Latest Minimum Bias and Underlying Event Measurements with the ATLAS Detector

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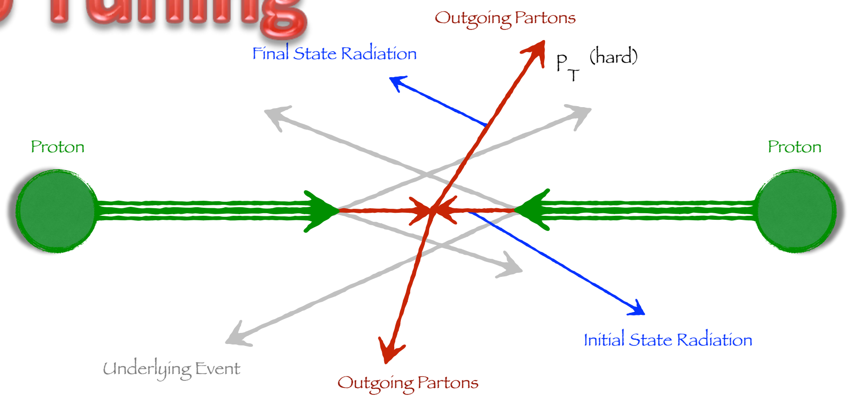
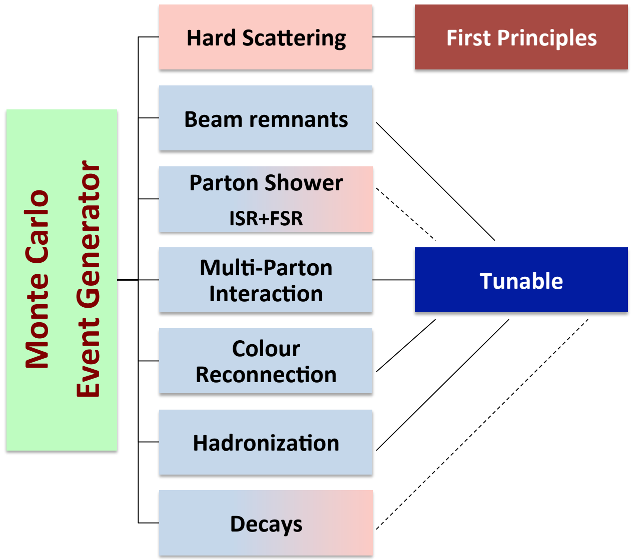
Soft QCD and Monte Carlo Tuning

- Hard QCD events constitute only a tiny fraction of the **total *pp* cross-section**, which is then **dominated by soft events** (peripheral processes) → while hard QCD processes can be studied by means of perturbative approaches, this is not possible for the soft QCD events
- The development of **Monte Carlo (MC) event generators** began shortly after the discovery of the partonic structure of hadrons and the formalisation of QCD as the theory of strong interactions → Models have to be developed with a set of **tunable parameters** to describe the hadron-level properties of final states dominated by soft QCD

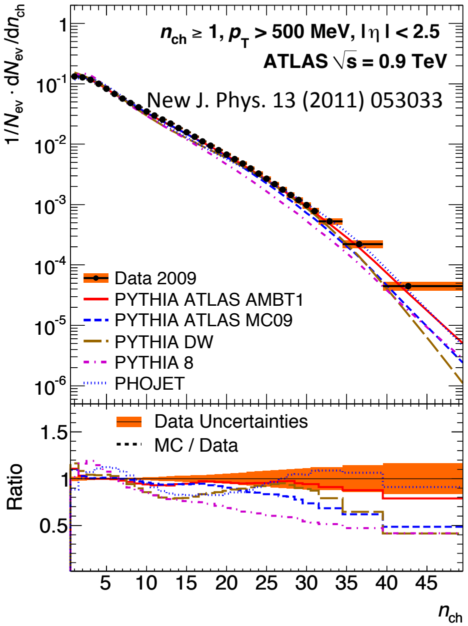


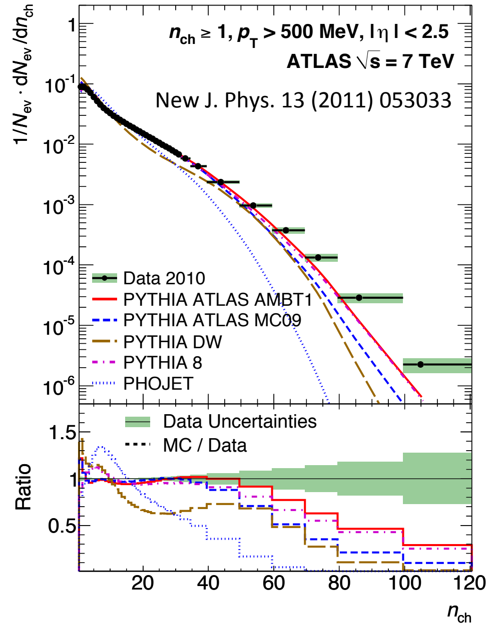


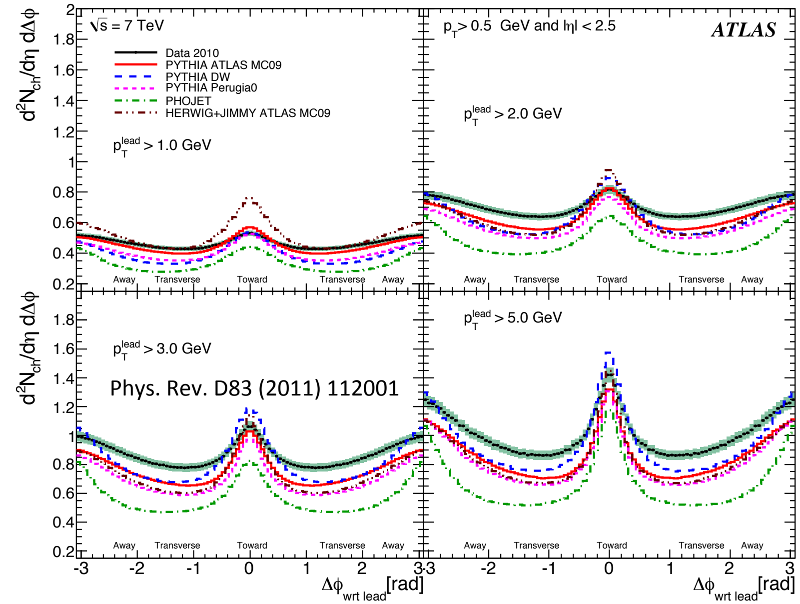
Inclusive charged-particle and underlying event measurements in *pp* collisions are the ideal test bed to provide insight into the soft QCD region:

- **Crucial for the tuning** of the Monte Carlo event generator
- **Essential to understand** and correctly simulate any other more **complex phenomena**
- **Ideal to study tracking performance** in the "early" stage of a new data taking…

What do we talk about today?







LHC Run 1 data showed a higher min bias and underlying event activity than that predicted by Monte Carlo models tuned to pre-LHC data.

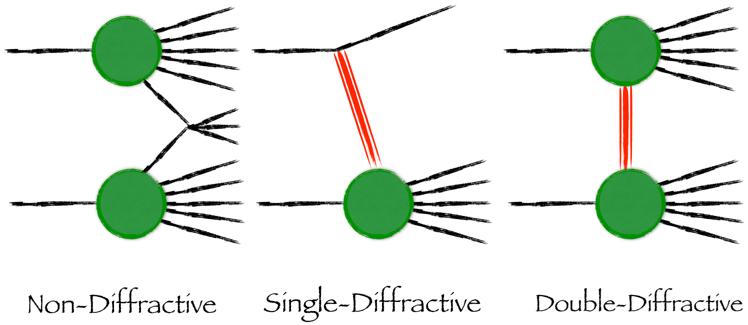
In this talk:

- **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, |η|< 2.5 (All the details in the next slides, Phys. Lett. B **758**, 67–88 (2016))
  - Reduced: p_T > 500 MeV, |η|< 0.8 (For comparison to the various detectors, Phys. Lett. B **758**, 67–88 (2016))
  - Extended: p_T > 100 MeV, |η|< 2.5 (To investigate the low p_T region - Eur. Phys. J. C (2016) 76:502)
- Comparison with **8 TeV** results recently published, Eur. Phys. J. C (2016) 76:403
  - High multiplicity phase spaces (**n_{ch}>20,50**) (first time in ATLAS)
- **Track-based underlying event at 13 TeV,** JHEP 03 (2017) 157

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 → good modeling of min bias events needed for pile-up simulation

- 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

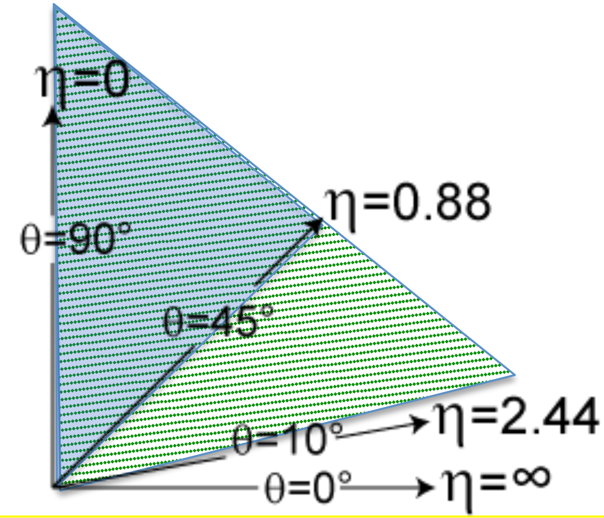
Goal:

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, |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 (06/2016)
  - 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

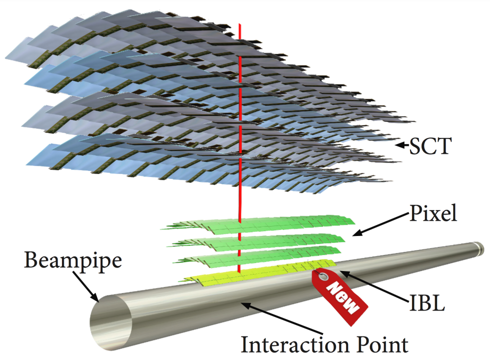
Latest Minimum Bias measurements in ALICE:
- 13 TeV (12/2015)
  - Pseudorapidity distribution in |η|<1.8 is reported for inelastic events and for events with at least one charged particle in |η|< 1
  - Transverse momentum distribution in 0.15 < p_T < 20 GeV/c and |η|< 0.8 for events with at least one charged particle in |η|< 1

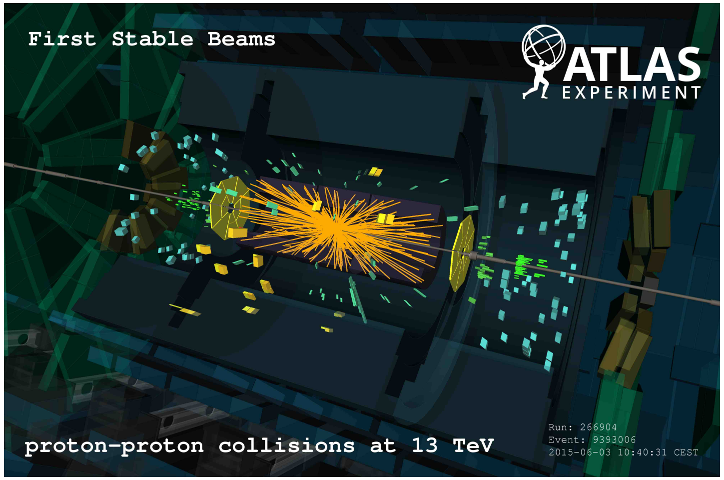
Minimum Bias measurements in LHCb:
- 7 TeV (12/2011)
  - p_T > 1 GeV, -2.5<η<-2.0, 2.0<η<4.5

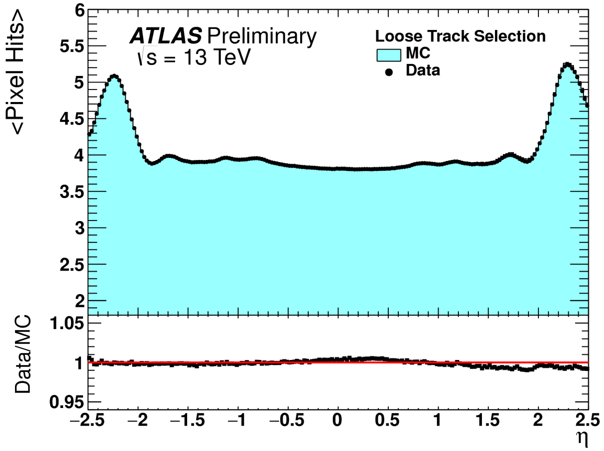
Summarising:
Very different detectors, but trying to have some common phase space to compare results!

Minimum Bias in ATLAS

- ATLAS is a general 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





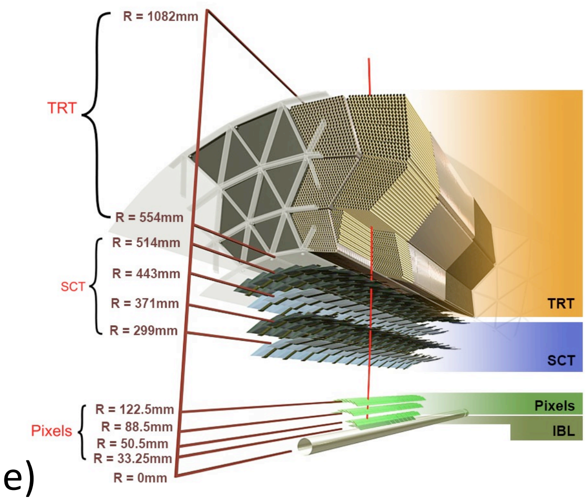


- To study an **Extended Phase Space** with p_T > 100 MeV a **robust low p_T reconstruction** is fundamental!
- Possible in Run 1, but much improved in RUN 2 thanks to the **IBL** which allows to use an extra measurement point
- **Critical evaluation of the systematics** when going to very low p_T
 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

Minimum Bias Analysis at 13 TeV: Event Selection

Mainly for reference, not for going into the details…

- 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:

- **Pythia 8**
  - 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:

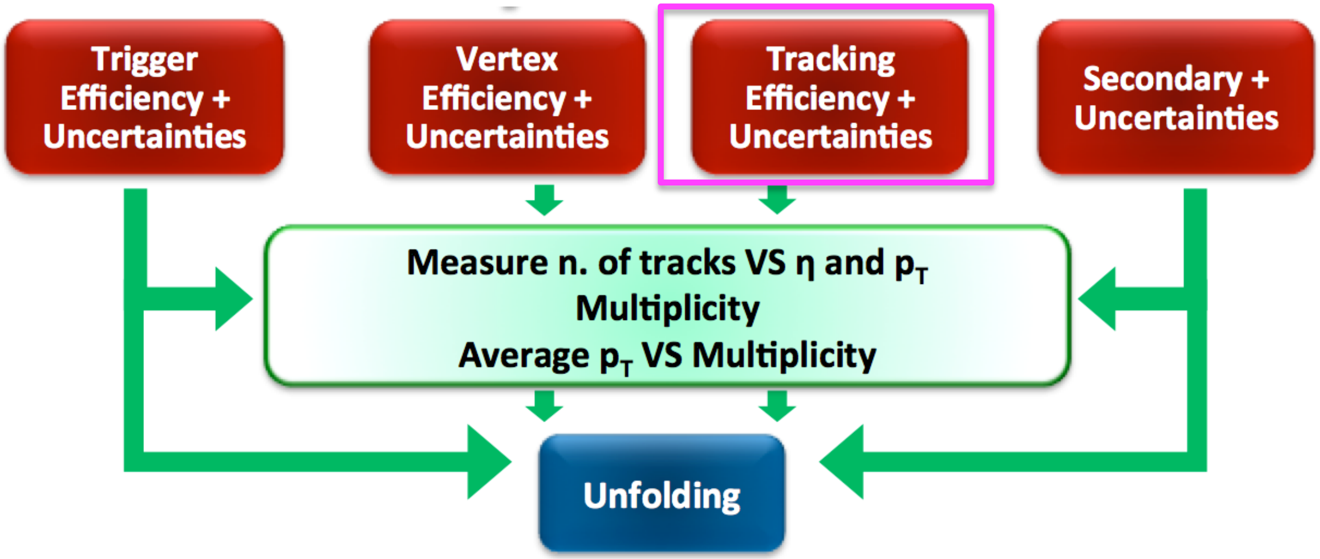
Using the two 13 TeV runs with low mean number of interactions per bunch crossing (<μ> ~ 0.005)

→

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

Analysis Flow



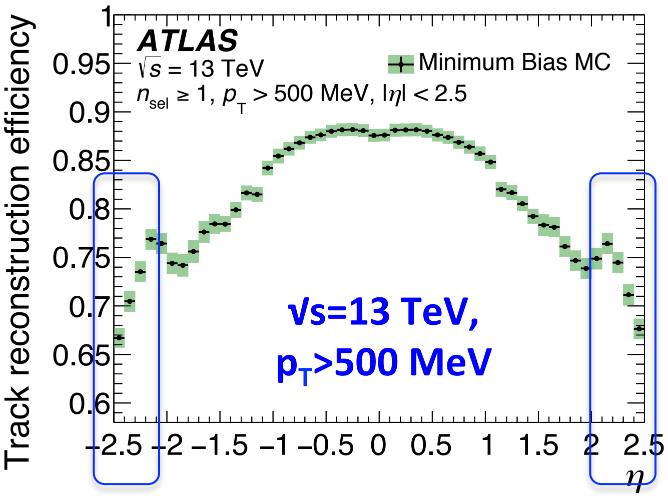
- Track reconstruction Efficiency: main ingredient for the Minimum Bias analysis

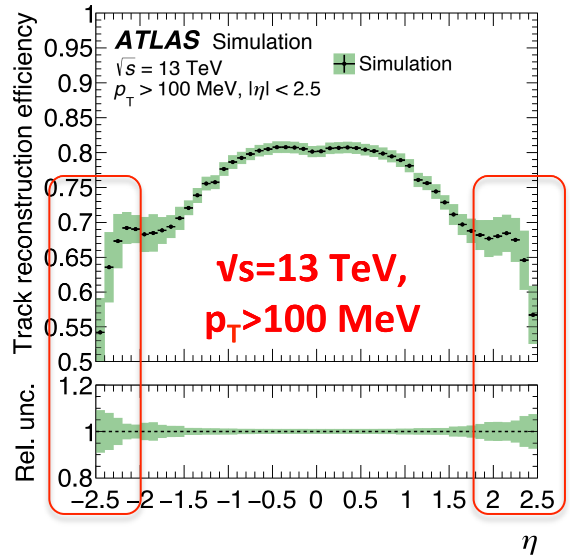
- Critical evaluation of the systematics when going to very low p_T

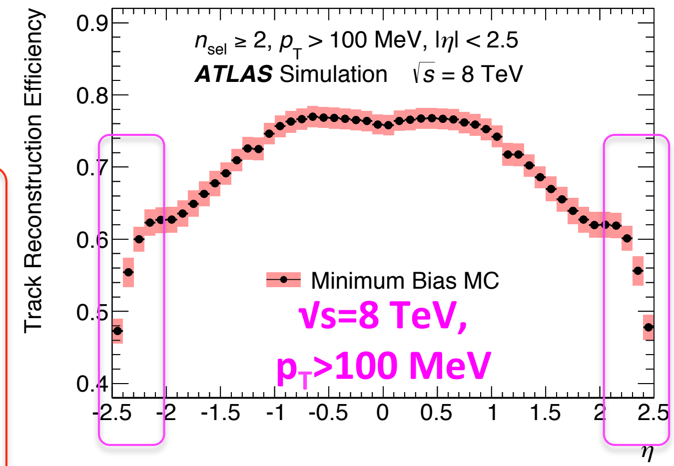
- At 13 TeV, different approaches taken for the nominal and the extended phase space → discussed in the next slides

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)

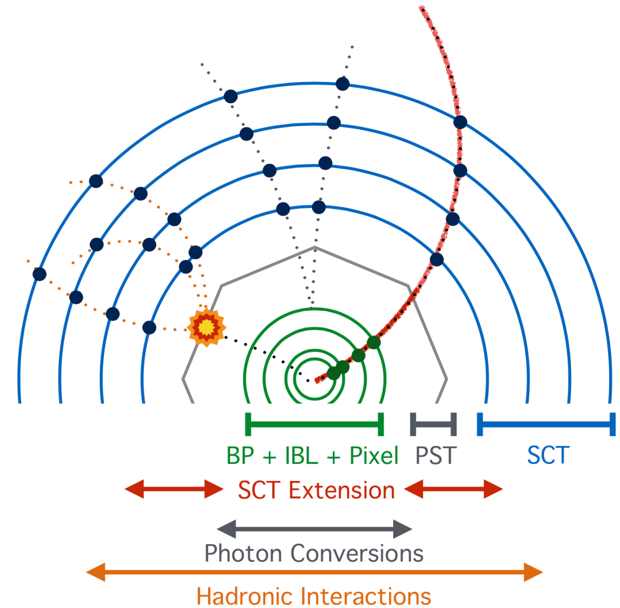
Systematic uncertainty dominated by the lack of knowledge of the ID material distribution!

Bonus 1 – 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**

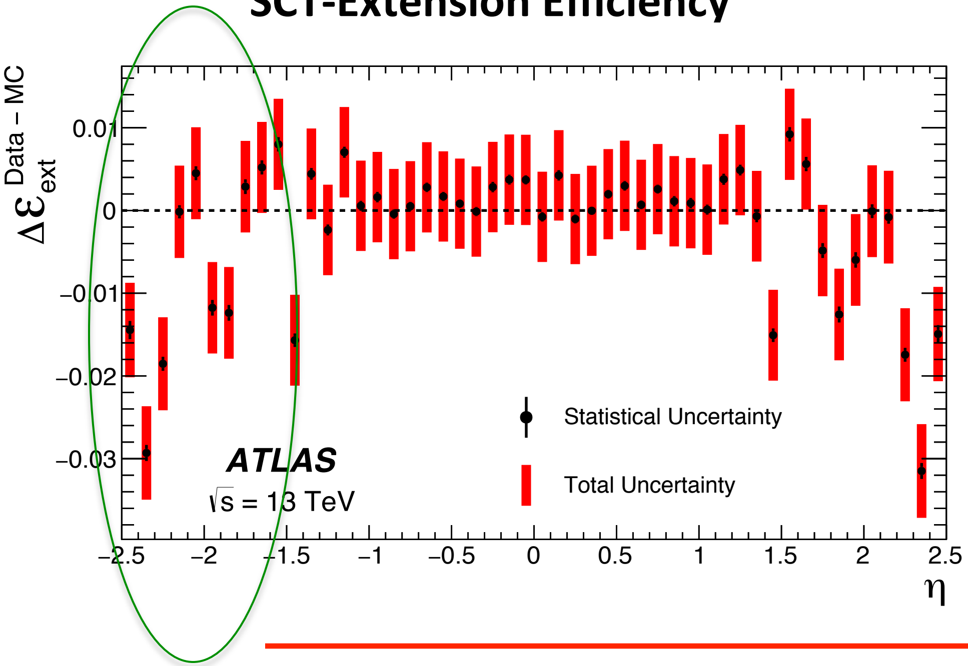


- Comprehensive results released by ATLAS in the paper "Study of the Material of the ATLAS Inner Detector for Run 2 of the LHC" (JINST 12 (2017) P12009) in December 2017
- Secondary vertices studies released also in Run 1: JINST 11 (2016) P11020, ATL-CONF-2010-007, ATL-CONF-2010-019

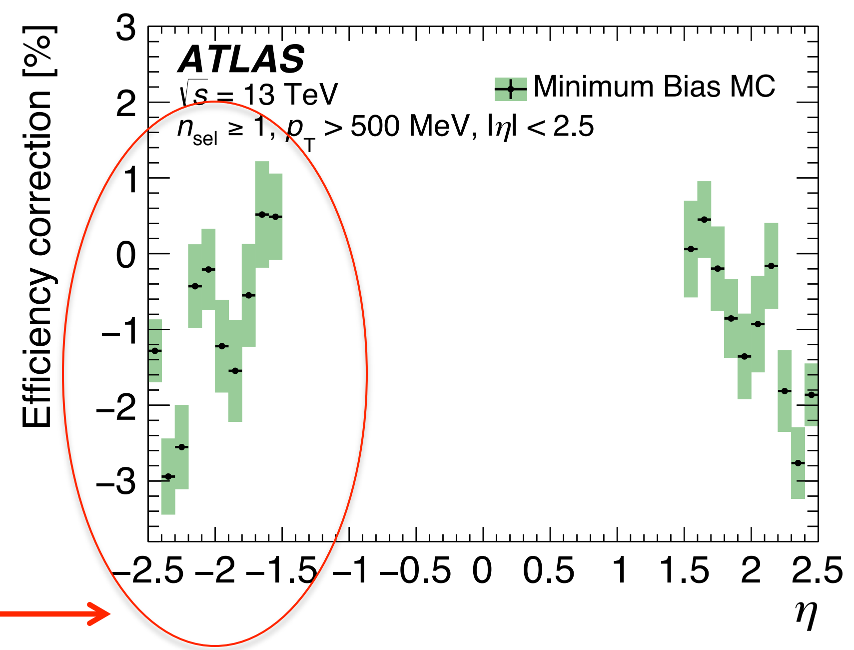
Data-driven correction to the Tracking Efficiency

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

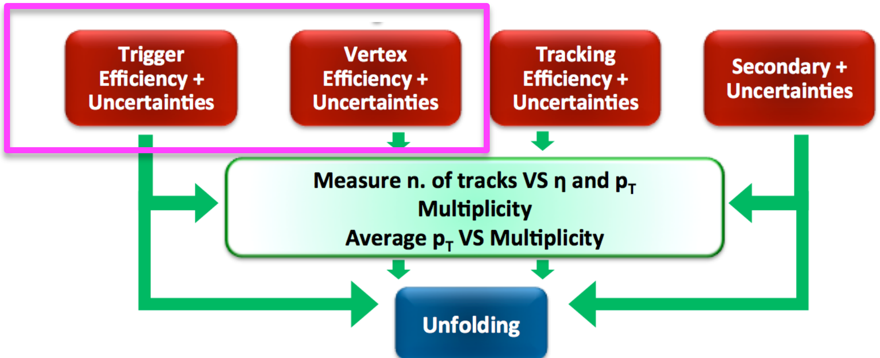


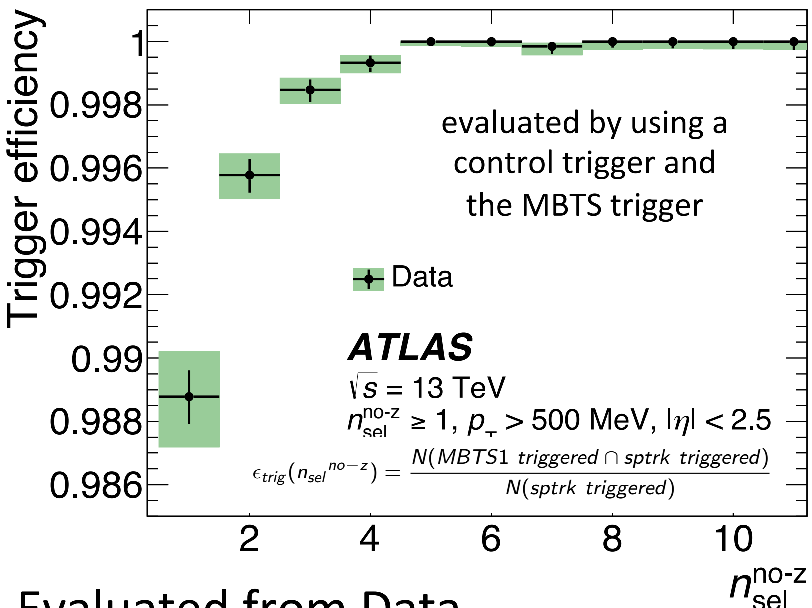
Tracking Efficiency Correction

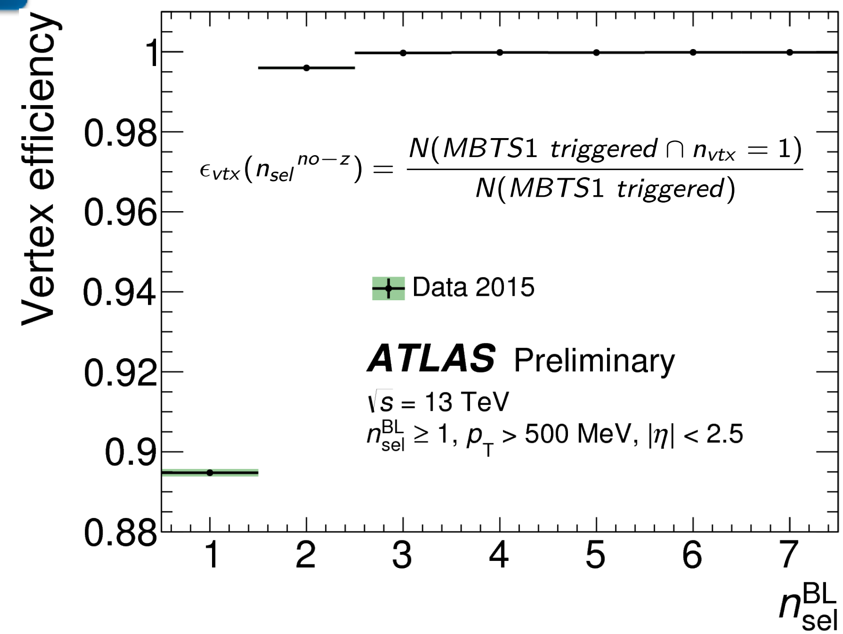


- Shape of the Data to Simulation ratio of the SCT-Extension Efficiency reflected into the shape of the correction applied to the Tracking Efficiency
- **Big reduction of the systematic uncertainties**
- Only applied in the Nominal phase space due to issues extrapolating to low p_T

Trigger and Vertex Reconstruction Efficiency

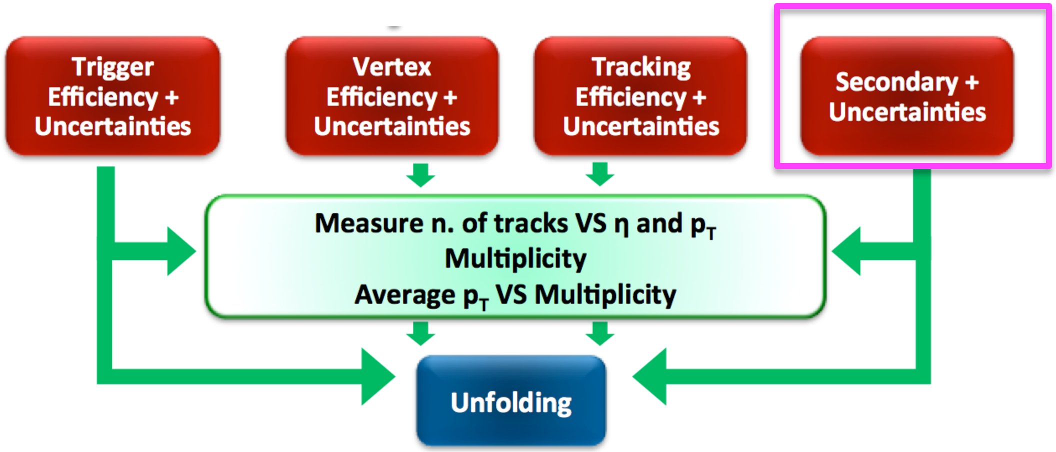






- Evaluated from Data
- Dependence on kinematic quantities studied:
  - negligible p_T-dependence
  - visible n_{sel}-dependence
  - negligible systematic uncertainties

Background evaluation



Background contributions to the tracks from primary particles include:

- Strange baryons → Next slide!
- Secondary particles → Measured in data by performing a fit to the transverse impact parameter distribution
- Fake tracks → Negligible in the 500 MeV phase space; Non-negligible in the 100 MeV phase space, treated as part of the background

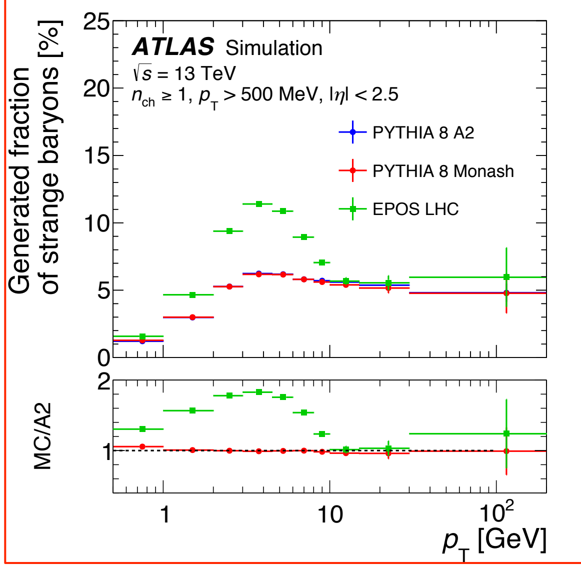
Strange Baryons

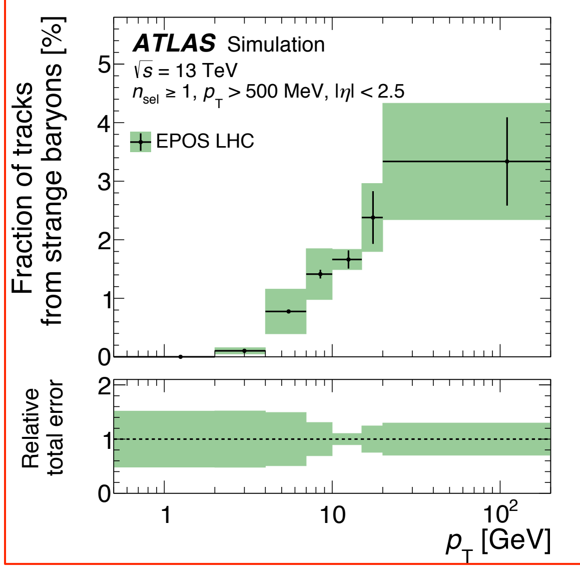
Common treatment of the Strange Baryons in all the 8 and 13 TeV analyses

- 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



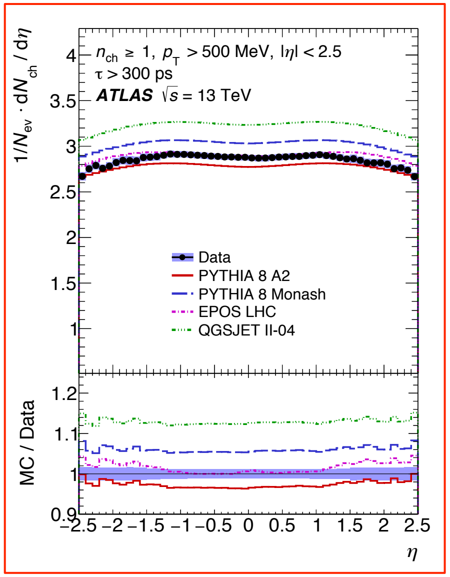


Final Results – 13 TeV

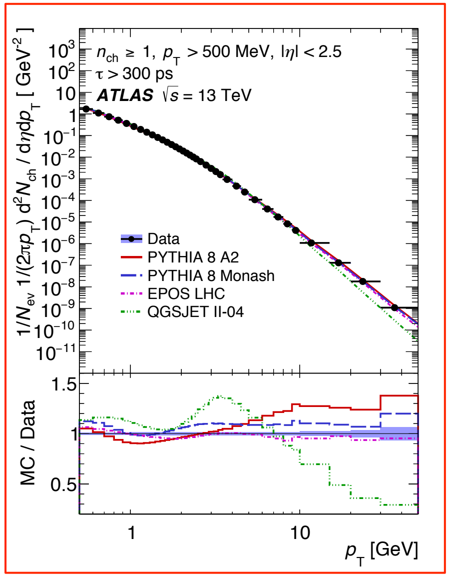
- Data
- PYTHIA 8 A2
- PYTHIA 8 Monash
- EPOS LHC
- QGSJET II-04

- Nominal Phase Space (p_T > 500 MeV, $|\eta|$< 2.5)

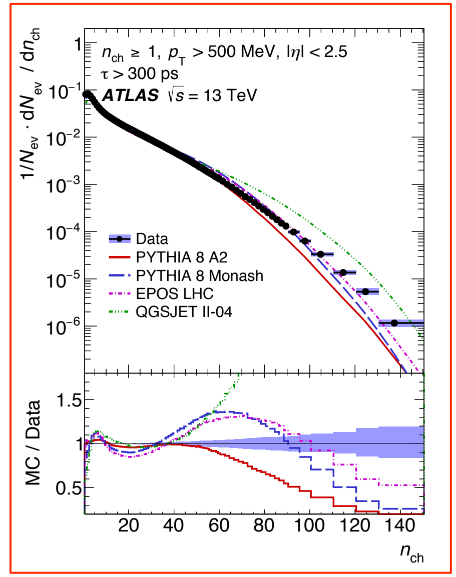
$dN_{ch}/d\eta$



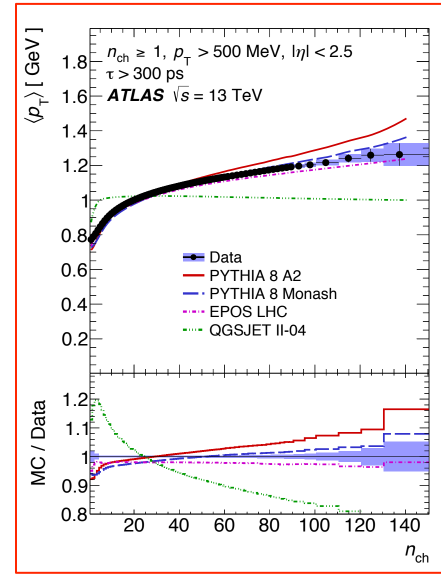
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



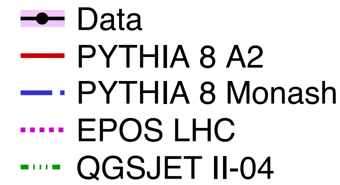
Models differ mainly in normalisation, shape similar

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

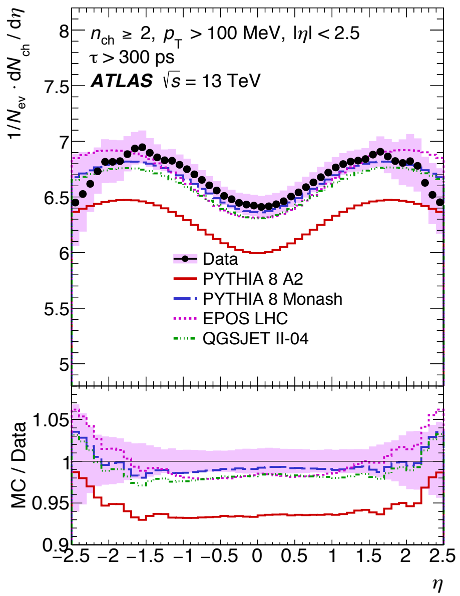
Some Models/Tunes give remarkably good predictions (EPOS, Pythia 8)

Final Results – 13 TeV

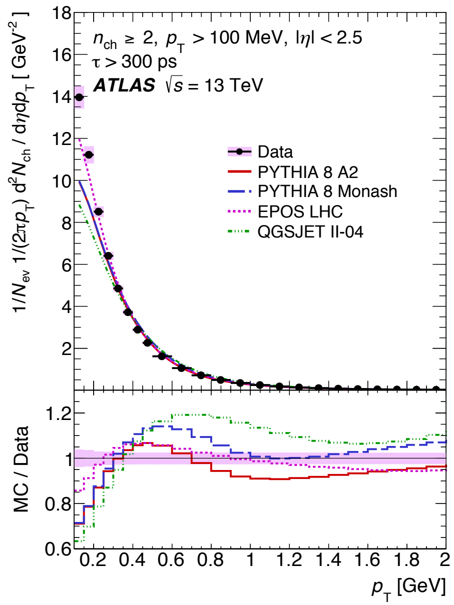


- Extended Phase Space ($p_T > 100$ MeV, $|\eta| < 2.5$)

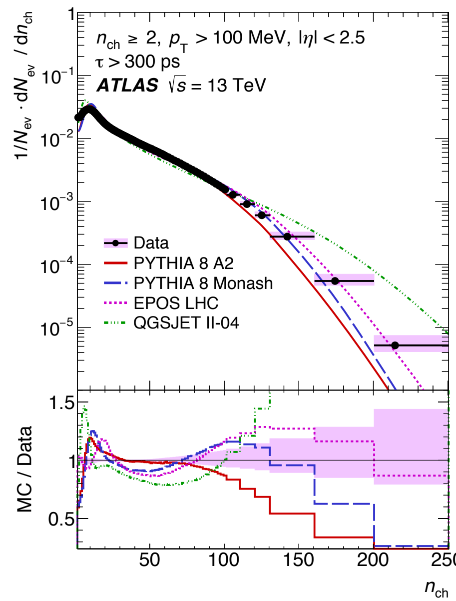
$dN_{ch}/d\eta$



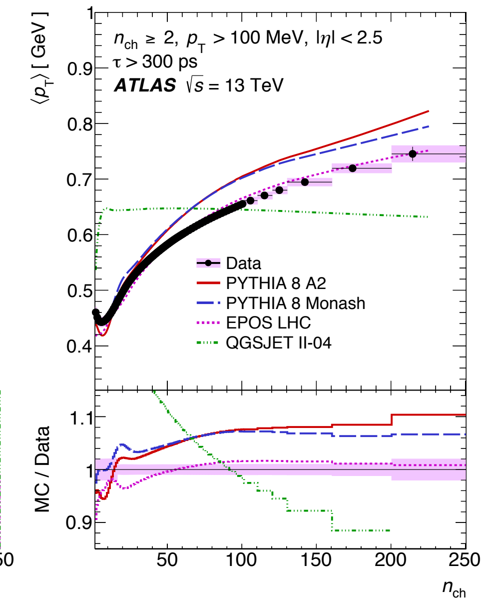
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



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



- Up to 7% of systematics in the high eta region
- Good prediction by all generators, 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

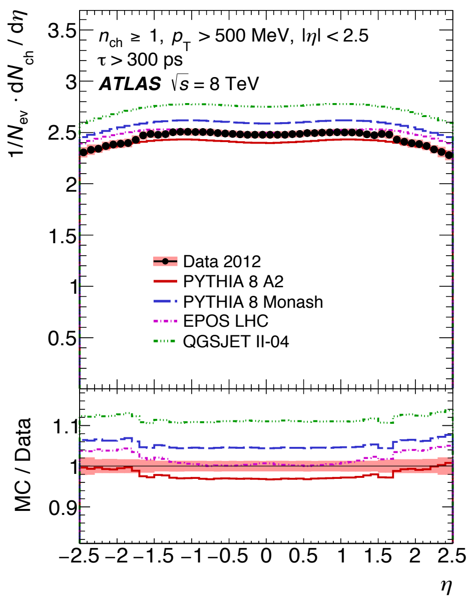
EPOS gives the best prediction!
Much clearer in this low p_T regime than in the nominal phase space!

Final Results – 8 TeV

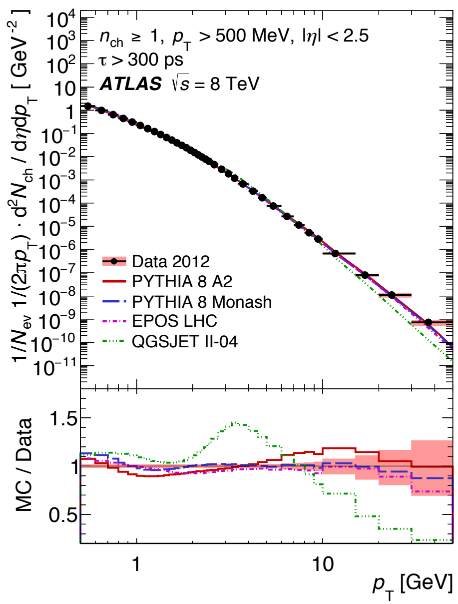
Data 2012
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

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

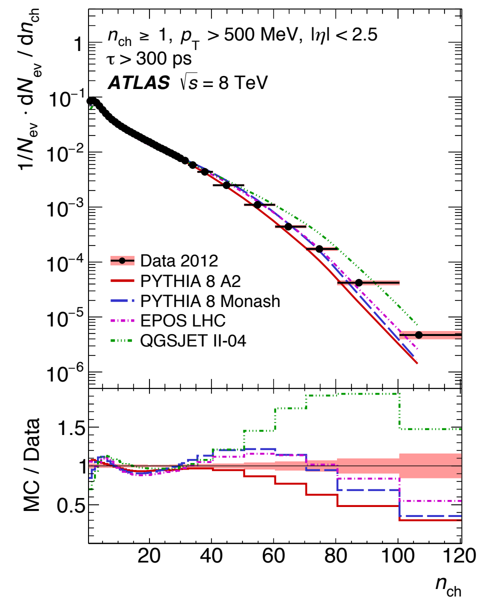
$dN_{ch}/d\eta$



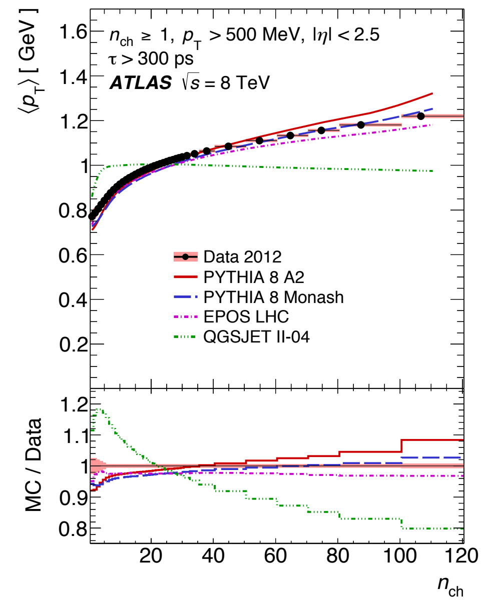
$d^2N_{ev}/d\eta dp_T$



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

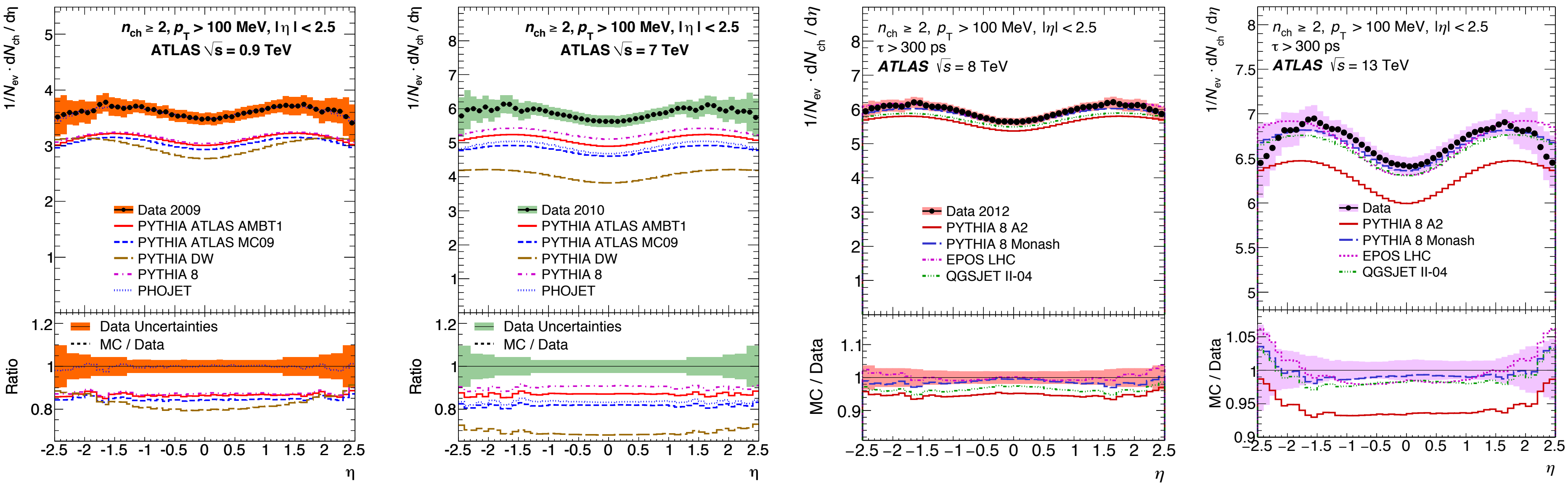
Above 1 GeV, good predictions given by Pythia 8 Monash

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!**

- From 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

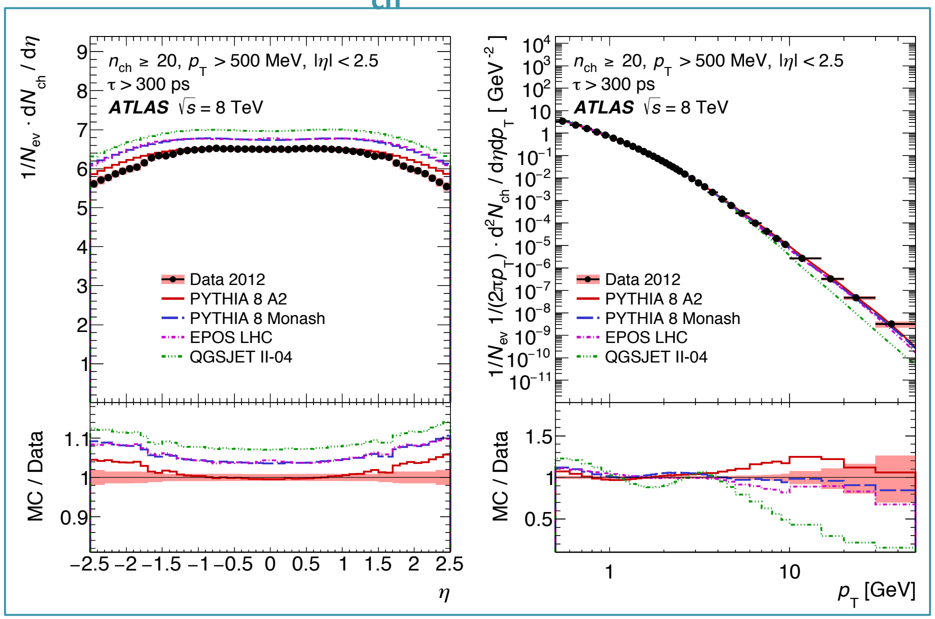
Bonus 2 – High Multiplicity Regime at 8 TeV

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

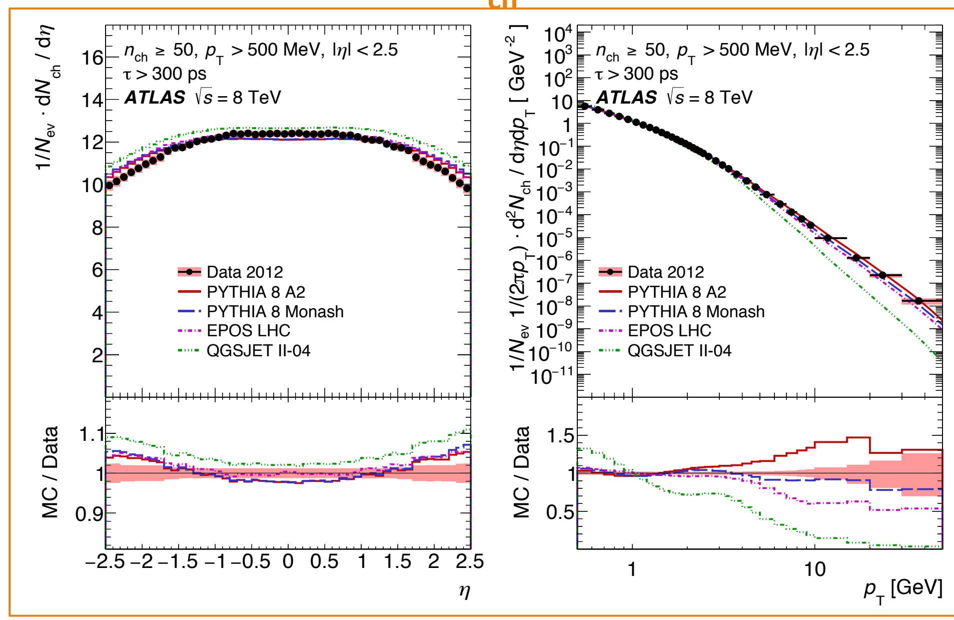
Phase Space		$1/N_{ev} \cdot dN_{ch}/d\eta$ at $\eta = 0$	
$n_{ch} \geq$	p_T[MeV] >	$\tau > 300$ ps (fiducial)	$\tau > 30$ ps (extrapolated)
2	100	5.64 ± 0.10	5.71 ± 0.11
1	500	2.477 ± 0.031	2.54 ± 0.04
6	500	3.68 ± 0.04	3.78 ± 0.05
20	500	6.50 ± 0.05	6.66 ± 0.07
50	500	12.40 ± 0.15	12.71 ± 0.18

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

$n_{ch} \geq 20$



$n_{ch} \geq 50$



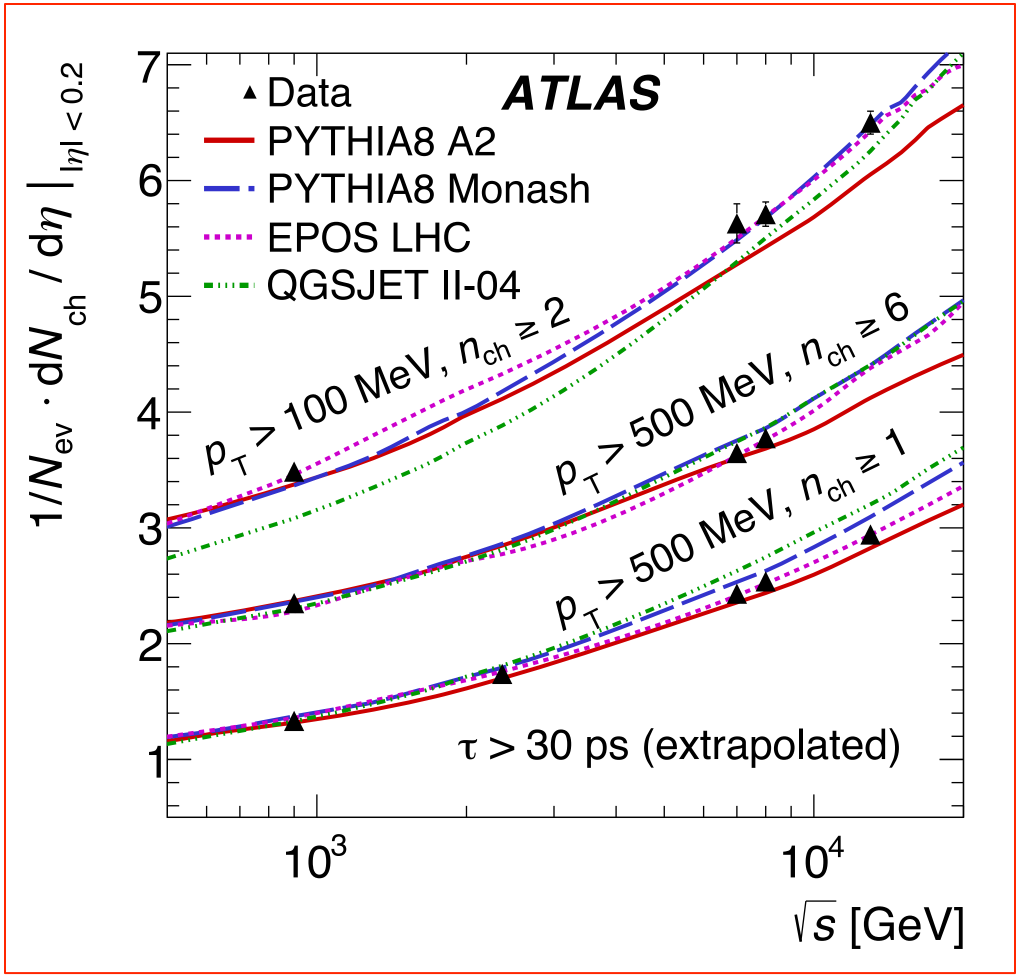
Pythia 8 A2 describes the plateau in the central region well

Fair prediction by Pythia 8 and EPOS at low p_T, but large deviation at high p_T

All models overestimate data at |η| > 1.7 but better description in the central region

Fair prediction by Pythia 8 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**!

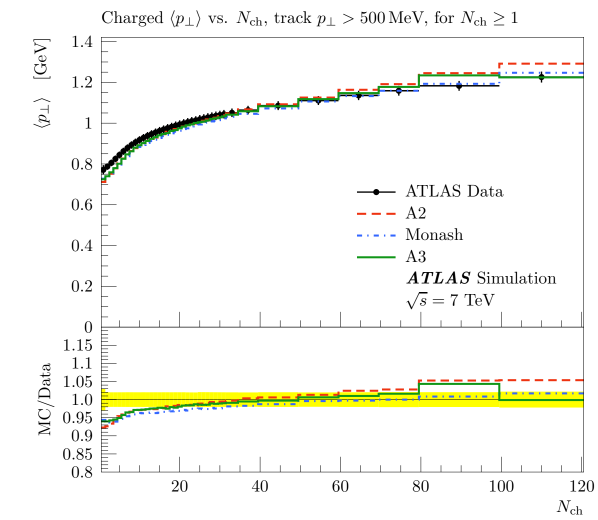
Bonus 3 – Pythia 8 A3

13 TeV MinBias results already used for a new Pythia 8 Tune: Pythia 8 – A3 (ATL-PHYS-PUB-2016-017)

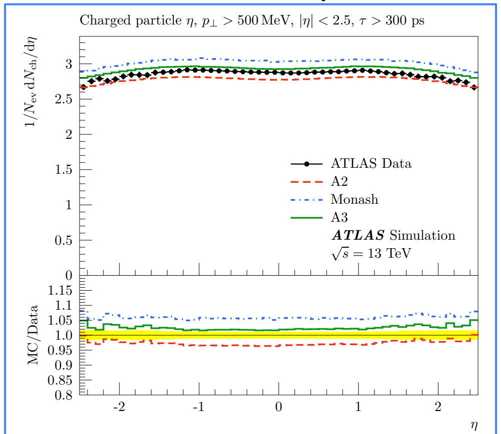
$\sqrt{s}$	Measurement type	Rivet name
13 TeV	MB	ATLAS_2016_I1419652 [3]
13 TeV	INEL XS	MC_XS [5]
7 TeV	MB	ATLAS_2010_S8918562 [11]
7 TeV	INEL XS	ATLAS_2011_I89486 [4]
7 TeV	RAPGAP	ATLAS_2012_I1084540 [15]
7 TeV	ETFLOW	ATLAS_2012_I1183818 [14]
900 GeV	MB	ATLAS_2010_S8918562 [11]
2.36 TeV	MB	ATLAS_2010_S8918562 [11]
8 TeV	MB	ATLAS_2016_I1426695 [16]

Not directly used for the tuning, but compared with A3 after the tuning

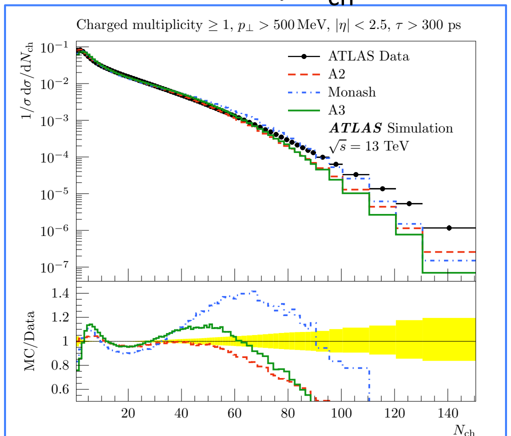
13 TeV, <p_T> vs multiplicity



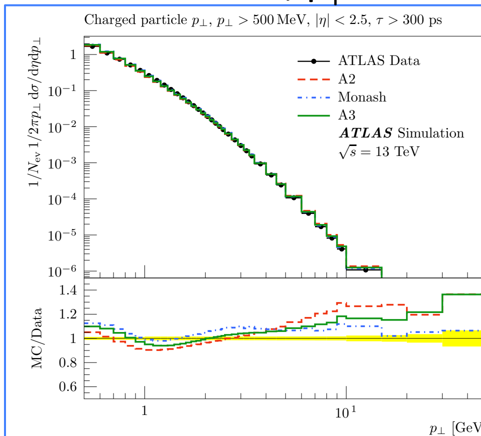
13 TeV, η



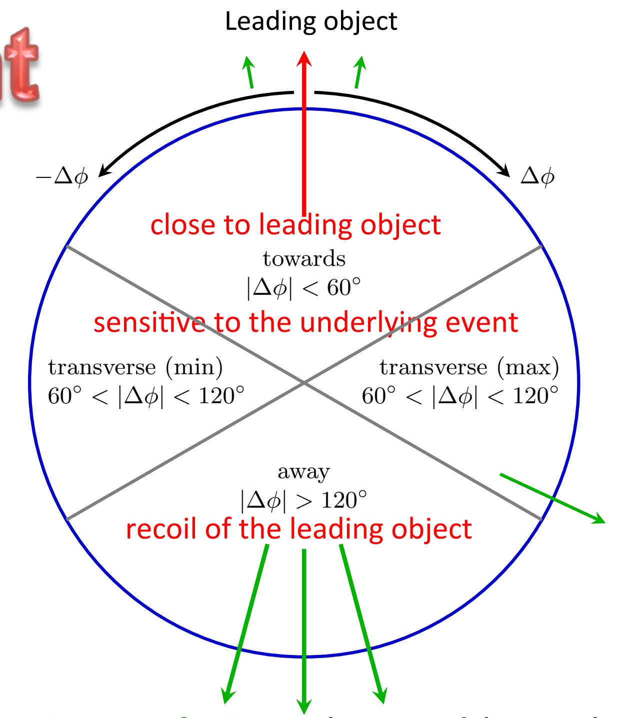
13 TeV, N_{ch}



13 TeV, p_T



Underlying Event



Underlying Event: activity accompanying any hard scattering in a collision event:

- Partons not participating in a hard-scattering process (beam remnants)
- multiple parton interactions (MPI)
- Initial and final state gluon radiation (ISR, FSR)

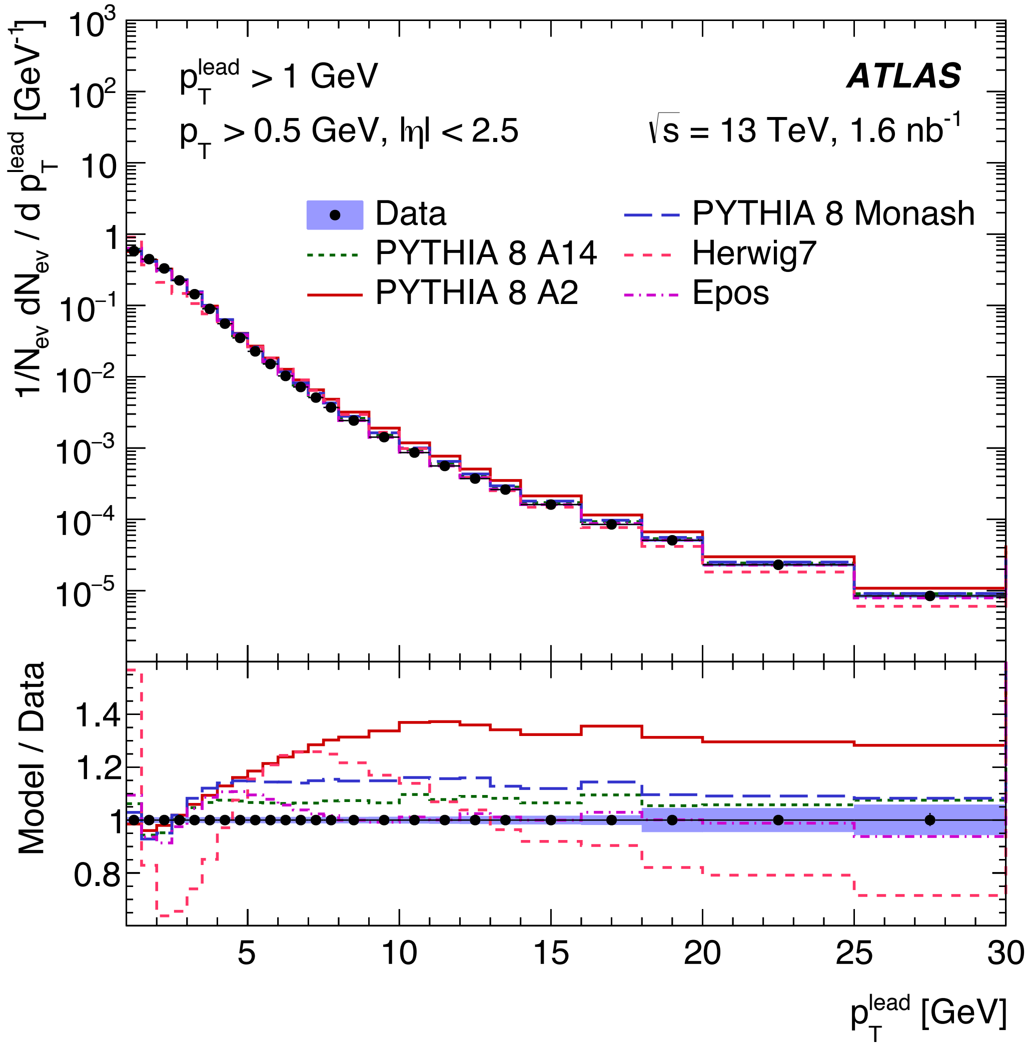
- Leading object can be defined variously:
  - Leading jet , Z (p_T), Leading track in Minimum Bias like events

- **13 TeV** analysis based on **leading track**:
  - **Same dataset and same event and track selection as the MinBias analysis** with an additional request: leading track with a p_T of at least 1 GeV
  - Monte Carlo Generators:

Generator	Version	Tune	PDF	Focus	From
PYTHIA 8	8.185	A2	MSTW2008 LO	MB	ATLAS
PYTHIA 8	8.185	A14	NNPDF2.3 LO	UE	ATLAS
PYTHIA 8	8.186	Monash	NNPDF2.3 LO	MB/UE	Authors
HERWIG 7	7.0.1	UE-MMHT	MMHT2014 LO	UE/DPS	Authors
EPOS	3.4	LHC	—	MB	Authors

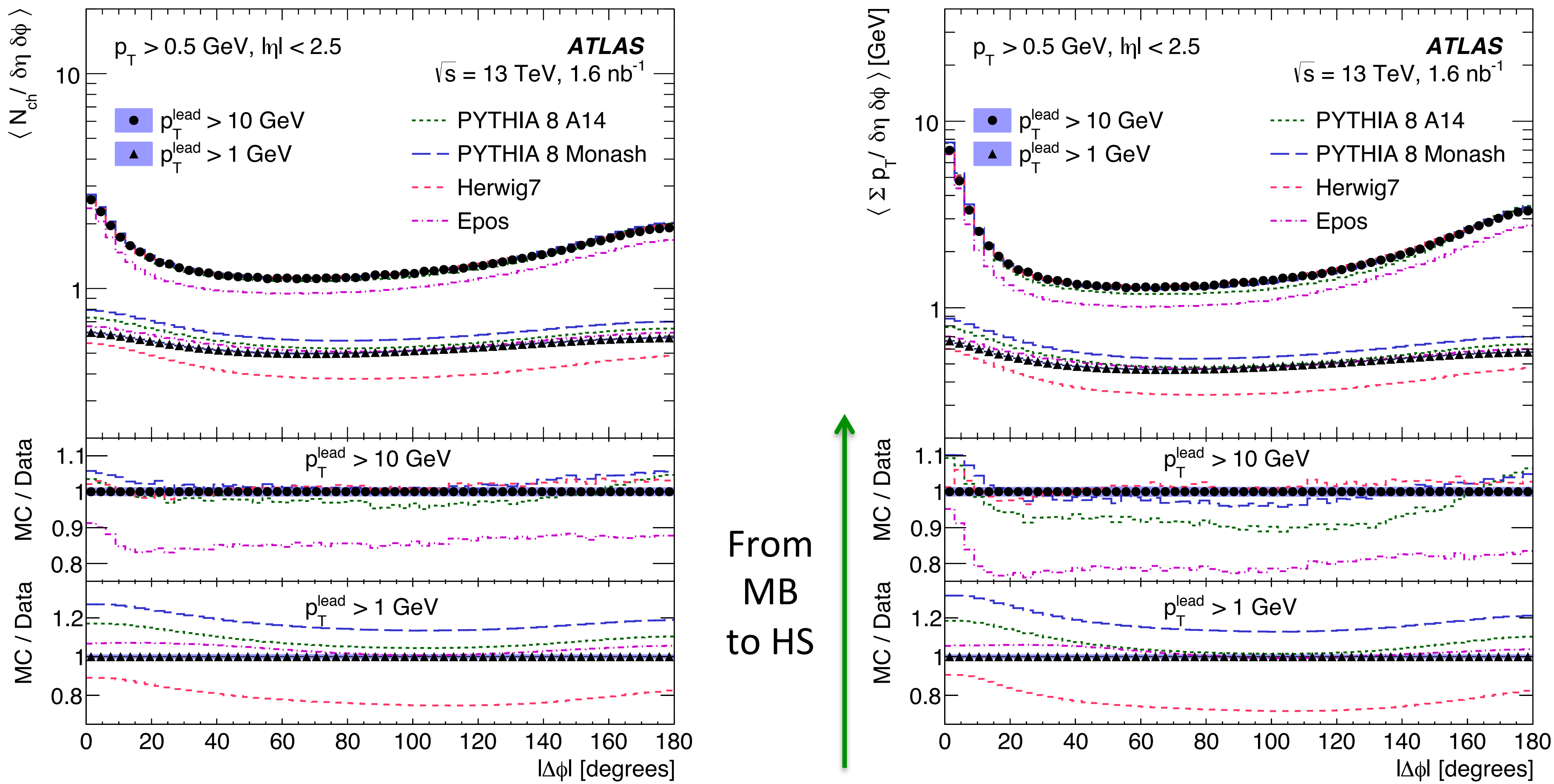
  - **Data-driven correction to the tracking efficiency applied also here, as well as strange baryons and secondaries treatment**
  - Results presented at particle level (azimuthal re-orientation of the event was also corrected for)
  - The tracking efficiency uncertainty is about 2% or less, mainly arising from the imperfect material description in the ID

Leading charged-particle p_T



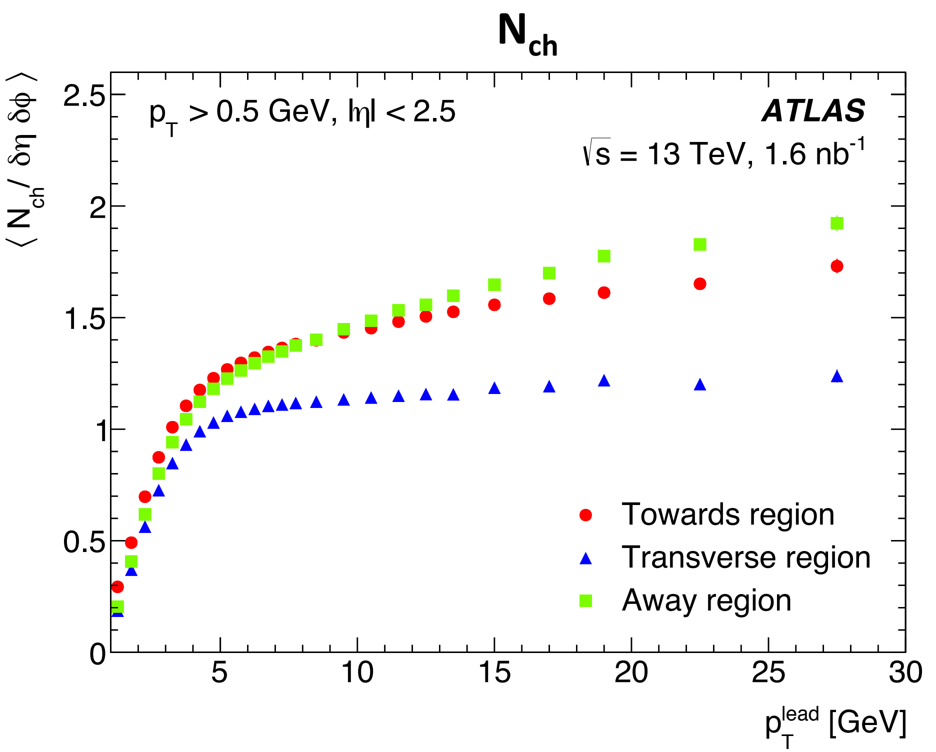
Leading charged particle p_T described by Pythia 8 A14/Monash and Epos LHC within 15% uncertainty

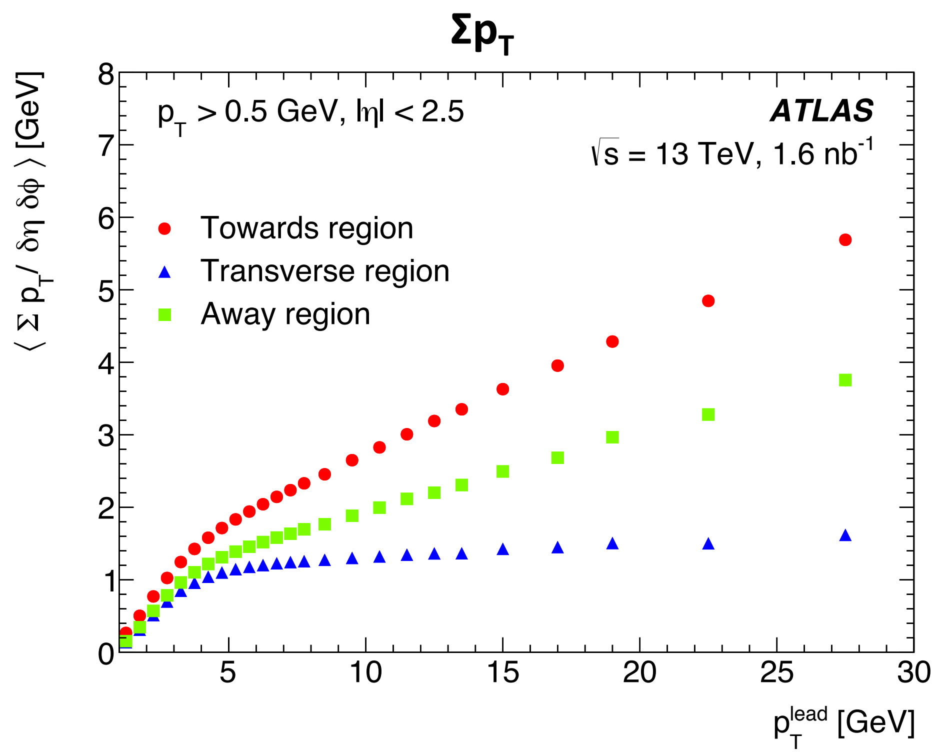
Angular distributions vs lead charged particle



- Overall reasonable agreement, but Min Bias tunes do better at lower p_T^{lead}, while UE tunes work better at higher momenta
- More visible shape as a function of $\Delta\varphi$ at high p_T^{lead}, evolution of event shape as a hard scattering component develops

N_{ch} and Σp_T density in trans/away/towards



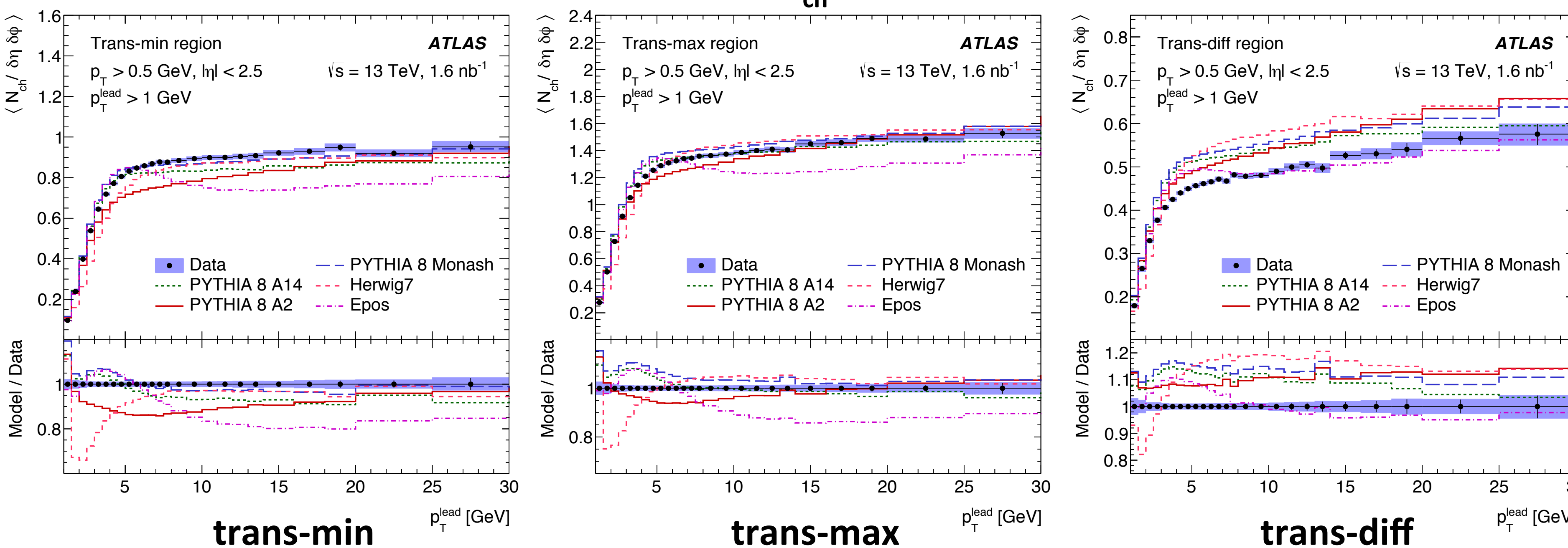


- Not strongly distinguished regions in the rapid rise up to ~ p_T^{lead} = 5 GeV
- Initial rise to a roughly stable value of ~1 charged particle or ~1GeV per unit η−φ area is known as the "pedestal effect" → reduction of the *pp* impact parameter with increasing p_T^{lead} hence the transition between MB and HS.
- **Plateau for the transverse region** at ~ p_T^{lead} = 5 GeV, **increasing activity for towards** and **cross-over for away in Nch**

N_{ch} density in transverse regions

- Trans-min sensitive to MPI effects, trans-max includes both MPI and hard-process, trans-diff clearest measure of hard process contaminations
- No obvious best model for all observables!

N_{ch}

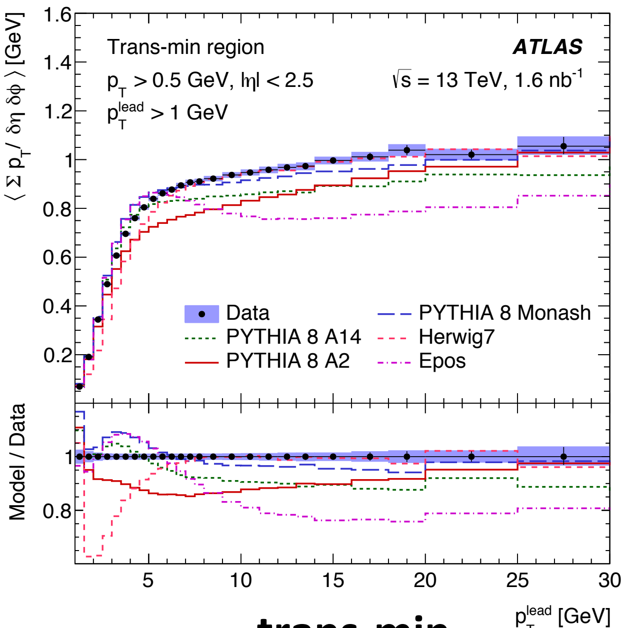


Good predictions of the plateau by Monash and Herwig 7	All but EPOS generator' predictions within a few percent	~10% overshoot by all models other than EPOS

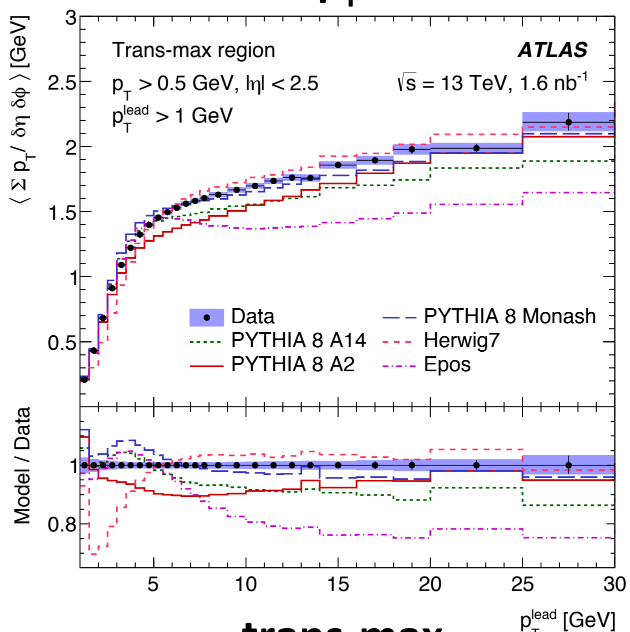
Σp_T density in transverse regions

- Trans-min sensitive to MPI effects, trans-max includes both MPI and hard-process, trans-diff clearest measure of hard process contaminations
- No obvious best model for all observables!

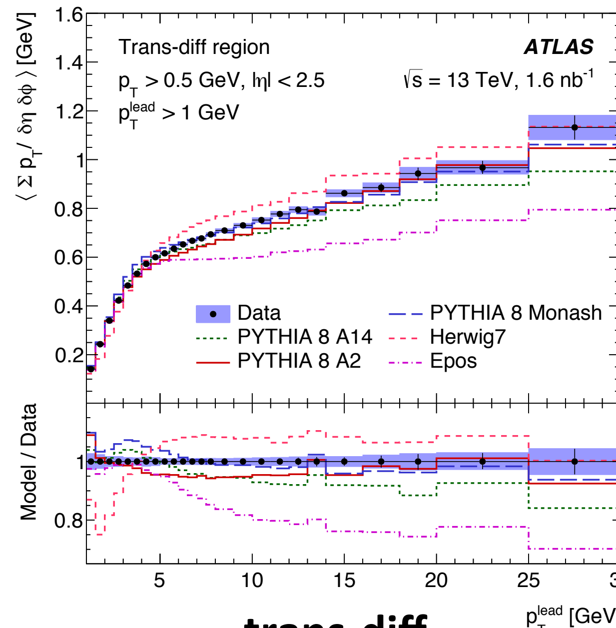
Σp_T



trans-min



trans-max



trans-diff

Good predictions of the plateau by Herwig 7 followed by Monash

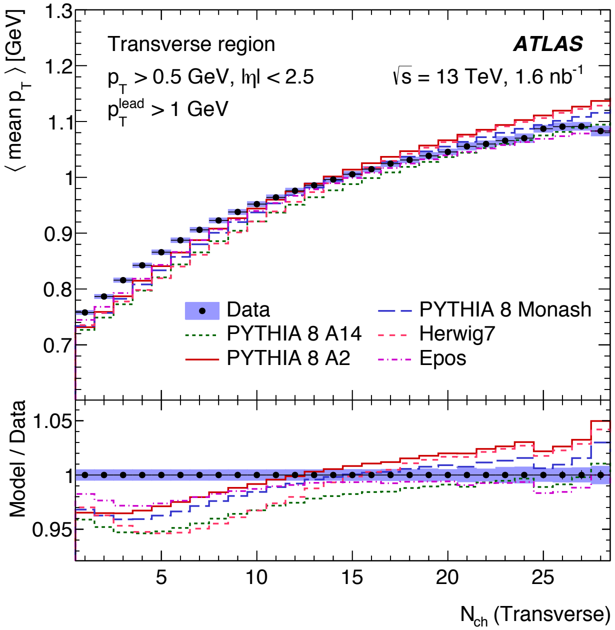
Pythia 8 A14 undershoots the data by ~10 %, EPOS by ~ 20%

Large spread of performances

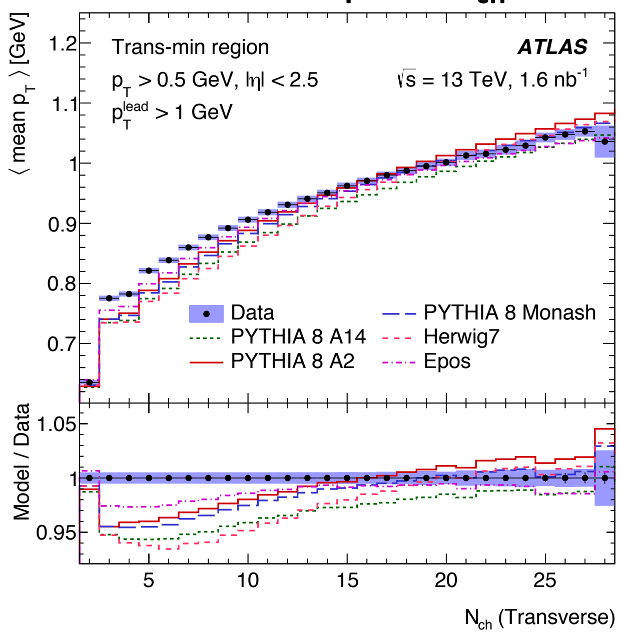
Mean p_T in transverse regions

- It illustrates the balance in UE physics between the p_T and multiplicity observables → affected by colour-reconnection and colour-disruption mechanisms
- <mean p_T> vs N_{ch} : correlation between two soft properties
- <mean p_T> vs p_T^{lead} is in the extra slides

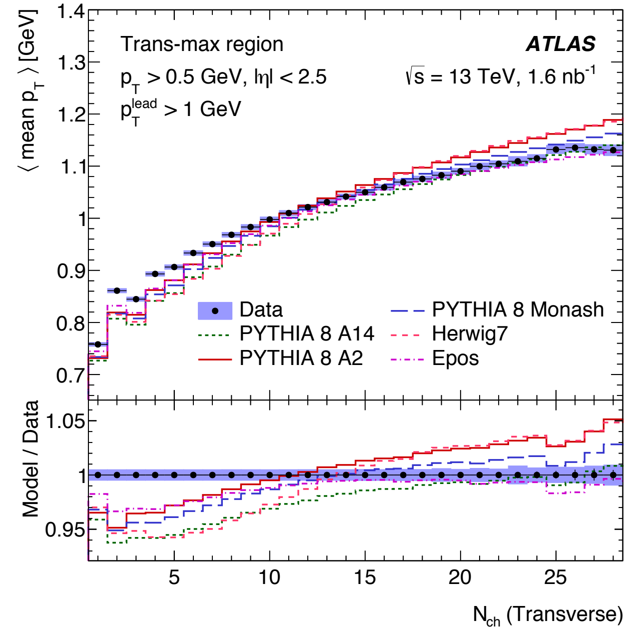
<mean p_T> vs N_{ch}



transverse



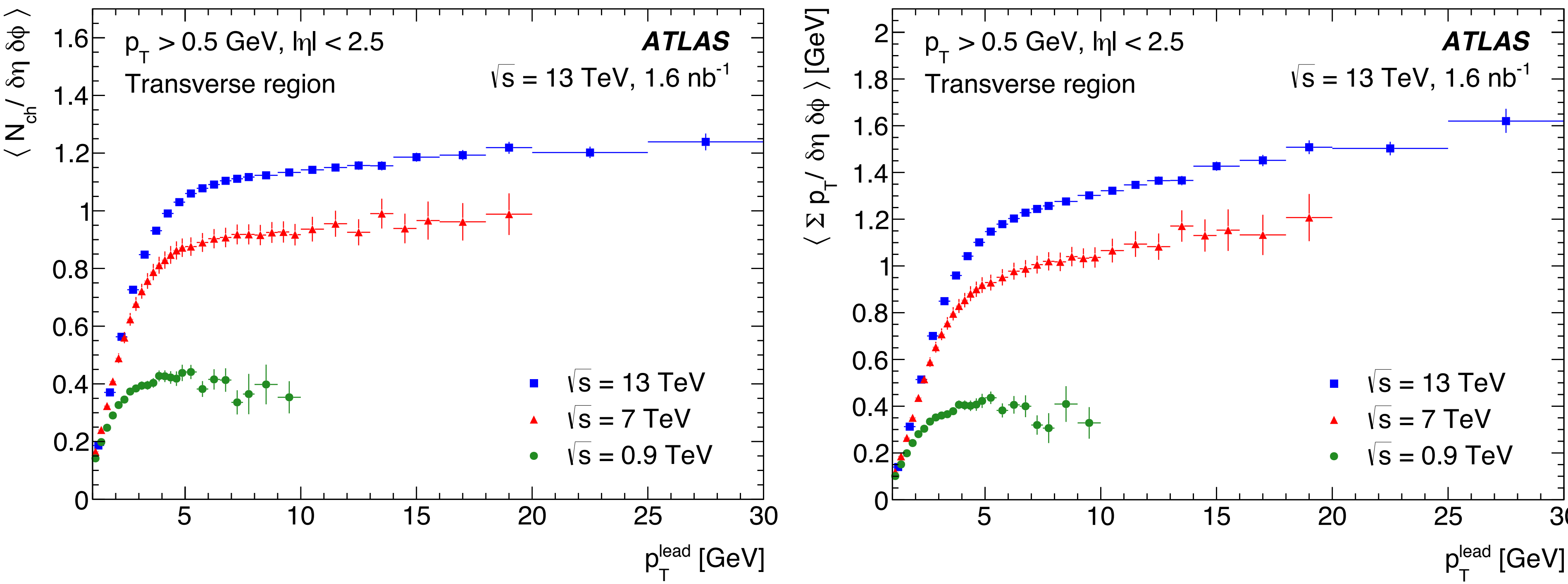
trans-min



trans-max

Up to ~ 5% underestimation for N_{ch} < 15 and overestimation for N_{ch} > 25, very good overall predictions by EPOS

Evolution of UE activity with √s



About 20% increase in the UE activity when going from 7 to 13 TeV *pp* collisions

Summary and conclusions

ATLAS: good benchmark to study soft QCD, fundamental studies for tuning of the soft part of Monte Carlo simulation

- **Minimum Bias Studies:**
  - Charged Particle Multiplicities @ 13 TeV
    - Nominal Phase Space, $p_T > 500$ MeV, $|\eta| < 2.5$
    - Extended phase space, $p_T > 100$ MeV, $|\eta| < 2.5$
    - Reduced phase space, $p_T > 500$ MeV, $|\eta| < 0.8$
  - The models have given **solid predictions for the latest centre of mass energy**, results already used in a **new Pythia 8 tune, A3**, applied in ATLAS for pile-up simulation

- **Underlying Event Studies:**
  - Track-based Underlying Event @ 13 TeV
  - The current models in use for **UE modelling typically describe data to 5% accuracy**, compared with **data uncertainties of less than 1%**, systematic mismodelling still visible

Thanks for your attention!

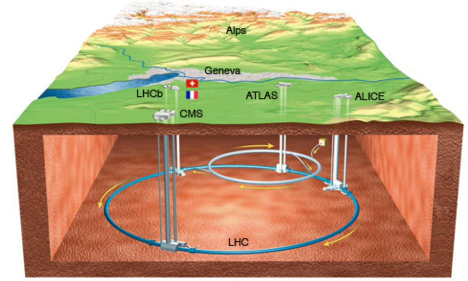
Valentina Cairo

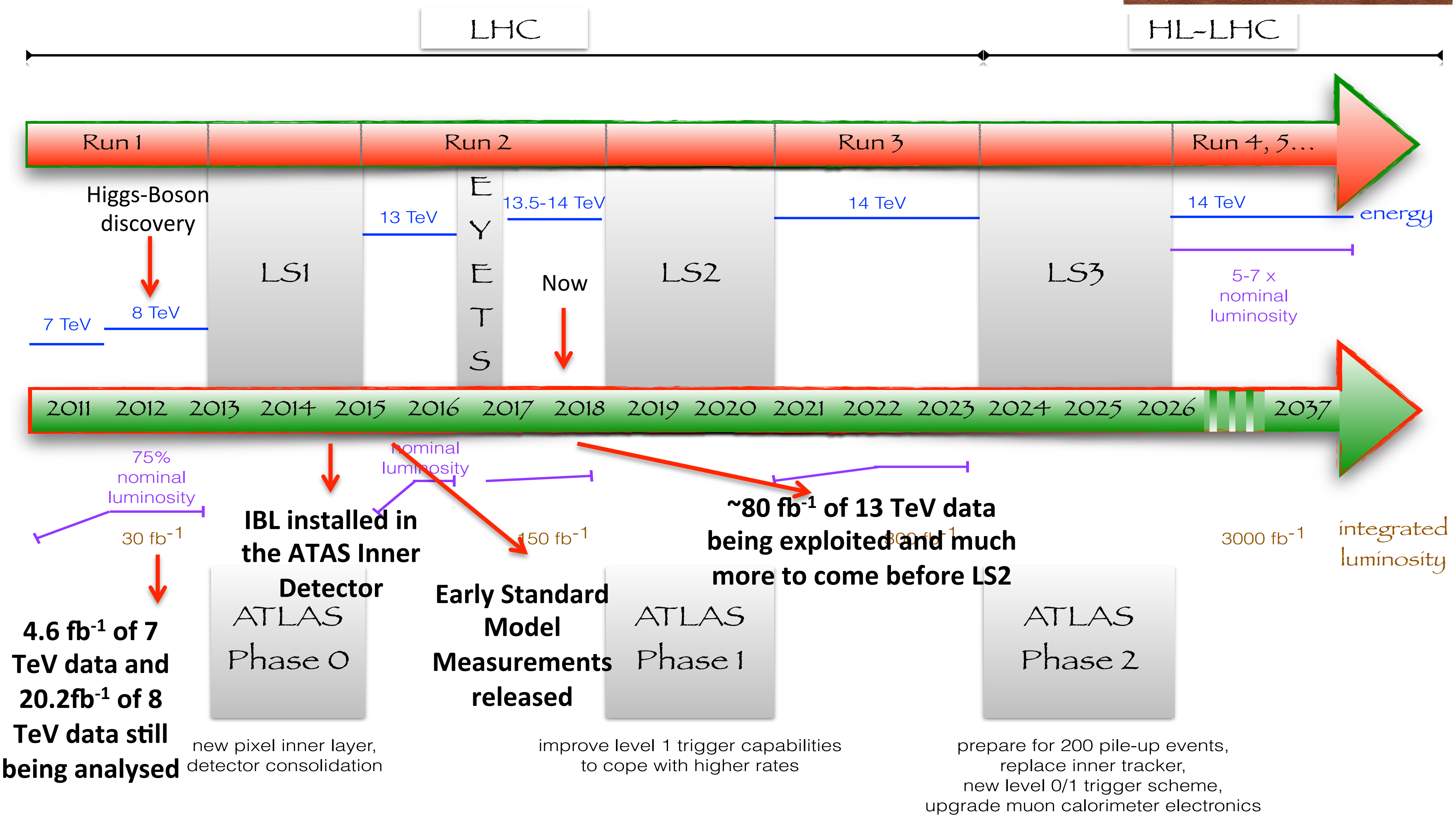
State University of New York at Albany

F. Cairo, From *Conn(ll)ecting the dots*

Extra Slides

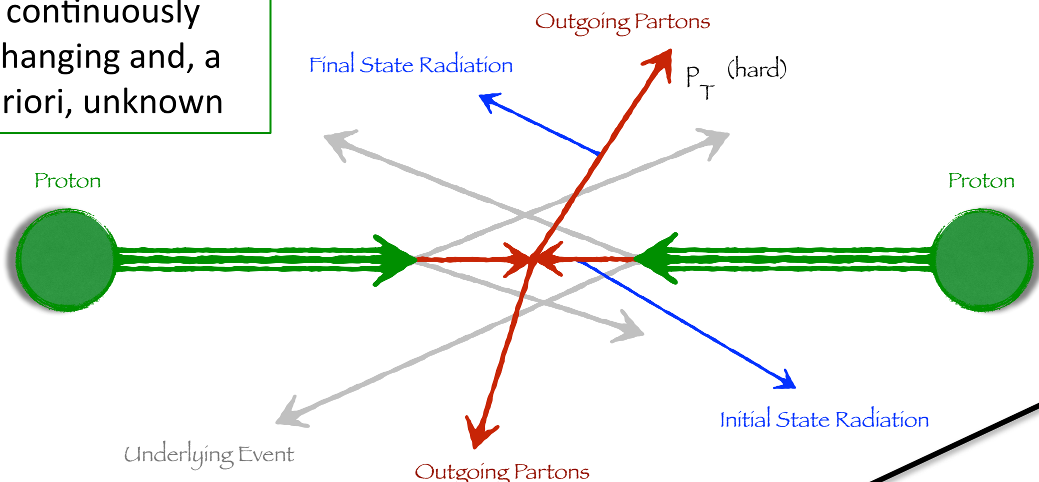
Large Hadron Collider Timeline



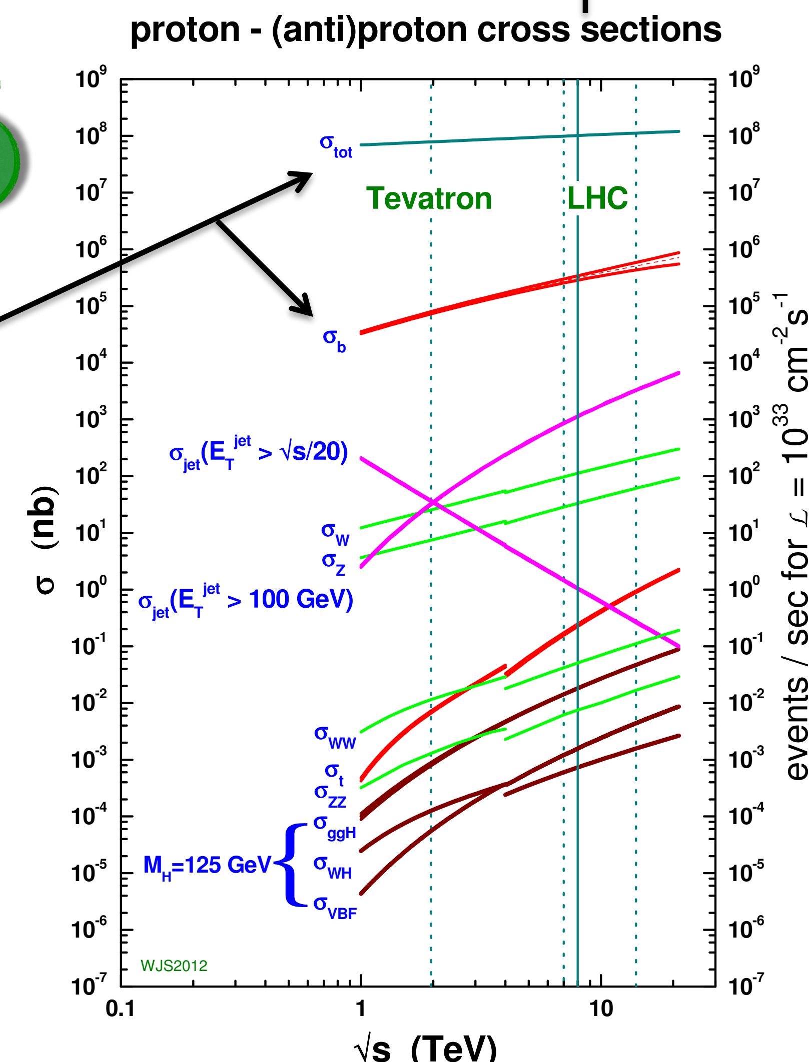


Proton-Proton Collisions

Partonic content is energy dependent, continuously changing and, a priori, unknown



probability that a pair of hadrons undergoes an interaction

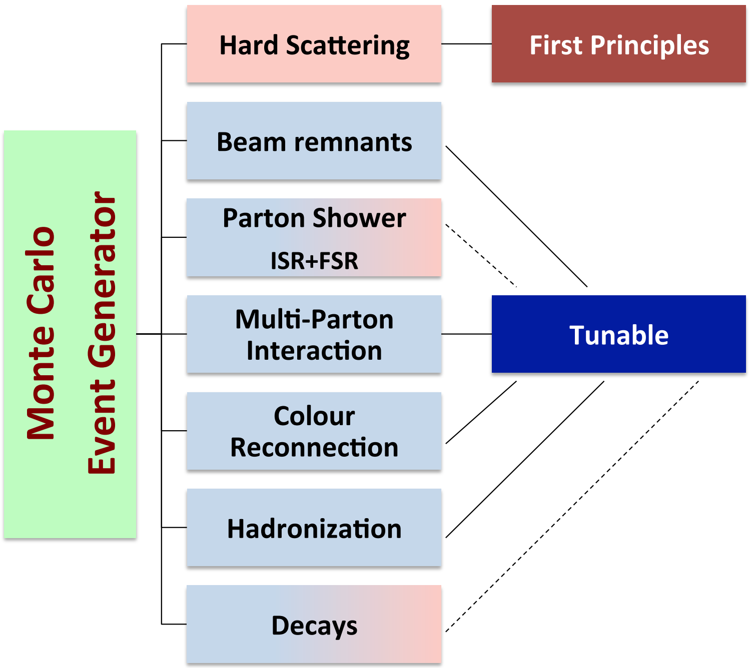


Hard QCD events constitute only a tiny fraction of the **total cross-section**, which is then **dominated by soft events** (peripheral processes).
In fact, the total production cross-section is orders of magnitude larger than very abundant hard QCD processes such as the production of b-quarks

Soft QCD and Monte Carlo Tuning

- While hard QCD processes can be studied by means of perturbative approaches, this is not possible for the soft QCD events

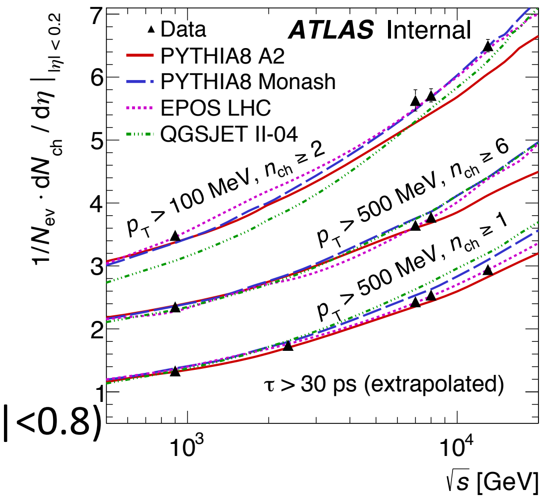
- The development of specialised software libraries based on Monte Carlo Methods, Monte Carlo (MC) event generators, to describe phenomenologically particle interactions began shortly after the discovery of the partonic structure of hadrons and the formalisation of QCD as the theory of strong interactions



- Models have to be developed with a set of **tunable parameters** to describe the hadron-level properties of final states dominated by soft QCD

- **Inclusive charged-particle and underlying event measurements** in *pp* collisions are the ideal test bed to provide insight into the strong interaction in the low energy, non-perturbative QCD region:
  - **Crucial for the tuning** of the Monte Carlo event generator
  - **Essential to understand** and correctly simulate any other more **complex phenomena**
  - **Ideal to study tracking performance** in the "early" stage of a new data taking…

LHC Results Overview

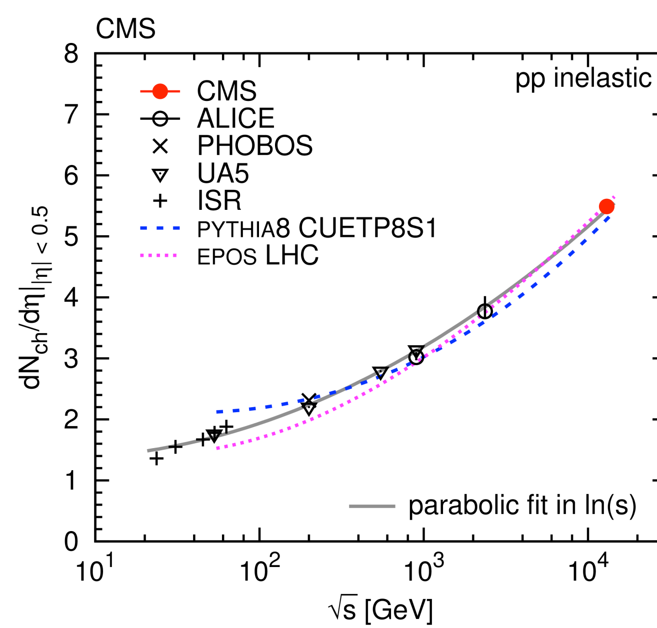


Minimum Bias measurements in ATLAS:

- 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:

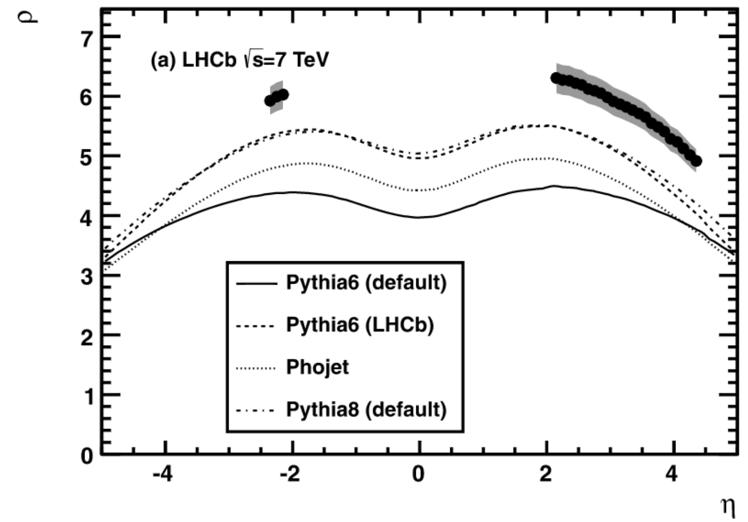
- 0.9, 2.36 (02/2010)
  - Charged hadrons
- 7 TeV (02/2010)
  - Charged hadrons
- 0.9, 2.36, 7 TeV (11/2010)
  - 5 pseudorapidity ranges from |eta|<0.5 to |eta|<2.4
- 8 TeV (05/2014) – with Totem
  - |η|<2.2, 5.3<|η|<6.4
- 13 TeV (07/2015)
  - no magnetic field



LHC Results Overview

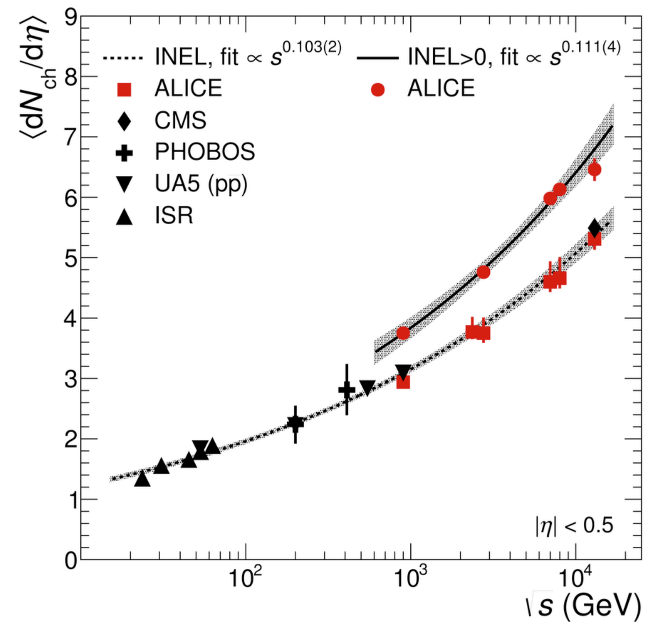
Minimum Bias measurements in LHCb:

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



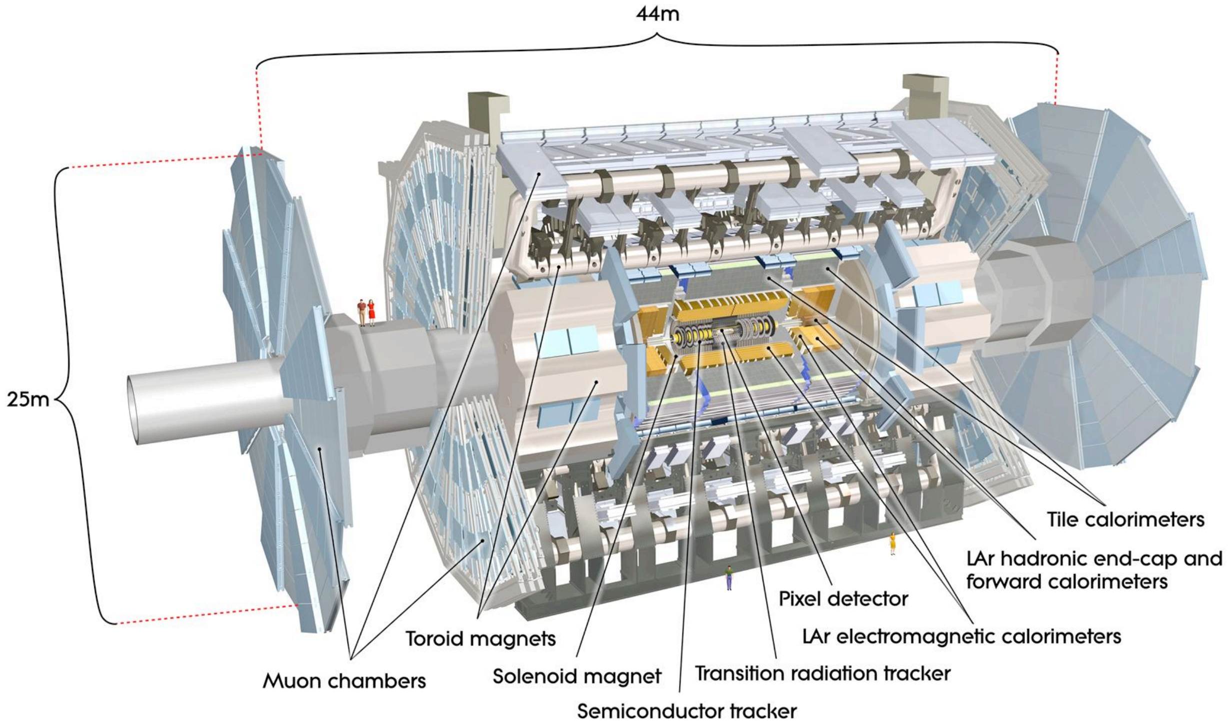
Latest Minimum Bias measurements in ALICE:

- 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 $|\eta|< 1$



ATLAS Experiment

- The ATLAS detector is a multi-purpose detector with a tracking system ideal for the measurement of particles kinematics



- After a 3-year data taking phase (Run 1, 2010-2012) and a 2-year shutdown (LS1, 2013-2014) for repairing and upgrade, the ATLAS Detector is again operational at the LHC Run 2 at $\sqrt{s}$=13TeV
- Run 2 started in Spring 2015 → by the end of 2016 collected ~ 40 fb^{-1} of data (about a factor of 2 wrt Run 1 data, which allowed for the discovery of the Higgs Boson)

Run1 MinBias

For the purpose of comparing the present measurements to different phenomenological models describing minimum-bias events, the following additional particle-level MC samples were generated:

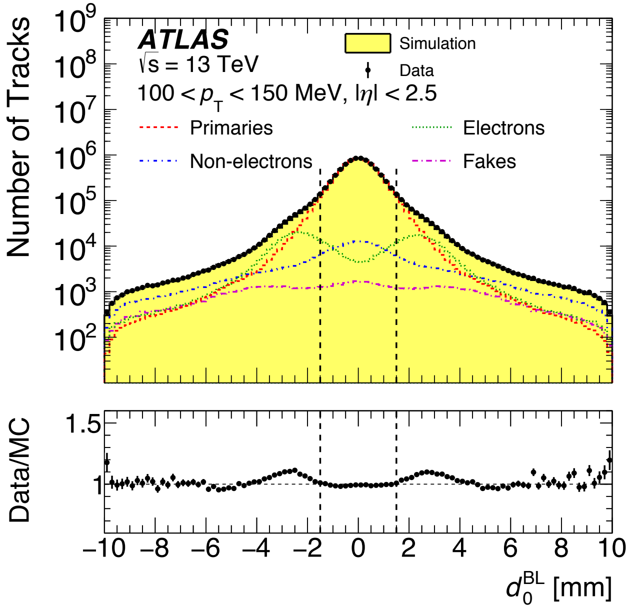
- the new ATLAS Minimum Bias Tune 1 (AMBT1) PYTHIA6 tune described in section 3.2;
- the DW [27] PYTHIA6 tune, which uses virtuality-ordered showers and was derived to describe the CDF Run II UE and Drell–Yan data;
- the PYTHIA8 generator[5] [28], in which the diffraction model produces much harder p_T and n_{ch} spectra for the SD and DD contributions than PYTHIA6. The default parton shower model is similar to the one used in PYTHIA6 MC09;
- the PHOJET generator[6] [29], which is used as an alternative model to PYTHIA-based generators. PHOJET relies on PYTHIA6[7] for the fragmentation of partons.

Table 1. Comparison of MC09c and AMBT1 parameters. The ranges of the parameter variations scanned are also given. The parameters declared as 'fixed' were fixed at the values obtained after an initial pass of the tuning.

Parameter	Related model	MC09c value	Scanning range	AMBT1 value
PARP(90)	MPI (energy extrapolation)	0.2487	0.18–0.28	0.250
PARP(82)	MPI (p_T^{min})	2.31	2.1–2.5	2.292
PARP(84)	MPI matter overlap (core size)	0.7	0.0–1.0	0.651
PARP(83)	MPI matter overlap (fraction in core)	0.8	Fixed	0.356
PARP(78)	CR strength	0.224	0.2–0.6	0.538
PARP(77)	CR suppression	0.0	0.25–1.15	1.016
PARP(93)	Primordial $k_\perp$	5.0	Fixed	10.0
PARP(62)	ISR cut-off	1.0	Fixed	1.025

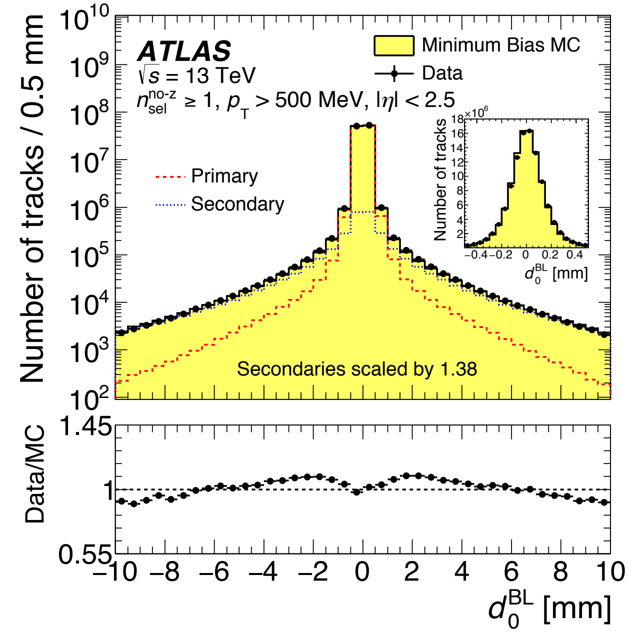
Secondaries

- 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

Corrections (min bias)

- 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

Systematic Uncertainties Breakdown

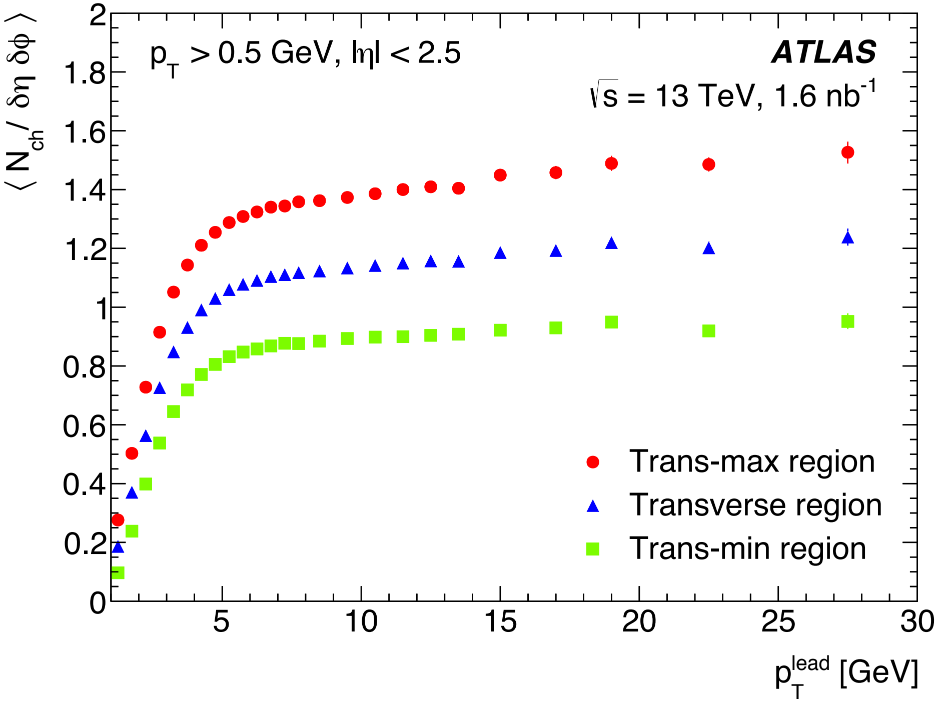
- Zooming-in on some of the systematic uncertainties at 13 TeV (full list in the extra slides)

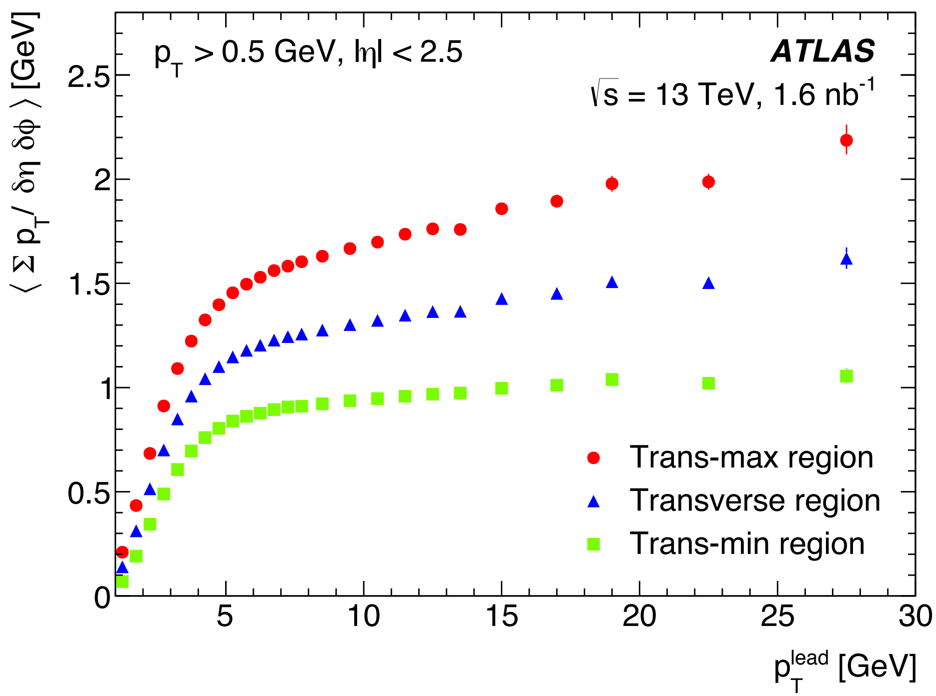
Systematic Uncertainty	Distribution	Size ($\sqrt{s}$=13 TeV, p_T>500 MeV)	Size ($\sqrt{s}$=13 TeV, p_T>100 MeV)
Track Reconstruction Efficiency	η	0.5% - 1.4%	1 – 7%
	p_T	0.7%	1 – 6%
Non-primaries	η	0.5%	0.5%
	p_T	0.5% - 0.9%	0.5% -1 %
Non-closure	η	0.7%	0.4-1%
	p_T	0% - 2%	1% -3%

- **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

Track-based Underlying Event at 13 TeV

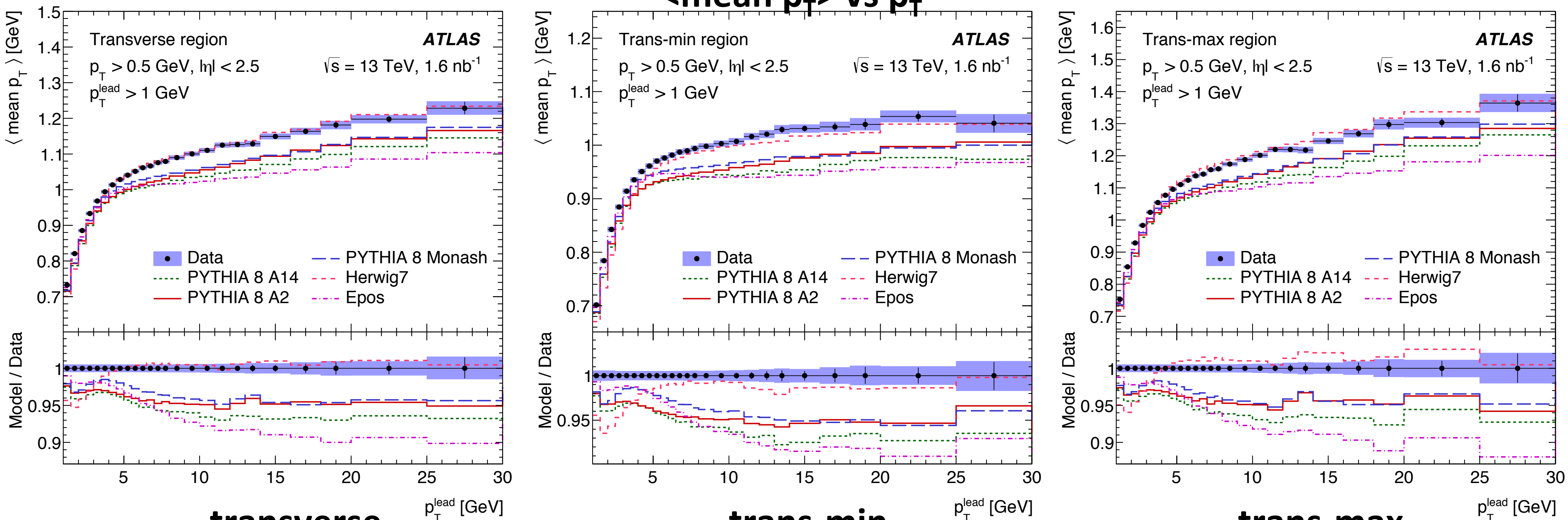




Mean p_T in transverse regions

- It illustrates the balance in UE physics between the p_T and multiplicity observables → affected by colour-reconnection or -disruption mechanisms
- <mean p_T> increases with p_T^{lead} (in fact Σp_T does not reach as flat a plateau as does N_{ch})

<mean p_T> vs p_T^{lead}



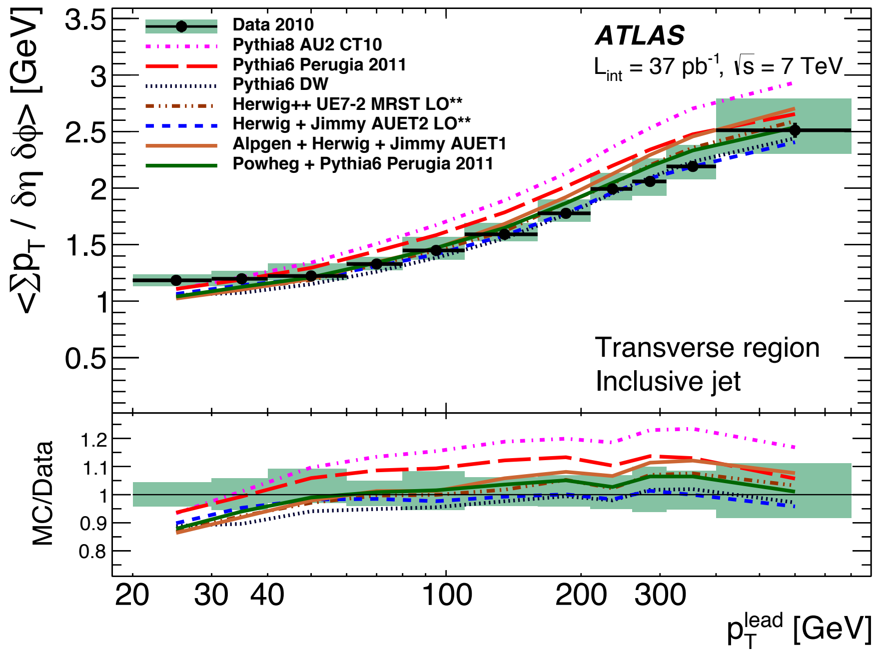
transverse **trans-min** **trans-max**

Best predictions given by Herwig 7 except in the low p_T^{lead} (min bias) region where the Herwig model is not expected to work

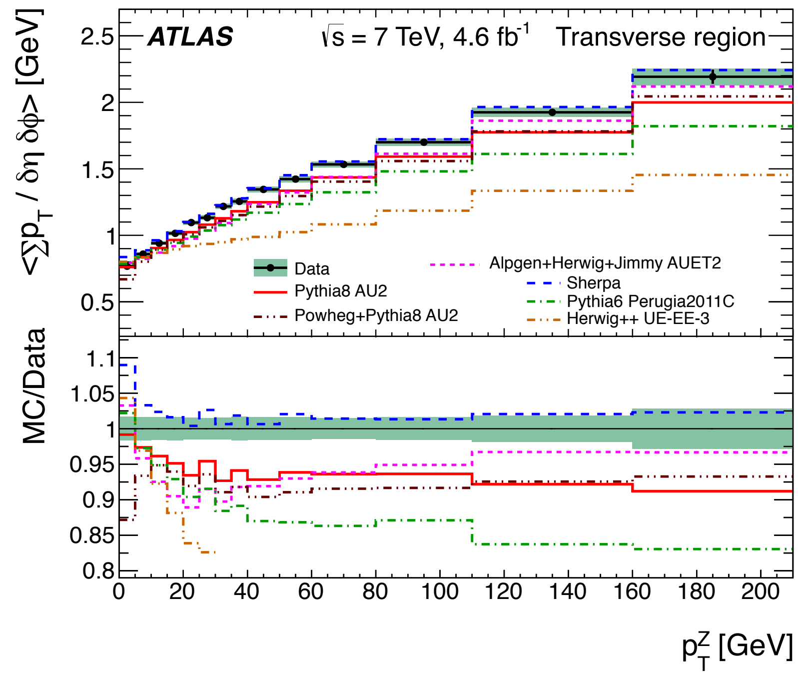
Underlying Events at 7 TeV: Jets and Z

Σp_T for underlying events vs leading jet and Z p_T:

http://arxiv.org/abs/1406.0392 **Leading Jet**



Z-boson http://arxiv.org/abs/1409.3433



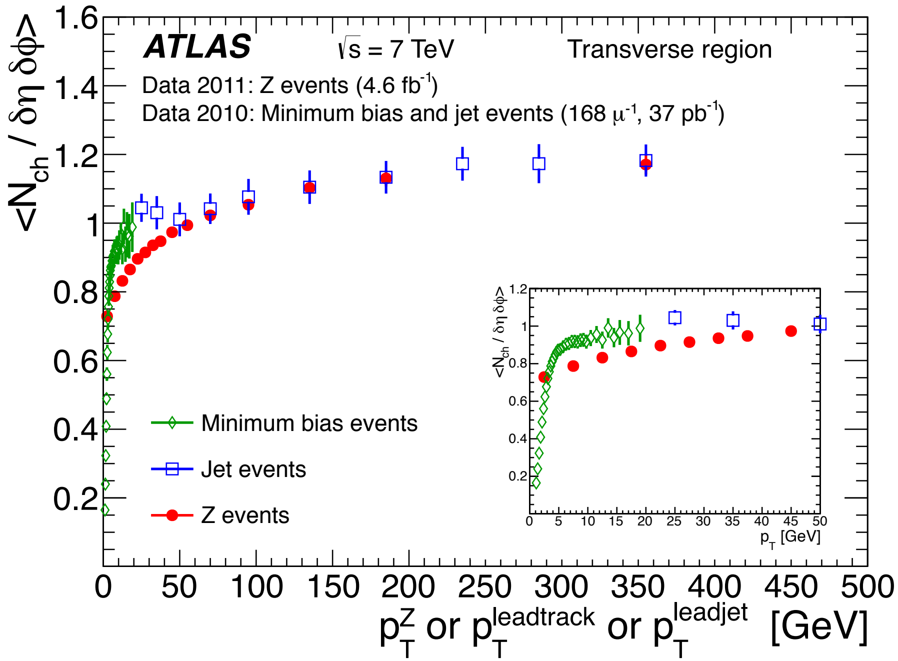
The tracks corresponding to the leptons forming the Z-boson candidate are excluded.

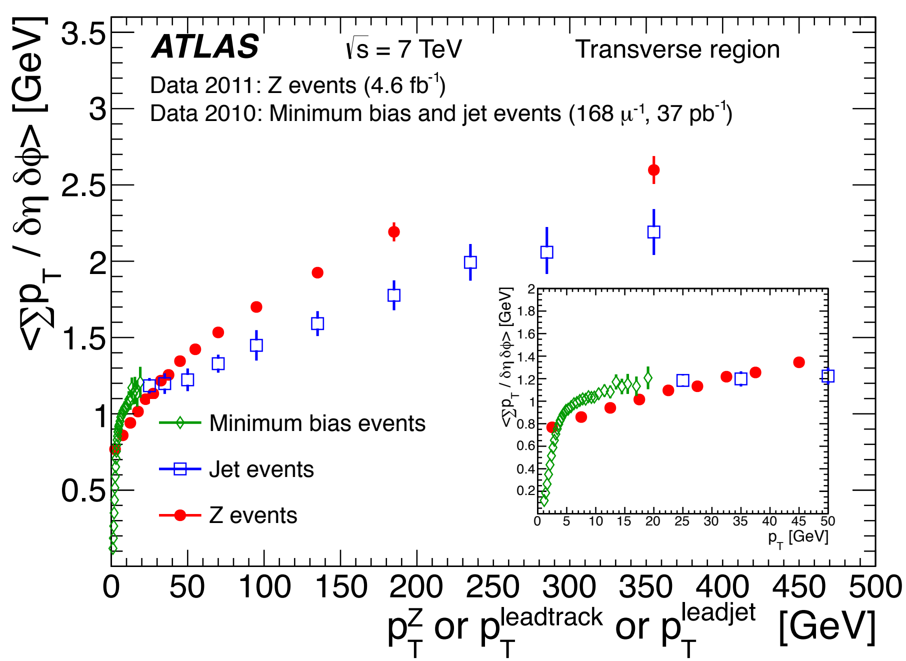
- Not perfect agreement between data and simulation (old tunes)
- For Z-boson, good description given by Sherpa, followed by PYTHIA 8, ALPGEN and POWHEG
- Multi-leg and NLO generator predictions are closer to the data than most of the pure parton shower generators -> these regions are affected by the additional jets coming from the hard interaction

Underlying Events at 7 TeV: Jets, Z and Tracks

Track density and Σp_T for underlying events vs leading jet or leading track or Z p_T:

http://arxiv.org/abs/1409.3433



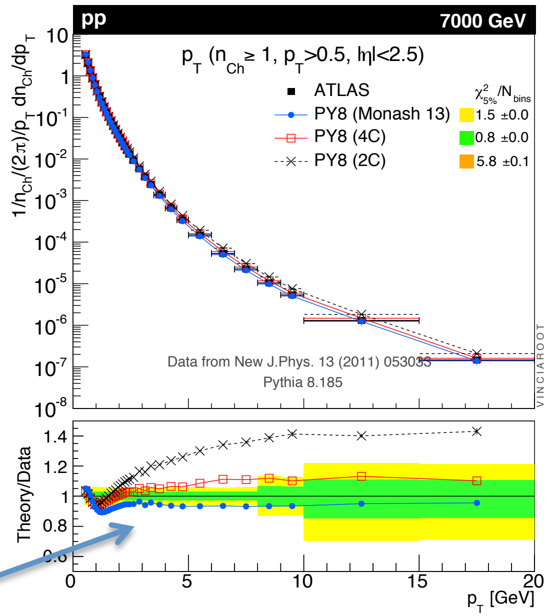


- Data are compatible between the different definitions
- Transition between leading track and jet
- In the track density distribution, Z-bosons and jets agree well at high p_T

Pythia 8 – MB & UE tunes

- Hadron-hadron interactions described by a model that splits the total inelastic cross section into **non-diffractive** (**ND**) and diffractive processes:
  - Non-diffractive part dominated by *t*-channel gluon exchange (simulation includes MPIs)
  - Diffractive part involves a color-singlet exchange (further divided into **single-diffractive** (**SD**) and **double-diffractive** (**DD**) dissociation)

- Tunes used in the latest measurements:
  - **A2** (MSTW2008 LO PDF)
    - Using 7 TeV ATLAS measurements of MB plus leading track and cluster UE
    - Specific Minimum Bias Tune (A2)
    - Specific Underlying event tune (AU2)
  - **Monash** (NNPDF2.3 LO PDF)
    - Updated fragmentation parameters, minimum-bias, Drell-Yan and underlying-event data from the LHC to constrain ISR and MPI parameters. SPS and Tevatron data to constrain the energy scaling.
    - Excellent description of 7 TeV MB p_T spectrum.

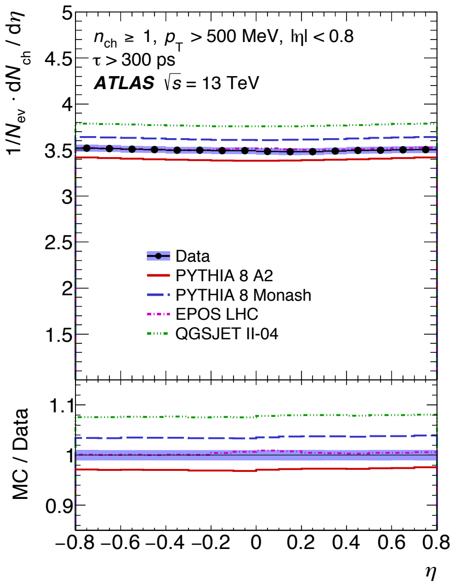


https://arxiv.org/pdf/1404.5630v1.pdf

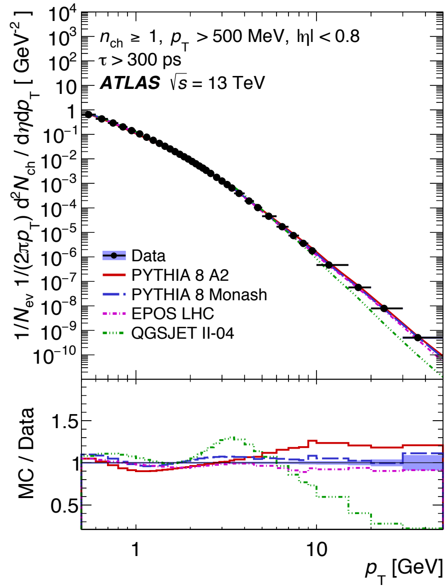
Final Results – 13 TeV

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

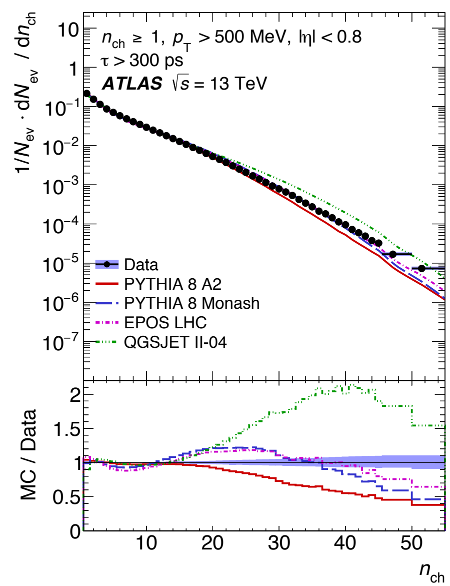
$dN_{ch}/d\eta$



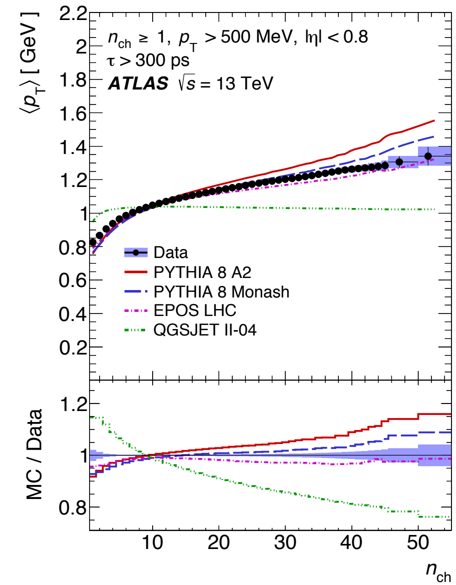
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



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



Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

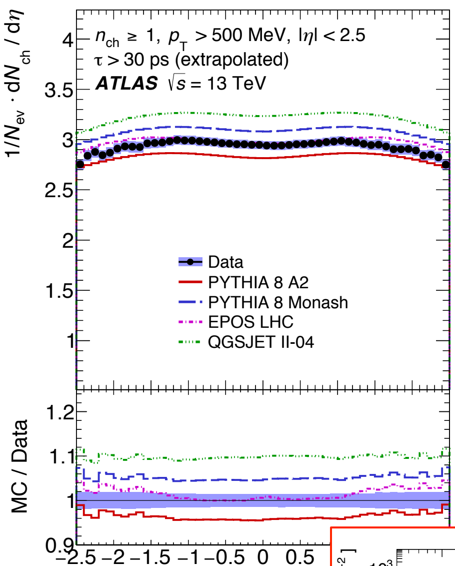
Low n_{ch} not well modelled by any MC; large contribution from diffraction;
Models without colour reconnection (QGSJET) fail to model scaling with nch very well

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)

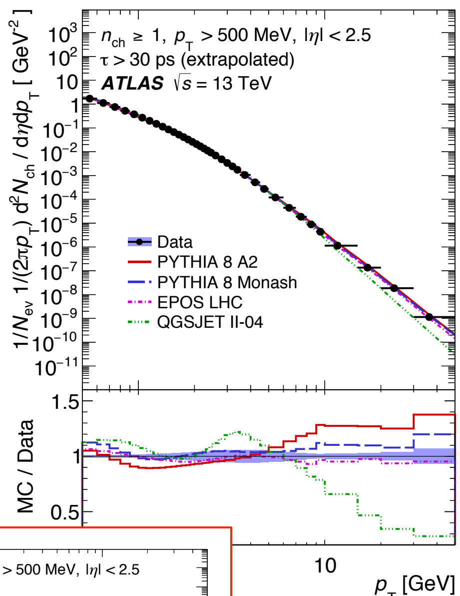
Final Results – 13 TeV

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

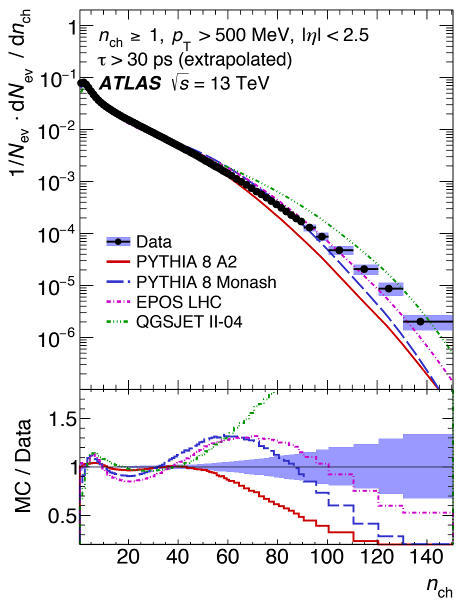
$dN_{ch}/d\eta$



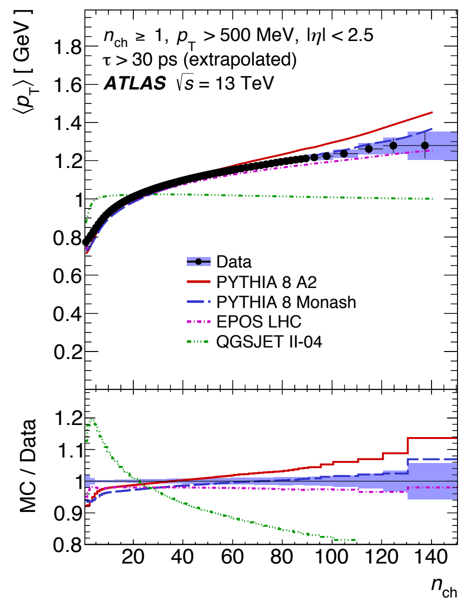
$d^2N_{ev}/d\eta dp_T$

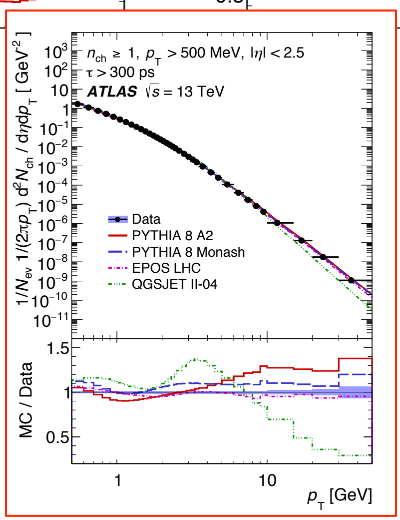


dN_{ev}/dn_{ch}



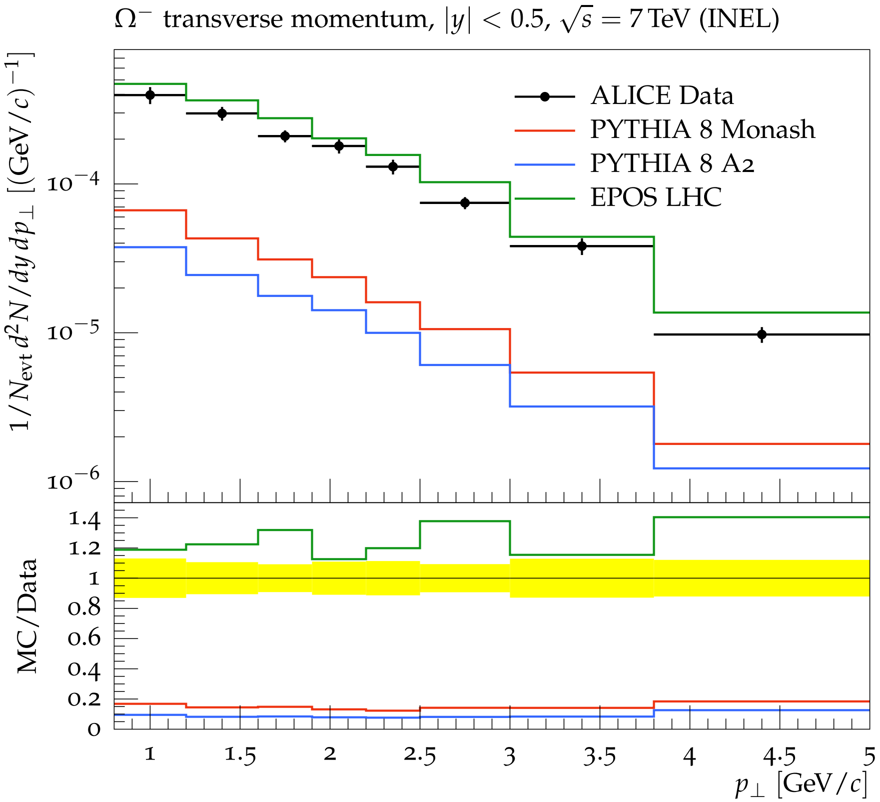
$<p_T>$ VS n_{ch}

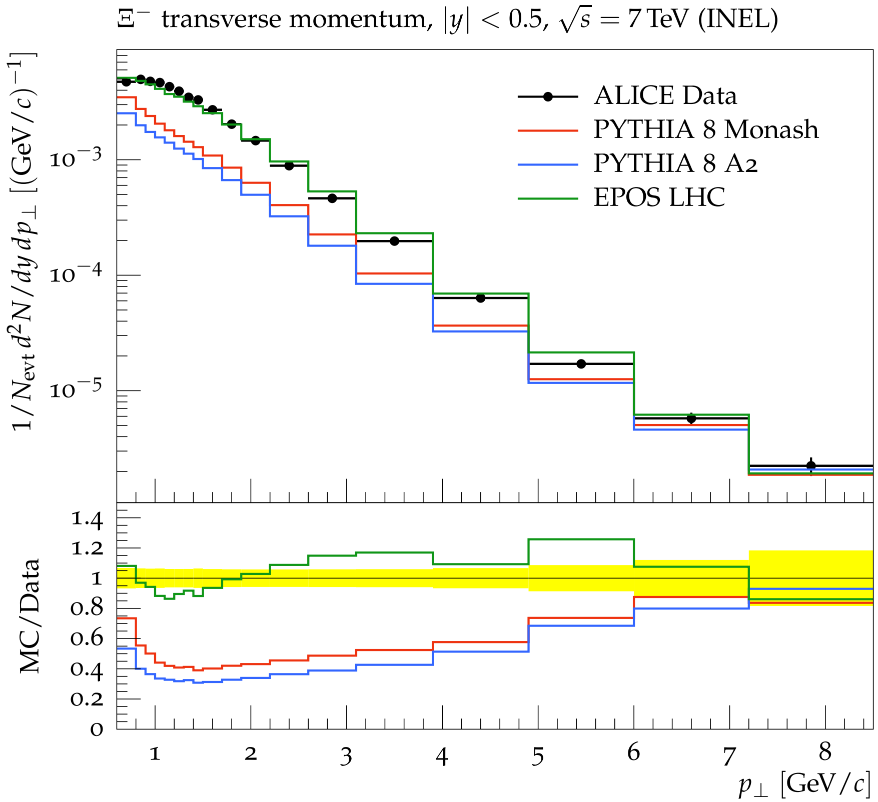




Largest impact is on the pt distribution

Stange Baryons





The rate of strange baryons (a) Ω- and (b) Ξ- as a function of their transverse momentum, pT. The data points correspond to the ALICE measurement Phys. Lett. B712 (2012) 309--318, and are compared to various Monte Carlo models. The plots are made with Rivet [Comput. Phys. Commun. 184 (2013) 2803].

Hadronic Interactions and Photon Conversions

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

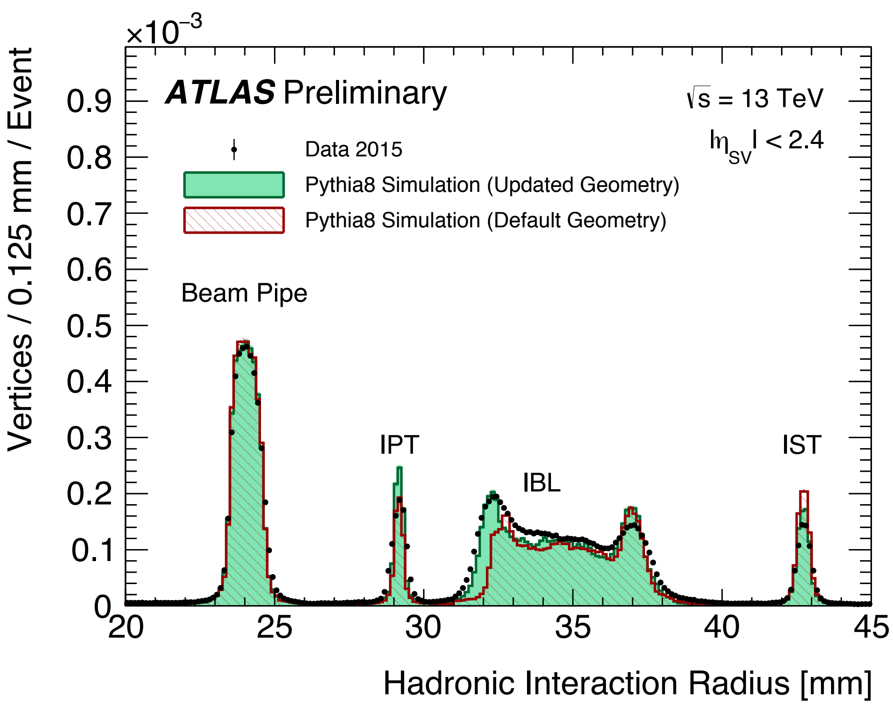
Excellent **radial resolution** (between **65 and 230 μm** from the beam pipe to Layer-1 depending on radius).

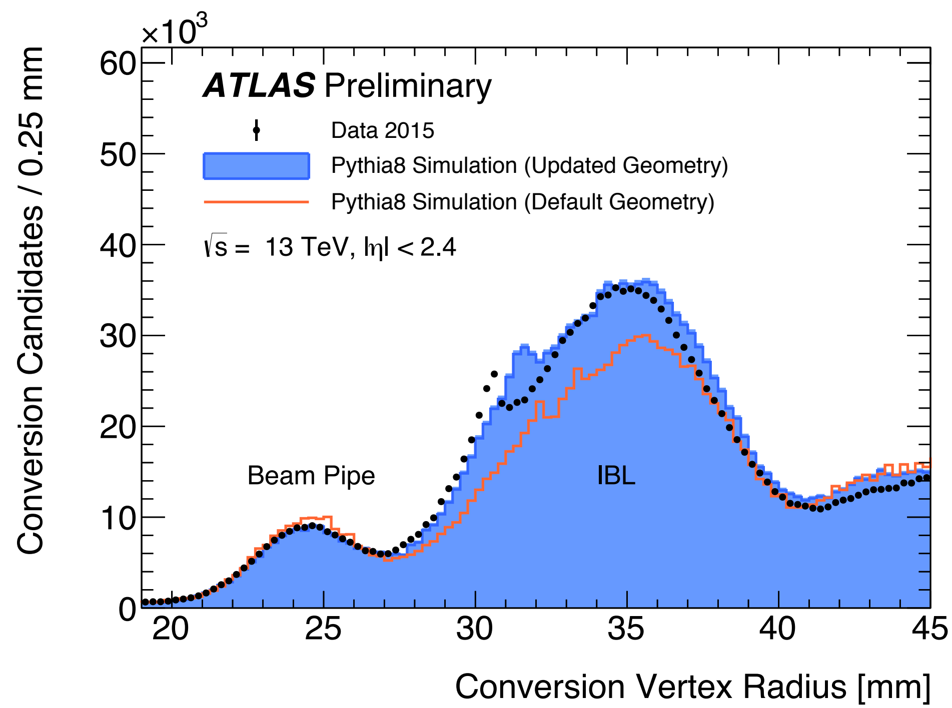
Probability for a **photon conversion** (very clean signal) is proportional to the traversed material.

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

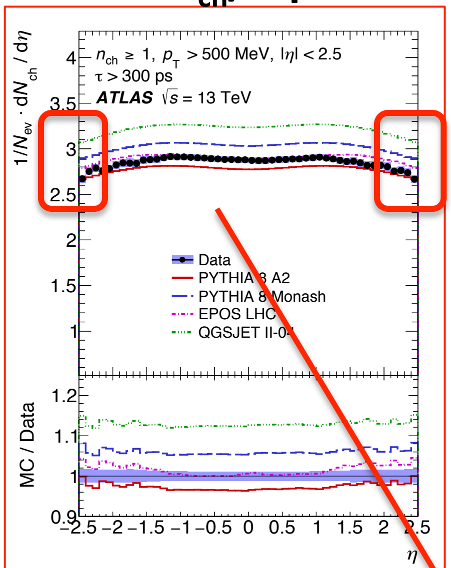
- In the 500 MeV phase space, the fakes are neglected because they drop rapidly with p_T such that the rate is negligible in that phase space

- 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

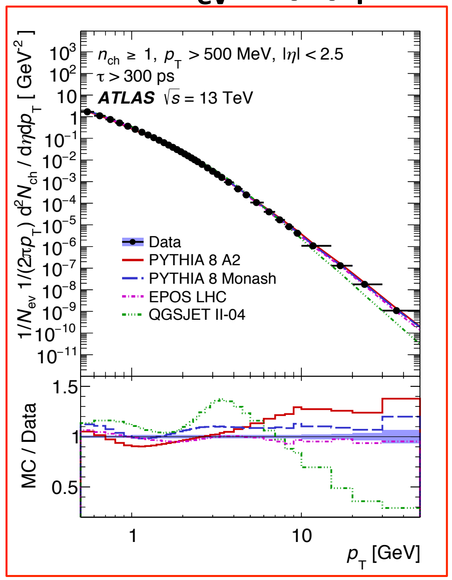
Final Results

- Nominal Phase Space (500 MeV)

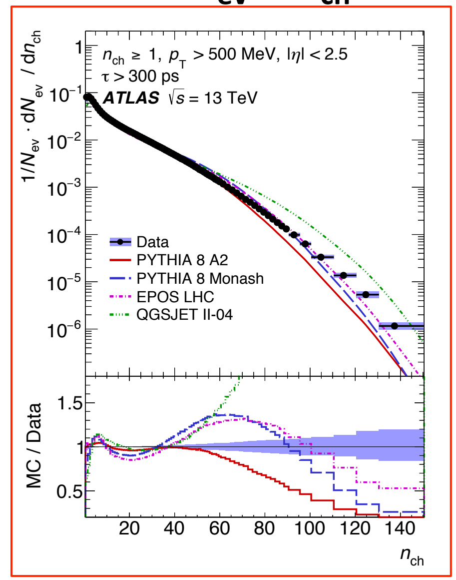
$dN_{ch}/d\eta$



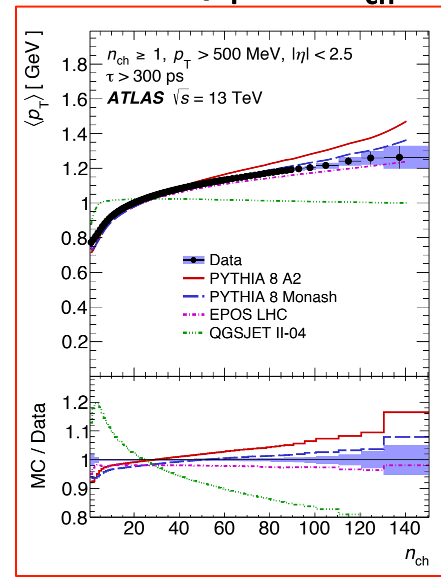
$d^2N_{ev}/d\eta dp_T$

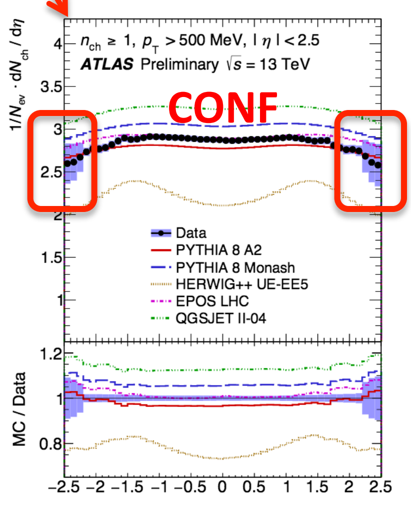


dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



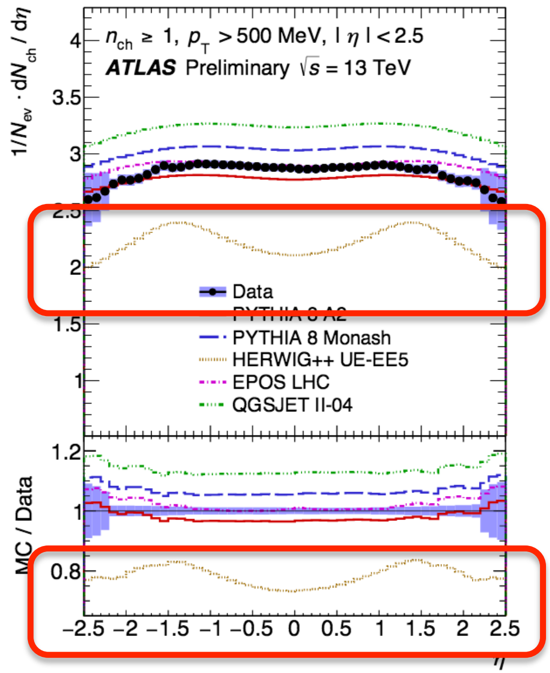


Big improvements in the systematic uncertainty evaluation thanks to the correction to the tracking efficiency driven by material studies

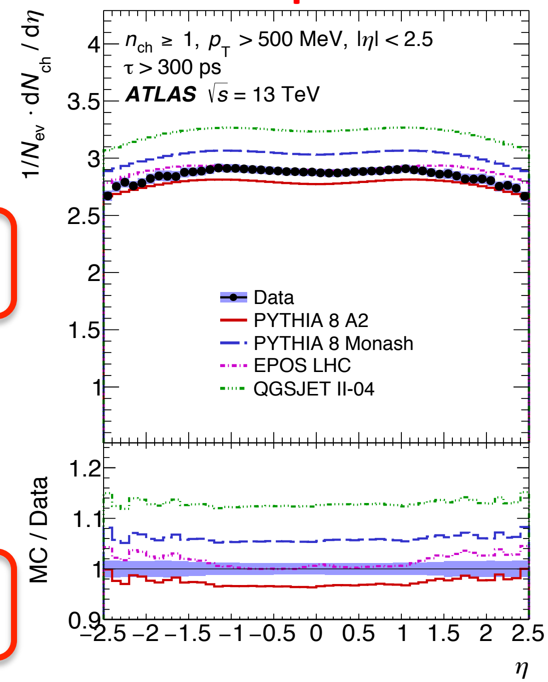
Final Results – Extra Generators Comparison

- Nominal Phase Space (500 MeV)

CONF



Paper



- 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

N-1 cut Systematic Uncertainty

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

- 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

χ^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

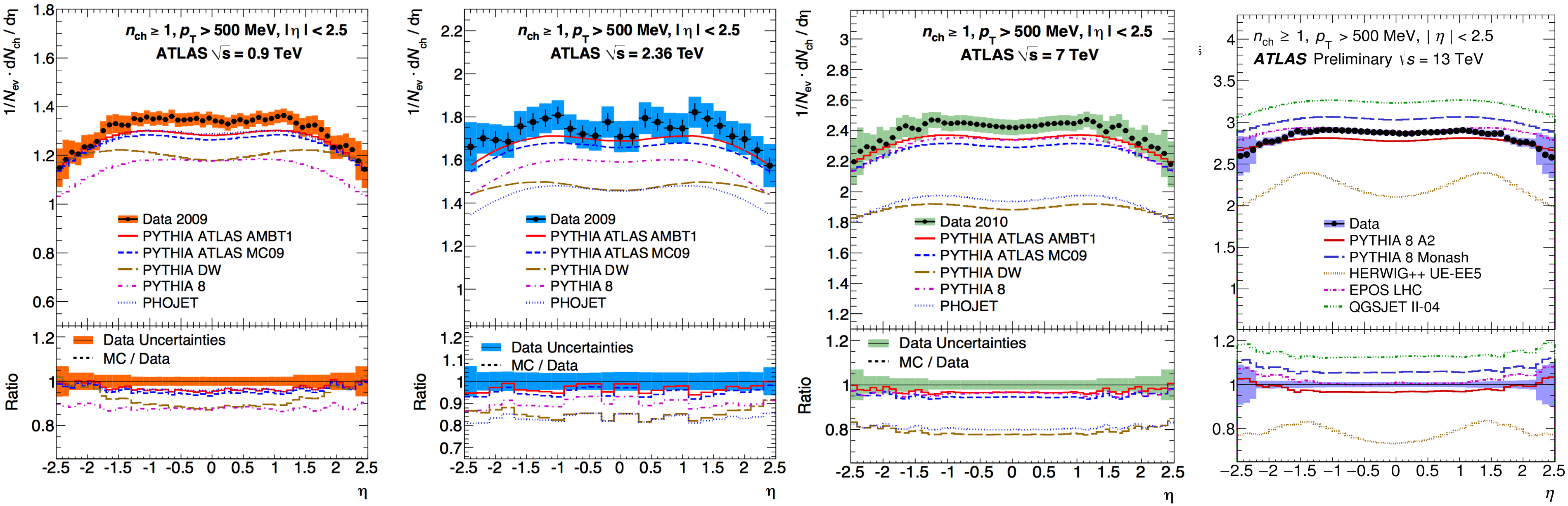
- A cut on χ2 probability of $P(\chi 2, n_{dof}) > 0.01$ is applied for tracks with $p_T > 10$ GeV to remove bad measured tracks

- 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

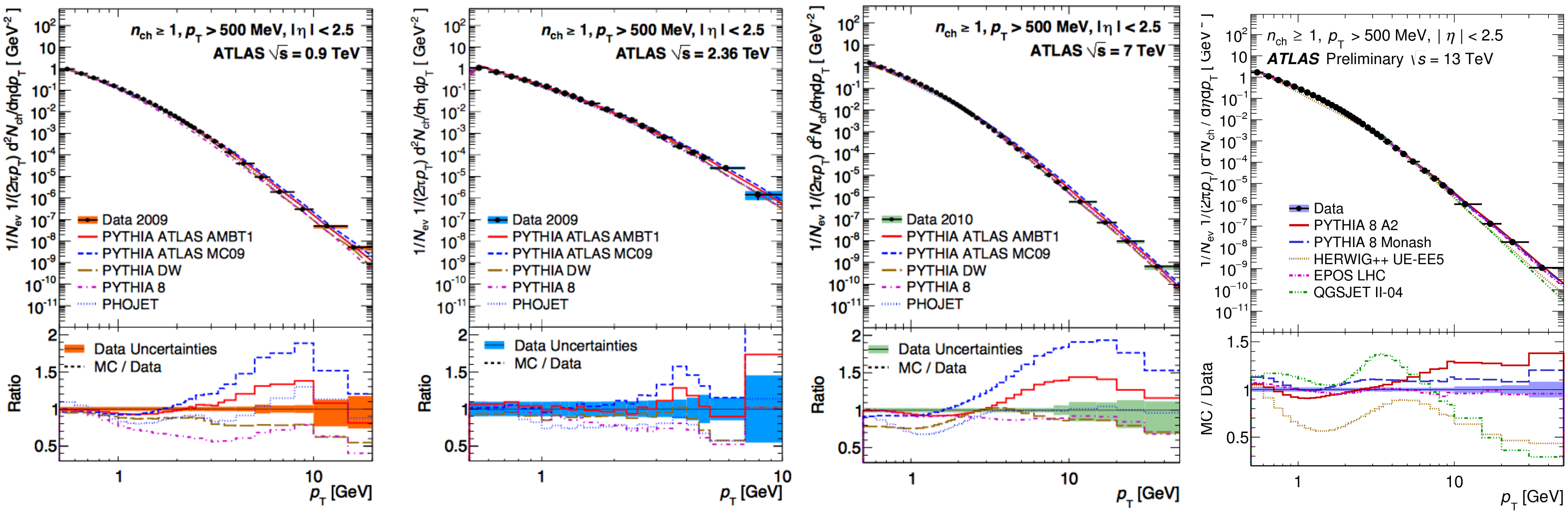
$dN_{ch}/d\eta$ http://arxiv.org/pdf/1012.5104v2.pdf



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

Different Centre of Mass Energy

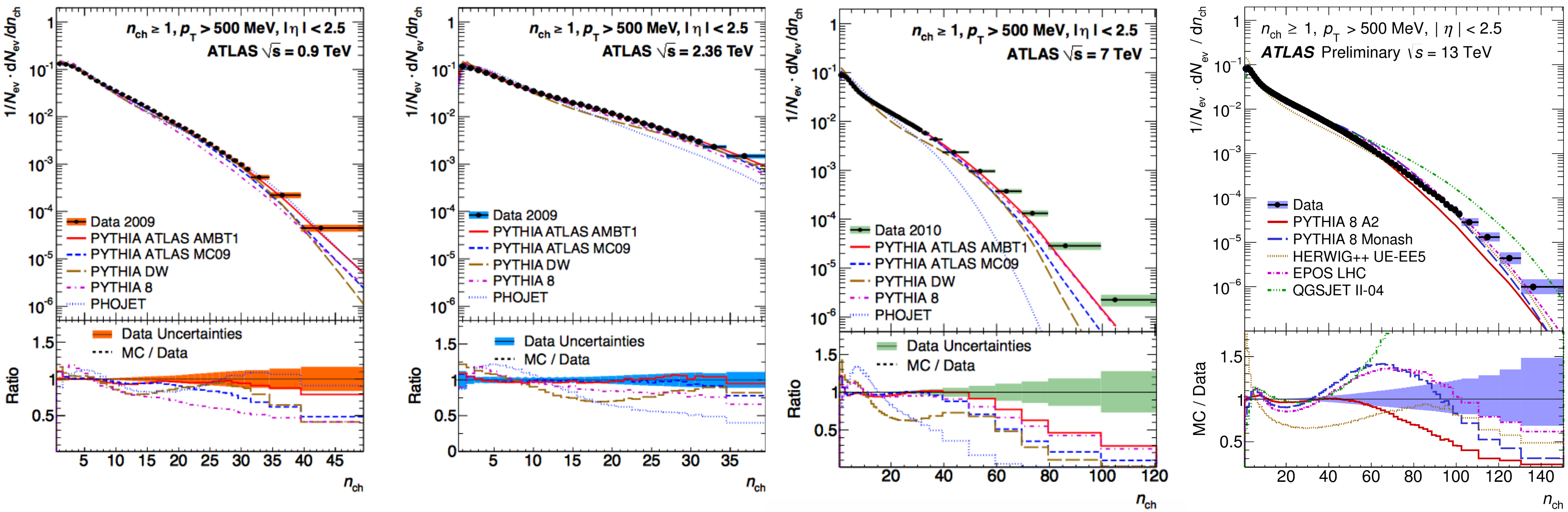
$d^2N_{ev}/d\eta dp_T$ http://arxiv.org/pdf/1012.5104v2.pdf



- Large disagreement at low p_T and high p_T

Different Centre of Mass Energy

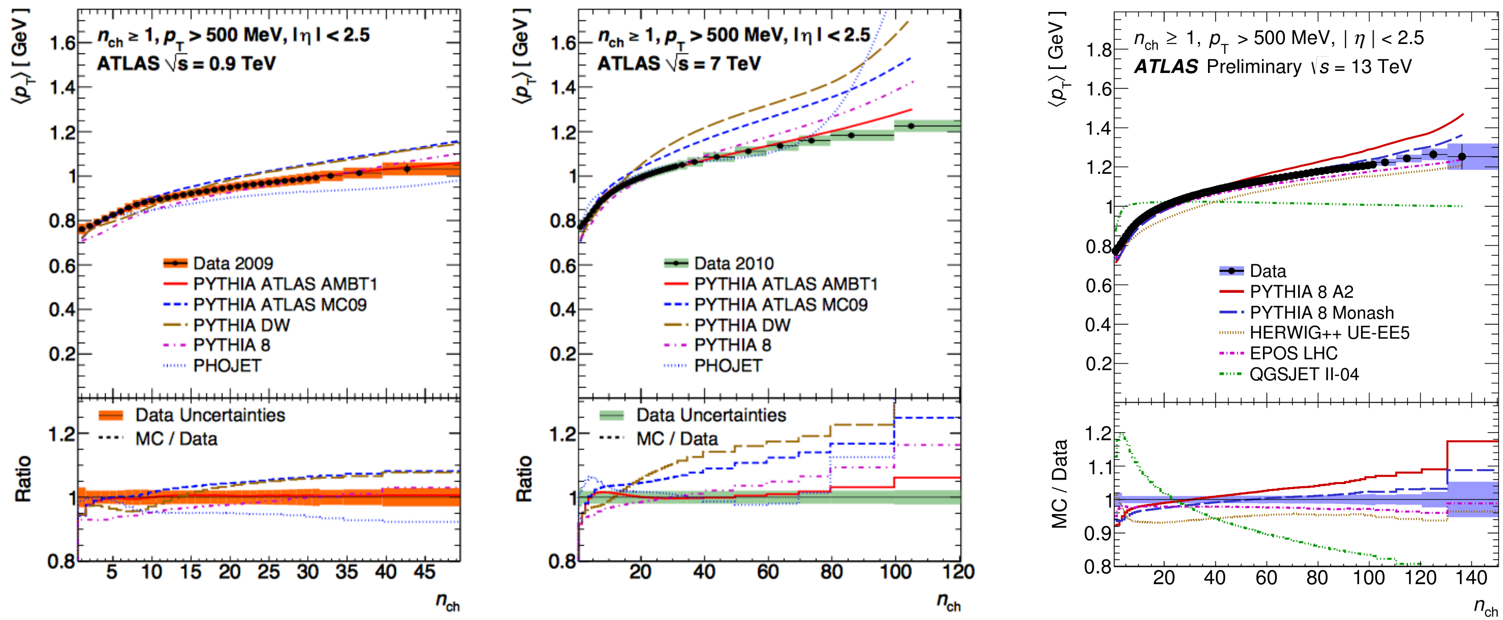
dN_{ev}/dn_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



- 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

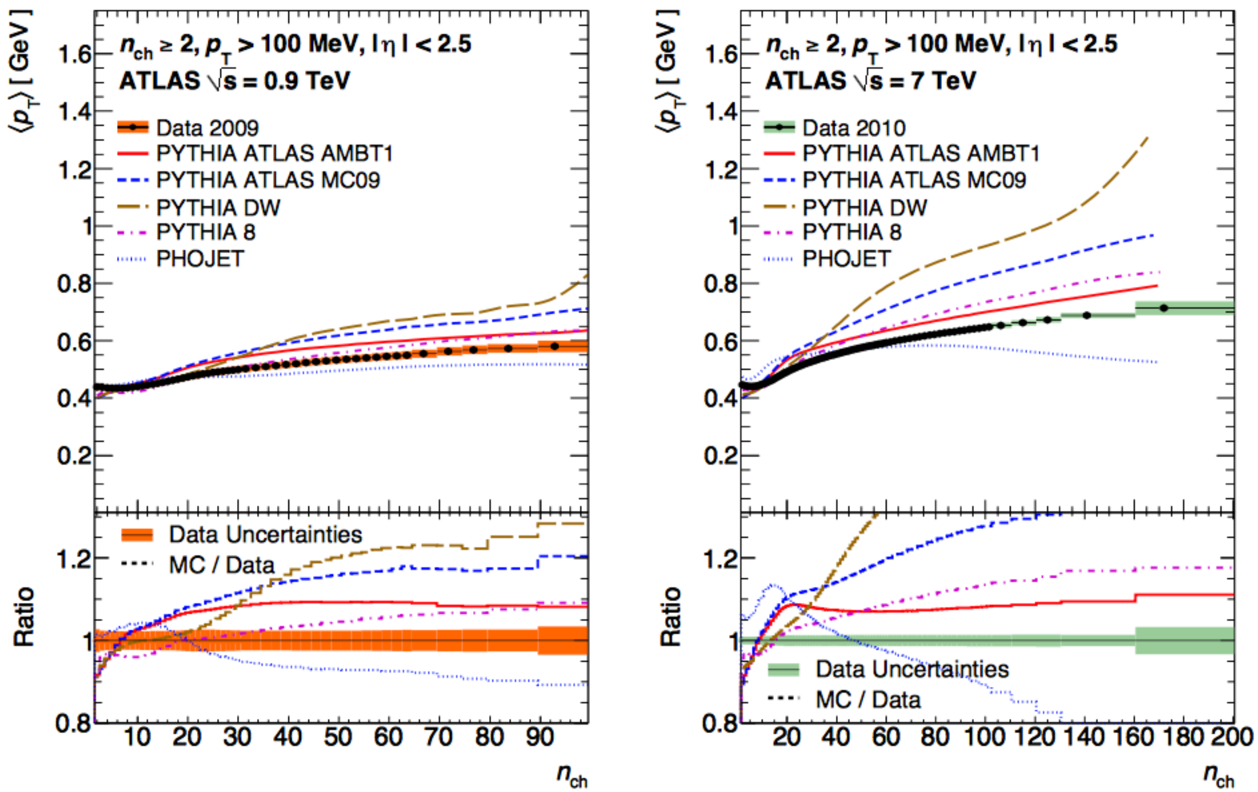


The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

- 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

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



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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 $\langle p_{\mathrm{T}} \rangle$ distribution is not produced for this energy as neither method is able to describe both the number of particles and their p_{T} accurately.

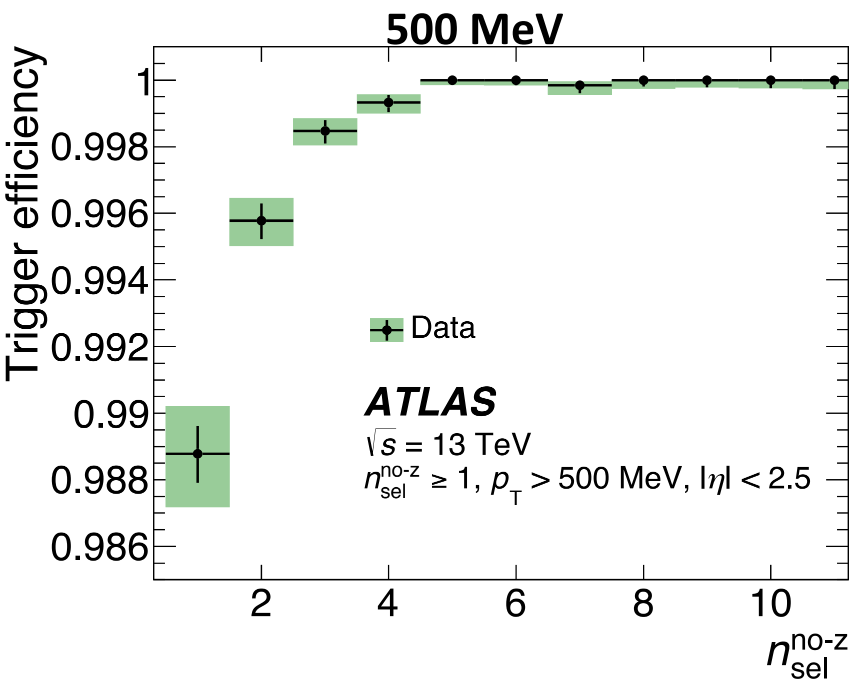
Strange Baryons

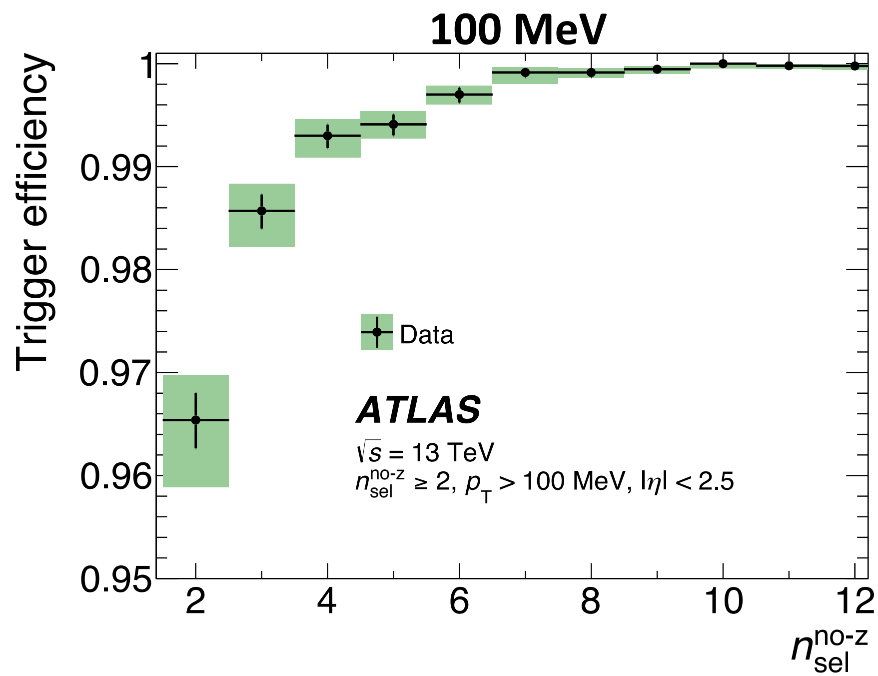
STRANGE BARYONS	
Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314^d
Ω^-	3334

Trigger Efficiency

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

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

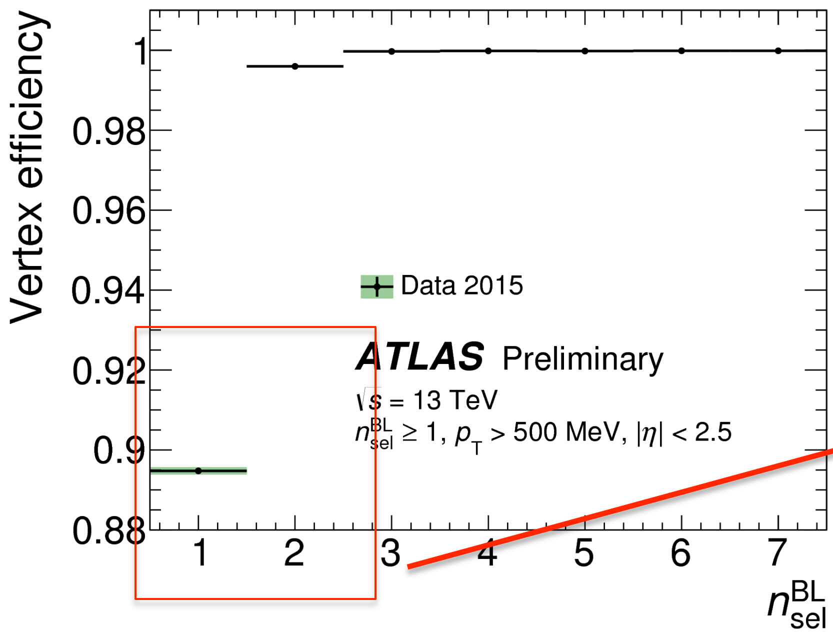


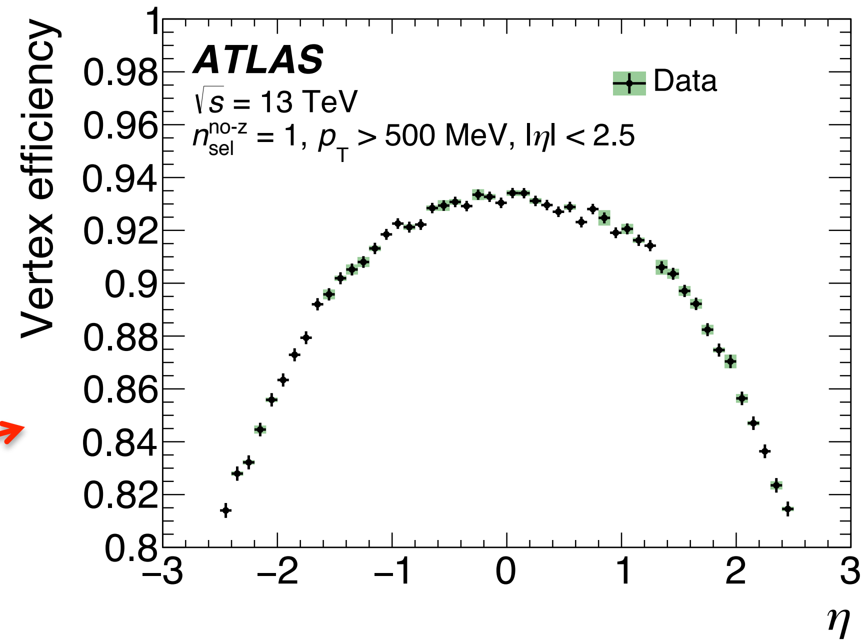


Systematic uncertainty:
- variation of the track selection; differences between MBTS A and C side ; non-collision beam background
- MC based: events failing both triggers

Vertex Efficiency

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





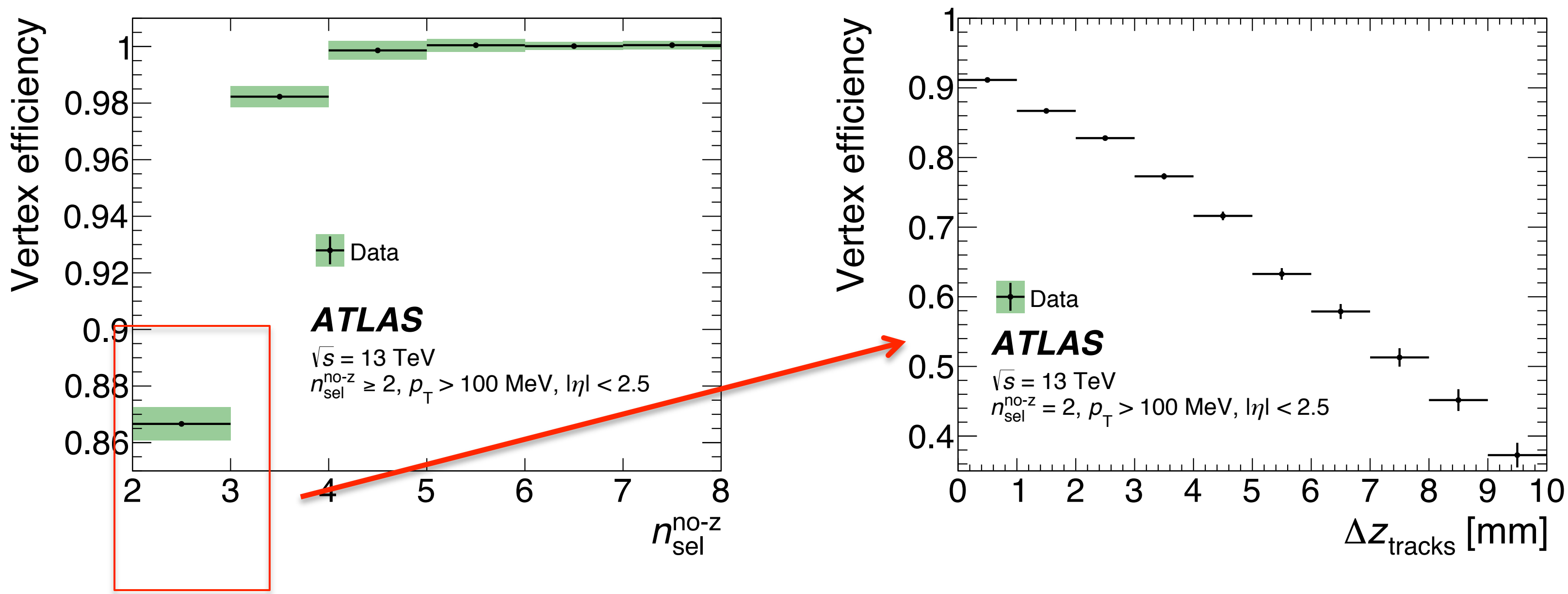
Efficiency for the first $n_{sel}{}^{no\text{-}z}$ bin depends on eta of the track

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 $n_{sel}{}^{no\text{-}z}$ 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 Range	$\left\lvert \frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta} \right\rvert$ 0 – 2.5	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta d p_T}$ 0.1 – 50 GeV	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$ 2 – 250	$\langle p_T \rangle$ vs. n_{ch} 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].

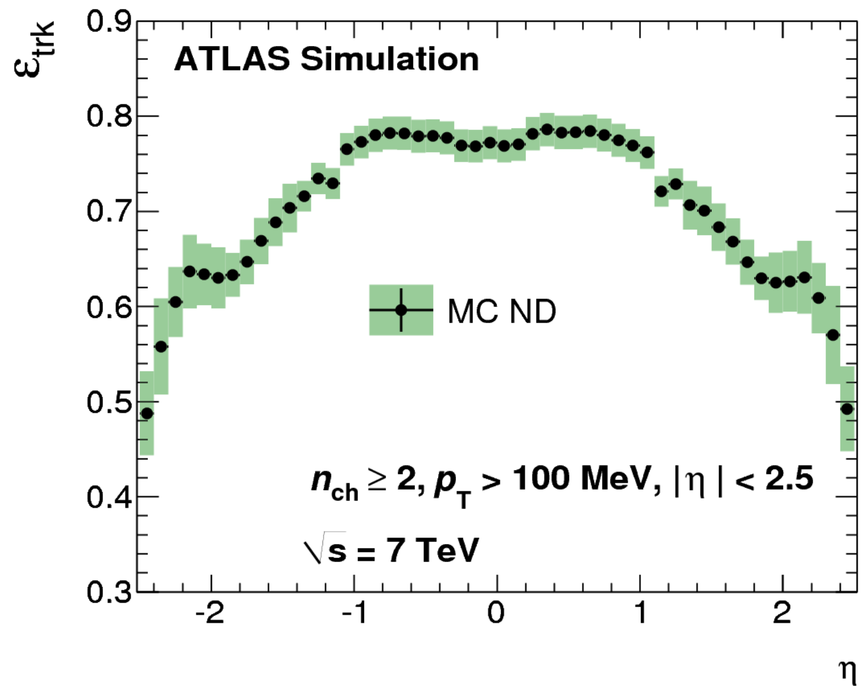
  An alternative tune, Monash [10], is used for comparison. It uses updated fragmentation parameters compared to A2 and minimum-bias, Drell-Yan, and underlying-event data from the LHC to constrain ISR and MPI parameters. In addition, it uses SPS and Tevatron data to constrain the energy scaling. It uses 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

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



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!

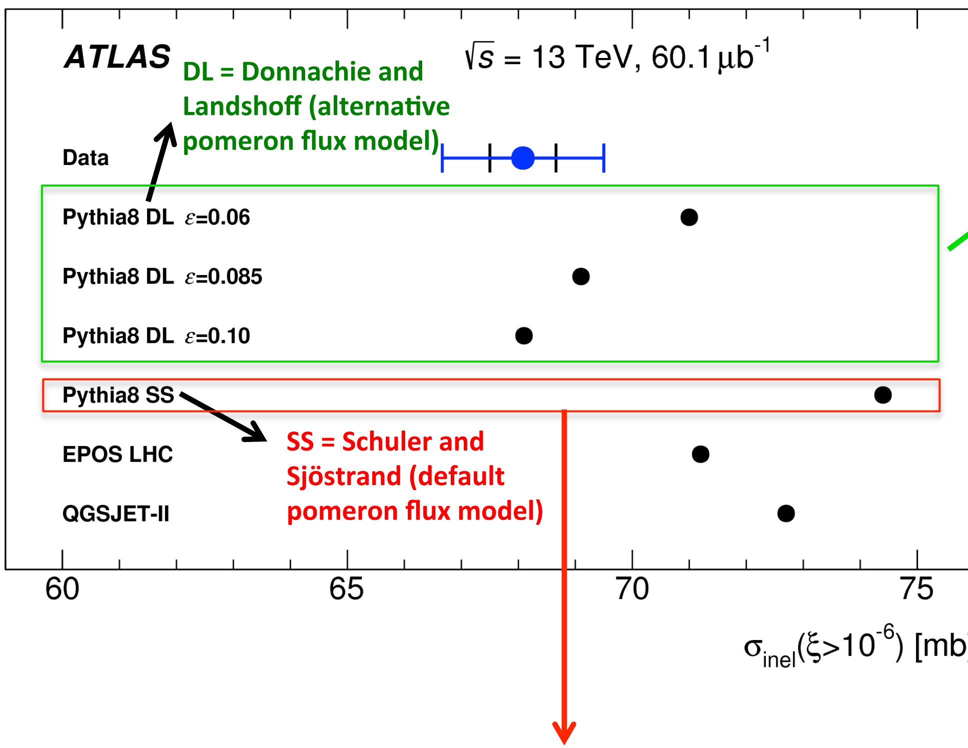
Track Reconstruction Efficiency Correction

$$\Delta\epsilon_{\text{trk}}^{PixServCorrection} = \frac{\Delta\epsilon_{\text{trk}}^{\text{mod}-\text{nom}}}{\Delta N_{\lambda_I}^{\text{mod}-\text{nom}}} \cdot \Delta N_{\lambda_I}^{\text{Data}-\text{MC}}.$$

The Context – Inelastic cross-section

- Primary MC samples for inelastic cross-section measurements are based on the Pythia 8 generator either with the A2 tune and the MSTW 2008 LO PDF set or with the Monash tune and the NNPDF 2.3 LO PDF set (same tunes as for MinBias)

In the DL model, the Pomeron Regge trajectory is given by $\alpha(t)=1+\varepsilon+\alpha' t$ with ε and α' free parameters. Default value (0.25) was used for α', but different values (from 0.06 to 0.10) were used for ε



DL models are all giving predictions compatible with the data (the best one being DL with ε=0.10)

SS model predicts 74.4 mb, and thus exceeds the measured value by ~ 4 σ

The Idea Behind Pythia8 - A3

- Summarising what shown in the previous slides:

  - ATLAS used Run 1 data at the center-of-mass energy of 7 TeV to tune Pythia's MPI parameters → **A2 tune for MB & pile-up event simulation**

  - **Reasonably good description of the ATLAS Run 2 charged particle distributions**, but overestimation of **the fiducial inelastic cross-section** compared to the ATLAS measurements **at both √s= 7 and 13 TeV**

  - <μ> in simulation reweighted to match data
    - rescaling factor (driven by the fraction of the visible cross section wrt the total inelastic cross section for data and for MC) of 1.11 with large uncertainties

- In this scenario, the idea was to try and get **an improved tune** which better **describes the visible inelastic cross-section** by still **giving good predictions of the charged particle distributions**…

Pythia8 - A3

- **Pythia 8** (v. 8.186) with PDFs taken from LHAPDF version 6.1.3
- **Rivet** Analysis Toolkit (v. 2.4.1)
- **PROFESSOR** MC tuning system (v. 1.4.beta)
- Many parameters used for the tuning, each of them evaluated in a sampling range
- Starting point is **Monash** :
  - The parameters not mentioned here are left unchanged wrt Monash
  - But… two important aspects changed:
    - **Double Gaussian profile with 2 free parameters** used in place of the exponential overlap function used by Monash
    - **DL diffraction model** used in place of the SS model used in Monash (and in all the others Pythia tunes)

Parameter	Sampling range		
MultipartonInteractions:pT0Ref	1.00	–	3.60
MultipartonInteractions:ecmPow	0.10	–	0.35
MultipartonInteractions:coreRadius	0.40	–	1.00
MultipartonInteractions:coreFraction	0.50	–	1.00
BeamRemnants:reconnectRange	0.50	–	10.0
Diffraction:PomFluxEpsilon	0.02	–	0.12
Diffraction:PomFluxAlphaPrime	0.10	–	0.40

DL models has two tunable parameters, which control the Pomeron Regge trajectory

Pythia8 - A3

- A wide range of analyses used for the tuning

$\sqrt{s}$	Measurement type	Rivet name
13 TeV	MB	ATLAS_2016_I1419652 [3]
13 TeV	INEL XS	MC_XS [5]
7 TeV	MB	ATLAS_2010_S8918562 [11]
7 TeV	INEL XS	ATLAS_2011_I89486 [4]
7 TeV	RAPGAP	ATLAS_2012_I1084540 [15]
7 TeV	ETFLOW	ATLAS_2012_I1183818 [14]
900 GeV	MB	ATLAS_2010_S8918562 [11]
2.36 TeV	MB	ATLAS_2010_S8918562 [11]
8 TeV	MB	ATLAS_2016_I1426695 [16]

Not directly used for the tuning, but compared with A3 after the tuning

Pythia8 - A3: Tuning Strategy

- New approach:
  - PROFESSOR was used in the past to parameterise each bin of each observable as a N-dimensional 3rd order polynomial (N being the number of tuned parameters). The χ^2 wrt the reference data was then minimised;
  - Now:
    1. Generate soft QCD inelastic *pp* events
    2. Tune to the MB observables first (only measurements available at many √s)
    3. Add other measurements and check effects on parameters
    4. Tune everything together and ensure things look reasonable
    5. Pick-up the values which give the best results compared to data

Parameter	Observation from Step 2	Observation from Step 3
`MultipartonInteractions:pT0Ref`	Within 2.4 and 2.5	-
`MultipartonInteractions:ecmPow`	Fixed at 0.21	Fixed at 0.21
`MultipartonInteractions:coreRadius`	Poorly constrained	Around 0.5
`MultipartonInteractions:coreFraction`	Poorly constrained	Poorly constrained
`BeamRemnants:reconnectRange`	Around 6 or between 1.5 to 2	Between 1.5 to 2
`Diffraction:PomFluxEpsilon`	Not constrained	Between 0.055 and 0.075
`Diffraction:PomFluxAlphaPrime`	Not constrained	0.25

Pythia8 - A3: Final Tune

- Weight files containing all available measurements at all centre-of-mass energies constructed to be used in Professor framework
- Final parameters chosen to get the best description of MB observables at $\sqrt{s}$ = 13 TeV
  - Not dramatic disagreement with MB distributions at lower $\sqrt{s}$
- It was controlled that Diffraction:PomFluxEpsilon parameter was within an appropriate range to get a description of the inelastic cross section

Parameter	A3 value	A2 value	Monash value
`MultipartonInteractions:pT0Ref`	2.45	1.90	2.28
`MultipartonInteractions:ecmPow`	0.21	0.30	0.215
`MultipartonInteractions:coreRadius`	0.55	-	-
`MultipartonInteractions:coreFraction`	0.90	-	-
`MultipartonInteractions:a1`	-	0.03	-
`MultipartonInteractions:expPow`	-	-	1.85
`BeamRemnants:reconnectRange`	1.8	2.28	1.8
`Diffraction:PomFluxEpsilon`	0.07 (0.085)	-	-
`Diffraction:PomFluxAlphaPrime`	0.25 (0.25)	-	-

Pythia8 Tunes Comparison

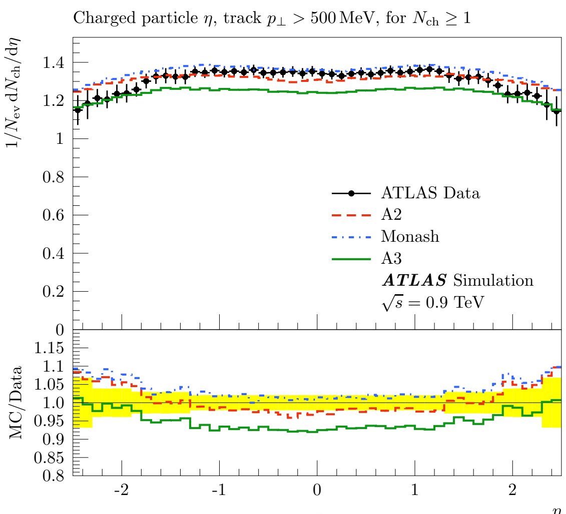
Wrt other tunes based on SS diffraction model:

- **Better description of the Fiducial Inelastic Cross section**

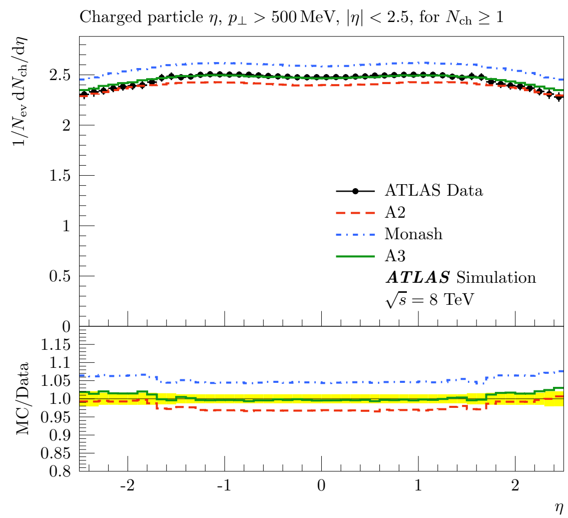
	ATLAS data (mb)	SS (mb)	A3 (mb)
At $\sqrt{s}$ = 13 TeV	68.1 ± 1.4	74.4	69.9
At $\sqrt{s}$ = 7 TeV	60.3 ± 2.1	66.1	62.3

- **Better description of charged particles η distributions at the highest centre-of-mass energy**

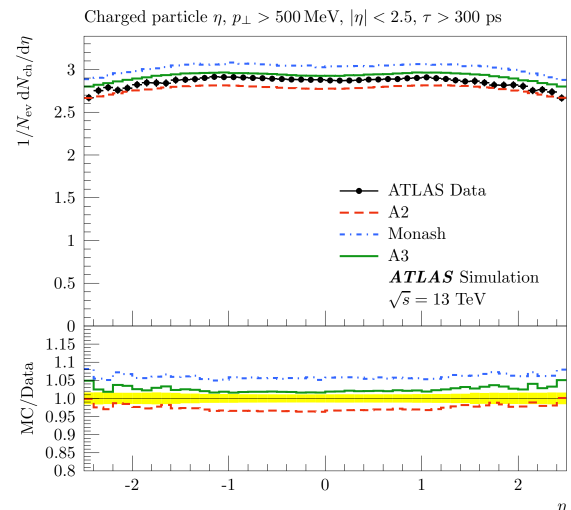
0.9 TeV



8 TeV



13 TeV



A3 underestimates the data at 0.9 TeV, but the focus of the study is the pile-up simulation at 13 TeV, thus this effect is negligible

Very good description by A3!

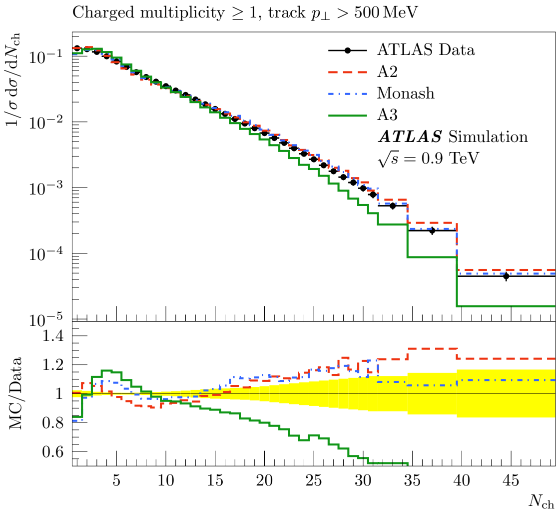
N.B. Distributions for every √s are in back-up

ATL-PHYS-PUB-2016-017

Pythia8 Tunes Comparison

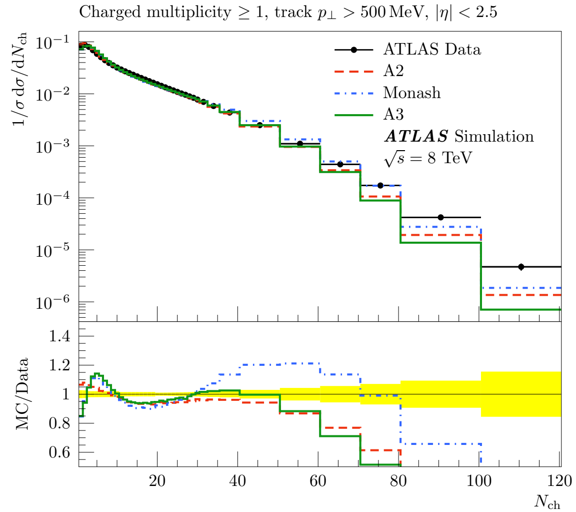
- **Charged particles multiplicity** predicted with a similar level of agreement by all generators at all √*s*, except at 0.9 TeV

0.9 TeV



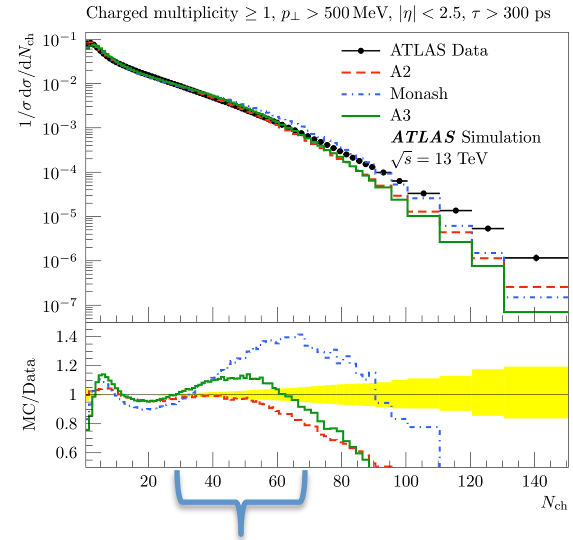
Not very good predictions given by A3 at the lowest √*s*

8 TeV



Shape of A3 prediction similar at all √*s*

13 TeV



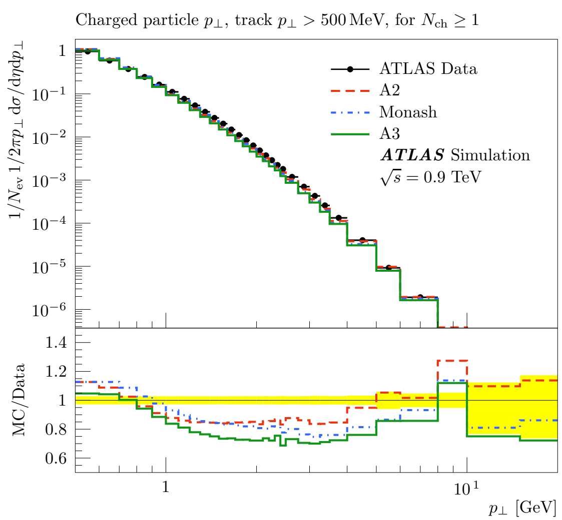
A2 describes the multiplicity better than A3

N.B. Distributions for every √*s* are in back-up

Pythia8 Tunes Comparison

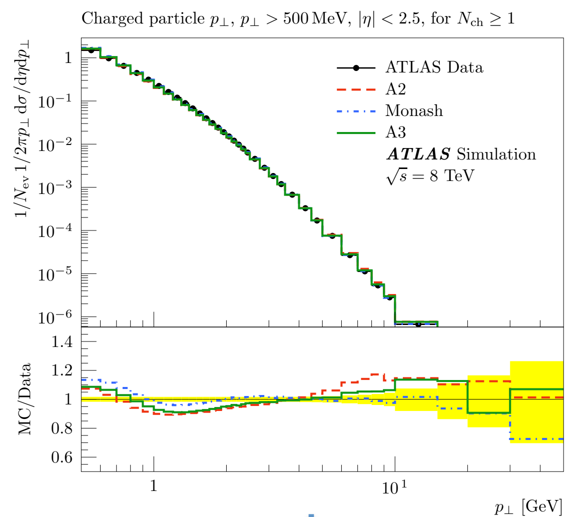
- **Charged particles p_T** predicted similarly by A3 and Monash

0.9 TeV



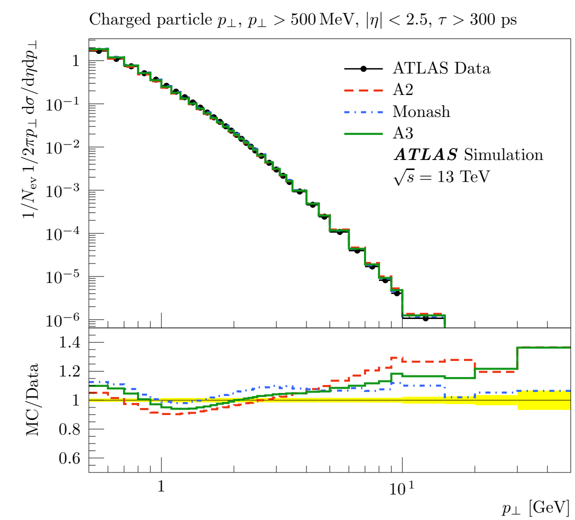
Not very good predictions given by A3 at the lowest √*s*

8 TeV



Similar predictions by all generators

13 TeV

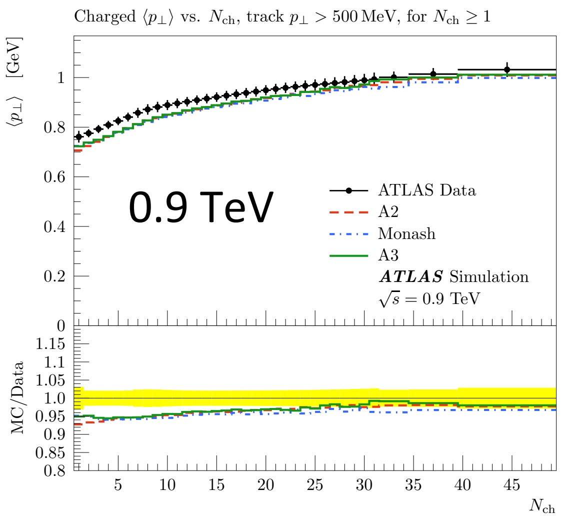


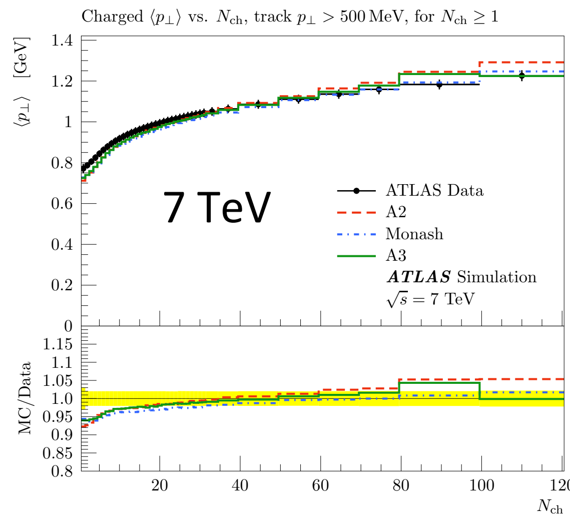
A3 describes the p_T spectrum better than A2

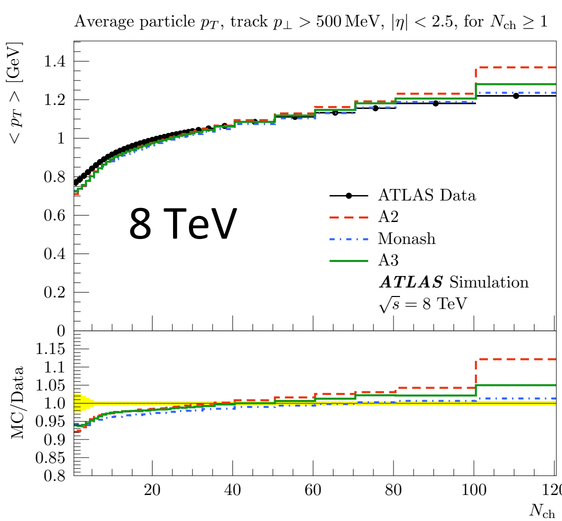
N.B. Distributions for every √*s* are in back-up

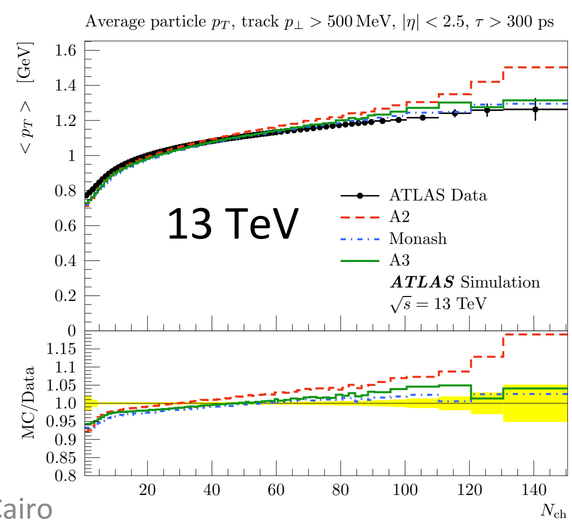
Pythia8 Tunes Comparison

- **Charged particles <p_T> vs multiplicity:** the choice of lower colour reconnection strength (*BeamRemnants:reconnectRange* = 1.8 in A3 and Monash, 2.28 in A2) led to slight improvement over A2









Pythia8 Tunes Comparison

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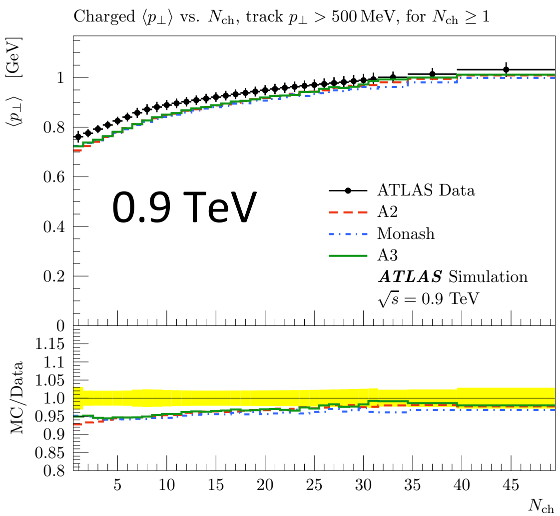
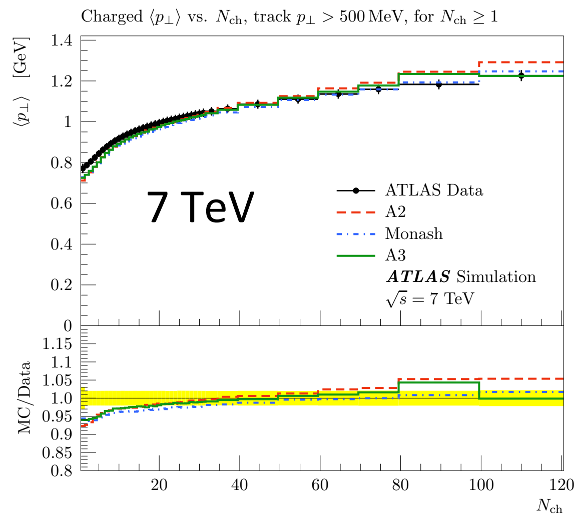
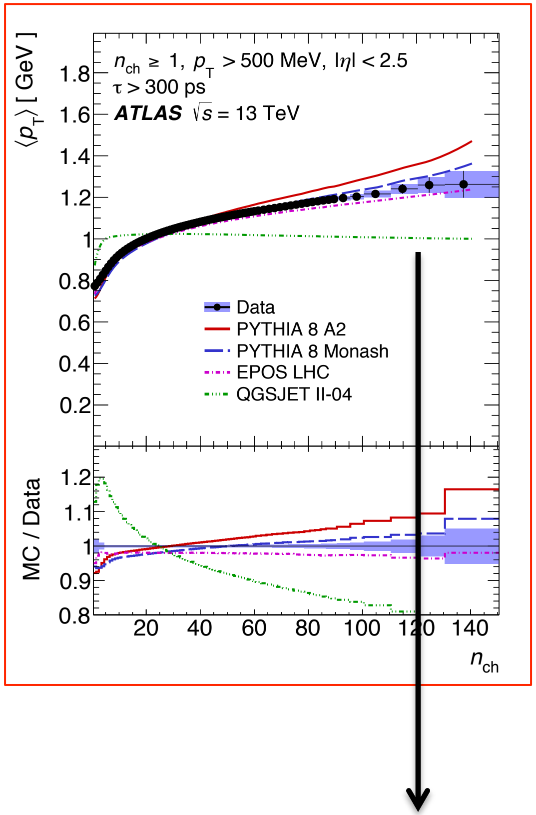
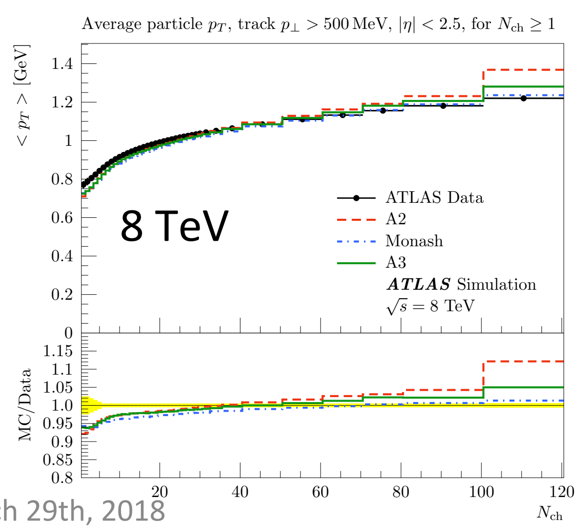
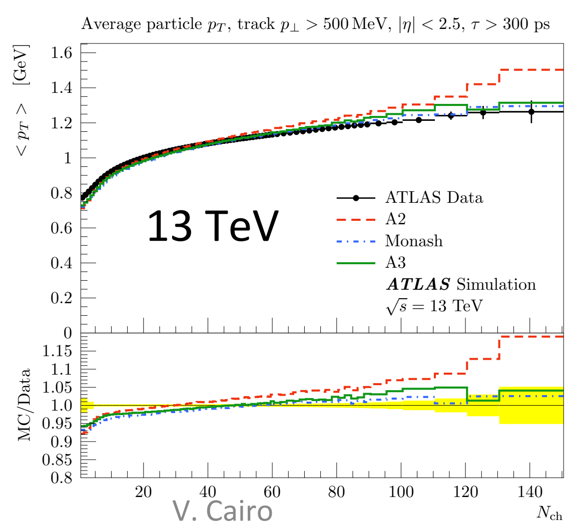






QGCJET has no colour reconnection

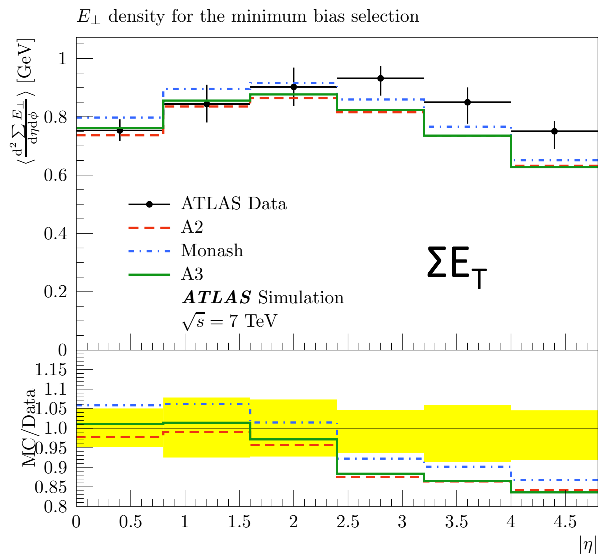


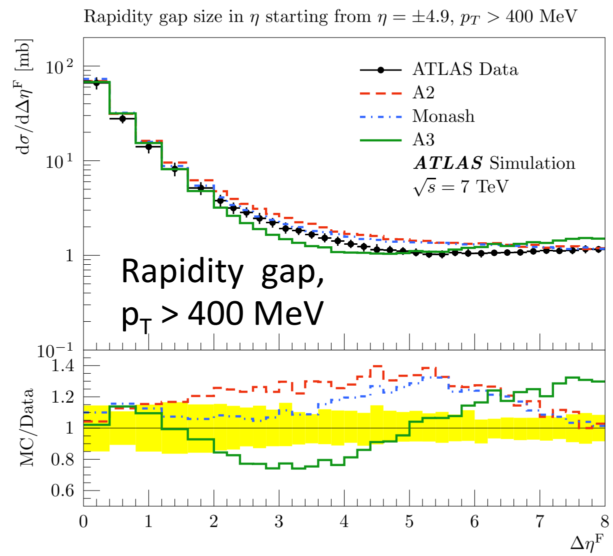


Pythia8 Tunes Comparison

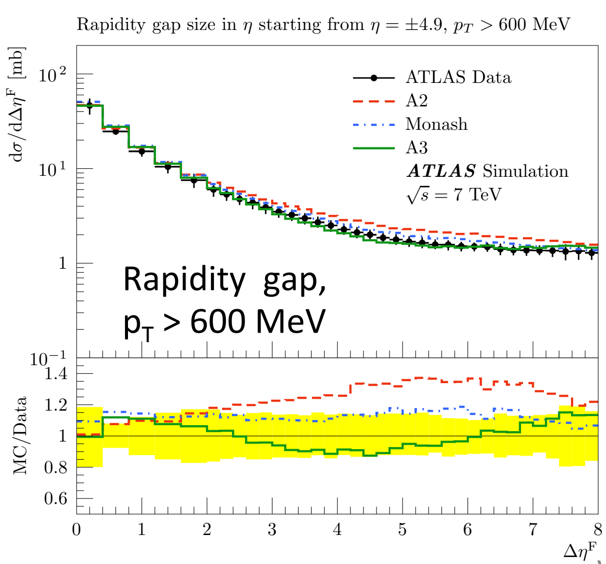
- **Transverse Energy Flow and Rapidity Gap distributions at 7 TeV**

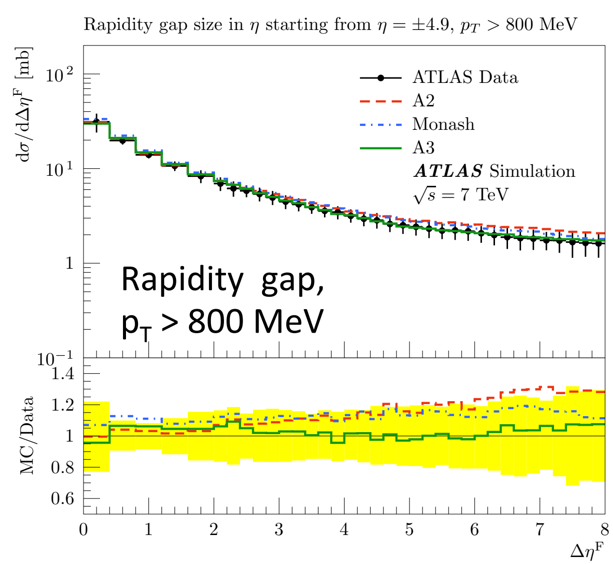
Good predictions given by A3 in the first bins





Good predictions given by A3 at high p_T, low p_T dominated by diffraction





Summary of Pythia 8 - A3

- **Features of A3:**

  - Aimed at modeling low-p_T QCD processes at the highest energies
  - Different diffraction model wrt other tunes (DL vs SS)
  - Early ATLAS Run 2 soft-QCD results at 13 TeV added in the tuning

- **Performance:**

  - Predictions of inelastic cross-sections closer to the measured values
  - Reasonable predictions of charged particles distributions

- **Message to take away:**

  - Acceptable description of data can be achieved by using the Donnachie-Landshoff model for diffraction
  - Possible starting point for further systematic studies of soft-QCD tunes
  - An improved and more reliable simulation of pile-up overlay can be obtained

Now moving to something else…