Central Exclusive Production and Soft QCD at LHCb

Lavinia-Elena Giubega

*on behalf of LHCb collaboration

Horia Hulubei National Institute for Physics and Nuclear Engineering

(IFIN-HH), Bucharest, Romania

Low-x Workshop,

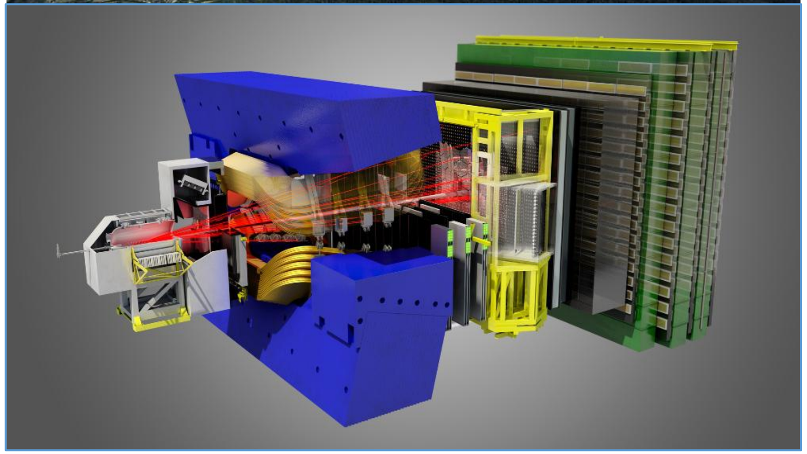
Nicosia, Cyprus

25-31 August 2019

LHCb experiment

- LHCb is one of the four main experiments on the LHC ring

- Its aim is to investigate the decays of hadrons that contain b&c quarks and so provide insight into the phenomenon of matter-antimatter asymmetries.



- The collaboration comprises of 1355 physicists and engineers from 79 institutes in 18 Countries

JINST 3 (2008) S080005

LHCb detector

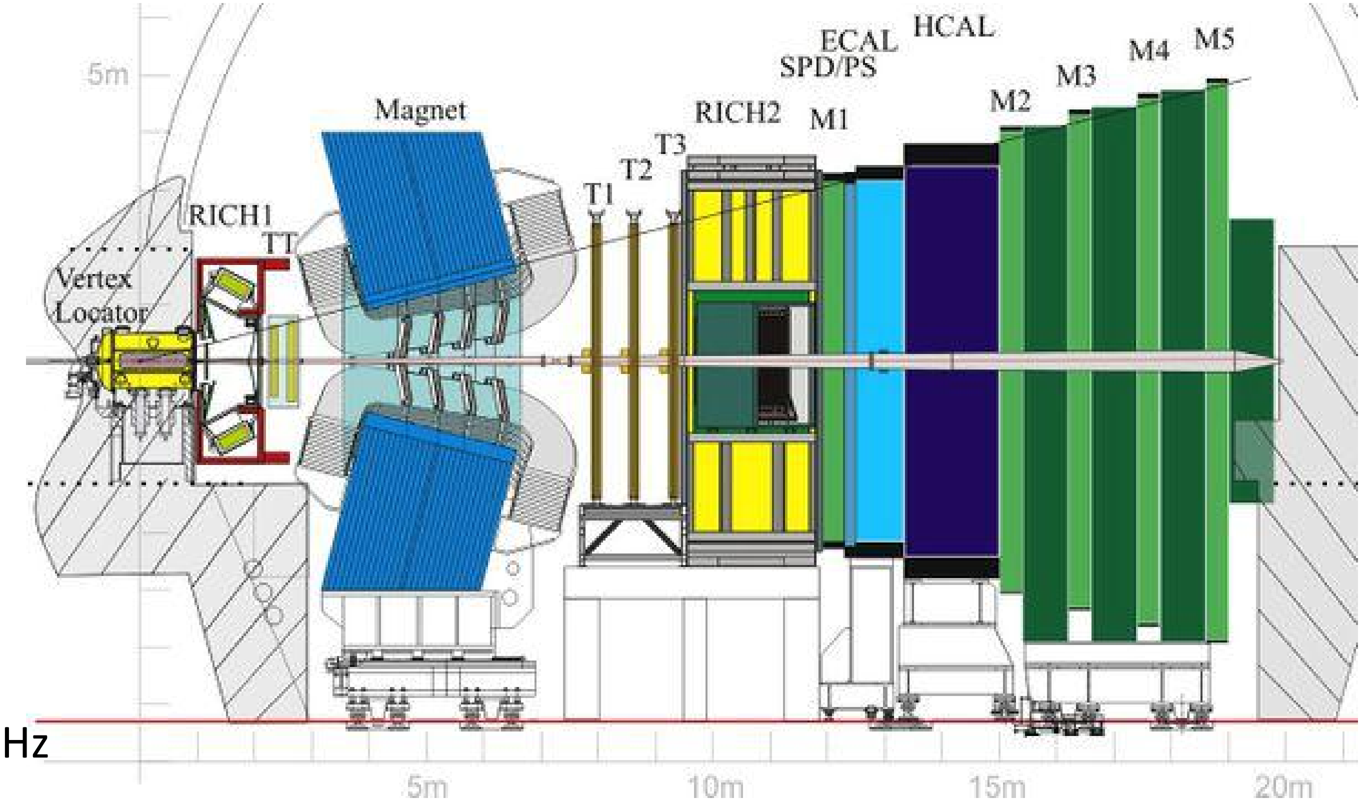
- The tracking system: VErtex LOcator (VELO) +T stations
- Two Ring Imaging Cherenkov detectors (RICH1 and RICH2): charged hadron identification in the momentum range from 2 to 100 GeV/c
- The calorimeter system:
- Scintillating Pad Detector (SPD)
- PreShower (PS)
- Electromagnetic Cal (ECAL)
- Hadronic Cal (HCAL)
- Muon detection system: M1-M5

- IP (impact parameter) resolution: 20 µm @ high-pT
- Momentum resolution:$\Delta p/p$=0.5 % at low momentum to 1.0% at 200 GeV/c
- Track reconstruction eff: ~96% for long tracks

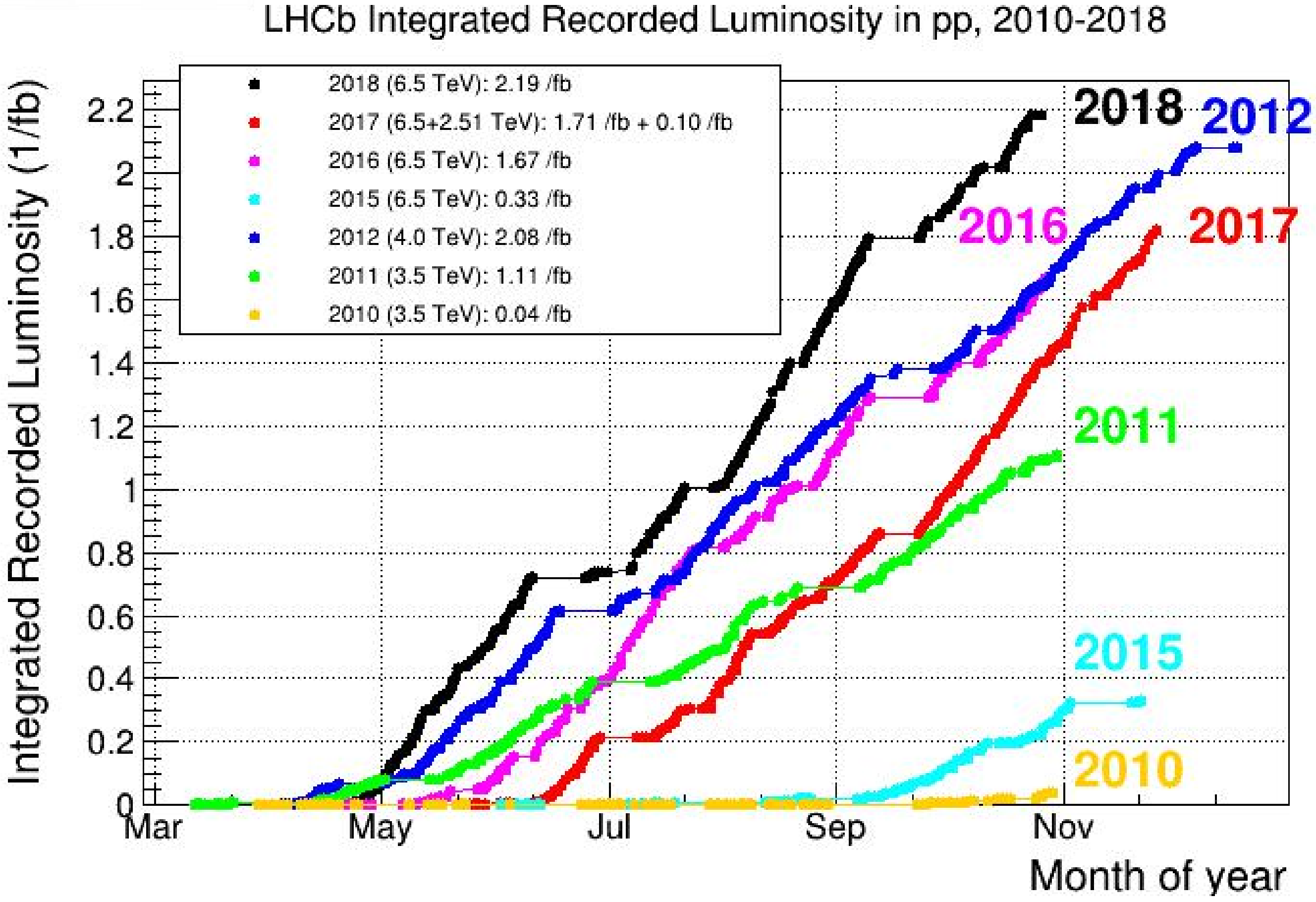
LHCb trigger: hardware -> reduces 40 MHz of data to 1 MHz
software trigger → 4 kHz

Unique pseudorapidity range:

- forward range:$2<\eta<5$
- backward range $-3.5<\eta<-1.5$



Ammount of data+LHCb upgrade



~ 10 fb^{-1} data recorded in RUN1+RUN2
after LS2: 50 fb^{-1}

After LS2(2021):

- proton–proton collision rate at LHCb will be increased by a factor of five
- the whole detector will read at the full rate of 40 MHz to allow event selection to be done more precisely and flexibly by the software
- RICH detectors will be equipped with a new mirror system.
- New silicon-microstrip sensors and SciFi tracking

more statistics -> reduced uncertainties

Latest LHCb public results:

13 July 2019: Observation of two new beauty baryon particles.

28 June 2019: Updated measurement of the CP-violating phase ϕs.

26 March 2019: Observation of new pentaquarks.

21 March 2019: Discovery of CP violation in charm particle decays.

http://lhcb-public.web.cern.ch/lhcb-public/

To be covered:

- **CEP results at LHCb @ 7 TeV:** Updated measurements of exclusive J/ψ andψ(2S) production cross-sections in pp collisions at √s=7 TeV [J. Phys. G 41 (2014) 055002]

- **Ion collisions:** Study of coherent J/ψ production in lead-lead collisions at √s=5 TeV with the LHCb experiment [LHCb-CONF-2018-003]→ Preliminary results

- **CEP with HeRSCHeL @LHCb:** Central exclusive production of J/ψ and ψ(2S) mesons in pp collisions at √s = 13 TeV [JHEP 10 (2018) 167]

- **SoftQCD@LHCb:** Measurement of the inelastic pp cross-section at centre-of-mass energie of √s = 13 TeV [JHEP 06 (2018) 100]

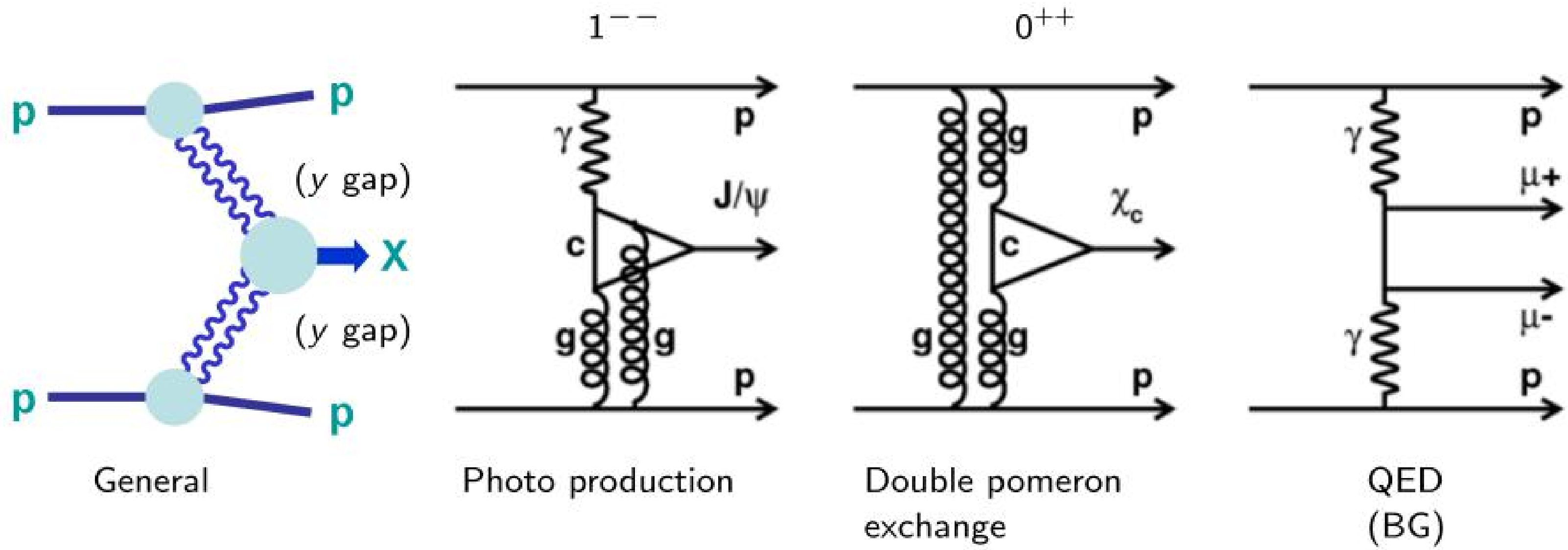
HepData record:

- record for J/ψ and ψ(2S) in CEP at 7 TeV: https://doi.org/10.17182/hepdata.66883

- record for inelastic cross-section measurement at 13 Tev: https://doi.org/10.17182/hepdata.89782

Introduction

- CEP is the process in which particles are produced by colourless propagators via the reaction *pp→p+X+p*



Signal signature

- ❑ central system
- ❑ large rapidity gaps between central system and outgoing protons

Background

- ❑ diffractive processes involving proton dissociation

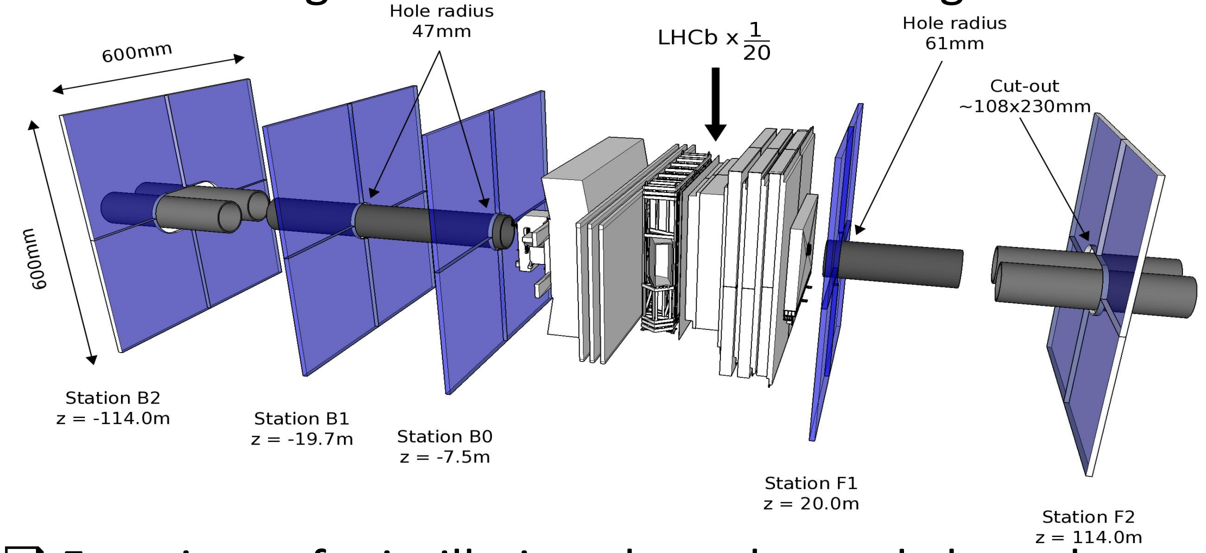
Possibilities

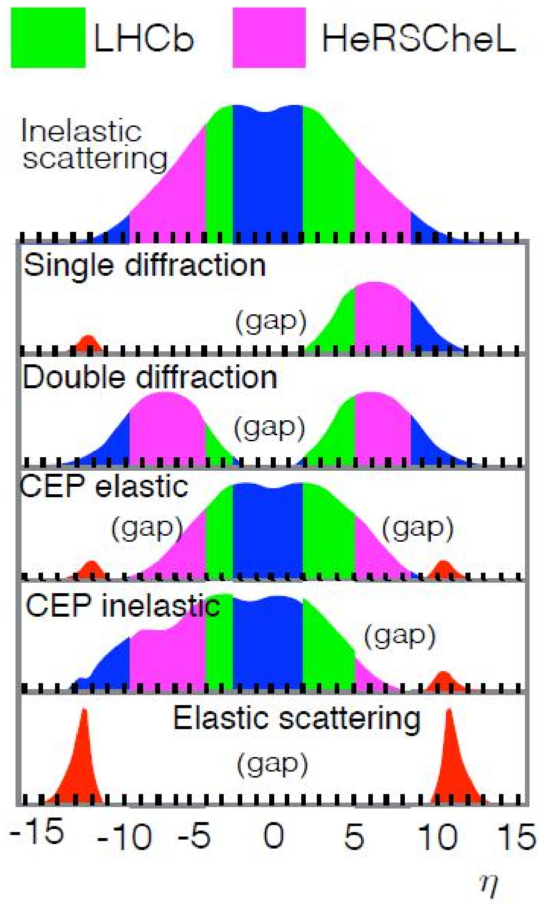
- ❑ transition between soft and hard pomeron → Soft QCD
- ❑ very clean final state →high benefit

JINST 13 (2018) 04

HeRSCheL-LHCb forward extension

The LHCb experiment is rapidly becoming a major actor in CEP searches, the HeRSCheL subdetector is now allowing to reduce the non-CEP background to a minimum





- ❑ 5 stations of scintillating planes located along the beampipe
- ❑ sensitive to activity (no tracking)

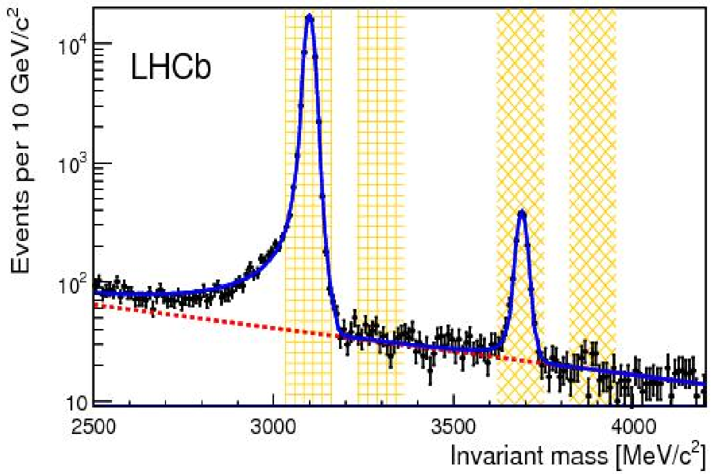
Detecting a CEP event requires the detection of rapidity gaps in the distribution of the final state particles

➤ HeRSCheL largely extends the ability to veto diffractive final states

J. Phys. G 41 (2014) 055002]

CEP published results at LHCb

J/ψ and ψ(2S) production @ 7 TeV



without HeRSCHeL

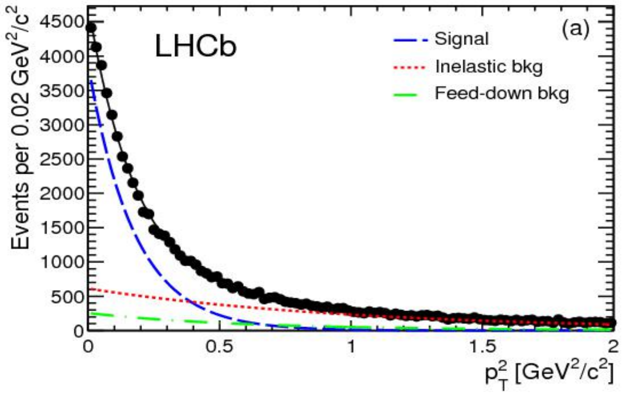
- 930 pb^{-1} of 2011 data at 7 TeV
- exactly two muons in the acceptance
- p_T (μ) >400 MeV/c

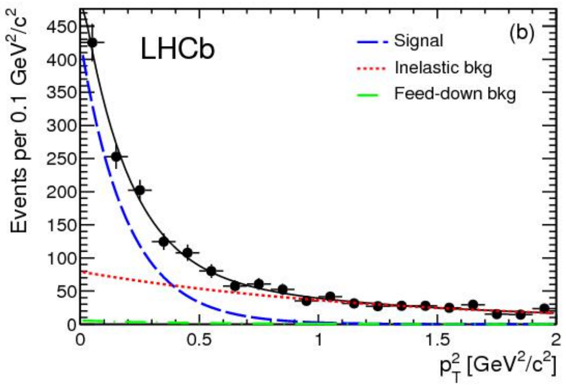
in good agreement with JMRT NLO theoretycal prediction

J. Phys.G41 (2014) 055009
[S. Jones, A. Martin, et. al]

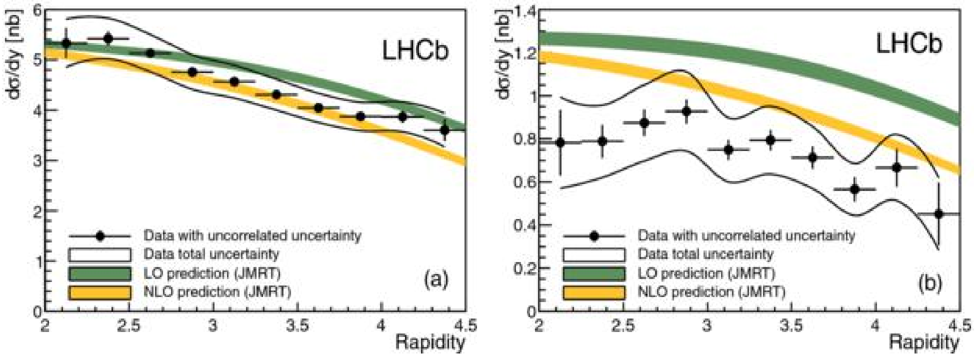
$$\sigma_{pp\to J/\Psi\to\mu^+\mu^-}(2.0<\eta_{\mu^\pm}<4.5) = 291\pm7\pm19\text{pb}$$

$$\sigma_{pp\to\Psi(2S)\to\mu^+\mu^-}(2.0<\eta_{\mu^\pm}<4.5) = 6.5\pm0.9\pm0.4\text{pb}$$





Transverse momentum squared distributions for (a) J/ψ and (b) ψ(2S)



Differential cross-section for (a) J/ψ and (b) ψ(2S) production compared to LO and NLO predictions

LHCb-CONF-2018-003

Coherent J/ψ production in lead-lead collisions at 5 TeV

Ultraperiheral collisions (UPC)

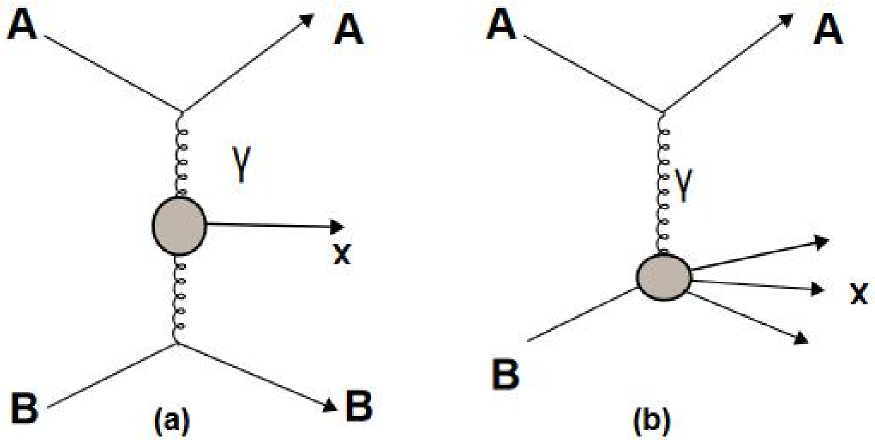
Introduction

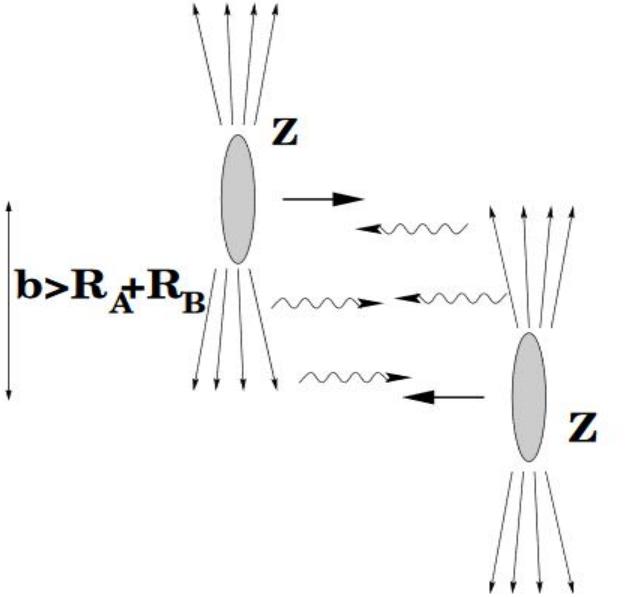
- reactions in which two ions interact via their *cloud* of virtual photons
- intensity of the electromagnetic field proportional with Z^2

UPC interactions

Caracteristics:

- ✓ low momentum transfer
- ✓ low transverse momentum
- ✓ the nucleus that emits the photon remains intact after the collision → no aditional particles





from Phys.Rept. 458 (2008) 1-171

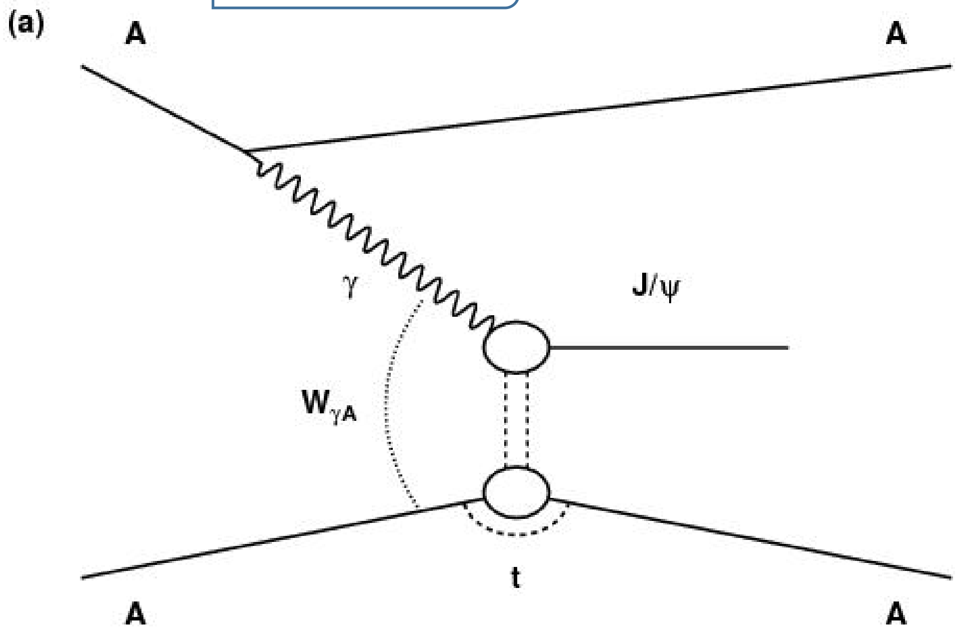
a) photon-photon collisions b) photonuclear collisions

Introduction

UPC photonuclear collisions

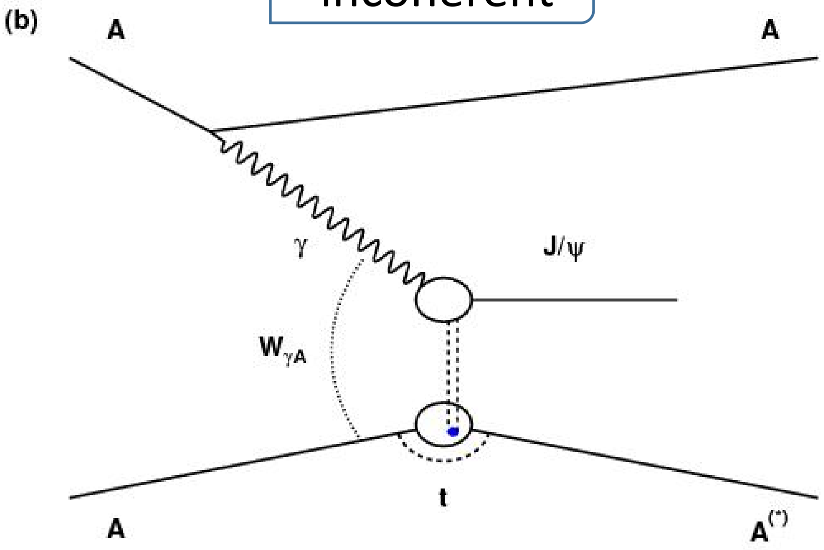
from Cepila, Jan et al. Phys.Rev. C97 (2018) no.2, 024901

coherent



a) the photon interacts with the whole nucleus

incoherent



b) the photon interacts with a single nucleon inside the nucleus

LHCb-CONF-2018-003

Data selection and mass fit

Coherent J/ψ production in PbPb ->Pb+J/ψ+Pb: γ "pomeron" →J/ψ

- Data set: lead-lead collisions at √s=5 TeV in 2015

- Event selection:

Hardware level: $J/\psi \to \mu^+\mu^-$

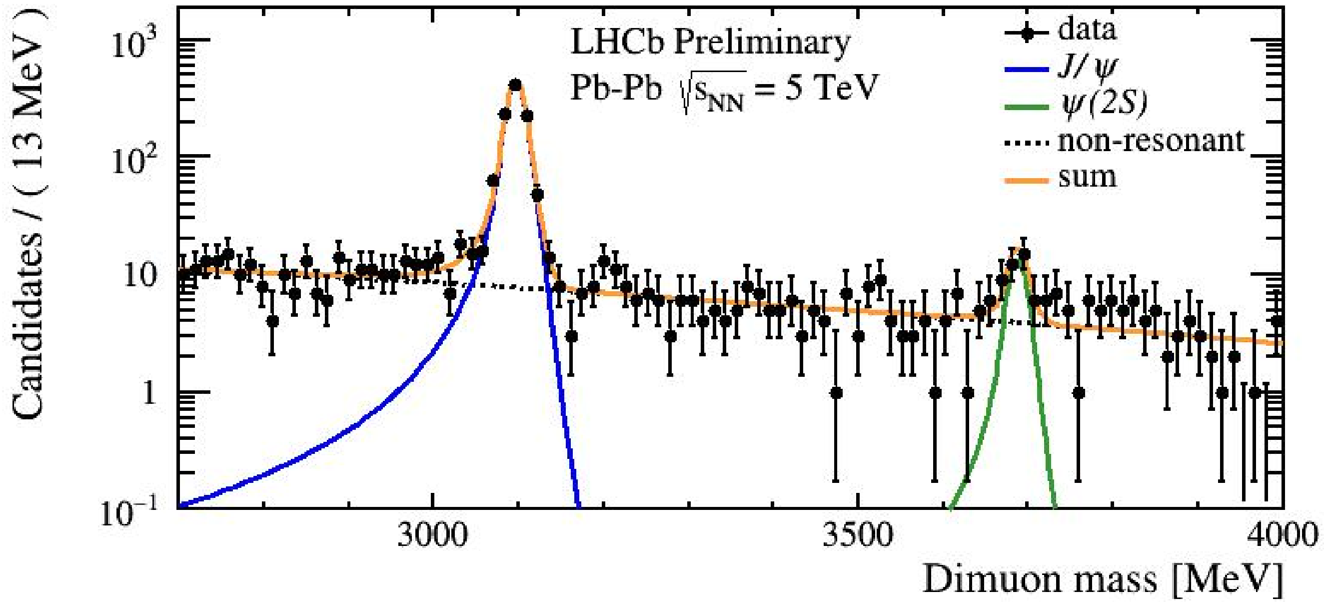
p_T (μ)>900 MeV

Software level: $M_{\mu+\mu-}$>2.7 GeV

- Offline selection:

muon selection: p_T>500 MeV in 2<η<5

J/ψ selection: p_T<1 GeV



J/ψ and ψ(2s): double sided Crystal-Ball function

non-resonant: exponential multiplied by a first-order polynomial

Signal determination and p_T fit

Signal yield determination

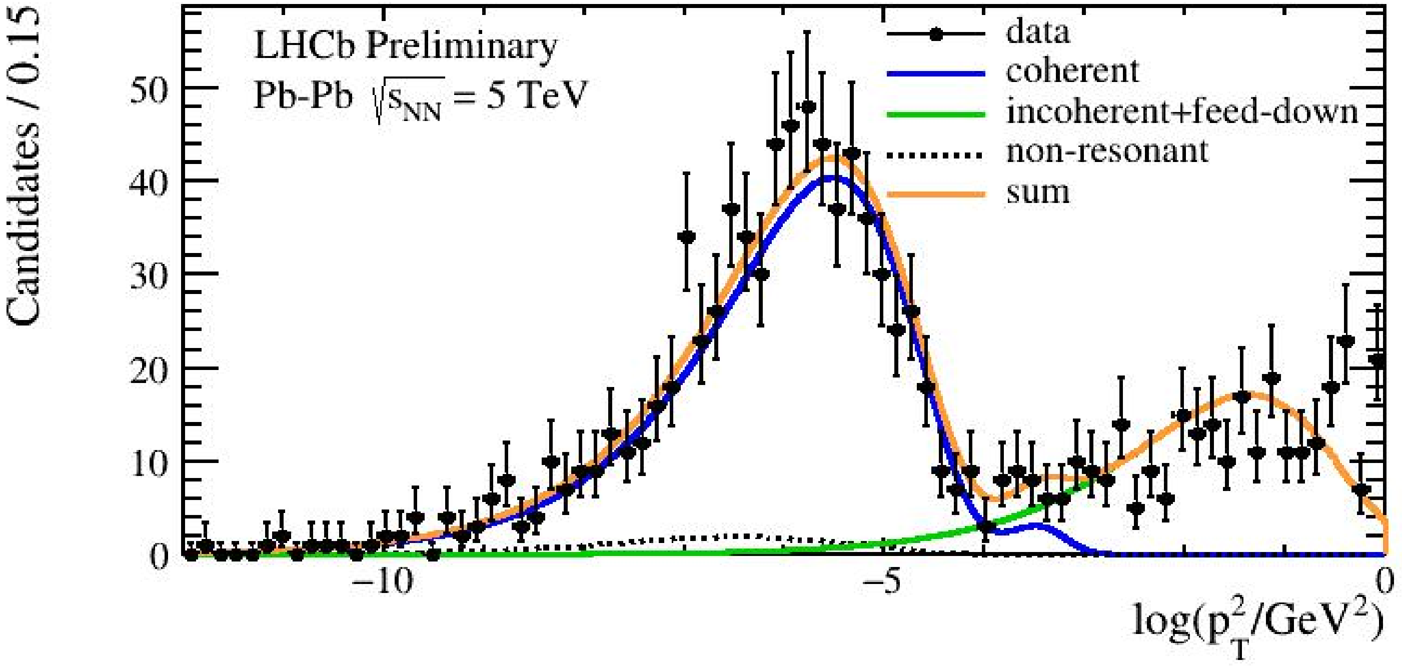
- 1st step:

fit on the invariant mass to determine all the J/ψ candidates (coherent and incoherent J/ψ, feed-down coming from ψ(2s))

- 2nd step:

fit on the $\log(p_T^2)$ of J/ψ to determine the signal yield in the presence of bkg. (incoherent J/ψ and feed-down ψ (2S))

background and signal are modelled by templates taken from the STARlight event generator



Distribution of $\log(p_T^2)$ of dimuon candidates.

Differential cross-section

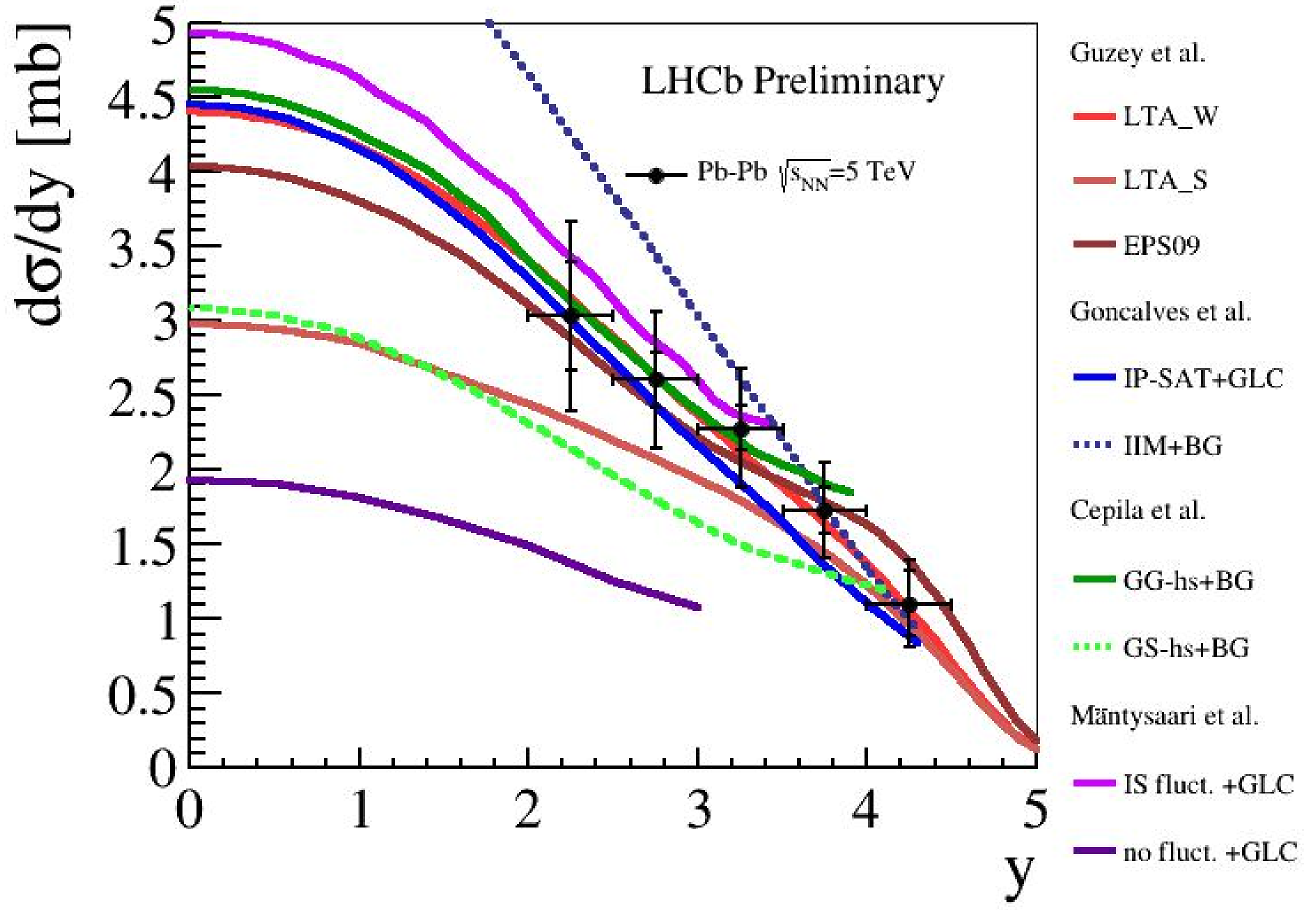
Coherent cross-section:

LHCb preliminary

σ=5.3 ±0.2(stat.)±0.5(syst)±0.7(lumi) mb

The analysis is repeated in bins of half unit rapidity y J/ψ

J/ψ rapidity	$d\sigma/dy$ (mb)
2.00-2.50	$3.0 \pm 0.4 \pm 0.3$
2.50-3.00	$2.60 \pm 0.19 \pm 0.25$
3.00-3.50	$2.28 \pm 0.15 \pm 0.21$
3.50-4.00	$1.73 \pm 0.15 \pm 0.17$
4.00-4.50	$1.10 \pm 0.22 \pm 0.13$



JHEP 10 (2018) 167

CEP with HeRSCheL@LHCb

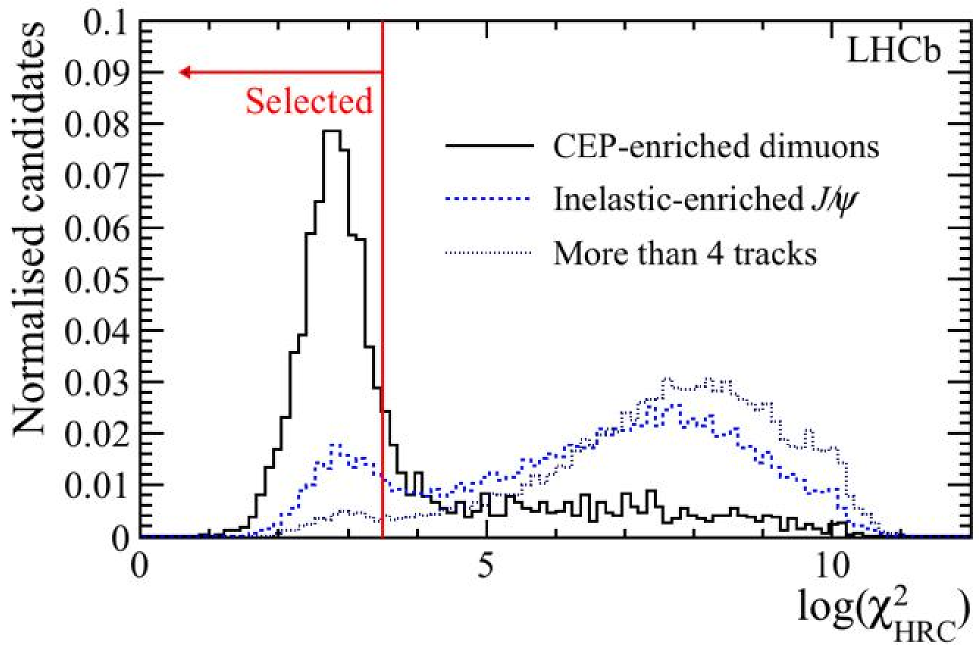
Central exclusive production of J/ψ and ψ(2S) mesons in pp collisions at √s = 13 TeV

- ❑ Measurement performed with 204 pb^{-1} data at 13 TeV

- ✓ μ=1.1 → half of the visible interactions there is a single pp collision

- ❑ Trigger requirements:

- ✓ Hardware: less than 30 deposits in the scintillating-pad detector (SPD); at least one muon with $p_T > 200$ MeV/c
- ✓ Software: < 10 reconstructed tracks; at least one reconstructed muon

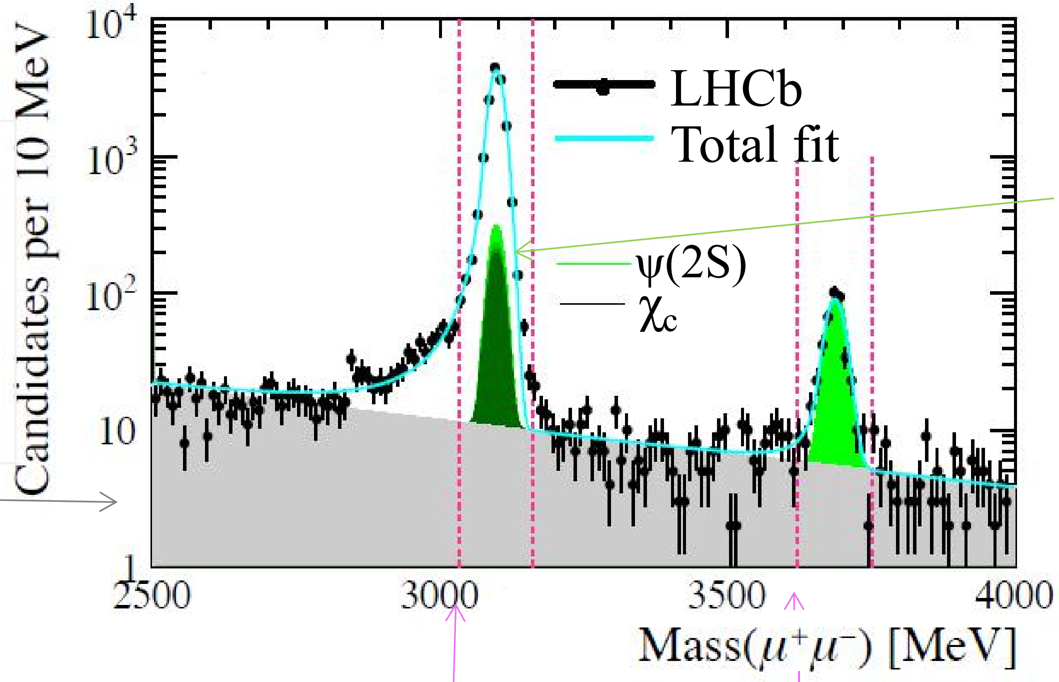


- ✓ 2 reconstructed muons in 2<η<4.5
- ✓ mass within 65 MeV/c^2 from J/ψ or ψ(2S) mass
- ✓ p^2_T<0.8GeV^2

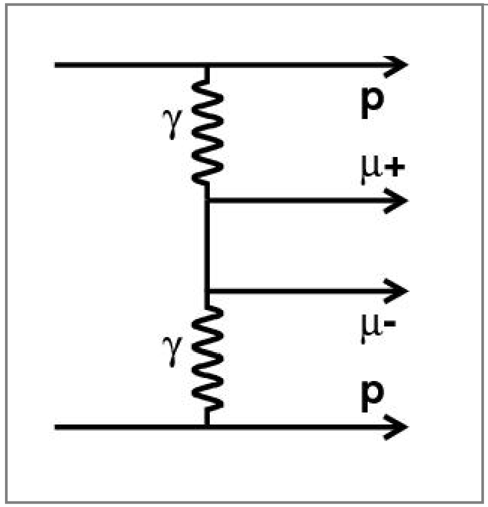
JHEP 10 (2018) 167

$pp \rightarrow p + \mu^+\mu^- + p$ signal and background

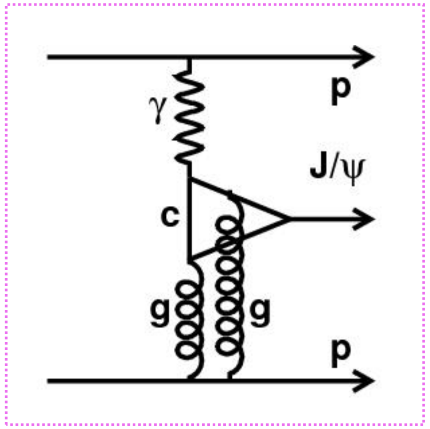
Non-resonant background
continuum lepton pair production

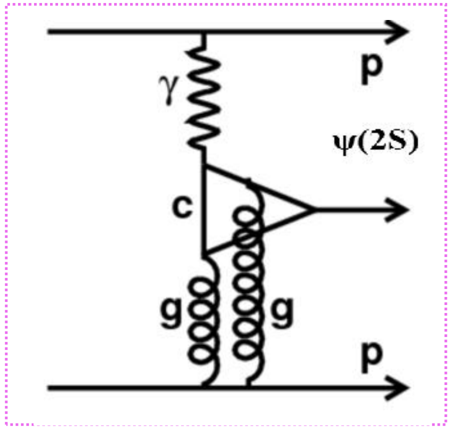


Feed-down background:
ψ(2S)/χ_c - undected remaining particles produced in association with J/ψ or outside the detector



❑ Signal



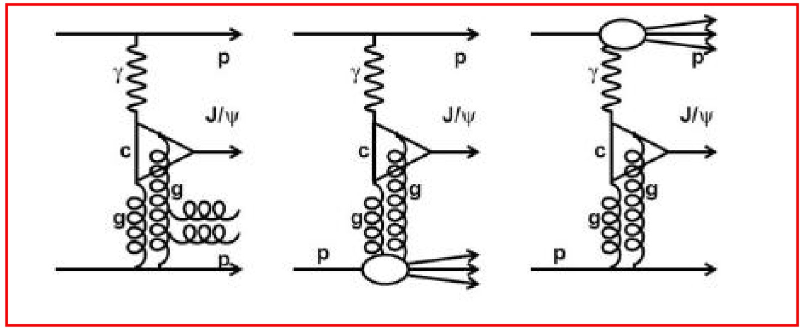


Proton dissociation contamination →

JHEP 10 (2018) 167

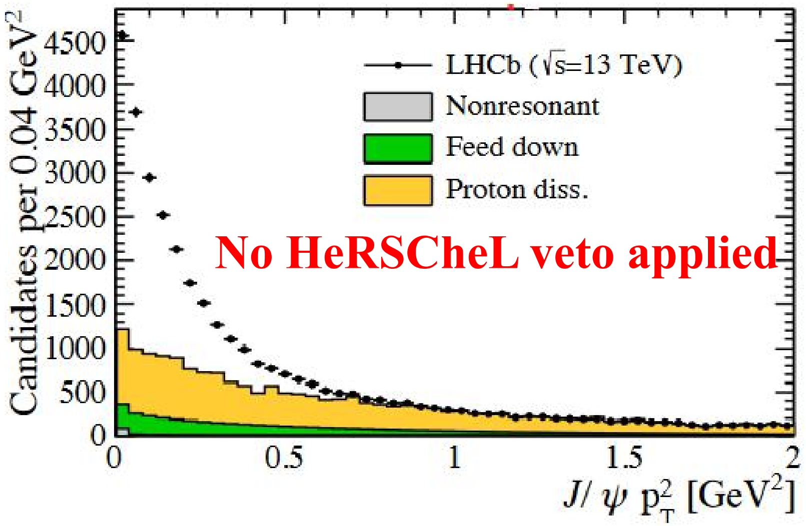
Proton dissociation background

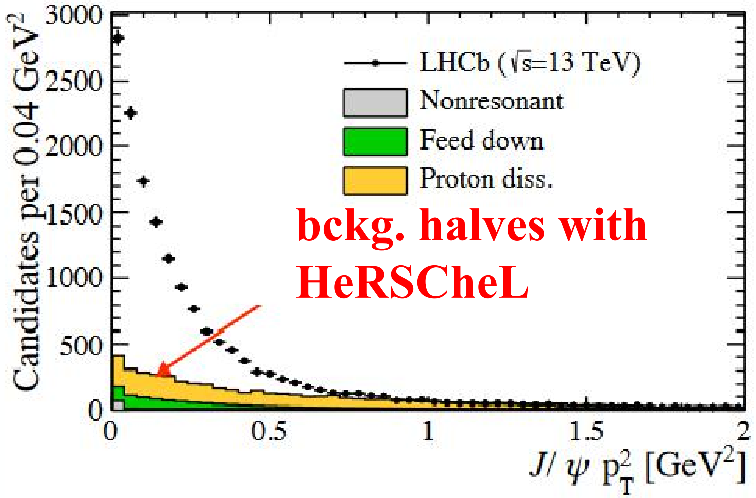
Inelastic production of mesons:
one or both protons dissociate or gluon radion



Ways to extract the proton dissociation background:

- fit data with 2 exponentials (one for the signal and one for the pr. diss. bkg)
- use the two independent samples below and above HeRSCheL veto to constrain the background





JHEP 10 (2018) 167

Cross section results

- Total cross-section

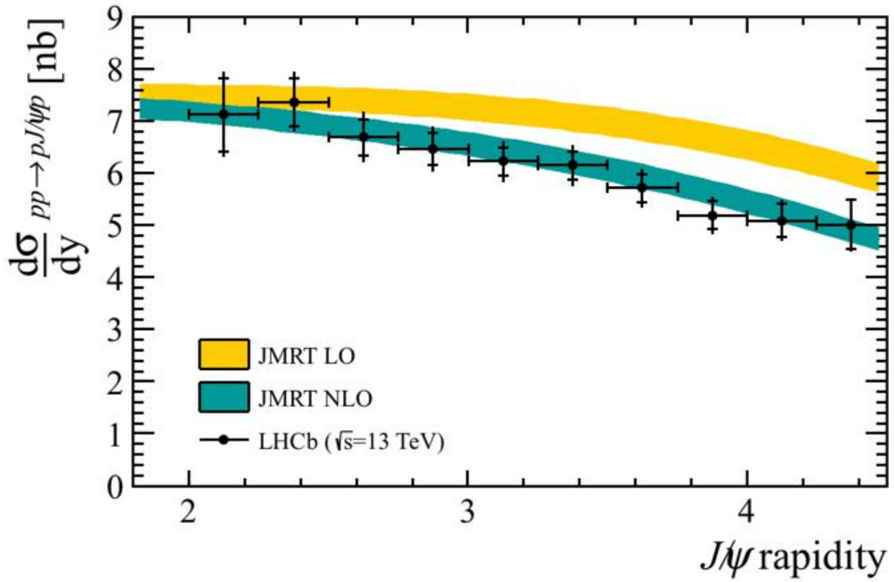
$\sigma_{J/\psi\to\mu+\mu-}$ (2 < η_μ <4.5)=399 ± 16(stat.) ± 10 (syst.)± 16 (lumi) pb

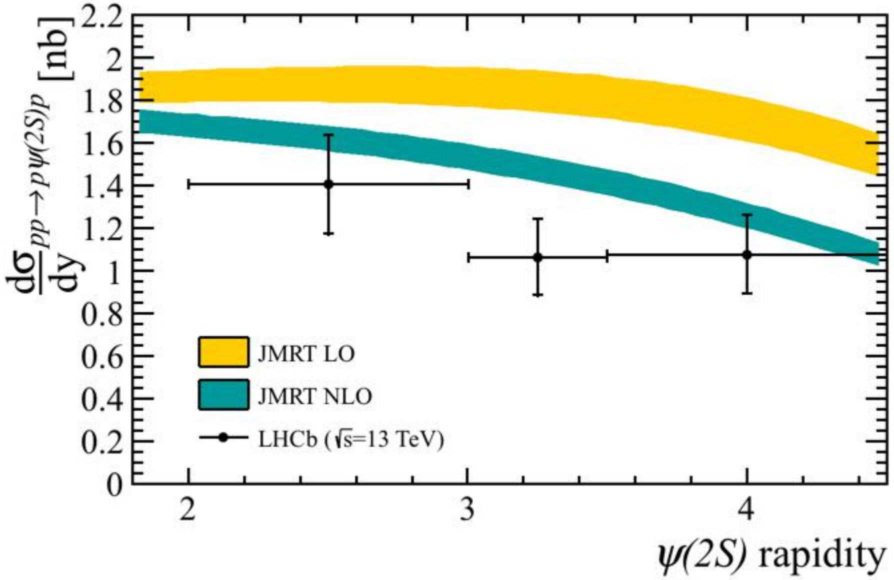
$\sigma_{\psi(2S)\to\mu+\mu-}$ (2 < η_μ <4.5)=10.2 ±1.0 (stat.) ± 0.3 (syst.) ± 0.4 (lumi) pb

JHEP 11 (2013)

J. Phys.G41 (2014) 055009

- Differential cross-sections with respect to rapidity: better agreement with JMRT NLO prediction





JHEP 10 (2018) 167

Systematic uncertainties
pp→p+ J/ψ or ψ(2S)+p

Source	J/ψ analysis (%)	ψ(2S) analysis(%)
HeRSCheL veto	1.7	1.7
2 VELO track	0.2	0.2
0 photon veto	0.2	0.2
Mass window	0.6	0.6
p^2_T veto	0.3	0.3
Proton dissociation	0.7	0.7
Feed-down	0.7	-
Nonresonant	0.1	1.5
Tracking efficiency	0.7	0.7
Muon ID efficiency	0.4	0.4
Trigger efficiency	0.2	0.2
Total excluding luminosity	2.5	2.7
Luminosity	3.9	3.9

main reduction:
4% before

- decrease of the main uncertainties compared to previous analysis (J. Phys. G 41 (2014) 055002)
- proton dissociation background uncertainty ↓ thanks to HeRSCheL detector
- better tracking understanding

Photoproduction cross section

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

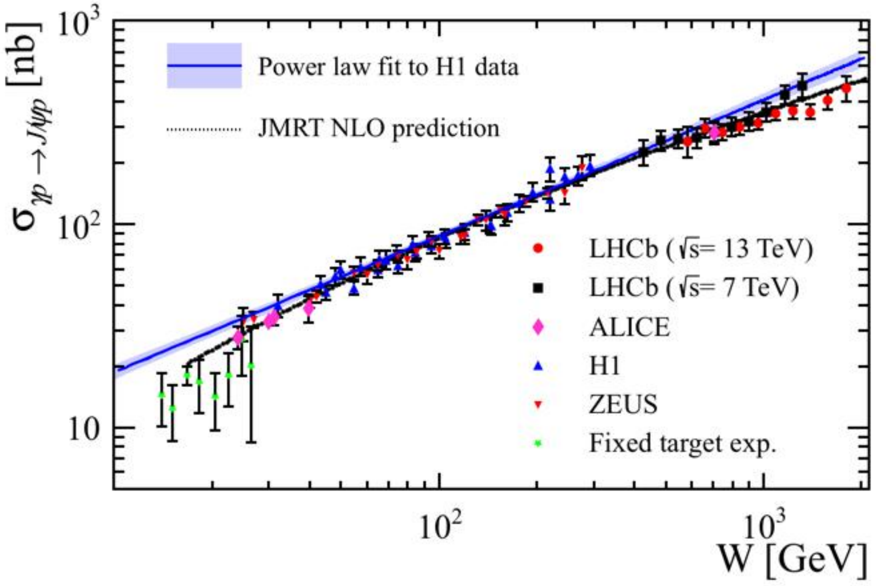
From [JHEP 11 (2013) 085]:

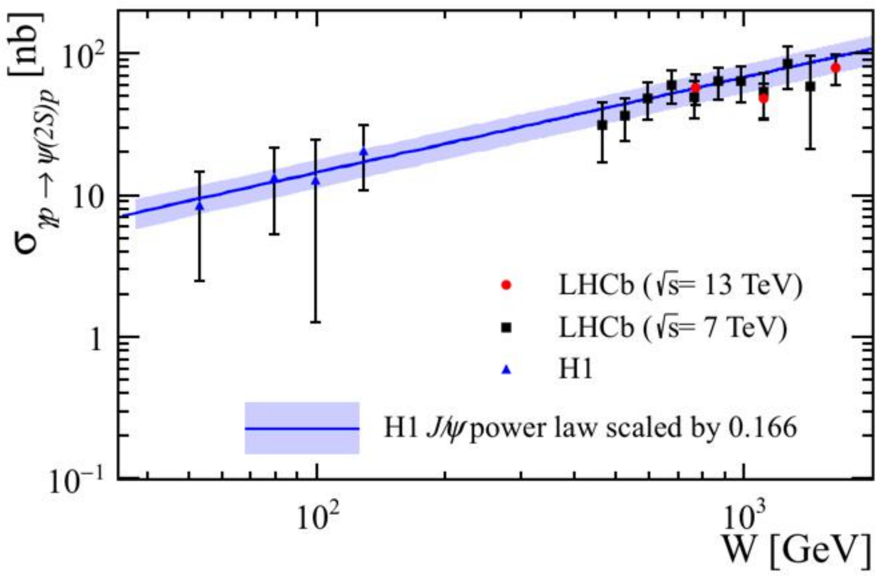
$$\sigma_{pp \to p\psi p} = r(W_+)k_+ \frac{dm}{dk_+}\sigma_{\gamma p \to \psi p}(W_+) + r(W_-)k_- \frac{dm}{dk_-}\sigma_{\gamma p \to \psi p}(W_-)$$

- r ($W_\pm$)-gap survival factor, from HERA (Table 2 from [JHEP 11 (2013) 085])
- $k_\pm$-photon energy
- dm/$dk_\pm$-photon flux
- $W^2_\pm = 2k_\pm\sqrt{s}$-invariant mass of the photon-proton system

JHEP 10 (2018) 167

Photoproduction cross section





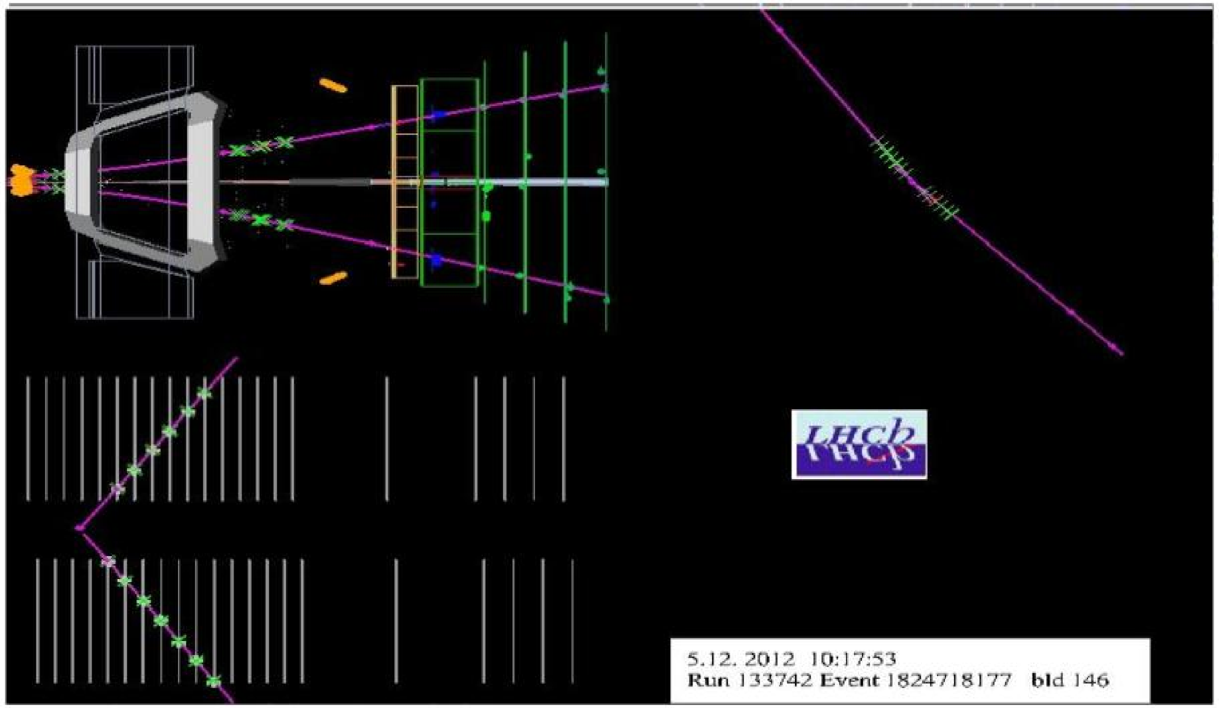
✓ J/ψ production

- in agreement with 7 TeV results where they overlap
- Reach extended to W~2 TeV
- Deviation from the power-law fit to H1 data at highest energies
- Good agreement with JMRT NLO prediction

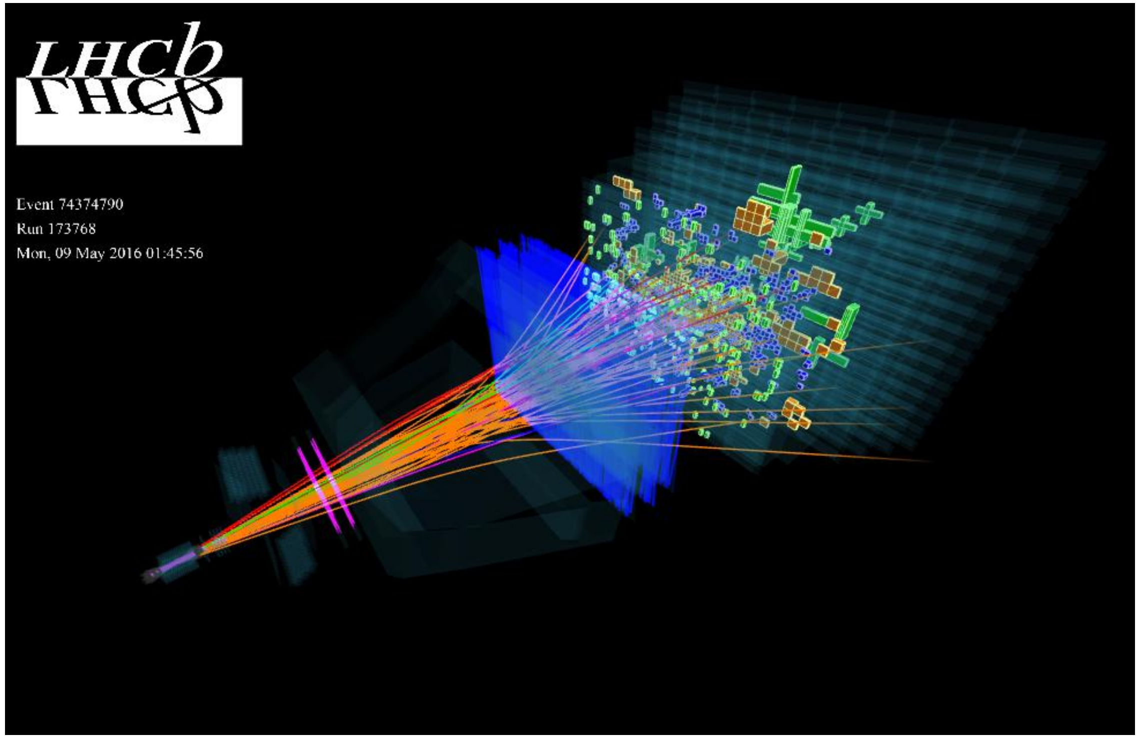
✓ ψ(2S) production

- Good agreement with H1 data extrapolation, which is scaled from the J/ψ power-law fit

From exclusive two particle final states to normal inelastic interactions



Two muons and no other activity



Typical event in LHCb

JHEP 06 (2018) 100

SoftQCD@LHCb

Measurement of the inelastic pp cross-section at centre-of-mass energie of √s = 13 TeV

Aim of the analysis: calculate the σ_{inel} using prompt and long-lived particles inside the LHCb acceptance and extrapolate it to the full phase space

- **Primary measurement**: fiducial cross section at √s = 13 TeV
- **Delivered result**: total inelastic cross-section

$\sigma_{inel} = \Sigma\sigma_x$ where $x \in \{ND, SD, DD\}$

Data used:

- pp collisions at centre-of-mass energy √s = 13 TeV
- both polarities of the LHCb dipole magnet
- 691 million events in 49 runs from 8 LHC fills

- ND: non-diffractive contribution
- SD: single diffractive contribution
- DD: double-diffractive contribution

JHEP 06 (2018) 100

Fiducial cross-section

Selection

- at least one long-lived prompt charged particle
- p>2 GeV/c
- Δt>30 ps
- pseudorapidity: $2<\eta<5$

$$\sigma_{acc} \equiv \frac{(\mu - \mu_{bkg}) N_{evt}}{L_{tot}}$$

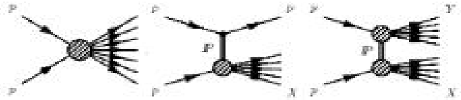
- **μ-μ_{bkg}** -average no. of int per event obtained from fraction of empty events and correcting for detector inefficiency and wrongly reconstructed tracks; the number of inelastic interactions per event described through a Poisson distribution.
- **N_{evt}**-number of collected events
- **L_{tot}**- integrated luminosity

σ_{acc}=62.2 ± 0.2 ±2.5 (lumi) mb

JHEP 06 (2018) 100

Extrapolation to full phase-space

$$\sigma_{inel} = F_T \sigma_{acc} = \sum_x \sigma_x \quad \text{where } x \in \{\mathrm{ND}, \mathrm{SDA}, \mathrm{SDB}, \mathrm{DD}\}$$



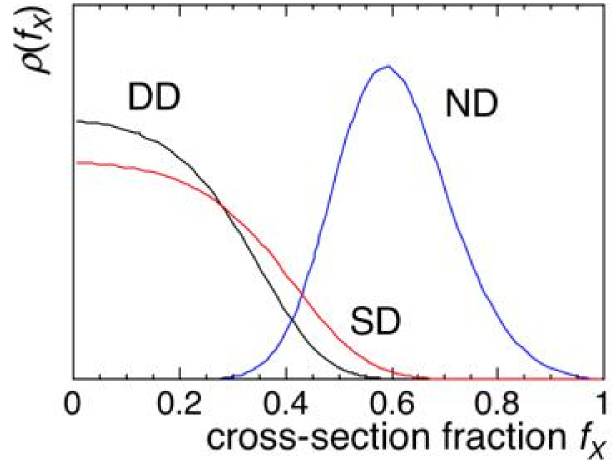
neglected: CEP and interference effects between different contributions

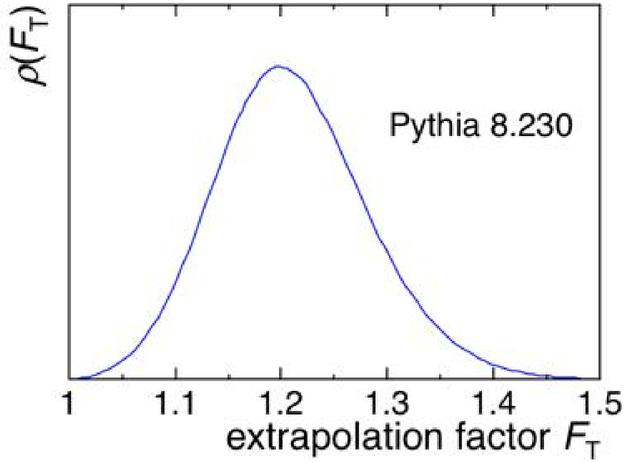
F_T-extrapolation factor determined from generator-level simulations

$$F_T = \frac{\sum_X \sigma_X}{\sum_X \sigma_X \upsilon_X} = \frac{1}{\sum_X f_X \upsilon_X} = 1.211 \pm 0.072$$

fraction of inelastic cross section obtained with MC and data constraint

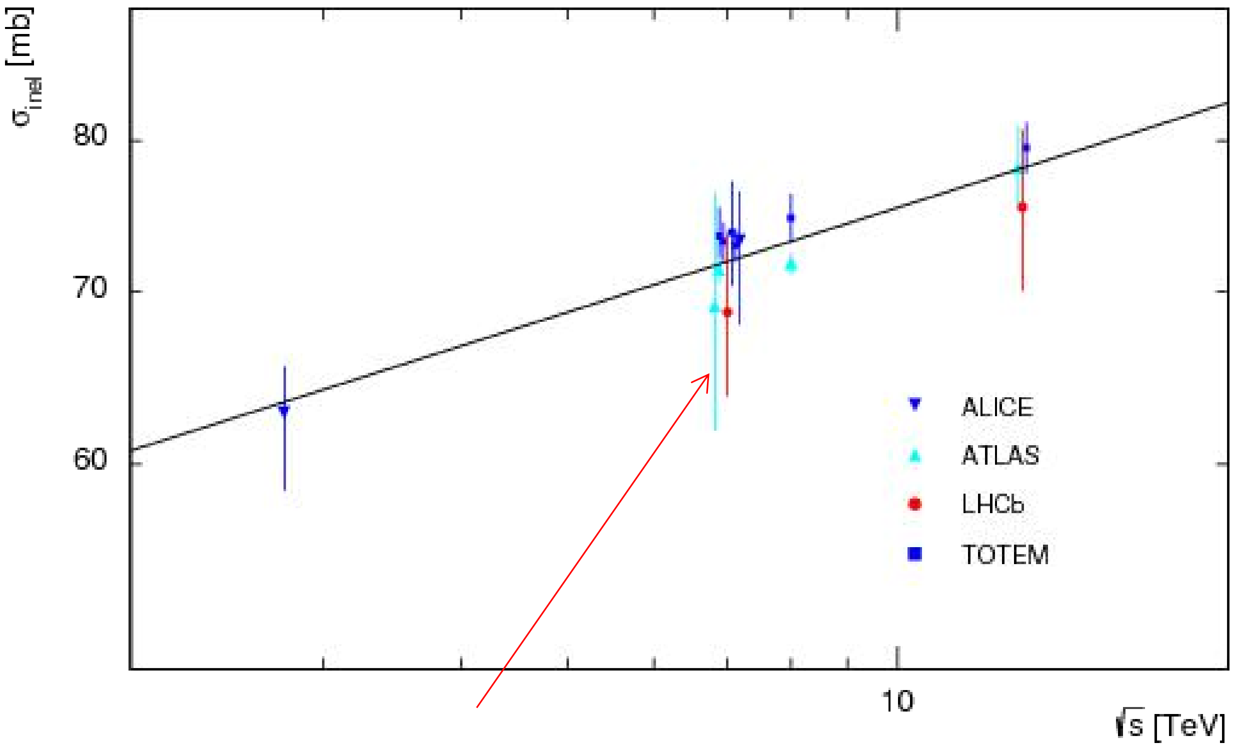
fraction of visible interactions with at least one prompt long-lived particle within the acc.





JHEP 06 (2018) 100

Total inelastic cross section



improved calibration of the luminosity scale :

- lumi unc. reduced from 3.5% to 1.7%
- exp. unc. reduced from 4.3% to 3.0%
- central value shifted up by 2.7%.

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

due to exp. unc. of the fiducial cross-section

due to the cross-section extrapolation

first value **JHEP 02 (2015) 029**

$$\sigma_{inel}(\sqrt{s} = 7\text{TeV}) = 66.9 \pm 2.9(\text{exp}) \pm 4.4(\text{extr})\text{mb}$$

updated **JHEP 06 (2018) 100**

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

Summary

- Central exclusive production results with Run 1 data shows a good agreement with the theory

- The coherent differential J/ψproduction cross-section, measured in bins of J/ψrapidity in lead-lead collisions at 5 TeV and compared with theoretical predictions → more data to be studied (2018 dataset) using HeRSCHel → reduction of the incoherent background is expected after vetoing significant energy detected in HeRSCheL

- J/ψ and ψ(2S) central exclusive production cross-sections with 2015 dataset have been calculated in pp data with $\sqrt{s}$=13 TeV

✓ *reduced level of background shows a good performonce of HeRSCheL*
✓ *both vector mesons agree with JMRT NLO prediction*
✓ *photo-production of* J/ψ*->deviation from power law extrapolation of HERA data*

- Inelastic pp cross-section

✓ *a new measurement of the inelastic pp cross-section was performed at 13 TeV and is in good agreement with the measurements by the ATLAS and TOTEM collaborations*

Thanks for your attention!