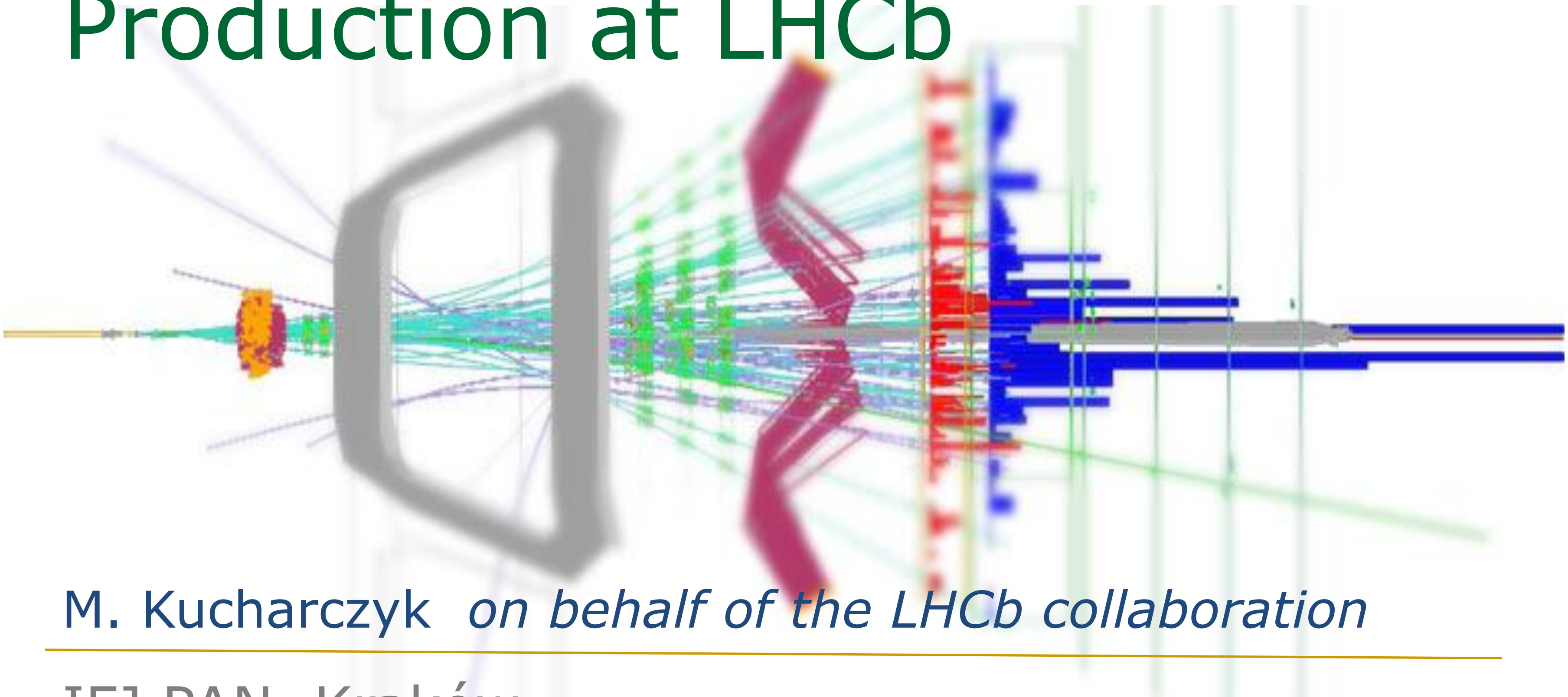
Soft QCD and Central Exclusive Production at LHCb



M. Kucharczyk *on behalf of the LHCb collaboration*

IFJ PAN, Kraków

DIS 2019, Turin
8-12 April 2019

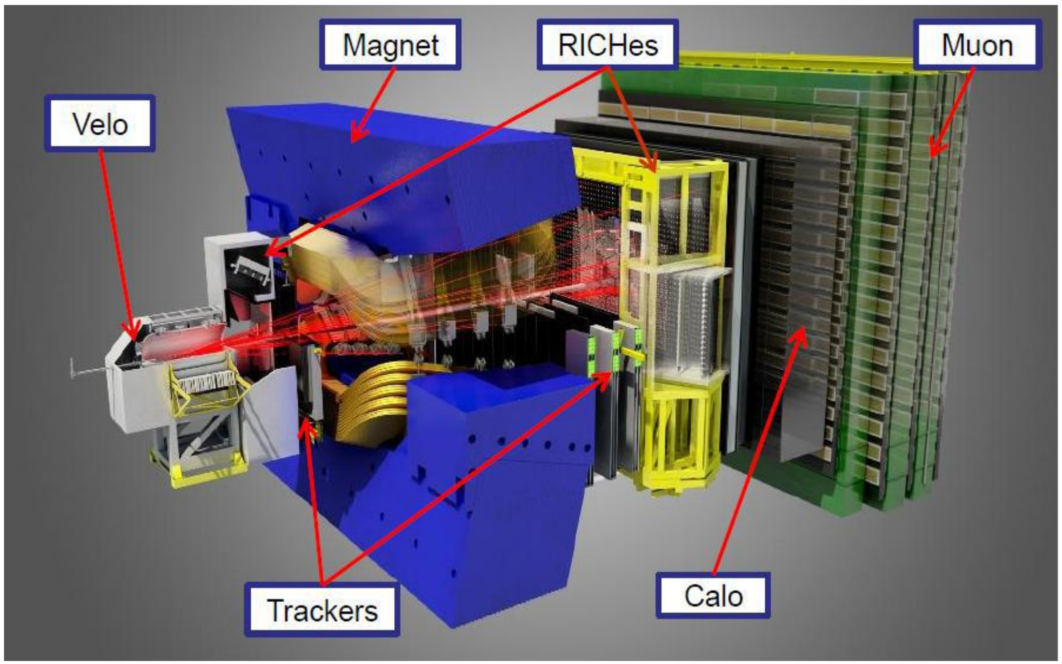
Outline

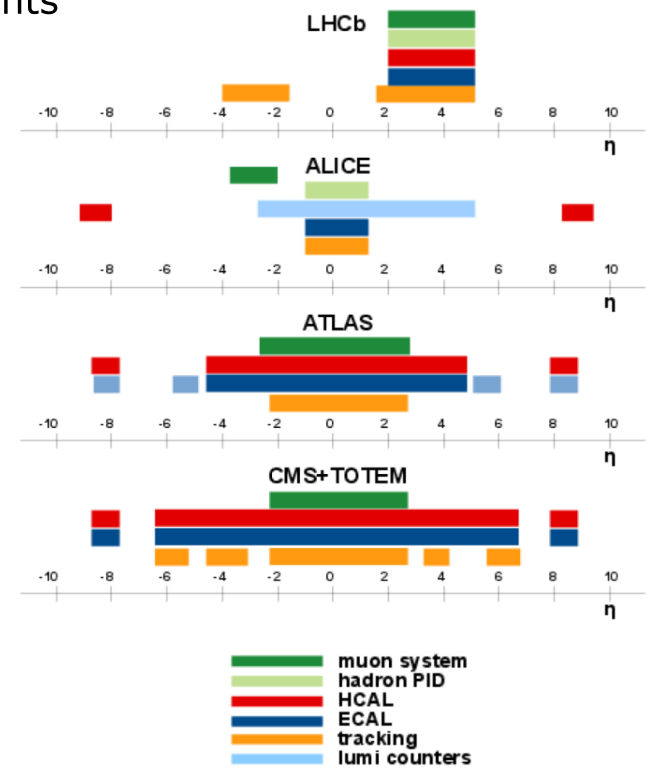
- LHCb - general purpose forward experiment
- Inelastic cross section at 13 TeV
- BEC for pion pairs in *p-p* collisions at 7 TeV
- Correlations in $b\bar{b}$ production at 7 and 8 TeV
- HeRSCheL detector
- Central Exclusive Production of J/ψ and $\psi(2S)$ at 13 TeV
- Conclusions

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 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20 μm for high-p_T tracks
- good PID separation up to 100 GeV *(misID ($\pi \rightarrow K$) ≈ 5% at 95% efficiency)*

Inelastic cross section at 13 TeV

[JHEP 06 (2018) 100]

Inelastic cross section at 13 TeV

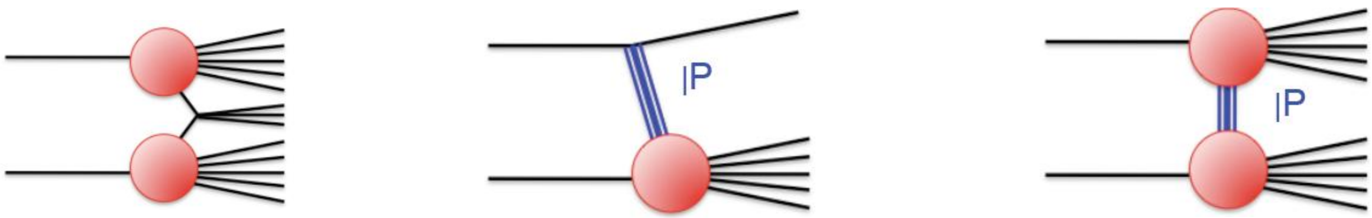
[JHEP 06 (2018) 100]

- fundamental in the phenomenology of high-energy hadronic interactions
- important for astroparticle physics

  → *description of extensive air showers induced by cosmic rays*

  → *modeling of the transport of cosmic ray particles in the interstellar medium*

Dominant processes



Non-Diffractive *(ND)*   Single-Diffractive *(SD)*   Double-Diffractive *(DD)*

- based on prompt long-lived particles inside the LHCb acceptance
- fiducial cross section
- extrapolate to the full phase space

  → *neglect interference and CEP*

Fiducial cross section

[JHEP 06 (2018) 100]

Selection

- $\geq$ 1 long-lived prompt charged particle
  $\rightarrow$ *mean lifetime > 30 ps*
- p > 2 GeV
- 2 < η < 5

10.7 nb^{-1} collected in 2015 at 13 TeV

$\rightarrow$ *unbiased triggers*

$\rightarrow$ *avoid background from previous crossing*

Fiducial cross section

$$\sigma_{\mathrm{acc}} = \frac{(\mu - \mu_{\mathrm{bkg}}) N_{\mathrm{evt}}}{\mathcal{L}}$$

N_{evt} - number of events

L - integrated luminosity

average number of interaction per event

$\rightarrow$ *from fraction of empty events*

$\rightarrow$ *corrected for detector inefficiency and wrongly reconstructed tracks*

$\rightarrow$ *assumed Poisson distribution*

$$\boxed{\sigma_{\mathrm{acc}}(\sqrt{s} = 13\ \mathrm{TeV}) = 62.2 \pm 2.5(\mathrm{exp})\ \mathrm{mb}}$$

$\rightarrow$ *dominant error from luminosity measurement*

$\rightarrow$ *negligible stat. error*

Extrapolation to full phase space

[JHEP 06 (2018) 100]
[JHEP 02 (2015) 029]

Extrapolate to full phase-space using simulation

$$\boxed{\sigma_{\mathrm{inel}} = F_{\mathrm{T}}\,\sigma_{\mathrm{acc}} = \sum \sigma_X \quad \text{with } X \in \{\mathrm{ND}, \mathrm{SD}, \mathrm{DD}\}}$$

$$F_T = \frac{1}{\sum_X f_X v_X}$$

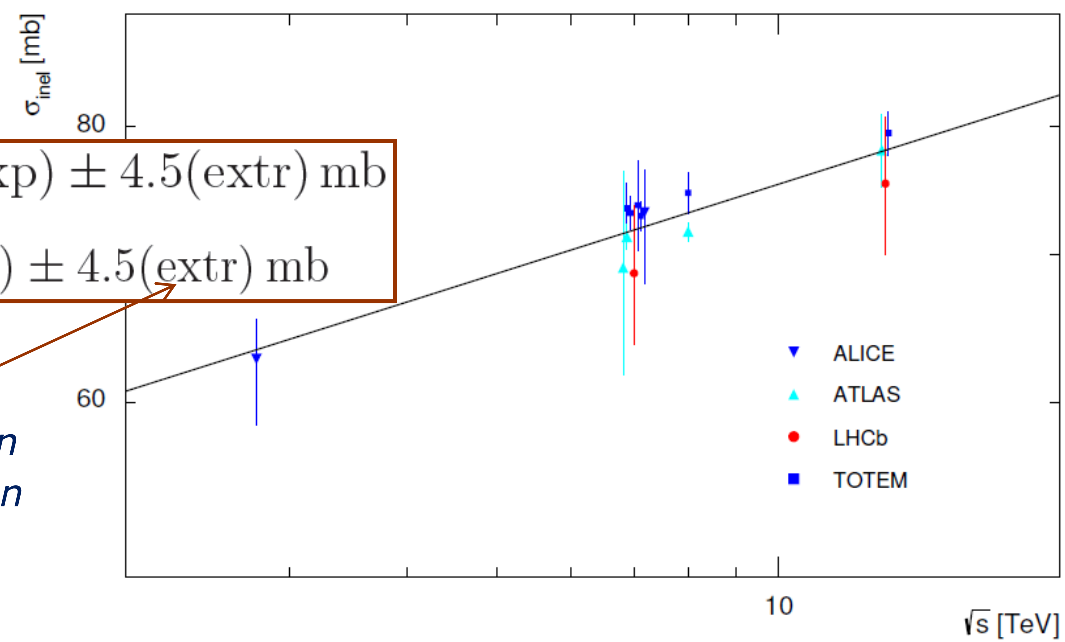
fraction of inelastic cross sections from MC & data constraint

visible interactions in acceptance from MC

neglected:

→ *CEP*

→ *interference between different contributions*



$$\sigma_{\mathrm{inel}}(\sqrt{s} = 13\,\mathrm{TeV}) = 75.4 \pm 3.0(\mathrm{exp}) \pm 4.5(\mathrm{extr})\,\mathrm{mb}$$

$$\sigma_{\mathrm{inel}}(\sqrt{s} = 7\,\mathrm{TeV}) = 68.7 \pm 2.1(\mathrm{exp}) \pm 4.5(\mathrm{extr})\,\mathrm{mb}$$

experimental error of fiducial cross section

cross section extrapolation

Bose-Einstein correlations

[JHEP 12 (2017) 025]

Correlation function

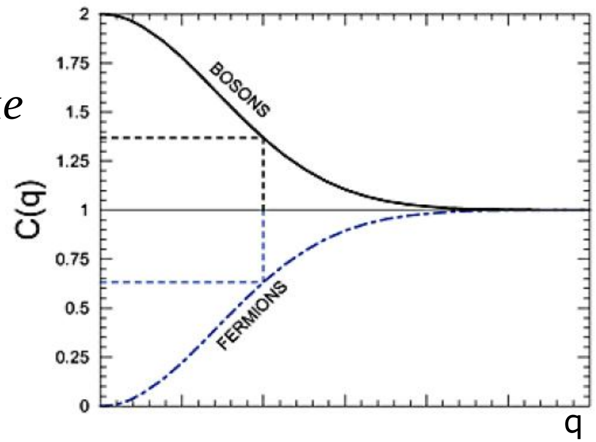
[JHEP 12 (2017) 025]

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

$N(Q)^{DATA}$ - 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 - chaoticity 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 *(DR)*

$$DR(Q) = \frac{C_2(Q)^{\mathrm{data}}}{C_2(Q)^{\mathrm{MC}}}$$ *MC 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:

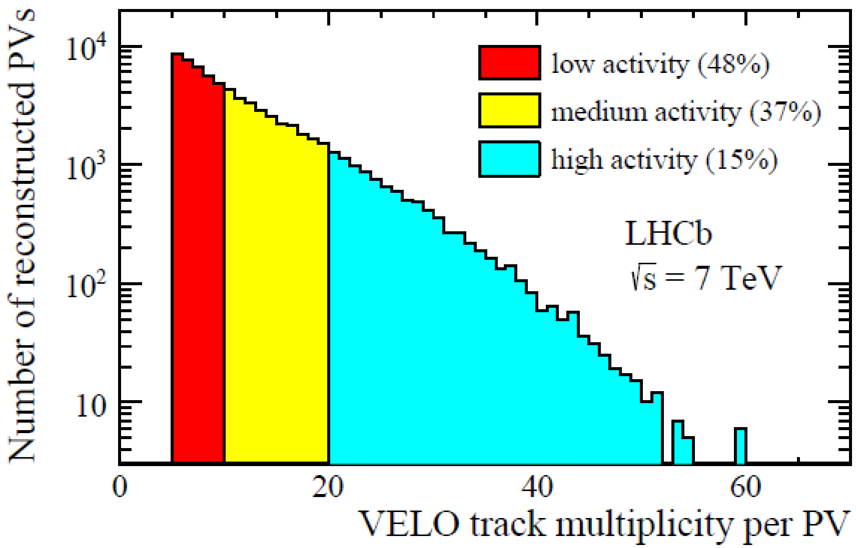
$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}, \quad \text{where} \quad \zeta = \pm\frac{\alpha m}{Q}$$

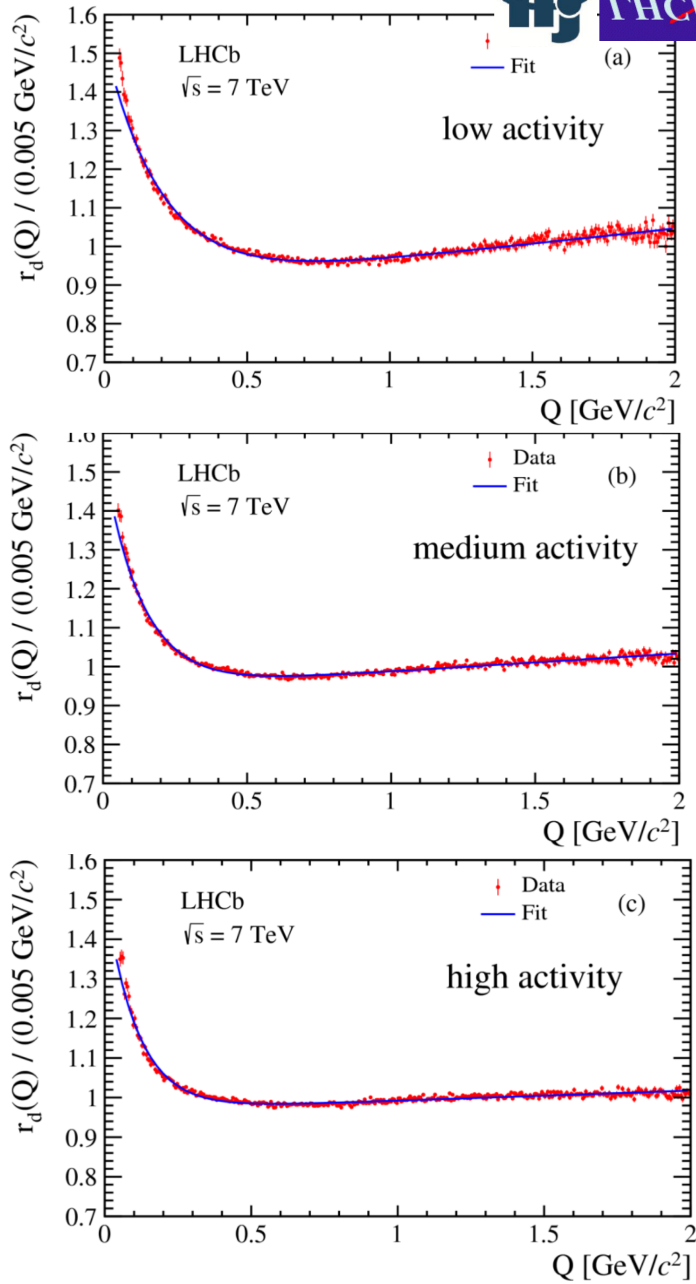
→ **systematics due to Coulomb correction found to be negligible**

Results

[JHEP 12 (2017) 025]

Fits to DR with Levy parametrization for 3 activity bins





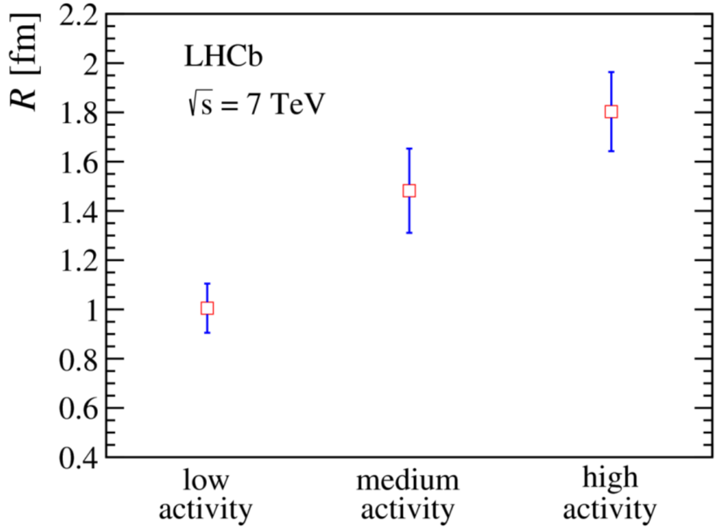
Activity	R [fm]	λ
Low	1.01 ± 0.01 ± 0.10	0.72 ± 0.01± 0.05
Medium	1.48 ± 0.02 ± 0.17	0.63 ± 0.01 ± 0.05
High	1.80 ± 0.03 ± 0.16	0.57 ± 0.01 ± 0.03

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

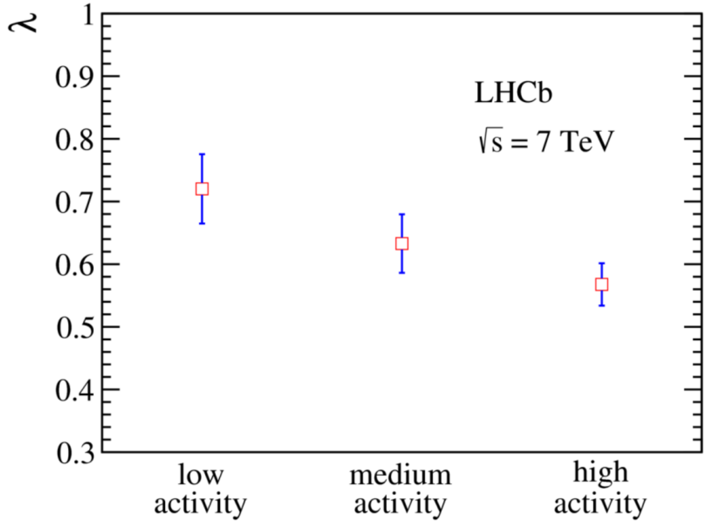
Results

[JHEP 12 (2017) 025]

Source size increases with activity



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 are slightly lower wrt ATLAS
- Need to measure the BEC parameters using a full three-dimensional analysis to perform a more detailed comparison

Correlations in $b\bar{b}$ production

[JHEP 11 (2017) 030]

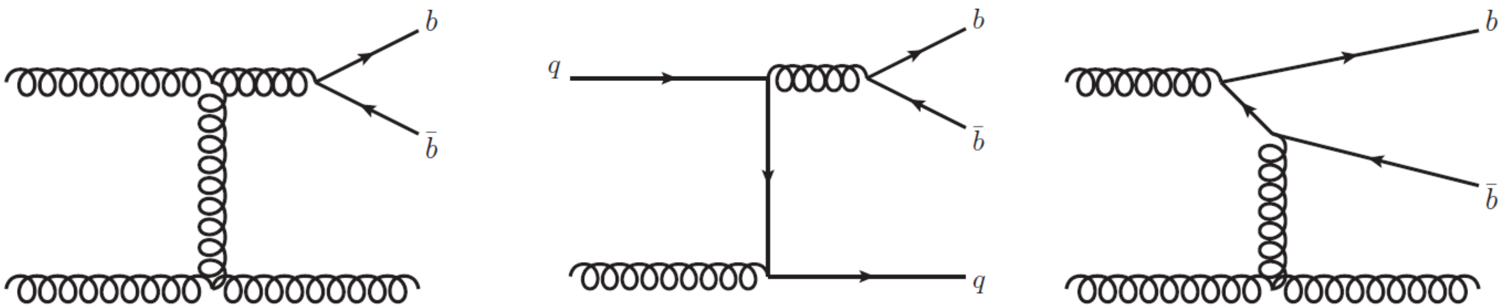
Correlations in $b\bar{b}$ production

[JHEP 11 (2017) 030]

- heavy-flavour production
  $\rightarrow$ *important tests for the predictions of QCD*

- kinematic correlations between heavy quark and antiquark
  $\rightarrow$ *better understanding of the production mechanism, i.e. contributions of gluon-splitting, flavour-creation and flavour excitation*

  $\rightarrow$ *better sensitivity to higher-order corrections wrt inclusive single-heavy-flavour production*



- correlations of beauty hadrons studied already at SPS, Tevatron and LHC

- LHCb $\rightarrow$ unique acceptance and detector dedicated for b-hadron physics

Differential cross sections

[JHEP 11 (2017) 030]

- inclusive *b*-hadrons decays $b \to J/\psi X,\ J/\psi \to \mu^+\mu^-$
- signal yield from fit to the 2D mass distribution of $\mu^+\mu^-$ pairs
- **normalized differential cross-sections**

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

kinematic variables

$|\Delta\Phi^*|$ - difference in azimuthal angle of 2 beauty hadrons

$|\Delta\eta^*|$ - difference in pseudorapidity of 2 beauty hadrons

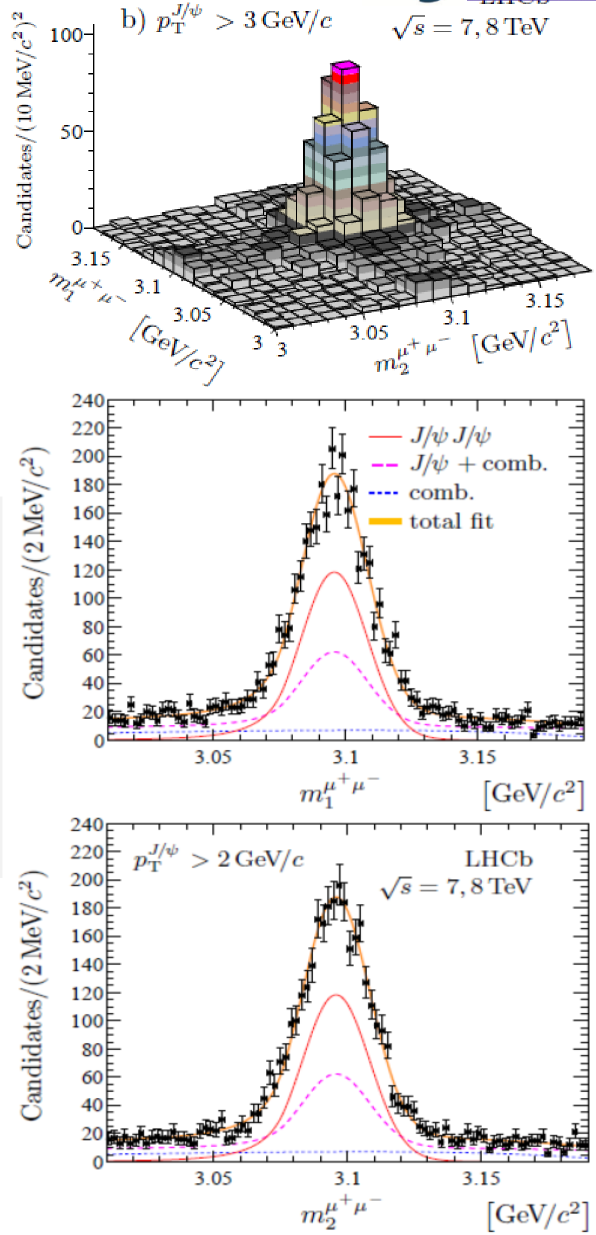
p_T asymmetry: $A_T \equiv (p_{T(J/\psi 1)} - p_{T(J/\psi 2)} / (p_{T(J/\psi 1)} + p_{T(J/\psi 2)})$

$m_{J/\psi J/\psi}$, $p_{T(J/\psi J/\psi)}$, $y_{(J/\psi J/\psi)}$ - mass, p_T and rapidity of J/ψ pair

Φ^* and η^* estimated from direction of vector between PV and J/ψ decay vertex

Most systematics cancel out in $\Delta N_i^{cor} / N_{cor}$ ratio

$\to$ *much smaller with respect to statistical error*



Results

$p_{T(J/\Psi)}$ > 2 GeV

[JHEP 11 (2017) 030]

- data compared with LO PYTHIA and NLO POWHEG and also data-driven model of uncorrelated *bb* production

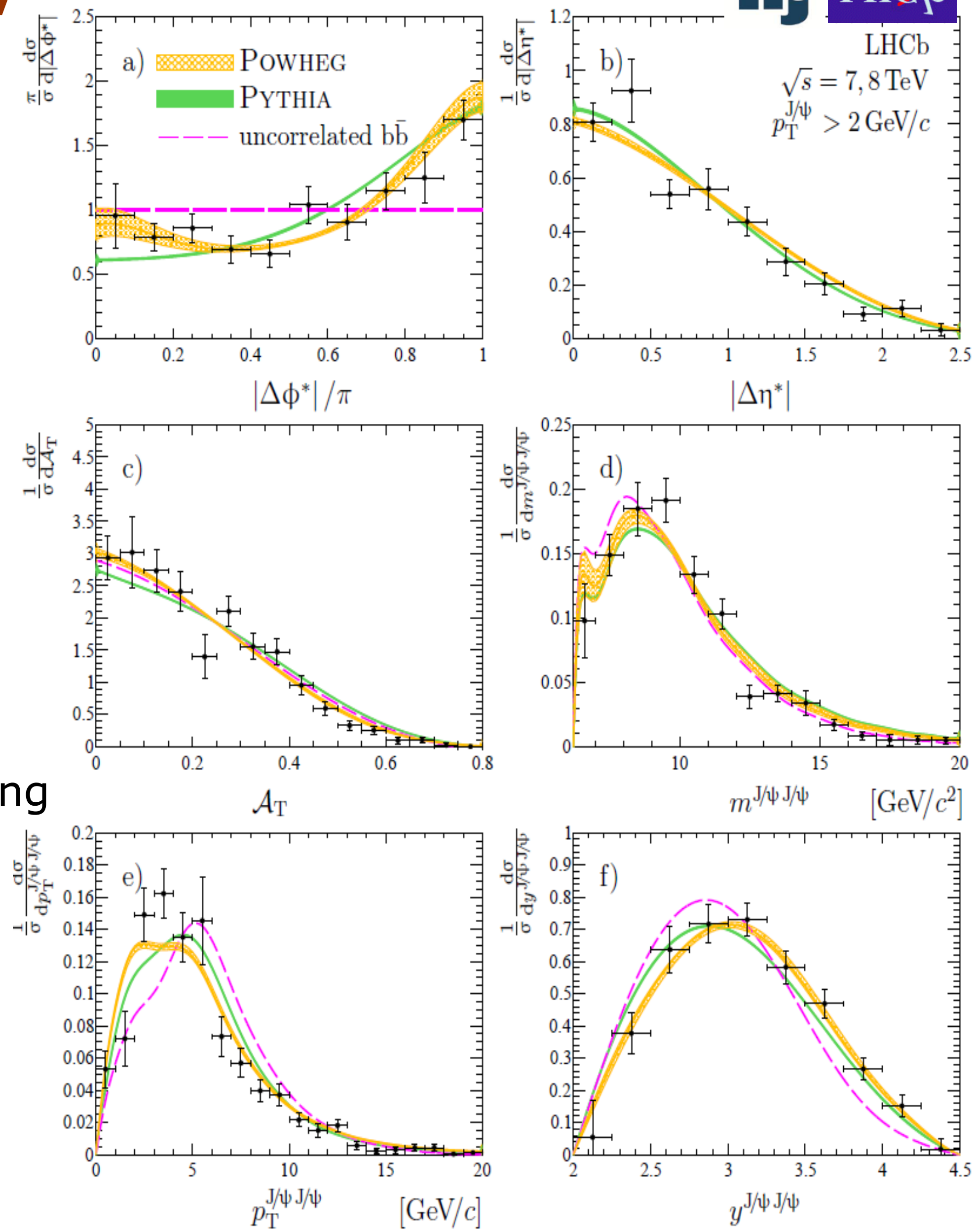
- both PYTHIA and POWHEG describe the data well

  → *only minor NLO effects compared to experimental precision*

- small contribution from gluon splitting at low |*ΔΦ**|

  → *opposite to cc*

  (as expected - suppressed due to large mass of b-quark)



Central Exclusive Production

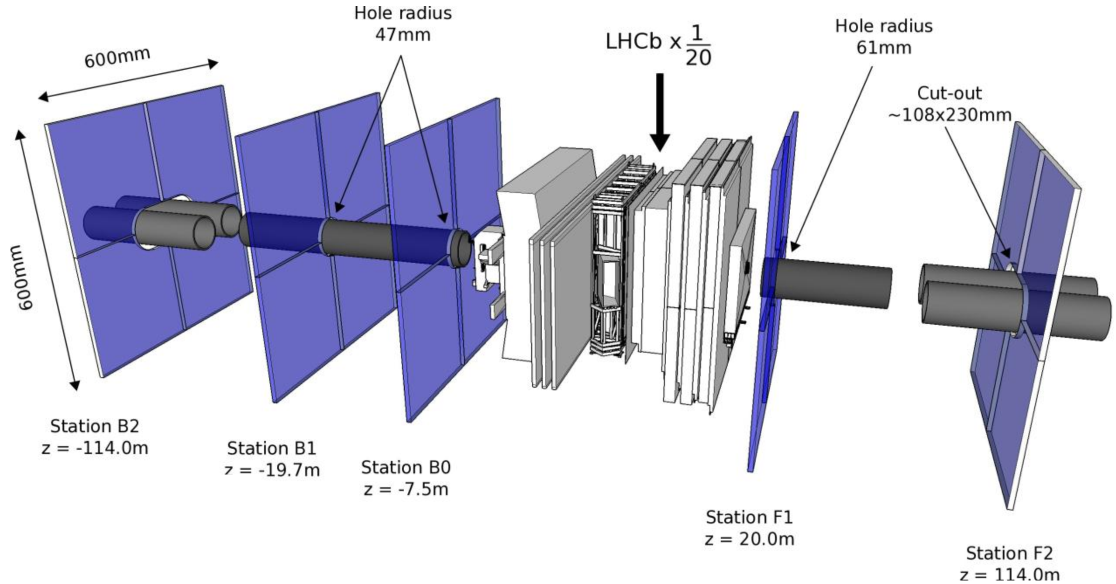
[JHEP 1810 (2018) 167]

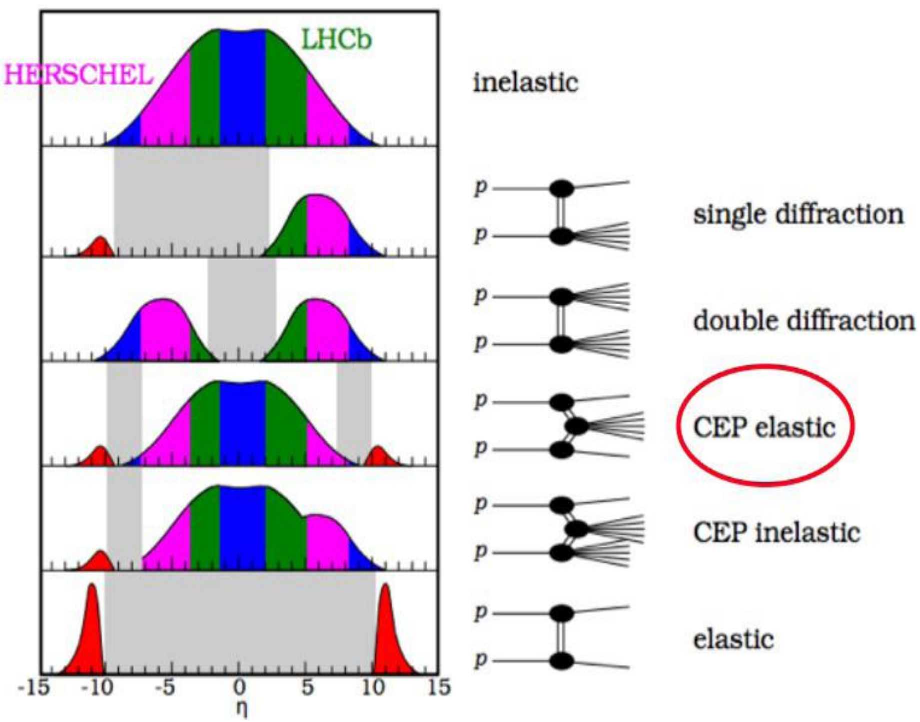
HeRSCheL

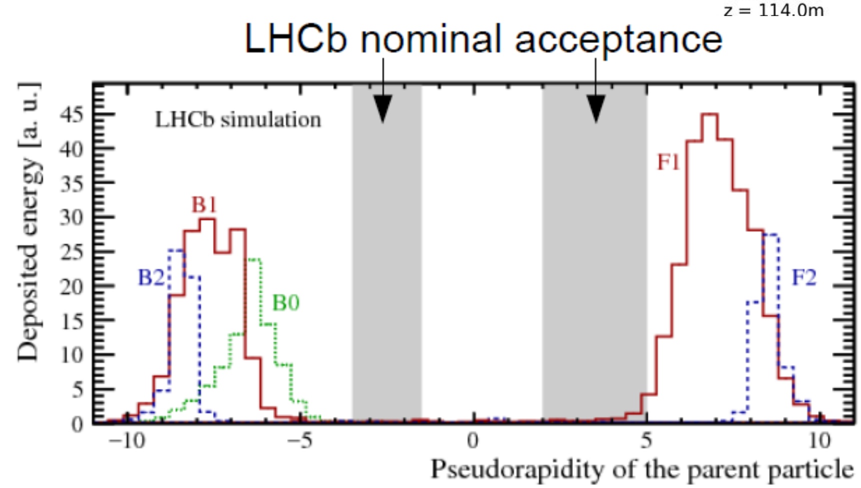
[JINST 13 (2018) 04, P04017]

HeRSChel - High Rapidity Shower Counters

- installed at the end of 2014
  → *increase η coverage (5 < |η| < 10)*
- read-out synchronic LHCb
  → *5 stations with 4 scintillators with PMT*
- able to detect forward particle showers and veto events







B0 – high-rapidity collisions

F1, B1- high-rapidity collisions

F2, B2 – showers from high rapidity neutral particles

LHCb results

Run I: *pp* collisions at 7,8 TeV *(2011-2012)*

- Measurement of the exclusive *Υ* production cross-section at 7 TeV and 8 TeV
  [JHEP 1509 (2015) 084]
- Observation of charmonium pairs produced exclusively in *pp* collisions
  [J. Phys. G41 (2014) no.11, 115002]
- Updated measurements of exclusive *J/ψ* and *ψ(2S)* production cross-sections in *pp* at 7 TeV
  [J. Phys. G41 (2014) 055002]
- Exclusive dimuon measurements: non-resonant and χ_c
  [LHCb-CONF-2011-022]

Run II *(with HeRSCheL)*: *pp* at 13 TeV, *PbPb* at 5 TeV *(2015)*

- Study of coherent J/ψ production in lead-lead collisions at 5 TeV
  [LHCb-CONF-2018-003]
- Central exclusive production of *J/ψ* and *ψ(2S)* mesons in *pp* collisions at 13 TeV
  [JHEP 1810 (2018) 167]

\+ preliminary results for *pPb* and *Pbp* at 8 TeV

Production of J/ψ and $\psi(2S)$ at 13 TeV

[JHEP 1810 (2018) 167]

Selection

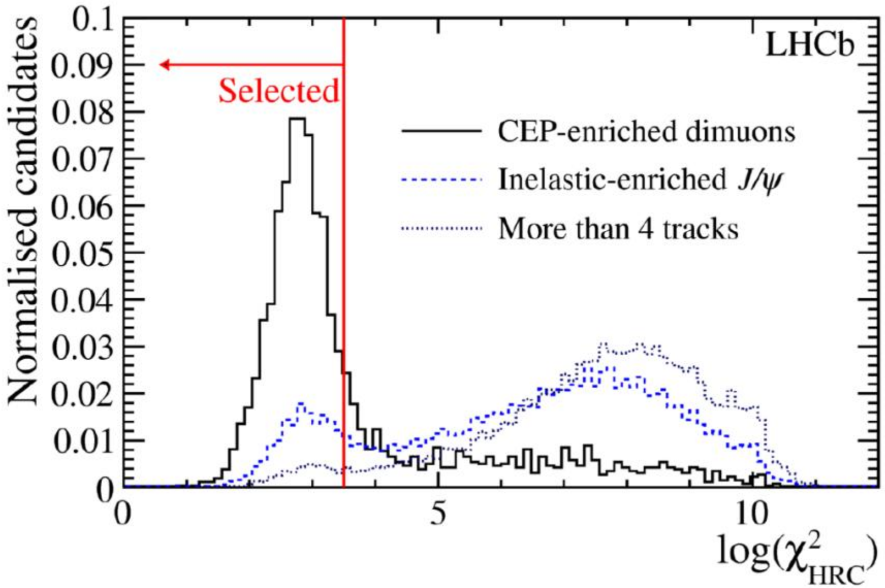
- 2 muons within $2 < \eta < 4.5$
- no additional tracks or energy
- J/ψ $p_T^2 < 0.8$ GeV^2
- within 65 MeV of the $M_{J/\psi}$

L = 204 pb^{-1} (2015)

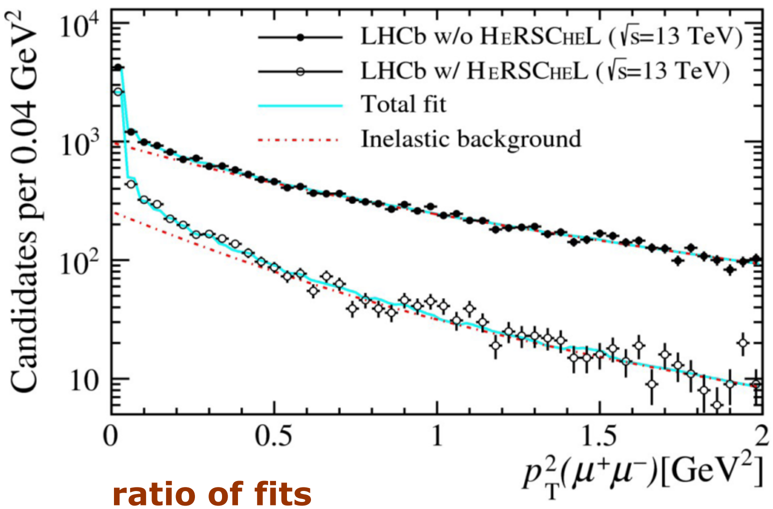
14753 J/ψ candidates

440 $\psi(2S)$ candidates

HeRSCheL activity requirement



χ^2_{HRC} quantifies the activity above noise, including correlations between counters



ratio of fits

→ *efficiency of the veto = 0.723±0.008*

CEP-enriched dimuons

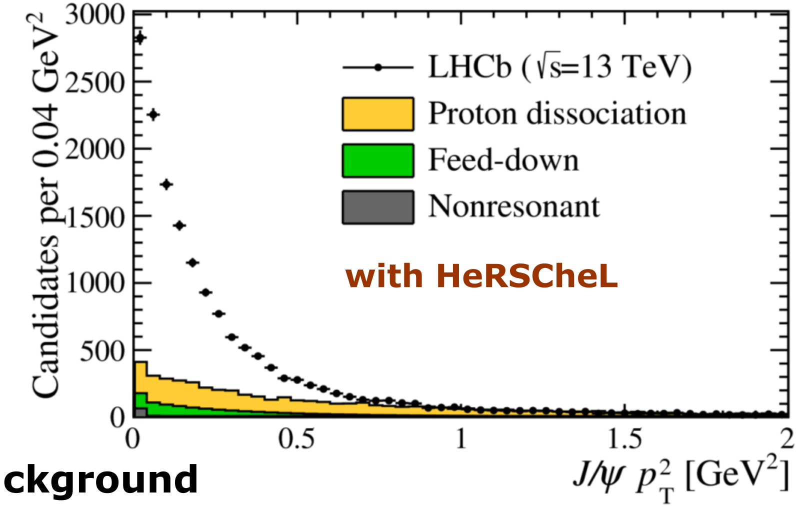
→ non-resonant dimuon events with $p^2_T < 0.01$ GeV^2 *(97% purity)*

Inelastic-enriched J/ψ

→ additional cut on J/ψ $p^2_T > 2$ GeV^2

Cross sections

[JHEP 1810 (2018) 167]

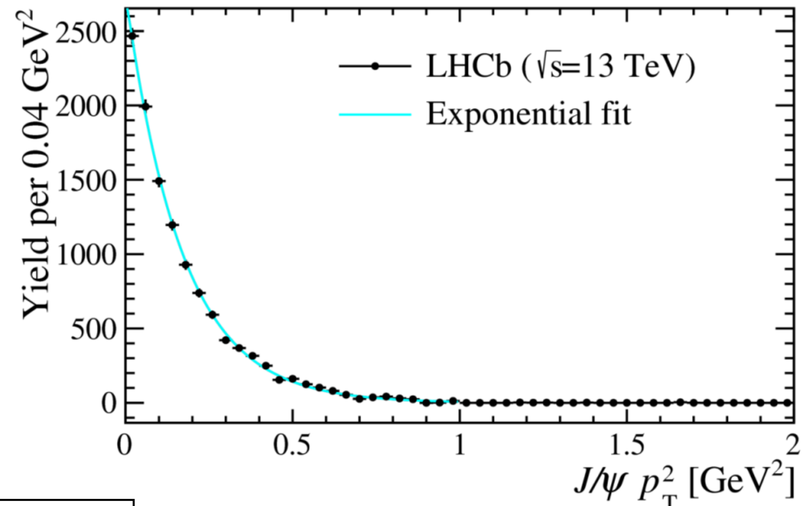


Efficiencies

- reconstruction and selection
  $\rightarrow$ *data driven methods*
- fraction of 1 interaction beam xings
  $\rightarrow$ *0.3662 ± 0.0003*

Background

- non-resonant dimuon
  $\rightarrow$ *from the invariant mass fit*
- feed-downs from $\chi_{cJ}(1P)$, $\psi(2S)$, …
  $\rightarrow$ *from data-calibrated simulation*
- proton dissociation $\rightarrow$ *fit to the $p^2{}_T$ distribution*



$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{\rm rec}\epsilon_{\rm sel}\Delta y \epsilon_{\rm single}\mathcal{L}_{\rm tot}},$$

$$\begin{aligned}\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta<4.5) &= 435\pm18\pm11\pm17\text{ pb}\\ \sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta<4.5) &= 11.1\pm1.1\pm0.3\pm0.4\text{ pb},\end{aligned}$$

Signal purity

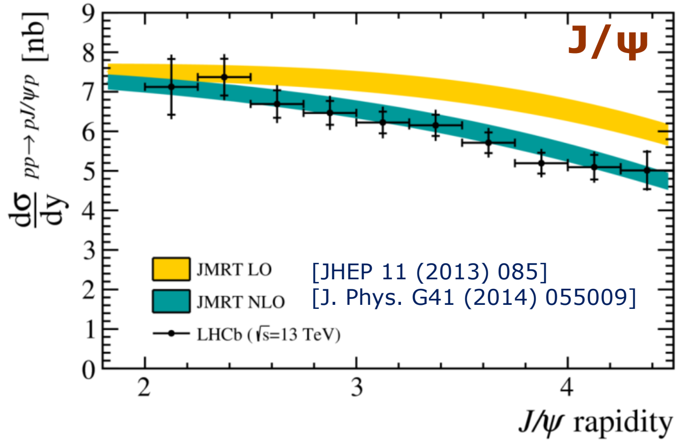
0.755 ± 0.015 for J/ψ

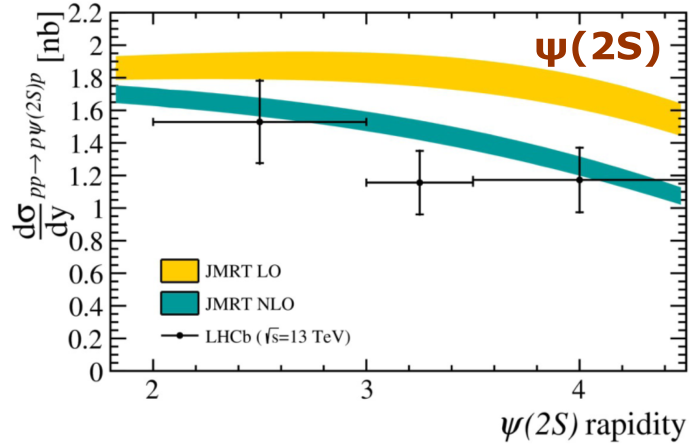
0.726 ± 0.061 for $\psi(2S)$

Results

[JHEP 1810 (2018) 167]

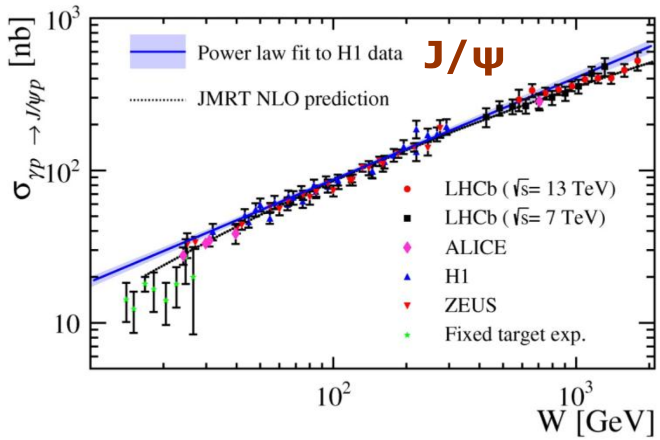
Results corrected by $J/\psi \to \mu\mu$ branching fractions and detector geometry

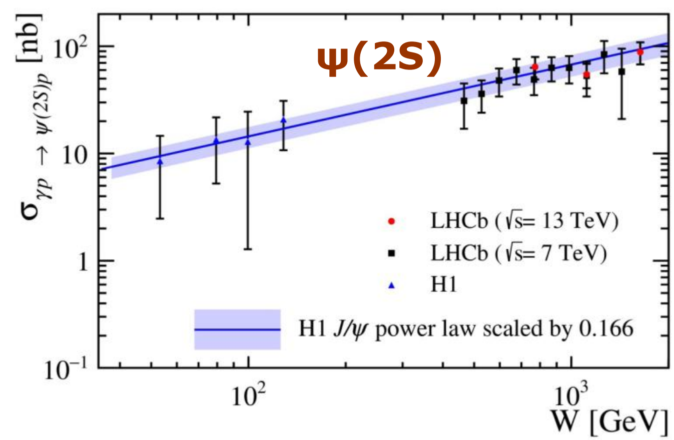




$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-).$$

r - gap survival factor, $\boldsymbol{k_\pm}$ - photon energy, $\boldsymbol{dn/dk_\pm}$ - photon flux, $\boldsymbol{W_\pm}$ - inv. mass of photon-proton system





- measured cross sections for *J/ψ* and *ψ(2S)* in better agreement with JMRT NLO
- derived cross section for *J/ψ* photoproduction differs from power-law extrapolation of H1 data

Conclusions

Inelastic *pp* cross-section in LHCb acceptance

- good agreement with results in other rapidity ranges

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

- measured correlation parameters slightly lower as compared to results in central η region
- LHCb shows a potential to perform a set of further quantum correlations analyses with different hadrons, collision energies, collision types etc.

Kinematic correlations for $b\bar{b}$ pairs at 7 and 8 TeV

- agreement with both PYTHIA (LO) and POWHEG (NLO) predictions
- larger samples needed for discrimination of theory predictions

Central exclusive production of J/ψ and $\psi(2S)$

- measured cross-section for J/ψ photoproduction differs from a power-law extrapolation of H1 data