Measurement of the particle production properties with the ATLAS Detector

S. Tokar, Comenius University, Bratislava

On behalf of the ATLAS collaboration

Outline of the talk

- ☐ Motivation for underlying event and Bose-Einstein correlations
- ☐ ATLAS detector
- ☐ Charged-particle distributions sensitive to the underlying event in $\sqrt{s}$ = 13 TeV proton–proton collisions with ATLAS/LHC
- ☐ Bose-Einstein correlations in $\sqrt{s}$ = 0.9 and 7 TeV *pp* collisions with ATLAS/LHC
- ☐ Conclusions

Motivation for underlying events and BEC

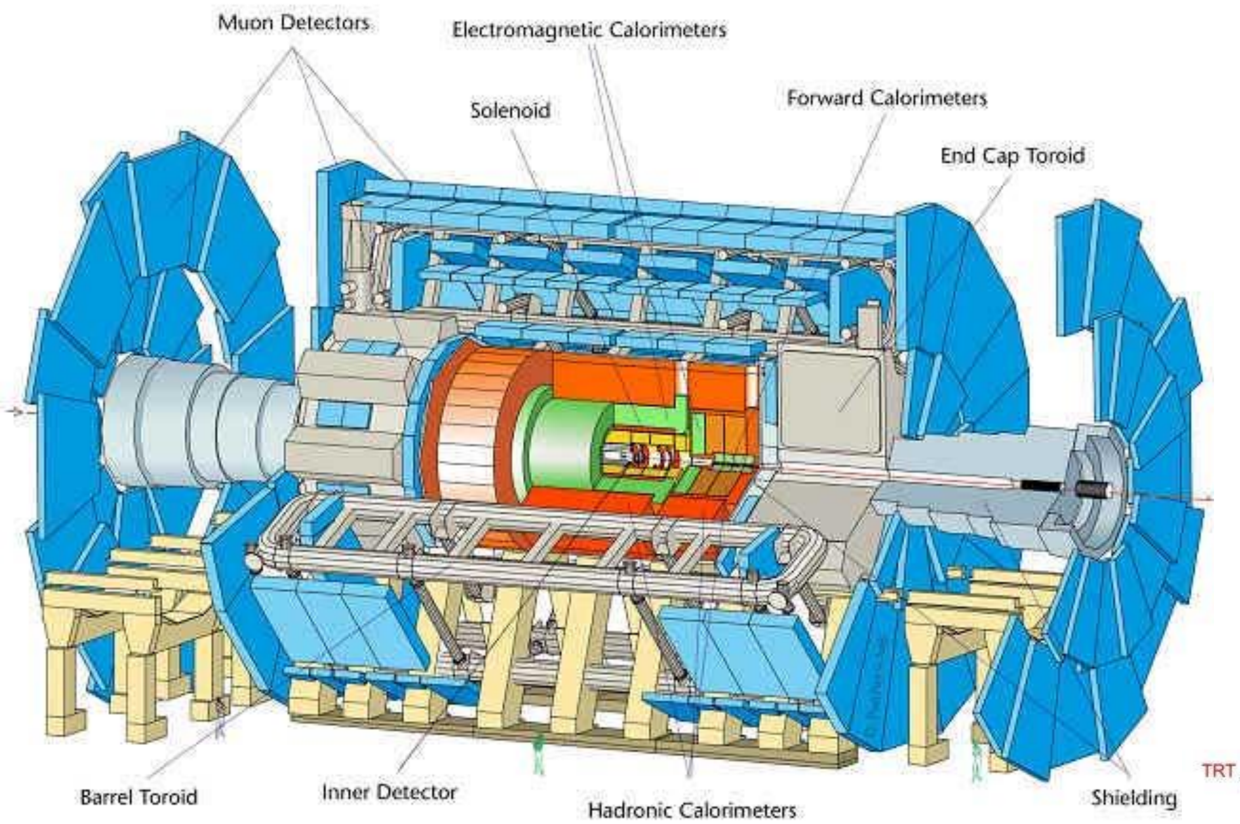
Underlying event: Searches for new physics, for any deep inelastic process at hadron colliders need:

- ✓ a good understanding of the primary short-distance hard scattering process;
- ✓ to understand the accompanying interactions of the rest of the proton–proton collision – the underlying event (UE);
- ✓ the UE is an intrinsic part of the same ***pp*** collision as any “signal” partonic interaction, accurate description of its properties by MC event generators is important.

Bose-Einstein correlations: important for understanding of nonperturbative aspects of hadronization processes.

- ✓ The space-time characteristics of hadronization process can be extracted;
- ✓ It can lead to an advancement in understanding of quark confinement.

Atlas experiment

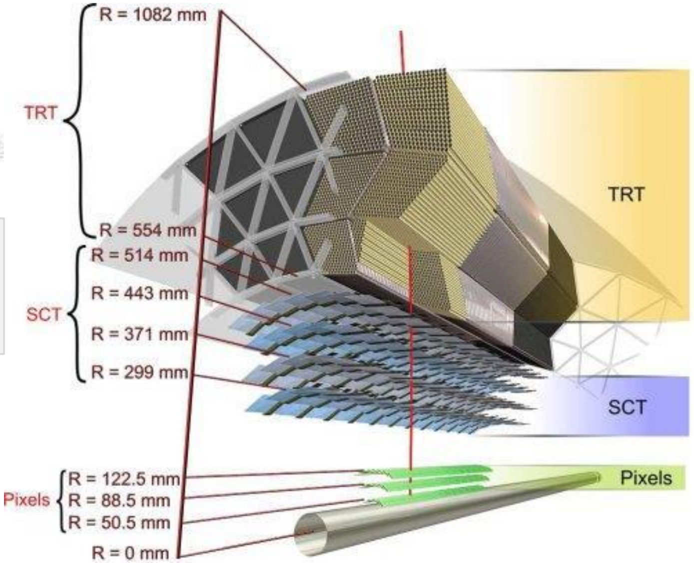


3 levels of detectors:

- ✓ Inner detector
- ✓ Calorimetric system
- ✓ Muon system

ATLAS inner detector

- The main tracking device
- $|\eta| < 2.5$, $p_T > 100$ MeV
- Silicon Pixels 50 x 400 μm^2
- Silicon Strips (SCT) 40 μm rad stereo strips
- Transition Radiation Tracker (TRT) up to 36 points/track



- ✓ 2011 (7 TeV): 5fb^{-1}
- ✓ 2012 (8 TeV): 21fb^{-1}
- ✓ 2016 (13TeV): 36fb^{-1}

MBTS used as a trigger

This talk: results based on 7 and 13 TeV data

Underlying event in $\sqrt{s} = 13$ TeV pp collisions

Underlying event (UE) sources:

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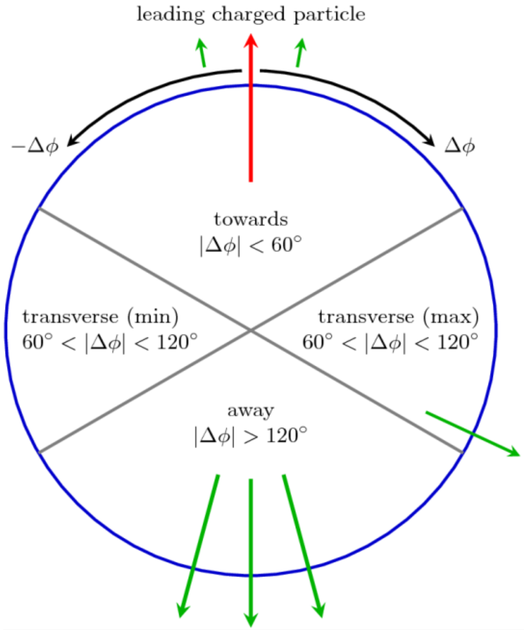
- ✓ initial- and final-state radiation (ISR, FSR),
- ✓ QCD evolution of colour connections between the parton hard scattering and the beam-proton remnants,
- ✓ additional hard scatters in the pp collision (multiple partonic interactions (MPI)).

UE observables: constructed from primary charged particles ($\tau > 300$ ps) in the range $|\eta| < 2.5$ with $p_T > 500$ MeV.

Azimuthal plane of event is segmented into, $|\Delta\phi| = |\phi - \phi_{lead}|$ regions *wrt* the leading (p_T) charge particle:

- $|\Delta\phi| < 60°$ ⇒ “towards region”;
- $60 < |\Delta\phi| < 120$ ⇒ “transverse region”;
- $|\Delta\phi| > 120$ ⇒ “away region”.

The leading charged particle, required with $p_T^{lead} > 1.5$ GeV, acts as an indicator of the main flow of hard-process energy.



Azimuthal plane division

Underlying event in √s = 13 TeV pp collisions

Definitions of the measured observables in terms of primary charged particles used at the UE study.

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

Averaged quantities vs $p_{\mathrm{T}}^{\mathrm{lead}}$ used to study the underlying-event effects.

Underlying event in √s = 13 TeV pp collisions

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Used in study: MC generators with tunes on the minimum-bias (MB), underlying event (UE) or double parton scattering (DPS) distributions.

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

Event and object selection

Trigger: one or more **minimum-bias trigger scintillators** (MBTS) hits above threshold on either side of the detector (efficiency : 99% at low multiplicity, 100% at high track multiplicities).

Primary vertex:

✓ Each event was required to contain a primary vertex reconstructed from at least **two tracks with p_T > 100 MeV** and selection requirements specific to vertexing;

✓ The primary vertex was identified as that with the **highest Σp_T^2** of its associated tracks;

✓ Events containing **> 1 primary vertex** with ≥4 associated tracks were removed.

Trigger + vertex selection: 66 million data events passed.

Tracks:

✓ reconstructed from hits in the silicon detectors and information from the TRT;

✓ each track required hits in both the **pixel system** and the **SCT**;

✓ requirement of a hit in the **innermost pixel layer** to reject secondary particles.

Tracks reconstr. within $|\eta| < 2.5$, $p_T > 500$ MeV, impact parameter ($\perp$, $\|$) wrt PV < 1.5 mm.

Correction to particle level

Measured UE distributions unfolded to the particle level, the observables corrected for detector effects:

- inefficiencies due to the trigger selection, vertexing, and track reconstruction

Weighting:

✓ Weight to compensate trigger and vertex loses (event-by-event):

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

$\varepsilon_{\mathrm{trig}}$ ≡ the trigger efficiency
$n^{\mathrm{BL}}_{\mathrm{sel}}$ ≡ the multiplicity of "beam line" selected tracks with norestriction on long. Impact param.

✓ To correct for inefficiencies in the track reconstruction (track-by-track):

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

f_{nonp}, f_{okr} and f_{sb} are the fractions of non-primary tracks, of out-of-kinematic-range tracks, and of weakly decaying charged strange baryons, respectively.

Correction of azimuthal re-orientation of the event - the leading charged particle is not reconstructed correctly ⇒ identification of the towards, transverse, and away regions can differ from that at particle level - HBOM method used.

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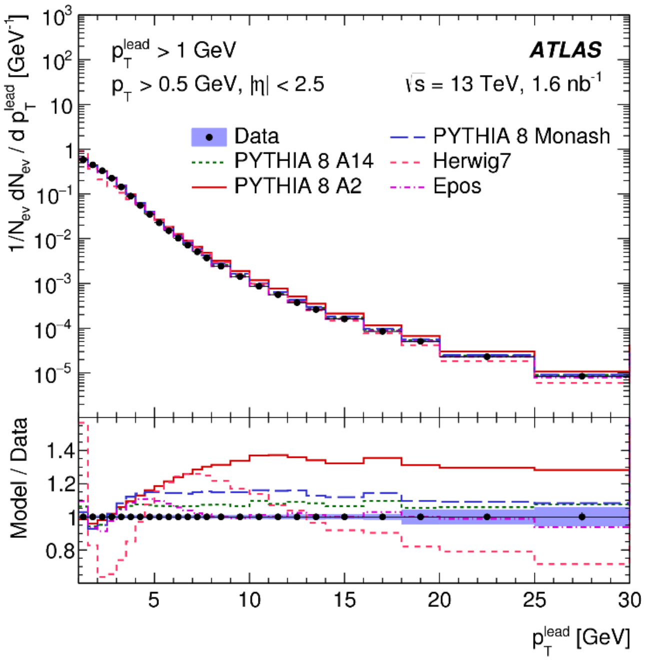
Systematic uncertainties

Main sources of systematic uncertainties:

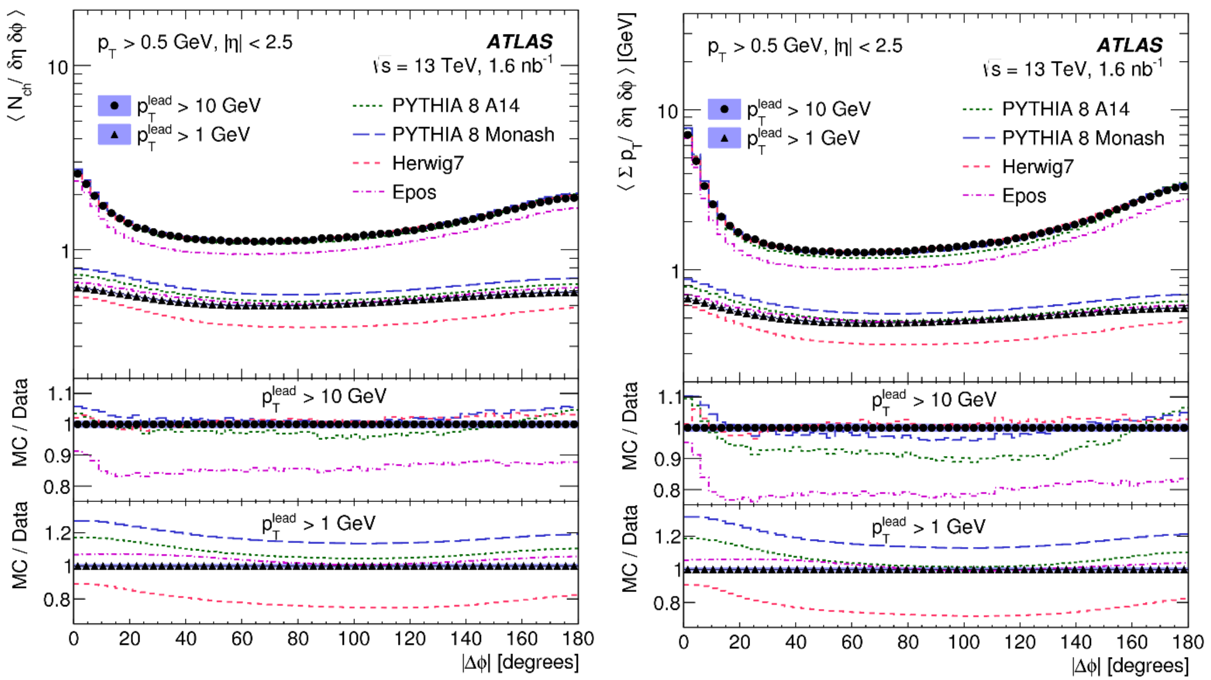
- Trigger and vertexing: found to be negligible.
- Track reconstruction: from imperfect knowledge of the material in ID.
- Non-primary particles: from modification of track weights - using variations of the fit range in the tail of impact parameter distributions, and different MC generators
- Unfolding: uncertainties associated with the HBOM unfolding at event azimuthal re-orientation correction - two sources (non-closure, parametrisation):

	Range of values			
Observable	Material	Non-primaries	Non-closure	Parameterisation
N_{ch} or Σp_T vs $\Delta\phi$	0.9%	0.6%	0 - 0.6%	0 - 0.4%
N_{ch} or Σp_T vs p_T^{lead}	0.5 - 1%	0.3 – 0.6%	0 - 2.5%	0 - 0.4%
<mean p_T> vs N_{ch}	0 - 0.5%	0 - 0.5%	0.5% (combined)	
<mean p_T> vs p_T^{lead}	0 - 0.4%	0 - 0.3%	0.5% (combined)	

Underlying event in $\sqrt{s}$ = 13 TeV pp collisions



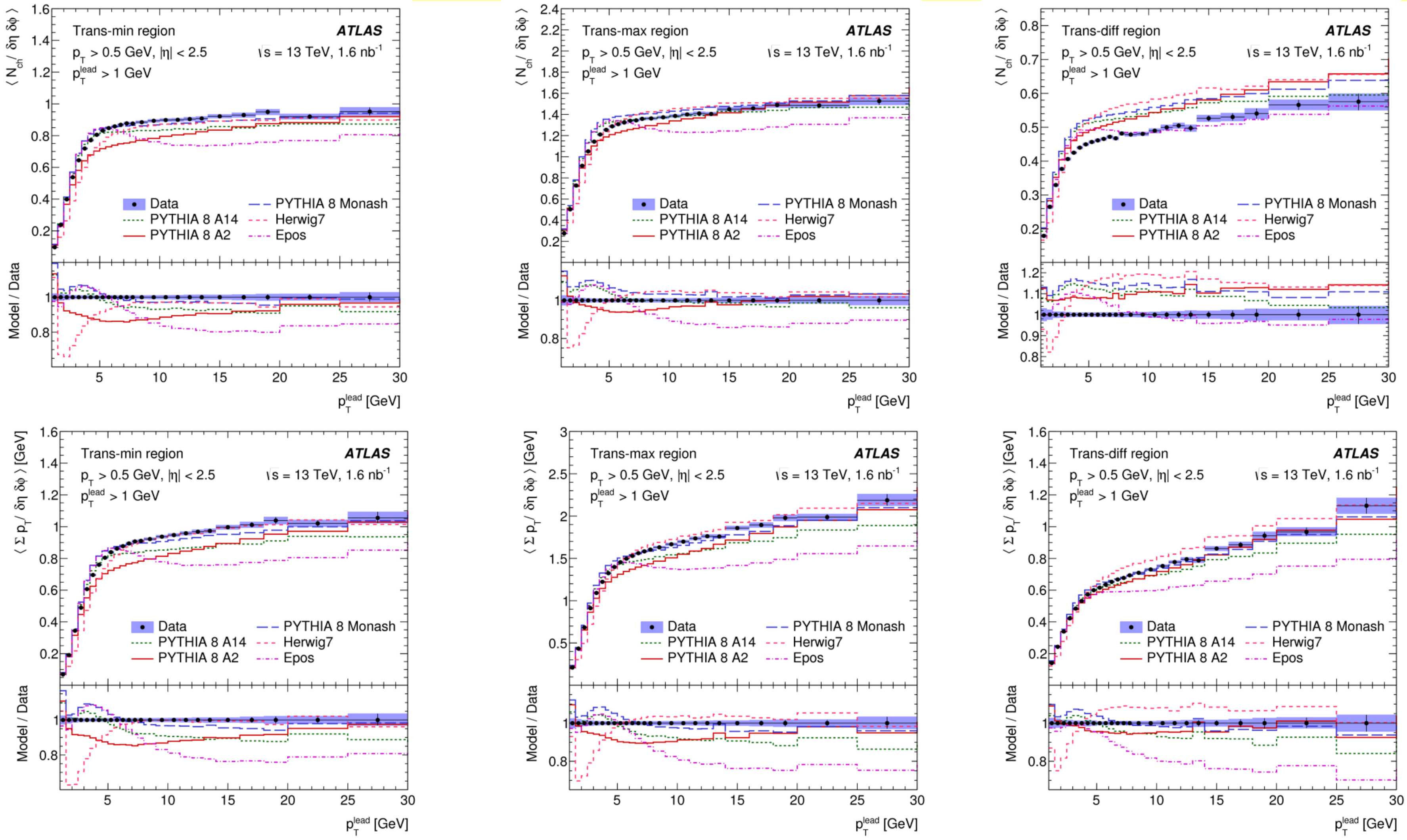
Transverse momentum distribution of the leading charged particle, $p_T^{lead} > 1$ GeV, *vs* various models



Distributions of mean densities of charged-particle multiplicity N_{ch} (left), and Σp_T (right) as a function of $|\Delta\phi|$ for $p_T^{lead} > 1$ GeV and $p_T^{lead} > 10$ GeV separately, with comparisons to MC gener. models.

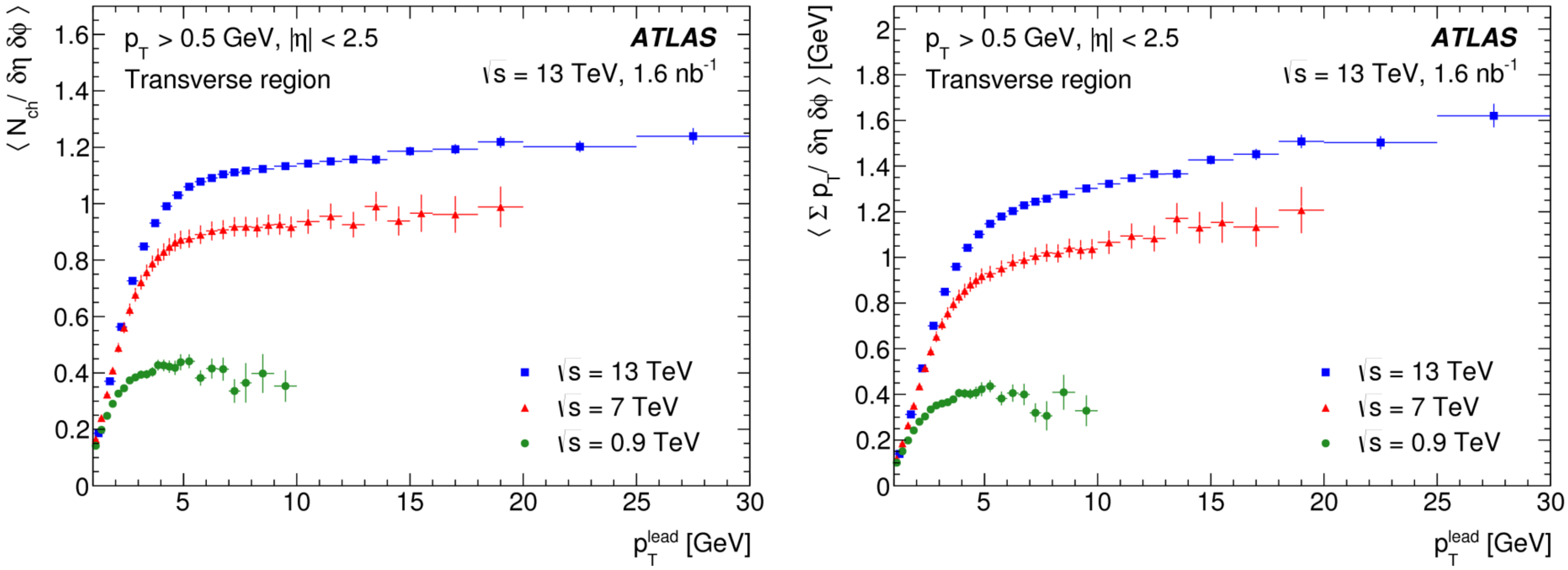
The error bars on data points represent statistical uncertainty and the blue band the total combined statistical and systematic uncertainty

Mean densities of charged-particle multiplicity and Σp_T



Mean densities of charged-particle multiplicity N_{ch} (top) and Σp_T (bottom) as a function of leading charged particle p_T in the trans-min (left), trans-max (middle) and trans-diff (right) azimuthal regions.

Mean charged-particle average transverse momentum



Mean charged-particle multiplicity (left) and $\sum p_T$ (right) densities as a function of transverse momentum of the leading charged particle measured for $\sqrt{s}$ = 0.9; 7 TeV [1] and 13 TeV centre-of-mass energies.

An increase in UE activity of approximately 20% is observed when going from 7 TeV to 13 TeV *pp* collisions.

Bose-Einstein Correlations

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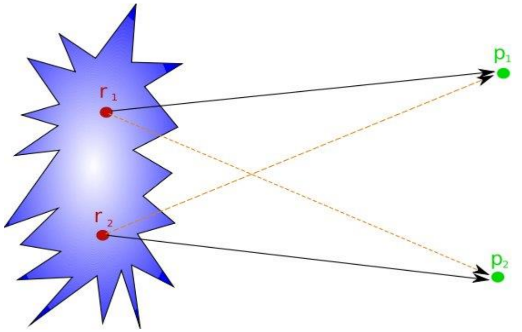
pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV

- 0.9 TeV $\Rightarrow$ 7 μb^{-1}
- 7 TeV $\Rightarrow$ 190 μb^{-1}
- 7 TeV $\Rightarrow$ 12.4 nb^{-1} (high multiplicity)

Theoretical background

BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space

$$C_2(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$



Plane wave approach (incoherent sum):

for **Gaussian source emission probability**

$$\boxed{C_2(Q) = 1 + \lambda e^{-Q^2 R^2}}$$

R is the source radius

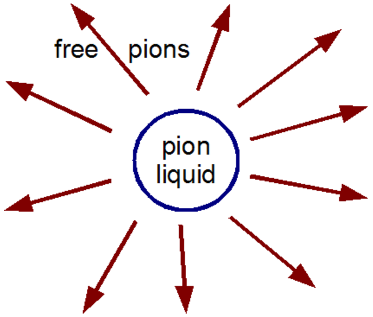
λ is the *incoherence factor (0,1)* introduced empirically

$Q^2 = -q^2 = (p_1 - p_2)^2 \equiv$ square of the four momentum difference

Quantum optical approach (taken from optics):

- ✓ based on squeezed coherent states
- ✓ leads to:

$$C_2(Q) = 1 + 2p(1-p)e^{-R^2Q^2} + p^2 e^{-2R^2Q^2}$$



p is the chaoticity: =0 (=1) for purely coherent (chaotic) sources

Two particle correlation function

The $C_2(Q) = \frac{N^{\mathrm{LS}}(Q)}{N^{\mathrm{ref}}(Q)}$ correlation function is a ratio of

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- ✓ Signal distribution $N^{\mathrm{LS}}(Q)$ with BEC: pairs of identical particles, like-sign pairs
- ✓ Reference distribution $N^{\mathrm{ref}}(Q)$ w/o BEC: does not contain identical particles, unlike-sign pairs or artificial distribution (event mixing, opposite hemisphere, ...)

Double ratio

$$R_2(Q) = \frac{C_2^{\mathrm{Data}}(Q)}{C_2^{\mathrm{MC}}(Q)}$$

- ✓ $R_2(Q)$ eliminates problems with energy-momentum conservation, topology, etc.
- ✓ MC (Pythia 6.421) doesn't contain BEC. The ATLAS studies are performed using the $R_2(Q)$ correlation function

Used parametrization for C_2 and R_2 functions:

$$C_2^{(\mathrm{G})}(Q) = C_0\left(1+\lambda e^{-R^2Q^2}\right)\cdot(1+\varepsilon Q)$$

spherical source with Gaussian distribution

$$C_2^{(\mathrm{E})}(Q) = C_0\left(1+\lambda e^{-RQ}\right)\cdot(1+\varepsilon Q)$$

... with Cauchy-Lorentz distribution

R ≡ the source size (radius); λ ≡ the incoherence factor

Event selection criteria + corrections

☐ Events pass the data quality criteria :

- ✓ Minimum Bias Trigger Scintillators (at each detector end) used as a trigger
- ✓ Primary vertex (2 tracks with $p_T > 100$ MeV, $|\eta|<2.5$)
  - Veto to any additional vertices with ≥ 4 tracks.
- ✓ Track requirements (# of hits, cuts on ⊥ and || impact parameter, track fit χ^2)
- ✓ Special event sample collected with High Multiplicity Trigger (HMT) at 7TeV.

☐ Correction on trigger and vertex reconstruction efficiency (ε_{trig}, ε_{vert})

$$w(n) = \frac{1}{\varepsilon_{\mathrm{trig}}(n)\cdot\varepsilon_{\mathrm{vert}}(n)}$$

- For multiplicities $n \geq 3$ these corrections are close to 1.
- Multiplicity unfolded to particle level

☐ Coulomb correction for track pair measured Q-distribution:

$$N_{meas}(Q) = G(Q)\cdot N(Q), \quad G(Q) = \frac{2\pi\eta}{e^{2\pi\eta}-1}$$

G(Q) ≡ Gamow penetration factor
N(Q) ≡ distribution free of Coulomb

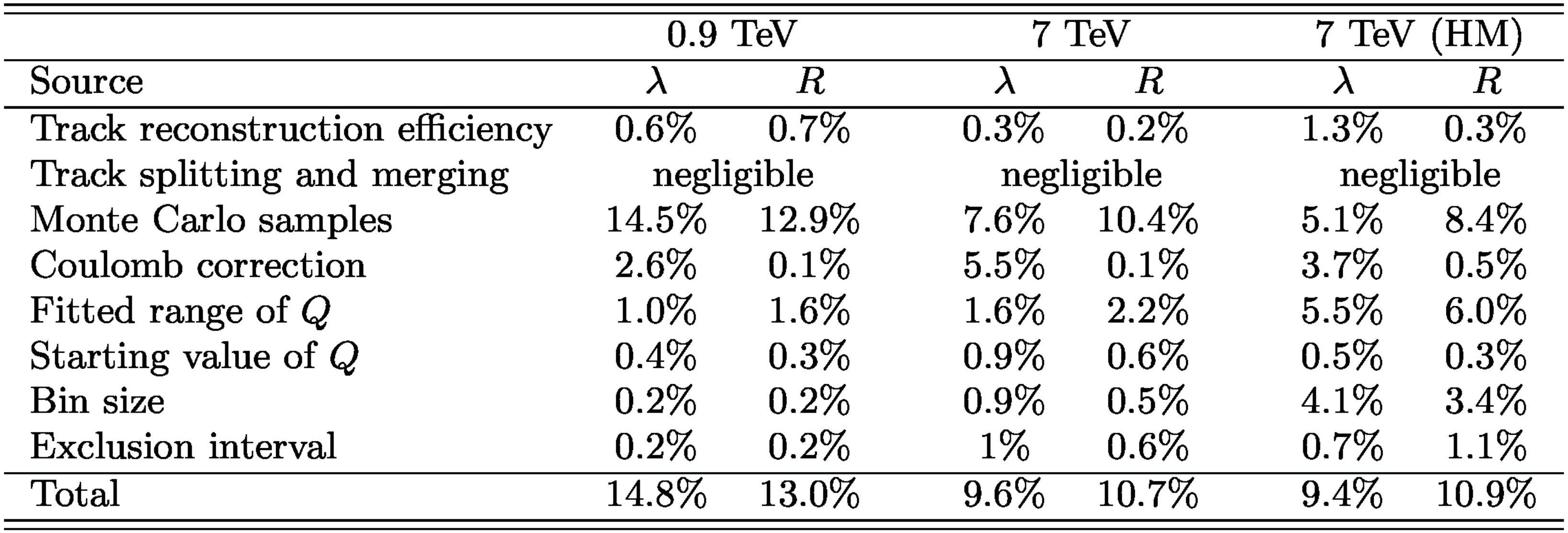
η ≡ Sommerfeld parameter (= $\pm\alpha m_\pi/Q$): $\eta > 0$ (< 0) for like-sign (unlike-sign) pairs.

The size of this correction does not exceed 20% for $\boldsymbol{Q} > 30$ MeV.

Systematic uncertainties

Systematic uncertainties on λ and R for the exponential fit.

- ✓ Two-particle double-ratio correlation function $R_2(Q)$.
- ✓ Full kinematic region at √*s* = 0.9 and 7 TeV for minimum-bias and high-multiplicity (HM) events.



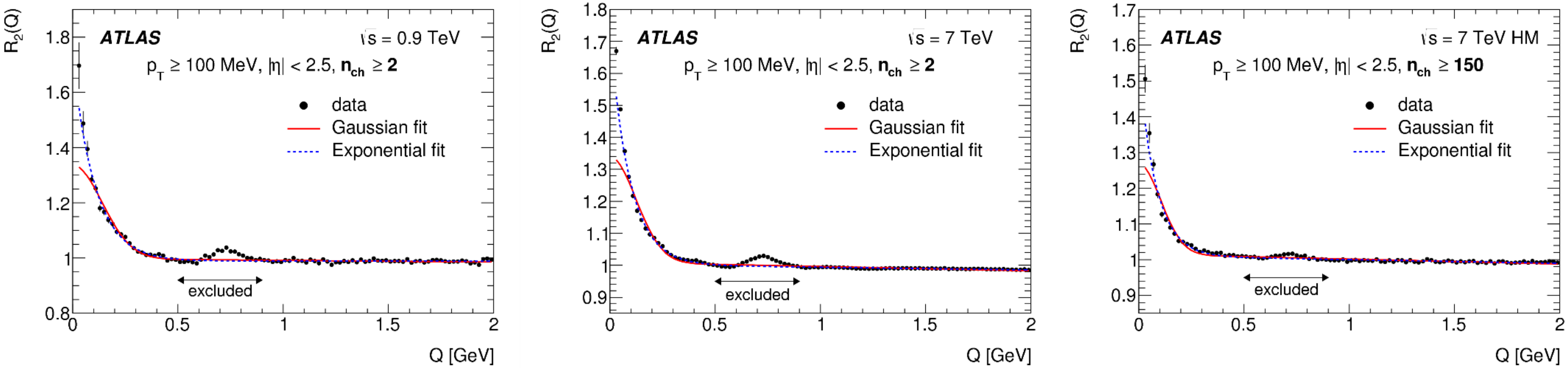
	0.9 TeV		7 TeV		7 TeV (HM)	
Source	λ	R	λ	R	λ	R
Track reconstruction efficiency	0.6%	0.7%	0.3%	0.2%	1.3%	0.3%
Track splitting and merging	negligible		negligible		negligible	
Monte Carlo samples	14.5%	12.9%	7.6%	10.4%	5.1%	8.4%
Coulomb correction	2.6%	0.1%	5.5%	0.1%	3.7%	0.5%
Fitted range of Q	1.0%	1.6%	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%

Double ratio correlation functions

Two-particle double-ratio correlation functions ***R***$_2$(Q) analyzed – considered:

- ✓ spherical shape with a Gaussian distribution of the source (Gaussian fit);
- ✓ radial Lorentzian distribution of the source (exponential fit)
- ✓ Extracted parameters: R (hadronization radius) and λ (incoherence factor)

Much better description obtained for the exponential fit.



The bump in resonance region is due to MC overestimation of resonances (mainly $\rho \rightarrow \pi + \pi$) $\Rightarrow$ region 0.5 – 0.9 GeV was excluded from the fit.

$\boldsymbol{R}$ = 1.83 $\pm$ 0.25, λ = (0.74 $\pm$ 0.11) fm at $\sqrt{s}$ = 0.9 TeV for $\boldsymbol{n}_{\mathrm{ch}} \geq$ 2
$\boldsymbol{R}$ = 2.06 $\pm$ 0.22, λ = (0.71 $\pm$ 0.07) fm at $\sqrt{s}$ = 7 TeV for $\boldsymbol{n}_{\mathrm{ch}} \geq$ 2
$\boldsymbol{R}$ = 3.36 $\pm$ 0.30, λ = (0.74 $\pm$ 0.11) fm at $\sqrt{s}$ = 7 TeV for $\boldsymbol{n}_{\mathrm{ch}} \geq$ 150

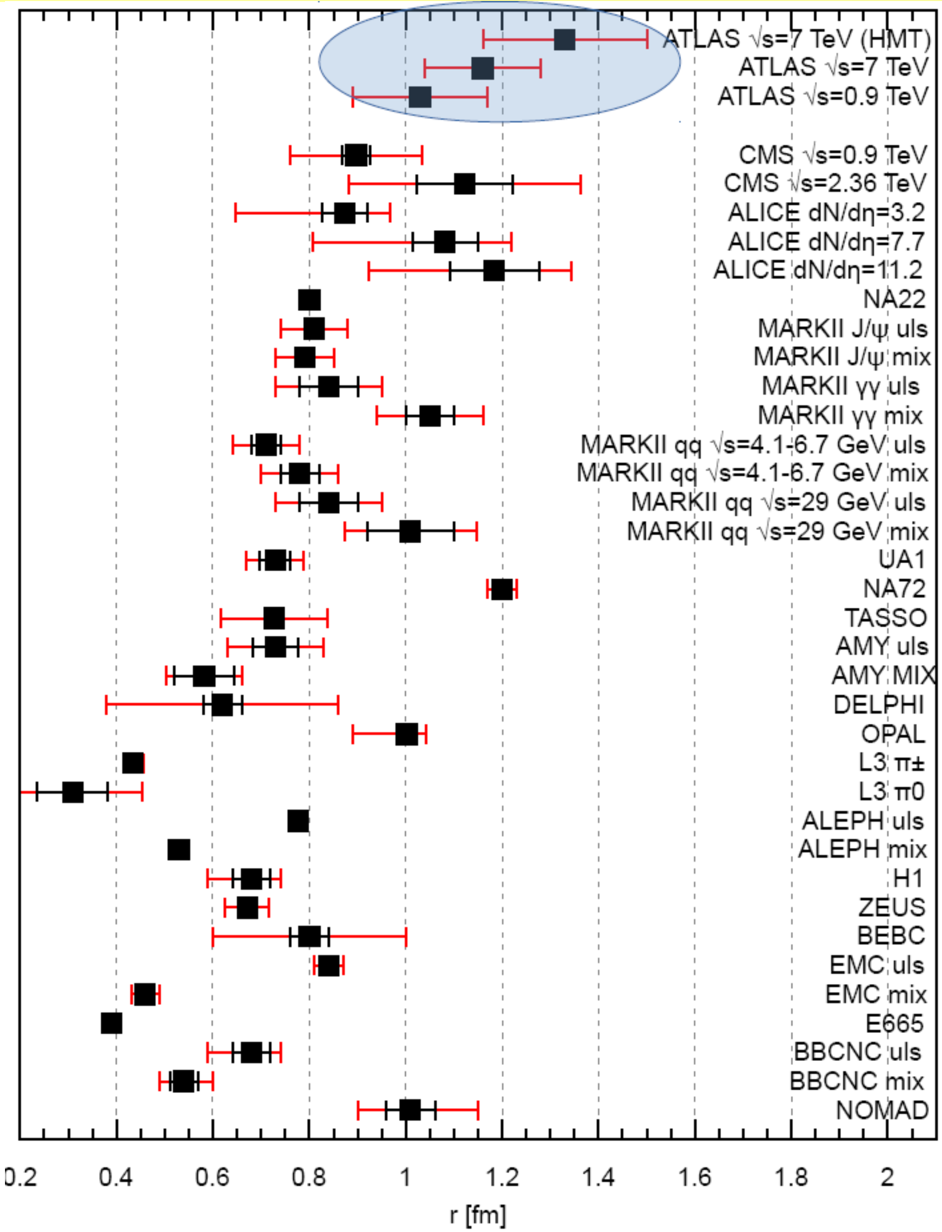
Comparison with other experiments

Most of the previous experiments* provided hadronization radius ***R*** measurement with a *Gaussian* fit.

Comparison to the exponential fit can be done using the factor √*π* :

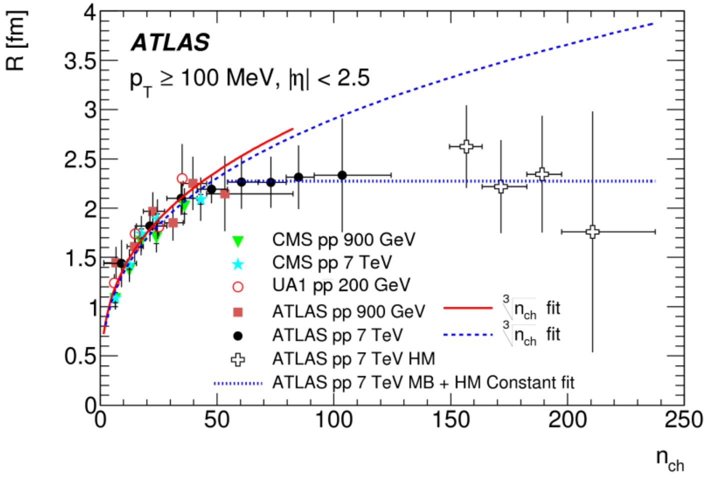
R(G) = *R*(E) / √*π*

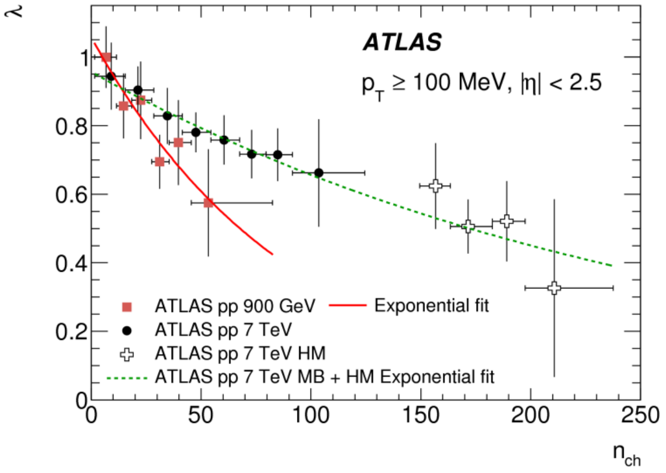
Energy[TeV]	R[fm]
0.9	1.03 ± 0.14
7	1.16 ± 0.12
7(HM)	1.33 ± 0.17



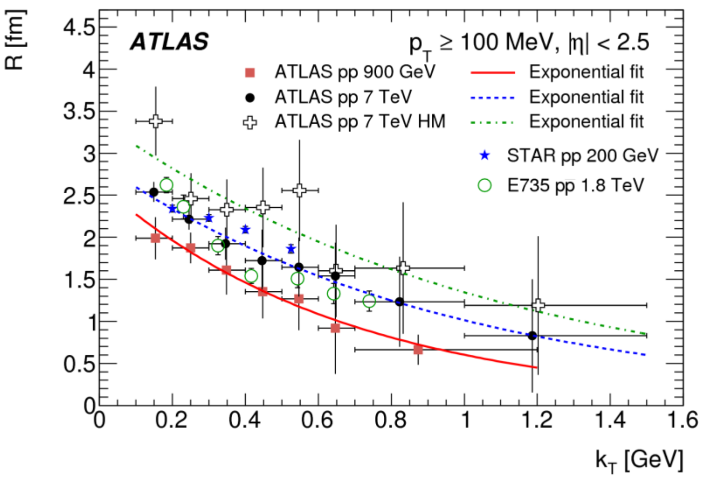
Parameters λ and R *vs* multiplicity and kT

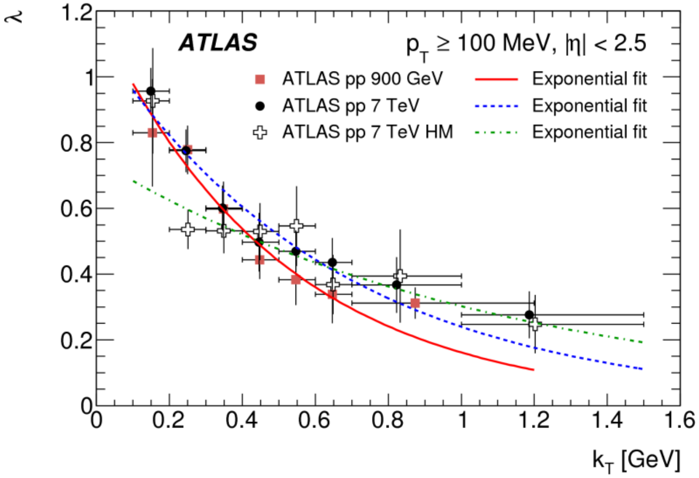
Multiplicity, $\boldsymbol{n_{ch}}$, dependence of $\boldsymbol{R}$ (left) $\boldsymbol{\lambda}$ (right) from the exponential fit to $\boldsymbol{R_2(Q)}$ at $\sqrt{s}$ = 0.9 and 7 TeV, compared to the CMS and UA1 results.





The k_T (=|$\mathbf{p}_{T,1}$ + $\mathbf{p}_{T,2}$|/2) dependence of $\boldsymbol{R}$ (left) and $\boldsymbol{\lambda}$ (right) – from the exponential fit to $\boldsymbol{R_2(Q)}$ at $\sqrt{s}$ = 0.9 TeV, 7 TeV and 7 TeV high-multiplicity events.





Conclusions

- ❑ Several distributions sensitive to UE measured for 13 TeV pp collisions (region's mean Σp_{T} and mean N_{ch} densities with $p_{\mathrm{T}}^{\mathrm{lead}}$,...)
- ❑ An improvement upon previous ATLAS measurements of UE using leading-track alignment achieved.
- ❑ An increase in UE activity by ≈20% is observed when going from 7 TeV to 13 TeV pp collisions.
- ❑ MC generators: for most observables the models describe the UE data to < 5% accuracy, but it is greater than experimental uncertainty.

- ❑ BEC of the pairs of identical charged particles measured within $|\eta| < 2.5$ and $p_{\mathrm{T}} > 100$ MeV in ***pp*** collisions at 0.9 and 7 TeV.
- ❑ Multiplicity dependence of the BEC parameters was investigated up to high multiplicities (≈ 240). A saturation effect seen in multiplicity
- ❑ Dependence of the BEC parameters on track pair k_{T} and on particle p_{T} was investigated.

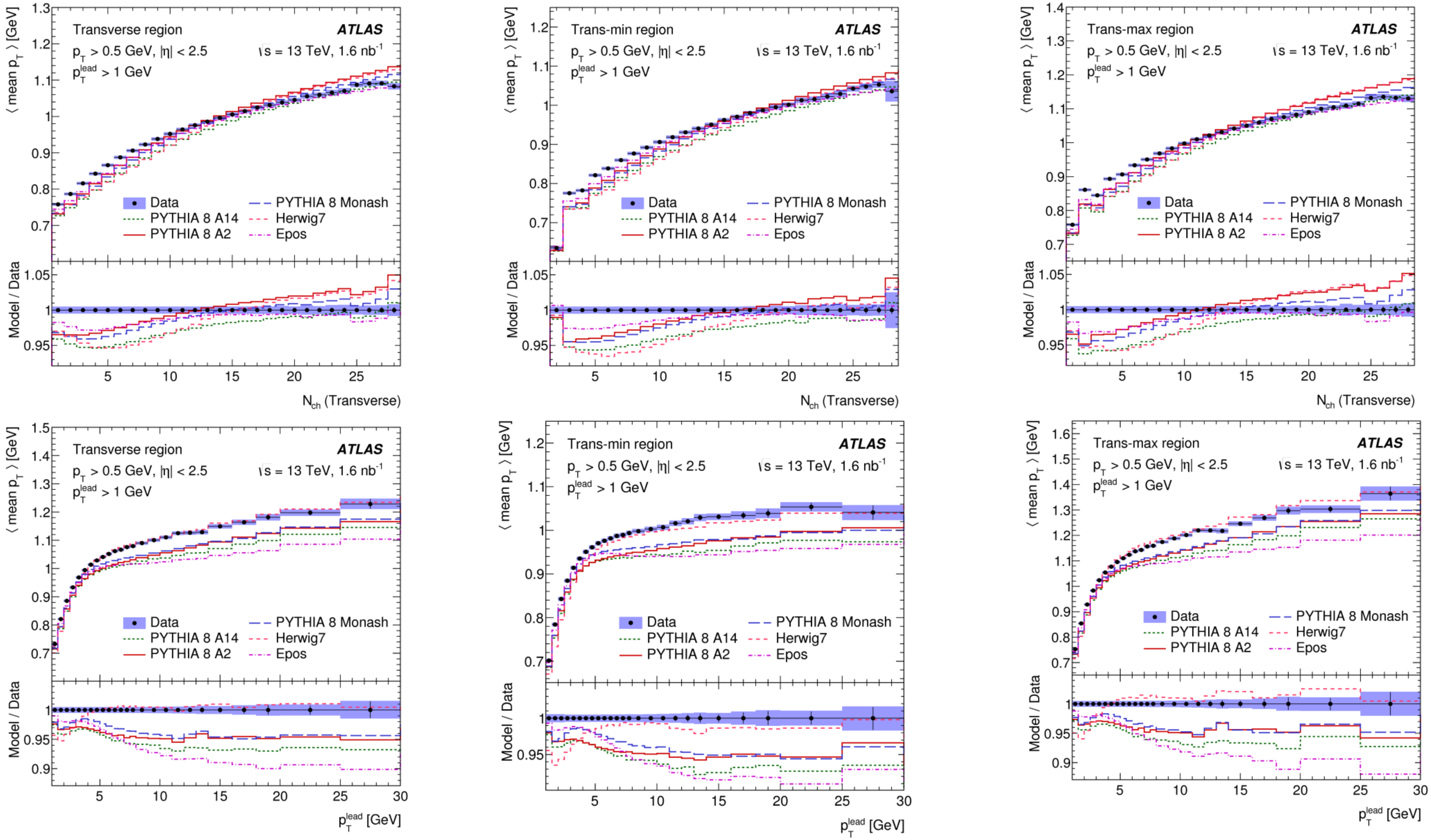
Appendix

An alternative interpretation of two-particle correlations - preliminary but yet public analysis on the hadronic chains at ATLAS:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-08/

Back up

Mean charged-particle average transverse momentum



Mean charged-particle average transverse momentum as a function of N_{ch}(transverse) (top) and leading charged particle p_T (bottom) in the transverse region (left), trans-min region (middle) and trans-max region (right) azimuthal regions.

Bose-Einstein correlations in *pp* at 7 TeV

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- Bose-Einstein correlations (BEC) represent a unique probe of the space-time characteristics of the hadronization region and allow the determination of the size and shape of the source from which particles are emitted.
- BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space $\Rightarrow$ it is a consequence of their wave function symmetry.
- Studies of the dependence of BEC on particle multiplicity and transverse momentum are of special interest. They help in the understanding of multiparticle production mechanisms.

Sumary on parametrization models

Goldhaber spherical source model (**GSSg**) $C_2^{(\mathrm{G})}(Q) = C_0\left(1+\lambda e^{-R^2Q^2}\right)\cdot(1+\varepsilon Q)$

Empirical model (**GSSe**). Used since it represents well the shape of the correlation

$$C_2^{(\mathrm{E})}(Q) = C_0\left(1+\lambda e^{-RQ}\right)\cdot(1+\varepsilon Q)$$

- ✓ R ≡ the source size (radius)
- ✓ λ ≡ the incoherence factor

Quantum Optics model (**QOg**).

$$C_2^{(\mathrm{GO})}(Q) = C_0\left(1+2p(1-p)e^{-R^2Q^2} + p^2e^{-2R^2Q^2}\right)\cdot(1+\varepsilon Q)$$

Empirical model inspired to the Quantum Optics model (**QOe**).

$$C_2^{(\mathrm{EO})}(Q) = C_0\left(1+2p(1-p)e^{-RQ} + p^2e^{-2RQ}\right)\cdot(1+\varepsilon Q)$$

p is the *chaoticity*: = 0 (= 1) for purely coherent (chaotic) sources.

Minimum-bias Event selection criteria

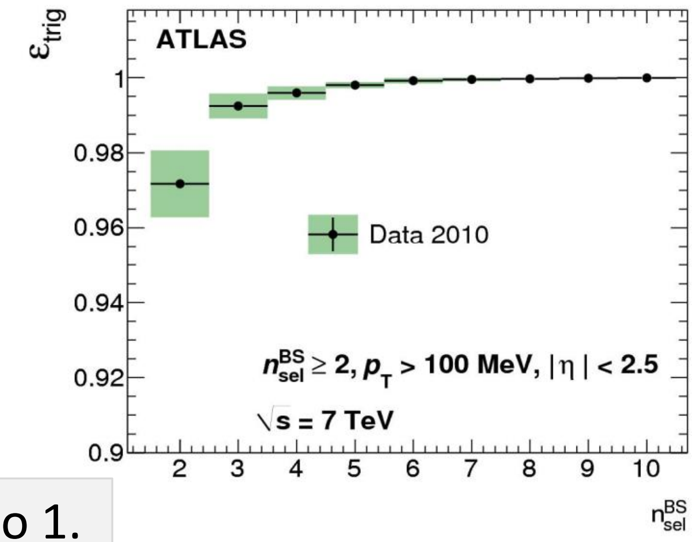
- ☐ Events pass the data quality criteria (all ID sub-systems on nominal condition, stable beam, defined beam spot):
  - ✓ Accept on single-arm Minimum Bias Trigger Scintillator.
  - ✓ Primary vertex (2 tracks with $p_T > 100$ MeV)
    - Veto to any additional vertices with ≥ 4 tracks.
  - ✓ At least 2 tracks with $p_T > 100$ MeV, $|\eta|<2.5$;
  - ✓ At least 1 first Pixel layer hit and 2, 4 or 6 SCT hits for $p_T > 100, 200, 300$ MeV respectively;
  - ✓ Cuts on the transverse impact parameter: $|d_0| < 1.5$ mm;
  - ✓ Cuts on the longitudinal impact parameter: $|z_0 \sin\theta| < 1.5$ mm;
  - ✓ Track fit χ^2 probability > 0.01 for tracks with $p_T > 10$ GeV.

Trigger and vertex reconstruction corrections

- ✓ Trigger efficiency: $\varepsilon_{\text{trig}}(n)$,
- ✓ Vertex reconstruction efficiency: $\varepsilon_{\text{vert}}(n)$

We use the formula:

$$w(n) = \frac{1}{\varepsilon_{\text{trig}}(n) \cdot \varepsilon_{\text{vert}}(n)}$$



For multiplicities $n \geq 3$ these corrections are close to 1.

- ✓ Multiplicity distributions – corrected to the particle level using an iterative Bayesian approach.
- ✓ Unfolding matrix is built using the ATLAS MC09 PYTHIA tune.
- ✓ Fraction of pile-up in the HM events
  - Fraction of events with pile-up: 1–2%, ⇒ charged particles from pile-up give a negligible contribution to primary vertex particles.

Coulomb correction

The measured $N(Q)$ distribution for the like or unlike signed particle pairs in presence of the Coulomb interaction is given by:

$$N_{meas}(Q) = G(Q) \cdot N(Q)$$

where $N_{\mathrm{meas}}(Q)$ is the measured distribution, $N(Q)$ is the distribution free of Coulomb interaction.

Gamow penetration *G*(*Q*) factor

$$G(Q) = \frac{2\pi\eta}{e^{2\pi\eta} - 1}$$

- ✓ Sommerfeld parameter *η*

The size of this correction does not exceed 20% for *Q* > 0.03 GeV.