Two-particle correlations at LHCb

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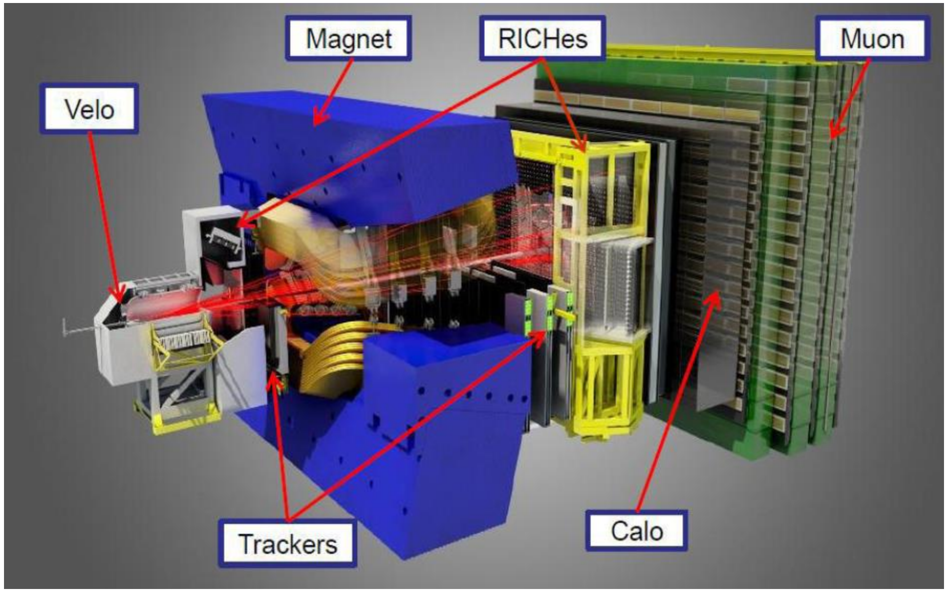
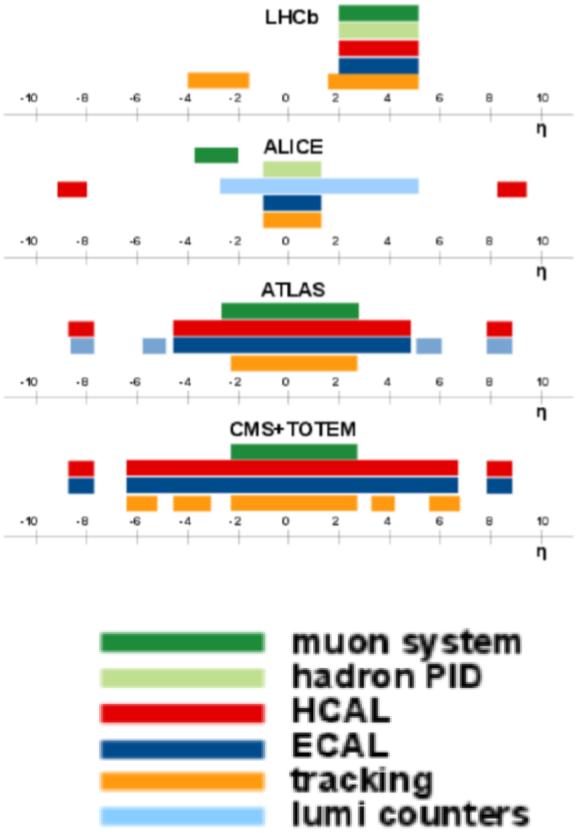
Outline

- LHCb detector
- Bose-Einstein correlations
- study of $b\bar{b}$ correlations
- summary

LHCb detector

- single-arm spectrometer designed mainly to study CP violation in B physics
- fully instrumented in 2 < η < 5 -> can serve as a **general purpose detector**
- complementary results wrt other LHC experiments





- $\Delta p/p$ ~ 0.5%-1.0% between 5-200 GeV/c
- impact parameter resolution of 20 μm
- good PID separation up to 100 GeV (misID (π->K) ~ 5%)

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

Bose-Einstein correlations

[JHEP 12 (2017) 025]

Motivation

HBT interferometry in particle physics

- correlations in four-momenta (q_1, q_2) of indistinguishable particles emitted from the same source:

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

- due to symmetrization (Bose-Einstein correlations – BEC) or antisymmetrization (Fermi-Dirac correlations – FDC) of the total wave function
- useful **tool to probe** the spatial and temporal **structure of the hadron emission volume**
- many results on BEC from SPS, LEP, RHIC, LHC (ALICE, ATLAS, CMS)
- LHCb measurement in a unique acceptance region

Correlation function

- **correlation function** (experimentally):

$$C_2(Q) = \frac{N(Q)^{SAME}}{N(Q)^{REF}}$$

distribution for pairs of same-sign pions from same PV **[BEC effect present]**

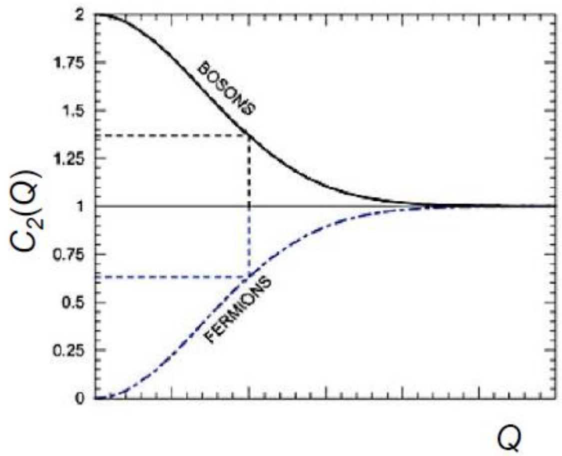
distribution for reference sample **[no BEC effect]**

- **event-mixed reference sample** is used:
  - pairs of pions from different events from PVs with same VELO track multiplicity
  - other correlations also removed -> construct **double ratio** (next slide)

- in this analysis - **Levy parametrization** + long-range correlations:

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

R – radius of a spherical static source
λ – chaoticity parameter
(0 – coherent source, 1 – chaotic emission)
N – normalization factor
δ – long-range correlations



Double ratio

- **double ratio** $r_d(Q)$ – an improved correlation function:

$$r_d(Q) = \frac{C_2(Q)^{DATA}}{C_2(Q)^{MC}}$$

BEC effect not simulated in MC

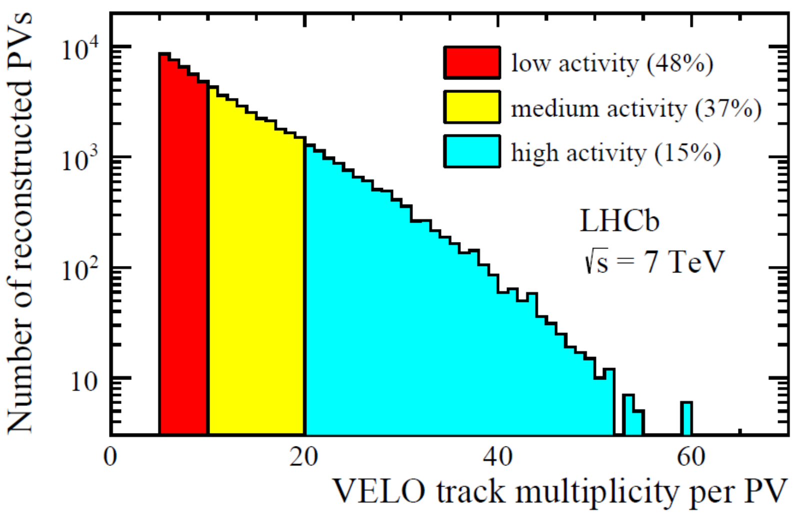
- MC correlation function contains **similar pattern of distortions** as correlation function for data, therefore constructing double ratio:
  - reduces possible imperfections of the reference sample
  - eliminates second order effects to large extent
  - corrects for long-range correlations (if properly simulated)

- Coulomb effect is not simulated in MC – corrected by applying **Gamov penetration factor** $G_2(Q)$ to the Q distribution for signal pairs in data:

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

Event multiplicity bins

- BEC parameters depend on total multiplicity of an event
- **VELO track multiplicity (N_{ch})** is a good probe of that quantity
- PVs are split into 3 multiplicity bins based on N_{ch}
- **activity classes** are defined as fractions of N_{ch} distribution (relative way):
  - independent of specific experiment features (e.g. efficiency, acceptance)
- **unfolding of N_{ch}** was also performed, which allows for comparison between experiments after taking into account different η acceptances (model-dependent)



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VELO N_{ch}	activity class	unfolded N_{ch}
5-10	(52-100)%	8-18
11-20	(15-52)%	19-35
21-60	(0-15)%	36-96

track multiplicities unfolded using PYTHIA 8 (in $2 < \eta < 5$)

Results (I)

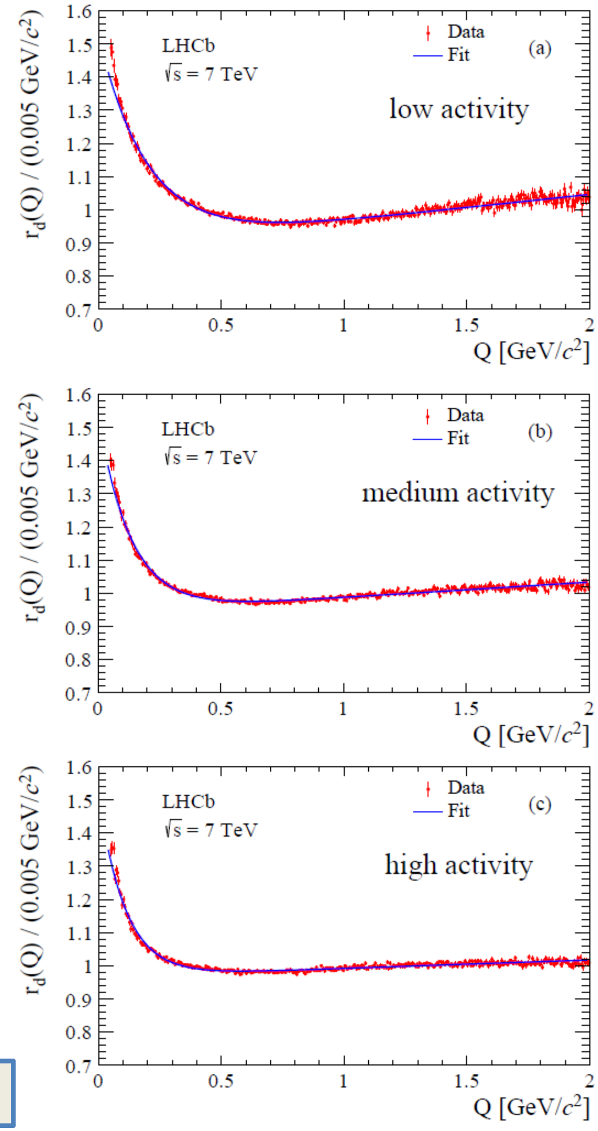
- fits to double ratio with Levy parametrization:

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

- clear **enhancement due to BEC** effect observed in Q->0

Activity class	R [fm]	λ
low	1.01 ± 0.01 ± 0.10	0.72 ± 0.01 ± 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 generator tunings and pile-up effects.



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Results (II)

Results show a trend compatible with previous observations at LEP and other LHC experiments:

- **source size increases with activity**
- **λ decreases with growing activity**

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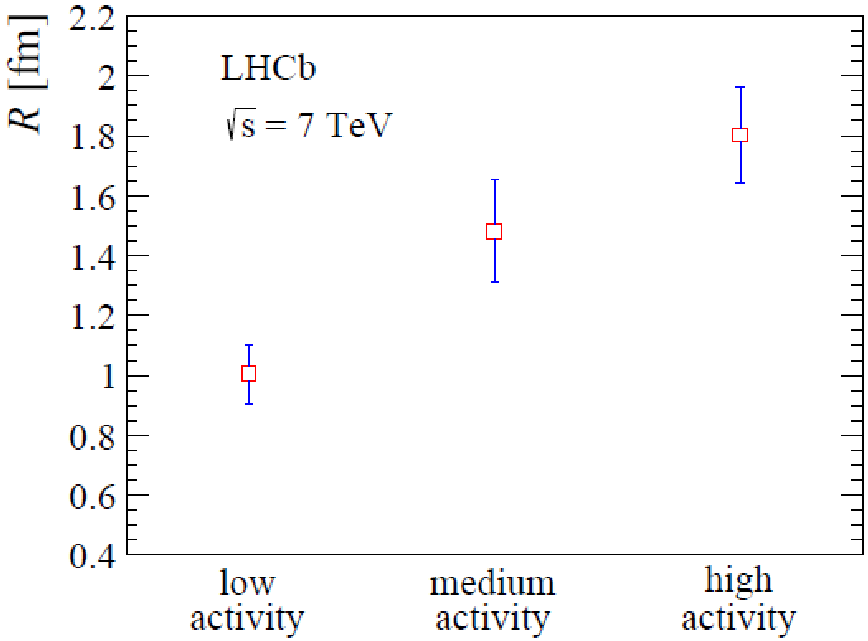
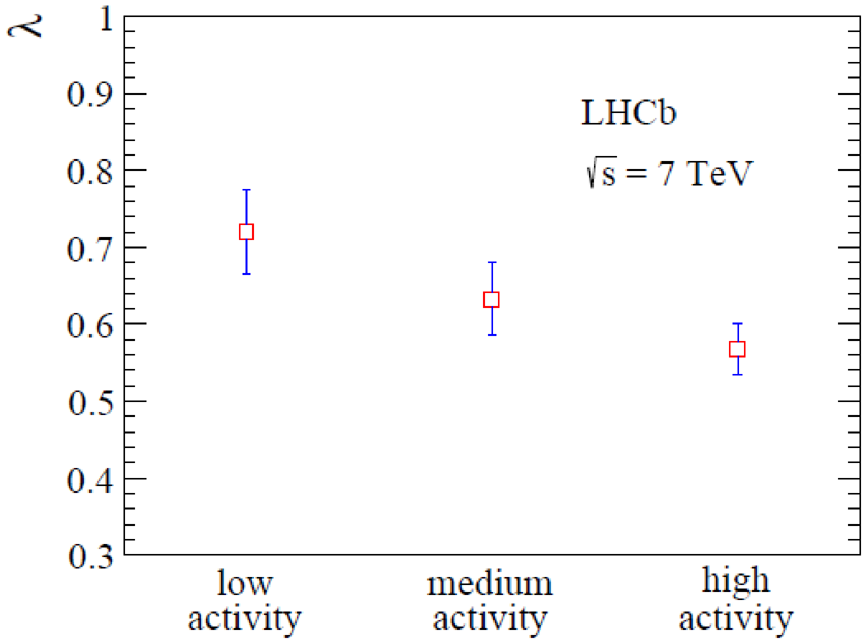




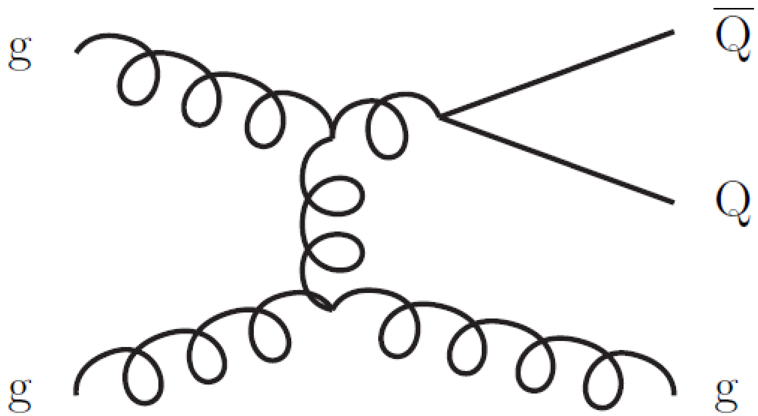
***R* and λ parameters** measured **in the forward region seem to be slightly lower** than results for central rapidity obtained by ATLAS (see backup)

Study of $\mathrm{b\bar{b}}$ correlations

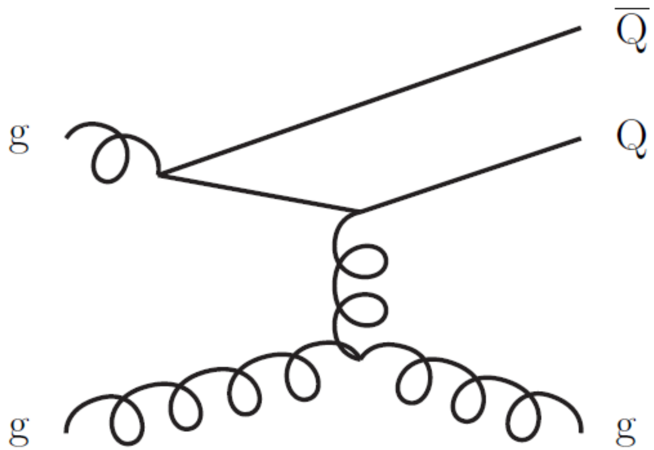
[JHEP 11 (2017) 030]

Motivation

- heavy-flavour production - important tests of QCD
- inclusive single-heavy-flavour production - limited sensitivity to higher-order QCD corrections (e.g. gluon splitting, flavour-excitation)
- those contributions can be studied in correlations between heavy quark and antiquark
- correlation measurements for $b\bar{b}$ were done at SPS, Tevatron and LHC
- LHCb – unique acceptance coverage + detector dedicated for B physics



gluon splitting



flavour-excitation

Analysis method

- beauty hadrons from inclusive decays into J/ψ:

  b -> J/ψX, where J/ψ -> $\mu^+\mu^-$

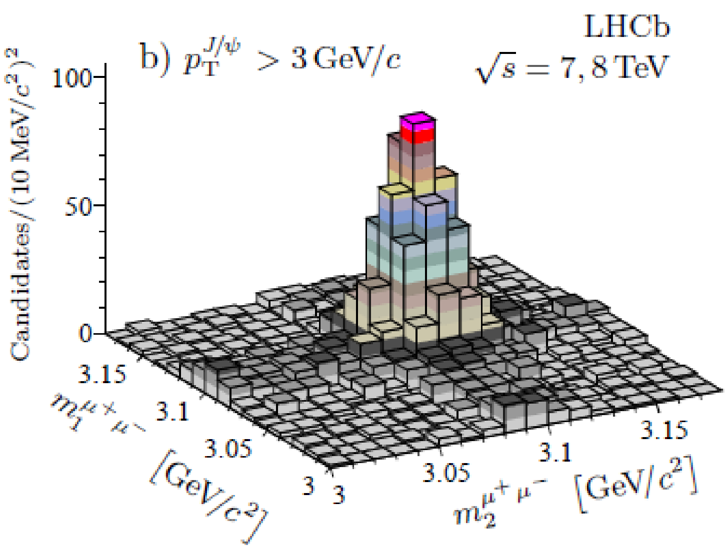
- **signal yield** determined from a fit to the 2D mass distribution of $\mu^+\mu^-$ pairs:

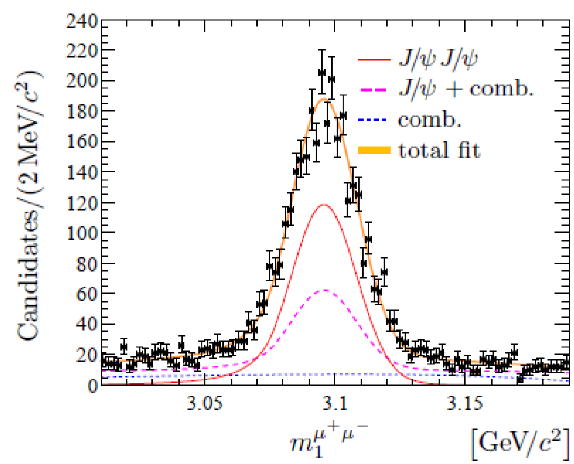
$$f(m_1, m_2) = N_{SS} * S(m_1)S(m_2) + \frac{N_{SB}}{2} * (S(m_1)B'(m_2) + B'(m_1)\,S(m_2)) + N_{BB} * B''(m_1, m_2)$$

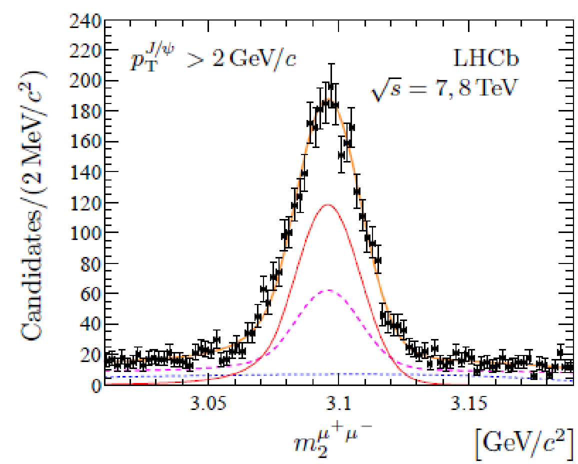
signal term (J/ψ+ J/ψ)

J/ψ + combinatorial background

pure combinatorial background







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Normalized differential cross-sections

- for a number of kinematic variables, **normalized differential cross-sections** are presented, defined here in a generic way:

$$\frac{1}{\sigma}\frac{d\sigma}{dv} \equiv \frac{1}{N^{cor}}\frac{\Delta N_i{}^{cor}}{\Delta v_i}$$

N^{cor} - total number of efficiency-corrected signal candidates
$\Delta N_i{}^{cor}$ - number of efficiency-corrected signal candidates in bin i of width Δv_i

- **kinematic variables** are defined below:
  - $|\Delta\Phi^*|$ - difference in azimuthal angle of 2 beauty hadrons**
  - $|\Delta\eta^*|$ - difference in pseudorapidity of 2 beauty hadrons**
  - $A_T \equiv (p_T{}^{J/\psi_1} - p_T{}^{J/\psi_2})/(p_T{}^{J/\psi_1} + p_T{}^{J/\psi_2})$ – asymmetry between p_T of J/ψ mesons
  - $m^{J/\psi J/\psi}$, $p_T{}^{J/\psi J/\psi}$, $y^{J/\psi J/\psi}$ - mass, p_T and rapidity of the J/ψ pair

Systematic uncertainty is much smaller than the statistic one and can be neglected (most of systematic sources cancel out in the $\Delta N_i{}^{cor}$/ N^{cor} ratio).

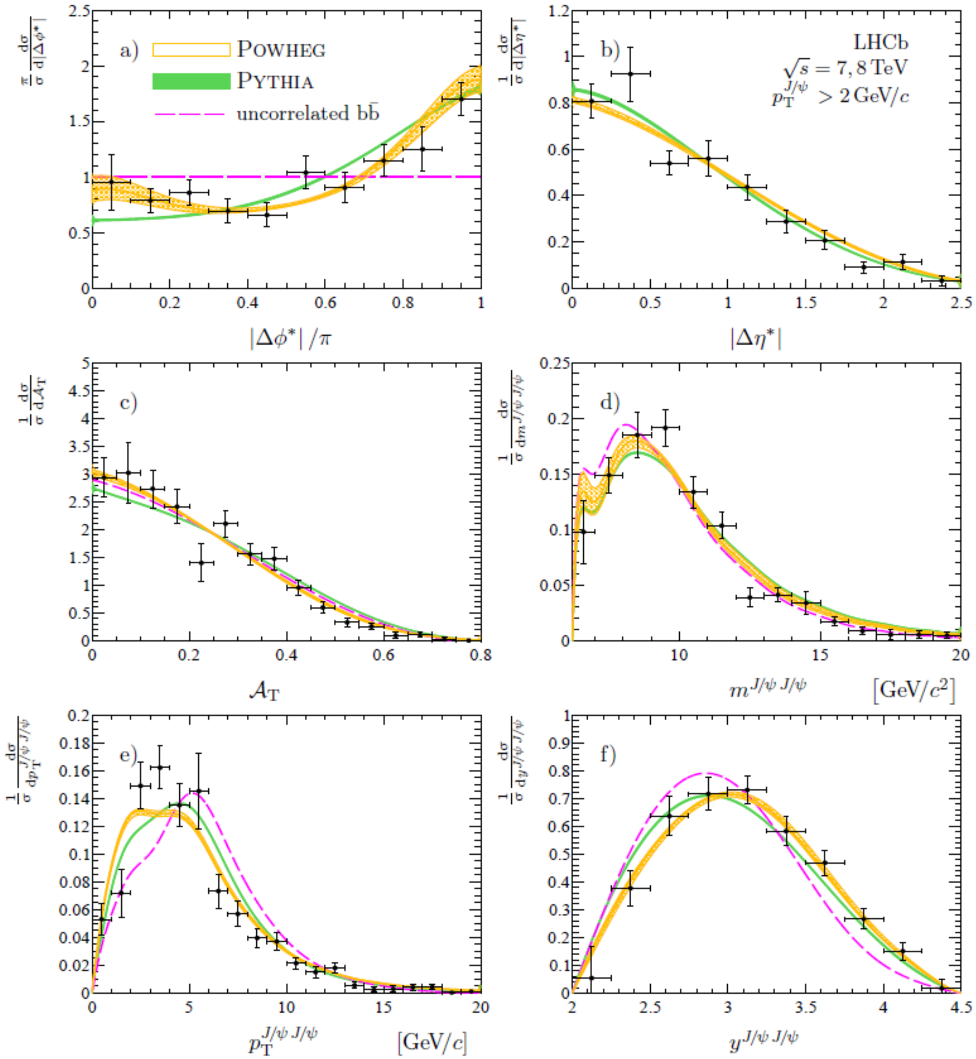
**) both Φ^* , η^* are estimated from the direction of the vector between PV to the J/ψ decay vertex

Results

$p_T^{J/\psi} > 2$ GeV/c

- distributions are compared with expectations from **PYTHIA (@LO)** and **POWHEG (@NLO)**, as well as an artificial data-driven model of uncorrelated $b\bar{b}$ production

- both PYTHIA and POWHEG well describe the data – **small NLO effects compared to the experimental precision**
- small contribution from gluon splitting at low $|\Delta\Phi^*|$ (otherwise than for $c\bar{c}$) -> expected, since it is suppressed due to a large mass of beauty quark



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Summary

Bose-Einstein correlations studied for same-sign pions at 7 TeV

- first measurement in the forward region $2 < \eta < 5$
- observed trends compatible with previous results and predictions
- BEC parameters in the forward region slightly lower wrt central rapidities
- this study shows the LHCb potential in BEC analyses

BEC analysis for p-Pb collisions ongoing

Kinematic correlations for $b\bar{b}$ pairs from p-p collisions at 7 and 8 TeV

- observed correlations agree with both PYTHIA (@LO) and POWHEG (@NLO), suggesting that the NLO effects in $b\bar{b}$ production are small compared to the experimental precision
- however, discriminating theory predictions is not possible with the present data - future measurements with larger samples needed

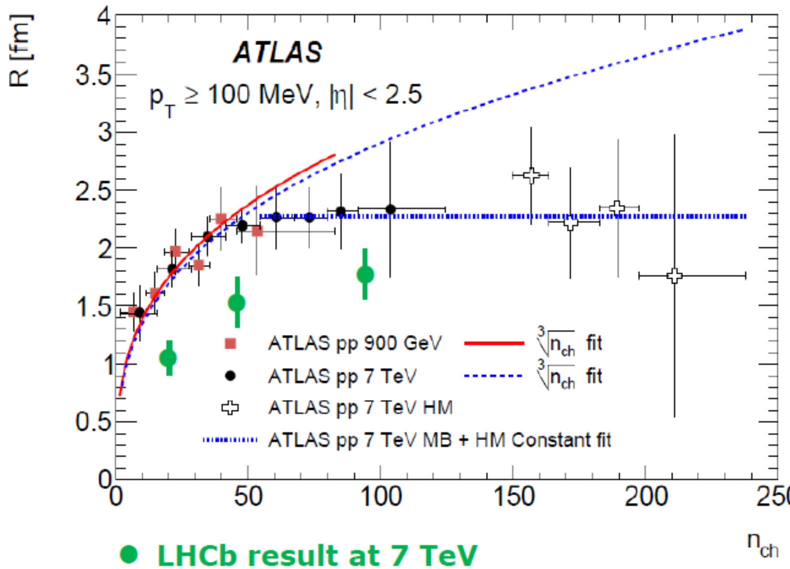
Thank you for your attention

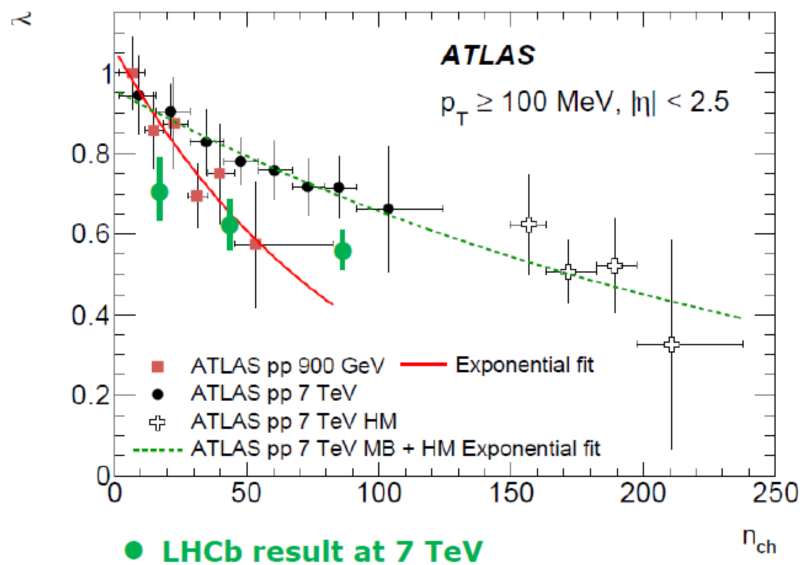
BACKUP SLIDES

BEC – results

Correspondence of unfolded N_{ch} bins between ATLAS ($|\eta| < 2.5$, $p_T > 0.1$ GeV/c) and LHCb ($2 < \eta < 5$) acceptances at 7 TeV found using PYTHIA 8:

- ***R* and *λ* parameters** measured **in the forward region are slightly lower** than results for central rapidity obtained by ATLAS
- need to measure the BEC parameters using a full 3D analysis to perform a more detailed comparison



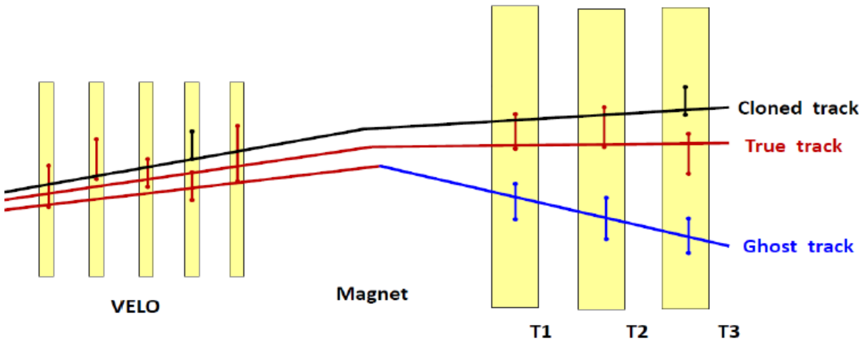


ATLAS: Eur. Phys. J. C75 (2015) 466
LHCb: JHEP 12 (2017) 025

BEC - track selection

- relatively loose selection of pions

Long track traversing whole detector
- loose particle identification cuts on pions
- $2 < \eta < 5$
- good track quality ($\chi^2/ndf < 2$)
- $p > 2$ GeV/c
- $p_T > 0.1$ GeV/c
- $IP < 0.4$ mm
- cut on probability to be a ghost track



- correlation function is not sensitive to single track efficiency, but can be sensitive to two-track effects such as cloned or ghost tracks*
- ghosts/clones not perfectly simulated -> cannot be fully corrected by DR
- if tracks share all same VELO hits -> keep one with best χ^2 - effect from clones/ghosts under control for $Q > 0.05$ GeV/c^2
- clones also suppressed by removing tracks with small tracks slope differences
- effects from ghosts present both in same-sign pairs and unlike-sign pairs – controlled by looking at DR for unlike-sign pairs (no BEC effect)

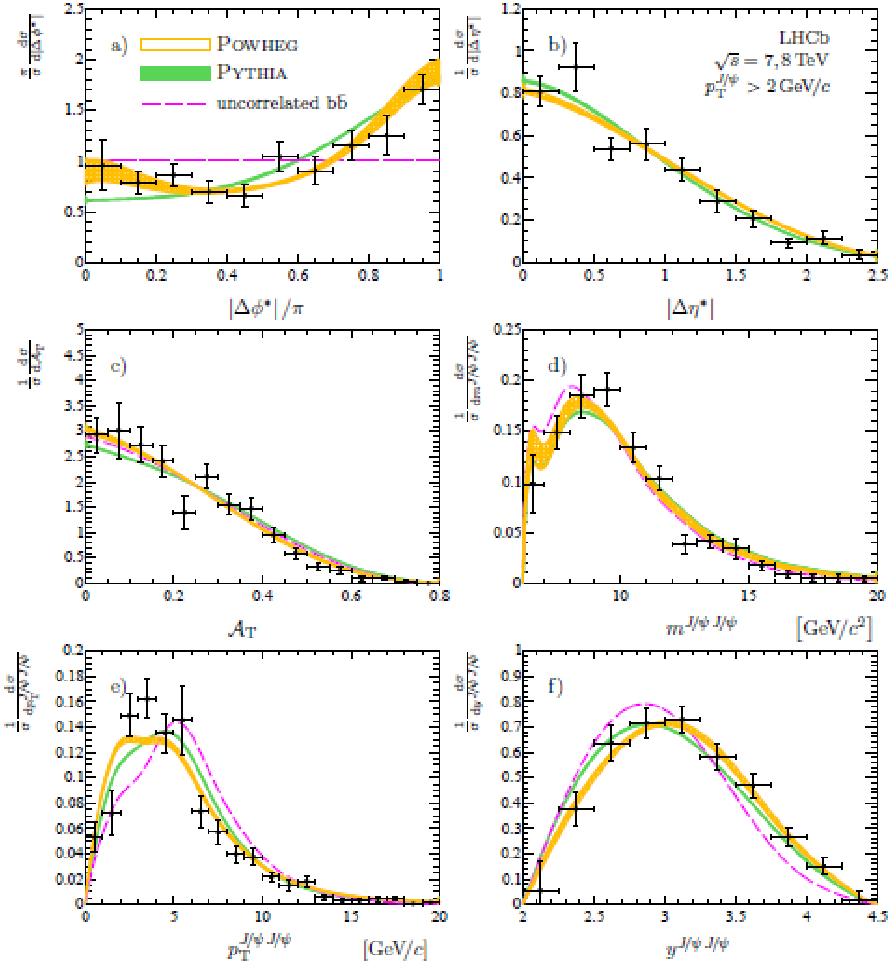
* clones – fake tracks reconstructed from hits originating mainly from a single particle
ghosts – fake tracks reconstructed from hits deposited by multiple particles

BEC - systematics

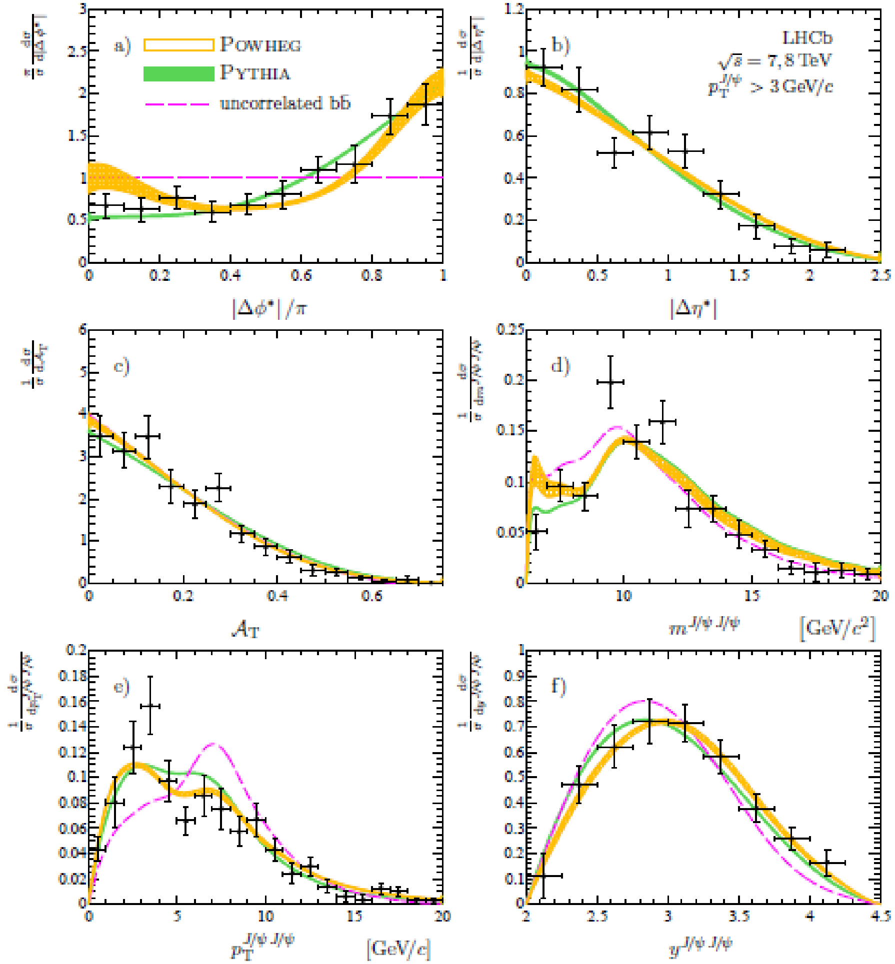
Source	Low activity		Medium activity		High activity	
	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]	ΔR [%]	$\Delta\lambda$ [%]
Generator tunings	6.6	4.3	8.9	3.5	6.5	1.5
PV multiplicity	5.9	5.8	6.1	4.5	3.9	4.3
PV reconstruction	1.8	0.1	1.4	1.2	0.1	<0.1
Fake tracks	0.4	1.1	1.7	3.9	1.1	0.8
PID calibration	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

$b\bar{b}$ - results (I)

$p_T^{J/\psi}$ > 2 GeV/c

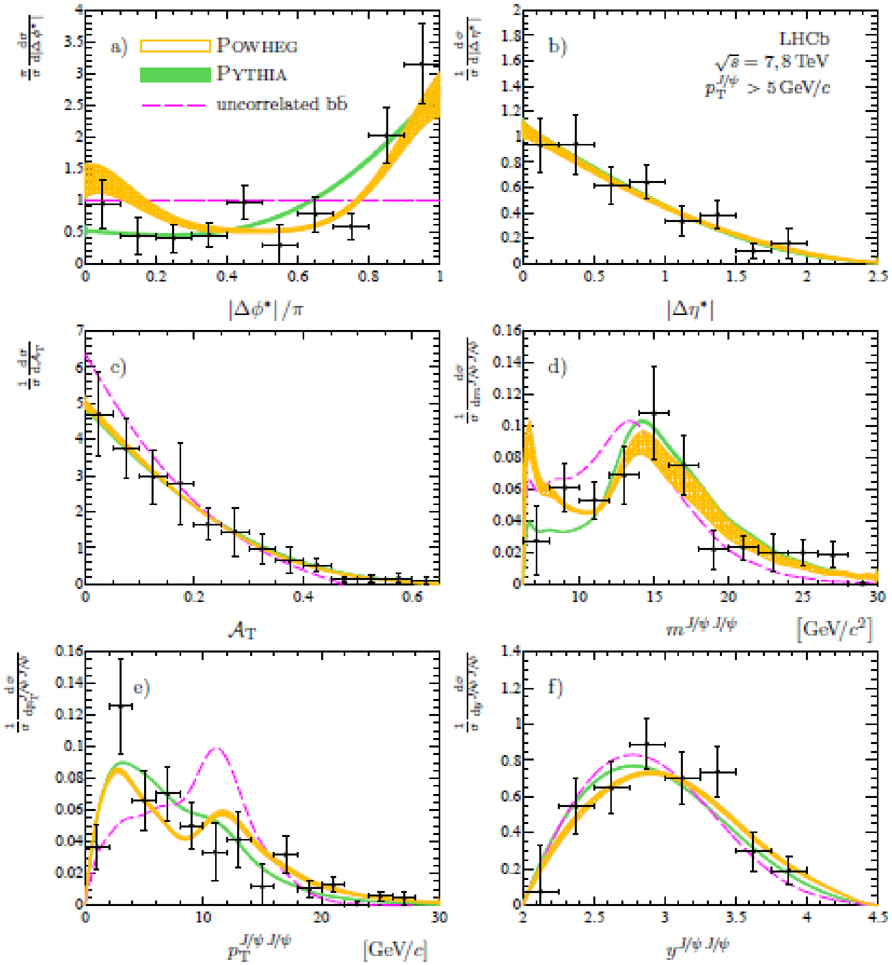


$p_T^{J/\psi}$ > 3 GeV/c

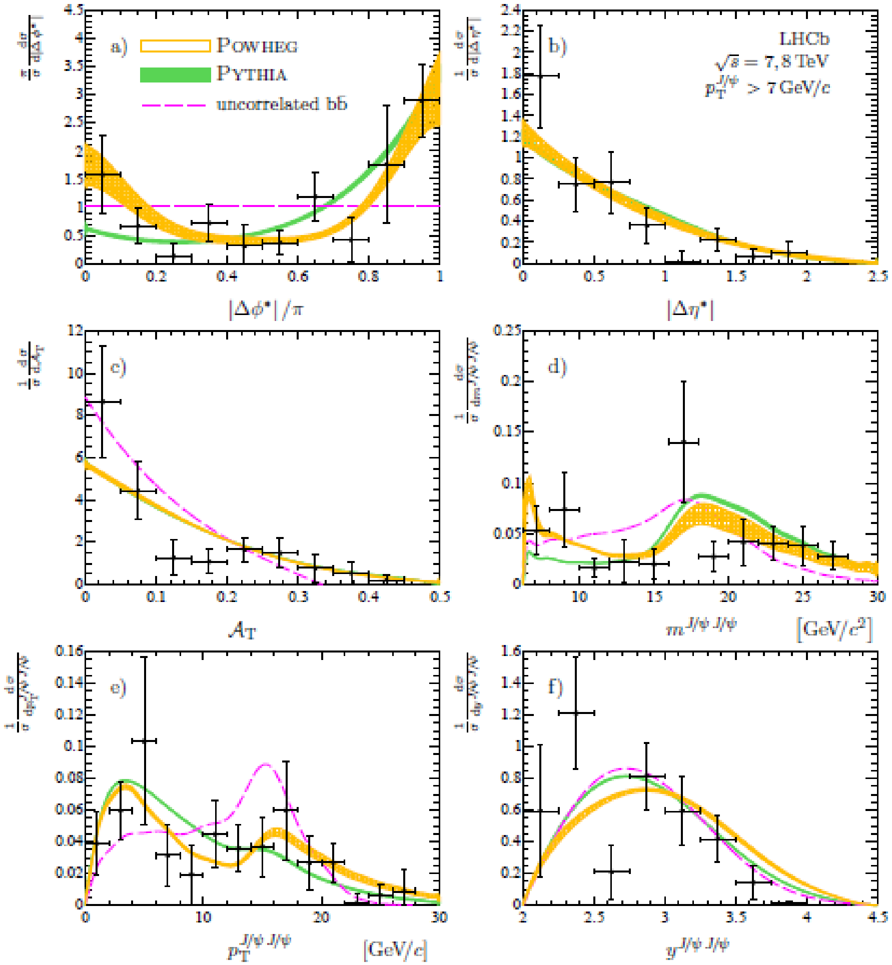


$b\bar{b}$ - results (II)

$p_T^{J/\psi}$ > 5 GeV/c



$p_T^{J/\psi}$ > 7 GeV/c



$b\bar{b}$ - systematics

Source	Uncertainty [%]
Signal determination	< 1.0
Muon identification	0.4
Track reconstruction	1.7
Trigger	1.2
Simulated sample size	< 0.1