Central exclusive production at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

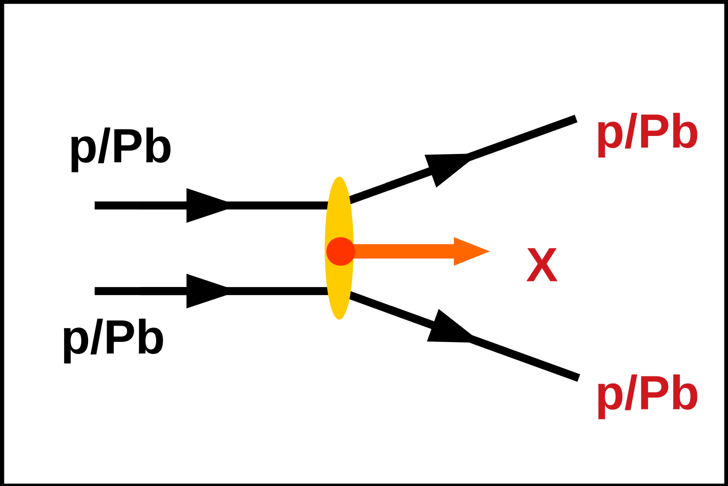
LHCb

Diffraction and Low-x 2018

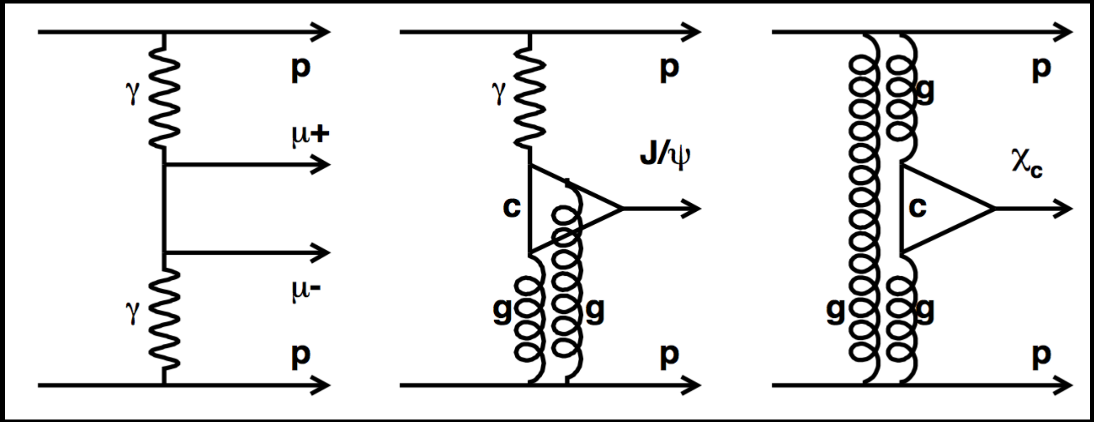
lape

Instituto de Física
Universidade Federal do Rio de Janeiro

Central Exclusive Production (CEP)



, e.g.,



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 $5x10^{-6}$

Run I / 2011-2012 / pp at 7-8 TeV

1) Measurement of the exclusive Υ production cross-section at 7 TeV and 8 TeV
JHEP 1509 (2015) 084.

2) Observation of charmonium pairs produced exclusively in pp collisions
J.Phys. G41 (2014) no.11, 115002.

3) Updated measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp at 7 TeV
J.Phys. G41 (2014) 055002.

4) Exclusive dimuon measurements: non-resonant and χ_c
LHCb-CONF-2011-022

Run II / 2015 / pp (PbPb) at 13 (5) TeV

1) Study of coherent J/ψ production in lead-lead collisions at 5 TeV
LHCb-CONF-2018-003

2) Central exclusive production of J/ψ and $\psi(2S)$ mesons in pp collisions at 13 TeV
arXiv:1806.04079 [hep-ex].

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THIS TALK

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Albert Bursche's talk (Saturday)

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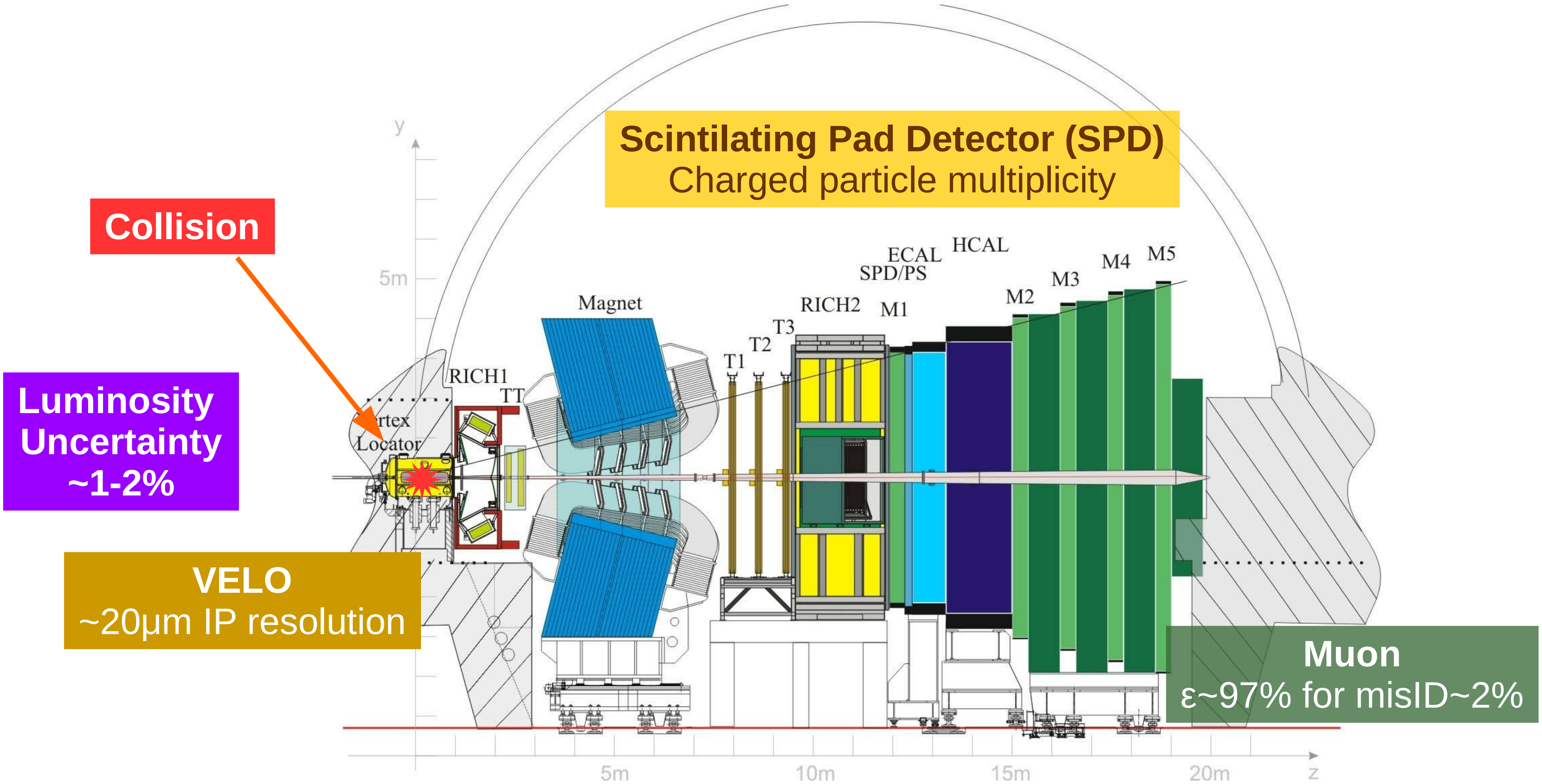
LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)
Designed for heavy flavour physics ↔ Exploited for general purpose physics
[Int. J. Mod. Phys. A 30, 1530022 (2015)]



Tracking (magnet)
0.4%-0.6% momentum resolution (0.2-100 GeV)

General Strategy

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

– Trigger on low multiplicity events
  → using SPD and/or tracks

– 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)

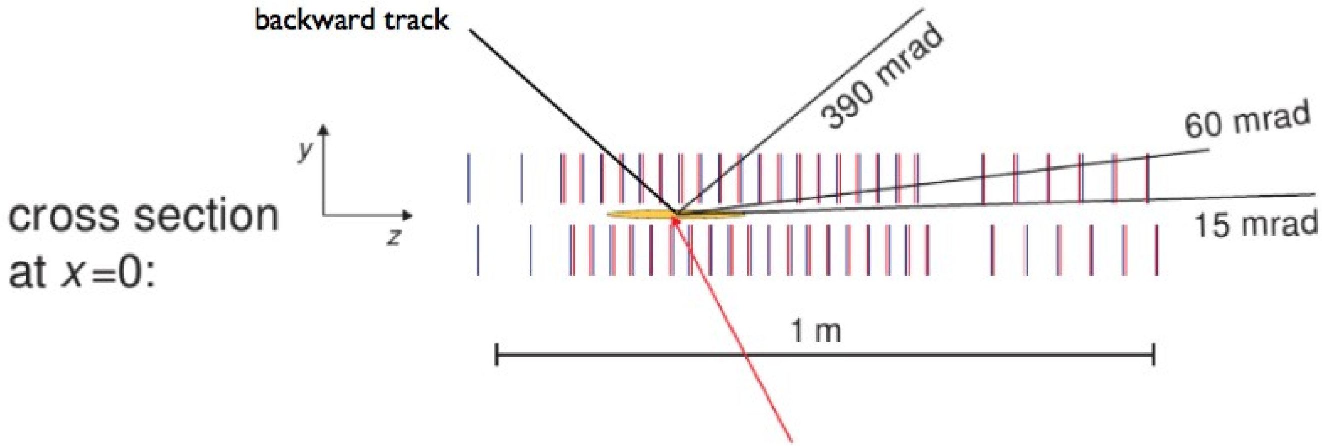
– Backgrounds:

→ feed-down: if X object is a resonance, it could be a decay product of Y

Ex: In J/ψ CEP: $\chi_c^0 \to J/\psi + \gamma$

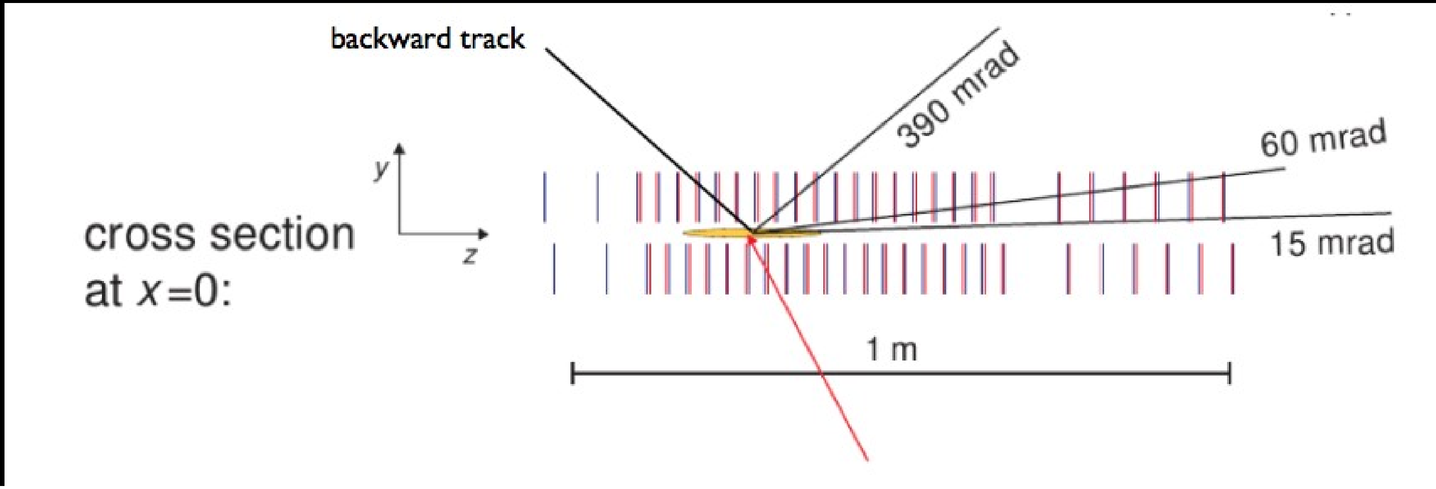
→ inelastic (proton dissociation): p_T^2 distribution is used to fit CEP and non-CEP

→ other diffractive production: estimated with event generators

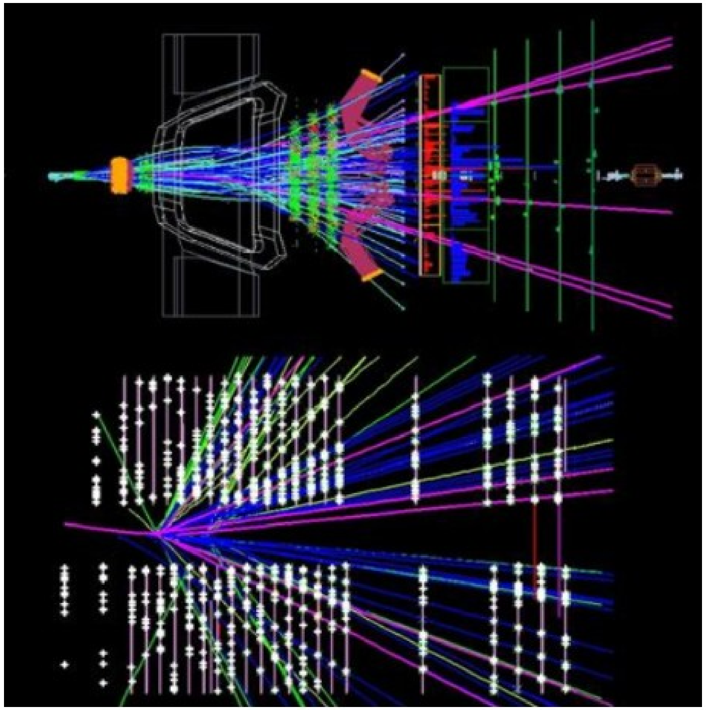


VELO (Vertex Locator)

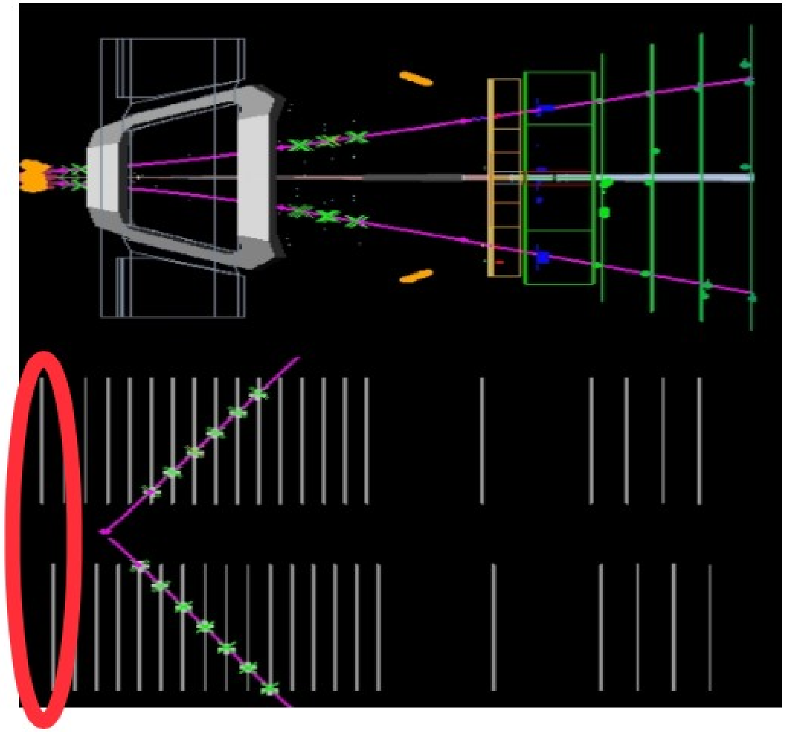
- → surrounds the interaction point
- → no magnetic field
- → reconstructs backward tracks $(-3.5<\eta<-1.5)$



Typical Event



CEP-like event: 2muons



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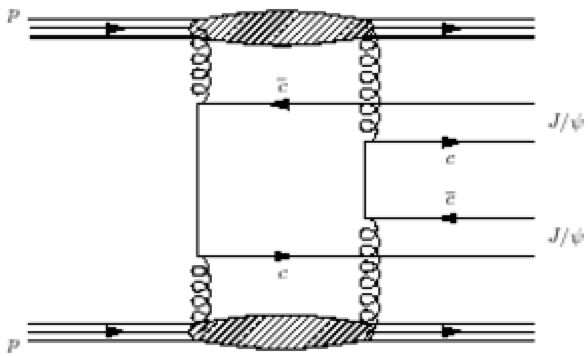
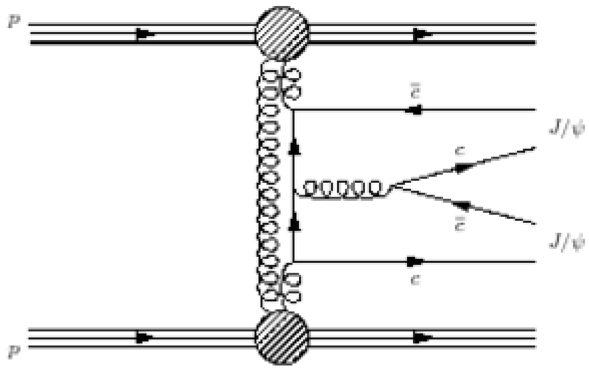
Charmonium pairs

J.Phys.G41 (2014)115002





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

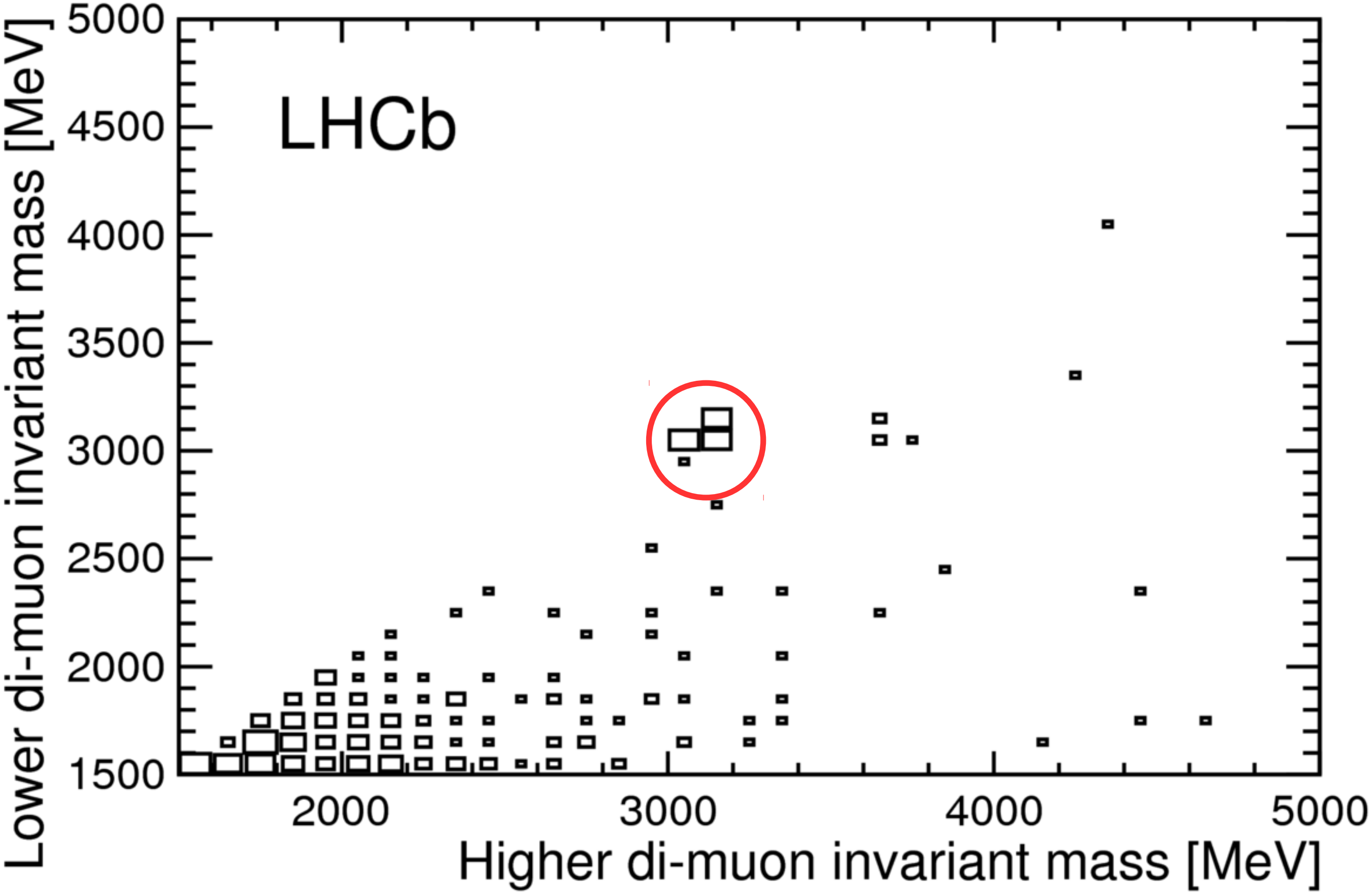
Trigger

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

Candidate selection

Exactly four forward tracks (three identified as muons)

J.Phys.G41 (2014)115002



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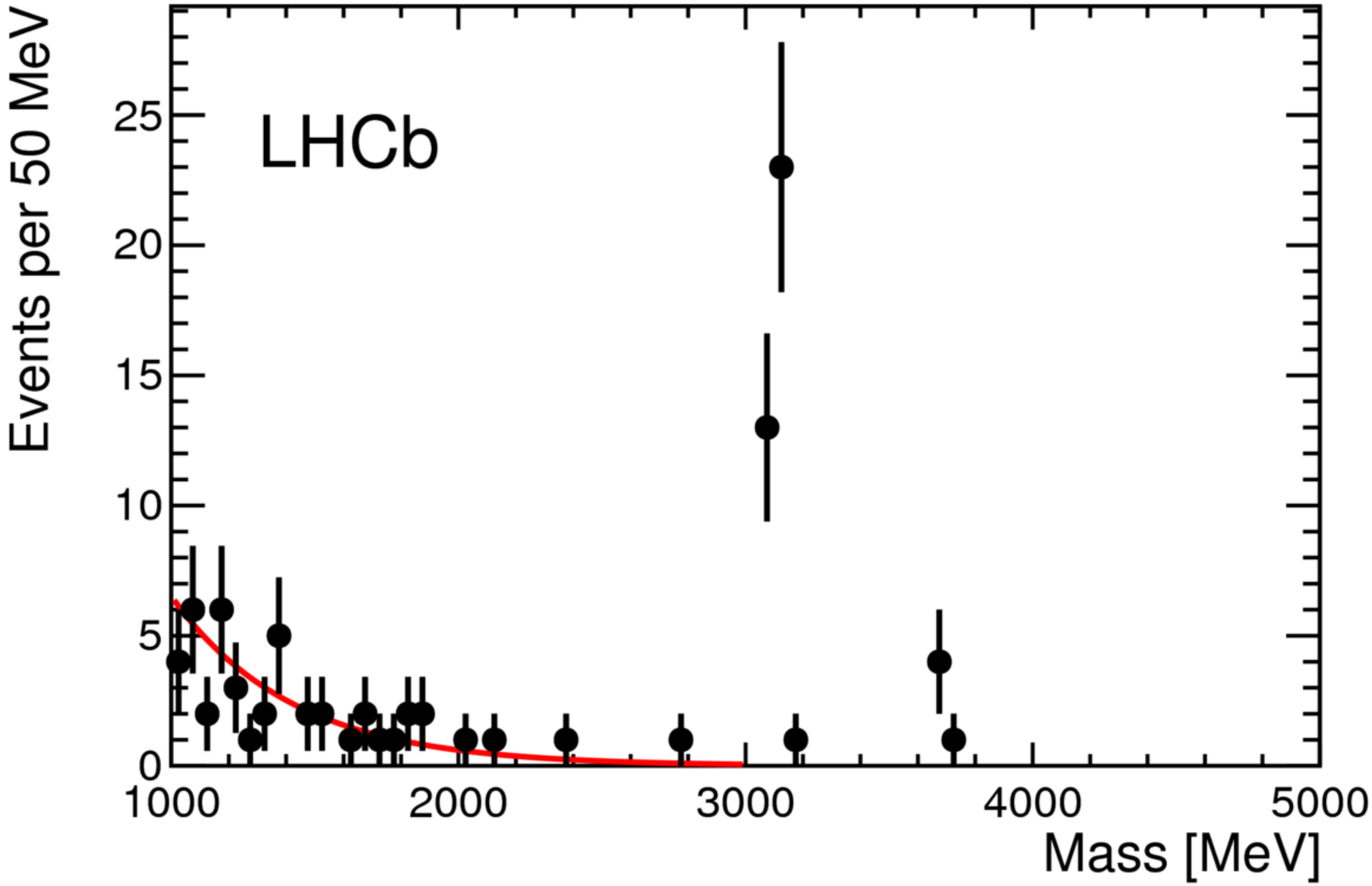


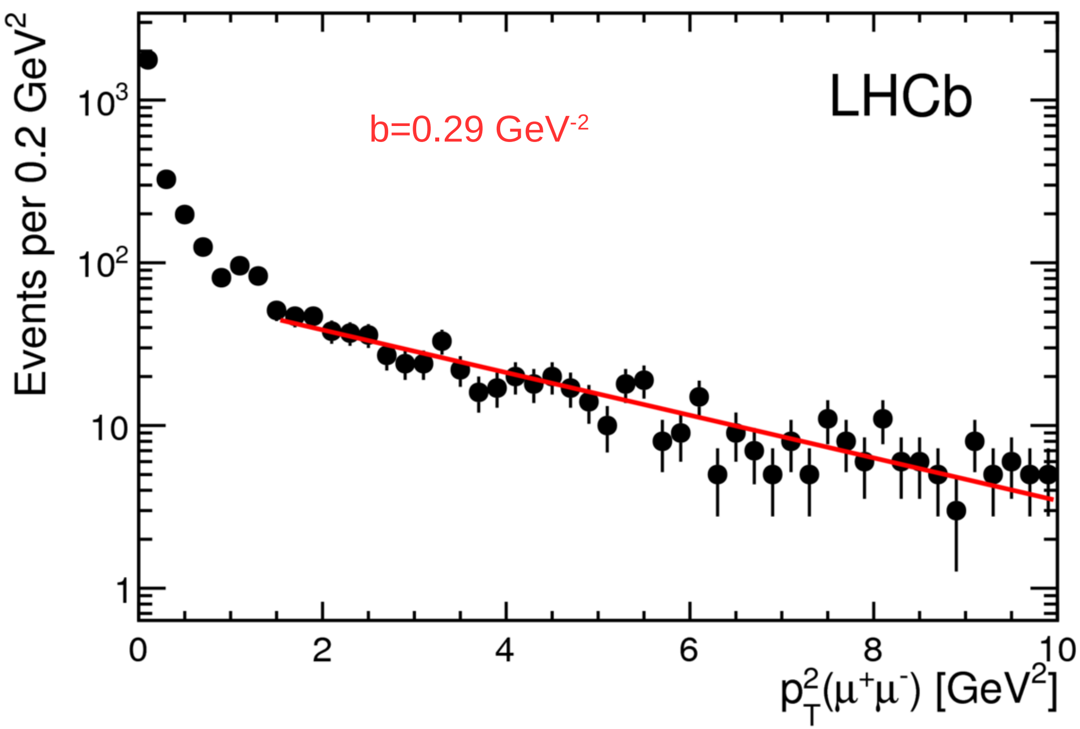
Mass of the second pair when the first pair has a mass consistent with the J/ψ or the ψ(2S)

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

J.Phys.G41 (2014)115002

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

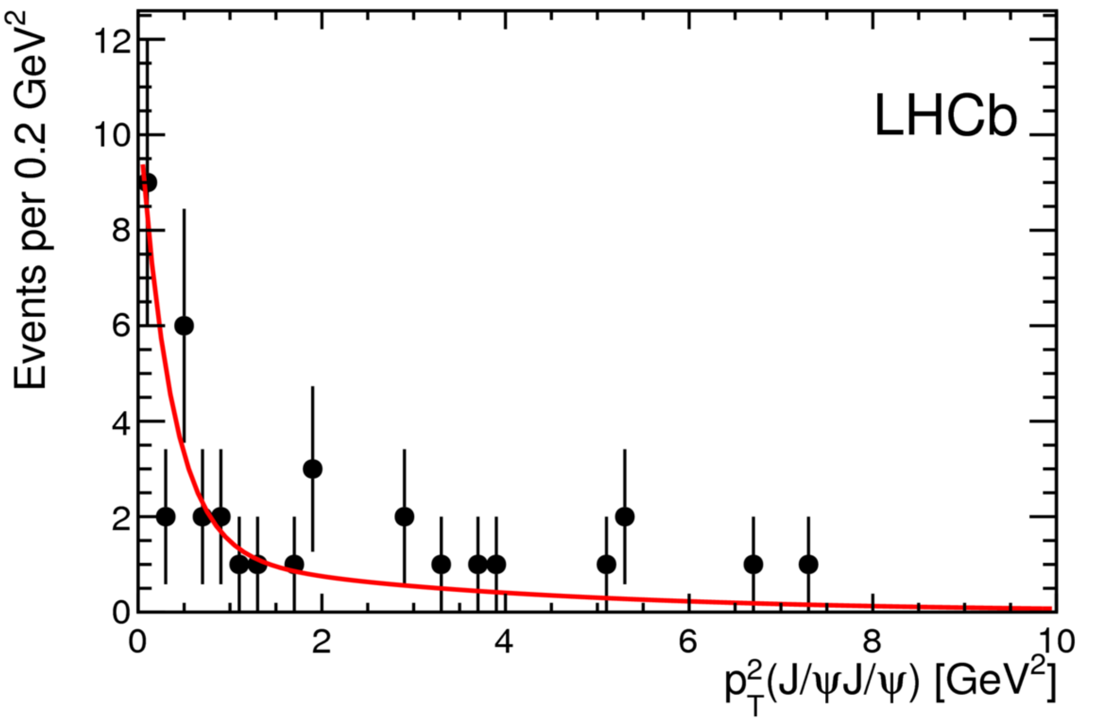
Proton dissociation slope estimated from p_T^2 fit using events with dimuon mass = [6,9] GeV



J.Phys.G41 (2014)115002

Signal estimated using a fit to data

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



$J/\psi J/\psi$ CEP → $b_s = 2.9 \pm 1.3\, GeV^{-2}$ and $f_{el} = 0.42 \pm 0.13$

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

Different signal slope from double charmonium to single charmonium

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

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

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

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

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

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

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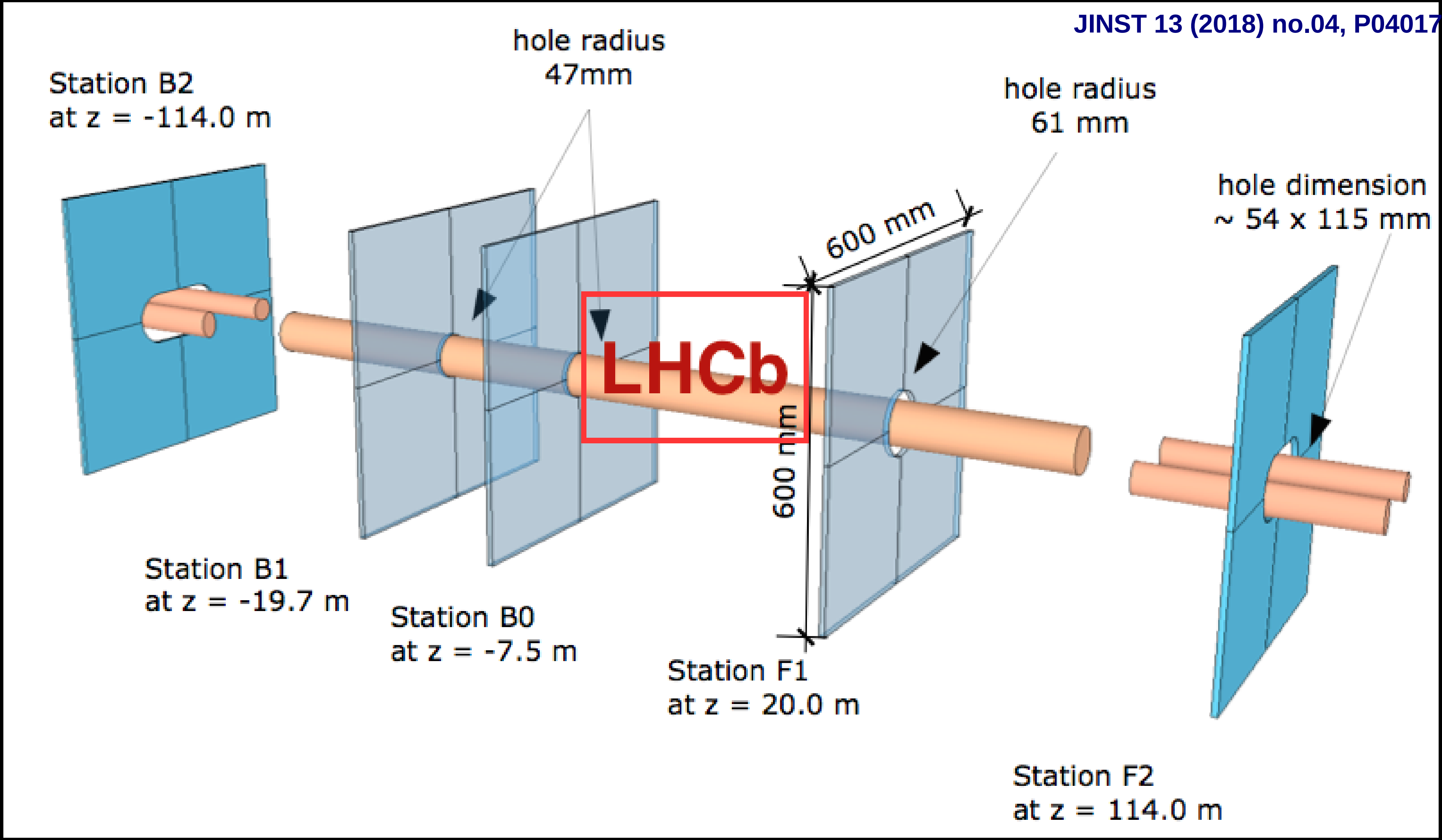
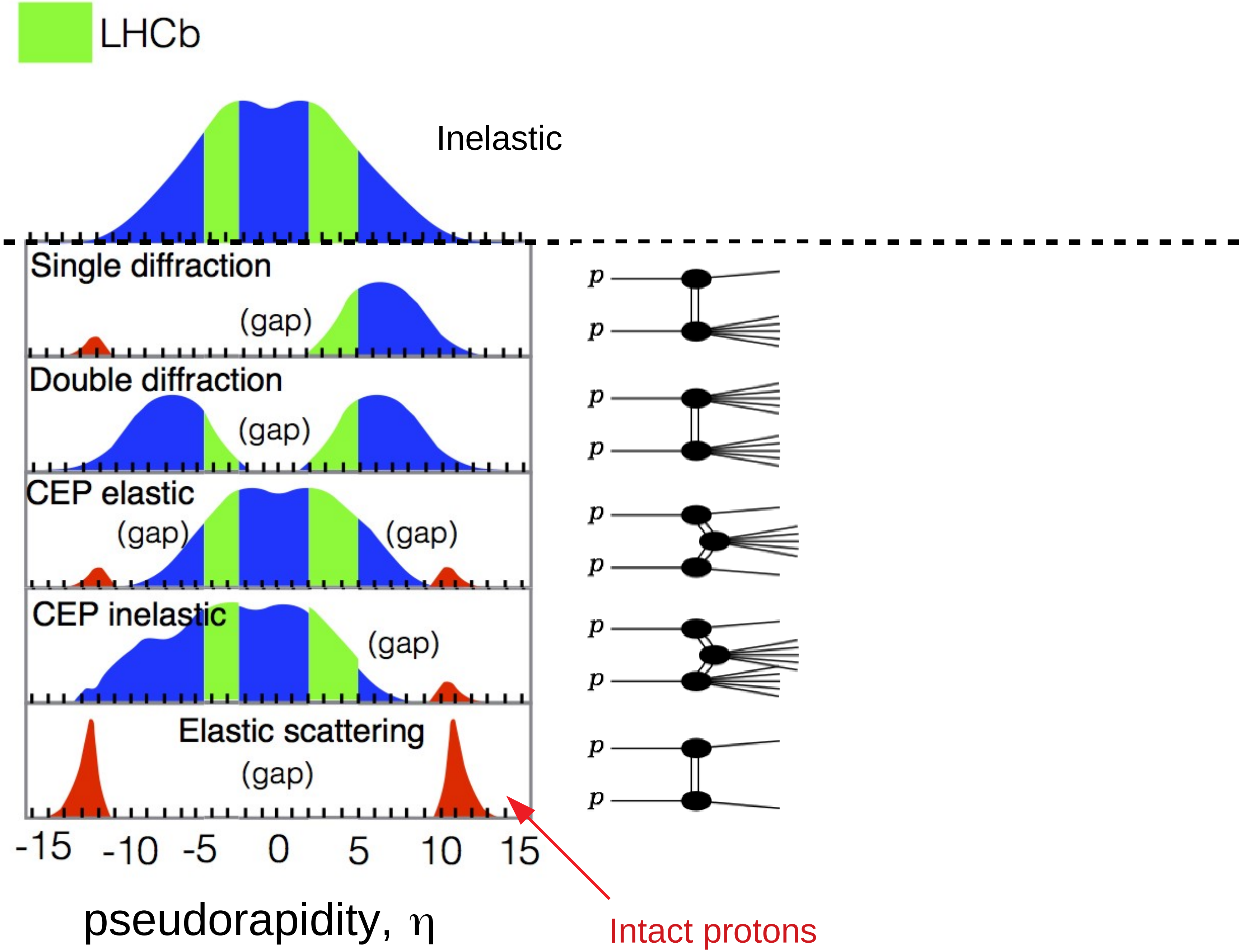
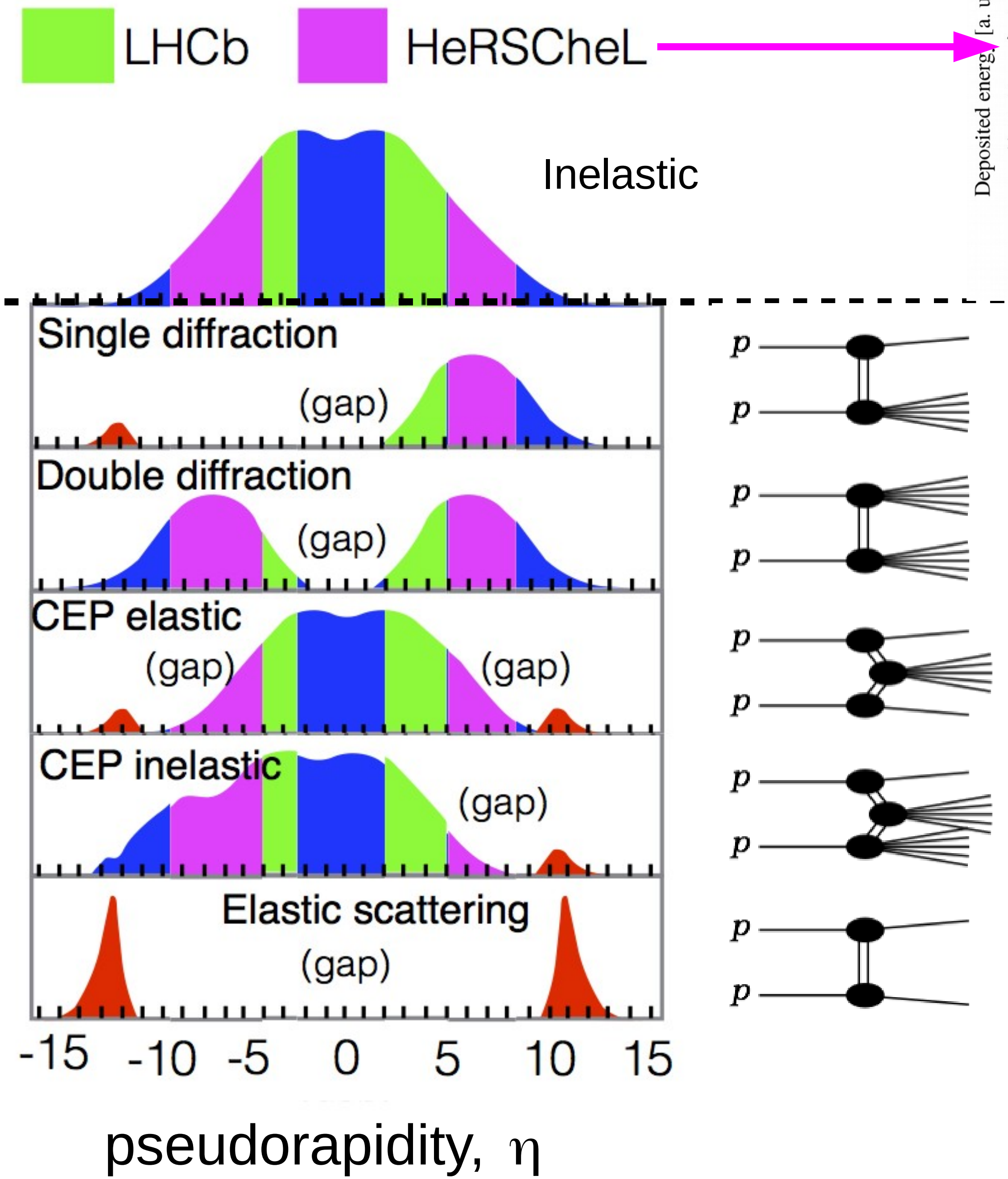
High **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL

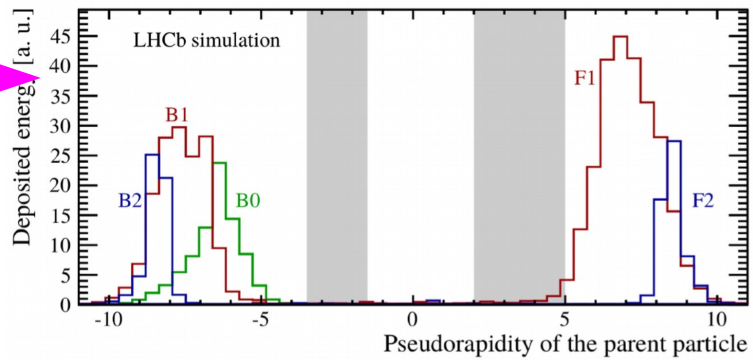
- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events wth these




LHCb
Inelastic
Single diffraction
(gap)
Double diffraction
(gap)
CEP elastic
(gap)
(gap)
CEP inelastic
(gap)
Elastic scattering
(gap)
-15 -10 -5 0 5 10 15
pseudorapidity, η
p
p
Intact protons

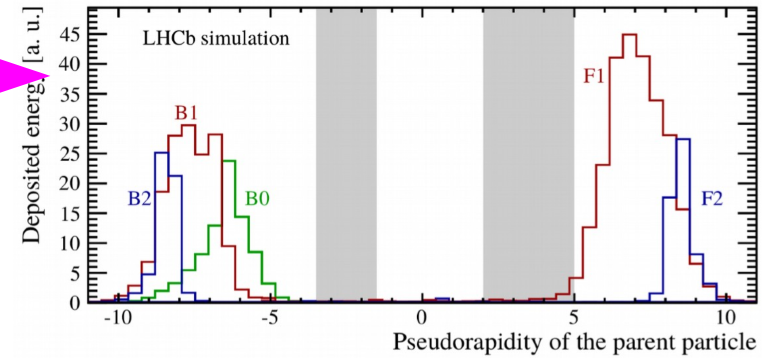


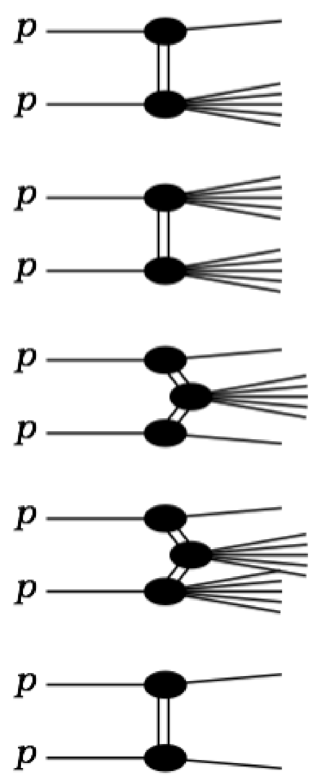
JINST 13 (2018) no.04, P04017



LHCb HeRSCheL

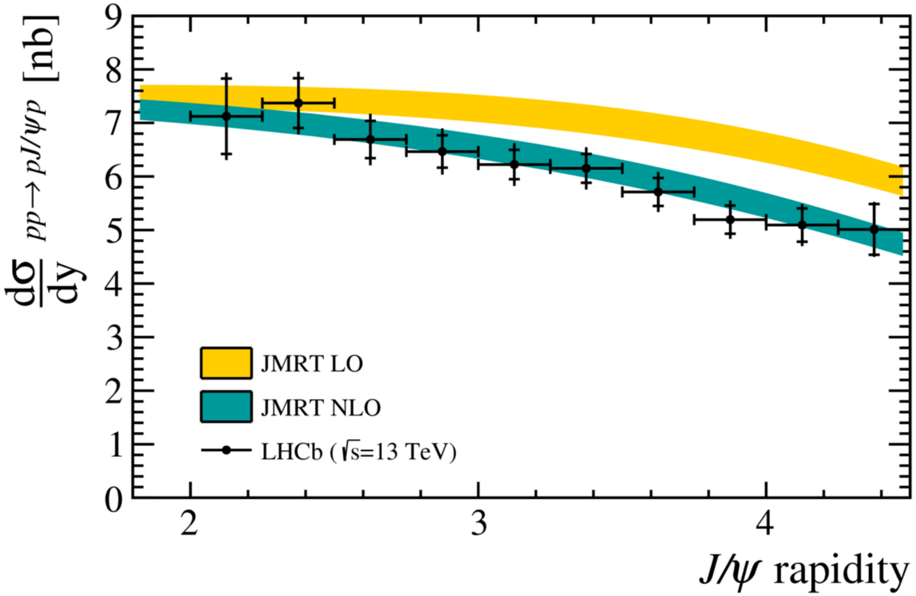
JINST 13 (2018) no.04, P04017

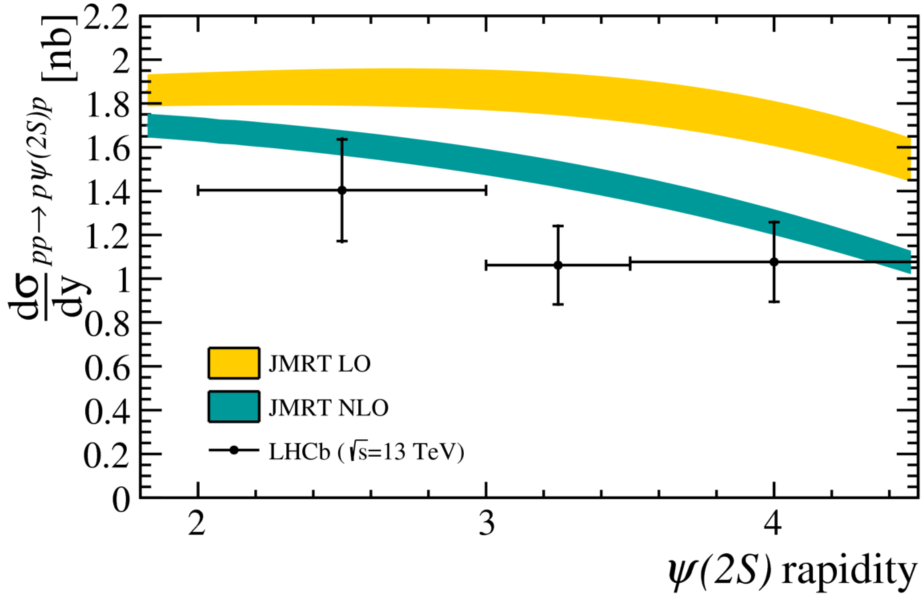




J/ψ and $\psi(2S)$ - 13 TeV

arXiv:1806.04079





$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{\rm rec}\epsilon_{\rm sel}\Delta y \epsilon_{\rm single}\mathcal{L}_{\rm tot}}$$

N → candidate events
P → signal purity
ϵ → efficiencies
Δy → rapidity bin width
L → luminosity

J/ψ and $\psi(2S)$ - 13 TeV

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{rec}\epsilon_{sel}\Delta y \epsilon_{single}\mathcal{L}_{tot}}$$

Selection

→ 2 reconstructed muons $(2<\eta<4.5)$

→ No additional tracks or photons

→ Herschel requirement (next slide)

→ Mass window requirements

→ $p_T^2 < 0.8\,GeV^2$

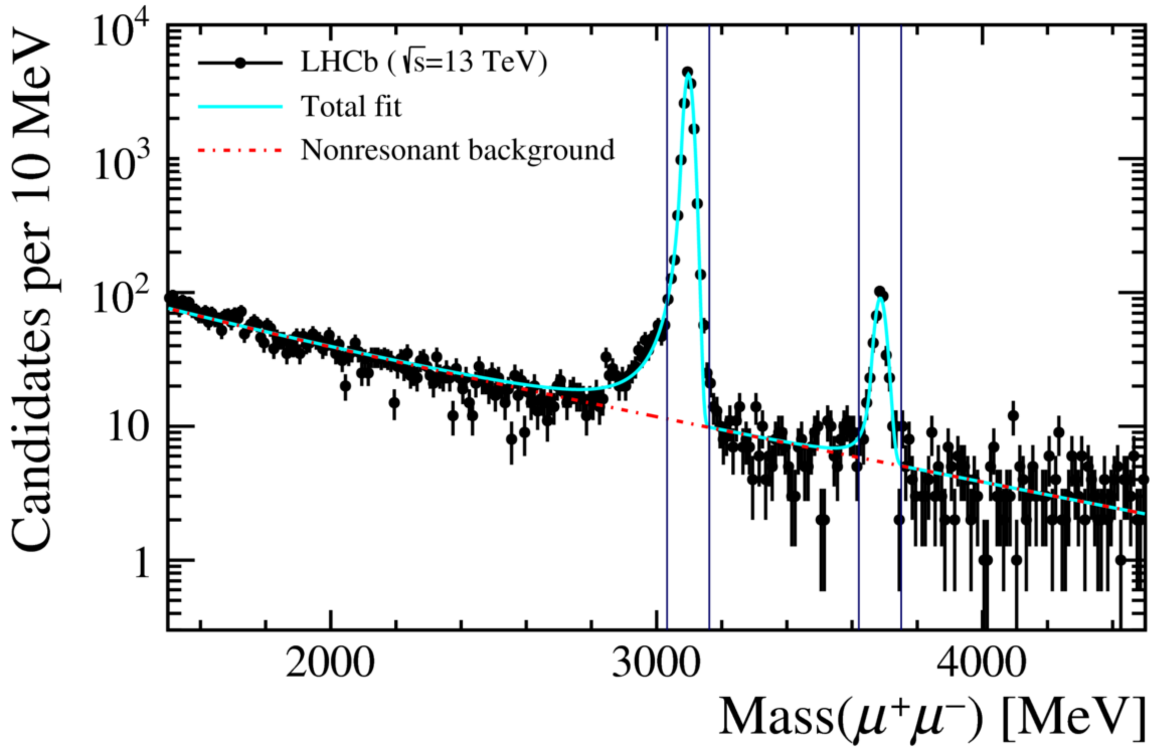
N → candidate events

P → signal purity

ϵ → efficiencies

Δy → rapidity bin width

L → luminosity



$L = 204\,pb^{-1}$ (2015)

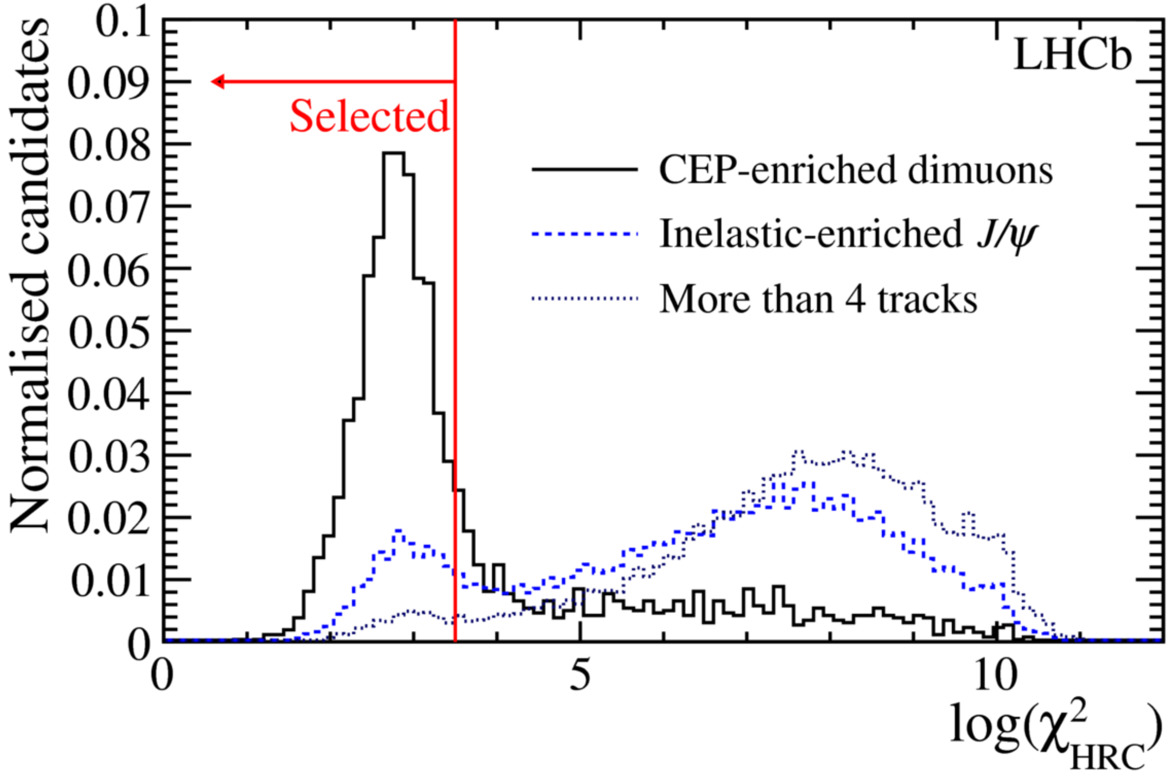
14753 J/ψ candidates

440 $\psi(2S)$ candidates

J/ψ and $\psi(2S)$ - 13 TeV

The HeRSCheL response is described using a variable χ^2_{HRC} that quantifies the activity above noise, taking account of correlations between thecounters.

Clear discrimination observed when comparing:
+CEP-enriched dimuons: $p_T^2 < 0.01\,GeV^2$
+More than four tracks
+Inelastic-enriched J/ψ: $p_T^2 > 1\,GeV^2$



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Background fractions for J/ψ ($\psi(2S)$)

→Non-resonant estimated from DiMuon mass: 0.009 (0.161)

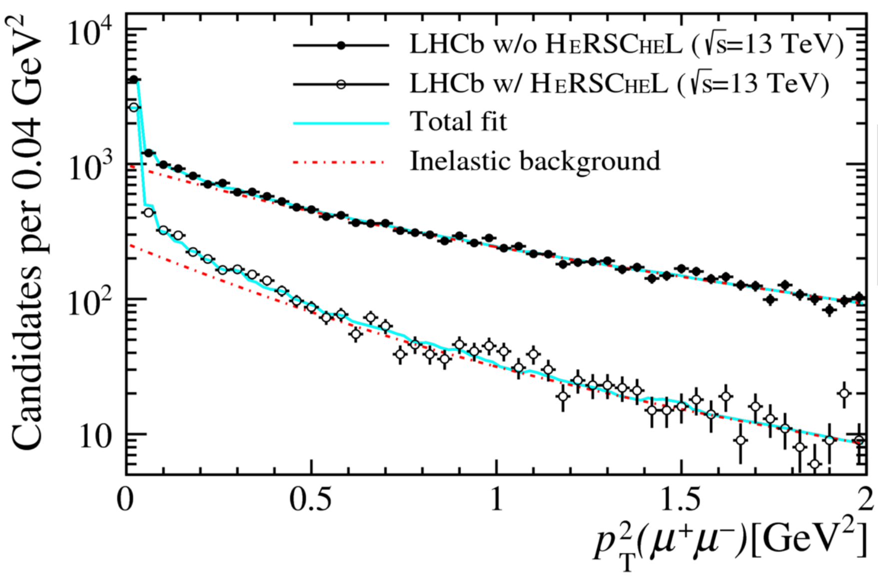
→Feed-down estimated using data: 0.06 (neglected)

→Proton dissociation with a new techinique (see next slide): 0.175 (0.11)

Efficiencies

≫ reconstruction and selection → data driven methods

≫ fraction of single interaction beam crossings → 0.3662 ± 0.0003



Fits to the p_T^2 distributions give the non-resonant CEP events with and without the HeRSCheL veto

The ratio of these gives the efficiency of the veto 0.723 ± 0.008

New Technique:

$N_{HRC} = \varepsilon N_{sig} + \beta(p_T)N_{bkg}$

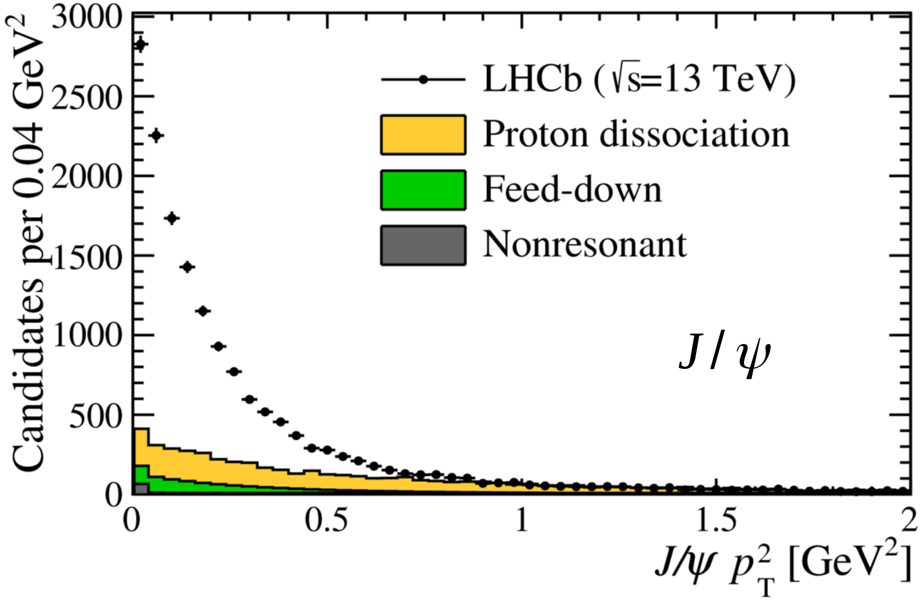
$N_{anti\text{-}HRC} = [1-\varepsilon]N_{sig} + [1-\beta(p_T)]\, N_{bkg}$

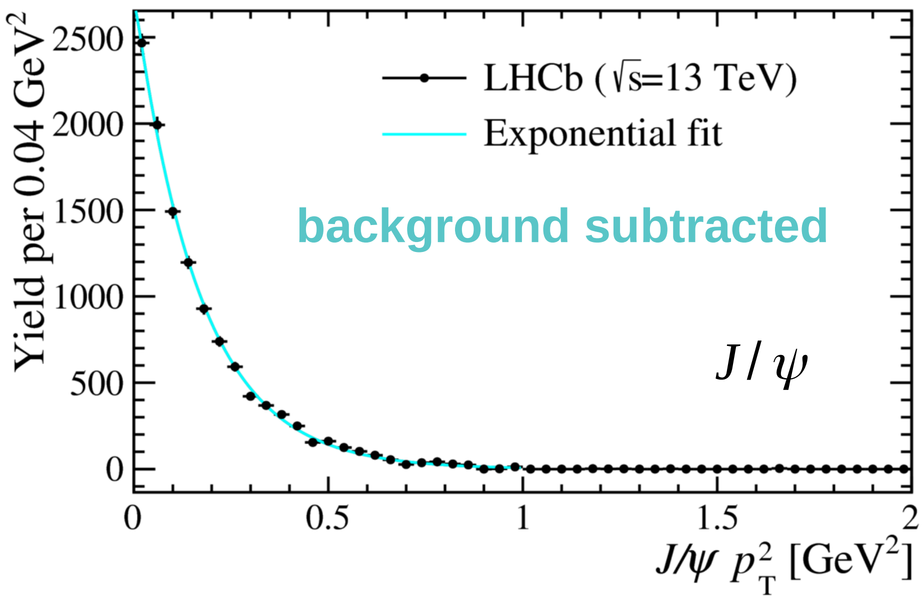
ε known from QED sample

Pure bkg sample obtained

Subtract bkg from total => Signal derived

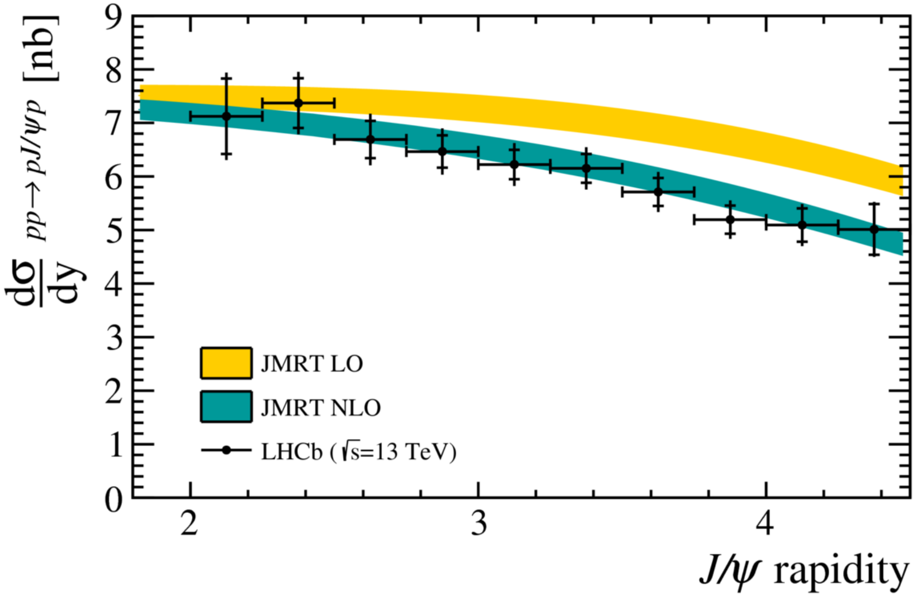
$$\beta = S_{\bar{\mathrm{H}}} - ((1-\epsilon_{\mathrm{H}})/\epsilon_{\mathrm{H}})S_{\mathrm{H}}$$

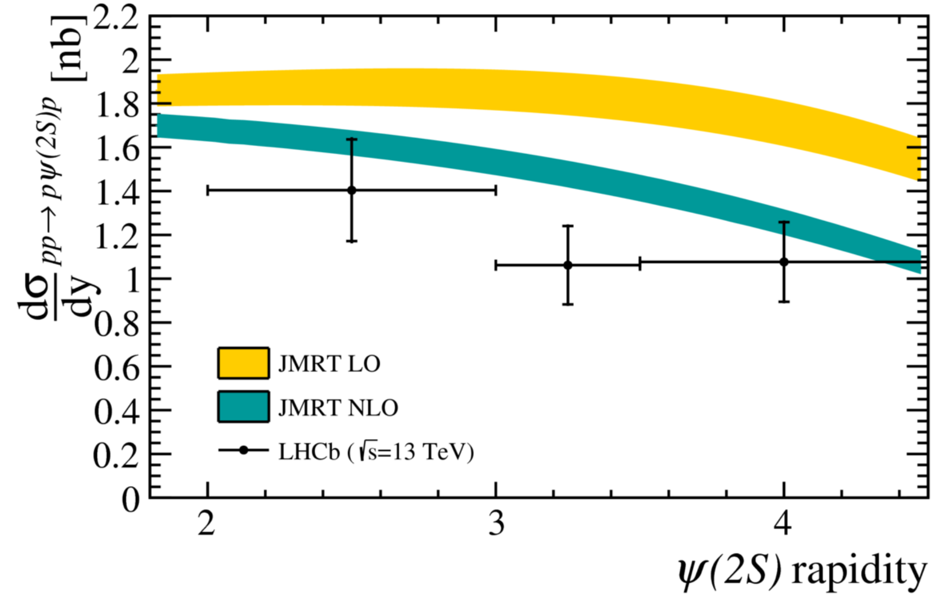




J/ψ and $\psi(2S)$ - 13 TeV

arXiv:1806.04079





NLO agrees better than LO

S. P. Jones, A. D. Martin, M. G. Ryskin, and T. Teubner, *Exclusive J/ψ production at the LHC in the k_T factorization approach*, J. Phys. **G44** (2017) 03LT01, arXiv:1611.03711.

S. P. Jones, A. D. Martin, M. G. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and Υ production at HERA and the LHC*, JHEP **11** (2013) 085, arXiv:1307.7099.

J/ψ and $\psi(2S)$ - 13 TeV

$$\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta<4.5) = 399\pm16\pm10\pm16\text{ pb},$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta<4.5) = 10.2\pm1.0\pm0.3\pm0.4\text{ pb}.$$

Source	J/ψ analysis (%)	$\psi(2S)$ 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_{T}^2 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

Systematic uncertainties factor two smaller than previous analysis at 7 TeV

J/ψ and $\psi(2S)$ - 13 TeV

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

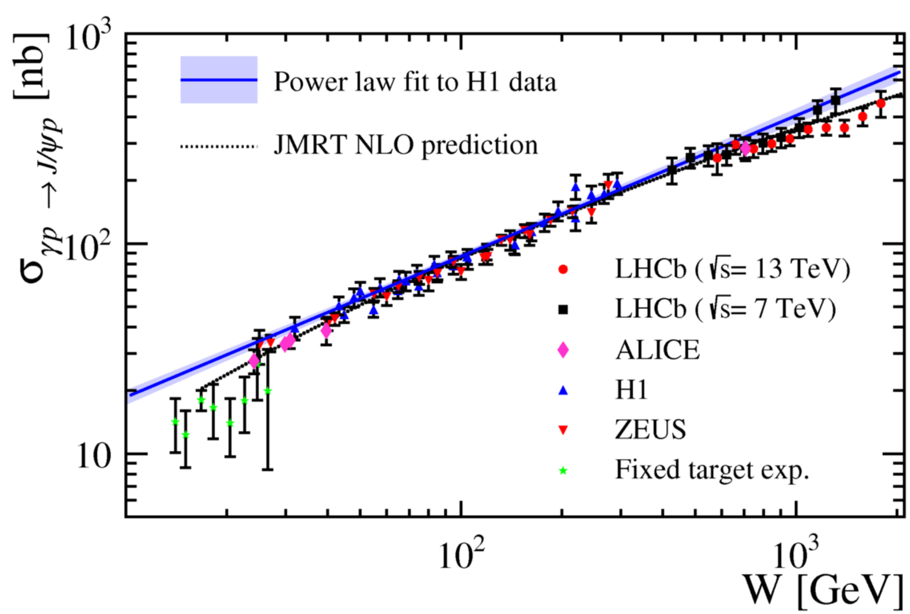
$dn/dk_\pm$ are photon fluxes for photons of energy $k_\pm \approx (M_{J/\psi}/2)\exp(\pm|y|)$

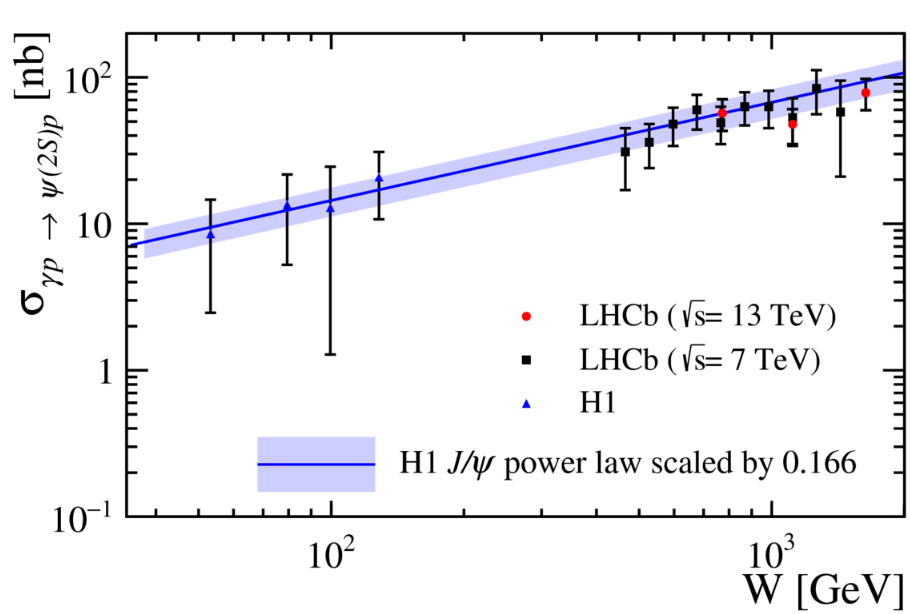
$(W_\pm)^2 = 2k_\pm\sqrt{s}$, and $r_\pm$ are absorptive corrections

Assuming HERA result for W_+

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

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





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SUMMARY

→ Extensive central exclusive production program at LHCb

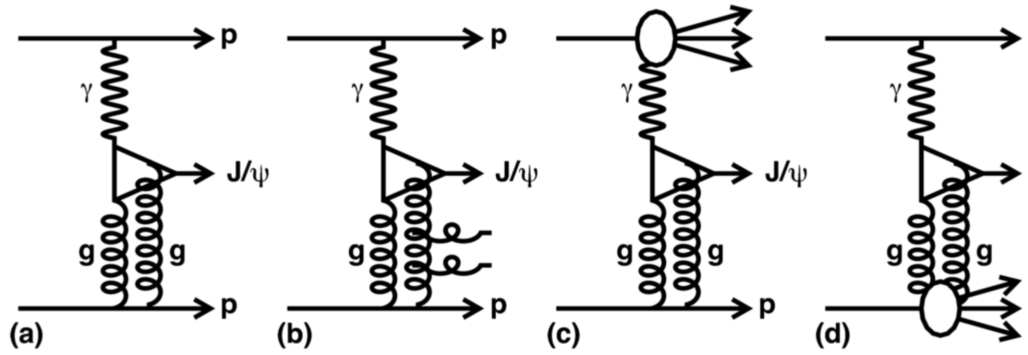
→ Important tests of QCD in the forward region

→ Active program to study CEP in pp, pPb and PbPb

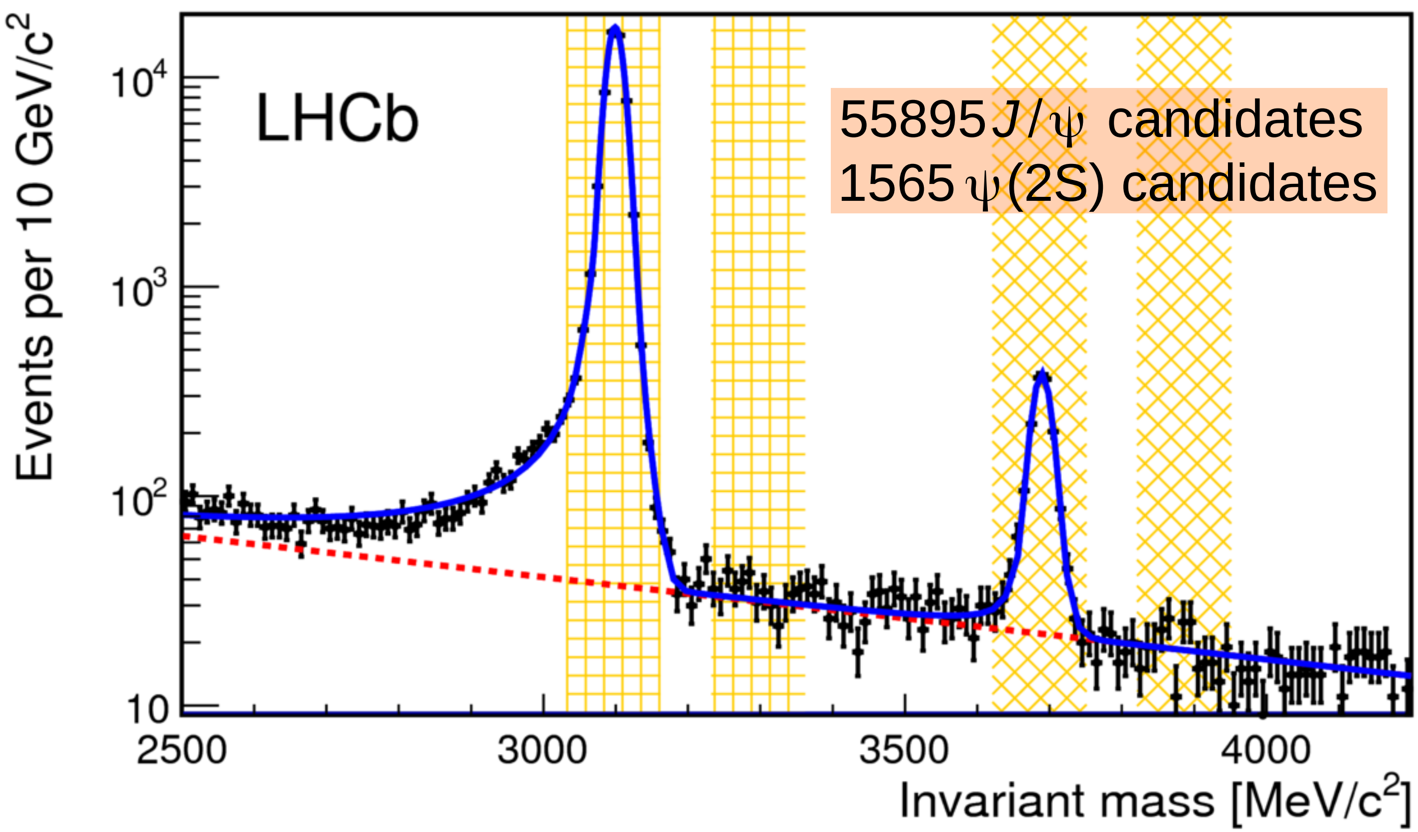
THANK YOU!!!!!

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})

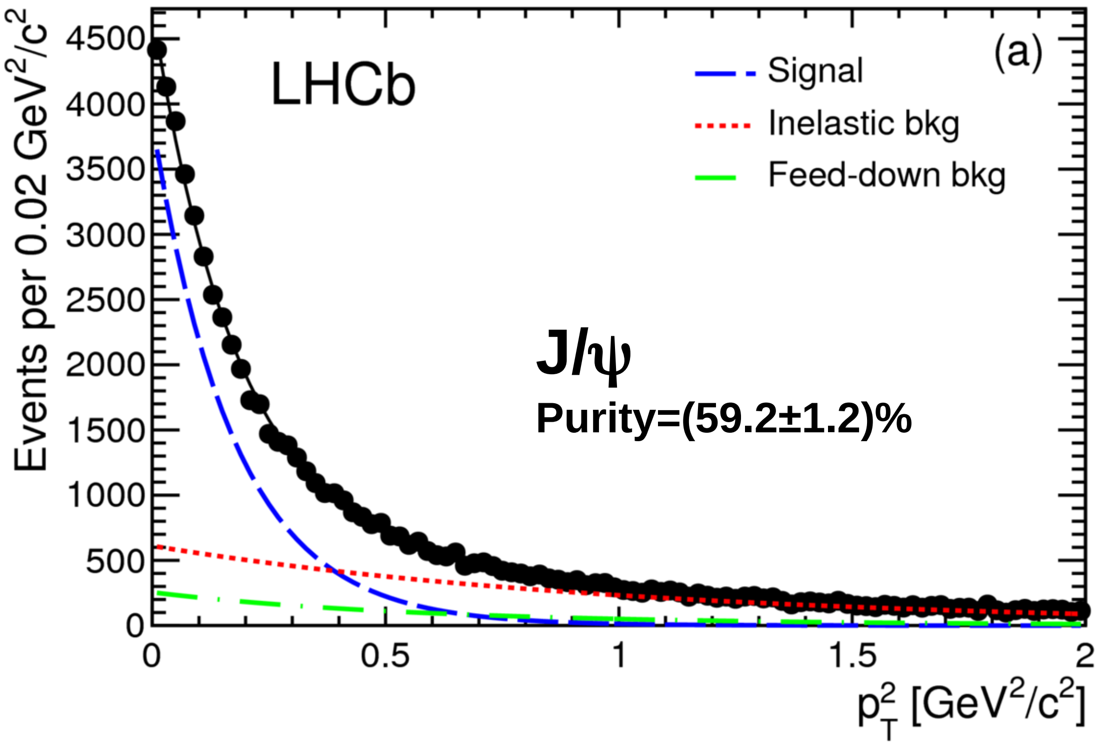
→ Feed-down background: data driven from reconstructed decays

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

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

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

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



background fractions

feed-down 10.1 %

inelastic 49.1 %

$$b_{\rm el} = 5.70 \pm 0.11\ {\rm GeV}^{-2}$$

$$b_{\rm in} = 0.97 \pm 0.04\ {\rm GeV}^{-2}$$

 J.Phys.G40 (2014) 055002

Template fit to data

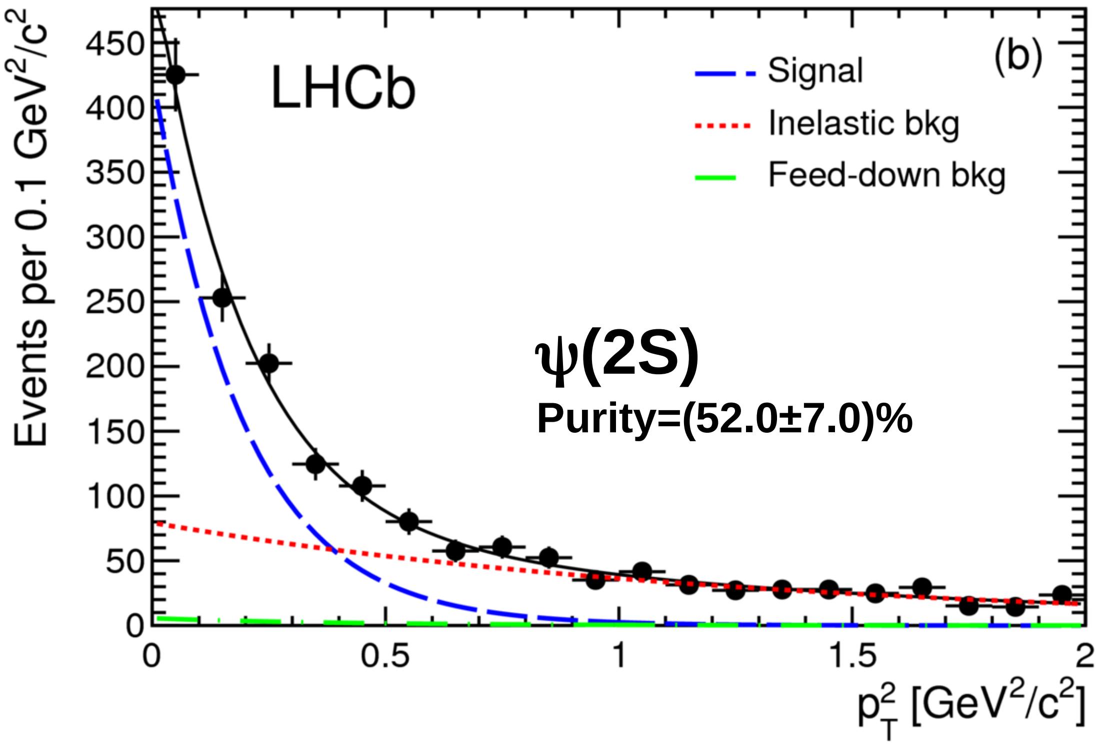
→ Inelastic background: exponential (HERA b_{in}~ 1 GeV^{-2})

→ Feed-down background: data driven from reconstructed decays

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

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

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



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

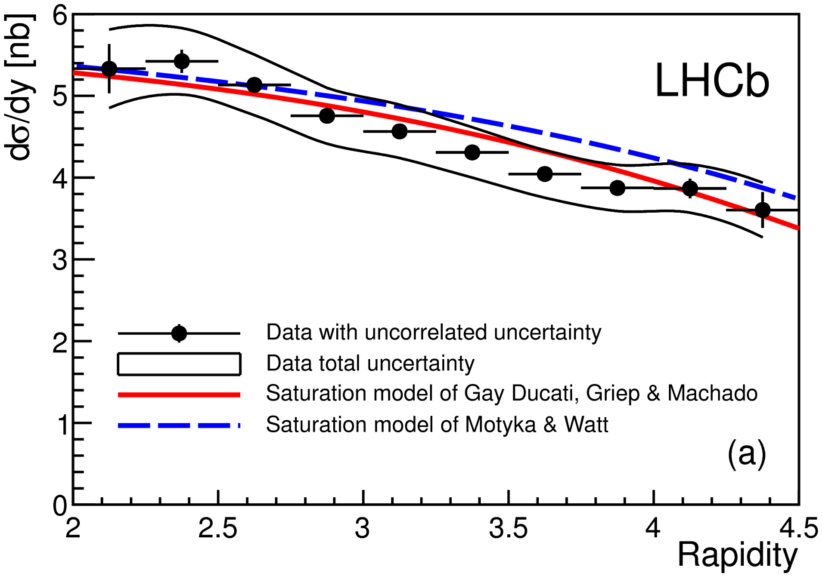
→ L is the integrate luminosity

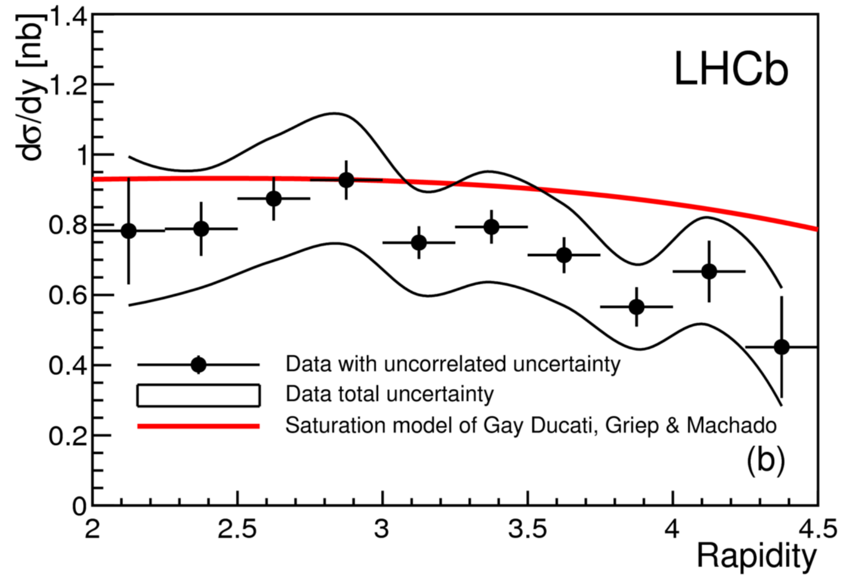
→ ϵ_i is the efficiency for selecting single interaction events

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

J/ψ and $\psi(2S)$ - 7 TeV

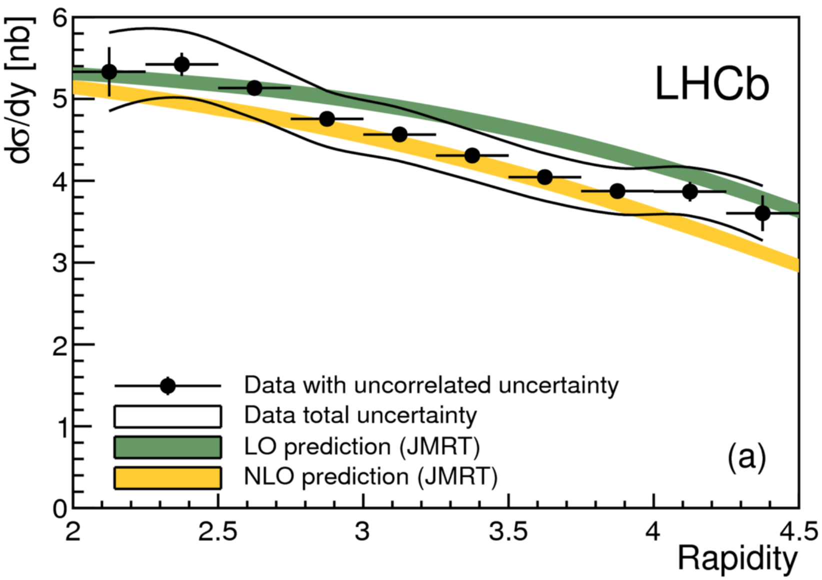
J.Phys.G40 (2014) 055002

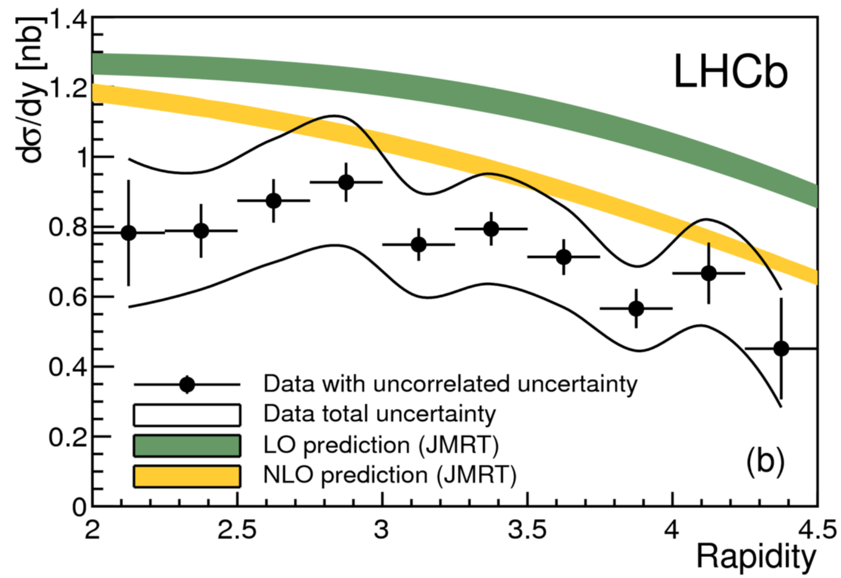




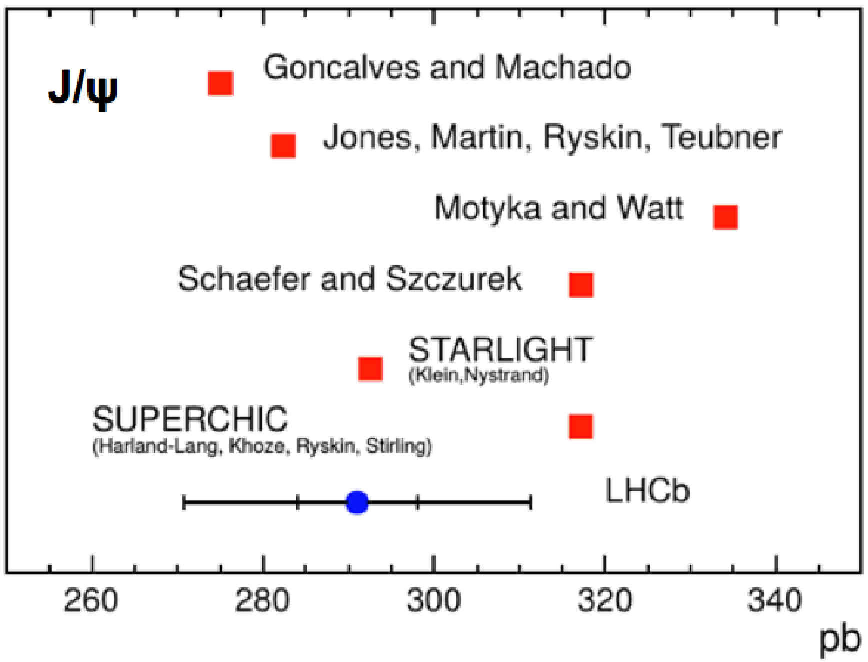
J/ψ

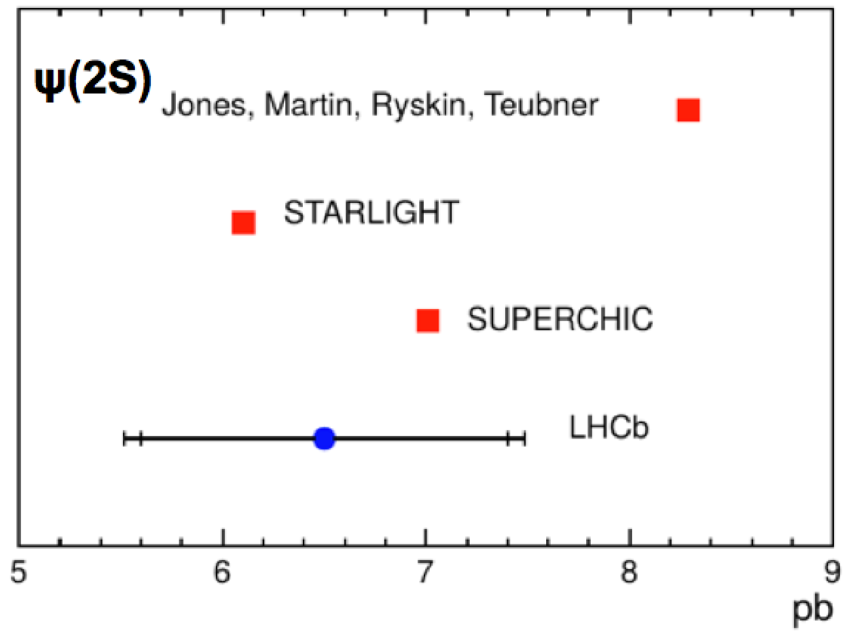
$\psi(2S)$





J.Phys.G40 (2014) 055002





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&SPhys. Rev. D76 (2007) 094014
Starlight: Phys. Rev. Lett. 92 (2004) 142003
Superchic: Eur. Phys. J. C65 (2010) 433

J.Phys.G40 (2014) 055002

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

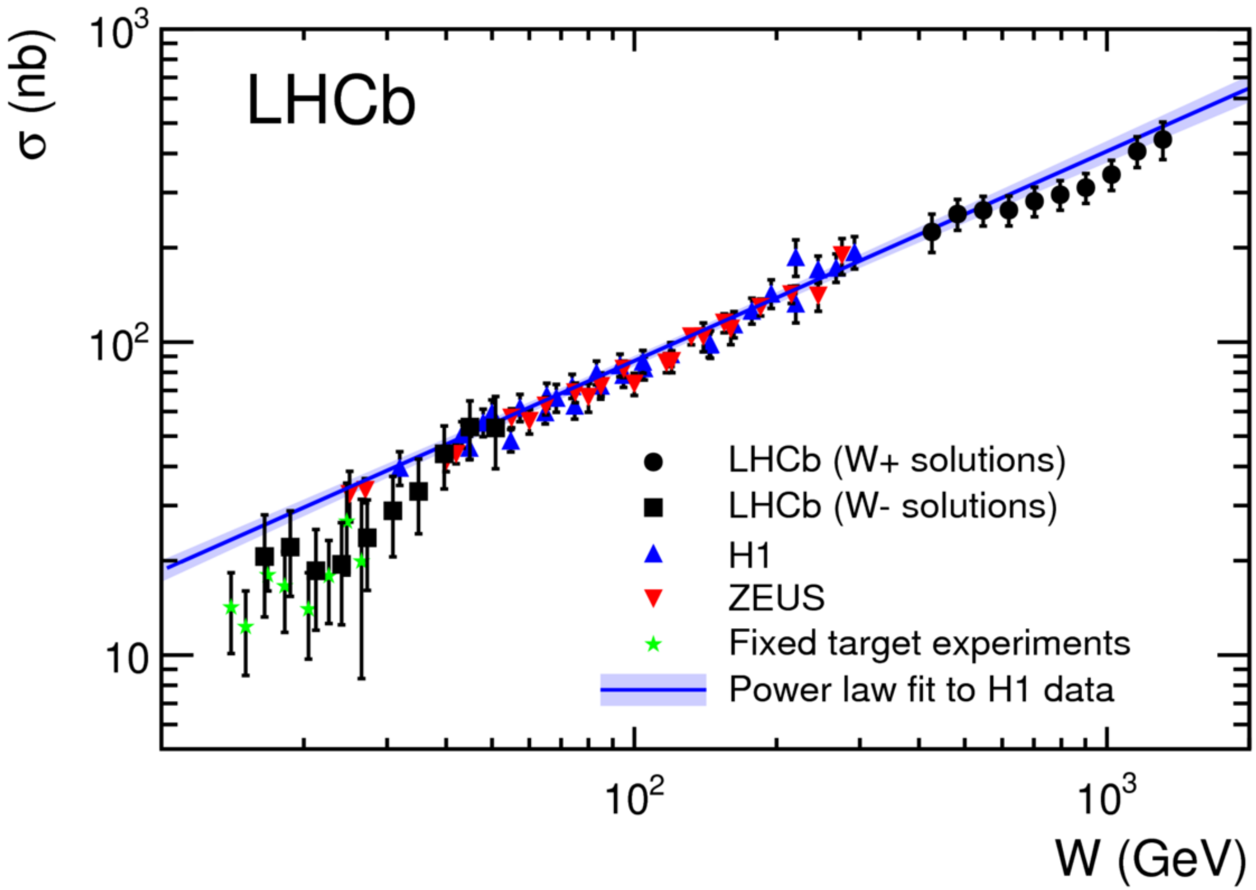
$dn/dk_\pm$ are photon fluxes for photons of energy $k_\pm \approx (M_{J/\psi}/2)\exp(\pm|y|)$

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

Assuming HERA result for W_+

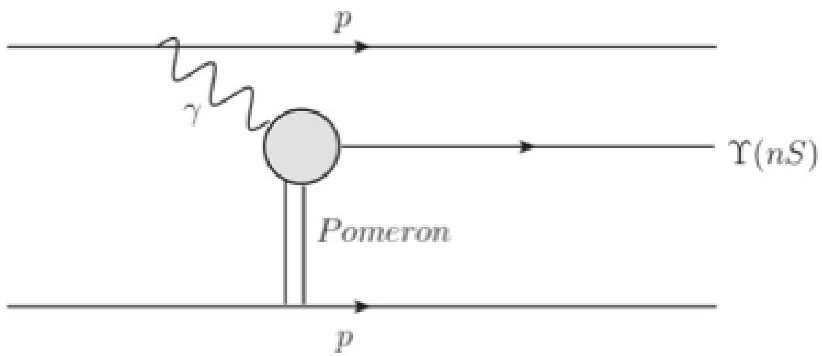
$\sigma(W) = 81(W/90\,GeV)^{0.67}\,nb$

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

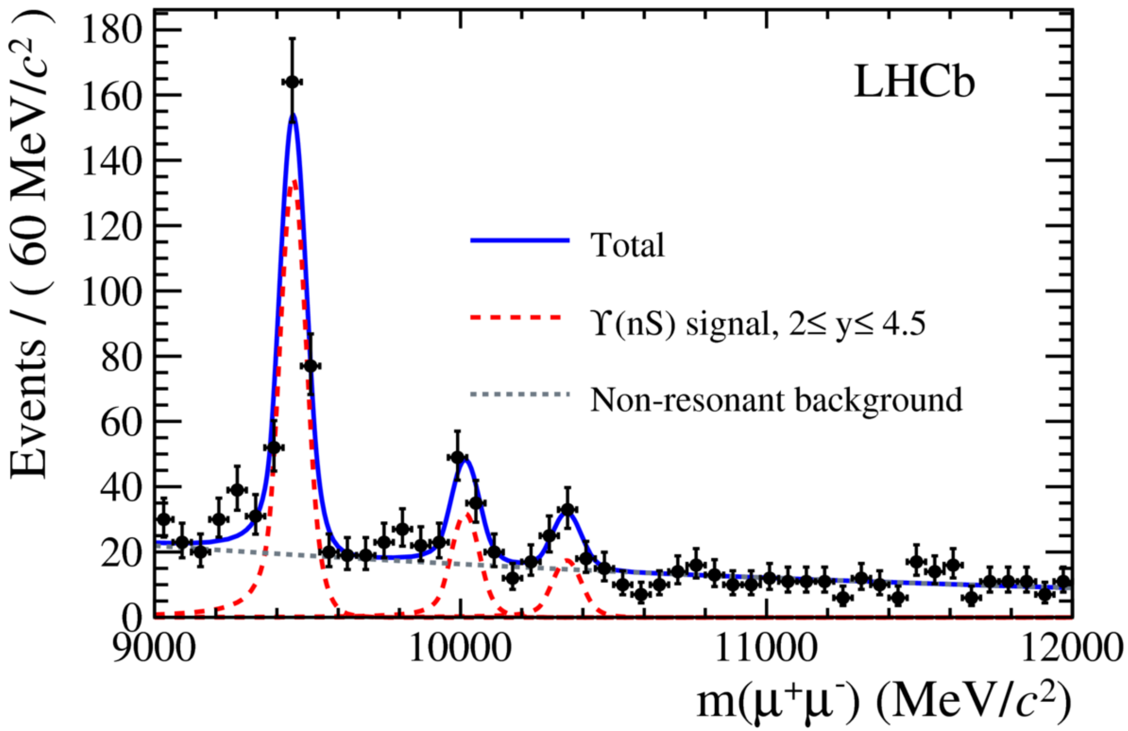


JHEP 09 (2015) 084

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



+ Analysis strategy similar to J/ψ



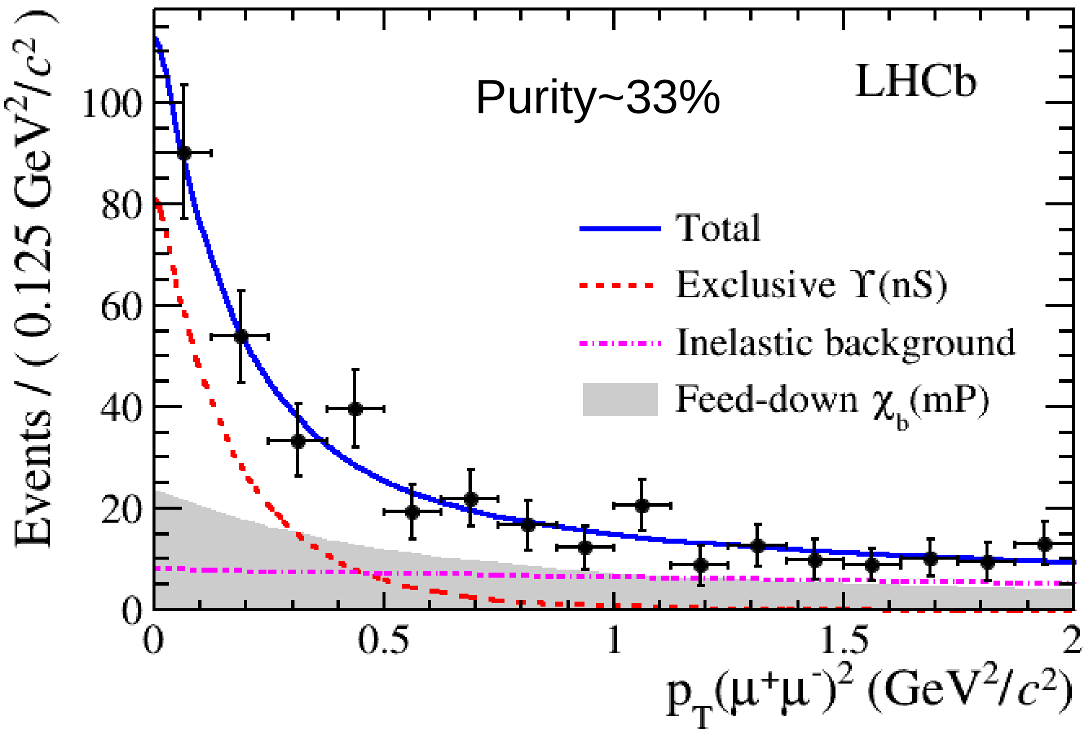
Background fractions

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

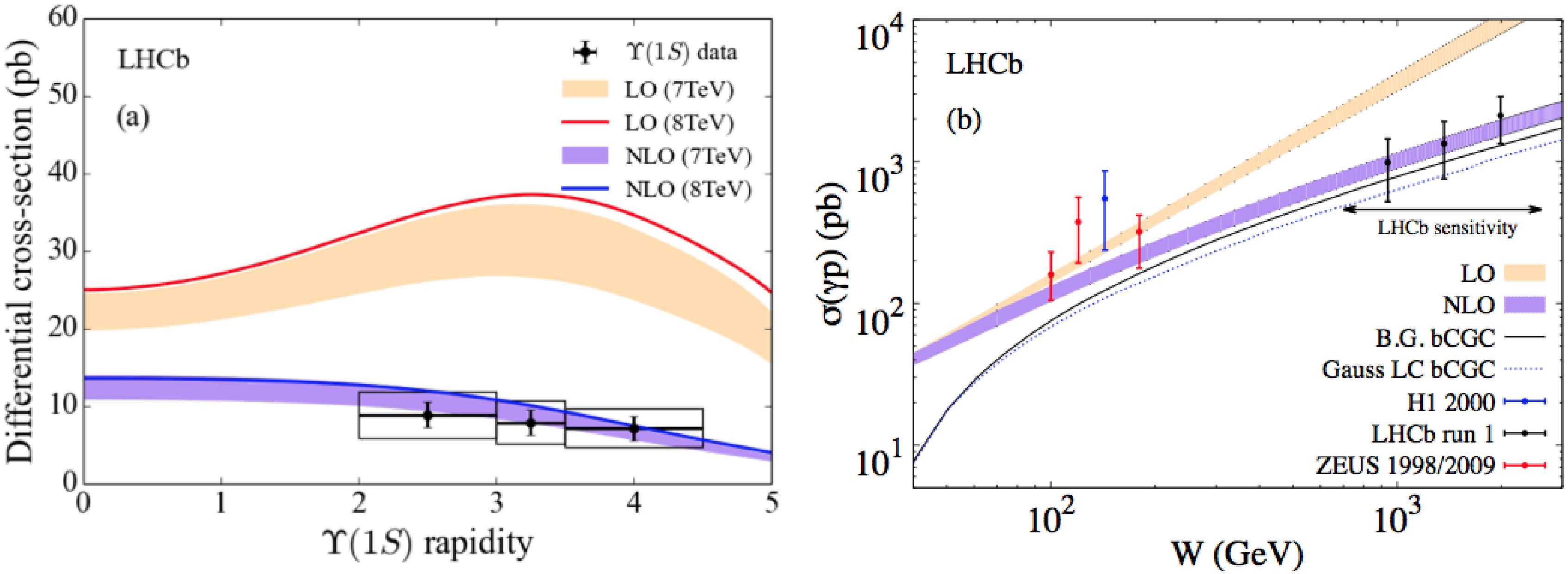
Signal template is obtained from SuperChiC



background fractions
feed-down 39%
inelastic 28%

Exclusive Υ production

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

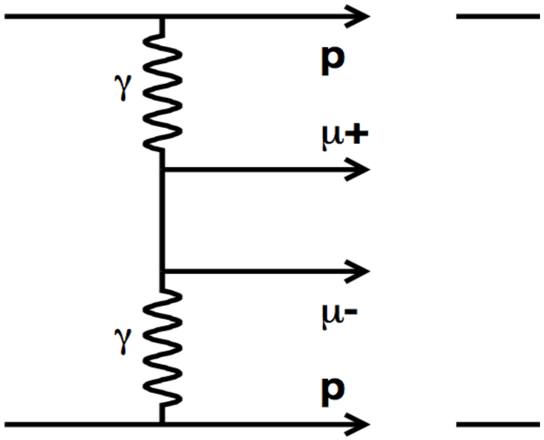


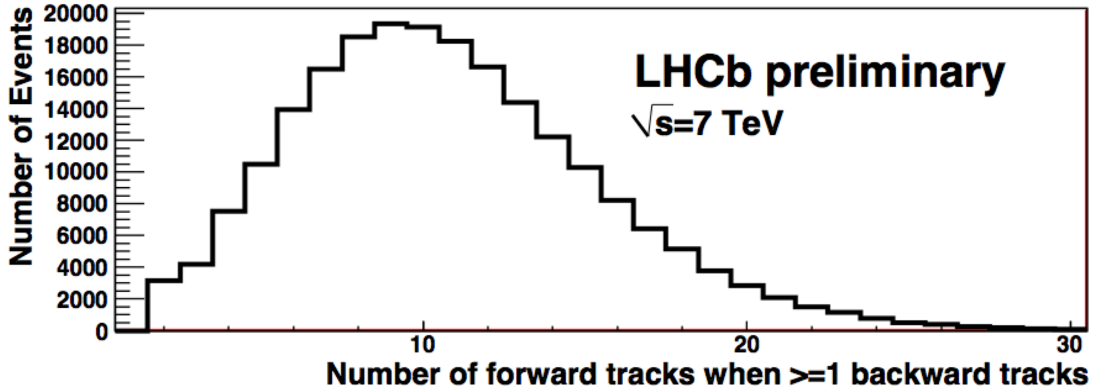
Rapidity dependence in agreement with NLO calculation

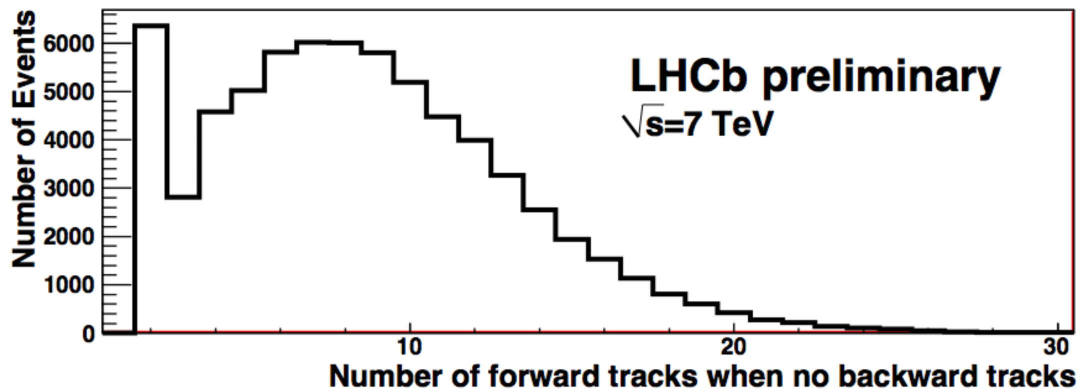
Photon-proton cross-section extrapolated from measurement can be compared with different phenomenological models

Non-resonant DiMuon

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







Non-resonant DiMuon

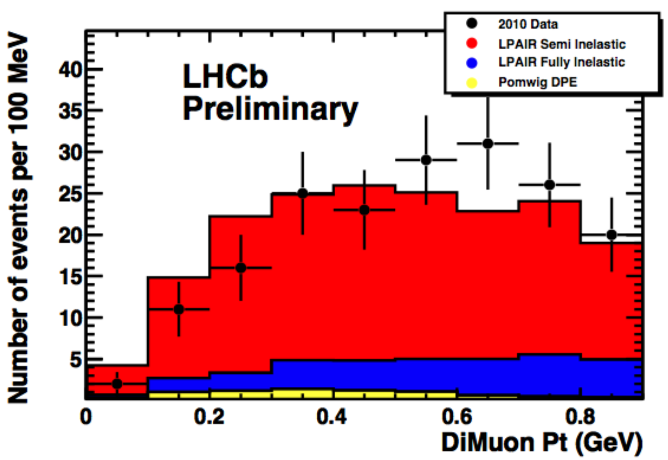
LHCb-CONF-2011-02

DiMuon selection

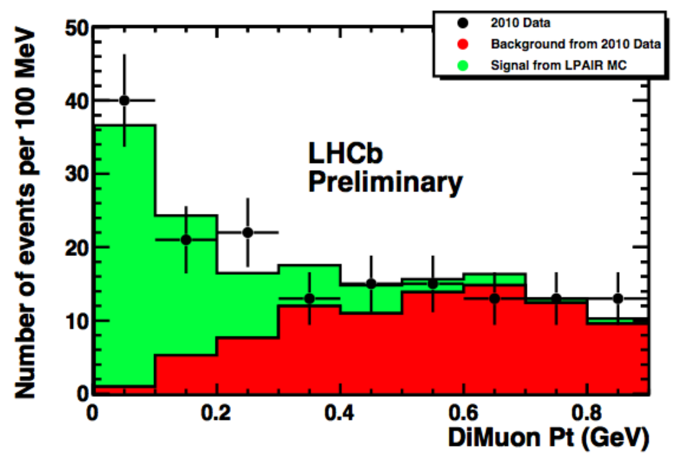
- Candidates of J/ψ and ψ(2S) are vetoed
- Muon p_T > 80 MeV
- DiMuon Mass > 2.5 GeV
- DiMuon p_T < 0.9 GeV

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

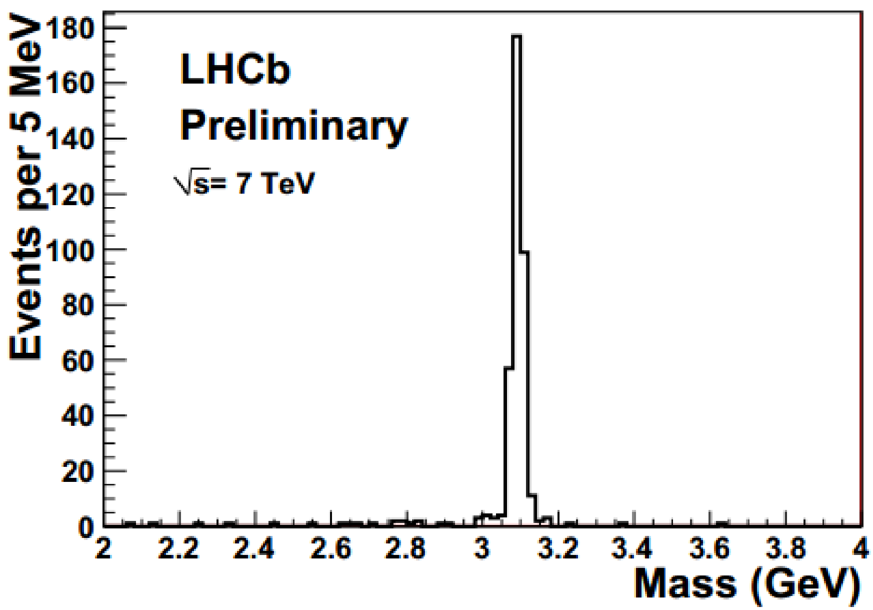
$$\sigma_{pp\to p\mu^+\mu^- p}(2 < \eta_{\mu+}, \eta_{\mu-} < 4.5; m_{\mu+\mu-} > 2.5\ \mathrm{GeV/c^2}) = 67 \pm 10 \pm 7 \pm 15\ \mathrm{pb}$$

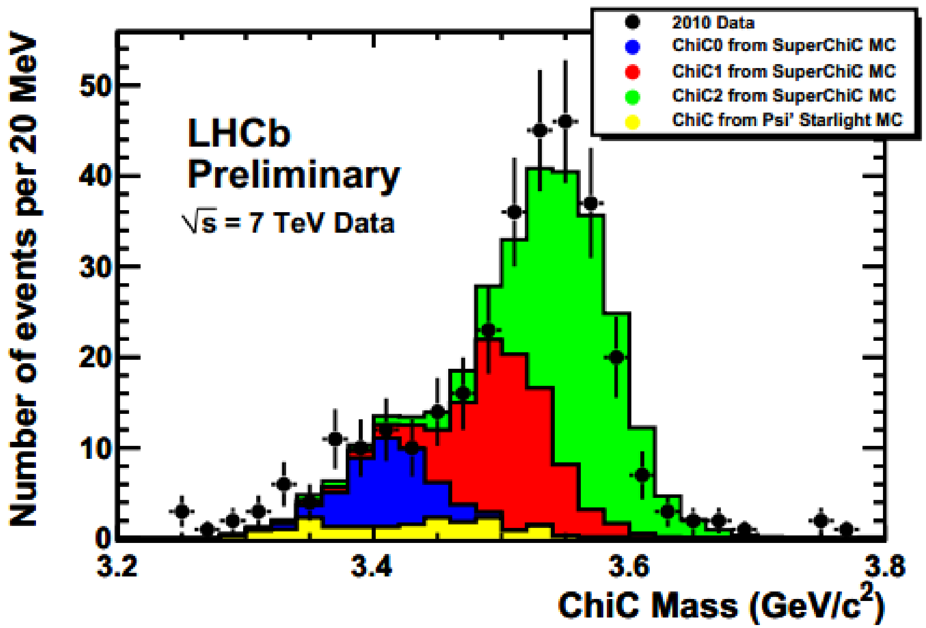
42 pb (LPAIR prediction)

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.

New Technique:

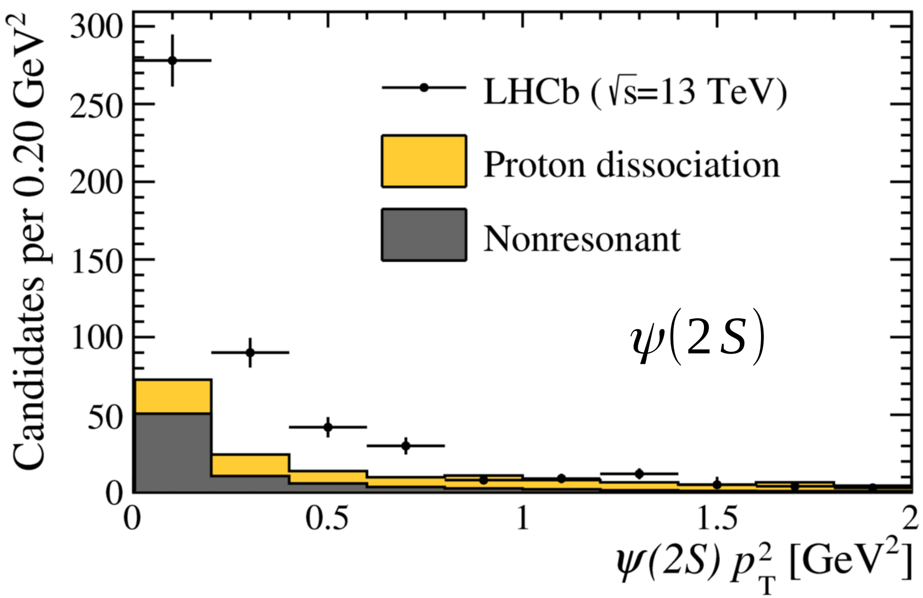
$N_{HRC} = \varepsilon N_{sig} + \beta(p_T) N_{bkg}$

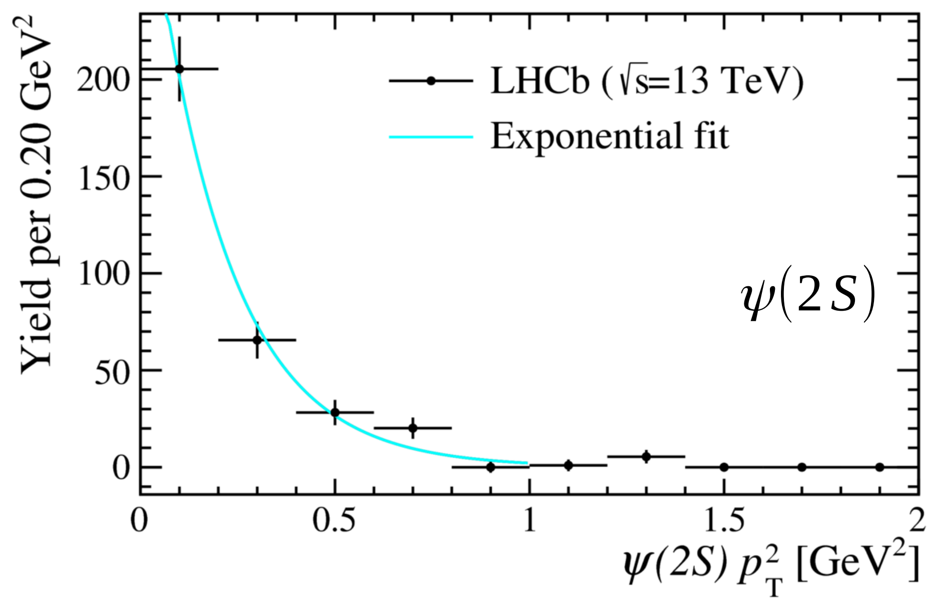
$N_{anti\text{-}HRC} = [1-\varepsilon] N_{sig} + [1-\beta(p_T)]\, N_{bkg}$

ε known from QED sample

Pure bkg sample obtained

Subtract bkg from total => Signal derived





J/ψ and $\psi(2S)$ - 13 TeV

y bin	2.0−2.25	2.25−2.5	2.5−2.75	2.75−3.0	3.0−3.25
N	259	1022	1644	2204	2482
Stat. unc. (%)	6.2	3.1	2.5	2.1	2.0
ϵ_{rec}	0.410	0.525	0.555	0.565	0.563
Stat. unc. (%)	5.9	4.2	3.3	2.8	2.6
Syst. unc. (%)	3.1	0.8	1.7	1.0	0.5
ϵ_{sel}	0.636	0.643	0.650	0.655	0.663
Stat. unc. (%)	1.2	1.2	1.2	1.2	1.2
Syst. unc. (%)	2.5	2.0	2.0	1.9	1.9
Purity	0.760	0.759	0.751	0.758	0.764
Stat. unc. (%)	2.7	2.2	2.2	2.1	2.1
Syst. unc. (%)	1.0	1.0	1.0	1.0	1.0
$\mathrm{d}\sigma/\mathrm{d}y$(pb)	40	123	183	242	272
Stat. unc. (%)	9.2	6.0	5.0	4.5	4.3
Syst. unc. (%)	4.3	2.7	3.1	2.7	2.6
Lumi. unc. (%)	3.9	3.9	3.9	3.9	3.9

y bin	3.25−3.50	3.50−3.75	3.75−4.0	4.0−4.25	4.25−4.5
N	2522	2112	1433	829	246
Stat. unc. (%)	2.0	2.2	2.6	3.5	6.4
ϵ_{rec}	0.587	0.599	0.588	0.551	0.518
Stat. unc. (%)	2.5	2.6	2.8	3.3	4.1
Syst. unc. (%)	0.6	0.6	0.5	0.8	0.9
ϵ_{sel}	0.665	0.670	0.670	0.676	0.667
Stat. unc. (%)	1.2	1.2	1.2	1.2	1.2
Syst. unc. (%)	1.9	1.9	1.9	1.9	2.0
Purity	0.763	0.749	0.748	0.732	0.738
Stat. unc. (%)	2.1	2.1	2.2	2.4	3.1
Syst. unc. (%)	1.0	1.0	1.0	1.0	1.0
$\mathrm{d}\sigma/\mathrm{d}y$(pb)	264	211	146	87	28
Stat. unc. (%)	4.3	4.4	4.8	5.7	8.5
Syst. unc. (%)	2.6	2.6	2.6	2.7	2.8
Lumi. unc. (%)	3.9	3.9	3.9	3.9	3.9

J/ψ and $\psi(2S)$ - 13 TeV

y bin	2.0–3.0	3.0–3.5	3.5–4.5
N	170	134	136
Stat. unc. (%)	7.7	8.6	8.6
$\epsilon_{\rm rec}$	0.633	0.644	0.622
Stat. unc. (%)	3.4	2.6	2.9
Syst. unc. (%)	1.3	0.6	0.6
$\epsilon_{\rm sel}$	0.650	0.664	0.671
Stat. unc. (%)	1.2	1.2	1.2
Syst. unc. (%)	1.9	1.9	1.9
Purity		0.726	
Stat. unc. (%)		8.4	
Syst. unc. (%)		1.7	
$d\sigma/dy$(pb)	4.0	6.1	3.2
Stat. unc. (%)	12.0	12.4	12.4
Syst. unc. (%)	2.9	2.7	2.7
Lumi. unc. (%)	3.9	3.9	3.9

J/ψ and ψ(2S) - 13 TeV

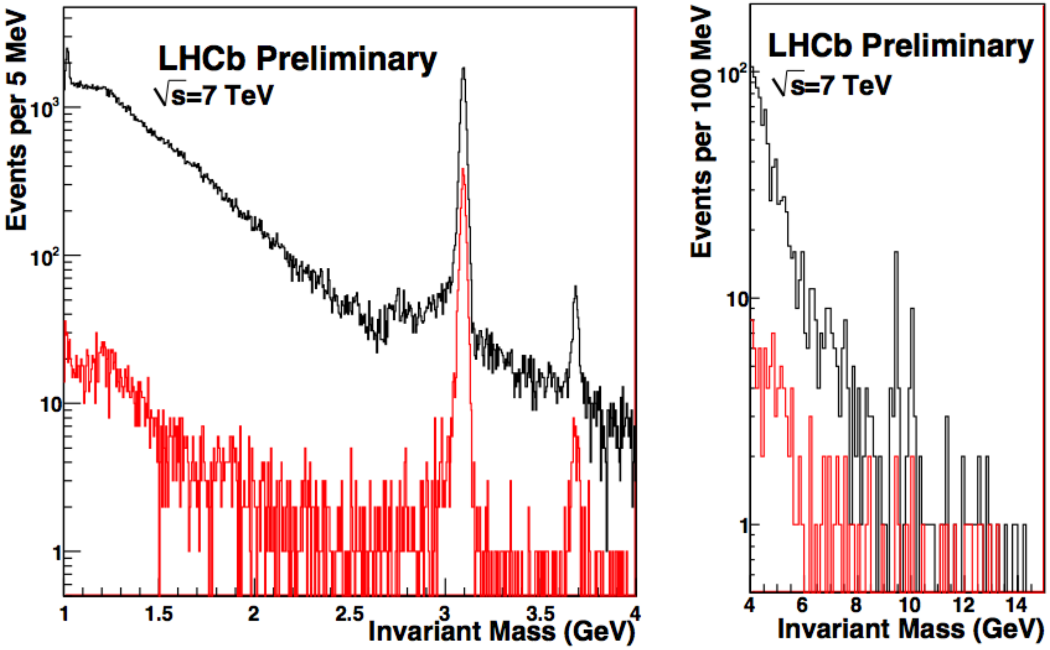
J/ψ y bin	2.00–2.25	2.25–2.50	2.50–2.75	2.75–3.00	3.00–3.25
$r(W_+)$	0.766	0.752	0.736	0.718	0.698
$r(W_-)$	0.882	0.885	0.888	0.891	0.894

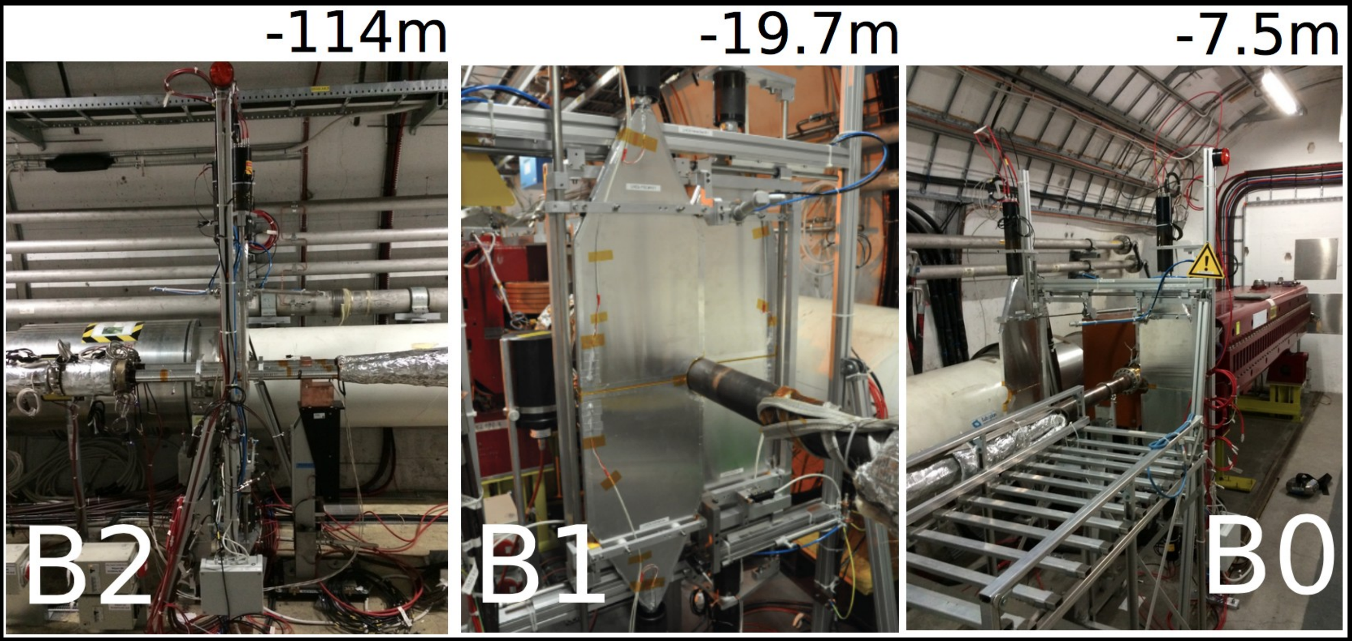
J/ψ y bin	3.25–3.50	3.50–3.75	3.75–4.00	4.00–4.25	4.25–4.50
$r(W_+)$	0.676	0.650	0.620	0.587	0.550
$r(W_-)$	0.897	0.899	0.902	0.904	0.906

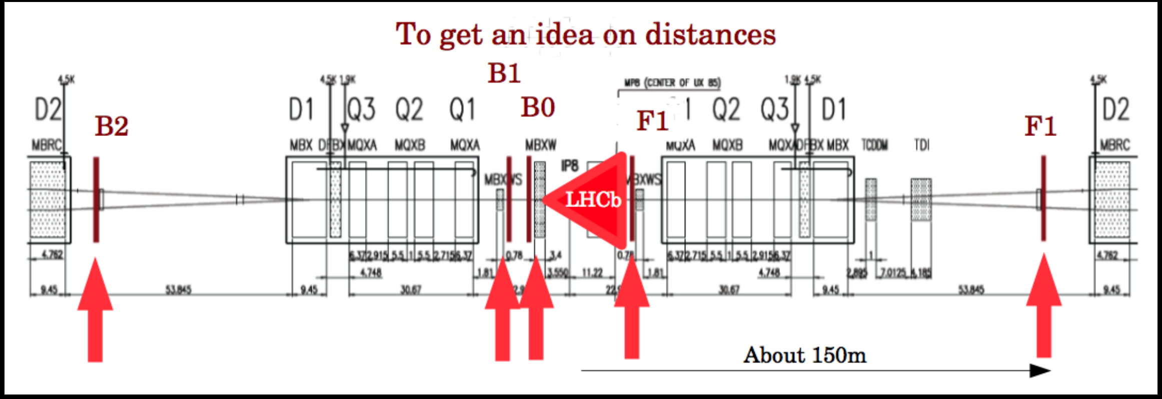
$\psi(2S)$ y bin	2.00–2.25	2.25–2.50	2.50–2.75	2.75–3.00	3.00–3.25
$r(W_+)$	0.757	0.741	0.724	0.705	0.683
$r(W_-)$	0.879	0.882	0.886	0.889	0.892

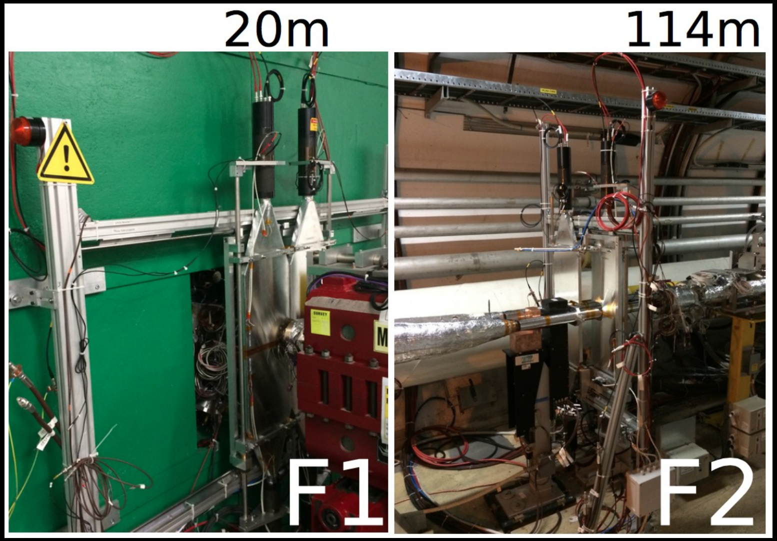
$\psi(2S)$ y bin	3.25–3.50	3.50–3.75	3.75–4.00	4.00–4.25	4.25–4.50
$r(W_+)$	0.658	0.630	0.598	0.562	0.522
$r(W_-)$	0.895	0.898	0.900	0.903	0.905

Non-resonant DiMuon

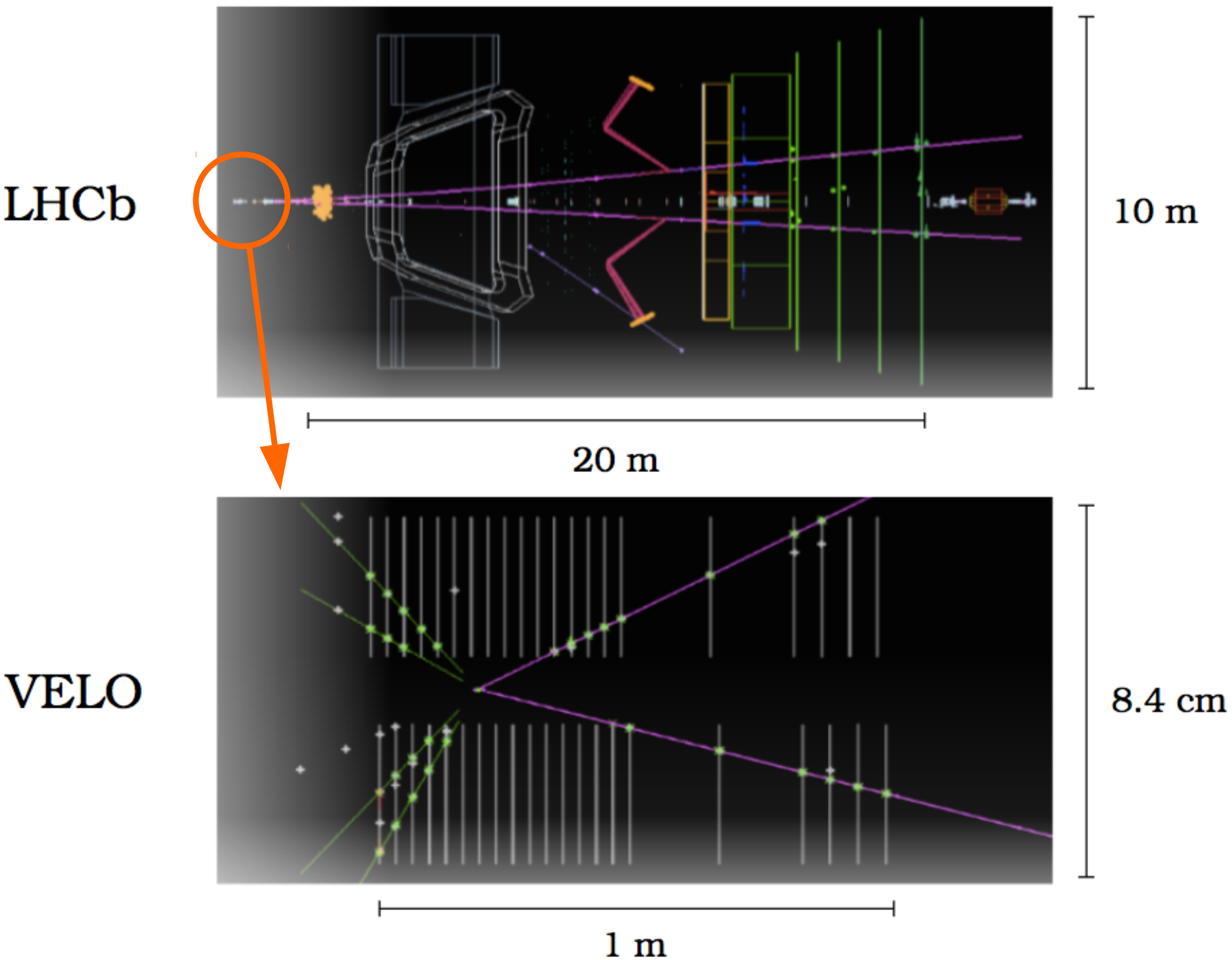



-114m
-19.7m
-7.5m
B2
B1
B0


To get an idea on distances
B1
D2
B2
D1
Q3
Q2
Q1
B0
F1
Q2
Q3
D1
F1
D2
MBRC
MBX
MQXA
MQXB
MQXA
MBXW
IP8
LHCb
MQXA
MQXB
TCDDM
TDI
MBRC
About 150m


20m
114m
F1
F2

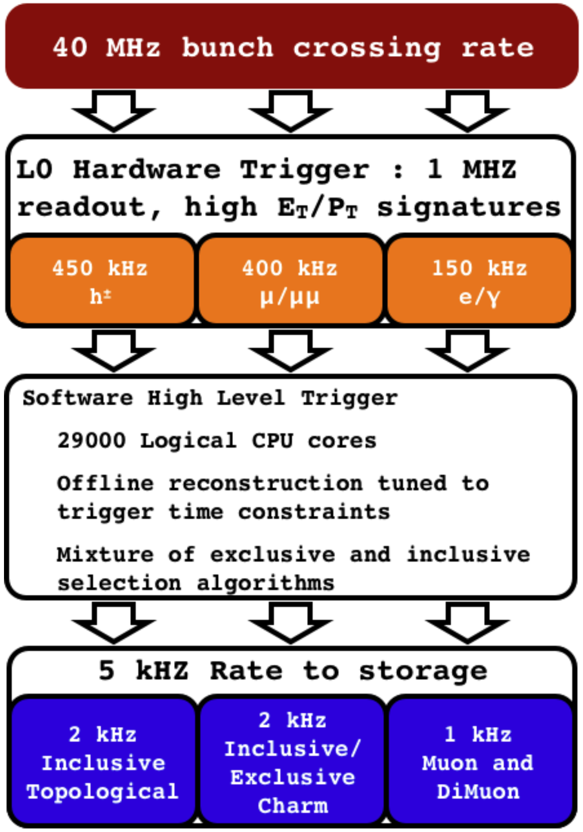
LHCb detector

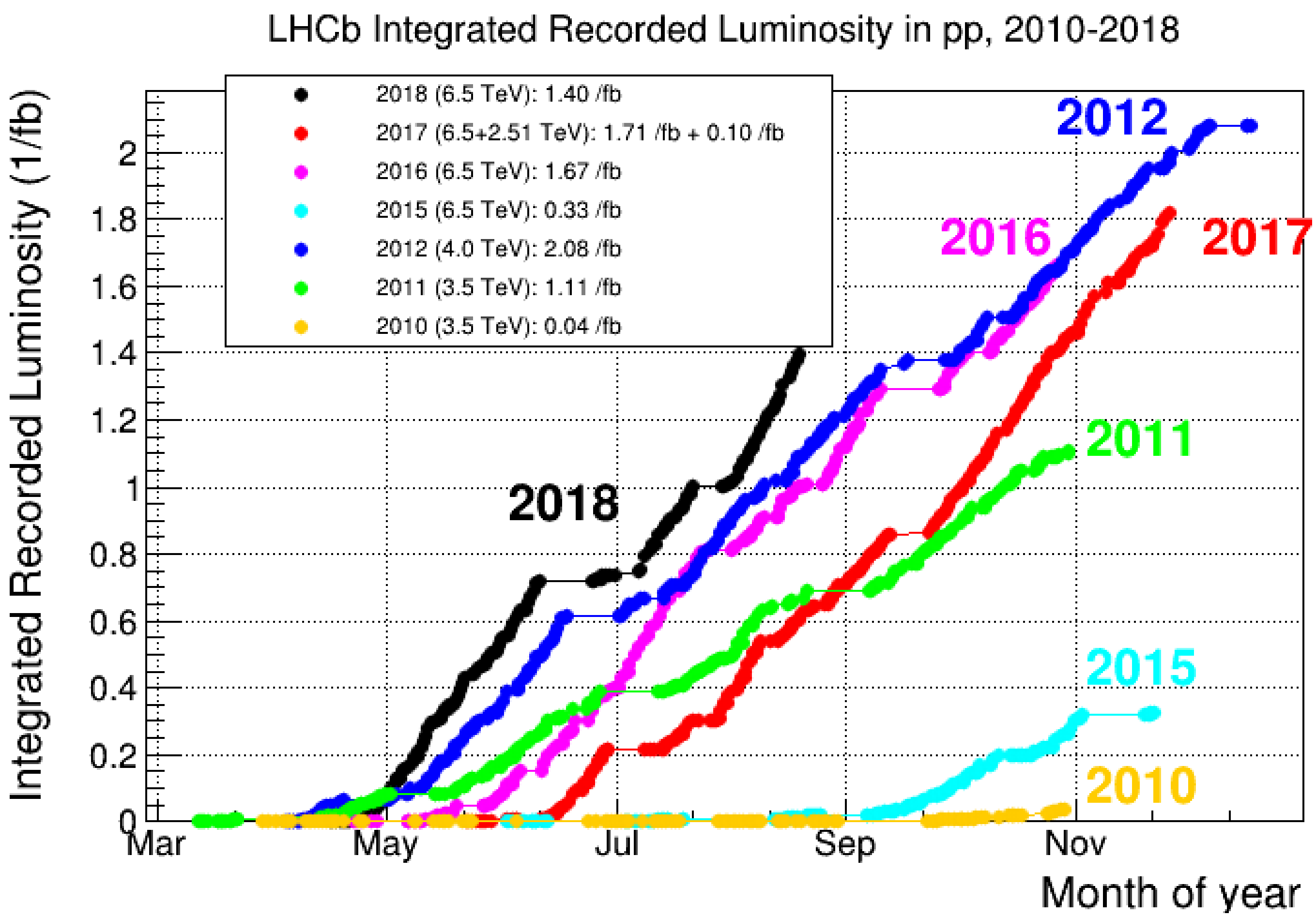


Backward track reconstruction is useful

Phil Ilten's slides – MPI at LHC

LHCb Data


40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
29000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
5 kHZ Rate to storage
2 kHz Inclusive Topological
2 kHz Inclusive/ Exclusive Charm
1 kHz Muon and DiMuon


LHCb Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 1.40 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Month of year
2012
2016
2017
2011
2018
2015
2010

	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.

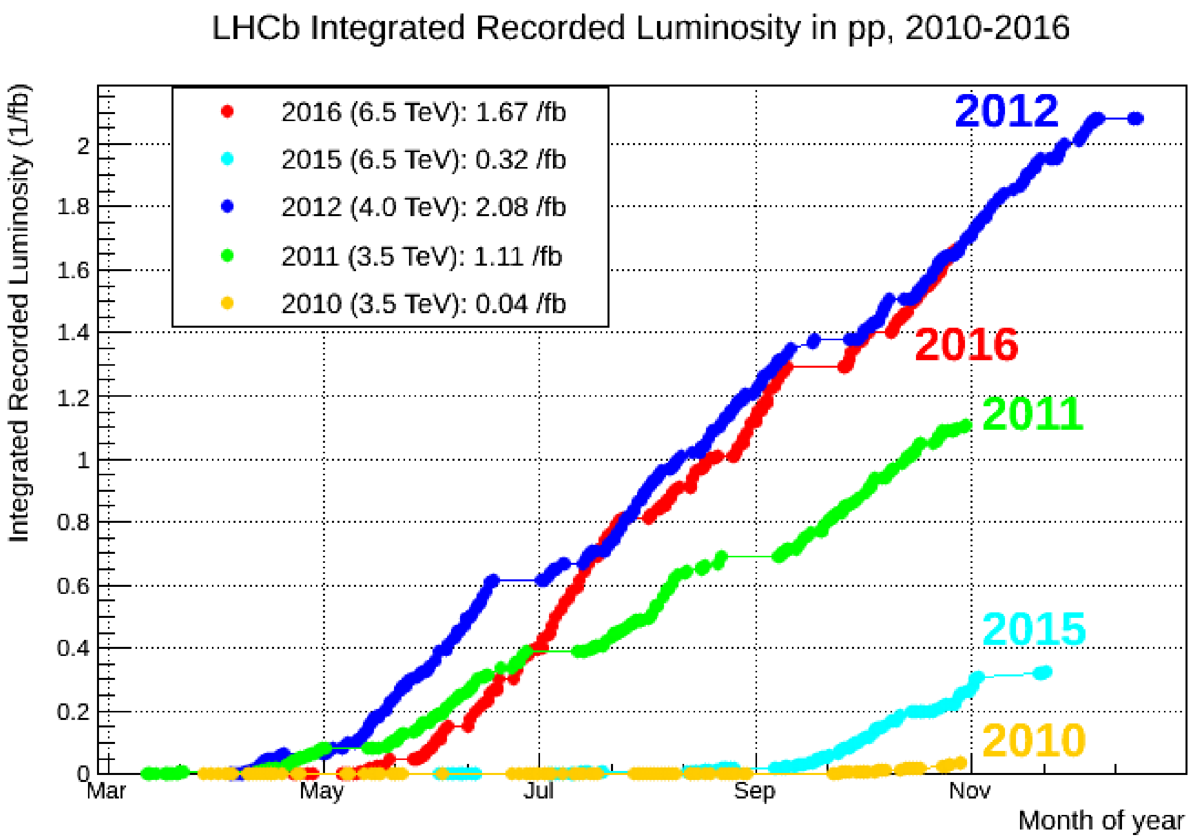
[12] V. P. Gonçalves and M. V. T. Machado, *Vector meson production in coherent hadronic interactions: an update on predictions for RHIC and LHC*, Phys. Rev. **C84** (2011) 011902, arXiv:1106.3036.

[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.

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%