PARTICLE CORRELATIONS AT LHCb

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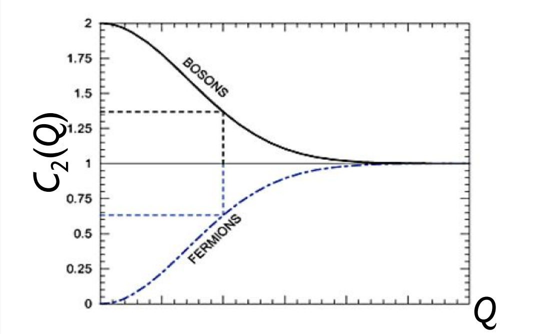
QUANTUM CORRELATIONS IN PARTICLE PHYSICS

- Goldhaber, Goldhaber, Lee and Pais, 1959
  - Bevalac/LBL experiment in Berkeley
  - Observation of the resonances by comparing Q distribution of unlike-sign pion pairs to same-sign – unexpected angular correlation [Phys. Rev. 120, 300]
- Correlations in four-momenta of indistinguishable particles emitted from the same source

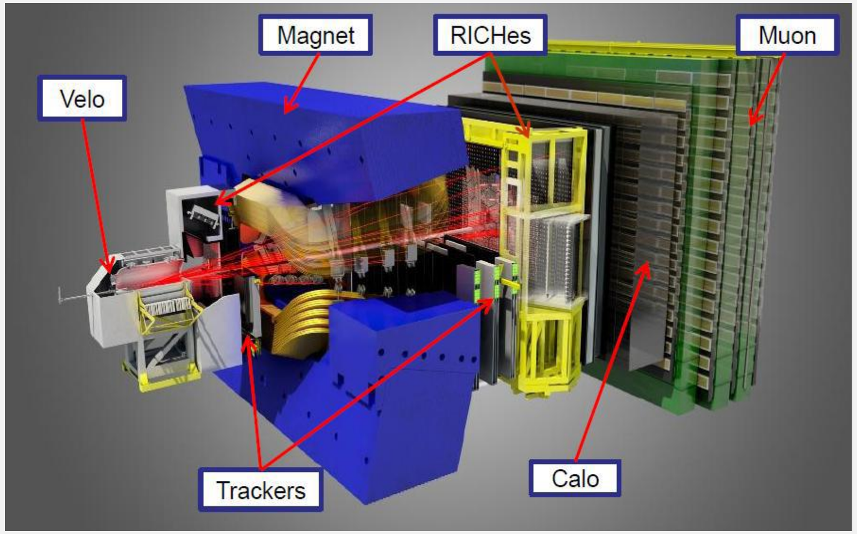
$$Q_{12} = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4\mu^2}$$

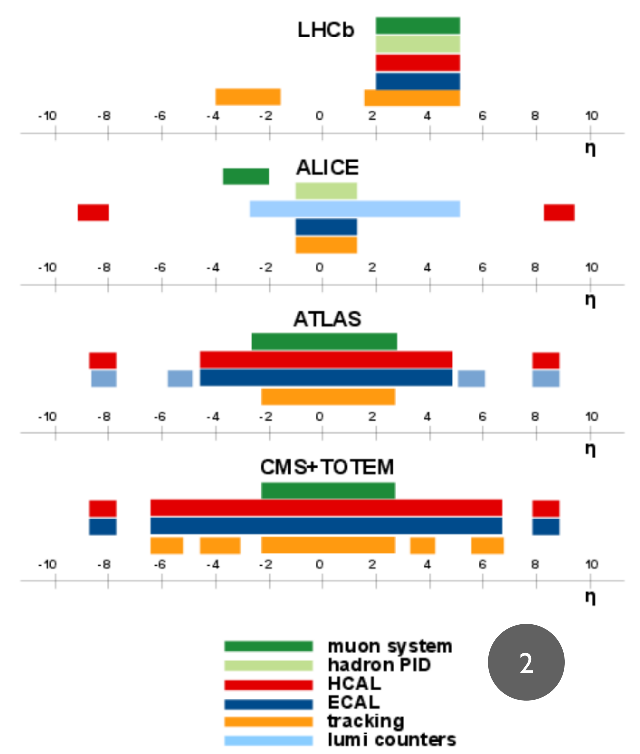


- Total wave function:
  - Bosons: symmetrization – Bose-Einstein Correlations
  - Fermions: anti-symmetrization – Fermi-Dirac Correlations
- Useful tool to probe spatial and temporal structure of hadronization region

LHCb EXPERIMENT

- Single arm spectrometer fully instrumented in forward region
- Designed to study CP violation in B, but also fixed target, heavy ion physics
- Precision coverage unique for LHCb: $2 < \eta < 5$
- Accurate momentum measurements
- Very good particle identification over momentum range 2 GeV/c – 100 GeV/c
- Complementary results with respect to other LHC experiments





BEC ANALYSES AT LHCb

- Published:
  - BEC for pions in proton-proton collisions at 7 TeV [JHEP 12 (2017) 025]
- Ongoing:
  - BEC for pions in proton-lead collisions at 5 TeV (in multiplicity and k_T bins)
  - 3-body correlations in proton-proton collisions at 7 TeV

[JHEP12(2017)025]

TWO-PION CORRELATION FUNCTION

DEFINITION

- $C_2(q_1, q_2) = \frac{P(q_1,q_2)}{P(q_1)P(q_2)}$

EXPERIMENTALLY

- $C_2(Q) = \frac{N(Q)^{DATA}}{N(Q)^{REF}}$ BEC present / No BEC (mix, MC, unlike)
- Reference sample: event mix – different events, same VELO multiplicity

- Parameterization:
  - Levy parameterization with $\alpha = 1$ (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 – chaoticity parameter
(0 – coherent source, 1 – chaotic source)
N – normalization factor
δ – long-range correlations

DATA SAMPLES AND CUTS
THE SAME AS FOR TWO-PION CORRELATIONS [JHEP12(2017)025]

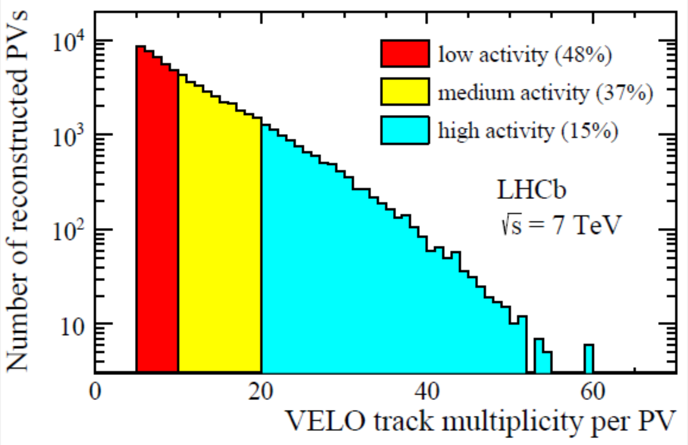
- Data 2011@7TeV
  - MinimumBias
- MC 2011
  - NoBias
  - PYTHIA 8, ~20M events
  - BEC effect switched off

parameter	value
η	2.0 – 5.0
Track χ^2	< 2.0
p	> 2.0 GeV
p_T	> 0.1 GeV
IP	< 0.4 mm

MULTIPLICITY BINS AND REFERENCE SAMPLE

- Effect depends on charged particle multiplicity
- Analysis performed in three bins of VELO track multiplicity per PV

VELO N_{ch}	Unfolded N_{ch}
5-10	8-18
11-20	19-35
21-60	36-96



- Reference sample: event mix
  - The same multiplicity, each particle from different event

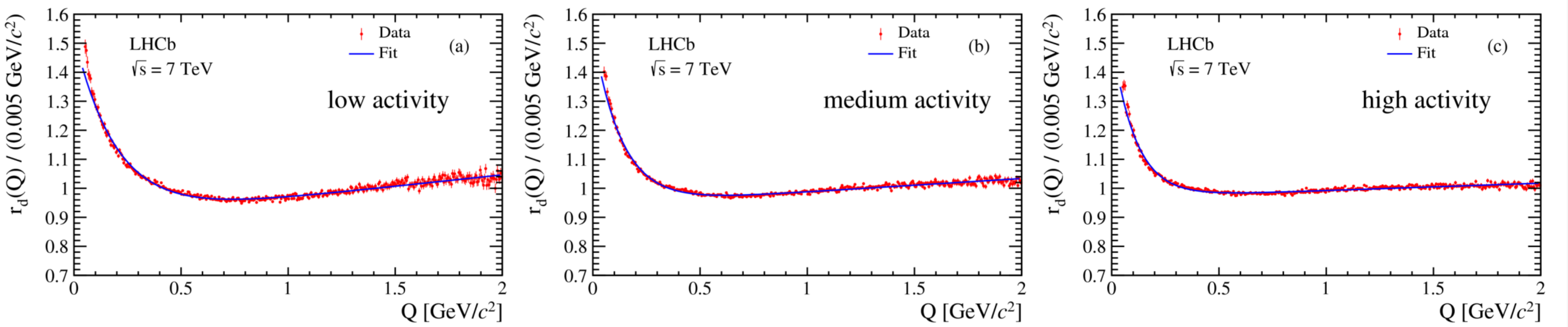
RESULTS ON TWO-PION CORRELATIONS

$$r_d(Q) = \frac{C(Q)^{DATA}}{C(Q)^{MC}}$$

MC without BEC

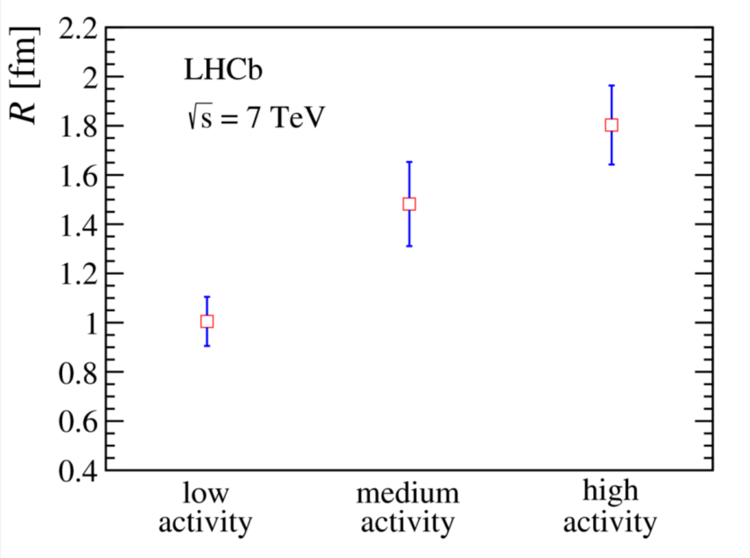
Activity	R [fm]	λ
Low	1.01 ± 0.01 ± 0.10	0.72 ± 0.01± 0.05
Medium	1.48 ± 0.02 ± 0.17	0.63 ± 0.01 ± 0.05
High	1.80 ± 0.03 ± 0.16	0.57 ± 0.01 ± 0.03

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

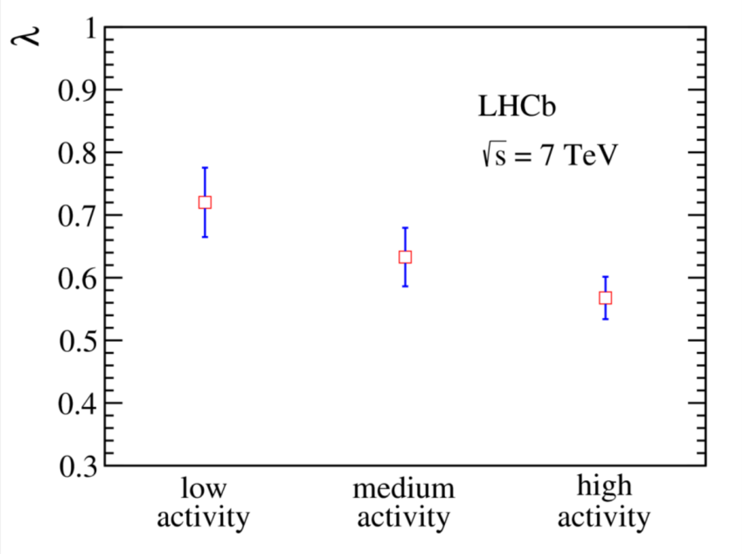


DEPENDENCE ON MULTIPLICITY

Source size increases with activity



Chaoticity 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 slightly lower wrt e.g. ATLAS [Eur. Phys. J. C75 (2015) 466]

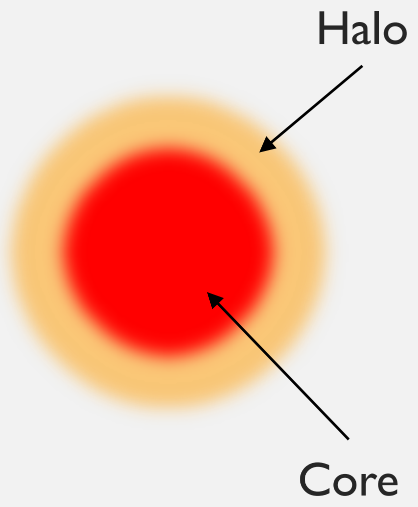
THREE-PION CORRELATIONS

Only the idea of the analysis presented because results are not published yet!

- Three-body correlation function:
  - $C_3(q_1, q_2, q_3) = \frac{P(q_1,q_2,q_3)}{P(q_1)P(q_2)P(q_3)}$
- Parameterization (within Core-Halo model) [T. Novak, arXiv:1801.03544]:
  - $C_3^{(fit)} = N(1+\delta Q_{12})(1+\delta Q_{13})(1+\delta Q_{23})G_3 C_3^{(0)}(Q_{12}, Q_{13}, Q_{23})$
    - G_3: Coulomb corrections factorized according to Riverside method [Phys. Rev. C 92, 014902]
- Levy-type $C_3^{(0)}$ function of the Q_{12}, Q_{13}, Q_{23} of the pion triplet
  - $C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) = 1 + \ell_3 e^{-0.5(|Q_{12}R|^\alpha + |Q_{13}R|^\alpha + |Q_{23}R|^\alpha)} + \ell_2\left(e^{-|Q_{12}R|^\alpha} + e^{-|Q_{13}R|^\alpha} + e^{-|Q_{23}R|^\alpha}\right)$
  - λ_2, R: from the previous analysis on the two-pion BEC [T. Novak, arXiv:1801.03544], [JHEP12(2017)025]
  - $\lambda_3 = C_3(Q_{12} = Q_{13} = Q_{23} \to 0) - 1 = \ell_3 + 3\ell_2$

THREE-PION CORRELATIONS
CORE-HALO MODEL

- We try to interpret the results of analysis within the framework of the core-halo model [Z. Phys. C71, 491 (1996), Eur. Phys. J. C (1999) 9, 275] following the idea from Phenix experiment [T. Novak, arXiv:1801.03544]
- Core
  - Direct production of pions
  - Hydrodynamic evolution or particle production from excited strings, followed by subsequent re-scattering of the particles
- Halo
  - Core is surrounded by pions emitted from the decay of long-lived hadronic resonances (ω, η, η', K^0) which are treated as belonging to the hadronic source



[arXiv:1801.03544]

THREE-PION CORRELATIONS
CORE-HALO MODEL – WHAT CAN WE MEASURE

- Analysis of $C_3(Q_{12}, Q_{13}, Q_{23})$ for the diagonal $Q_{12} = Q_{13} = Q_{23}$
- Fraction of the core
  - $f_c = \frac{N_{core}}{N_{core}+N_{halo}}$
  - We may directly determine from the two- and three-pion correlations
- Partially coherent emission from the core
  - $p_c = \frac{N_{coherent}}{N_{coherent}+N_{incoherent}}$
  - Correlation strength depends on partial coherence (within core-halo model)

- Values of f_c and p_c can be determined using λ_2 and λ_3
- Core-halo independent parameter
  - $\kappa_3 = 0.5\,(\lambda_3 - 3\lambda_2)/\lambda_2^{3/2} = 1$
  - The deviation of κ_3 from one may indicate extra effects in the core, for example not fully thermalized core, or partial coherence in the core

STATUS OF THE 3-PION ANALYSIS

- Fit is ready using $C_3^{(fit)}(Q_{12}, Q_{13}, Q_{23})$ (Gamow factor used for factorized Coulomb correction)
- Dependence on N_{ch}(dependence on k_T also planned)
- Central values of following parameters are measured:
  - $\lambda_2, \lambda_3, f_c, p_c, \kappa_3$
- The systematics is still to be done (ongoing)!

CONCLUSIONS

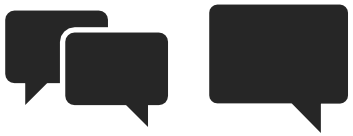
First measurement of BEC in the forward region $2 < \eta < 5$

- measured correlation parameters slightly lower as compared to results in central η region

3-pion BEC analysis

- Interpretation within core-halo model
- Work ongoing

LHCb shows a potential to perform a set of BEC analyses in unique kinematic region, complementary to the central rapidity detectors.



BACKUP SLIDES

BEC – CLONES AND GHOSTS

Cloned tracks

two or more tracks reconstructed by mistake from the hits originating from a single particle

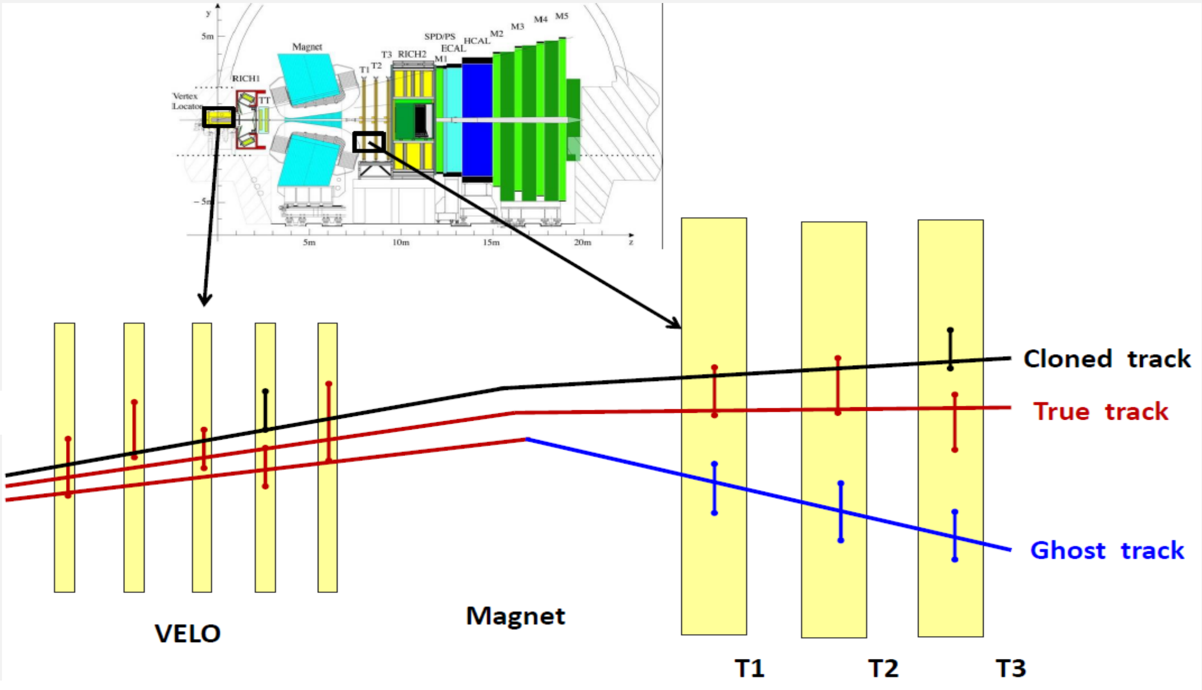
- Cloned pairs of tracks with small opening angle

  → *in low-Q region*
  → *may affect BEC signal*

Ghost tracks

wrongly reconstructed tracks which combine the hits deposited by multiple particles

- Ghosts populate wide *Q* range



ghosts / clones may affect the BEC signal forming pairs with small opening angle → *low Q*
not perfectly simulated → *cannot be fully corrected by DR*

Effect from ghosts present in LIKE and UNLIKE

- **controled by double ratio for unlike-sign pairs corrected for Coulomb effect** *(no BEC effect)*

Contamination from clones investigated looking at tracks slope differences at *Q* → *0*

BEC – TRACK PAIR SELECTION

Ghost tracks

- most of ghosts already removed $\rightarrow$ *tracks with high probability to be a ghost removed*
- additional cut: *if tracks share same VELO hits* $\rightarrow$ *keep one with best* χ^2

$\rightarrow$ **after selection ghosts are under control for** $Q > 0.05$ **GeV/c²**

$\rightarrow$ **systematic uncertainty low compared to dominant contributions**

Cloned tracks

- clones removed by cut on : $|\Delta t_x| < 0.3$ mrad & $|\Delta t_y| < 0.3$ mrad

(t - tangent of the track momenta of two particles)

$\rightarrow$ **contribution from clones marginal for** $Q > 0.05$ **GeV/c²**

Two-particle efficiencies under control in $Q > 0.05$ **GeV/c²**

$\rightarrow$ analysis in **0.05 GeV/c² <** Q **< 2.0 GeV/c²**

Coulomb effect

Removed with Gamov penetration factor for Q distribution in data:

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

$\rightarrow$ **systematics due to Coulomb correction found to be negligible**

BEC - SYSTEMATICS

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

THREE-PION CORRELATIONS

- Source function: Levy-type source
  - $S(r) = \mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
- Three-body correlation function:
  - $C_3(q_1, q_2, q_3) = \frac{P(q_1,q_2,q_3)}{P(q_1)P(q_2)P(q_3)}$
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  - δ, N: background and normalization
- Levy-type $C_3^{(0)}$ function of the Q_{12}, Q_{13}, Q_{23} of the pion triplet
  - $C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) = 1 + \ell_3 e^{-0.5(|Q_{12}R|^\alpha + |Q_{13}R|^\alpha + |Q_{23}R|^\alpha)} + \ell_2\left(e^{-|Q_{12}R|^\alpha} + e^{-|Q_{13}R|^\alpha} + e^{-|Q_{23}R|^\alpha}\right)$
  - λ_2, R: from the previous analysis on the two-pion BEC [T. Novak, arXiv:1801.03544], [JHEP12(2017)025]
  - $\alpha = 1$: Cauchy

Only the methodology of the analysis because results are not published yet!

THREE-PION CORRELATIONS

- Analysis of $C_3(Q_{12}, Q_{13}, Q_{23})$ for the diagonal $Q_{12} = Q_{13} = Q_{23}$
- Three-pion correlation strength:
  - $\lambda_3 = C_3(Q_{12} = Q_{13} = Q_{23} \to 0) - 1 = \ell_3 + 3\ell_2$
- Coulomb corrections
  - factorized according to Riverside method [Phys. Rev. C 92, 014902]
  - $G_3(Q_{12}, Q_{13}, Q_{23}) \approx G_2(Q_{12})G_2(Q_{13})G_2(Q_{23})$
  - Thus we correct $C_2(Q_{12}), C_2(Q_{13}), C_2(Q_{23})$ independently (the same as for two-pion analysis) using Gamow factor