Measurements of the Charged Particle Distributions with the ATLAS detector

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University of Calabria & CERN

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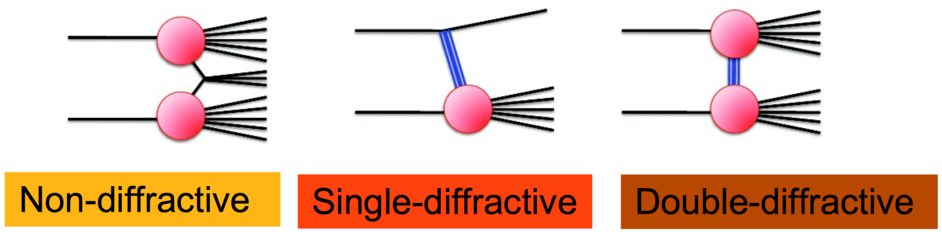
Why is Minimum Bias important?

- Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region

- Inelastic pp collisions have different compositions



- Main source of background when more than one interaction per bunch crossing

- Perturbative QCD can not be used for low transfer momentum interactions
  - ND described by QCD-inspired phenomenological models (tunable)
  - SD and DD hardly described and few measurements available

Goal:

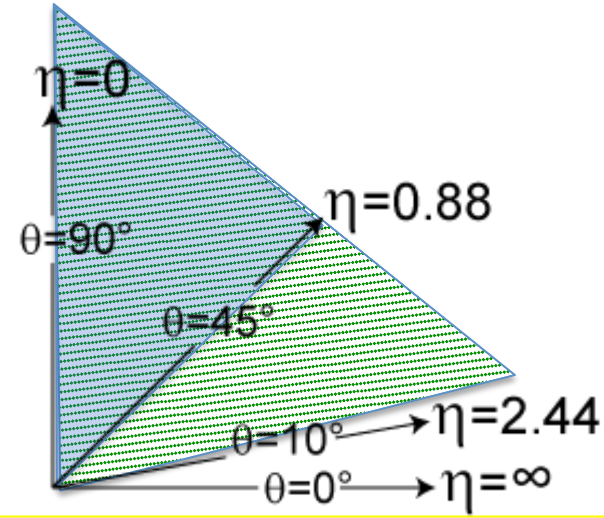
Measure spectra of primary charged particles corrected to hadron level

Inclusive measurement – do not apply model dependent corrections -> allow theoreticians to tune their models to data measured in well defined kinematic ranges

Minimum Bias at the LHC

Minimum Bias measurements in ATLAS:

- 0.9 TeV (03/2010)
  - 1 phase space (1 charged particle, 500 MeV, $|\eta|<2.5$)
- 0.9, 2.36, 7 TeV (12/2010)
  - 3 phase spaces (1, 2, 6 charged particles, 100-500 MeV, $|\eta|<2.5$)
- 0.9, 7 TeV (12/2010)
  - CONFNote – 2 phase spaces (1 charged particle, 500-1000 MeV, $|\eta|<0.8$)
- 8 TeV (03/2016)
  - 5 phase spaces (1, 2, 6, 20, 50 charged particles, 100-500 MeV, $|\eta|<2.5$)
- 13 TeV (02/2016)
  - 2 phase spaces (1 charged particle, 500 MeV, $|\eta|<2.5$, 0.8)
- 13 TeV (06/2016)
  - 1 phase space (2 charged particles, 100 MeV, $|\eta|<2.5$)



Minimum Bias measurements in CMS:

- 0.9, 2.36 (02/2010)
  - Charged hadrons
- 7 TeV (02/2010)
  - Charged hadrons
- 0.9, 2.36, 7 TeV (11/2010)
  - 5 pseudorapidity ranges from |eta|<0.5 to |eta|<2.4
- 8 TeV (05/2014) – with Totem
  - $|\eta|<2.2$, $5.3<|\eta|<6.4$
- 13 TeV (07/2015)
  - no magnetic field

Latest Minimum Bias measurements in ALICE:

- 13 TeV (12/2015)
  - Pseudorapidity distribution in $|\eta|<1.8$ is reported for inelastic events and for events with at least one charged particle in $|\eta|< 1$
  - Transverse momentum distribution in $0.15 < p_T < 20$ GeV/c and $|\eta|< 0.8$ for events with at least one charged particle in $|\eta|< 1$

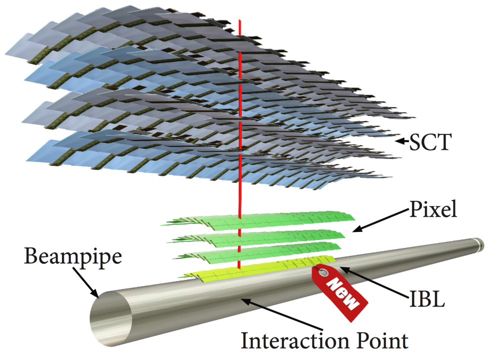
Minimum Bias measurements in LHCb:

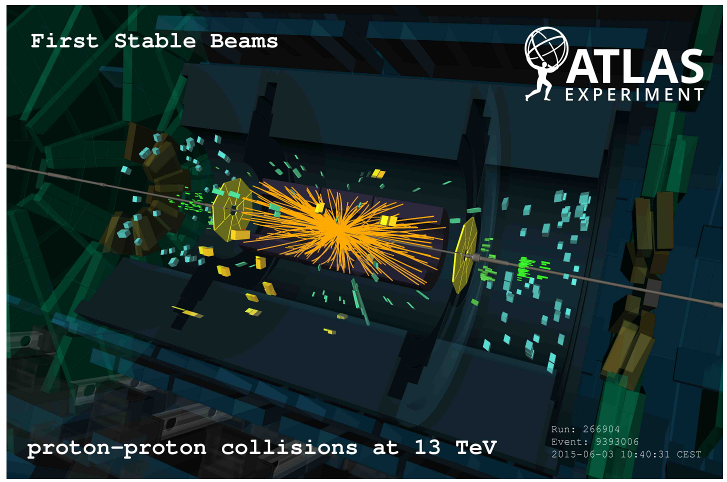
- 7 TeV (12/2011)
  - $p_T > 1$ GeV, $-2.5<\eta<-2.0$, $2.0<\eta<4.5$

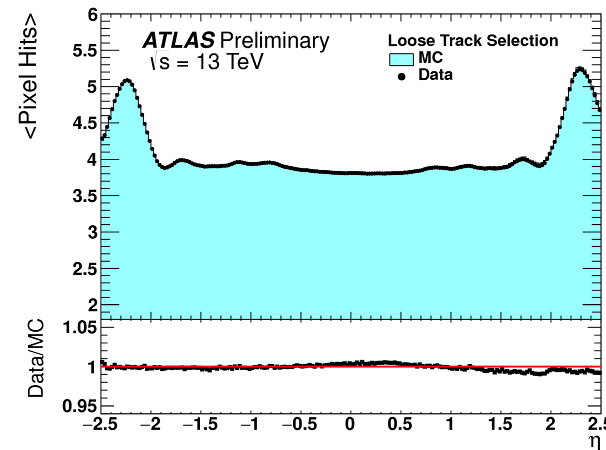
Summarising:
Very different detectors, but trying to have some common phase space to compare results!

Minimum Bias in ATLAS

- The ATLAS detector is a multi-purpose detector with a tracking system ideal for the measurement of particle kinematics
  - New **Insertable B-Layer** (**IBL**) added to the tracking system during Long Shutdown 1

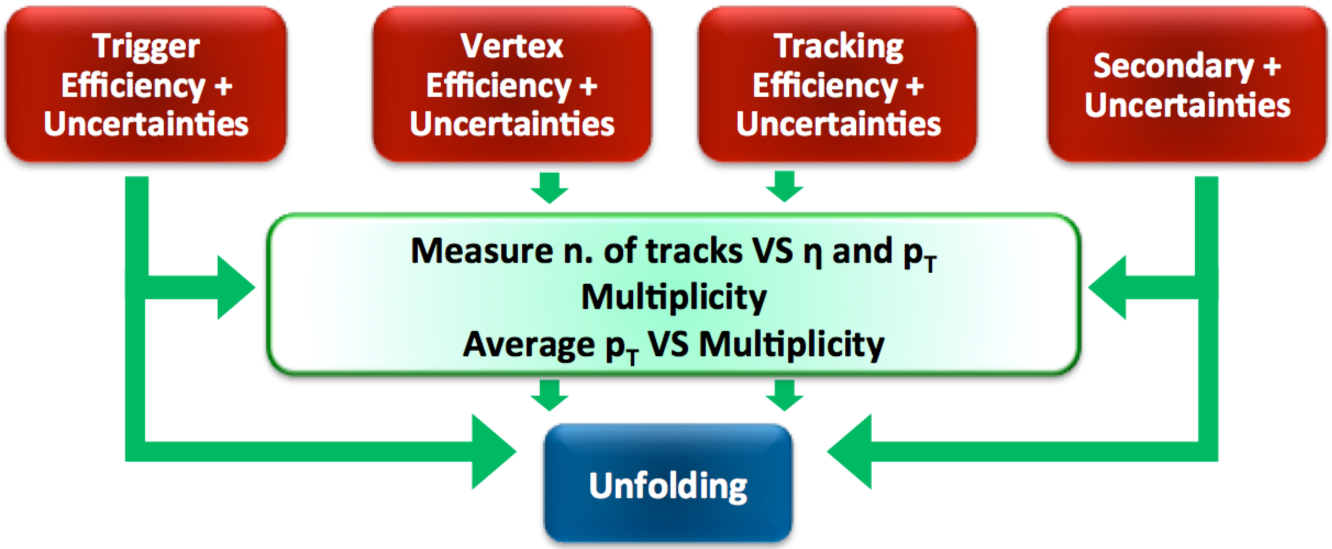






- To study an **Extended Phase Space** with p_T > 100 MeV a **robust low p_T reconstruction** is fundamental!
- Possible in Run 1, but much improved in RUN 2 thanks to the **IBL** which allows to use an extra measurement point
- **Critical evaluation of the systematics** when going to very low p_T
  - Main source is the accuracy with which the amount of material in the Inner Detector is known
  - **Material studies are fundamental** → details in the next slides

Analysis Overview

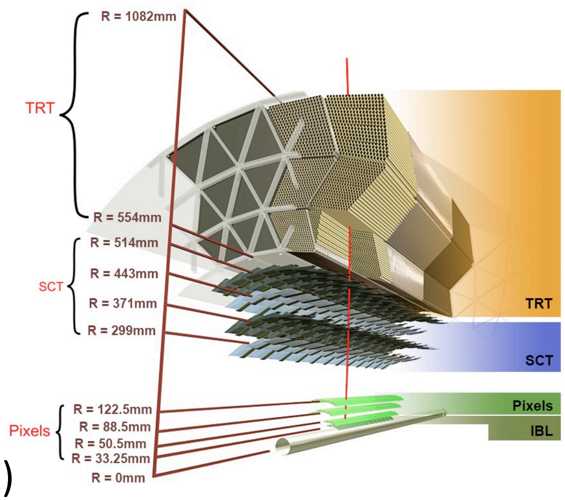


In this talk:

- **Focus on** the nominal phase space investigated within the **Minimum Bias analysis at 13 TeV** and comparison with the other phase spaces, where relevant:
  - Nominal: $p_T > 500$ MeV, $|\eta| < 2.5$ (All the details in the next slides, link)
  - Reduced: $p_T > 500$ MeV, $|\eta| < 0.8$ (For comparison to the various detectors, link)
  - Extended: $p_T > 100$ MeV, $|\eta| < 2.5$ (To investigate the low p_T region, link)
- Comparison with results at lower center-of-mass energy
  - **8 TeV** results recently published, link
  - High multiplicity phase spaces (**n_{ch}>20,50**) investigated for the first time in ATLAS for a more comprehensive understanding of the minimum bias events

Minimum Bias Analysis at 13 TeV: Event Selection

- Accepted on single-arm Minimum Bias Trigger Scintillator (MBTS)
- Primary vertex (2 tracks with p_T >100 MeV)
- Veto on any additional vertices with ≥ 4 tracks
- At least 1 selected track:
    - $p_T > 500$ MeV and $|\eta| < 2.5$ (Nominal phase space) or $|\eta| < 0.8$ (Reduced phase space)
- Or at least 2 selected tracks:
    - $p_T > 100$ MeV and $|\eta| < 2.5$ (Extended phase space)
- For each track:
    - At least 1 Pixel hit
    - At least
        - 2 SCT hits if $p_T < 300$ MeV
        - 4 SCT hits if $p_T < 400$ MeV
        - 6 SCT hits if $p_T > 400$ MeV
    - IBL hit required
    - $|d_0^{BL}| < 1.5$ mm (transverse impact parameter w.r.t beam line)
    - $|\Delta z_0 \sin\vartheta| < 1.5$ mm (Δz_0 is the difference between track z_0 and vertex z position)
    - Track fit χ^2 probability > 0.01 for tracks with $p_T > 10$ GeV



Primary Charged Particles: charged particles with a mean lifetime > 300 ps, either directly produced in pp interactions or from subsequent decays of directly produced particles with < 30 ps → strange baryons excluded (more details in the next slides)

Data and Simulation Samples

Simulation:

- **Pythia8**
  - A2 → ATLAS Minimum Bias tune, based on MSTW2008LO
  - Monash → alternative tune, based on NNPDF2.3LO
- **EPOS 3.1** → effective QCD-inspired field theory, tuned on cosmic rays data
- **QGSJET-II** → based on Reggeon Field Theory, no color reconnection

Data:

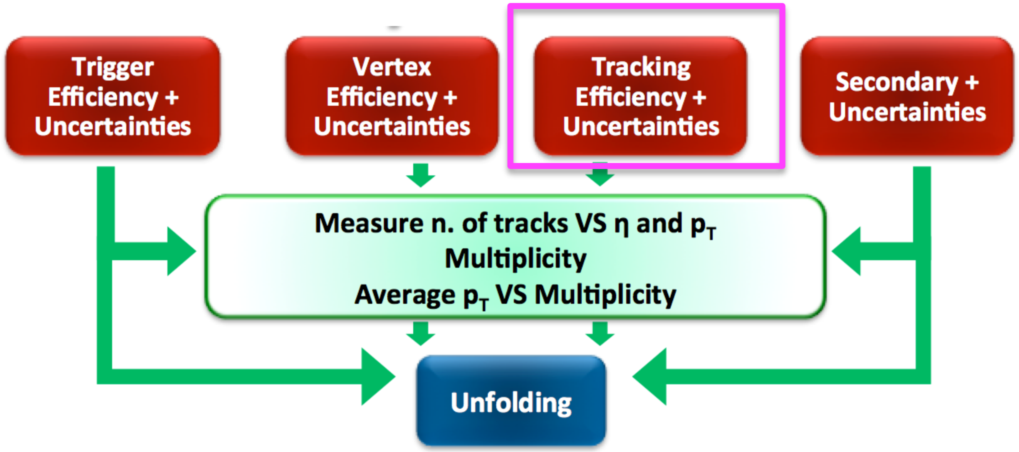
Using the two 13 TeV runs with low mean number of interactions per bunch crossing (<μ> ~ 0.005)

→

151 μb^{-1}
8,870,790 events selected, with
106,353,390 selected **tracks**
(500 MeV)

In the 100 MeV case: nearly double tracks, but more difficult measurement due to increased impact from multiple scattering at low pt and imprecise knowledge of the material in the ID

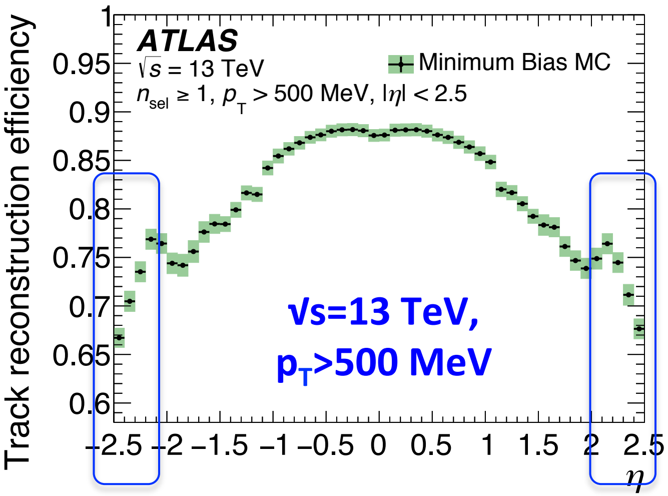
Track Reconstruction Efficiency

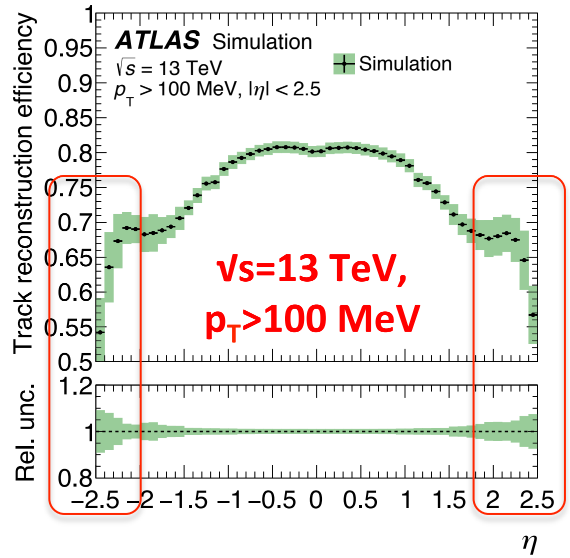


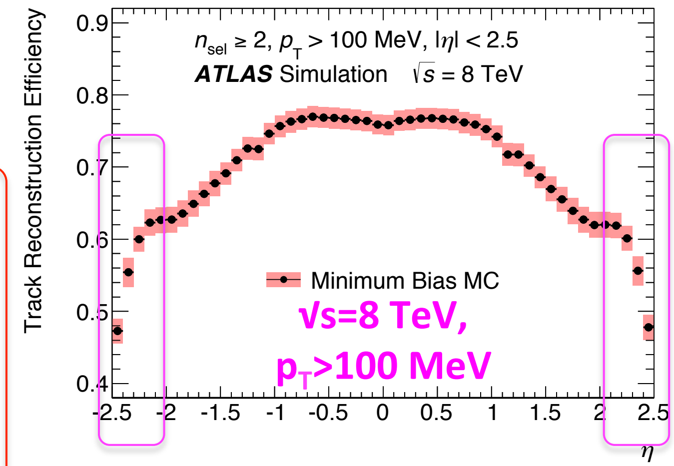
- Main ingredient for the Minimum Bias analysis
- Critical evaluation of the systematics when going to very low p_T
- At 13 TeV, different approaches taken for the nominal and the extended phase space → discussed in the next slides

Track Reconstruction Efficiency

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







Systematic Uncertainty	Size ($\sqrt{s}$=13 TeV, p_T>500 MeV)	Size ($\sqrt{s}$=13 TeV, p_T>100 MeV)	Size ($\sqrt{s}$=8 TeV, p_T>100 MeV)
Track Selection	0.5%	0.5%	0.5% - 8%
χ^2 probability	0.5% - 5%	0.2% - 7%	
Material	0.6% - 1.5%	1% - 9%	1.6% - 3.5% (up to 8% for p_T < 150 MeV)

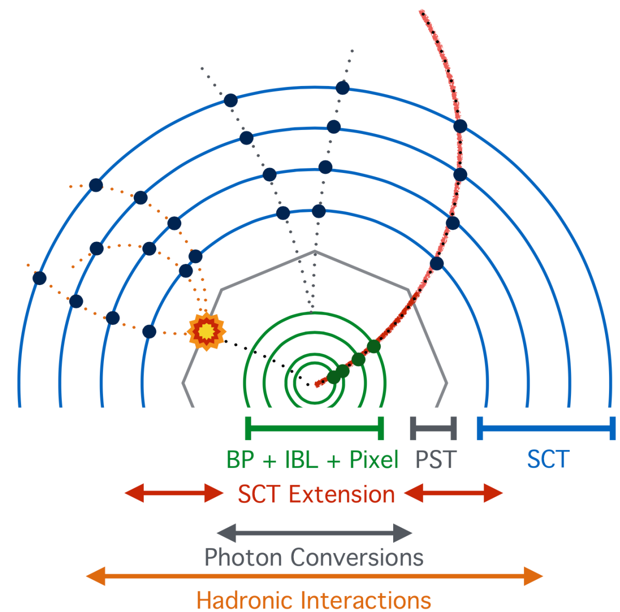
Systematic uncertainty dominated by the lack of knowledge of the material distribution!

Material Studies

- The accuracy with which the amount of material in the ID is known contributes the **largest source of uncertainty on** the simulation-based estimate of the **track reconstruction efficiency**

- Complementary tracking studies to probe the changes made to the ID during LS1
  - new **smaller beam pipe installed together with the IBL**
  - new **more robust pixel service connections** installed at the same time

METHOD	SENSITIVE REGION
Hadronic Interactions Rate	Beam Pipe – Pixel – First SCT layer
Photon Conversions Rate	Beam Pipe – Pixel – First SCT layer
SCT Extension Efficiency	Pixel Services



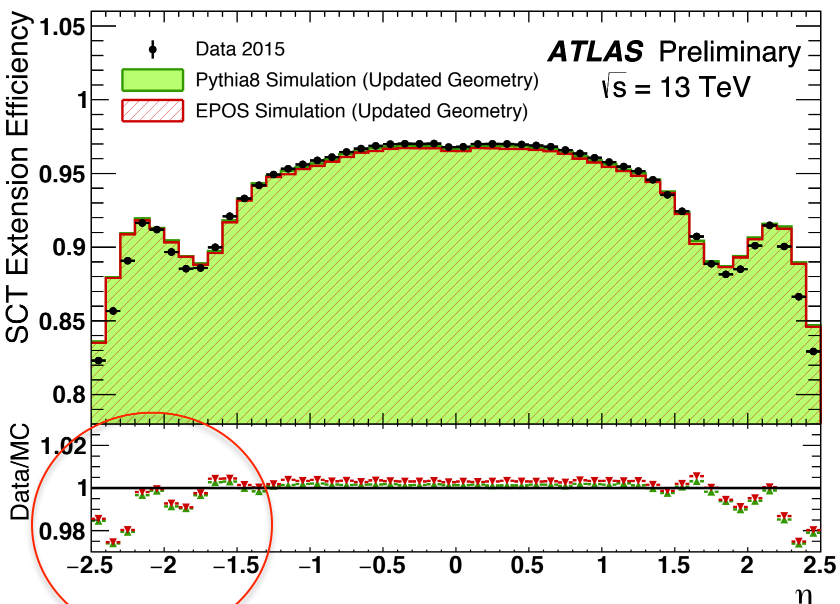
- First qualitative results released in a PUBNote (ATL-PHYS-PUB-2015-050) in November 2015

Data-driven correction to the Tracking Efficiency

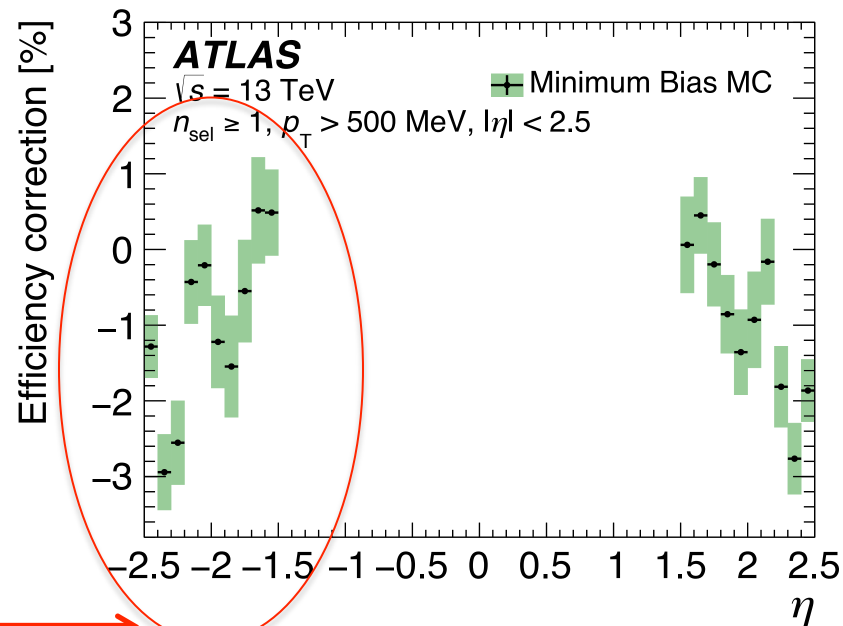
- **SCT-Extension Efficiency**: rate of pixel stand-alone tracks successfully extended to include SCT clusters and to build a full silicon track → $\varepsilon_{ext} \equiv \frac{N_{tracklet}(\text{matched})}{N_{tracklet}}$

- In the **500 MeV** phase space, the track reconstruction efficiency in the region **1.5 < |η| < 2.5** is corrected using the results from the SCT-Extension Efficiency

SCT-Extension Efficiency

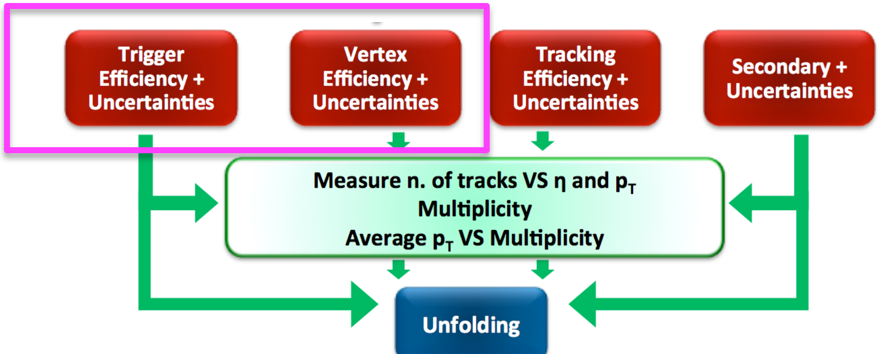


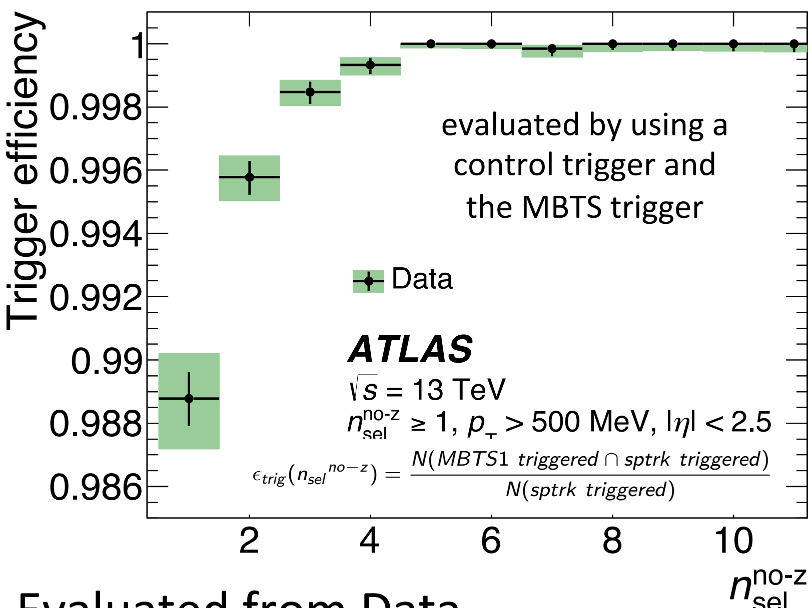
Tracking Efficiency Correction

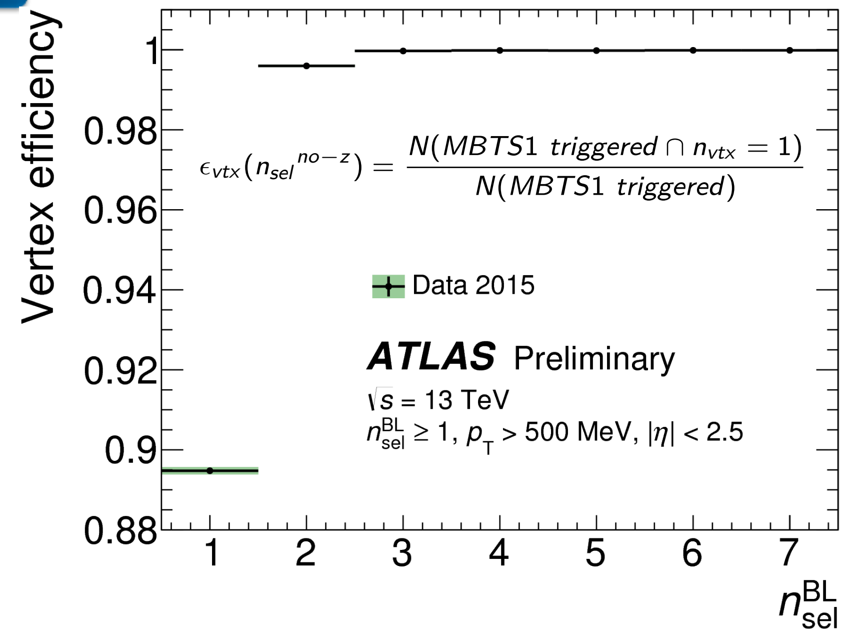


- Shape of the Data to Simulation ratio of the SCT-Extension Efficiency reflected into the shape of the correction applied to the Tracking Efficiency
- **Big reduction of the systematic uncertainties**
- Only applied in the Nominal phase space due to issues extrapolating to low p_T

Trigger and Vertex Reconstruction Efficiency

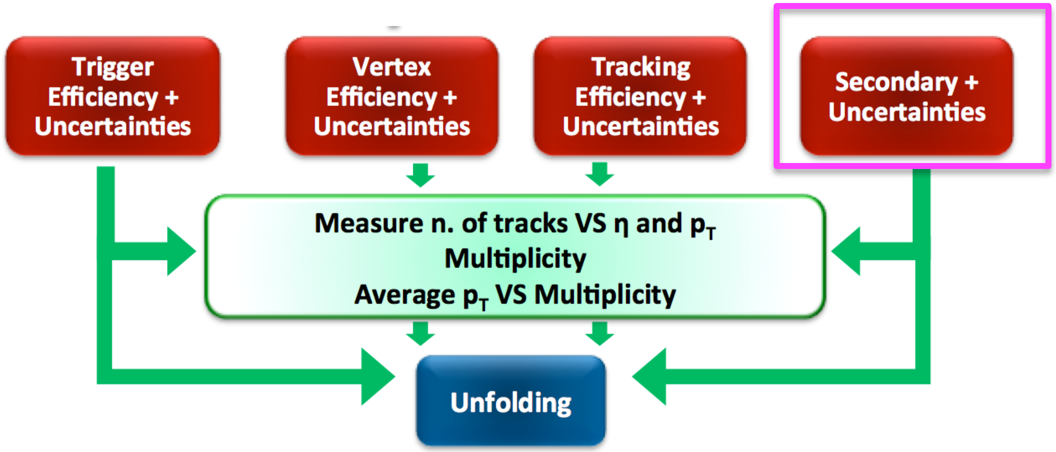






- Evaluated from Data
- Dependence on kinematic quantities studied:
  - negligible p_T-dependence
  - visible n_{sel}-dependence
  - negligible systematic uncertainties

Background evaluation



Background contributions to the tracks from primary particles include:

- Strange baryons
- Secondary particles
- Fake tracks
    - Negligible in the 500 MeV phase space
    - Non-negligible in the 100 MeV phase space
    - Treated as part of the background

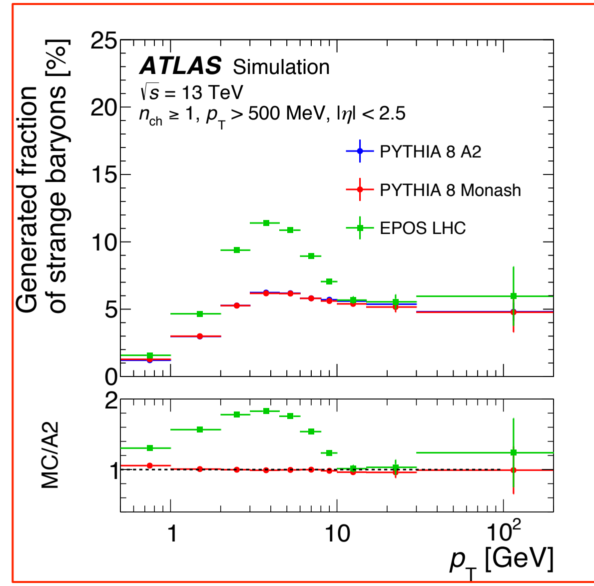
Strange Baryons

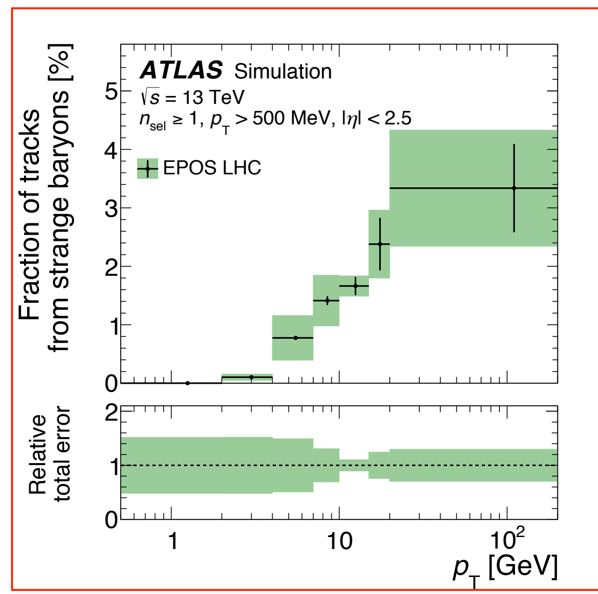
Common treatment of the Strange Baryons in all the 8 and 13 TeV analysis

- Particles with lifetime 30 ps < τ < 300 ps (**strange baryons**) are **no longer considered primary particles** in the analysis, decay products are treated like secondary particles

- **Low reconstruction efficiency** (<0.1%) and **large variations in predicted rates** lead to a model dependence (very different predictions in Pythia8 and EPOS)

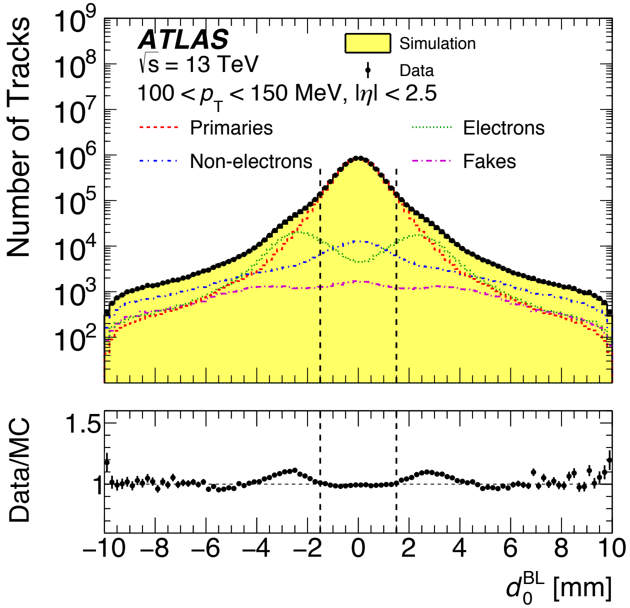
- **Final results produced with and without the strange baryons** to allow comparison with previous measurements





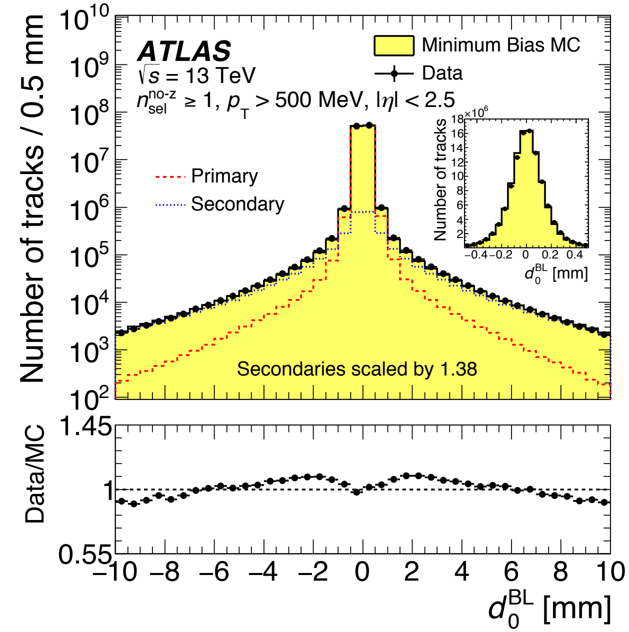
Secondaries

- Rate measured in data by performing a fit to the transverse impact parameter distribution
- **More detailed evaluation of secondaries in the 100 MeV phase-space with respect to the 500 MeV**



Create templates from:

- p_T < 500 MeV, split templates: primary, non-electrons, electrons and fakes
- $p_T \geq$ 500 MeV, combined template: primary and secondary



- Split templates only for p_T < 500 MeV:
  - Different shape of the transverse impact parameter distribution for electron and non-electron secondary particles → d_0^{BL} reflects the radial location at which the secondaries were produced
  - Different processes for conversion and hadronic interaction leading to differences in the radial distributions → electrons mostly produced from conversions in the beam pipe
  - Fraction of electrons increases as p_T decreases

Systematic Uncertainties Breakdown

- Zooming-in on some of the systematic uncertainties at 13 TeV (full list in the extra slides)

Systematic Uncertainty	Distribution	Size (√s=13 TeV, p_T>500 MeV)	Size (√s=13 TeV, p_T>100 MeV)
Track Reconstruction Efficiency	η	0.5% - 1.4%	1 – 7%
	p_T	0.7%	1 – 6%
Non-primaries	η	0.5%	0.5%
	p_T	0.5% - 0.9%	0.5% -1 %
Non-closure	η	0.7%	0.4-1%
	p_T	0% - 2%	1% -3%

- **Main systematic uncertainty** on the final measurement **due to the uncertainty on the track reconstruction efficiency**

- **Smaller systematics** in the nominal phase space than in the extended one **thanks to the data-driven correction** applied to the tracking efficiency

Corrections

- Trigger and Vertex efficiency: event-wise correction

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

- Tracking efficiency: track-wise correction

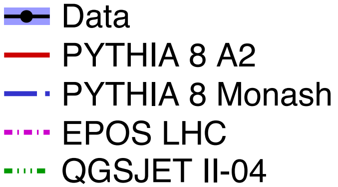
$$w_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{1}{\varepsilon_{\mathrm{trk}}(p_{\mathrm{T}}, \eta)} \cdot (1 - f_{\mathrm{sec}}(p_{\mathrm{T}}, \eta) - f_{\mathrm{sb}}(p_{\mathrm{T}}) - f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta)),$$

- f_{sec}: secondary tracks
- f_{sb}: strange baryons
- f_{okr}: outside kinematic range

- Bayesian unfolding to correct both the multiplicity n_{ch} and p_T
  - Additional correction for events out of kinematic range e.g. events with ≥1 particles but < 1 track

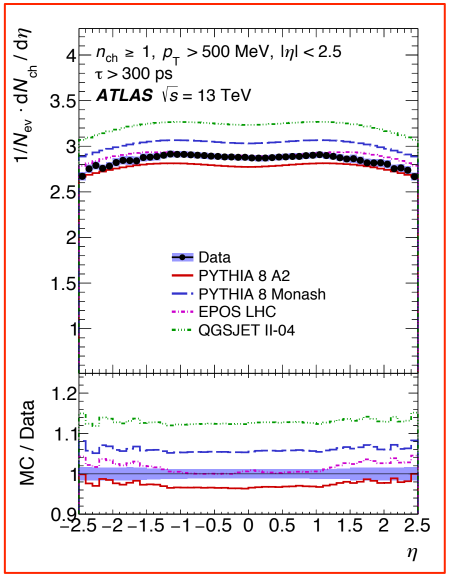
- Mean p_T vs n_{ch} bin-by-bin correction of average p_T, then n_{ch} migration

Final Results – 13 TeV

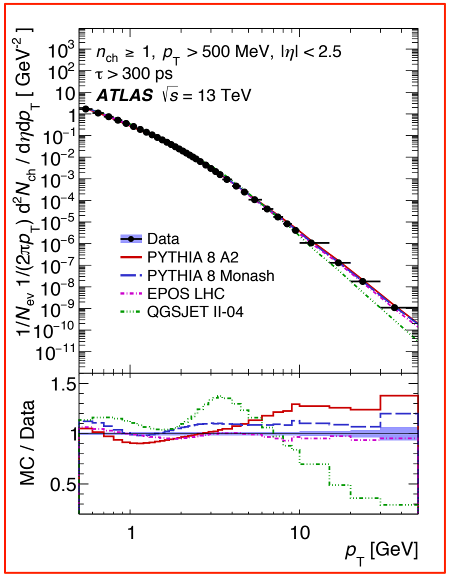


- Nominal Phase Space (p_T > 500 MeV, |η|< 2.5)

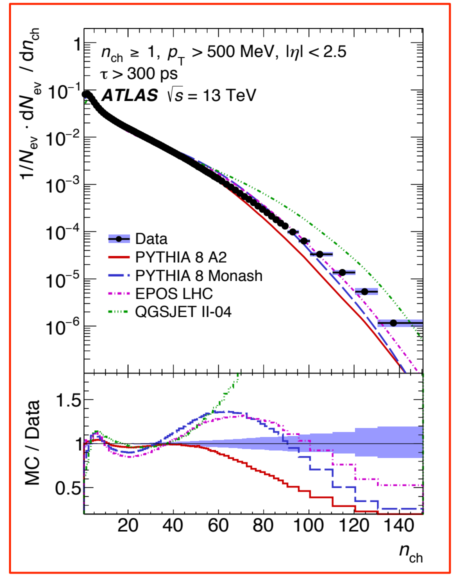
$dN_{ch}/d\eta$



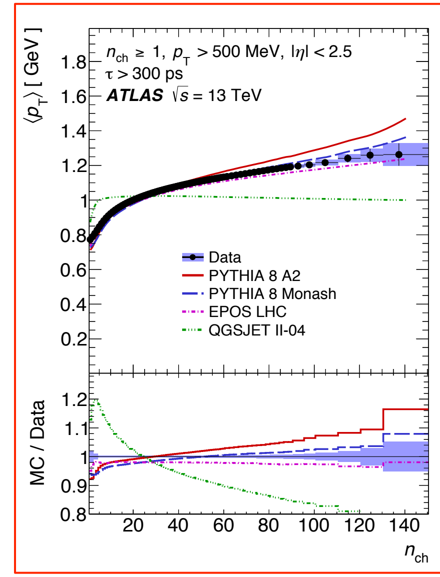
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



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



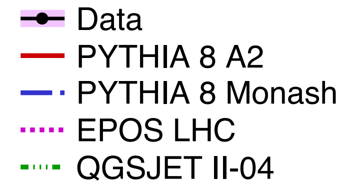
Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

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

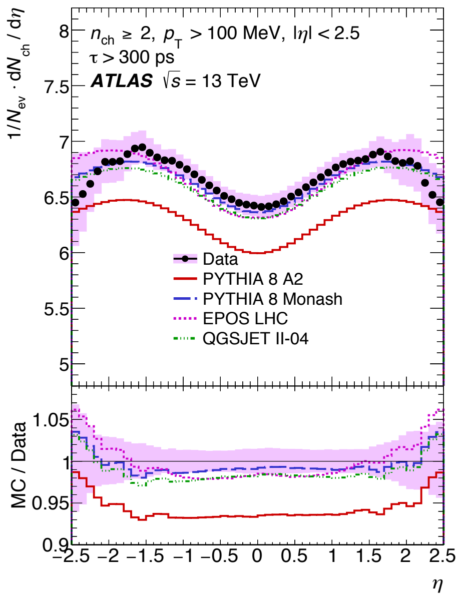
Some Models/Tunes give remarkably good predictions (EPOS, Pythia8)

Final Results – 13 TeV

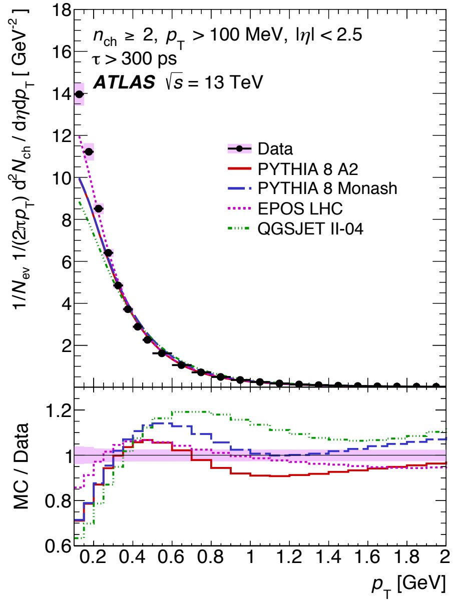


- Extended Phase Space (p_T > 100 MeV, |η|< 2.5)

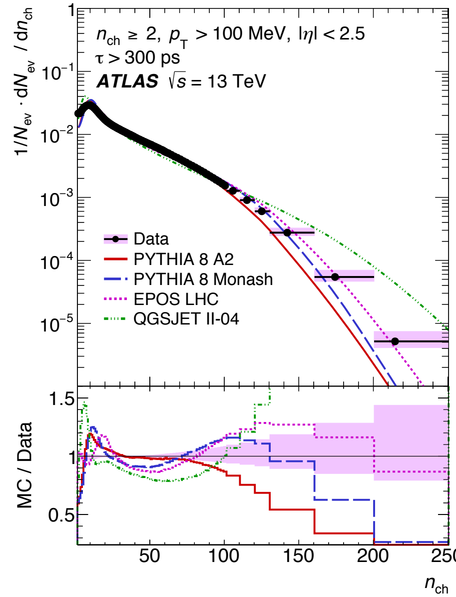
$dN_{ch}/d\eta$



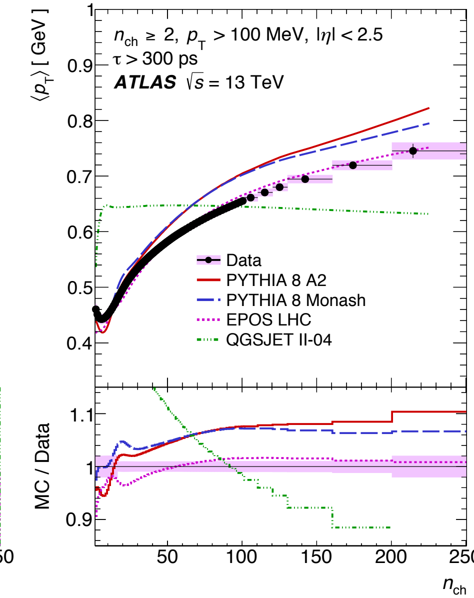
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



<p_T> VS n_{ch}



- Up to 7% of systematics in the high eta region
- Good prediction by all the generator, except Pythia 8 A2 which lies below the data

Difficult predictions in the low p_T region

Good data/MC agreement given by EPOS (within 2%), worse predictions given by the other generators

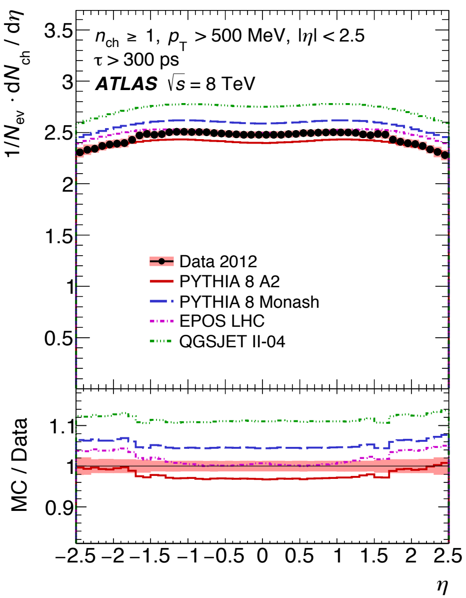
EPOS gives the best prediction!
Much clearer in this low p_T regime than in the nominal phase space!

Final Results – 8 TeV

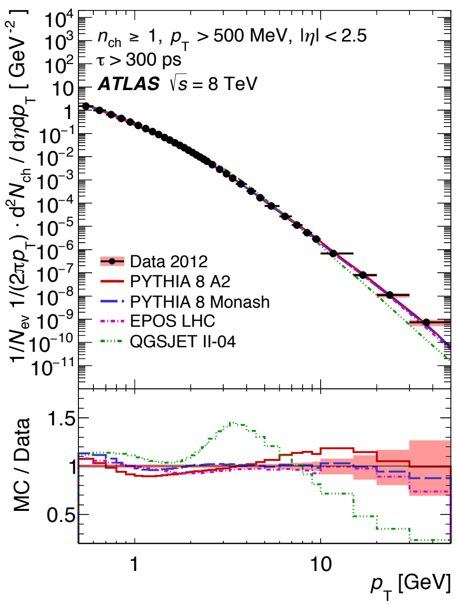
Data 2012
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

- Nominal Phase Space (p_T > 500 MeV, |η|< 2.5)

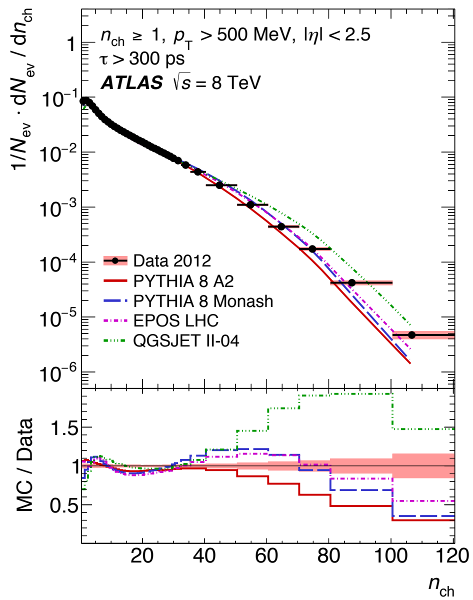
$dN_{ch}/d\eta$



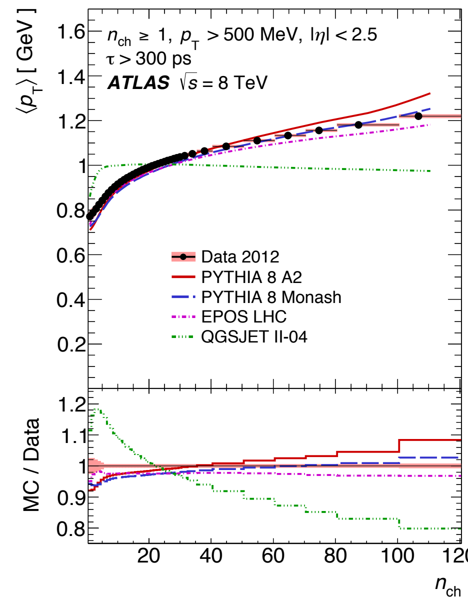
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



- EPOS gives good prediction in the central region and overestimates data in the forward region
- Pythia 8 A2 lies below the data, while Pythia 8 Monash and QGSJet overestimate data

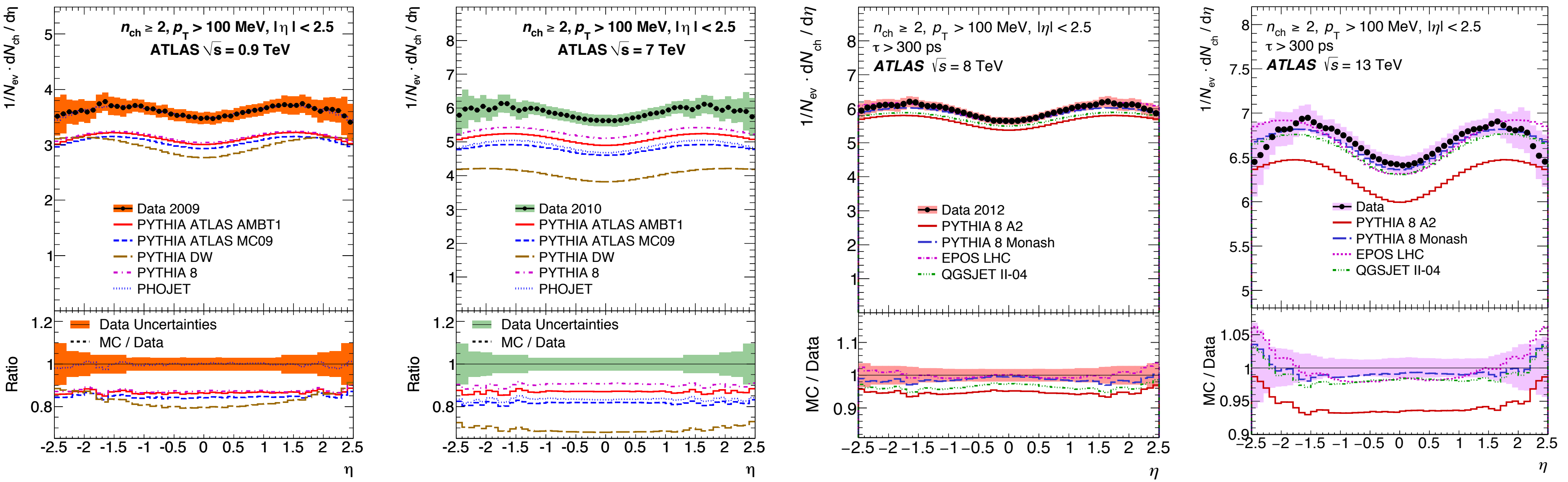
Above 1 GeV, good predictions given by Pythia 8 Monash

None of the models is consistent with the data although the Epos LHC model provides a fair description

EPOS gives the best prediction!

Final Results – Comparison with previous analyses

- Extended Phase Space (p_T >100 MeV, |η|< 2.5)



- **Strong dependence on the ID material in the forward region!**

- Form 7 to 8 TeV, up to 50% improvement in the central region and 65% improvement in the high eta region thanks to the good knowledge of the material in the ID achieved at the end of Run 1

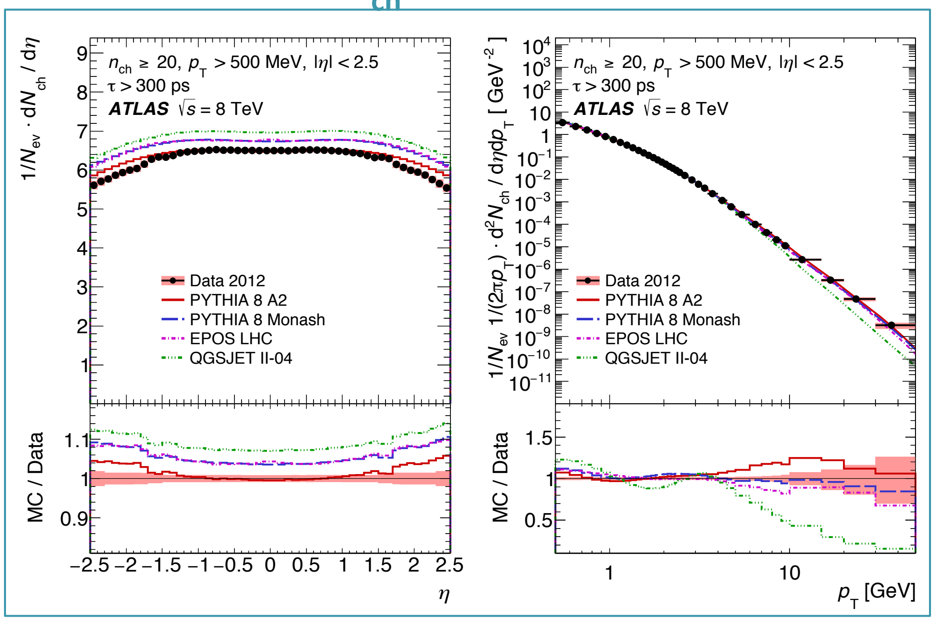
Bonus – High Multiplicity Regime at 8 TeV

- Compared with earlier studies, the 8 TeV analysis also presents ATLAS measurements of final states at high multiplicities of $n_{ch} \geq 20$ and $n_{ch} \geq 50$

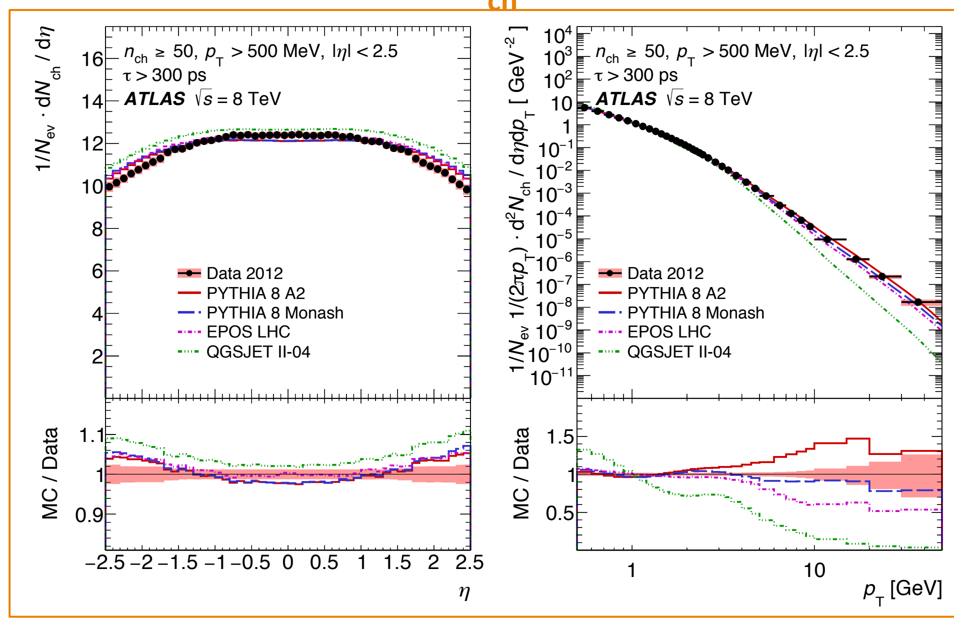
Phase Space		$1/N_{ev} \cdot dN_{ch}/d\eta$ **at** $\eta = 0$	
$n_{ch} \geq$	p_T[MeV] $>$	$\tau > 300$ ps (fiducial)	$\tau > 30$ ps (extrapolated)
2	100	5.64 ± 0.10	5.71 ± 0.11
1	500	2.477 ± 0.031	2.54 ± 0.04
6	500	3.68 ± 0.04	3.78 ± 0.05
20	500	6.50 ± 0.05	6.66 ± 0.07
50	500	12.40 ± 0.15	12.71 ± 0.18

Data 2012
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

$n_{ch} \geq 20$



$n_{ch} \geq 50$



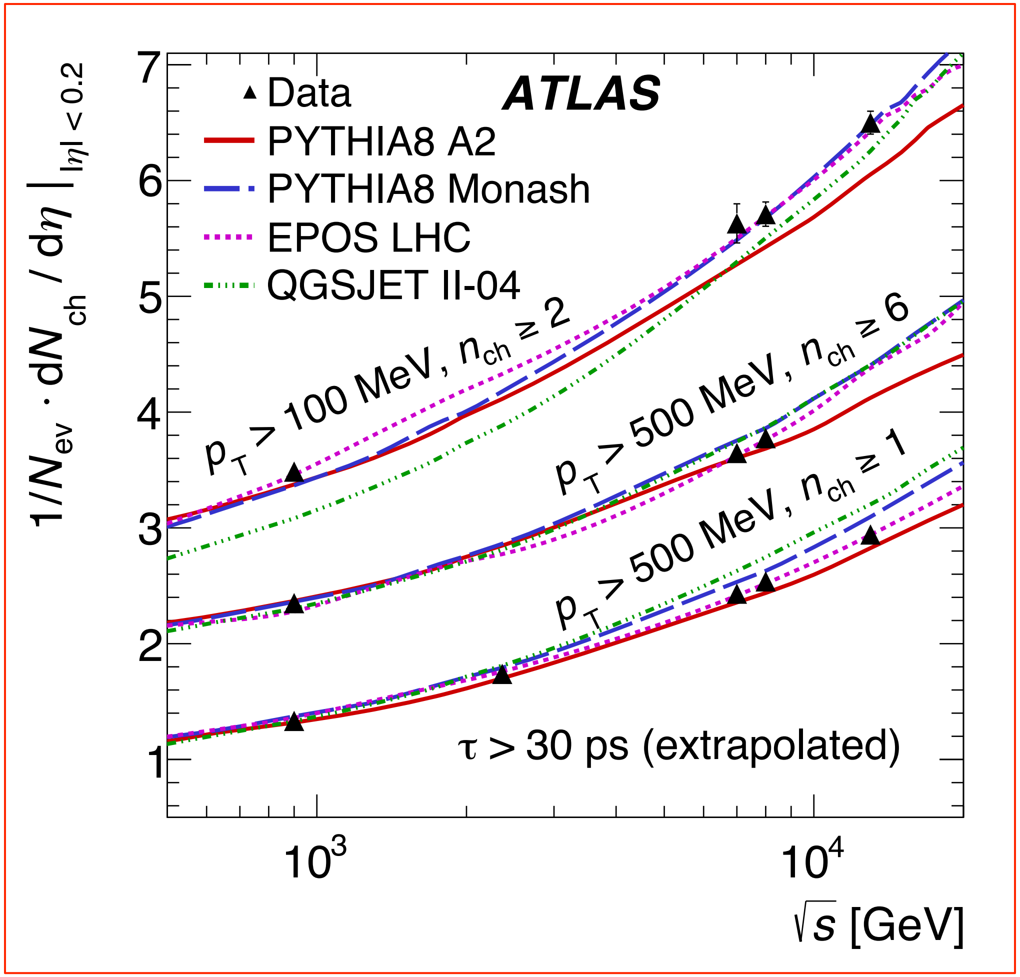
Pythia 8 A2 describes the plateau in the central region well

Fair prediction by Pythia8 and EPOS at low p_T, but large deviation at high p_T

All models overestimate data at $|\eta| > 1.7$ but better description in the central region

Fair prediction by Pythia8 and EPOS at low p_T, but large deviation at high p_T

Final Results



- Mean number of **primary charged particles increases by a factor of 2.2** when √s increases by a factor of about 14 **from 0.9 TeV to 13 TeV**!
- Looking at the overall picture, **best predictions for this observable is given by EPOS followed by Pythia 8 A2 and Monash**!

Summary

ATLAS: nice detector to study soft QCD!

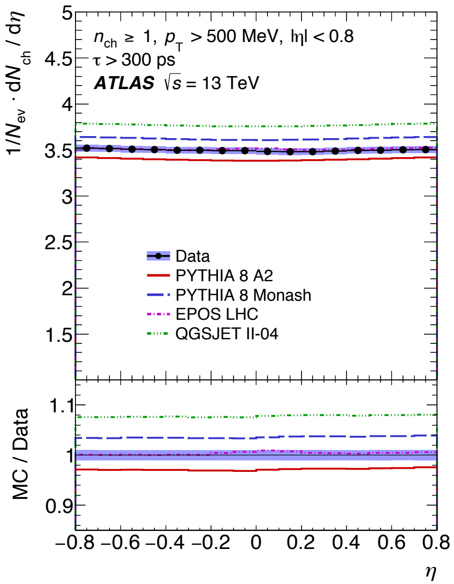
- **Minimum Bias Studies:**
  - **Track-based analysis**
    - Main systematic uncertainties from Inner Detector material estimate
  - **Charged Particle Multiplicities @ 13 TeV**
    - Nominal: p_T > 500 MeV, $|\eta|$< 2.5 (link)
    - Reduced: p_T > 500 MeV, $|\eta|$< 0.8 (link)
    - Extended: p_T > 100 MeV, $|\eta|$< 2.5 (link)
  - **Charged Particle Multiplicities @ 8 TeV**
    - Many phase spaces investigated (link)
      - Reduced systematics with respect to the 7 TeV measurements
      - High multiplicity region (n_{ch}>20,50) studied extensively for the first time
  - **In general, best predictions given by EPOS-LHC**

Extra Slides

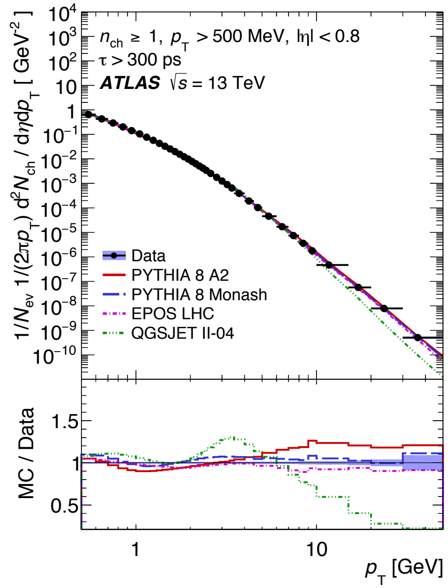
Final Results – 13 TeV

- Reduced Phase Space (p_T > 500 MeV, |η|< 0.8)

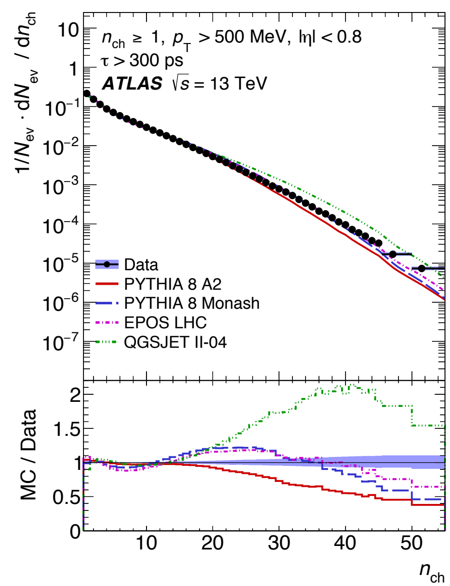
$dN_{ch}/d\eta$



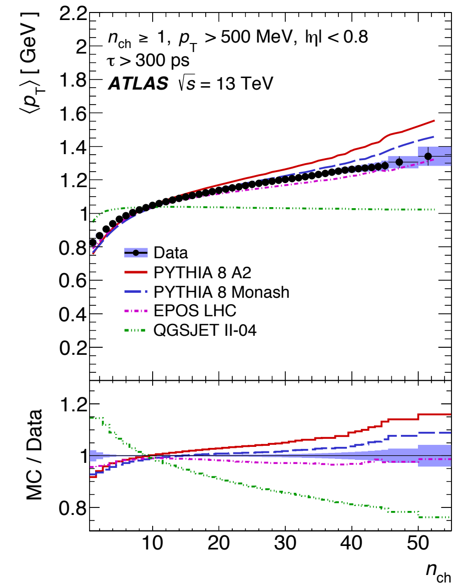
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

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

The level of agreement between the data and MC generator predictions follows the same pattern as seen in the main phase space:
Some Models/Tunes give remarkably good predictions (EPOS, Pythia8)

Hadronic Interactions and Photon Conversions

Inelastic **hadronic interactions** produce multiple charged particles when hadrons interact with the detector material.

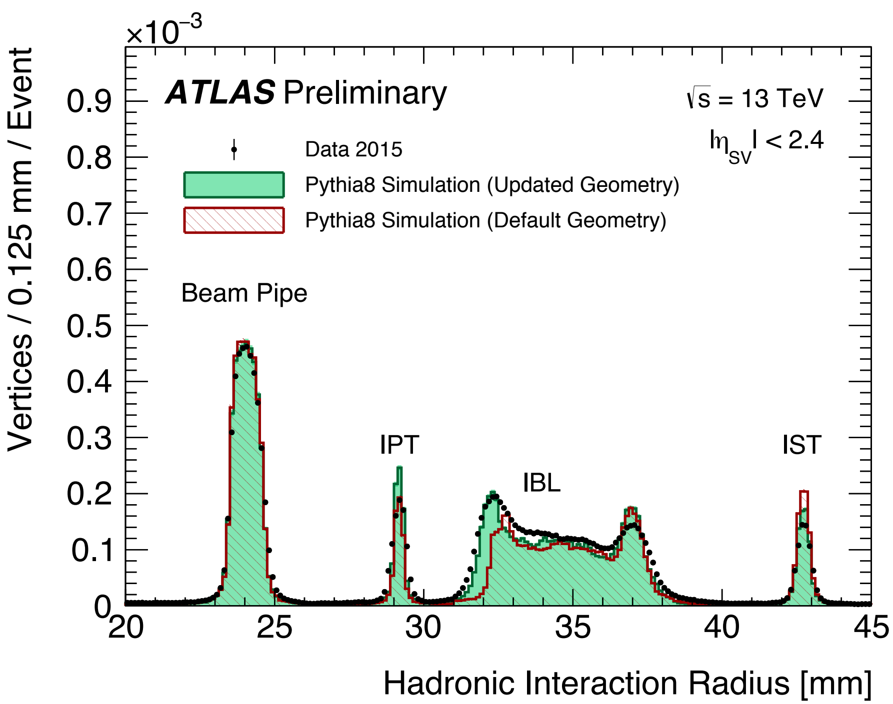
Excellent **radial resolution** (between **65 and 230 μm** from the beam pipe to Layer-1 depending on radius).

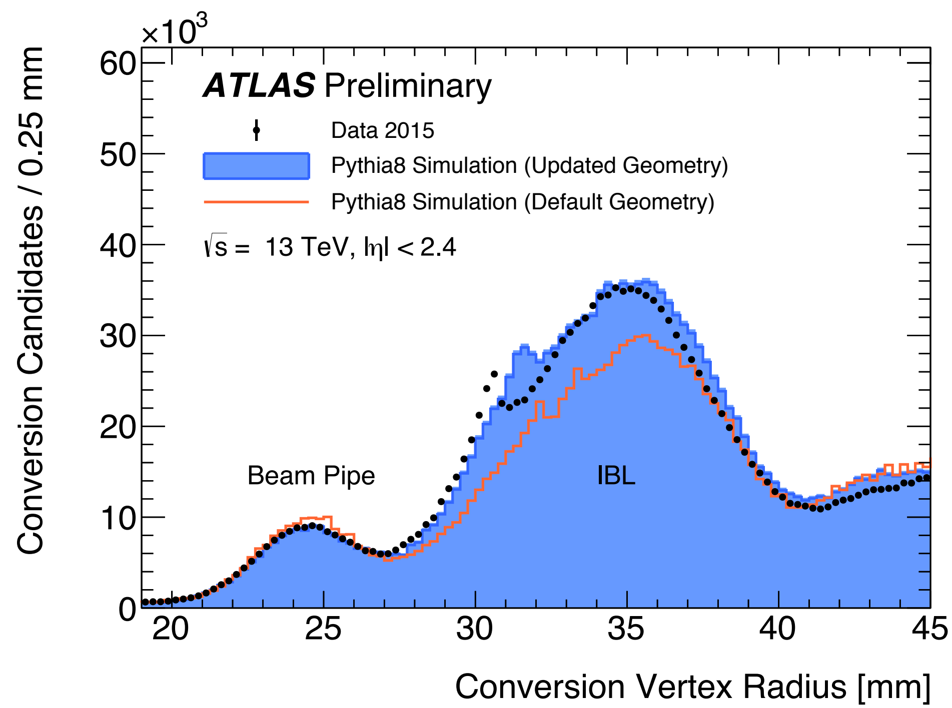
Probability for a **photon conversion** (very clean signal) is proportional to the traversed material.

High statistics source of photon conversions from di-photon decays of light neutral mesons copiously produced in *pp* collisions

These methods allowed to improve the IBL description in simulation

- **30% of material was missing in the "default geometry"**





Fakes

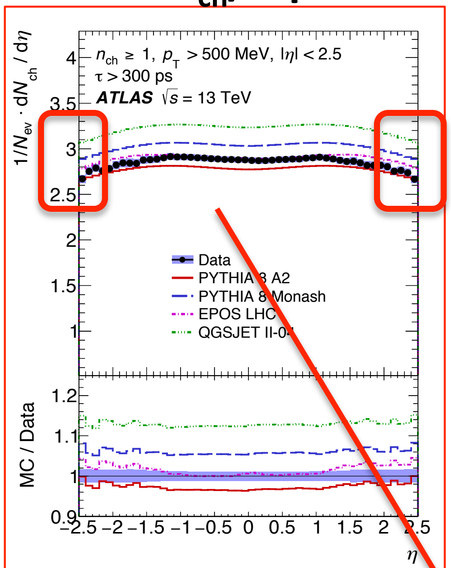
- In the 500 MeV phase space, the fakes are neglected because they drop rapidly with p_T such that the rate is negligible in that phase space

- In the 100 MeV case, fakes are treated as part of the background with a 50% systematic uncertainty following the recommendation of Inner Detector Combined Performance group

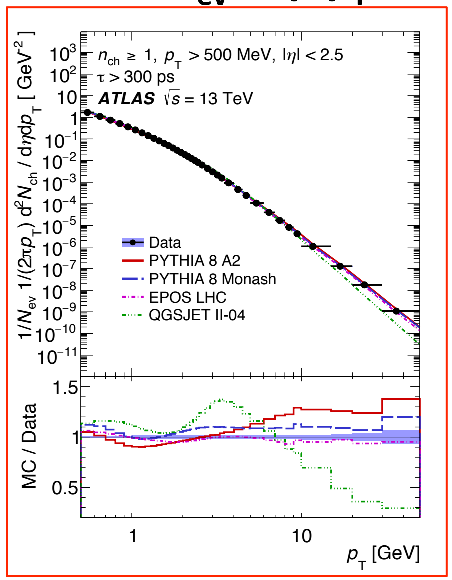
Final Results

- Nominal Phase Space (500 MeV)

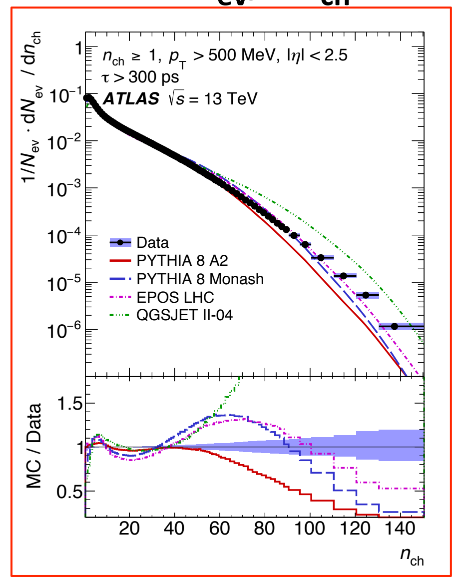
$dN_{ch}/d\eta$



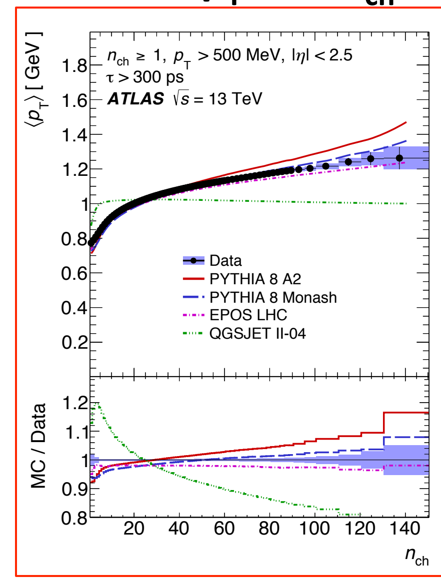
$d^2N_{ev}/d\eta dp_T$

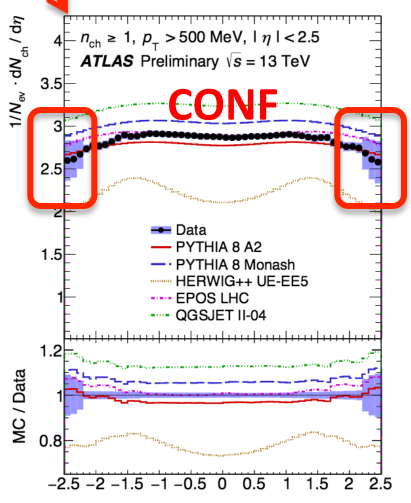


dN_{ev}/dn_{ch}



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

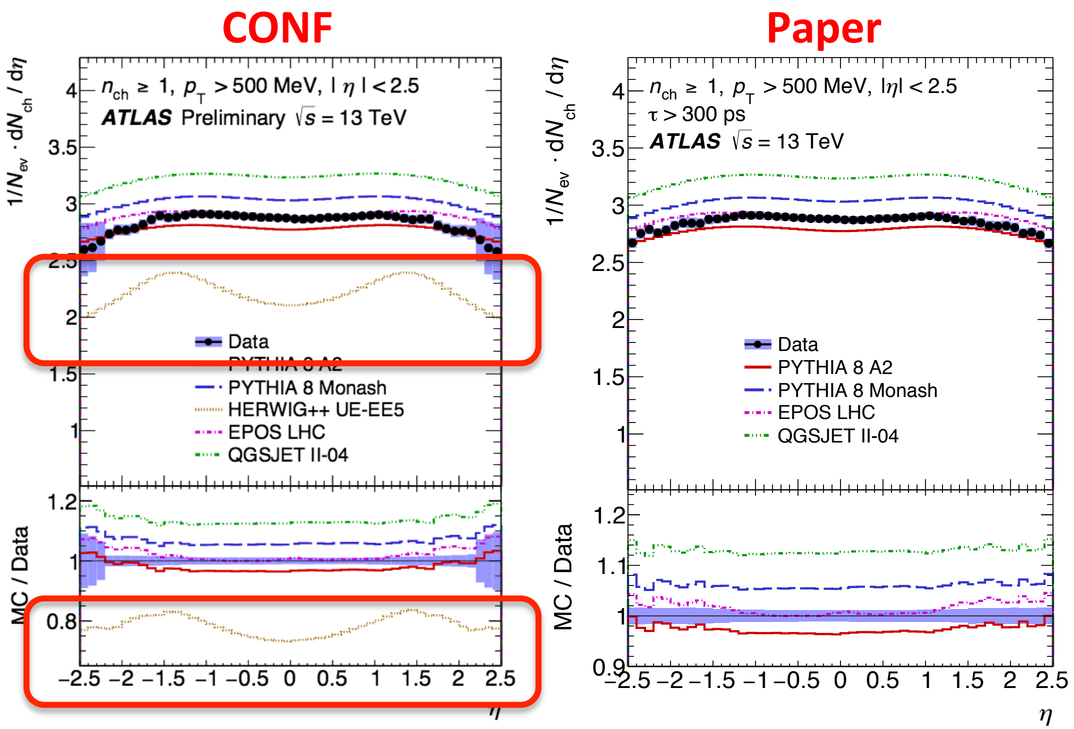




Big improvements in the systematic uncertainty evaluation thanks to the correction to the tracking efficiency driven by material studies

Final Results – Extra Generators Comparison

- Nominal Phase Space (500 MeV)



- Herwig was dropped bacause the tune (based on CTEQ6L1 PDF) used for the CONFNote was not the optimal one
  → updated plots with the tune (based on MRST PDF) suggested by the expert
  → improved data/MC agreement

Corrections (100 MeV phase space)

- Trigger and Vertex efficiency: event-wise correction

$$w_{ev}(n_{sel}^{no\text{-}z}, \Delta z_{tracks}) = \frac{1}{\varepsilon_{trig}(n_{sel}^{no\text{-}z})} \cdot \frac{1}{\varepsilon_{vtx}(n_{sel}^{no\text{-}z}, \Delta z_{tracks})}.$$

- Tracking efficiency: track-wise correction

$$w_{trk}(p_T, \eta) = \frac{1}{\varepsilon_{trk}(p_T, \eta)} \cdot (1 - f_{nonp}(p_T, \eta) - f_{okr}(p_T, \eta) - f_{sb}(p_T, \eta) - f_{fake}(p_T, \eta)).$$

f_{nonp}: non-primary tracks

f_{okr}: outside kinematic range

f_{sb}: strange baryons

f_{fake}: fake tracks

- Bayesian unfolding to correct both the multiplicity n_{ch} and p_T
  - Additional correction for events out of kinematic range e.g. events with ≥1 particles but < 1 track

- Mean p_T vs n_{ch} bin-by-bin correction of average p_T, then n_{ch} migration

Data-driven correction to the Tracking Efficiency

- When trying to use the data-driven correction in the low p_T phase space, it leads to un-physical fluctuations
- Many checks performed, but issue not found → therefore, this correction is not applied in the 100 MeV phase-space analysis and instead larger systematic uncertainties are applied, as recommended by the Inner Detector Combined Performance group:
  - 5% extra material overall
  - 10% extra material IBL (Minimum Bias is the only 2015 ATLAS analysis which used the improved IBL geometry)
  - 50% extra material in the Pixel Services Region
- Final results discussed in the next slides

Additional checks

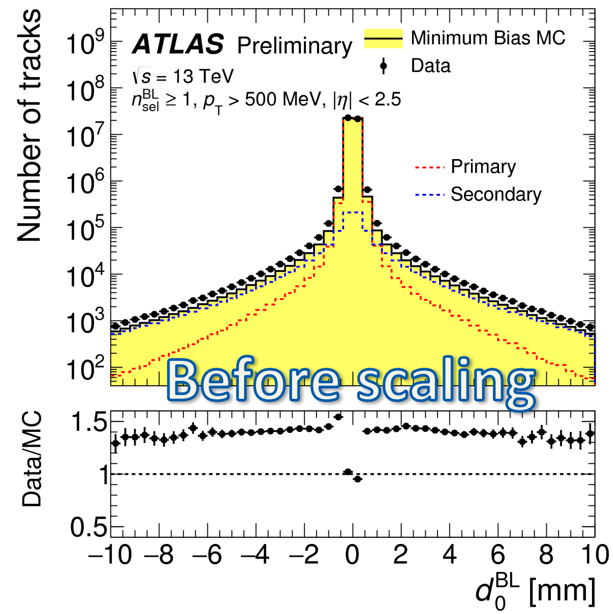
Problems that may be encountered when extrapolating the data-driven correction to low p_T tracks:

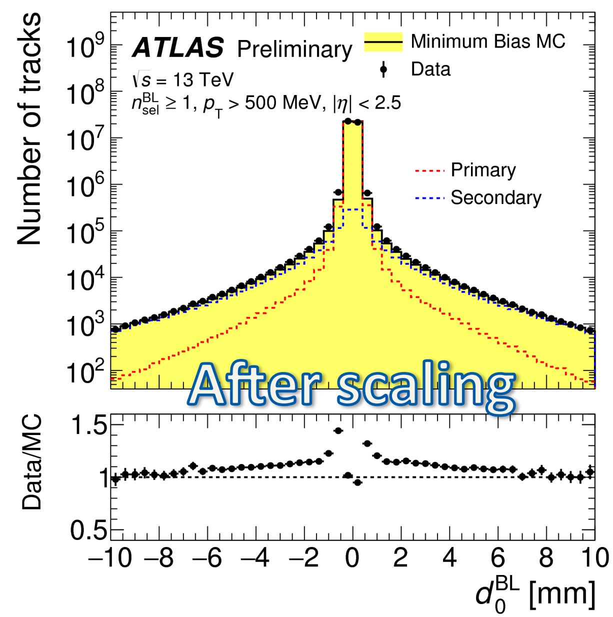
- Errors in the propagation of the systematics and correction → checked
- Track parameters resolution → checked → negligible
- Eta bin-to-bin migration → checked → negligible
- Linearity of the tracking efficiency with the material in the low p_T regime → checked

The issue was not found → Therefore this correction is not applied in the 100 MeV analysis and instead larger systematic uncertainties are applied

Non-Primary Tracks Estimation

- Non primary tracks are the biggest background
  - Rate measured in data by performing a fit to the transverse impact parameter distribution
  - 2.2% ± 0.6% of our reconstructed tracks within the signal region
- High pT tracks
  - measurable fraction of the tracks originate from low pT tracks (scattering, in flight decays)
  - Our ability to select & remove these tracks was assessed in data
  - At most 1% of tracks between 30-50GeV





N-1 cut Systematic Uncertainty

$$\epsilon_{\rm cut}(p_{\rm T},\eta) = \frac{N^{\rm tracks}_{\rm all\,cuts}(p_{\rm T},\eta)}{N^{\rm tracks}_{\rm N-1\,cuts}(p_{\rm T},\eta)}$$

- All Pixel hit requirements and all SCT hit requirements removed for the N-1 test

0.5%

- Large differences are observed at high p_T for the efficiency of both cuts, this is the result of a high fraction of poorly measured tracks entering the denominator when loosening the cuts

X^2 Probability Cut Systematic Uncertainty

- Badly measured low momentum charged particles are sometimes reconstructed as a high momentum track

- These tracks are a sizeable fraction at high reconstructed p_T because of the steeply falling p_T distribution and they are caused by interactions and multiple scattering with the material -> usually have a bad χ2 fit probability

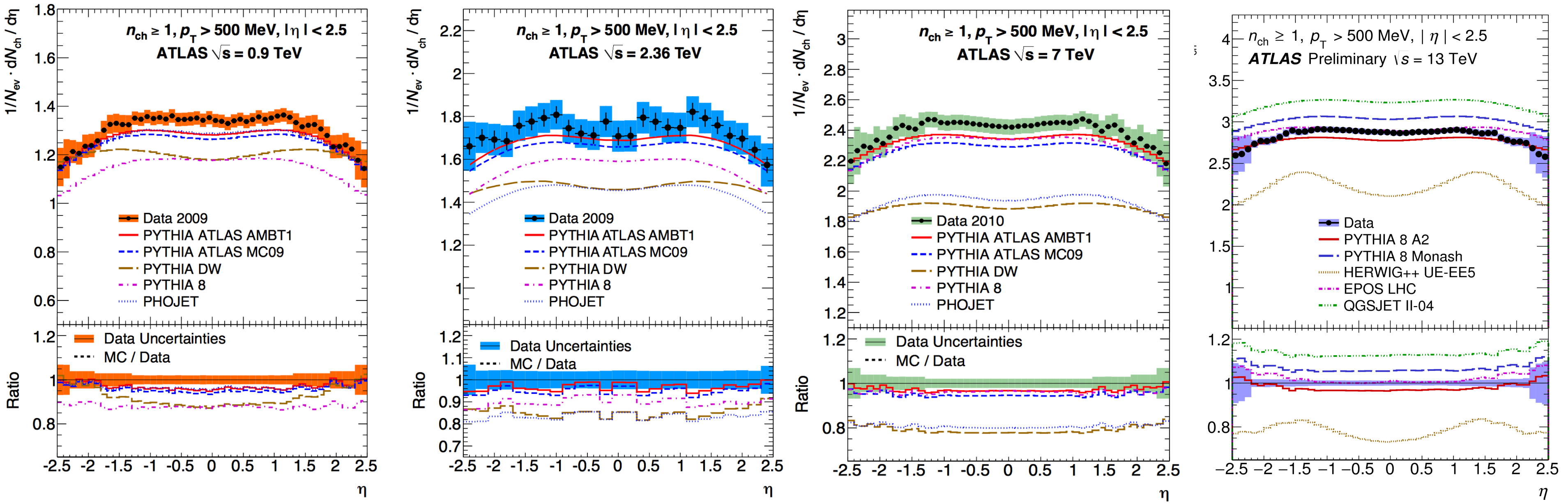
- A cut on χ2 probability of $P(\chi 2, n_{dof}) > 0.01$ is applied for tracks with $p_T > 10$ GeV to remove bad measured tracks

- The uncertainty on the remaining amount of mis-measured tracks has been determined to be less than 0.2% at 10 GeV rising up to 7% above above 50 GeV

- The uncertainty in the efficiency of the cut is assessed to be to 0.5% below 50 GeV and 5% above 50 GeV

Different Centre of Mass Energy

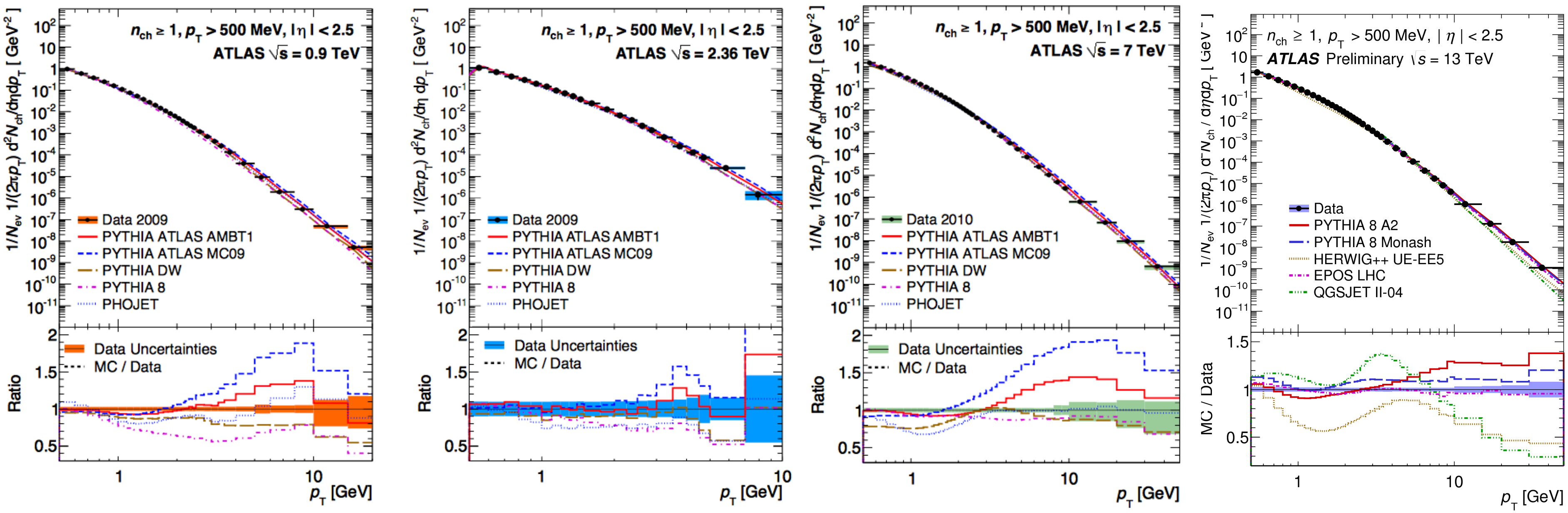
$dN_{ch}/d\eta$ http://arxiv.org/pdf/1012.5104v2.pdf



- Models differ mainly in normalisation, shape similar
- Track multiplicity underestimated

Different Centre of Mass Energy

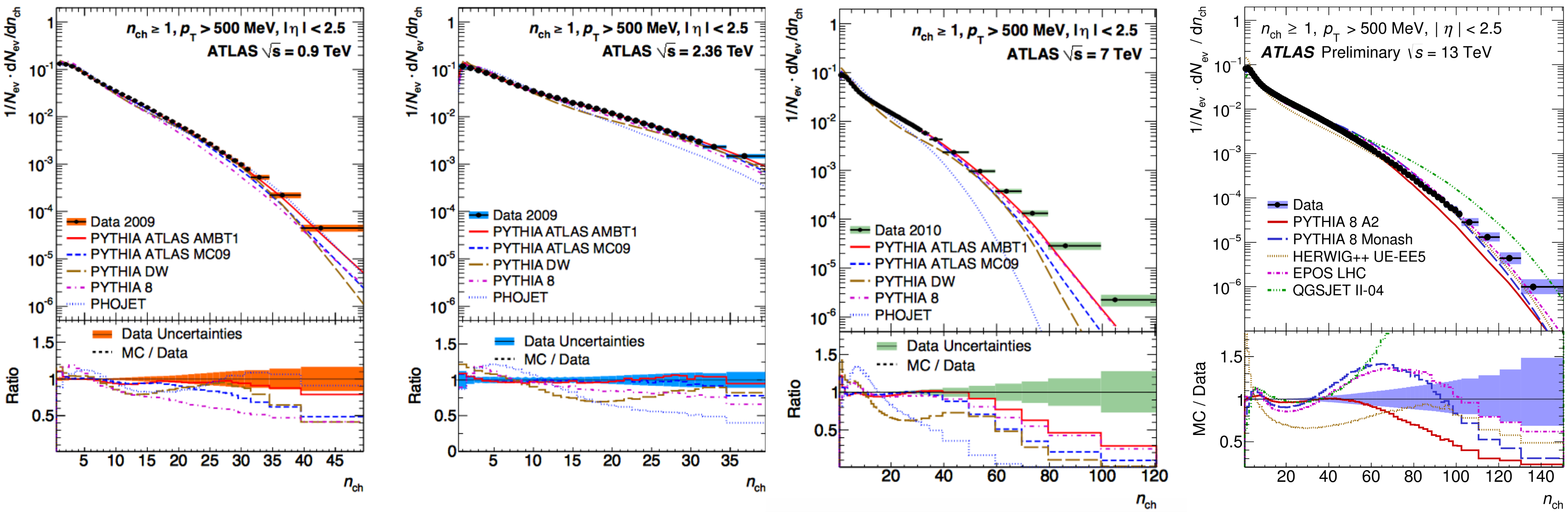
$d^2N_{ev}/d\eta dp_T$ http://arxiv.org/pdf/1012.5104v2.pdf



- Large disagreement at low p_T and high p_T

Different Centre of Mass Energy

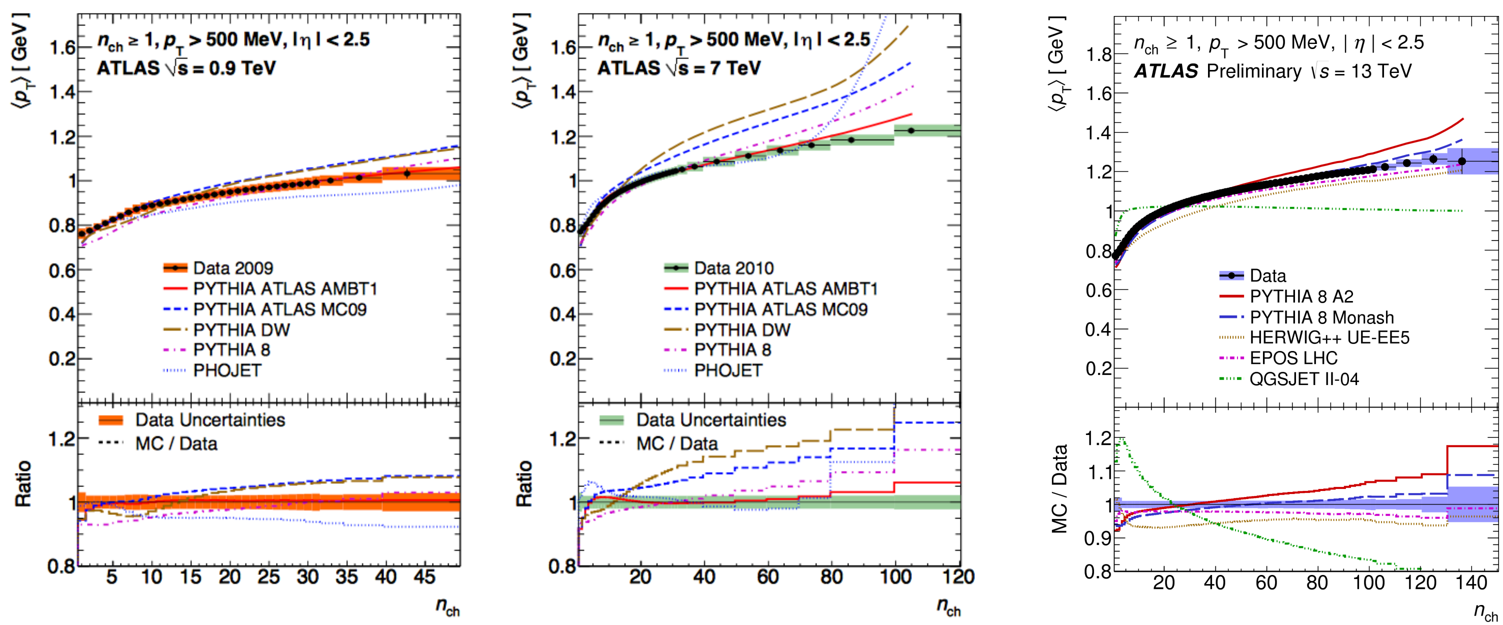
dN_{ev}/dn_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



- Low n_{ch} not well modelled by any MC; large contribution from diffraction

Different Centre of Mass Energy

$\langle p_T \rangle$ vs. n_{ch} http://arxiv.org/pdf/1012.5104v2.pdf

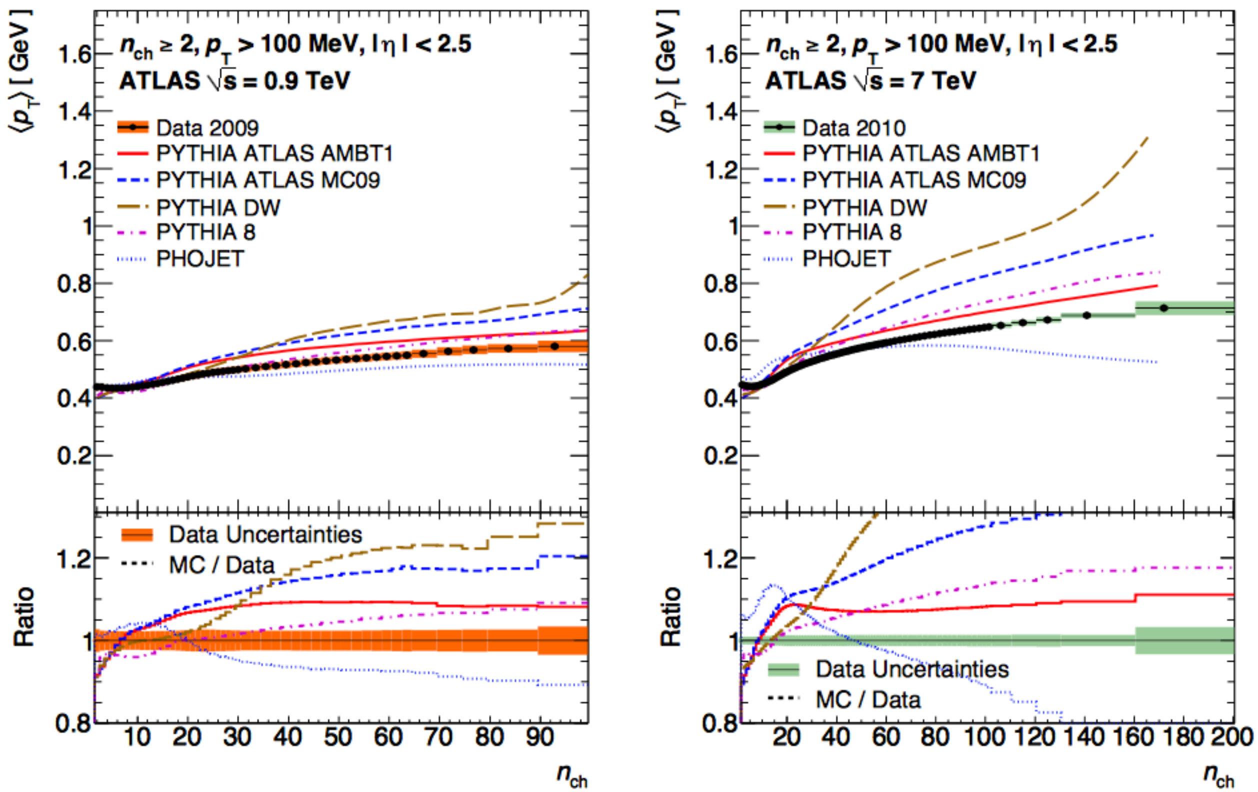


The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

- Pythia8 with hard diffractive component give best description
- Shape at low n_{ch} sensitive to ND, SD, DD fractions especially when using a 100 MeV selection

Different Centre of Mass Energy

$<p_T>$ vs. n_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



- Pythia8 with hard diffractive component give best description
- Shape at low n_{ch} sensitive to ND, SD, DD fractions especially when using a 100 MeV selection

Different Centre of Mass Energy

The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

$<p_T>$ vs. n_{ch}

http://arxiv.org/pdf/1012.5104v2.pdf

4.3.2 Track Reconstruction Algorithms at 2.36 TeV

Operation of the SCT at standby voltage during 2.36 TeV data taking led to reduced SCT hit efficiency. Consequently, ID tracks are reconstructed at this centre-of-mass energy using looser requirements on the numbers of hits and holes [4] [44, 45]. There are no simulation samples that fully describe the SCT operating at reduced voltage. A technique to emulate the impact of operating the SCT in standby was developed in simulation; this corrects the Monte Carlo without re-simulation by modifying the silicon clusterisation algorithm used to study the tracking performance. However, the final ID track efficiency at $\sqrt{s}$ = 2.36 TeV was determined using a correction to the track reconstruction efficiency derived from data at $\sqrt{s}$ = 0.9 TeV.

Pixel tracks were reconstructed using the standard track reconstruction algorithms limited to Pixel hits and with different track requirements. There is little redundant information, because at least three measurement points are needed to obtain a momentum measurement and the average number of Pixel hits per track is three in the barrel. Therefore the Pixel track reconstruction efficiency is very sensitive to the location of inactive Pixel modules. The total distance between the first and the last measurement point in the pixel detector, as well as the limited number of measurement points per track, limit the momentum resolution of the tracks; therefore the Pixel tracks were refit using the reconstructed primary vertex as an additional measurement point. The refitting improves the momentum resolution by almost a factor of two. However, the Pixel track momentum resolution remains a factor of three worse than the resolution of ID tracks.

The selection criteria used to define good Pixel and ID tracks are shown in Table 3. The total number of accepted events and tracks at this energy are shown in Table 4. These two track reconstruction methods have different limitations; the method with the best possible measurement for a given variable is chosen when producing the final plots. The Pixel track method is used for the n_{ch} and η distributions, while the ID track method is used for the p_T spectrum measurement; the $\langle p_T \rangle$ distribution is not produced for this energy as neither method is able to describe both the number of particles and their p_T accurately.

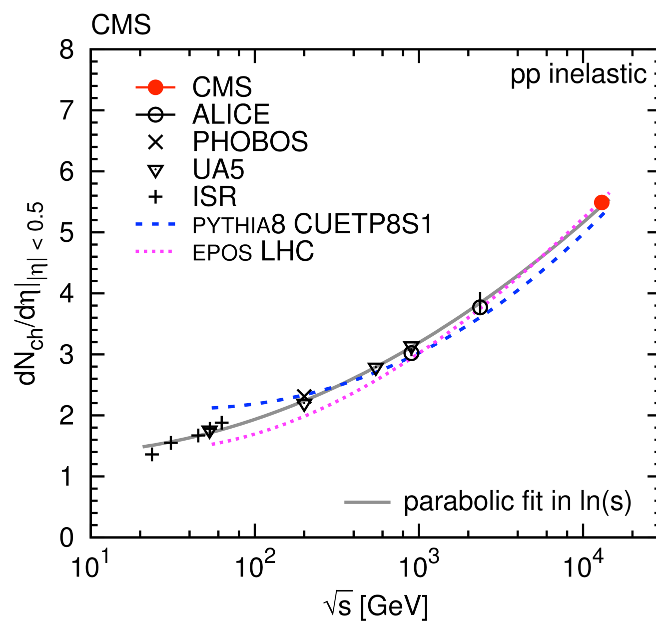
LHC Results Overview

Minimum Bias measurements in ATLAS:

- 0.9 TeV (03/2010)
  - 1 phase space (1 charged particle, 500 MeV, |η|<2.5)
- 0.9, 2.36, 7 TeV (12/2010)
  - 3 phase spaces (1, 2, 6 charged particles, 100-500 MeV, |η|<2.5)
- 0.9, 7 TeV (12/2010)
  - CONFNote – 2 phase spaces (1 charged particle, 500-1000 MeV, |η|<0.8)
- 8 TeV (03/2016)
  - 5 phase spaces (1, 2, 6, 20, 50 charged particles, 100-500 MeV, |η|<2.5)
- 13 TeV (02/2016)
  - 2 phase spaces (1 charged particle, 500 MeV, |η|<2.5, 0.8)
- 13 TeV (in second circulation)
  - 1 phase space (2 charged particles, 100 MeV, |η|<2.5)

Minimum Bias measurements in CMS:

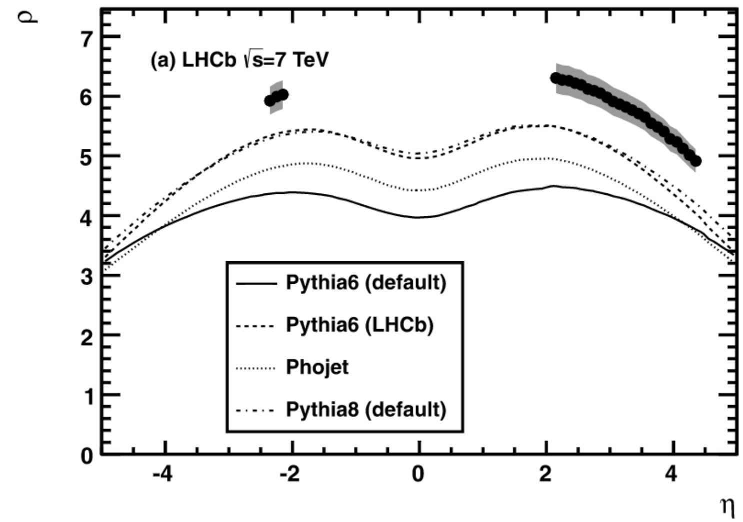
- 0.9, 2.36 (02/2010)
  - Charged hadrons
- 7 TeV (02/2010)
  - Charged hadrons
- 0.9, 2.36, 7 TeV (11/2010)
  - 5 pseudorapidity ranges from |eta|<0.5 to |eta|<2.4
- 8 TeV (05/2014) – with Totem
  - |η|<2.2, 5.3<|η|<6.4
- 13 TeV (07/2015)
  - no magnetic field



LHC Results Overview

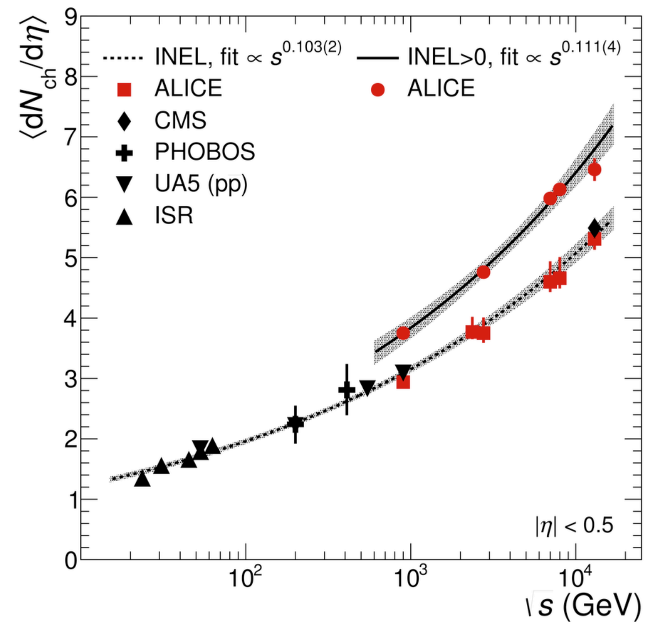
Minimum Bias measurements in LHCb:

- [7 TeV](#) (12/2011)
  - $p_T > 1$ GeV, $-2.5<\eta<-2.0$, $2.0<\eta<4.5$



Latest Minimum Bias measurements in ALICE:

- [13 TeV](#) (12/2015)
  - Pseudorapidity distribution in $|\eta|<$ 1.8 is reported for inelastic events and for events with at least one charged particle in $|\eta|<$ 1
  - Transverse momentum distribution in $0.15 < p_T < 20$ GeV/c and $|\eta|<$ 0.8 for events with at least one charged particle in $|\eta|<$ 1



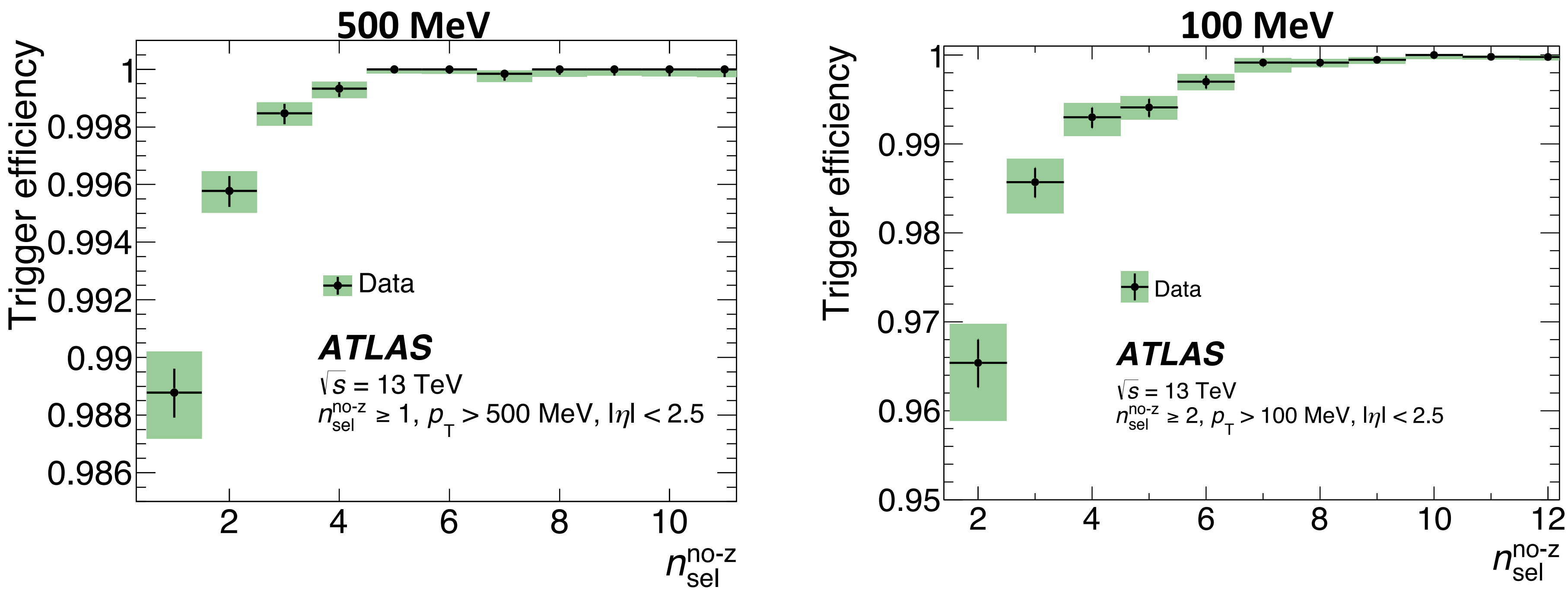
Strange Baryons

STRANGE BARYONS	
Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314^d
Ω^-	3334

Trigger Efficiency

- Trigger efficiency is evaluated by using a control trigger and the MBTS trigger:

$$\epsilon_{trig}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap sptrk\ triggered)}{N(sptrk\ triggered)}$$

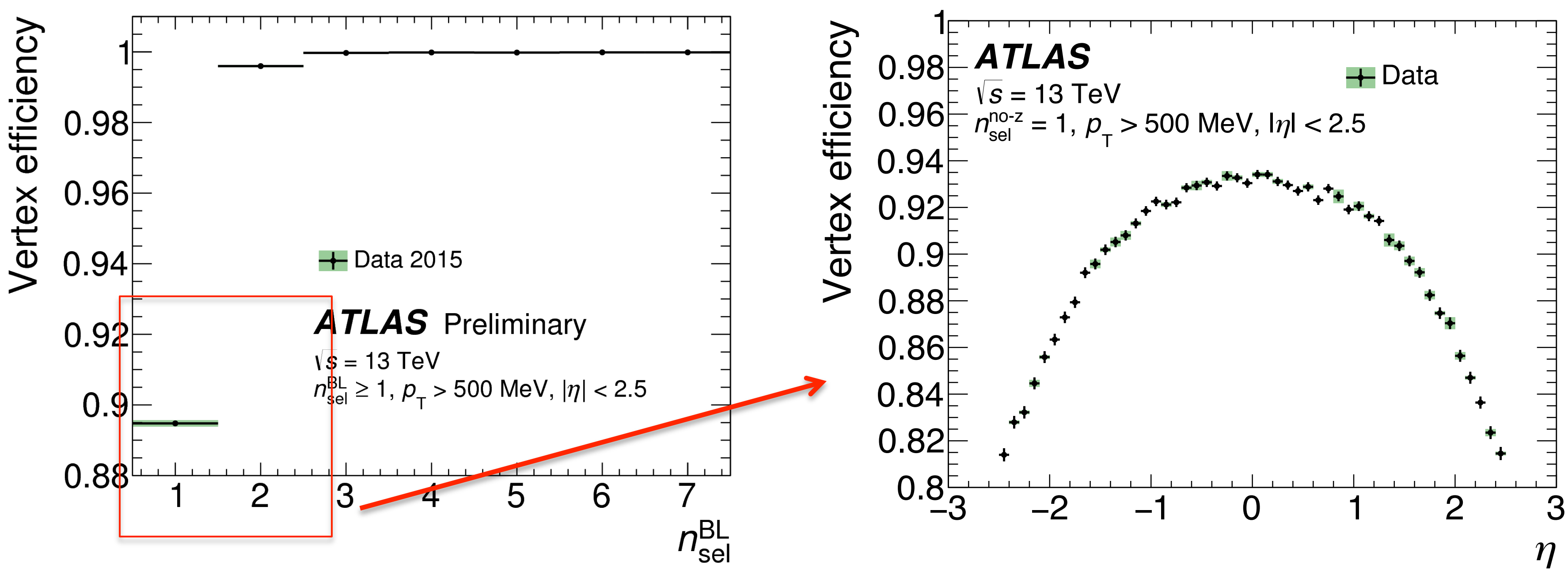


Systematic uncertainty:

- variation of the track selection; differences between MBTS A and C side ; non-collision beam background
- MC based: events failing both triggers

Vertex Efficiency

$$\epsilon_{vtx}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap n_{vtx} = 1)}{N(MBTS1\ triggered)}$$



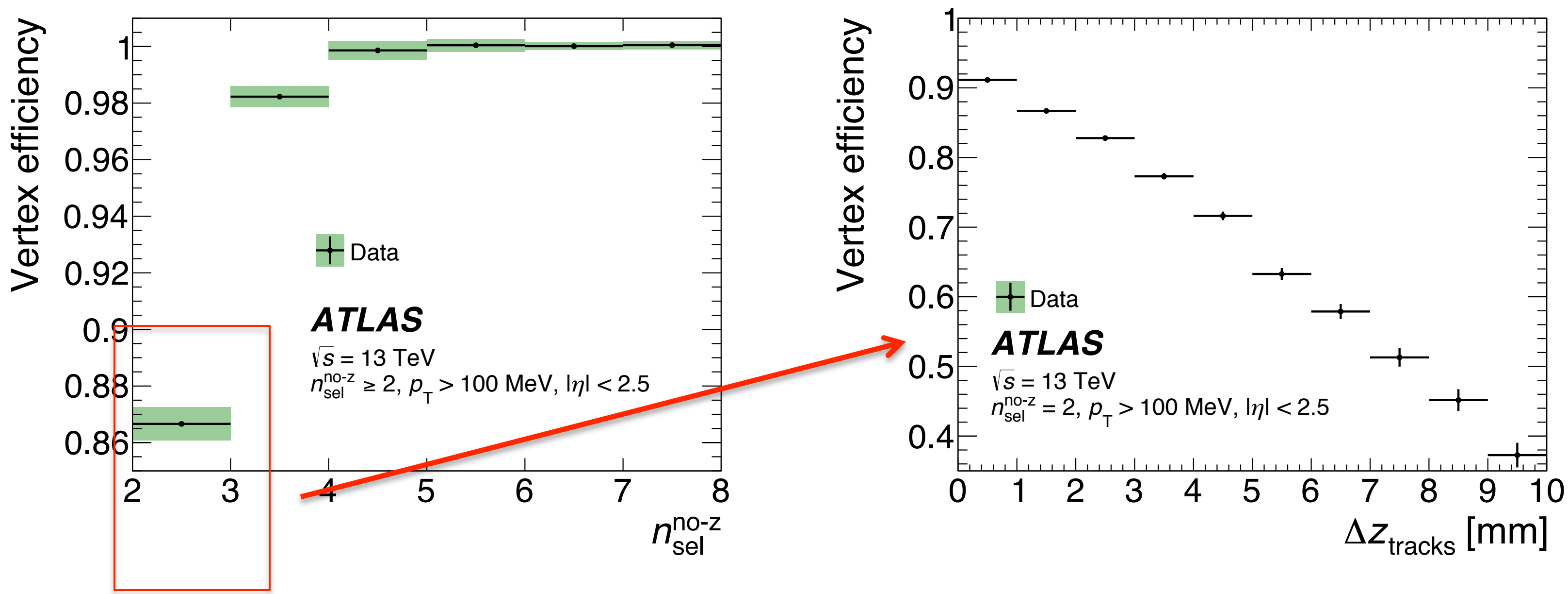
Efficiency for the first $n_{sel}{}^{no-z}$ bin depends on eta of the track

Systematic uncertainty:

- non-collision beam background which is strongly reduced by the vertex requirement

Vertex Efficiency

$$\epsilon_{vtx}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap n_{vtx} = 1)}{N(MBTS1\ triggered)}$$



Efficiency for the first $n_{sel}{}^{no-z}$ bin depends on Δz between the tracks

Systematic uncertainty:

- non-collision beam background which is strongly reduced by the vertex requirement

Systematic Uncertainties Breakdown

500 MeV

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%

100 MeV

Distribution	$\left\lvert\frac{1}{N_{\mathrm{ev}}}\cdot\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}\right\rvert$	$\frac{1}{N_{\mathrm{ev}}}\cdot\frac{1}{2\pi p_{\mathrm{T}}}\cdot\frac{\mathrm{d}^2N_{\mathrm{ch}}}{\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}}$	$\frac{1}{N_{\mathrm{ev}}}\cdot\frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}}$	$\langle p_{\mathrm{T}}\rangle$ vs. n_{ch}
Range	0 – 2.5	0.1 – 50 GeV	2 – 250	0 – 160 GeV
Track reconstruction	1 – 7%	1% – 6%	0% – $^{+38\%}_{-20\%}$	0% – 0.7%
Track background	0.5%	0.5% – 1%	0% – $^{+7\%}_{-1\%}$	0% – 0.1%
p_{T} spectrum	–	–	0% – $^{+3\%}_{-9\%}$	0% – $^{+0.3\%}_{-0.1\%}$
Non-closure	0.4% – 1%	1% – 3%	0% – 4%	0.5% – 2%

Table 1: Summary of MC tunes used to compare to the corrected data. The generator and its version are given in the first two columns, the tune name and the PDF used are given in the next two columns.

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

In PYTHIA 8 inclusive hadron–hadron interactions are described by a model that splits the total inelastic cross section into non-diffractive (ND) processes, dominated by *t*-channel gluon exchange, and diffractive processes involving a colour-singlet exchange. The simulation of ND processes includes multiple parton–parton interactions (MPI). The diffractive processes are further divided into single-diffractive dissociation (SD), where one of the initial protons remains intact and the other is diffractively excited and dissociates, and double-diffractive dissociation (DD) where both protons dissociate. The sample contains approximately 22% SD and 12% DD processes. Such events tend to have large gaps in particle production at central rapidity. A pomeron-based approach is used to describe these events [15].

EPOS provides an implementation of a parton-based Gribov–Regge [16] theory, which is an effective QCD-inspired field theory describing hard and soft scattering simultaneously.

QGSJET-II provides a phenomenological treatment of hadronic and nuclear interactions in the Reggeon field theory framework [17]. The soft and semi-hard parton processes are included in the model within the "semi-hard pomeron" approach. EPOS and QGSJET-II calculations do not rely on the standard parton distribution functions (PDFs) as used in generators such as PYTHIA 8.

Different settings of model parameters optimised to reproduce existing experimental data are used in the simulation. These settings are referred to as tunes. For PYTHIA 8 two tunes are used, A2 [18] and MONASH [19]; for EPOS the LHC [20] tune is used. QGSJET-II uses the default tune from the generator. Each tune utilises 7 TeV minimum-bias data and is summarised in Table 1, together with the version of each generator used to produce the samples. The PYTHIA 8 A2 sample, combined with a single-particle MC simulation used to populate the high-p_{T} region, is used to derive the detector corrections for these measurements. All the events are processed through the ATLAS detector simulation program [23], which is based on GEANT4 [24]. They are then reconstructed and analysed by the same program chain used for the data.

The PYTHIA 8 [3], HERWIG++ [4], EPOS [5] and QGSJET-II [6] event generators are used in this analysis.

- In PYTHIA 8 [3], inclusive hadron-hadron interactions are described by a model that splits the total inelastic cross section into non-diffractive and diffractive processes. The non-diffractive part is dominated by t-channel gluon exchange. Its simulation includes multiple parton-parton interactions (MPI). The diffractive part involves a color-singlet exchange. It is further divided into single-diffractive dissociation (SD) where one of the initial hadrons remains intact and the other is diffractively excited and dissociates, and double-diffractive dissociation (DD) where both hadrons dissociate. The sample contains ~22% SD and ~12% DD processes.

  To reproduce experimental data, the ATLAS minimum-bias tune A2 [7] is used, which is based on the MSTW2008LO PDF [8]. It provides a good description of minimum bias events and of the transverse energy flow data, a calorimeter-based minimum bias analysis performed with $\sqrt{s} = 7$ TeV data [9].

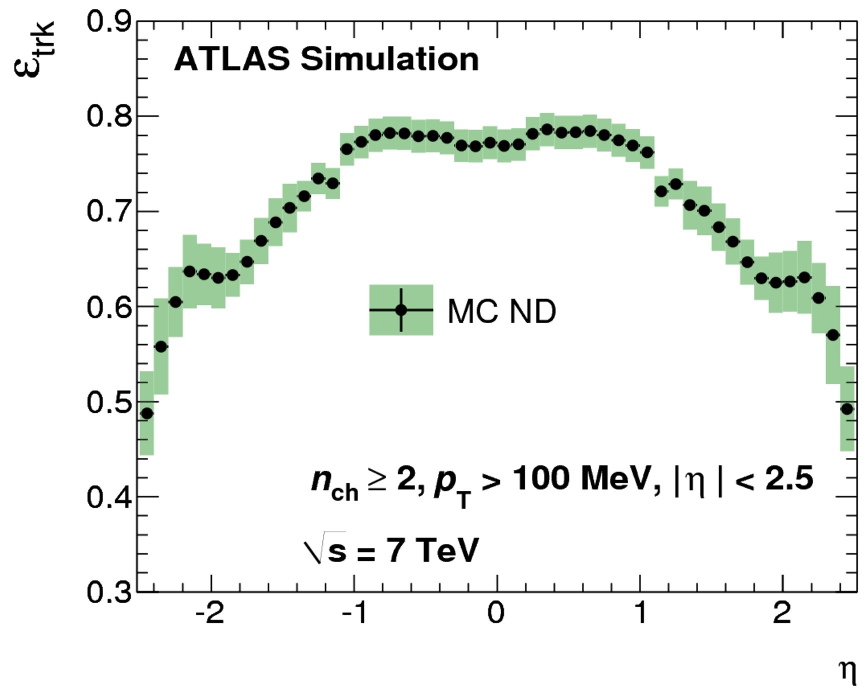
  An alternative tune, Monash [10], is used for comparison. It uses updated fragmentation parameters compared to A2 and minimum-bias, Drell-Yan, and underlying-event data from the LHC to constrain ISR and MPI parameters. In addition, it uses SPS and Tevatron data to constrain the energy scaling. It uses the NNPDF2.3LO PDF [11]. This tune gives an excellent description of 7 TeV minimum bias p_T spectrum.

- EPOS stands for *Energy conserving quantum mechanical approach, based on Partons, parton ladders, strings, Off-shell remnants, and Splitting of parton ladders*. The latest version 3.4 is used, which is equivalent to 1.99 version with the so called LHC tune. It provides an implementation of a parton-based Gribov-Regge theory, which is an effective QCD-inspired field theory describing the hard and soft scattering simultaneously. Hence, the calculations do not rely on the standard parton distribution functions (PDFs) as used in generators like PYTHIA 8 and HERWIG++.

- QGSJET-II offers a phenomenological treatment of hadronic and nuclear collisions at high energies, being developed in the Reggeon Field Theory framework. The soft and semi hard parton processes are included in the model within the "semi hard Pomeron" approach. Nonlinear interaction effects are treated by means of Pomeron Pomeron interaction diagrams.The latest model version comprises three important updates: treatment of all significant enhanced diagram contributions to the underlying dynamics, including ones of Pomeron loops, re-calibration of the model with new LHC data, and improved treatment of charge exchange processes in pion-proton and pion-nucleus collisions.

Track Reconstruction Efficiency

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



Systematic Uncertainty	Size (7 TeV, similar in all phase spaces)
Track Selection	**1%**
Material	**2% - 15%**
χ^2 probability	**10% (only for $p_T > 10$ GeV)**

Systematic uncertainty dominated by the lack of knowledge of the material distribution!