Low-x physics at LHCb

Lucas Meyer Garcia

on behalf of the LHCb Collaboration

July 10

2025 European Physical Society Conference on High Energy Physics

Outline

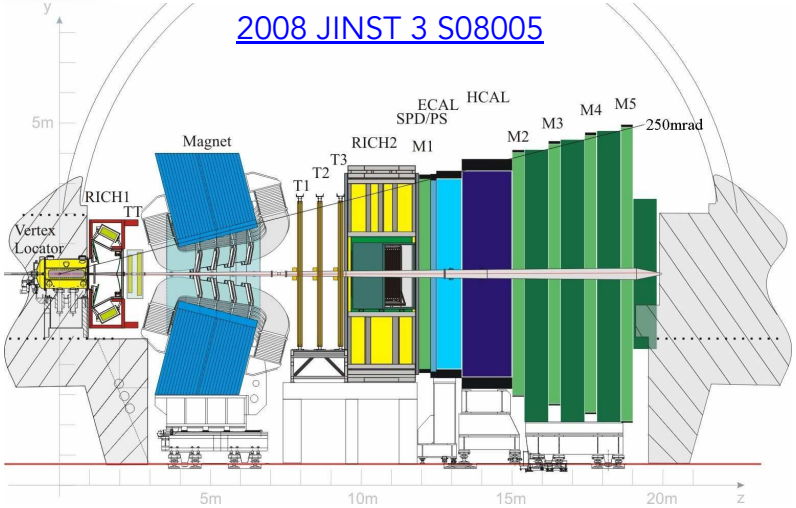
pp

- Measurement of exclusive J/ψ and $\psi(2S)$ production at $\sqrt{s}$ = 13 TeV SciPost Phys. 18, 071 (2025)
- Observation of Exotic $J/\psi\phi$ Resonant Structure in Diffractive Processes in Proton-Proton Collisions Phys. Rev. Lett. 134, 031902

PbPb

- Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions JHEP 06 (2023) 146
- Coherent photoproduction of ρ^0, ω and excited vector mesons in ultraperipheral PbPb collisions 10.48550/arXiv.2506.06250
- First observation of the $\phi(1020)$ meson in the K^+K^- mass spectrum of ultra-peripheral PbPb collisions at forward rapidity LHCb-CONF-2024-006

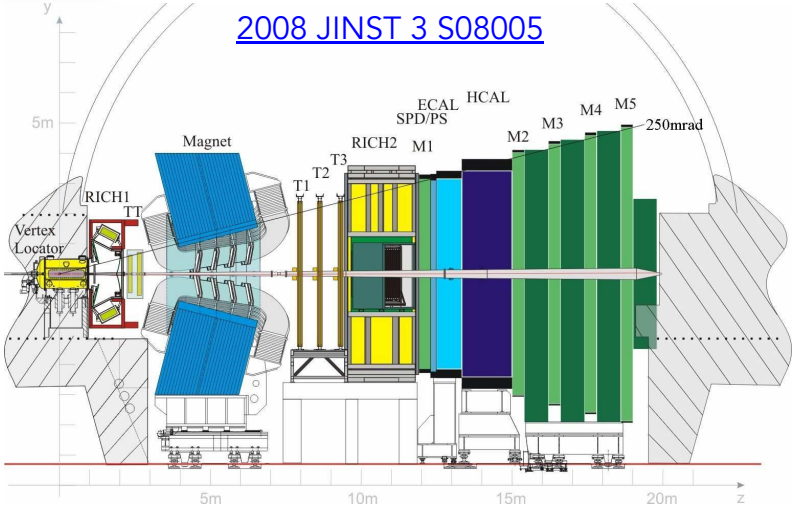
The LHCb detector

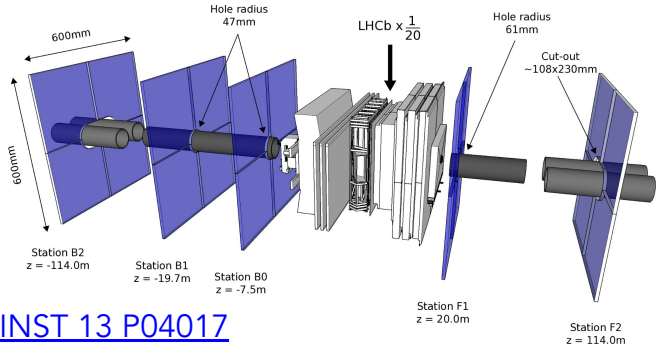


- Designed for b-physics, but exploited for general physics
- Fully instrumented in the forward region $2 < \eta < 5$
  - ➡ Limited backwards coverage $-3.5 < \eta < -1.5$
- Excellent momentum resolution, vertexing and PID capabilities

The LHCb detector

2008 JINST 3 S08005





2018 JINST 13 P04017

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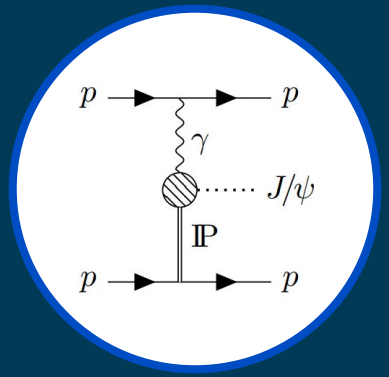
- Fully instrumented in the forward region $2 < \eta < 5$
  - ➡ Limited backwards coverage $-3.5 < \eta < -1.5$
- Excellent momentum resolution, vertexing and PID capabilities

- Coverage further extended by HeRSCheL detector
  - ➡ Scintillating panels installed away from main detector
  - ➡ Covers $5 < |\eta| < 10$

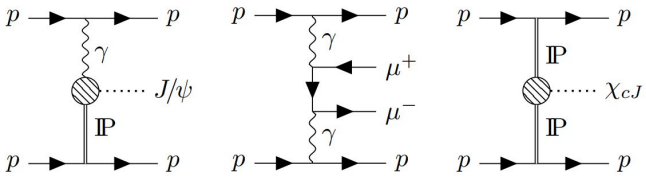
Measurement of exclusive J/ψ and $\psi(2S)$ production at $\sqrt{s}$ = 13 TeV



SciPost Phys. 18, 071 (2025)

Motivation and strategy

- Central Exclusive Production: quasi-elastic process where protons remain intact
  - ➡ Mediated by colorless propagators: photon or Pomeron
- Can help constrain gluon PDF at bjorken-x values down to 10^{-6}
- Sheds light on the nature of the Pomeron
- Clear signature: Large rapidity gaps
  - ➡ Select muon pairs in otherwise empty events
  - ➡ Exploits HeRSCheL



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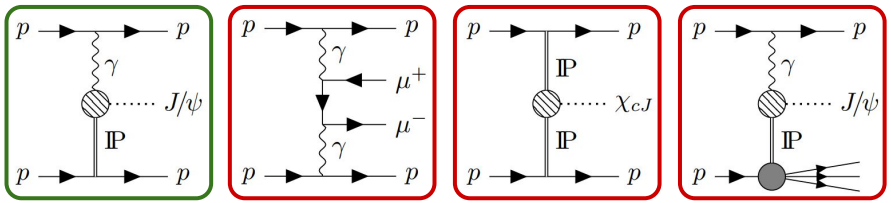
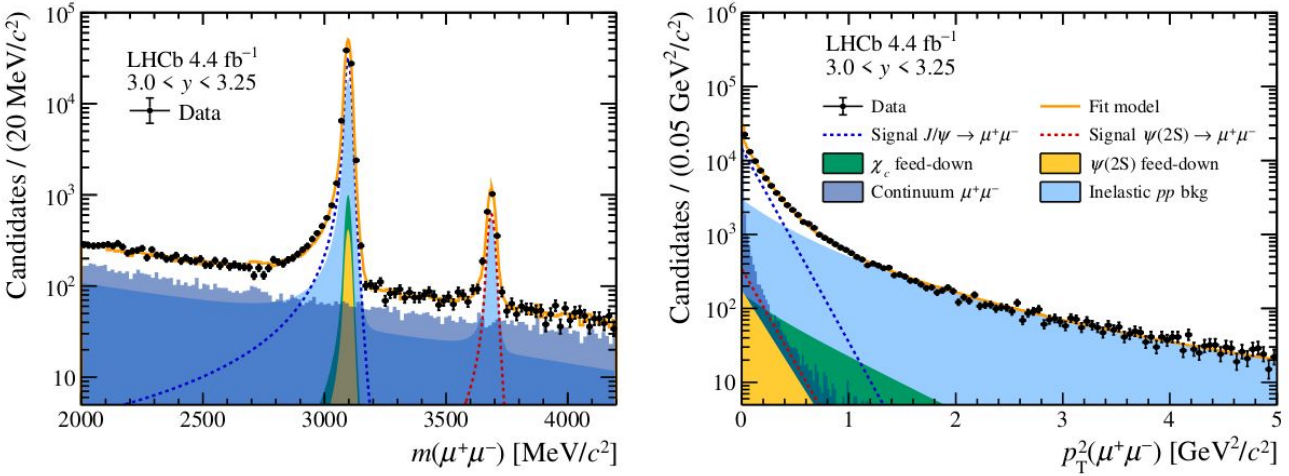


SciPost Phys. 18, 071 (2025)

- Signal: Photo-produced J/ψ or $\psi(2S)$
- Background:
  - ➡ QED dimuon production
  - ➡ Feed-down from higher-mass charmonia
  - ➡ Proton dissociation (PD)

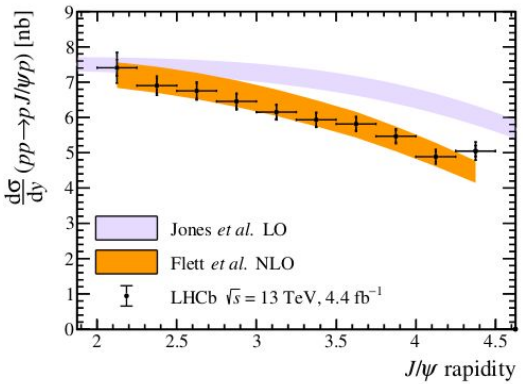
Extracting J/ψ and $\psi(2S)$ CEP yields

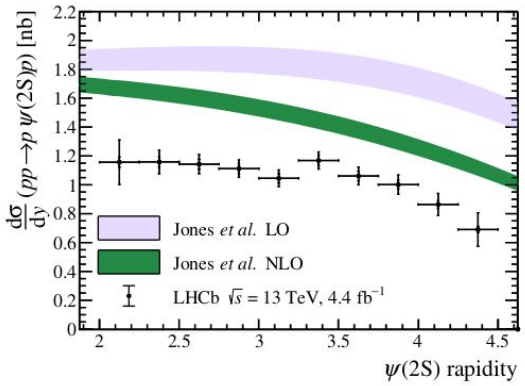


SciPost Phys. 18, 071 (2025)

- Signal yields measured in 10 rapidity intervals via 2D unbinned extended maximum-likelihood fit
  - ➡ Shape of proton dissociation background extracted from fit to control samples
  - ➡ Shape of QED background determined with SuperChic 2 generator
  - ➡ Feed-down from χ_c and $\psi(2S)$ to J/ψ estimated with input from simulation and normalized to data

J/ψ and $\psi(2S)$ CEP cross-section measurements





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- J/ψ cross-sections agrees with NLO prediction
- $\psi(2S)$ cross-sections overestimated by both LO and NLO predictions

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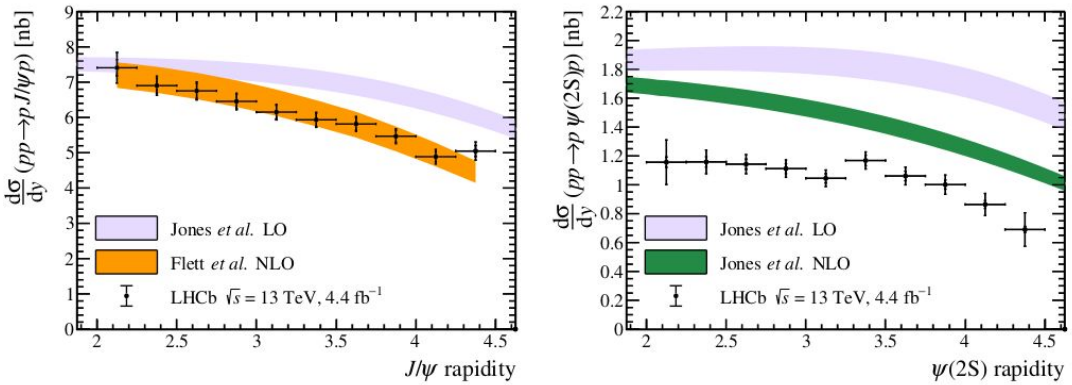

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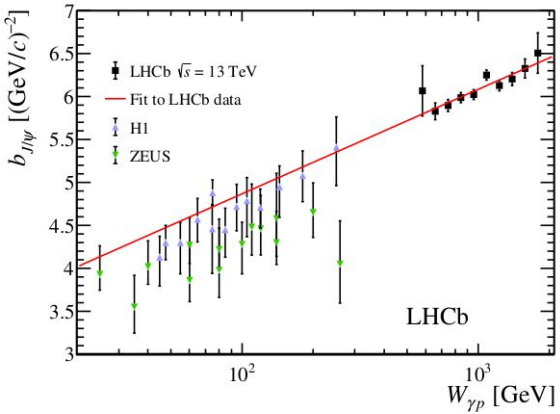


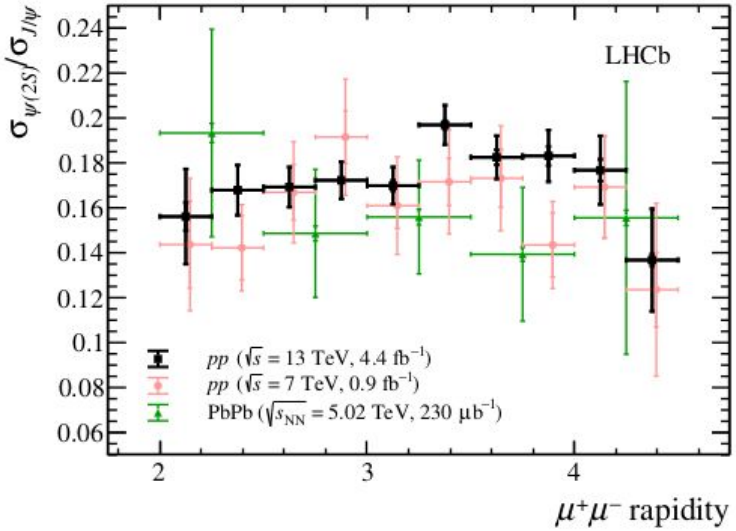
- p_T^2 dependence of cross-sections is measured in pp for the first time

$$d\sigma/dp_T^2 \sim e^{-bp_T^2}, \qquad b = b_0 + 4\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)$$

- Consistent with H1 and Zeus measurements

J/ψ and $\psi(2S)$ CEP cross-section measurements

- Ratio of J/ψ and $\psi(2S)$ cross-sections consistent with previous LHCb studies

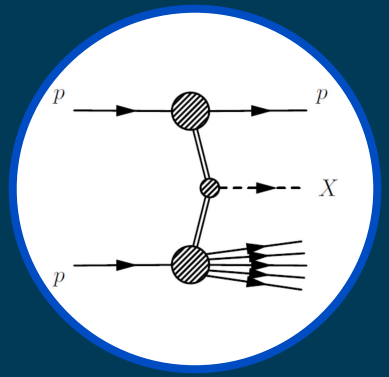


SciPost Phys. 18, 071 (2025)

- Integrated ratio consistent with H1 and ZEUS measurements

$$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = 0.1763 \pm 0.0029 \pm 0.0008 \pm 0.0039$$

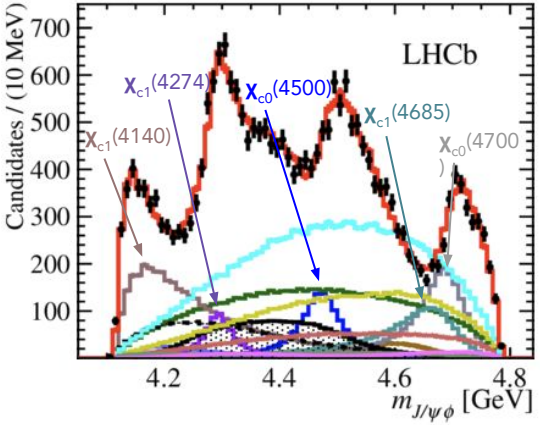
Observation of Exotic $J/\psi\phi$ Resonant Structure in Diffractive Processes in Proton-Proton Collisions



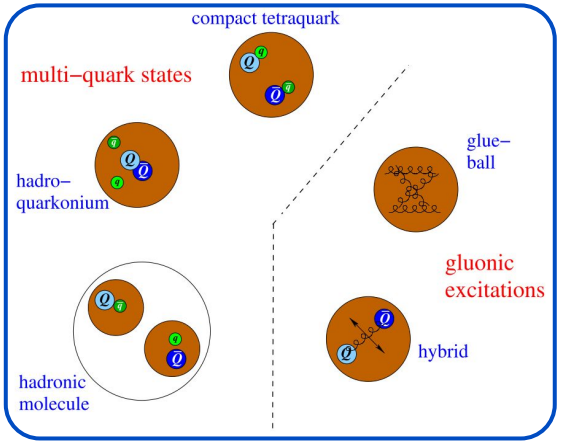
Phys. Rev. Lett. 134, 031902

Motivation

- First study of $J/\psi\phi$ production in diffractive processes in pp collisions
- Several exotic states previously observed in $B^+ \rightarrow J/\psi\phi K^+$ decays
  - ➡ Five of those exotic candidates can be produced in photon-photon or pomeron-pomeron processes
- May help narrow down interpretations and distinguish between compact tetraquarks and molecular states



Phys. Rev. Lett. 127, 082001

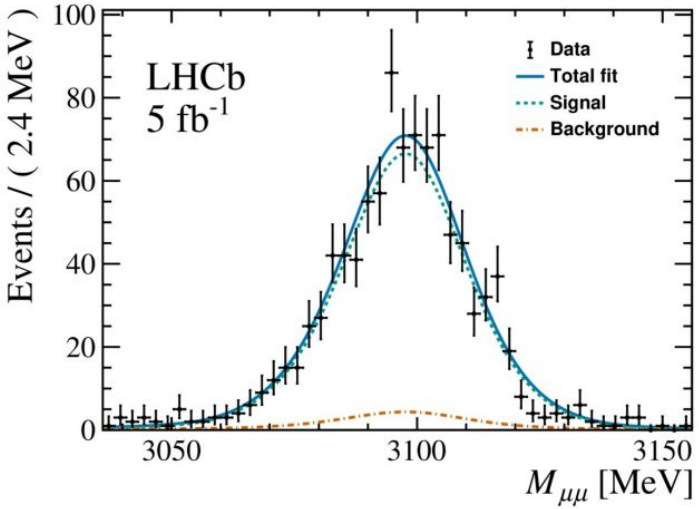


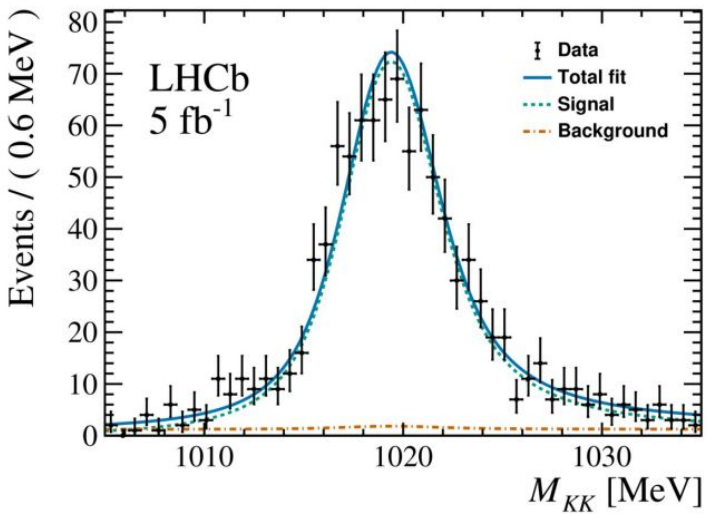
Physics Reports 873 (2020) 1–154

Selection strategy

- Selection strategy: Events with two muons, two kaons and no additional tracks
  - ➡ Veto on HeRSCheL not applied

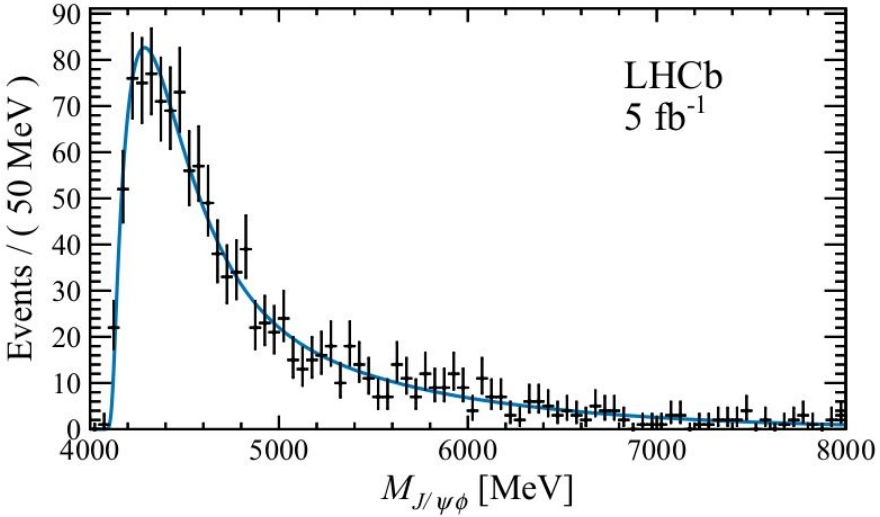
Phys. Rev. Lett. 134, 031902





- Clear J/ψ and ϕ signals
  - ➡ 2D unbinned fit indicates sample purity of 93%

High-multiplicity sample

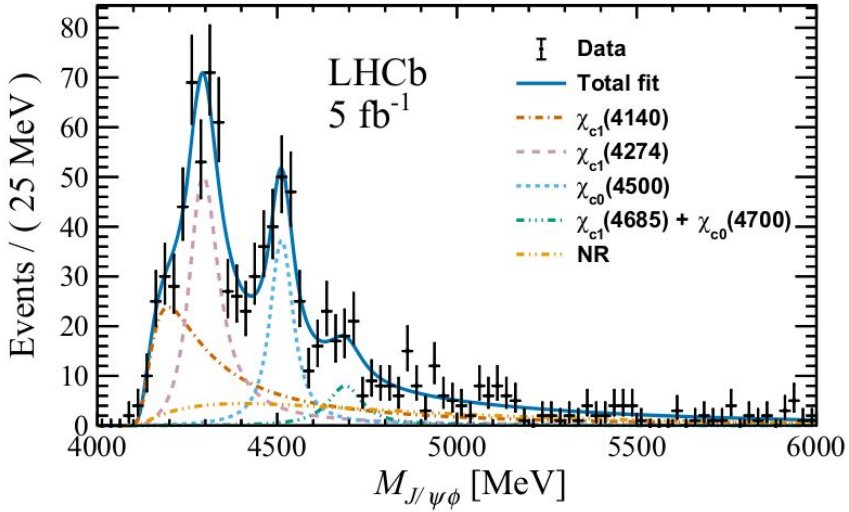


Phys. Rev. Lett. 134, 031902

- Same selection requirements, except for an inverted offline multiplicity requirement:
  - ➡ More than 4 tracks
- No clear mass structure

$J/\psi\phi$ diffractive cross-section measurements

Phys. Rev. Lett. 134, 031902



- Fit performed with previously observed resonances in B decays.
  - ➡ Turn-on derived from sideband sample
  - ➡ Non-resonant contribution modeled by an exponential function
  - ➡ No interference assumed

$J/\psi\phi$ diffractive cross-section measurements

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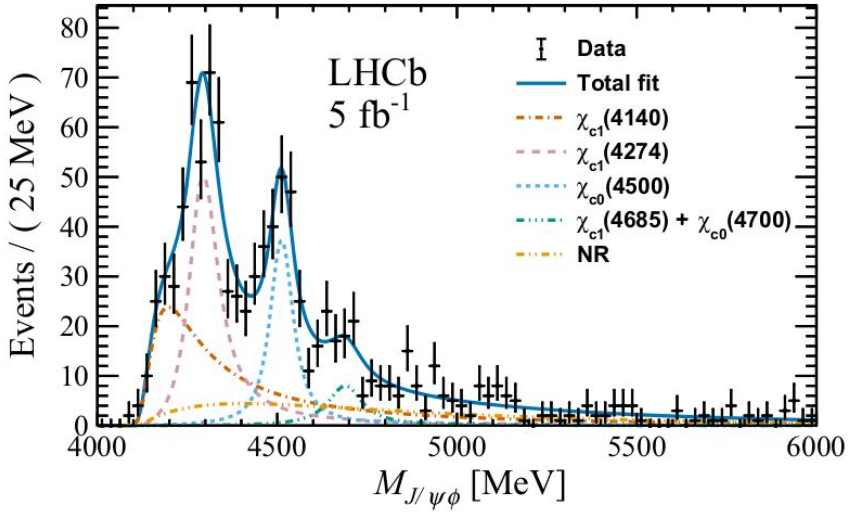


$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.80 \pm 0.15^{+0.26}_{-0.29})\ \text{pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.73^{+0.14\ +0.16}_{-0.13\ -0.19})\ \text{pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.42^{+0.09\ +0.07}_{-0.08\ -0.05})\ \text{pb},$$

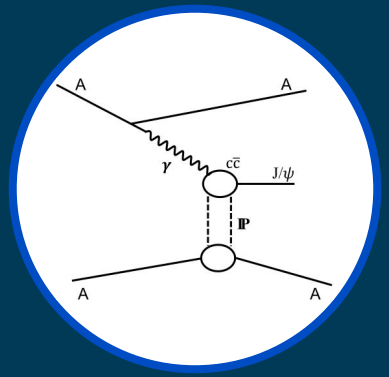
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07\ +0.034}_{-0.06\ -0.040})\ \text{pb},$$

$$\sigma_{\text{NR}} \times \mathcal{B}_{\text{eff}}^{\text{NR}} = (0.43^{+0.24\ +0.22}_{-0.18\ -0.16})\ \text{pb},$$

- Fit performed with previously observed resonances in B decays.
  - ➡ Turn-on derived from sideband sample
  - ➡ Non-resonant contribution modeled by an exponential function
  - ➡ No interference assumed

- Significances for $\chi_{c1}(4140)$, $\chi_{c1}(4274)$ and $\chi_{c0}(4500)$ are 2.3σ, 4.1σ and 6.1σ.
- Several clear resonant structures are observed and well-described by resonant model
- First observation of $X \to J/\psi\phi$ production in diffractive processes!

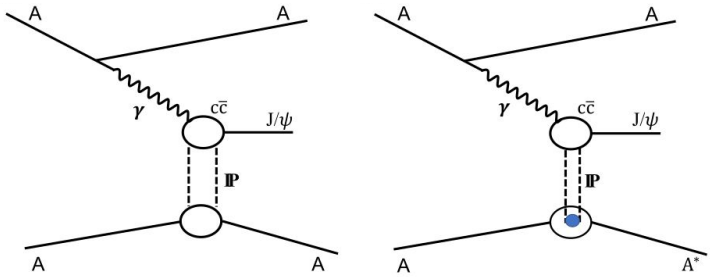
Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions



JHEP 06 (2023) 146

Motivation and strategy

- Ultra-peripheral collisions (UPC): Impact parameter greater than sum of nuclei radii
  - ➡ Also mediated by colorless propagators
- Can help constrain nuclear gluon PDF at bjorken-x values down to 10^{-5}
- Excellent laboratory to study nuclear shadowing effects at low x



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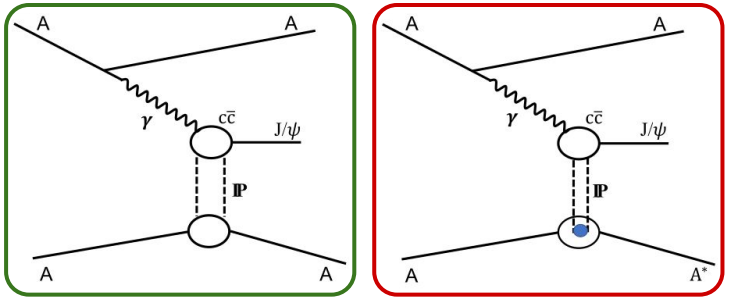
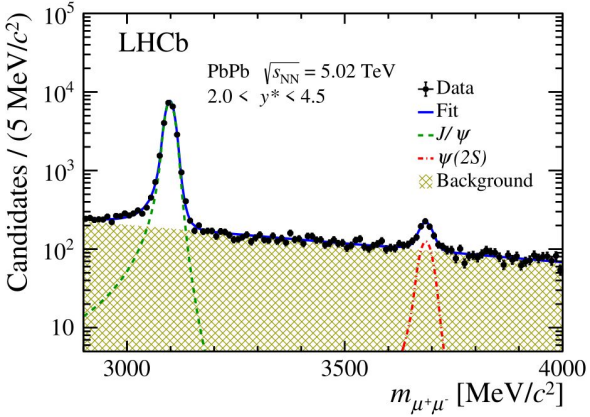


JHEP 06 (2023) 146

- Coherent UPC:
  - ➡ Pomeron couples to whole nucleus
  - ➡ Vector meson produced with low p_T
  - ➡ Nucleus more likely to survive ⇒ Rapidity gaps
- Incoherent UPC:
  - ➡ Pomeron couples to individual nucleon
  - ➡ Nucleus more likely to dissociate ⇒ Additional particles particles in detector acceptance

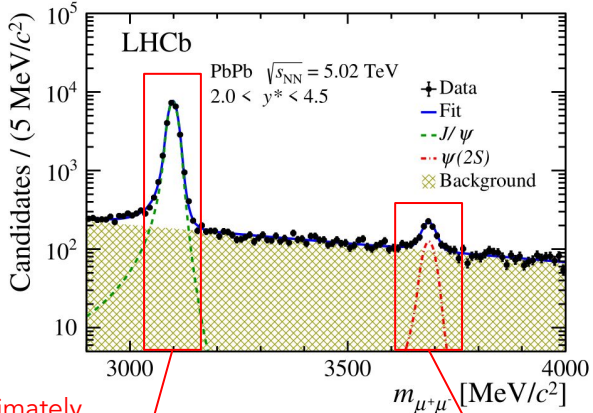
Extracting J/ψ and ψ(2S) coherent UPC yields



JHEP 06 (2023) 146

- Select muon pairs in events with no additional activity
- Perform unbinned maximum likelihood fit to dimuon mass distribution
- Determine background yield in J/ψ and ψ(2S) mass windows

Extracting J/ψ and $\psi(2S)$ coherent UPC yields



* Approximately to scale

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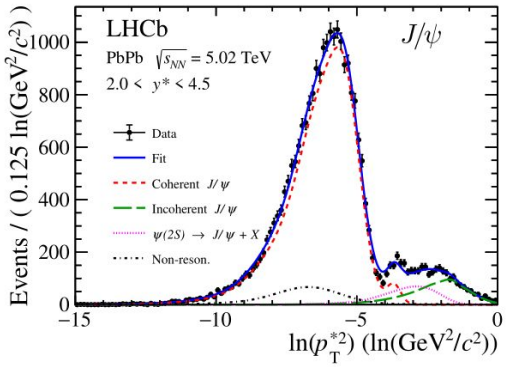
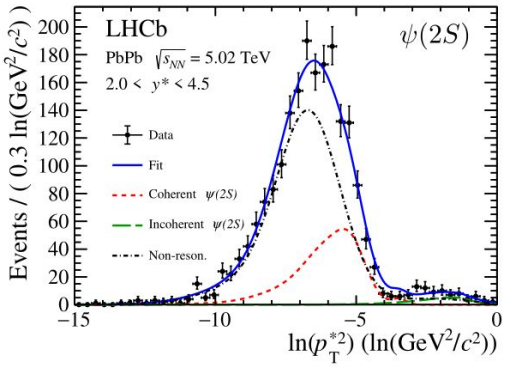
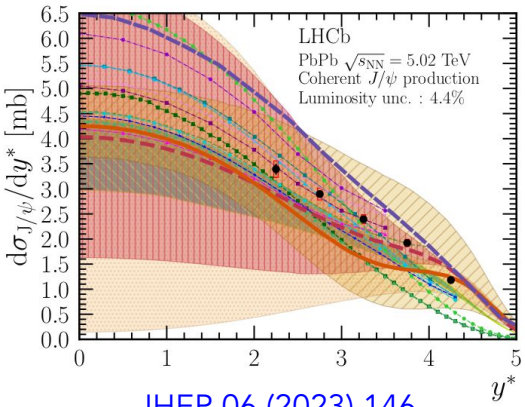
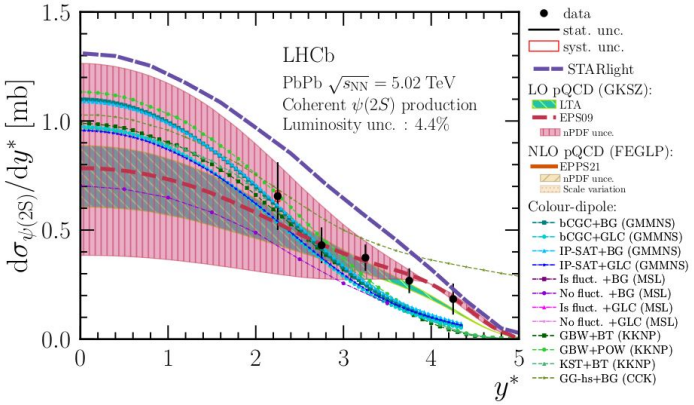




- Perform fits to ln(p_T^2) distribution to extract coherent yield
  - ➡ Non-resonant shape extracted from control sample
  - ➡ Remaining contributions produced with STARlight generator

J/ψ and $\psi(2S)$ coherent UPC cross-sections





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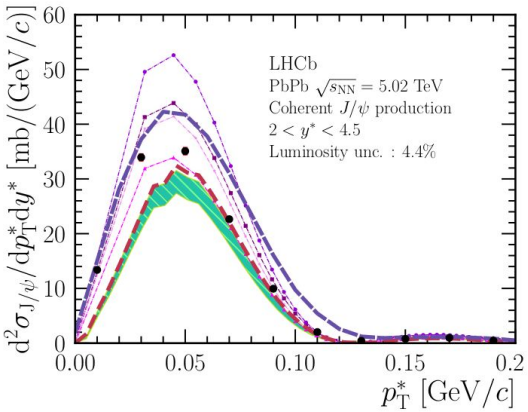
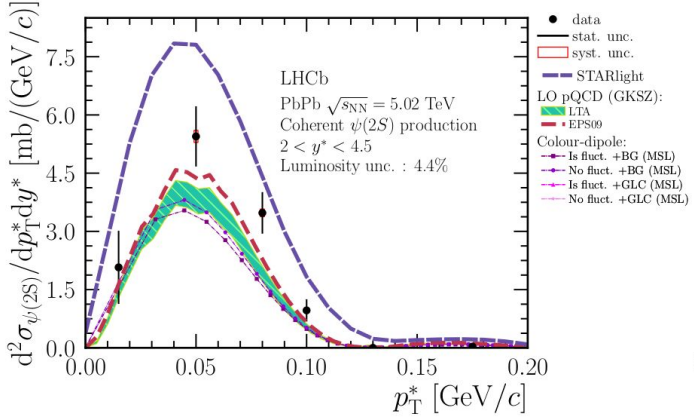




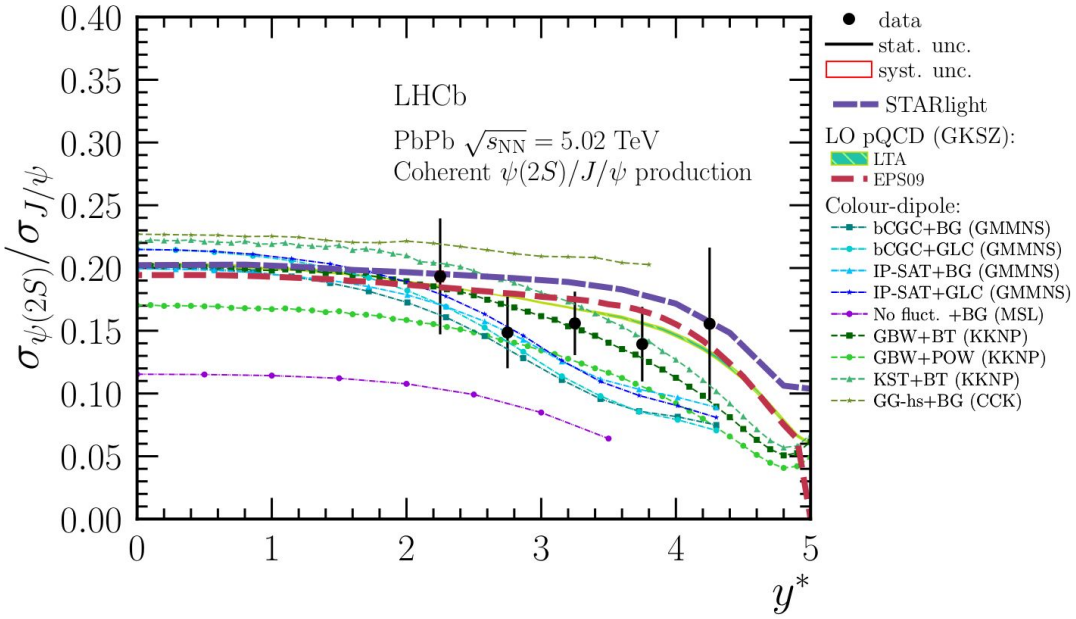
- Differential cross-section determined in intervals of rapidity and transverse momentum
- Most precise coherent J/ψ measurement to date
- First coherent $\psi(2S)$ measurement in the forward region

$$\sigma^{\text{coh}}_{J/\psi} = 5.965 \pm 0.059 \pm 0.232 \pm 0.262\,\text{mb}$$
$$\sigma^{\text{coh}}_{\psi(2S)} = 0.923 \pm 0.086 \pm 0.028 \pm 0.040\,\text{mb}$$

Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

- Ratio of J/ψ and ψ(2S) cross-sections also compared with available predictions

$$\sigma^{\mathrm{coh}}_{\psi(2S)}/\sigma^{\mathrm{coh}}_{J/\psi} = 0.155 \pm 0.014 \pm 0.003$$



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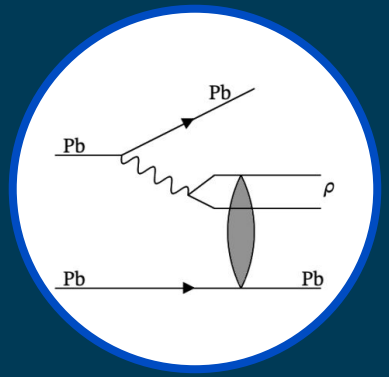
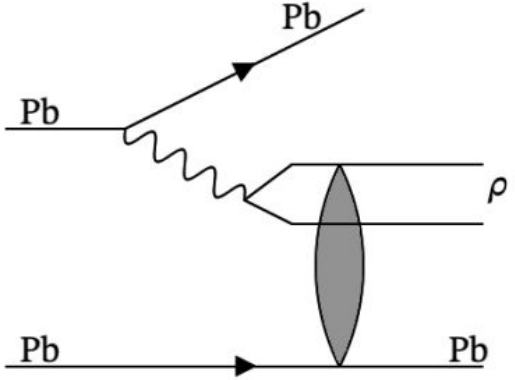
Coherent photoproduction of ρ^0, ω and excited vector mesons in ultraperipheral PbPb collisions



10.48550/arXiv.2506.06250

Motivation and strategy

- At LHCb, ρ^0 coherent UPC can probe Bjorken-x down to 10^{-6}
- Explore dipion final states
  - ➡ Dominated by ρ^0, but also expect contributions from ω and excited states
- Selected tracks identified as pions in events with no additional particles
- Also require decay vertex consistent with interaction region, and veto tracks identified as muons or electrons
  - ➡ Reduce background from converted photons



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Extracting yields

- Dipion mass distribution is fitted with several models
- Best description achieved with H1 parameterization

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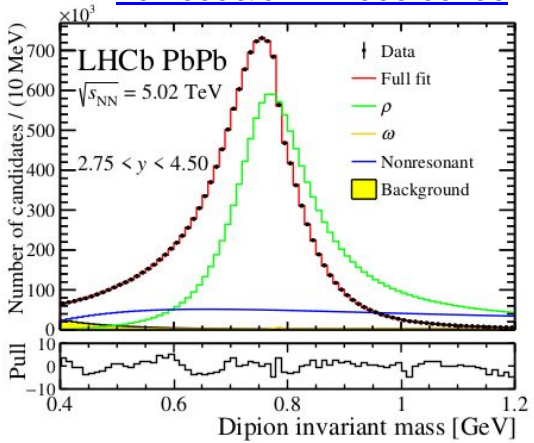

$$\mathcal{S}(m_{\pi\pi}) = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| f_\rho \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + f_\omega \exp(i\phi_\omega) \frac{m^2_{\pi\pi}}{m^2_\omega} \mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{f_{\rm nr}}{(m^2_{\pi\pi} - 4m^2_\pi + \Lambda^2)^\delta} \right|^2$$

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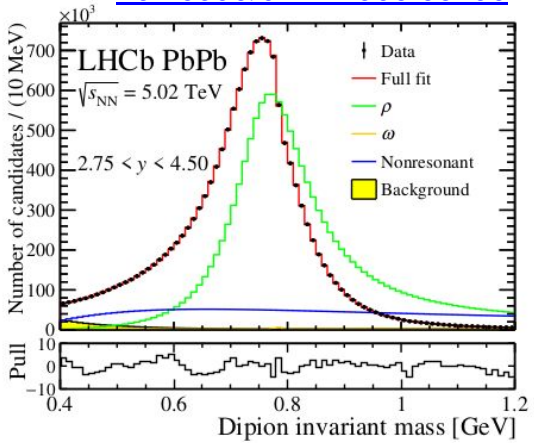

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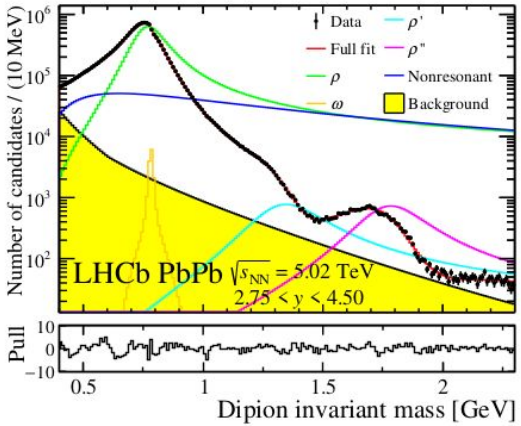
- To describe a wider mass range, the model must be extended with two excited states and a new phase

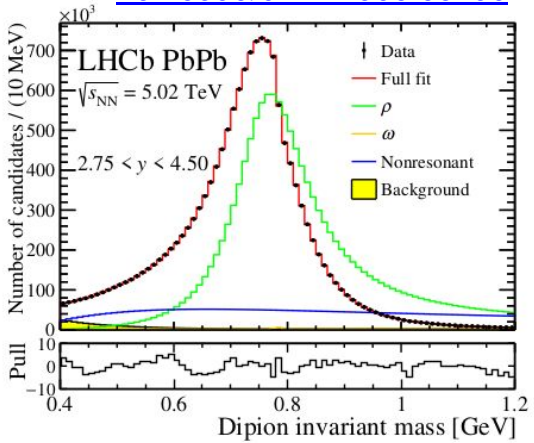


$$\mathcal{S}(m_{\pi\pi}) = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| f_\rho \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + f_\omega \exp(i\phi_\omega) \frac{m^2_{\pi\pi}}{m^2_\omega} \mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{f_{\rm nr} \exp(i\phi_{\rm nr})}{(m^2_{\pi\pi} - 4m^2_\pi + \Lambda^2)^\delta} + f_{\rho'} \exp(i\phi_{\rho'}) \mathcal{BW}_{\rho'}(m_{\pi\pi}) + f_{\rho''} \exp(i\phi_{\rho''}) \mathcal{BW}_{\rho''}(m_{\pi\pi}) \right|^2$$

Extracting yields

- Dipion mass distribution is fitted with several models
- Best description achieved with H1 parameterization

10.48550/arXiv.2506.06250



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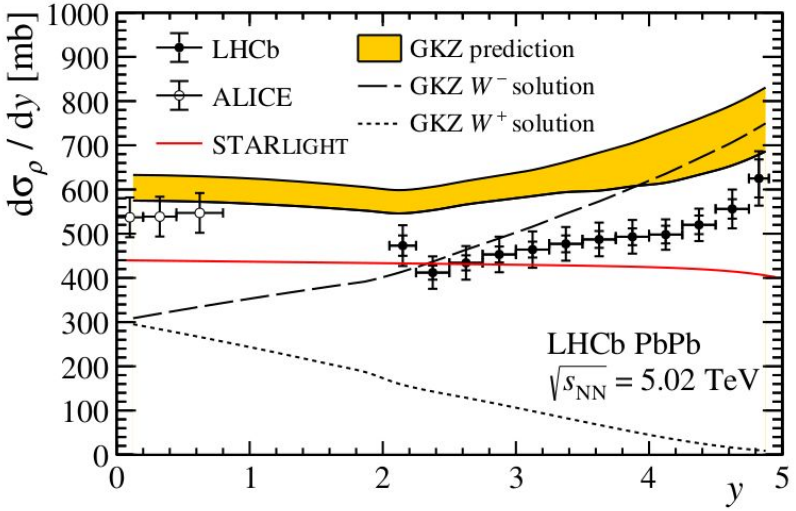
- To describe a wider mass range, the model must be extended with two excited states and a new phase

Consistent with $\rho(1450)$ and $\rho(1700)$

	This analysis	PDG24
$m_{\rho'}$ [MeV]	1350 ± 20	1465 ± 25
$\Gamma_{\rho'}$ [MeV]	320 ± 40	400 ± 60
$m_{\rho''}$ [MeV]	1790 ± 20	1720 ± 20
$\Gamma_{\rho''}$ [MeV]	290 ± 40	250 ± 100

$$\mathcal{S}(m_{\pi\pi}) = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| f_\rho \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + f_\omega \exp(i\phi_\omega) \frac{m^2_{\pi\pi}}{m^2_\omega} \mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{f_{\rm nr} \exp(i\phi_{\rm nr})}{(m^2_{\pi\pi} - 4m^2_\pi + \Lambda^2)^\delta} + f_{\rho'} \exp(i\phi_{\rho'}) \mathcal{BW}_{\rho'}(m_{\pi\pi}) + f_{\rho''} \exp(i\phi_{\rho''}) \mathcal{BW}_{\rho''}(m_{\pi\pi}) \right|^2$$

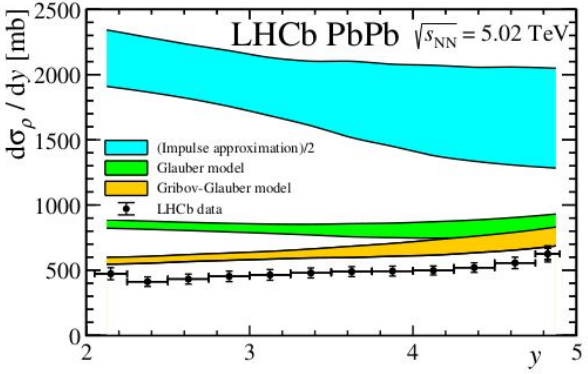
ρ UPC cross-section measurements



- Cross-section determined in 12 rapidity intervals
  - ➡ Also measured for ω and the two excited states
- Data suggests GKZ model underestimates shadowing
  - ➡ Model reproduces trend in data, but systematically overestimates cross-sections

10.48550/arXiv.2506.06250
GKZ model: Phys. Rev. C 93, 055206
STARlight: Comput. Phys. Commun. 212 (2017) 258

ρ UPC cross-section measurements

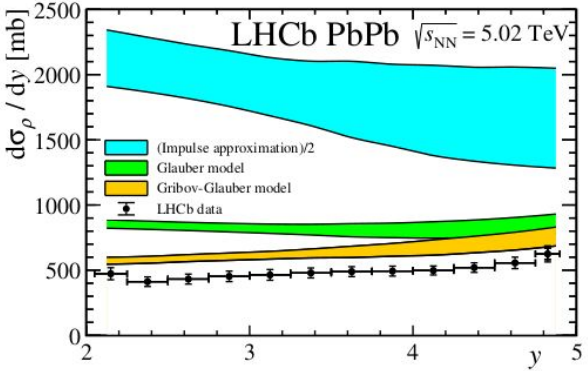


10.48550/arXiv.2506.06250

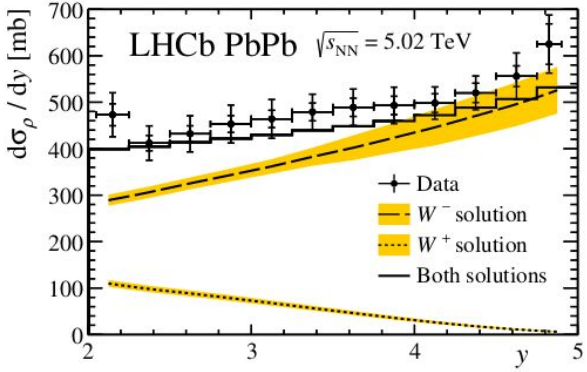
- Impulse approximation (no shadowing) clearly disagrees with data
- Inclusion of shadowing with Glauber (elastic) and Gribov-Glauber (elastic+inelastic) models improves agreement, but further suppression needed

Impulse approximation: Phys. Rev. 85 (1952) 636
Glauber, Glauber-Gribov models: Phys. Lett. B752 (2016) 51

ρ UPC cross-section measurements



10.48550/arXiv.2506.06250



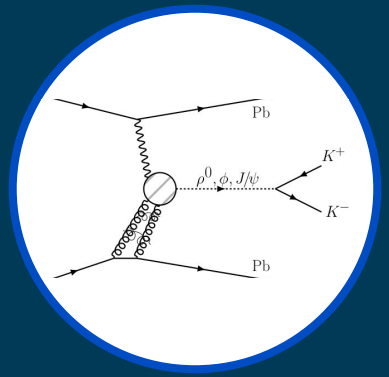
- Impulse approximation (no shadowing) clearly disagrees with data
- Inclusion of shadowing with Glauber (elastic) and Gribov-Glauber (elastic+inelastic) models improves agreement, but further suppression needed

- Suppression factors fitted to data compared to Gribov-Glauber model
  - ➡ 0.84 ± 0.04 for x~5×10^{-3}
  - ➡ 0.83 ± 0.06 for x~5×10^{-6}

$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}\to\mathrm{Pb}\rho\mathrm{Pb}}}{\mathrm{d}y} = (S^{+}_{\mathrm{model}})^2 \left(k\frac{\mathrm{d}N_\gamma}{\mathrm{d}k}\right)^{+} \sigma^{\mathrm{model}}_{\gamma\mathrm{Pb}\to\rho\mathrm{Pb}}(W^+) + (S^{-}_{\mathrm{model}})^2 \left(k\frac{\mathrm{d}N_\gamma}{\mathrm{d}k}\right)^{-} \sigma^{\mathrm{model}}_{\gamma\mathrm{Pb}\to\rho\mathrm{Pb}}(W^-)$$

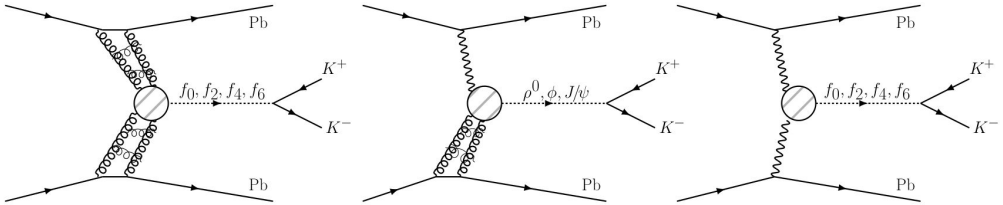
Impulse approximation: Phys. Rev. 85 (1952) 636
Glauber, Glauber-Gribov models: Phys. Lett. B752 (2016) 51

First observation of the $\phi(1020)$ meson in the K^+K^- mass spectrum of ultra-peripheral PbPb collisions at forward rapidity



LHCb-CONF-2024-006

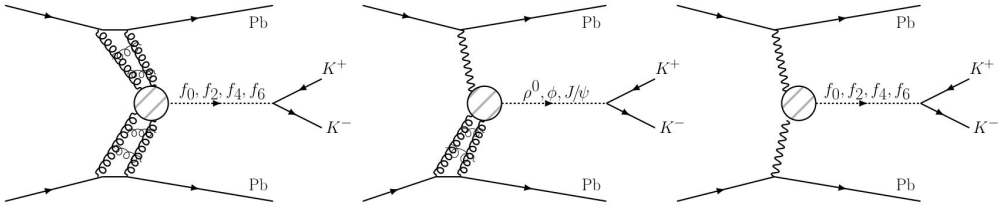
Analysis strategy and results

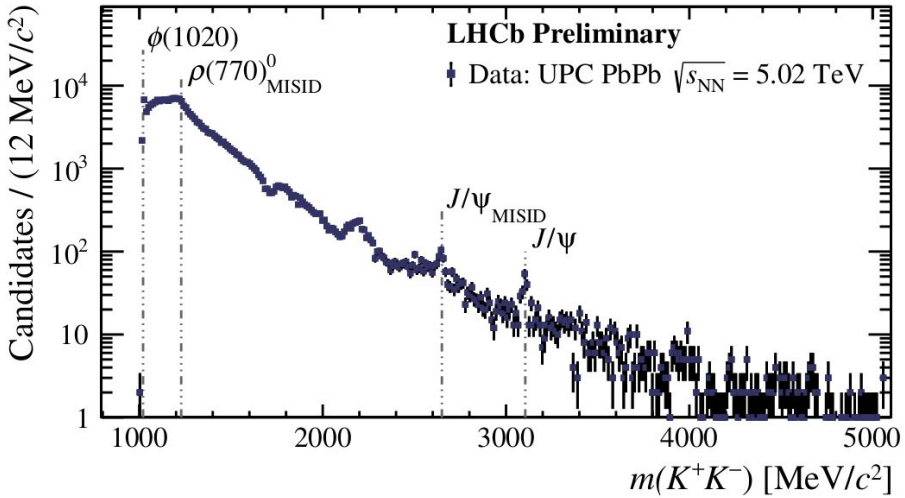


- Select events with two kaons and no other activity
  - ➡ Apply HeRSCheL veto
  - ➡ Dikaon p_T < 100 MeV
- Tight K PID requirements to suppress large ρ misid background

LHCb-CONF-2024-006

Analysis strategy and results



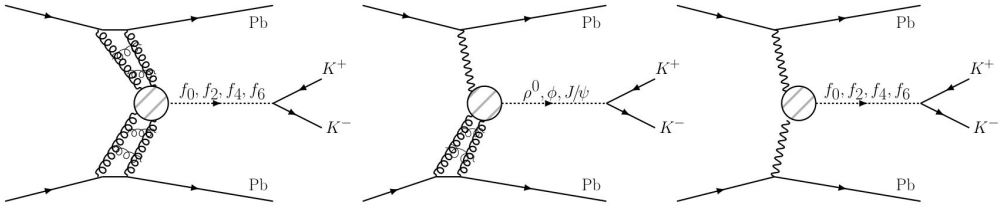


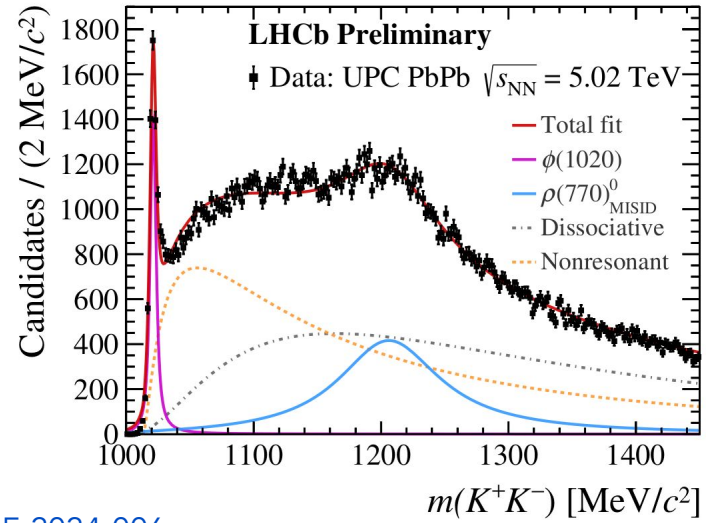
- Select events with two kaons and no other activity
  - ➡ Apply HeRSCheL veto
  - ➡ Dikaon p_T < 100 MeV
- Tight K PID requirements to suppress large ρ misid background

- Rich spectrum
  - ➡ Large variety of states can be studied using UPCs

LHCb-CONF-2024-006

Analysis strategy and results





- Select events with two kaons and no other activity
  - ➡ Apply HeRSCheL veto
  - ➡ Dikaon p_T < 100 MeV
- Tight K PID requirements to suppress large ρ misid background

- Focus on low-mass region
- ϕ observed with significance over 5σ
  - ➡ First observation in the forward region

LHCb-CONF-2024-006

Conclusions

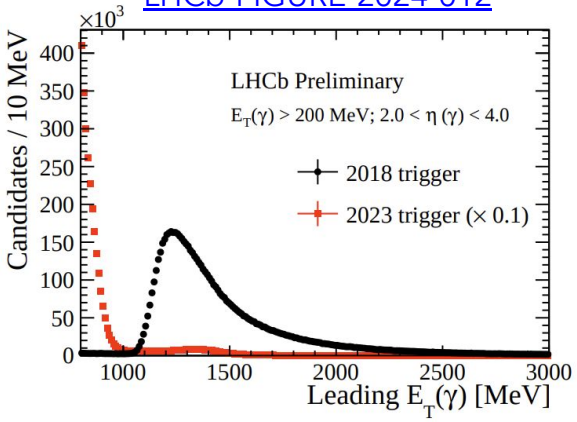
- Differential cross-sections are measured for the CEP/UPC production of vector mesons at LHCb
- Studies of low-x physics at LHCb can help constrain proton and nuclear gluon PDF at x down to 10^{-6}
- First observation of exotic states in diffractive processes can help determine their nature
- UPC studies at LHCb show that nuclear shadowing is still not fully accounted for in the tested models
  - ➡ Additional suppression required

Conclusions

- Differential cross-sections are measured for the CEP/UPC production of vector mesons at LHCb
- Studies of low-x physics at LHCb can help constrain proton and nuclear gluon PDF at x down to 10^{-6}
- First observation of exotic states in diffractive processes can help determine their nature
- UPC studies at LHCb show that nuclear shadowing is still not fully accounted for in the tested models
  - ➡ Additional suppression required

- Run 3 fully-software trigger is able to select photons with a much lower E_T threshold
  - ➡ Enables the study of lower-mass resonances
  - ➡ Data-taking ongoing; New UPC studies expected

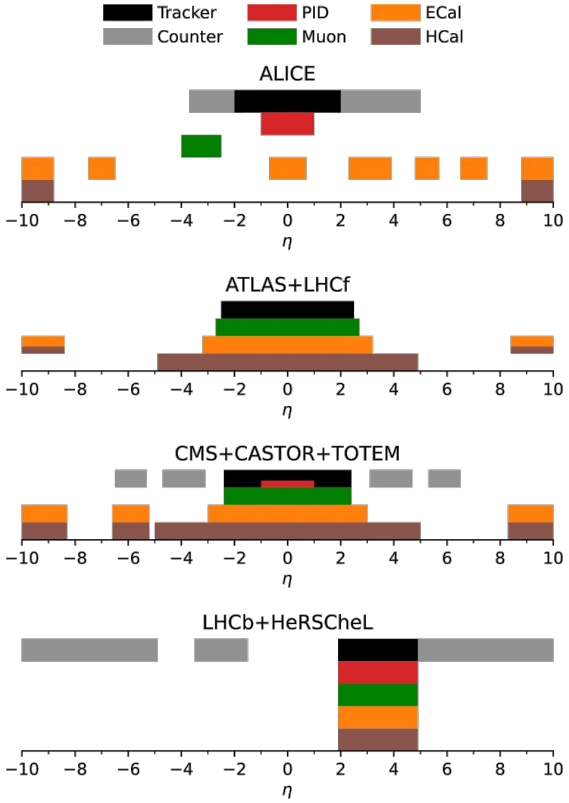
LHCb-FIGURE-2024-012



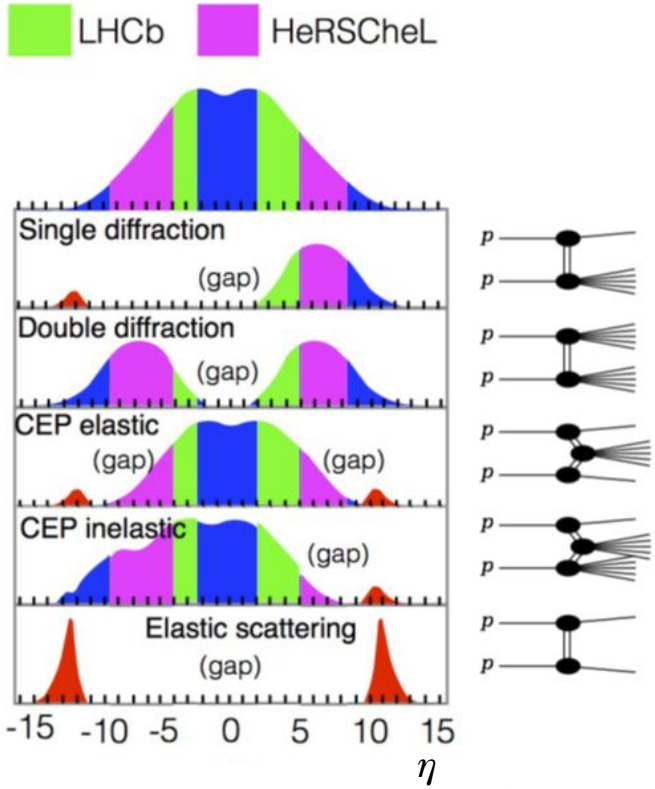
Thank you!

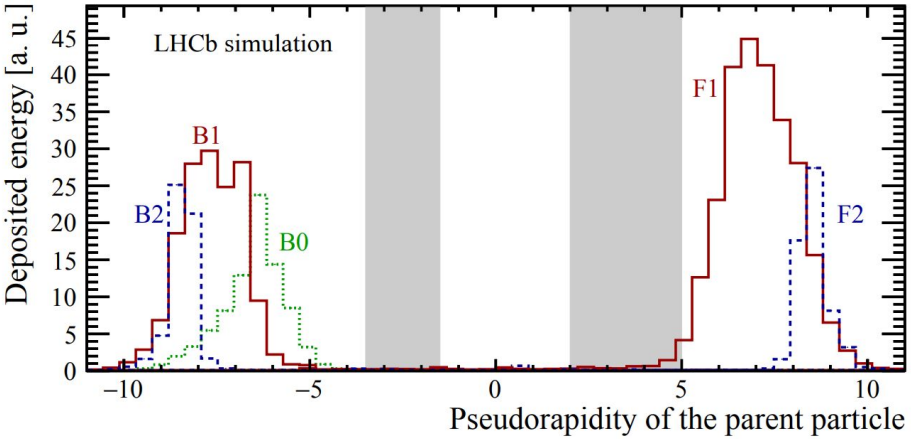
Backup

LHCb coverage



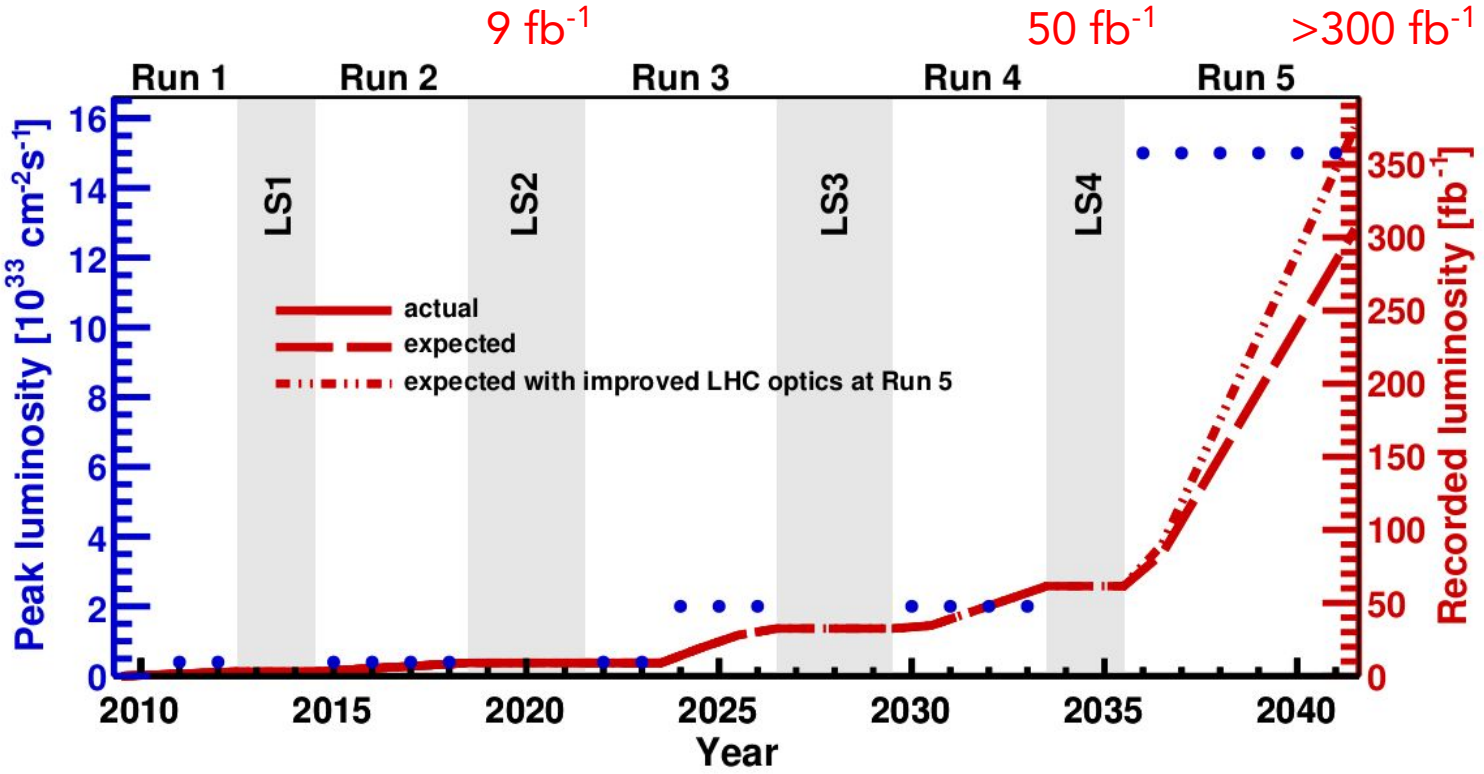
HeRSCheL detector





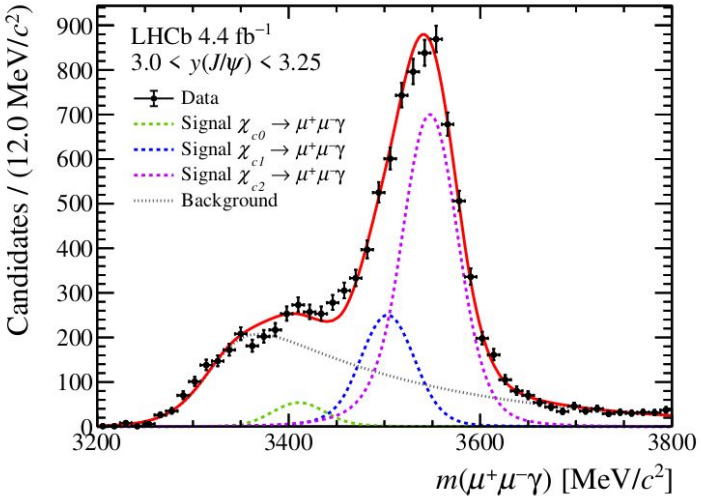
2018 JINST 13 P04017

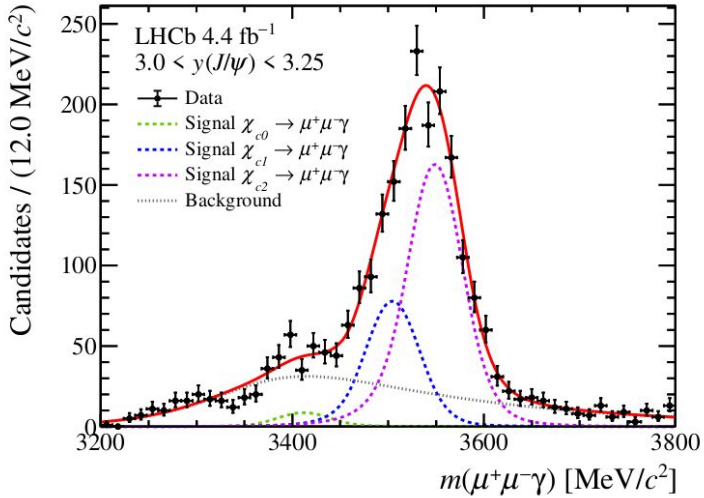
Luminosity



LHCb-TDR-026

- Fits to J/ψ γ mass distributions in signal (left) and PD control (left) samples.



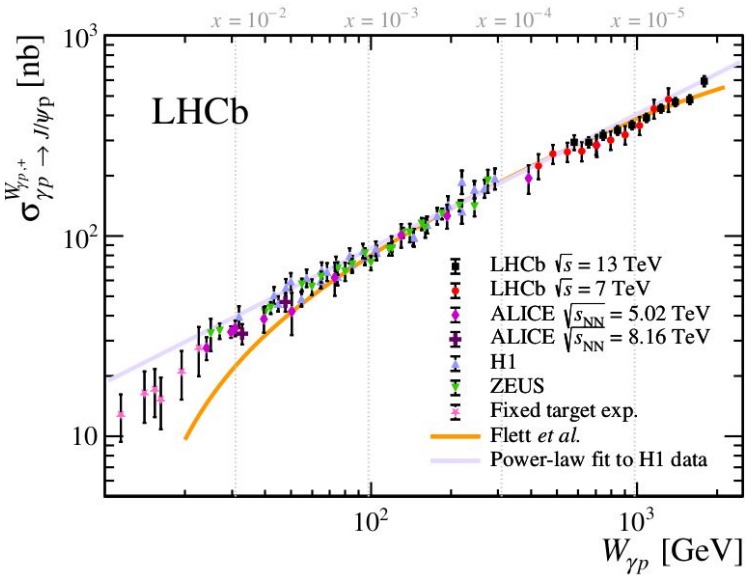


SciPost Phys. 18, 071 (2025)

- Photon-proton cross-section can be calculated:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(pp \to p\psi p) = S^2(W_{\gamma p,+})\left(k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\right)\sigma^{W_{\gamma p,+}}_{\gamma p\to\psi p} + S^2(W_{\gamma p,-})\left(k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\right)\sigma^{W_{\gamma p,-}}_{\gamma p\to\psi p}$$

- And compared to data from ep colliders:

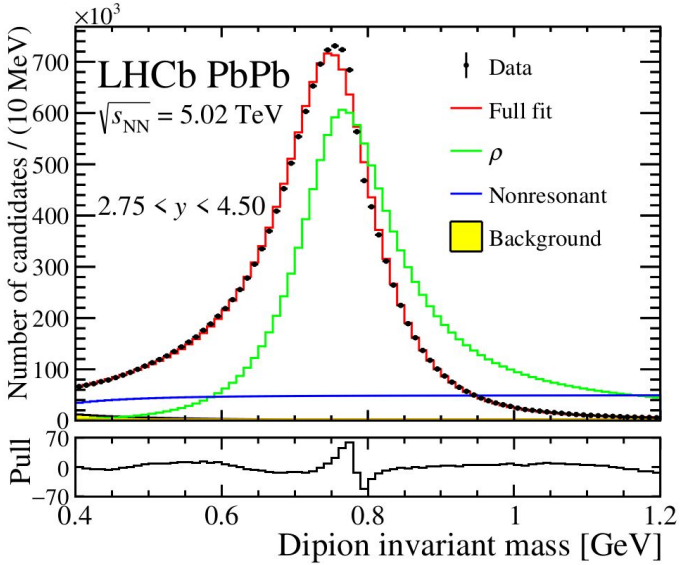


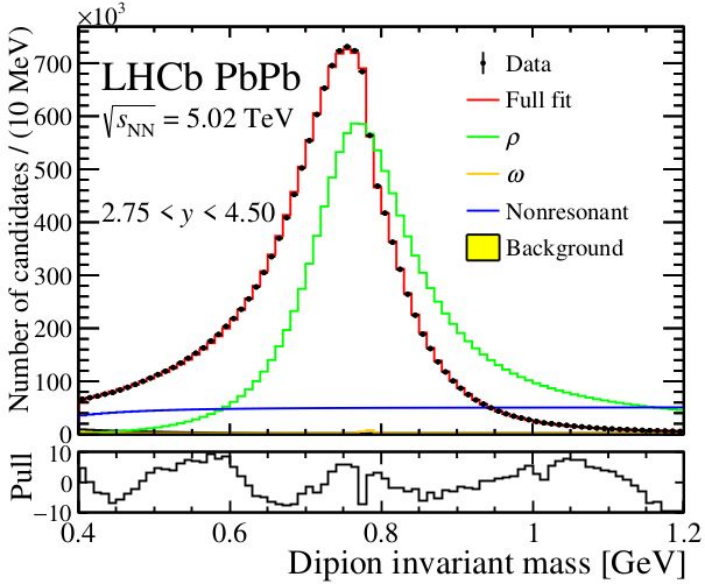
SciPost Phys. 18, 071 (2025)

	Phys. Rev. Lett. 134, 031902	Phys. Rev. Lett. 127, 082001
Parameter (MeV)	Current analysis	Ref. [13]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6^{+4}_{-5}$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22\ +33}_{-18\ -19}$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0\ +3.2}_{-6.2\ -2.7}$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20\ +24}_{-16\ -9}$	$77 \pm 6^{+10}_{-8}$

- Alternative fit models

10.48550/arXiv.2506.06250



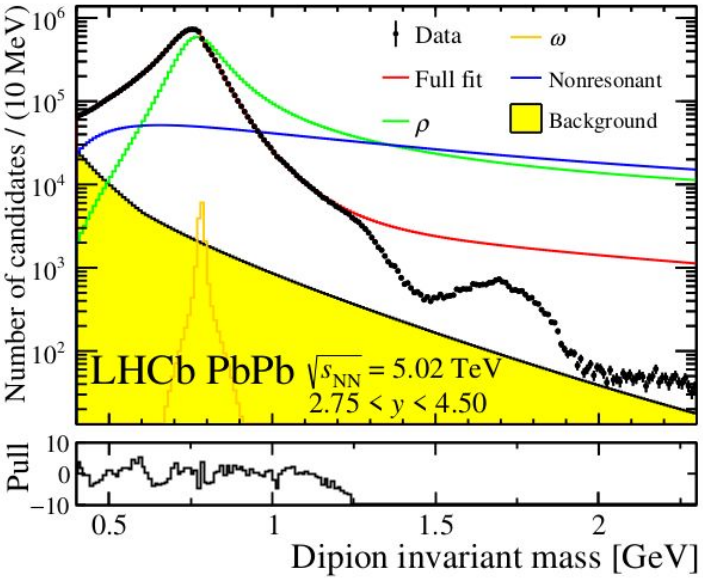


$$\mathcal{S}(m_{\pi\pi}) \propto \left| f_\rho \frac{\sqrt{m_{\pi\pi} m_\rho \Gamma(m_{\pi\pi})}}{m_{\pi\pi}^2 - m_\rho^2 + i m_\rho \Gamma(m_{\pi\pi})} + f_{\mathrm{nr}} \right|^2,$$

$$\Gamma(m_{\pi\pi}) = \Gamma_\rho \frac{m_\rho}{m_{\pi\pi}} \frac{q(m_{\pi\pi})}{q(m_\rho)}$$

$$\mathcal{S}(m_{\pi\pi}) = \left| f_\rho \frac{\sqrt{m_{\pi\pi} m_\rho \Gamma(m_{\pi\pi})}}{m_{\pi\pi}^2 - m_\rho^2 + i m_\rho \Gamma(m_{\pi\pi})} + f_{\mathrm{nr}} + f_\omega \exp(i\phi_\omega) \frac{\sqrt{m_{\pi\pi} m_\omega \Gamma_\omega}}{m_{\pi\pi}^2 - m_\omega^2 + i m_\omega \Gamma_\omega} \right|^2$$

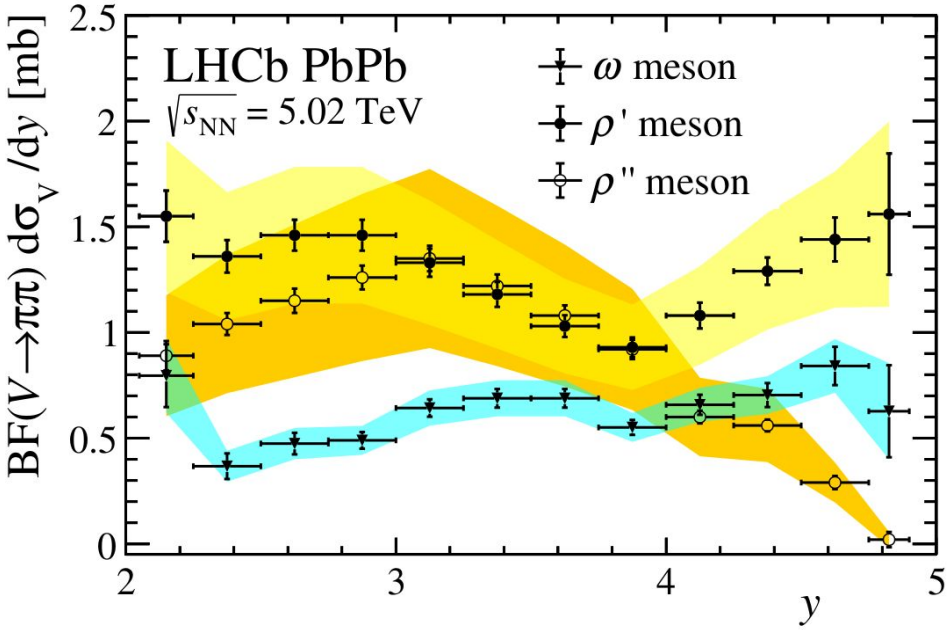
- ρ^0 + ω + NR model on extended mass range (No excited states)



$$\mathcal{S}(m_{\pi\pi}) = \left| f_\rho \frac{\sqrt{m_{\pi\pi} m_\rho \Gamma(m_{\pi\pi})}}{m_{\pi\pi}^2 - m_\rho^2 + i m_\rho \Gamma(m_{\pi\pi})} + f_{\rm nr} + f_\omega \exp(i\phi_\omega) \frac{\sqrt{m_{\pi\pi} m_\omega \Gamma_\omega}}{m_{\pi\pi}^2 - m_\omega^2 + i m_\omega \Gamma_\omega} \right|^2$$

10.48550/arXiv.2506.06250

- Differential cross-sections for ω and excited states



10.48550/arXiv.2506.06250