Electromagnetic quarkonium production in nuclear collisions

Dukhishyam Mallick on behalf of the ALICE Collaboration

IJCLab, CNRS/IN2P3, Université Paris-Saclay, Orsay

QWG 2024, IISER Mohali, India

Outline

- Introduction : physics motivation and experimental apparatus
- Photoproduction of vector mesons (VM) : Quarkonium
  - Results from ultra-peripheral heavy-ion collisions (UPCs)
  - Results from heavy-ion collisions with nuclear overlap (PCs)
- Summary and outlook

16th International Workshop on Heavy Quarkonium (QWG 2024)
February 26- March 1, 2024
Indian Institute of Science Education and Research Mohali, India

Photon induced processes in heavy-ion collisions (HICs)

ALICE

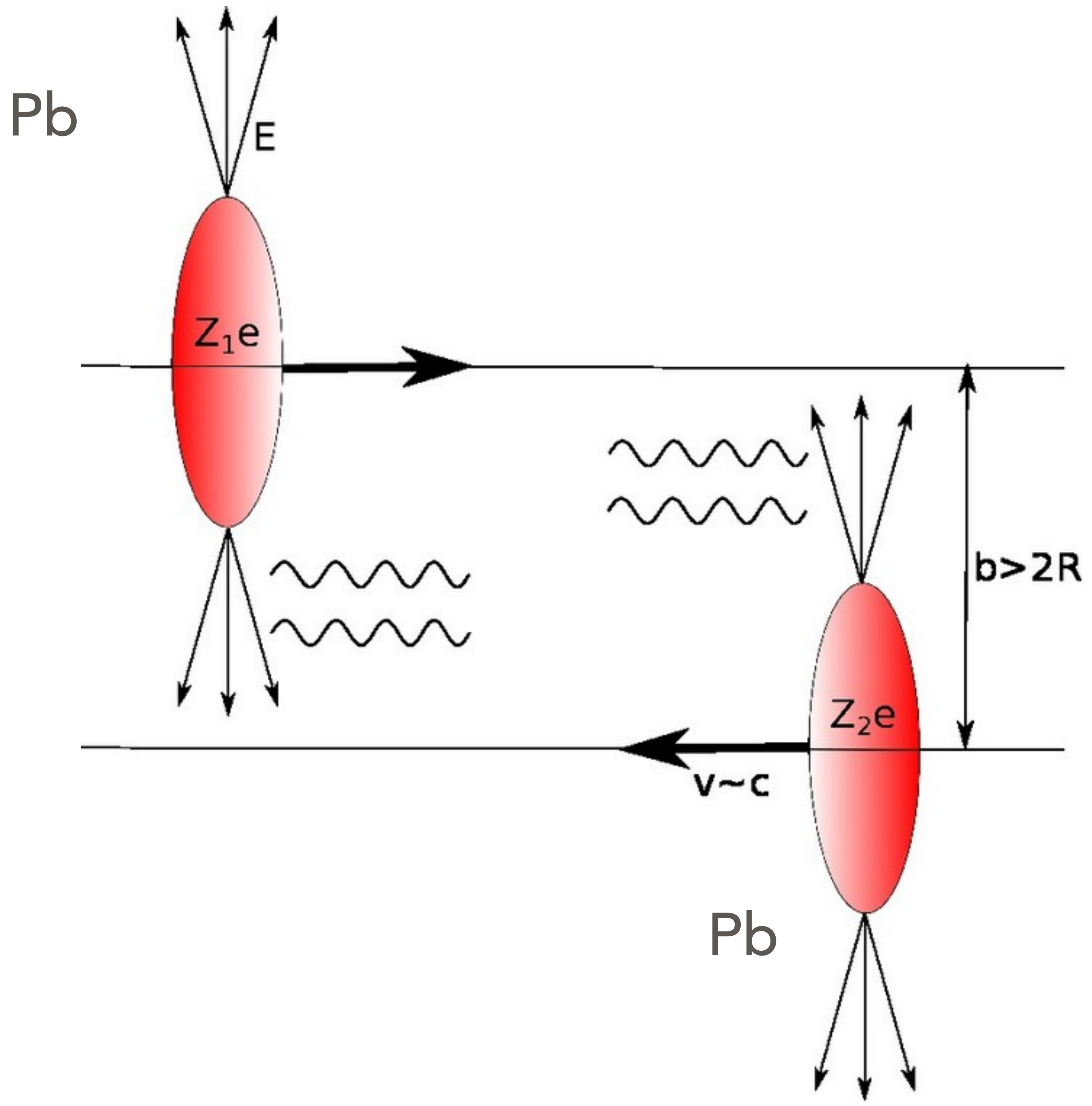
Large Hadron Collider (LHC) acts as a photon collider

Relativistic heavy-ions are strong EM field emitters

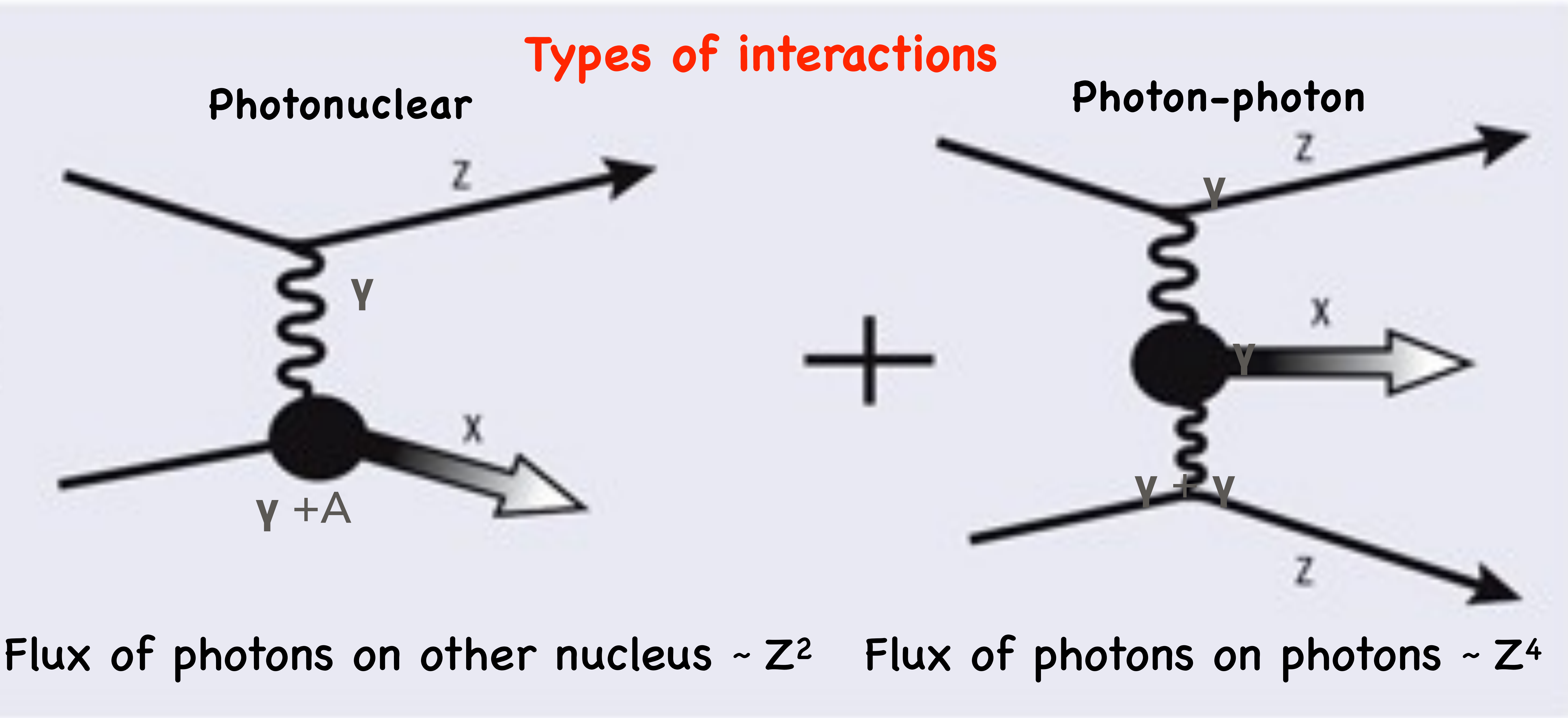
In HICs: |B| ~ 10^{16} T, Earth: |B| ~ 10^{-5} T,

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

UltraPeripheral Collisions (UPCs) : b > 2R



=

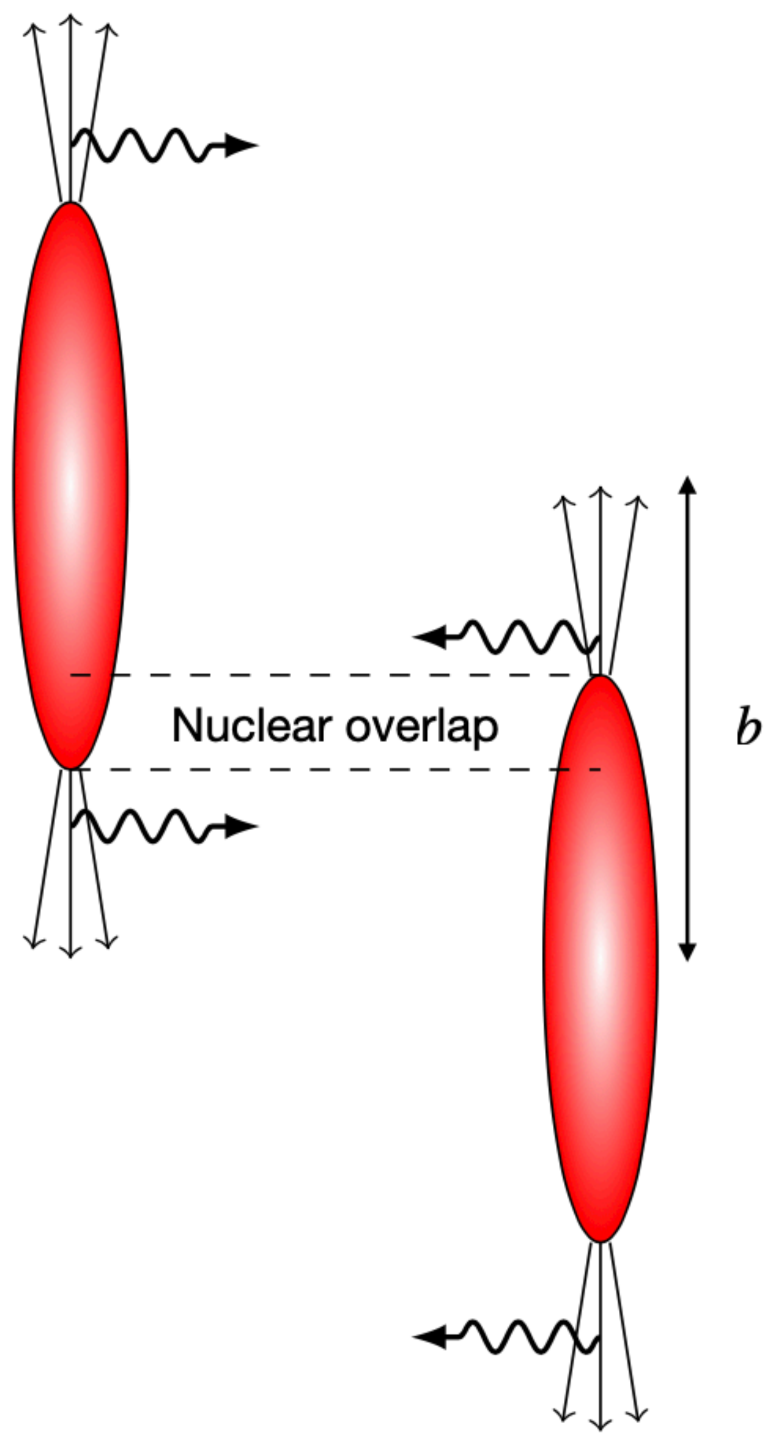


Electromagnetic interactions are dominant

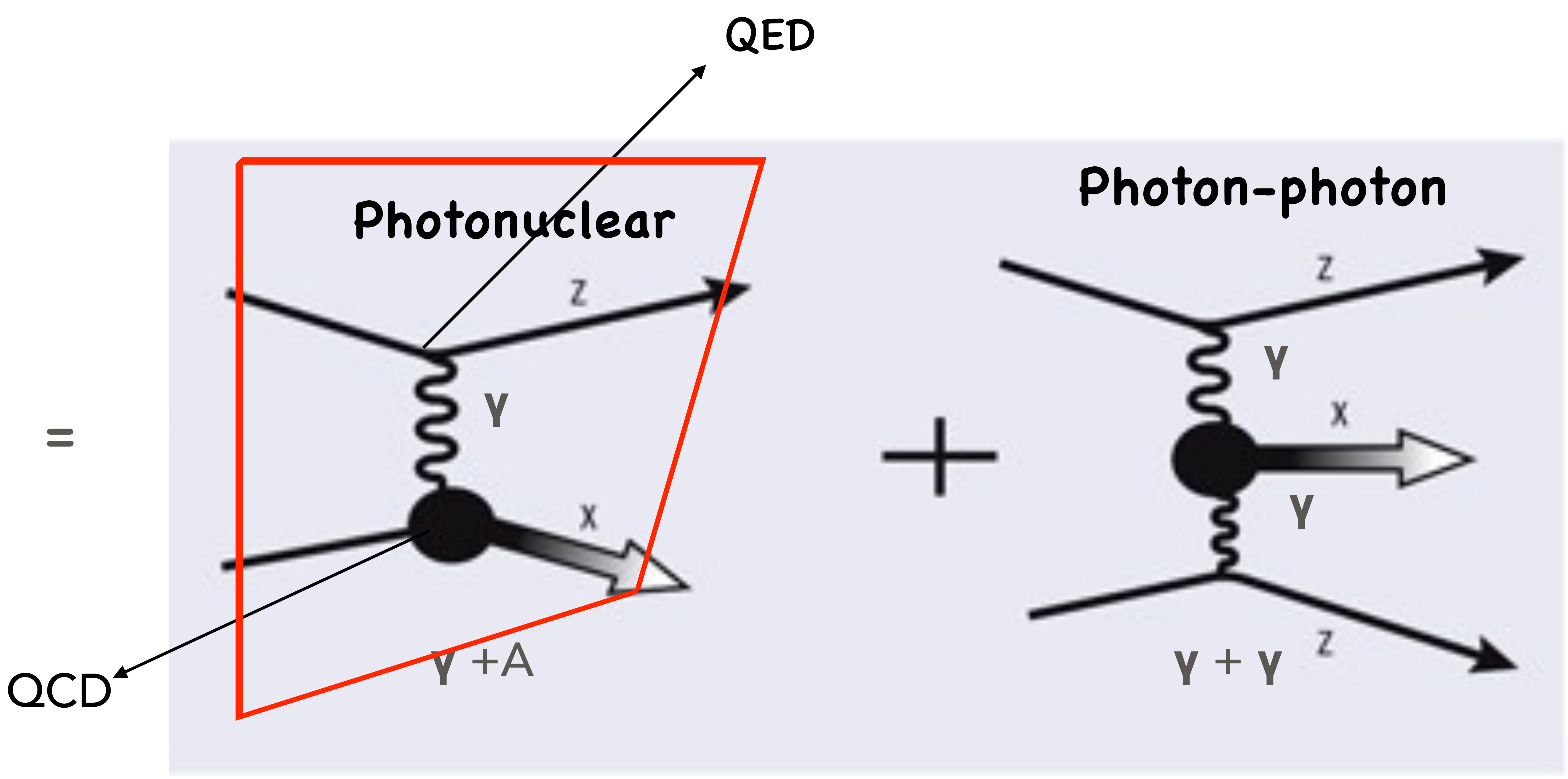
Photon induced processes in heavy-ion collisions (HICs)

In events with nuclear overlap

Peripheral Collisions (PCs): large b, b ≤ 2R



=



Electromagnetic interactions also observed

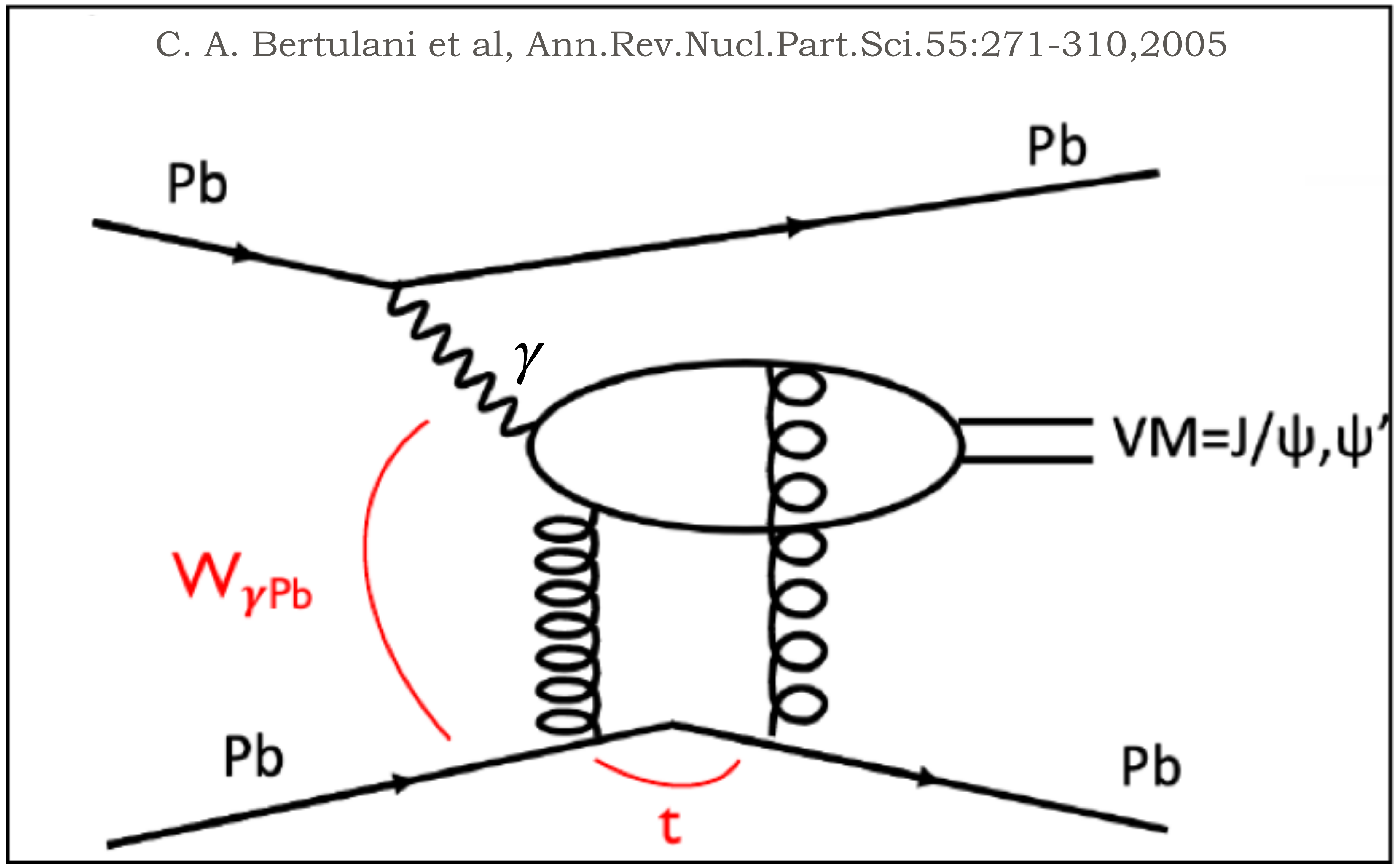
in presence of hadronic interactions

Photonuclear and photon-photon processes are important to study UPCs and PCs with nuclear overlap

-> Good probe to test both QCD and QED phenomena

Vector meson photoproduction in HICs

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



$W_{\gamma Pb}$: Center-of-mass energy per nucleon of the γPb system

t : Mandelstam variable = $-\ p_T^2$

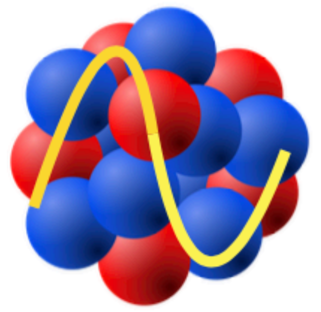
☑ **Clean experimental signatures**

☑ **Coherent photoproduction of VM**

Photon (γ) couples coherently to all nucleons

$\langle p_T \rangle_{J/\psi}$ ~ 60 MeV/c

Usually no breaking of target



– **Probe gluon distribution in various Bjorken-x region in nuclei**

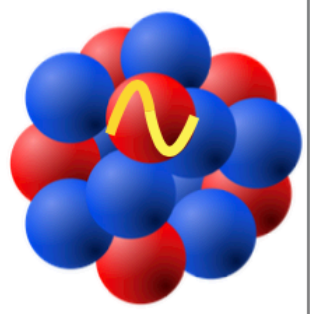
$$x = \frac{m_{J/\psi}}{\sqrt{s_{NN}}} \times \exp(\pm y)$$

☑ **Incoherent photoproduction of VM**

Photon (γ) couples to single nucleon

$\langle p_T \rangle_{J/\psi}$ ~ 500 MeV/c

Usually target nucleus breaks



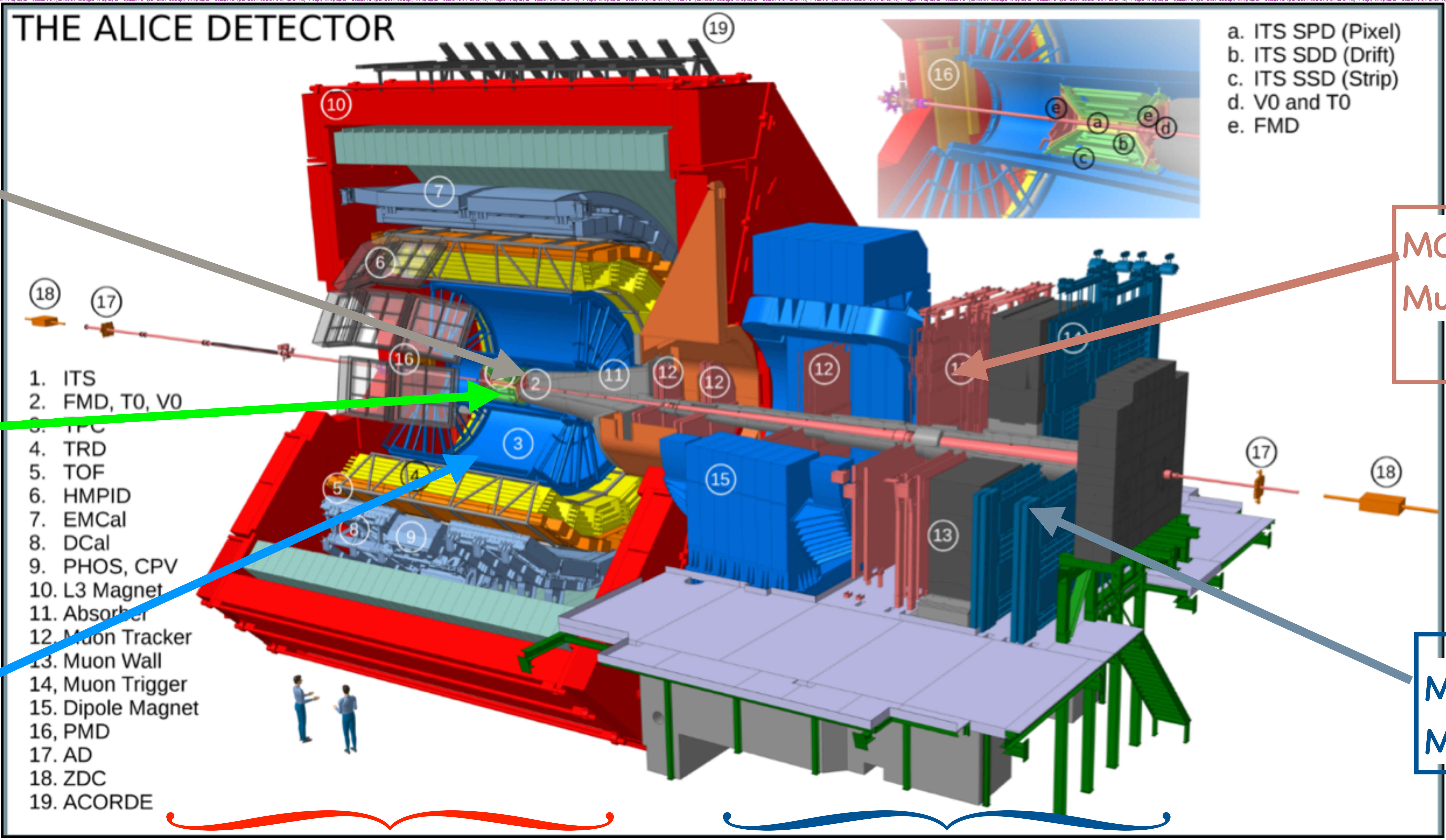
– **Sensitive to the spatial gluon distribution (subnucleonic fluctuations)**

The 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

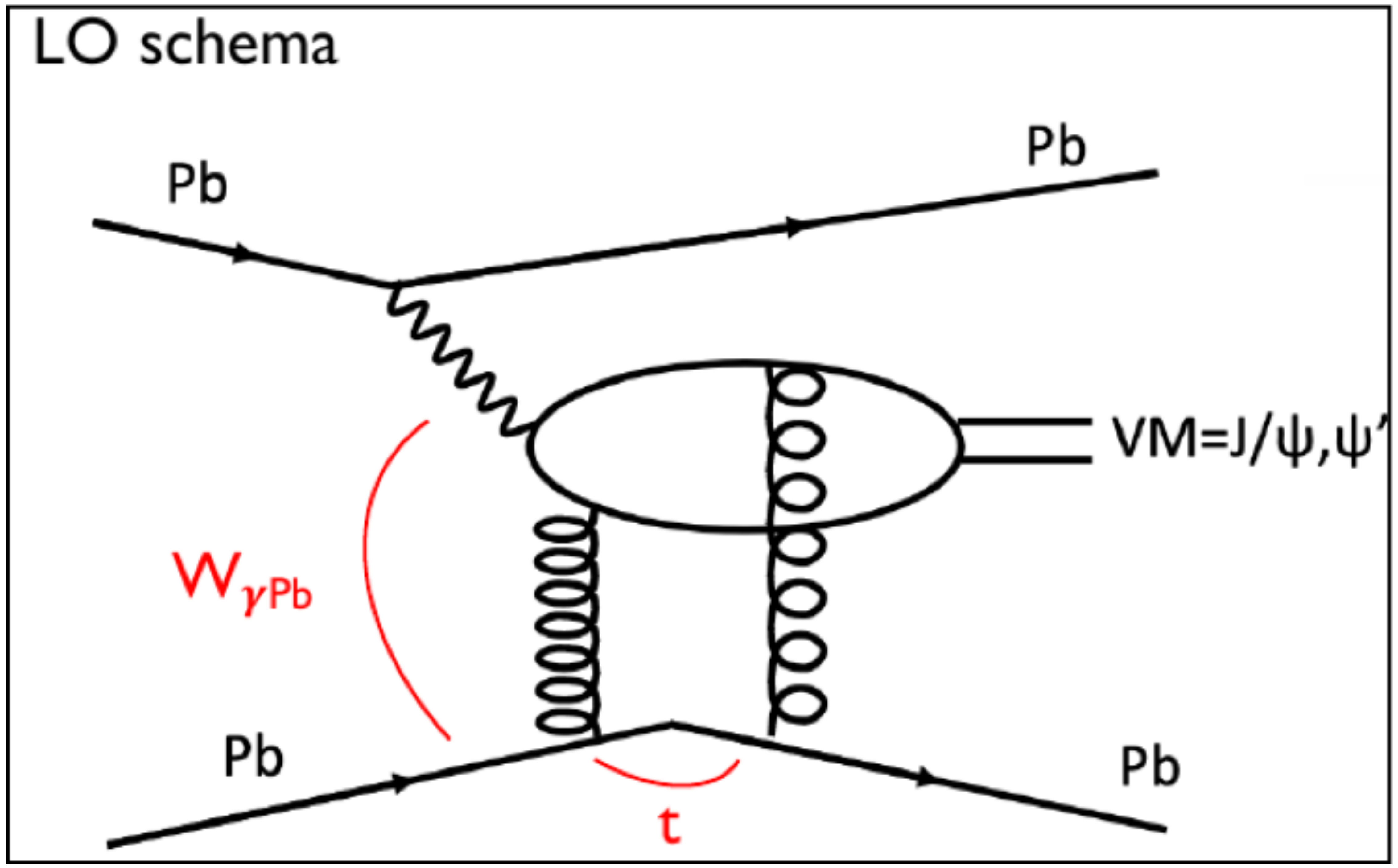
Central barrel: $|y| < 0.9$

$J/\psi \rightarrow e^+e^-$

Muon Spectrometer : $2.5 < y < 4.0$

$J/\psi \rightarrow \mu^+\mu^-$

VM photoproduction in Ultraperipheral Collisions (UPCs)



Published/recent results:

ALICE

Coherent J/Ψ and Ψ(2S) at forward and midrapidity Pb—Pb collisions at 5.02 TeV. Phys. Lett. B 798 (2019) 134926, EPJC 81 (2021) 712

Energy dependence of coherent J/Ψ in Pb—Pb collisions at 5.02 TeV, JHEP 10 (2023) 119

Coherent J/Ψ polarization in Pb-Pb collisions at 5.02 TeV, arXiv:2304.10928

Incoherent J/Ψ in Pb—Pb collisions at 5.02 TeV, arXiv:2305.06169

STAR

Exclusive J/Ψ and Ψ(2S) at midrapidity in Au—Au collisions at 200 GeV

arXiv:2311.13632

J/Ψ photoproduction cross section vs. y in UPC

y-dependence of coherent J/Ψ cross section observed

Nuclear suppression factor due to gluon shadowing

$$S_{Pb} = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}} \qquad x = \frac{m_{J/\psi}}{\sqrt{s_{NN}}} \times \exp(\pm y)$$

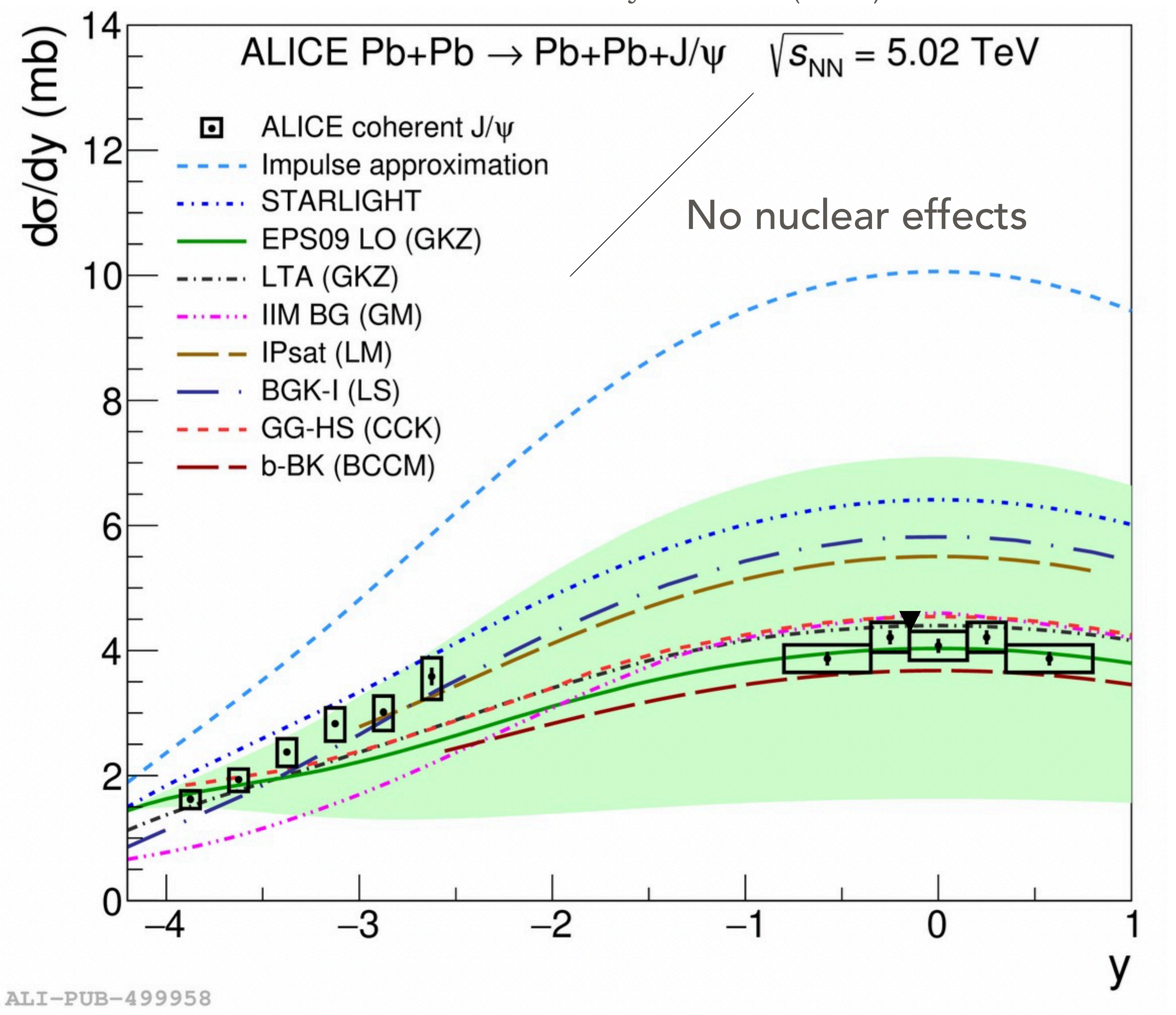
$\sigma_{\gamma Pb}$ = photo nuclear cross section of γPb system from data

$\sigma^{IA}_{\gamma Pb}$ = photo nuclear cross section of γPb system from impulse approximation calculation

S_{Pb} = 0.64 at Bjorken-x ~ 10^{-3} and mid y

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. 83,065202 (2011)] and [PRC. 87, 032201 (2013)] BGK-I (LS): [PRC. 99(4), 044905 (2019)]
GG-HS (CCK): [PRC. 97(2), 024901 (2018)], and [PLB 766, 186-191 (2017)]
b-BK (BCCM): [PLB 817, 136306 (2021)]

Eur. Phys. J. C 81 (2021) 712

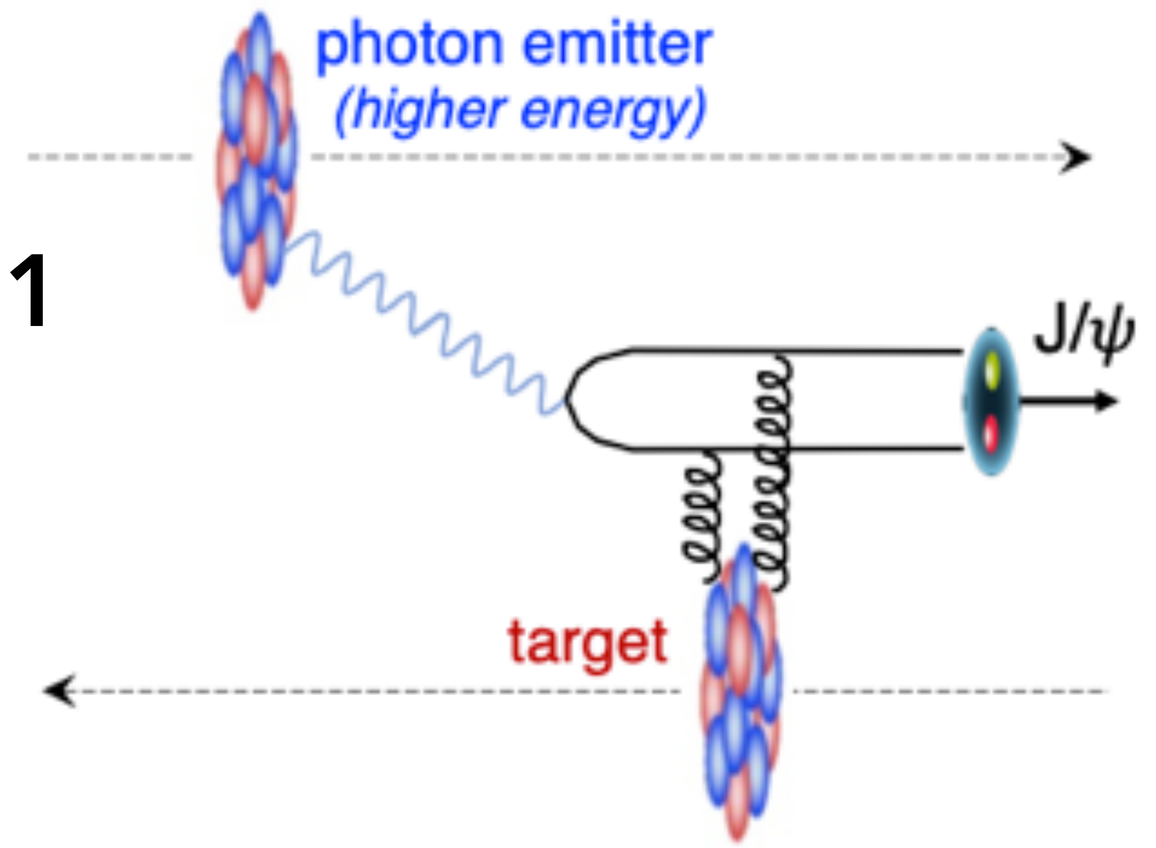


Models cannot describe the full rapidity dependence

Rapidity dependence : Photon energy ambiguity

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

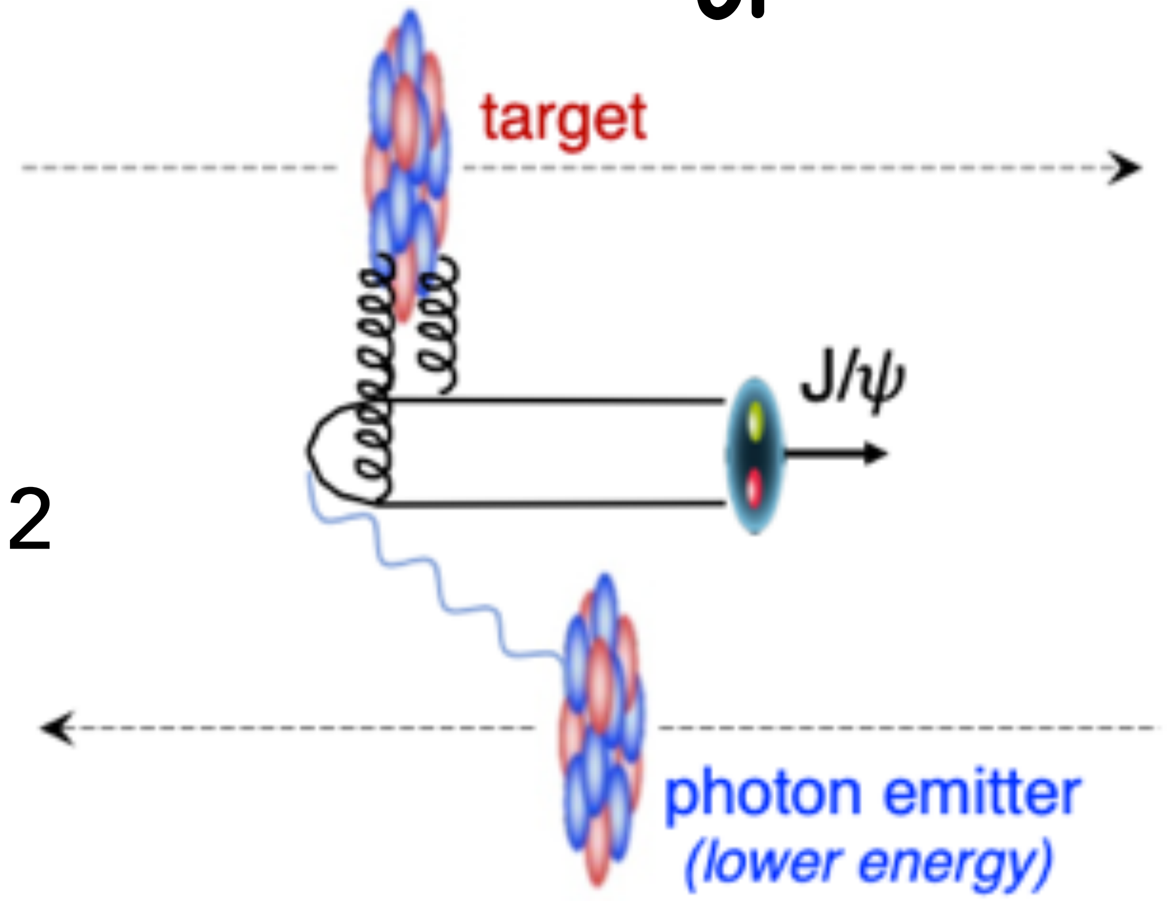
1



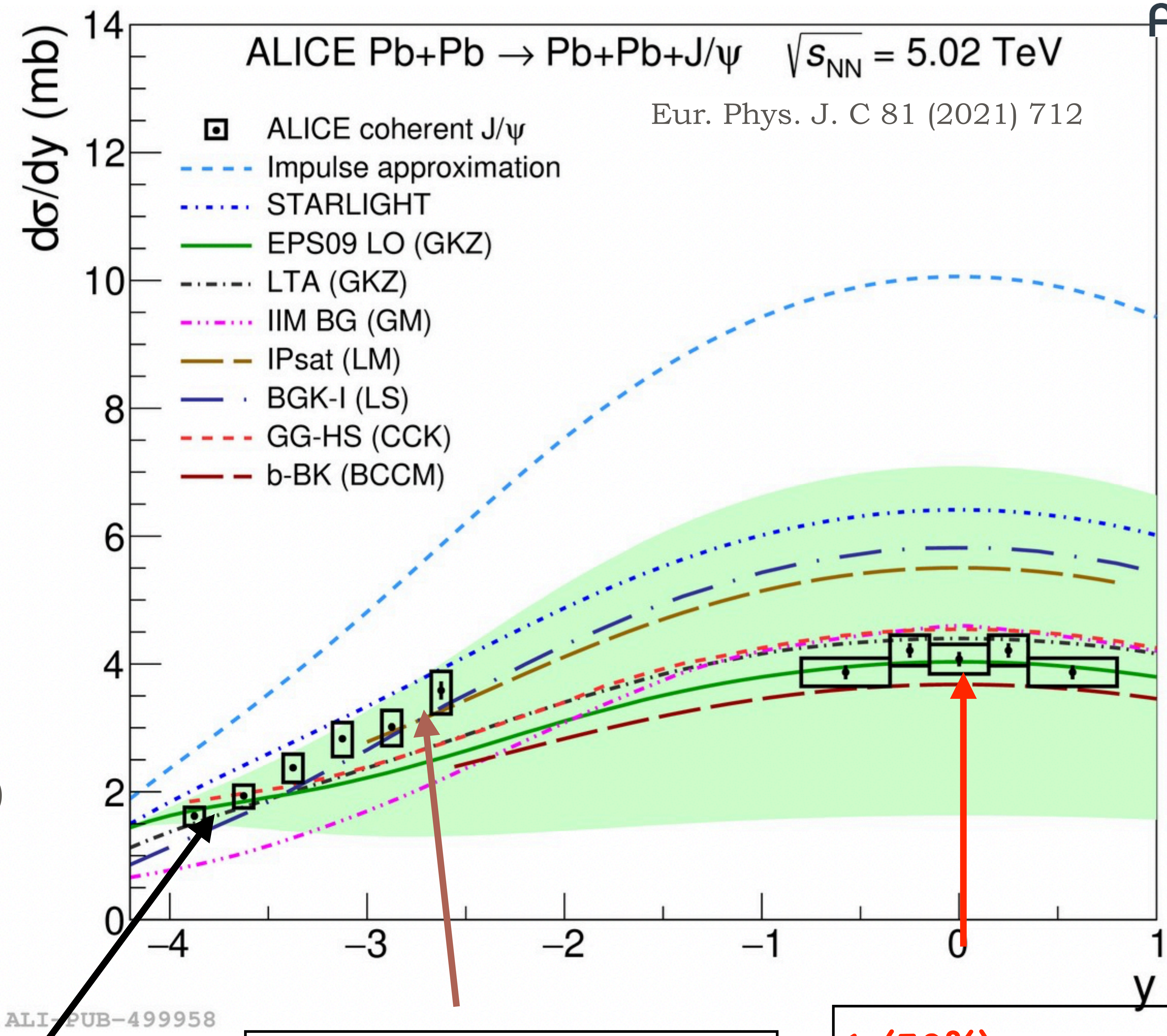
$$x = \frac{m_{J/\psi}^2}{W_{\gamma \mathrm{Pb}}^2}$$

or

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

ALICE

Measured cross section from Pb-Pb collisions

Photon flux at rapidity ±y in the impact parameter range (b1,b2)

$$\frac{d\sigma_{\mathrm{PbPb}}}{dy} = n_\gamma(y; b_{1,2})\sigma_{\gamma\mathrm{Pb}}(y) + n_\gamma(-y; b_{1,2})\sigma_{\gamma\mathrm{Pb}}(-y)$$

Photonuclear cross section: QCD!

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): modelling 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)

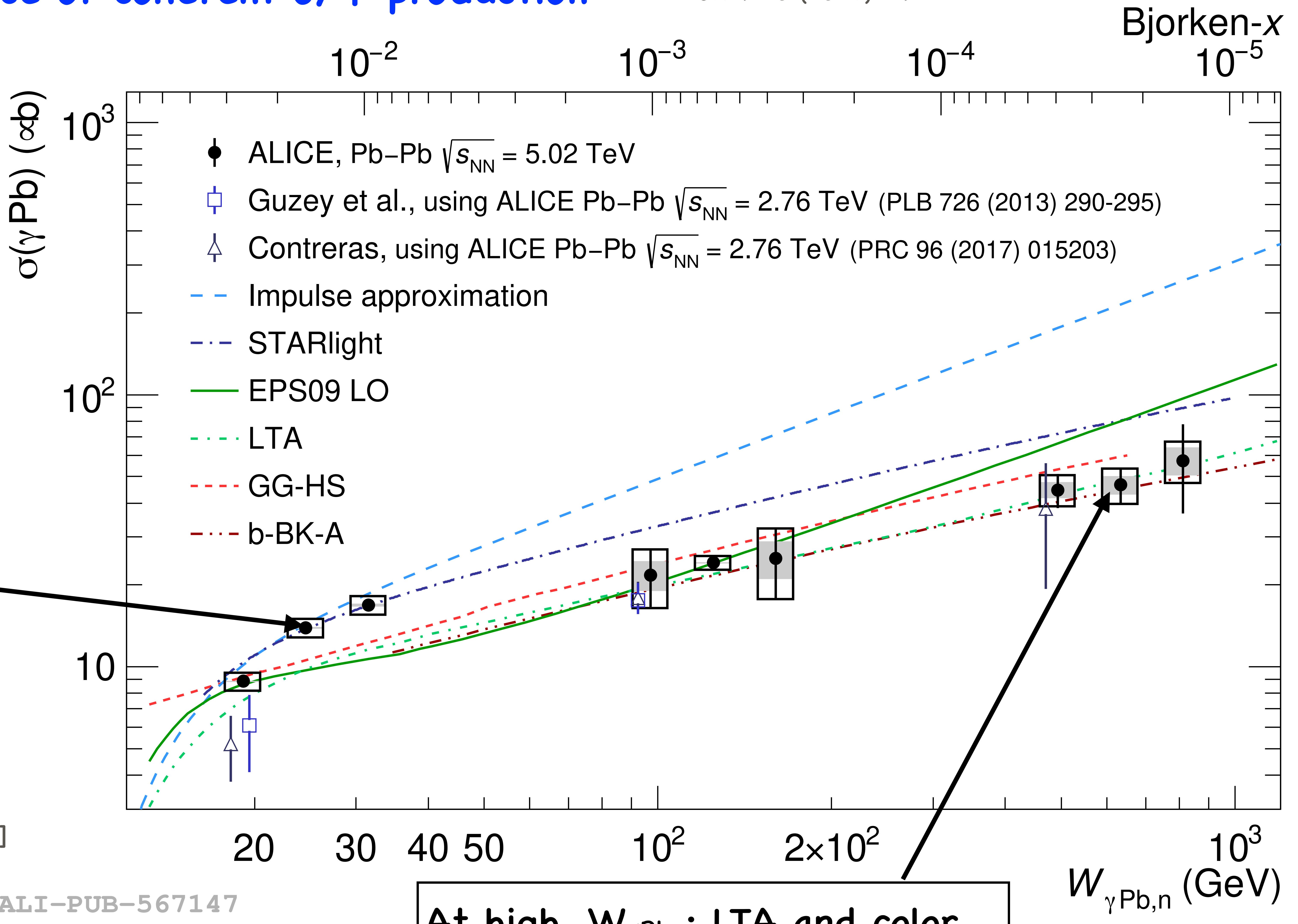
Photo production of VM: $\sigma_{\gamma Pb}$ vs. $W_{\gamma Pb}$ or x

ALICE

Energy dependence of coherent J/Ψ production

JHEP 10 (2023) 119

First measurement of the energy dependence of the photonuclear cross section ($\sigma_{\gamma Pb}$) down to Bjorken-x ~ 10^{-5} JHEP 10 (2023) 119



At low $W_{\gamma Pb}$: Impulse approximation (IA) and STARlight

At high $W_{\gamma Pb}$: LTA and color dipole models(GG-HS, b-BK-A)

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)]
GG-HS (CCK): [PRC. 97(2), 024901 (2018)], and [PLB 766, 186–191 (2017)]
b-BK (BCCM): [PLB 817, 136306 (2021)]

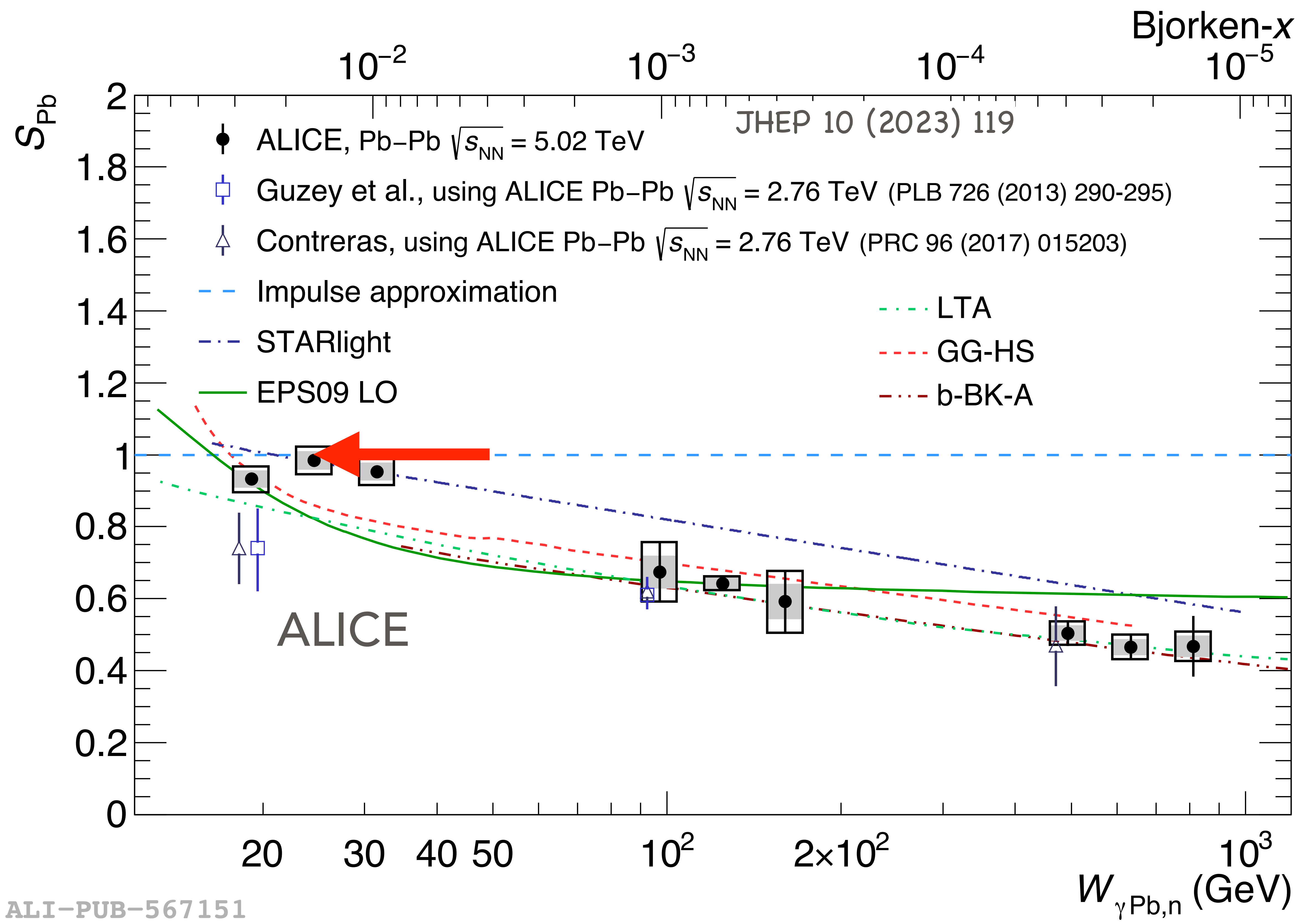
No model describes the whole energy/Bjorken-x range!

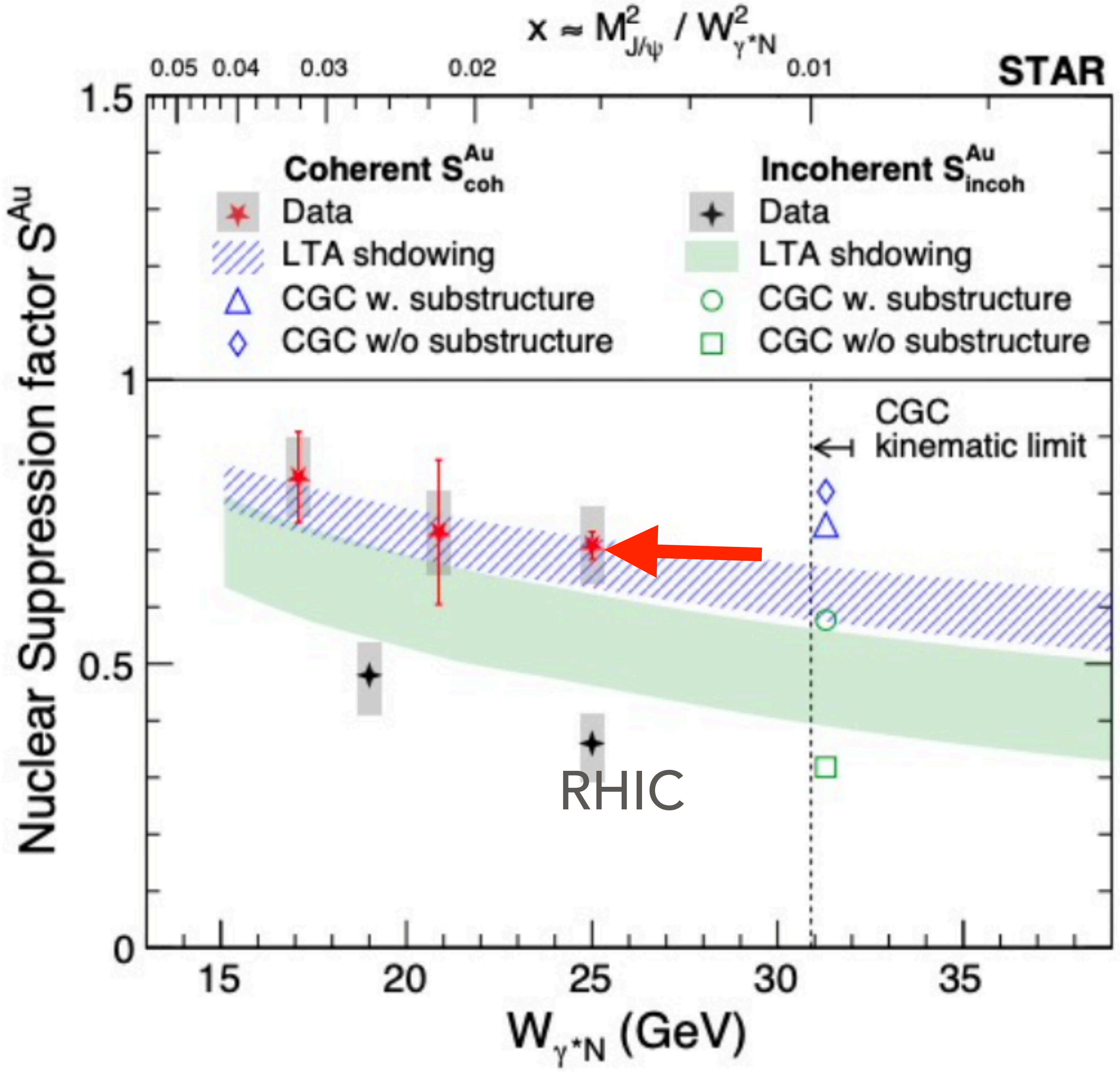
Nuclear suppression factor at LHC and RHIC energies

Nuclear suppression factor due to gluon shadowing

$$S_{Pb/Au} = \sqrt{\frac{\sigma_{\gamma Pb/Au}}{\sigma^{IA}_{\gamma Pb/Au}}}$$

arXiv:2311.13637





At LHC energies , $W_{\gamma Pb}$ = 813 GeV, S_{Pb} = 0.47 ± 0.05 ± 0.03
At RHIC energies, $W_{\gamma Au}$ = 25 GeV, S_{Au} = 0.71 ± 0.04 ± 0.07

CGC Model, H. Mäntysaari et al.,arXiv:2207.03712
LTA model, M.Strickman et al., arXiv:2303.12052

Strong suppression due to nuclear gluon shadowing is observed at both RHIC and LHC energies

At similar $W_{\gamma N}$ (~ 25 GeV), the suppression at ALICE is smaller than at RHIC

Incoherent t-dependent J/Ψ photoproduction cross section

First t-dependent incoherent J/Ψ photoproduction measurement by ALICE Collaboration

—> Sensitive to fluctuations of the gluon distributions in the transverse plane

t : Mandelstam variable = - p_T^2

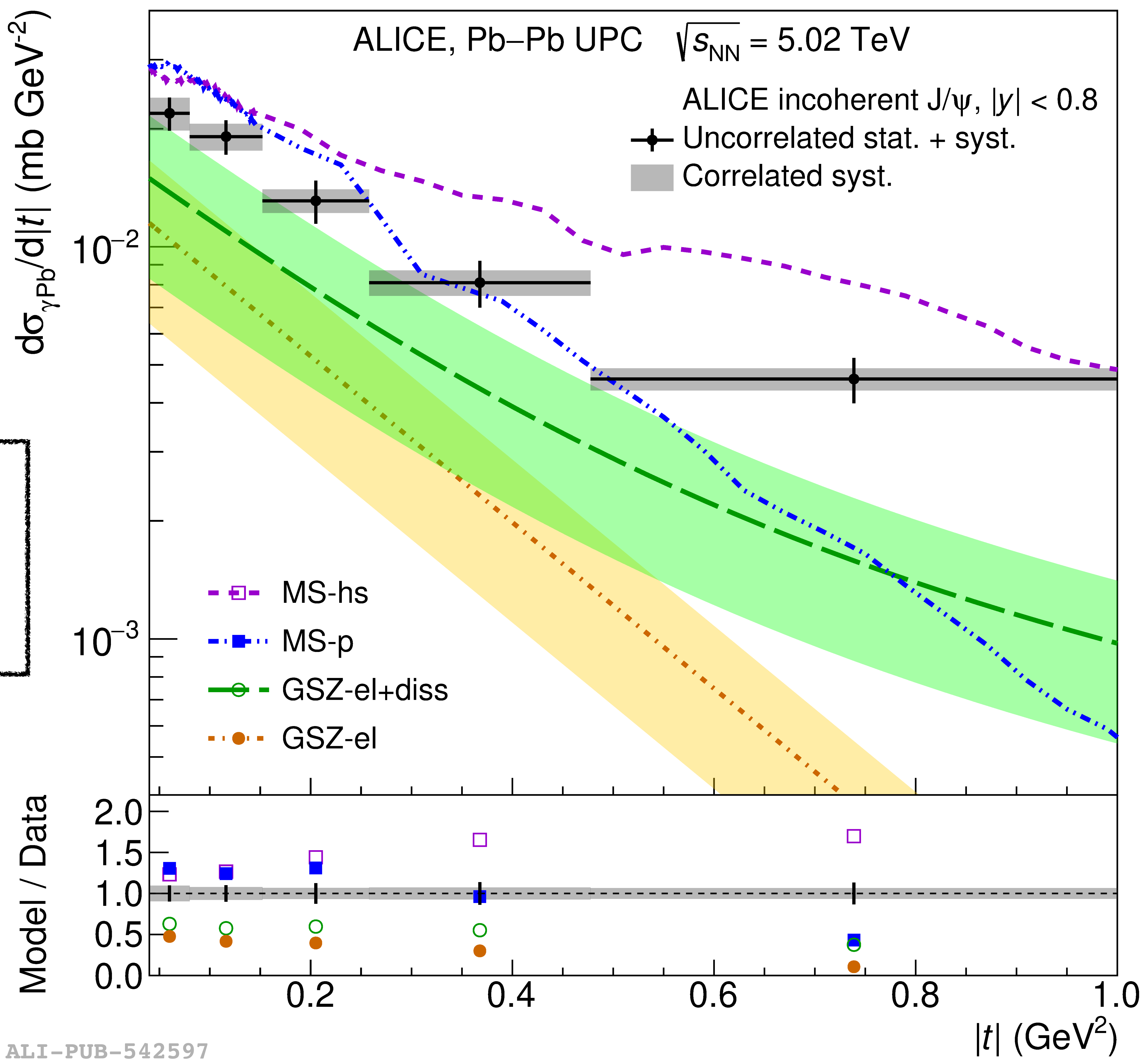
(Slope of) data favor models with gluonic subnucleon fluctuations (hot spots fluctuation event by event in MS-hs, and dissociation including shadowing in GSZ el+dis)

MS (saturation): - Based on IPsat model, PLB 772 (2017) 832

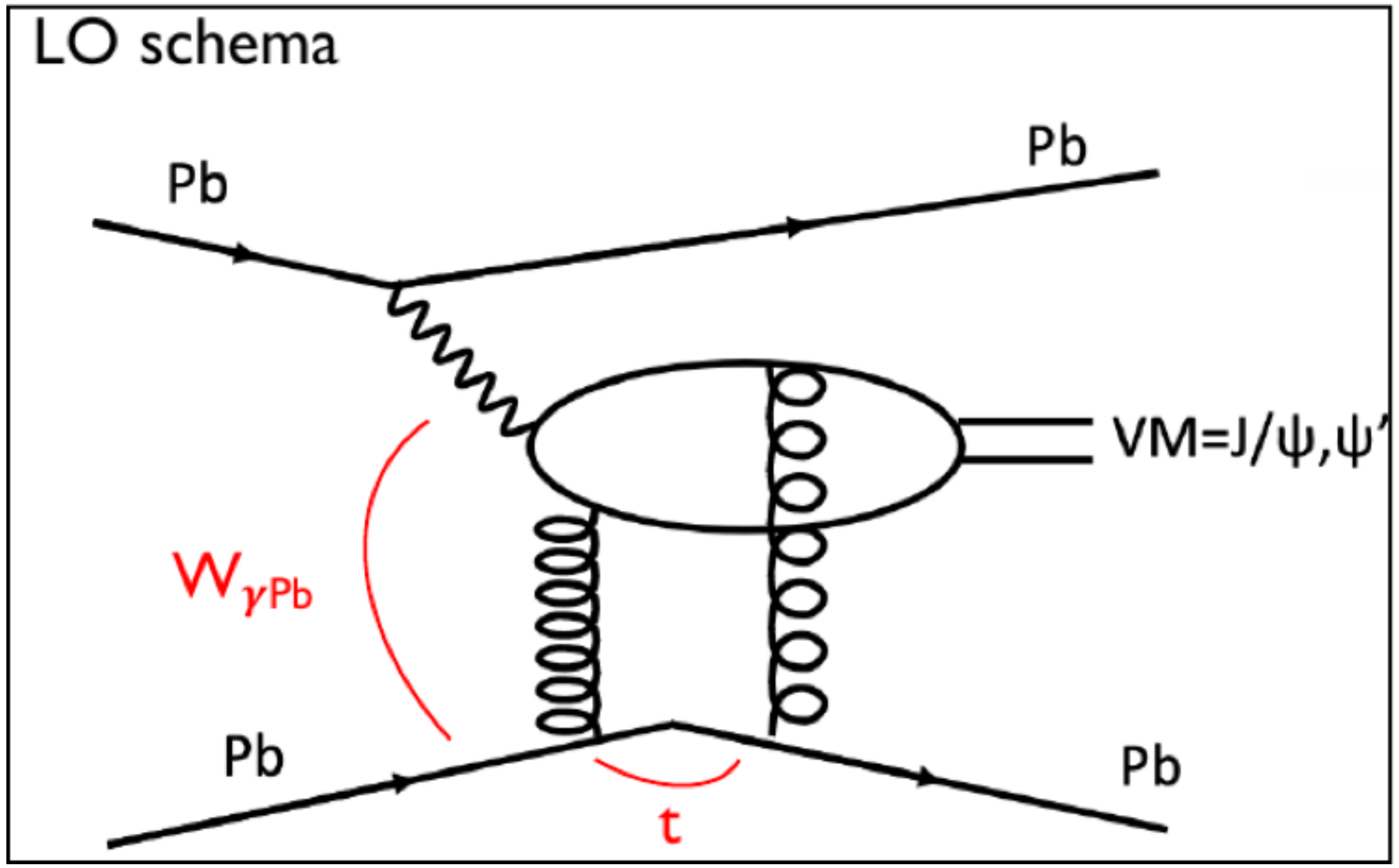
GSZ (shadowing): VDM based on LTA shadowing including elastic and/or dissociative part, PRC 99 (2019) 015201

MSS (saturation): Based on JIMWLK equations, PRD 106, 7 (2022) 074019

ALICE, arXiv:2305.06169, accepted by PRL



photoproduction of VM in events with nuclear overlap



Published/preliminary results:

ALICE in peripheral and semicentral Pb—Pb at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV. PRL 116, 222301(2016), PLB 846 (2023) 137467

Preliminary results:

First y-differential J/Ψ photoproduction cross section (forward y), first J/Ψ polarization measurement at low p_T (forward y), coherent J/Ψ photoproduction cross section vs. centrality (mid y) in Pb—Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

STAR in peripheral and semicentral Au—Au and Cu-Cu at $\sqrt{s_{NN}}$ = 200 GeV. PRL 123, 132302 (2019

LHCb in peripheral Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV PRC 105 (2022) L03201

VM photoproduction in heavy-ion collisions with nuclear overlap

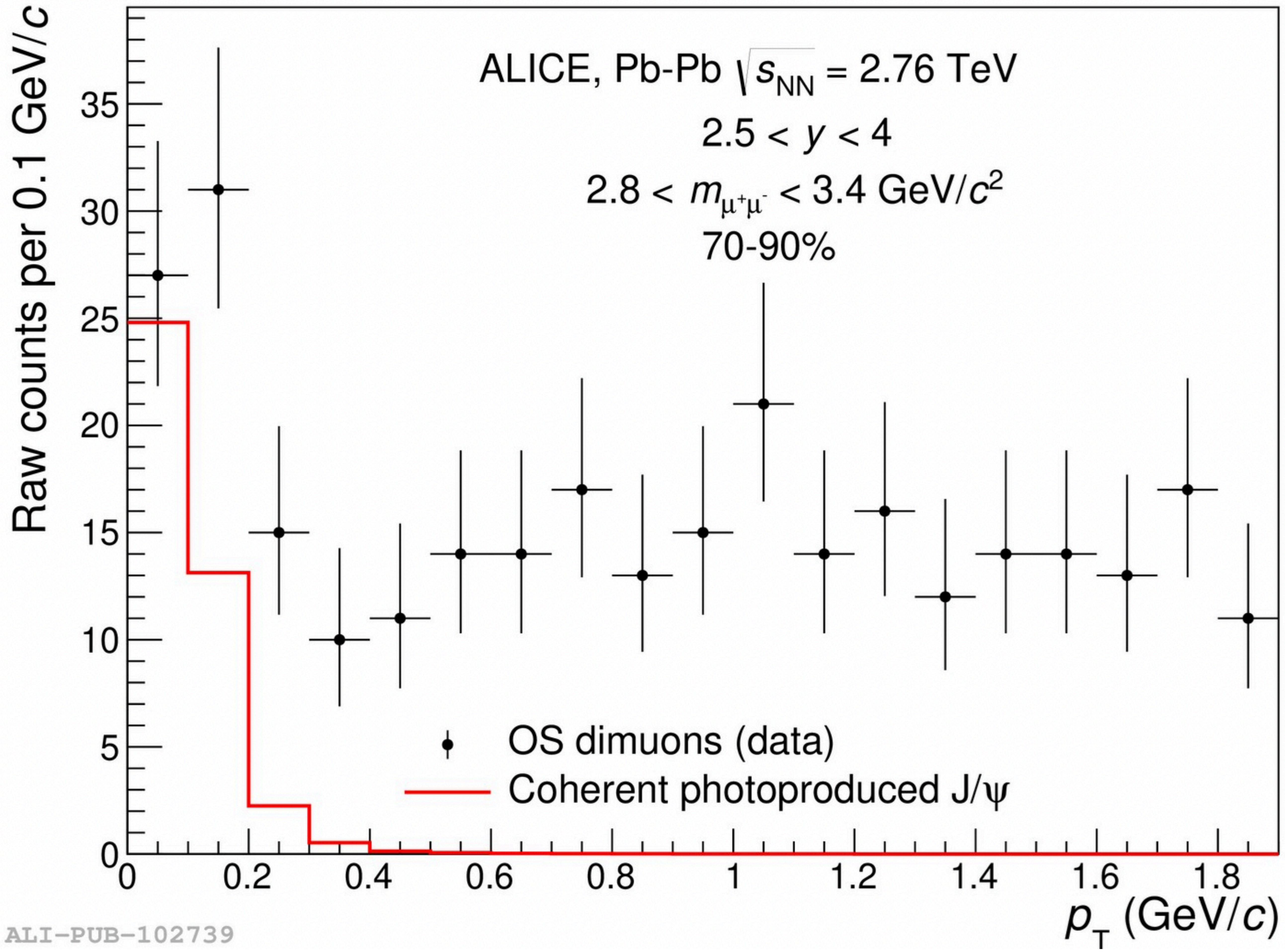
ALICE

PRL 116, 222301(2016)

STARlight MC : Comp. Phys. Comm. 212 (2017) 258.

First J/ψ excess for p_T < 0.3 GeV/c observed by ALICE Collaboration at forward rapidity in the centrality 70–90% for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, PRL 116, 222301(2016)

-> Interpreted as a sign of dominant **contribution from coherent photoproduction mechanism** to the very low p_T J/Ψ yield in peripheral events.



Similar J/ψ excess yield measurements were performed by LHCb Collaboration, PRC 105 (2022) L03201 and by STAR Collaboration, PRL 123, 132302 (2019)

VM photoproduction in heavy-ion 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-Pb} = yield of J/ψ in Pb—Pb collisions

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

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

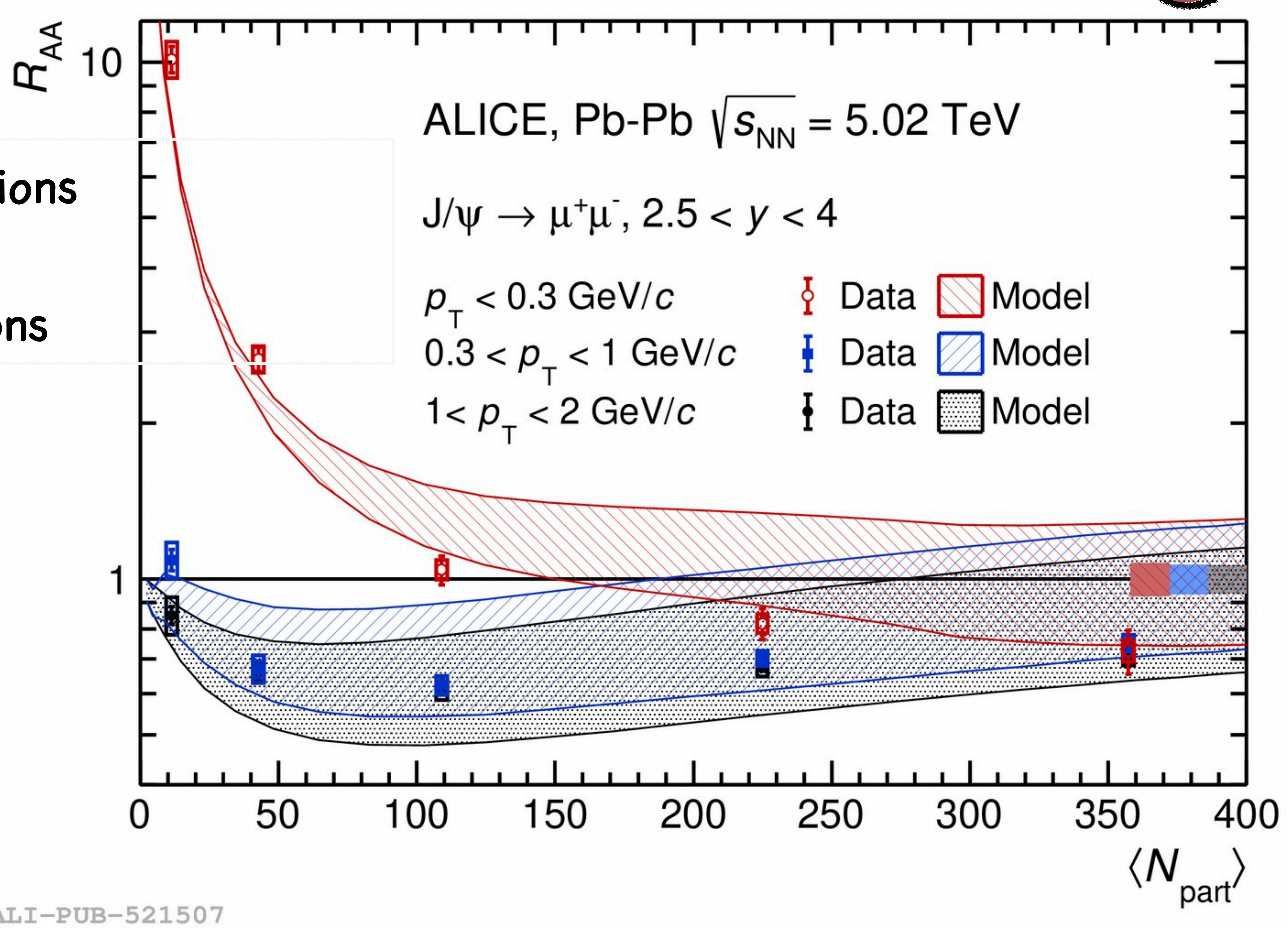
Enhancement at very low p_T

R_{AA} reaches 10 !

First significant measurement of a very low-p_T J/Ψ excess in semi-central collisions at LHC (5.6σ for 30-50% centrality, $<N_{part}>$ ~ 100)

—>Excess at very low-p_T supports **a plausible origin from a photoproduction mechanism**

PLB 846 (2023) 137467
Model: W. Shi et al., PLB 777 (2018)



70-90% 50-70% 30-50%. 10-30%. 0-10%

Increase of J/Ψ R_{AA} in agreement with model including a dominant photoproduction mechanism at low p_T in most peripheral collisions

Coherent J/ψ photoproduction : centrality dependence

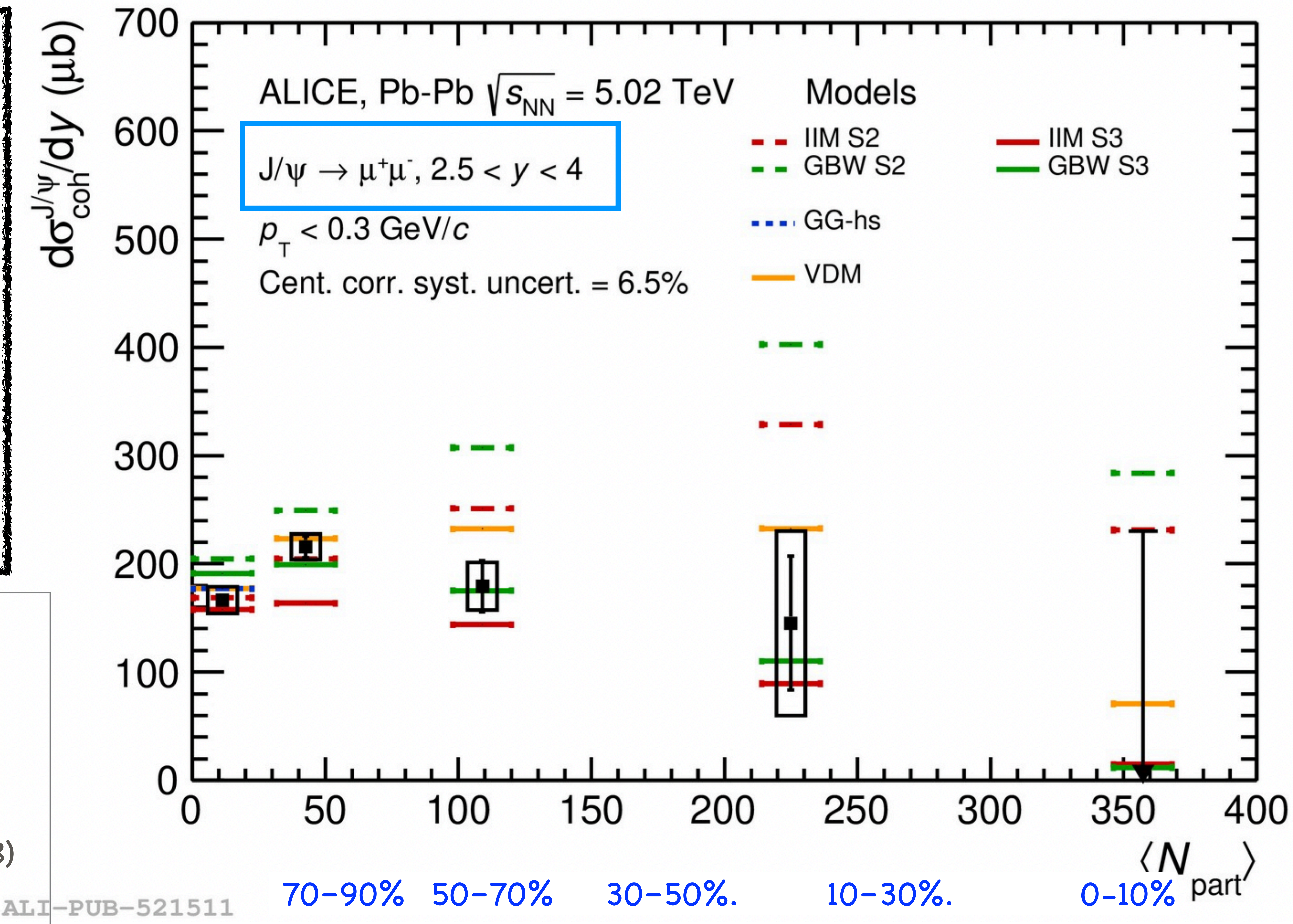
ALICE

Forward rapidity

Phys. Lett. B 846 (2023) 137467

Measurements of the coherent photoproduced J/Ψ cross section **at forward rapidity show no signficant centrality dependence**

Data are qualitatively described by **a large number of models developed for UPC and extended to account for the nuclear overlap**



70-90% 50-70% 30-50%. 10-30%. 0-10%

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

[1]Equivalent photon approximation + Vector dominance model (VDM), M. Klusek-Gawenda et al., PRC93, 044912 (2016)

[2] Coherent VM photoproduction: Different coupling assumptions between nucleus (photon emitter) and spectator (pomeron emitter) , W. Zha, PRC 97, 044910 (2018)

[3] GBW/IIM dipole model : M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)

i. UPC like : b-dependence (S1).

ii. Effective photon flux (S2)

iii. Effective photon flux + photo nuclear cross section (S3)

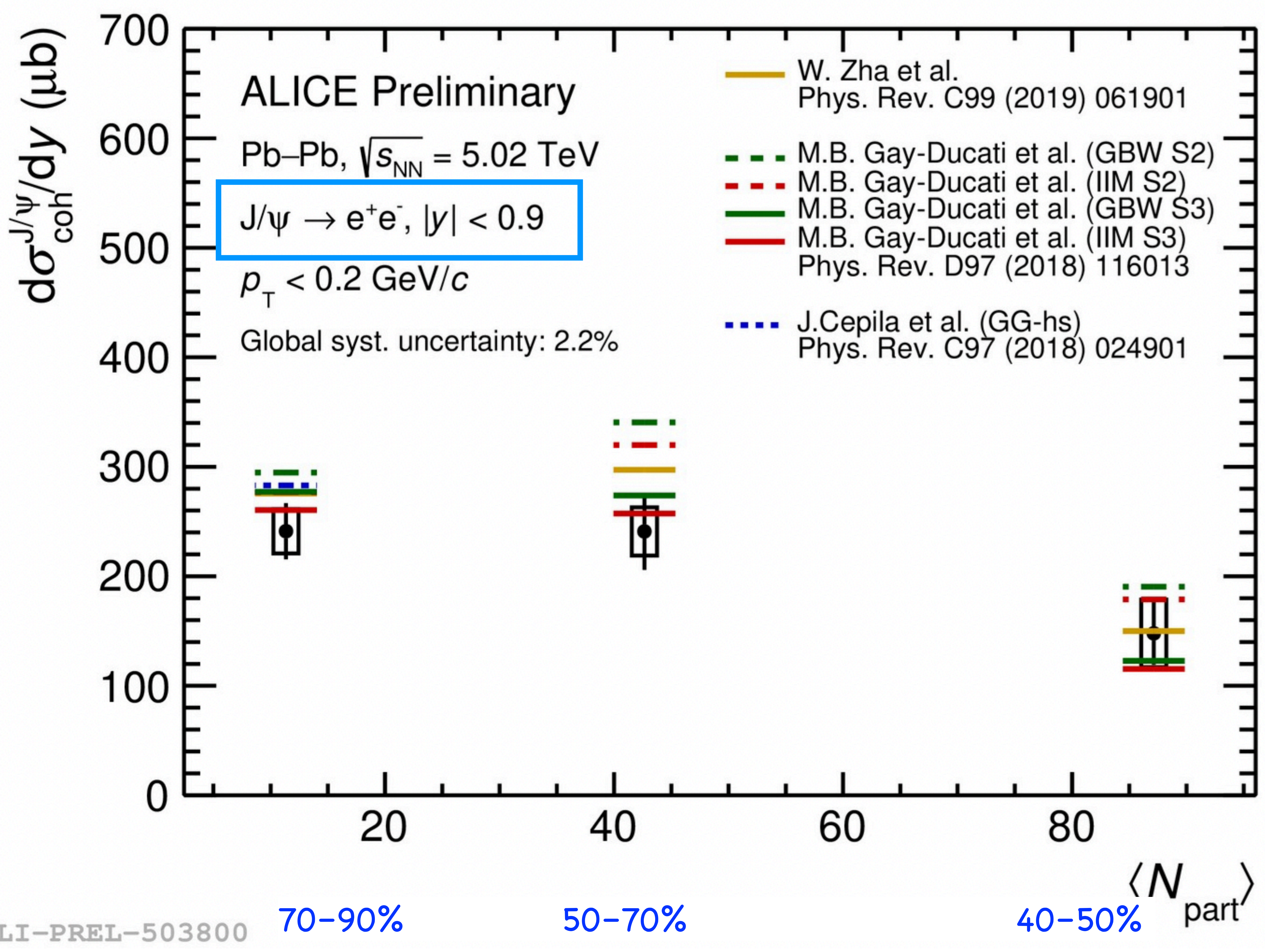
[4] Coherent J/ψ photonuclear production in an energy-dependent hot-spot model, J. Cepila et al., Phys. Rev. C 97, 024901 (2018)

Coherent J/ψ photoproduction : centrality dependence

midrapidity

Both measurements at mid and forward rapidity don't show a significant centrality dependence

Data are qualitatively described by a large number of models developed for UPC and extended to account for the nuclear overlap



Understanding of the existence of coherent J/Ψ photoproduction in heavy ion collisions with nuclear overlap is theoretically challenging

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

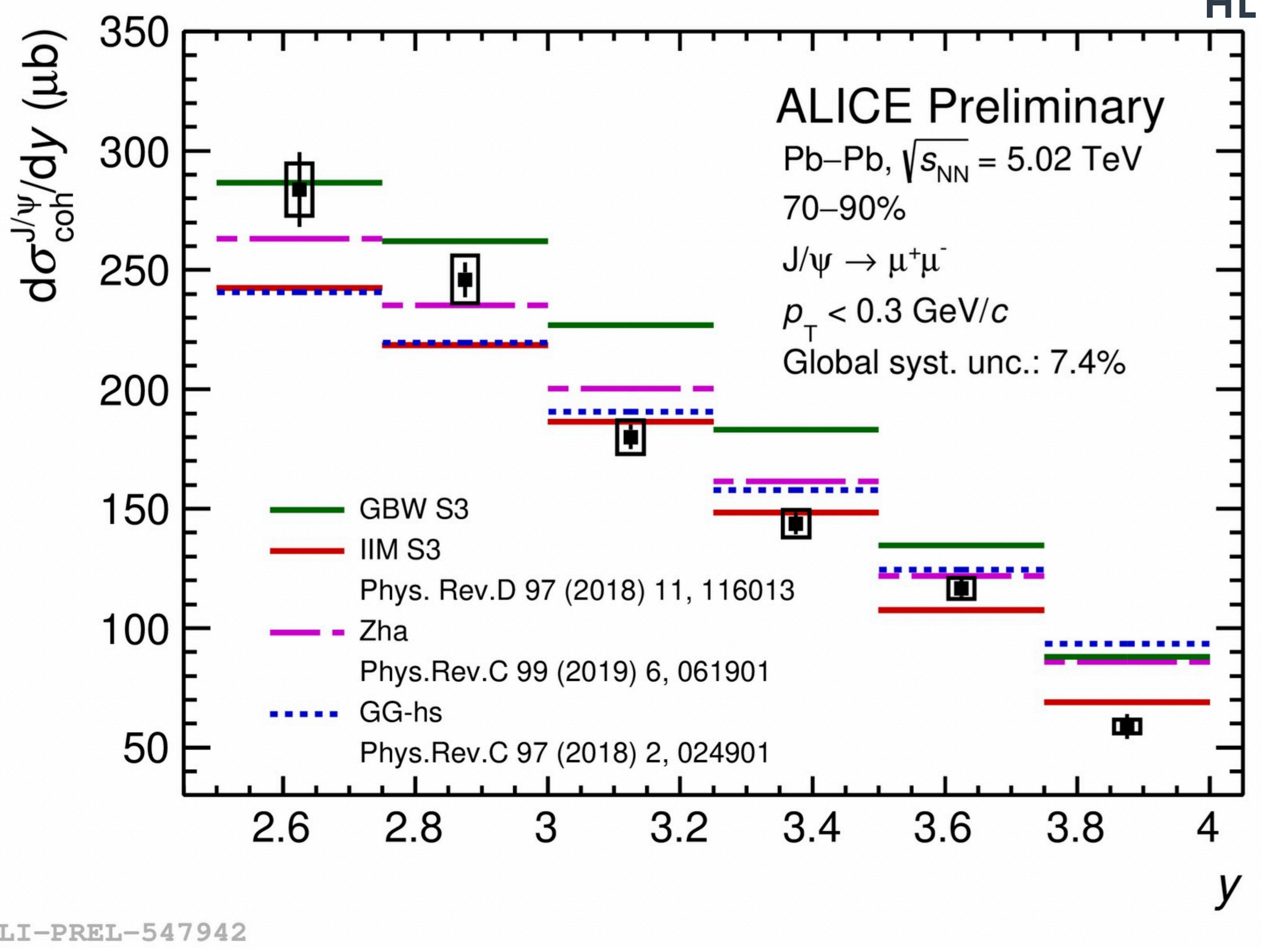
Coherent J/ψ photoproduction : rapidity dependence

GG -hs : γ-flux with constraints on impact parameter range J. Cepila et al., PRC 97, 024901 (2018)

Zha : assumptions on γ-pomeron coupling (nucleus+spectator) W. Zha, PRC 97, 044910 (2018)

GBW/IIM S3 : effective photon flux and photonuclear cross section considered w.r.t UPC calculations (accounting for nuclear overlap)

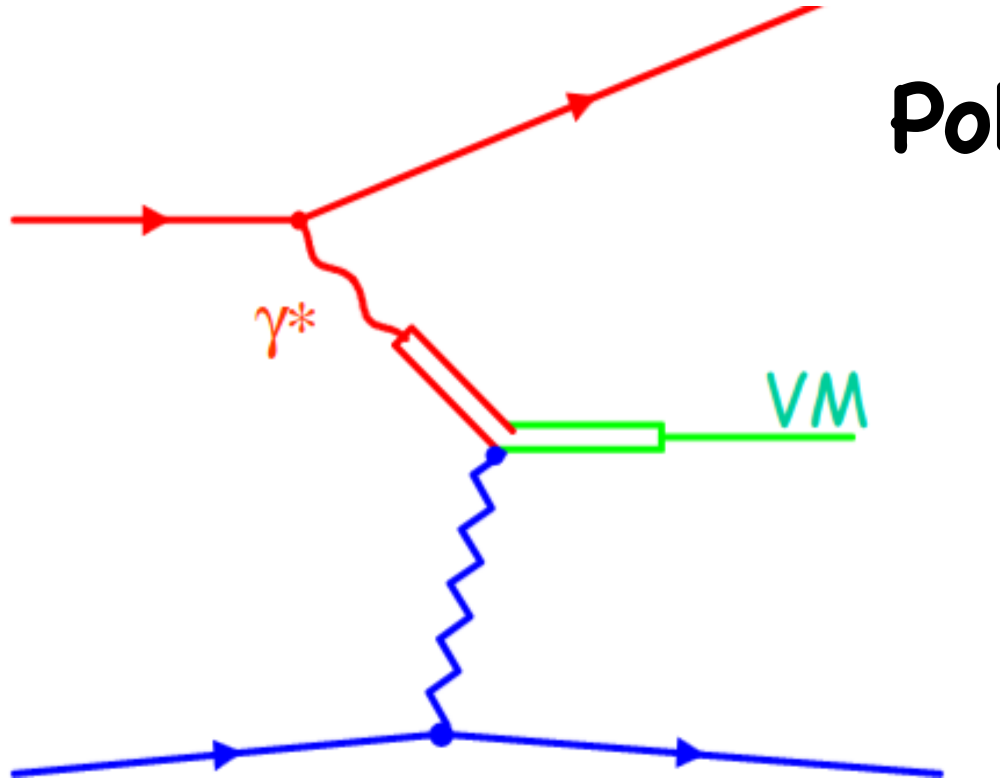
M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)



Models initially developed for VM photoproduction in UPC and modified for PC are able **to describe qualitatively the magnitude of the cross section, but fail at reproducing the y-dependence,** similar behaviour hold as well for UPC measurement, Eur. Phys. J. C 81 (2021) 712

Better description of UPC data by models needed to interpret the peripheral and semi-central data

Polarization : Coherent vector meson photoproduction



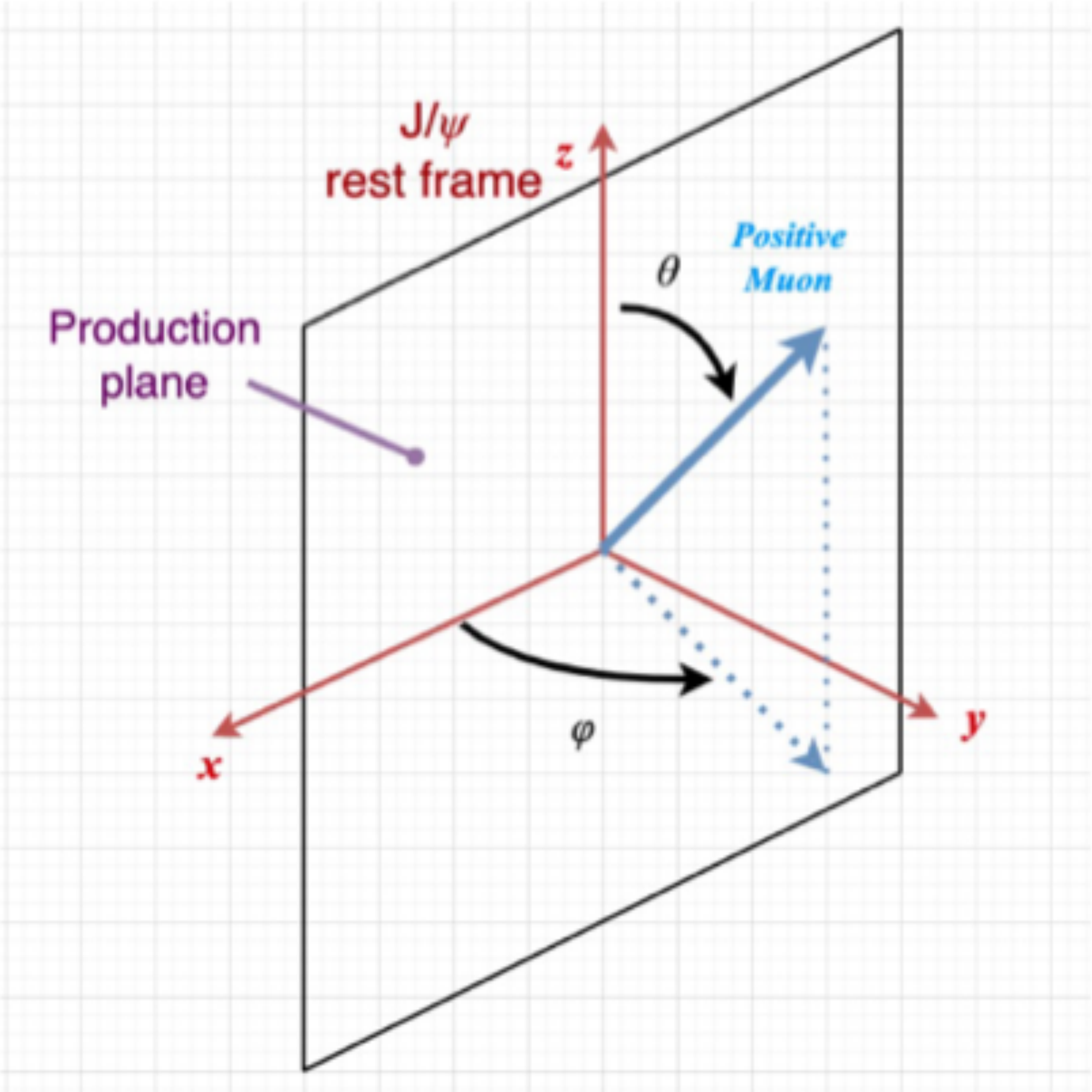
Polarization refers to the particle spin alignment with respect to a chosen direction

s-channel helicity conservation (SCHC): helicity or polarization of photon transferred to vector meson (J/ψ)

—> Vector meson expected to keep the polarization of the incoming photon

PLB 31 (1970) 387-390, JETP Lett. 68 (1998) 696-703

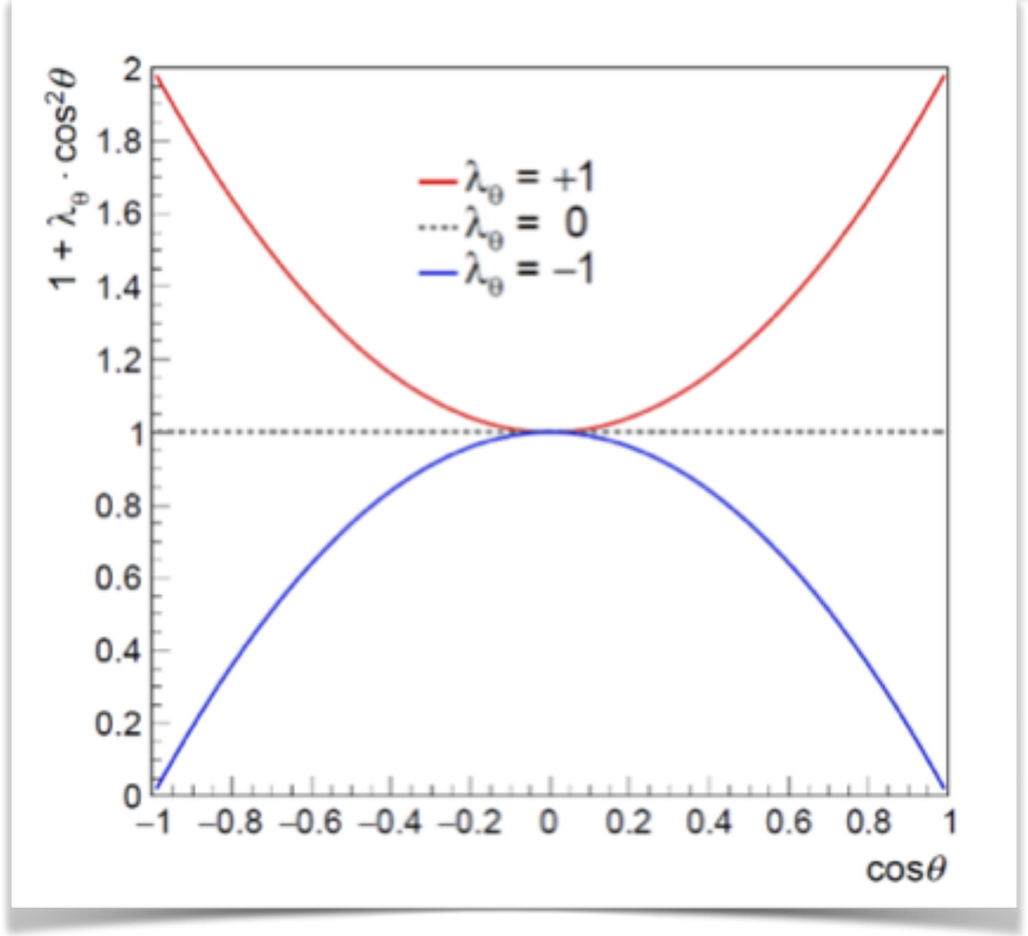
Helicity frame, z-axis (polarization axis): flight direction of the J/ψ in its rest frame



Dilepton decay angular distribution

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

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



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

Coherently photoproduced J/ψ polarization in Pb–Pb collisions

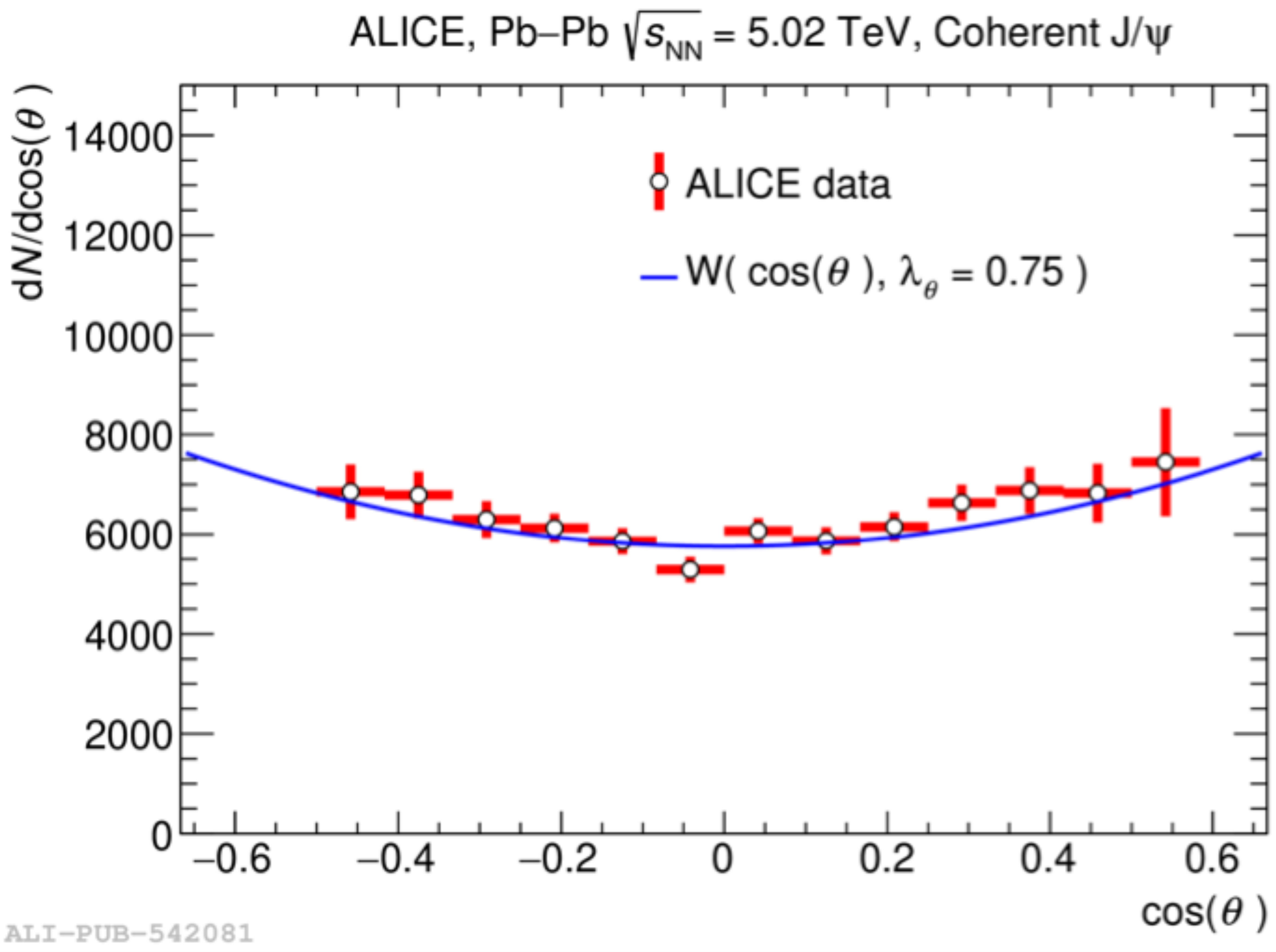
ALICE

First coherently photoproduced J/ψ polarization measured in UPCs at $\sqrt{s_{NN}}$ = 5.02 TeV arXiv:2304.10928

λ_θ values, for UPC, are found to be consistent with unity within uncertainties

-> J/Ψ transversely polarized

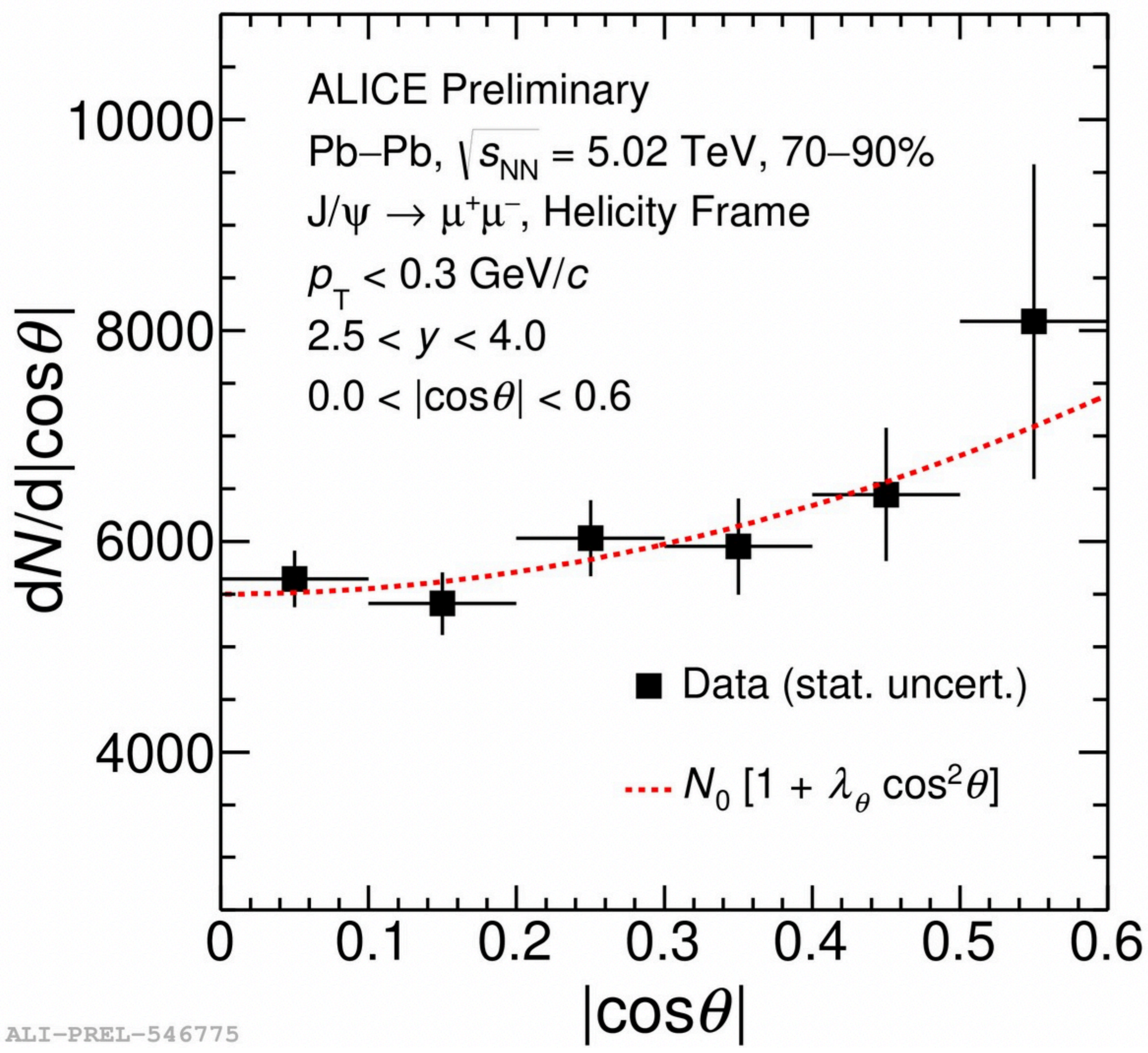
->Consistent with SCHC hypothesis

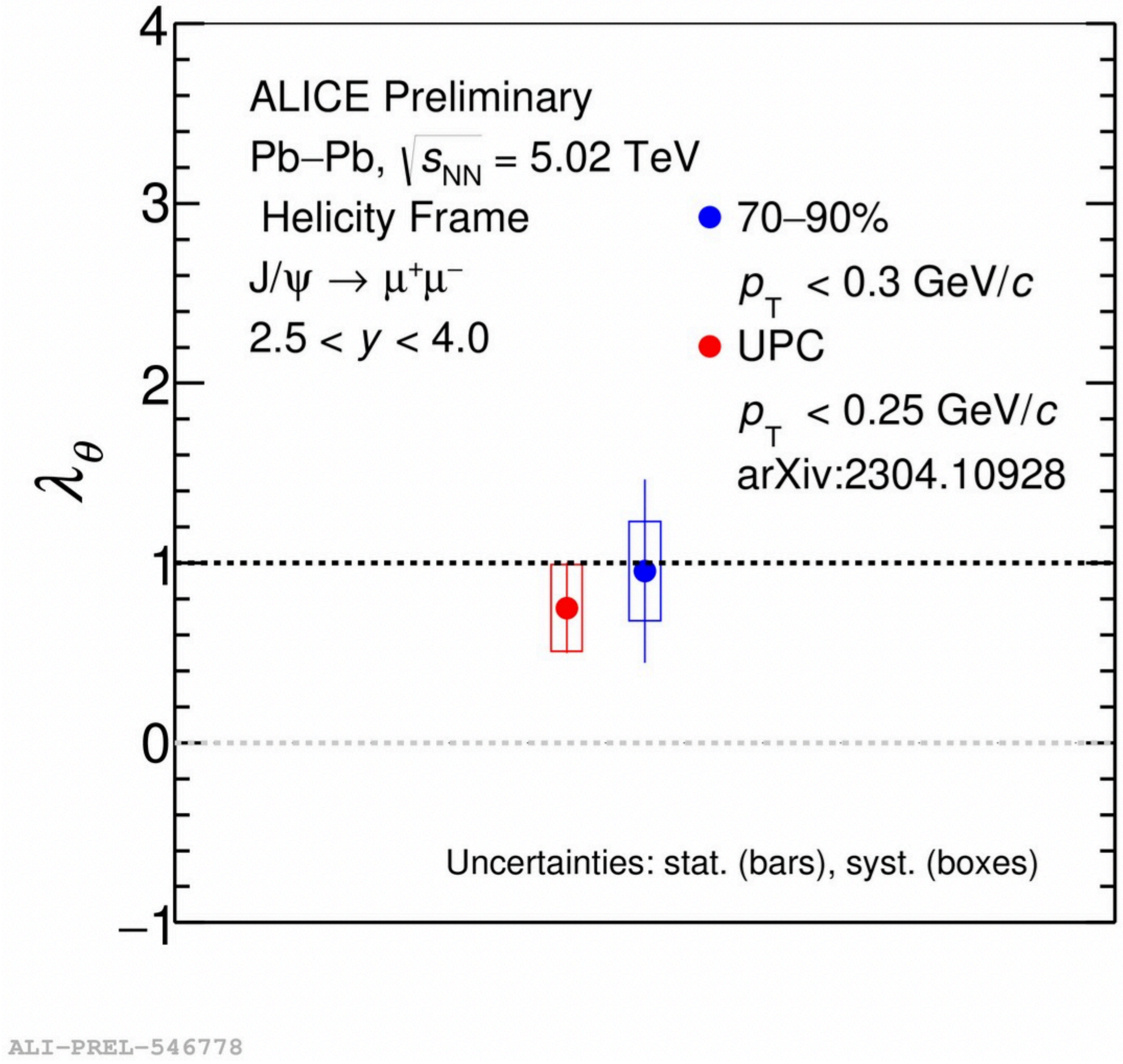


Can we make a similar observation for J/ψ at low p_T (< 0.3 GeV/c) in Pb—Pb collisions with nuclear overlap (70–90%) ?

-> Additional challenge w.r.t UPC measurement: presence of hadronic J/ψ contribution

Inclusive J/ψ polarization in Pb-Pb collisions for p_T < 0.3 GeV/c





Fit to the AxE corrected J/ψ yield to extract λ_θ suggests a **transverse polarization**

λ_θ value of inclusive J/ψ for p_T < 0.3 GeV/c **consistent with UPC measurement**

Summary

☑ VM photoproduction in UPCs

- ✓ Nuclear gluon structure probed at LHC with coherent J/Ψ in the Bjorken-x region ~10^{-2} – 10^{-5}
- ✓ Probed gluon fluctuations at sub-nucleon scale for the first time in |t|-dependent incoherent J/Ψ photoproduction
- ✓ Coherent J/Ψ transverse polarization observed in UPCs

☑ Coherent VM photoproduction in events with nuclear overlap

- ✓ Excess of J/Ψ yield at low p_T at mid and forward rapidity -> supports coherent photoproduction origin
- ✓ First y–differential coherently photoproduced J/ψ cross section at forward rapidity and low p_T < 0.3 GeV/c -> Available model calculations fail to reproduce measured y-dependence (similar to UPC)
- ✓ First inclusive J/Ψ polarization measurement at forward rapidity and low p_T < 0.3 GeV/c -> Hint for transverse polarization, agreement with SCHC hypothesis and with UPC measurement

Photoproduced quarkonium is an ideal probe for photon-induced processes

Outlook

ALICE Run 3/4 and other LHC experiments will collect a large Pb-Pb data sample :

-> Possibility to explore more differential measurements for photon-induced processes at LHC energies

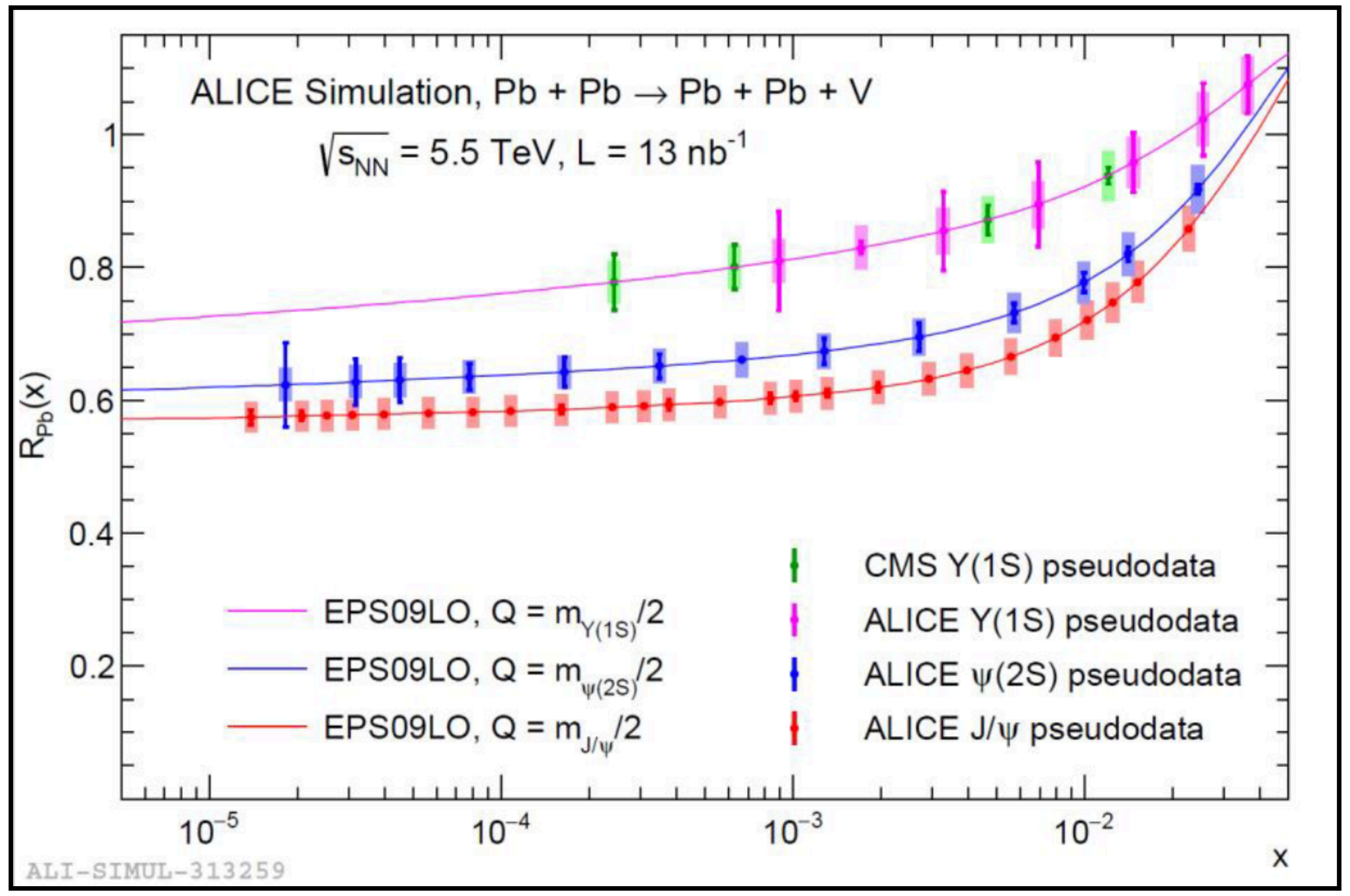
- **For photoproduction of vector mesons in Pb—Pb collisions with nuclear overlap :**

-> Possibility to study J/ψ photoproduction in the most central collisions at forward and midrapidity

-> Better precision on multi-differential cross section and polarization measurements to constrain the models

-> Access to excited states i.e., Ψ(2S) to look for possible QGP effects on the photoproduced probe

Run 3/4: UPC



Run 3/4: UPC

CERN Yellow Rep.Monogr. 7 (2019) 1159 — PbPb — L_{Pb-Pb} = 13/nb

Meson	σ	All Total	$\lvert y\rvert < 0.9$ Total	$\lvert y\rvert < 2.4$ Total	$2.5 < y < 4.0$ Total	$2 < y < 5$ Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Back up

VM photo production cross section vs. y at LHC experiments

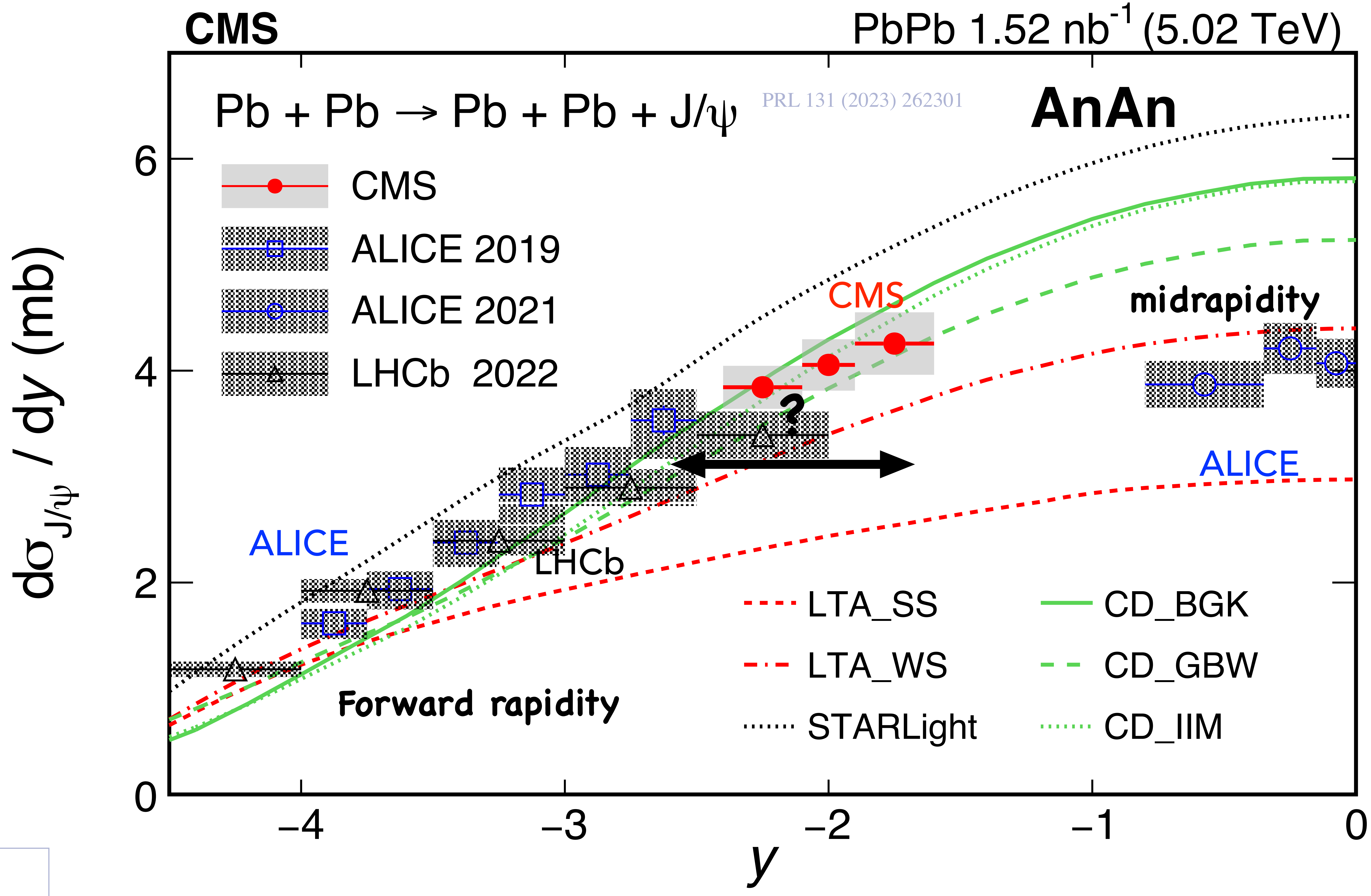
Forward region (ALICE, CMS, LHCb):

$J/\Psi \rightarrow \mu^+\mu^-$

Midrapidity region (ALICE) :

$J/\Psi \rightarrow \mu^+\mu^-, e^+e^-, pp$

Compatibility between ALICE and LHCb at forward rapidity but values are found different among experiments in the rapidity, $-2.5 < y < -1.5$

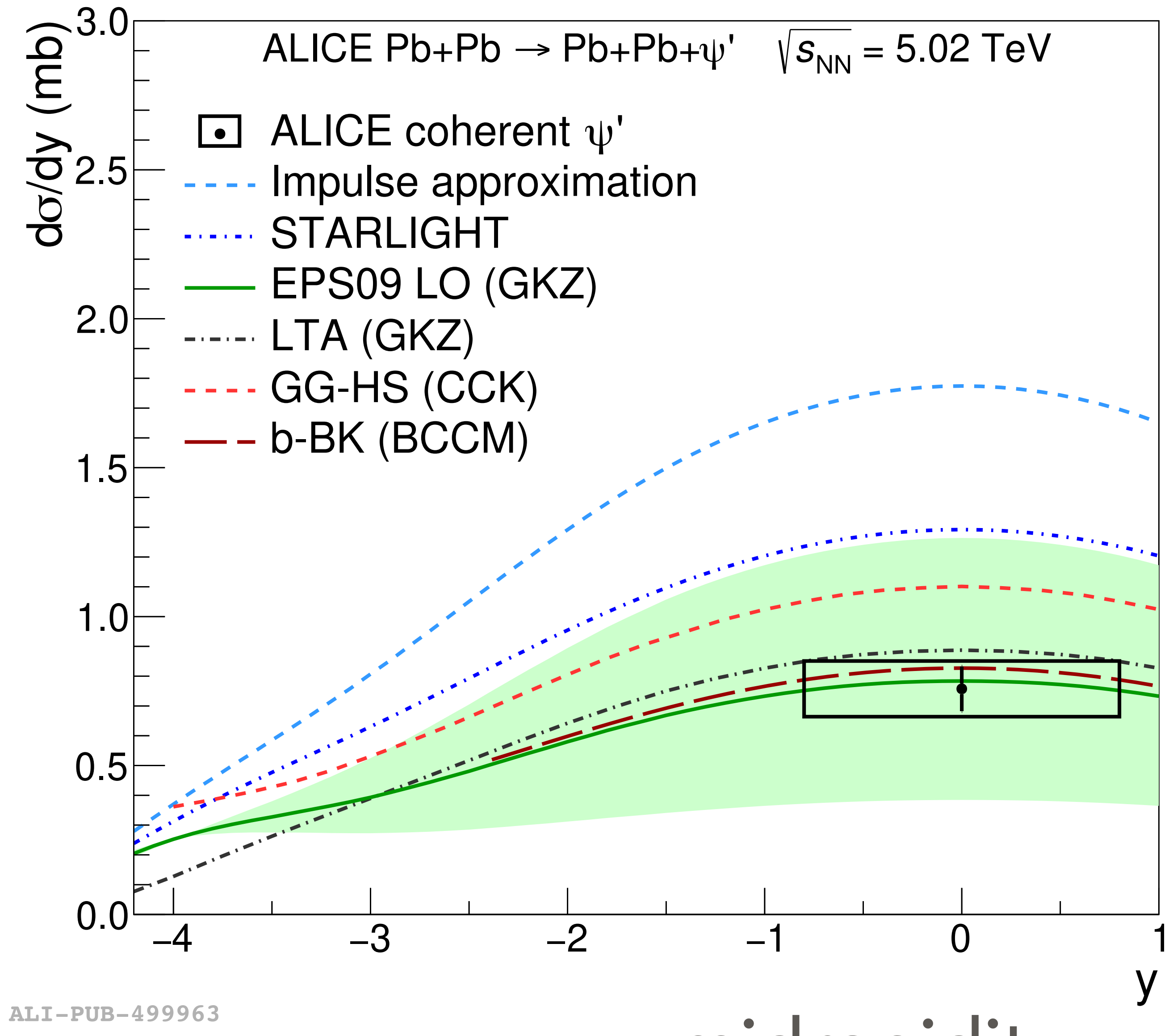


ALICE: EPJ C 81 (2021) 712
LHCb: JHEP 07 (2022) 117, JHEP 06 (2023) 146
CMS: PRL 131 (2023) 262301

Models cannot describes the full rapidity dependence

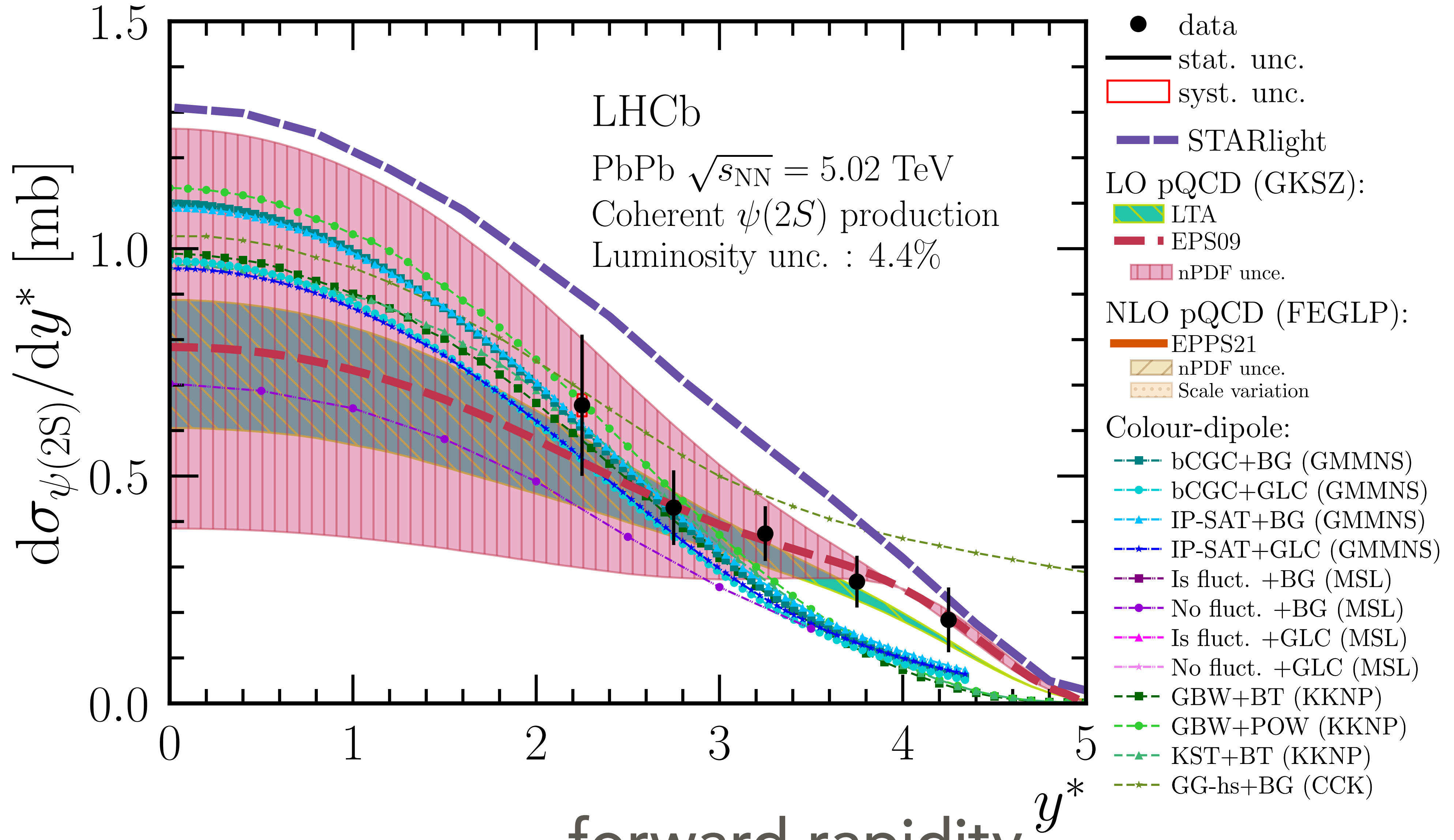
Coherent Ψ(2S) photoproduction cross section

ALICE: Eur. Phys. J. C 81 (2021) 712



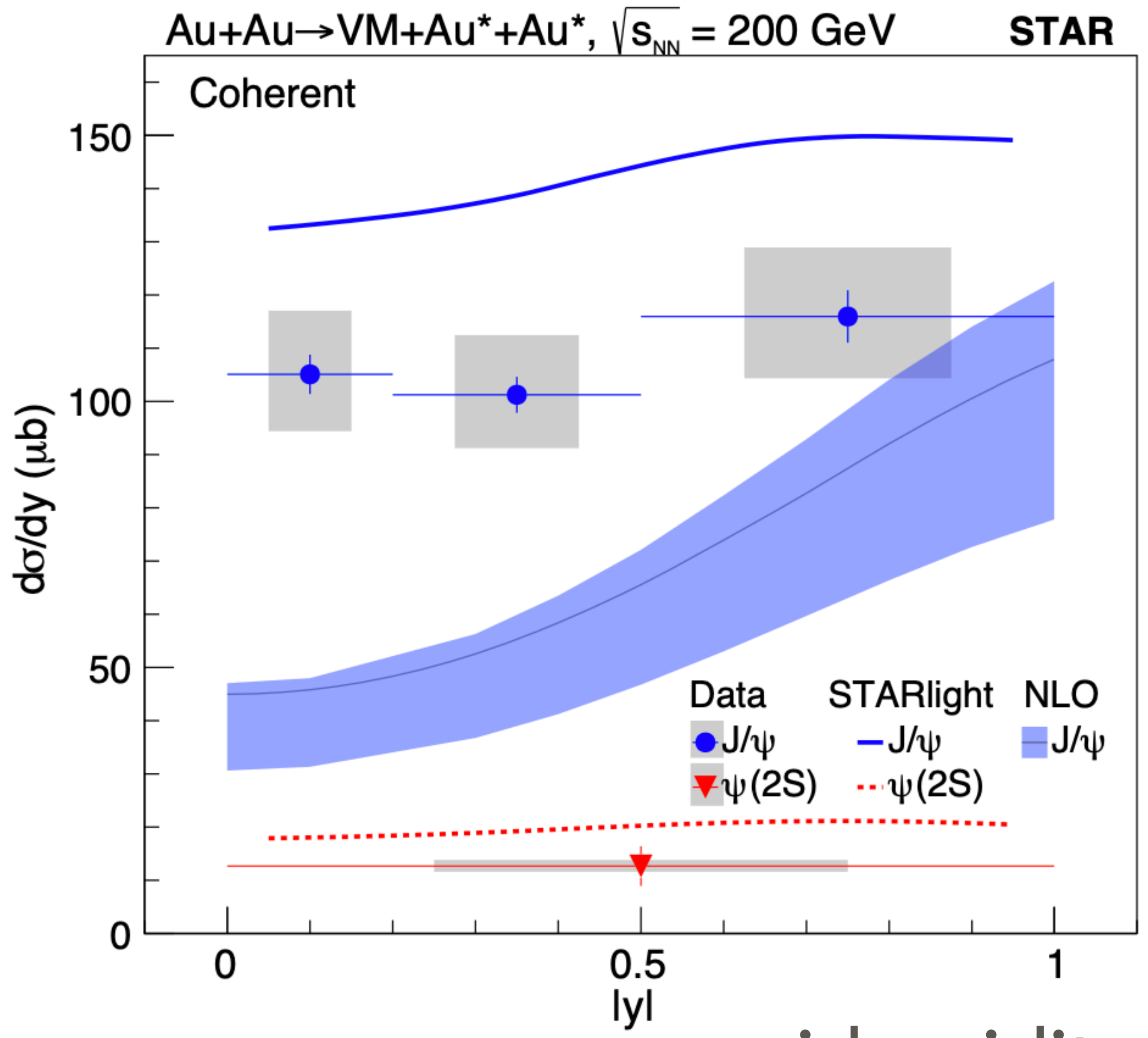
midrapidity

LHCb, JHEP 06 (2023) 146



forward rapidity

RHIC, arXiv:2311.13632



midrapidity

Nuclear gluon shadowing factor, S_{Pb} = 0.66 ± 0.06, consistent with the value obtained from J/Ψ

First y-differential Ψ(2S) photoproduction cross section by LHCb

First midrapidity Ψ(2S) by STAR Collaboration

VM photoproduction in heavy-ion collisions with nuclear overlap

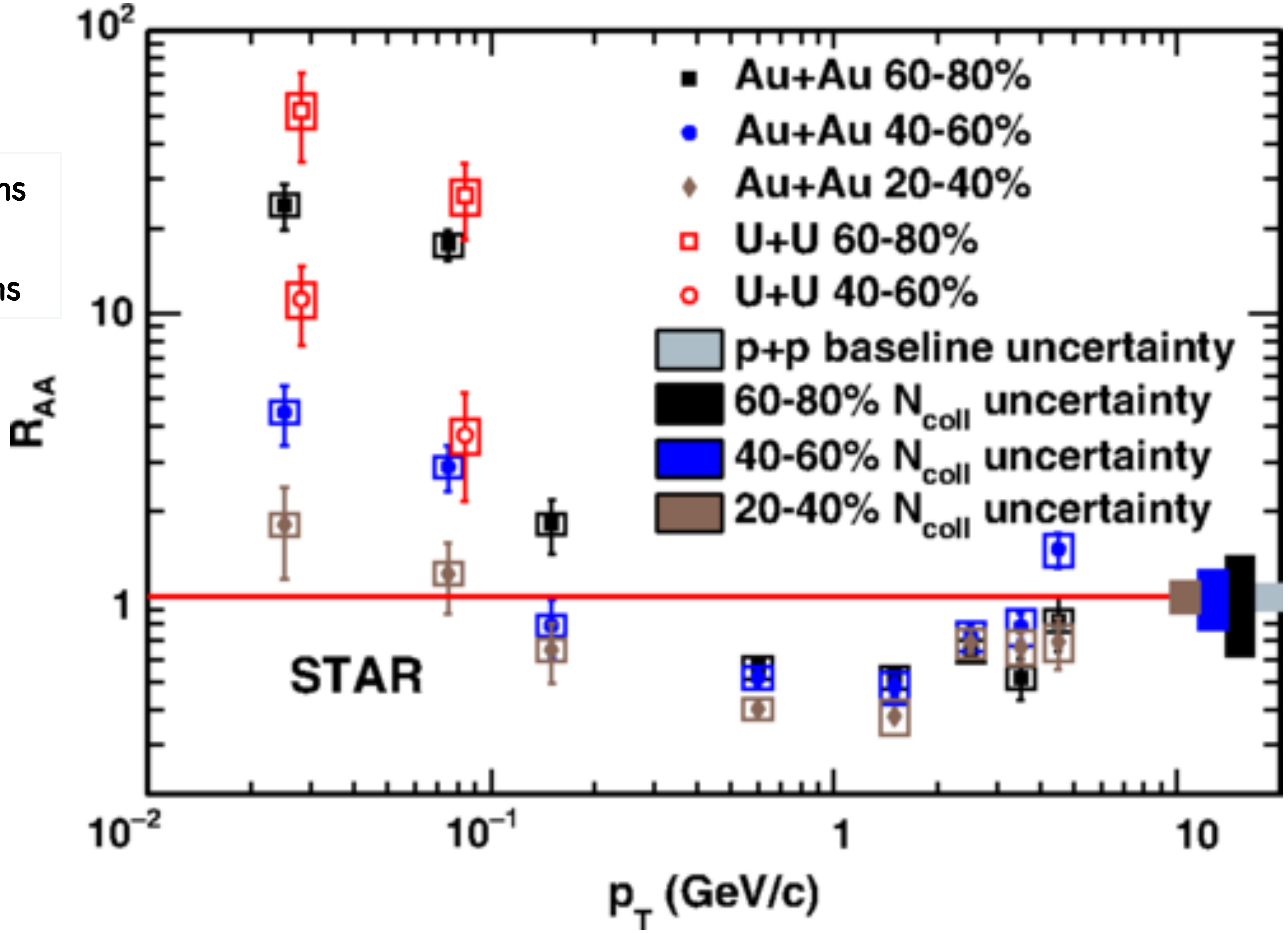
ALICE

RHIC energies

PRL 123, 132302 (2019)

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

Y^{Au-Au} = yield of J/ψ in Au—Au collisions
$<T_{AA}>$ = Nuclear thickness function
σ^{PP} = J/ψ cross section in pp collisions



First measurement of J/Ψ excess observed by STAR Collaboration, at midrapidity in peripheral and semi-central Au-Au and U-U events at $\sqrt{s_{NN}}$ = 200 GeV

—> This supports also a photoproduction origin

Photon energy ambiguity : solve simultaneously

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

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

A =UPC

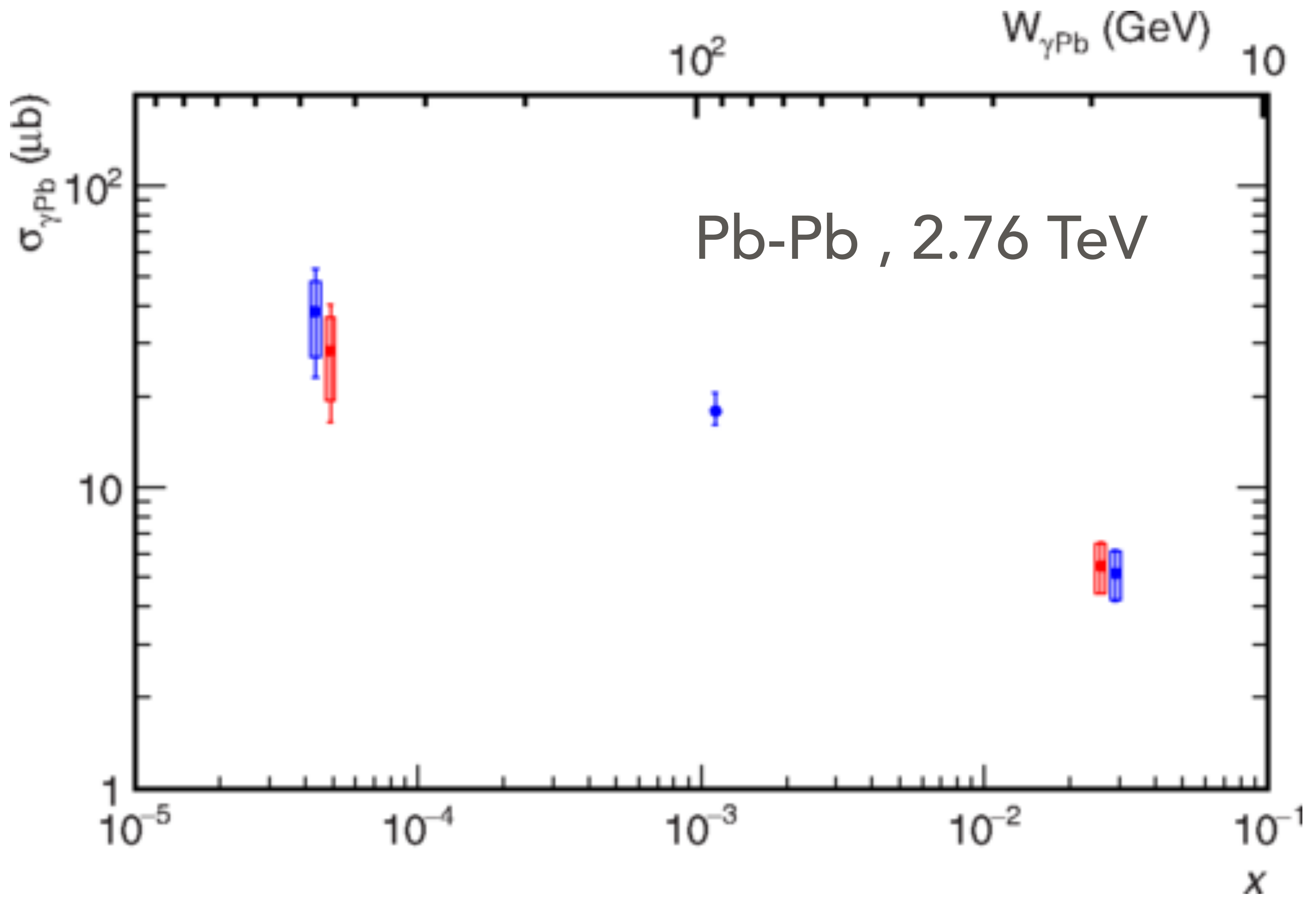
$$\left(\frac{d\sigma_{\rm PbPb}}{dy}\right)_B = n_\gamma(y;\{b\}_B)\sigma_{\gamma \rm Pb}(y)+n_\gamma(-y;\{b\}_B)\sigma_{\gamma \rm Pb}(-y)$$

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

Theoretical developement : for VM photo production

Models calculations are available for photoproduced J/Ψ with nuclear overlap collisions

[1] Equivalent photon approximation + Vector dominance model (VDM), M. Klusek-Gawenda et al., PRC93, 044912 (2016)

[2] Coherent VM photoproduction: Different coupling assumptions between nucleus (photon emitter) and spectator (pomeron emitter)

W. Zha, PRC 97, 044910 (2018)

[3] GBW/IIM dipole model : M. B. Gay Ducati et al., Phys. Rev. D97, 116013 (2018)
i. UPC like : b-dependence (S1).
ii. Effective photon flux (S2)
iii. Effective photon flux + photo nuclear cross section (S3)

[4] Coherent photoproduction and hadroproduction consistently accounting for modification with cold and hot nuclear matters.,
W. Shi et al., Phys. Lett. B 777, 399-405, (2018)

[5] Coherent and incoherent J/ψ photonuclear production in an energy-dependent hot-spot model, J. Cepila et al.,
Phys. Rev. C 97, 024901 (2018)

Estimation of coherent J/Ψ yield

Estimation of coherent J/Ψ yield at a given p_T

via channel $J/\psi \rightarrow \mu^+\mu^-$

$$\frac{d\sigma^{coh\ J/\Psi\ photo}_{Pb-Pb}}{dy}[p_T < 0.3\ GeV/c] = \frac{N^{coh}_{J/\Psi}}{(\mathscr{A} * \varepsilon)^{coh\ J/\Psi}.BR(J/\Psi \rightarrow \mu^+\mu^-).\mathscr{L}.\Delta y}$$

J/ψ (Acceptance*Efficiency)

J/ψ decay branching ratio

Integrated luminosity of the Pb-Pb data sample

in each dy , [0 < p_T < 0.3 GeV/c]

$$N^{J/\Psi raw\ yield}_{AA} - N^{h\ J/\Psi}_{AA} = N^{J/\Psi excess}_{AA} \rightarrow N^{coh}_{J/\Psi} = \frac{N^{J/\Psi excess}_{AA}}{1 + f_I + f_D}$$

This contributions are estimated from UPC processes for in this kinematics, Phys. Lett. B 798 (2019) 134926,

$$N^{h,J/\Psi}_{AA.} = \int_{p_{T1}}^{p_{T2}} \frac{dN^{h}_{AA}}{dp_T} dp_T = \mathcal{N} \times \int_{p_{T1}}^{p_{T2}} \frac{d\sigma^{h}_{pp}}{dp_T} \times R^{h}_{AA}(p_T) \times (\mathcal{A} \times \epsilon)^{h}_{AA}(p_T) dp_T$$

Data driven approach: (same procedure adopted as discussed in Ref. Phys. Lett. B 846 (2023) 137467)

i.Hadronic proton-proton differential cross section
ii.Evolution of the nuclear modification factor at low p_T

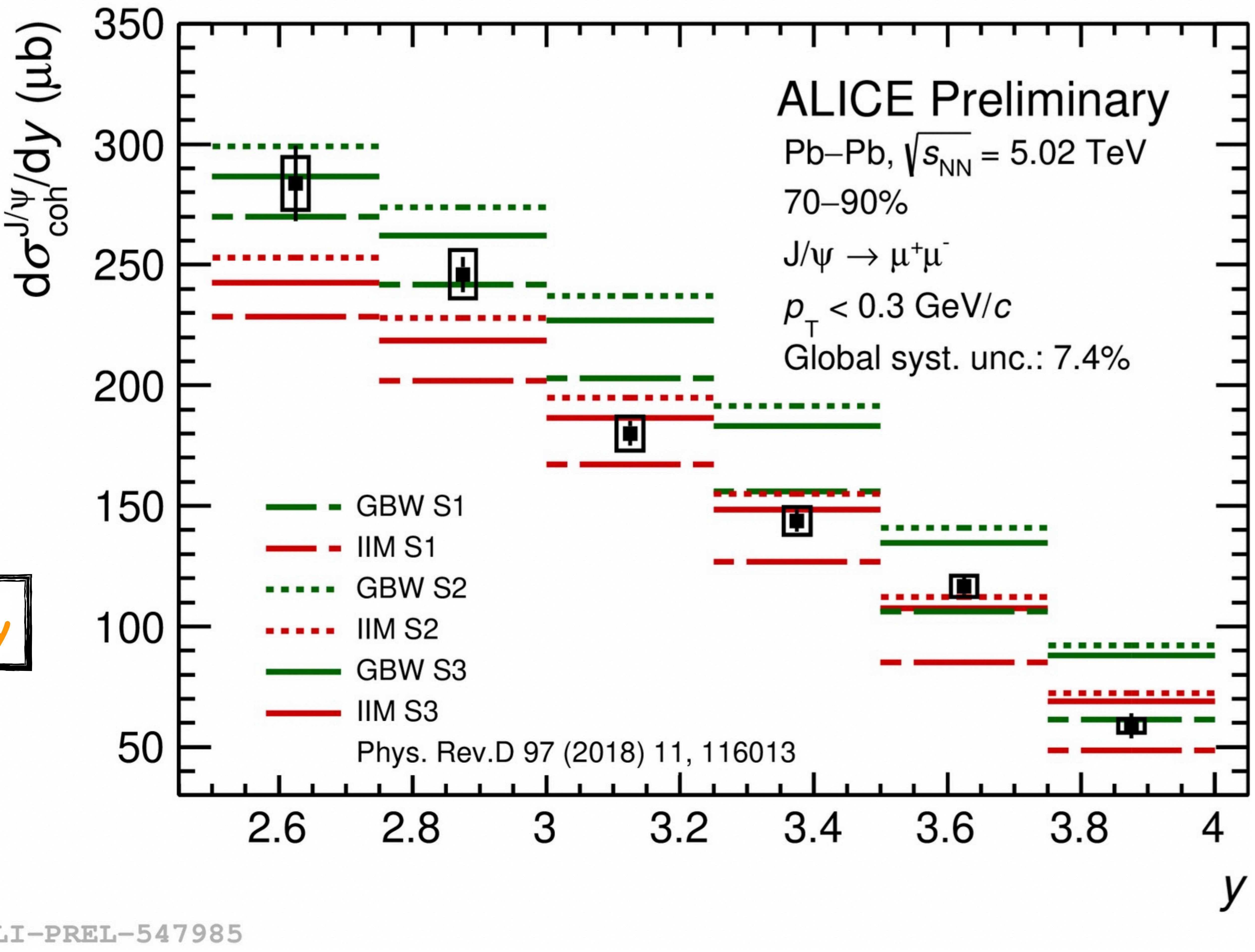
Coherent J/ψ photoproduction : rapidity dependence

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

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

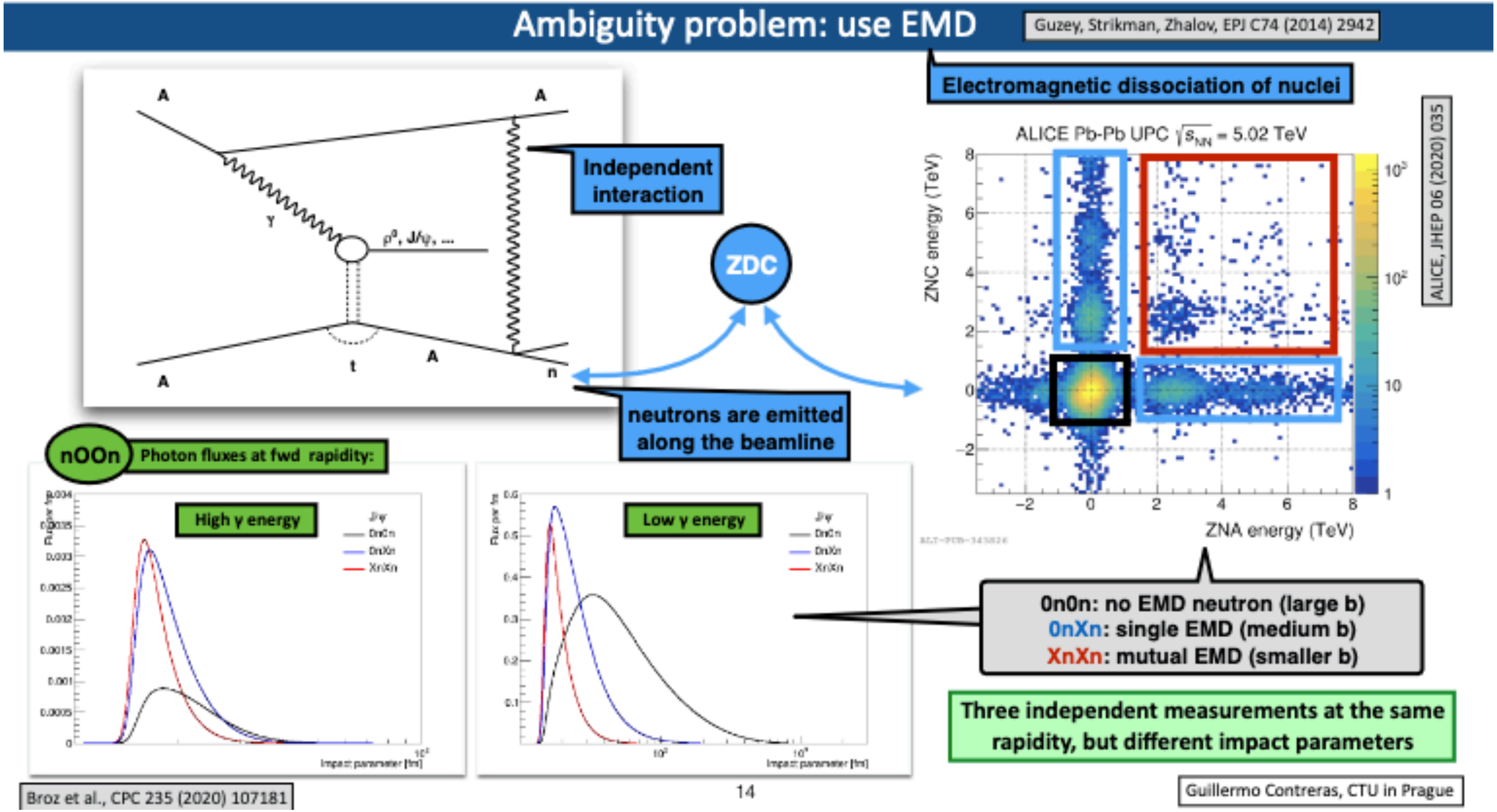
No model describe the measurements in the entire measured y

Similar observations are also seen UPC measurement, Eur. Phys. J. C 81 (2021) 712 with ALICE and LHCb, JHEP 06 (2023) 146



Understanding the VM photoproduction y-differential cross section measurement with including effect of the nuclear overlap further theoretical inputs are needed

Photon energy ambiguity : Neutron emission



Models in UPCs

- **Black disk limit:**
  - Frankfurt, Strikman, Zhalov, *Phys. Lett.* B537 (2002) 51–61.
  - total cross section of the interaction is equal to 2π R_A^2.
- **STARlight:**
  - Klein, Nystrand, Seger, Gorbunov, Butterworth, Comput. Phys. Commun. 212 (2017) 258–268; Klein and Nystrand, Phys. Rev. C 60 (1999) 014903.
  - Based on a phenomenological description of the exclusive production of VM off nucleons, the optical theorem, and a Glauber-like eikonal formalism, does not take into account the elastic part of the elementary VM–nucleon cross section.
  - Includes multiple scattering, **no gluon shadowing**.
- **GKZ (Guzey, Kryshen and Zhalov):**
  - Guzey, Kryshen, Zhalov, Phys. Rev. C93 (2016) 055206; Frankfurt, Guzey, Strikman, Zhalov, Phys. Lett. B752 (2016) 51–58.
  - Based on a modified **vector dominance model**, in which the hadronic fluctuations of the photon interact with the nucleons in the nucleus according to the Gribov-Glauber model of **nuclear shadowing**
- **GMMNS (Goncalves, Machado, Morerira, Navarra and dos Santos):**
  - Gonçalves, Machado, Moreira, Navarra, dos Santos, Phys. Rev. D96 (2017) 094027; Iancu, Itakura, Munier, Phys. Lett. B590 (2004) 199–208,
  - Based on the Iancu-Itakura-Munier (IIM) implementation of **gluon saturation** within the **colour dipole model** coupled to a boosted-Gaussian description of the wave function of the vector meson.
- **CCKT (Cepila, Contreras, Krelina and Tapia):**
  - Cepila, Contreras, Tapia Takaki, Phys. Lett. B766 (2017) 186–191; Cepila, Contreras, Krelina, Tapia Takaki, Nucl. Phys. B934 (2018) 330–340; N. Armesto, Eur. Phys. J. C26 (2002) 35–43
  - Based on the **colour dipole model** with the structure of the nucleon in the transverse plane described by so-called **hot spots**, regions of high gluonic density, whose number increases with increasing energy. The nuclear effects are implemented along the ideas of the Glauber model. Version without hot spots (named *nuclear*) and including them.
  - Indicates **gluon saturation**.

- **Guzey at al.**
  - **Look at GKZ**
- **Krelina et al.**
  - Cepila, Contreras, Krelina, Phys. Rev. C97 (2018) 024901; Kopeliovich, Krelina, Nemchik, Potashnikova, arXiv:2008.05116
  - variations of the colour-dipole model based on CGC theory.
  - GBW + BT: Golec-Biernat-Wusthof (GBW) model include light-front colour dipoles; Buchmuller-Tye (BT) potentials which describe data for proton-electron generation of charmonium.
  - GWB + POW: GWB model and power-like (POW) potentials which describe data for proton-electron generation of charmonium.
  - KST + BT: Kopeliovich-Schafer-Tarasov (KST) model include light-front colour dipoles and Buchmuller-Tye (BT) potentials
  - GG-hs +BG look at **GG-HS model**, boosted-Gaussian (BG) vector wave function; meson mainly consists of a quark-anti-quark pair, and the spin and polarization are the same as that of the photon.
- **Mantysaari et al.**
  - H. Mantysaari and B. Schenke, Phys. Lett. B772 (2017) 832; Lappi and H. Mantysaari, PoS DIS2014 (2014) 069,
  - (No fluct. +BG) the cross-section is calculated using the colour-dipole model, including a subnucleon scale uctuation based on CGC theory.
- **Goncalves et al.**
  - Goncalves et al., Phys. Rev. D96 (2017) 094027; Goncalves and Machado, Eur. Phys. J. C40 (2005) 519,
  - depend on the dipole-hadron scattering amplitude and vector-meson wave function.
  - bCGC+BG: The impact-parameter-CGC (bCGC) model: dipole-hadron scattering amplitude given by the solution of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation and the Balitski-Kovchegov (BK)equation + impact parameter dependence on the saturation scale. Assumption of boosted-Gaussian (BG) vector wave function
  - bCGC+GLC: bCGC with Gauss-LC (GLC) vector wave function
  - IP-SAT+BG: the impact-parameter saturation (IP-SAT) model where dipole-hadron scattering amplitude depends on a gluon distribution evolved through the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equation
  - IP-SAT+GLC: the impact-parameter saturation (IP-SAT) model with Gauss-LC (GLC) vector wave function