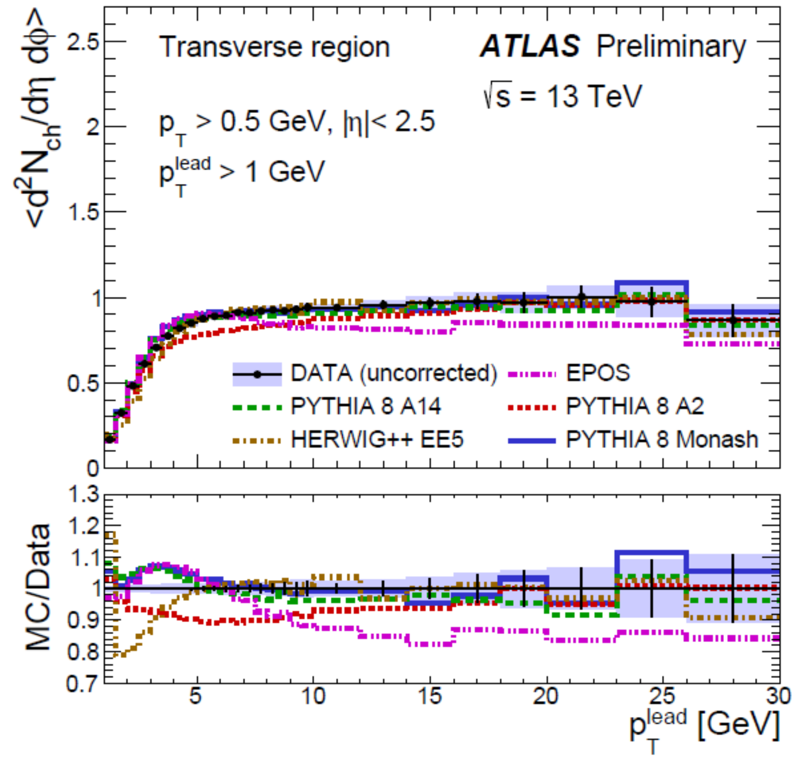
Expect a gradual transition from MB to hard scattering events.

MB tunes better at low p_T^{lead} ;UE tunes do better at high p_T^{lead}

Herwig++ not expected to give a good description for MB at low p_T^{lead}

$$\left\langle \frac{d^2 \sum p_T}{d\eta d\left|\Delta\phi\right|} \right\rangle \text{ vs } p_T^{lead} \qquad \left\langle \frac{d^2 N_{ch}}{d\eta d\left|\Delta\phi\right|} \right\rangle \text{ vs } p_T^{lead}$$





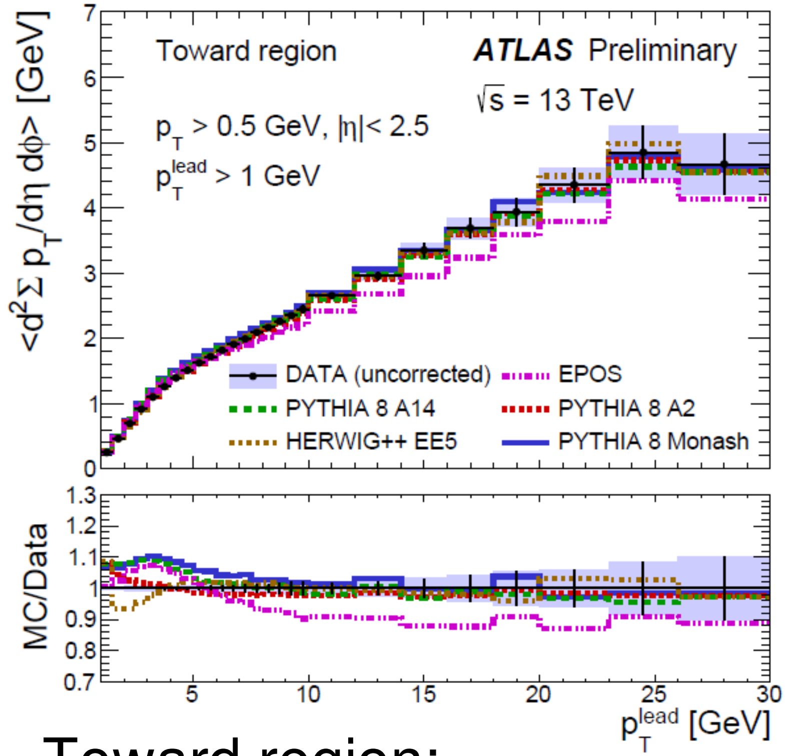
Transverse region

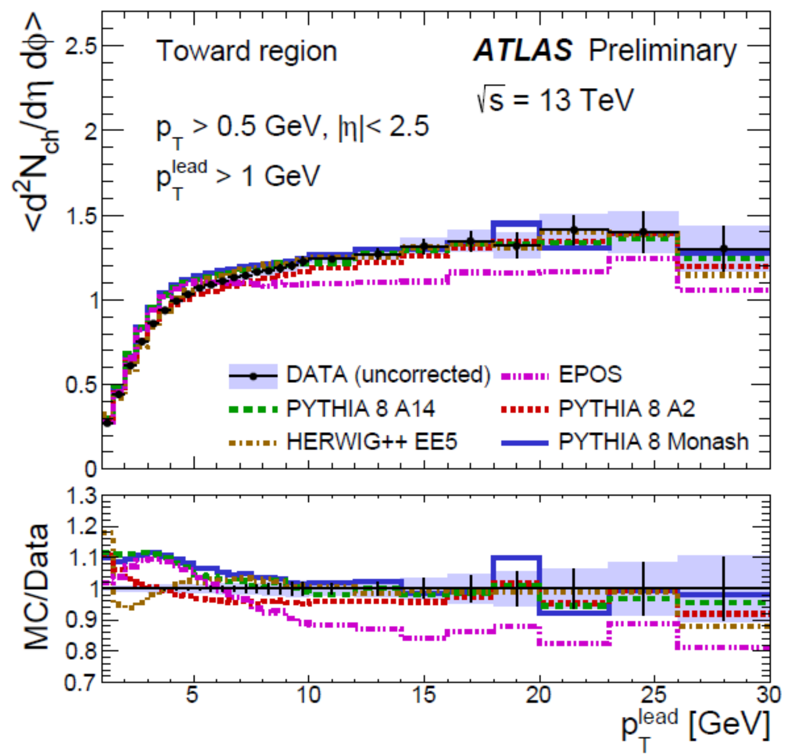
Plateau for $p_T^{lead} > 6$ GeV

Pythia 8 and Herwig++ tunes closest to the data.

No model describes well the inititial rise.

$$\left\langle \frac{d^2 \sum p_T}{d\eta d|\Delta\phi|} \right\rangle \text{ vs } p_T^{lead} \qquad \left\langle \frac{d^2 N_{ch}}{d\eta d|\Delta\phi|} \right\rangle \text{ vs } p_T^{lead}$$





Toward region:

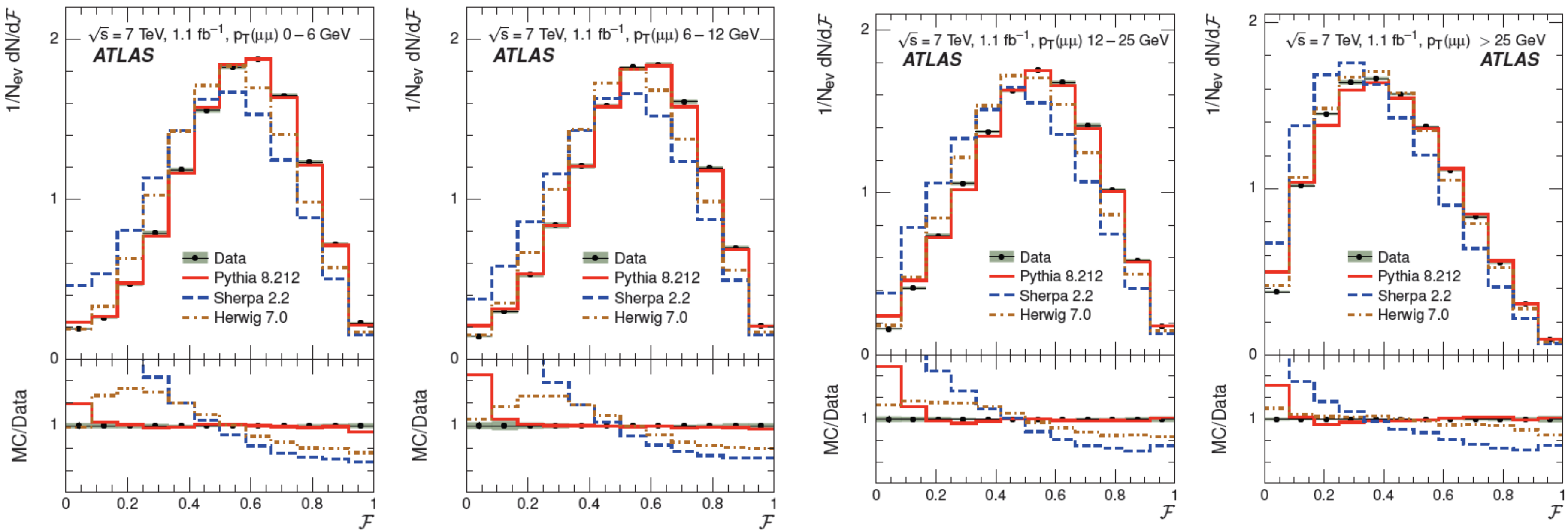
Increasing $\left\langle \frac{d^2 \sum p_T}{d\eta d|\Delta\phi|} \right\rangle$ for higher $p_T^{lead} \Rightarrow$ jet activity

Pythia 8 and Herwig++ tunes closest to the data.

Summary

- Measurements sensitive to the underlying event measured by ATLAS
- Event shapes in Drell-Yan events (7 TeV)
- Final state distributions in minimum bias data (13 TeV)
- Large discriminatory power between phenomenological models of the UE.

$$\frac{1}{N_{ev}} \bullet \frac{dN}{dF} \quad \text{vs} \quad dF \quad ; \quad Z \to \mu^{+} + \mu^{-}$$



Low jet activity

High jet activity

$$p_T\left(\mu^{+}\mu^{-}\right)$$