XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS16)

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Measurements of the charged-particle distributions (in *pp* collisions) with the ATLAS detector at the LHC

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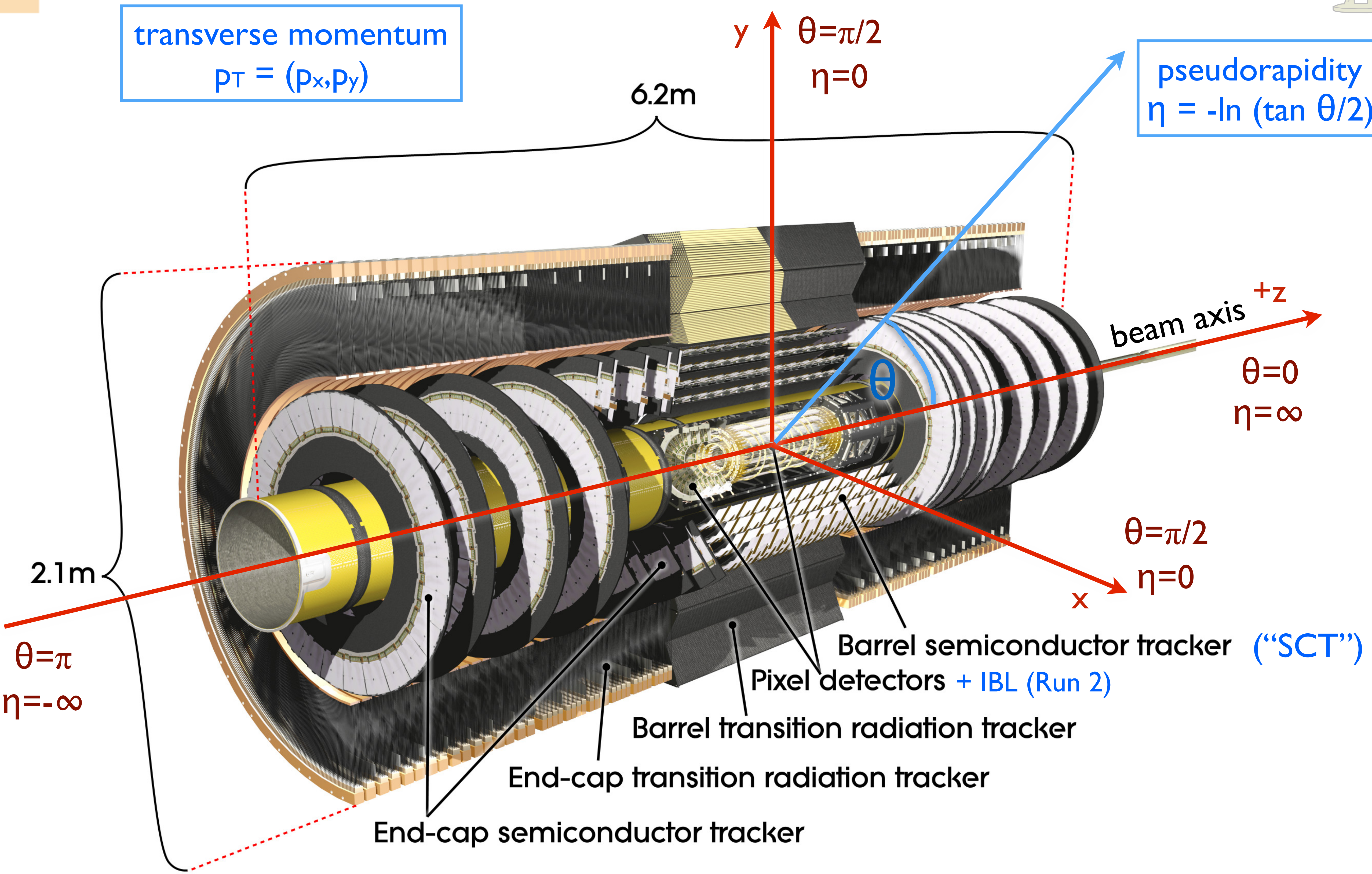
on behalf of the ATLAS collaboration

8 TeV: arxiv:1603.02439 (EPJC)
13 TeV: arxiv:1602.01633 (PLB)

The ATLAS inner tracker ("ID")



Introduction

p_T>	n_{ch}>=	0.9	7 TeV	8 TeV	13 TeV
100	2	yes	yes	**yes**	*in prog.*
500	1	yes	yes	**yes**	**yes**
500	6	yes	yes	**yes**	
500	20			**yes**	
500	50			**yes**	

- measuring distributions of stable charged primary particles at $\sqrt{s}$ = 8 TeV and 13 TeV
  - including first ATLAS measurements in high-multiplicity phase spaces @ p_T>500 MeV
  - important for tuning of phenomenological soft QCD models to data (e.g. for pileup simulation)

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

charged-particle density vs eta

charged-particle density vs p_T

charged-particle multiplicity per event

mean p_T vs charged-particle multiplicity

- track-based measurement — from detector level to particle level
  - apply corrections for trigger & reconstruction inefficiencies and other detector effects
  - using (almost) same procedure as in previous ATLAS measurements @ 0.9–7 TeV

Overview

Differences between previous and new analyses

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_{ch} phase spaces			yes		paper scope + MC tuning
final Run-1 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_T-spectrum)
Geant4 physics list	QGSP_BERT	QGSP_BERT	FTFP_BERT	FTFP_BERT	improves simulation of antiprotons

- Very similar to previous analyses — well-established procedure
  - new: removal of strange baryons (new fiducial definition of "primary" particles: τ > 300 ps)
  - 8 TeV {
  - new: measuring additional high-multiplicity phase spaces
  - new: using final Run-1 geometry with reduced material uncertainty (±5% passive ID material)
    - thus we achieved the smallest total systematics of all ATLAS Minimum Bias analyses of the Run-1 period!
  - new: using Pythia 8 A2 MSTW2008LO as a baseline MC tune for the analysis (corrections etc.)
  - new: using improved physics list for MC detector simulation samples

Minimum Bias analysis

Analysis procedure

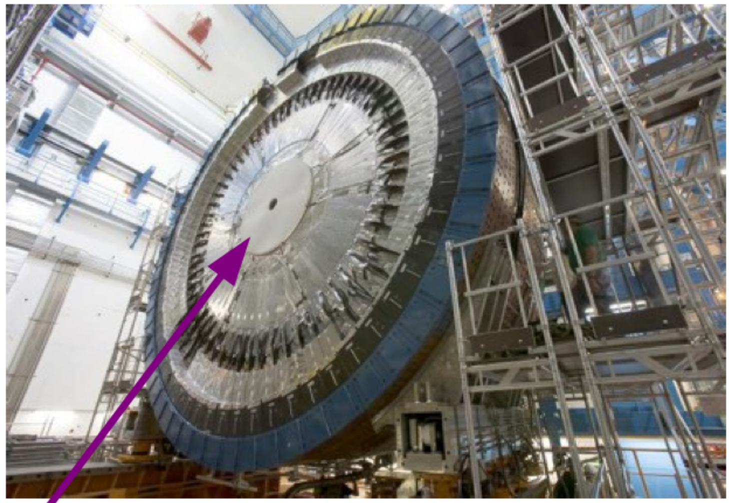
Step	Details	Impact
record *pp*-collision data sample	require low <μ> to minimise pile-up contamination	~9m "good" events
select "good" events and tracks	require MBTS trigger, reconstructed vertex, no pile-up, track quality	systematics
	check for Event backgrounds	(negligible)
	check for remaining pile-up 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)

Minimum Bias analysis

Event and Track selection

Event selection

- MBTS trigger signal
- $\mu < 0.01$ (to suppress pile-up)
- reconstructed primary vertex with >=2 tracks
  - veto events with any additional vertex with >=4 tracks
- >= X "selected" tracks (n_{sel}) passing track selection



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

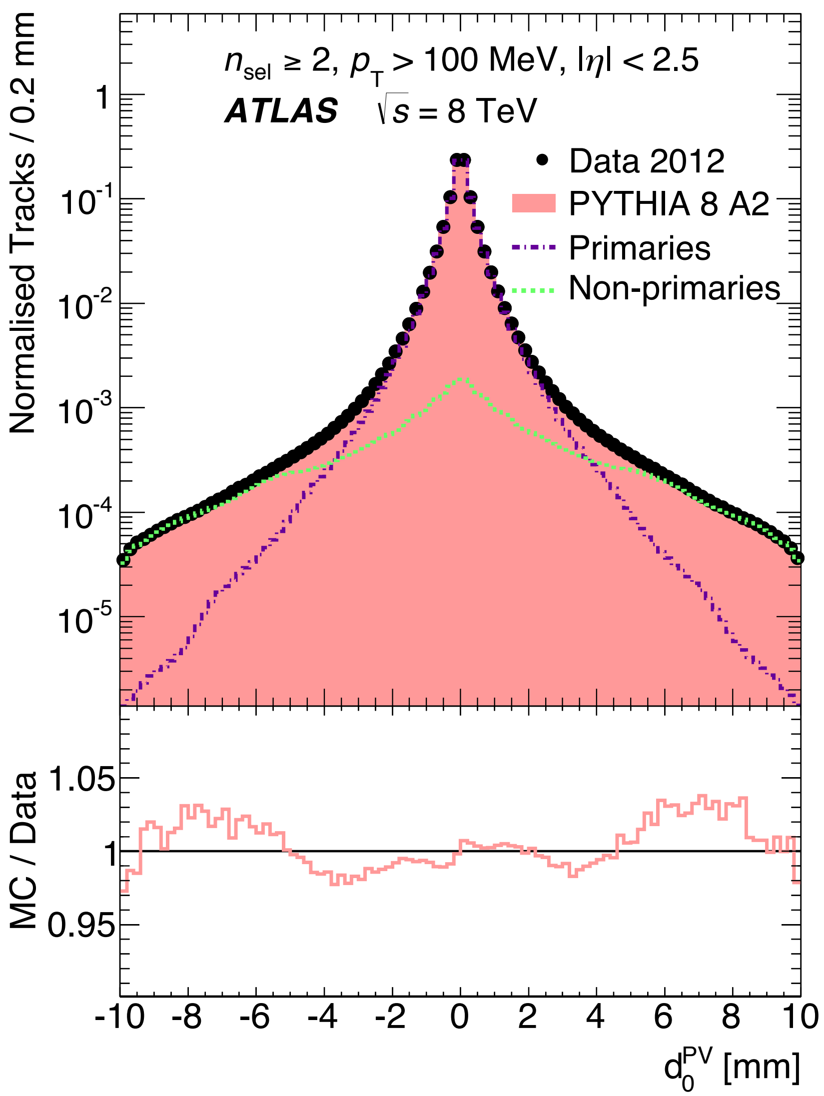
32 scintillation counters

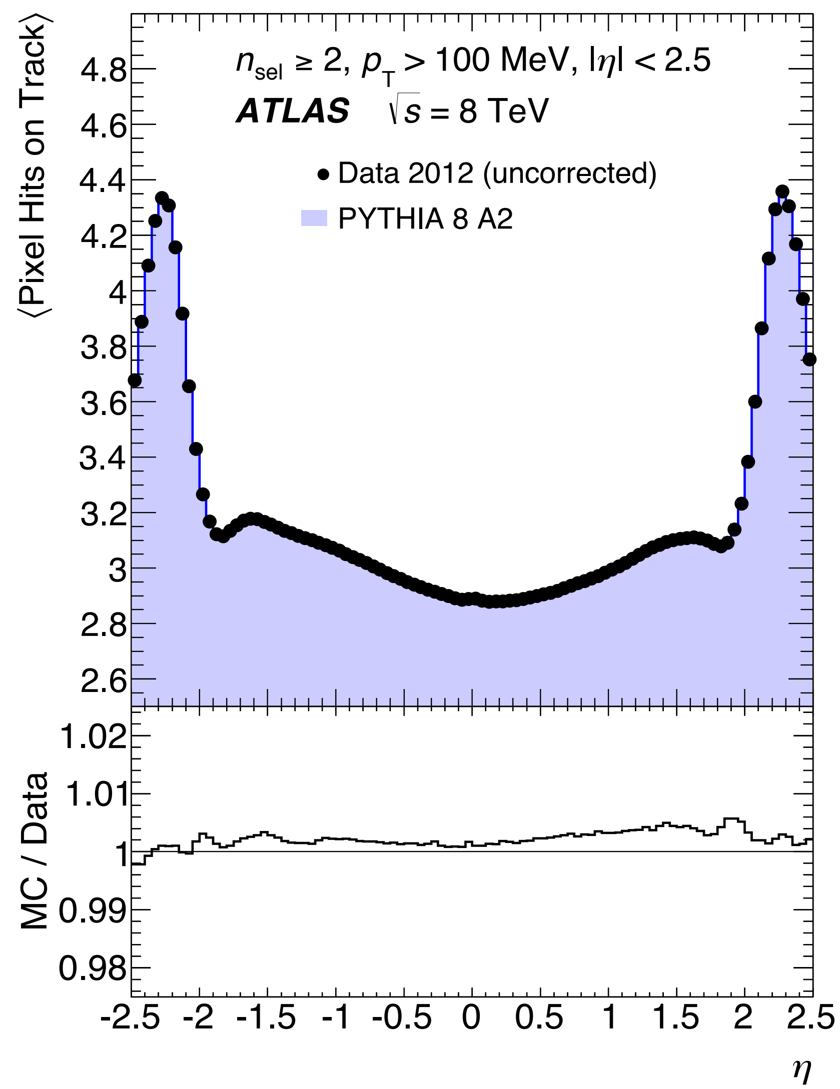
Track selection

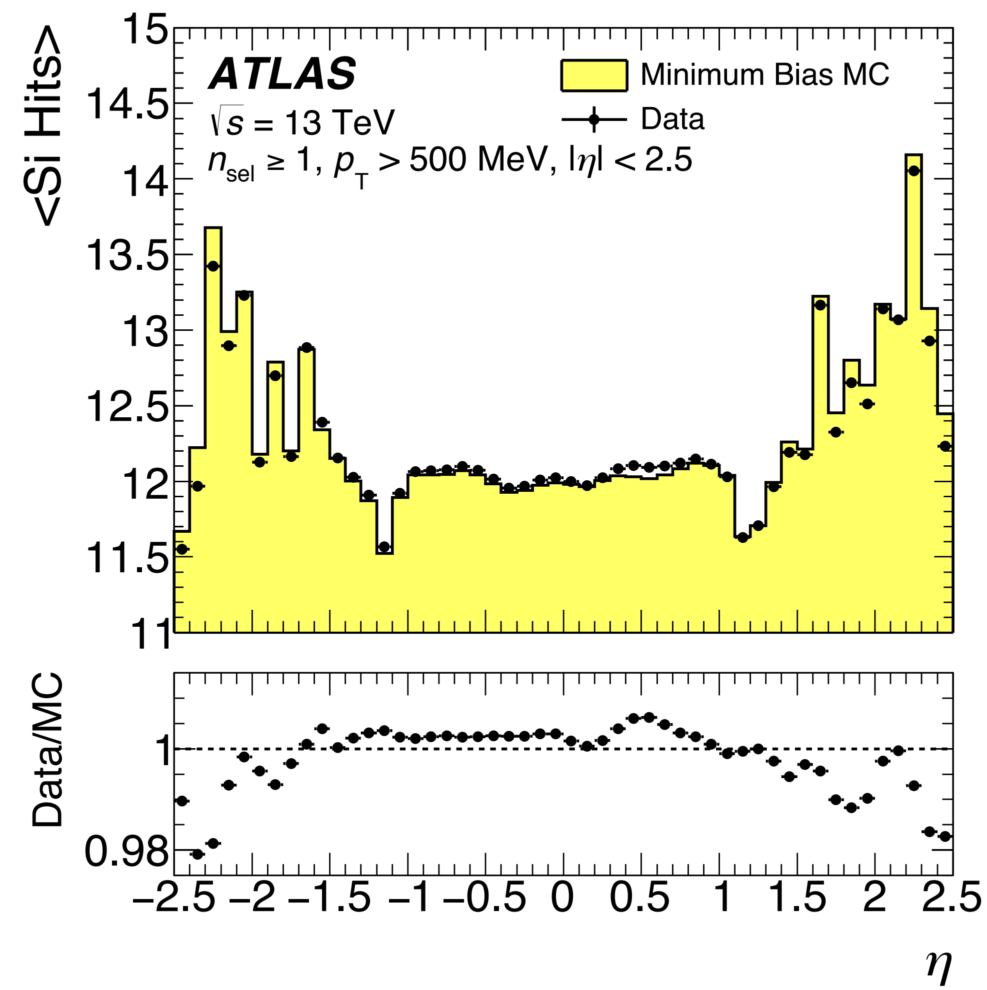
- $|d_0^{PV}| < 1.5$ mm
- $|z_0^{PV} \sin(\theta)| < 1.5$ mm
- χ^2 probability > 0.01 for p_T > 10 GeV
- innermost Pixel layer hit if expected**
- >=1 Pixel hit
- >=2,4,6 SCT hits* for p_T>100,200,300 MeV
  - * = sum of SCT hits + inactive SCT modules on track
  - ** = or IBL hit if expected (for 13 TeV analysis)

Track reconstruction performance

IP and hits-on-track distributions







IP distributions show good MC / Data agreement in signal region (after p_T reweighting) and in tails (after applying scale factors for secondaries, derived from MC template fits)

Distributions of average number of hits on track show very good MC / Data agreement

Correction procedure

$$w_{\mathrm{ev}}(n_{\mathrm{sel}}^{\mathrm{BS}}) = \frac{1}{\varepsilon_{\mathrm{trig}}(n_{\mathrm{sel}}^{\mathrm{BS}})} \cdot \frac{1}{\varepsilon_{\mathrm{vtx}}(n_{\mathrm{sel}}^{\mathrm{BS}}, x)} \cdot w_{\mathrm{zvrtx}}$$

event-level weight | trigger efficiency | vertex efficiency | vertex z reweighting

MC: $\varepsilon_{trig} = 1$
data: $w_{zvrtx} = 1$

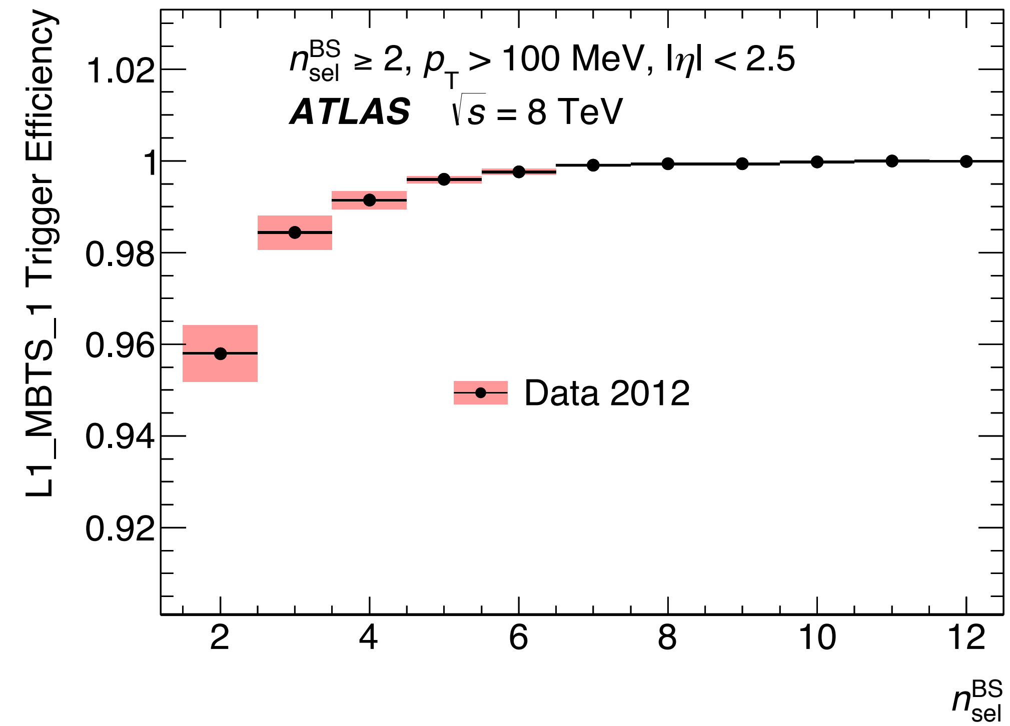
$$w_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{1}{\varepsilon_{\mathrm{trk}}(p_{\mathrm{T}}, \eta)} \cdot (1 - f_{\mathrm{nonp}}(p_{\mathrm{T}}, \eta) - f_{\mathrm{SB}}(p_{\mathrm{T}}, \eta) - f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta))$$

track-level weight | tracking efficiency | non-primaries | strange baryons | outside kinematic range

Trigger and vertex efficiency

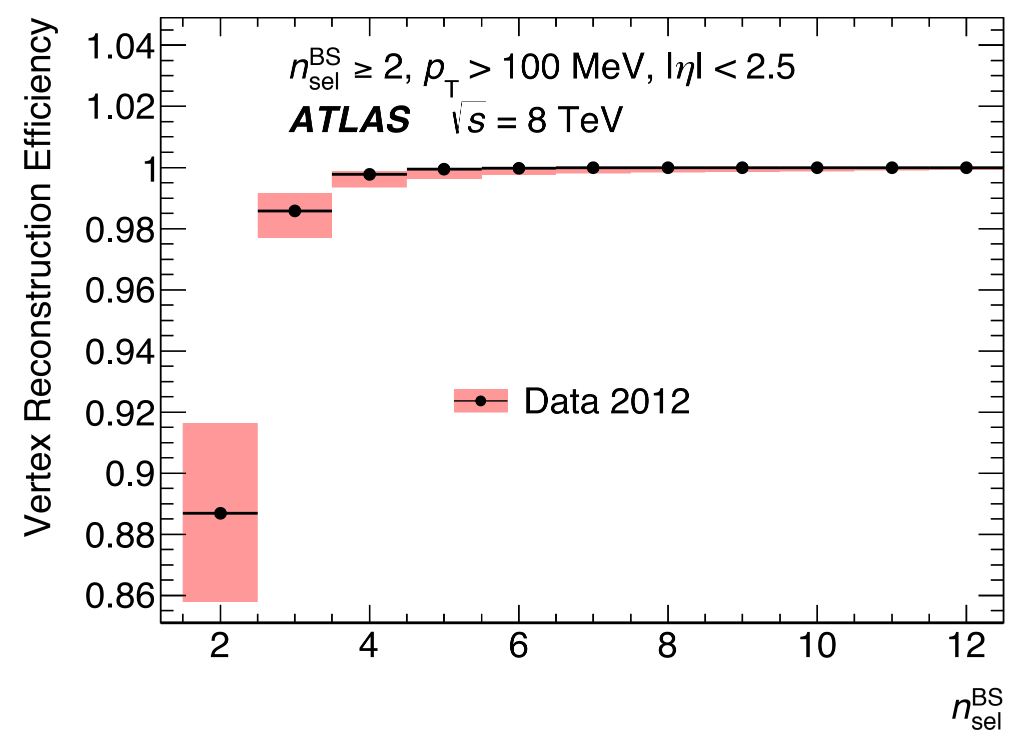
MBTS trigger efficiency

- calculated from events selected by a random space-point trigger
- parameterised as a function of n_{sel}^{BS}
  - using nominal track selection requirements, except for IPs

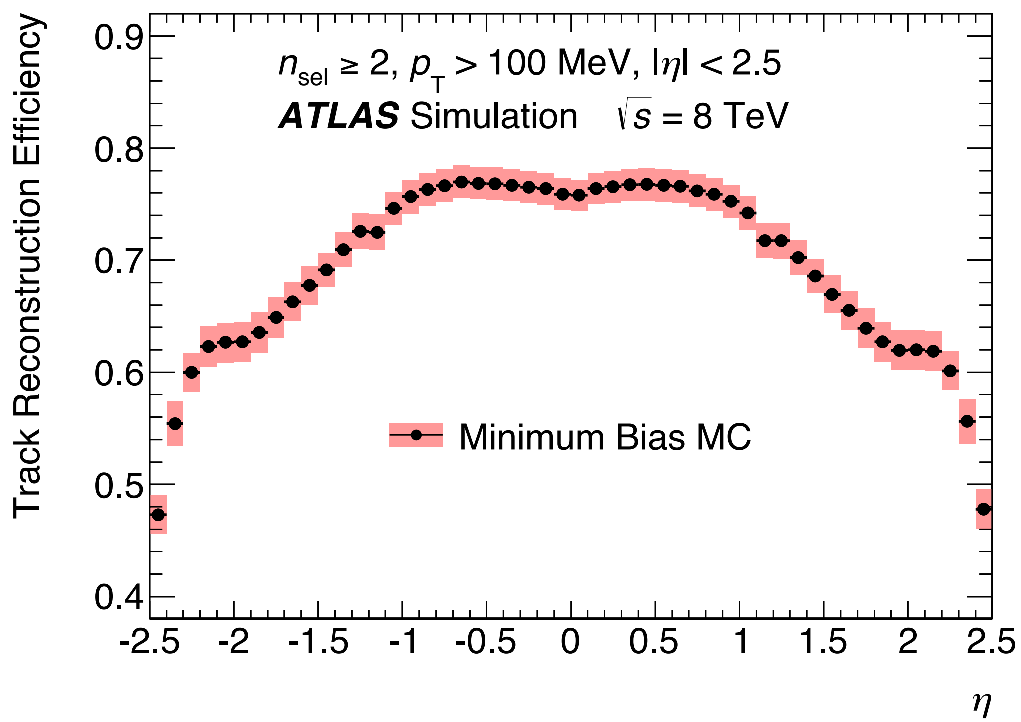


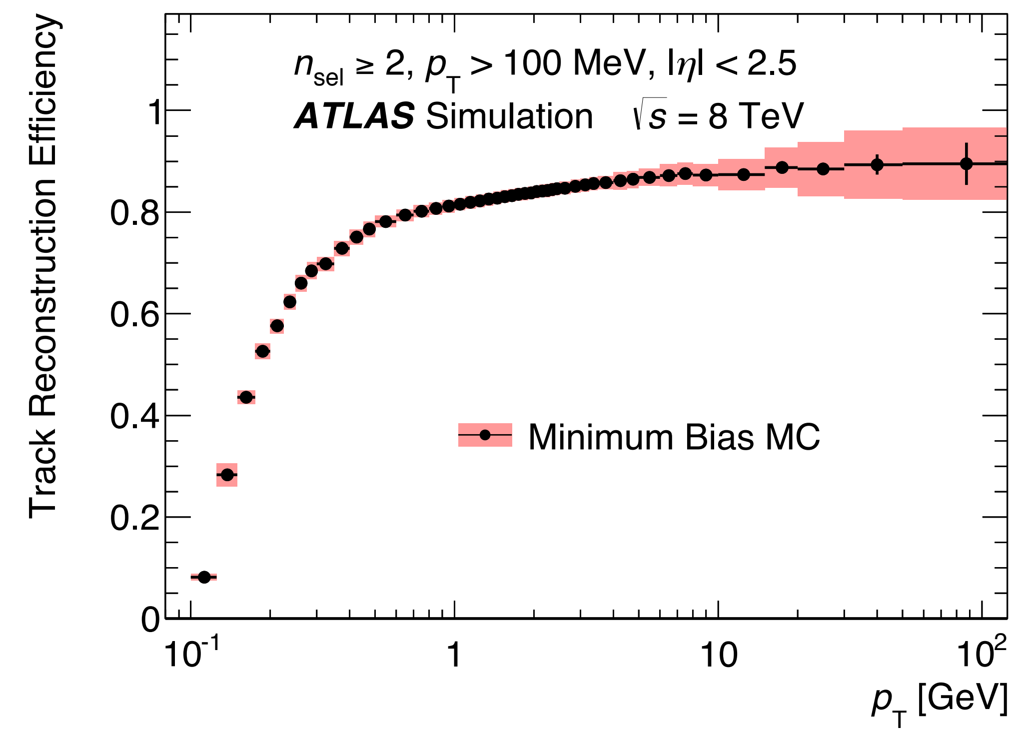
Vertex reconstruction efficiency

- = probability that a reconstructed primary vertex is found in a triggered event
- parameterised as a function of n_{sel}^{BS}
  - for $n_{sel}^{BS}=1$ @ $p_T>500$ MeV: η dependent efficiency
  - for $n_{sel}^{BS}=2$ @ $p_T>100$ MeV: Δz_0 dependent efficiency
- beam background is suppressed in event selection



Track reconstruction efficiency



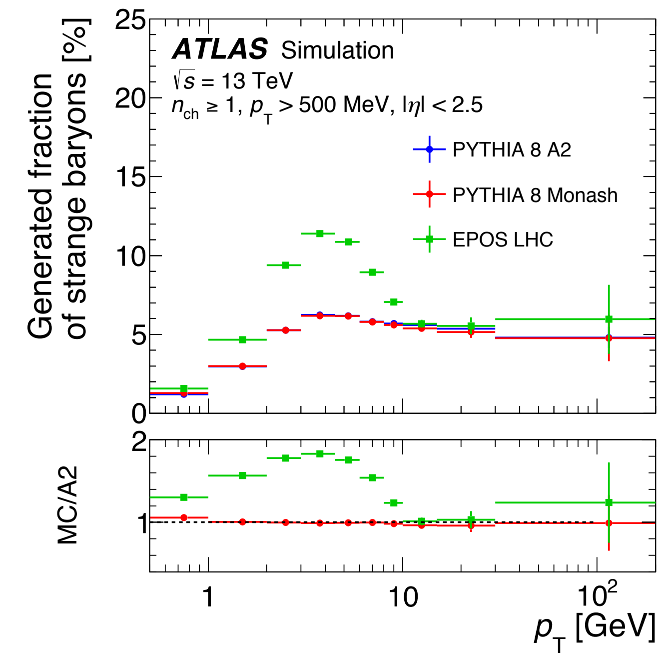


- **Tracking Efficiency = matched tracks / all gen. stable particles**
  - determined from MC simulation
    - 8 TeV uses cone matching: $\Delta R = \text{sqrt}((\Delta\eta)^2 + (\Delta\varphi)^2) < 0.15$
    - 13 TeV uses hit probability matching, and includes a data-driven correction in $|\eta|>1.5$ region due to Pixel services
  - (η, p_T)-binned tracking efficiency is applied as correction factor for each individual track
  - leading systematic is due to ID material uncertainty

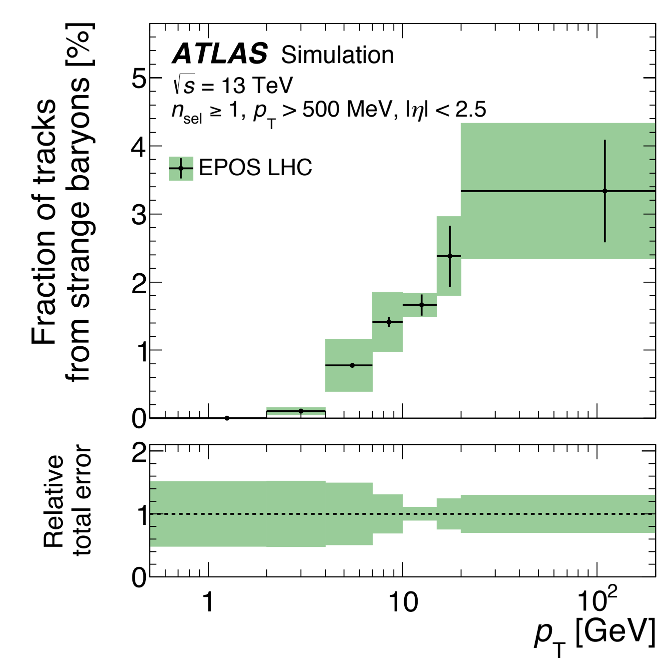
$$\varepsilon_{trk}(p_T,\eta) = \frac{N_{rec}^{matched}(p_T,\eta)}{N_{gen}(p_T,\eta)}$$

Strange baryons

- updated “stable primary particle” definition: τ > 300 ps
  - we reconstruct tracks from short-lived charged strange baryons + their decay products
    - such particles have a proper lifetime between 30 ps < τ < 300 ps
    - these have a very low tracking efficiency (which increases with p_T)
  - MC models predict different generated particle yields! →



    - this would introduce a large model-dependence of the tracking efficiency!
  - these particles are now excluded from our fiducial definition
    - fraction of reconstructed SB tracks is subtracted from measurement



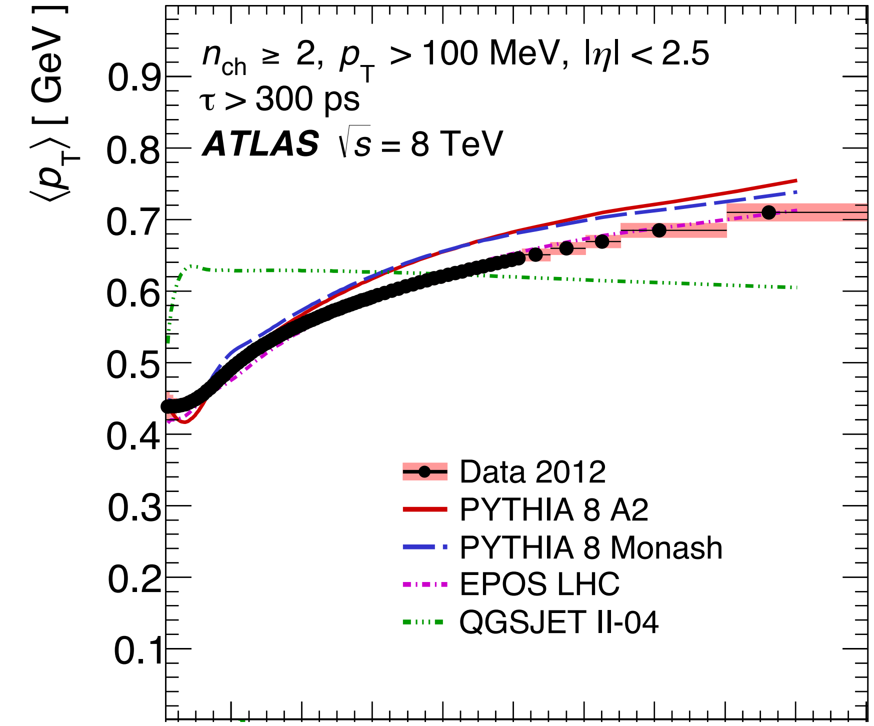
  - for comparison with older measurements:
    - SB fraction can be added via extrapolation factor derived from MC generator
    - baseline: EPOS LHC (describes SB fraction in data more accurately)
- this is new in 8+13 TeV measurements!

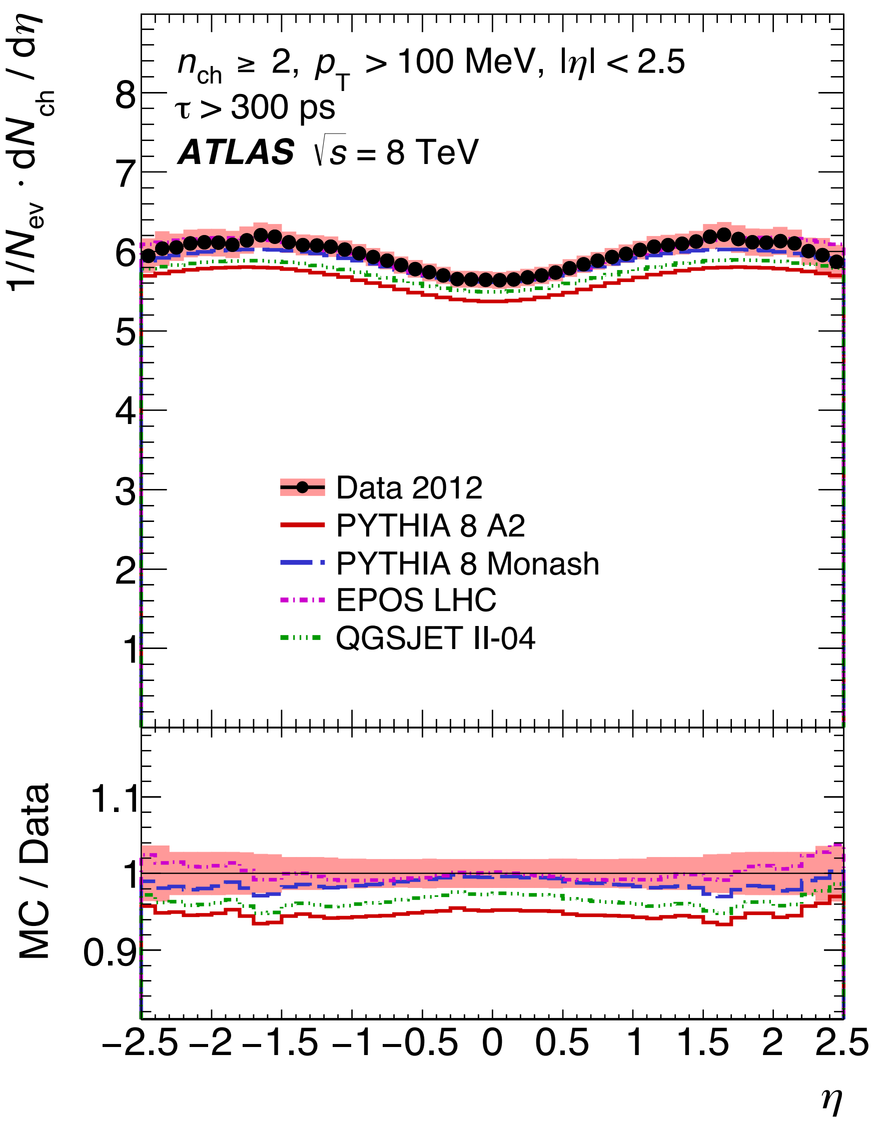
Results @ 8 TeV

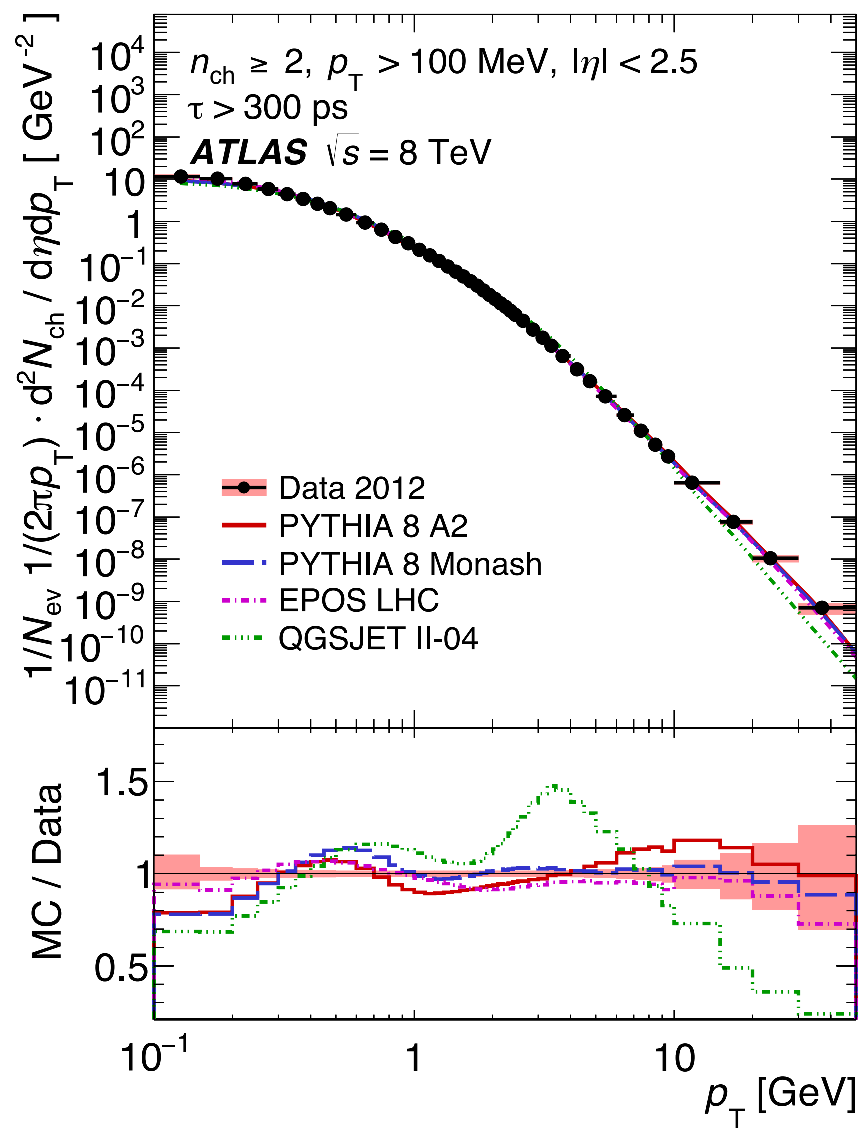
p_T>100 MeV:

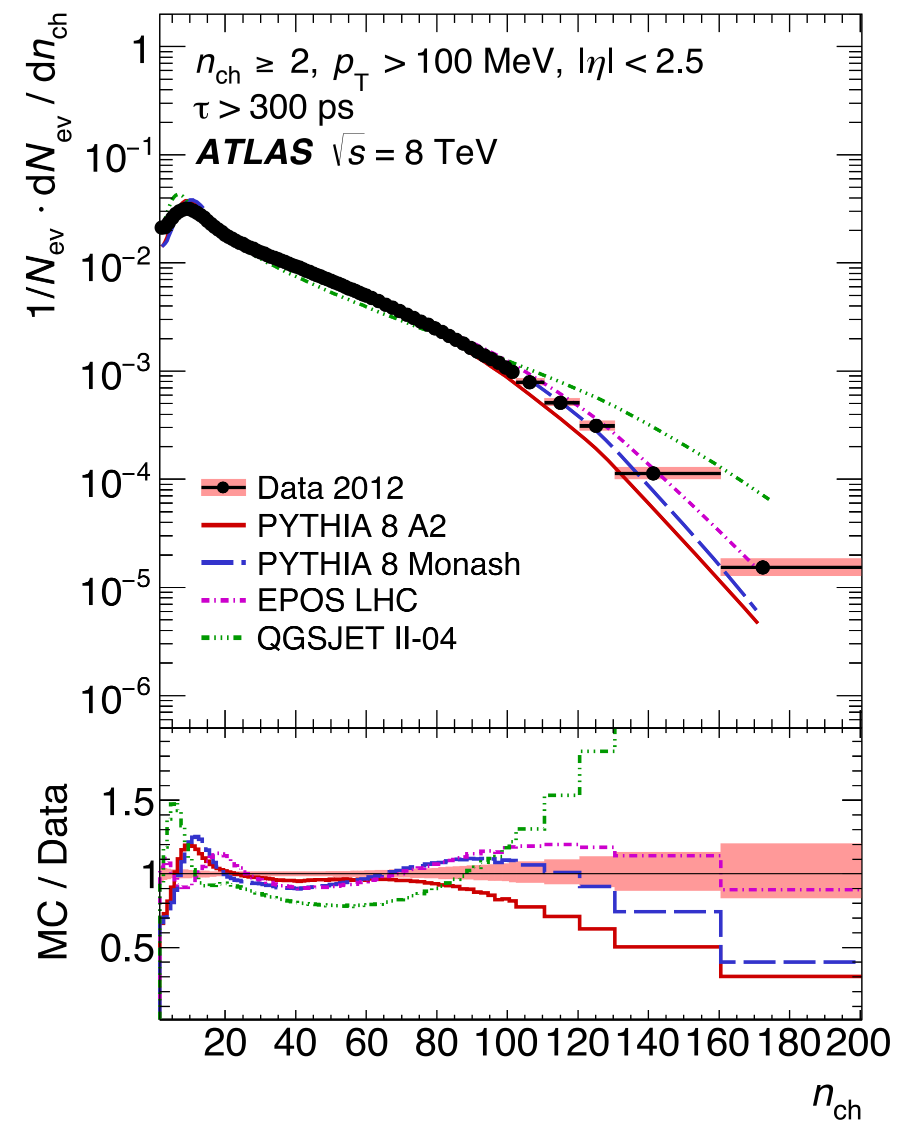
$$dN_{ch}/d\eta|_{\eta=0} = 5.644 \pm 0.003 \text{ (stat.)} \pm 0.103 \text{ (syst.)}$$

(~40% reduction of systematics w.r.t. 7 TeV analysis)







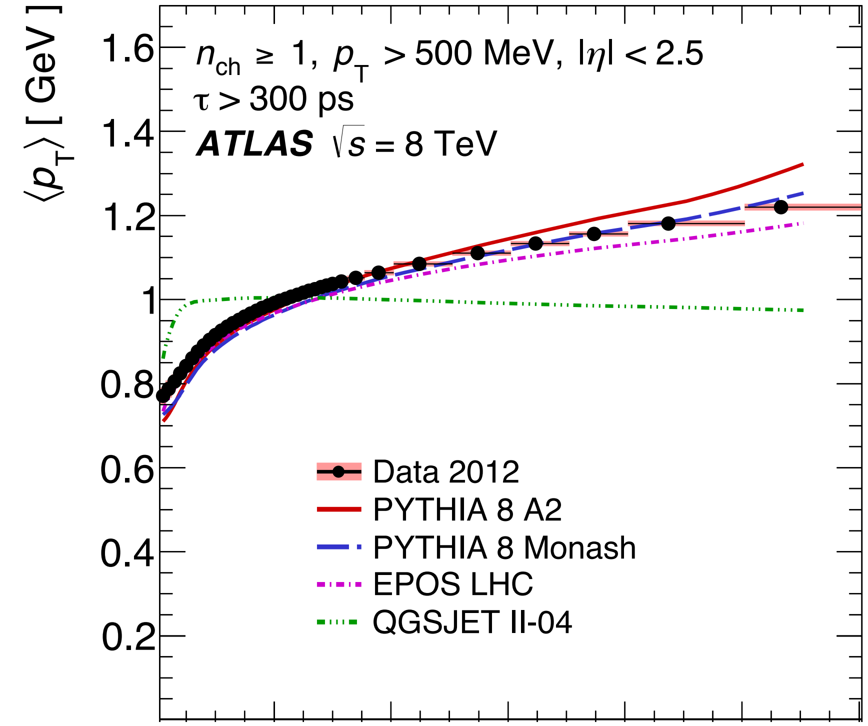


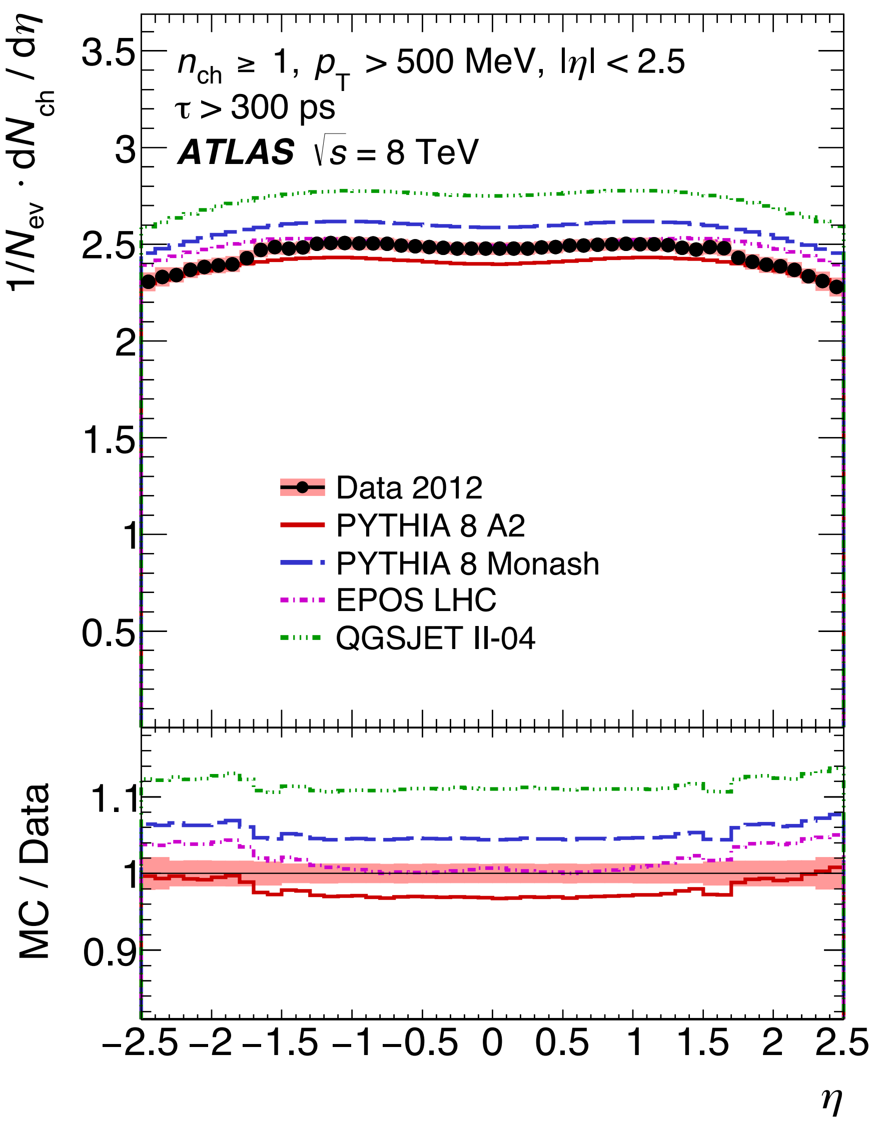
Results @ 8 TeV

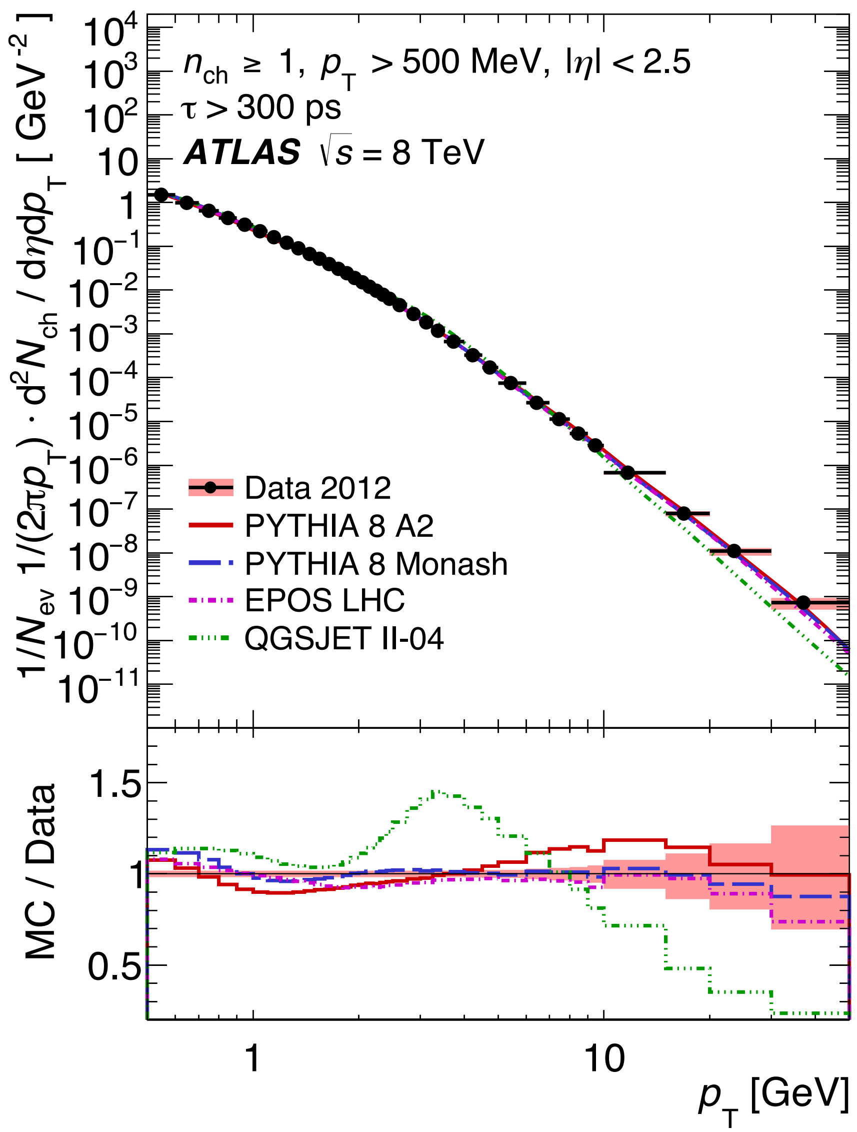
p_T>500 MeV:

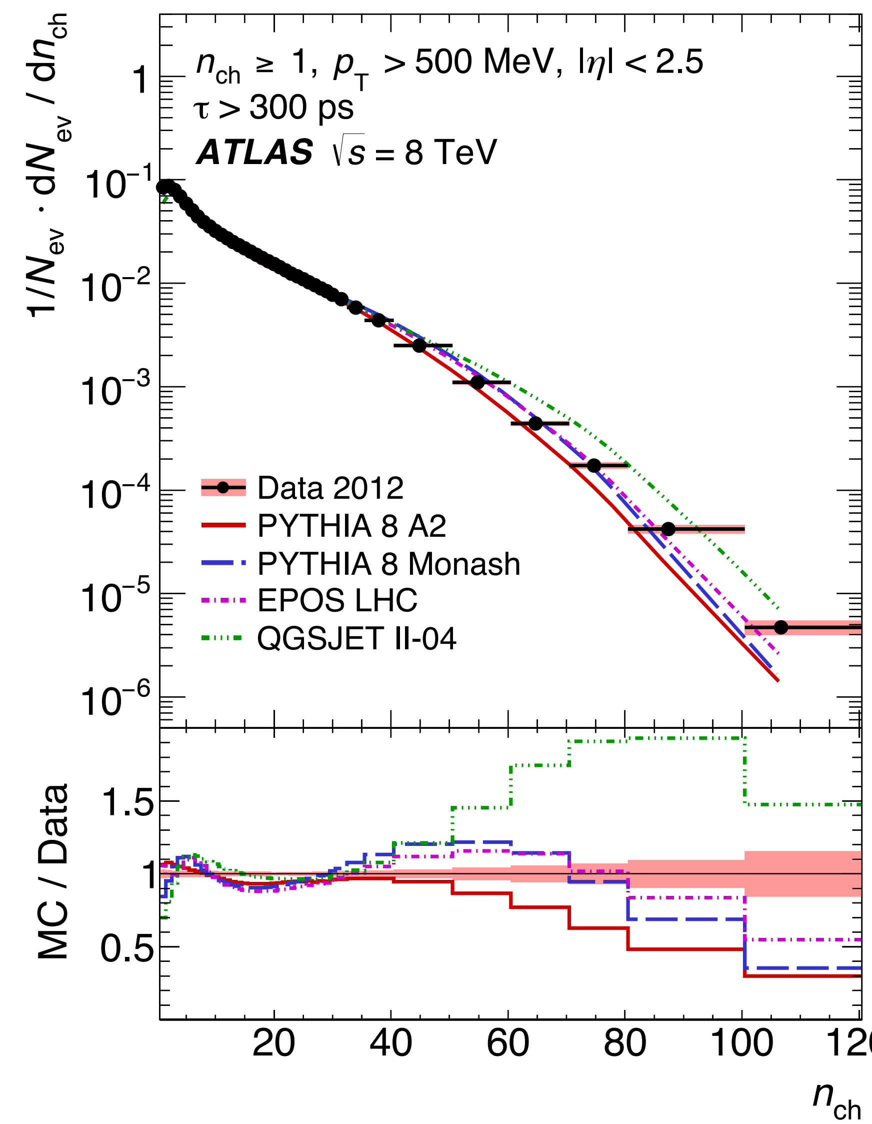
$$dN_{ch}/d\eta|_{\eta=0} = 2.477 \pm 0.001 \text{ (stat.)} \pm 0.031 \text{ (syst.)}$$

(~30% reduction of systematics w.r.t. 7 TeV analysis)







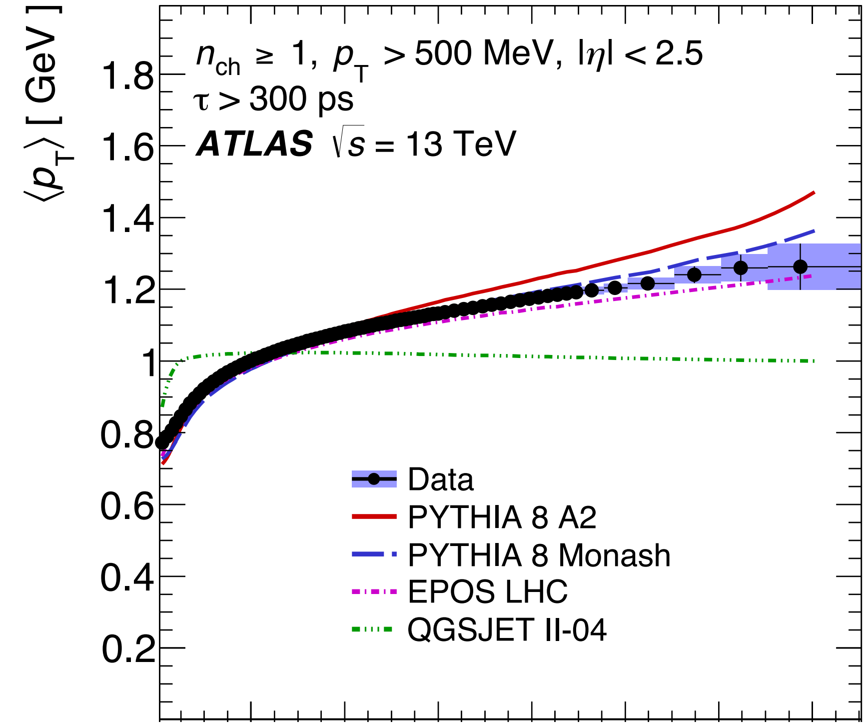


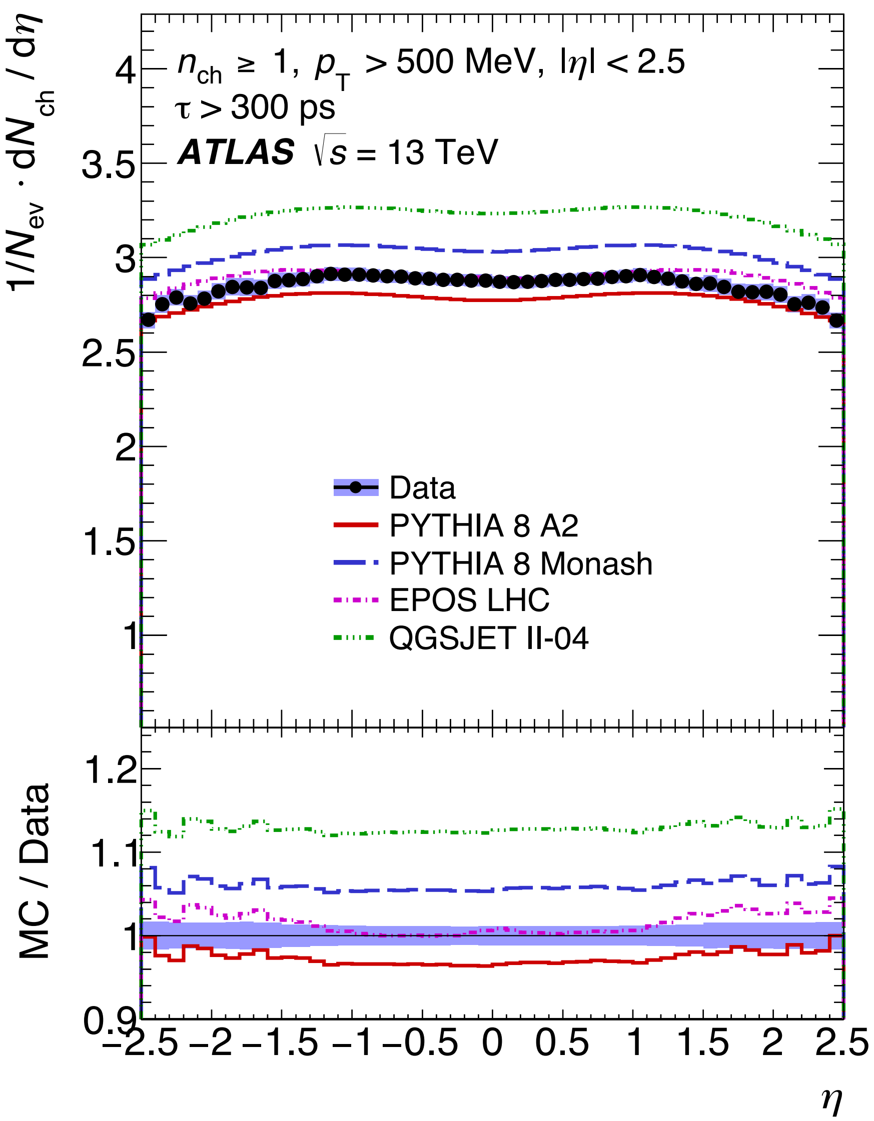
Results @ 13 TeV

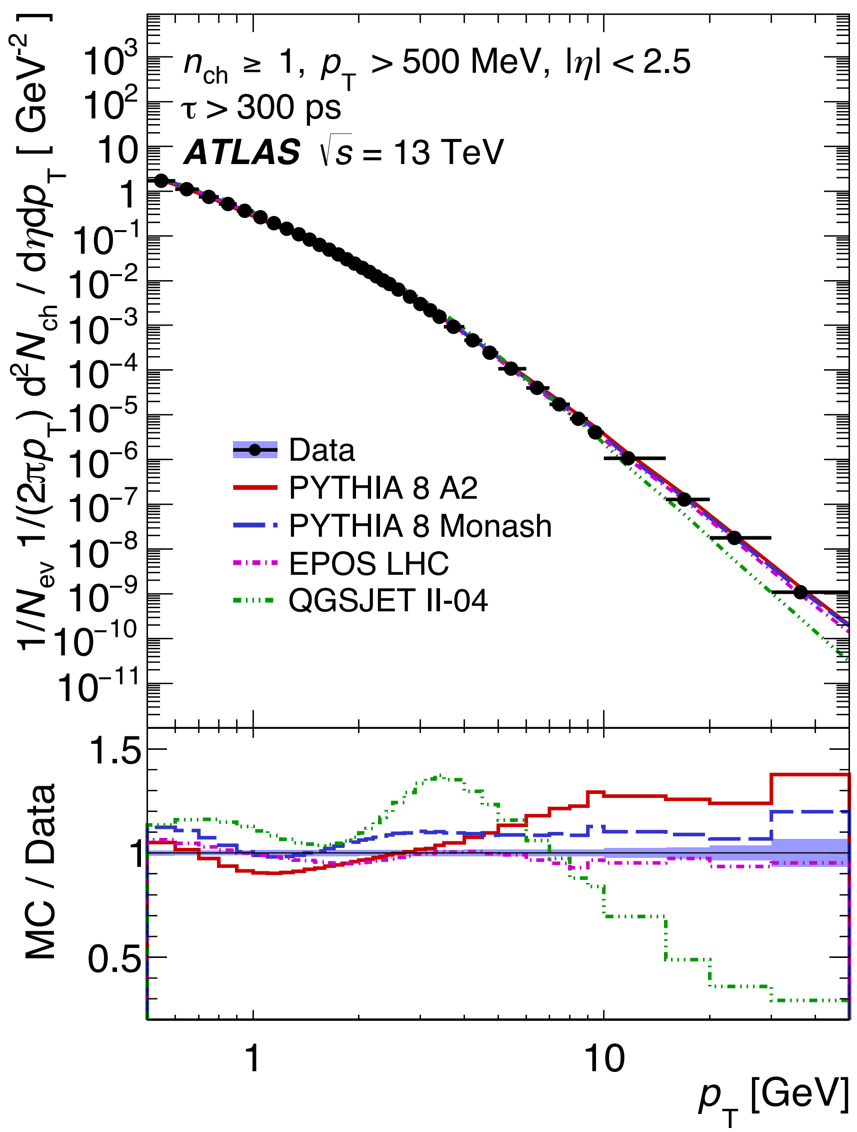
p_T>500 MeV:

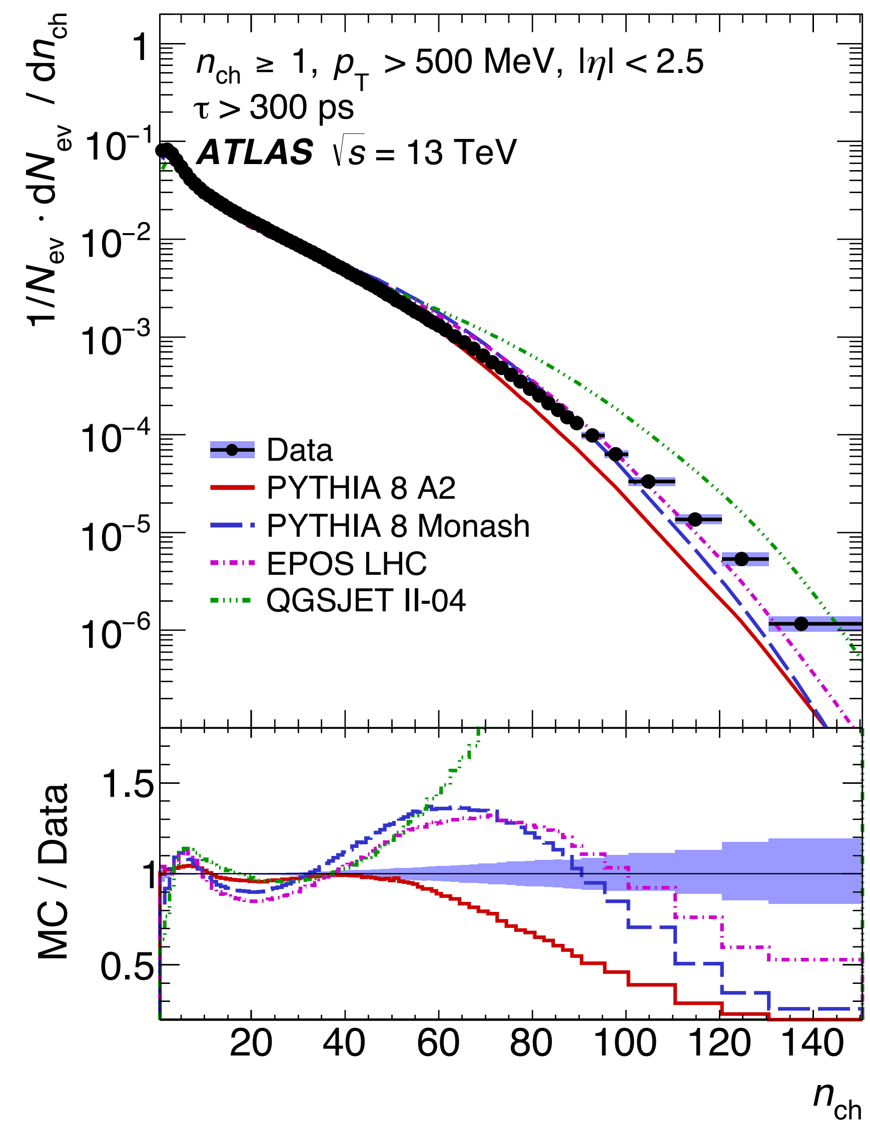
$$dN_{ch}/d\eta|_{\eta=0} = 2.874 \pm 0.001 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$$

(~30% reduction of systematics w.r.t. 7 TeV analysis)



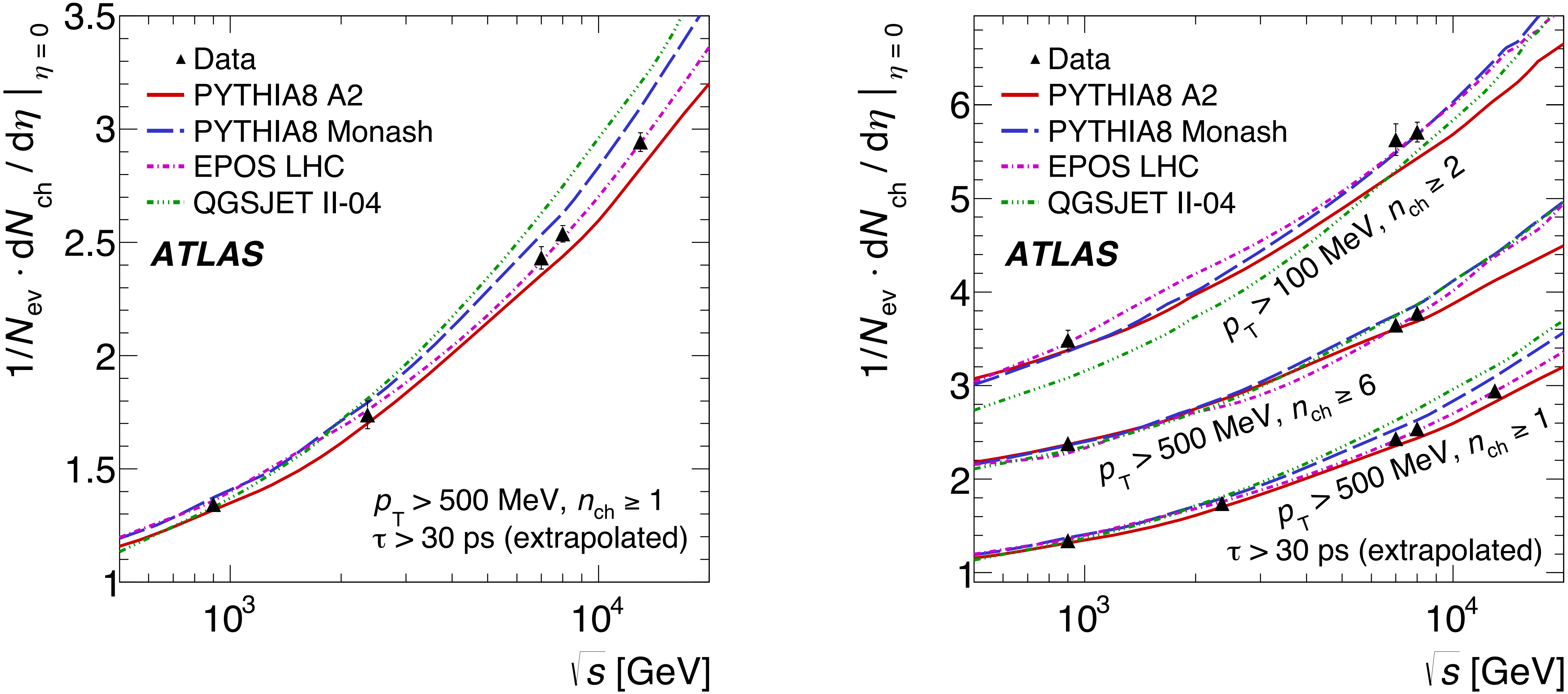






Central charged-particle density

0.9–13 TeV



results for 8 and 13 TeV are extrapolated to τ > 30 ps, and compared with previous measurements and latest MC tunes (in all phase spaces shown here, the EPOS LHC tune describes the data best, followed by the two PYTHIA 8 tunes)

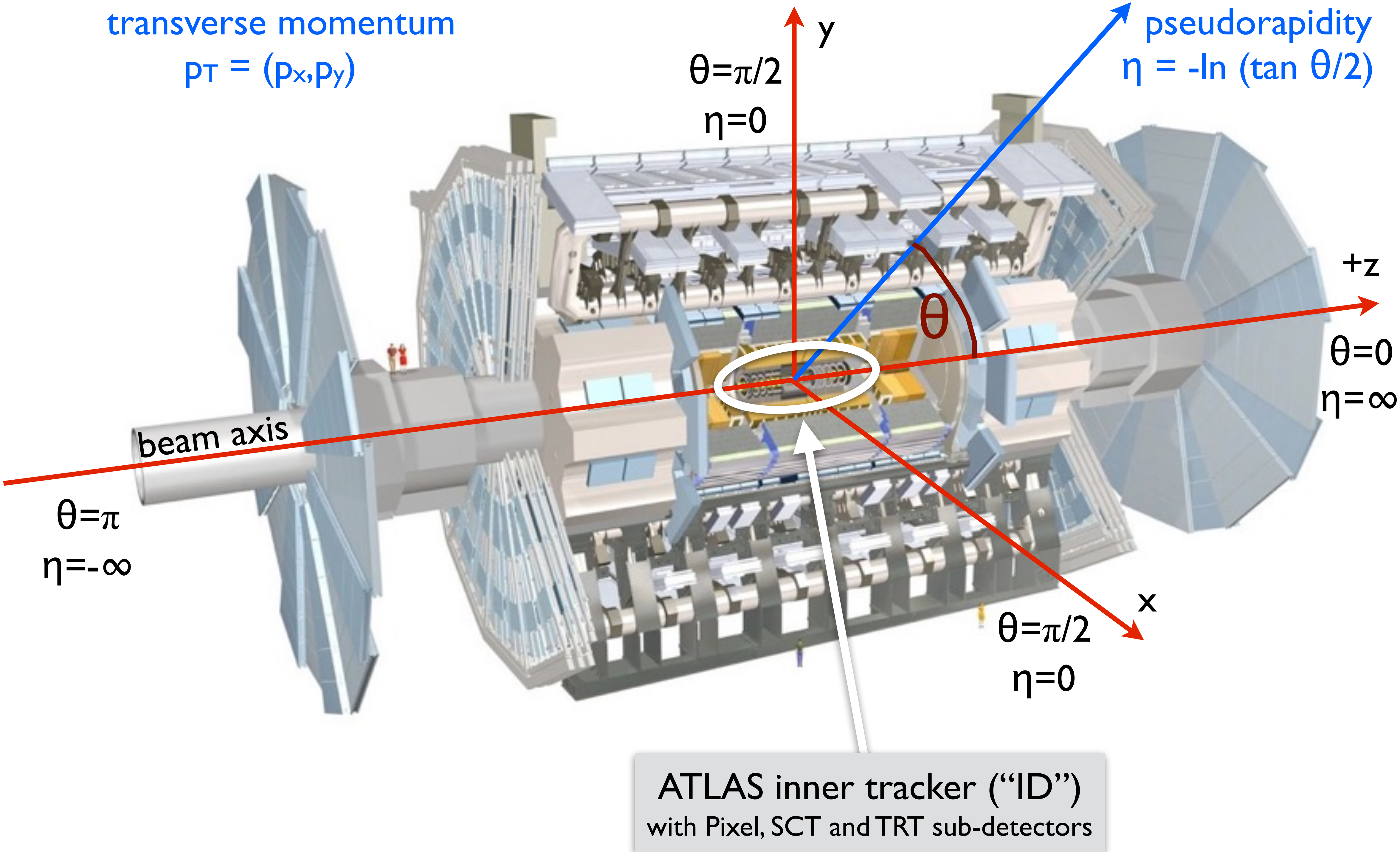
Conclusions

- new ATLAS measurements at 8 TeV and 13 TeV have much smaller systematics
  - mainly due to reduced uncertainty of the ID material budget (= dominant source)
  - total systematics of central charged-particle density: we achieved 30-40% reduction w.r.t. previous measurements
- additional high-multiplicity phase spaces were measured at 8 TeV
  - these results are expected to provide further valuable constraints for MC generator tuning
- additional restricted phase space $|\eta<0.8|$ was measured at 13 TeV
  - this facilitates comparison of results with other LHC experiments
- the corrected data were compared with generator predictions made by four MC tunes
  - EPOS LHC — PYTHIA 8 A2 — PYTHIA 8 Monash — QGSJET-II
  - overall the best predictions are achieved by EPOS LHC followed by the two PYTHIA 8 tunes
  - models tuned to Run 1 data (up to 7 TeV) are found to describe the MPI energy extrapolation well
- results have been submitted to EPJC (8 TeV) and PLB (13 TeV)
  - 8 TeV: arxiv:1603.02439
  - 13 TeV: arxiv:1602.01633

thank you for your attention!

Backup

The ATLAS experiment



Overview

phase spaces and MC tunes

Phase spaces

- same as in 0.9 and 7 TeV analyses
  - p_T>100 MeV, n_{ch}>=2
  - p_T>500 MeV, n_{ch}>=1 and 6
- + new high-multiplicity phase spaces
  - p_T>500 MeV, n_{ch}>=20 and 50

p_T>	n_{ch}>	0.9	7	8	13
100	2	yes	yes	yes	
500	1	yes	yes	yes	yes
500	6	yes	yes	yes	
500	20			yes	
500	50			yes	

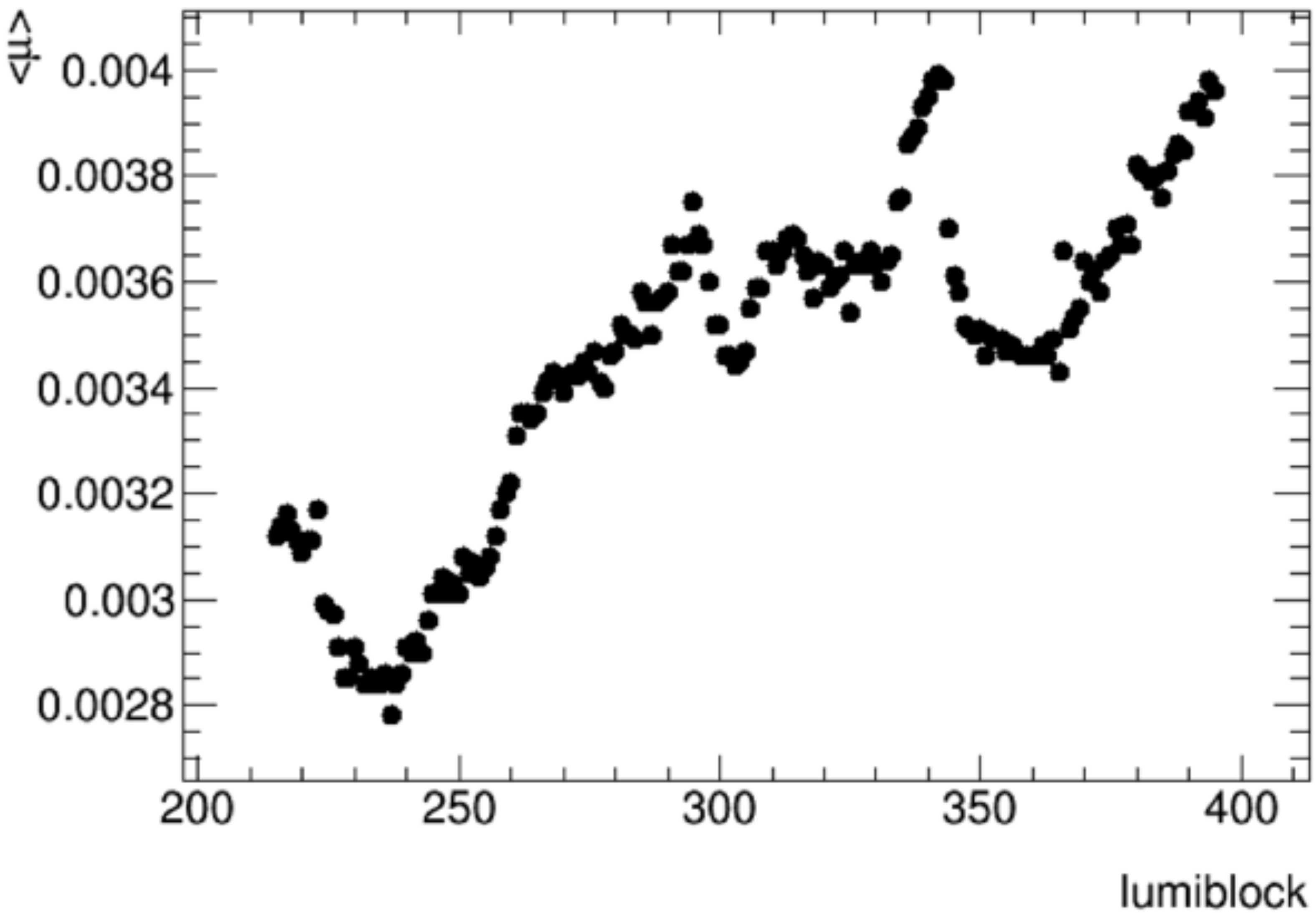
MC event generators

- Pythia 8 A2: baseline for most corrections
- Epos LHC: for strange baryon extrapolation

Generator	Tunes	shown in paper	used in analysis
Pythia 8	**A2 MSTW2008 LO**	**yes**	**yes**
Epos	**LHC tune**	**yes**	**yes**
Pythia 8	Monash NNPDF23 LO	yes	13 TeV
QGSJET	II-04 (LHC tune)	yes	
Pythia 6	AMBT2B CTEQ6 L1		8 TeV
Pythia 6	Innsbruck CTEQ6 L1		
Herwig++	UE-EE-5 CTEQ6 L1		
Herwig++	UE-EE-4 CTEQ6 L1		

Minimum Bias analysis

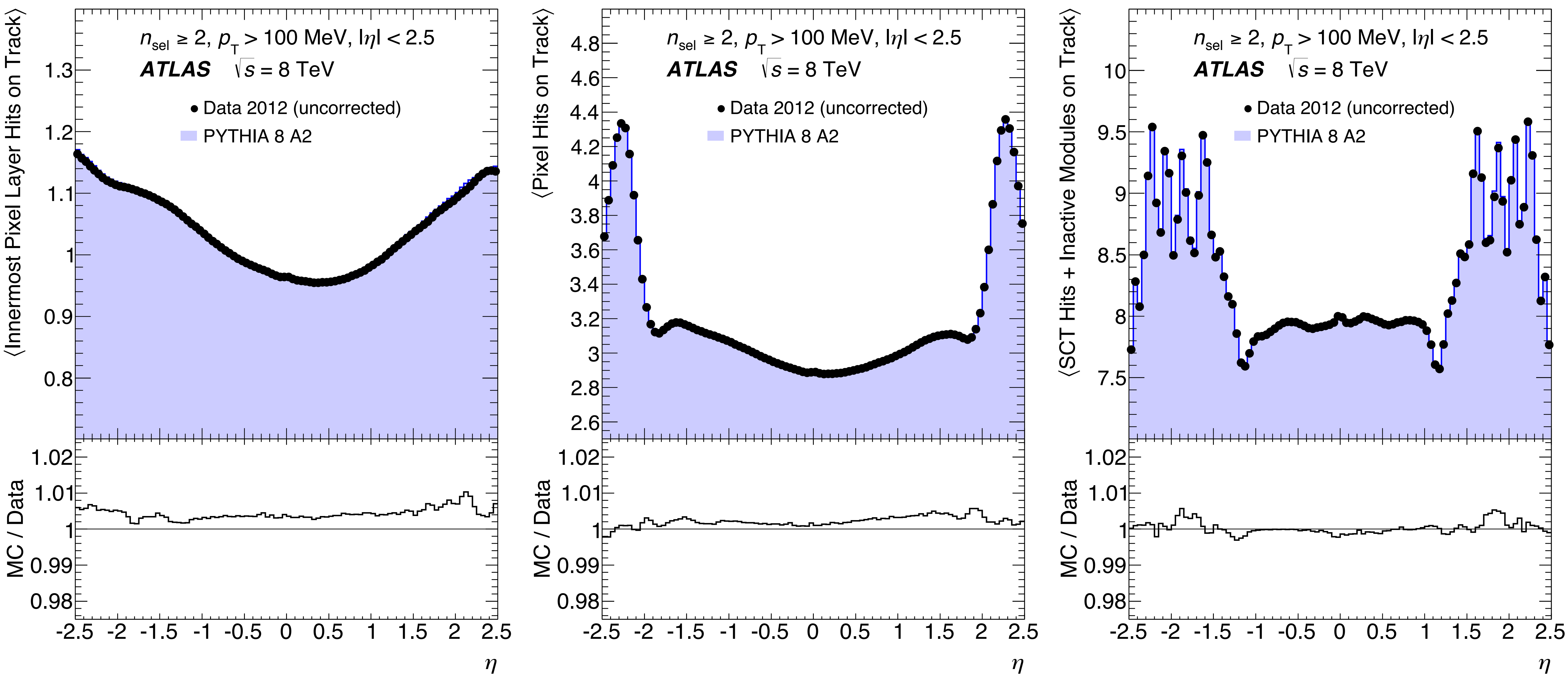
8 TeV dataset



~160 μb^{-1} data from low-μ run 200805 was recorded on 5th/6th April 2012, with μ<0.004 in the good LB range (215-395), recording a total of 11.45m events, out of which 9.17m events were finally selected in the p_T>100 MeV phase space.

Track reconstruction performance

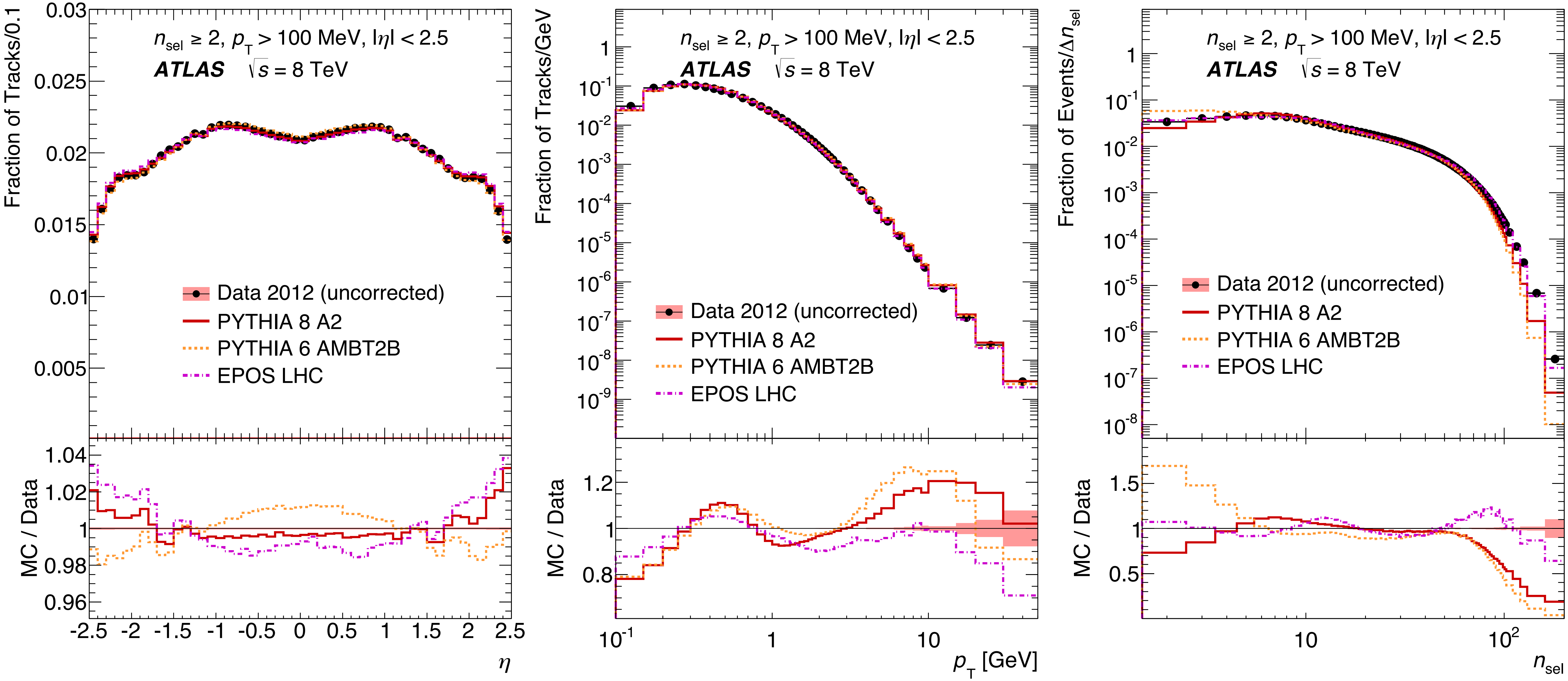
Hits on Track (p_T>100 MeV)



very good agreement between data/MC after p_T reweighting

Detector-level distributions

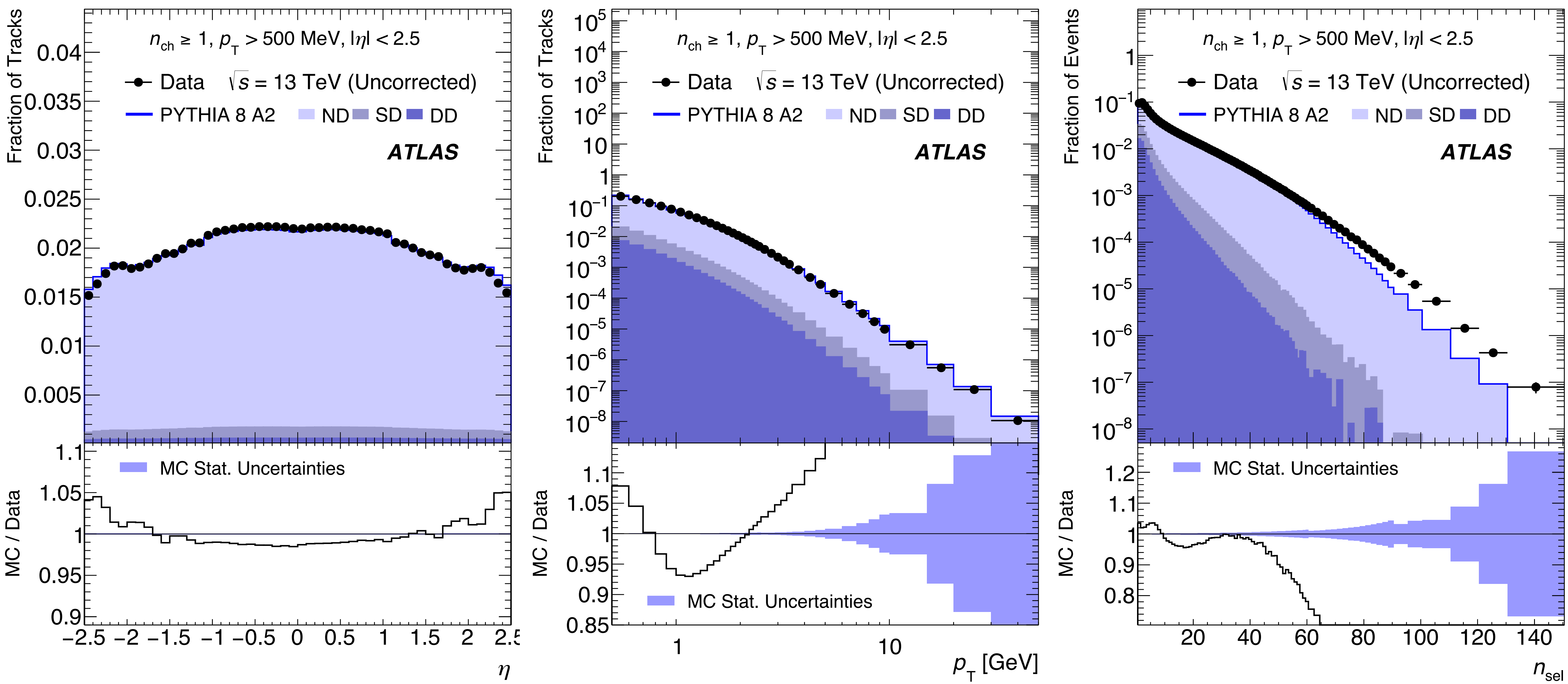
MC vs Data @ 8 TeV (p_T>100 MeV)



detector-level distributions before applying corrections for detector effects and reconstruction inefficiencies

Detector-level distributions

MC vs Data @ 13 TeV (p_T>500 MeV)



before applying corrections for detector effects and reconstruction inefficiencies