Monte Carlo tuning for Multiple Parton Interactions from the ATLAS data

Valentina Cairo

On behalf of the ATLAS collaboration

University of Calabria & CERN

Outline

The modelling of Minimum Bias (MB) and Underlying Event (UE) is a crucial component in the description of soft QCD processes:

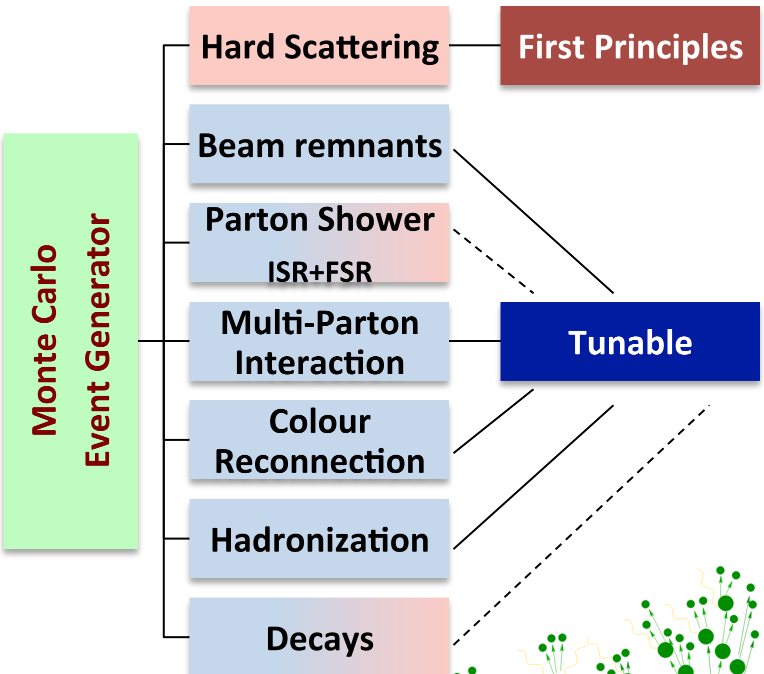
- Both described by multi-parton interactions (MPI) models
  - MPI: results of proton collisions containing more than one partonic interaction due to collective and beam remnant effects.

In this talk, the focus will be on:

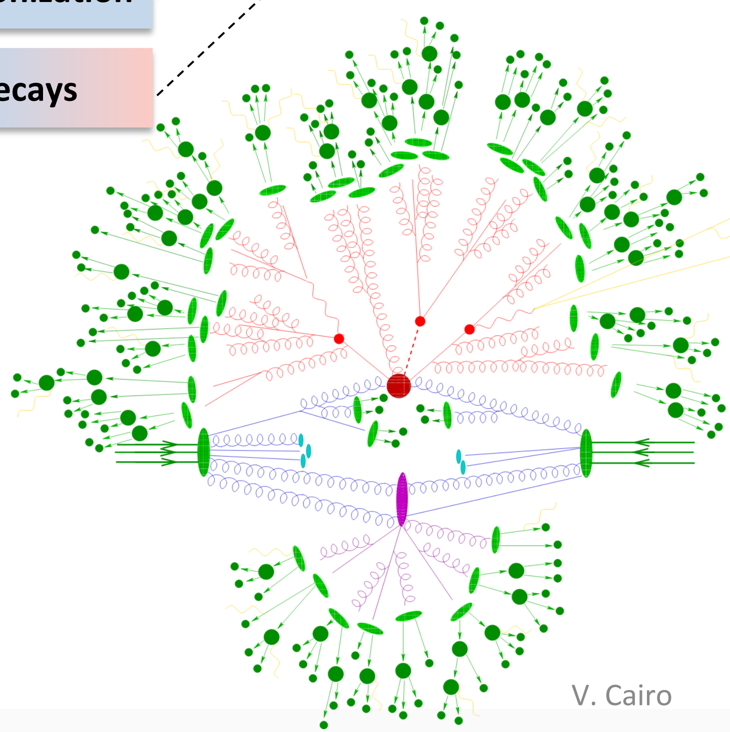
- Quick overview of charged particle multiplicities, inelastic cross section, underlying events (details on MB, cross-sections and UE are given respectively in Jiri's, Christian's and Robert's talks)

- Results of tunes of the Pythia8 MPI parameters to recent ATLAS measurements at 7, 8 and 13 TeV. Tuning in presence of matching with leading and next-to-leading matrix elements are also presented.
  → Pythia A3 (ATL-PHYS-PUB-2016-017)
  → MADGRAPH5_AMC@NLO+Pythia8 (ATL-PHYS-PUB-2015-048)

Monte Carlo Tuning



- Monte Carlo generators used to simulate events in High Energy Physics and other applications
- ATLAS uses **Pythia 8** as a Monte Carlo Event Generator for many purposes
  - Main generator used to simulate **pile-up:** Accurate description is fundamental because it impacts the reconstruction of many physics objects, such as jets, photons, electrons and missing transverse energy

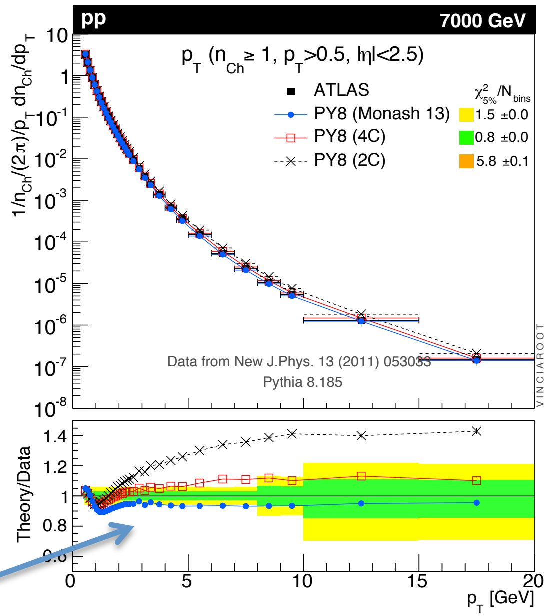


- Pile-up dominated by events with **low momentum transfer**
  - Generally described by **phenomenological models**
    - Models steered by **tunable parameters**
    - Need to be **constrained with data → MC Tuning (parameter set = tune)**

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** (MSTW2008LO 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**
    - 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

The Context – Minimum Bias

Unfolded data compared to the following set of Monte Carlo Generators and Tunes in the most recent charged particle measurements:

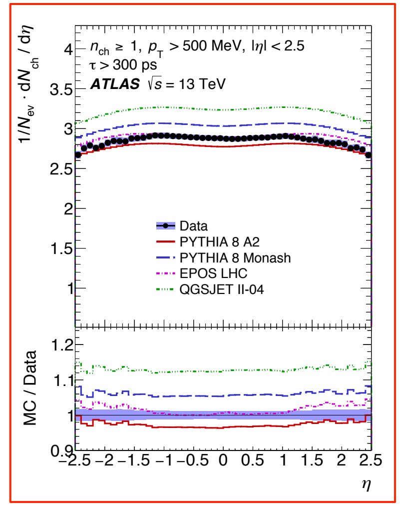
- PYTHIA 8 A2
- PYTHIA 8 Monash
- EPOS LHC
- QGSJET II-04

Generator	Version	Tune	PDF
PYTHIA 8	8.185	A2	MSTW2008LO [17]
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [18]
EPOS	LHCv3400	LHC	N/A
QGSJET-II	II-04	default	N/A

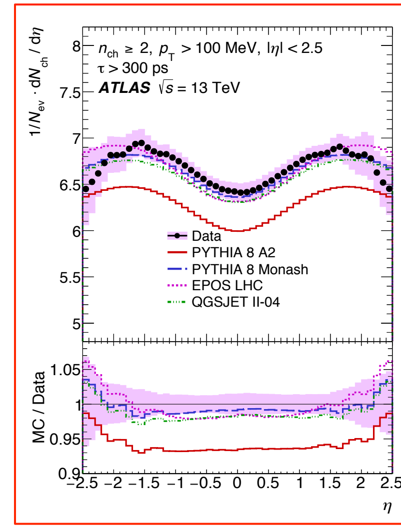
Best predictions given by EPOS (particularly in the low p_T regime), but Pythia 8 – A2 and Monash give reasonable results…

13 TeV

500 MeV

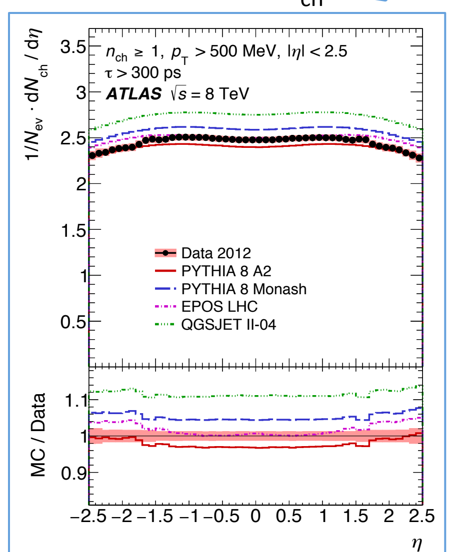


100 MeV

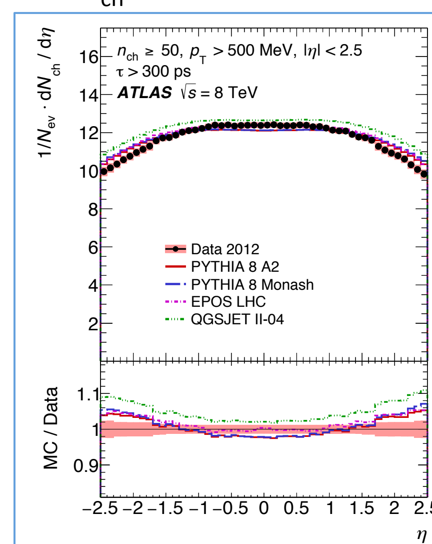


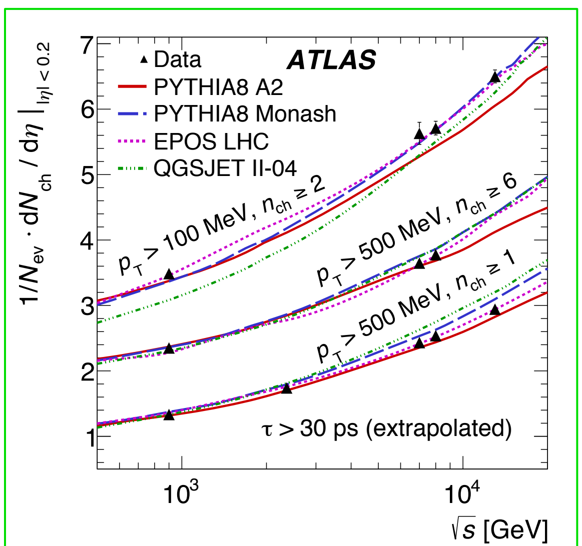
8 TeV

1 n_{ch}



50 n_{ch}

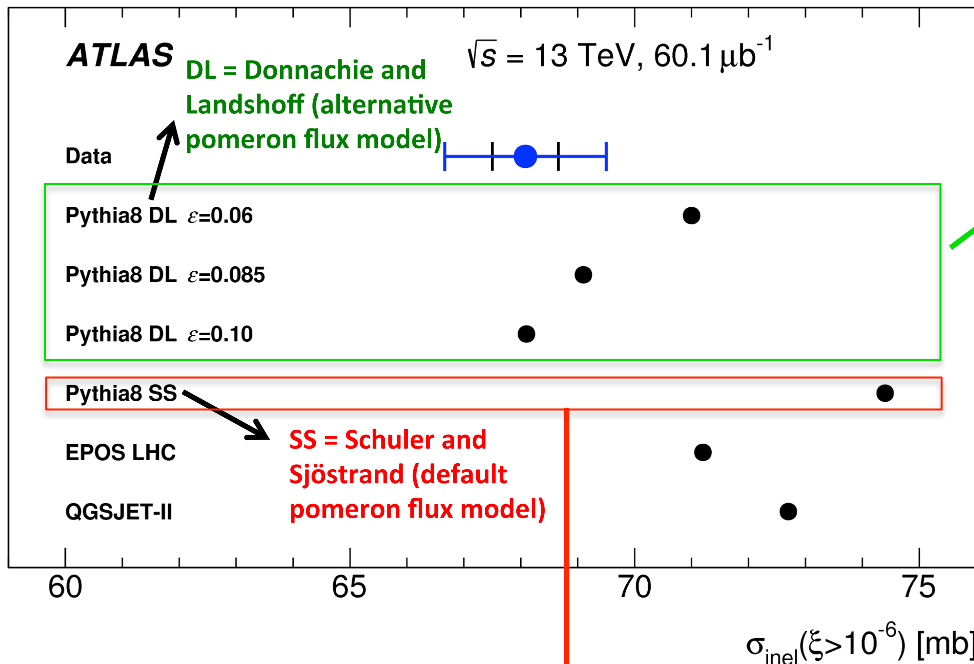




The Context – Inelastic cross-section

- 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 $\sqrt{s}$= 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 $\sqrt{s}$)
    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

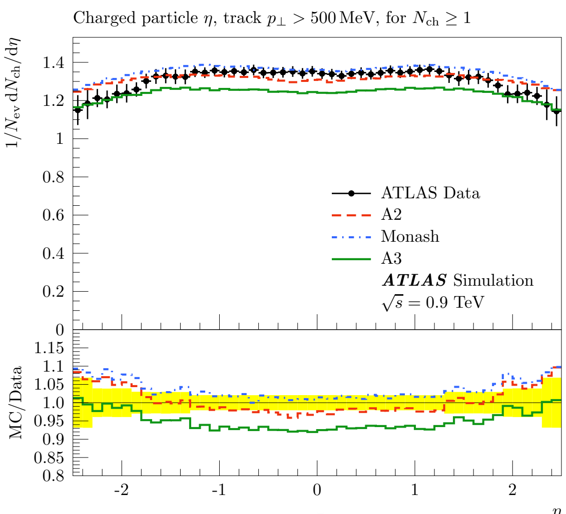
Wrt other tunes based on SS diffraction model:

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

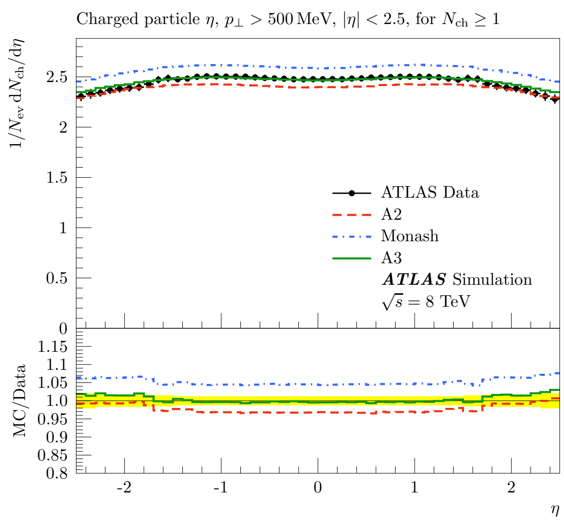
	ATLAS data (mb)	SS (mb)	A3 (mb)
At $\sqrt{s}$ = 13 TeV	68.1 ± 1.4	74.4	69.9
At $\sqrt{s}$ = 7 TeV	60.3 ± 2.1	66.1	62.3

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

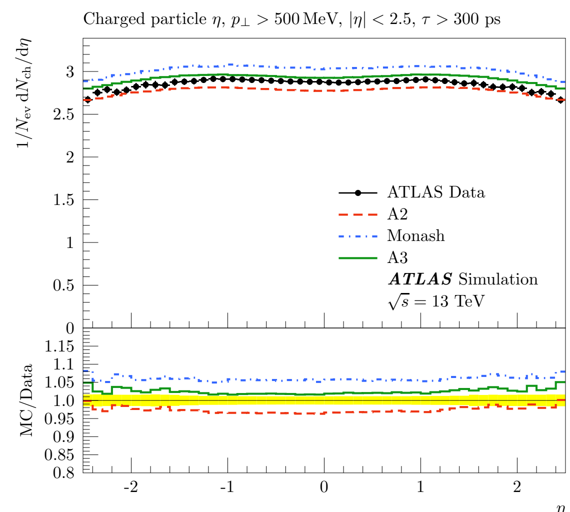
0.9 TeV



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

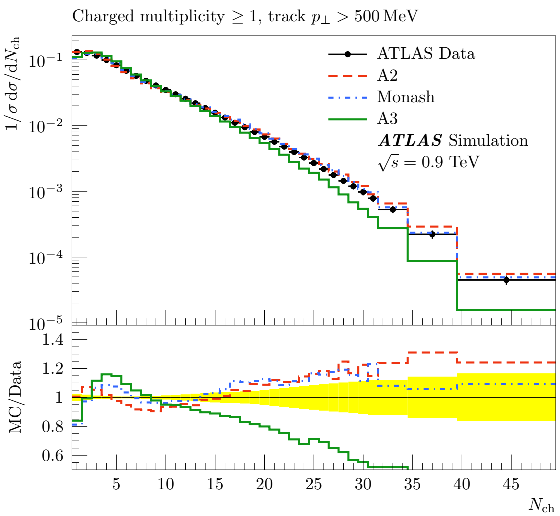
Very good description by A3!

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

Pythia8 Tunes Comparison

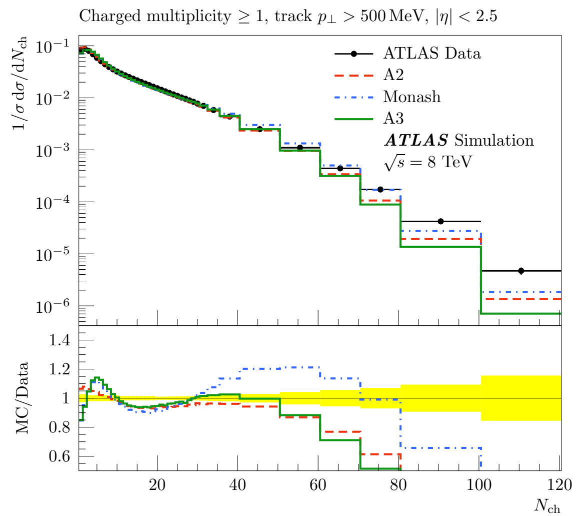
- **Charged particles multiplicity** predicted with a similar level of agreement by all generators at all √*s*, except at 0.9 TeV

0.9 TeV



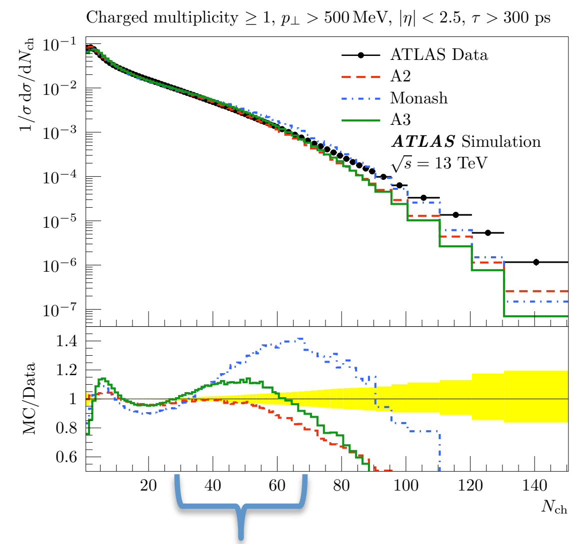
Not very good predictions given by A3 at the lowest √*s*

8 TeV



Shape of A3 prediction similar at all √*s*

13 TeV



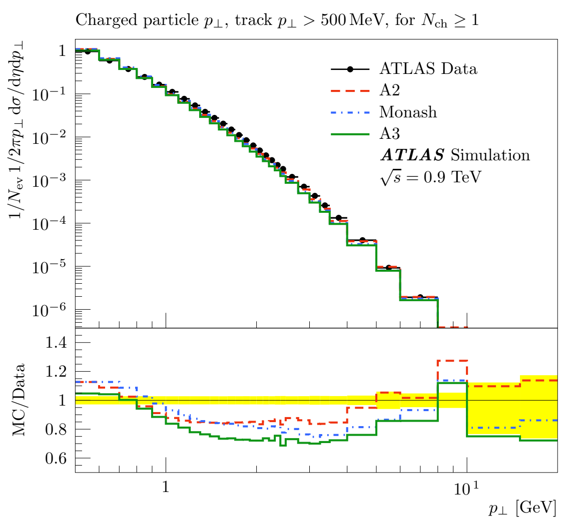
A2 describes the multiplicity better than A3

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

Pythia8 Tunes Comparison

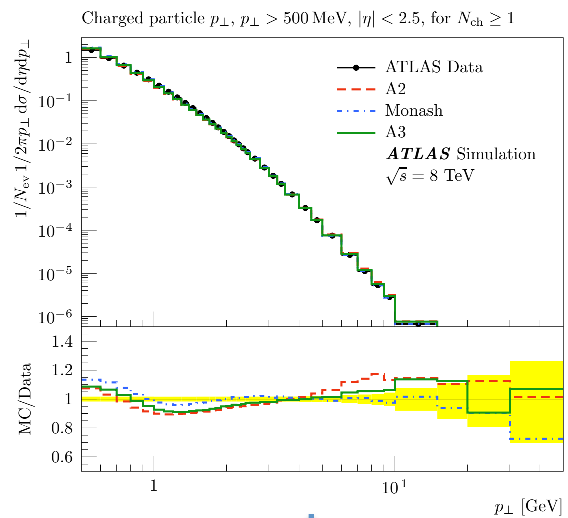
- **Charged particles p_T** predicted similarly by A3 and Monash

0.9 TeV



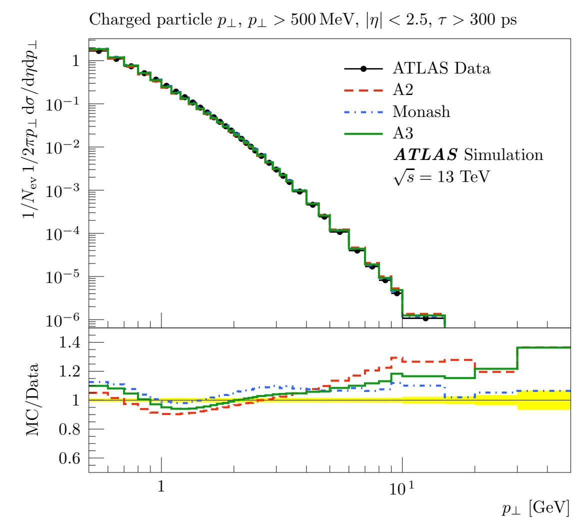
Not very good predictions given by A3 at the lowest √*s*

8 TeV



Similar predictions by all generators

13 TeV

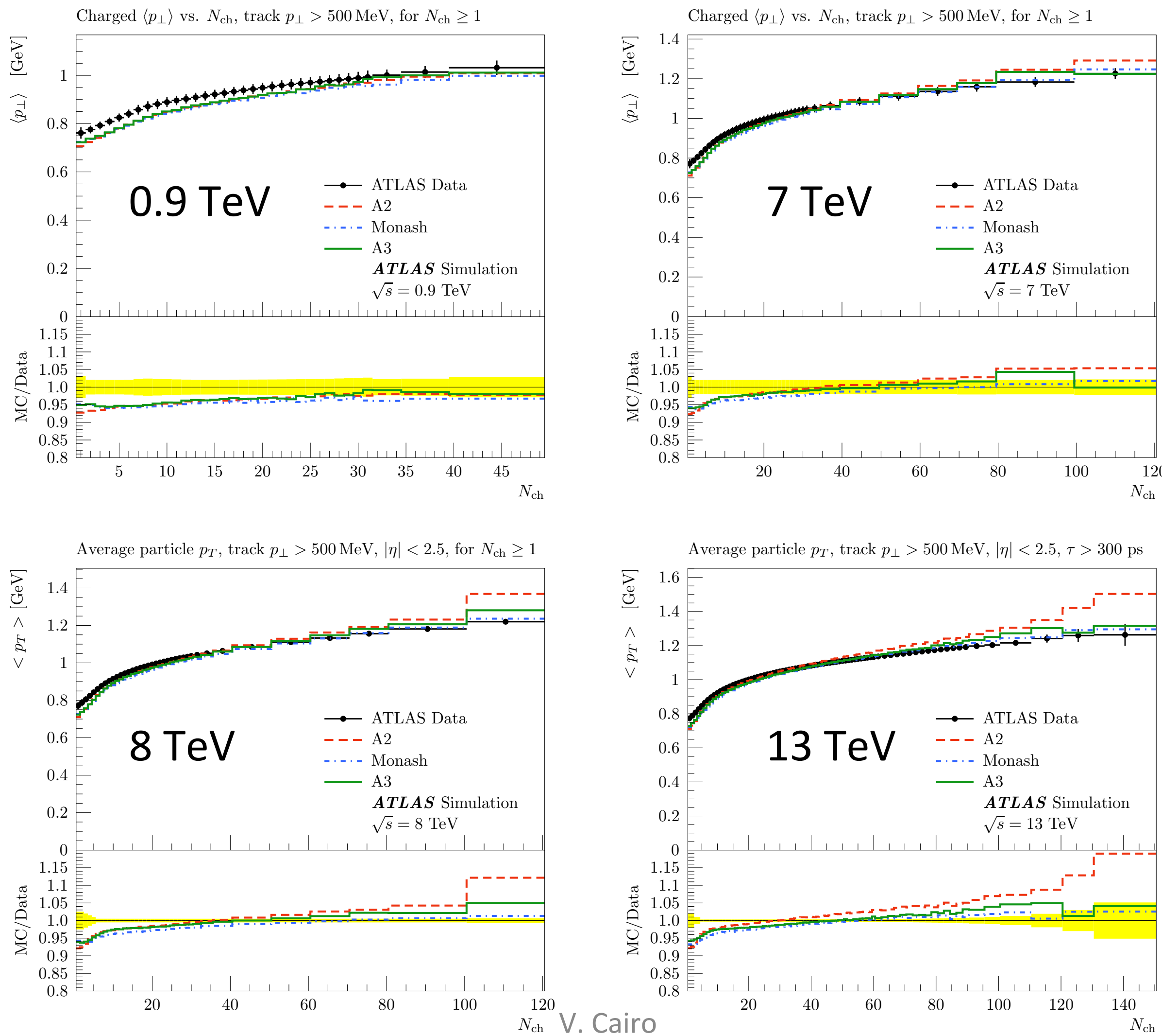


A3 describes the p_T spectrum better than A2

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

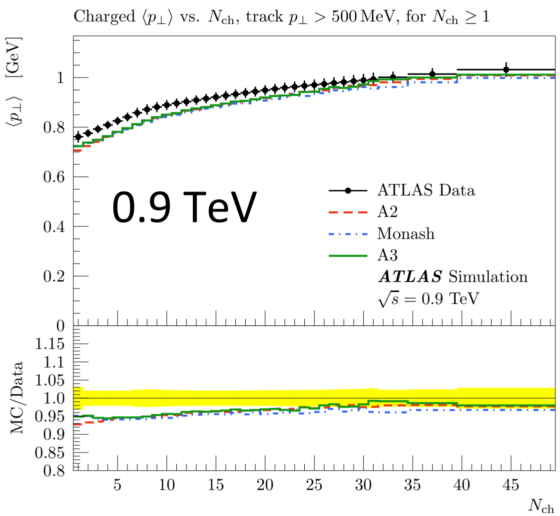
Pythia8 Tunes Comparison

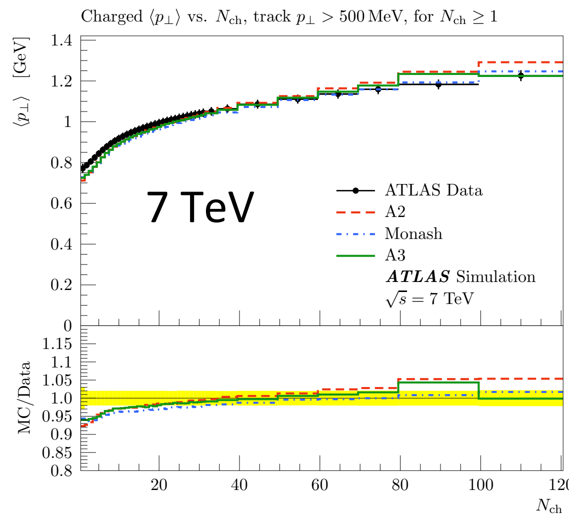
- **Charged particles <p_T> vs multiplicity:** the choice of lower colour reconnection strength (*BeamRemnants:reconnectRange* = 1.8 in A3 and Monash, 2.28 in A2) led to slight improvement over A2

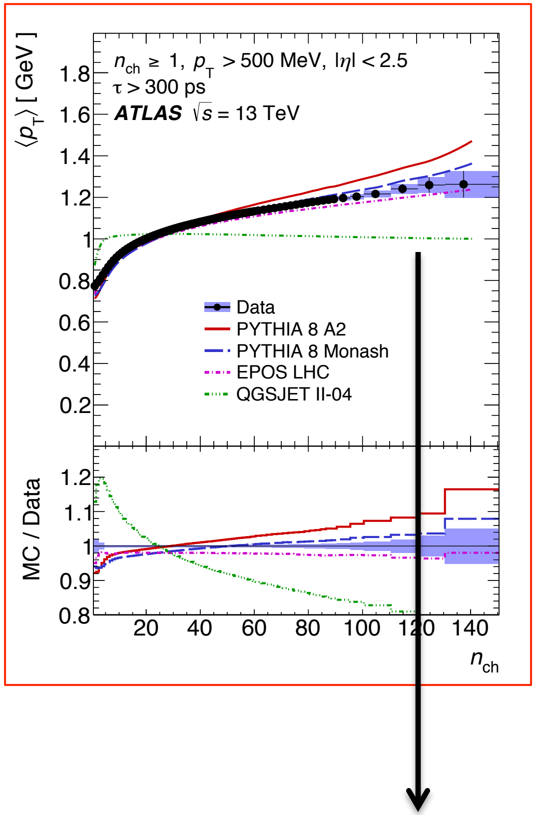


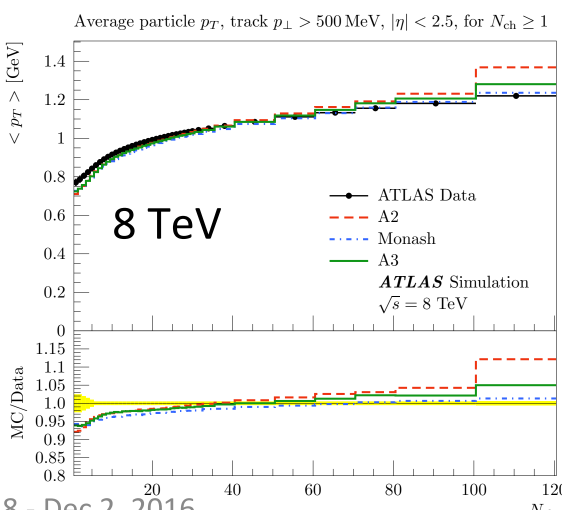
Pythia8 Tunes Comparison

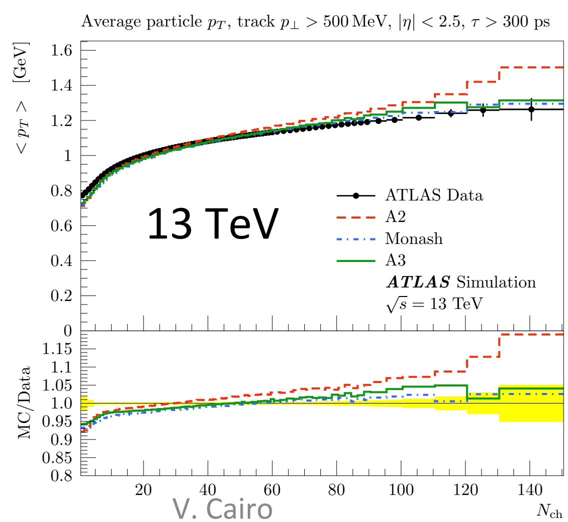
- **Charged particles <p_T> vs multiplicity:** the choice of lower colour reconnection strength (*BeamRemnants:reconnectRange* = 1.8 in A3 and Monash, 2.28 in A2) led to slight improvement over A2









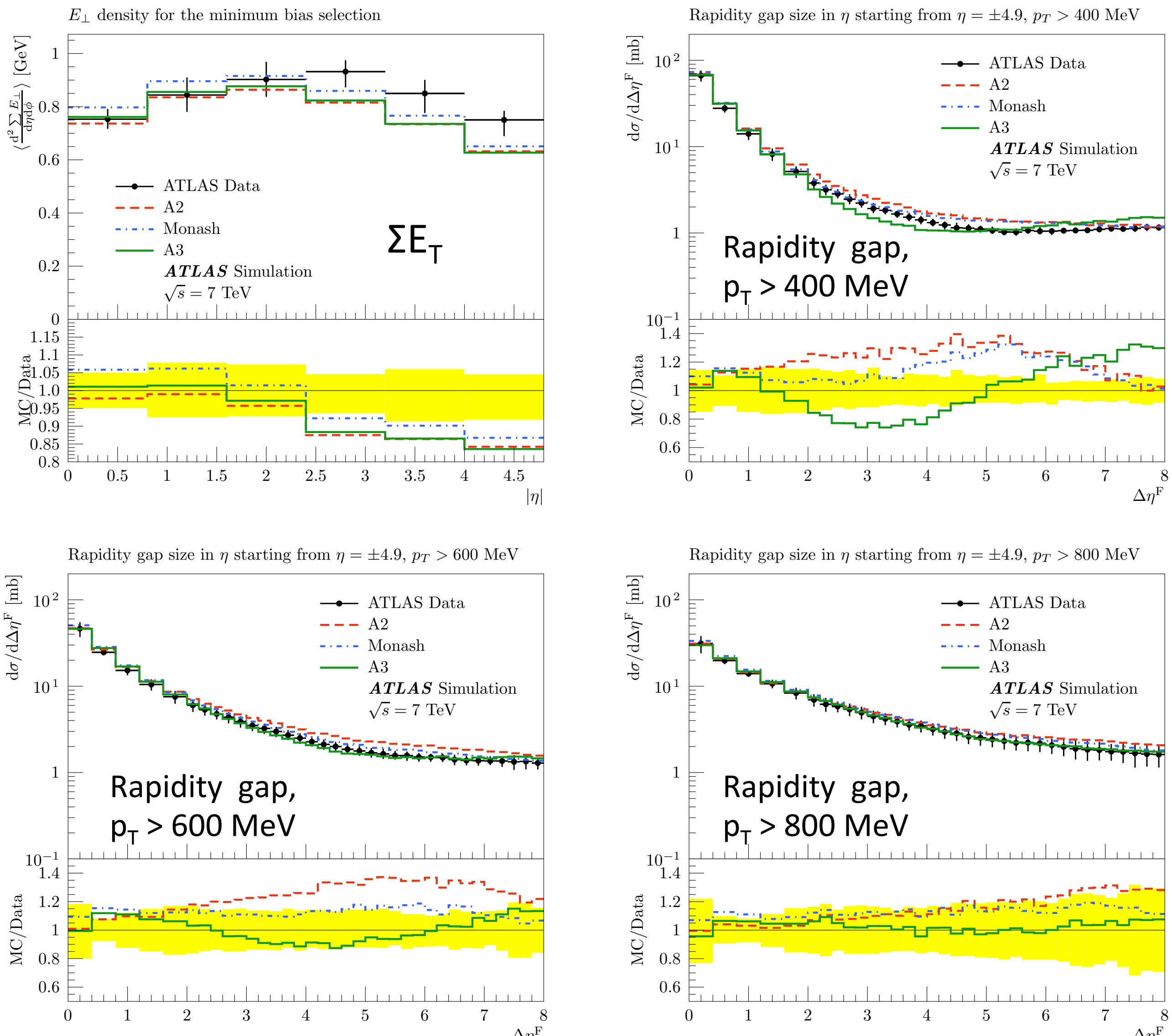


QGCJET has no colour reconnection

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

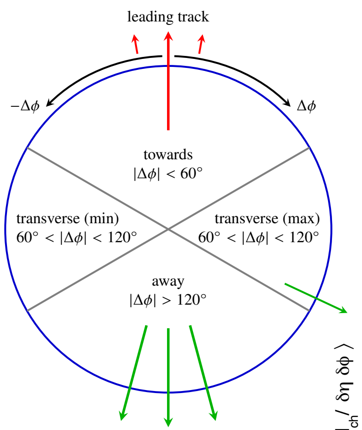
- **Message to take away:**

  - 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…

Underlying Event

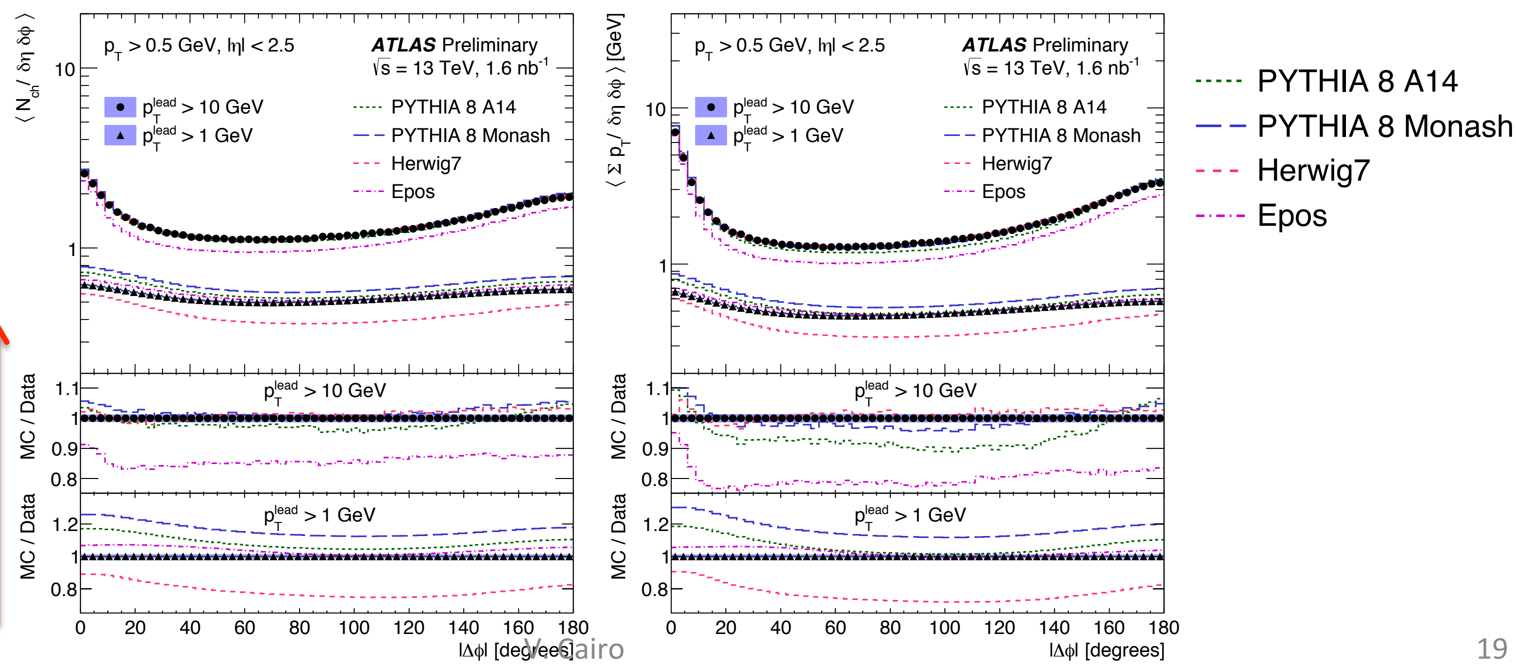
- UE gets contributions from **ISR/FSR**, from the QCD evolution of **colour connections** between the hard scattering and the beam-proton remnants and from **MPI**
  - Significantly influenced by physics not currently calculable from first principles
- Crucial measurements to provide input for empirical tuning of the free parameters of phenomenological UE models in MC event generators → **A14** used as a baseline



ATLAS' dedicated underlying event tune (A14 = ATLAS 2014)
Largely described in last year ATLAS MPI talk

UE at 13 TeV

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



p_T

transition from relatively isotropic minimum-bias scattering to the emergence of hard partonic scattering structure and a dominant axis of energy flow

MADGRAPH5_AMC@NLO+Pythia8

Parton Shower & MPI tune with NLO ME attachment

- Already described in last year ATLAS MC Tuning talk during this same conference, but mentioned again here for completeness
- Tune based on **ATLAS Run 1 data at 7 TeV** for three different inclusive processes:
  - **Jets, Z-boson, ttbar production**
- 2 tunes
  - **A15-MG5aMCNLO-TTBAR** → applicable only for ttbar processes
  - **A15-MG5aMCNLO** → applicable in general for all processes
- 2 PDFs used
  - CT10 used for MG5_aMC@ NLO (NLO PDF)
  - NNPDF23LO for Pythia 8.186 (LO PDF)
- 7 parameters (3 categories: **α strong at the Z-boson mass and infrared cutoffs for ISR, FSR and MPI**, and the **primordial transverse momentum**) tuned
- Other parameters left unchanged from **A14**, which was based on Monash

Parameter	Pythia8 settings	Definition	Sampling range
$p_{\mathrm{T0,Ref}}^{\mathrm{ISR}}$ [GeV]	`SpaceShower:pT0Ref`	ISR p_{T} cutoff	0.75 – 2.5
α_S^{ISR}	`SpaceShower:alphaSvalue`	ISR α_S	0.115 – 0.140
$p_{\mathrm{T,min}}^{\mathrm{FSR}}$ [GeV]	`TimeShower:pTmin`	FSR p_{T} cutoff	0.5 – 2.0
α_S^{FSR}	`TimeShower:alphaSvalue`	FSR α_S	0.115 – 0.15
$p_{\mathrm{T0,Ref}}^{\mathrm{MPI}}$ [GeV]	`MultipartonInteractions:pT0Ref`	MPI p_{T} cutoff	1.5 – 3.0
α_S^{MPI}	`MultipartonInteractions:alphaSvalue`	MPI α_S	0.115 – 0.140
P. $k_{\mathrm{T,hard}}$ [GeV]	`BeamRemnants:primordialKThard`	Hard interaction primordial $k_{\perp}$	1.5 – 2.0

MADGRAPH5_AMC@NLO+Pythia8

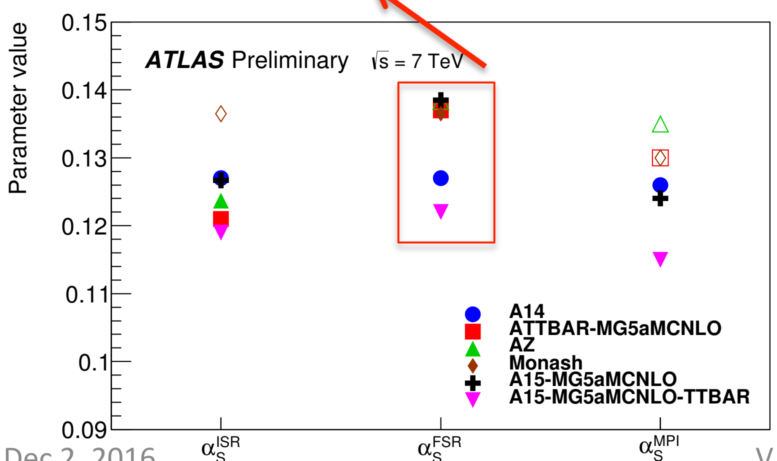
Global tune of PS+MPI using Z, ttbar and jets events

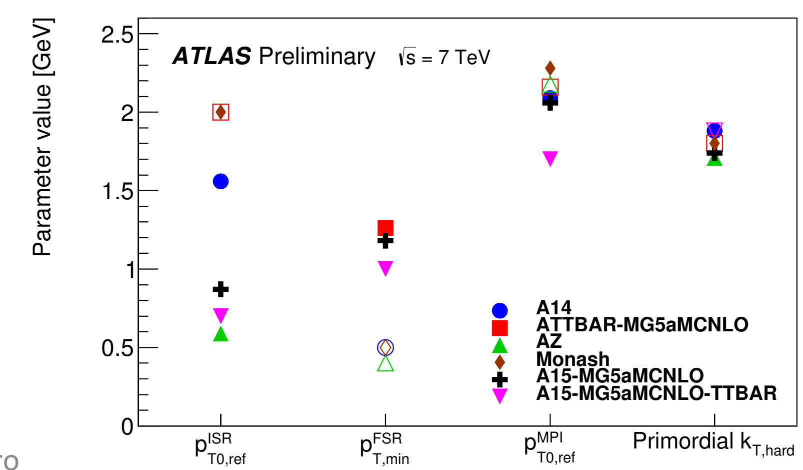
ATTBAR-MG5aMC@NLO+Pythia8 tune (Local Recoil), in ATTBAR optimised ISR and FSR using ttbar at 7 TeV, adjusted MPI p_T cut off using Z-boson underlying event at 7 TeV

Pythia 8 standalone tune of ISR and MPI at low p_T^Z (PS effects dominate) → necessary for precision electroweak measurements

Parameter	A14	ATTBAR	AZ	A15-MG5aMCNLO	A15-MG5aMCNLO-TTBAR
α_S^{FSR}	0.127	0.137	(0.1383)	0.1385	0.122
$p_{T,min}^{FSR}$ [GeV]	(0.5)	1.26	(0.4)	1.18	1.0
α_S^{ISR}	0.127	0.121	0.1237	0.1267	0.119
$p_{T0,Ref}^{ISR}$ [GeV]	1.56	(2.0)	0.59	0.87	0.7
α_S^{MPI}	0.126	(0.130)	(0.135)	0.124	0.115
$p_{T0,Ref}^{MPI}$ [GeV]	2.09	(2.16)	(2.18)	2.06	1.7
P. $k_{T,hard}$ [GeV]	1.88	(1.8)	1.71	1.74	(1.88)
R. range	1.71	(1.8)	(1.5)	(1.71)	(1.71)

α_S^{FSR} smaller in A14, restored to the LEP value in A15

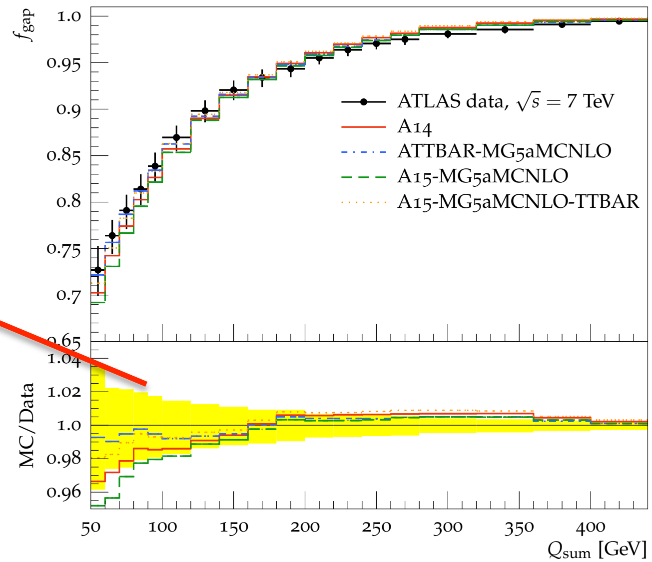




ATL-PHYS-PUB-2015-048

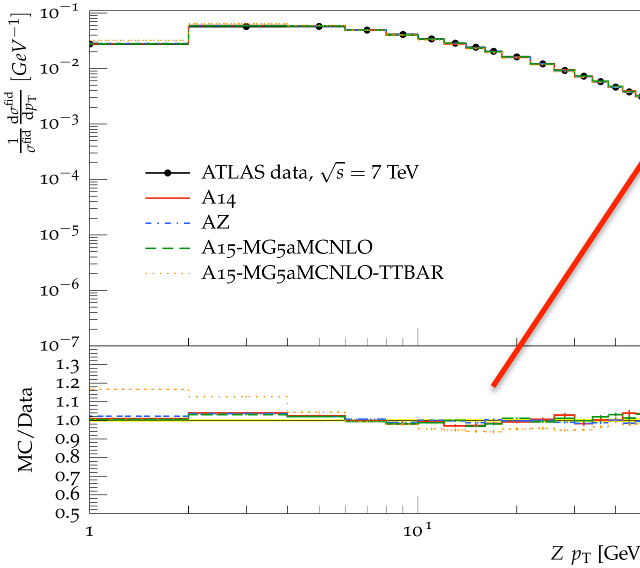
MADGRAPH5_AMC@NLO+Pythia8: Results

Gap fraction vs. Q_{sum} for veto region: $|y| < 2.1$



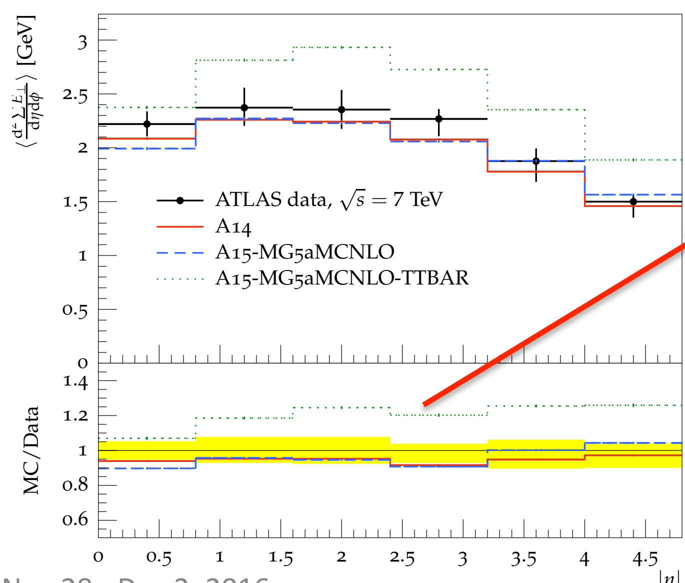
Specific ttbar tunes give the best predictions of the gap fraction, very sensitive to ISR

$Z \rightarrow \mu\mu$ "dressed", Inclusive



Better descriptions by tunes developed using Z-boson measurements → tensions in ISR parameters between the different measurements sensitive to it

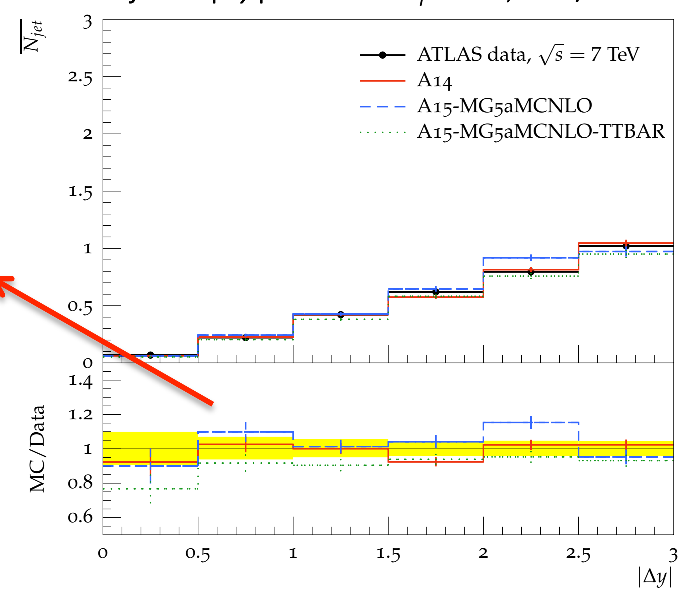
E_T density for the dijet selection in the transverse region



Distributions sensitive to the underlying event cannot be described by dedicated *tt* tunes

Njet vs $|\Delta y|$ for $150 < P_T < 180$, Fwd/Bwd

No maior differences are seen between the tunes



Summary of MADGRAPH5_AMC@NLO+Pythia8

- **Features of MADGRAPH5_AMC@NLO+Pythia8** 
  - Parton Shower & MPI tune with NLO ME attachment
  - ATLAS results at 7 TeV on Z-bosons, jets and ttbar used
  - 2 tunes: A15-MG5aMCNLO-TTBAR and A15-MG5aMCNLO
- **Performance:** 
  - Marginal improvement in modelling with respect to previous tunes
- **Message to take away:** 
  - Overall the gains are small enough, so ATLAS continues to use A14 for this matched setup

As a side note...

- Many Monte Carlo generator setups recently studied for the top quark pair production
    - Not related to MPI, but interesting how different PS generators lead to different predictions

Not for going into the details, but just to show that many combinations have been tested...

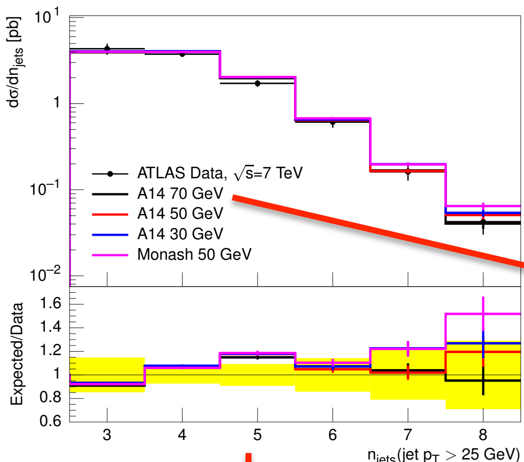
Sample Name	ME Gen.	PS/UE Gen.	ME PS/UE PDF	PS Tune	Matching (Merging)
POWHEG+PYTHIA6	POWHEG-BOX r2330.3	PYTHIA 6.427	CT10 & CTEQ6L1	P2012	Powheg Matching ($h_{damp} = m_{top}$)
POWHEG+HERWIG++	POWHEG-BOX r2330.3	HERWIG++ 2.7.1	CT10 & CTEQ6L1	UE-EE-5	Powheg Matching
POWHEG+HERWIG7	POWHEG-BOX r2330.3	HERWIG7 7.0.1	CT10 & MMHT2014lo68cl	H7-UE-MMHT	Powheg Matching
MG5_aMC+HERWIG++	MG5_aMC@NLO 2.2.1	HERWIG++ 2.7.1	CT10 CTEQ6L1	UE-EE-5	MC@NLO
MG5_aMC+HERWIG7	MG5_aMC@NLO 2.2.1	HERWIG7 7.0.1	NNPDF3.0 MMHT2014lo68cl	H7-UE-MMHT	MC@NLO
MG5_aMC+PYTHIA8	MG5_aMC@NLO 2.2.1	PYTHIA 8.183	NNPDF3.0 NNPDF2.3LO	A14	MC@NLO
MG5_aMC+PYTHIA8 LO	MG5_aMC@NLO LO 2.2.1	PYTHIA 8.210	NNPDF3.0 NNPDF2.3LO	A14	CKKW-L Merging
MG5_aMC+PYTHIA8 FxFx	MG5_aMC@NLO 2.3.3	PYTHIA 8.210	NNPDF3.0 NNPDF2.3LO	A14	MC@NLO (FxFx) (μ_Q = 70 GeV)
SHERPA	SHERPA 2.2	SHERPA	NNPDF3.0	Default	MC@NLO (MEPS@NLO) (Q=30 GeV)

ATL-PHYS-PUB-2016-016

As a side note…

- Limited number of unfolded distributions currently available at $\sqrt{s}$ = 13 TeV
- 7 TeV data/MC comparisons still provide important checks of the generators' performance.
- Particle-level comparisons to unfolded data performed using Rivet v2.4.0

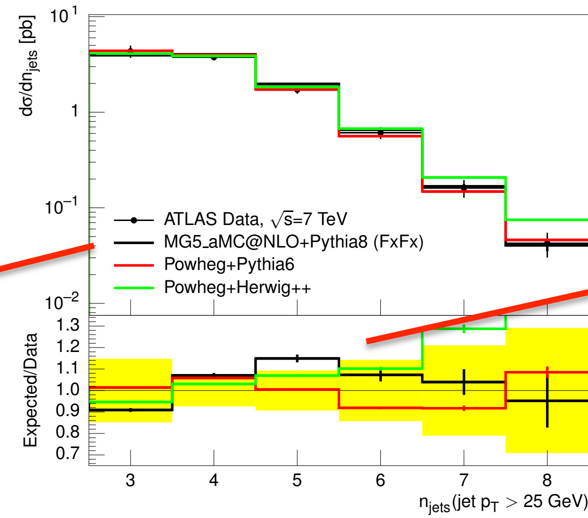
ttbar cross section vs jet mult. for jets above 25 GeV



All predictions within the uncertainties, with Monash getting worse at high multiplicities because of the lower value of α_s used in this tune

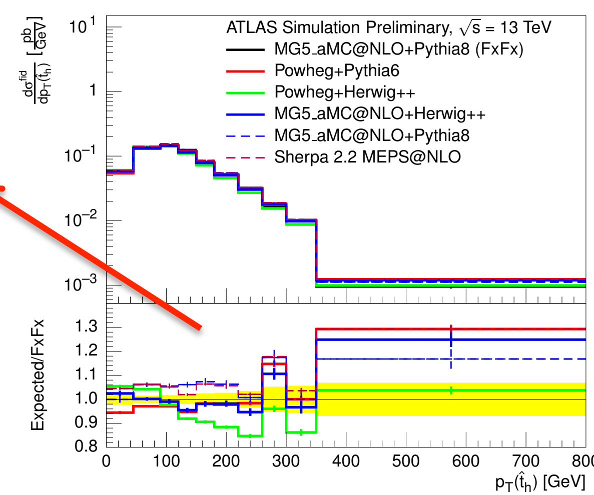
A14 with merging scale μ_Q= 70 GeV works very well and it was chosen

ttbar cross section vs jet mult. for jets above 25 GeV



A14 predictions are similar to the ones from Powheg +Pythia6 (used as a default in ATLAS) → μ_Q= 70 GeV merging scale adopted for 13 TeV samples to be used in Run 2 analyses

ttbar cross section vs hadronic pseudo-top quark p_T



Although samples have been corrected to a common value for the total cross section, shape-dependent differences (up to ~20%) are seen among generators

Summary

ATLAS: good detector to study soft QCD!

- Recently developed **Pythia 8 - A3** tune (including 13 TeV data) for pile-up modelling
  - <u>Fairly good predictions of charged particle multiplicity</u>
  - <u>Improvements in the fiducial inelastic cross-section predictions</u>
  - <u>Promising for pile-up description</u>

- No tune available yet for UE including 13 TeV measurements (analysis results about to be published)

- **MADGRAPH5_AMC@NLO + Pythia 8**
  - 2 tunes (using 7 TeV data)
    - A general one (<u>A15-MG5aMCNLO</u>)
    - A ttbar specific one (<u>A15-MG5aMCNLO-TTBAR</u>)

- Many studies recently done for **PS tuning** to study **top pair productions**


¡GRACIAS!


La ultima y nos vamos.

Extra slides

Methodology:

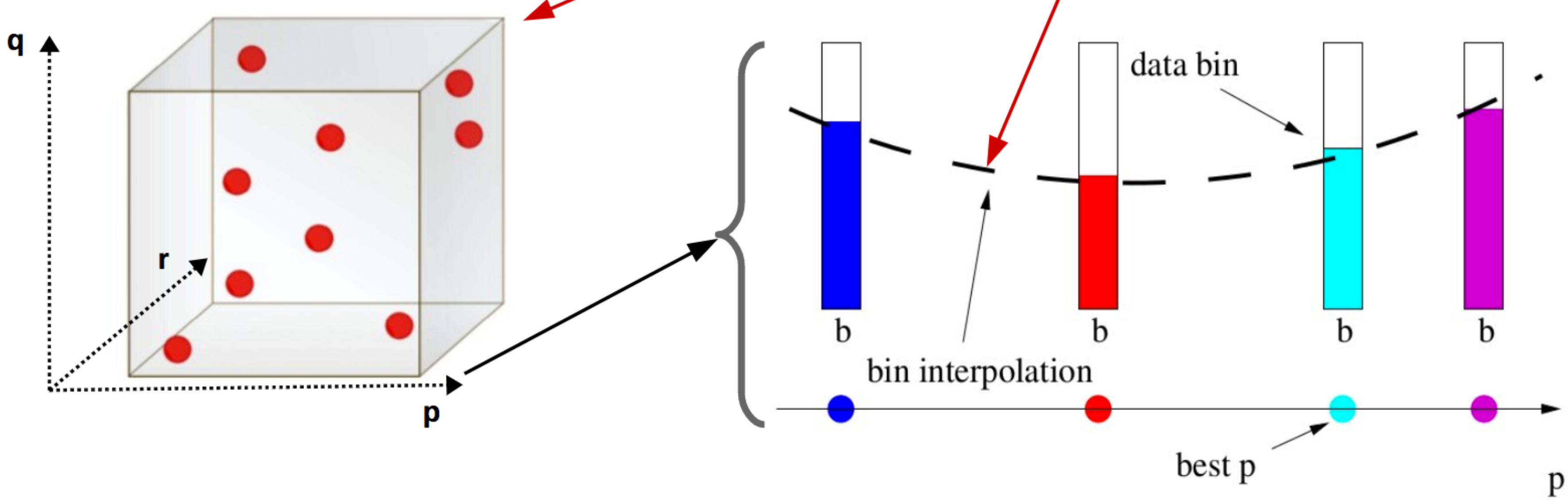
1. Choose parameter & parameter ranges
2. Choose relevant experimental data
   Process & fiducial cuts
   Sensitive Observables
3. Sample N-parameter hypercube
4. Generate samples for 'n' anchor points
5. Analytic approx of observable response to parameter changes.
6. X^2 minimisation of analytic approximation over full MC parameter space in MC/Data comparison.

Tools

- Human intuition
- Rivet Tool Kit
  - Particle Level Analysis
  - Data Analysis repository
- Professor
  - Random Sampling of parameter hypercube
  - Analytic approximation of observable response to parameter

$$f_b(\vec{P}) = a_0^b + \sum_i B_i^b p'_i + \sum_{i \leqslant j} C_{ij}^b p'_i p'_j + \dots$$

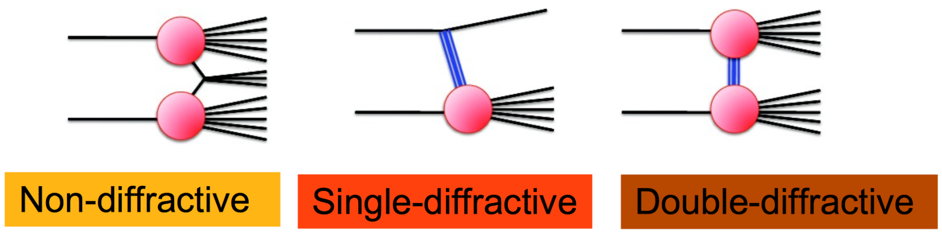
  - χ^2 minimisation



Introduction and Outline

- 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

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)

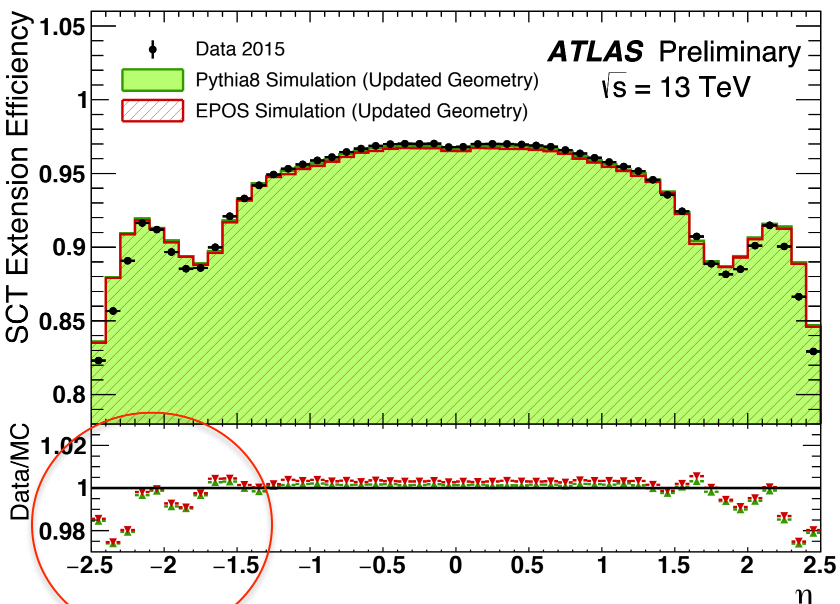
In the 100 MeV case: nearly double tracks, but more difficult measurement due to increased impact from multiple scattering at low pt and imprecise knowledge of the material in the ID

Data-driven correction to the Tracking Efficiency

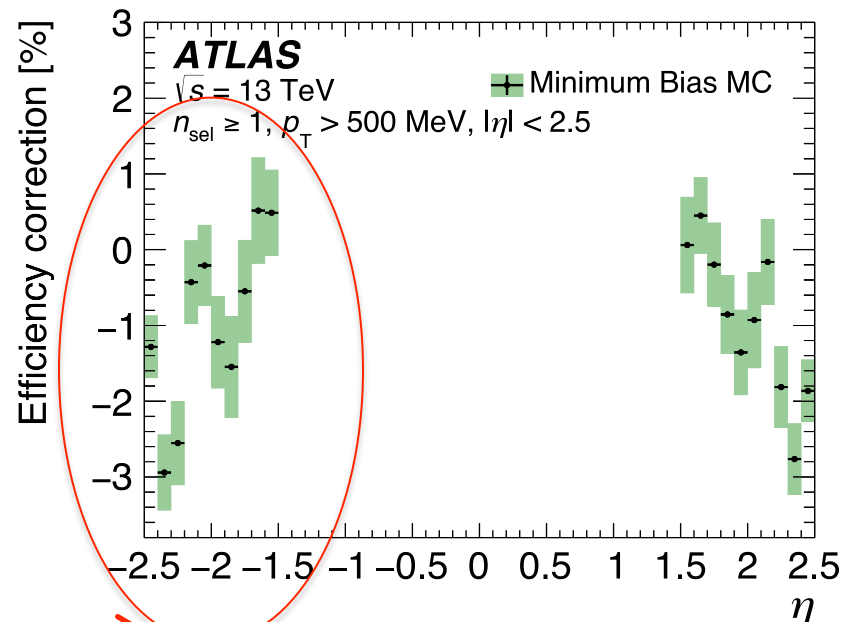
- **SCT-Extension Efficiency**: rate of pixel stand-alone tracks successfully extended to include SCT clusters and to build a full silicon track → $\varepsilon_{ext} \equiv \frac{N_{tracklet}(\text{matched})}{N_{tracklet}}$

- 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

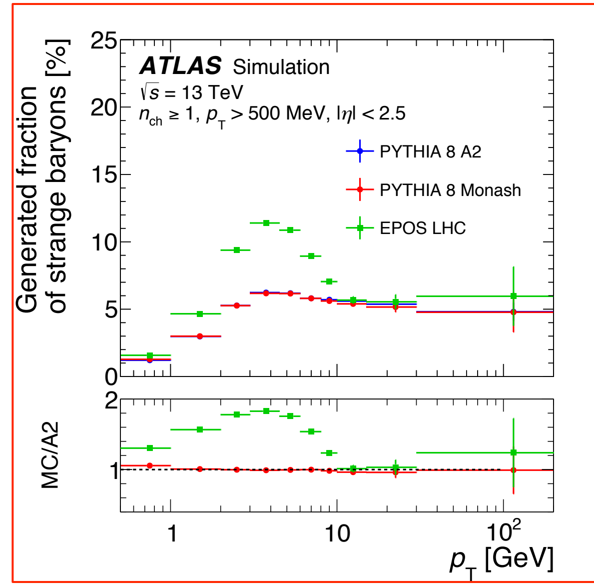
Strange Baryons

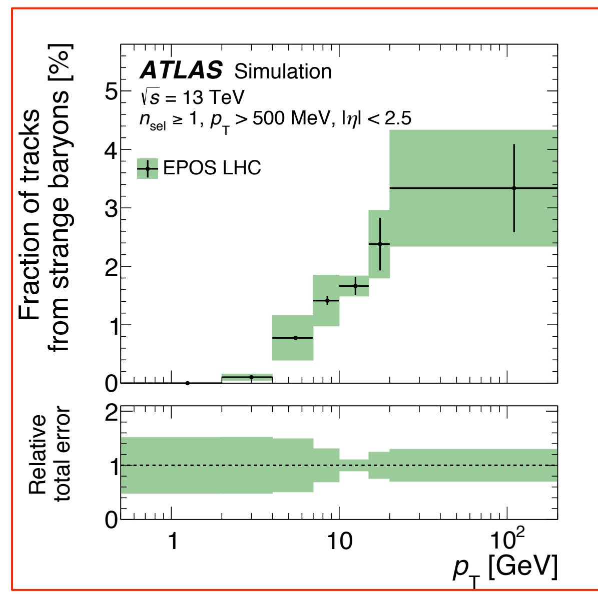
Common treatment of the Strange Baryons in all the 8 and 13 TeV analysis

- 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)

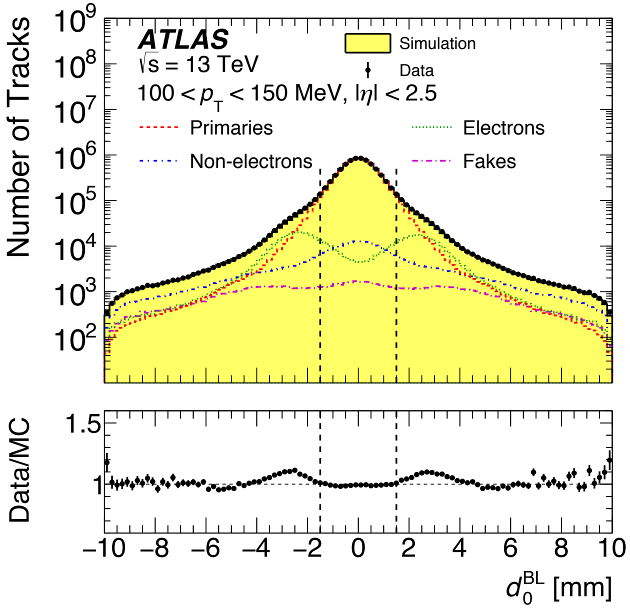
- **Final results produced with and without the strange baryons** to allow comparison with previous measurements





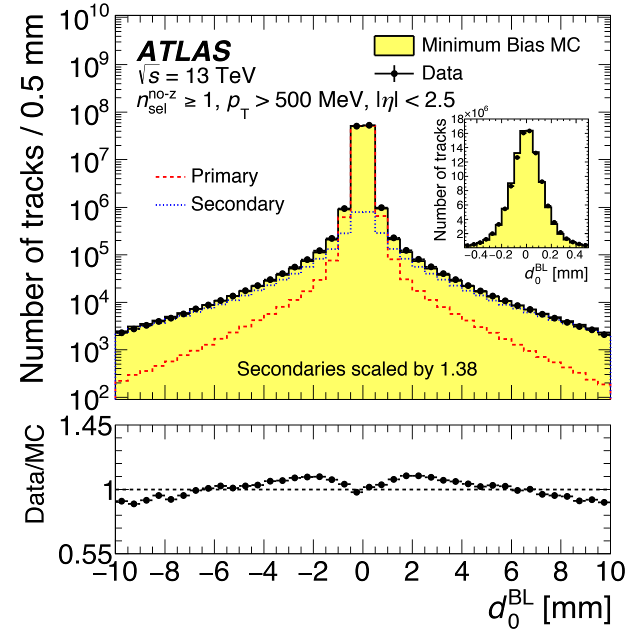
Secondaries

- 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 ≥ 500 MeV, combined template: primary and secondary



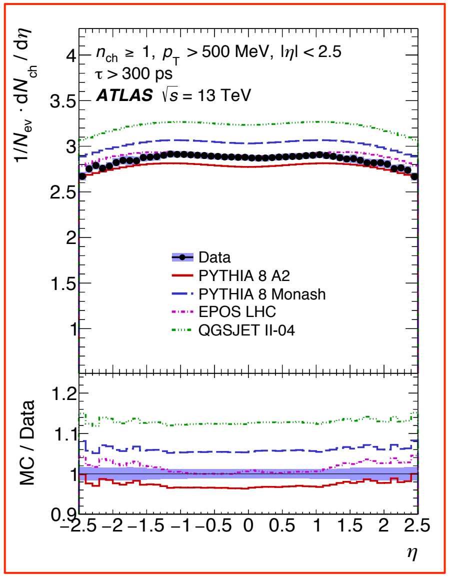
- Split templates only for p_T < 500 MeV:
  - Different shape of the transverse impact parameter distribution for electron and non-electron secondary particles → d_0^{BL} reflects the radial location at which the secondaries were produced
  - Different processes for conversion and hadronic interaction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

Final Results – 13 TeV

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

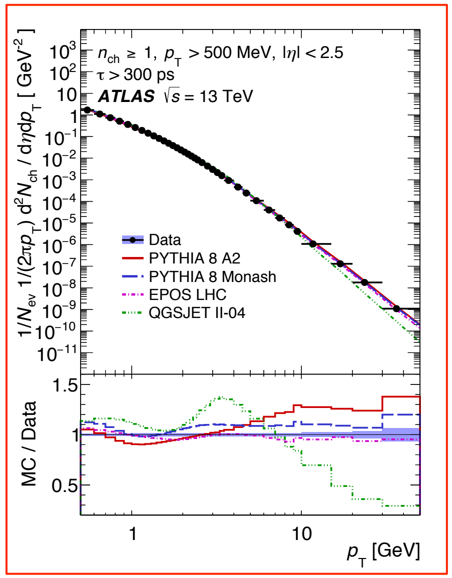
- Nominal Phase Space (p_T > 500 MeV, $|\eta|$< 2.5)

$dN_{ch}/d\eta$



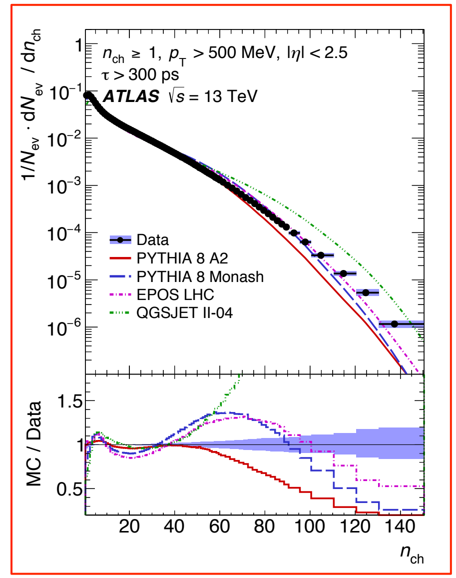
Models differ mainly in normalisation, shape similar

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

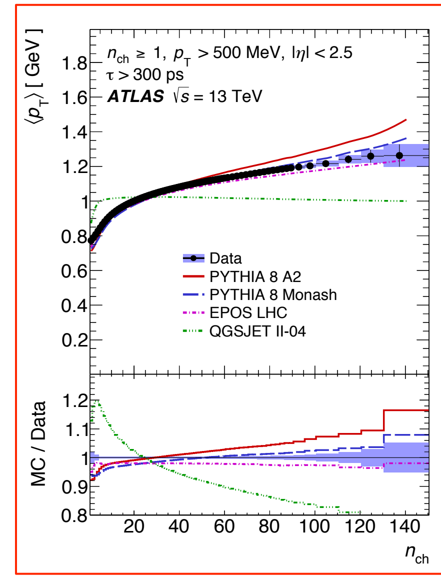


Measurement spans 10 orders of magnitude

dN_{ev}/dn_{ch}



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



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

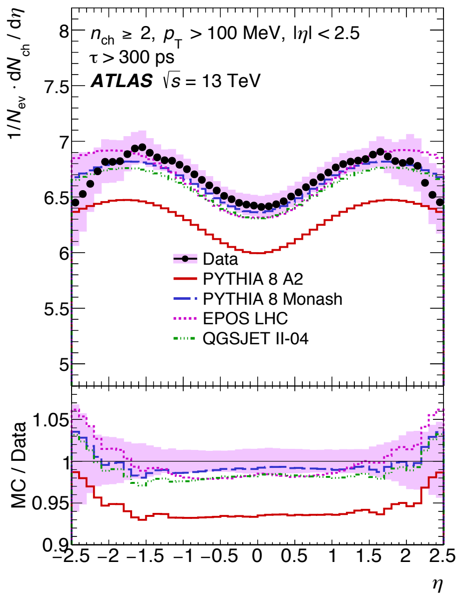
Some Models/Tunes give remarkably good predictions (EPOS, Pythia8)

Final Results – 13 TeV

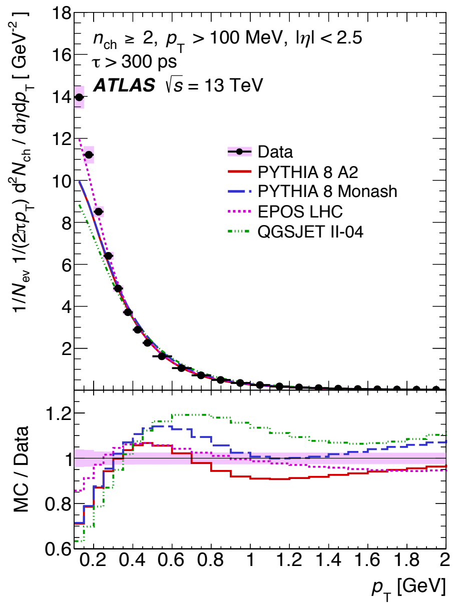
Data
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

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

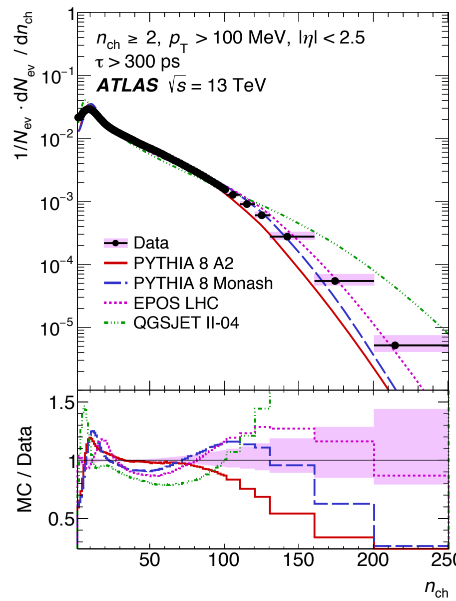
$dN_{ch}/d\eta$



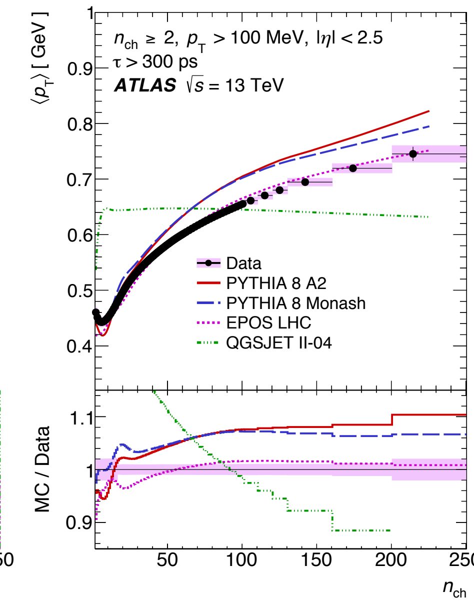
$d^2N_{ev}/d\eta dp_T$



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 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

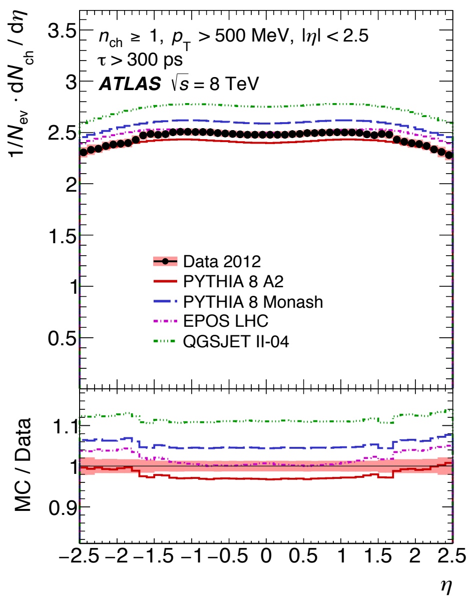
EPOS gives the best prediction!
Much clearer in this low p_T regime than in the nominal phase space!

Final Results – 8 TeV

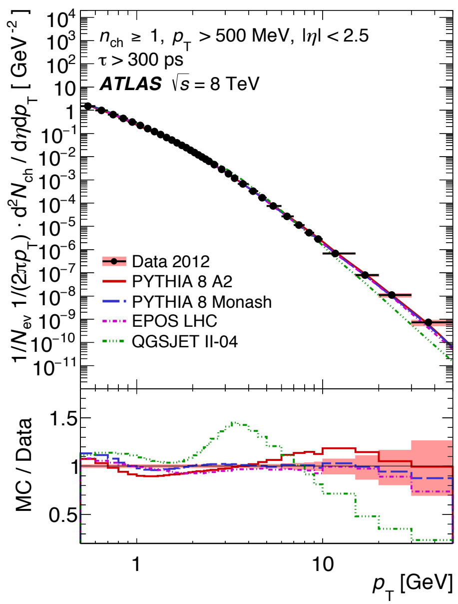
- Data 2012
- PYTHIA 8 A2
- PYTHIA 8 Monash
- EPOS LHC
- QGSJET II-04

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

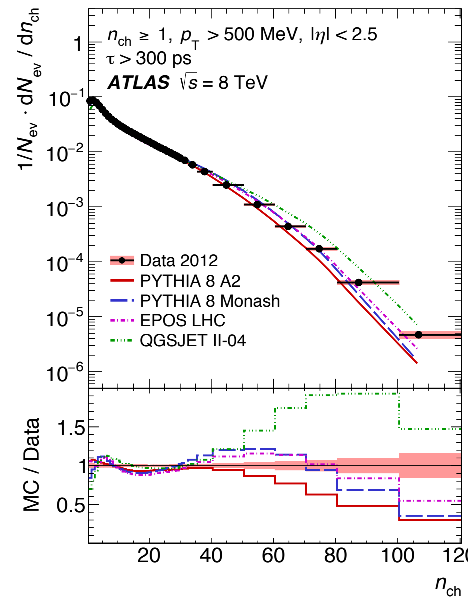
$dN_{ch}/d\eta$



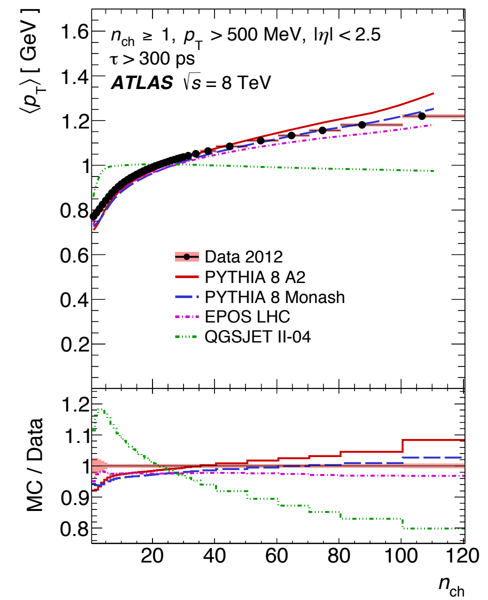
$d^2N_{ev}/d\eta dp_T$



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

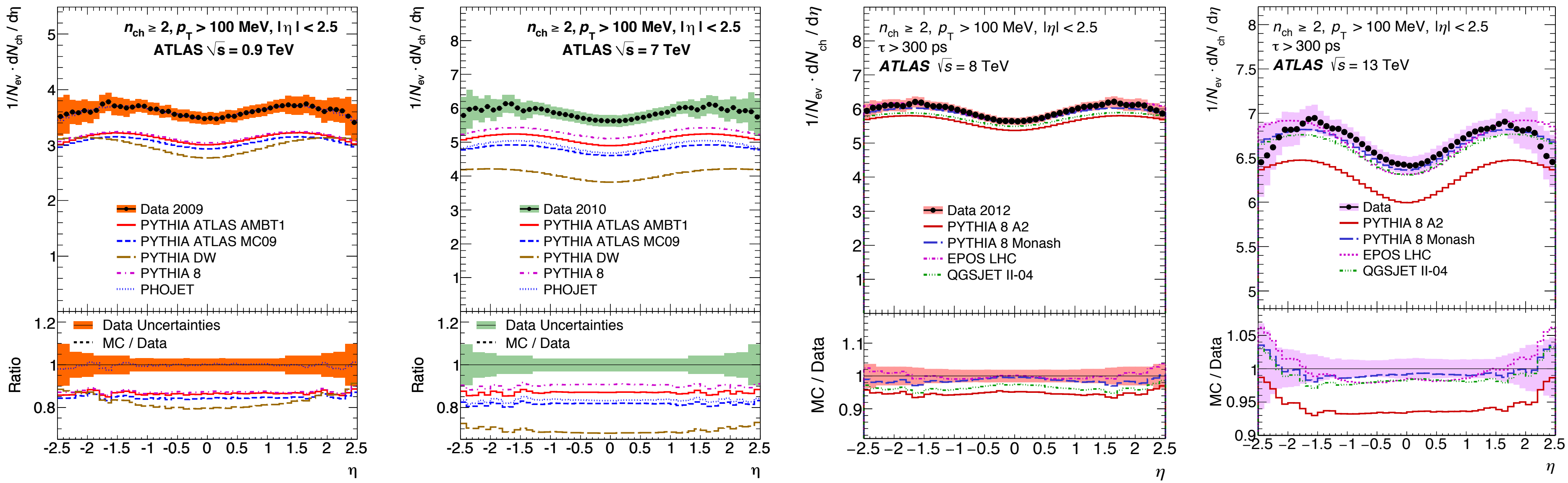
Above 1 GeV, good predictions given by Pythia 8 Monash

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

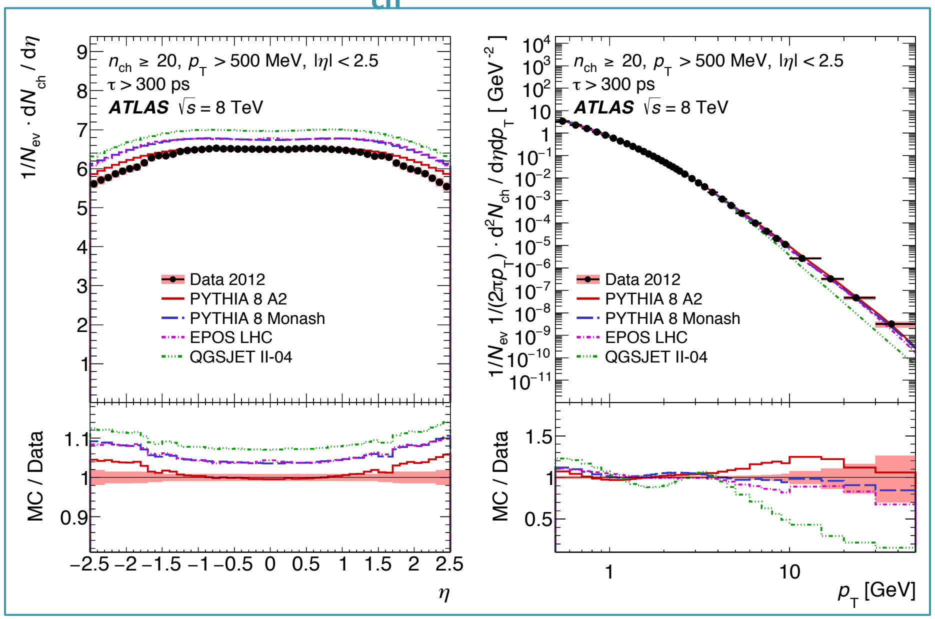
Bonus – High Multiplicity Regime at 8 TeV

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

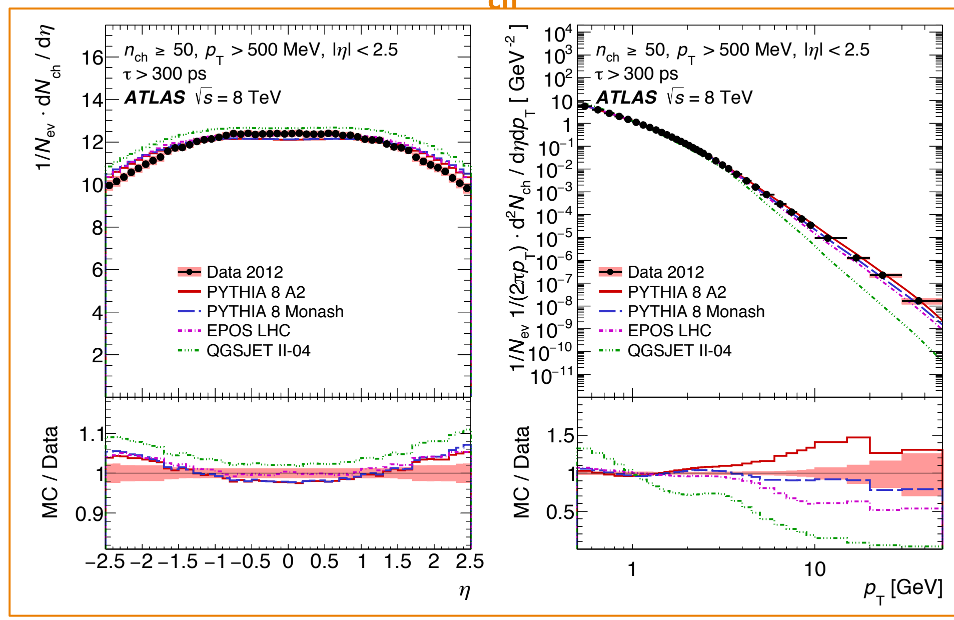
Phase Space		$1/N_{ev} \cdot dN_{ch}/d\eta$ at $\eta = 0$	
$n_{ch} \geq$	p_T[MeV] >	$\tau > 300$ ps (fiducial)	$\tau > 30$ ps (extrapolated)
2	100	5.64 ± 0.10	5.71 ± 0.11
1	500	2.477 ± 0.031	2.54 ± 0.04
6	500	3.68 ± 0.04	3.78 ± 0.05
20	500	6.50 ± 0.05	6.66 ± 0.07
50	500	12.40 ± 0.15	12.71 ± 0.18

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

$n_{ch} \geq 20$



$n_{ch} \geq 50$



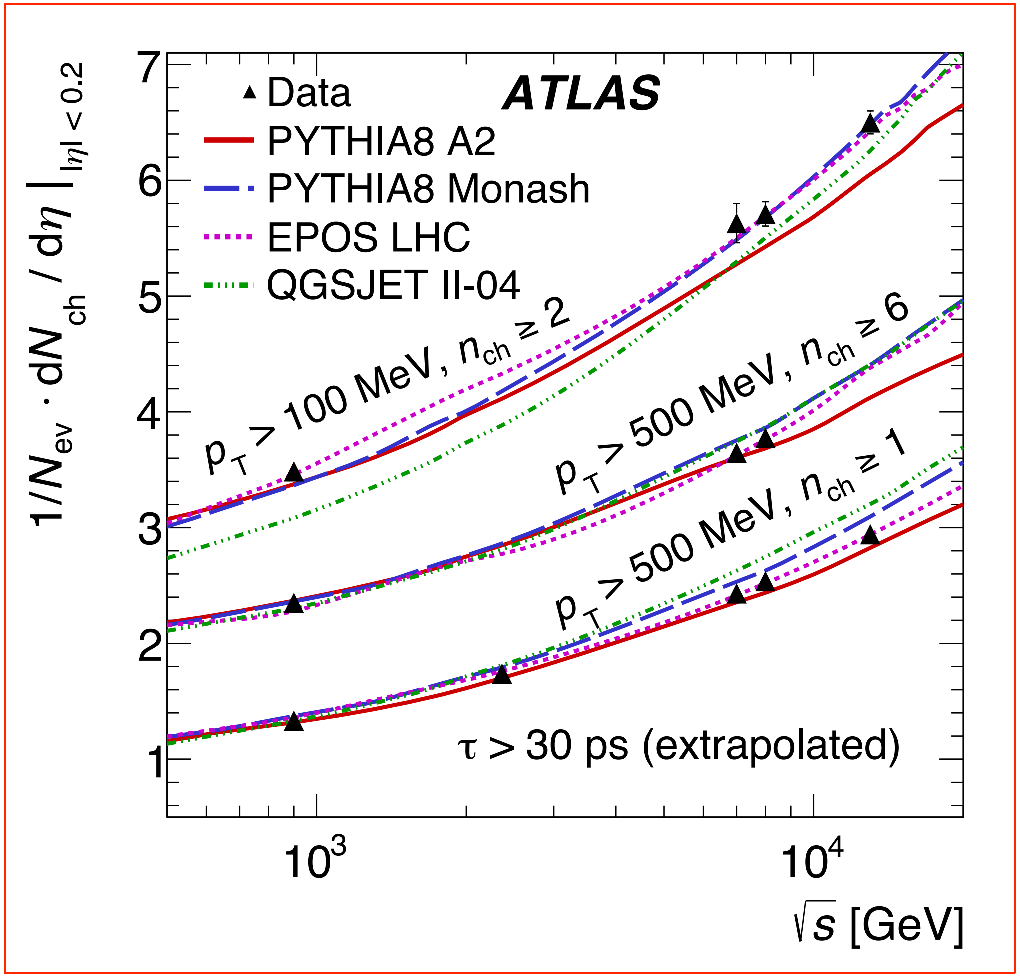
Pythia 8 A2 describes the plateau in the central region well

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

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

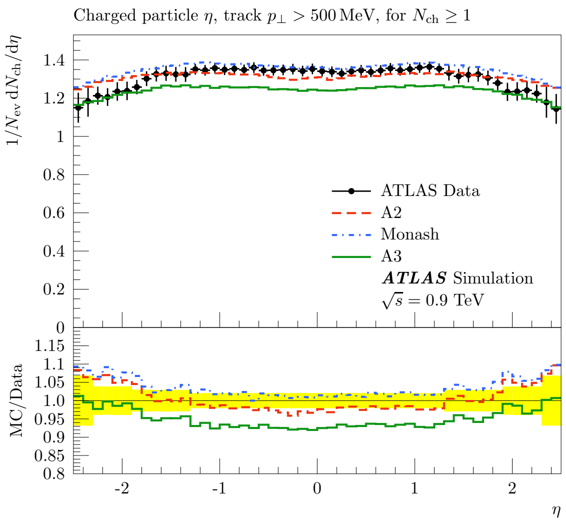
Fair prediction by Pythia8 and EPOS at low p_T, but large deviation at high p_T

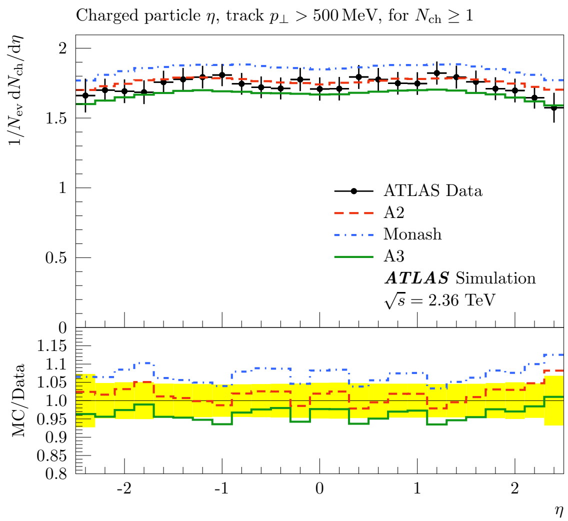
Final Results

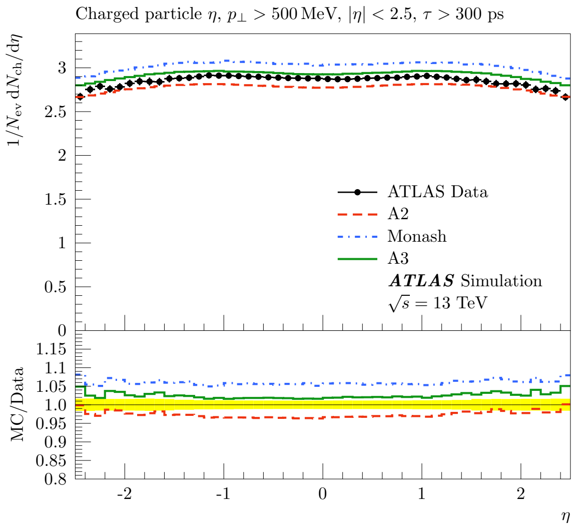


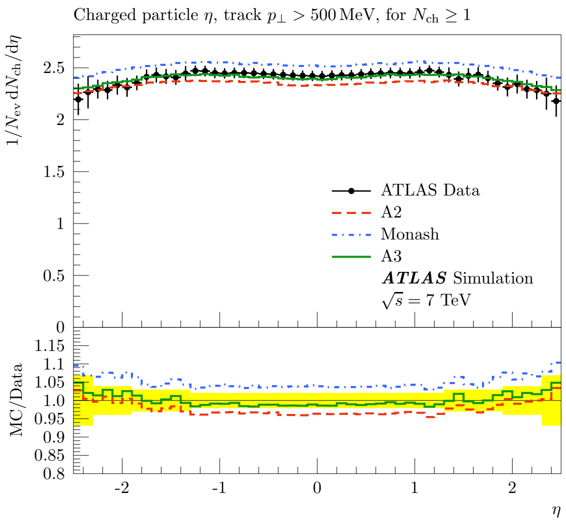
- Mean number of **primary charged particles increases by a factor of 2.2** when √s increases by a factor of about 14 **from 0.9 TeV to 13 TeV**!
- Looking at the overall picture, **best predictions for this observable is given by EPOS followed by Pythia 8 A2 and Monash**!

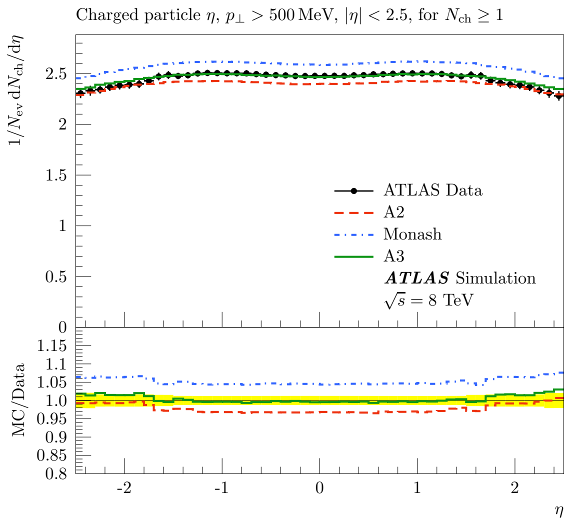
MinBias eta


Charged particle η, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 0.9$ TeV
$1/N_{ev}\, dN_{ch}/d\eta$
MC/Data
η

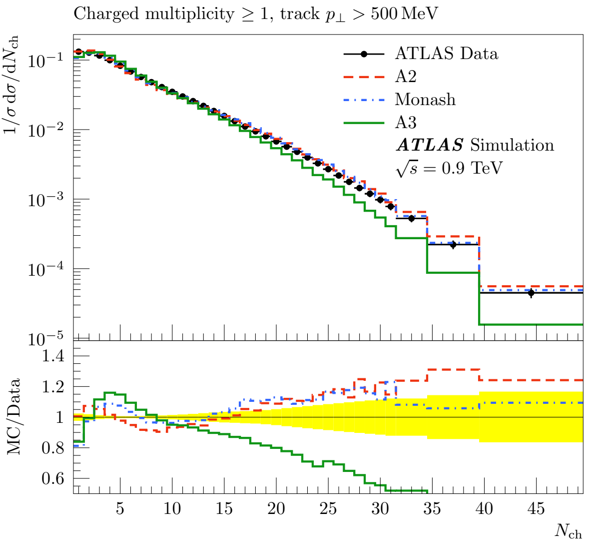

Charged particle η, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 2.36$ TeV
$1/N_{ev}\, dN_{ch}/d\eta$
MC/Data
η

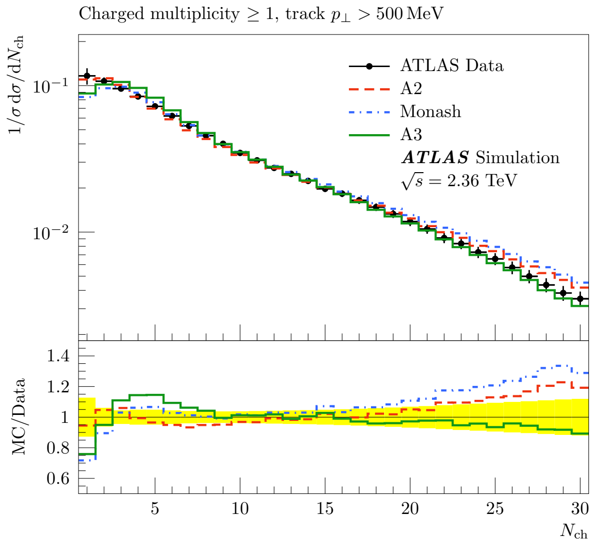

Charged particle η, $p_\perp > 500$ MeV, $|\eta| < 2.5$, $\tau > 300$ ps
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 13$ TeV
$1/N_{ev}\, dN_{ch}/d\eta$
MC/Data
η

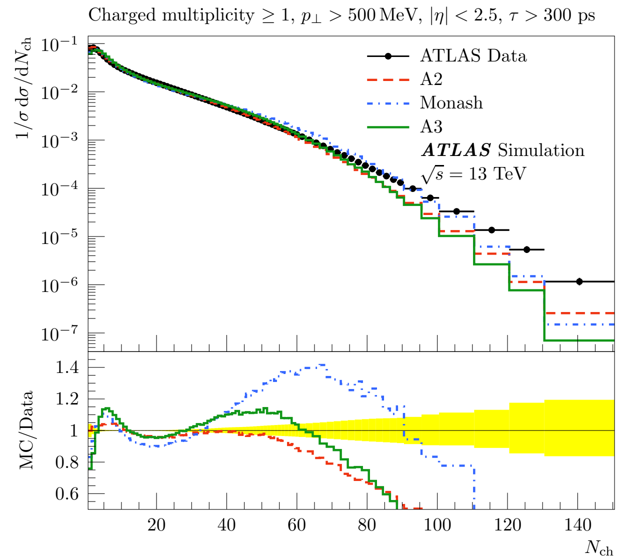

Charged particle η, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 7$ TeV
$1/N_{ev}\, dN_{ch}/d\eta$
MC/Data
η

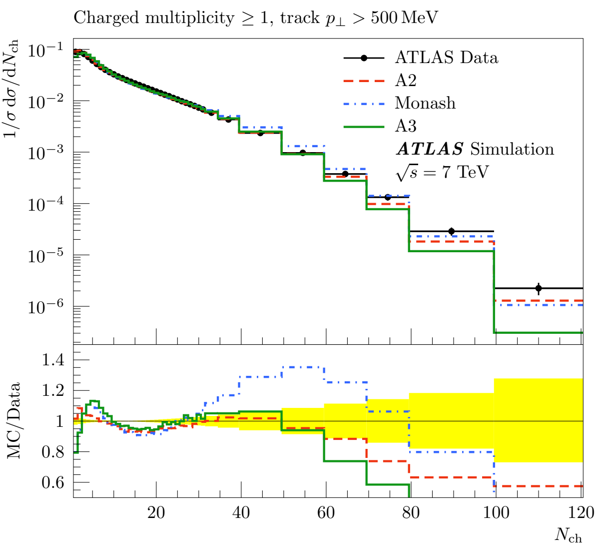

Charged particle η, $p_\perp > 500$ MeV, $|\eta| < 2.5$, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 8$ TeV
$1/N_{ev}\, dN_{ch}/d\eta$
MC/Data
η

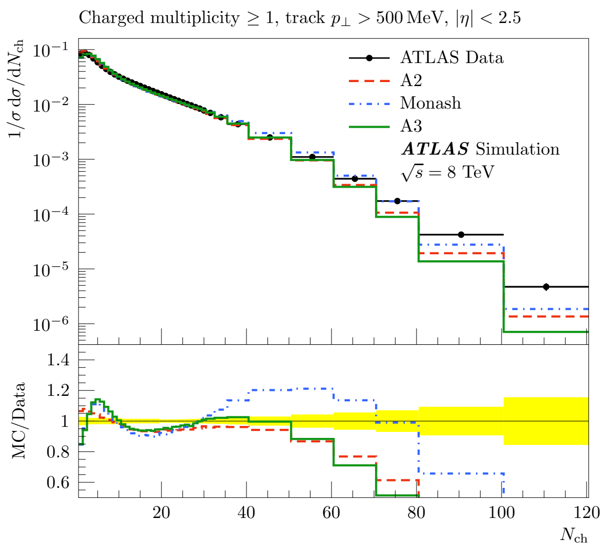
MinBias multiplicity



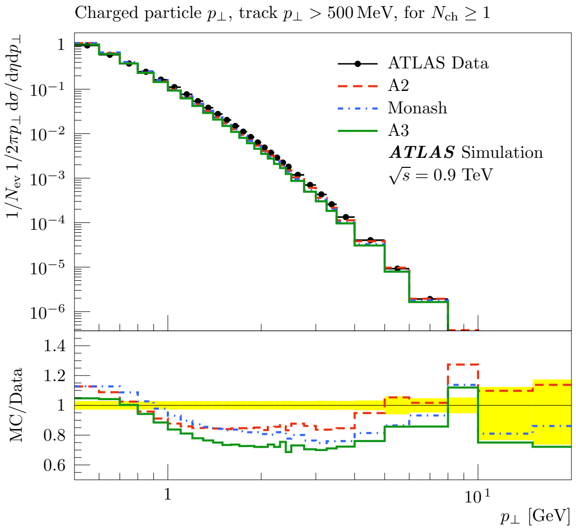




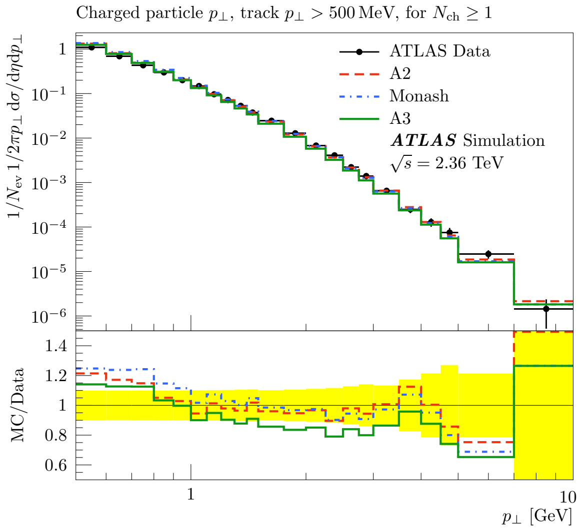




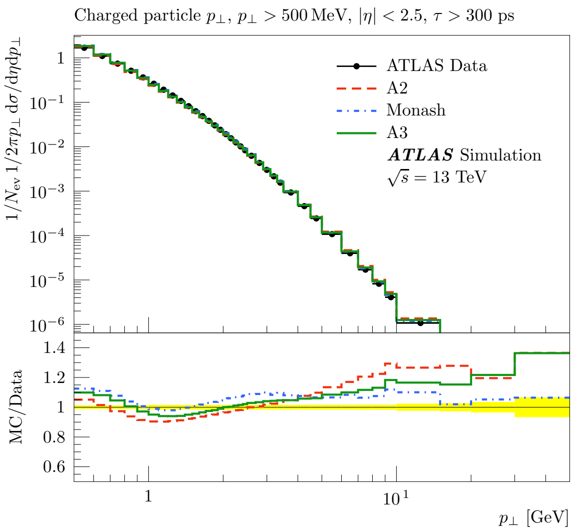
MinBias p_T



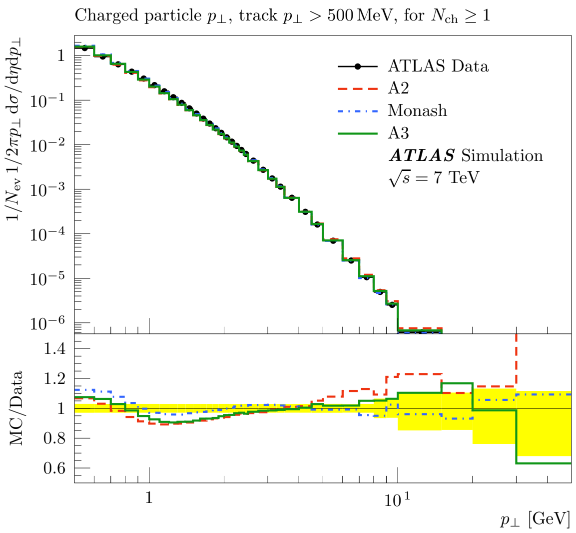
Charged particle $p_\perp$, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 0.9$ TeV
$1/N_{ev}\ 1/2\pi p_\perp\ d\sigma/d\eta dp_\perp$
MC/Data
$p_\perp$ [GeV]



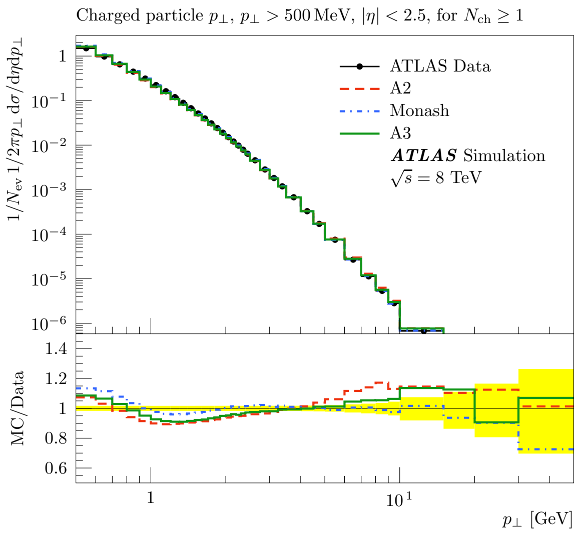
Charged particle $p_\perp$, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 2.36$ TeV
$1/N_{ev}\ 1/2\pi p_\perp\ d\sigma/d\eta dp_\perp$
MC/Data
$p_\perp$ [GeV]



Charged particle $p_\perp$, $p_\perp > 500$ MeV, $|\eta| < 2.5$, $\tau > 300$ ps
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 13$ TeV
$1/N_{ev}\ 1/2\pi p_\perp\ d\sigma/d\eta dp_\perp$
MC/Data
$p_\perp$ [GeV]

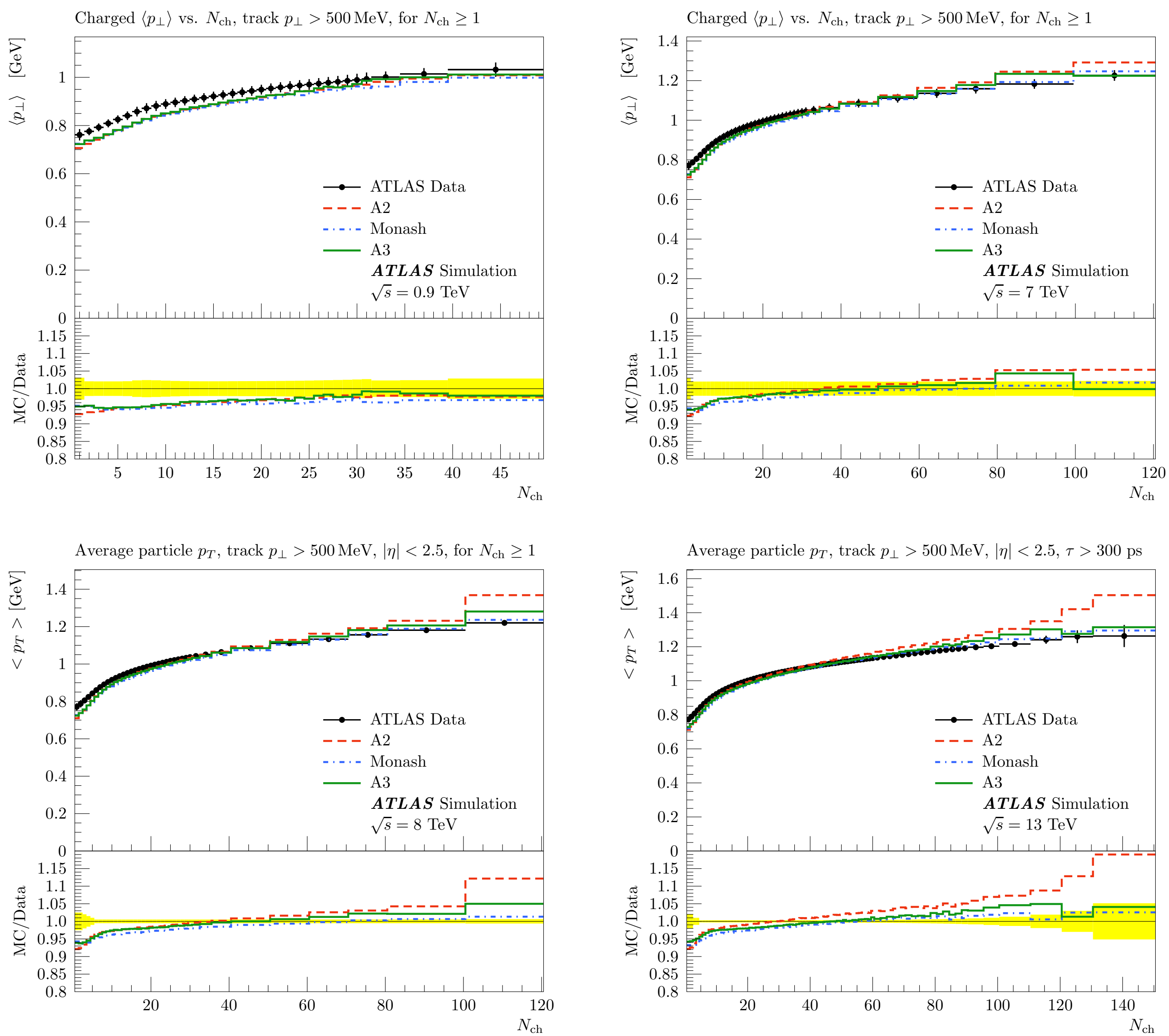


Charged particle $p_\perp$, track $p_\perp > 500$ MeV, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 7$ TeV
$1/N_{ev}\ 1/2\pi p_\perp\ d\sigma/d\eta dp_\perp$
MC/Data
$p_\perp$ [GeV]

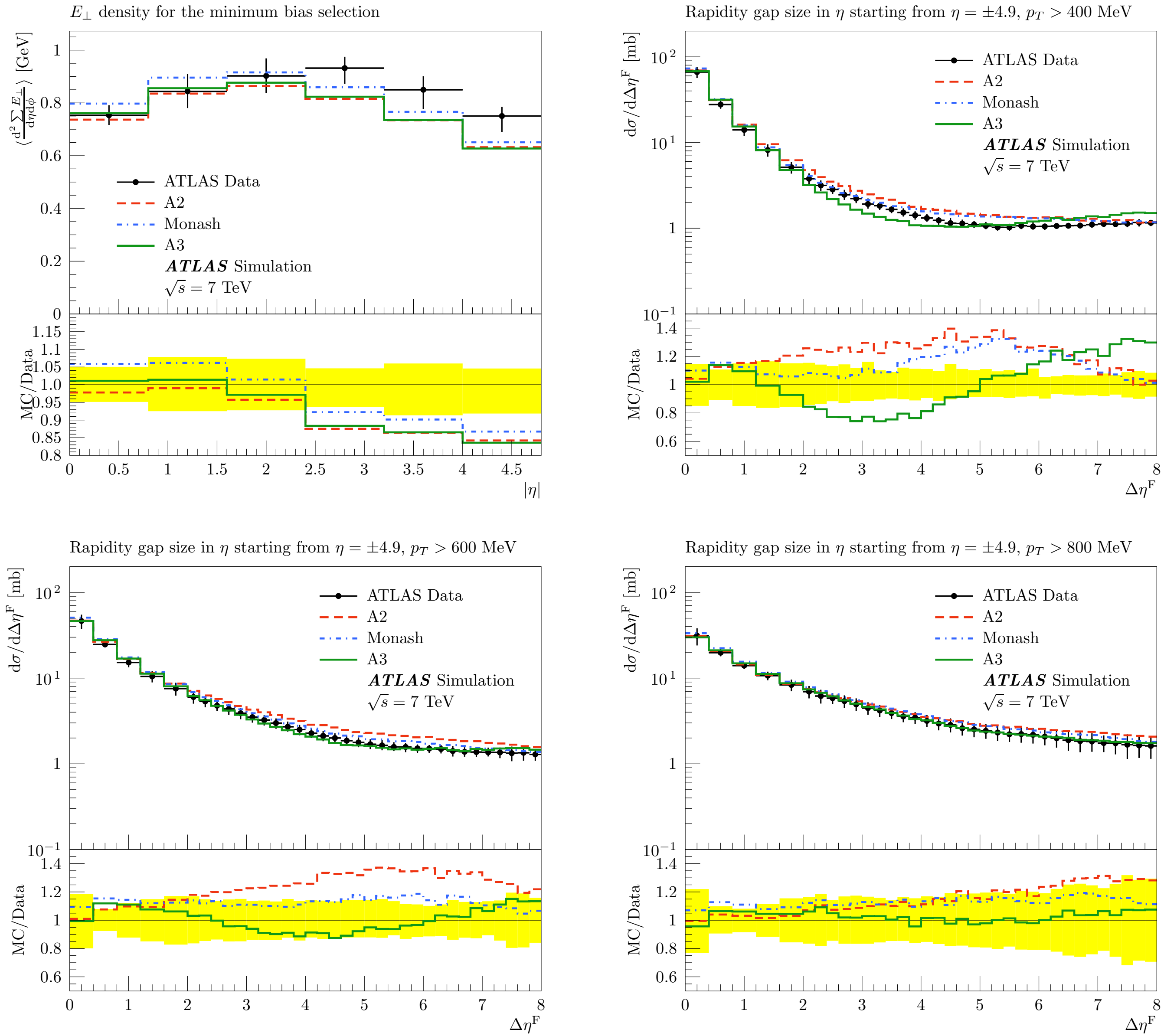


Charged particle $p_\perp$, $p_\perp > 500$ MeV, $|\eta| < 2.5$, for $N_{ch} \geq 1$
ATLAS Data
A2
Monash
A3
ATLAS Simulation
$\sqrt{s} = 8$ TeV
$1/N_{ev}\ 1/2\pi p_\perp\ d\sigma/d\eta dp_\perp$
MC/Data
$p_\perp$ [GeV]

MinBias <p_T> vs multiplicity



Transverse energy flow and rapidity gas



Summary

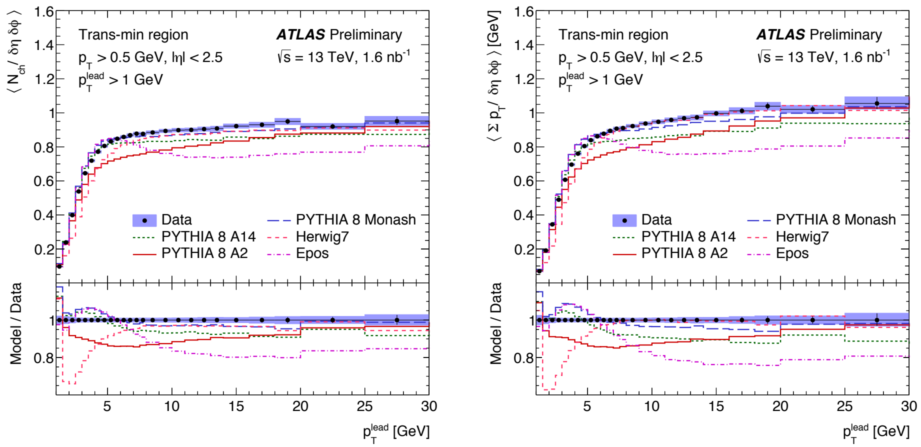
χ2/Ndof values for A2, Monash and A3 tunes

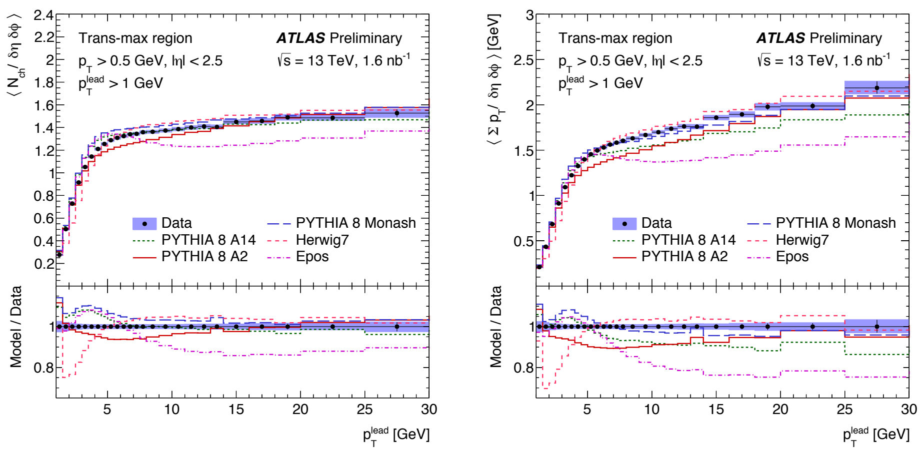
	A2	Monash	A3	Ndof
Charged particle pseudorapidity				
At $\sqrt{s} = 0.9$ TeV	1.1	1.4	6.5	50
At $\sqrt{s} = 2.36$ TeV	0.3	2.2	0.7	25
At $\sqrt{s} = 7$ TeV	1.7	3.0	0.3	50
At $\sqrt{s} = 8$ TeV	4.0	13.3	0.4	50
At $\sqrt{s} = 13$ TeV	5.1	20.5	3.5	50
Charged particle multiplicity				
At $\sqrt{s} = 0.9$ TeV	11.1	10.5	34.5	34
At $\sqrt{s} = 2.36$ TeV	0.3	1.0	0.2	11
At $\sqrt{s} = 7$ TeV	14.7	33.8	26.5	39
At $\sqrt{s} = 8$ TeV	12.3	19.2	14.0	39
At $\sqrt{s} = 13$ TeV	32.5	64.4	94.2	81
Charged particle transverse momentum				
At $\sqrt{s} = 0.9$ TeV	18.3	27.8	54.2	31
At $\sqrt{s} = 2.36$ TeV	0.7	1.2	1.3	22
At $\sqrt{s} = 7$ TeV	4.8	1.6	2.9	36
At $\sqrt{s} = 8$ TeV	13.5	4.8	8.4	36
At $\sqrt{s} = 13$ TeV	35.1	18.3	16.6	37
Charged particle mean transverse momentum against multiplicity				
At $\sqrt{s} = 0.9$ TeV	3.3	4.1	2.1	34
At $\sqrt{s} = 7$ TeV	2.2	2.9	1.9	39
At $\sqrt{s} = 8$ TeV	16.3	26.8	14.2	39
At $\sqrt{s} = 13$ TeV	28.3	33.1	21.6	81
Transverse energy flow				
	1.8	1.3	1.7	6
Rapidity gap				
$p_T > 400$ MeV	6.2	3.5	4.2	35
$p_T > 600$ MeV	4.4	1.1	0.4	35
$p_T > 800$ MeV	0.7	0.6	0.1	25

Underlying Events at 13 TeV

ATLAS Internal figures, to be fixed

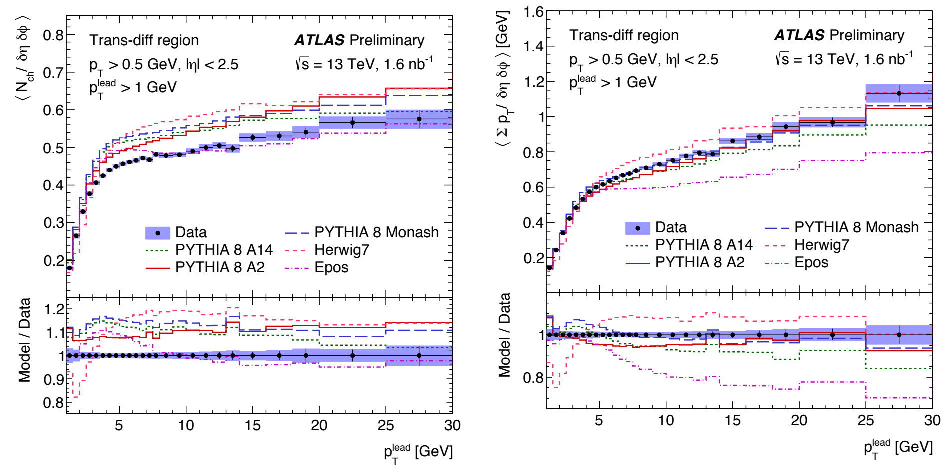
Trans-min





Trans-max

Trans-diff

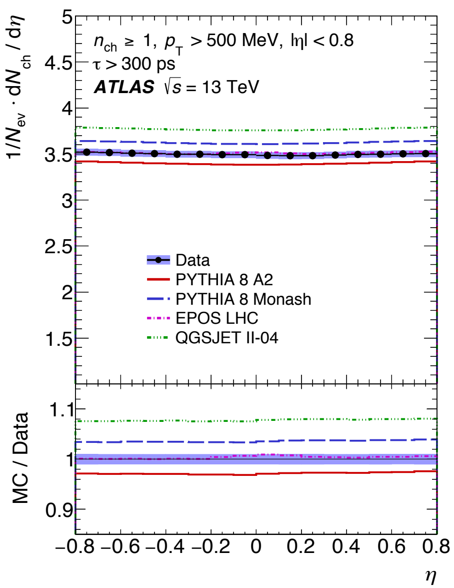


Symbol	Description
Independent variables	
p_T^{lead}	Transverse momentum of the leading charged particle
N_{ch}^{trans}	Number of charged particles in the transverse region
$\lvert\Delta\phi\rvert$	Absolute difference in particle azimuthal angle from the leading charged particle
Dependent variables	
$\langle N_{ch}/\delta\eta\delta\phi\rangle$	Mean number of charged particles per unit η–ϕ (in radians)
$\langle \sum p_T/\delta\eta\delta\phi\rangle$	Mean scalar p_T sum of charged particles per unit η–ϕ (in radians)
$\langle$mean $p_T\rangle$	Mean of the per-event average p_T of charged particles ($\geq$ 1 charged particle required)

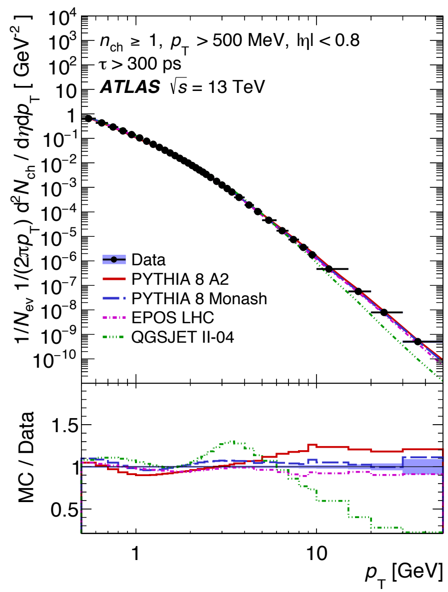
Final Results – 13 TeV

- Reduced Phase Space (p_T > 500 MeV, $|\eta|$< 0.8)

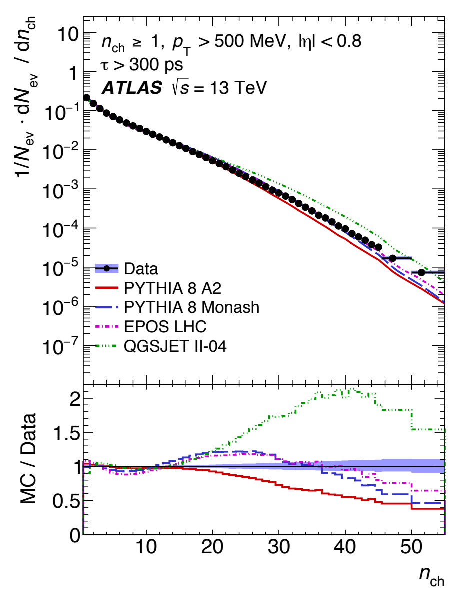
$dN_{ch}/d\eta$



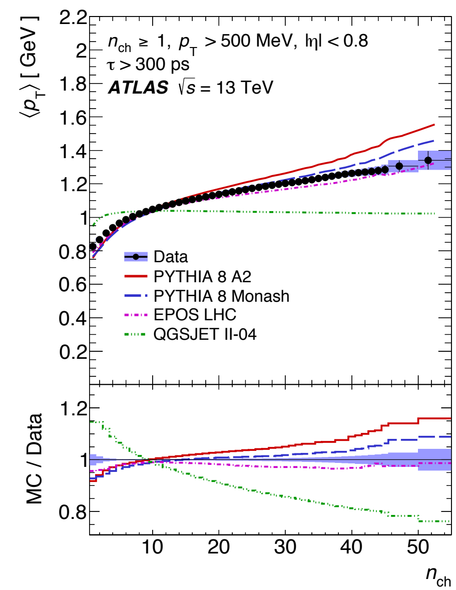
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



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



Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

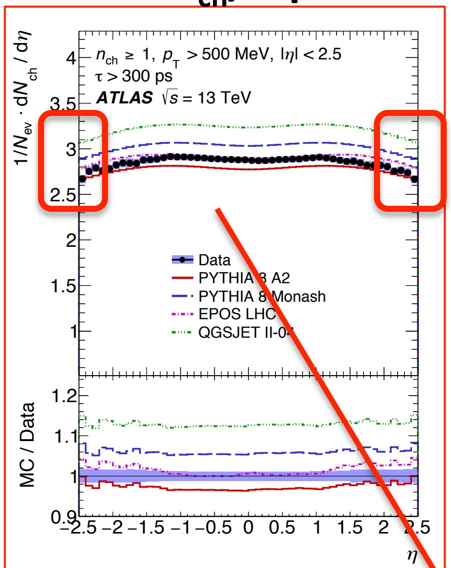
Low n_{ch} not well modelled by any MC; large contribution from diffraction;
Models without colour reconnection (QGSJET) fail to model scaling with nch very well

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)

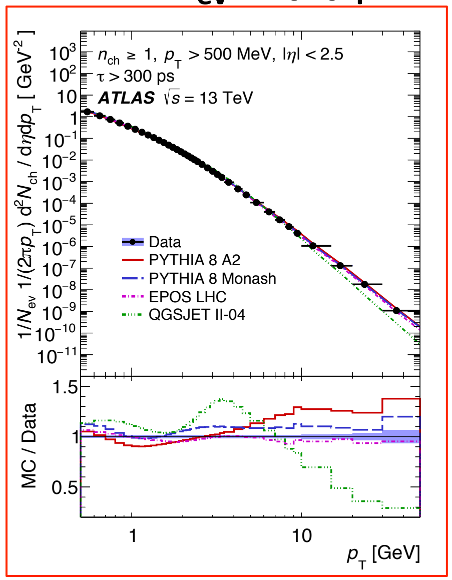
Final Results

- Nominal Phase Space (500 MeV)

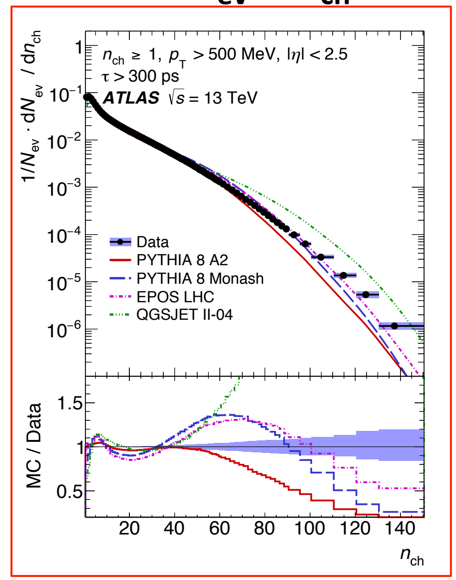
$dN_{ch}/d\eta$



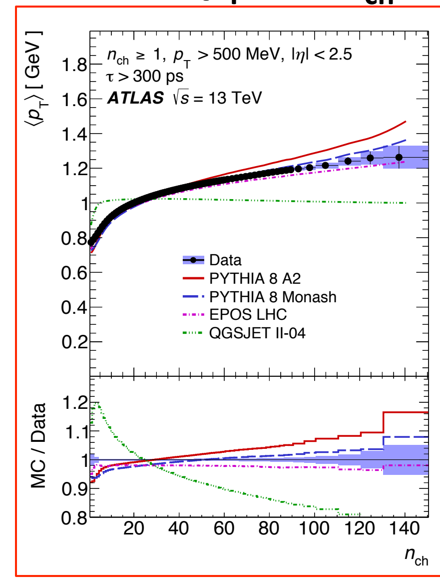
$d^2N_{ev}/d\eta dp_T$

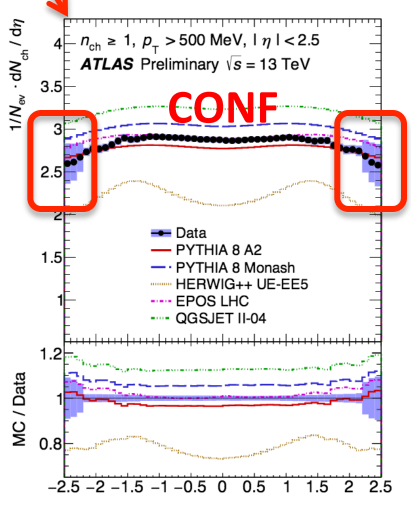


dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



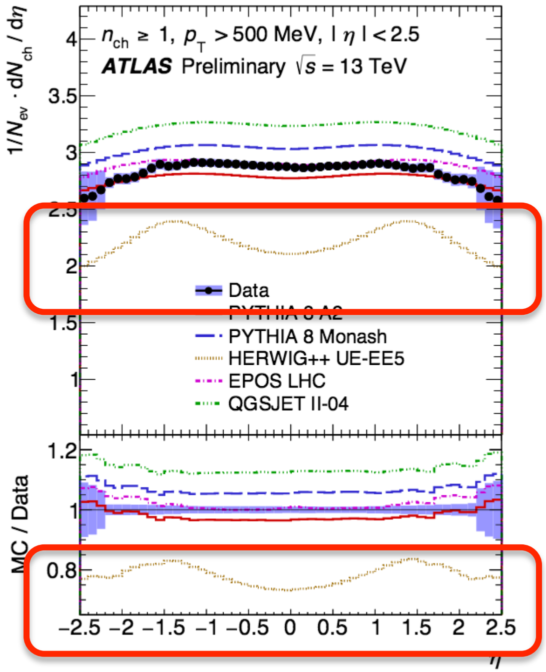


Big improvements in the systematic uncertainty evaluation thanks to the correction to the tracking efficiency driven by material studies

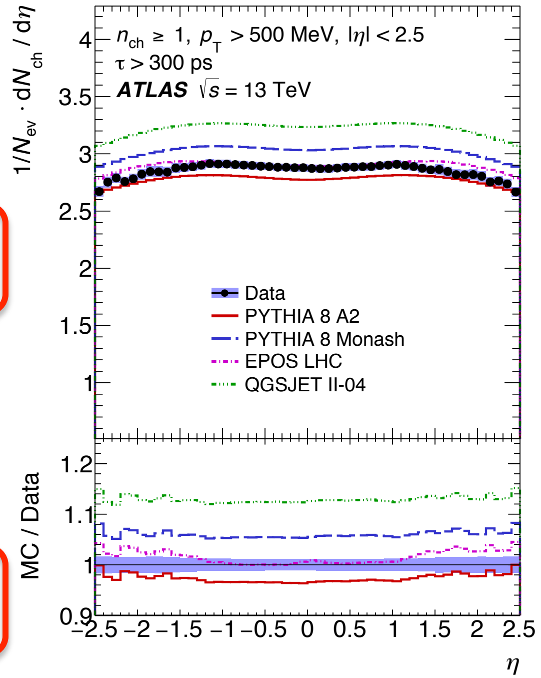
Final Results – Extra Generators Comparison

- Nominal Phase Space (500 MeV)

CONF



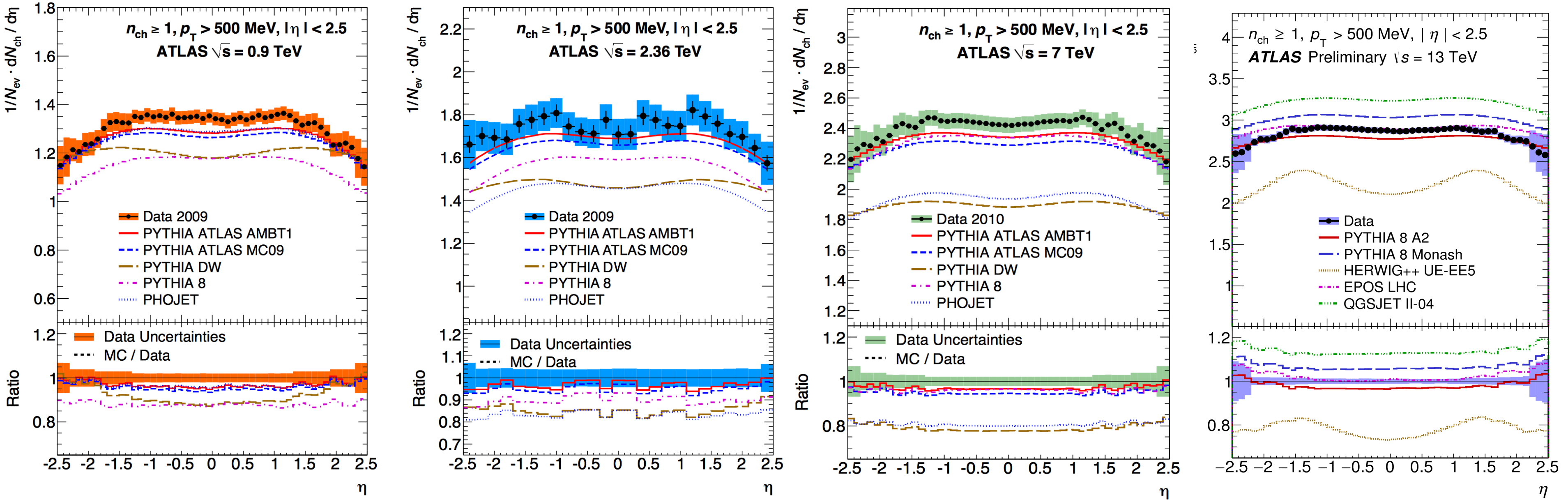
Paper



- 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

Different Centre of Mass Energy

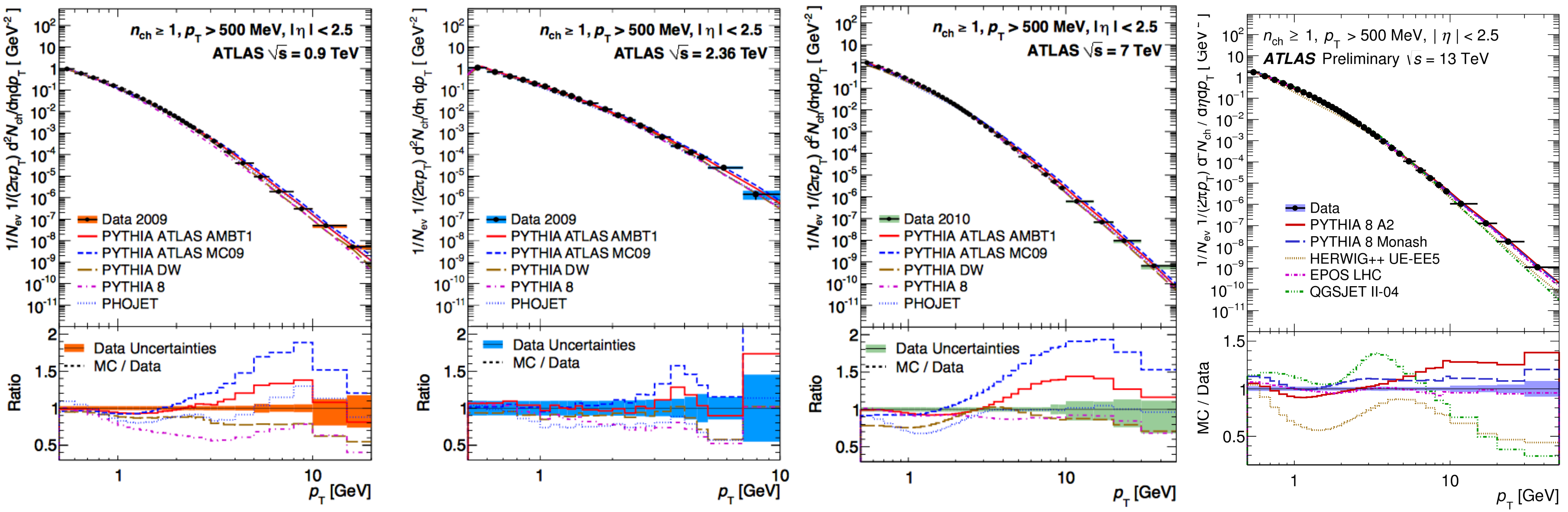
$dN_{ch}/d\eta$ http://arxiv.org/pdf/1012.5104v2.pdf



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

Different Centre of Mass Energy

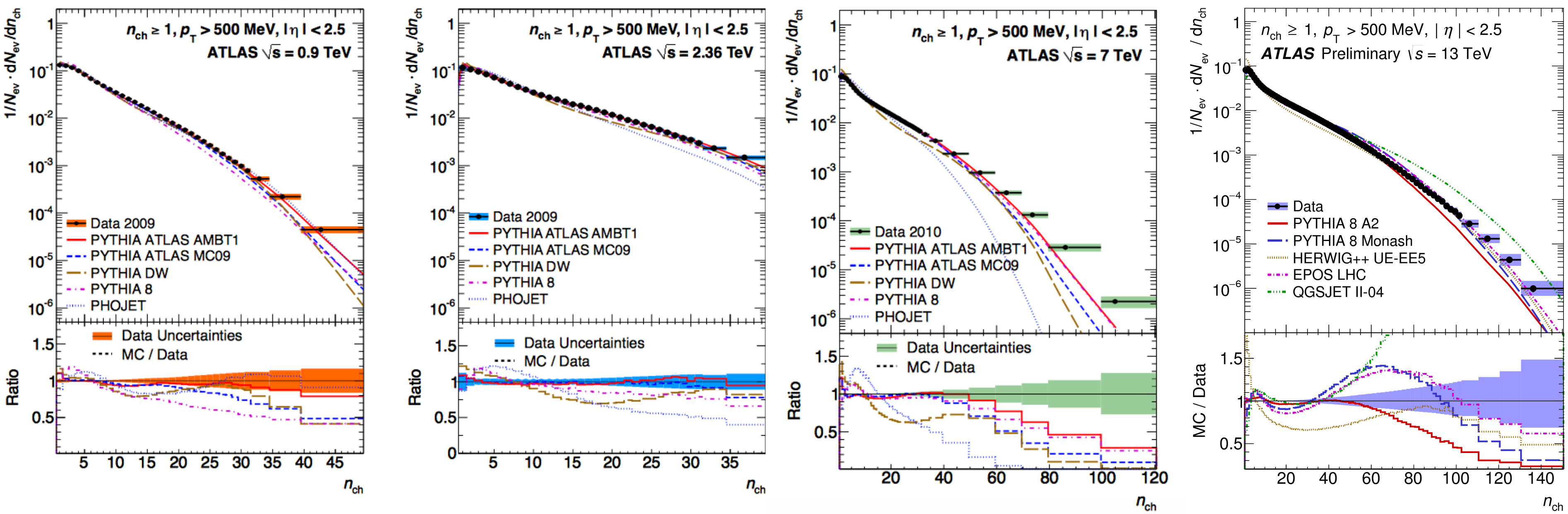
$d^2N_{ev}/d\eta dp_T$ http://arxiv.org/pdf/1012.5104v2.pdf



- Large disagreement at low p_T and high p_T

Different Centre of Mass Energy

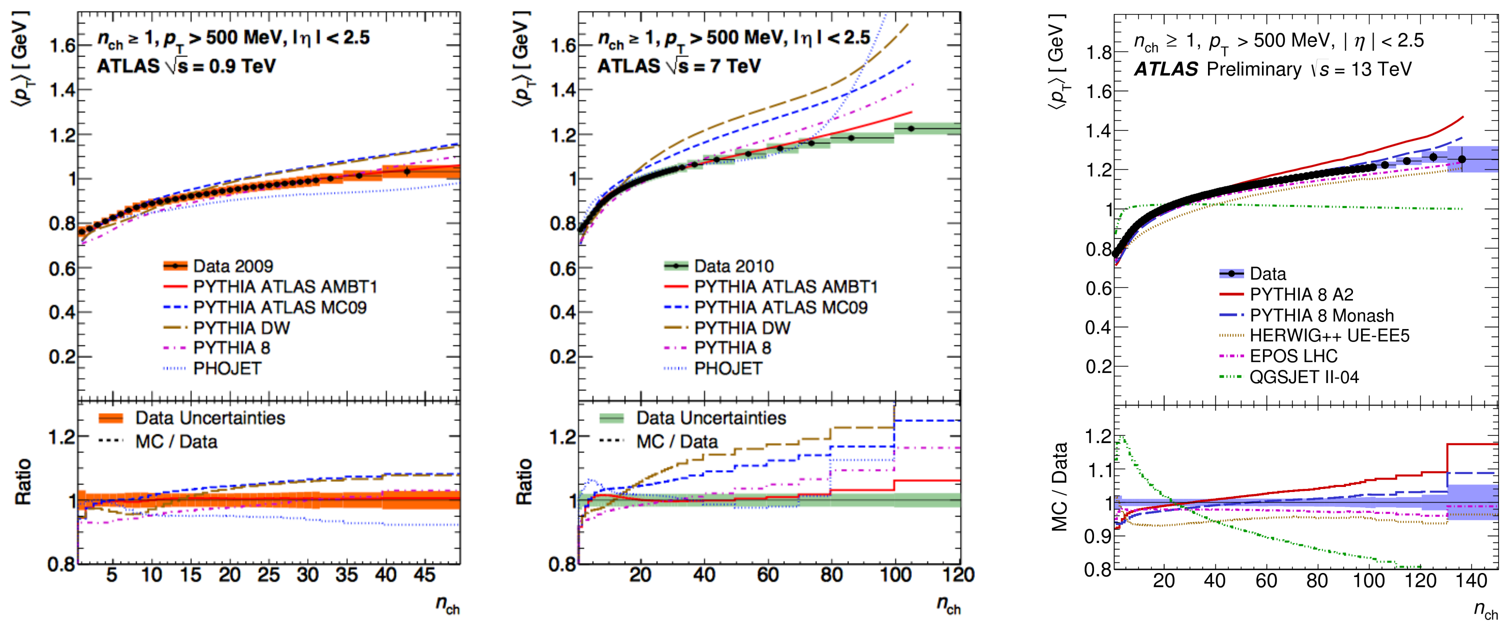
dN_{ev}/dn_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



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

Different Centre of Mass Energy

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

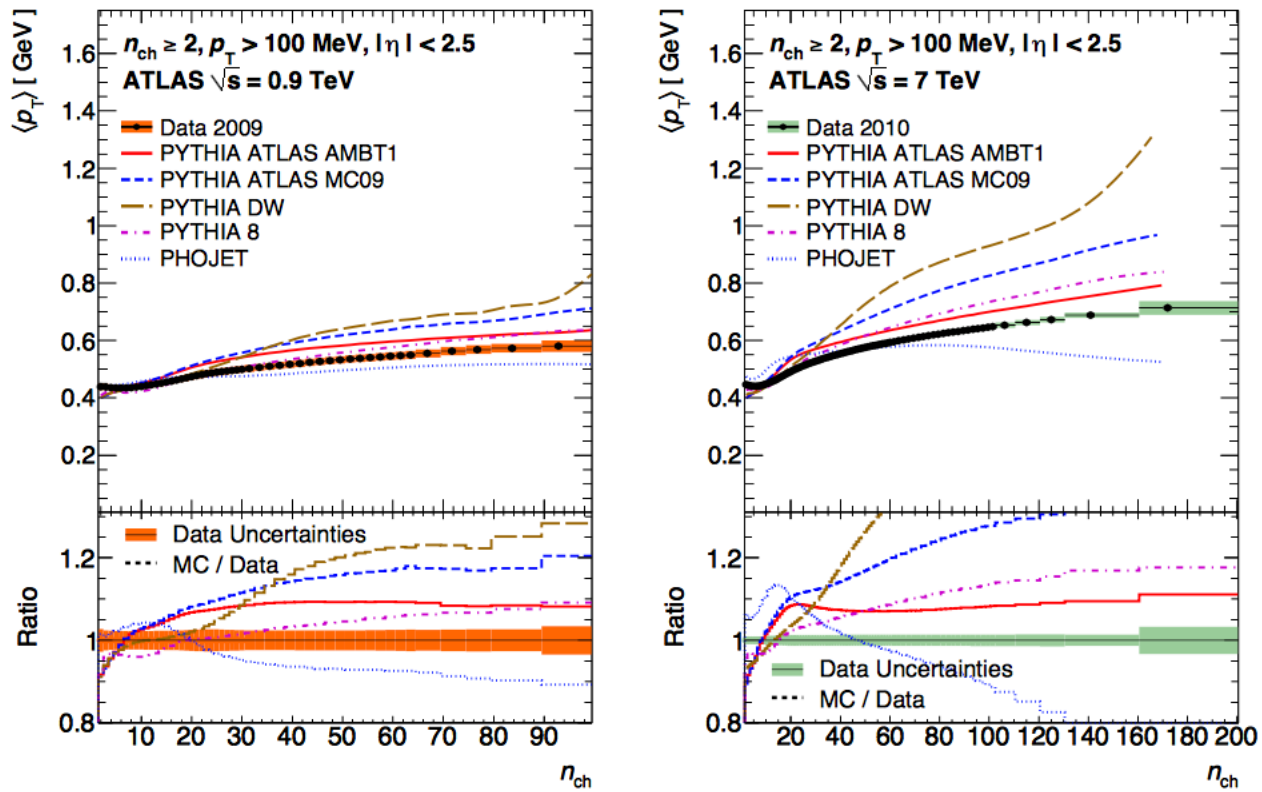


The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

- 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



- 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

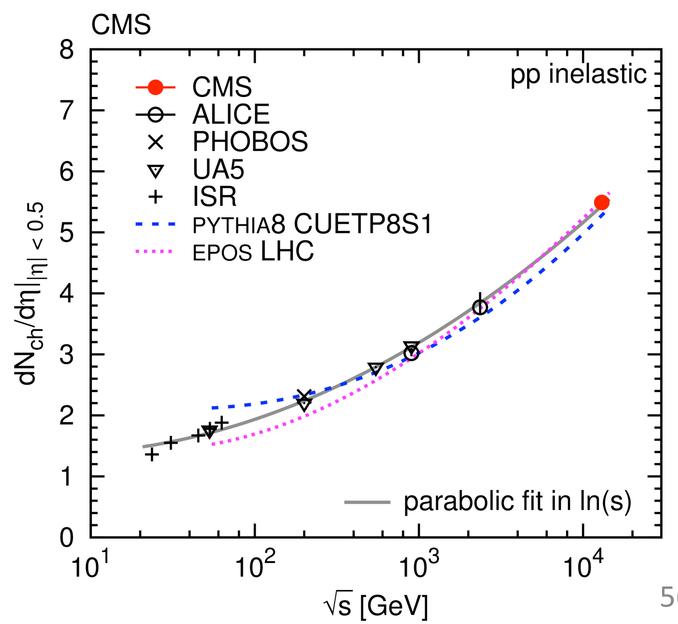
LHC Results Overview

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:

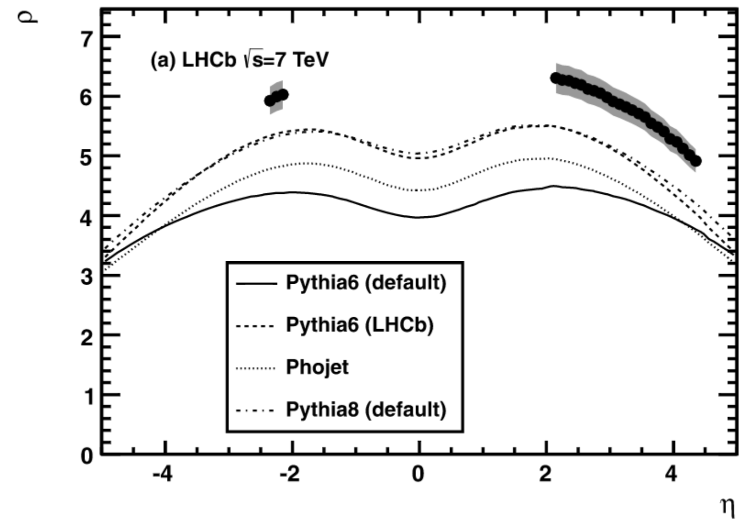
- 0.9, 2.36 (02/2010)
  - Charged hadrons
- 7 TeV (02/2010)
  - Charged hadrons
- 0.9, 2.36, 7 TeV (11/2010)
  - 5 pseudorapidity ranges from |eta|<0.5 to |eta|<2.4
- 8 TeV (05/2014) – with Totem
  - |η|<2.2, 5.3<|η|<6.4
- 13 TeV (07/2015)
  - no magnetic field



LHC Results Overview

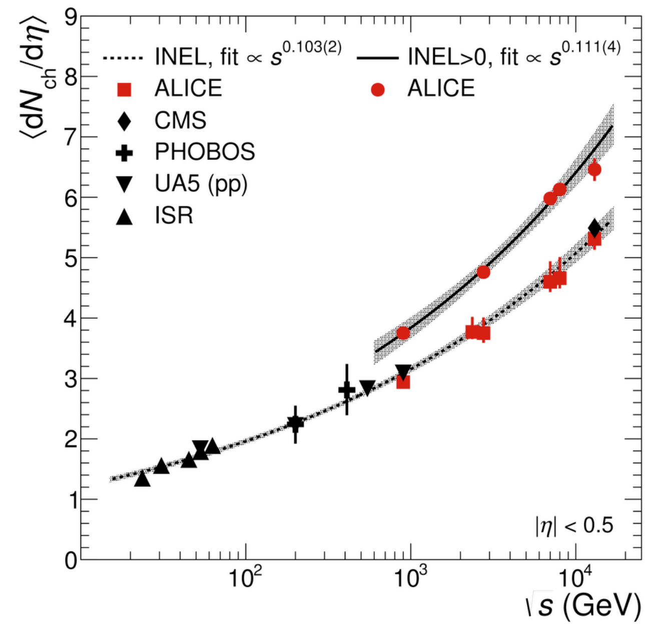
Minimum Bias measurements in LHCb:

- 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 $|\eta| < 1$



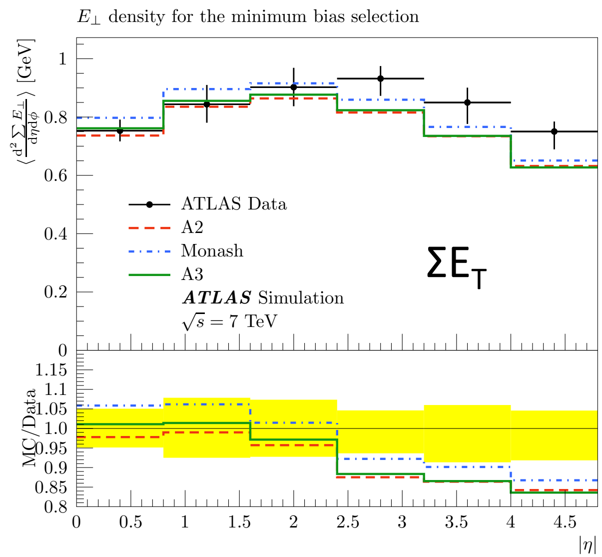
Strange Baryons

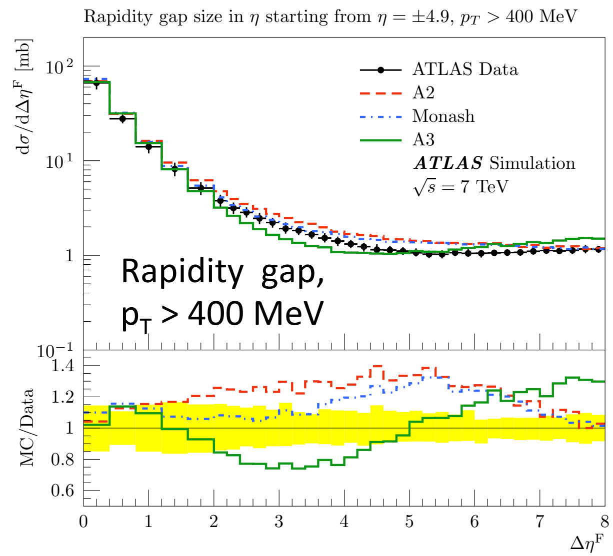
STRANGE BARYONS	
Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314^d
Ω^-	3334

Pythia8 Tunes Comparison

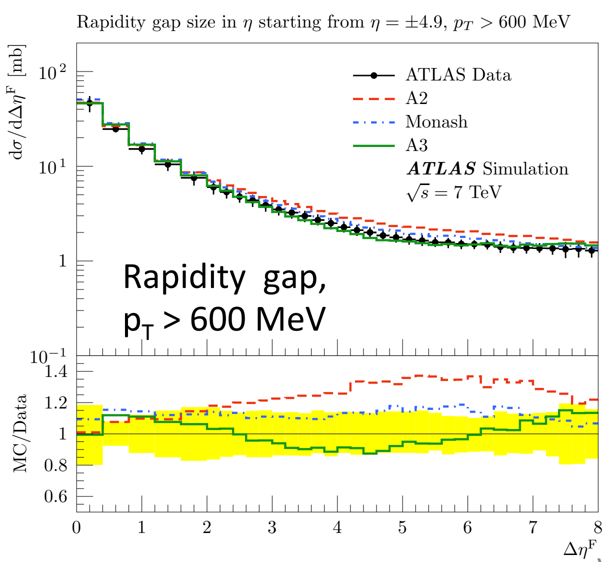
- **ΣE_T and rapidity gaps distributions at 7 TeV**

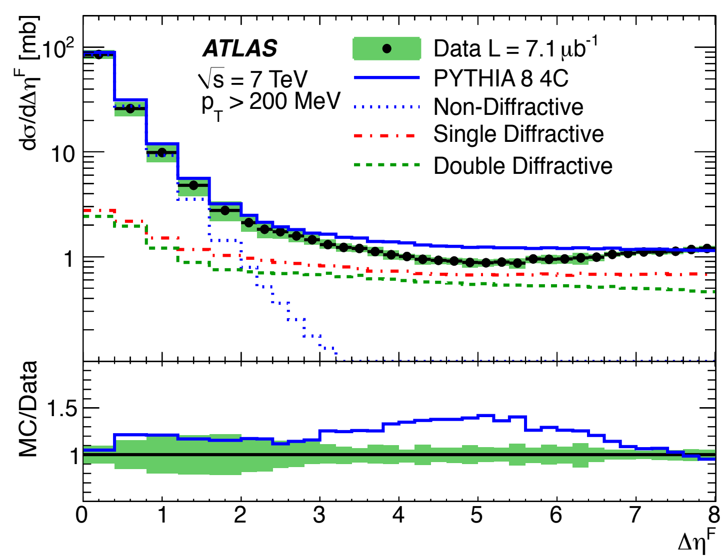
Good predictions given by A3 in the first bins





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





MC

- In HERWIG++ [17], inclusive hadron-hadron interactions are simulated by applying a MPI model for the non-diffractive processes to events without hard scattering. It is therefore possible to generate an event with zero 2→2 partonic scatters, in which only beam remnants are produced without anything between them. These types of events look similar to double-diffractive dissociation, even though HERWIG++ does not have any explicit model for diffractive processes.

  The version 2.7.1 is used with a 7 TeV underlying event tune, UE-EE-5-CTEQ6 [25] with CTEQ6L1 PDF [26] , which employs color reconnection and energy dependent MPI minimum p_{T} cutoff. It provides simultaneously a good description of both the underlying event and the double parton scattering data by tuning the deep parton interaction (DPI) effective cross section.

- 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.

MADGRAPH5_AMC@NLO+Pythia8

Observable	$t\bar{t}$ tune	General tune
$t\bar{t}$ gap fractions [12]		
Gap fraction vs Q_0 and Q_{sum} for $\|y\| < 2.1$ (2 dist.)	1	5
$t\bar{t}$ jet shapes [13]		
Differential light-jet shapes $\rho(r)$ for different p_T regions (5 dist.)	1	5
$t\bar{t}$ N_{jets} & jet p_T [14]		
$t\bar{t}$ cross section vs. jet multiplicity for dif. jet p_T cuts (4 dist.)	1	0
$t\bar{t}$ cross section vs. 1^{st} to 5^{th} jet p_T (5 dist.)	1	0
$t\bar{t}$ cross section vs. jet multiplicity for jets above 25 and 80 GeV (2 dist.)	0	5
$t\bar{t}$ cross section vs. 1^{st} and 5^{th} jet p_T (2 dist.)	0	5
Z/γ^* boson angular correlations [16]		
Z ϕ^*_η spectrum for $Z \to ee$ - region with $\phi^*_\eta < 0.5$ (1 dist.)	0	5
Z/γ^* boson p_T [18]		
Z p_T spectrum for $Z \to \mu\mu$ - region with $p_T < 50$ GeV (1 dist.)	0	5
Z/γ^* boson underlying event [17]		
$\sum p_T$ vs. Z p_T in toward & transverse regions - low $p_T(Z)$ (2 dist.)	0	5
N_{ch} vs. Z p_T in toward & transverse regions - for $p_T(Z)$ (2 dist.)	0	5
Dijet jet shapes [19]		
Jet shape ρ (49 dist.) for dif. p_T and η regions	0	1
Dijet azimuthal decorrelations [20]		
Dijet azimuthal decorrelations in three p_T^{max} regions (3 dist.)	0	1
Dijet gap fractions [21]		
Gap fraction vs $\|\Delta y\|$ with Fwd/Bwd jets - region with $\|\Delta y\| < 3.0$ (5 dist.)	0	1
$\overline{N_{jet}}$ vs $\|\Delta y\|$ with Fwd/Bwd jets - region with $\|\Delta y\| < 3.0$ (4 dist.)	0	1
Multi-jet cross sections [22]		
3-to-2 jet ratios for $p_T^{jets} > 80$ GeV & $p_T^{jets} > 110$ GeV ($R = 0.6$) (2 dist.)	0	1
Track-jet properties [23]		
Charged jet $\rho_{ch}(r)$ for dif. p_T and y regions ($R = 0.4$) (16 dist.)	0	1
Jet mass and substructure [24]		
For Cambridge-Aachen R=1.2 jets: jet mass, τ_{21} and τ_{23} (12 dist.)	0	1
For anti-kt R=1.0 jets: jet mass, $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, τ_{21} and τ_{23} (15 dist.)	0	1
Track-jet UE [25]		
Mean N_{ch} vs. p_T^{lead} in trans. region - for $p_T^{lead} > 30$ GeV (5 dist.)	0	1
Mean p_T vs. p_T^{lead} in trans. region - for $p_T^{lead} > 30$ GeV (5 dist.)	0	1
η dependence on E_T [26]		
$\sum E_T$ for the dijet selection (6 dist.)	0	1
Leading jet UE [27]		
$\sum p_T^{ch}$ vs. p_T^{lead} in trans-min region for $p_T^{lead} > 200$ GeV (1 dist.)	0	1
N_{ch} vs. p_T^{lead} in trans-min region for $p_T^{lead} > 200$ GeV (1 dist.)	0	1

Table 1: The specific observables and tuning ranges from the Rivet analyses chosen for the two tunes developed: A15-MG5aMCNLO-TTBAR and A15-MG5aMCNLO. The last two columns provide the weights used in each tune.