Study of Bose-Einstein correlations for same-sign charged pions at $\sqrt{s}$ = 7 TeV

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On behalf of LHCb Collaboration

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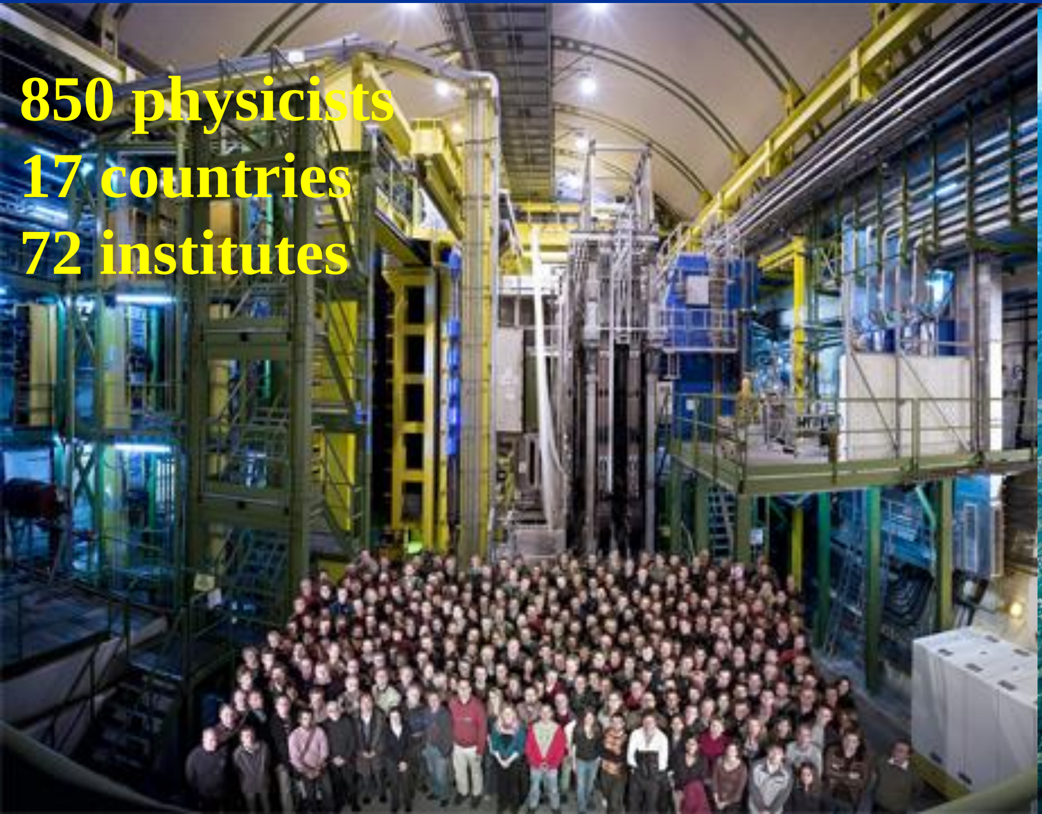
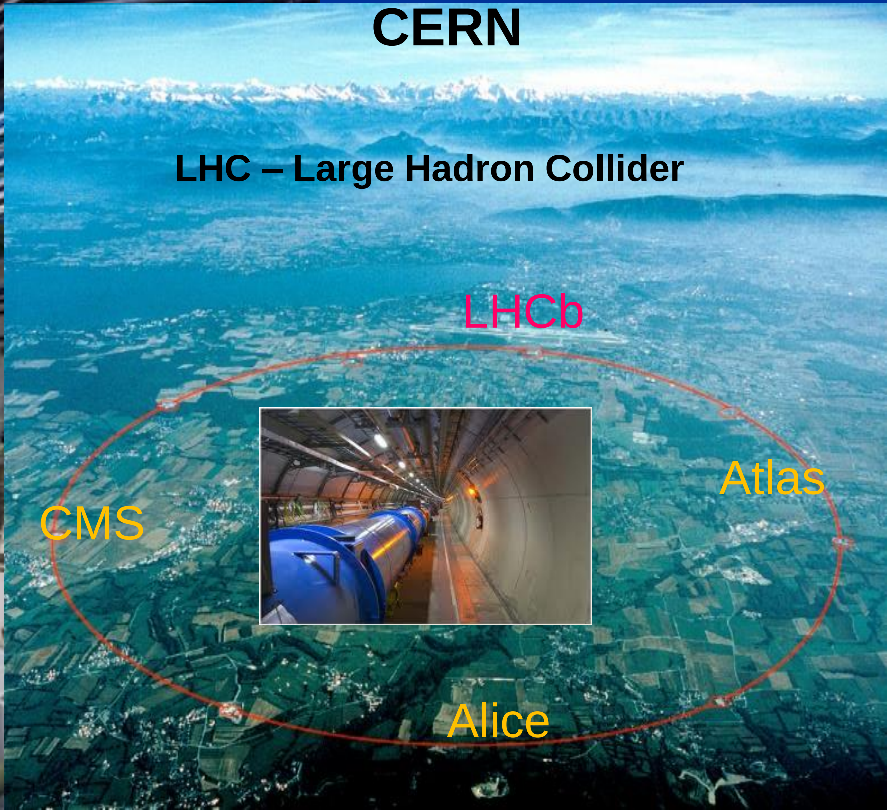
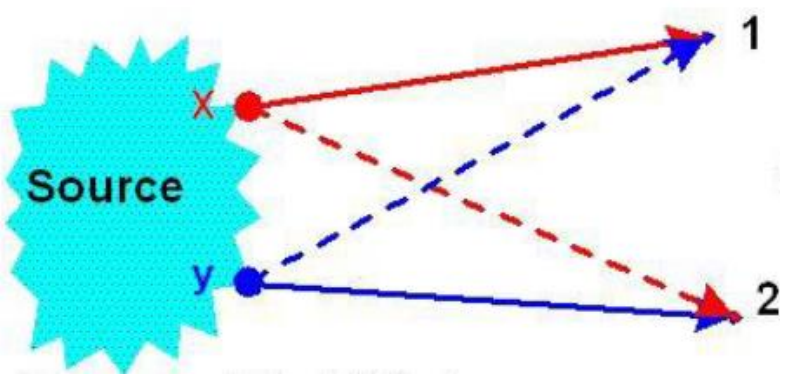




Outline

- Introduction
- LHCb experiment
- Analysis method
- Data selection
- Results
- Summary



Bose-Einstein Correlations = BEC

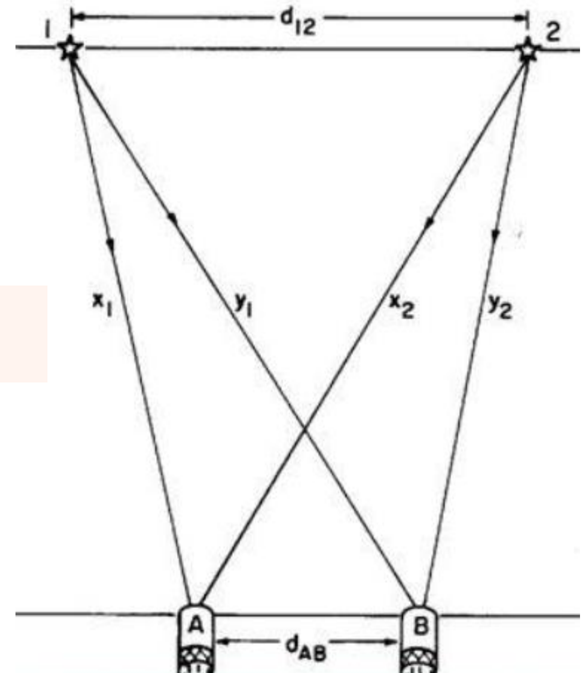
LHCb result: [arXiv:1709.01769]

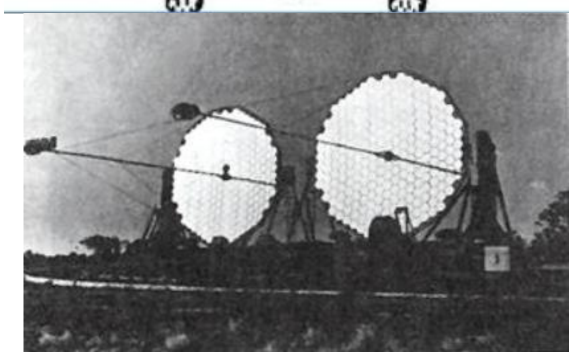
HBT interferometry

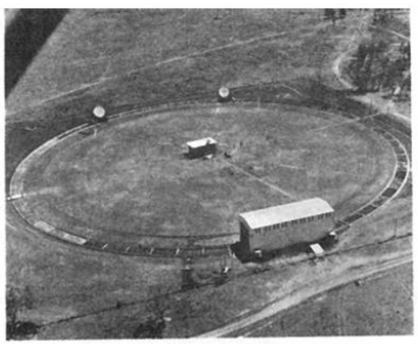
In 1950s Robert **H**anbury **B**rown an Richard Q. **T**wiss (radio astronomy engineers) found
correlations between photons from different sources

Initially this observation was not accepted as contradicting Quantum Mechanics

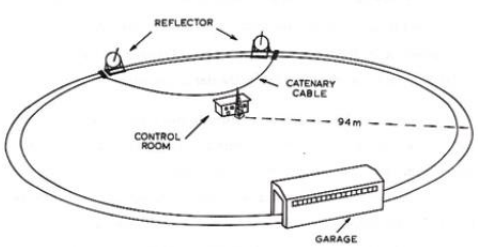
It turned out that the observed effect does not contradict Quantum Mechanics but oppositely, it is a consequence related to Bose-Einstein statistics







Intensity interference (second order interference) to measure the diameters of radio sources



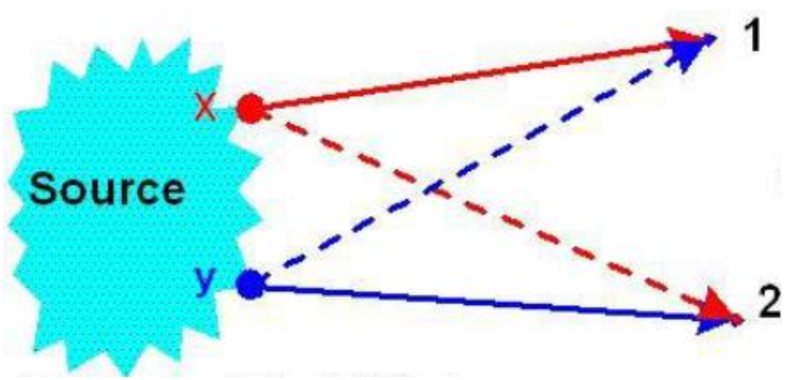
By changing the distance between detectors, one can measure the diameter of emitting source

From interferometry to particle physics

1959 - Goldhaber, Goldhaber, Lee and Pais

G. Goldhaber et al., Phys. Rev. 120 (1960) 300

- Experiment at the Bevalac/LBL, in Berkeley to look for the resonances by comparing *Q* distribution of unlike-sign pairs $\pi^+\pi^-$ to same-sign pair $\pi^+\pi^+$ or $\pi^-\pi^-$.
- No resonance was discovered (not enough statistics) but unexpected angular correlation among same-sign pions was observed
- Counterpart of the HBT effect in particle physics



Quantum interference effect between indistinguishable particles emitted by a finite source

$$Q = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4\mu^2}$$

q_1, q_2 – four-momenta of particles 1,2

Q plays similar role as variable distance between telescopes in HBT interferometry

Useful tool to probe the spatial and temporal structure of the hadron emission volume

Correlation function

$$C_2(q_1,q_2) = \frac{\mathcal{P}(q_1,q_2)}{\mathcal{P}(q_1)\mathcal{P}(q_2)} = \frac{\mathcal{P}(q_1,q_2)}{\mathcal{P}_{ref}(q_1,q_2)}$$

$$C_2(Q) = \frac{\rho_2(Q)^{data}}{\rho_2(Q)^{ref}}$$

$\rho_2(Q)^{data}$ Q distribution for same-sign pair in data – includes quantum correlations

$\rho_2(Q)^{ref}$ Q distribution for reference sample – no quantum correlations

Goldhaber parametrization - historically first

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

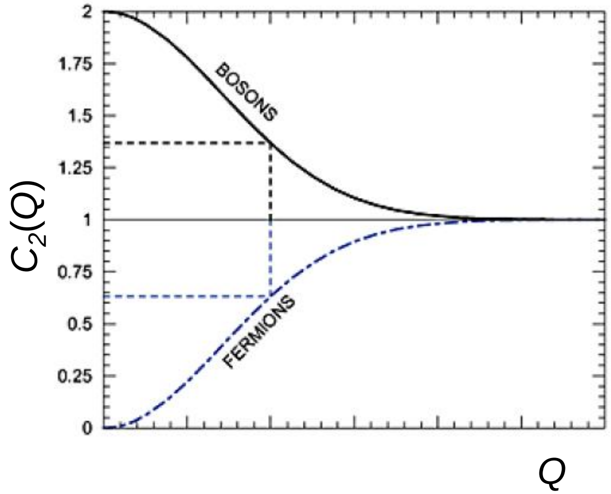
+ for bosons
- for fermions

R - radius of the spherical source

λ - chaoticity parameter

λ=0 fully coherent source

λ=1 completely chaotic source



Levi parametrization used in this analysis.

$$C_2(Q) = N(1 \pm \lambda e^{-RQ}) \times (1 + \delta \cdot Q)$$

Shape of long range correlations (higher Q)

Choice of reference sample

The reference sample should be free from Bose-Einstein Correlations (BEC) while possessing other correlations related to e. g. charge, energy-momentum conservation, particle decays, event topology etc.

$$C_2(Q) = \frac{\rho_2(Q)^{data}}{\rho_2(Q)^{ref}}$$

Reference sample

Event-mix – pairs of same-sign charged pions each originating from different events

derived from data but random pairing eliminates BEC and all other non trivial correlations

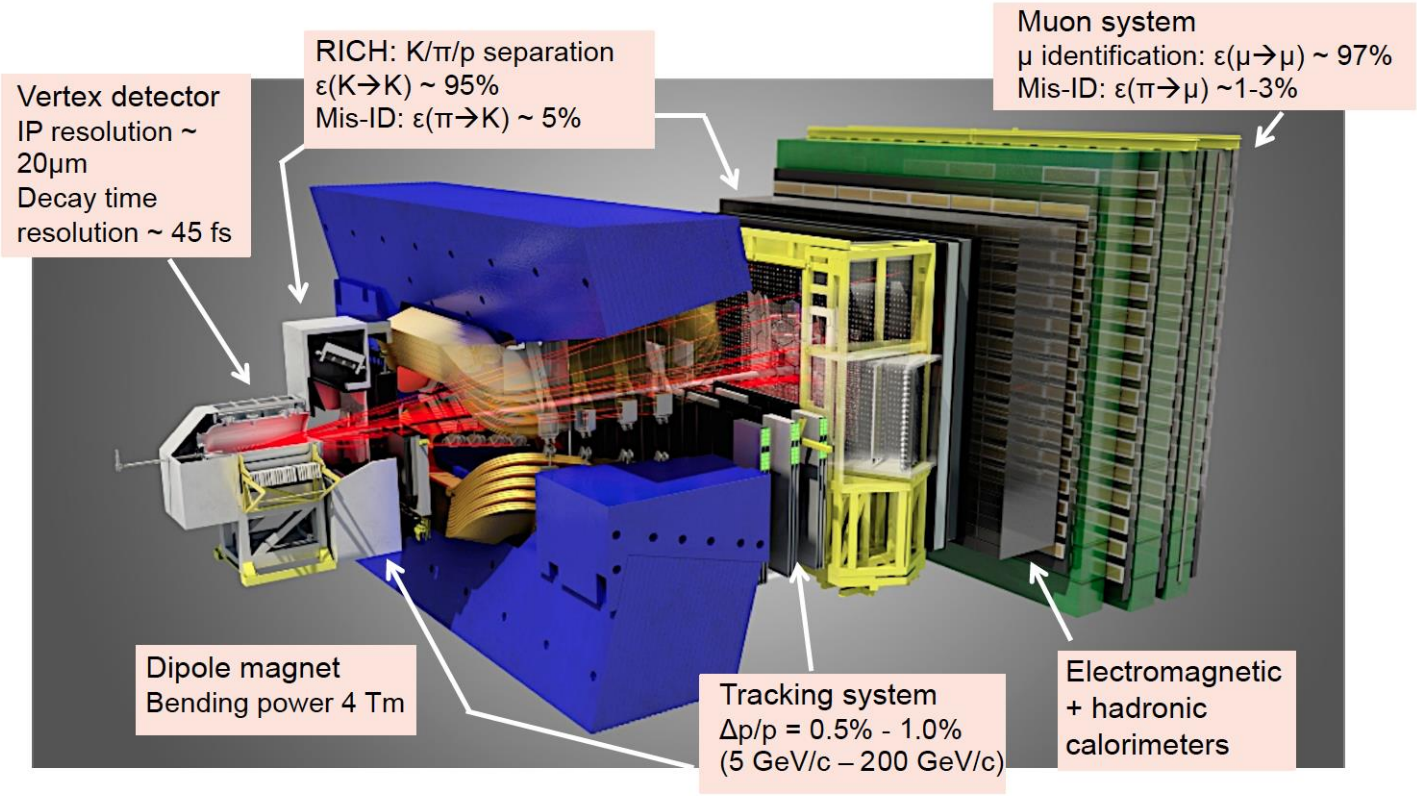
Double Ratio - an improved correlation function.

$$DR(Q) = \frac{\rho_2(Q)^{data}}{\rho_2(Q)^{ref,data}} \Bigg/ \frac{\rho_2(Q)^{MC}}{\rho_2(Q)^{ref,MC}} = \frac{C_2(Q)^{data}}{C_2(Q)^{MC}}$$

- MC correlation function contains similar pattern of distortions as correlation function for data
- By dividing them, one can correct for imperfections of the reference sample construction and eliminate second order effects to large extent

The LHCb detector

Primary goal of LHCb: **Precision Measurements of CP-Violation, search for New Physics in CPV processes and rare decays**



JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

But LHCb is fully instrumented in $2 < \eta < 5$, therefore can serve as a general purpose detector in the forward region

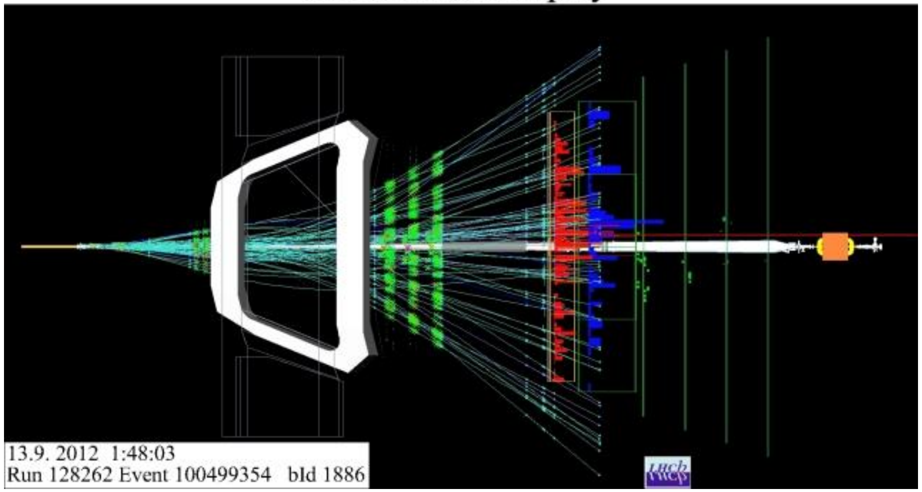
Single track selection

Relatively loose selection of pions

Long track traversing whole detector:

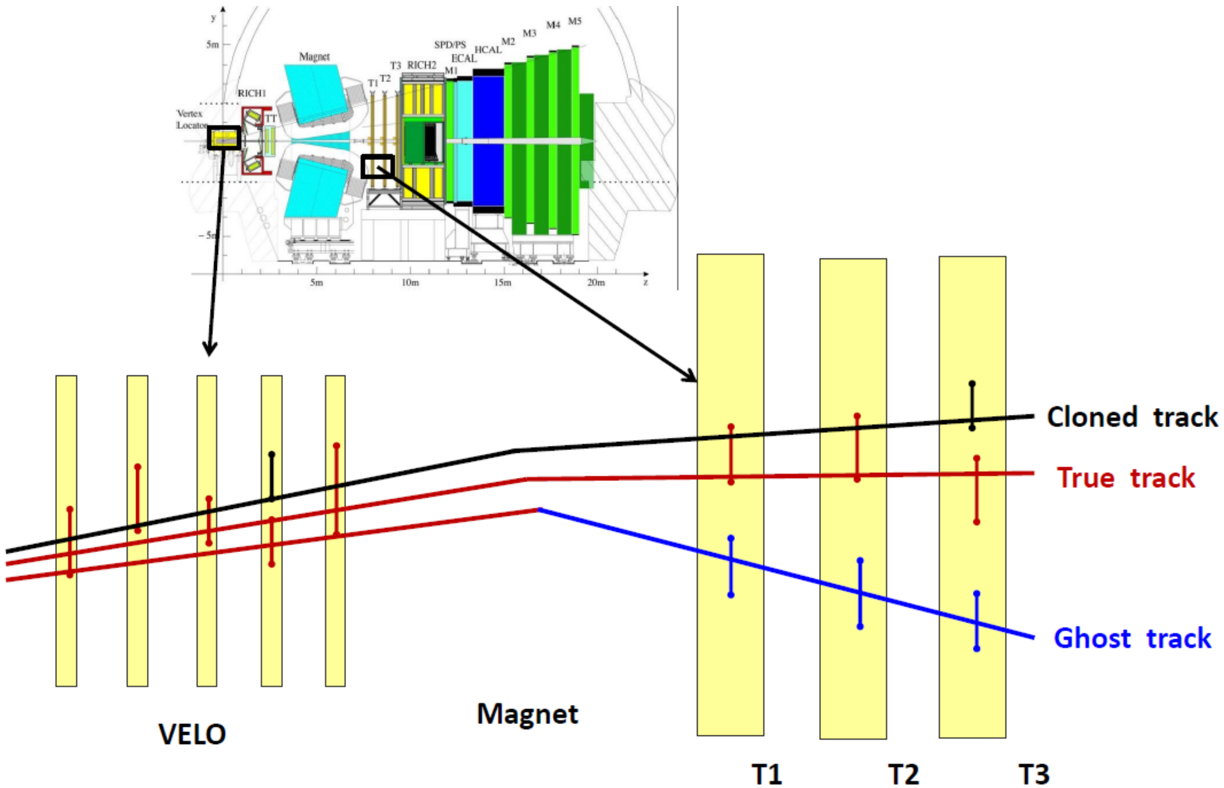
- loose particle identification requirements for π
- $2 < \eta < 5$
- good quality of track fit (χ^2 / NDF < 2)
- momentum > 2 GeV/c
- transverse momentum > 0.1 GeV/c
- impact parameter (IP) < 0.4 mm
- cut on probability to be a ghost track

LHCb Event Display



- Correlation function is not sensitive to single track efficiency but can be sensitive to two-track effects such as cloned tracks or ghost tracks.
- Two-track efects do not influence the baseline LHCb analyses but for BEC one has to pay special attention.

Clones and ghosts



Cloned tracks - two or more tracks reconstructed by mistake from the hits originating mainly from single particle

- Clones form pairs of tracks with small opening angle, - fall into the low Q region and may affect the BEC signal

Ghost tracks - wrongly reconstructed tracks which combine the hits deposited by multiple particles

- Ghost populate wide Q range

Track pair selection

Clones removal:

- Pion pairs are removed if differences of tangents of track momenta are similar i.e. both Δt_x and Δt_y < 0.3 mrad.

Influence of clones for Q>0.05 GeV/c^2 was reduced to a marginal level

Ghosts removal:

- Remove tracks with high probability to be a ghost (dedicated parameter assigned to track)
- If tracks share most of the VELO hits then keep track with better χ^2 / NDF

After selection ghosts are under control for Q region Q>0.05 GeV/c^2 .

Systematic uncertainty estimated to be low compared to dominant contributions

Coulomb effect :

- Correction is known. Apply Gamov penetration factor to the Q distribution.

$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}, \quad \text{where} \quad \zeta = \pm\frac{\alpha m}{Q}.$$

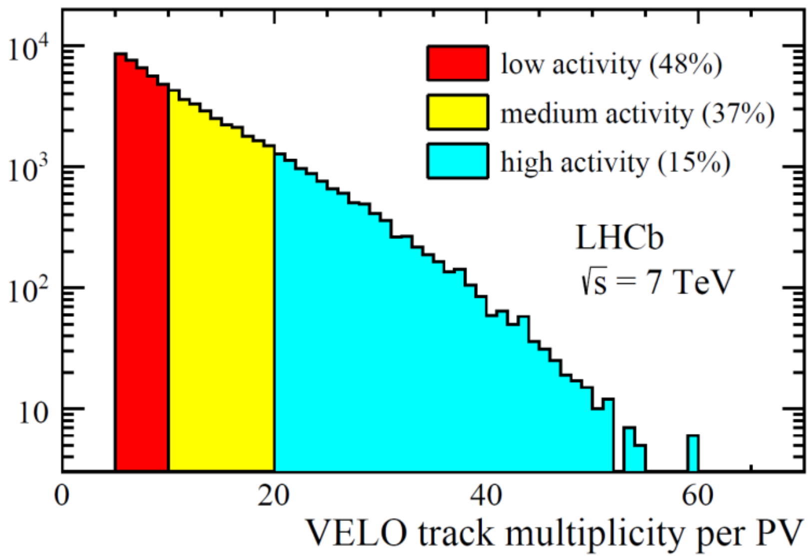
Uncertainty due to Coulomb correction was checked to be negligible

Two particle efficiencies are under control for Q > 0.05 GeV/c^2.
- **Checked by Double Ratio for unlike pions (no BEC but other effects present)**

Q range for analysis: 0.05 GeV/c^2 < Q < 2 GeV/c^2

Three multiplicity bins

- R, radius of the source depends on total multiplicity N_{tot} of an event
- N_{ch} – VELO multiplicity of charged tracks is good probe of N_{tot}
- To check the $R(N_{ch})$ dependence, total sample was split into 3 multiplicity bins



Bin	VELO N_{ch}	Activity class
1	5-10	(52-100)%
2	11-20	(15-52)%
3	21-60	(0-15)%

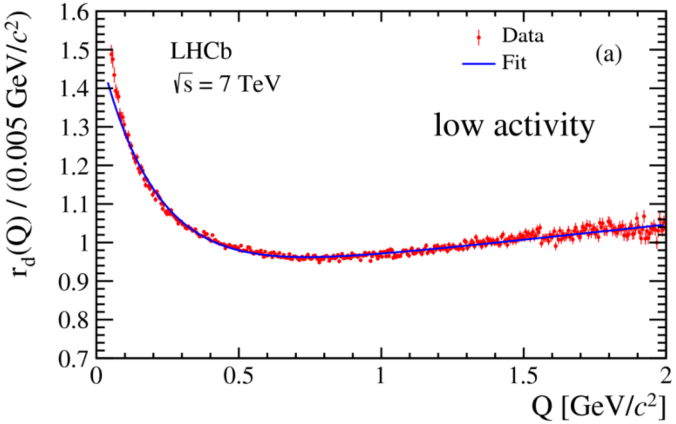
N_{ch} bins were chosen to have similar number of pairs in each bin.

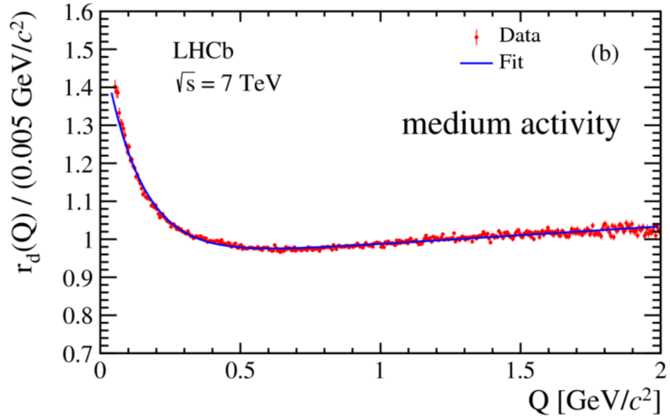
For example: activity class (0-15)% corresponds to 15 % of all events with highest VELO multiplicity.

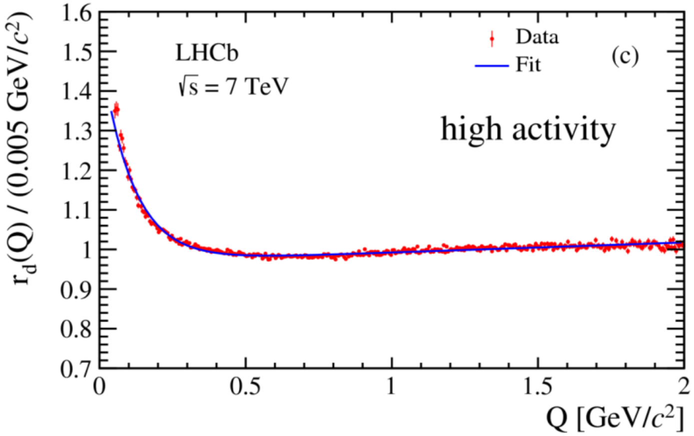
Activity classes seem to be the best parameter to compare results between various experiments (better than unfolded ones because of not overlapping η ranges)

- largely insensitive to detector acceptance and efficiency
- largely model independent

Results







$$C_2(Q) = N(1 \pm \lambda e^{-RQ}) \times (1 + \delta \cdot Q)$$

Activity class	R [fm]	λ
Low	1.01 ± 0.01 ± 0.10	0.72 ± 0.01± 0.05
Medium	1.48 ± 0.02 ± 0.17	0.63 ± 0.01 ± 0.05
High	1.80 ± 0.03 ± 0.16	0.57 ± 0.01 ± 0.03

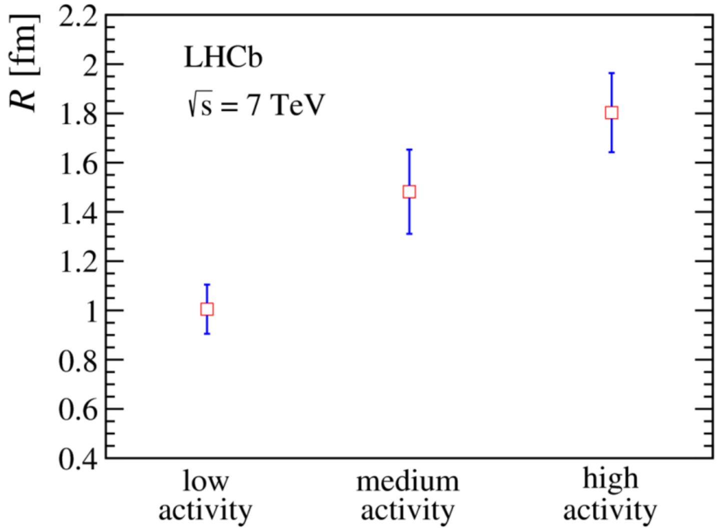
Systematic uncertainty dominates ~ 10 %

Clear BEC signal observed

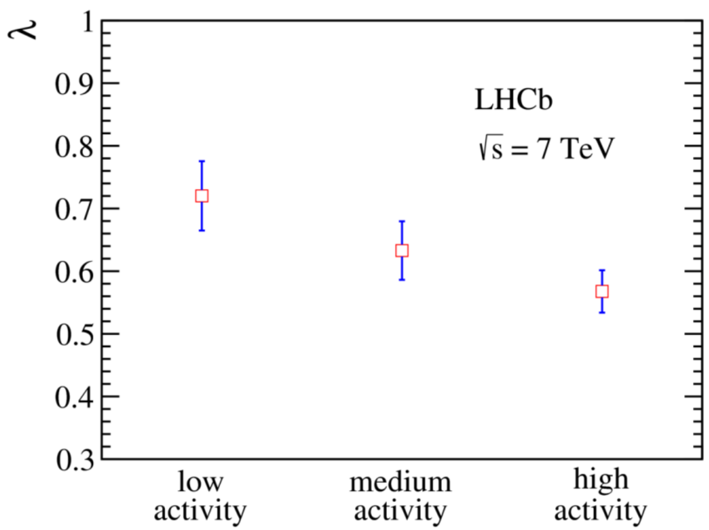
- χ^2 / NDF of the fit to Levy parametrization is ~1.6.
  - Levy parametrization is an effective 1-D approximation for static source.
  - 3-D parametrization fits better data as it includes information about time evolution of the emitting source.

Results

[arXiv:1709.01769]



Size grows with activity



Larger sources appear more coherent

- Direct comparison between experiments not straightforward (different η ranges)
- LHCb values and trends compatible with other results from LHC (ATLAS, CMS and ALICE)

Summary

Bose-Einstein correlations have been studied for same-sign pions produced in p-p collisions at $\sqrt{s_{NN}}$ = 7 TeV

- First measurement in the forward region (2<η<5) in three event activity bins

Possible future analysis

- different collisions: pp, pPb
- different beam energies: e.g. pp 7,8,13 TeV; p-Pb 5TeV
- 3-D analysis for pions
- 3-body correlations for pions

Backup slides

Systematic uncertainties - summary

Summary of systematic uncertainties for the 3 bins of PV VELO track multiplicities

Source	Low activity		Medium activity		High activity	
	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]
Generator tunings	6.6	4.3	8.9	3.5	6.5	1.5
PV multiplicity	5.9	5.8	6.1	4.5	3.9	4.3
PV reconstruction	1.8	0.1	1.4	1.2	0.1	<0.1
Fake tracks	0.4	1.1	1.7	3.9	1.1	0.8
PID calibration	1.3	0.3	0.8	0.6	2.7	0.9
Requirement on pion PID	2.9	1.8	1.6	0.1	1.3	0.1
Fit range at low-Q	1.2	1.0	1.2	1.5	1.8	2.7
Fit range at high-Q	1.8	0.1	2.1	0.8	2.4	1.4
Total	9.8	7.6	11.4	7.3	8.8	5.6