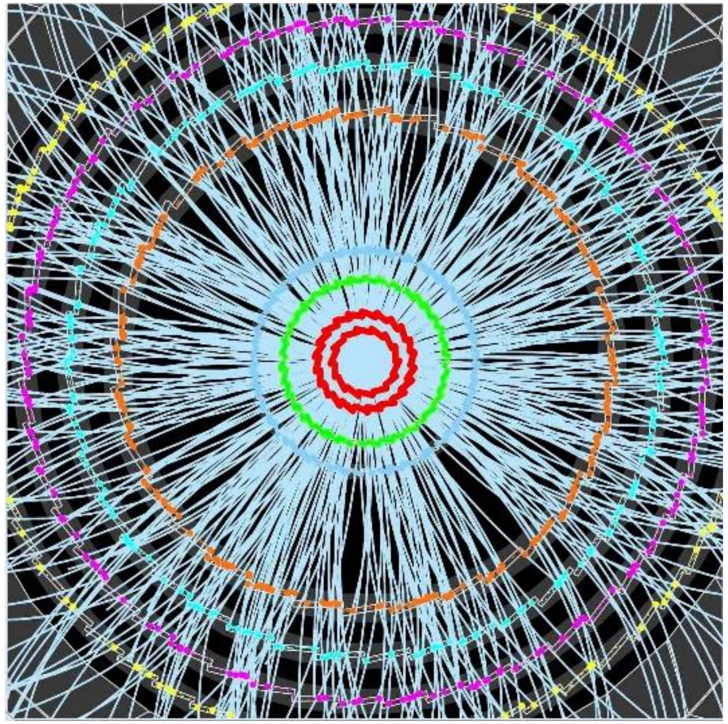
Measurement of Minimum Bias Observables with ATLAS

Jiří Kvita, 28th Nov 2016

Palacký University, RCPTM, Olomouc, Czech Republic

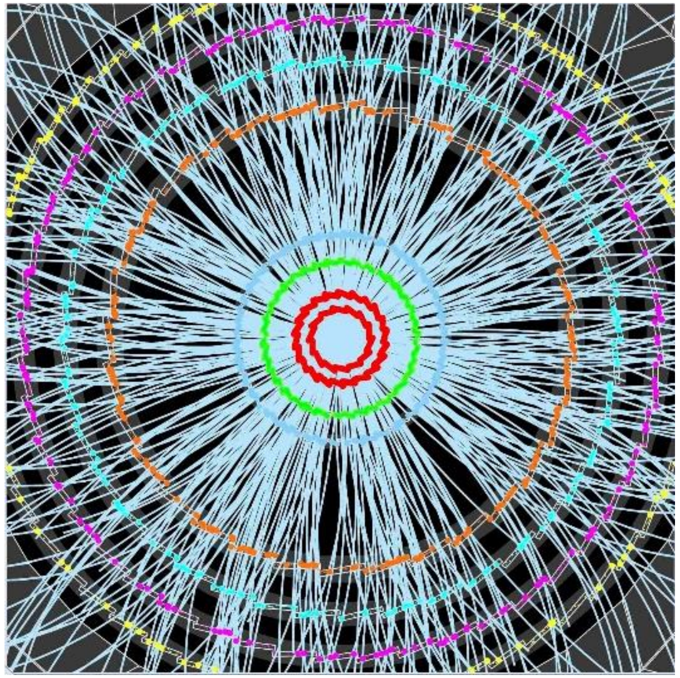
Outline

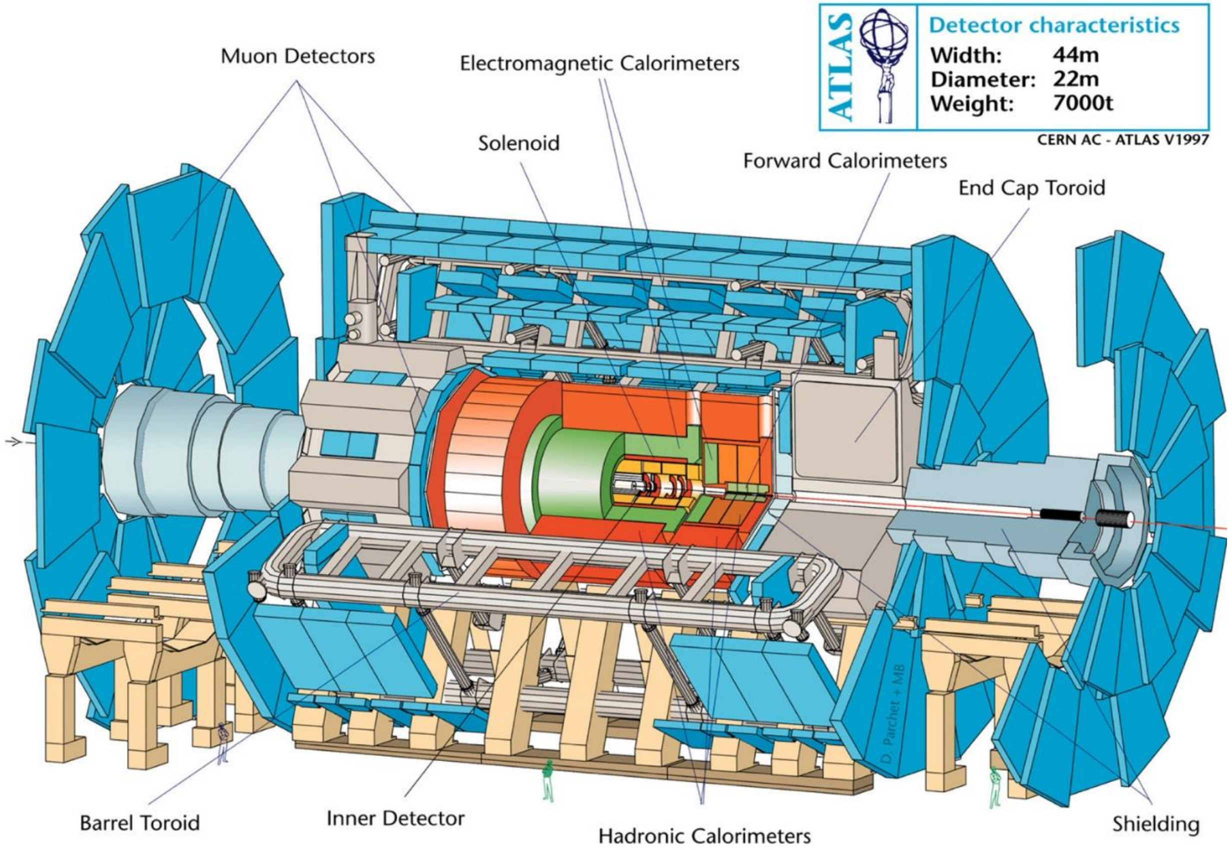
- Motivation
- ATLAS Inner Detector
- Samples, Selection
- Observables
- Corrections
- Systematics
- **NEW results since last MPI:**
  - **8 TeV** Results
  - **13 TeV** Results
- Conclusions



Motivation

- Measurements of charged particle multiplicities
  - important input for pile-up modelling in *pp* collisions.
  - provide insight into many aspects of non-perturbative physics in hadron collisions.
  - at several central-mass energies challenge models predictions up to O(10) TeV scales.
  - connection to cosmic ray physics.

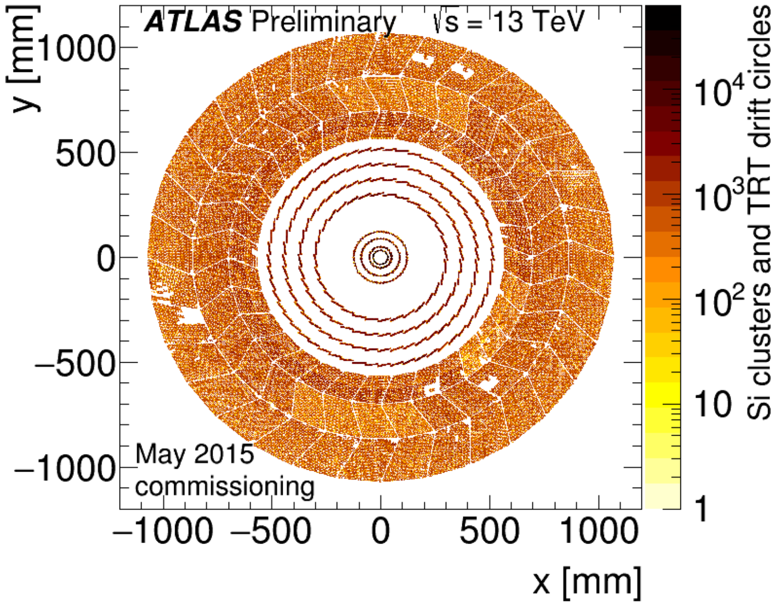




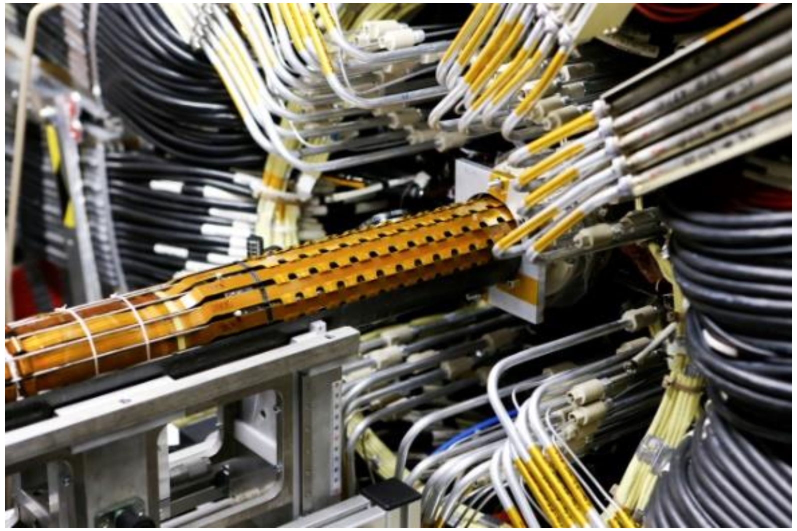
ATLAS Inner Detector

- Charged particles are identified by a set of silicon pixel and strip, and transition radiation detectors, providing excellent position, vertex and PID resolution.
- Discrimination between primary and secondary particles created in interactions in material or via decays.
- An additional layer of pixel detectors inserted for 13 TeV collisions – Insertable b-layer, IBL, allowed by a novel reduced-radius beam pipe.
  - Important for *b*-tagging and vertex resolution.
  - Pixel size: 50 x 250 μm.

Positions of clusters in IBL, pixel, strip and TRT detectors.



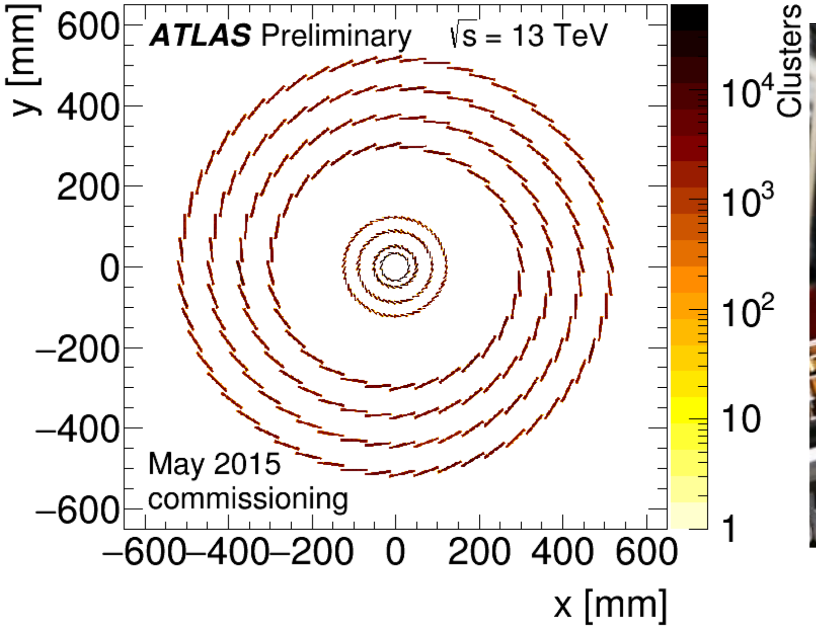
IBL insertion



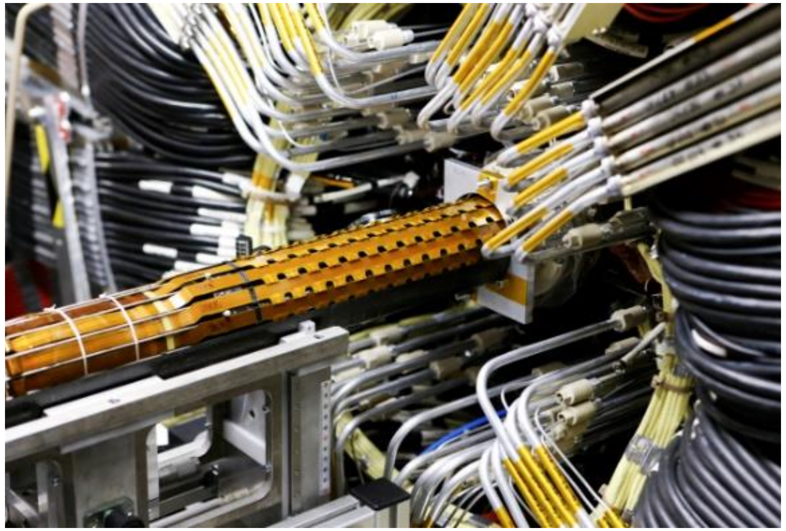
ATLAS Inner Detector

- Charged particles are identified by a set of silicon pixel and strip, and transition radiation detectors, providing excellent position, vertex and PID resolution.
- Discrimination between primary and secondary particles created in interactions in material or via decays.
- An additional layer of pixel detectors inserted for 13 TeV collisions – Insertable b-layer, IBL, allowed by a novel reduced-radius beam pipe.
  - Important for *b*-tagging and vertex resolution.
  - Pixel size: 50 x 250 μm.

Positions of clusters in IBL, pixel, strip detectors.

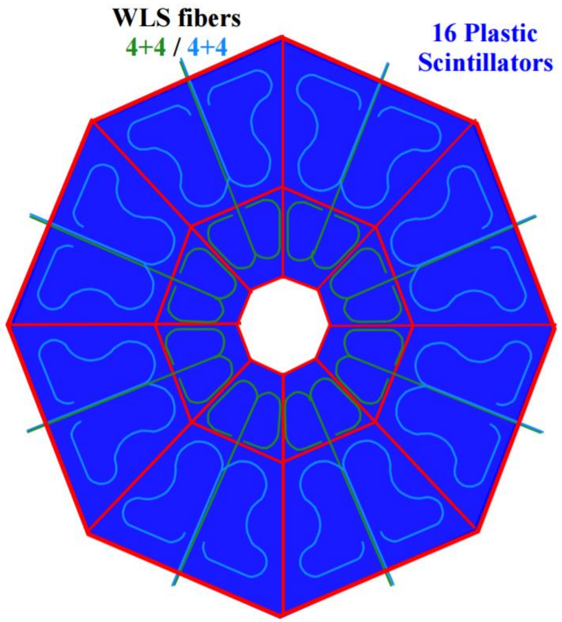


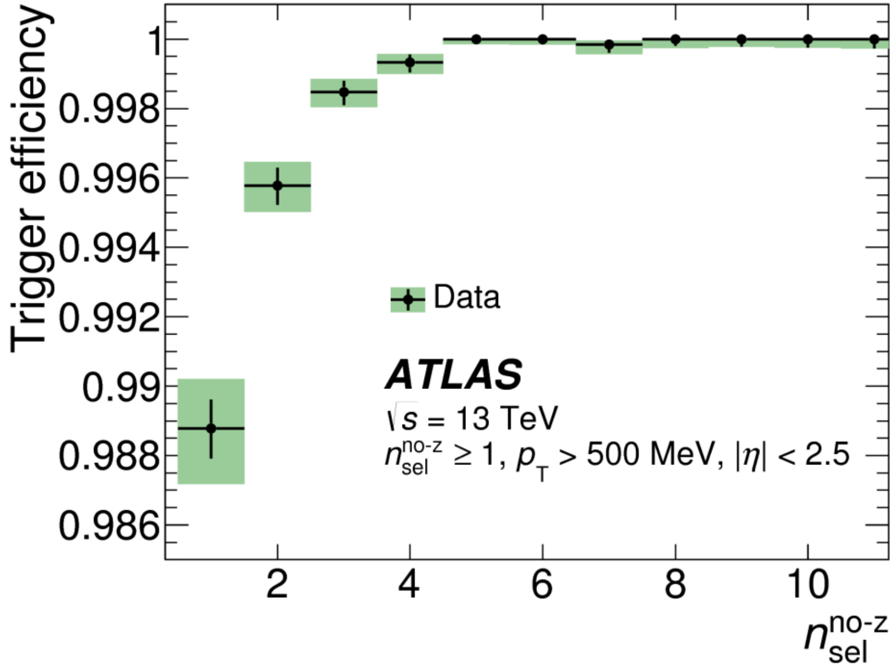
IBL insertion



Sample and Event Selection

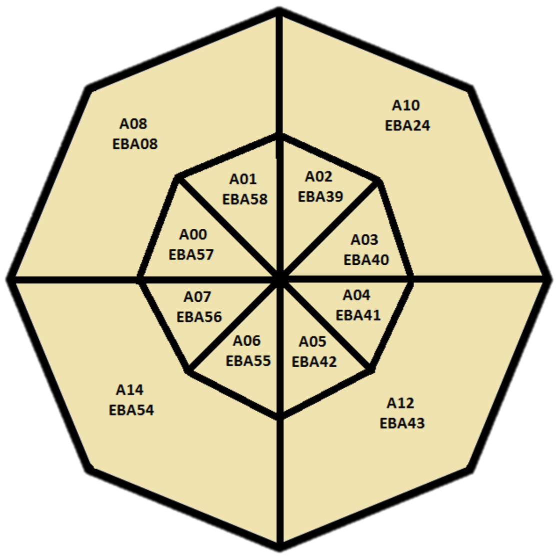
- **Minimum-Bias Trigger Scintilators** (MBTS).
- Two octants connected to PMTs, covering rapidity 2.1 to 3.8.
  - Very efficient and radiation hard.
- Special LHC fills at low pile-up, **will describe 8 and 13 TeV results.**
  - See arXiv::1012.5104 for 0.9, 2.36 and 7 TeV results.
- Includes single and double diffractive processes as well as non-diffractive, populating different rapidity and multiplicity regions.

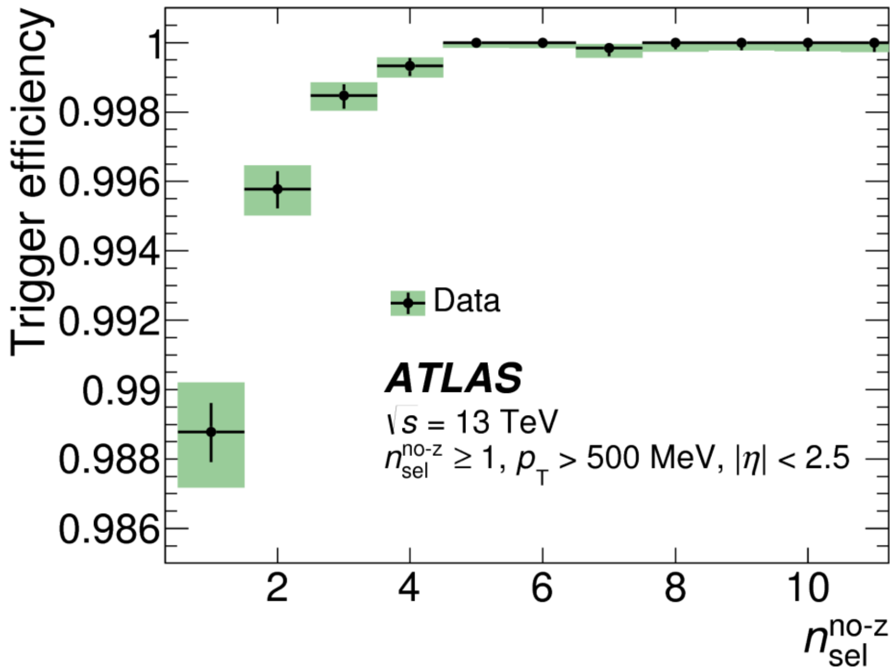




Sample and Event Selection

- **Minimum-Bias Trigger Scintilators** (MBTS), upgraded for 13 TeV collisions.
- 8+4 scintilators connected to PMTs, covering rapidity 2.1 to 3.8.
  - Very efficient and radiation hard.
- Special LHC fills at low pile-up (μ = 0.005!), **will describe 8 and 13 TeV results.**
  - See arXiv::1012.5104 for 0.9, 2.36 and 7 TeV results.
- Includes single and double diffractive processes as well as non-diffractive, populating **different rapidity and multiplicity regions which are all probed by data.**





Observables

- Both 8 and 13 TeV analyses measure the following spectra:
- **Charged particles multiplicities as function of rapidity and p_T:**

$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}} \qquad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} \qquad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}}$$

- **Average transverse momentum in multiplicity bins:** $\langle p_{\mathrm{T}} \rangle$ vs n_{ch}
- All distributions are corrected (**unfolded**) to stable particles level.

- **Stable particles:** τ > 300 ps (cτ > 9 cm)
  - Include decay products of particles with τ < 30 ps (cτ < 9 mm)
  - NEW: **Exclude** particles with 30 < τ < 300 ps:
    - **Charged strange baryons** with low (0,3%) reconstruction efficiency due to late decay and few silicon hits.
    - **Inconsistencies in their description among models, would yield a large systematics uncertainty.**

Corrections and Analysis @ 8 TeV

- Event weighted to compensate for finite trigger and vertex efficiency:

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

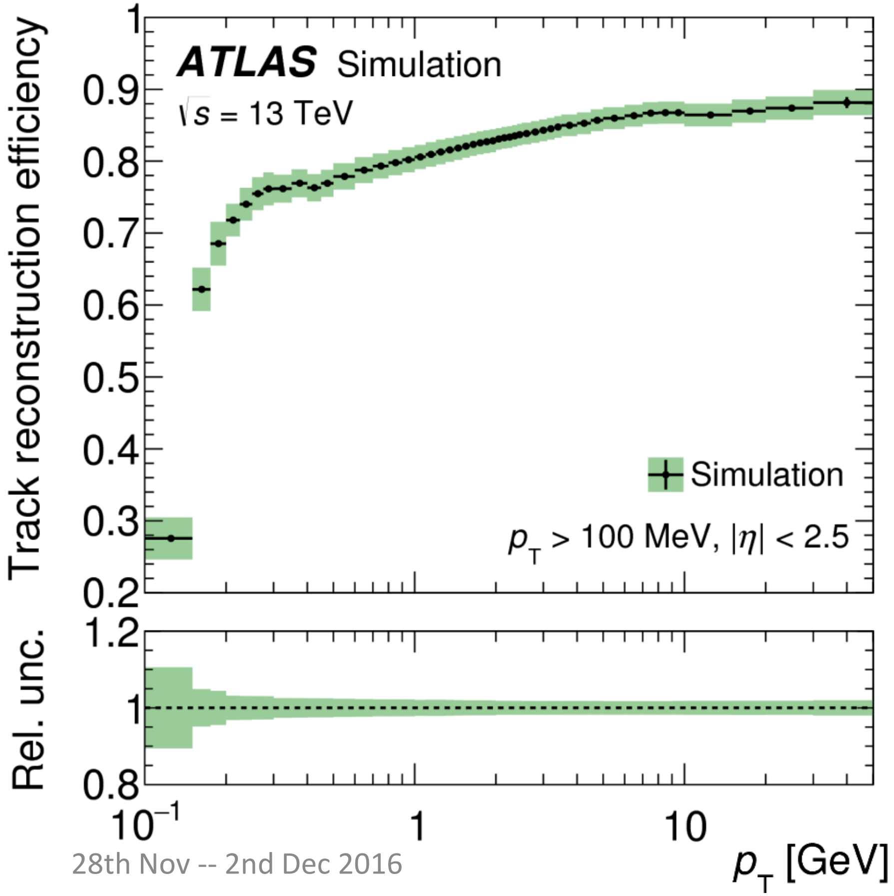
- Each selected track weighted to compensate for finite tracking efficiency and non-prompt particles, strange baryons (EPOS) and out-of-kinematic region fractions:

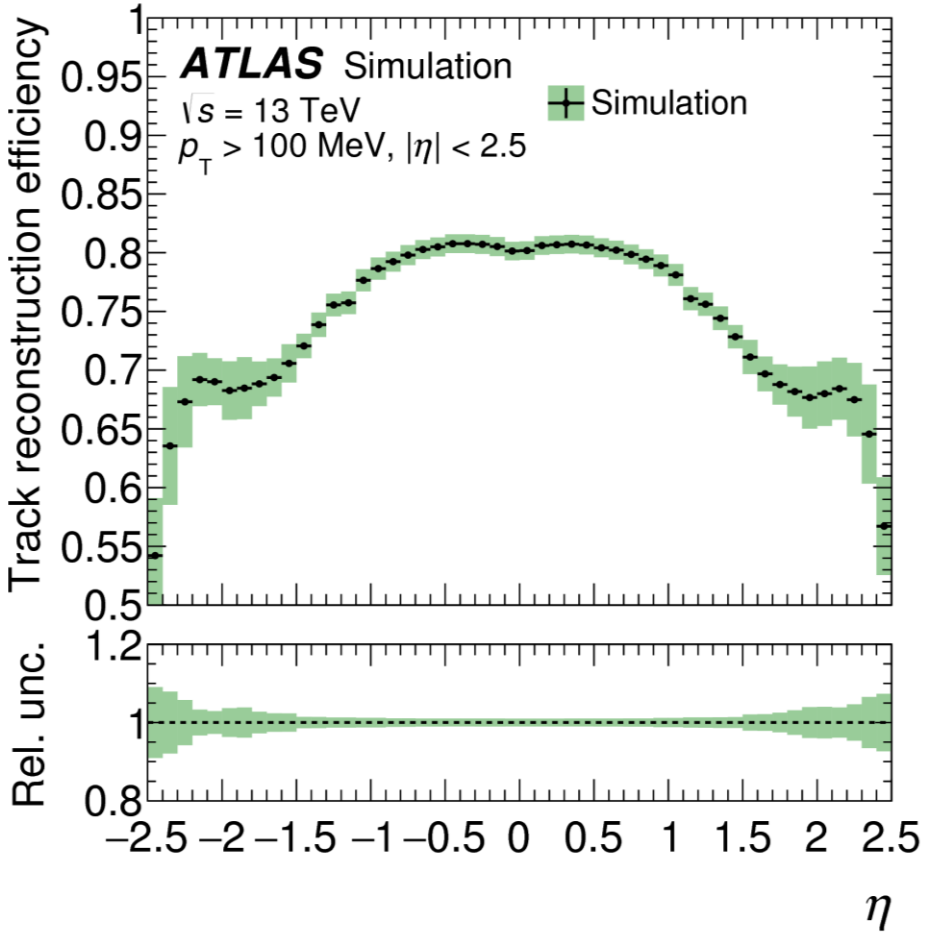
$$w_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{1 - f_{\mathrm{nonp}}(p_{\mathrm{T}}, \eta) - f_{\mathrm{sb}}(p_{\mathrm{T}}, \eta) - f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta)}{\varepsilon_{\mathrm{trk}}(p_{\mathrm{T}}, \eta)}$$

- **Why the 8 TeV measurement when 7 TeV available?**
  - New tracking algorithm.
  - Better material description, smaller systematics.
  - More fiducial regions of particles multiplicities, more constraining results.

Tracks Selection and Efficiency

- Tracks within $|\eta| < 2.5$, $|d_0| < 1.5$ mm, hits requirements in pixels and strips.
  - Good χ^2 for high-p_T tracks, require hit in first silicon layer if expected etc.
- >= **1 trk** for the p_T > **500 MeV** analysis.
- >= **2 trk** for the p_T > **100 MeV** analysis.





Systematic uncertainties

- Affect the corrections.
  - Trigger, tracking and vertexing efficiencies.
- Different spectra in data and MC
  - Lead to different efficiency, 2% effect, 5% in high multiplicities.
- **Material description in simulation**
  - About a 5% uncertainty at 8 TeV.
- Secondaries fraction scale between data and MC.
  - Minor source due to low background levels.
- Particles composition
  - Affects efficiency depending on particle type.
  - Only a 1% effect.
- Momentum resolution
  - Negligible except on p_T spectra.
- Unfolding non-closure (1%)

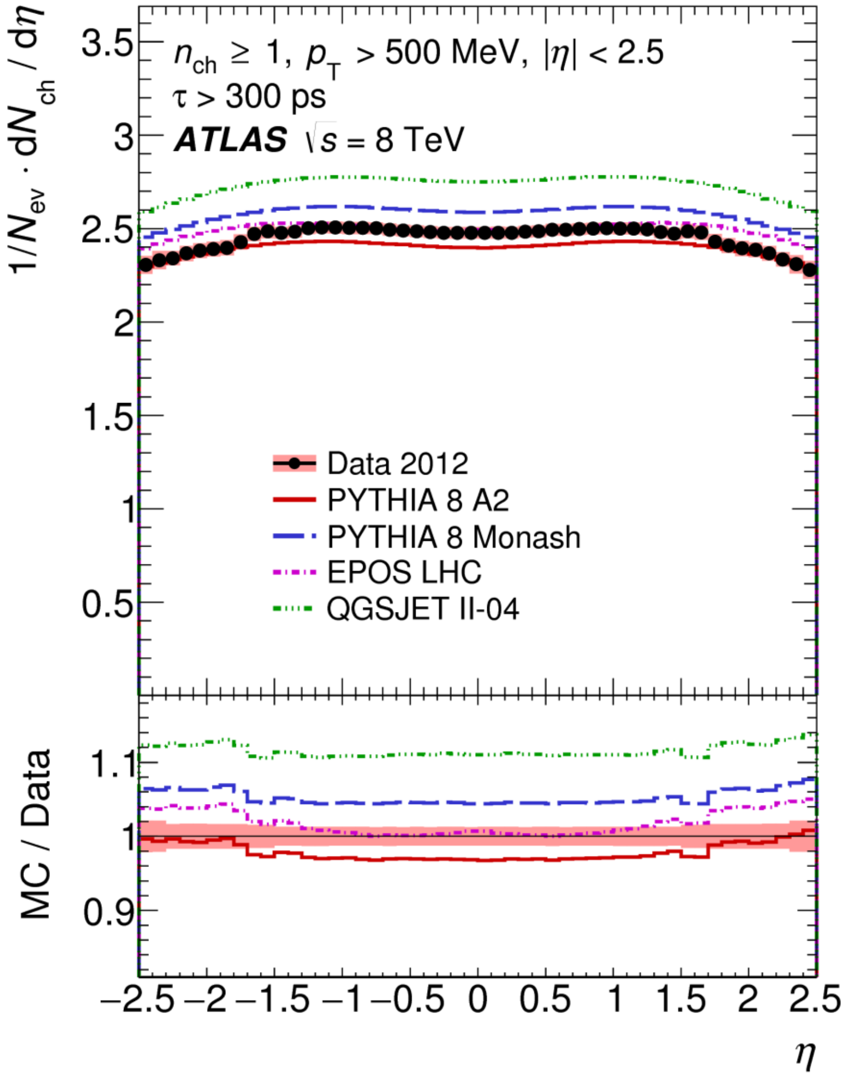
Table 2: Summary of systematic uncertainties on the η, p_T and n_{ch} distributions.

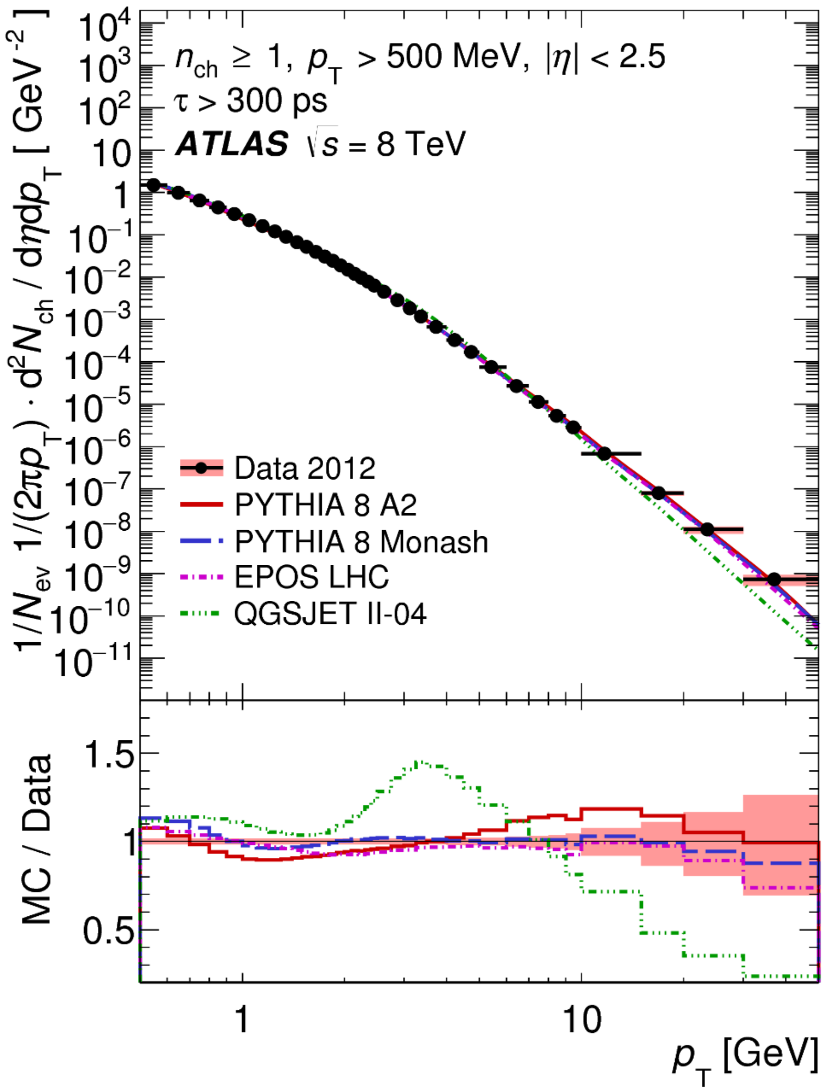
Source	Distribution	Range of values
Track reconstruction efficiency	η	0.5% – 1.4%
	p_T	0.7%
	n_{ch}	$0\% - ^{+17\%}_{-14\%}$
Non-primaries	η	0.5%
	p_T	0.5% – 0.9%
	n_{ch}	$0\% - ^{+10\%}_{-8\%}$
Non-closure	η	0.7%
	p_T	0% – 2%
	n_{ch}	0% – 4%
p_T-bias	p_T	0% – 5%
High-p_T	p_T	0% – 1%

8 TeV Results, 500 MeV Analysis :: $n_{ch} \geq 1$

- 9M events, 160 μb^{-1} :: arXiv::1603.02439, Eur. Phys. J. **C** (2016) 76:403.
- **Track impact parameters wr.t. beam spot (BS).**
- Per-event charge particles multiplicity best described by EPOS.
- **All generators describe well the η shape.**
- **QGSJET does not describe the p_T dependence.**

- A2 tuned on 7 TeV data.
- Monash is a more general purpose tune (SPS and Tevatron data).



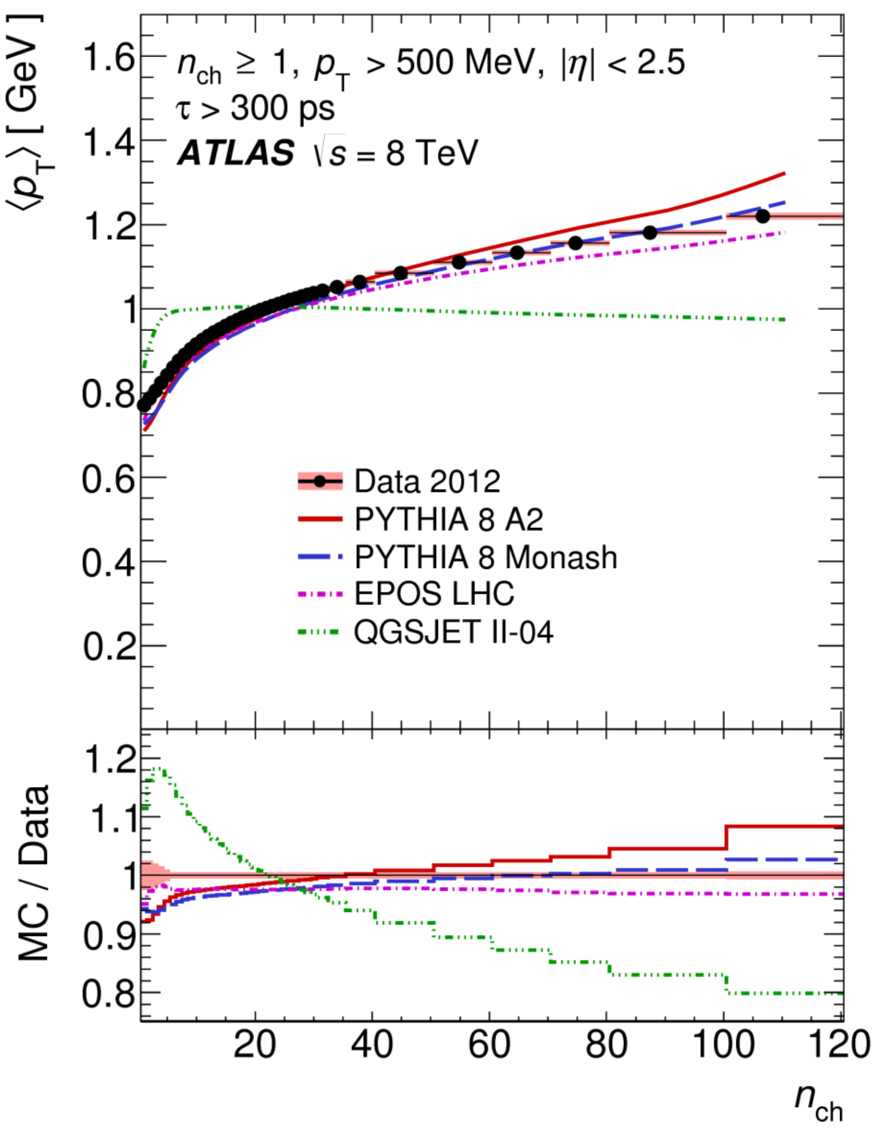


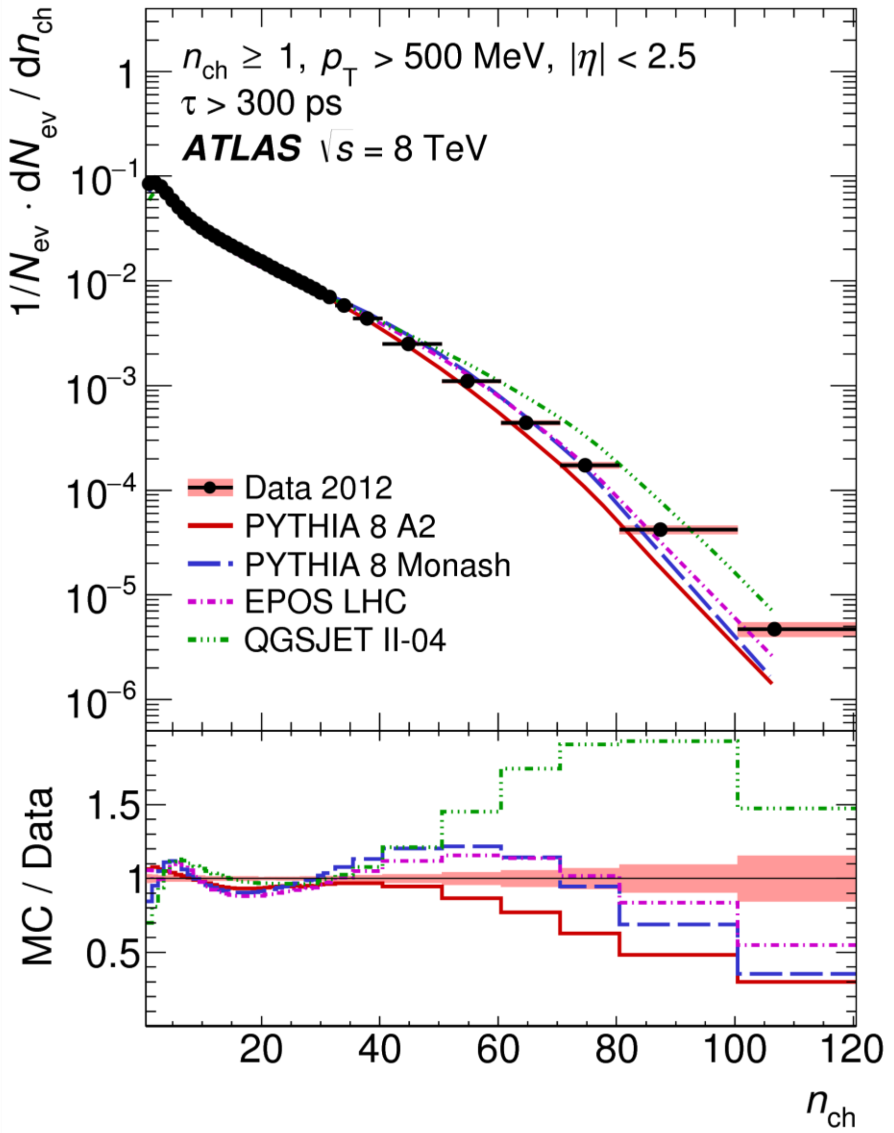
8 TeV Results, 500 MeV Analysis :: $n_{ch} \geq 1$

- 9M events, 160 μb^{-1} :: arXiv::1603.02439, Eur. Phys. J. **C** (2016) 76:403.

- **Reasonable description of data by Pythia A2 and Monash tunes, and EPOS.**
- **Average p_T not described by QGSJET, which also deviates at large multiplicities.**

- A2 tuned on 7 TeV data.
- Monash is a more general purpose tune.

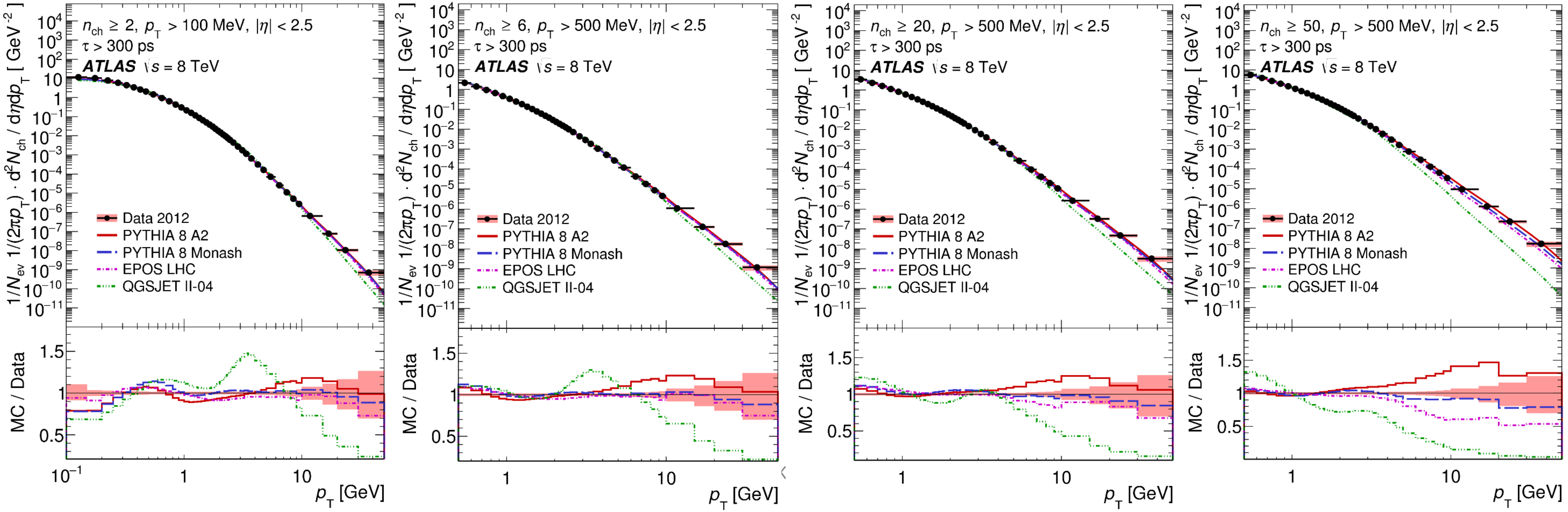




8 TeV Results, 500 MeV Analysis

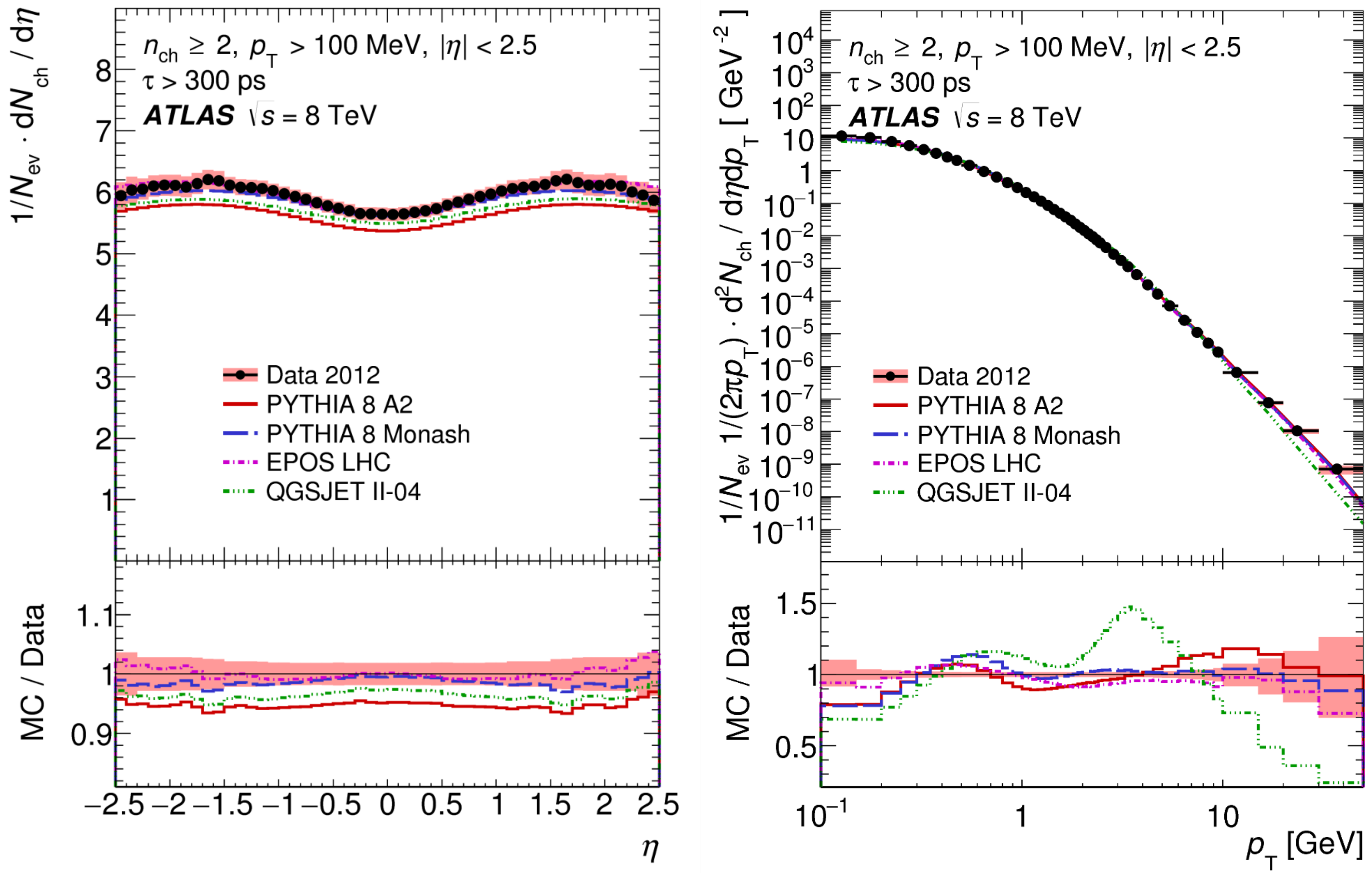
- Additional phase spaces of different charged particles multiplicities:
  - n_{ch} >= **2** , n_{ch} >= **6**, n_{ch} >= **20**, n_{ch} >= **50**
- **Very good Monash performance, also EPOS, less of A2, failing QGSJET.**
- Multiplicities as function of p_T in different multiplicity phase-spaces:

n_{ch} >= **2** | n_{ch} >= **6** | n_{ch} >= **20** | n_{ch} >= **50**



8 TeV Results :: the 100 MeV Analysis :: $n_{ch} \geq 2$

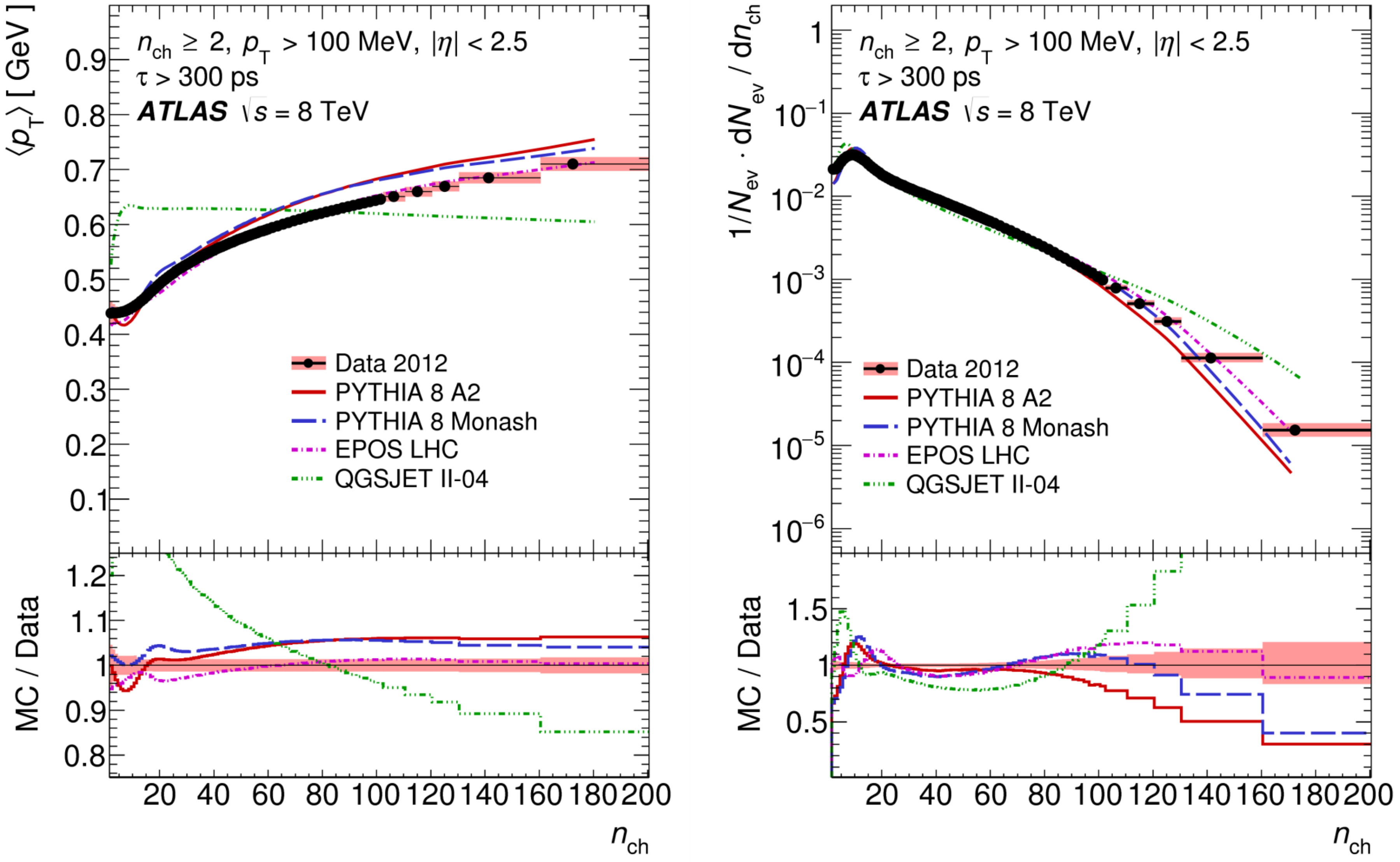
- **All generators differ at forward rapidities**, though within systematic uncertainties.
- Pythia8 A2 and QGSJET describe η shape but fails at overall normalization.
- Only reasonable p_T dependence description, where QGSJET shows largest deviations.



8 TeV Results :: the 100 MeV Analysis :: $n_{ch} \geq 2$

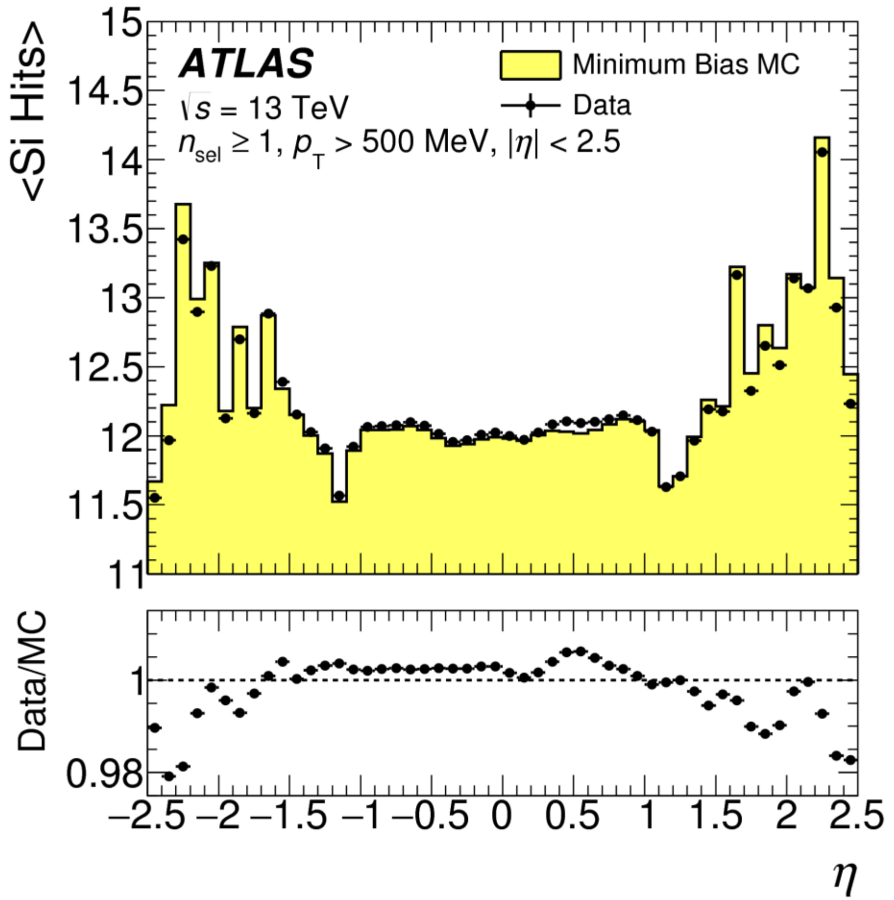
- **Pythia8 tunes and EPOS work reasonably well for the multiplicity shape.**

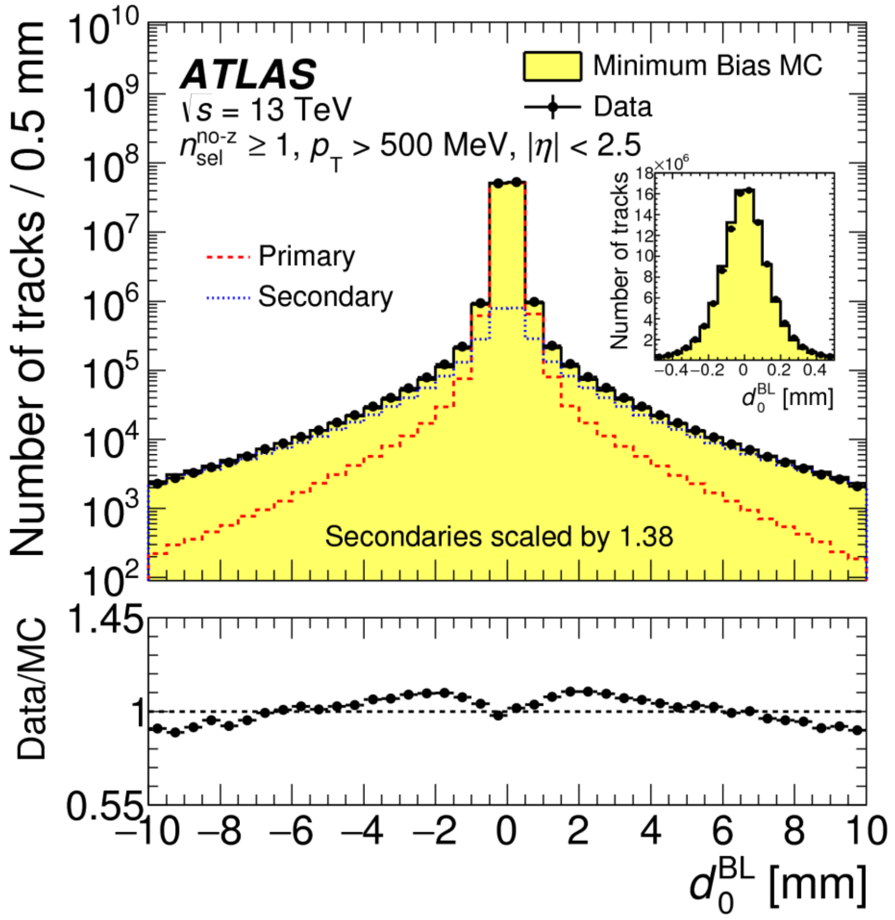
- QGSJET fails for $<p_T>$ while EPOS is best.
- All generators fail at low and high n_{ch}.
- **More pronounced structures.**



13 TeV Results :: the 500 MeV Analysis

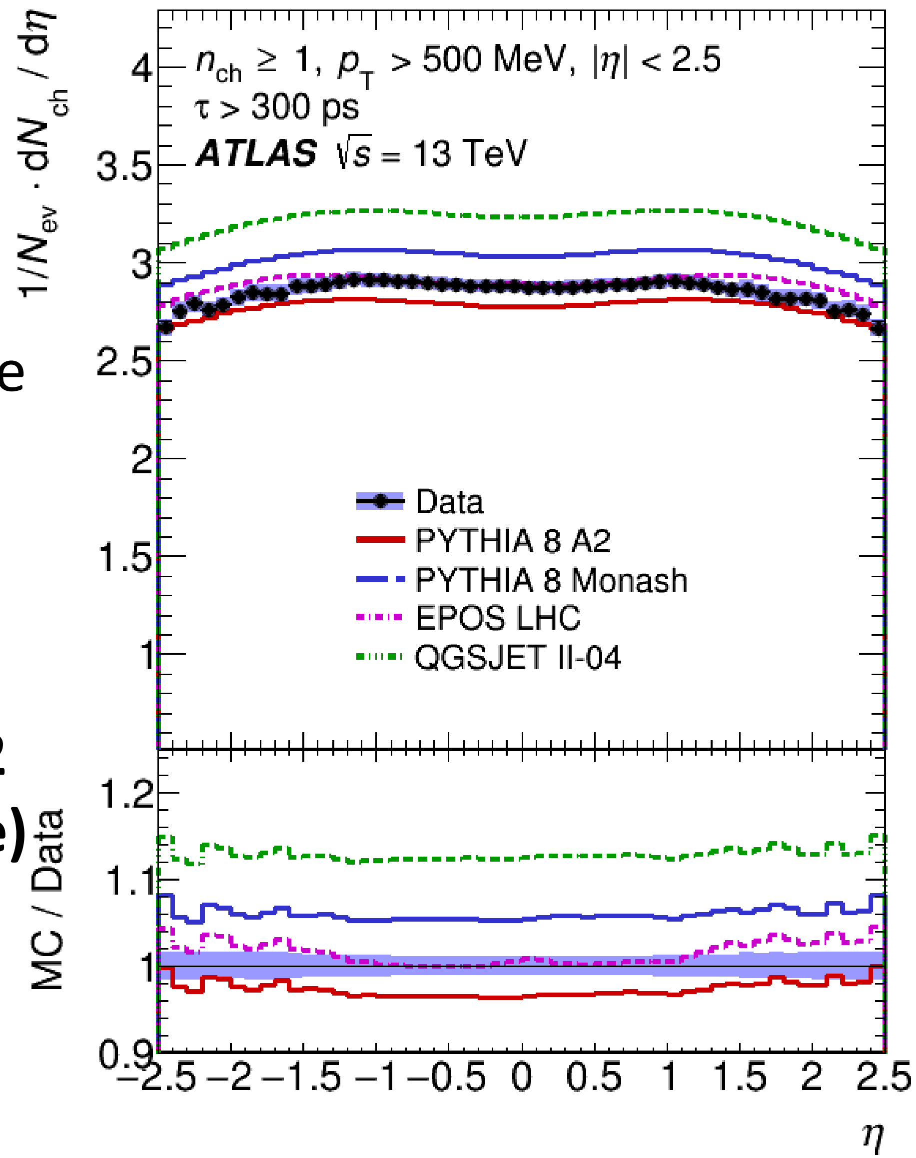
- 9M events, 170 μb^{-1} :: arXiv::1602.01633, Physics Letters **B** (2016), Vol. 758, pp. 67-88.
- **Impact parameter w.r.t. the beam line (BL) position.**
- Good detector performance and data/simulation agreement.

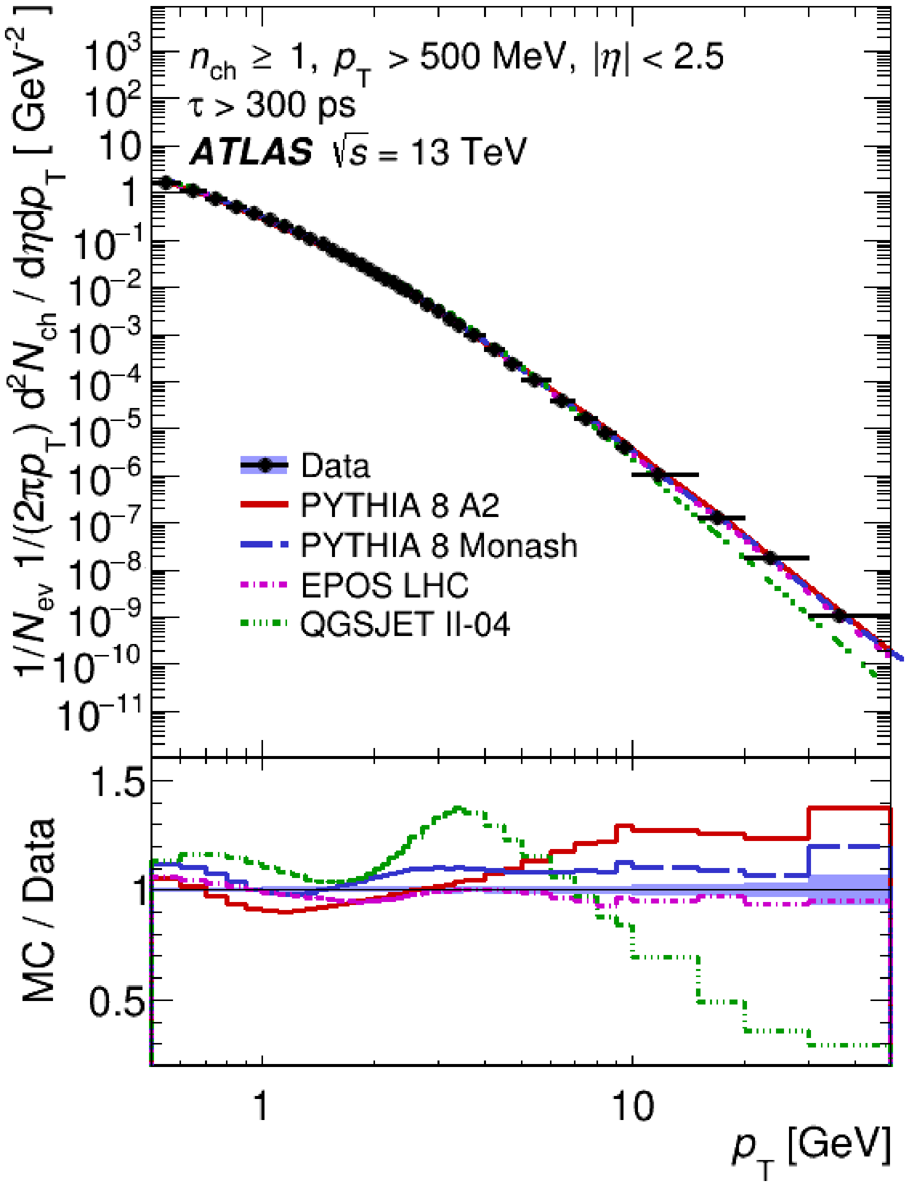




13 TeV Results :: the 500 MeV Analysis :: $n_{ch} \geq 1$

- Systematics dominated measurements.
- Per-event **charge particles multiplicity best described by EPOS.**
- All generators describe the η dependence.
- QGSJET does not describe the n_{ch} p_T dependence.
- **Fair description by A2 (which is a 7 TeV tune) of 13 TeV data!**

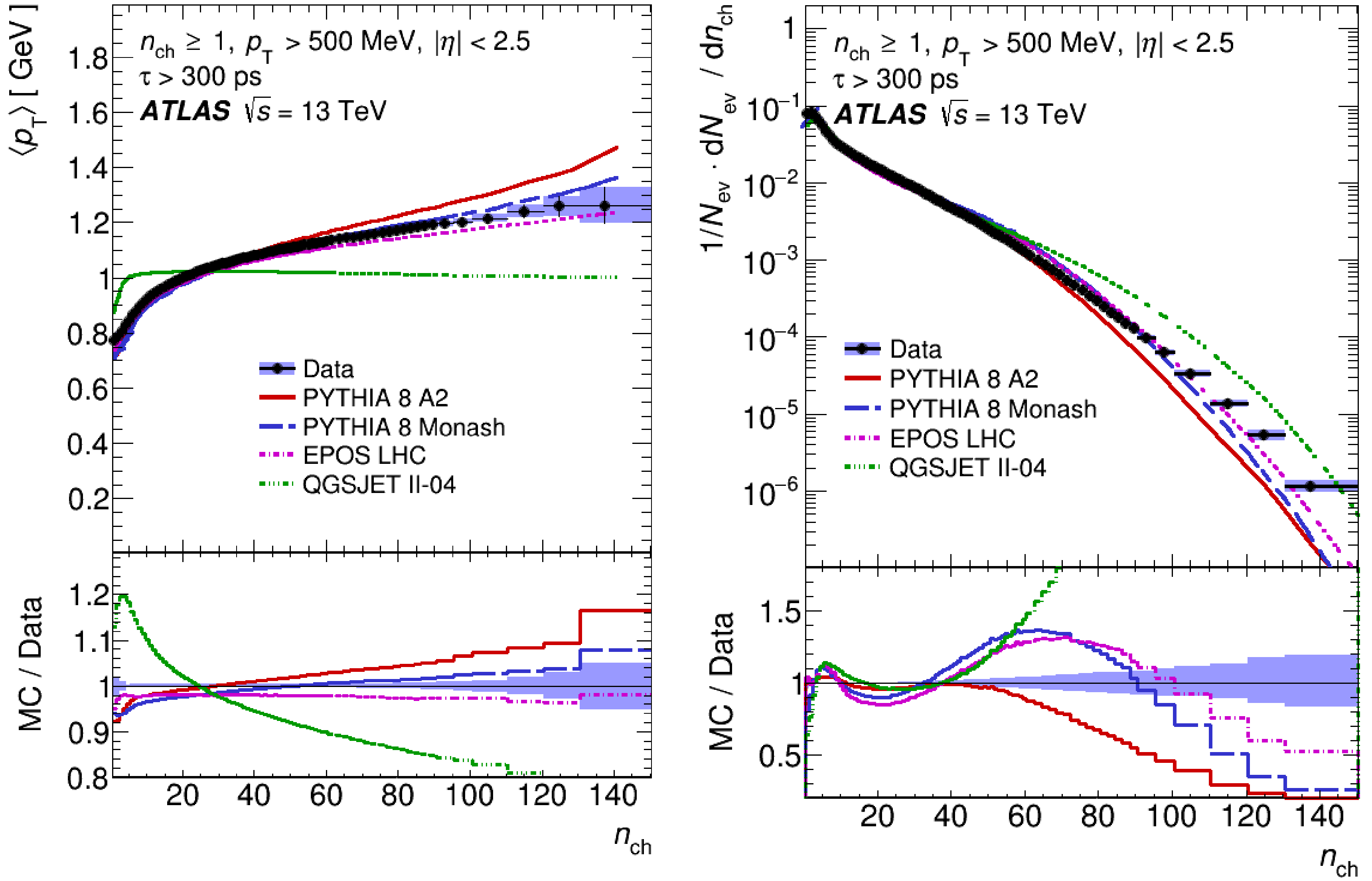




13 TeV Results :: the 500 MeV Analysis :: $n_{ch} \geq 1$

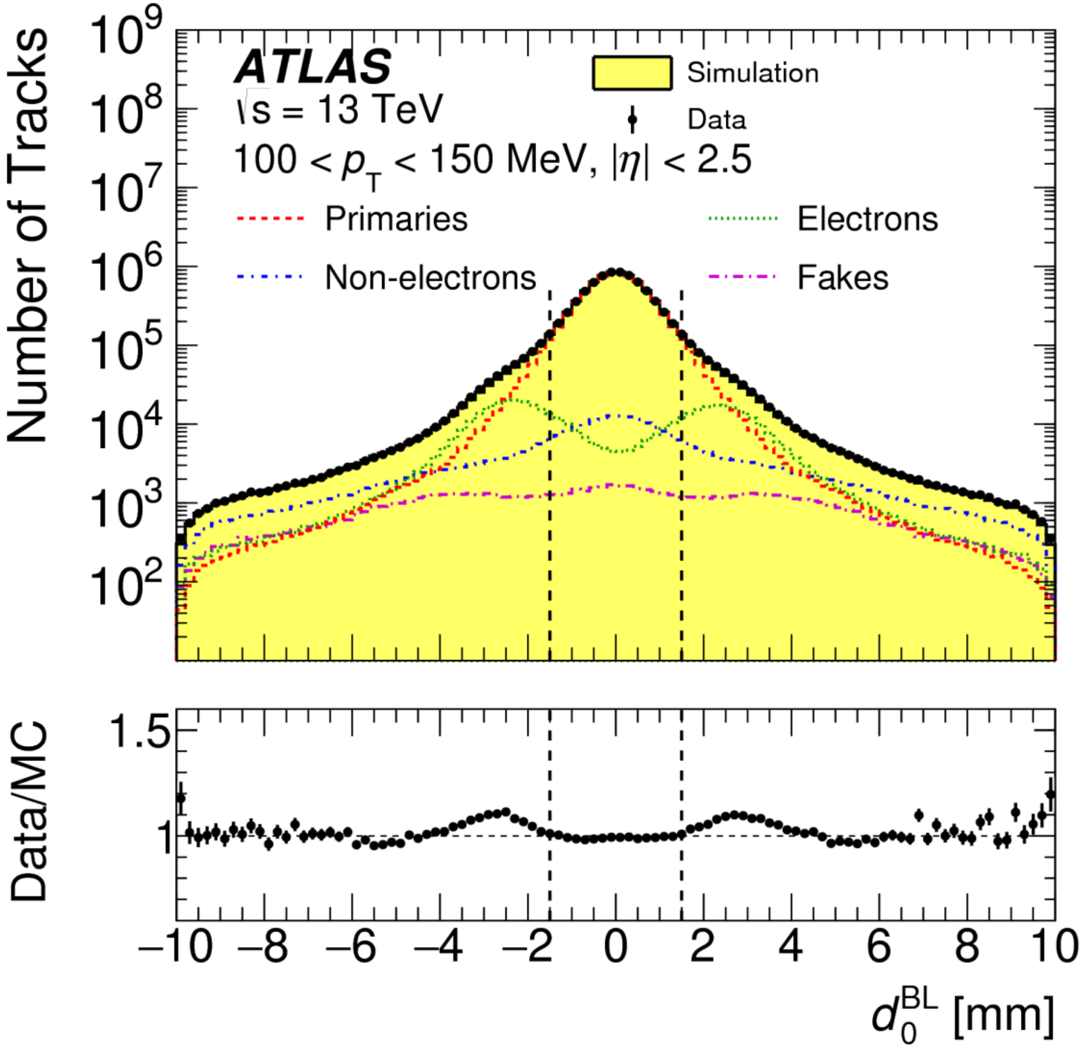
- Systematics dominated measurements.

- Reasonable description of data by Pythia A2 and Monash tunes, and EPOS, **which are all 7 TeV tunes.**
- Average p_T not described by QGSJET.



13 TeV Results :: the 100 MeV Analysis

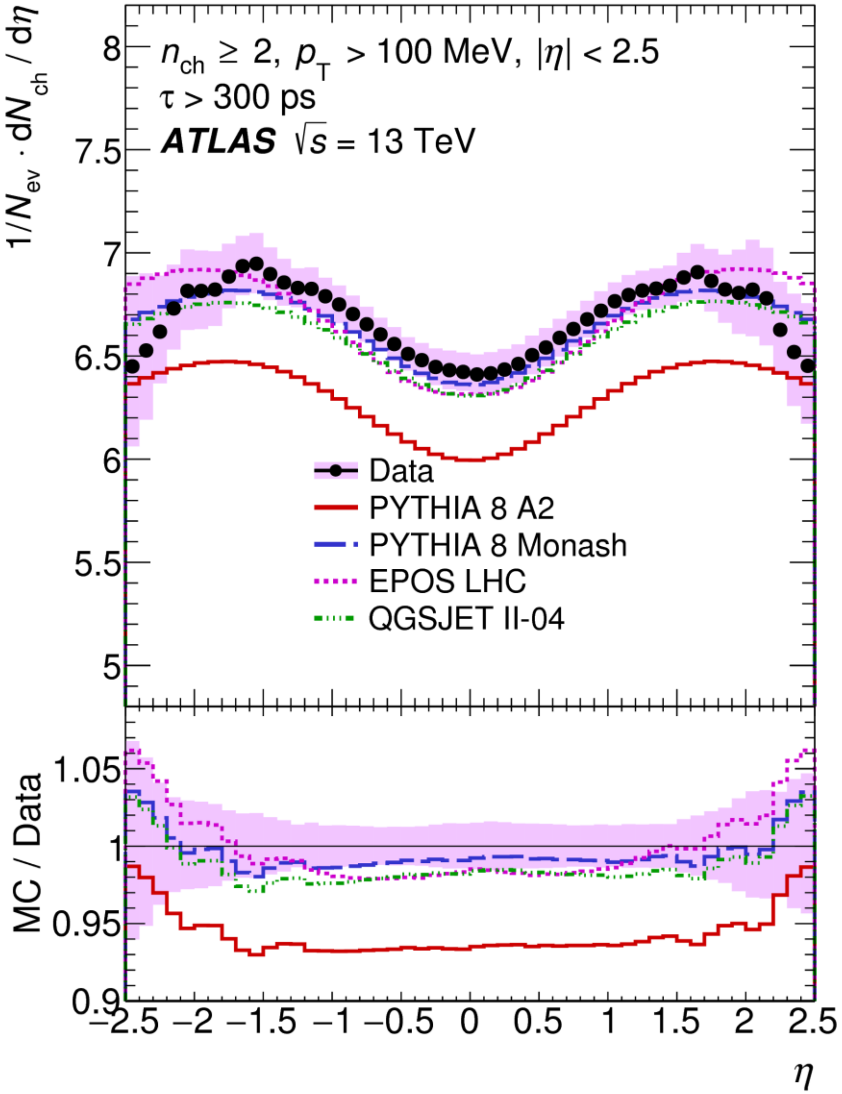
- 9M events, 151 μb^{-1} :: arXiv::1606.01133, Eur. Phys. J. **C** 76 (2016) 502.
- Background from beam-halo/gas negligible.
- **Background from non-primary particles.**
  - Photon conversions to e^+e^-.
  - Secondaries from hadronic interactions in material.
  - Fake tracks.
- Dominate **tails in the transverse impact parameter distribution**.
- Tails used to scale secondaries fraction in MC to match observed yield in data.
- **Secondaries yield extrapolated to the analysis phase space** defined as $|d_0| < 1.5$ mm (dashed vertical lines)
- Their contribution subtracted from data.

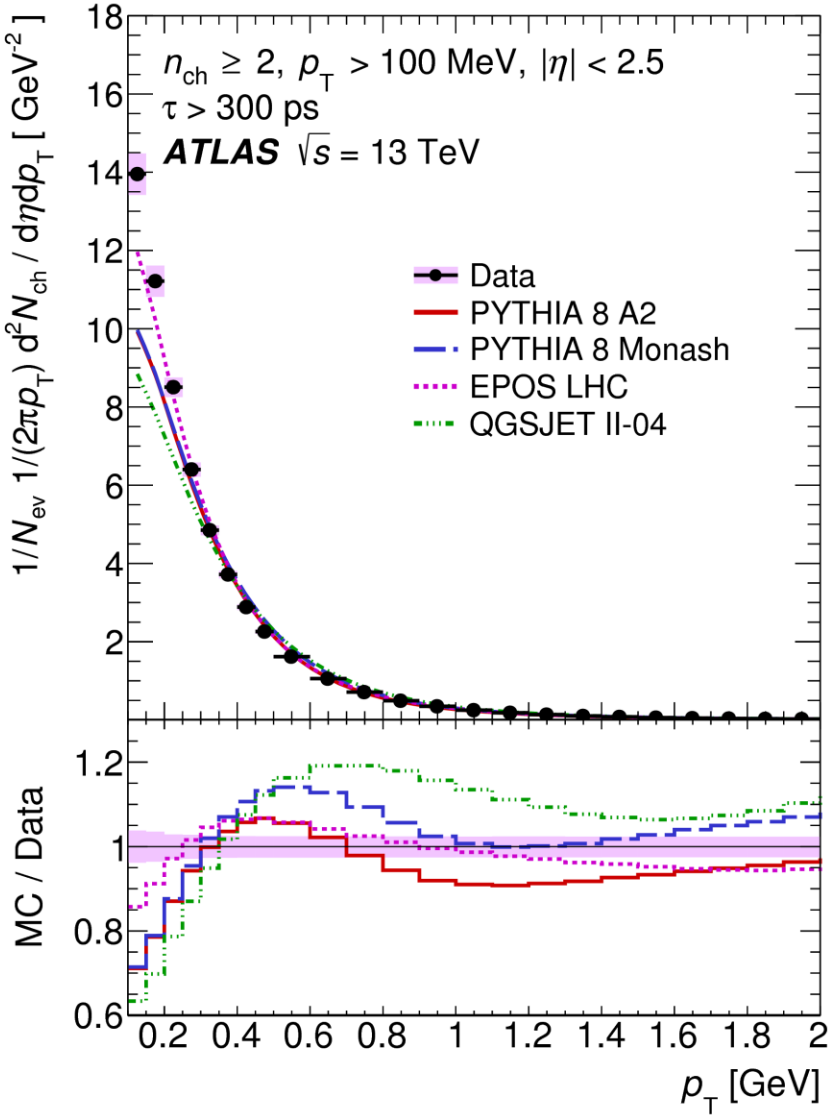


13 TeV Results :: the 100 MeV Analysis :: $n_{ch} \geq 2$

- **All generators differ at forward rapidities**, though within systematic uncertainties.

- Pythia8 A2 describes shape but fails at overall normalization.
- Diffractive component and total cross-section expected to be better described by an coming Pythia A3 tune.
- Only reasonable p_T dependence description, where QGSJET shows largest deviations.

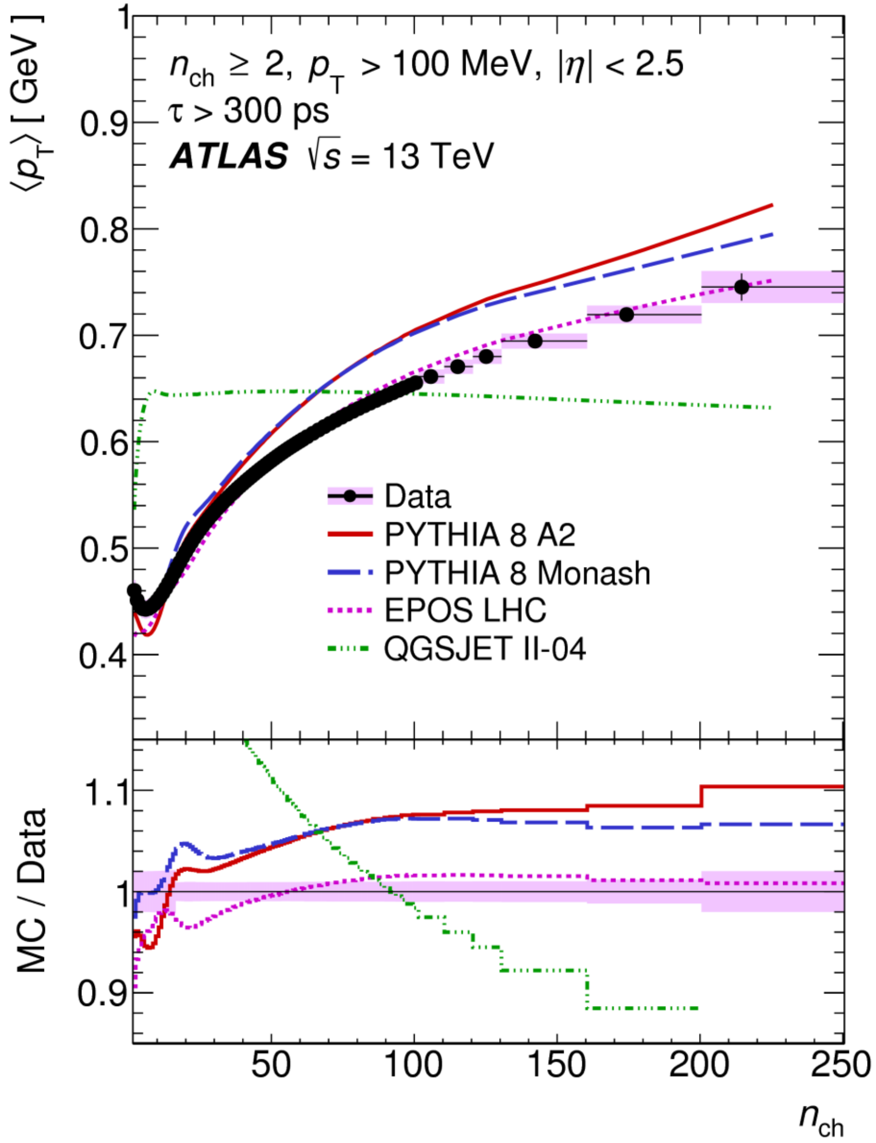


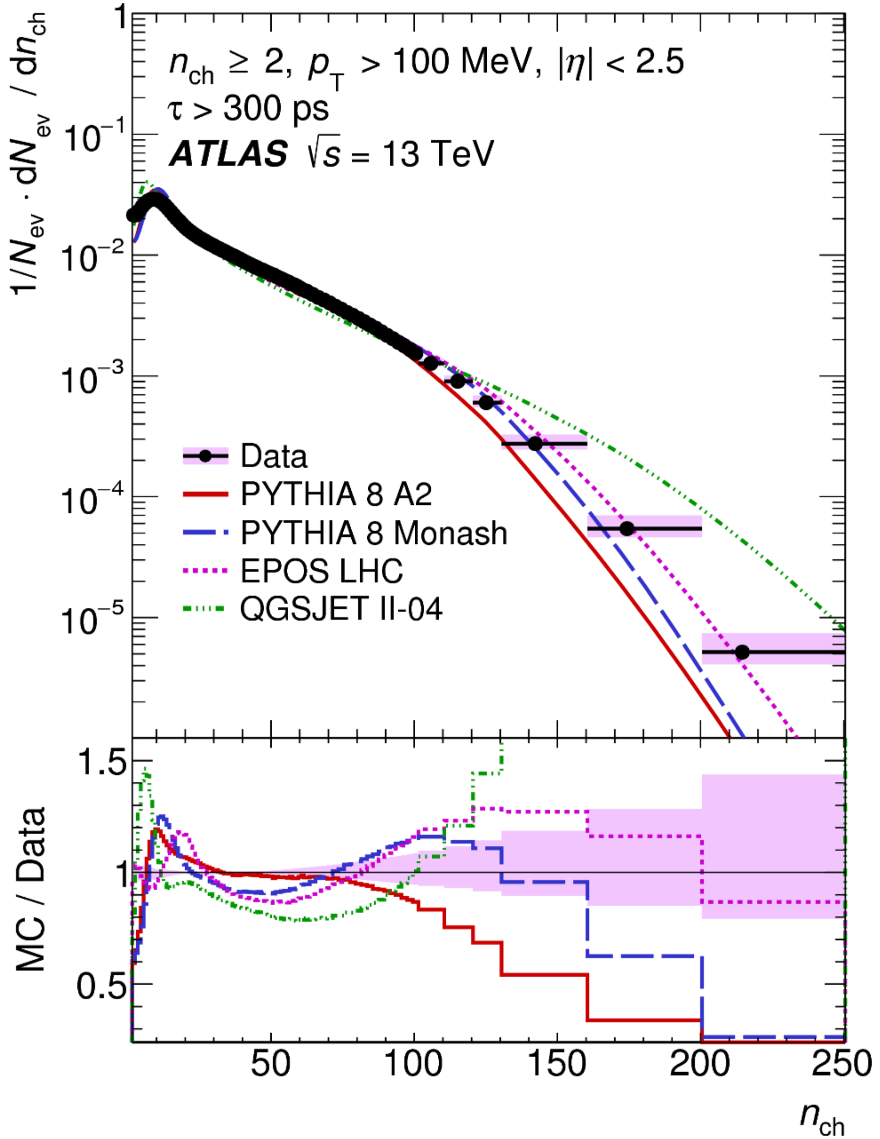


13 TeV Results :: the 100 MeV Analysis :: $n_{ch} \geq 2$

- **Pythia8 tunes and EPOS work well for the multiplicity shape.**
- QGSJET fails for $<p_T>$ while EPOS is best.
- All generators fail at low and high n_{ch}.

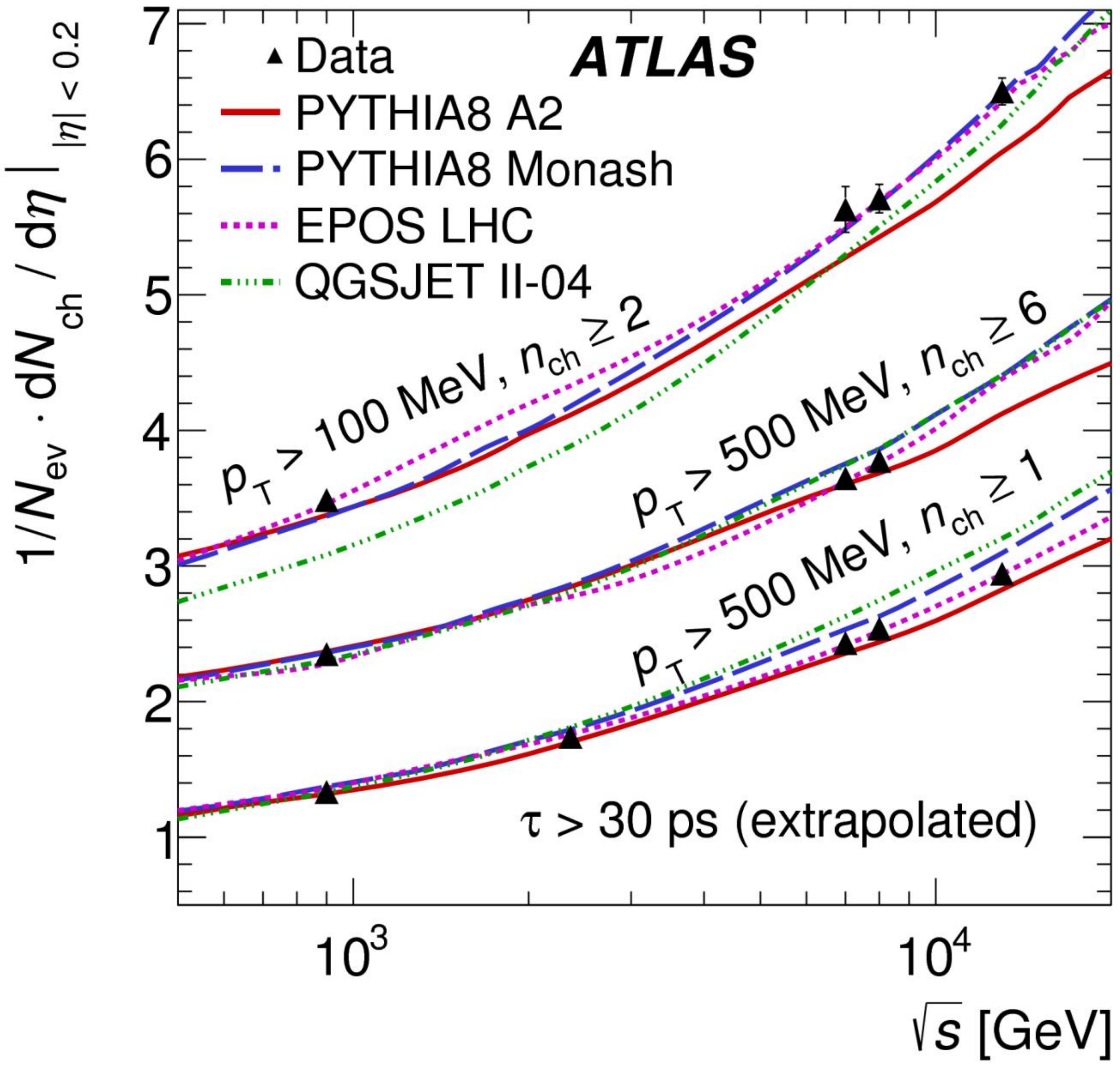
- **ATLAS 13 TeV results also available in the |*η*|<0.8 phase-space to compare to ALICE and CMS.**





Conclusions

- Right: ATLAS also measured charged particles multiplicities per event per unit η in central region at
  - 900 GeV :: 2.36 TeV :: 7 TeV
  - NEW! 8 TeV :: 13 TeV
    - Re-inclusion of strange baryons for comparion.
- Different levels of agreement to various MC generators and their tunes observed.
- **Fair description of the 13 TeV data by EPOS, and Pythia Monash and A2 tunes.**
- **Hints of non-description in forward η.**
- **Failure of modes in small and large multiplicities.**

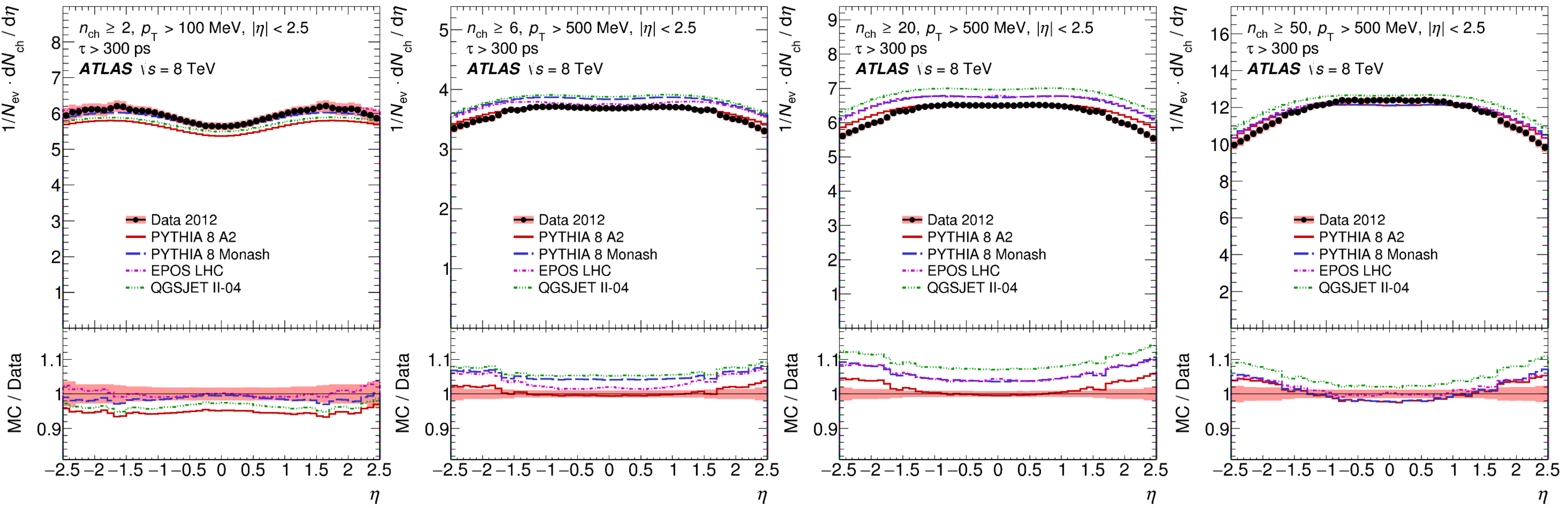


Data
ATLAS
PYTHIA8 A2
PYTHIA8 Monash
EPOS LHC
QGSJET II-04
p_T > 100 MeV, n_{ch} ≥ 2
p_T > 500 MeV, n_{ch} ≥ 6
p_T > 500 MeV, n_{ch} ≥ 1
τ > 30 ps (extrapolated)
$1/N_{ev} \cdot dN_{ch}$
1
2
3
4
5
6
10^3

8 TeV Results, 500 MeV Analysis

- Additional phase spaces of different charged particles multiplicities:
  - n_{ch} >= **2** , n_{ch} >= **6**, n_{ch} >= **20**, n_{ch} >= **50**
- **Very good Monash performance, also EPOS, less of A2, failing QGSJET.**
- Multiplicities as function of η in different multiplicity phase-spaces:

n_{ch} >= **2** | n_{ch} >= **6** | n_{ch} >= **20** | n_{ch} >= **50**



8 TeV Results, 100-500 MeV Analysis

- Multiplicity results

Phase Space		$1/N_{ev} \cdot dN_{ch}/d\eta$ at $\eta = 0$	
$n_{ch} \geq$	$p_T >$	$\tau >$ 300 ps (fiducial)	$\tau >$ 30 ps (extrapolated)
2	100 MeV	5.64 ± 0.10	5.71 ± 0.11
1	500 MeV	2.477 ± 0.031	2.54 ± 0.04
6	500 MeV	3.68 ± 0.04	3.78 ± 0.05
20	500 MeV	6.50 ± 0.05	6.66 ± 0.07
50	500 MeV	12.40 ± 0.15	12.71 ± 0.18

13 TeV Tunes Used

- Generators settings

Generator	Version	Tune	PDF
PYTHIA 8	8.185	A2	MSTW2008LO [21]
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [22]
EPOS	LHCv3400	LHC	N/A
QGSJET-II	II-04	default	N/A

Vertex Selection

- Primary vertex formed by at least 2 tracks of p_T at least 100 MeV.
- Veto events with another primary vertex (PV) formed by 4 or more tracks.
- Keep event otherwise, as these are often split PV or secondary vertex reconstructed as PV.