Coherent vector meson photoproduction and polarization in HICs with nuclear overlap

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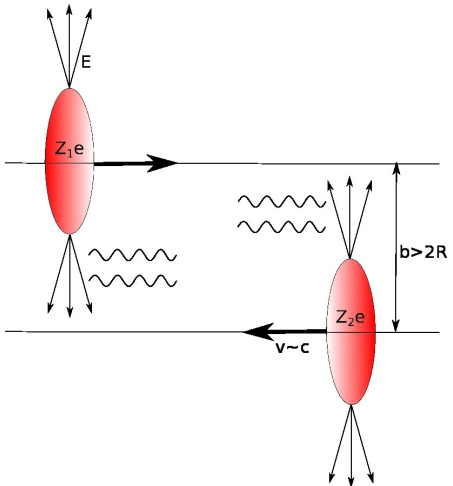
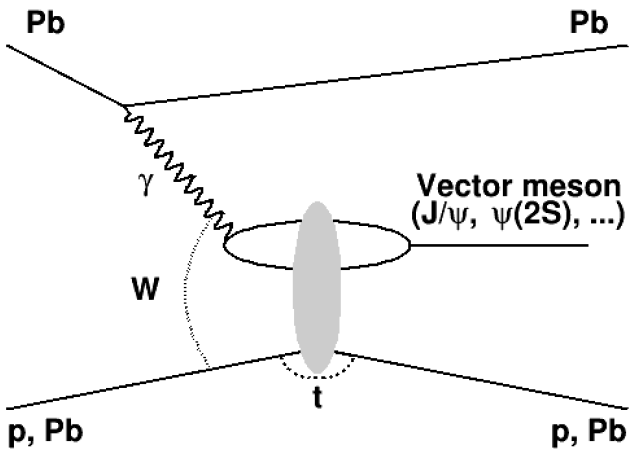
Afnan Shatat for the ALICE Collaboration
IJCLab Orsay, CNRS/IN2P3, Université Paris Saclay
afnan.shatat@cern.ch

Vector meson photoproduction in HICs

Relativistic heavy ions are strong EM field emitters

Vector Meson (VM): meson of $J^P = 1^-$





Coherent, $\langle p_T \rangle \approx 60$ MeV/c

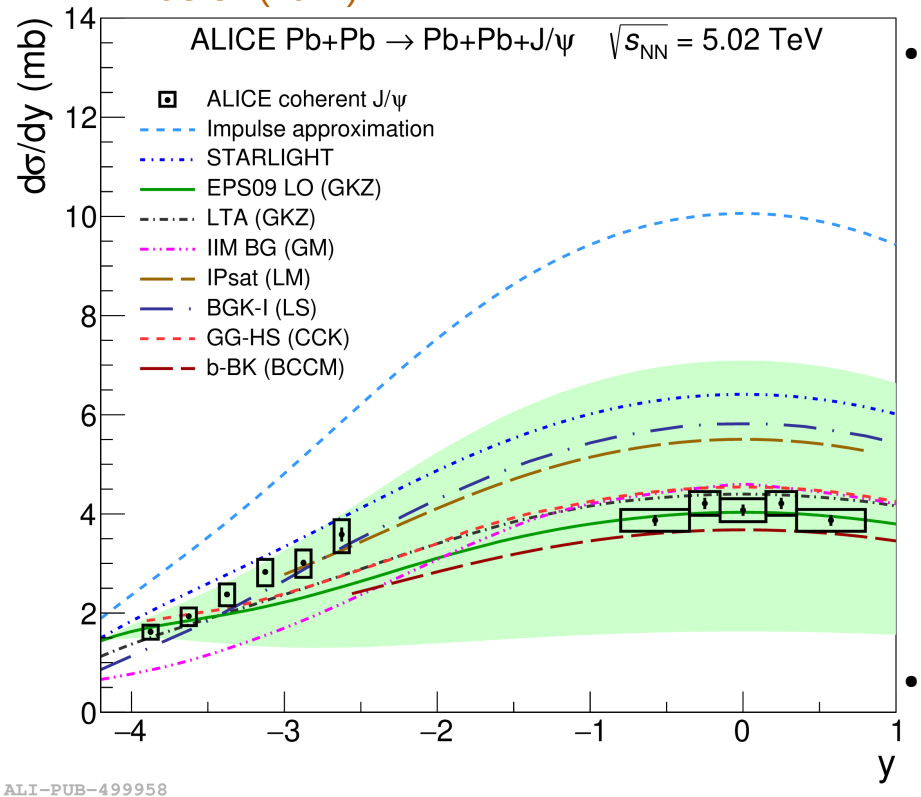
Incoherent, $\langle p_T \rangle \approx 500$ MeV/c

b: impact parameter

- **Ultra Peripheral Collisions (UPC): *b* > 2R**
- **Peripheral Collisions (PC): *b* < 2R and *b large***

Vector meson photoproduction in UPC

EPJC 81 (2021) 712



- Models including nuclear shadowing cannot describe at the same time the mid and forward rapidity cross section

Impulse approximation: [PRC88, 014910 (2013)]
STARLIGHT: [Comp. Phys. Comm. 212 (2017) 258]
EPS09 LO (GKZ): [PRC. 93(5), 055206 (2016)]
LTA (GKZ): [Phys. Rep.512, 255–393 (2012)]
IIM BG (GM): [P.RC 90, 015203 (2014)] and [J. Phys.G 42(10), 105001 (2015)]
Ipsat (LM) : [PRC. 99(4), 044905 (2019)]
BGK-I (LS): [PRC. 83,065202 (2011)] and [PRC. 87, 032201 (2013)],
GG-HS (CCK): [PRC. 97(2), 024901 (2018)], and [PLB 766, 186–191 (2017)]
b-BK (BCCM): [PLB 817, 136306 (2021)]

- VM photoproduction serves as a probe of the gluon distribution in the target nucleus at low Bjorken-*x*

$$x_B = (m_{J/\psi}/\sqrt{s_{\mathrm{NN}}}) \times \exp(\pm y)$$

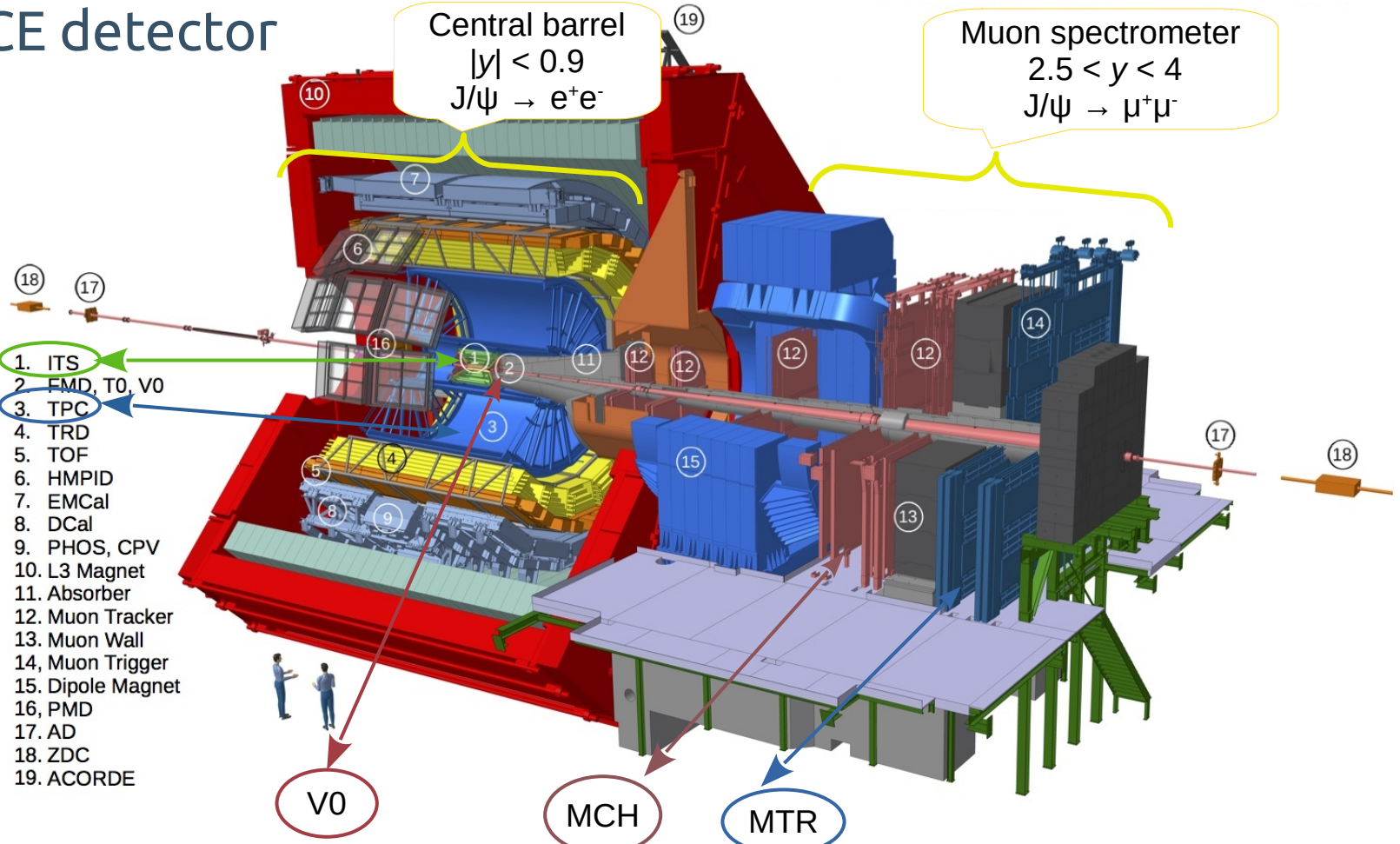
The ALICE detector
In Run 2

Central barrel
$|y| < 0.9$
$J/\psi \rightarrow e^+e^-$

Muon spectrometer
$2.5 < y < 4$
$J/\psi \rightarrow \mu^+\mu^-$

ITS:
inner tracker, vertexing

TPC:
tracking and PID



Minimum bias trigger, centrality determination, background rejection

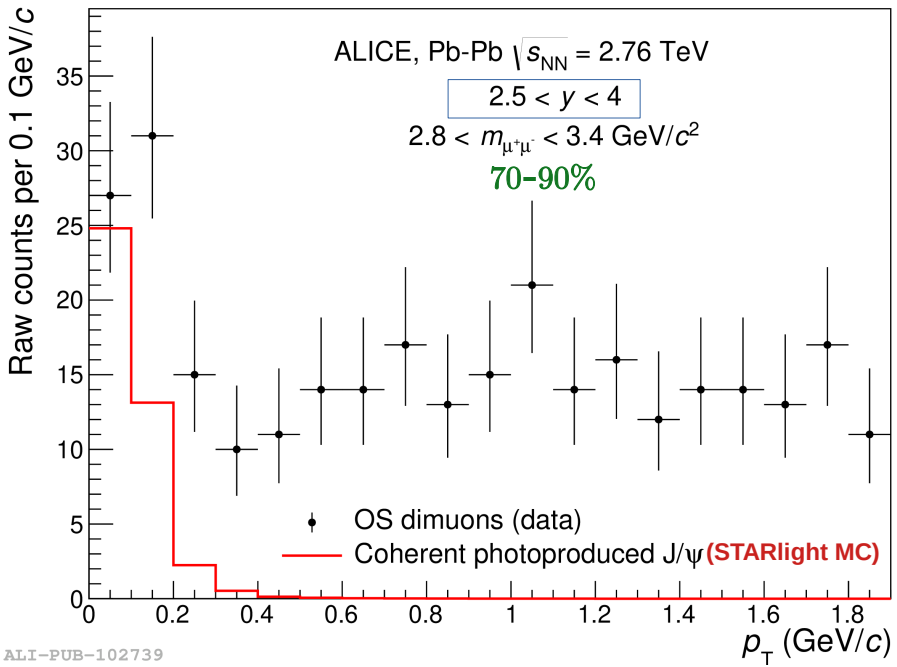
Muon tracker

Muon trigger

Coherent J/ψ photoproduction in Pb–Pb collisions with nuclear overlap

Significant J/ψ excess for p_T < 0.3 GeV/c in 70–90% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV.

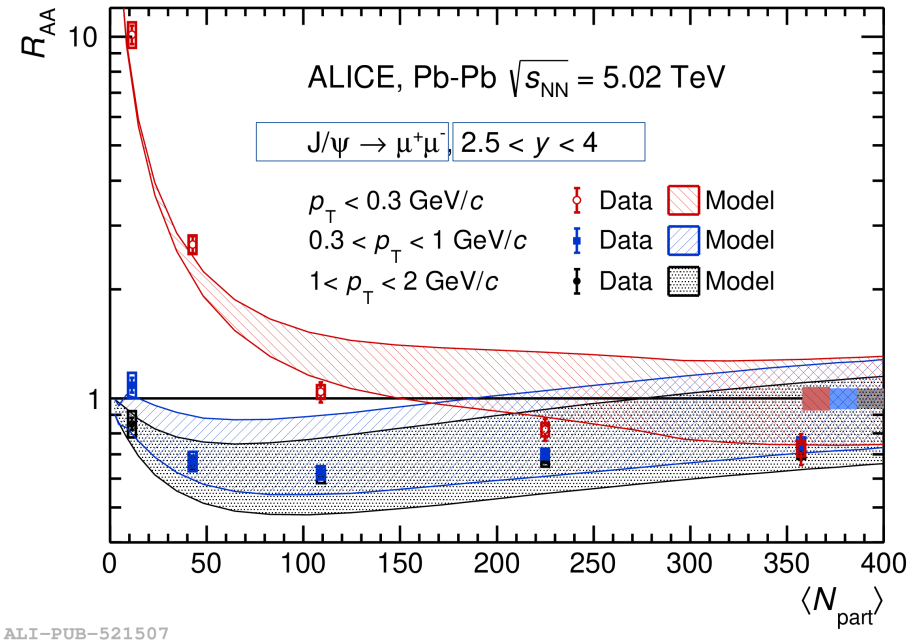
PRL 116, 222301(2016)
STARlight MC : Comp. Phys. Comm. 212 (2017) 258.



Associated with a dramatic increase of the R_{AA}

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \times \sigma_{pp}^{J/\psi}}$$

Phys. Lett. B 846 (2023) 137467 Model: W. Shi et al., Phys. Lett. B 777 (2018)

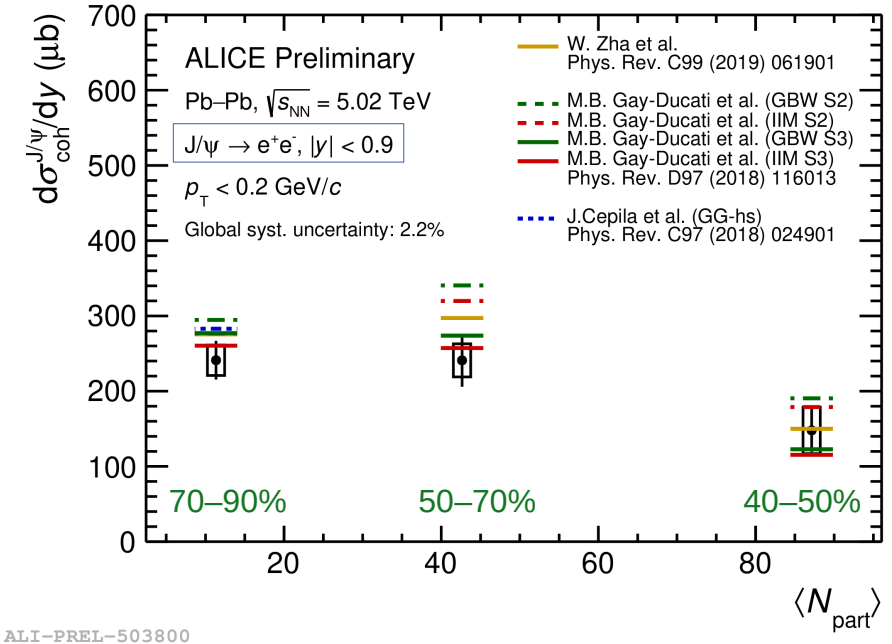


70–90% 0–10%

Observed also by STAR [PRL 123, 132302 (2019)] and LHCb [PRC. 105 (2022) L032201].

Centrality dependence of coherent J/ψ photoproduction

- **Both measurements at mid and forward rapidity don't show a significant centrality dependence***
- Measurements are qualitatively described by a large number of models developed for UPC and extended to account for the nuclear overlap



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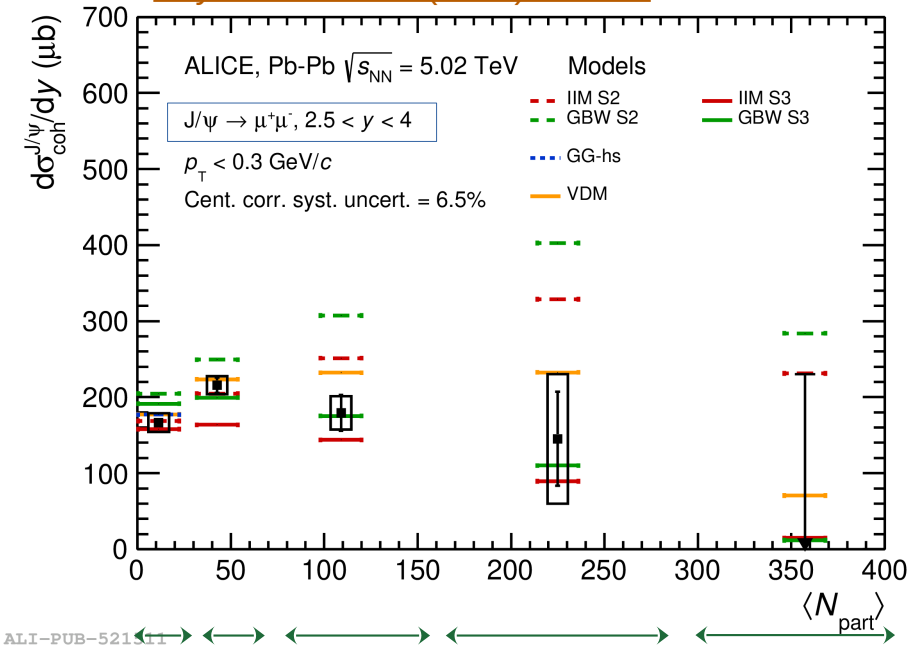
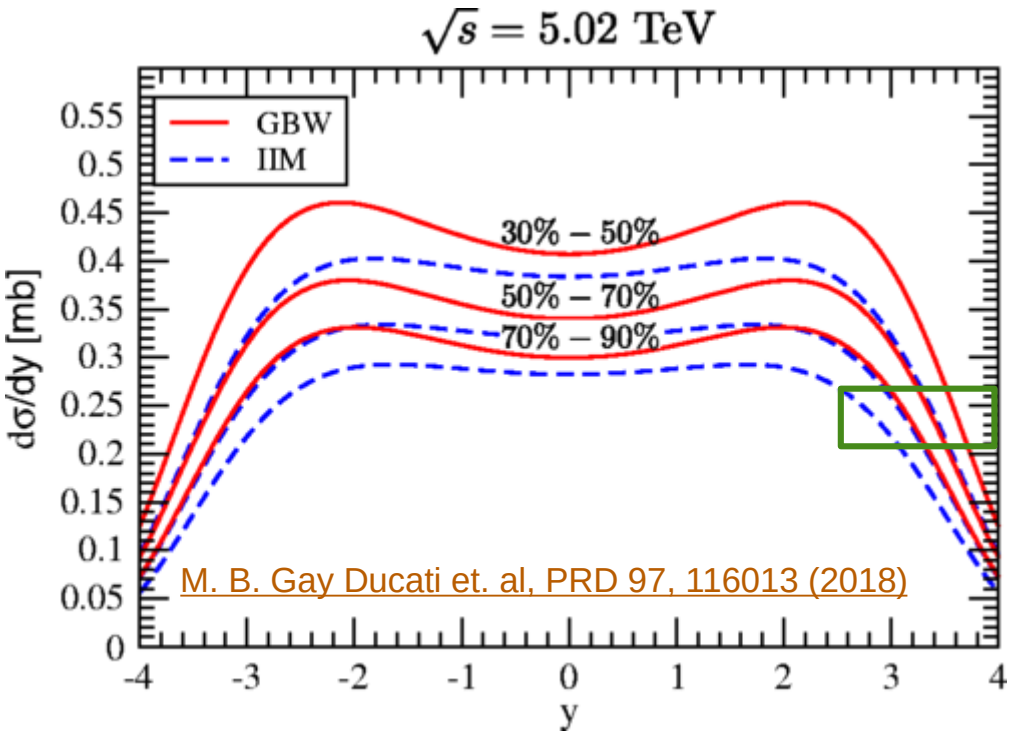


* The cross section is not normalized to the centrality interval width

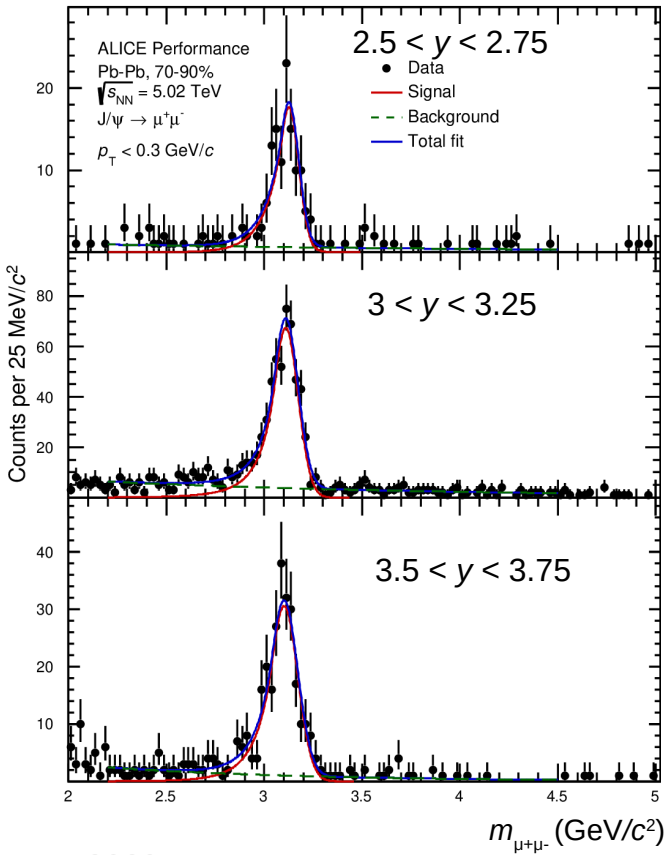
y-dependence in Pb–Pb collisions

- Models predict a strong *y*-dependence of the VM photoproduction cross section
- **Additional differential measurements are needed to better constrain models, as in UPC**



➔ **A new measurement is performed as a function of rapidity** in Pb–Pb collisions with nuclear overlap

State of art: raw J/ψ yield in rapidity intervals

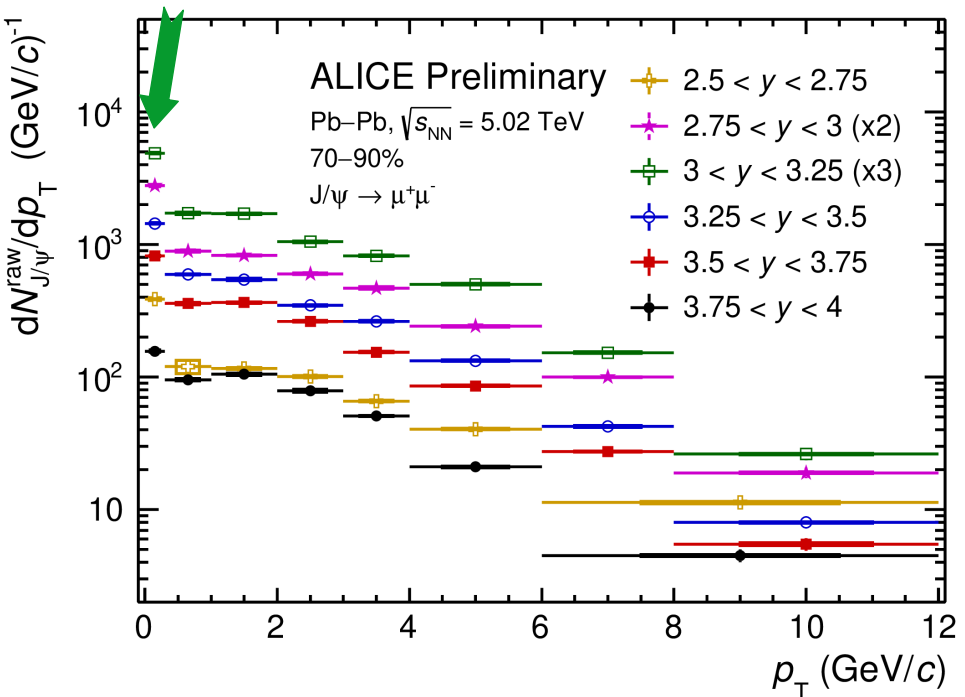


ALI-PERF-538924

J/ψ → μ⁺μ⁻ , 70–90%, 2.5 < *y* < 4, p_T < 0.3 GeV/*c*

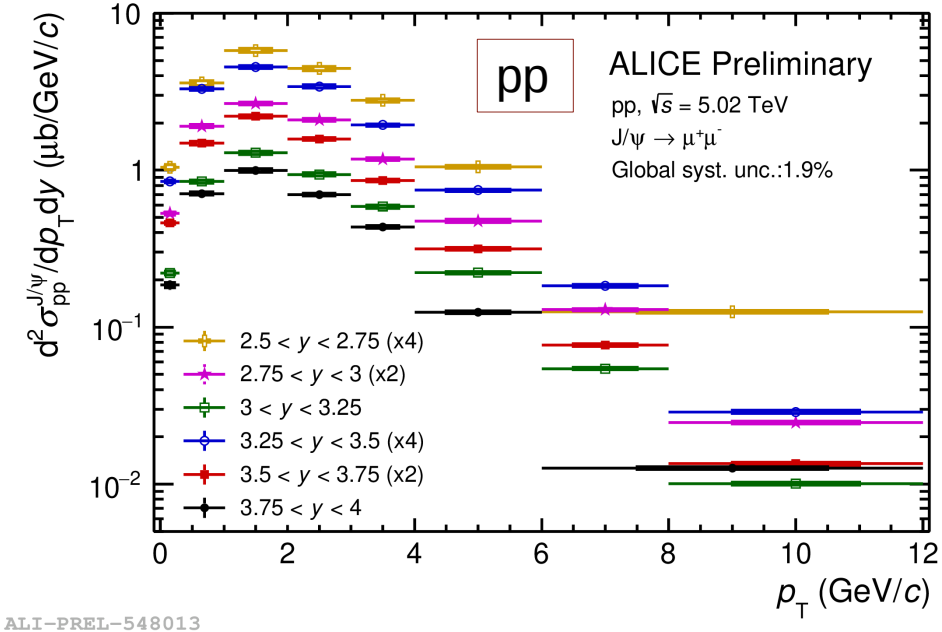
- J/ψ signal extraction from the **invariant-mass distribution** of the decay daughters
- **Raw yield excess is observed for p_T < 0.3 GeV/*c* for all *y-bins***

Raw = hadronic + photoproduction



ALI-PREL-548019

Modelization of hadronic J/ψ yield contribution for $p_T < 0.3$ GeV/c



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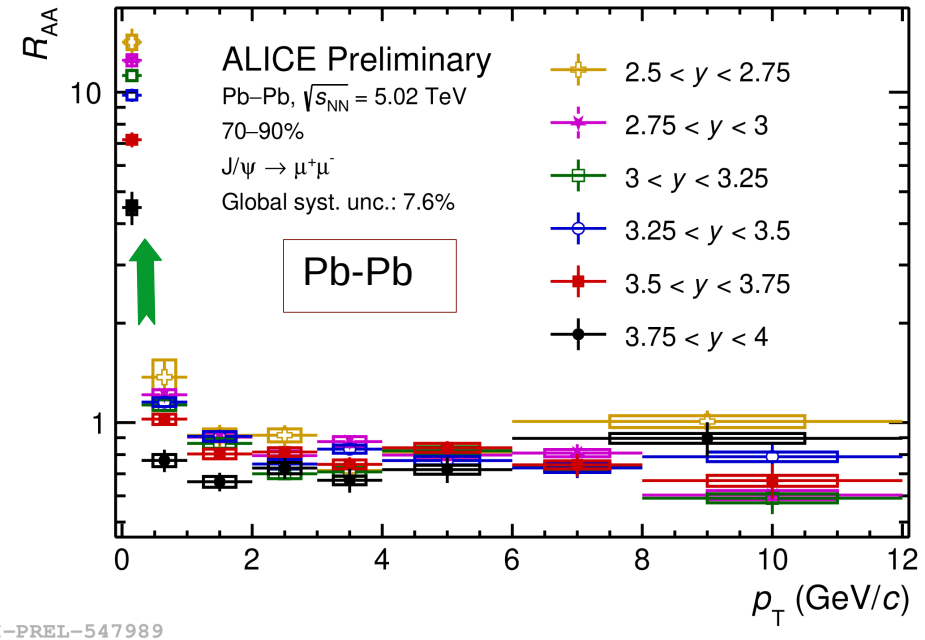
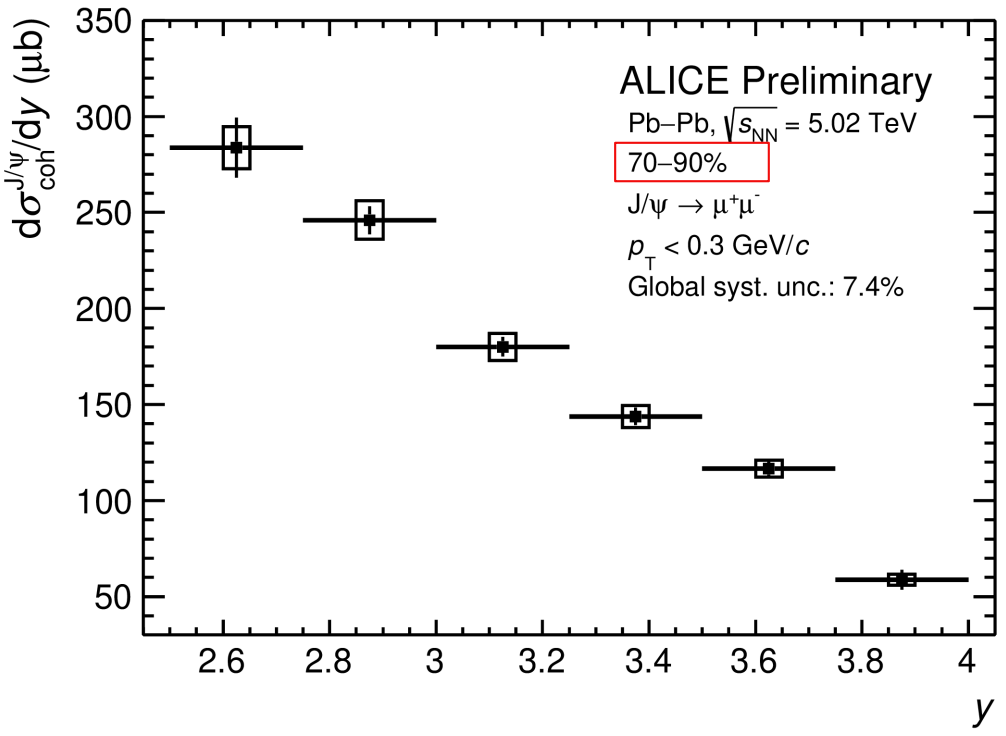


ALI-PREL-547989

- The R_{AA} largely increases for $p_T < 0.3$ GeV/c and it has a hierarchy in y, the most forward R_{AA} is the least enhanced
- The J/ψ cross section in pp collisions and the R_{AA} are used as inputs for modeling the expected hadronic J/ψ yield
- J/ψ excess yield = J/ψ raw yield – J/ψ hadronic yield
- The coherent J/ψ yield is obtained by correcting the excess yield for the fraction of incoherent J/ψ and the fraction of coherent ψ(2S)→J/ψ evaluated in UPC.

y-dependence of the coherent J/ψ photoproduction cross section

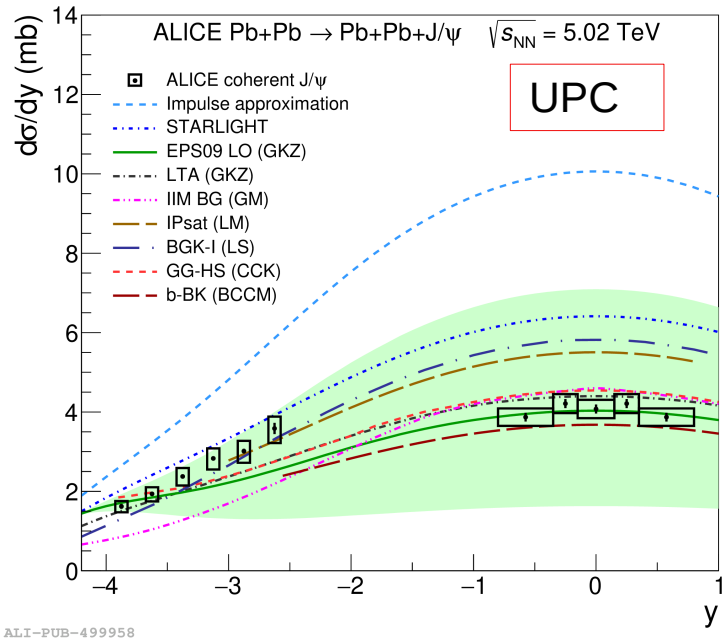
- A strong rapidity dependence is seen

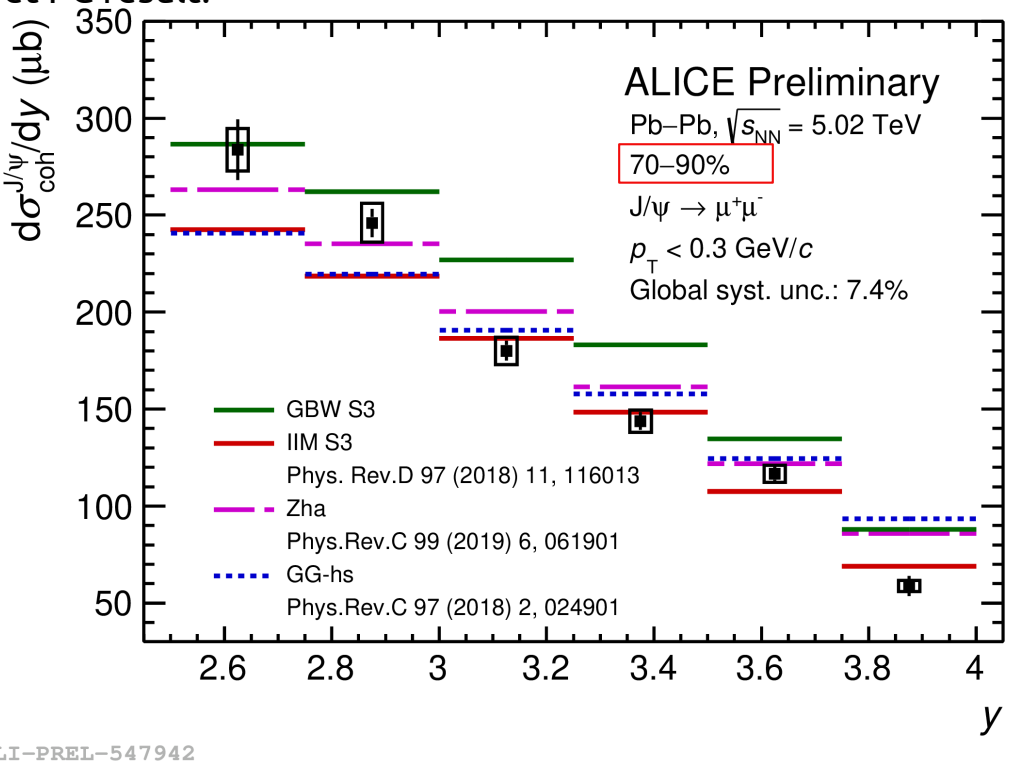


ALI-PREL-548022

y-dependence of the coherent J/ψ photoproduction cross section

- A strong rapidity dependence is seen
- Models initially developed for VM photoproduction in UPC and modified for PC can describe qualitatively the magnitude of the cross section, but fail at reproducing the *y*-trend, similarly to UPC.
- Need better understanding of the UPC result to interpret PC result.





y-dependence of the coherent J/ψ photoproduction cross section

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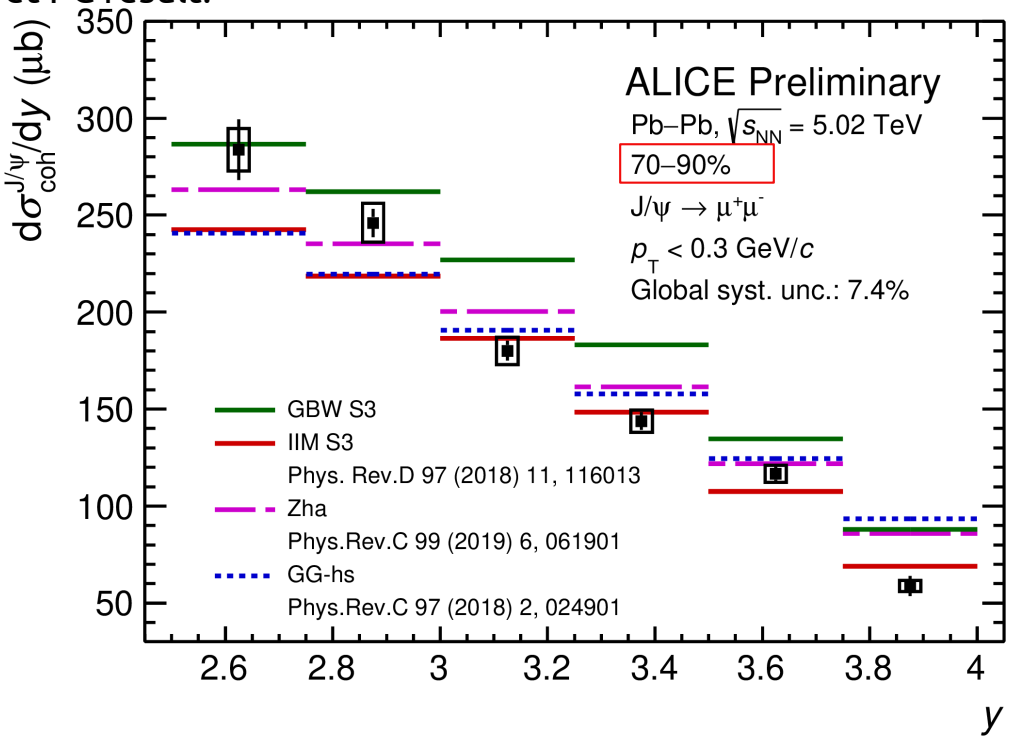
Considerations on the models:

- GG-hs: photon flux with constraints on impact parameter range
- Zha : viewing the VM photoproduction as a double-slit experiment at Fermi-scale, taking into account the nuclear overlap effects
- GBW S3, IIM S3: effective photon flux and photonuclear cross section considered w.r.t UPC calculations (see next slide)

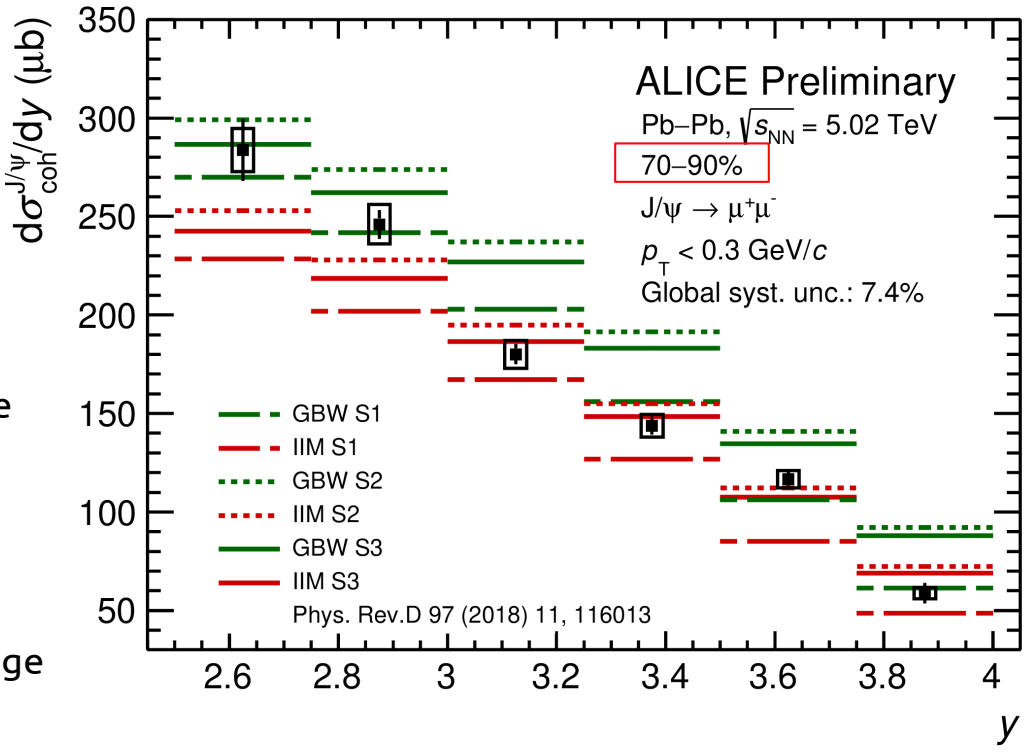


ALI-PREL-547942

y-dependence of the coherent J/ψ photoproduction cross section

GBW/IIM: extending UPC models to PCs considering the overlap region

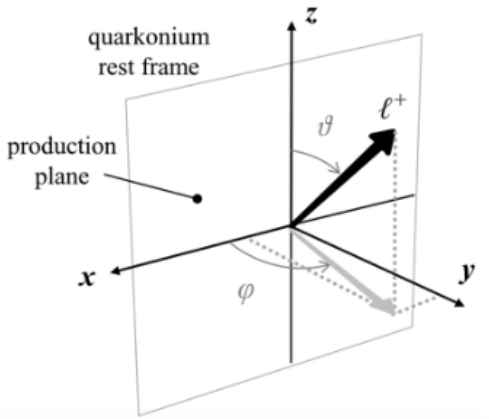
- GBW S1, IIM S1: no relevant modifications w.r.t the UPC calculations
- GBW S2, IIM S2: effective photon flux where only photons reaching the spectator region are considered
- GBW S3, IIM S3: S2 + modification of the photonuclear cross section (exclusion of the overlap region)



ALI-PREL-547985

- Any effect related to the nuclear overlap is expected to be small in the peripheral 70-90% centrality range
- Measurement in more central collisions is needed to constrain the models
- Understanding the nuclear overlap effect on the VM photoproduction cross section is still a theoretical challenge

The coherent photoproduced J/ψ polarization in Pb–Pb collisions



P. Faccioli et al. EPJC 69 (2010) 673

- *S*-channel helicity conservation suggests that the photon helicity is transferred to the produced vector meson, J/ψ.
- In helicity frame, J/ψ polarization is a measurement of its spin alignment with respect to the J/ψ flight direction in the lab frame.
- A transverse polarization is observed for coherently photoproduced J/ψ in UPC.

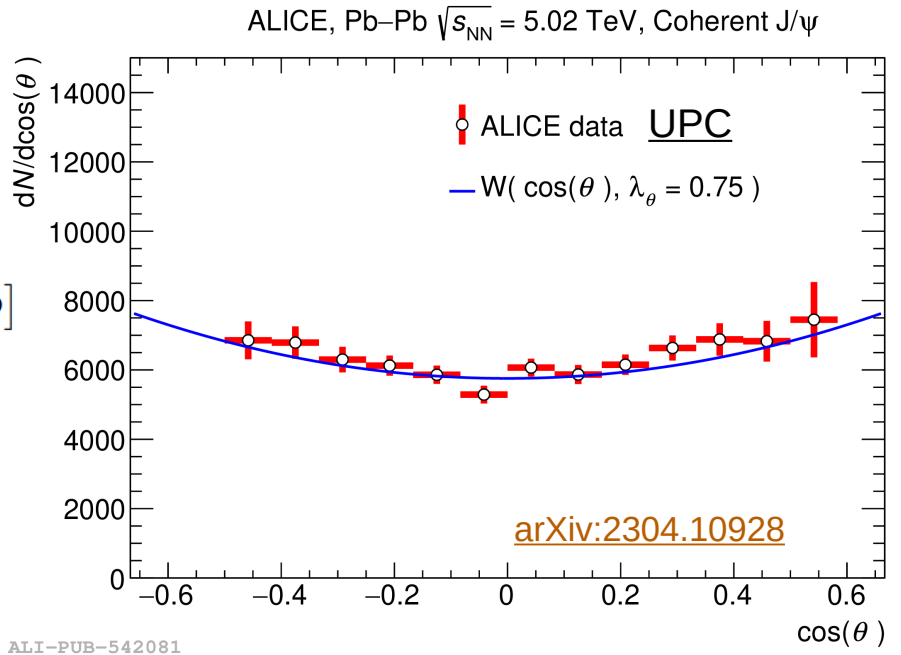
J/ψ polarization is studied via decay to dimuons, the corresponding **dimuon angular distribution** is:

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\left[1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi\right]$$

$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (0,0,0) \Rightarrow$ No polarization

$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (+1,0,0) \Rightarrow$ Transverse polarization

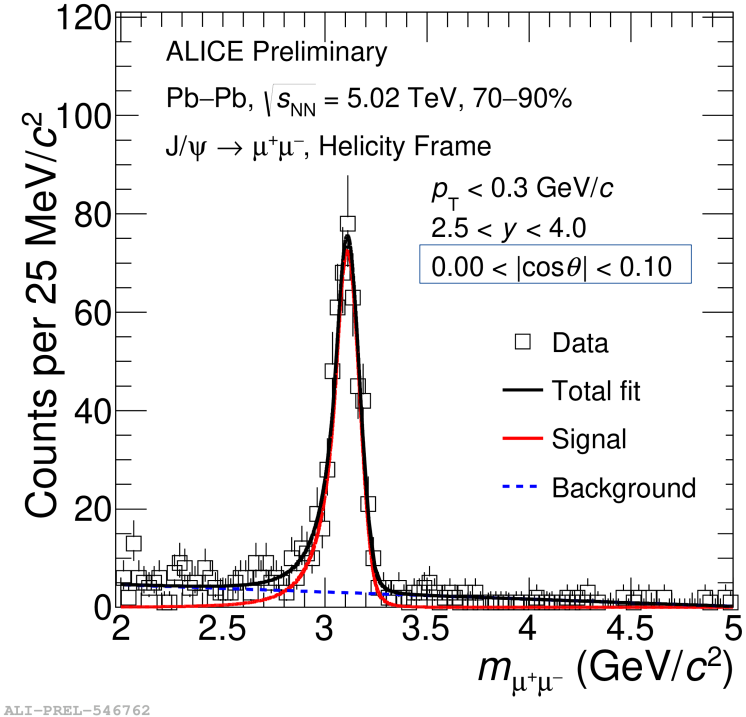
$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (-1,0,0) \Rightarrow$ Longitudinal polarization

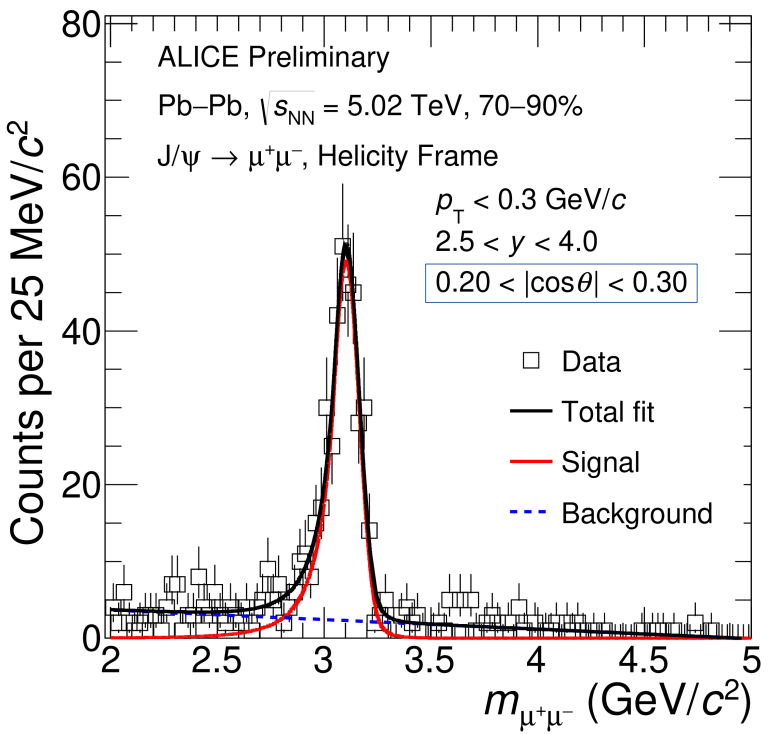


J/ψ signal extraction in angular intervals

$J/\psi \rightarrow \mu^+\mu^-$, 70–90%, $2.5 < y < 4$, $p_T < 0.3$ GeV/c

The J/ψ signal is extracted in six $\cos\theta$ intervals using the dimuon invariant mass distribution

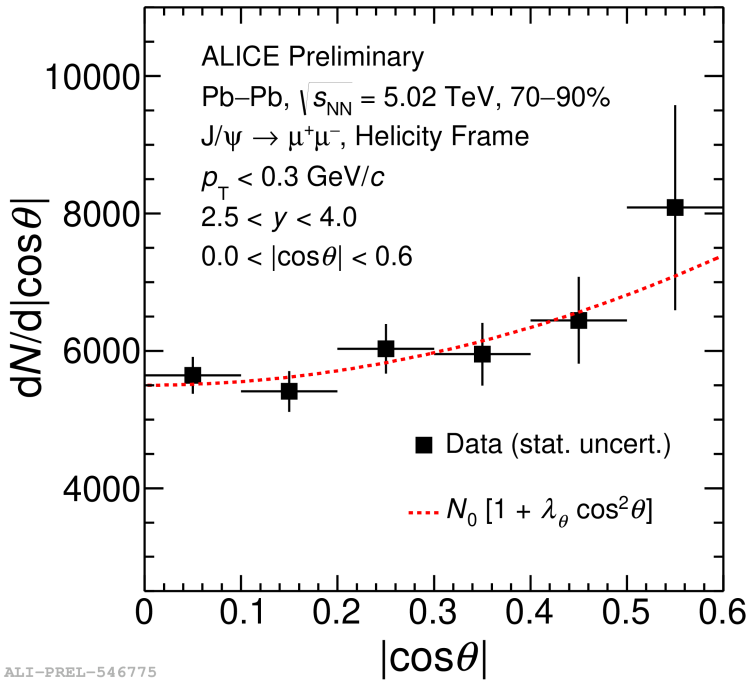




Inclusive J/ψ polarization in Pb–Pb collisions

J/ψ → $\mu^+\mu^-$, 70–90%, 2.5 < y < 4, p_T < 0.3 GeV/c

- A hint for transverse polarization from cosθ angular distribution



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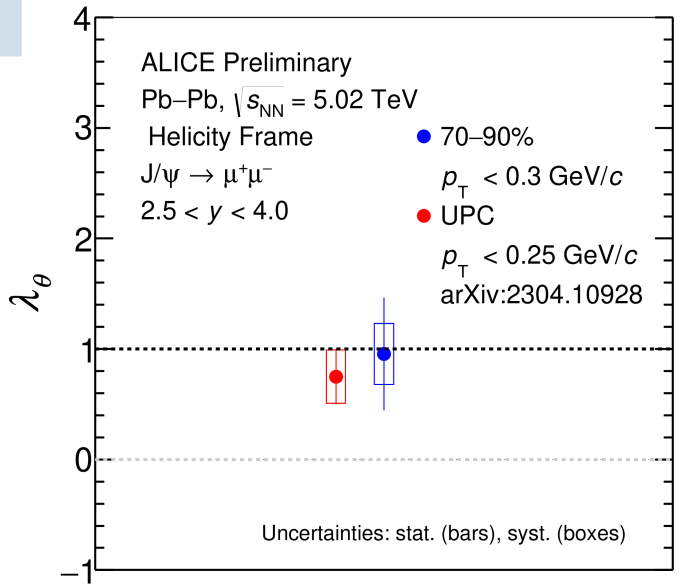


ALI-PREL-546778

- The λ_θ parameter is consistent with the UPC measurement for coherently photoproduced J/ψ within uncertainties
  - ➔ As expected in this kinematic region, where J/ψ coherent photoproduction dominates over the J/ψ hadronic production [Phys. Lett. B 846 (2023) 137467]

Summary

- **First *y*-differential measurement of coherent J/ψ photoproduction cross section** in peripheral Pb–Pb collisions (PC) with nuclear overlap at $\sqrt{s_{NN}}$ = 5.02 TeV for p_T < 0.3 GeV/*c*
  - Shows a strong *y*-dependence similar to that observed in Ultraperipheral collisions (UPC).
  - Many models that includes or not the nuclear overlap effect can describe qualitatively the cross section magnitude, but fail in describing the y-trend, similarly to the UPC .
  - Need better understanding of the UPC result and more central measurement to constrain the models.
  - **First inclusive J/ψ polarization measurement for p_T < 0.3 GeV/*c*** in peripheral Pb–Pb collisions with nuclear overlap at $\sqrt{s_{NN}}$ = 5.02 TeV
    - In agreement with the UPC transverse polarization measurement and consistent with a major contribution from a photoproduction process in the region of study.

Outlook

- **The coherent J/ψ photoproduction cross section measurement can be exploited to extract the photonuclear cross sections in two Bjorken-*x* regions** [J.G. Contreras, Phys. Rev. C 96, 015203 (2017)]

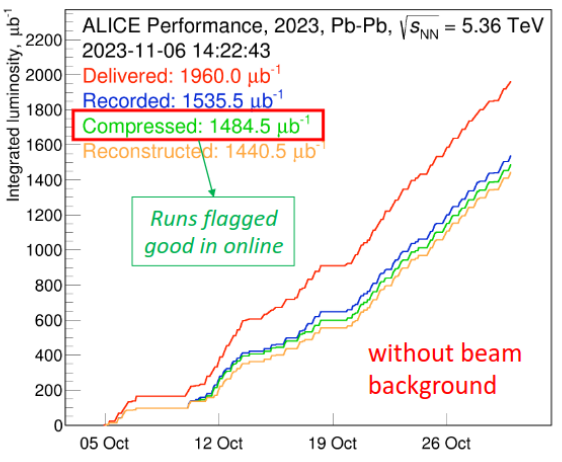
- **ALICE in LHC Run 3 will provide a large Pb–Pb data sample (1.5 nb^{-1} in 2023)**
  - Will permit to study J/ψ photoproduction in the most central collisions, to better constrain models (especially the role of spectator nucleons in the coherence condition)
  - Look at heavier vector mesons could become also possible to pin down possible QGP effects on the measured probes.

Backup

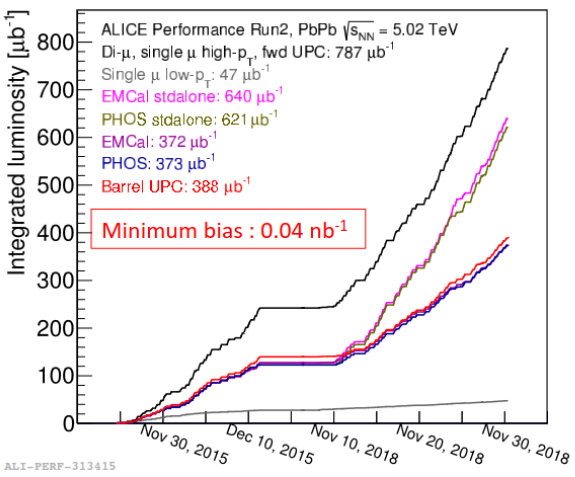
Luminosity in Run2 and Run 3

- **LHC Run 2 (2015-2018) @ $\sqrt{s_{NN}}$ = 5.02 TeV,**
  L_{int}~ (700 μb^{-1} of Pb–Pb, 1.2 pb^{-1} of pp) data collected with the dimuon trigger at $2.5 < y < 4$
- **LHC Run 3 (2022-2025) @ $\sqrt{s_{NN}}$ = 5.36 TeV**
  - **L_{int} =1.5 nb^{-1} of Pb-Pb data (2023)**
  - Goal of Run 3 (5.3 nb^{-1} of Pb-Pb data)

➢ **2023: 1.96 nb^{-1} delivered**

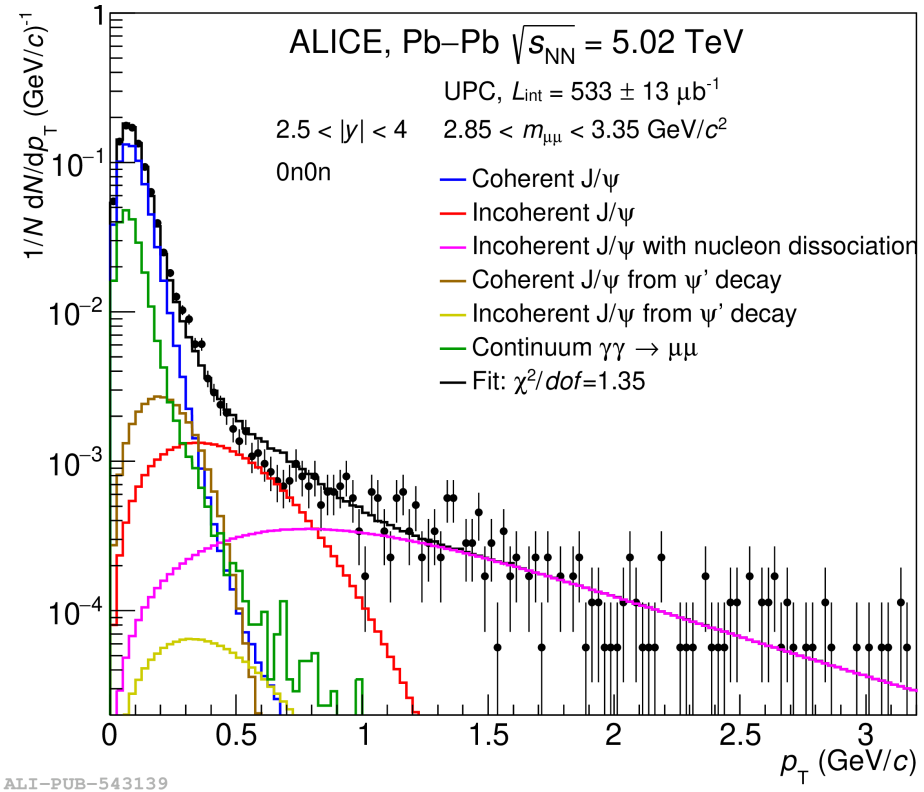


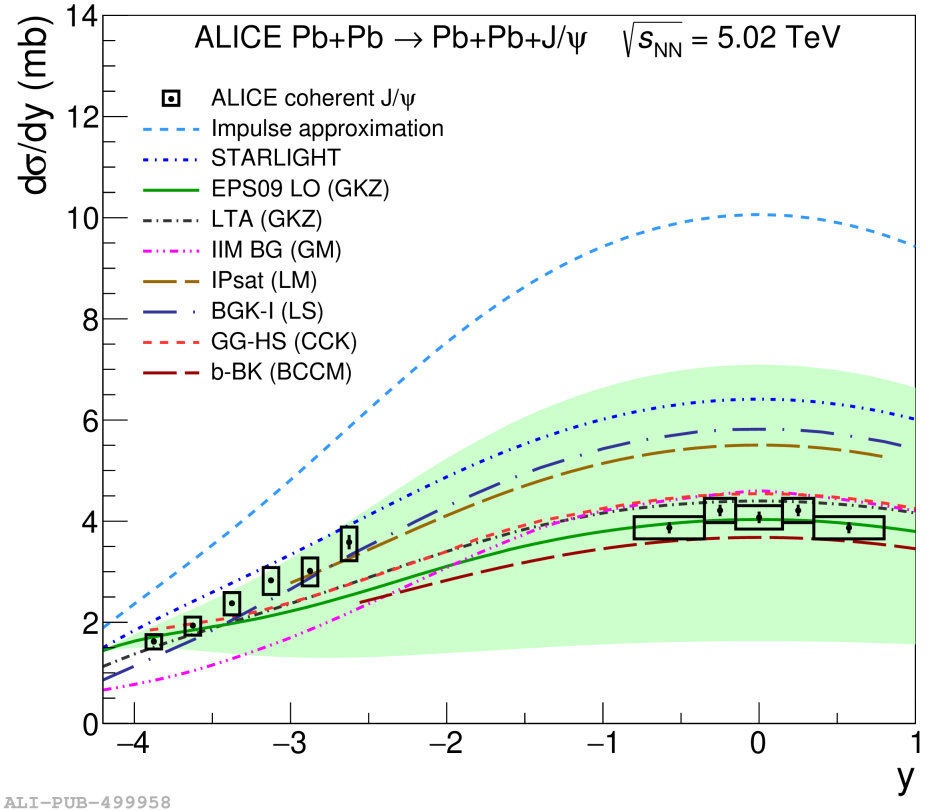
➢ **Run 1+2 : 1.5 nb^{-1} delivered**



A. Ferrero, R. Munzer, M. Danisch, ALICE RC report, RC report, March 2023.

Photoproduction in UPC





Impulse approximation neglect nuclear shadowing, while data is consistent with models that consider the nuclear shadowing

Photon-emitter ambiguity

- Each colliding nucleus could serve as a photon emitter, the other acts as a target (+/- y)
- Contribution from low/ high x_g $x_B = (m_{J/\psi}/\sqrt{s_{\mathrm{NN}}}) \times \exp(\pm y)$
- Proposed solution by [J. G. Contreras, PRC 96, 015203 (2017)] :
  - use PC measurement with the previous UPC measurement to disentangle the contribution from the low and high energy photon-nucleus interaction.
- Caveat: this suggestion considers the photon-nucleus cross sections in both PC and UPC to be the same.