PARTON DISTRIBUTION FUNCTIONS AND INTRINSIC CHARM AT LHCb

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

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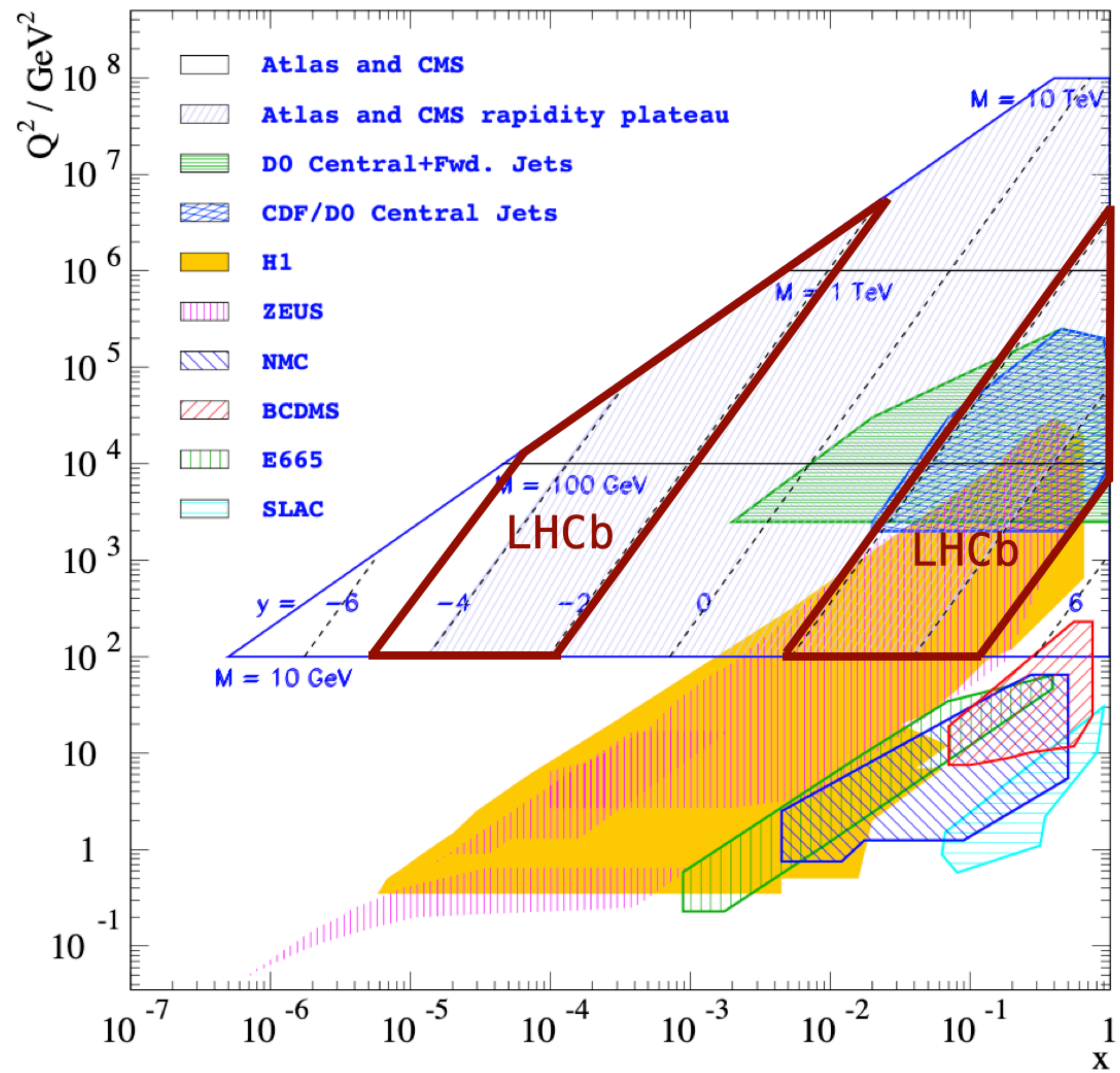
on behalf of the LHCb collaboration

PARTON DISTRIBUTION FUNCTIONS (PDFs) AT LHCb

LHCb coverage complementary 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 $x > 0.1$.

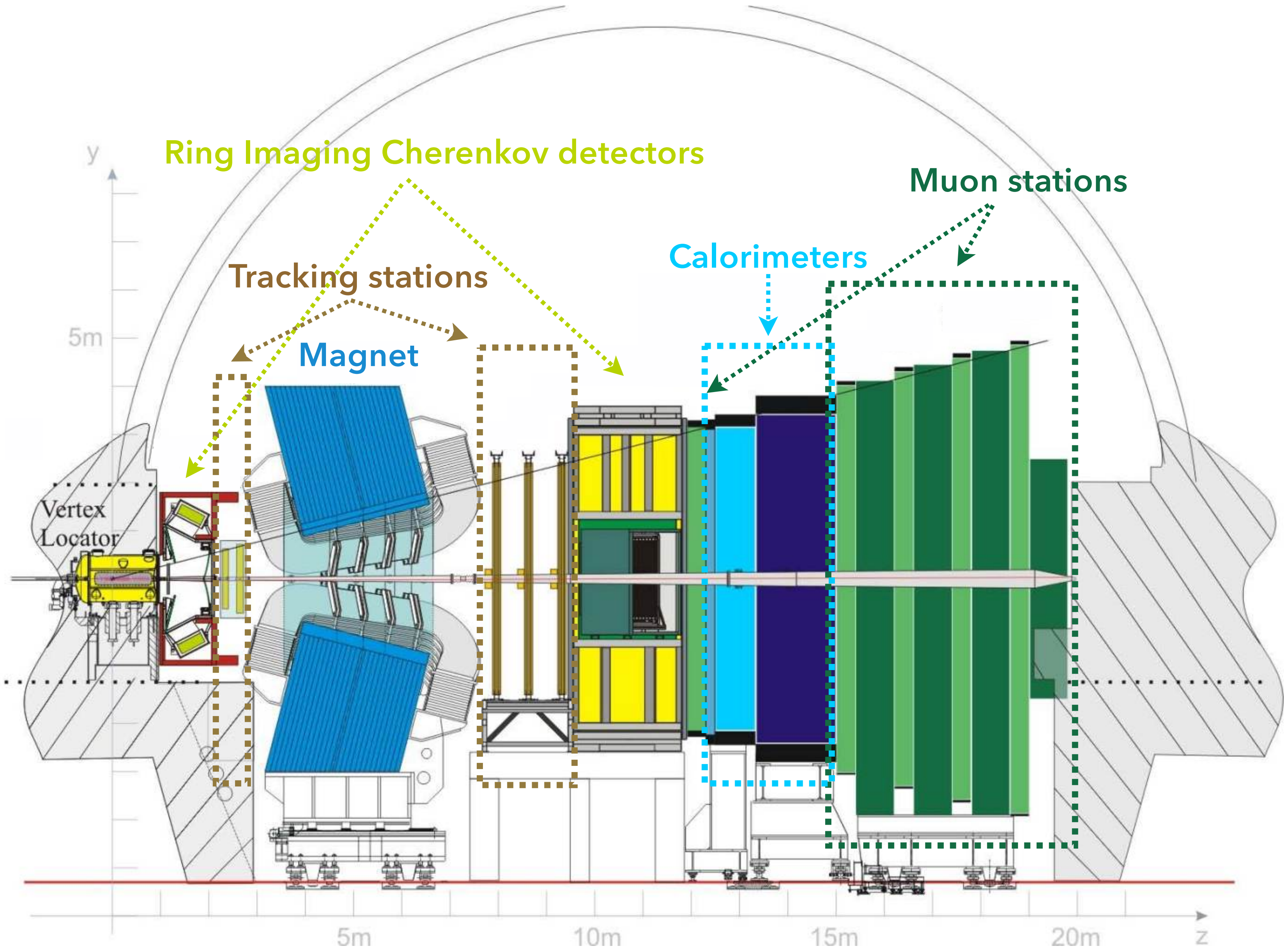


[Braz. J. Phys. 37 (2c), 793-797]

LHCb DETECTOR

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

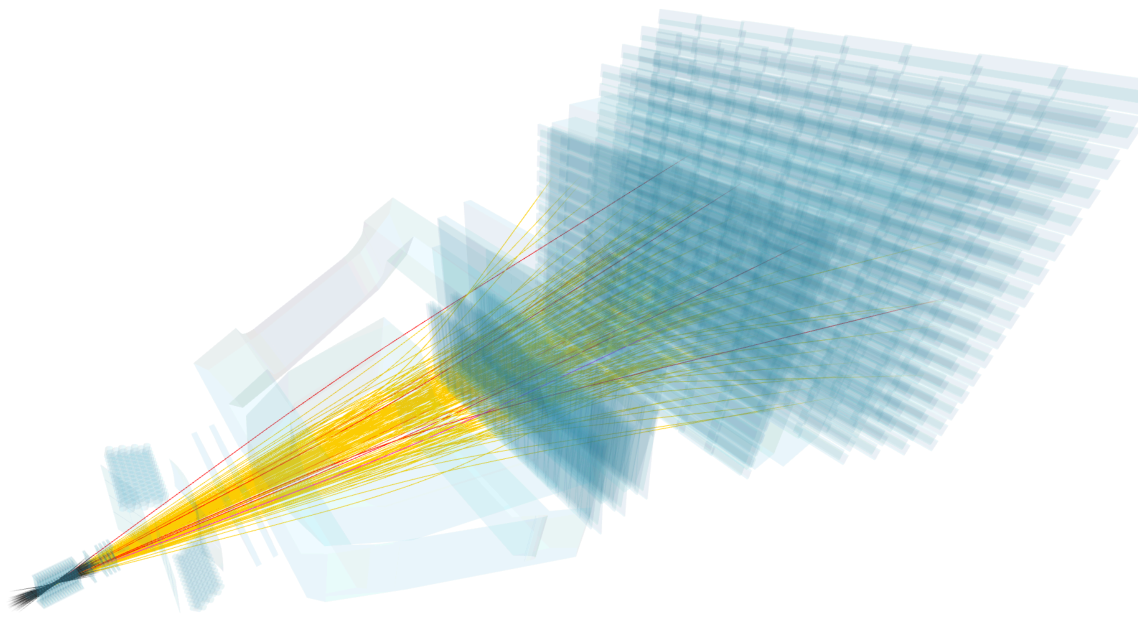
- Designed for b- and c-physics, but functions as a general purpose detector.
- Very high p resolution $(0.5 - 1\,\%\ (5 - 200\ \mathrm{GeV}))$ and particle identification performance.
- b- and c-jet tagging based on exceptional vertex reconstruction system.



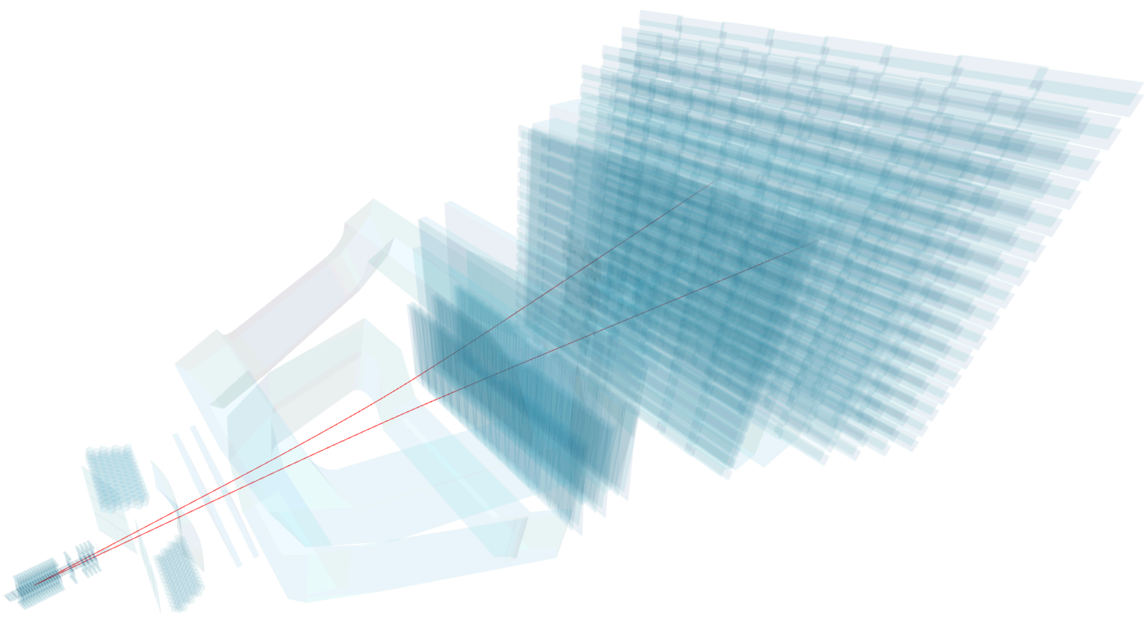
$J/\psi, \psi(2S)$ CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

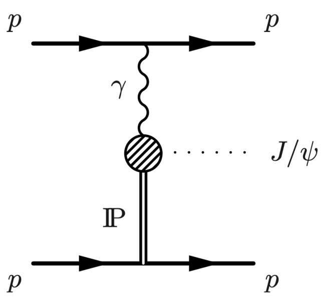
- CEP event: diffractive process of the form $pp \to p + X + p$
- Mediated by the exchange of a colourless object (photon-pomeron for $J/\psi, \psi(2S)$).
- Looks like this at LHCb:



Inelastic pp collision



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



CENTRAL EXCLUSIVE PRODUCTION IN pp COLLISIONS

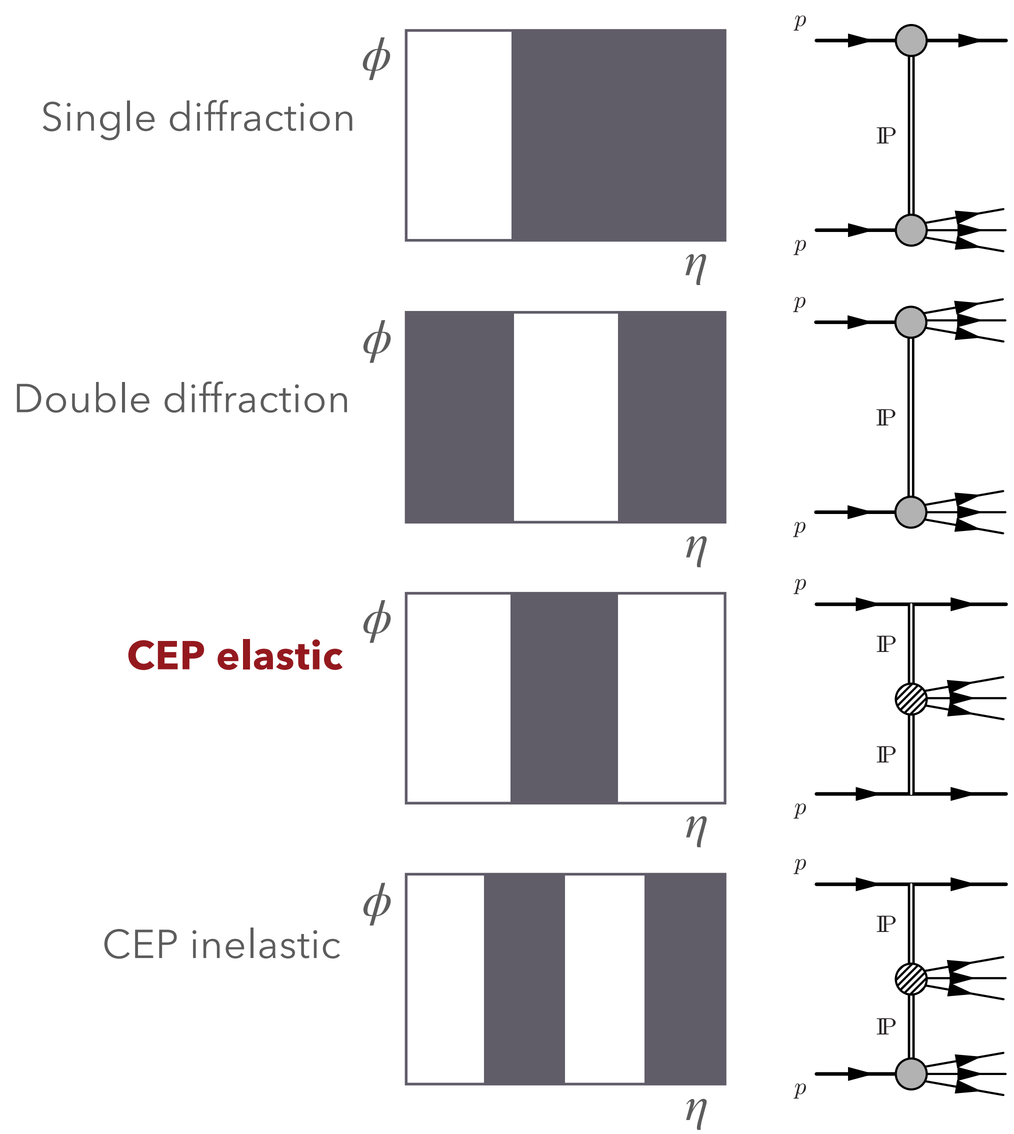
- CEP: diffractive process of the form $pp \to p + X + p$
- Mediated by the exchange of a colourless object.
- The cross-section for J/ψ and $\psi(2S)$ CEP can be calculated in pQCD and (at LO) is $\propto g(x)^2$, where $g(x)$ is the gluon PDF.

With LHCb:

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

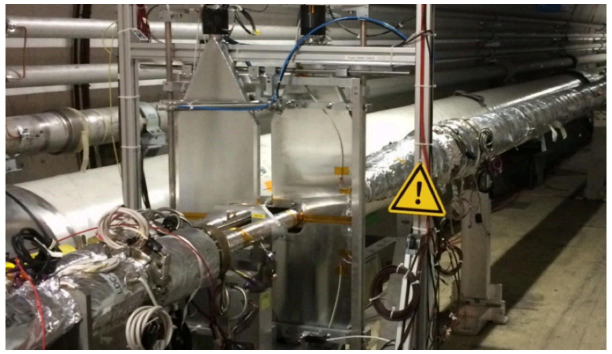
η vs azimuth ϕ for diffractive pp interactions

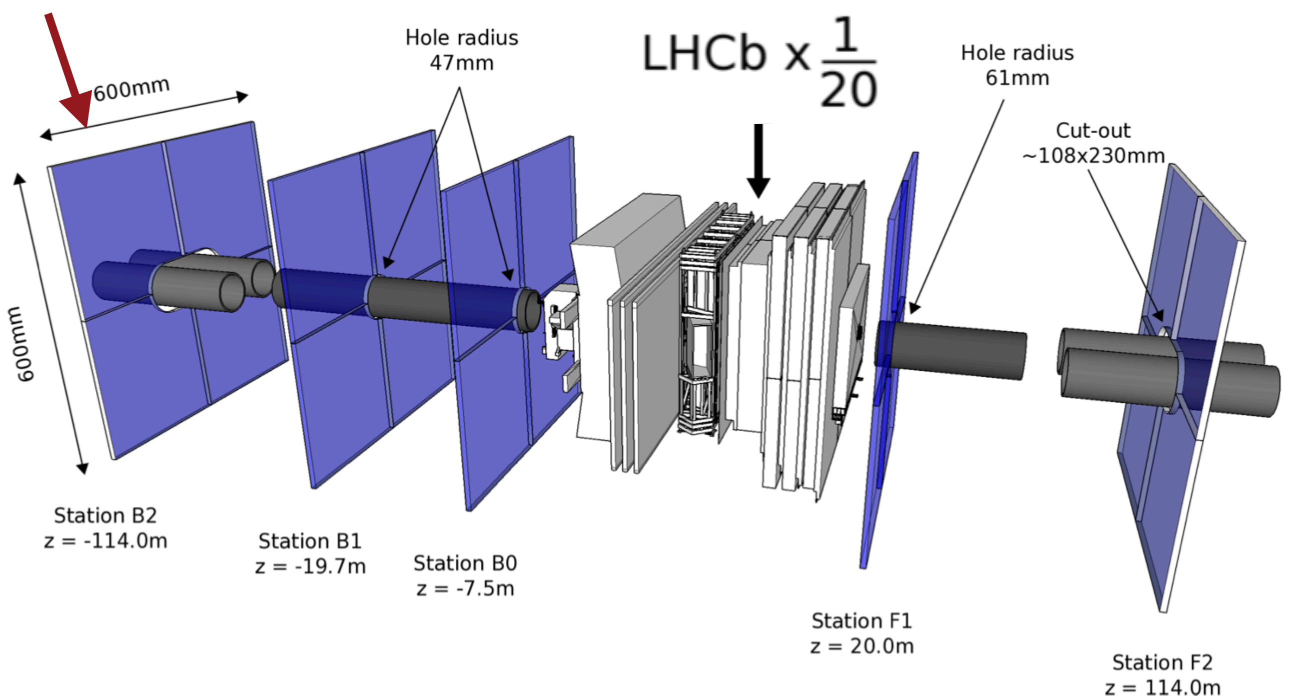
based on [arXiv:0806.0883]



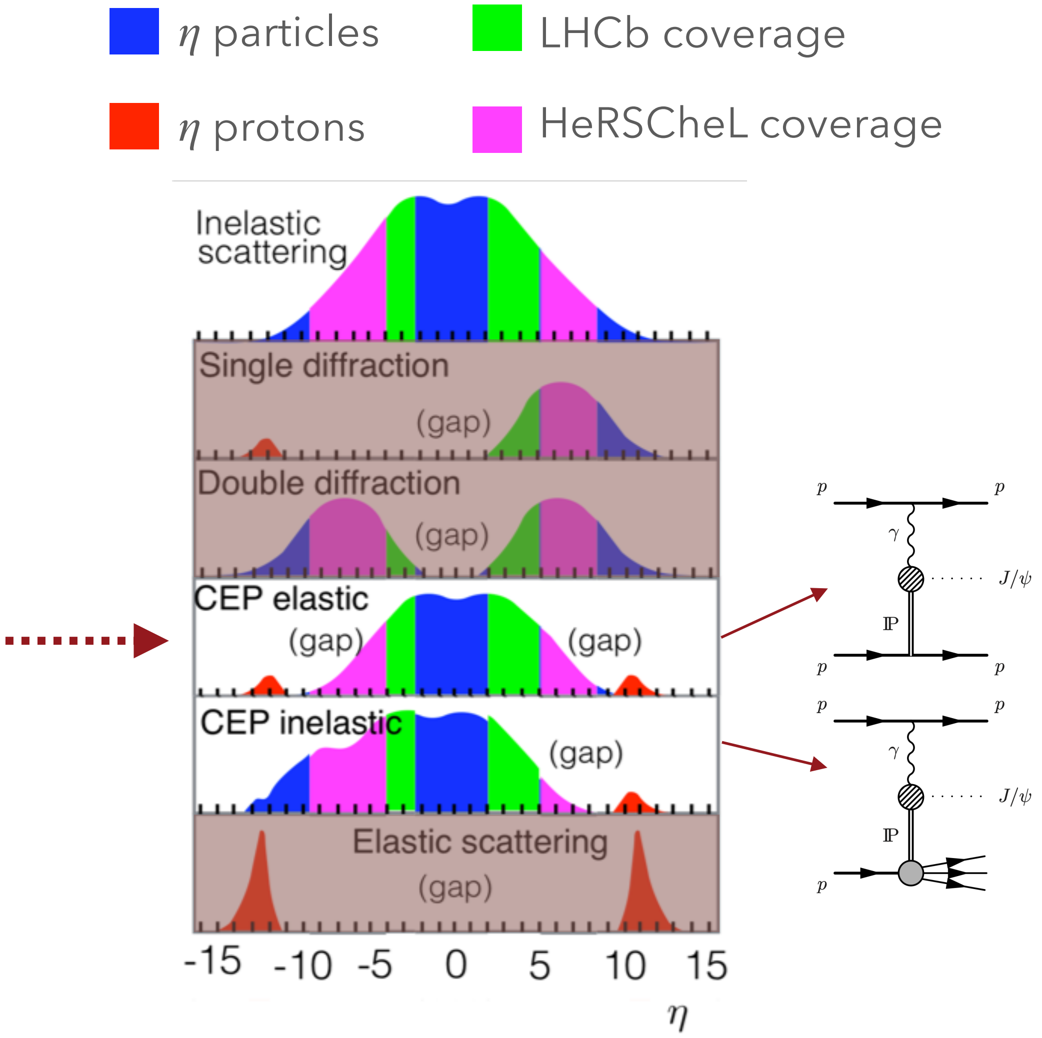
HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR LHCb

- 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 HeRSChеL [JINST 13 (2018) no.04, P04017].



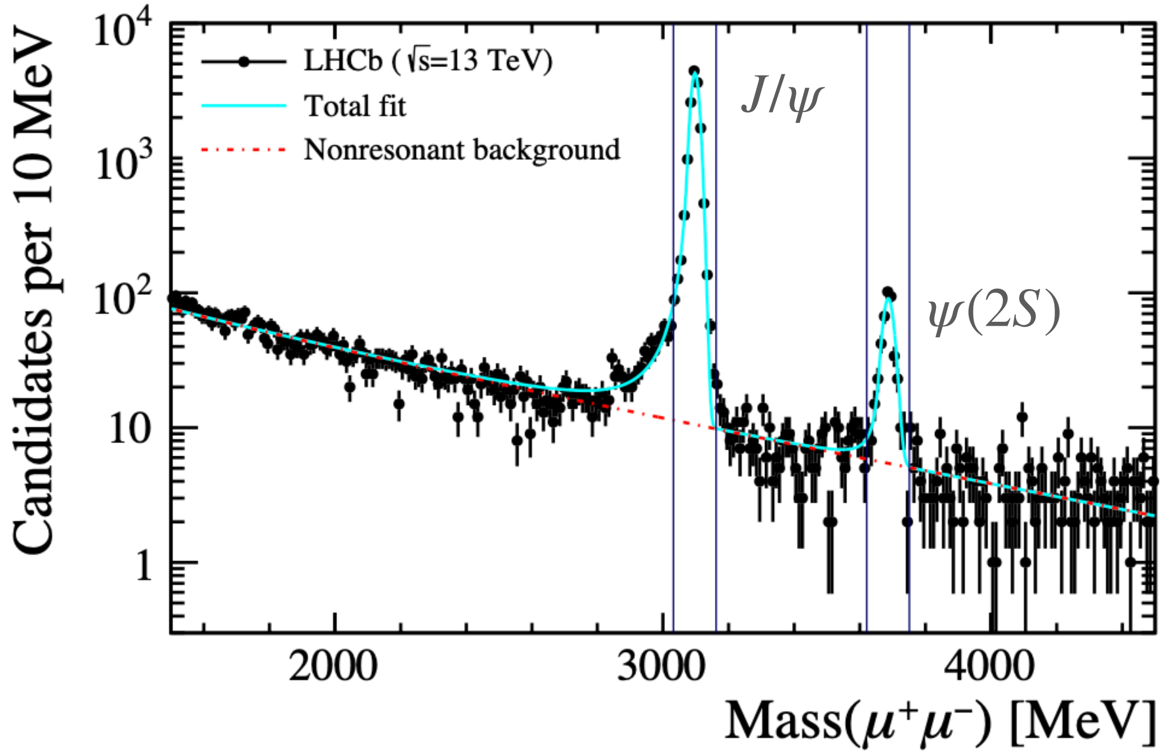


5 stations x 4 scintillating pads in each station



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

[JHEP 10 (2018) 167]

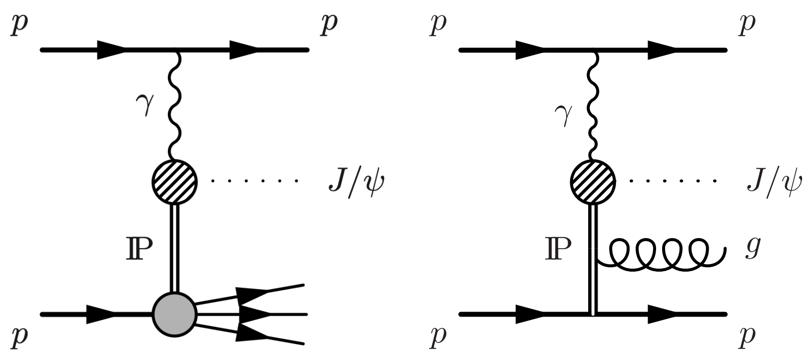


Selection:

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

Backgrounds:

- ✳ Continuum dimuon production ($\gamma\gamma$ fusion).
- ✳ Peaking at the J/ψ mass: χ_{c_J} 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.

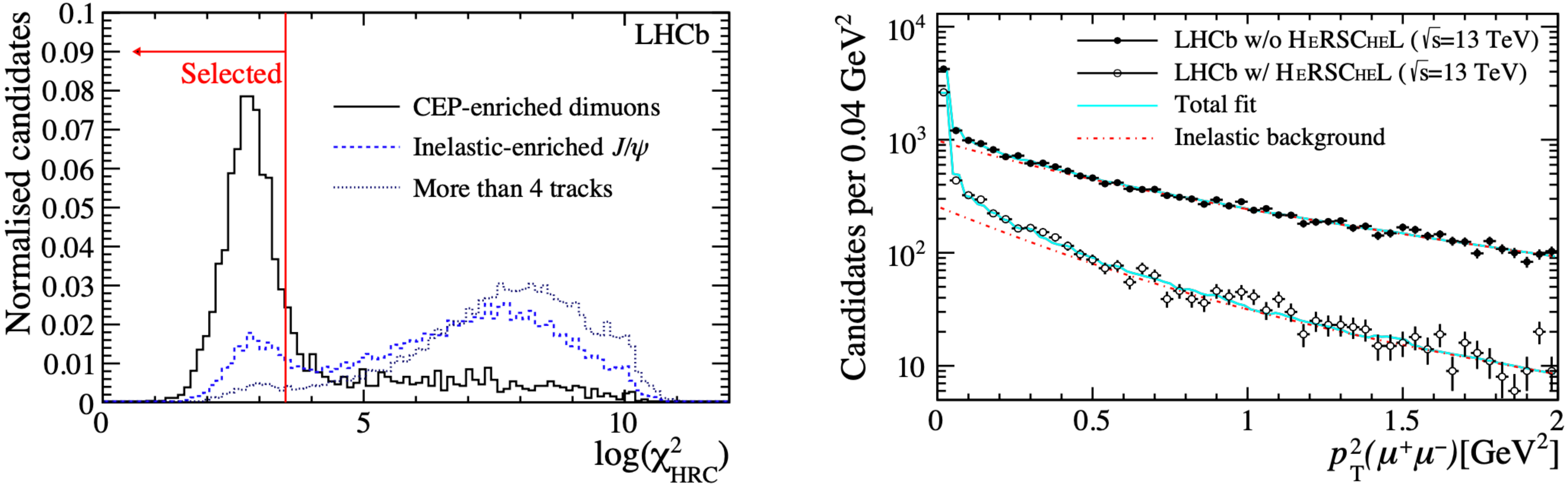


CEP J/ψ AND $\psi(2S)$ IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

[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 $= 0.723 \pm 0.008$

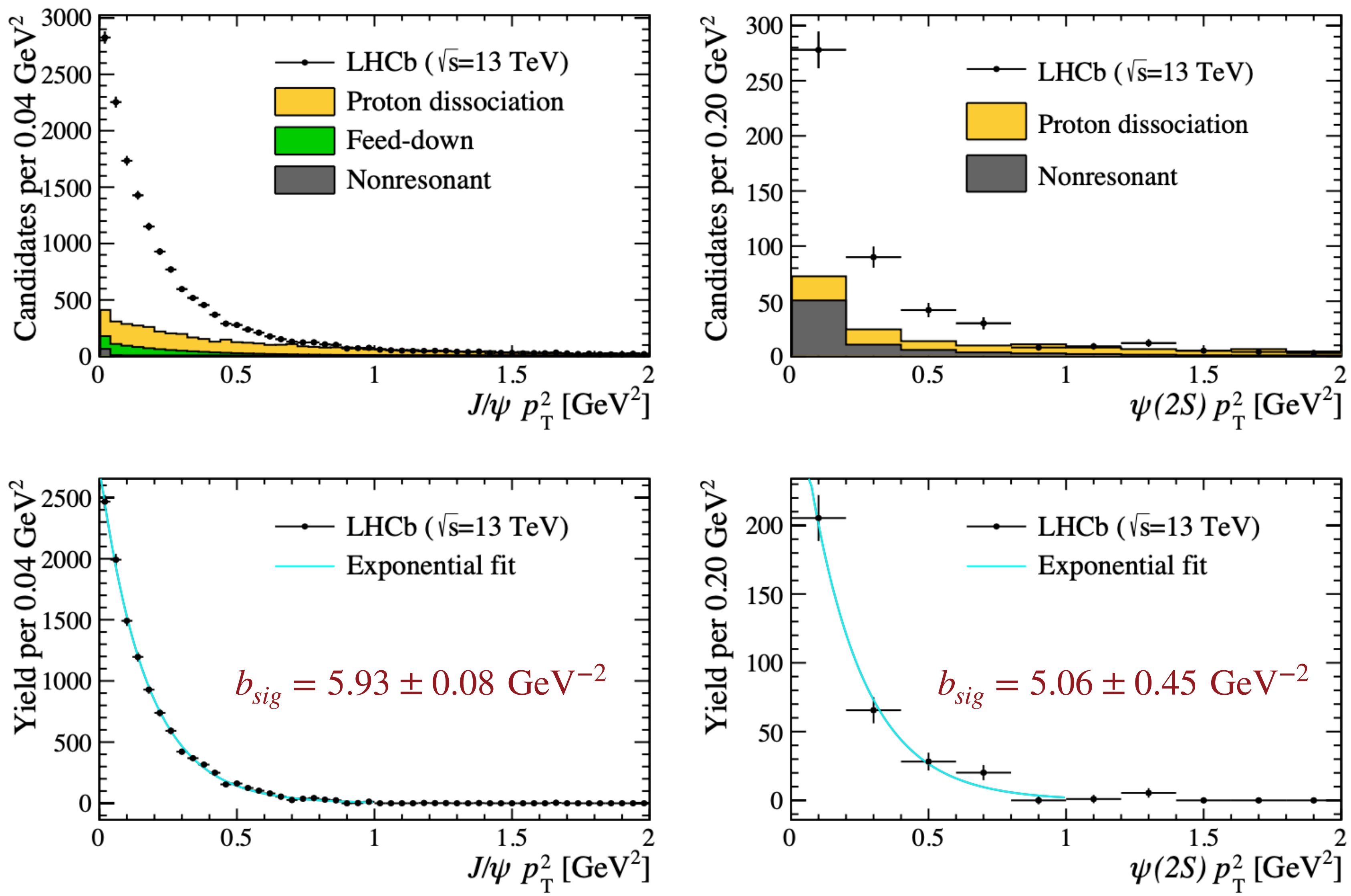


- Estimate inelastic background by using two samples: above and below HeRSCheL veto (more in backup).

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: $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^2 \sim \exp(-b_{sig}p_\mathrm{T}^2)$, $b_{sig} \approx 6\ \mathrm{GeV}^{-2}$ → In agreement!



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

[JHEP 10 (2018) 167]

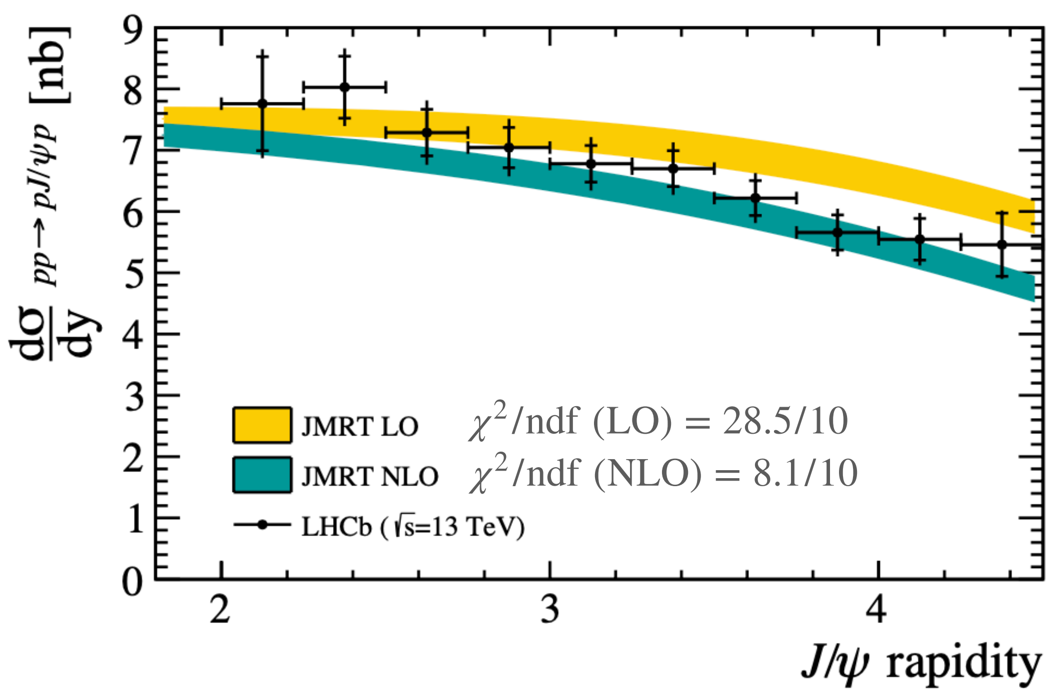
- Cross-section calculation per rapidity bin y with $\mathscr{L}_{tot} = 204 \pm 8$ pb^{-1}:

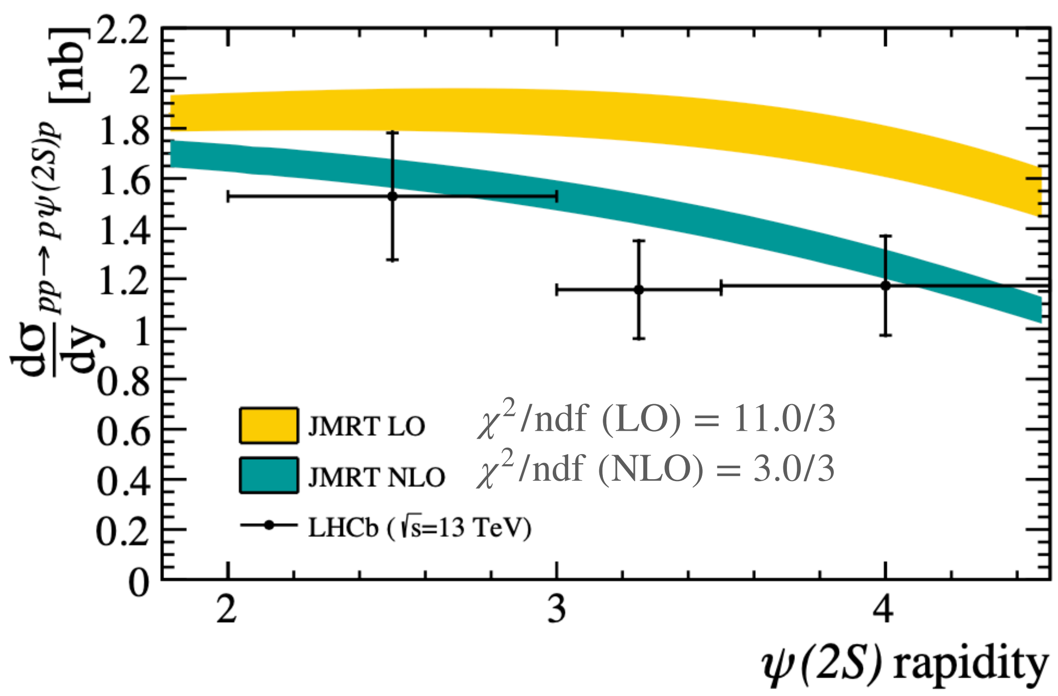
$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy} = \frac{N_{sig}}{\epsilon_{tot} \cdot \Delta y \cdot \epsilon_{single} \cdot \mathscr{L}_{tot}}$$

- Integrated luminosity, $\mathscr{L}_{\rm tot}$, multiplied by the fraction of events with no additional interactions, $\epsilon_{\rm single}$.

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

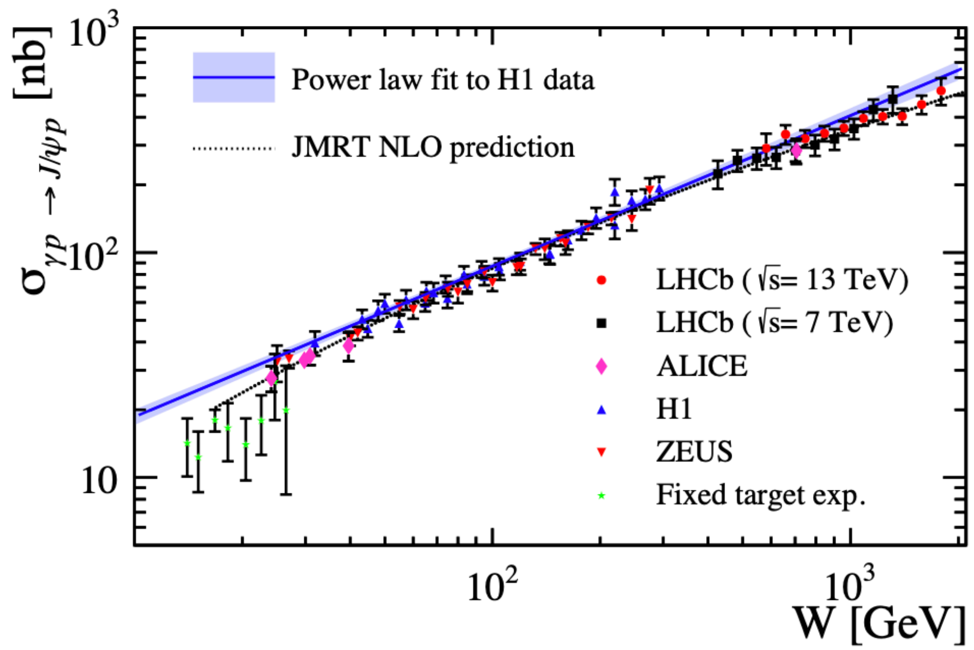
$\sigma_{\psi(2S)\to\mu^+\mu^-} = 11.1 \pm 1.1$ (stat.) ± 0.3 (syst.) ± 0.4 (lumi.) pb

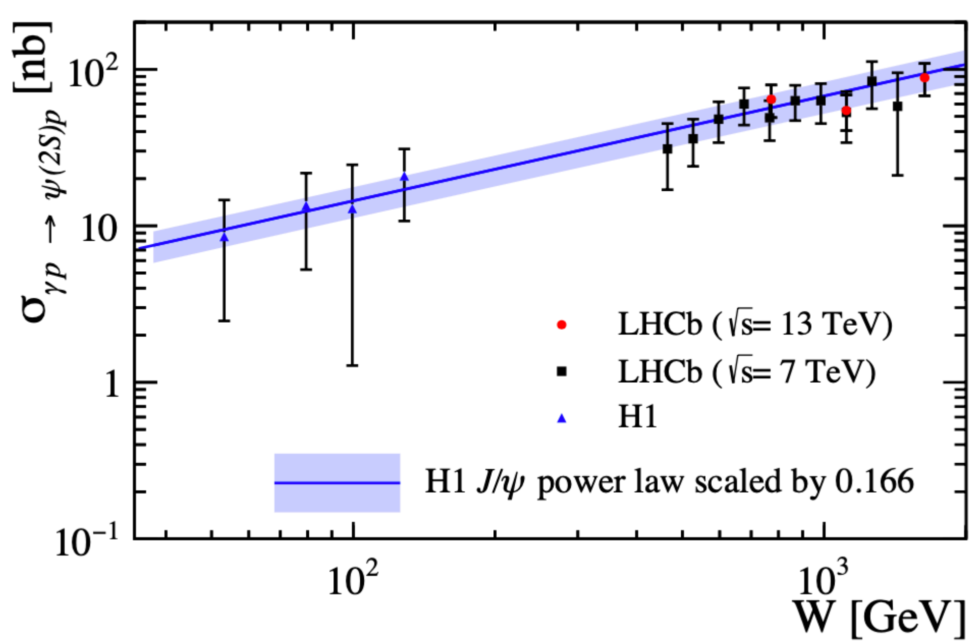




CEP J/ψ AND $\psi(2S)$ IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

[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!

Z BOSONS PRODUCED IN ASSOCIATION WITH CHARM

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

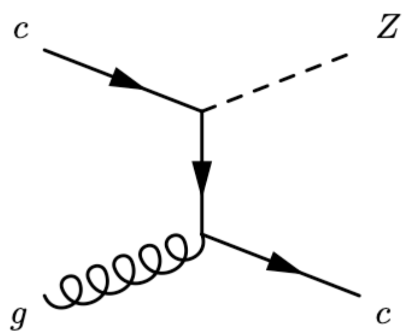
[LHCB-PAPER-2021-029]

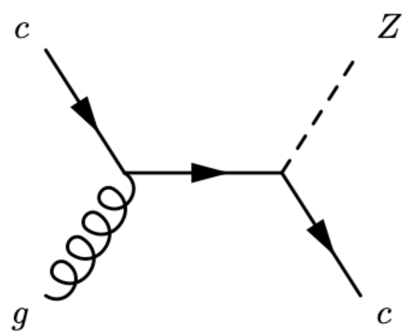
- Proton charm content:
  - ✓ Extrinsic charm, from perturbative gluon radiation ($g \to c\bar{c}$).
  - ? Intrinsic charm (IC), as valence-like c-content in the proton (proton as $|uudc\bar{c}\rangle$).
    - Predicted by Light Front QCD (LFQCD).

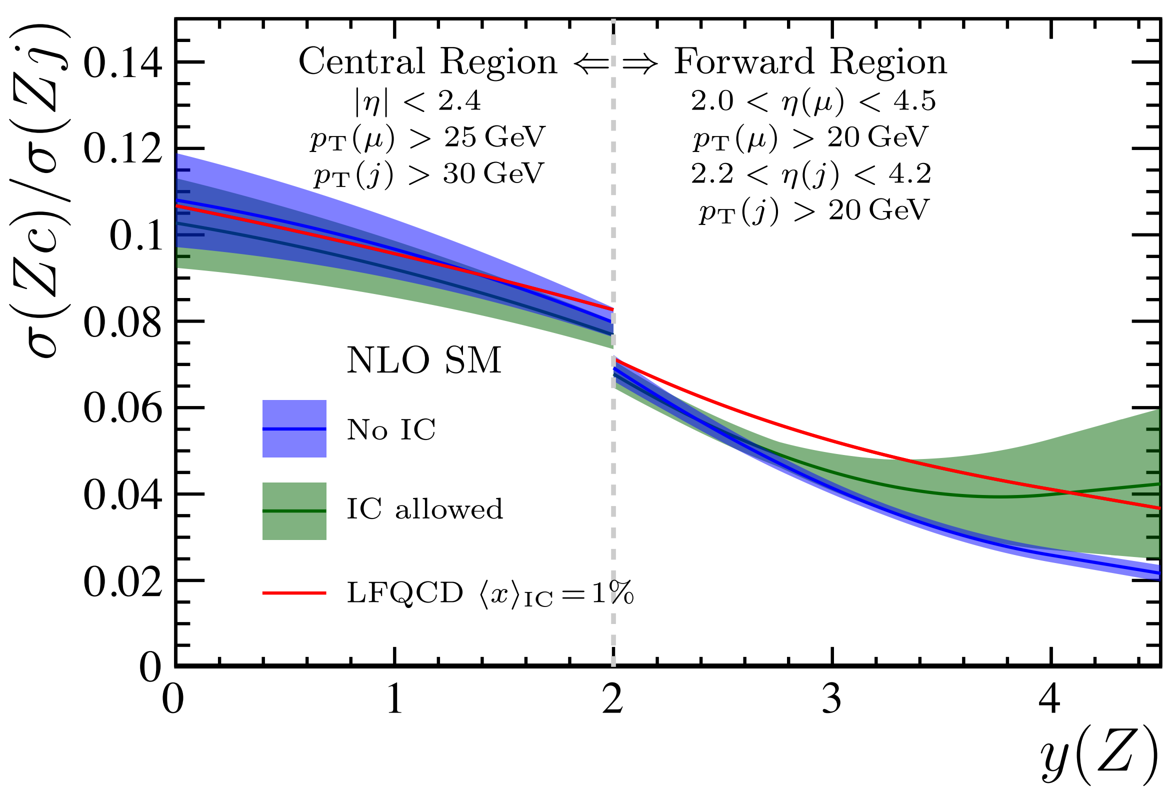
- Former measurements done at low-Q^2: difficult theoretical treatment of hadronic and nuclear effects.

- Global PDF analyses do not exclude IC at the percent level!

- Proposal: measure $\mathscr{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$ in the forward region (hadronic and nuclear effects negligible) [Phys. Rev. D 93, 074008 (2016)].
  - Zc is at high-Q^2, forward rapidity → 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.

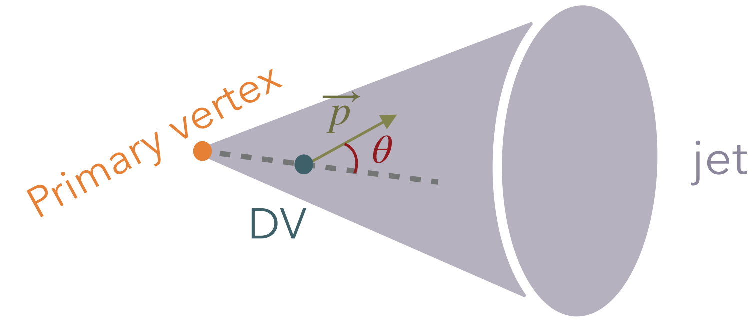
- Measure $\mathscr{R}_j^c = N(c\text{-tag})/[\epsilon(c\text{-tag}) \cdot N(j)]$

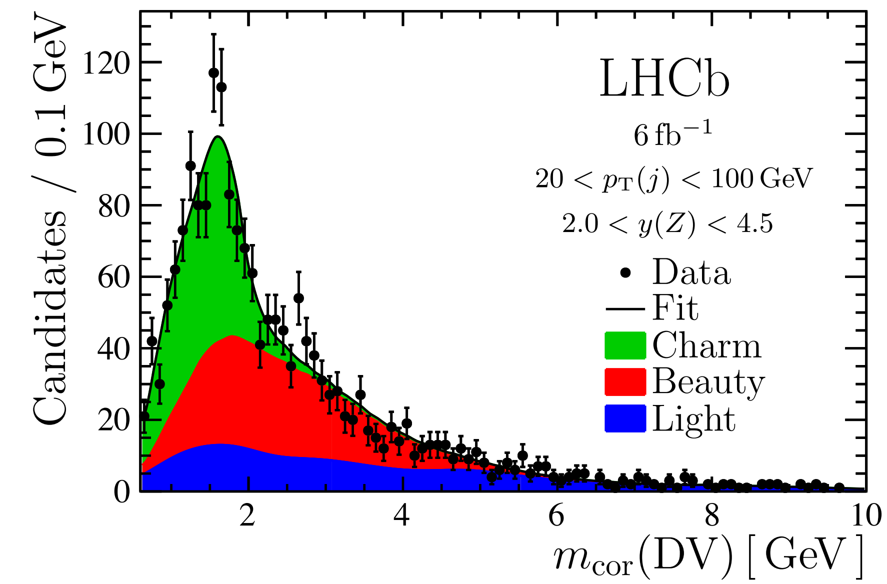
- Select events with $Z \to \mu^+\mu^-$ and at least one jet with $p_T > 20$ GeV$/c$.

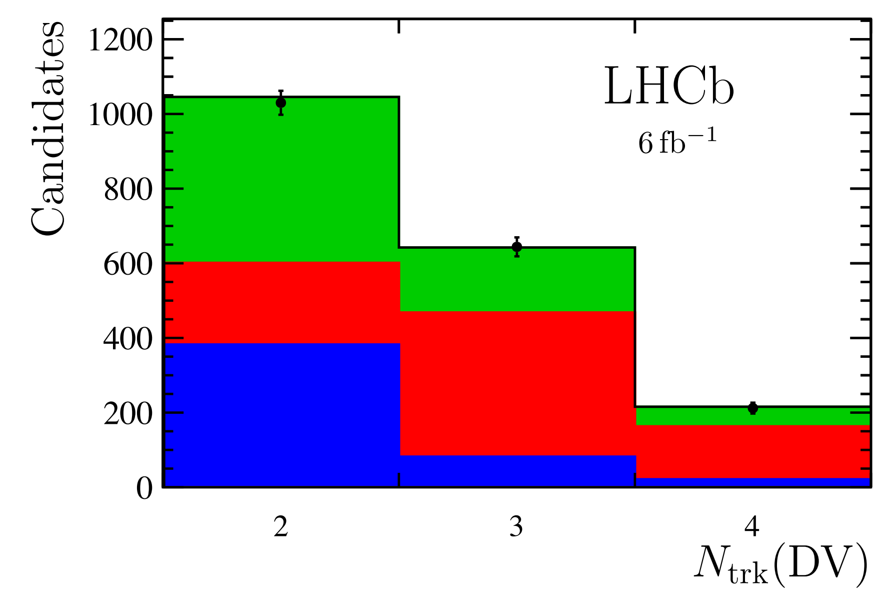
- Identify c-jets using displaced-vertex (DV) tagger in bins of $p_T(j)$ and $y(Z)$:
  - Perform 2D fit to corrected DV-mass and number of tracks in DV (templates obtained from calibration samples).

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

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







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

[LHCB-PAPER-2021-029]

* c-tagging efficiency, $\epsilon(c\text{-tag})$, determined in simulation and calibrated in data.

* Ratio of Z_c and Z_j cancels most systematic uncertainties.
* Dominant systematic uncertainty related to the c-tagging efficiency.

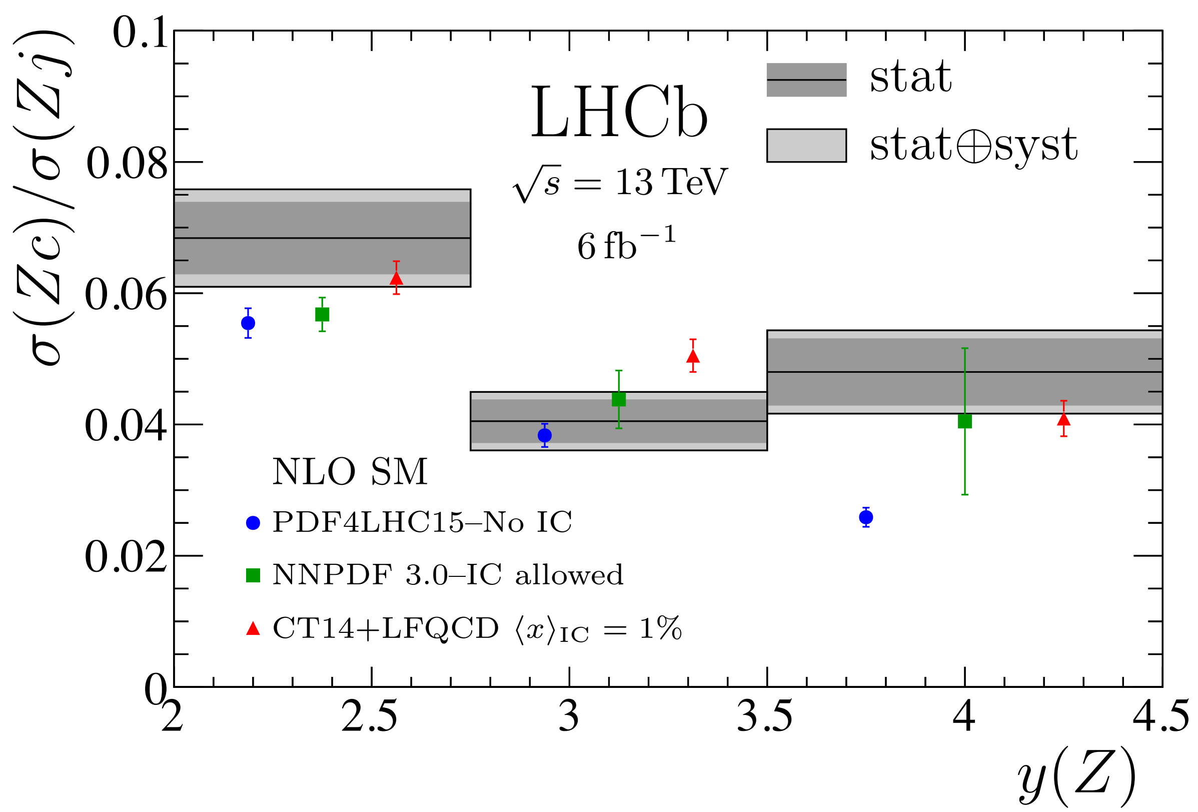
Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

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

[LHCB-PAPER-2021-029]

- Comparison to 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

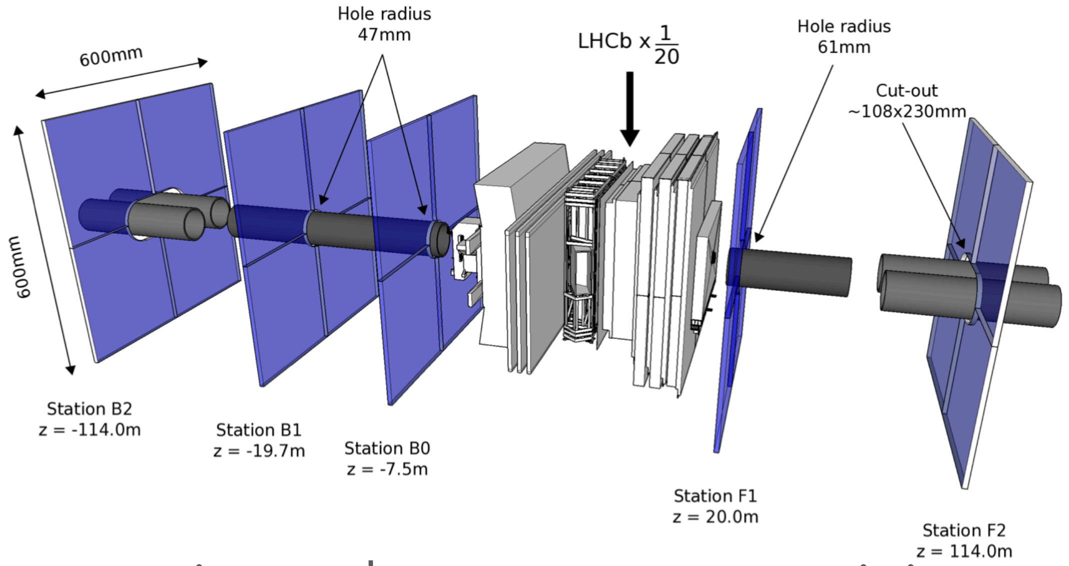
- LHCb operating as a general purpose forward experiment, complementary to ATLAS and CMS.

- For low-x: $J/\psi, \psi(2S)$ CEP, update with more data coming soon, higher statistics for $\psi(2S)$.

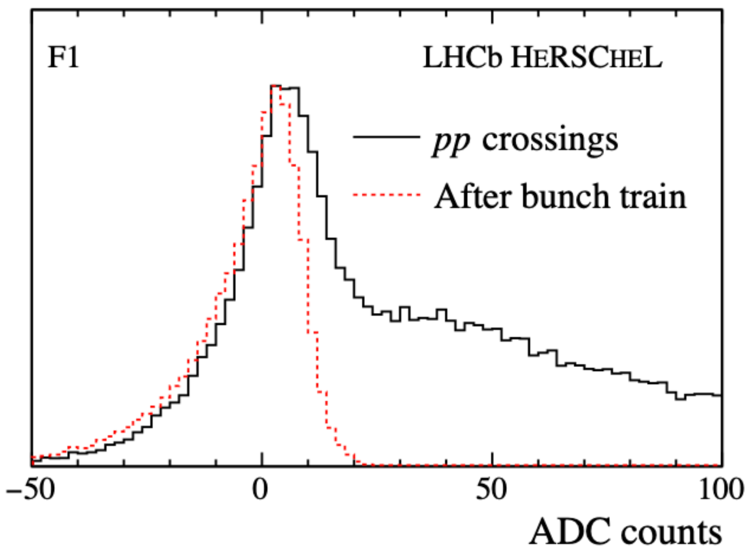
- For high-x: the $Z + c$ jet measurement shows the first direct evidence of IC.
    - Inclusion in global PDF analyses pending.
    - Measurement statistically limited, stay tuned for update with Run 3 data!

THANK YOU FOR YOUR ATTENTION!

HERSCHEL: HIGH RAPIDITY SHOWER COUNTERS FOR 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



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

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

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:

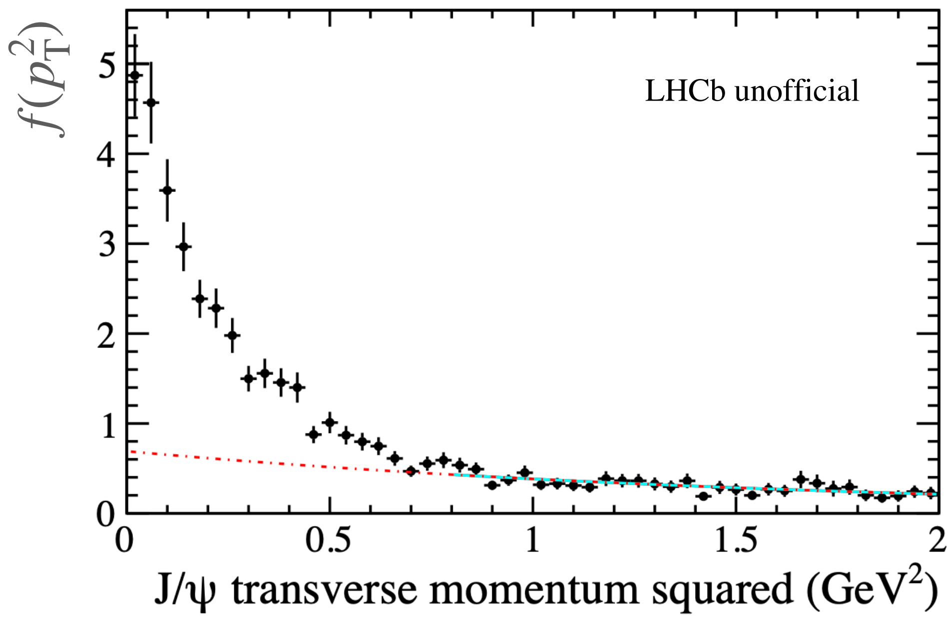
- Take p_{T}^2 distribution with non-resonant $\mu\mu$ and feed-down bkg removed
- Define two samples and define a variable with exclusive events, β:

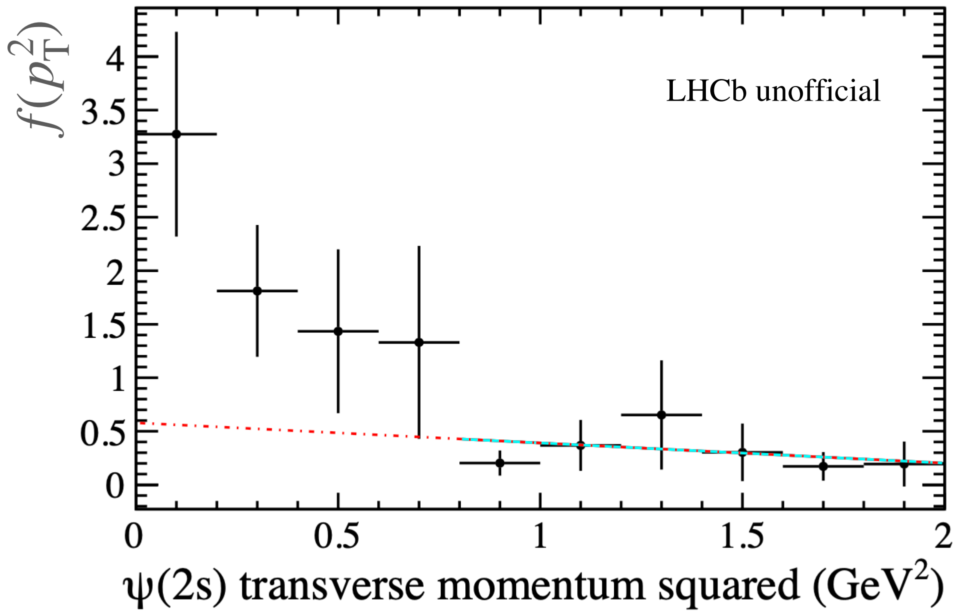
S_H for $\log(\chi^2_{HRC}) < 3.5$

$S_{\overline{H}}$ 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

[JHEP 10 (2018) 167]

- 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 $\delta = 0.67 \pm 0.03$.

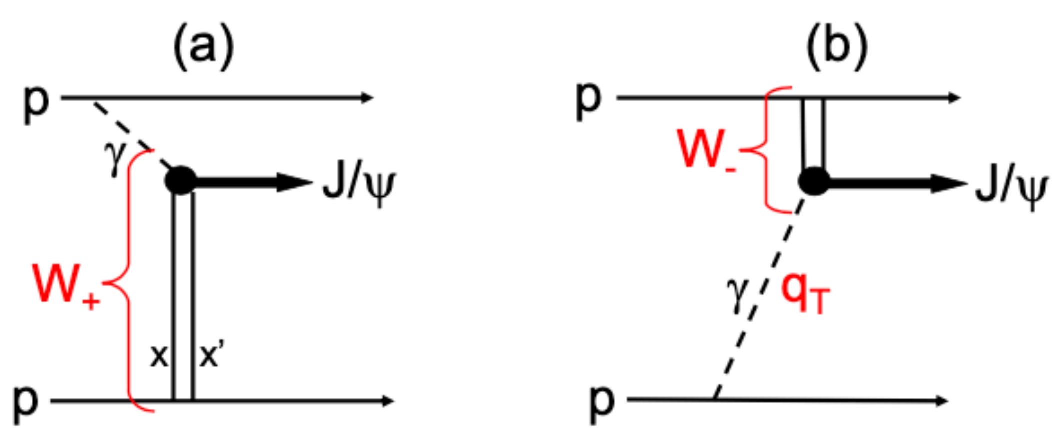


Figure 2: The two diagrams describing exclusive J/ψ production at the LHC. The vertical lines represent two-gluon exchange. Diagram (a), the W_+ component, is the major contribution to the $pp \to p + J/\psi + p$ cross section for a J/ψ produced at large rapidity y. Thus such data allow a probe of very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

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

[LHCB-PAPER-2021-029]

- 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 $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$correcting for detector response and branching and fragmentation functions.