52nd International Symposium on Multiparticle Dynamics (ISMD 2023)

Central Exclusive Production at LHCb

Tomasz Szumlak

on behalf of the **LHCb Collaboration**

AGH - University of Krakow

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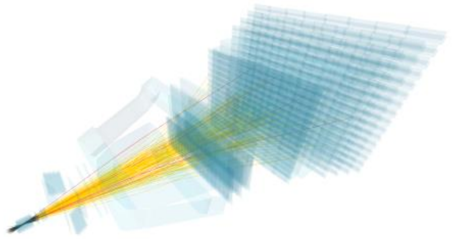
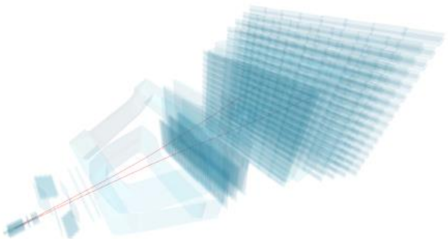
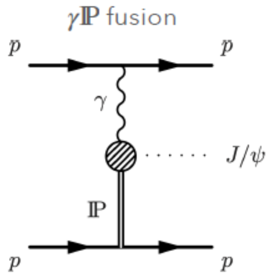
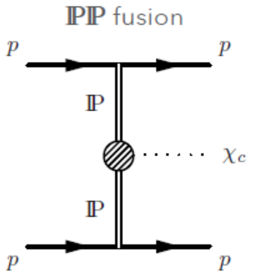








Outline

- ❑ Bit of theory and motivation
- ❑ How to „catch" a CEP event – **The gap**
- ❑ CEP@LHCb here: $J/\psi, \psi(2S)$, Υ, and χ_{c0}, χ_{c1}, χ_{c2}
- ❑ Summary

Central Exclusive Production @LHCb

CEP – definition

- Central exclusive production is a type of diffractive process that can be denoted qualitatively as follows

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

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

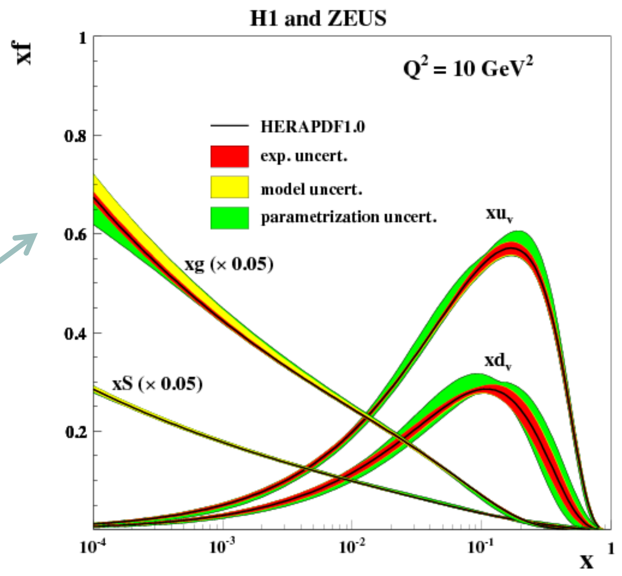
- However, they **lose energy** in order to produce the final system ***X*** that can be **observed in the detector**

- **„⊕” denotes symbolically the rapidity gaps**

  - **Only** the central system is produced. Apart from that there should be no **activity otherwise**, thus, **exclusive** proces
  - In principle four-momenta of the scattered hadrons (protons) can be measured by very forward detectors
  - In the case of the LHCb **both protons remain un-tagged**

Central Exclusive Production @LHCb

- Exclusive processes are very important for studying QCD
- May help **improve understanding of soft scale** (non-perturbative) QCD
- Studying notorious **pomeron** interactions
- Improve knowledge on low-**x** behavior of parton PDF (in LO $\sigma \propto (gluon\ PDF)^2$)
  - Sharp rise of gluon PDF for decreasing **x**
  - LHCb is potentially sensitive to the gluon PDF down to **x** ~ $5 \cdot 10^{-6}$
  - Studying saturation (BFKL evolution)
  - Facilitate to understand production processes such gg → X (gg → H)



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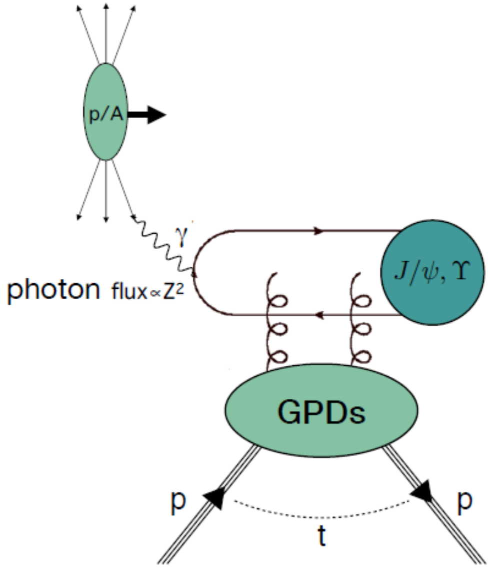
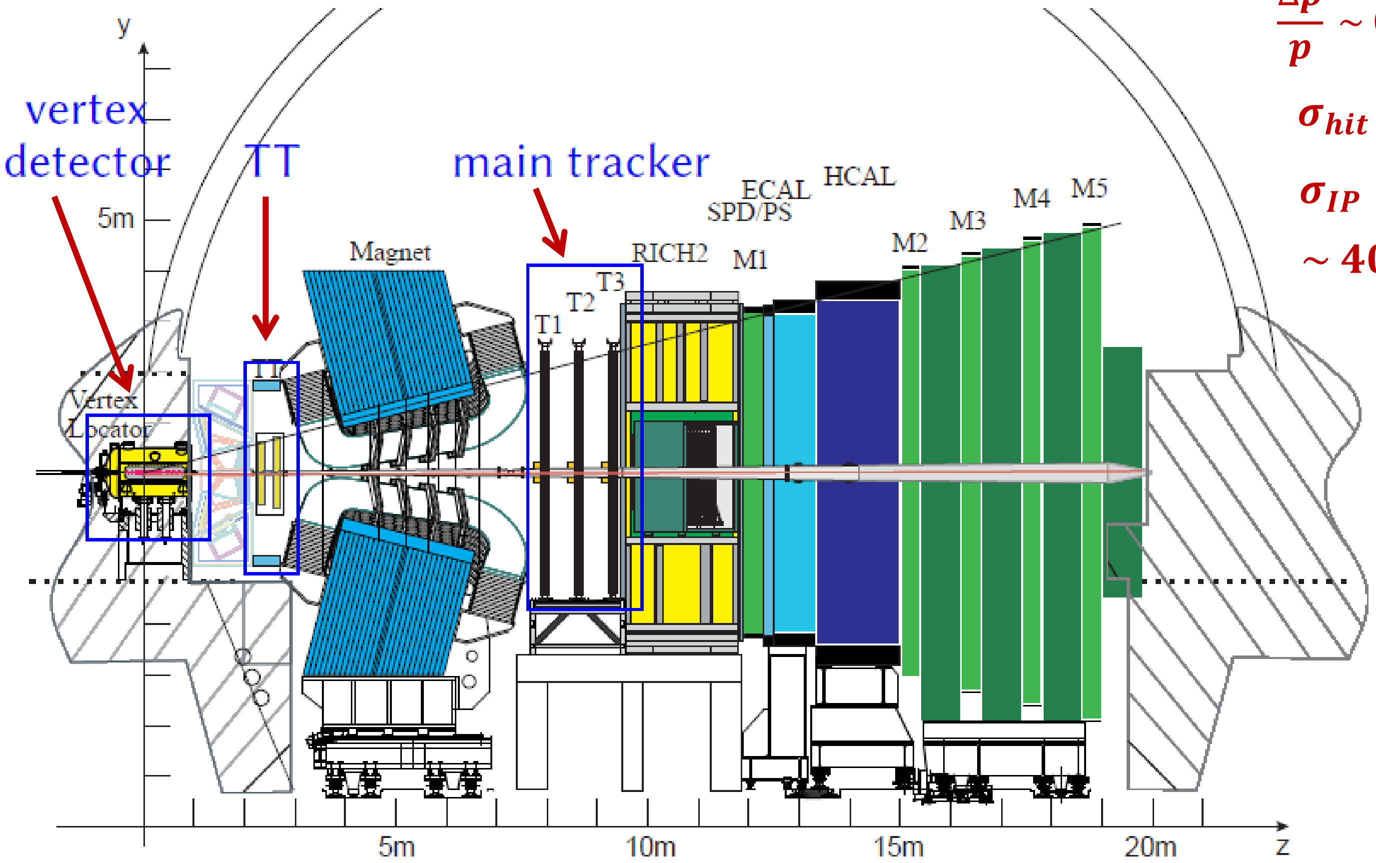


Introduction – LHCb detector

- 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]

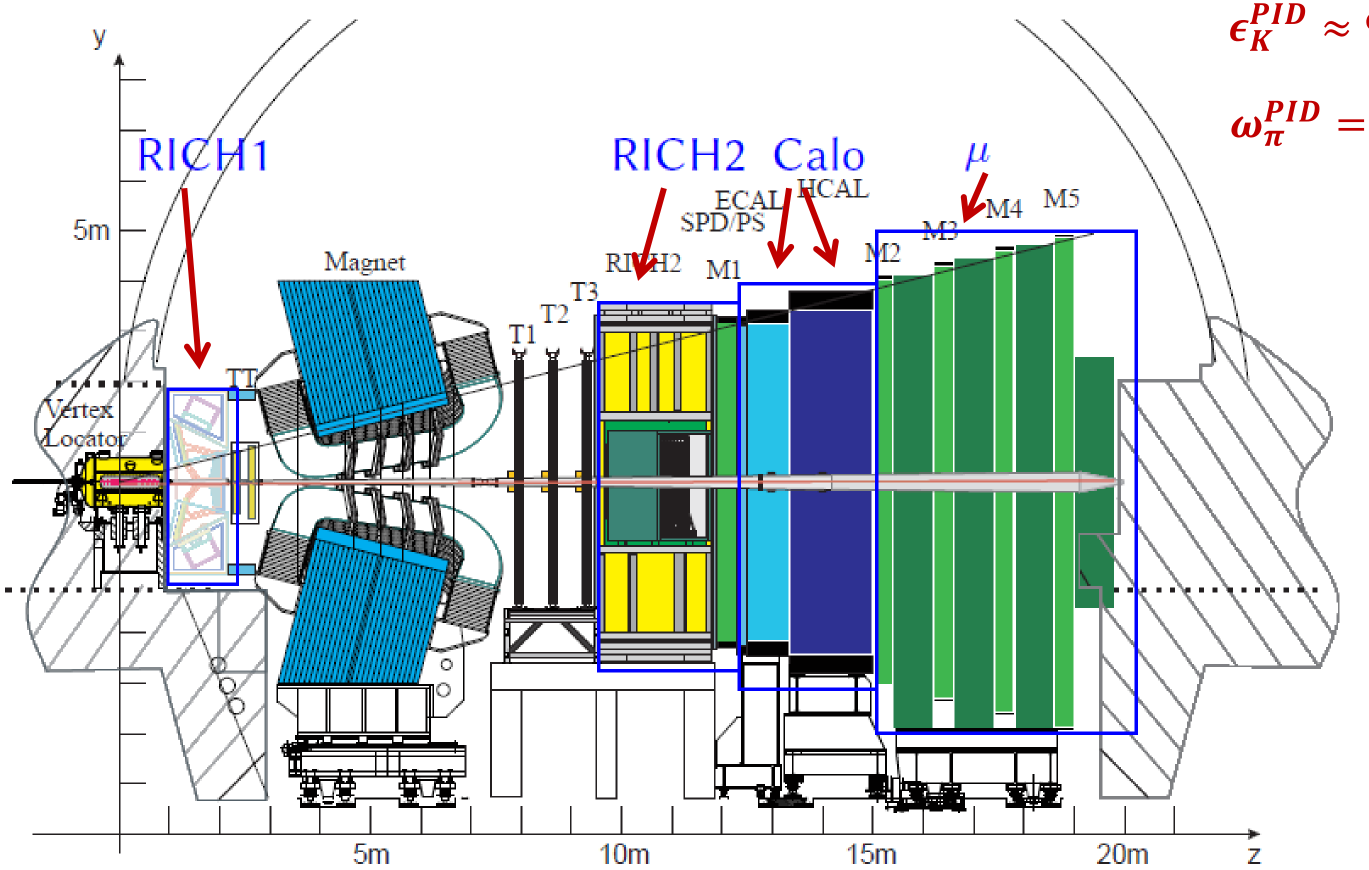
Introduction – LHCb detector

- ❑ Tracking system – precise momentum reconstruction, vertexing, decay time resolution

- ❑ Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert

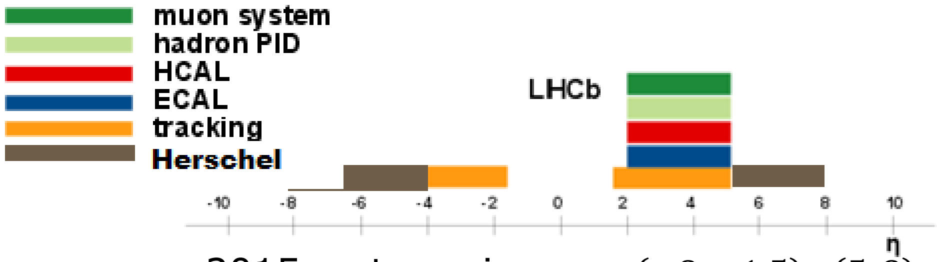
$\epsilon_{K}^{PID} \approx 95\%$

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

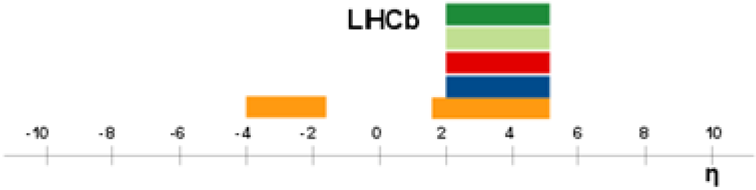


[JINST 3 (2008) S08005]

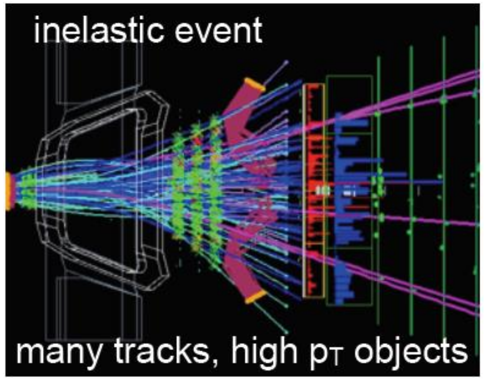
The Gap…

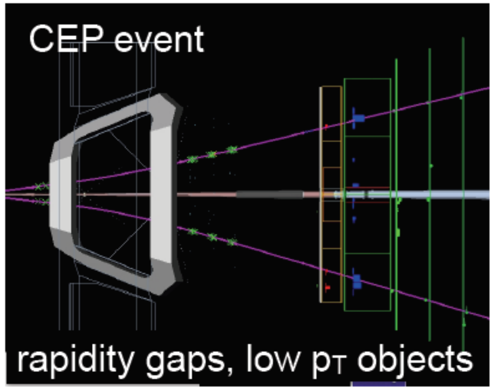


> 2015, veto region $\eta \in (-8, -1.5), (5, 8)$

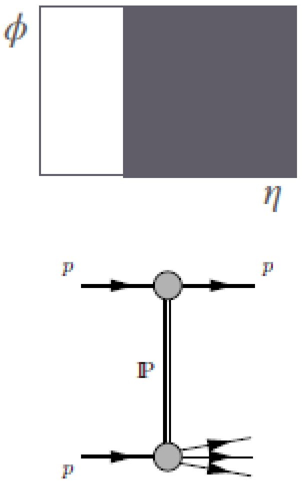


< 2015, veto region $\eta \in (-3.5, -1.5)$

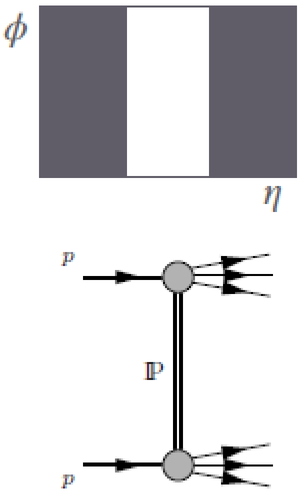




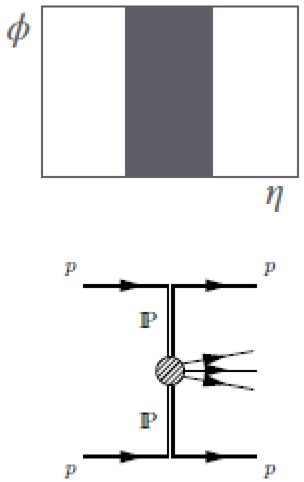
Single diffraction



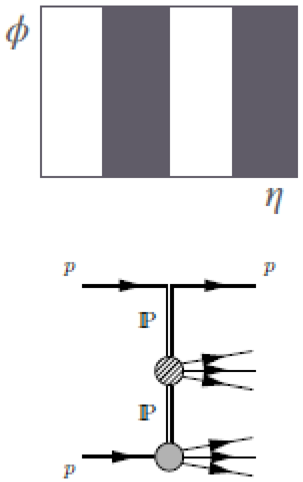
Double diffraction



CEP elastic

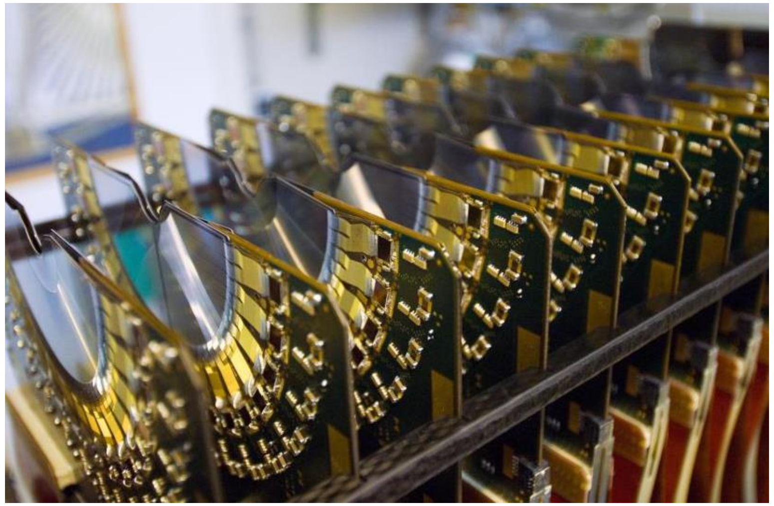


CEP inelastic



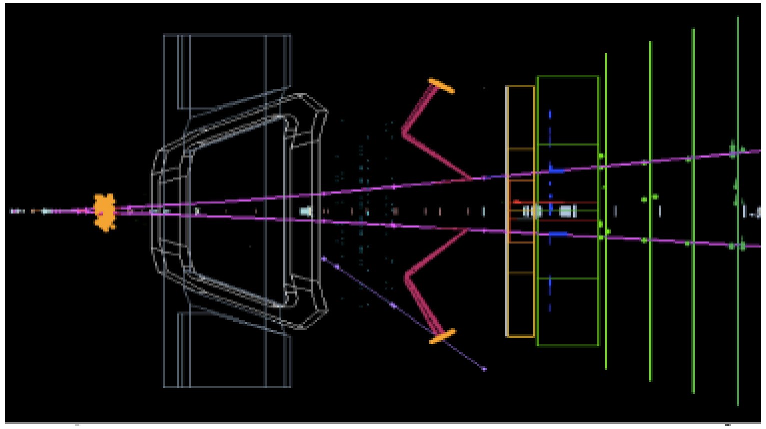
based on [arXiv:0806.0883]

The LHCb Gap explorers: VELO



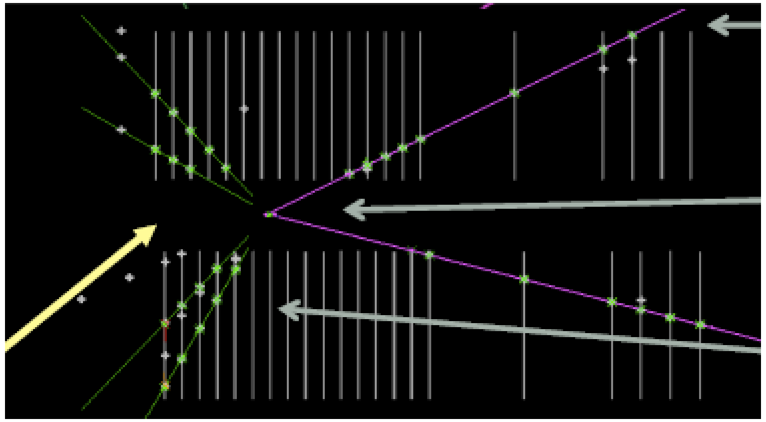
~20 m

~ 10 m



~1 m

~ 10 cm



$\mu^{\pm}$

PV

„Backward tracks”

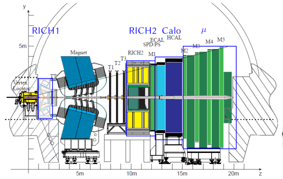
Clearly not a CEP event…

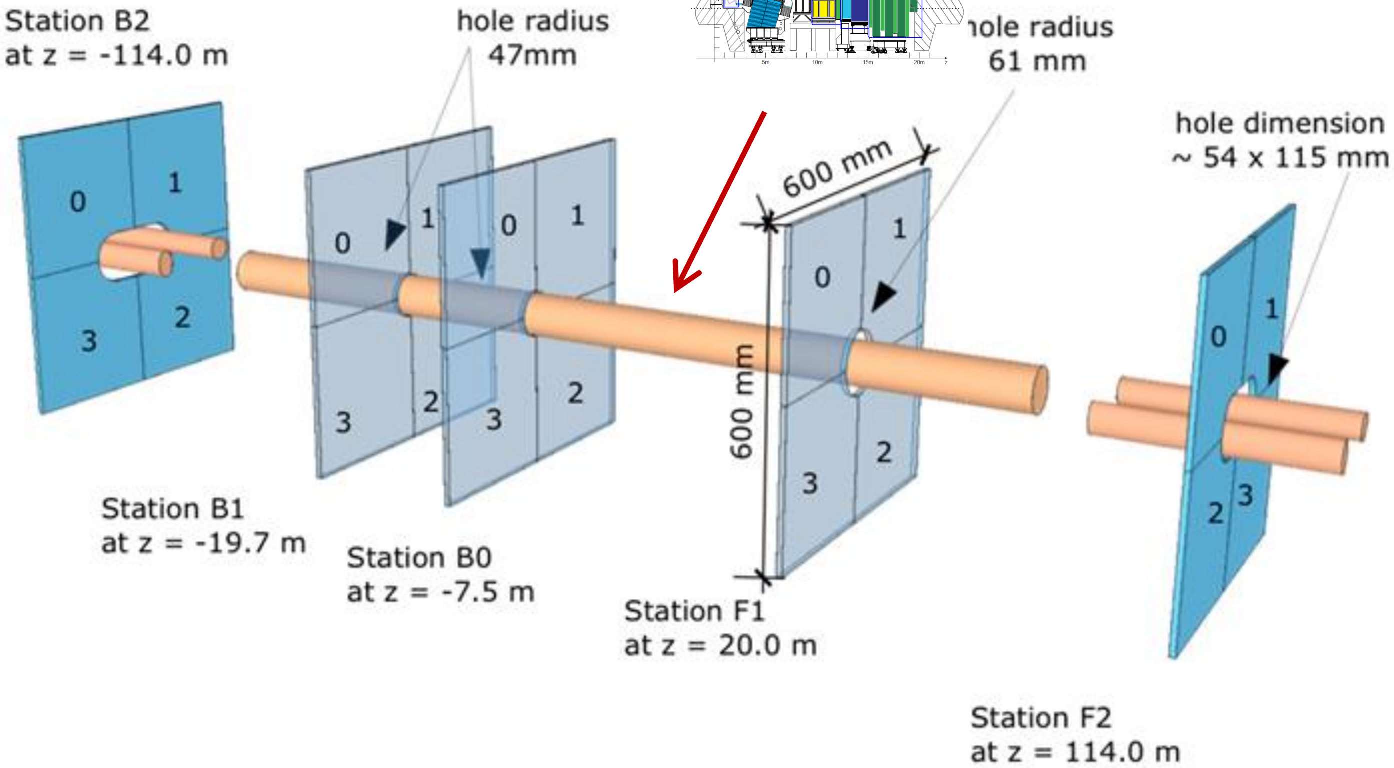
- **VErtex LOcator (VELO)**
    - 84 micro-strip silicon sensors close to the IR
    - Precise track and vertex reconstruction
    - The best single hit spatial resolution at LHC
    - Allows for **backward track reconstruction**
    - No momentum information for backward tracks

The LHCb Gap explorers: Herschel

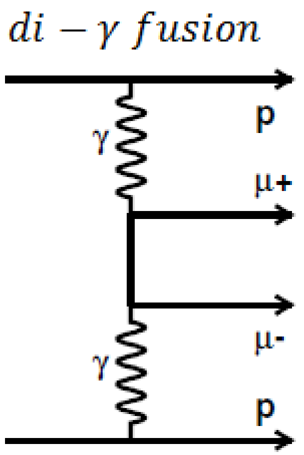
High **R**apidity **S**hower **C**ounters for **L**HCb

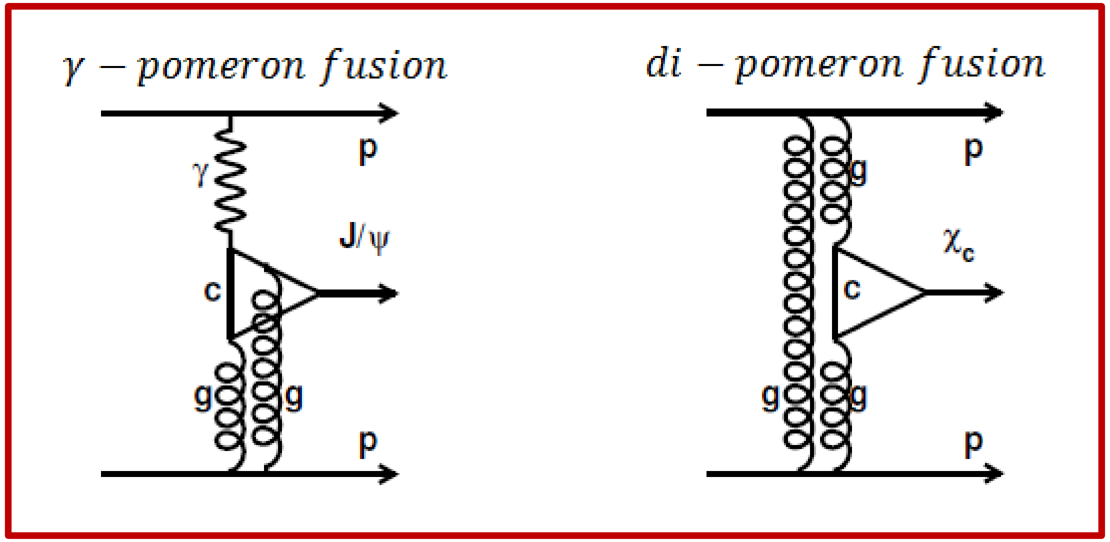
- 5 stations containing 4 scintillators with PMT
- Used to detect particle showers coming from the PVs
- Roughly ~ 500 hits per station





CEP with di-muon final states

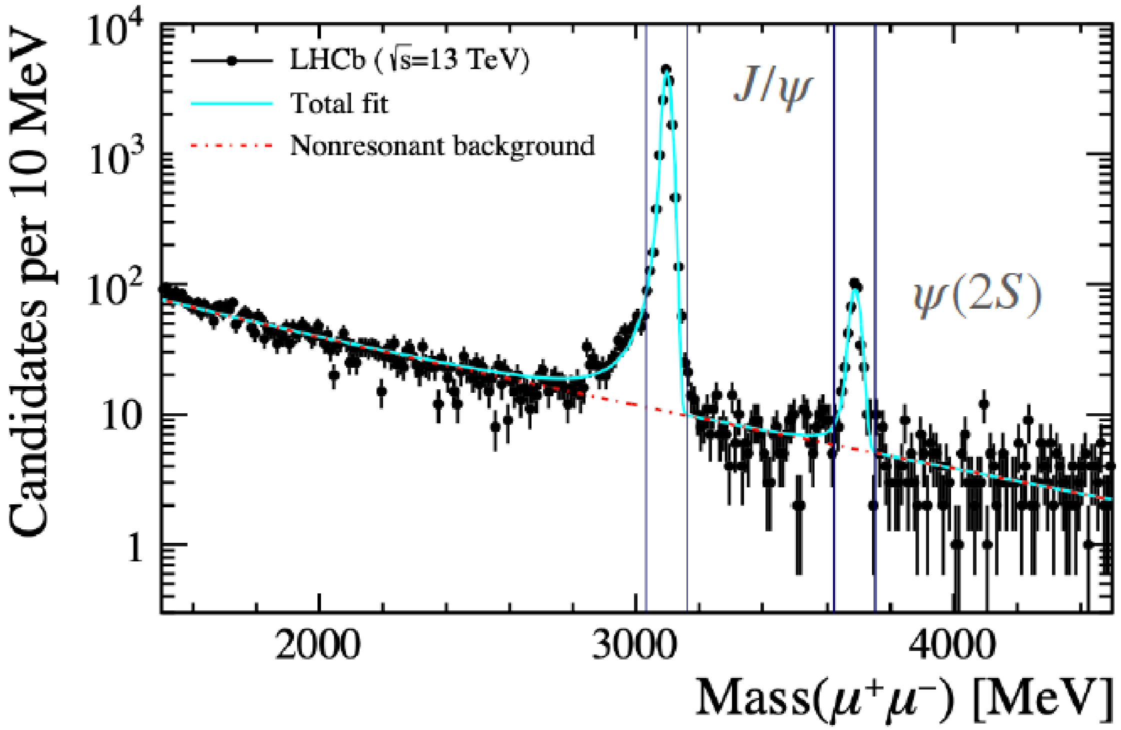




- Elastic scattering with intact and un-tagged protons
  - Two muons and rapidity gaps
- Proceed via exchange of colourless objects (γ, pomeron)
- Studied in detail by theorists
  - **LPAIR** (**A.G Shamov and V.I Telnov, NIM A, 494 (2002), 51**)
  - **STARlight** (**S.R. Klein and J. Nystrand, Phys. 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**)

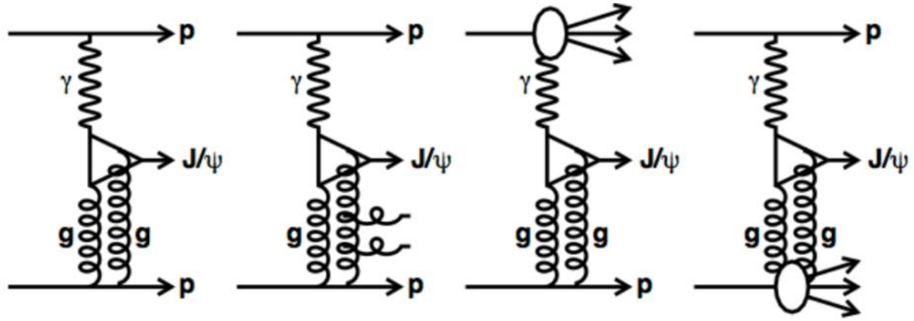
[JHEP 10 (2018) 167]

CEP J/ψ and $\psi(2S)$ @$\sqrt{s} = 13$ TeV



- Model of the mass spectra
  - $\mathcal{L} = 204\ \mathrm{pb}^{-1}$
  - Signal peak – Crystal-Ball function
  - Background – exponential

- The dominant background



- In general, harder p_T spectrum of produced J/ψ is expected

- Decays $\psi(2S) \rightarrow J/\psi\, X$, where X is not detected
  - Can be significantly suppressed by hard 2 track only cut

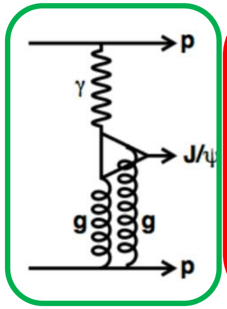
- Radiative decays $\chi_c \rightarrow J/\psi\, \gamma$, where γ goes undetected
  - Suppressed by requiring no photons

- Feed-down to $\psi(2S)$ is expected to be small

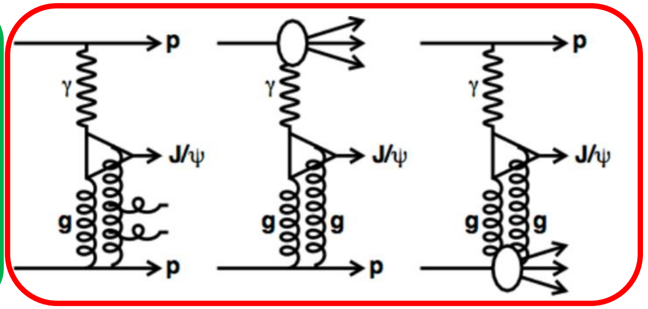
CEP J/ψ and $\psi(2S)$ @$\sqrt{s} = 13$ TeV

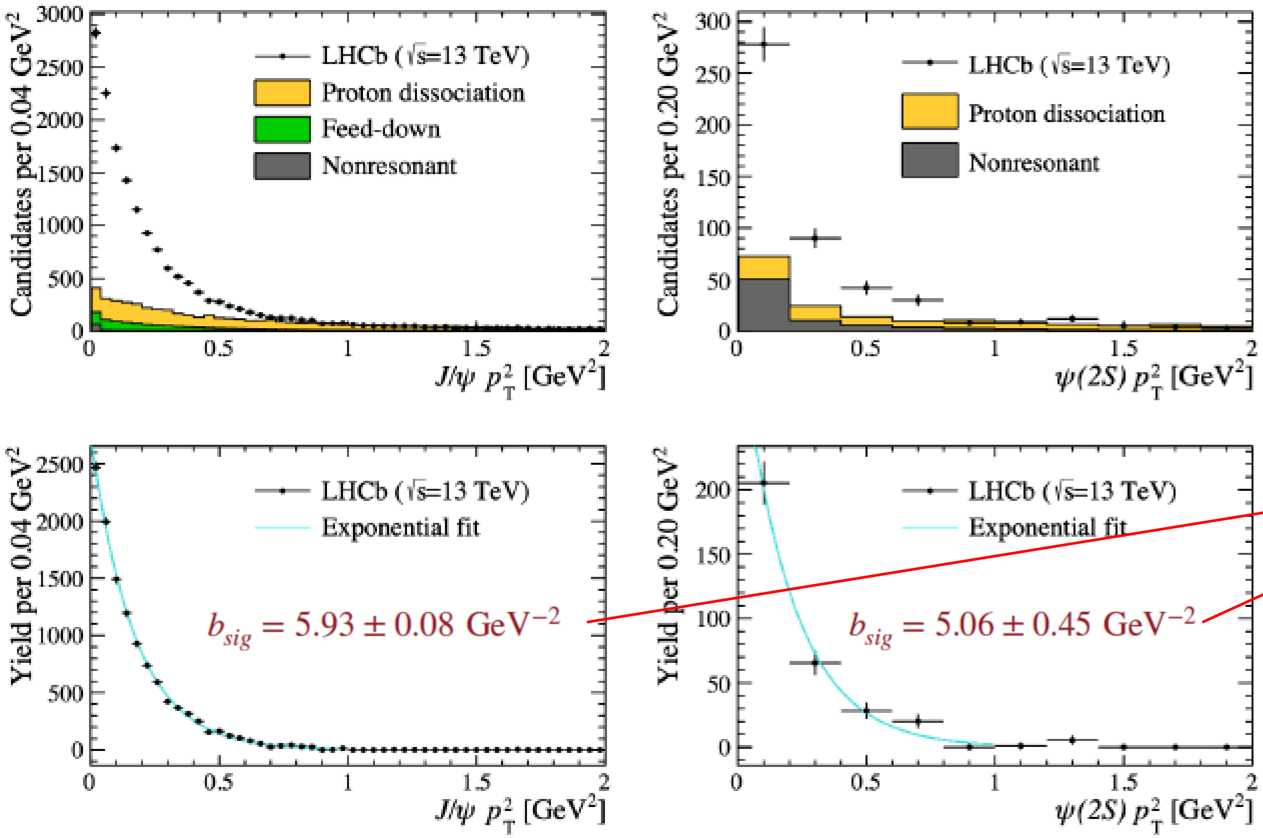
[JHEP 10 (2018) 167]

Signal



Background





Regge theory predictions

$$d\sigma/dp_T^2 \sim \exp(-b_{sig} p_T^2)$$

$$b_{sig} \approx 6 \text{ GeV}^{-2}$$

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**
- **Feed-down background**
- **Inelastic background**

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

CEP J/ψ and $\psi(2S)$ @$\sqrt{s} = 13$ TeV

[JHEP 10 (2018) 167]

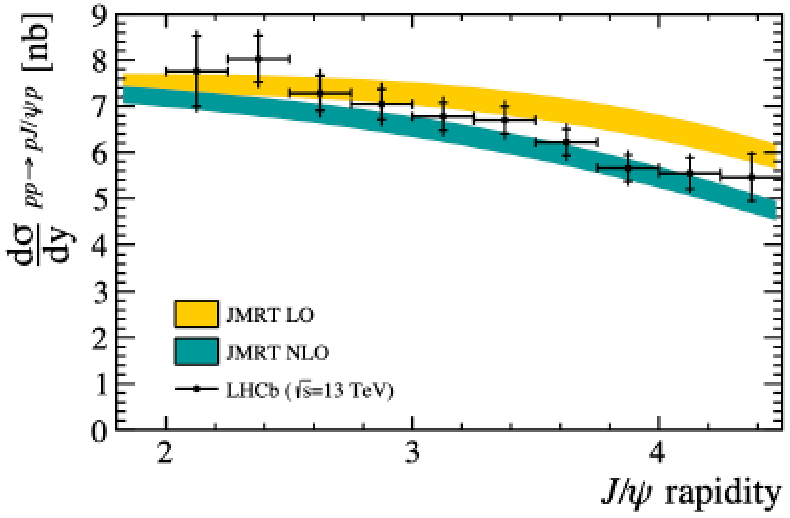
- Integrated cross-sections

$$\sigma_{J/\psi\rightarrow\mu^+\mu^-}(2.0 \leq \eta(\mu^\pm) < 4.5) = 435.0 \pm 18(\text{stat}) \pm 11(\text{sys}) \pm 17(lumi)\ \text{pb}$$

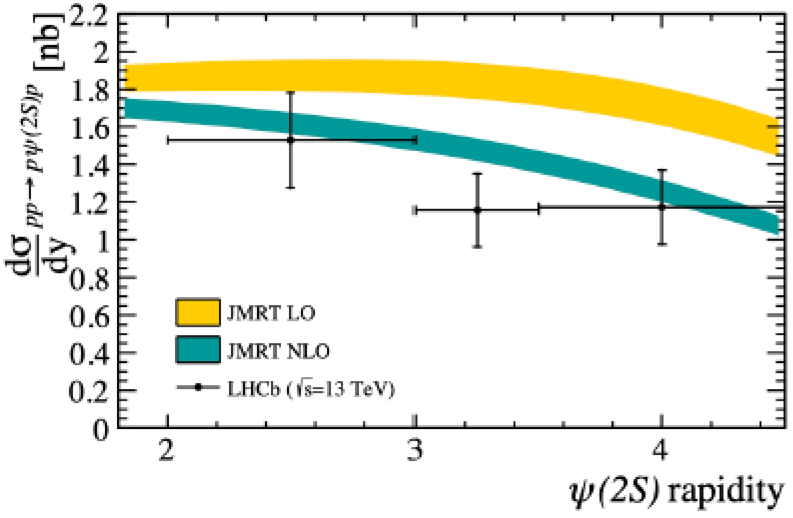
$$\sigma_{\psi(2S)\rightarrow\mu^+\mu^-}(2.0 \leq \eta(\mu^\pm) < 4.5) = 11.1 \pm 1.1(\text{stat}) \pm 0.3(\text{sys}) \pm 0.4(lumi)\ \text{pb}$$

- Differential cross-sections

J/ψ



$\Psi(2S)$



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 – LHCb data

Calculated

Extracted from HERA

$\frac{dn}{dk_\pm}$ – 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 for photon-proton c.m. Energy – this is fixed the W_- using HERA H1 parametrisation

See next slide for comparison!!

Comparison with other experiments

[JHEP 10 (2018) 167]

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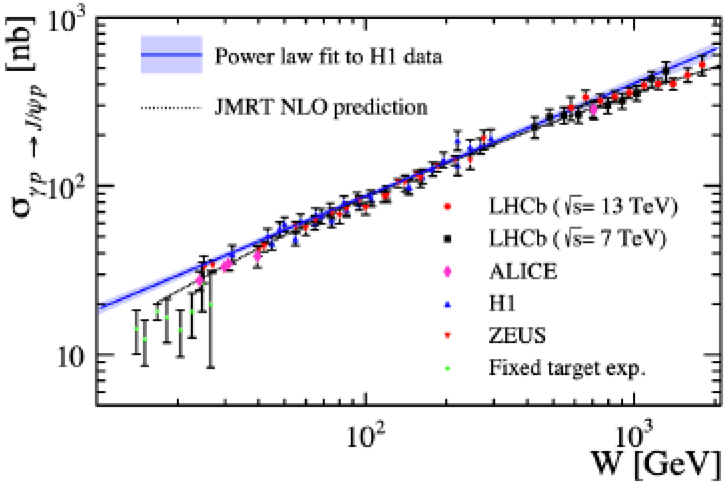
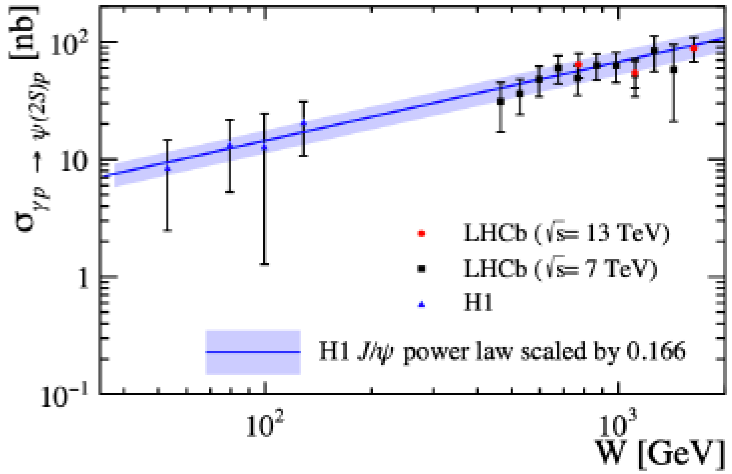




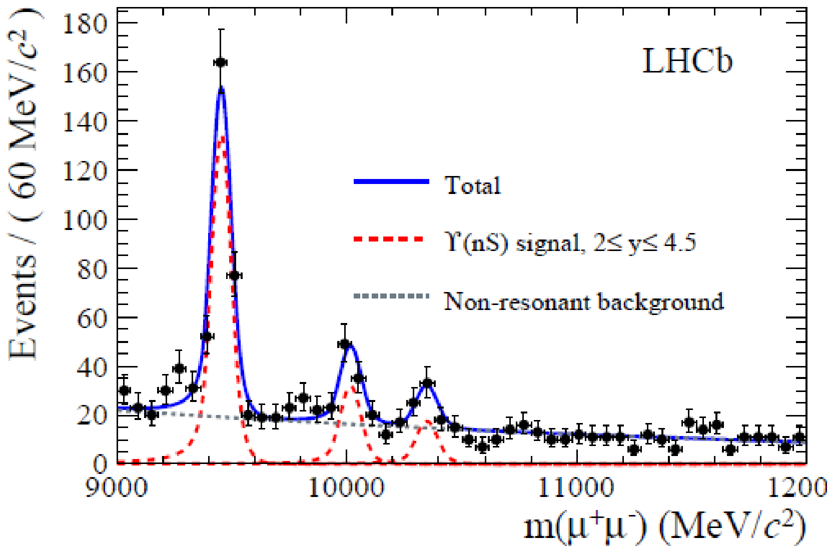
- **Obtained results are compatible with the HERA data**!
- Some deviation from simple power law prediction (Regge theory) seen
  - Update with a larger data sample on the way!

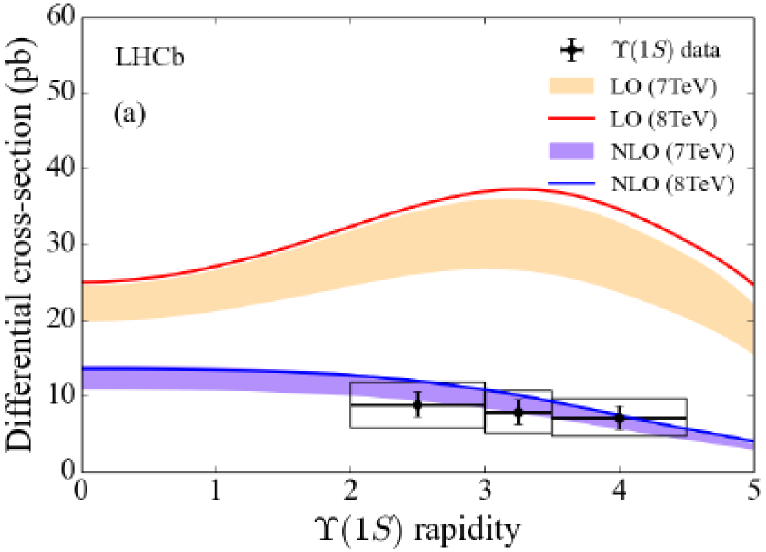
CEP $\Upsilon(nS)$ @$\sqrt{s} = 7$ TeV and @$\sqrt{s} = 8$ TeV

[JHEP 1509 (2015) 084]

- 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 $2 \le y(\Upsilon) < 4.5$ and $2 \le \eta(\mu^{\pm}) < 4.5$
- In case of $\Upsilon(3S)$, due to significant $\eta_b(3P) \rightarrow \Upsilon(3S) + \gamma$ contamination, only the upper limit for the production cross-section determined

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

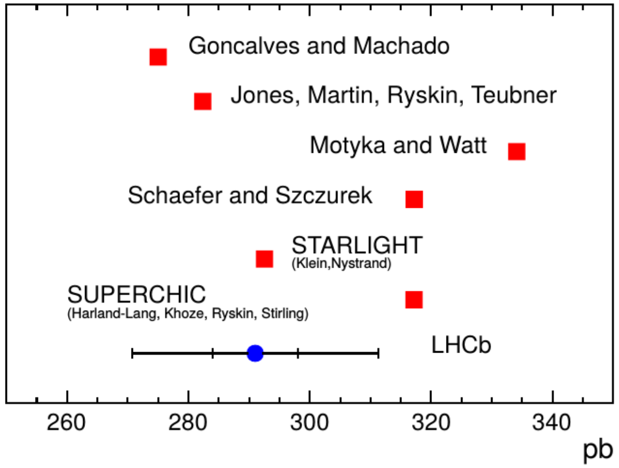




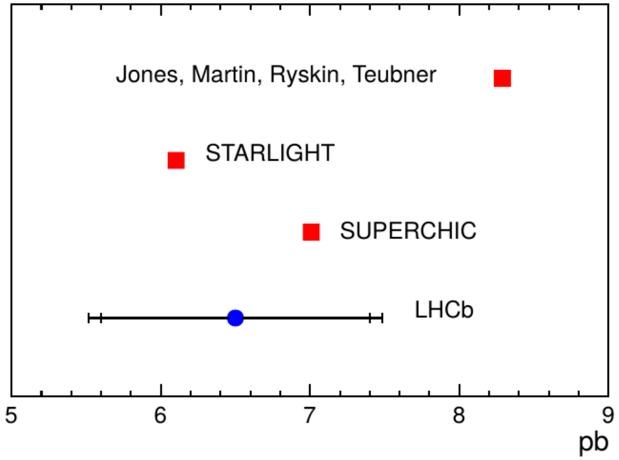
Cross section measurement

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

J/ψ



$\Psi(2S)$



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

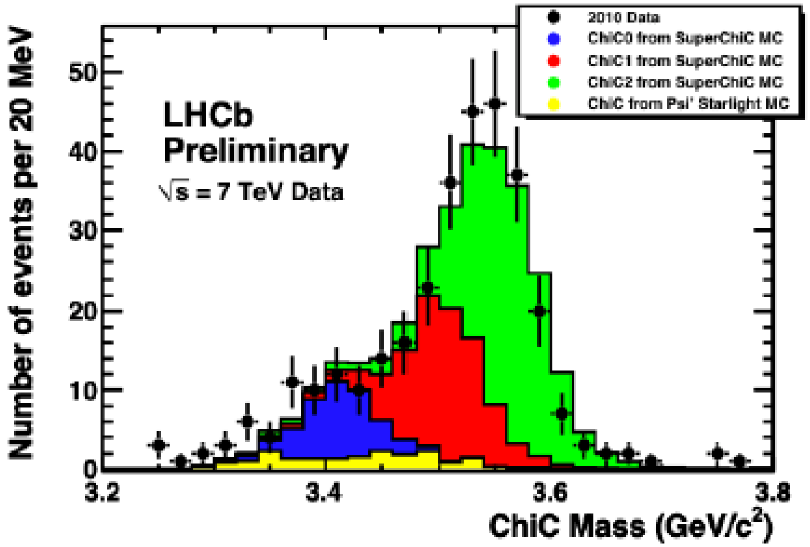
CEP χ_{c0}, χ_{c1}, χ_{c2} $@\sqrt{s} = 7$ TeV

[LHCB-CONF-2011-022]

- Reconstruction of $\chi_{cJ} \to \mu^+\mu^-\gamma$ is basically a carbon copy of J/ψ selection with additional photon with $E_T > 200$ MeV
- After selection fit to the mass distribution of $\mu^+\mu^-\gamma$ using signal shapes taken from SuperChic generator
- Background modelled using $\psi(2S) \to \chi_{cJ}\gamma, J/\psi\gamma, J/\psi\pi^0\pi^0$ (the last final state with only one photon reconstructed)

Estimated cross-sections weighted with the respective branching ratios

$$\sigma(pp \to p\,\chi_{c0}p) = 9.3 \pm 2.2 \pm 3.5 \pm 1.8\,pb$$
$$\sigma(pp \to p\,\chi_{c1}p) = 16.4 \pm 5.3 \pm 5.8 \pm 3.2\,pb$$
$$\sigma(pp \to p\,\chi_{c2}p) = 28.0 \pm 5.4 \pm 9.7 \pm 5.4\,pb$$



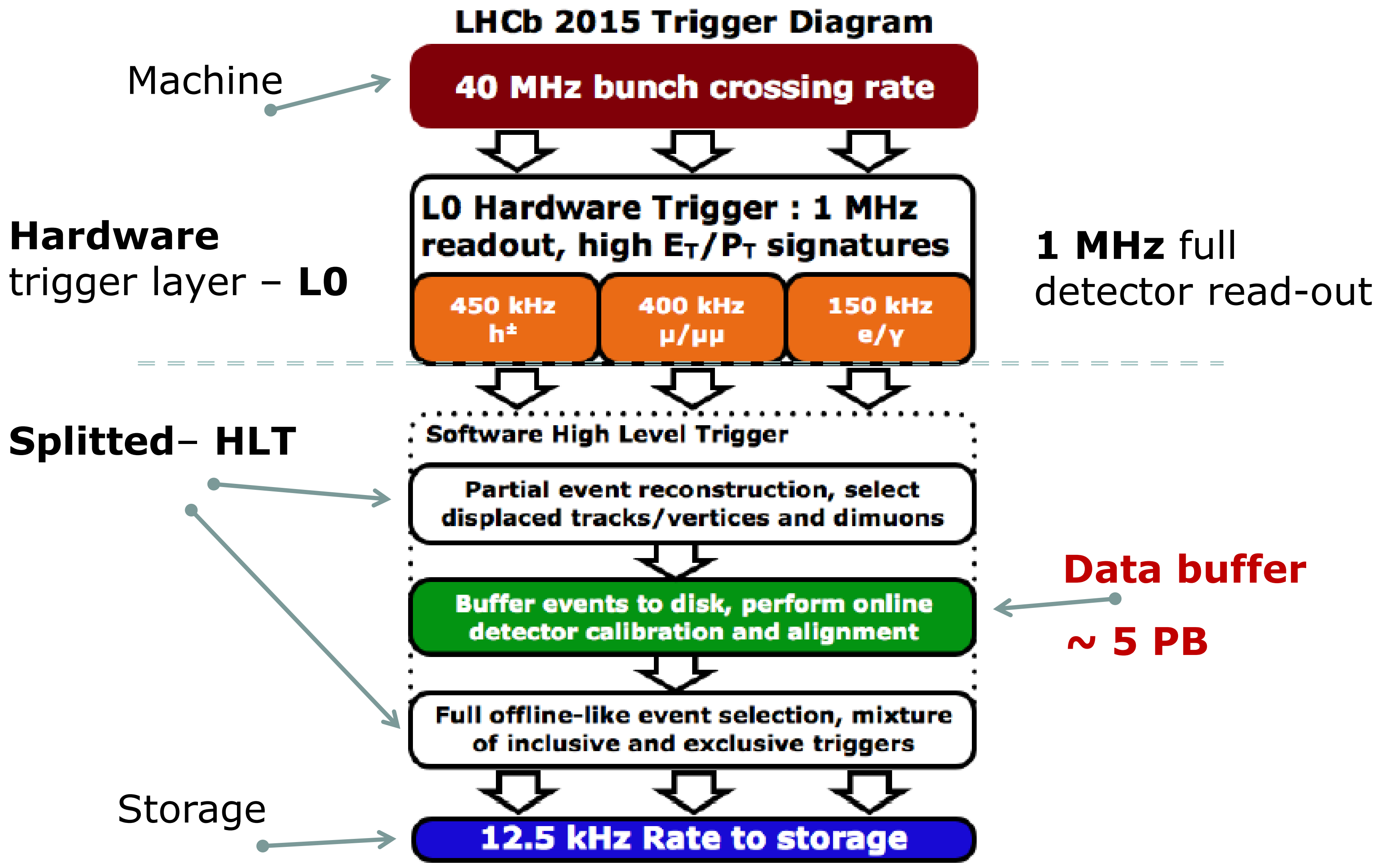
Summary

- **CEP processes are an important part of the LHCb physics programme**
- Enhanced trigger system and Herschel detector improved considerably Run 2 results (still more to come with Run 2 data)
- More analyses ongoing (CEP ϕ production, $J/\psi\phi$ pair production, charmonium production, CEP in heavy ion runs)

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 $gg \to X$ ($gg \to H$)
  - For low mass final state mainly spectroscopy studies
  - For higher masses testing QCD and pomeron structure

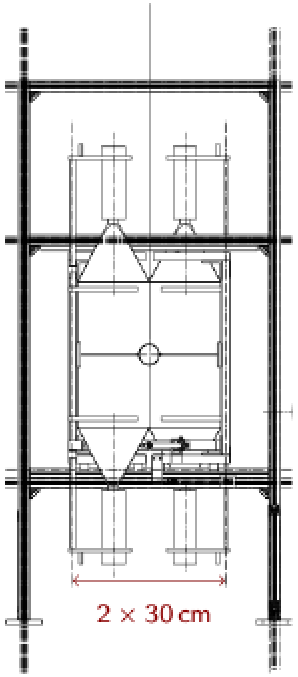
RUN II LHCb Trigger

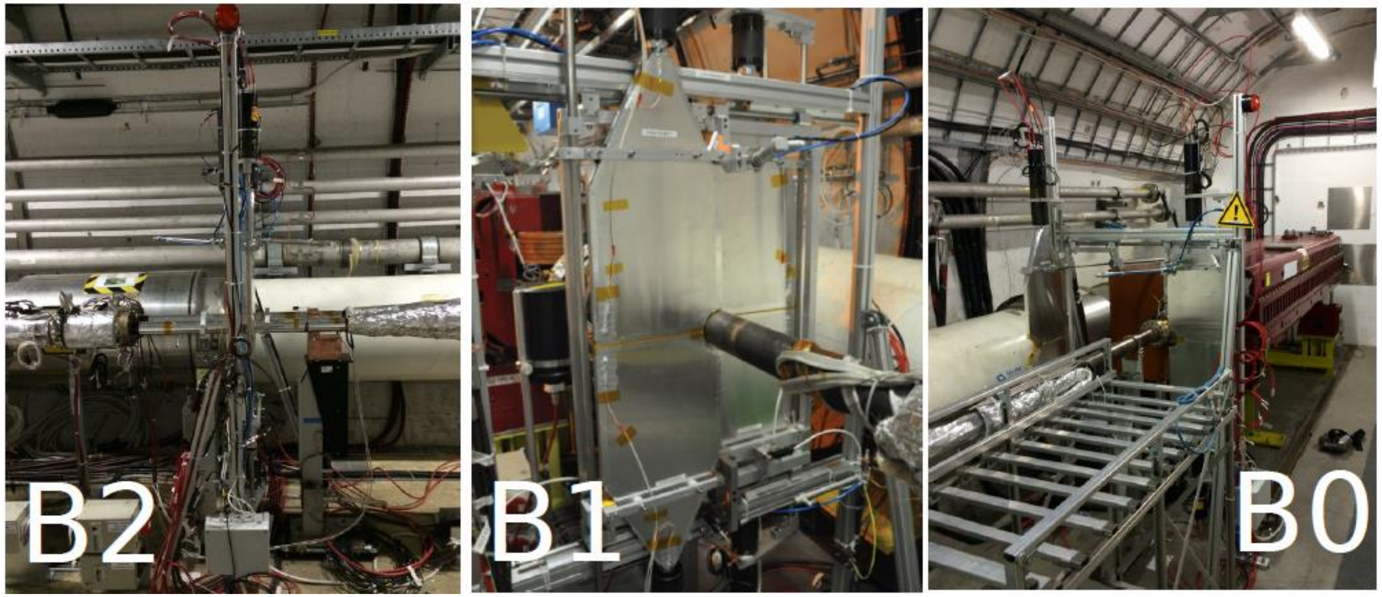


Signal selection (highlights)

- Low level (hardware) trigger L0
  - a muon candidate, p_T > 400 MeV
  - a di-muon candidate, p_T > 80 MeV (each track)
  - less than 20 (10 for 2011) SPD hits
- 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 ΔM = 65 MeV around expected J/ψ or $\psi(2S)$ mass

The LHCb Gap explorers: Herschel





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