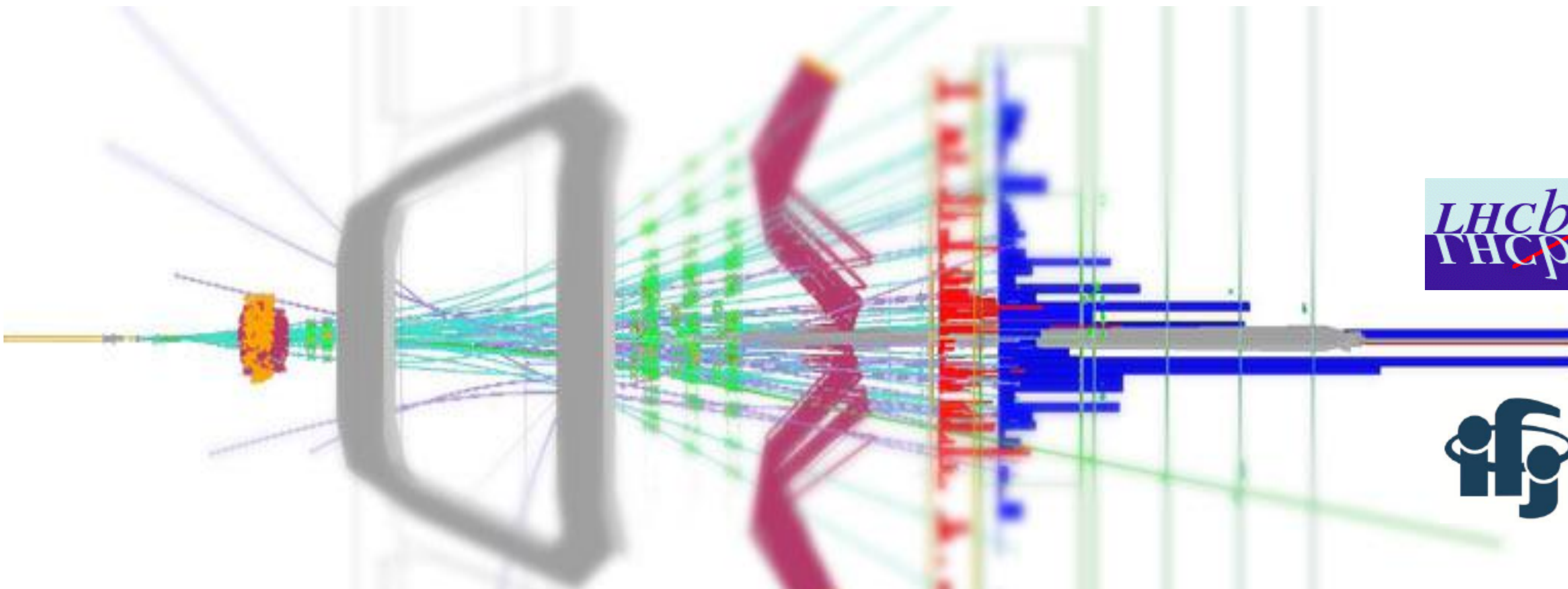
Bose-Einstein correlations at LHCb



Marcin Kucharczyk *on behalf of LHCb collaboration*

IFJ PAN, Krakow

WPCF 2023 - XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop 2023

Catania, 06-10 November 2023

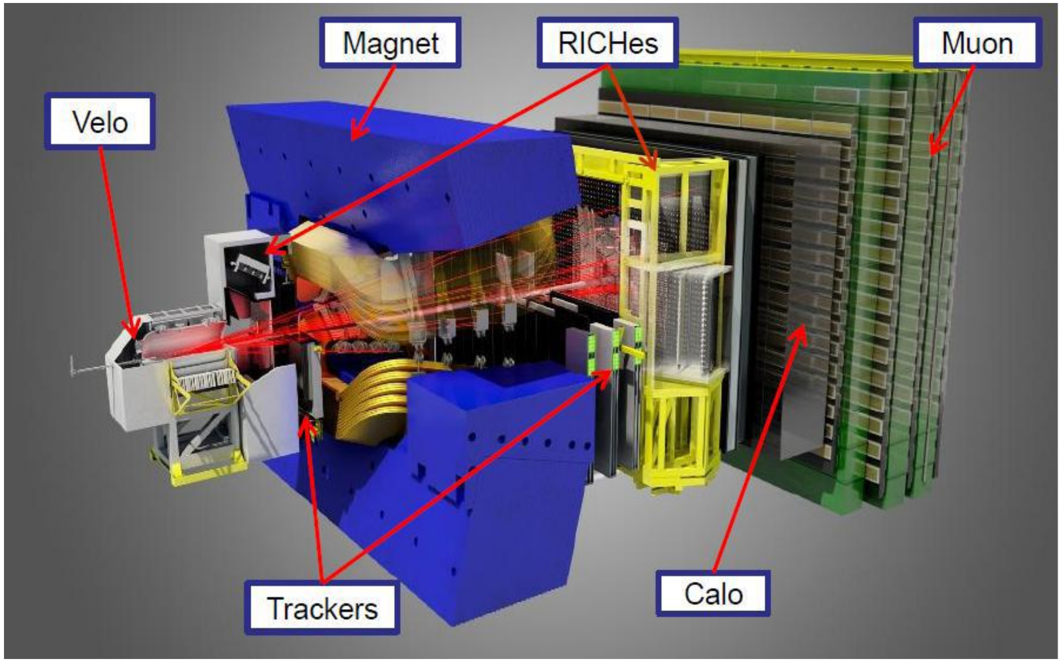
Outline

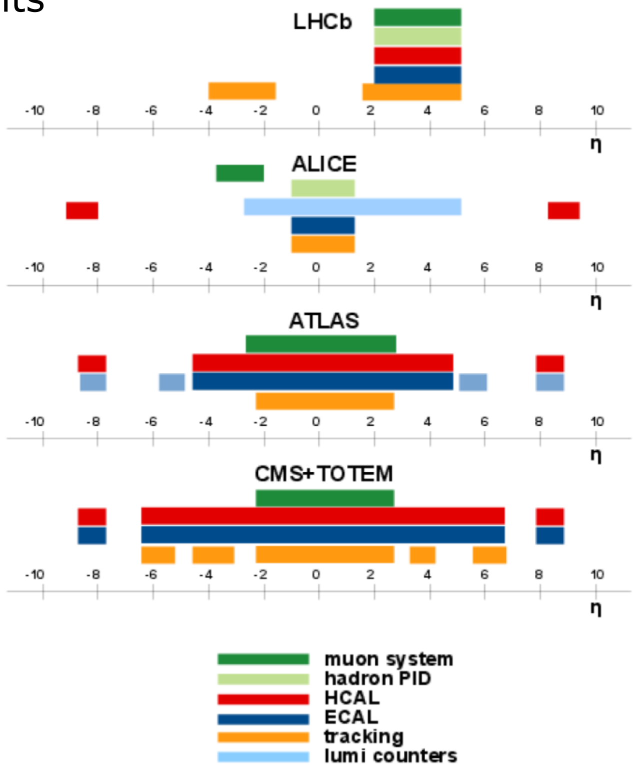
- LHCb - general purpose forward experiment
- BEC for pion pairs in *pp* collisions at 7 TeV
- New result - BEC in *pPb*
- Three-paricle correlations in *pp* collisions - ongoing
- Conclusions

LHCb detector

[Int. J. Mod. Phys. A30 (2015) 1530022]

- single arm spectrometer fully instrumented in forward region → GPD in forward region
- designed to study CP violation in *B*, but also fixed target, heavy ion physics
- precision coverage unique for LHCb: $2 < \eta < 5$
- complementary results with respect to other LHC experiments





[IJMPA 30 (2015) 1530022]

- momentum resolution between 0.5% at 5 GeV to 1.0% at 200 GeV
- impact parameter resolution of 20 μm for high-p_T tracks
- good PID separation up to 100 GeV *(misID ($\pi \to K$) ≈ 5% at 95% efficiency)*

Bose-Einstein correlations in *pp* collisions

[JHEP 12 (2017) 025, Nucl. Phys. A982 (2019) 347–350]

Correlation function

[JHEP 12 (2017) 025]

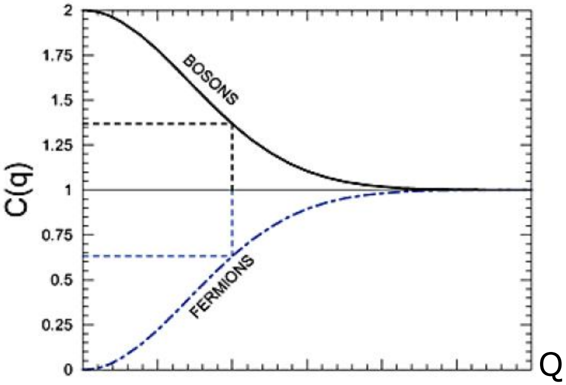
- Correlations exist between indistinguishable particles emitted from the same emitter volume
- Useful tool to probe the spatial and temporal structure of the hadron emission volume

Experimentally: $C_2(Q) = \frac{N(Q)^{DATA}}{N(Q)^{REF}}, \quad REF = mix, MC, unlike$

$N(Q)^{DATA}$ - distribution for same-sign pairs in data *(BEC present)*

$N(Q)^{REF}$ - distribution for reference sample with no BEC effect

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



Event-mixed reference sample used

- pions from different events from PVs with same VELO track multiplicity *(long-range correl.)*
- derived from data
- other correlations also removed $\rightarrow$ construct double ratio *(next slide)*

Parametrization of correlation function

- Levy parametrization with α =1 (Cauchy) + long-range correlations

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

- *R* - the radius of a spherical static source
- λ - intercept parameter
  (0 – coherent source, 1 – chaotic case)
- *N* - normalisation factor
- δ - long range correlations

Double ratio

[JHEP 12 (2017) 025]

Improved correlation function - double ratio *(r_d)*

$$r_{\mathrm{d}}(Q) \equiv \frac{C_2(Q)^{\mathrm{data}}}{C_2(Q)^{\mathrm{simulation}}}$$

simulation without BEC

- reduce possible imperfections in the construction of the reference sample
- eliminate second order effects to large extent
- correct for long range correlations *(if properly simulated)*

By construction the correlation function is largely independent of

- single particle acceptance and efficiency
- effects due to the detector occupancy, acceptance and material
- selection cuts
- two-track efficiency effects if properly simulated

Coulomb effect

Removed with Gamov penetration factor for *Q* distribution in data:

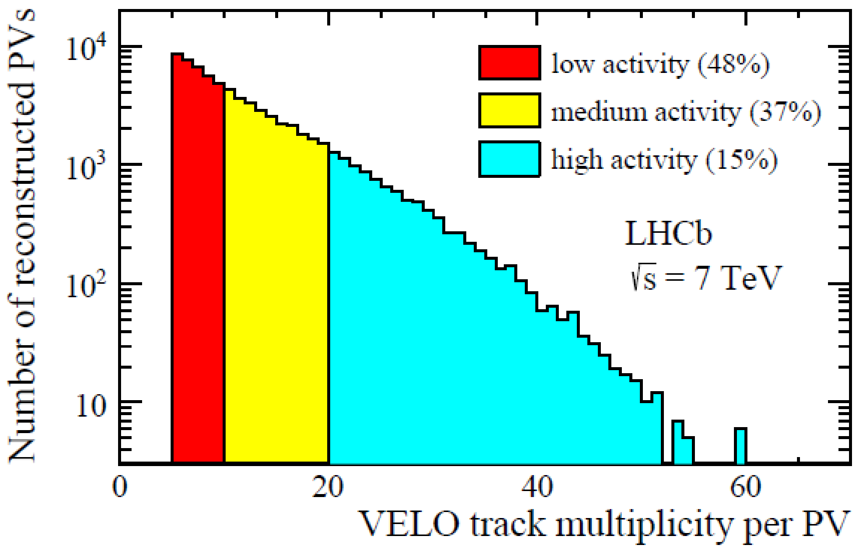
$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}, \quad \text{where} \quad \zeta = \pm\frac{\alpha m}{Q}$$

→ **systematics due to Coulomb correction found to be negligible**

Results

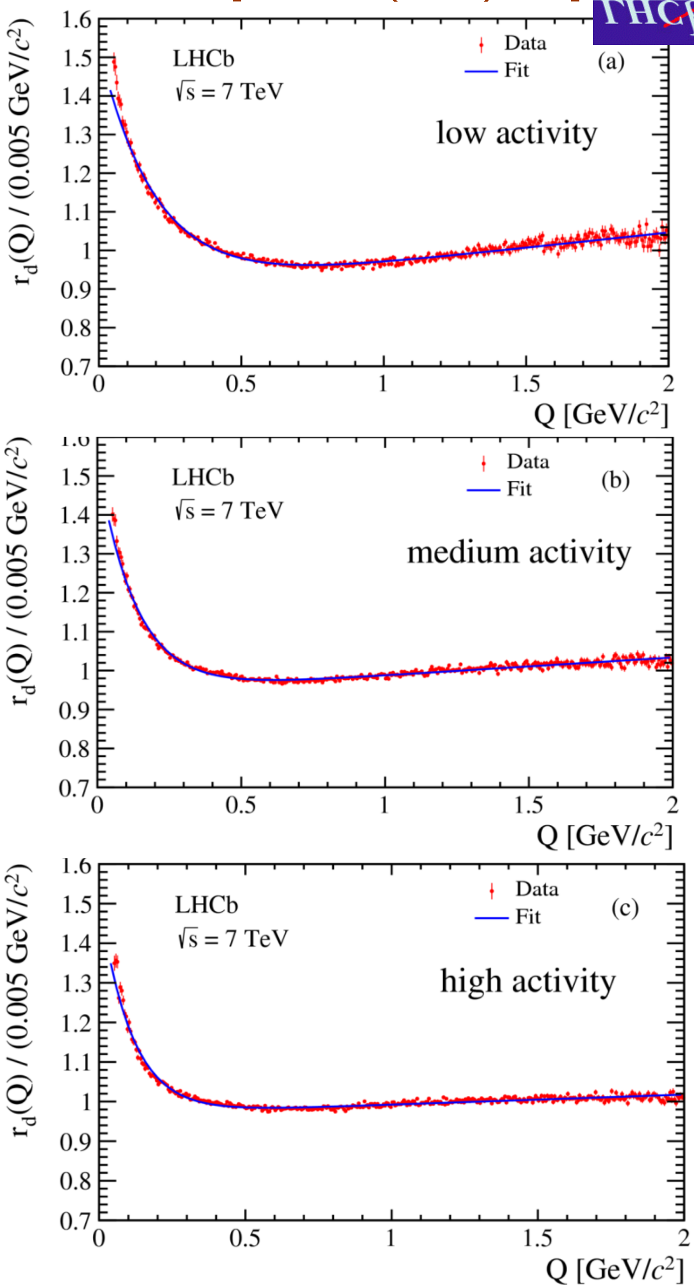
[JHEP 12 (2017) 025]

Fits to r_d with Levy parametrization for 3 activity bins



Activity	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**

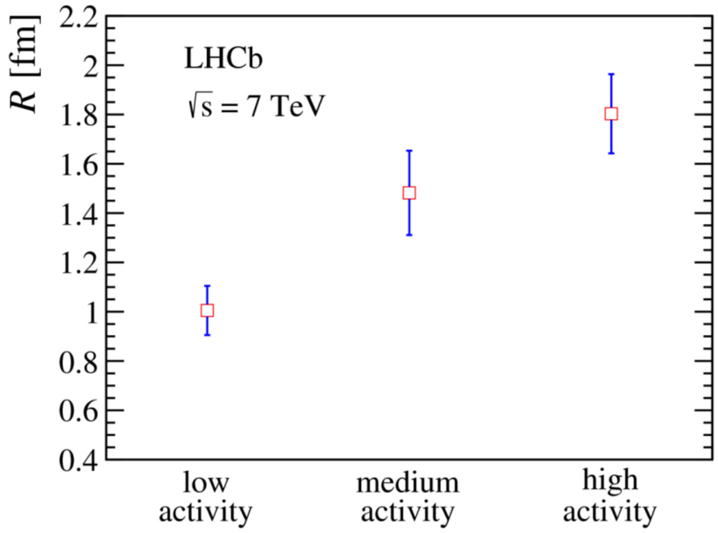
Systematic uncertainty (~10%) dominated by the generator tunings and pile-up effects



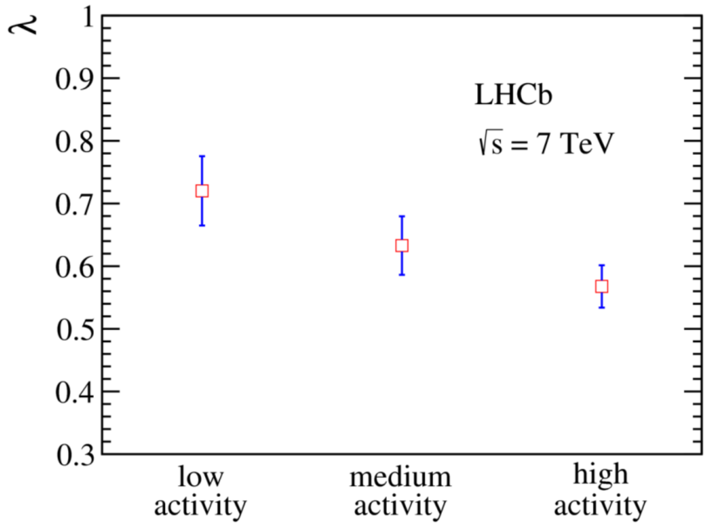
Results

[JHEP 12 (2017) 025]

Source size increases with activity



Intercept par. decreases with activity



Direct comparison between experiments not straightforward *(different η ranges)*

A trend compatible with previous observations at LEP and the other LHC experiments and with some theoretical models

R and λ parameters measured in the forward region lower wrt central rapidity detectors, e.g. ATLAS

Bose-Einstein correlations in *pPb* collisions

[JHEP 09 (2023) 172]

Motivation

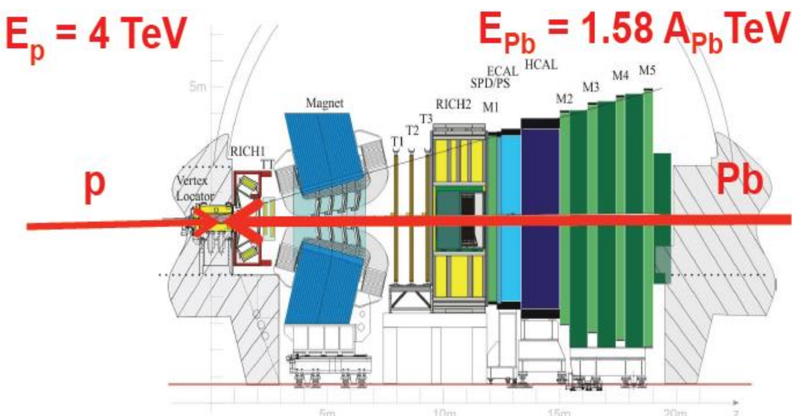
- Useful tool to probe geometric size of the particle-emitting source at the kinetic freeze-out
- Small systems *(e.g. pp, pPb)* are of particular interest for theoretical models of particle production
- Analysis for *pp* in LHCb *(JHEP 12 (2017) 025)*
- Direct comparison of the results in two different small systems (*pp* vs *pPb)*
  $\rightarrow$ may give additional constraints for theoretical models
- First such a measurement for *pPb* collisions in the forward direction
  $\rightarrow$ unique contribution to study dependence of source size on rapidity

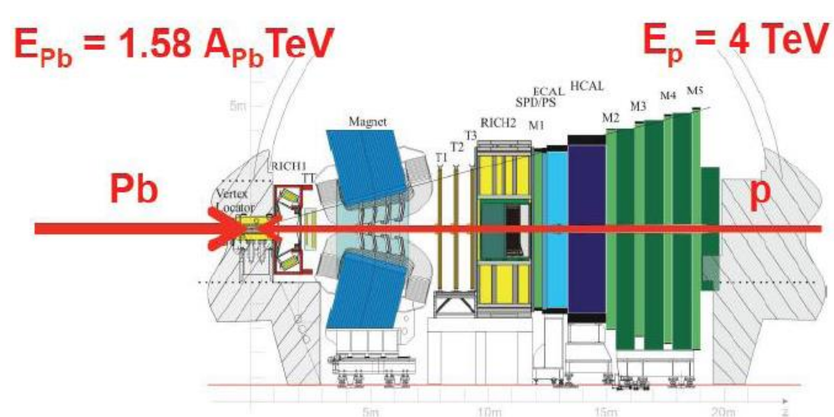
Setup for proton-lead

- *p-Pb / Pb-p* data collected at $\sqrt{s_{NN}}$ = 5 TeV
- **Asymmetric beams:** nucleon-nucleon center-of-mass system shifted by Δy = 0.47 in the proton beam direction

Forward production *(p-Pb)*
rapidity coverage: $1.5 < y_{CMS} < 4.5$
collected data *(2013)*: ~1.1 nb^{-1}

Backward production *(Pb-p)*
rapidity coverage: $-5.5 < y_{CMS} < -2.5$
collected data *(2013)*: ~0.5 nb^{-1}



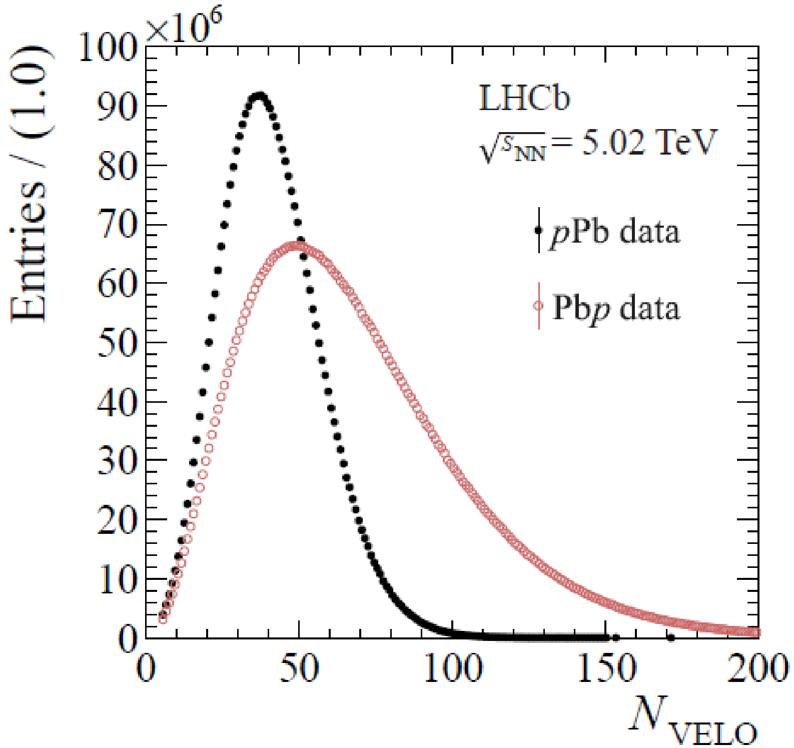


y_{CMS} = rapidity in nucleon-nucleon centre-of-mass system, with forward direction *(positive values)* in direction of the proton/beam

Multiplicity bins

[JHEP 09 (2023) 172]

- Single PV sample
- Common N_{VELO} bins for *pPb/Pbp* to enable direct comparison between *pPb/Pbp* samples



N_{VELO} distribution for signal pairs

		Sample fraction [%]	
bin#	N_{VELO}	pPb	Pbp
1	5–9	< 2	< 2
2	10–14	2	2
3	15–19	4	2
4	20–24	7	3
5	25–29	10	4
6	30–34	13	5
7	35–39	14	6
8	40–44	10	5
9	45–49	10	6
10	50–54	8	6
11	55–59	7	7
12	60–64	5	6
13	65–79	6	15
14	80–89	–	7
15	90–99	–	7
16	100–114	–	6
17	115–139	–	7
18	140–179	–	4

Parametrization

[JHEP 09 (2023) 172]

Parametrization using Bowler-Sinyukov formalism

Phys. Lett. B270 (1991) 69, Phys. Lett. B432 (1998) 248

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

Ω(Q) - describes background contribution

K(Q) - correction for final-state Coulomb interactions in the pair

N - normalisation factor

Levy parametrization with index of stability fixed to unity used to describe the BEC effect

Eur. Phys. J. C36 (2004) 67-78

Correlation parameters:

***R* – correlation radius**: interpreted as radius of a static, spherically-symmetric source

***λ* – intercept parameter**: strength of the correlation at *Q → 0 GeV*

λ provides information on:

→ *fraction of pairs containing products of long-lived particles decays*

→ *coherence of the particle emission*

→ *experimental effects, such as nonidentical particles in the signal pairs*

Coulomb correction

[JHEP 09 (2023) 172]

Coulomb interactions in particle pairs may affect the shape of $C_2(Q)$ in BEC signal region

- Depletion in $C_2(Q)$ is expected due to the repulsive interaction for the SS pairs *(opposite for the OS ones)*
- Need to be taken into account in the final fit

  → **point-like sources**: Gamov penetration factor $K_{Gamov}(Q)$

  → **not-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, approximation valid for Levy sources with α = 1, developed by CMS in their *pPb* analysis *(Phys. Rev. C97 (2018) 42)* is used:

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

$\zeta = \alpha m \,/\, Q$ $\quad$ *α - fine-structure constant, m - particle mass*

$$K_{Gamov}^{\text{SS}}(\zeta) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}\,,\quad K_{Gamov}^{\text{OS}}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

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

Background parametrization

[JHEP 09 (2023) 172]

Non-femtoscopic background studied using DATA in $C_2(Q)$ for oppositely-charged (OS) pions

- no theoretical models describing the shape of the non-femtoscopic background
- 'ad-hoc' parametrizations commonly used to describe the data
  - → ***cluster contribution:*** *reasonable description in low-Q region using simple Gaussian parametrization with amplitude A_{bkg} and width σ_{bkg}*
  - → ***long-range correlations:*** *commonly used linear form with factor δ*

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

long-range correlations

cluster contribution

[Phys. Rev. C97 (2018) 064912]

- long range correlations dominate higher-Q range
- cluster contributions mostly in low-Q region
- z parameter fitted with parametrization motivated by OS/SS combinatorics

Due to a high contribution of the multibody resonance effects in very low-Q region, lower fit range for the OS pairs is usually limited wrt SS pairs

Removal of resonances

[JHEP 09 (2023) 172]

- Goal is to remove most peaking ones that may significantly disturb the background fit
  not aiming to completely remove all the Q-regions affected by resonances

- Effects related to resonances wear off quickly with growing particle multiplicity

- Choice of both list of resonances and widths of excluded ranges optimized in similar analyses *(e.g. Phys. Rev. C96 (2017) 064908, Phys. Rev. C97 (2018) 064912)*

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

- Effects related to resonance removal are included in systematics with relatively small contribution *(max. 4%)*

Global background fit

[JHEP 09 (2023) 172]

Correlation function for opposite sign pairs

$$C_2^{\mathrm{OS}}(Q) = N \times K(Q) \times \Omega(Q)$$

- Background parameters determined in global OS fit in all N_{VELO} bins to obtain the best description of data
- Negative log-likelihood function minimized for all bins simultaneously
- Common background parameters across bins and free *N, δ*

Parametrization *(in terms of N_{VELO})* for A_{bkg} and σ_{bkg}

$$\sigma_{\mathrm{bkg}}(N_{\mathrm{VELO}}) = \sigma_0 + \sigma_1 \exp\left(-\frac{N_{\mathrm{VELO}}}{N_0}\right) \qquad A_{\mathrm{bkg}}(N_{\mathrm{VELO}}) = \frac{A_0}{(N_{\mathrm{VELO}})^{n_A}}$$

[Phys. Rev. C97 (2018) 064912]

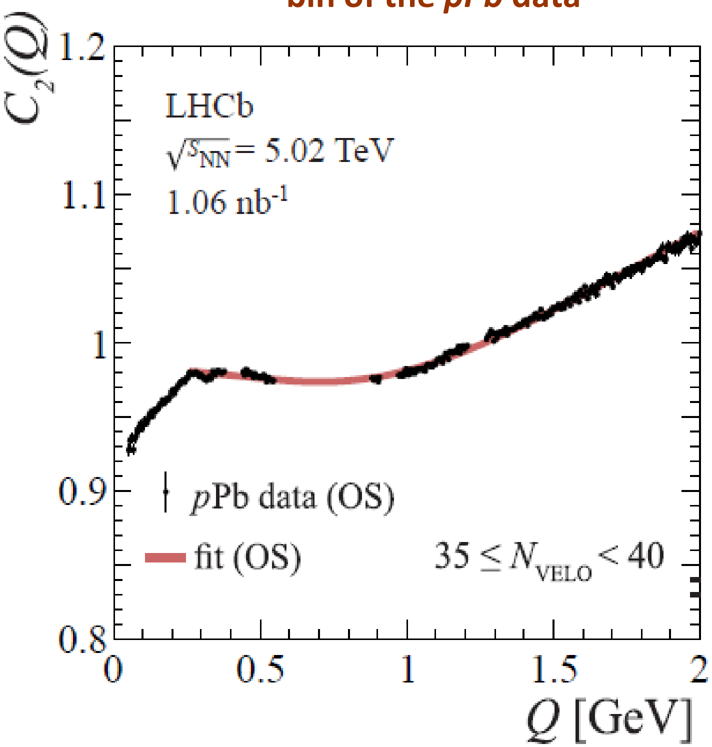
In practice:

- best stability of fits obtained with fixed scale N_0 of multiplicity dependence for σ_{bkg}
- the value based on the results obtained with N_0 free for the *pPb* sample
- choice of this scale is studied in systematics

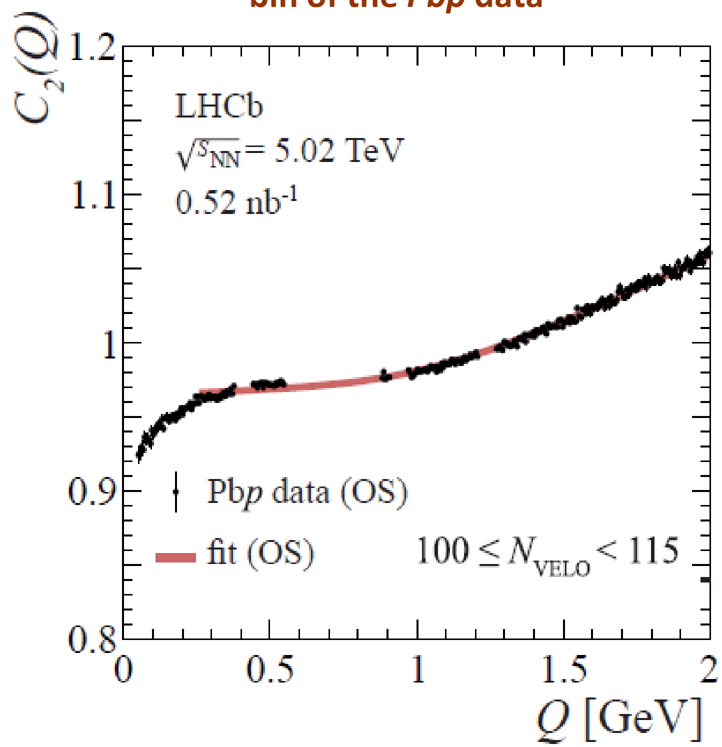
Global background fit - results

[JHEP 09 (2023) 172]

OS fit result in an example bin of the *pPb* data



OS fit result in an example bin of the *Pbp* data



MinFcn/ndf ~2 in a global fit

Two separate sets of params for *pPb/Pbp* samples

→ *independent datasets cover diff. η regions*

Dataset	A_0 [GeV]	n_A	σ_0 [GeV]	σ_1 [GeV]
pPb	2.838 ± 0.109	0.8438 ± 0.0111	0.4799 ± 0.0018	0.1744 ± 0.0060
Pbp	1.107 ± 0.022	0.5036 ± 0.0049	0.5613 ± 0.0013	0.0 ± 10^{-3}

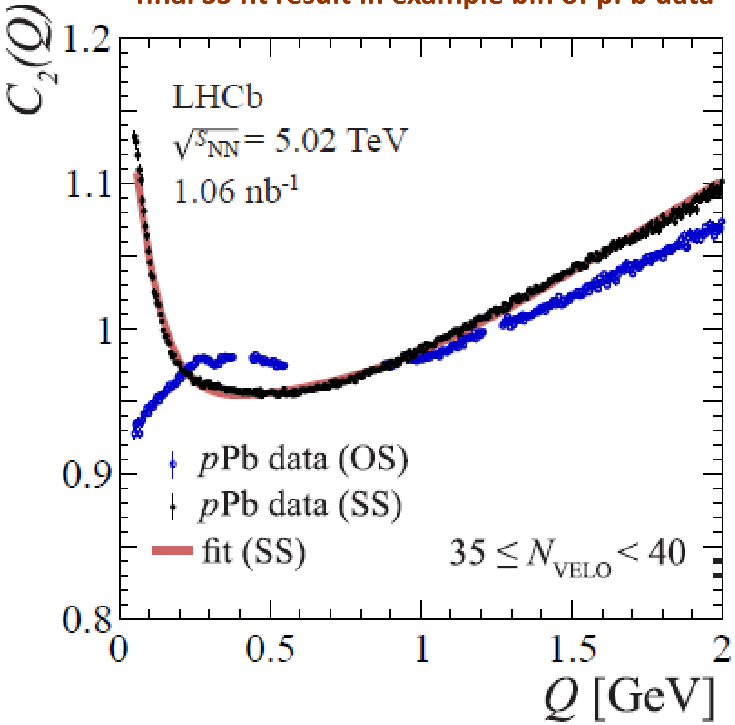
Final fit for signal pairs

[JHEP 09 (2023) 172]

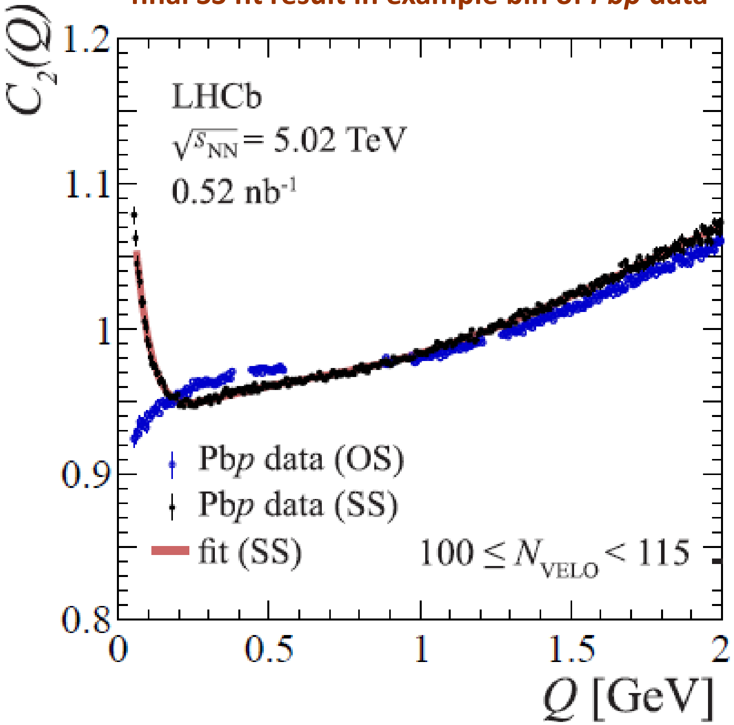
Fully data-driven approach

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

final SS fit result in example bin of pPb data



final SS fit result in example bin of *Pbp* data

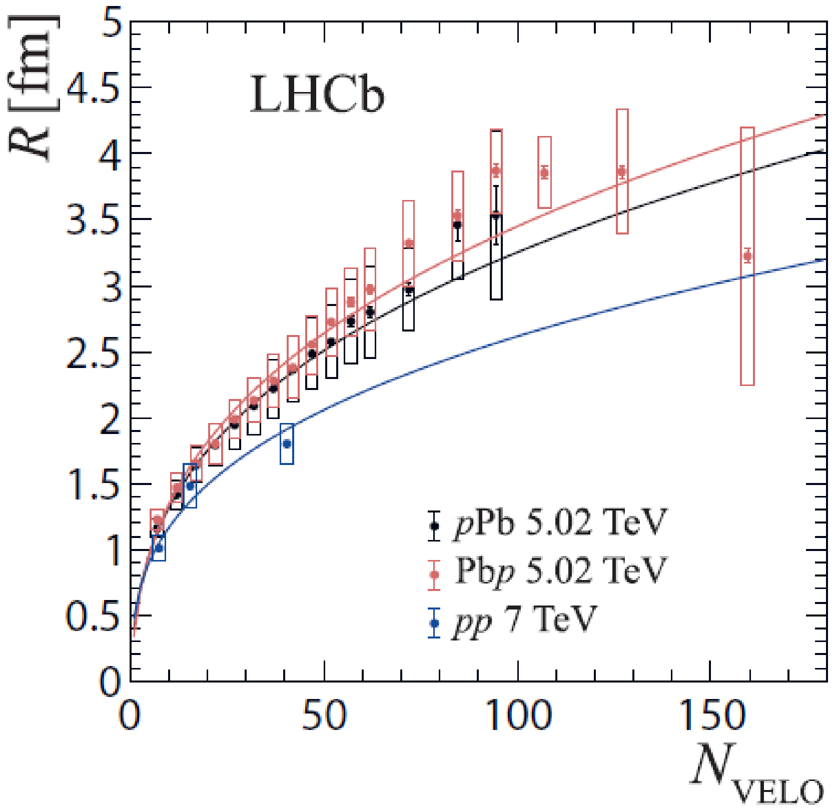


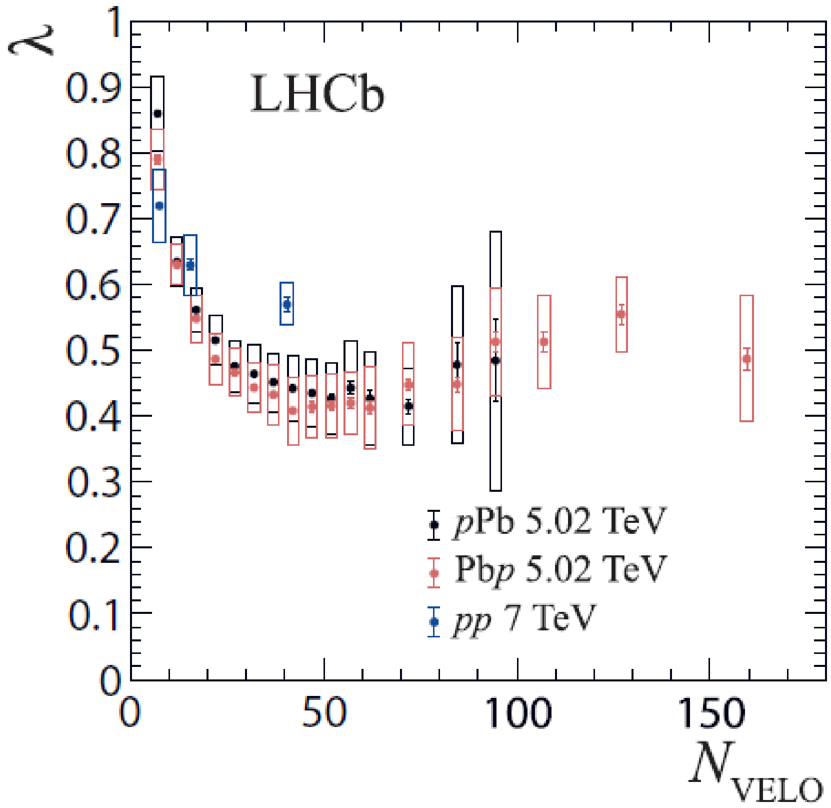
Systematic uncertainty (from 5% / 6% up to 12.0% / 16.5% for the *R* / *λ* parameter)
Dominated by background scaling procedure, pion PID and ghosts removal

Final results

[JHEP 09 (2023) 172]

- Solid lines (left plot) show scaling of R with the cube root of N_{VELO}
  → *hydrodynamic models predictions*
- Two beam modes (*pPb/Pbp*): studying the system in the forward/backward direction





Central R-values for *Pbp* sample systematically higher as compared to *pPb*

Hints for the dependence of correlation parameters on rapidity

Three-particle correlations within core-halo model - ongoing

- inspired by Phenix analysis in *Au-Au (arXiv:1801.03544)*
- experimental measure of coherence and thermalization in the source
- first time in proton-proton collisions in the frame of core-halo

$$C_3^{(fit)} = N(1+\delta Q_{12})(1+\delta Q_{13})(1+\delta Q_{23})G_3(Q_{12},Q_{13},Q_{23})C_3^{(0)}(Q_{12},Q_{13},Q_{23})$$

- analysis of $C_3(Q_{12},Q_{13},Q_{23})$ for diagonal $Q_{12}=Q_{13}=Q_{23}$
- Coulomb factorized according to Riverside method *(Phys. Rev. C92, 014902)*

Core-halo parameters:

λ_2 - *two-particle correlation strength*

λ_3 - *three-particle correlation strength*

f_c - *fraction of the particles that originate from the core*

p_c - *fraction of the core particles emitted coherently*

κ_3 - *describes additional effects like partial coherence or not fully thermalized core*

Results not published yet

$\rightarrow$ *signs of coherent particle emission can be observed*

Conclusions

Bose-Einstein correlations studied in 2 types of small systems (*pp/pPb*)

Both are first measurements of BEC in the forward region

- two alternative methods to take into account non-femtoscopic background
- scaling of R with cube root of N_{ch} observed (hydrodynamic models)
- hints for the dependence of correlation parameters on rapidity
- ongoing - three-particle correlations within core-halo model

LHCb shows a potential to perform further quantum correlations analyses

- *pp* @ 13 TeV and *pPb* @ 8.16 TeV (access to higher values of N_{ch})
- analyzes in k_T bins (more detailed tests of hydrodynamic models)
- 3D analyses, *PbPb* collisions, BEC in *D*-meson pairs

Backup

Results

[JHEP 09 (2023) 172]

	*p*Pb dataset		Pb*p* dataset	
N_{VELO}	R [fm]	λ	R [fm]	λ
5–9	$1.159 \pm 0.010 \pm 0.070$	$0.860 \pm 0.006 \pm 0.056$	$1.227 \pm 0.013 \pm 0.080$	$0.791 \pm 0.007 \pm 0.045$
10–14	$1.413 \pm 0.010 \pm 0.105$	$0.635 \pm 0.004 \pm 0.037$	$1.469 \pm 0.013 \pm 0.108$	$0.630 \pm 0.005 \pm 0.031$
15–19	$1.638 \pm 0.011 \pm 0.131$	$0.562 \pm 0.004 \pm 0.033$	$1.658 \pm 0.014 \pm 0.135$	$0.548 \pm 0.005 \pm 0.036$
20–24	$1.790 \pm 0.011 \pm 0.161$	$0.516 \pm 0.004 \pm 0.036$	$1.801 \pm 0.015 \pm 0.148$	$0.487 \pm 0.005 \pm 0.038$
25–29	$1.944 \pm 0.012 \pm 0.189$	$0.476 \pm 0.004 \pm 0.039$	$1.989 \pm 0.017 \pm 0.150$	$0.467 \pm 0.005 \pm 0.036$
30–34	$2.088 \pm 0.014 \pm 0.214$	$0.464 \pm 0.004 \pm 0.044$	$2.130 \pm 0.019 \pm 0.169$	$0.444 \pm 0.005 \pm 0.037$
35–39	$2.218 \pm 0.016 \pm 0.225$	$0.452 \pm 0.005 \pm 0.044$	$2.279 \pm 0.021 \pm 0.206$	$0.433 \pm 0.006 \pm 0.045$
40–44	$2.364 \pm 0.019 \pm 0.250$	$0.443 \pm 0.005 \pm 0.049$	$2.380 \pm 0.024 \pm 0.233$	$0.409 \pm 0.006 \pm 0.051$
45–49	$2.482 \pm 0.023 \pm 0.271$	$0.435 \pm 0.006 \pm 0.052$	$2.554 \pm 0.027 \pm 0.220$	$0.415 \pm 0.007 \pm 0.047$
50–54	$2.575 \pm 0.028 \pm 0.281$	$0.427 \pm 0.008 \pm 0.053$	$2.725 \pm 0.031 \pm 0.259$	$0.416 \pm 0.008 \pm 0.048$
55–59	$2.730 \pm 0.036 \pm 0.322$	$0.443 \pm 0.010 \pm 0.070$	$2.875 \pm 0.035 \pm 0.252$	$0.420 \pm 0.009 \pm 0.046$
60–64	$2.799 \pm 0.046 \pm 0.341$	$0.427 \pm 0.012 \pm 0.070$	$2.972 \pm 0.040 \pm 0.306$	$0.412 \pm 0.010 \pm 0.062$
65–79	$2.972 \pm 0.045 \pm 0.318$	$0.415 \pm 0.011 \pm 0.059$	$3.322 \pm 0.028 \pm 0.324$	$0.448 \pm 0.007 \pm 0.062$
80–89	$3.462 \pm 0.115 \pm 0.410$	$0.479 \pm 0.033 \pm 0.118$	$3.531 \pm 0.043 \pm 0.337$	$0.449 \pm 0.011 \pm 0.070$
90–99	$3.535 \pm 0.219 \pm 0.635$	$0.485 \pm 0.062 \pm 0.196$	$3.871 \pm 0.052 \pm 0.320$	$0.513 \pm 0.015 \pm 0.081$
100–114	–	–	$3.854 \pm 0.049 \pm 0.270$	$0.513 \pm 0.015 \pm 0.072$
115–139	–	–	$3.863 \pm 0.049 \pm 0.468$	$0.555 \pm 0.016 \pm 0.057$
140–179	–	–	$3.225 \pm 0.053 \pm 0.979$	$0.487 \pm 0.016 \pm 0.096$

Systematics - summary

[JHEP 09 (2023) 172]

Listed ranges correspond to the lowest and highest values of the given input determined across most of the N_{VELO} bins in the *pPb* and *Pbp* samples

	*p*Pb dataset		Pb*p* dataset	
Contribution	$\sigma_{\text{syst}}(R)$ [%]	$\sigma_{\text{syst}}(\lambda)$ [%]	$\sigma_{\text{syst}}(R)$ [%]	$\sigma_{\text{syst}}(\lambda)$ [%]
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

Negligible contributions are not listed

Background scaling

[JHEP 09 (2023) 172]

As the cluster contribution is expected to be larger for OS pairs as compared to SS ones, due to charge conservation, additional scaling factor is introduced with a theoretically motivated form (OS/SS pairs combinatorics):

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

Parameters *a* and *b* are determined by first fitting same-sign pair correlation function in each bin with fixed background and *z* as free parameter, and then performing fit of $z(N_{VELO})$

In low multiplicity bins the distortions related to background / resonances etc. are more prominent

- expect to have more significant fluctuations in the fits in such bins

This is why we follow theoretically-motivated method *(used also e.g. in Phys. Rev. C97 (2018) 064912 or JHEP 03 (2020) 014)* **to have a smooth description in all multiplicity bins**

- avoid in this way transmitting such fluctuations to the final SS fits
- avoid potential biases in the final results

Exact shape of the *z* distribution not so relevant

- we study the systematic uncertainty related to this method