Bose-Einstein correlations and results on minimum bias interactions, underlying event and particle production from ATLAS

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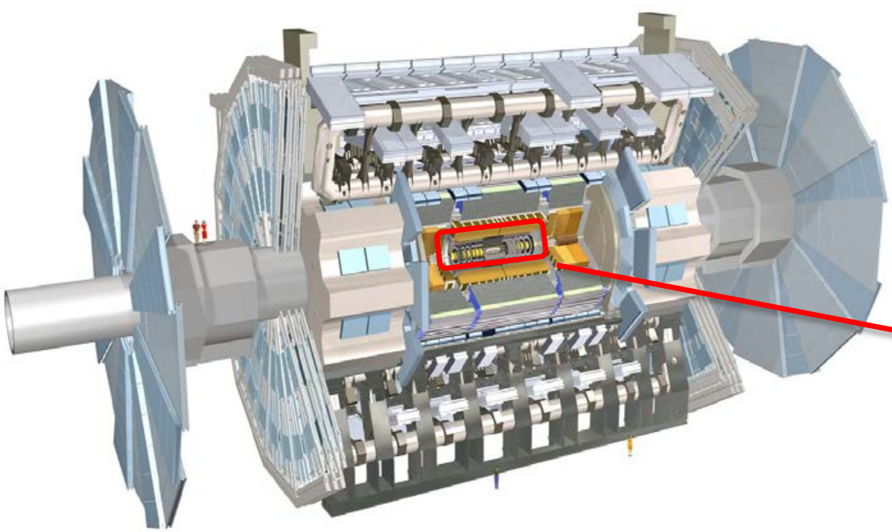
XLV International Symposium on Multiparticle Dynamics
Wildbad Kreuth, Germany, 4 – 9 October 2015

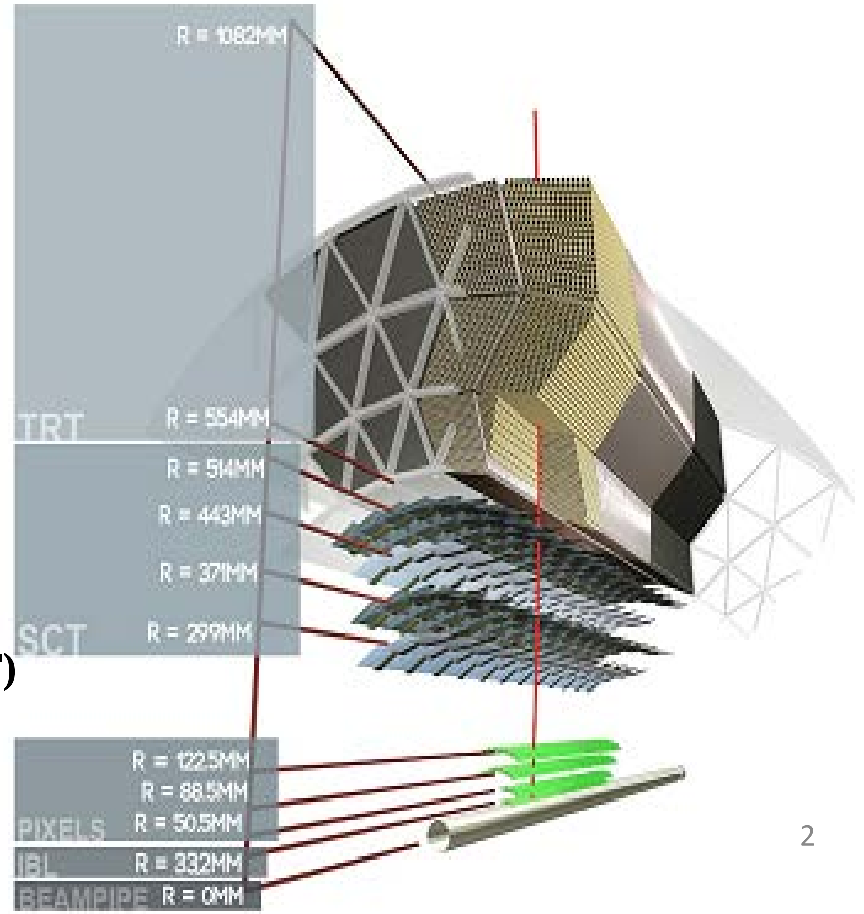
Overview

The focus of ATLAS is high-p_T physics, and also provides a window onto important <u>softer QCD processes</u>. These have intrinsic interest but also the understanding of underpins searches for new physics.

Selected topics, *often 13 TeV first results*. ►Bose Einstein Correlations ►Charged-particles distributions ►Underlying event ►Particles production

ATLAS now has data 0.9 – 13 TeV in the same detector, allowing scale evolution to be probed.





ATLAS Inner Detector (ID) **main tracking device**:

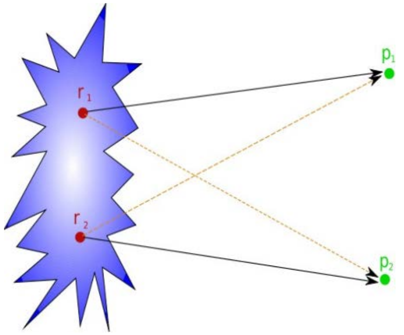
Consists of **Pixel, Silicon strip (SCT) and drift tube (TRT) detectors.** Single hit resolution between 10 µm (Pixel) and 130 µm (TRT).

<u>New: ***Insertable B-Layer* (IBL)** in the Pixel</u>.

Bose-Einstein Correlations

Correlations in phase space **between two identical bosons** from symmetry of wave functions.

- ► Enhances likelihood of two particles close in phase space
- ► Allows one to 'probe' the source of the bosons in size and shape
- ► Dependence on particle multiplicity and transverse momentum probes the production mechanism



Correlation function $C_2(Q)$ a ratio of probabilities:

$$C_2(Q) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} = C_0\left(1 + \Omega(\lambda, RQ)\right)\cdot\left(1 + Q\varepsilon\right), \qquad Q^2 = -(p_1 - p_2)^2$$

$$\Omega^G(\lambda, RQ) = \lambda e^{-R^2Q^2}$$

$$\Omega^E(\lambda, RQ) = \lambda e^{-RQ}$$

C_0 is a normalisation, **ε** accounts for long range effects, **R** is the effective radius parameter of the source, **λ** is the strength of the effect parameter, 0/1 for coherent/chaotic source. Two possible parameterisation: Gaussian and Exponential.

$$C_2(Q) = \frac{N^{++,--}(Q)}{N^{ref}(Q)}$$

N_{ref} without BEC effect from: unlike-charge particles (UCP), opposite hemispheres, event mixing. **Basic Reference**: distribution of UCP pairs of non-identical particle taken from the same event.

$$R_2(Q) = \frac{C_2^{Data}(Q)}{C_2^{MC}(Q)} = \frac{\rho(++,--)\big/\rho(+-)}{\rho^{MC}(++,--)\big/\rho^{MC}(+-)}$$

The studies are carried out using the **double ratio correlation function**. The **$R_2(Q)$** eliminates problems with energy-momentum conservation, topology, resonances etc. **MC without BEC.**

Inclusive Double Ratio correlation functions

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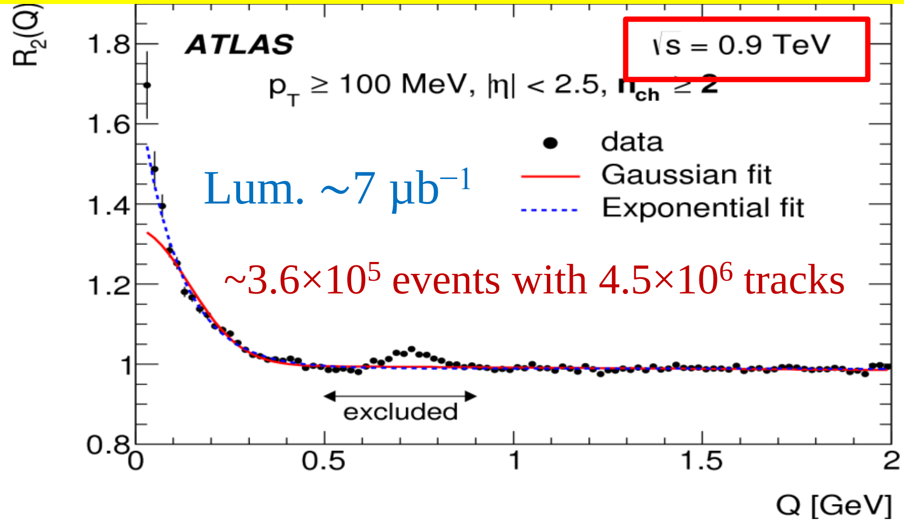

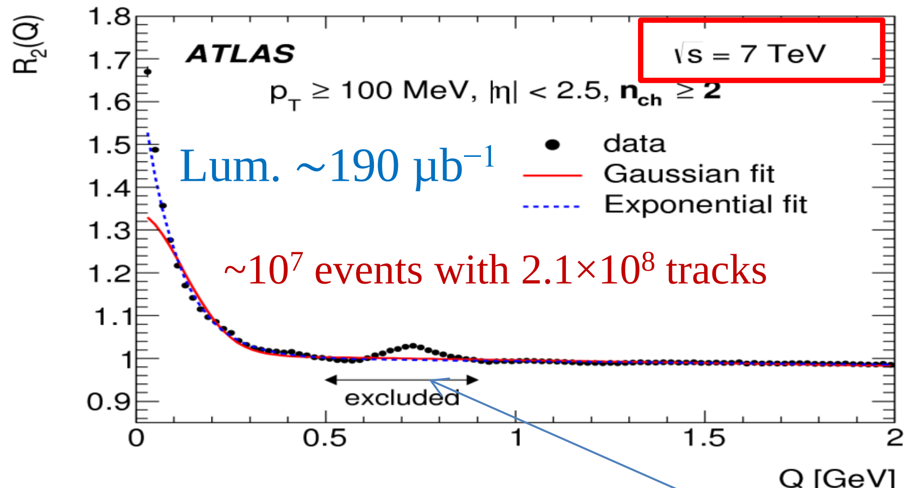

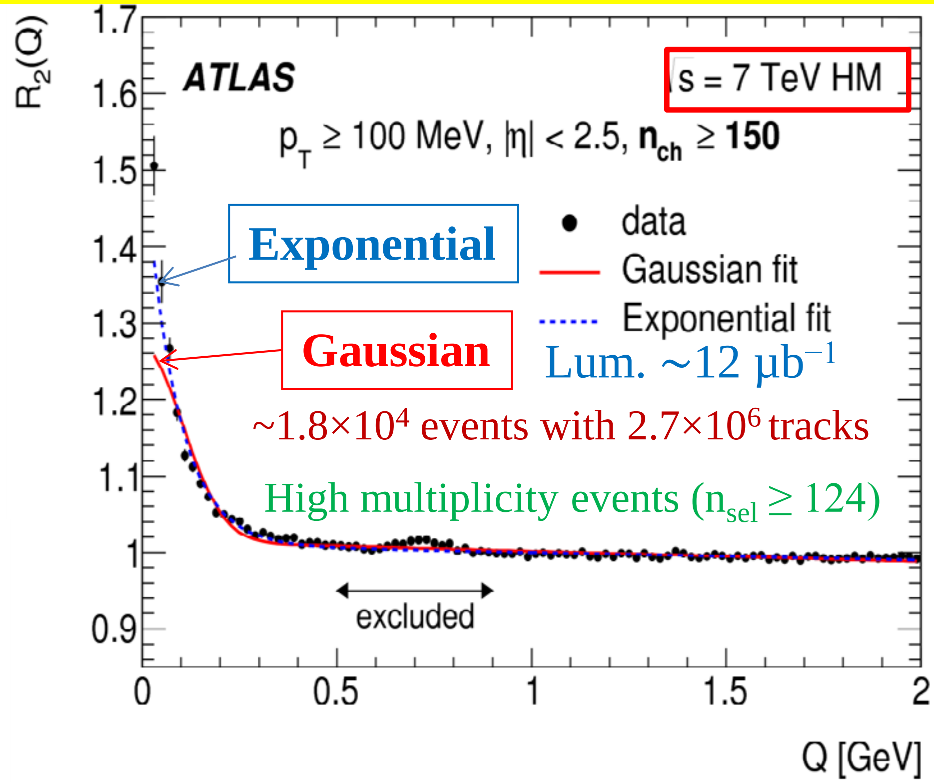

Studies of one-dimensional BEC effects in **pp** collisions for **p_T>100 MeV and $|\eta|$ < 2.5** at centre-of-mass energies of **0.9 and 7 TeV**.

Fit to extract strength and source size. **Goldhaber** spherical shape with a **Gaussian** distribution of the source. **Exponential**, radial Lorentzian distribution of the source -> **much better at low Q.**

Bump in ρ-meson region because **MC overestimates ρ→ππ**, therefore **region 0.5 – 0.9 GeV excluded** from the fit. **Q region is from 0.02 to 2 GeV.**

Comparison with other experiments

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The results of BEC parameters for **Exponential fits of R_2 used total uncertainties**

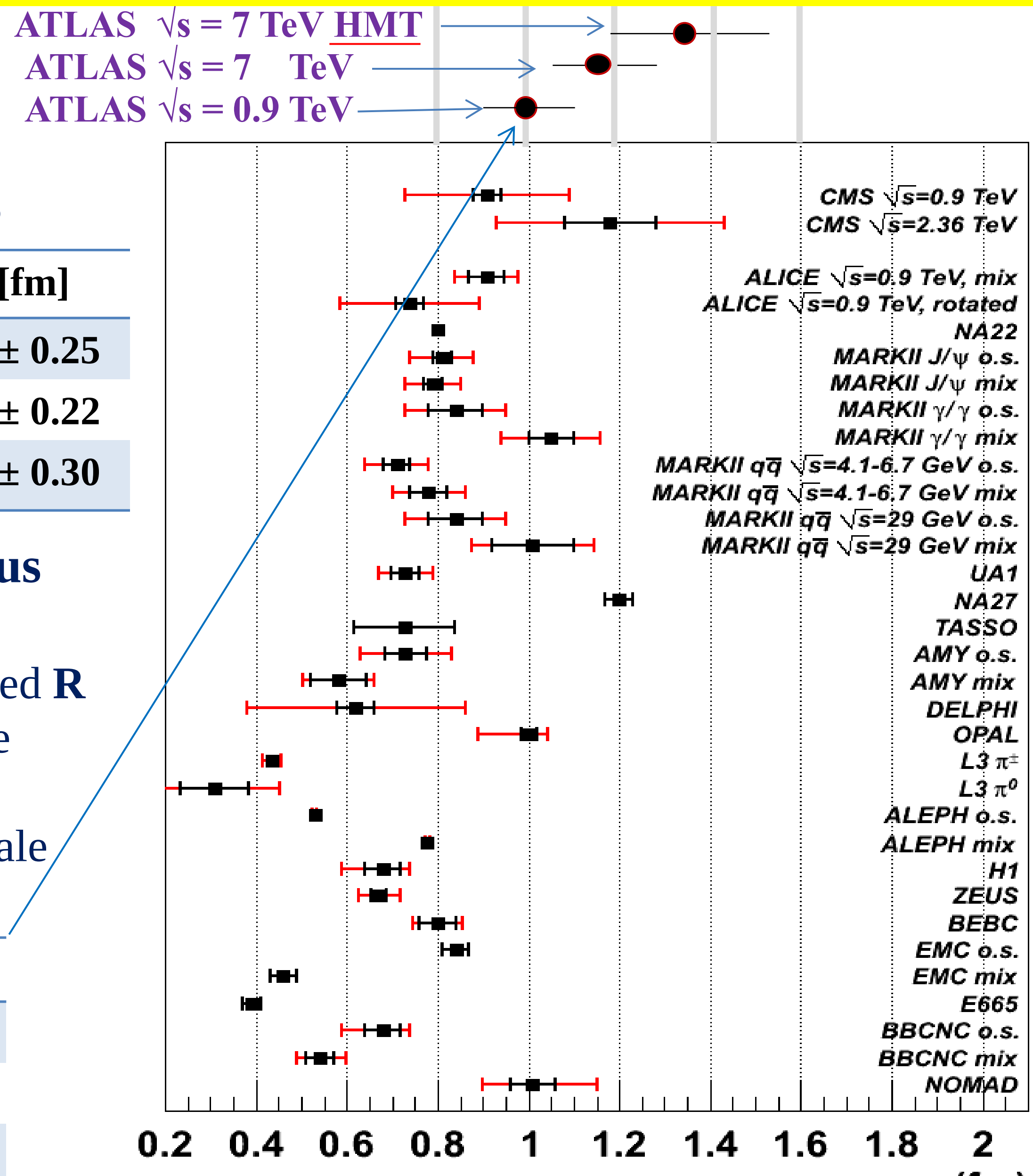
Statistical uncertainties are below 2–4 %

Energy [GeV]	n_{ch}	λ	R [fm]
0.9	≥2	0.74 ± 0.10	1.83 ± 0.25
7	≥2	0.71 ± 0.07	2.06 ± 0.22
7 (HM)	≥150	0.74 ± 0.06	2.36 ± 0.30

Comparison with results of previous experiments

Most of the previous experiments provided **R** measurement using the Gaussian fit. The calculation of **Gaussian** result from the Exponential fit can be done using the scale factor $\sqrt{\pi}$: $R^{(G)} = R^{(E)} / \sqrt{\pi}$

Energy [GeV]	n_{ch}	R [fm]
0.9	≥2	1.03 ± 0.14
7	≥2	1.16 ± 0.12
7 (HM)	≥150	1.33 ± 0.17



Multiplicity dependence of λ and R BEC parameters

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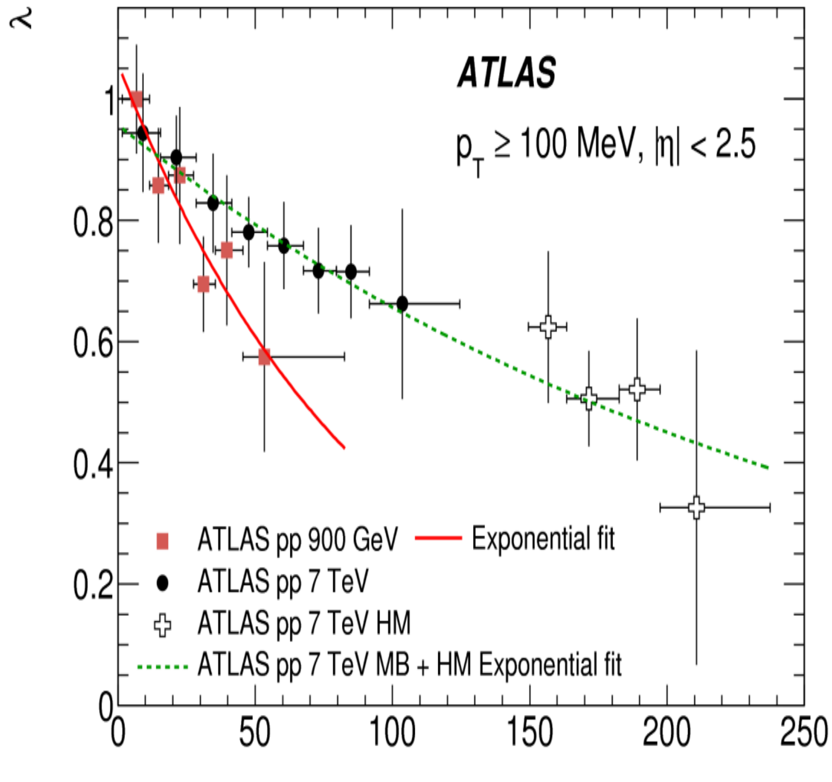
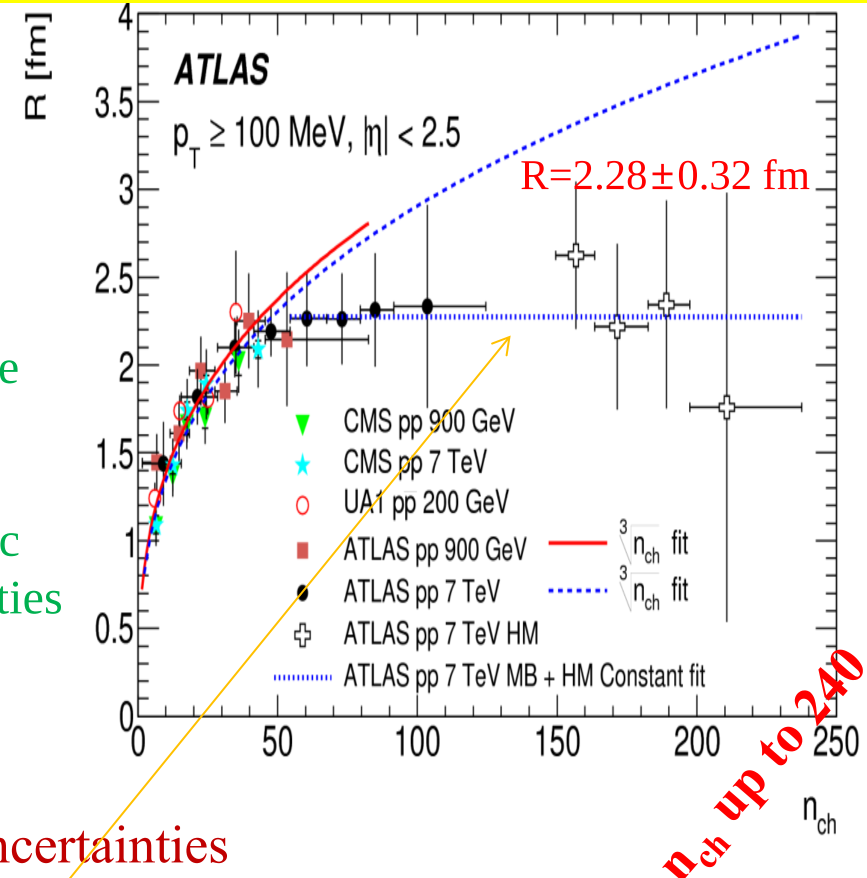


The error bars – quadratic sum of the statistical and the systematic uncertainties



► λ and R are energy independent within the uncertainties

► λ exponentially decrease with multiplicity

► R of the $\alpha \cdot n_{ch}^{1/3}$ fit for ***$n_{ch} \leq 55$ at 0.9 TeV is $\alpha = 0.64 \pm 0.07$ fm,***
at 7 TeV is $\alpha = 0.63 \pm 0.05$ fm

► **R** is a ***Constant*** for $n_{ch} > 55$ at 7 TeV ***R=2.28±0.32 fm*** **observed for the first time**

► Pomeron-based model: Predicted ***plateau for n_{ch} ~60-80 with R =2.2 fm*** and ***decreasing of R to 1 fm for higher multiplicity.*** **PL B703(2011) 288**

k_T DEPENDENCE OF λ AND R PARAMETERS

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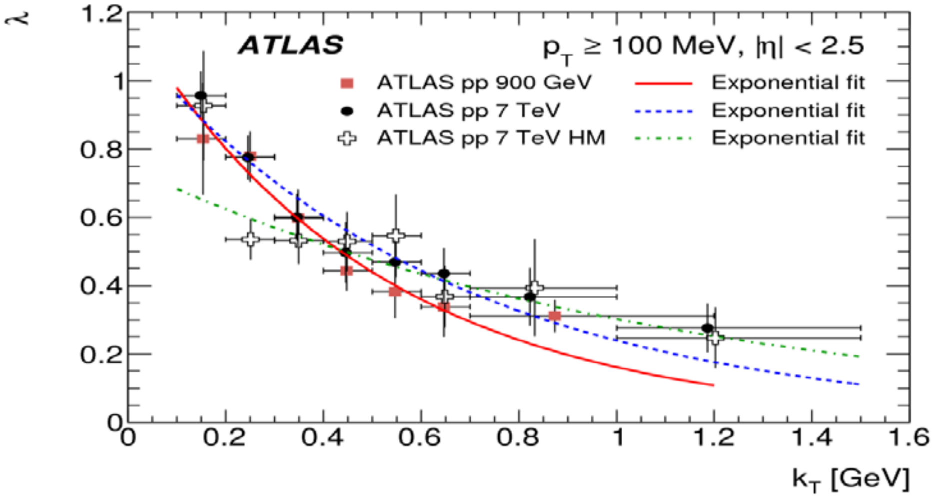
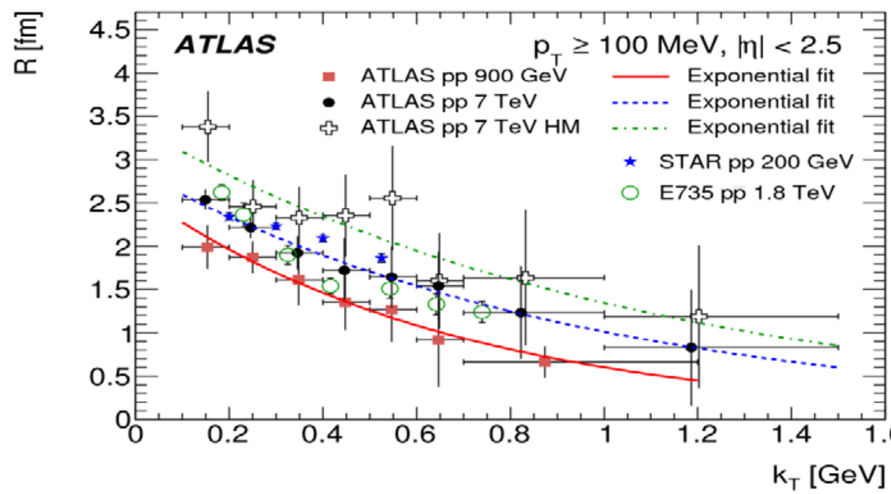
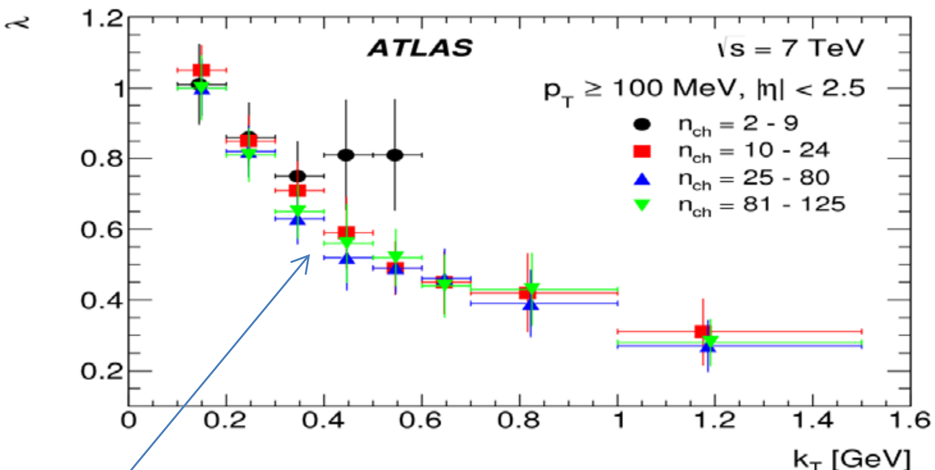
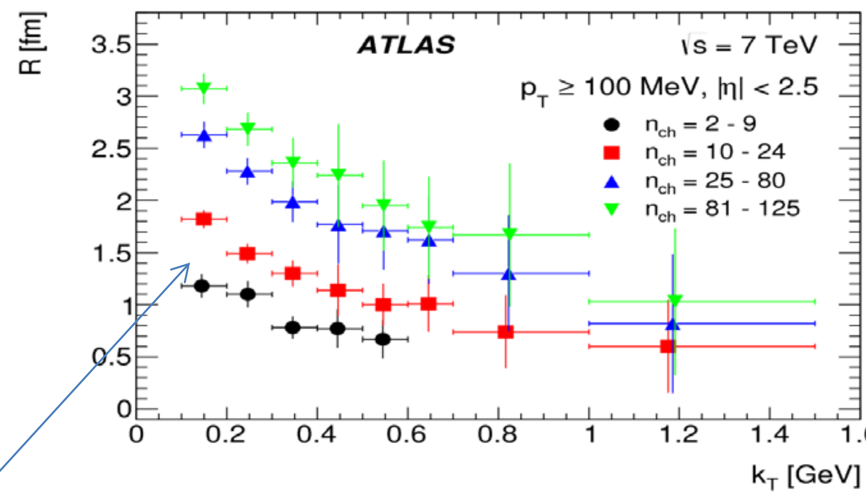
$$k_T = \frac{(\vec{p}_{T,1} + \vec{p}_{T,2})}{2}$$





►λ and *R* are energy-independent within uncertainties; ►λ and R decrease exponentially with k_T; ►Good agreement with earlier (non-LHC) measurements





►No k_T –dependence of λ for different multiplicity intervals

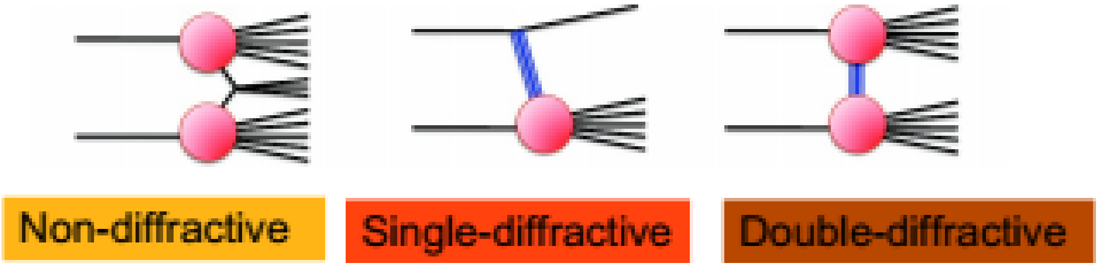
► k_T –dependence of R shows R increasing with multiplicity interval

Charged-particle distributions at 13 TeV

ATLAS-CONF-2015-028

The composition of inelastic p-p collisions:

Statistics: 9 million inelastic interactions



Perturbative QCD describes only the hard-scattered partons, all the rest is predicted with **phenomenological models.**

ND: QCD motivated models with many parameters;

Background when >1 interactions per bunch crossing;

SD+DD not well constrained by models.

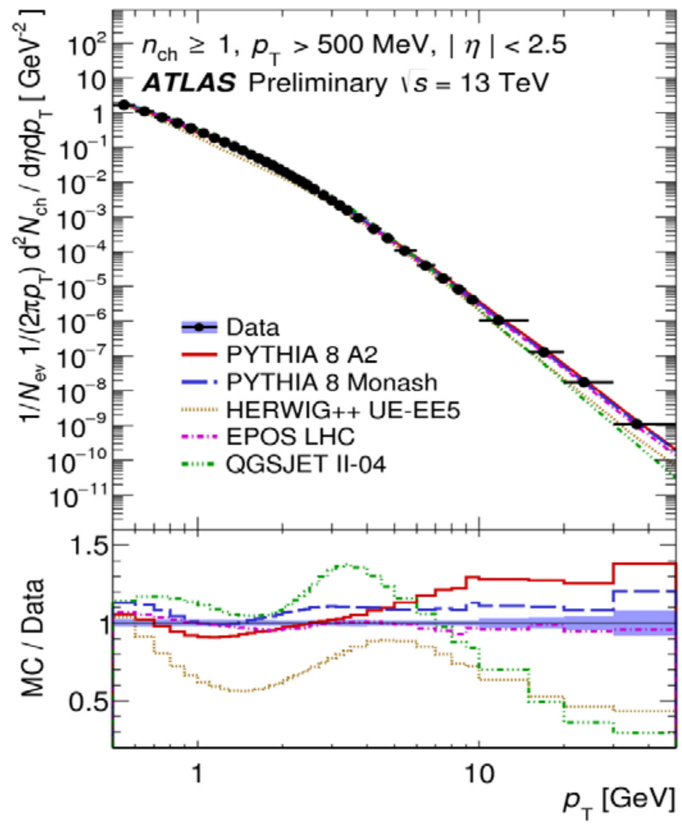
Strange baryons with $30 < \tau < 300$ ps are excluded.

Task: measure spectra of primary charged particles corrected to hadron level.

Multiplicity vs.η; Multiplicity vs. p_T; Multiplicity distribution

$$\frac{1}{N_{ch}} \cdot \frac{dN_{ch}}{d\eta}, \quad \frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta dp_T}, \quad \frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}, \quad \langle p_T \rangle \ vs. \ n_{ch}$$

Measurement – do not apply model dependent corrections and allow to tune models to data measured in well defined kinematic range.

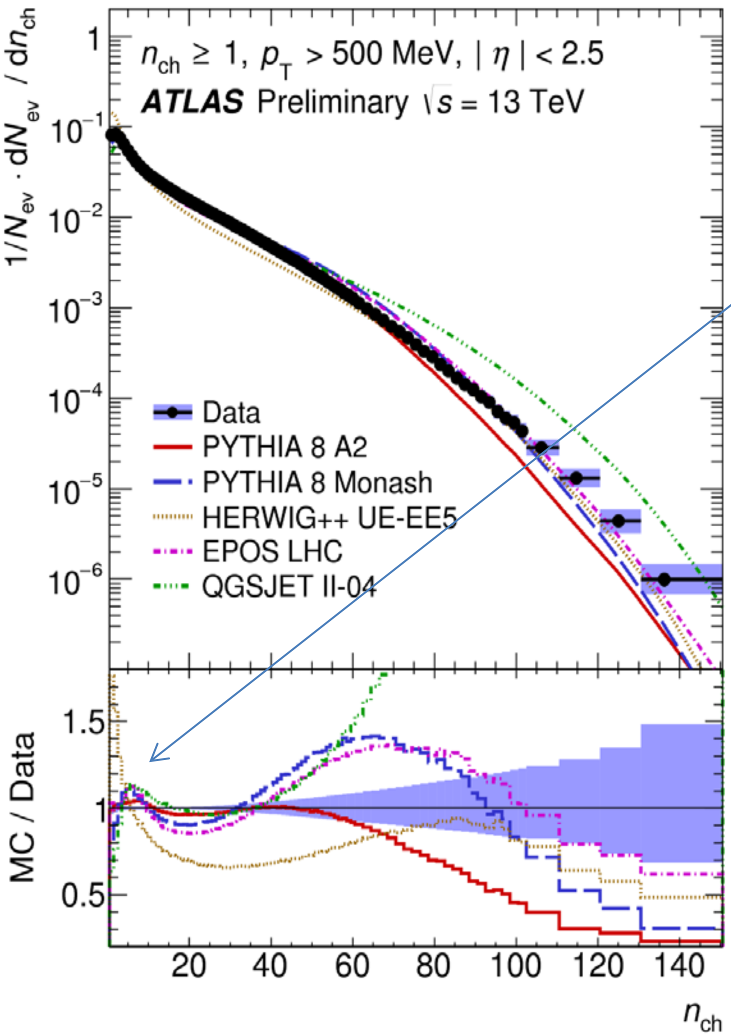


Charged-particle multiplicity as a function of $\mathbf{p_T}$ for events with **$n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$**

Measurement spans **10 orders of magnitude**. **EPOS and Pythia 8 Monash** give remarkably good predictions.

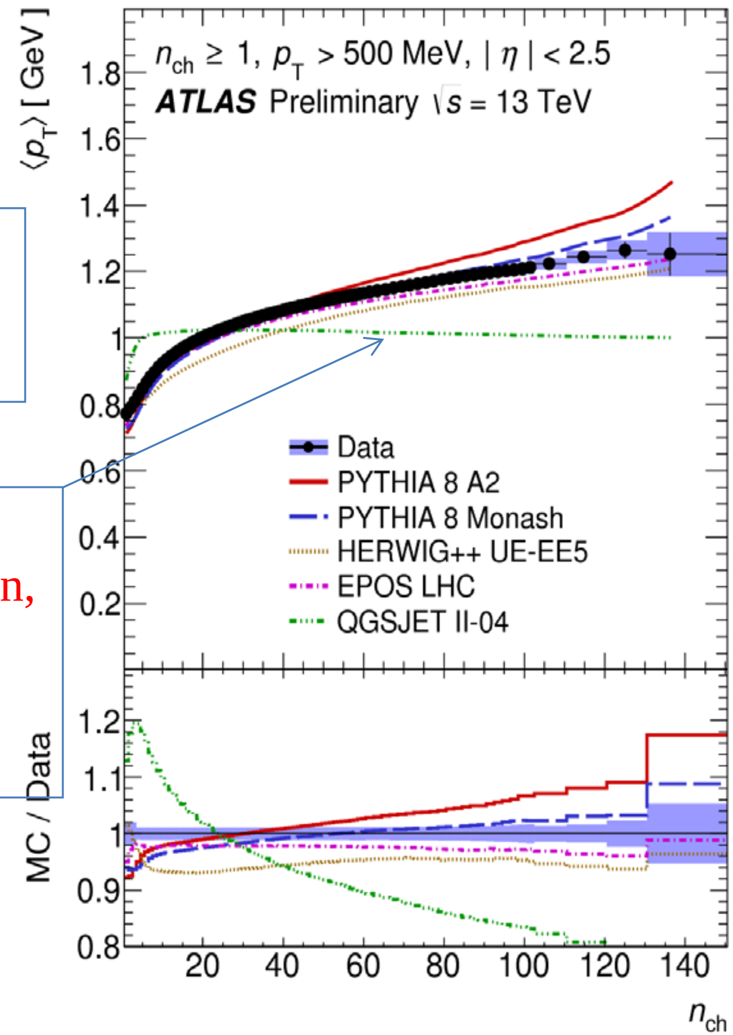
More details for 13 TeV results on Friday by Hideyuki Oide

dN_{ev}/dN_{ch} AND $\langle p_T \rangle$ VS N_{ch} ATLAS-CONF-2015-028



Low n_{ch} not well modelled by any MC

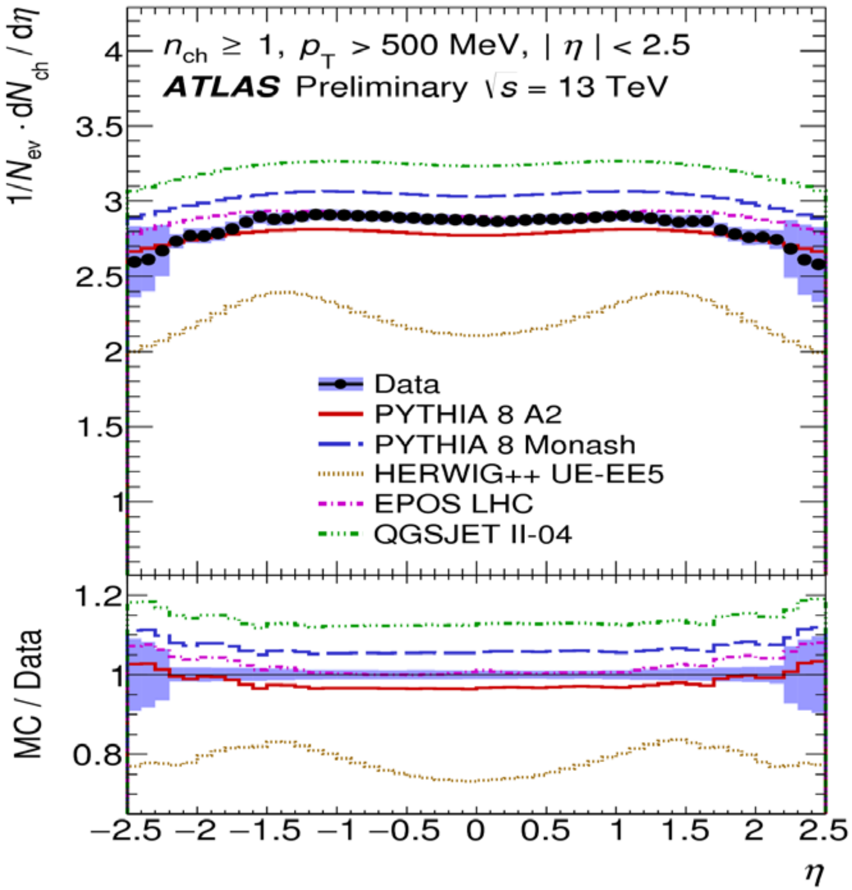
Models without colour reconnection, **QGSJET,** fail to model scaling with n_{ch}



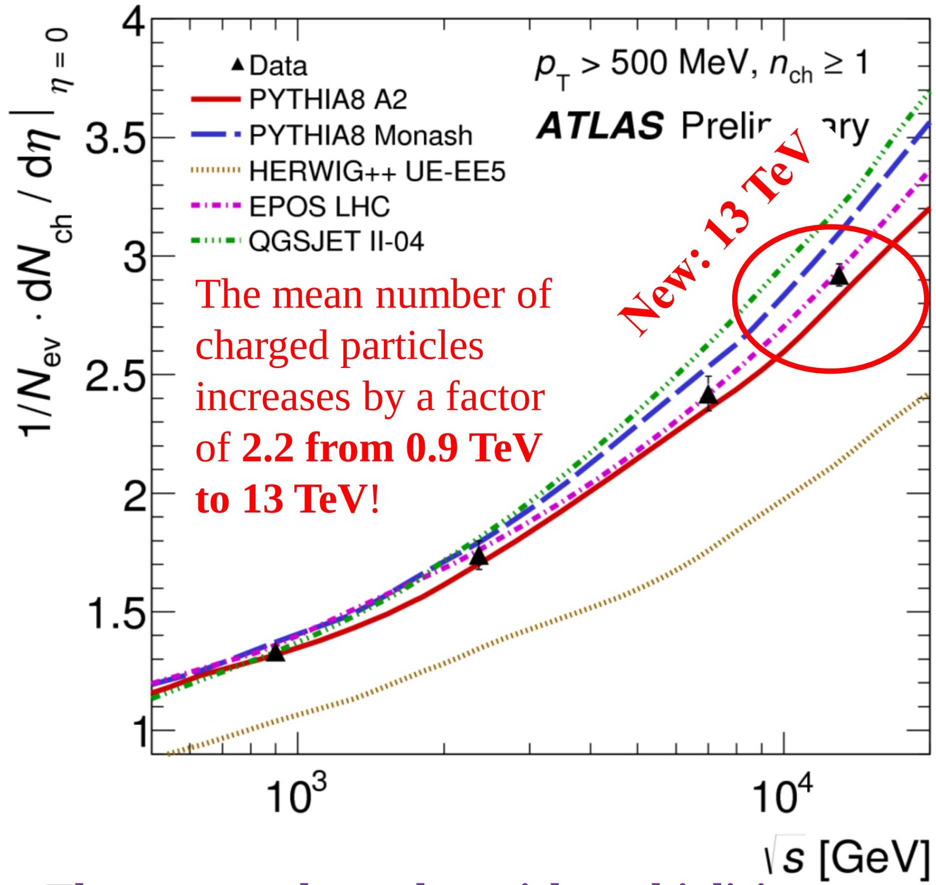
Charged-particle events and **mean transverse momentum** as a functions of **multiplicity**. The dots represent the data and the curves the predictions from different MC models.
The bottom inserts show the ratio of the MC/Data.

$dN_{CH}/d\eta$ AND AVERAGE MULTIPLICITY

ATLAS-CONF-2015-028



Charged-particle multiplicity as a function of η



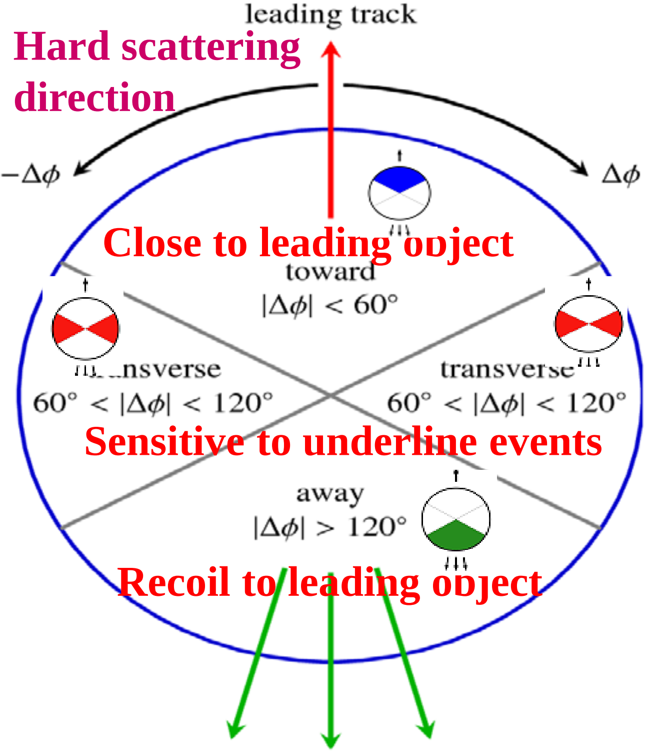
The same shape in Models but different normalisation. Except **HERWIG** which is tuned entirely on ***UE***. **EPOS** and **Pythia 8 A2** give remarkably good predictions

The average charged-particle multiplicity per unit of rapidity for η=0 as a function of the centre-of-mass **energy from 0.9 to 13 TeV.** The definition of charged-particle includes charged strange baryons

Analysis is ongoing: Reduced |η|<0.8 for comparison to the various detectors; Extended for p_T> 0.1 GeV; High multiplicity events

Underlying Event

ATL-PUB-2015-019; EPJC 74 (2014) 3195
EPJC 74 (2014) 2965



The underlying event (UE) is defined as the 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**)

These soft interactions cannot be calculated with perturbative QCD:

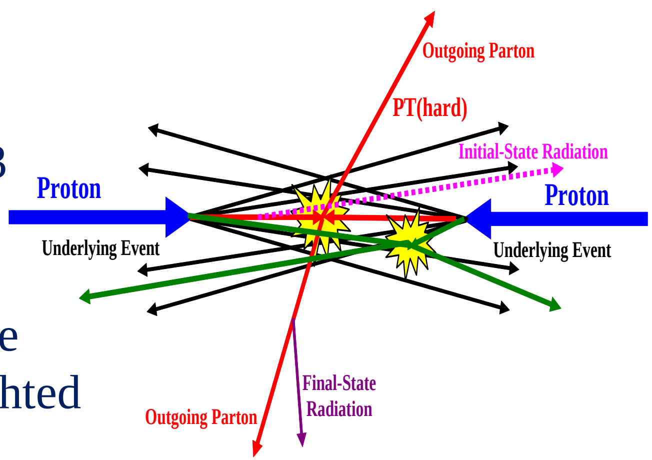
- ► Free parameters to be tuned using data

Leading object can be defined variously:

- ► Leading jet , Z (p_T), Leading track in Minimum Bias like events

Preliminary 13 TeV analysis based on Leading track:

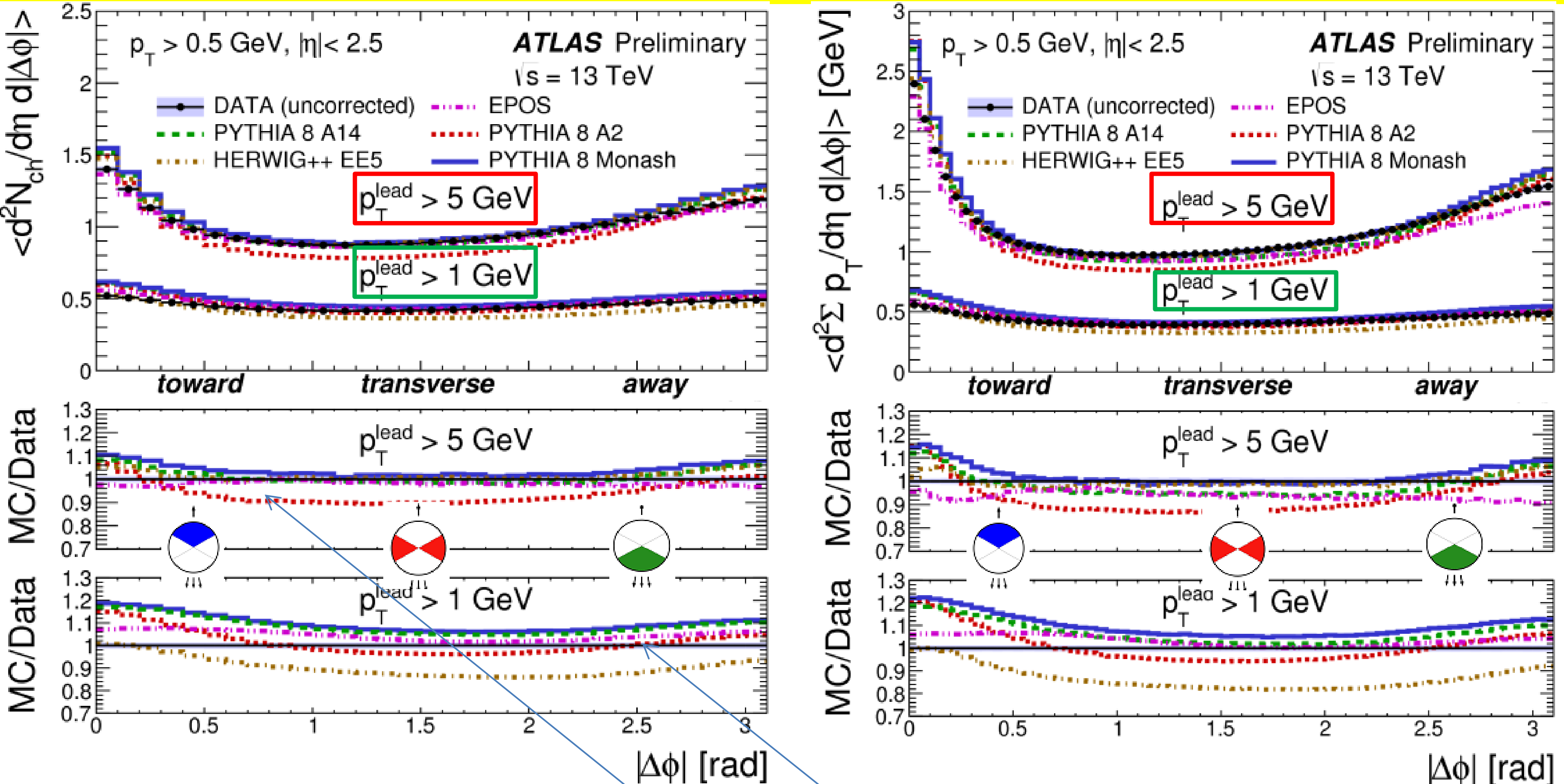
- ► Same dataset and same event and track selection as the MB13 analysis with an ***additional requirement*: leading track with a p_T of at least 1 GeV**
- ► Results presented at detector level, without any correction (the width of the vertex distribution along the Z axis in MC is reweighted to match the data)
- ► The tracking efficiency uncertainty is about ≤**2%**
- ► No correction for secondary tracks is performed



More details for 13 TeV results on Friday by Hideyuki Oide

Underlying event Leading track vs |Δφ| at 13 TeV

ATL-PUB-2015-019



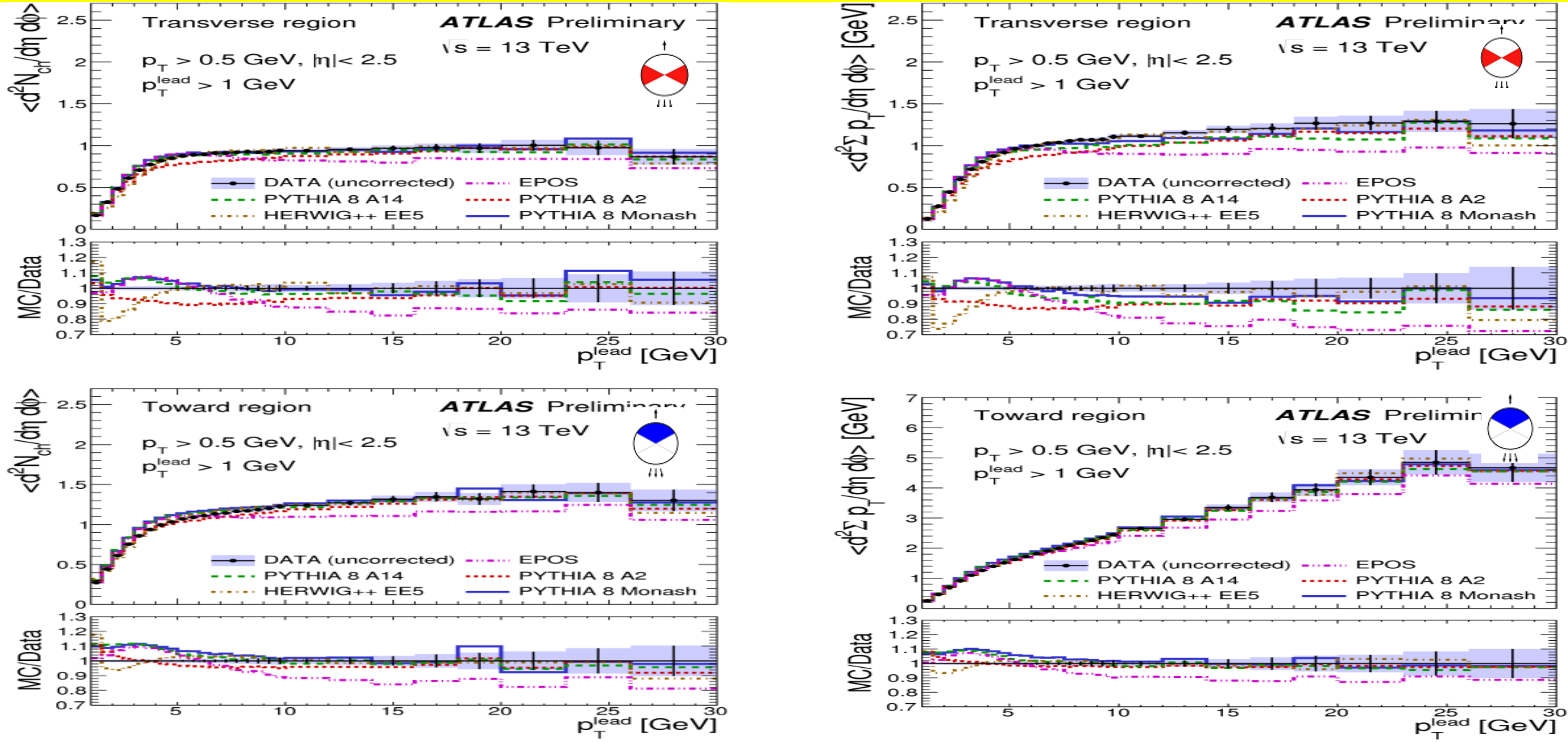
Comparison of detector level data and MC predictions for the |Δφ| **distributions** of **average track multiplicity density** (left) and **average scalar p_T sum density of tracks** (right).

The leading track is defined to be at Δφ = 0, and excluded from the distributions.

- ► Good Data/MC agreement with Minimum-Bias tune (**A2**) at $p_T^{lead} > 1$ GeV
- ► Good Data/MC agreement with UE tunes (**Herwig++, Monash, A14**) at $p_T^{lead} > 5$ GeV

Underlying event Leading track vs p_T^{LEAD} at 13 TeV

ATL-PUB-2015-019



Comparison of detector level data and MC predictions for **average track multiplicity density values** (left column) and **average scalar p_T sum density of tracks** (right column) as a function of **track p_T^{lead}** in the transverse (top row) and toward (bottom row) regions.

► These detector level distributions show discriminating power between different MC models

► However, none of the models are very discrepant from data, building confidence in MPI energy extrapolation model used in these generators

► <u>From 10 GeV: good description for the UE tunes. The EPOS 15% off in the plateau</u>

Underlying event Z and Jets at 7 TeV

EPJC 74 (2014) 3195
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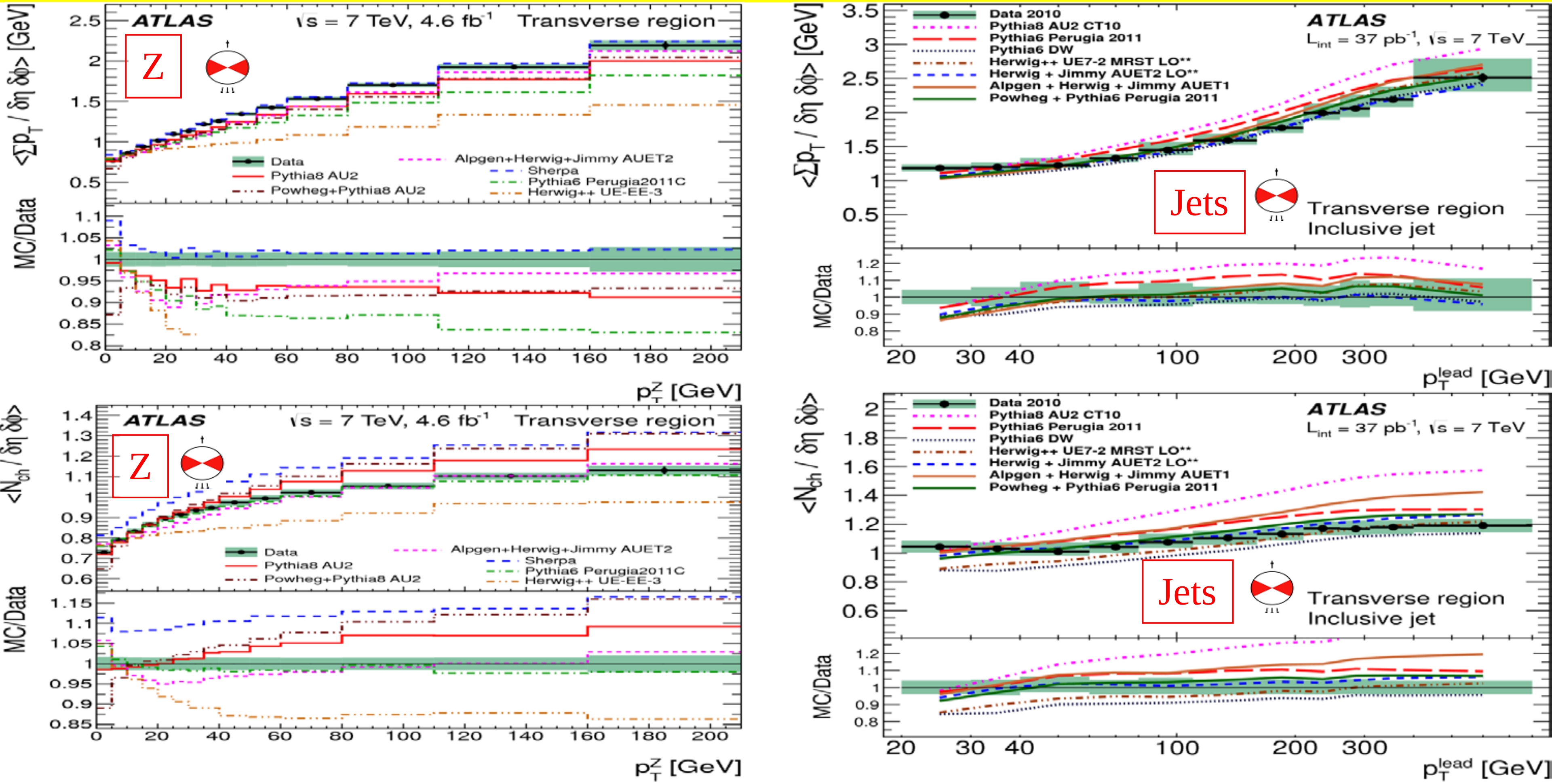


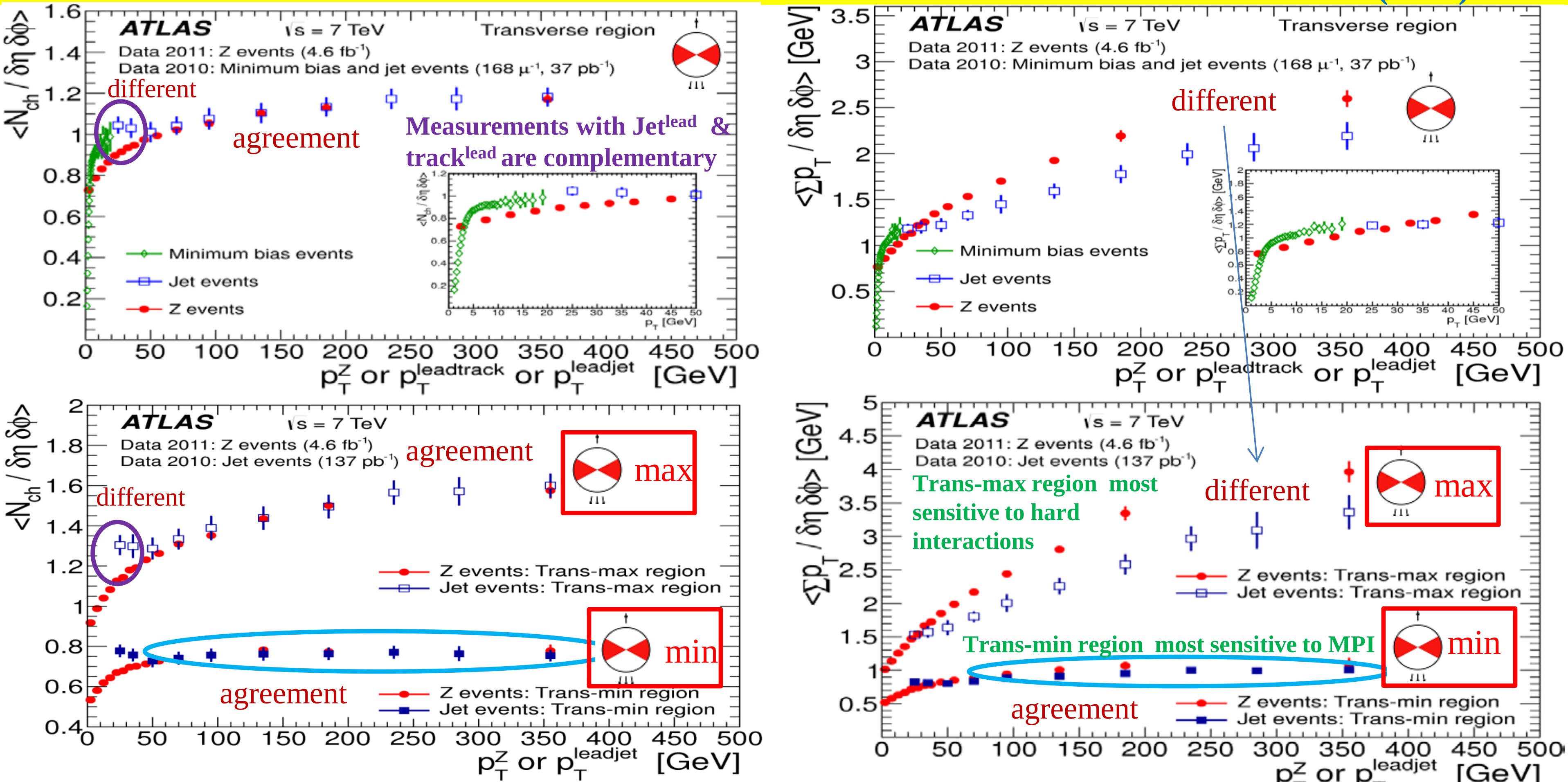
Comparison of detector level data and MC predictions for **average scalar p_T sum density of tracks** (top row) and **average track multiplicity density values** (bottom row) as a function of Z (left column) and leading jet (right column) **transverse momentum.**

► For Jets: **Not perfect agreement** between **data and simulation Herwig** better than **Pythia6**

► For Z-boson: Good description given by **Sherpa**, followed by **PYTHIA 8**, **ALPGEN** and **POWHEG**

Underlying event Z and Jets at 7 TeV

EPJC 74 (2014) 3195

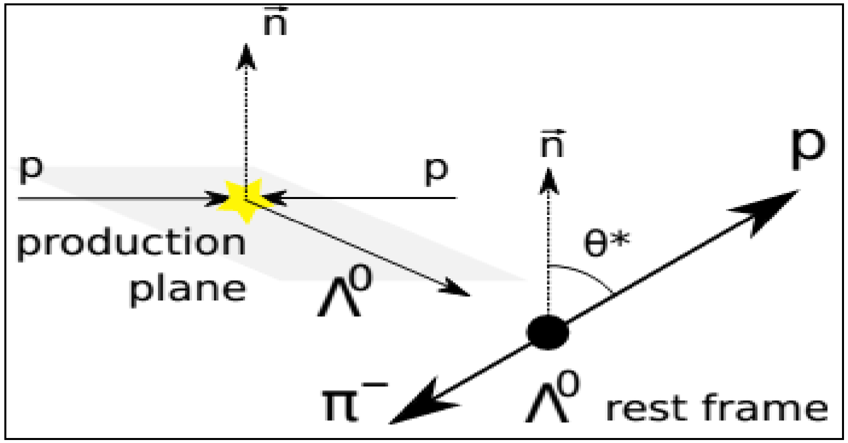


Charged particle multiplicity average values (left row) and **scalar p_T sum density average values** (right row) **compared** between **leading charged particle** (*MB*), **leading jet and *Z* boson events**, respectively as functions of leading track p_T, leading jet p_T and *Z* boson p_T.

- ► **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**

Λ AND $\bar{\Lambda}$ HYPERONS TRANSVERSE POLARIZATION AT 7 TEV

PR D91 (2015) 032004



P_Λ = –0.010 ±0.005(stat) ±0.004 (syst)

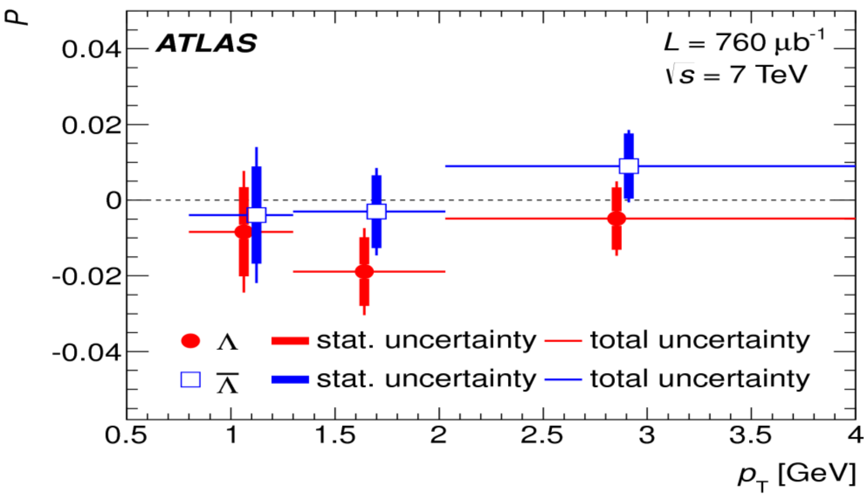
$P_{\bar{\Lambda}}$ = 0.002 ±0.006(stat) ±0.004(syst)

$0.8<p_T<15$ GeV; $|\eta|<2.5$; $5\times10^{-5}<x_F<0.01$,

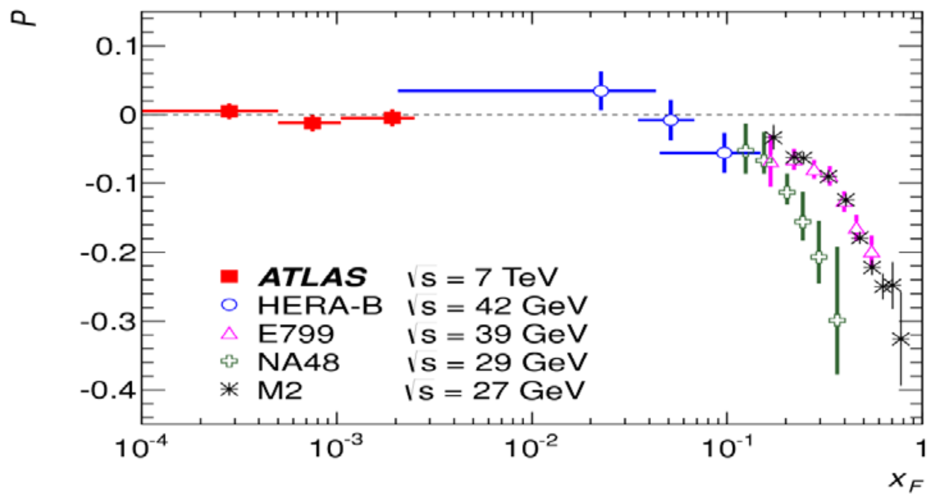
1100 MeV< $m_{p\pi}$ <1127 MeV

Polarizations in p_T and x_F bins: **less than 2%** (consistent with zero within estimated uncertainty).

Polarization of anti-Λ was measured consistent with zero by all the previous experiments.



Transverse polarization of Λ and anti-Λ hyperons as a function **of p_T.**



The Λ transverse polarization measured by ATLAS compared to **lower energy** experiments.

►**Some energy dependence could be introduced** → about 50% of Λ in ATLAS are produced in decays (Pythia). **Assume:** polarization of the original baryons diluted in the decay→ **Measured polarization expected to be consistent with or smaller than the extrapolation**.

$\varphi(1020)$ Differential Production Cross Section at 7 TeV

EPJC 74 (2014) 2895

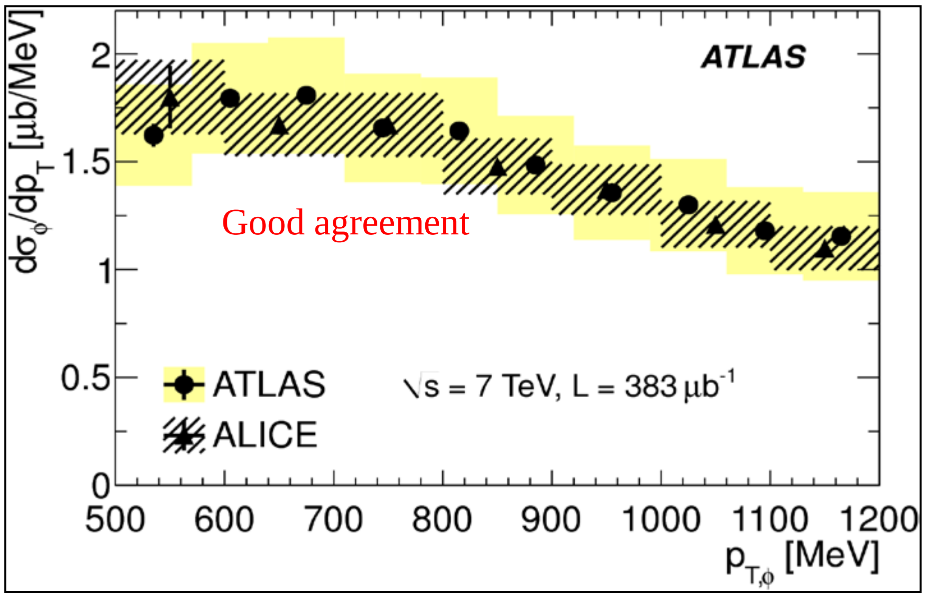
$pp \to \varphi + X,\ \varphi \to K^+K^-$

$K^{\pm}$ are identified by ***dE/dx*** in the **Pixel** detector.

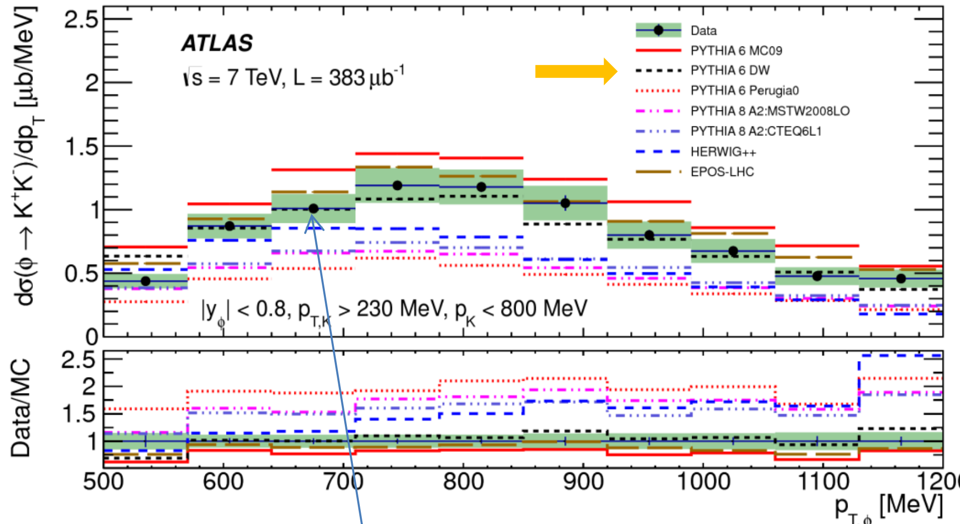
Fiducial volume: **$500 < p_T(\varphi) < 1200$ MeV, $|y(\varphi)| < 0.8$, $p_T(K^{\pm}) > 230$ MeV, $p(K^{\pm}) < 800$ MeV**

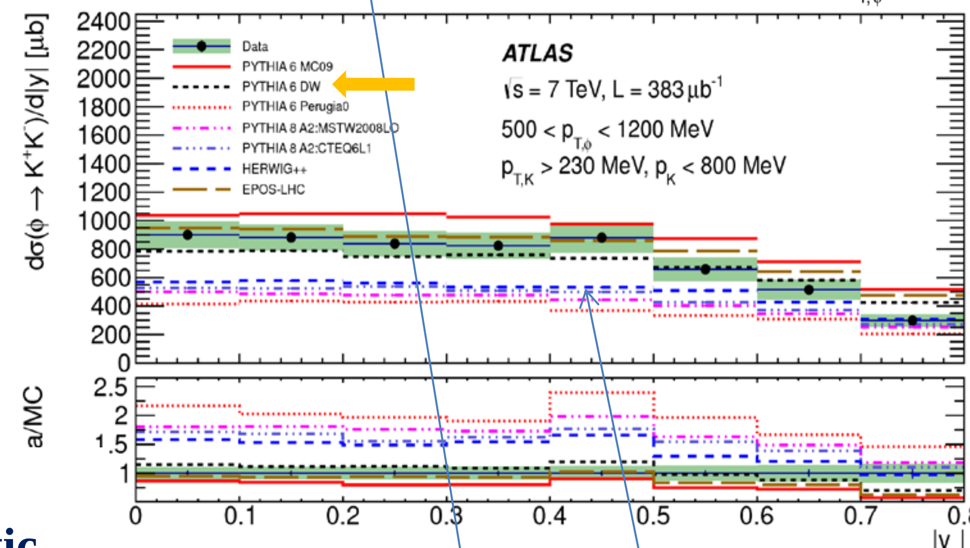
Sensitive to *s*-quark and low-*x* gluon densities.

Also **constrains fragmentation models.**



The $\varphi(1020)$-meson cross section vs. $p_{T,\varphi}$, **extrapolated using PYTHIA6 to the kinematic region with $0.5 < p_{T,\varphi} < 1.2$ GeV and $|y_\varphi| < 0.5$,** is compared to the **ALICE.**





The $\varphi(1020) \to K{+}K{-}$ cross section for as a function of $p_{T,\varphi}$ and $|y_\varphi|$.

The fiducial cross section: $\sigma \cdot Br(\varphi \to K{+}K{-}) = 570 \pm 8_{stat} \pm 66_{syst} \pm 20_{lumi}$ μb

Summary

- **Bose-Einstein correlations at 0.9 & 7 TeV: for the first time a saturation effect** in the multiplicity dependence of the extracted BEC radius parameter is observed: ***R=2.28±0.32 fm for n_{ch}>55***. The k_T dependence of R is obtained to increase with increase of multiplicity.
- **Charged-particle multiplicity measurements at 13 TeV *using pp-collisions* are presented**. Of the models considered EPOS reproduces the data the best, PYTHIA 8 A2 and MONASH give reasonable descriptions.
- **Underlying event analysis with 13 TeV** data are shown: reasonable agreement of tunes used in Atlas MC with new data. Diverse studies done at 7 TeV*: Z, leading jet and leading track.* Needed for tuning of the soft part of Monte Carlo simulation.
- **Transverse polarisation of Λ and anti-Λ hyperons at 7 TeV** consistent with 0 at low x_F confirming the behaviour of previous experiments showing a decrease of polarization as function of x_F.
- **The measurement of φ(1020) differential cross section at 7 TeV** can provide useful input for turning and development of phenomenological models in order to improve MC generators.

THANKS A LOT TO ATLAS COLLEAGUES!

MANY THANKS TO YOU FOR ATTENTION!

BACKUP SLIDES

Publications

New 13 TeV results:

- *Charged-particle distributions in $\sqrt{s}$ =13 TeV pp interactions measured with the ATLAS detector at the LHC* (*ATLAS-CONF-2015-028*)
- *Leading Track Underlying Event at 13 TeV* (*ATL-PHYS-PUB-2015-019*)

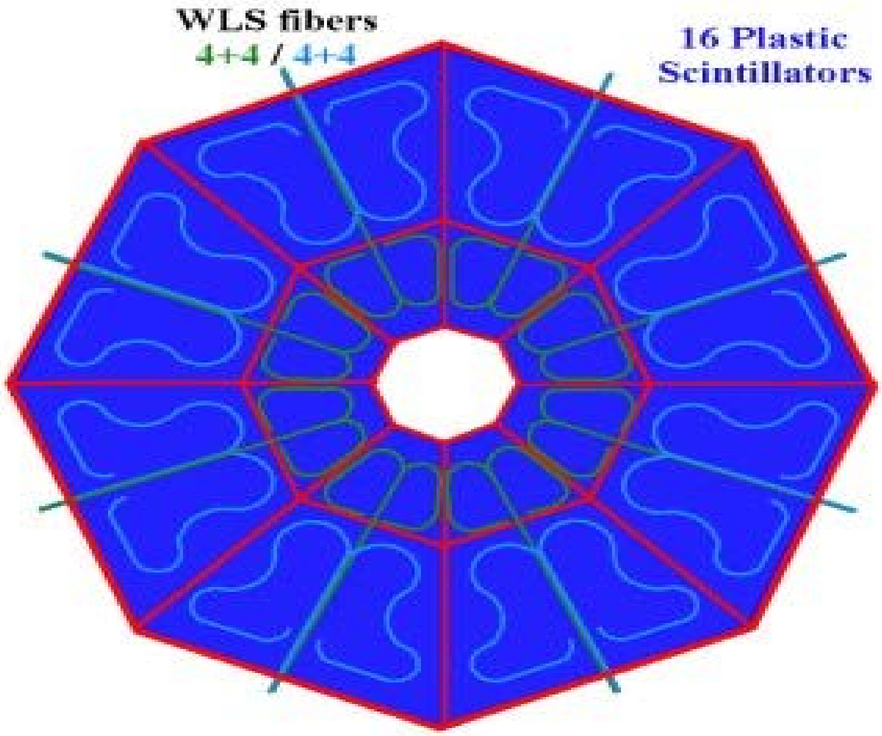
New 7 TeV results:

- *Two-particle Bose-Einstein correlations in pp collisions at $\sqrt{s}$= 0.9 and 7 TeV measured with the ATLAS detector* (*Eur.Phys.J. C75 (2015) 3644)*
- *Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector* (*Eur.Phys.J. C74 (2014) 2965*)
- *Measurement of the underlying event in jet events from $\sqrt{s}$=7 TeV proton–proton collisions with the ATLAS detector* (*Eur.Phys.J. C74 (2014) 2965*)
- *Measurement of the transverse polarization of Λ and anti-Λ hyperons produced in proton-proton collisions at $\sqrt{s}$=7 TeV using the ATLAS detector* (*Phys. Rev. D 91 (2015) 032004*)
- *The differential production cross section of the ϕ (1020) meson in $\sqrt{s}$ = 7 TeV pp collisions measured with the ATLAS Detector* (*Eur.Phys.J. C74 (2014) 2895*)

Minimum Bias Trigger Scintillator

32 independent wedge-shaped plastic scintillators (16 per side) read out by PMTs, $2.09<|\eta|<3.84$*

* Pseudorapidity is defined as $\eta = -½ \ln(\tan(\theta/2))$, θ is the polar angle with respect to the beam.



- Designed for triggering on min bias events, >99% efficiency
- MBTS timing used to veto halo and beam gas events
- Also being used as gap trigger for various diffractive subjects

Minimum-bias Event selection criteria

Events pass the data quality criteria ("good events": all ID sub-systems nominal cond., stable beam, defined beam spot)

- Accept on signal-arm Minimum Bias Trigger scintillator
- Primary vertex (2 tracks with p_T>100 MeV),
- Veto to any additional vertices with ≥4 tracks.
- At least 2 tracks with p_T>100 MeV, $|\eta|<2.5$
- At least 1 first Pixel layer hit & 2, 4, or 6 SCT hits for p_T>100, 200, 300 MeV respectively.
- IBL hit required if expected (if not expected, next to innermost hit required if expected)
- Cuts on the transverse impact parameter: $|d_0^{BL}|<1.5$ mm (w.r.t beam line)
- Cuts on the longitudinal impact parameter: $|\Delta z_0 \sin\Theta|<1.5$ mm (Δz_0 is difference between tracks z_0 and vertex z position)
- Track fit χ^2 probability >0.01 for tracks with p_T>10 GeV

Correct distributions for detector effects:

- where possible the data used to reduce the MC dependencies
- Monte Carlo derived corrections for tracking

Systematic uncertainties for BEC

The systematic uncertainties of the inclusive fit parameters, *R* and λ, of the exponential model are summarized in Table 1. The systematic uncertainties are combined by adding them in quadrature and the resulting values are given in the bottom row of Table 1. The same sources of uncertainty are considered for the differential measurements in n_{ch} and the average transverse momentum k_T of a pair, and their impact on the fit parameters is found to be similar in size.

Table 1. Systematic uncertainties on λ and R for the exponential fit of the two-particle double-ratio correlation function $R_2(Q)$ in the full kinematic region at $\sqrt{s}$ =0.9 and 7 TeV for minimum-bias and high-multiplicity (HM) events.

	0.9 TeV		7 TeV		7 TeV (HM)	
Source	λ	R	λ	R	λ	R
Track reconstruction efficiency	0.6%	0.7%	0.3%	0.2%	1.3%	0.3%
Track splitting and merging	negligible		negligible		negligible	
Monte Carlo samples	14.5%	12.9%	7.6%	10.4%	5.1%	8.4%
Coulomb correction	2.6%	0.1%	5.5%	0.1%	3.7%	0.5%
Fitted range of Q	1.0%	1.6%	1.6%	2.2%	5.5%	6.0%
Starting value of Q	0.4%	0.3%	0.9%	0.6%	0.5%	0.3%
Bin size	0.2%	0.2%	0.9%	0.5%	4.1%	3.4%
Exclusion interval	0.2%	0.2%	1%	0.6%	0.7%	1.1%
Total	14.8%	13.0%	9.6%	10.7%	9.4%	10.9%

Systematic uncertainties for UE Jets & Z

Table 3 Summary of systematic uncertainties for inclusive jet and exclusive dijet profiles vs. p_T^{lead}. The "efficiency" uncertainties include material uncertainties in the tracker and calorimeter geometry modelling. The "JES" uncertainty source for jets refers to the jet energy scale calibration procedure [49]

Quantity	Inclusive jets			Exclusive dijets		
	Pile-up and merged vertices			Pile-up and merged vertices		
All observables	1–3 %			1–5 %		
Charged tracks	Unfolding	Efficiency		Unfolding	Efficiency	
$\sum p_T$	3 %	1–7 %		3–13 %	2–7 %	
N_{ch}	1–2 %	3–4 %		3–22 %	3–7 %	
mean p_T	1 %	0–4 %		1–9 %	1 %	
Calo clusters	Unfolding	Efficiency		Unfolding	Efficiency	
$\sum E_T$, $\|\eta\| < 4.8$	2–3 %	4–6 %		5–21 %	4–9 %	
$\sum E_T$, $\|\eta\| < 2.5$	3–5 %	4–6 %		1–21 %	4–7 %	
Jets	Energy resolution	JES	Efficiency	Energy resolution	JES	Efficiency
p_T^{lead}	0.3–1 %	1–4 %	0.1–2 %	0.4–3 %	1–3 %	0.3–3 %

Table 3 Typical contributions to the systematic uncertainties (in %) on the unfolded and corrected distributions of interest in the toward and transverse regions for the profile distributions. The range of values in the columns 3–5 indicate the variations as a function of p_T^Z, while those in the last column indicate the variations as a function of N_{ch}. The column labelled *Correlation* indicates whether the errors are treated as correlated or not between the electron and muon channels

Observable	Correlation	N_{ch} vs p_T^Z	$\sum p_T$ vs p_T^Z	Mean p_T vs p_T^Z	Mean p_T vs N_{ch}
Lepton selection	No	0.5–1.0	0.1–1.0	<0.5	0.1–2.5
Track reconstruction	Yes	1.0–2.0	0.5–2.0	<0.5	<0.5
Impact parameter requirement	Yes	0.5–1.0	1.0–2.0	0.1–2.0	<0.5
Pile-up removal	Yes	0.5–2.0	0.5–2.0	<0.2	0.2–0.5
Background correction	No	0.5–2.0	0.5–2.0	<0.5	<0.5
Unfolding	No	0.5–3.0	0.5–3.0	<0.5	0.2–2.0
Electron isolation	No	0.1–1.0	0.5–2.0	0.1–1.5	<1.0
Combined systematic uncertainty		1.0–3.0	1.0–4.0	<1.0	1.0–3.5

MC models for Minimum bias and underlying event at 13 TeV

Generator	Version	Tune	PDF	7 TeV data MB	UE
PYTHIA 8	8.185	A2	MSTW2008LO [19]	yes	no
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [20]	yes	yes
HERWIG++	2.7.1	UE-EE-5-CTEQ6L1	CTEQ6L1 [21]	no	yes
EPOS	3.1	LHC	N/A	yes	no
QGSJET-II	II-04	default	N/A	yes	no
Pythia8	**8.186**	**A14**	**NNPDF2.3LO**	**UE/Shower**	

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 and the last two columns

MC models for underlying event at 7 TeV

Table 2 Main features of the Monte-Carlo models used. The abbreviations ME, PS, MPI, LO and NLO respectively stand for matrix element, parton shower, multiple parton interactions, leading order and next to leading order in QCD

Generator	Type	Version	PDF	Tune
PYTHIA 6	LO PS	6.425	CTEQ6L1 [29]	Perugia2011C [30]
PYTHIA 8	LO PS	8.165	CTEQ6L1	AU2 [31]
HERWIG++	LO PS	2.5.1	MRST LO** [32]	UE-EE-3 [33]
Sherpa	LO multi-leg	1.4.0	CT10 [34]	Default
	ME + PS	/1.3.1		
ALPGEN	LO multi-leg ME	2.14	CTEQ6L1	
+ HERWIG	+ PS	6.520	MRST**	AUET2 [35]
+JIMMY	(adds MPI)	4.31		
POWHEG	NLO ME	–	CT10	
+ PYTHIA 8	+ PS	8.165	CT10	AU2

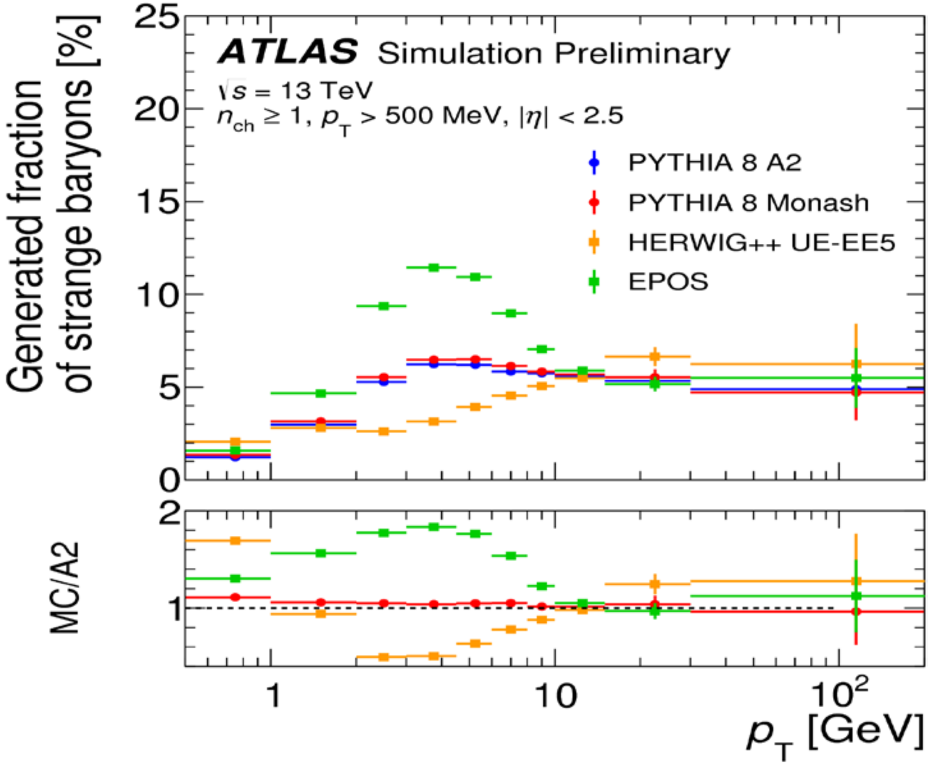
MC models for underlying event for Jets at 7 TeV

Table 2 Details of the MC models used in this paper. It should be noted that all tunes use data from different experiments for constraining different processes, but for brevity only the data which had most weight in each tune is listed. A "main data" value of "LHC" indicates data taken at $\sqrt{s}$ = 7 TeV, although $\sqrt{s}$ = 900 GeV data were also included with much smaller weight in the ATLAS tunes. Some tunes are focused on describing the minimum bias (MB) distributions better, while the rest are tuned to describe the underlying event (UE) distributions, as indicated in "focus". The detector-simulated MC configurations used for data correction are separated from those used in the results comparison plots, for clarity. For the POWHEG+PYTHIA 6 entry, separate parton distribution functions (PDFs) were used for the matrix element and parton shower/multiple scattering aspects of the modelling, indicated with "ME" and "PS/MPI" respectively

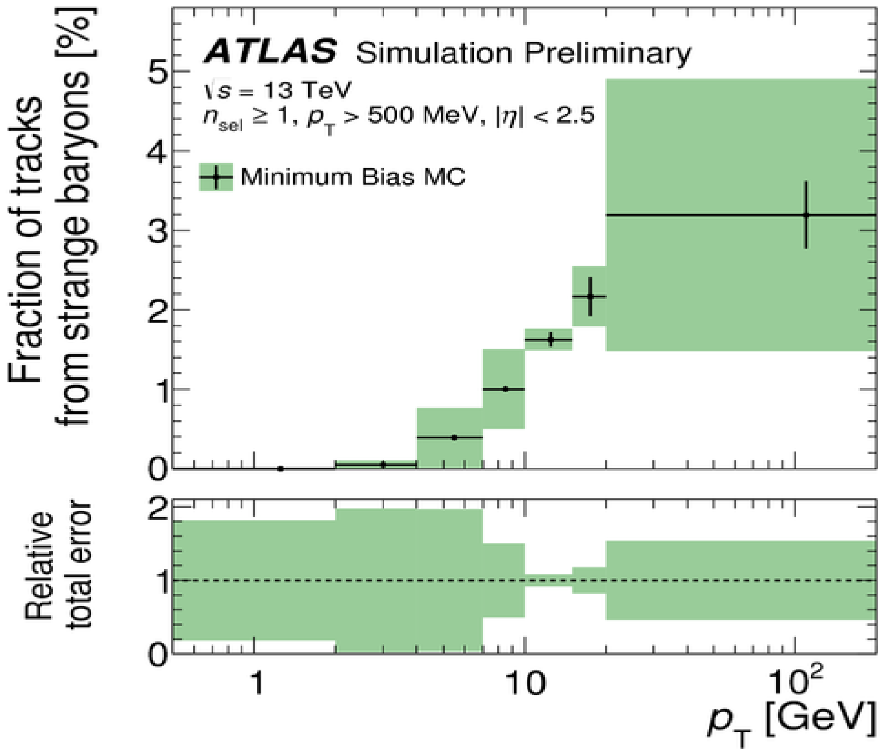
Generator	Version	Tune	PDF	Focus	Main data	Used for
PYTHIA 8	8.157	AU2 [28]	CT10 [29]	UE	LHC	MC/data comparison
PYTHIA 6	6.425	Perugia 2011 [30]	CTEQ5L [31]	UE	LHC	MC/data comparison
PYTHIA 6	6.421	DW [32]	CTEQ5L	UE	Tevatron	MC/data comparison
HERWIG++	2.5.1	UE7-2 [33]	MRST LO** [34]	UE	LHC	MC/data comparison
HERWIG+JIMMY	6.510	AUET2 [35]	MRST LO**	UE	LHC	MC/data comparison
ALPGEN+HERWIG+JIMMY	2.13 + 6.510	AUET1 [35]	CTEQ6L1 [36]	UE	LHC	MC/data comparison
POWHEG+PYTHIA 6	r2169 + 6.425	Perugia 2011	CT10 (ME) + CTEQ5L (PS/MPI)	UE	LHC	MC/data comparison
PYTHIA 6	6.425	AMBT1 [37]	MRST LO* [38]	MB	Early LHC	Data correction
HERWIG++	2.5.0	LO*_JETS [39]	MRST LO*	UE	Tevatron	Correction systematics

Strange baryons

- **Particles with lifetime 30 ps < τ < 300 ps are no longer considered primary particles in the analysis, decay products are treated like secondary particles.**
- All of these particles were **strange baryons:** with low reconstruction efficiency (<0.1%) and large variations in predicted rates lead to a model dependence
- Primary particles have τ > 300 ps

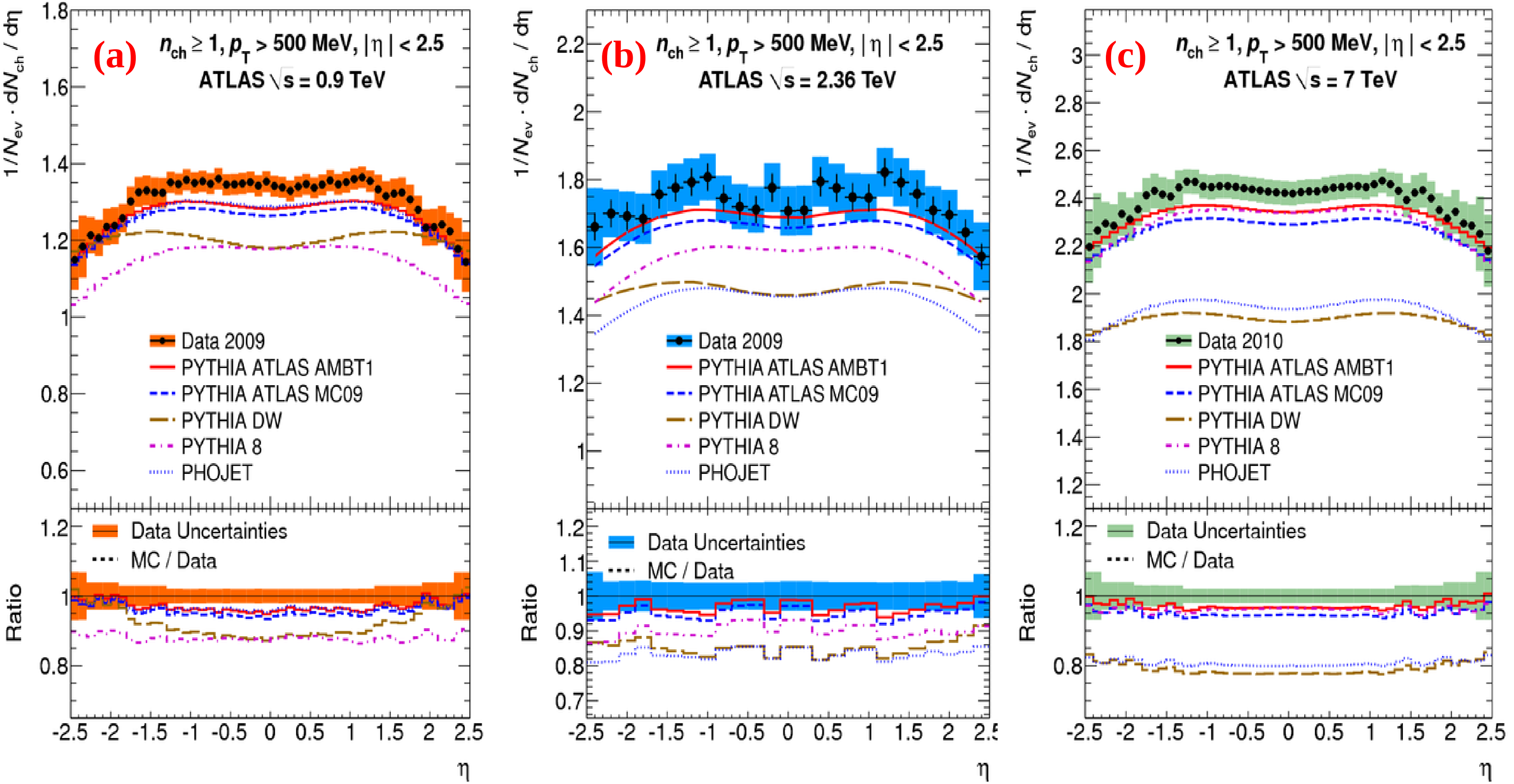


The fraction of strange baryons in generated particles as a function of particle p_T as predicted by various generators.



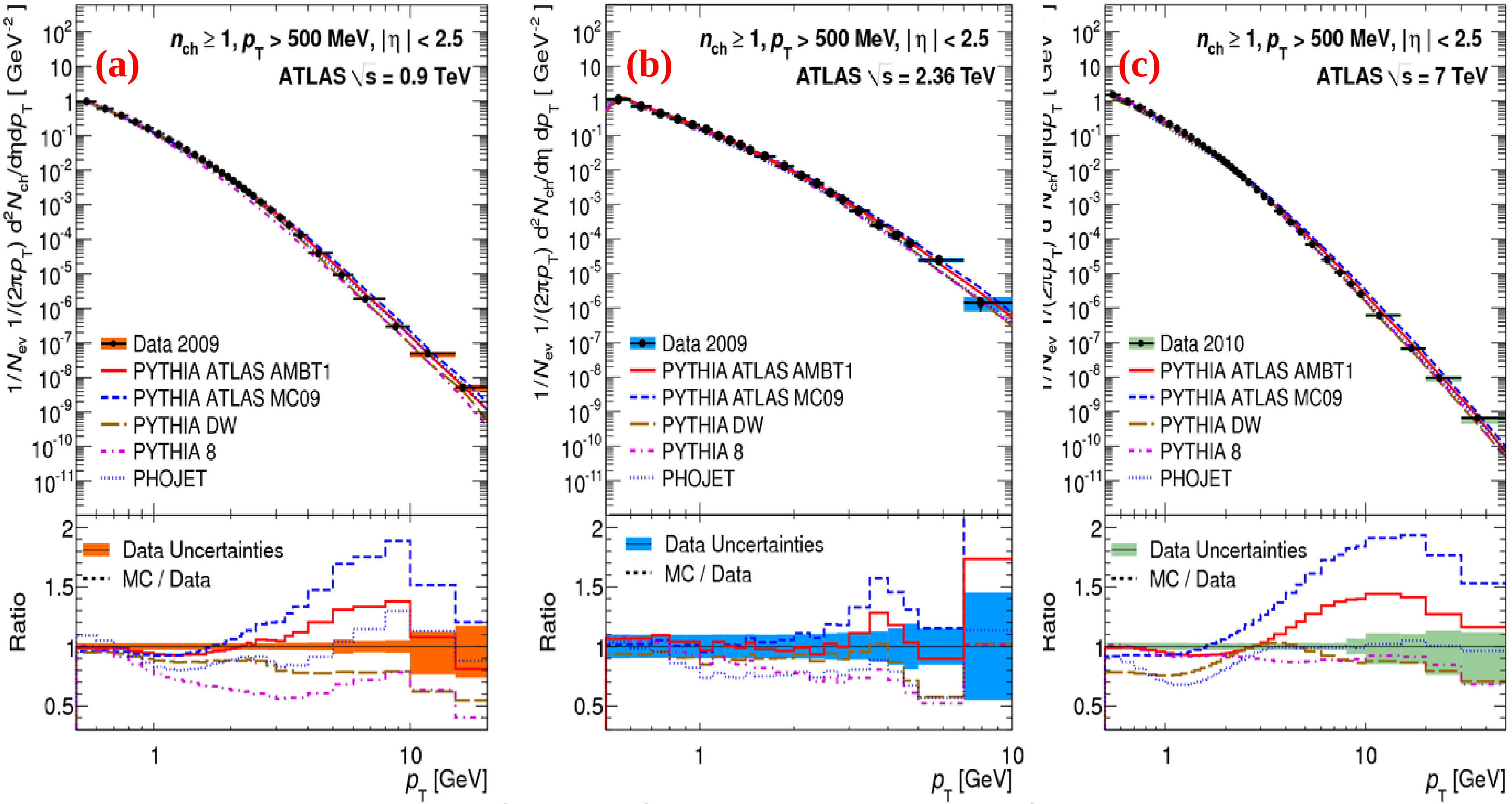
The fraction of reconstructed tracks coming from strange baryons as a function of track p_T as predicted by PYTHIA8 A2.

Charged-particle multiplicities as a function of η



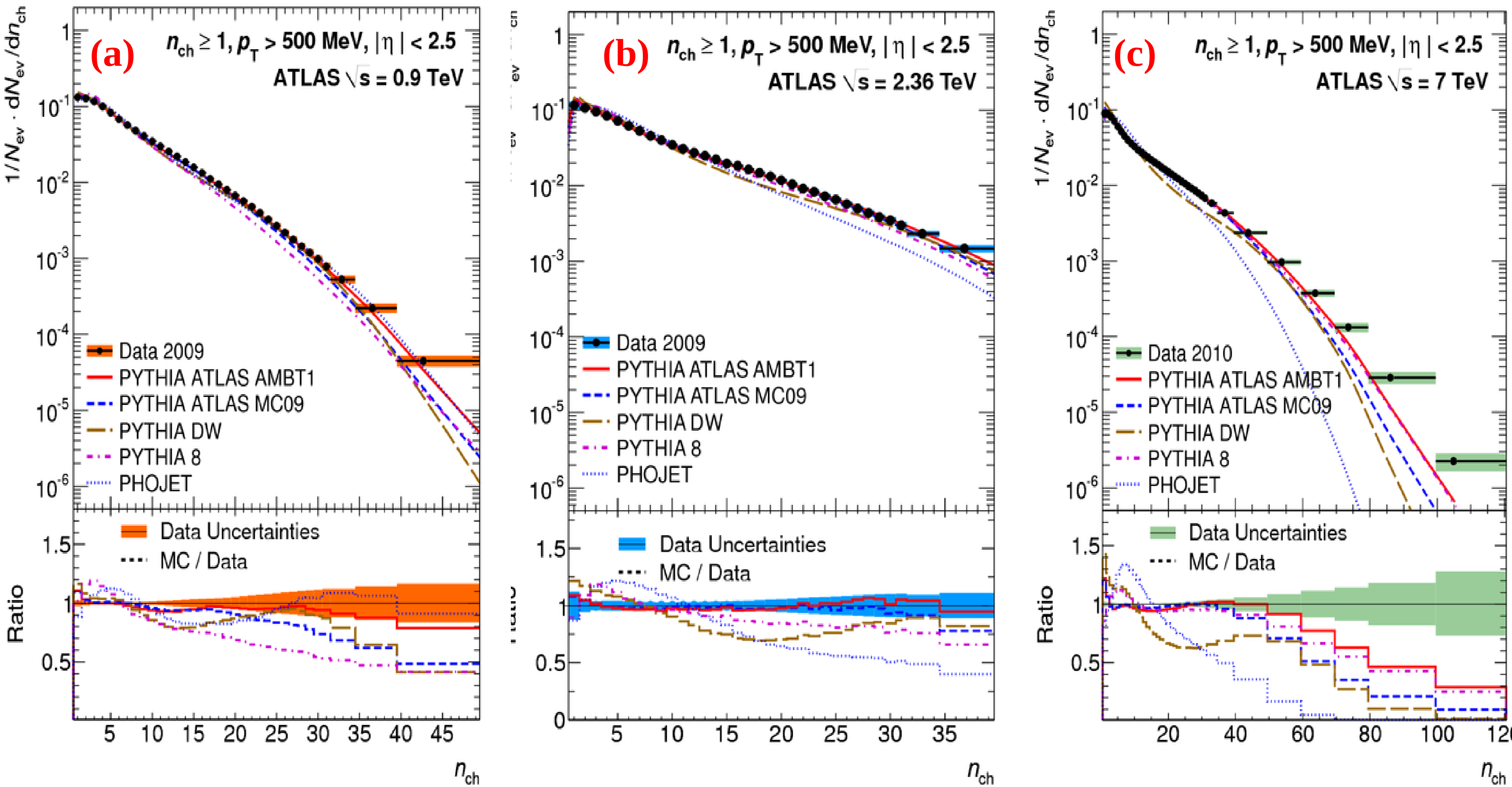
Charged-particle multiplicities as a function of the pseudorapidity for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.

CHARGED-PARTICLE MULTIPLICITIES AS A FUNCTION OF p_T



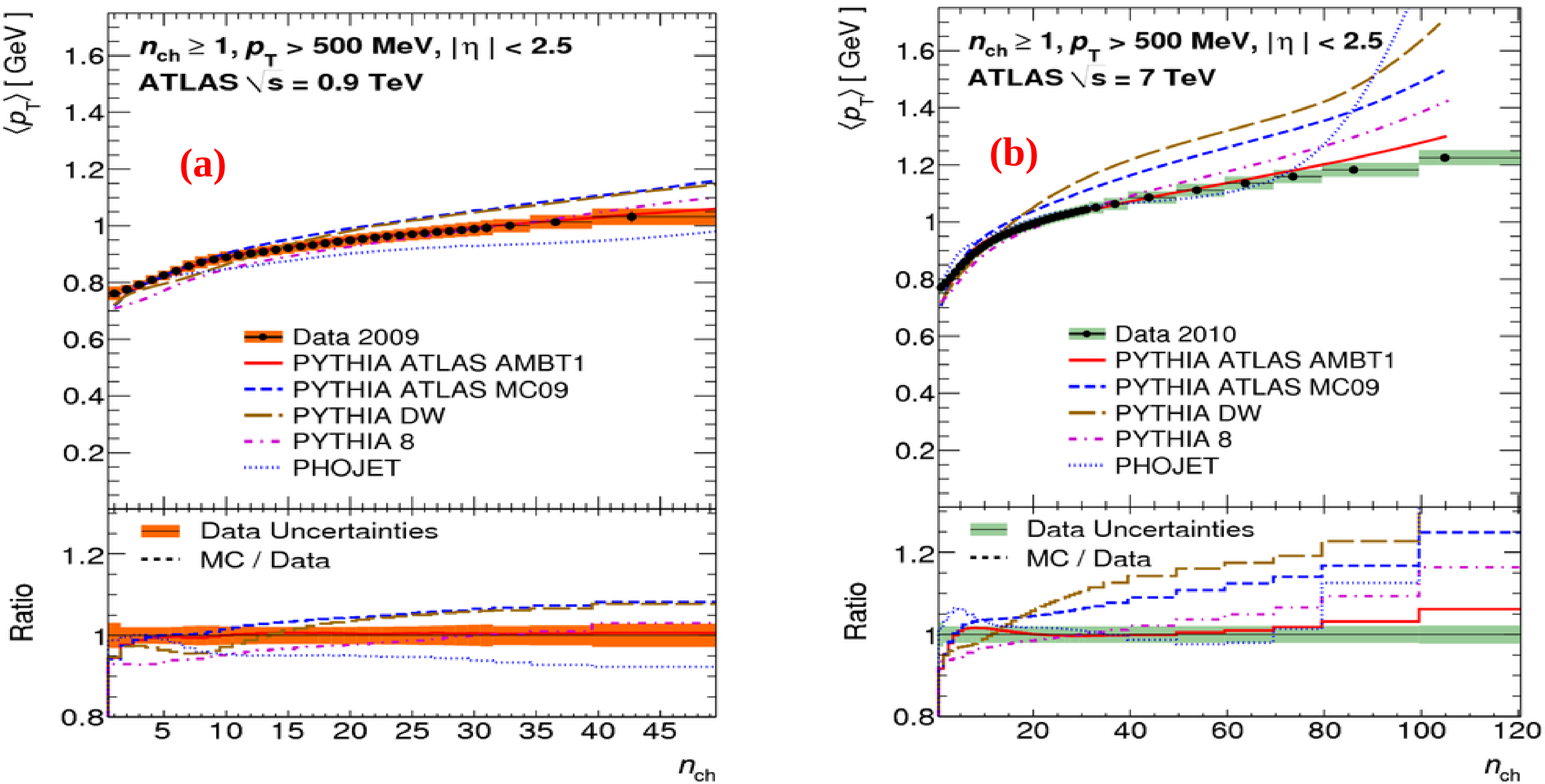
Charged-particle multiplicities as a function of the transverse momentum for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$ = 0.9 (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.

Charged-particle multiplicities distribution



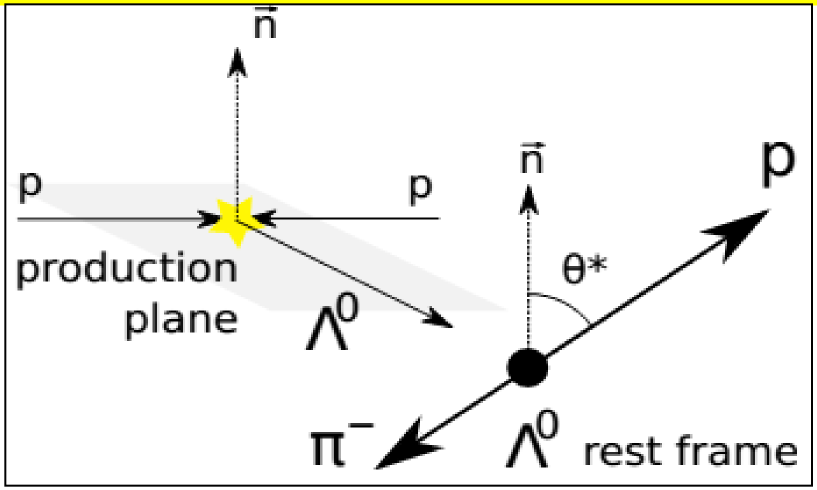
Charged-particle multiplicities distribution for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$= 0.9 (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.

Average transverse momentum as a function of multiplicities



Average transverse momentum as a function of the number of charged particles in the event for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s}=$ 0.9 (a) and 7 (b). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.

Λ and $\overline{\Lambda}$ hyperons Transverse Polarization

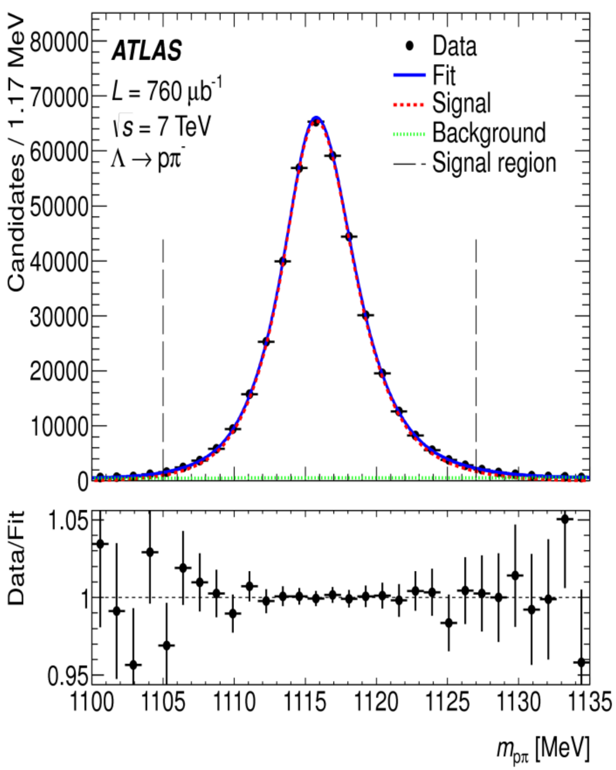


The Λ hyperons are spin-1/2 particles and their polarization is characterized by a polarization vector P. Its component transverse to the Λ momentum is of interest since for hyperons produced via the strong interaction parity conservation requires that the parallel component is zero. Huge Λ sample allows to measure Λ polarisation P by measuring the decay angle cosθ* between the decay proton and Λ flight directions.

Probability distribution of θ* is

$$g(t;p) = \frac{1}{2}(1+\alpha P t),\ t = \cos\vartheta^*$$

were $\alpha = 0.642 \pm 0.013$ is world average of the P-violating decay asymmetry for Λ.



Probability distribution function modified by detector efficiency and resolution effects (t' cosine of the measured decay angle)

$$E(P) = \int_{-1}^{1} g_{\det}(t';P)dt' = E(0) + [E(1) - E(0)]P$$

From previous experiments:

- polarization measured only in experiment with fixed target up to 40 GeV in the cms system and t up to 62 GeV at ISR.
- the magnitude of the Λ polarization increases with pT until it saturates at about 1 GeV.
- the magnitude of the Λ polarization decreases with decreasing $|x_F|$.
- the Λ polarization does not depend strongly on the center of mass energy, tested up to 40 GeV.

φ(1020) Differential Production Cross Section at 7 TeV

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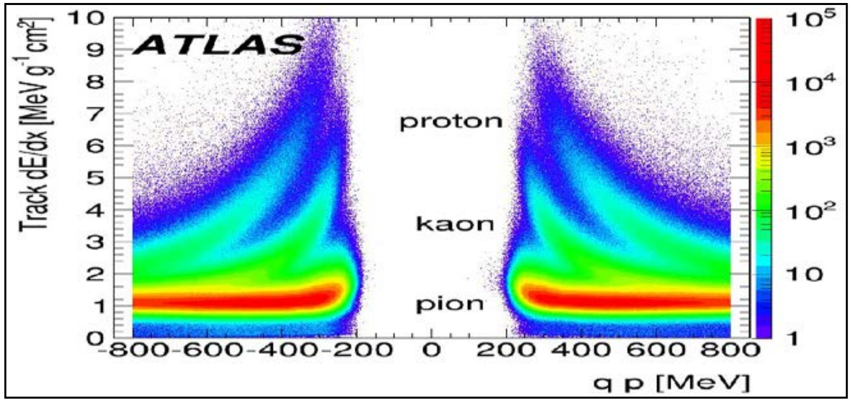
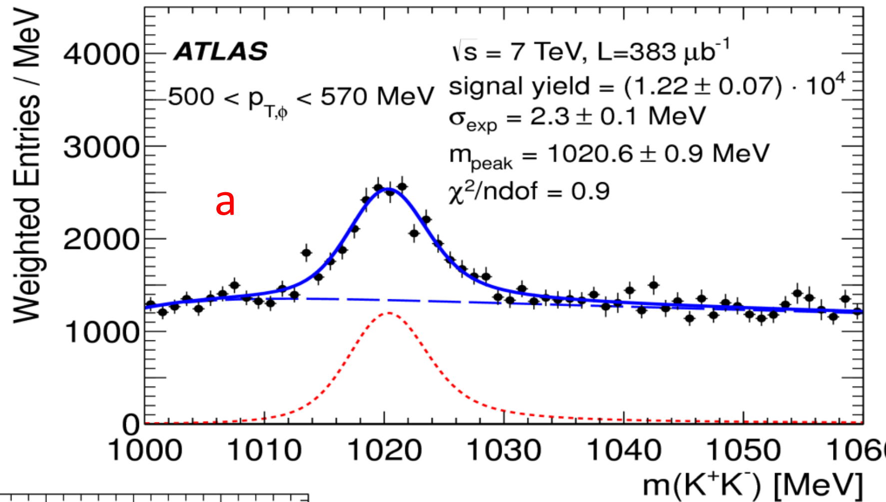
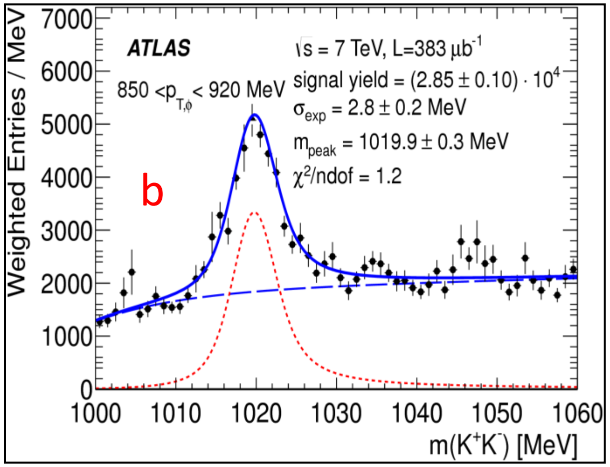
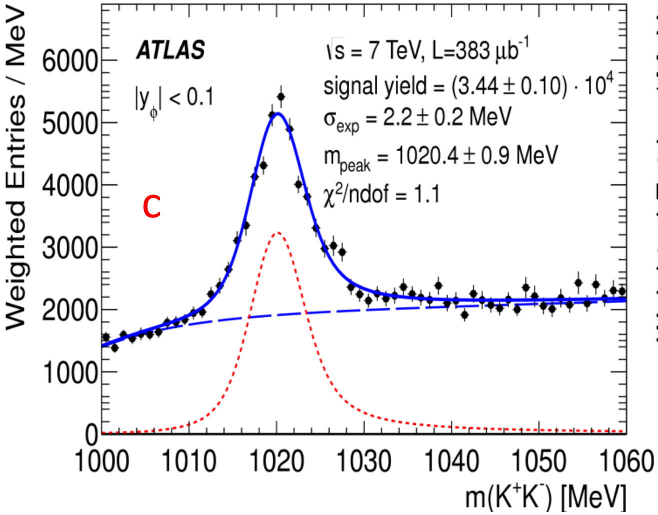
$\varphi(1020) \rightarrow K+K-$

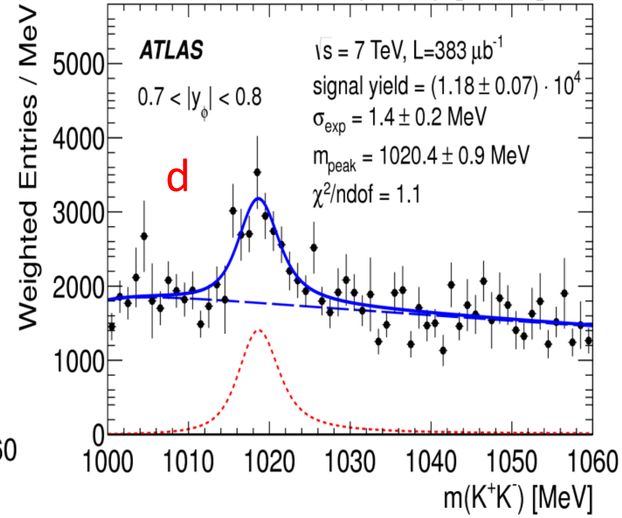


The truncated mean for the energy loss per track as a function of signed momentum for tracks.









Examples of invariant $K+K-$ mass distributions in the data (*dots*) compared to results of the fits (*solid lines*), as described in the text, for **a** the lowest $p_{T,\varphi}$ bin, **b** one of the middle $p_{T,\varphi}$ bins, **c** the most central $|y_\varphi|$ bin and **d** most forward $|y_\varphi|$ bin. The *dashed curves* show the background contribution and the *dotted red curves* demonstrates the signal contributions, with parameters listed in the legend.