J/Ψ photoproduction and polarization in peripheral Pb–Pb collisions with ALICE

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Photon-induced processes in heavy-ion collisions

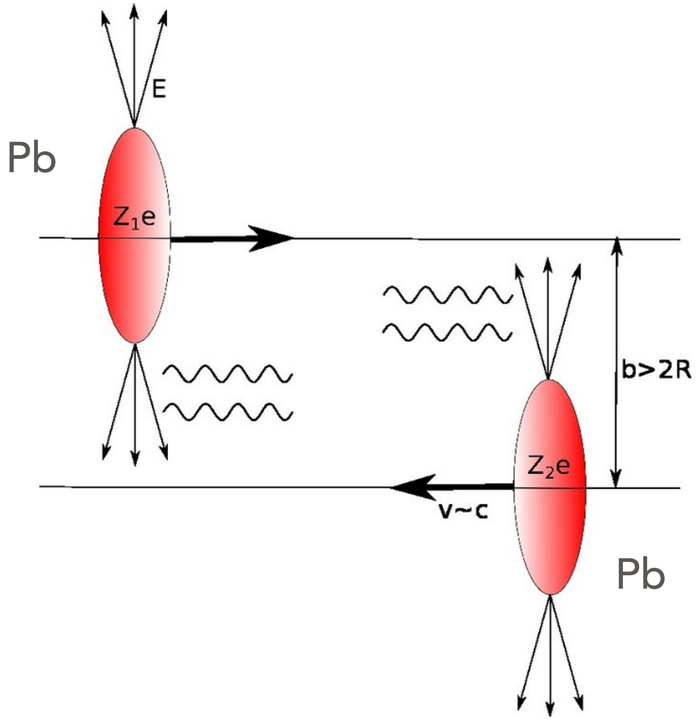
Large Hadron Collider (LHC) acts as a photon collider

Relativistic heavy-ions are strong Electromagnetic(EM) field emitters: EM fields ~ photon flux

In heavy-ion collisions: $|B| \sim 10^{16}$ T, Earth: $|B| \sim 10^{-5}$ T

V. Skokov et al, Int. J. Mod. Phys.A 24 (2009), 5925-5932

Ultraperipheral collisions (UPC) : b > 2R



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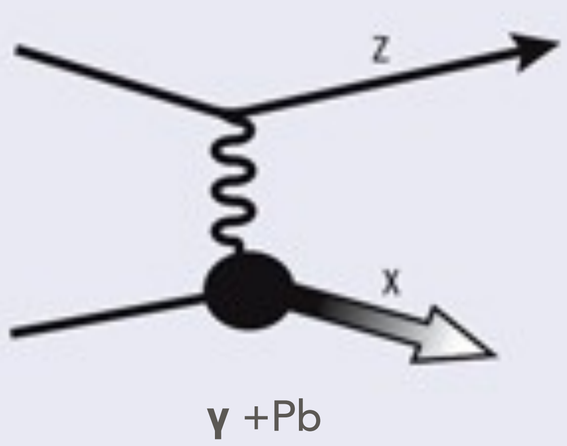
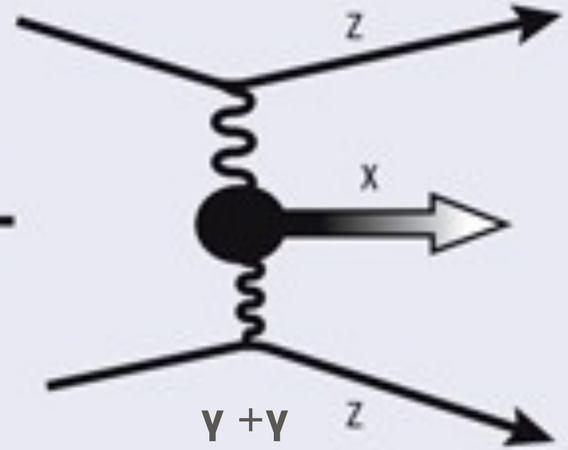
Types of interactions



Flux of photons ~ Z^2

+



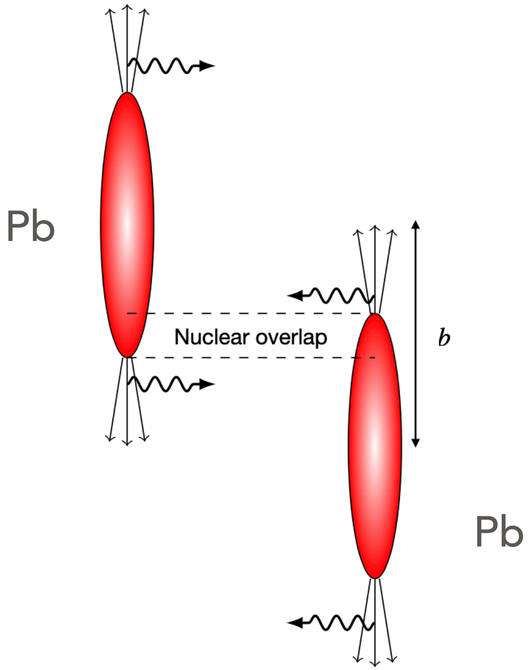
Flux of photons on photons ~ Z^4

❑ **Electromagnetic interactions are dominant**

Photon-induced processes in heavy-ion collisions

Peripheral collisions (PC): large b, b ≤ 2R

Central collisions: small b, b << 2R



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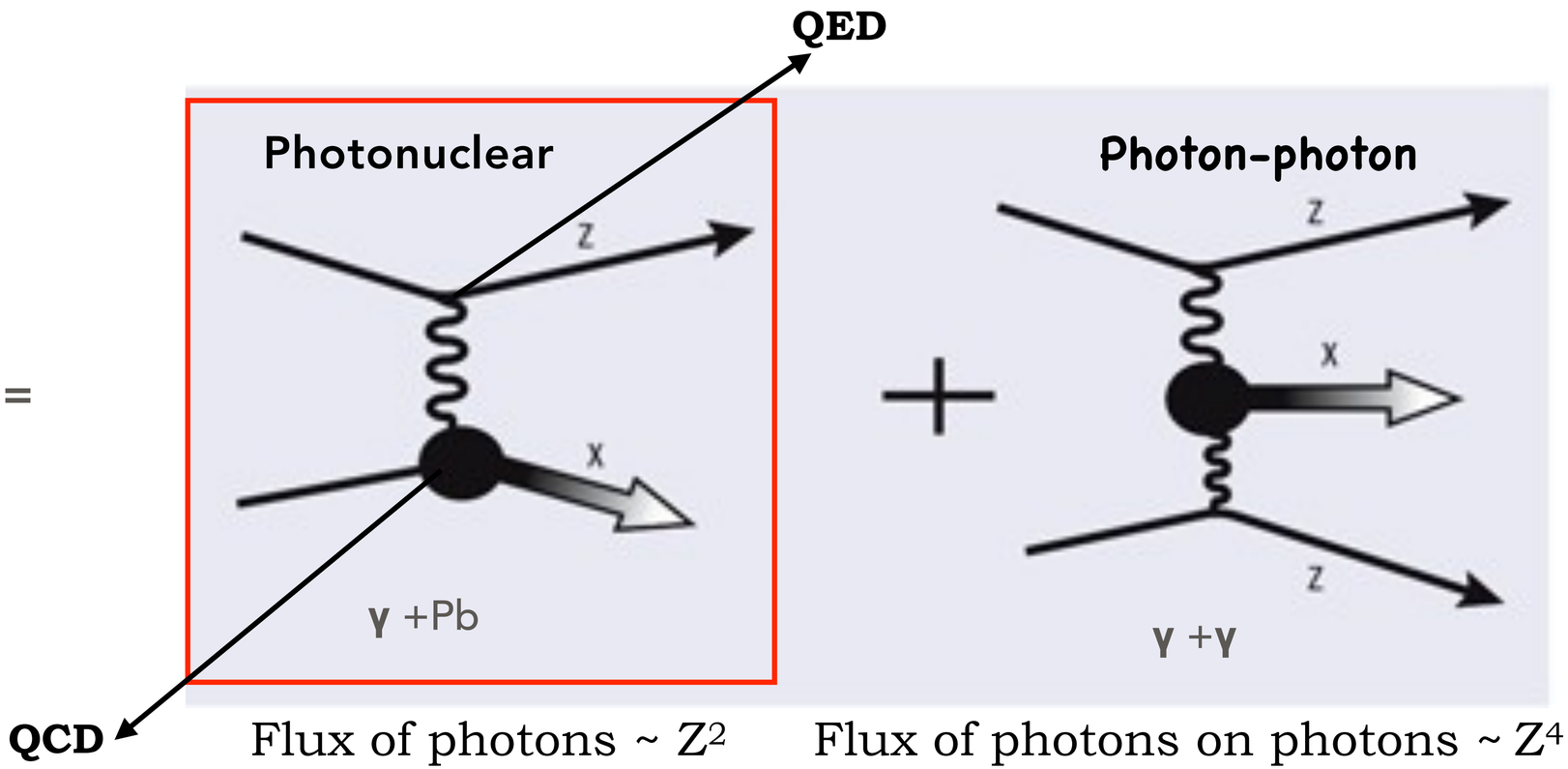
Types of interactions



Flux of photons ~ Z^2

Flux of photons on photons ~ Z^4

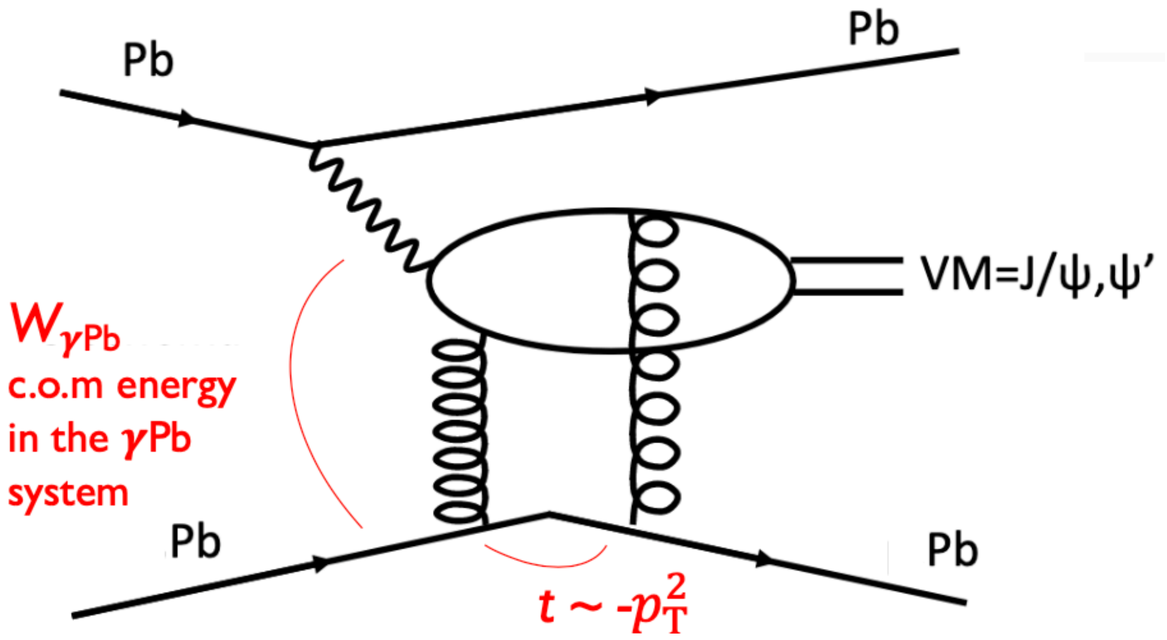
- **Electromagnetic interactions are also observed** in AA events with nuclear overlap (i.e., in presence of hadronic interaction)
- UPC and AA collisions with nuclear overlap are important tools to study **photonuclear interactions**

Vector meson photoproduction

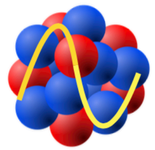
Vector meson (VM) : spin =1, $J^P = 1^-$, i.e: J/Ψ, Ψ(2S)

C. A. Bertulani et al, Ann.Rev.Nucl.Part.Sci.55:271-310,2005

LO schema

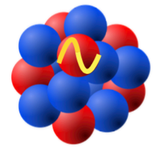


- Clean experimental signatures
- Coherent photoproduction of VM
  - Photon (γ) couples coherently to all nucleons
  - $\langle p_T \rangle_{J/\Psi} \sim$ **60 MeV/*c***
  - Usually no breaking of target



Coherent process

- Incoherent photoproduction of VM
  - Photon (γ) couples to single nucleon
  - $\langle p_T \rangle_{J/\Psi} \sim$ **500 MeV/c**
  - Usually target nucleus breaks



Incoherent process

- Production of a **very low-p_T vector meson (for coherent process)**
- Access to **gluon distributions in nuclei at low Bjorken-*x*,** constraints to initial stages of heavy-ion collisions, 10^{-5} < Bjorken-x < 10^{-2} at LHC energies

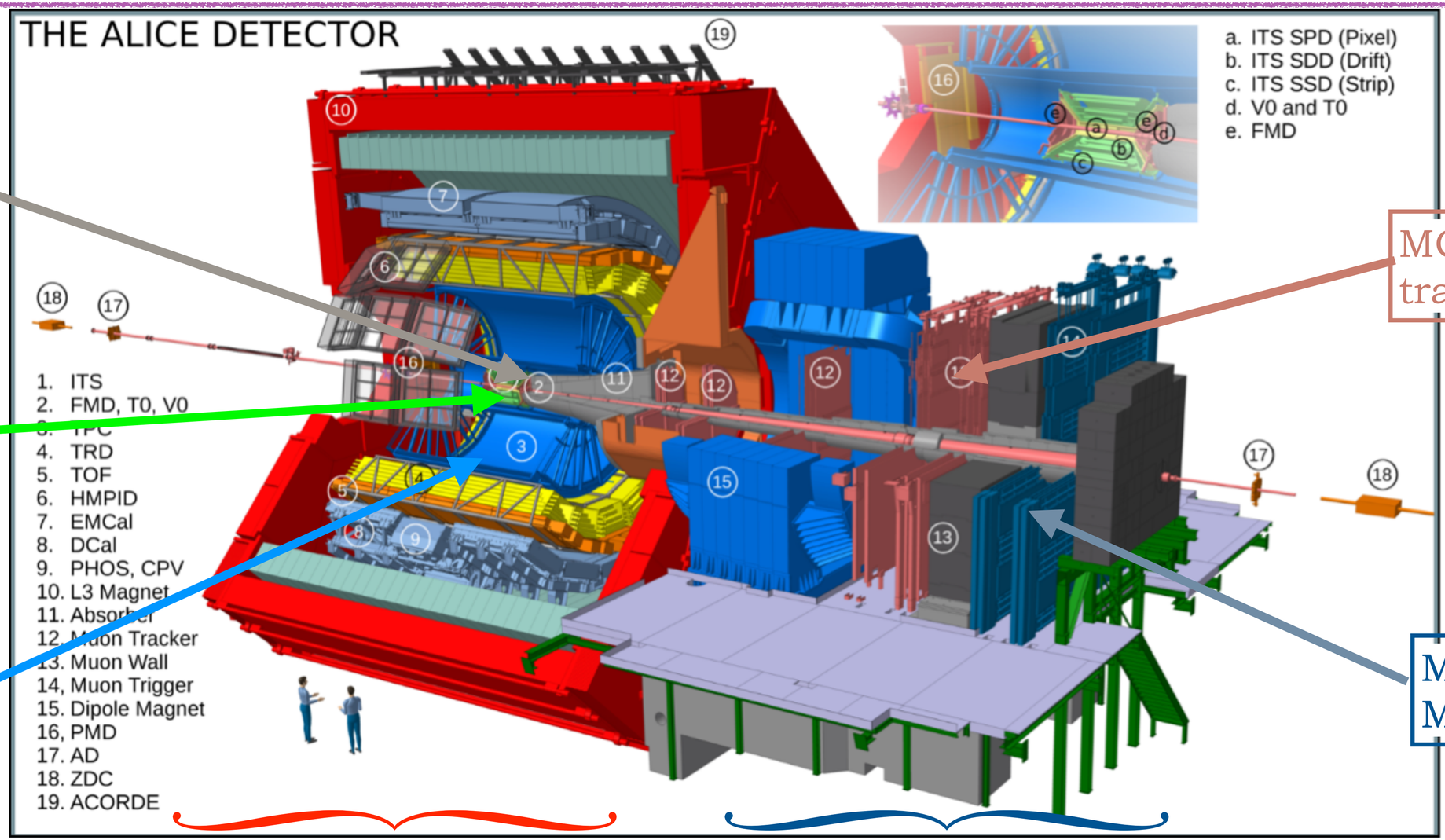
$$x = \frac{m_{J/\psi}}{\sqrt{s_{NN}}} \times \exp(\pm y)$$

ALICE Apparatus in Run 2 (2015-2018)

V0 : triggering, centrality determination, background rejection

ITS :Tracking, vertex reconstruction

TPC : Tracking, Particle identification (PID)



MCH: Muon tracking

MTR: Muon trigger

Central barrel: $|y| < 0.9$
$J/\Psi \longrightarrow e^+e^-$

Muon spectrometer : $2.5 < y < 4.0$
$J/\Psi \longrightarrow \mu^+\mu^-$

VM photoproduction in collisions with nuclear overlap

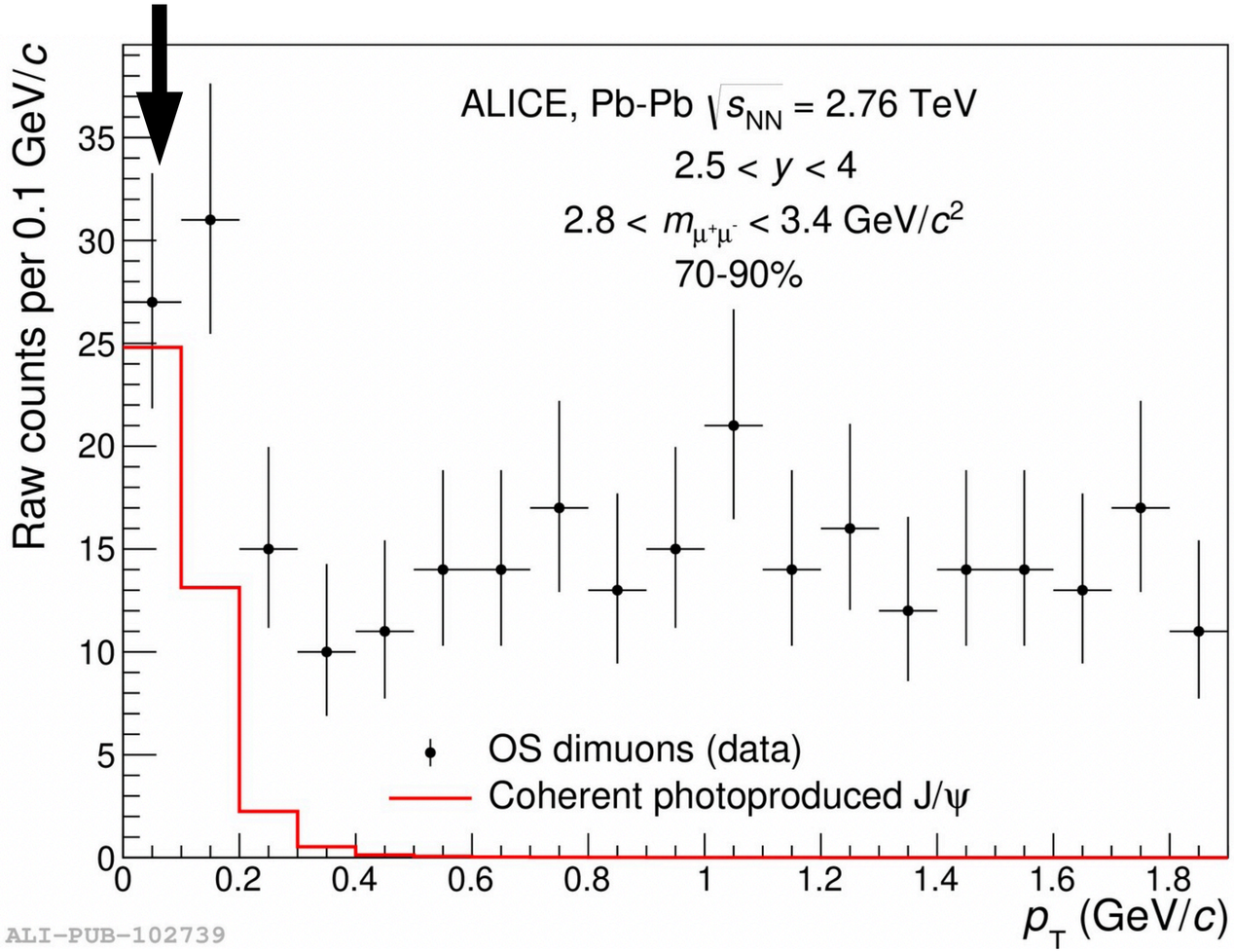
- Very low p_T J/ψ **excess** for peripheral Pb–Pb collisions (PC) first measured in ALICE at $\sqrt{s_{NN}}$ = 2.76 TeV and forward y [1],[2]

➡Significance: 5.4σ (70-90%), 3.4σ (50-70%), 1.4σ (30-50%)

➡ Interpreted as **coherent photoproduction**

- Similar J/ψ excess yield measurement was confirmed by LHCb Collaboration [3]

- Also similar observation was seen at lower energies by STAR Collaboration [4]



[1] ALICE Coll., Phys. Rev. Lett 116, 222301(2016)
[2] STARlight MC, Comp. Phys. Comm. 212 (2017) 258
[3] LHCb Coll., Phys.Rev. C 105 (2022) L03201
[4] STAR Coll., Phys.Rev.Lett 116, 222301(2016)

VM photoproduction in collisions with nuclear overlap

Associated with a dramatic increase of the R_{AA},

$$R_{AA}(p_T) = \frac{Y^{Pb-Pb}_{J/\psi}}{< T_{AA} > \sigma^{pp}_{J/\psi}}$$

$Y^{Pb\text{-}Pb}$ = yield of J/ψ in Pb–Pb collisions

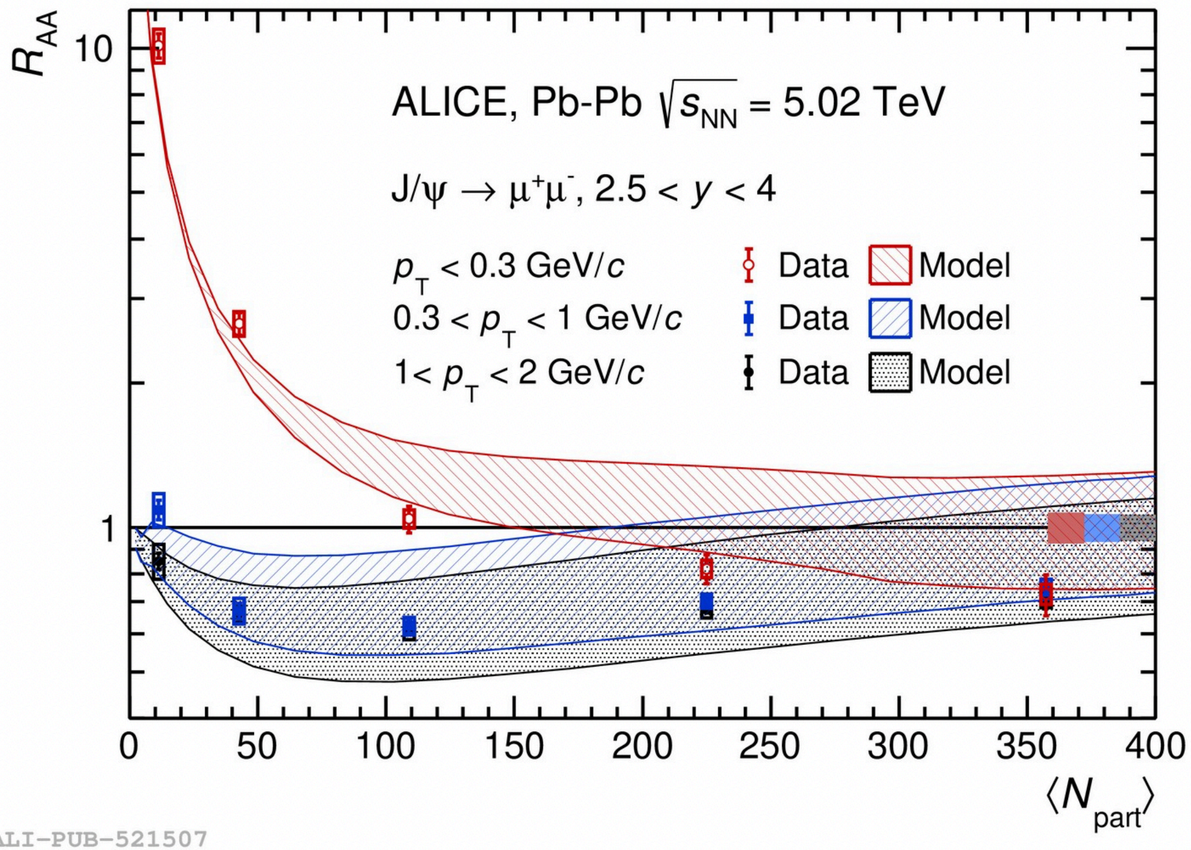
$<T_{AA}>$ = nuclear thickness function

σ^{pp} = J/ψ cross section in pp collisions

- **Enhancement at very low p_T**, R_{AA} reaches 10 ! [1]
- Agreement with model including a dominant **coherent photoproduction mechanism** at low p_T in most peripheral collisions [2]

➡ Interpreted as **coherent photoproduction**

Model : coherent photoproduction + hadroproduction with effects of QGP [2]



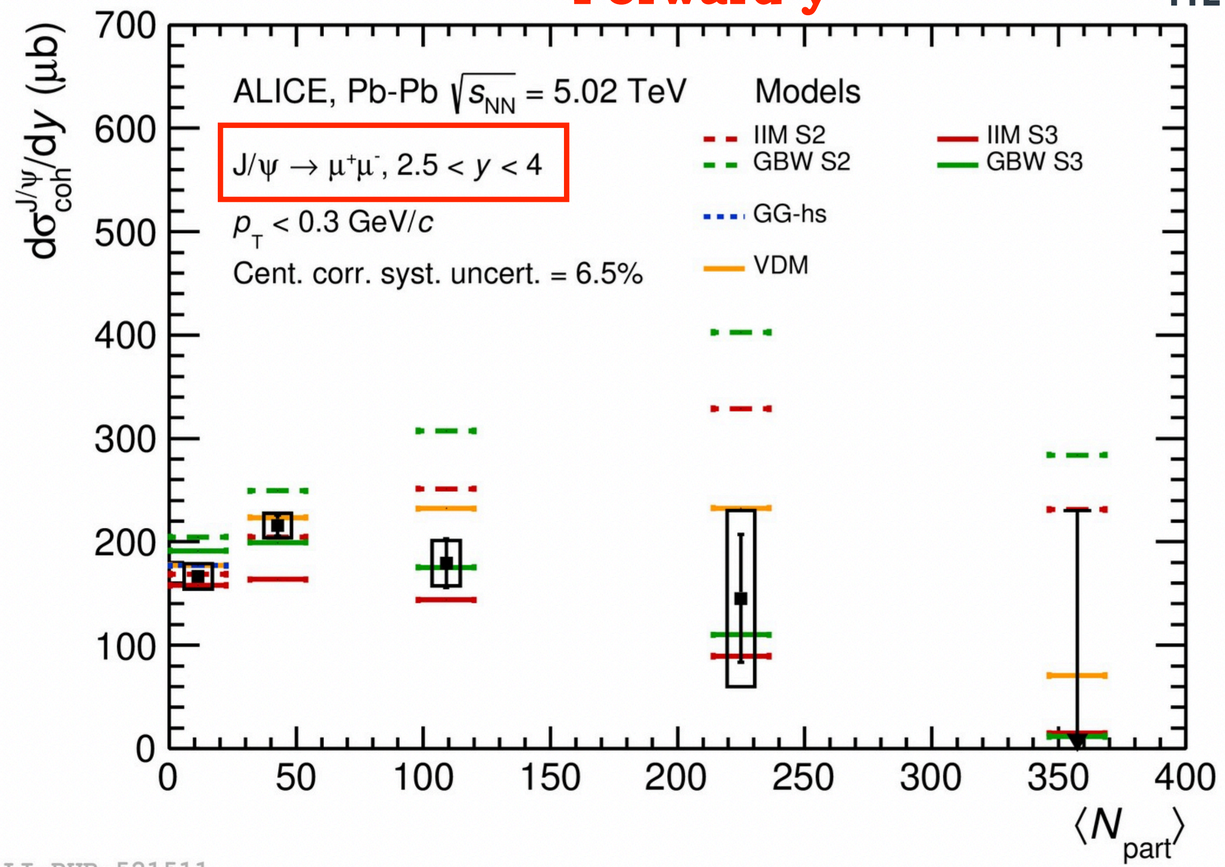
[1] ALICE Coll., Phys. Lett. B 846, 137467 (2023)

[2] Model: W. Shi et al., Phys. Lett. B 777, 399-405 (2018)

Coherent J/ψ photoproduction: centrality dependence

- **No centrality dependence** of the coherent J/ψ photoproduction cross section within uncertainties [1]

Forward-y



ALI-PUB-521511

70–90% 50–70% 30–50% 10–30% 0-10%

Caveat: the cross section is not normalized to the centrality interval width

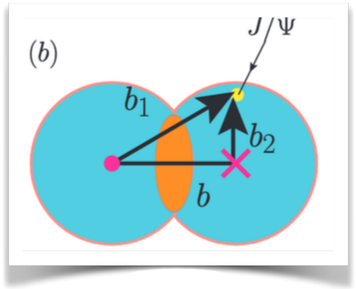
[1] ALICE Coll., Phys. Lett. B 846, 137467 (2023)

Coherent J/ψ photoproduction: centrality dependence

GG-hs : energy-dependent hot-spot model [1]
— γ flux constraints on b range

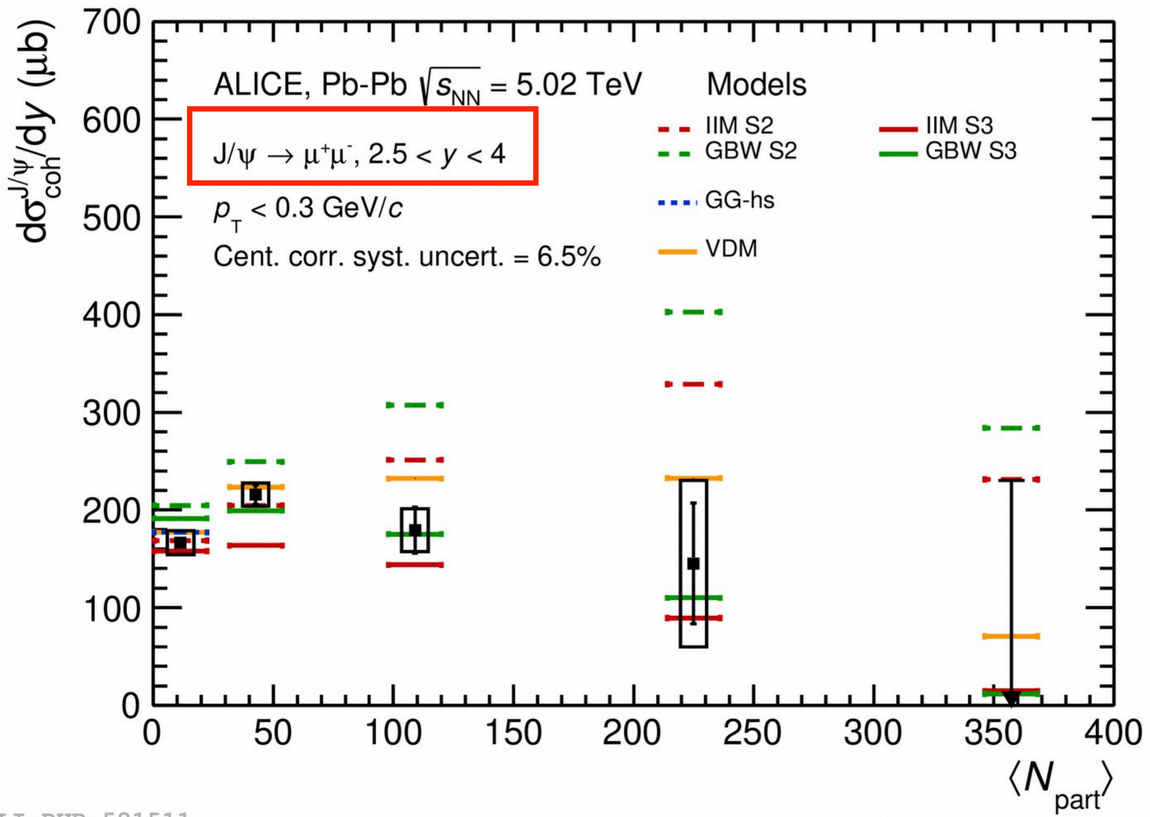
VDM : Vector dominance model [2]
— only γ flux reaching the spectator region [fixed area]

GBW/IIM : dipole models [3]
— S2: only γ flux reaching the spectator region
[b-dependent area] + unmodified $\sigma_{\gamma Pb}$
— S3: S2 + modified $\sigma_{\gamma Pb}$ [exclusion of overlap region]



[1] J. Cepila et al., Phys. Rev. C 97, 024901 (2018)
[2] M. Klusek-Gawenda et al., Phys.Rev.C 93, 044912 (2016)
[3] M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)

Forward-*y*

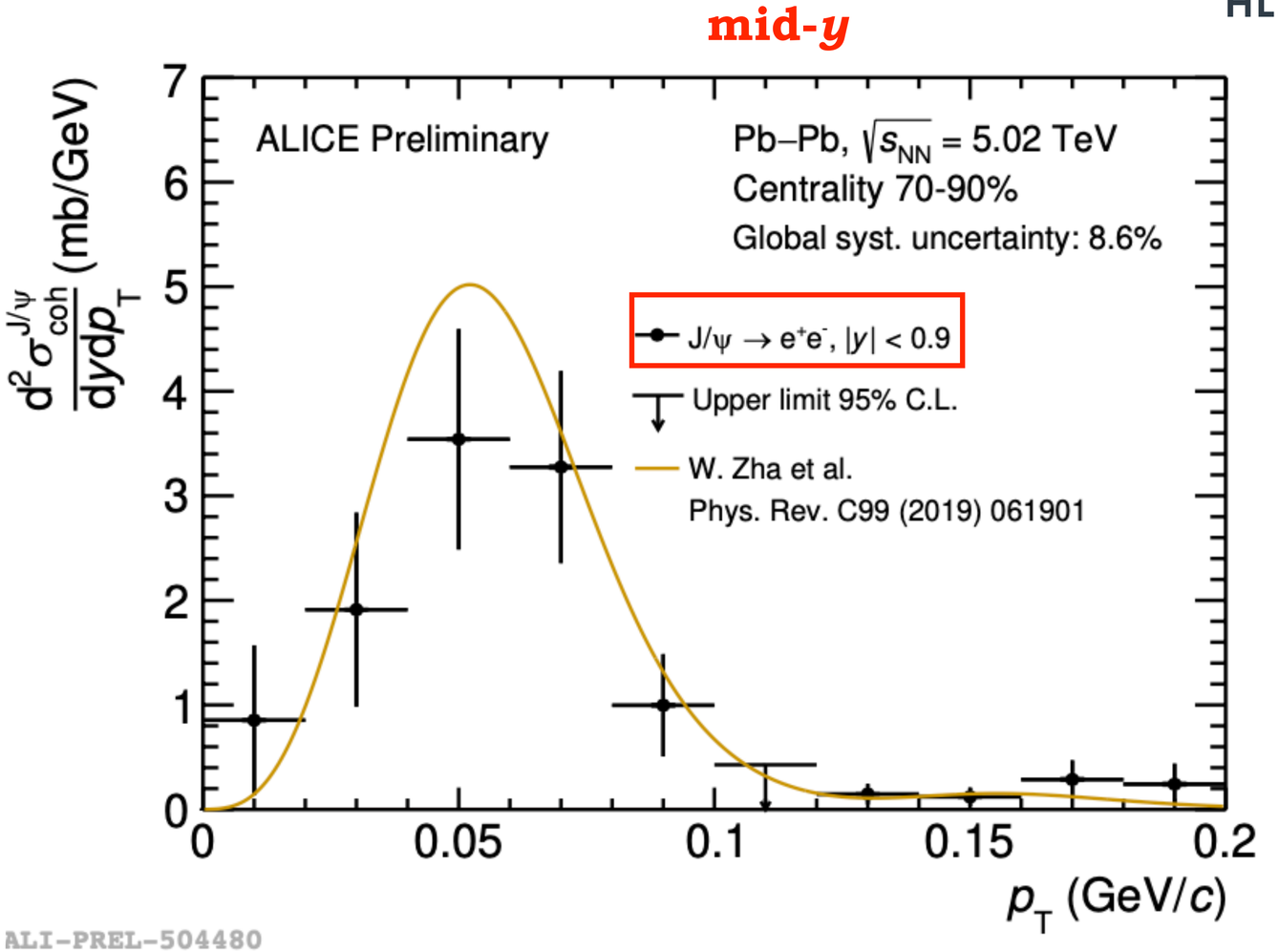


70–90% 50–70% 30–50% 10–30% 0-10%

Models with either **a modification of the γ flux (VDM) or both γ flux and $\sigma_{\gamma Pb}$** (IIM/GBW) can describe the order of magnitude of the cross section in semicentral events

Coherent J/ψ photoproduction: p_T and centrality dependence

- Very low p_T J/ψ **excess** for peripheral Pb–Pb collisions (PC) measured in ALICE at $\sqrt{s_{NN}}$ = 5.02 TeV and mid y
- **p_T shape reproduced by model** including modified γ flux and $\sigma_{\gamma Pb}$ to account for the overlap [1]
- **Model**: veiwing the VM photoproduction as a double-slit experiment at Fermi-scale in heavy-ion collisions [1]



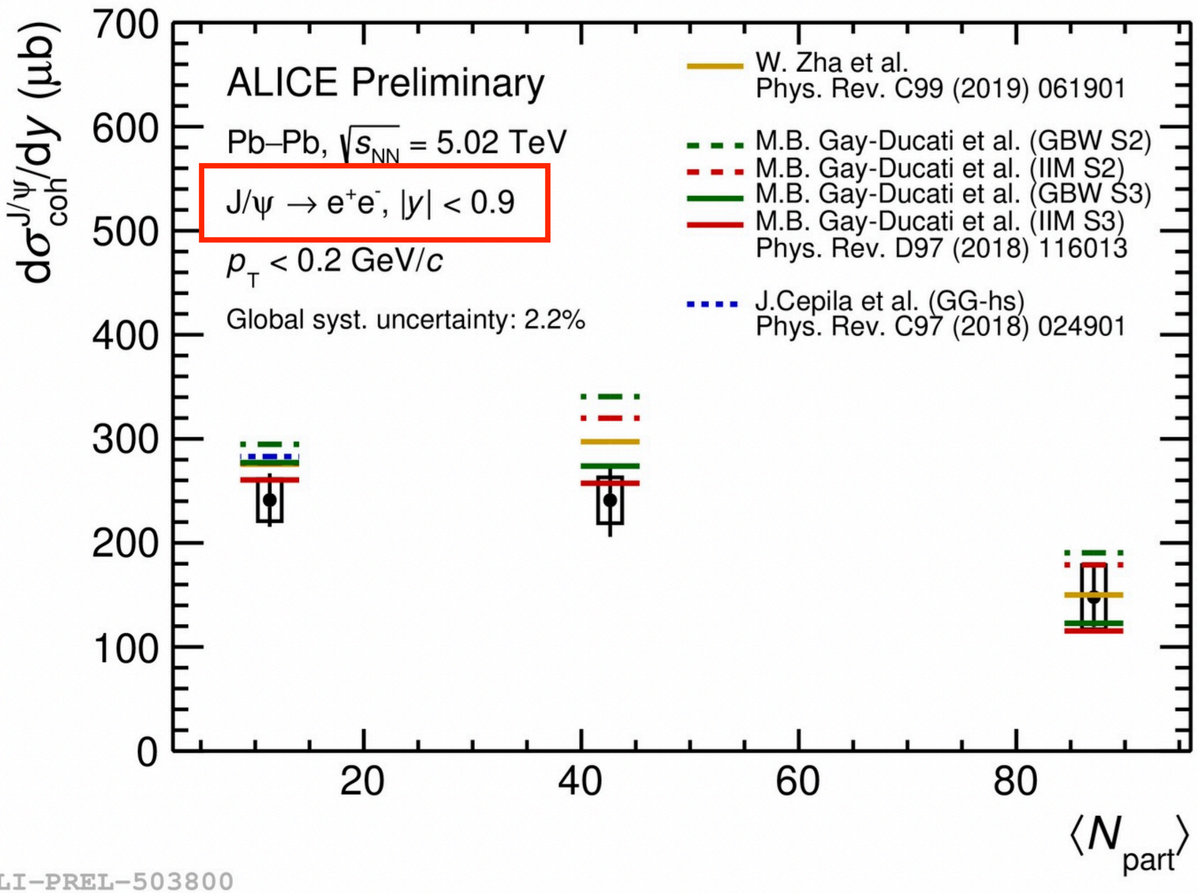
[1] W. Zha et al., Phys. Rev. C 99, 061901(2019)

Coherent J/ψ photoproduction: p_T and centrality dependence

- **No centrality dependence** of the coherent J/ψ photoproduction cross section within uncertainties

- Same models reproduce **the order of magnitude of the cross section at mid and forward rapidity**

mid-y



Caveat: the cross section is not normalized to the centrality interval width

[1] M. Klusek-Gawenda et al., Phys.Rev.C 93, 044912 (2016)

[2] M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)

[3] J. Cepila et al., Phys. Rev. C 97, 024901 (2018)

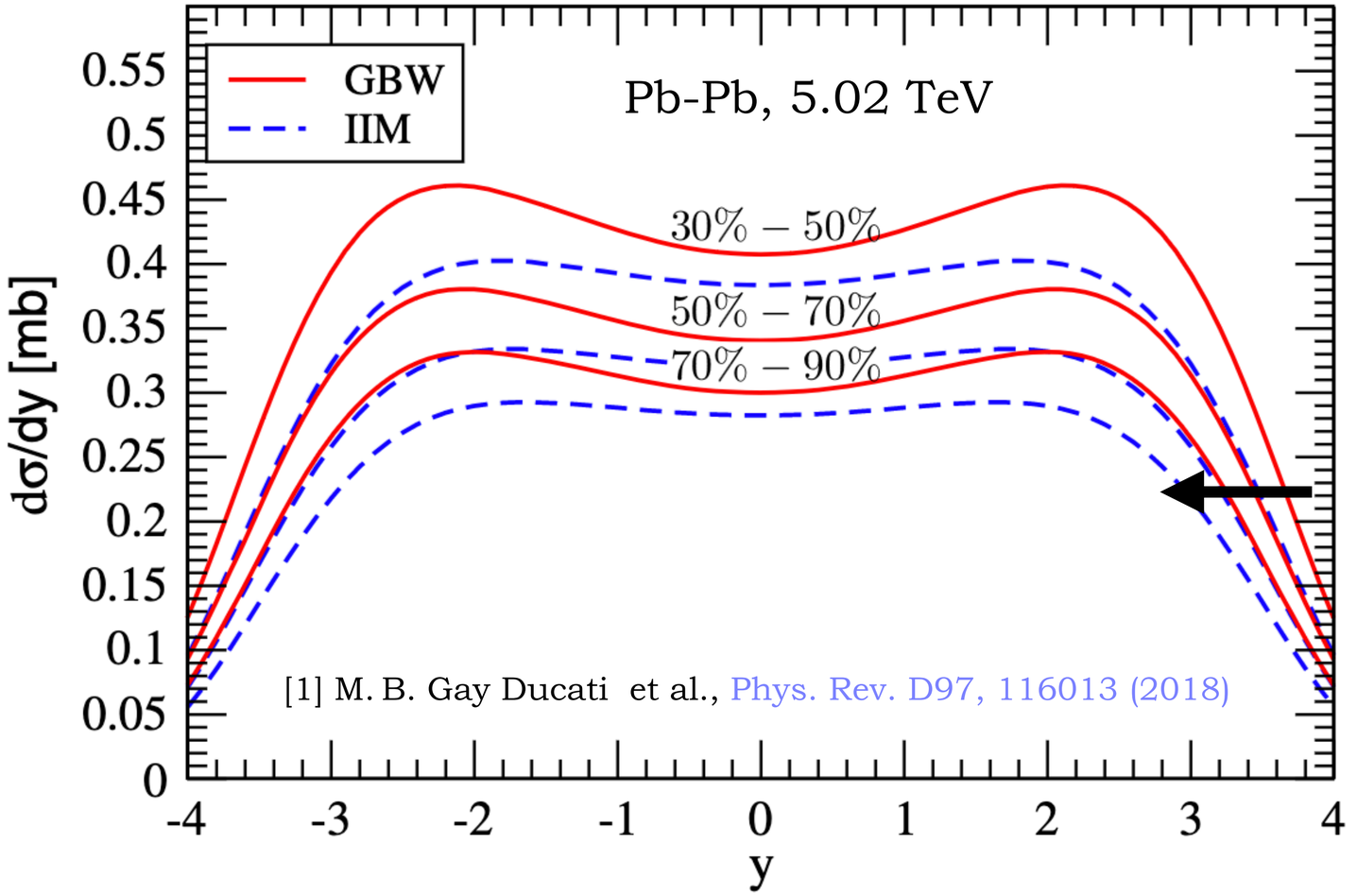
[4] W. Zha et al., Phys. Rev. C 99, 061901(2019)

y-differential coherent J/ψ photoproduction in Pb–Pb collisions

GBW : light cone dipole formalism

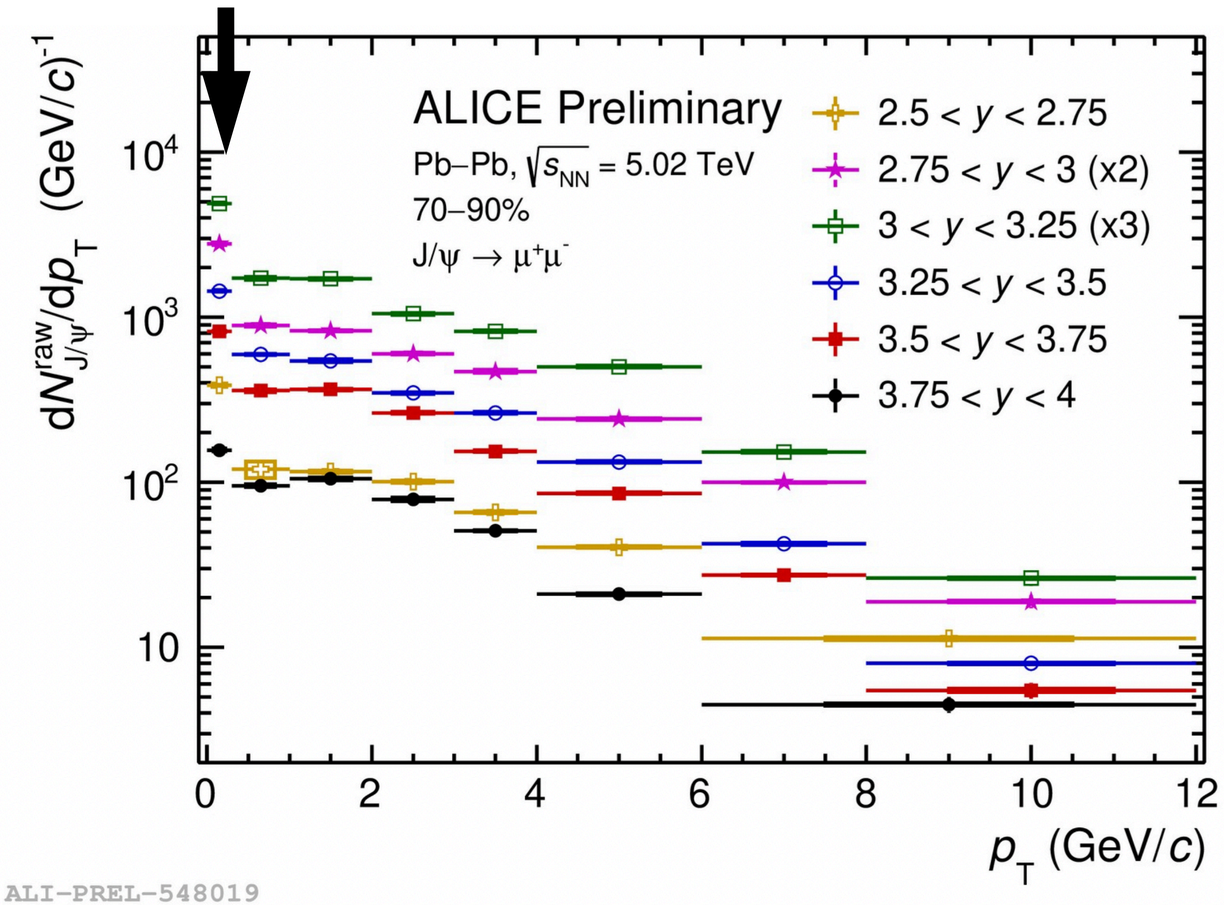
IIM : color glass condensation approach

- Models (GBW/IIM) predict a strong *y*-dependence of the VM photoproduction cross section in Pb-Pb collisions [1]



- **Cross section measurement at forward-*y*** in peripheral events (70-90%) performed
  - ➡ will provide further constraints to differentiate various models

y-differential J/ψ photoproduction in peripheral Pb–Pb collisions



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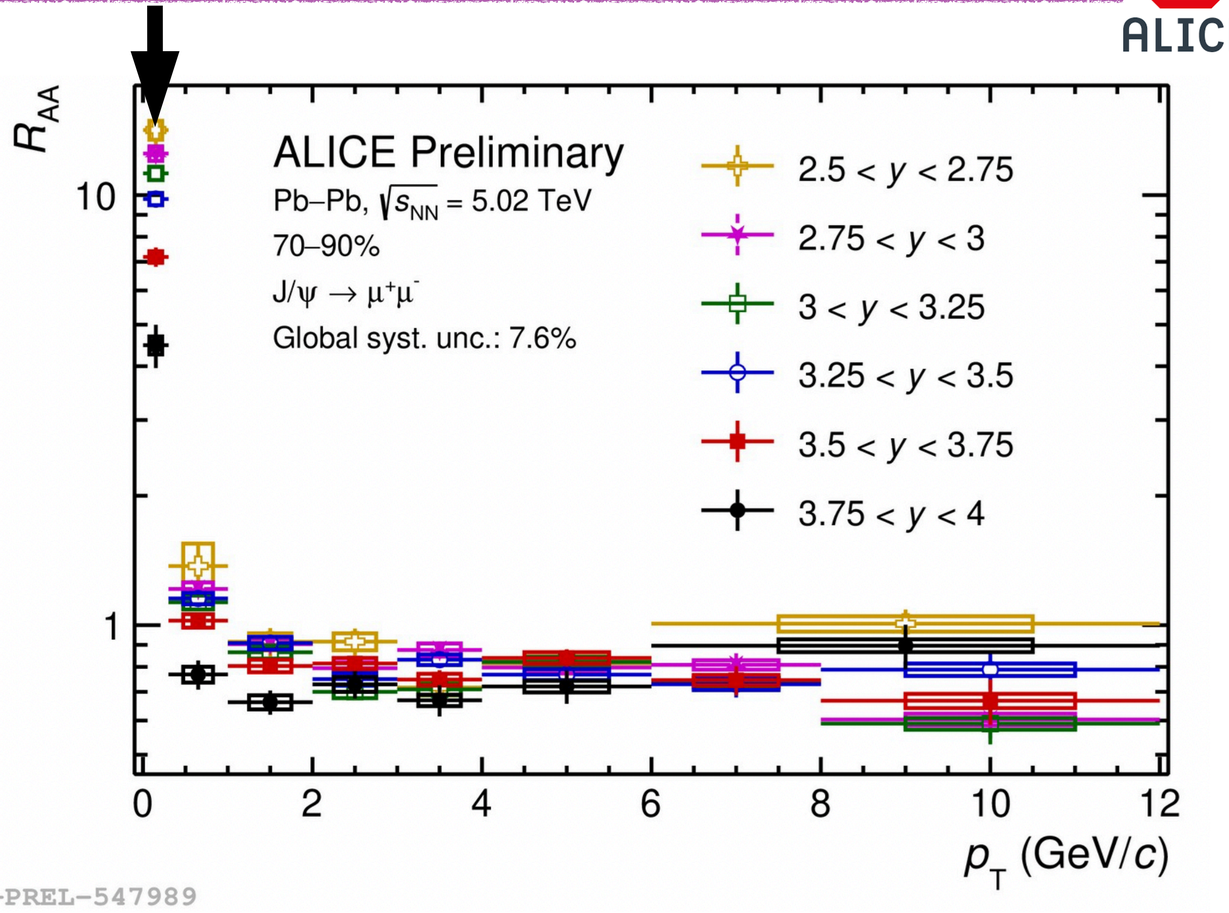


ALI-PREL-547989

- **Clear J/ψ low p_T excess** in all rapidity intervals in peripheral Pb–Pb events
- Also quantified in terms of R_{AA} >> 1 with an **increasing R_{AA} from 3.75 < *y* < 4 to 2.5 < *y* < 2.75**

Coherent J/ψ photoproduction: rapidity dependence

- **J/ψ excess yield**

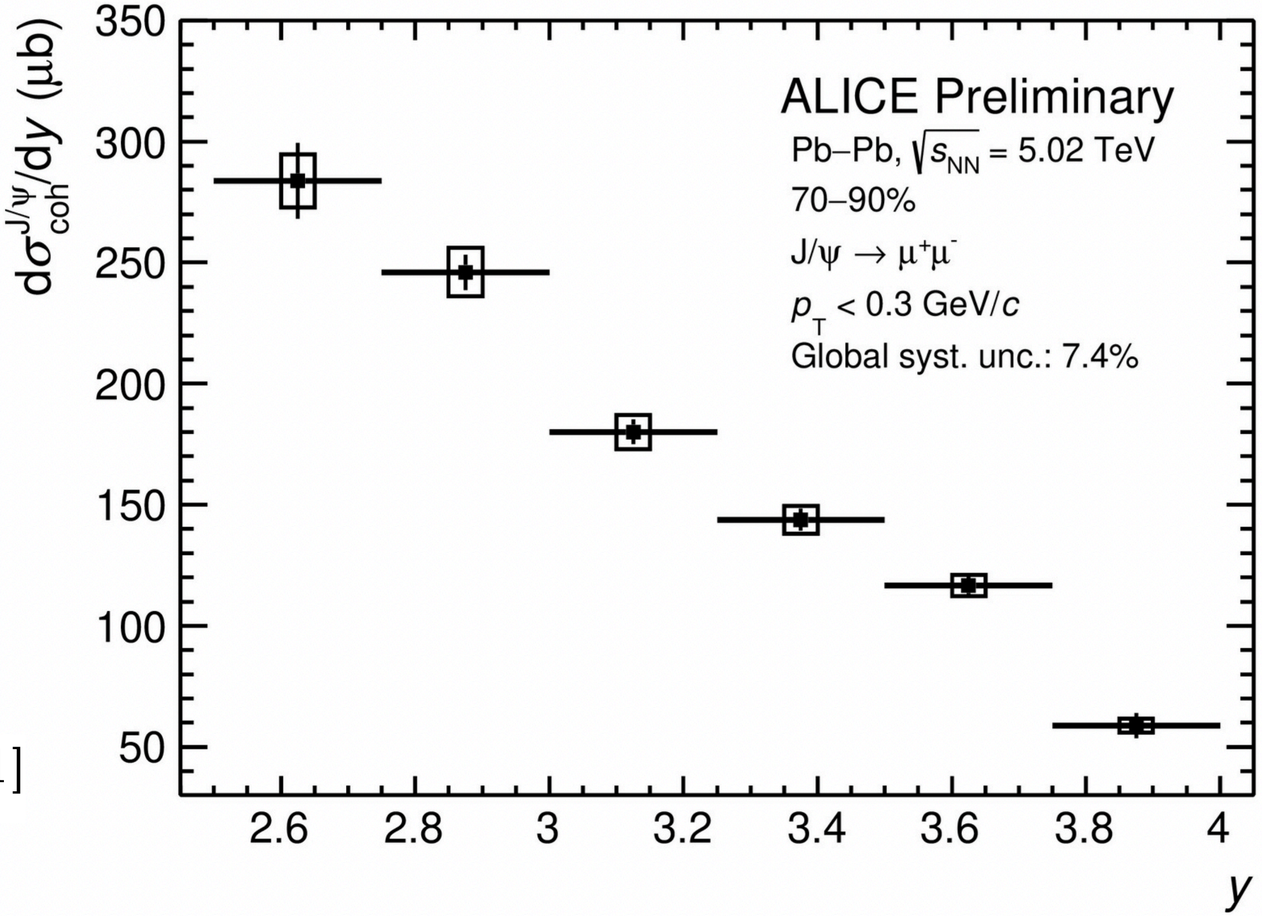
  = J/ψ raw yield – J/ψ estimated hadronic yield

- **Coherent J/ψ yield**

$$Y_{\mathrm{J}/\psi}^{\mathrm{coherent}} = \frac{Y_{J/\psi}^{\mathrm{excess}}}{1 + f_I + f_D}$$

by correcting the excess yield for the fraction of incoherent J/ψ (f_I) and the fraction of coherent ψ(2S)→ coherent J/ψ + X (f_D), evaluated in UPC [1]

- **A strong rapidity dependence is seen**



[1] ALICE Coll., Phys. Lett. B 846 (2023) 137467

Coherent J/ψ photoproduction: rapidity dependence

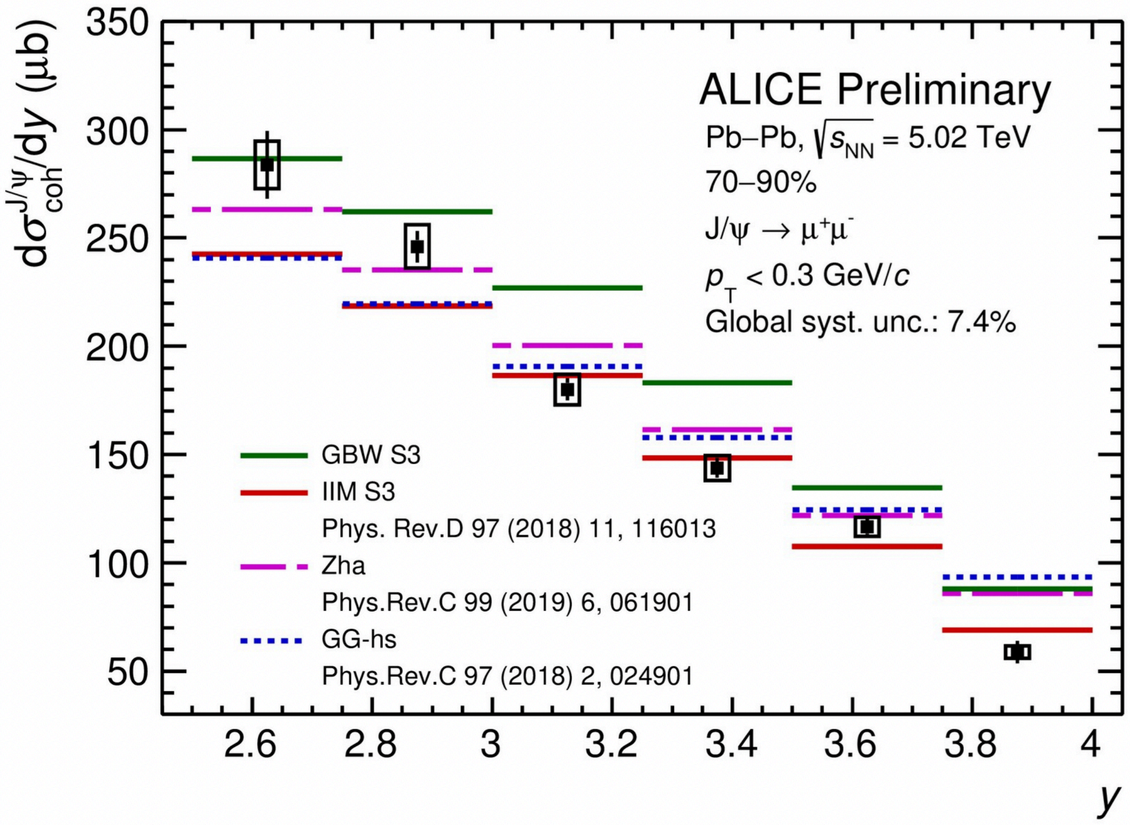
- **Qualitative description of the magnitude** of the cross section by the UPC-like models modified for the centrality range 70–90%

- Models **fail at reproducing the rapidity dependence**, similar observation as in UPC [1]

GG-hs: γ flux with constraints on b

Zha: Nucleus (γ emitter) – Spectator (pomeron emitter) scenario or double -slit scenario

IIM/GBW, S3: only γ reaching the spectator region considered, $\sigma_{\gamma\mathrm{Pb}}$ modified



ALI-PREL-547942

[1] ALICE Coll., Eur. Phys. J. C 81 (2021) 712

[2] M. Klusek-Gawenda et al., Phys.Rev.C 93, 044912 (2016)

[3] M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)

[4] J. Cepila et al., Phys. Rev. C 97, 024901 (2018)

[5] W. Zha et al., Phys. Rev. C.99, 061901 (2019)

[6] W. Zha et al., Phys. Rev. C.97, 044910 (2018)

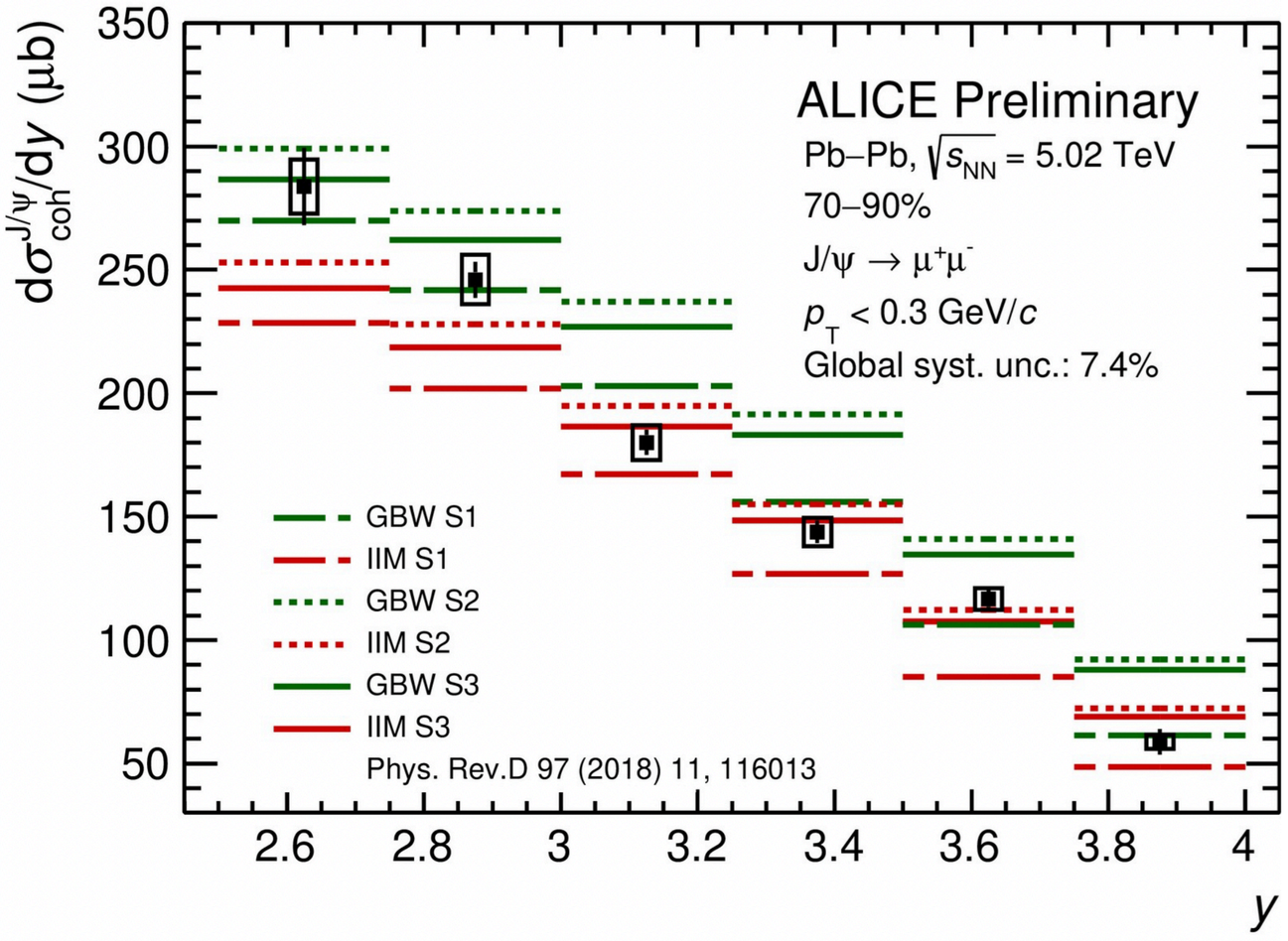
Coherent J/ψ photoproduction : rapidity dependence

- **GBW/IIM**: extending UPC models to PCs considering the impact of the nuclear overlap [1]

— -S1: UPC like (γ flux with constraints on b)

- - S2: Effective photon flux (only γ reaching the spectator region considered, $\sigma_{\gamma Pb}$ unmodified)

— S3: Effective photon flux + photonuclear cross section (S2 + $\sigma_{\gamma Pb}$ modified for exclusion of overlap region)



- Models describe qualitatively the magnitude of the cross section, but **fail at reproducing the y-dependence**

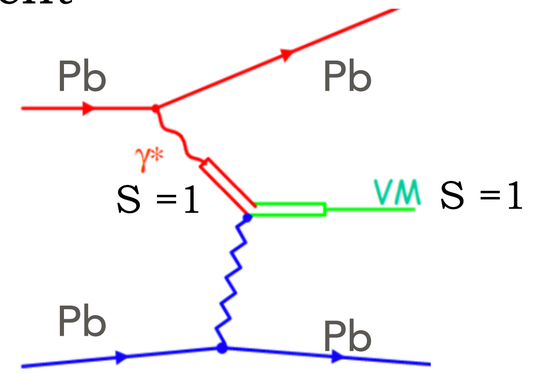
[1] M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)

➡ **VM photoproduction cross section with nuclear overlap effect** is still a theoretical challenge

Inclusive J/ψ polarization in peripheral Pb–Pb collisions

- Test vector meson (VM) photoproduction mechanism via polarization measurement

- **Photoproduction process:** VM expected to keep the (transverse) polarization of incoming photon due to **s-channel helicity conservation (SCHC)** [1]



SCHC hypothesis

Observable :

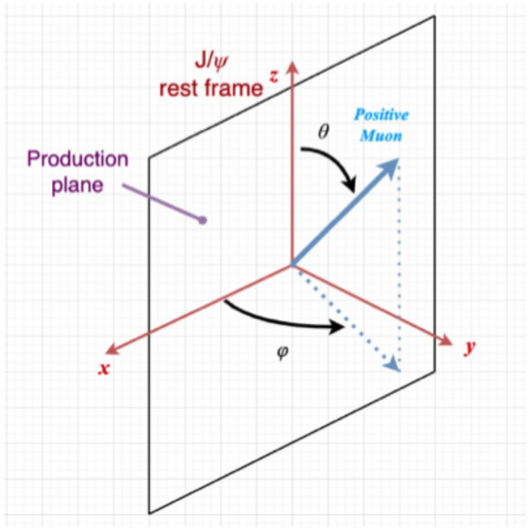
- Polarization: particle spin alignment with respect to a chosen direction
- Helicity frame (HX): momentum direction of the VM
- Dilepton decay angular distribution [2] :

$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos2\phi+\lambda_{\theta\phi}\sin2\theta\cos\phi)$$

$(\lambda_\theta,\lambda_\phi,\lambda_{\theta\phi}) = (0,0,0) \Rightarrow$ 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



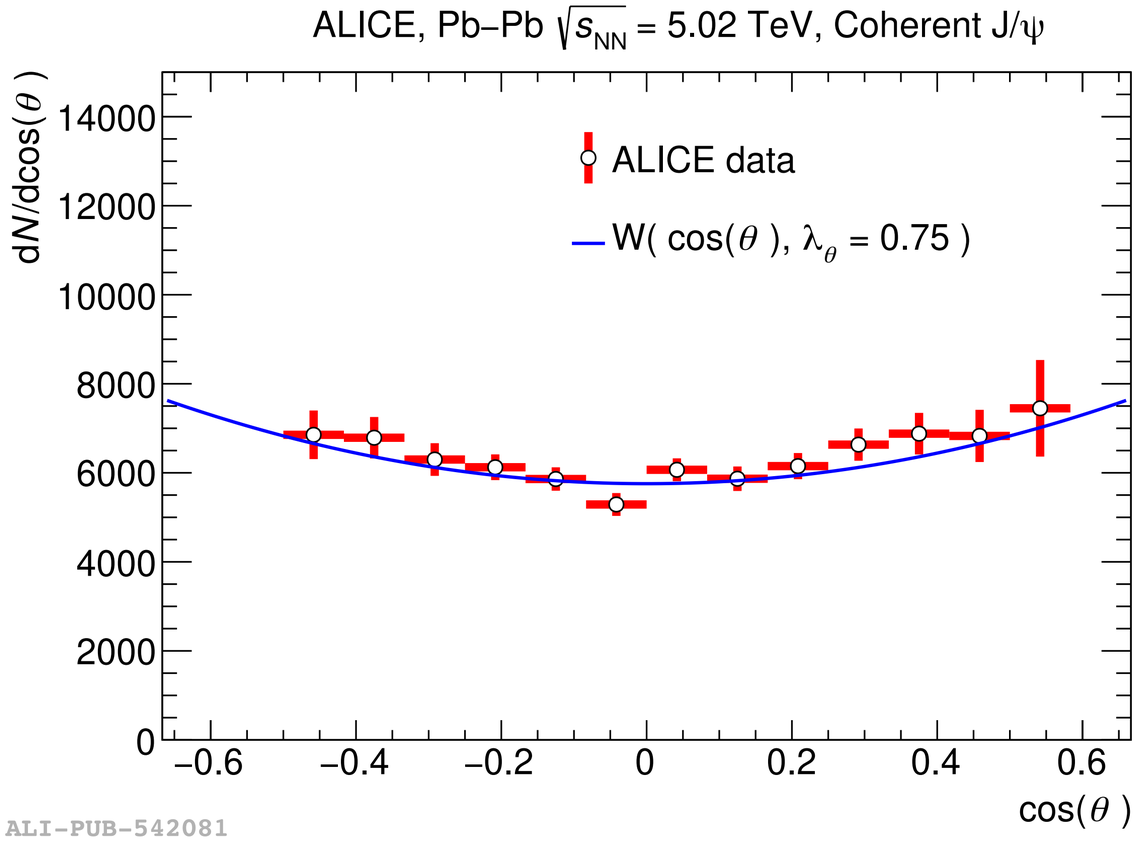
[1] F. J. Gilman et al., Phys.Lett B 31 (1970) 387-390

[2] P. Faccioli et al., Eur. Phys.J.C69:657-673, 2010

Inclusive J/ψ polarization in peripheral Pb–Pb collisions

- ALICE UPC polarization results for **coherently photoproduced J/ψ consistent with SCHC** [1]

[1] ALICE Coll., arXiv:2304.10928

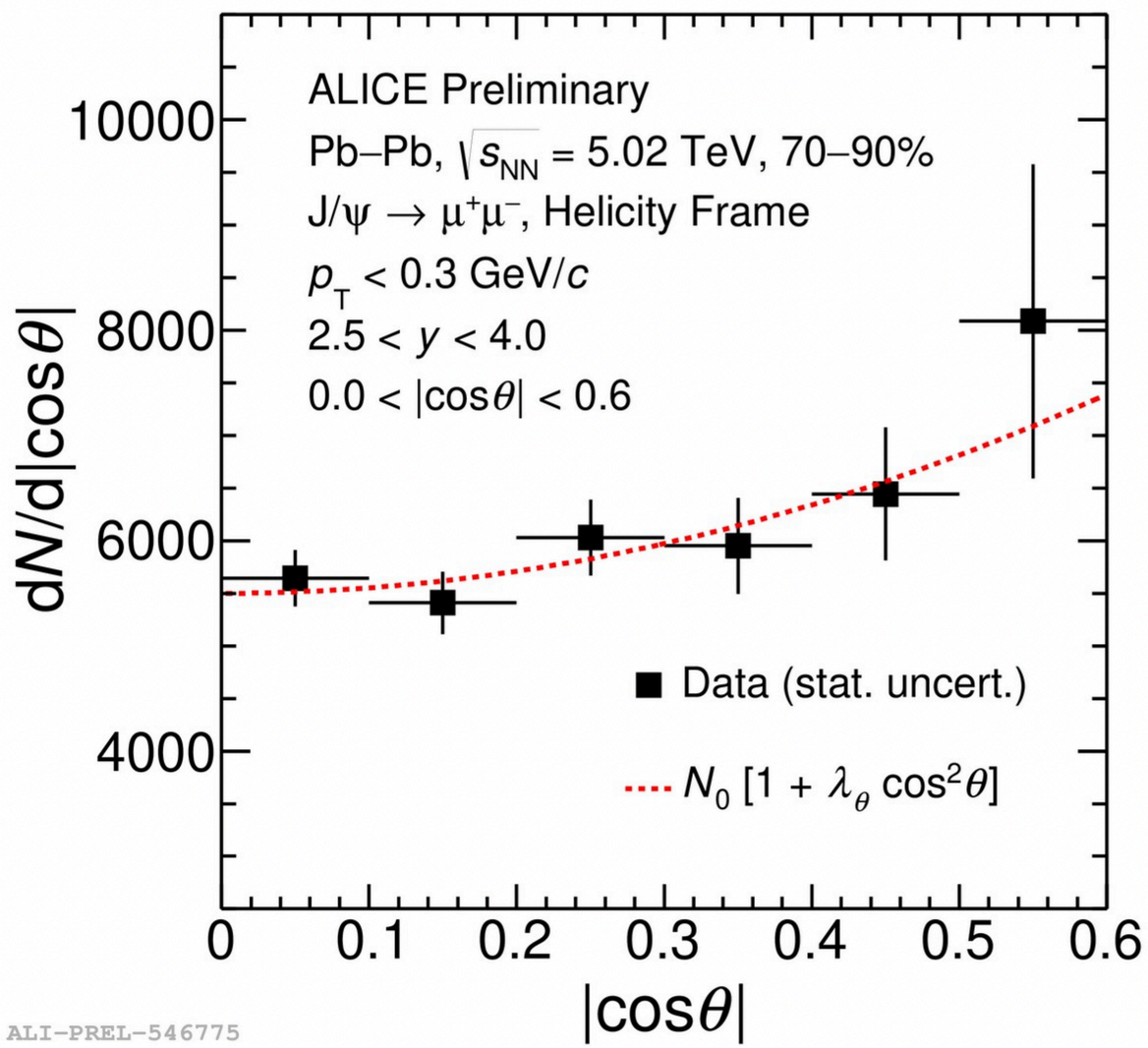


- **Inclusive J/ψ polarization measurement** at low p_T (< 0.3 GeV/c) in the 70-90% centrality range performed

  ➡ Can be used as proxy to **study coherently photoproduced J/ψ polarization**

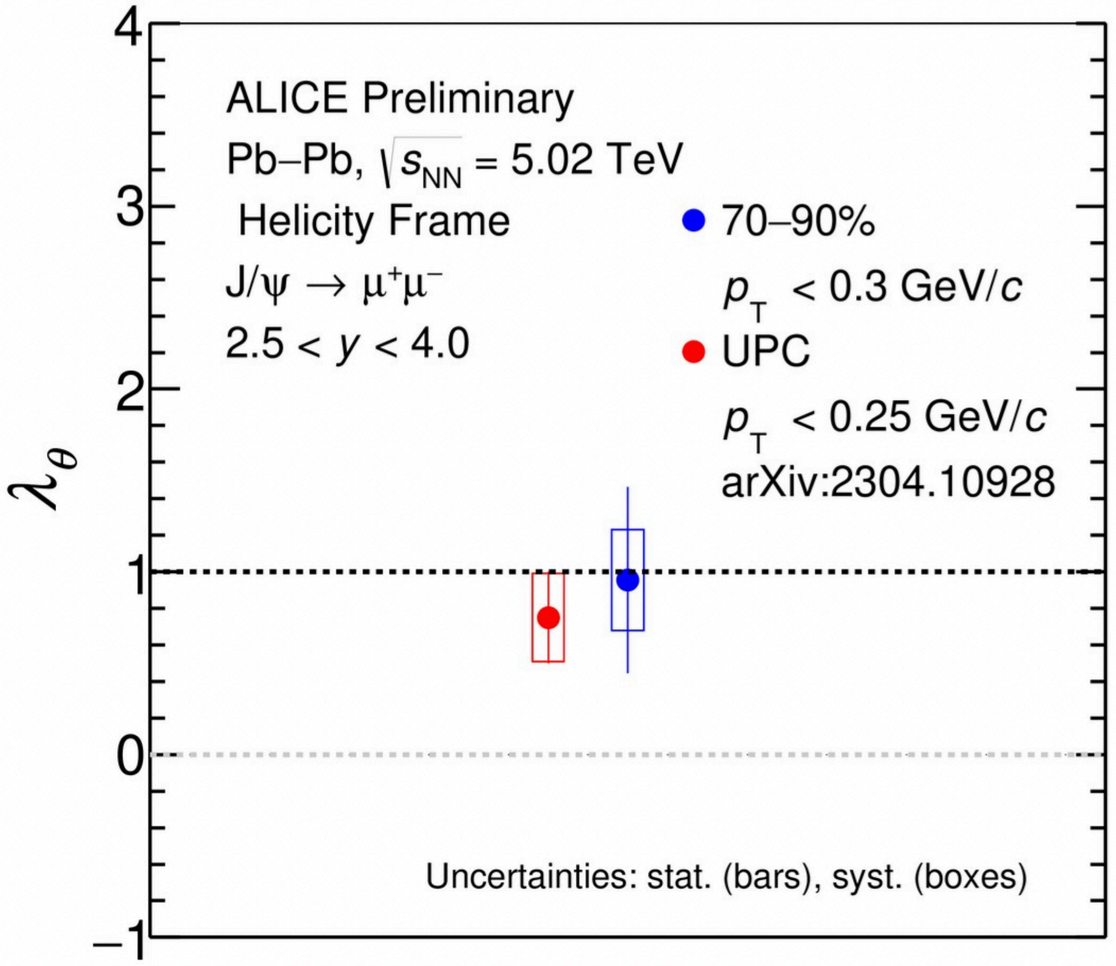
Inclusive J/ψ polarization in peripheral Pb–Pb collisions

- Angular cosθ distribution of J/ψ decay products **hints a transverse polarization**



Inclusive J/ψ polarization in peripheral Pb–Pb collisions

- λ_θ value for inclusive J/ψ in 70-90% centrality range and for p_T < 0.3 GeV/c **consistent with UPC results and with the observation of SCHC**



ALI-PREL-546778

Summary

- ALICE has carried out a **wide range of measurements of photoproduced J/ψ** in Pb–Pb collisions with nuclear overlap at LHC energies

- All measurements (Integrated, y- and p_{T}-differential cross section, polarization) supports **consistently a photoproduction origin for the J/ψ at low $\mathbf{p_T}$** in peripheral Pb-Pb collisions

➡**Strong *y*-dependence** of coherently photoproduced J/ψ cross section is observed, similar to UPC

➡ **UPC-like models modified to account for the nuclear overlap** are able to describe the magnitude of the cross sections

➡ Inclusive J/Ψ polarization measurement **consistent with SCHC hypothesis and UPC measurement**

Outlook

- **Coherent J/ψ photoproduction cross section** measurement can be used to extract the **photonuclear cross sections ($\sigma_{\gamma Pb}$)** in two Bjorken-x regions

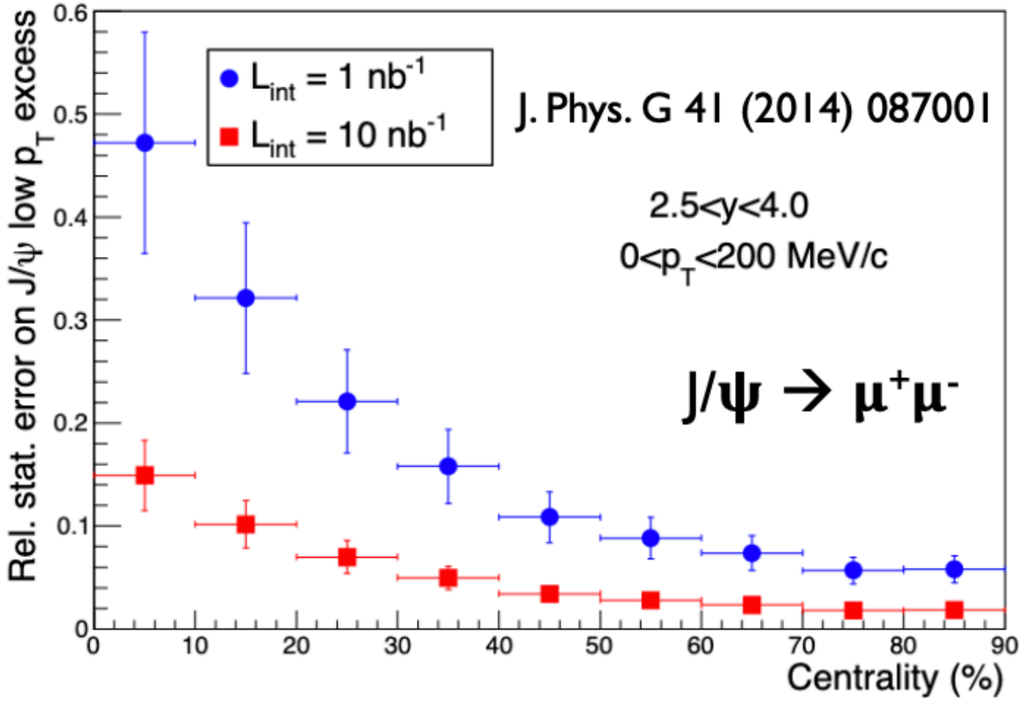
  [J.G. Contreras, Phys. Rev. C 96, 015203 (2017)]

- **Perspectives for Run 3 + 4 (L_{int} ~ 10 nb^{-1} in Pb–Pb)**

  ➡ Explore more differential measurements (with improved precision) for J/Ψ, **towards most central collisions both at mid and forward *y*,** in order to better constrain models (y-dependence, p_T-dependence, polarization)

  ➡ Measurement of other excited states i.e., **Ψ(2S) for possible QGP effects on the photoproduced probe**

ALICE Projections : Run 3 + 4

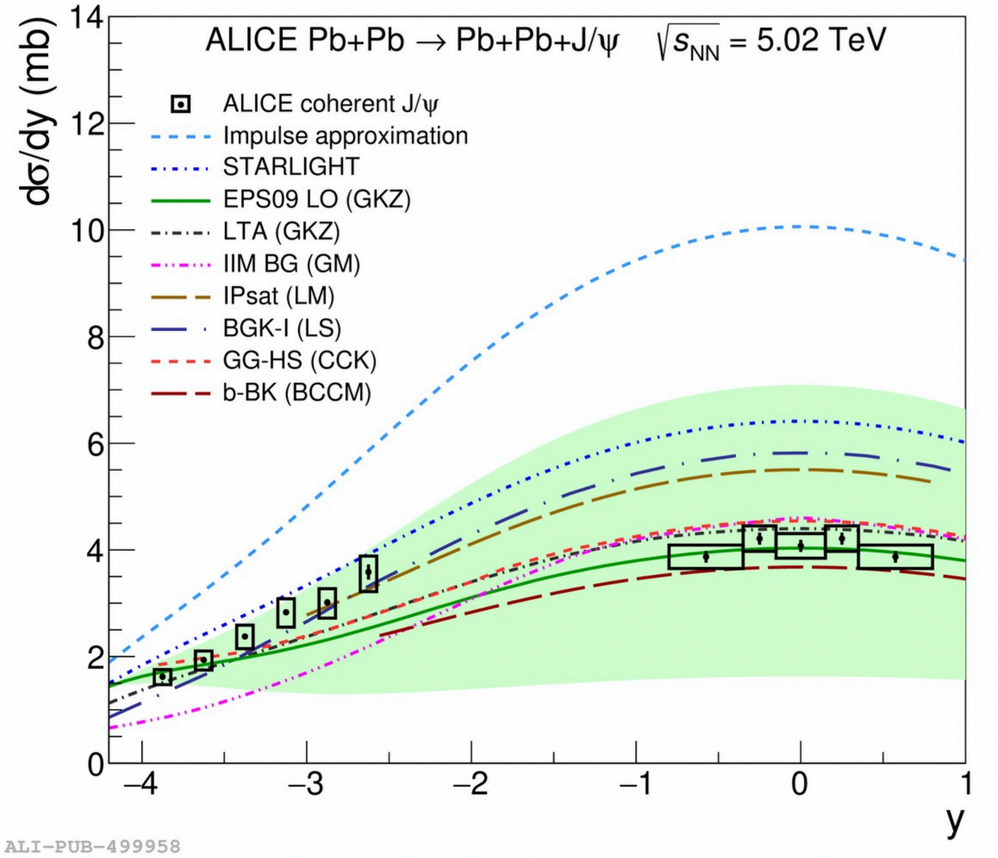


Back up

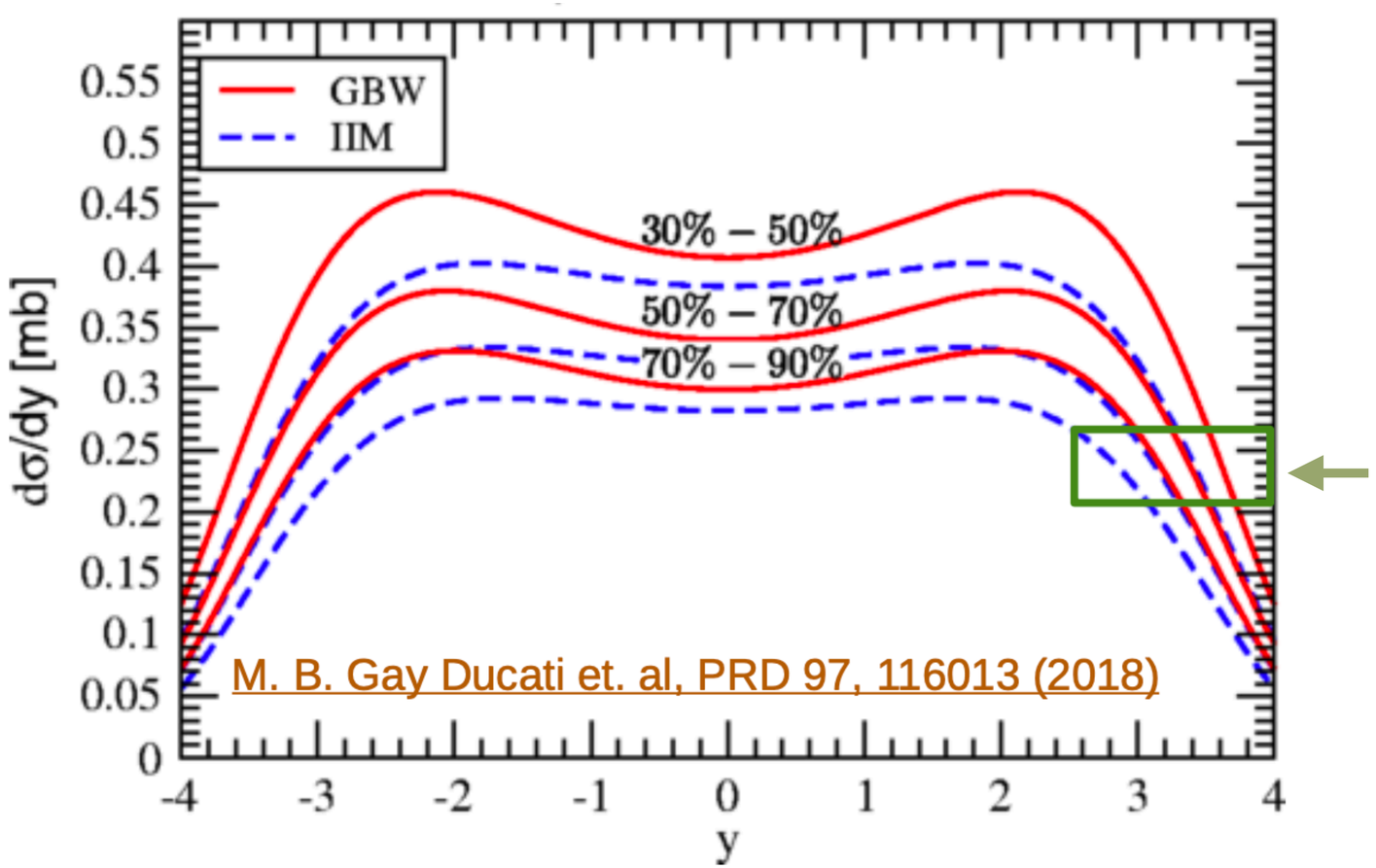
y-differential coherent J/ψ photoproduction in Pb–Pb collisions

UPC measurement

Phy.Lett.B 798 (2019) 134926
Eur. Phys. J. C 81 (2021) 712



- Models predict a strong *y*-dependence of the VM photoproduction cross section in Pb-Pb collisions



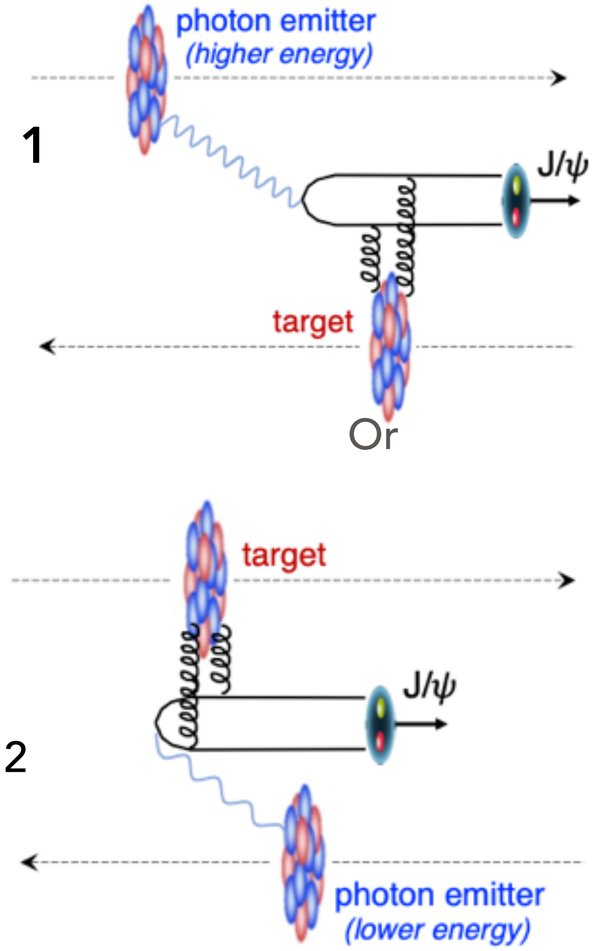
- y-dependence of coherent J/Ψ cross section observed

y-differential cross section at forward-y in peripheral events

Additional differential measurements in PC required to constrain models

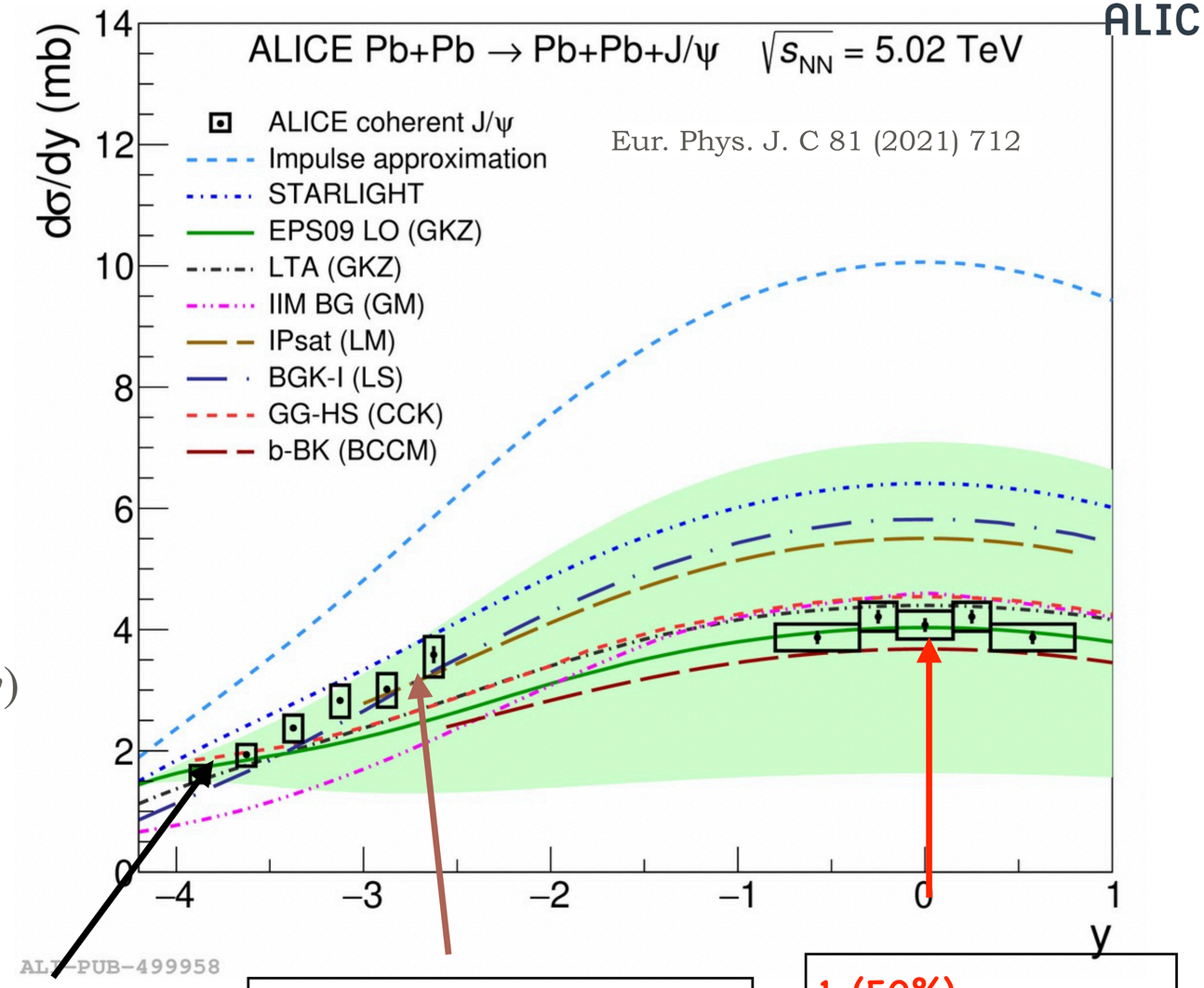
Rapidity dependence : Photon energy ambiguity

In symmetric collisions, depending on the photon emitter: two values of Bjorken-x probed



$$x = \frac{m_{J/\psi}^2}{W_{\gamma \mathrm{Pb}}^2}$$

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



1 (5%), x ~ 1.1 x 10^{-5}

2 (95 %), x ~3.3 x 10^{-2}

1 (40%), x ~ 5.1 x 10^{-4}

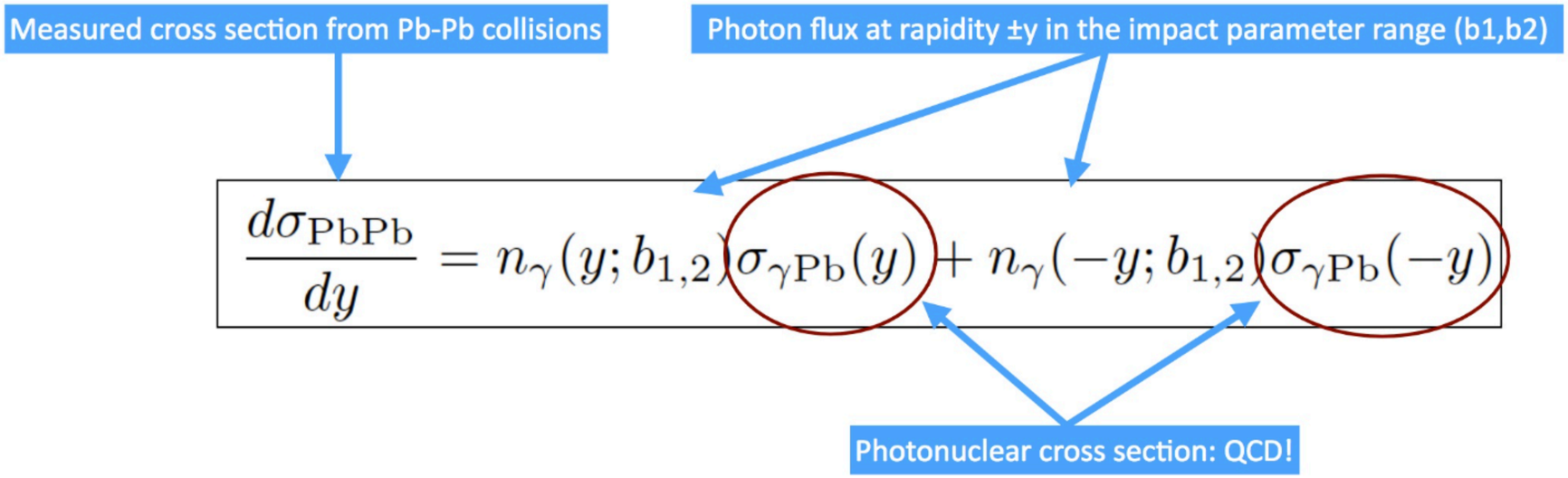
2 (60 %), x ~ 0.7 x 10^{-2}

1 (50%)

2 (50%)

at y=0, x ~ 10^{-3}

Solution to photon energy ambiguity



At y=0,

$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}}}{\mathrm{d}y} = 2n_\gamma(y, \{b\})\sigma_{\gamma\mathrm{Pb}}(y)$$

Proposed solution by [V. Guzey et al., PLB 726 (2013), 290-295 and J. G. Contreras, PRC 96, 015203 (2017)]

Electromagnetic dissociation of nuclei (EMD): modeling of photon fluxes associated to neutron emission

1. ALICE Collaboration, JHEP 10 (2023) 119
2. CMS Collaboration, PRL 131 (2023) 262301
3. STAR Collaboration, arXiv:2311.13632 (submitted to PRC), arXiv:2311.13637 (submitted to PRL)

Simultaneously solving the cross section measurements from UPCs and PCs

1. J. Contreras et al., PRC 96, 015203 (2017)

Photon energy ambiguity : solve simultaneously

Perform two independent measurements at the same rapidity, but different impact parameter, then solve the equations.

$$\left(\frac{d\sigma_{\mathrm{PbPb}}}{dy}\right)_A = n_\gamma(y;\{b\}_A)\sigma_{\gamma\mathrm{Pb}}(y)+n_\gamma(-y;\{b\}_A)\sigma_{\gamma\mathrm{Pb}}(-y)$$

A =UPC

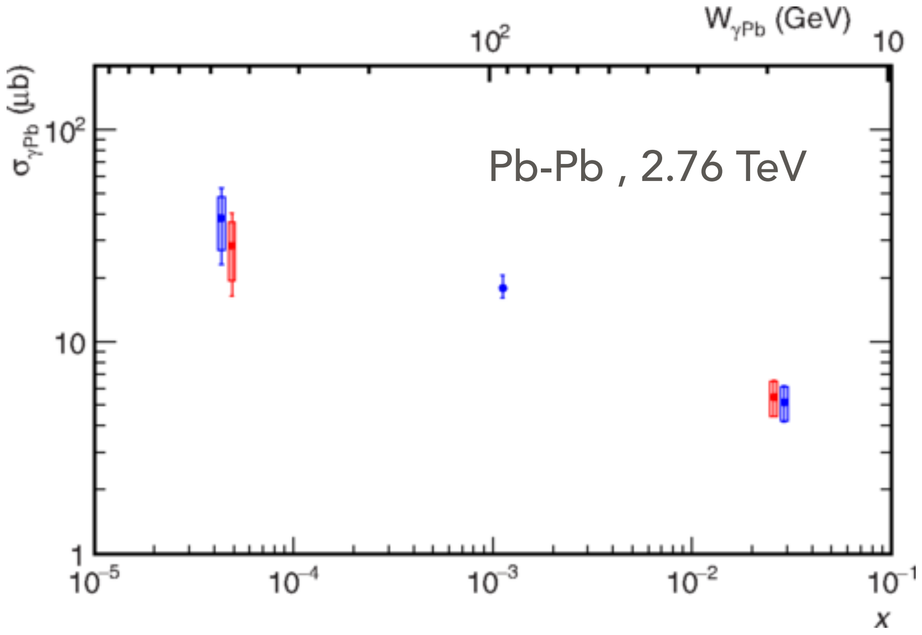
$$\left(\frac{d\sigma_{\mathrm{PbPb}}}{dy}\right)_B = n_\gamma(y;\{b\}_B)\sigma_{\gamma\mathrm{Pb}}(y)+n_\gamma(-y;\{b\}_B)\sigma_{\gamma\mathrm{Pb}}(-y)$$

B= PC

For example, use peripheral and ultra-peripheral collisions

JGC, PRC **96**, 015203 (2017)

Phys. Rev. C 96, 015203 (2017)

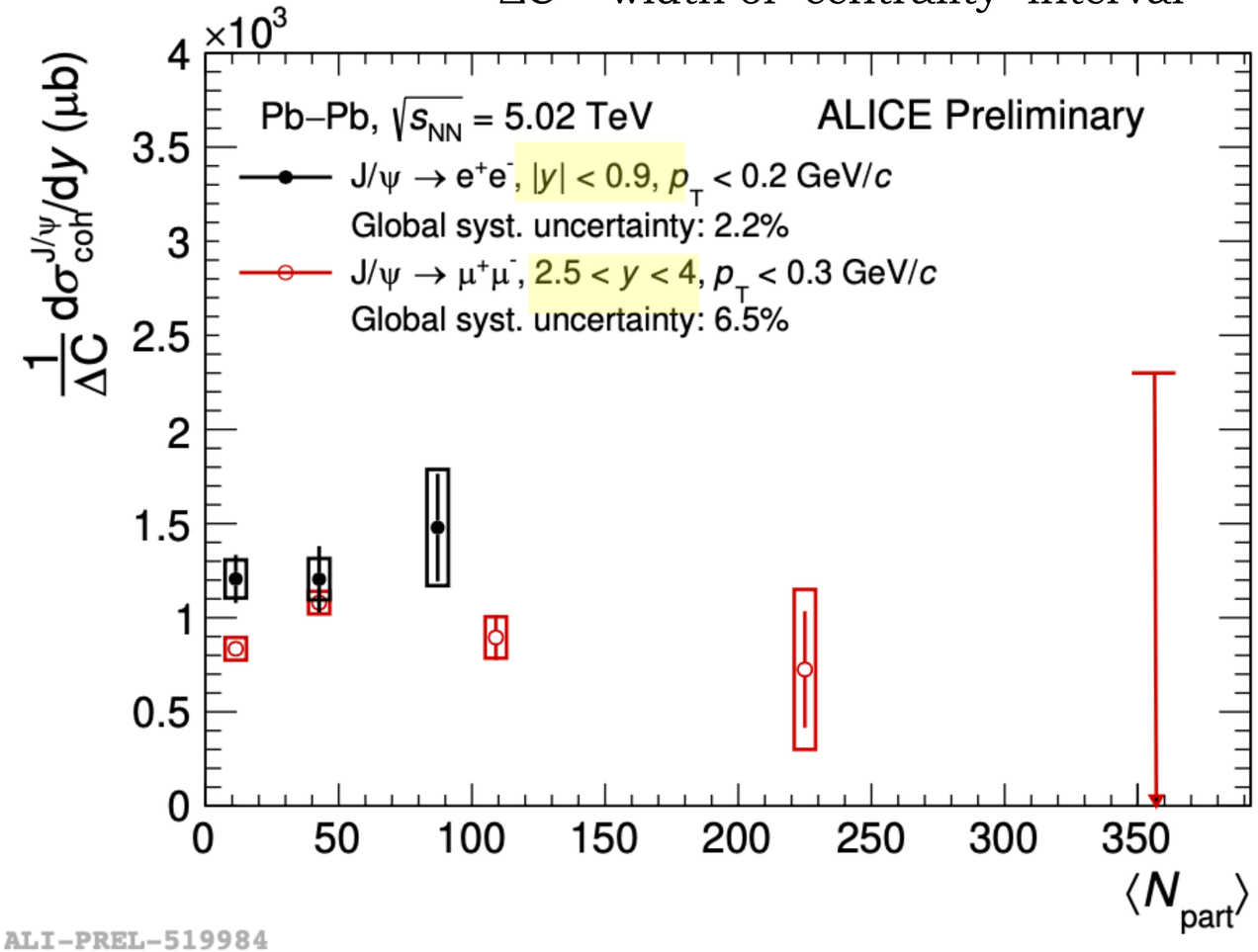


Caveat : this calculation considers the photon-nuclear cross sections in both PC and UPC to be the same.

Using new rapidity-dependent results will provided further constraints on photonuclear cross section computations

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

ΔC = width of centrality interval



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Larger J/ψ photoproduction cross section at mid-y than at forward-y (as expected from models).

No strong centrality dependence at both rapidities