Measurements on hadron production in proton-proton collisions with the ATLAS detector

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Overview

- Bose-Einstein correlations
  - Motivation
  - Experimental procedure
  - Extraction of an effective radius of hadroproduction region and the incoherence parameter from the fits of the two-particle spectra
- Summary

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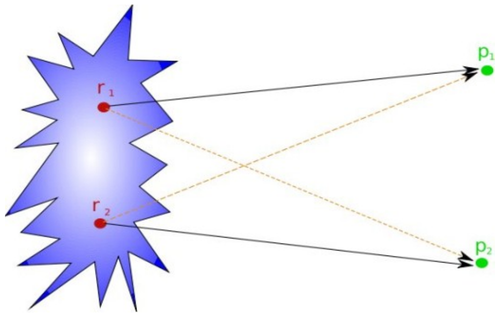
Motivation

- Bose-Einstein correlations (BEC) represent a unique probe of the space-time geometry 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. 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.

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 $C_2(Q)$ is a ratio of probabilities:

$$C_2(Q) = \frac{P(\boldsymbol{p_1}, \boldsymbol{p_2})}{P(\boldsymbol{p_1}) \cdot P(\boldsymbol{p_2})}$$

Probability to observe two particles with momenta p_1 and p_2

$$Q^2 = -(\boldsymbol{p_1} - \boldsymbol{p_2})^2$$

Probability to observe one particle with momenta p_1, p_2 respectively

$$C_2(Q) = C_0 \cdot [1 + \Omega(\lambda, RQ)] \cdot (1 + Q\varepsilon)$$

Normalization constant

Long distance correlation

BEC effect:

- described by a function with two parameters:
  - the effective radius ***R***,
  - the strength parameter ***λ*** – incoherence or chaoticity factor

Parametrization models

- **GSSg** model. The *Goldhaber spherical source model*.

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

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

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

  - ***R*** is the source *radius*
  - ***λ*** is the *incoherence* factor (0, 1) introduced empirically.

- **QOg** model. *Quantum Optics* model.

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

- **QOe** model. *Empirical* but inspired to the Quantum Optics model.

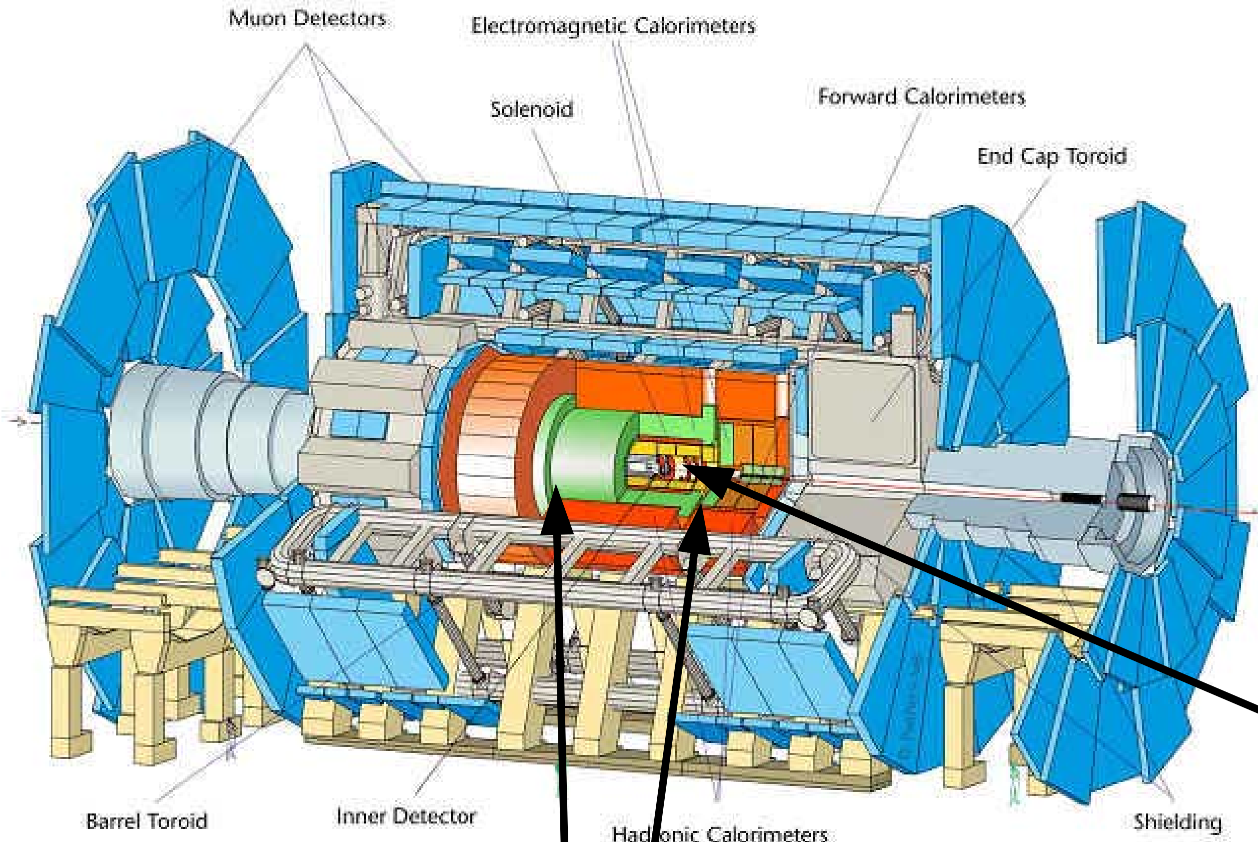
$$C_2^{(EO)}(Q) = C_0 \cdot \left(1 + 2\,p\left(1 - p\right) e^{-RQ} + p^2\, e^{-2 RQ}\right) \cdot \left(1 + Q\,\varepsilon\right)$$

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

Two particle correlation function

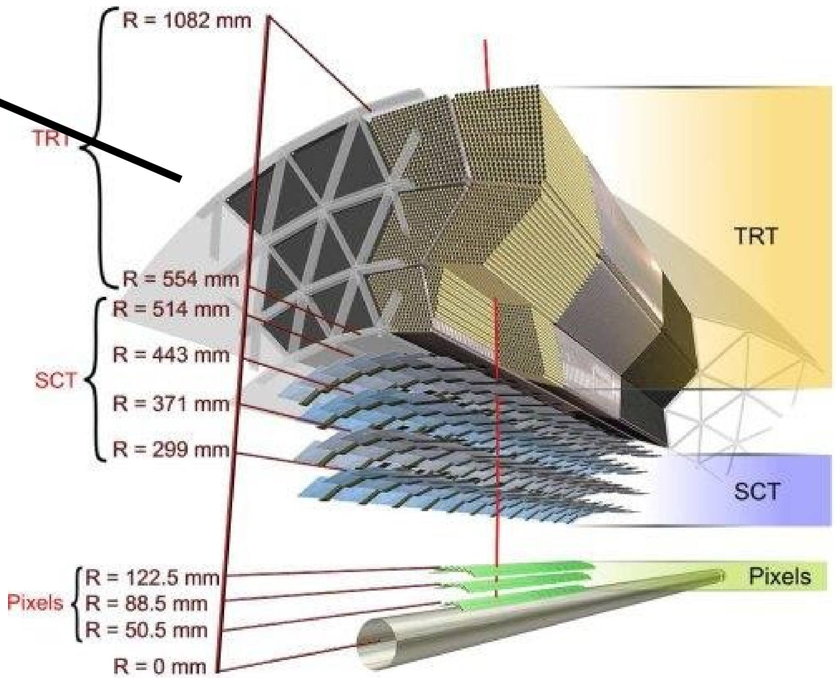
- The $C_2(Q) = \frac{N^{\text{ls}}(Q)}{N^{\text{ref}}(Q)}$ correlation function is a ratio of
  - Signal distribution $N^{\text{ls}}(Q)$ with BEC: contains pairs of identical particles, like-sign pairs
  - Reference distribution $N^{\text{ref}}(Q)$ w/o BEC: does not contain identical particles, unlike-sign pairs or artificial distribution (event mixing, opposite hemisphere, rotated tracks)
- Double ratio $R_2^{\text{DR}}(Q) = \frac{C_2^{\text{Data}}(Q)}{C_2^{\text{MC}}(Q)}$
  - $R_2(Q)$ eliminates problems with energy-momentum conservation, topology, etc. MC doesn't contain BEC
  - The studies are carried out using the $R_2(Q)$ correlation function

The ATLAS Detector



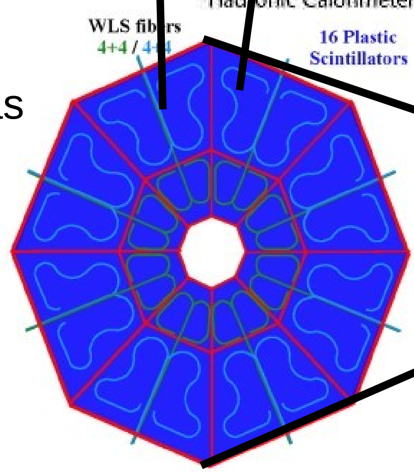
ATLAS inner detector

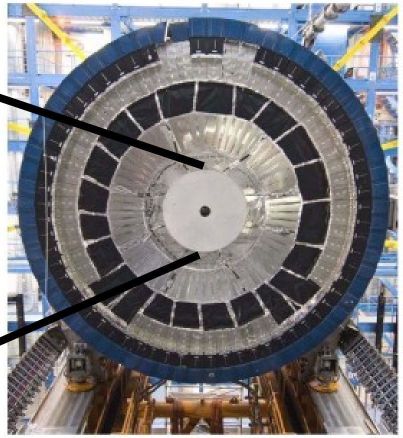
- The main tracking device
- $|\eta| < 2.5$, $p_T > 100$ MeV
- Silicon Pixels 50 x 400 μm^2
- Silicon Strips (SCT) 40 μm rad stereo strips
- Transition Radiation Tracker (TRT) up to 36 points/track



MBTS - Minimum Bias Trigger Scintillator

- $2.09 < |\eta| < 3.084$
- Designed for triggering on min bias events >99% efficiency





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

Data and MC samples

- Study based on the Min Bias data sets and MC samples generated by PYTHIA 6 with ATLAS MC09, DW, Perugia runes, Phojet 1.12.1.35, and EPOS 1.99. The MC samples do not contain the BEC effect.
- Statistics: at 900 GeV: **3.6×10^5** events with **4.5×10^6** tracks and at 7 TeV: **1×10^7** events with **2.1×10^8** tracks passed selection criteria.
- Integrated luminosities: **7 μb^{-1}** at 0.9 TeV and **190 μb^{-1}** at 7 TeV.
- High Multiplicity (HM) dataset at 7 TeV was studied for the first time in BEC analyses. Statistic for 7 TeV (HM) **1.8×10^4** events (**2.7×10^6** tracks) were selected (integrated luminosity **12.4 nb^{-1}**).
- Track and event selection criteria applied
- Tracking and event efficiencies, unfolding to particle level.

Monte-Carlo samples

Four recent versions of MC event generators were used to provide calculation of R_2 correlation functions and for systematic studies.

- The MC models do not contain the BEC effect.

Generator	Version	Tune	PDF	Focus of Tune	Statistic
PYTHIA 6	6.421	MC09	MRST LO	MB/UE	1.1×10^7@ 0.9 TeV 2.7×10^7@ 7 TeV MBT 1.8×10^6@ 7 TeV HMT
PYTHIA 6	6.421	Perugia0	CTEQ 5L	MB	
PHOJET	1.12.1.35	no tune	MRST LO	MB/UE	
EPOS	1.99 v2965	LHC	CTEQ6.6 LO	MB	HMT only

- Large MC samples of minimum-bias and high-multiplicity events were generated with PYTHIA 6.421 ATLAS MC09 set of optimised parameters with non-diffractive, single-diffractive and double-diffractive processes included in proportion to the cross sections predicted by the model.

For the study of systematic effects, additional MC samples were produced using the PHOJET 1.12.1.35, PYTHIA with the Perugia0 tune, and the EPOS 1.99 v2965 for the HM analysis.

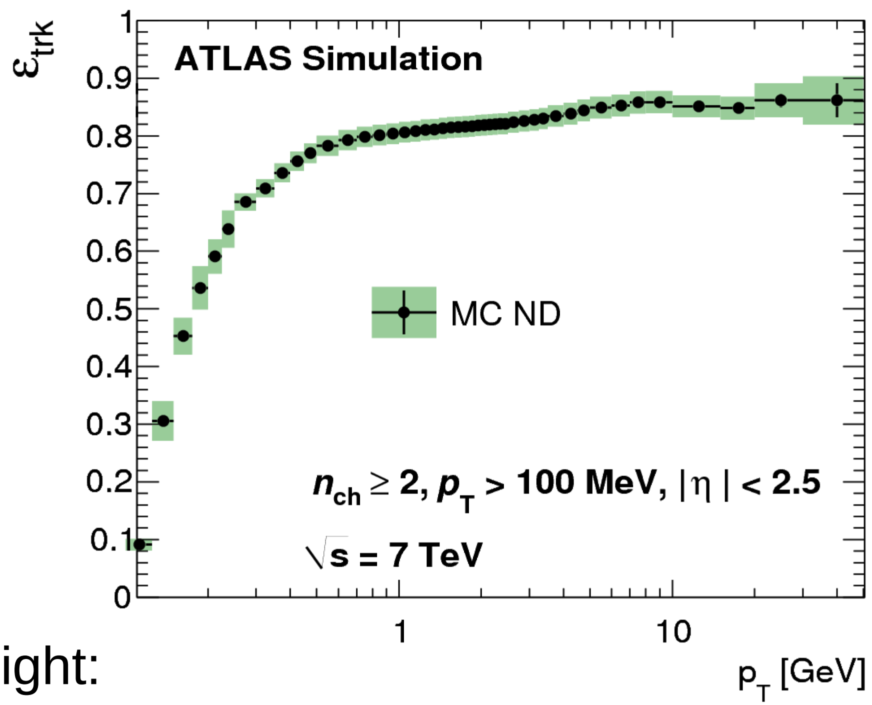
- The PHOJET program uses the Dual Parton Model for low-pT physics and is interfaced to PYTHIA for the fragmentation of partons.

- The EPOS generator is based on an implementation of the QCD inspired Gribov-Regge field theory describing soft and hard scattering simultaneously, and relies on the same parton distribution functions as used in PYTHIA.

Track reconstruction corrections

Performed corrections for:

- The track reconstruction efficiency: $\varepsilon(p_T, \eta)$,
- The fraction of secondary particles: $f_{sec}(p_T, \eta)$,
- The fraction of selected tracks for which the corresponding primary particles are outside the kinematic range: $f_{okr}(p_T, \eta)$,
- The fake tracks: $f_{fake}(p_T, \eta)$,



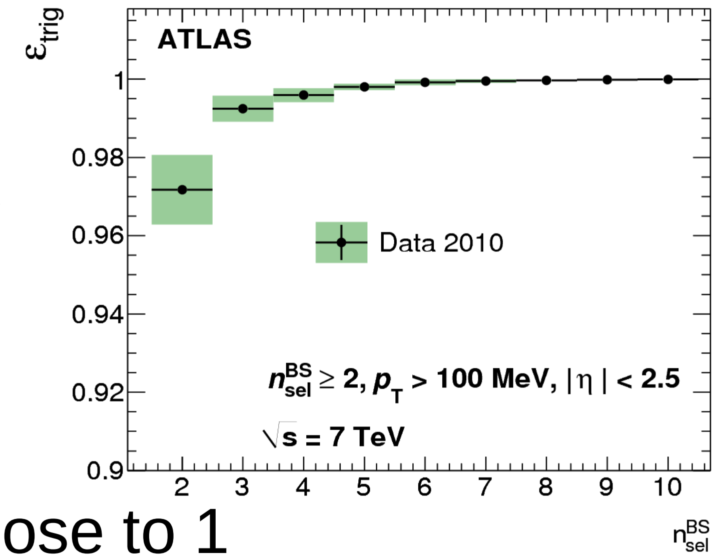
Summarizing all correction factors in an event weight:

$$w_i(p_T, \eta) = \frac{(1 - f_{sec}(p_T, \eta)) \cdot (1 - f_{okr}(p_T, \eta)) \cdot (1 - f_{fake}(p_T, \eta))}{\varepsilon(p_T, \eta)}$$

- The effect of events lost due to the trigger and vertex reconstruction - corrected using event-by-event weights applied to each pair of particles.
- The resolution of Q – obtained to be better than 5 MeV – to exclude track fake reconstruction the Q-threshold 20 MeV was taken.

Trigger and vertex reconstruction corrections

- The trigger efficiency: $\varepsilon_{\text{trig}}(n)$,
- The vertex reconstruction efficiency: $\varepsilon_{\text{vert}}(n)$



We use the formula: $$w(n) = \frac{1}{\varepsilon_{trig}(n) \cdot \varepsilon_{vert}(n)}$$

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

- The multiplicity distributions – corrected to the particle level using an iterative method (Bayesian approach).
- The 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 particle from the pile-up vertex do not contribute much to each primary vertex (negligible).

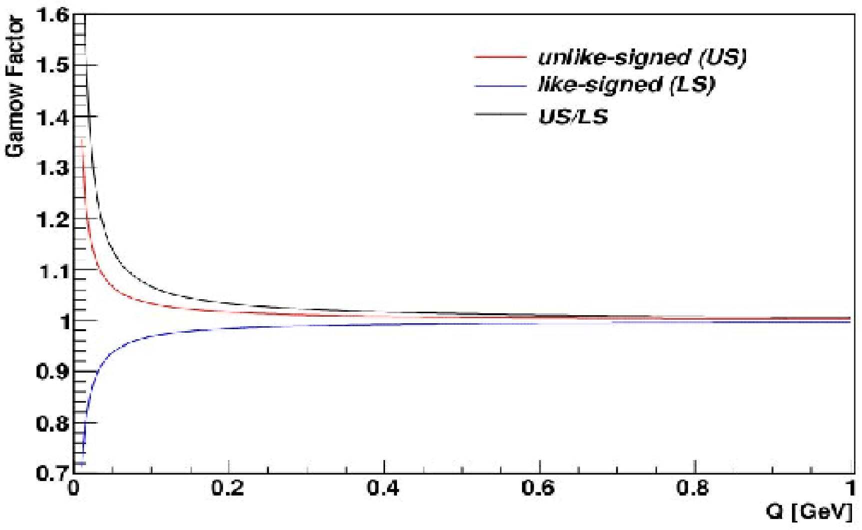
Coulomb correction

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

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

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

- Gamow penetration $G(Q)$ factor $G(Q) = \dfrac{2\pi\eta}{e^{2\pi\eta} - 1}$
- Sommerfeld parameter η $\eta = \dfrac{\pm\alpha m}{|Q|}$



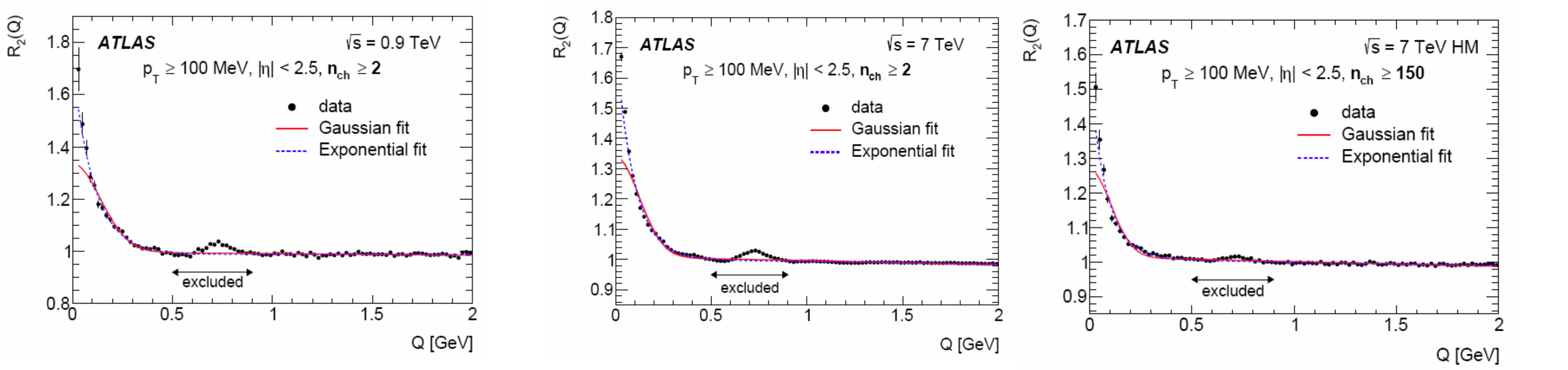
The size of this correction not to exceed 20% for $Q > 0.03$ GeV.

Systematic uncertainties

Systematic uncertainties on ***λ*** and ***R*** for the exponential fit of the two-particle double-ratio correlation function $\boldsymbol{R}_2$(Q) in the 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%

Inclusive Double Ratio correlation functions



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. The *Q* region is from 0.02 to 2 GeV.

$$\lambda = 0.74 \pm 0.11,\ R = 1.83 \pm 0.25 \text{ at } \sqrt{s} = 0.9 \text{ TeV for } n_{\rm ch} \geq 2,$$
$$\lambda = 0.71 \pm 0.07,\ R = 2.06 \pm 0.22 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{\rm ch} \geq 2,$$
$$\lambda = 0.52 \pm 0.06,\ R = 2.36 \pm 0.30 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{\rm ch} \geq 150.$$

Comparison with other experiments

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

The comparison to the exponential fit can be done using the scale factor $\sqrt{\pi}$:

$$R^{(G)} = R^{(E)} / \sqrt{\pi}$$

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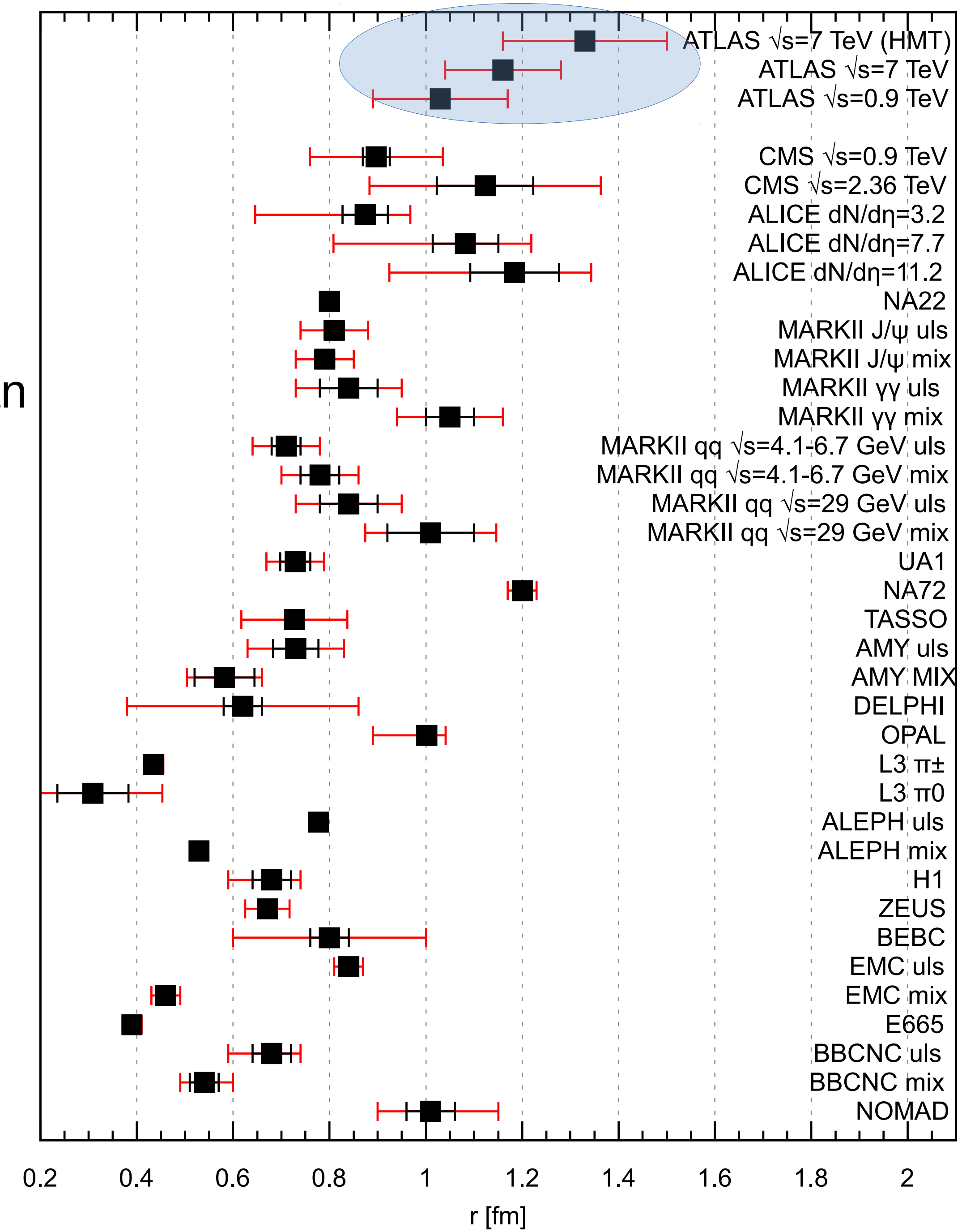
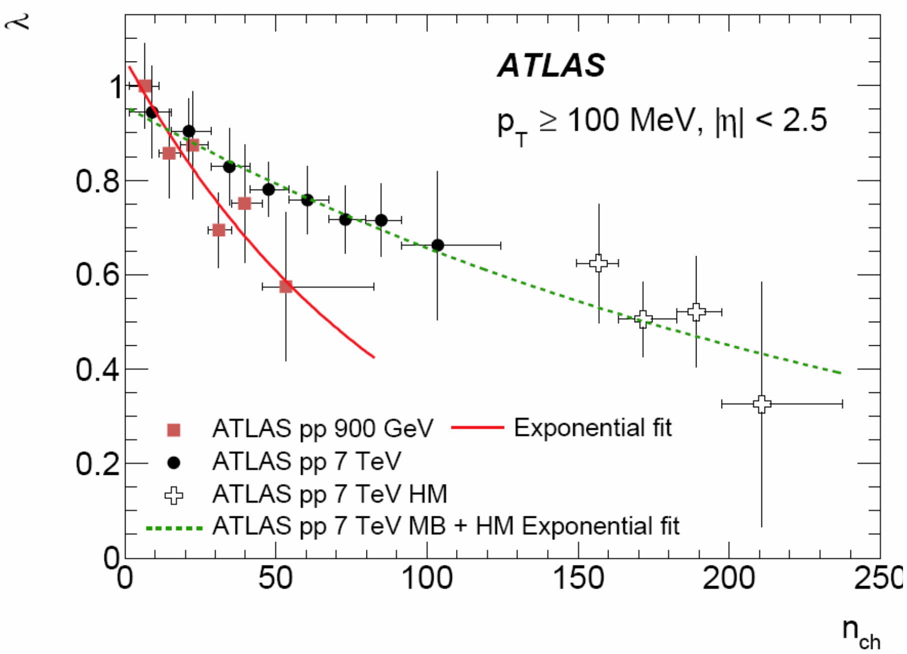
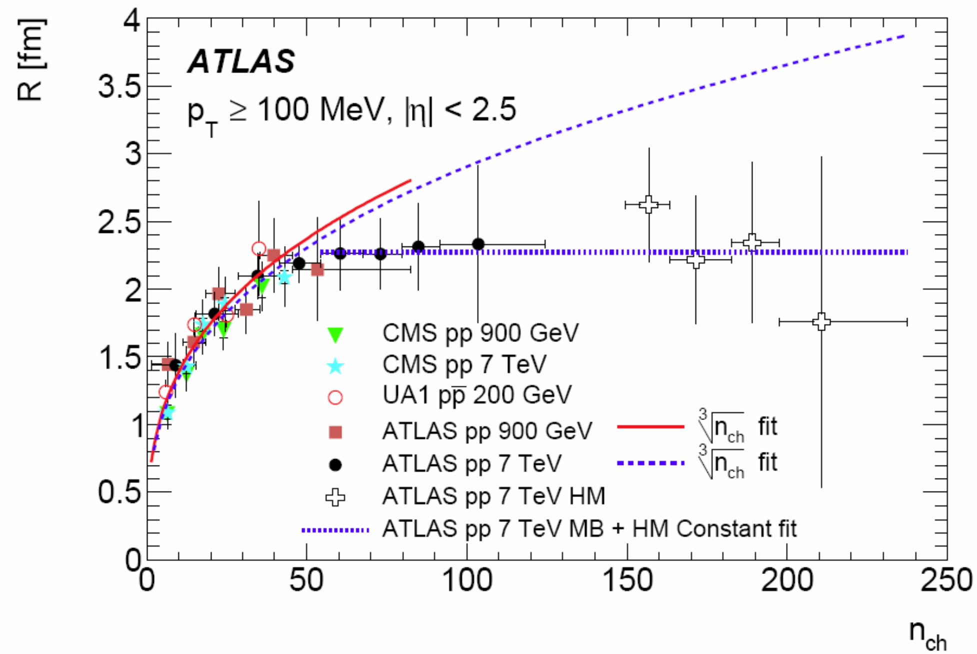
* see backup slide for references

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



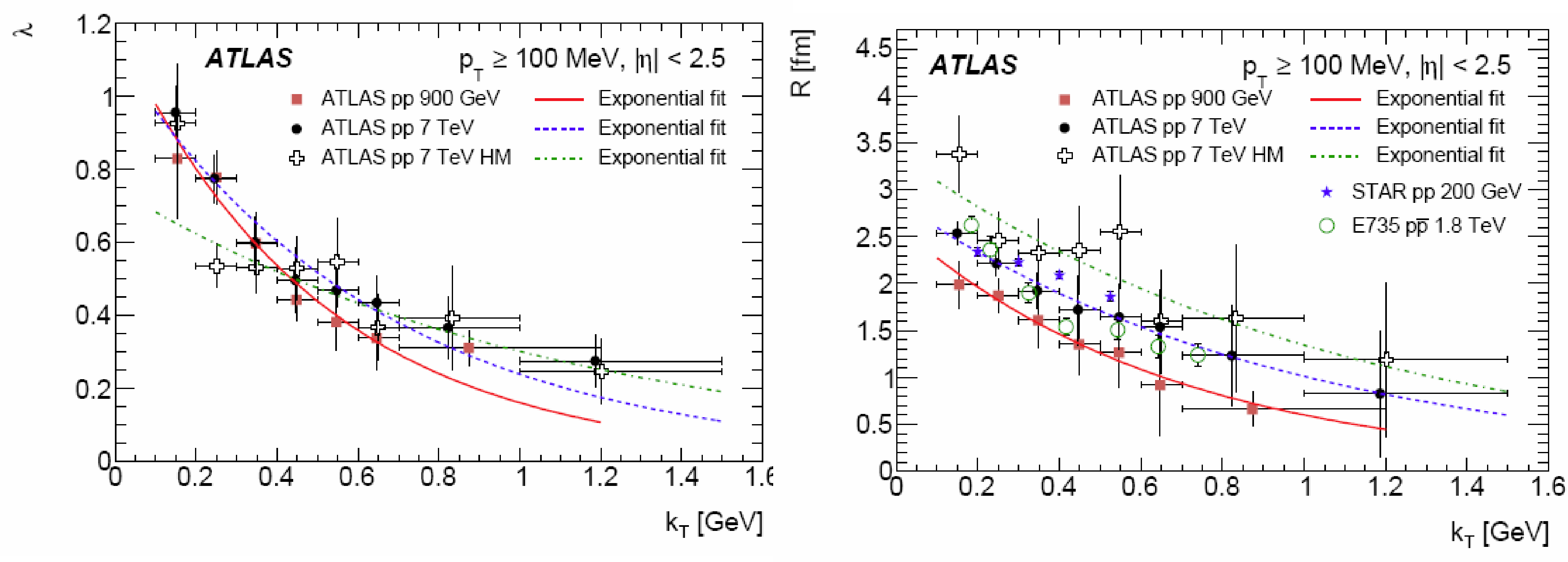
Parameters λ and *R* vs particle multiplicity





- Multiplicity, n_{ch}, dependence of (left) ***λ*** and (right) ***R*** from the exponential fit to $R_2(Q)$ functions at $\sqrt{s}$ = 0.9 and 7 TeV, compared to measurements of the CMS and UA1 experiments.
- The curves are the results of (***λ***) the exponential and (***R***) $3\sqrt{n_{ch}}$ for $n_{ch} < 55$ fits.
- The dotted line in (***R***) is a result of a constant fit to minimum-bias and high-multiplicity events data at 7 TeV for $n_{ch} \geq 55$ ⇒ saturation of ***R*** at high multiplicities: – expected in a Pomeron-based model
- The error bars – quadratic sum of the statistical and systematic uncertainties.

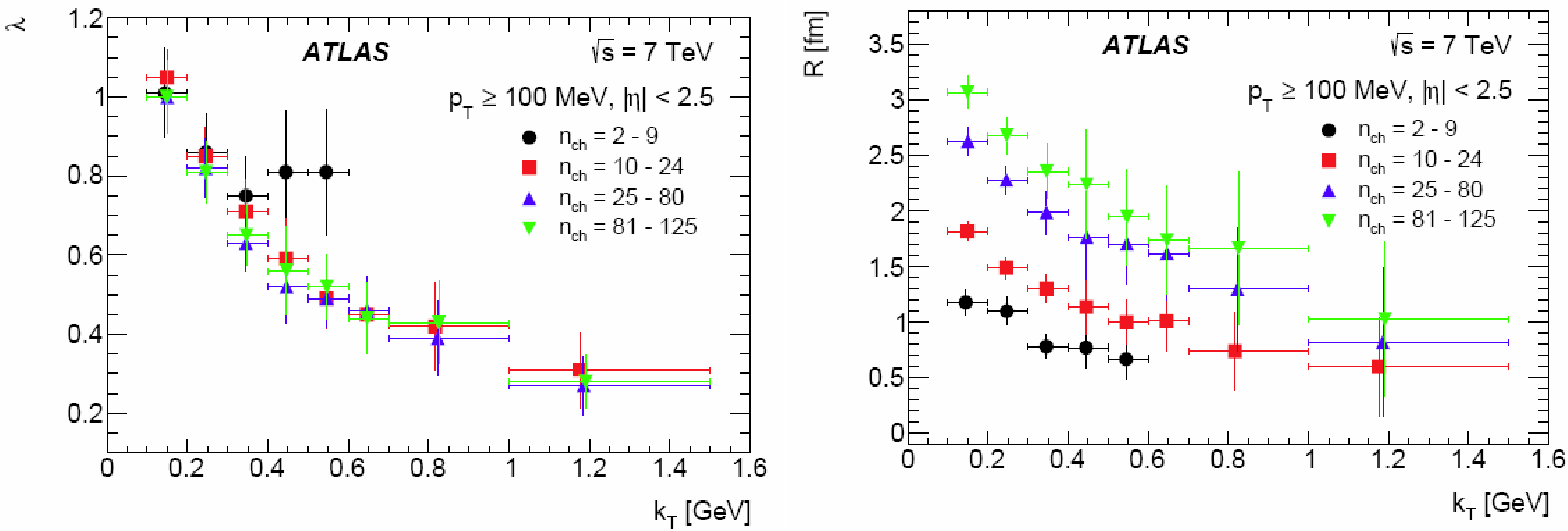
Parameters λ and R vs track pair k_T



The k_T dependence of $\boldsymbol{\lambda}$ (left) and ***R*** (right) – from the exponential fit to two-particle double ratio at $\sqrt{s}$ = 0.9 TeV, 7 TeV and 7 TeV high-multiplicity events. The curves – results of the exponential fits.

- The average transverse momentum k_T of the particle pairs $k_T = |p_{T,1} + p_{T,2}| / 2$. Results – compared to measurements by the E735 experiment (Tevatron), and by the STAR experiment (RHIC) .
- The error bars – the quadratic sum of the statistical and systematic uncertainties.

k_T dependences of λ and R for different multiplicity regions



The k_T dependence of $\boldsymbol{\lambda}$ (left) and $\boldsymbol{R}$ (right) - from the exponential fit to $R_2(Q)$ function at $\sqrt{s}$ = 7 TeV for the different multiplicity regions: $\mathbf{2 \leq n_{ch} \leq 9}$ (circles), $\mathbf{10 \leq n_{ch} \leq 24}$ (squares), $\mathbf{25 \leq n_{ch} \leq 80}$ (triangles) and $\mathbf{81 \leq n_{ch} \leq 125}$ (inverted triangles).

- The decrease of $\boldsymbol{\lambda}$ with k_T is nearly independent of multiplicity for $\boldsymbol{n_{ch}} > 9$.
- ***R***-parameter decreases with k_T and exhibits an increase with increasing multiplicity
- The error bars – the quadratic sum of the statistical and systematic uncertainties.

Conclusions

- The Bose-Einstein correlations of the pairs of identical charged particles have been measured with $|\eta| < 2.5$ and $p_T > 100$ MeV in **pp** collisions at 0.9 and 7 TeV with the ATLAS detector at the LHC.
- Multiplicity dependence of the BEC was investigated up to very high multiplicities (≈ 240). A saturation effect in multiplicity dependence of the extracted BEC radius was observed at level $\boldsymbol{R = 2.28 \pm 0.32}$ **fm**.
- Dependence of the BEC parameters on track pair k_T and on particle p_T was investigated.
- The dependence of the BEC parameters on k_T is investigated for different multiplicity regions up to high multiplicity.
- Ongoing analysis of 8 and 13 TeV data.

Backup slides

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