# Bose-Einstein correlations in pPb collisions at LHCb

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# Overview / outline

**similar studies (pPb) @ LHC**

| |
|---|
| **ALICE:** **Phys. Rev. C 91 (2015) 034** |
| **ATLAS:** **Phys. Rev. C 96 (2017) 064** |
| **CMS:** **Phys. Rev. C 97 (2018) 042** |

- Introduction & context.
- BEC studies @ LHCb.
- Data & selection.
- Analysis method.
- Conclusions.

## ANALYSIS STATUS

**Publication procedure** in the LHCb experiment is **ongoing**.
The presented results are **unofficial**.

Poster at the last year's school: LHCb-TALK-2020-202.

## FUNDING / SUPPORT

This study has been supported by Narodowe Centrum Nauki (grants 2013/11/B/ST2/03829 and 2018/29/N/ST2/01641), KNOW and the PLGrid Infrastructure.

# Introduction & context

## Bose-Einstein correlations (BEC):

- correlations in four-momenta $(q_1, q_2)$ of identical bosons emitted from the same source, studied in a Lorentz-invariant variable $Q = \sqrt{-(q_1 - q_2)^2}$
- emerging from symmetrization of the total wave function describing the bosonic system
- **tool to probe the geometric size** of the particle-emitting source at the kinetic freeze-out.

## Motivation for the current study:

- **small systems** (e.g. pp, pPb) are of particular interest for phenomenological models describing the particle production (insight into early system dynamics):
  - e.g. hydrodynamic and CGC-based ones **Phys. Rev. Lett 113 (2014) 102301**
  - frameworks unifying these two approaches started being considered recently **Phys. Lett. B 803 (2020) 135322**
- a similar analysis done already at LHCb for pp – **direct comparison of pp / pPb** results
- first measurement of this kind for pPb collisions in the forward direction (**study of the potential dependence on pseudorapidity**). **JHEP 12 (2017) 025**

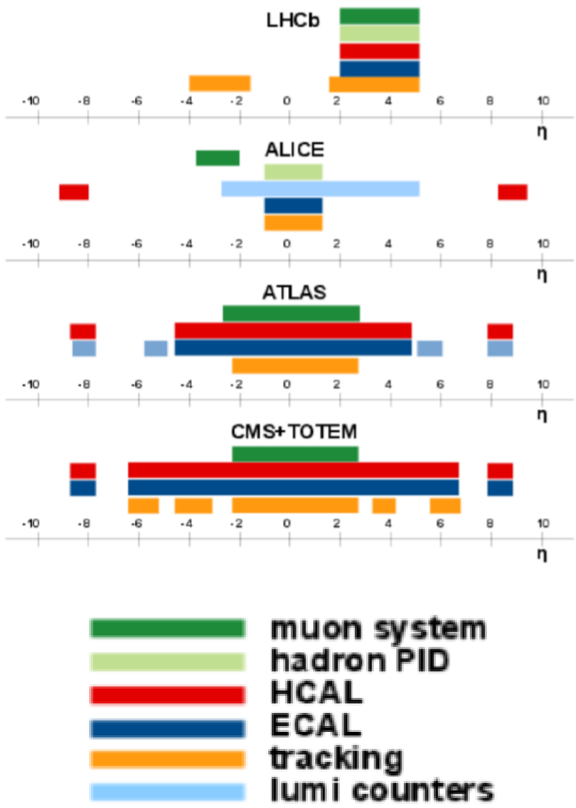
# BEC studies @ LHCb

**LHCb detector:** JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

- **single-arm spectrometer** designed mainly to study CP violation in B physics
- fully instrumented in $2 < \eta < 5$ -> can serve as a **general purpose detector** in the **forward region.**

**BEC analyses at LHCb:**

- pp @ 7 TeV (2-pion) **[published]** JHEP 12 (2017) 025
- pp @ 7 TeV (3-pion) **[publication procedure ongoing]**
- pPb @ 5.02 TeV (2-pion) **[publication procedure ongoing].**




The LHCb detector has a **unique acceptance** among other LHC experiments -> **complementary results**.

# Data & selection

**Data** collected in 2013 (pPb @ 5.02 TeV):

- two beam modes (pPb/Pbp) with **asymmetric beams**
- effectively corresponds to studying the **pPb system in the forward and the backward direction***
- 70M (64M) minimum-bias events in the pPb (Pbp) sample after preselection.

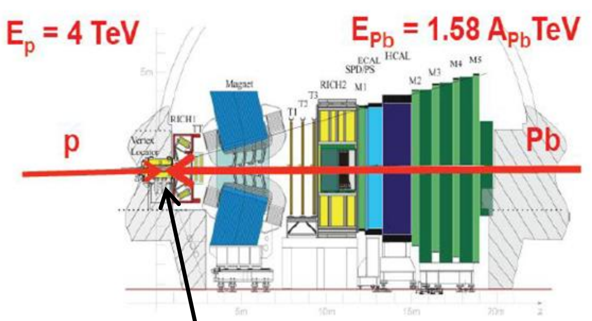
**Simulation** used only for auxiliary studies (such as optimisation of the selection criteria):

- using EPOS LHC **Phys. Rev. C 92 (2015) 3, 034906**
- 12M events for each beam mode after preselection.

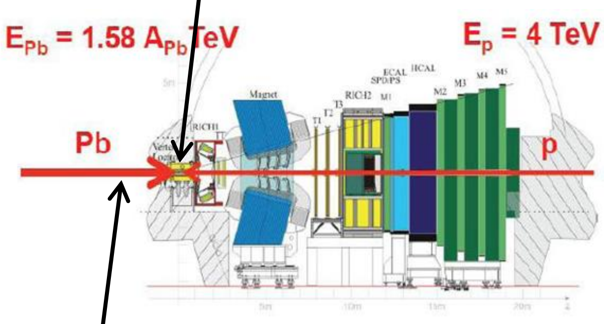
**Selection** mainly aiming for an unbiased, high-purity sample of prompt pions with a good track and vertex assignment quality:

- additional requirements to control contribution from misreconstructed tracks
- more details in the backup.

*) $1.5 < \eta_{CMS} < 4.5$ and $-5.5 < \eta_{CMS} < -2.5$, respectively;
$\eta_{CMS}$ corresponds to pseudorapidity in the nucleon-nucleon centre-of-mass system




**Vertex locator (VELO)** used in the determination of **charged-particle multiplicity.**

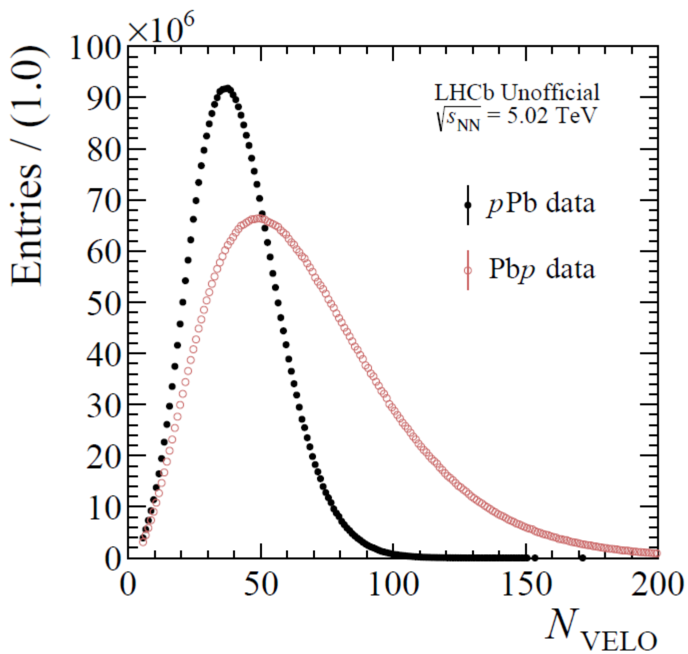



Higher multiplicity expected when Pb goes `towards` the detector.

# Multiplicity bins

- BEC effect depends on the charged-particle multiplicity in a primary vertex (PV).
- Reconstructed VELO-track multiplicity $N_{VELO}$ is used as a measure of this quantity.

**$N_{VELO}$ distribution for signal pairs**




|  |  | sample fraction [%] |  |
|---|---|---|---|
| bin# | $N_{VELO}$ | $p$Pb | Pb$p$ |
| 1 | [5–10) | < 2 | < 2 |
| 2 | [10–15) | 2 | 2 |
| 3 | [15–20) | 4 | 2 |
| 4 | [20–25) | 7 | 3 |
| 5 | [25–30) | 10 | 4 |
| 6 | [30–35) | 13 | 5 |
| 7 | [35–40) | 14 | 6 |
| 8 | [40–45) | 10 | 5 |
| 9 | [45–50) | 10 | 6 |
| 10 | [50–55) | 8 | 6 |
| 11 | [55–60) | 7 | 7 |
| 12 | [60–65) | 5 | 6 |
| 13 | [65–80) | 6 | 15 |
| 14 | [80–90) | – | 7 |
| 15 | [90–100) | – | 7 |
| 16 | [100–115) | – | 6 |
| 17 | [115–140) | – | 7 |
| 18 | [140–180) | – | 4 |

**Common $N_{VELO}$ bins**, to enable **direct comparisons** between the pPb/Pbp samples.

# Correlation function

- Constructed for pairs of **signal particles** (prompt, same-sign* charged pions originating from the same PV):

$$C_2(Q) = \frac{N_{ref}}{N_{sig}} * \frac{N_{sig}(Q)}{N_{ref}(Q)}.$$

distribution for SS pairs from the same PV **[BEC present]**

distribution for pairs from the reference sample **[no BEC effect]**

- **Event-mixed reference** sample is used:
  - pairs of particles from different events (single PVs) with similar $N_{\mathrm{VELO}}$ and PV position along the beam axis
  - same selection as for the signal.

**Phys. Lett. B 270 (1991) 69**
**Phys. Lett. B 432 (1998) 248**

**Eur. Phys. J. C 36 (2004) 67-78**

- Parametrised using the **Bowler-Sinyukov** formalism and a **Levy-type source with $\alpha_{\mathrm{L}} = 1$**:

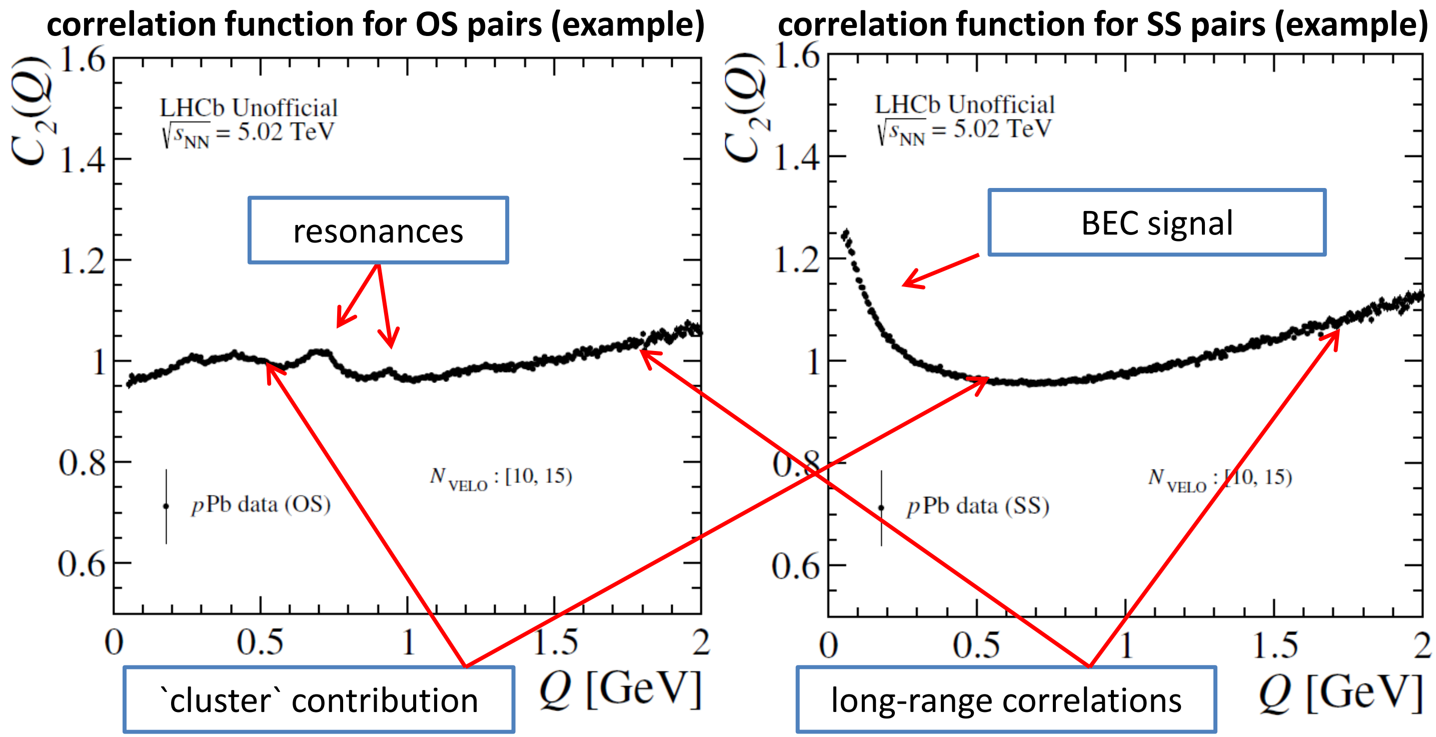
$$C_2(Q) = N\left[1 - \lambda + \lambda K(Q) \times \left(1 + e^{-|RQ|}\right)\right] \times \Omega(Q)$$

where:
  - ***R* – correlation radius, *λ* – intercept parameter**
  - $\Omega(Q)$ - describes the **background** contribution
  - $K(Q)$ - correction for **final-state Coulomb interactions** in the particle pair (see backup)
  - $N$ - **normalisation** factor.

*) SS: same-sign charged (pions)
OS: opposite-sign charged (pions)

# Analysis strategy

- **Background parametrisation extracted from the OS distributions.**
- Determine the **scaling** of the background amplitude **between OS/SS pairs**.
- Use the scaled background parametrisation in the final SS fits.




Fully **data-driven** approach.
Based on a **method established by CMS**.

pPb: Phys. Rev. C 97 (2018) 042
pp: JHEP 03 (2020) 014

# Background parametrisation

**Individual contributions** of the various background components are **not \`theoretically\` known** and \`ad-hoc\` parametrisations are usually employed to best describe the data:

- **long-range correlations** : a commonly used linear form with a factor $\boldsymbol{\delta}$ is assumed
- **cluster contribution** : a reasonable description of the low-$Q$ region is found using a simple Gaussian shape with amplitude $\boldsymbol{A_{\mathrm{bkg}}}$ and width $\boldsymbol{\sigma_{\mathrm{bkg}}}$
- the $\boldsymbol{A_{\mathrm{bkg}}}$ and $\boldsymbol{\sigma_{\mathrm{bkg}}}$ values are parametrised in terms of $N_{\mathrm{VELO}}$ (**uniformity across bins**).

long-range correlations

\`cluster\` contribution

$$\Omega(Q) = \underbrace{(1+\delta Q)}_{\text{long-range correlations}} \times \underbrace{\left[1 + z\frac{A_{\mathrm{bkg}}}{\sigma_{\mathrm{bkg}}\sqrt{2\pi}} \exp\left(-\frac{Q^2}{2\sigma^2_{\mathrm{bkg}}}\right)\right]}_{\text{cluster contribution}}$$

**Phys. Rev. C 97 (2018) 042**

$$\sigma_{\mathrm{bkg}}\left(N_{\mathrm{VELO}}\right) = \sigma_0 + \sigma_1 \exp\left(-\frac{N_{\mathrm{VELO}}}{N_0}\right)$$

$$A_{\mathrm{bkg}}\left(N_{\mathrm{VELO}}\right) = \frac{A_0}{\left(N_{\mathrm{VELO}}\right)^{n_A}}$$

Background parameters are determined in a **global OS fit** in all $N_{\mathrm{VELO}}$ bins to obtain the **best description of the data**.

- a negative log-likelihood function is minimised for all bins simultaneously (see backup)
- common background parameters across bins and free $N, \delta$.

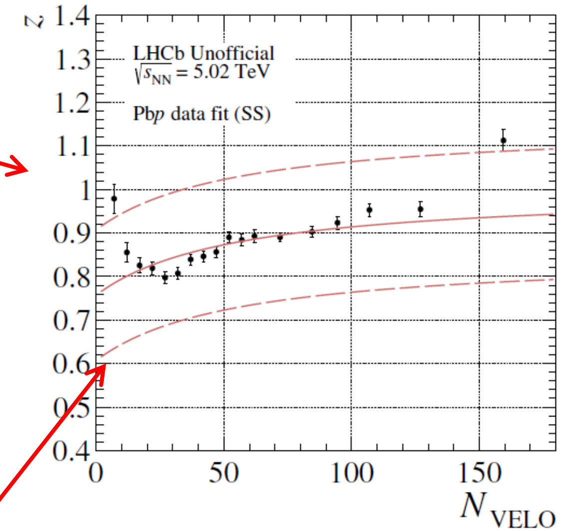
| dataset | $A_0$ [GeV] | $n_A$ | $\sigma_0$ [GeV] | $\sigma_1$ [GeV] | MinFcn/ndf |
|---|---|---|---|---|---|
| $p$Pb | $2.838 \pm 0.109$ | $0.8438 \pm 0.0111$ | $0.4799 \pm 0.0018$ | $0.1744 \pm 0.0060$ | 7944/3686 |
| Pb$p$ | $1.107 \pm 0.022$ | $0.5036 \pm 0.0049$ | $0.5613 \pm 0.0013$ | $\sim 10^{-11} \pm 10^{-3}$ | 9218/4424 |

# Example fits

- Perform SS fits with a **free scaling parameter $z$** and background fixed from the OS fits.
- Fit the $z$ values in a function of $N_{\mathrm{VELO}}$ using a **parametrisation motivated by the OS/SS pairs combinatorics**. Phys. Rev. C 97 (2018) 042

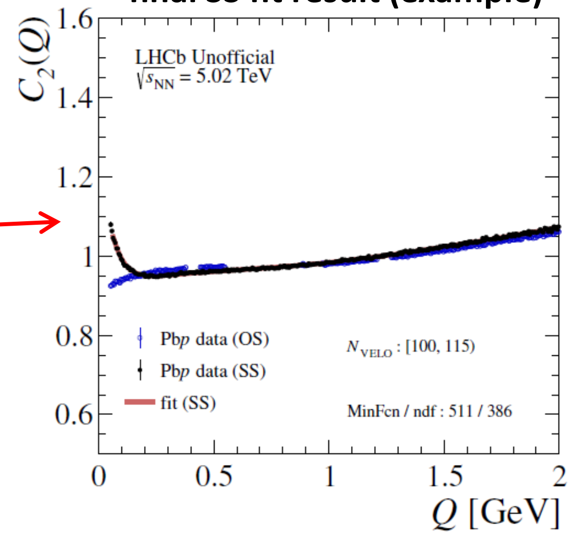
$$z(N_{\mathrm{VELO}}) = \frac{aN_{\mathrm{VELO}} + b}{1 + aN_{\mathrm{VELO}} + b}$$

| dataset | $a$ | $b$ |
|---|---|---|
| $p$Pb | $0.0443 \pm 0.0040$ | $1.86 \pm 0.12$ |
| Pb$p$ | $0.0749 \pm 0.0069$ | $3.12 \pm 0.27$ |




**Shifted $z$ parametrisations** used in the study of the **systematic uncertainty** are also indicated.

final SS fit result (example)




- Determine correlation parameters from the final SS fits with **fixed $z$ values** (negative log-likelihood fits – see backup).

Max MinFcn/ndf ~ 4 in the final SS fits.

# Systematic uncertainty

Contributions to the systematic uncertainty related to:

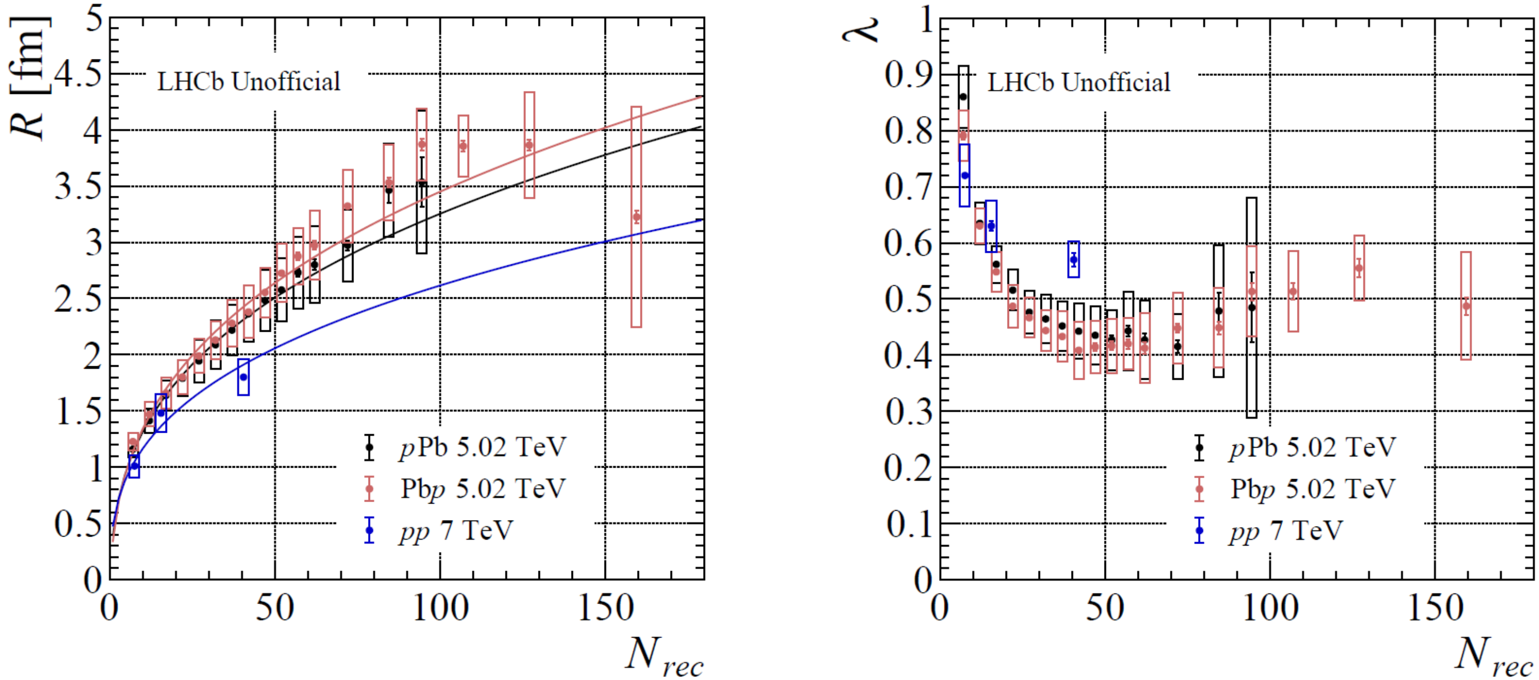
- background determination
- optimisation of the selection criteria
- correction for the final-state Coulomb interactions
- range of the final SS fits
- construction of the reference sample.

**SUMMARY**

- **Total uncertainty up to 12% (16.5%) for the $R$ ($\lambda$) parameters.**
- **Dominant** contribution related to the **background scaling** procedure (see slide 10) – up to 9% (11%) for the $R$ ($\lambda$) parameters.

These values correspond to most of the $N_{\text{VELO}}$ bins (higher values, which are not representative for the remaining part of the dataset, are observed in 3 bins; this is mainly due to limited statistics in these bins – see backup for details).

# Conclusions




**Scaling of $R$ with the cube root of $N_{rec}$** has been observed (see the fit results above). This behaviour is **compatible** with **predictions of hydrodynamic models** on the system evolution.

**Phys. Rev. C 83 (2011) 044915, Phys. Lett. B 720 (2013) 250, Phys. Lett. B 725 (2013) 139, Phys. Rev. Lett 113 (2014) 102301**

**Hints of $R$-dependence on pseudorapidity** are visible (central values for Pbp are systematically higher than in pPb). The pPb/Pbp samples correspond to the forward/backward direction in the pPb system.

*) reconstructed charged-particle multiplicity $N_{rec}$ is equivalent to $N_{\text{VELO}}$
**) error bars – statistical uncertainties; boxes – systematic ones

**pp: JHEP 12 (2017) 025**

# Summary

**Bose-Einstein correlations* for identical pions in pPb @ 5.02 TeV at LHCb:**

- the $R$ and the $\lambda$ parameters determined in common $N_{VELO}$ bins for the pPb and the Pbp sample
- observed behaviour of $R$ with respect to charged-particle multiplicity compatible with predictions of hydrodynamic models
- indications of the $R$-dependence on pseudorapidity visible.

The presented results are **complementary** to other measurements at the LHC and provide **exclusive input** for the development of phenomenological models.

**Prospects for future BEC studies @ LHCb:**

- accessing higher multiplicities in pp @ 13 TeV and pPb @ 8.16 TeV (test saturation)
- extending the analysis into $k_T$ bins (test hydrodynamic models)
- PbPb collisions, 3D studies.

*) the presented results are unofficial, the publication procedure in the LHCb experiment is ongoing

# Backup

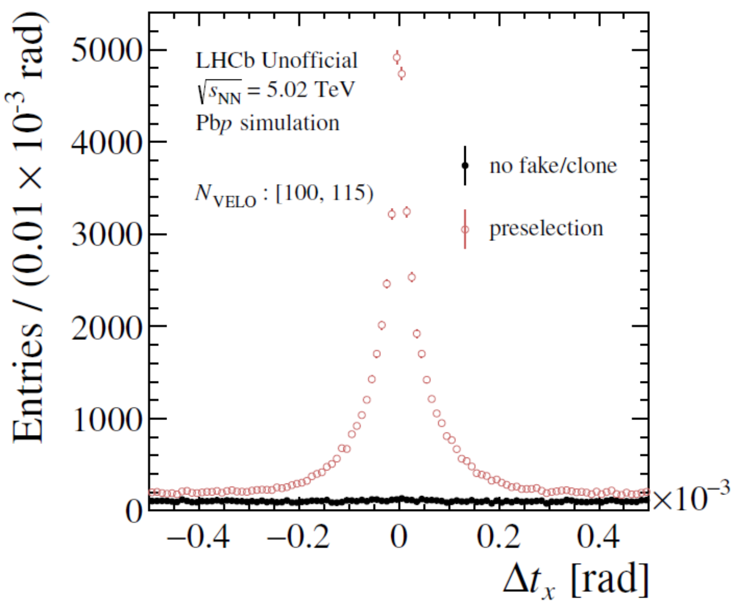
# Selection – final requirements

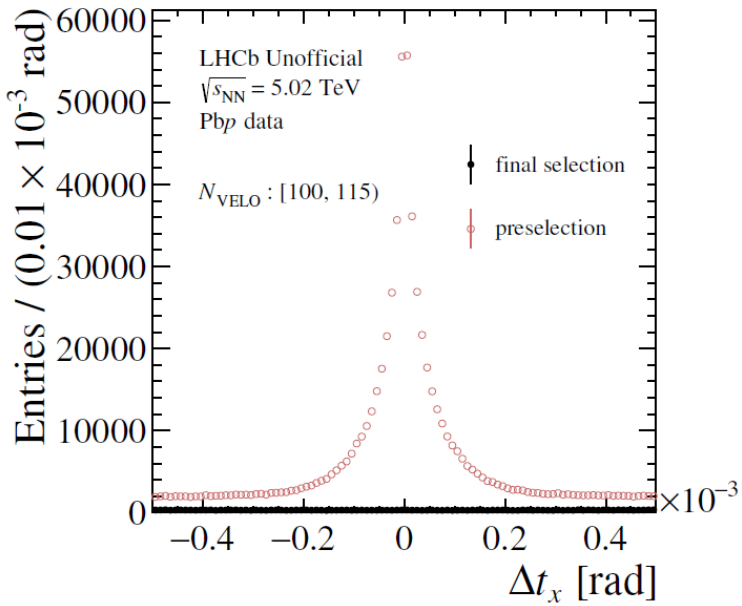
| selection | requirement |
| --- | --- |
| PV | visible PVs<br>single PV, $-160 < z_{\mathrm{PV}} < 60\,\mathrm{mm}$ |
| track type | long, charged, no muon signature<br>no shared VELO segments |
| track $\eta$ | 2.0–5.0 |
| track $\chi^2$ | $< 2.0$ |
| track $p$ | $> 2.0\,\mathrm{GeV}$ |
| track $p_{\mathrm{T}}$ | $> 0.1\,\mathrm{GeV}$ |
| track $IP$ | $< 0.4\,\mathrm{mm}$ |
| $ProbNN$(ghost) | $< 0.25$ |
| $ProbNN$(kaon,proton) | $< 0.50$ |
| $ProbNN$(pion) | $> 0.65$ |
| pair $\lvert\Delta t_x\rvert, \lvert\Delta t_y\rvert$ | $\lvert\Delta t_x\rvert > 0.3\,\mathrm{mrad}$ OR $\lvert\Delta t_y\rvert > 0.3\,\mathrm{mrad}$ |
| pair $Q$ | $> 0.05\,\mathrm{GeV}$ |

*) $\Delta t_x, \Delta t_y$ : differences in the track slopes in a pair in the *x* and *y* direction

# Selection – misreconstructed tracks

- **Dedicated** selection criteria to remove the **misreconstructed tracks** (mostly discard tracks that share all of the VELO segments, $Q > 0.05$ GeV, requirements on the differences in the track slopes in a pair).
- Clone tracks (same charge, similar trajectory) are especially important to control as they can affect the signal region.

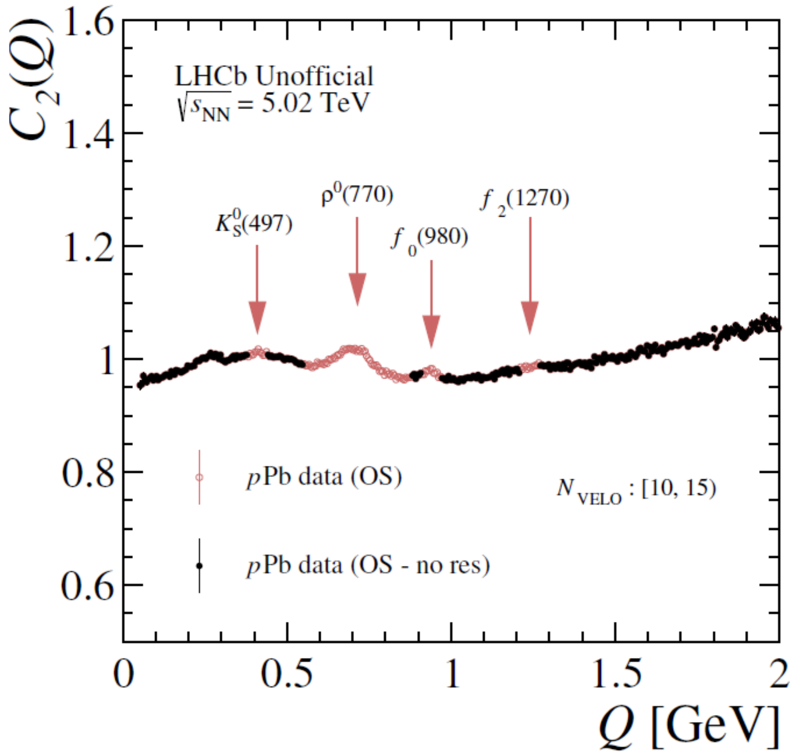



Misreconstructed tracks **very well controlled** in the data (similar effect after applying the final selection as compared to artificially removing them in the simulation).

# Resonances

**Resonances decaying to $\pi^+\pi^-$** pairs are clearly visible in the correlation functions of the OS pairs and degrade the fit quality. The affected $Q$ ranges are excluded from the fits to the OS correlation function.




Excluded ranges are **optimised** to provide **good quality of fits** to the OS correlation functions. Effects of the particular boundary choice are studied in the systematics.

| resonance | $Q$ range [ GeV ] |
|---|---|
| $\rho^0(770)$ | 0.55–0.88 |
| $K^0_S(497)$ | 0.38–0.44 |
| $f_0(980)$ | 0.91–0.97 |
| $f_2(1270)$ | 1.21–1.27 |

# Coulomb correction

**Final-state Coulomb interactions** in the particle pair can affect the shape of the correlation function in the BEC signal region. A depletion in the correlation function is expected due to the repulsive interaction for the SS pairs (opposite for the OS ones).

They need to be taken into account in the fit procedure using:

- **Gamov penetration factor $K_{Gamov}(Q)$** - valid for **point-like sources**
- **full correction $K(Q)$** – more detailed approach, taking into account the source size (calculated numerically in the most generic form).

In this study, a $K(Q)$ approximation given below is used. It is a form **valid for Levy sources with $\alpha_{\mathrm{L}} = 1$** and was developed by CMS in their pPb analysis.

**Phys. Rev. C 97 (2018) 042**

$$K(Q) = K_{Gamov}(Q)\left(1 + \frac{\alpha\pi m R_{\mathrm{eff}}}{1.26 + QR_{\mathrm{eff}}}\right)$$

where: $\zeta = \alpha m \,/\, Q$ ; α : fine-structure constant, $m$ : particle mass

$$K^{\mathrm{SS}}_{Gamov}(\zeta) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}\ ,\ \ K^{\mathrm{OS}}_{Gamov}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

In the case of pion pairs (relatively **small source size**), no significant difference between the full correction and the one using a simple **Gamov factor** is expected. In many analyses, the latter is **sufficient** and is used to simplify the fit method.

# Negative log-likelihood fit

Phys. Rev. C 66 (2002) 54906
Phys. Rev. C 96 (2017) 064

The following minimisation method was proposed to account for **potential bins with small number of counts** in the $Q$ distributions.

**Contents of the histograms representing $Q$** signal and reference distributions are assumed to be **Poisson distributed** (`counting` experiment). Correlation function is defined as the ratio of the content means and the corresponding **binned negative log-likelihood ratio** is constructed:

$$-2\ln\mathcal{L} = 2\sum_i \left\{ A_i \ln\left[\frac{(1+C_i)A_i}{C_i(A_i+B_i+2)}\right] + (B_i+2)\ln\left[\frac{(1+C_i)(B_i+2)}{A_i+B_i+2}\right]\right\}$$

where $A_i$ and $B_i$ are the bin contents of the signal and the reference $Q$ histograms and $C_i$ corresponds to the fit function value at the bin centre.

The expression above is **minimised** using the **MINUIT** package.

With an **increasing sample** size, this fit method becomes **equivalent** to a `regular` fit to the constructed correlation function using the **least-squares method**.

# Systematic uncertainty - contributions

| | $p$Pb dataset | | Pb$p$ dataset | |
|---|---|---|---|---|
| contribution | $\sigma_{syst}(R)$ [%] | $\sigma_{syst}(\lambda)$ [%] | $\sigma_{syst}(R)$ [%] | $\sigma_{syst}(\lambda)$ [%] |
| background scaling | 4.5–9.0 | 3.5–11.0 | 4.5–6.5 | 3.0–9.5 |
| background fit range | 1.0–3.0 | 0.5–3.5 | 2.0–3.5 | 0.5–4.0 |
| background fit – fixed $N_0$ | 0.5–3.0 | 0.5–3.0 | $< 0.5$ | $< 0.5$ |
| background fit – resonances | 0.5–4.0 | 0.5–4.0 | 1.5–3.0 | 0.5–3.5 |
| PID optimisation | 0.5–1.5 | 0.5–5.0 | 0.5–10.5 | 0.5–8.5 |
| fake tracks | 0.5–5.5 | 1.0–8.0 | 0.5–4.5 | 0.5–8.0 |
| requirement on $z_{PV}$ | 0.5–1.5 | 0.5–3.0 | 0.5–2.0 | 0.5–3.5 |
| Coulomb correction | 0.5–1.5 | 1.0–2.5 | 0.5–2.0 | 0.5–3.0 |
| SS fit range (min) | 1.5–5.0 | 1.0–8.5 | 0.5–3.5 | 0.5–5.5 |
| SS fit range (max) | 0.5–1.0 | 0.5–2.0 | 0.5–2.0 | 0.5–3.0 |
| reference sample | 0.5–2.0 | 0.5–3.0 | 0.5–2.0 | 0.5–4.0 |
| total | 6.0–12.0 | 6.0–16.5 | 6.5–12.0 | 5.0–16.0 |

The values given above correspond to most of the $N_{VELO}$ bins. Higher values (which are **not representative** for the remaining part of the dataset) are observed in the **edge bins with highest multiplicities** (3 bins are concerned: 2 in the pPb and 1 in the Pbp sample). It is mainly related to limited statistics in these bins. The large errors are indicated in the figures with the final results.