Soft QCD and Central Exclusive Production at LHCb

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on behalf of the LHCb collaboration

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Outline

covered in this talk

	Collision Energy	Reference
Bose-Einstein correlation of same-sign charged pions	7 TeV	[*JHEP* (2017) 12:p. 025]
Total inelastic cross-section	13 TeV	[*JHEP* (2018) 06:p. 100]
Exclusive J/ψ and $\psi(2S)$ production	13 TeV	[*JHEP* (2018) 10:p. 167]

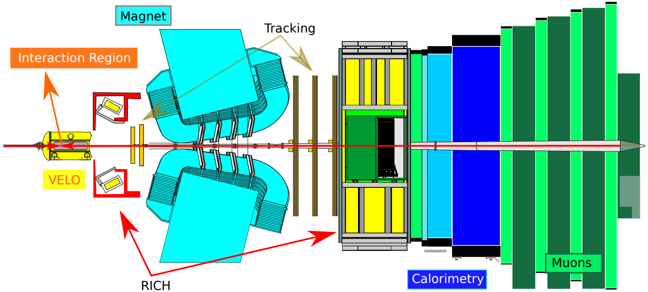
[*JINST* (2008) 3:S08005]

optimised to study decays of heavy flavour hadrons

- fully instrumented between $2.0 \leq \eta \leq 5.0$
- partial coverage between $-3.5 \leq \eta \leq -1.5$ (Velo)
- extended coverage at high rapidities in Run 2 (HeRSChel)
- excellent tracking, vertexing and PID capabilities
- average pile-up ~ 2

_pp_ datasets

Year	Energy	Lumi
2011	7 TeV	1.0 fb^{-1}
2012	8 TeV	2.0 fb^{-1}
2015-2018	13 TeV	6.0 fb^{-1}



Bose-Einstein Correlations

- 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
- Bose-Einstein Correlations (BEC) measured using same-sign pairs of pions in pp collisions at LHCb at 7 TeV

$$C_2(Q) = \frac{N^{data}(Q)}{N^{\text{ref}}(Q)}, Q = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4m^2}$$

$N^{\text{data}}(Q)$ - same-sign pion pairs in data

$N^{\text{ref}}(Q)$ - same-sign pairs in reference sample **without** BEC effect

- event mixed sample used as reference sample
  - pions from different events in data with same multiplicity mixed

BEC - Double Ratio

[*JHEP* (2017) 12:p. 025]

- correlation function described using Levy paramaterisation

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

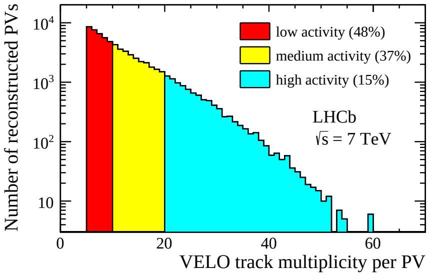
  R - radius, λ - chaoticity parameter, N - normalisation, δ - long range correlations

- construct double ratio of correlation function in data and MC

  $r_d = C_2(Q)^{data}/C_2(Q)^{MC}$

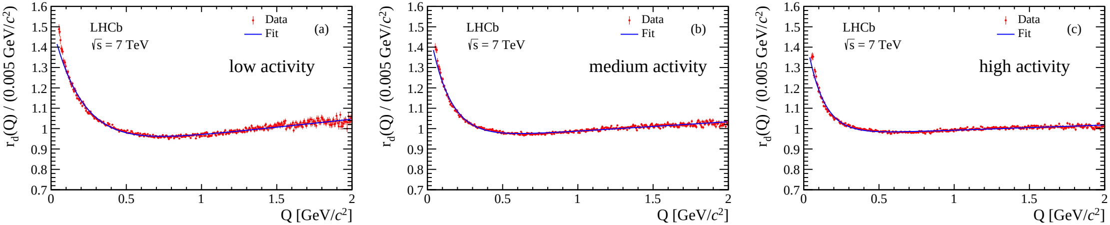
  - reduce possible imperfections in the construction of the reference sample
  - eliminate second order effects to large extent
  - correct for long range correlations

- parameters extracted from fit to r_d in three bins of event activity



BEC - Fits

- fit performed to double ratio in three bins of event activity

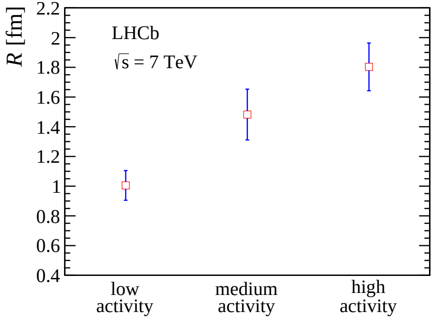


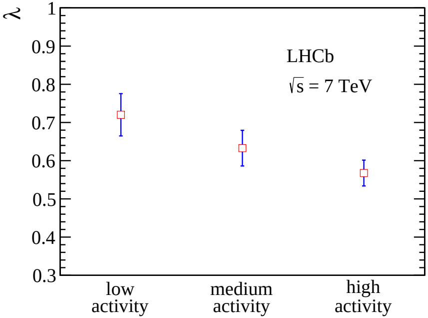
Activity	N_{ch}	R [fm]	λ	δ [GeV^{-1}]
Low	[8,18]	$1.01 \pm 0.01 \pm 0.10$	$0.72 \pm 0.01 \pm 0.05$	$0.089 \pm 0.002 \pm 0.044$
Medium	[19,35]	$1.48 \pm 0.02 \pm 0.17$	$0.63 \pm 0.01 \pm 0.05$	$0.049 \pm 0.001 \pm 0.009$
High	[36,96]	$1.80 \pm 0.03 \pm 0.16$	$0.57 \pm 0.01 \pm 0.03$	$0.026 \pm 0.001 \pm 0.010$

- systematic uncertainty ($\sim$ 10%) dominated by generator tunings and pile-up effects

BEC - Results

[*JHEP* (2017) 12:p. 025]

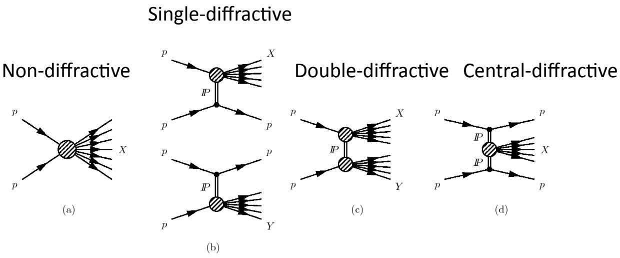




- source size increases with activity, while chaoticity decreases
- comparable trend with previous observations at LEP and the LHC
- parameters in forward region slightly lower than ATLAS [*Eur. Phys. J.* (2015) C75:p. 466], however comparison not straightforward
- full 3D analysis required to perform more detailed comparison

Measurement of the inelastic cross-section at 13 TeV

[*JHEP* (2018) 06:p. 100]



- the inelastic *pp* cross-section is a fundamental quantity in the phenomenology of high energy hadronic interactions
- measured in the forward region at LHCb using 10.7 nb^{-1} of data collected in 2015 at 13 TeV
  - unbiased triggers rejecting backgrounds from previous crossing
- Events selected containing at least one long-lived charged particle (mean lifetime > 30 ps)
  - $p > 2$ GeV, $2 < \eta < 5$

Inelastic Cross-section - Extrapolation to full phase space

[*JHEP* (2018) 06:p. 100]

- cross-section in forward acceptance defined as

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

  N_{evt} - total number of recorded events

  $\mu - \mu_{bkg}$ - average number of interactions per crossing

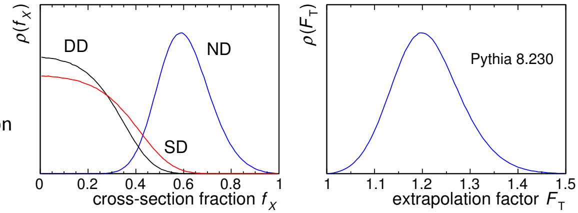
  $\sigma_{acc}(\sqrt{s} = 13\,\text{TeV}) = 62.2 \pm 2.5(\text{exp})\text{mb}$

- extrapolation to full phase space performed using simulation

  $$\sigma_{\text{inel}} = F_{\text{T}} \cdot \sigma_{\text{acc.}} = \sum_X \sigma_X \ , X \in \{ND, SD, DD\}$$

  $$F_{\text{T}} = \frac{1}{\sum_X f_X v_X}$$

- f_X - fraction of inelastic cross-section obtained with MC using data constraint
- v_X - visible interactions inside acceptance



Inelastic Cross-section - Results

[*JHEP* (2018) 06:p. 100]

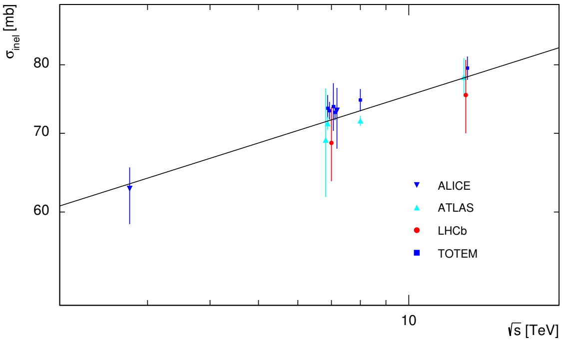
- Measurement of inelastic cross-section performed at 13 TeV

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

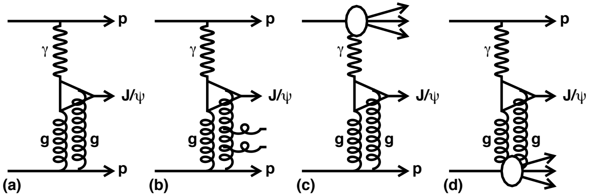
- Measurement at 7 TeV updated with improved luminosity determination (3.5% to 1.7%)

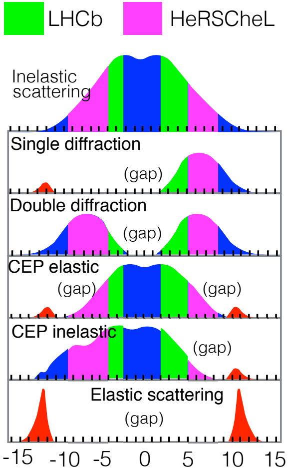
  $\sigma_{\text{inel.}}(\sqrt{s} = 7\,\text{TeV}) = 68.7 \pm 2.1(\text{exp.}) \pm 4.5(\text{extr})\text{mb}$

- experimental uncertainty dominated by luminosity, total by extrapolation uncertainty



Exclusive J/ψ and $\psi(2S)$ production

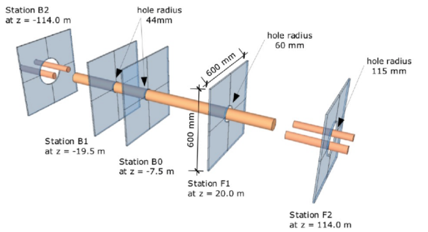


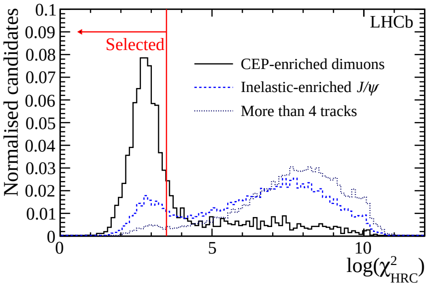


- Central Exclusive Production - exchange of neutral, colourless particles - protons remain intact
- powerful tool to probe the pomeron and constrain the gluon PDF
  - exclusive J/ψ, Υ production cross-section $\propto (xg(x, \bar{Q}^2))^2$
- experimental signature - events with just two muon tracks in the final state
- LHCb is ideal environment to perform measurements
  - relatively low number of pile-up collisions
  - backward VELO coverage can be exploited to identify rapidity gap

HeRSCheL

[*JINST* (2018) 13:P04017]

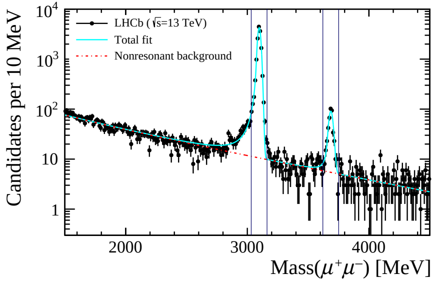


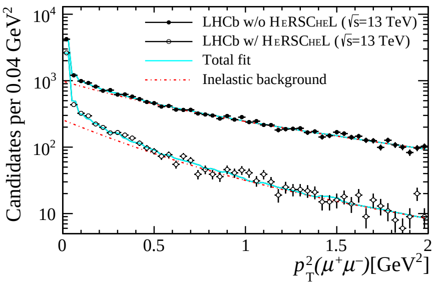


- High Rapidity Shower Counters for LHCb (HeRSCheL) installed ahead of Run-II
- Extends LHCb coverage into very forward region
  - Detect showers from high rapidity particles interacting with the beam pipe
  - Reject inelastic backgrounds where proton disassociates
- observable χ^2_{HRC} quantifies the activity above noise, including correlations between counters

CEP J/ψ and $\psi(2s)$ - selection

[*JHEP* (2018) 10:p. 167]

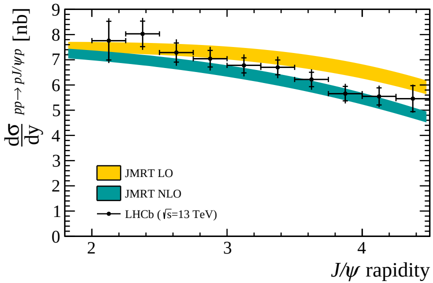


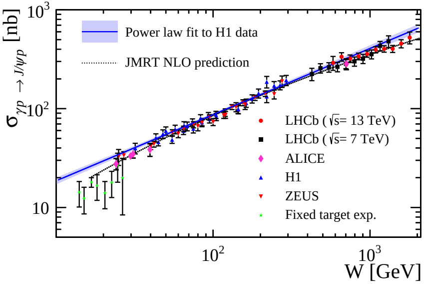


- two reconstructed muons in event
  - no additional tracks or energy in event
- low activity in HeRSCheL, $p_T^2 < 0.8$ GeV^2
- inelastic background determined using fit to p_T^2
  - shapes determined using data-driven methods

[*JHEP* (2018) 10:p. 167]

CEP J/ψ and $\psi(2s)$ - results





- good agreement with next-to-leading-order JMRT prediction
- measured cross-section can be related to photoproduction cross-section $\sigma_{\gamma p} \rightarrow J\psi p$ and compared to other experiments
  - W - invariant mass of proton-photon system
- J/ψ results show deviation from pure power-law extrapolation of H1 data
- $\psi(2S)$ results are consistent within statistics

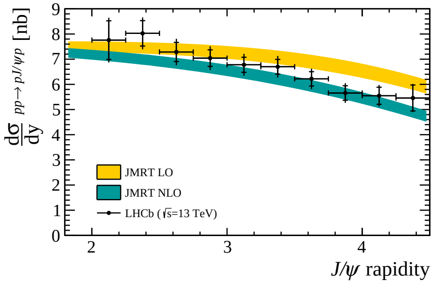
Conclusion

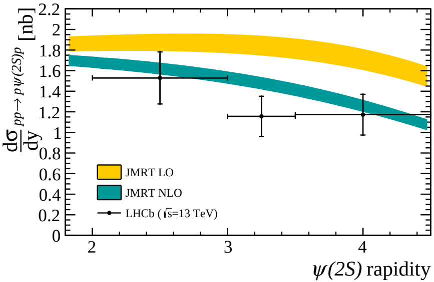
- Bose-Einstein correlation of same-sign charged pions
  - same trends observed as other experiments
  - full 3D analysis required to perform a detailed comparison
- Inelastic pp cross section
  - improved result at $\sqrt{s} = 7$ TeV
  - total inelastic cross section at $\sqrt{s} = 13$ TeV compatible with other experiments
- exclusive J/ψ and $\psi(2S)$ production cross-sections measured in pp data with $\sqrt{s} = 13TeV$
  - better understanding of the backgrounds with respect to previous measurements thanks to HeRSCheL

backup

CEP J/ψ and $\psi(2s)$ - results

[*JHEP* (2018) 10:p. 167]





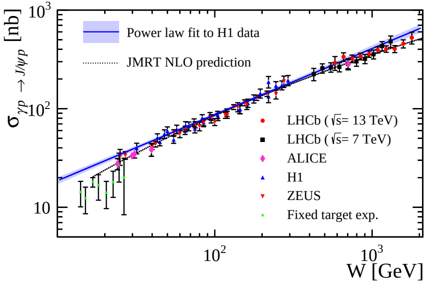
$$\sigma_{J/\psi\to\mu\mu}(2.0 < \eta_\mu < 4.5) = 300 \pm 16 \pm 10 \pm 16$$

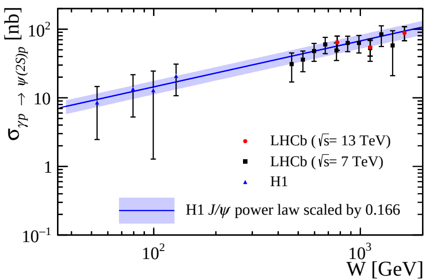
$$\sigma_{\psi(2s)\to\mu\mu}(2.0 < \eta_\mu < 4.5) = 10.2 \pm 1.0 \pm 0.3 \pm 0.4$$

- good agreement with next-to-leading-order JMRT prediction

Photoproduction Cross-section

[*JHEP* (2018) 10:p. 167]





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

- measured cross-section can be related to photoproduction cross-section $\sigma_{\gamma p} \to J\psi p$ and compared to other experiments
- J/ψ results show deviation from pure power-law extrapolation of H1 data
- $\psi(2S)$ results are consistent within statistics