Photoproduction in pA and peripheral heavy-ion collisions

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Outline

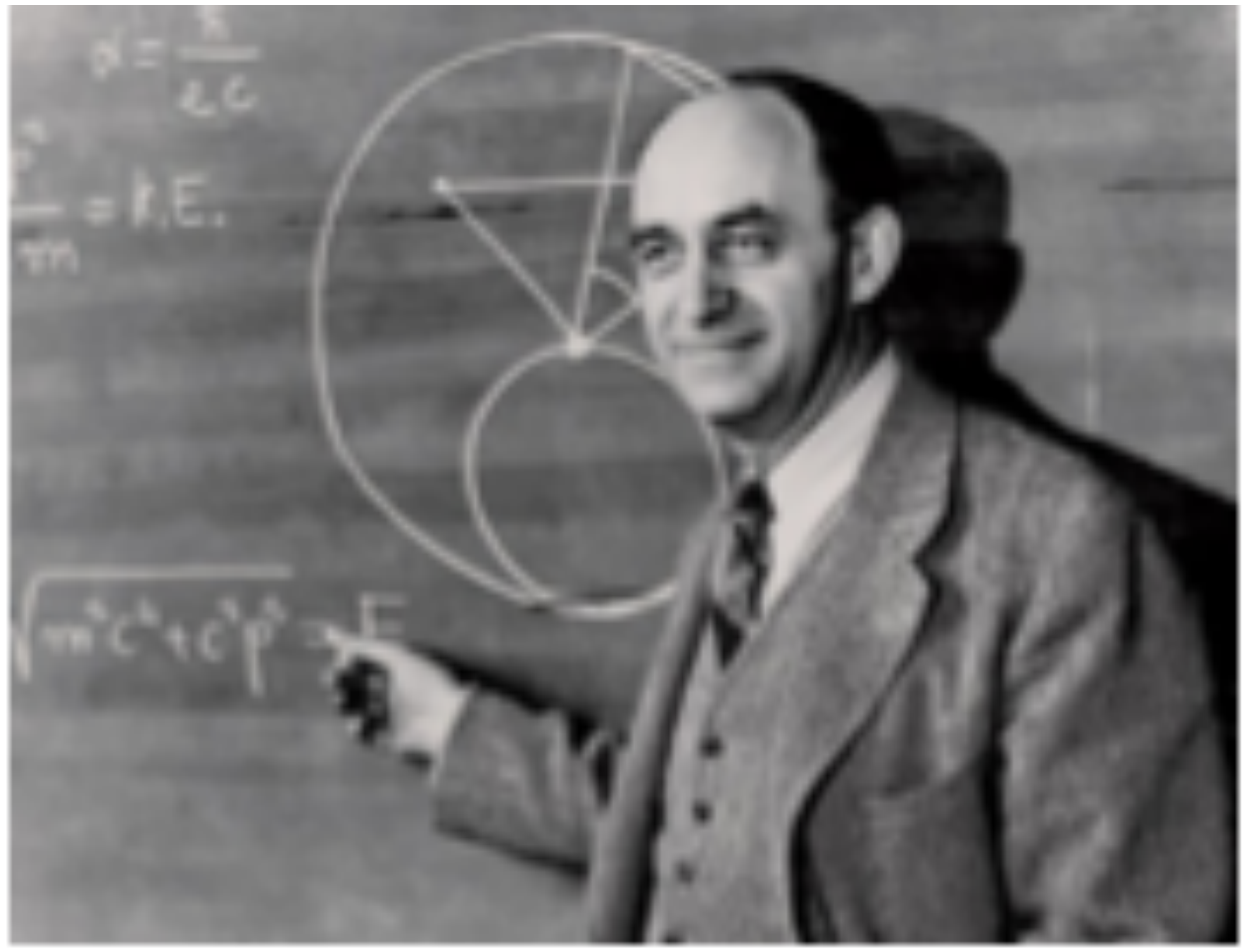
- Introduction to photon-induced processes
- PartI : Results of photo production of VM in pA collisions
  - ➡ Exclusive photo production
  - ➡ Dissociative photo production
- PartII : Results from photon-induced interactions in heavy-ion collisions with nuclear overlap
  - ➡ Photo (Coherent) production cross section
    - — Transverse momentum, centrality, and rapidity
    - — Photon-energy ambiguity
  - ➡ Polarization
  - ➡ Azimuthal anisotropy and entanglement-enabled spin interference and etc.
- Summary and outlook

*In this talk, I will cover the results biased on personal selection

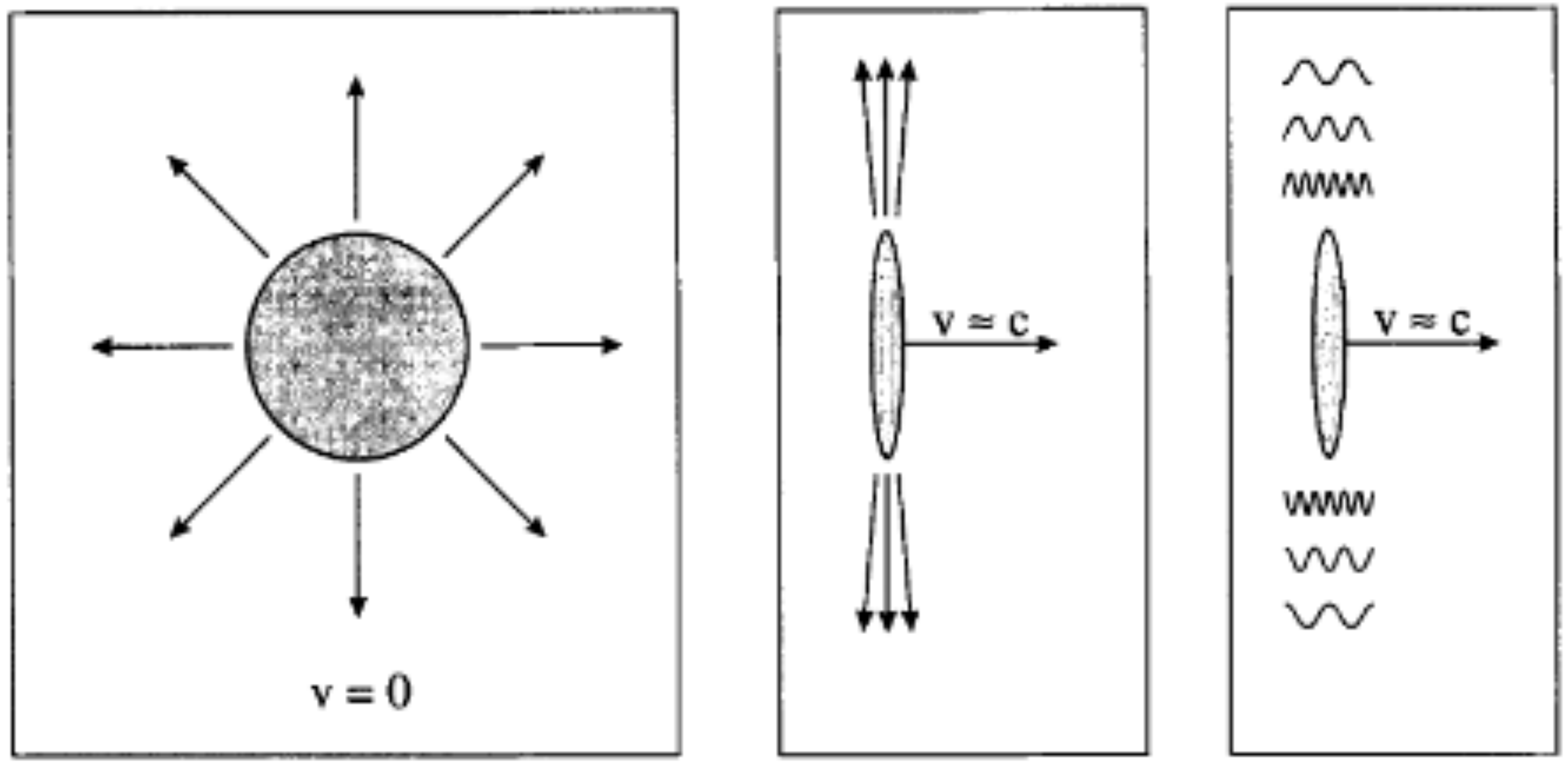
Using the LHC as γγ, γPb and γp collider

The most powerful collider not only for pp and Pb-Pb collisions, but also for **photon-photon and photon-hadron interactions**

Equivalent photon approximation (EPA)



E.Fermi



Fast moving charged particles produce strong electromagnetic field [1]

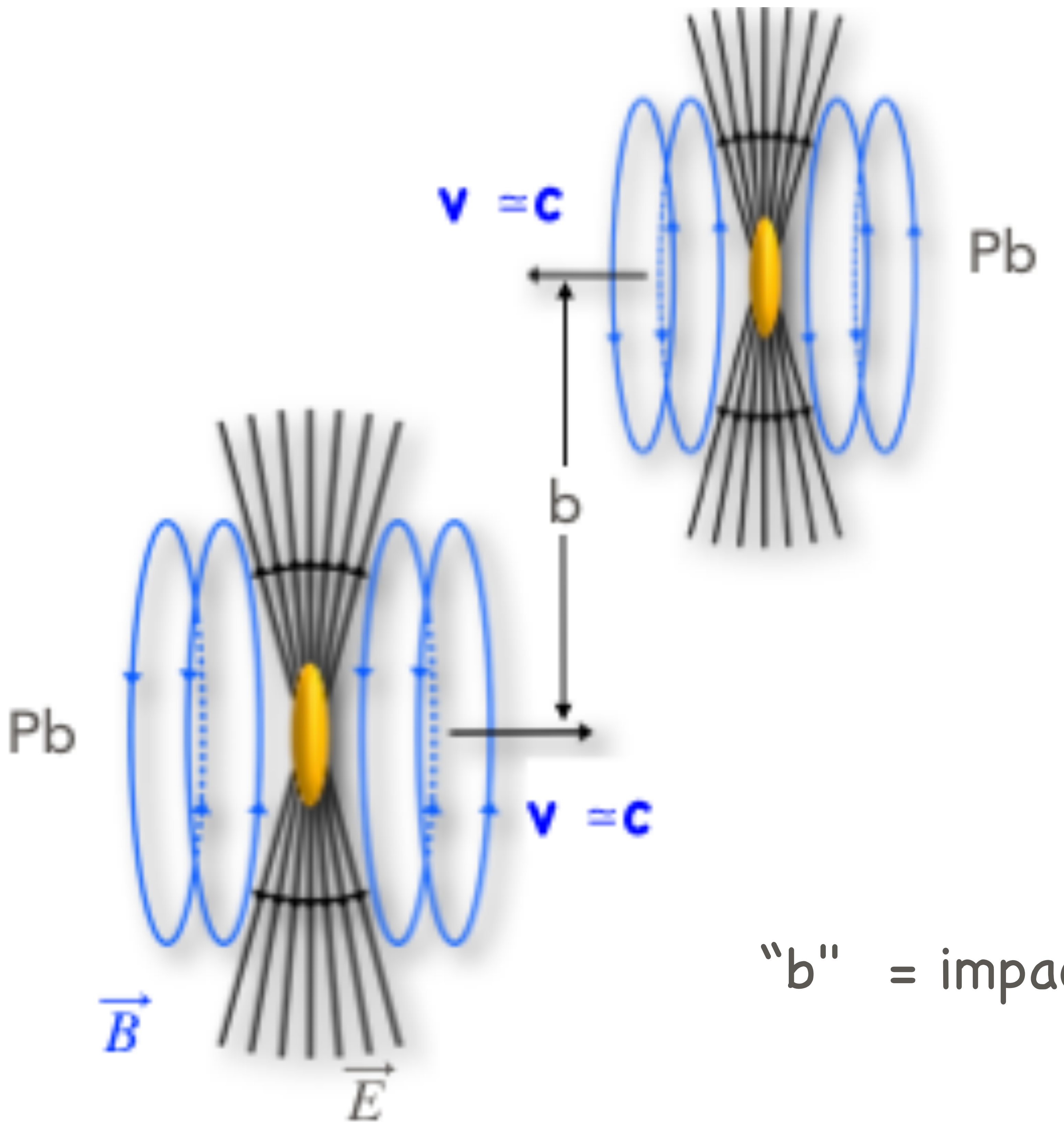
Electromagntic fileds ≈ photon fluxes

[1] E. Fermi, Nuovo Cim.,2:143-158, arXiv:hep-th/0205086 (1925)
[2] C.F. von Weizsacker, Z. Phys. 88, 612 (1934)
[3] E. J. WILLIAM S, Kgl. Danske Videnskab. Selskab Mat.-Fys. Medd. 13, 4 (1935)]

Later, this method was extended to relativistic region(v ≈ c) by **Weizsacker-Williams , known as EPA Method** **[2.3]**

Equivalent photon approximation (EPA) in heavy-ion collisions

Relativistic heavy-ions are strong EM field emitters



"b" = impact parameter

Electromagnetic fields

In heavy-ion collisions (HIC) :

$|E| \sim 5\times10^{16} - 10^{18}$ V/cm

$|B| \sim 10^{14} - 10^{16}$ T

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

Magnetic field in other systems

Pulsar ~ 10^{11} T

Earth ~ 10^{-5} T

Strongest EM fields **in the Universe**

EM fields can be treated in terms of photon quanta or flux

Maximum photon energy

LHC ~ 80 GeV

RHIC ~ 3 GeV

$E_{\gamma,\,max} \approx \gamma\hbar c/R$

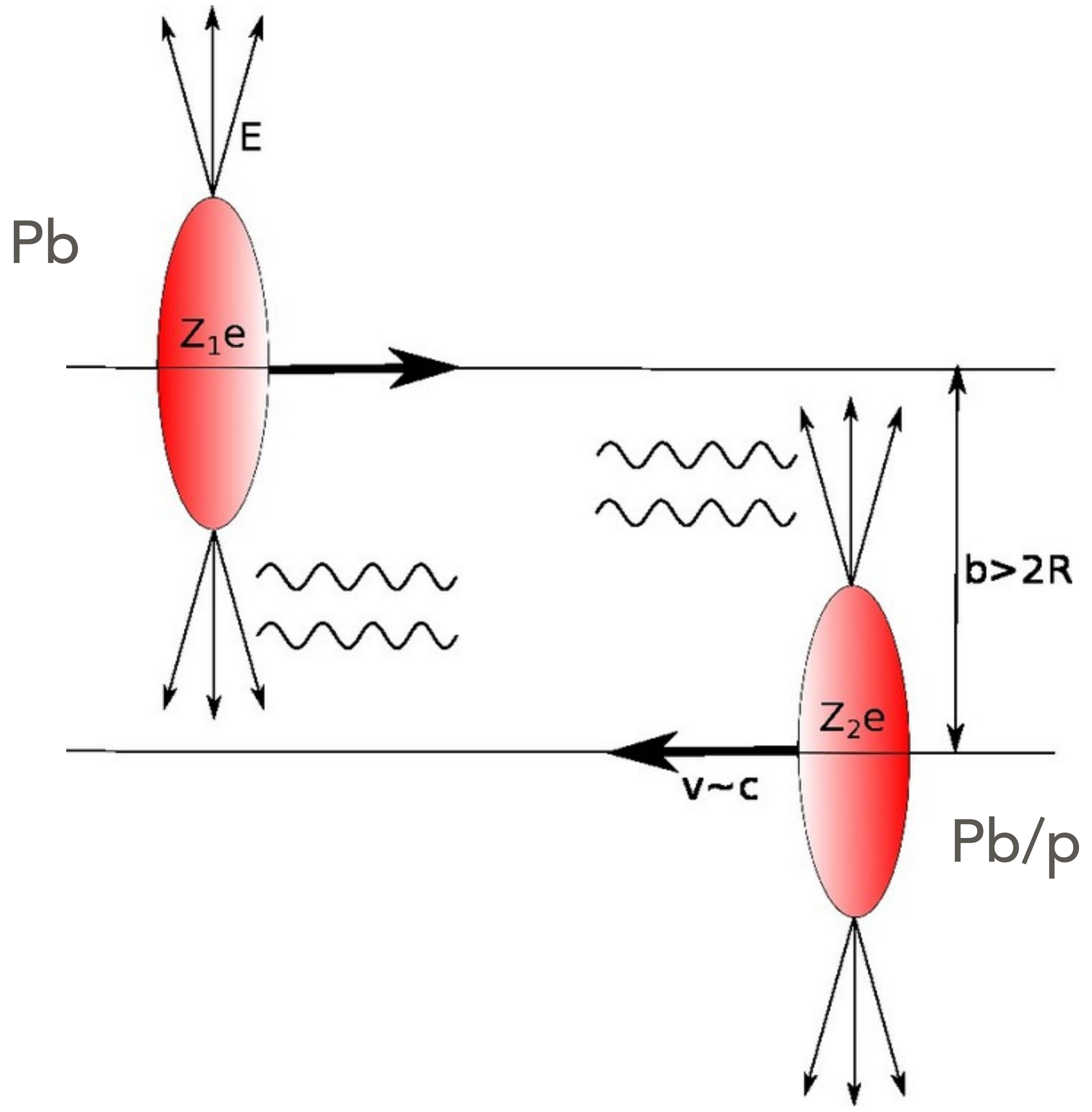
γ = Lorentz factor

R = Radius of the nucleus

Different type of interactions in ultra peripheral collisions

Intro.

UltraPeripheral Collisions (UPCs) : $b > R_1 + R_2$



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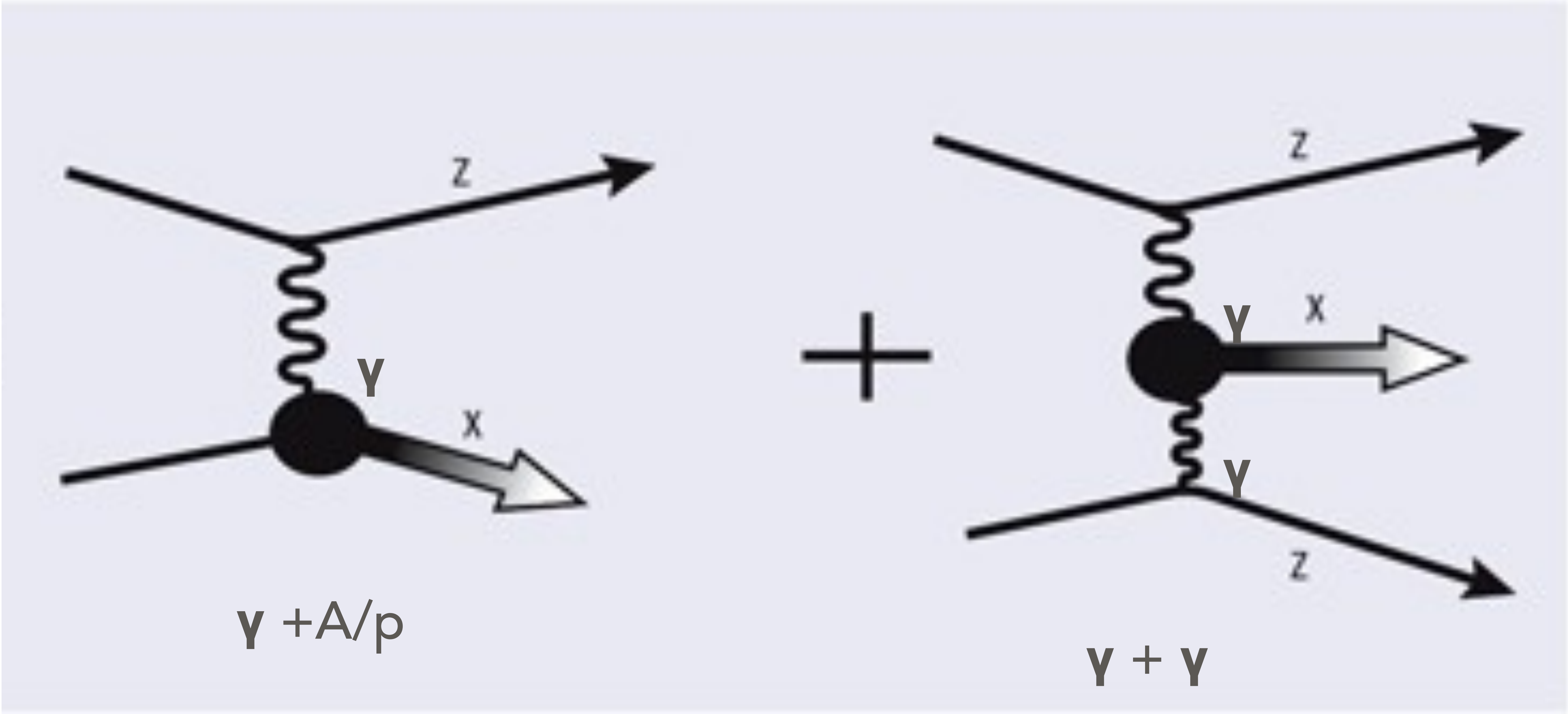
Types of interactions



Flux of photons on other nucleus ~ Z^2 (nuclei >> proton)
Flux of photons on photons ~ Z^4

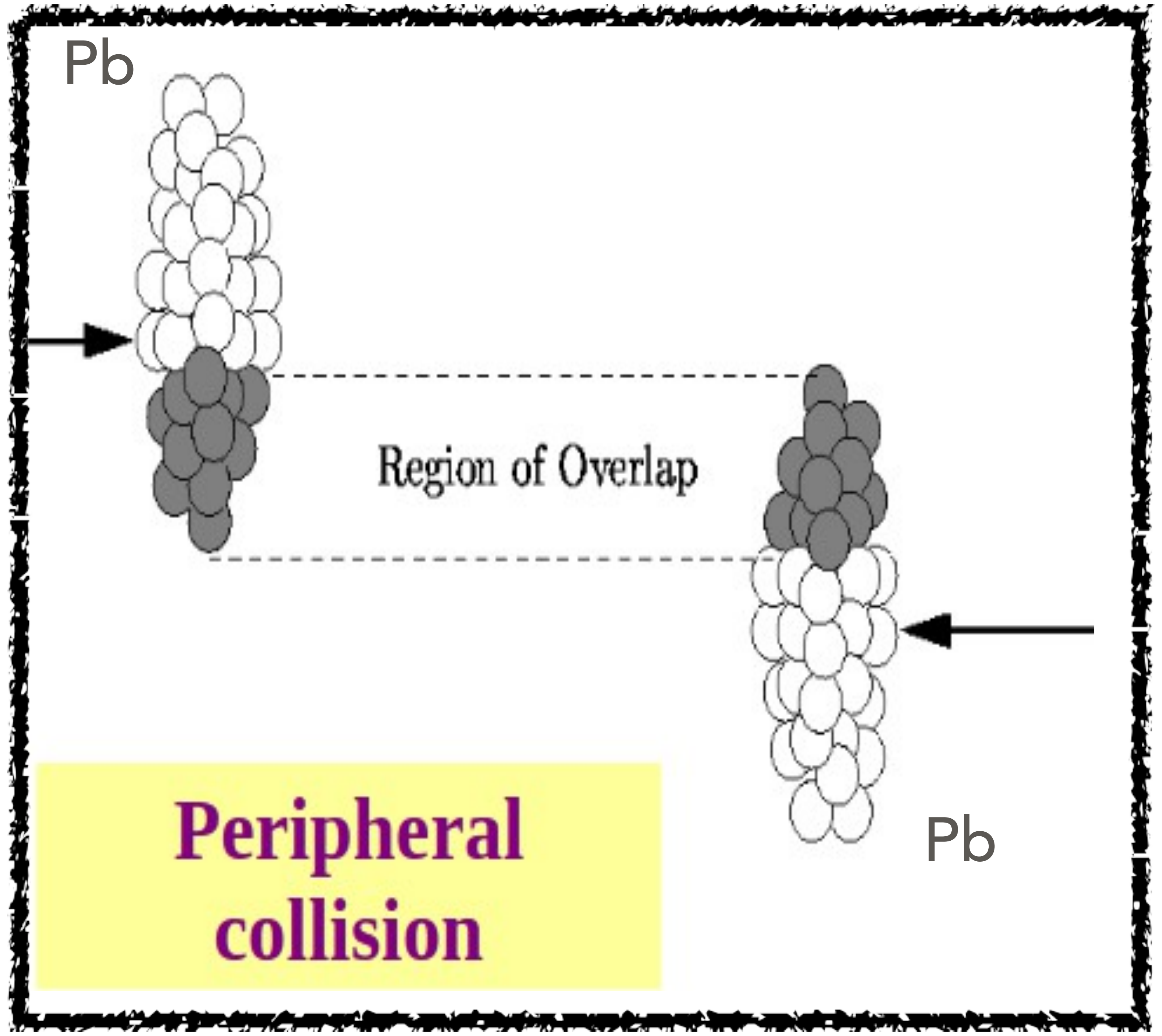
Electromagnetic interactions are dominant

Hadronic interactions are suppressed

Different type of interactions in peripheral collisions

Intro.

Peripheral Collisions (PC) : large b , b ≤ $R_1 + R_2$



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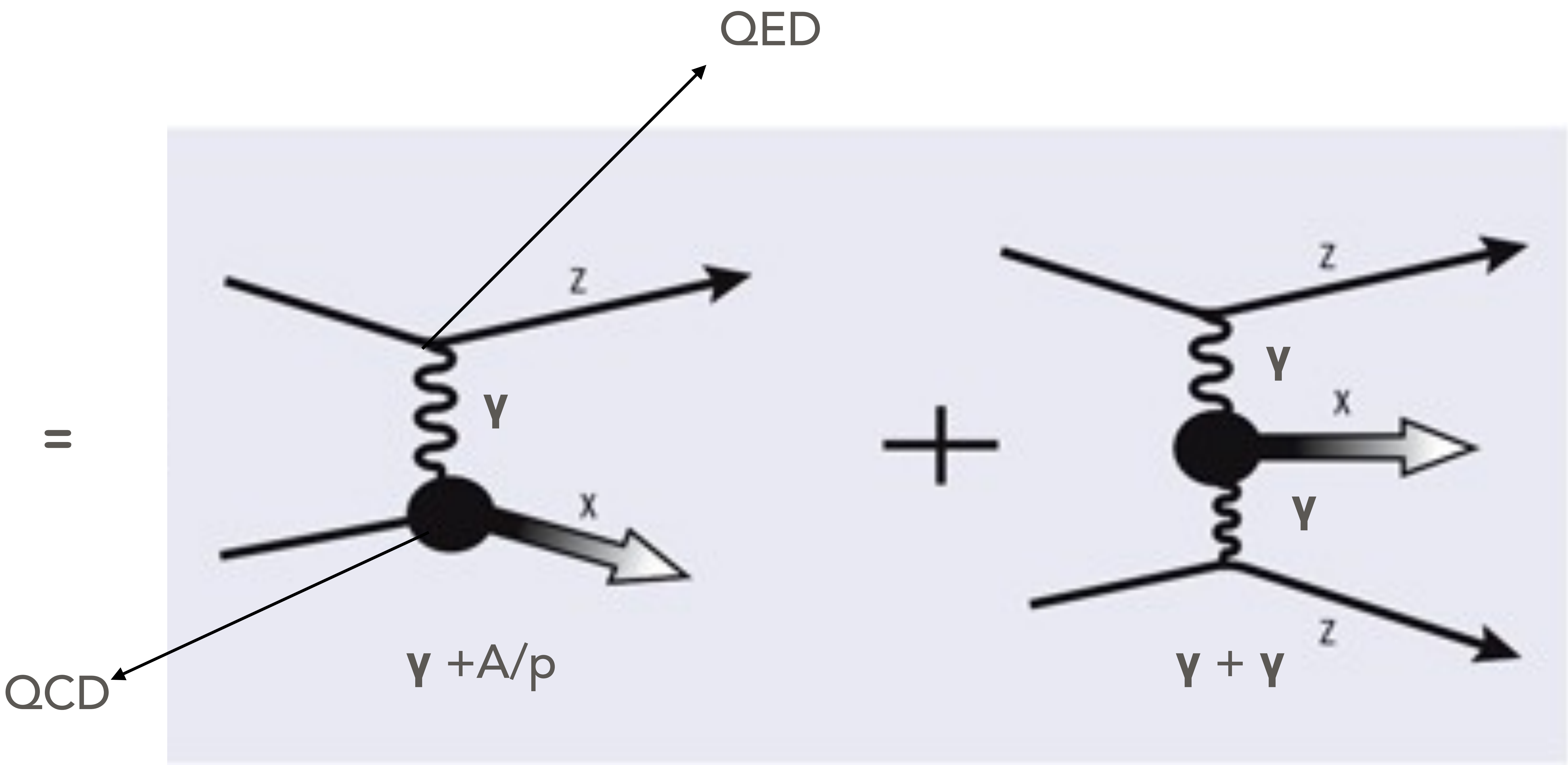
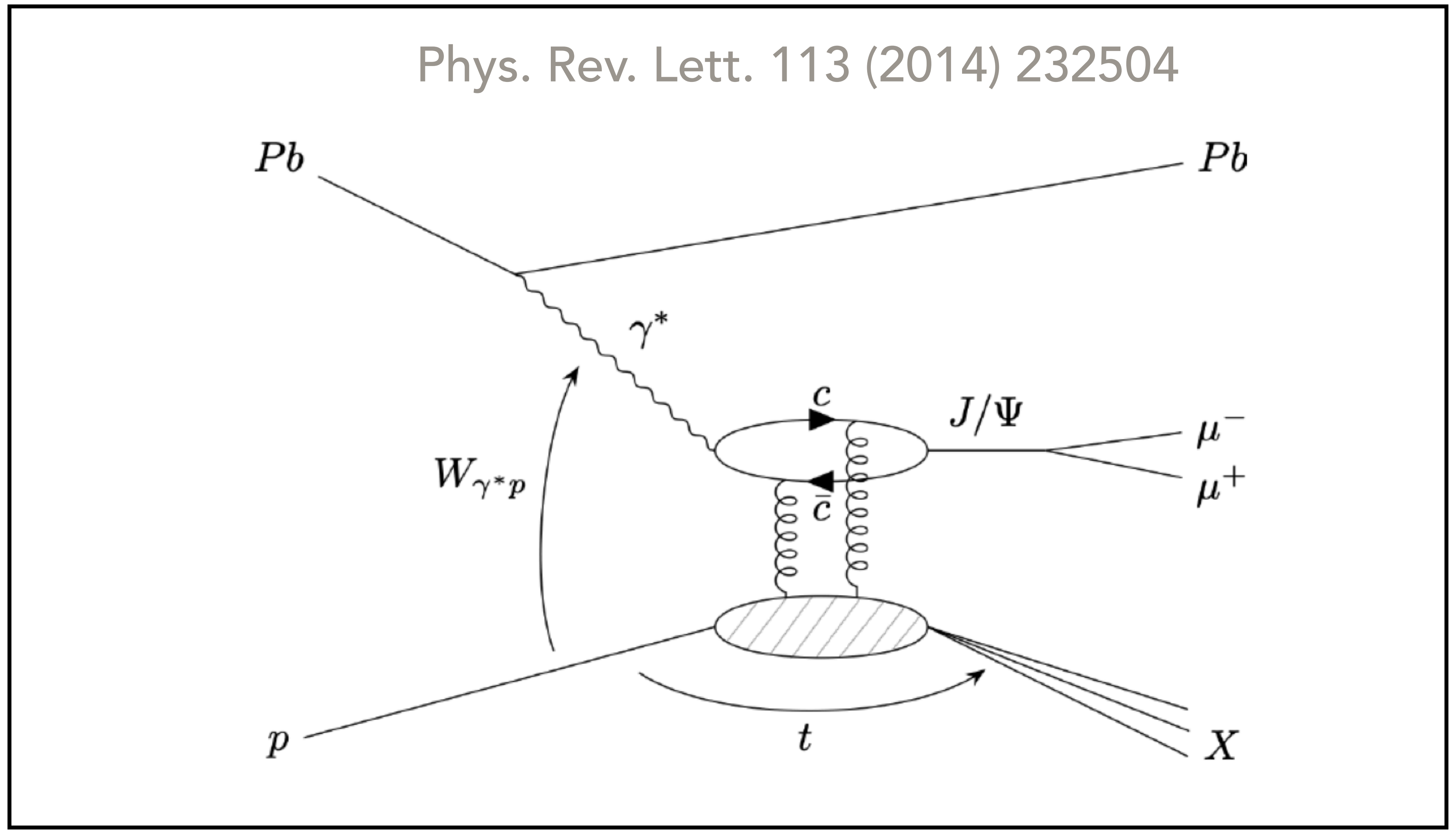


Photonuclear and photon-photon processes are important to study UPCs and PCs with nuclear overlap

-> Good probe to test both QCD and QED phenomena

photo production of vector mesons and dilepton pairs

γp interactions



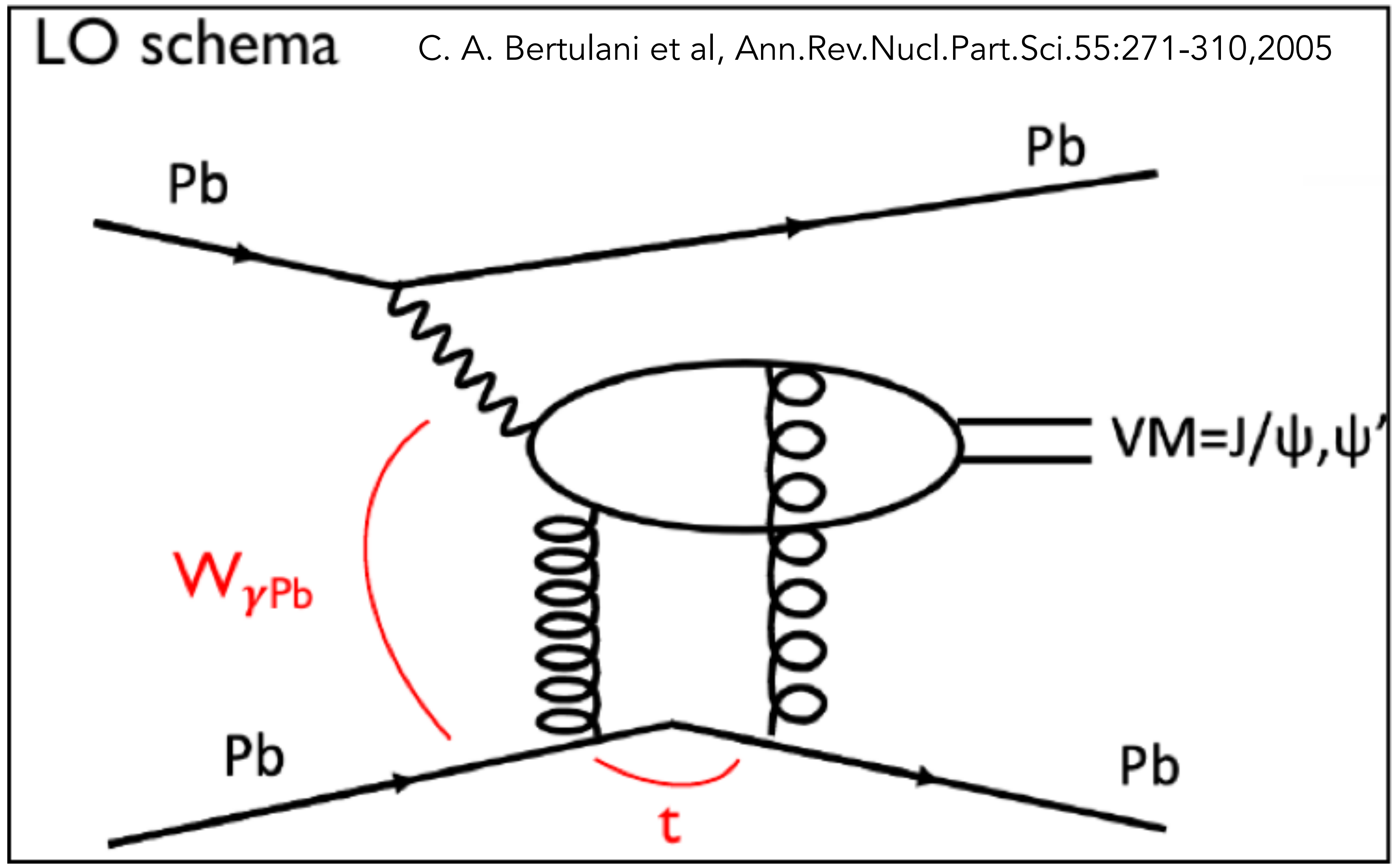
$W_{\gamma p/Pb}$: Center-of-mass energy of photon-lead system

t: Mandelstam variable $= - p_T^2$

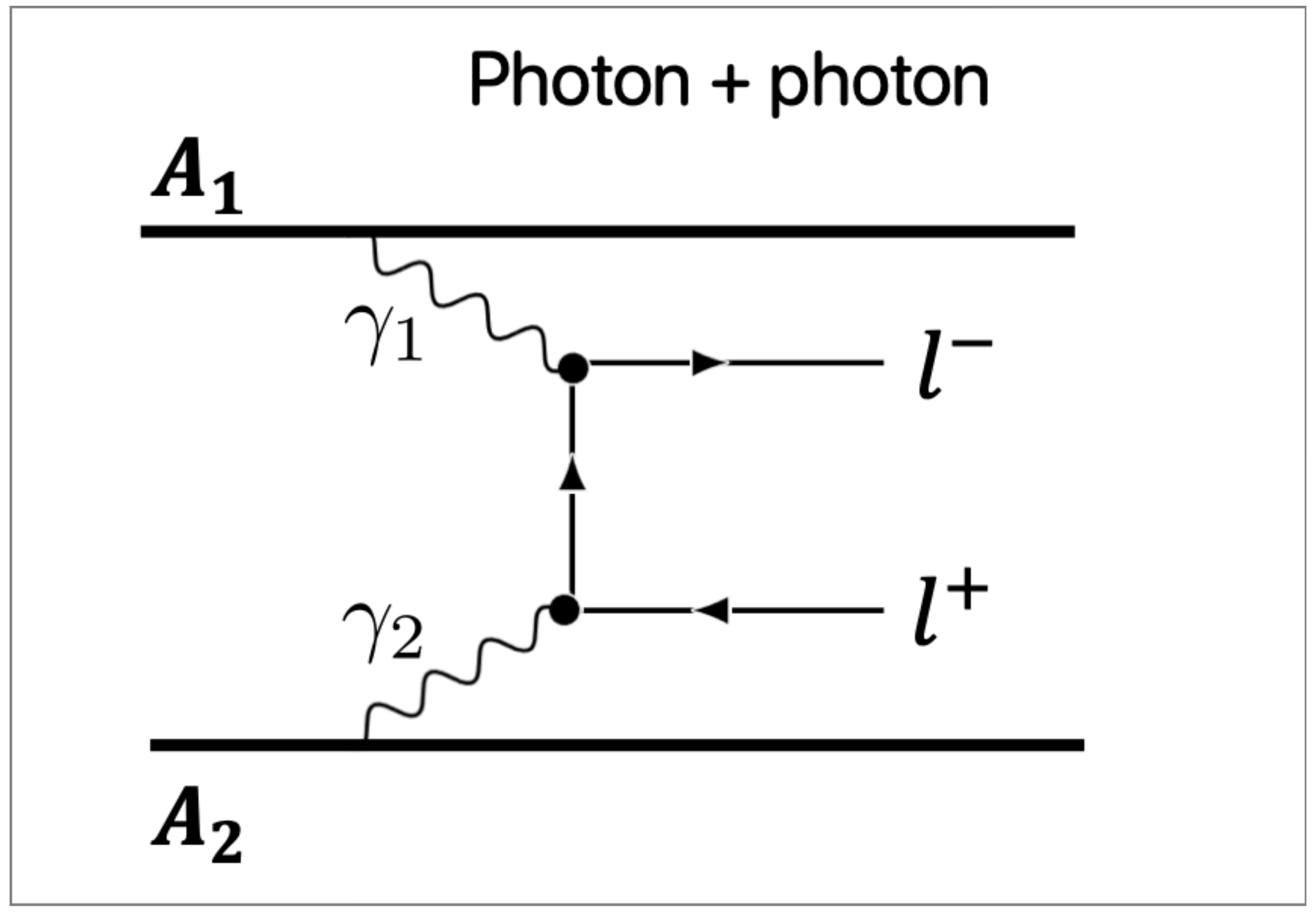
$$x = \frac{m_{J/\psi}}{\sqrt{s_{NN}}} \times \exp(\pm y)$$

γPb interactions

LO : Leading order



$\gamma\gamma$ interactions



- Clean experimental signature
- VM photo production :
  - -> Probing density distributions inside nucleon/nucleus at low Bjorken-x
- Dilepton pair production : Test QED
  - -> Breit Wheeler mechanism (G. Breit, Phys. Rev. 46 (1934) 1087)

Different photon-induced processes

For more details : Adam Matyja talk, Tue, 09/0

photo production in pA collisions

Exclusive VM photo production :

p⊗Pb → Pb ⊗ VM ⊗ p

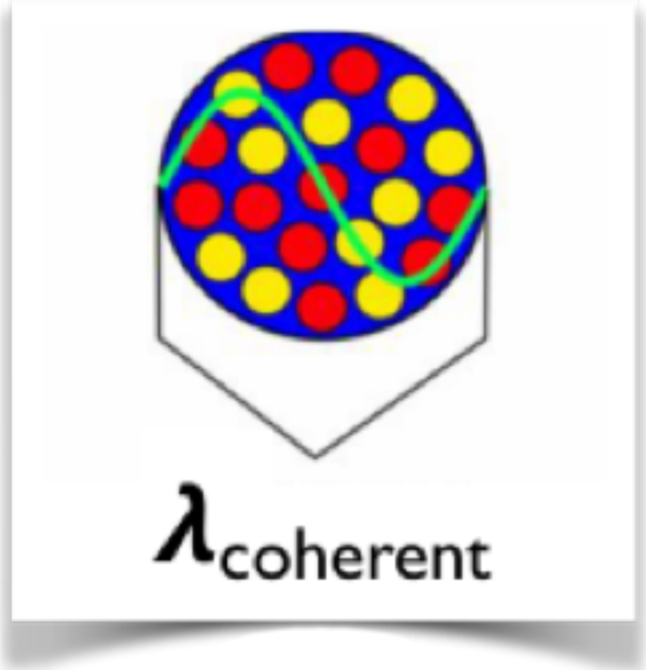
Dissociate or semi exclusive VM photo production:

p⊗Pb → Pb ⊗ VM ⊗ p'

Photon-induced processes in AA collisions

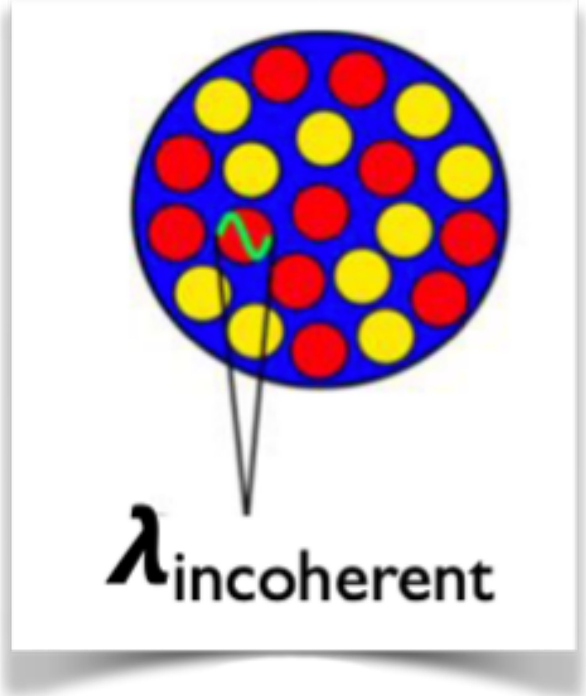
Coherent photo production

Photon (γ) couples coherently to all nucleons
$\langle p_T \rangle_{J/\Psi}$ ~ 1/R ~ 60 MeV/c
Usually no breaking of target

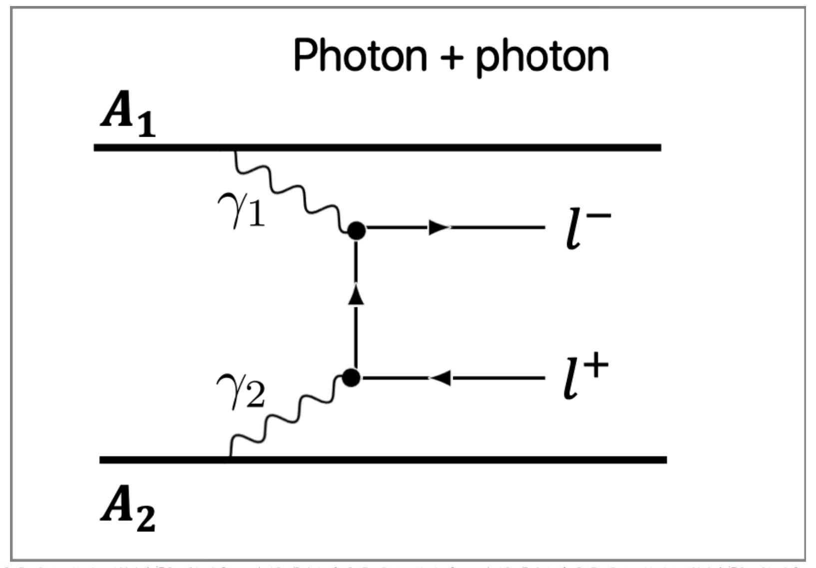


Incoherent photo production

Photon (γ) couples to single nucleon
$\langle p_T \rangle_{J/\Psi}$ ~ 500 MeV/c
Usually target nucleus breaks

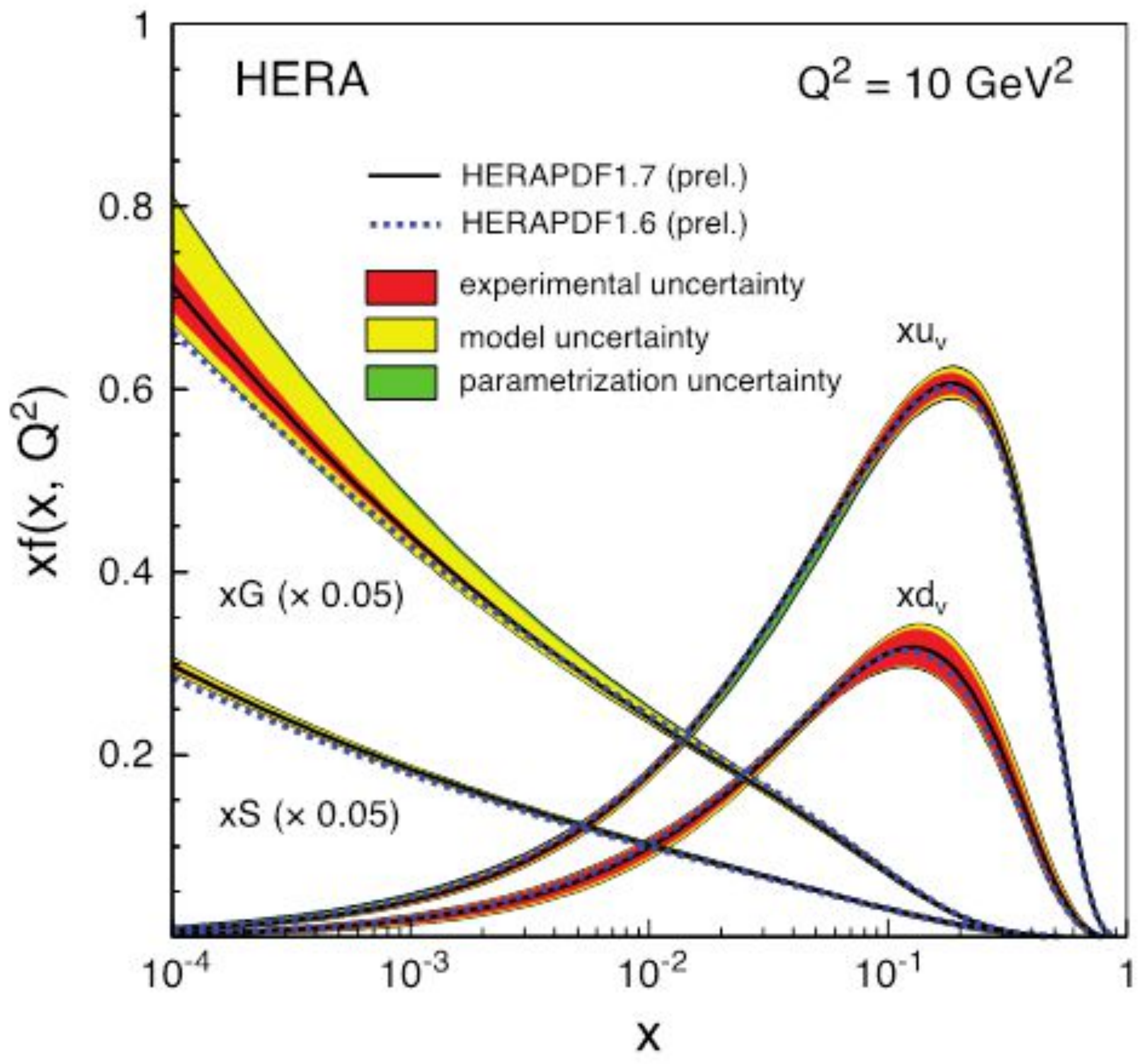


Dilepton pair production: $\gamma\gamma$ -> ll



Photoproduction in asymmetric pA/dA collisions

Parton distribution function



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

To probe gluon saturation effects inside proton or nuclei (deuteron) for Bjorken-x ~ 10^{-2} - 10^{-6}

[1] Exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, ALICE Coll., **Phys. Rev. Lett. 113 (2014) 232504**

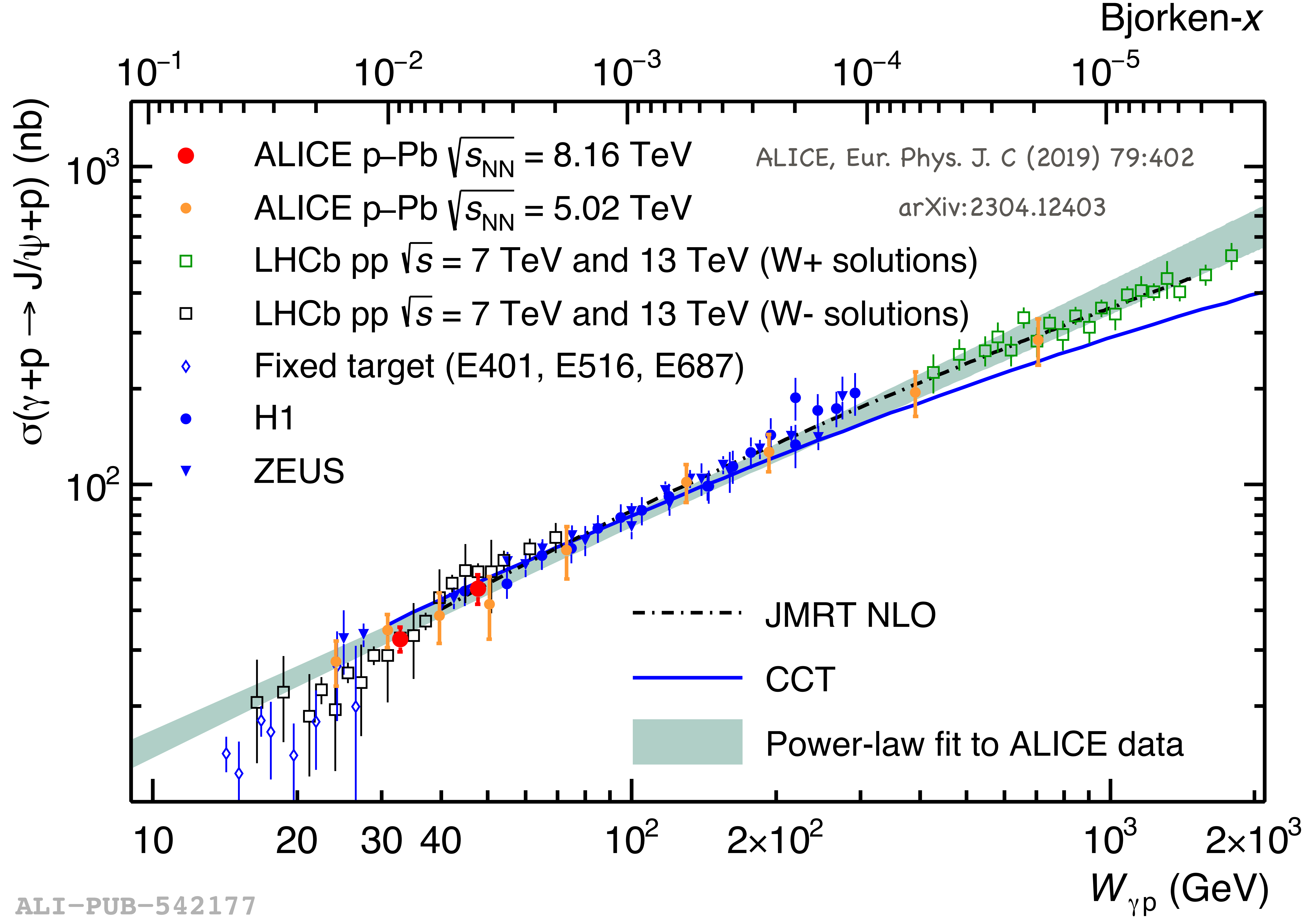
[2] Energy dependence of exclusive J/ψ photoproduction off protons in ultra-peripheral p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, **ALICE, Eur. Phys. J. C (2019) 79:402**

[3] Exclusive and dissociative J/ ψ photoproduction, and exclusive dimuon production, in p–Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV, arXiv:2304.12403 **(ALICE Coll., accepted in PRD)**

[4] Measurement of exclusive Υ photoproduction in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, **CMS PAS FSQ-13-009**

[5] Probing the Gluonic Structure of the Deuteron with J/ψ Photoproduction in d – Au Ultraperipheral Collisions, **STAR Coll., Phys. Rev. Lett 128, 122303 (2022)**

Exclusive J/ψ photoproduction cross section off protons



For more details : Adam Matyja talk, Tue, 09/01

$$\sigma(\gamma+p\to J/\psi+p)=N\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}$$

$$W_0 = 90\ \text{GeV}$$

$$N = 71.8 \pm 4.1\ \text{nb}$$

$$\delta = 0.70 \pm 0.05$$

Good agreement between experiments within uncertainties

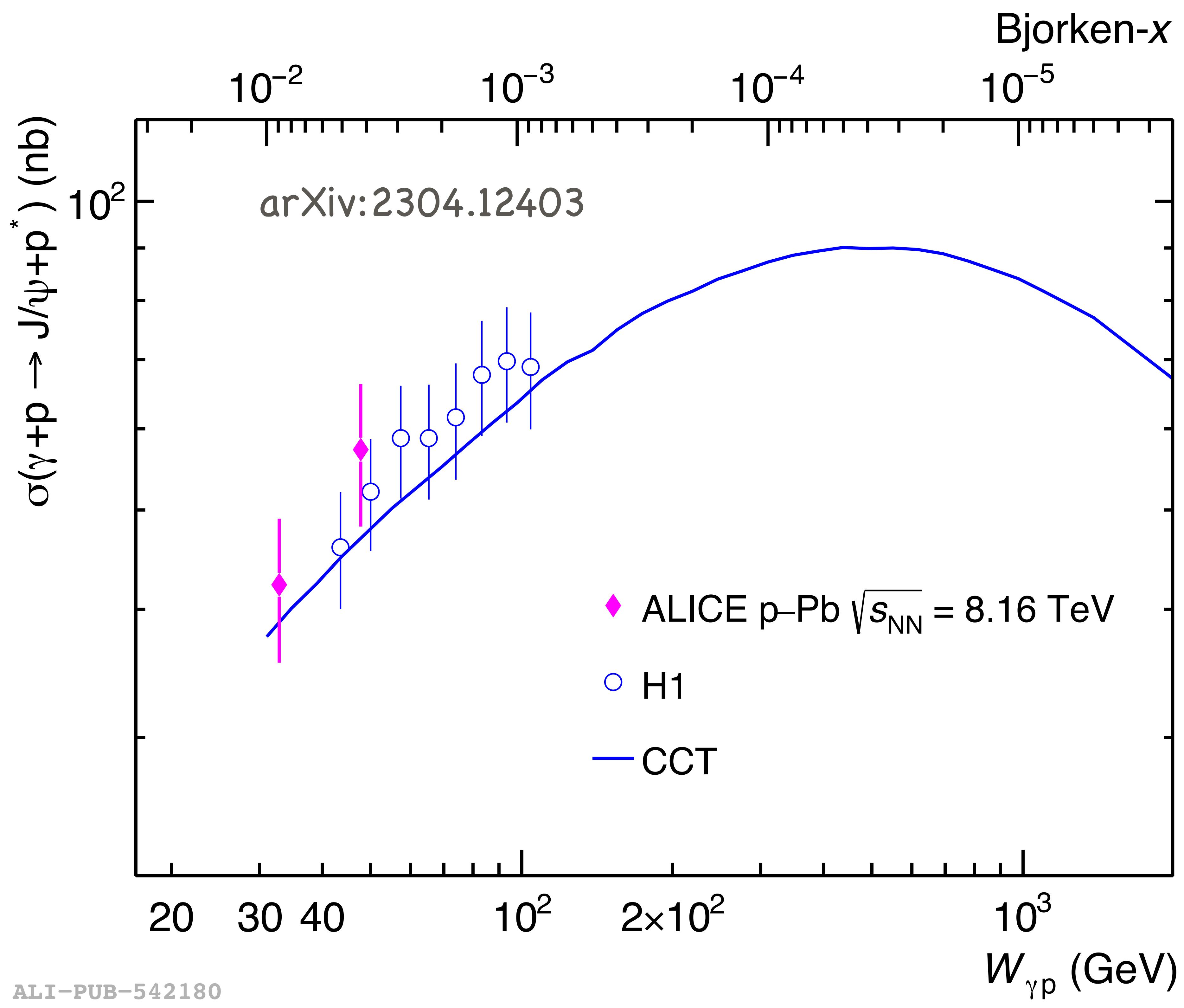
JMRT calculation with NLO and CCT calculation on color dipole based model incorporate a fluctuating hot spot structure of proton

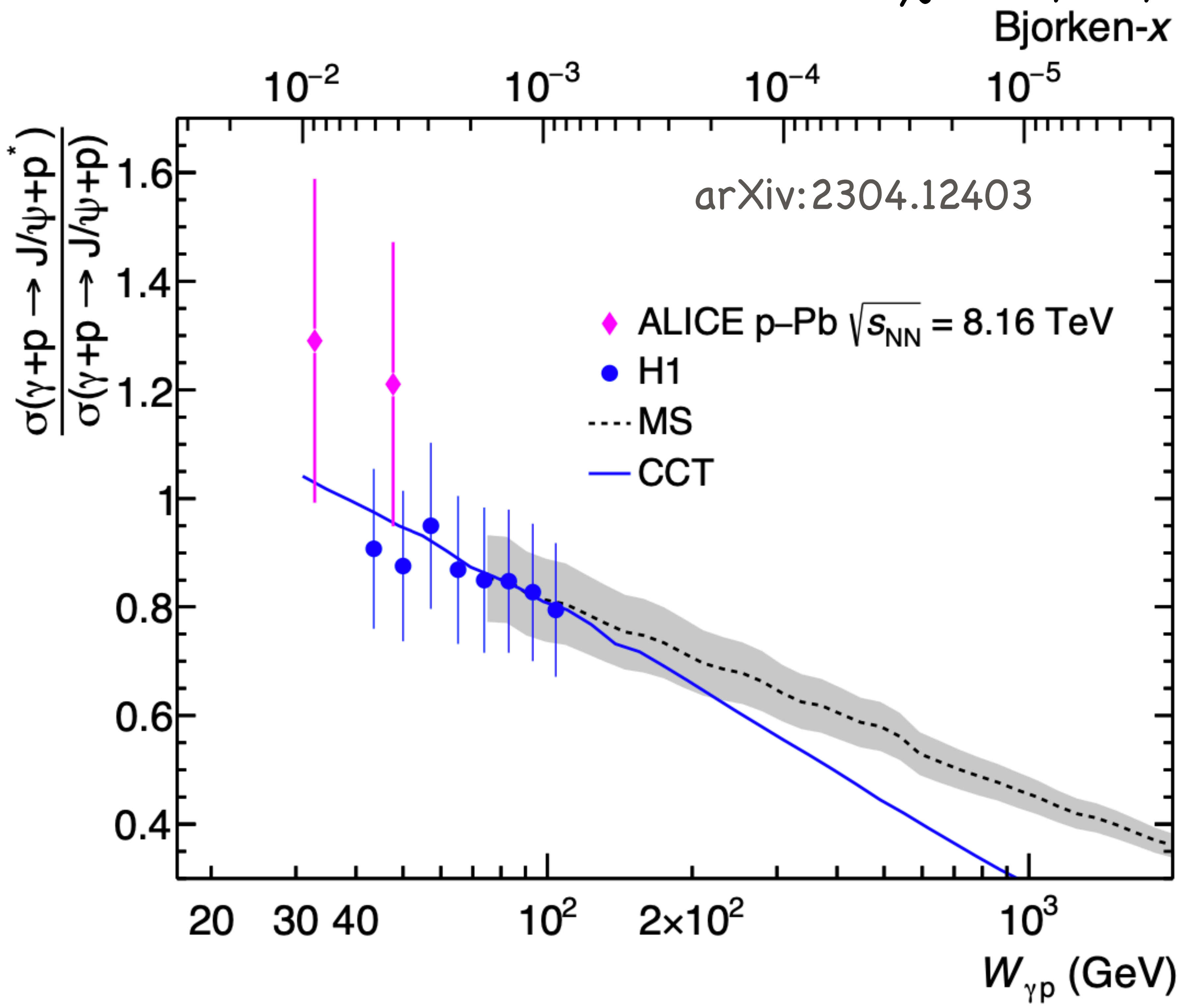
At high $W\gamma p$: CCT model predictions deviates from the linear-power law trend and measurement

No significant change in the gluon density behavior of the proton between HERA and LHC energies

Dissociative J/ψ photoproduction cross section off protons

For more details : Adam Matyja talk, Tue, 09/01





First measurement of the energy dependent dissociative J/ψ cross section at the LHC. — Agreement with HERA results

CCT model with saturation agrees with data

H1: EPJ C73 (2013) 2466.

CCT: PLB 766 (2017) 186;

- colour dipole + energy dependent hot spot model.

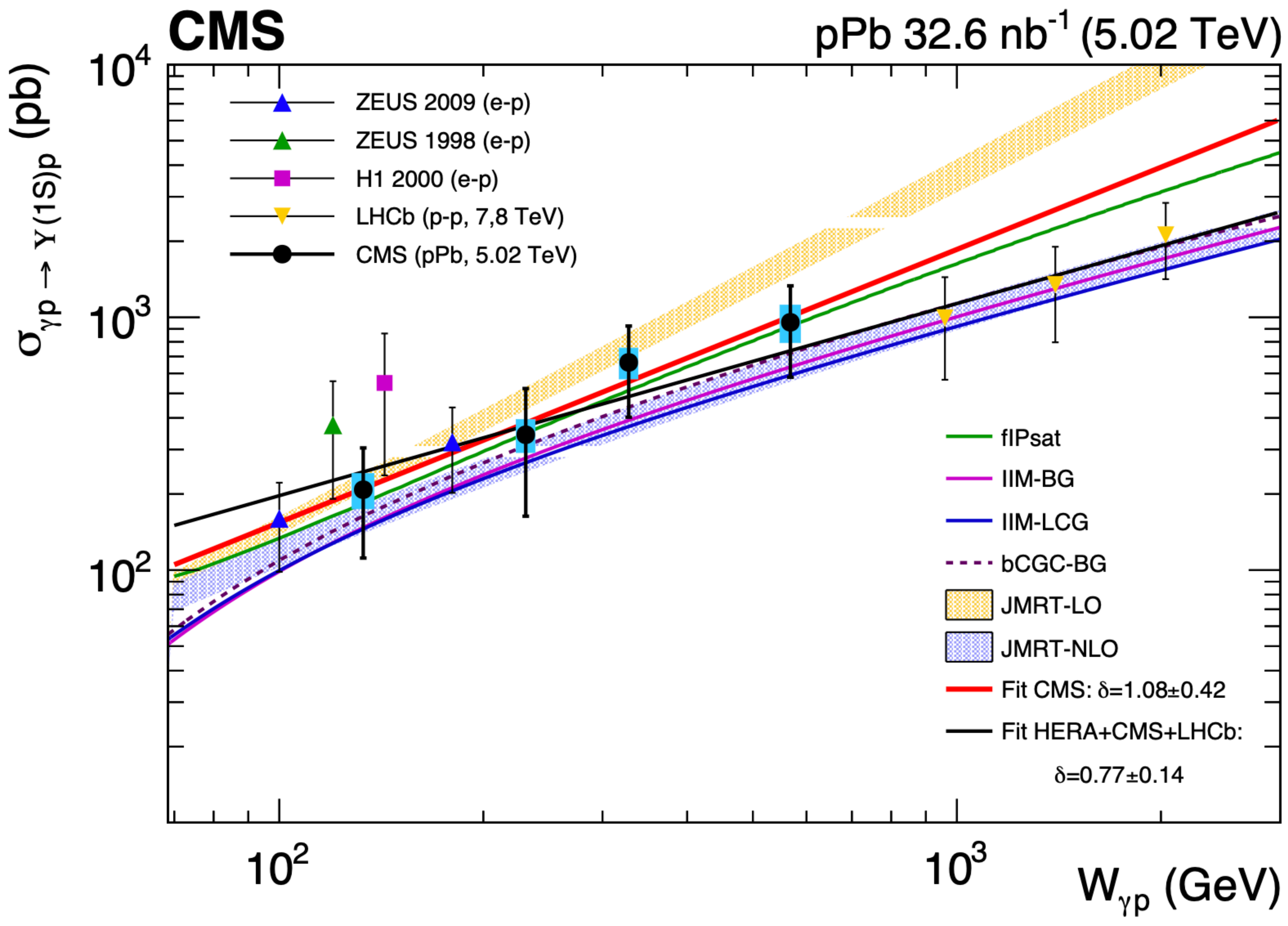
MS: PRD 98 (2018) 034013;

- perturbative JIMWLK + constrains from fits to H1 data.

First step to probe the fluctuation of the subnucleonic structure in protons at high energies

Exclusive J/ψ photoproduction cross section off protons

CMS Collaboration , Eur. Phys. J. C 82 (2022) 343

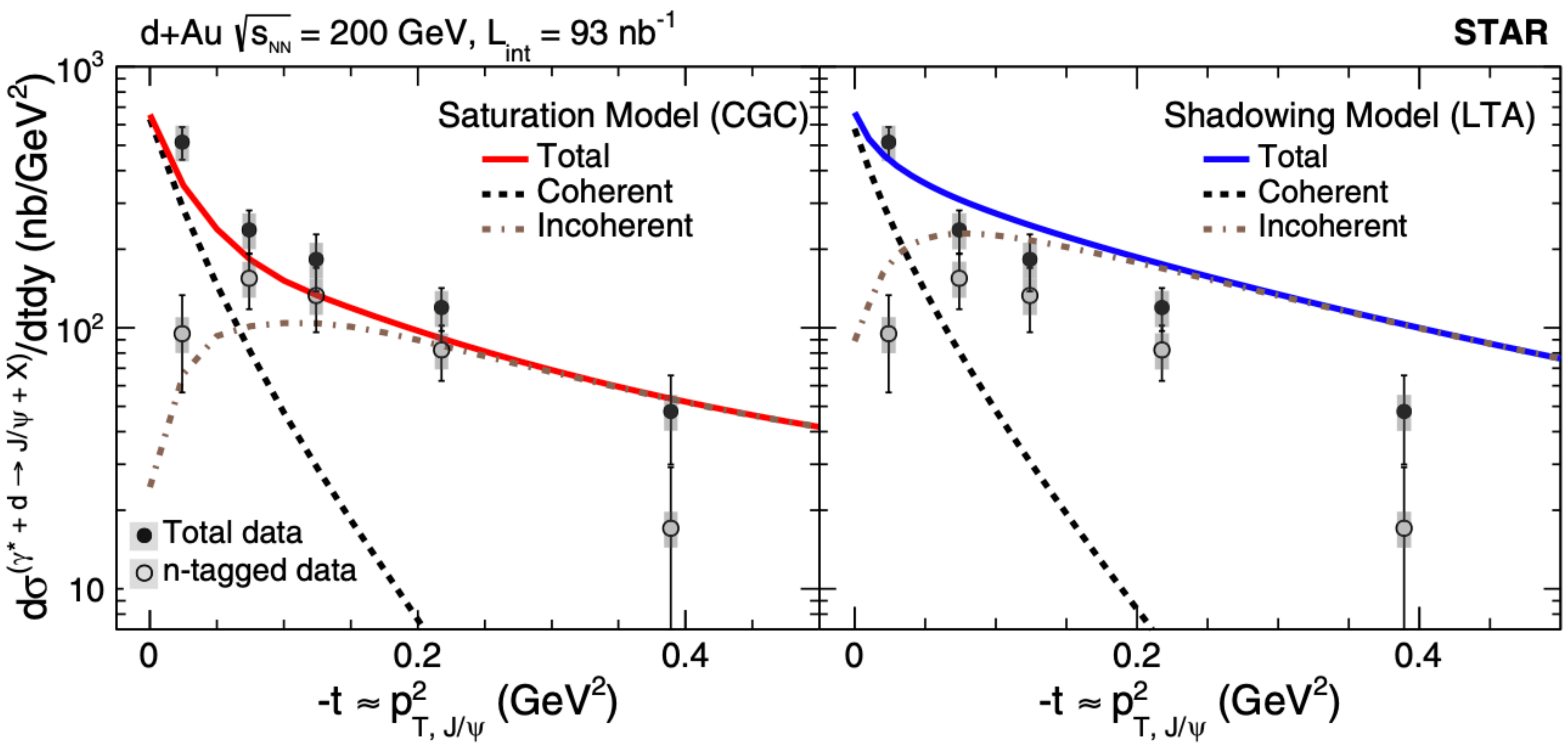


First measurement of the exclusive photoproduction of Υ(nS) mesons in p-Pb collisions at LHC energies

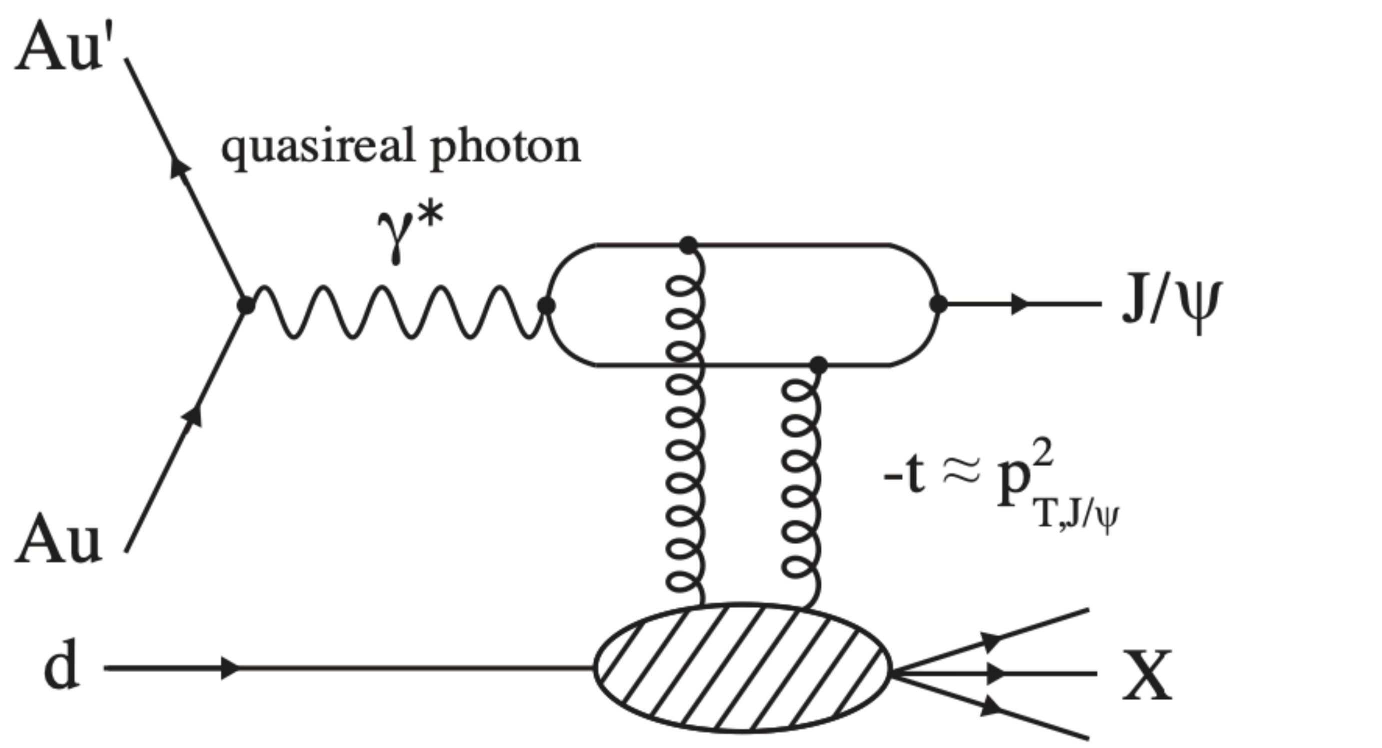
— Good agreement between experiments within uncertainties

— Follow linear power-law dependence of gluon density no clear saturation effects inside proton for measured photon-energy value.

Probing gluon distributions off nuclei target in dAu



Phys. Rev. Lett 128, 122303 (2022)



. 1. Photoproduction of J/ψ in $d+$Au UPCs, where X esents the deuteron (coherent) or deuteron-dissociative (in- rent) system.

First measurement of J/ψ photoproduction off the deuteron in dAu collisions
-> The data are found to be in better agreement with the saturation model incoherent regions

Current status photoproduction results in small systems

Experimental measurements

Goal: Test gluon saturation effects inside proton/nuclei

LHCb : Exclusive production of J/ψ and ψ(2S) mesons in pp 13 TeV, JHEP10(2018)167

ALICE : Exclusive and dissociative J/ψ photoproduction in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV, arXiv:2304.12403

CMS : Measurement of exclusive Υ photoproduction in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, CMS PAS FSQ-13-009, CMS Collaboration , Eur. Phys. J. C 82 (2022) 343

→

- ➡ No significant change in the gluon density behavior of the proton between HERA and LHC energies
- ➡ Exploration of the fluctuations of the subnucleonic structure in the proton

RHIC : Diffractive J/ψ meson production in d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV →

Ideal baseline for testing nuclear (saturation or nuclear shadowing) effects

Theoretical studies : QCD evolution based evidence for the onset of gluon saturation in exclusive photo-production of vector mesons, A. Arroyo Garcia et al., Phys. Lett. B 795 (2019) 569–575

One of the key predictions of gluon saturation: **observation of slow down of growth of gluon density with growing energy**

✓ Precision measurements (going to higher $W_{\gamma p}$ or low -x) of J/ψ and ψ(2S) will be explored with ALICE in Run 3

✓ Comparative study of similar measurements LHC experiments (i.e. exclusive and dissociative measurement with LHCb) can provide information on gluon saturation

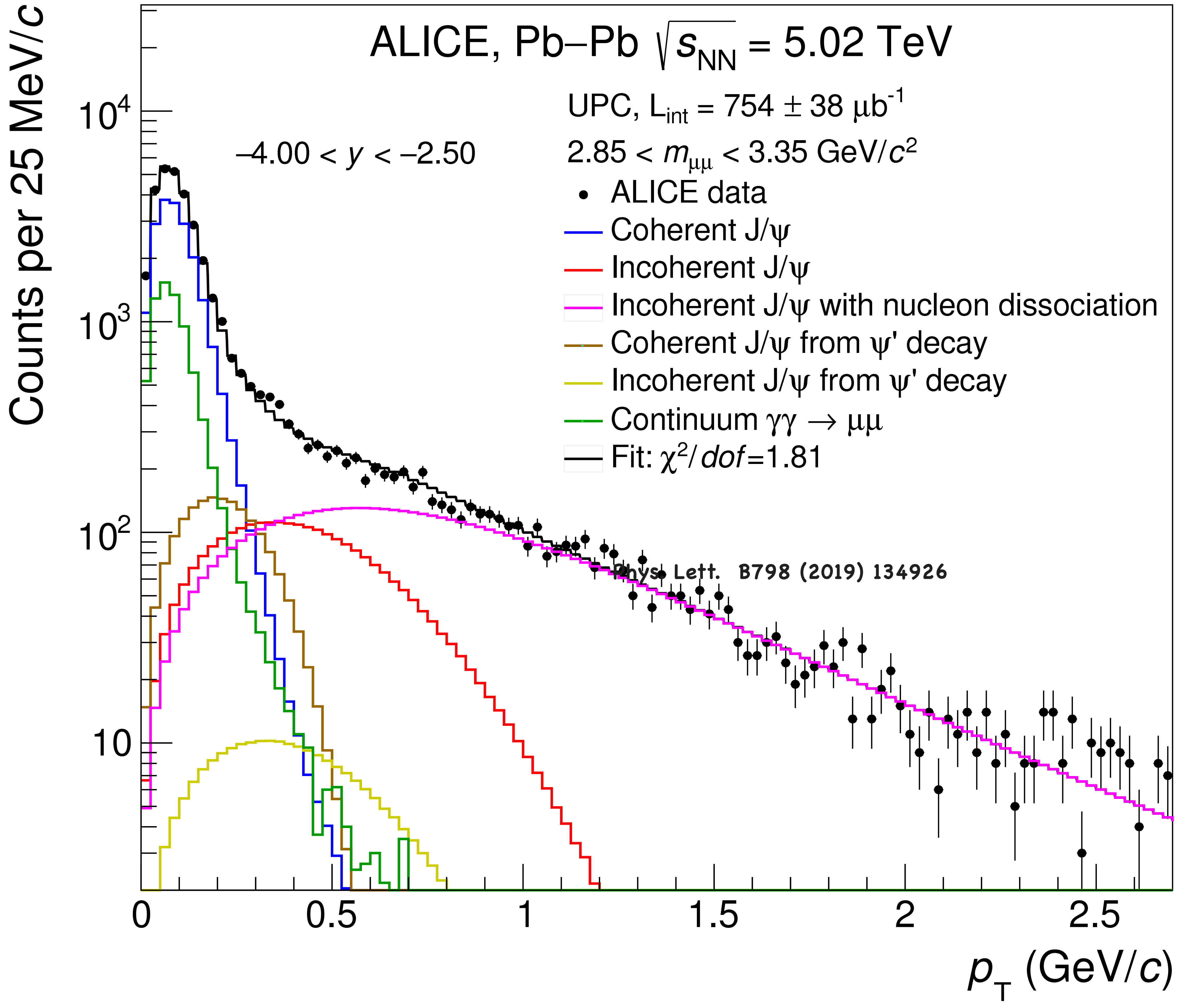
Photoproduction of VM in UPCs

Photo production cross section (σ) measurement

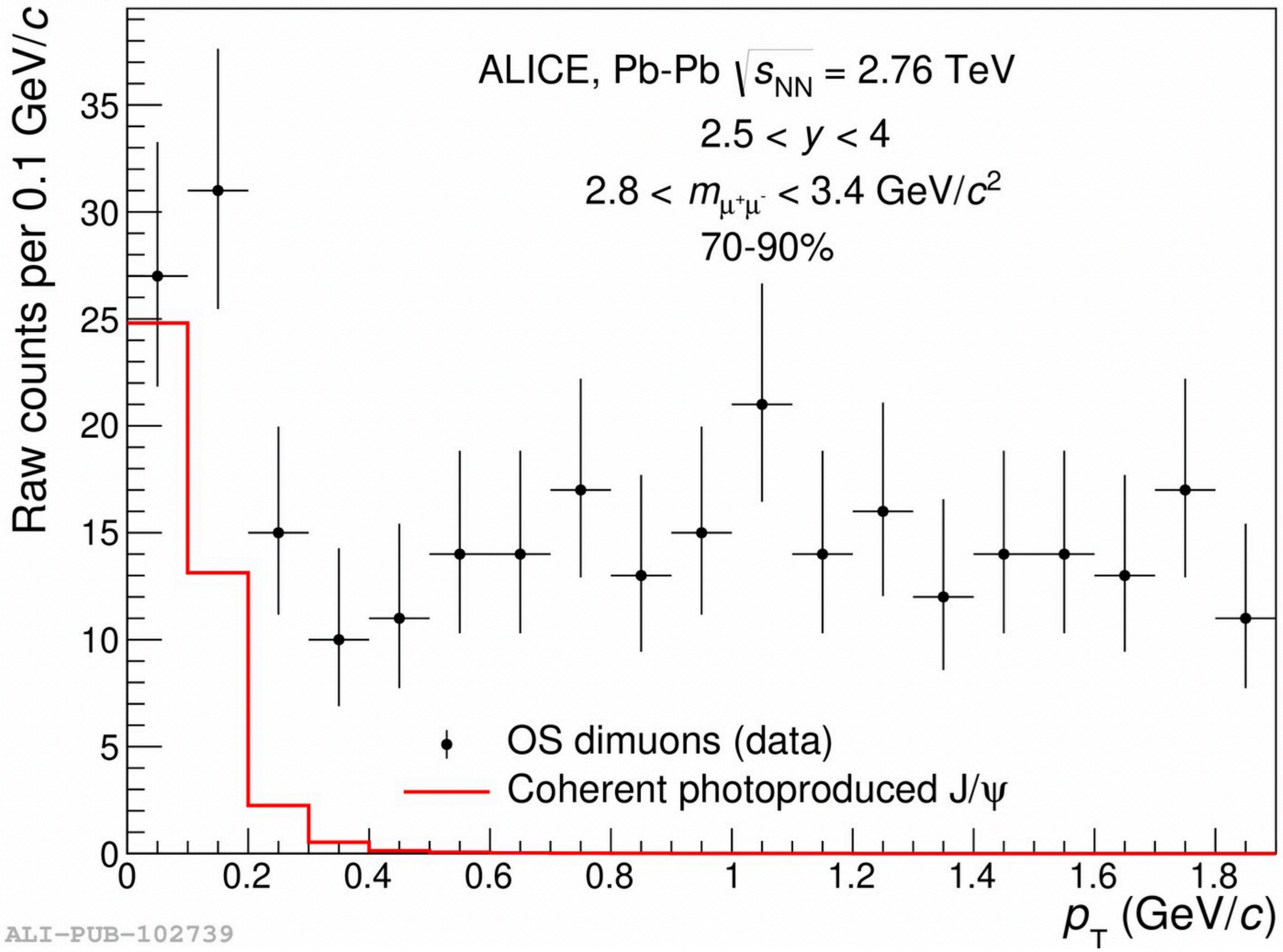
Transverse momentum (p_T),
Centrality (<N_{Part}>)
Rapidity (y)

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

Illustration of p_T distributions of different processes for UPCs



First observation of VM photoproduction in heavy-ion collisions with nuclear overlap



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

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

-> Interpreted as dominant contribution from coherent photoproduction

-> Significance : 5.4σ (70-90%), 3.4σ (50-70%)

Similar p_T and *y*-differential J/ψ excess yield measurement are seen with other LHC experiments , PRC 105 (2022) L03201 -> **Interpreted as a sign of a dominant contribution from coherent photoproduction**

VM photoproduction in heavy-ion collisions with nuclear overlap

Other experiments : STAR Collaboration

First measurement of the t-dependence of the J/Ψ excess

-> Supports also photoproduction origin

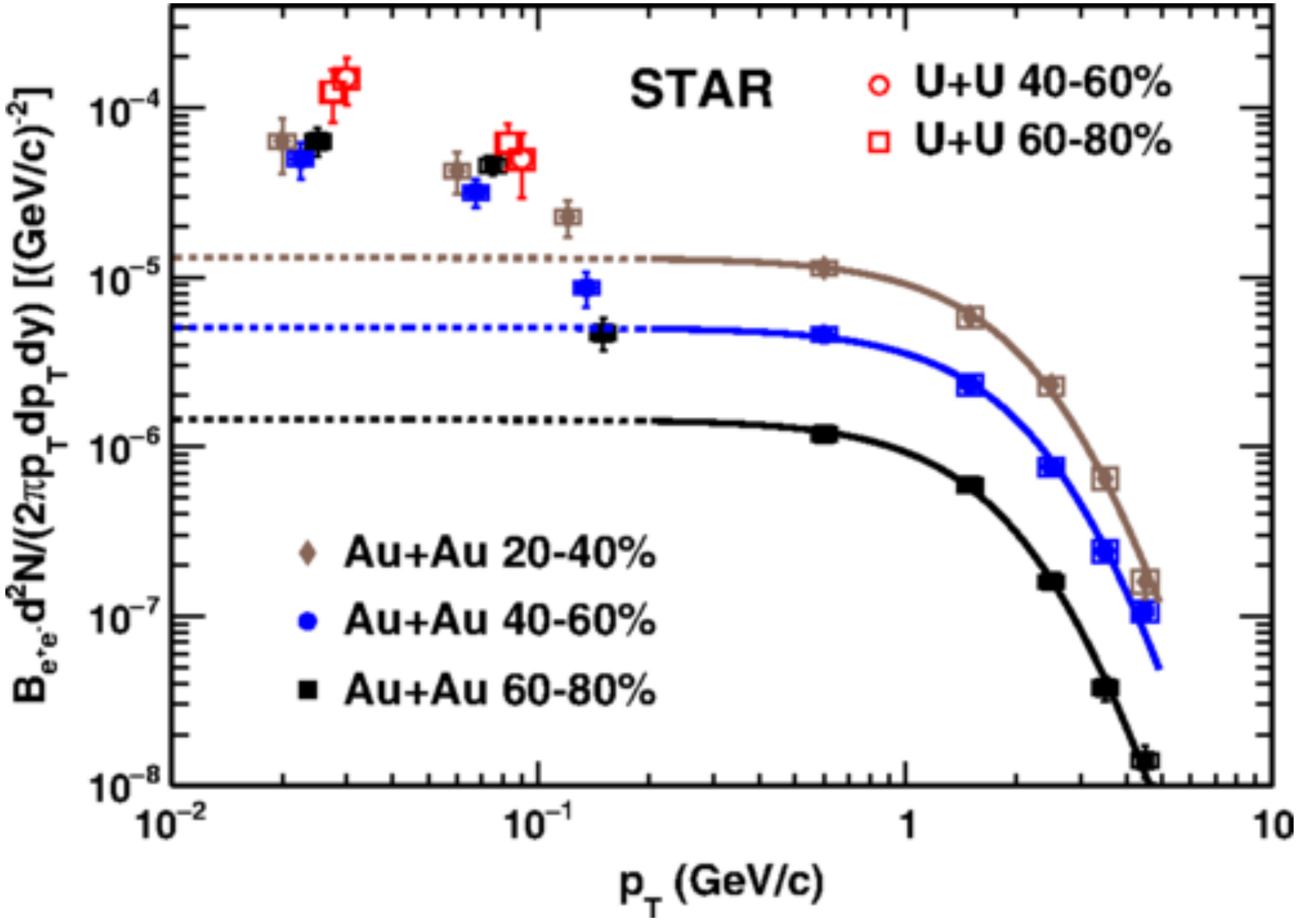
$$R_{AA}(p_T) = \frac{Y^{Au-Au}_{J/\psi}}{< T_{AA} > \sigma^{pp}_{J/\psi}}$$

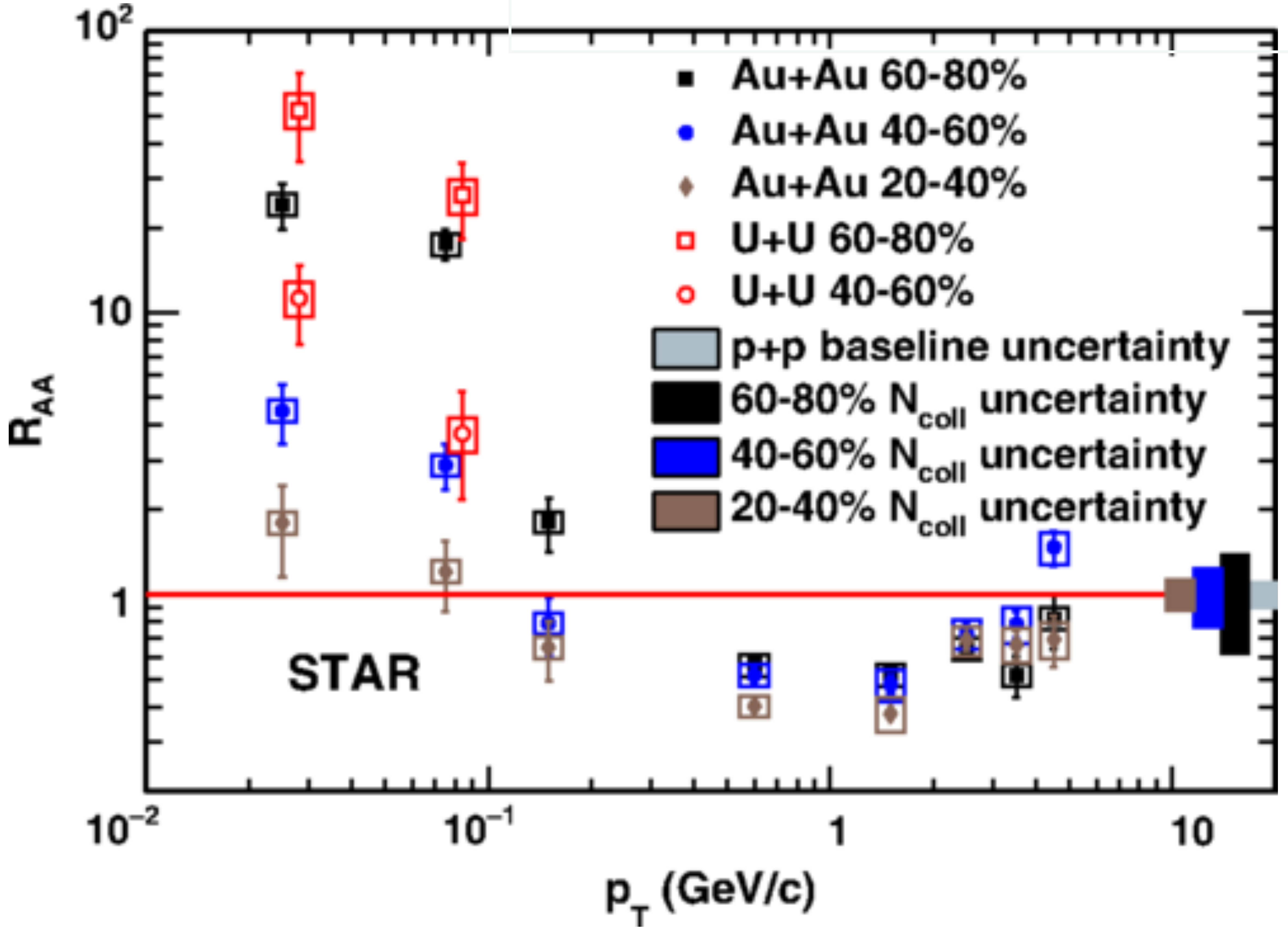
Production cross section

Y^{Au-Au} = yield of J/ψ in Au—Au collisions

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

σ^{pp} = cross section of pp, Phys. Rev. C 93, 024919 (2016).

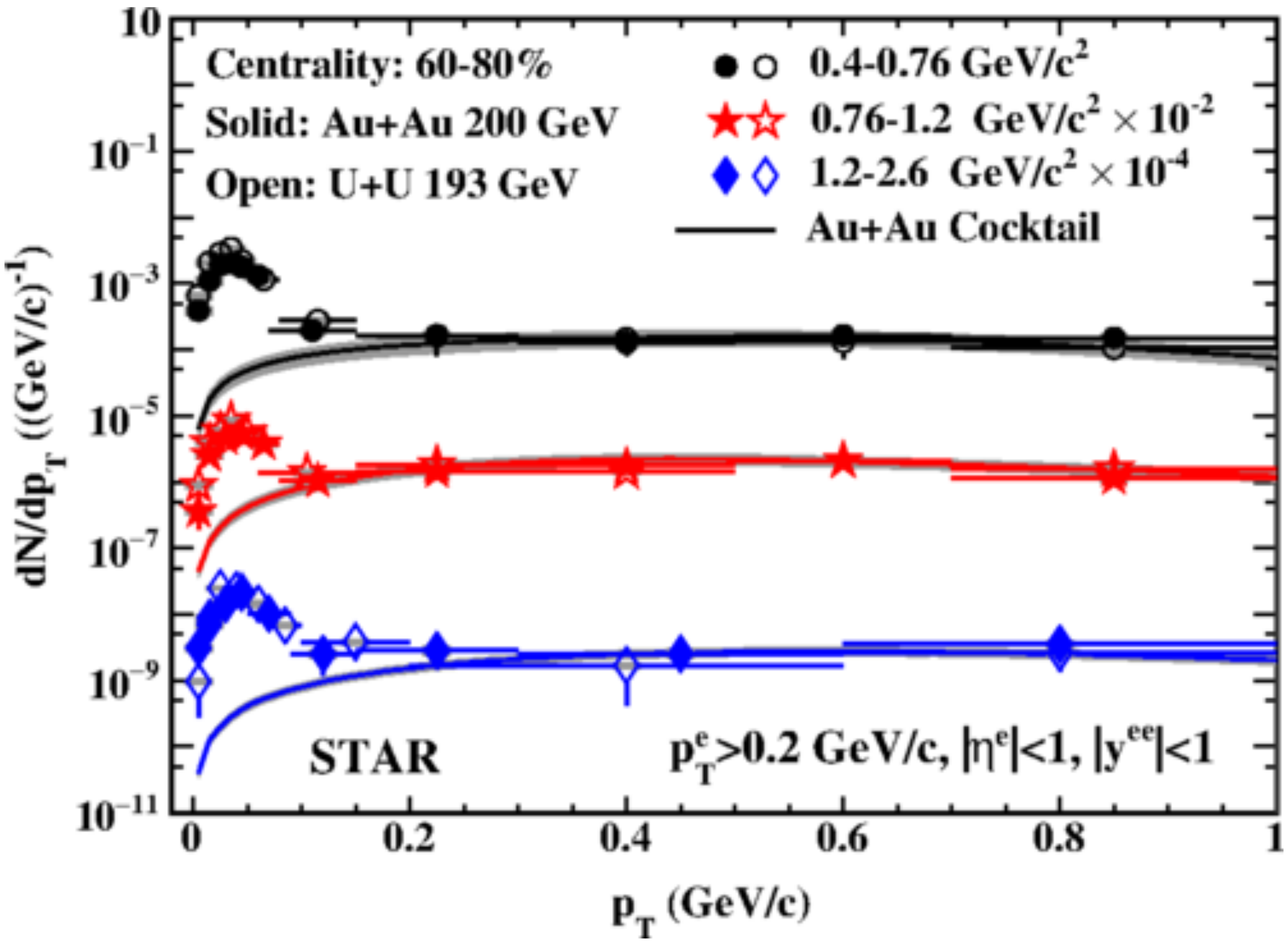




Similar observation by STAR Collaboration at lower energy in U-U and Au-Au collisions (PRL 123, 132302 (2019))

Dielectron production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

$\gamma\gamma$ interact.



STAR Collaboration,
Phys. Rev. Lett 121, 132301 (2018)

Very low-p_T dielectron excess is observed by STAR, at midrapidity in Au–Au and U–U collisions

Model calculations describe the observed excess yields but fail to reproduce the p_T^2 distributions.

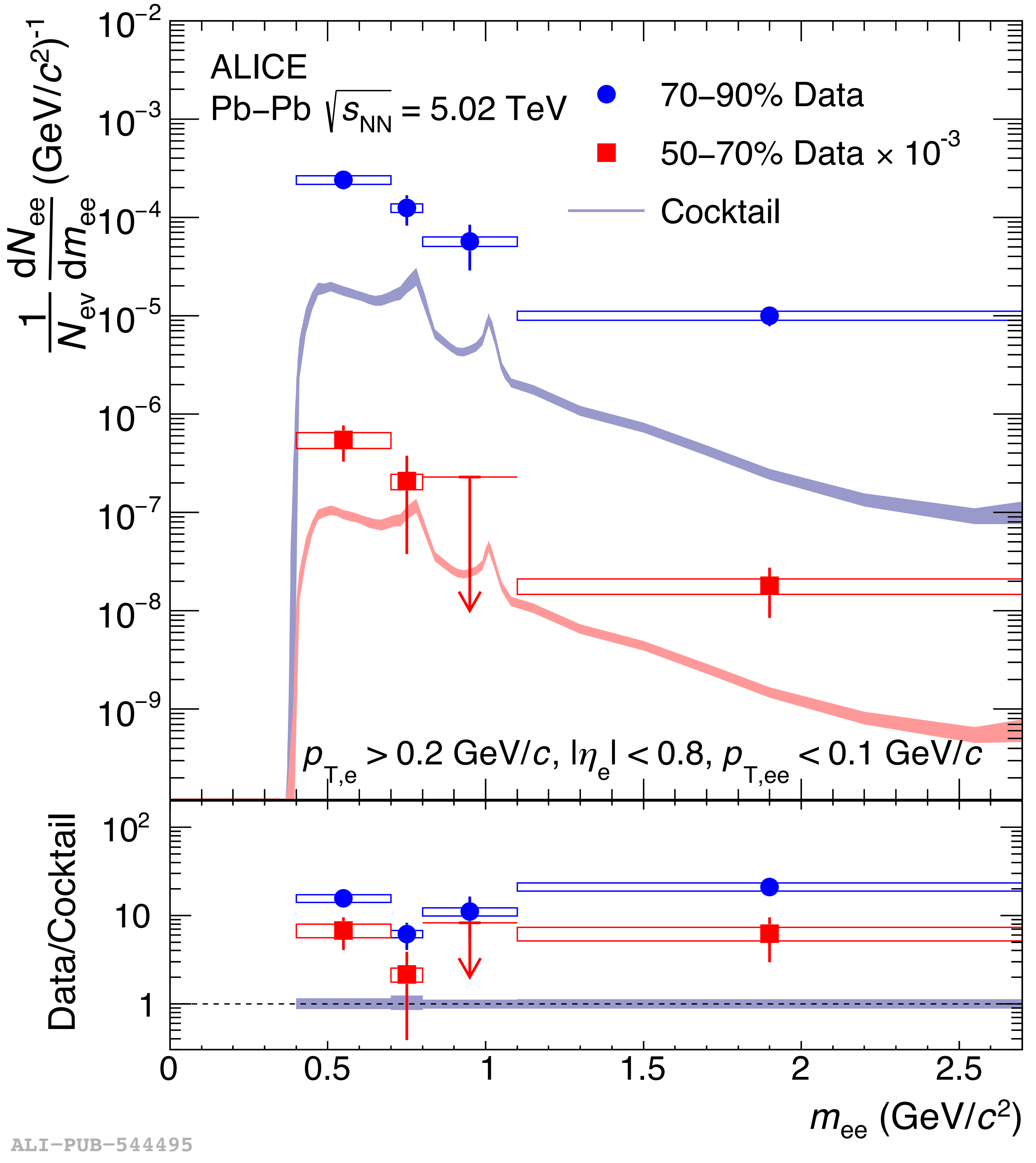
W. M. Zha et al., Phys. Lett. B 781, 182 (2018)

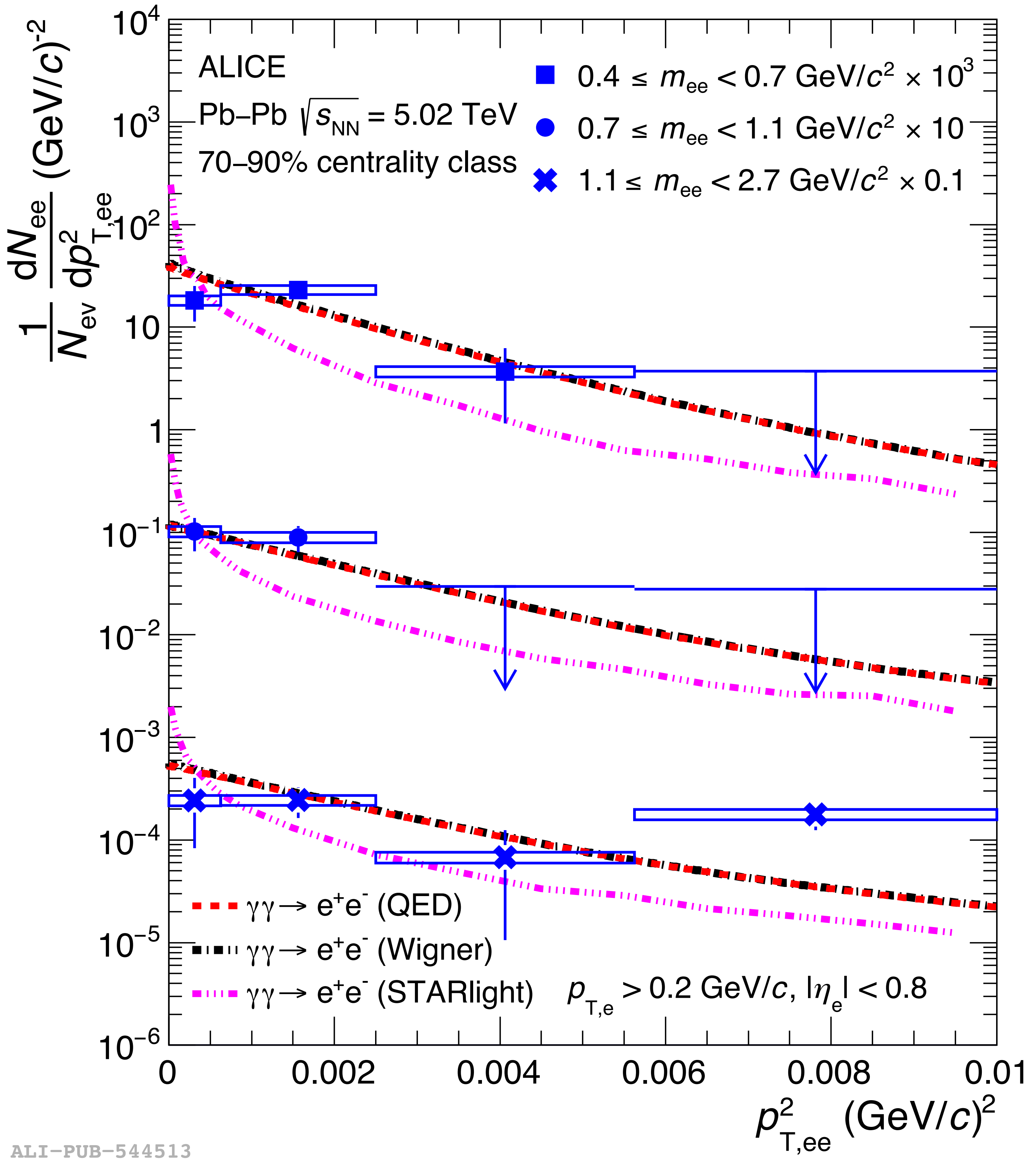
S. R. Klein, Phys. Rev. C 97, 054903 (2018)

Dielectron production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

First measurement at LHC of a dielectron excess at very low-p_T and low invariant mass in peripheral Pb–Pb collisions

JHEP 06 (2023) 024





Data disfavor STARlight prediction whereas lowest-order QED[1] and Wigner[2] calculations are reproducing the measurements

-> From comparison with models: p_T broadening observed in HIC originates predominantly from initial EM field strength which varies significantly with b

Observation by ATLAS of centrality-dependent acoplanarity for muon pairs produced via $\gamma\gamma$ scattering in hadronic Pb–Pb collisions for 4 < $m_{\mu+\mu-}$ < 45 GeV/c^2, PRL 121, 212301 (2018)

Recent ATLAS results, in Ref. Phys. Rev. C 107, 054907 (2023) suggested that no significant contribution from interactions of the muons with magnetic fields

[1] QED : W. Zha et al., Phys. Lett. B 800 (2020) 135089, J. D. Brandenburg et al., Eur. Phys. J. A 57 (2021) 299

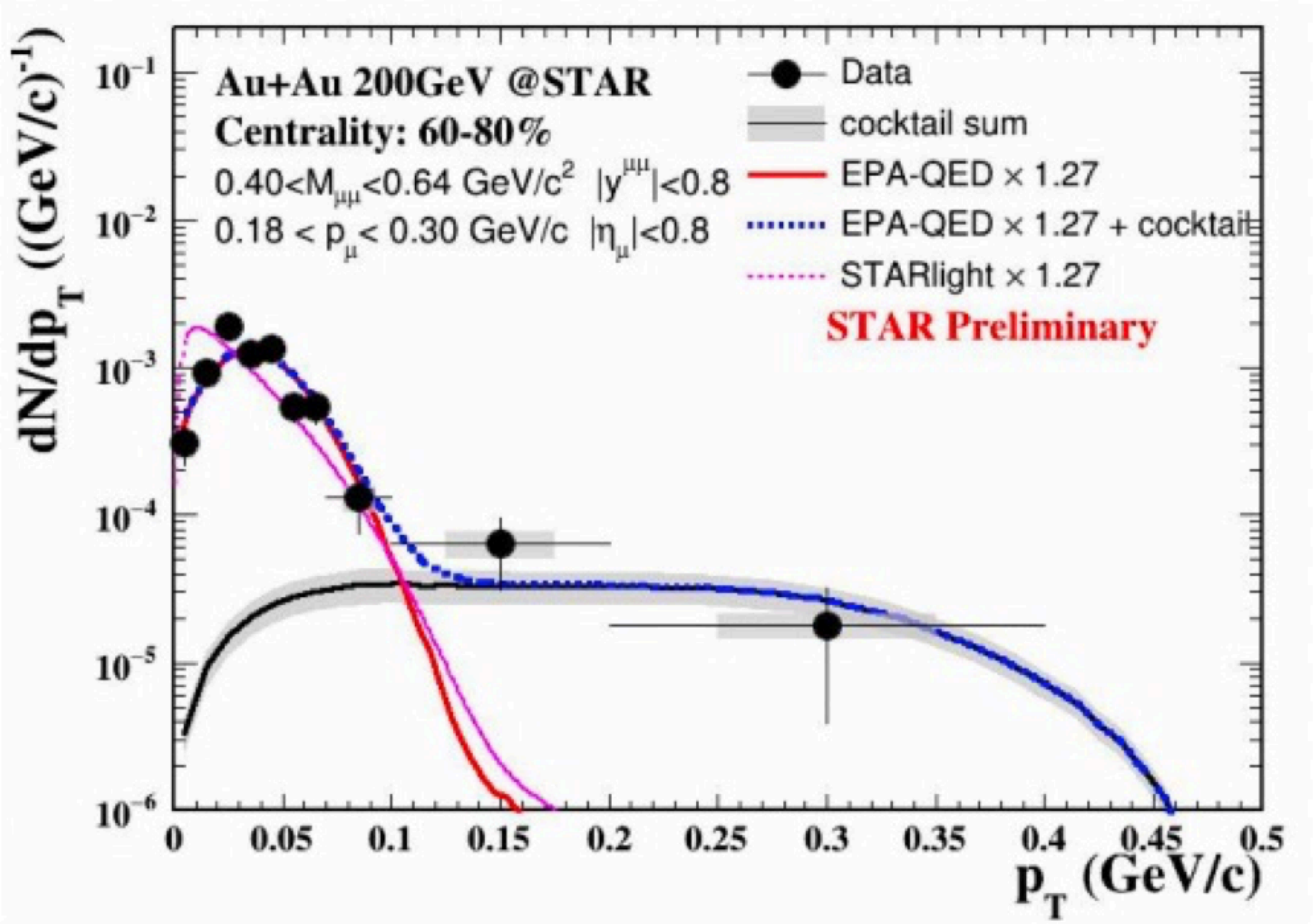
[2] **Wigner** M. Klusek-Gawenda *et al.*, Phys. Lett. B. 814 (2021) 136114

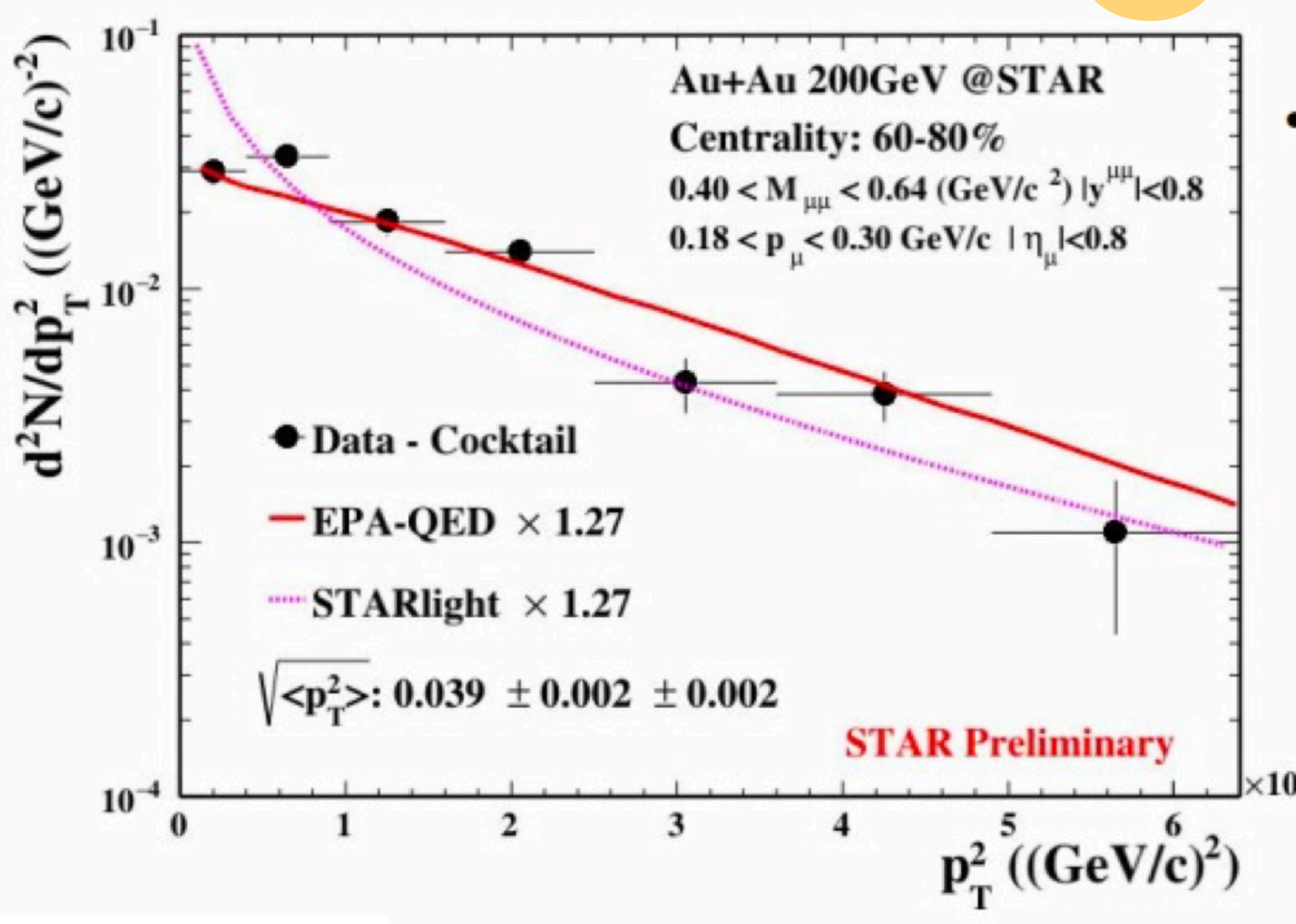
[3] STARlight: S.R. Klein et al., Comput. Phys. Commun. 212 (2017) 258, S.R. Klein, Phys. Rev. C. 97 (2018) 054903

Dimuon production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

First measurement of dimuon production in high mass region at low p_T with nuclear overlap collisions

NEW





EPA -QED based model describe the measurements at low p_T -> Supports that the enhancement originates from photon-induced processes

Theoretical developement : for VM photo production

Production cross section

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)

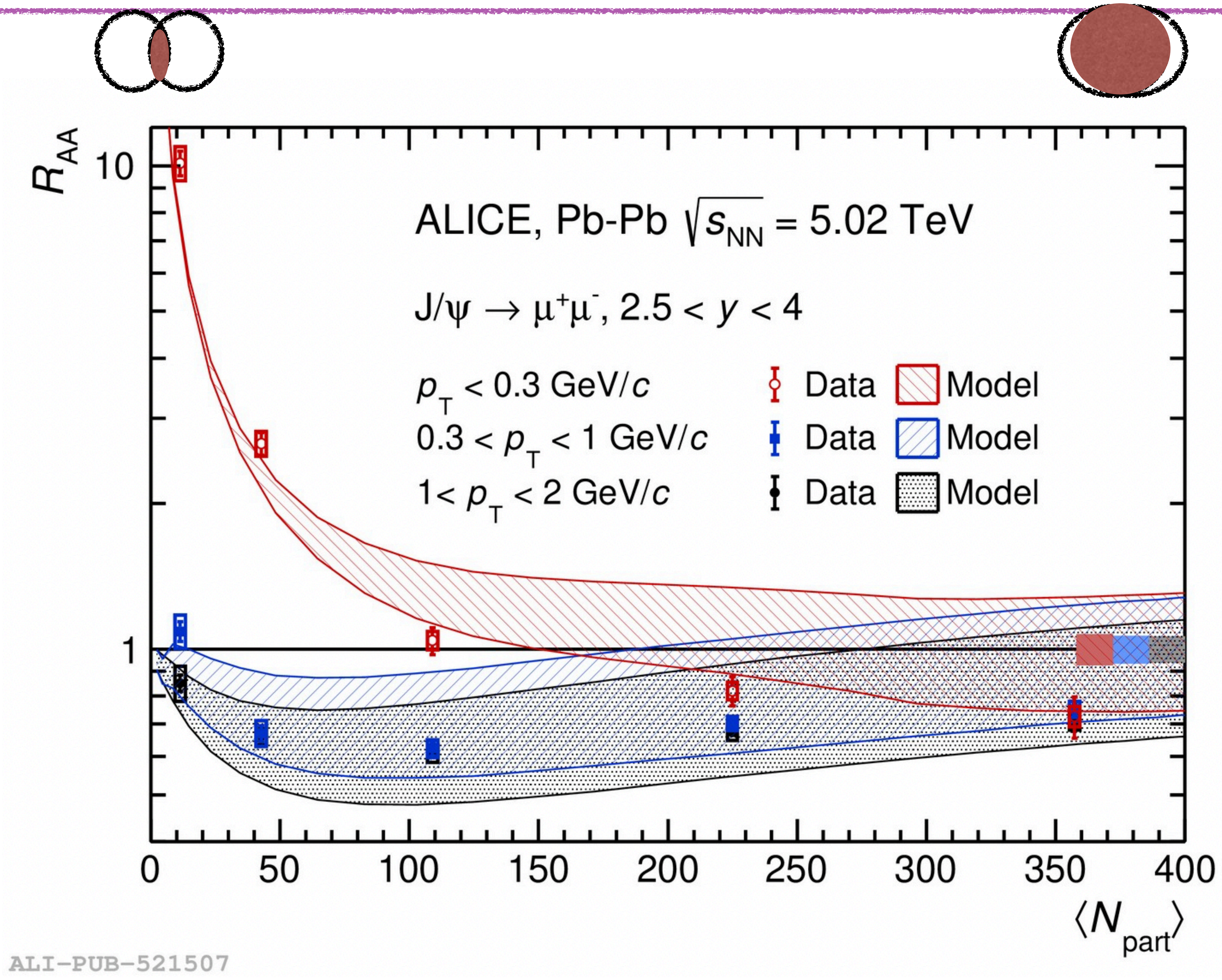
i. UPC like : b-dependence (S1).
ii. Effective photon flux (S2)
iii. Effective photon flux + photo nuclear cross section (S3)

[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)

VM photoproduction in heavy-ion collisions with nuclear overlap

Production cr



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

NEW

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

Phys. Lett. B 846 (2023) 137467

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

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

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

Enhancement at very low p_T

R_{AA} reaches 10 !

-> **Coherent J/Ψ photo production is the plausible origin**

First significant measurement in semi central collisions at LHC

5.6 **σ** for 30–50% centrality bin ($<N_{part}>$ ~ 100)

1.4**σ** for 10– 30% centrality bin ($<N_{part}>$ ~ 220)

Understanding of the existence of coherent J/Ψ photoproduction in semi-central heavy-ion collisions is theoretically challenging

Removing hadronic contamination

Production cross section

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,

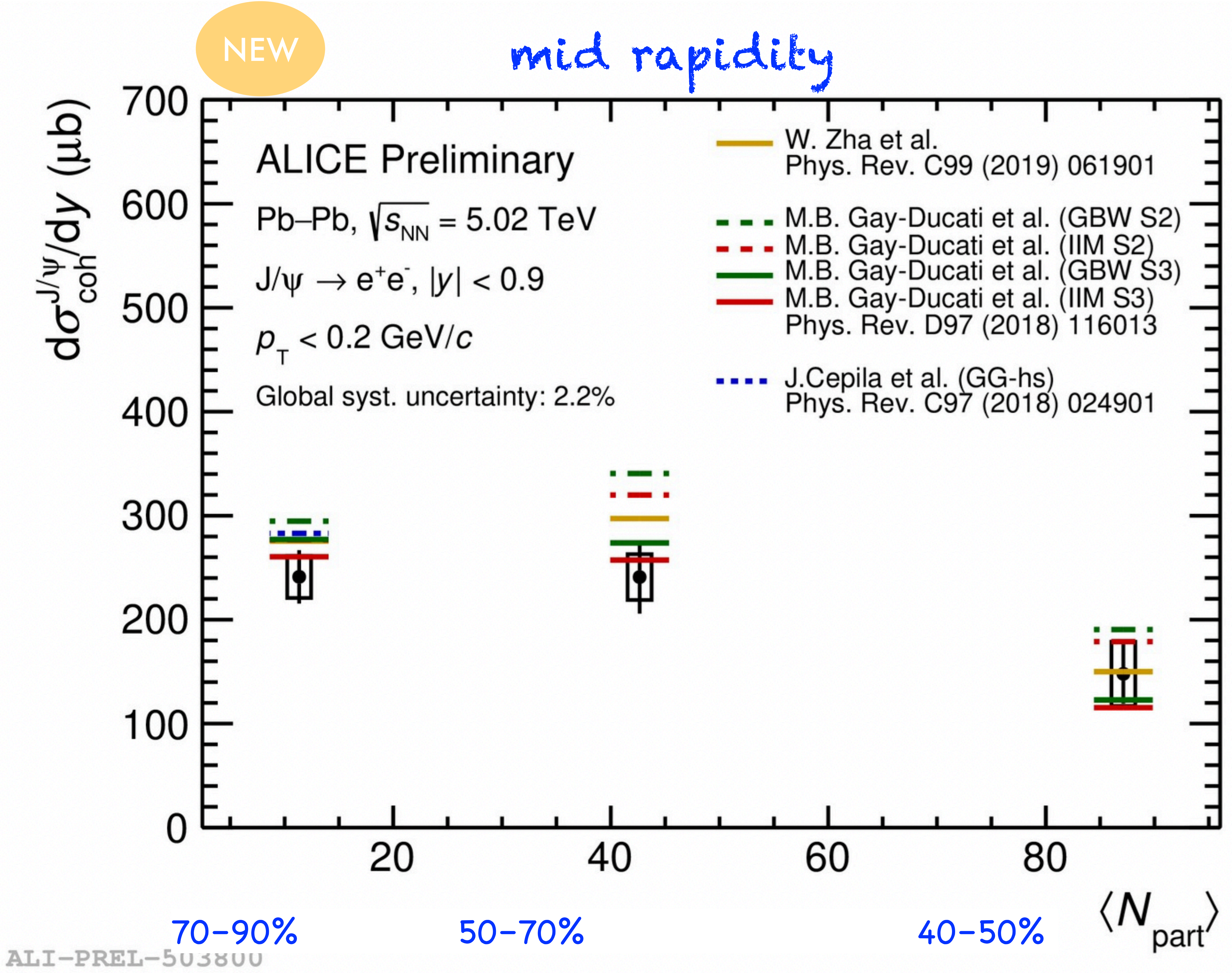
$$N^{h,J/\Psi}_{AA.} = \int_{p_{T1}}^{p_{T2}} \frac{dN^{h}_{AA}}{dp_T} dp_T = \mathcal{N} \times \int_{p_{T1}}^{p_{T2}} \frac{d\sigma^{h}_{pp}}{dp_T} \times R^{h}_{AA}(p_T) \times (\mathcal{A} \times \epsilon)^{h}_{AA}(p_T) dp_T$$

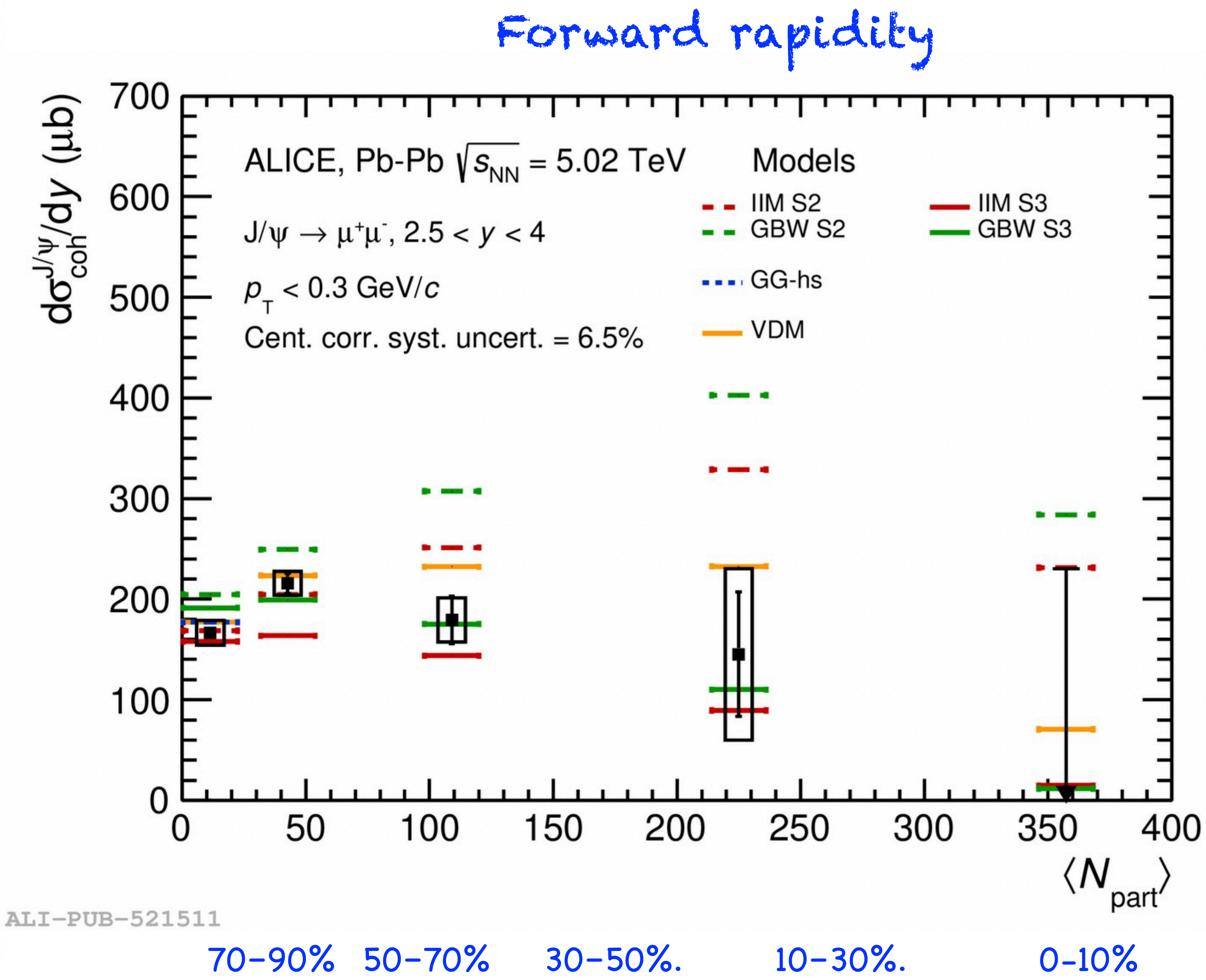
Data driven approach: (same procedure adopted as discussed in Ref. Phys. Lett. B 846 (2023) 137467)

i.Hadronic proton-proton differential cross section

ii.Evolution of the nuclear modification factor at low p_T

Coherent J/ψ photoproduction : centrality dependence





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

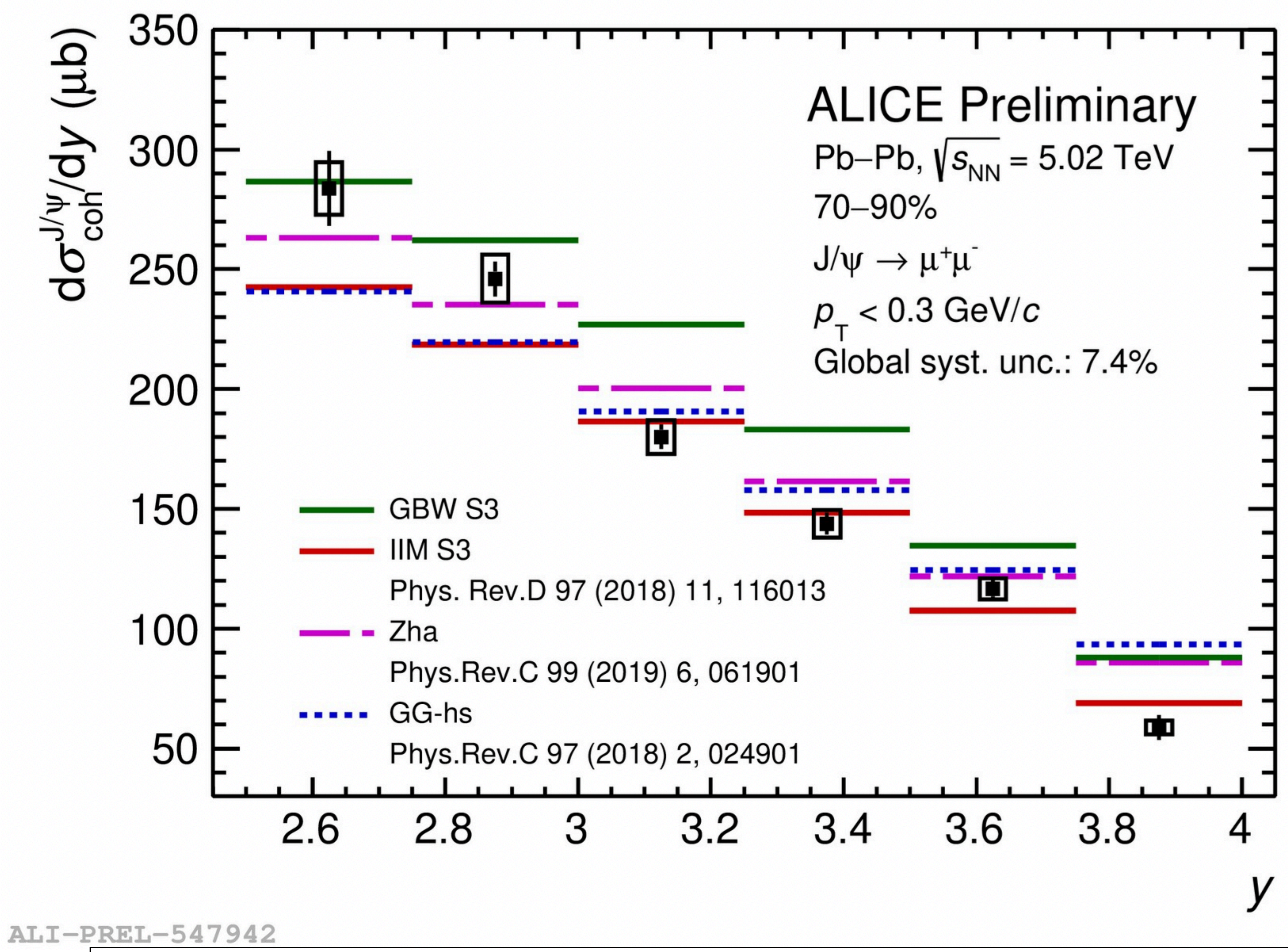
Both measurements at mid and forward rapidity don't show a significant centrality dependence

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

Understanding of the existence of coherent J/Ψ photoproduction in semi-central heavy-ion collisions is theoretically challenging

Coherent J/ψ photoproduction : rapidity dependence

NEW



Models considerations:

GG -hs : photon flux with constraints on impact parameter range

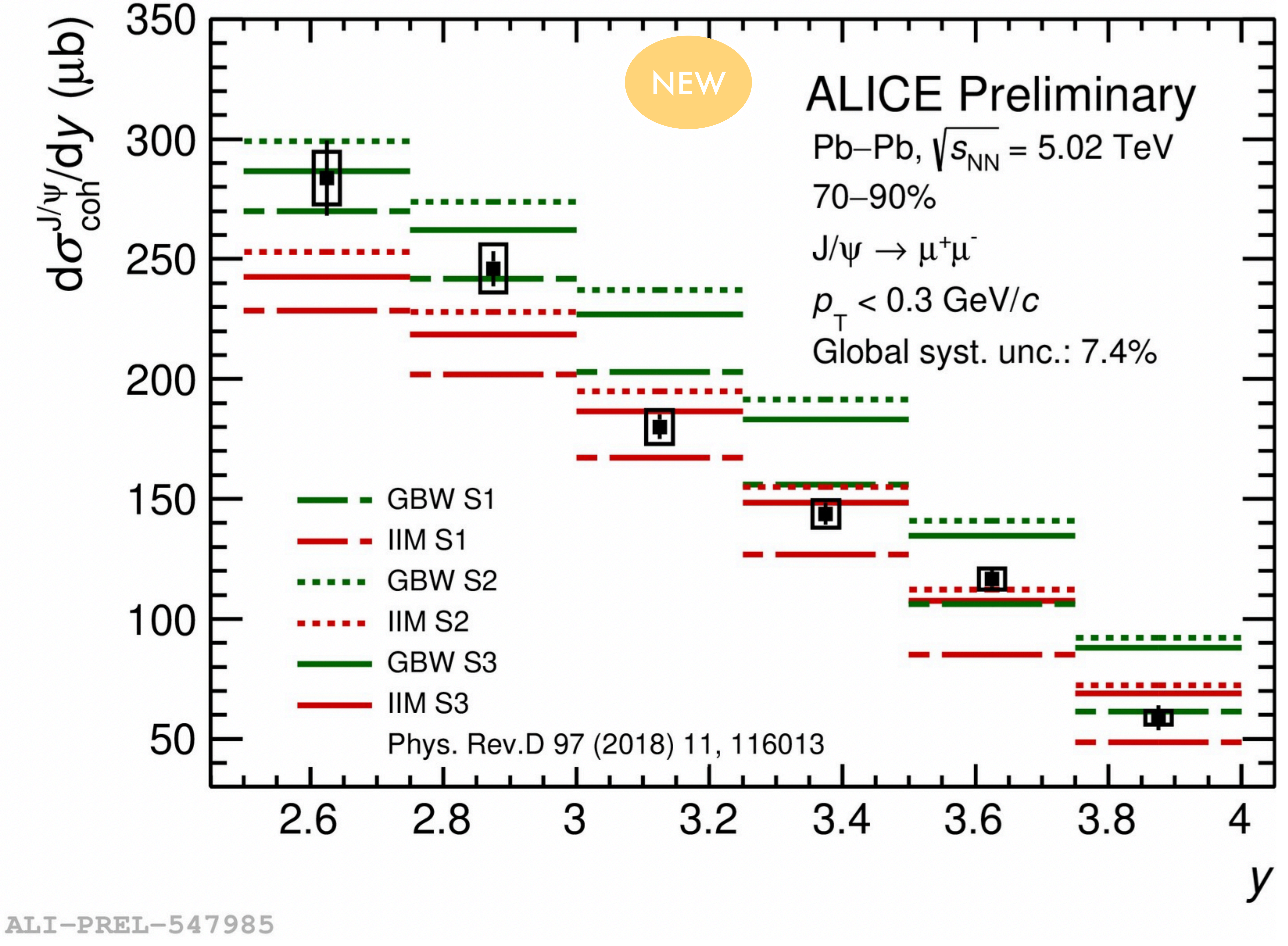
Zha : assumptions on photon-pomeron coupling (nucleus+spectator)

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

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 behavior hold as well **for UPC measurement, Eur. Phys. J. C 81 (2021) 712**

Coherent J/ψ photoproduction : rapidity dependence

Production cross section



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)

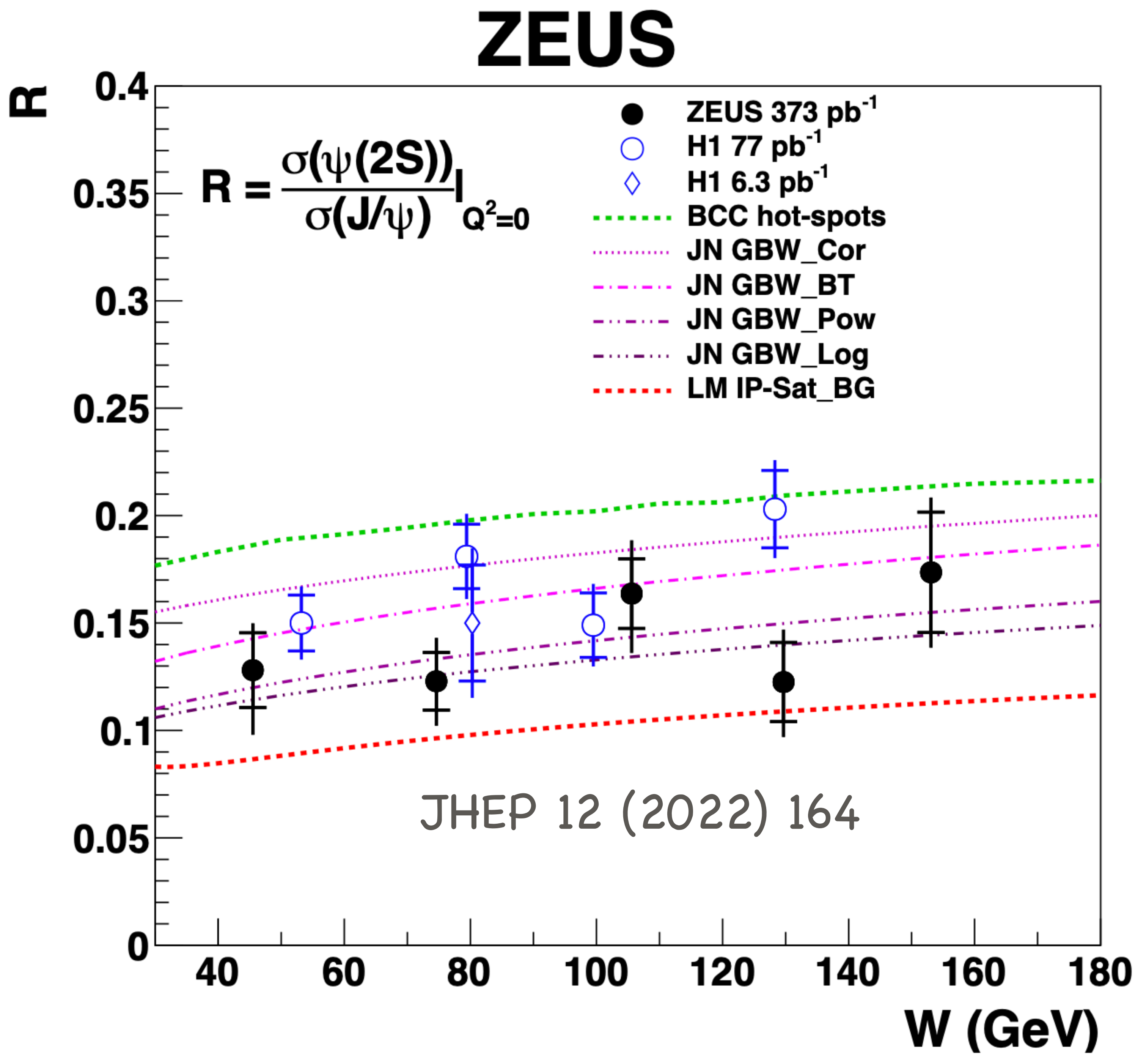
No model describe the measurements in the entire measured y

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

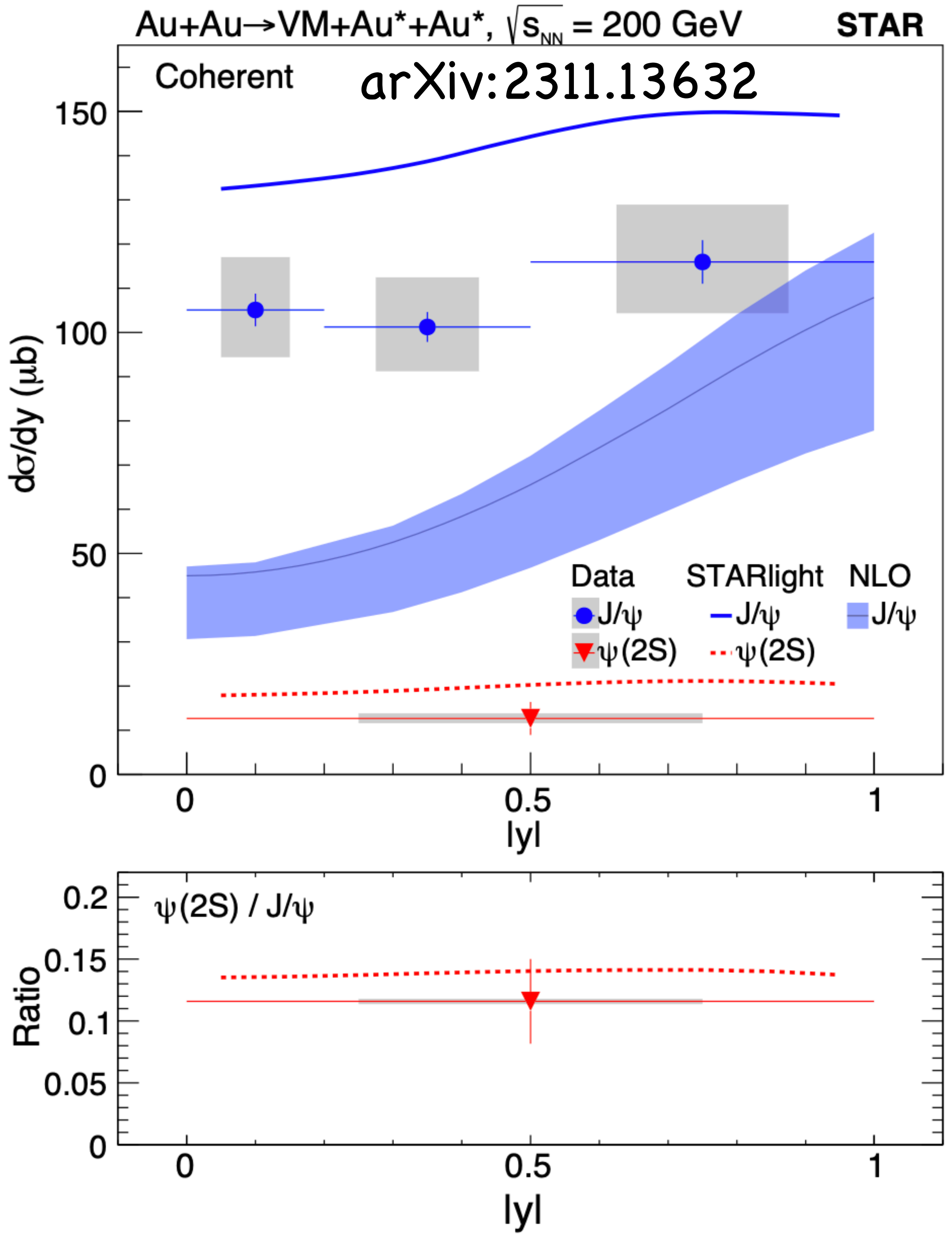
Understanding the VM photoproduction y-differential cross section measurement with including effect of the nuclear overlap is theoretical challenge

Coherent $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ ratios HIRA to LHC energies

HERA



RHIC



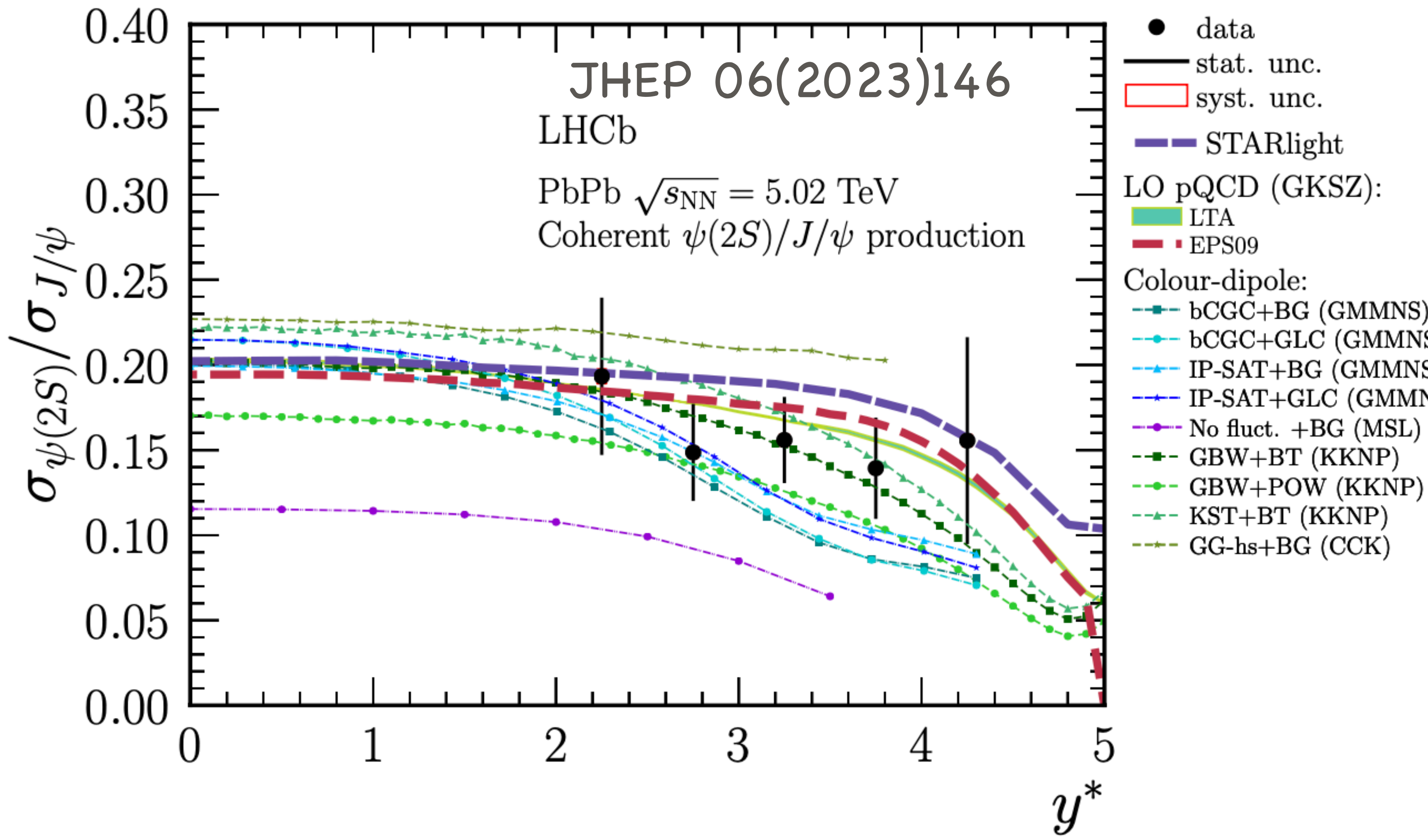
LHC

Production cross section

ALICE, at midrapidity

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

0.18 ± 0.0185(stat.) ± 0.028(syst.)



✓Do we expect similar ratios for going to HERA to LHC energies ?

✓Precision and more differential coherent photo production (i.e Ψ(2S) cross section measurements) are important at LHC and RHIC energies

✓Also same ratios can be explored in heavy-ion collisions with nuclear overlap ?

— This ratios can be used as a tool to probe potential QGP like effects on the photo produced charmonia

Photon energy ambiguity : symmetric collisions

Each colliding nucleus could serve as a photon emitter, the other acts as a target

For details see Adam Matyja talk, Tue, 09/01

Phys. Rep. 364 (2002) 359

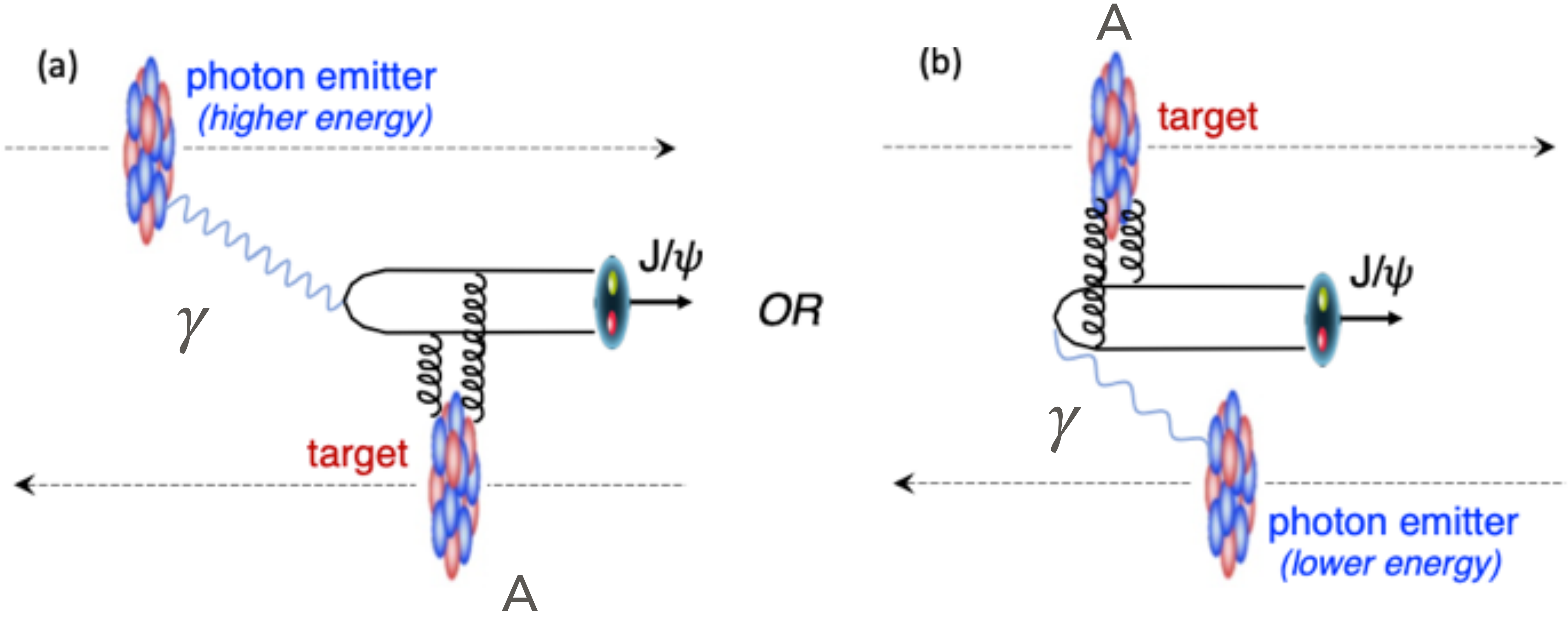
The sum of two different amplitudes :

$$A+\gamma \rightarrow J/\psi + A \quad E_\gamma(A+\gamma) = \frac{M_{J/\psi}}{2} e^{-y_{J/\psi}}$$

$$\gamma + A \rightarrow J/\psi + A \quad E_\gamma(\gamma+A) = \frac{M_{J/\psi}}{2} e^{+y_{J/\psi}}$$

At y=0, both contributions are identical

If y ≠ 0 , both If rapidity is not equal to zero, gamma energies are different, and relative contribution of (γ+A)/ (A+γ) are not unity, it depends on impact parameter



$$x = \frac{m^2_{J/\psi}}{W^2_{\gamma \mathrm{Pb}}} \qquad x = \frac{m_{J/\psi}}{\sqrt{s_{\mathrm{NN}}}} \times \exp(\pm y)$$

For a fixed mass ($m_{J/\psi}$) and center-of-mass energy ($\sqrt{s_{NN}}$)

Different region of Bjorken-x region can be accessed depending on $W_{\gamma A}$ and y

Photon energy ambiguity : In Symmetry collisions

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)]

For details see Adam Matyja talk, Tue, 09/01

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

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

Simultaneously solving using the cross section measurements from UPCs and PCs

1. ALICE : Phys. Rev. C 96, 015203 (2017)

Photon energy ambiguity : solve simultaneously

PEA

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

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

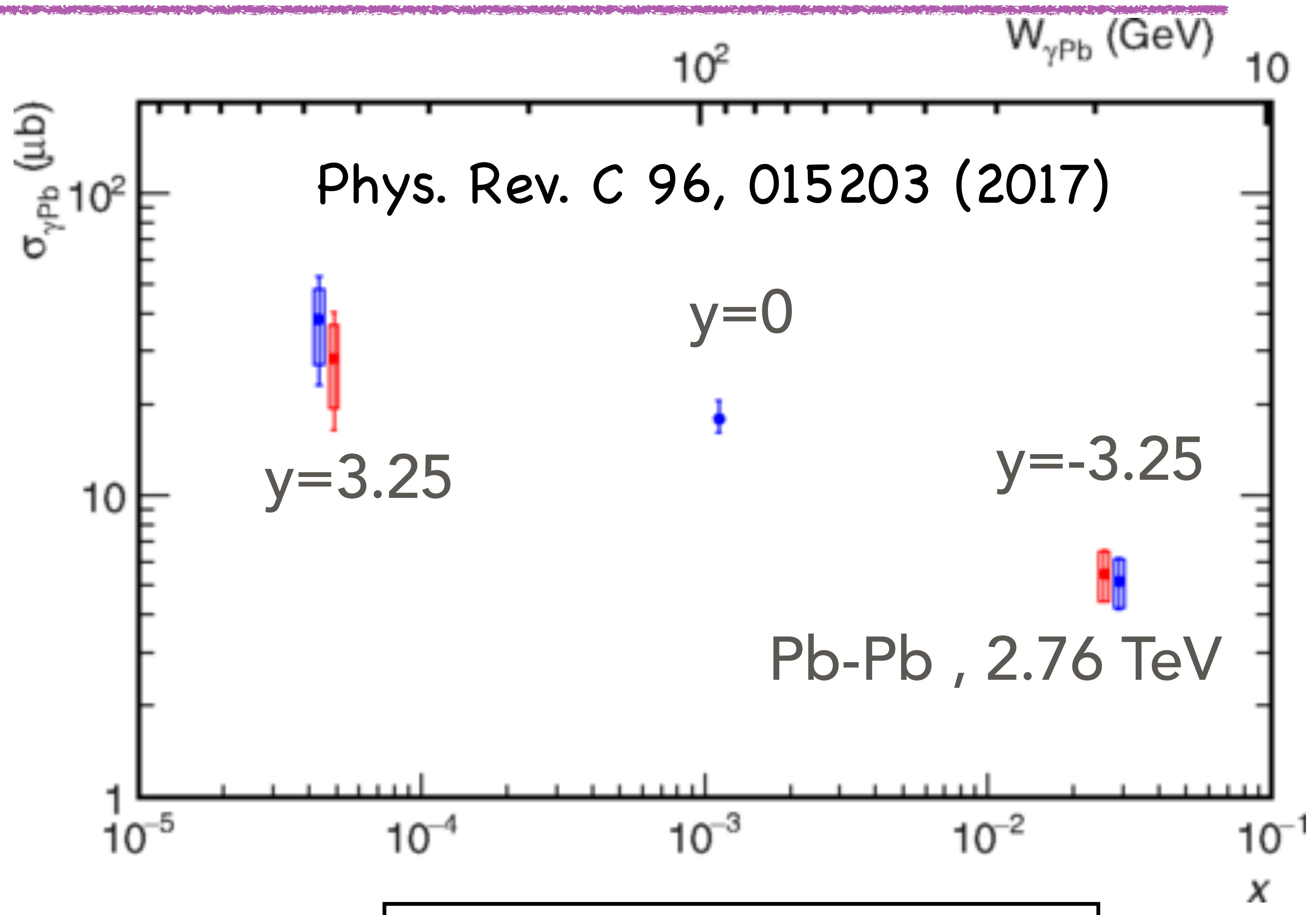
A =UPC

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

B= PC

For example, use peripheral and ultra-peripheral collisions

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



$$\sigma_{\gamma\mathrm{Pb}}(W_{\gamma\mathrm{Pb}} = 18.2\ \mathrm{GeV}) = 5.2 \pm 1.0\,(\mathrm{stat.}) \pm 1.0\,(\mathrm{syst.})\ \mu\mathrm{b},$$

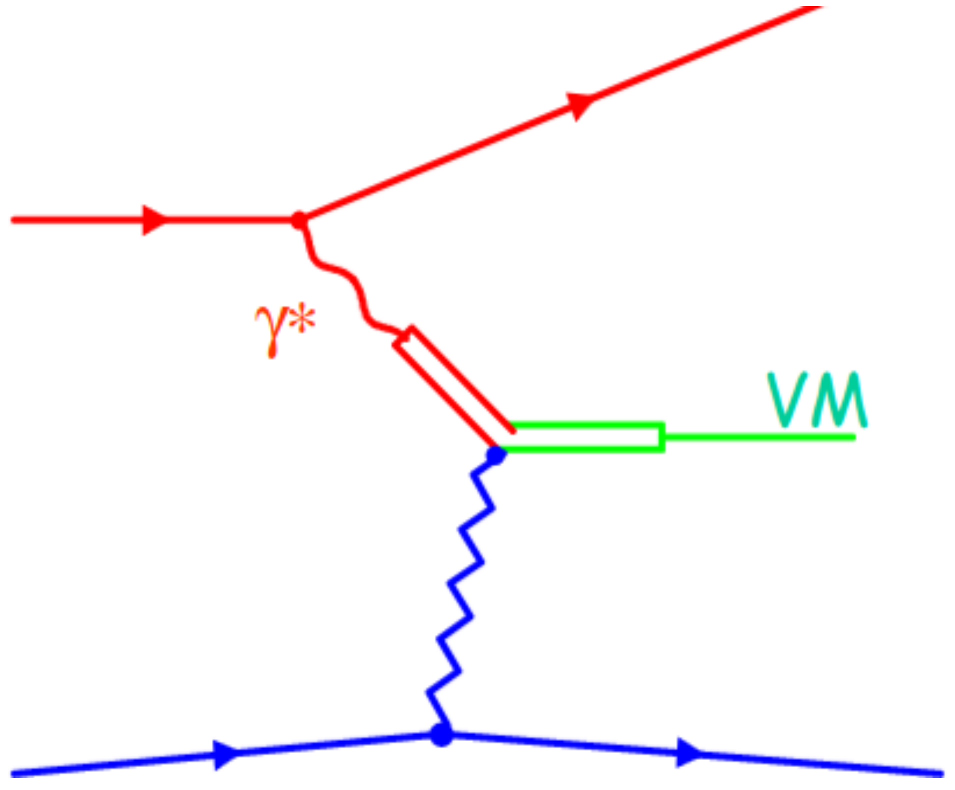
$$\sigma_{\gamma\mathrm{Pb}}(W_{\gamma\mathrm{Pb}} = 92.4\ \mathrm{GeV}) = 17.9^{+2.6}_{-1.8}\,(\mathrm{stat.} + \mathrm{syst.})\ \mu\mathrm{b},$$

$$\sigma_{\gamma\mathrm{Pb}}(W_{\gamma\mathrm{Pb}} = 469.5\ \mathrm{GeV}) = 38.1 \pm 15.0\,(\mathrm{stat.})\,^{+9.9}_{-11.3}\,(\mathrm{syst.})\ \mu\mathrm{b}.$$

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

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

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)

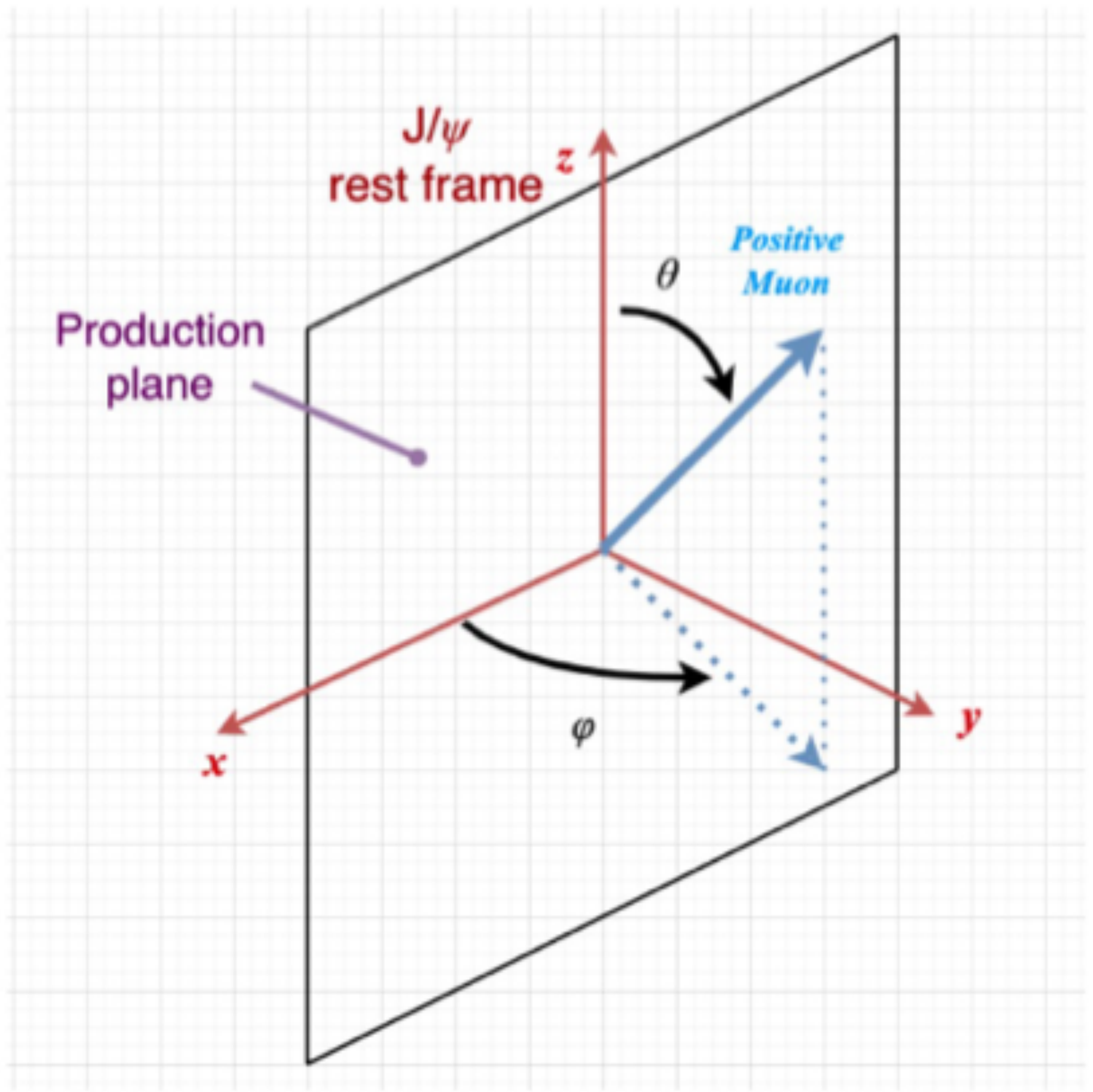
Vector meson (VM) has retained same helicity and polarization as that of the initial photon that interacted with the target

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

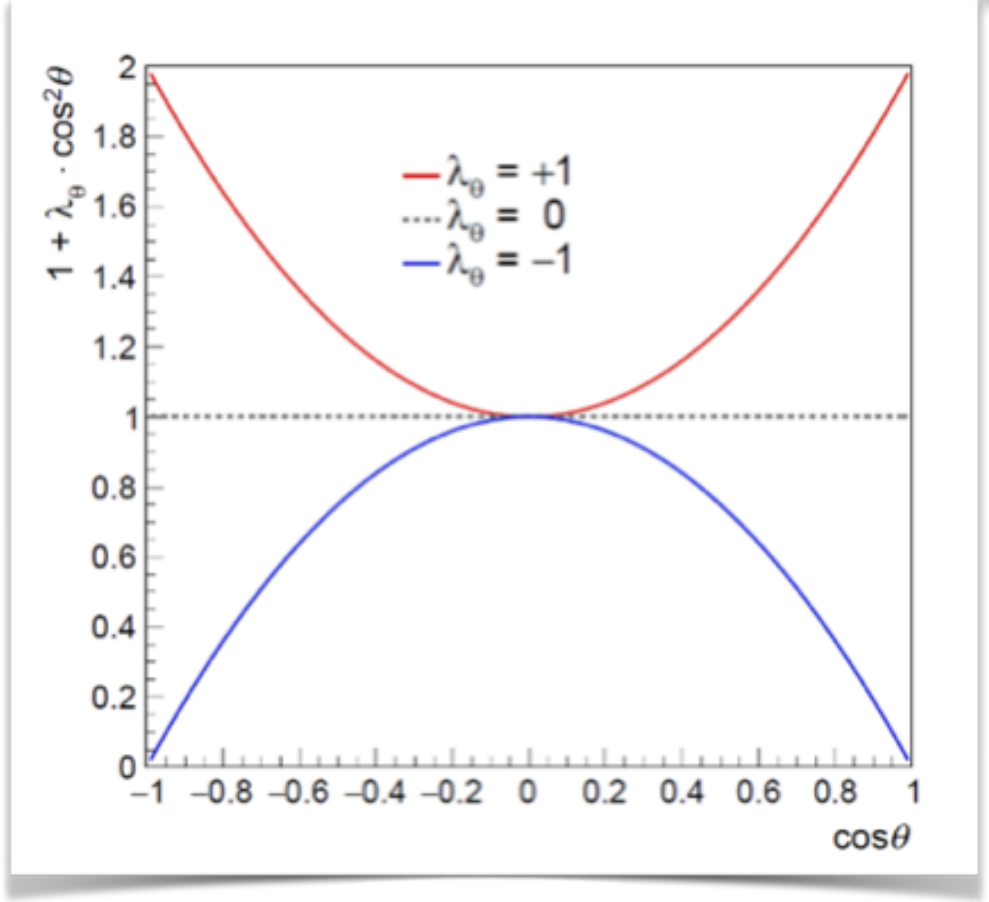


$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

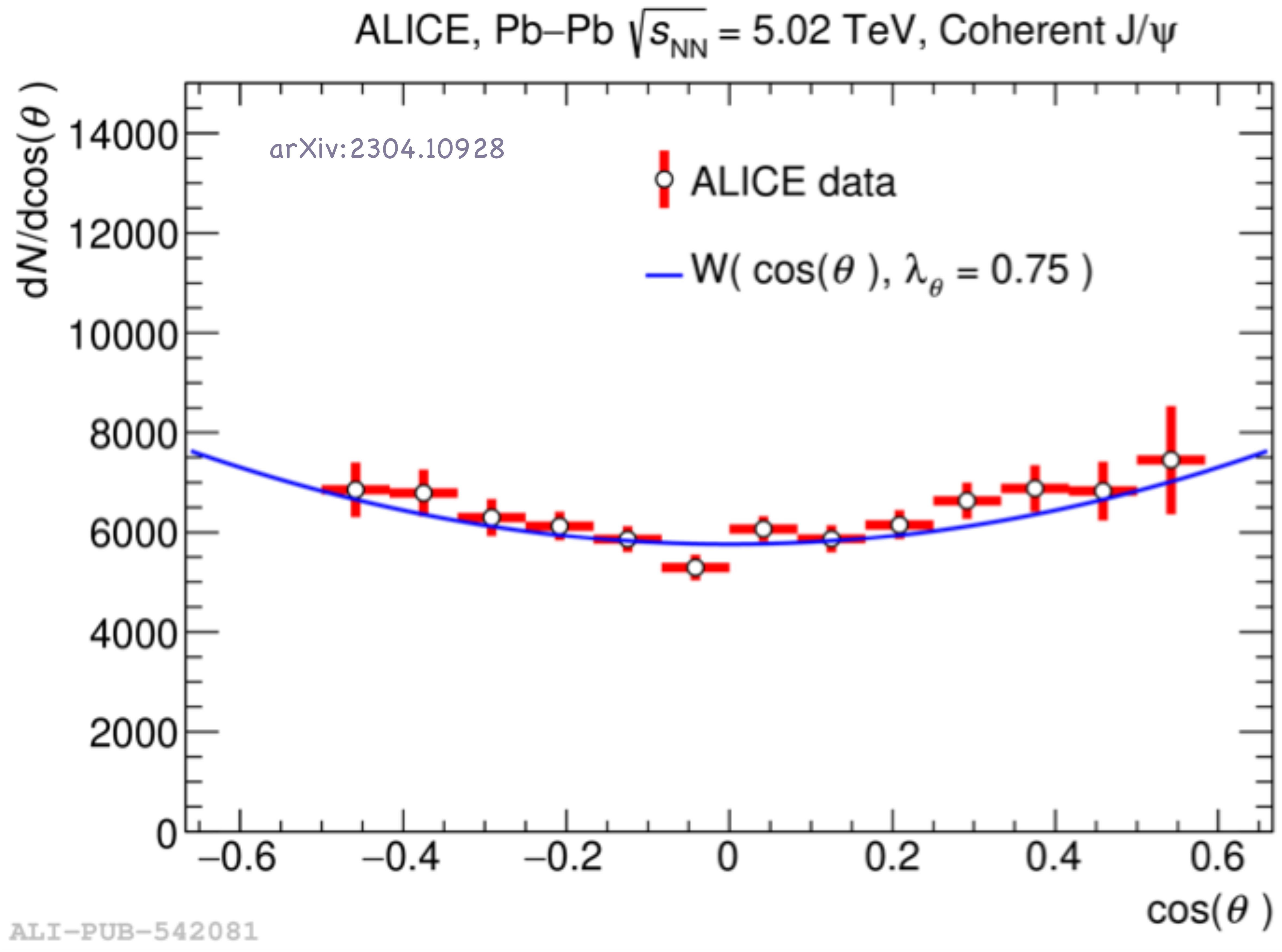
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0)$ ⟹ No polarization

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

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



Polarization : Coherent vector meson photo production in UPC



Coherently photoproduced J/ψ in UPCs at $\sqrt{s_{NN}}$ = 5.02 TeV

Transversely polarized

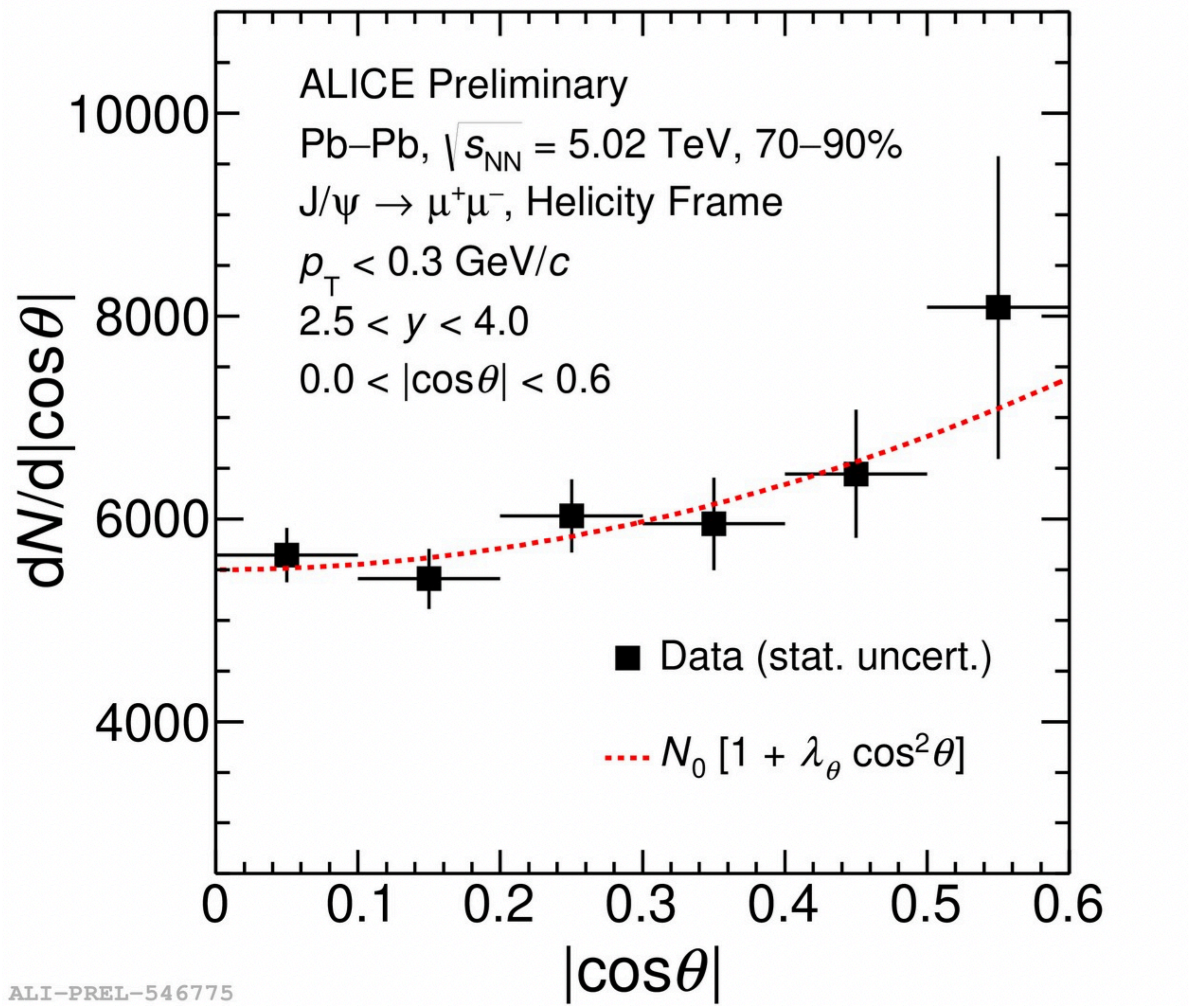
Consistent with SCHC hypothesis

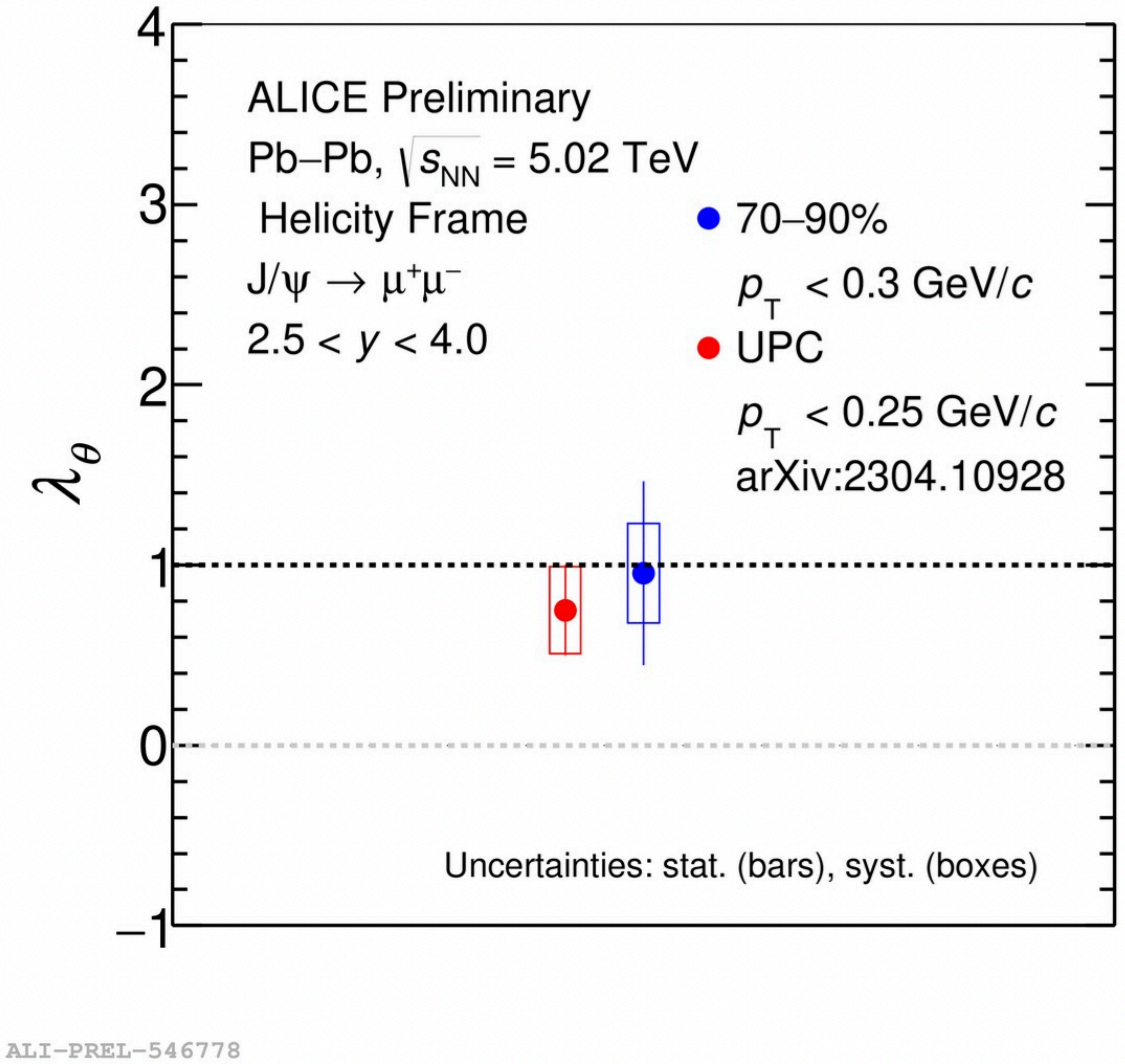
Do we expect similar observation for J/ψ at low p_T (< 0.3 GeV/c) in Pb–Pb collisions with nuclear overlap (70-90%) ?

Additional challenge w.r.t UPC measurement : deal with a contamination from hadronic J/ψ

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

NEW



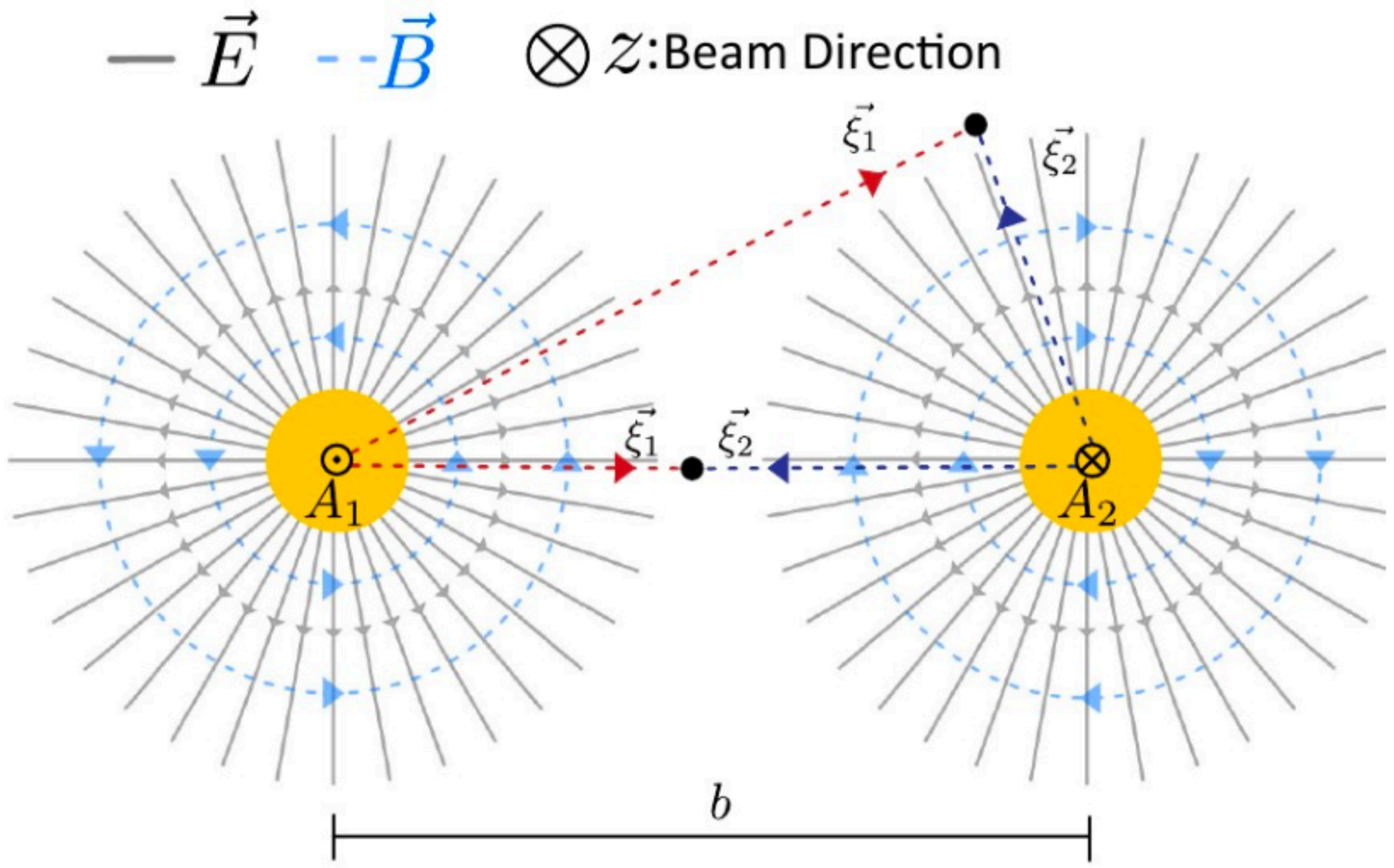


The λ_θ parameter is **consistent with the UPC measurement for inclusive J/Ψ with p_T < 0.3 GeV/c within uncertainties**

→ As expected in this kinematic region, where J/ψ coherent photoproduction dominates over the J/ψ hadronic production [arXiv:2204.10684]

Entanglement-enabled spin interference in photon-induced interactions

E-field points radially outward
B-field : Circulating in azimuthal direction



Highly Lorentz contracted nuclei produces strong EM filed,

polarization vector "ξ" is aligned with the radial direction of emitted source

=> photons are produced in this process as linearly polarized

Spin 1 photon polarization => VM meson polarization

=> polarization transferred to decay daughters via orbital angular momentum

Observable :
Azimuthal modulation in the momentum distribution w.r.t the polarization direction

Theoretical :

Interference in Exclusive Vector Meson Production in Heavy-Ion Collisions,

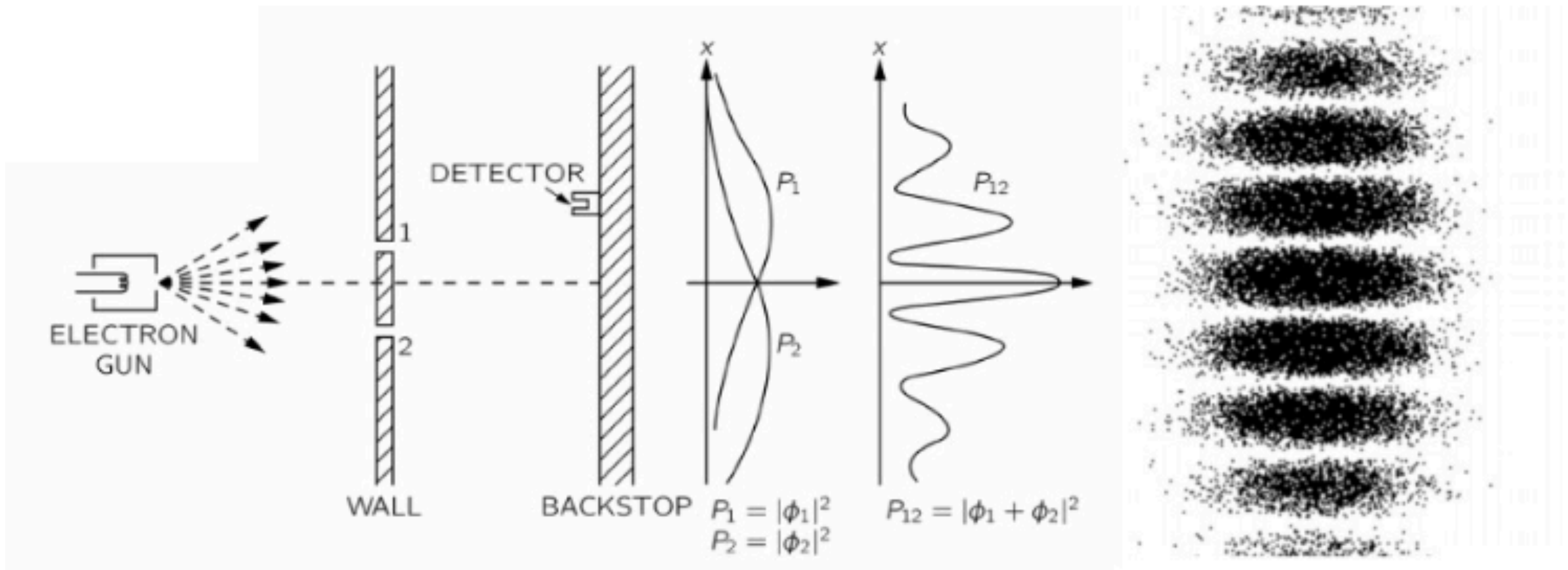
Klein et. al, Phys. Rev. Lett. 84, 2330 (2000)

Probing the linear polarization of photons in ultraperipheral Heavy-ion Collisions,

C. Li et al., Phy. Lett. B 795, 576-580 (2019)

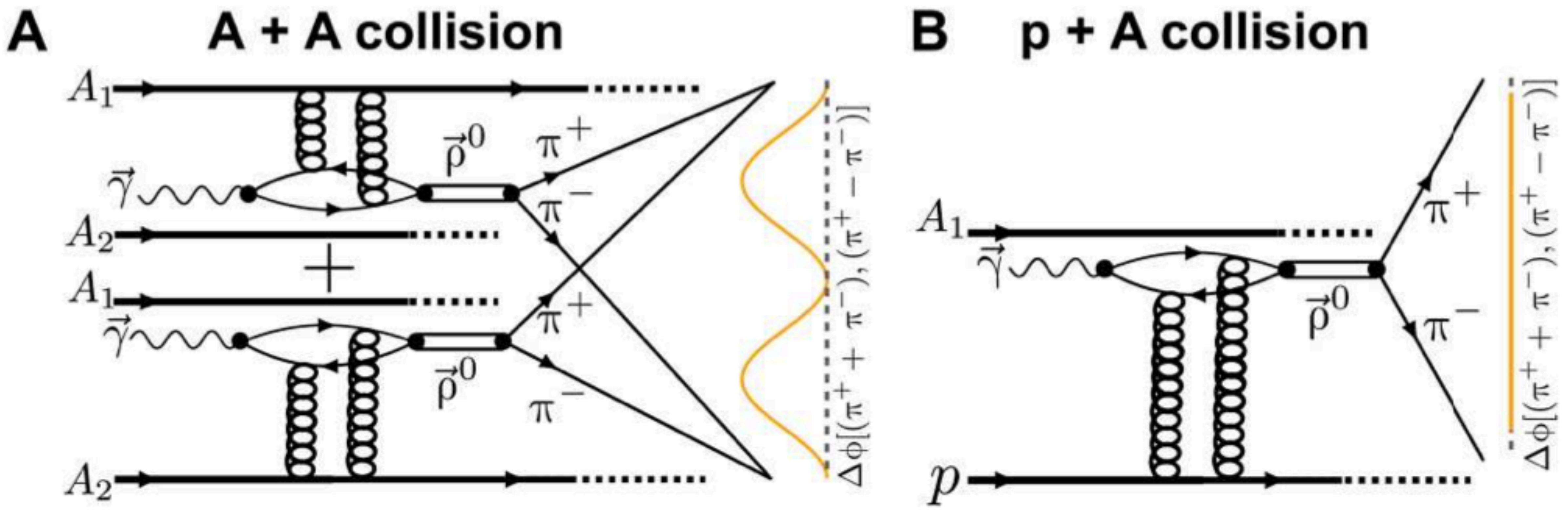
Impact parameter dependence of the azimuthal asymmetry in lepton pair production in heavy ion collisions, Cong Li, et al., Phy. Rev. D 101, 034015 (2020)

Lorentz Boost + Linearly polarized + Interference

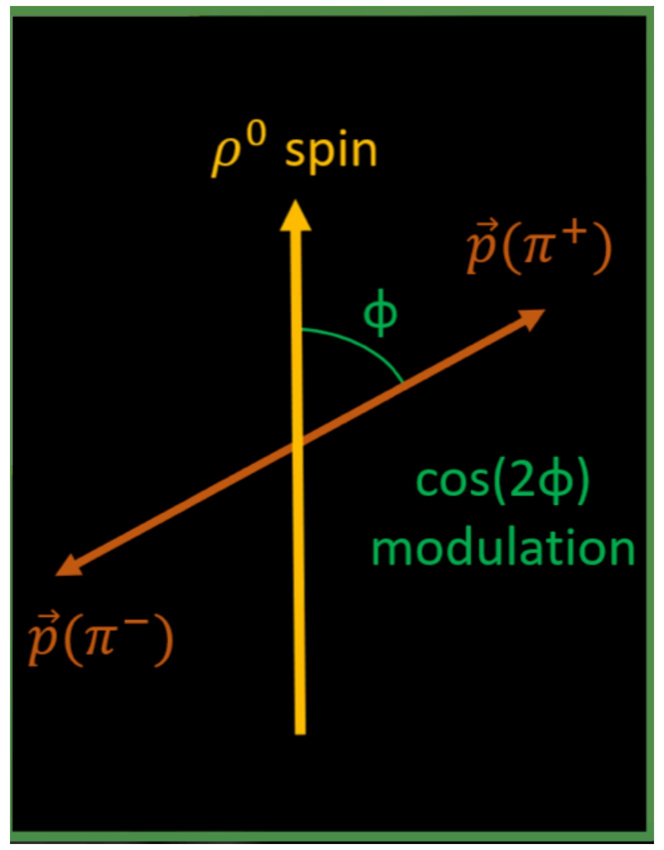


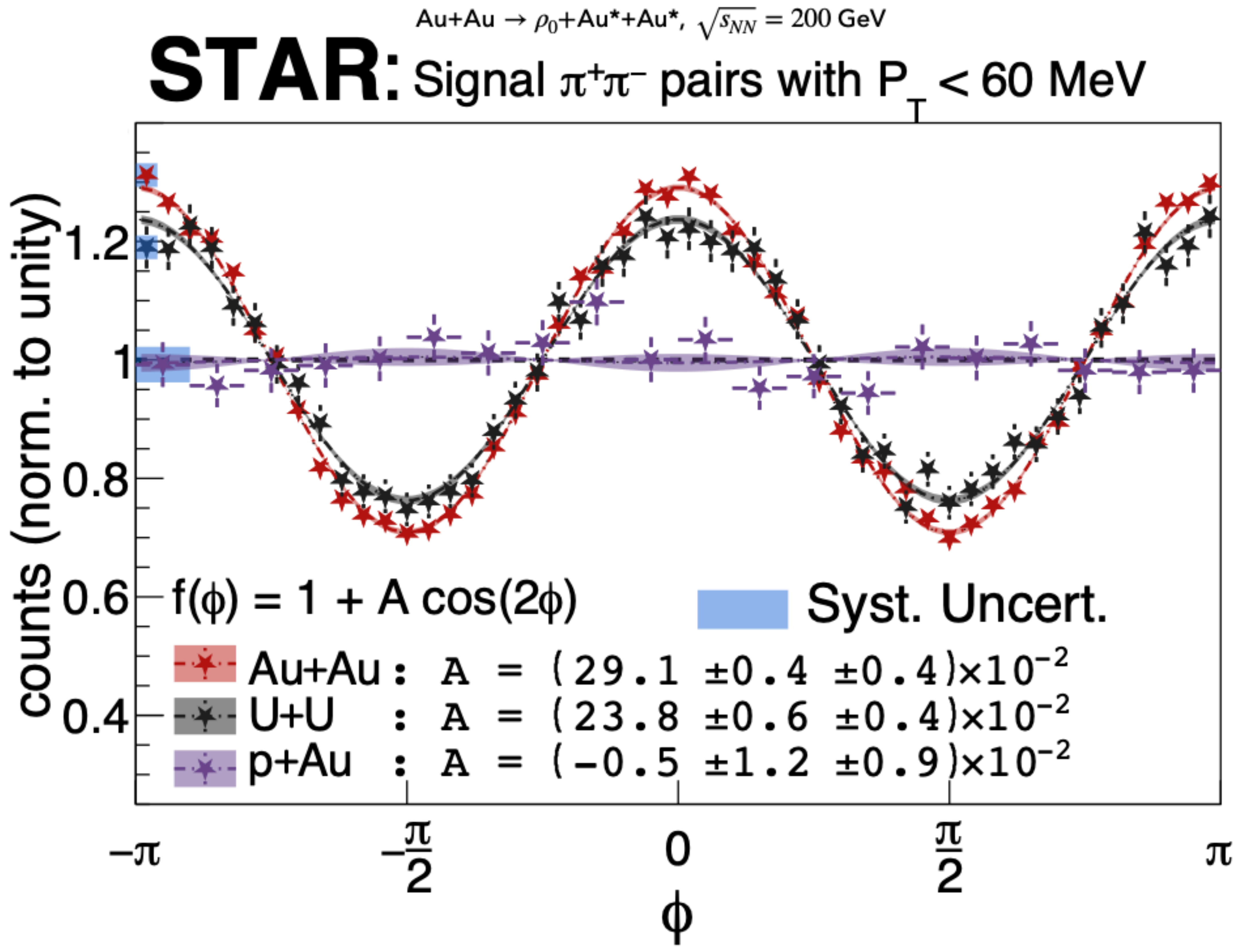
Entanglement-enabled spin interference in exclusive VM photo production

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions
Sci.Adv.g (2023) 1, abq3903



Azimuthal modulation in the momentum distribution w.r.t the polarization direction





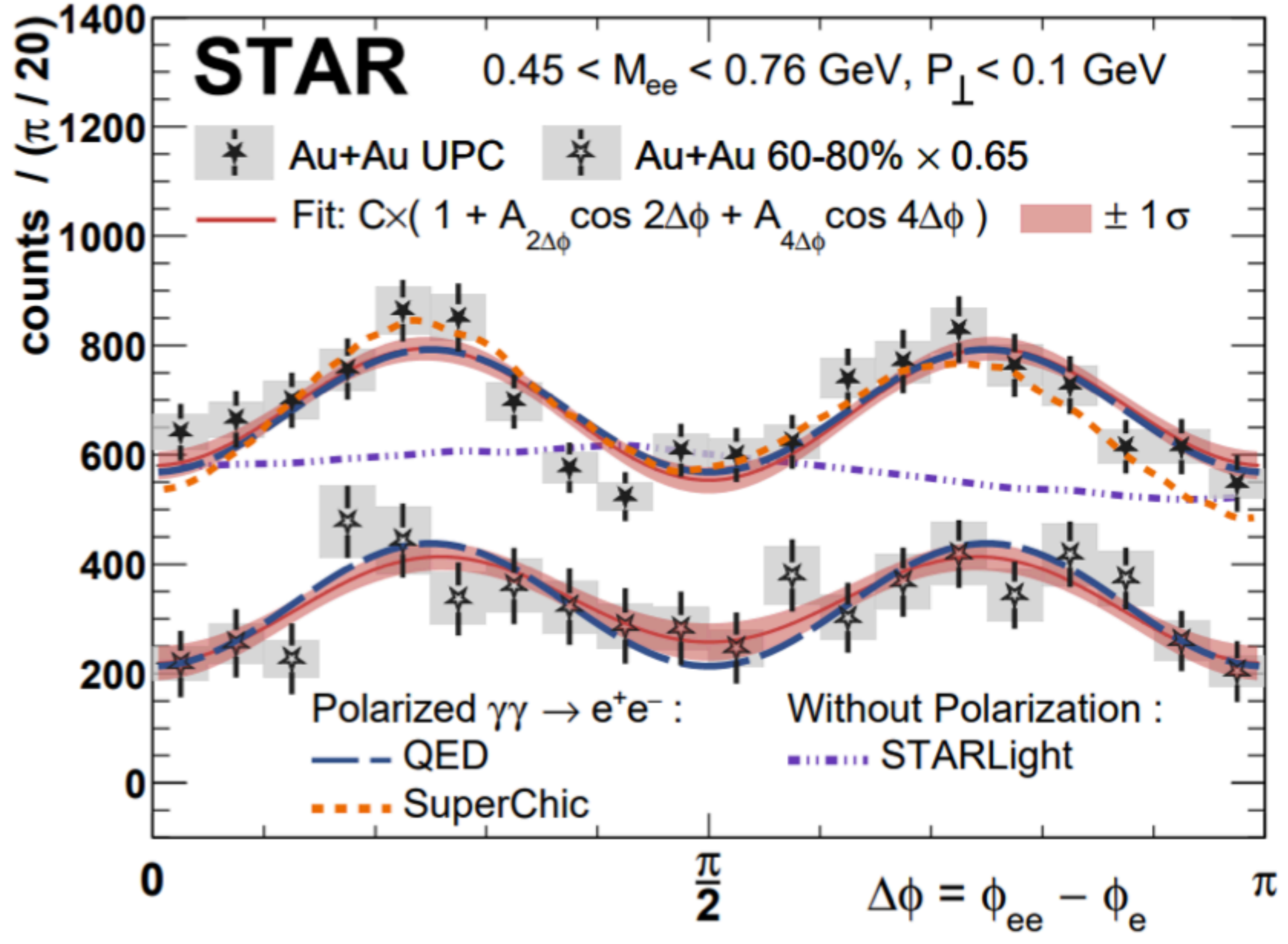
Modulation is observed for ρ^0 in Au-Au, U-U collisions but not in p-Au collisions, Sci.Adv.g (2023) 1, abq 3903

Similar measurements can be explored for UPC and PCs at LHC energies

Similar observation is also seen for J/Ψ in UPCs at RHIC,
[QM2023, UPC2023]
(Link : https://indico.cern.ch/event/1263865/timetable/#20231210)

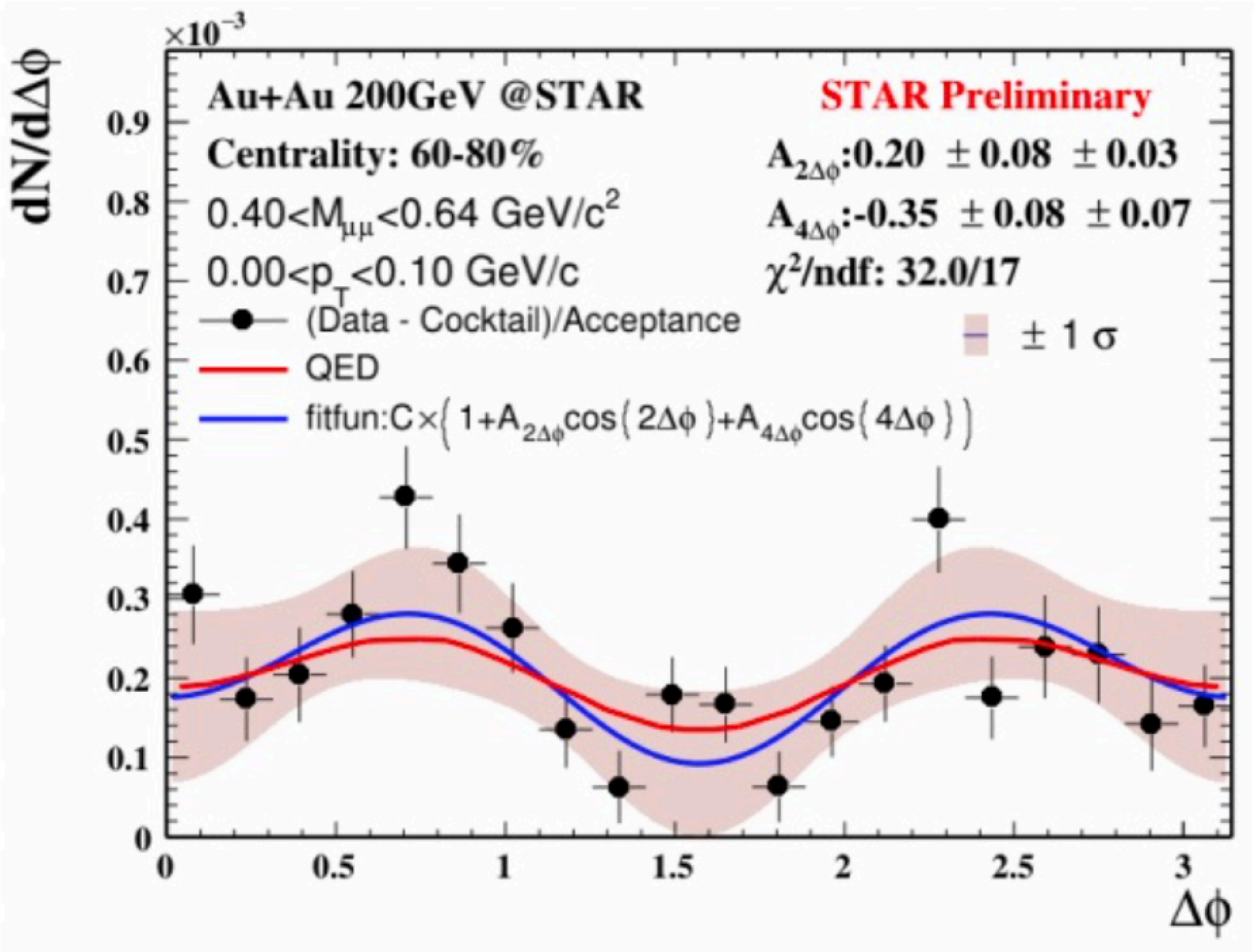
Angular modulation of dilepton pairs with nuclear overlap collisions

Birefringence of the QED vacuum,
STAR Collaboration, Phys. Rev. Lett. 127 (2021) 052302



NEW

UPC2023,
https://indico.cern.ch/event/1263865/timetable/#20231210



di-muons

Cos(2Δφ) azimuthal asymmetry sensitive to daughter mass ∝ $m2/p2$
— Expected to be sizable for $\mu+\mu-$ pair production

Δφ modulation is observed for dilepton pairs of
0.4 < M < 0.64 GeV/c² in Au-Au collisions with nuclear overlap

C. Li et al., Phy. Lett. B 795, 576-580 (2019)

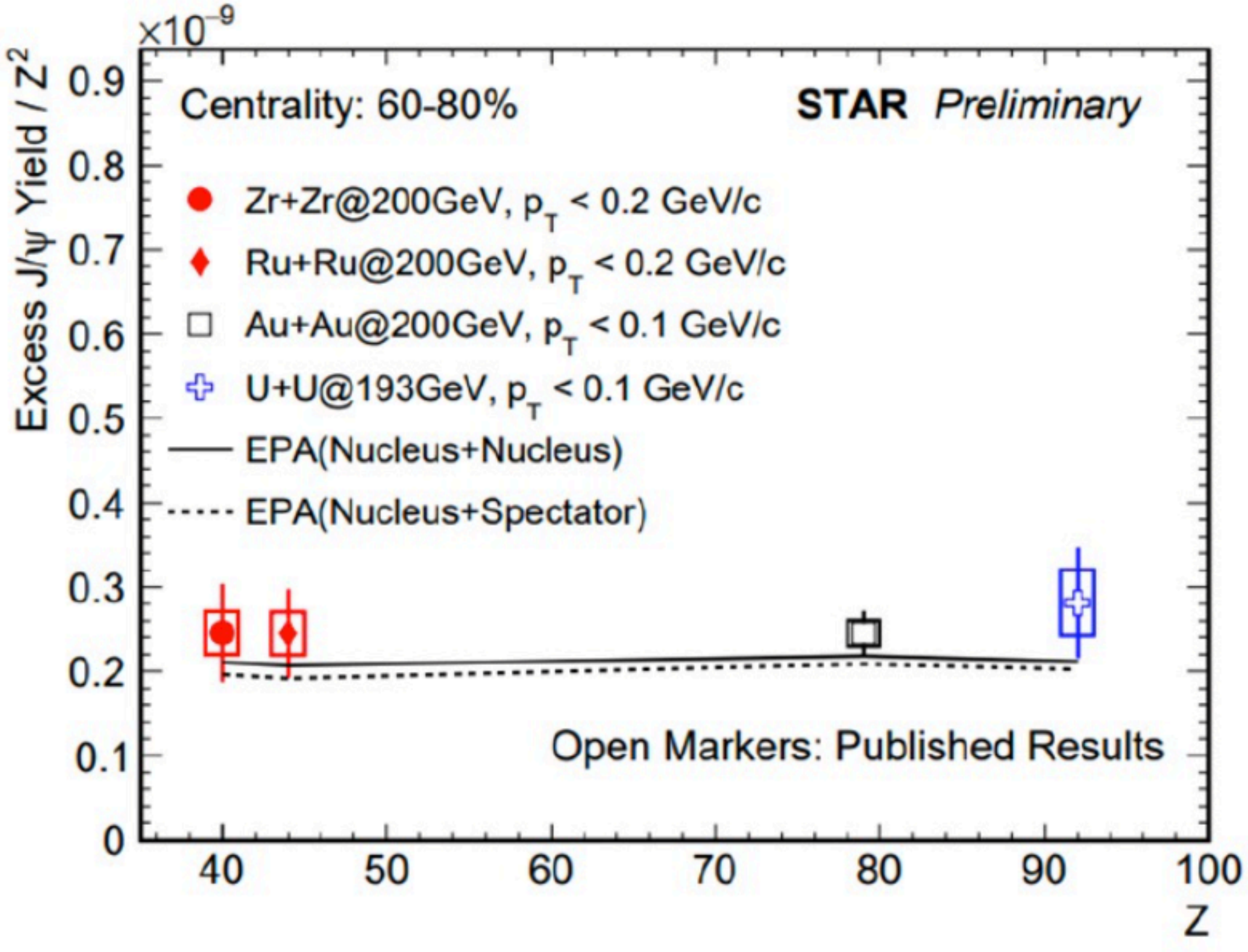
Similar measurements can be explored for UPC and PCs at LHC energies

Initial electromagnetic field dependence VM and dilepton yields with nuclear overlap collisions

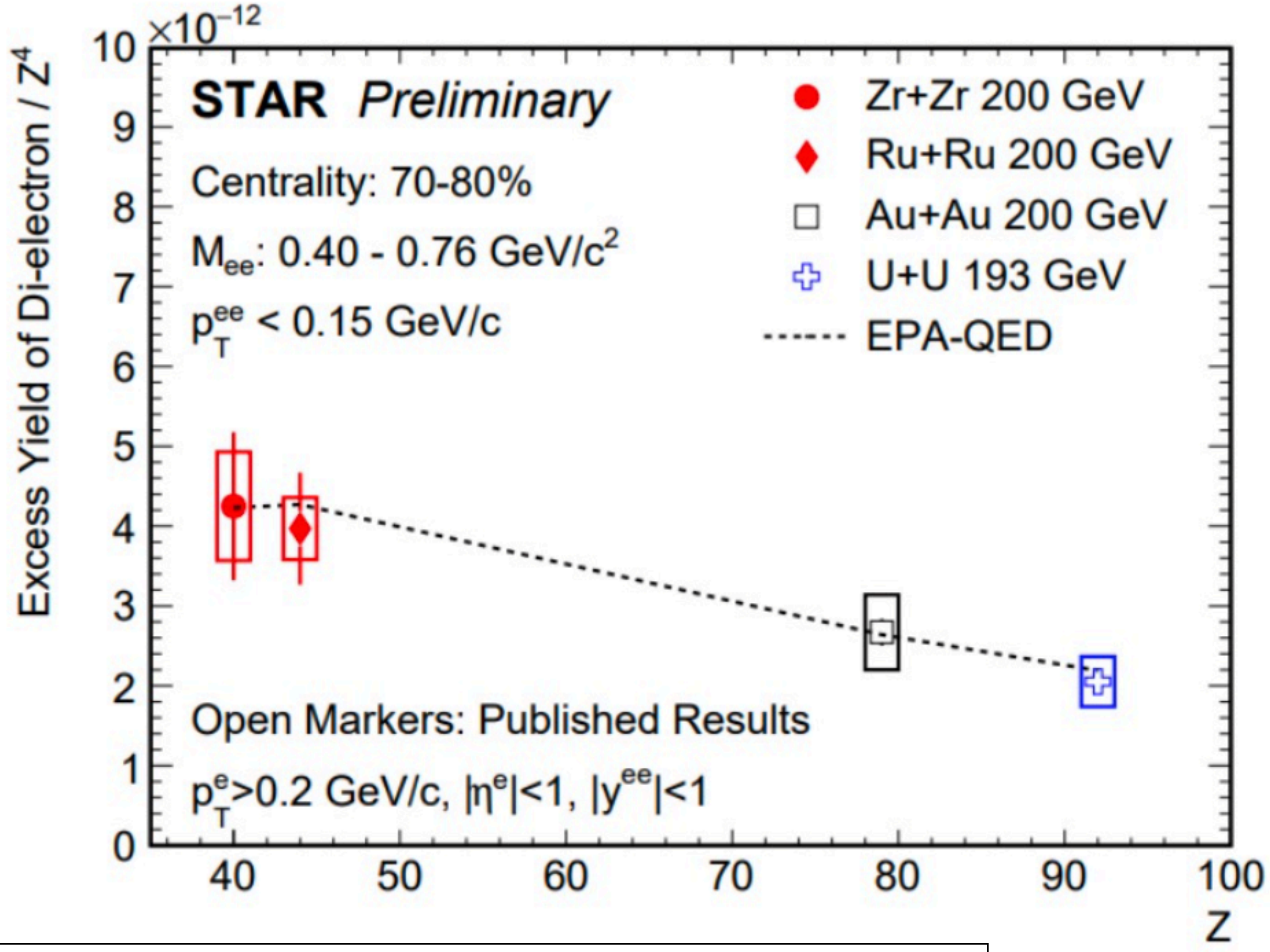
System size dependence : Test of Z-scaling

NEW

Photonuclear interactions



Gamma-Gamma interactions



Photoproduced J/Ψ yields in photonuclear interactions are seem to scale with Z^2

Dielectron yields produced via gamma-gamma interaction are scaled with Z^4 , it seems not constant as a function of Z (isobar cases show an enhancement w.r.t Au-Au collisions and also described by EPA-QED based model

Is it same idea to test at LHC energies or very lower energies ??

Summary and Outlook

- Photoproduction in pA and peripheral heavy-ion collisions have been provided a reach set of physics opportunity that was initially observed in ultra peripheral collisions (UPCs)

- pp/pA collisions:
  - ✓ No significant gluon saturation effects

- AA collisions with nuclear overlap :
  - ✓ Excess of yield
  - ✓ Coherent photo production cross section vs. centrality, rapidity
  - ✓ Understanding photon-energy ambiguity
  - ✓ Polarization
  - ✓ Spin-enabled interference effects
  - ✓ Azimuthal anisotropy: angular modulation in $\Delta\varphi$
  - ✓ Z-scaled using isobar

experimental signature of these phenomena are observed in photon-induced processes with nuclear overlap collisions

Outlook

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

- **ALICE Run 3 and other LHC experiments will collect a large Pb–Pb data sample in the future** 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) -> **precision and more differential measurements**

- Look at **heavier vector mesons could become also possible to pin down possible QGP effects on the measured probes and precision polarization measurement of J/ψ and other VMs**

- More precise and differential studies can be possible to explored in heavy-ion collisions with nuclear overlap at LHC energies
  - Angular modulation on azimuthal anisotropy
  - Entanglement enabled spin interference effects
  - Breit-Wheler processes
  - Imaging of nucleus with nuclear overlap
  - Exotic search (four pion, $t\bar{t}$ pair production etc.)

Back up

Conclusions

- Photoproduction in pA and peripheral heavy-ion collisions have provided a reach set of physics (photo production cross sections, polarization, entanglement-enabled spin interference , azimuthal anisotropy etc.) that was initially observed in ultra peripheral collisions

➡ **No significant gluon saturation effects** off the proton target is observed from HERA to LHC energies (currently accessible Wyp or range)

➡ Significant excess of yield in peripheral collisions is observed centrality up to 30-50% and y-differential intervals in most peripheral colliisons -> interpreted as **coherent photoproduction as dominant underlying mechanism**

➡ Also excess of J/Ψ yields is observed from dilepton productions were discussed different **aspects sensitivity to initial magnetic field** with nuclear overlap heavy-ion collisions

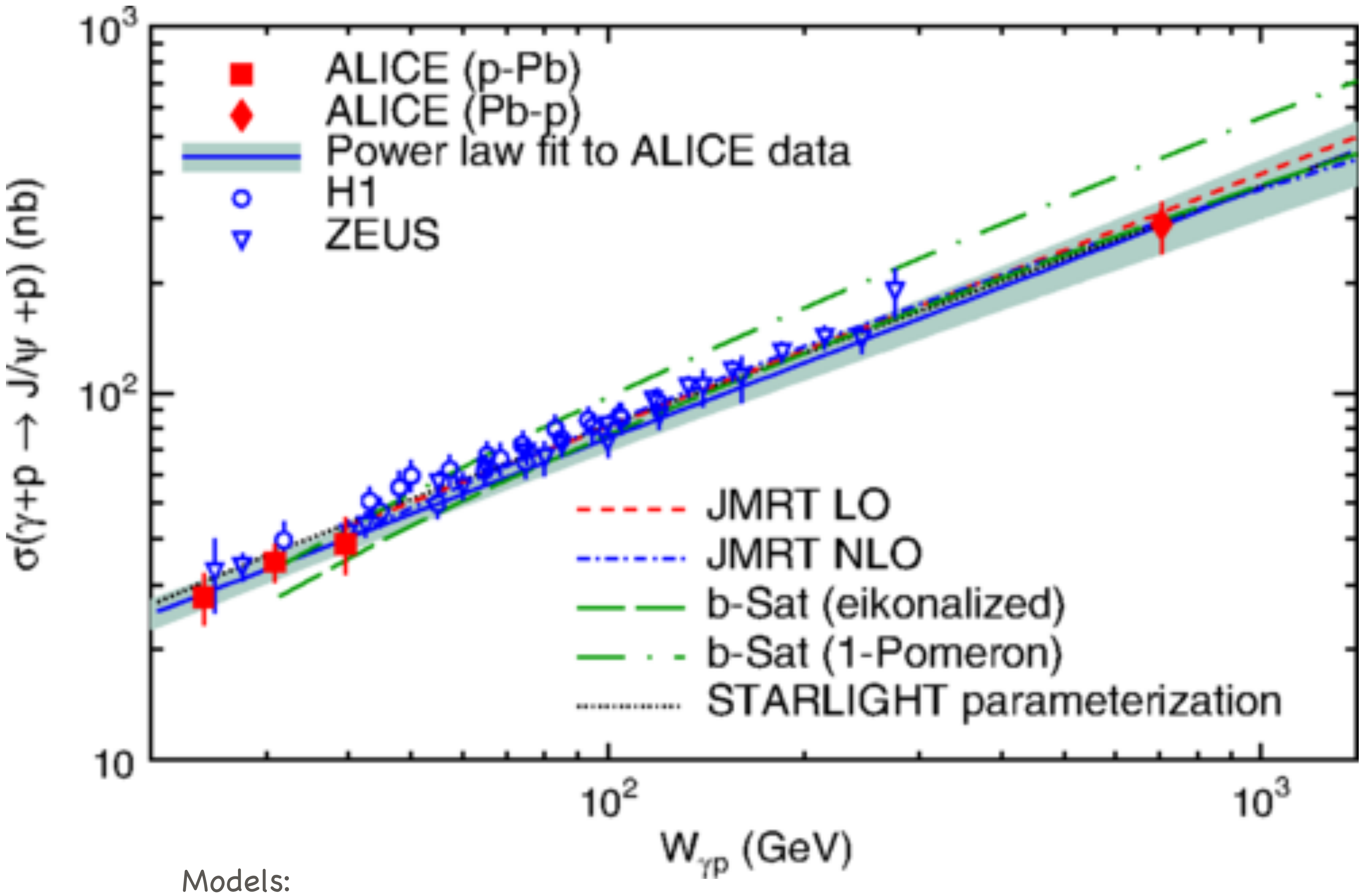
➡ Y-differential measurement for J/Ψ in peripheral collisions provide further input to **understand photon-energy ambiguity**

➡ **Polarization** measurements supports s-channel helicity conservation, provide a test of the VM production mechanism and supports the photoproduction scenario

➡ Angular modulation, testing sensitivity of initial magnetic field using the isobar were used to study the Z scaling of the yield in heavy-ion collisions with nuclear overlap at RHIC energies.

First exclusive J/ψ photoproduction cross section off protons

Phys. Rev. Lett. 113 (2014) 232504



Goal: Test gluon saturation effects inside proton in experimentally

σ is proportional to the square of the gluon PDF of the proton, M. G. Ryskin, Z. Phys. C 57, 89 (1993)

J/Ψ photo production cross section follow a power law scaling behaviour in Bjorken-x scaling variable between ~2×10^{-2} and ~2×10^{-5} (i.e, photon energy in c.m.s frame in 20 to 700 GeV)

$\sigma \propto (W\gamma p)^{\delta}$,

δ =0.69 +- 0.02 (ZEUS)

δ =0.67 +- 0.03 (H1)

δ =0.68 +- 0.06 (ALICE)

Models:
JMRT LO : Leading order (LO) based on power law + no saturation
JMRT NLO : JMRT LO with next Leading order (NLO) correction, S. P. Jones et al, J. High Energy Phys. 11 (2013) 085
b-Sat(eikonalized) and b-Sat(1-Pomeron): Color glass condensate approach + saturation effects, (constraining it to HERA data alone.), H. Kowalski et al, Phys. Rev. D 74, 074016 (2006)., L. Abelleira Fernandez et al., arXiv:1211.4831.

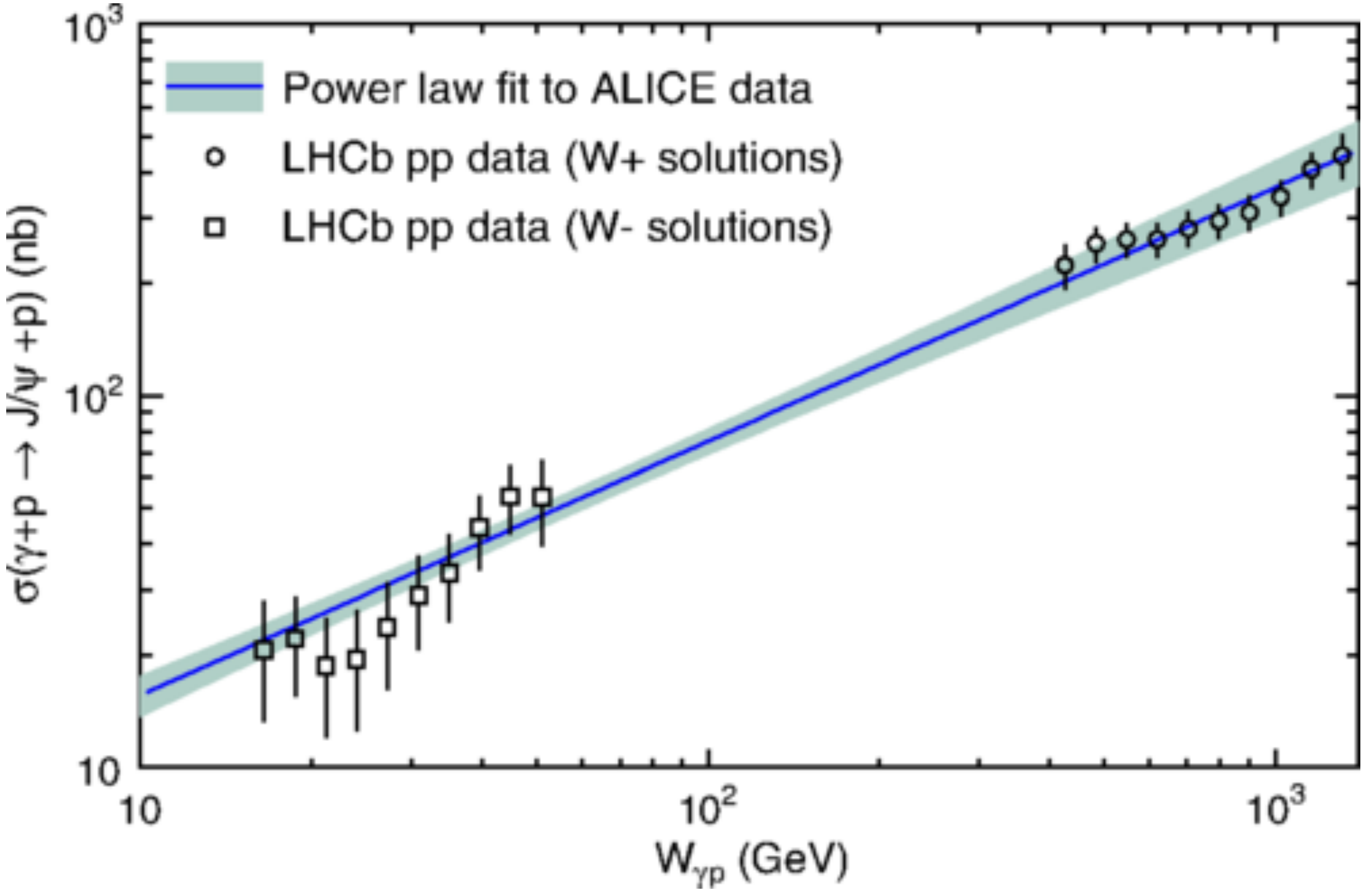
STARLIGHT parameterization : on a power law fit using only fixed-target, and HERA data, with δ = 0.65 ± 0.02, F. Gelis et al, Annu. Rev. Nucl. Part. Sci. 60, 463 (2010)

-> No significant change in the gluon density behavior of the proton between HERA and LHC energies

First exclusive J/ψ photoproduction cross section off protons

Phys. Rev. Lett. 113 (2014) 232504

Goal: Test gluon saturation effects inside proton in experimentally



Symmetric system, suffers from the intrinsic impossibility of identifying the photon emitter and the photon target. photon source can not be identified.

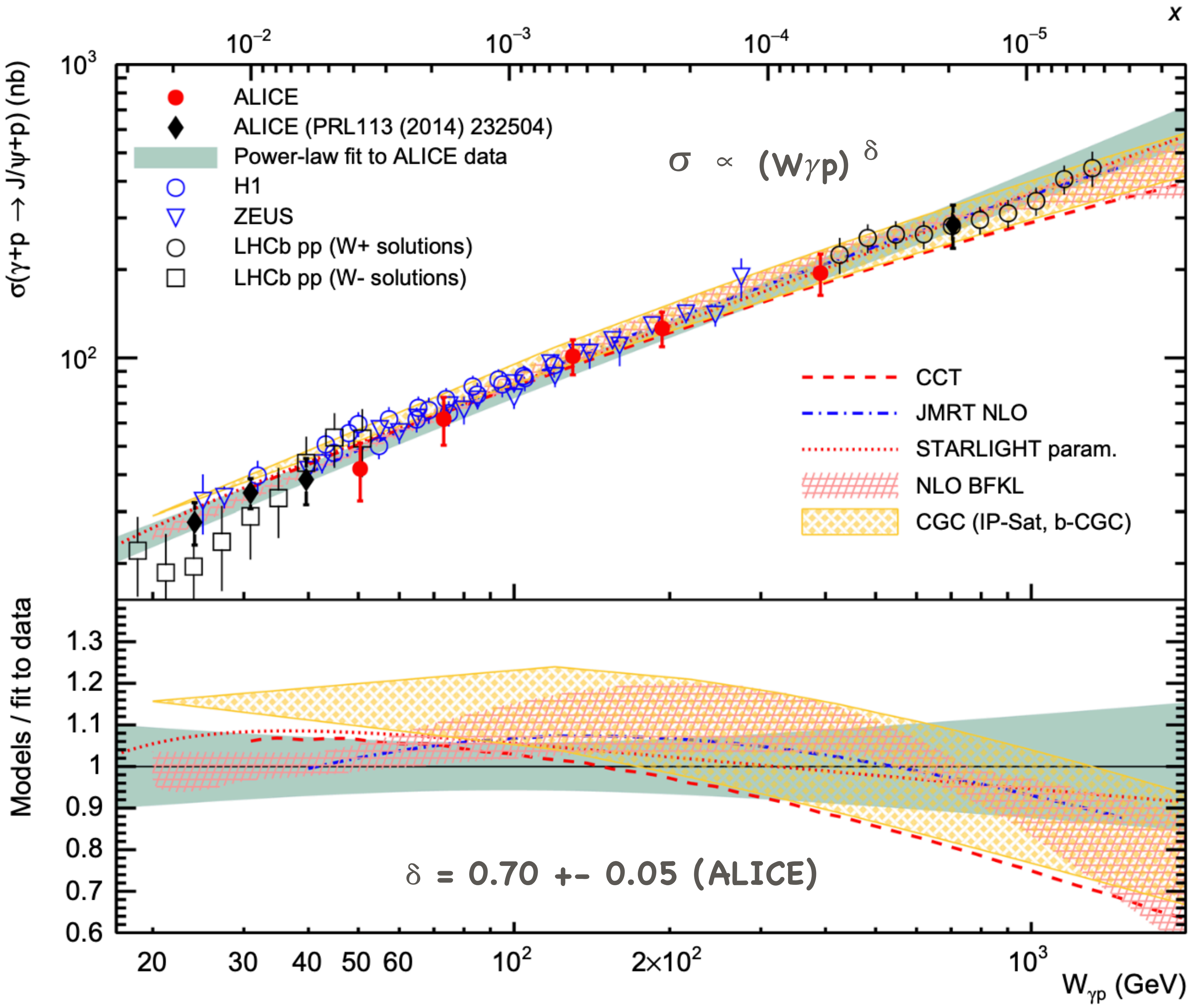
Large uncertainty in the hadronic survival probability in pp collisions, as well as an unknown contribution from production through Odderon-Pomeron fusion

Despite these ambiguities and assumptions the LHCb solutions turned out to be compatible with the power law dependence extracted from ALICE data.

Exclusive J/ψ photoproduction cross section off protons

Eur. Phys. J. C (2019) 79:402

Energy dependence



JMRT NLO : Leading order (LO) based on power law + no saturation, with next Leading order (NLO) correction, S. P. Jones et al, J. High Energy Phys. 11 (2013) 085

b-Sat(eikonalized) and b-Sat(1-Pomeron): Color glass condensate approach + saturation effects, (constraining it to HERA data alone.), H. Kowalski et al, Phys. Rev. D 74, 074016 (2006)., L. Abelleira Fernandez et al., arXiv:1211.4831.

STARLIGHT parameterization : on a power law fit using only fixed-target, and HERA data, with **δ** = 0.65 ± 0.02, F. Gelis et al, Annu. Rev. Nucl. Part. Sci. 60, 463 (2010)

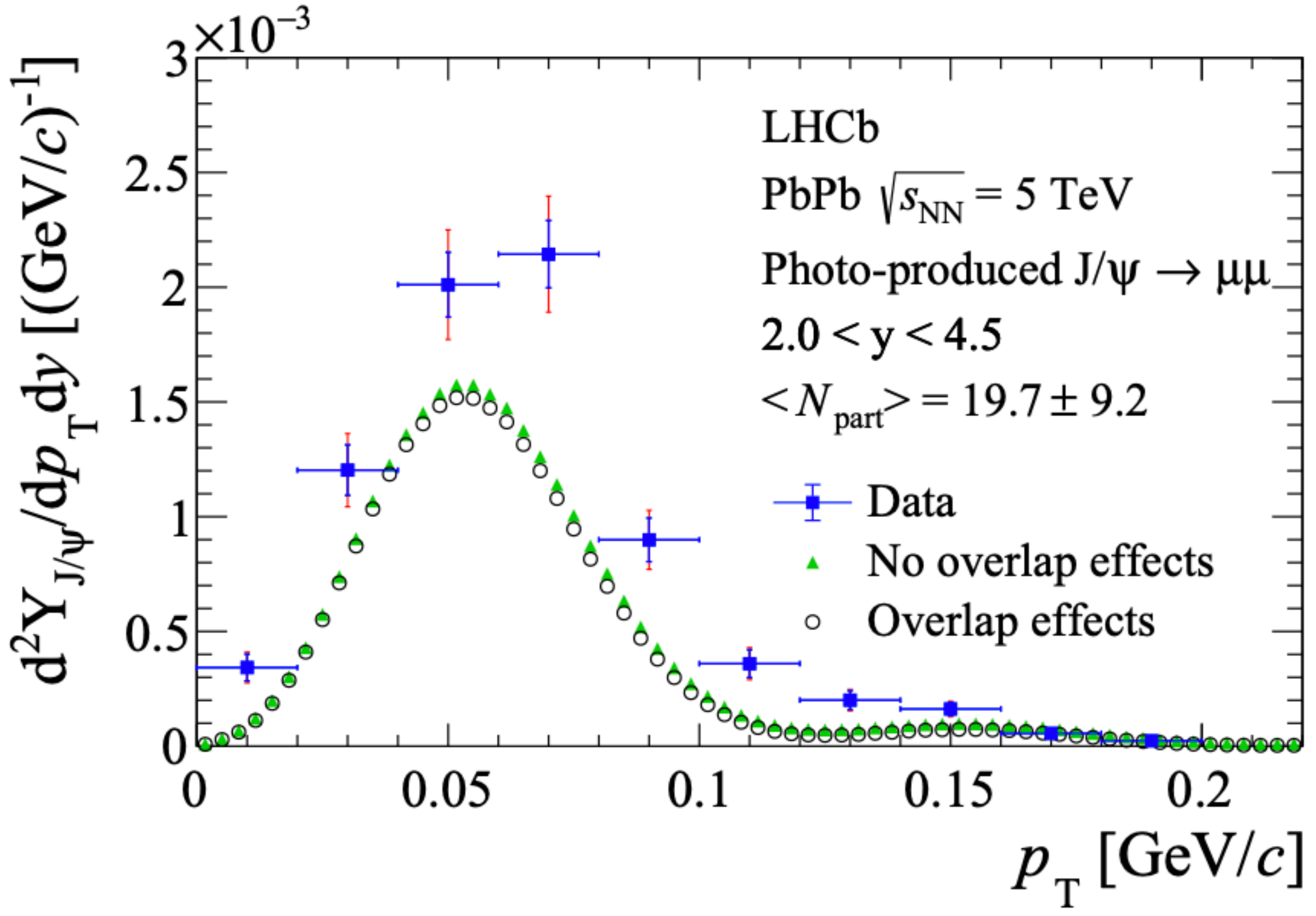
CCT: based on the colour dipole approach, and incorporating the energy dependence of geometrical fluctuations of the proton structure in the impact parameter plane

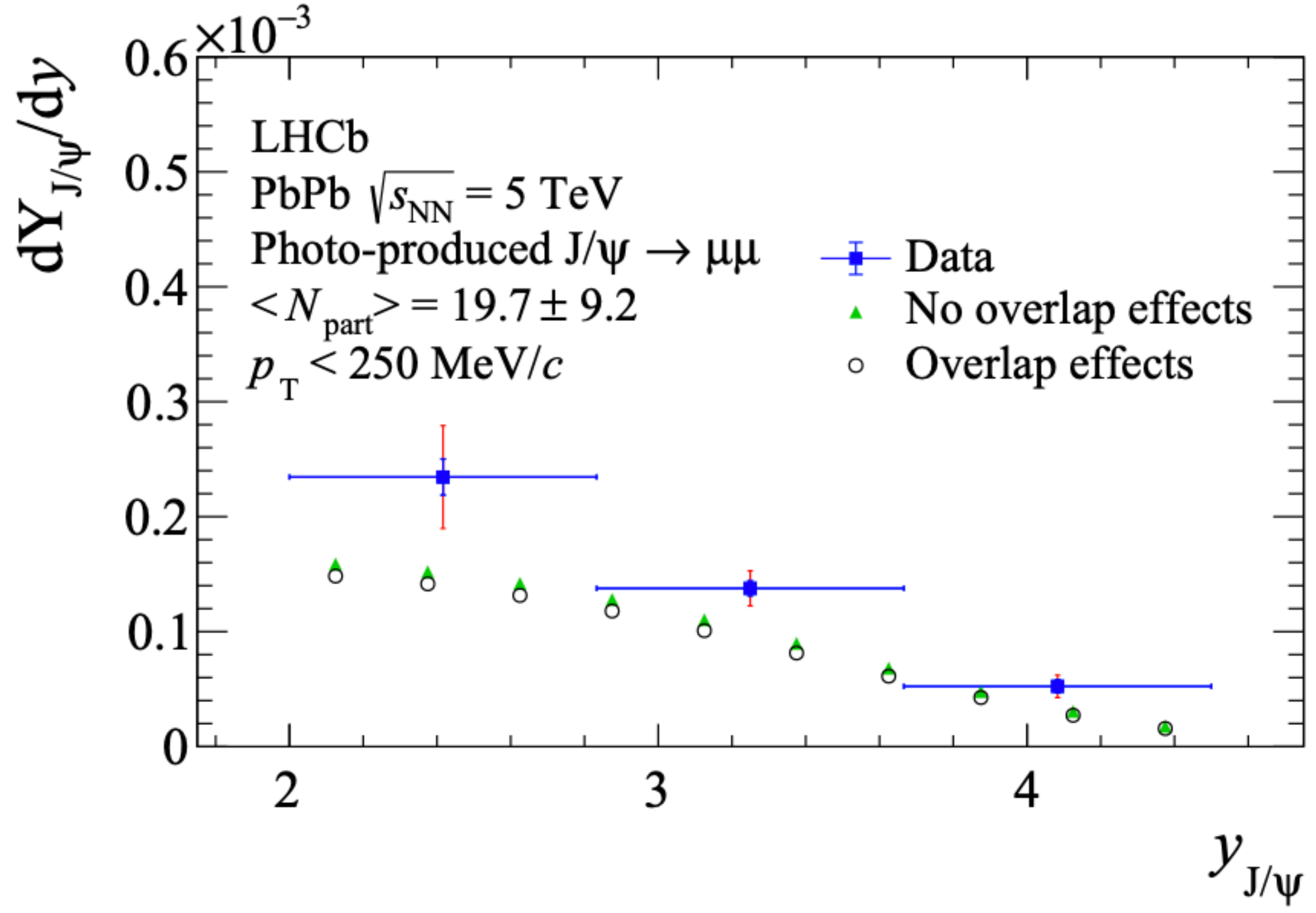
VM photoproduction in heavy-ion collisions with nuclear overlap

Production cross section

Other experiments : LHCb Collaboration

Similar observation by LHCb Collaboration, PRC 105 (2022) L03201





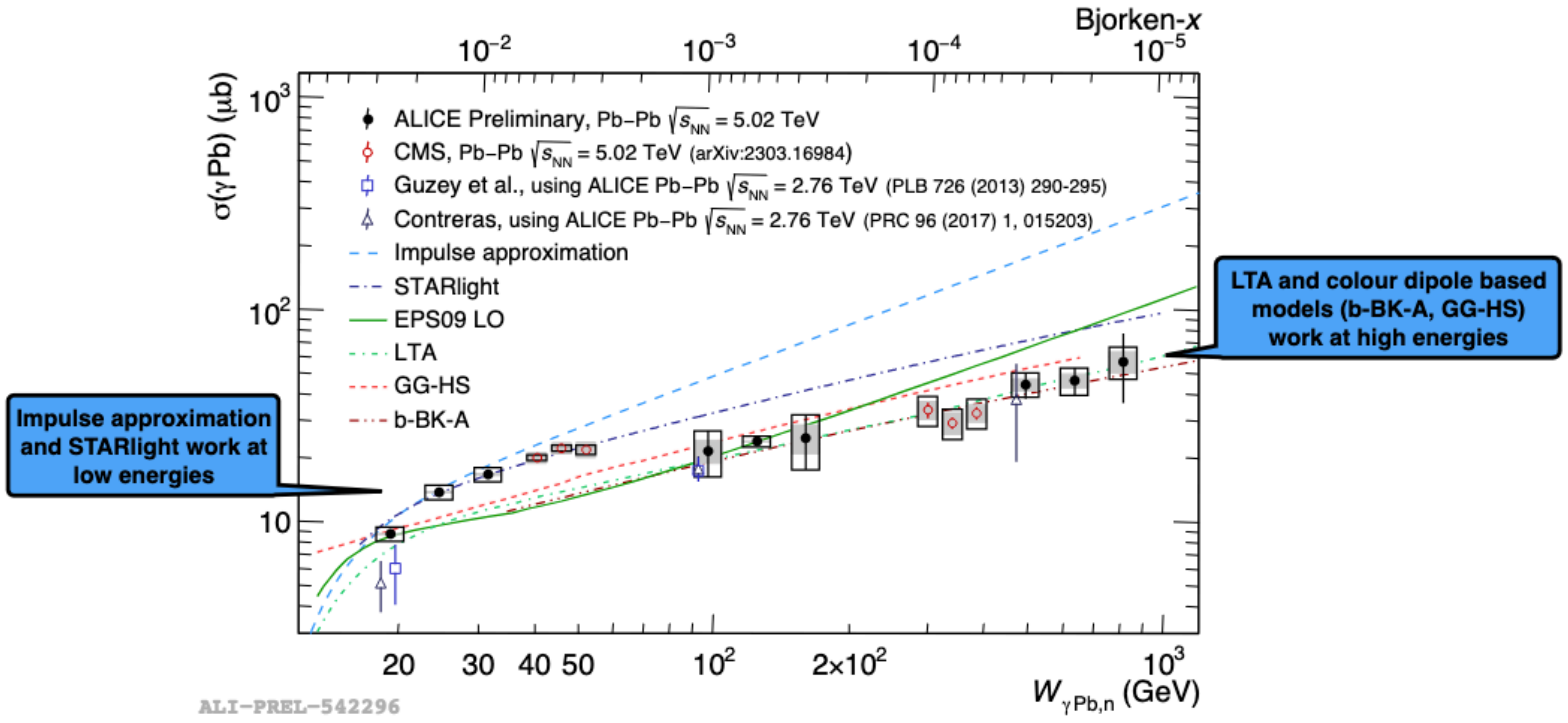
p_T and *y*-differential J/ψ excess yield measurement

-> **Interpreted as a sign of a dominant contribution from coherent photoproduction**

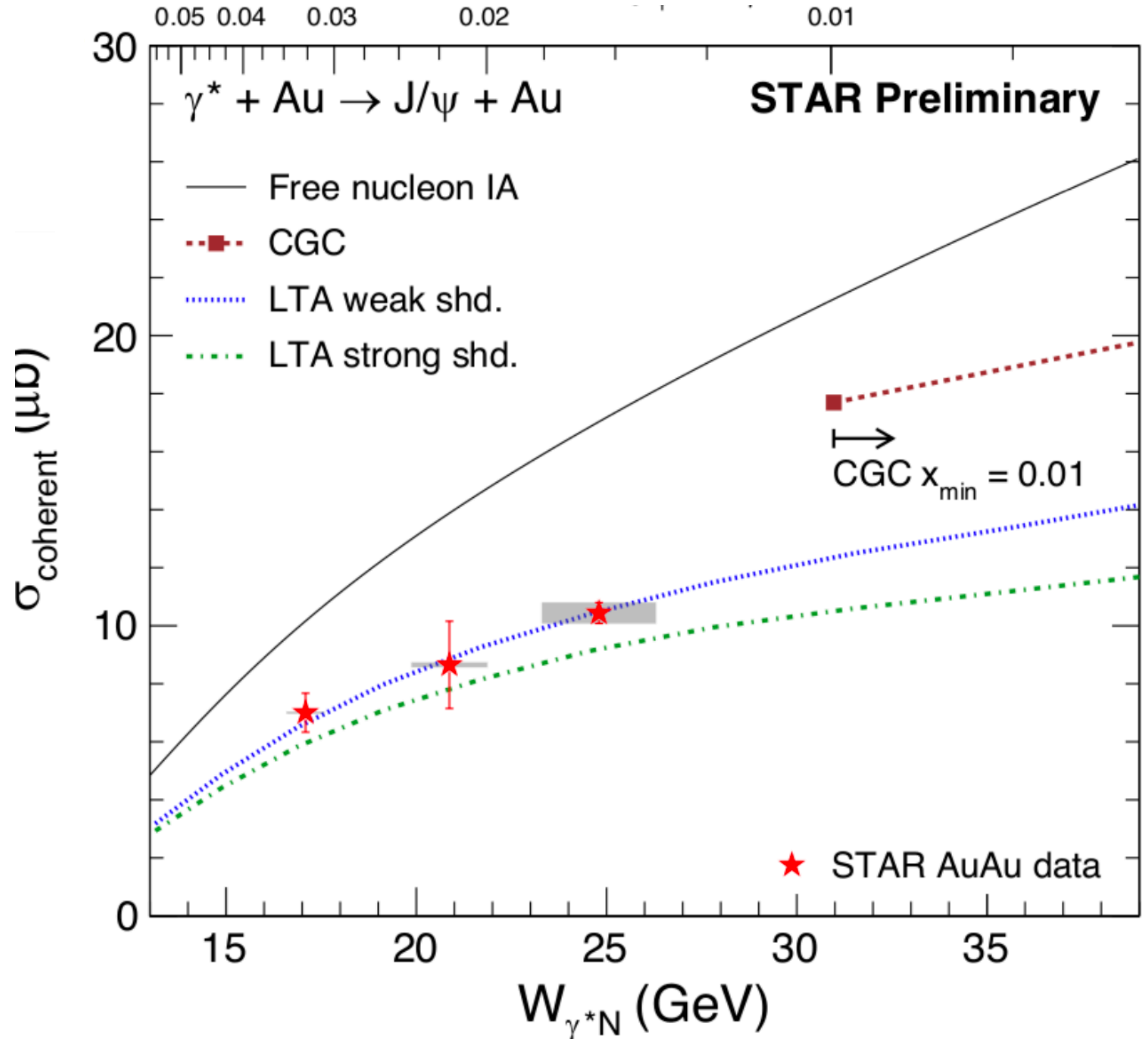
Photo production of VM: $\sigma_{\gamma Pb}$ vs. $W_{\gamma Pb}$ or x

For details see Adam Matyja talk , QAsT 2024, Tue, 09/01

LHC



RHIC



Results are calculated based on EMD using different neutron emission

Recent measurement photo nuclear cross section ($\sigma_{\gamma Pb}$) access to go low-x (10^{-5})

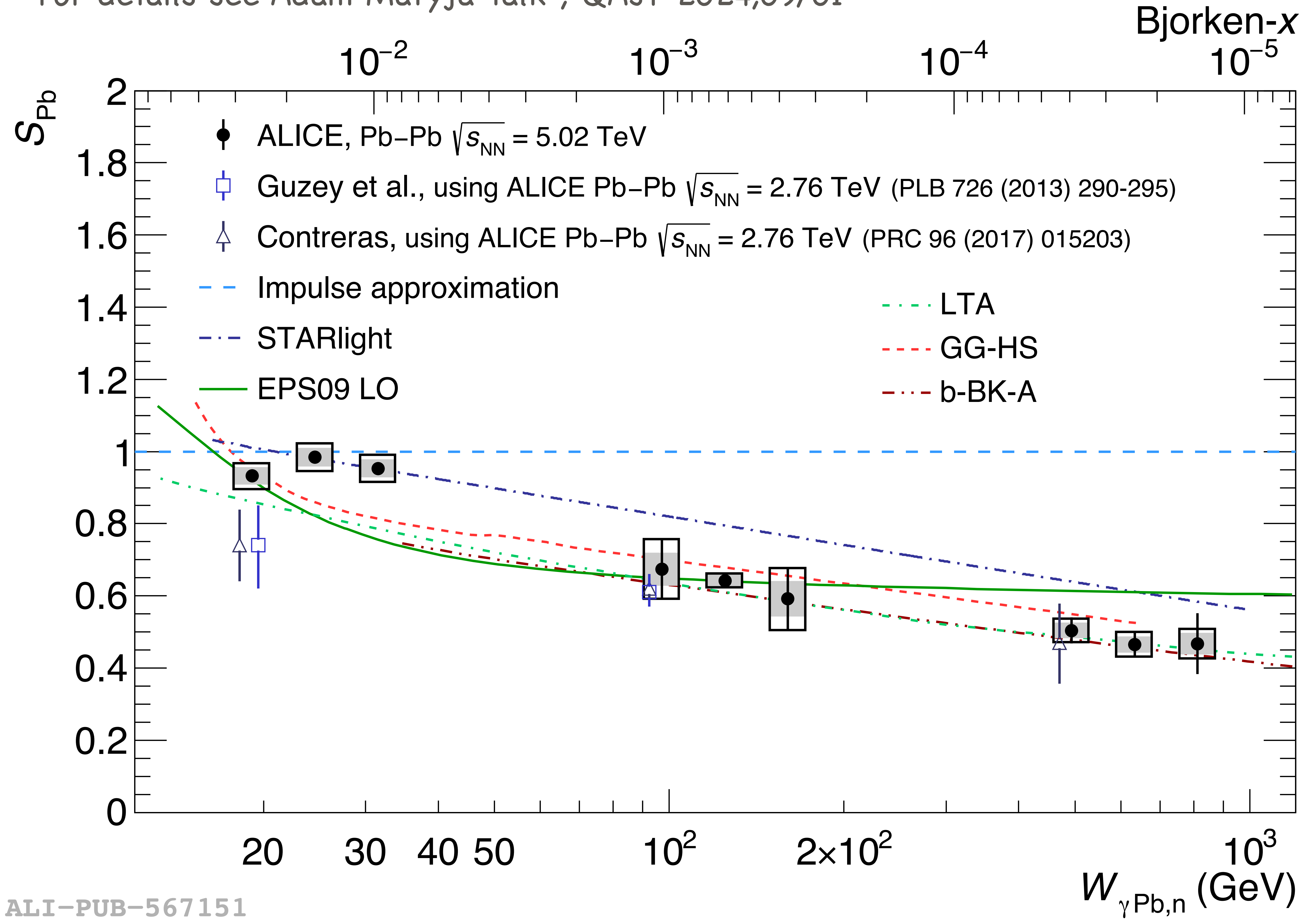
At low -x data favors both saturation and shadowing models

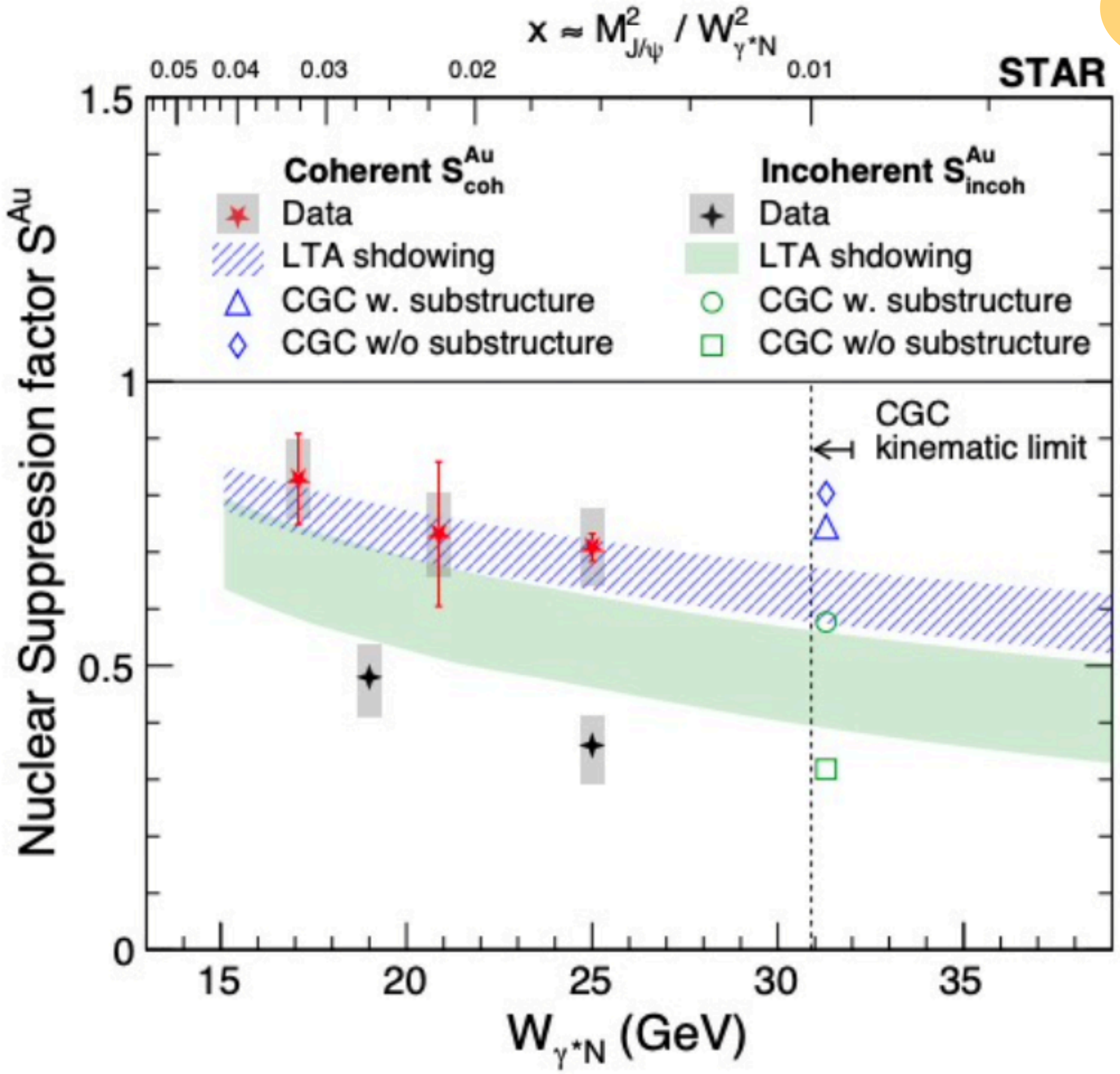
No model describes the measurement in the entire Bjorken-x range

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

For details see Adam Matyja talk , QAsT 2024,09/01

NEW





CGC Model, H. Mäntysaari et al.,arXiv:2207.03712

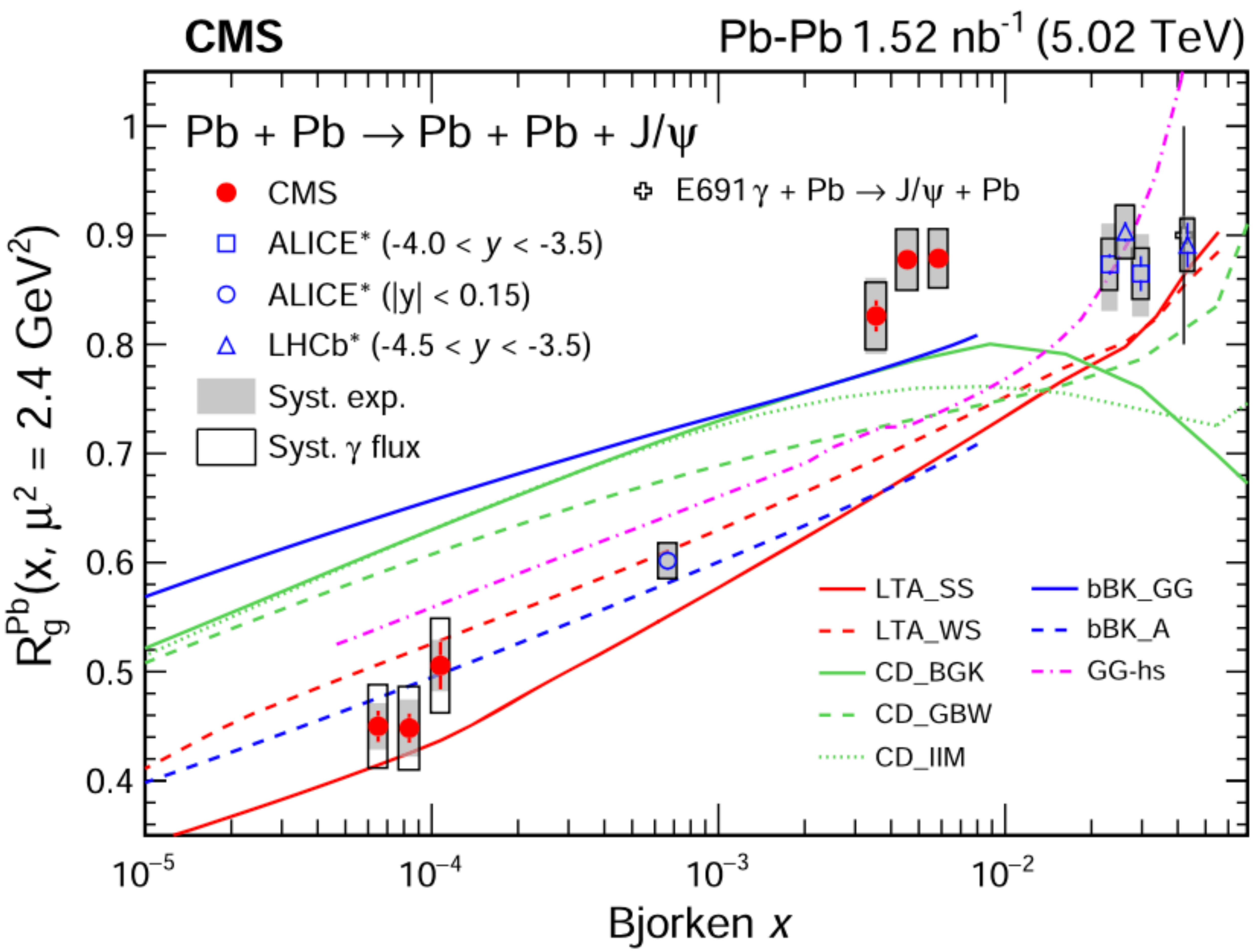
LTA model, M.Strickman et al., arXiv:2303.12052

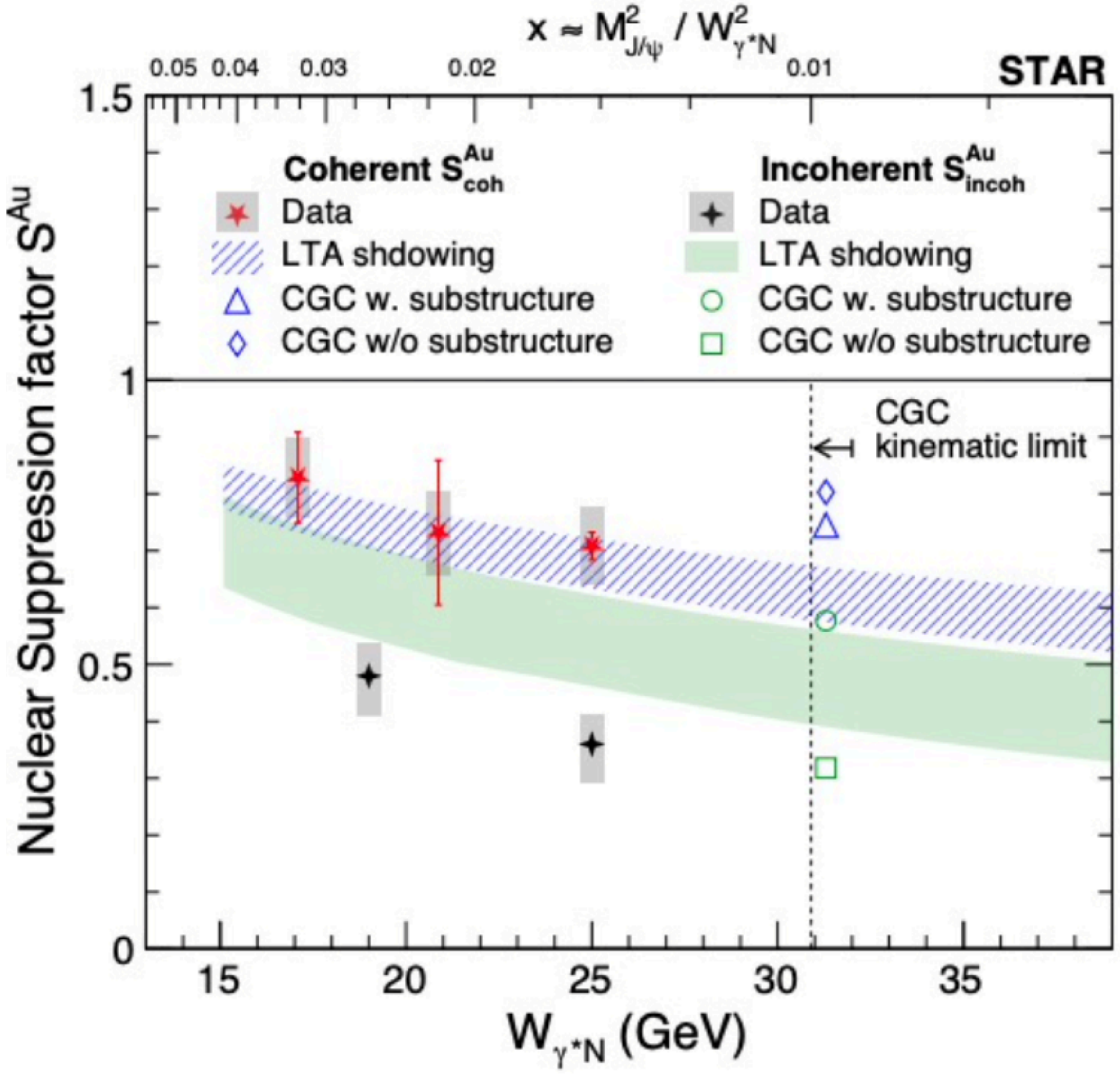
Nuclear suppression factor due to gluon shadowing $S_{Pb/Au} = \sqrt{\frac{\sigma_{\gamma Pb/Au}}{\sigma^{IA}_{\gamma Pb/Au}}}$

No model can describe the measurement in entire x range, further theoretical inputs are needed

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

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

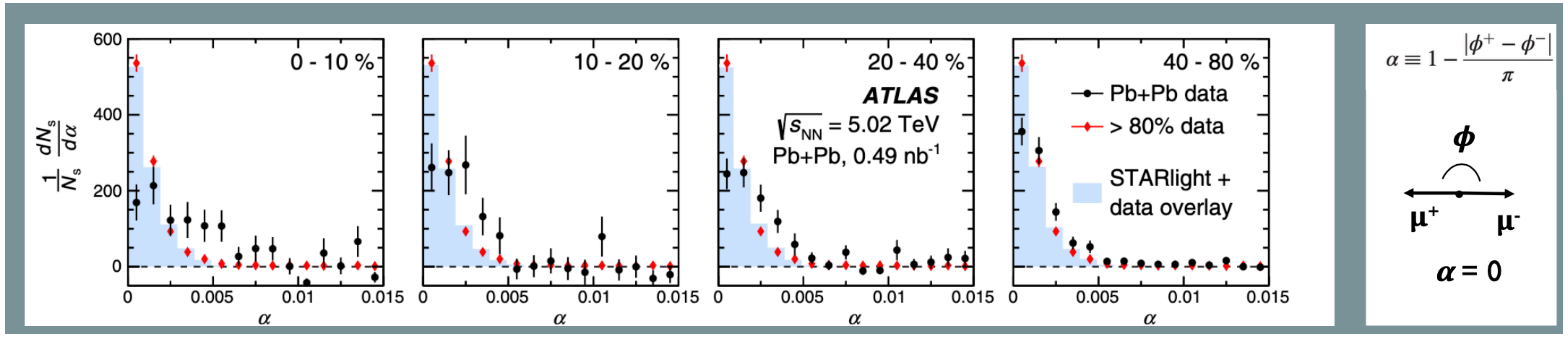


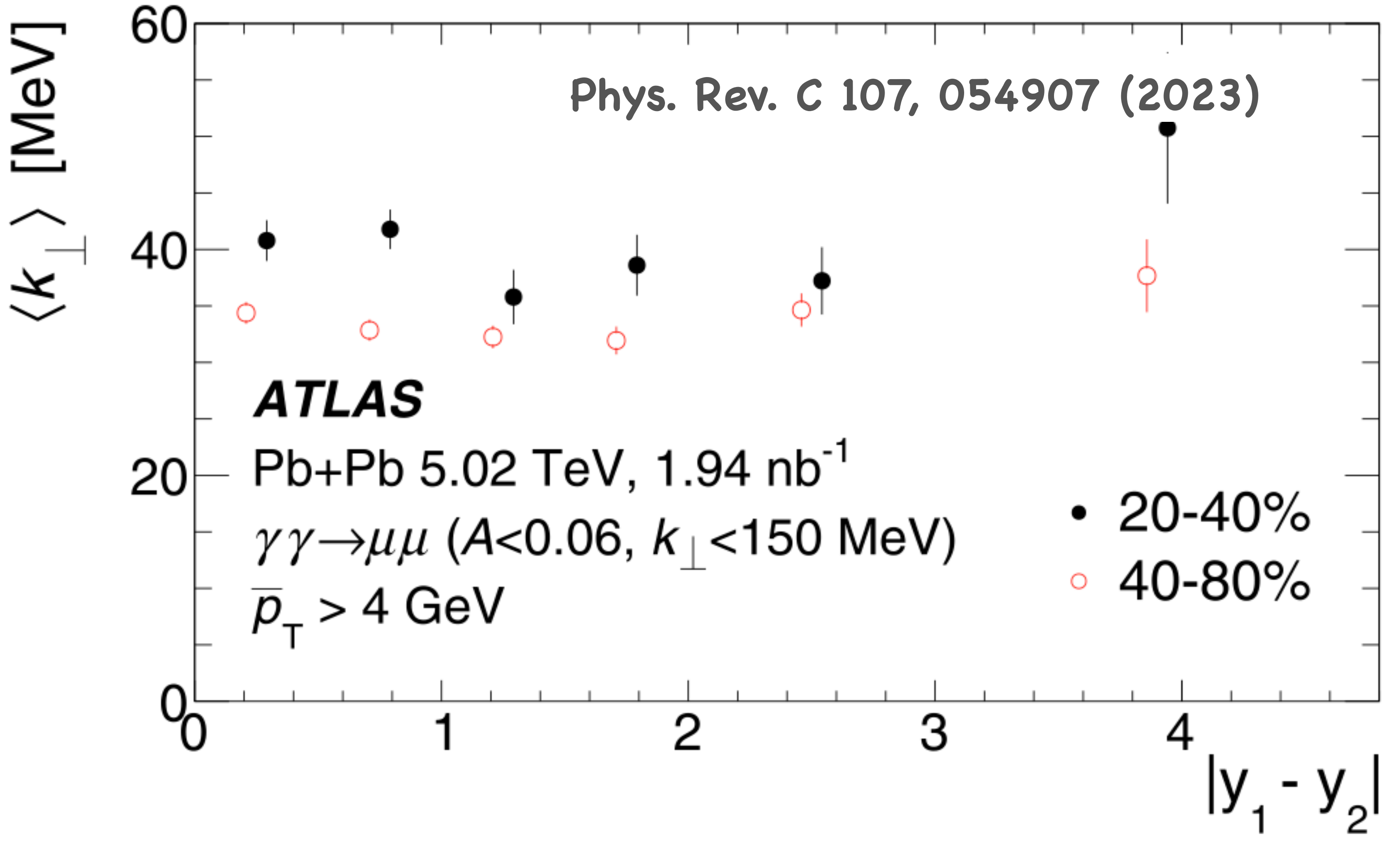


Strong suppression due to nuclear gluon shadowing is observed at both RHIC and LHC energies

Dimuon production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

Observation by ATLAS of centrality-dependent acoplanarity for muon pairs produced via $\gamma\gamma$ scattering in hadronic Pb–Pb collisions for $4 < m_{\mu^+\mu^-} < 45$ GeV/c², PRL 121, 212301 (2018)

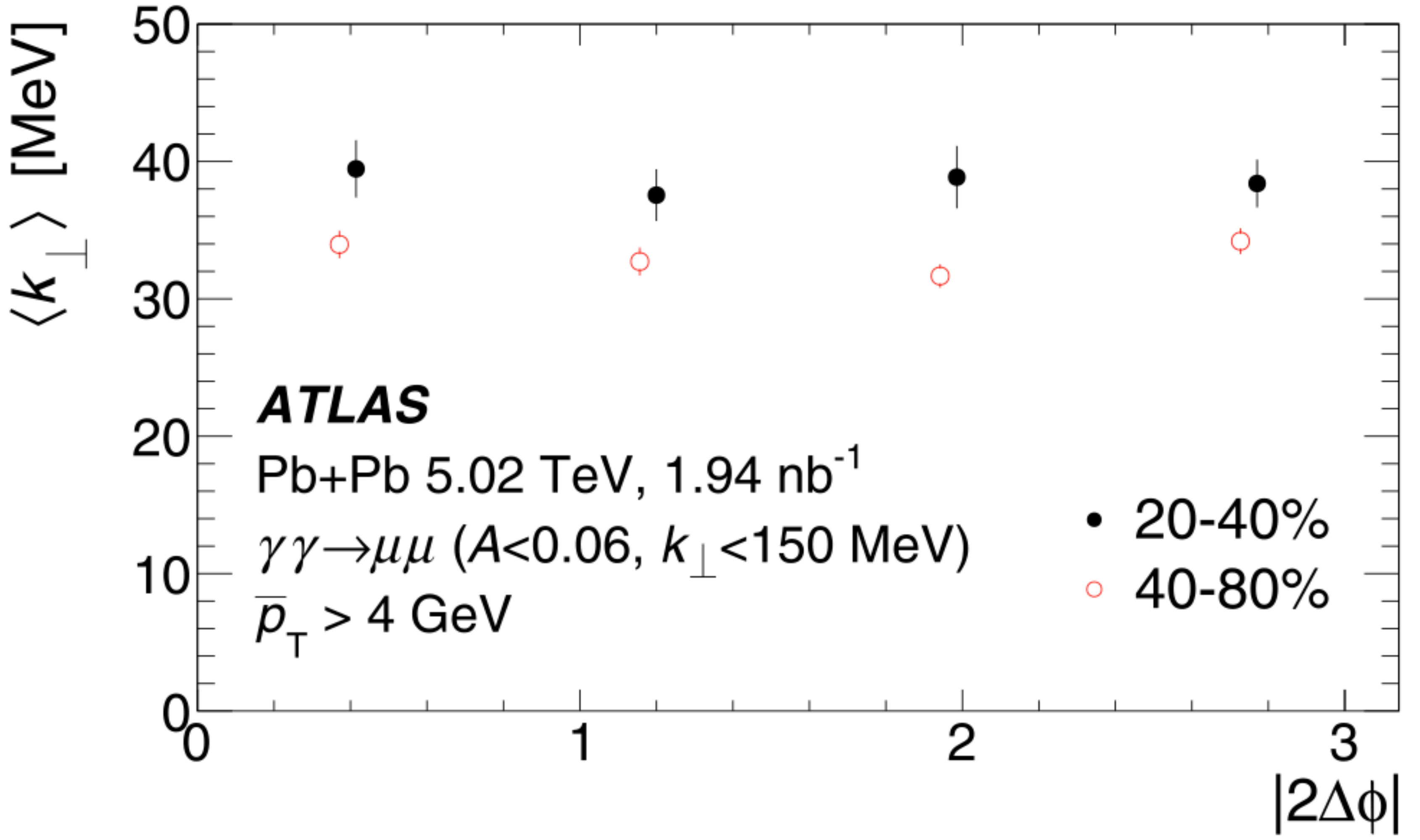




Originally interpreted as a sign of em. scattering of the muons with a hot and dense medium

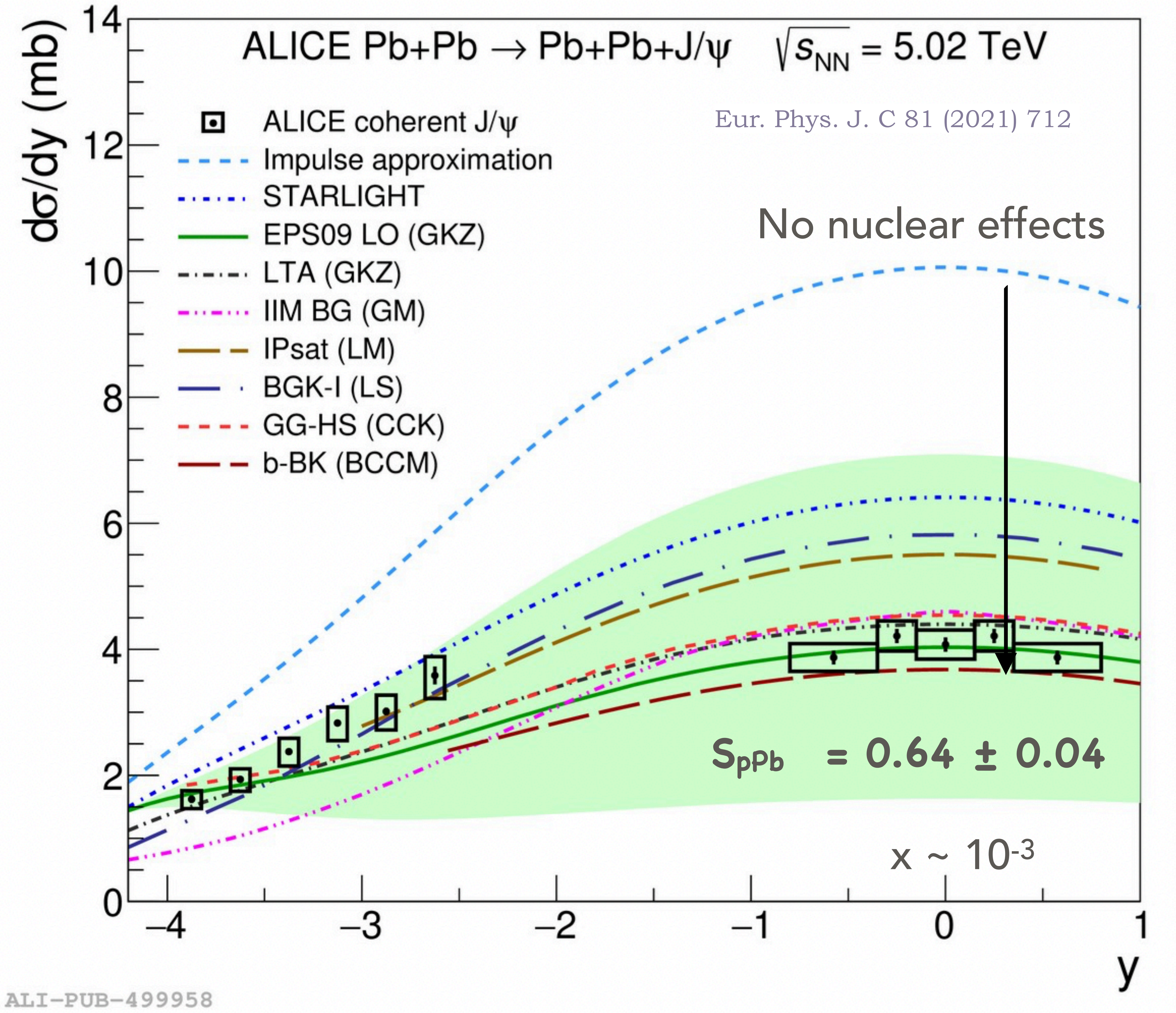
Distributions of α, and the associated transverse momentum scale $k_\perp$,

$$k_\perp \equiv \tfrac{1}{2}(p_{T1} + p_{T2})(\pi - |\phi_1 - \phi_2|) = \pi\alpha\bar{p}_T, \qquad (1)$$



-> Broadening of the α and k⊥ distributions does not have significant contribution from interactions of the muons with magnetic fields generated in the quark-gluon plasma.

VM photo production cross section vs. y in UPC



Nuclear suppression factor (shadowing) = $S_{\rm pPb} = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}}$

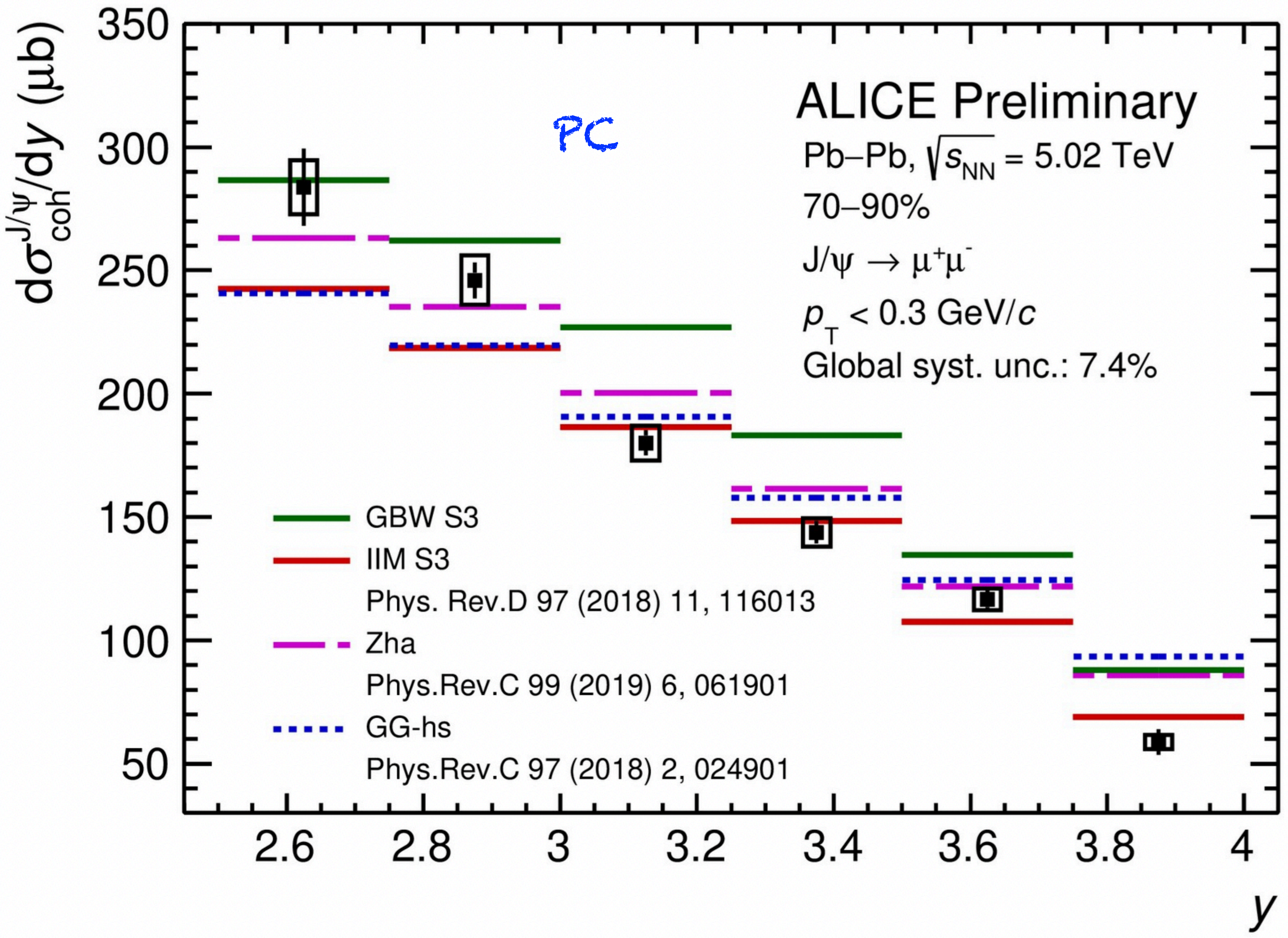
Impulse approximation: [PRC88, 014910 (2013)]
STARLIGHT: [Comp. Phys. Comm. 212 (2017) 258]
EPS09 LO (GKZ): [PRC. 93(5), 055206 (2016)]
LTA (GKZ): [Phys. Rep.512, 255–393 (2012)]
IIM BG (GM): [P.RC 90, 015203 (2014)] and [J. Phys.G 42(10), 105001 (2015)]
Ipsat (LM) : [PRC. 83,065202 (2011)] and [PRC. 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)]

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

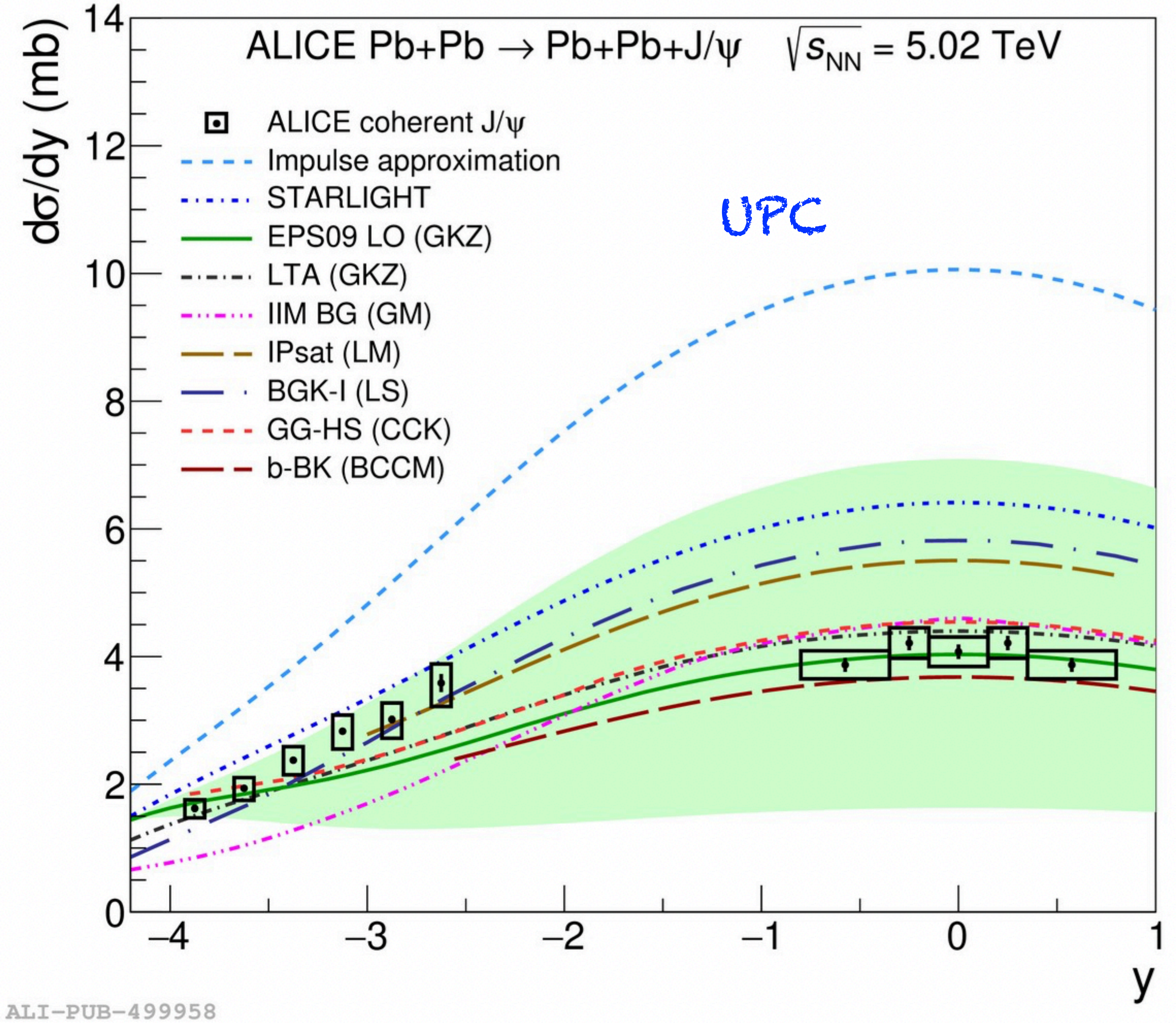
Models including nuclear shadowing are in agreement with the measurement

Models cannot describe at the same time the mid and forward rapidity cross section measurements

J/ψ photoproduction cross section vs. y



Phys. Lett. B798 (2019) 134926



A strong rapidity dependence is seen

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,** similarly to UPC.

Polarization : photoproduction of vector mesons

ρ^0 meson measurement : consistent with SCHC

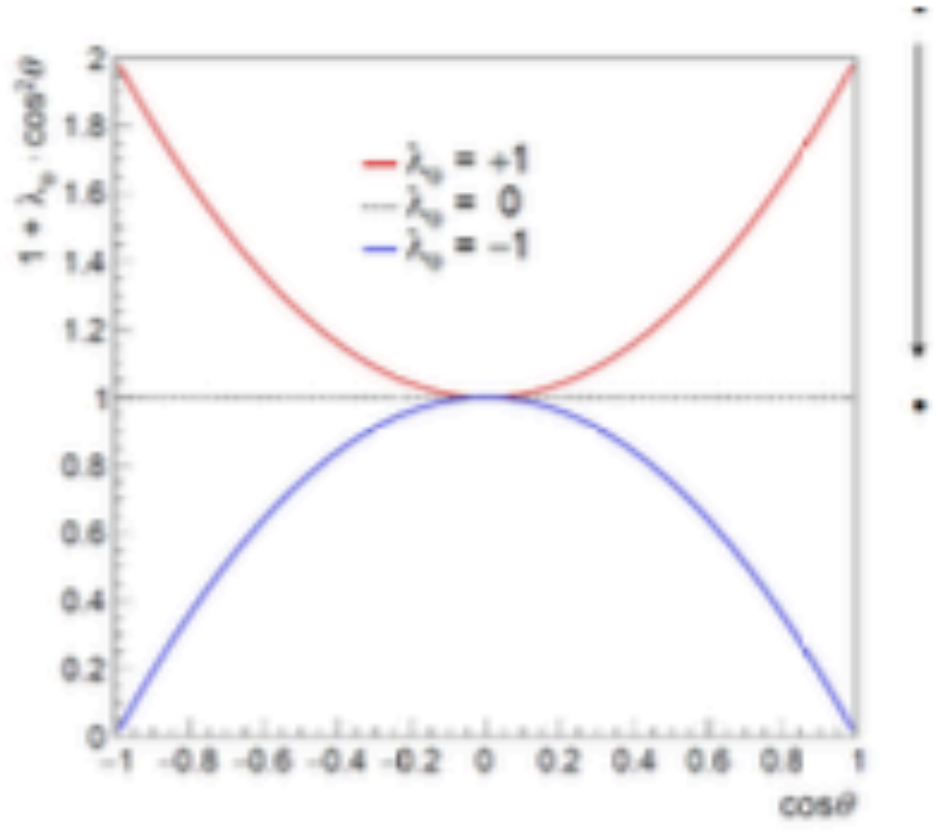
Phys. Rev. D 7, 3150, (1970) by SLAC Collaboration
Z. Phys. C 53, 581–594, (1992) by CERN SPS

ρ^0 [1] , ω[2] and φ [3] photoproduction by CLAS Collaboration : SCHC violation
[1] Eur. Phys. J. A 39, 5–31, (2009)
[2] Int. J. Mod. Phys. Conf. Ser. 26,1460063, (2014)
[3] Phys.Rev.C 90, 019901, (2014)

ρ0 photoproduction by STAR Collaboration : consistent with SCHC
Phys. Rev. C 77 (2008) 034910

Exclusive J/ψ photoproduction by H1 and ZEUS collaborations : consistent with SCHC
[1] Eur. Phys. J. C 46 , 585–603 (2006)

[2] Nucl. Phys. B 695, 3–37 (2004)



Do we see similar observation for J/ψ at low p_T (< 0.3 GeV/c) in Peripheral Pb-Pb collisions with nuclear overlap?

✓ Is the **J/ψ transversely polarized** and therefore obey **the SCHC hypothesis** ?

✓ Another way to test the **production mechanism** at the origin of the J/ψ **very low p_T excess**

✓ Also **complementary to the UPCs** measurement

$$r^{04}_{00} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$

$$r^{04}_{1,-1} = \frac{\lambda_\varphi}{2}\cdot(1+r^{04}_{00}) .$$

Observables : Extract angular variables and spin density matrix element