

PARTON DISTRIBUTION FUNCTIONS AND INTRINSIC CHARM AT LHC***b***

Low- x – PDFs and QCD session I
27 September 2021

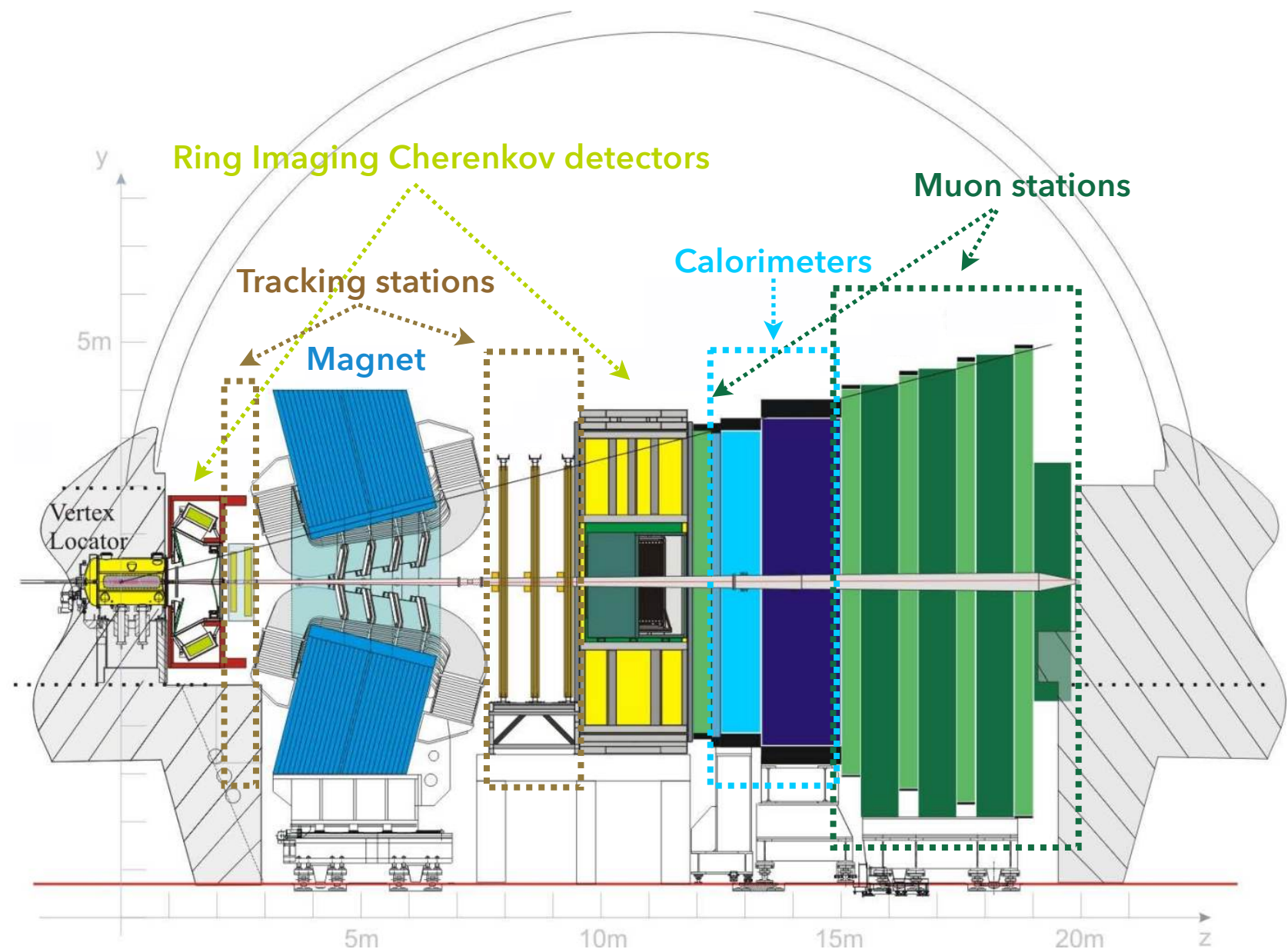
Cristina Sánchez Gras
*on behalf of the LHC***b*** collaboration*



LHC***b*** 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 and particle identification performance.
- * b - and c -jet tagging based on exceptional vertex reconstruction system.

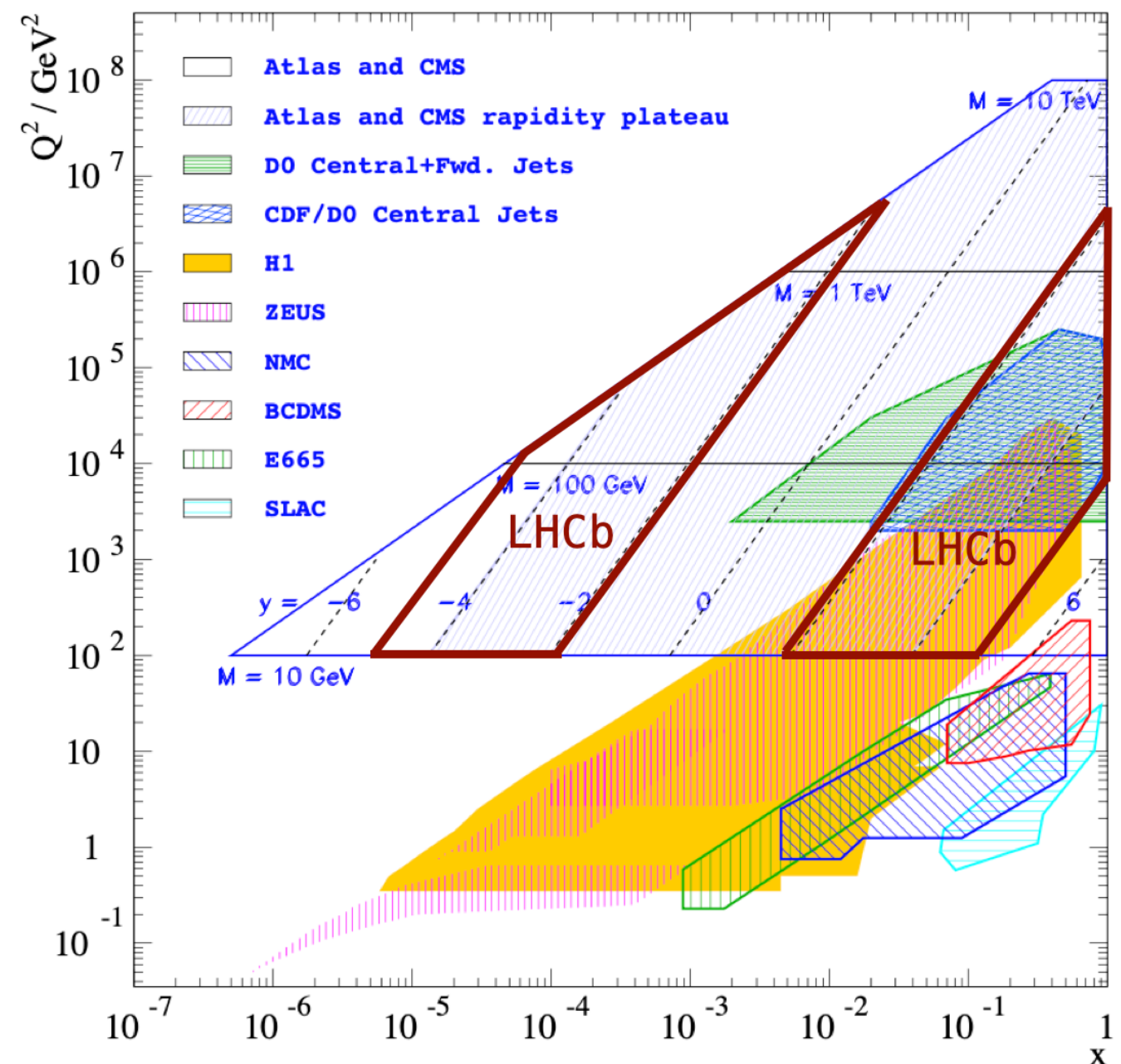


PARTON DISTRIBUTION FUNCTIONS (PDFs) AT LHC***b***

LHCb coverage complimentary to that of ATLAS, CMS → sensitive to high and low Bjorken- x .

In this presentation:

- ▶ **Low- x :** $J/\psi, \psi(2S)$ central exclusive production in pp collisions can probe the gluon PDF down to $x \sim 10^{-6}$.
- ▶ **High- x :** proton intrinsic charm in $Z + c$ jet could show up at $x > 0.1$.

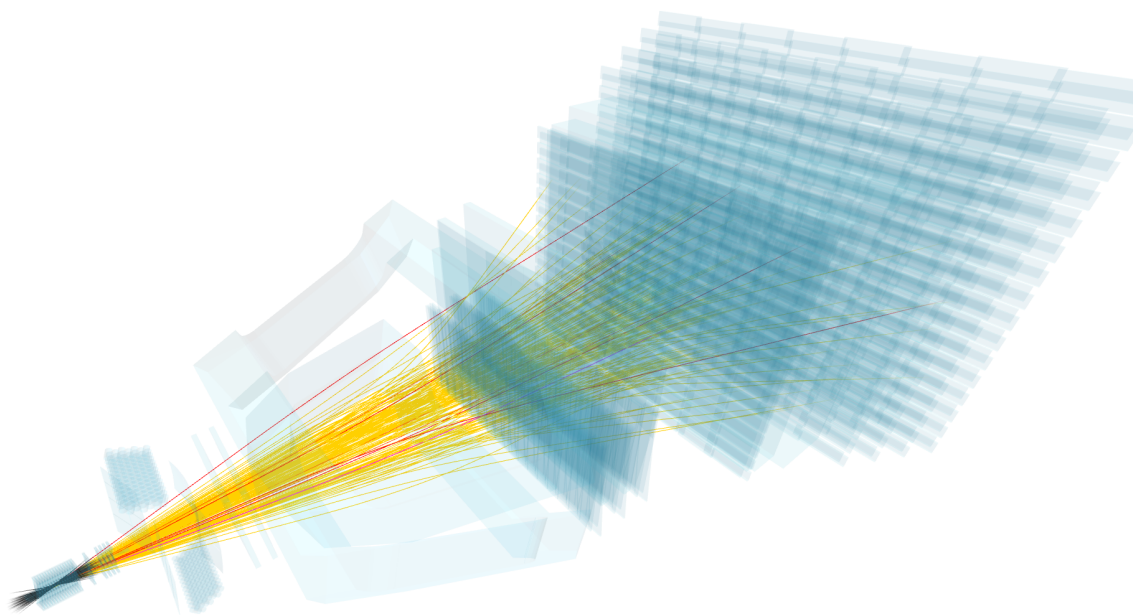


$J/\psi, \psi(2S)$ **CENTRAL EXCLUSIVE PRODUCTION** IN pp COLLISIONS

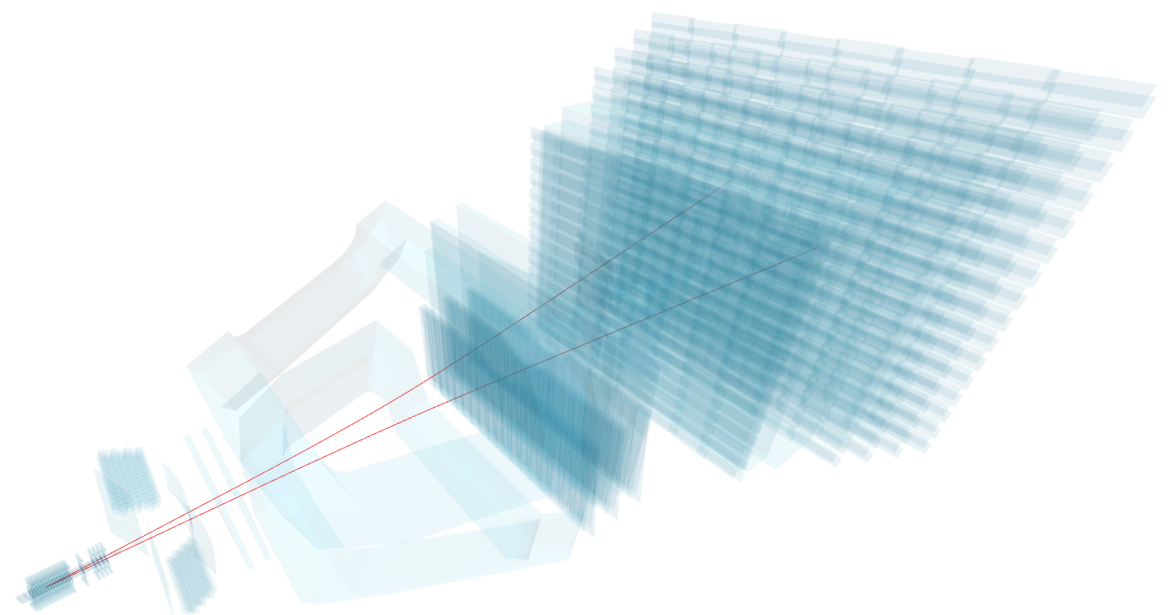
CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

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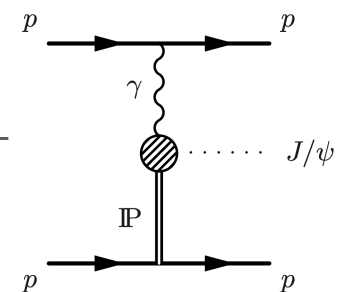
- * CEP event: diffractive process of the form $pp \rightarrow p + X + p$
- * Looks like this at LHCb:



Inelastic pp collision



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



CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

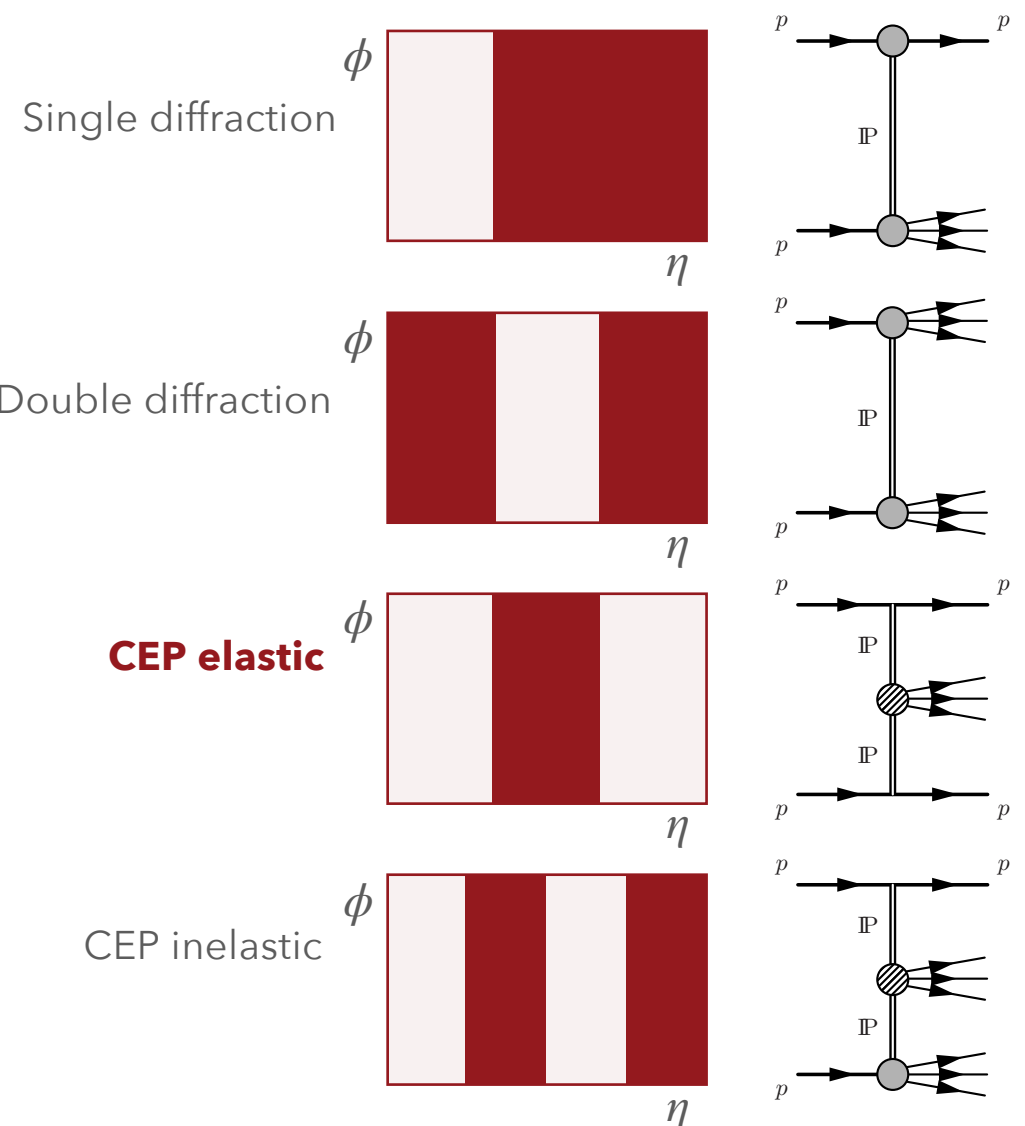
- * CEP: diffractive process of the form $pp \rightarrow p + X + p$
- * Mediated by the exchange of a colourless object.
- * The cross-section for J/ψ and $\psi(2S)$ central exclusive production can be calculated in pQCD and (at LO) is proportional to the square of the gluon PDF, $g(x)$.

With LHCb:

- In pp collisions: probe $g(x)$ at very low Bjorken- x values, down to $x \sim 10^{-6}$.

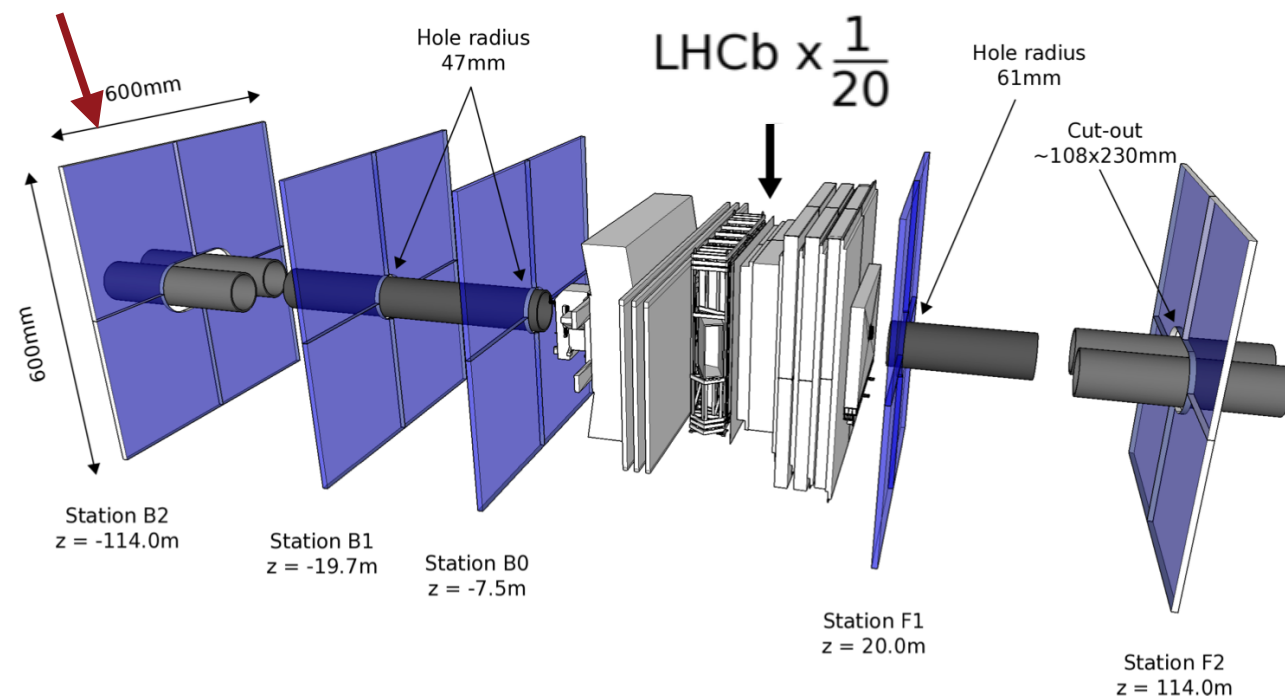
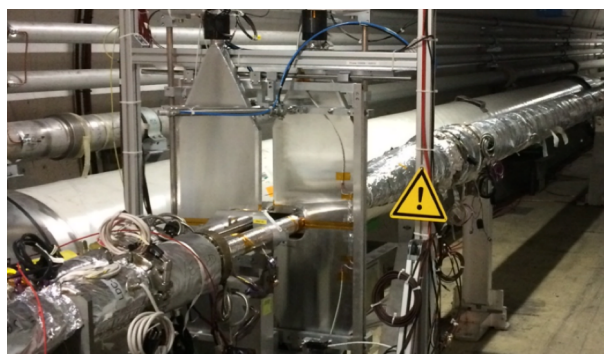
η vs azimuth ϕ for diffractive pp interactions

based on [\[arXiv:0806.0883\]](https://arxiv.org/abs/0806.0883)



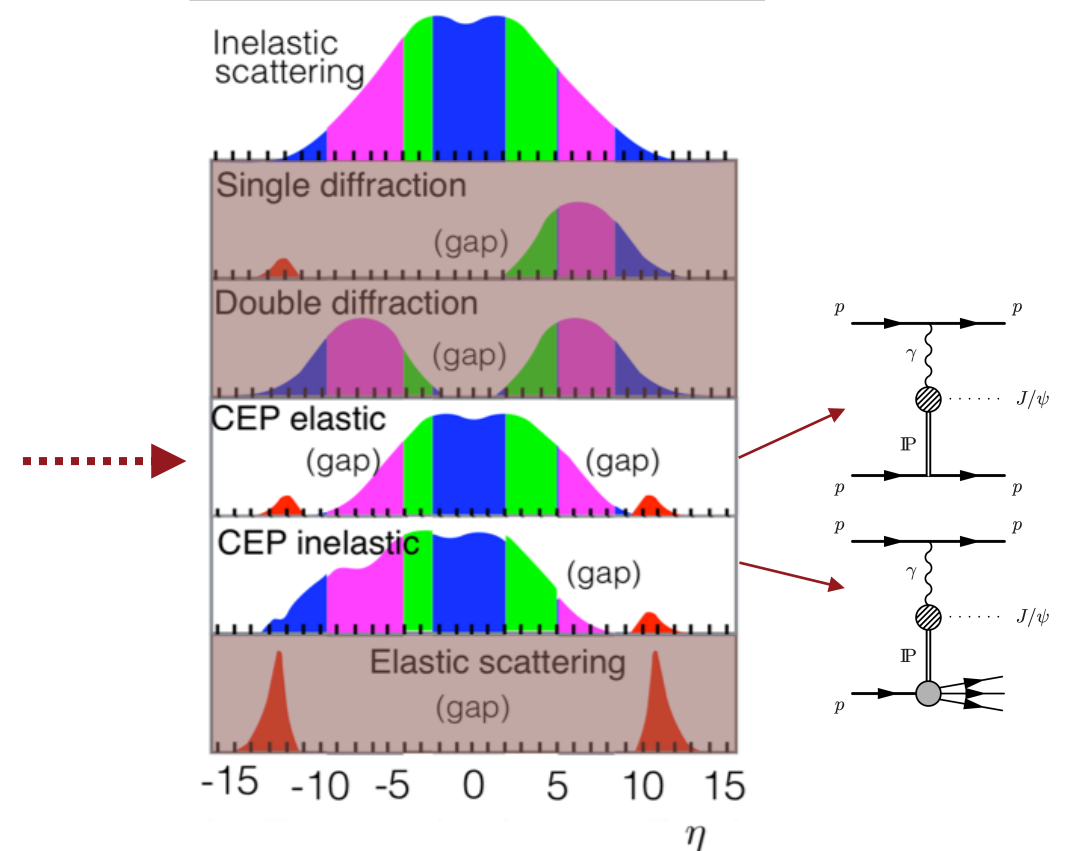
HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHC*b*

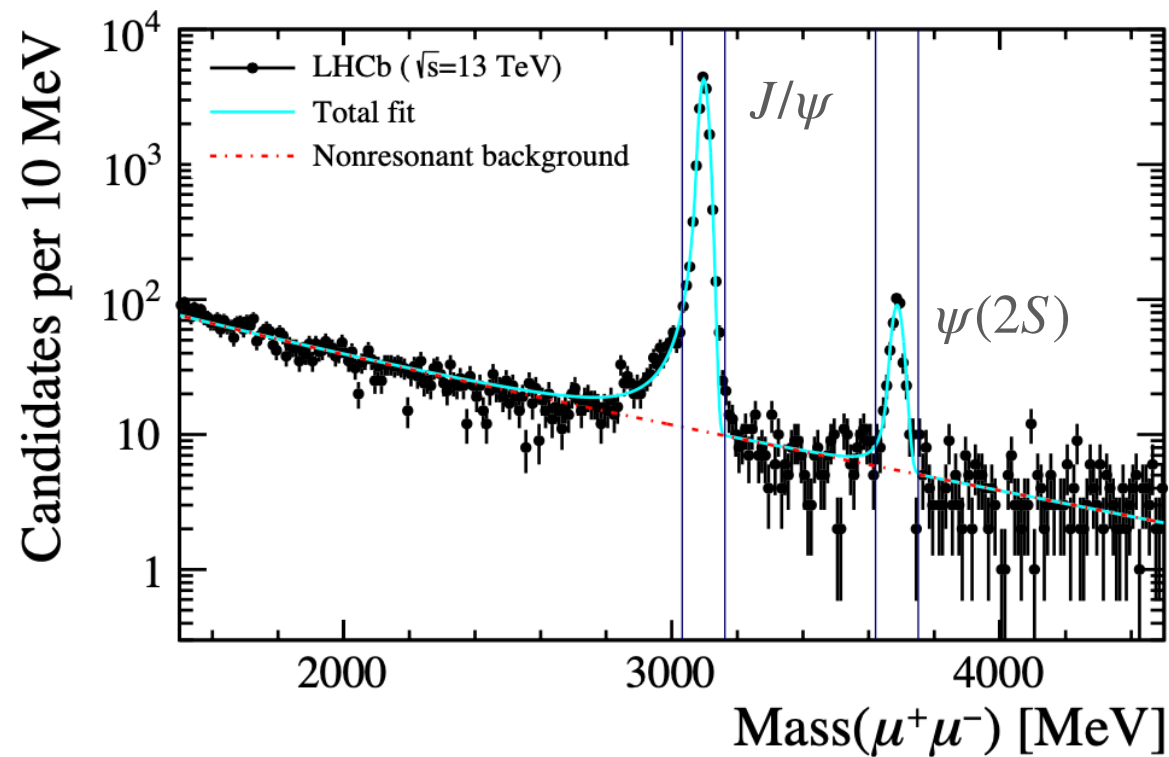
- * Need to detect proton remnants → increase the LHC*b* coverage to $1.5 < \eta < 10$ in the forward and $-10 < \eta < -5$, $-3.5 < \eta < -1.5$ in the backward regions with HeRSChEL.



5 stations x 4 scintillating pads in each station

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



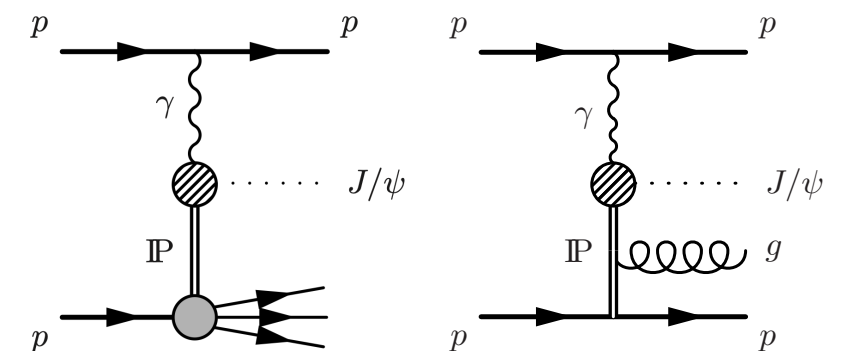


Selection:

- ✓ 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

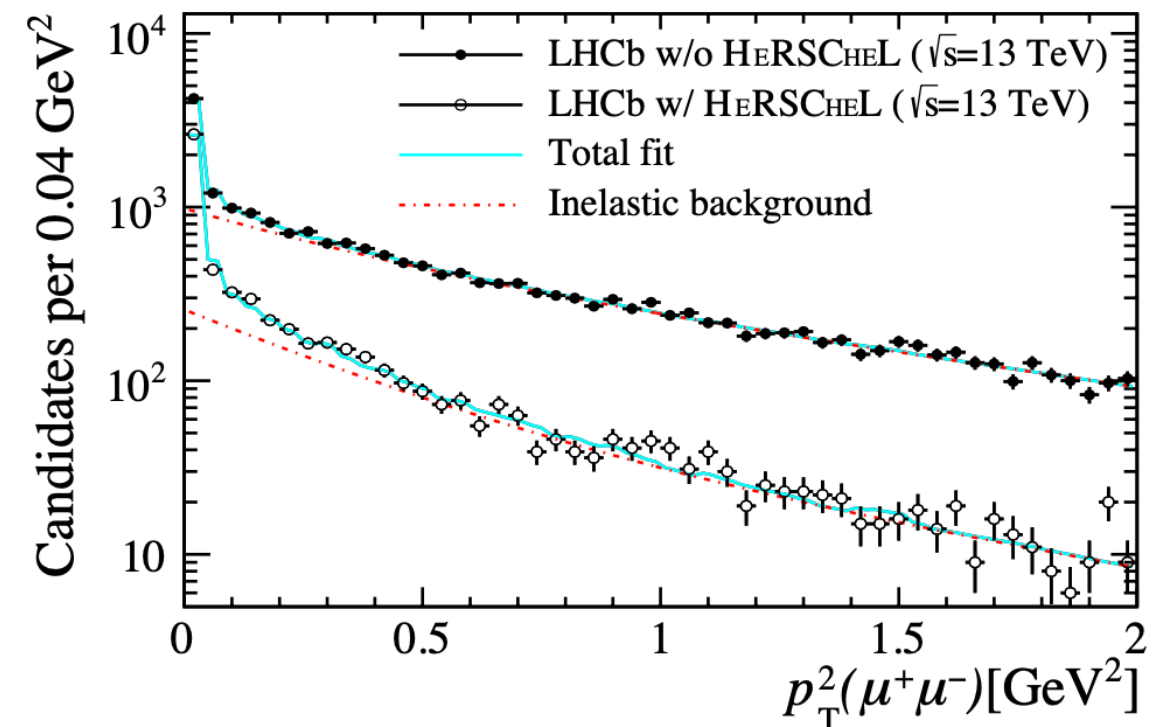
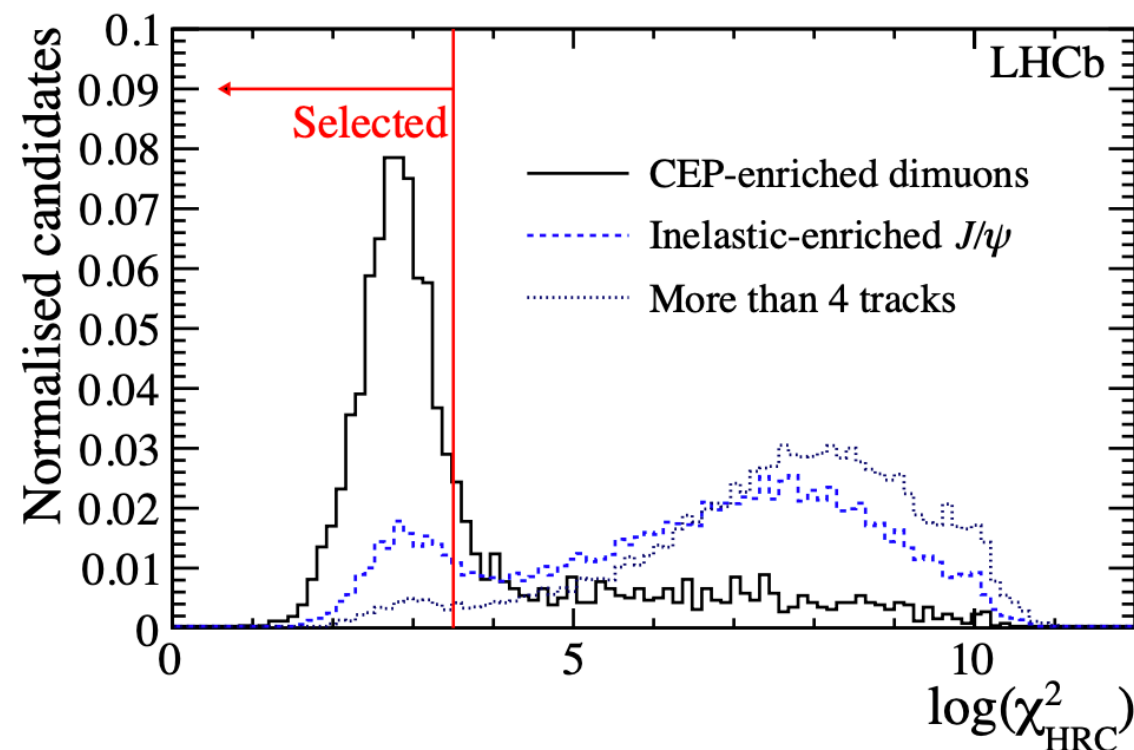
Backgrounds:

- * 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.



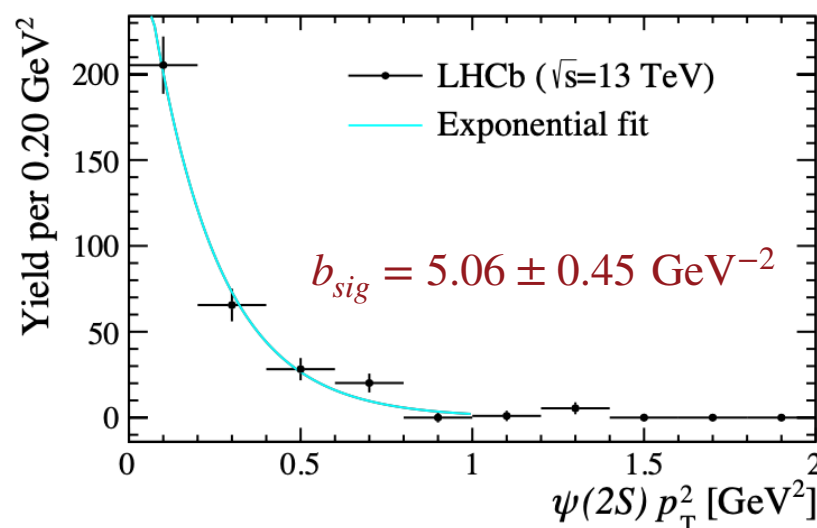
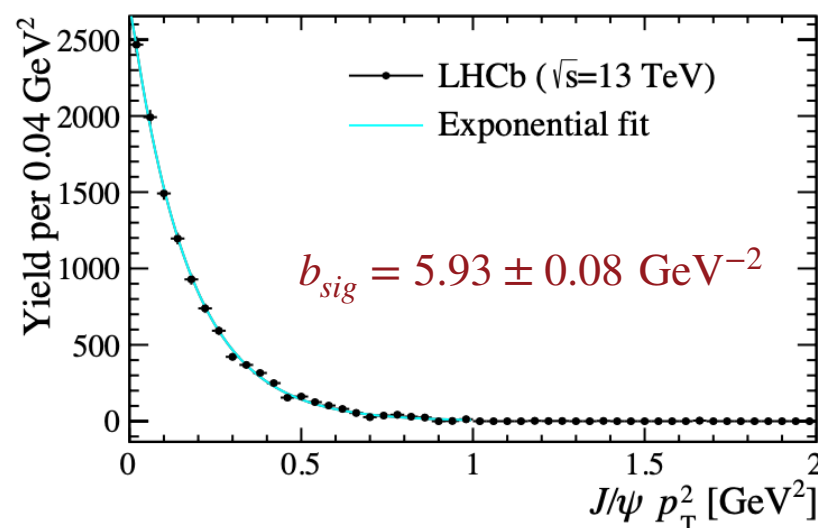
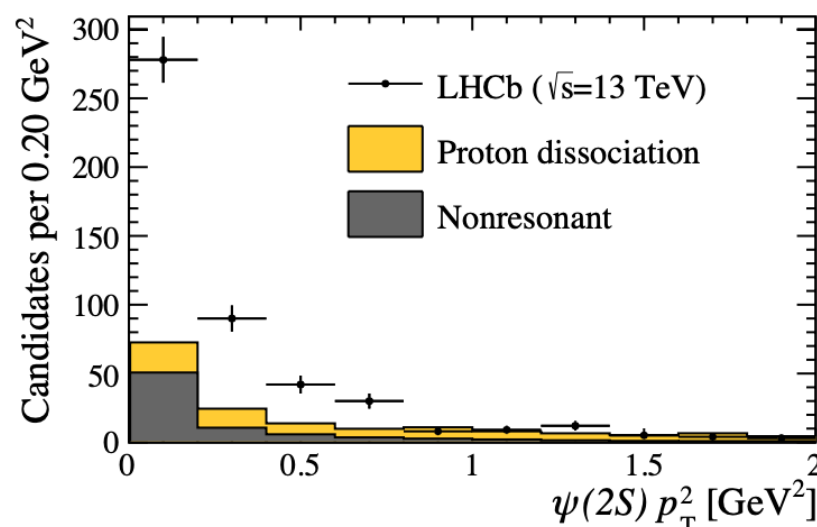
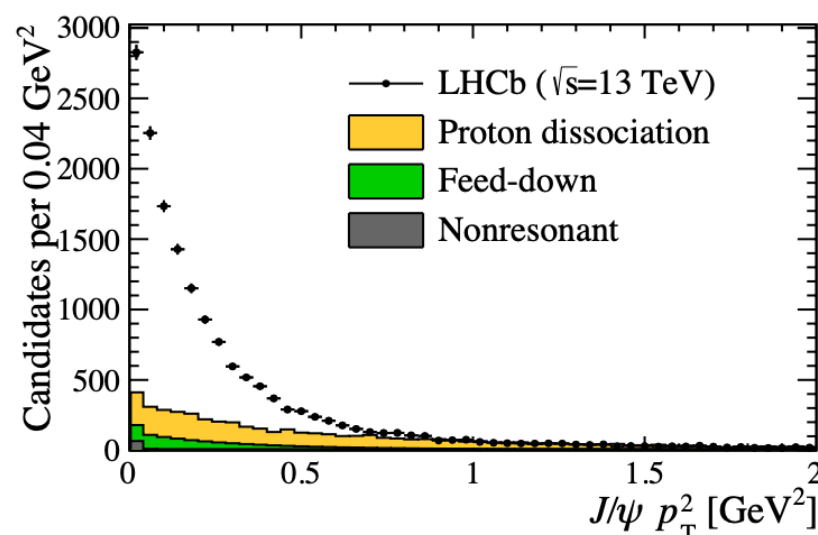
- * Build a figure of merit with the HeRSCheL information to measure the activity in the detector: $\log(\chi_{HRC}^2)$. No (low) activity = elastic CEP!

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



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

- * 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

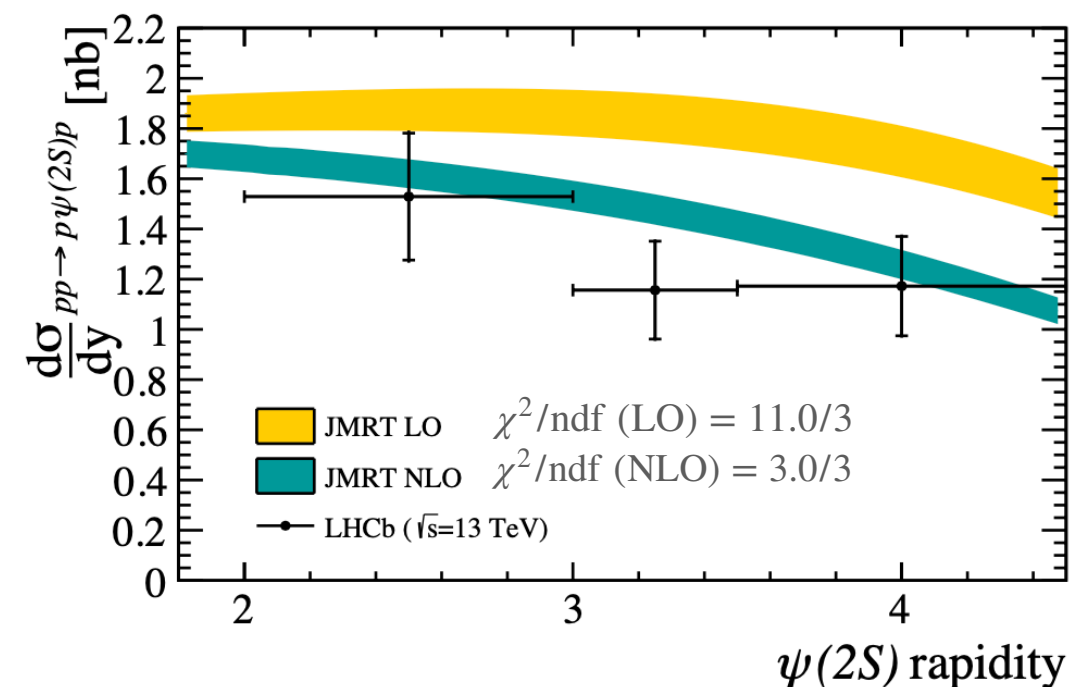
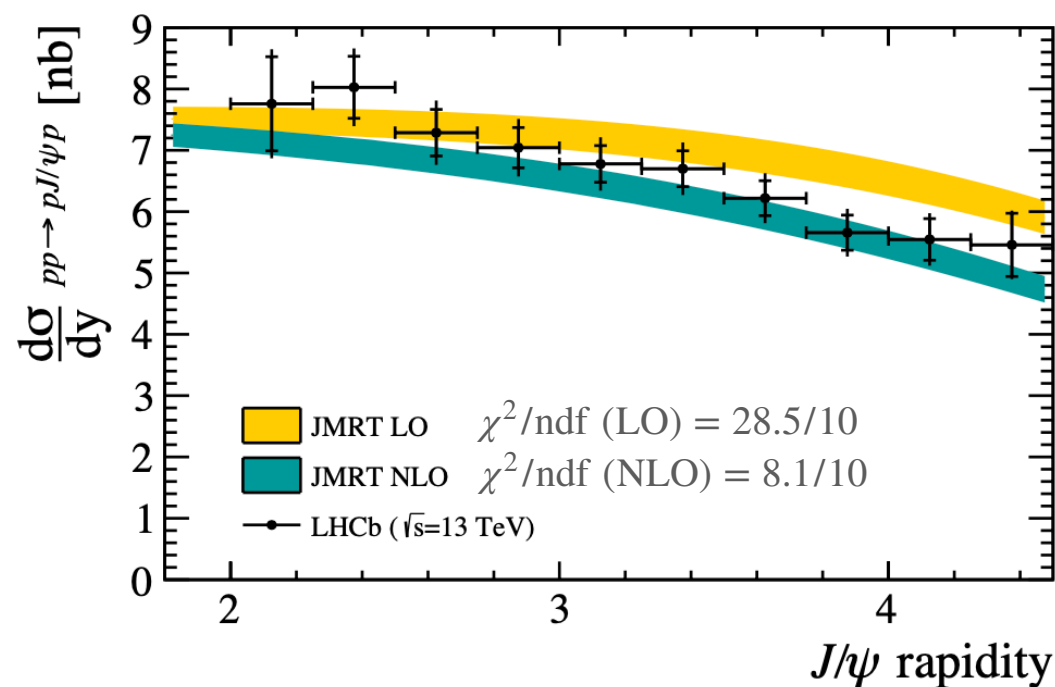
[JHEP 10 (2018) 167]

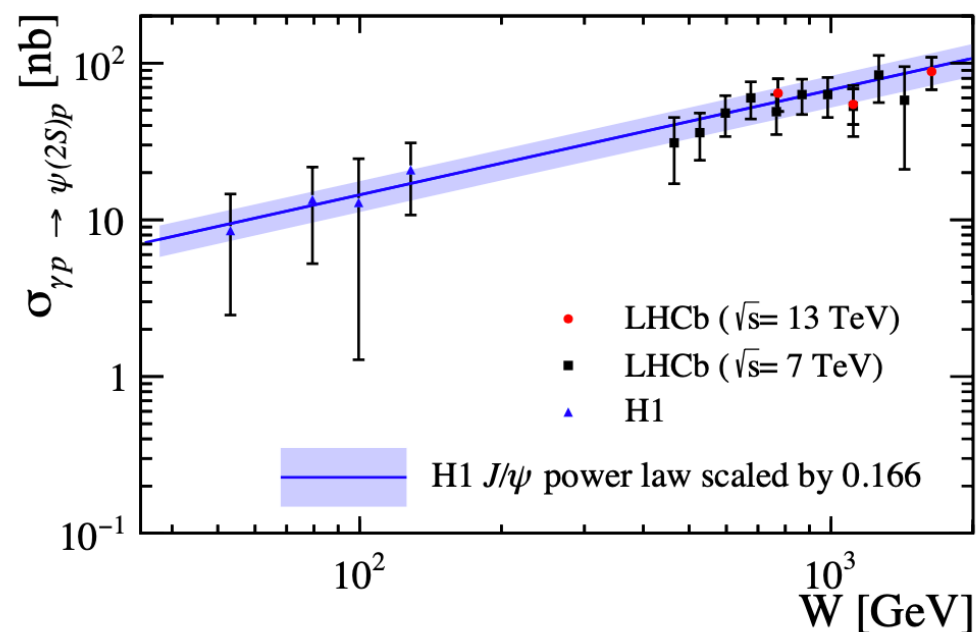
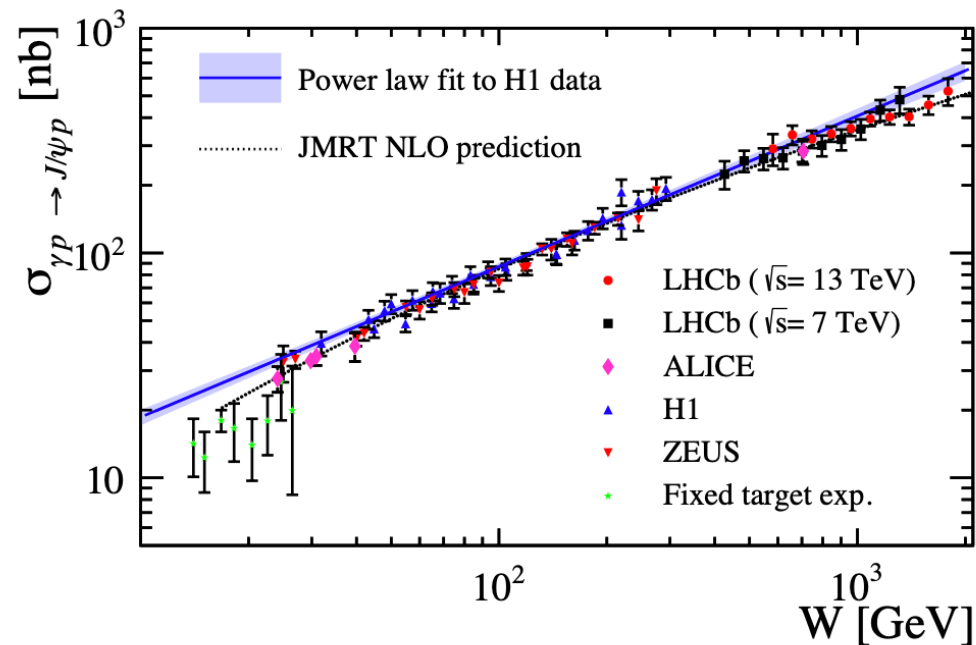
- * Cross-section calculation per rapidity bin y with $\mathcal{L}_{tot} = 204 \pm 8 \text{ pb}^{-1}$:

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

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

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





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

$$\sigma_{pp \rightarrow p\psi p} = \overset{\text{LHCb data}}{\downarrow} r(W_+)k_+ \frac{dn}{dk_+} \overset{\text{Calculated}}{\downarrow} \sigma_{\gamma p \rightarrow \psi p}(W_+) + r(W_-)k_- \frac{dn}{dk_-} \overset{\text{Taken from HERA}}{\downarrow} \sigma_{\gamma p \rightarrow \psi p}(W_-)$$

- $r(W_{\pm})$ 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.

* Working on an update with more data!

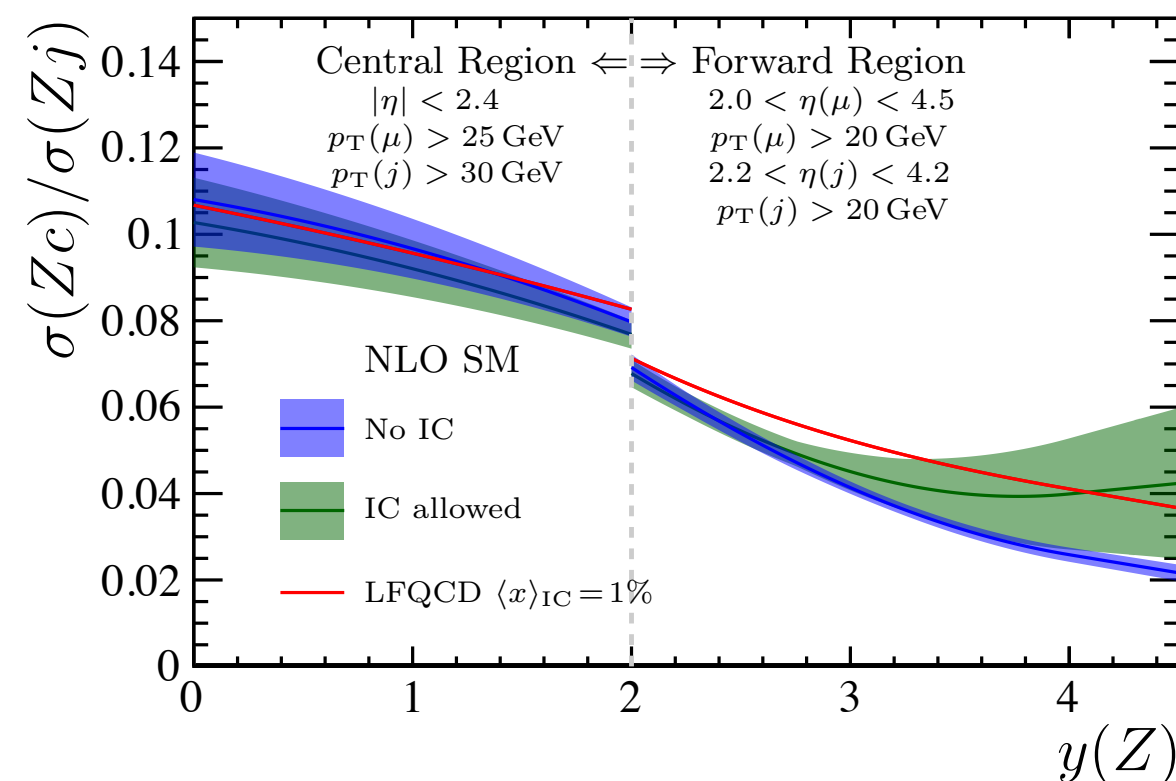
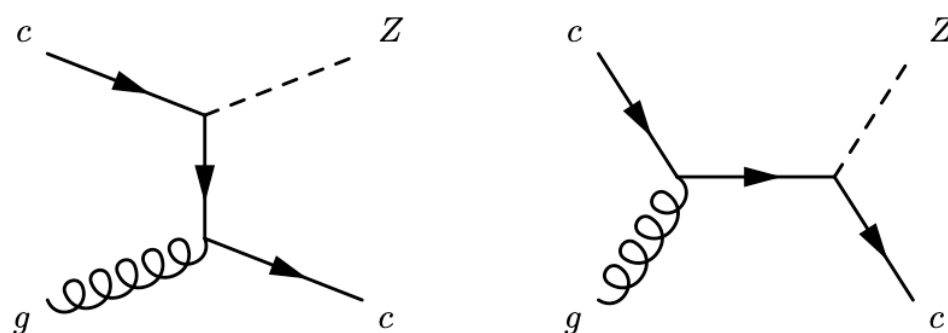
Z BOSONS PRODUCED IN ASSOCIATION WITH CHARM

INTRINSIC CHARM (IC) WITH $Z + c$ -jet

[LHCB-PAPER-2021-029]

- * Proton charm content:
 - ✓ Extrinsic charm, from perturbative gluon radiation ($g \rightarrow c\bar{c}$).
 - ? Intrinsic charm (IC), as valence-like c -content in the proton (proton as $|uudc\bar{c}\rangle$).
 - Predicted by Light Front QCD (LFQCD).
- * Former measurements done at low- Q^2 : difficult theoretical treatment of hadronic and nuclear effects.
- * Global PDF analyses do not exclude IC at the percent level!

- * Measure $\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$ in the forward region (hadronic and nuclear effects negligible).
 - Zc is at high- Q^2 , forward rapidity $\rightarrow$ high- x .



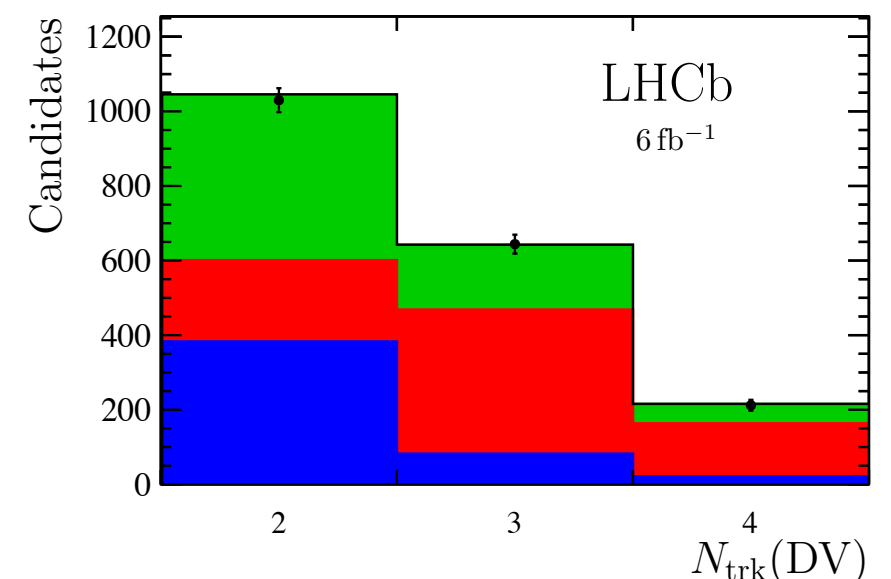
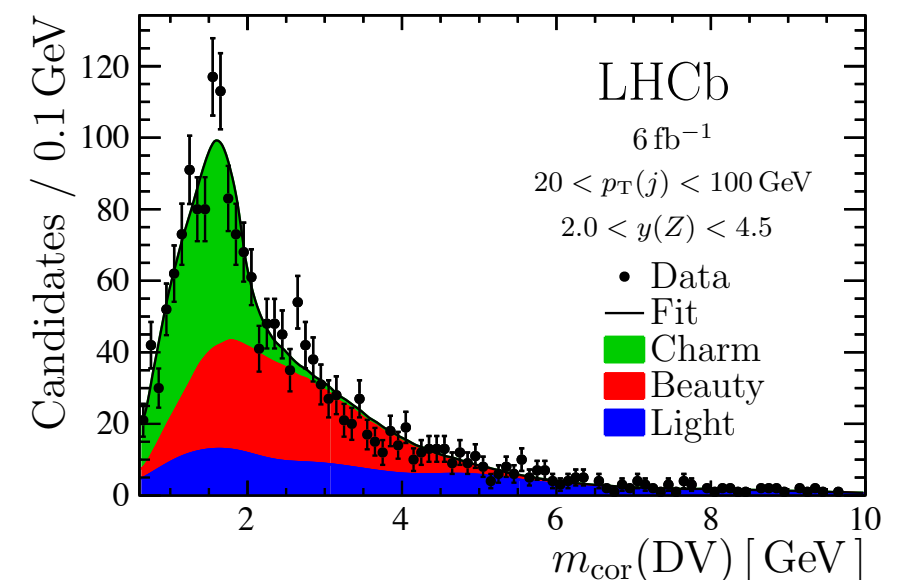
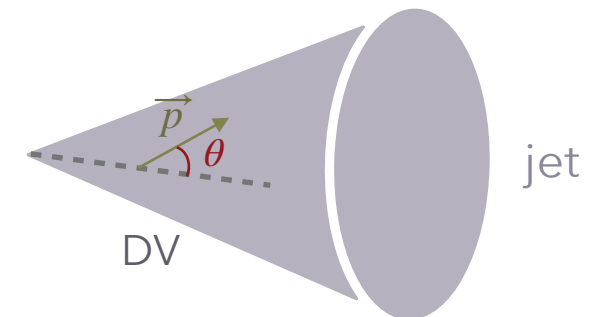
INTRINSIC CHARM (IC) WITH $Z + c$ -jet

[LHCB-PAPER-2021-029]

- * Full Run 2 pp dataset corresponding to 6 fb^{-1} of integrated luminosity.
- * Measure $\mathcal{R}_j^c = N(c\text{-tag}) / [\epsilon(c\text{-tag}) \cdot N(j)]$
- * Select events with $Z \rightarrow \mu^+ \mu^-$ and at least one jet with $p_T > 15 \text{ GeV}/c$.
- * Identify c -jets using displaced-vertex (DV) tagger in bins of $p_T(j)$ and $y(Z)$:
 - Perform 2D fit to corrected DV-mass and number of tracks in DV (templates obtained from calibration samples).

$$m_{\text{cor}}(\text{DV}) \equiv \sqrt{m(\text{DV})^2 + [p(\text{DV}) \sin \theta]^2} + p(\text{DV}) \sin \theta$$

- Unfold $p_T(j)$ distributions of Z_c and Z_j yields in each $y(Z)$ bin.



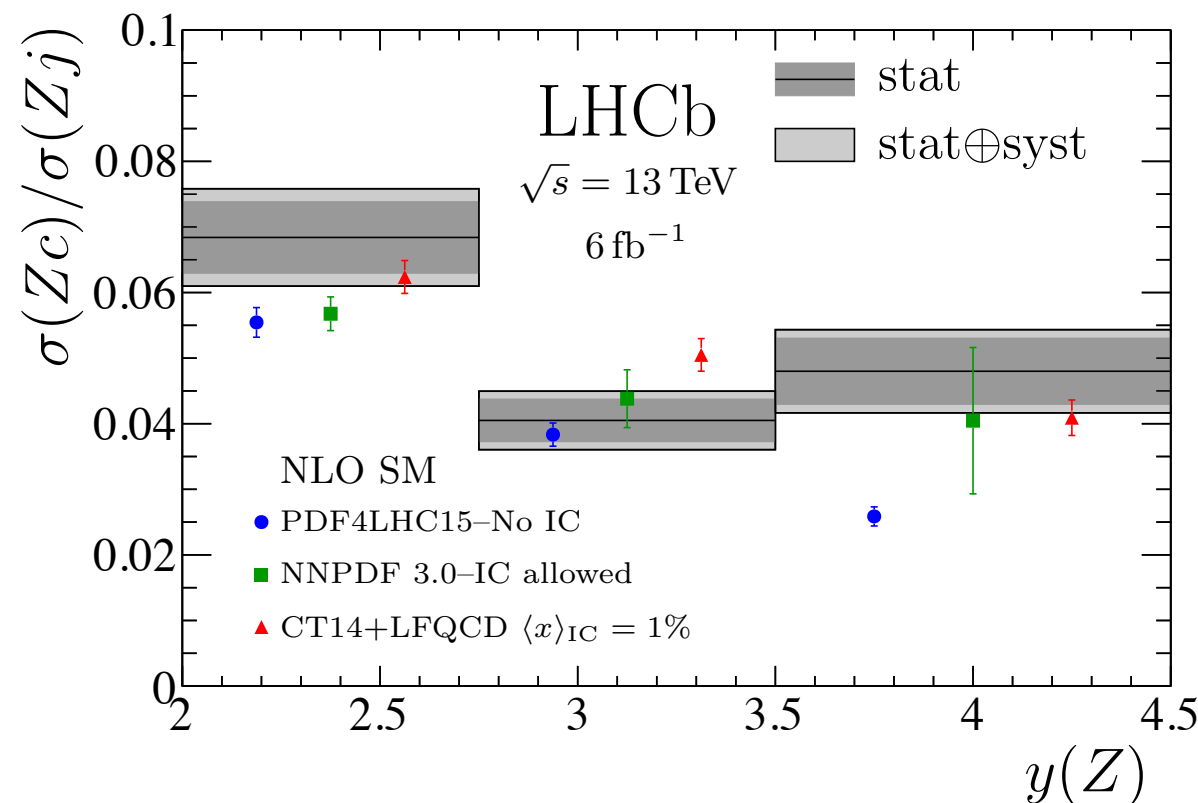
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- * c -tagging efficiency, $\epsilon(c\text{-tag})$, determined in simulation and corrected by using tag-and-probe on a dijet calibration sample as the ratio of:
 - DV-tagged c -jet yield obtained through the same procedure as for Z_c .
 - Total number of c -jets: reconstruct $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ correcting for detector response and branching and fragmentation functions.
- * Ratio of Z_c and Z_j cancels most systematic uncertainties.
- * Dominant systematic uncertainty related to the c -tagging efficiency.

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_T scale & resolution	1%
Total	8%

INTRINSIC CHARM (IC) WITH $Z + c$ -jet

[LHCB-PAPER-2021-029]

- * Comparison to SM predictions with **no IC**, **IC allowed** and **IC with mean momentum fraction of 1%**.
- * First two $y(Z)$ bins consistent with both no IC and IC allowed.
- * Data consistent with IC models in the highest $y(Z)$ bin!
 - $\sim 3\sigma$ away from no IC theory.
- * Results need to be added to global PDF analyses to draw conclusions.



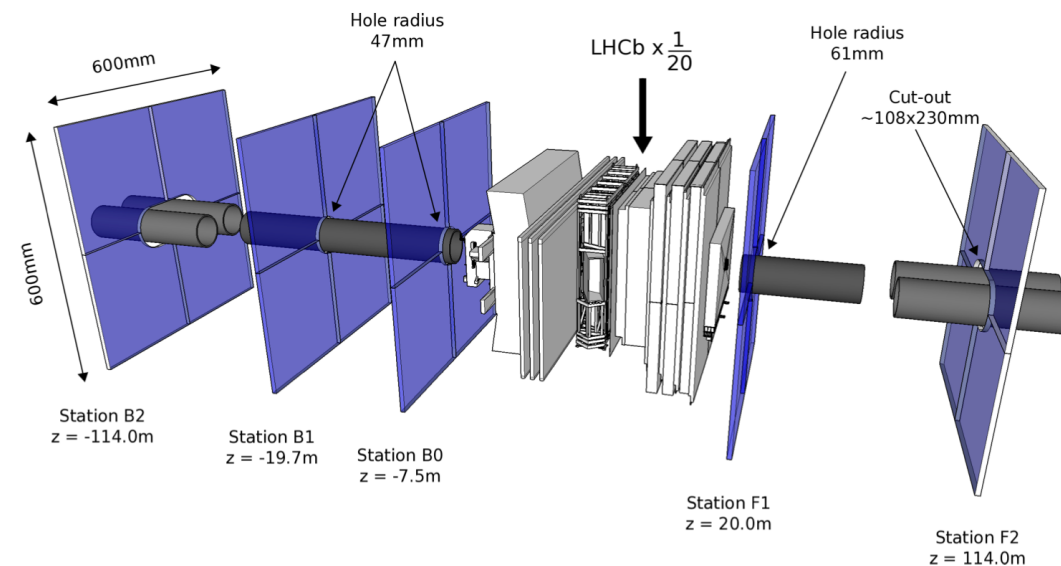
$y(Z)$	$\mathcal{R}_j^c (\%)$
2.00–2.75	$6.84 \pm 0.54 \pm 0.51$
2.75–3.50	$4.05 \pm 0.32 \pm 0.31$
3.50–4.50	$4.80 \pm 0.50 \pm 0.39$
2.00–4.50	$4.98 \pm 0.25 \pm 0.35$

CONCLUSIONS

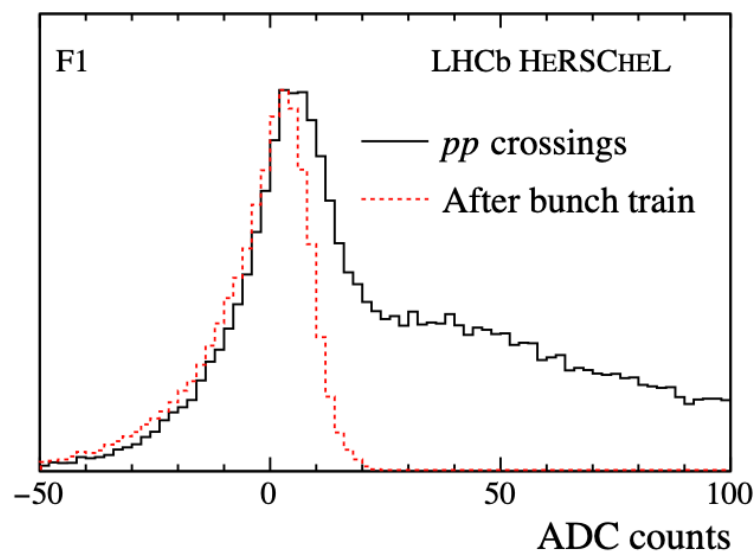
- * LHCb operating as a general purpose forward experiment, complementary to ATLAS and CMS.
- * For **low- x** : J/ψ , $\psi(2S)$ CEP, update with more data coming soon, higher statistics for $\psi(2S)$.
- * For **high- x** : the $Z + c$ jet measurement shows the first direct evidence of IC.
 - Inclusion in global PDF analyses pending.
 - Measurement statistically limited, stay tuned for update with Run 3 data!

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



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

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

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

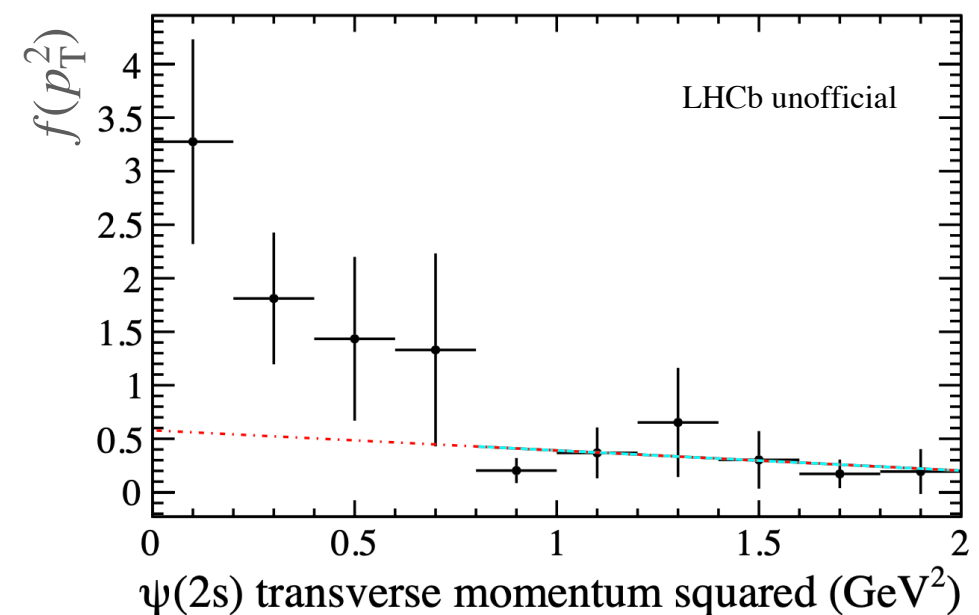
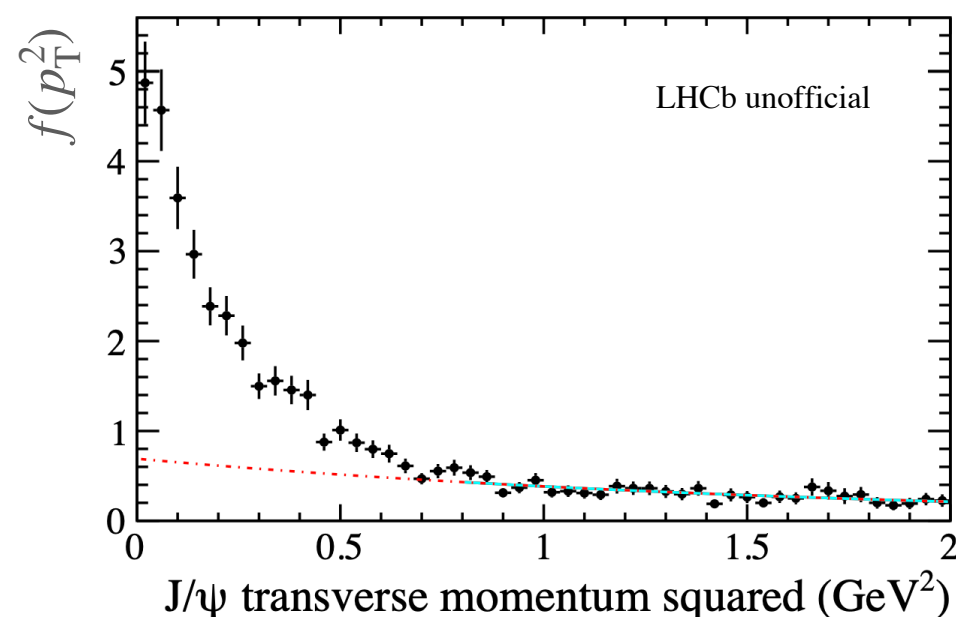
Estimating the contribution of the proton dissociation background:

* 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 :

$$\left. \begin{array}{l} S_H \text{ for } \log(\chi_{HRC}^2) < 3.5 \\ S_{\bar{H}} \text{ for } \log(\chi_{HRC}^2) > 3.5 \end{array} \right\} \beta = S_{\bar{H}} - ((1 - \epsilon_H)/\epsilon_H) S_H \text{ with } \epsilon_H \text{ the efficiency for a CEP event to be in } S_H$$

* Proton dissociation bkg: scale β by $f(p_T^2) \equiv S_H(p_T^2)/\beta(p_T^2)$



* 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

- * 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 $\delta = 0.67 \pm 0.03$.

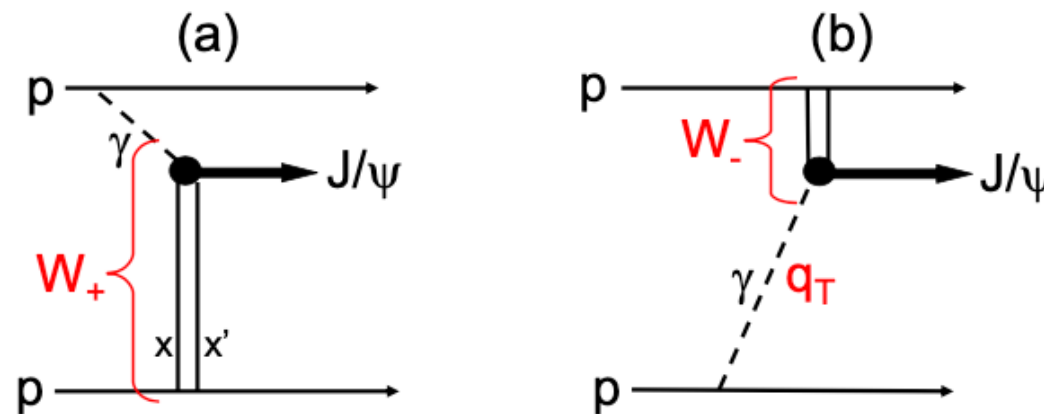


Figure 2: The two diagrams describing exclusive J/ψ production at the LHC. The vertical lines represent two-gluon exchange. Diagram (a), the W_+ component, is the major contribution to the $pp \rightarrow p + J/\psi + p$ cross section for a J/ψ produced at large rapidity y . Thus such data allow a probe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