Charged-particle multiplicities at different pp interaction centre-of-mass energies measured with the ATLAS detector at the LHC

MPI@LHC 2015

Roberto Iuppa on behalf of the ATLAS Collaboration

University and INFN of Rome Tor Vergata and CERN

Outline

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- Soft QCD and Minbias in ATLAS: detectors and observables
- Minbias analysis at 13 TeV
  - Definitions of the Minbias analysis
  - Monte Carlo generators and simulation
  - Event selection
  - Trigger
  - Vertexing
  - Tracking
  - Reweighting and unfolding
  - Results
- Evolution of results from 0.9 to 13 TeV
- Conclusions

Soft QCD / Minbias

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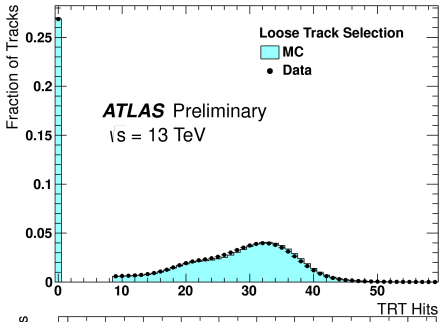
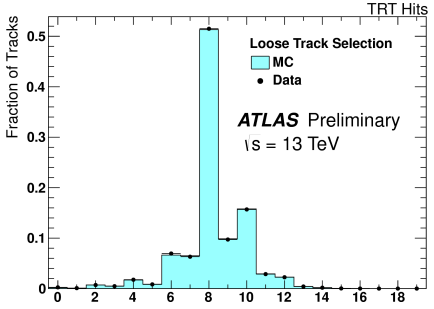
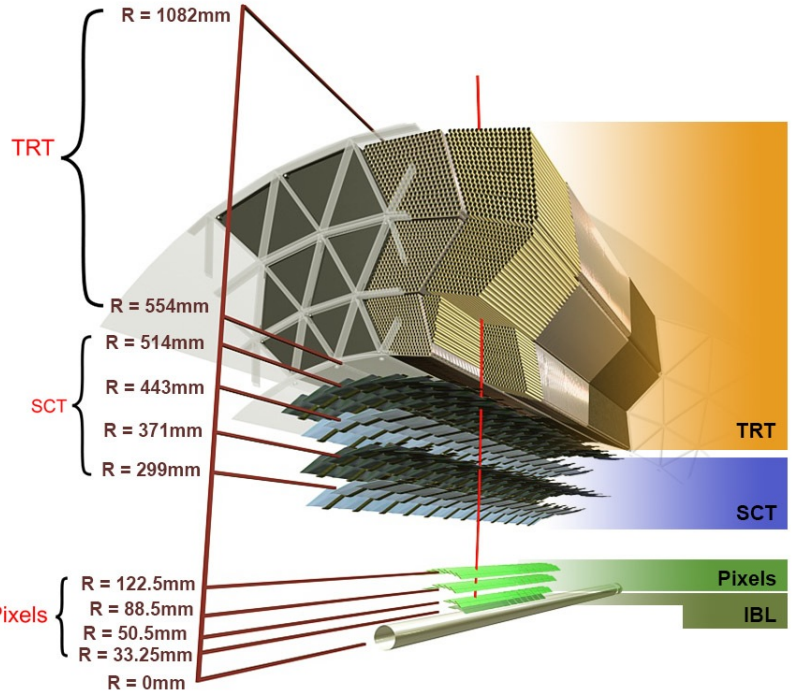
Useful link: ATLAS note on tracking performance
https://cds.cern.ch/record/2037683?ln=en





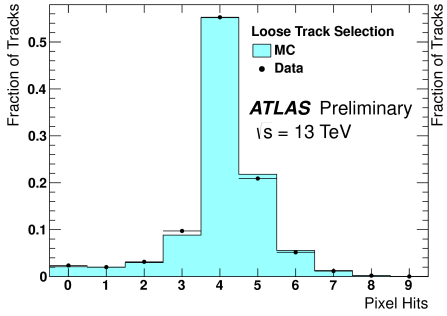


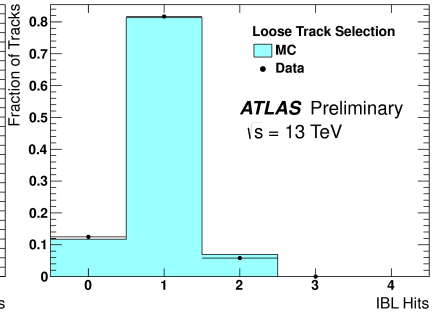
<u>Cross sections included in Pythia8 for 13 TeV pp collisions:</u>
56.79 **mb** – non diffractive
12.83 **mb** – single diffractive
8.798 **mb** – double diffractive

3-4 x 10^{14} such collisions already delivered by LHC in Run2…
for minimum bias we consider only 10x 10^6 events

Soft-QCD interactions: low momentum transfer.
Important also for hard interactions:

- PileUp events are mostly due to Soft-QCD interactions
- The models of the Underlying event are tuned by looking at Soft-QCD data.





Definitions

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Reference of the analysis at 13 TeV:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-028/

Measurement of the multiplicity of primary charged particles using about **169/μb** of data recorded at 13 TeV (about the same luminosity used in previous publications).

Primary charged particles: those with lifetime $\tau > 0.3\ 10^{-10}$ s directly produced in pp interactions or coming from subsequent decays of particles with shorter lifetime.
Caveat: particles with lifetime $0.3\ 10^{-10}\ \text{s} < \tau < 3.0\ 10^{-10}$ s (1 cm – 10 cm) are not included in the fiducial particle definition (the result would be very generator-dependent). **New for this analysis.**

Fiducial phase-space: events containing at least one charged particle in the kinematic range $|\eta| < 2.5$, $p_T > 500$ MeV/c .
Other phase spaces are explored, namely

- $|\eta| < 0.8$, $p_T > 500$ MeV/c (for comparison with CMS and ALICE, not in the conf note linked),
- $|\eta| < 2.5$, $p_T > 100$ MeV/c (few data available, model predictions very different, Physics dominated by diffractive processes; it has a dedicated analysis).

The result of the analysis is in the form of these distributions:

$$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta} \qquad \frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta\, dp_T} \qquad \frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$$

$\langle p_T \rangle$ as a function of n_{ch}

Monte Carlo and simulation

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Generator	Version	Tune	PDF	7 TeV MB	Data UE	From
PYTHIA 8	8.185	A2	MSTW2008LO	yes	no	ATLAS
PYTHIA 8	8.186	Monash	NNPDF23LO	yes	yes	Authors
HERWIG++	2.7.1	UEEE5	CTEQ6L1	no	yes	Authors
EPOS	3.4	LHC	-	yes	no	Authors
QGSJET-II	II-04	default	-	yes	no	Authors

- Pythia8 A2 used as baseline for non-diffractive (ND), single- and double-diffractive (SD and DD) processes.
- Pythia8 Monash, Herwig++ and EPOS used to assess the generator and tune dependence of results.
- Pythia8 A2 samples ran with Geant4 with 2.5%, 5% and 10% more passive material to assess the dependence on the material description.

Event and track selection

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Events are required to satisfy these criteria:

- to fire a L1 MBTS trigger (side A or C)
- to contain a primary vertex
- not to contain a second vertex with four or more tracks
- to have at least one good track:
  - $|\eta|<2.5$, pT>500 MeV/c
  - having the IBL hit expected to be there
  - having at least 6 SCT hits
  - transverse parameter with respect to the beam line: $|d_0| < 1.5$ mm
  - longitudinal parameter with respect to the primary vertex: $|\Delta(z_0 \sin\vartheta)| < 1.5$ mm
  - χ^2 probability greater than 0.01 if p_T>10 GeV/c (low p_T tracks removal, 1% residual)

	Simulation **Events**	% passing	Data **Events**	% passing
Before cuts	10000000		10855221	
After requiring a primary vertex is present	8323843	83.24%	9343833	86.08%
After pileup suppression	8323504	99.99%	9316964	99.71%
After requiring 1 track above p_T > 500 MeV	7984705	95.93%	8870790	95.21%

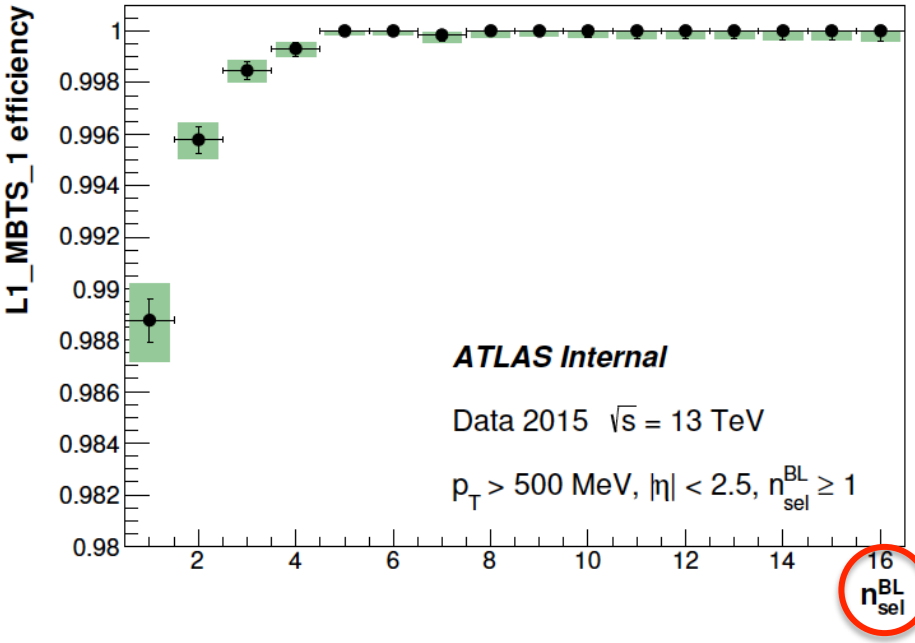
	Simulation **Tracks**	% passing	Data **Tracks**	% passing
All Tracks	293317640		347194760	
p_T > 500 MeV	137242338	46.79%	155759984	44.86%
$\|\eta\|$ < 2.5	134359043	97.90%	152557877	97.94%
Innermost hit requirement	129037285	96.04%	140837448	92.32%
Pixel Hit > 1	112547309	87.22%	121075669	85.97%
SCT Hits > 6	103795189	92.22%	111705230	92.26%
$\|d_0\|$ < 1.5 mm	98074303	94.49%	107545661	96.28%
$\|\Delta(z_0 \cdot \sin\theta)\|$ < 1.5 mm	96726666	98.63%	106354071	98.89%
χ^2 probability	96726099	100.00%	106353390	100.00%

Differences between data and MC accounted for by *reweighting*. Information on primaries retrieved by ***unfolding***.

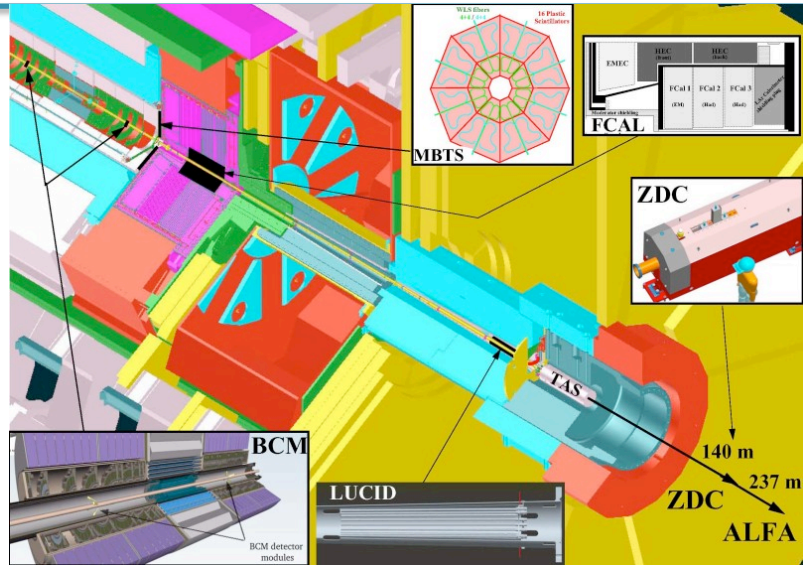
Trigger

The **trigger efficiency** is **measured** over a data sample selected **using a randomly-seeded control trigger**, filtered at the HLT *(at least 2 pixel hits with TOT>20 b.c., at least 3 SCT hits. At least 1 track with pT>200 MeV/c with long. impact param less than 40 mm with respect to the ATLAS nominal centre)*.

No vertex requirement to avoid correlation with vertex efficiency.



Impact parameter w.r.t. the beam line.



Huge joint efforts by MinBias trigger and Tile groups to improve the apparatus w.r.t. Run 1.

Systematics:

1. asymmetry A/C side (1% for n_{sel}=1 → 0.12% syst.)
2. variations of the track selection (0.1% syst.):
   a. transv. param. removed;
   b. cut on z for events with primary vertex.

Vertex finding

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Tracks used:

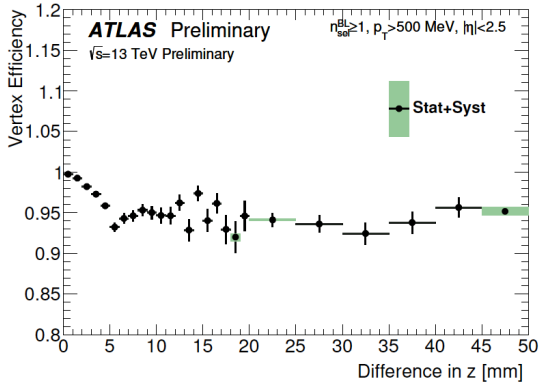
- p_T>100 MeV
- at least 1 Pixel hit, 4 SCT and 6 Silicon hits
- transv. and long. impact parameters with respect to the beam spot (BS):

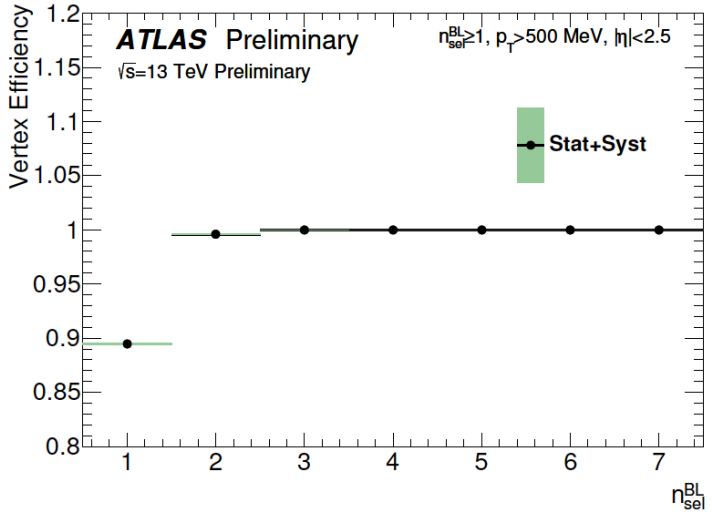
$$\left|d_0^{BS}\right| < 4 \text{ mm}, \left|z_0^{BS}\right| < 1000 \text{ mm}, \left|\sigma_{d_0}^{BS}\right| < 5 \text{ mm}, \left|\sigma_{z_0}^{BS}\right| < 10 \text{ mm}$$

The vertex efficiency is however parametrized as a function of the selected tracks with p_T>500 MeV, i.e. n_{sel}^{BL} and computed on triggered events.

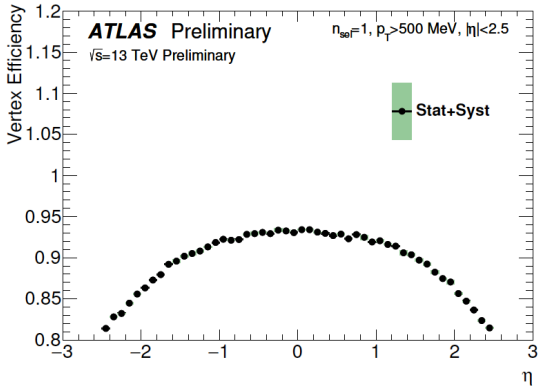
Systematics considered: non-collision beam background (estimated via non-colliding bunches) subtracted. Contribution subtracted taken as uncertainty (0.1%).

As a function of Δz for n_{sel}^{BL}≥2





As a function of ηfor n_{sel}^{BL}=1



Background to events and tracks

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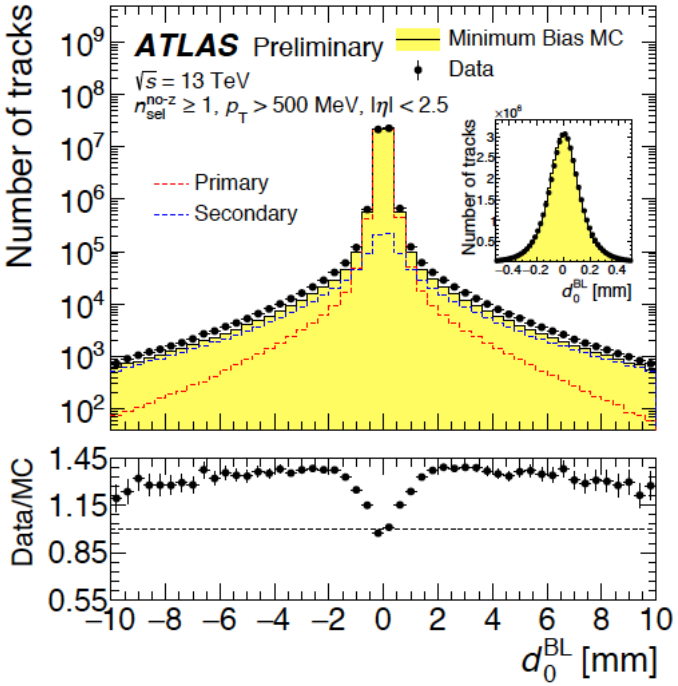
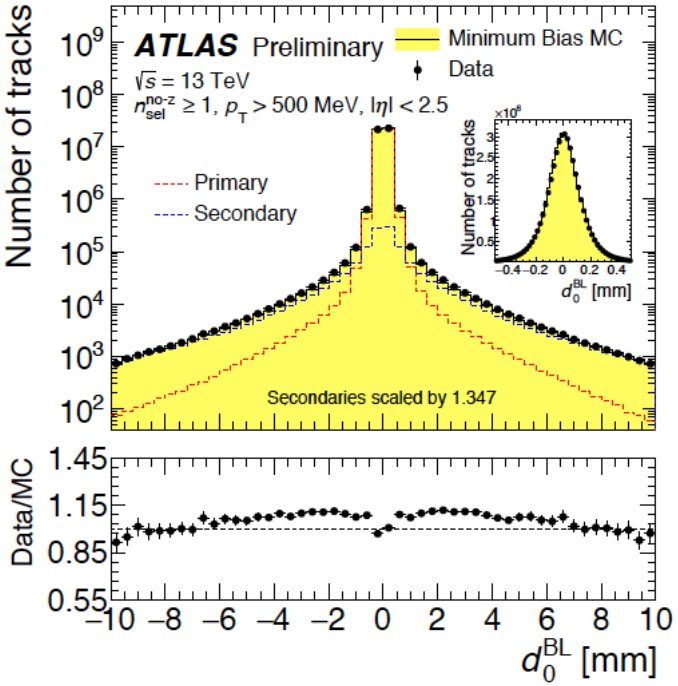
Event backgrounds: cosmic rays (10^{-6}), beam-induced (10^{-4}), multi-interactions events ($2X10^{-4}$).

Primary track backgrounds: hadronic interactions in the material (dominant) and decays from strange particles (mostly K^0 and Λ^0). *Photon conversions are negligible at this energy.*

Secondaries fraction: 2.28%±0.56%





Strange baryons removal

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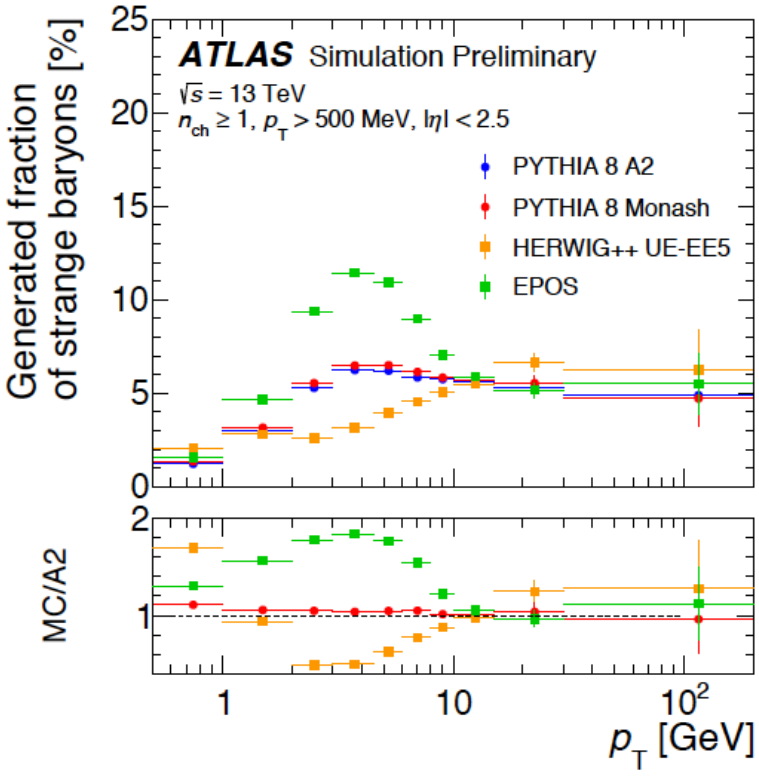
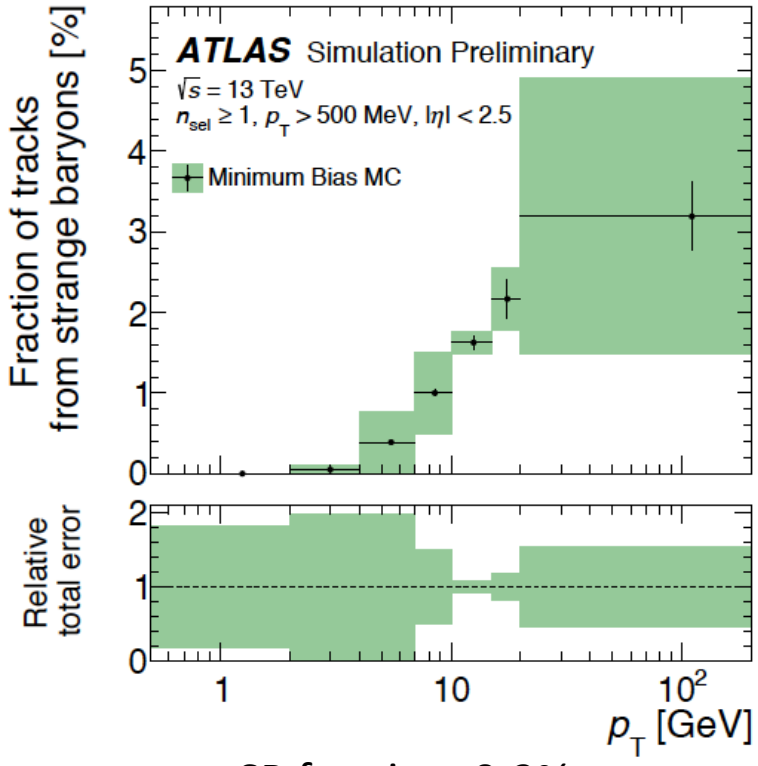
Differently than in previous analyses, we exclude here all particles with mean lifetime in the range 30-300 ps and their decay products from the fiducial phase space definition. These are mostly charged strange baryons which decay after a short distance.





SB fraction: 0-3%

Track reconstruction

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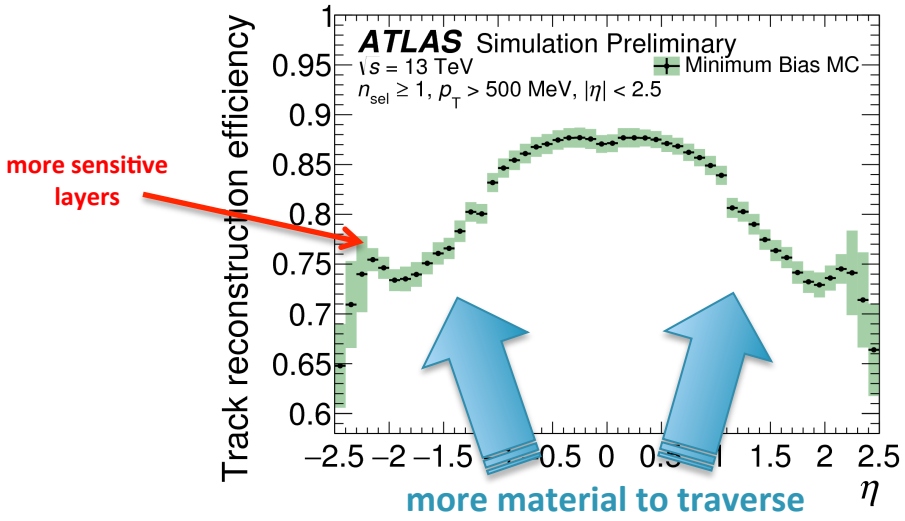
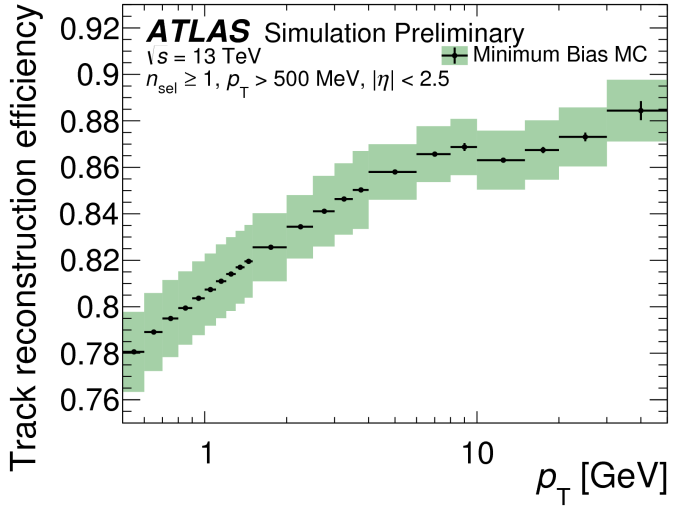
Track reconstruction efficiency determined from the simulation.





Systematic uncertainties: track selection, material (many changes to be accounted for) and χ^2 cut.

Systematic Uncertainty	Size	Region
Track Selection	0.5 %	flat in p_T and η
Material	1-3 %	decreases with p_T, increases with $\lvert\eta\rvert$
χ^2 prob. cut efficiency	0.5% - 5%	only for $p_T > 10$ GeV increases with p_T

estimated with the "N-1" method

treated together with the alignment-related uncertainty

Correction procedure

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The correction procedure allows to intepret the observation in terms of primary particles. It is based on *weighting* and *unfolding*.

The weighting is performed at event and track level.

$$w_{\mathrm{ev}}(n_{\mathrm{sel}},\eta) = \frac{1}{\epsilon_{\mathrm{trig}}(n_{\mathrm{sel}}^{\mathrm{BL}})} \cdot \frac{1}{\epsilon_{\mathrm{vtx}}(n_{\mathrm{sel}}^{\mathrm{BL}},\eta)},$$

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

Systematics accounter for in the **unfolding** procedure:

Distribution	Systematic uncertainty	Status
all	material	included
all	secondaries	included
all	strange baryons	included
all	effect badly measured tracks	included
n_{ch}	uncertainty on $\varepsilon^{\mathrm{miss}}$	taken into account by varying input distribution
n_{ch},p_{T}	propagation of stat uncert. due to matrix	included

Vertex and trigger systematics are neglected, as they contribute only for n_{sel}=1 at 0.2%, and there the track-efficiency and non-closure systematics are 4% each.
For each result distribution, the non-closure is assumed as systematic.

Results 1/2

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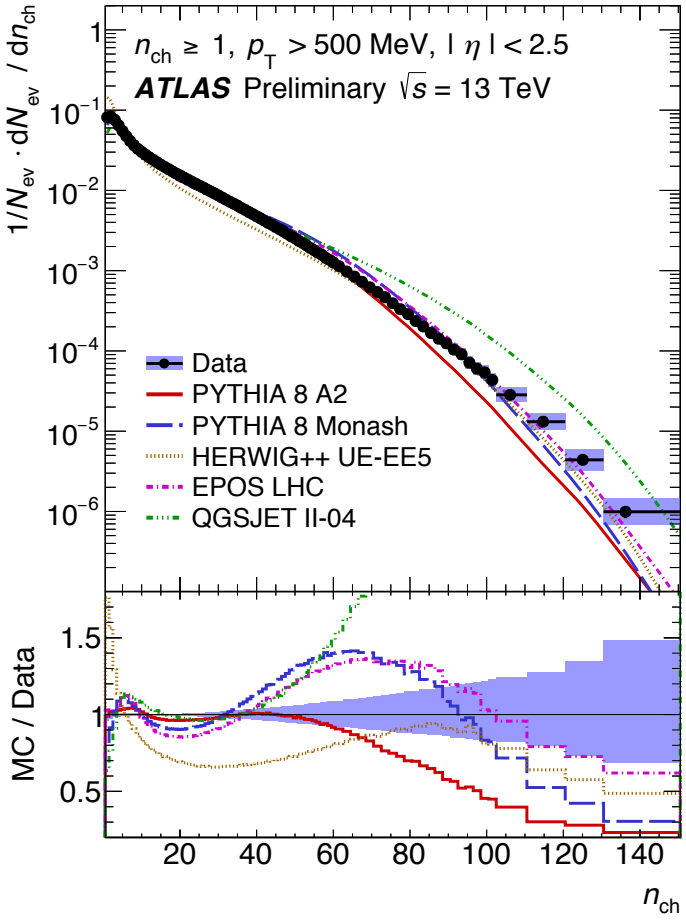
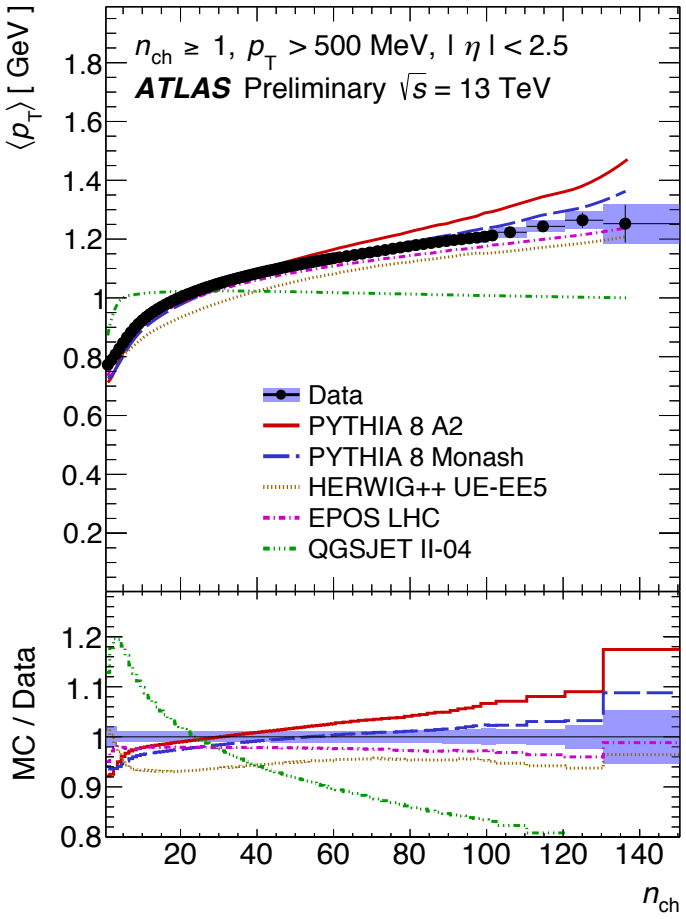


dN_{ev}/dn_{ch} & <pT> vs. n_{ch}

- Low n_{ch} not well modelled by any MC; large contribution from diffraction
- Models without colour reconnection (QGSJET) fail to model scaling with n_{ch} very well



Results 2/2

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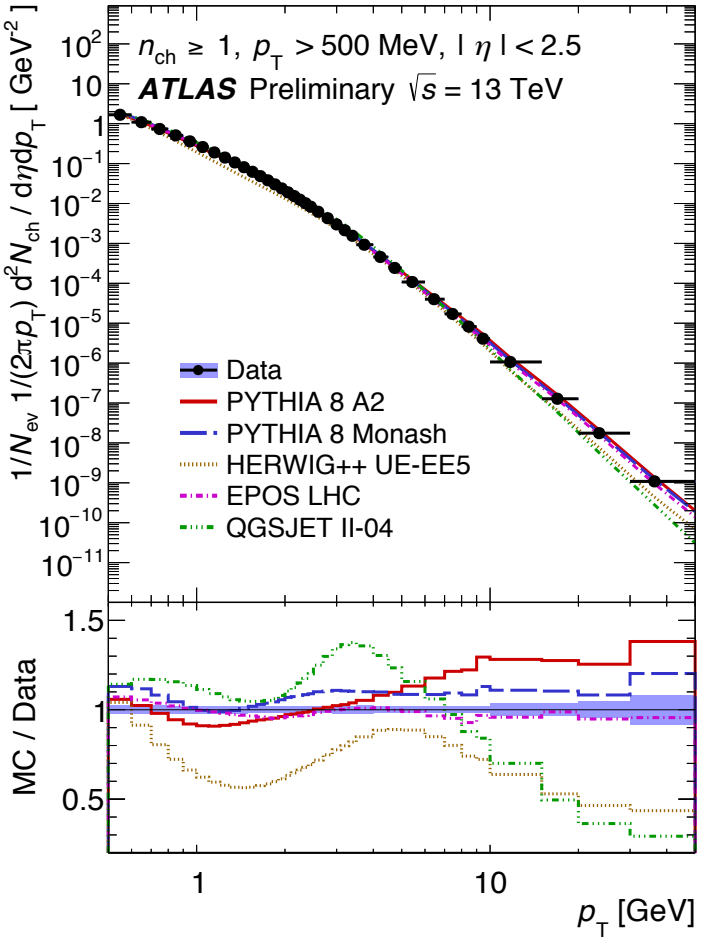
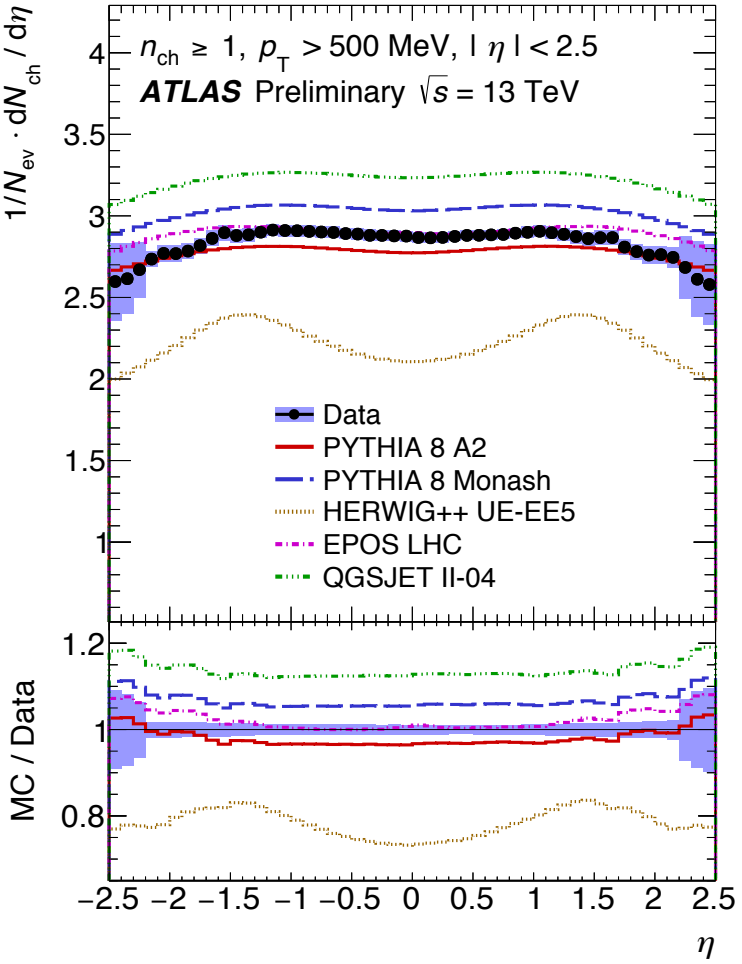


$dN_{ch}/d\eta$

- Models differ mainly in normalisation, shape similar
- Exception is HERWIG tuned entirely on UE.

$d^2N_{ev}/d\eta dp_T$

- Measurement spans 10 orders of magnitude
- Some Models/Tunes give remarkably good predictions (EPOS, Pythia)



0.9→13 TeV: dN_{ev}/dn_{ch}

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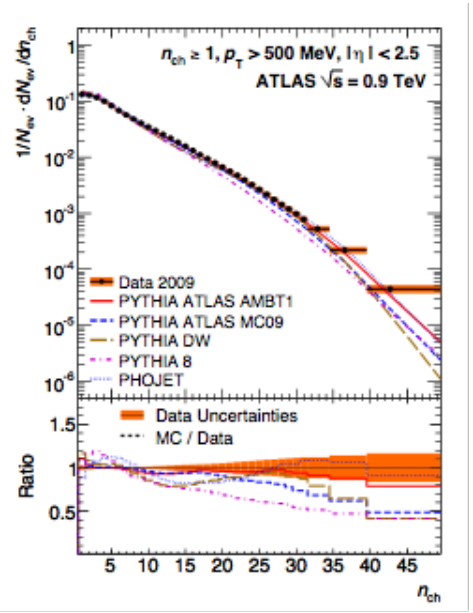

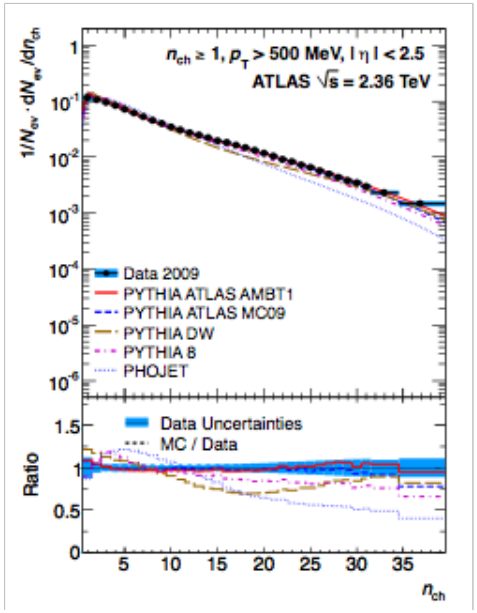

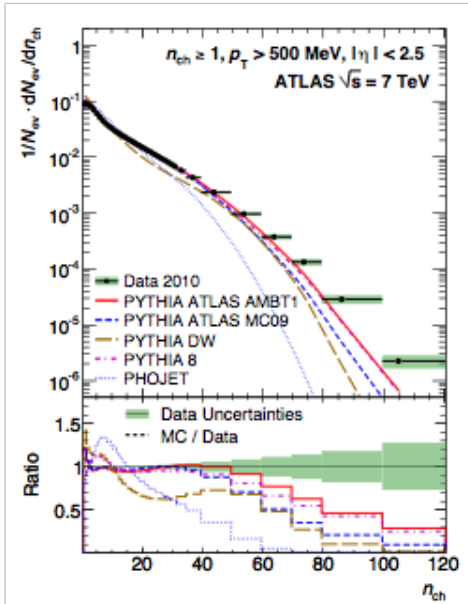

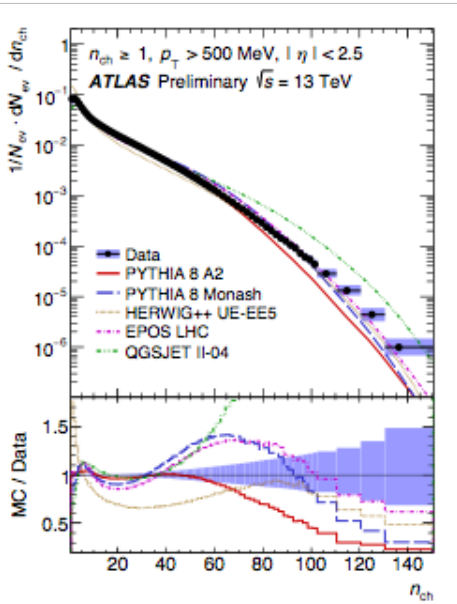

Low n_{ch} not well modelled by any MC; the contribution from diffractive interactions is more relevant there.

0.9→7.0 TeV results: http://arxiv.org/abs/1012.5104

0.9→13 TeV: $dN_{ch}/d\eta$

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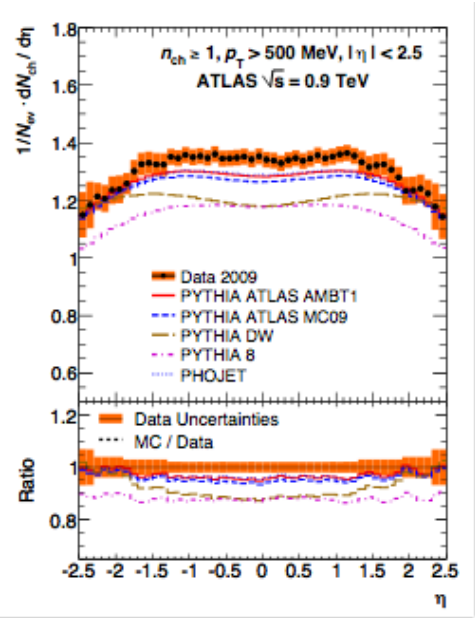

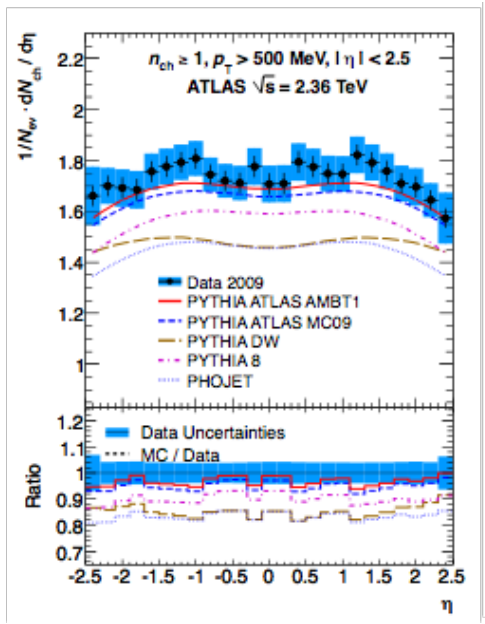

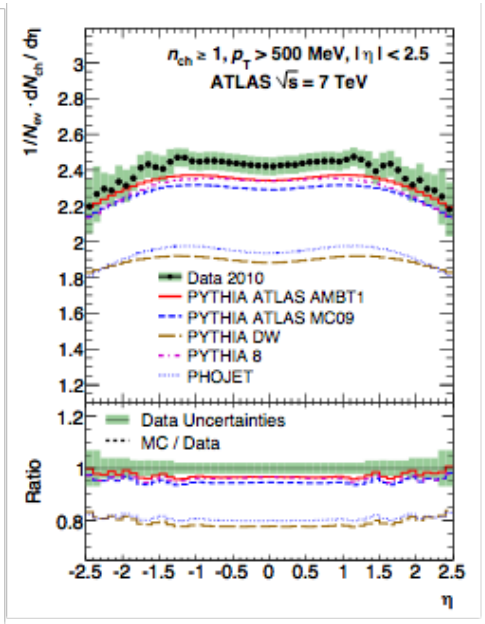

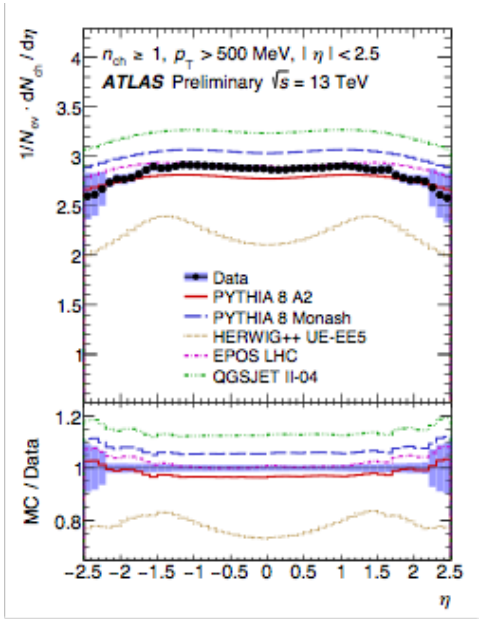

Difference among models in normalisation, quite simlar shape.
Track multiplicity underestimated up to 13 TeV (overestimation at 13 TeV).

0.9→7.0 TeV results: http://arxiv.org/abs/1012.5104

0.9→13 TeV: $d^2N_{ch}/d\eta dp_T$

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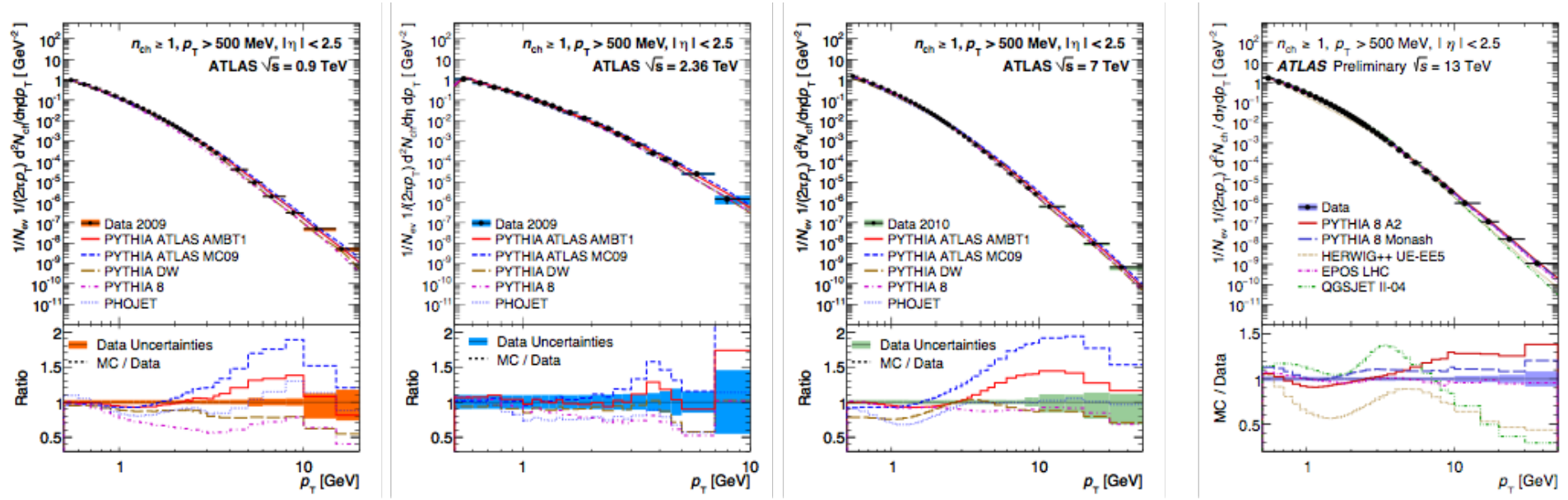
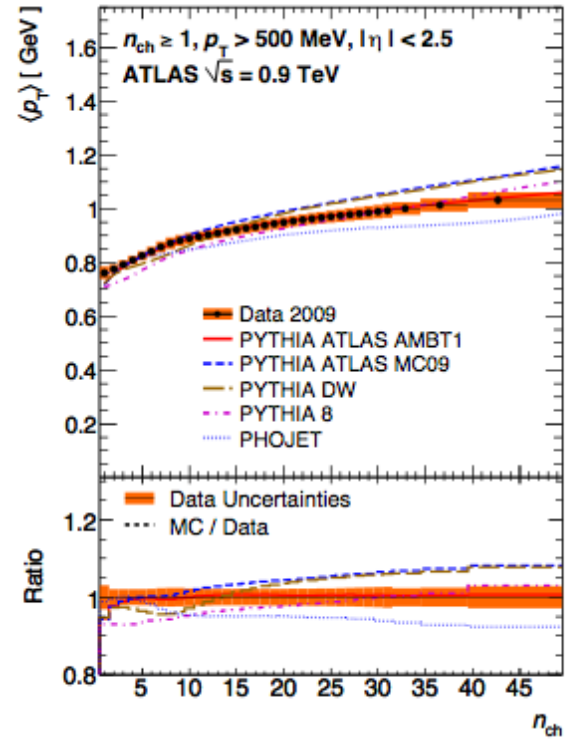
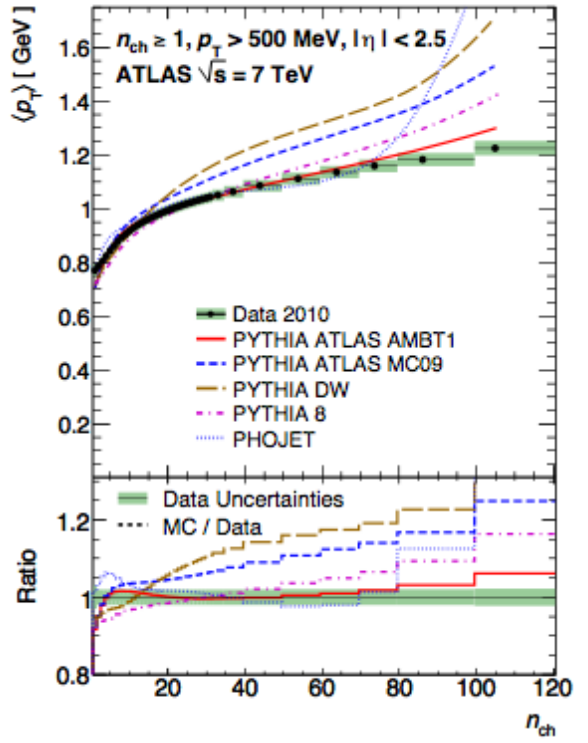


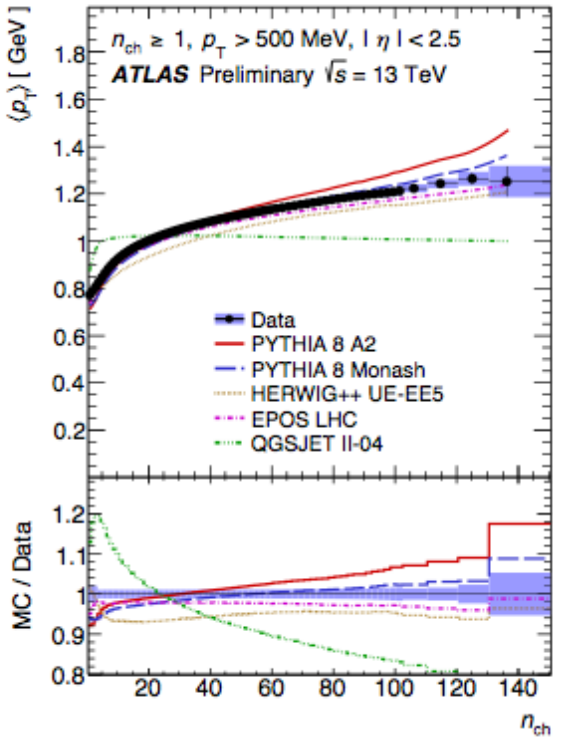
10 orders of magnitude measurement…
Disagreement mostly at low p_T and high p_T

0.9→7.0 TeV results: http://arxiv.org/abs/1012.5104

$\langle p_T \rangle$ vs n_{ch}







Shape at low n_{ch} sensitive to ND, SD, DD fractions. Important to improve models there. The analysis in the phase space with $p_T > 100$ MeV/c will be important to this extent.

0.9→7.0 TeV results: http://arxiv.org/abs/1012.5104

Conclusions

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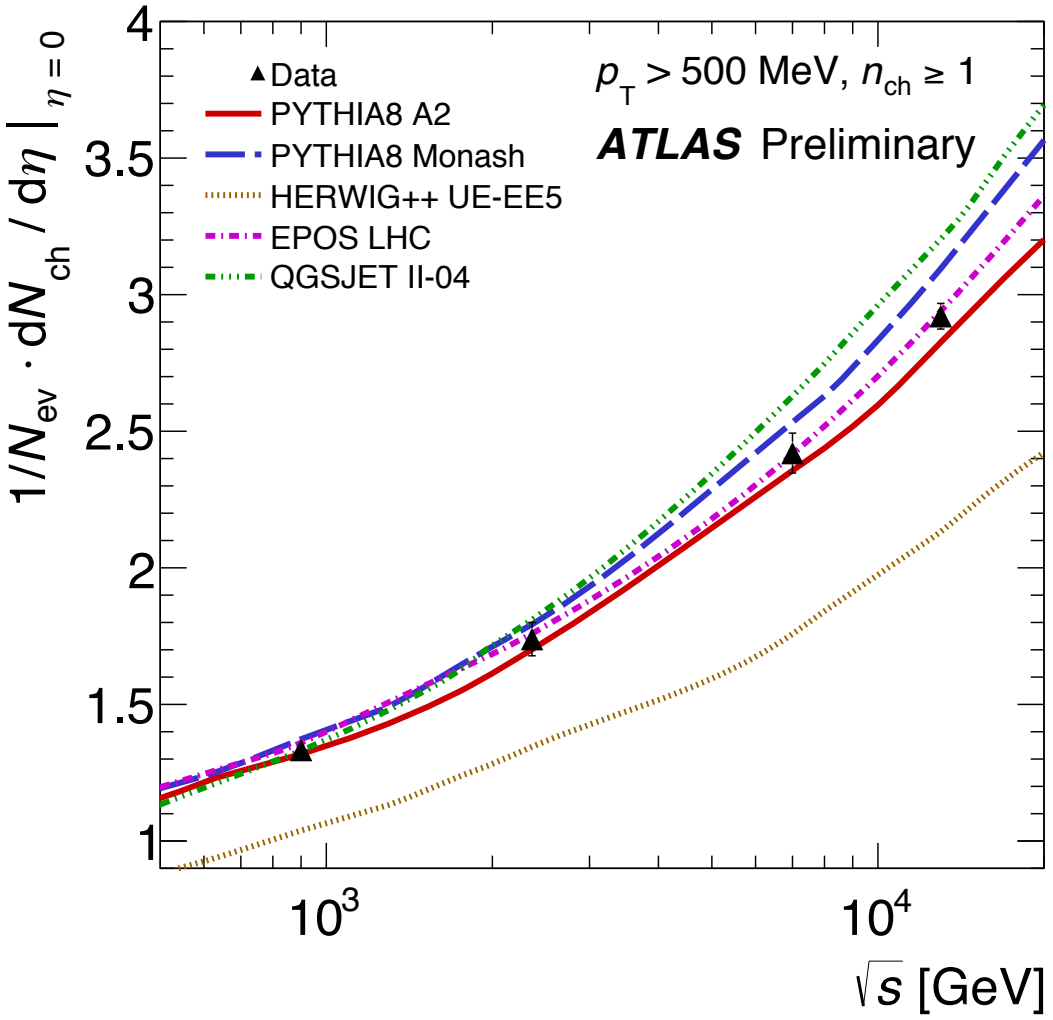
- ATLAS's first measurement of charged particle multiplicities @ 13 TeV, p_T > 500 MeV has been presented.
- Good agreement with predictions from various models, in spite of jumping by a factor two in the center-of-mass-energy.
- Together with the 0.9, 2.36, 7 TeV measurements, this one provides a good set of references for models and generators.



Backup

Non-collision background

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- The level of non-collisions beam background was estimated in data by measuring the time difference between hits in the MBTS detector on the two different sides of the detector