

CENTRAL EXCLUSIVE PRODUCTION OF J/ψ AND $\psi(2S)$ MESONS AT LHCb

virtual Quarkonia as Tools
23 March 2021

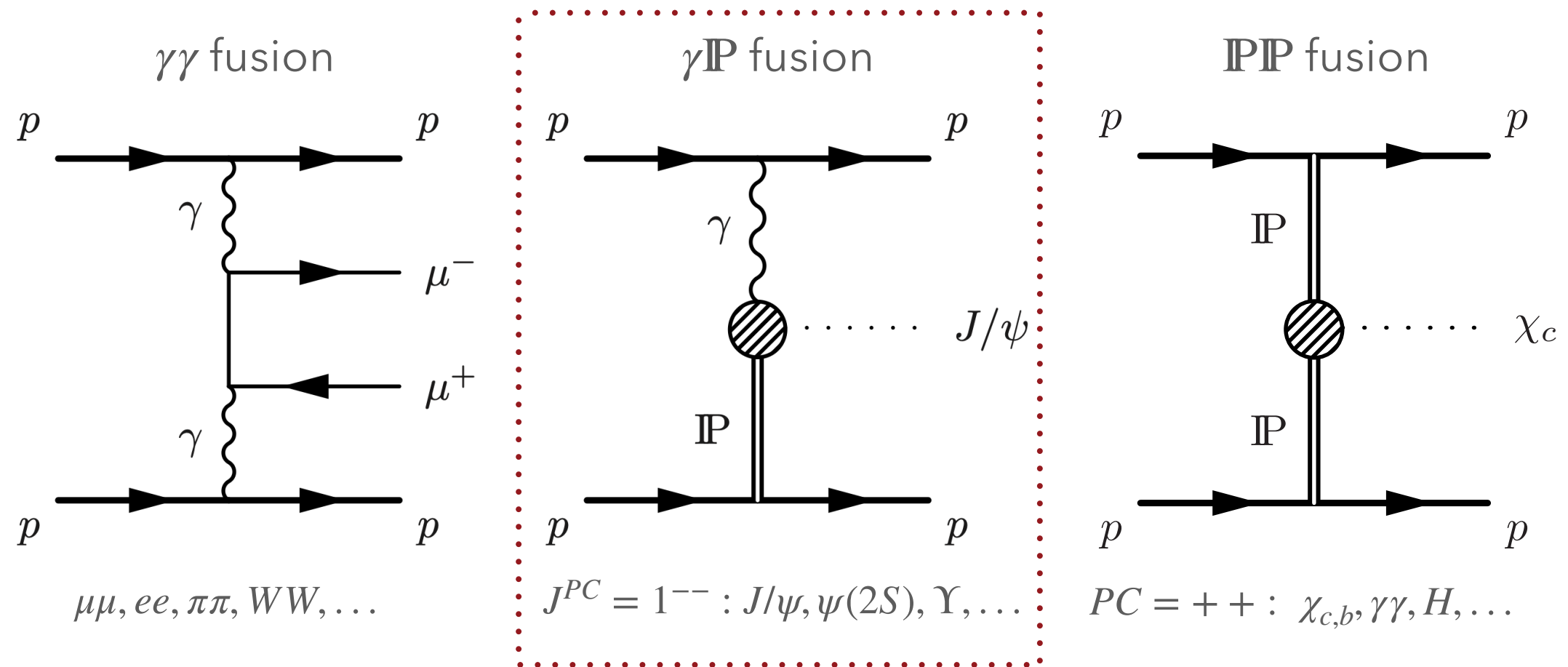
Cristina Sánchez Gras
on behalf of the LHCb collaboration

Nikhef



CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

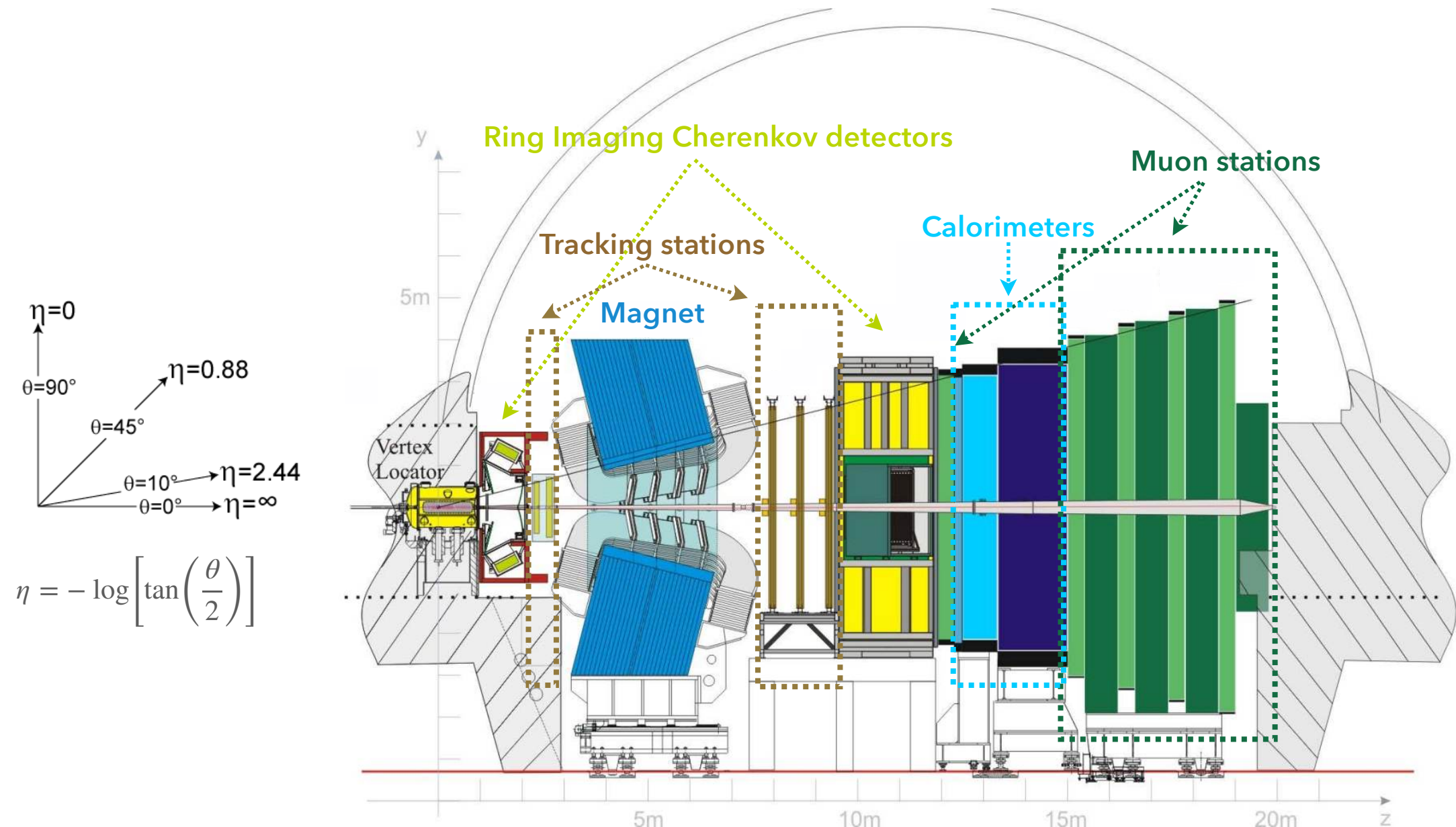
- * CEP event: diffractive process of the form $pp \rightarrow p + X + p$
- * Mediated by the exchange of a colourless object:



- * $\mathbb{P}$: pomeron, two or more gluons in a colour-singlet state

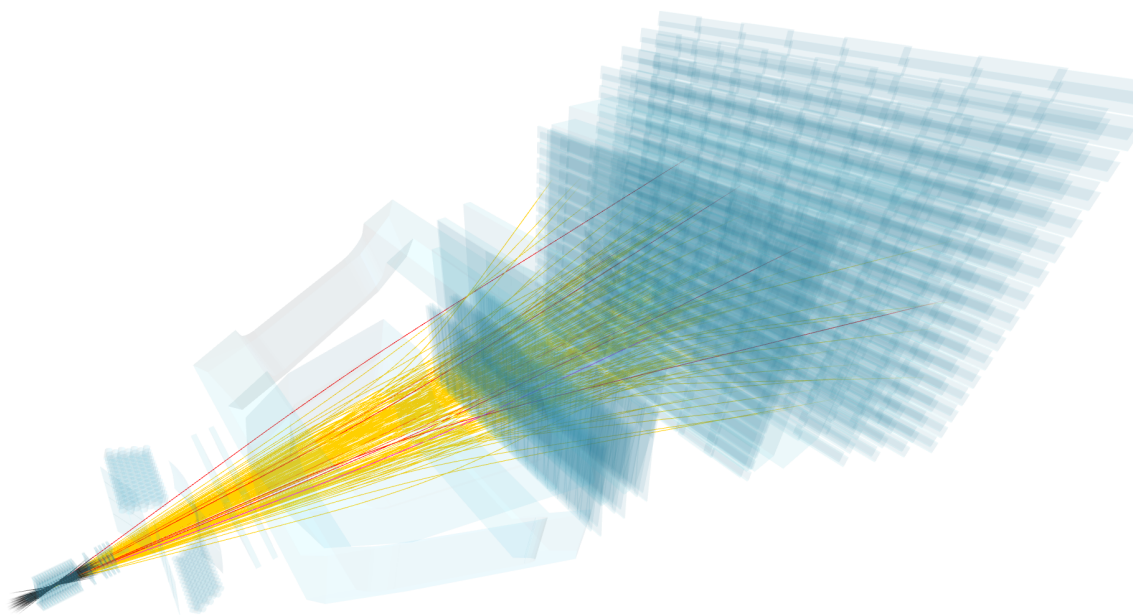
LHCb DETECTOR

- * LHCb detector: located at the LHC, fully instrumented in the pseudorapidity (η) range $2 < \eta < 5$, partially in $-3.5 < \eta < -1.5$

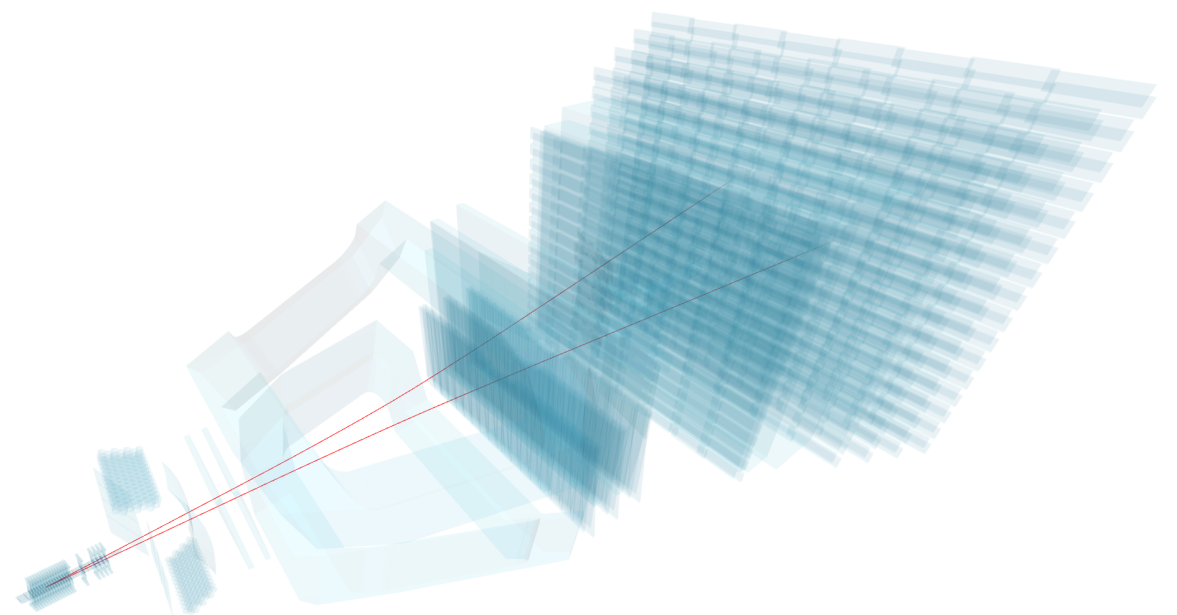


CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

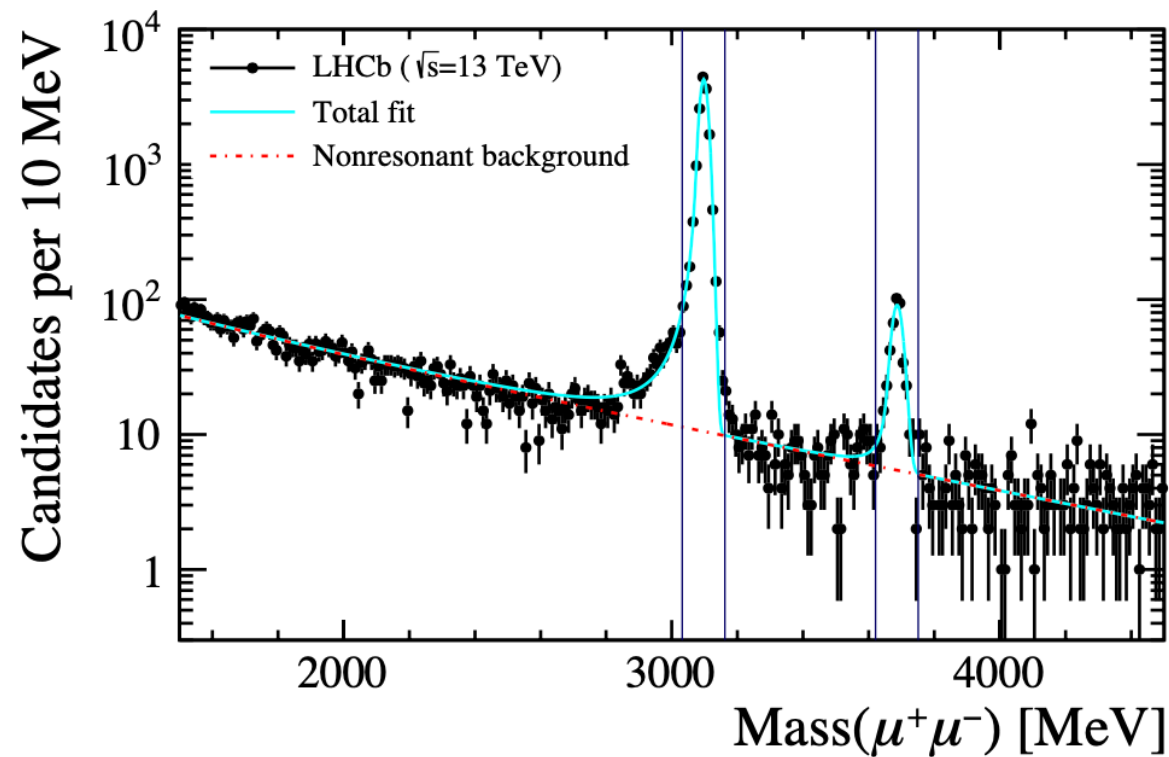
- * CEP event: diffractive process of the form $pp \rightarrow p + X + p$
- * Looks like this at LHCb:



Inelastic pp collision



CEP pp collision

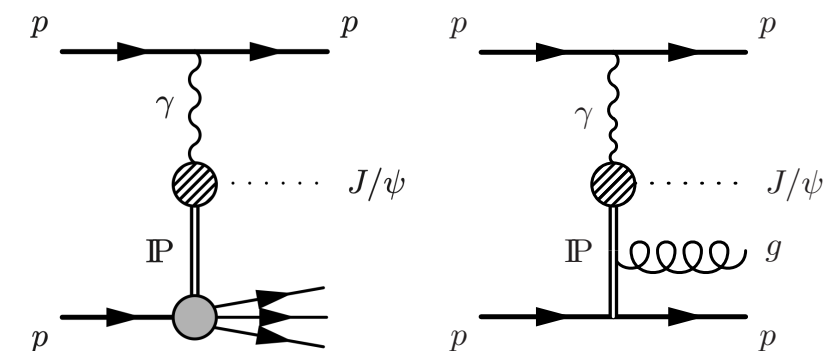


Selection:

- ✓ Exactly two reconstructed tracks
- ✓ $2.0 < \eta_{\mu^+, \mu^-} < 4.5$
- ✓ $m_{\mu^+ \mu^-}$ within ± 65 MeV of the $J/\psi, \psi(2S)$ mass
- ✓ $p_T^2 < 0.8 \text{ GeV}^2$
- ✓ HeRSChEL veto to suppress inelastic production

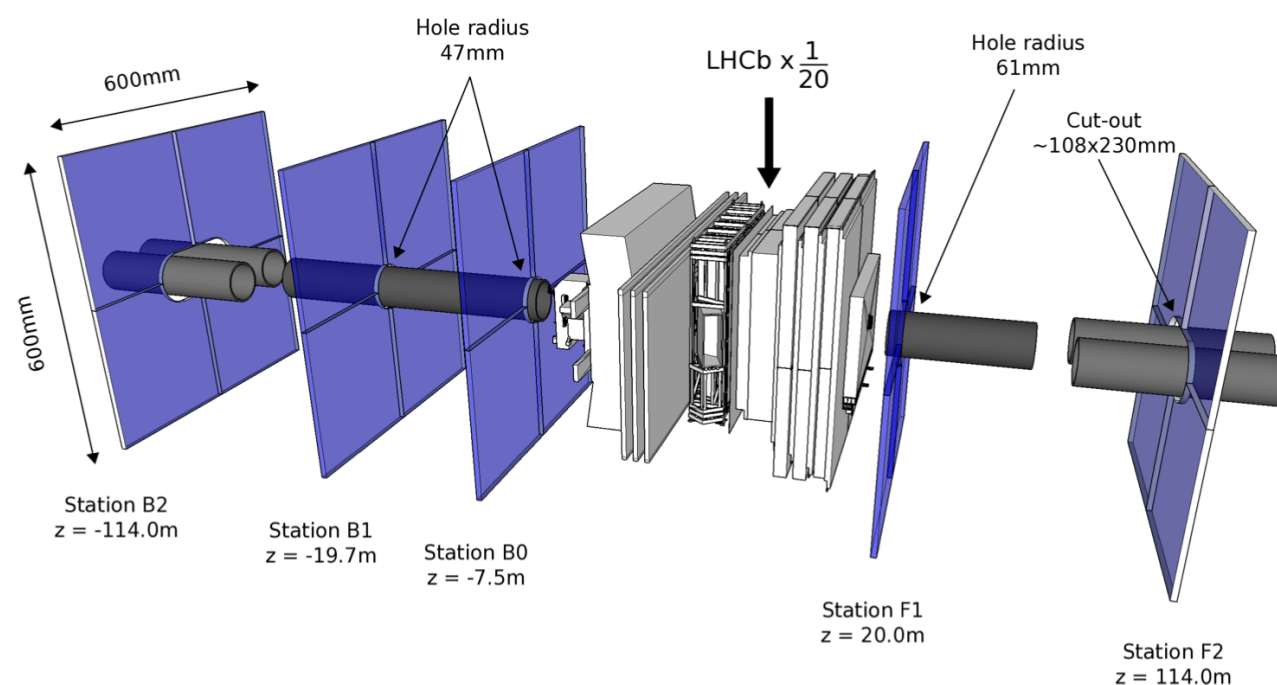
* Backgrounds:

- * Continuum dimuon production ($\gamma\gamma$ fusion)
- * Peaking at the J/ψ mass: χ_{cJ} feed-down ($\mathbb{P}\mathbb{P}$ fusion), $\psi(2S)$ feed-down ($\gamma\mathbb{P}$ fusion)
- * Inelastic production: a proton dissociates or there is gluon emission



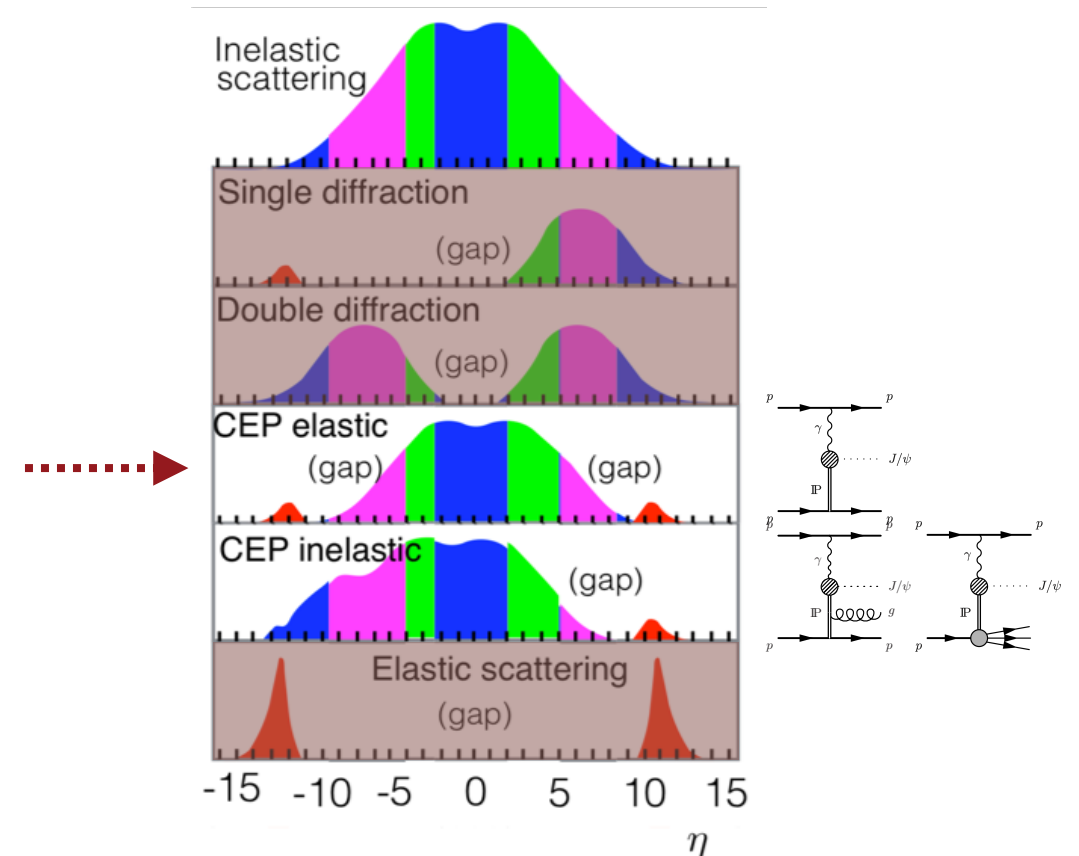
HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHC*b*

- * Need to detect proton remnants → increase the LHC*b* coverage to $1.5 < \eta < 10$ in the forward and $-10 < \eta < -5$, $-3.5 < \eta < -1.5$ in the backward regions with HeRSChEL.

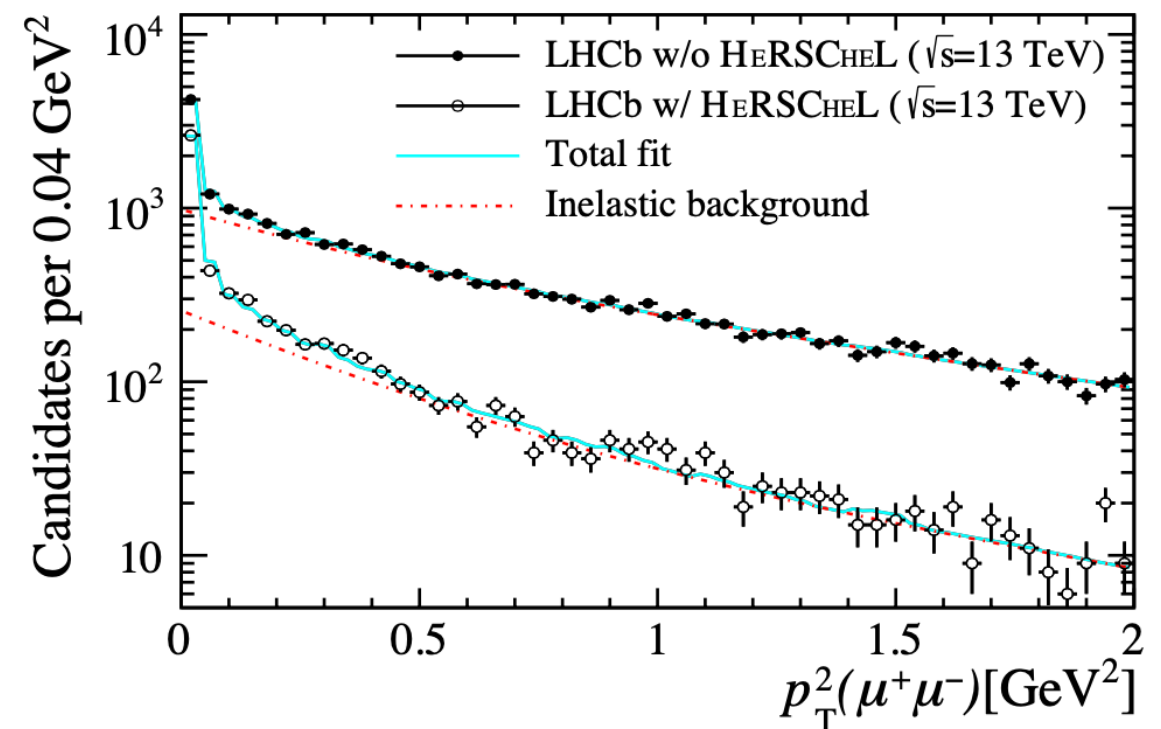
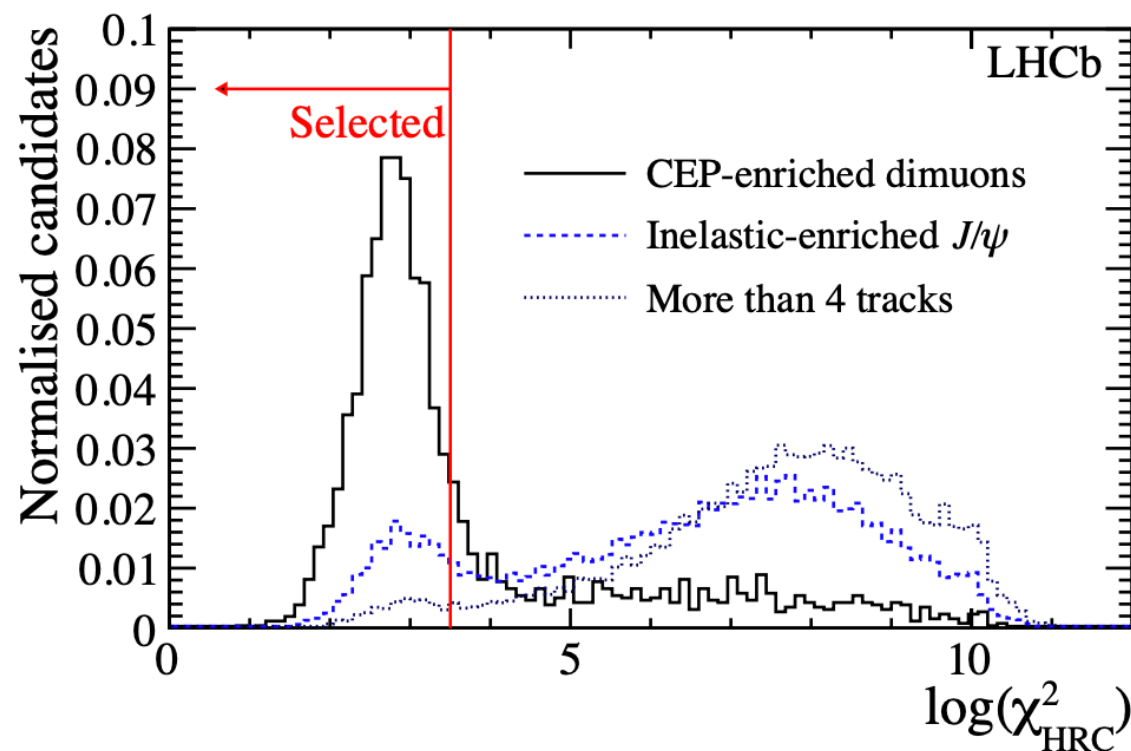


5 stations x 4 scintillating pads in each station

■ η particles ■ LHC*b* coverage
■ η protons ■ HeRSChEL coverage



- * Build a figure of merit with the HeRSCheL information to measure the activity in the detector: $\log(\chi^2_{HRC})$. No (low) activity = elastic CEP!
- * Use the continuum dimuon sample to choose a cut on $\log(\chi^2_{HRC})$ and to estimate its efficiency

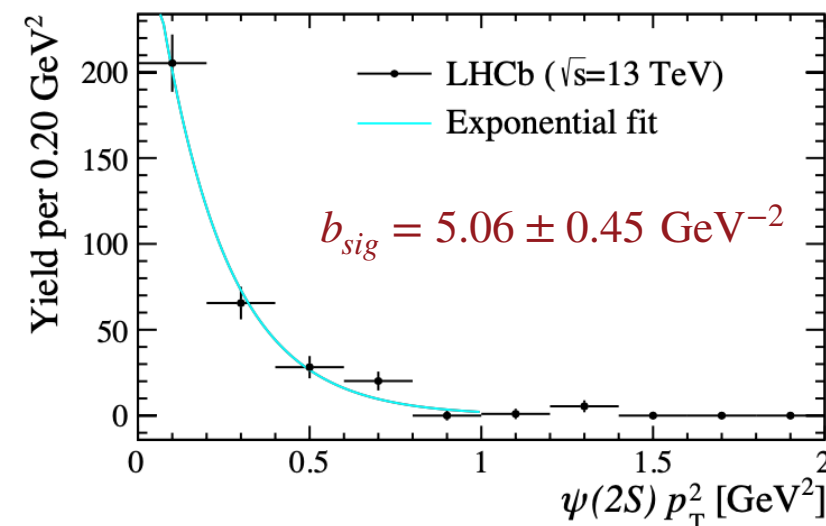
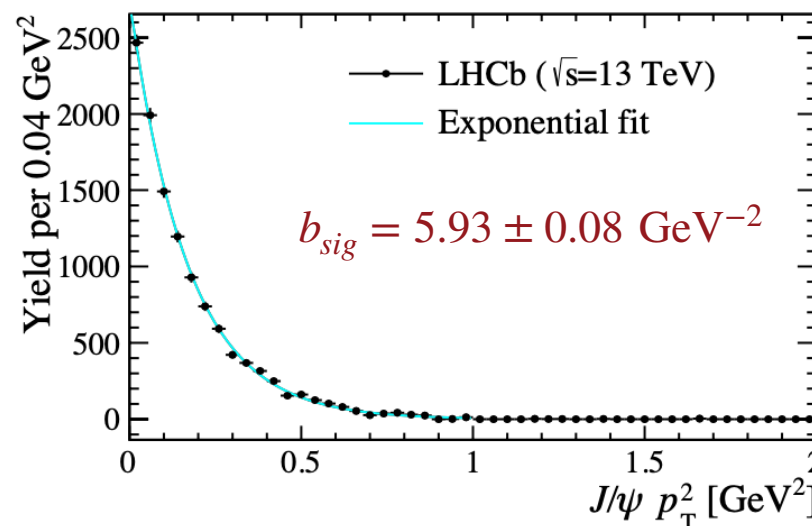
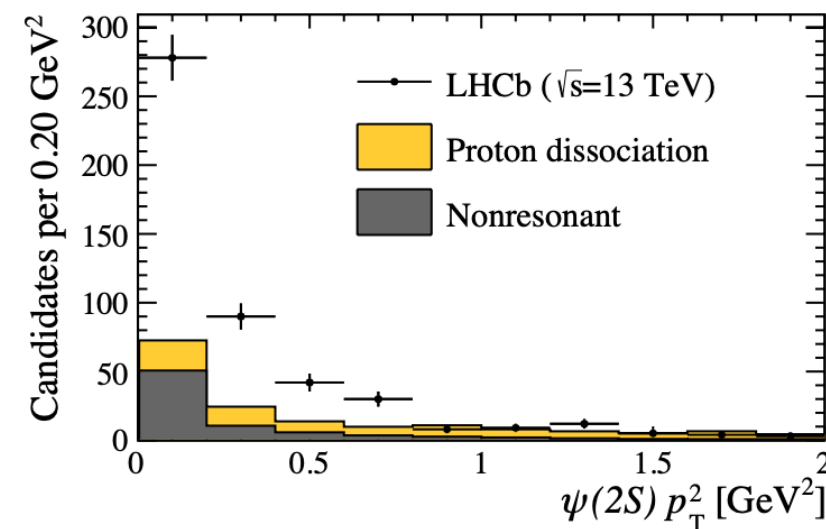
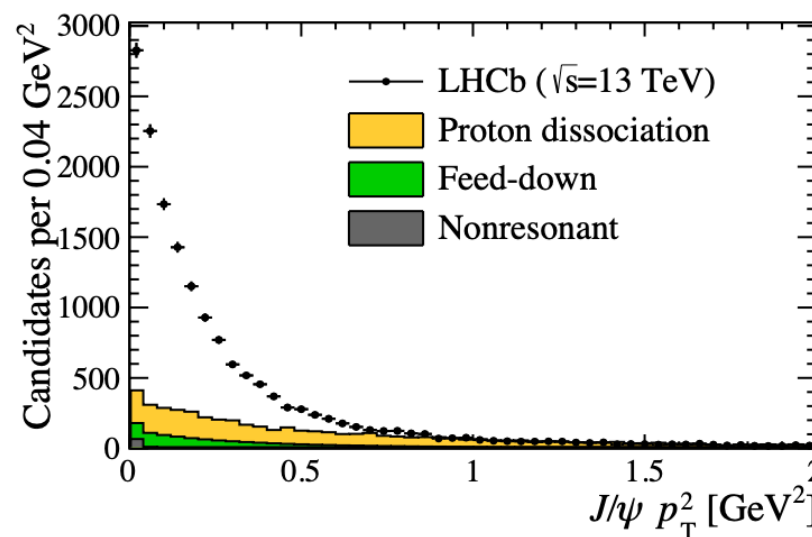


- * Estimate inelastic background by using two samples: above and below HeRSCheL veto (more in backup)

CEP J/ψ AND $\psi(2S)$ IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

[JHEP 10 (2018) 167]

- * Signal extraction: remove background from each sample, fit the remaining curve with a single exponential
- * Regge theory: $d\sigma/dp_T^2 \sim \exp(-b_{sig} p_T^2)$, $b_{sig} \approx 6 \text{ GeV}^{-2} \rightarrow$ In agreement!



CEP J/ψ AND $\psi(2S)$ IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

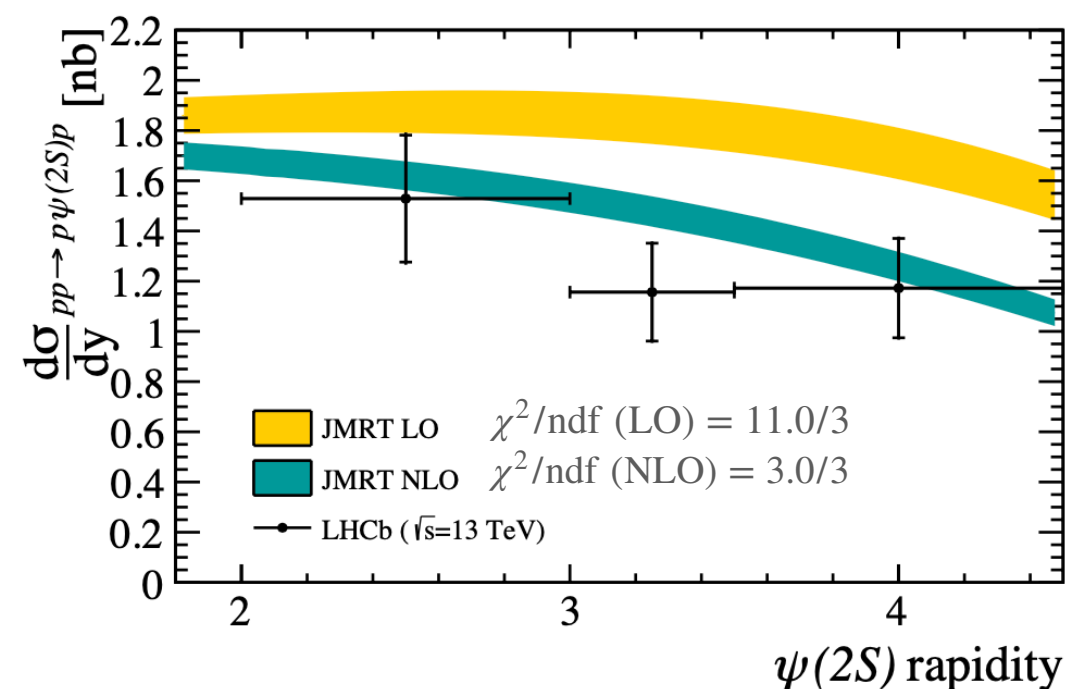
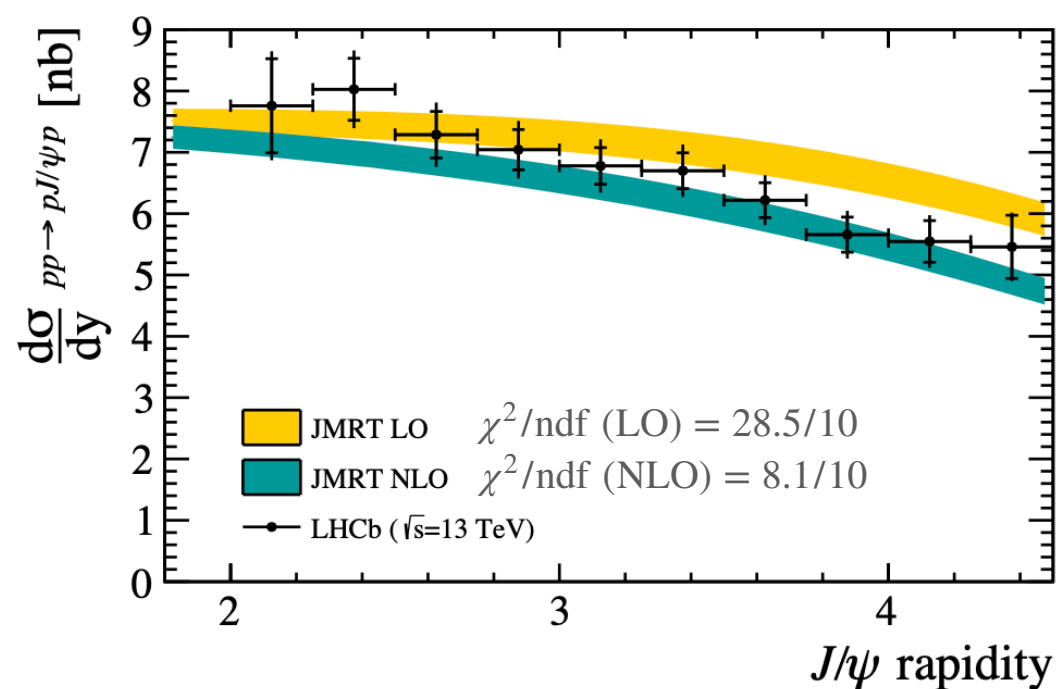
[JHEP 10 (2018) 167]

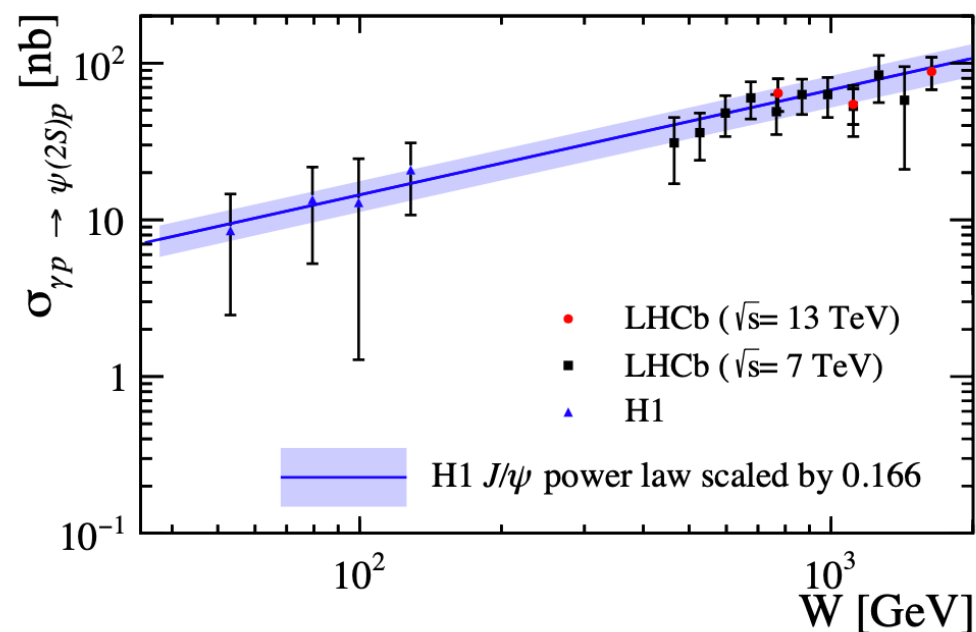
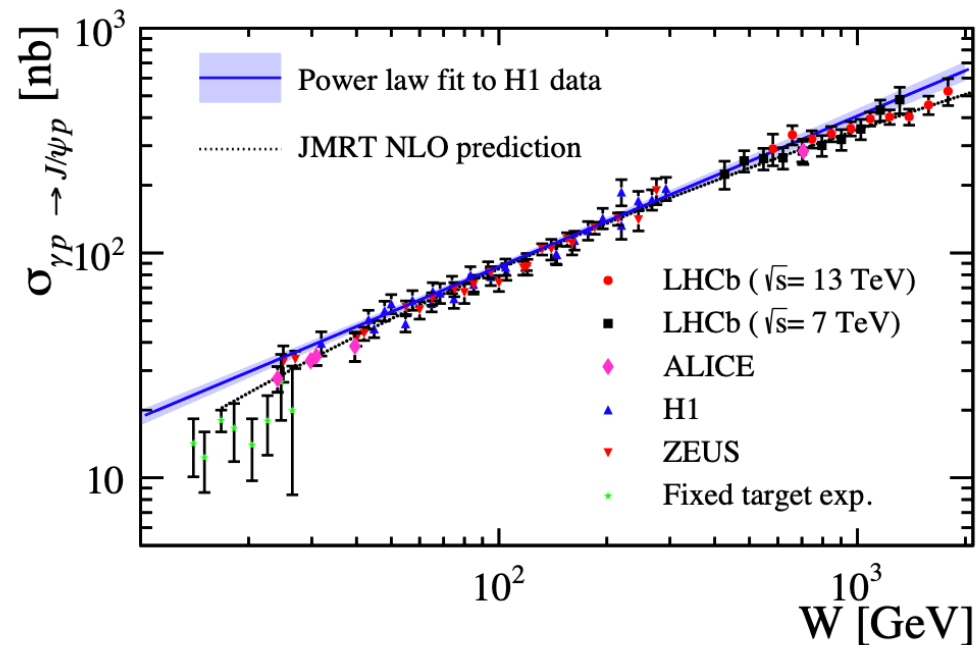
- * Cross-section calculation per rapidity bin y with $\mathcal{L}_{tot} = 204 \pm 8 \text{ pb}^{-1}$:

$$\frac{d\sigma_{\psi \rightarrow \mu^+ \mu^-}}{dy} = \frac{N_{sig}}{\epsilon_{tot} \cdot \Delta y \cdot \epsilon_{single} \cdot \mathcal{L}_{tot}}$$

- * Integrated luminosity, $\mathcal{L}_{tot}$, multiplied by the fraction of events with no additional interactions, ϵ_{single}

$$\sigma_{J/\psi \rightarrow \mu^+ \mu^-} = 435 \pm 18 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 17 \text{ (lumi.) pb} \quad \sigma_{\psi(2S) \rightarrow \mu^+ \mu^-} = 11.1 \pm 1.1 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \pm 0.4 \text{ (lumi.) pb}$$





Photoproduction cross-section, $\sigma_{\gamma p \rightarrow \psi p}(W_+)$:

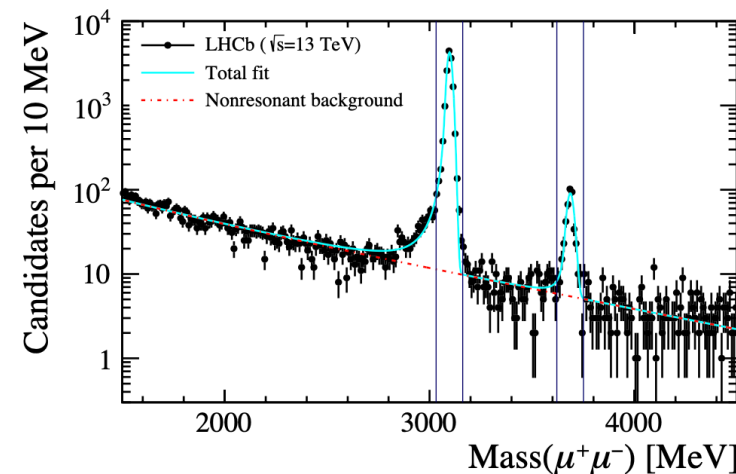
$$\sigma_{pp \rightarrow p\psi p} = r(W_+)k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow \psi p}(W_+) + r(W_-)k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow \psi p}(W_-)$$

- ▶ $r(W_{\pm})$ is the gap survival factor
- ▶ $k_{\pm} \equiv M_{\psi}/2e^{\pm|y|}$ is the photon energy
- ▶ $dn/dk_{\pm}$ is the photon flux
- ▶ $W_{\pm} = 2k_{\pm}\sqrt{s}$ is the γp system invariant mass

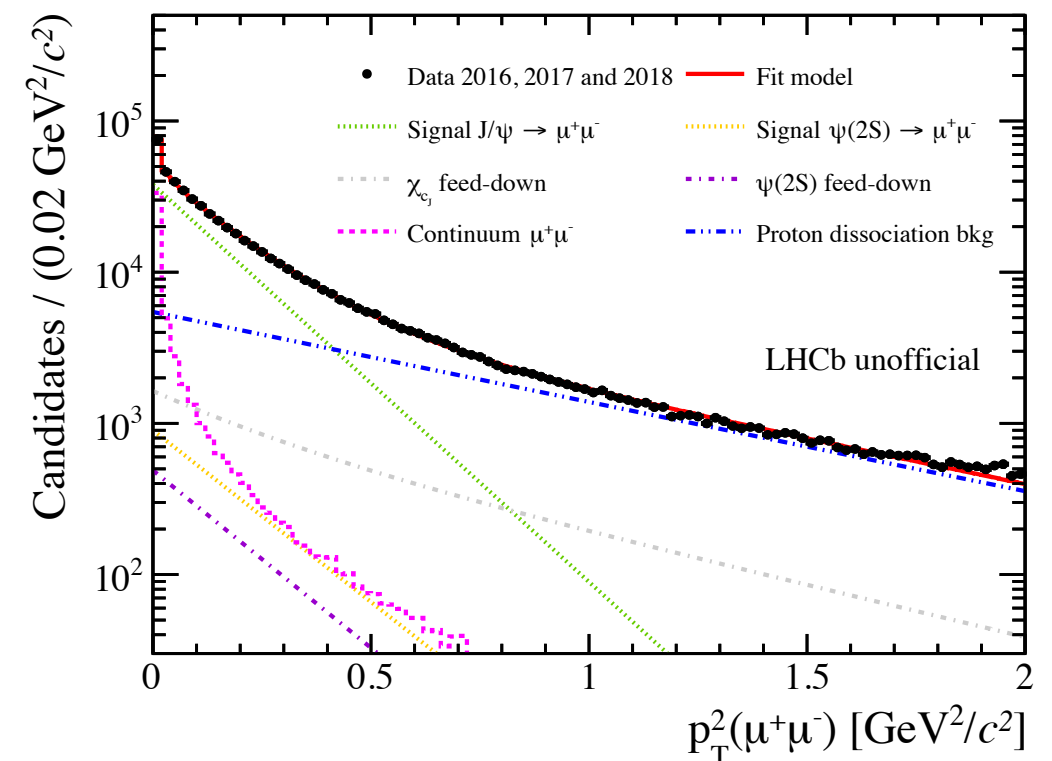
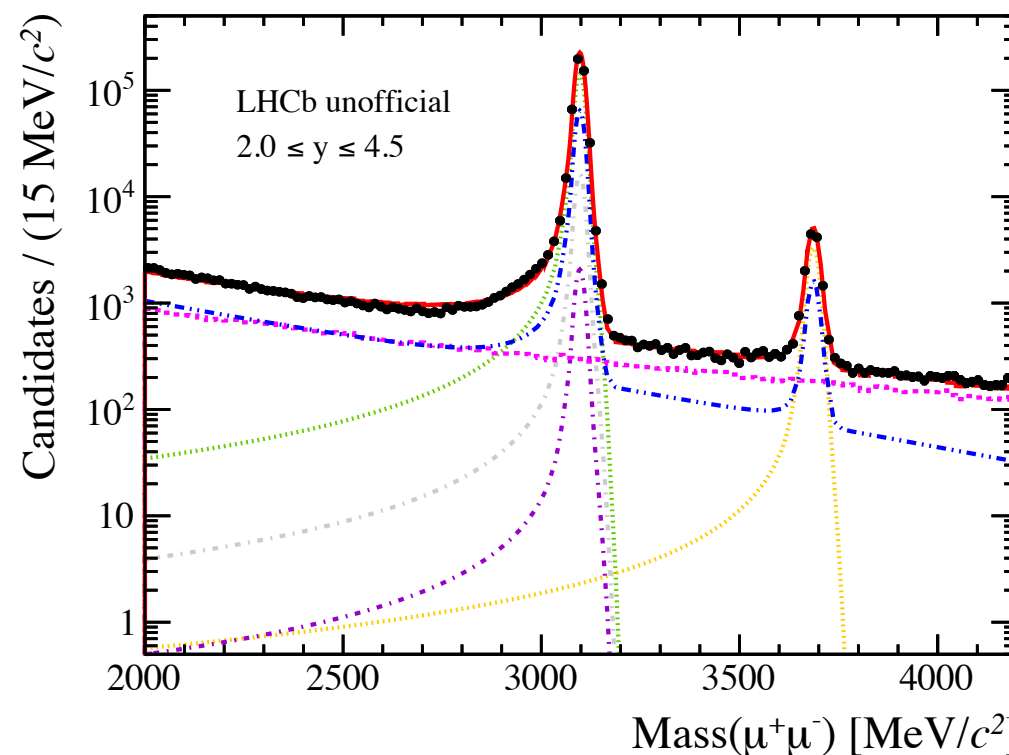
* 2-fold ambiguity: W_+ , W_- contribute to the same LHCb rapidity bin $\rightarrow$ we fix W_- from the HERA H1 parametrisation

* Currently working on an update including more data:

2015 data (presented here) →

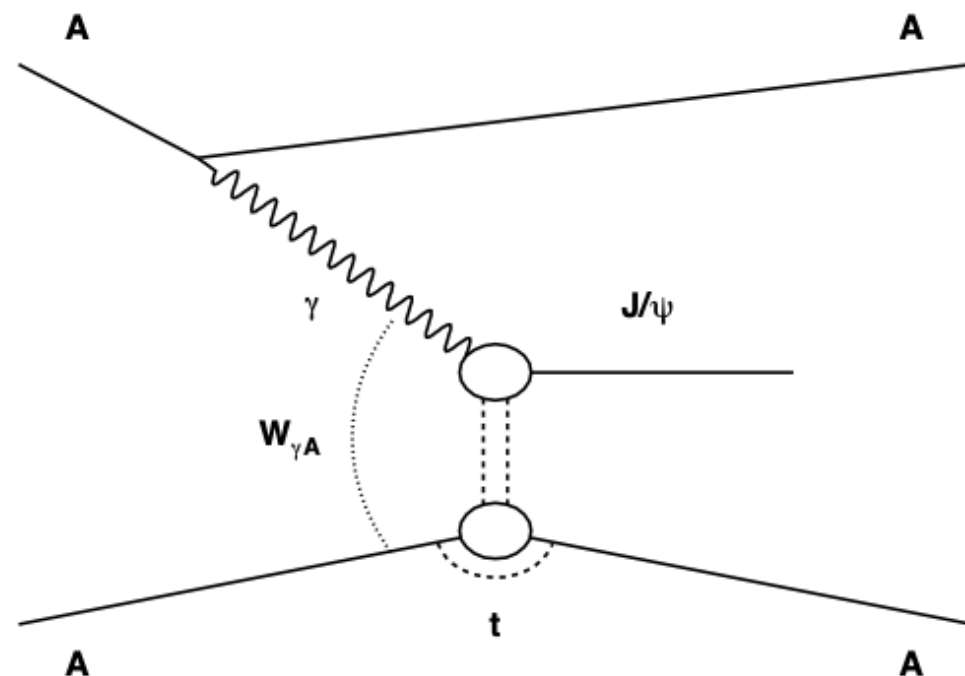


2016, 17 and 18 data (ongoing)
→ about 3 times more data!

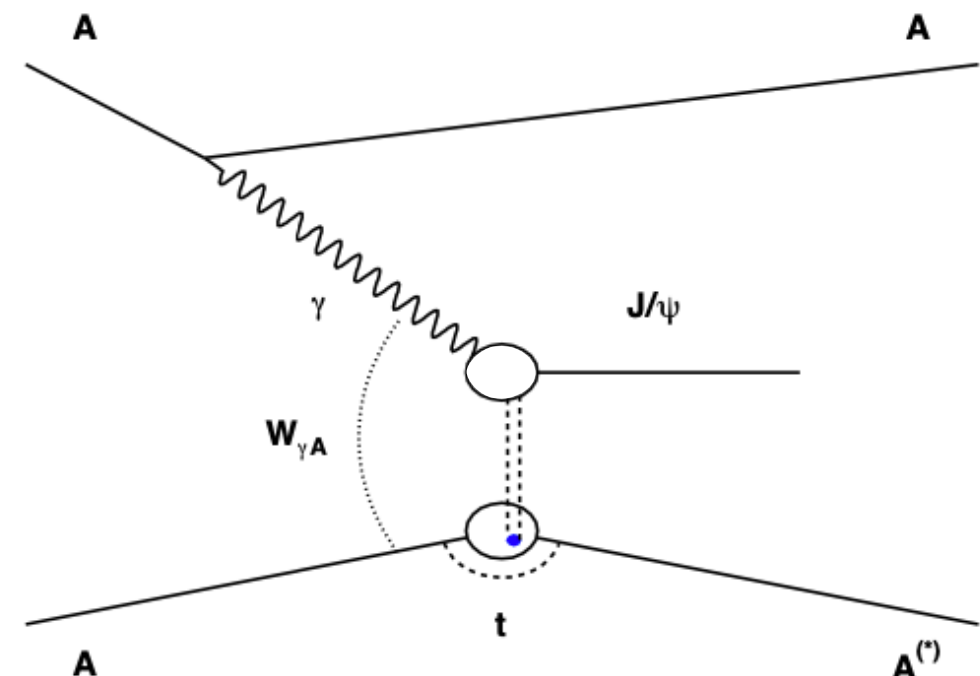


* Also working on a measurement with electrons instead of muons

- * Diffractive process of the form $\text{PbPb} \rightarrow \text{Pb} + X + \text{Pb}$

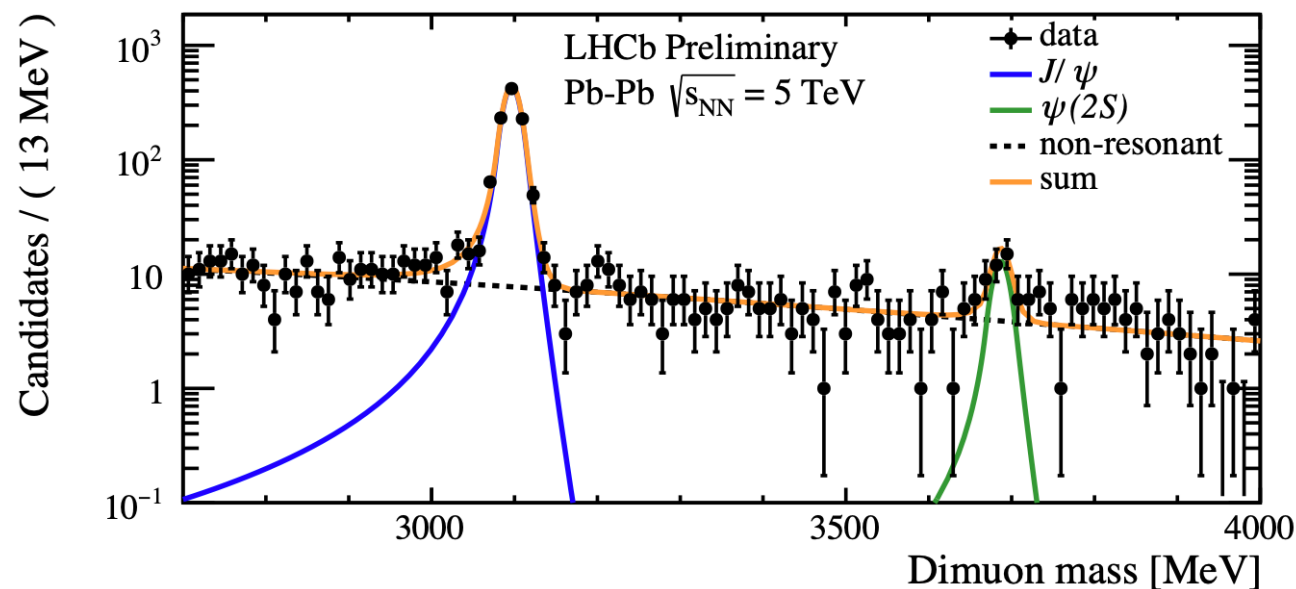


Coherent production:
 γ interacts with the
whole nucleus A



Incoherent production: γ
scatters a nucleon off A

- * Coherent: γA interaction can be modelled by pomeron exchange

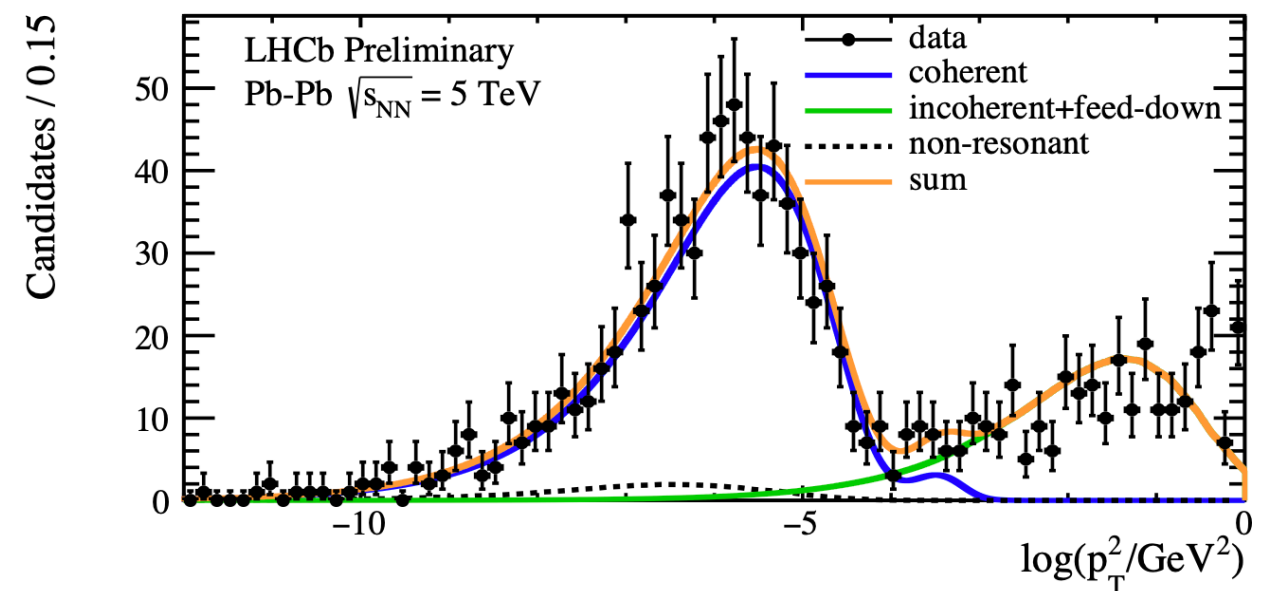


Selection:

- ✓ Two reconstructed muons
- ✓ Muons: $p_T > 500$ MeV, $2.0 < \eta_{\mu^+, \mu^-} < 4.5$
- ✓ $m_{\mu^+ \mu^-}$ within ± 65 MeV of the J/ψ mass
- ✓ J/ψ : $p_T < 1$ GeV, $2.0 < y < 4.5$

* Backgrounds:

- * Incoherent J/ψ production
- * J/ψ from feed-down of (in)coherent $\psi(2S)$ production
- * Signal and bkg (except non-resonant) in $\log(p_T^2)$ fit modelled with STARlight generator

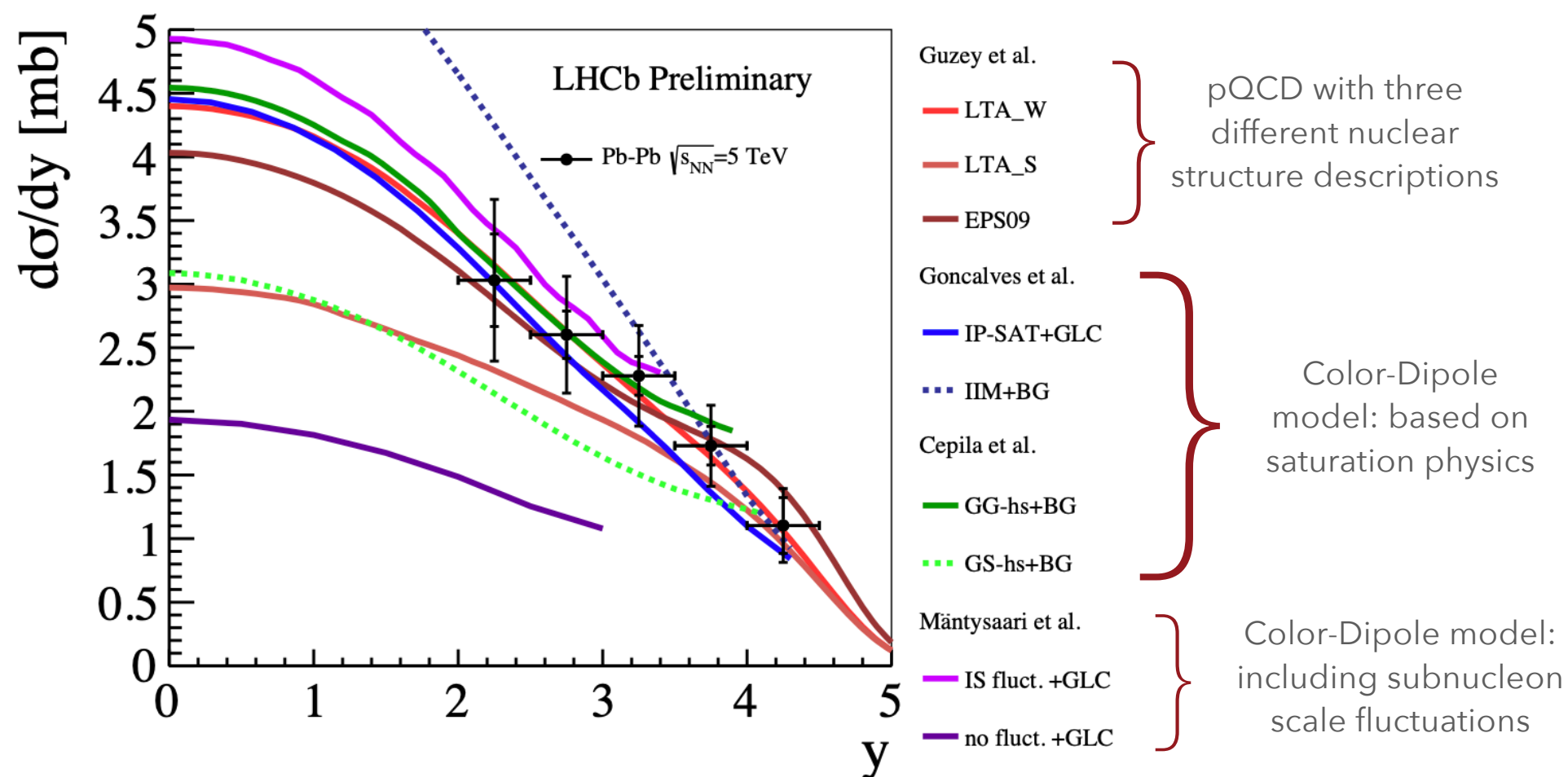


- * Cross-section calculation per rapidity bin y with $\mathcal{L}_{tot} = 10.1 \pm 1.3 \mu\text{b}^{-1}$:

$$d\sigma(\text{PbPb} \rightarrow \text{Pb} + J/\psi + \text{Pb})/dy = n_{coh}/(\epsilon_{tot} \cdot \Delta y \cdot \mathcal{L}_{int} \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-))$$

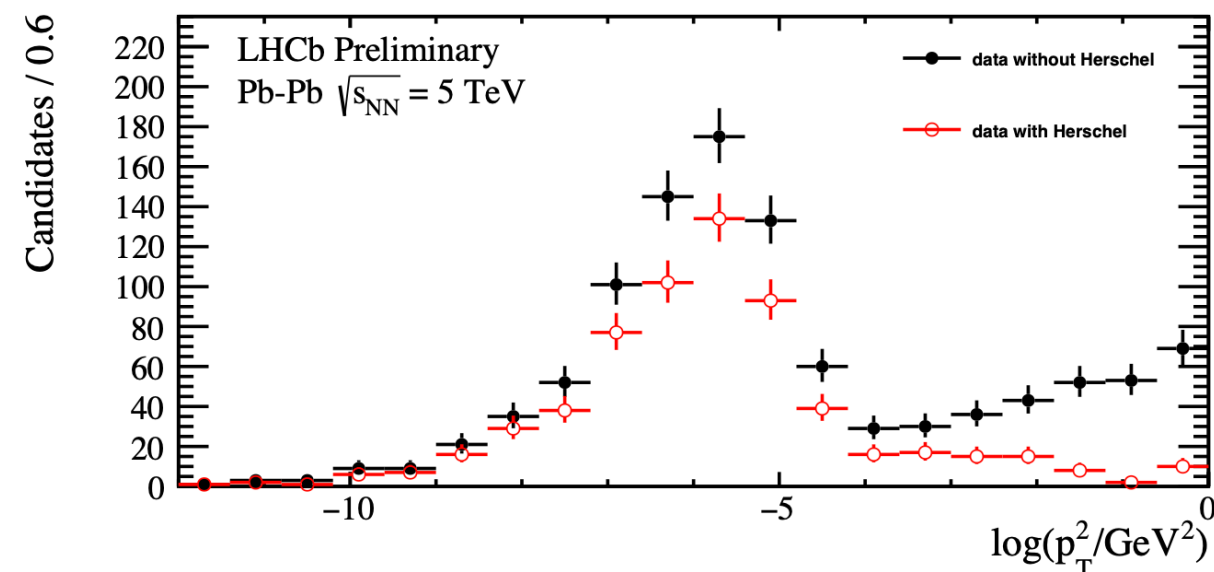
$$\sigma_{J/\psi \rightarrow \mu^+ \mu^-} = 5.3 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 0.7 \text{ (lumi.) mb}$$

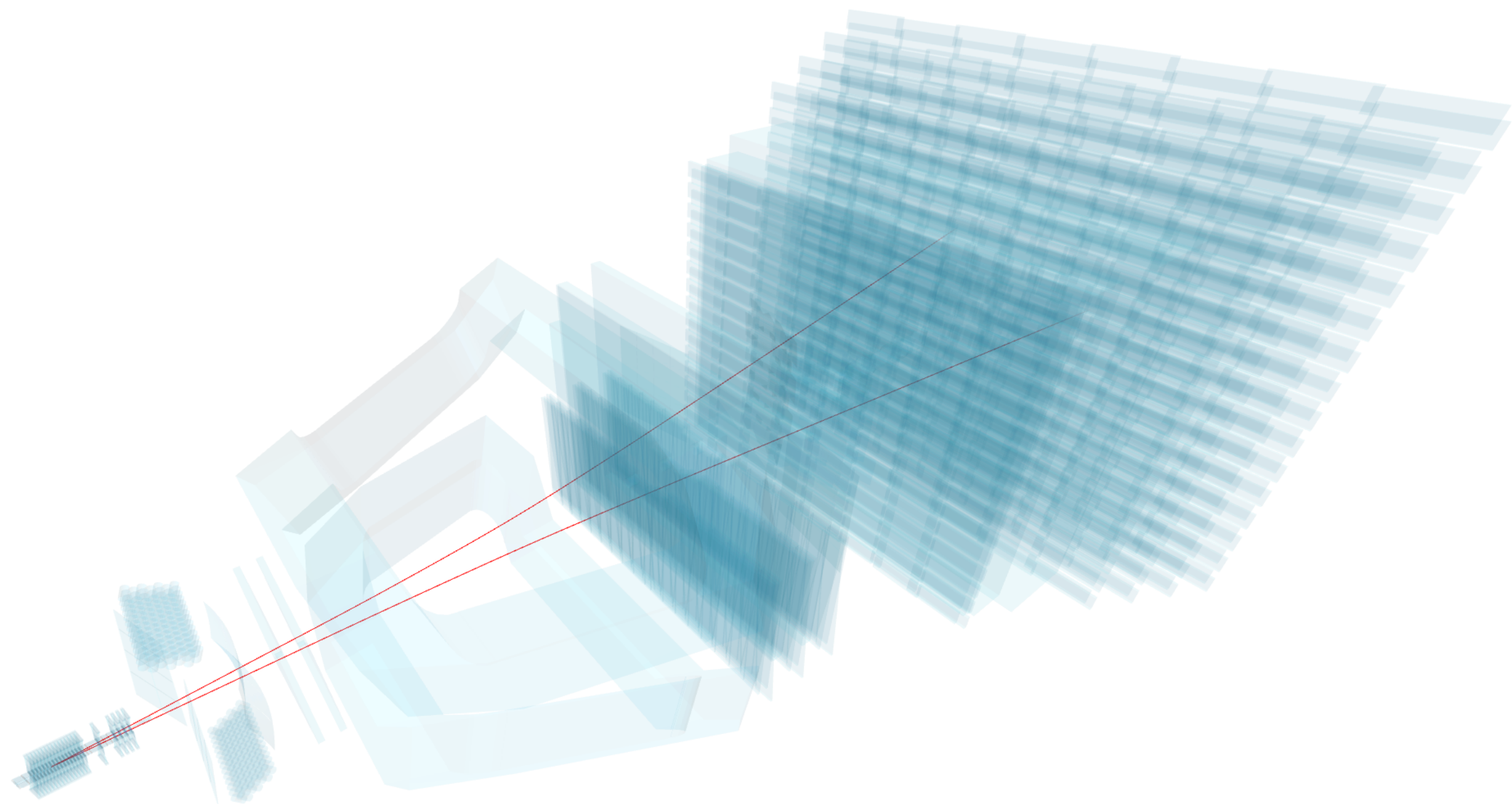
- * Comparison to some theoretical models:



OUTLOOK

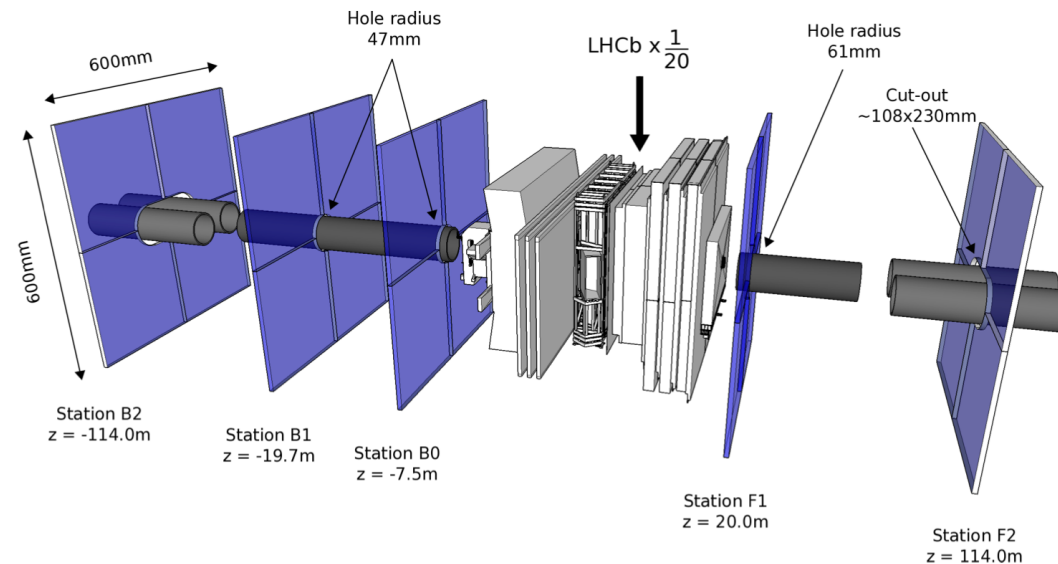
- * For pp collisions:
 - * Update with more data coming soon, higher statistics for $\psi(2S)$
 - * Measurement with electrons for J/ψ and $\psi(2S)$
- * For PbPb collisions:
 - * Preliminary studies show how HeRSChEL can reduce the incoherent contribution. Update coming soon!



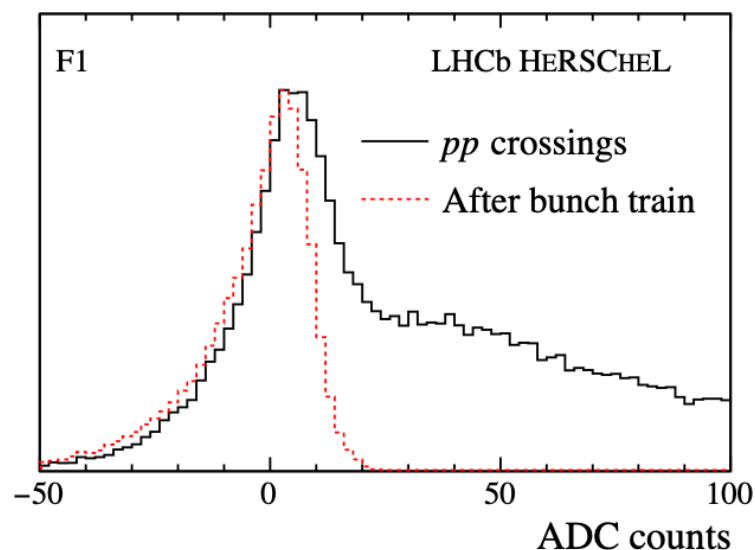


THANK YOU FOR YOUR ATTENTION!

HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHC*b*



- * Around zero ADC counts in each counter: no activity
- * Long tail to higher numbers of ADC counts: significant activity
- * Construct a χ^2 quantity to combine the activity in all detectors



$$\chi_{HRC}^2 = X^T C^{-1} X$$

$$X_i = \frac{x_i - \mu_i}{\sigma_i}, \quad x_i > \mu_i$$

$$X_i = \frac{x_i - \mu_i}{\sigma_i(1 + \lambda_i x_i)}, \quad x_i < \mu_i$$

* Systematic uncertainties:

Table 1: Summary of relative systematic uncertainties on the total cross-section.

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

* Cross-section calculation:

$$d\sigma_{\psi \rightarrow \mu^+ \mu^-}/dy = N_{sig}/(\epsilon_{tot} \cdot \Delta y \cdot \epsilon_{single} \cdot \mathcal{L}_{tot})$$

Table 3: Tabulation of numbers entering the cross-section calculation for the $\psi(2S)$ analysis with statistical and systematic uncertainties for the integrated luminosity of $\mathcal{L}_{tot} = 204 \pm 8 \text{ pb}^{-1}$ and the fraction of single-interaction beam crossings, $\epsilon_{single} = 0.3329 \pm 0.0003$.

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
ϵ_{rec}	0.633	0.644	0.622
Stat. unc. (%)	3.4	2.6	2.9
Syst. unc. (%)	1.3	0.6	0.6
ϵ_{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	
$d\sigma/dy(\text{pb})$	4.4	6.6	3.4
Stat. unc. (%)	12.0	12.4	12.4
Syst. unc. (%)	2.9	2.7	2.7
Lumi. unc. (%)	3.9	3.9	3.9

Table 2: Tabulation of numbers entering the cross-section calculation for the J/ψ analysis with statistical and systematic uncertainties for the integrated luminosity of $\mathcal{L}_{tot} = 204 \pm 8 \text{ pb}^{-1}$ and the fraction of single-interaction beam crossings, $\epsilon_{single} = 0.3329 \pm 0.0003$.

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
$d\sigma/dy(\text{pb})$	44	134	200	263	296
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
$d\sigma/dy(\text{pb})$	288	230	159	95	31
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

- * Cross-section without fiducial requirements on the muons to compare with theory:

Table 4: Tabulation, in bins of meson rapidity, of the fraction of decays with both muons in the range $2.0 < \eta < 4.5$ and the differential cross-sections for J/ψ and $\psi(2S)$ production calculated without fiducial requirements on the muons.

J/ψ y bin	2.0–2.25	2.25–2.5	2.5–2.75	2.75–3.0	3.0–3.25
Acc.	0.095 ± 0.003	0.280 ± 0.005	0.460 ± 0.006	0.627 ± 0.006	0.733 ± 0.005
$\frac{d\sigma}{dy}(\text{nb})$	7.76 ± 0.77	8.03 ± 0.51	7.29 ± 0.38	7.04 ± 0.33	6.78 ± 0.30
J/ψ y bin	3.25–3.50	3.50–3.75	3.75–4.0	4.0–4.25	4.25–4.5
Acc.	0.721 ± 0.005	0.620 ± 0.006	0.471 ± 0.006	0.287 ± 0.006	0.094 ± 0.004
$\frac{d\sigma}{dy}(\text{nb})$	6.70 ± 0.29	6.22 ± 0.28	5.66 ± 0.29	5.55 ± 0.34	5.46 ± 0.52
$\psi(2S)$ y bin	2.0–3.0	3.0–3.5	3.5–4.5		
Acc.	0.362 ± 0.003	0.726 ± 0.004	0.372 ± 0.003		
$\frac{d\sigma}{dy}(\text{nb})$	1.53 ± 0.25	1.16 ± 0.19	1.17 ± 0.20		

- * Photoproduction cross-section, $\sigma_{\gamma p \rightarrow \psi p}(W_+)$:

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

- * Two contributions: W_+ , W_- corresponding to the emitted photon being parallel or antiparallel to the LHCb beam axis
- * W_+ contributes 2/3 of the times in LHCb. W_- taken from the HERA H1 parametrisation:
 $\sigma_{\gamma p \rightarrow J/\psi p} = a(W/90\text{GeV})^\delta$, $a = 81 \pm 3$ pb and $\delta = 0.67 \pm 0.03$

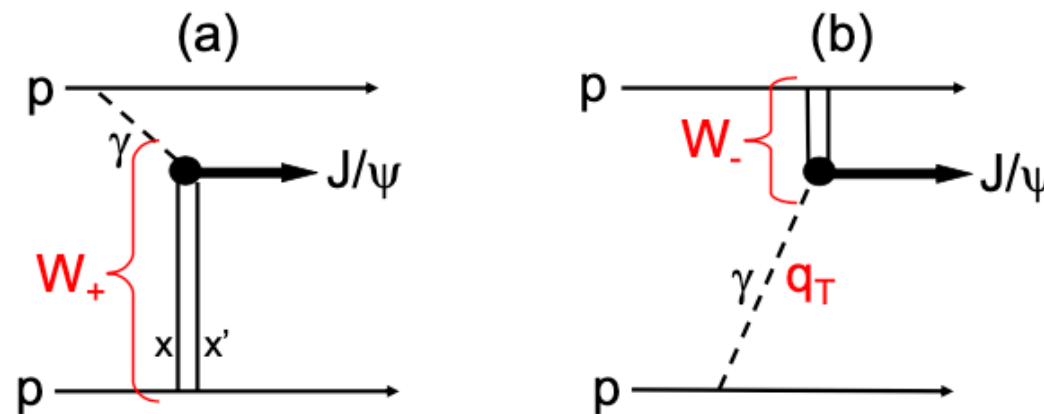


Figure 2: The two diagrams describing exclusive J/ψ production at the LHC. The vertical lines represent two-gluon exchange. Diagram (a), the W_+ component, is the major contribution to the $pp \rightarrow p + J/\psi + p$ cross section for a J/ψ produced at large rapidity y . Thus such data allow a probe of very low x values, $x \sim M_{J/\psi} \exp(-y)/\sqrt{s}$; recall that for two-gluon exchange we have $x \gg x'$. [arXiv:1307.7099 \[hep-ph\]](https://arxiv.org/abs/1307.7099)

- * Cross-section calculation: $d\sigma(\text{PbPb} \rightarrow \text{Pb} + J/\psi + \text{Pb})/dy = n_{coh}/(\epsilon_{tot} \cdot \Delta y \cdot \mathcal{L}_{int} \cdot \mathcal{B})$

Table 2: Cross-section measured differentially in J/ψ rapidity. The first quoted uncertainty is statistical and the second systematic, where the luminosity component (correlated across all bins) has been removed.

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

- * Systematic uncertainties:

Table 1: Relative systematic uncertainties considered for the cross-section measurement of coherent J/ψ production. The first two contributions are taken from Ref. [21].

Source	Relative uncertainty (%)
Reconstruction efficiency	2.1–4.5
Selection efficiency	3.2
Hardware trigger efficiency	3.0
Software trigger efficiency	1.6–5.3
Momentum smearing	3.3
Mass fit model	3.9
Feed-down background	5.8
Branching Fraction	0.6
Luminosity	13.0