Central exclusive production of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV

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On behalf of the LHCb collaboration

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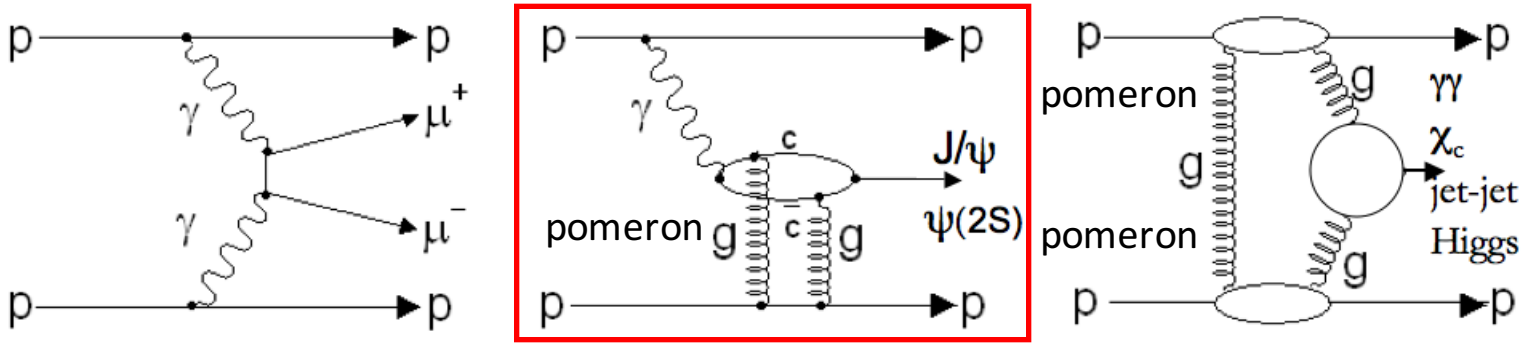
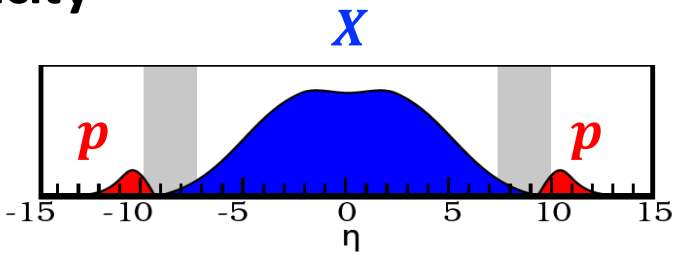
Introduction

- Central exclusive production: $p + p \rightarrow p + X + p$



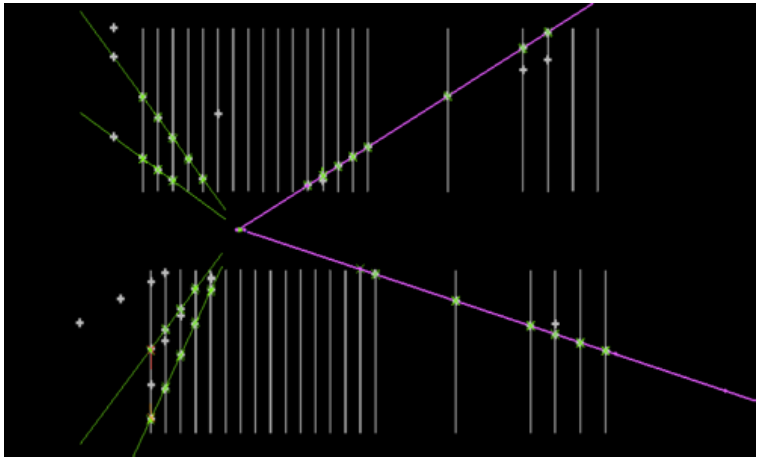
- ✓**Clean final state with low event multiplicity**
- ✓***X* well isolated in rapidity**
- ✓Provides essential QCD information



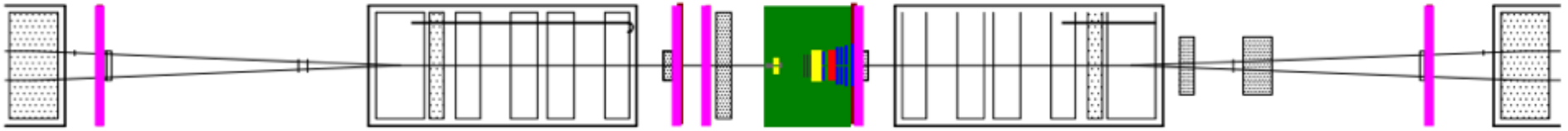
- J/ψ and $\psi(2S)$ in CEP are produced through the fusion of a photon and a pomeron (a colorless strongly-coupled object), and can provide
  - ✓A test of QCD
  - ✓An investigation of the nature of the pomeron
  - ✓A means for constraining the gluon parton distribution function

CEP at LHCb

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$
  - ✓Rapidity range complementary to other experiments
  - ✓Dedicated CEP trigger lines
  - ✓Low pile-up environment
  - ✓VELO has backward coverage $-3.5 < \eta < -1.5$



- ✓ **HERSCHEL**: new high rapidity shower counters in RunII;
  η coverage largely increased! Can reduce non-CEP backgrounds powerfully



VELO&Herschel: $-10 < \eta < -5, -3.5 < \eta < -1.5, 1.5 < \eta < 10$

Dataset and selections

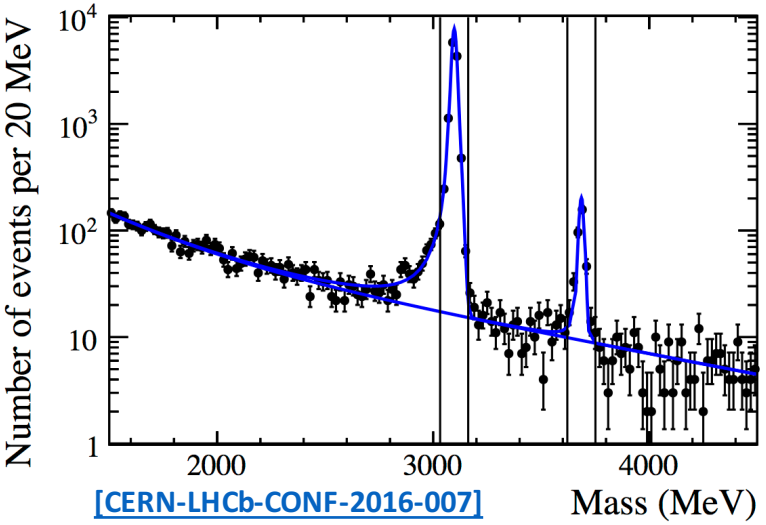
- Measurement performed using $204\ \mathrm{pb}^{-1}$ data at $\sqrt{s} = 13\ \mathrm{TeV}$

- Trigger requirements
  - ✓**Hardware**: less than 30 deposits in the scintillating-pad (SPD); at least one muon with $p_{\mathrm{T}} > 200\ \mathrm{MeV}/c$
  - ✓**Software**: < 10 reconstructed tracks; at least one muon

- Event selection
  - ✓Two muons with $2 < \eta < 4.5$
  - ✓$M(\mu^+\mu^-) \in M(\psi) \pm 65\ \mathrm{MeV}/c^2$
  - ✓$p_{\mathrm{T}}^2(\mu^+\mu^-) < 0.8\ (\mathrm{GeV}/c)^2$
  - ✓Events with
    1) additional VELO tracks **or**
    2) neutral energy $> 200\ \mathrm{MeV}$ **or**
    3) significant deposits in HERSCHEL

    (Σ_H: sum of normalized signals in each channel) are removed

*Without $M(\mu^+\mu^-)$ cut



[CERN-LHCb-CONF-2016-007]

Cross-section calculation

- Differential cross-sections in bins of rapidity are measured
- Master relation

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}\left(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5\right)=\frac{pN}{\epsilon_{\mathrm{rec}}\epsilon_{\mathrm{sel}}\Delta y\epsilon_{\mathrm{single}}L}$$

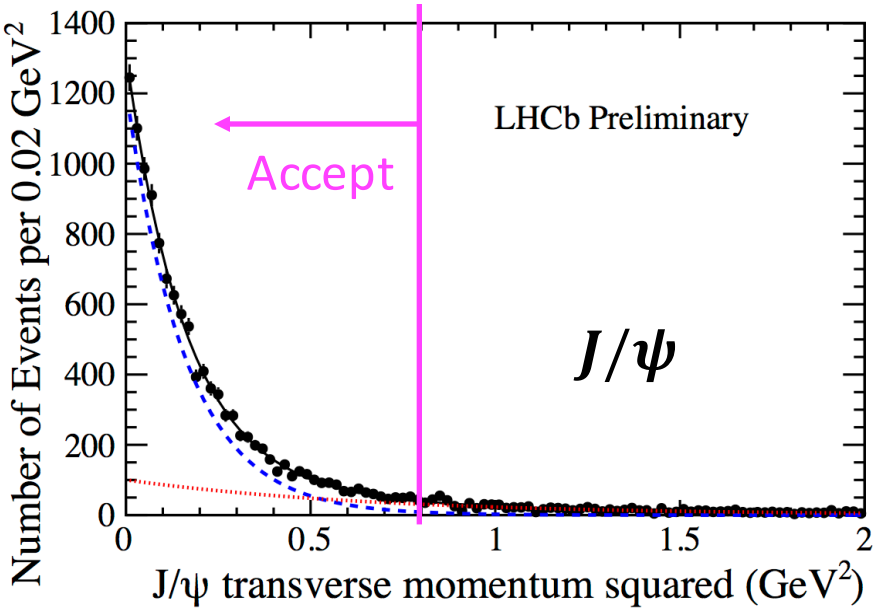
- ✓ p: signal purity
- ✓ N: number of selected events
- ✓ $\epsilon_{\mathrm{rec/sel}}$: reconstruction/selection efficiency
- ✓ Δy: width of the rapidity bin
- ✓ L: integrated luminosity
- ✓ $\epsilon_{\mathrm{single}}=\mu e^{-\mu}$: fraction of single interaction beam-crossings, assuming number of visible pp interactions follows Poisson distribution

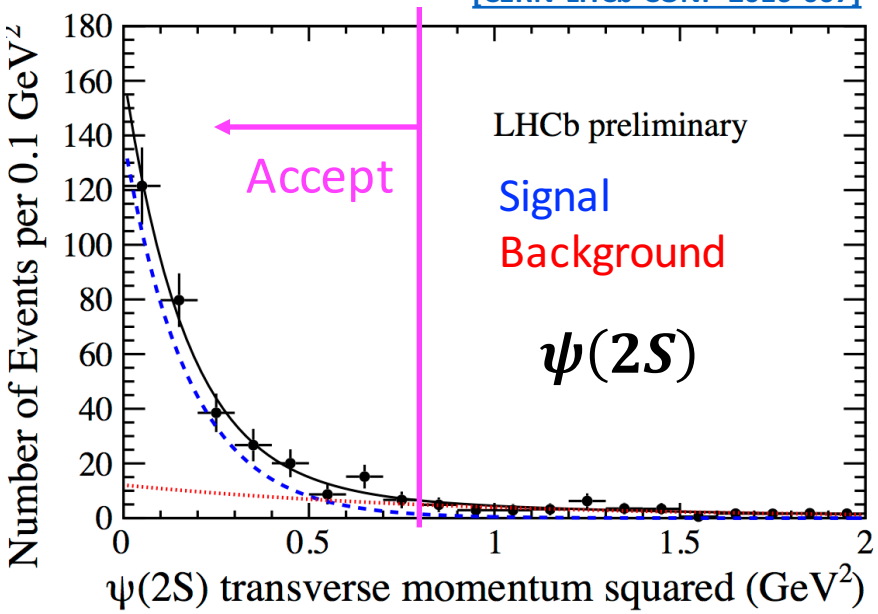
$$P(n)=\mu^n e^{-\mu}/n!$$

Signal purity p

- Remaining background sources
  1) Non-resonant dimuon: fit to $M(\mu^+\mu^-)$ distribution
  2) Feed-down of CEP χ_c or $\psi(2S)$ to J/ψ
     - $\boldsymbol{\psi(2S)}$: determined using simulated events normalized to $\psi(2S) \to \mu^+\mu^-$ signal in data
     - $\boldsymbol{\chi_c}$: determined using calibration sample reconstructed with $J/\psi + \gamma$, scaled by the ratio of J/ψ to $J/\psi + \gamma$ in the simulated χ_c sample
  3) Non-exclusive events where remnants are undetected

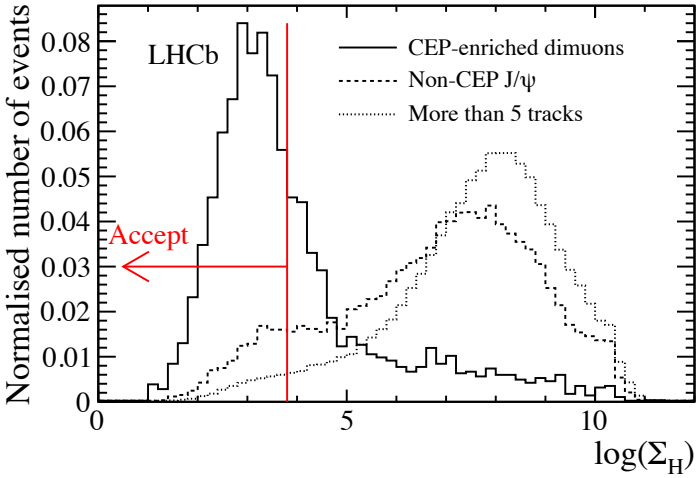
[CERN-LHCb-CONF-2016-007]





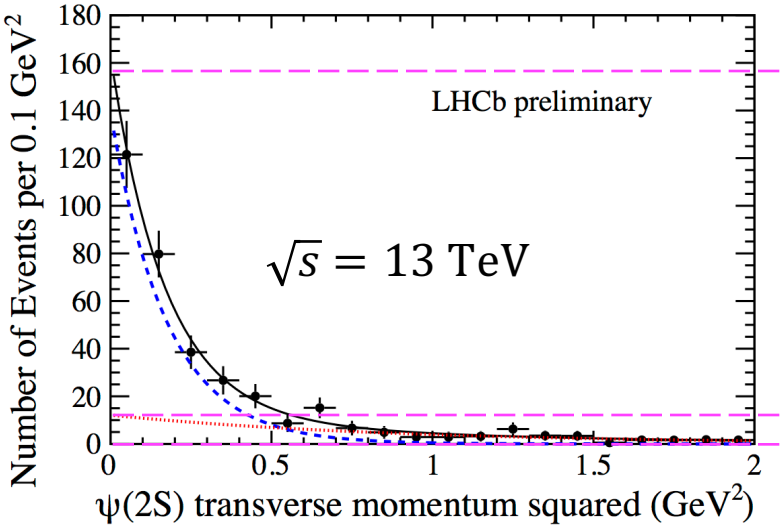
Utilization of HERSCHEL

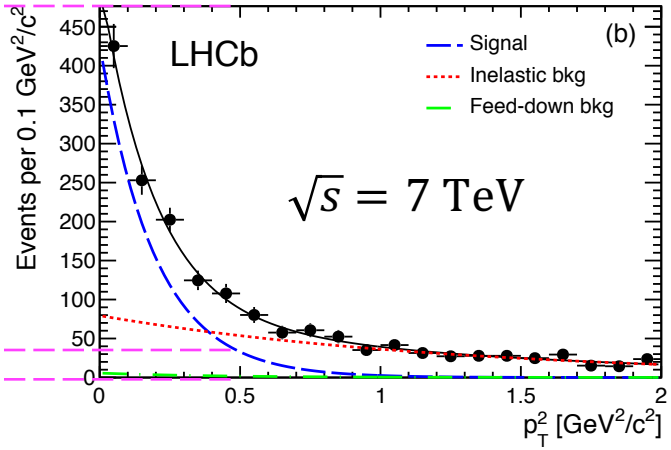
- Good discrimination between CEP and non-CEP candidates



[CERN-LHCb-CONF-2016-007]

- Background level roughly halved compared to RunI analysis





$\psi(2S)$

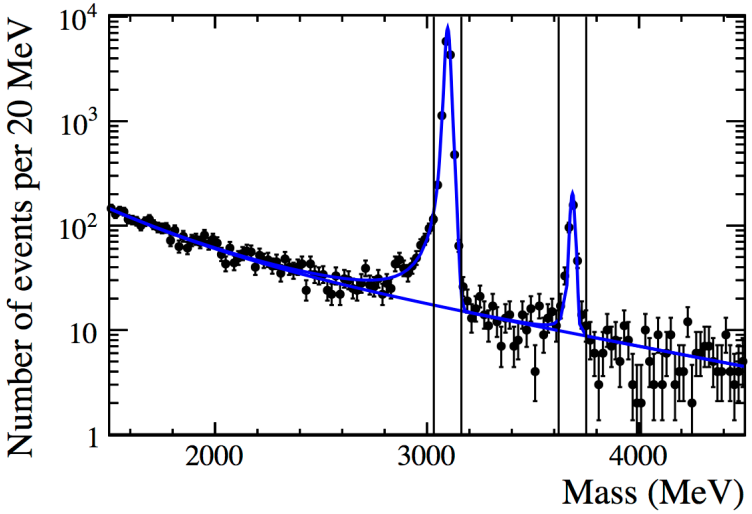
[CERN-LHCb-CONF-2016-007]

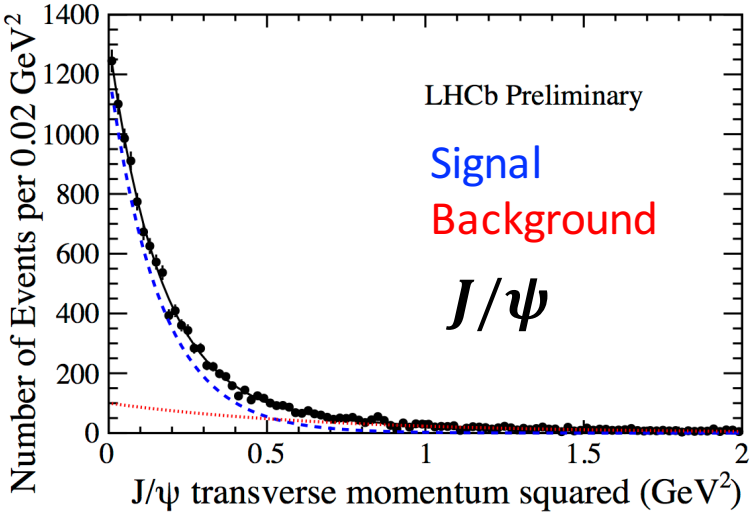
[J. Phys. G41 (2014) 055002]

Efficiencies ϵ_{rec} and ϵ_{sel}

- Reconstruction efficiency ϵ_{rec}
  - ✓Product of trigger, tracking and muon identification efficiency
  - ✓Each determined from simulation and calibrated using data
- Selection efficiency ϵ_{sel}
  - ✓$\boldsymbol{M(\mu^+\mu^-)}$ **cut**: fit to $M(\mu^+\mu^-)$ distribution
  - ✓$\boldsymbol{p_T^2(\mu^+\mu^-)}$ **cut**: fit to $p_{\mathrm{T}}^2(\mu^+\mu^-)$ distribution

[CERN-LHCb-CONF-2016-007]





- ✓**Veto** on VELO, HERSCHEL or photon activity: fit to $p_{\mathrm{T}}^2(\mu^+\mu^-)$ distribution of non-resonant data sample with/without the cut

Systematic uncertainties

Source	J/ψ analysis Uncertainty (%)	$\psi(2S)$ analysis Uncertainty (%)
Proton dissociation	4.0	4.0
Tracking efficiency	4.0	4.0
Non-resonant background	0.1	1.4
Feed-down background	0.6	-
Mass-window	0.4	0.4
HERSCHEL Veto	1.5	1.5
Luminosity	3.9	3.9
Total excluding luminosity	5.9	6.1

[CERN-LHCb-CONF-2016-007]

- Proton dissociation:

  Uncertainty due to imperfect modelling in the fit to $p_T^2(\mu^+\mu^-)$; determined using alternative models

- Tracking efficiency:

  Uncertainty due to variation of efficiencies determined from the calibration data sample

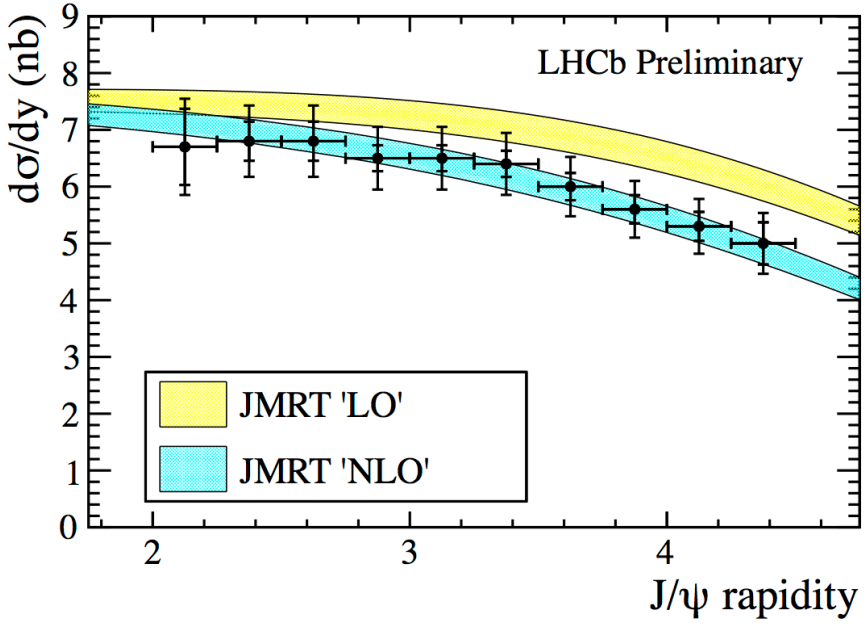
Cross-sections

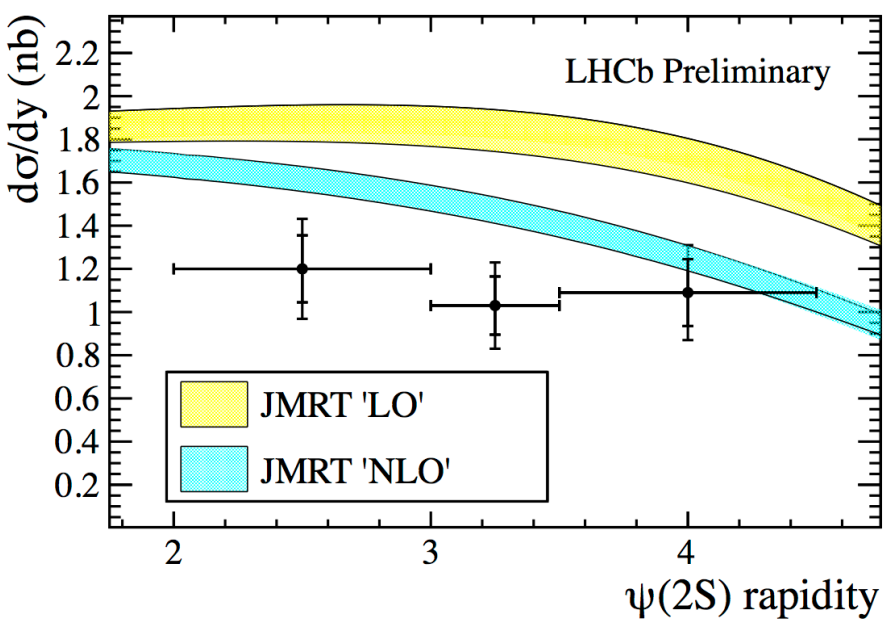
- Total cross-sections

$$\sigma_{J/\psi\to\mu^+\mu^-}\left(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5\right)=407\pm8(\text{stat})\pm24(\text{syst})\pm16(\text{lumi})\ \text{pb}$$

$$\sigma_{\psi(2S)\to\mu^+\mu^-}\left(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5\right)=9.4\pm0.9(\text{stat})\pm0.6(\text{syst})\pm0.4(\text{lumi})\ \text{pb}$$

- Differential cross-sections with respect to rapidity
  - ✓Better agreement with JMRT NLO predictions [JHEP 11 (2013) 085] [J. Phys. G41 (2014) 055009]



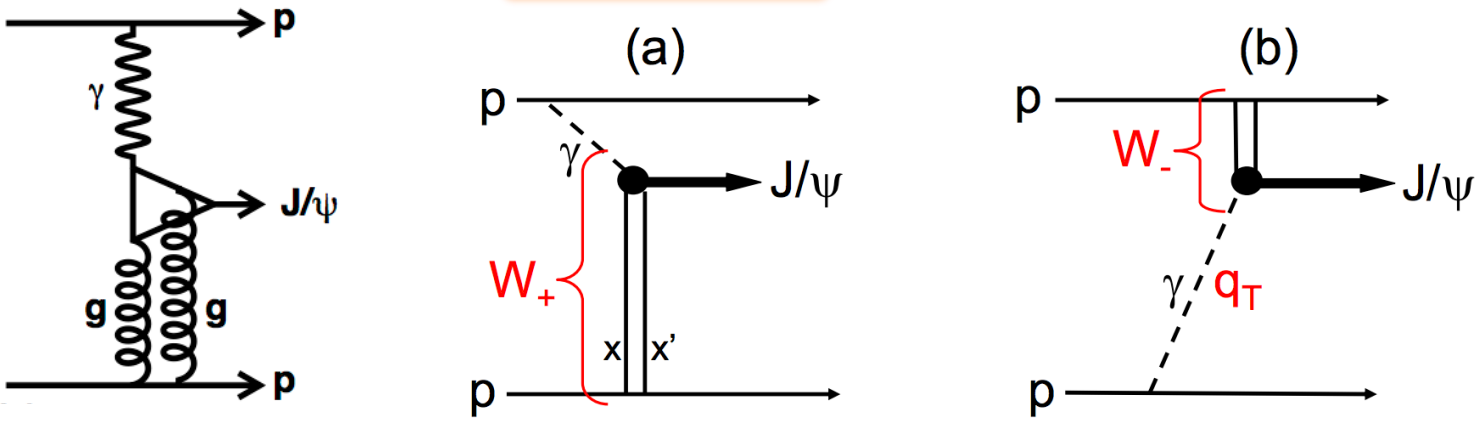


[CERN-LHCb-CONF-2016-007]

Photo-production cross-section

➢ Relation with the photo-production cross-section $\sigma_{\gamma p\to\psi p}$

$$\sigma_{pp\to pXp} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W^+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W^-)$$



[JHEP 11 (2013) 085]

✓ $r(W_\pm)$: gap survival factor; taken from previous studies

✓ $k_\pm$: photon energy, $= m_\psi/2\times e^{\pm|y|}$

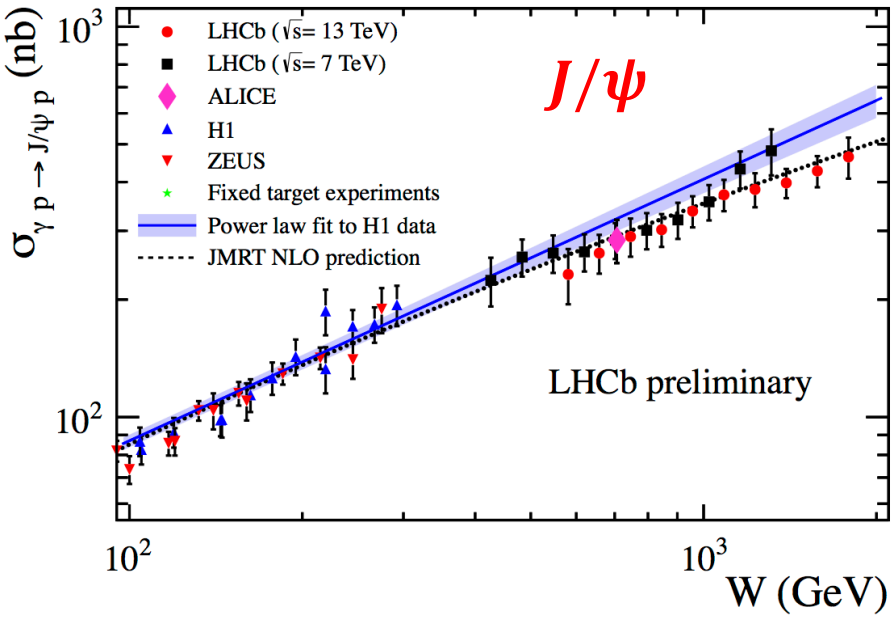
✓ $\frac{dn}{dk_\pm}$: photon flux; taken from previous studies

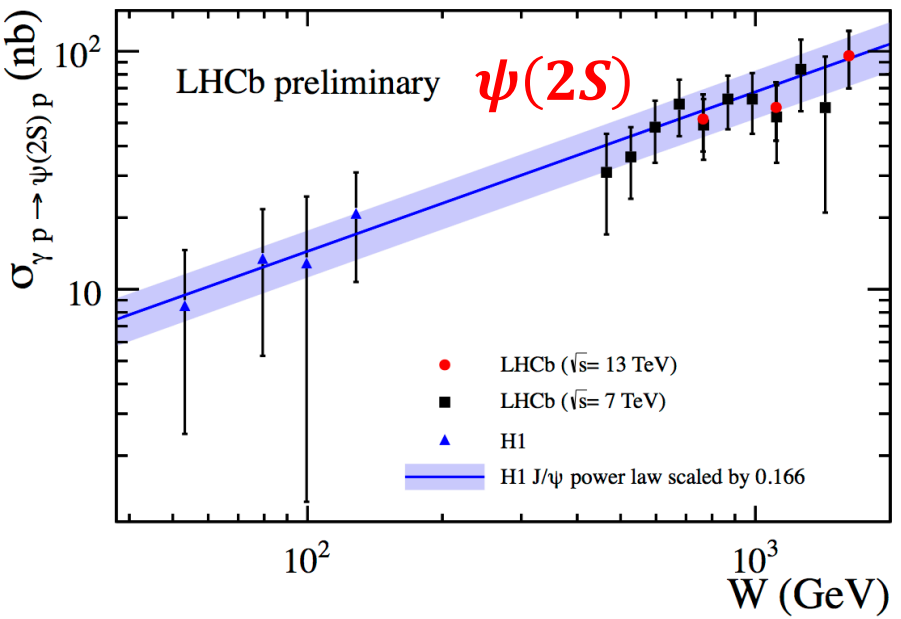
✓ $W_\pm$: center-of-mass energy of the photon-proton system;

$$W_\pm = \sqrt{m_\psi \times e^{\pm|y|} \times \sqrt{s}}$$

can explore $W = 2$ TeV with $\sqrt{s} = 13$ TeV data collected by LHCb; the highest energy so far!

Photo-production cross-section (cont.)





- J/ψ production:
  - ✓In agreement with 7 TeV results where they overlap
  - ✓Reach extended to $W \sim 2$ TeV
  - ✓Deviation from the power-law fit to H1 data at highest energies
  - ✓Good agreement with JMRT NLO prediction [JHEP 11 (2013) 085] [J. Phys. G41 (2014) 055009]

[J. Phys. G41 (2014) 055002] [CERN-LHCb-CONF-2016-007]

- $\psi(2S)$ production:
  - ✓Good agreement with H1 data extrapolation, which is scaled from the J/ψ power-law fit
  - ✓Larger statistics needed

Summary

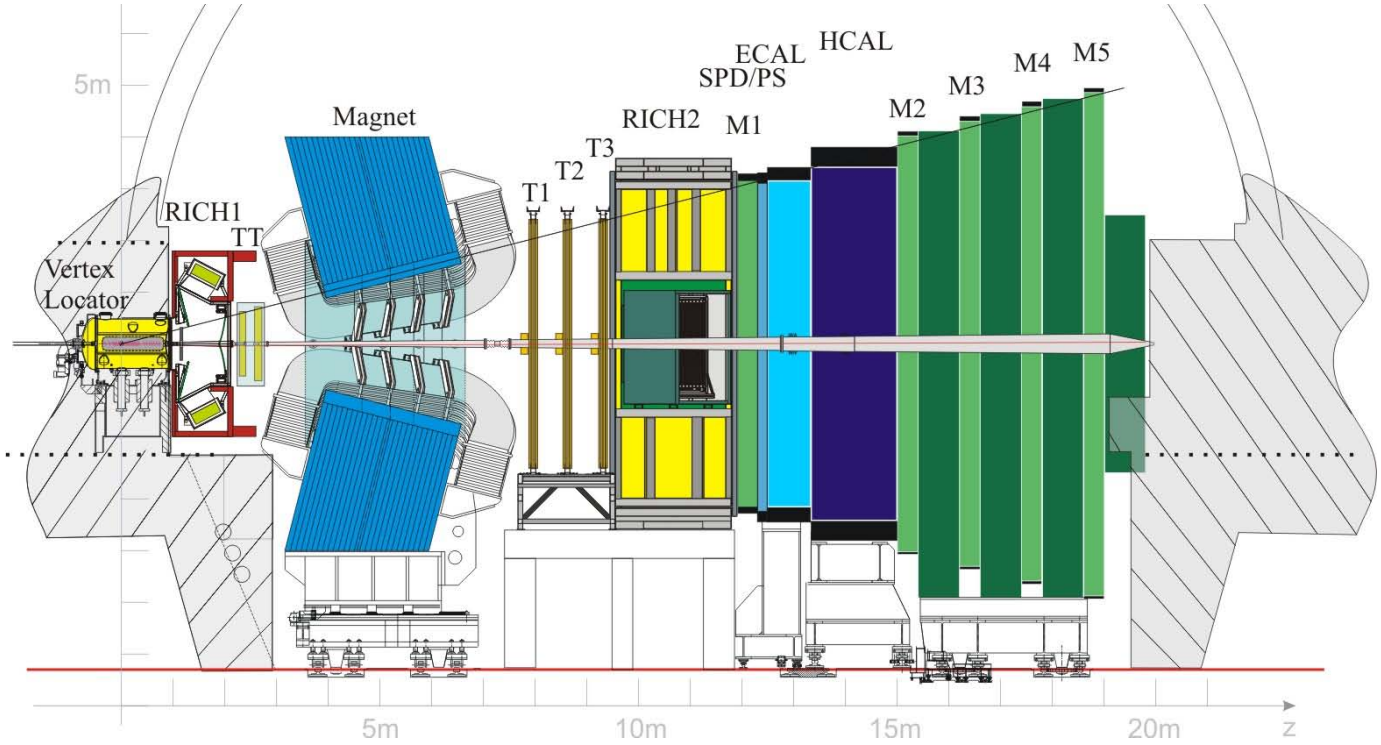
- Central exclusive J/ψ and $\psi(2S)$ production at $\sqrt{s} = 13$ TeV measured using data collected by LHCb
  - ✓Low background level shows good performance of HERSCHEL
  - ✓Both J/ψ and $\psi(2S)$ show better agreement with JMRT NLO prediction
  - ✓The photo-production cross-section of J/ψ shows deviation from power-law extrapolation of HERA data
  - ✓More data is needed to make a critical comparison for $\psi(2S)$

Thank you!

Backup

The LHCb detector

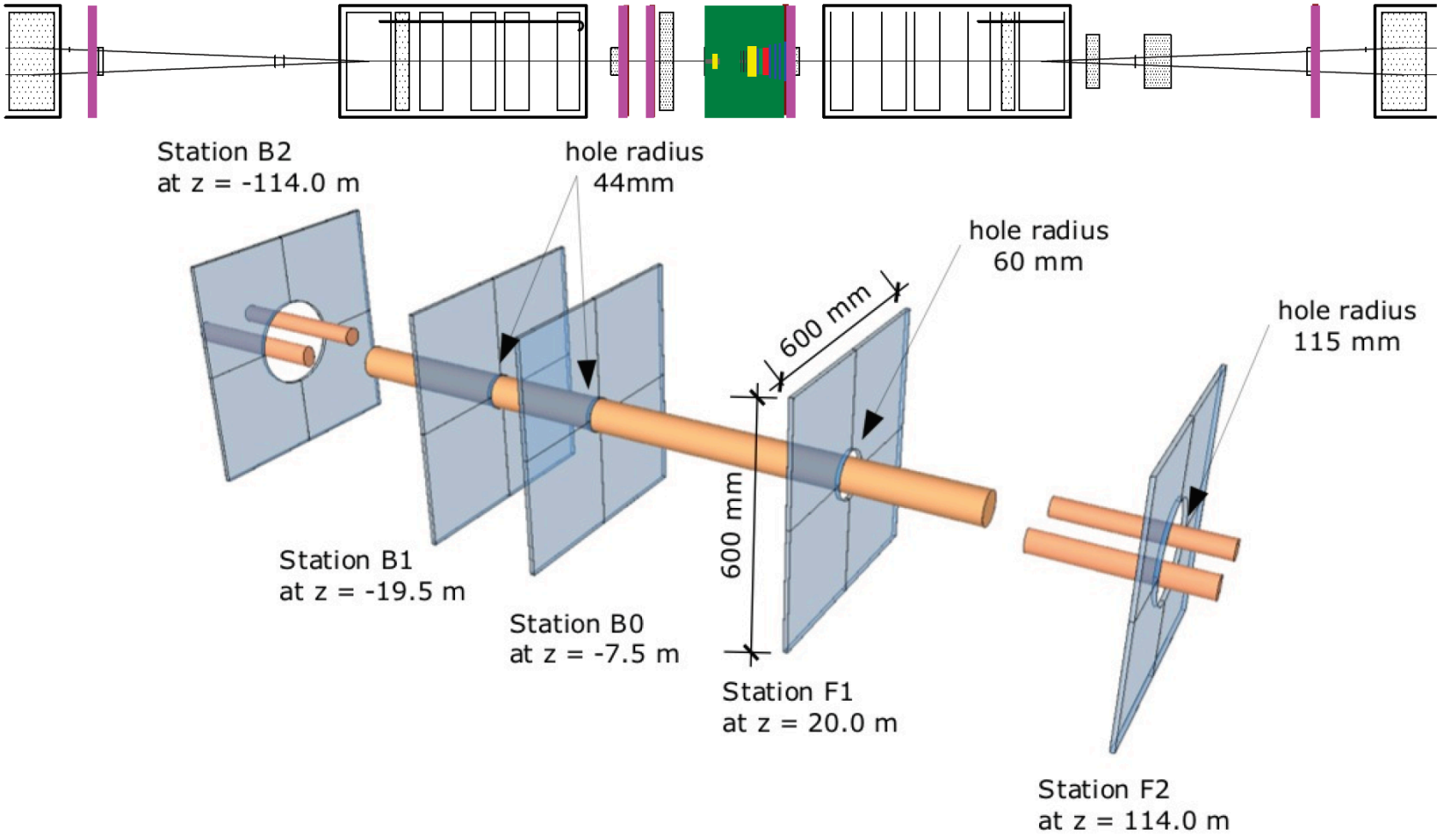
➢A single-arm forward region spectrometer covering $2 < \eta < 5$



[JINST 3 (2008) S08005]

- ✓ **Vertex Locator:** $\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}, \sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
- ✓ **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100\ \mathrm{GeV}/c$
- ✓ **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- ✓ **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- ✓ **ECAL:** $\sigma_E/E \sim 10\%/\sqrt{E} \otimes 1\%$ (E in GeV)
- ✓ **HCAL:** $\sigma_E/E \sim 70\%/\sqrt{E} \otimes 10\%$ (E in GeV)

Herschel



VELO&Herschel: $-10 < \eta < -5, -3.5 < \eta < -1.5, 1.5 < \eta < 10$

HepData record

- Record of J/ψ and $\psi(2S)$ in CEP at $\sqrt{s} = 7$ TeV: http://dx.doi.org/10.17182/hepdata.66883

- Record of J/ψ and $\psi(2S)$ in CEP at $\sqrt{s} = 13$ TeV will be available when the paper is published