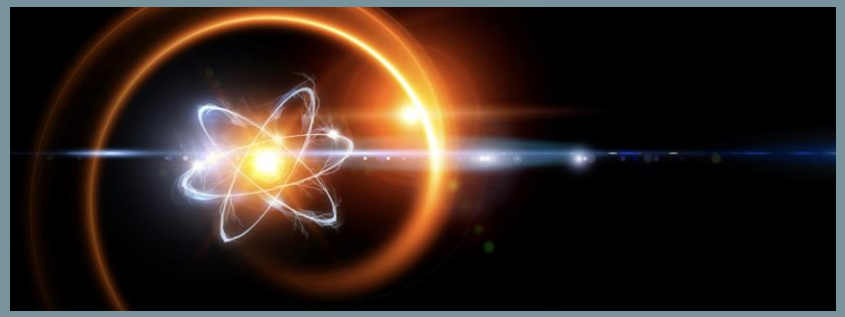
Photoproduction in peripheral pA and AA collisions

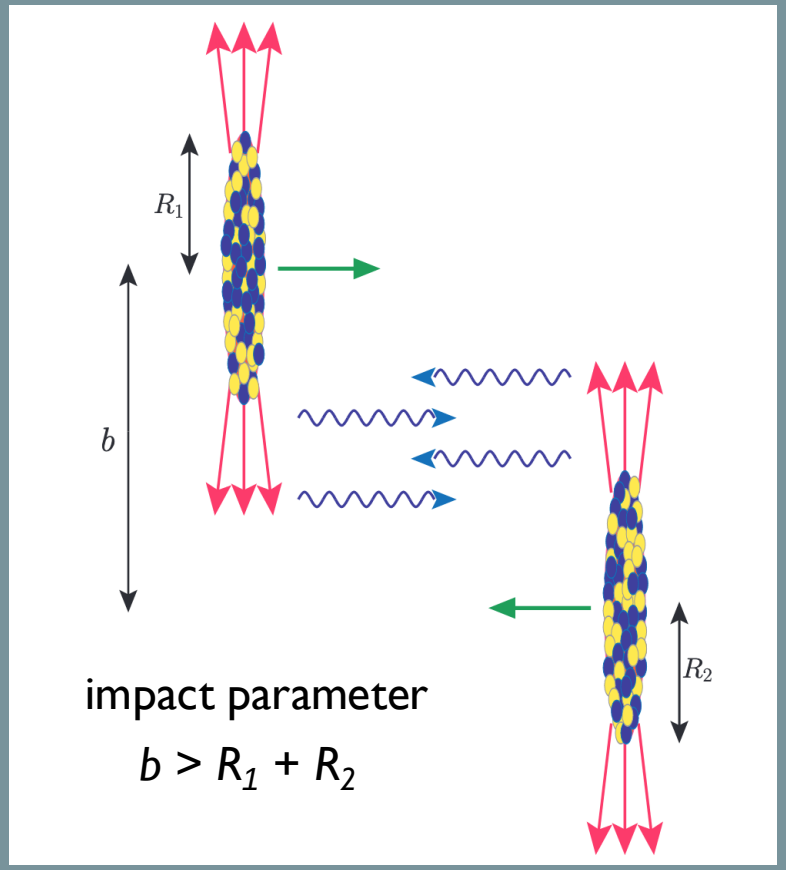
L. Massacrier

IJCLab Orsay, CNRS/IN2P3, Université Paris-Saclay



Towards improved hadron tomography with hard exclusive reactions, 5-9th Aug. 2024, Trento, Italy

Photon induced processes and ultraperipheral Pb–Pb collisions



- The EM field of Pb nuclei can be described as beam of quasi-real photons (number of photons proportional to Z^2)

→ Use LHC as photon-photon or photon-hadron collider

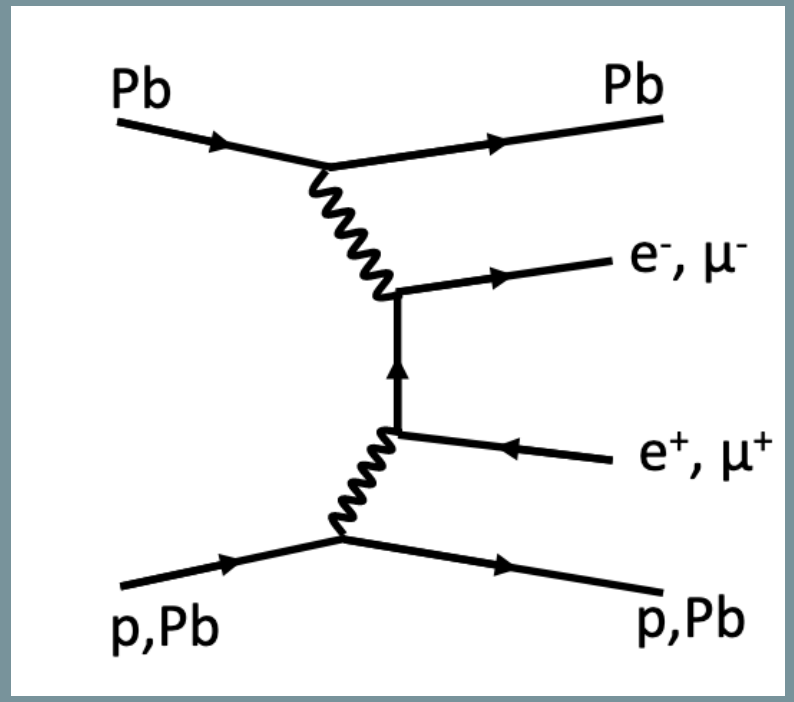
- Ultraperipheral collisions (UPC): interactions with b larger than the sum of the radii of the incoming nuclei. Involve at least one photon:
  - Hadronic interactions strongly suppressed
  - Electromagnetic interactions dominant
  - Clean experimental signature: few tracks produced, large rapidity gaps

- Photon induced reactions well studied in UPC

See talk of D. Mallick

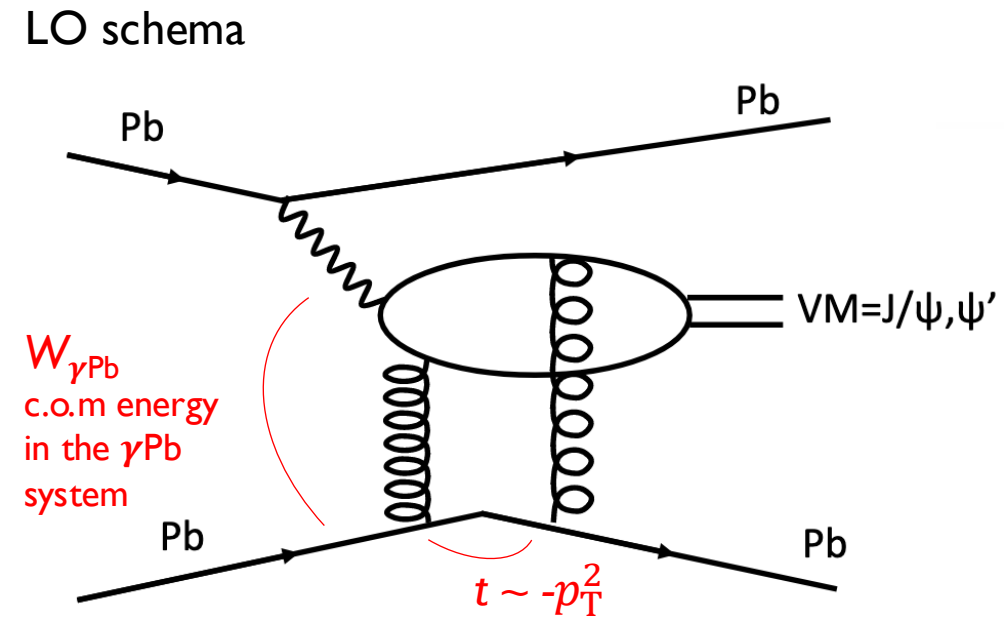
- But also present in non-UPC (ie. in events where an hadronic interaction also occurs) → focus of this presentation

Dilepton production in two-photon interactions



- Breit Wheeler mechanism (G. Breit, Phys. Rev. 46 (1934) 1087):
  - Production of very low p_T lepton pair
- Test QED (at LO + possibly higher order corrections)
  - ~ 15% effect for the reduction of the cross section at LHC energies A. J. Baltz, Phys. Rev. C 80, 034901
- Map the EM field produced in heavy-ion collisions
  - Larger Lorentz-boost factor w.r.t RHIC
  - Maximum electric field reached 30 times larger than at RHIC

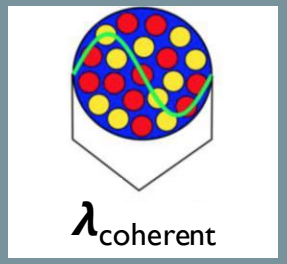
Vector meson (VM) photoproduction



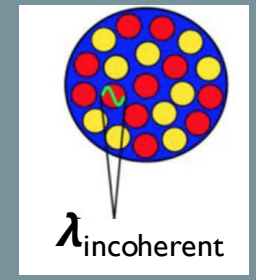
- Photon oscillates into a quark-antiquark pair
- Production of a very low-p_T vector meson (for coherent process)
- Gives access to gluon distributions in nuclei at low Bjorken-x, provides constraints to initial stages of heavy-ion collisions

10^{-5} < Bjorken-x < 10^{-2} at LHC energies

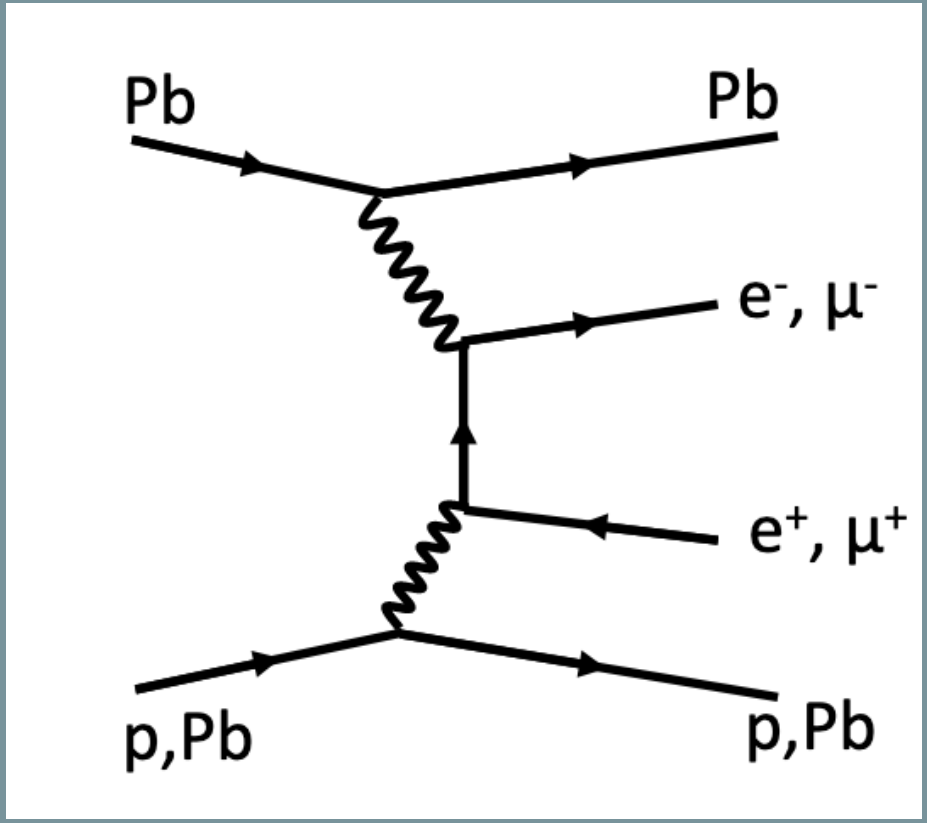
- Coherent photoproduction of VM
  - γ couples coherently to all nucleons
  - $\langle p_T \rangle^{J/\Psi}$ ~ 60 MeV
  - Usually no breaking of target nucleus



- Incoherent photoproduction of VM
  - γ couples to a nucleon
  - $\langle p_T \rangle^{J/\Psi}$ ~ 500 MeV
  - Usually target nucleus breaks



Dilepton production in two-photon interactions



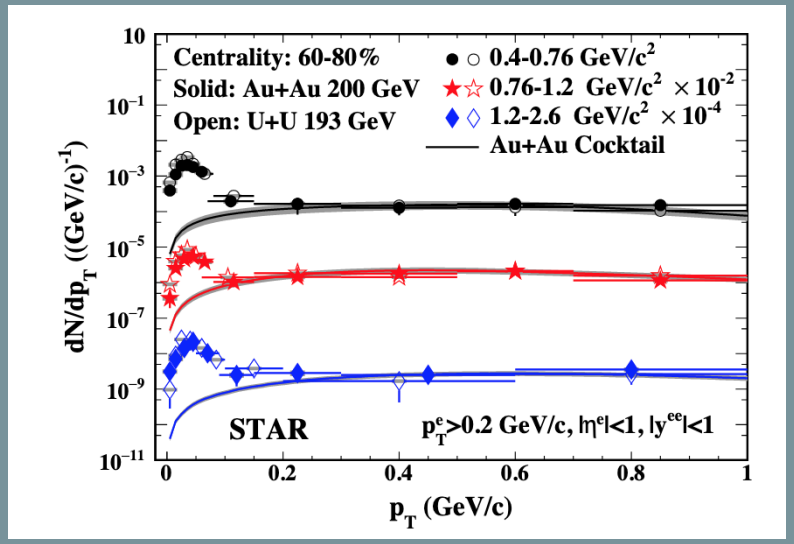
Dilepton production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

- Very low-p_T dielectron excess observed by STAR, at mid-y for $0.4 < m_{e^+e^-} < 2.6$ GeV/c^2 in Au–Au and U–U collisions (centrality 60-80%) : compatible with expectations from $\gamma\gamma$ intercations but p_T^2 distribution not reproduced (intially interpreted as possible sign of strong magnetic field trapped in a conducting QGP)

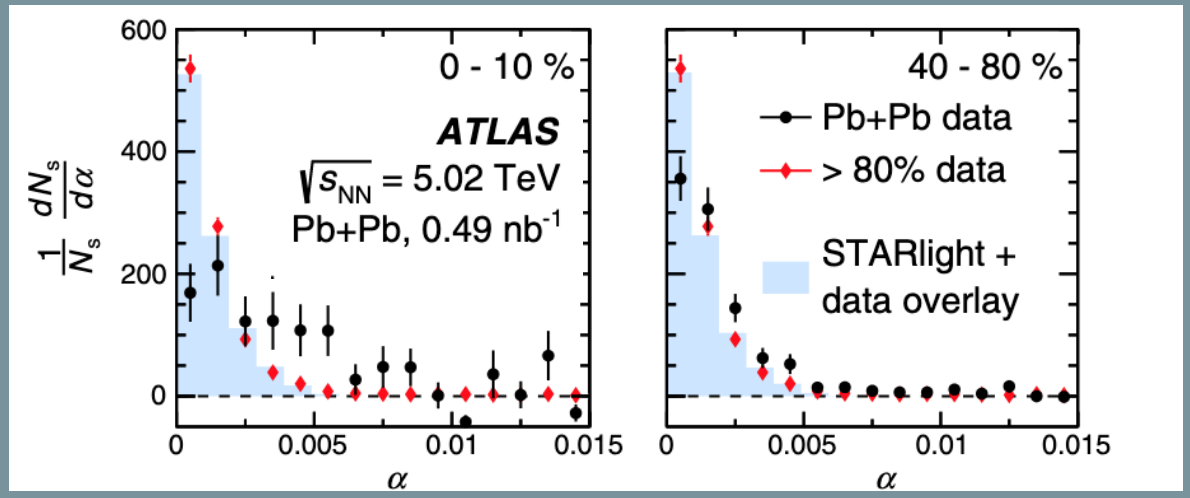
- Observation by ATLAS of centrality-dependent acoplanarity for muon pairs produced via $\gamma\gamma$ scattering, for $4 < m_{\mu^+\mu^-} < 45$ GeV/c^2 → initially interpreted as a sign of em. scattering of the muons with a hot and dense QGP medium

- Inclusion of a *b*-dependence of photon-k_T distribution in QED calculations reproduce both STAR and ATLAS data (without need for medium induced or final state effects)

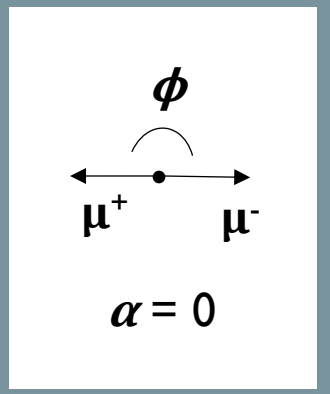
STAR Collaboration, PRL 121, 132301 (2018)



ATLAS Collaboration, PRL 121, 212301 (2018)



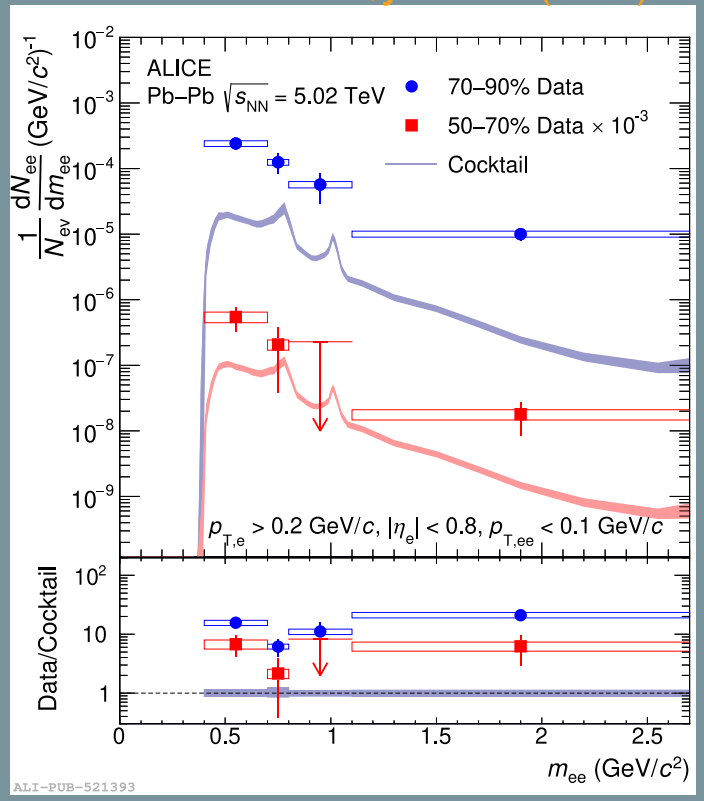
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

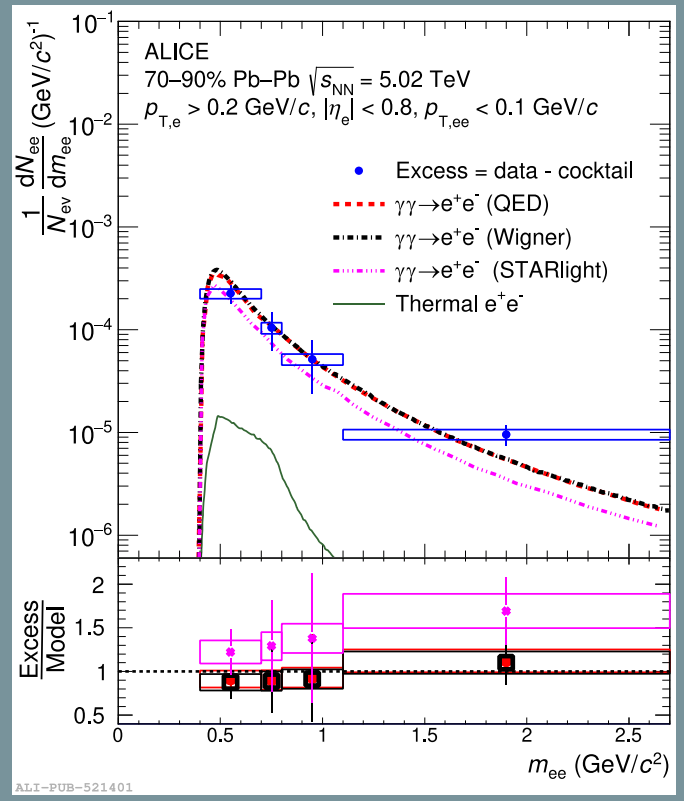


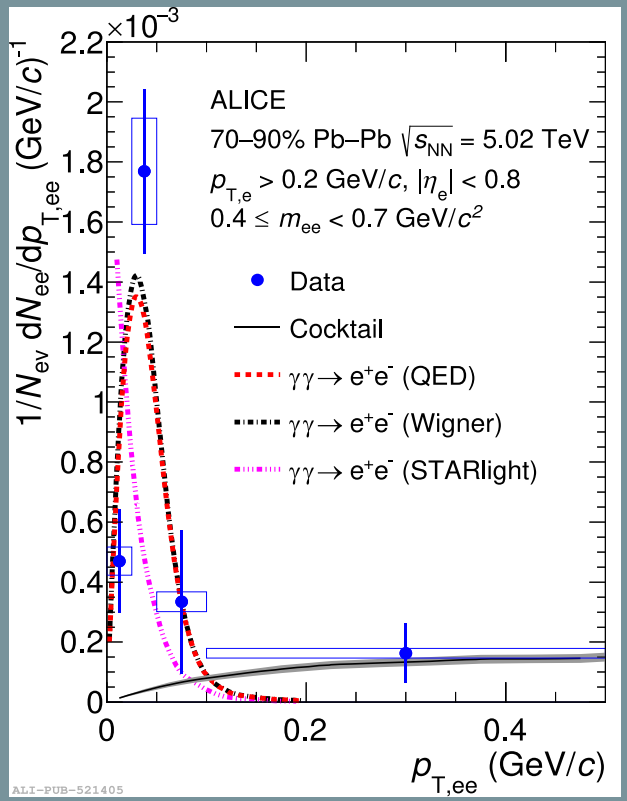
Dilepton production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

- Similar measurement by ALICE of a dilepton excess at very low-p_T for $0.4 < m_{e^+e^-} < 2.6$ GeV/c^2 in peripheral Pb–Pb
  - Data cannot be described by cocktail of e^+e^- expected hadronic sources
  - At low $p_{T,ee}$, thermal radiation from medium is expected to be one order of magnitude smaller than observed excess
- Clear peak observed at low p_{Tee} in the 70-90% centrality range
- Data described by $\gamma\gamma$ interaction models including the b-dependence of the photon-k_T distribution (QED, Wigner)

ALICE Collaboration, JHEP 06 (2023) 024





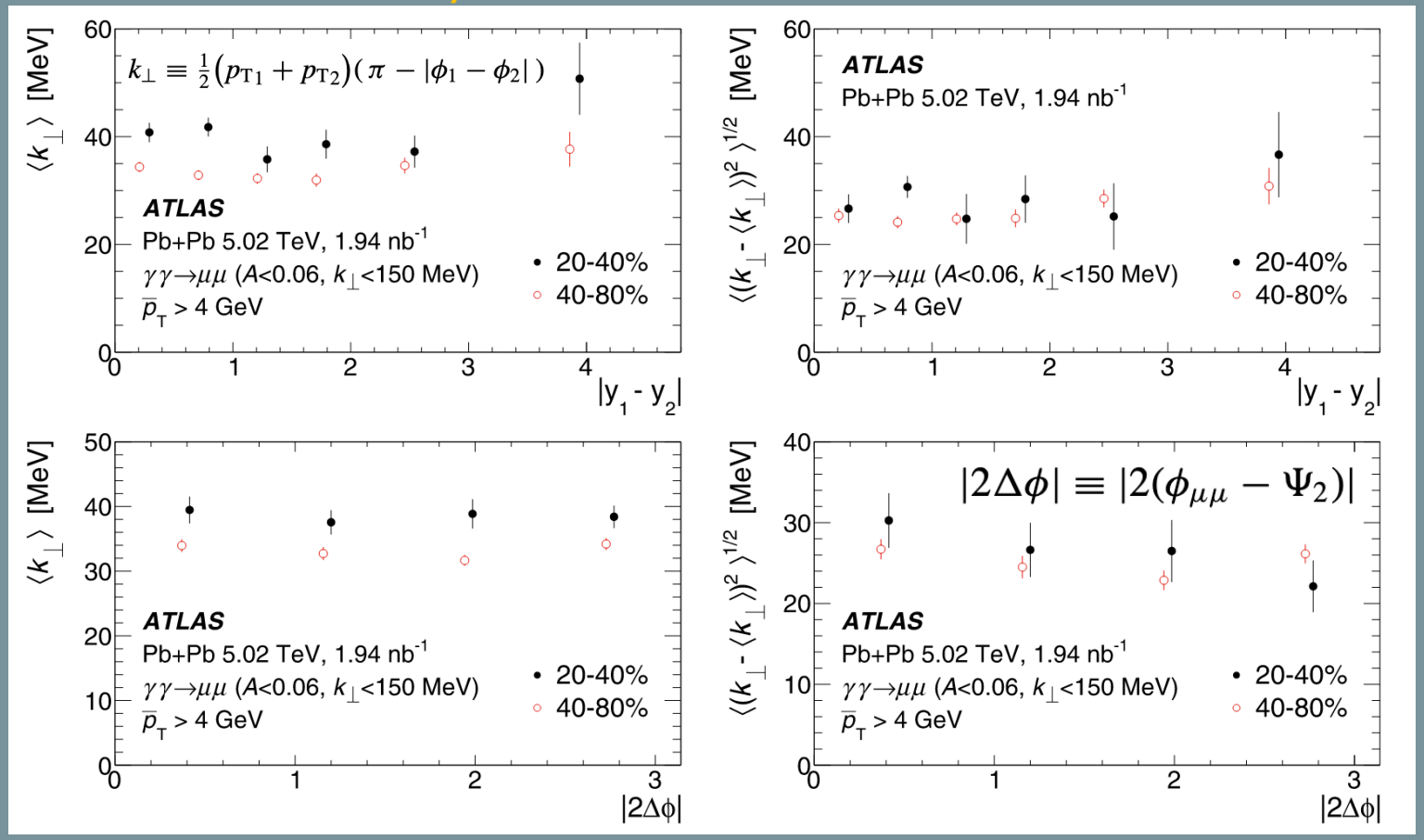


QED:
W. Zha *et al.*, Phys. Lett. B 800 (2020) 135089
J. D. Brandenburg *et al.*, Eur. Phys. J. A 57 (2021) 299
Wigner:
M. Klusek-Gawenda *et al.*, Phys. Lett. B. 814 (2021) 136114
STARlight:
S.R. Klein *et al.*, Comput. Phys. Commun. 212 (2017) 258
S.R. Klein, Phys. Rev. C. 97 (2018) 054903

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

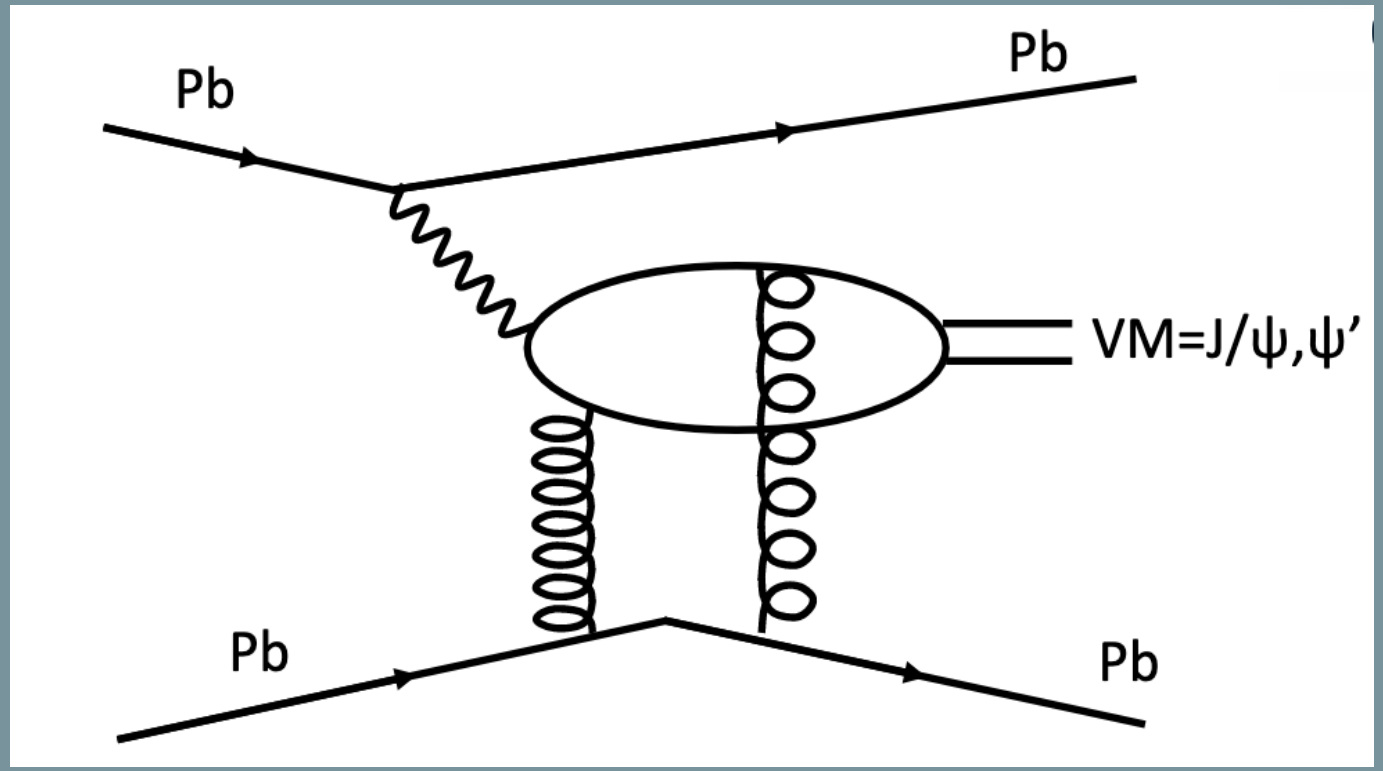
- New measurement by ATLAS with full Run 2 Pb—Pb statistics, to further inspect possible role from initial e.m fields

ATLAS Collaboration, Phys. Rev. C 107, 054907



- $k_\perp$ less sensitive to muon momentum than acoplanarity → better observable to probe role from e.m fields
- From theory, if centrality-dependent modification of α (or $k_\perp$) comes from initial e.m, the broadening should vary as a function of th(Δy), or Δϕ (orientation of dimuon w.r.t 2nd order EP angle [correlated to the direction of e.m field])
- No dependence of the broadening with Δy or Δϕ → rules out interaction of leptons with e.m fields generated by a QGP

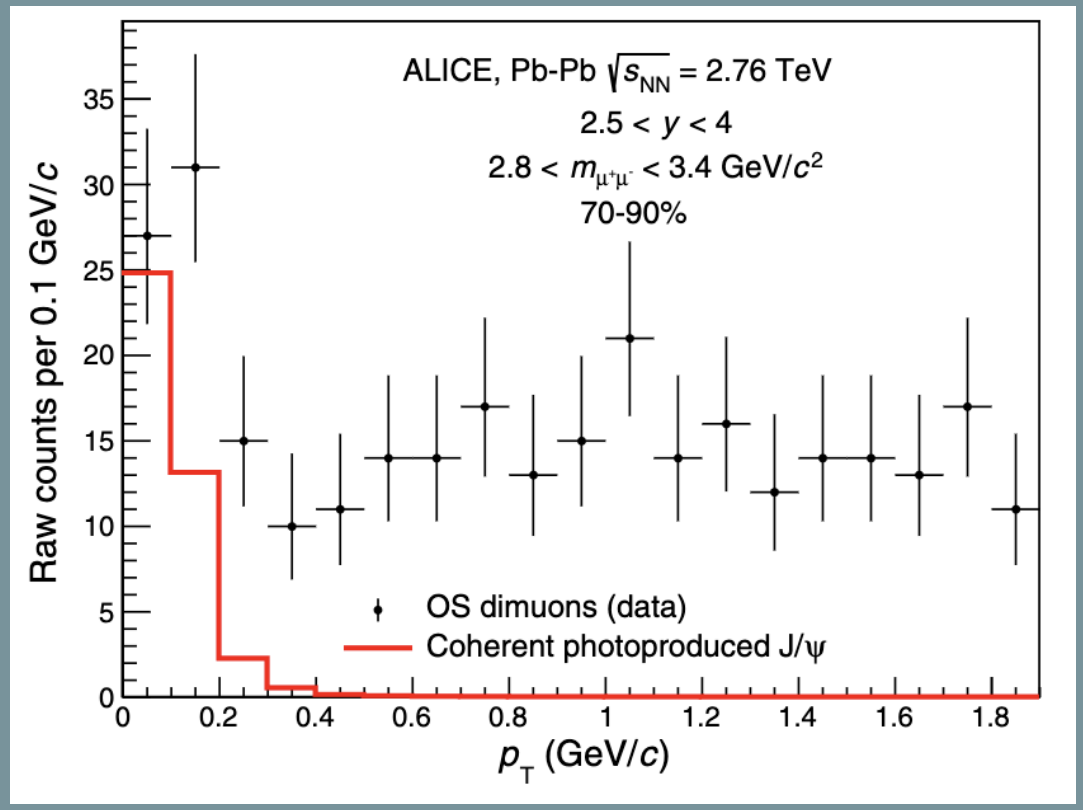
Vector meson (VM) photoproduction



First observation of VM photoproduction in Pb–Pb collisions with nuclear overlap

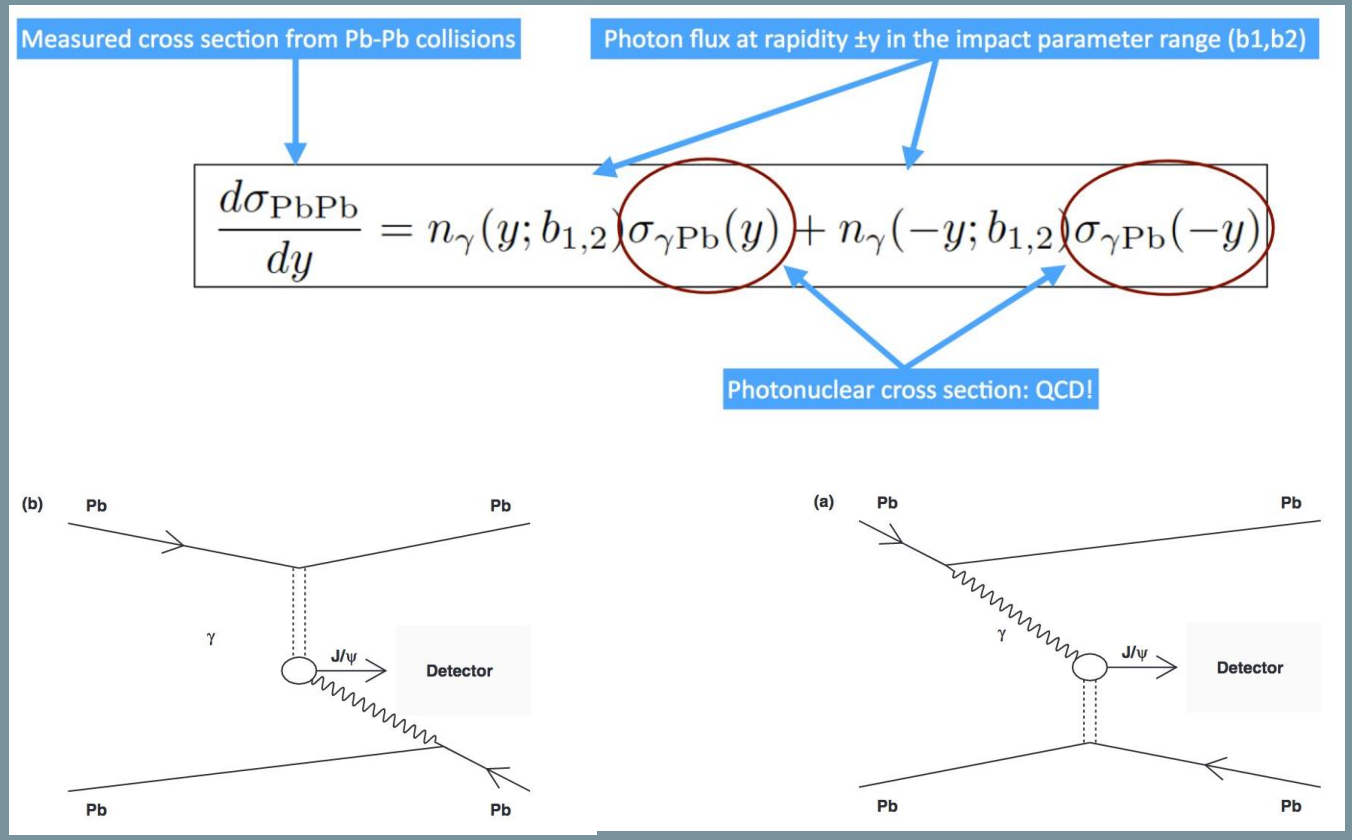
- Very low-p_T J/ψ excess in peripheral Pb–Pb collisions first measured in ALICE at forward y and $\sqrt{s_{NN}}$ = 2.76 TeV
  - Interpreted as coherent photoproduction
  - Significance: of the excess:
    5.4σ (70-90%), 3.4σ (50-70%), 1.4σ (30-50%)

ALICE Collaboration, PRL 116, 222301 (2016)



Opened questions on VM photoproduction in heavy-ion collisions with nuclear overlap

- Theoretical challenges:
  - Survival of coherence condition for a broken nucleus? Only spectator nucleons participating to coherence?
- A potential new probe of charmonium color screening in the QGP?
- A novel way to access $\sigma_{\gamma Pb}$ when combined to UPC measurement? (see J.G. Contreras, Phys. Rev. C 96, 015203 (2017))
  → Need to understand time ordering of the interaction and theoretical open questions related to the treatment of the nuclear overlap



- First theoretical approches developed since 2016 based on UPC-like models with modified photon flux and/or modified photonuclear cross section to account for overlap

Opened questions on VM photoproduction in heavy-ion collisions with nuclear overlap

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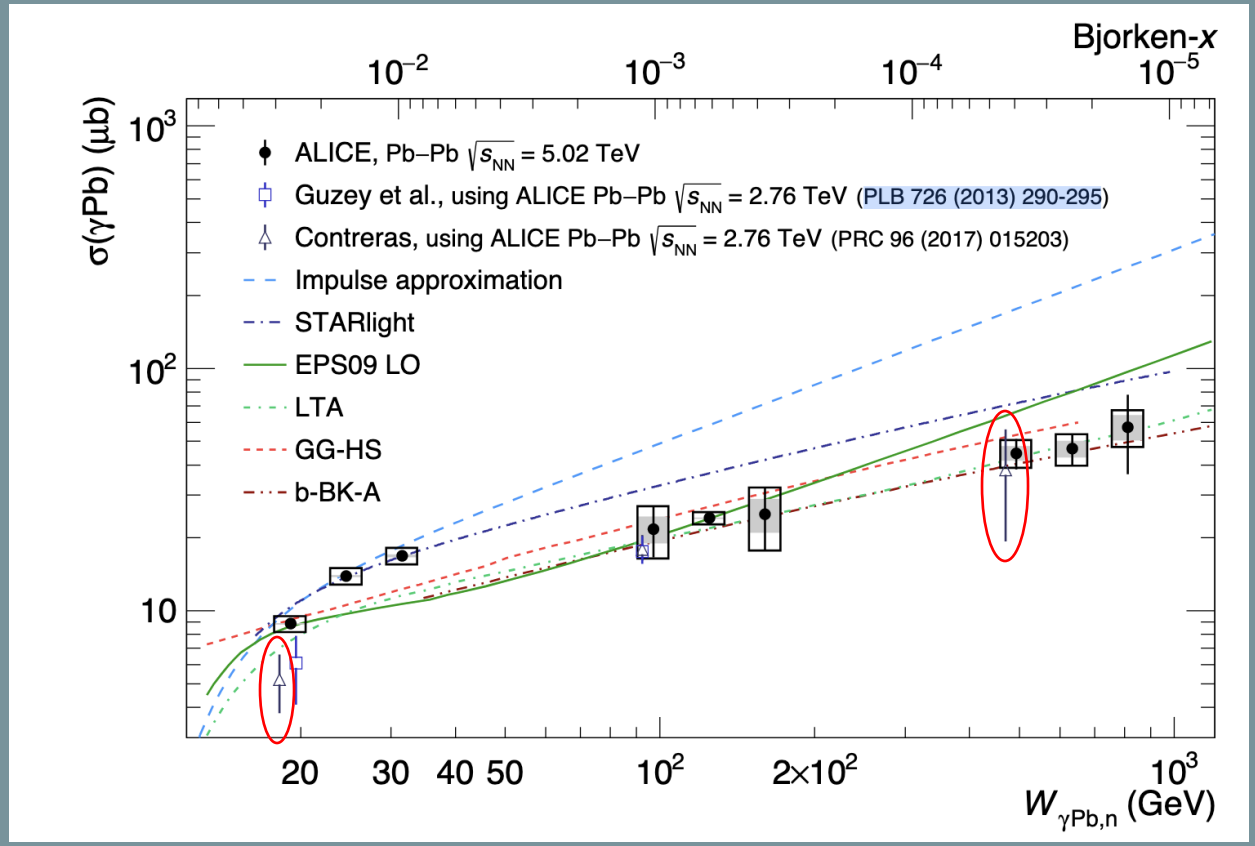
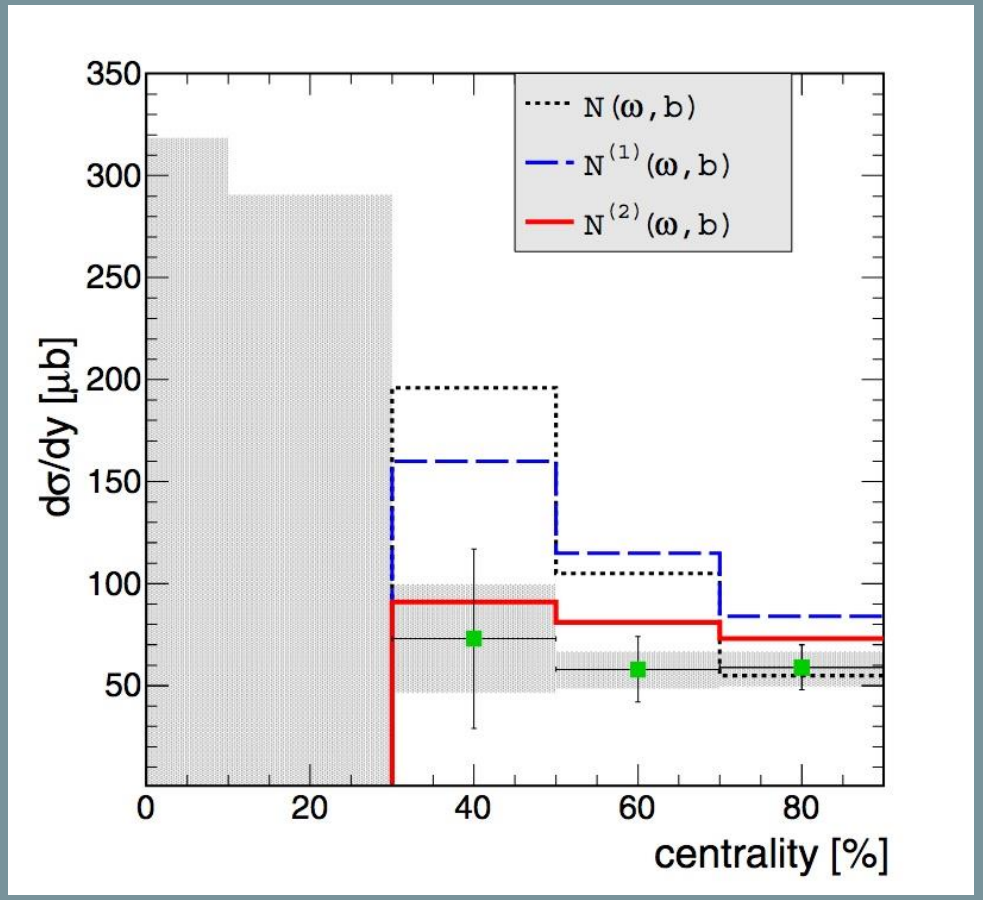


ALICE Collaboration, JHEP 10 (2023) 119

- First theoretical approches developed since 2016 based on UPC-like models with modified photon flux and/or modified photonuclear cross section to account for overlap

First theoretical developments to describe VM photoproduction in Pb–Pb collisions with nuclear overlap

M. Klusek-Gawenda, PRC 93, 044912 (2016)



Equivalent photon approximation + vector dominance model

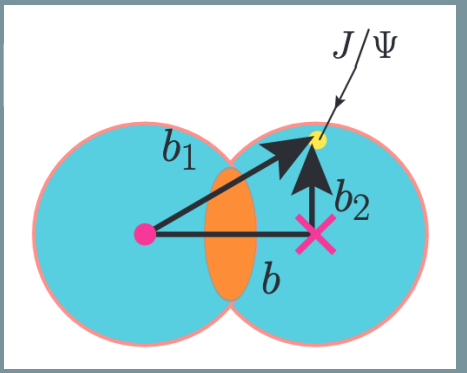
- Standard photon flux (UPC)
- Effective photon flux (considering geometrical constraints for the photon to reach the nucleus medium)

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - b_2)}{\pi R_A^2} \mathrm{d}^2 b_1$$

- Effective photon flux (considering photons reaching the spectator nucleon region only)

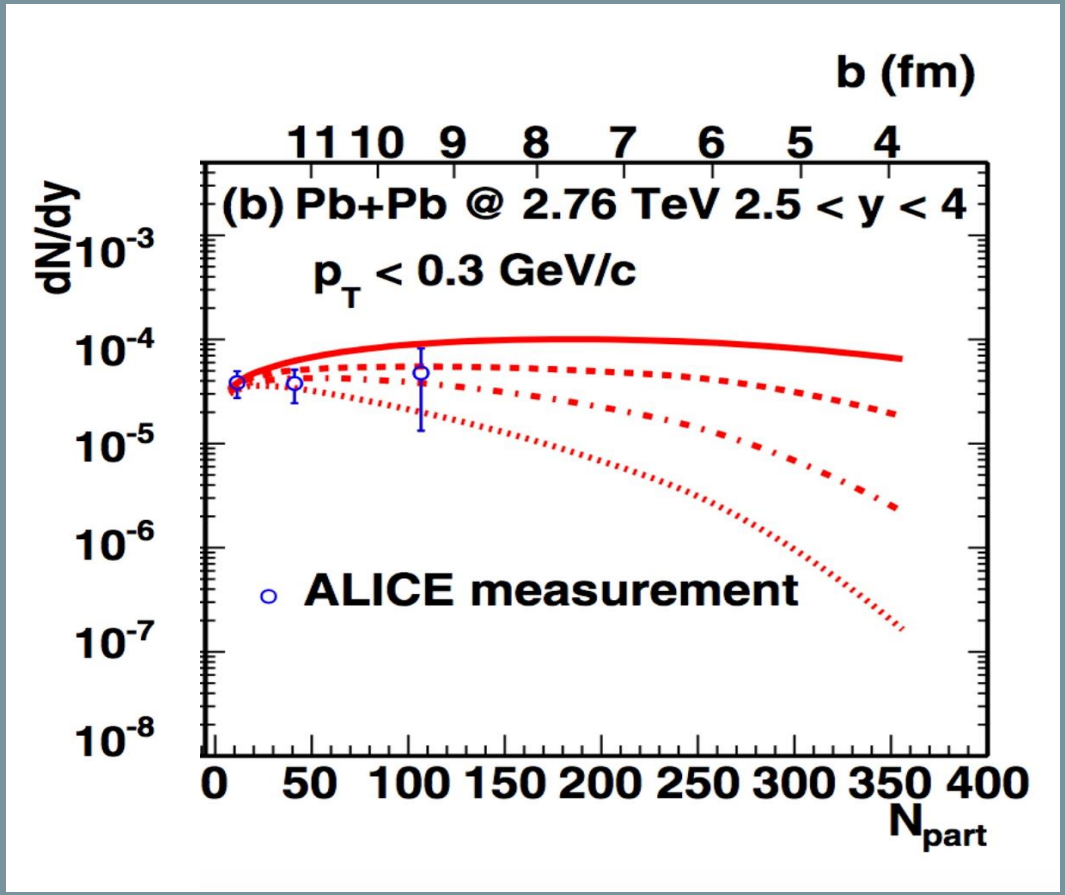
$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - b_2) \times \theta(b_1 - R_A)}{\pi R_A^2} \mathrm{d}^2 b_1$$

- ALICE data (Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV)
- ALICE syst. uncertainties



First theoretical developments to describe VM photoproduction in Pb–Pb collisions with nuclear overlap

W. Zha, PRC 97, 044910 (2016)



- Strong interactions in the overlapping region of incoming nuclei may disturb the coherent production, leaving room for different coupling assumptions between photon and pomeron:

N + N	Nucleus (γ emitter) – Nucleus (pomeron emitter)
N + S	Nucleus (γ emitter) – Spectator (pomeron emitter)
S + N	Spectator (γ emitter) – Nucleus (pomeron emitter)
S + S	Spectator (γ emitter) – Spectator (pomeron emitter)

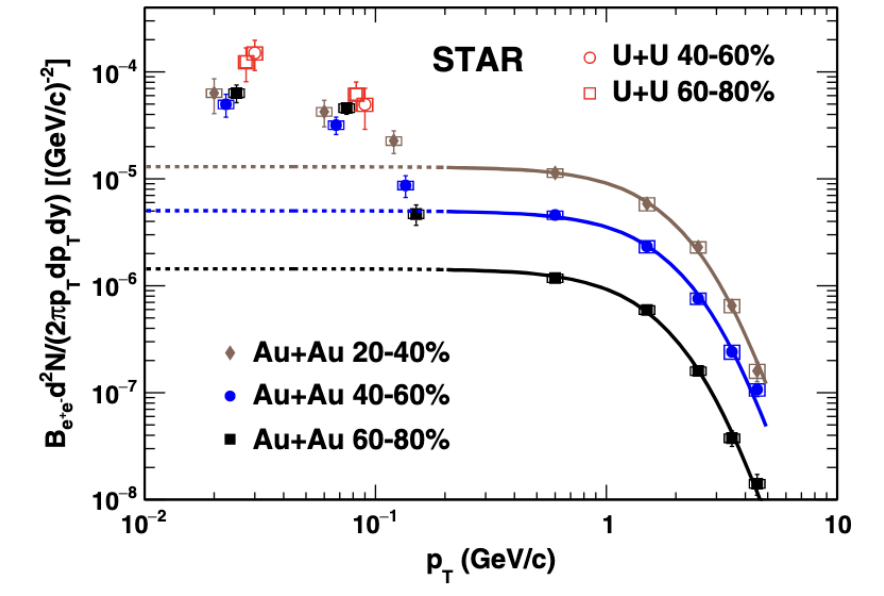
- ALICE Run 1 data consistent with all 4 scenarios within uncertainties
- Need more precise data and measurement towards most central collisions (challenging!) to constrain theoretical models

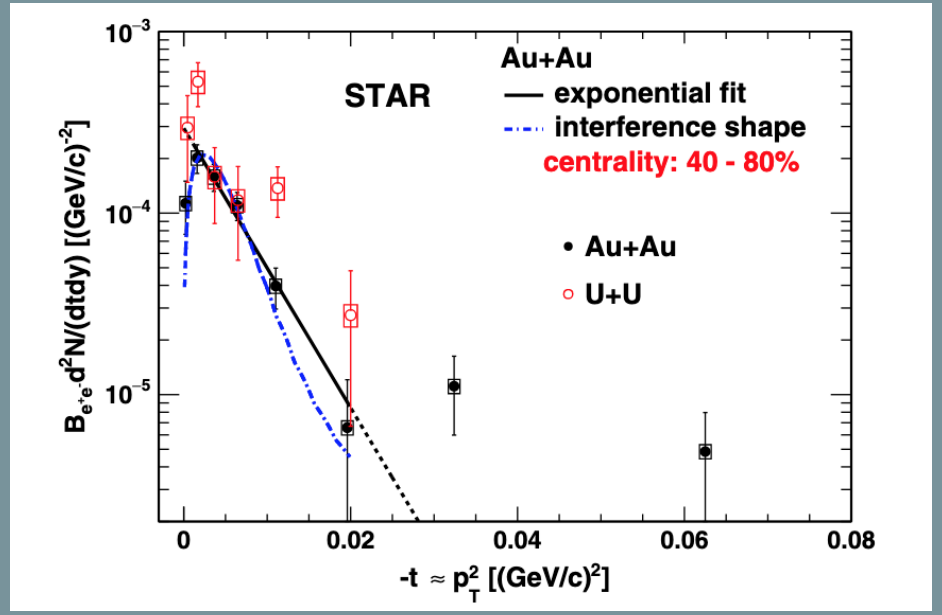
- Recent work by same authors (Phys. Rev. C 99, 061901) considering target nucleus as double slits (interference patterns)

VM photoproduction in Pb–Pb collisions with nuclear overlap (STAR)

- Observation confirmed by STAR Collaboration at lower energy in U–U (193 GeV), Au–Au collisions (200 GeV), at mid-y
  - First measurement of the *t*-dependence of the J/ψ excess :
    - Slope parameter of exponential fit related to the position of the interaction sites within the target
    - Can be used to investigate interference patterns
  - Supports also photoproduction origin

STAR Collaboration, PRL 123, 132302 (2019)

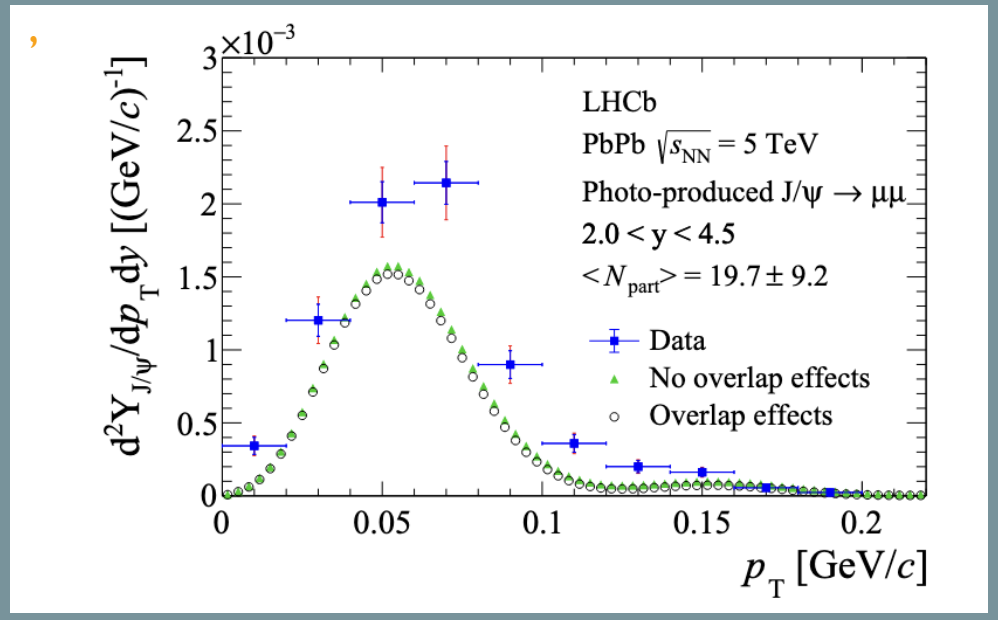


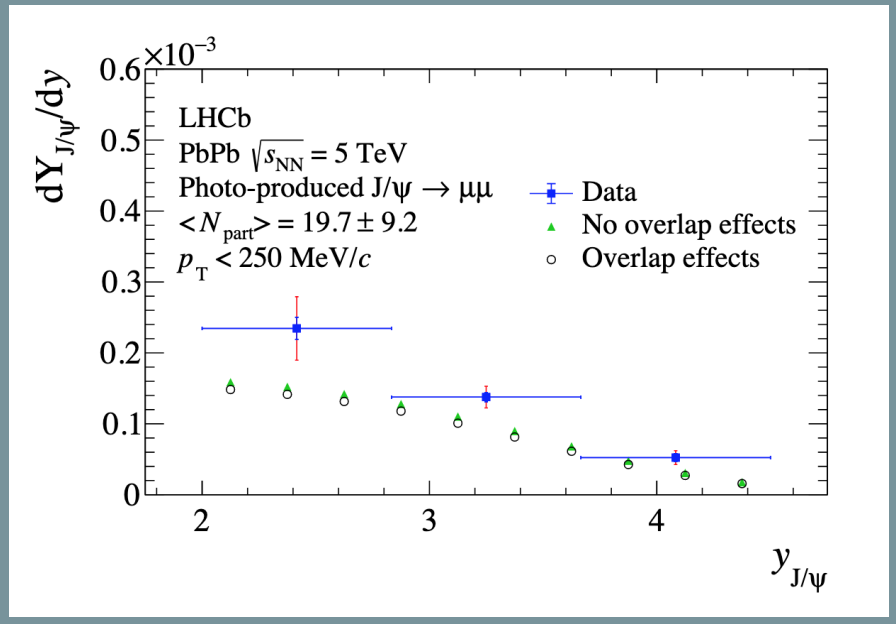


VM photoproduction in Pb–Pb collisions with nuclear overlap (LHCb)

- Observation confirmed in Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV by LHCb (restricted to peripheral events $<N_{part}> \sim 19.7$)
  - First p_T and y-differential J/ψ excess yield measurement
  - Qualitative (but not quantitative) description of the data by a model (including or not) the effect of the nuclear overlap (although limited in peripheral events)

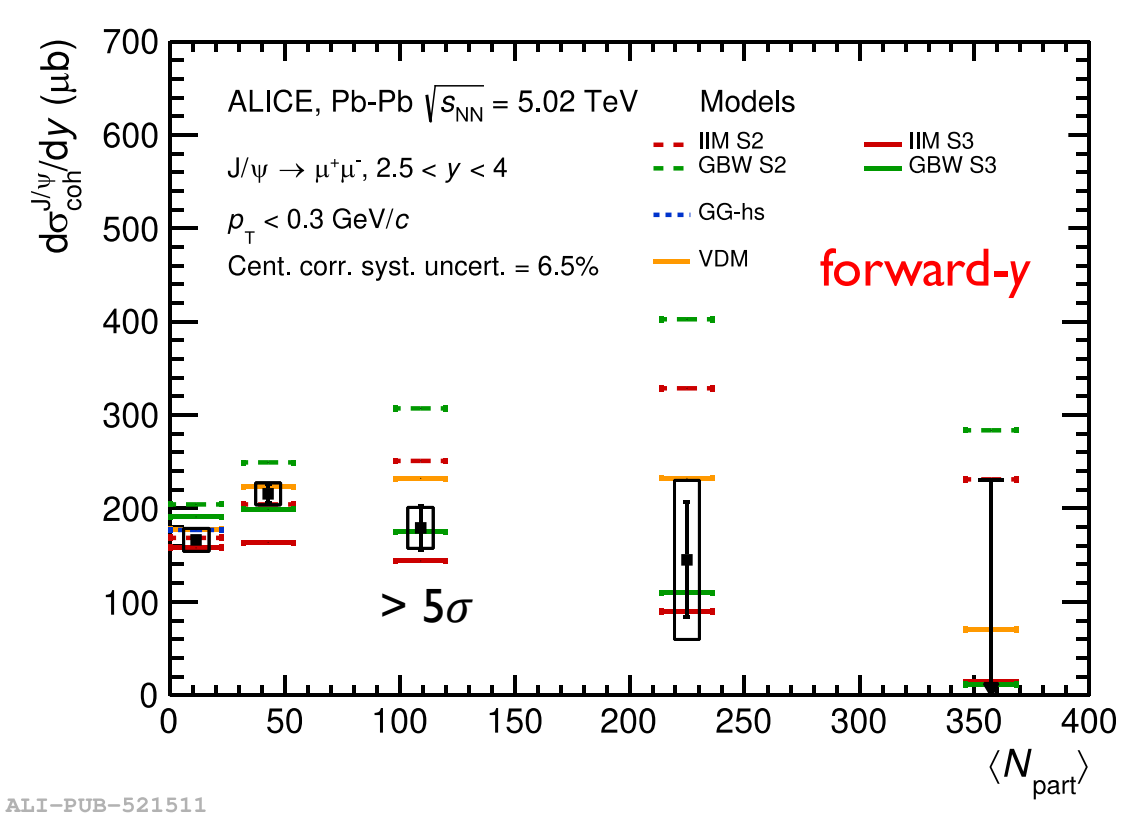
LHCb Collaboration, PRC 105 (2022) L032201
W. Zha, PRC 97, 044910 (2016), Phys. Rev. C 99, 061901





VM photoproduction in Pb–Pb collisions with nuclear overlap (ALICE) : centrality dependence (forward y)

Phys. Lett. B 846 (2023) 137467



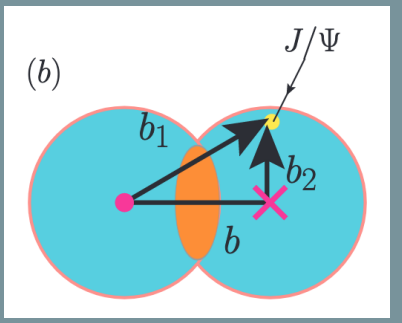
Centrality: (70-90%) (50-70%) (30-50%) (10-30%) (0-10%)
Caveat: No normalization to the centrality interval width

- No centrality dependence of the coherent J/ψ photoproduction cross section within uncertainties
- Models with either a modification of the γ flux (VDM) or a modification of the γ flux + $\sigma_{\gamma Pb}$ (IIM/GBW S3) describe semicentral data

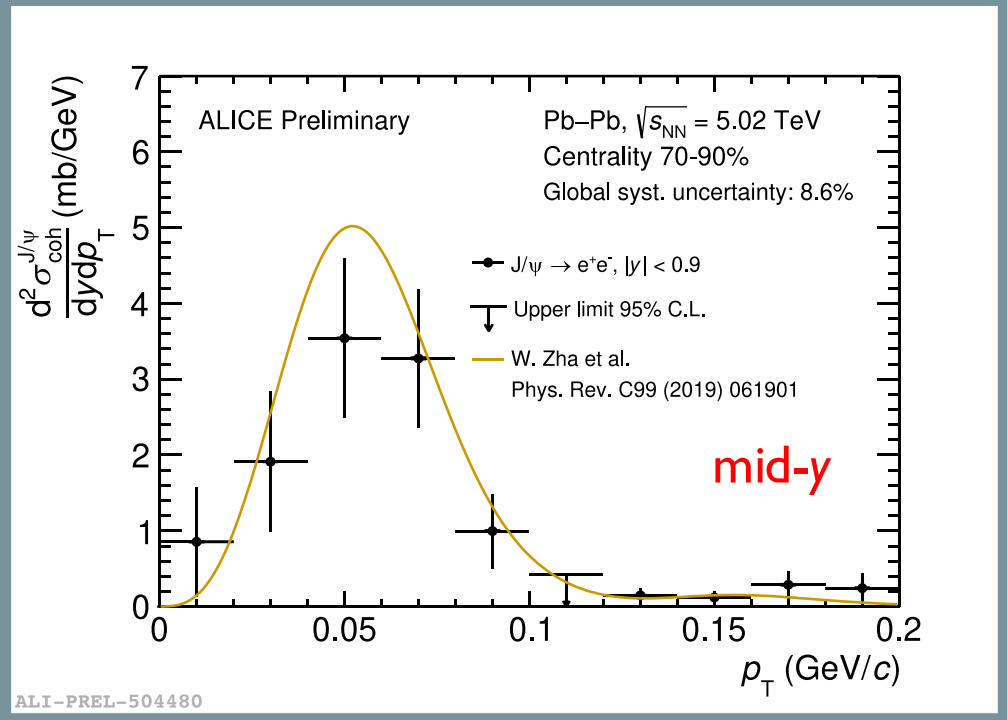
GG-hs: J. Cepila et al., Phys. Rev. C. 97 (2018) 024901
- γ flux with constraints on b range

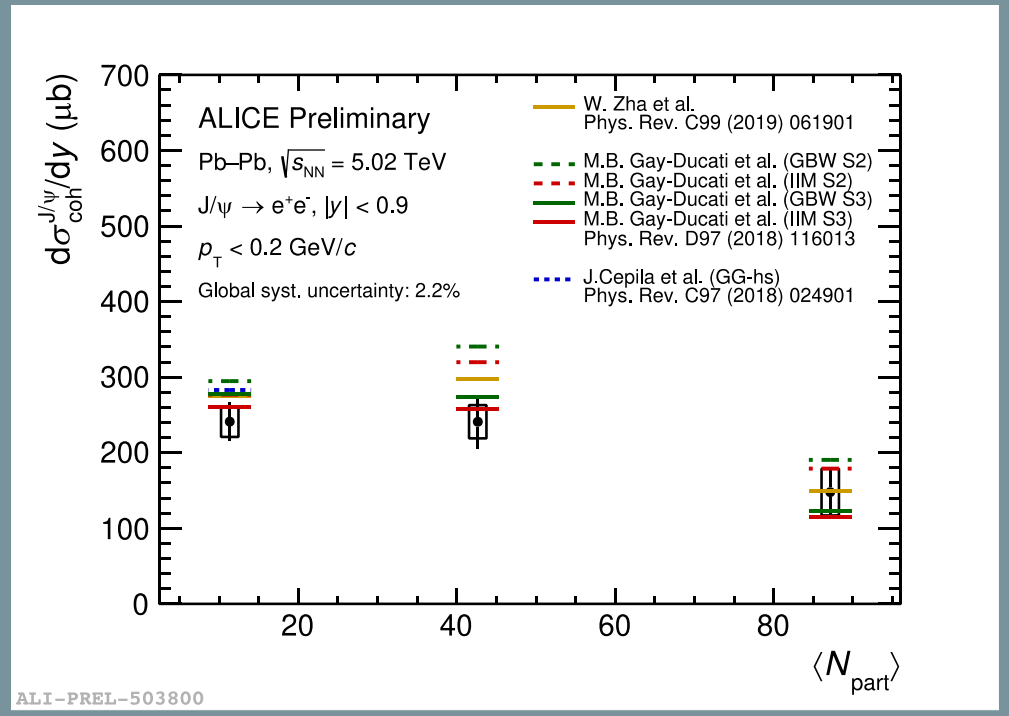
VDM: M. Klusek-Gawenda et al., Phys. Lett. B. 790 (2019) 339
- only γ reaching the spectator region considered [fixed area]
- $\sigma_{\gamma Pb}$ unmodified

IIM/GBW: M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013
- only γ reaching the spectator region considered [b-dependent area]
- S2: $\sigma_{\gamma Pb}$ unmodified
- S3: $\sigma_{\gamma Pb}$ modified (exclusion of overlap region)



VM photoproduction in Pb–Pb collisions with nuclear overlap (ALICE) : p_T and centrality dependence (mid y)





Model references (see slide 17)

Centrality: (70-90%) (50-70%) (40-50%)
Caveat: No normalization to the centrality interval width

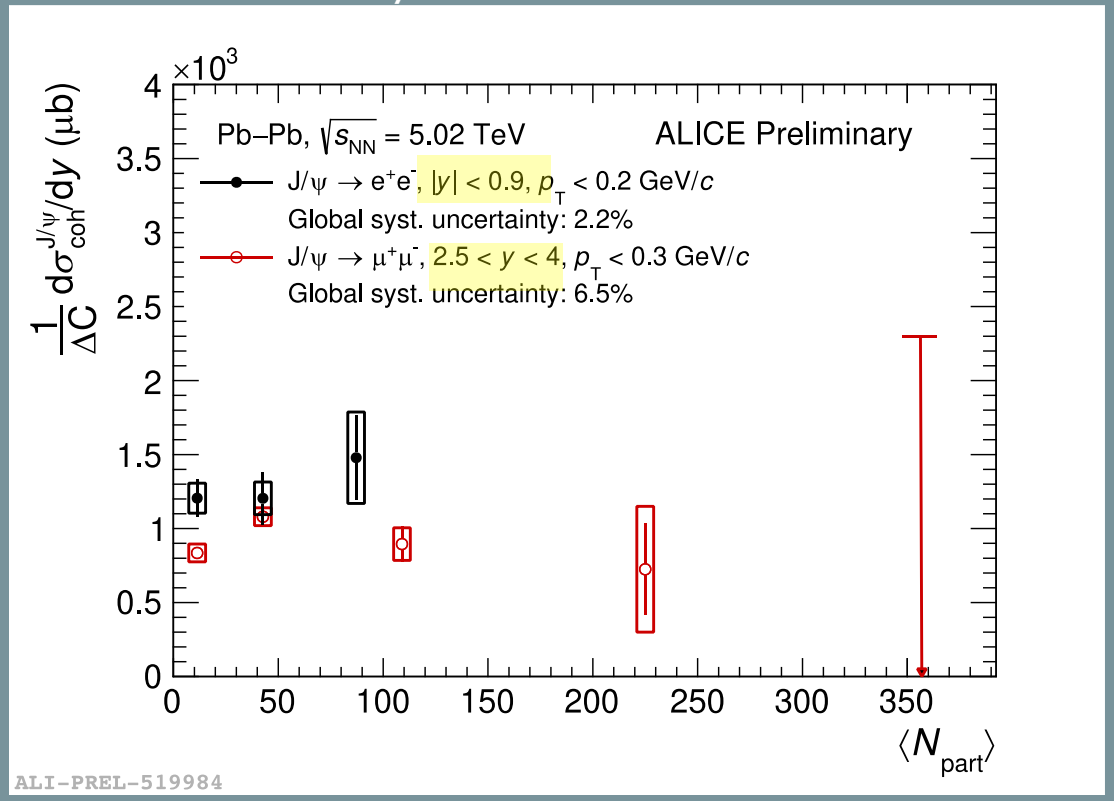
- p_T-differential J/ψ photoproduction cross section measured at mid-y in peripheral Pb–Pb
- p_T shape reproduced by model including modified γ flux and $\sigma_{\gamma Pb}$ to account for the overlap (although limited in 70-90%)

W. Zha et al., Phys. Rev. C99 (2019) 061901: Nucleus (γ emitter) – Spectator (pomeron emitter) scenario + shadowing + interferences

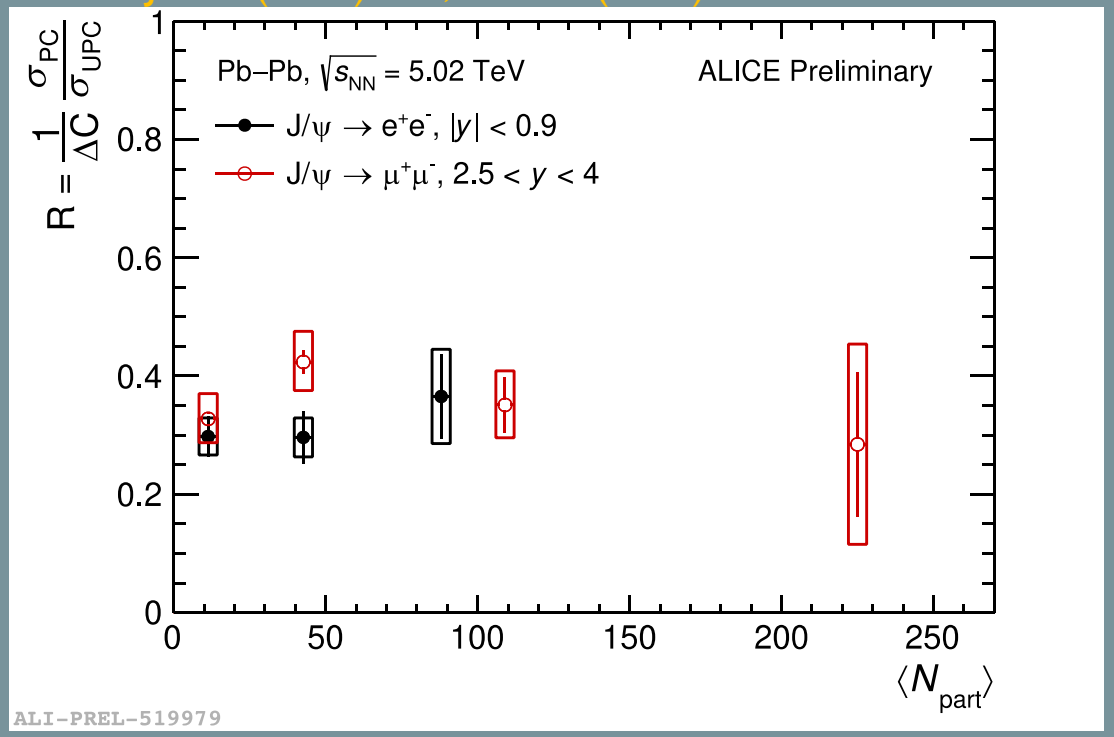
- Same models reproduce at the same time the order of magnitude of the cross section at mid and forward rapidity

VM photoproduction in Pb–Pb collisions with nuclear overlap (ALICE) : forward and mid y comparison

ΔC: width of centrality interval

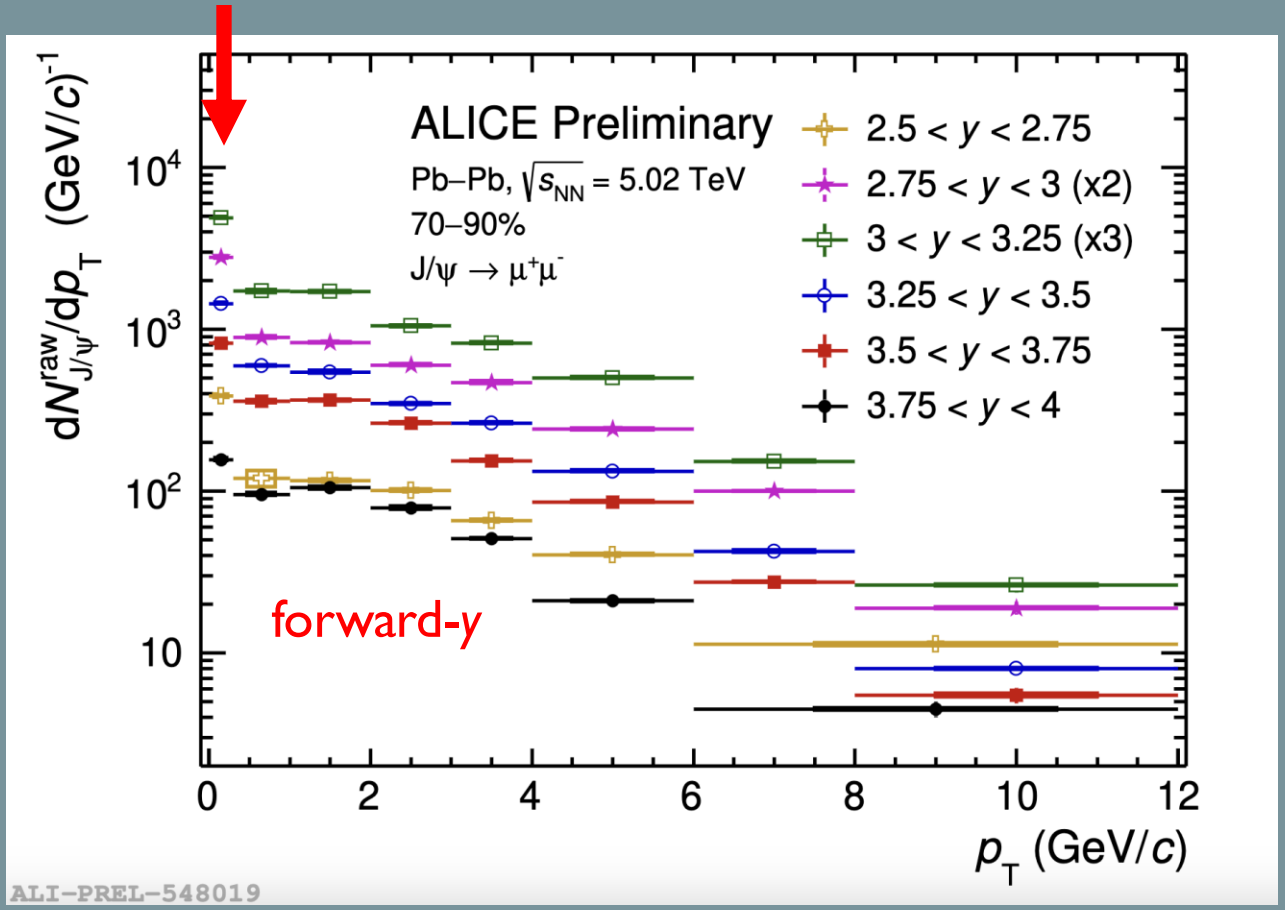


PC: Phys. Lett. B 846 (2023) 137467
UPC: EPJC 81 (2021) 712, PLB 98 (2019) 134926



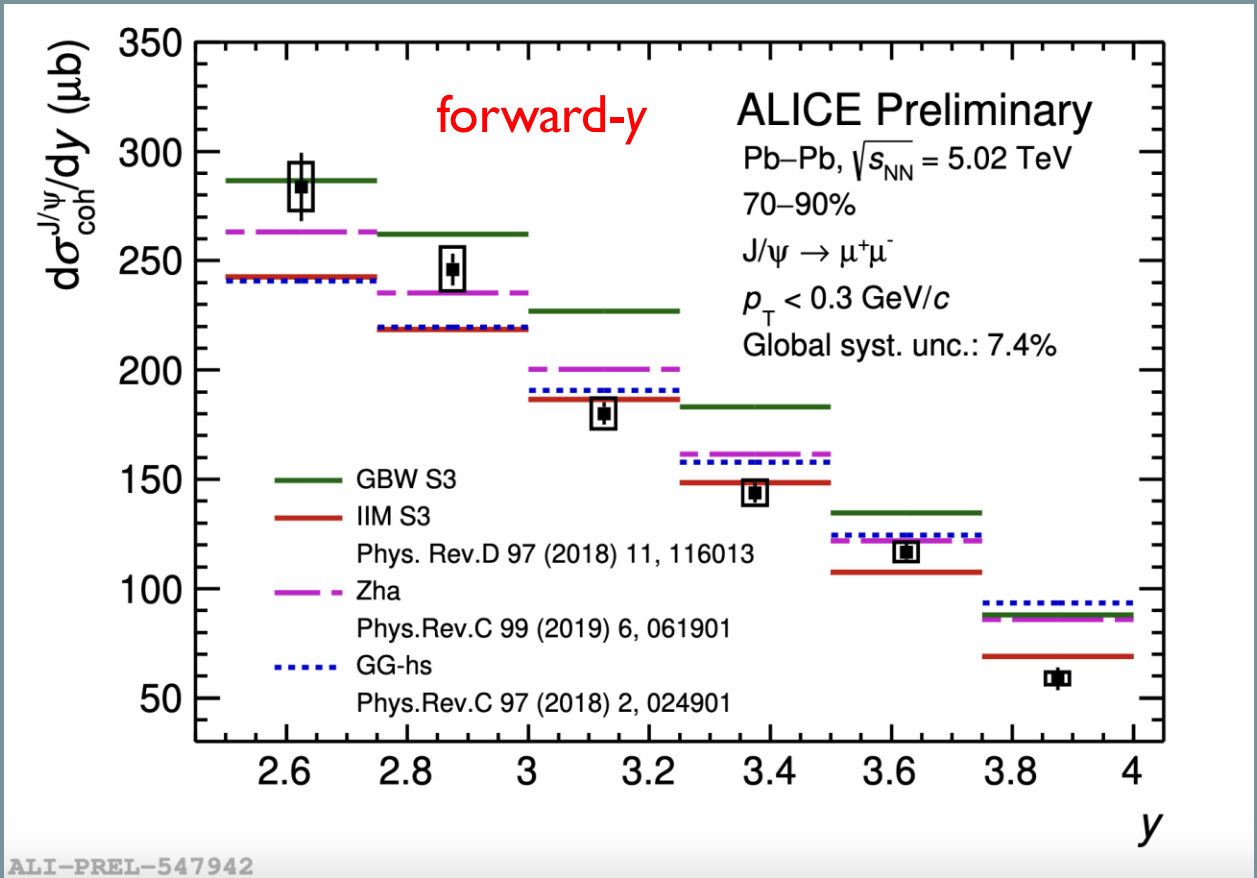
- Larger J/ψ photoproduction cross section at mid-y than at forward-y (as expected from models). No strong centrality dependence at both rapidities.
- J/ψ photoproduction ratio in Pb–Pb to UPC (in the same rapidity window) → similar ratio for mid-y and forward-y.
  - Ratio flat with centrality → no evidence for a decrease of σ_{PC} because of the nuclear overlap or medium effects

y-differential coherent J/ψ photoproduction in peripheral Pb–Pb collisions (ALICE)



- Multidifferential measurements to further contrain models (strong rapidity dependence expected in the forward region)
- Clear J/ψ low p_T excess in all rapidity intervals in peripheral Pb–Pb events

y-differential coherent J/ψ photoproduction in peripheral Pb–Pb collisions (ALICE)



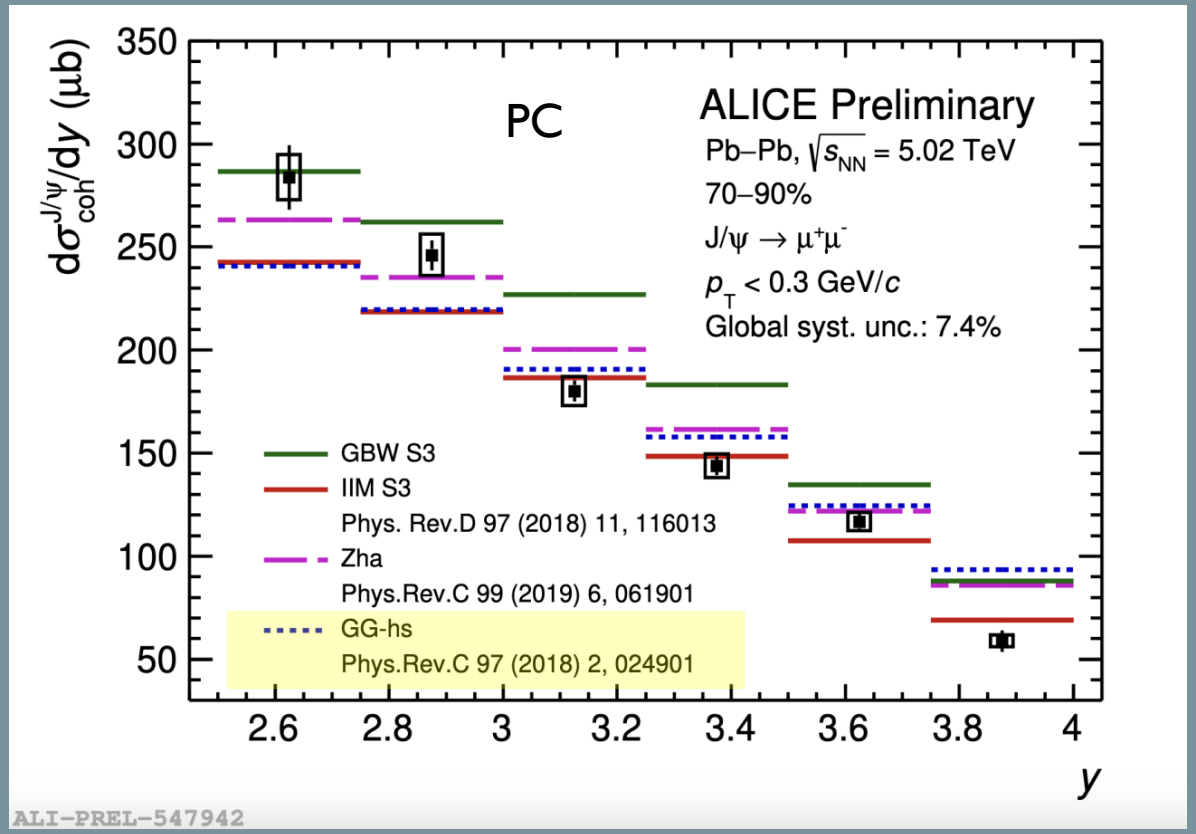
- Qualitative description of the magnitude of the cross section by the UPC-like models modified for the centrality range 70-90%
- Difficulties at reproducing the rapidity dependence for all models, but also the case in UPC !

GG-hs: J. Cepila et al., Phys. Rev. C. 97 (2018) 024901
- γ flux with constraints on b

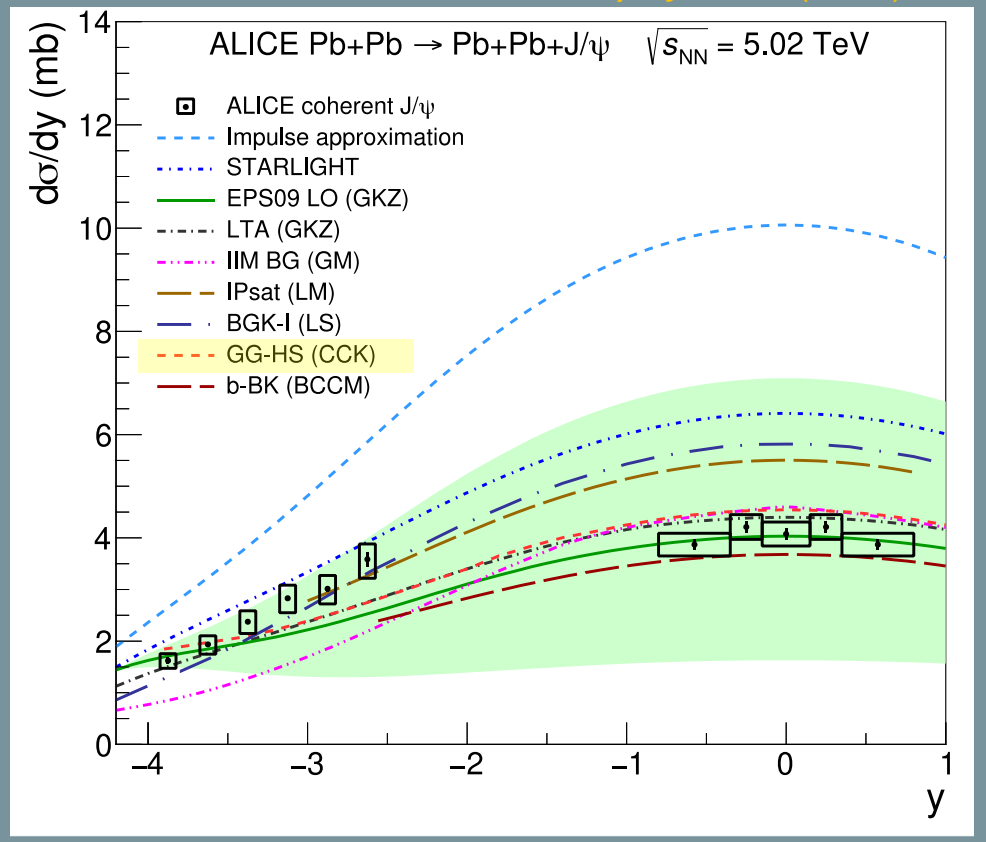
Zha: W. Zha et al., Phys. Rev. C 99 (2019) 6, 061901
- Double slit experiment ~ Nucleus (γ emitter) – Spectator (pomeron emitter) scenario + shadowing + interferences

IIM/GBW: M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013
- S3: only γ reaching the spectator region considered $\sigma_{\gamma Pb}$ modified

y-differential coherent J/ψ photoproduction in peripheral Pb–Pb collisions (ALICE)

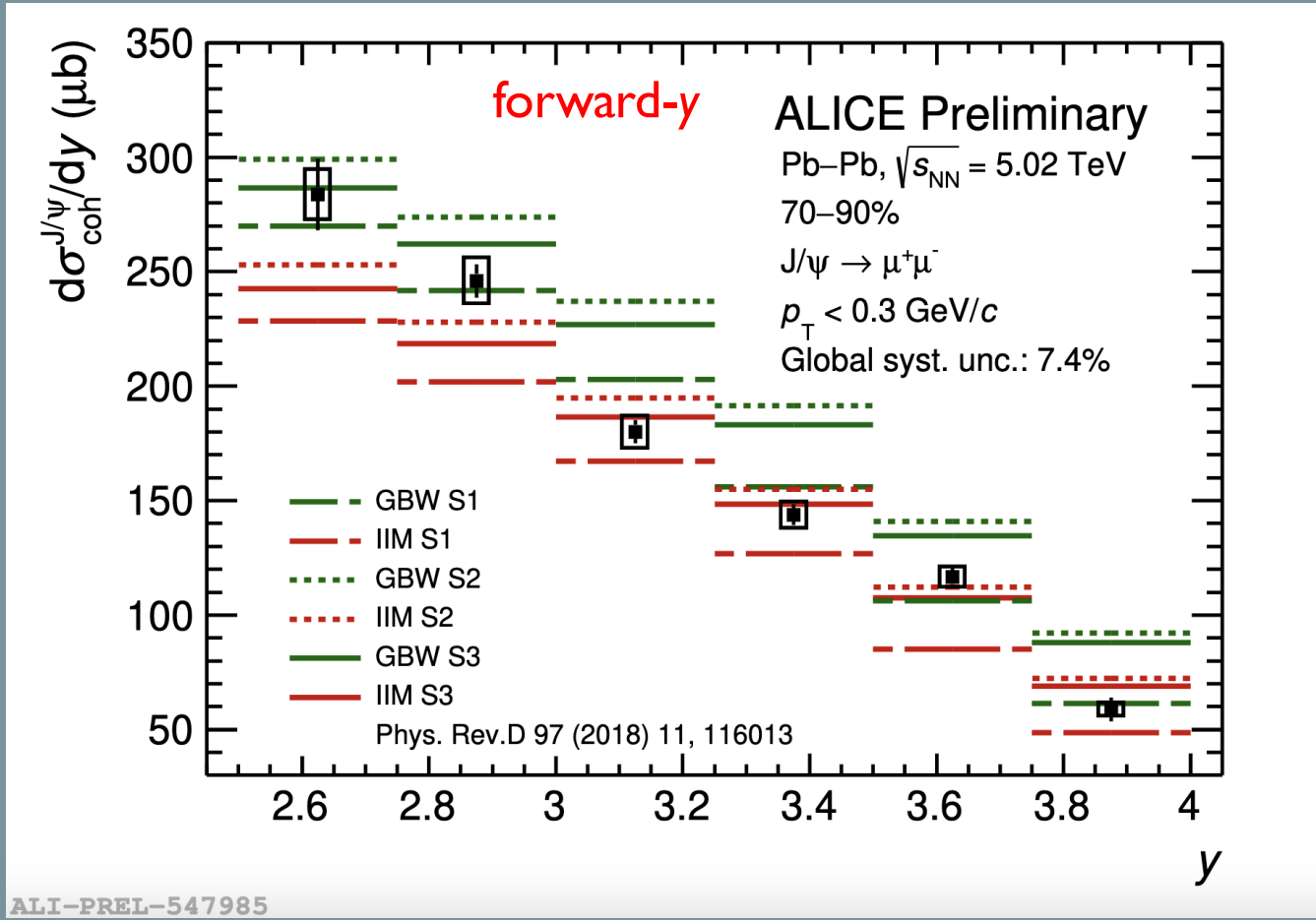


ALICE Collaboration, Eur. Phys. J. C 81 (2021) 712



- Difficulties for models to reproduce the y-dependence, similarly for UPC and PC
- Need better theoretical description of y-dependent cross sections from UPC data to interpret PC data and possible modifications related to the nuclear overlap

y-differential coherent J/ψ photoproduction in peripheral Pb–Pb collisions (ALICE)



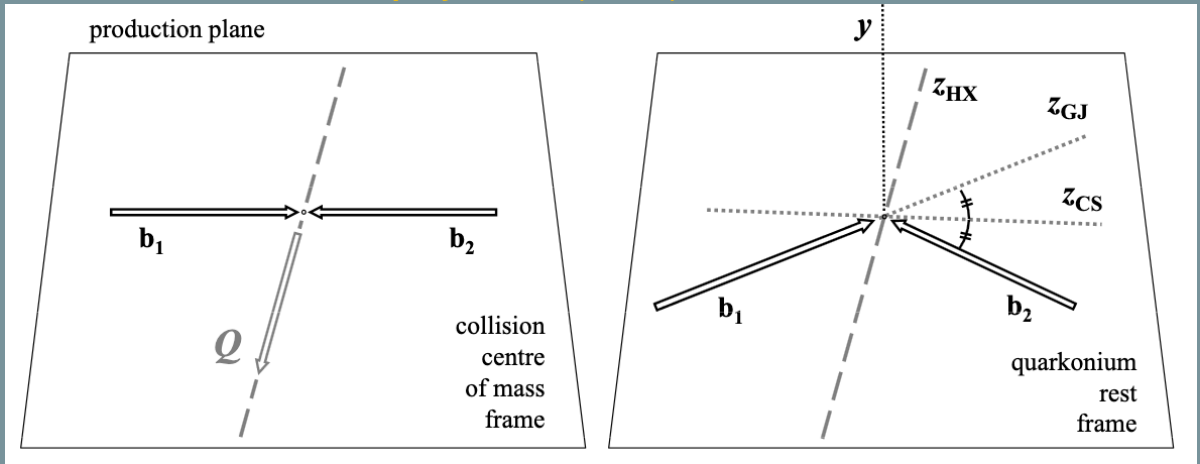
IIM/GBW: M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013
- S1: no significant modification w.r.t UPC (γ flux with constraints on b)
- S2: only γ reaching the spectator region considered, $\sigma_{\gamma Pb}$ unmodified
- S3: only γ reaching the spectator region considered, $\sigma_{\gamma Pb}$ modified (exclusion of overlap region)

- IIM vs GBW: different assumptions on the color dipole cross section used as input for $\sigma_{\gamma Pb}$ calculations
- Effect of the nuclear overlap (in 70-90%) on the J/ψ photoproduction cross section predicted by model as large as theoretical assumptions done on color dipole cross section

→ Multidifferential studies in more central collisions (ie. bigger overlap) important to further constrain models

Inclusive J/ψ polarization at very low p_T in peripheral Pb–Pb collisions

P. Faccioli et al., Eur. Phys. J. C 69 (2010) 657-673



- Polarization: particle spin alignment w.r.t a chosen direction
- Related to dilepton decay angular distribution:

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

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

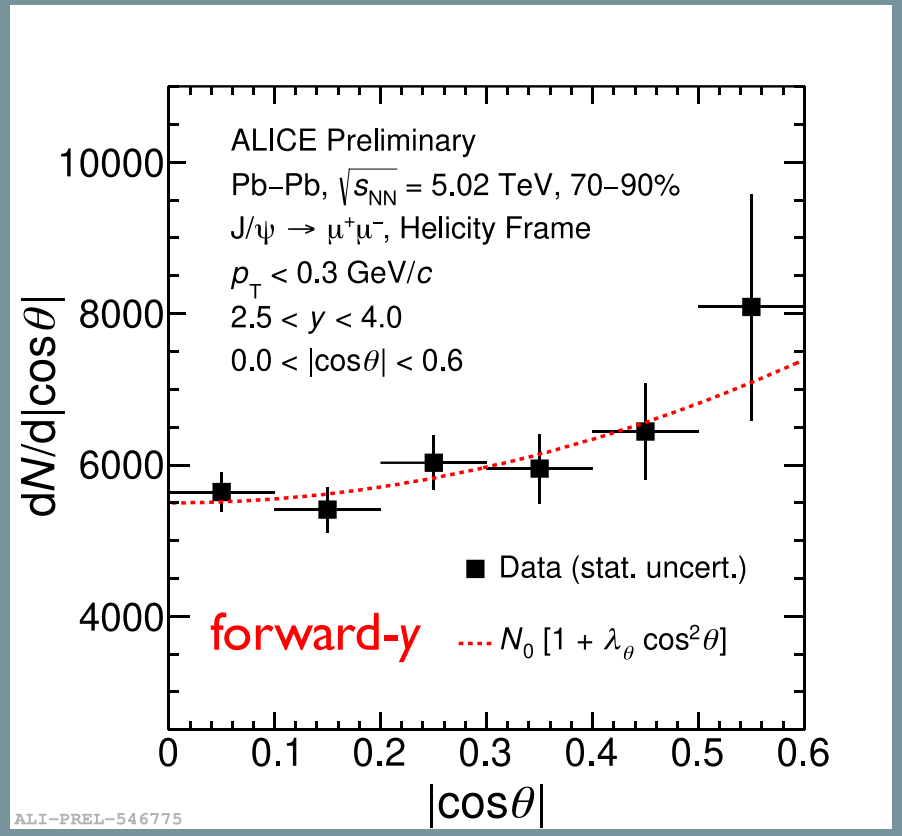
- Helicity frame (HX): direction of the VM in the collision c.o.m frame

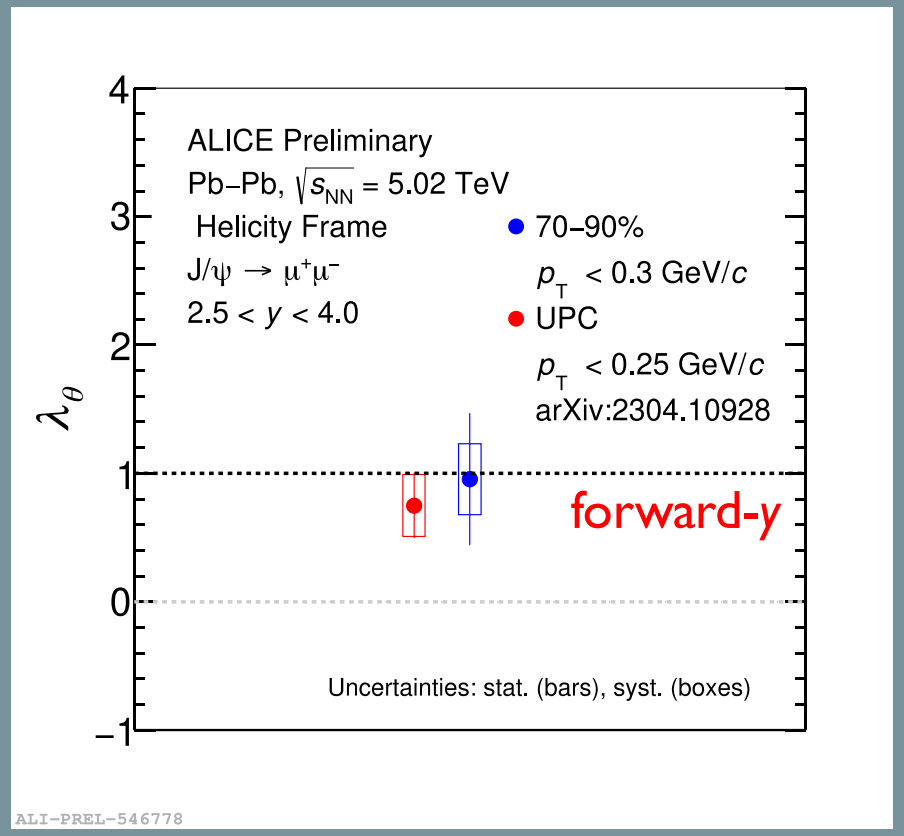
- Test VM production mechanism via polarization measurement:
  - Photoproduction process: VM expected to keep the (transverse) polarization of incoming photon due to s-channel helicity conservation (SCHC)

    F. J. Gilman et al., Phys Lett B 31 (1970) 387-390
  - ALICE UPC polarization results for coherently photoproduced J/ψ consistent with SCHC arXiv:2304.10928
  - Inclusive J/ψ at low p_T in the 70-90% centrality range used as proxy to study coherently photoproduced J/ψ
    - Yield dominated by photoproduced J/ψ, hadronic J/ψ unpolarized (in HX) in Pb–Pb

    Phys. Lett. B 815 (2021) 136146

Inclusive J/ψ polarization at very low p_T in peripheral Pb–Pb collisions





- Angular distribution of J/ψ decay products hints at transverse polarization (~ 2σ)
- 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 SCHC

conclusion and outlook

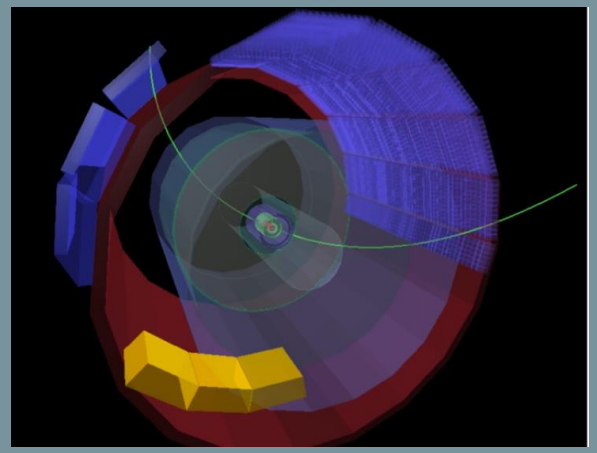
- Several measurements of $\gamma\gamma$ to dilepton pair production at RHIC and LHC from peripheral (to central) AA collisions
  - Several observables reproduce by models including b-dependence of photon k_T distribution
  - The presence of medium induced effects (eg. strong e.m fields) seems ruled out by latest ATLAS measurements

- Wide variety of measurements performed at RHIC and LHC to probe coherent J/ψ photoproduction in AA collisions with nuclear overlap from peripheral to central events (multi-differential cross sections, polarization…):
  - All measurements give a consistent picture pointing to coherent photoproduction mechanism
  - UPC-like models modified to account for the nuclear overlap are able to describe the magnitude of the cross sections
  - Stronger constraints on models inputs needed (using eg. UPC measurements)
  - Multi-differential measurements towards most central collisions are needed to understand the impact of the nuclear overlap on the coherence condition

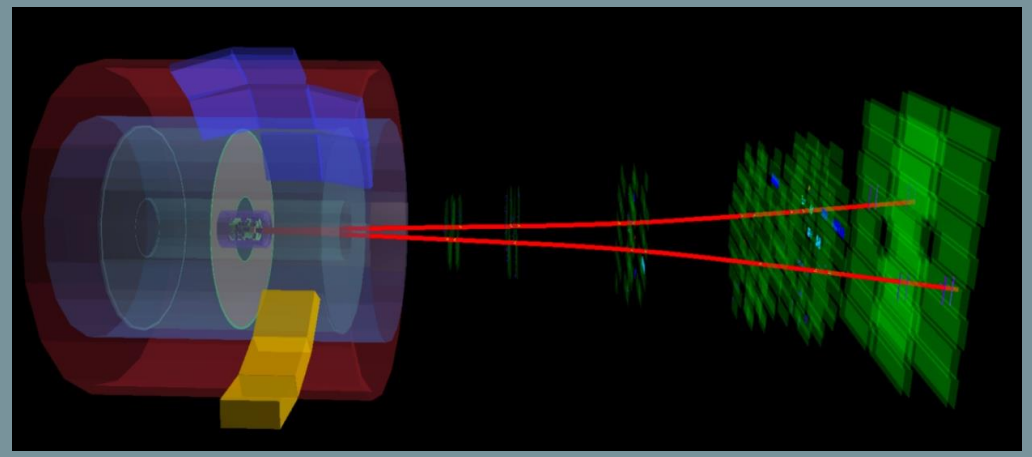
- Perspectives for LHC Run 3 + 4 (L_{int} ~ 10 nb^{-1} in Pb–Pb) for quarkonium photoproduction:
  - Significant signal at both mid- and forward-y in most central events
  - Multi-differential measurements towards most central collisions (y-dependence, p_T-dependence (mid y), polarization)
  - Look at other quarkonium states for the first time → ψ(2S)/J/ψ to probe possible QGP effects

BACKUP

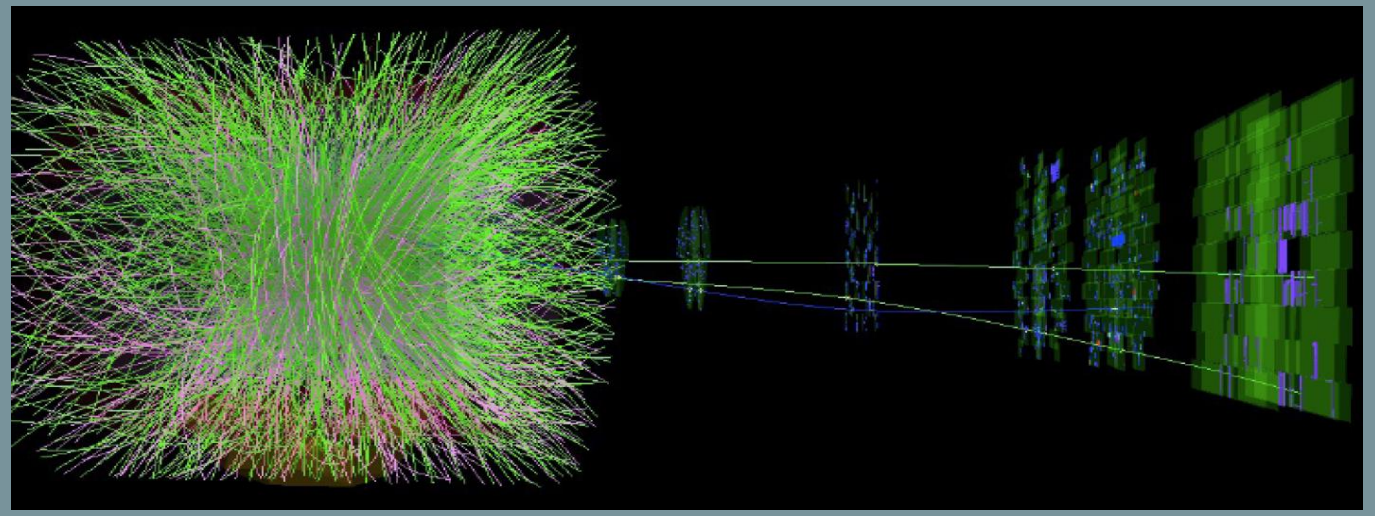
Event display: UPC events versus hadronic events (ALICE)



UPC event in the central barrel



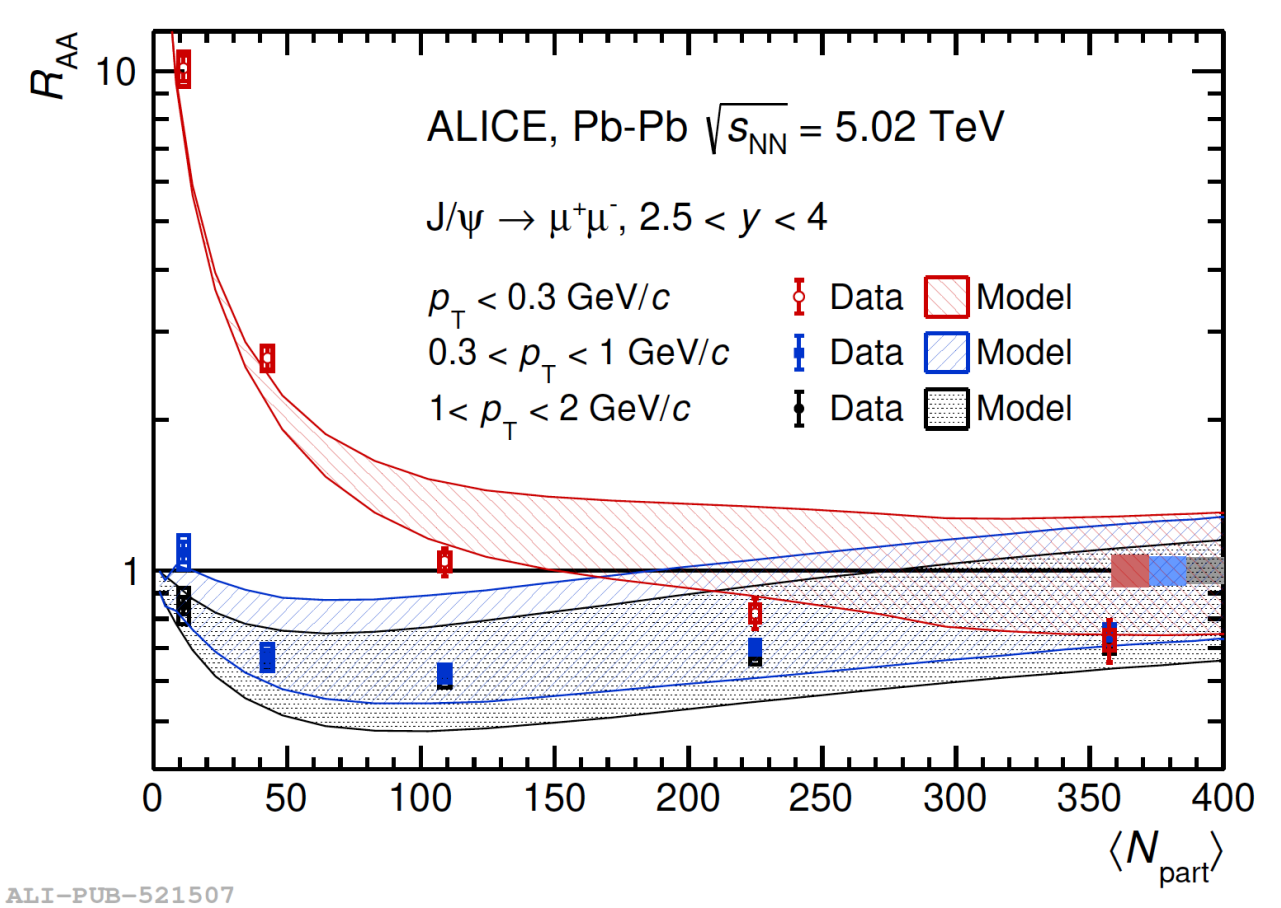
UPC event in the muon spectrometer



Pb–Pb hadronic event

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

Phys. Lett. B 846 (2023) 137467



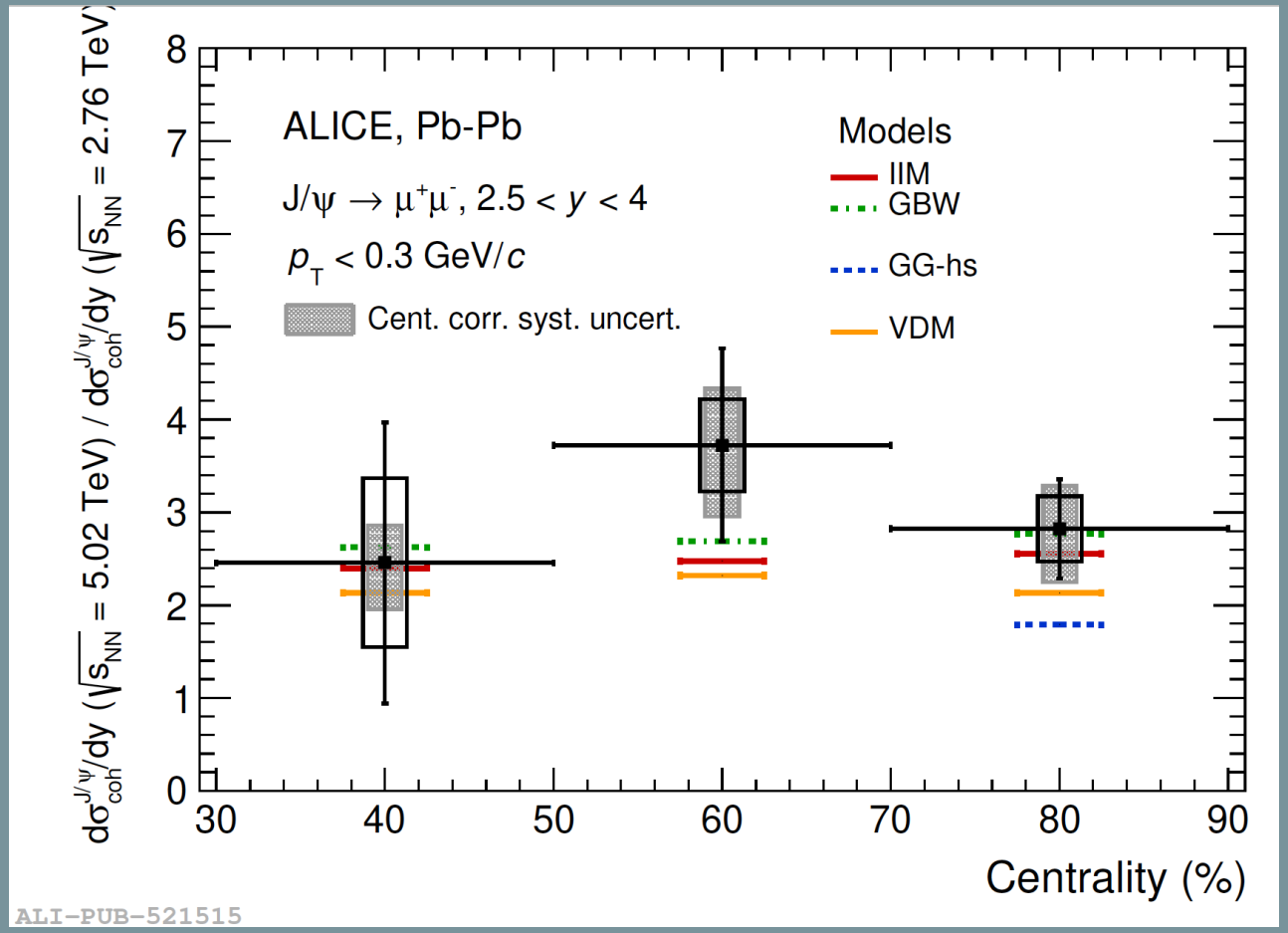
W. Shi et al., Phys. Lett. B 777 (2018) 399-405

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

- J/ψ R_{AA} for p_T < 0.3 GeV/c significantly larger than in 1 < p_T < 2 GeV/c where hadroproduction dominates (except in most central events)
- Hint for incoherent photoproduction in 70-90% for 0.3 < p_T < 1 GeV/c (~2σ deviation w.r.t 1 < p_T < 2 GeV/c)
- Data well described by a model including hot medium effects on J/ψ production (primordial J/ψ survival, regeneration)+ J/ψ photoproduction (p_T < 0.3 GeV/c). QGP effects on photoproduced J/ψ are also considered

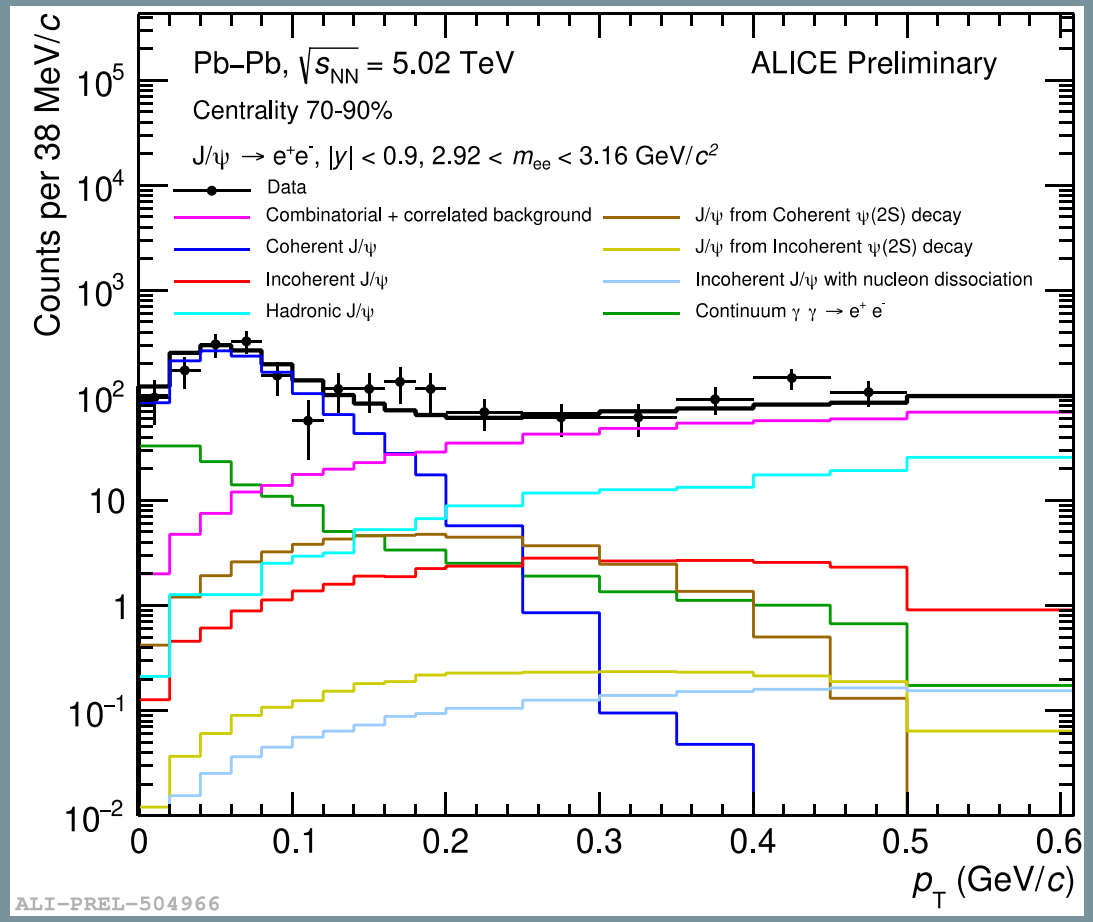
J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

Phys. Lett. B 846 (2023) 137467



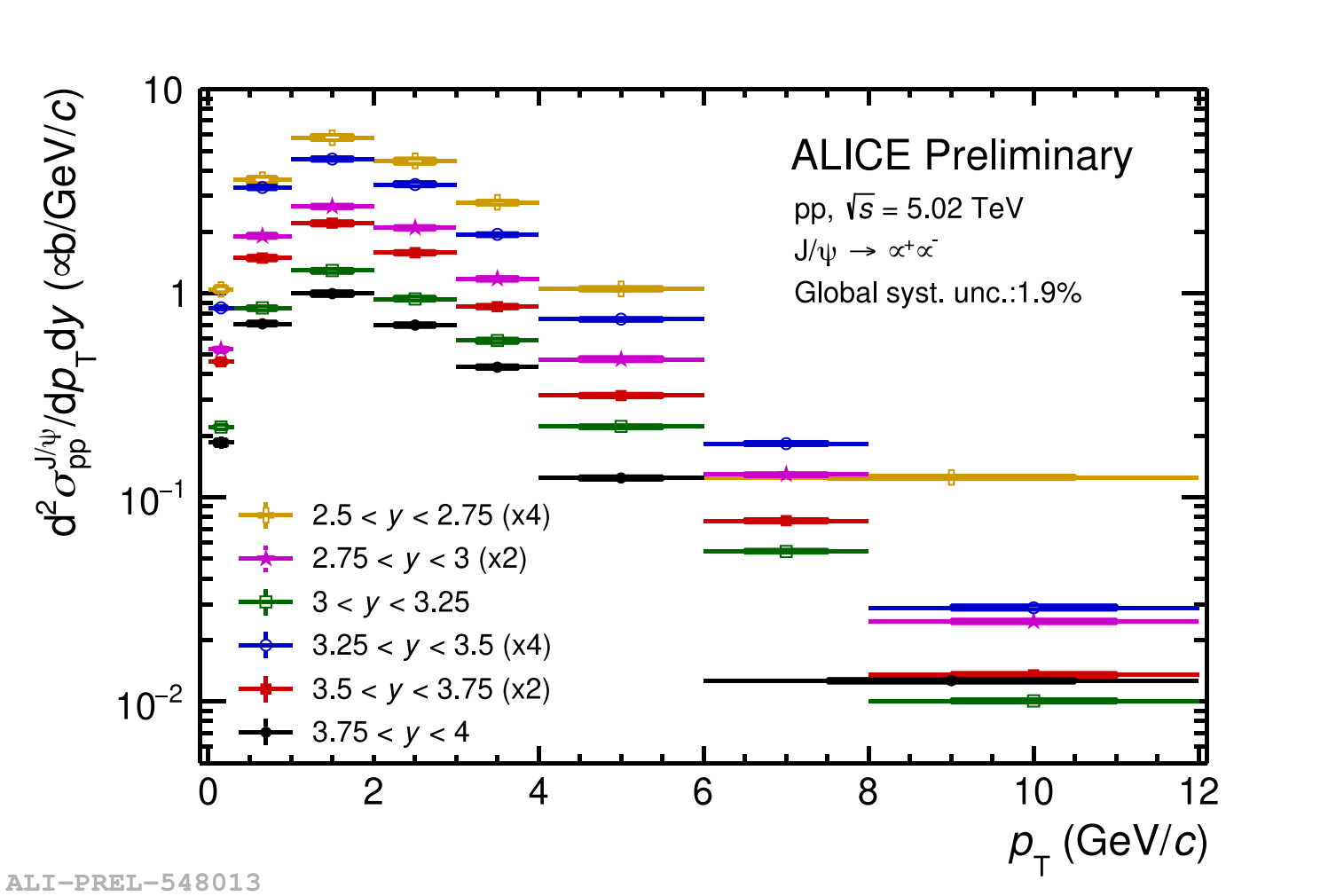
- J/ψ photoproduction cross section increases with the c.m.s energy and doesn't depend on the centrality
- VDM and IIM/GBW models reproduce fairly well the cross section ratio in the three centrality intervals

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-y)



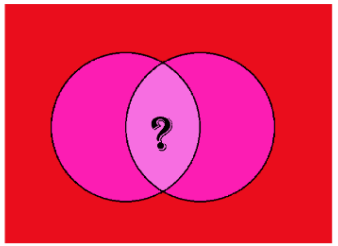
- Coherent J/ψ yield measured using an unbinned (m_{ee}, p_T) likelihood fit
- Photoproduced J/ψ components obtained from STARlight

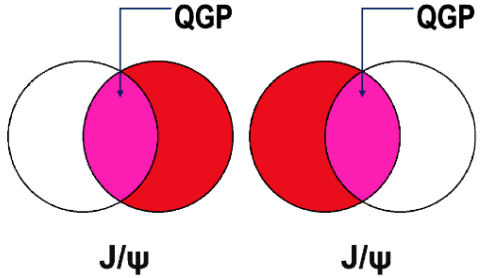
y-differential J/ψ production cross section in pp collisions (forward-y)



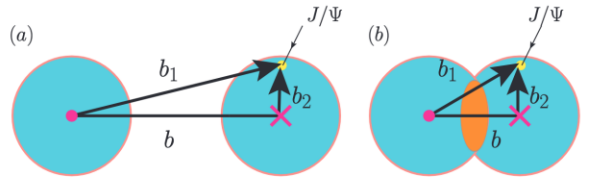
VDM model

M. Klusek-Gawenda, PRC 93, 044912 (2016), from presentation of M. Klusek-Gawenda at HF2022 workshop





Impact parameter space



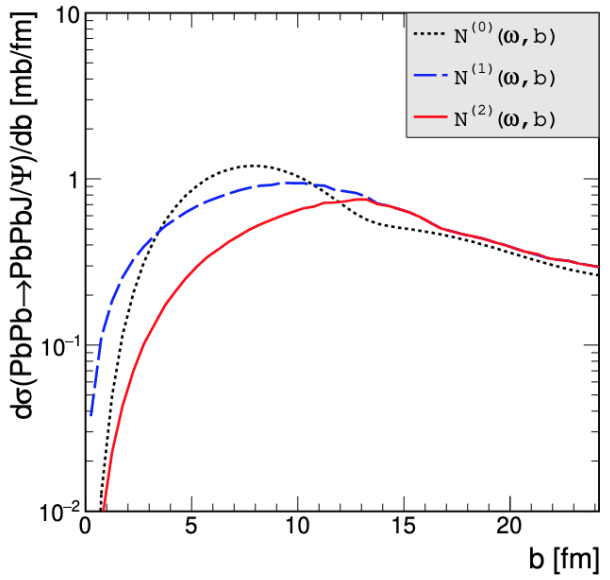
J/ψ photoproduction for (a) ultraperipheral and (b) central heavy ion collisions.

The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))}{\pi R_A^2} \mathrm{d}^2 b_1$$

$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))(b_1 - R_A)}{\pi R_A^2} \mathrm{d}^2 b_1$$

$$\sigma(N^{(0)}, UPC) = \sigma(N^{(1)}, UPC) = \sigma(N^{(2)}, UPC)$$



IIM/GBW model

M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013

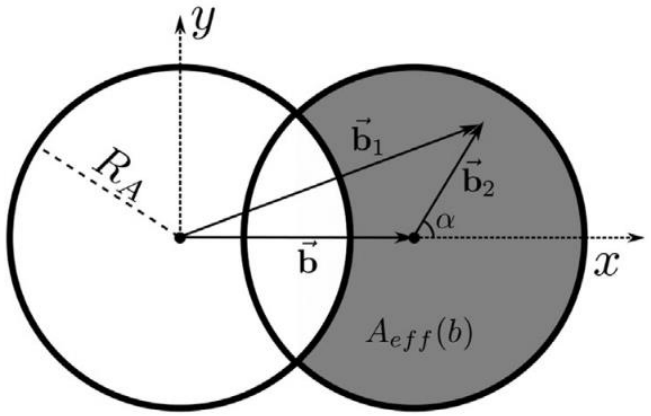


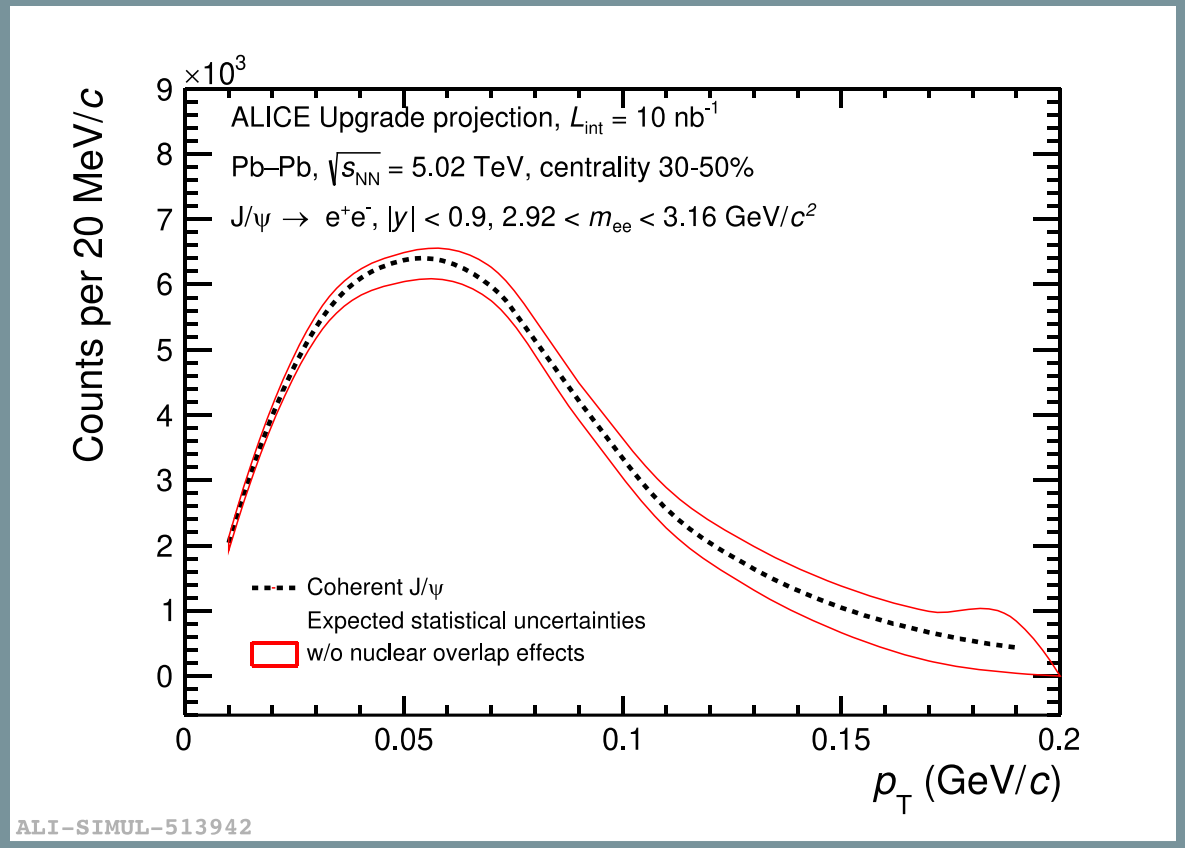
FIG. 2. Schematic drawing used in the construction of the effective photon flux.

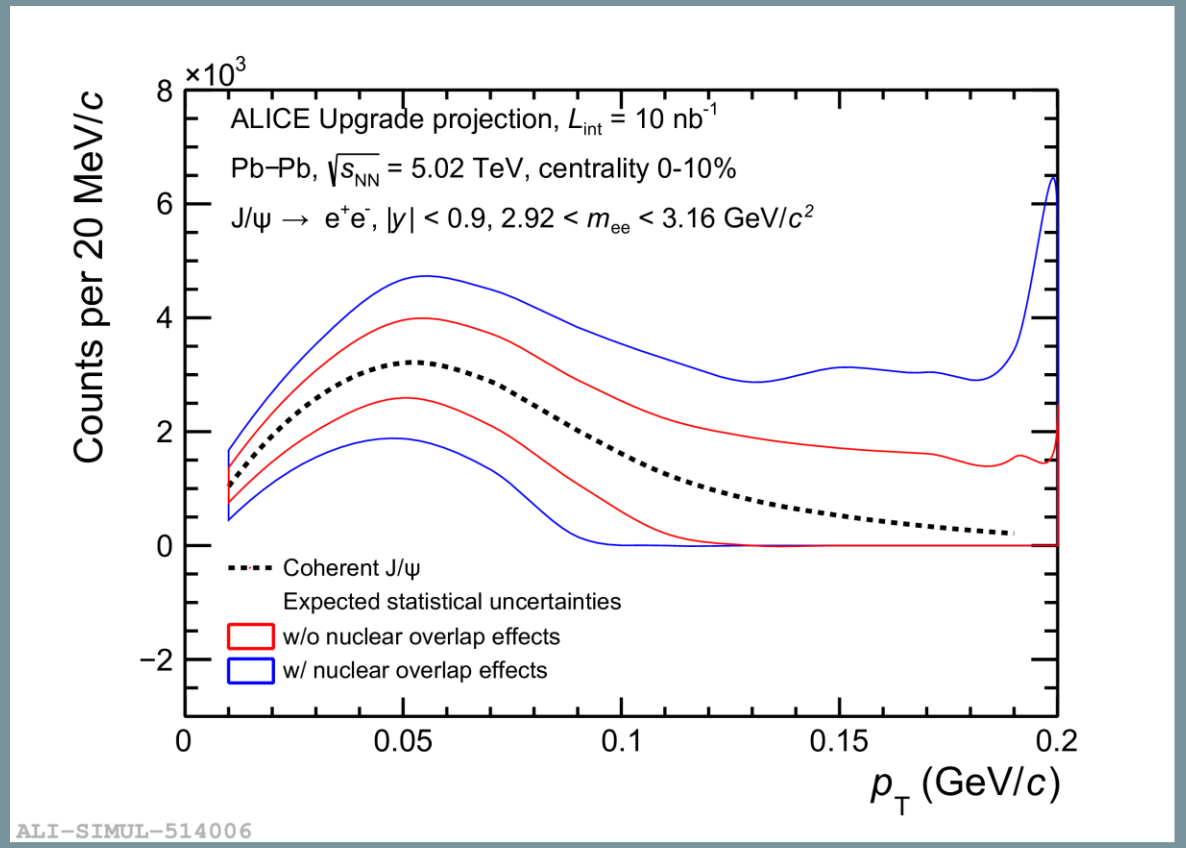
$$N^{\text{eff}}(\omega,b)=\frac{1}{A_{\text{eff}}(b)}\int d^2b_1 N(\omega,b_1)\theta(R_A-b_2)\theta(b_1-R_A), \tag{12}$$

where

$$A_{\text{eff}}(b)=R_A^2\left[\pi-2\cos^{-1}\left(\frac{b}{2R_A}\right)\right]+\frac{b}{2}\sqrt{4R_A^2-b^2}.$$

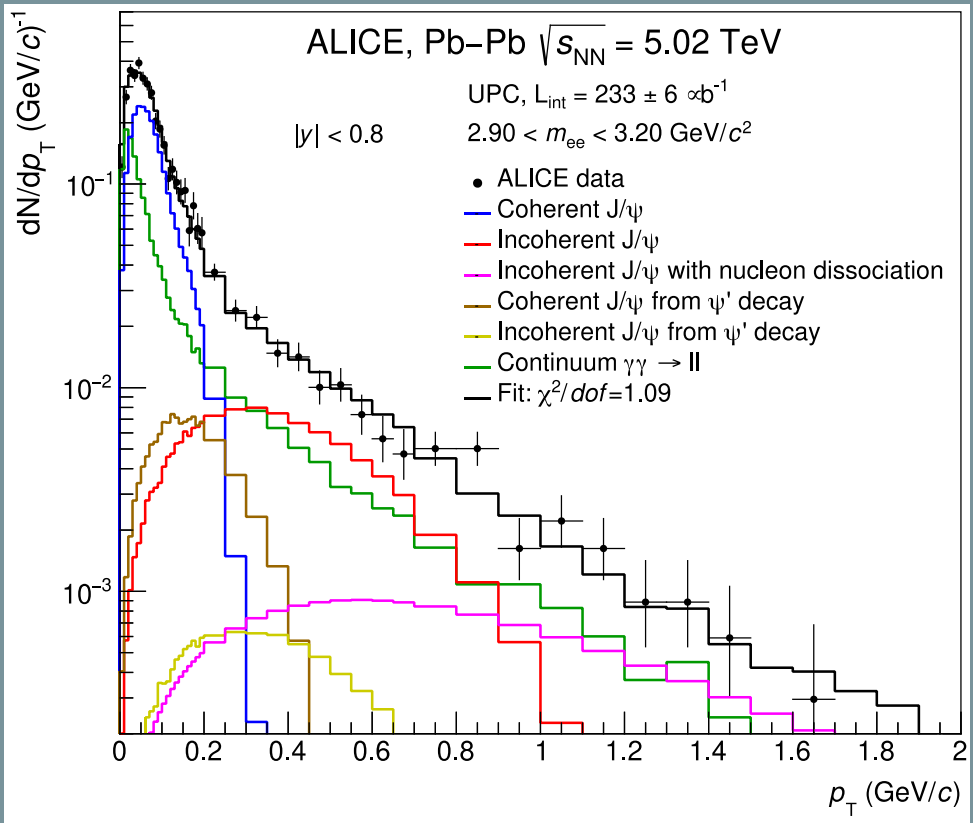
Projections for J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-y) : Run 3+4

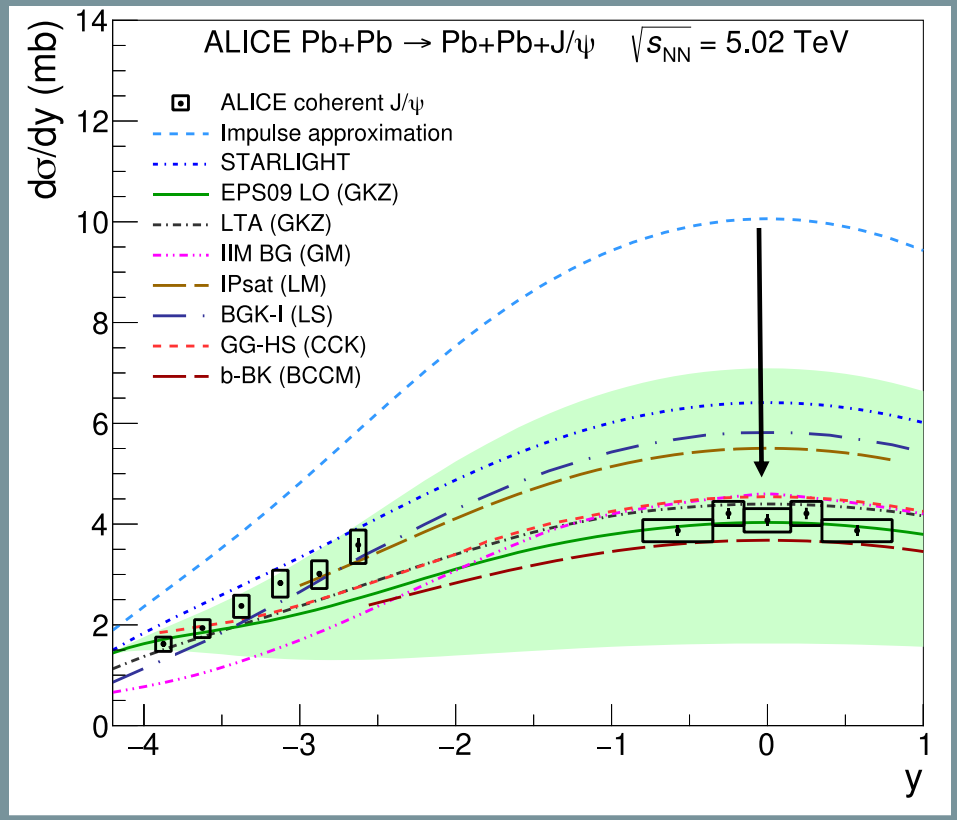




Results from photon induced processes in UPC

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

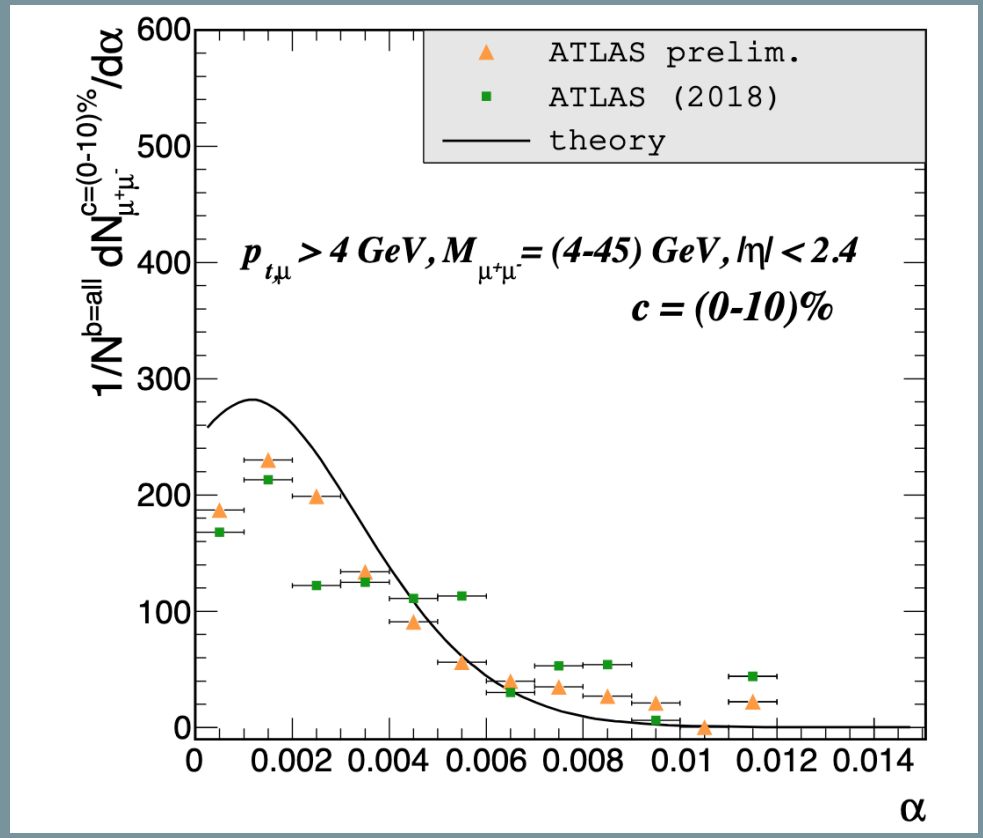




- Nuclear gluon shadowing of S_{Pb} = 0.64 ± 0.04 for Bjorken-x ~ 10^{-3}
- Provides important constraints to initial state of HIC

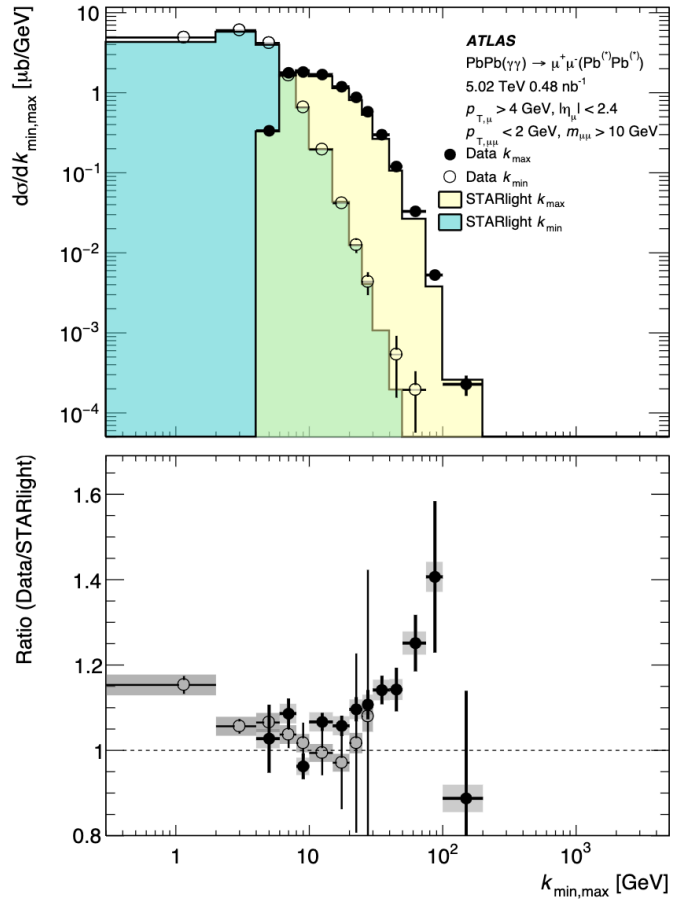
Dilepton production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

M. Klusek-Gawenda, J. Phys. Lett. B 814 (2021) 136114



UPC dileptons: initial photon energy

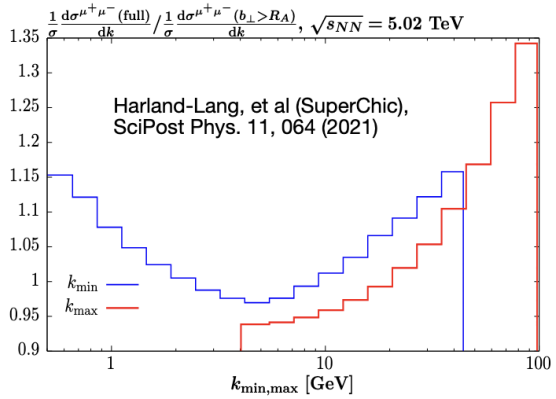
UPC dileptons: initial photon energy



Can combine $m_{\mu\mu}$ and $y_{\mu\mu}$ to estimate photon energies

$$k_{1,2} = (m_{\mu\mu}/2)\exp(\pm y_{\mu\mu})$$

Overall good agreement but clear enhancements at low and high k: consistent with relaxing impact parameter cuts in STARlight (Harland-Lang, et al)



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