LHCb Results on Central Exclusive Production

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on behalf of the **LHCb Collaboration**

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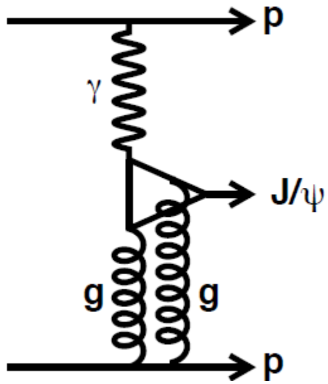
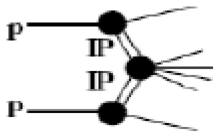


Outline

- ❑ Central Exclusive Production
- ❑ How to catch a CEP event – The gap
- ❑ Story so far and the latest results
- ❑ Future plans
- ❑ Summary

Central Exclusive Production @LHCb



CEP – definition

- Central exclusive production can be denoted qualitatively as follows

$$h_1(p_1) + h_2(p_2) \to h_1(p_1') \oplus \boldsymbol{X} \oplus h_2(p_2')$$

- Interacting hadrons do not undergo any „catastrophic process" (such dissociation) instead they interact via exchanging a colourless object and **remain intact**

- However, they **lose energy** in order to produce the final system ***X*** that can be **observed in the detector**

- **„⊕"** denotes symbolically the rapidity gaps
  - **Only** the central system is produced, apart from that there should be no **activity otherwise**, thus, **exclusive** process

- In principle four-momenta of the scattered hadrons (protons) can be measured by very forward detectors

- In case of the LHCb both protons remain un-tagged

Central Exclusive Production @LHCb

- Exclusive processes are at the heart of QCD

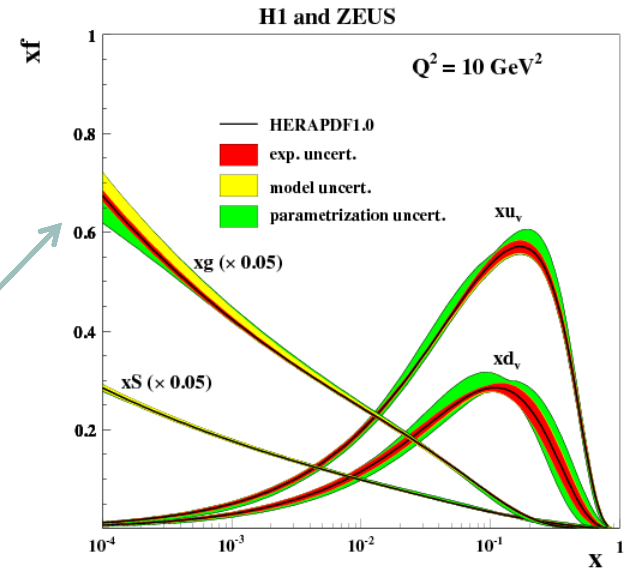
- May help **improve understanding of soft scale** (non-perturbative) QCD

    - Actually almost all interesting things happen here (composite hadrons we observe)

- Studying **pomeron** interactions
- Search for oderon

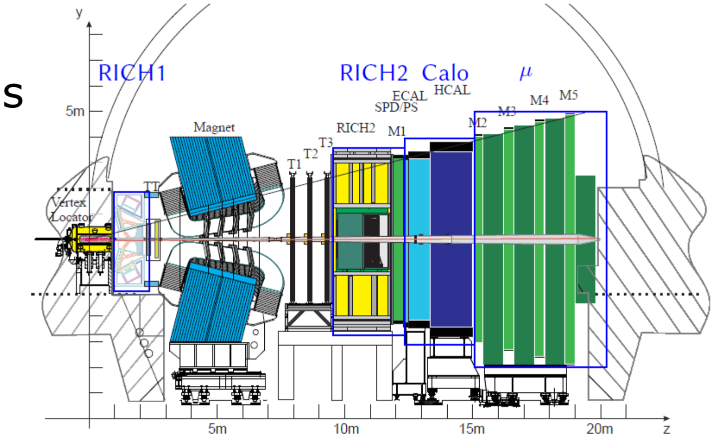
- Improve knowledge on low-**x** behavior of parton PDF

    - Sharp rise of gluon PDF for decreasing **x**
    - LHCb is sensitive to the gluon PDF down to **x** ~ $5 \cdot 10^{-6}$
    - Studying saturation (BFKL evolution)
    - Help understand in general processes such gg → X (gg → H)



Introduction – LHCb detector

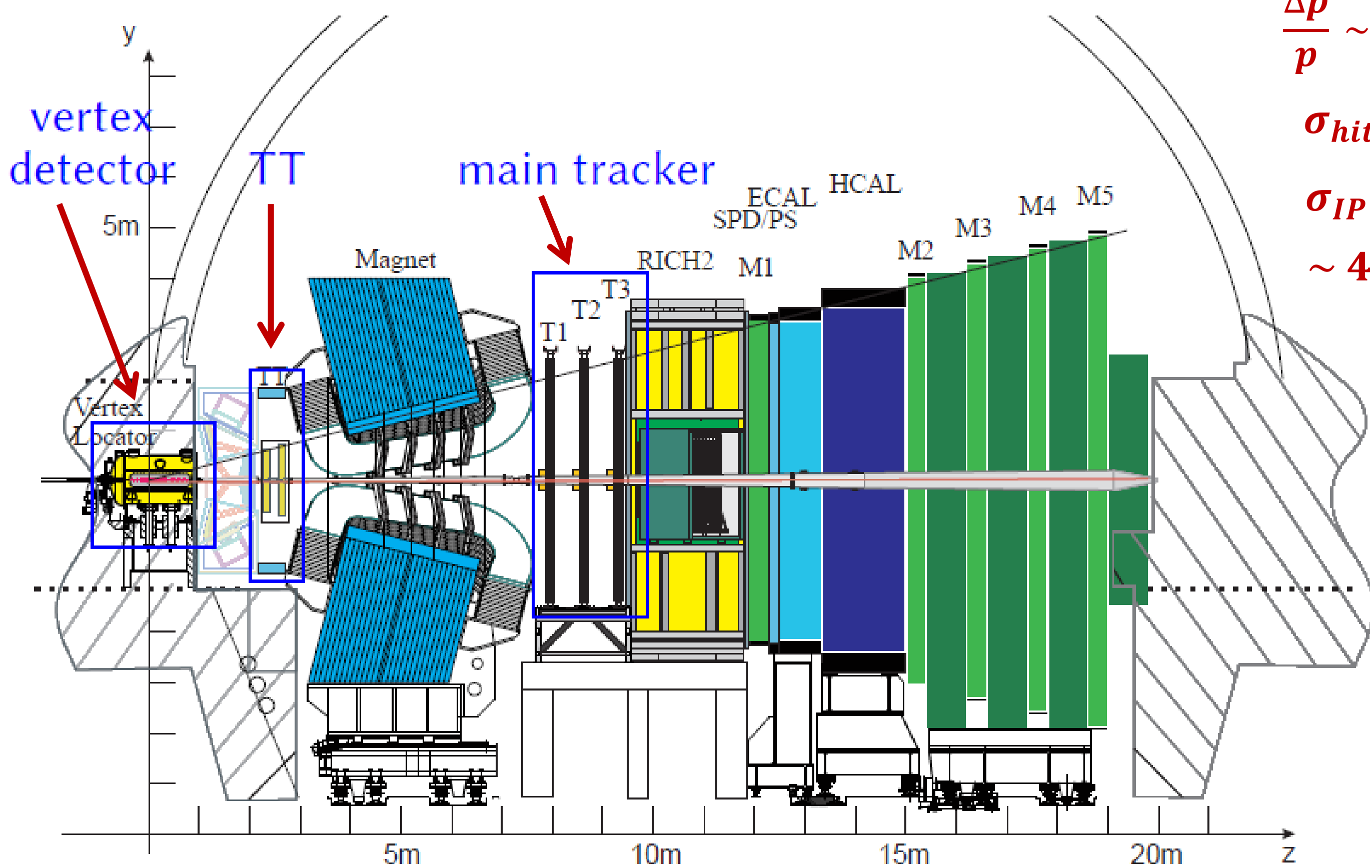
- **LHCb** is dedicated for studying **heavy quark flavour physics**
- It is a **single arm forward spectrometer** (**$2 < \eta < 5$**)
- Excellent tracking capabilities provided by:
  - Vertex detector **VELO**
  - Upstream and downstream tracking stations
  - 4 Tm warm dipole magnet



- Particle identification done by:
  - RICH detectors
  - Calorimeters
  - Muon stations
- Partial information from calorimeters and muon system contribute to **L0 trigger** (hardware) that works at LHC clock – **40 MHz**
- **Full** detector readout at **1 MHz**

Introduction – LHCb detector

- Tracking system – precise momentum reconstruction, vertexing, decay time resolution
- Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert



$\frac{\Delta p}{p} \sim 0.5 - 1.0\ \%$

$\sigma_{hit} \approx 4\ \mu m$

$\sigma_{IP} \approx 13\ \mu m$

$\sim 40 - 50\ fs$

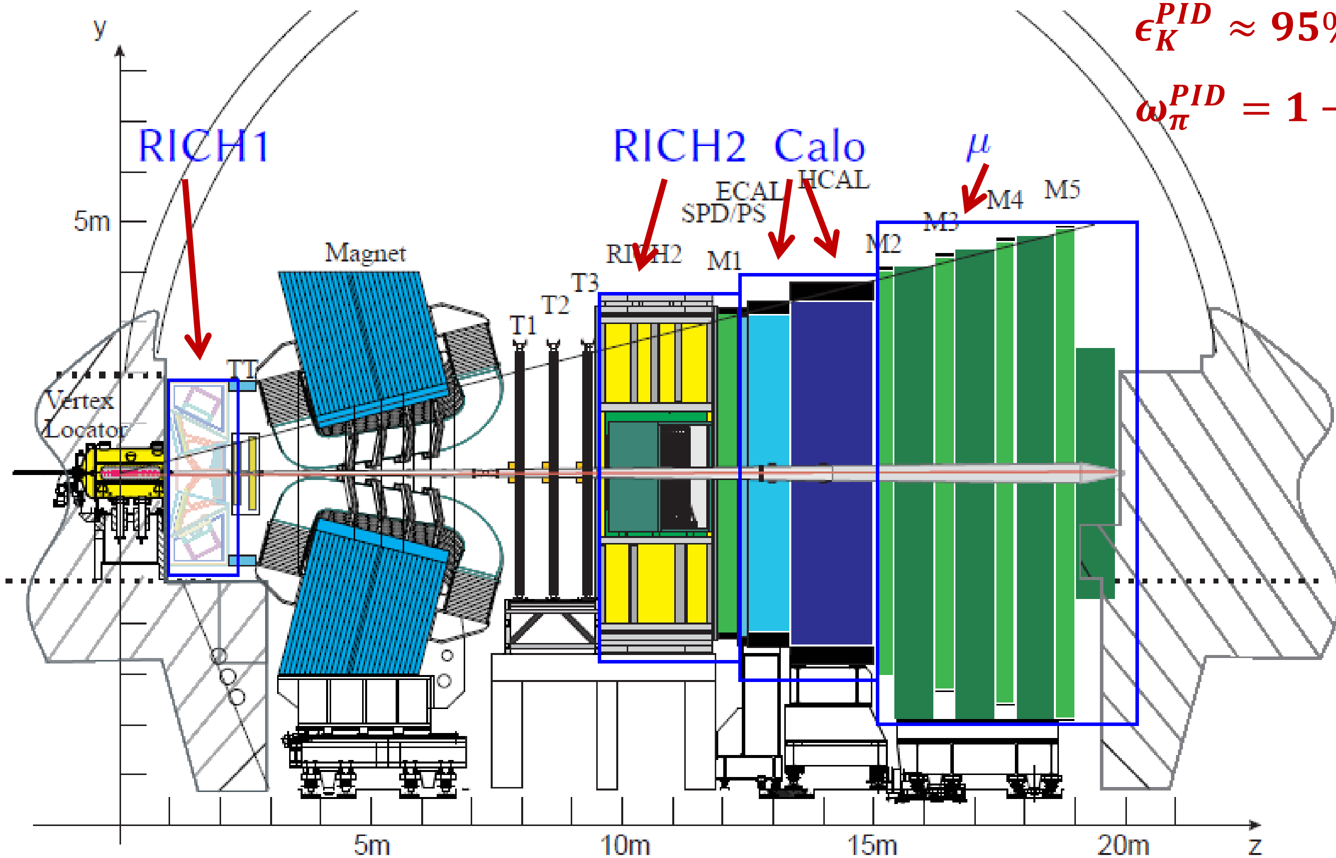
[JINST 3 (2008) S08005]

Introduction – LHCb detector

- ❑ Tracking system – precise momentum reconstruction, vertexing, decay time resolution
- ❑ Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert

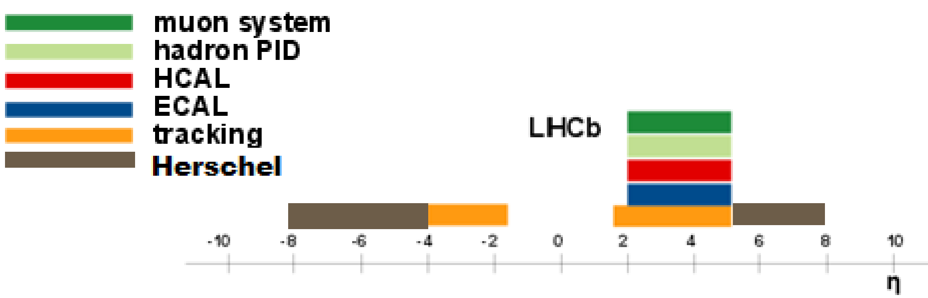
$\epsilon_K^{PID} \approx 95\%$

$\omega_\pi^{PID} = 1 - \epsilon_\pi^{PID} \approx 10\%$

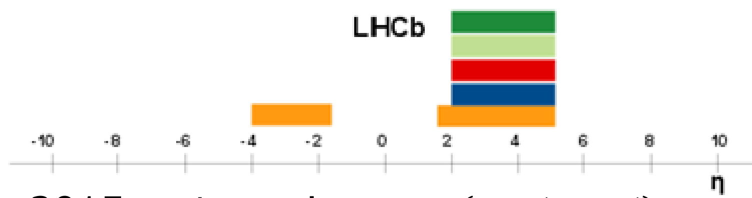


[JINST 3 (2008) S08005]

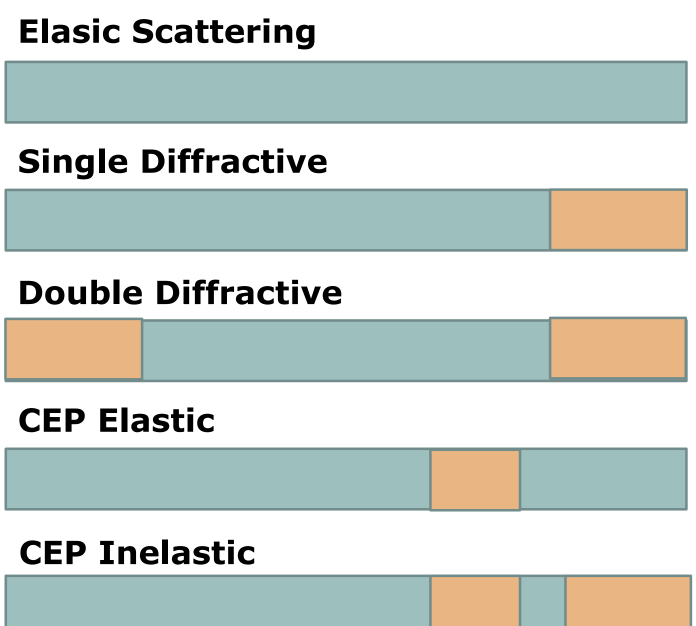
The Gap…

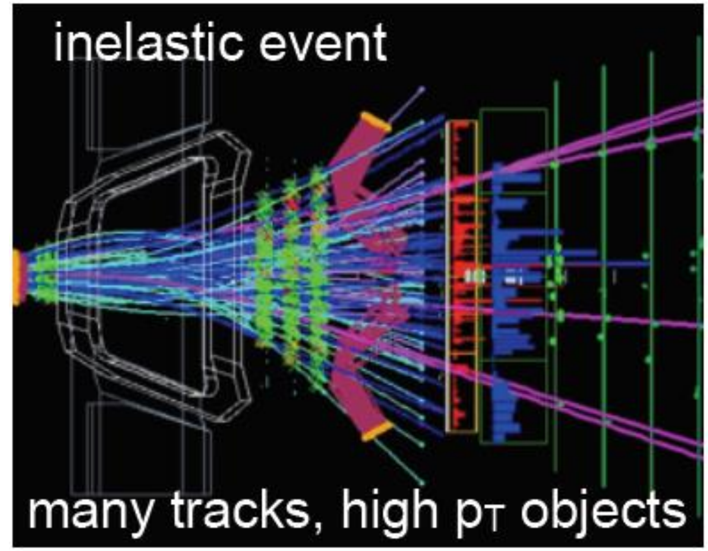


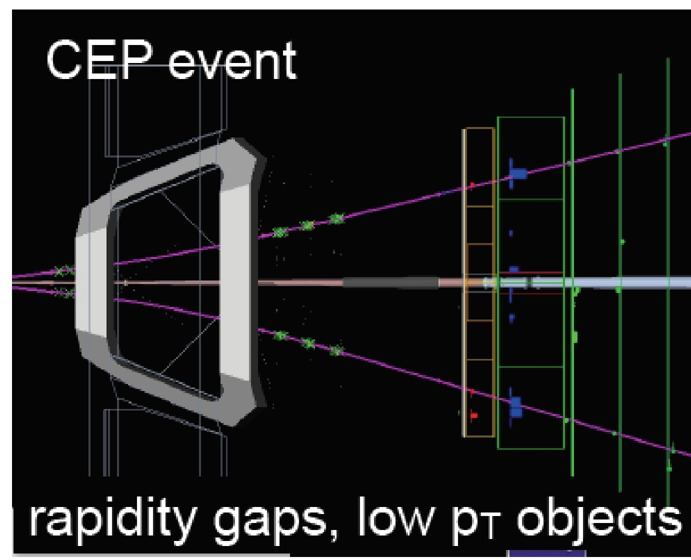
> 2015, veto region $\eta \in (-8,-1.5), (5,8)$



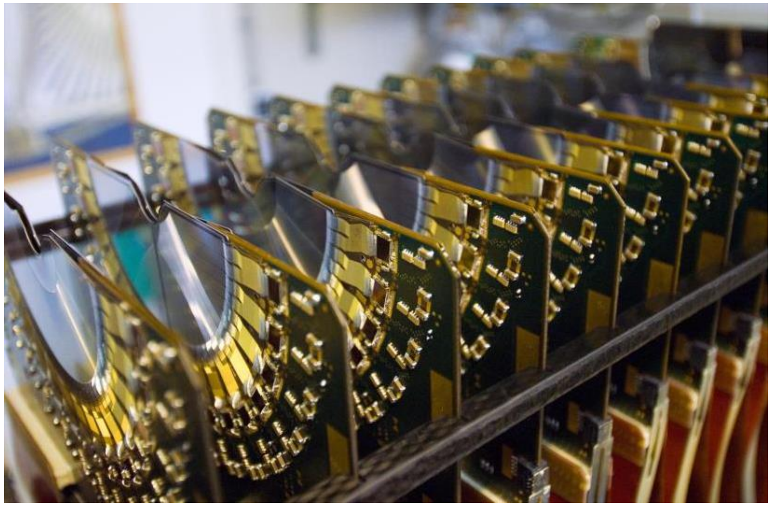
< 2015, veto region $\eta \in (-3.5,-1.5)$

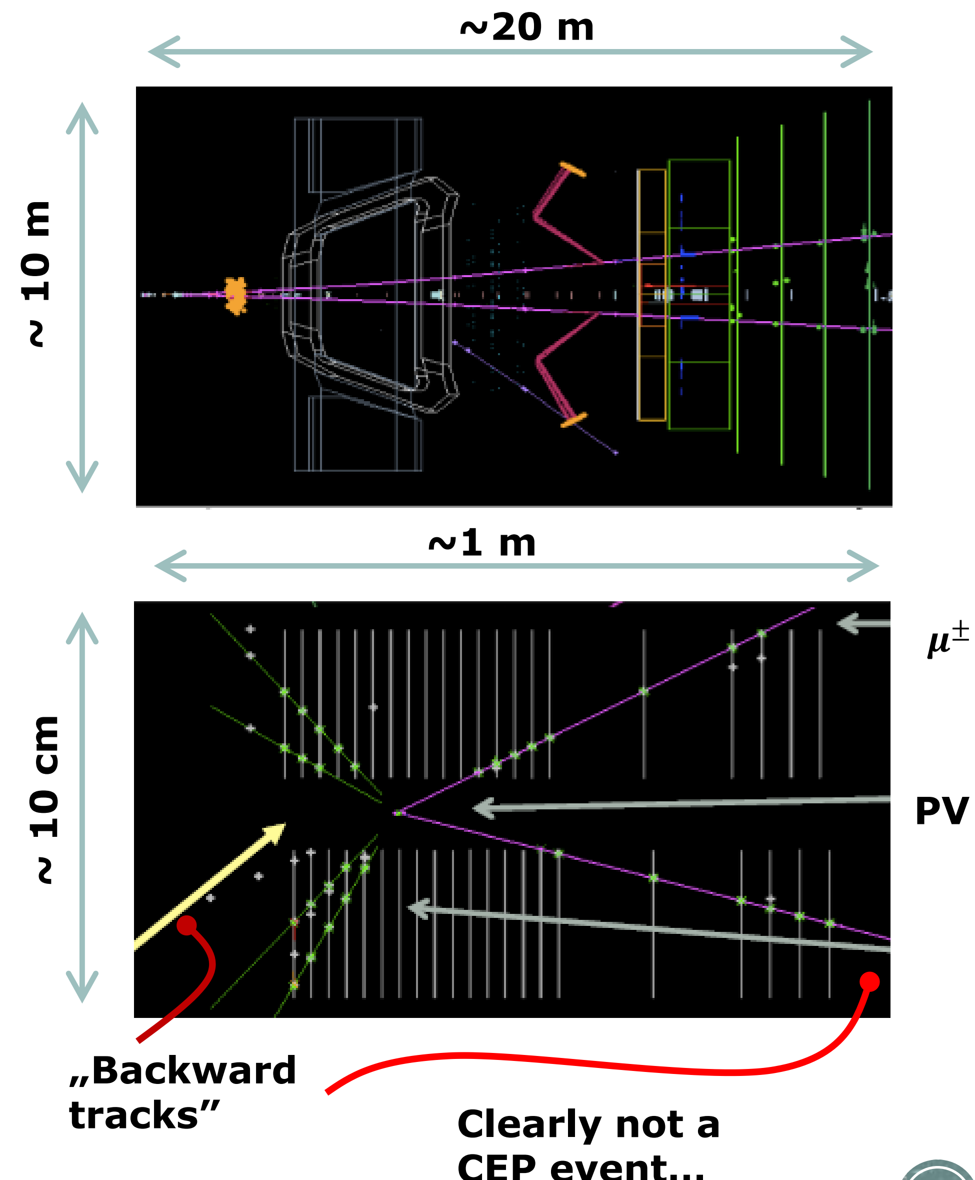






The LHCb Gap explorers: VELO



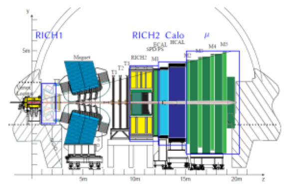


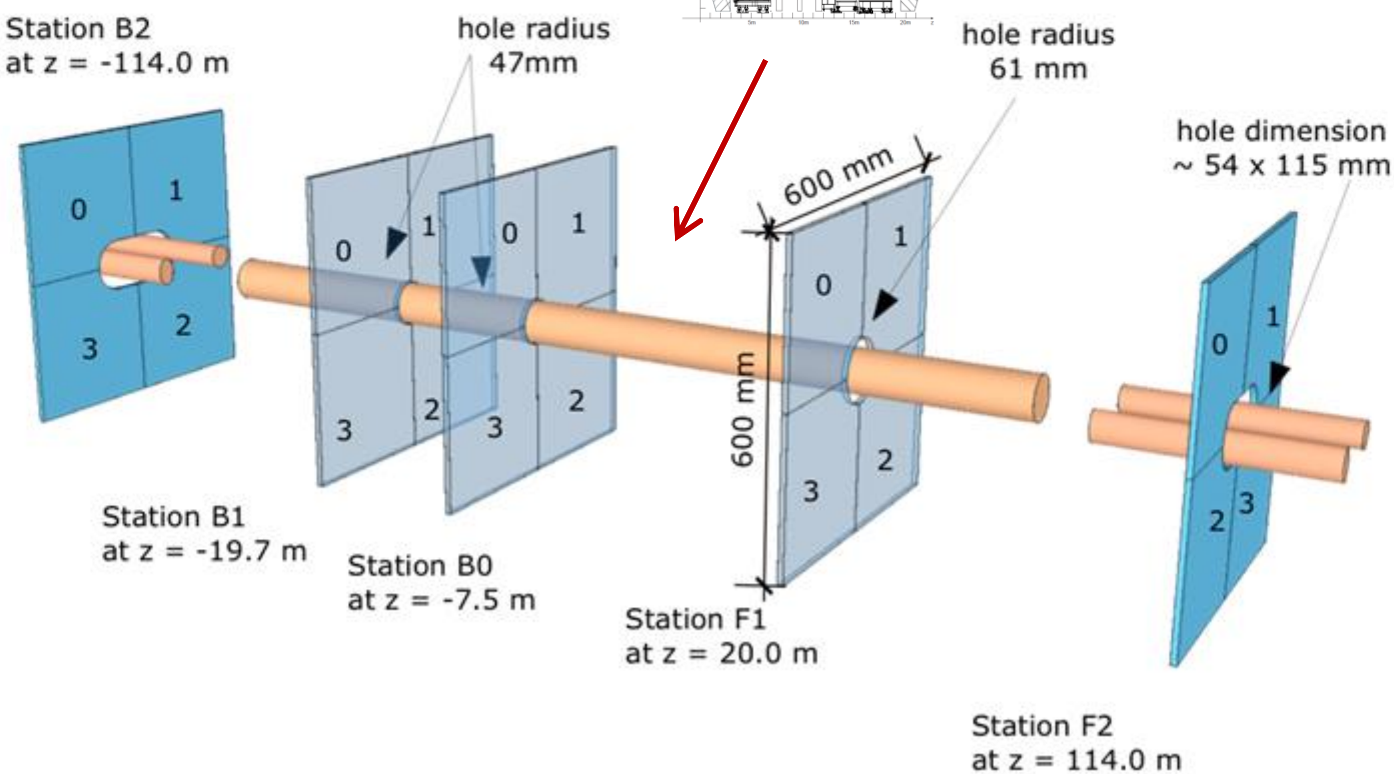
- **VErtex LOcator (VELO)**
  - 84 micro-strip silicon sensors close to the IR
  - Precise track and vertex reconstruction
  - The best single hit spatial resolution at LHC
  - Allows for **backward track reconstruction**
  - No momentum information for backward tracks

The LHCb Gap explorers: Herschel

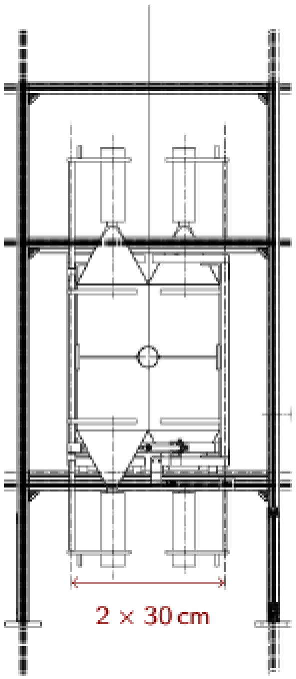
High **R**apidity **S**hower **C**ounters for **L**HCb

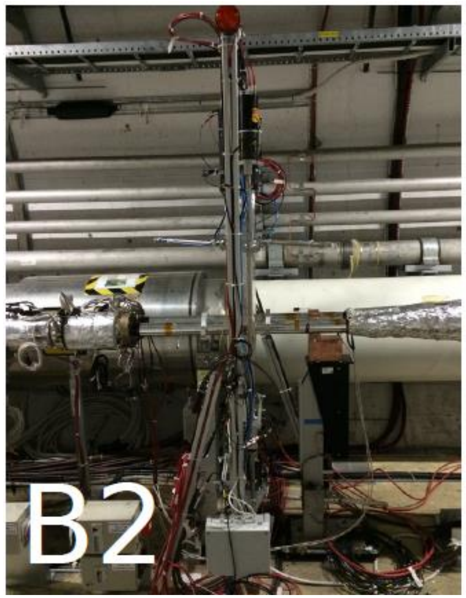
- 5 stations containing 4 scintillators with PMT
- Used to detect particle showers coming from the primary vertices (PVs)
- Roughly ~ 500 hits per station

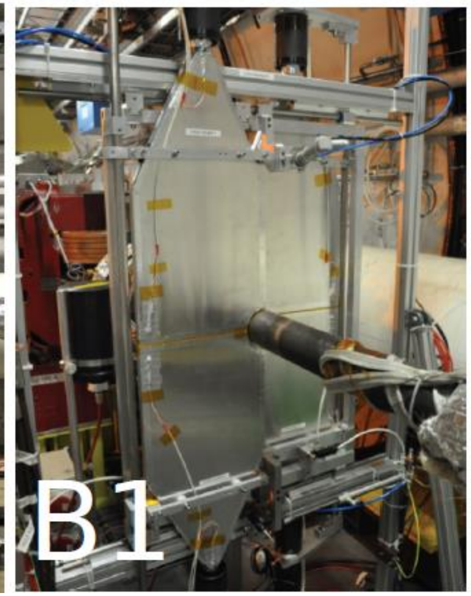




The LHCb Gap explorers: Herschel

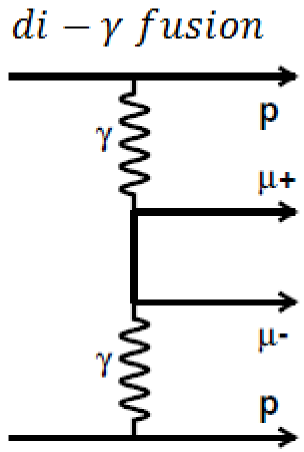


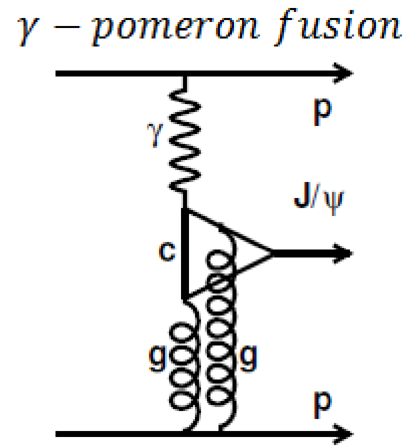


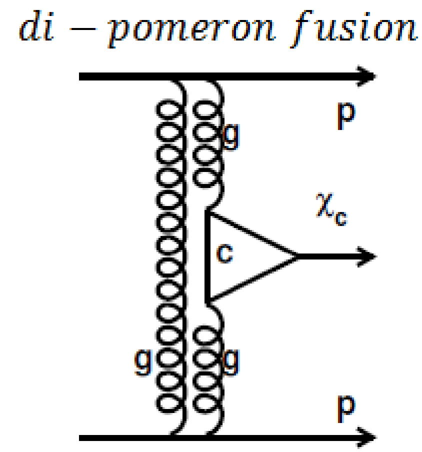


- ❑ Stations are instrumented with a pneumatic motion system
- ❑ Can be retracted and parked when no data taking
- ❑ Installed and integrated into the LHCb DAQ at the end of 2014

CEP with di-muon final state







- Elastic scattering with intact and un-tagged protons
    - Two muons (a gamma) and rapidity gaps
- Proceed via exchange of colourless objects (γ, pomeron)
- Studied in detail by theorists

    - **LPAIR** (**A.G Shamov and V.I Telnov, NIM A, 494 (2002), 51**)
    - **STARlight** (**S.R. Klein and J. Nystrand, Phys. Rev. Lett., 92 (2004), 142003**)
    - **SuperChiC** (**L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C, 65 (2010), 433**)

CEP analyses for Run I data samples

- Central Exclusive Production of J/ψ and $\psi(2S)$

Data-taking year	Energy	Integrated Luminosity	Paper
2010	7 TeV	$37 pb^{-1}$	JPG 40 (2013) 045001
2011	7 TeV	$930 pb^{-1}$	JPG 41 (2014) 055002

- Central Exclusive Production of $\Upsilon(nS)$

Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	$945\ pb^{-1}$	JHEP 09 (2015) 084
2012	8 TeV	$1985\ pb^{-1}$	

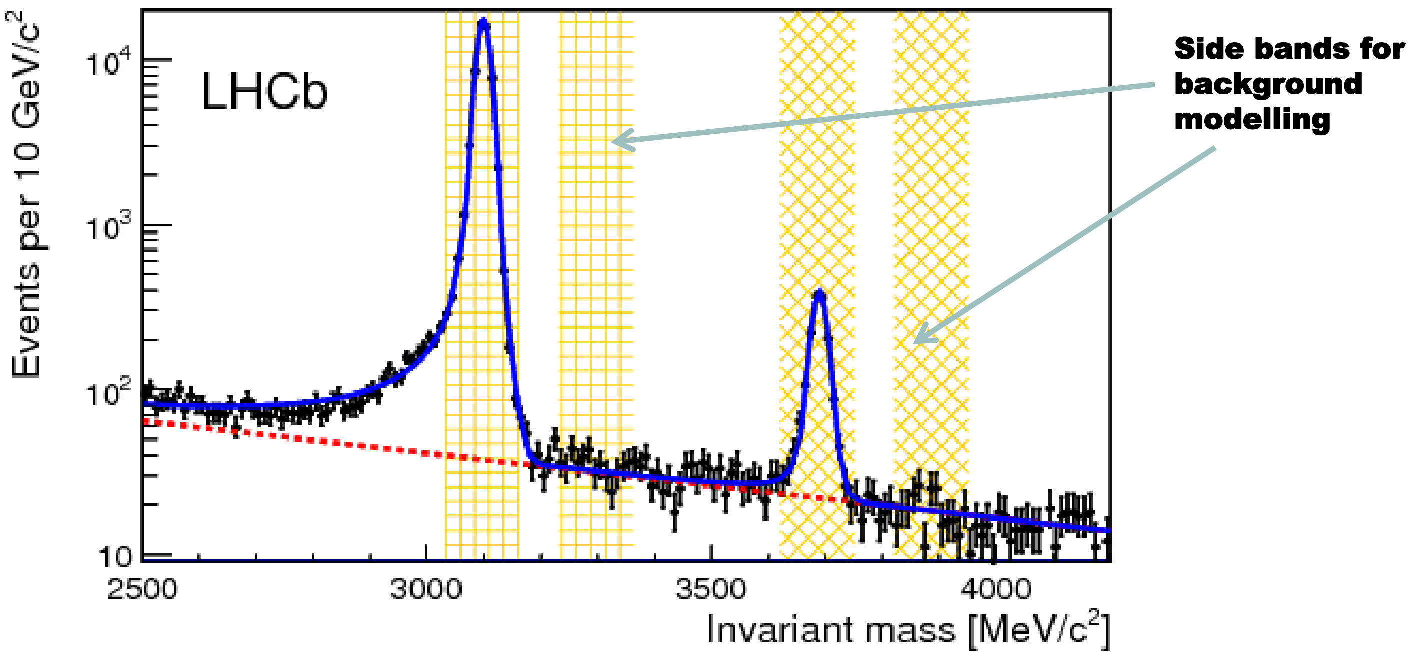
- Double Charmonia Production

Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	$945\ pb^{-1}$	JPG 40 (2013) 045001
2012	8 TeV	$1985\ pb^{-1}$	

Signal selection

- Low level (hardware) trigger L0
  - a muon candidate, p_T > 400 MeV
  - a di-muon candidate, p_T > 80 MeV (each track)
- Software HLT (High Level Trigger)
  - a di-muon candidate p_T < 800 MeV
  - M(di-muon) > 2.7 GeV
- Offline selection
  - both muons within LHCb acceptance ($2.0 < \eta < 4.5$)
  - no photons, no backward tracks (VELO veto)
  - mass window for a di-muon $\Delta M = 65$ MeV around expected J/ψ or $\psi(2S)$ mass

Selected signal (2011)



- Model of the mass spectra
  - Signal peak – Crystal-Ball function
  - Background – exponential

- Observed events

  - **55895** exclusive J/ψ and **1565** exclusive ψ(2S) – **2011**

J. Phys. G 41 (2014) 055002

Cross-section measurement

- **Differential cross-section times branching fraction** to two muons with pseudorapidity defined by the LHCb angular acceptance

- Measured in bins of meson rapidity **y**

p – Purity

- **Non-resonant background (1%/17%)**
- **Feed-down background (10%/2%)**
- **Inelastic background (40%/40%)**

N_i – Number of events in a given rapidity bin

$$\left(\frac{d\sigma}{dy}\right)_i = \frac{1}{\varepsilon_{single}\mathcal{L}} \frac{pN_i}{\varepsilon_i \Delta y}$$

ε_{single} – Selection of events with one p-p interaction per crossing

- **This follows very well the Poisson distribution (~ 21%)**

$\mathcal{L}$ – Sample integrated luminosity

ε_i – Efficiency:

- **Trigger (L0+HLT)**
- **Tracking**
- **Muon PID**
- **Signal selection**

Total efficiency varies from 0.66 to 0.89 depending on rapidity bin

Purity estimation: feed-down component

- The source of this background is exclusive production of other mesons

- Mainly problem for selecting J/ψ events

- Decays **ψ(2S)** $\rightarrow$ **J/ψ X**, where **X** is not detected

  - Can be significantly suppressed by hard 2 track only cut
  - Estimated using STARlight model
  - **(2.5 ± 0.2)** % of selected J/ψ events

- Radiative decays $\boldsymbol{\chi_c} \rightarrow$ **J/ψ γ**, where **γ** goes undetected

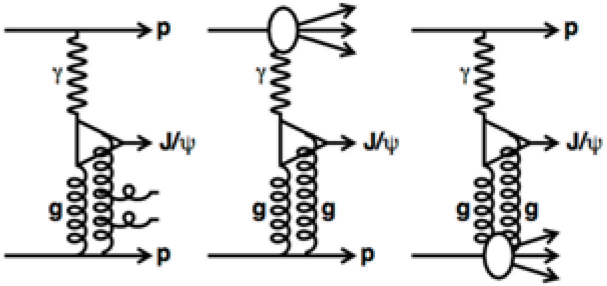
  - Suppressed by requiring no photons
  - Estimated using SuperChiC model
  - **(7.6 ± 0.9)** % of selected J/ψ events

- Feed-down to ψ(2S) is expected to be small - coming from **X(3872)**

  - Results based on studies involving photon veto in selection algorithm gave **(2.0 ± 0.2)** % of selected ψ(2S) events

Purity estimation: inelastic scattering

- This is the dominant background



- In general harder p_T spectrum of produced J/ψ is expected
- Was estimated using collision data (e.g., 2011 sample)
  - **(34 ± 6)** % for J/ψ events
  - Similar estimate is assumed for ψ(2S)
- Overall purities:
  - **(59.2 ± 1.2)** % for J/ψ events
  - **(52.0 ± 7.0)** % for ψ(2S) events
  - **p_T < 0.8 GeV²**

Run I results: $J/\psi \to \mu\mu$ and $\psi(2S) \to \mu\mu$ production

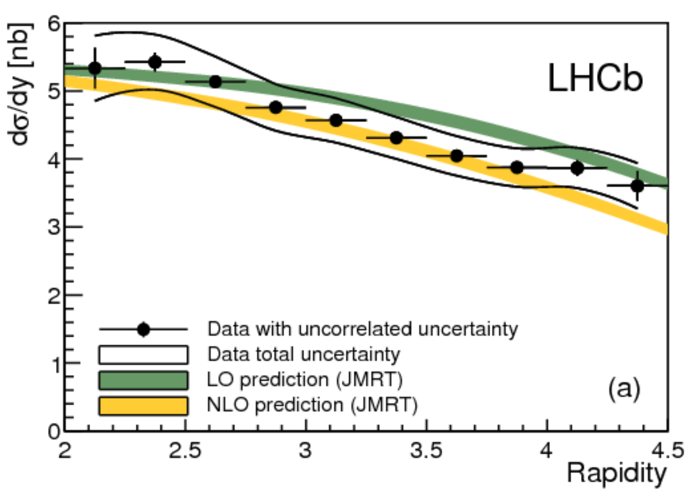
- Integrated cross-sections

$$\boxed{\sigma_{J/\psi\to\mu^+\mu^-}(2.0 \le \eta(\mu^\pm) < 4.5) = 291.0 \pm 7(\text{stat}) \pm 19(\text{sys})\ \text{pb}}$$

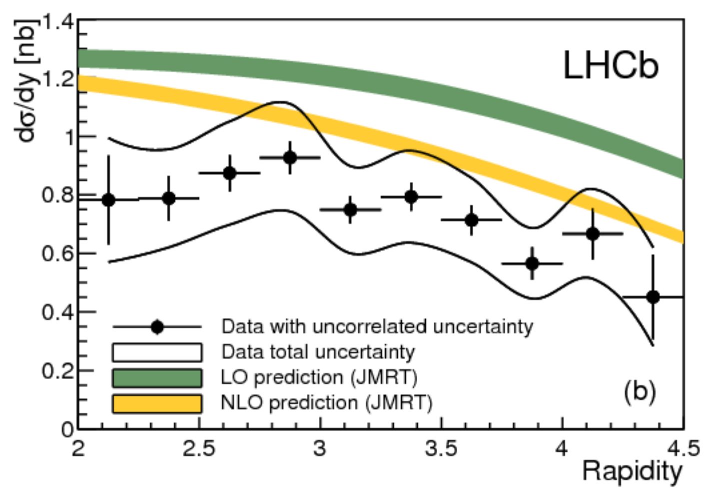
$$\boxed{\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 \le \eta(\mu^\pm) < 4.5) = 6.7 \pm 0.9(\text{stat}) \pm 0.4(\text{sys})\ \text{pb}}$$

- Differential cross-sections

J/ψ



Ψ(2S)

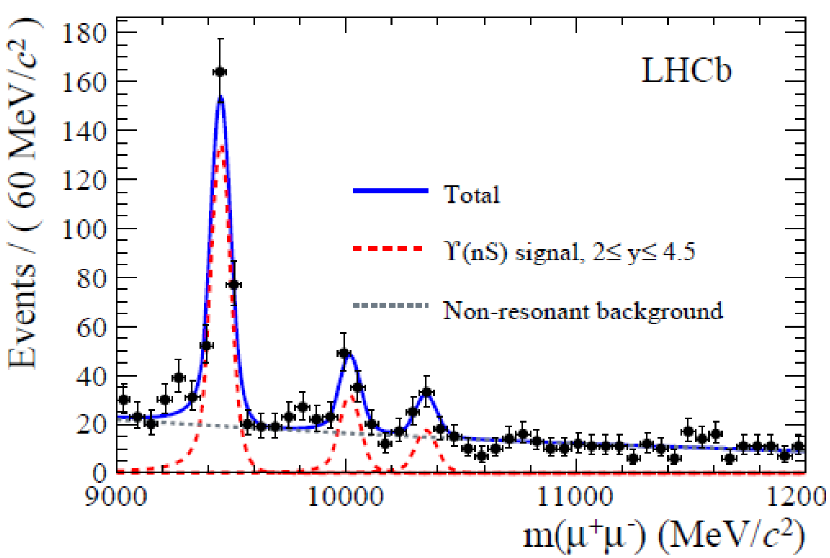


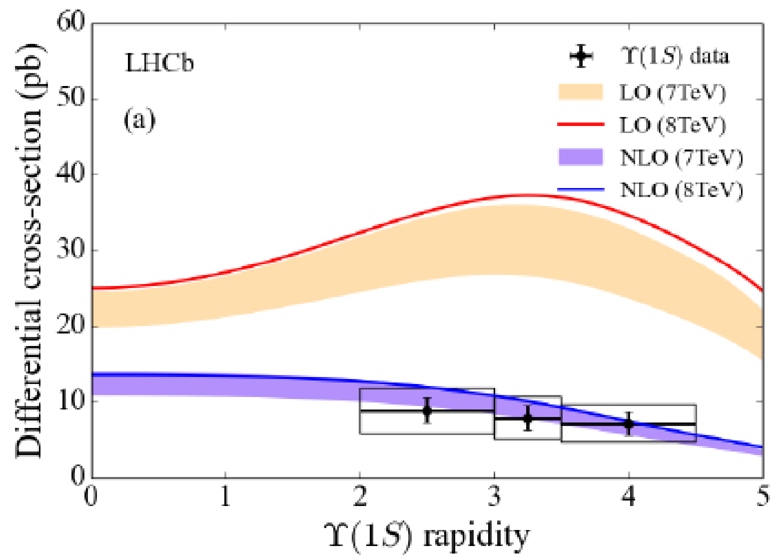
[arXiv:1401.3288, J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002]

Run I results $\Upsilon(nS)$ production

- Also, more recently LHCb performed first observation of $\Upsilon(nS)$ via CEP processes ($\mathcal{L}_{int} = 2.9\ \mathrm{pb}^{-1}$)
- $\Upsilon(nS)$ were reconstructed using di-muon decay channel and kinematical range defined by $2 \leq y(\Upsilon) < 4.5$ and $2 \leq \eta(\mu^{\pm}) < 4.5$
- In case of $\Upsilon(3S)$, due to significant $\eta_b(3P) \to \Upsilon(3S) + \gamma$ contamination, only the upper limit for the production cross-section determined

$$\boxed{\begin{aligned} \sigma(pp \to p\Upsilon(1S)p) &= 9.0 \pm 2.1 \pm 1.7\ \mathrm{pb} \\ \sigma(pp \to p\Upsilon(2S)p) &= 1.3 \pm 0.8 \pm 0.3\ \mathrm{pb} \end{aligned}}$$

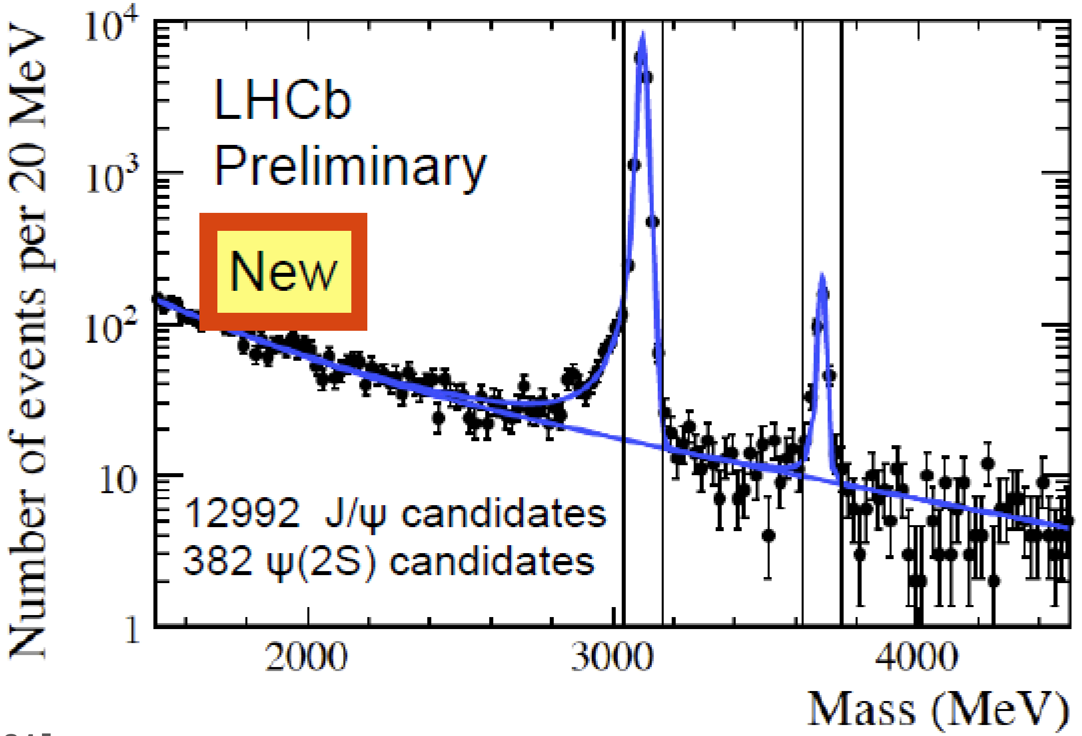




[arXiv:1505.08139, JHEP 1509 (2015) 084]

New results from Run II @13 TeV (2015)

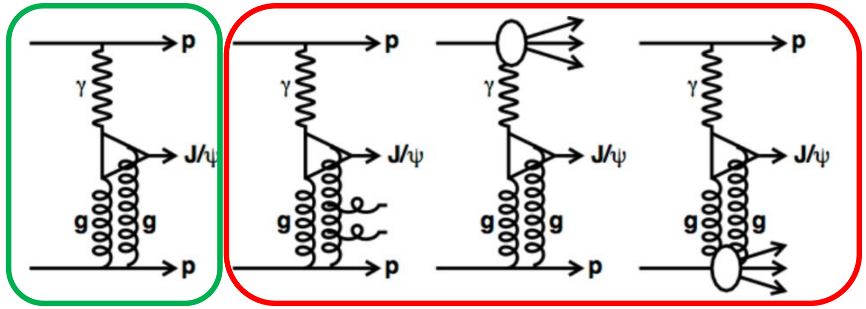
- New analysis using 200 pb^{-1} of data recorded at $\sqrt{s} = 13\ \mathrm{TeV}$
- Selection of candidates:
  - two muons with $\eta \in (2, 4.5)$
  - No additional activity in the detectors (tracks, Energy deposites)
  - Di-muon mass, $\mathrm{m}_{\mu\mu}$, within 65 MeV of $m_{J/\psi}$
  - **Herschel VETO (NEW!)**



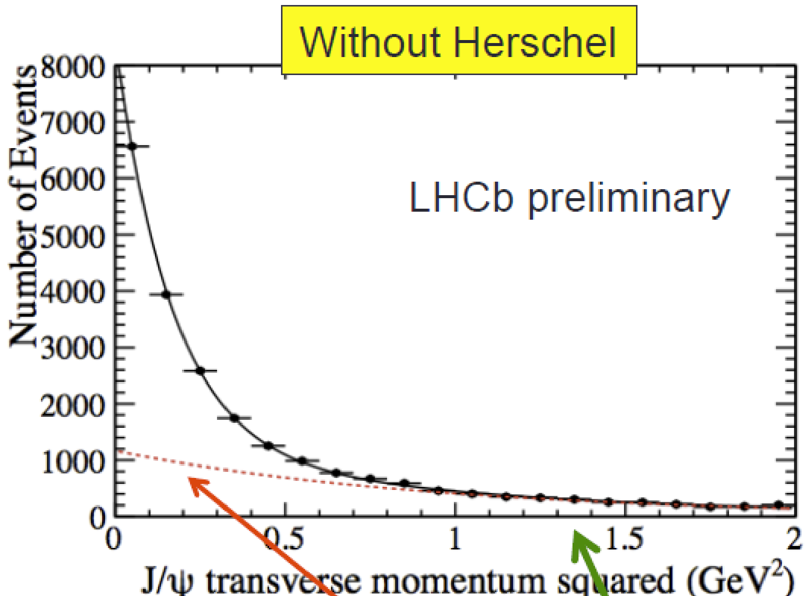
[LHCb-CONF-2016-007-001]

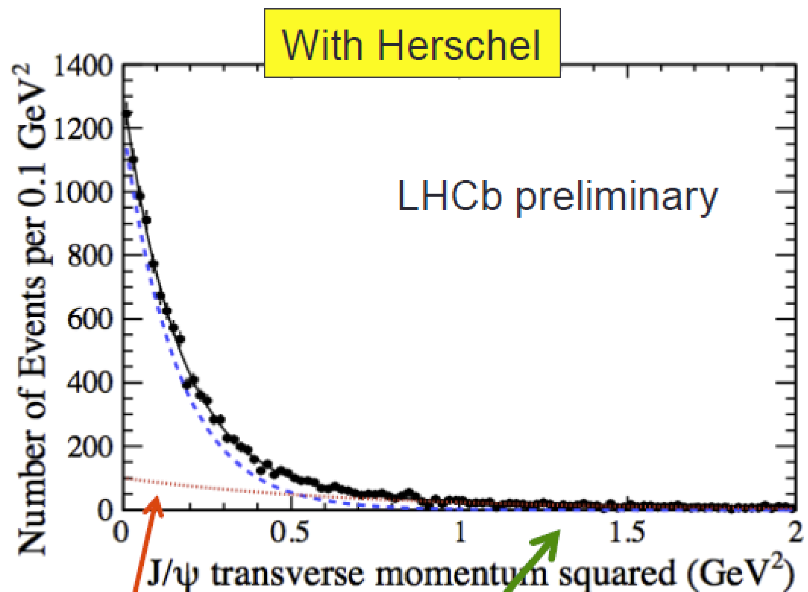
New results from Run II @13 TeV - background

Signal



Background





[LHCb-CONF-2016-007-001]

Estimate of proton dissociation background

Strong suppression of non-elastic events

Background ~ halved relative to previous analysis!!

New results from Run II @13 TeV – corss sections

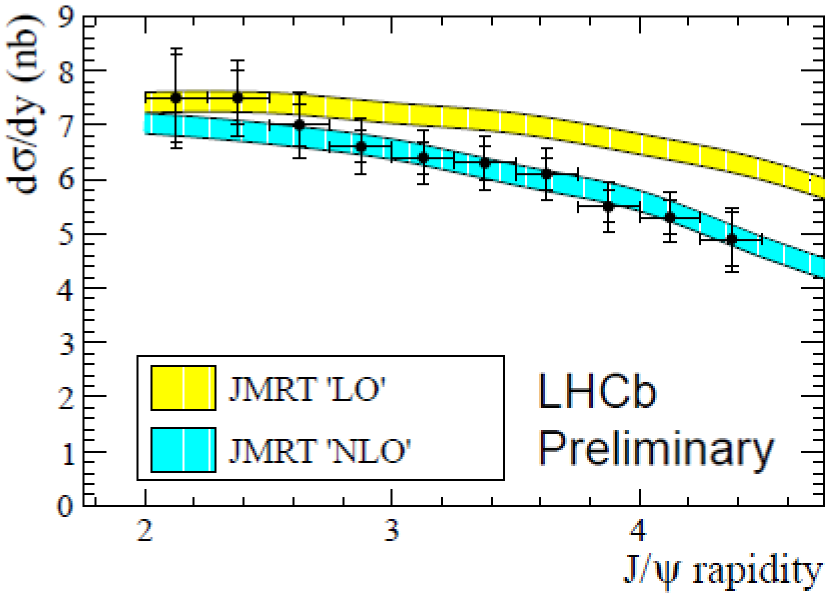
- Integrated cross-sections

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 \leq \eta(\mu^{\pm}) < 4.5) = 411.0 \pm 16(\text{stat}) \pm 21(\text{sys}) \pm 16\ \text{pb}$$

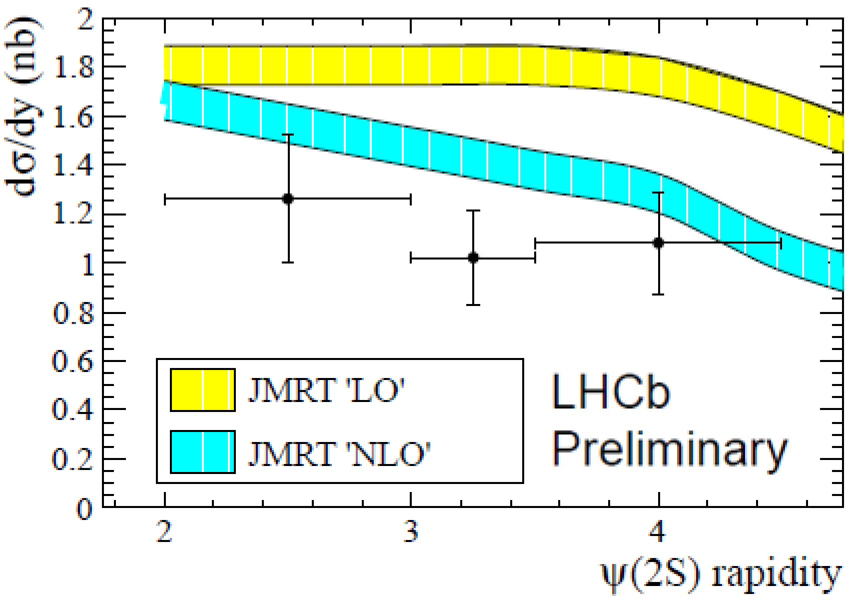
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 \leq \eta(\mu^{\pm}) < 4.5) = 9.4 \pm 1.3(\text{stat}) \pm 0.5(\text{sys}) \pm 0.4\text{pb}$$

- Differential cross-sections

J/ψ



Ψ(2S)



[LHCb-CONF-2016-007-001]

Comparison with other experiments

- The LHCb measurement can be related to photoproduction using:

$$\frac{d\sigma_{pp\to pJ/\psi p}}{dy} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p\to pJ/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p\to pJ/\psi p}(W_-)$$

Measured

Extracted

$\frac{dn}{dk_\pm}$ photon flux: Weizsacker-Williams approximation

$k_\pm \approx (M_{J/\psi}/2)\exp(\pm|y|)$ photon energy

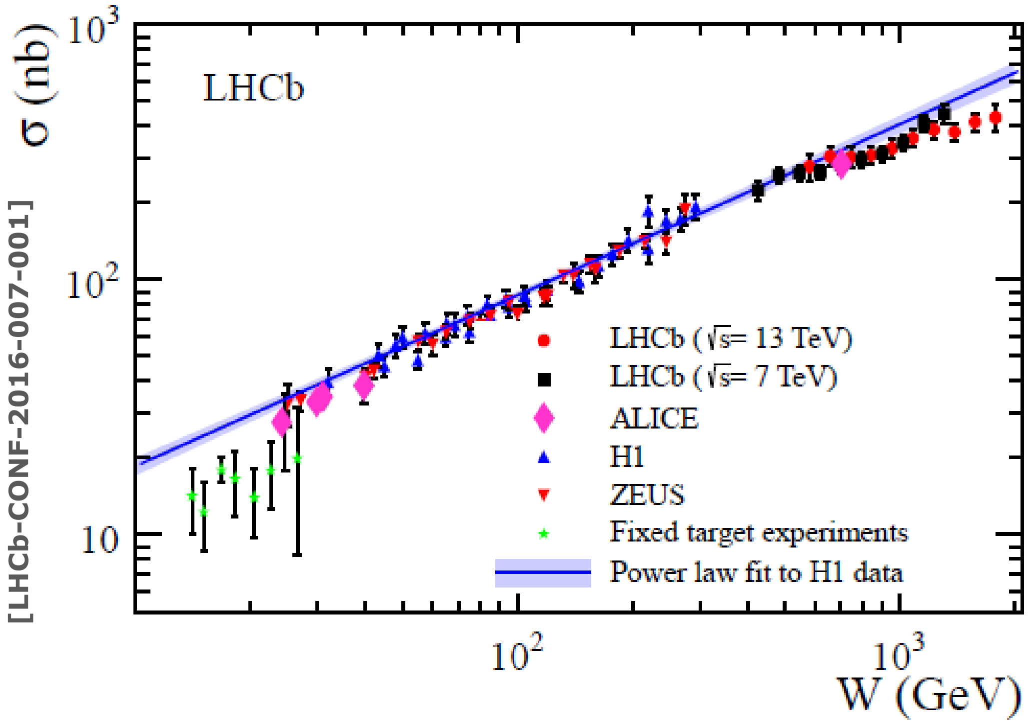
$(W_\pm)^2 = 2k_\pm\sqrt{s}$ mass of the photon-proton system

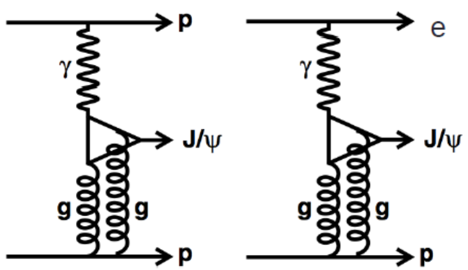
- Twofold ambiguity for LHCb – for each rapidity bin we have two solutions (see next slide) for photon-proton c.m. energy

Comparison with other experiments

- The LHCb measurement can be related to photoproduction using:

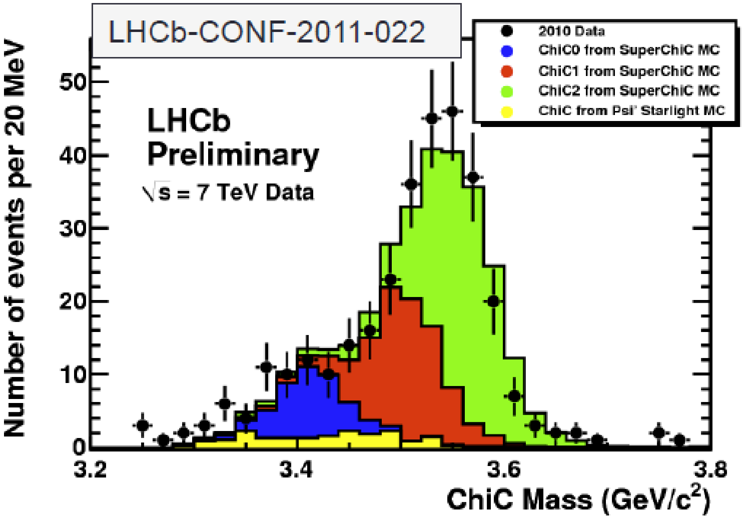
$$\frac{d\sigma_{pp\to pJ/\psi p}}{dy} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to pJ/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to pJ/\psi p}(W_-)$$





- **Obtained results are compatible with the HERA data**!
- **Some deviation** from simple power law prediction (Regge theory) seen
  - this may be explained either by saturation or higher order diagrams

Future analyses



- Great interest in studying χ_c production
- Go beyond J/ψ and $\psi(2S)$ and look for $\phi \rightarrow \mu\mu$ decay
- Use new, improved trigger to look at hadronic modes
- Herschel can be used to describe proton dissociation
- New tools (based on the VELO information) to enhance the VETO decision
- Low mass spectroscopy using pion and kaon final states
- Exotics modes
- Use ion run data to study CEP

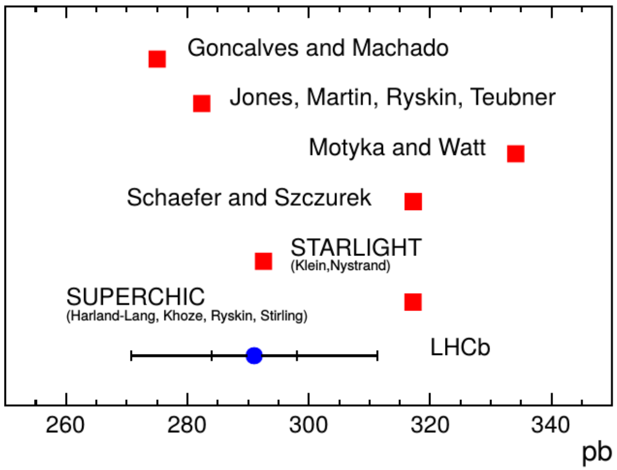
Summary

- **CEP processes became an important part of the LHCb physics programme**
- Published results using Run I data and muon final states
- Enhanced trigger and Herschel give a very good prospects for new great results with Run II data
- First results using Herschel@LHCb for CEP J/ψ and $\psi(2S)$ presented
- RUN II just begun! More exciting results ahead of us!

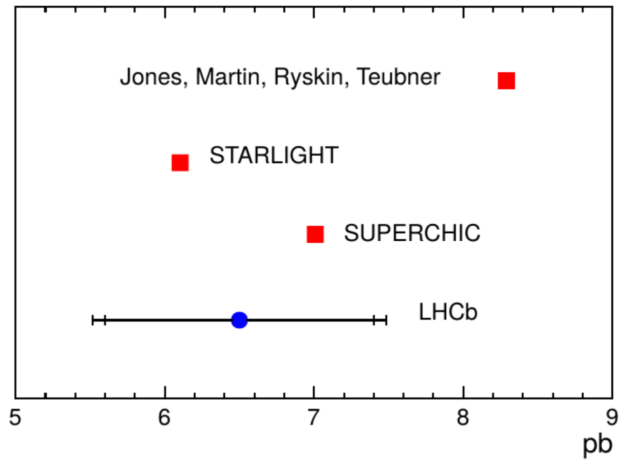
Cross section measurement

- Comparison with theoretical predictions – **good agreement!**
  - NLO describes data better than LO based predictions
  - better description for J/ Ψ than for Ψ(2S)
  - uncertainties are highly correlated between the bins

J/ψ



Ψ(2S)



Phys. Rev. C84 (2011) 011902 , JHEP 1311 (2013) 085
Phys. Rev. D78 (2008) 014023, Phys. Rev. D76 (2007) 094014
Phys. Rev. Lett. 92 (2004) 142003, Eur. Phys. J. C65 (2010) 433

Central Exclusive Production - motivation

- Exclusive processes are very important probes for testing QCD
- Studying **pomeron-γ** (photo-production) interactions
  - At leading order it can be interpreted as a pair of gluons
  - Probes gluon P.D.F. at small fraction, x, of proton momentum
  - For kinematical reach of the LHCb $\mathbf{x \approx 5 \cdot 10^{-6}}$
  - For higher mass final state X perturbative calculations viable
- Double **pomeron exchange** (pomeron-pomeron fusion)
  - Final state must be neutral – no open flavour
  - Help understand in general processes such $gg \rightarrow X$ ($gg \rightarrow H$)
  - For low mass final state mainly spectroscopy studies
  - For higher masses testing QCD and pomeron structure

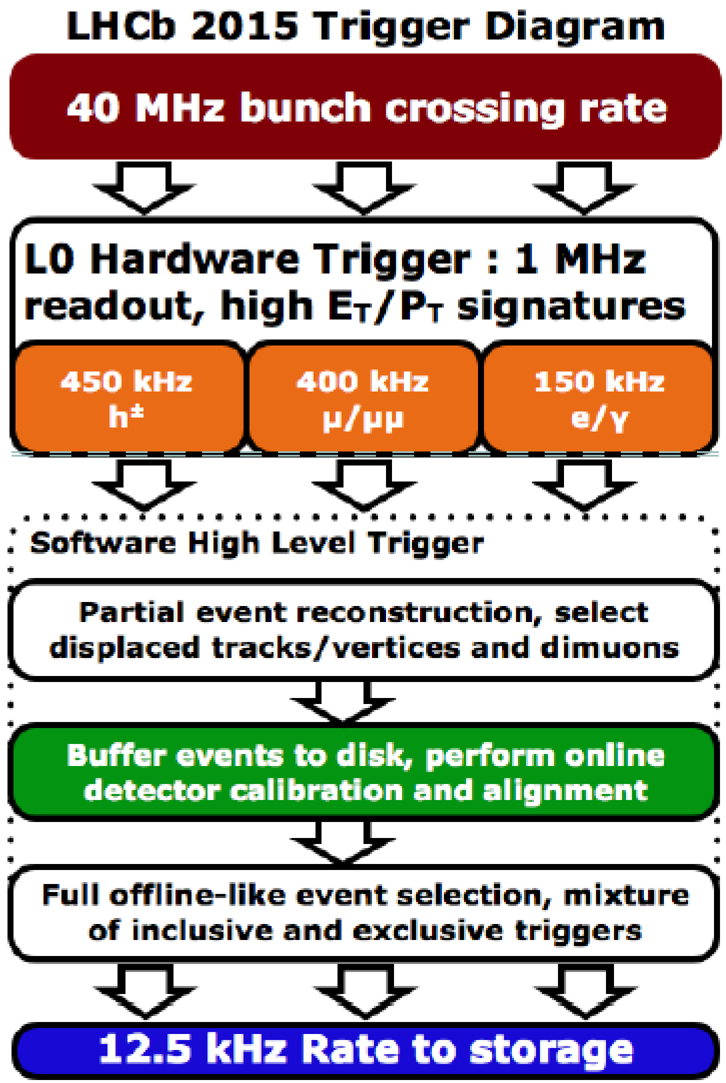
RUN II LHCb Trigger

Machine

Hardware
trigger layer – **L0**

Splitted– HLT

Storage



1 MHz full
detector read-out

Data buffer

~ 5 PB