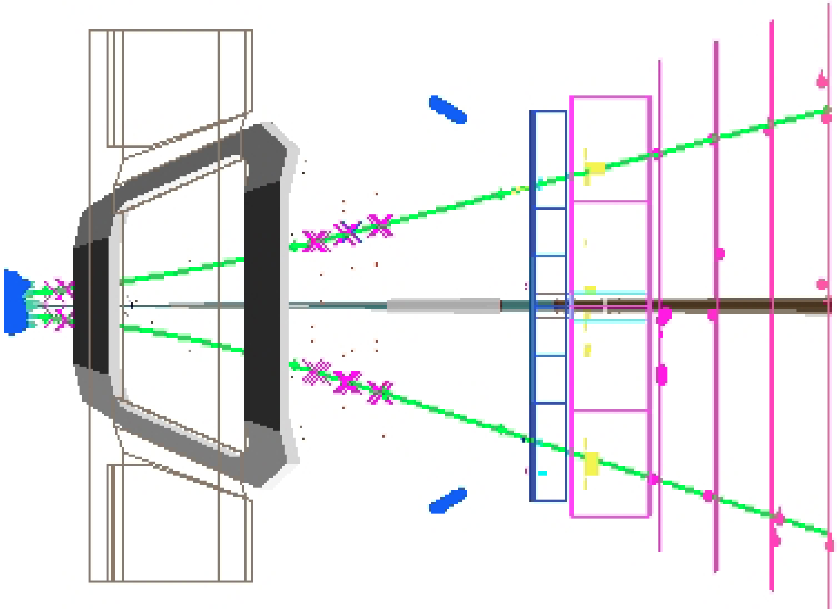


Central exclusive production at LHCb

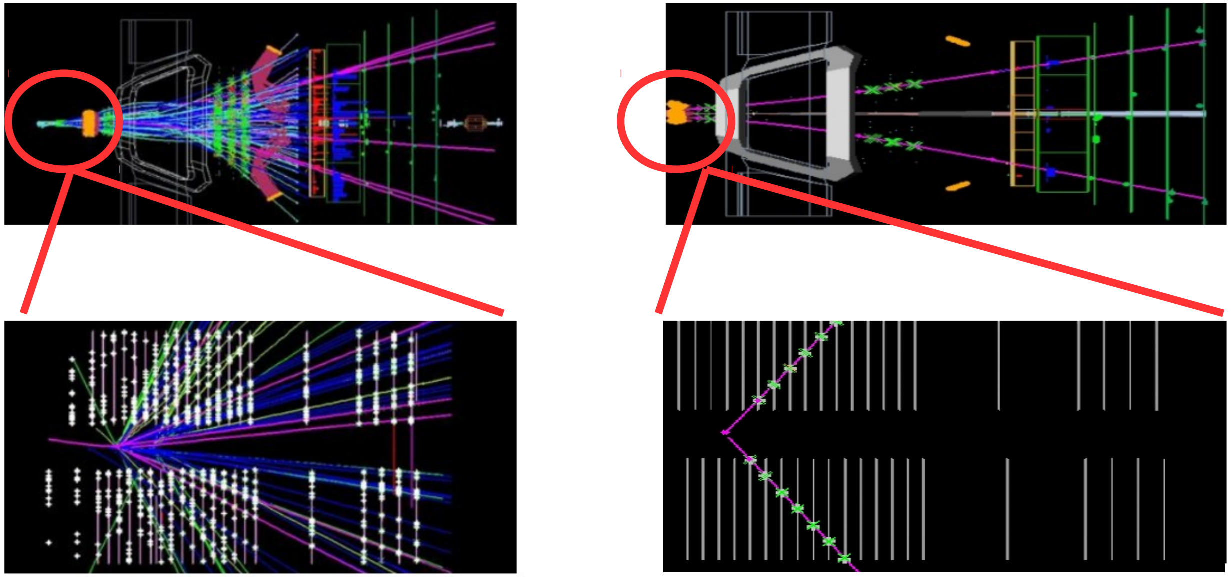
Low-x meeting, Bari, June 13-17
Katharina Müller
on behalf of the LHCb collaboration
Physik Institut, University of Zurich

University of Zurich$^{\text{UZH}}$

LHCb

Outline

- Central Exclusive Production (CEP)
- LHCb detector
- Results of CEP @ 7, 8 and 13 TeV
- Outlook

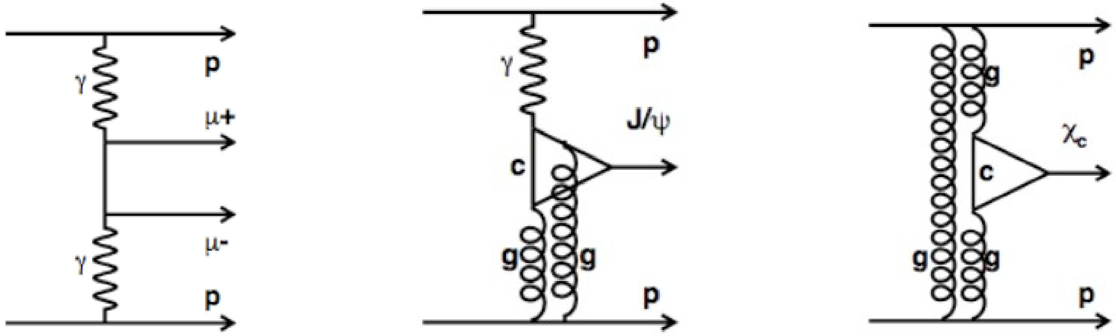


Central exclusive production (CEP): Introduction

exchange of a colourless object: eg. γ, pomeron

→ exclusive candidate (eg two muons) + rapidity gaps

→ protons escape undetected in beampipe



Non-resonant di-muon (di-γ fusion)

eg J/Ψ, Ψ(2S) (γ-pomeron fusion)

eg $\chi_c \rightarrow J/\Psi\ \gamma$ (di-pomeron exchange)

test of QCD and the pomeron in clean environment

search for the odderon and saturation effects
resonant production → sensitivity to gluon distribution at low Bjorken-x ($5 \cdot 10^{-6}$)

non-resonant production: pure QED process, precisely known

→ could be used for luminosity measurement

measured at HERA/Tevatron but different γp energy, W

LHCb detector

Int. J. Mod. Phys. A 30 (2015) 1530022

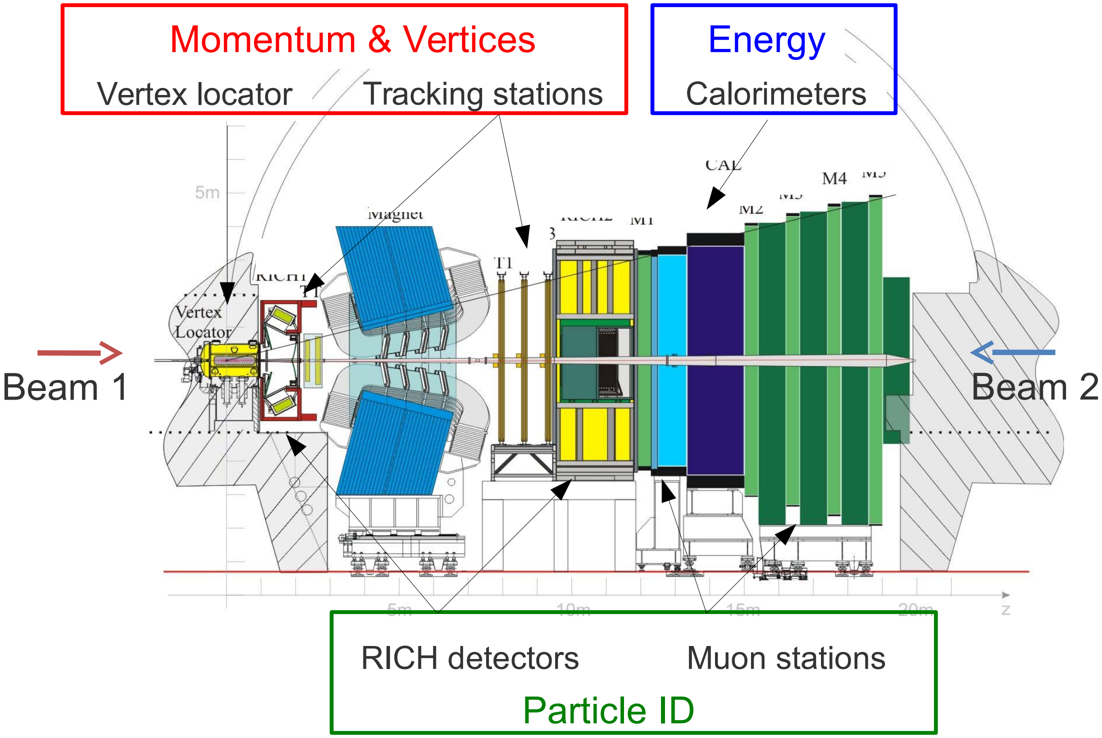
single arm spectrometer – designed for precision measurements in b and c physics

fully instrumented in the forward region (2 < η < 5)

some detection capability in backward region (-3.5 < η < -1.5)

very flexible trigger → able to trigger on low momentum, low multiplicity objects

run II: additional scintillators upstream and downstream (up to 114 m)



Momentum & Vertices

Vertex locator

Tracking stations

Energy

Calorimeters

Beam 1

Beam 2

RICH detectors

Muon stations

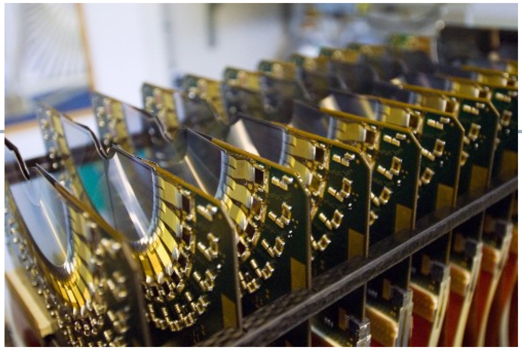
Particle ID

VELO: 20 μm impact parameter resolution

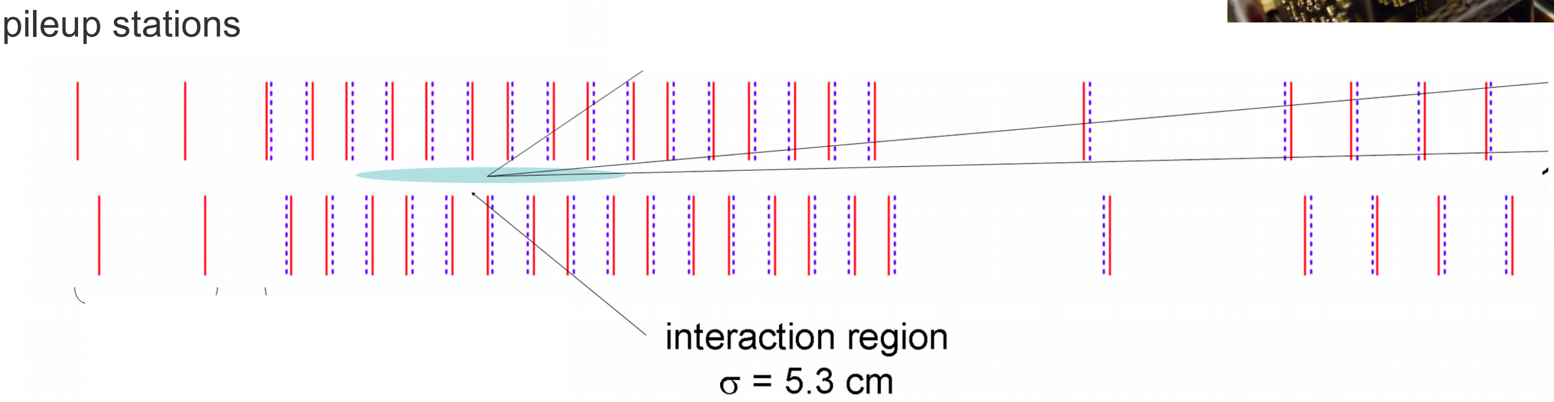
Muons: 97% efficiency for 2% misid

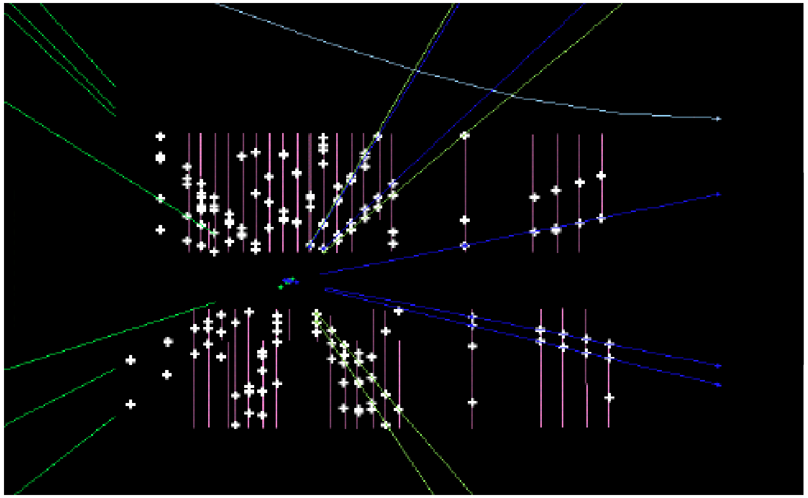
SPD: Scintillating pad detector in front of ECAL → event multiplicity

LHCb Vertex locator (VELO)



silicon strip vertex detector surrounding interaction region
no magnetic field, R and φ sensors





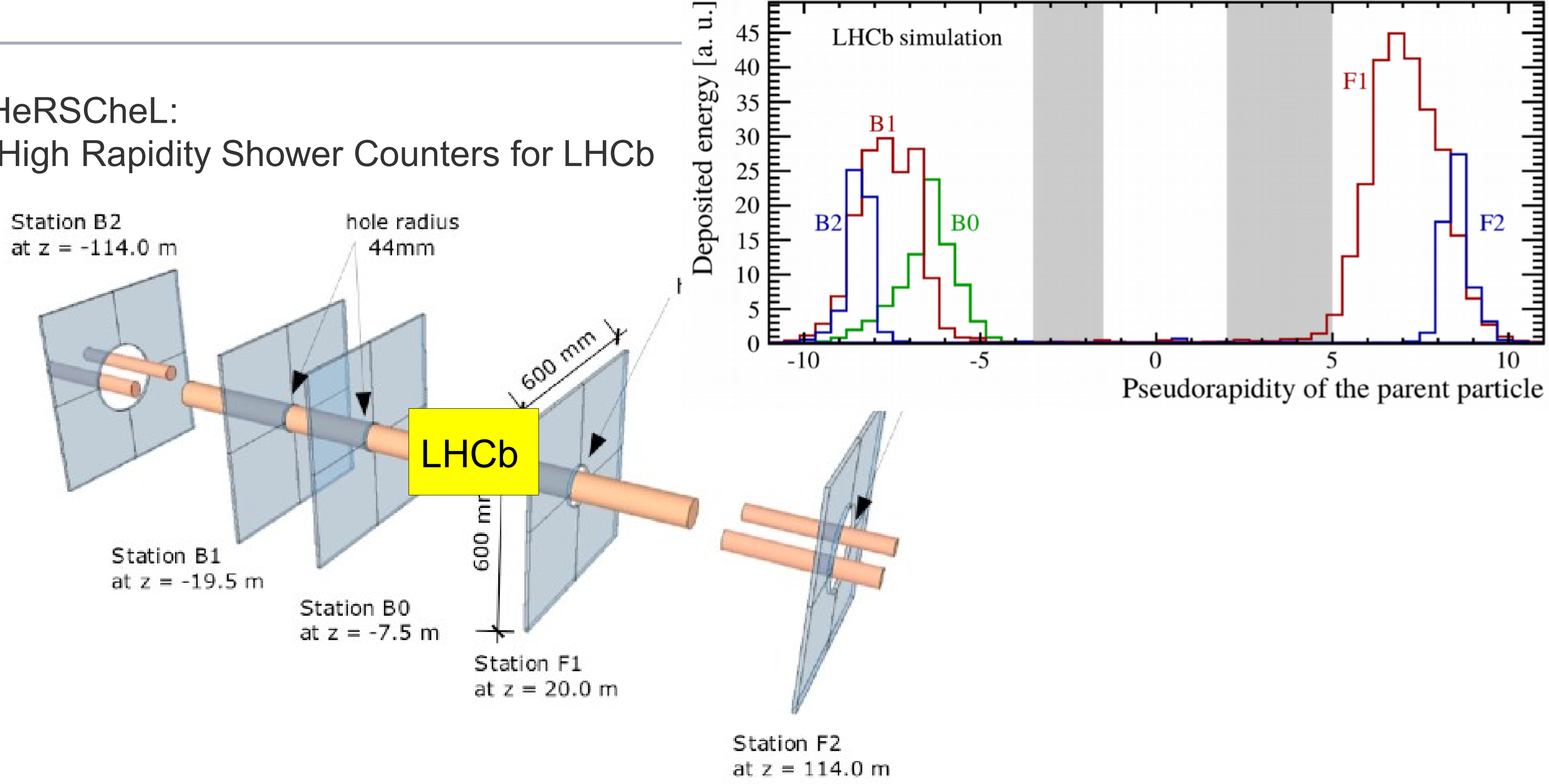
forward: 1.5 < η < 5.0
backward: -3.5 < η < -1.5

backwards tracks re-constructable
(no momentum information)

rapidity gap coverage
forward: 3.5
backward: ~ 1-2 units, depending on z vertex position

Run II – new detectors

HeRSCheL:
High Rapidity Shower Counters for LHCb



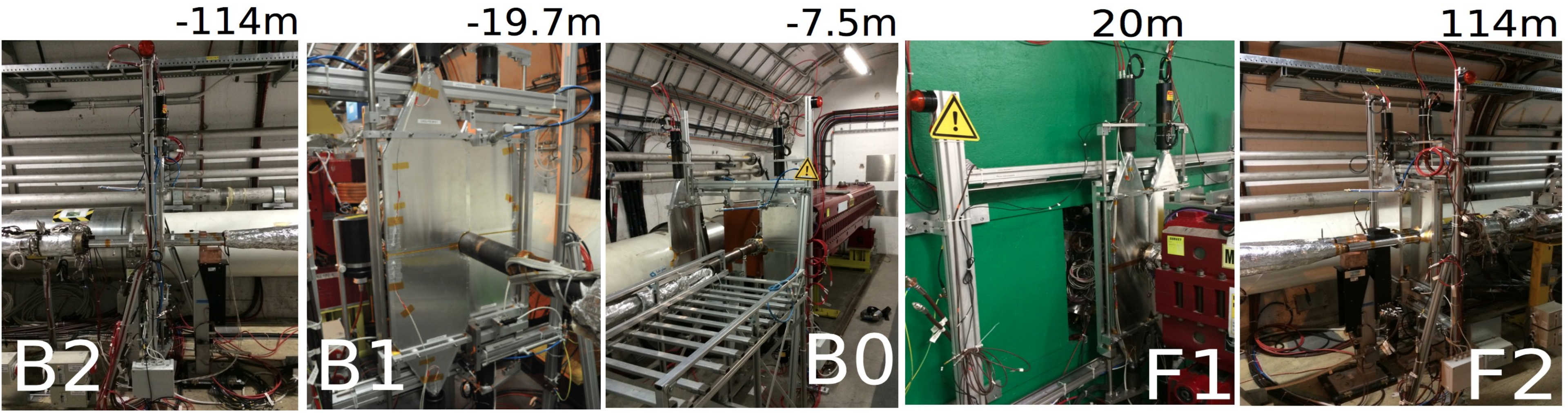
run II: additional scintillators upstream and downstream (up to 114 m)
→ increase pseudorapidity coverage: $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

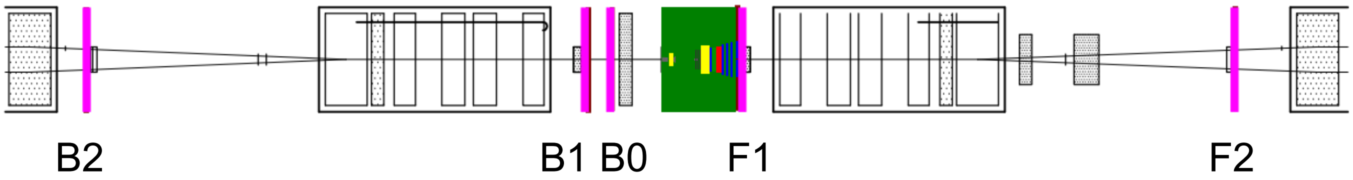
five stations: three backwards, two forward

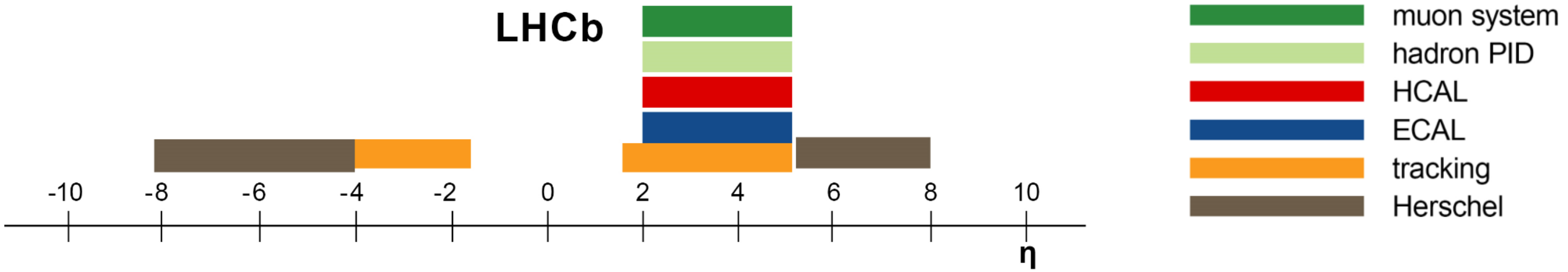
detectors four plastic scintillator plates, 20 mm thick - retractable

→ improvements in triggering and background rejection for CEP events

LHCb detector – new detectors







HeRSCheL pseudorapidity coverage: −8.0 < η< -3.5 , 5.0 <η< 8.0
LHCb (run II) −8.0 < η< -1.5 , 2.0 <η< 8.0

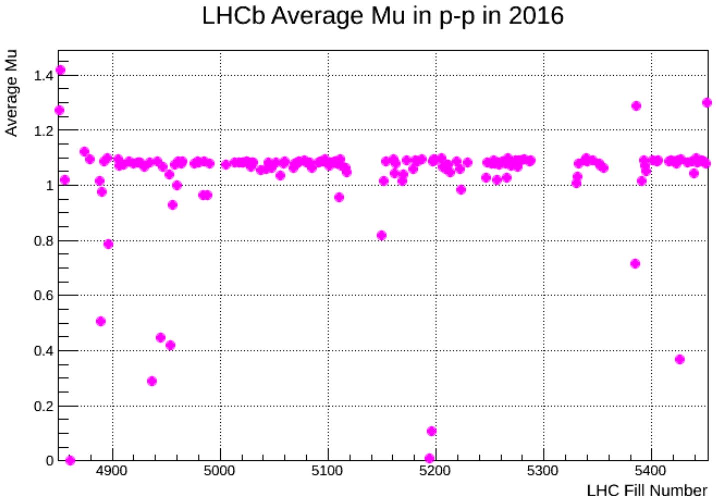
LHCb running

low pileup → following results based on events with one primary interaction (PV)

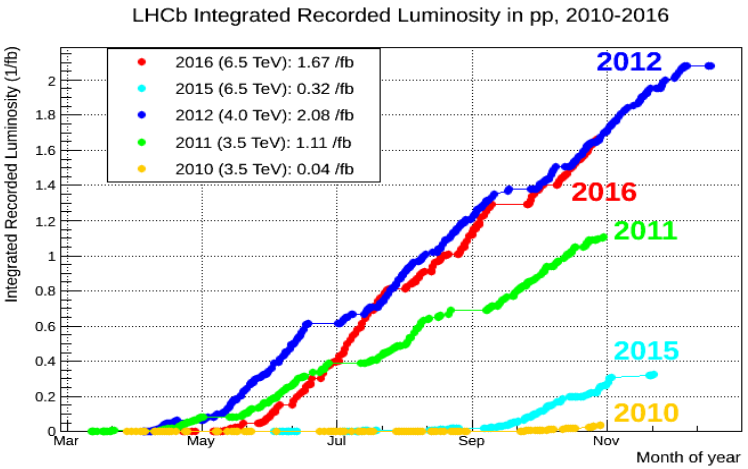
fraction of crossings with N interactions, f(N),
with μ average number of interactions

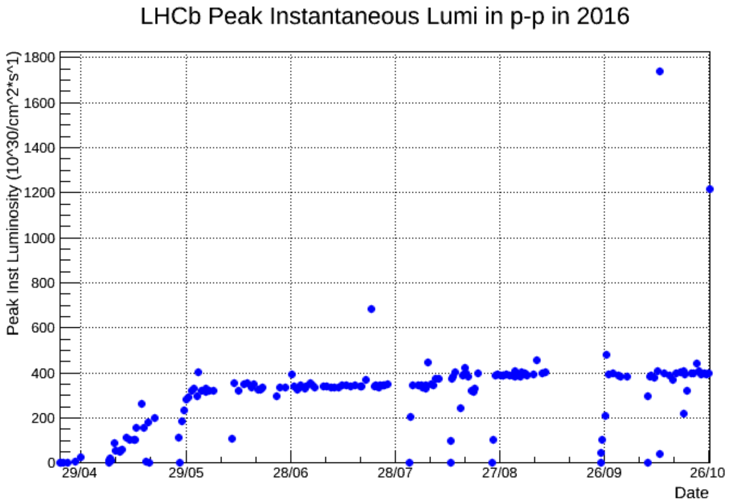
$$f(N)=\frac{e^{-\mu}\mu^{N}}{N!}$$

			μ	f(1PV)
2011:	1.1 fb^{-1}	7 TeV	1.6	25%
2012:	2.1 fb^{-1}	8 TeV	1.4	29%
2015:	300 pb^{-1}	13 TeV	1.1	35%
2016:	1.7 fb-1	13 TeV	1.1	35%


LHCb Average Mu in p-p in 2016

luminosity leveling – very stable data taking conditions


LHCb Integrated Recorded Luminosity in pp, 2010-2016


LHCb Peak Instantaneous Lumi in p-p in 2016

LHCb CEP analyses

CEP with di-muon final states

- J/ψ and $\psi(2S)$ @ 7 TeV, J.Phys. G41 (2014) 055002
- J/ψ and ψ 2S @ 13 TeV, LHCb-CONF-2016-007
- $\Upsilon(nS)$ @ 7 TeV and 8 TeV, JHEP 1509 (2015) 084
- double charmonia @ 7 TeV and 8 TeV, J.Phys. G41 (2014) no.11, 115002
- di-muon continuum @ 7 TeV, LHCb-CONF-2011-022
- χ_c ($\rightarrow J/\psi\gamma$) @ 7 TeV, LHCb-CONF-2011-022

CEP with hadronic final states

- double open-charm
- di-pion spectrum
- χ_c ($\rightarrow \pi\pi$, KK)
- 'light' two- (and four-) hadron final states

CEP with photon final states

- di-photon

CEP in pA , Ap and AA collisions

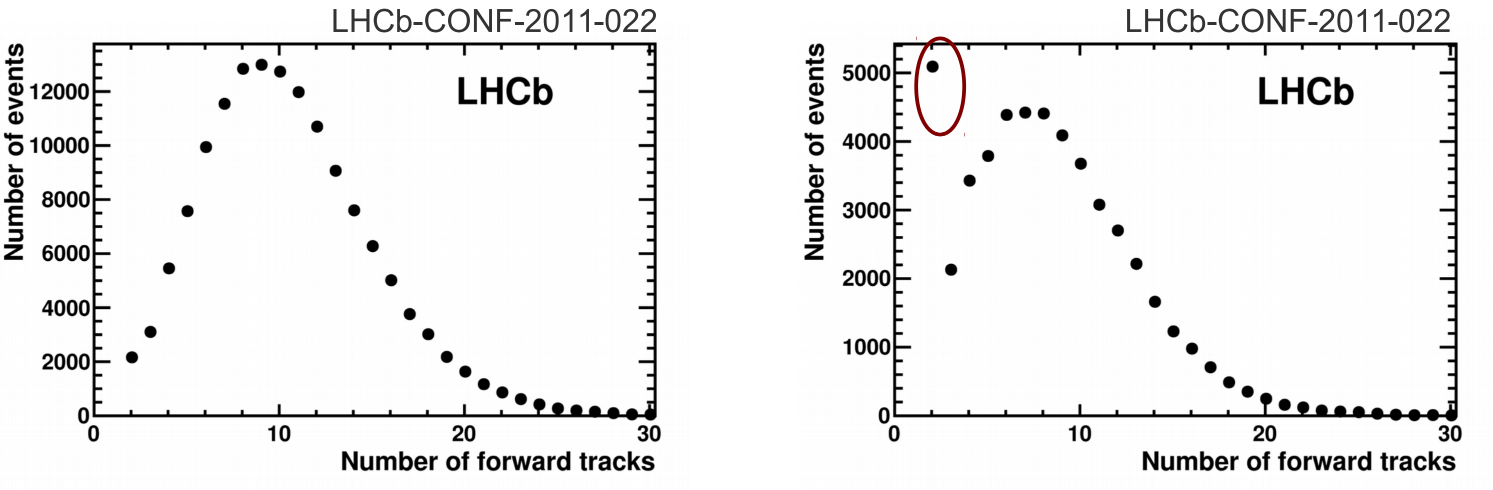
many ongoing exclusive analyses Run I & II

Measuring exclusivity @ LHCb

- number of forward and backward tracks in VELO

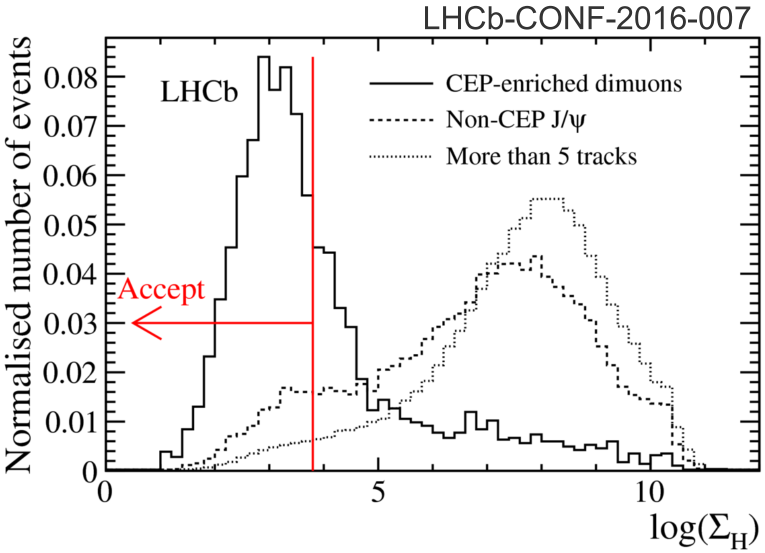
all events

no backward tracks



- number of SPD hits
- cut on normalised ADC signal in each of the 20 scintillators of HeRSCheL

$$\Sigma_H = \sum_{i=1}^{20}\left(\frac{ADC_i}{2.5RMS_i}\right)^2$$



J/Ψ, Ψ(2S) @ 7 TeV

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

- 1/fb @ 7 TeV
- two muon, no other activity in event
- $M_{\mu\mu}$ within 65 MeV of $m_{J/\psi}$, $m_{\psi(2S)}$

→ 55985 J/ψ and 1565 ψ(2s) candidates

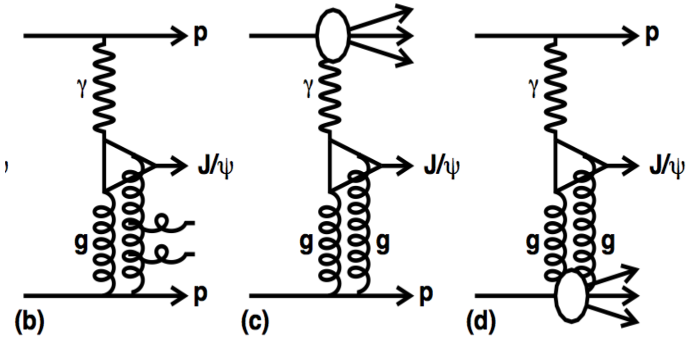
backgrounds

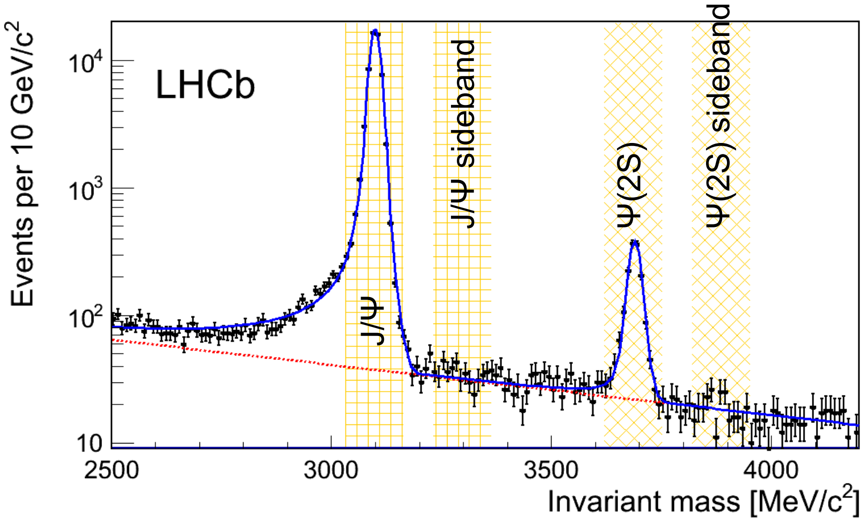
- non resonant: J/ψ 1%, ψ(2s) 17%
- feed down: J/ψ: 10% from χ_c and ψ(2s)

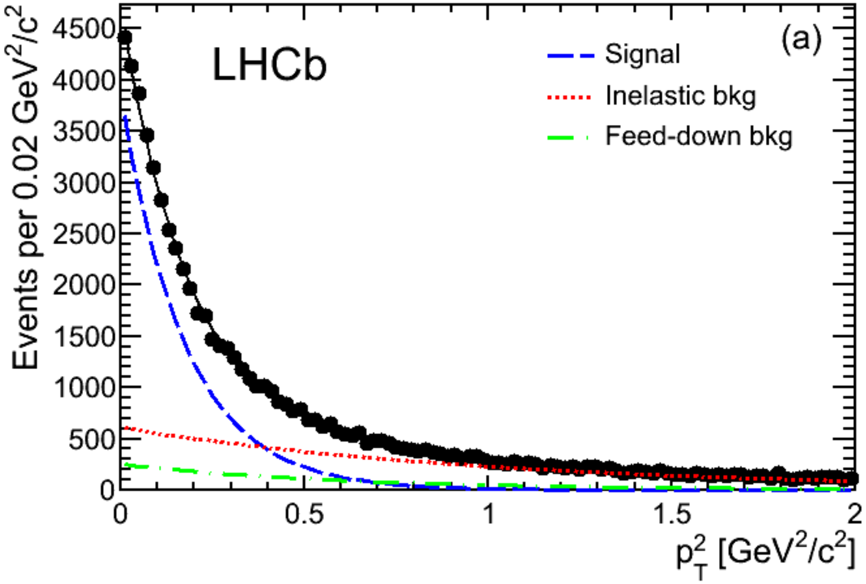
  ψ(2s): 2% X(3872) and χ_c(2P)
- inelastic background with extra particles out of LHCb acceptance – dominant

from proton dissociation and gluon radiation

estimated from p_T^2 distribution







J/Ψ, Ψ(2S) @ 7 TeV

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

- 1/fb @ 7 TeV
- two muon, no other activity in event
- $M_{\mu\mu}$ within 65 MeV of $m_{J/\psi}$, $m_{\psi(2S)}$
- $p_T^2 < 0.8$ GeV²

backgrounds

- non resonant: J/ψ 1%, ψ(2s) 17%
- feed down: J/ψ: 10% from χ_c and ψ(2s)
  ψ(2s): 2% X(3872) and χ_c(2P)
- inelastic background: about 40%

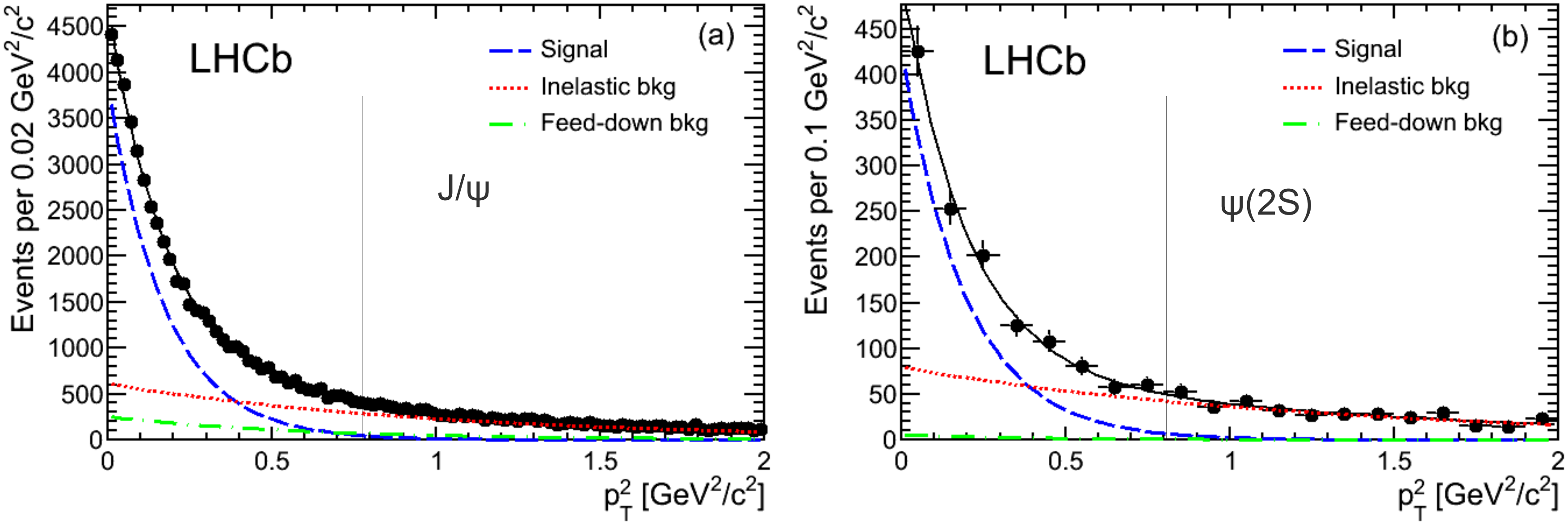
fit to determine inelastic contribution

$$f_s e^{-b_s p_T^2} + f_b e^{-b_b p_T^2} f_f F_f p_T^2$$

- signal and inelastic background: exponential
- feed-down shape from data

exp. slopes b agree well with expectation from HERA:

LHCb exp. from HERA	LHCb fit
$b_s \sim 6$ GeV^{-2}	$b_s = 5.70 \pm 0.11$ GeV^{-2}
$b_b \sim 1$ GeV^{-2}	$b_b = 0.97 \pm 0.04$ GeV^{-2}



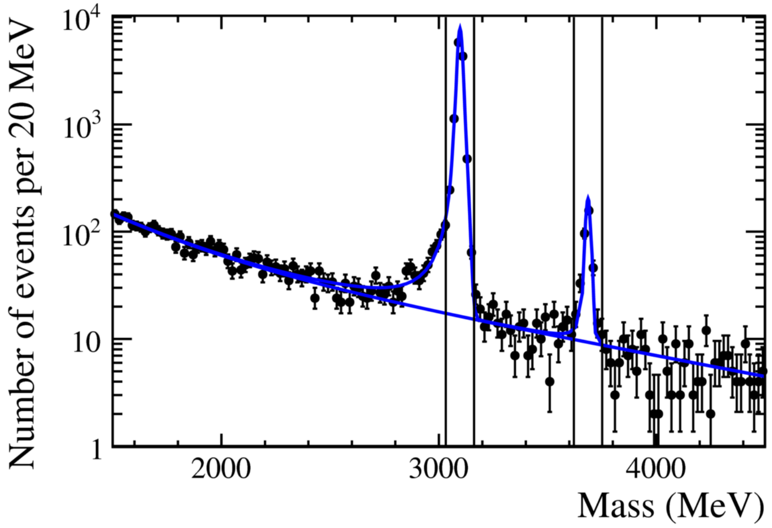
CEP of J/Ψ and Ψ(2S) @ 13 TeV

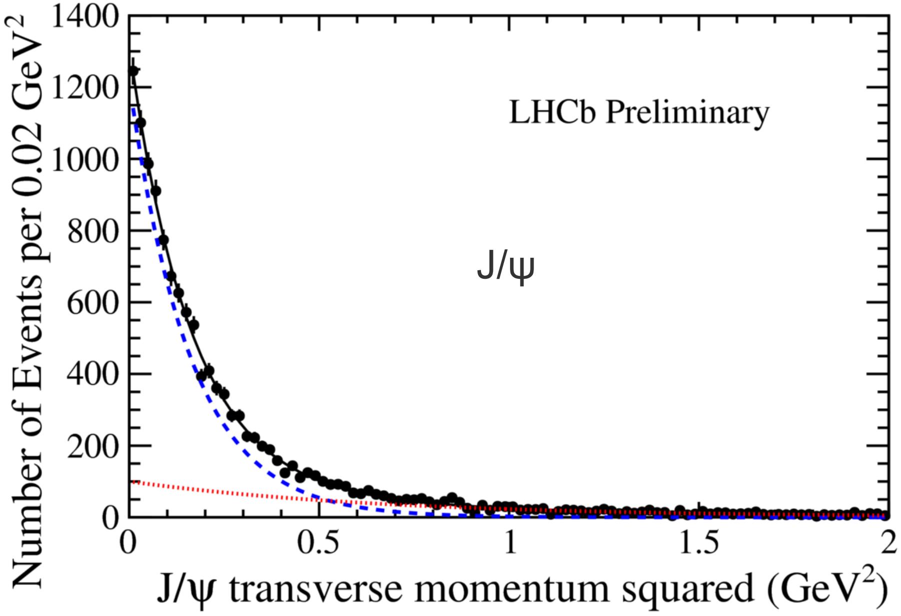
LHCb-CONF-2016-007

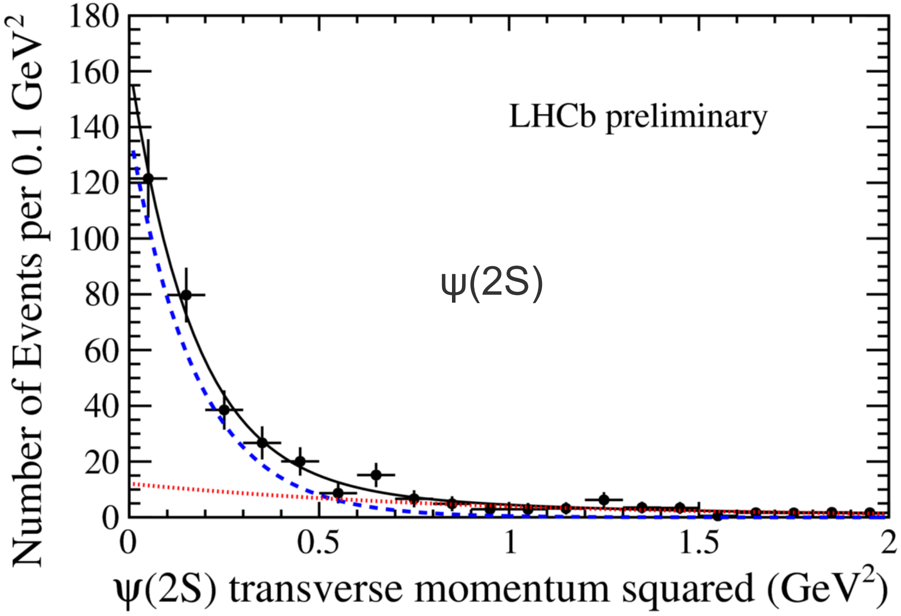
2015 dataset @ 13 TeV with L=204/pb
12992 J/ψ candidates, 382 ψ(2S) candidates
same selection plus HeRSCHeL veto

- non resonant: J/ψ 1%, ψ(2s) 18%
- feed-down: J/ψ 6% (10% @ 7 TeV)
- inelastic ~20%

→ inelastic background: run I ~40% → run II ~20%





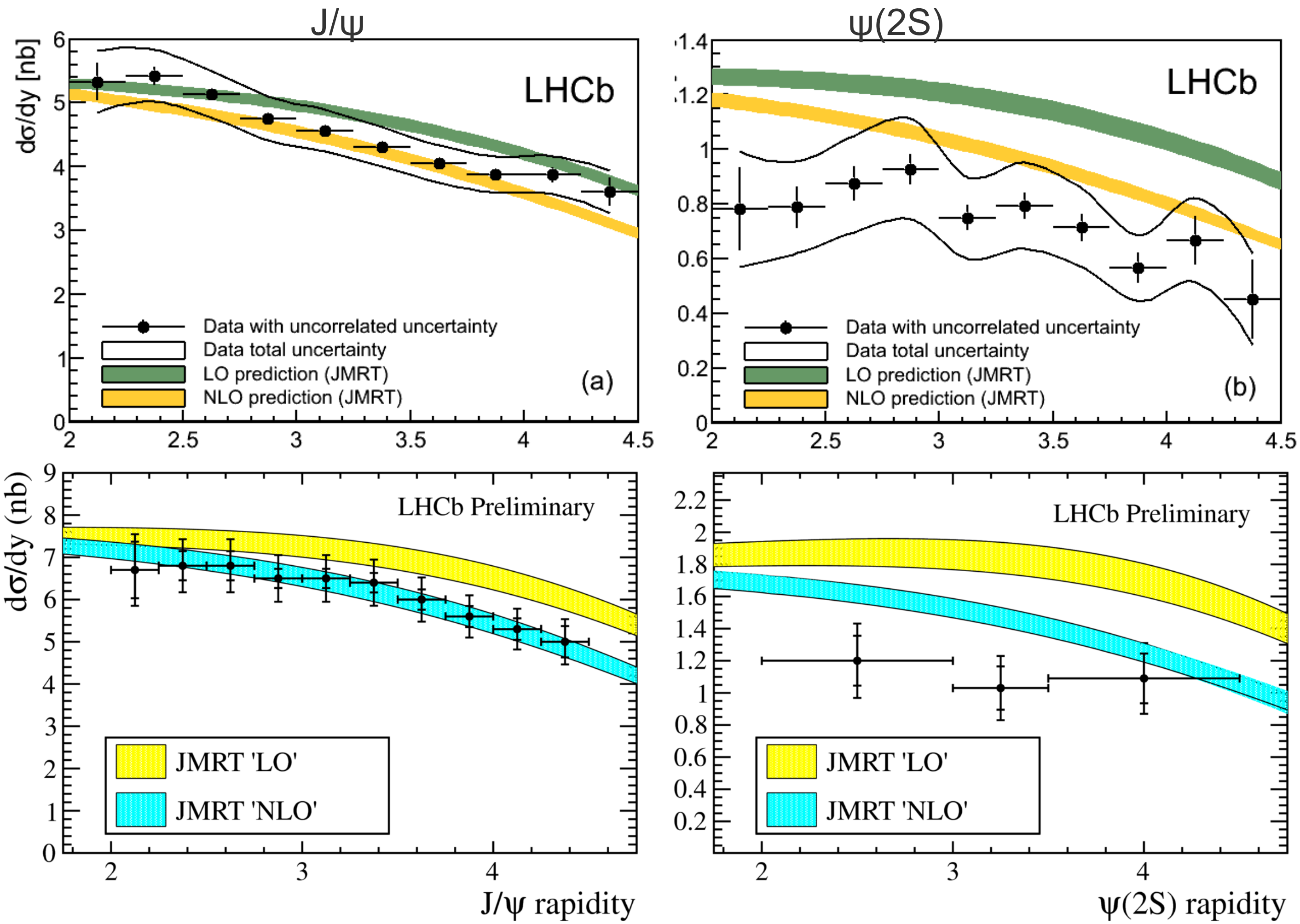


J/Ψ, Ψ(2S) @ 7 & 13 TeV

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002
LHCb-CONF-2016-007

7 TeV

13 TeV



- dominant uncertainty:purity 2% J/ψ, 13% ψ(2S)
- uncertainties highly correlated between bins
- shape better described by NLO prediction or models including saturation

JRMT:
JHEP 1311 (2013) 085

J/Ψ and Ψ(2S) photoproduction x-section

LHCb-CONF-2016-007

$$\overbrace{\frac{d\sigma}{dy}_{pp\to pVp}}^{\text{measured}} = r(y)\left[k_+\frac{dn}{dk_+}\overbrace{\sigma_{\gamma p\to Vp}(W^+)}^{\text{from HERA/extracted}} + k_-\frac{dn}{dk_-}\overbrace{\sigma_{\gamma p\to Vp}(W^-)}^{\text{extracted/from HERA}}\right]$$

gap survival

photon flux

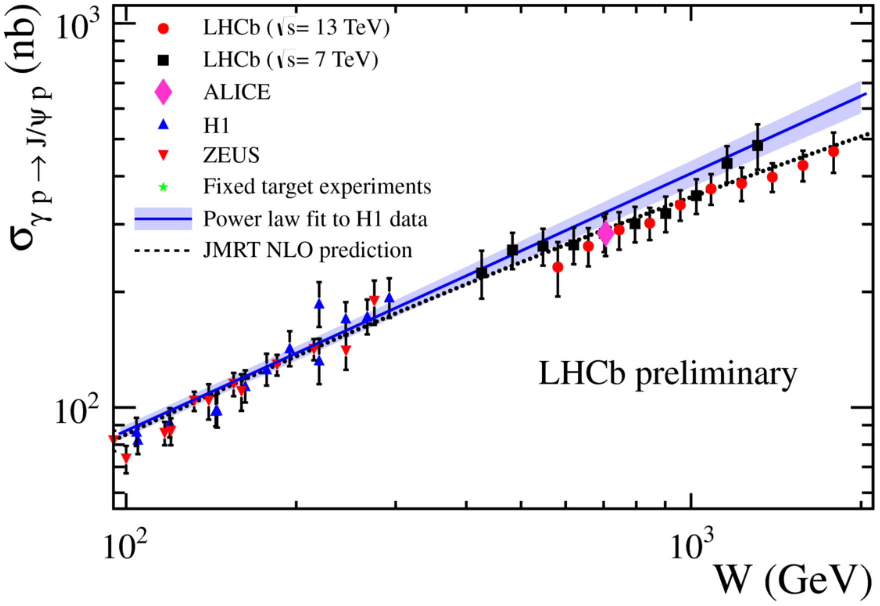
$k_\pm = m_\psi / 2e^{\pm y}$ - photon energy

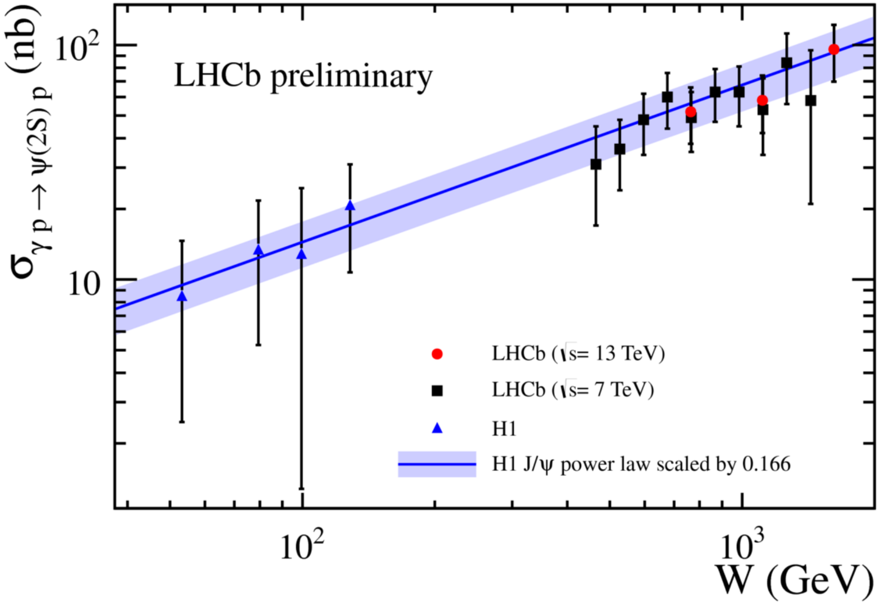
$dn/dk_\pm$ - photon flux

$W^2_\pm = 2k_\pm s$ – inv. mass of the γp system

→ two correlated points (W^+, W^-) for each measurement in y, W:γp centre-of-mass energy

- 13 TeV data allows significant extension of the reach in W
- 7 & 13 TeV results are in agreement
- comparison with HERA → simple power law insufficient to describe J/ψ but data well described by NLO, ψ(2S) results are consistent, but uncertainties large





CEP of ϒ @at 7 and 8 TeV

JHEP 1509 (2015) 084

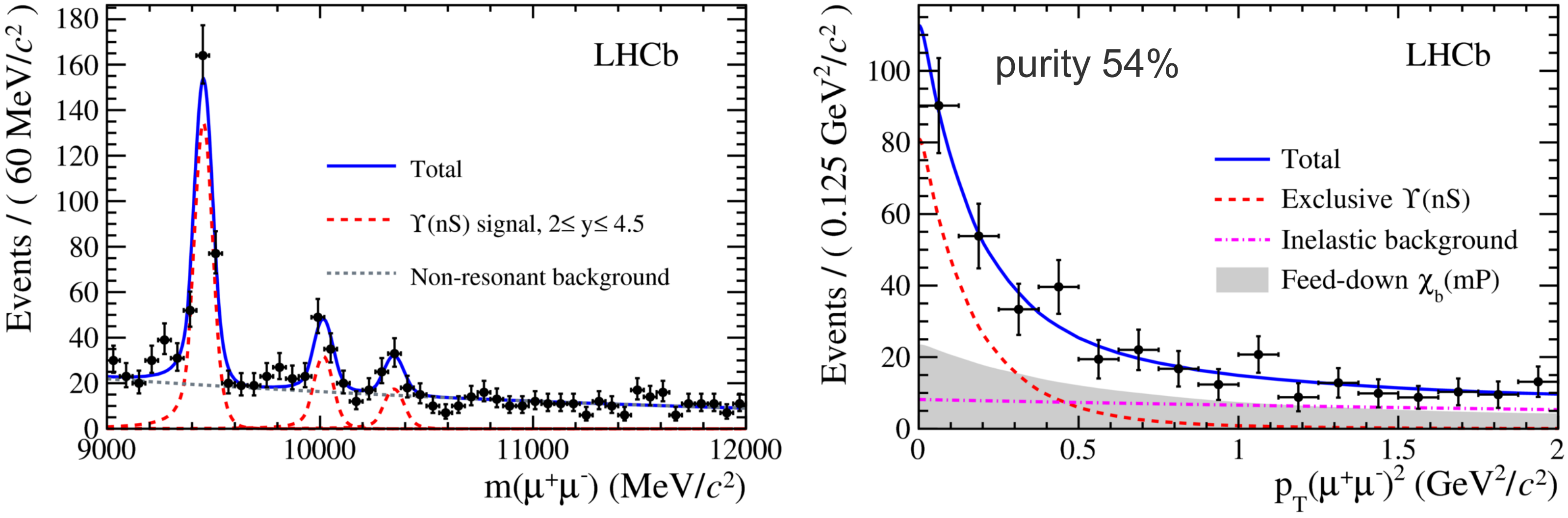
Run-I data set L=1/fb at 7 TeV and L=2/fb at 8 TeV

analysis strategy similar to J/ψ, $p_T^2 < 2$ GeV^2

background

- non-resonant: fit to di-muon mass
- feed-down, $\chi_b \rightarrow \Upsilon\gamma$: simulation and data input
- inelastic background: from fit to p_T^2 (non-resonant background sPlot subtracted)
- signal template is obtained from SuperChiC

dominant uncertainty: background from feed down and inelastic events



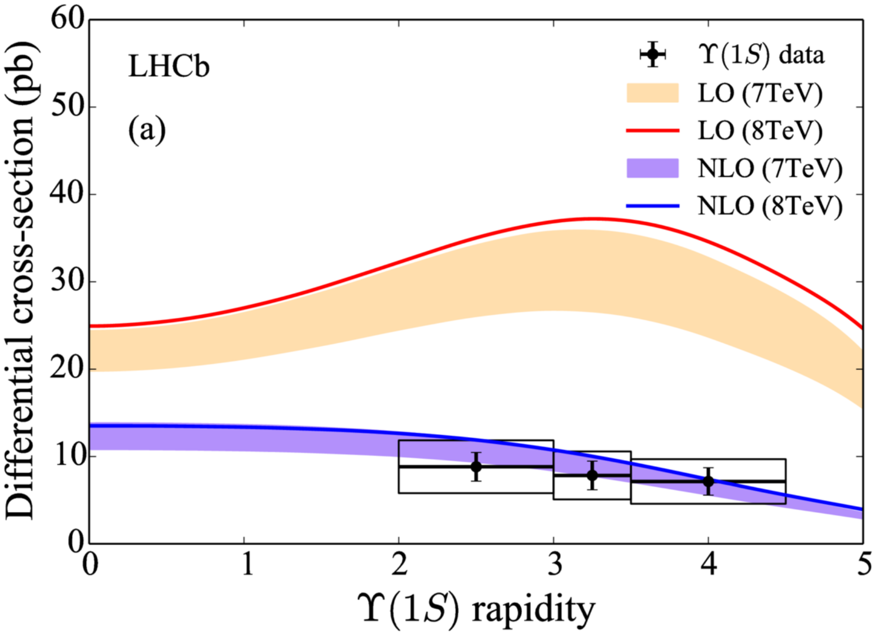
CEP of Υ @at 7 and 8 TeV

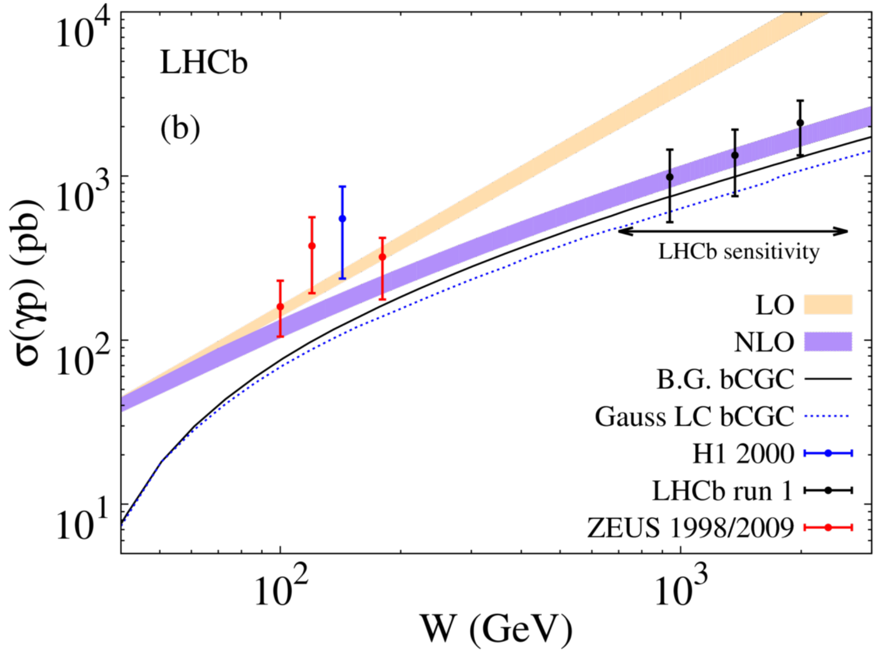
JHEP 1509 (2015) 084

integrated cross-sections: $2.0 < \eta(\mu) < 4.5$
$\sigma(\Upsilon(1S)\to\mu^+\mu^-) = 9.0 \pm 2.1$ (stat) ± 1.7(sys) pb
$\sigma(\Upsilon(2S)\to\mu^+\mu^-) = 1.3 \pm 0.8$ (stat) ± 0.3(sys)pb
upper limit: $\sigma(\Upsilon(3S)\to\mu^+\mu^-) < 3.4$pb @ 95% C.L.

W- solution very small - neglected

→ strong preference of NLO prediction
colour glass condensate (CGC) formalism does describe data [Phys.Lett B742 (2015) 172]



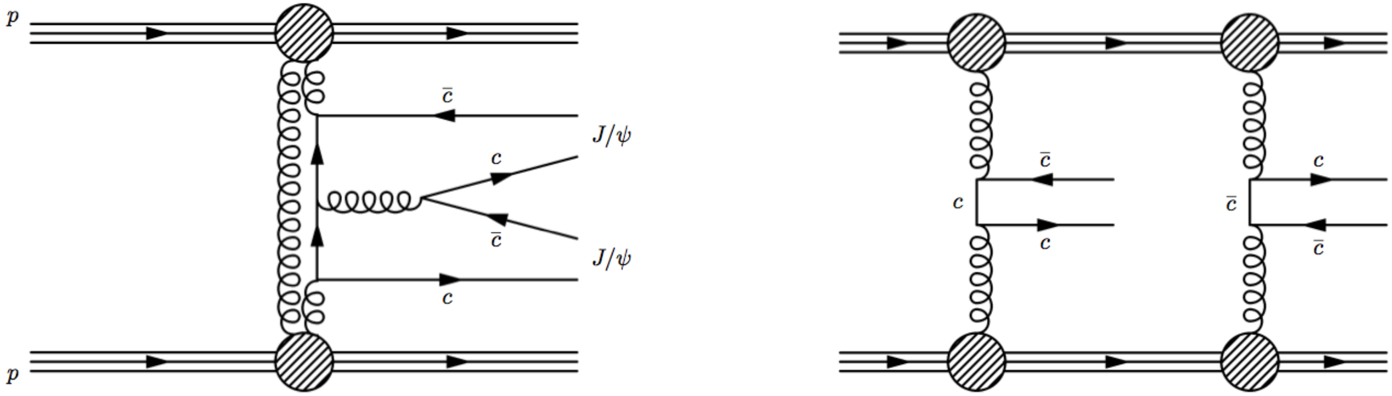


CEP: double charmonium production

J. Phys. G41 115002

measurement of J/ψJ/ψ, J/ψψ(2S),ψ(2S)ψ(2S) and $\chi_c\ \chi_c$ production

exchange of two pomerons



→ cross section and mass spectrum sensitive to exotics, such as glueballs or tetraquarks

- comparison of exclusive and inclusive J/ψ mass spectra
  → helps to understand J/ψ pairs production

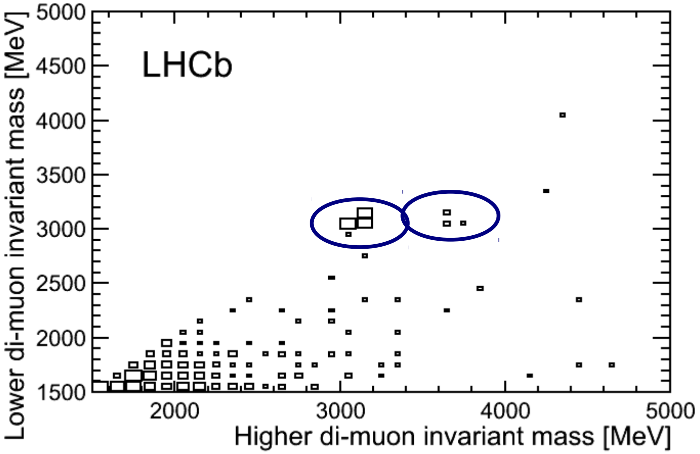
analysis based on full run I data: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

- cross-sections for J/ψ J/ψ and J/ψ ψ(2S) pairs measured by LHCb
- upper limits established for ψ(2S) ψ(2S) and $\chi_{c(0,1,2)}\chi_{c(0,1,2)}$

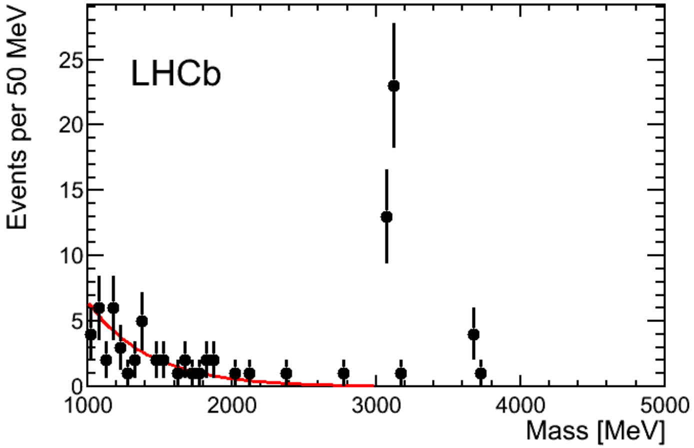
CEP: double charmonium production

J. Phys. G41 115002

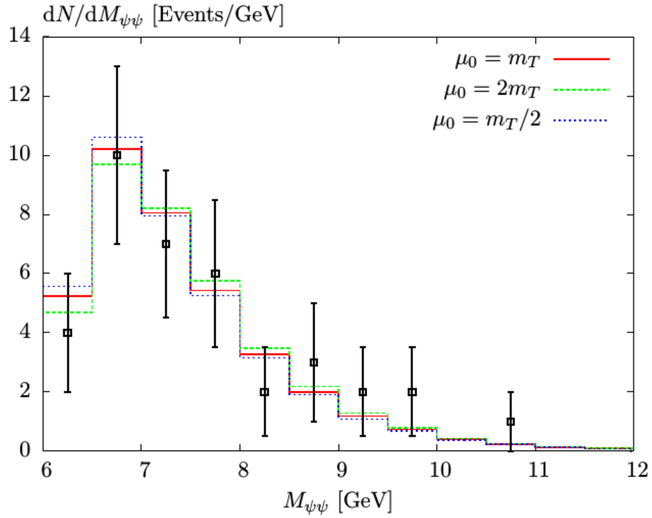
selection: four tracks – three identified as muons, no photons, no other tracks in VELO



invariant mass of di-muon pairs



invariant mass of 2^{nd} di-muon pair



four-muon invariant mass

observed J/ψ J/ψ mass spectrum agrees with theory (arXiv:1409.4785)

CEP: double charmonium production

J. Phys. G41 115002

event yield in 3/fb : 37 $J/\psi J/\psi$, 5 $J/\psi\psi(2S)$, 0 $\psi(2S)\psi(2S)$, 1/0/0 $\chi_c\chi_c$ (0/1/2)

→ first observation of CEP of charmonium pair mesons

→ x-section for the decay into four muons in the LHCb acceptance
non-resonant and feed-down background removed
but still includes inelastic contributions

$\sigma(J/\psi\ J/\psi) = 58 \pm 10(\text{stat}) \pm 6(\text{sys})$ pb

$\sigma(J/\psi\ \psi(2S)) = 63\,^{+27}_{-18}(\text{stat}) \pm 10(\text{sys})$ pb

$\sigma(\psi(2S)\psi(2S)) < 237$ pb

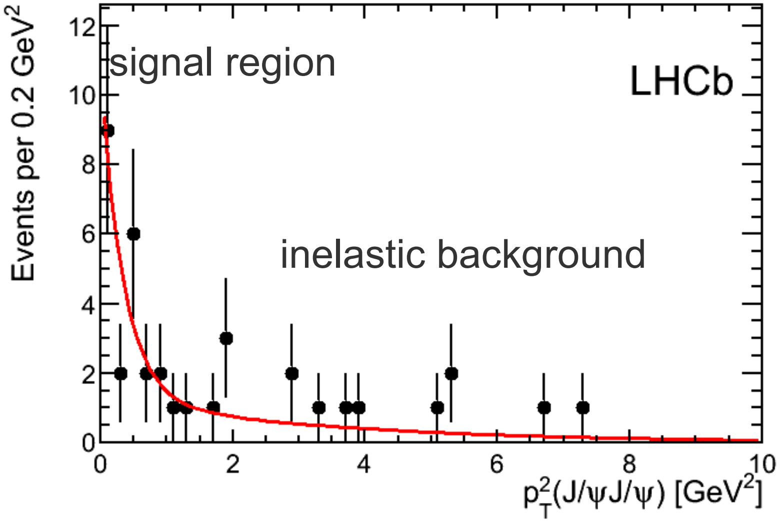
$\sigma(\chi_{c0}\chi_{c0}) < 69$ pb

$\sigma(\chi_{c1}\chi_{c1}) < 45$ pb

$\sigma(\chi_{c2}\chi_{c2}) < 141$ pb

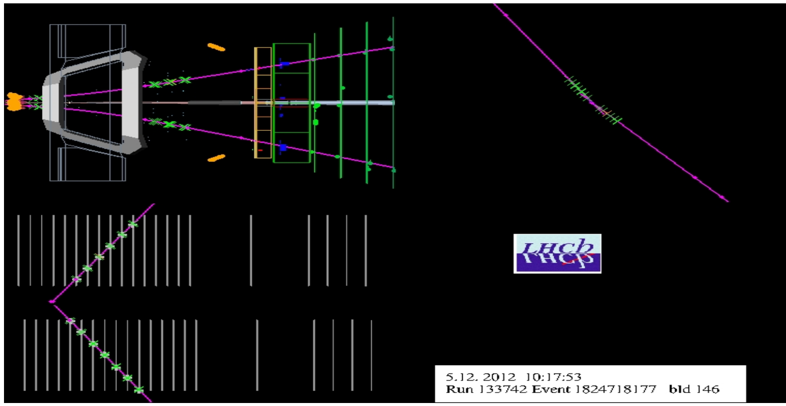
fraction of elastic events: 42 ± 13%

CEP: $\sigma(J/\Psi J/\Psi) = 24 \pm 9$ pb
Theory: $\sigma(J/\Psi J/\Psi) \approx 8$ to 36 pb
[arXiv:1409.4785]



Conclusions

- LHCb’s forward acceptance provides unique window on CEP
- Spectroscopy in a very clean environment
- QCD studies
  - very low-x gluon PDF
  - sensitivity to shadowing
  - nature of pomeron
  - sensitivity to glueballs, odderons, tetraquarks
- Results
  - J/ψ, ψ(2S), ϒ production
  - double-charmonium
- Outlook
  - increased sensitivity
  - expect to collect 5/fb with low pileup → unique measurements possible
    also in proton-ion or heavy-ion collisions



→ many more interesting measurements also with hadronic final states to come!

Backup

CEP of J/Ψ and Ψ(2S) @ 13 TeV

LHCb-CONF-2016-007

integrated cross-sections $2.0 < \eta(\mu) < 4.5$:

13 TeV

$\sigma(J/\psi\to\mu^+\mu^-)$ = 411.0 ± 16 stat ± 21 sys ± 16 (lumi) pb

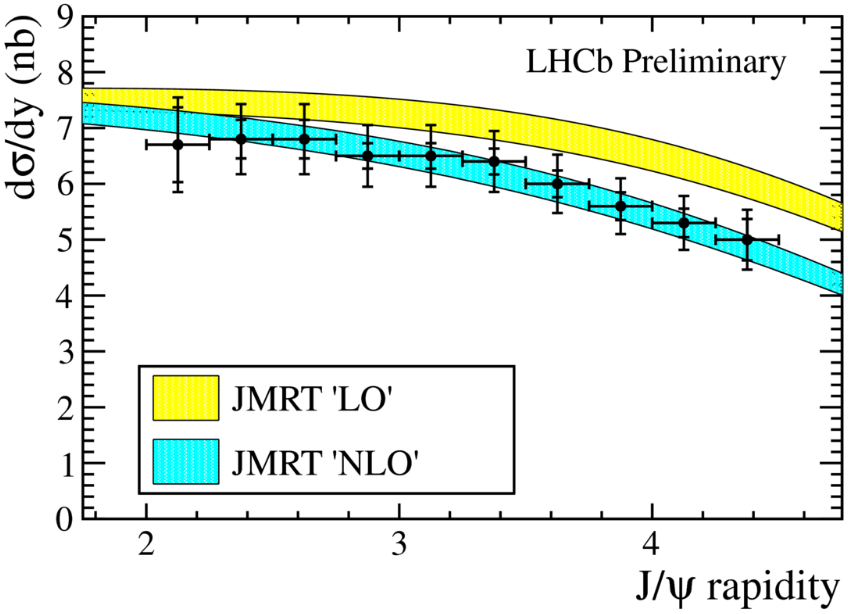
$\sigma(\psi(2S)\to\mu^+\mu^-)$ = 9.4 ± 1.3 stat ± 0.5 sys ± 0.4 (lumi) pb

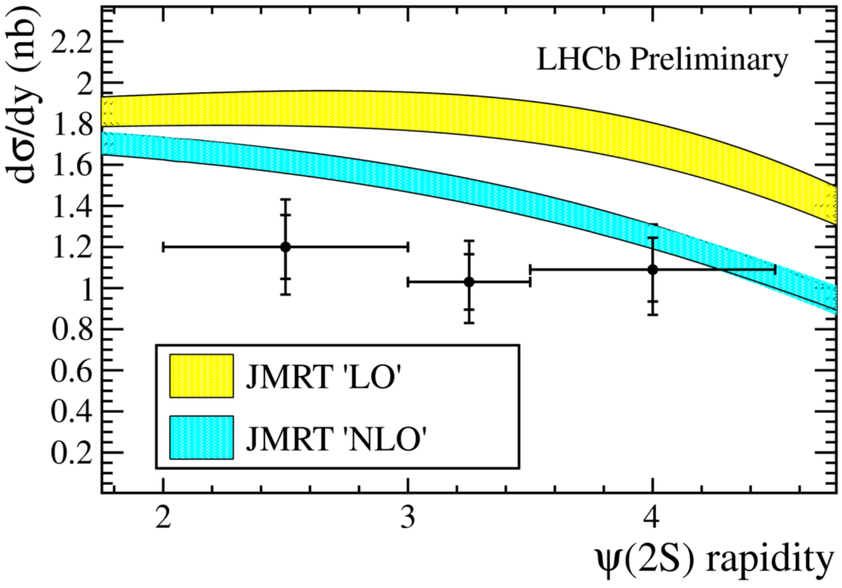
7 TeV

$\sigma(J/\psi\to\mu^+\mu^-)$ = 291.0 ± 7 stat ± 19(sys)pb

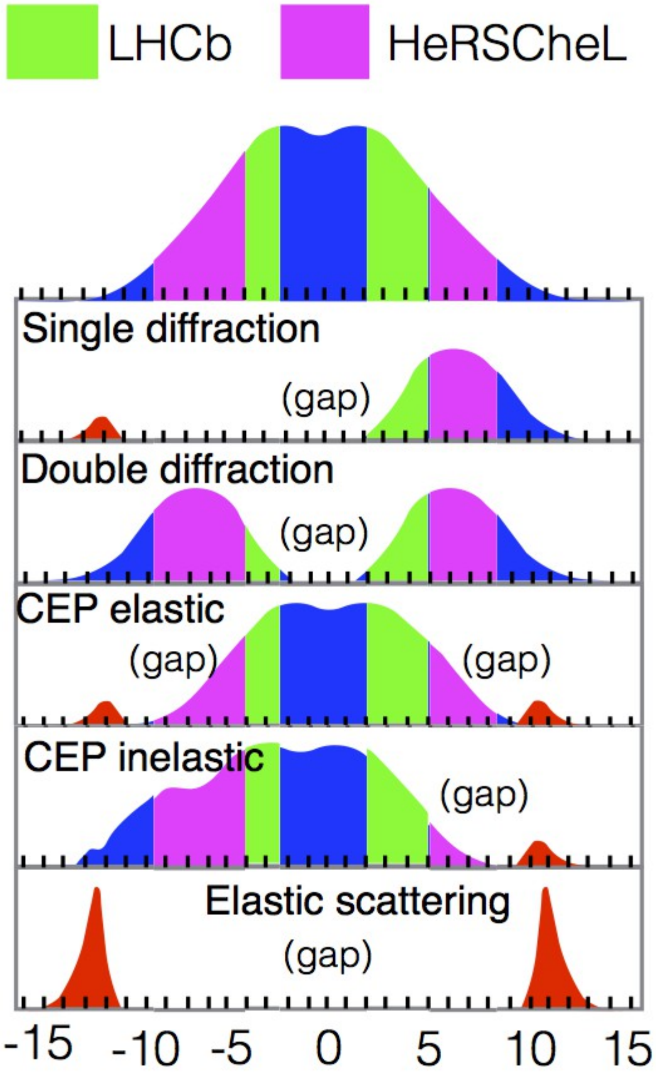
$\sigma(\psi(2S)\to\mu^+\mu^-)$ = 9.4 ± 1.3 stat ± 0.5 sys ± 0.4 (lumi) pb

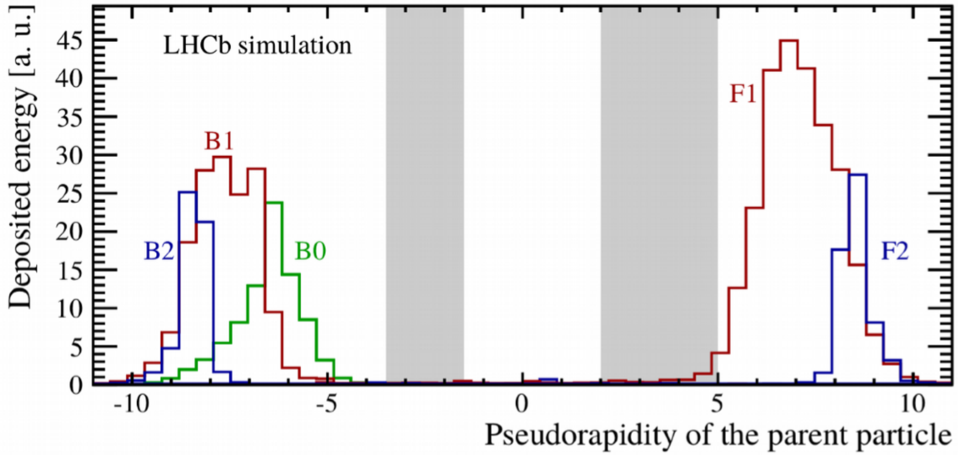
13 TeV → better agreement with NLO predictions

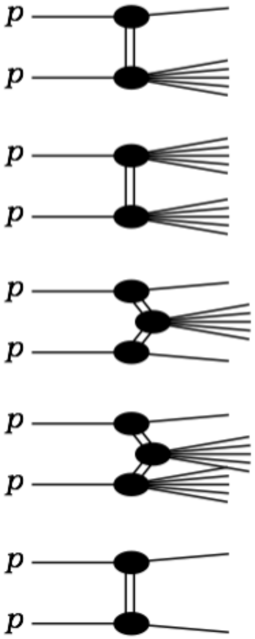




LHCb collision signatures





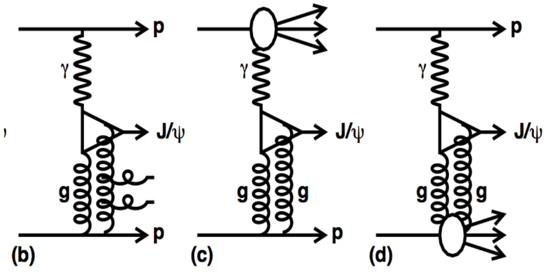


CEP events:
only few particles
(muons, hadrons, photons..)

CEP backgrounds:
additional particles,
usually very forward

J/Ψ, Ψ(2S) @ 7 TeV

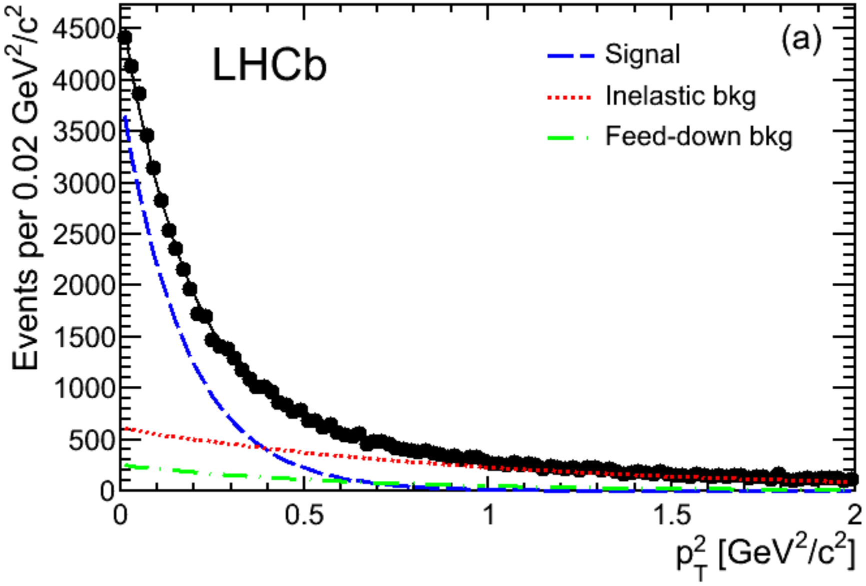
J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002



Backgrounds

- non resonant: small for J/ψ (0.8±0.1)%
  significant for ψ(2s) (17.0±0.3)%
- feed down: from higher resonances
  J/ψ: (7.6 ± 0.9)% from χ_c and (2.5 ± 0.2)% from ψ(2s)
  ψ(2s): (2.0 ± 2.0)% from X(3872) and $\chi_c(2P)$
- inelastic background with extra particles out of LHCb acceptance - dominant
  estimated from p_T^2 distribution

$$f_s e^{-b_s p_T^2} + f_b e^{-b_b p_T^2} f_f F_f p_T^2$$



- signal and inelastic background: exponential
- feed-down: shape from data
- fit slope and normalization of signal and backgrounds

exp. slopes b agree well with expectation from HERA:

LHCb exp. from HERA	LHCb fit
$b_s \sim 6$ GeV^{-2}	$b_s = 5.70 \pm 0.11$ GeV^{-2}
$b_b \sim 1$ GeV^{-2}	$b_b = 0.97 \pm 0.04$ GeV^{-2}

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J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

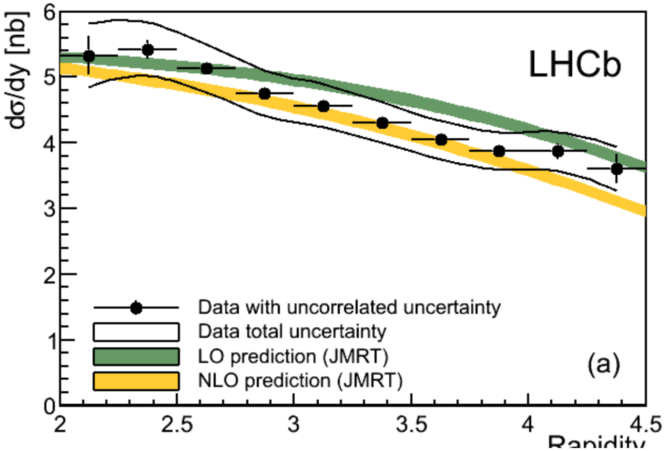
J/ψ

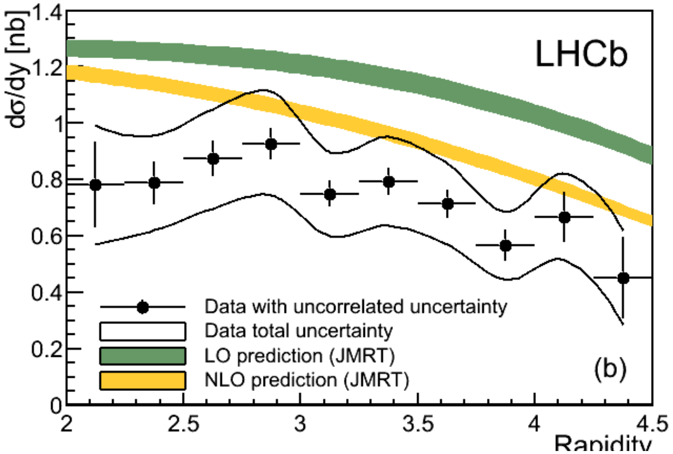
ψ(2S)

LO,NLO

JRMT:

JHEP 1311 (2013) 085





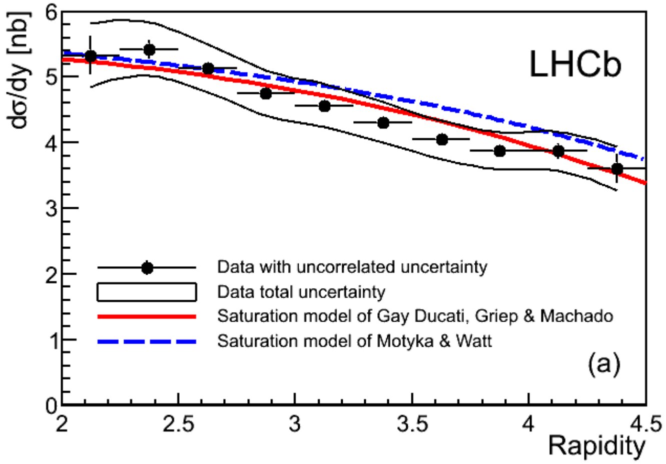
Saturation

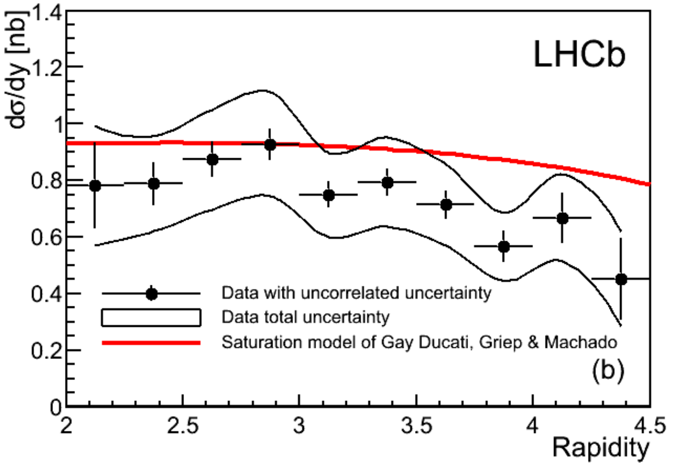
M&W:

Phys. Rev. D78 (2008) 0140

GGM:

Phys.Rev. D88 (2013) 01750





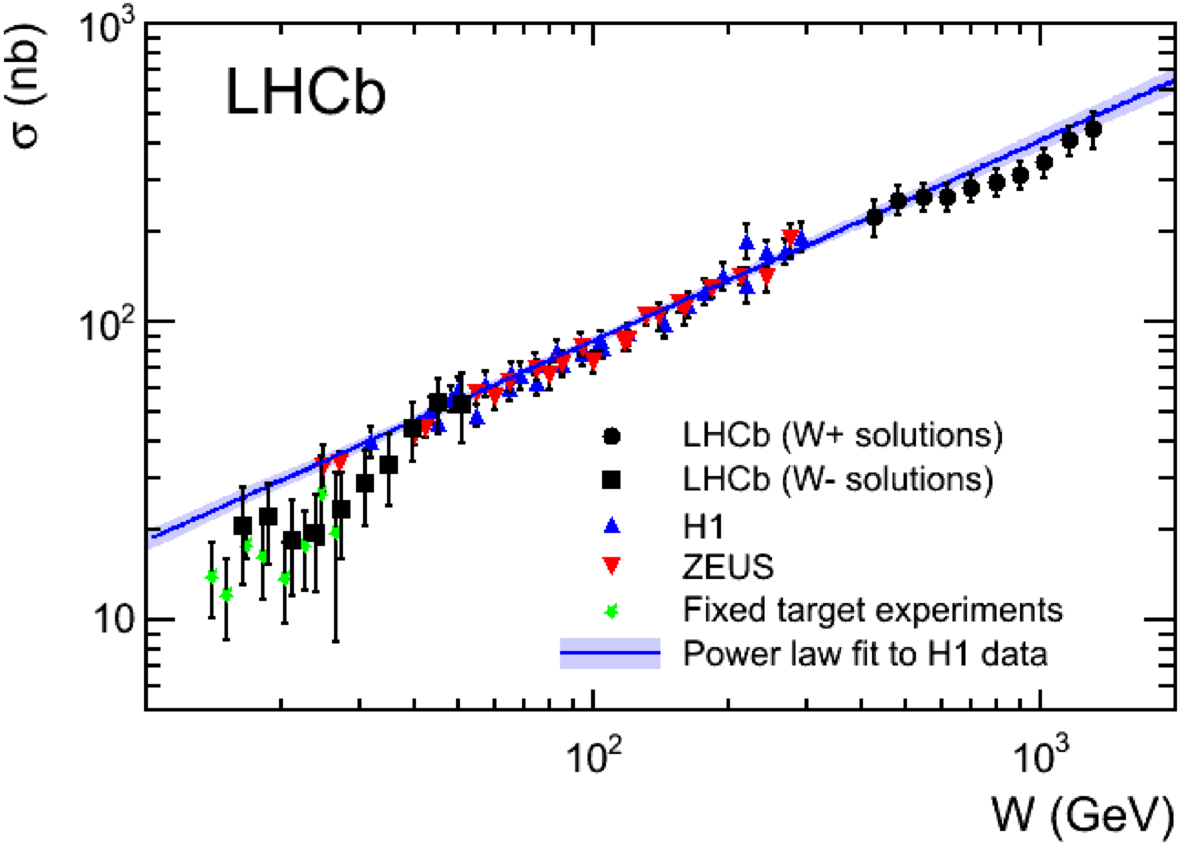
- dominant uncertainty:purity 2% J/ψ, 13% ψ(2S)
- uncertainties highly correlated between bins
- shape better described by NLO prediction or models including saturation

J/Ψ, Ψ(2S) photoproduction x-section

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

compare to HERA γp data using known photon flux for a photon (energy k)

$$\overbrace{\frac{d\sigma}{dy}_{pp\rightarrow pVp}}^{\text{measured}} = r(y)\left[k_+\frac{dn}{dk_+}\overbrace{\sigma_{\gamma p\rightarrow Vp}(W^+)}^{\text{from HERA/extracted}} + k_-\frac{dn}{dk_-}\overbrace{\sigma_{\gamma p\rightarrow Vp}(W^-)}^{\text{extracted/from HERA}}\right]$$



→ two correlated points for each measurement (W^+, W^-) in y

→ good agreement with low energy fixed target data

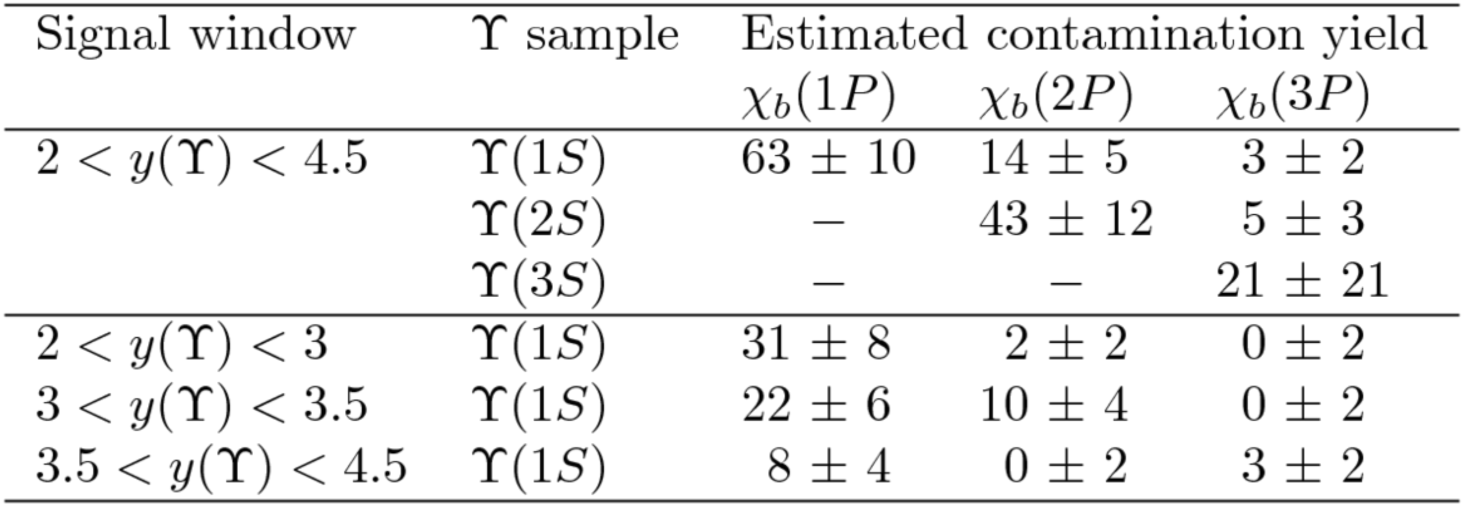
deviation from power law:

- higher order
- saturation effects

CEP of Υ – feed down and uncertainties

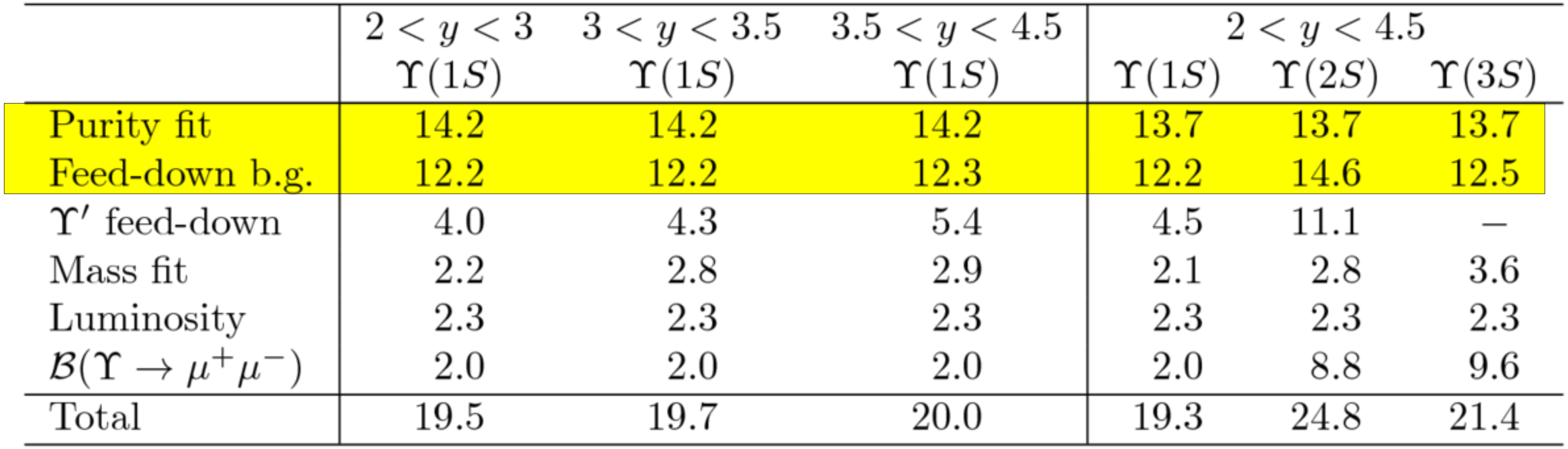
JHEP 1509 (2015) 084

feed down backgrounds



Signal window	Υ sample	Estimated contamination yield		
		$\chi_b(1P)$	$\chi_b(2P)$	$\chi_b(3P)$
$2 < y(\Upsilon) < 4.5$	$\Upsilon(1S)$	63 ± 10	14 ± 5	3 ± 2
	$\Upsilon(2S)$	–	43 ± 12	5 ± 3
	$\Upsilon(3S)$	–	–	21 ± 21
$2 < y(\Upsilon) < 3$	$\Upsilon(1S)$	31 ± 8	2 ± 2	0 ± 2
$3 < y(\Upsilon) < 3.5$	$\Upsilon(1S)$	22 ± 6	10 ± 4	0 ± 2
$3.5 < y(\Upsilon) < 4.5$	$\Upsilon(1S)$	8 ± 4	0 ± 2	3 ± 2

systematic uncertainties



	$2 < y < 3$	$3 < y < 3.5$	$3.5 < y < 4.5$	$2 < y < 4.5$		
	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Purity fit	14.2	14.2	14.2	13.7	13.7	13.7
Feed-down b.g.	12.2	12.2	12.3	12.2	14.6	12.5
Υ' feed-down	4.0	4.3	5.4	4.5	11.1	–
Mass fit	2.2	2.8	2.9	2.1	2.8	3.6
Luminosity	2.3	2.3	2.3	2.3	2.3	2.3
$\mathcal{B}(\Upsilon \to \mu^+\mu^-)$	2.0	2.0	2.0	2.0	8.8	9.6
Total	19.5	19.7	20.0	19.3	24.8	21.4

CEP: double charmonium production

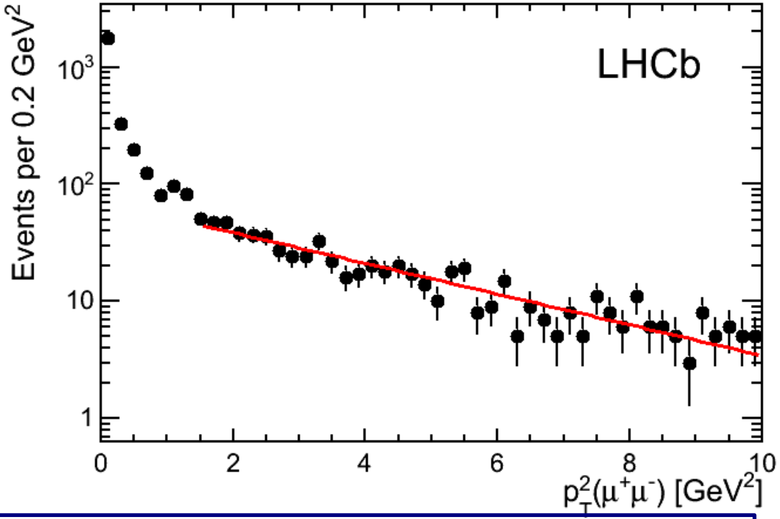
J. Phys. G41 115002

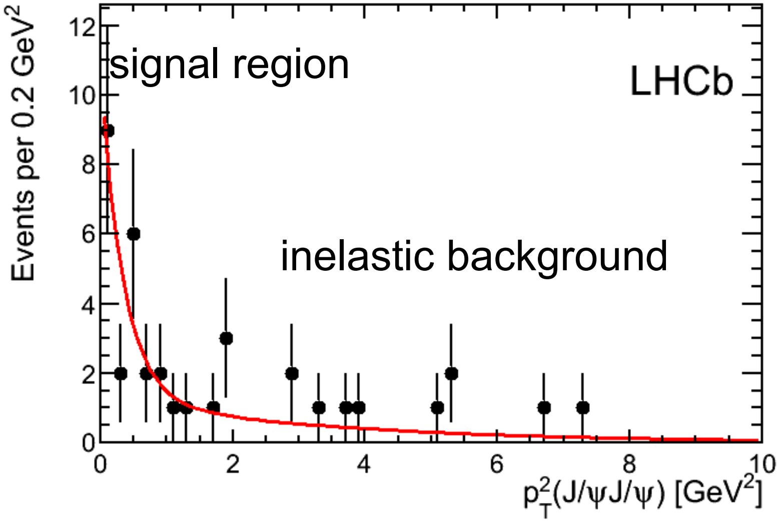
fraction of elastic events: $$d\sigma/d p_T^2 = f_s b_s e^{-b_s p_T^2} + (1-f_s) b_b e^{-b_b p_T^2}$$

elastic (b_s) & inelastic (b_b) components

- take b_b from fit to background sample: b_b= 0.29 ± 0.02 GeV^{-2}
- perform fit to determine b_s and f_s b_s= 2.9 ± 1.3 GeV^{-2}, f_s = 0.42 ± 0.13

background sample:
CEP di-μ candidates with 6 < $M_{\mu\mu}$ < 9 GeV





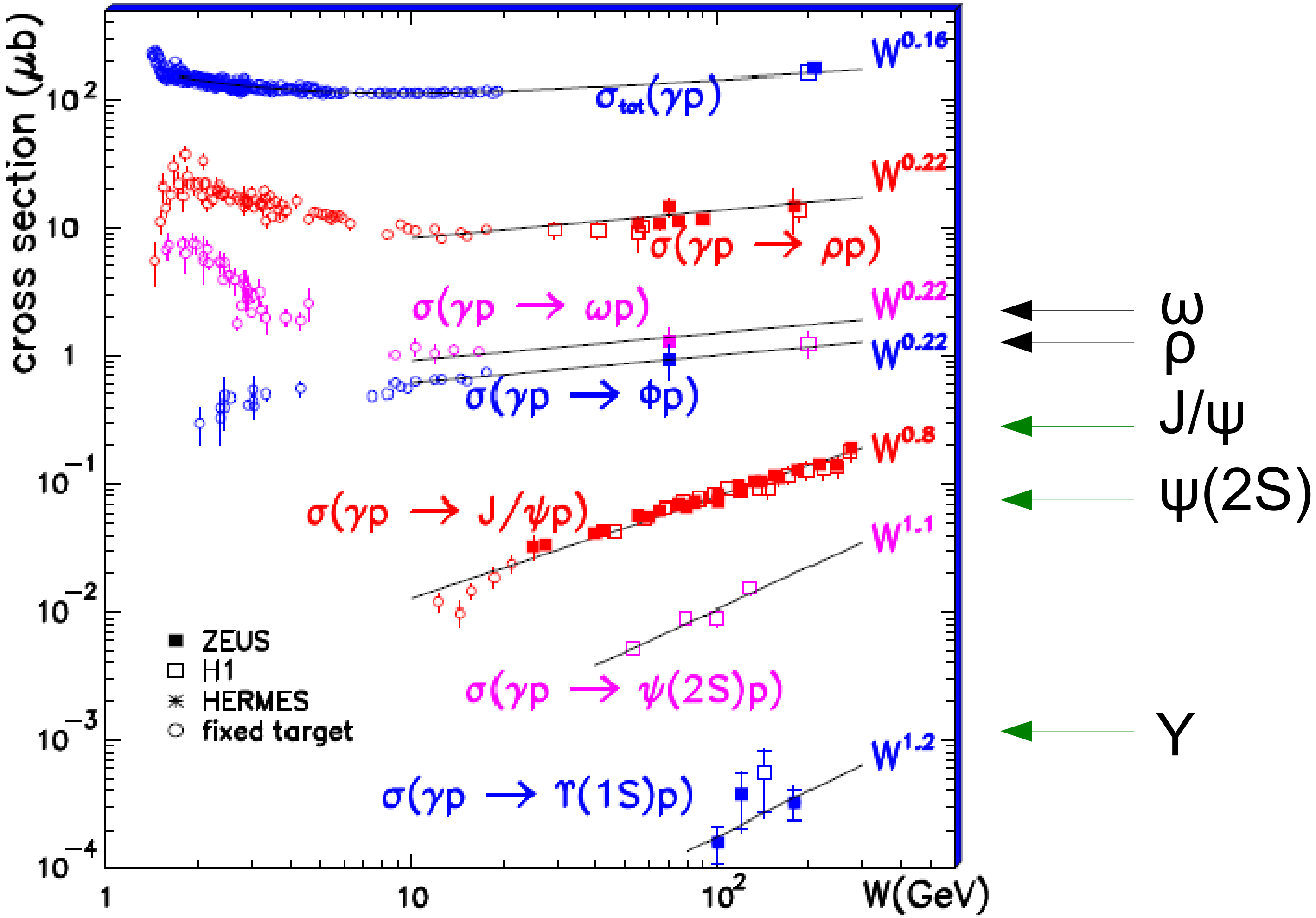
CEP: σ(J/ΨJ/Ψ) = 24 ± 9 pb
Theory: σ(J/ΨJ/Ψ) ≈ 8 to 36 pb

arXiv:1409.4785

CEP outlook

work ongoing with other final states, also in hadronic channels

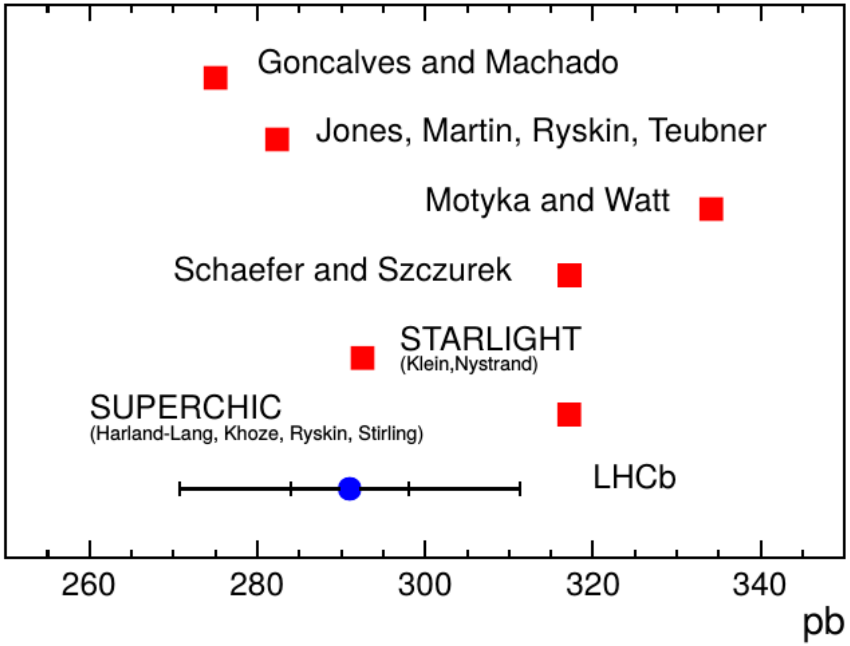
10.3204/DESY-PROC-2012-03/58

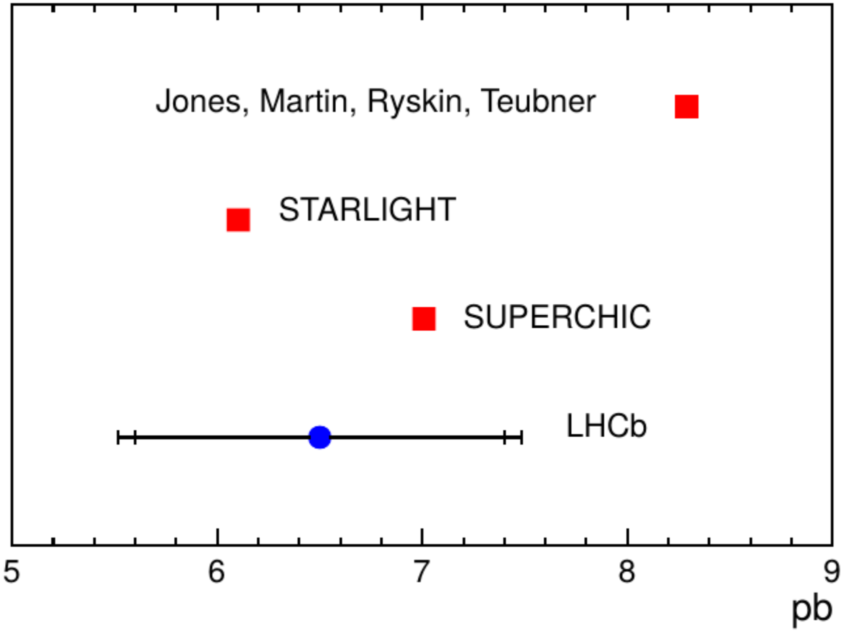


J/Ψ, Ψ(2S) @ 7 TeV

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

total cross sections:





cross section times BF to two muons with $2.0 < \eta < 4.5$

$\sigma(J/\psi) = 291 \pm 7(\text{stat}) \pm 19(\text{syst})$ pb
$\sigma(\psi(2S)) = 6.5 \pm 0.9(\text{stat}) \pm 0.4(\text{syst})$ pb

→ in good agreement with predictions

G&M:	Phys. Rev. C84 (2011) 011902
JRMT:	JHEP 1311 (2013) 085
M&W:	Phys. Rev. D78 (2008) 014023
Sch&S	Phys. Rev. D76 (2007) 094014
Starlight:	Phys. Rev. Lett. 92 (2004) 142003
Superchic:	Eur. Phys. J. C65 (2010) 433

J/Ψ, Ψ(2S) photoproduction x-section

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

J/Ψ production cross section measured as a function of rapidity
→ results can then be compared to H1/ZEUS data using photon flux for a photon of energy k

- correct for gap survival
- each rapidity bin: two solutions for W
- take LO extrapolation from HERA for W $^{+(-)}$, extract solution for W $^{-(+)}$

$$\overbrace{\frac{d\sigma}{dy}}^{\text{measured}}_{pp\to pVp} = r(y)\left[k_+\frac{dn}{dk_+}\overbrace{\sigma_{\gamma p\to Vp}(W^+)}^{\text{extracted/from HERA}} + k_-\frac{dn}{dk_-}\overbrace{\sigma_{\gamma p\to Vp}(W^-)}^{\text{from HERA/extracted}}\right]$$

$$r(y)= 0.85-\frac{0.1|y|}{3} \quad \text{absorptive correction, gap survival}$$

$$\frac{dn}{dk}=\frac{\alpha_{cm}}{2\pi k}[1+(1-\frac{2k}{\sqrt{s}})^2](\log A-\frac{11}{6}+\frac{3}{A}-\frac{3}{2A^2}+\frac{1}{3A^3}) \quad \text{photon energy spectrum}$$