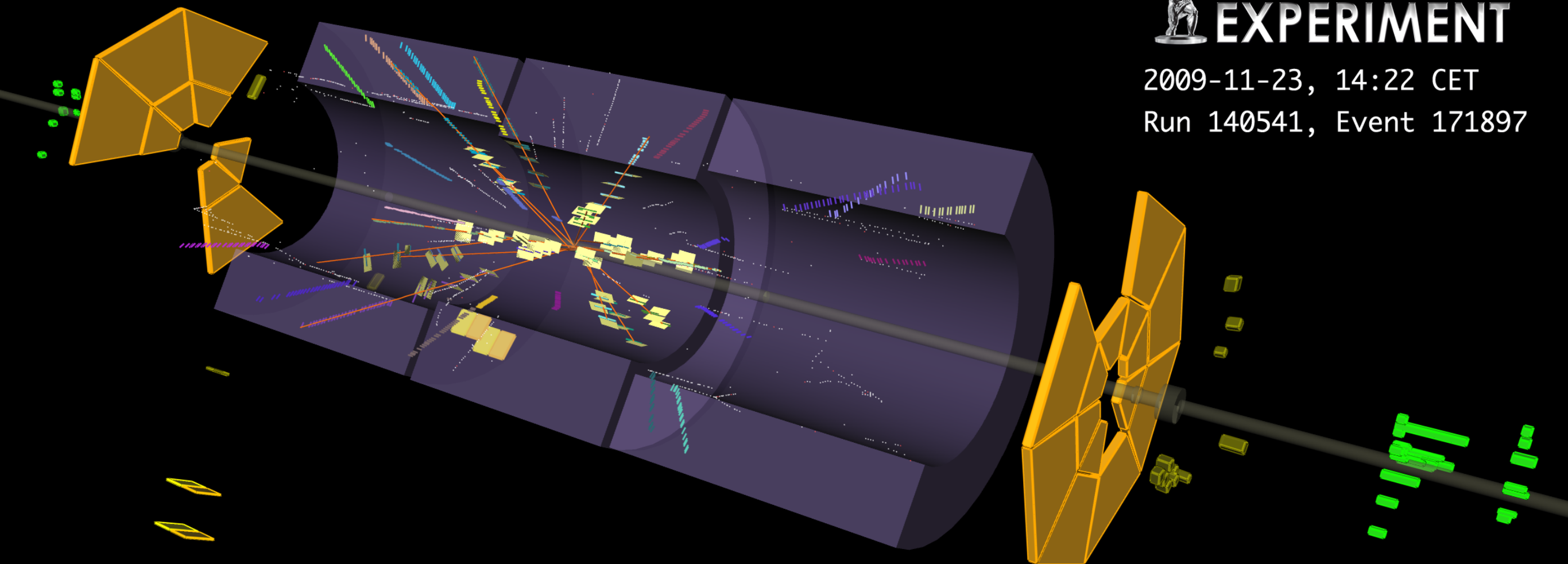




**ATLAS**  
EXPERIMENT

2009-11-23, 14:22 CET

Run 140541, Event 171897



Minimum bias and underlying event  
measurements with the ATLAS detector



# Soft QCD - why bother ?

- Phenomenological models of sQCD need experimental constraint
  - perturbation theory not applicable
  - needs well described sQCD for understanding pile-up and underlying event activity in **all** LHC measurements (nowadays  $\mu^{\text{peak}} > 40$  )
  - measurement done as (mainly) differential distributions

$$\frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ch}}}{d\eta}, \quad \frac{1}{N_{\text{ev}}} \cdot \frac{1}{2\pi p_{\text{T}}} \cdot \frac{d^2 N_{\text{ch}}}{d\eta dp_{\text{T}}}, \quad \frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ev}}}{dn_{\text{ch}}} \quad \text{and} \quad \langle p_{\text{T}} \rangle \text{ vs. } n_{\text{ch}}$$

- Long standing history & improvements in ATLAS

analysis differences	0.9 TeV	7 TeV	8 TeV	13 TeV	benefits @ 8+13 TeV
remove strange baryons			yes	yes	reduces model dependence
high- $n_{\text{ch}}$ phase spaces			yes		paper scope + MC tuning
final Run-I geometry			yes	yes (+IBL)	reduces material uncertainty
baseline MC tune for analysis	Pythia 6	Pythia 6	Pythia 8 A2	Pythia 8 A2	reduces systematics (e.g. $p_{\text{T}}$ -spectrum)
Geant4 physics list	QGSP_BERT	QGSP_BERT	FTFP_BERT	FTFP_BERT	improves simulation of antiprotons
low $p_{\text{T}}$ ( 100 MeV )	yes	yes	yes	yes	reduced systematics

# Charged particle distribution measurement

- ▶ Track counting measurement with correction to particle level

- attempt to minimally bias your trigger selection
- understanding the detector effects is biggest experimental challenge

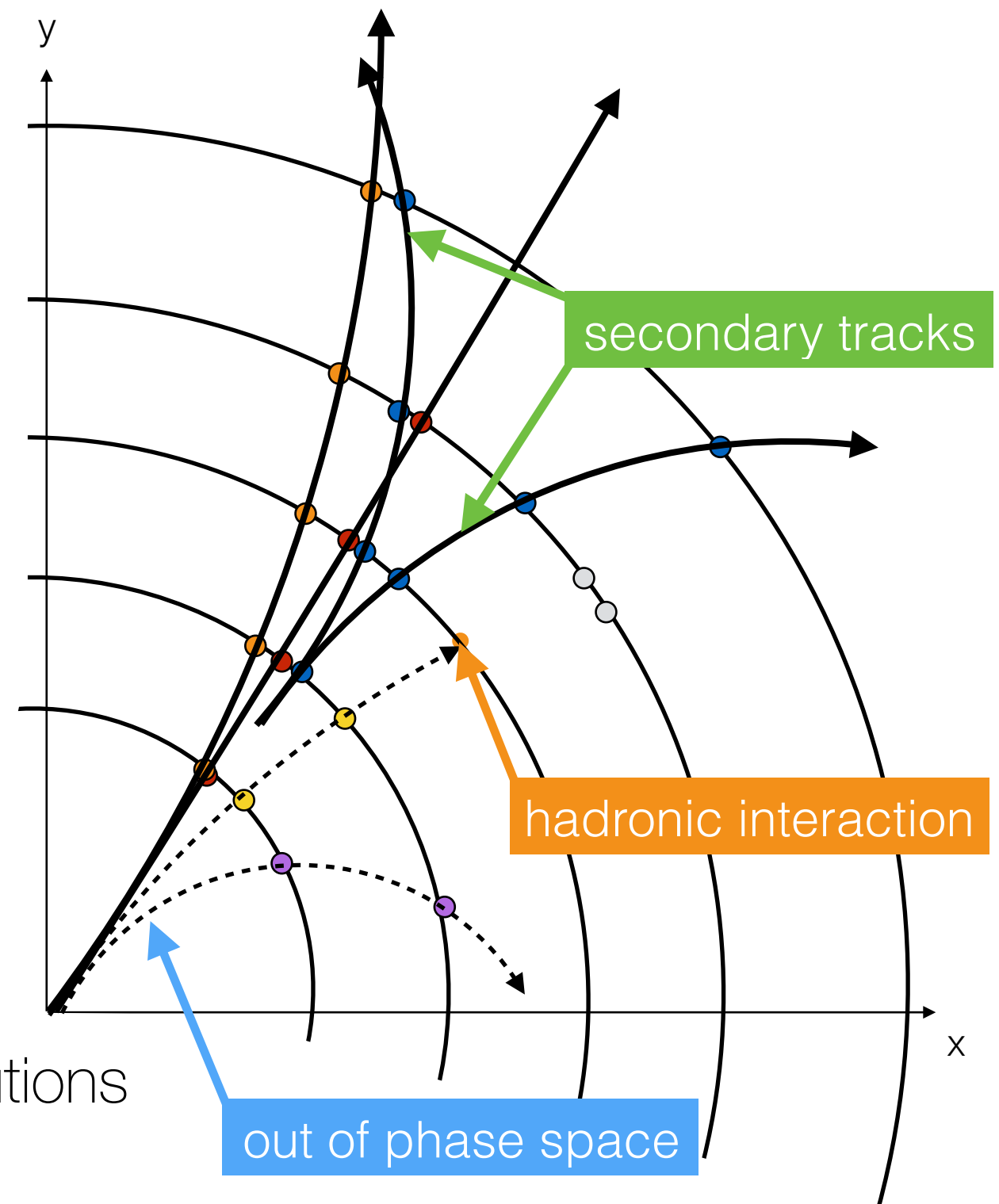
*track reconstruction efficiency/systematics needs to be well understood (dominant)*

*additionally corrections to trigger efficiency, vertex efficiency and phase space needed*

- ▶ Typically first measurements at “new” collision energy

- need dedicated run with minimal pile-up
- very beneficial for detector understanding

- ▶ Access to global event shape distributions





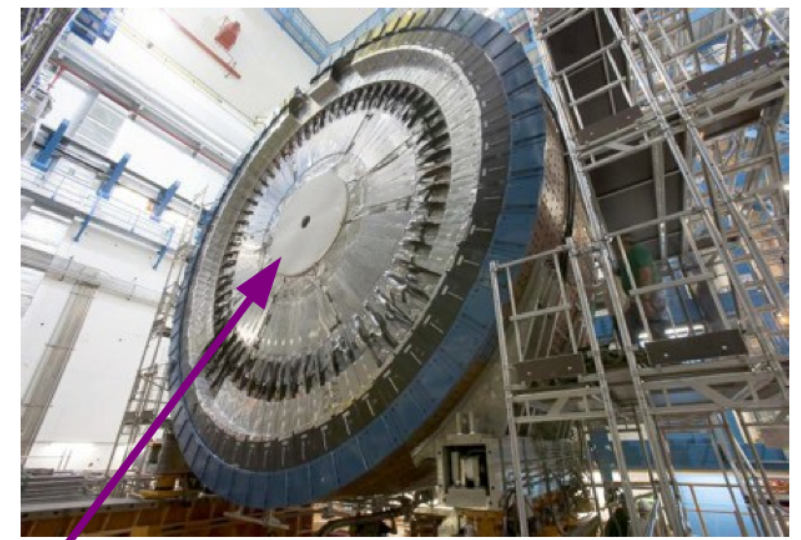
# Analysis procedure | Selection

## ► Event selection

- MBTS trigger selection
- $\mu < 0.01$  to suppress pile-up track counting
- require reconstructed vertex with minimum 2 tracks  
(veto event with additional vertex with  $> 4$  tracks)
- require a minimum number of selected tracks ( $n_{\text{sel}}$ )

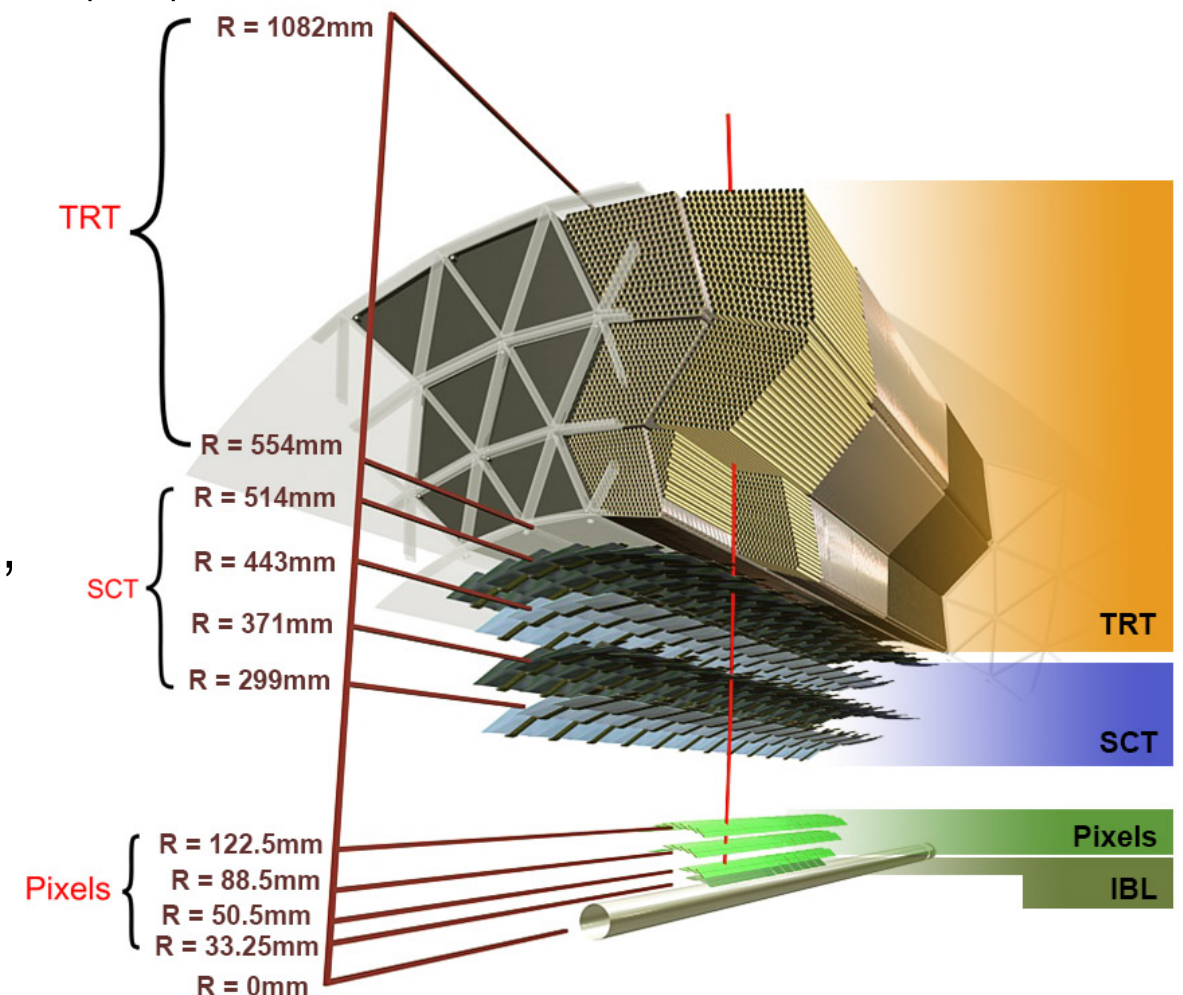
## ► Track selection

- $|d_0^{\text{PV}}| < 1.5 \text{ mm}$   $|z_0^{\text{PV}} \sin(\theta)| < 1.5 \text{ mm}$
- fit  $\chi^2$  probability  $> 0.01$  for  $p_T > 10 \text{ GeV}$
- innermost pixel hit if module active/crossed, minimum 1 hit in the pixel detector
- minimum 2/4/6 hits in the strip detector for  $p_T > 0.1/0.2/0.3 \text{ GeV}$



MBTS = Minimum Bias Trigger Scintillators  
( $2.08 < |\eta| < 3.75$ )

**32** scintillation counters





# Analysis procedure | Correction

## ► Event weights

$$w_{\text{ev}}(n_{\text{sel}}^{\text{BS}}) = \frac{1}{\epsilon_{\text{trig}}(n_{\text{sel}}^{\text{BS}})} \cdot \frac{1}{\epsilon_{\text{vtx}}(n_{\text{sel}}^{\text{BS}}, x)} \cdot w_{\text{z vtx}}$$

A **trigger efficiency**  
(=1 for MC)

B **vertex efficiency**

C **vertex z position (MC)**  
(=1 for data)

## ► Track weights

$$w_{\text{trk}}(p_{\text{T}}, \eta) = \frac{1}{\epsilon_{\text{trk}}(p_{\text{T}}, \eta)} \cdot (1 - f_{\text{nonp}}(p_{\text{T}}, \eta) - f_{\text{SB}}(p_{\text{T}}, \eta) - f_{\text{okr}}(p_{\text{T}}, \eta))$$

1 **track reconstruction efficiency**

2 **non-primary fraction**

3 **strange baryon fraction**

4 **out of phase space**  
(resolution effects)

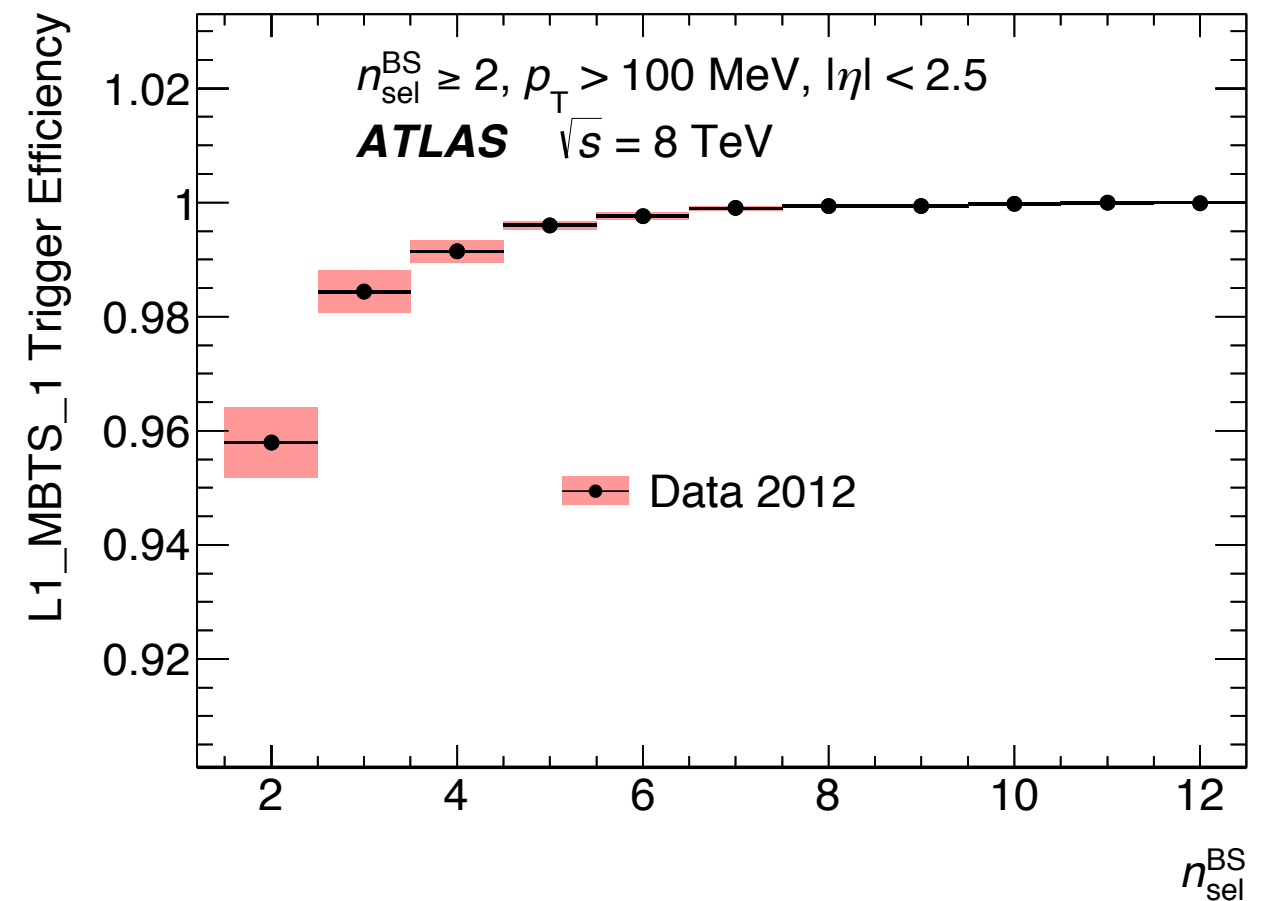
# Analysis procedure | Details

Step	Details	Impact
record <i>pp</i> -collision data sample	require low $\langle\mu\rangle$ to minimise pile-up contamination	~10m “good” events
select “good” events and tracks	require MBTS trigger, reconstructed vertex, no pile-up, track quality	systematics
	check for Event backgrounds	(negligible)
	check for remaining pile-up events	(negligible)
	check for split vertices	(negligible)
	check detector performance (e.g. hits on track, IP distributions)	(see control plots)
correct for detector inefficiencies	apply trigger and vertex efficiency (from Data)	systematics
	apply tracking efficiency (from MC simulation)	systematics
correct for non-primary tracks	subtract secondary particles (from MC template fits)	systematics
	subtract strange baryons (from MC, using Epos tune)	systematics
	check for combinatorial fakes (from MC simulation)	(negligible)
unfold distributions	apply Bayesian unfolding (for resolution + migration effects)	systematics
compare with MC predictions	PYTHIA 8 A2, PYTHIA 8 Monash, EPOS LHC, QGSJET-II	(see final results)
	show central charged particle density vs $\sqrt{s}$	(see final results)

# Event weights

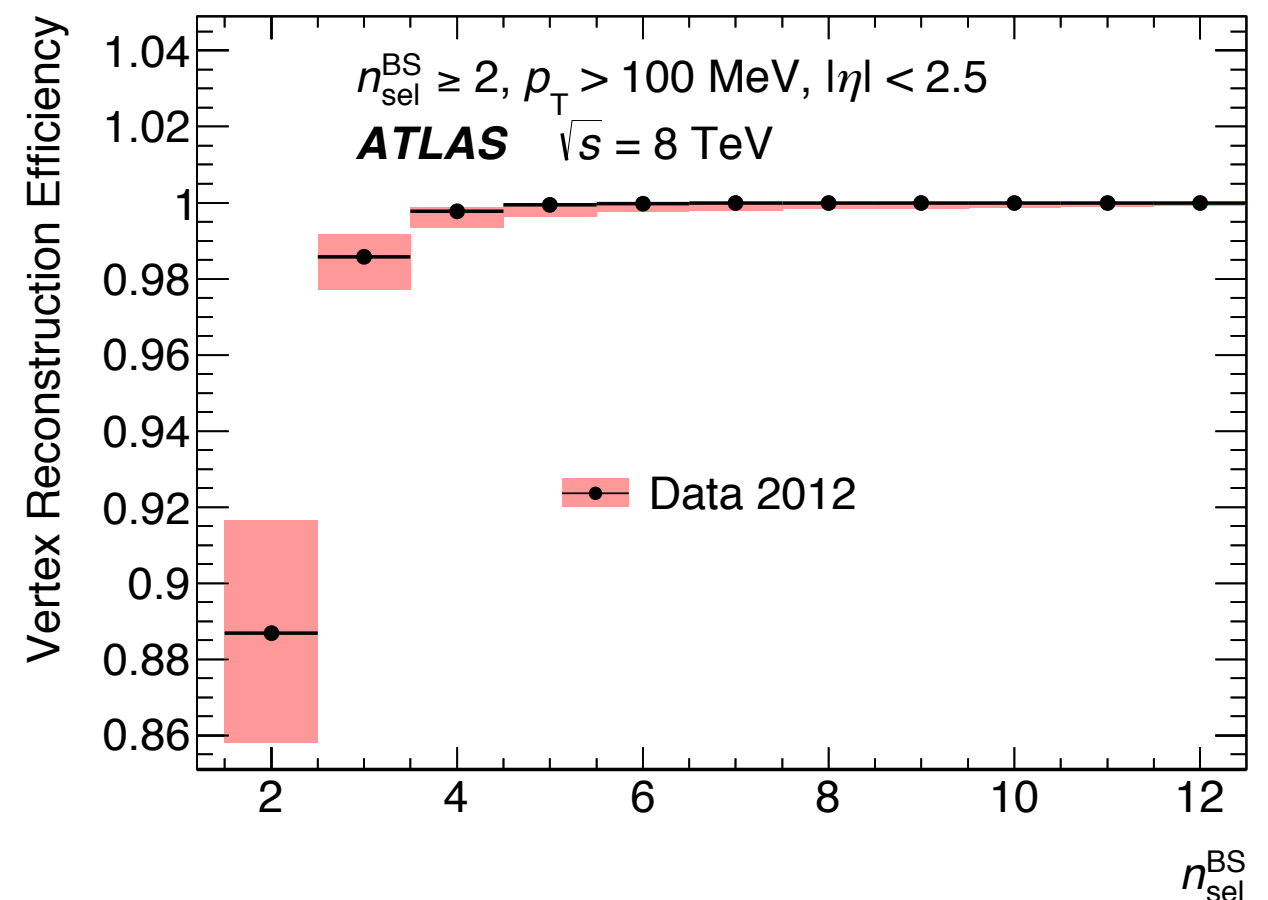
## trigger efficiency A

- measured from data using a random space point trigger
- parameterised as  $n_{\text{sel}}^{\text{BS}}$   
analysis track selection w/o PV  
(uses beam spot instead)



## vertex reconstruction efficiency B

- probability to find a vertex on a triggered event  
measured from data
- parameterised as  $n_{\text{sel}}^{\text{BS}}$   
 $n_{\text{sel}}^{\text{BS}} \geq 2$  for  $p_T > 0.1 \text{ GeV}$  analysis  
 $n_{\text{sel}}^{\text{BS}} \geq 1$  for  $p_T > 0.5 \text{ GeV}$  analysis





# Track weights

## track reconstruction efficiency

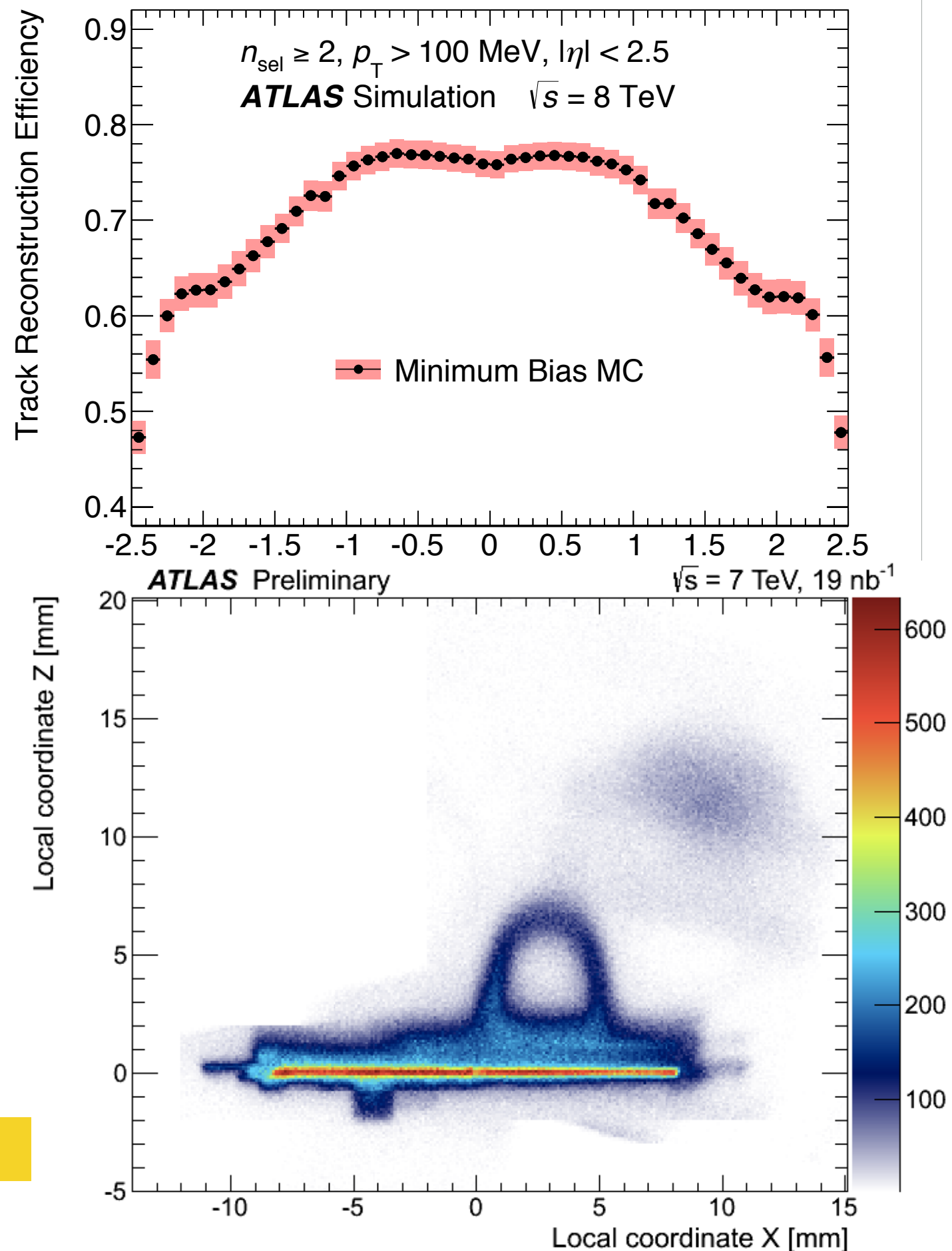
A

- estimated from MC simulation, binned in 2D ( $\eta$ ,  $p_T$ )  
relies on correct modelling of the tracker material
- dominant systematic uncertainty for these analyses  
assumes material modelling of the inner tracker to 5 % accuracy
- supported by many studies of the tracker material budget  
hadron interaction rates (vertexing)  
photon conversion  
track length requirements
- in general excellent modelling of the data by full simulation

JINST 7 (2012) P01013

ATL-PHYS-PUB-2015-050

IDTR-2016-001



# Track weights

## track reconstruction efficiency

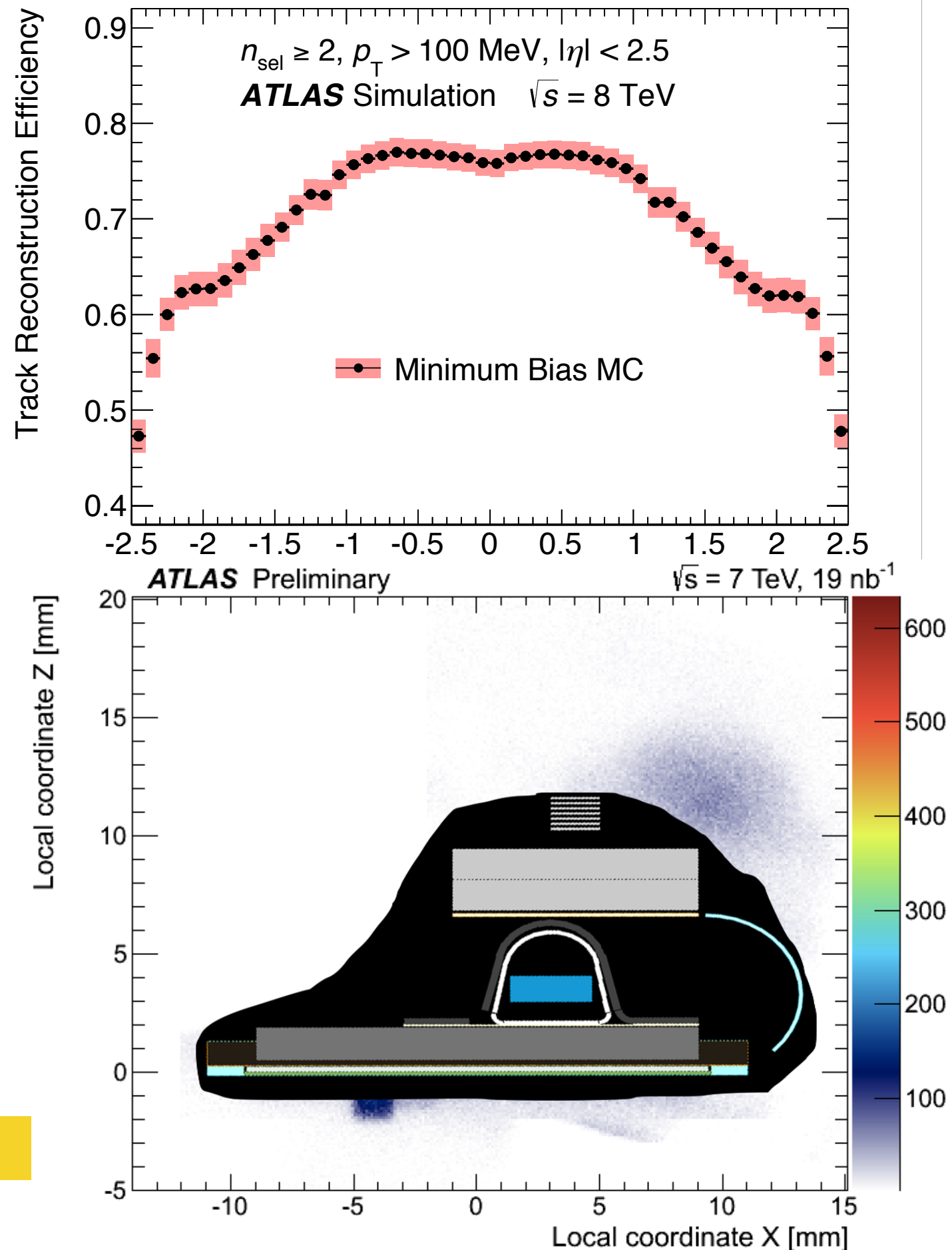
A

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- dominant systematic uncertainty for these analyses  
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JINST 7 (2012) P01013

ATL-PHYS-PUB-2015-050

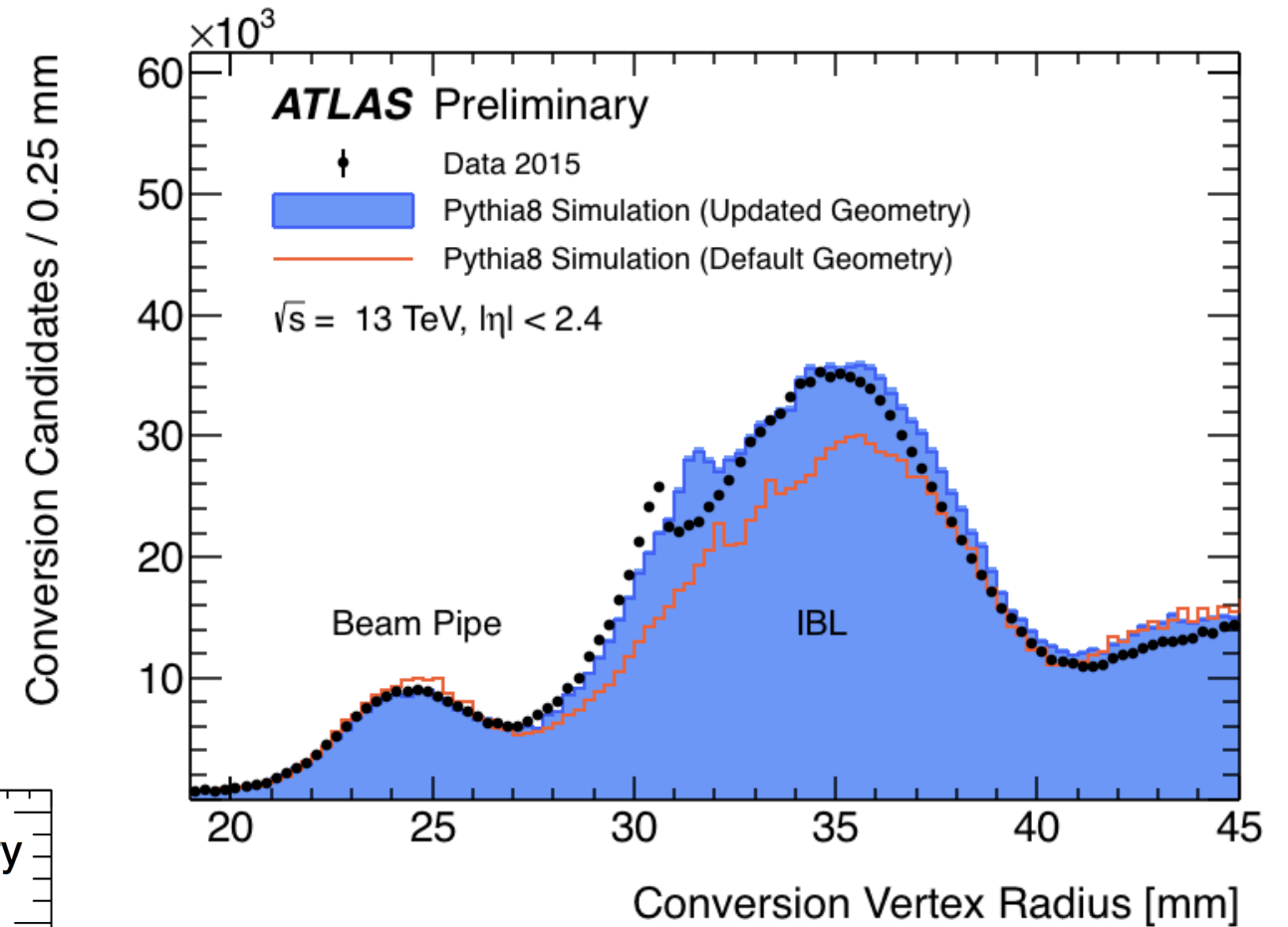
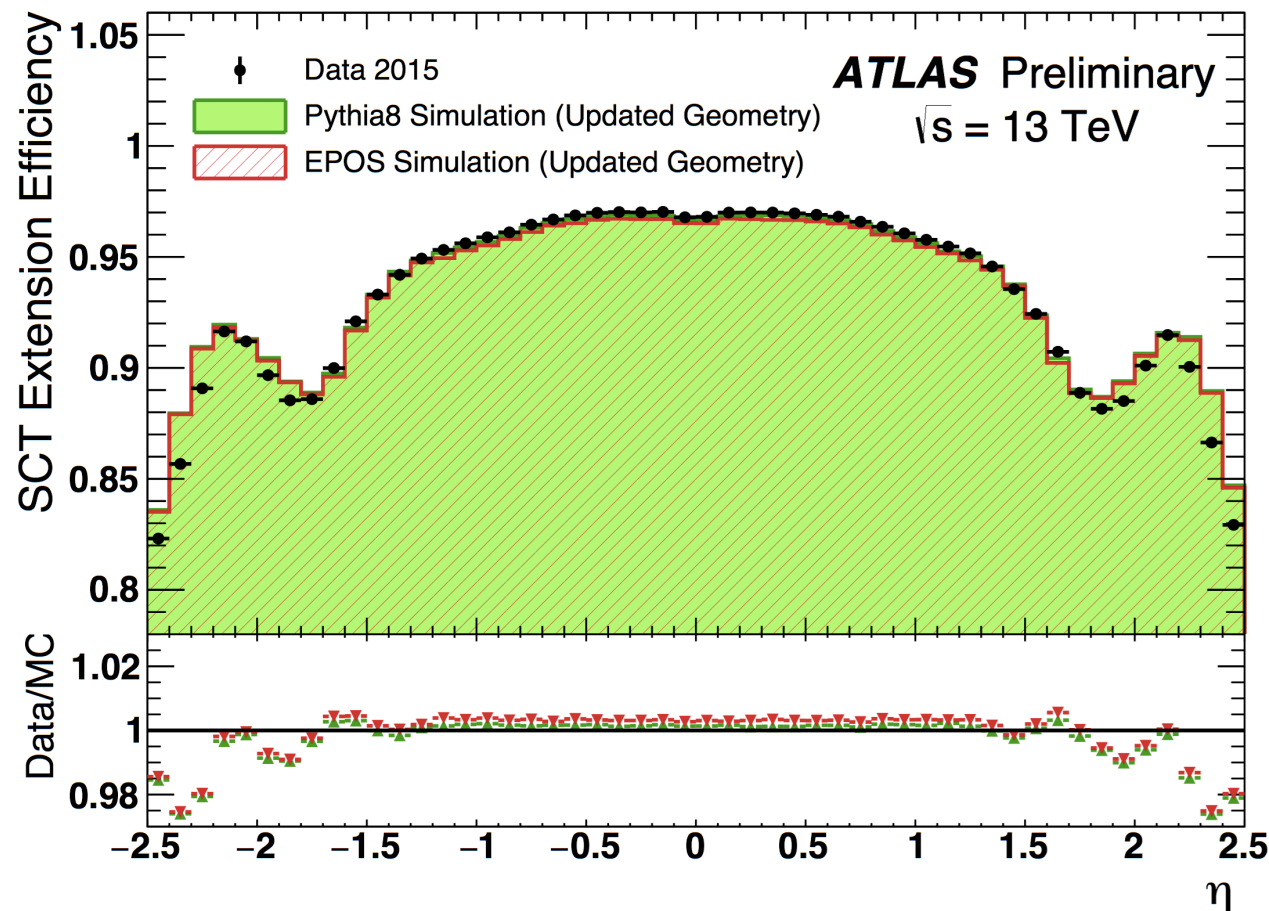
IDTR-2016-001



# Track weights | Material studies

- For Run-2 the Inner Detector geometry had to be mapped out again

- insertion of the IBL
- replacement of the inner patch panels

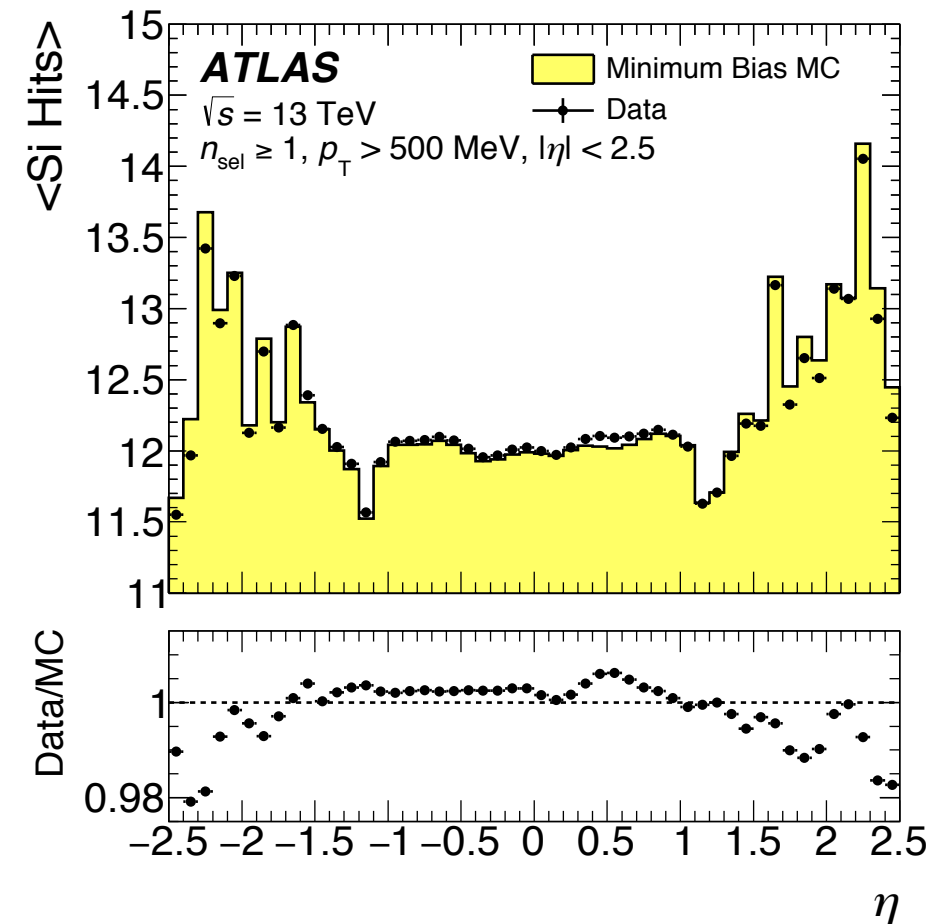
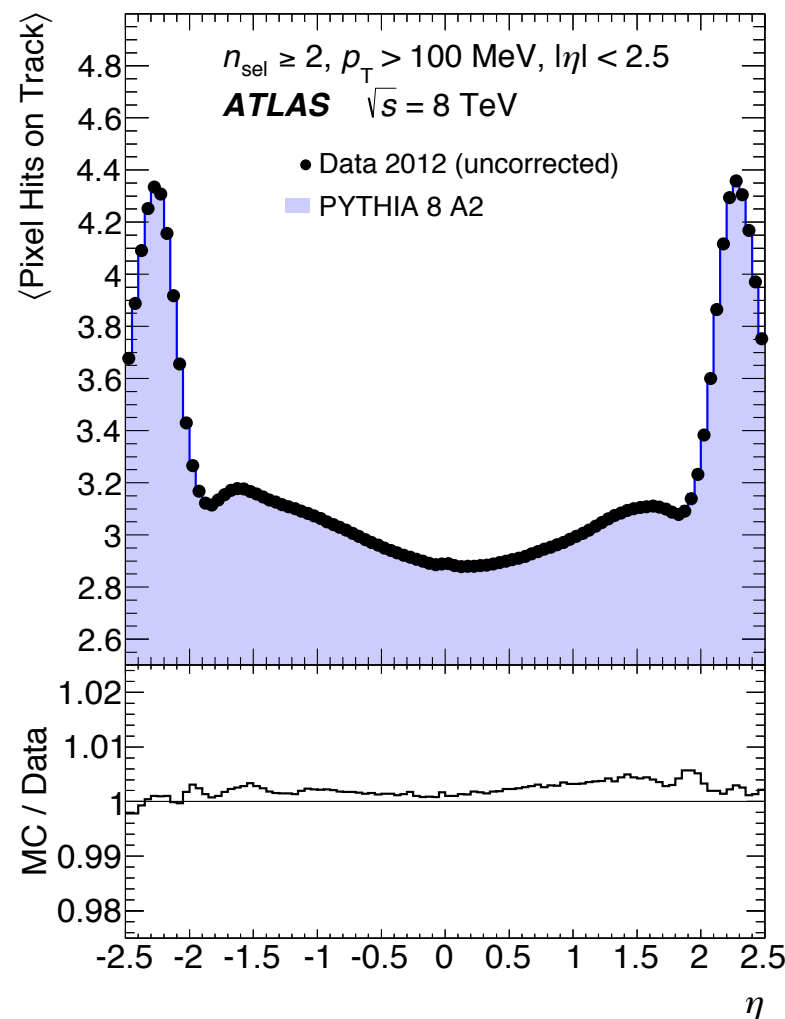
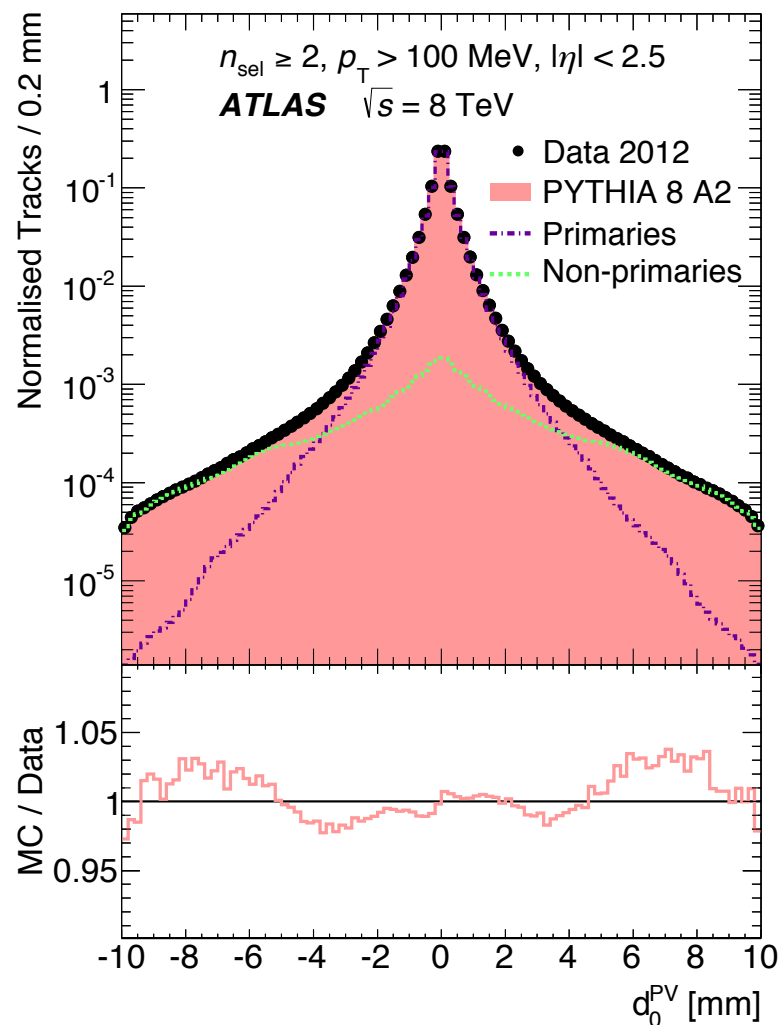


- Similar quality of description reached as for final Run-1 description
- comparable systematic uncertainties with of 13 TeV results with final Run-1 results



# Track reconstruction performance

- ▶ Track reconstruction performance evaluation is essential
  - excellent modelling of track parameters and properties by simulation puts confidence in estimating key parameters from simulation
  - result of years of detailed detector modelling in the full simulation



# Track weights

## non-primary fraction

2

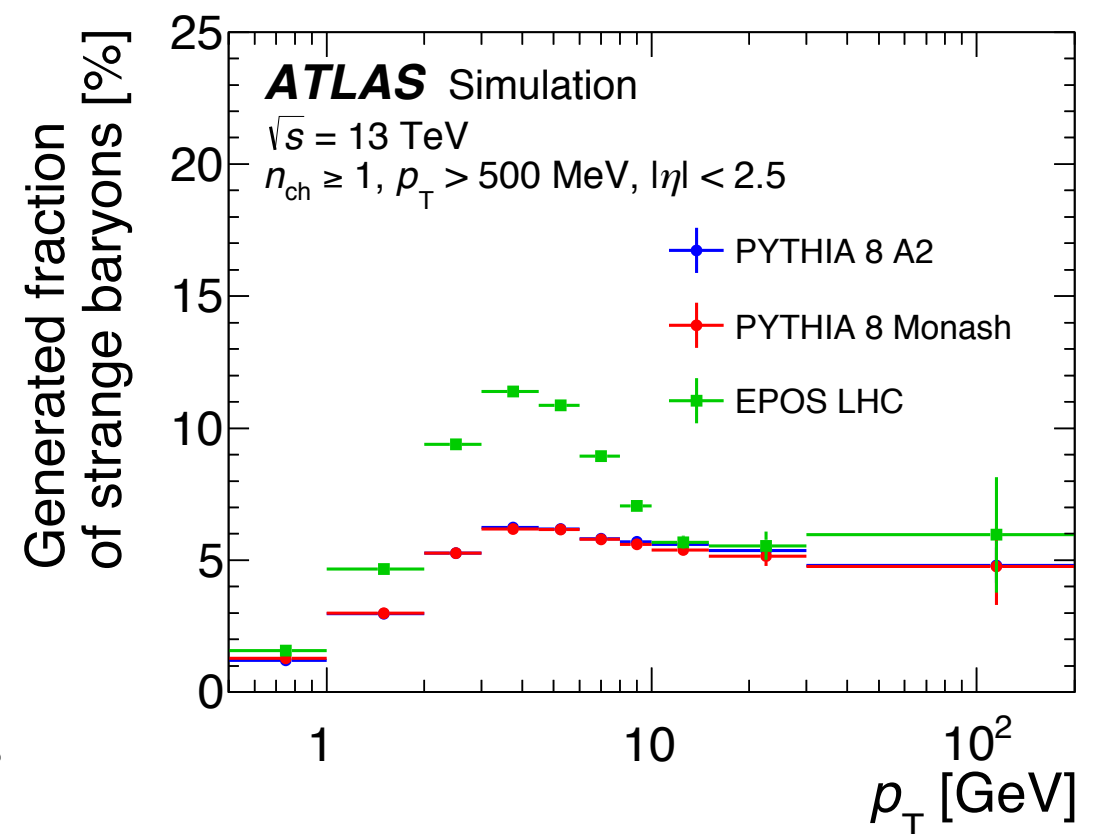
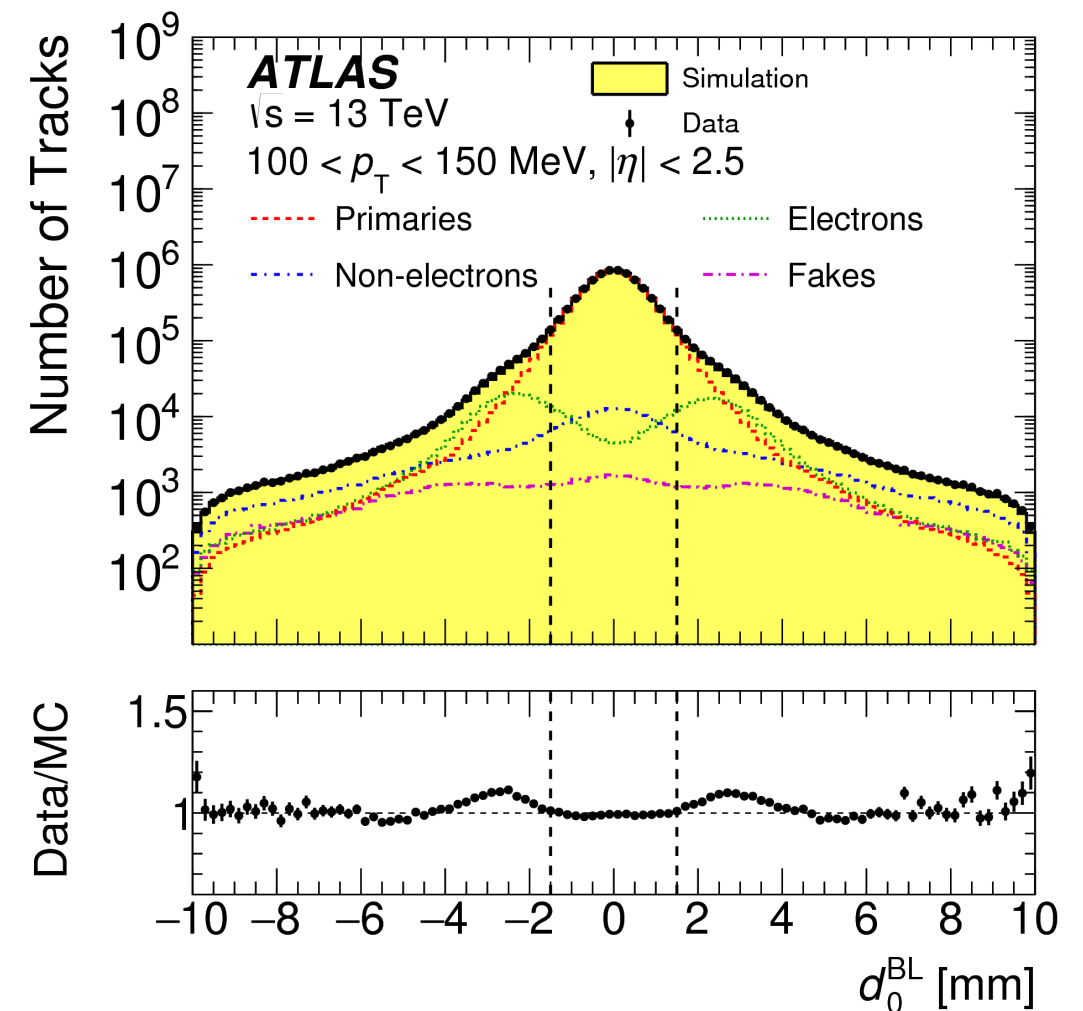
- for analysis ( $p_T > 500$  MeV) no distinction between fakes and secondaries done
- estimated via a template fit to the impact parameter distribution

*done w.r.t beam line to avoid event biases*

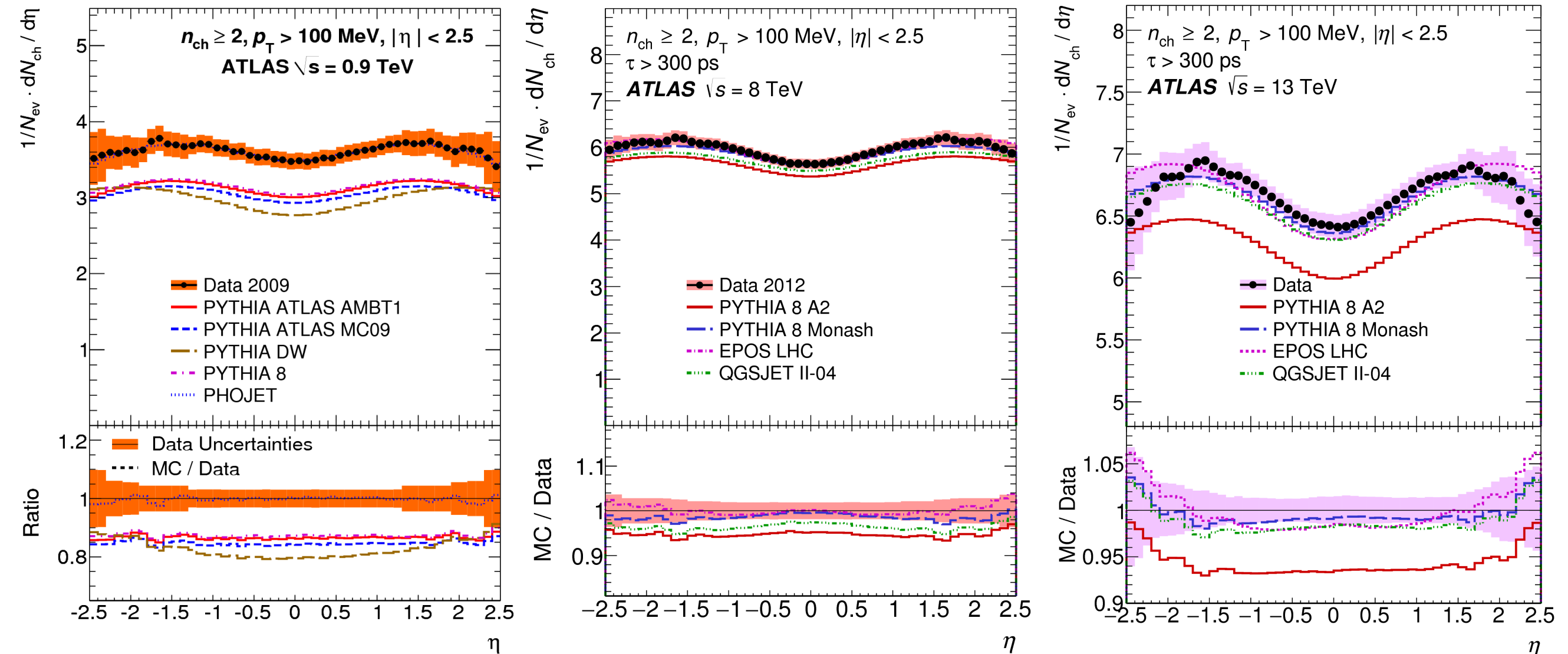
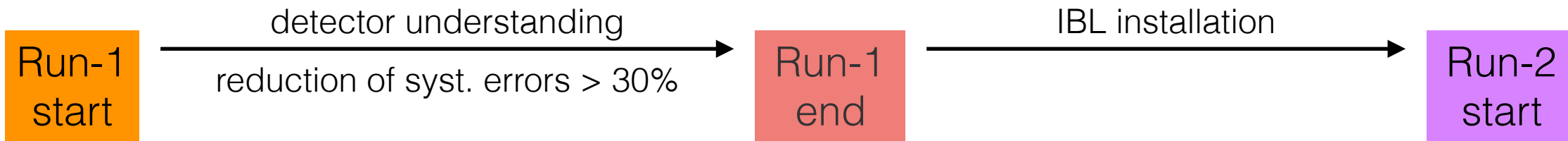
## strange baryon fraction

3

- updated stable particle definitions:  $\tau > 300$  ps
- includes many strange baryons
- very low tracking efficiency, strongly varies with transverse momentum
- generators predict very different fractions
- removed for 8/13 TeV from fiducial definition
- decreases generator dependency, EPOS LHC extrapolation for comparison with older analyses



# Charged particle multiplicities | Result History

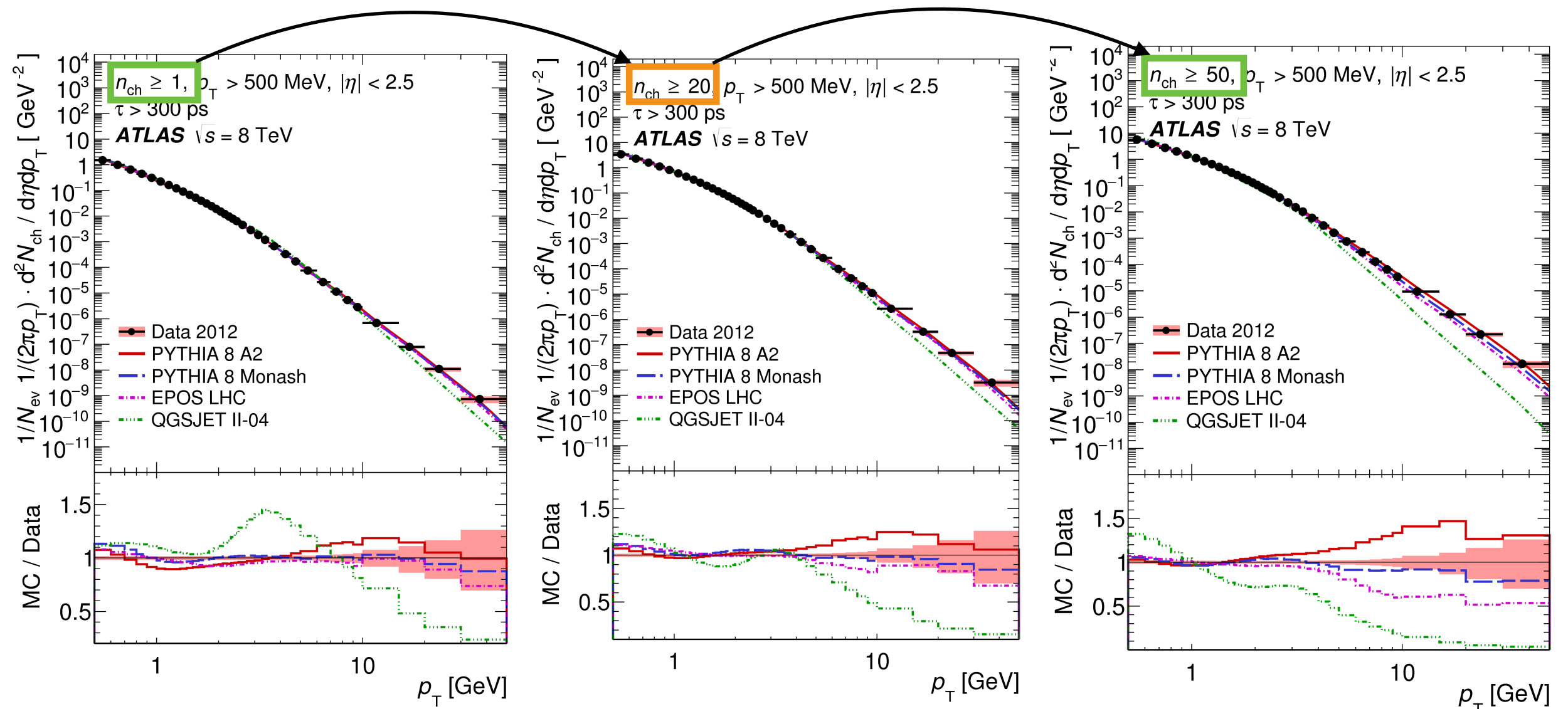


- ▶ Fairly good shape modelling by most generators
  - measurements are continuously used for tuning
  - EPOS (LHC tune) very good modelling at 8 TeV



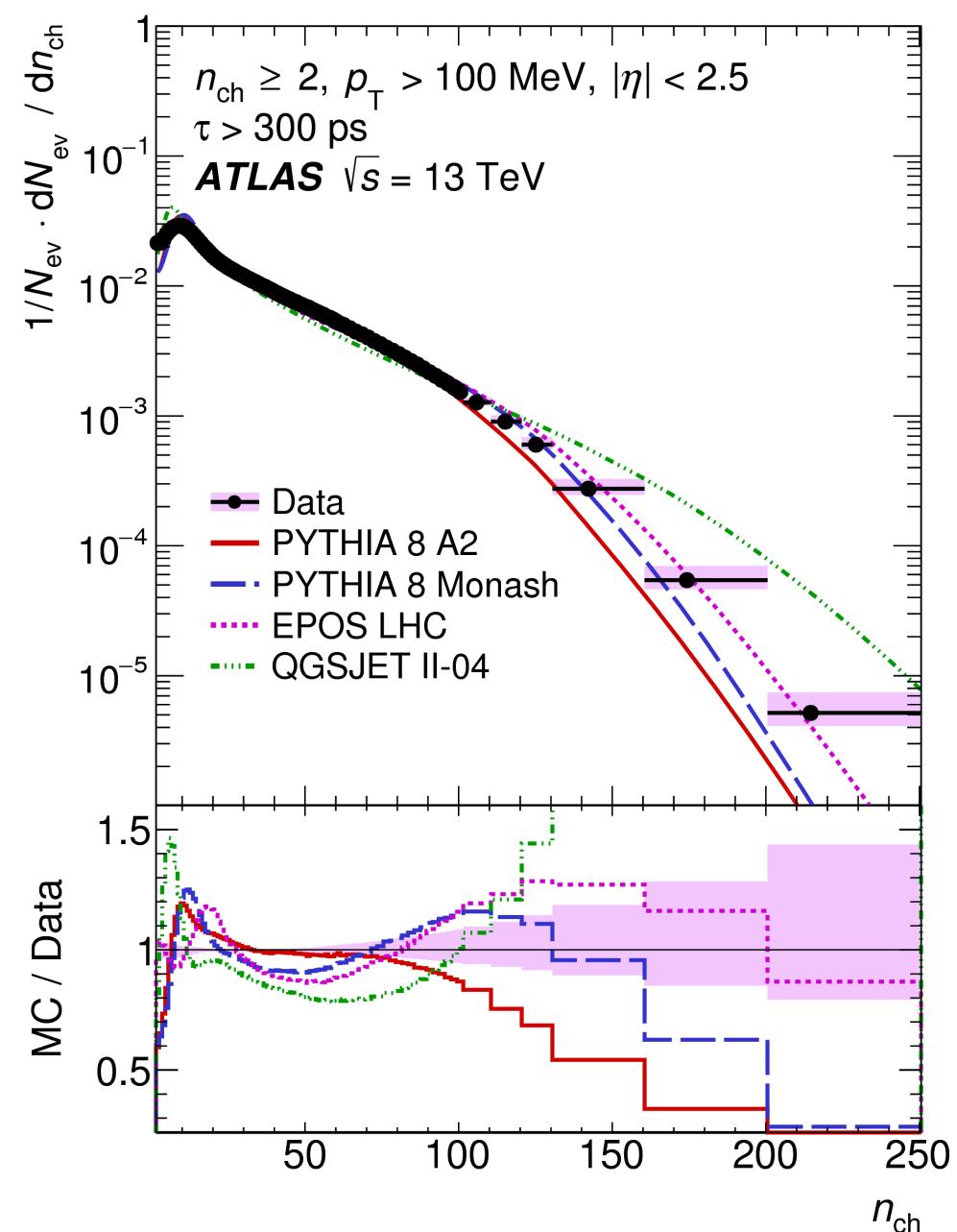
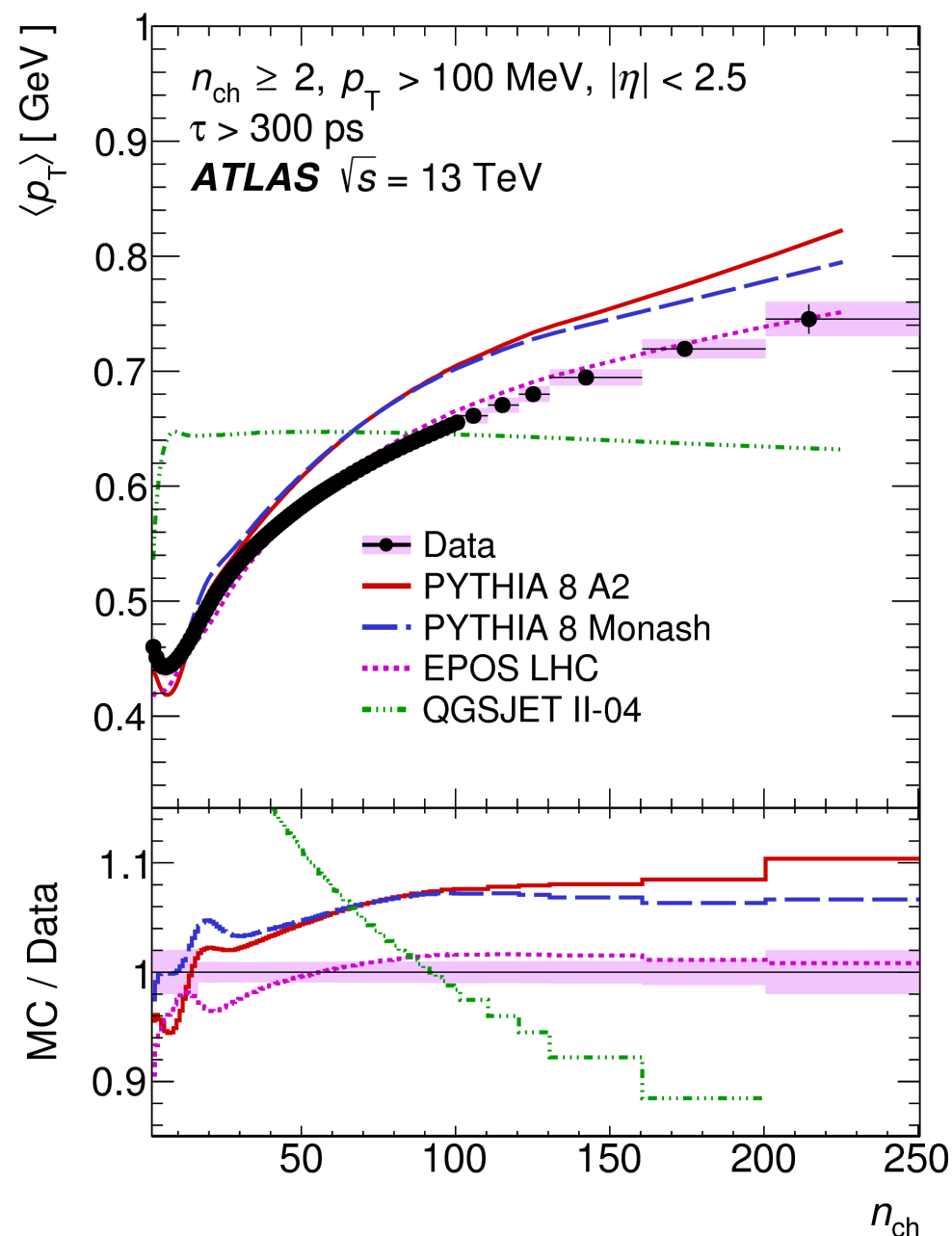
# Charged particle multiplicities | Results 8 TeV

- ▶ 8 TeV analysis extended to high multiplicity phase-spaces
  - event selections with  $n_{\text{ch}} = 1, 6, 20, 50$
  - most generators have seen limited tuning in this corner
  - deviations from data start getting bigger



# Charged particle multiplicities | Results 13 TeV

- ▶ 13 TeV result gives a new tuning point with large lever arm
  - high precision measurements for two phase space definitions
  - good description of data through EPOS for event quantities

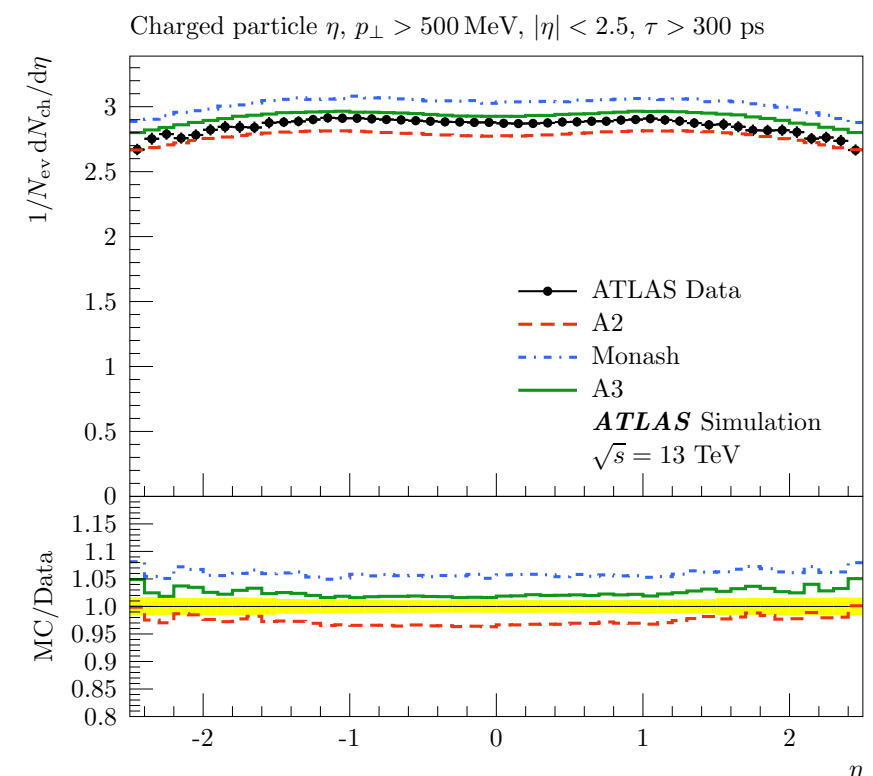
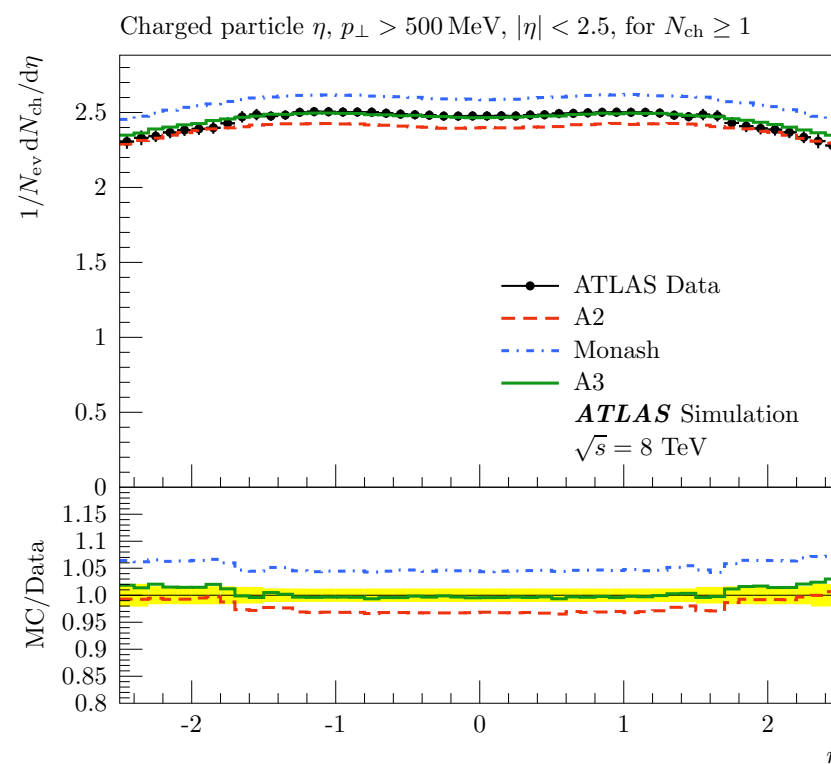
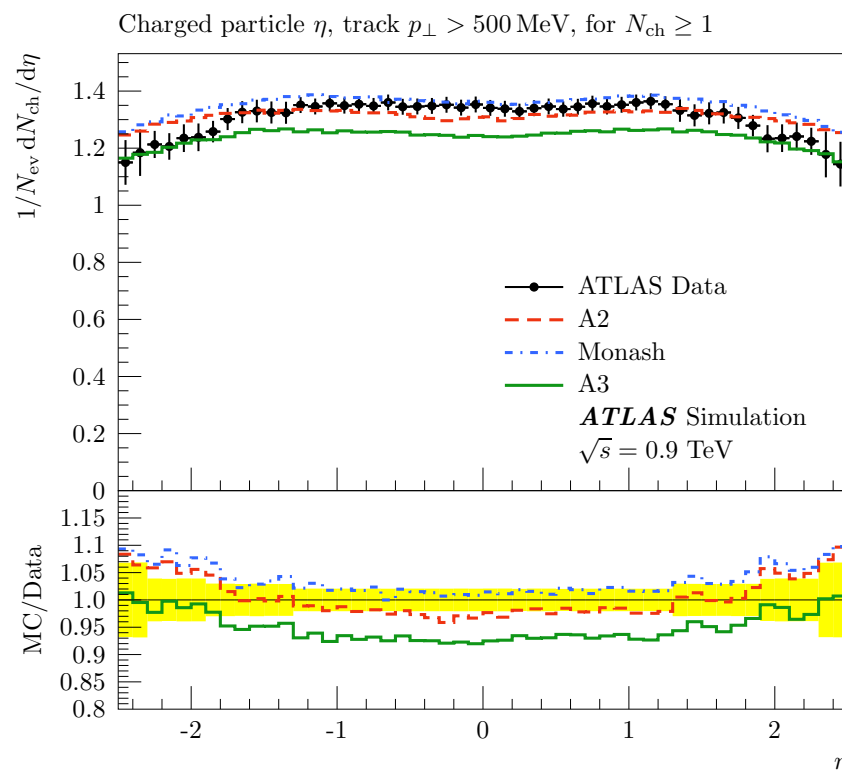


# Charged particle multiplicities | Tuning

- Set of ATLAS measurements (**0.9/7/13 TeV**) used for PYTHIA tuning/testing
  - ATLAS Pythia A3 starting from Monash tune, using NNPDF 2.3LO PDF
  - testing Pythia 8 description with Donnachie-Landshoff diffractive model

$\sqrt{s}$  [TeV]    used measurements

0.9	charged particle distribution
7	charged particle distribution, transverse energy flow, fiducial inelastic cross-section, rapidity gap analysis
13	charged particle distribution, fiducial inelastic cross-section





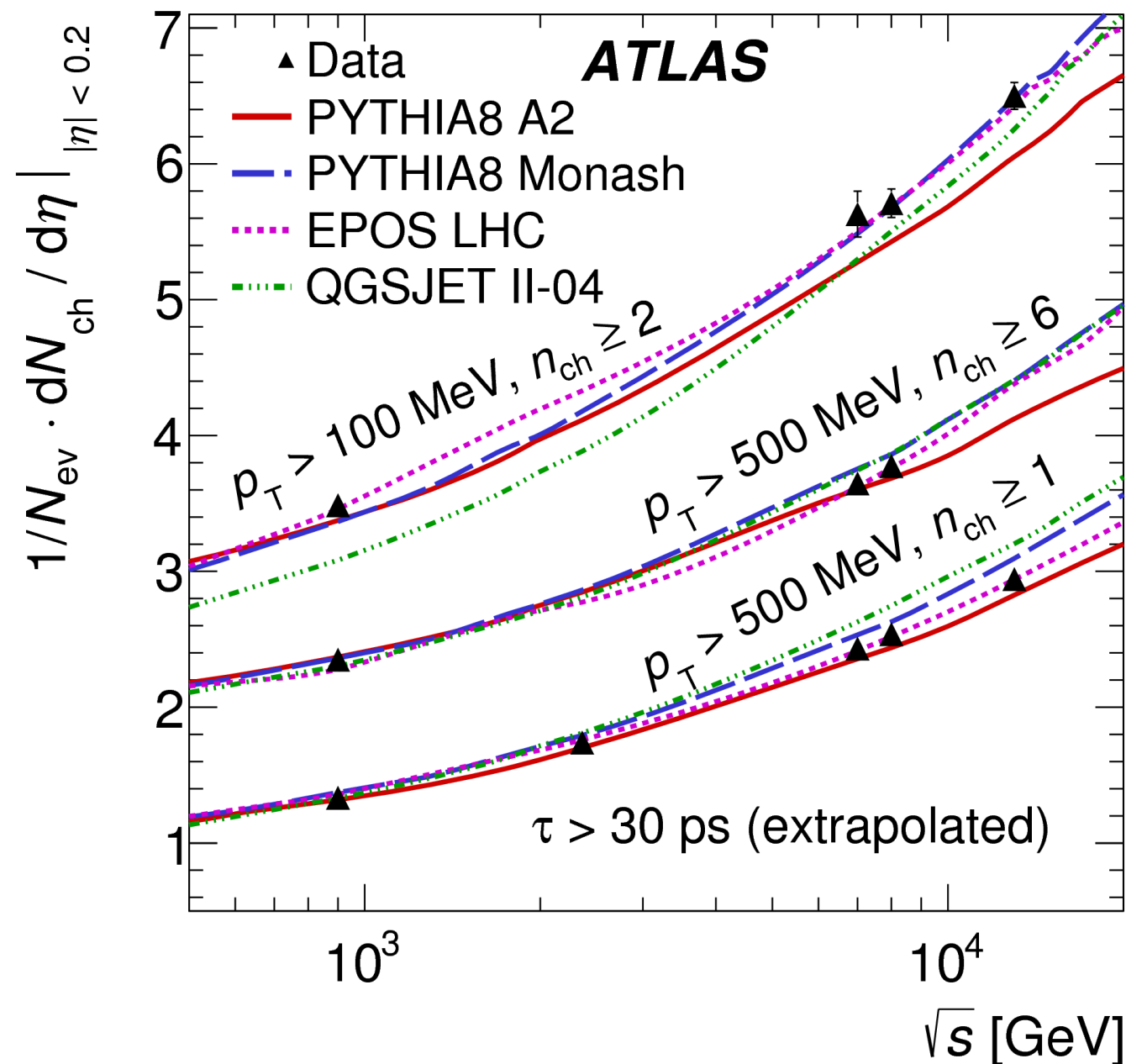
\*without strange baryon removal

$p_T > 0.5 \text{ GeV}, n_{ch} \geq 1$

$\sqrt{s} \text{ [TeV]}$	$dN_{ch}/d\eta \mid \eta=0$	$\pm \text{ stat}$	$\pm \text{ sys}$	References
0.9	1.343*	0.004	0.027	<a href="#">NJP 13 (2011) 053033</a>
2.36	1.74*	0.019	0.058	
7	2.43*	0.001	0.050	
8	2.477	0.001	0.031	<a href="#">Eur. Phys. J. C (2016) 76:403</a>
13	2.874	0.001	0.033	<a href="#">PLB (2016), Vol. 758, pp. 67-88</a>

$p_T > 0.1 \text{ GeV}, n_{ch} \geq 2$

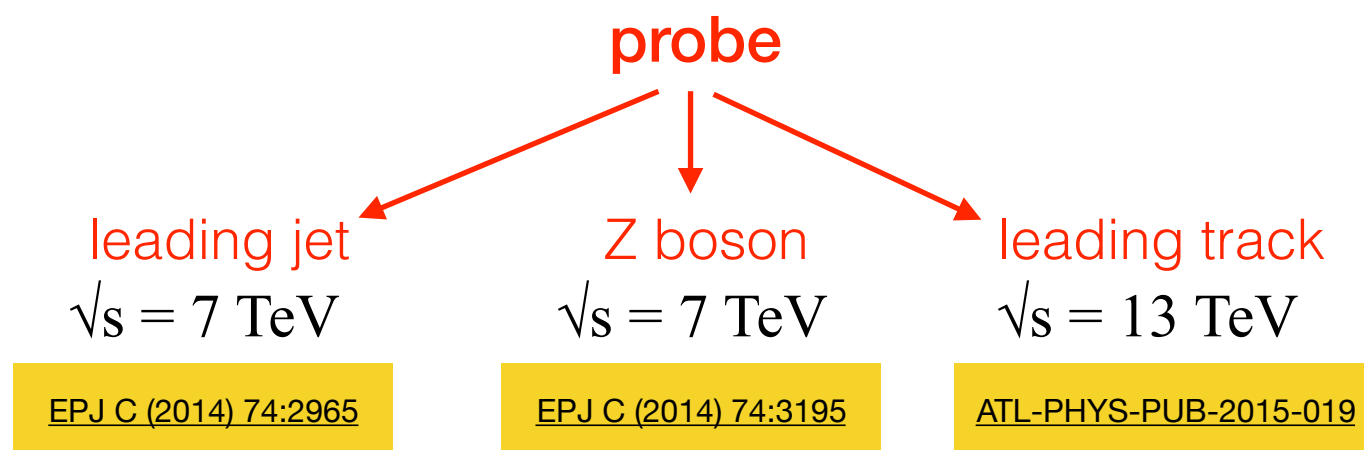
[arXiv:1606.01133](#)



Charged particle  
multiplicities  
| **Result Summary**

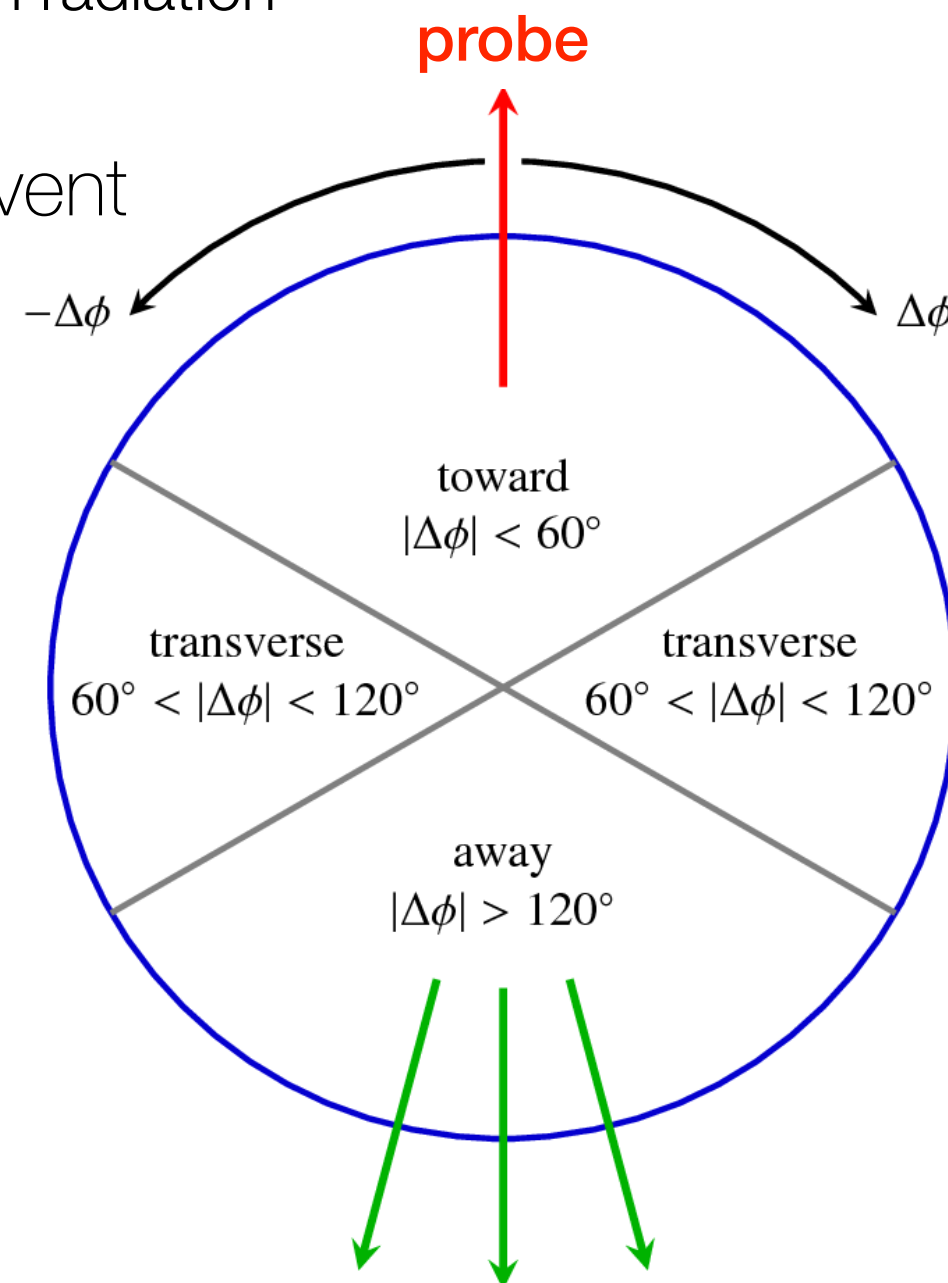
# Underlying event (UE) analyses

- ▶ Charged particle measurement\* accompanying hard scatter
  - partons not included in hard scatter (beam remnants)
  - additional scatters in same p-p collision (multi parton interactions, MPI)
  - contributions from initial (ISR) and final (FSR) gluon radiation
- ▶ phase space definition for the underlying event



- measurements (leading track)

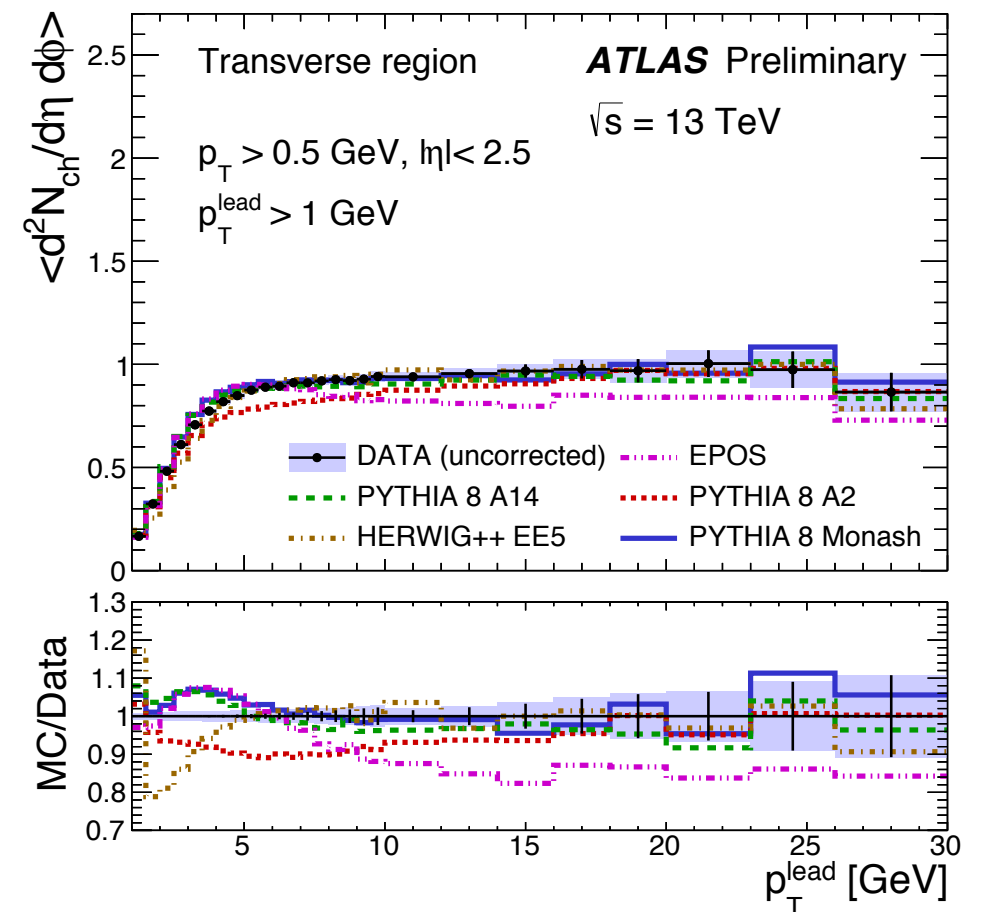
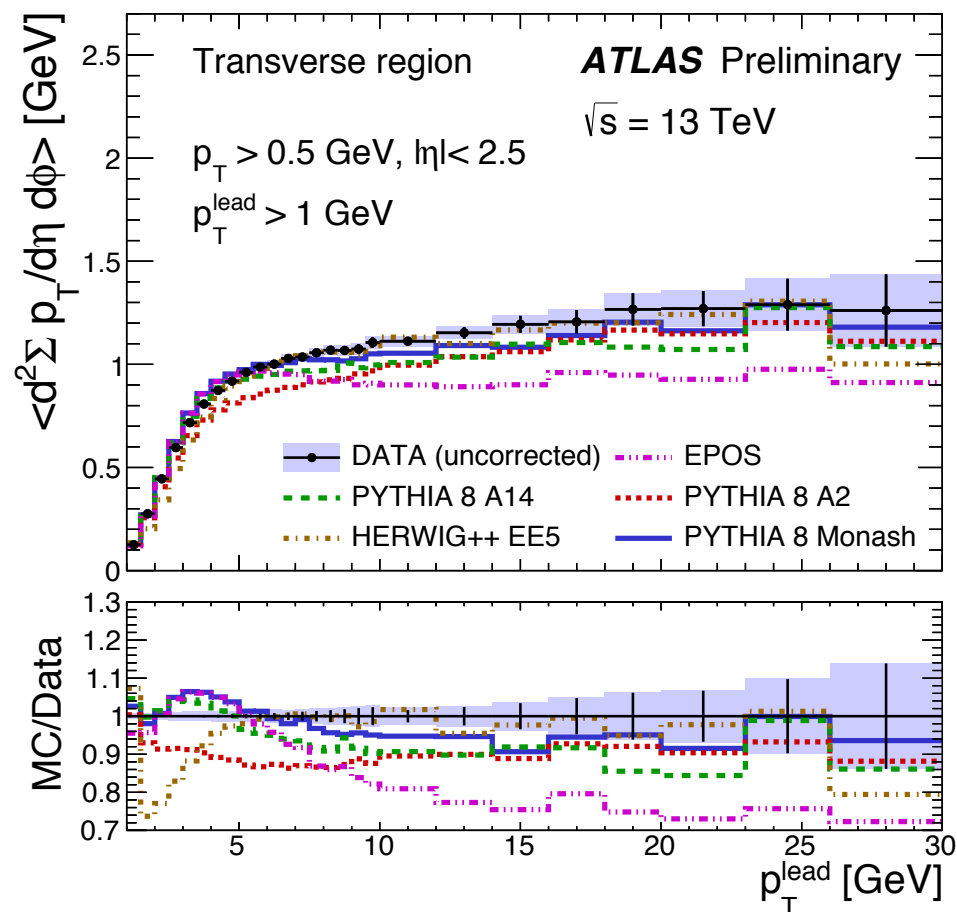
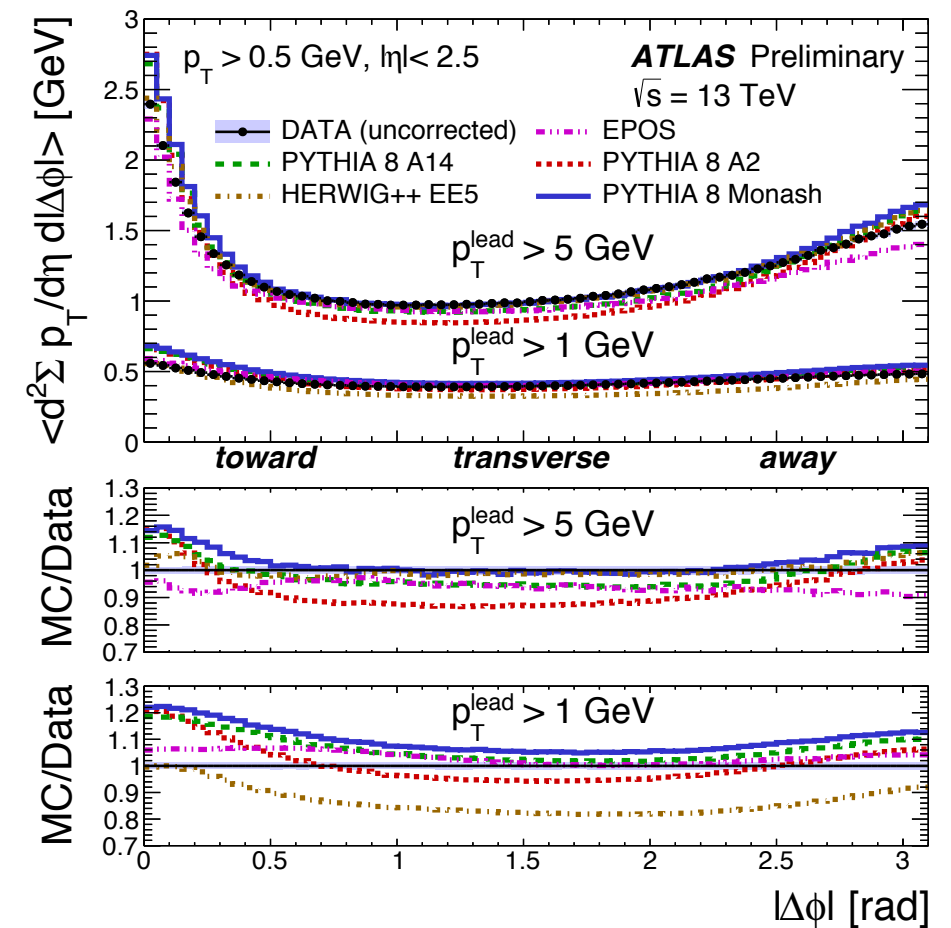
Observable	Definition
$\langle d^2 N_{\text{ch}} / d\eta d\phi \rangle$	Number of tracks per unit $\eta-\phi$
$\langle d^2 \sum p_T / d\eta d\phi \rangle$	Scalar sum of track $p_T$ per unit $\eta-\phi$



\*very similar/identical experimental technique and systematics as slides 3-8

# Underlying event | Results

- ▶ Leading track analysis
  - analysis separated into 3 regions
  - requirement on  $p_T > 1 \text{ GeV}$
- ▶ Good modelling by Pythia 8 tunes
  - shapes generally well modelled



# Conclusion

- ▶ ATLAS has a full set of minimum bias and underlying event analyses
  - covering different centre of mass energies and phase space definitions
- ▶ Recent 8 TeV and 13 TeV improved sys. uncertainties significantly
  - mainly due to better understanding of the tracker material description after IBL insertion can still improve w.r.t. Run-1 description helps many other precision measurements
  - better understanding of strange baryon handling
- ▶ Rich dataset for generator tuning available
  - data only corrected for detector effects, no model corrections/extrapolations
  - data available as HepData
- ▶ Underlying event results of similar quality and importance
  - give confidence in current UE simulation





- ▶ Alternative way to look at UE is by looking at global event shape variables
  - analyse the charged particle distributions in  $Z \rightarrow \ell\ell$  at 7 TeV
  - binned in transverse momentum bins of  $e\bar{e}/\mu\bar{\mu}$  candidate pairs
  - comparison shows good agreement with HERWIG 7

