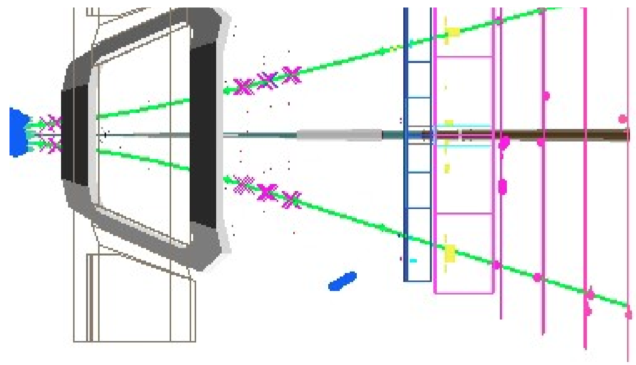


Central exclusive quarkonia production in the forward region at LHCb

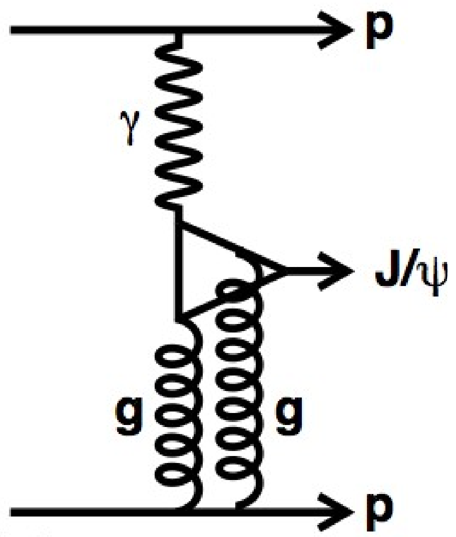
Kruger conference, December 1-6, 2014

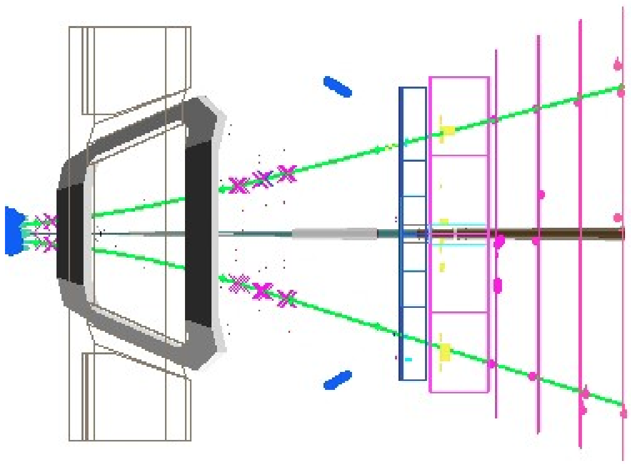
Katharina Müller

on behalf of the LHCb collaboration

Outline

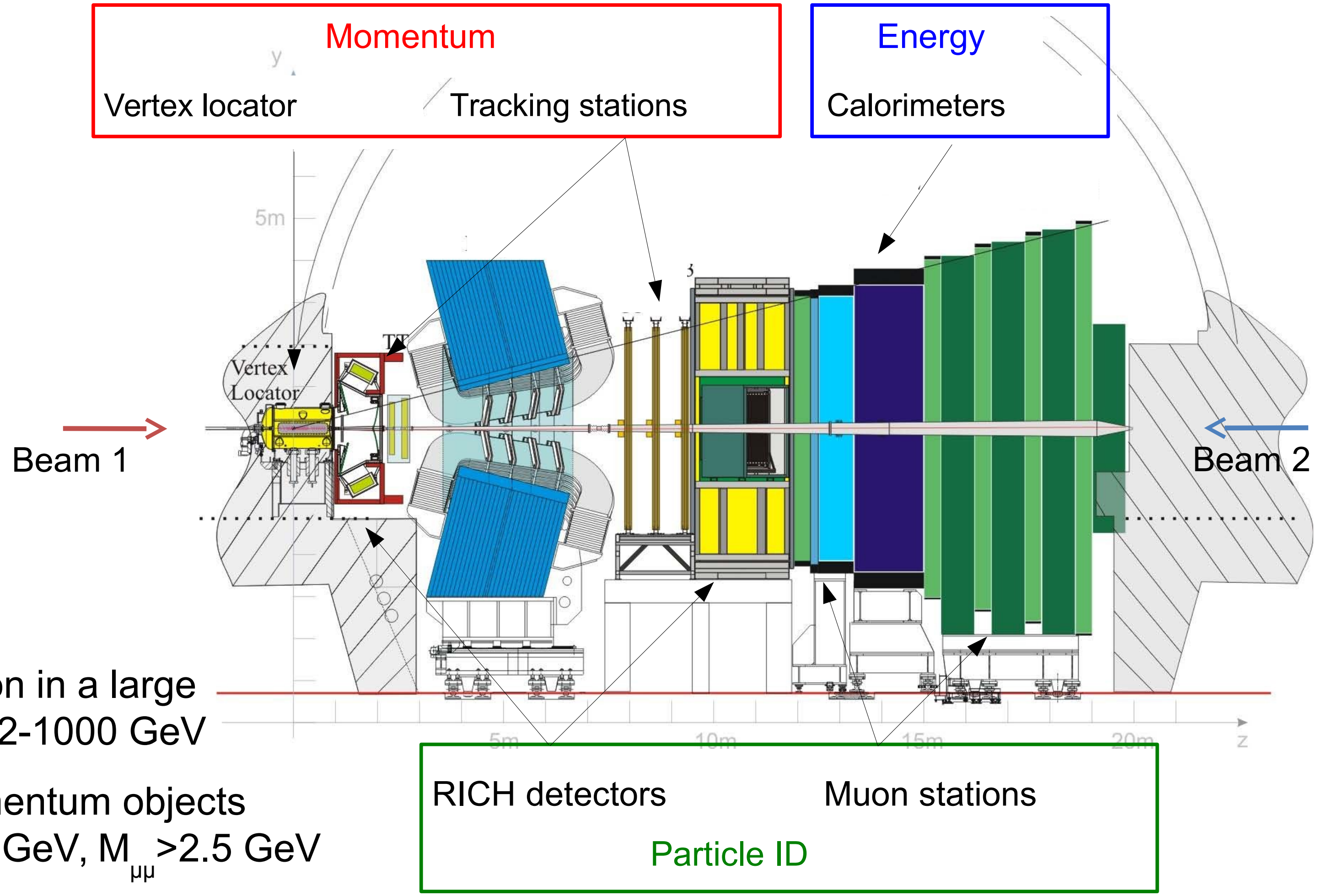
- LHCb detector
- Central Exclusive Production (CEP) @ LHCb
  - J/ψ and ψ(2S) → μ μ
  - Double charmonium
  - Detector upgrade
  - Outlook
- Conclusions





LHCb Detector – more than a beauty detector

fully instrumented in the forward region ($2 < \eta < 5$)
some detection capability in backward region ($-3.5 < \eta < -1.5$)
→ LHCb is a general purpose high resolution spectrometer

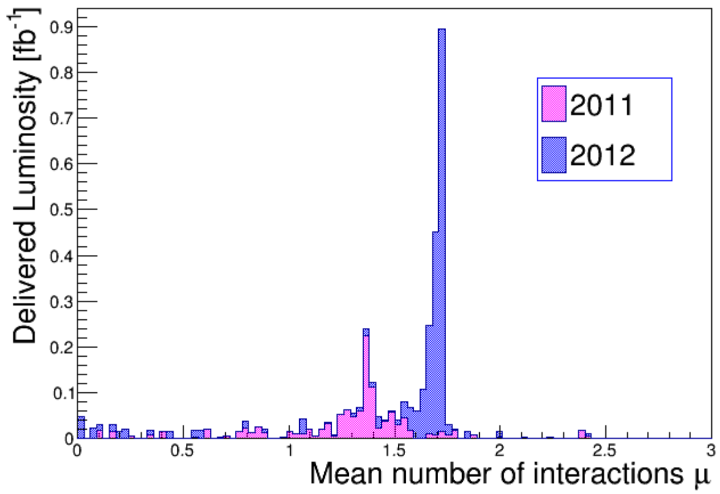


- excellent tracking
- particle identification in a large momentum range: 2-1000 GeV
- trigger on low momentum objects $p_\mu > 3$ GeV, $p_T^\mu > 0.5$ GeV, $M_{\mu\mu} > 2.5$ GeV

LHCb running

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

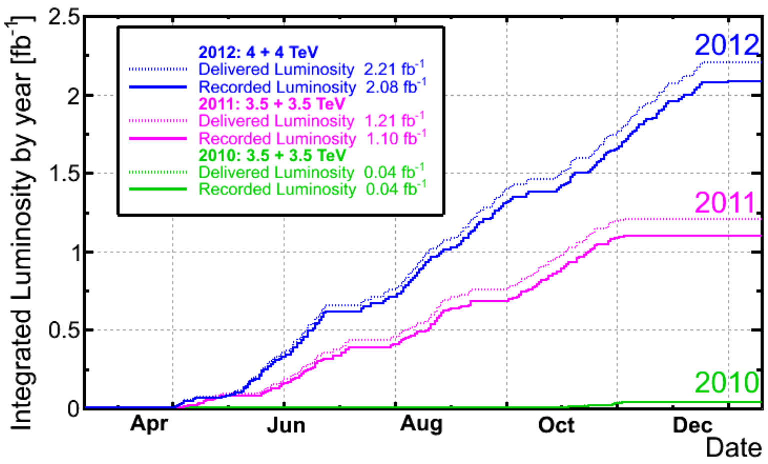
	luminosity	cms energy	fraction of 1 PV events
2011:	1.1 fb-1	7 TeV	24%
2012:	2.1 fb-1	8 TeV	21%

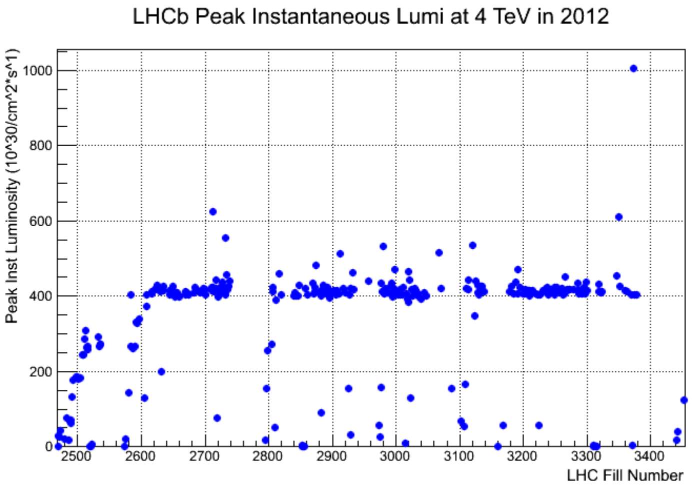


Fraction of crossings with N interactions

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

luminosity levelling – very stable data taking conditions





Central exclusive production (CEP): Introduction

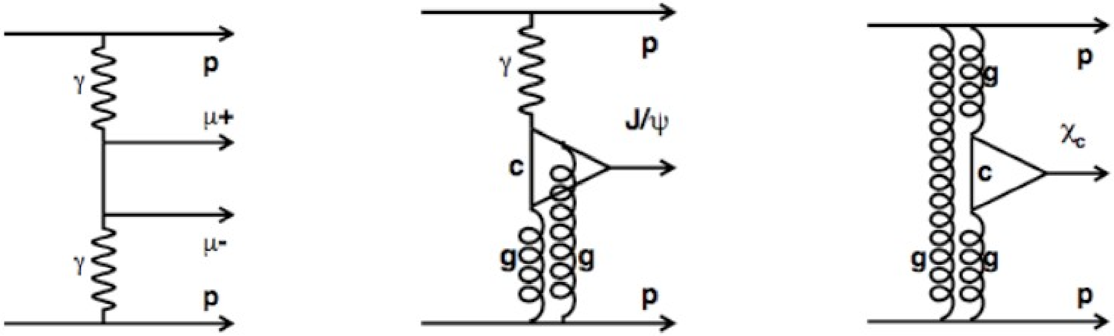
exchange of a colourless object: γ, pomeron

→ exclusive candidate (eg two muons from J/Ψ decay) + rapidity gaps

→ protons escape undetected in beampipe

formally: $$h_1(p_1) + h_2(p_2) \rightarrow h_1(p_1') \oplus X \oplus h_2(p_2')$$

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)



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

theoretical predictions

LPAIR A.G.Shamov and V.I.Telnov, NIM A 494 (2002) 51

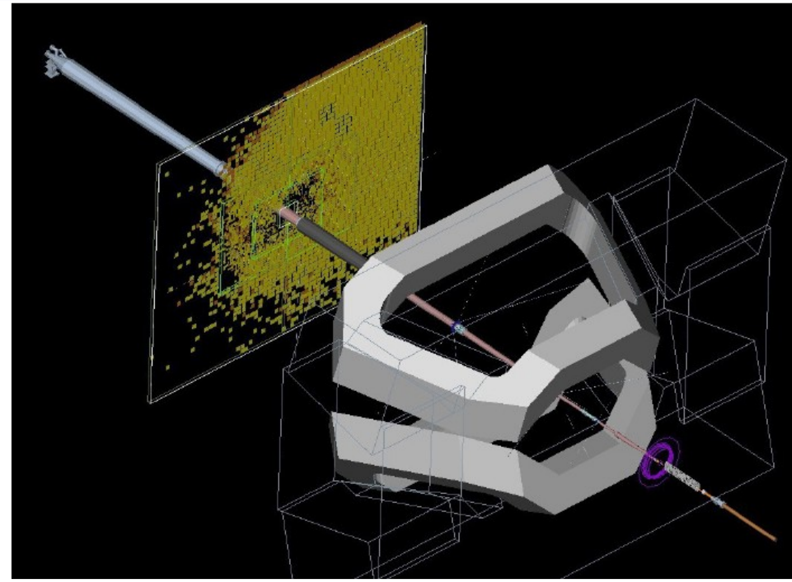
Starlight S.R.Klein and J.Nystrand, Phys. Rev. Lett. 92 (2004) 142003

SuperChiC LA.Harland-Lang, V.A.Khoze, M.G.Ryskin, W.J.Stirling, arXiv:0909.4748[hep-ph]

CEP with di-muons: J/Ψ, Ψ(2S)

Signature

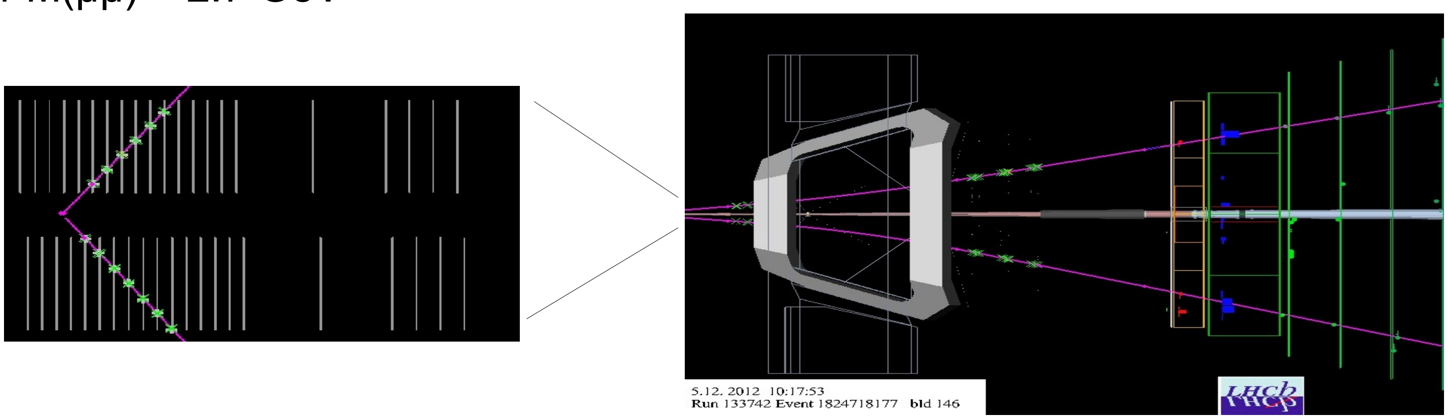
- two muons
- no other activity in event
- di-muon system: low p_T



Trigger:

- hardware:
  one μ (p_T> 400 MeV)
  or two μ (p_T> 80 MeV)
  low multiplicity in scintillator pad detector in front of calorimeter
- software:
  di-μ candidate with p_T< 900 MeV
  or M(μμ) > 2.7 GeV

VELO
8.4 cm

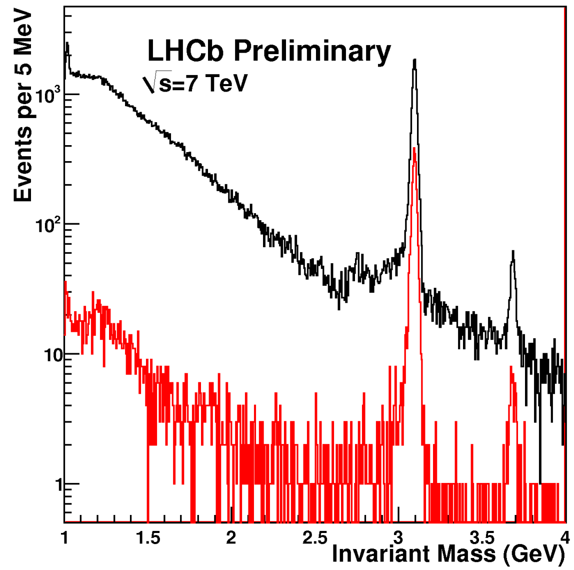


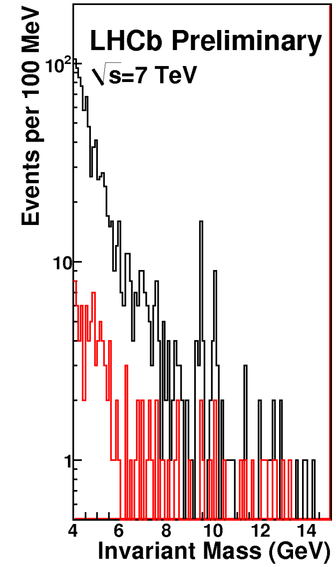
LHCb
10 m

Exclusive di-muon selection

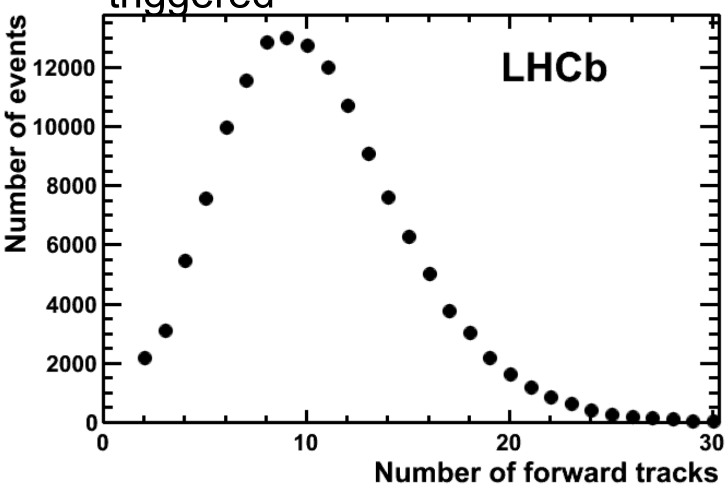
triggered:
two μ, little activity in calorimeter

exclusive:
two forward, no backward tracks

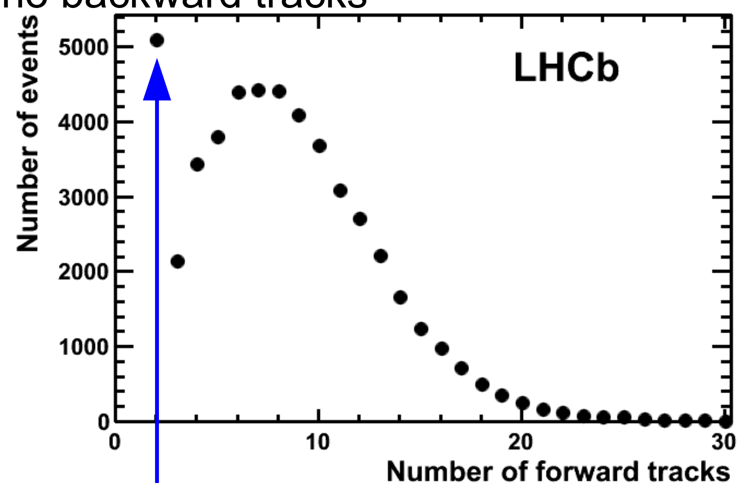




triggered



no backward tracks



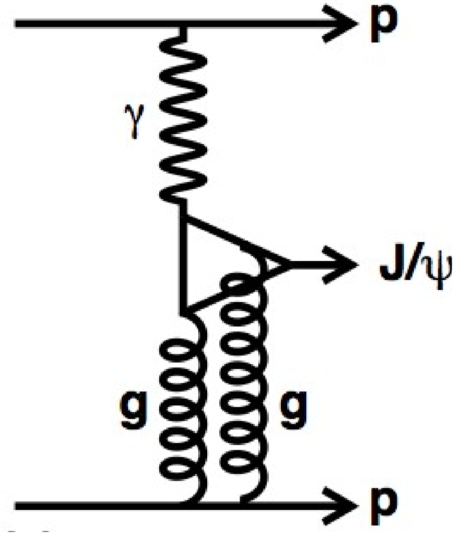
candidates for exclusive production

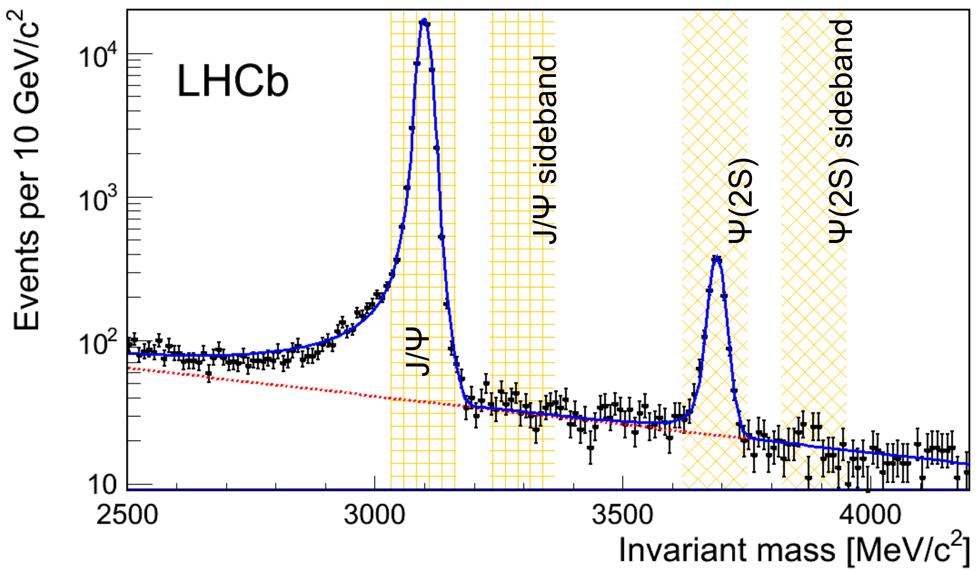
CEP of J/Ψ and Ψ(2S)

Selection

- 1 fb^{-1} @ 7 TeV
- event with one interaction: 24% of total luminosity
- precisely two forward muons
- no backward tracks
- no photons
- p_T^2 (μμ)< 0.8 GeV^2
- M(μμ) within 65 MeV of nominal mass

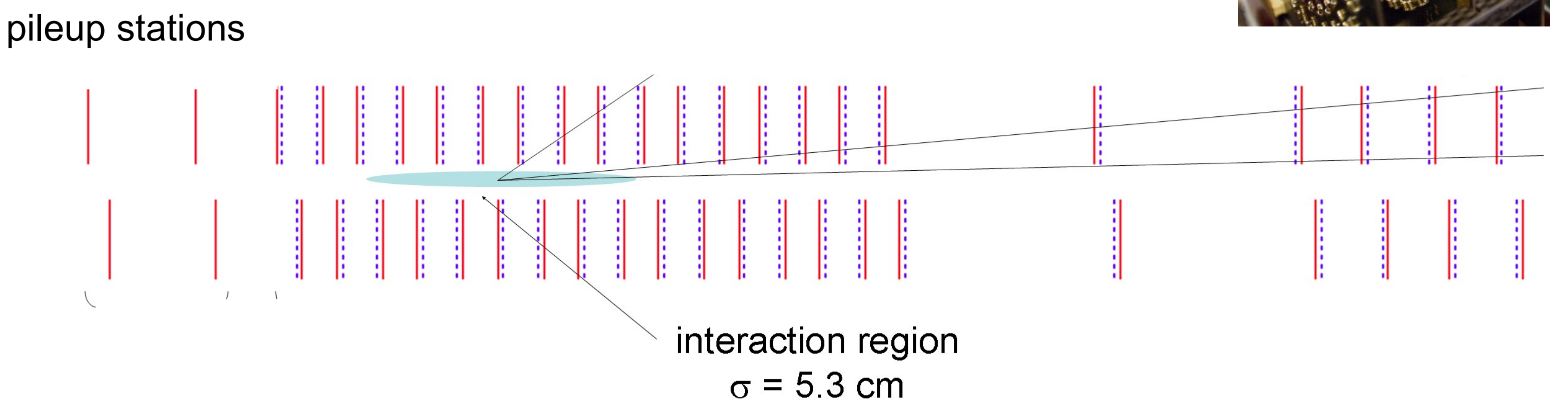
→ 55985 J/ψ and 1565 ψ(2s) candidates

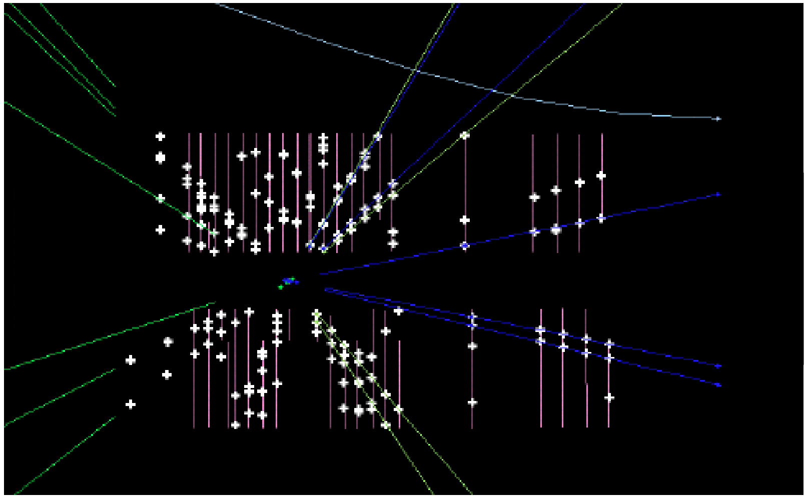




LHCb Vertex locator (VELO)

84 micro-strip silicon sensors close to the IR
→ precise track and vertex reconstruction





acceptance:
forward: $1.5 < \eta < 5.0$
backward: $-3.5 < \eta < -1.5$

backwards tracks re-constructable
(no momentum information)

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

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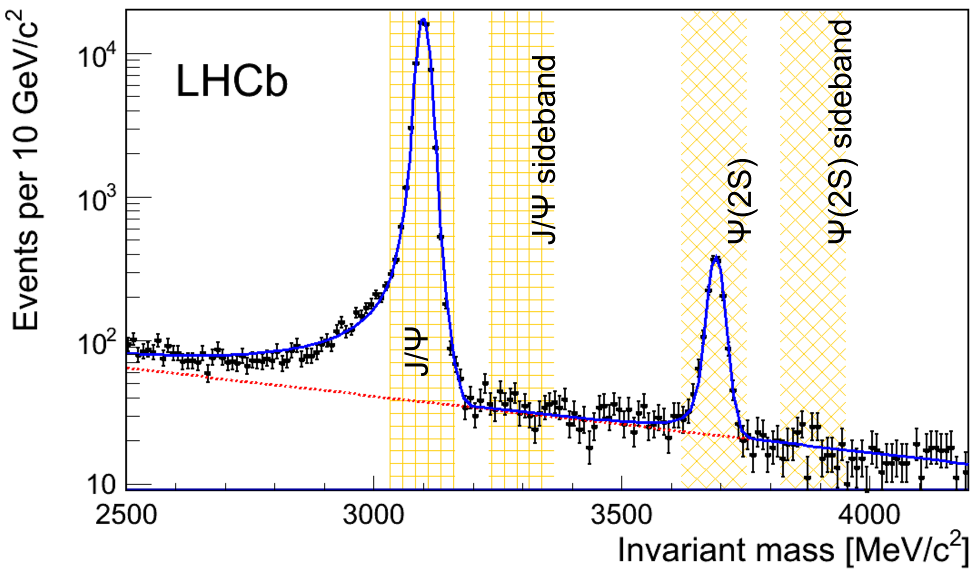
Backgrounds

- non resonant: small for J/ψ (0.8±0.1)%
  significant for ψ(2s) (17.0±0.3)%
- feed down: 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)
- dominant: inelastic background with extra particles out of LHCb acceptance
  estimated from p_T^2 distribution



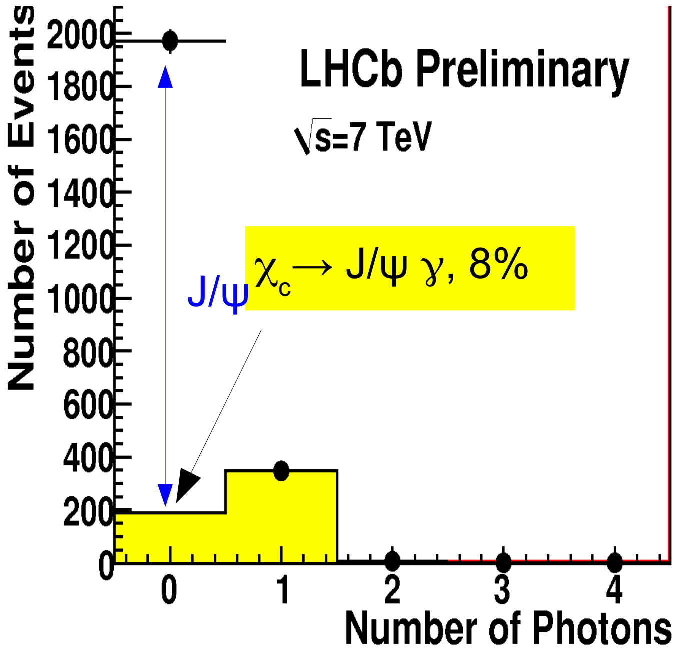
Backgrounds from feed down – J/ψ only

estimated from simulation, normalised to background enriched sample

- from $\chi_c \rightarrow J/\psi\ \gamma$:

  suppressed: no photons
  estimate residual background from MC, normalised to data

  contribution: $(7.6 \pm 0.9)\%$



- from $\psi(2s) \rightarrow J/\psi\ X$:

  suppressed: exactly two tracks
  estimated from measured $\psi(2s)$ cross section scaling to ratio in MC

  contribution: $(2.5 \pm 0.2)\%$

- for $\psi(2s)$: $(2.0 \pm 2.0)\%$ from X(3872)

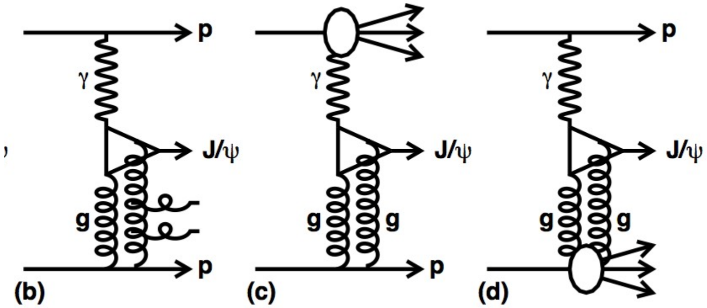
  estimated from data, relaxing cut on photon

MC: SuperChiC LA.Harland-Lang, V.A.Khoze, M.G.Ryskin, W.J.Stirling, arXiv:0909.4748[hep-ph]

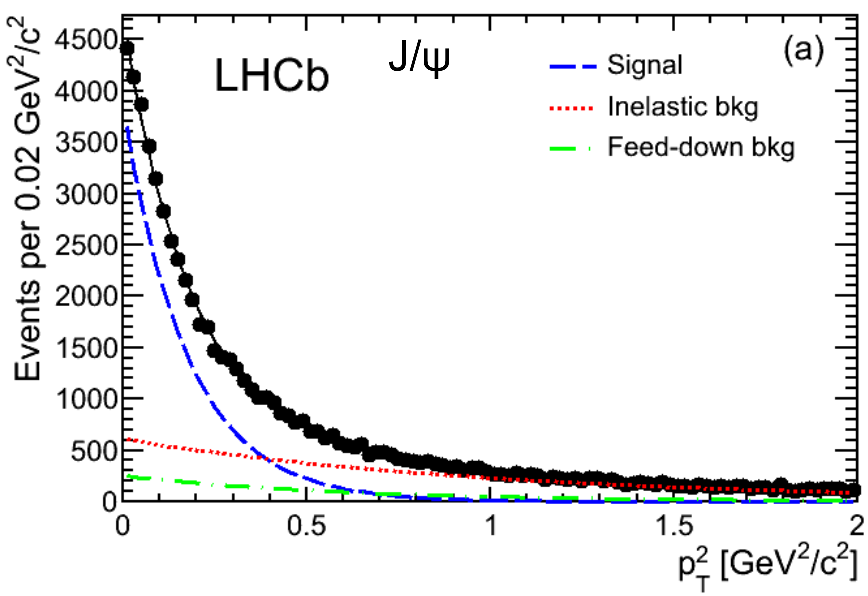
CEP: Inelastic background

proton dissociation or gluon radiation
→ estimated from data: fit p_T^2 distribution

exclusive: exponential distribution (Regge theory)
inelastic background: exponential but harder p_T^2 distribution



- signal and inelastic background: exponential
- feed-down: shape from data $\chi_c \to J/\psi\gamma$ and $\psi(2S) \to J/\psi\pi\pi$
- fit slope and normalization of signal and background



slope b agrees well with expectation from HERA:

LHCb expected from HERA
$b_s \sim 6$ GeV^{-2}
$b_b \sim 1$ GeV^{-2}

LHCb Fit:
$b_s = 5.70 \pm 0.11$ GeV^{-2}
$b_b = 0.97 \pm 0.04$ GeV^{-2}

CEP: Inelastic background

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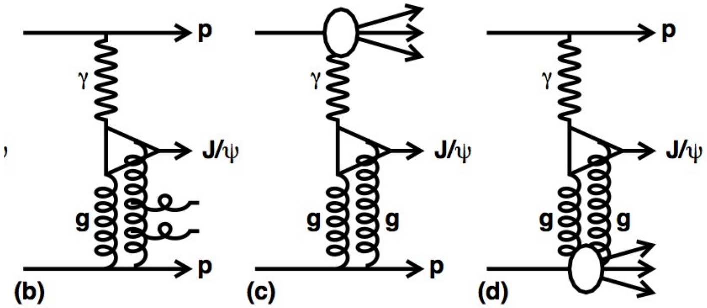
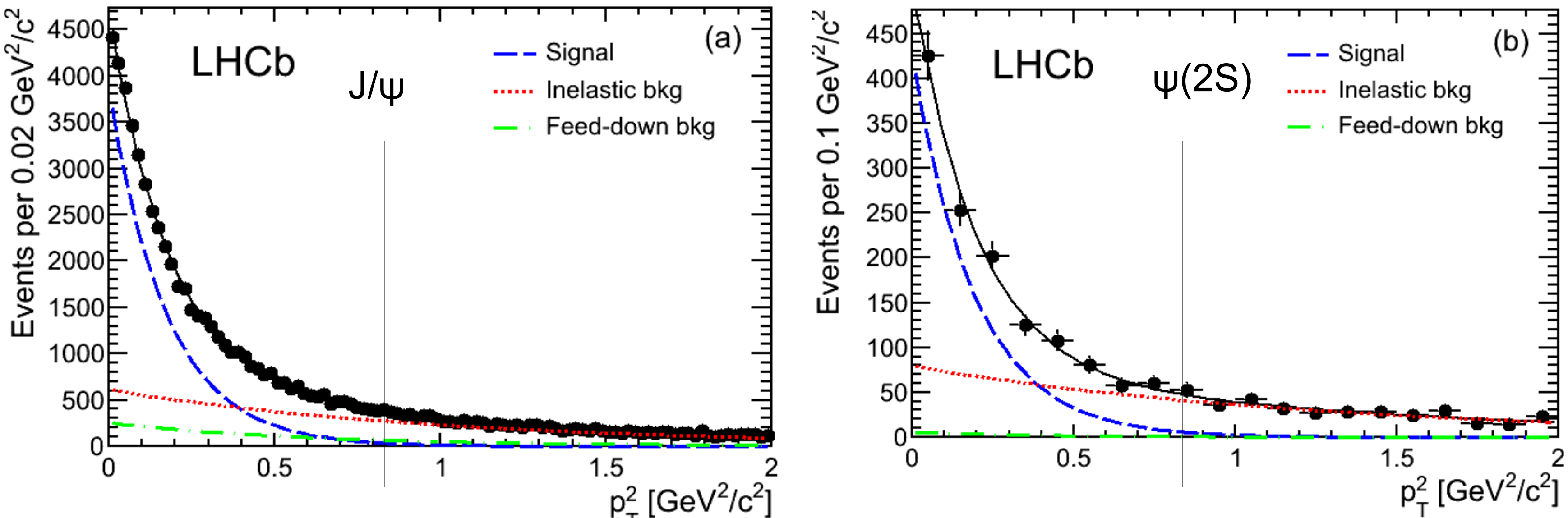
proton dissociation or gluon radiation
→ estimated from data: fit p_T^2 distribution

exclusive: exponential distribution (Regge theory)
inelastic background: exponential but harder p_T^2 distribution



- signal and inelastic background: exponential
- feed-down: shape from data $\chi_c \to J/\psi\gamma$ and $\psi(2S) \to J/\psi\pi\pi$
- fit slope and normalization of signal and background



purity $p_T^2 < 0.8$ GeV^2: 0.59 ± 0.01 for J/ψ and 0.52 ± 0.07 for ψ(2S)

Cross section

measurement differential in rapidity

ρ: purity
- feed down background (10% / 2%)
- non resonant background (1% / 17%)
- inelastic background (41% / 48%)

N: number of observed events

$$\sigma = \frac{\rho N}{\epsilon L}$$

ε: efficiency
- trigger, tracking, μ ID, selection (simulation)
- single interaction beam crossing

$$P(n) = \mu^n \exp(-\mu)/n!$$

n number of visible pp interactions
μ average number of visible interactions
efficiency 24.1%

L: luminosity

CEP: total cross-section

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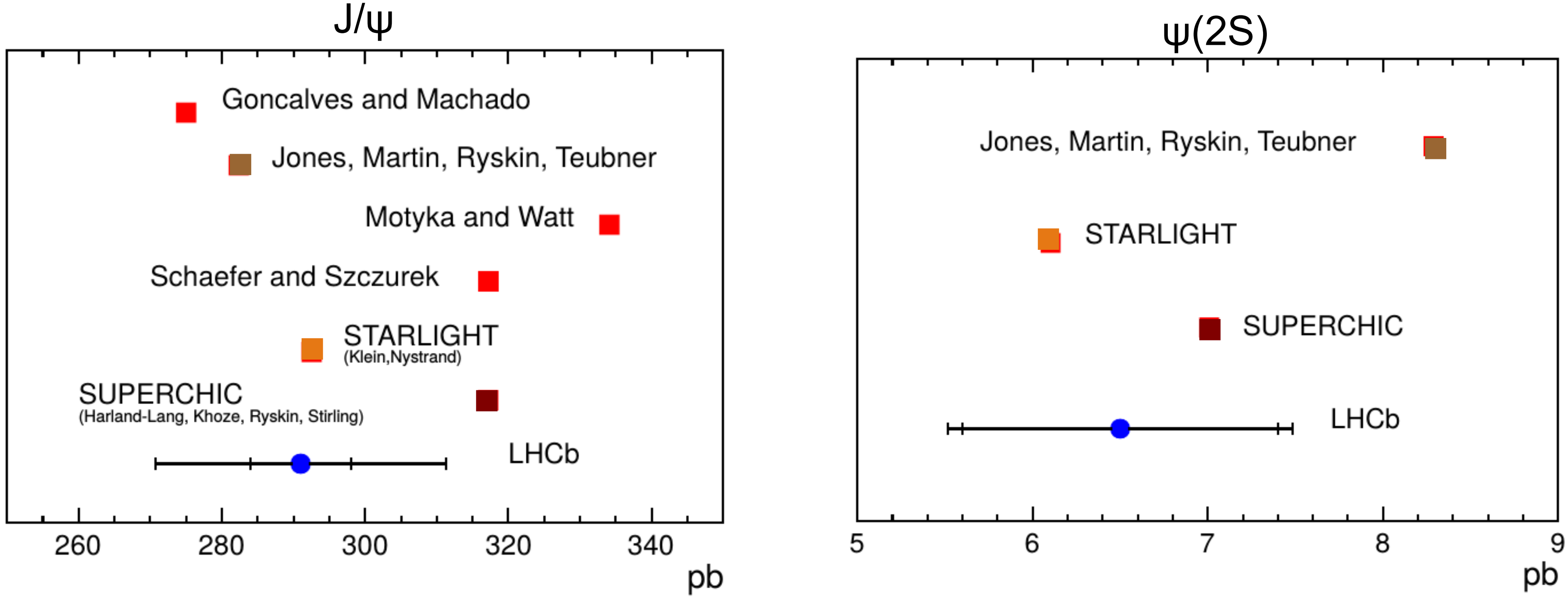

cross section times BF to two muons with $2.0 < \eta < 4.5$

$\sigma(J/\psi) = 291 \pm 7(\text{stat}) \pm 19(\text{syst})$ 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

CEP: differential cross section

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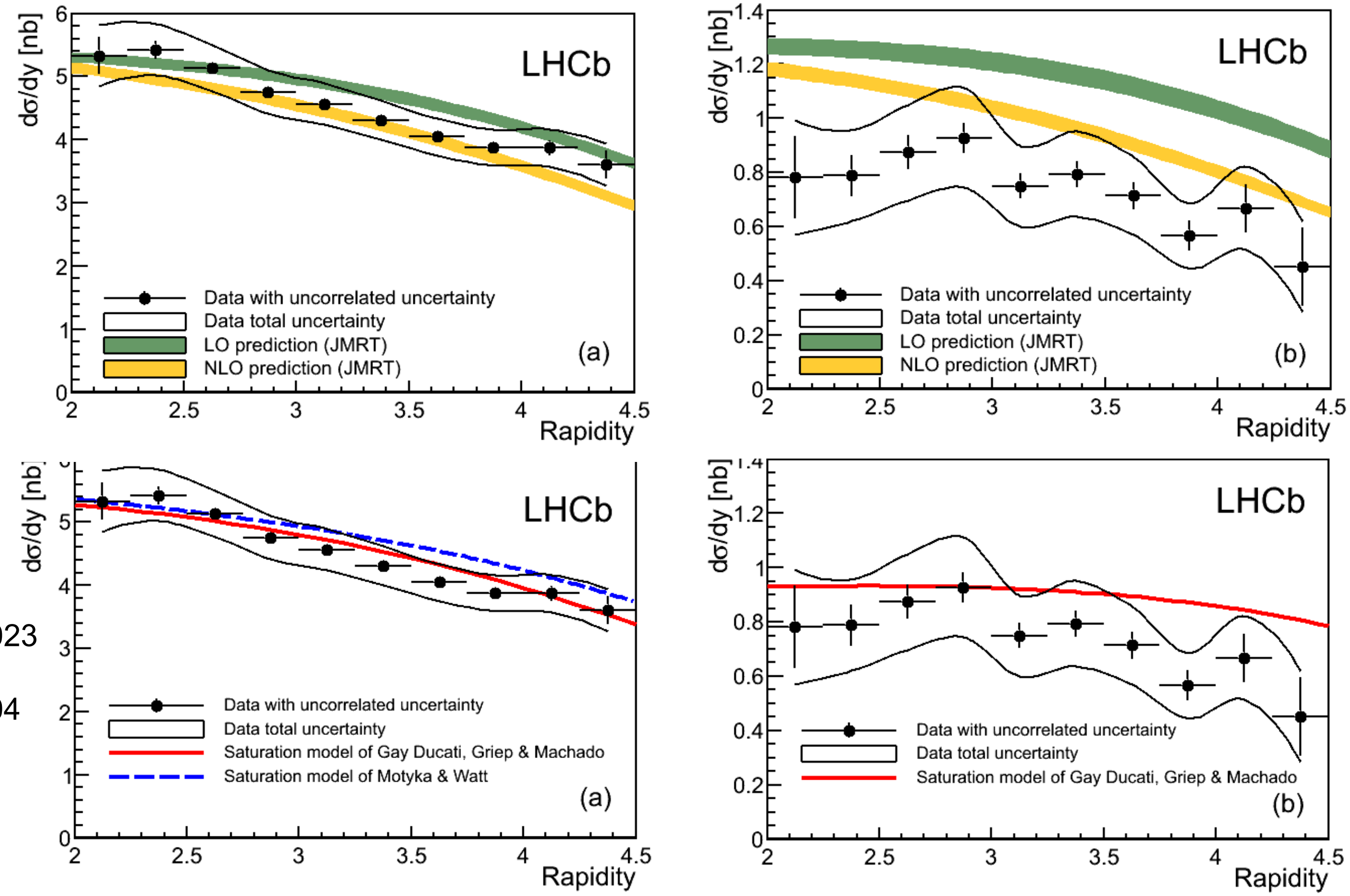
J/ψ ψ(2S)

LO,NLO
JRMT:
JHEP 1311 (2013) 085

Saturation
M&W:
Phys. Rev. D78 (2008) 014023
GGM:
Phys.Rev. D88 (2013) 017504



- uncertainties highly correlated between bins
- shape better described by NLO prediction or models including saturation

J/ψ Photoproduction cross section

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 $W^{-(+)}$

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

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

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

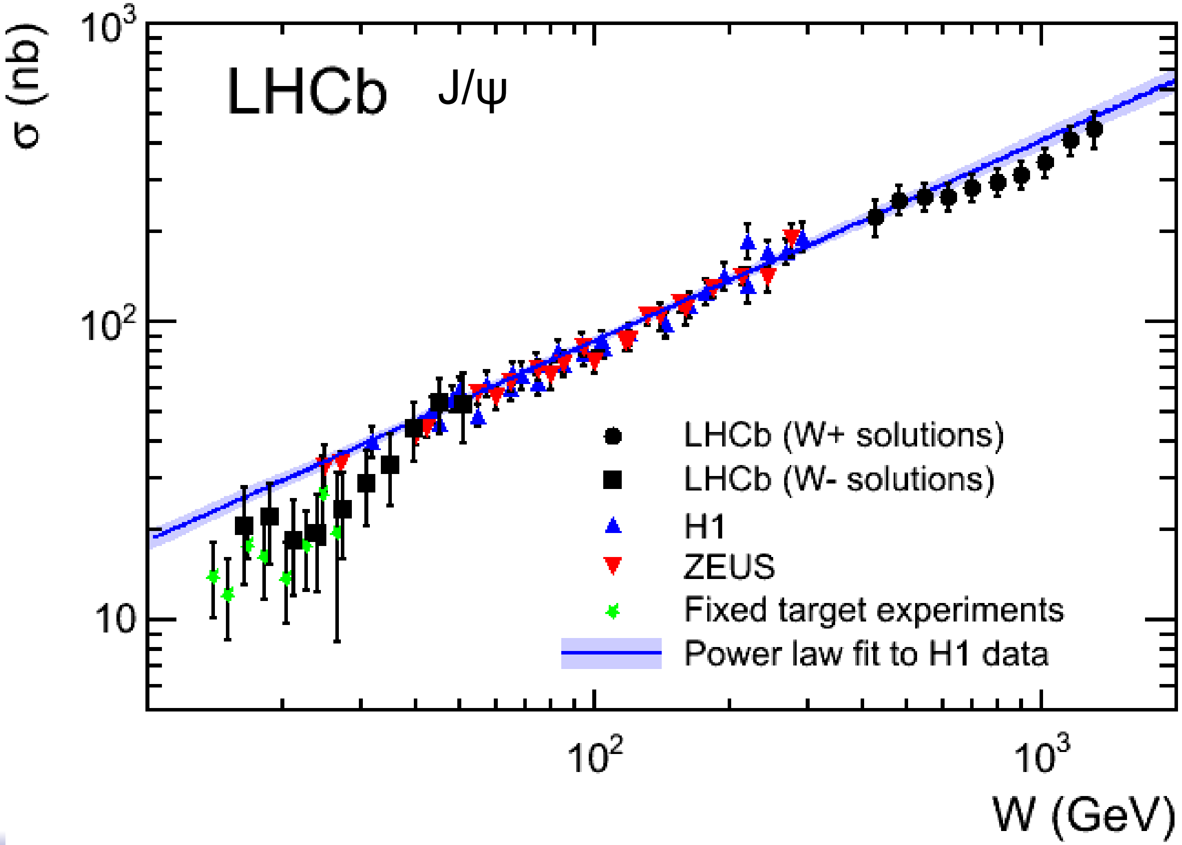
CEP: γp cross-section

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

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

gap survival

photon flux



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

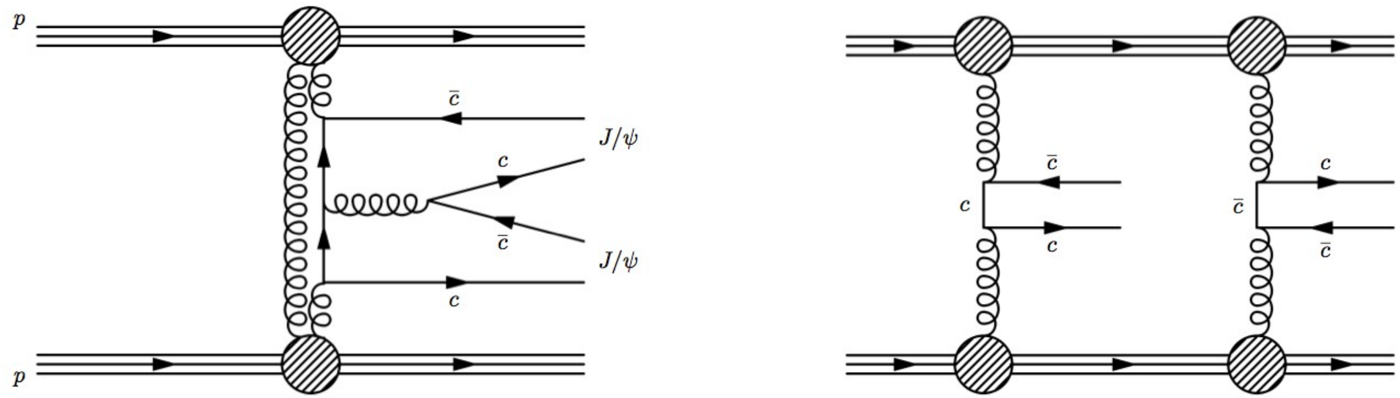
→ good agreement with low energy fixed target data

deviation from power law:
- higher order
- saturation effects

CEP: double charmonium production

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 $\chi_{c(0,1,2)}\chi_{c(0,1,2)}$

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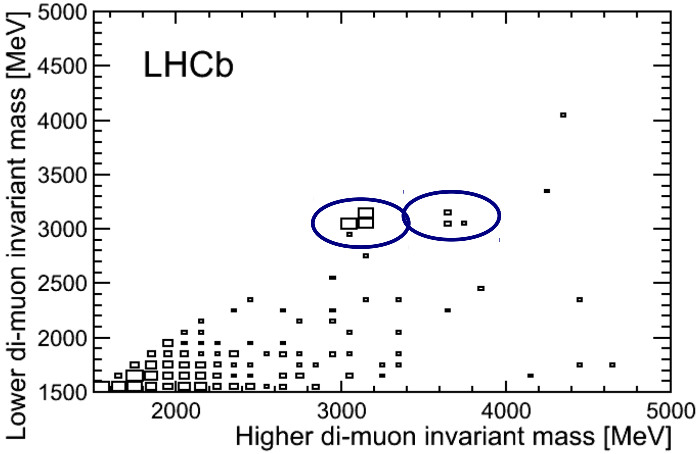
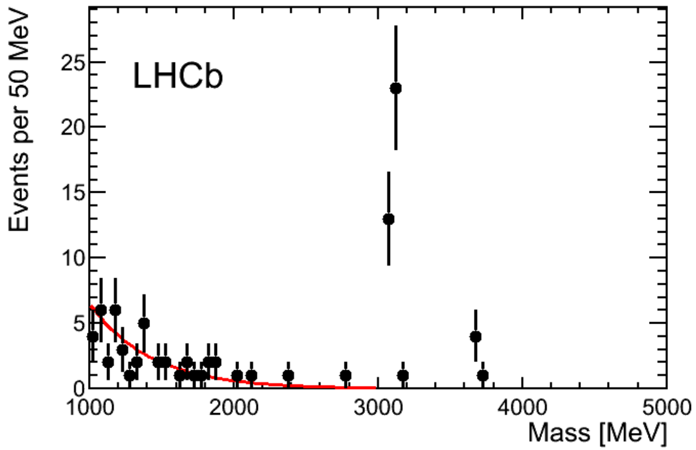
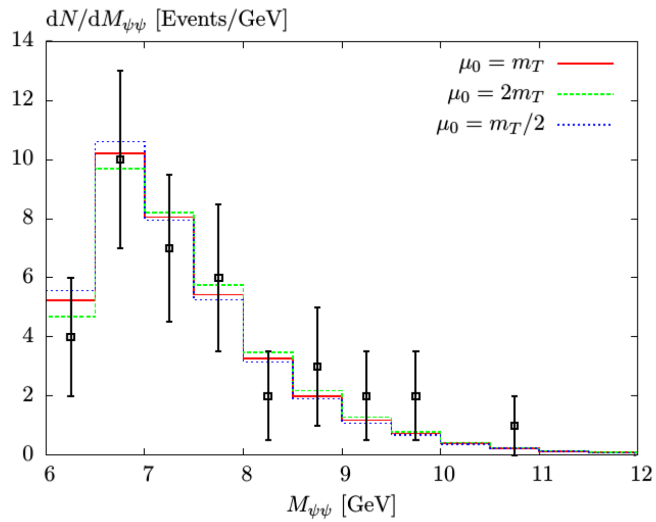
selection: four tracks – three identified as muons, no photons, no other tracks in VELO



invariant mass of di-muon pairs



invariant mass of 2nd di-muon pair



four-muon invariant mass

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

CEP: double charmonium production

event yield in 3 fb^{-1}(1 fb^{-1}@ 7 TeV, 2 fb^{-1}@ 8 TeV):

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

after correcting for non-resonant and feed-down background:

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

for the decay into four muons in the LHCb acceptance
this includes inelastic contributions

CEP: double charmonium production

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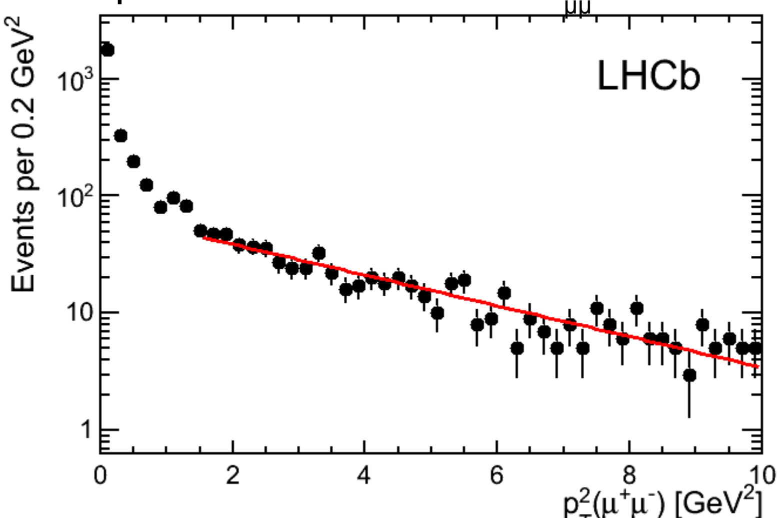
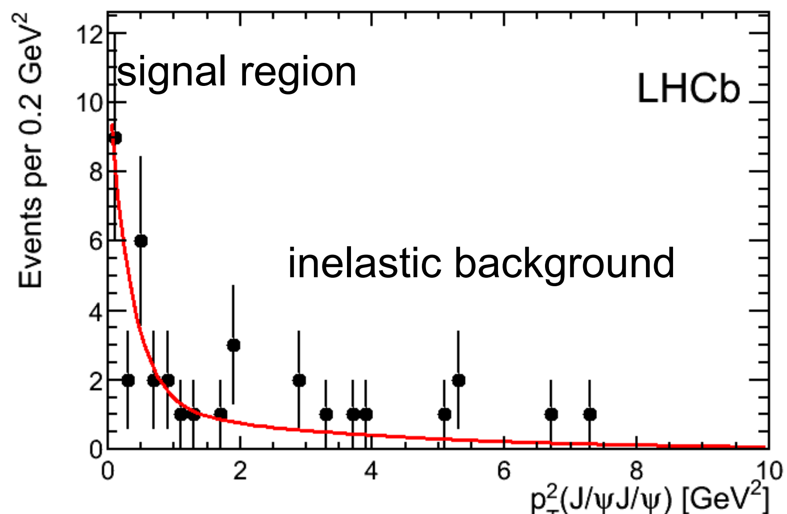
fraction of elastic events: $$d\sigma/d\,p_T^2 = f_{el}\, b_s\, e^{-b_s p_T^2} + (1-f_{el})\, b_b\, e^{-b_b p_T^2}$$

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_{el} b_s= 2.9 ± 1.3 GeV^{-2}, f_{el} = 0.42 ± 0.13

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





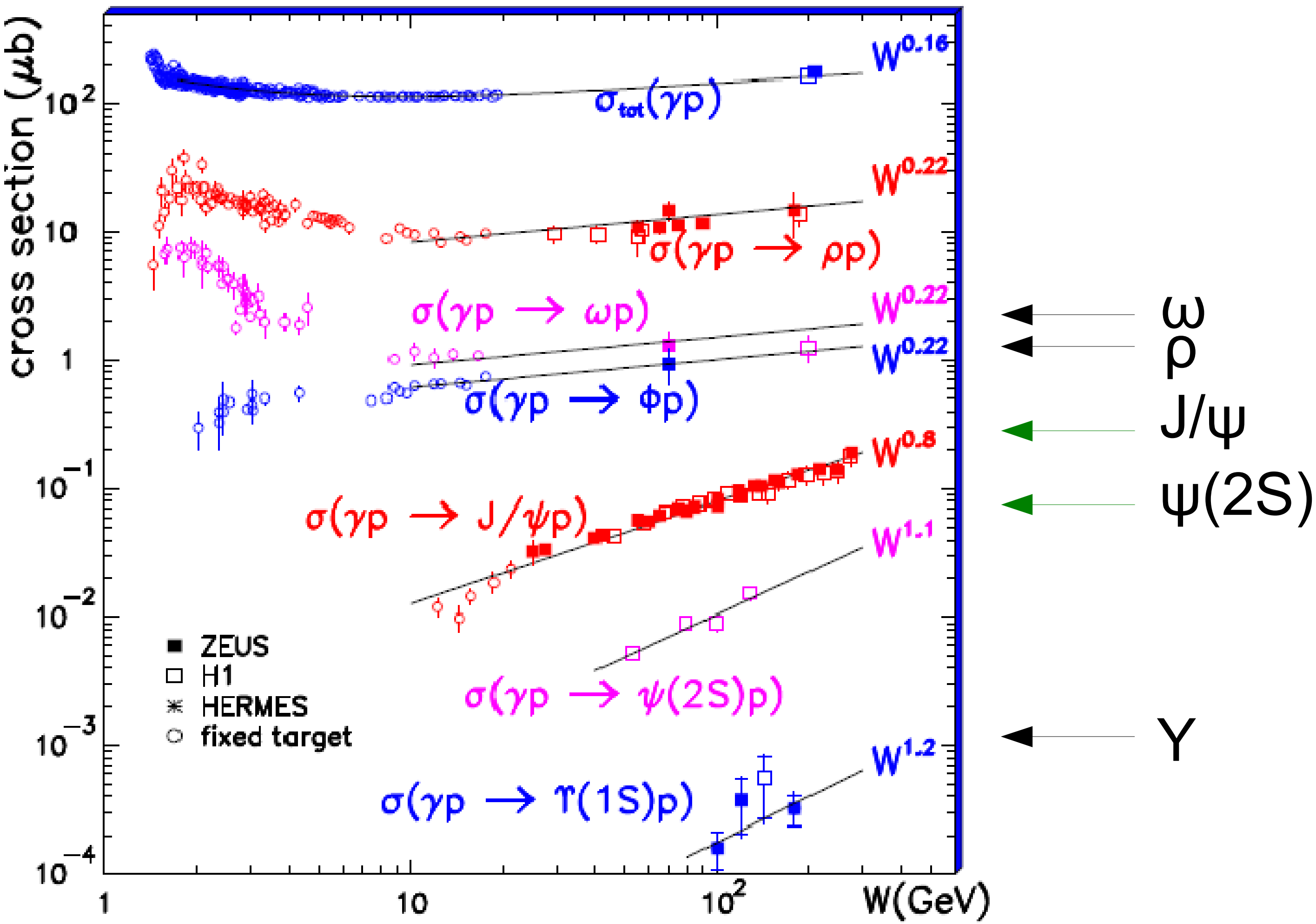
CEP: σ(J/ΨJ/Ψ) = 24 ± 9 pb
Theory: σ(J/ΨJ/Ψ) ≈ 8 to 36 pb

arXiv:1409.4785

CEP outlook

work ongoing with other final states, also in hadronic channels

10.3204/DESY-PROC-2012-03/58



increase rapidity gap with scintillators in forward and backward region

detect showers from high rapidity particles interacting with beam pipe elements

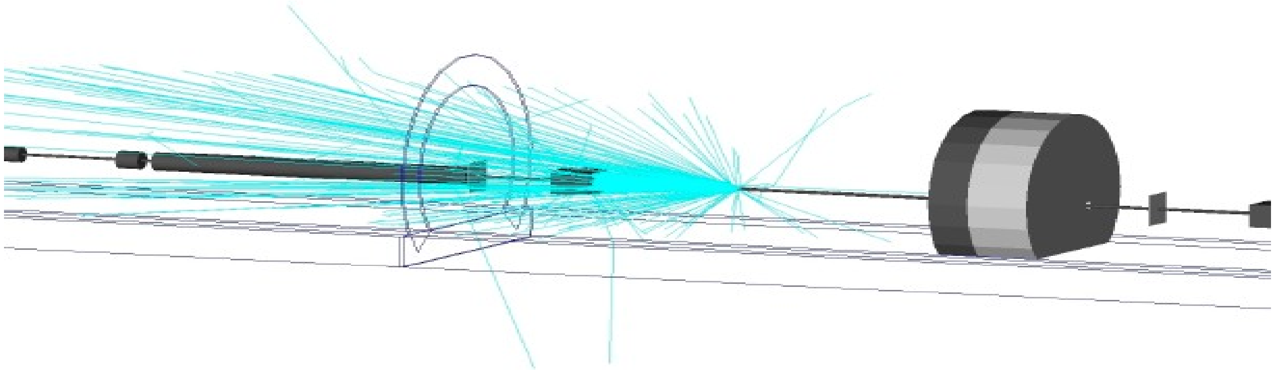
→ improve veto on inelastic background

→ better control of the background

→ better precision

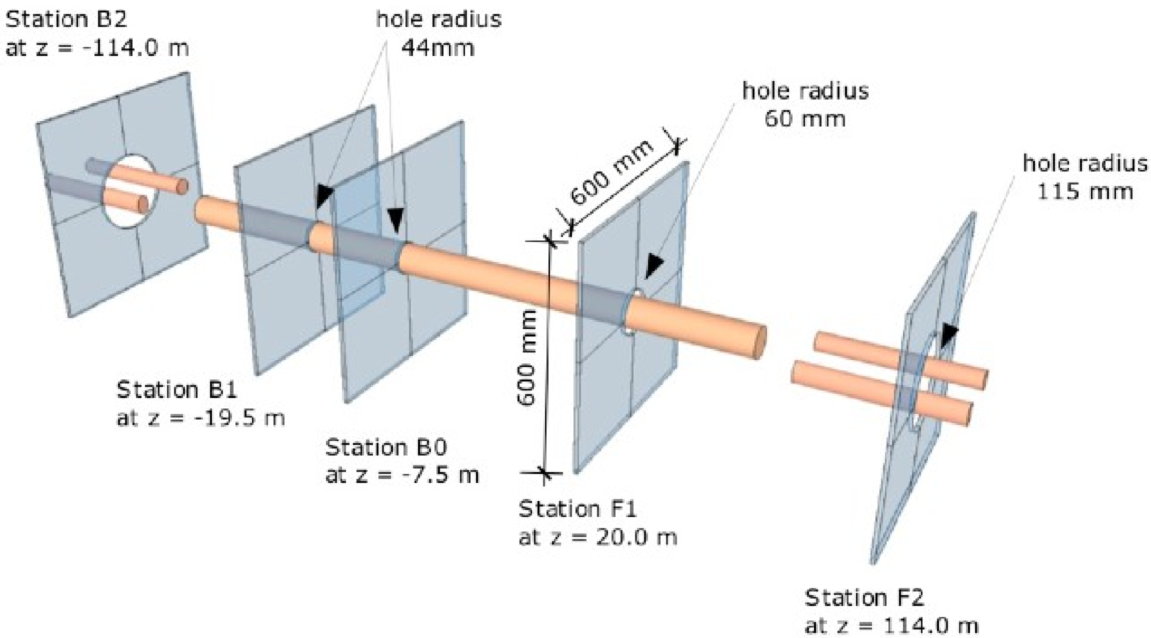
simulation: veto region for charged and neutral particles $5<|\eta|<8$

→ extra 6 units in pseudorapidity.



Detector Upgrade

HeRSCheL: High Rapidity Shower Counters for LHCb

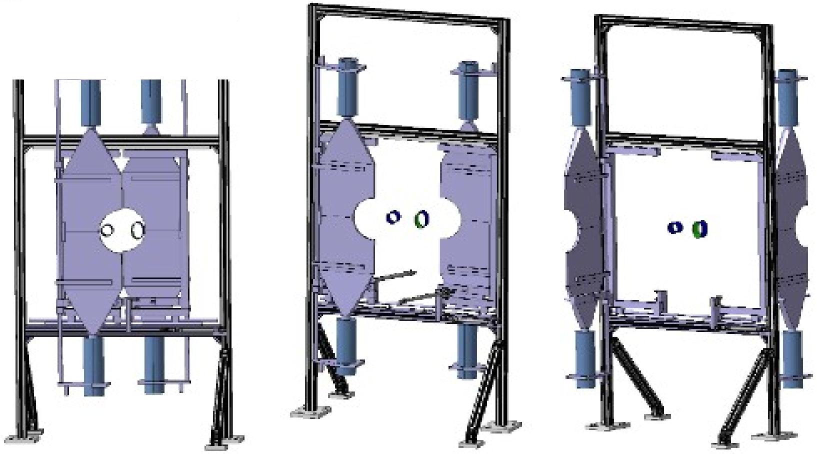


five stations: three backwards, two forward

detectors: four plastic scintillator plates,

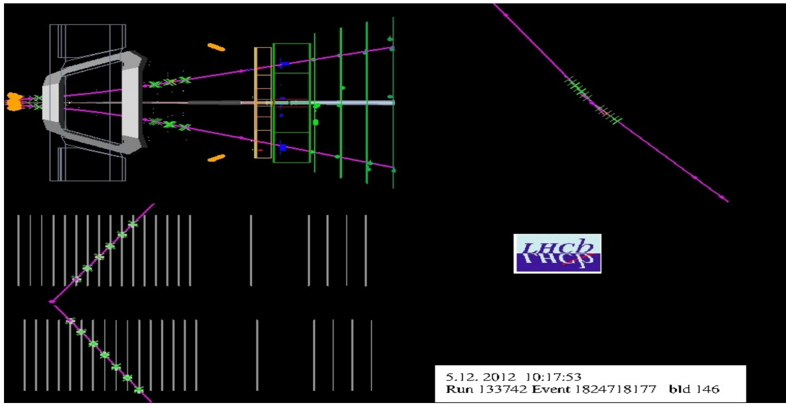
20 mm thick - retractable

→ expect improvements in triggering and background rejection for CEP events for the run starting in 2015



Conclusions

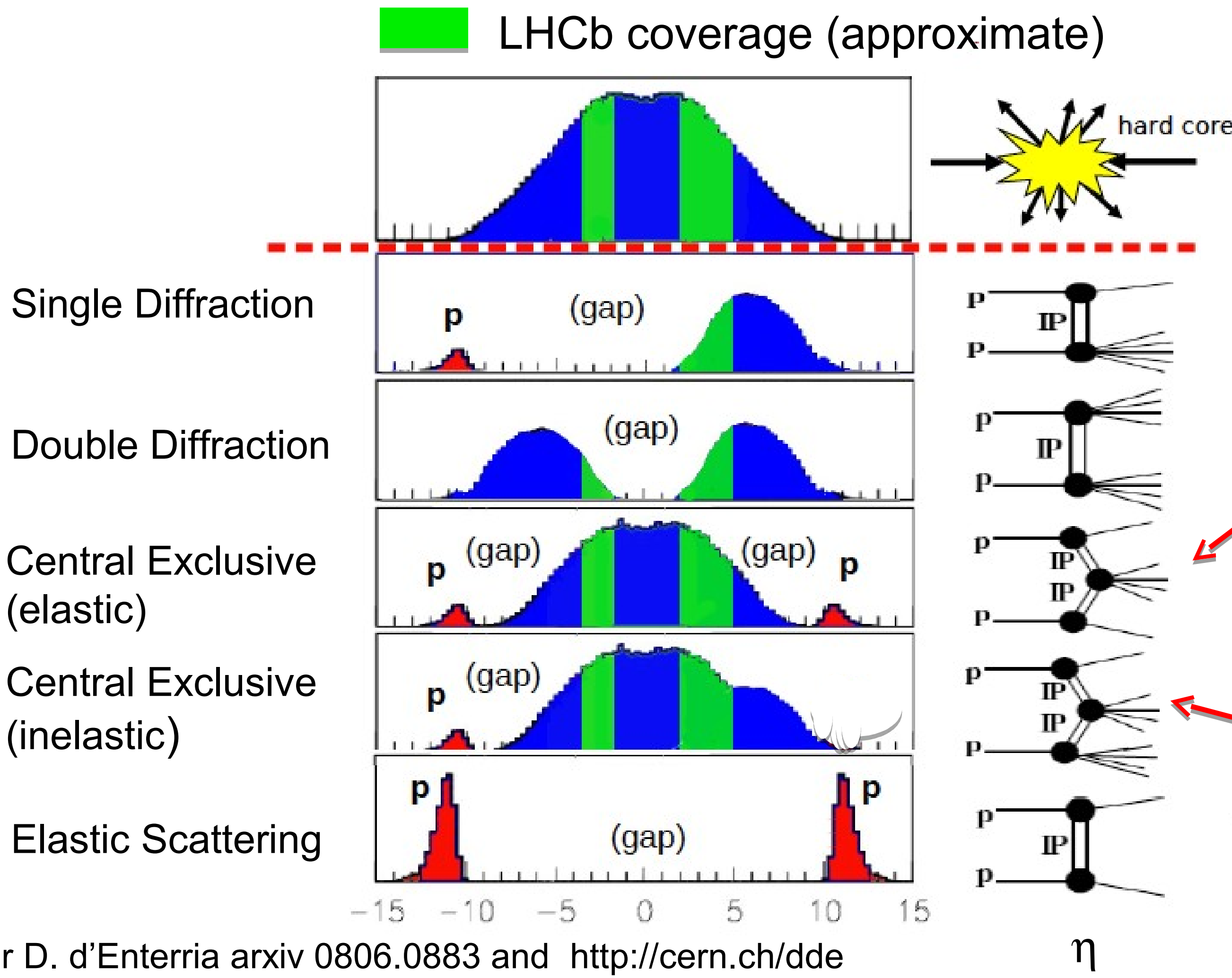
- LHCb's forward acceptance provides unique window on CEP
- Spectroscopy in a very clean environment
- QCD studies
  - very low-x gluon PDF
  - sensitivity to shadowing
  - nature of Pomeron
  - sensitivity to glueballs, odderons, tetraquarks
- Analyses Run 1:
  - Jψ/ψ(2S) and double-charmonium CEP
  - Many more to come with di-muon and hadronic final states
- Outlook Run II
  - Increased sensitivity after shutdown (new scintillator detectors)
  - Expect to collect 5 fb^{-1} with low pileup → unique measurements possible



→ Many more interesting measurements to come!

Backup slides

CEP outlook



CEP events:
Trigger on and reconstruct
a handful of particles
(muons, hadrons, photons..)

CEP backgrounds:
reject events with
additional particles,
usually very forward

After D. d'Enterria arxiv 0806.0883 and http://cern.ch/dde

CEP systematic uncertainties

J. Phys. G40 (2013) 045001

Correlated uncertainties expressed as a percentage of the final result

ϵ_{sel}	1.4%
Purity determination (J/ψ)	2.0%
Purity determination ($\psi(2S)$)	13.0%
*ϵ_{single}	1.0%
*Acceptance	2.0%
*Shape of the inelastic background	5.0%
*Luminosity	3.5%
Total correlated statistical uncertainty (J/ψ)	2.4%
Total correlated statistical uncertainty ($\psi(2S)$)	13.0%
Total correlated systematic uncertainty	6.5%

LHCb running

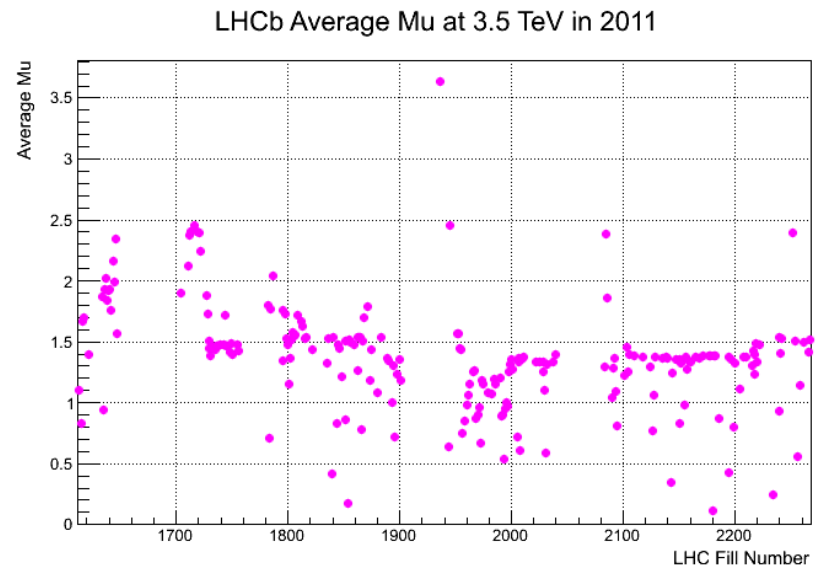
2010   36 pb^{-1} @ 7 TeV

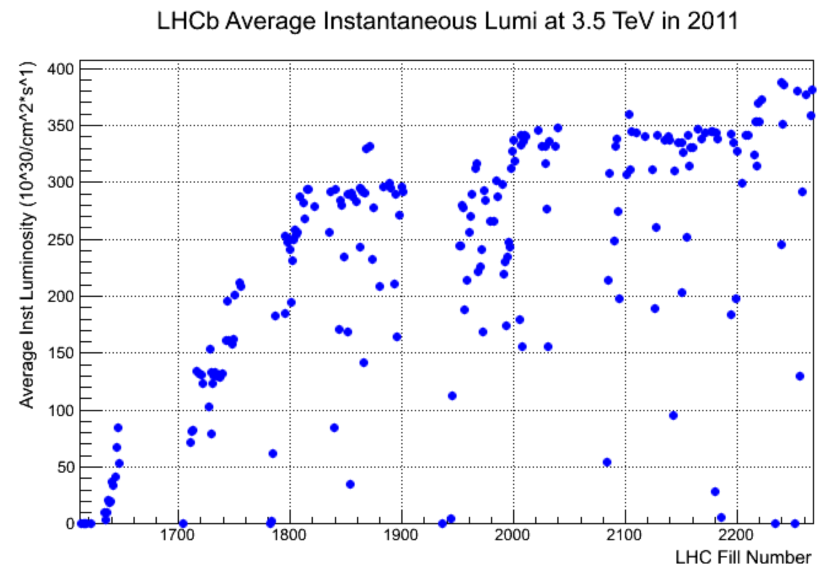
2011   1 fb^{-1} @ 7 TeV

2012   2 fb^{-1} @ 8 TeV

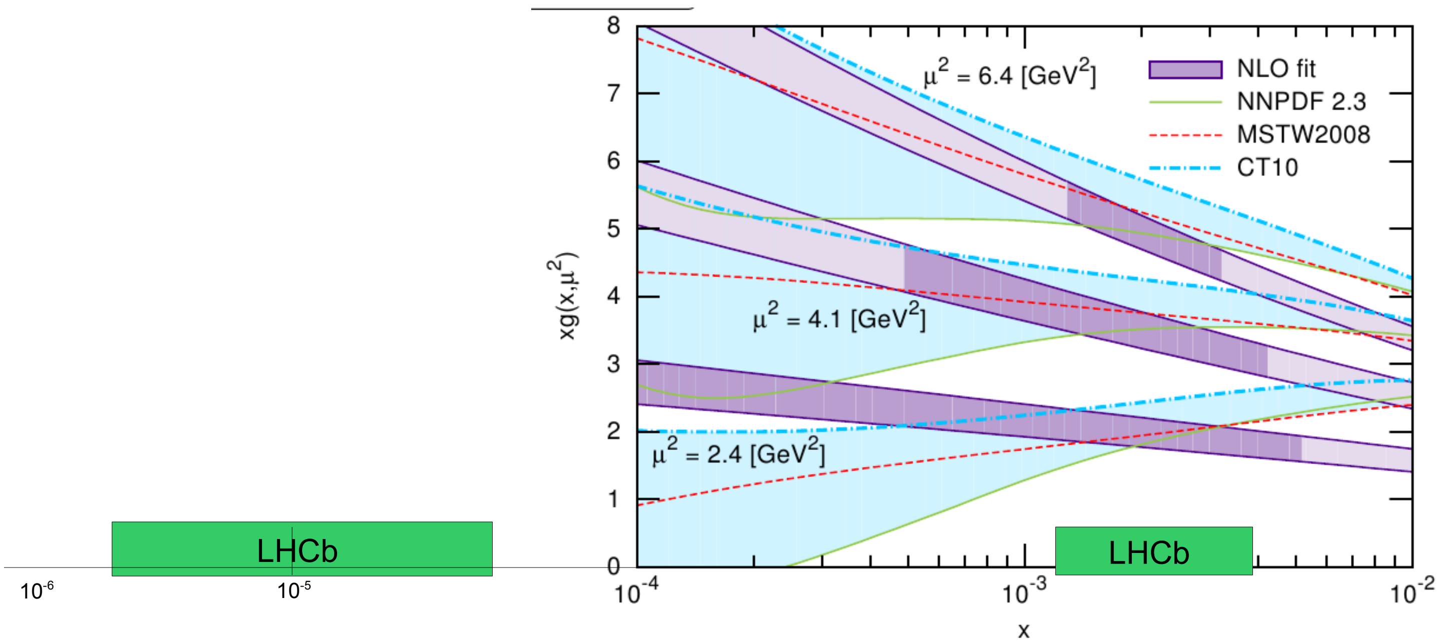
2013   2 nb^{-1} @ 5 TeV proton-lead

Since 2011: Luminosity levelling:
Continuous adjusting of beam overlap
→ roughly constant luminosity
→ stable running conditions
High data taking efficiency:>90%





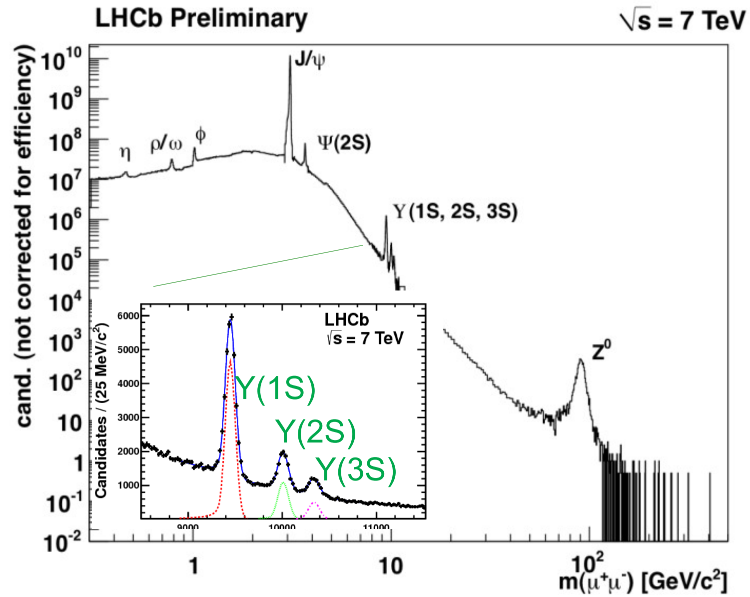
NLO gluon resulting from a fit using LHCb exclusive J/Psi production compared to the global fits. arXiv: 1307.7099



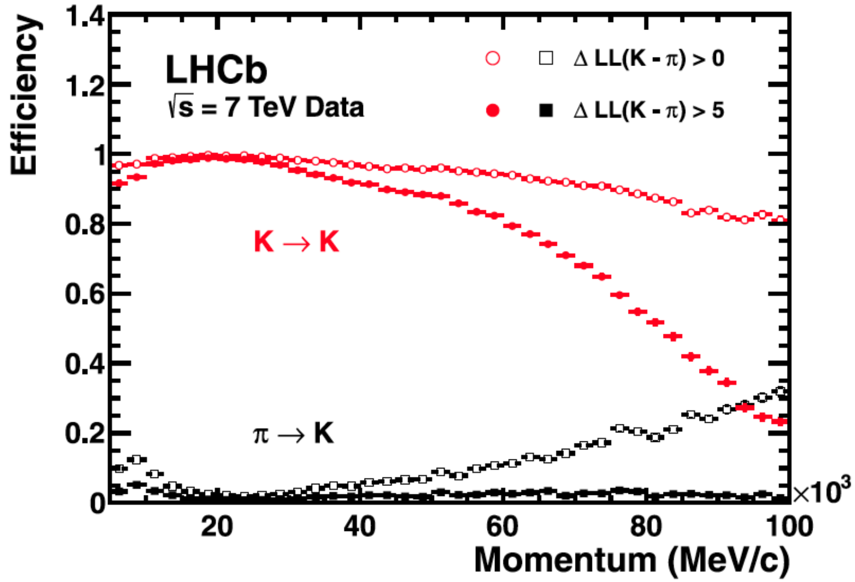
Sensitivity to gluon PDF in a region which is poorly constrained

LHCb Performance

- Momentum resolution:
  0.4% at 5 GeV to 0.6% at 100 GeV
- Vertex resolution:
  σ_{xy}:10-50 μm, σ_z: 100-300 μm
- Track impact parameter resolution:
  13 -20 μm
- Particle ID:
  Muon ID ε=97%; mis-id: 0.7%
  Kaon ID ε=90%; π mis-id< 5%



Kaon identification



Vertex resolution, data and simulation