Central exclusive production in LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

QCD challenges in pp, pA and AA collisions at high energies

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

LHCb

Instituto de Física
Universidade Federal do Rio de Janeiro

Outline

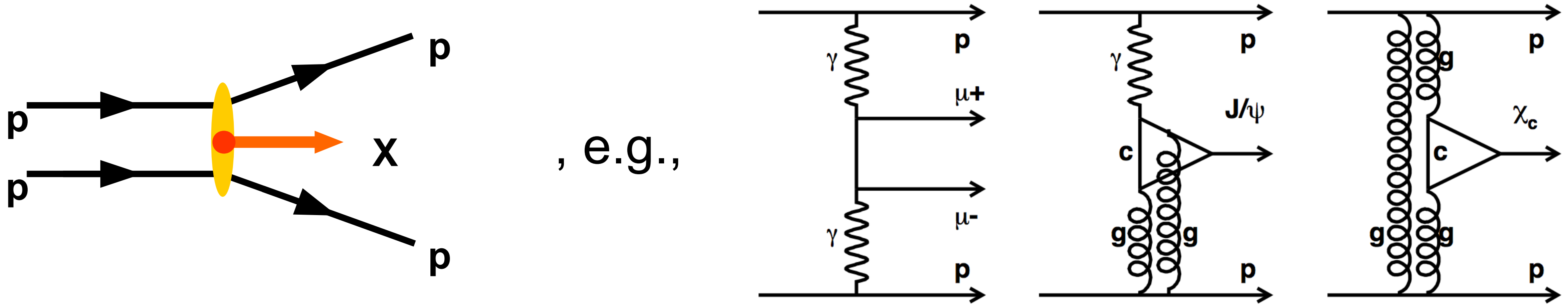
→ **Motivation**

→ **LHCb detector**

→ **LHCb central exclusive production results**

- J/ψ and $\psi(2S)$
- Double charmonium
- Non-resonant dimuon
- χ_c

Central Exclusive Production (CEP)

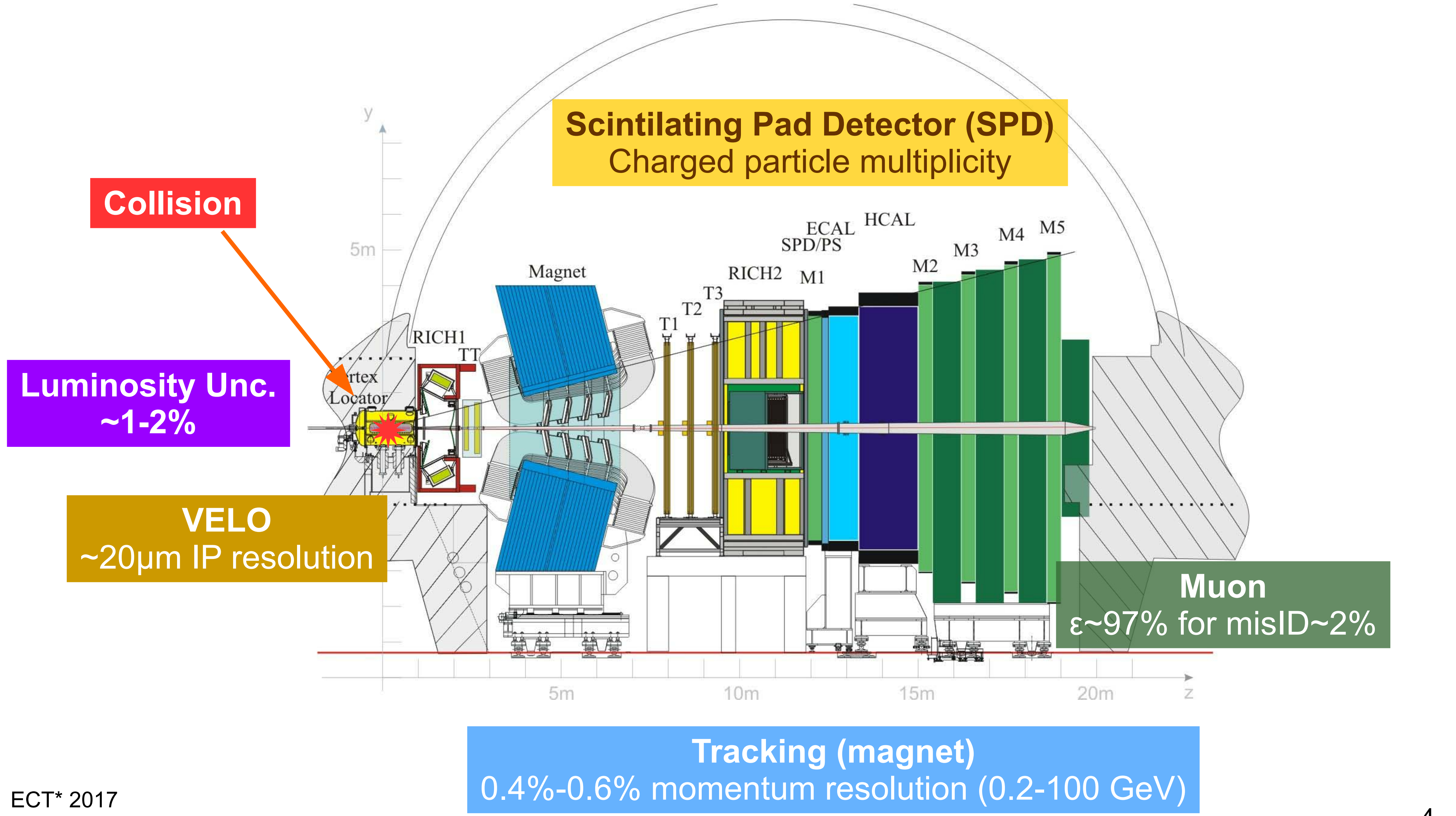


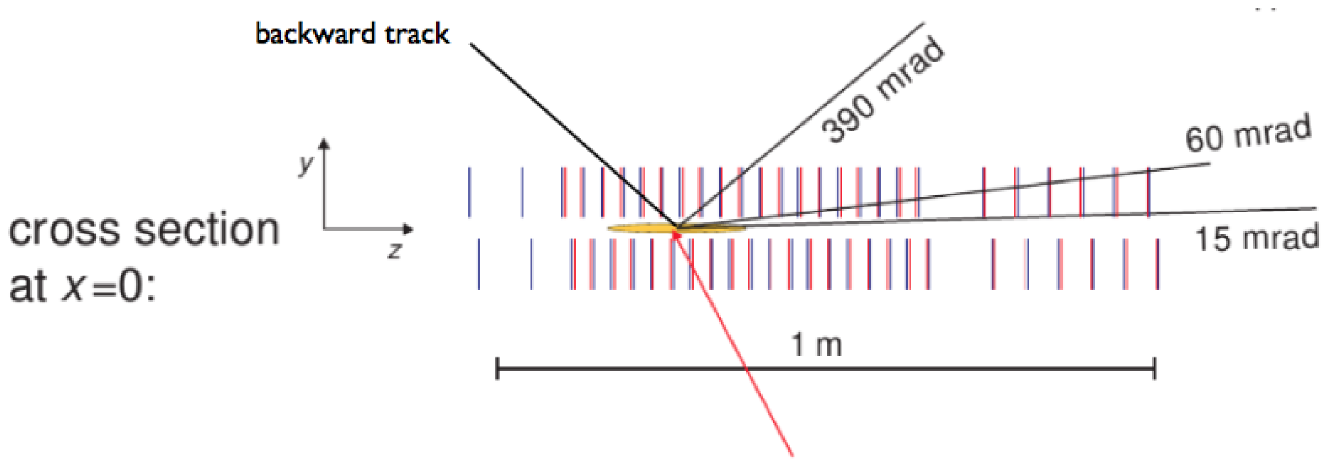
Motivation

– colorless object production (X) in a very clean environment: theory vs data
– understanding of soft → hard QCD scale
– input to phenomenological models: saturation, pomeron/oderon interaction, …
– sensitive to low-x gluon density in the proton down to $5\text{x}10^{-6}$

LHCb Detector

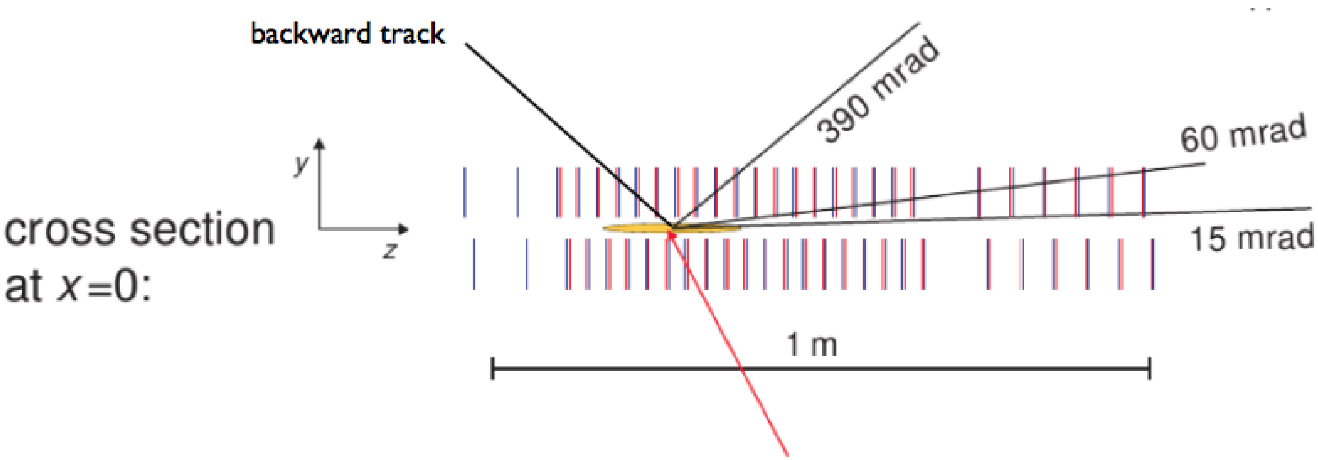
LHCb is a single arm spectrometer fully instrumented in the forward region ($2.0<\eta<5.0$)
Designed for heavy flavour physics ↔ Explored for general purpose physics



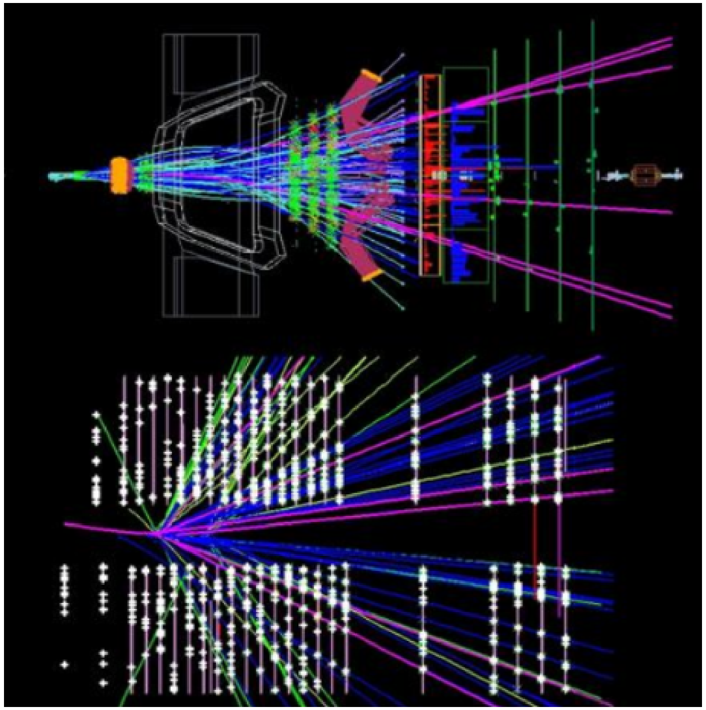


VELO
- → surrounds the interaction point
- → no magnetic field
- → allows backward tracks $(-3.5<\eta<-1.5)$

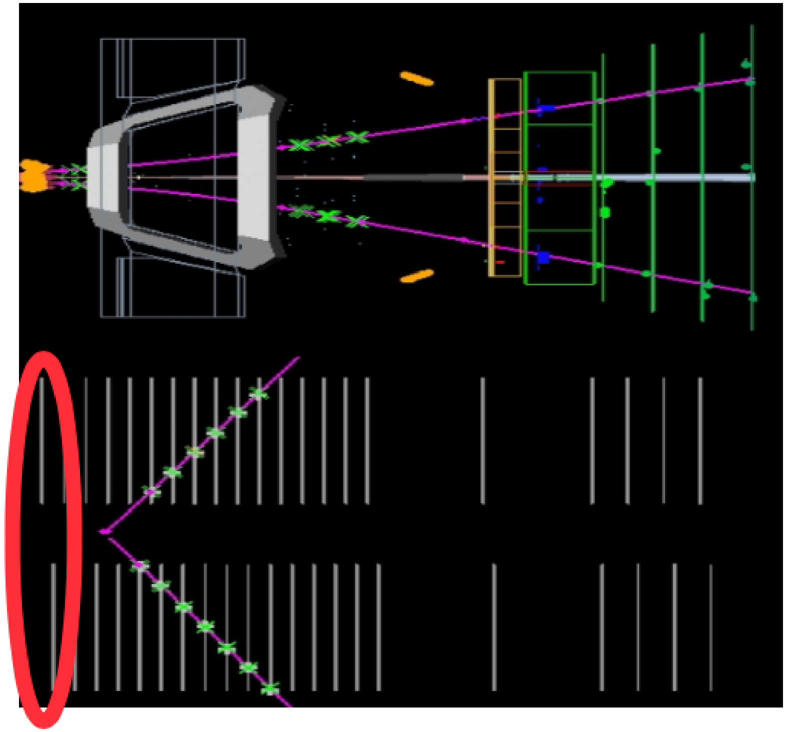
LHCb detector



Typical Event



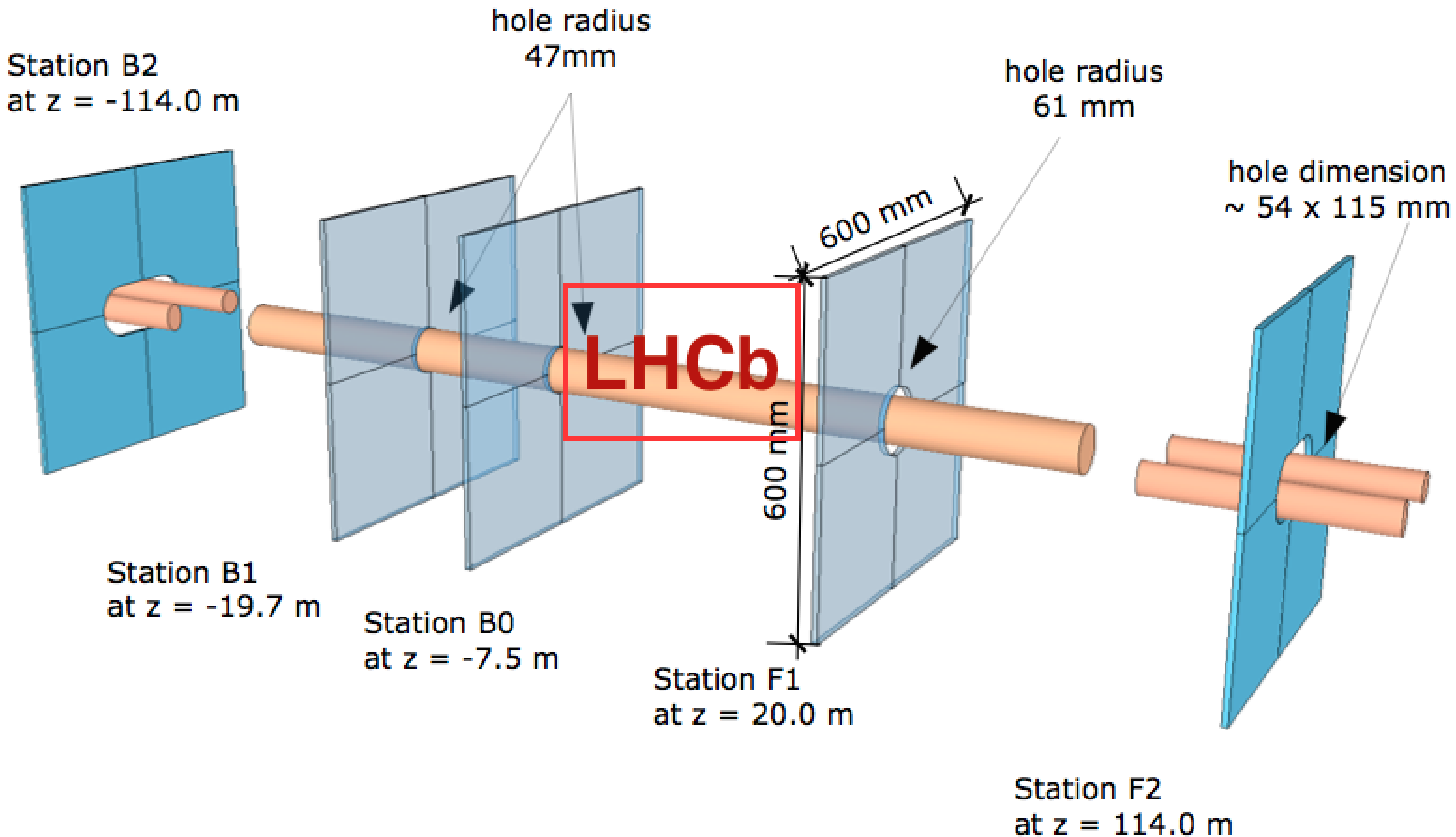
CEP-like event: 2muons



LHCb detector

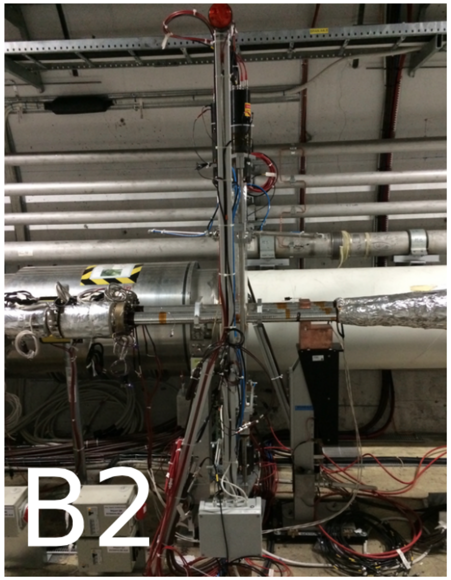
High **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL

- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events wth these

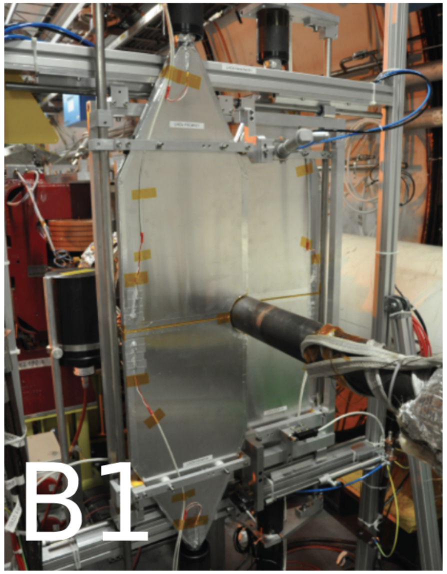


LHCb detector

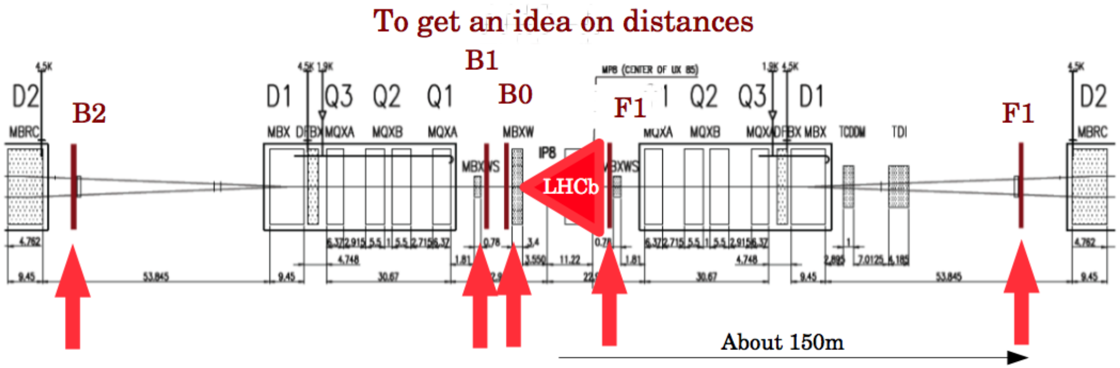
-114m



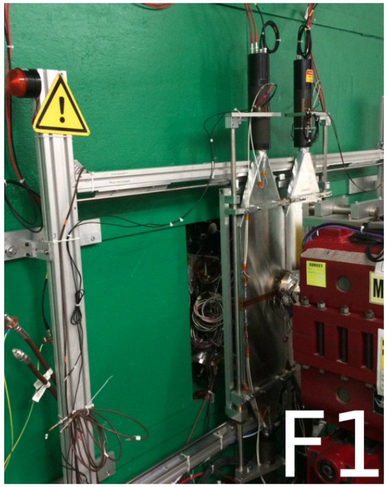
-19.7m



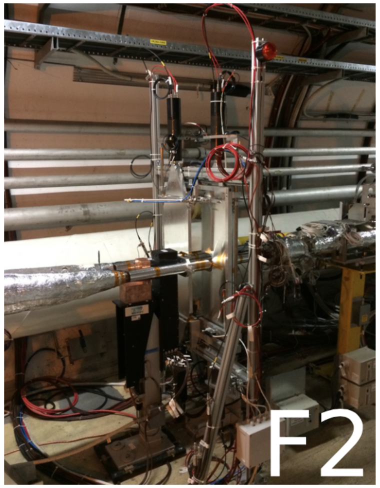
-7.5m



20m

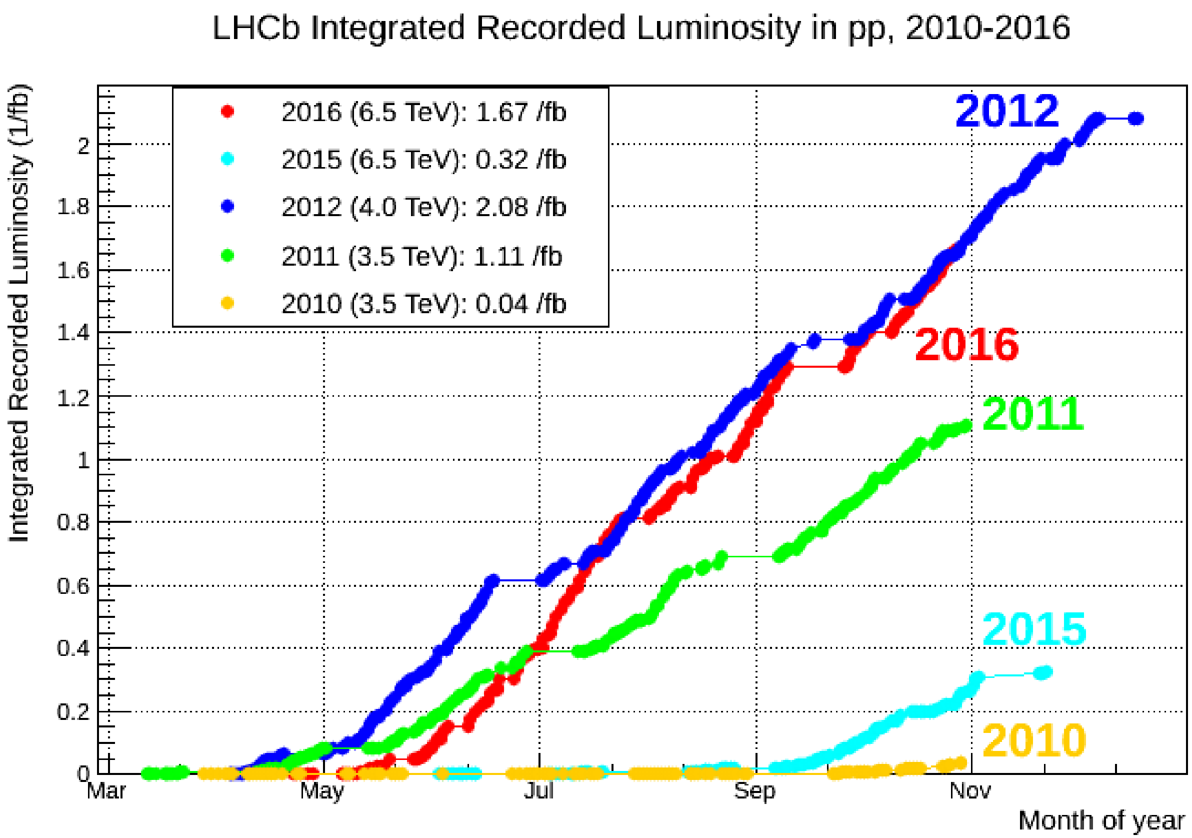


114m



LHCb datasets

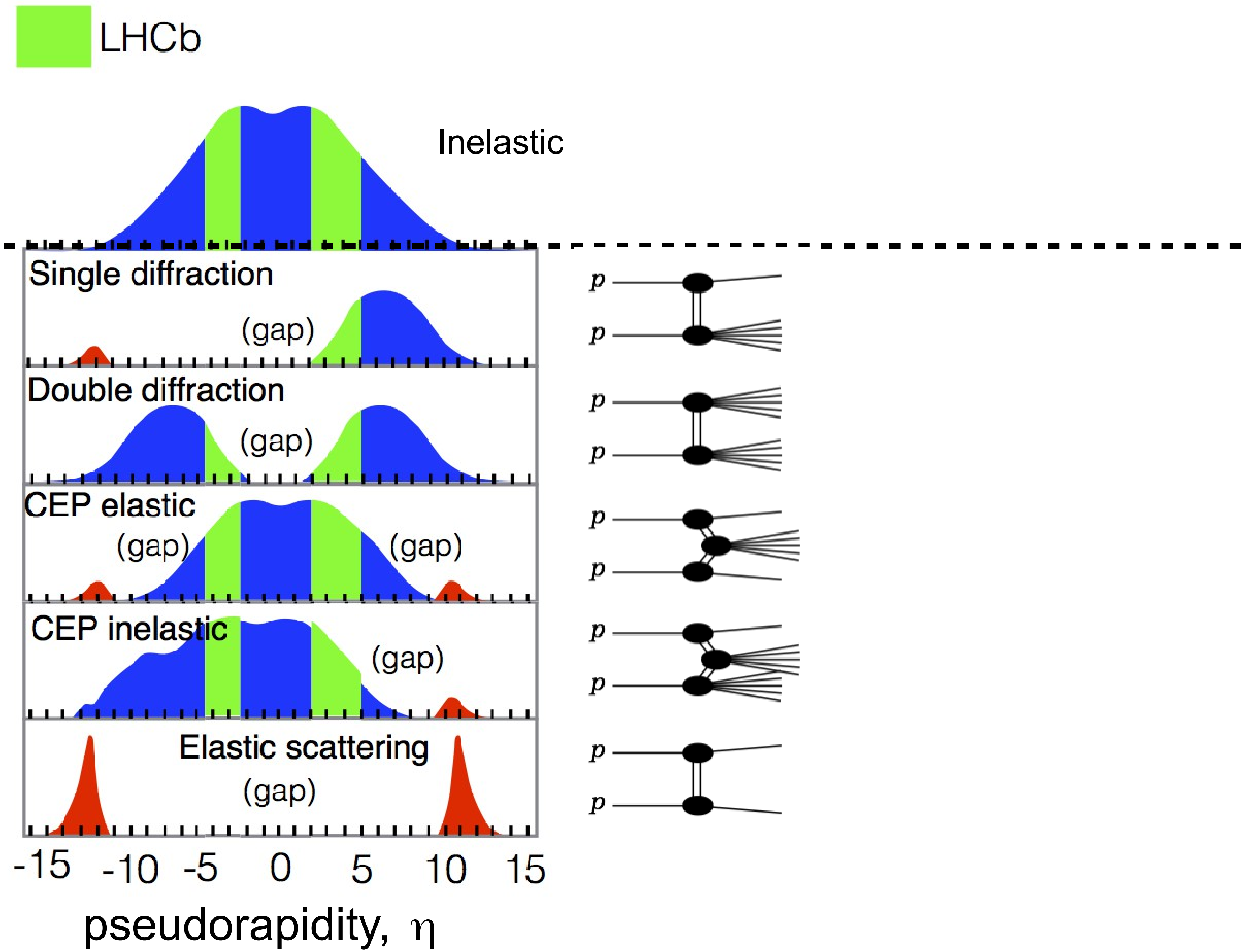
Data used in the results presented in these slides:
2010 → L=36/pb at 7 TeV
2011 → L=1/fb at 7 TeV
2012 → L=2/fb at 8 TeV
2015 → L=204/pb at 13 TeV



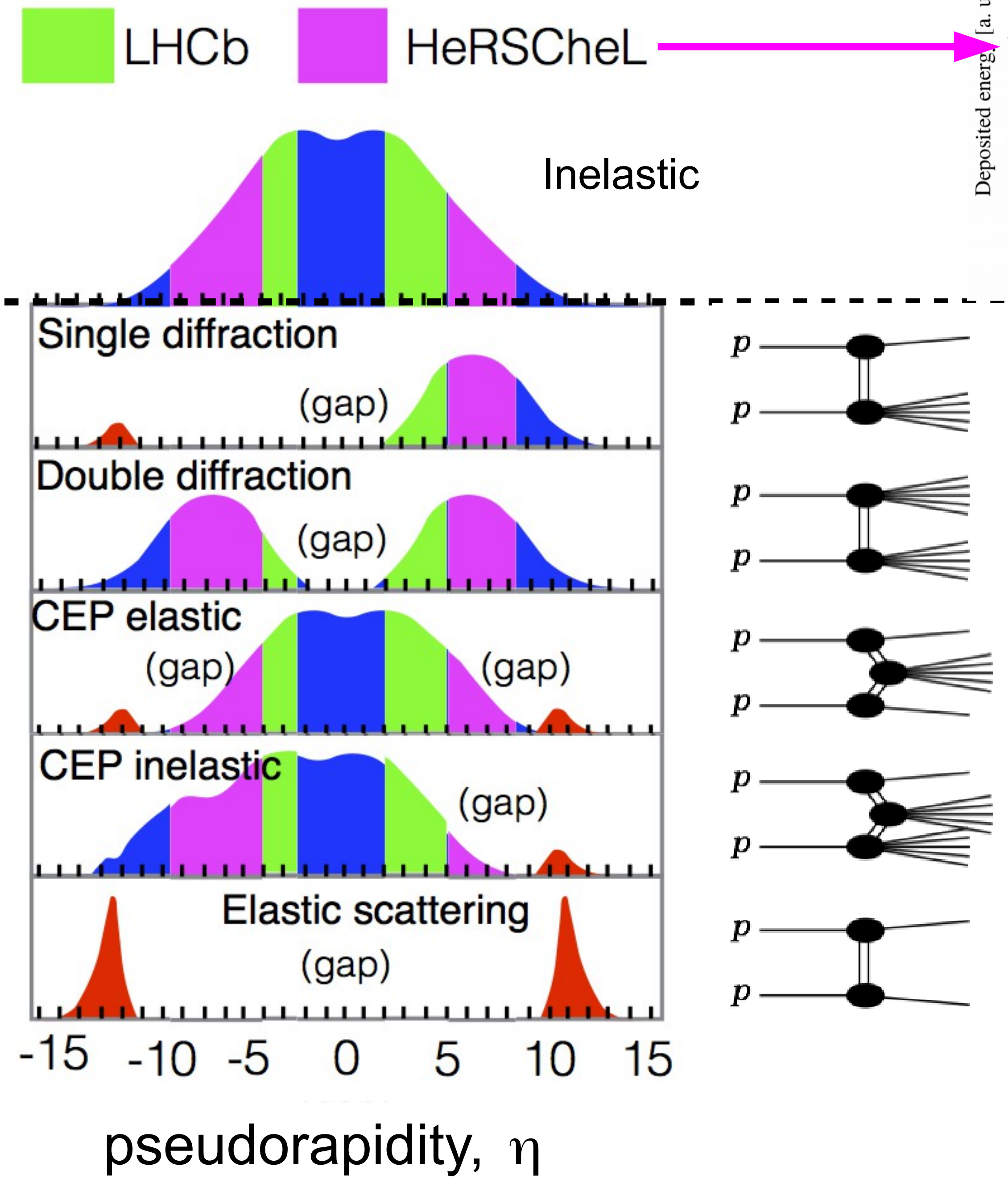
Pile-up conditions
$P(N) = e^{\mu}\mu^N/N!$
μ = average number of visible interactions

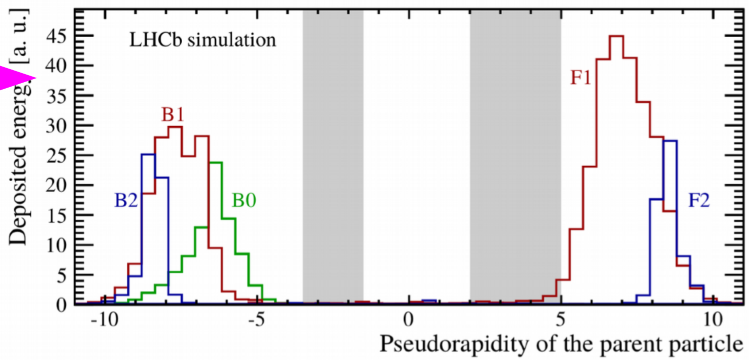
2010 → μ~1.6, P(1)~21%
2011 → μ~1.4, P(1)~25%
2012 → μ~1.7, P(1)~19%
2015 → μ~1.1, P(1)~35%

Collision signatures at LHCb



Collision signatures at LHCb





CEP at LHCb

General Strategy

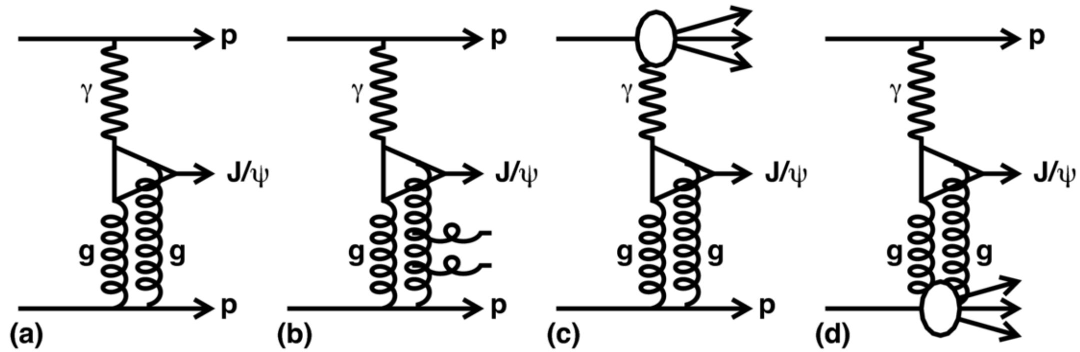
– LHCb has no proton tag detectors
  → use regions void of particle production (gaps)

– Trigger on low multiplicity events
  → using SPD and/or tracks (future results will use Herschel at Run-II)
– Select candidate and no other activity in the detector
  → Detector acceptance: $2.0<\eta(\text{track})<4.5$
  → Require no backward tracks: $-1.5<\eta<-3.5$ (+Herschel at Run-II)

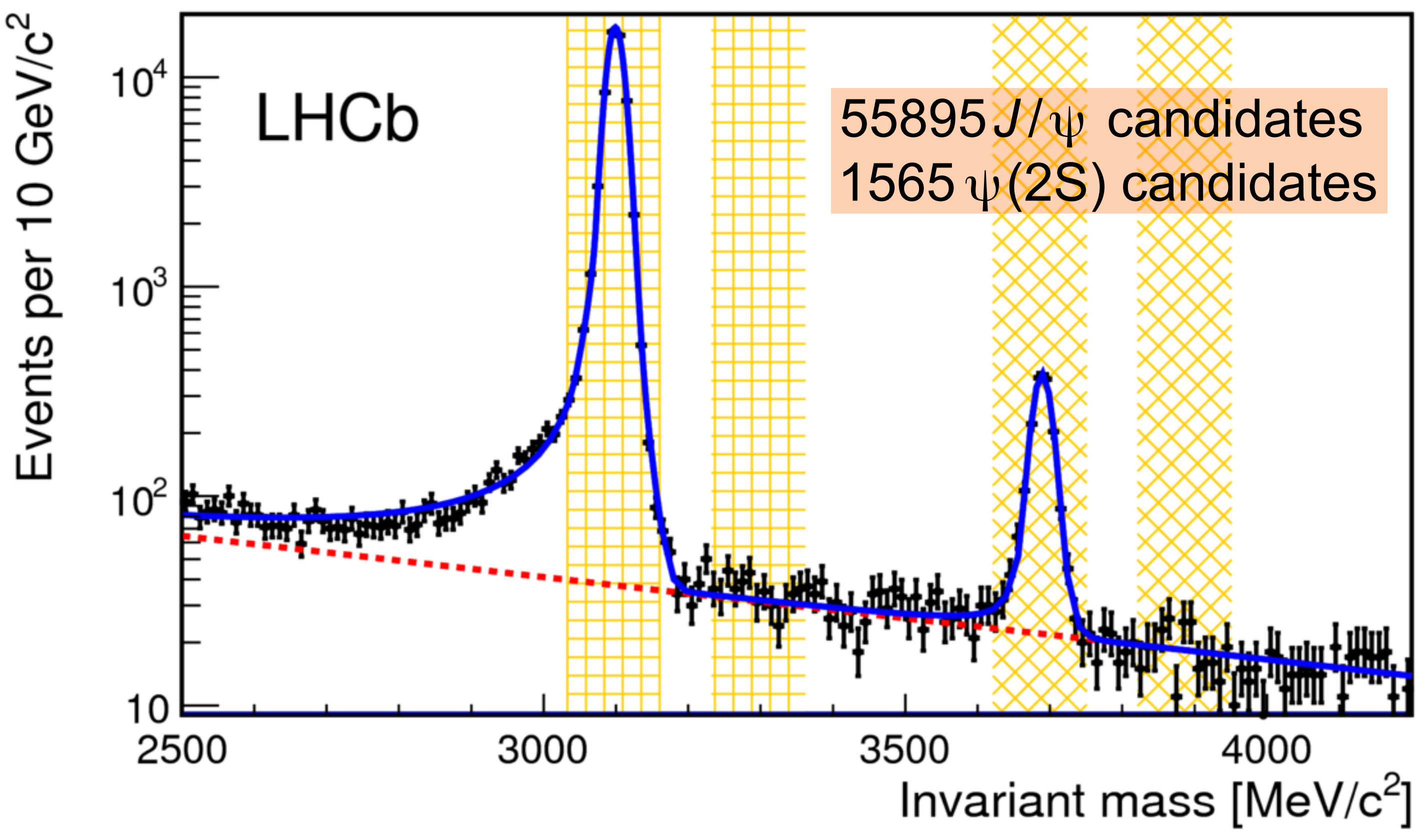
– Backgrounds:
→ feed-down: if X object is a resonance, it could be a decay product of Y
  Ex: In J/ψ CEP: $\chi_c^0 \to J/\psi+\gamma$
→ inelastic (proton dissociation): p_T^2 distribution is used to fit CEP and non-CEP
→ other diffractive production: estimated with event generators

J.Phys.G40 (2014) 055002

2011 dataset with L=1/fb



Signal fit – Crystal-Ball function (ad-hoc asymmetric function)
Background fit - expoential



Template fit to data

→ Inelastic background: exponential (HERA extrapolation b_{in}~1 GeV^{-2})

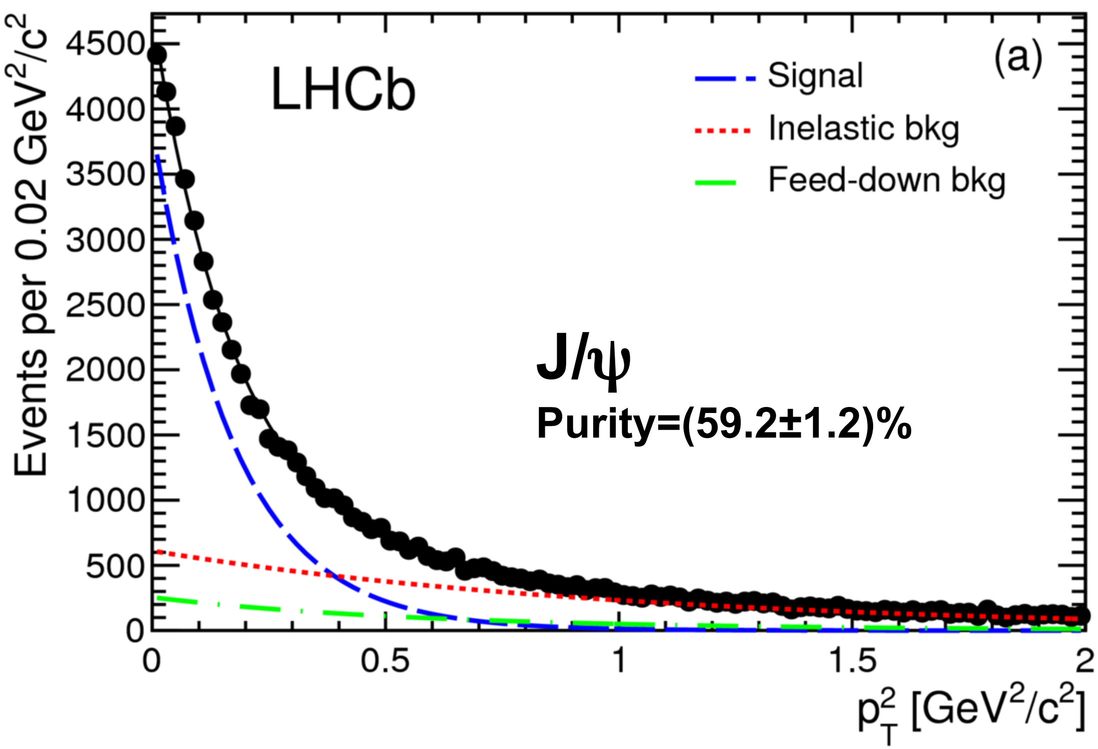
→ Feed-down background: data driven from reconstructed decays

→ Signal: exponential (HERA b_{el}~ 6 GeV^{-2})

→ J/ψ feed-down: $(\chi_{c0}, \chi_{c1}, \chi_{c2}), \psi(2S)$

→ $\psi(2S)$ feed-down: $X(3872), \chi_c(2P)$

$$f_{el}\, e^{-b_{el} p_T^2} + f_{in}\, e^{-b_{in} p_T^2} + f_{fd} \mathcal{P}_{fd}(p_T^2)$$



background fractions
feed-down 10.1 %
inelastic 49.1 %

$$b_{el} = 5.70 \pm 0.11 \text{ GeV}^{-2}$$
$$b_{in} = 0.97 \pm 0.04 \text{ GeV}^{-2}$$

J.Phys.G40 (2014) 055002

Template fit to data

→ Inelastic background: exponential (HERA b_{in}~ 1 GeV^{-2})

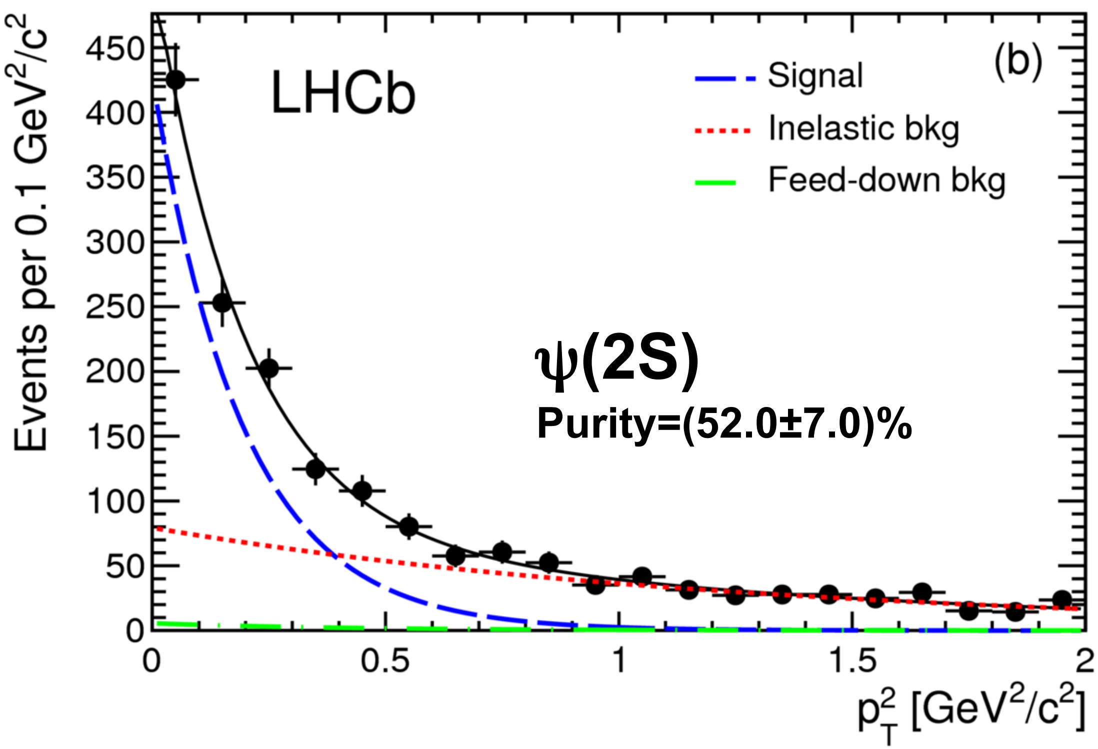
→ Feed-down background: data driven from reconstructed decays

→ Signal: exponential (HERA b_{el}~ 6 GeV^{-2})

→ J/ψ feed-down: $(\chi_{c0}, \chi_{c1}, \chi_{c2}), \psi$(2S)

→ ψ(2S) feed-down: $X(3872), \chi_c$(2P)

$$f_{\rm el}\, e^{-b_{\rm el} p_{\rm T}^2} + f_{\rm in}\, e^{-b_{\rm in} p_{\rm T}^2} + f_{\rm fd} \mathcal{P}_{\rm fd}(p_{\rm T}^2)$$



background fractions
feed-down 2.0 %
inelastic 36.0 %

$$b_{\rm el} = 5.1 \pm 0.7\ {\rm GeV}^{-2}$$

$$b_{\rm in} = 0.8 \pm 0.2\ {\rm GeV}^{-2}$$

Cross-section measurement

$$\left(\frac{d\sigma}{dy}\right)_i = \frac{\rho N_i}{A_i \epsilon_i \Delta y (\epsilon_{single} L)}$$

For each bin i, we have

→ N_i is the number of candidates

→ ρ is the purity

→ A_i is the acceptance

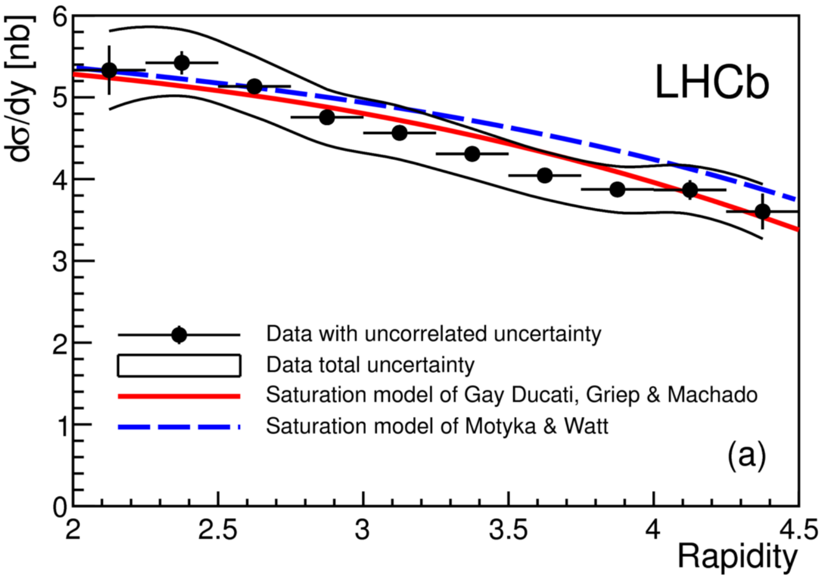
→ Δy is the bin width

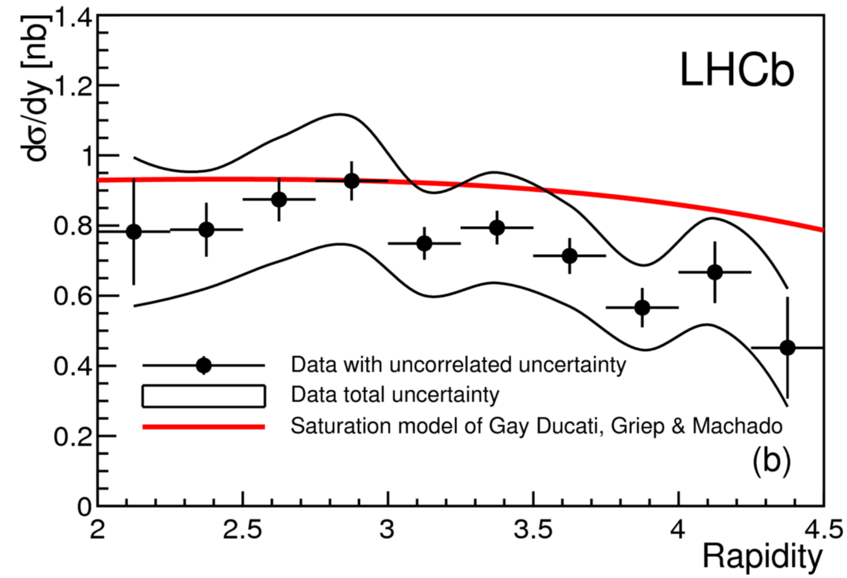
→ L is the integrate luminosity

→ ϵ_i is the efficiency for selecting single interaction events

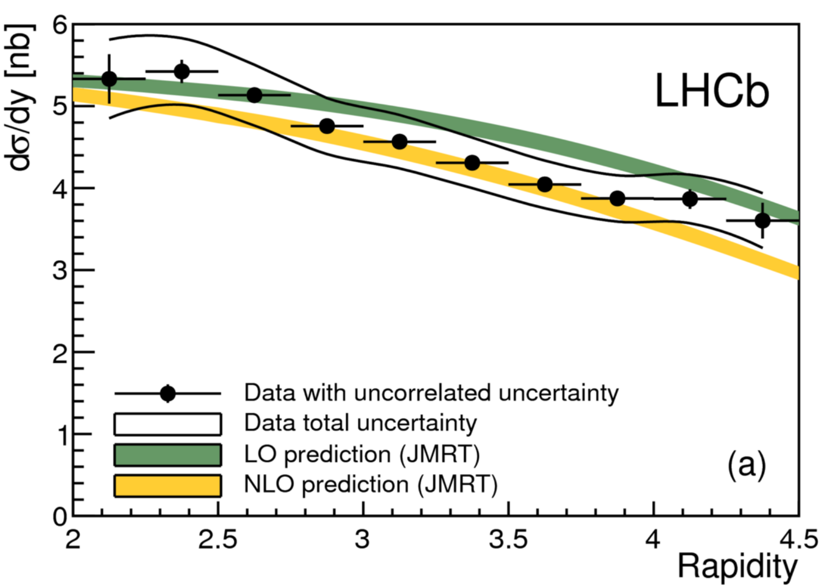
Correlated uncertainties expressed as a percentage of the final result	
$\epsilon_{\rm sel}$	1.4%
► Purity determination (J/ψ)	2.0%
► Purity determination ($\psi(2S)$)	13.0%
*$\epsilon_{\rm single}$	1.0%
*Acceptance	2.0%
*Shape of the inelastic background	5.0%
*Luminosity	3.5%

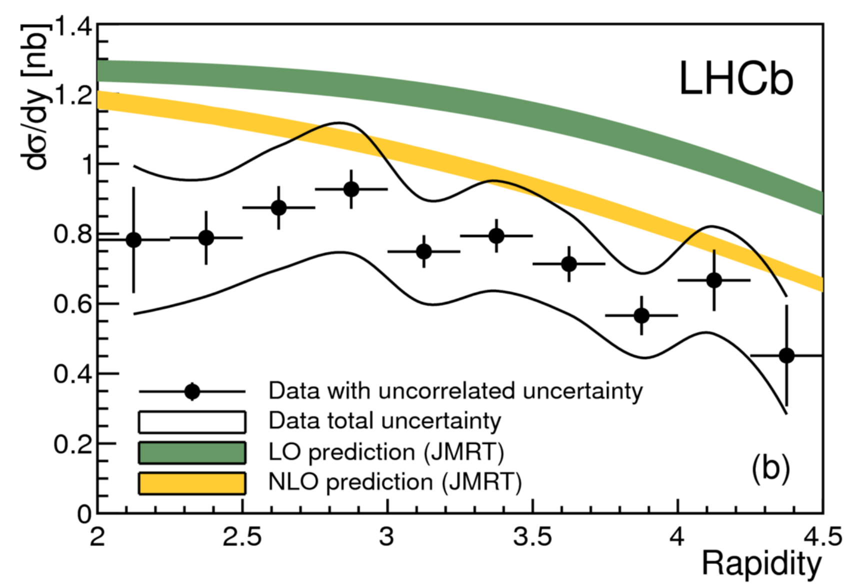
J/ψ and $\psi(2S)$ - 7 TeV





J/ψ $\psi(2S)$





J/ψ and $\psi(2S)$ - 7 TeV

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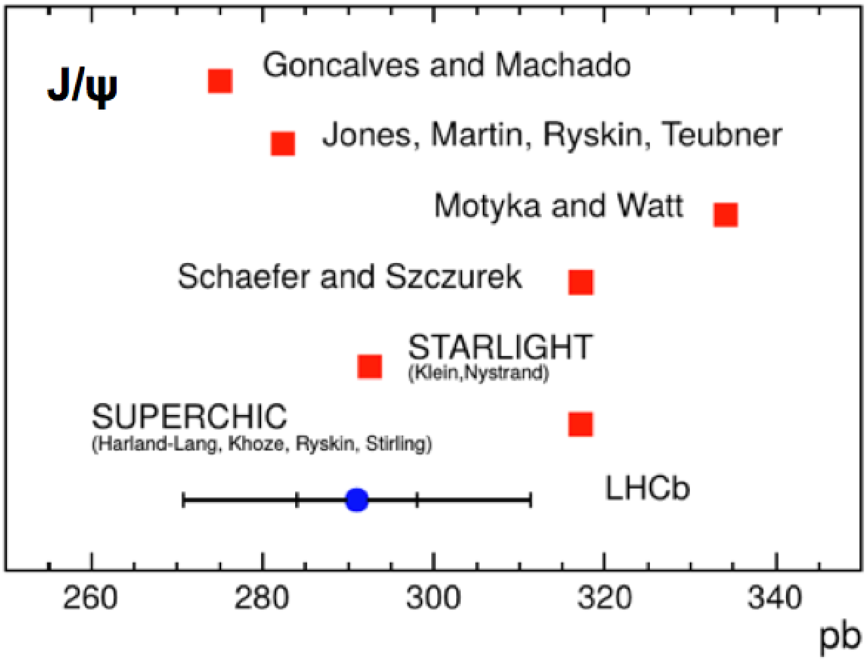
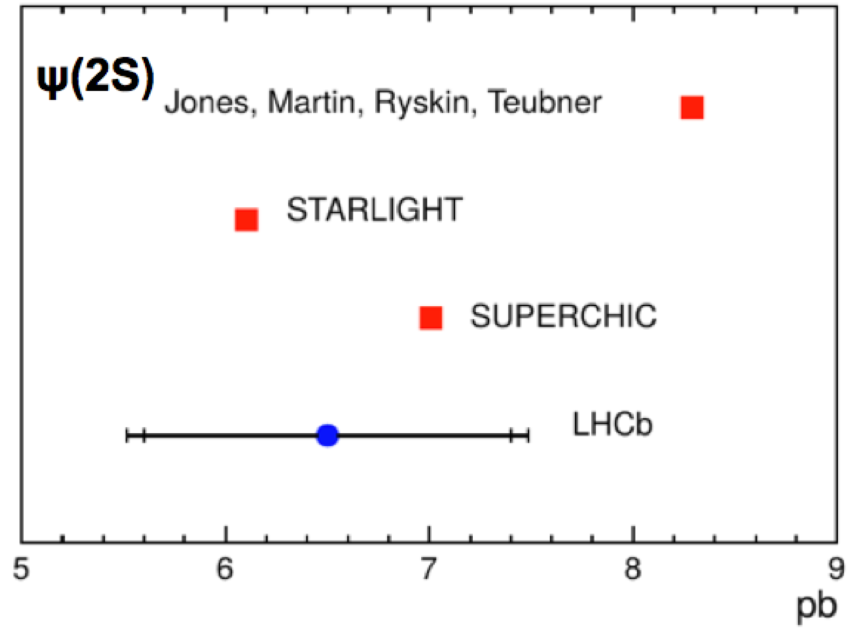




Cross section times BF to two muons with $2.0 < \eta < 4.5$

$\sigma(J/\psi)$ = 291 ± 7(stat) ± 19(syst) pb

$\sigma(\psi(2S))$ = 6.5 ± 0.9(stat) ± 0.4(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&SPhys. Rev. D76 (2007) 094014
Starlight: Phys. Rev. Lett. 92 (2004) 142003
Superchic: Eur. Phys. J. C65 (2010) 433

J/ψ and $\psi(2S)$ - 7 TeV

$$\frac{d\sigma}{dy}_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

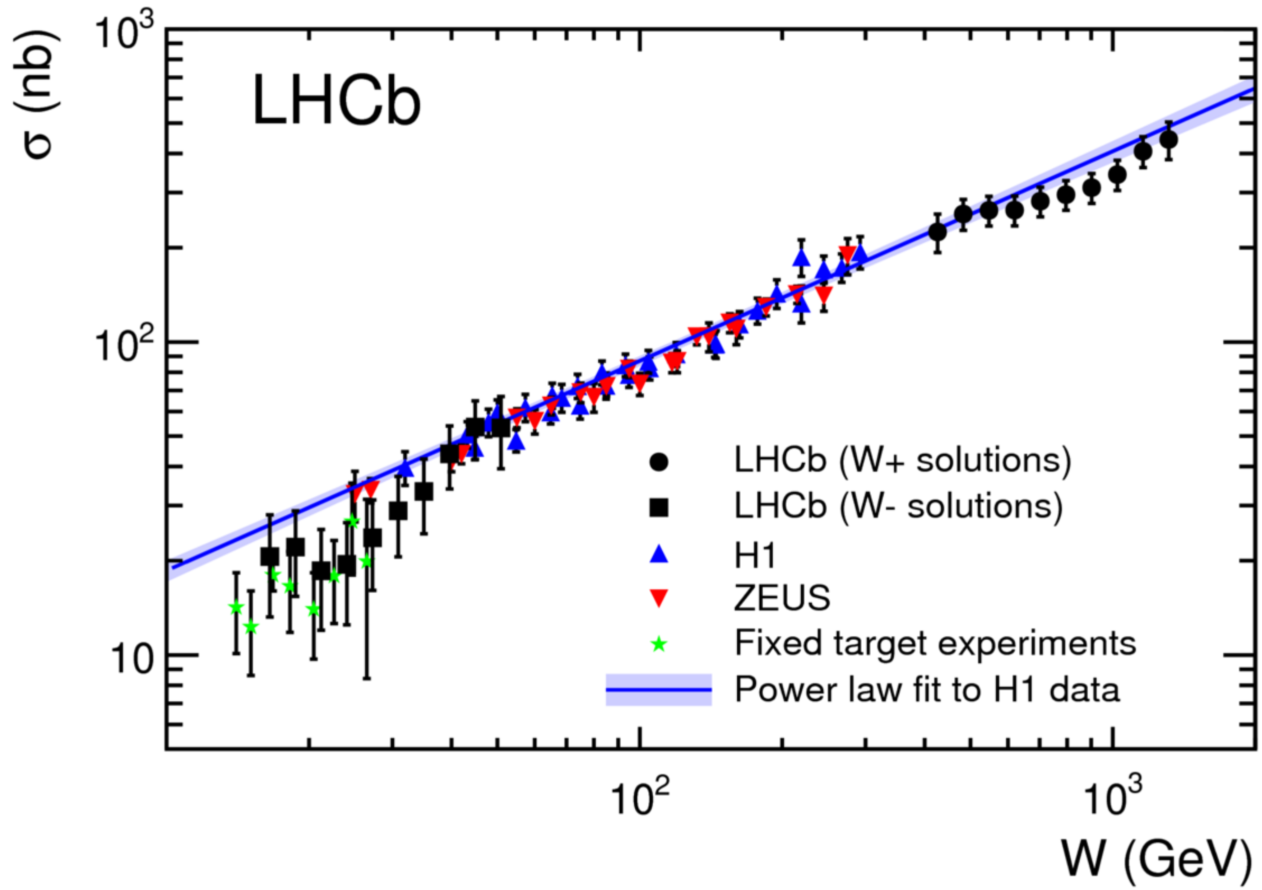
$dn/dk_\pm$ are photon fluxes for photons of energy $k_\pm \approx (M_{J/\psi}/2)\exp(\pm|y|)$

$(W_\pm)^2 = 2k_\pm\sqrt{s}$, and $r_\pm$ are absorptive corrections

Assuming HERA result for W_+

$\sigma(W) = 81(W/90\,GeV)^{0.67}\,nb$

one can obtain $\sigma(W_-)$
and vice-versa

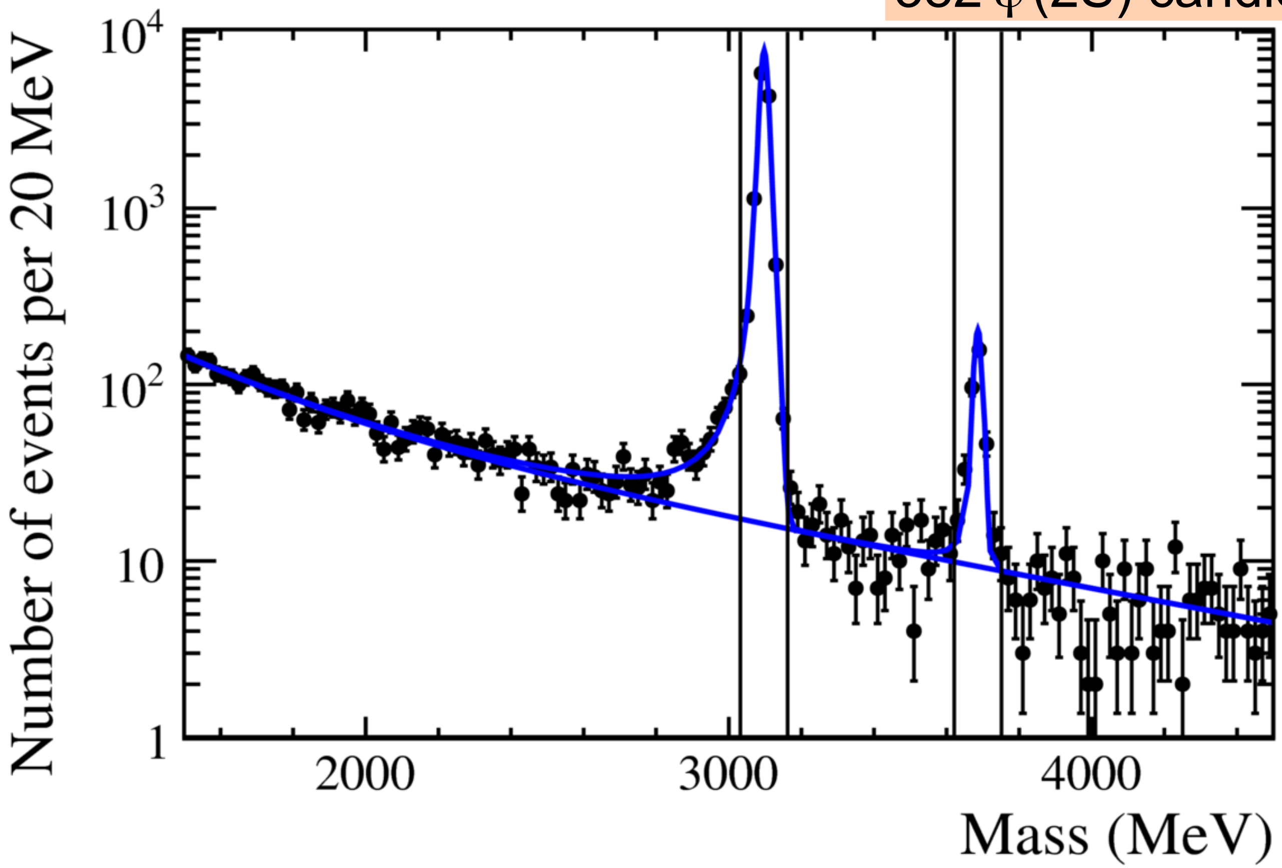


J/ψ and $\psi(2S)$ - 13 TeV

LHCb-CONF-2016-007

2015 dataset with L=204/pb

12992 J/ψ candidates
382 $\psi(2S)$ candidates



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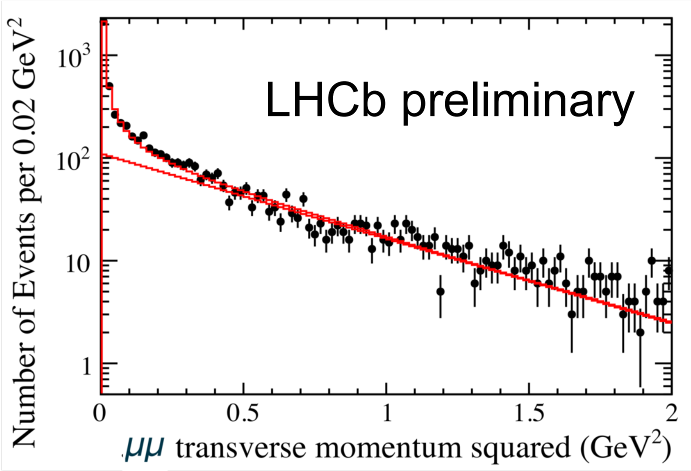
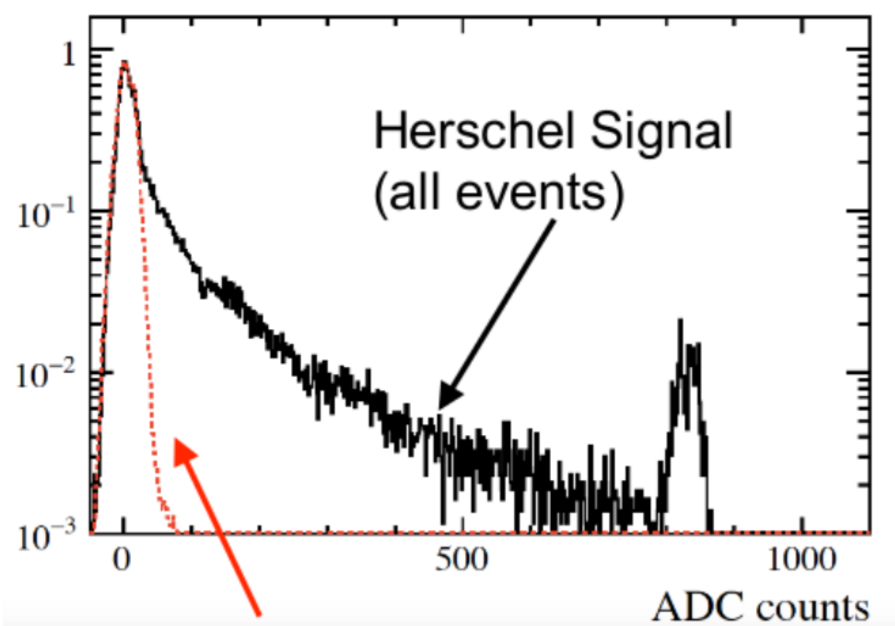
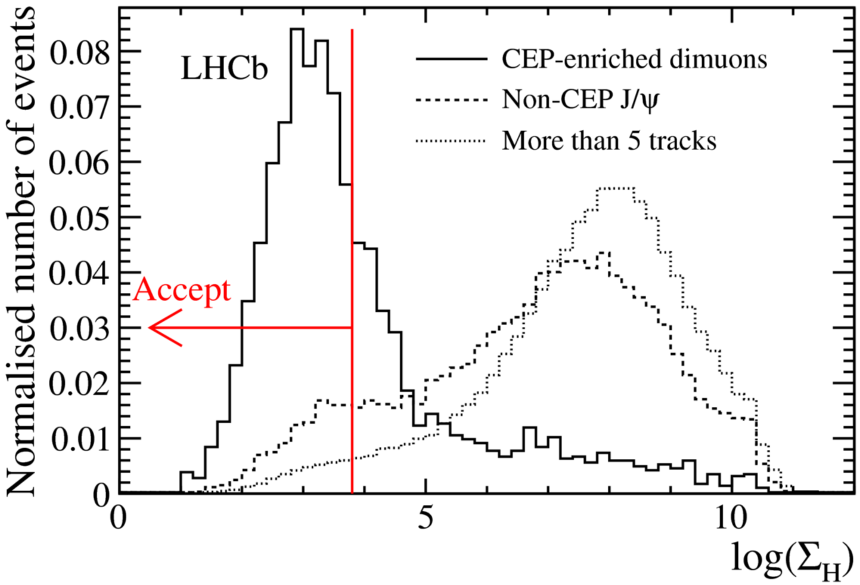
Herschel requirement

Using non-resonant DiMuon events, high multiplicity and high p_T J/ψ





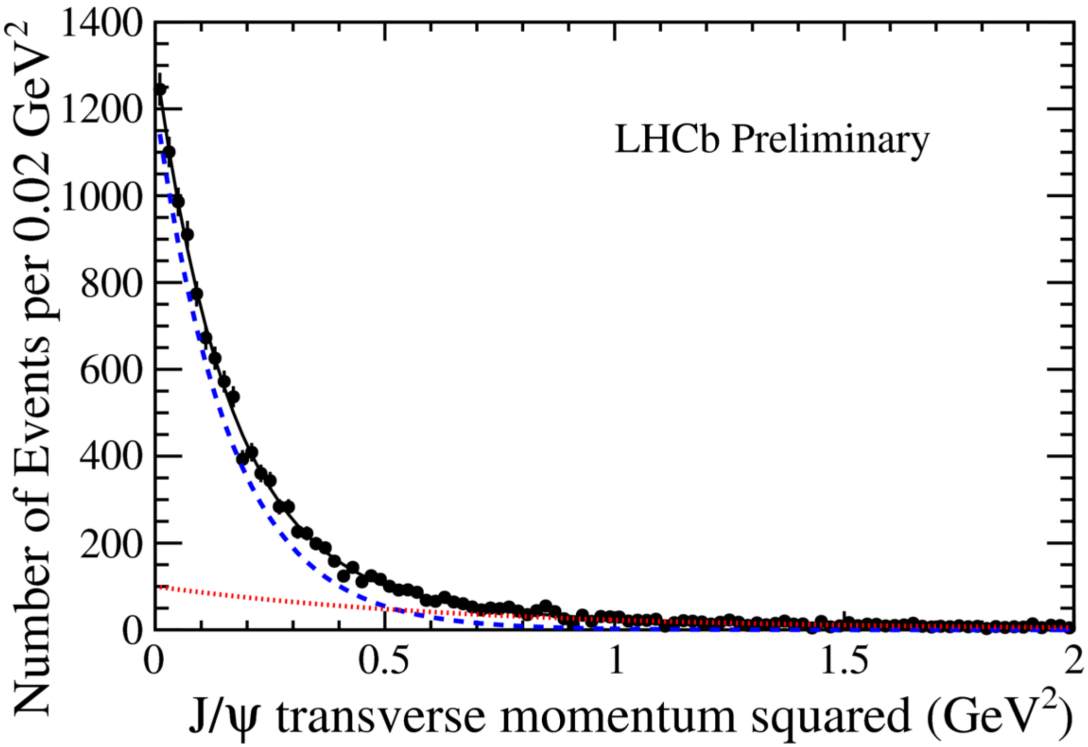


Log of the quadratic sum of the normalized signals in each of the 20 channels

Background fractions

- Non-resonant estimated from DiMuon mass → 0.009
- Feed-down estimated using data → 0.059 (compared to 0.101 at 7 TeV)
- Proton dissociation extracted from fit to p_T^2 after subtracting non-resonant and feed-down background

$$f_{\rm el} b_s \exp\left(-b_s p_{\rm T}^2\right) + (1 - f_{\rm el}) b_b \exp\left(-b_b p_{\rm T}^2\right)$$

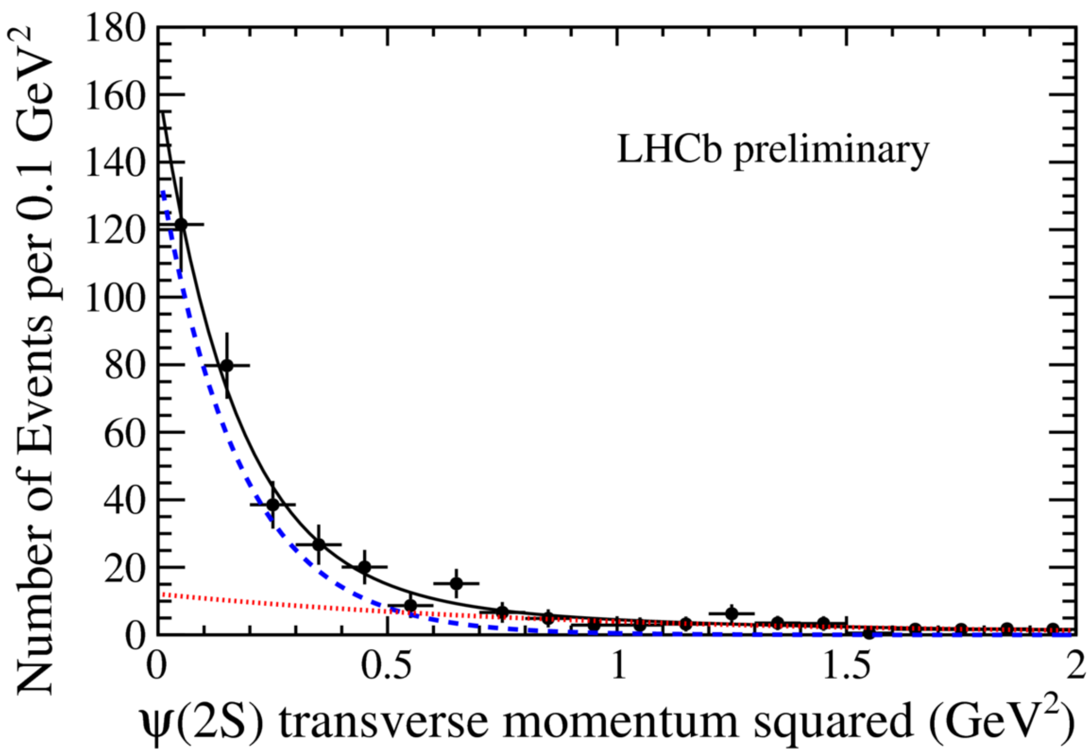


b_s=6.2±0.2 GeV^{-2} b_b=1.5±0.1 GeV^{-2} f_{el}=0.805±0.027

Background fractions

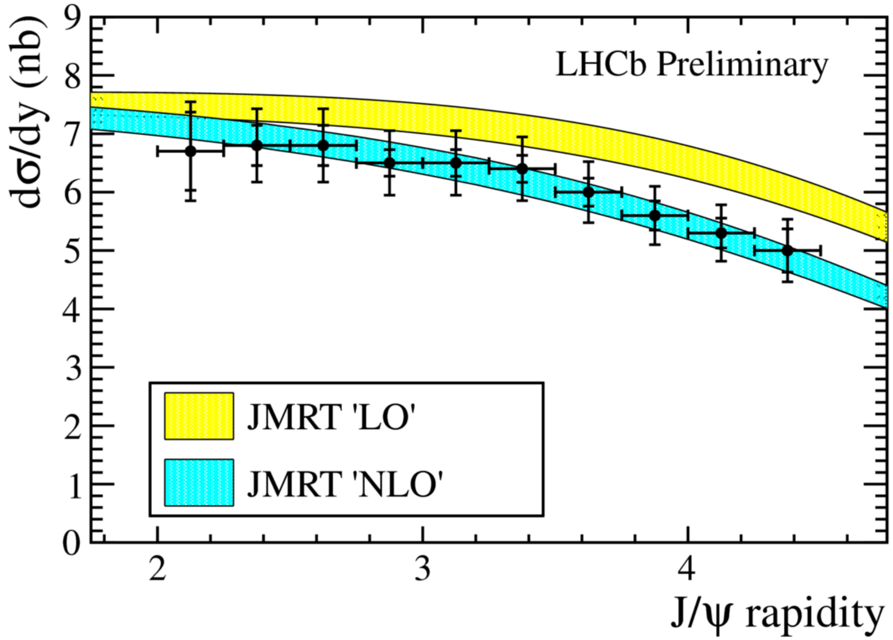
- Non-resonant estimated from DiMuon mass → 0.175
- Feed-down neglected in this preliminary result
- Proton dissociation extracted from fit to p_T^2 after subtracting non-resonant and feed-down background

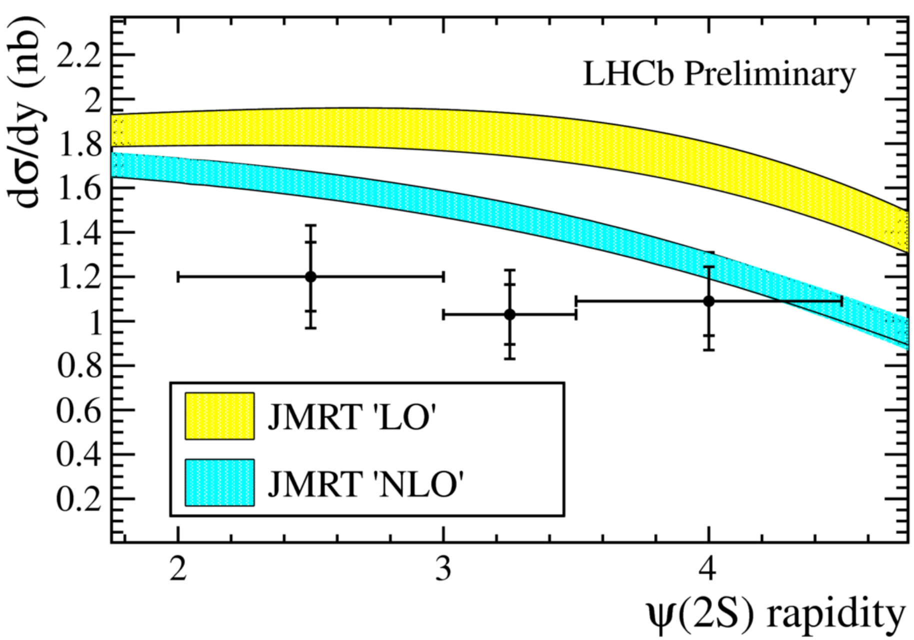
$$f_{\rm el} b_s \exp\left(-b_s p_{\rm T}^2\right) + (1 - f_{\rm el}) b_b \exp\left(-b_b p_{\rm T}^2\right)$$

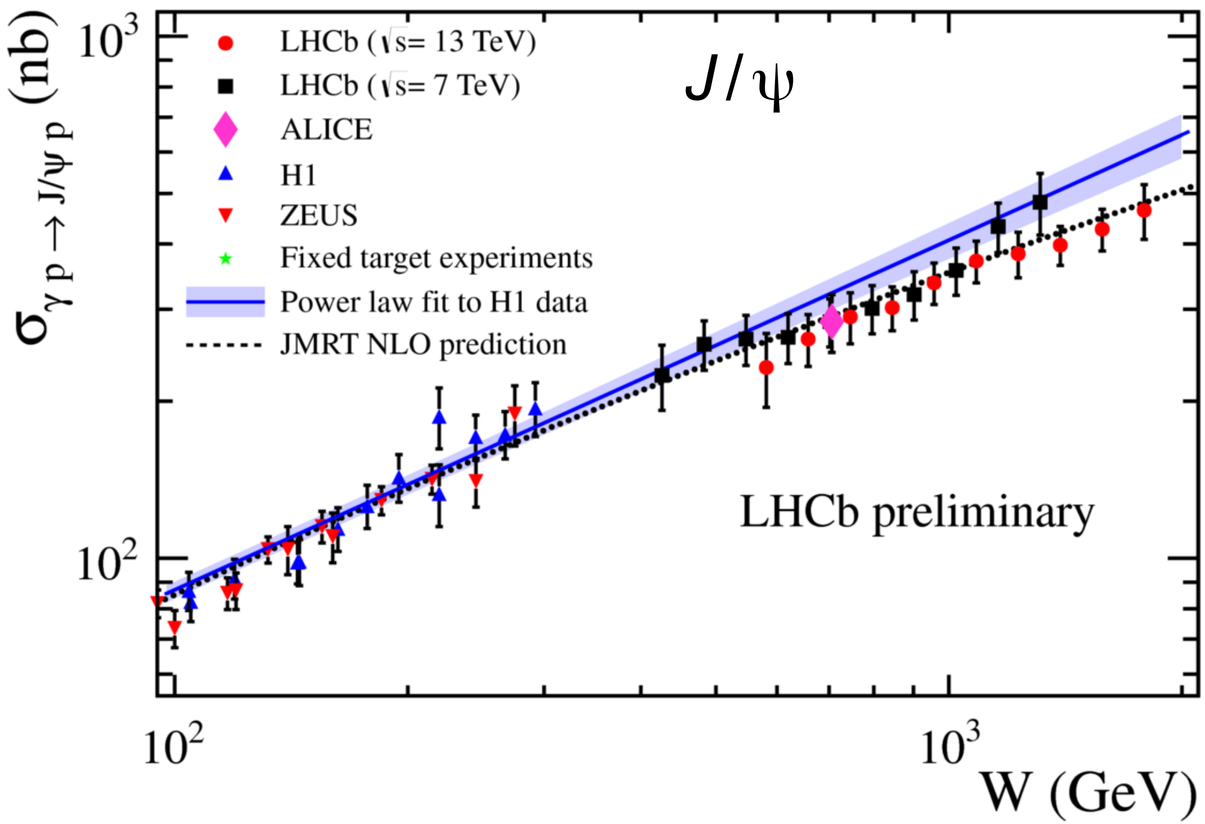


b_s=5.7±1.0 GeV^{-2} b_b=1.1±0.6 GeV^{-2} f_{el}=0.79±0.13

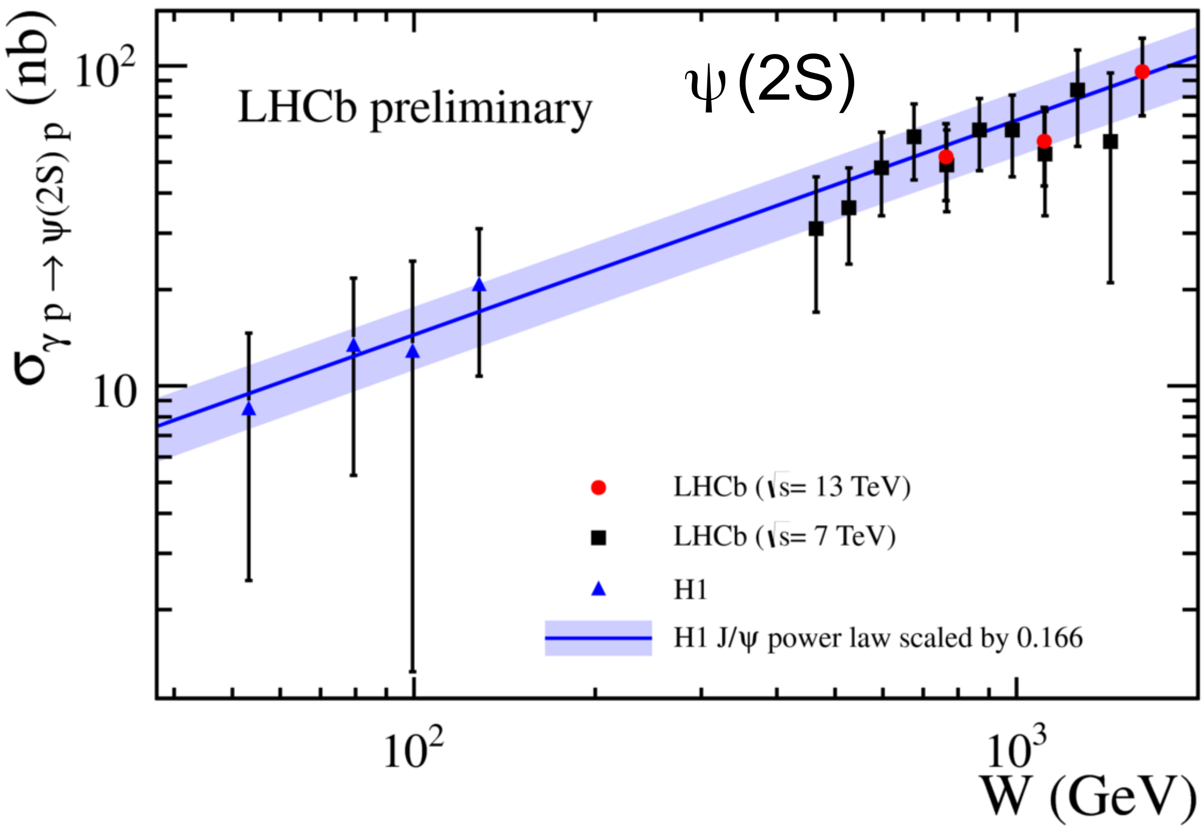
LHCb-CONF-2016-007







7 and 13 TeV results are in agreement
Power-law fit is not sufficient to explain data
Good agreement with JMRT NLO



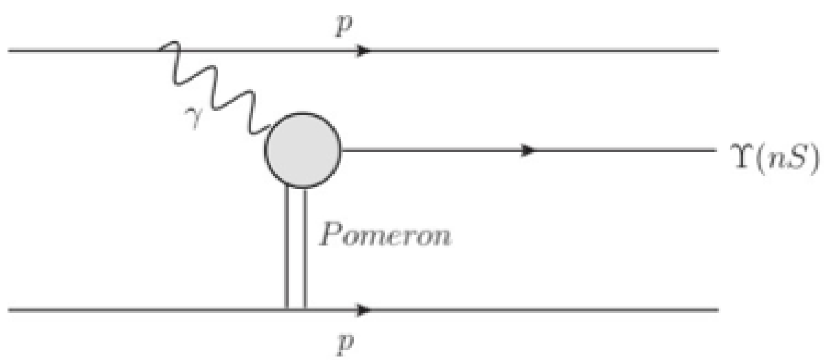
Only W_{+} solution possible

Good agreement with H1 extrapolation

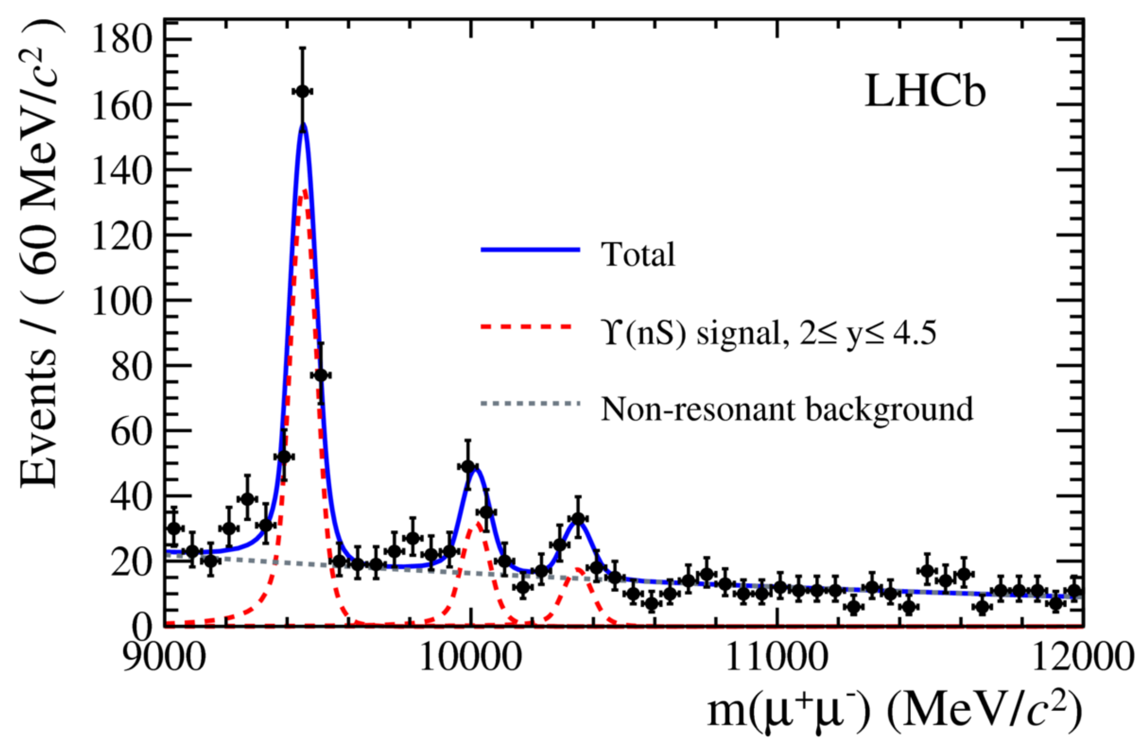
Exclusive Υ production

JHEP 09 (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



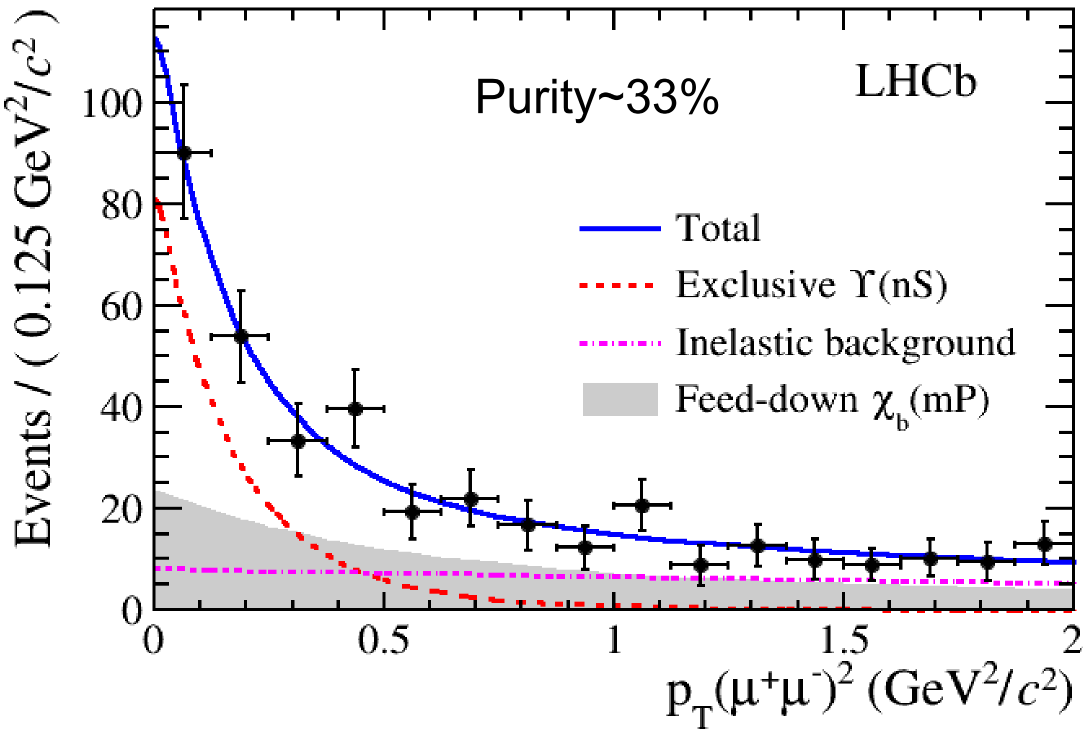
Background fractions

Non-resonant estimated from DiMuon mass

Feed-down estimated using simulation and data input $\chi_b \rightarrow \Upsilon + \gamma$

Proton dissociation extracted from fit to p_T^2 using sWeights

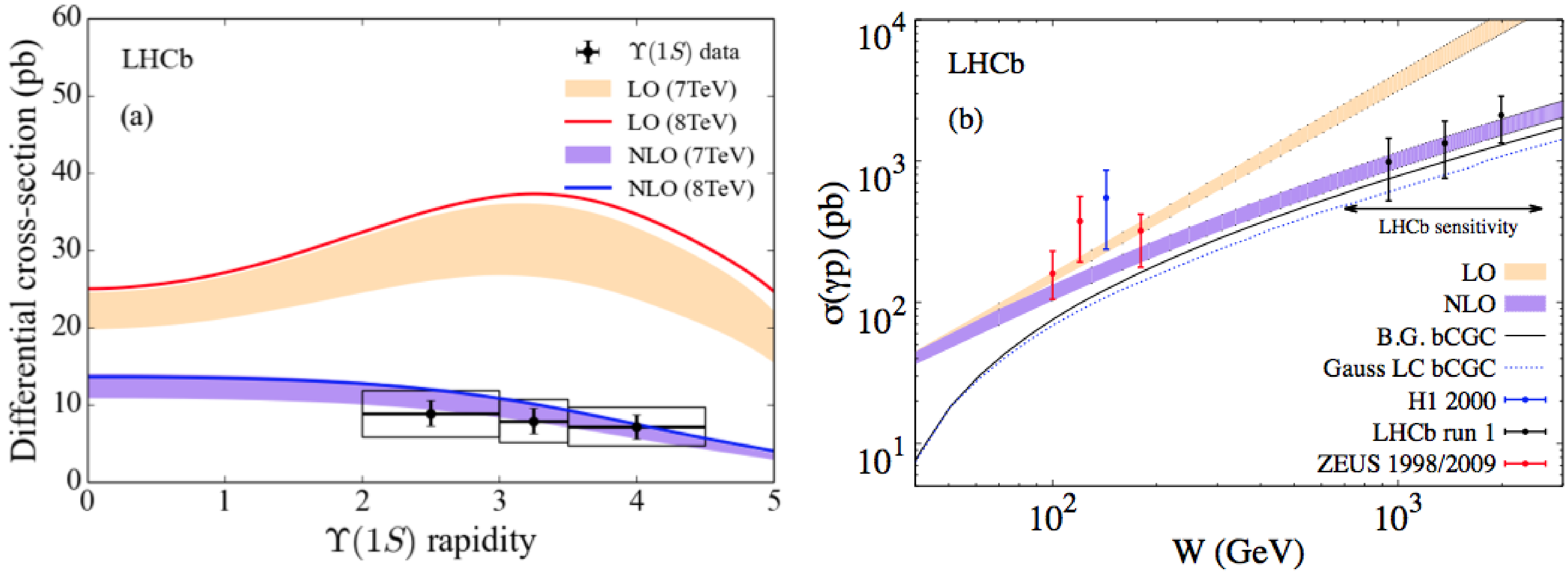
Signal template is obtained from SuperChiC



background fractions
feed-down 39%
inelastic 28%

JHEP 09 (2015) 084

$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb}$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb}$$

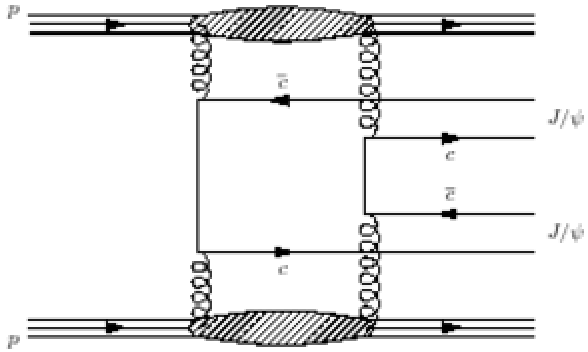


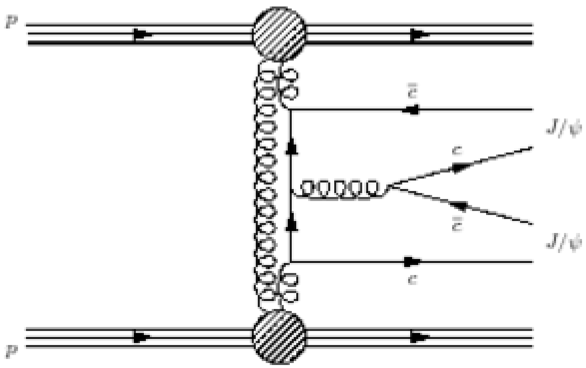
Rapidity dependence in agreement with NLO calculation

Photon-proton cross-section extrapolated from measurement can be compared with different phenomenological models

Charmonium pairs

J.Phys.G41 (2014)115002





2011 dataset with L=1/fb
2012 dataset with L=2/fb

Trigger

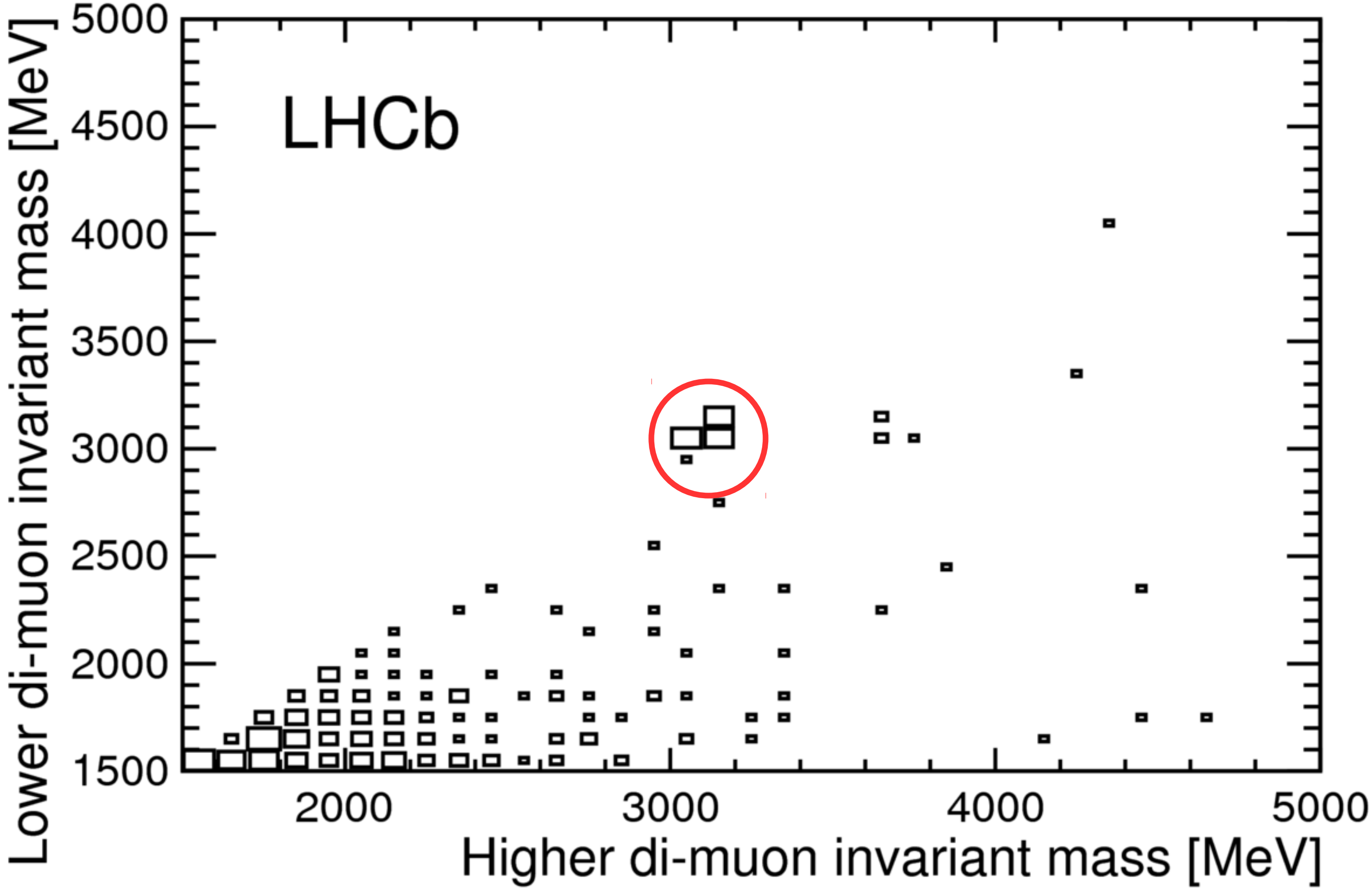
DiMuon (p_T(muon)>400 MeV) in coincidence with SPD multiplicity < 10

Candidate selection

Exactly four forward tracks (three identified as muons)

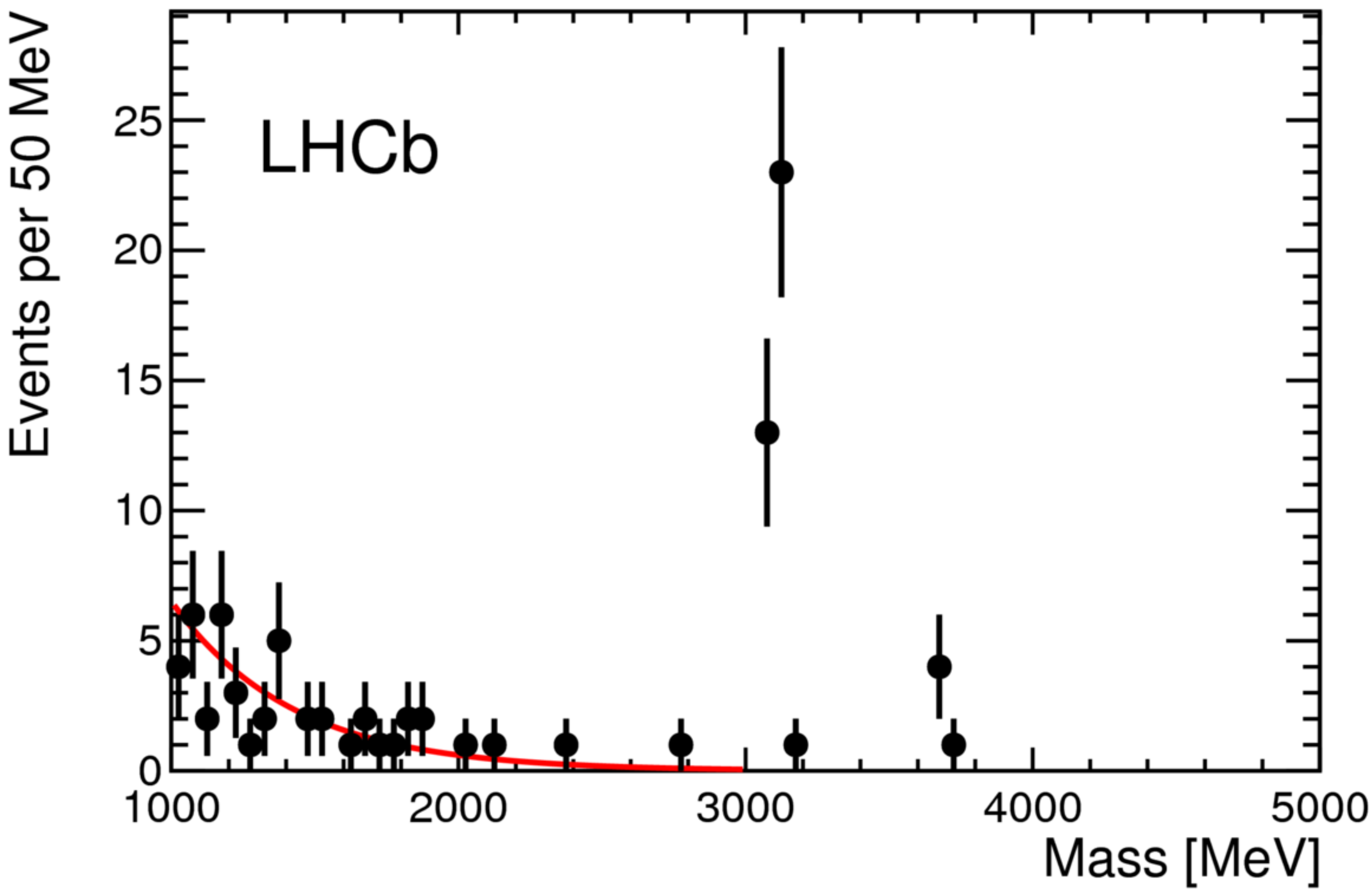
Charmonium pairs

J.Phys.G41 (2014)115002



Charmonium pairs

J.Phys.G41 (2014)115002



Mass of the second pair when the first pair has a mass consistent with the J/ψ or the ψ(2S)

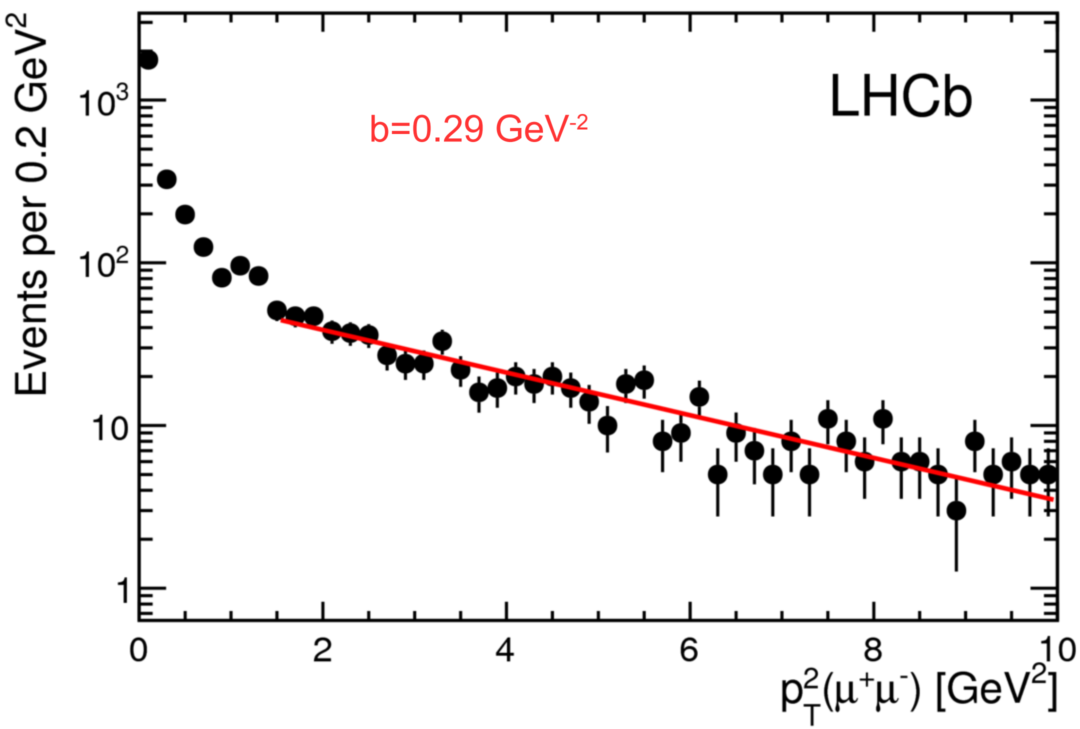
Extrapolation of exponential fit up to 2500 MeV is used to estimate non-resonant background
=> 0.3±0.1(0.07±0.02) for J/ψ (ψ(2S))

Charmonium pairs

J.Phys.G41 (2014)115002

Feed-down from $J/\psi\ \psi(2S)$ as $J/\psi\ J/\psi$ estimated from data => 2.9±2.0

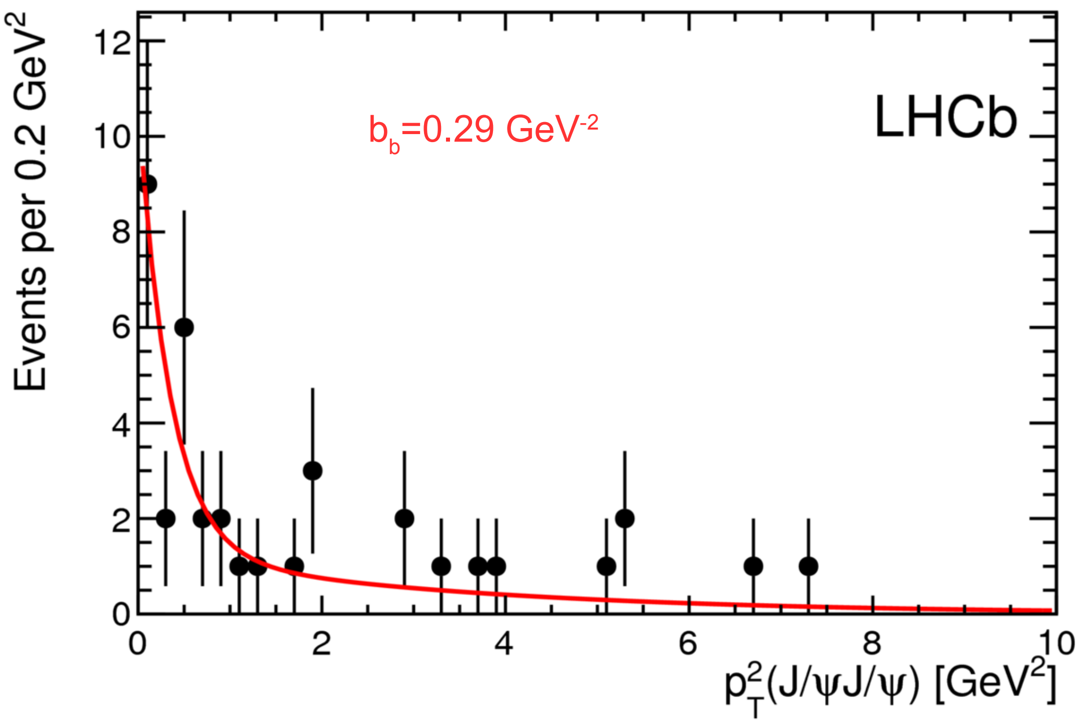
Proton dissociation estimated from p_T^2 fit using events with DiMuon mass = [6,9] GeV



J.Phys.G41 (2014)115002

Signal estimated using a fit to data

$$f_{\rm el} b_s \exp\left(-b_s p_{\rm T}^2\right) + (1 - f_{\rm el}) b_b \exp\left(-b_b p_{\rm T}^2\right)$$



$b_s = 2.9 \pm 1.3\, GeV^{-2}$ and $f_{el} = 0.42 \pm 0.13$

J/ψ CEP $\rightarrow b_s = 5.70 \pm 0.11\, GeV^{-2}$

Different signal slope from double charmonium to single charmonium

Charmonium pairs

J.Phys.G41 (2014)115002

Candidates
37 J/ψ-J/ψ
5 J/ψ-ψ(2S)
0 ψ(2S)-ψ(2S)

Cross-section measurements without proton dissociation correction
Limits calculated at 90% CL

$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}$$

$$\frac{\sigma(J/\psi\, \psi(2S))}{\sigma(J/\psi\, J/\psi)} = 1.1^{+0.5}_{-0.4}$$

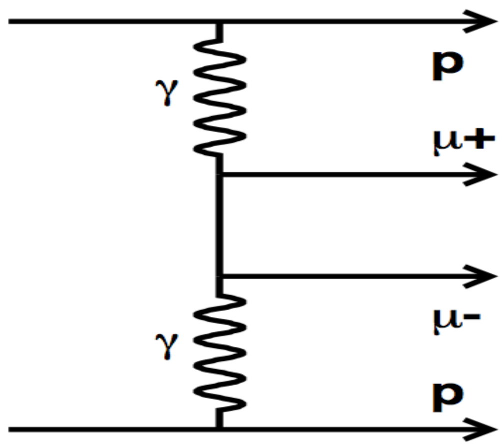
$$\frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = 0.17 \pm 0.02$$

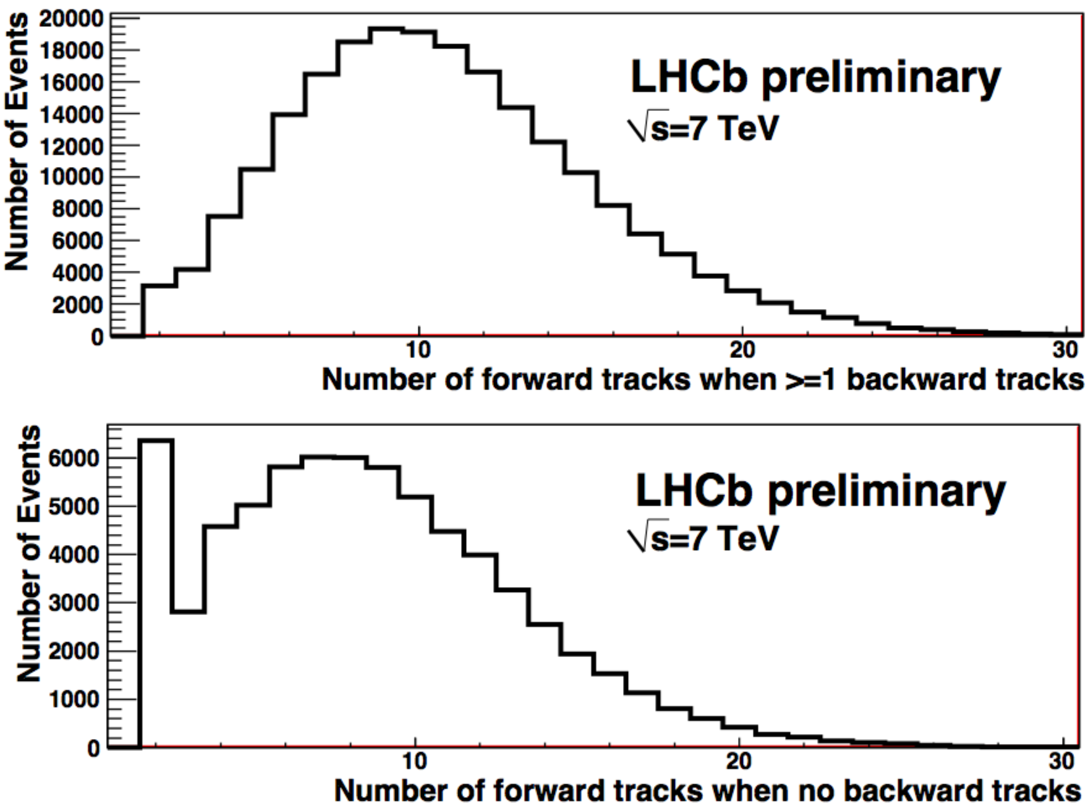
$$\sigma^{J/\psi\, J/\psi} / \sigma^{J/\psi}|_{\text{exclusive}} = (2.1 \pm 0.8) \times 10^{-3}$$

$$\sigma^{J/\psi\, J/\psi} / \sigma^{J/\psi}|_{\text{inclusive}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$$

Non-resonant DiMuon

- Data collected in 2010 (L=36/pb)





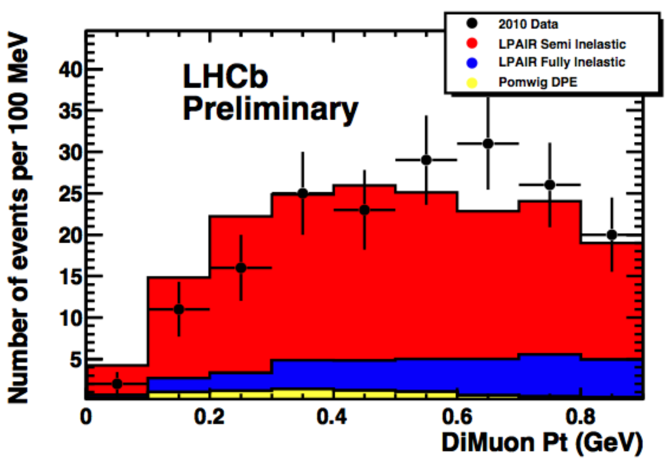
Non-resonant DiMuon

DiMuon selection

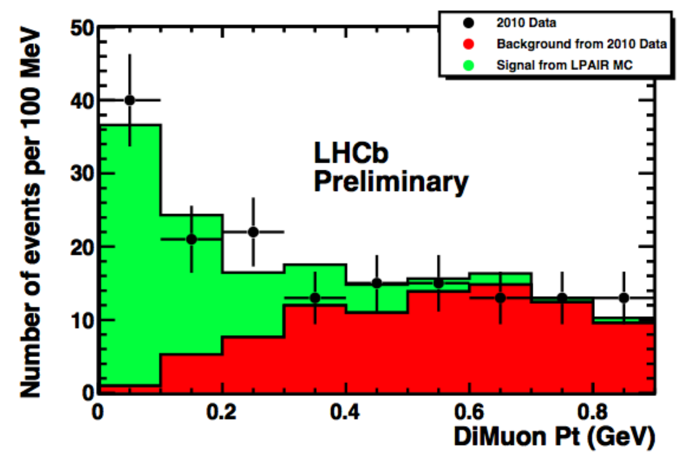
- Candidates of J/ψ and ψ(2S) are vetoed
- Muon p_T > 80 MeV
- DiMuon Mass > 2.5 GeV
- DiMuon p_T < 0.9 GeV

Background

- Muon mis-id: random triggers without muon id cuts
- Diffractively produced DiMuon contribution estimated by POMWIG
- Inelastic production estimated using LPAIR and normalized to data



More than 2 fwd tracks

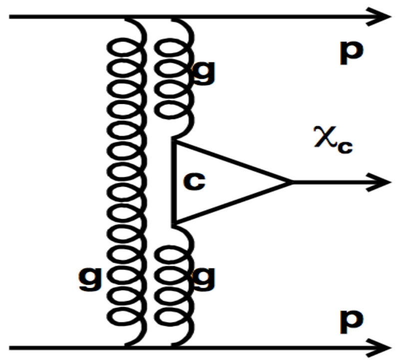


Only 2 fwd tracks

$$\sigma_{pp\to p\mu^+\mu^-p}(2 < \eta_{\mu+}, \eta_{\mu-} < 4.5; m_{\mu+\mu-} > 2.5\ \mathrm{GeV/c^2}) = 67 \pm 10 \pm 7 \pm 15\ \mathrm{pb}$$

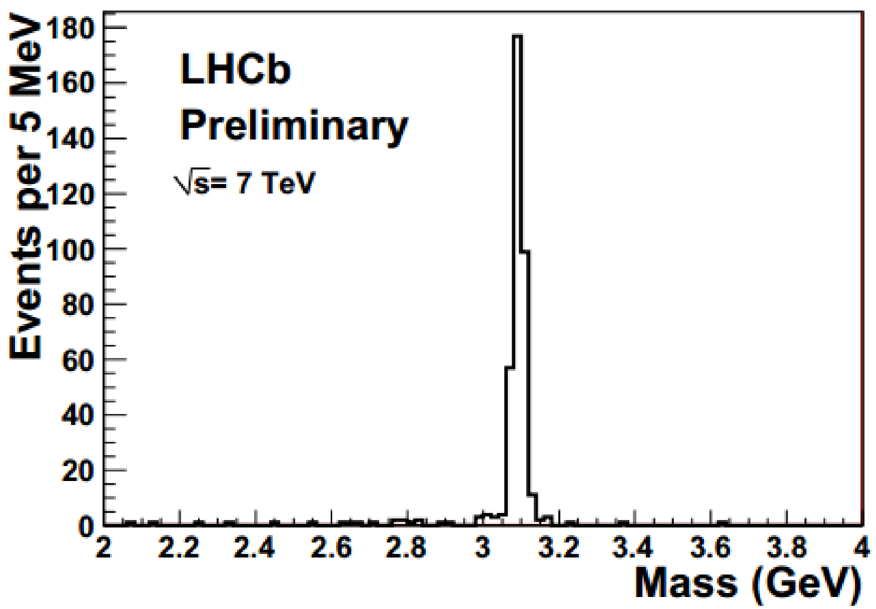
42 pb (LPAIR prediction)

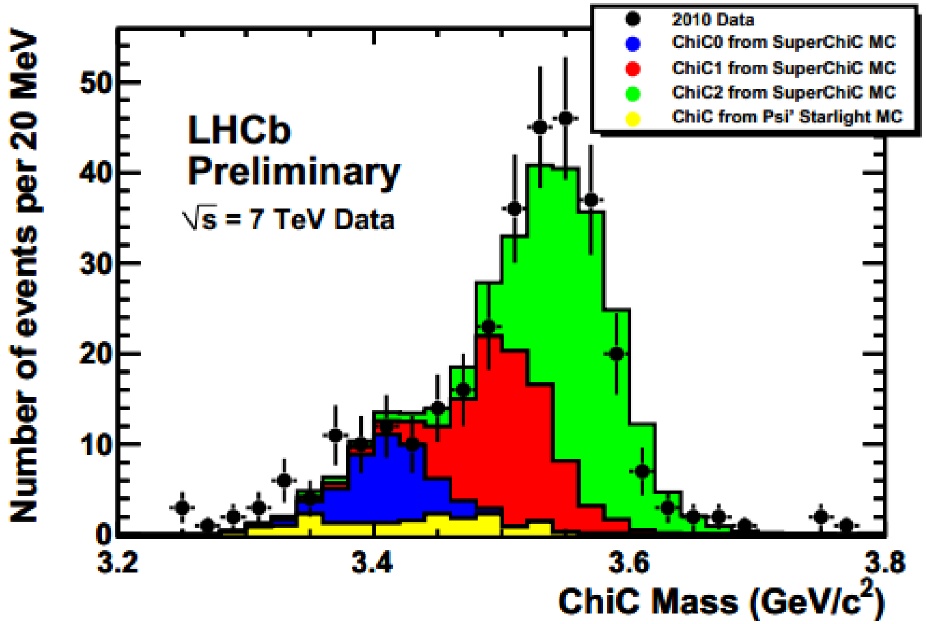
Analysis update is ongoing.



→ Same data as non-resonant DiMuon
→ J/ψ candidate plus one photon (E_T>200 MeV)

+ Exclusive spectrum estimated by SuperChic fitted to data
+ Inelastic contamination higher than other CEP (60%)





$$\sigma_{\chi_{c0}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5)=9.3\pm2.2\pm3.5\pm1.8\text{ pb}$$

$$\sigma_{\chi_{c1}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5)=16.4\pm5.3\pm5.8\pm3.2\text{ pb}$$

$$\sigma_{\chi_{c2}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5)=28.0\pm5.4\pm9.7\pm5.4\text{ pb}$$

Analysis update is ongoing.

Summary

→ Extensive central exclusive production program at LHCb

→ Important tests of QCD in the forward region

→ LHCb has an active program to study CEP
+ odderon and glueball searches
+ more final states
+ other diffractive production
+ …

Summary

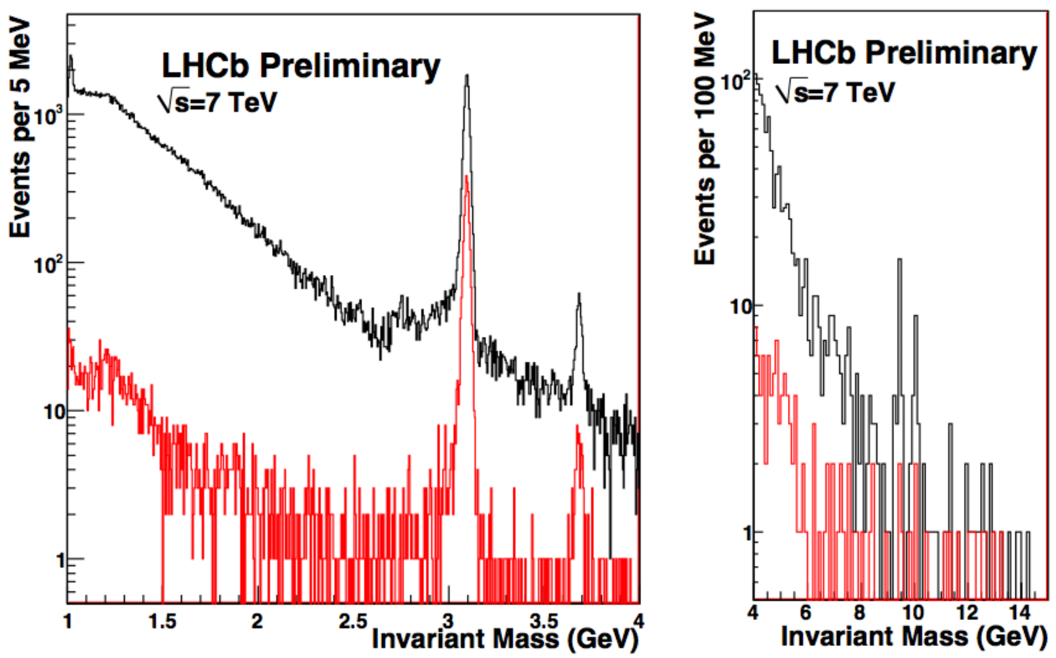
→ Extensive central exclusive production program at LHCb

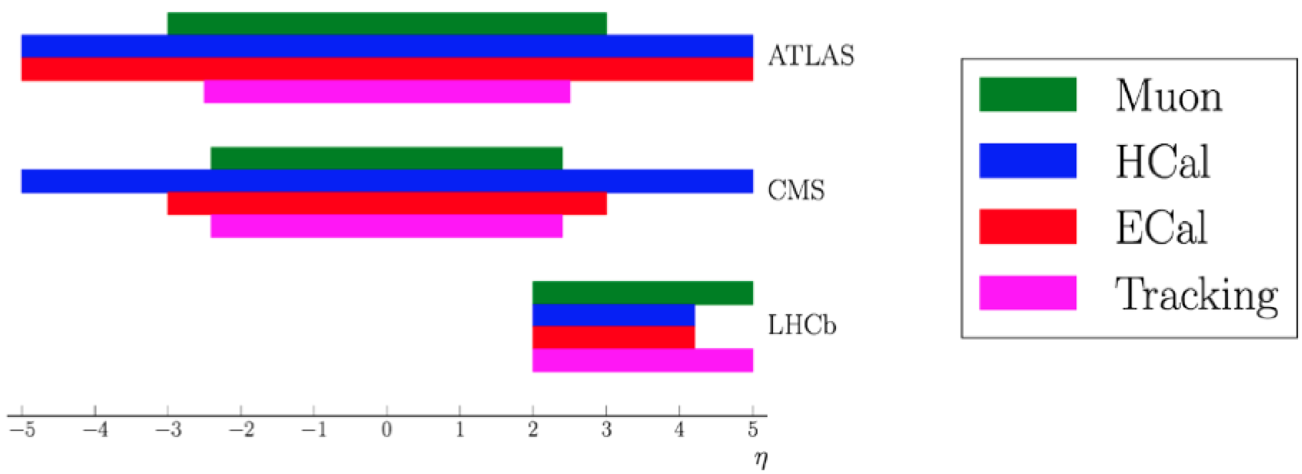
→ Important tests of QCD in the forward region

→ LHCb has an active program to study CEP
  + odderon and glueball searches
  + more final states
  + other diffractive production
  + ...

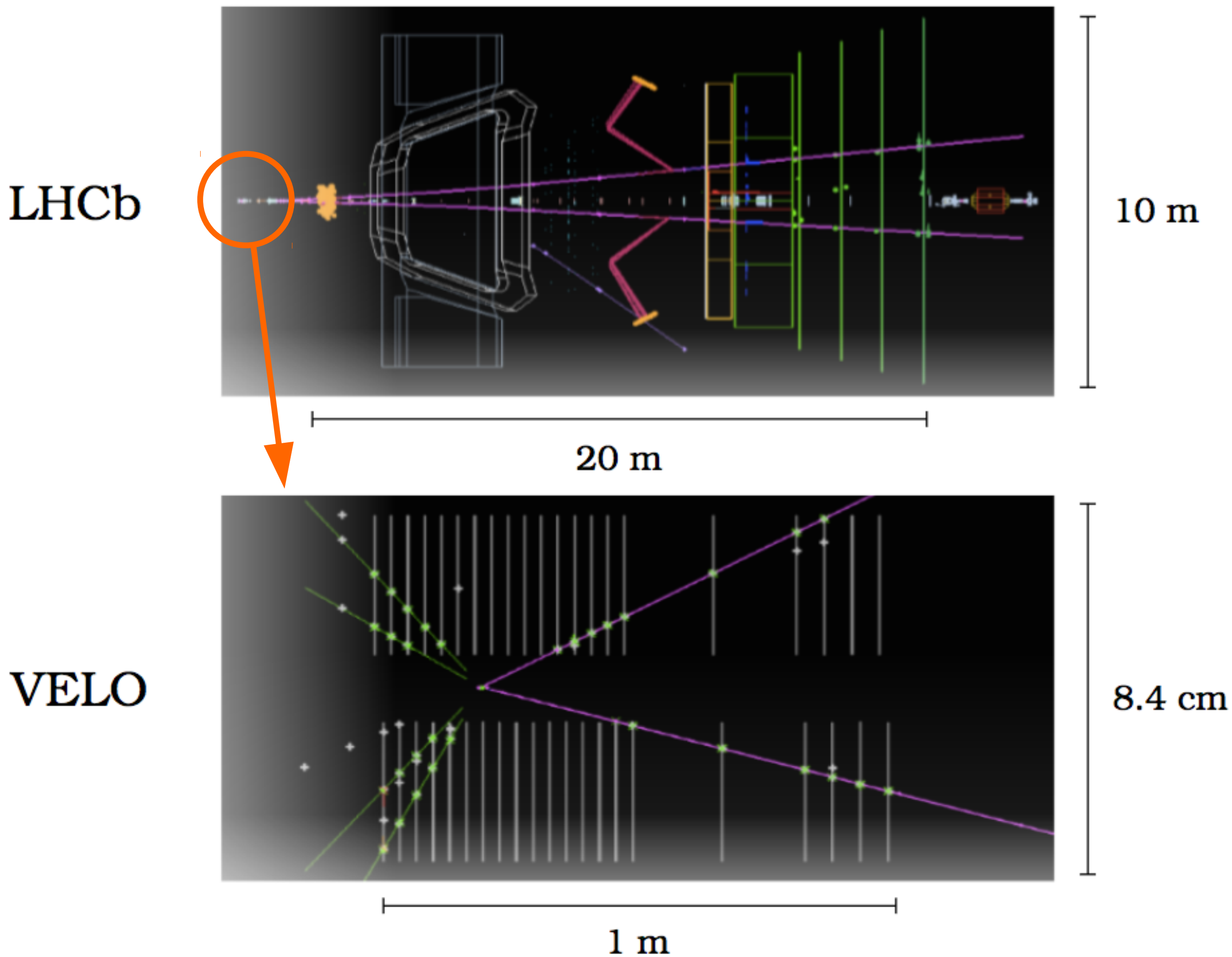
Thank you!

Non-resonant DiMuon



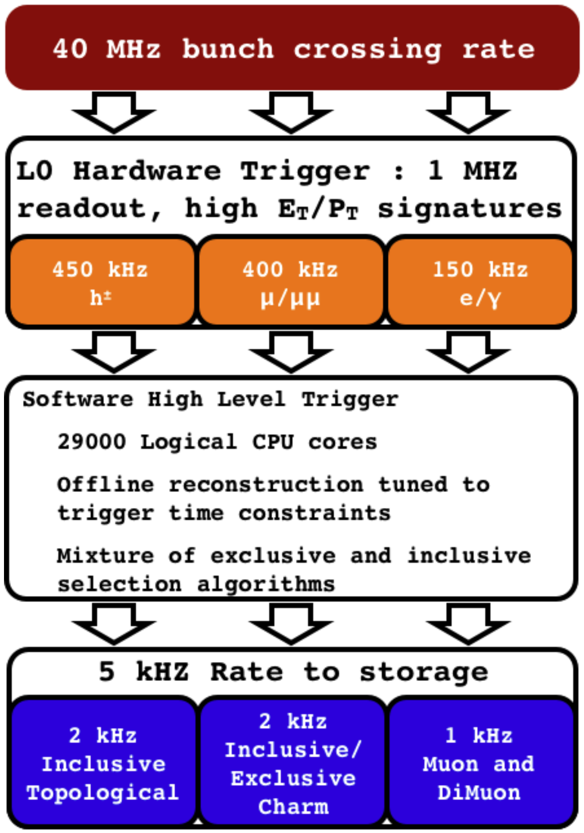

ATLAS
CMS
LHCb
−5
−4
−3
−2
−1
0
1
2
3
4
5
η
Muon
HCal
ECal
Tracking

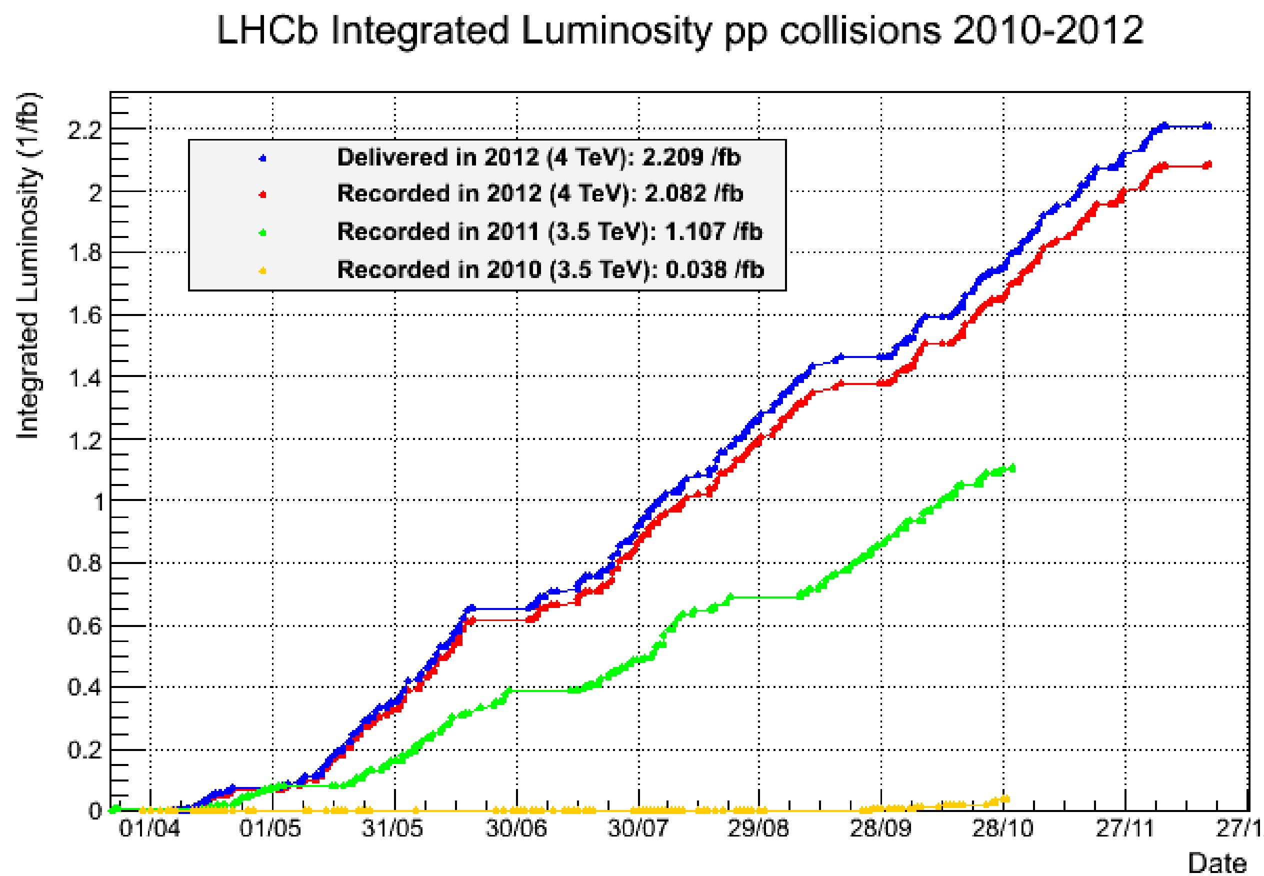
LHCb detector



Backward track reconstruction is useful

Phil Ilten's slides – MPI at LHC





>90% data taking efficiency

>99% DQ efficiency

2010 → 37/pb at $\sqrt{s}$ = 7 TeV

2011 → 1.0/fb at at $\sqrt{s}$ = 7 TeV

2012 → 2/fb at at $\sqrt{s}$ = 8 TeV

Central exclusive J/ψ and ψ(2S)

J.P.G40 (2013) 045001

	Predictions [pb]	$\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}$	$\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}$
[12]	Gonçalves and Machado	275	
[11]	STARLIGHT	292	6.1
[7]	Motyka and Watt	334	
[10]	SUPERCHIC	396	
[13]	Schäfer and Szczurek	710	17
	LHCb measured value	$307 \pm 21 \pm 36$	$7.8 \pm 1.3 \pm 1.0$

[10] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, *Central exclusive χ_c meson production at the Tevatron revisited*, Eur. Phys. J. **C65** (2010) 433, arXiv:0909.4748.

[11] S. R. Klein and J. Nystrand, *Photoproduction of quarkonium in proton-proton and nucleus-nucleus collisions*, Phys. Rev. Lett. **92** (2004) 142003.

[12] V. P. Gonçalves and M. V. T. Machado, *Vector meson production in coherent hadronic interactions: an update on predictions for RHIC and LHC*, Phys. Rev. **C84** (2011) 011902, arXiv:1106.3036.

[13] W. Schäfer and A. Szczurek, *Exclusive photoproduction of J/ψ in proton-proton and proton-antiproton scattering*, Phys. Rev. **D76** (2007) 094014, arXiv:0705.2887.

[7] L. Motyka and G. Watt, *Exclusive photoproduction at the Fermilab Tevatron and CERN LHC within the dipole picture*, Phys. Rev. **D78** (2008) 014023, arXiv:0805.2113.