EXPERIMENTAL OVERVIEW ON EXCLUSIVE QUARKONIUM PRODUCTION IN *pp*

Quarkonia as Tools
11 January 2022

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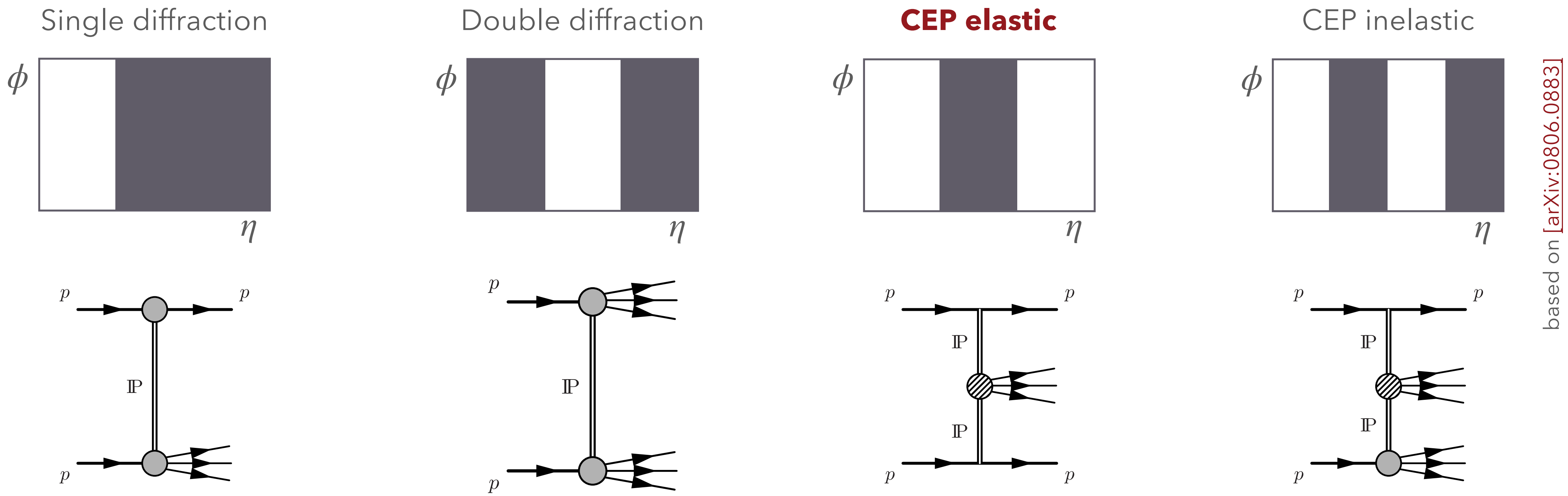
on behalf of the LHCb collaboration

CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

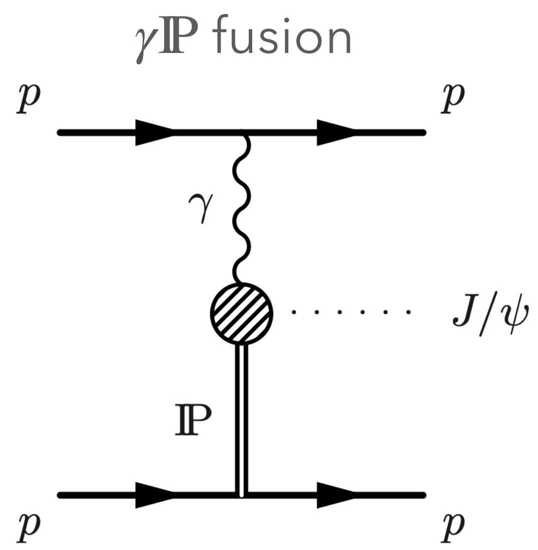
- CEP: diffractive process of the form $pp \to p + X + p$
- Mediated by the exchange of a colourless object.
  - Low p_{T}^2, Regge theory: pomeron, odderon…
- η vs azimuth ϕ for diffractive pp interactions:

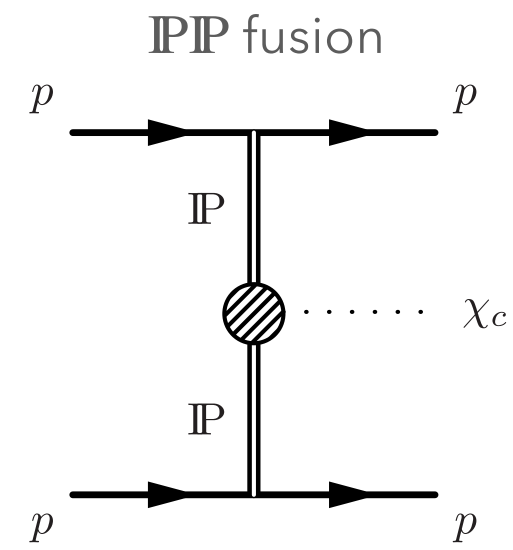


- Experimental signature: events with **large rapidity gaps**.

EXCLUSIVE QUARKONIUM PRODUCTION IN pp COLLISIONS

- **Photoproduction** (photon-pomeron fusion): vector meson production ($J/\psi, \psi(2S), \Upsilon$).
- **Double pomeron exchange** (DPE): $\chi_{c0}, \chi_{c1}, \chi_{c2}$ and double charmonia production.





In this presentation:

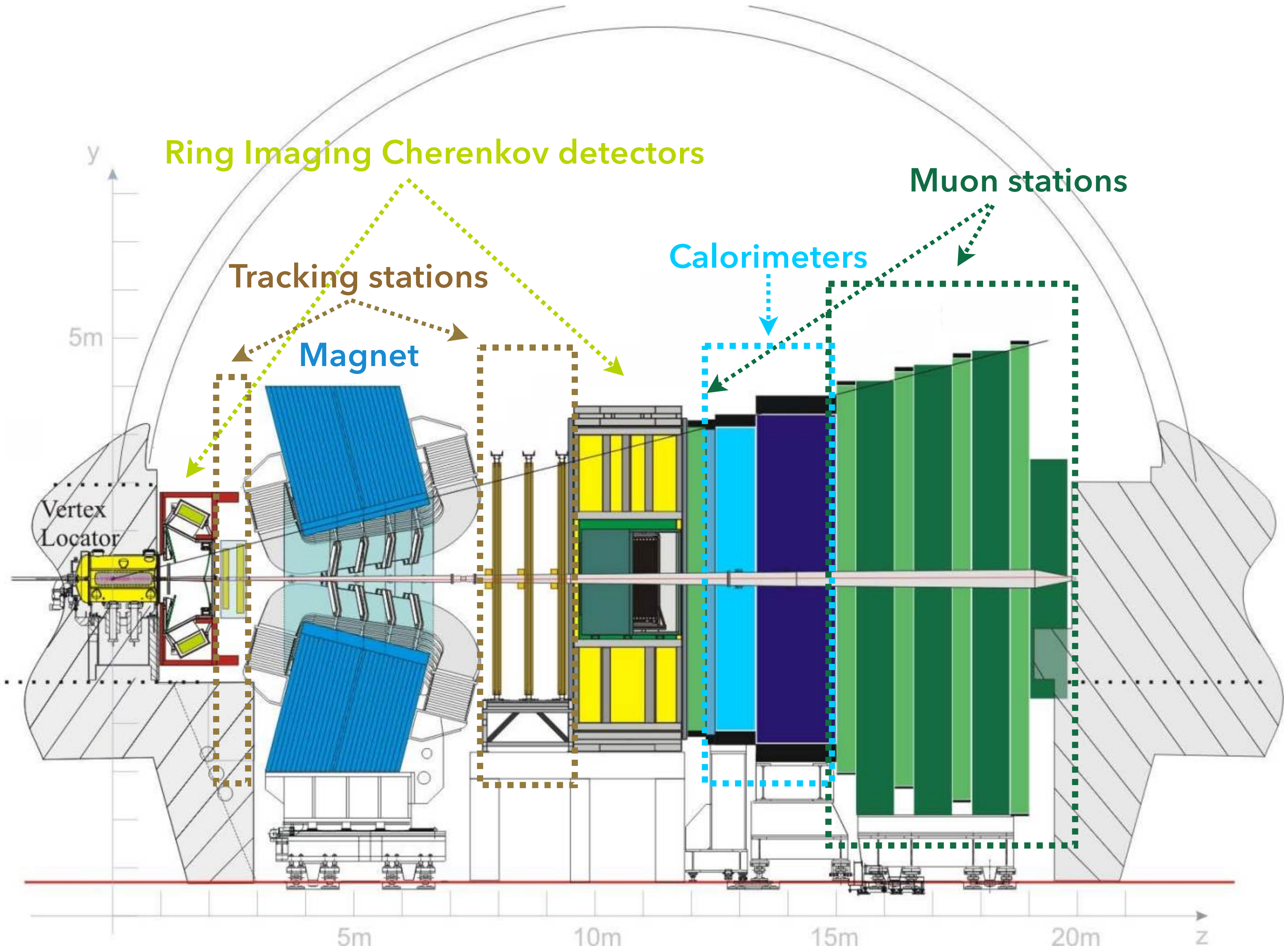
- LHCb results on $J/\psi, \psi(2S), \Upsilon, \chi_{c0}, \chi_{c1}, \chi_{c2}$ and double charmonium production.
- CDF-II ($p\bar{p}$ collisions) results on $J/\psi, \psi(2S)$ and χ_{c0} production.

LHC*b* RESULTS IN *pp* COLLISIONS

LHCb DETECTOR

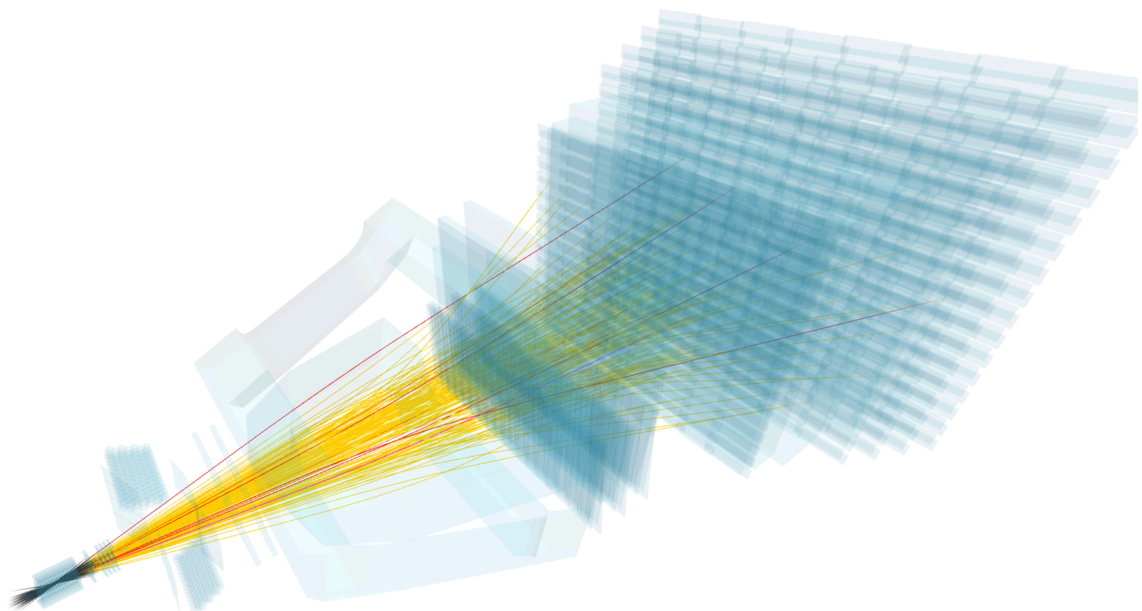
LHCb detector: located at the LHC, fully instrumented in the pseudorapidity (η) range $2 < \eta < 5$, partially in $-3.5 < \eta < -1.5$.

- Designed for b- and c-physics, but functions as a general purpose detector.
- Very high p resolution ($0.5 - 1\,\%$ ($5 - 200$ GeV)) and particle identification performance.

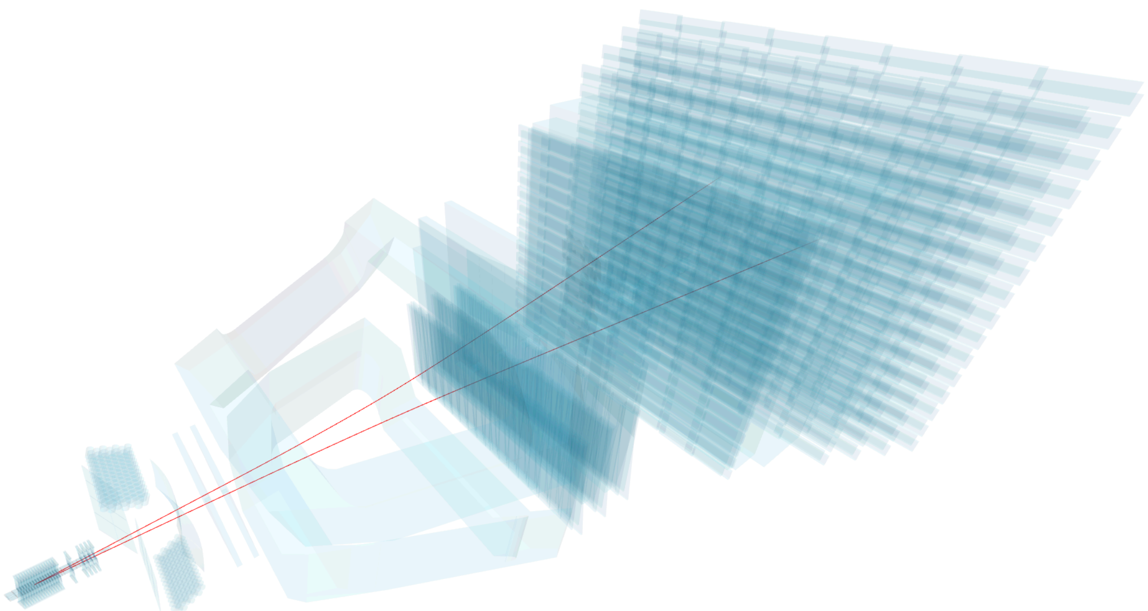


CENTRAL EXCLUSIVE PRODUCTION IN LHCb

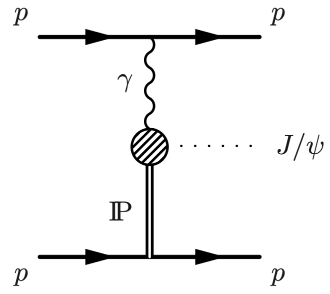
- Looks like this at LHCb:



Inelastic pp collision

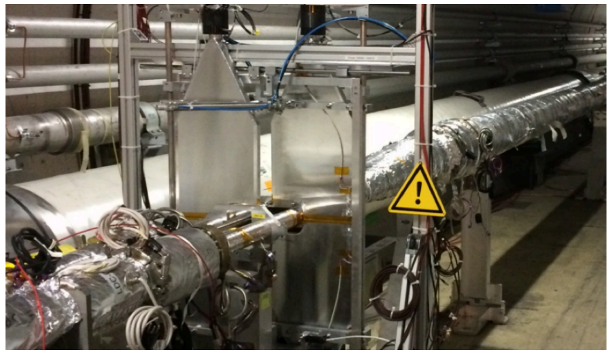


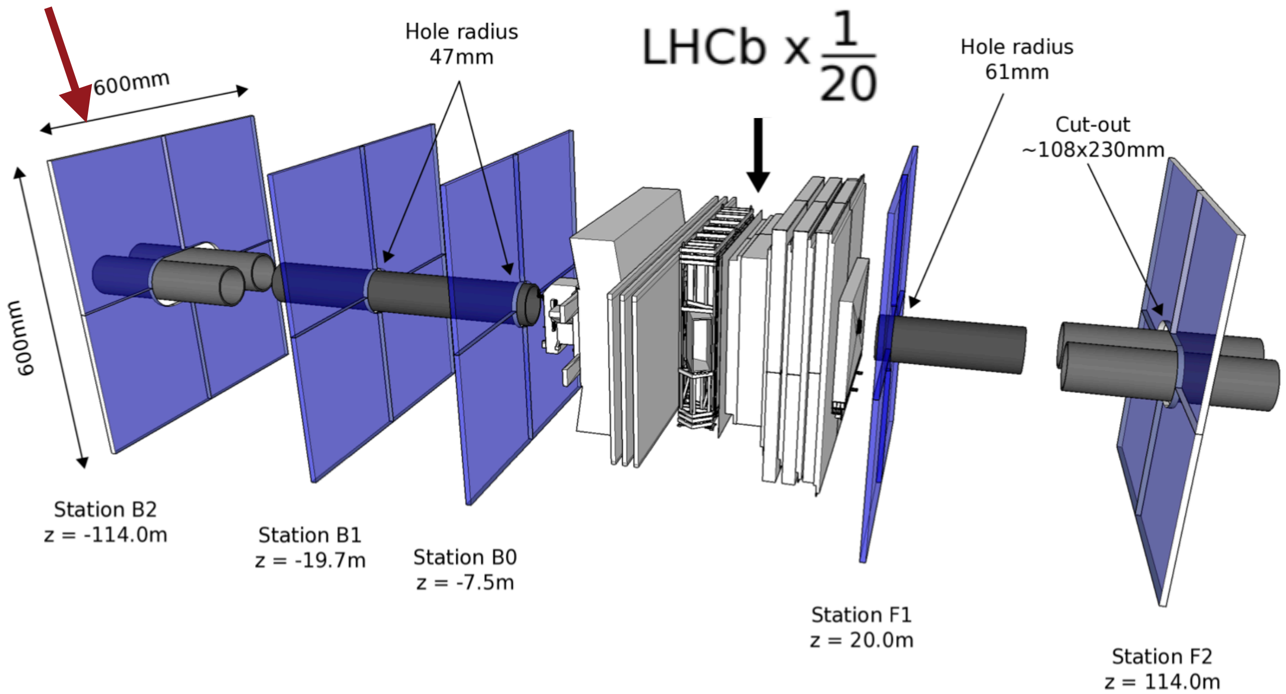
CEP pp collision, $J/\psi \to \mu^+\mu^-$



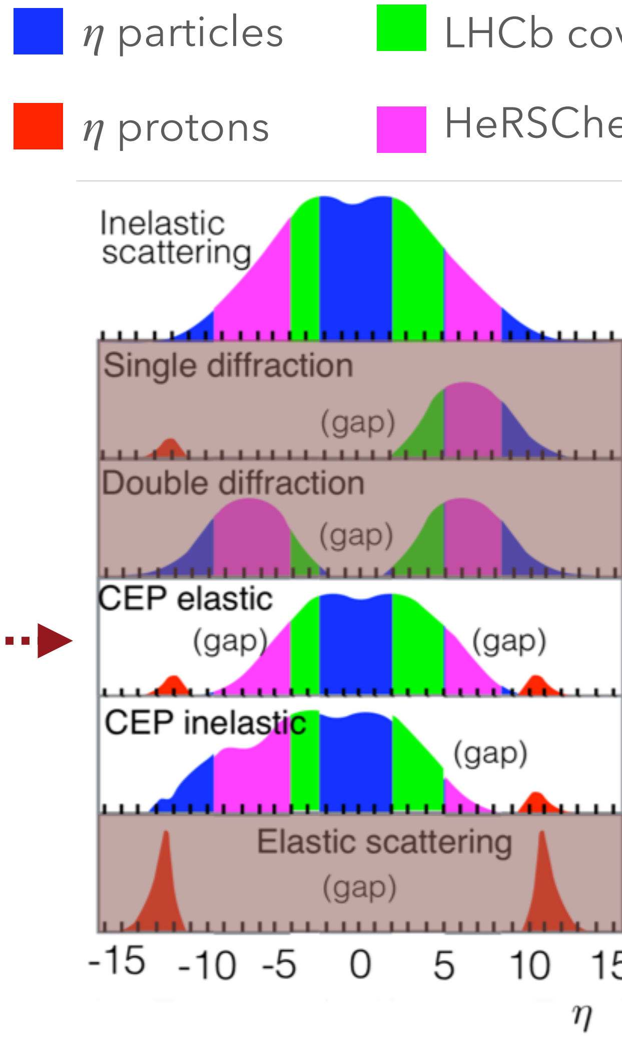
HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHCb

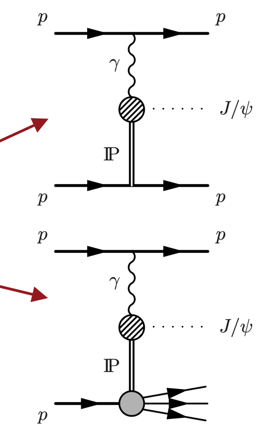
- Need to detect proton remnants → increase the LHCb coverage to $1.5 < \eta < 10$ in the forward and $-10 < \eta < -5, \; -3.5 < \eta < -1.5$ in the backward regions with HeRSChel [JINST 13 (2018) no.04, P04017].





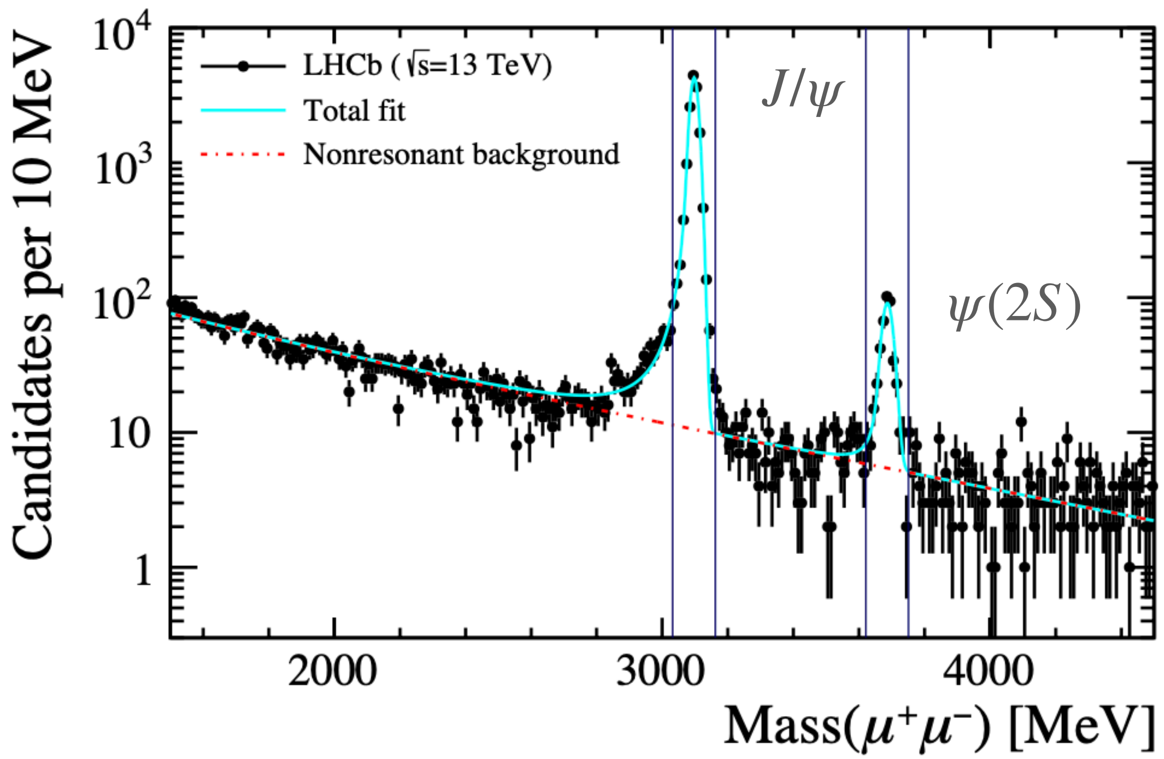
5 stations x 4 scintillating pads in each station





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

[JHEP 10 (2018) 167]



At LO in pQCD, cross-section ∝ (gluon PDF)².

→ Can reach Bjorken-x values down to $x \sim 10^{-6}$.

Selection:

✓ Two reconstructed tracks with $2.0 < \eta_{\mu^{\pm}} < 4.5$.

✓ $p_T^2 < 0.8$ GeV^2.

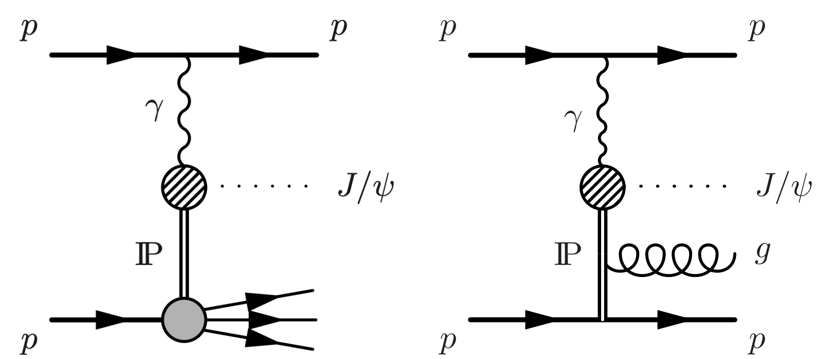
✓ HeRSCheL veto to suppress inelastic events.

Backgrounds:

✳ Continuum dimuon production ($\gamma\gamma$ fusion).

✳ Peaking at the J/ψ mass: χ_{c_J} and $\psi(2S)$ feed-down.

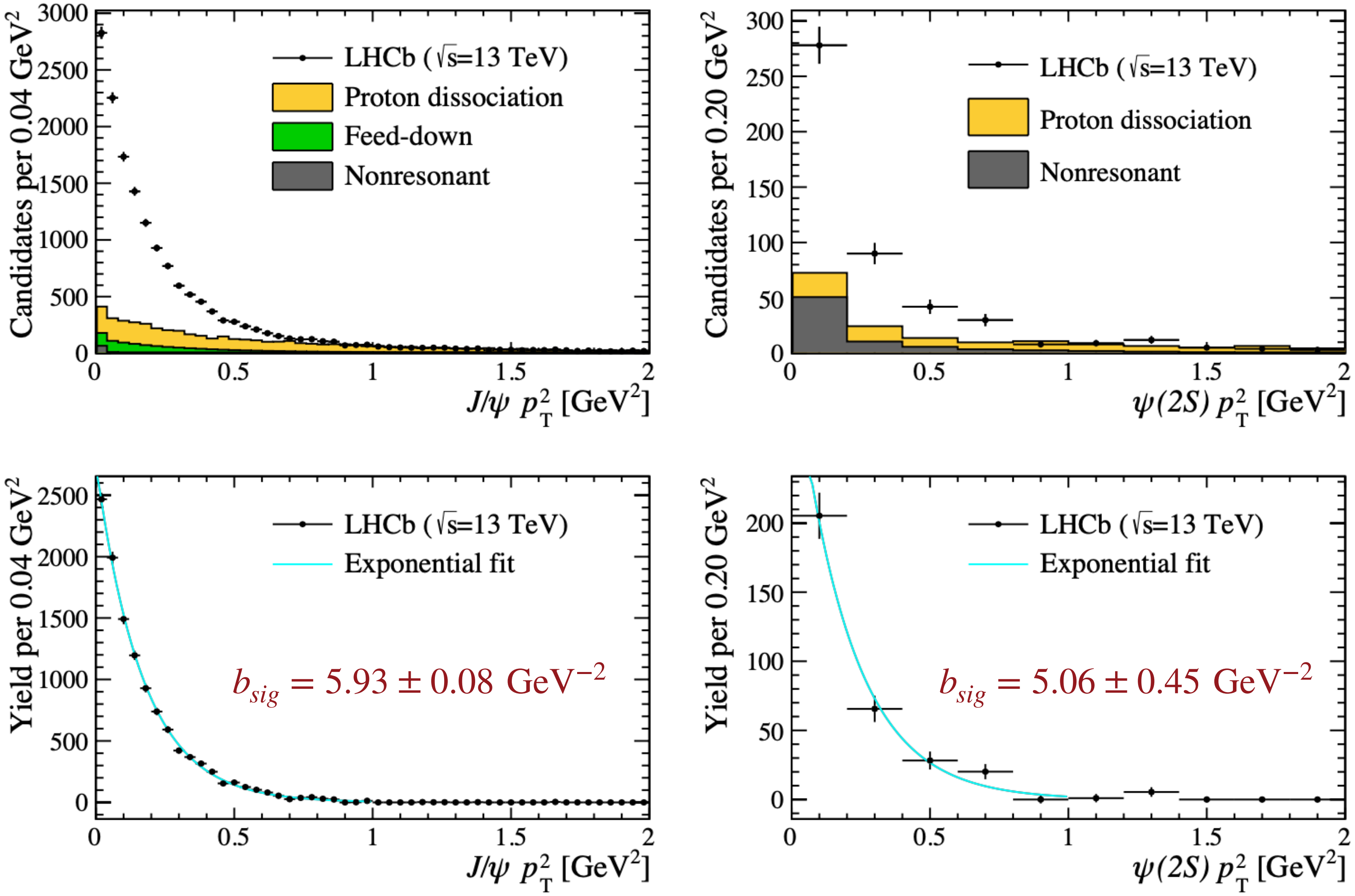
✳ Inelastic production: a proton dissociates or there is gluon emission.



CEP J/ψ AND $\psi(2S)$ IN LHCb 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: $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^2 \sim \exp(-b_{sig}p_\mathrm{T}^2)$, $b_{sig} \approx 6\ \mathrm{GeV}^{-2}$ → In agreement!



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

[JHEP 10 (2018) 167]

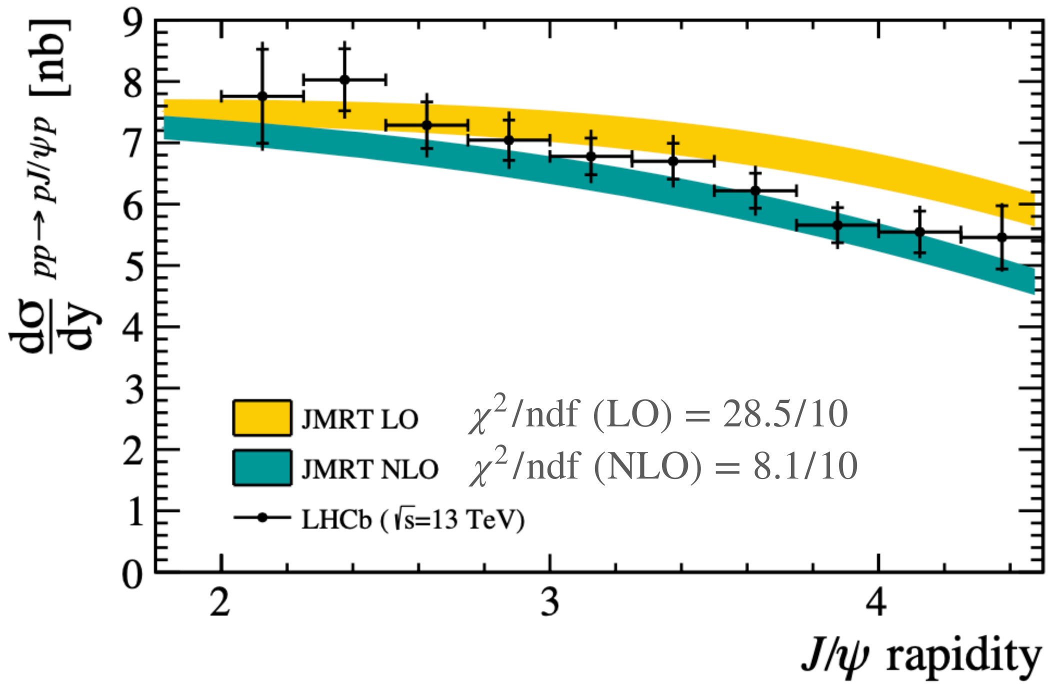
- Cross-section calculation per rapidity bin y with $\mathscr{L}_{\text{tot}} = 204 \pm 8\ \text{pb}^{-1}$:

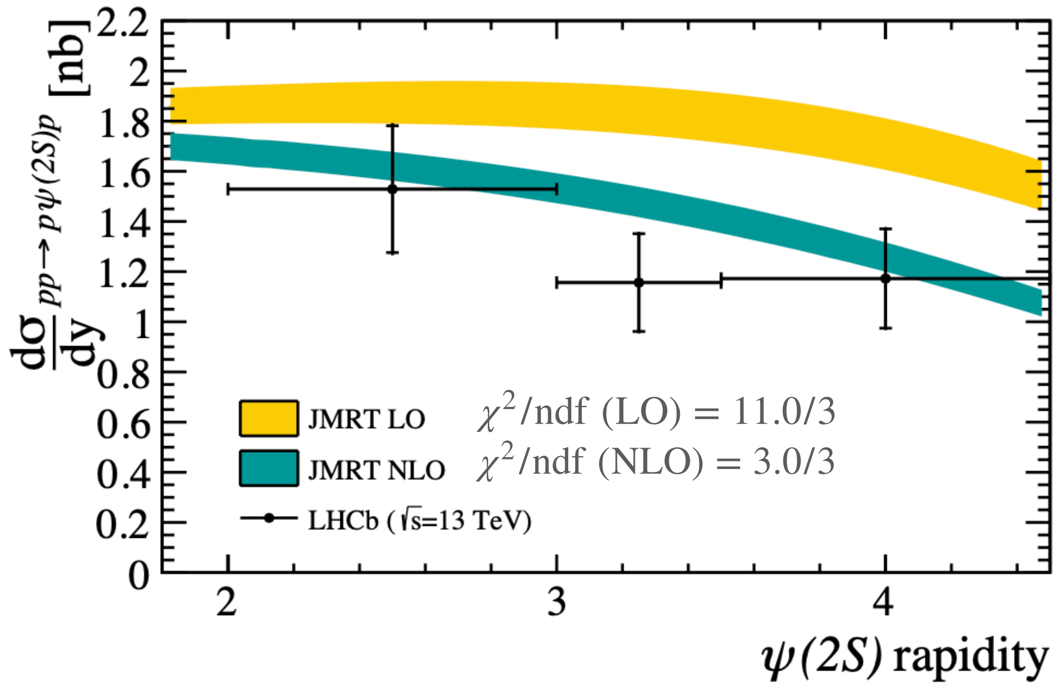
$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy} = \frac{N_{\text{sig}}}{\epsilon_{\text{tot}} \cdot \Delta y \cdot \epsilon_{\text{single}} \cdot \mathscr{L}_{\text{tot}}}$$

- ϵ_{tot} is the total reconstruction and selection efficiency.
- The integrated luminosity, $\mathscr{L}_{\text{tot}}$, is multiplied by the fraction of events with no additional interactions, ϵ_{single}.

$\sigma_{J/\psi\to\mu^+\mu^-} = 435 \pm 18\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 17\ (\text{lumi.})\ \text{pb}$

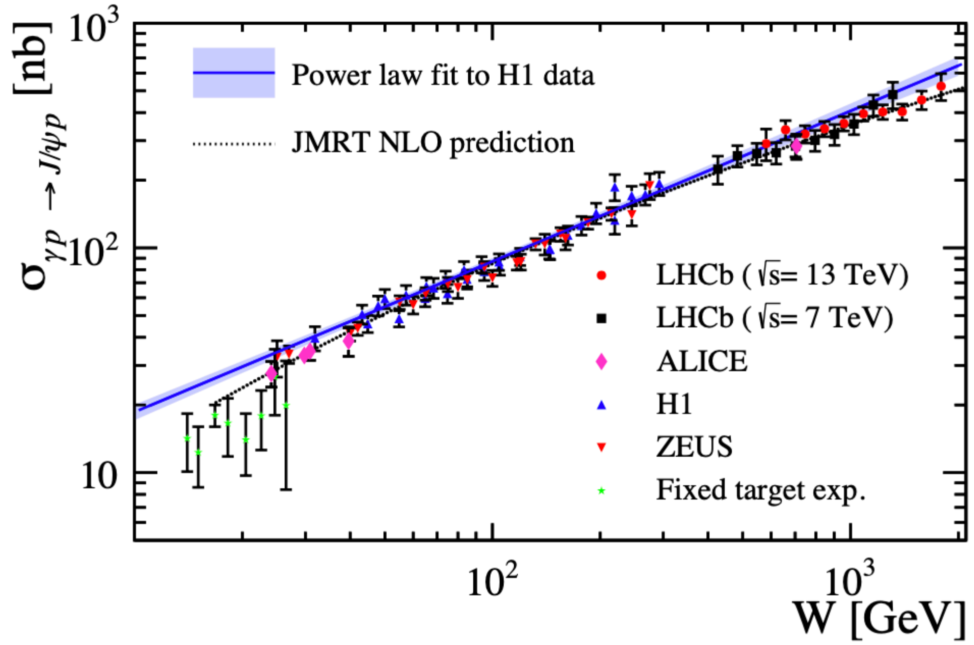
$\sigma_{\psi(2S)\to\mu^+\mu^-} = 11.1 \pm 1.1\ (\text{stat.}) \pm 0.3\ (\text{syst.}) \pm 0.4\ (\text{lumi.})\ \text{pb}$

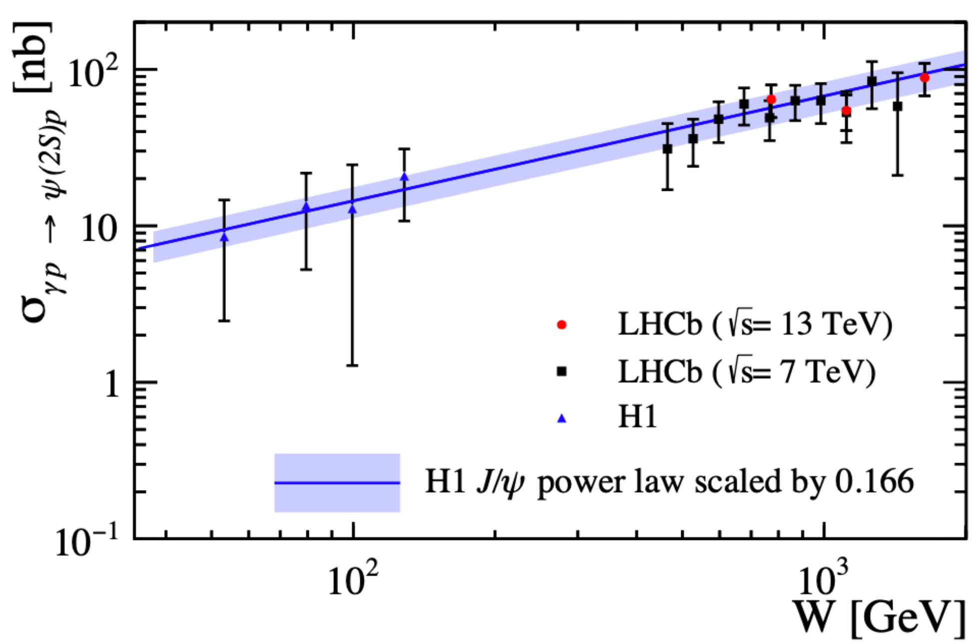




CEP J/ψ AND $\psi(2S)$ IN LHCb AT $\sqrt{s} = 13$ TeV

[JHEP 10 (2018) 167]





Photon-proton cross-section, $\sigma_{\gamma p \to \psi p}(W_+)$:

LHCb data — Calculated — Taken from HERA

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

γ parallel to LHCb beam axis — γ antiparallel to LHCb beam axis

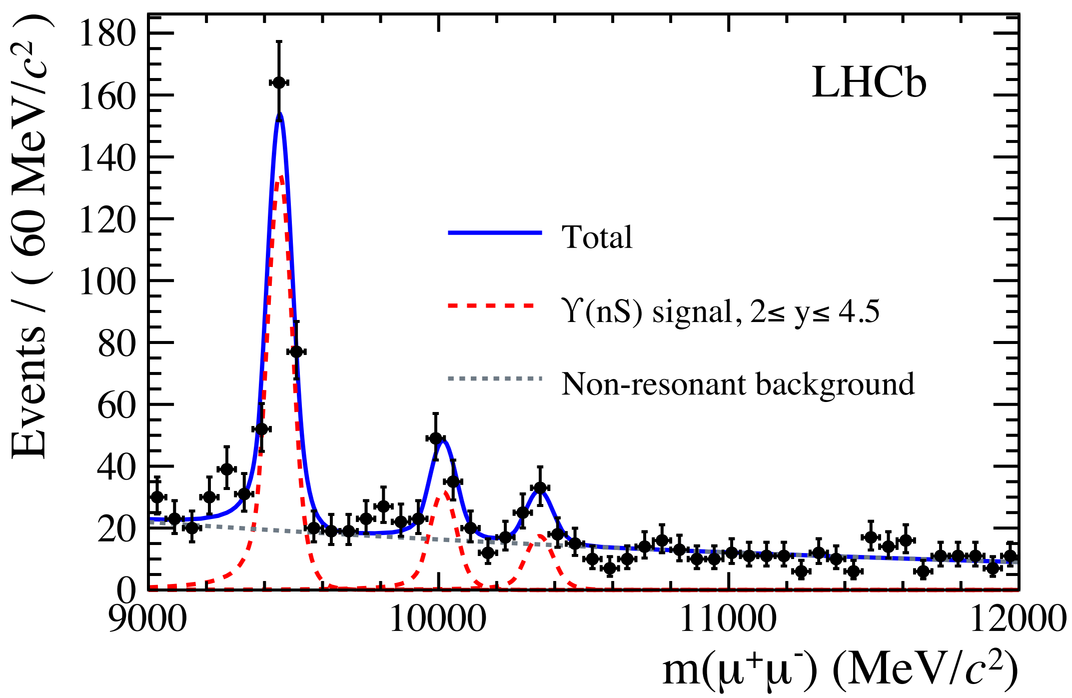
- $r(W_\pm)$ is the gap survival factor
- $k_\pm \equiv M_\psi/2e^{\pm|y|}$ is the photon energy
- $dn/dk_\pm$ is the photon flux
- $W_\pm = 2k_\pm\sqrt{s}$ is the γp system invariant mass

* 2-fold ambiguity: W_+, W_- contribute to the same LHCb rapidity bin → we fix W_- from the HERA H1 parametrisation.
* Working on an update with more data!

CEP $\Upsilon(nS)$ IN LHC*b* AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

[JHEP 1509 (2015) 084]

- Same motivation as for the $J/\psi, \psi(2S)$ analysis: can reach $x \sim 10^{-5}$.
- Three states $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, selected similarly to J/ψ and $\psi(2S)$ but without HeRSCheL information: not installed until Run 2 ($\sqrt{s} = 13$ TeV) .
- Backgrounds:
  - Continuum dimuon production ($\gamma\gamma$ fusion).
  - Peaking at the $\Upsilon(nS)$ mass: $\chi_b(mP) \to \Upsilon(nS)\gamma$ feed-down.
  - Inelastic production: a proton dissociates or there is gluon emission.
- Signal events obtained in two steps:
  1. Fit the mass shape and obtain *sWeights* for signal and continuum background.



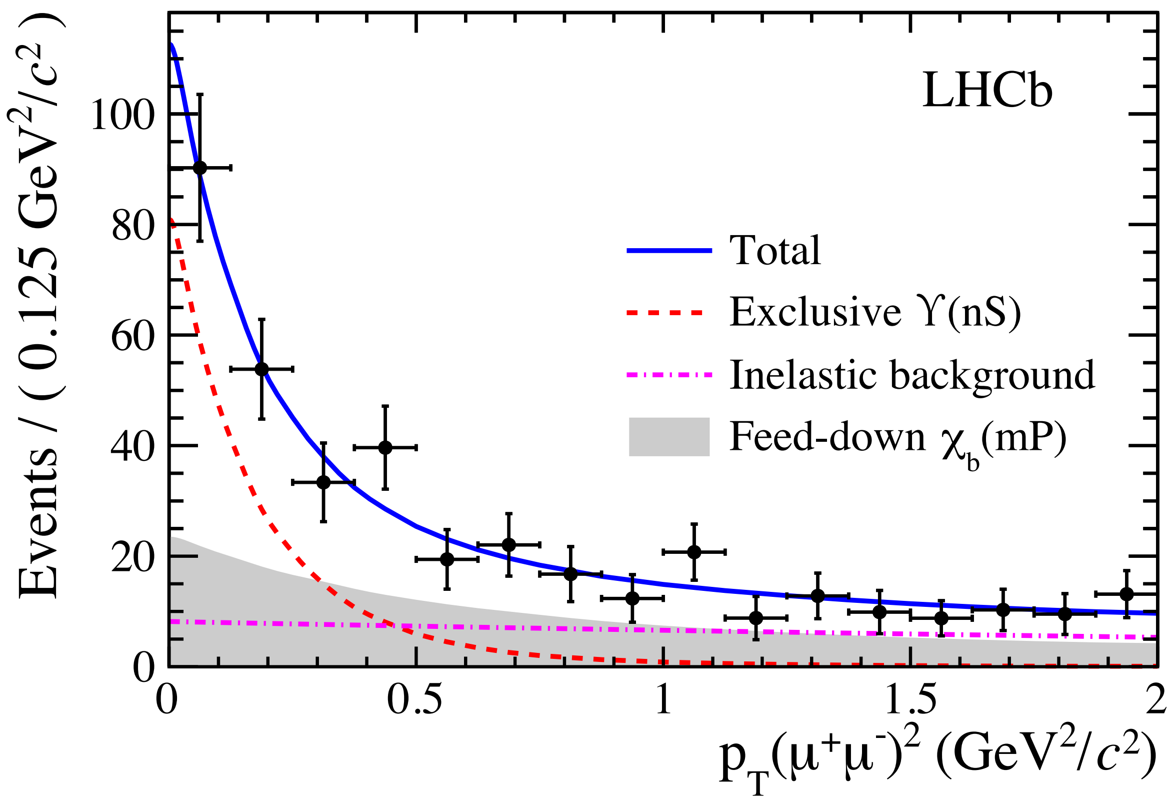
CEP $\Upsilon(nS)$ IN LHCb AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

[JHEP 1509 (2015) 084]

- **Signal events** obtained in two steps:

  2. The cross-section has the dependence $d\sigma/dp_{\mathrm{T}}^2 \sim \exp(-bp_{\mathrm{T}}^2)$: the signal yield can be obtained after fitting the signal-weighted p_{T}^2 distribution.

     - Signal and feed-down background modelled with SuperChic.



CEP $\Upsilon(nS)$ IN LHCb AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

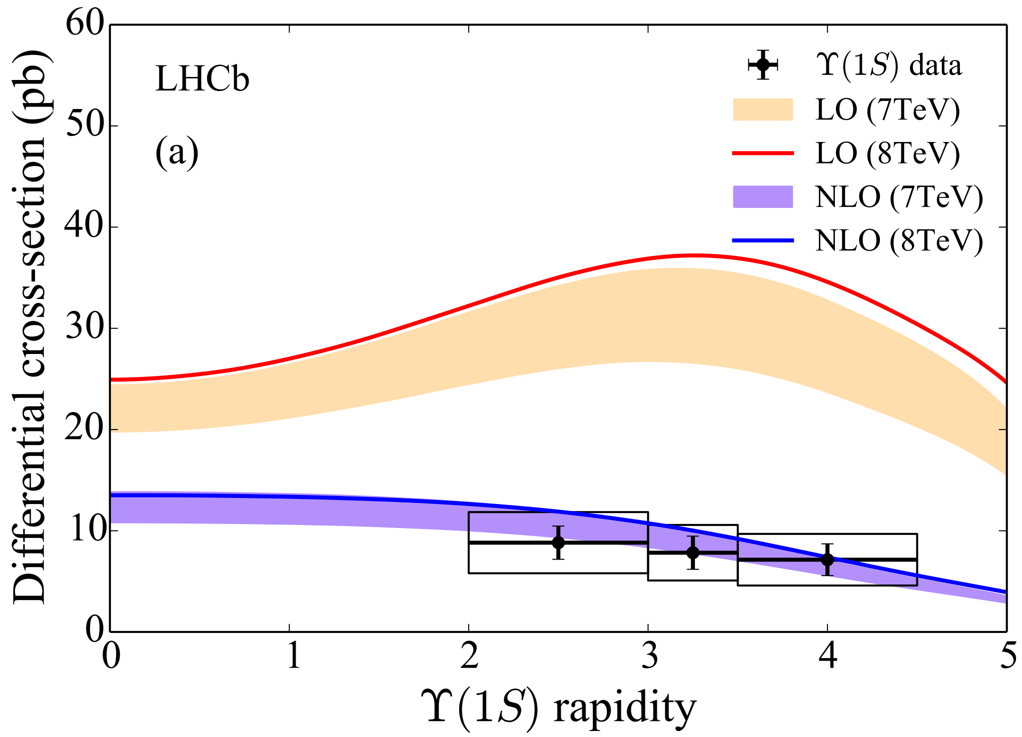
[JHEP 1509 (2015) 084]

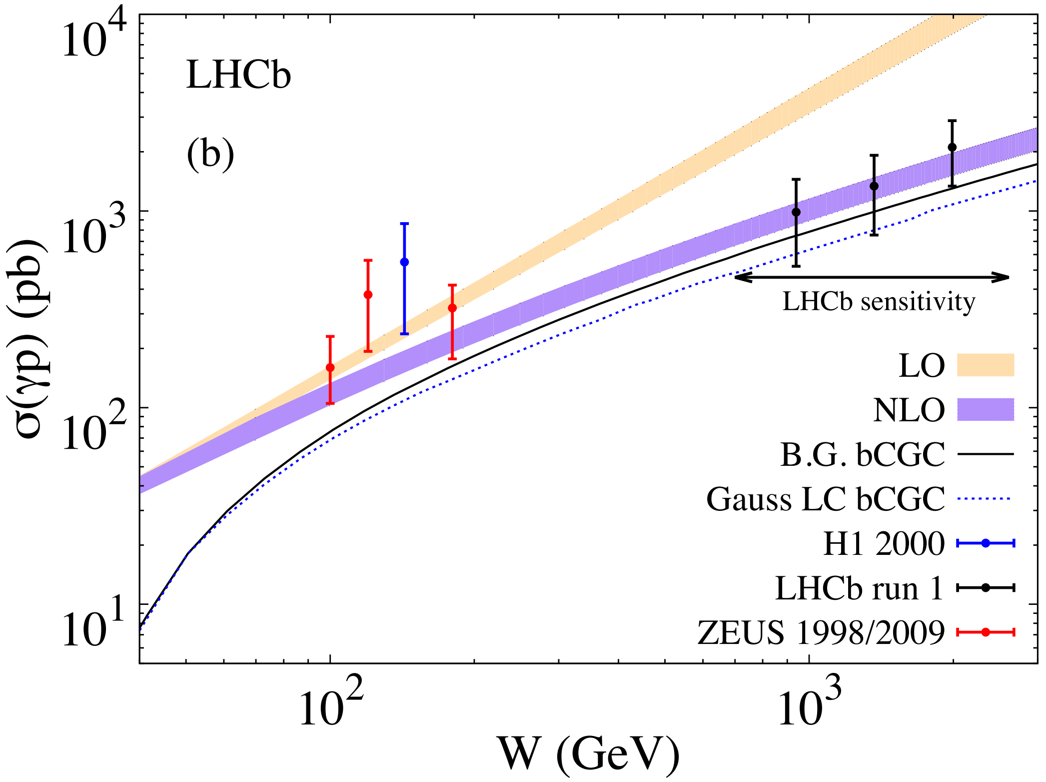
- The cross-sections with $2.9\ \mathrm{fb}^{-1}$ of data are:

$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1\ \text{(stat.)} \pm 1.7\ \text{(syst.) pb}$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8\ \text{(stat.)} \pm 0.3\ \text{(syst.) pb}$$
$$\sigma(pp \to p\Upsilon(3S)p) < 3.4\ \text{pb @95 \% C.L.}$$

  - Calculated in three rapidity bins for $\Upsilon(1S)$.

- Also calculated for $\Upsilon(1S)$ is the photoproduction cross-section $\sigma_{\gamma p \to \Upsilon p}(W_+)$, similarly to the J/ψ case.
  - Good agreement with the NLO prediction.



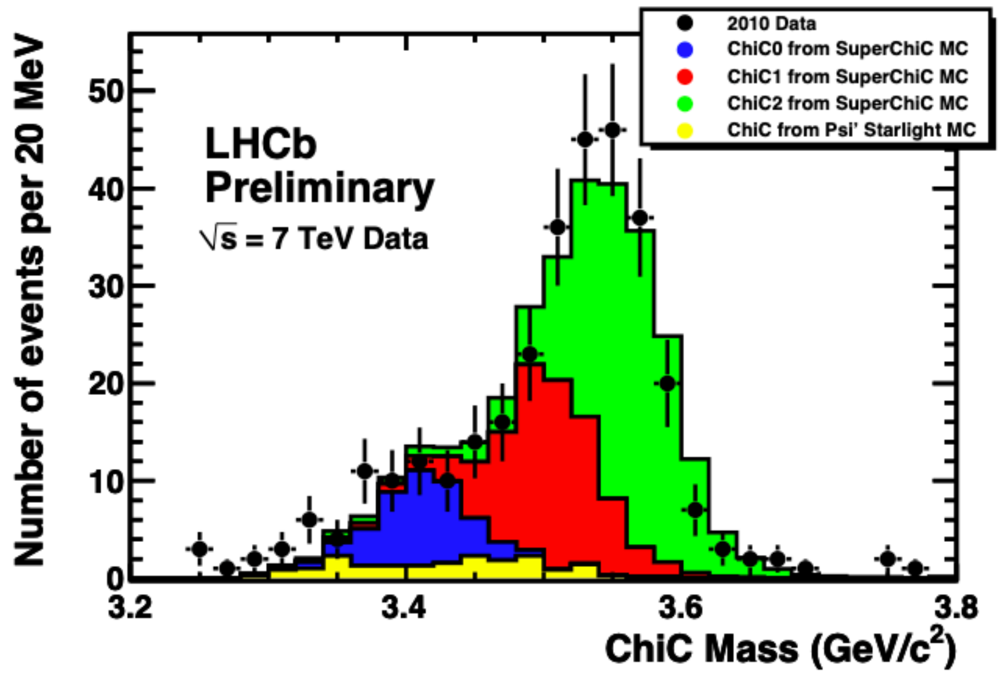


CEP $\chi_{c0}, \chi_{c1}, \chi_{c2}$ IN LHC*b* AT $\sqrt{s} = 7$ TeV

[LHCB-CONF-2011-022]

- Reconstruction of $\chi_{cJ} \to \mu^+\mu^-\gamma$: same selection as for J/ψ plus a photon with $E_T > 200$ MeV.
- Fit to $\mu^+\mu^-\gamma$ mass spectrum with:
  - Signal: $\chi_{c0}, \chi_{c1}, \chi_{c2}$ shapes taken from simulation (SuperChic).
  - Background: $\psi(2S)$ that decay to $\chi_{cJ}\gamma, J/\psi\eta$ or $J/\psi\pi^0\pi^0$ with only one photon reconstructed.
  - The ratio of $\chi_{c0} : \chi_{c1} : \chi_{c2}$ is $1 : 2.2 \pm 0.6 : 3.9 \pm 0.7$.
- Fit the J/ψ p_T^2 spectrum to determine number of exclusive events.
- The cross-sections ($\times BR$) are:

$$\sigma(pp \to p\chi_{c0}p) = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb}$$
$$\sigma(pp \to p\chi_{c1}p) = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb}$$
$$\sigma(pp \to p\chi_{c2}p) = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb}$$

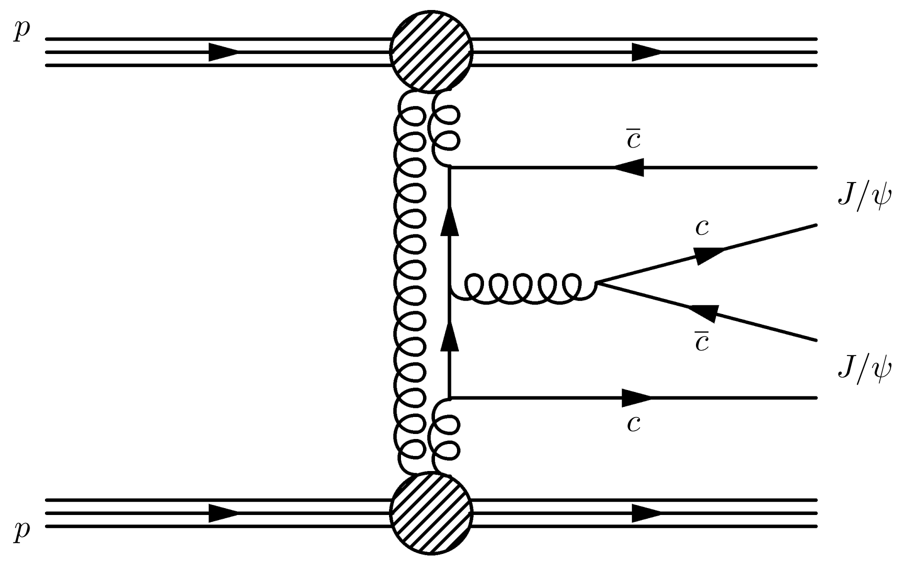


CHARMONIUM PAIRS IN LHCb AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

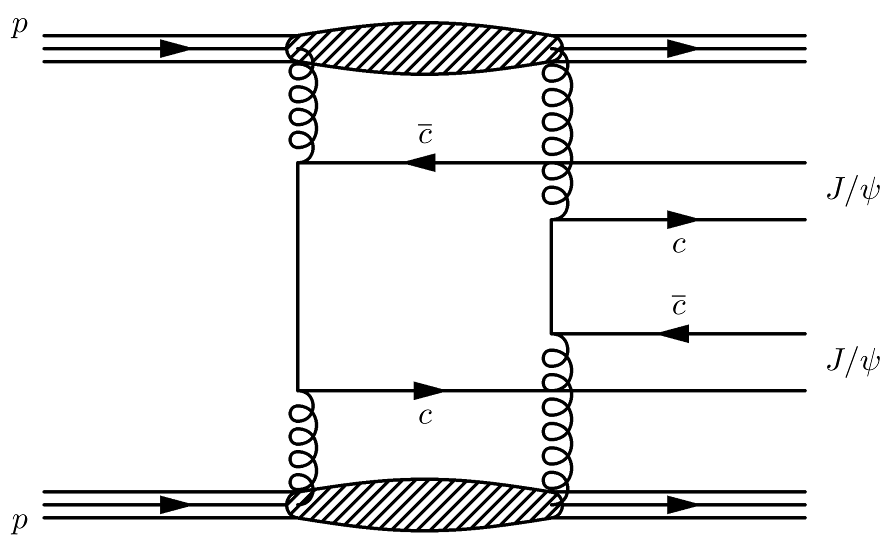
[J. PHYS. G41 (2014) 115002]

- Charmonium pair production sensitive to glueballs or tetraquarks.
  - Production mechanism: DPE ($\mathbb{P}\mathbb{P}$ fusion).

One t-channel gluon much softer than the other



Similar gluon exchange

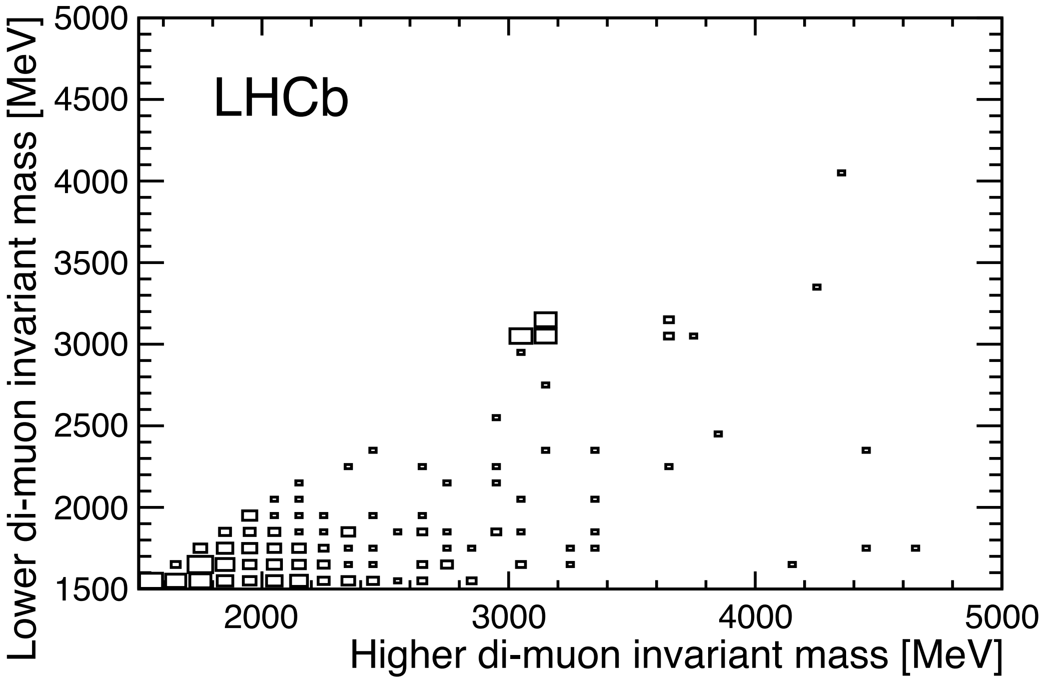


- Search for $J/\psi J/\psi, J/\psi\psi(2S), \psi(2s)\psi(2s), \chi_{cJ}\chi_{cJ}$ pairs.
- Similar selection as described previously for the $J/\psi, \psi(2S)$ and χ_{cJ} analyses.
  - $J/\psi, \psi(2S) \to \mu^+\mu^-$ and $\chi_{cJ} \to J/\psi\gamma$: detector signature four muons (+ 2 photons)

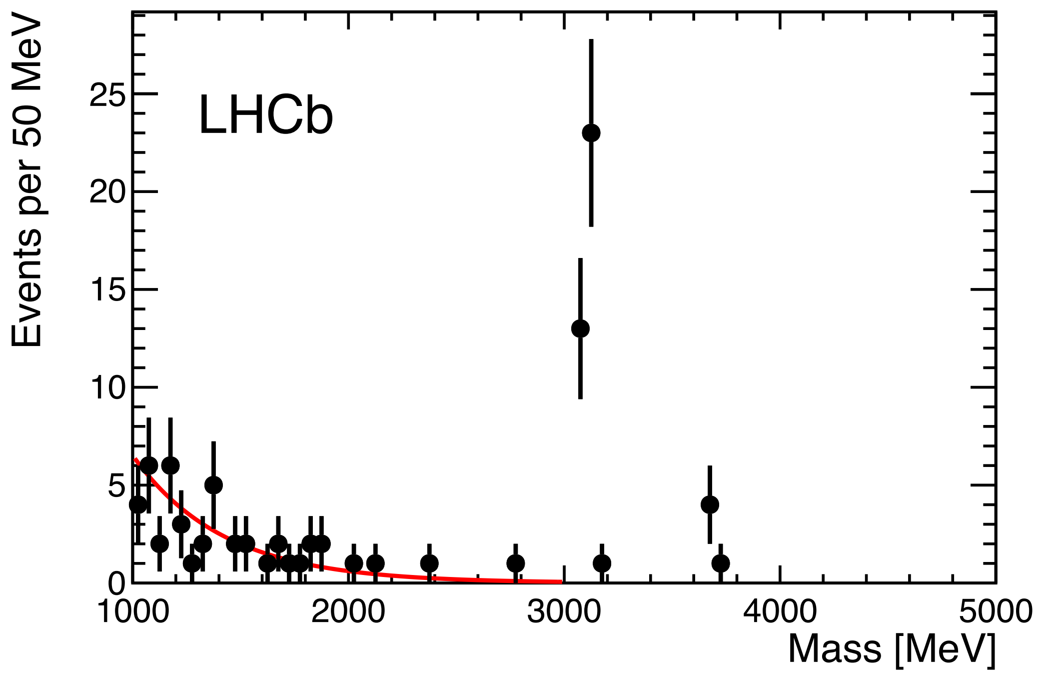
CHARMONIUM PAIRS IN LHCb AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

[J. PHYS. G41 (2014) 115002]

- Invariant mass of dimuon candidates accumulation around J/ψ and $\psi(2S)$ masses.
- Require one to be compatible with the J/ψ or $\psi(2S)$ mass, show the invariant mass of the other dimuon candidate.



Red curve: exponential fit to non-resonant background



- This yields:
  - 37 $J/\psi J/\psi$ candidates, 5 $J/\psi\psi(2S)$ candidates and no $\psi(2S)\psi(2S)$ candidates.
  - Searching for $\chi_{cJ}\chi_{cJ}$: 1 $\chi_{c0}\chi_{c0}$ candidate, no $\chi_{c1,2}\chi_{c1,2}$ candidates.

CHARMONIUM PAIRS IN LHCb AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

[J. PHYS. G41 (2014) 115002]

- Backgrounds:
  - Non-resonant background: only considered for $J/\psi, \psi(2S)$ and fit with an exponential curve.
  - Feed-down considered for $J/\psi J/\psi$ and $\chi_{cJ}\chi_{cJ}$:
    - From $J/\psi\psi(2S)$ pairs where $\psi(2S) \rightarrow J/\psi X$ that are sometimes reconstructed as only J/ψ or χ_{cJ}.
    - No evidence found for χ_{cJ} feed-down to the $J/\psi J/\psi$ sample.

- The cross-sections are estimated to be:

$$\sigma^{J/\psi J/\psi} = 65 \pm 11 \text{ (stat.)} \pm 6 \text{ (syst.) pb}$$
$$\sigma^{J/\psi\psi(2S)} = 63^{+27}_{-18}\text{(stat.)} \pm 10 \text{ (syst.) pb}$$
$$\sigma^{\psi(2S)\psi(2S)} < 237 \text{ pb } @90\,\% \text{ C.L.}$$
$$\sigma^{\chi_{c0}\chi_{c0}} < 69 \text{ pb } @90\,\% \text{ C.L.}$$
$$\sigma^{\chi_{c1}\chi_{c1}} < 45 \text{ pb } @90\,\% \text{ C.L.}$$
$$\sigma^{\chi_{c2}\chi_{c2}} < 141 \text{ pb } @90\,\% \text{ C.L.}$$

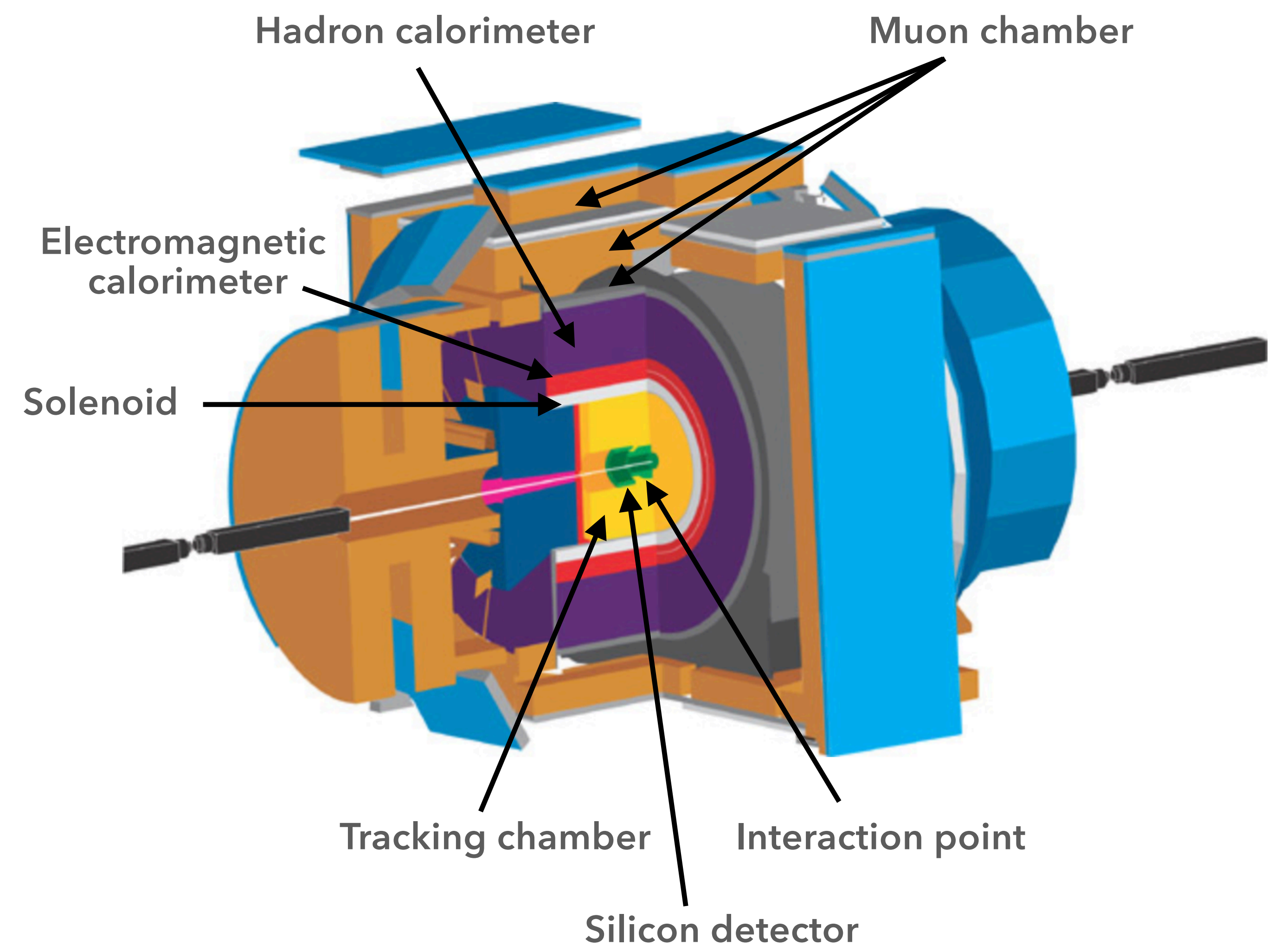
CDF-II RESULTS IN $p\bar{p}$ COLLISIONS

CEP $J/\psi, \psi(2S)$ AND χ_{c0} IN CDF-II AT $\sqrt{s} = 1.96$ TeV

[PRL 102 (2009) 242001]

Collider Detector at Fermilab (CDF-II)
→ Located at the Tevatron, a $p\bar{p}$ collider.

- ✳ 100% efficiency reconstructing isolated tracks with $p_T \geq 1$ GeV$/c$, $|\eta| < 0.6$.
- ✳ Beam shower scintillation counters along the beam pipe to detect $p(\bar{p})$ fragmentation with $|\eta| < 7.4$.

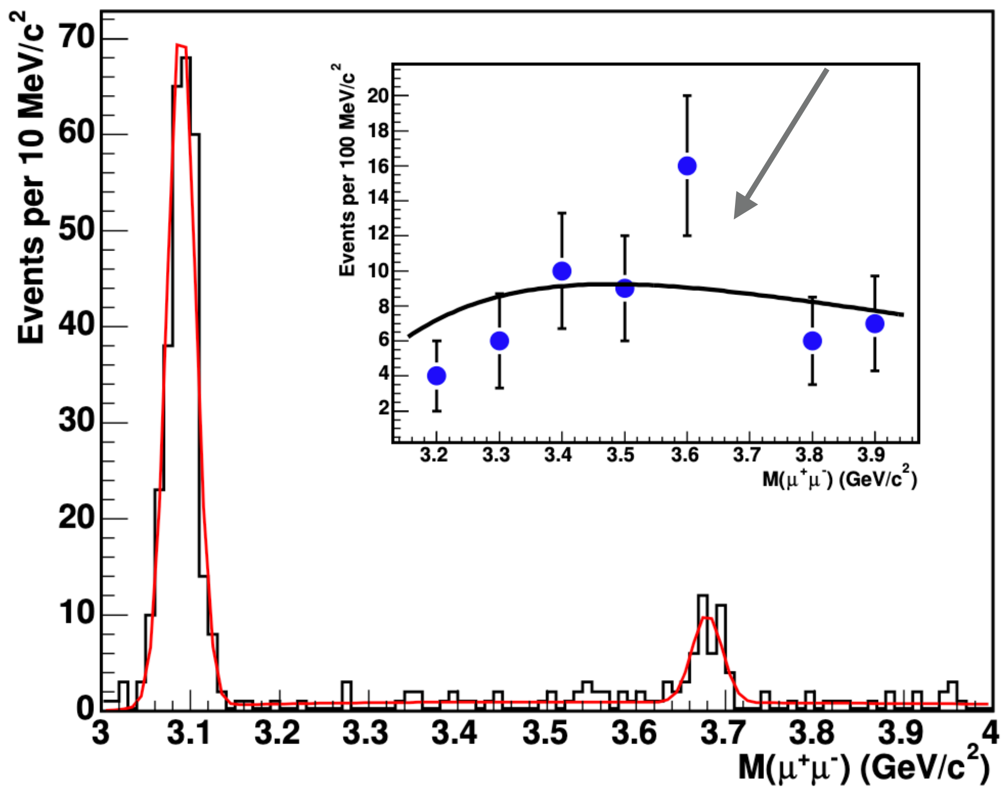


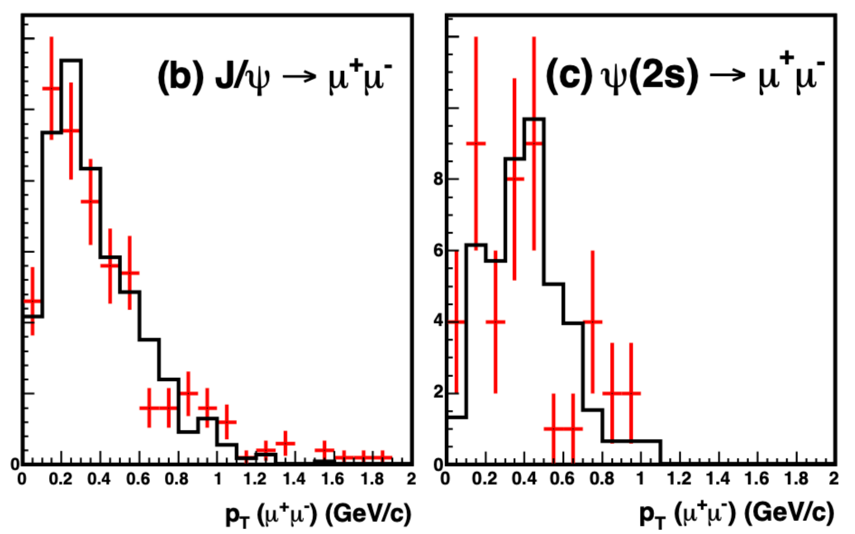
CEP $J/\psi, \psi(2S)$ AND χ_{c0} IN CDF-II AT $\sqrt{s} = 1.96$ TeV

[PRL 102 (2009) 242001]

- Two muon tracks with $p_T \geq 1.4$ GeV/c, $|\eta| < 0.6$ and
  - no other particle for J/ψ and $\psi(2S)$ reconstruction,
  - only one additional EM shower for χ_{c0} reconstruction with $E_T > 80$ MeV.
- Dimuon spectrum fit with two gaussians and a shape to fit the non-resonant background.
- Probability of $p(\bar{p})$ fragmentation with all products in $|\eta| < 7.4$ is 0.14 ± 0.02 (syst.).
- J/ψ and $\psi(2S)$ p_T^2 distribution fit by STARLIGHT.

Inset: fit to the region above the J/ψ mass (excluding $\psi(2S)$) – non-resonant bkg.





CEP $J/\psi, \psi(2S)$ AND χ_{c0} IN CDF-II AT $\sqrt{s} = 1.96$ TeV

[PRL 102 (2009) 242001]

- For χ_{c0} reconstruction, two muon tracks and one EM shower with $E_{\mathrm{T}} > 80$ MeV are required.
  - 65 events found for $\chi_{c0} \rightarrow J/\psi\gamma$.
  - All events taken as χ_{c0} events, as the p_{T}^2 of J/ψ from χ_{c0} matches that simulated by CHICMC.

- The cross-section values are:

$$\sigma(pp \rightarrow pJ/\psi p) = 3.92 \pm 0.25\ (\text{stat.}) \pm 0.52\ (\text{syst.})\ \text{nb}$$
$$\sigma(pp \rightarrow p\psi(2S)p) = 0.53 \pm 0.09\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \text{nb}$$
$$\sigma(pp \rightarrow p\chi_{c0}p) = 76 \pm 10\ (\text{stat.}) \pm 10\ (\text{syst.})\ \text{nb}$$

CEP $J/\psi, \psi(2S)$ AND χ_{c0} IN CDF-II AT $\sqrt{s} = 1.96$ TeV

[PRL 102 (2009) 242001]

Comparison with LHCb results:

For LHCb: $\sigma \times BR$

	LHCb (pp) (stat. + syst. + lumi.) $\sqrt{s} = 7$ TeV	LHCb (pp) (stat. + syst. + lumi.) $\sqrt{s} = 13$ TeV	CDF ($p\bar{p}$) (stat. + syst.) $\sqrt{s} = 1.96$ TeV
$\sigma(J/\psi \to \mu^+\mu^-)$		$435 \pm 18 \pm 11 \pm 17$ pb	$3.92 \pm 0.25 \pm 0.52$ nb
$\sigma(\psi(2S) \to \mu^+\mu^-)$		$11.1 \pm 1.1 \pm 0.3 \pm 0.4$ pb	$0.53 \pm 0.09 \pm 0.10$ nb
$\sigma(\chi_{c0} \to \mu^+\mu^-\gamma)$	$9.3 \pm 2.2 \pm 3.5 \pm 1.8$ pb		$76 \pm 10 \pm 10$ nb
$\sigma(\chi_{c1} \to \mu^+\mu^-\gamma)$	$16.4 \pm 5.3 \pm 5.8 \pm 3.2$ pb		
$\sigma(\chi_{c2} \to \mu^+\mu^-\gamma)$	$28.0 \pm 5.4 \pm 9.7 \pm 5.4$ pb		

- Distinguishing between χ_{cJ} states complicated for both experiments.
  - CDF-II assumption: χ_{c0} is the dominant state, χ_{c1}, χ_{c2} negligible.
  - For LHCb, $\sigma^{\chi_{c0}} < \sigma^{\chi_{c1}} < \sigma^{\chi_{c2}}$.

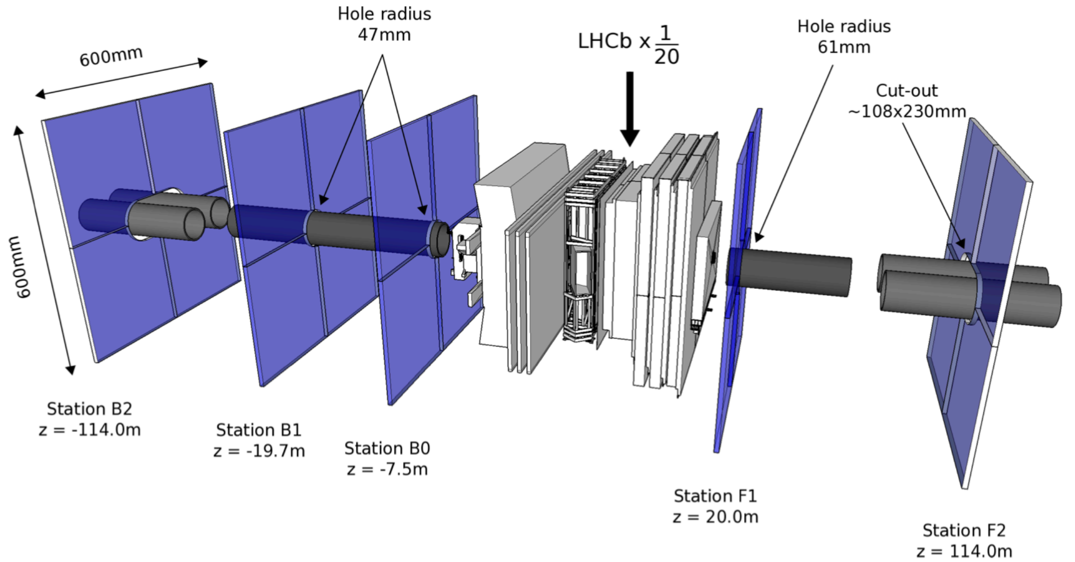
SUMMARY

	LHCb (pp) (stat. + syst. + lumi.) or (stat. + syst.)			CDF ($p\bar{p}$) (stat. + syst.)
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 1.96$ TeV
$\sigma(J/\psi \to \mu^+\mu^-)$			$435 \pm 18 \pm 11 \pm 17$ pb	$3.92 \pm 0.25 \pm 0.52$ nb
$\sigma(\psi(2S) \to \mu^+\mu^-)$			$11.1 \pm 1.1 \pm 0.3 \pm 0.4$ pb	$0.53 \pm 0.09 \pm 0.10$ nb
$\sigma(\chi_{c0} \to \mu^+\mu^-\gamma)$	$9.3 \pm 2.2 \pm 3.5 \pm 1.8$ pb			$76 \pm 10 \pm 10$ nb
$\sigma(\chi_{c1} \to \mu^+\mu^-\gamma)$	$16.4 \pm 5.3 \pm 5.8 \pm 3.2$ pb			
$\sigma(\chi_{c2} \to \mu^+\mu^-\gamma)$	$28.0 \pm 5.4 \pm 9.7 \pm 5.4$ pb			
$\sigma(\Upsilon(1S) \to \mu^+\mu^-)$	$9.0 \pm 2.1 \pm 1.7$ pb			
$\sigma(\Upsilon(2S) \to \mu^+\mu^-)$	$1.3 \pm 0.8 \pm 0.3$ pb			
$\sigma(\Upsilon(3S) \to \mu^+\mu^-)$	< 3.4 pb @95 % C.L.			
$\sigma(J/\psi J/\psi)$	$65 \pm 11 \pm 6$ pb			
$\sigma(J/\psi\psi(2S))$	$63^{+27}_{-18} \pm 10$ pb			
$\sigma(\psi(2S)\psi(2S))$	< 237 pb @90 % C.L.			
$\sigma(\chi_{c0}\chi_{c0})$	< 69 pb @90 % C.L.			
$\sigma(\chi_{c1}\chi_{c1})$	< 45 pb @90 % C.L.			
$\sigma(\chi_{c2}\chi_{c2})$	< 141 pb @90 % C.L.			

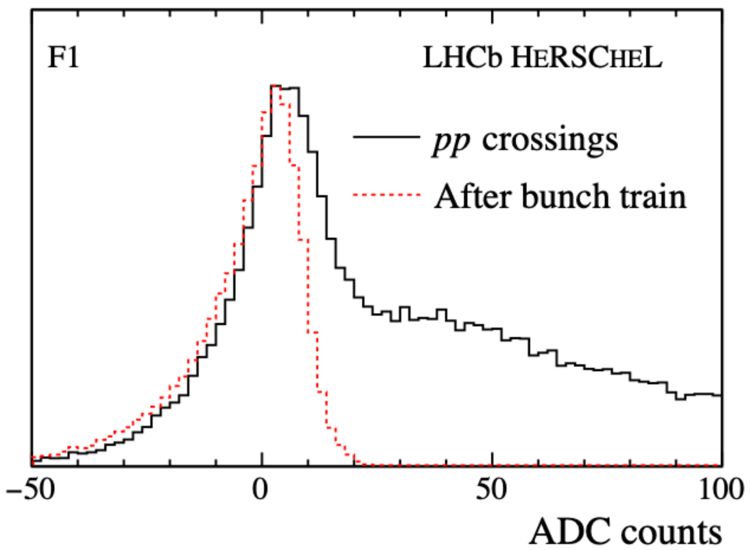
Lots of results, and lots of room for improvement with more data!

THANK YOU FOR YOUR ATTENTION!

HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHCb



- 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.



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

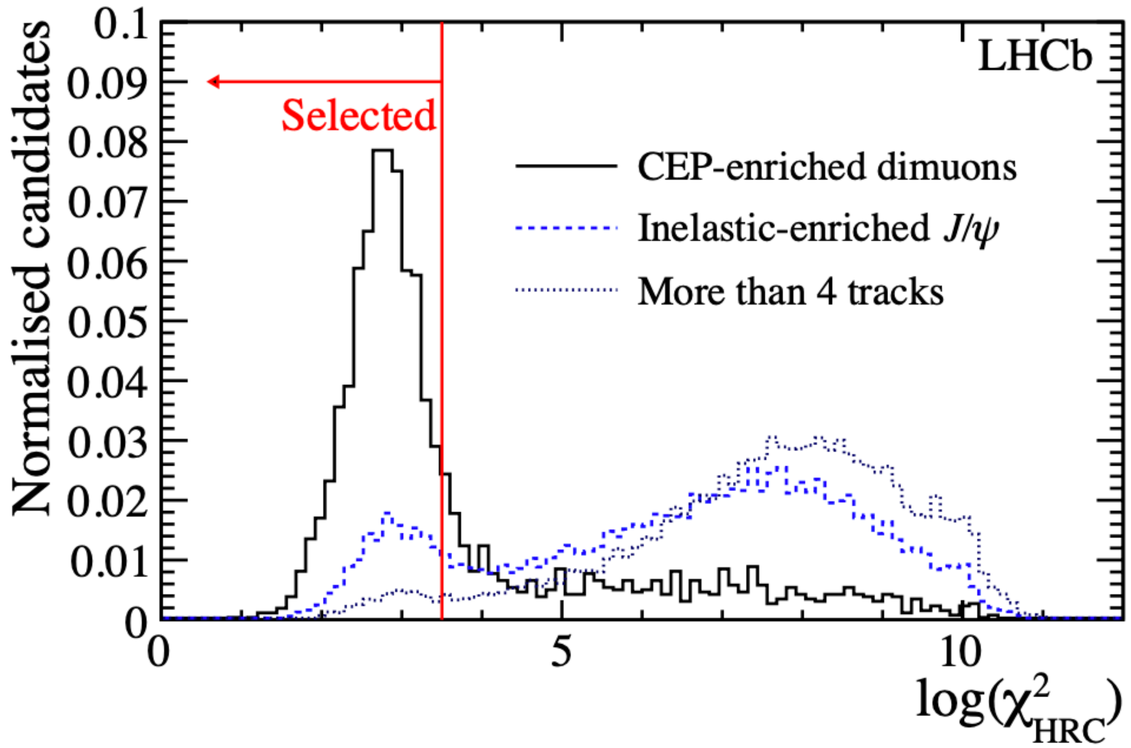
$$X_i = \frac{x_i - \mu_i}{\sigma_i}, \quad x_i > \mu_i$$
$$X_i = \frac{x_i - \mu_i}{\sigma_i(1+\lambda_i x_i)}, \quad x_i < \mu_i$$

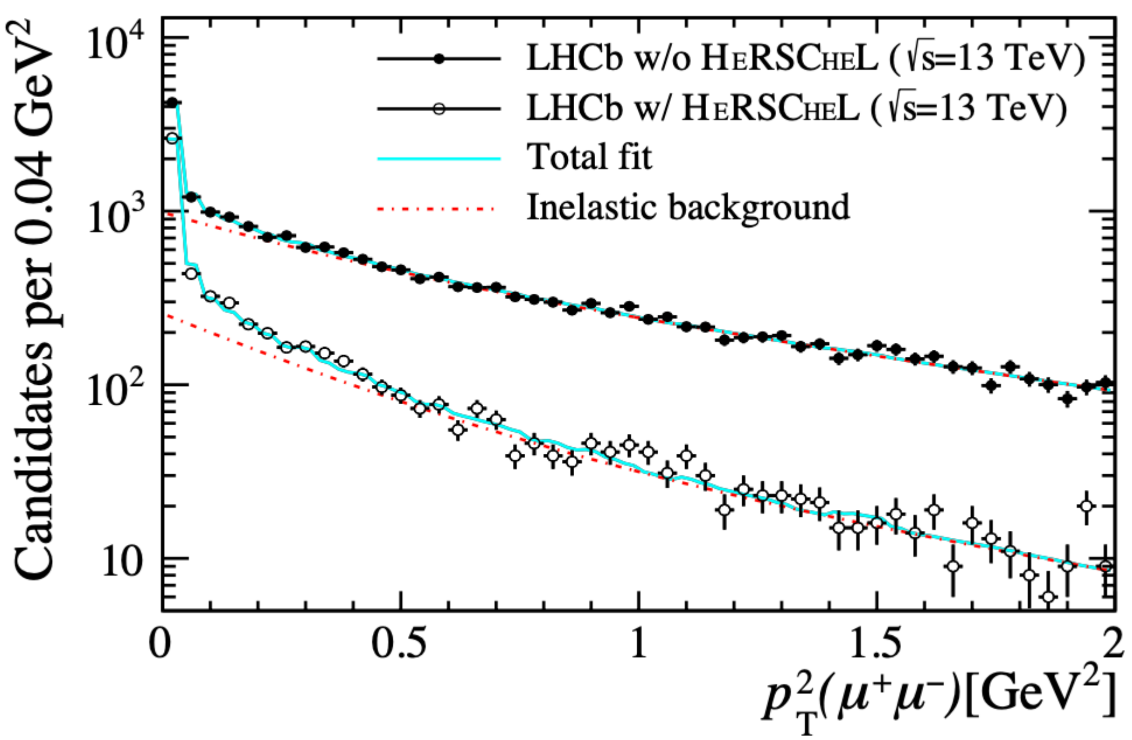
CEP J/ψ AND $\psi(2S)$ IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

[JHEP 10 (2018) 167]

- 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!

Chosen cut : $\log(\chi^2_{HRC}) < 3.5$, efficiency $= 0.723 \pm 0.008$





- Estimate inelastic background by using two samples: above and below HeRSCheL veto.

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

[JHEP 10 (2018) 167]

Estimating the contribution of the proton dissociation background:

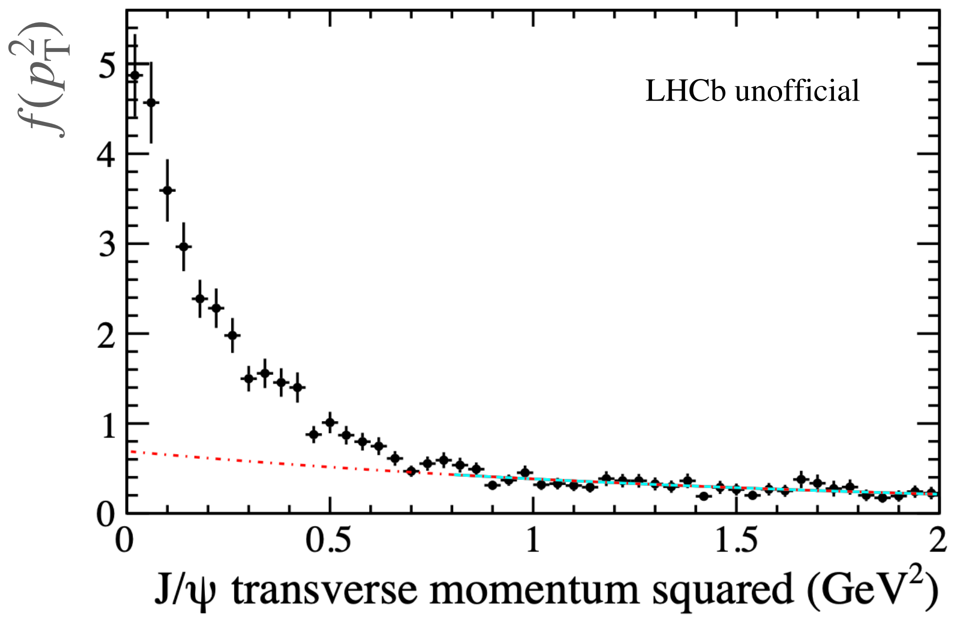
* Take p_T^2 distribution with non-resonant $\mu\mu$ and feed-down bkg removed
* Define two samples and define a variable with exclusive events, β:

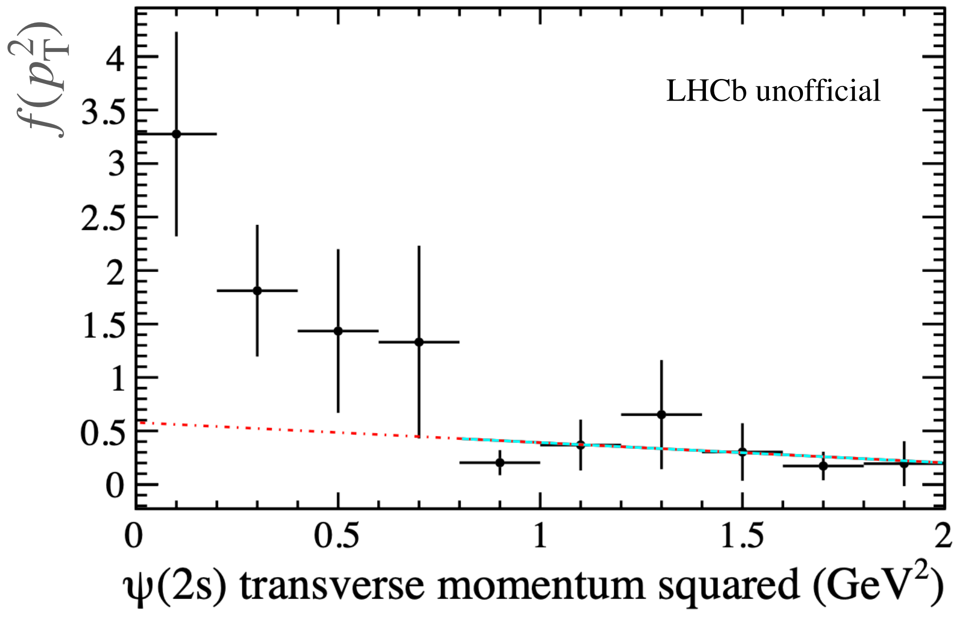
S_H for $\log(\chi^2_{HRC}) < 3.5$

$S_{\overline{H}}$ for $\log(\chi^2_{HRC}) > 3.5$

$\beta = S_{\overline{H}} - ((1-\epsilon_H)/\epsilon_H)\ S_H$ with ϵ_H the efficiency for a CEP event to be in S_H

* Proton dissociation bkg: scale β by $f(p_\mathrm{T}^2) \equiv S_H(p_\mathrm{T}^2)/\beta(p_\mathrm{T}^2)$





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

[JHEP 10 (2018) 167]

* 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

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

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

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+)+r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

- 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: $\sigma_{\gamma p\to J/\psi p} = a(W/90\mathrm{GeV})^{\delta}$, $a = 81 \pm 3$ pb and $\delta = 0.67 \pm 0.03$.

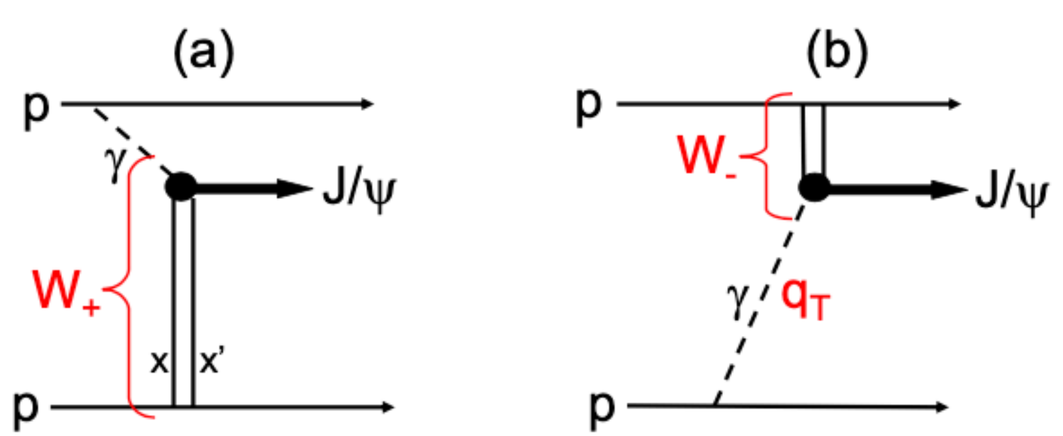


Figure 2: The two diagrams describing exclusive J/ψ production at the LHC. The vertical lines represent two-gluon exchange. Diagram (a), the W_+ component, is the major contribution to the $pp \to p + J/\psi + p$ cross section for a J/ψ produced at large rapidity y. Thus such data allow a probe of very 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]

CEP Υ IN pp COLLISIONS AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV

[JHEP 1509 (2015) 084]

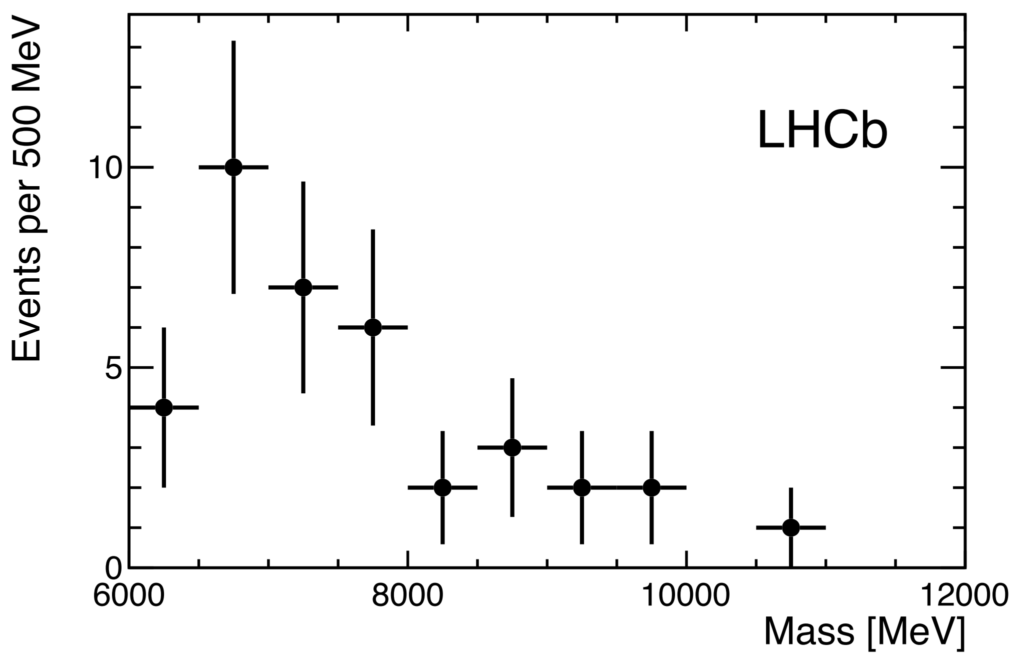
- Systematic uncertainties:

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

DOUBLE CHARMONIUM AT $\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV [J. PHYS. G41 (2014) 115002]

- Invariant mass of four-muon system:

37 $J/\psi J/\psi$ candidates



5 $J/\psi\psi(2S)$ candidates