Charmonia production in Heavy Ion collisions at LHCb

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LHCb charmonia results in heavy ion collisions

- **Probe nuclear matter effects:**
  - J/ψ and $\psi(2S)$ production in pPb @ 5.02 TeV and 8.16 TeV:
    - @ 5.02 TeV: J/ψ [JHEP 02 (2014) 72], $\psi(2S)$ [JHEP 03 (2016) 133],
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  - $\psi(2S)$ to J/ψ ratio in pp @ 13 TeV: [JHEP 05 (2024) 243]
- **Probe nature of $\chi_{c1}(3872)$:**
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- **Photoproduction:**
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  - J/ψ in PbPb peripherial collisions: [Phys. Rev. C105 (2022) L032201]
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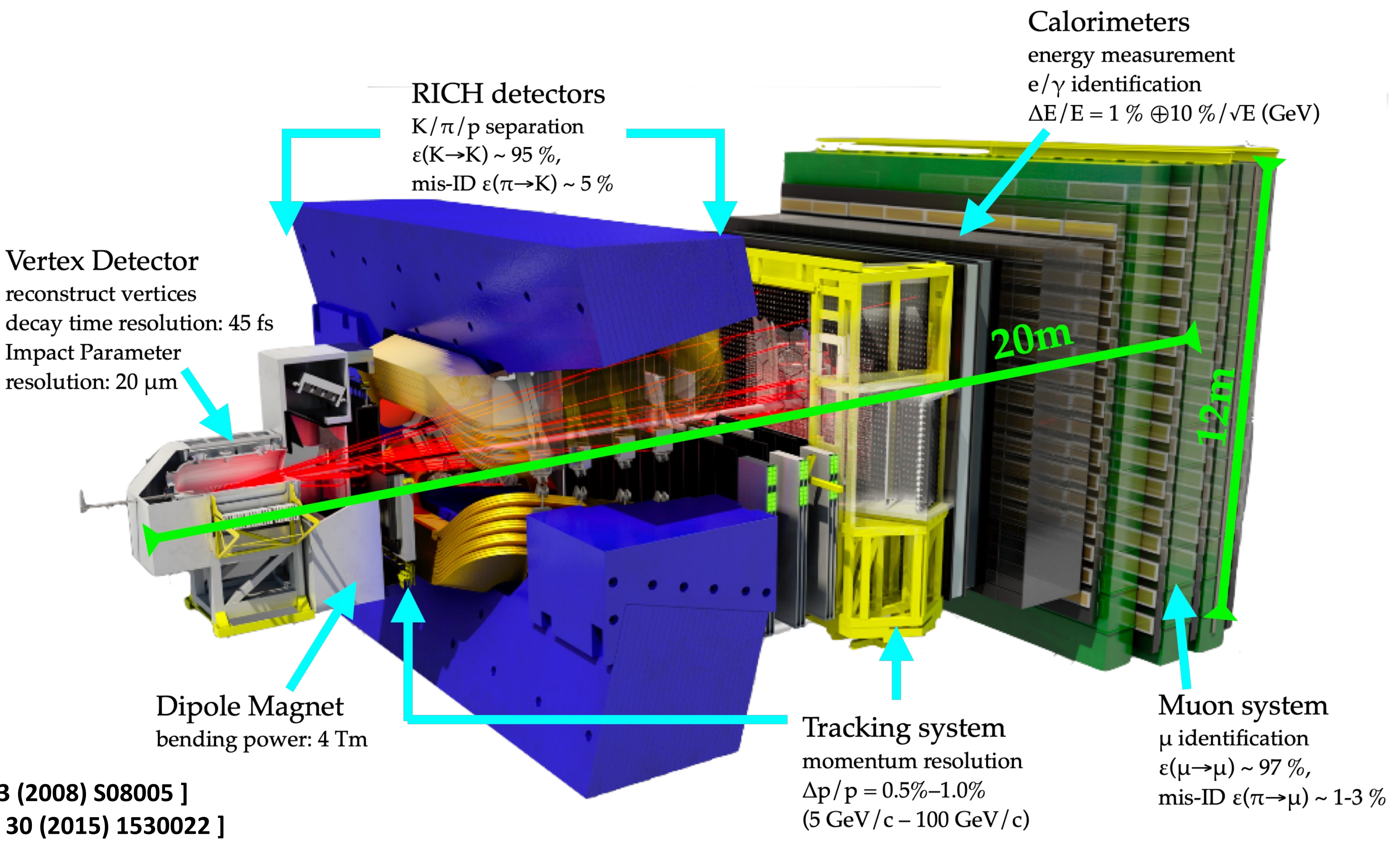
- **Fixed target results:**
  - J/ψ and D^0 in pHe and pAr collisions, first fixed-target result: [Phys. Rev. Lett. 122 (2019) 132002]
  - J/ψ and D^0 in pNe and PbNe collisions: [Eur. Phys. J. C83 (2023) 625], [Eur. Phys. J. C83 (2023) 658]

The LHCb detector (Run2)

- LHCb is the only dedicated detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage

  $2 < \eta < 5$

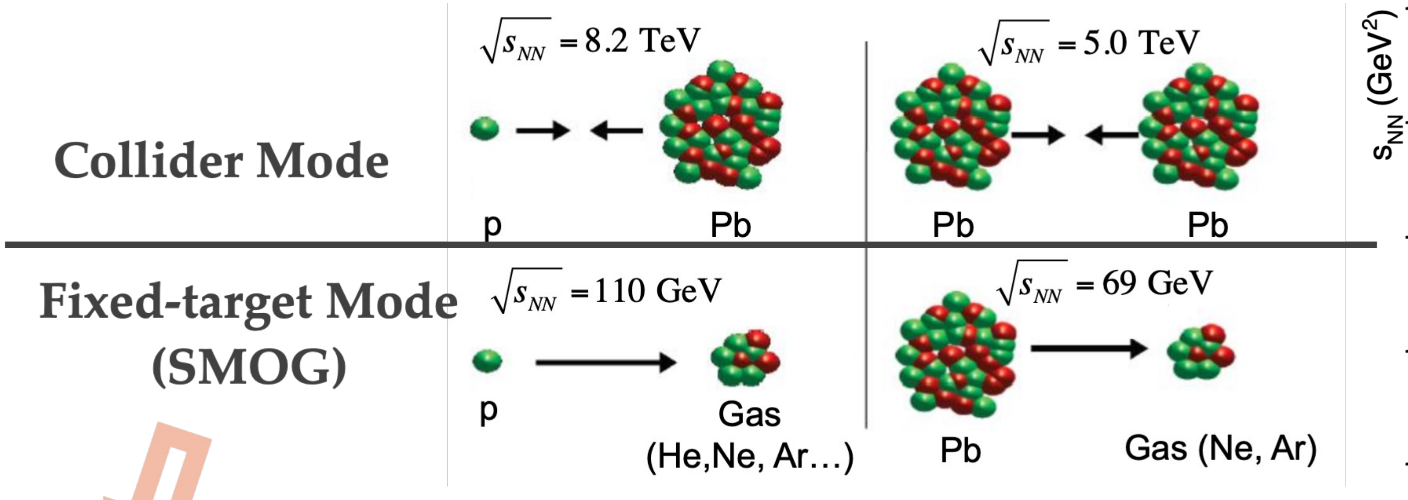
- A high precision device, down to very low-p_T, excellent particle ID, precise vertex and track reconstruction.

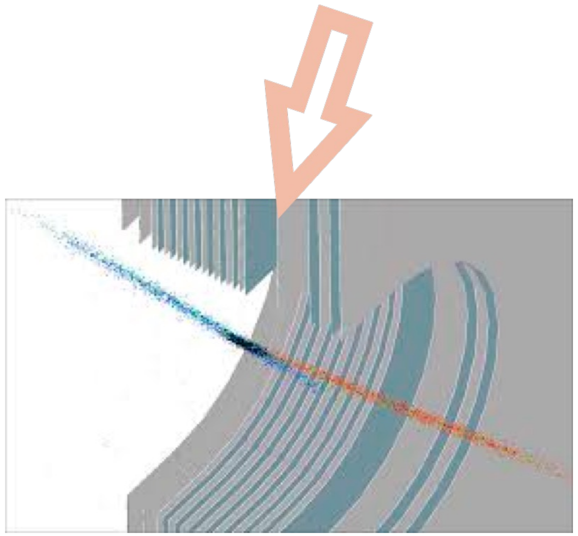


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

LHCb Run2 heavy ion data

Both the collider mode and fixed-target mode running at the same time





Collider mode:

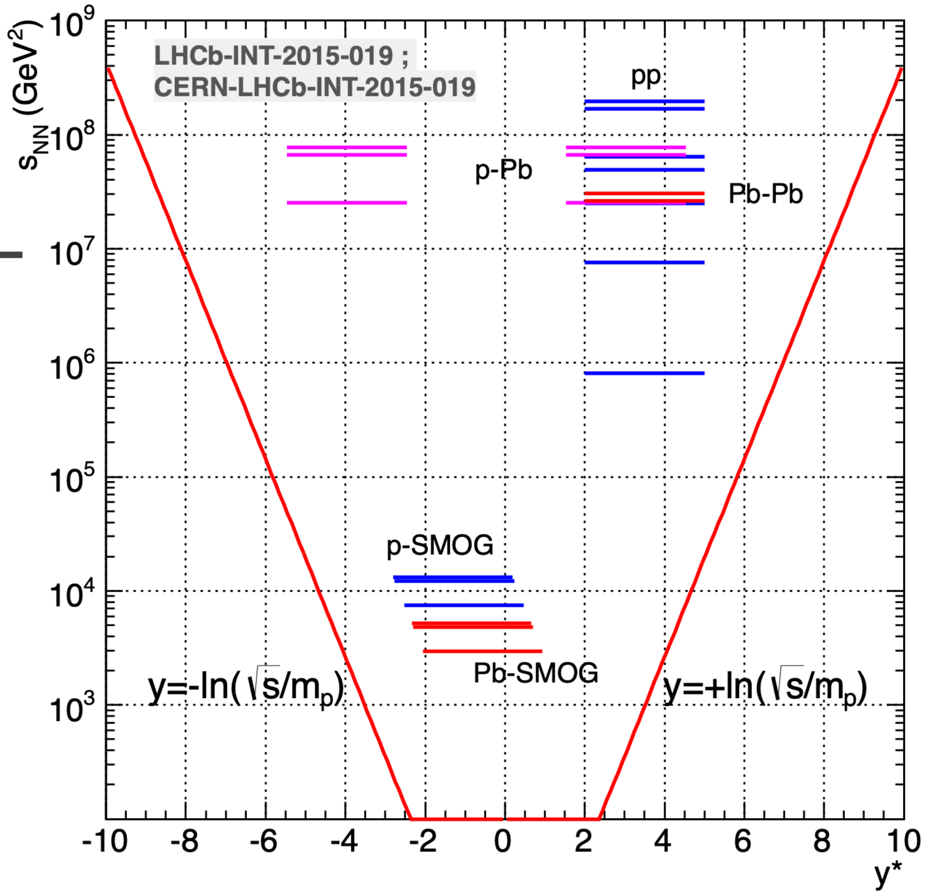
Forward and backward coverage

Fixed-target mode:

Central and backward coverage

$\sqrt{s_{NN}}$: 69 - 110 GeV,

Kinematic acceptance



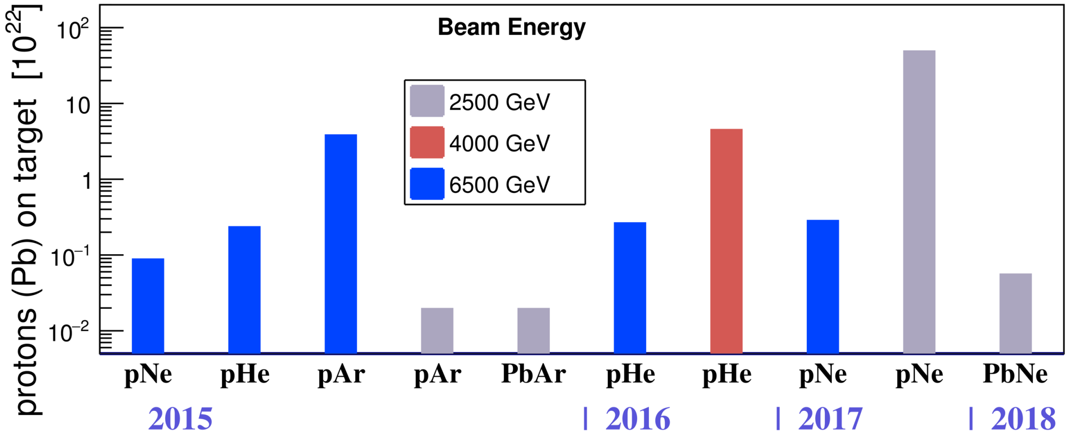
LHCb Run2 heavy ion data

Collider mode datasets:

	2013		2016		2015	2017	2018
$\sqrt{s_{NN}}$	5.02 TeV		8.16 TeV		5.02 TeV	5.02 TeV	5.02 TeV
	pPb	Pbp	pPb	Pbp	PbPb	XeXe	PbPb
$\mathcal{L}$	1.1 nb^{-1}	0.5 nb^{-1}	13.6 nb^{-1}	20.8 nb^{-1}	10 μb^{-1}	0.4 μb^{-1}	$\sim$ 210 μb^{-1}

Fixed target mode datasets:

$$\int \mathcal{L}dt \sim 5\text{nb}^{-1} \times \frac{(protons\ on\ target)}{10^{22}} \times \frac{p_{gas}}{2\times 10^{-7}\text{mbar}} \times \text{Exp\_efficiency}$$



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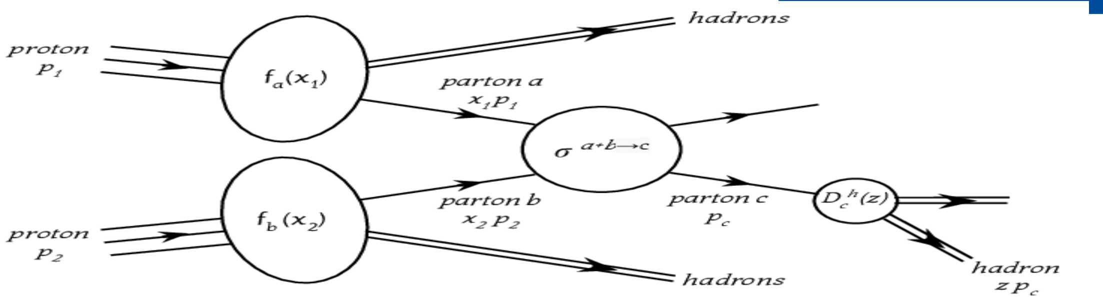
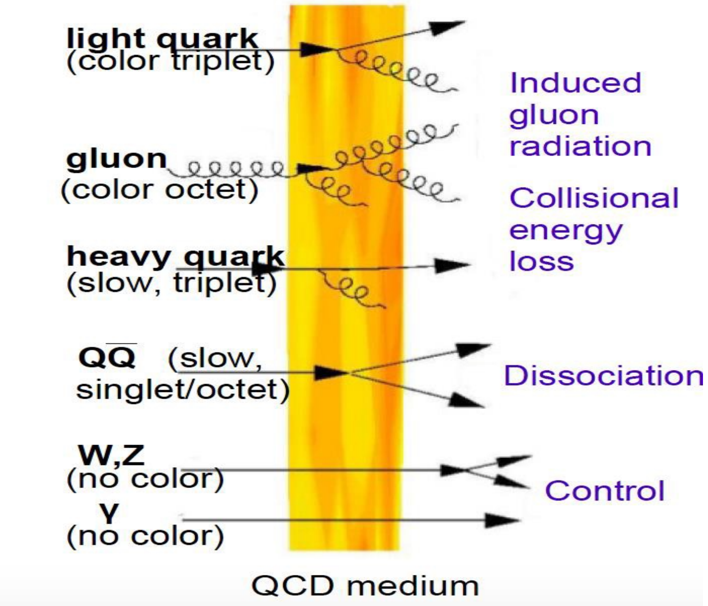
Probe nuclear matter effects

- Charmonium dominantly produced in initial hard scattering then interact with the QGP medium.
  - τ_{HF} (≈ 0.05 – 0.1 fm/c) < τ_{QGP} (≈ 0.3 fm/c at LHC)
- Production in small system (pp, pA):
  - Probes the initial state cold nuclear matter (CNM) effects: Nuclear shadowing, gluon saturation, k_T broadening, etc., constraining nPDFs.
- Production in large system (AA):
  - Hard probes of the QGP medium through in-medium suppression and enhancement of the production yields



PDFs/nPDFs Non-perturbative ⊗ Hard scatter perturbative ⊗ Fragmentation Non-perturbative



J/ψ and $\psi(2S)$ production in pPb collisions

First heavy ion publication from LHCb!

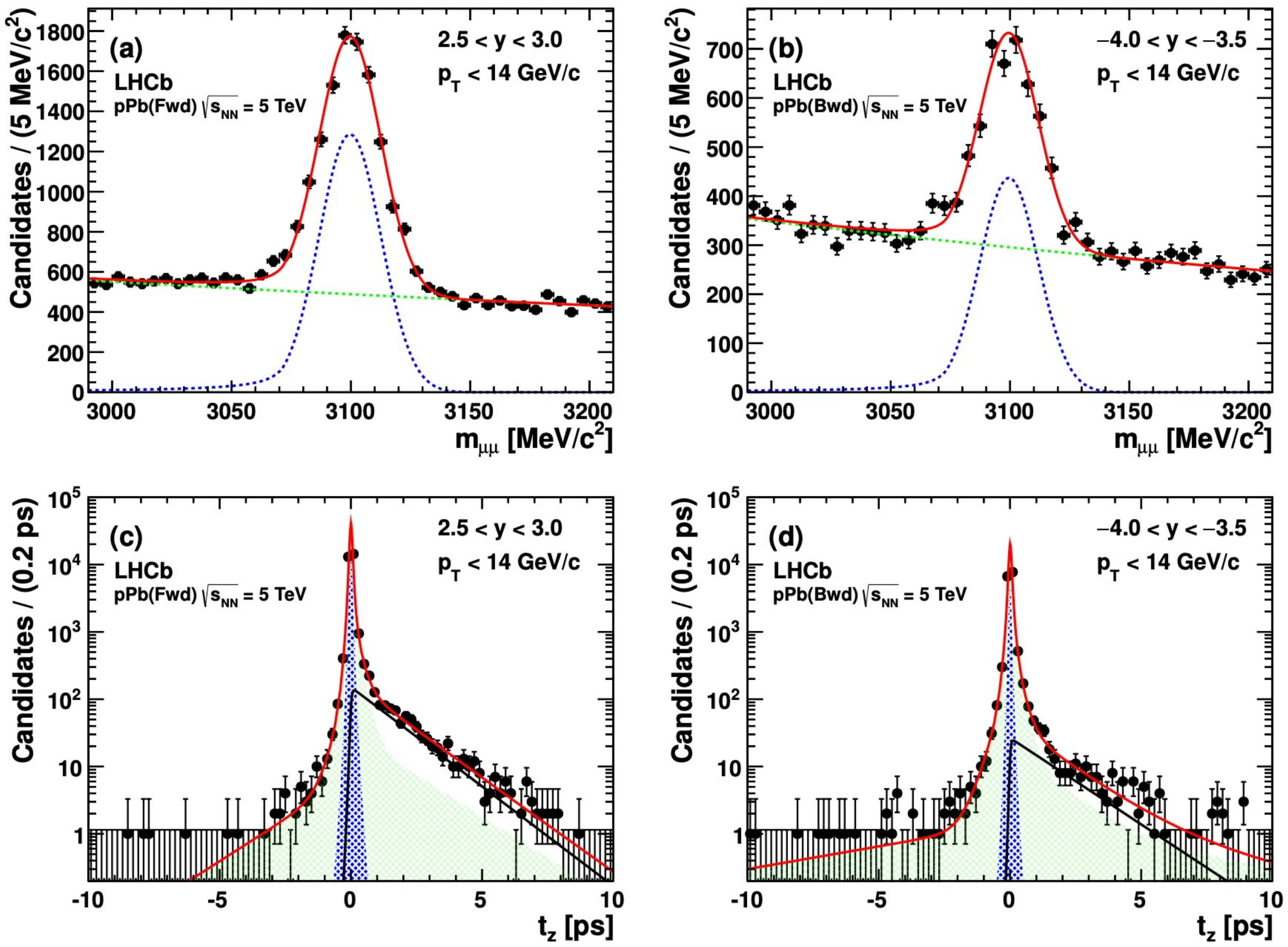
pPb @ 5.02 TeV: J/ψ [JHEP 02 (2014) 72], $\psi(2S)$ [JHEP 03 (2016) 133],
pPb @ 8.16 TeV: J/ψ [PLB 774 (2017) 159], $\psi(2S)$ [JHEP 04 (2024) 111],

- Production differential cross-section measured in pPb for both 5.02 TeV and 8.16 TeV
- Spontaneous fit to dimuon mass and pseudo-proper time for both forward and backward collisions
- for both prompt and non-prompt production (from b-decay)
- Also measured nuclear modification factors:

$$R_{p\mathrm{A}}(y, p_{\mathrm{T}}, \sqrt{s_{NN}}) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{A}}(y, p_{\mathrm{T}}, \sqrt{s_{NN}})/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}(y, p_{\mathrm{T}}, \sqrt{s_{NN}})/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}},$$

- And forward-backward ratio:

$$R_{\mathrm{FB}}(y, p_{\mathrm{T}}, \sqrt{s_{NN}}) \equiv \frac{\sigma_{p\mathrm{Pb}}(+|y|, p_{\mathrm{T}}, \sqrt{s_{NN}})}{\sigma_{p\mathrm{Pb}}(-|y|, p_{\mathrm{T}}, \sqrt{s_{NN}})}.$$



J/ψ and $\psi(2S)$ production in pPb collisions

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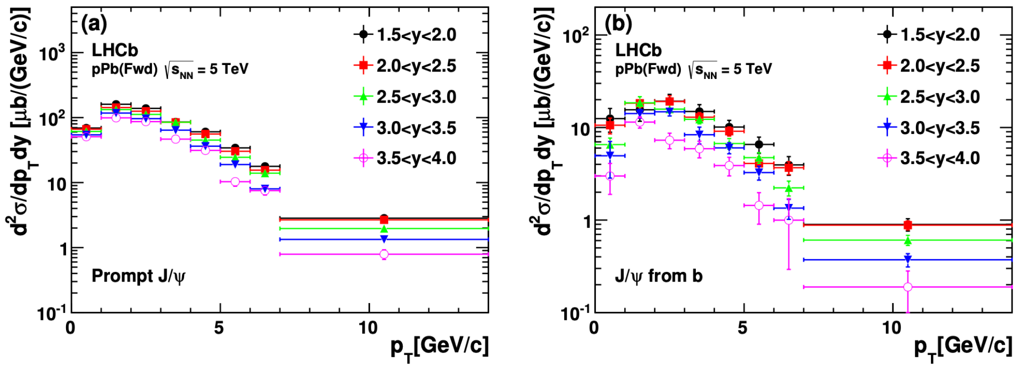
Differential cross-section

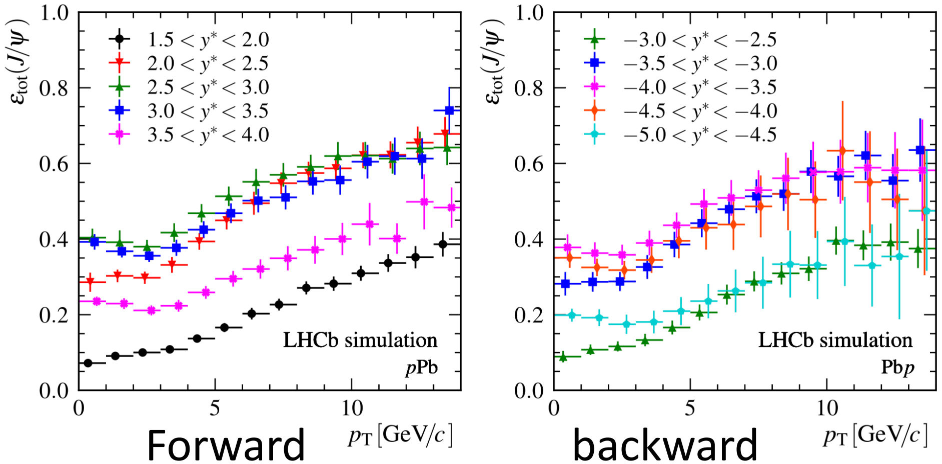
pPb @ 5.02 TeV

pPb @ 8.16 TeV

J/ψ

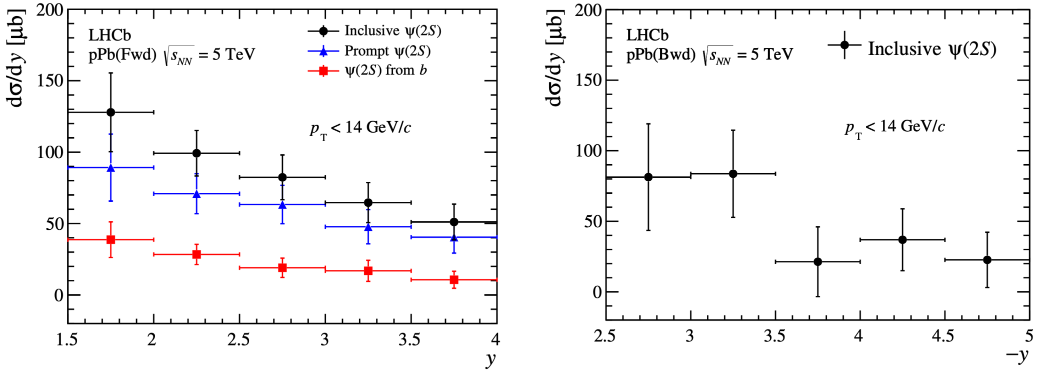


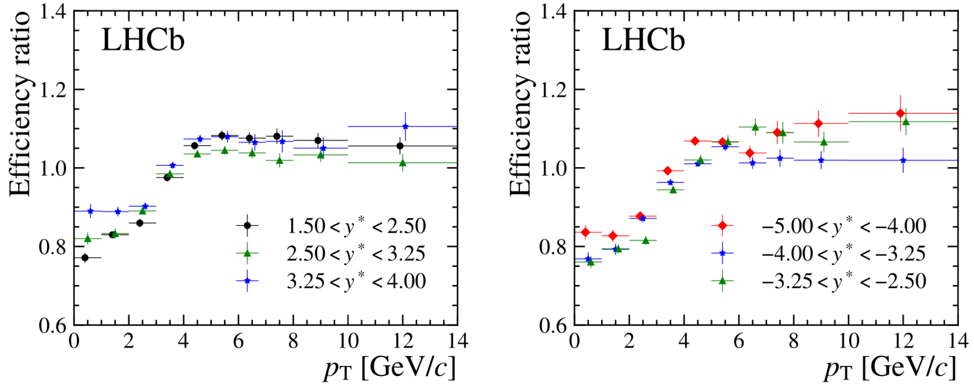
Forward backward



Forward backward

$\psi(2S)$





J/ψ and $\psi(2S)$ production in pPb collisions

pPb @ 5.02 TeV: J/ψ [JHEP 02 (2014) 72], $\psi(2S)$ [JHEP 03 (2016) 133],
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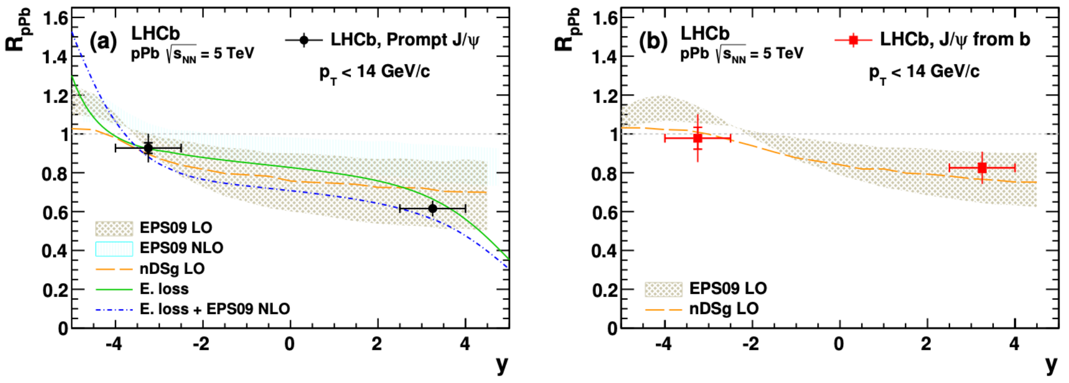
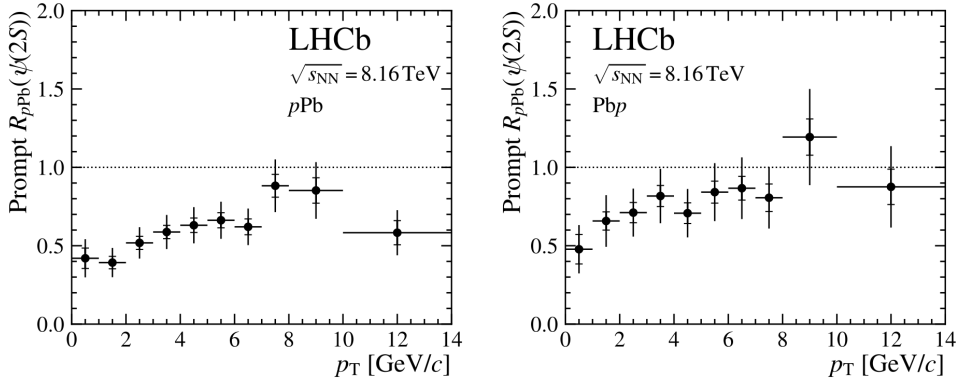
Nuclear modifications

pPb @ 5.02 TeV

pPb @ 8.16 TeV

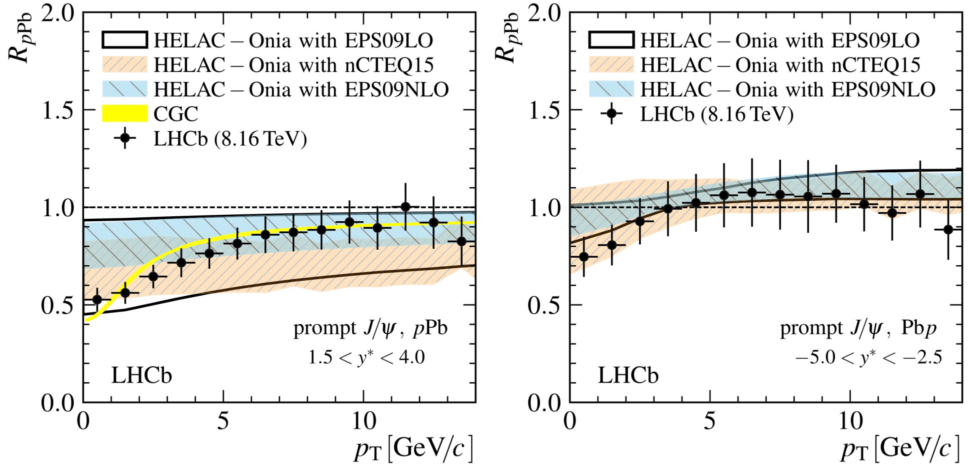
J/ψ





Forward

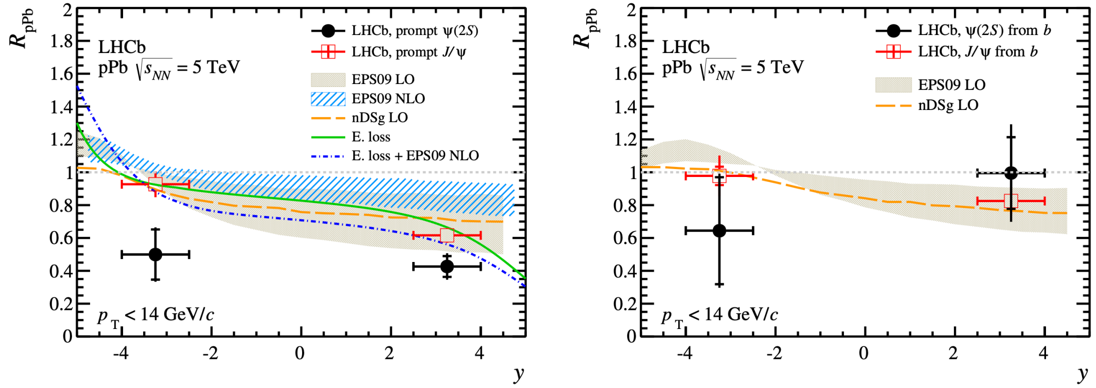
backward



prompt

non-prompt

$\psi(2S)$



J/ψ and $\psi(2S)$ production in pPb collisions

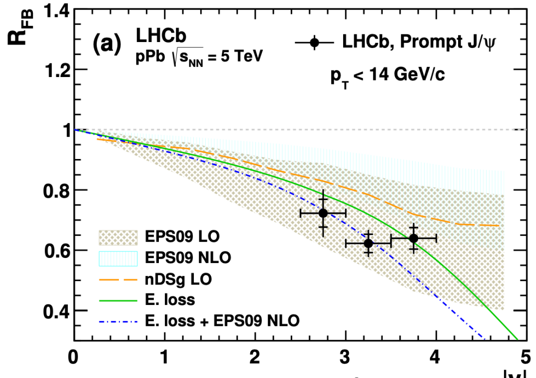
pPb @ 5.02 TeV: J/ψ [JHEP 02 (2014) 72], $\psi(2S)$ [JHEP 03 (2016) 133],
pPb @ 8.16 TeV: J/ψ [PLB 774 (2017) 159], $\psi(2S)$ [JHEP 04 (2024) 111],

Forward-backward ratio:

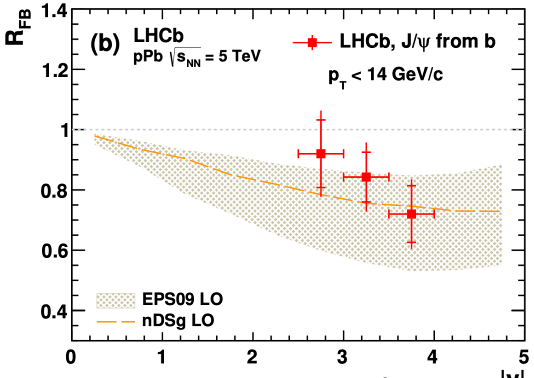
pPb @ 5.02 TeV

pPb @ 8.16 TeV

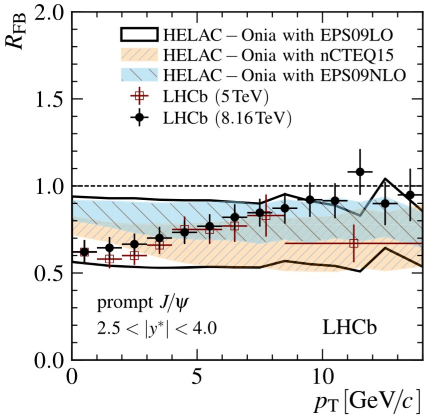
J/ψ



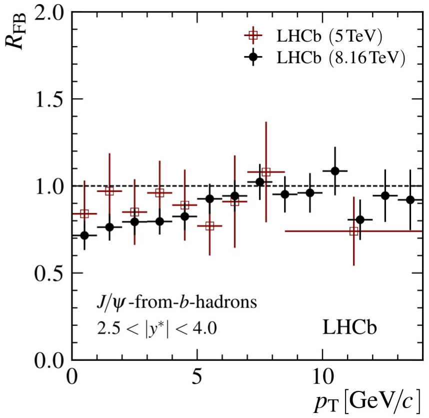
prompt



non-prompt

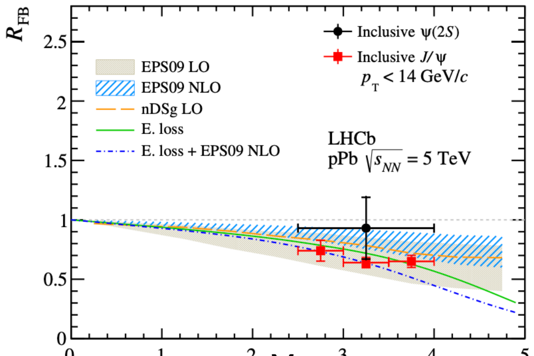


Prompt

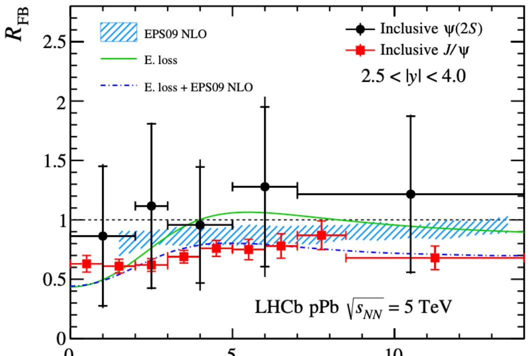


from-b-decay

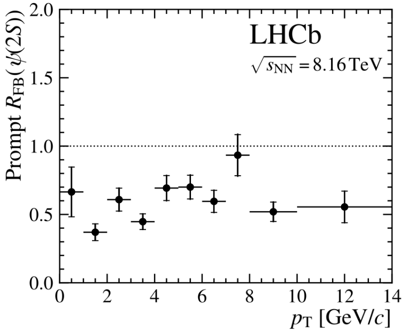
$\psi(2S)$

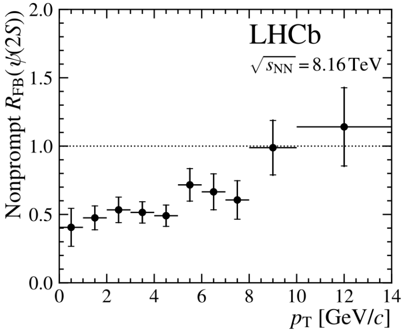


Y



p_T

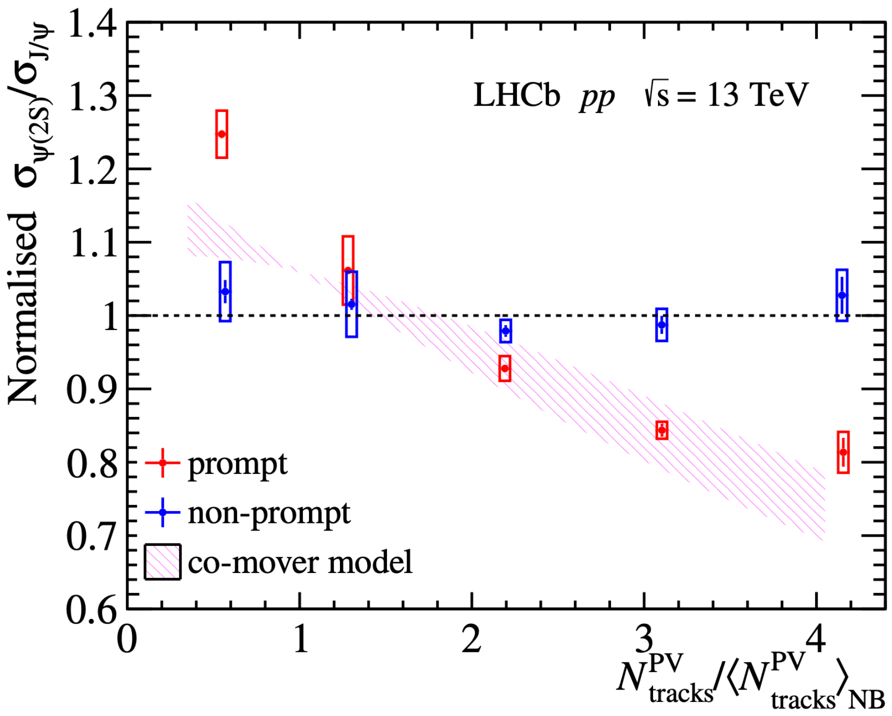


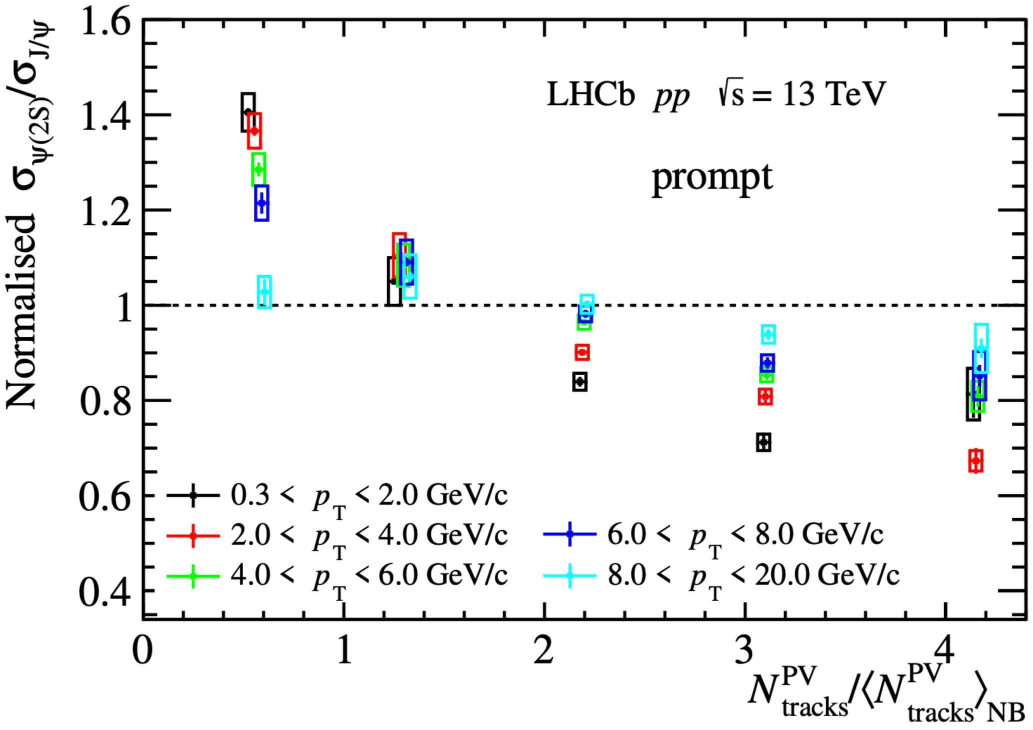


$\psi(2S)$ to J/ψ ratio in pp collisions

[JHEP 05 (2024) 243]

- Initial-state effects cancelled,
- Prompt ratio decrease with multiplicity, nonprompt independent on multiplicity.
- Larger dependence on multiplicity at low p_T.





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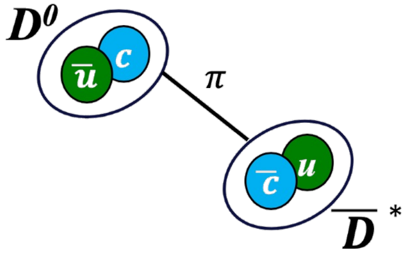
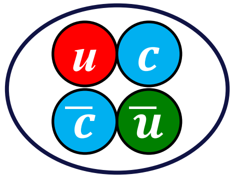
$\chi_{c1}(3872)$ to $\psi(2S)$ ratio in pp

- Prompt: Increasing suppression of $\chi_{c1}(3872)$ production relative to $\psi(2S)$ as event activity increases
- From-b-decay: No significant change in relative production, as expected for decays in vacuum. Ratio is set by b decay branching fractions.
- Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data

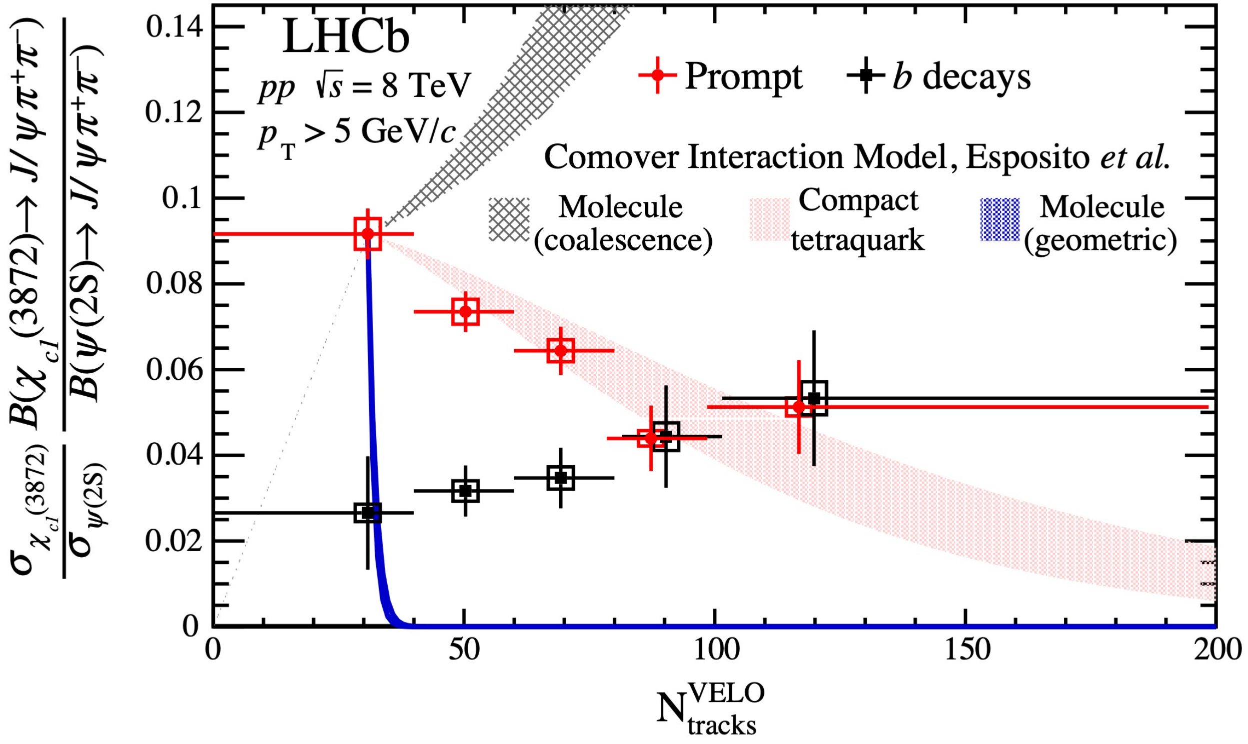
$D^0\overline{D}^*$ **Molecule**



Compact tetraquark



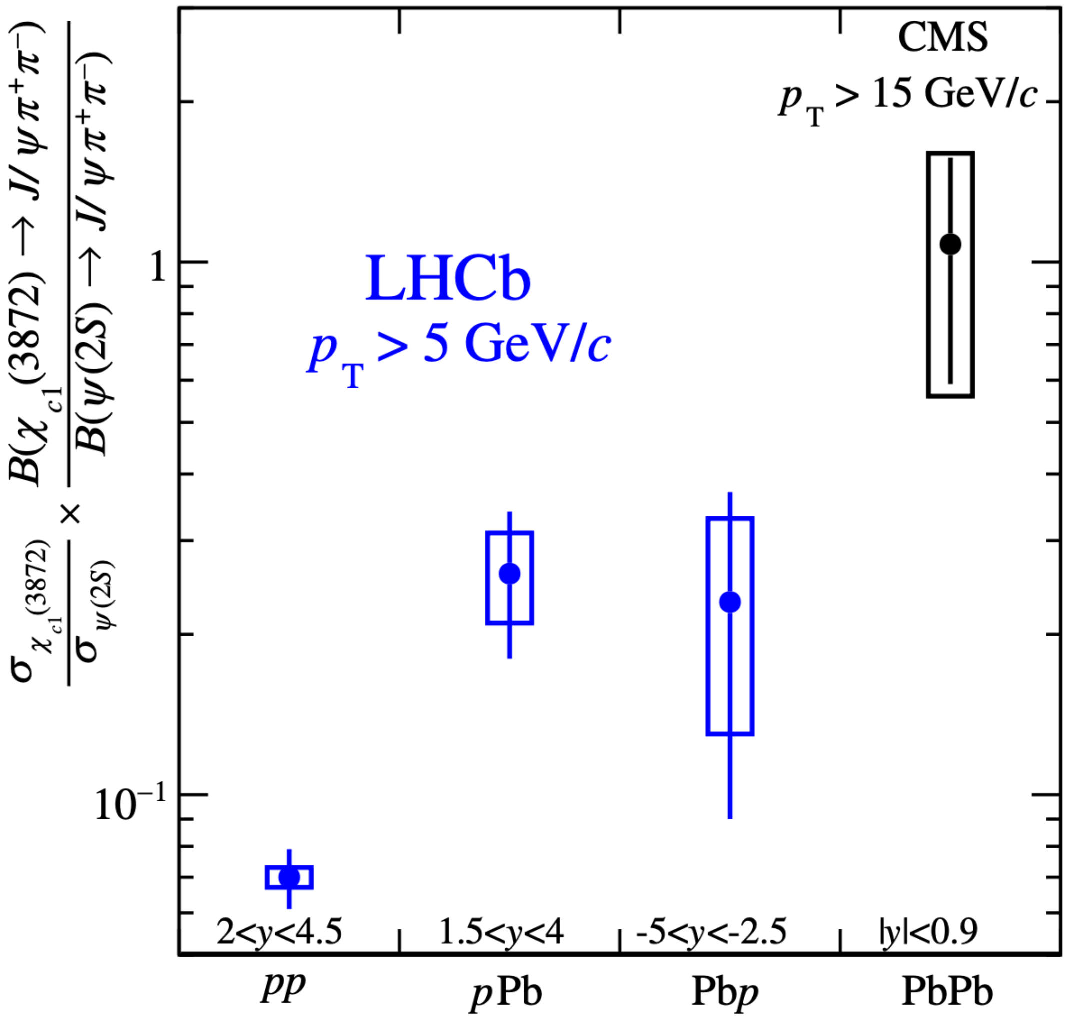
[Phys. Rev. Lett. 126 (2021) 092001]

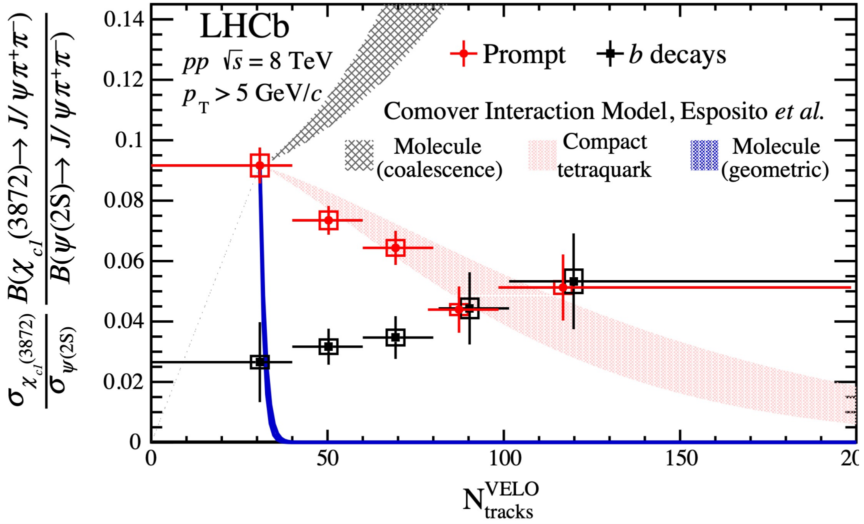


$\chi_{c1}(3872)$ to $\psi(2S)$ ratio in pPb

[Phys. Rev. Lett. 132 (2024) 242301]

- $\chi_{c1}(3872)$ to $\psi(2S)$ ratio in pPb measured and compared with pp and CMS PbPb results
- Ratio increase with system sizes, but decrease with multiplicity in pp collisions, indicate coalescence is allowed to become the dominant mechanism towards large system
- The exotic $\chi_{c1}(3872)$ experiences different dynamics than conventional charmonium state $\psi(2S)$





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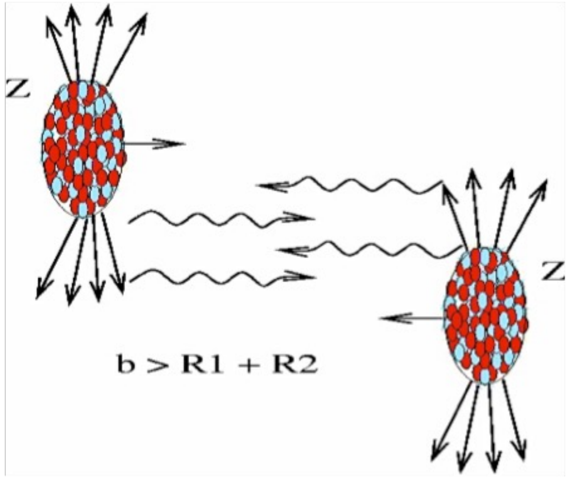
Rich photon-induced physics program at LHCb

- CEP J/ψ production in pp collisions has already been measured at LHCb at 7 TeV pp
- Focusing on the CEP charmonium production in 2018 PbPb collisions

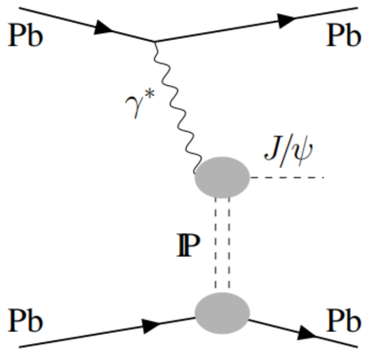
CEP J/ψ and $\psi(2S)$ @ 7 TeV	J. Phys. G40 (2013) 045001
Updated CEP J/ψ and $\psi(2S)$ at 7 TeV	J. Phys. G41 (2014) 055002
CEP Υ @ 7 TeV	JHEP 09 (2015) 084
CEP J/ψ and $\psi(2S)$ @ 13 TeV	JHEP 10 (2018) 167
CEP J/ψ @ 8.16 TeV 2015 PbPb UPC	JHEP 07 (2022) 117
CEP J/ψ and $\psi(2S)$ @ 8.16 TeV 2018 PbPb UPC	**JHEP 06 (2023) 146**

Photoproduction of charmonia

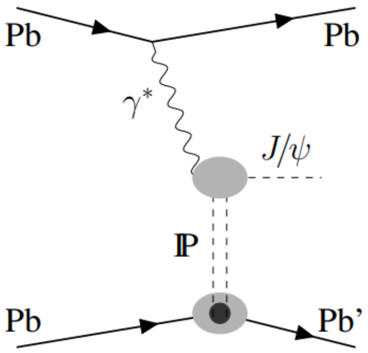
- **Ultra-peripheral collisions (UPC)**: Two nuclei bypass each other with an impact parameter greater than the sum of their radii



- **Photon-induced interactions are enhanced by the strong electromagnetic field of the nucleus**
  - Coherent J/ψ and ψ(2S) production gives constraints on the gluon Probability Density Functions,
  - (J/ψ) / ψ(2S) ratio measurement is helpful to constrain the choice of the vector meson wave function in dipole scattering models [e.g. PLB 772 (2017) 832, PRC (2011) 011902]



Coherent J/ψ production: photon interact with the whole nucleus coherently



Incoherent J/ψ production: photon interact with particular nucleons in the nucleus

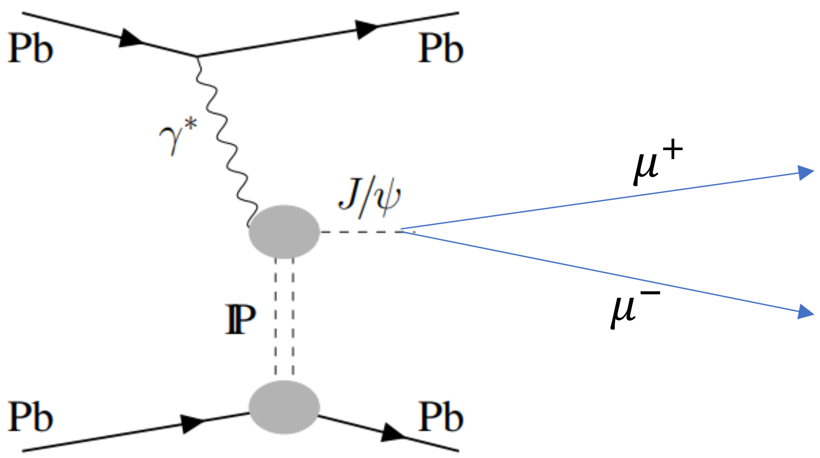
J/ψ and $\psi(2S)$ in PbPb ultra-peripherial collisions

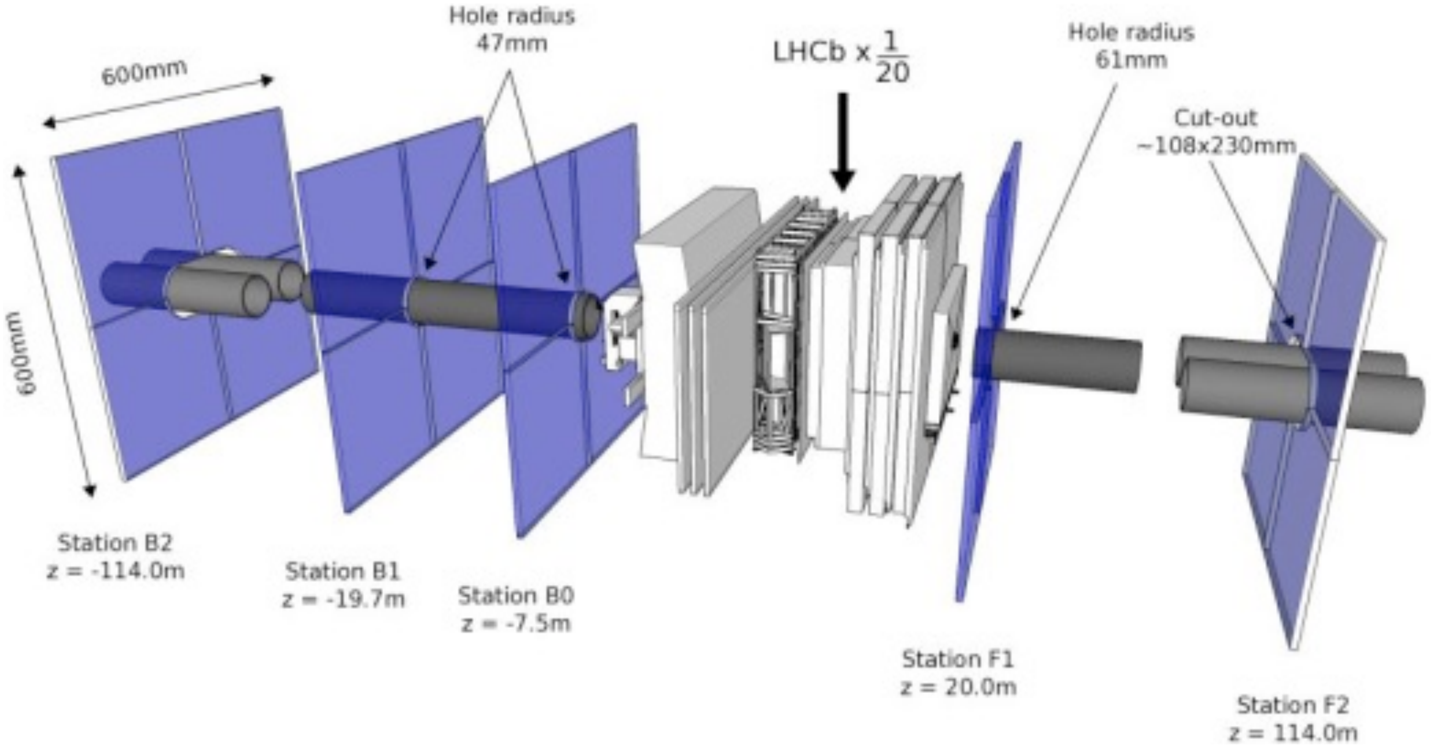
[JHEP 06 (2023) 146]

- Require a near empty detector with only two long tracks reconstructed, with acceptance cuts:

$$2.0 < \eta^{\mu} < 4.5\,, p_{\mathrm{T}}^{\mu} > 700\mathrm{MeV},$$
$$p_{T}^{\mu\mu} < 1\mathrm{GeV}, |\Delta\phi_{\mu\mu}| > 0.9\pi$$

- **HERSCHEL** detector [JINST 13 (2018) 04 P04017] is used to further purify the selection

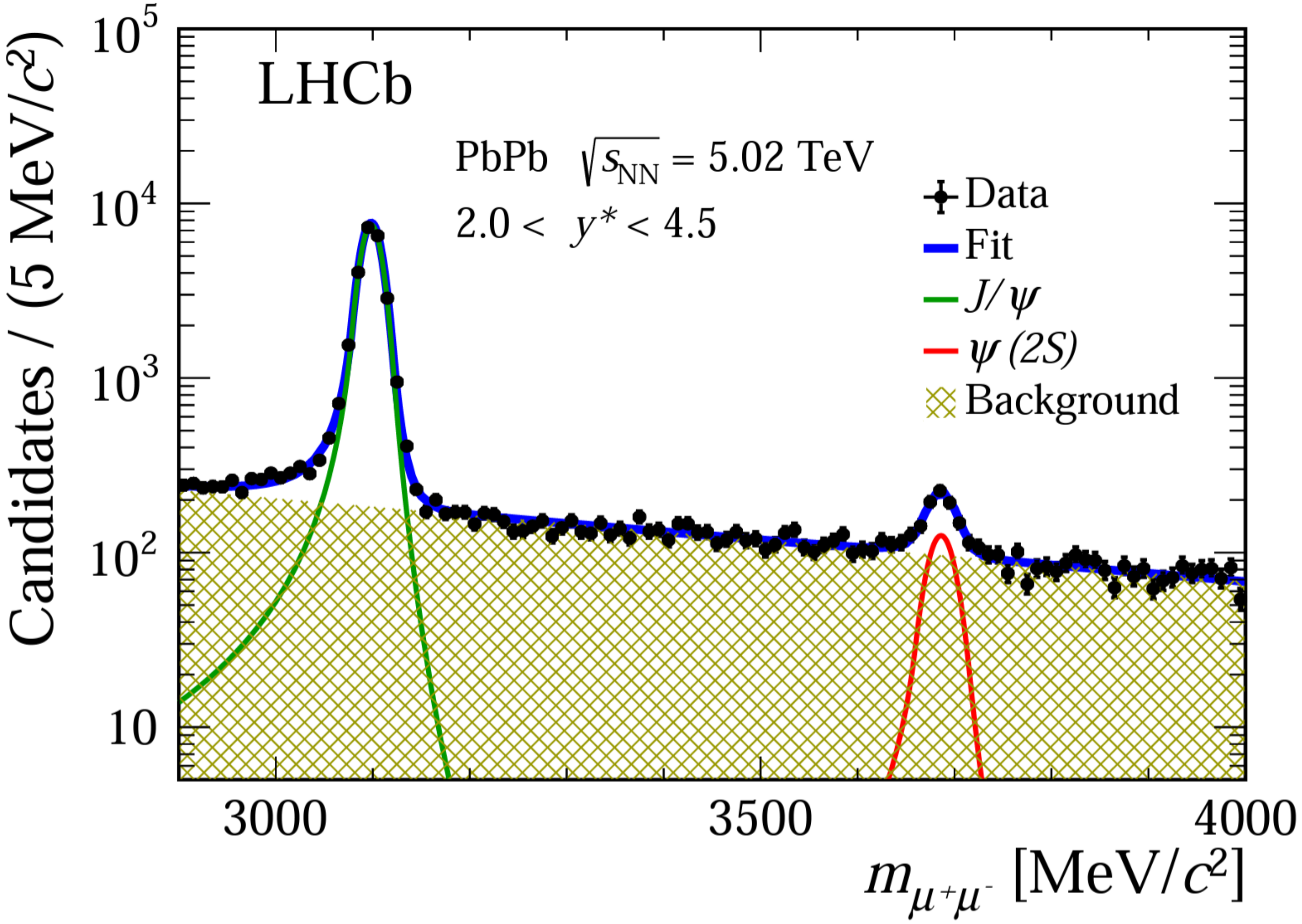




Signal extraction (1)

JHEP 06 (2023) 146

- **Charmonia yields are extracted from dimuon mass fit**
  - Double sided crystal ball function for the J/ψ and $\psi(2S)$ signals
  - Exponential for the non-resonance background (mainly $\gamma\gamma \rightarrow \mu\mu$ process)

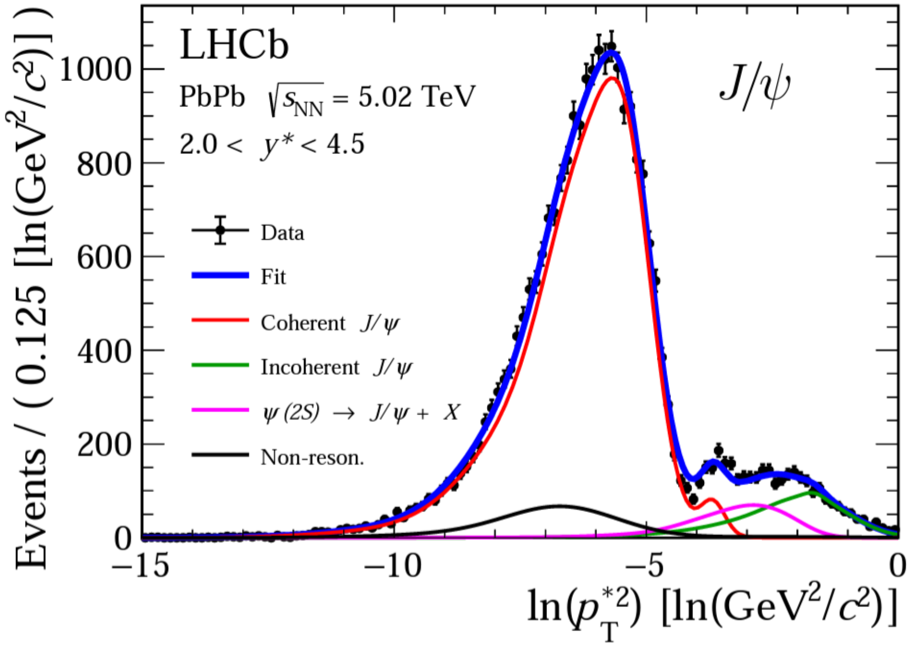


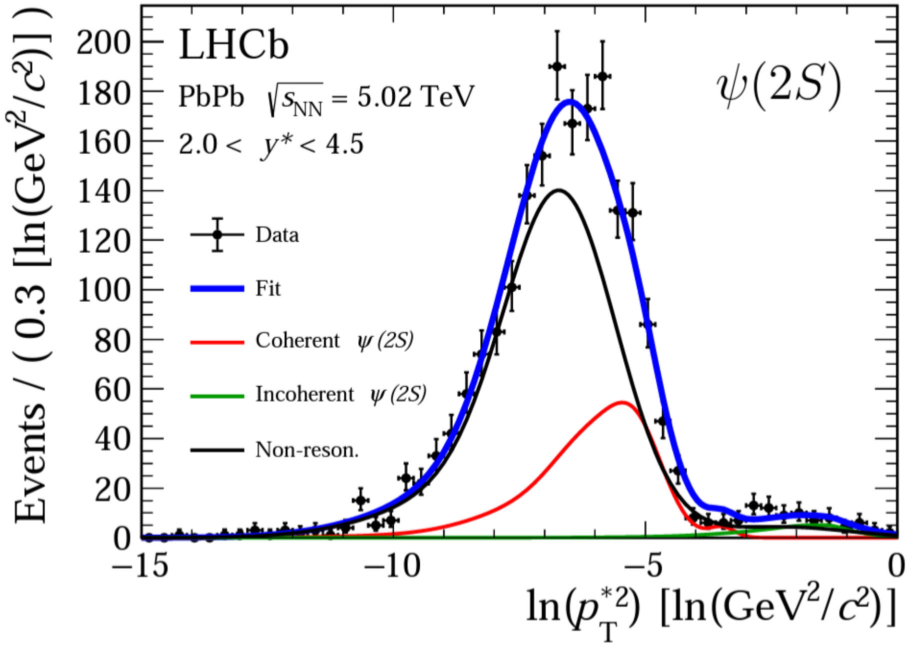
Signal extraction (2)

JHEP 06 (2023) 146

- **Coherent production signal is extracted from a $\ln(p_T^{*2})$ fit**
  - Coherent, incoherent, and feed-down shapes modelled using STARLight + EvtGen + PHOTOs + GEANT4 Simulation
  - Non-resonance shapes determined from data side-band

$\ln(p_T^{*2})$ fit





J/ψ and $\psi(2S)$ in PbPb ultra-peripheral collisions

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- **Integrated cross-section and ratio (most precise measurements in the forward region at the moment):**

$$\sigma^{\text{coh}}_{J/\psi} = 5.965 \pm 0.059(stat) \pm 0.232(syst) \pm 0.262(\text{lumi})\ \text{mb},$$
$$\sigma^{coh}_{\psi(2S)} = 0.923 \pm 0.086(stat) \pm 0.028(syst) \pm 0.040(\text{lumi})\ \text{mb},$$
$$\sigma^{coh}_{J/\psi} / \sigma^{coh}_{\psi(2S)} = 0.155 \pm 0.014(stat) \pm 0.003\ (syst).$$

- **Systematic uncertainties:**

Source	Relative uncertainty [%]	
	$\sigma^{\text{coh}}_{J/\psi}$	$\sigma^{\text{coh}}_{\psi(2S)}$
Tracking efficiency	0.5–2.0	0.5–2.0
PID efficiency	0.9–1.6	0.9–1.6
Trigger efficiency	2.7–3.7	2.1–2.5
HeRSCheL efficiency	1.4	1.4
Background estimation	1.2	1.2
Signal shape	0.04	0.04
Momentum resolution	0.9–34	1.3–27
Branching fraction	0.6	2.1
Luminosity	4.4	4.4

J/ψ and $\psi(2S)$ in PbPb ultra-peripherial collisions

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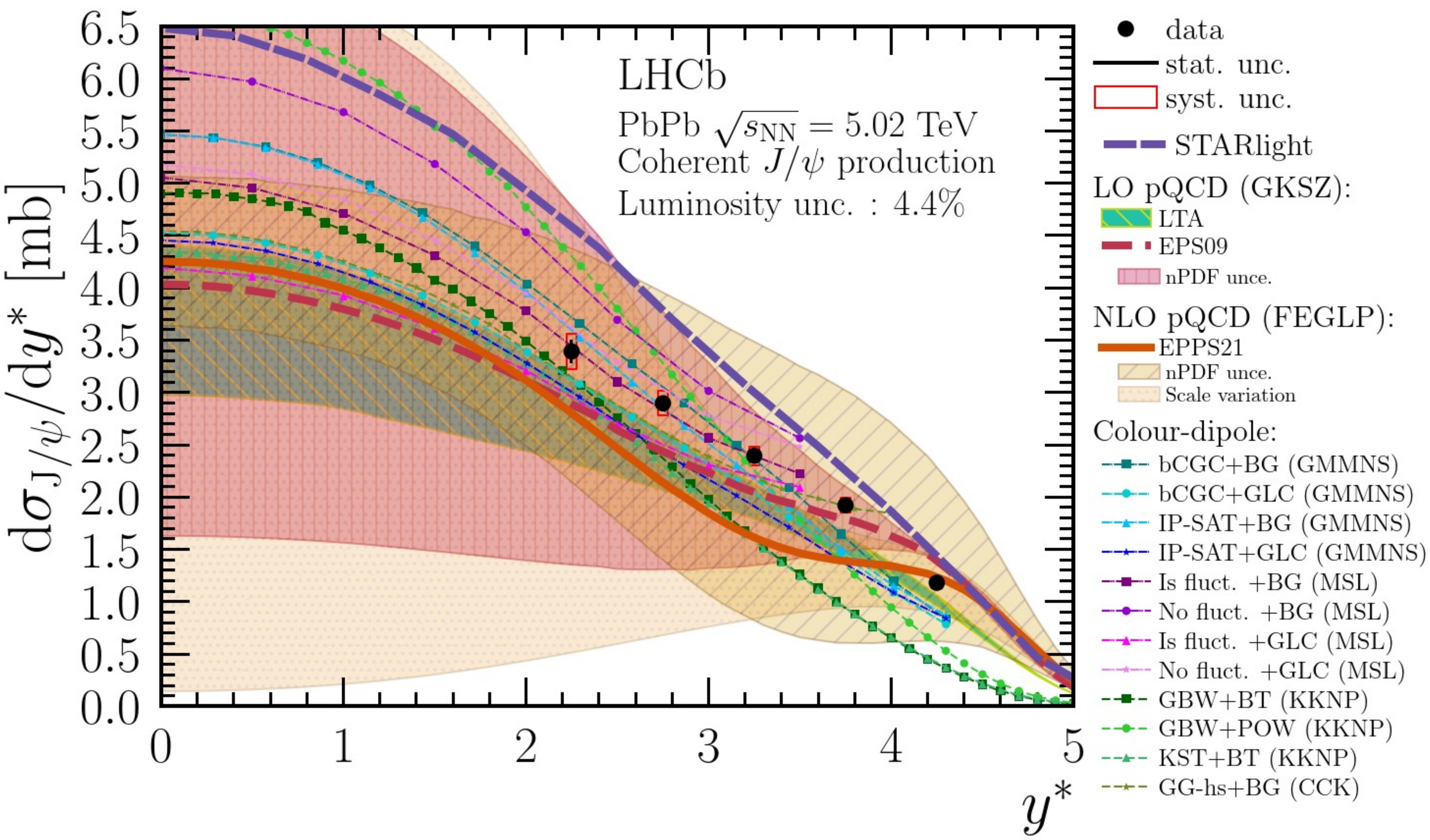
- **The most precise coherent J/ψ production measurement in PbPb UPC in forward rapidity to date**
- **The high precision LHCb data are of great value in theoretical model fine-tuning**
- **Compare to most recent theoretical calculations:**
  - **p-QCD calculations:** include **new NLO p-QCD calculation PDF uncert**. and **factorization / renormalization scale uncert.**
  - **Color-dipole models:** draw different model tuning options as theoretical variations



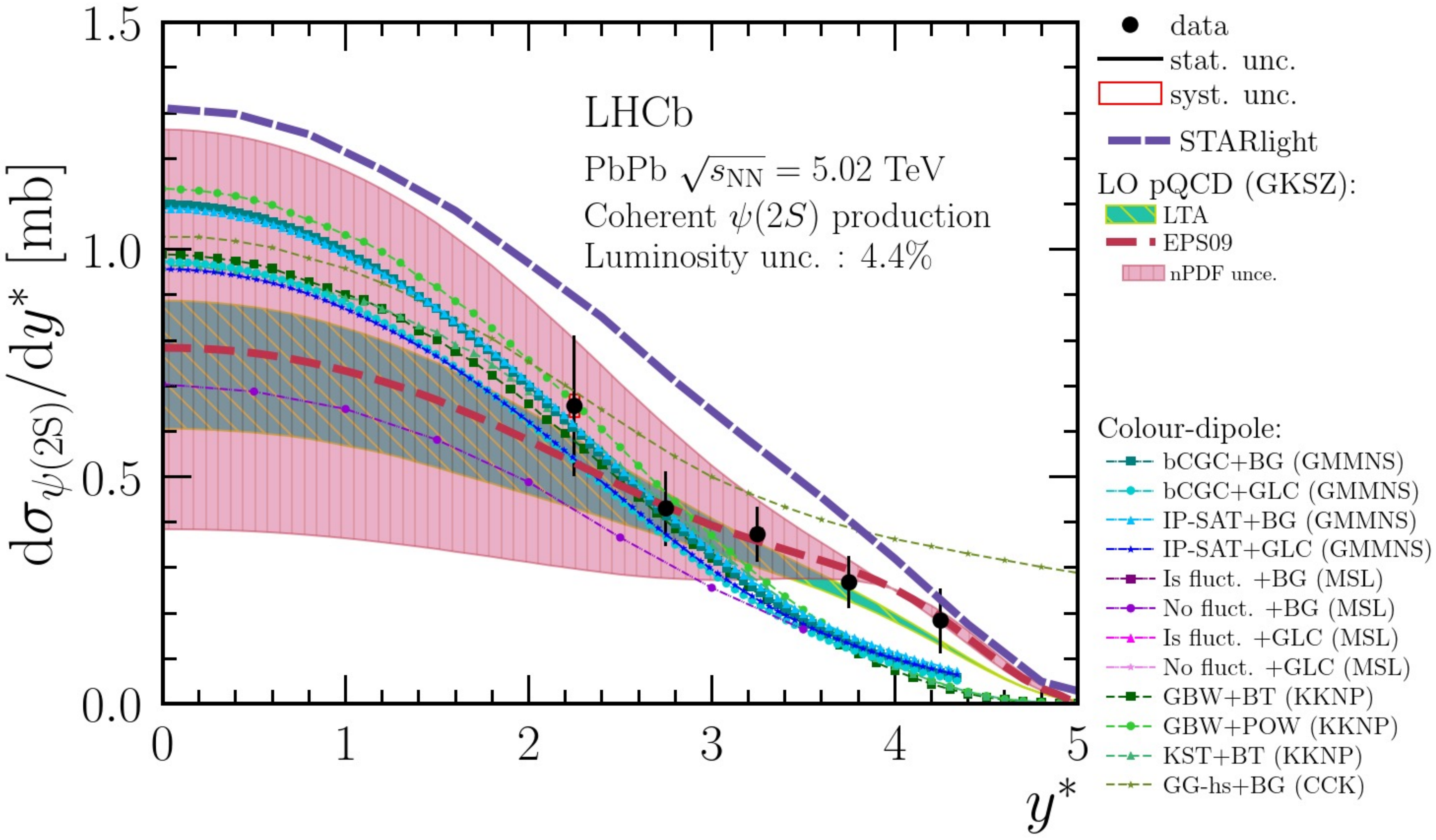
J/ψ and $\psi(2S)$ in PbPb ultra-peripheral collisions

JHEP 06 (2023) 146

- The **first coherent $\psi(2S)$ measurement** in forward rapidity at the LHC

Compared to pQCD and color-dipole models

GKSZ: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
GMMNS: PRD 96 (2017) 094027, EPJC 40 (2005) 519,
MSL: PLB 772 (2017) 832, PoS DIS2014 (2014) 069,
KKNP: PRD 107 (2023) 054005
CCK: PRC 97 (2018) 024901



J/ψ and $\psi(2S)$ in PbPb ultra-peripheral collisions

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- **The first cross-section ratio between J/ψ and $\psi(2S)$ vs. rapidity measurement in forward rapidity region at the LHC**

Compared to pQCD and color-dipole models

GKSZ: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
FEGLP: PRC 106 (2022) 035202.
GMMNS: PRD 96 (2017) 094027, EPJC 40 (2005) 519,
MSL: PLB 772 (2017) 832, PoS DIS2014 (2014) 069,
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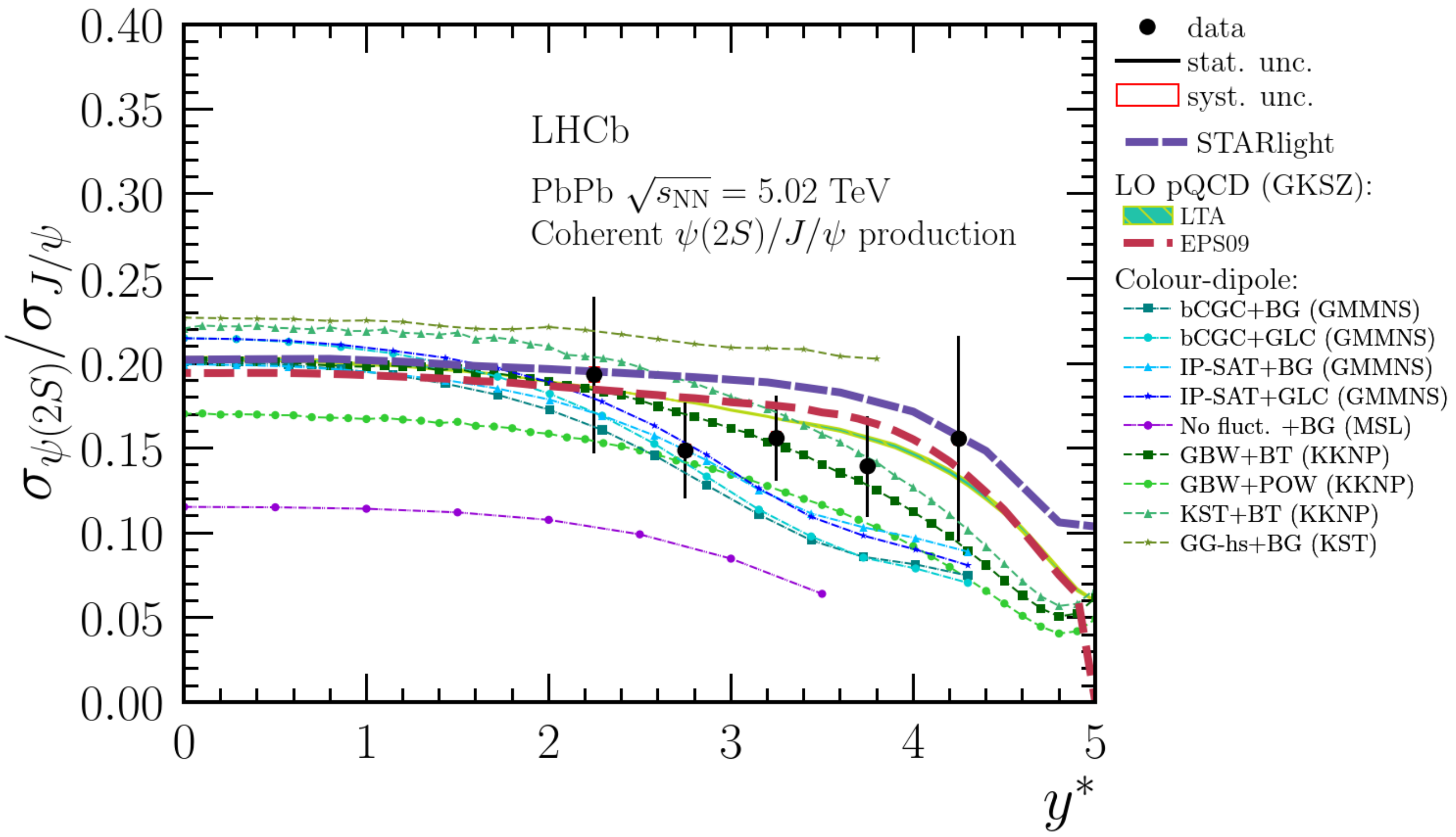
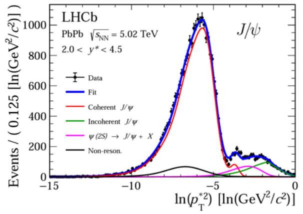


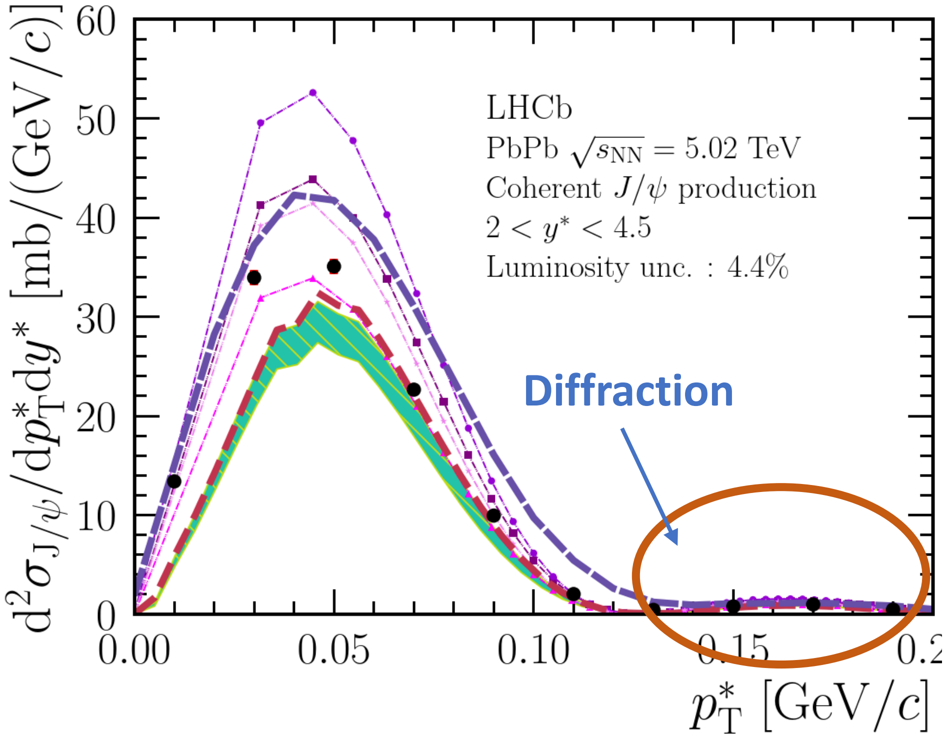
J/ψ and $\psi(2S)$ in PbPb ultra-peripherial collisions

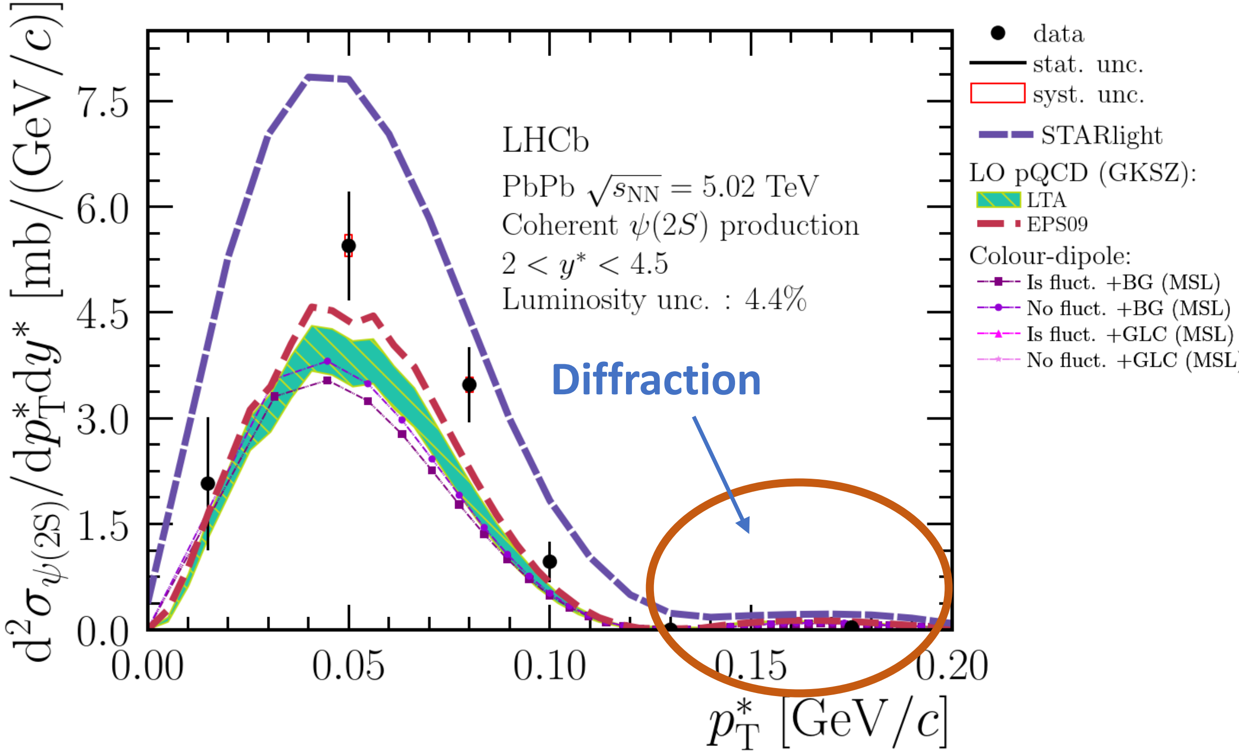
JHEP 06 (2023) 146

- **The first measurement of the coherent J/ψ and $\psi(2S)$ production cross-section vs. p_{T} in PbPb UPC**

Compared to pQCD and color-dipole models







GKSZ: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
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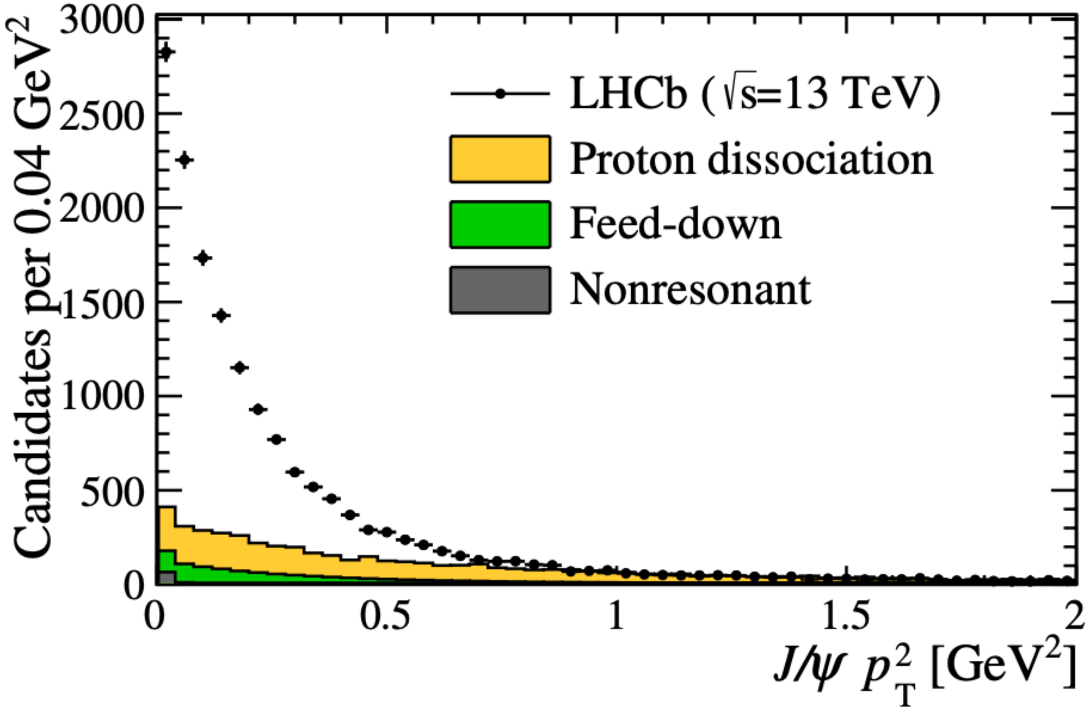
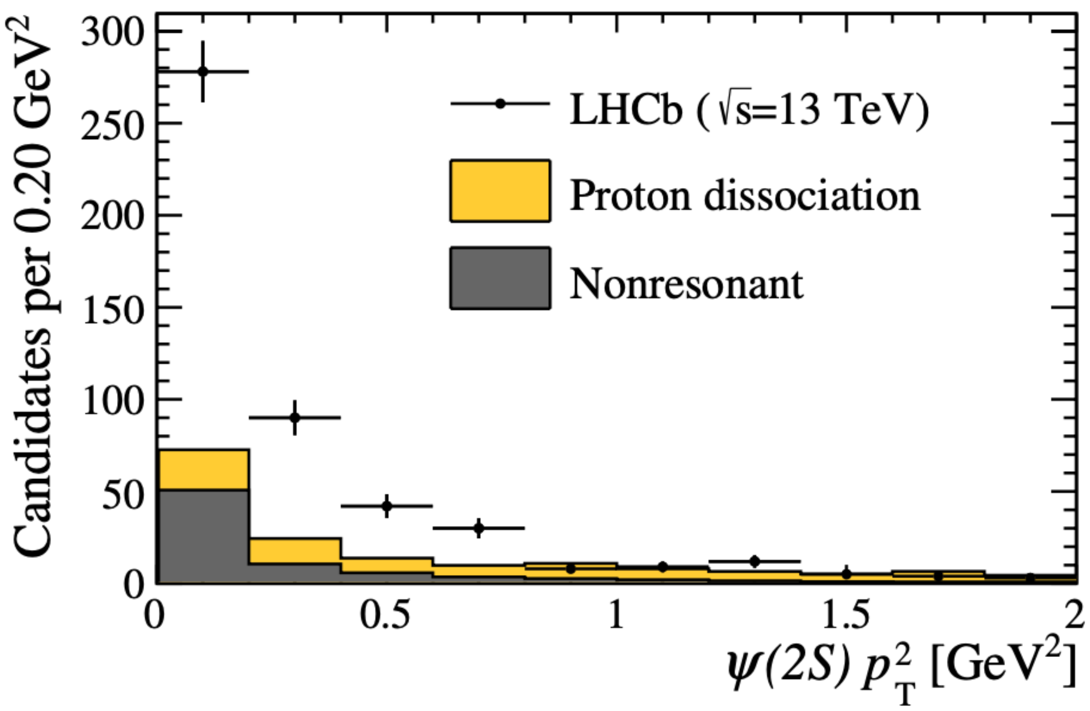
J/ψ and $\psi(2S)$ in pp CEP at 13 TeV

- Central exclusive photoproduction of J/ψ and $\psi(2S)$ in pp collisions (only ~204 pb^{-1})

JHEP 10 (2018) 167





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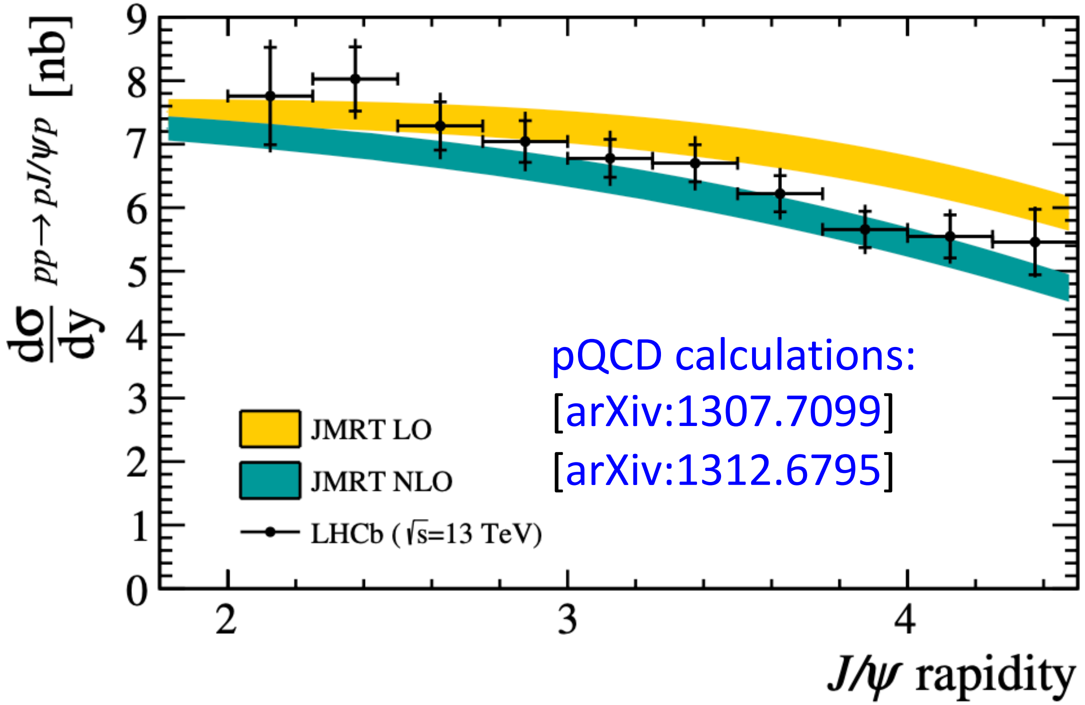
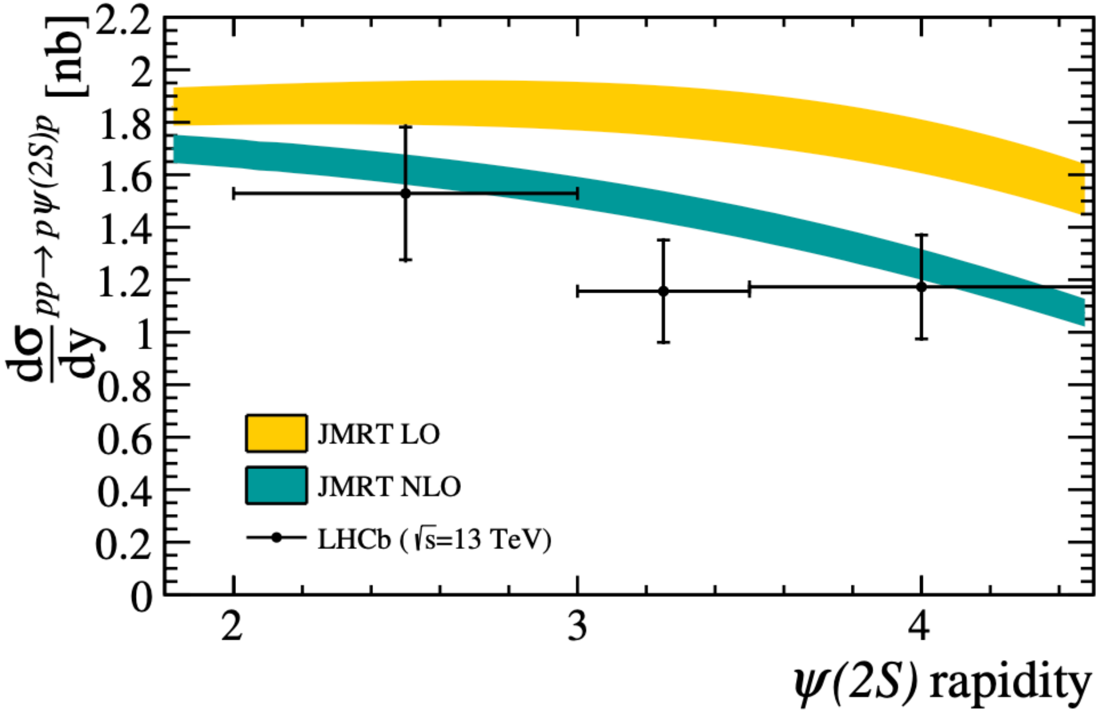
JHEP 10 (2018) 167

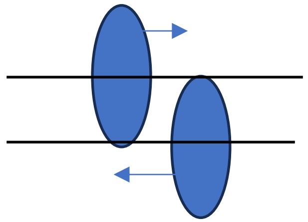


pQCD calculations:
[arXiv:1307.7099]
[arXiv:1312.6795]

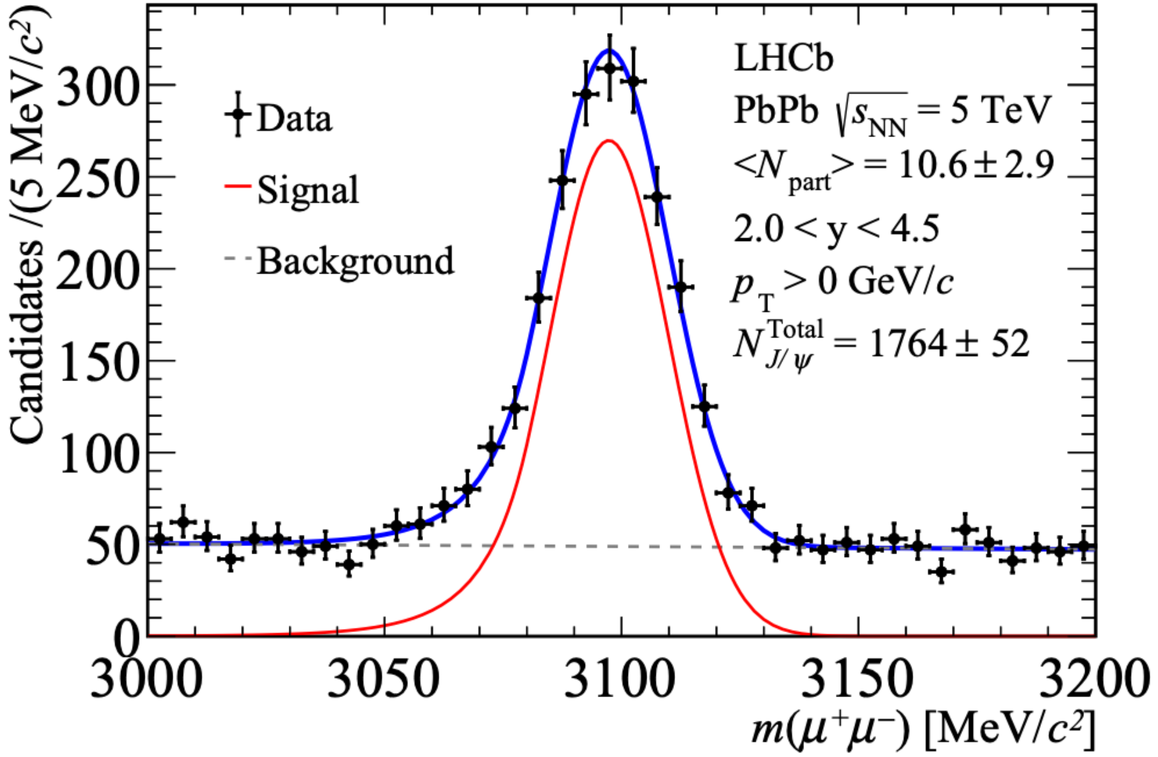


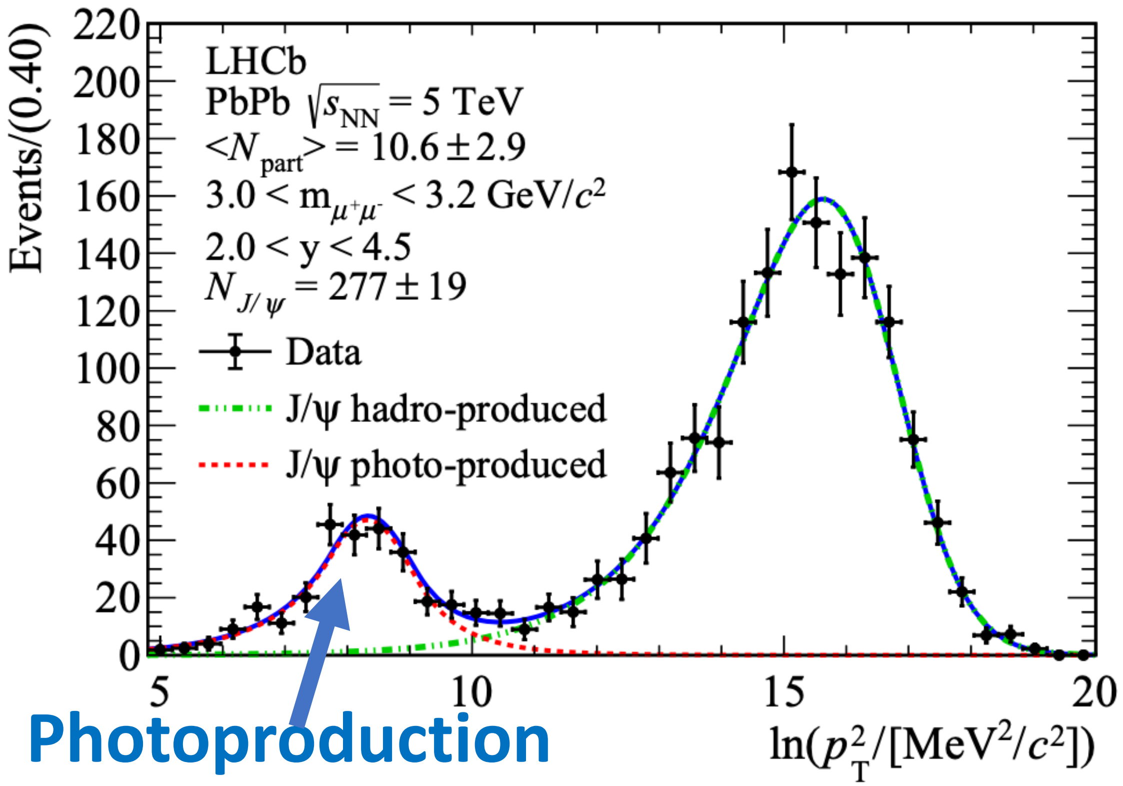
J/ψ photoproduction in PbPb peripherial collisions

- “Peripheral” means collided with centrality > 50%
- Photoproduction also observed when PbPb collided.



[Phys. Rev. C105 (2022) L032201]





Photoproduction

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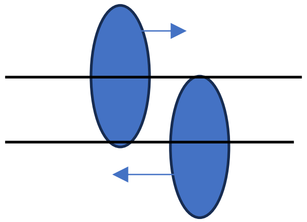
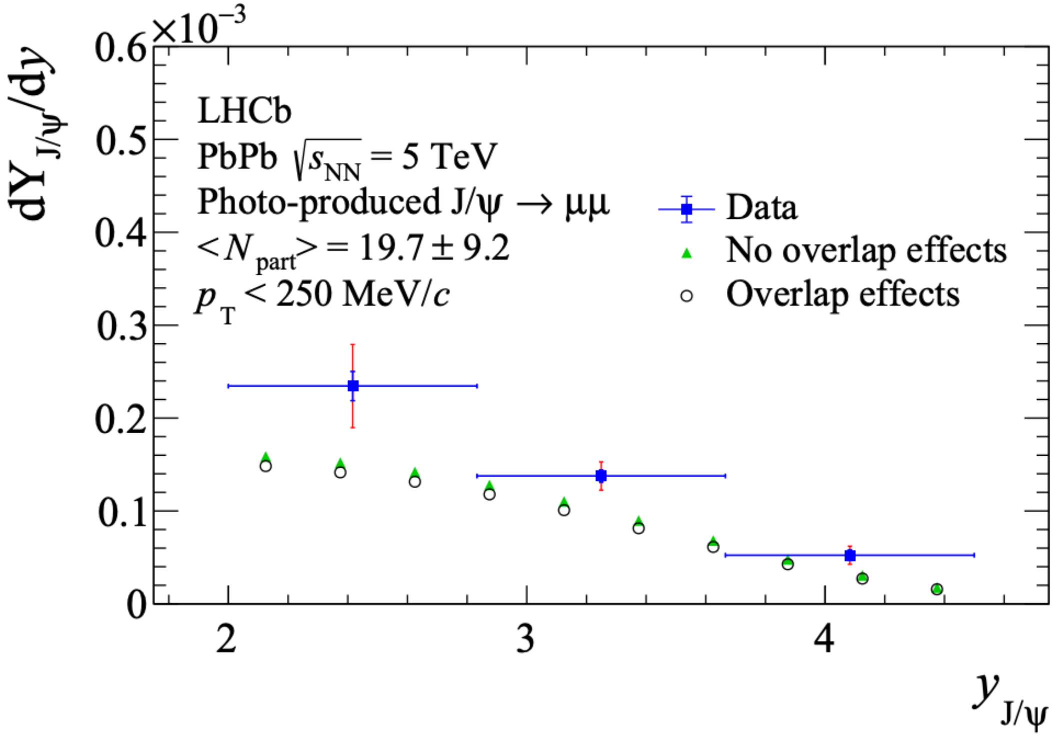
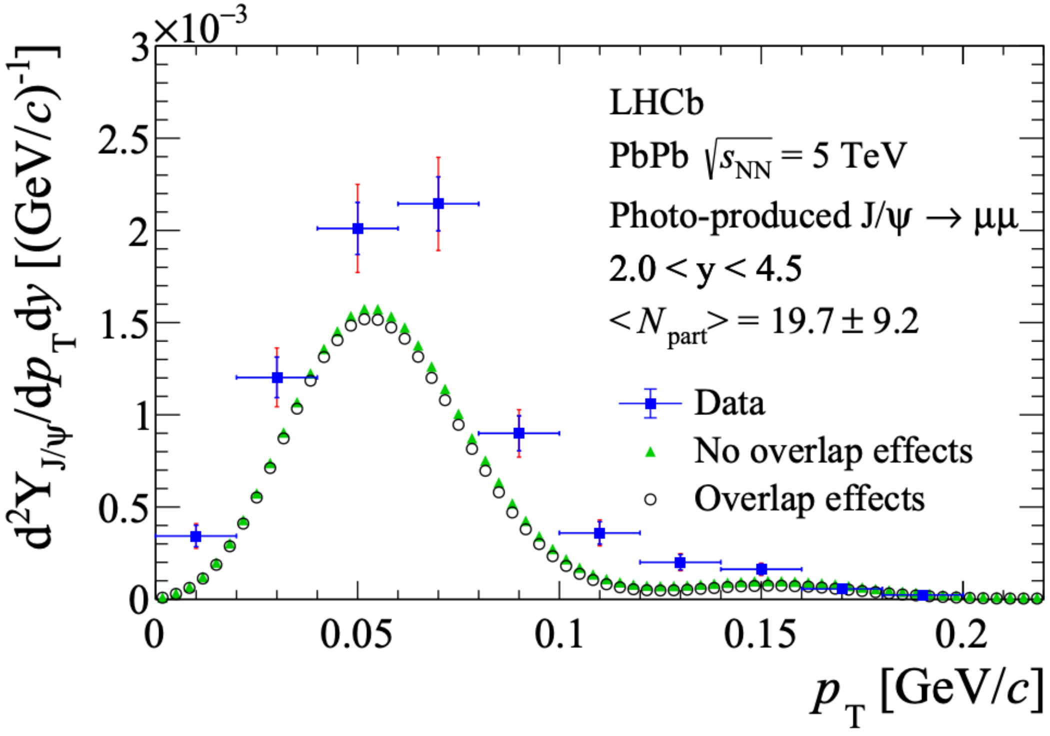


[Phys. Rev. C105 (2022) L032201]





LHCb charmonia results in heavy ion collisions

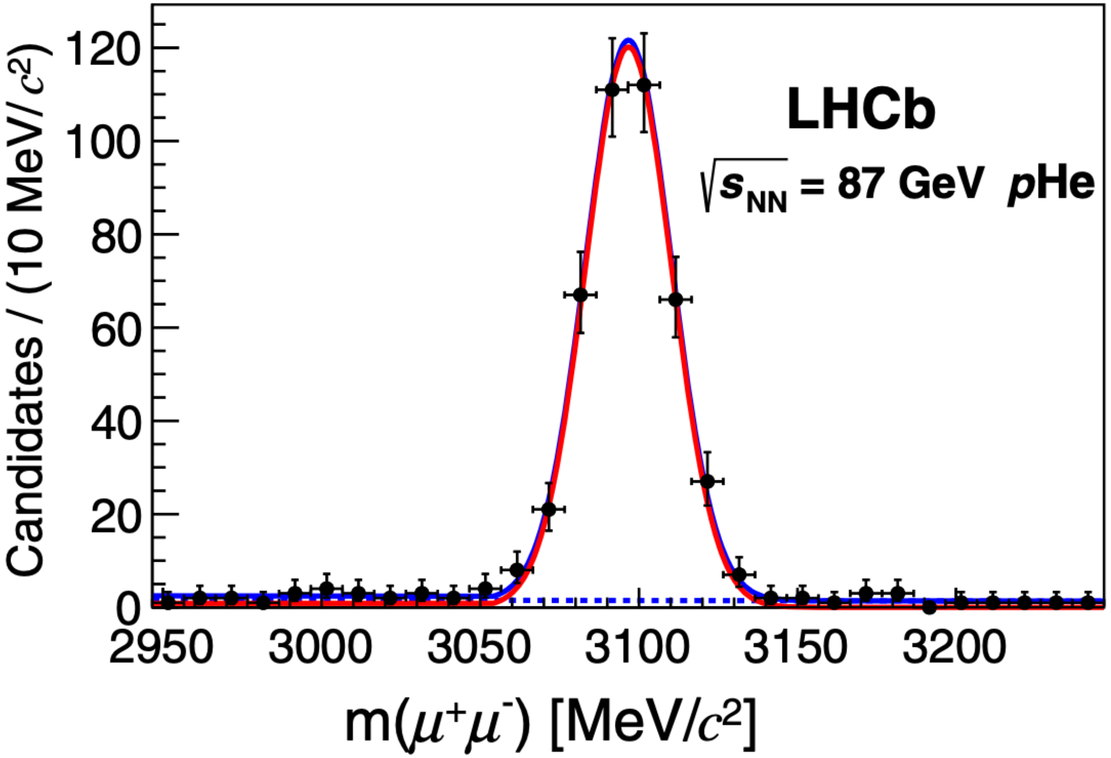
- Probe nuclear matter effects:
  - J/ψ and $\psi(2S)$ production in pPb @ 5.02 TeV and 8.16 TeV:
    - @ 5.02 TeV: J/ψ [JHEP 02 (2014) 72], $\psi(2S)$ [JHEP 03 (2016) 133],
    - @ 8.16 TeV: J/ψ [Phys. Lett. B774 (2017) 159], $\psi(2S)$ [JHEP 04 (2024) 111],
  - $\psi(2S)$ to J/ψ ratio in pp @ 13 TeV: [JHEP 05 (2024) 243]
- Probe nature of $\chi_{c1}(3872)$:
  - $\chi_{c1}(3872)$ to $\psi(2S)$ ratio in pp: [Phys. Rev. Lett. 126 (2021) 092001],
  - $\chi_{c1}(3872)$ to $\psi(2S)$ ratio in pPb @8.16 TeV: [Phys. Rev. Lett. 132 (2024) 242301]
- Photoproduction:
  - J/ψ and $\psi(2S)$ in PbPb ultra-peripherial collisions: [JHEP 06 (2023) 146]
  - J/ψ in PbPb peripherial collisions: [Phys. Rev. C105 (2022) L032201]
  - J/ψ and $\psi(2S)$ in pp central exclusive production: [JHEP 10 (2018) 167]
- **Fixed target results:**
  - J/ψ and D^0 in pHe and pAr collisions, first fixed-target result: [Phys. Rev. Lett. 122 (2019) 132002]
  - J/ψ and D^0 in pNe and PbNe collisions: [Eur. Phys. J. C83 (2023) 625], [Eur. Phys. J. C83 (2023) 658]

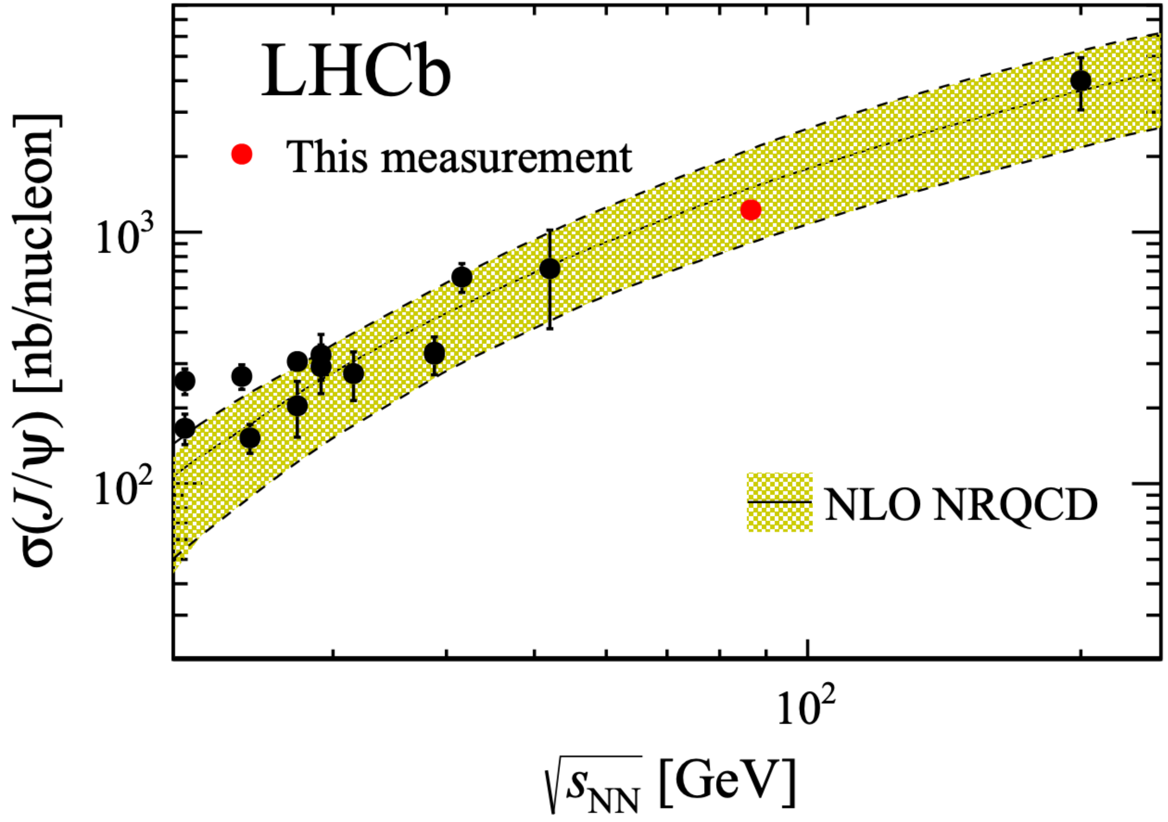
J/ψ and D^0 in pHe and pAr collisions

- pHe at 86.6 GeV; and pAr at 110.4 GeV

first LHCb fixed-target result

[Phys. Rev. Lett. 122 (2019) 132002]





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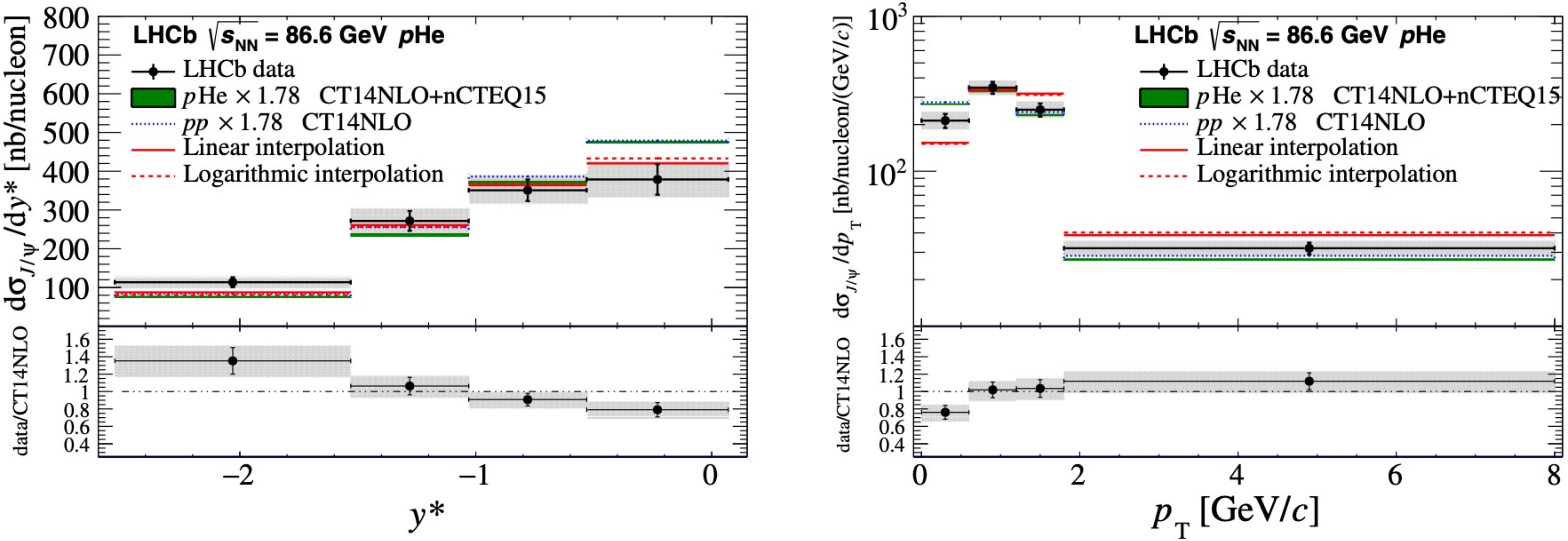

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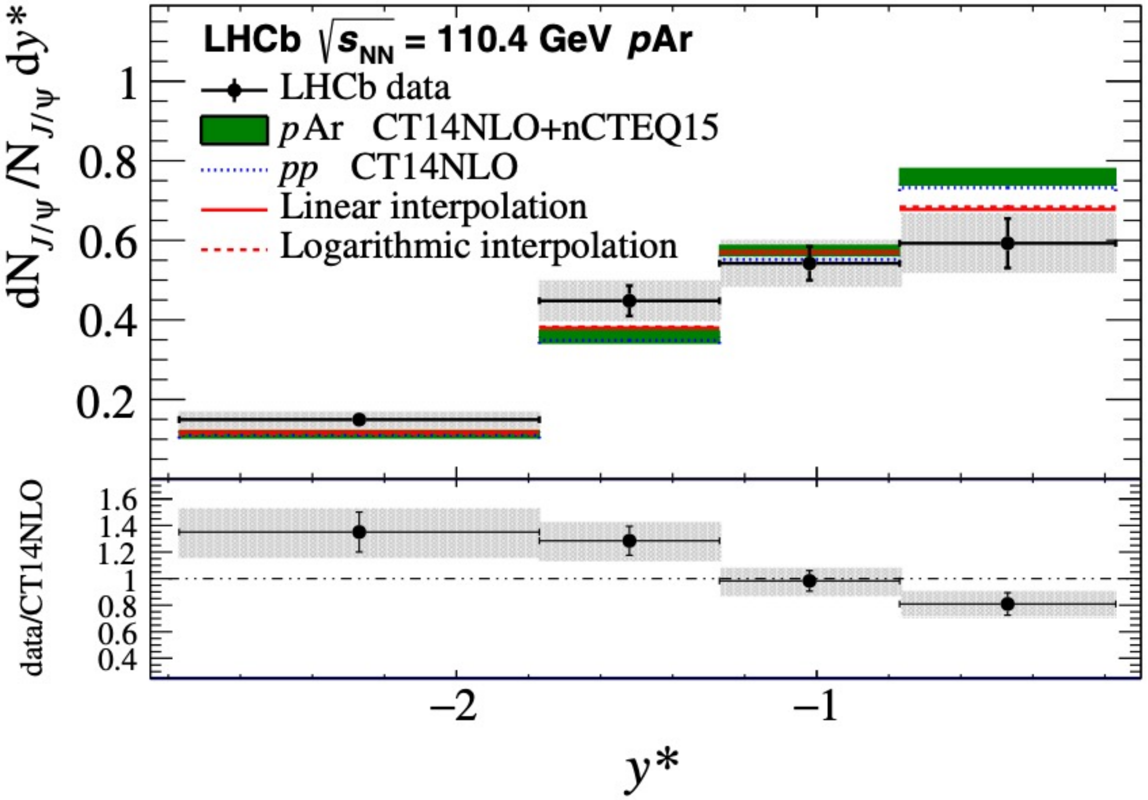
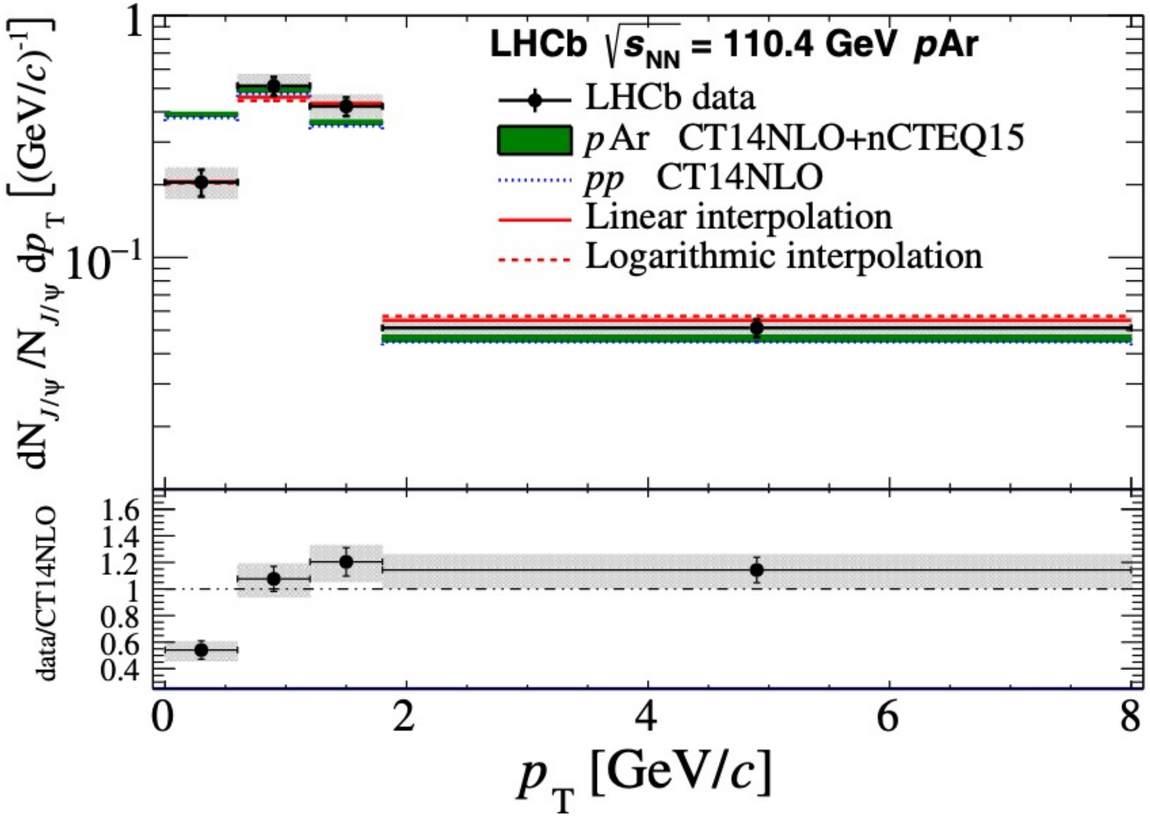
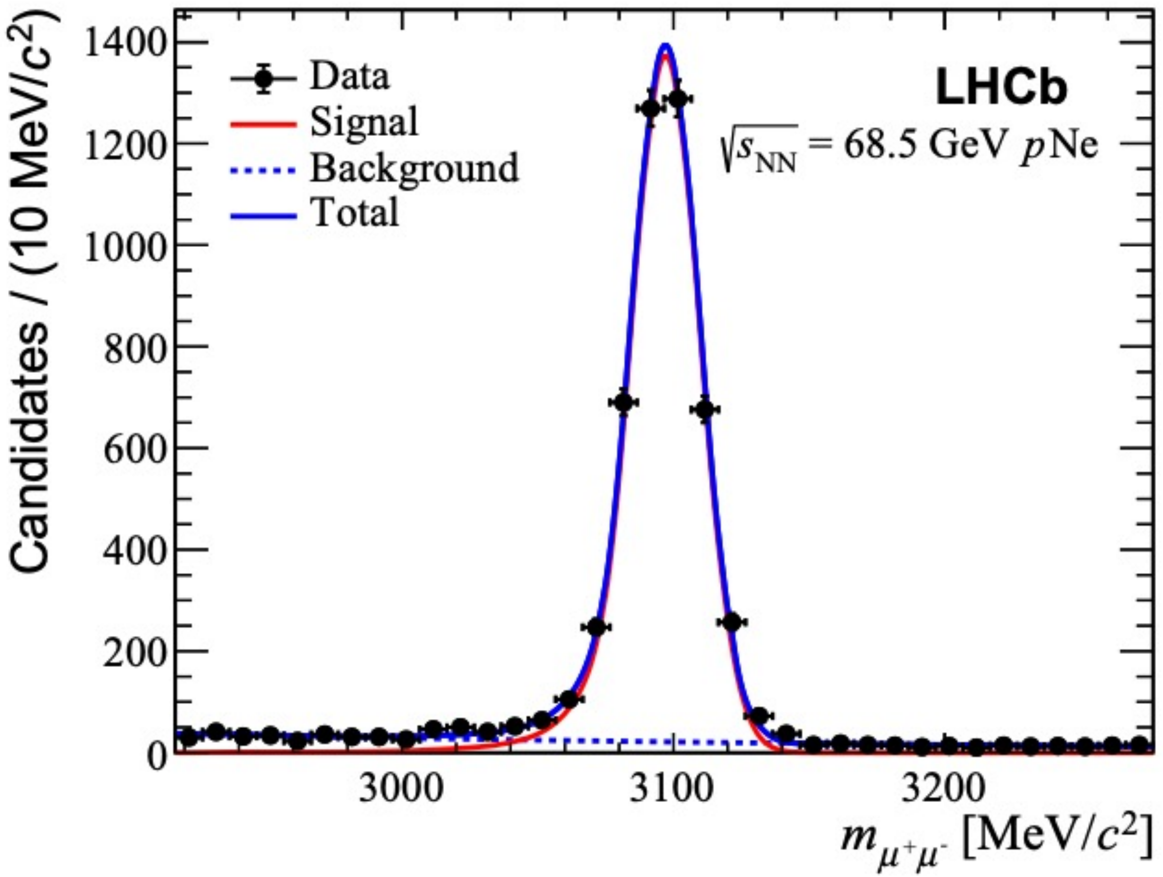


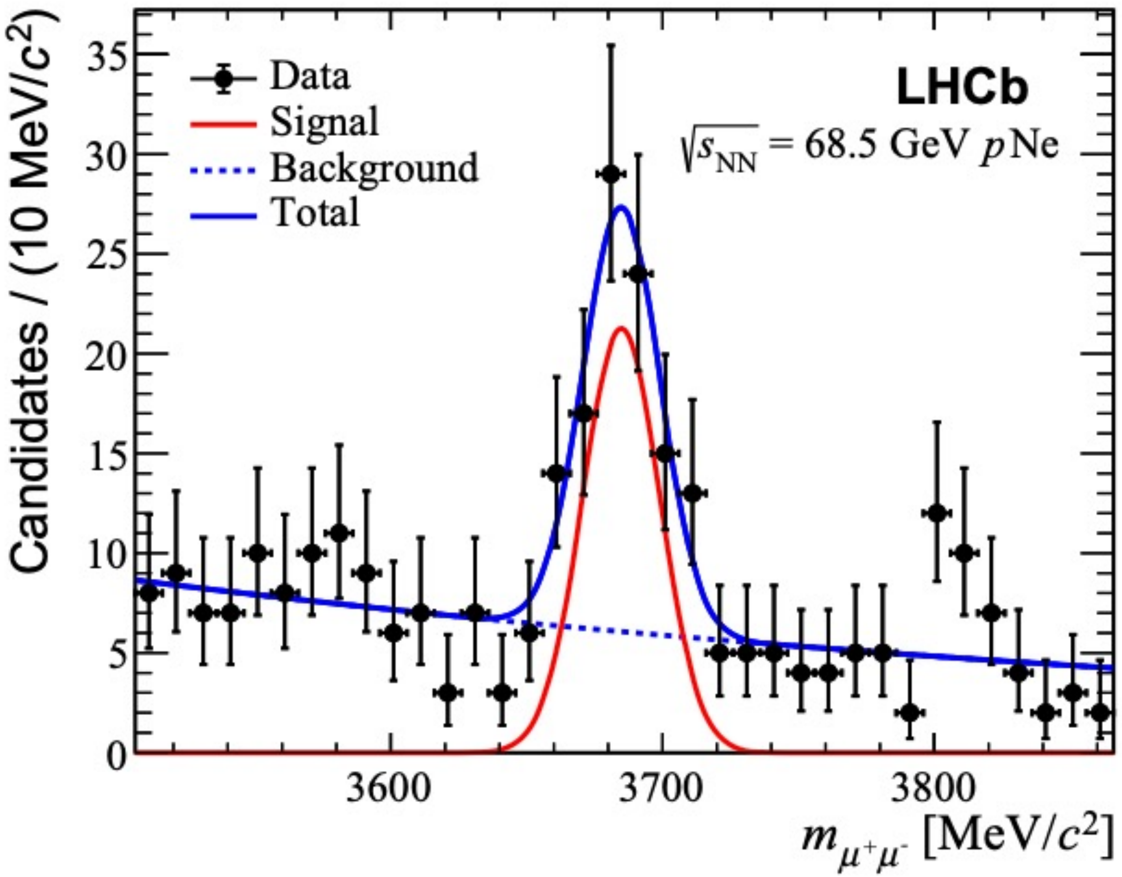


J/ψ and D^0 in pNe and PbNe collisions

- pNe and PbNe at 68.5 GeV

[Eur. Phys. J. C83 (2023) 625],
[Eur. Phys. J. C83 (2023) 658]





J/ψ and D^0 in pNe and PbNe collisions

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[Eur. Phys. J. C83 (2023) 625],
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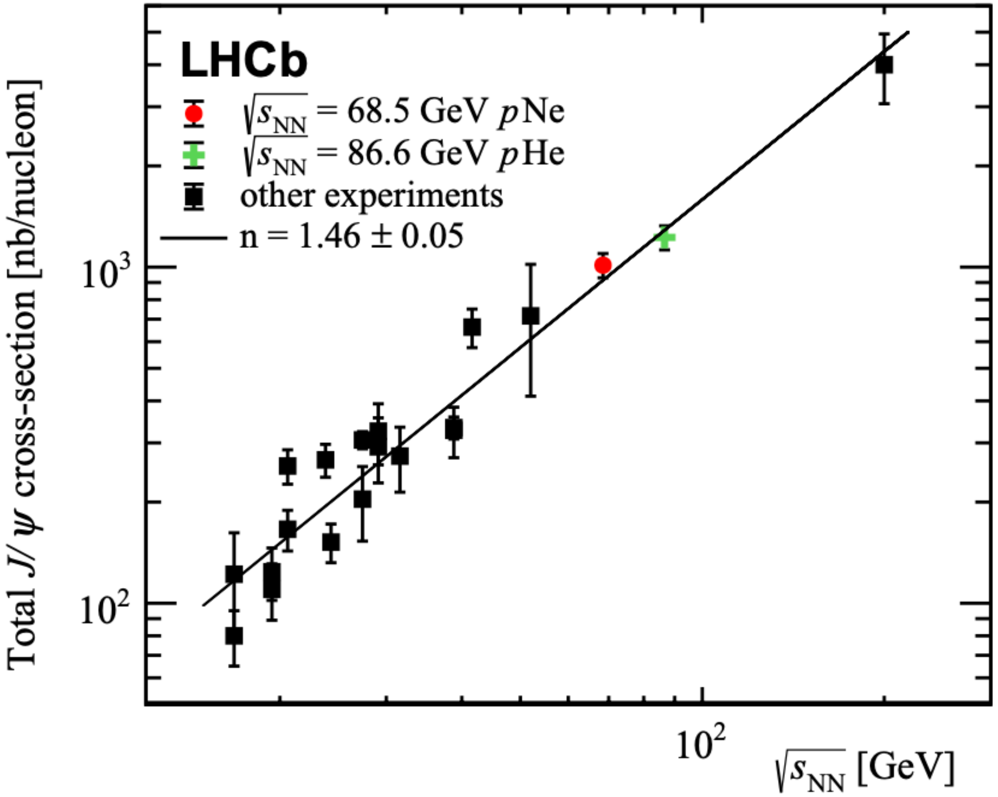

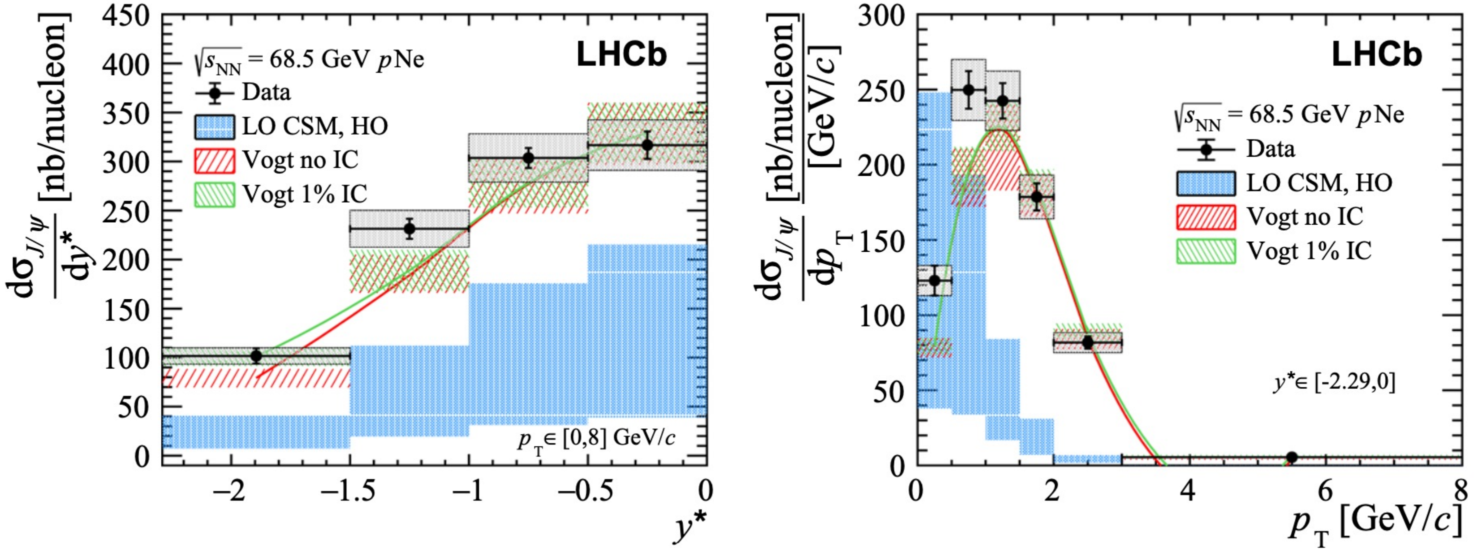

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[Eur. Phys. J. C83 (2023) 625],
[Eur. Phys. J. C83 (2023) 658]

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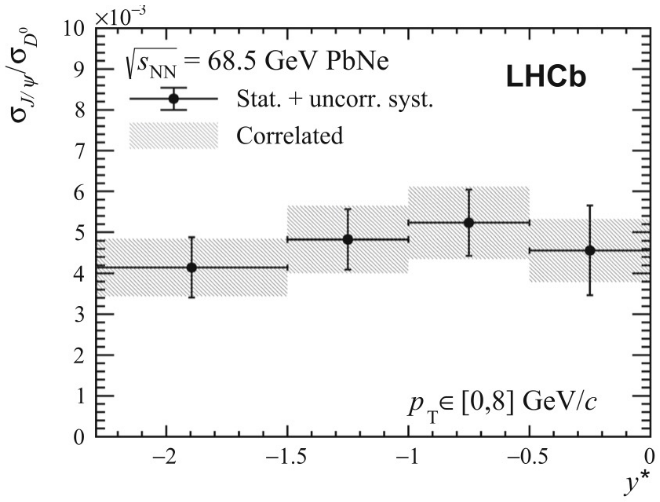

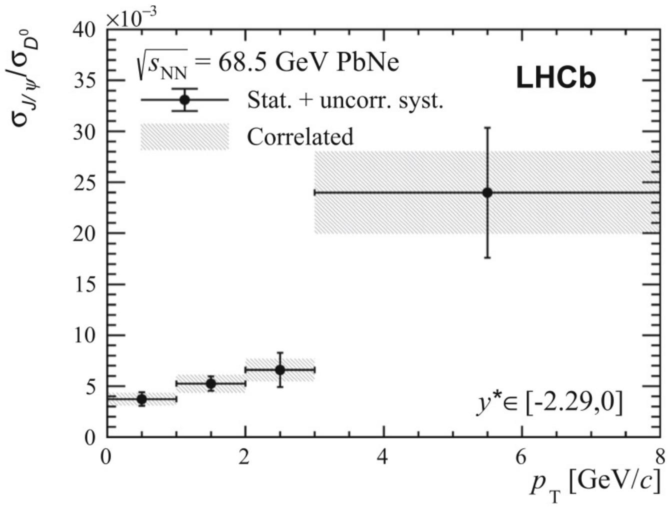

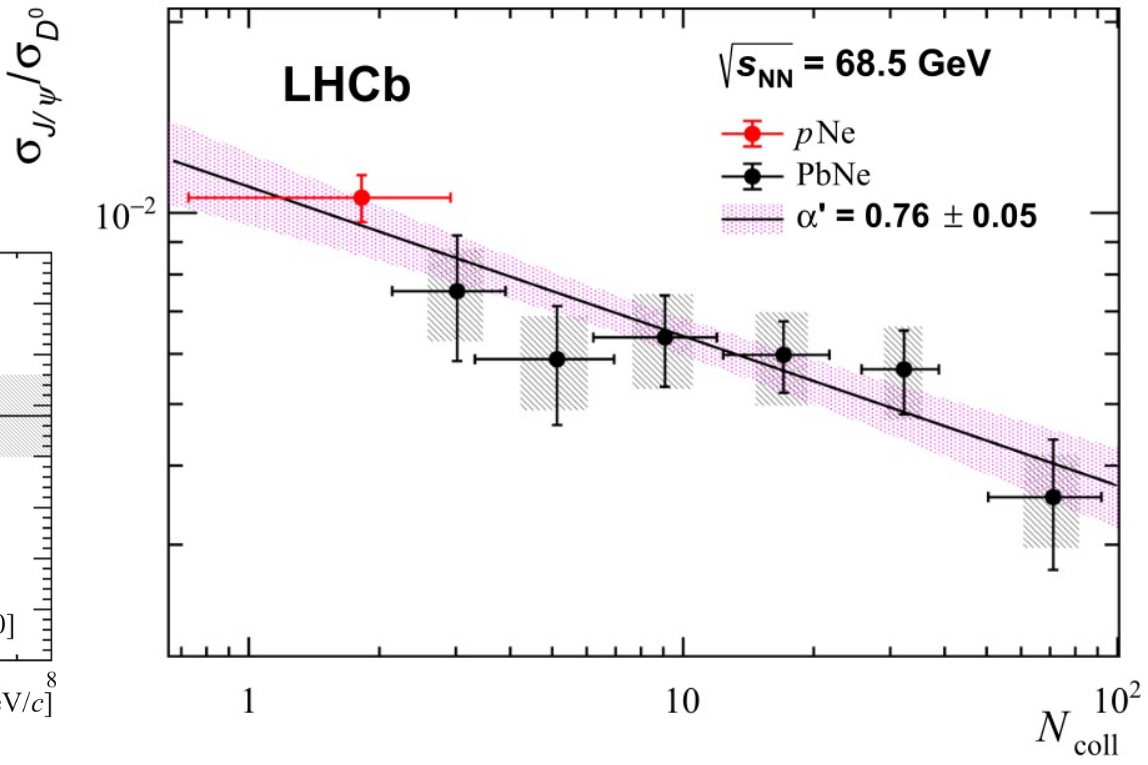

Take away

- Charmonium as tools:
  - Production cross-section: probe nuclear matter effect
  - Ratio $\chi_{c1}(3872)$ to $\psi(2S)$: probe nature of $\chi_{c1}(3872)$
  - Photoproduction: constraint gluon PDFs
- Study charmonium production: Fixed target production at pHe, pAr, pNe, PbNe
- Rich program at LHCb on charmonium related physics
- Expecting new ideas!