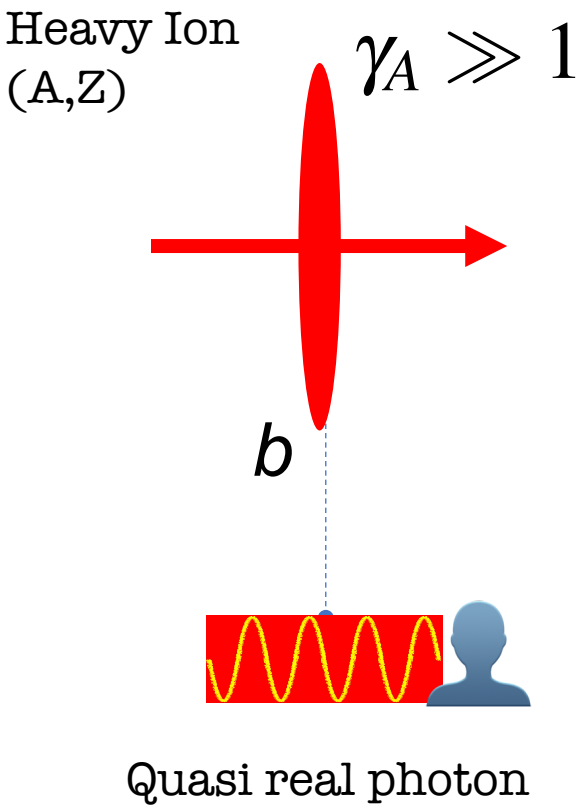
New experimental ideas at the LHC regarding coherent photo-production in overlap with hadronic interaction and the link with potential QGP studies : “Imaging of Heavy Ion Collisions”

Gines MARTINEZ, Researcher CNRS,
Subatech (IMT Atlantique Nantes Université CNRS/IN2P3)
GDR QCD Workshop (https://indico.in2p3.fr/event/30433/)
IJCLab, Orsay, October 11th-12th 2023

- Introduction
- Photo-production of J/psi
- Photo-production in nuclear collisions
- Imaging the heavy ion collision
- Conclusions & Perspectives

Heavy ions at ultra relativistic energies: a (high intensity) photon source



Nucleus is charged (Ze)

At v close to c (Lorentz factor γ_A>>1), at a given impact parameter b the charged particle behaves as a high density photon cloud. It's the Weizsäcker-Williams photon distribution that could be seen as the photon distribution function of the nucleus

The quasi-real photon of one of the nucleus/nucleon/charged particle can interact :

- With other photon of the other nucleus (photon-photon interactions)
- With the other nucleus (photonuclear interactions)

The Weizsäcker-Williams photon distribution requires that the induced momentum in the nucleus reference system is not relativistic : $Q < M_A c$

J.D. Jackson Classical Electrodynamics, section 15.4, 2nd edition Wiley

Weizsäcker-Williams photon distribution (EPA)

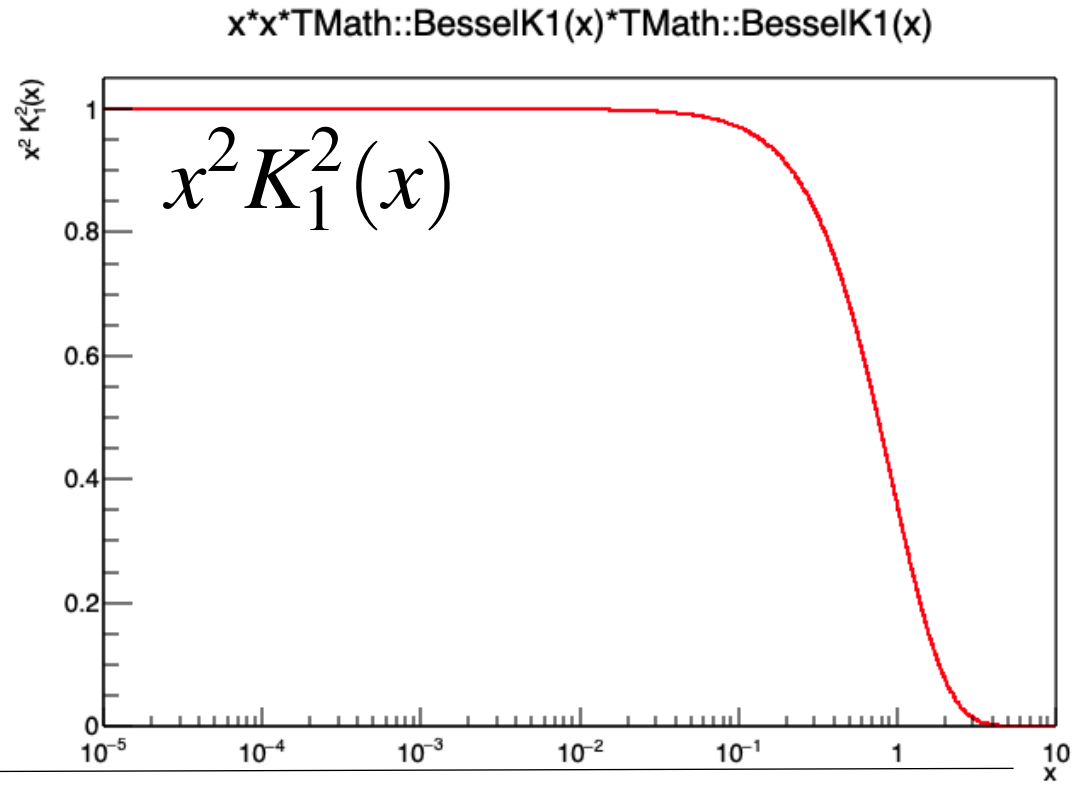
Photon flux

Modified Bessel Function of order unity

$$N(E_\gamma, b) = \frac{Z^2 \alpha_{QED}}{\pi^2 b^2} x^2 K_1^2(x)$$

$$x = \frac{E_\gamma b}{\gamma_A}$$

Photon flux (Z=82, b=14 fm) :
0.025 photons/fm^2
2.5x10^{28} photons/m^2



$$x^2 K_1^2(x) \approx 1 \text{ for } x \lesssim 1$$

$$E_\gamma < \frac{\gamma_A}{R} \approx 1.5(40) \text{ GeV at RHIC(LHC)}$$

J.D. Jackson Classical Electrodynamics, section 15.4, 2nd edition Wiley

Exclusive J/psi photo-production

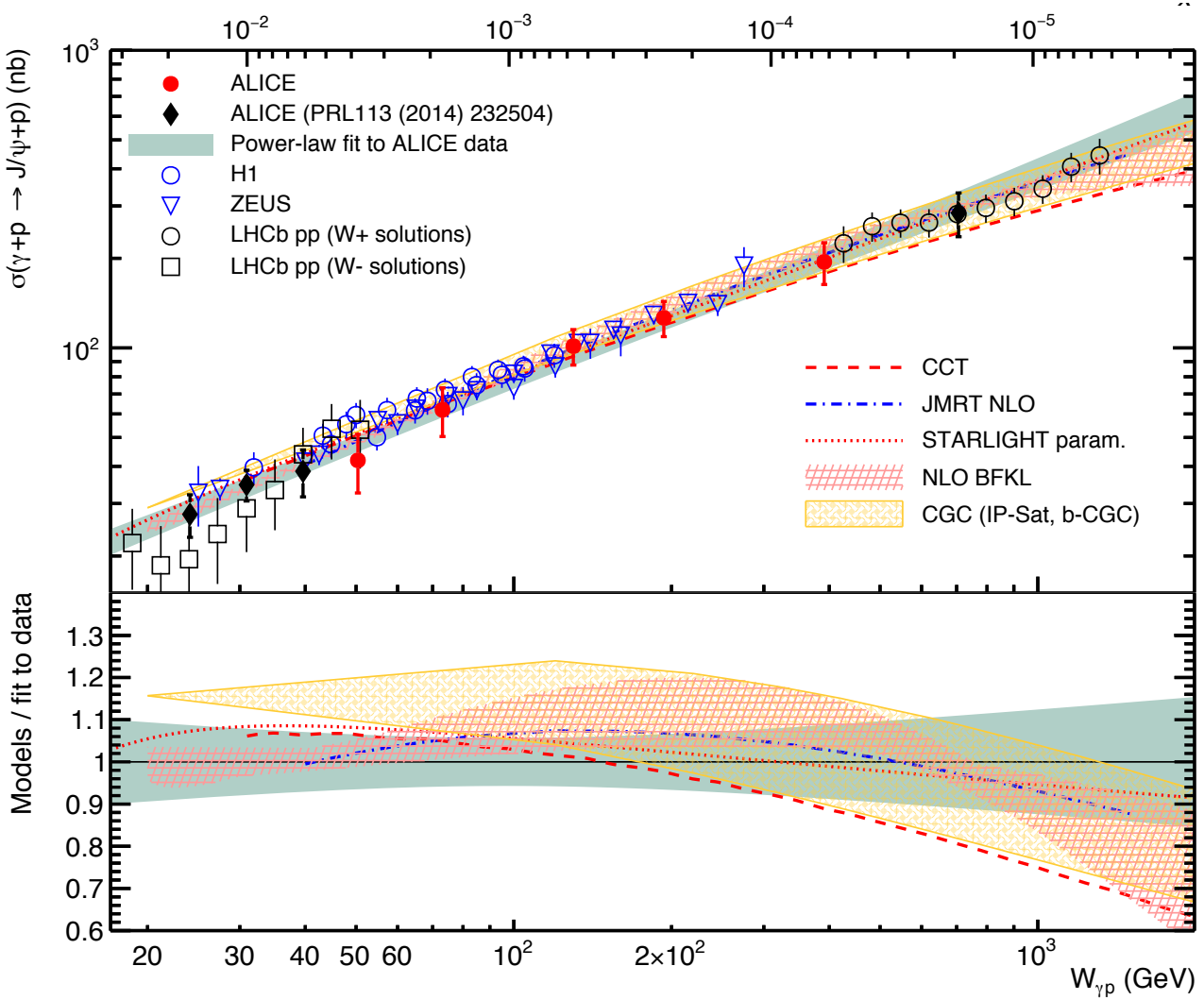
$$\sigma(\gamma + p \to J/\psi + p) = N\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}$$

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

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

$$\delta = 0.70 \pm 0.05$$

The photon has the same quantum numbers as the J/psi : $J^{PC} = 1^{--}$
Non-colour exchange, just photon gets mass



ALICE Coll., Eur. Phys. J. C (2019) 79: 402 arXiv:1809.03235v2

$\gamma + p \to J/\psi + p$ A little bit of kinematics

$$p_1 = p_\gamma = (E_\gamma, 0, 0, E_\gamma)$$

$$p_2 = p_p = \left(\frac{\sqrt{s_{pp}}}{2}, 0, 0, -\frac{\sqrt{s_{pp}}}{2} \right) \text{ car } m_p \ll \sqrt{s_{pp}}$$

$$p_3 = p_{J/\psi} = \left(m_T \cosh(y), p_x, p_y, m_T \sinh(y) \right)$$

$$p_T^2 = p_x^2 + p_y^2$$

$$m_T^2 = m_{j/\psi}^2 + p_T^2$$

$$p_4 = p_{p'} = (p_{p'}, -px, -py, p_{p'z})$$

$$E_\gamma = \frac{m_T}{2} e^y$$

Energy - Momentum Conservation

$$\left.\begin{array}{l} p_T \ll p_{p'z} \\ p_T \ll m_{J/\psi} \end{array}\right\} \quad E_\gamma = \frac{m_{J/\psi}}{2} e^y \qquad t = -p_T^2$$

$$s = W_{\gamma p}^2 = 2\sqrt{s_{pp}} E_\gamma$$

$$t = (p_1 - p_3)^2 =$$

$$E_\gamma^2 - 2E_\gamma m_T \cosh(y) + m_T^2 \cosh^2(y) - p_T^2 - E_\gamma^2 + 2E_\gamma m_T \sinh(y) - m_T^2 \sinh^2(y)$$

Coherence

For $t \rightarrow 0$, the wave functions becomes larger than the radius of the of the source (nucleon or nucleus)

The interaction could have taken place in any region of the source (coherence interference).

The amplitudes contributes coherently

In incoherent photo-production, cross-sections (the square of the amplitudes)

$$\lambda_T = \frac{h}{p_T}$$

$$\frac{d\sigma_{J\psi+p}}{dt} \propto |F_{2G}(t)|^2 \text{ for } |t| \ll \frac{1}{R_s}$$

$$\left| \sum_{i=0}^{A} \text{Amplitude}_{J\psi+p} \right|^2 = A^2 \times \text{Amplitude}_{J\psi+p}$$

$$\sum_{i=0}^{A} |\text{Amplitude}_{J\psi+p}|^2 = A \times \text{Amplitude}_{J\psi+p}$$

Perturbative QCD calculation

$$\frac{d\sigma^T(\gamma p \to J/\Psi + p)}{dt} = \frac{|M|^2}{16\pi s^2} = [F_N^{2G}(t)]^2 \frac{\alpha_s{}^2 \Gamma_{ee}^J m_J^3}{3\alpha_{e.m.}} \pi^3 \left[\bar{x}G(\bar{x},\bar{q}^2)\frac{2\bar{q}^2 - |q_t^J|^2}{(2\bar{q}^2)^3}\right]^2$$

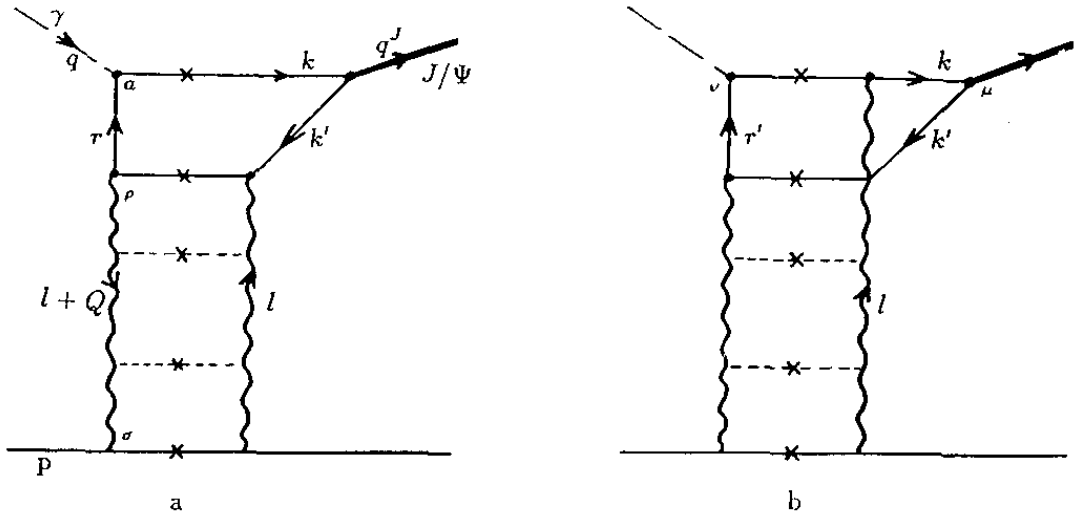


Fig. 1a, b. Feynman diagrams for diffractive J/Ψ production

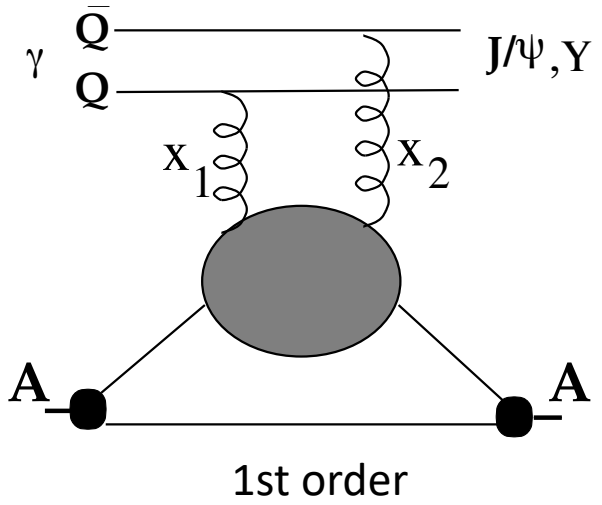
M.G. Ryskin, Diffractive J/ψ electroproduction in LLA QCD, Z. Phys. C 57 (1993) 89, https://doi.org/10.1007/BF01555742

Photons goes to c-cbar pair. Two gluon colourless interaction J/ψ is produced. The gluon distribution function $G(x,Q^2)$ is probed at leading order

At $t \sim 0$, two gluon interactions in the proton interference constructively : coherent production (but in a nucleon de process is known as incoherent in the AA UPC jargon), and therefore the t distribution is given the two-gluon form factor of the nucleon, $F^{2G}(t)$, expected to be close to the EM form factor : mean p_T of the J/psi ~ $1/R_N \sim 250$ MeV/c

Note. At 2nd order this scenario is completely difference, and quarks PDF also contribute, even dominate due to a cancellation of the gluon LO and NLO contribution. See presentation de K. J. Eskola Hard Probes 2023.

Coherence in γ-A collisions



Coherence of the full distribution of gluon pairs in the nucleus increase the cross-section by a A^2 factor

t distribution is given by the two-gluon distribution inside the nucleus, very close to the electromagnetic nucleus from factor

$$\frac{d\sigma_{\gamma A\to VA}}{dt} = |F(t)|^2 \frac{d\sigma_{\gamma A\to VA}}{dt}\bigg|_{t=0}$$

Nucleus form factor

$p_{T,J/psi} \sim 1/R_A$, for lead ~ 30 MeV

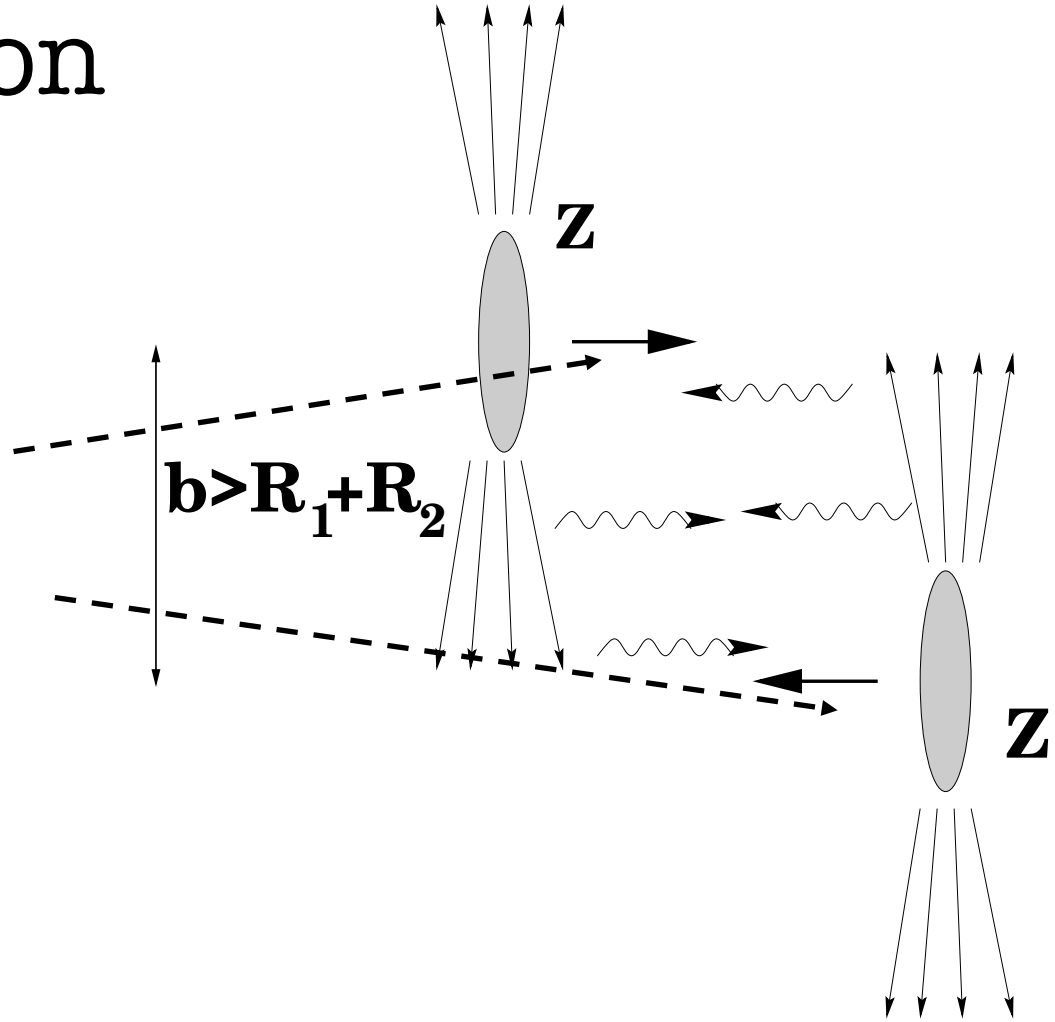
A.J. Baltz et al., The Physics of Ultraperipheral Collisions at the LHC, Phys Rep 458 (2008)171 https://arxiv.org/abs/0706.3356

Coherent photo production in A+A UPC

The sum of two different amplitudes :

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

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



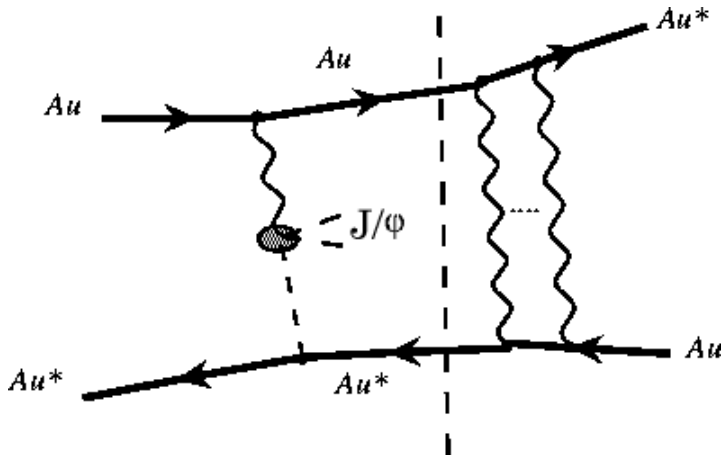
At y=0, both contributions are identical.

If rapidity is not equal to zero, gamma energies are different, and relative contribution (γ+A)/ (A+γ) are not unity and it depends strongly on impact parameter.

G. Baur et al., Coherent gamma-gamma and gamma-A interactions in very peripheral collisions at relativistic ion colliders, Phys Rep 364 (2002) 359 https://arxiv.org/abs/hep-ph/0112211

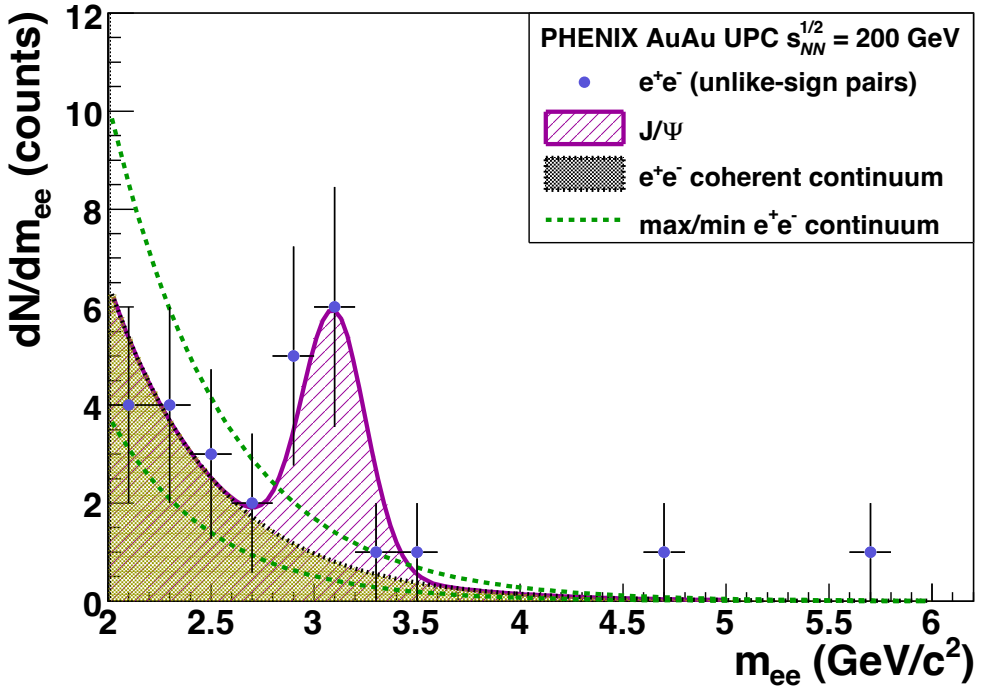
Ultra Peripheral Collisions

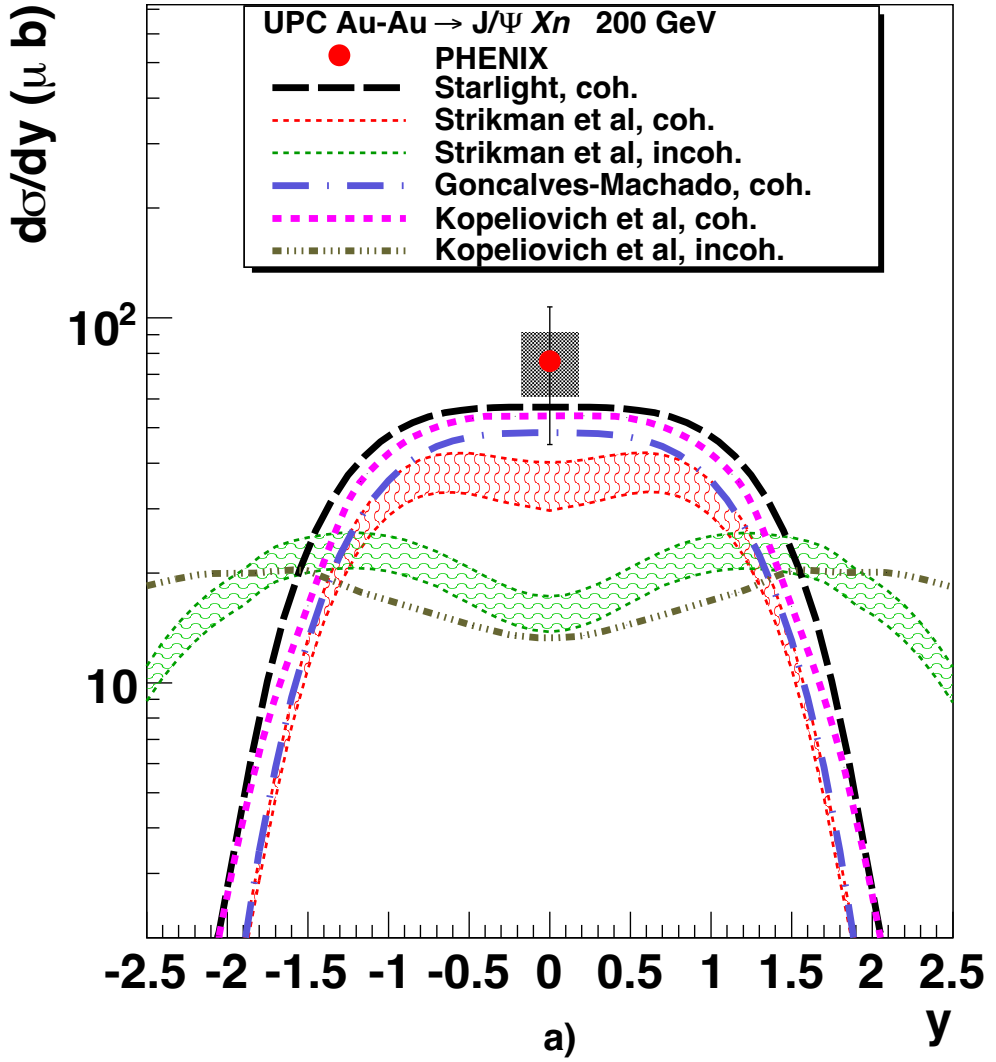
- Coincidence with a heavy ion bunch crossing in a collider (very short time window coincidence)
- Veto on the full detector
- Except for produced particles. For instance, the two tracks in the rapidity range where the J/psi (VM or dilepton) is measured.
- No identification of the heavy ions after the collision.
- In some cases, detection of neutrons evaporated from the heavy ions



Probability of a secondary heavy ion excitation is very high at RHIC and LHC energies
In additions, neutron evaporation depends on the centrality in UPC

Pioneering J/psi UPC Measurement at RHIC



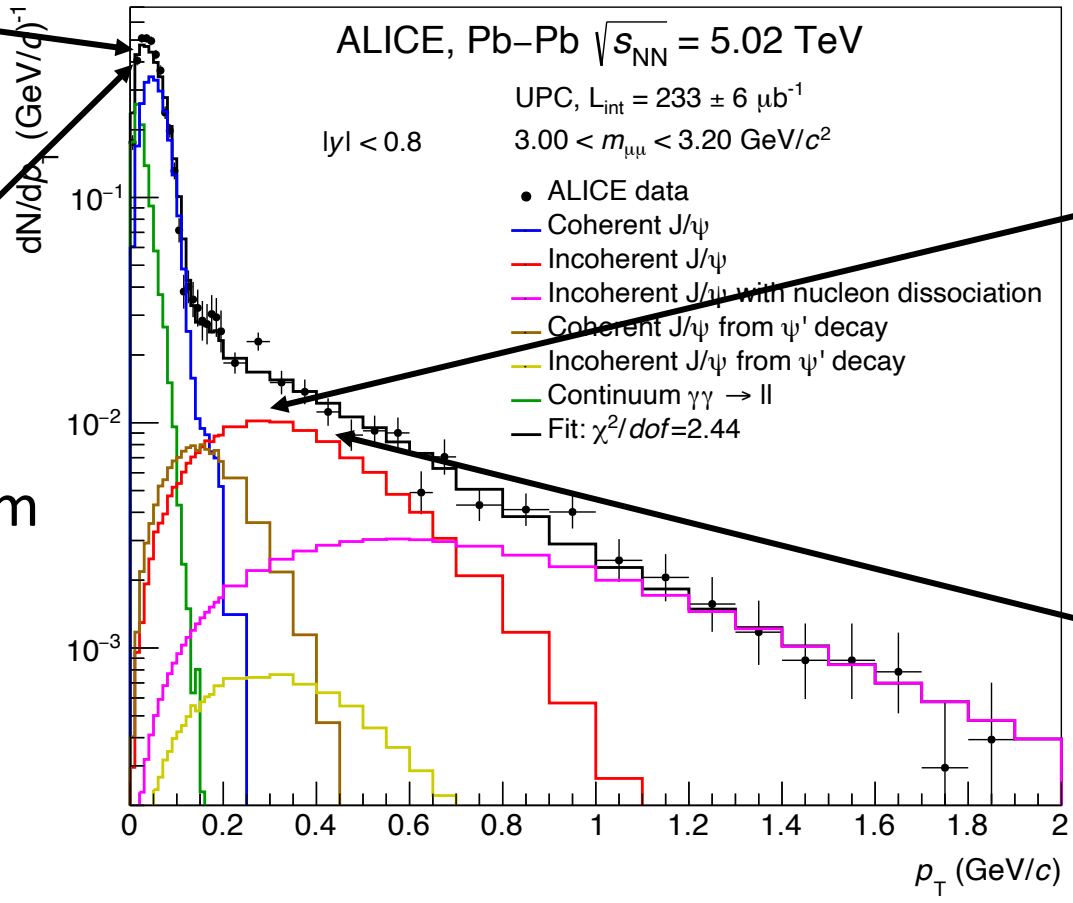


Au-Au at 200 GeV

Phenix Collaboration, Photoproduction of J/psi and of high mass e+e- in ultra-peripheral Au+Au collisions at 200 GeV, Physics Letters B 679 (2009) 321-329, ArXiv: 0903.2041 DOI: 10.1016/j.physletb.2009.07.061

J/psi photo-production Pb-Pb UPC at LHC

Coherence : $A^2 \cdot d\sigma_{\gamma+p}/dp_T$



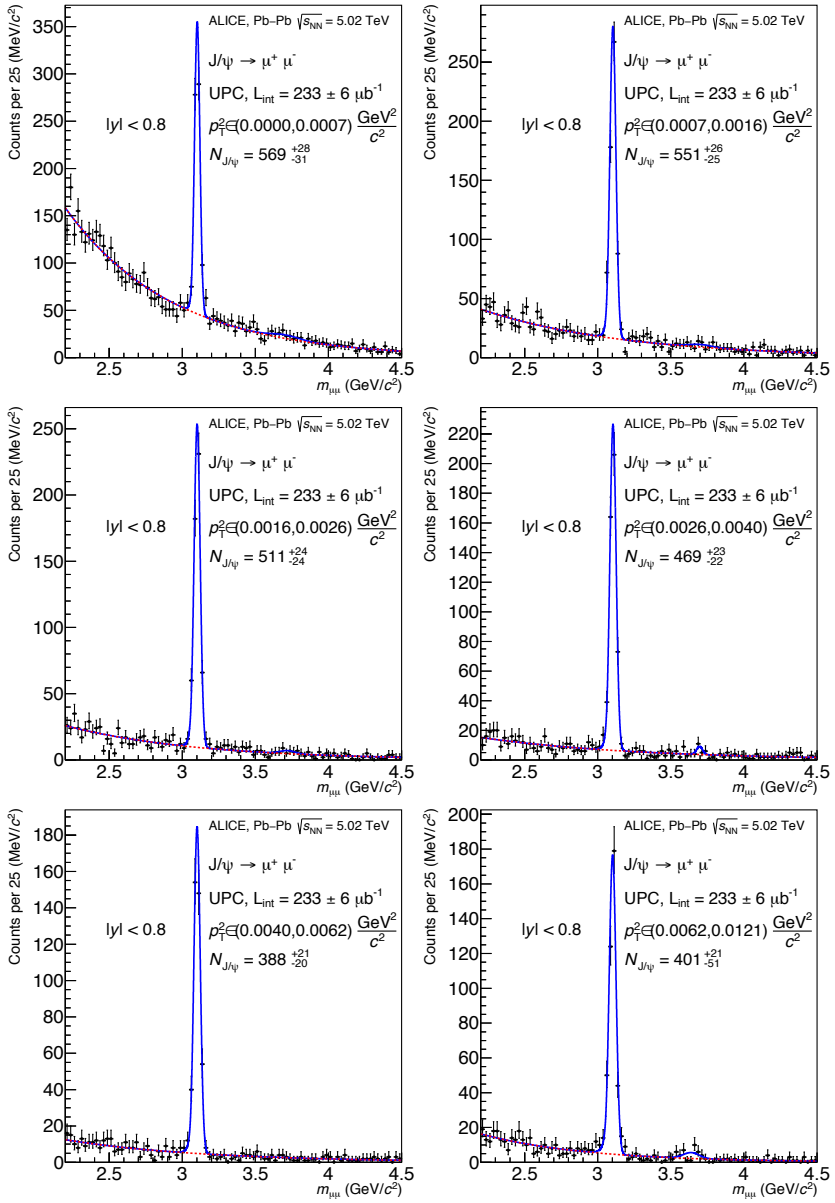
Shape given by the form factor of the nucleus

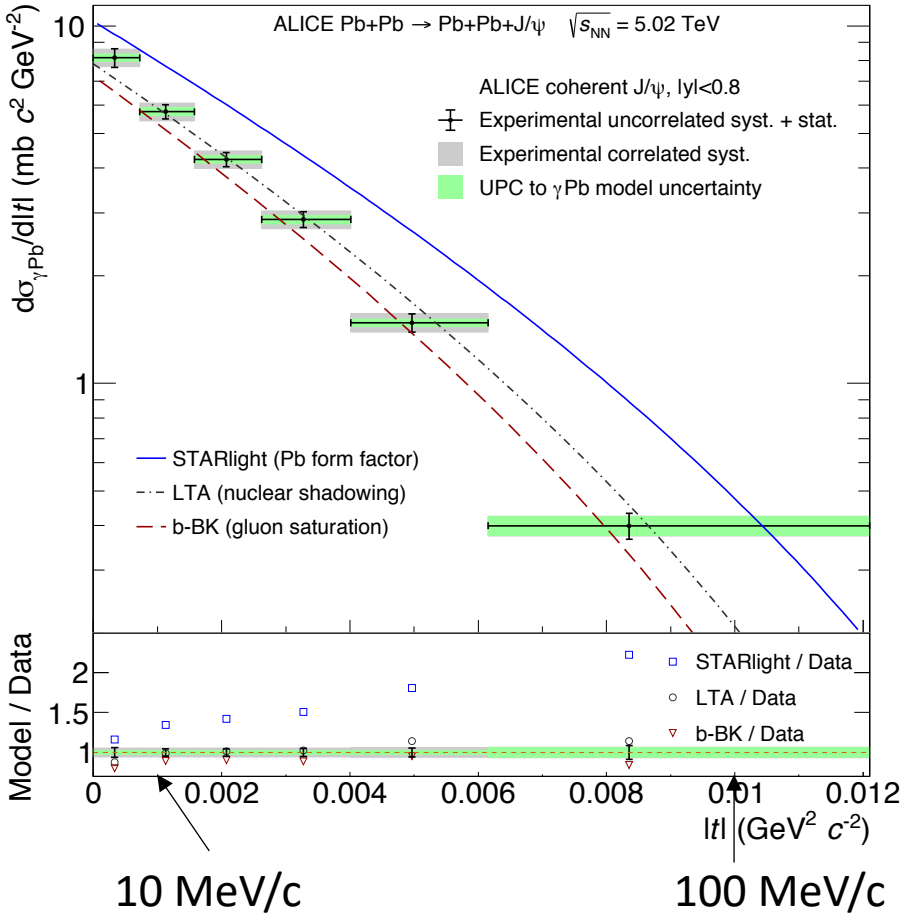
Incoherence $A \cdot d\sigma_{\gamma+p}/dp_T$

Shape given by the form factor of the nucleon

ALICE Coll., Eur. Phys. J. C (2021) 81: 8 arXiv:2101.04577

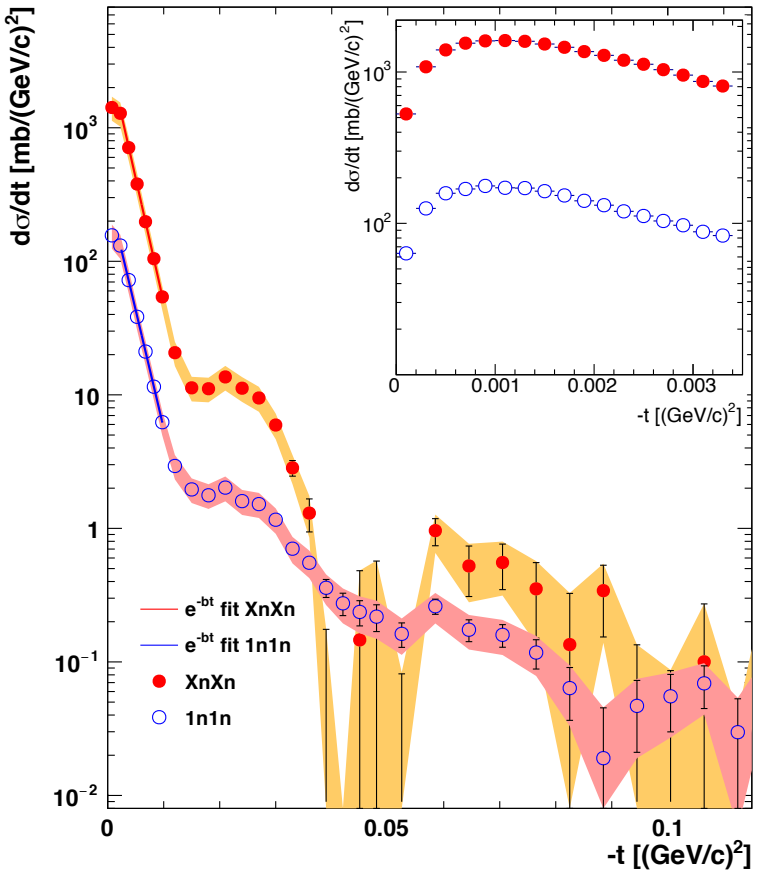
J/ψ in UPC collisions with ALICE



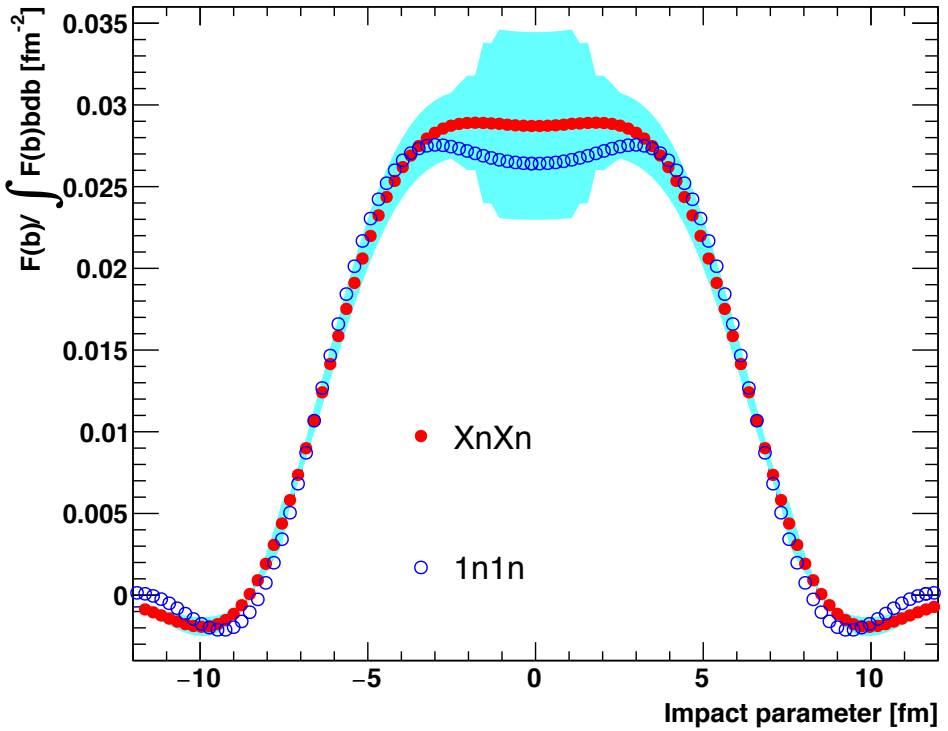


ALICE Collaboration, Measurement of the t-dependence of coherent J/ψ photoproduction at midrapidity in ultra-peripheral Pb–Pb collisions at 5.02 TeV, Physics Letters B 817 (2021) 136280

Imaging the nucleus in UPC



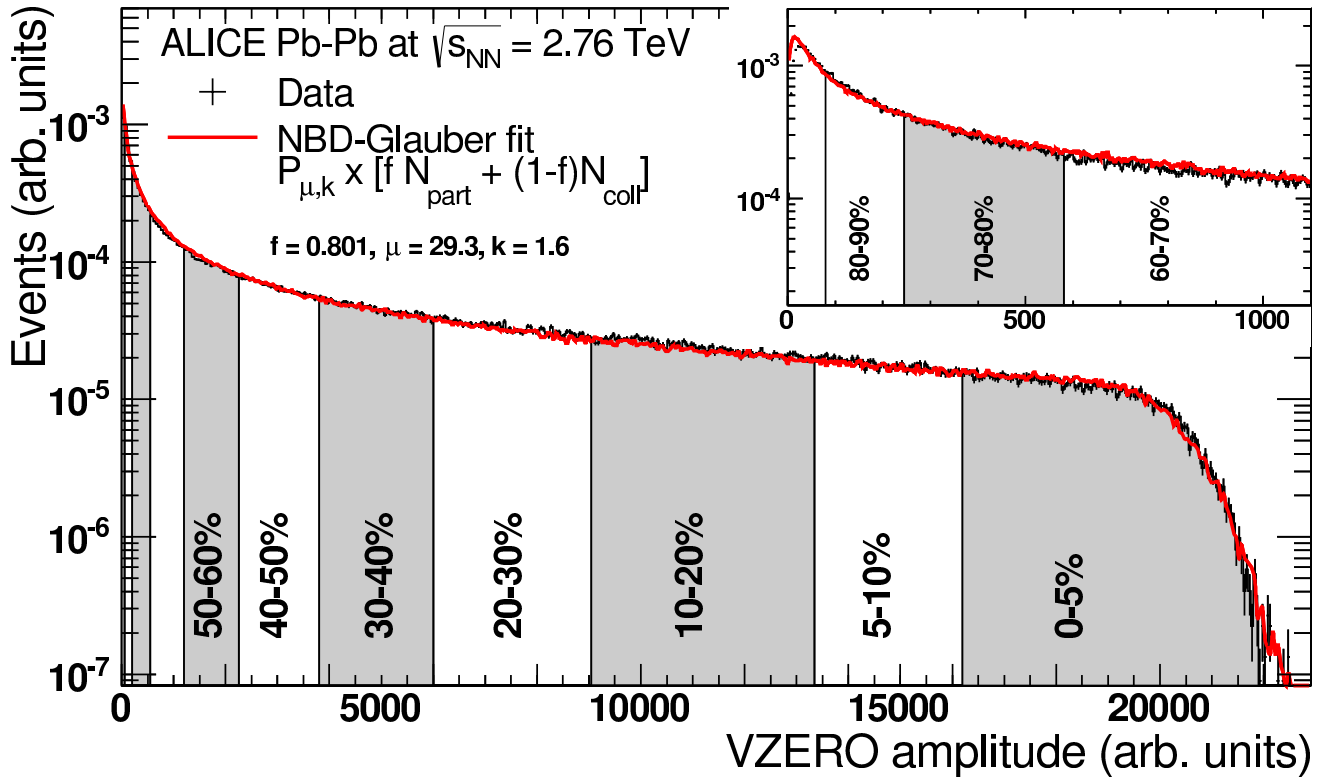
ρ⁰ meson coherent photo production in Au-Au at RHIC energies



STAR Collaboration, Coherent diffractive photo-production of ρ⁰ mesons on gold nuclei at RHIC, Phys. Rev. C96 (2017) 054904 https://arxiv.org/abs/1702.07705

Nuclear Heavy Ion Collisions

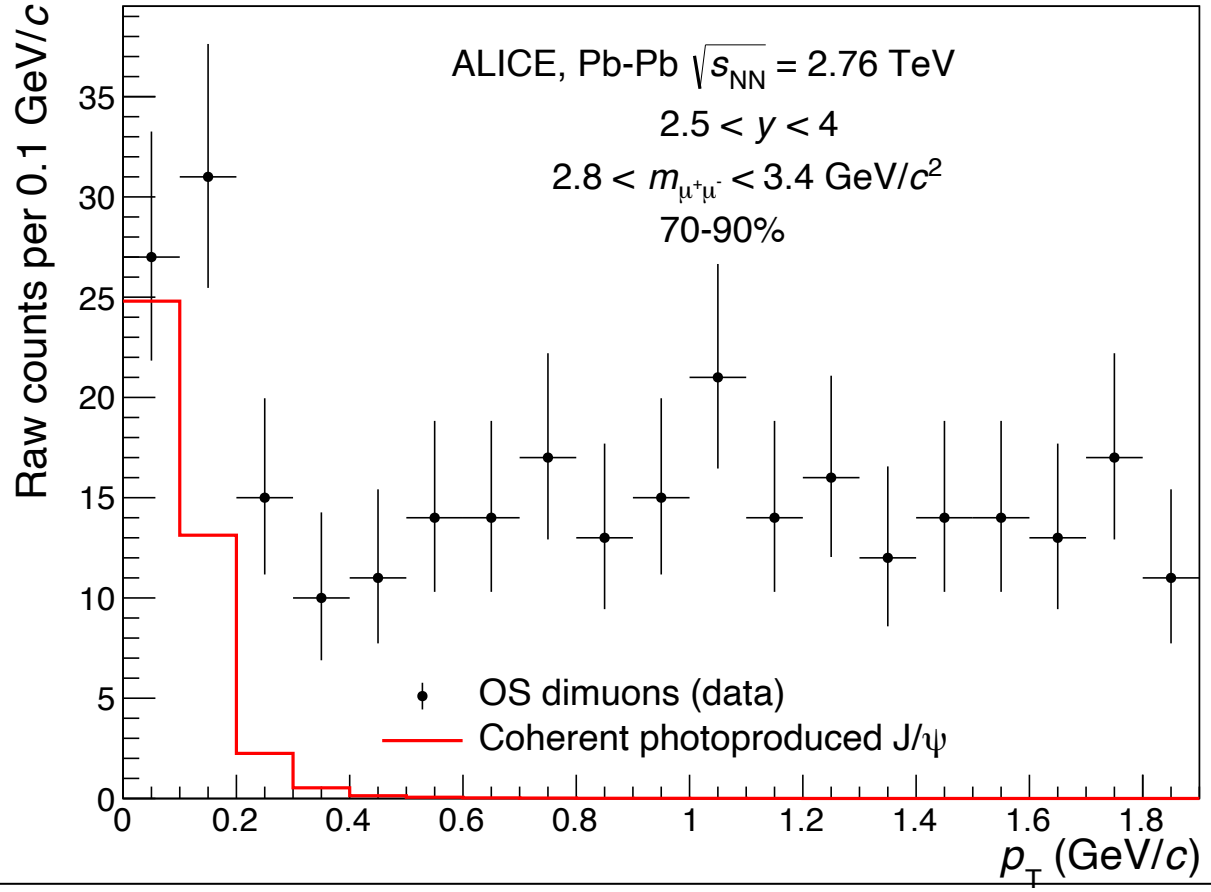
- Coincidence with a heavy ion bunch crossing in a collider
- Particle measured at mi-rapidity region (several units of rapidity around y=0 at the LHC)
- Additional physics selection conditions (vertexing, reduction of EM processes contamination, rejection of beam-gaz, ...)
- Determination of the centrality (VZERO for ALICE)

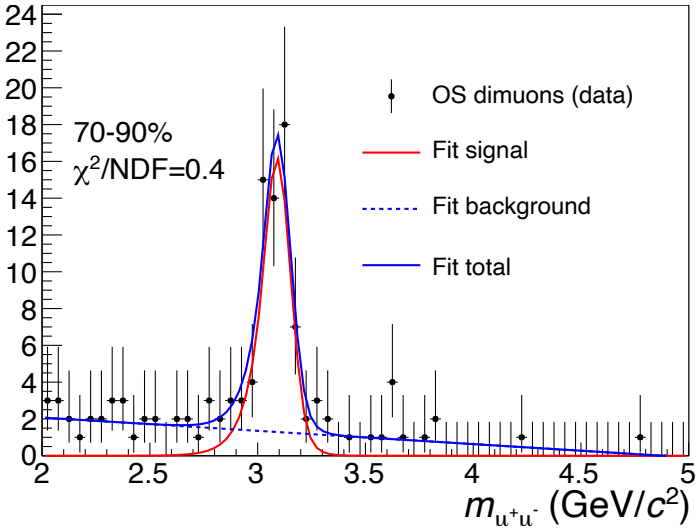


NBD-Glauber fit allows to determine the impact parameter distribution associated to each centrality bin

ALICE Collaboration, Centrality Determination of Pb-Pb collisions at 2.76 TeV with ALICE Physical Review C 88 (2013) 4, 044909, arXiv : 1301.4361 [nucl-ex] DOI:10.1103/PhysRevC.88.044909

Measurement of an excess in the yield of J/ψ at very low pT in Pb–Pb collisions at 2.76 TeV





- Very low p_T excess of J/psi in peripheral Pb-Pb collisions at the LHC
- Enhancement for p_T < 250 MeV/c
- Expected transverse momentum resolution of the apparatus is about 150 MeV/c, the enhancement is dominated by detector effects
- At LHC, calculations by Joakim Nystrand, showed that coherent photo-production cross-section becomes comparable to hadronic J/psi photo-production.

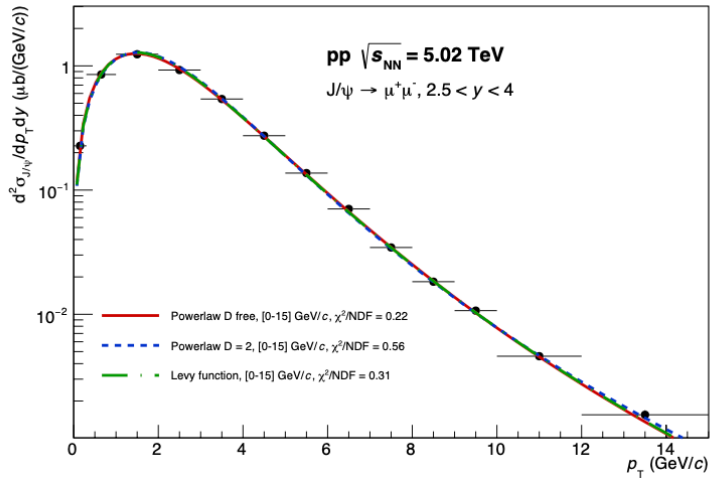
ALICE Collaboration, Measurement of an excess in the yield of J/ψ at very low p_T in Pb-Pb collisions at 2.76 TeV, Physical Review Letters 116 (2016) 222301, https://arxiv.org/abs/1509.08802

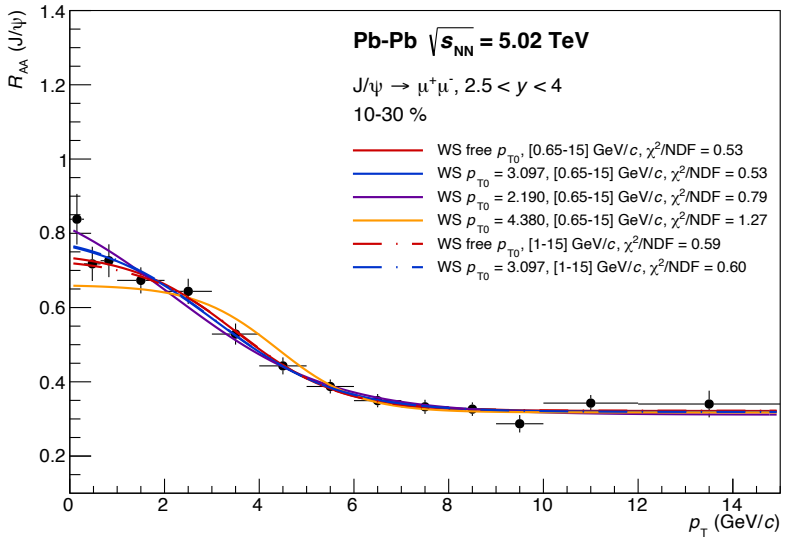
Removing hadronic contamination

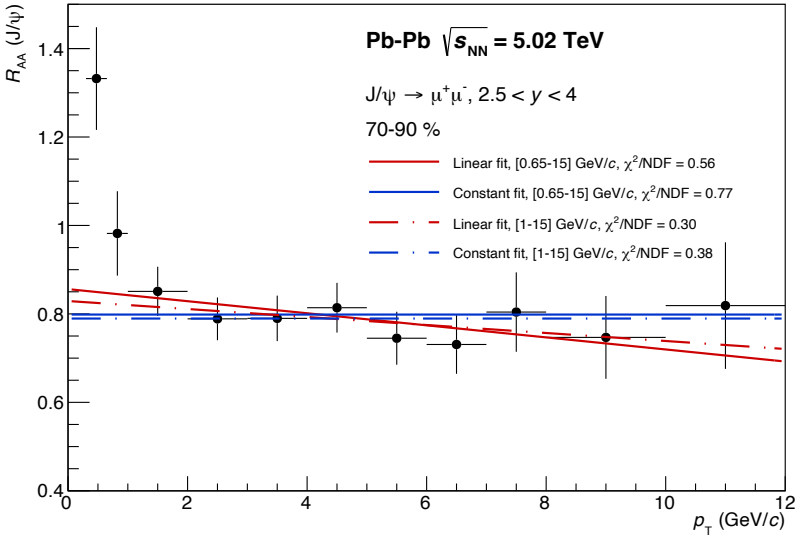
Two main ingredients :

- Hadronic proton-proton differential cross-section
- Evolution of the nuclear modification factor at low pT

$$\int_{p_{T1}}^{p_{T2}} \frac{\mathrm{d}N_{AA}^{h}}{\mathrm{d}p_T}\mathrm{d}p_T = \mathcal{N} \times \int_{p_{T1}}^{p_{T2}} \frac{\mathrm{d}\sigma_{pp}^{h}}{\mathrm{d}p_T} \times R_{AA}^{h}(p_T) \times (\mathcal{A} \times \epsilon)_{AA}^{h}(p_T)\mathrm{d}p_T$$



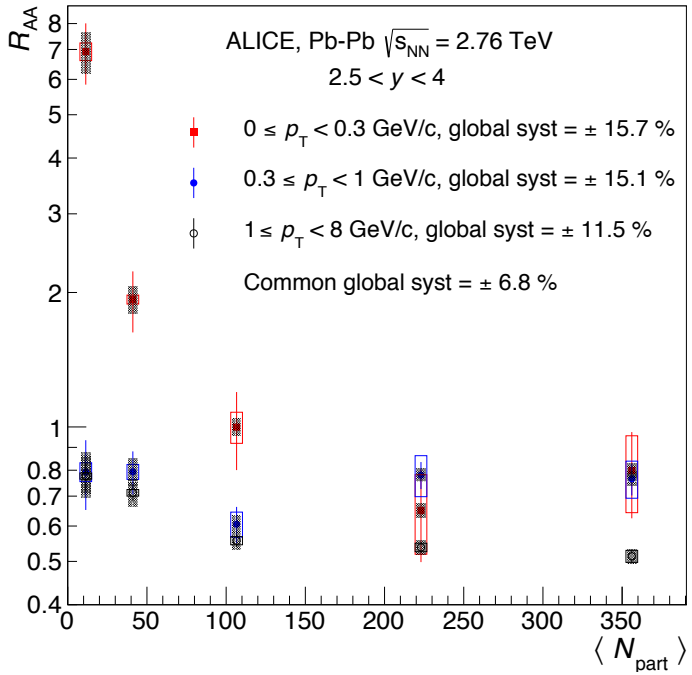




Ophelie BUGNON, PhD Thesis Report, Mesure de la production de J/ψ lors de collisions Pb-Pb à √s=5.02 TeV avec le spectromètre à muons de l'expérience ALICE-CERN, https://theses.hal.science/tel-04086938v1

Scale of R_{AA} evolution much larger than $1/R_A$
Peripheral collisions R_{AA} evolutions is flat
Apparatus resolution is a key point

J/ψ photo-production in nuclear collisions



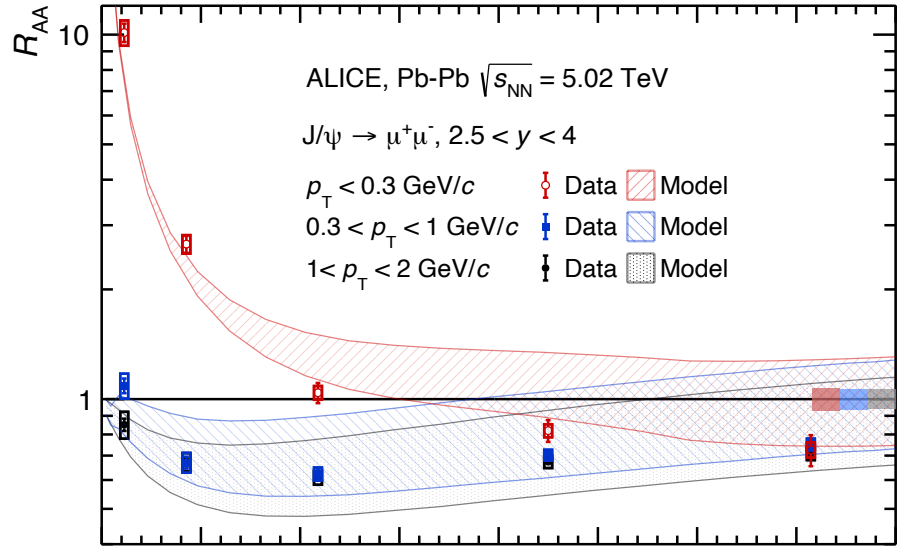
- Enhancement at very low p_T
- R_{AA} reaches 7!
- Coherent J/psi photo-production is the only plausible origin
- In agreement with first calculations

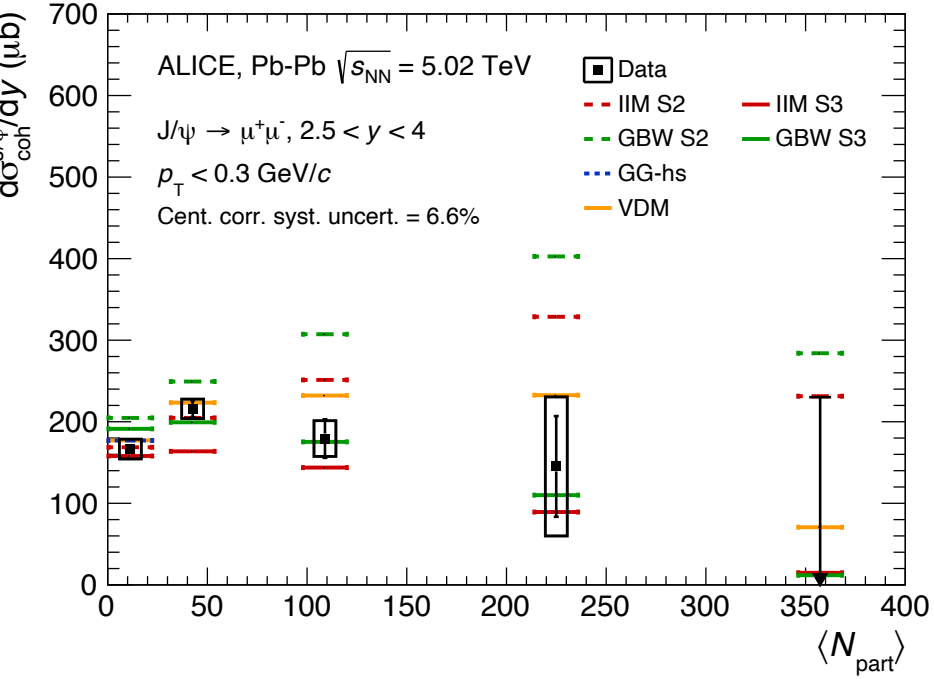
Cent. (%)	$N_{AA}^{J/\psi}$	$N_{AA}^{h\,J/\psi}$	$N_{AA}^{excess\,J/\psi}$	$d\sigma_{J/\psi}^{coh}/dy$ (μb)
0–10	$339 \pm 85 \pm 78$	$406 \pm 14 \pm 55$	< 251	< 318
10–30	$373 \pm 87 \pm 75$	$397 \pm 10 \pm 61$	< 237	< 290
30–50	$187 \pm 37 \pm 15$	$126 \pm 4 \pm 15$	$62 \pm 37 \pm 21$	$73 \pm 44\ ^{+26}_{-27} \pm 10$
50–70	$89 \pm 13 \pm 2$	$39 \pm 2 \pm 5$	$50 \pm 14 \pm 5$	$58 \pm 16\ ^{+8}_{-10} \pm 8$
70–90	$59 \pm 9 \pm 3$	$8 \pm 1 \pm 1$	$51 \pm 9 \pm 3$	$59 \pm 11\ ^{+7}_{-10} \pm 8$

M. B. Gay Ducati and S. Martins, Heavy meson photoproduction in peripheral AA collisions, Phys. Rev. D 97 no. 11, (2018) 116013, : https://arxiv.org/abs/1804.09836

ALICE Collaboration, Measurement of an excess in the yield of J/ψ at very low p_T in Pb-Pb collisions at 2.76 TeV, Physical Review Letters 116 (2016) 222301, https://arxiv.org/abs/1509.08802

J/ψ photo-production in nuclear collisions





Centrality class	$\langle N_{part} \rangle$	$N_{raw}^{J/\psi}$	$N_{hadro}^{J/\psi}$	$N_{excess}^{J/\psi}$	$d\sigma_{coh}^{J/\psi}/dy$ (μb)
0–10%	357.3 ± 0.8	$8351 \pm 762 \pm 312$	$8713 \pm 86 \pm 873$	< 2406 (95% CL)	< 230 (95% CL)
10–30%	225.0 ± 1.2	$9624 \pm 571 \pm 278$	$8274 \pm 60 \pm 742$	$1350 \pm 574 \pm 792$	$145 \pm 62 \pm 85$
30–50%	109.0 ± 1.1	$4280 \pm 225 \pm 105$	$2562 \pm 23 \pm 178$	$1718 \pm 226 \pm 207$	$179 \pm 24 \pm 22$
50–70%	42.7 ∓ 0.7	$2763 \pm 98 \pm 68$	$674 \pm 8 \pm 40$	$2089 \pm 98 \pm 79$	$216 \pm 10 \pm 12$
70–90%	11.3 ± 0.2	$1758 \pm 57 \pm 32$	$138 \pm 3 \pm 9$	$1620 \pm 57 \pm 33$	$167 \pm 6 \pm 12$

- 1.6 x10^3 coherent photo-produced J/ψ in 70-90% for 0.76 nb^{-1} integrated luminosity
- 5σ in 30-50% centrality bin (N_{part} ~100)
- 1.4σ "signal" in 10-30% centrality bin (N_{part} ~220)

ALICE Collaboration, Photoproduction of low-pT J/ψ from peripheral to central Pb–Pb collisions at 5.02 TeV
Physics Letters B 846 (2023) 137467
arXiv :2204.10684 [nucl-ex]
DOI: 10.1016/j.physletb.2022.137467

Characterizing photo-production source form factor in AA nuclear collisions

1. Measuring yield and the mean pT as a function of centrality :

If only spectator contributes to the photo-producitoin in peripheral AA collisions, mean pT should increase with centrality

2. High precision measurement of the “heavy ion collision” form factor

UPC versus Peripheral Collisions

UPC	PC
Impact parameter not defined (2R,∞)	Impact parameter range well defined : Δb ~ ± 1 fm
Softer photon spectrum	Harder photon spectrum
Hadronic free	Hadronic contamination
Reaction plane cannot be measured	Reaction plane can be measured (at least ψ_2)
Total transverse momentum	Transverse momentum can be decomposed in in-plane and out of plane
No hot matter is formed	Quarkonium could be suppressed by the hot medium
Small interference effect	Larger interference effect

Centrality selection

Reaction plane determination

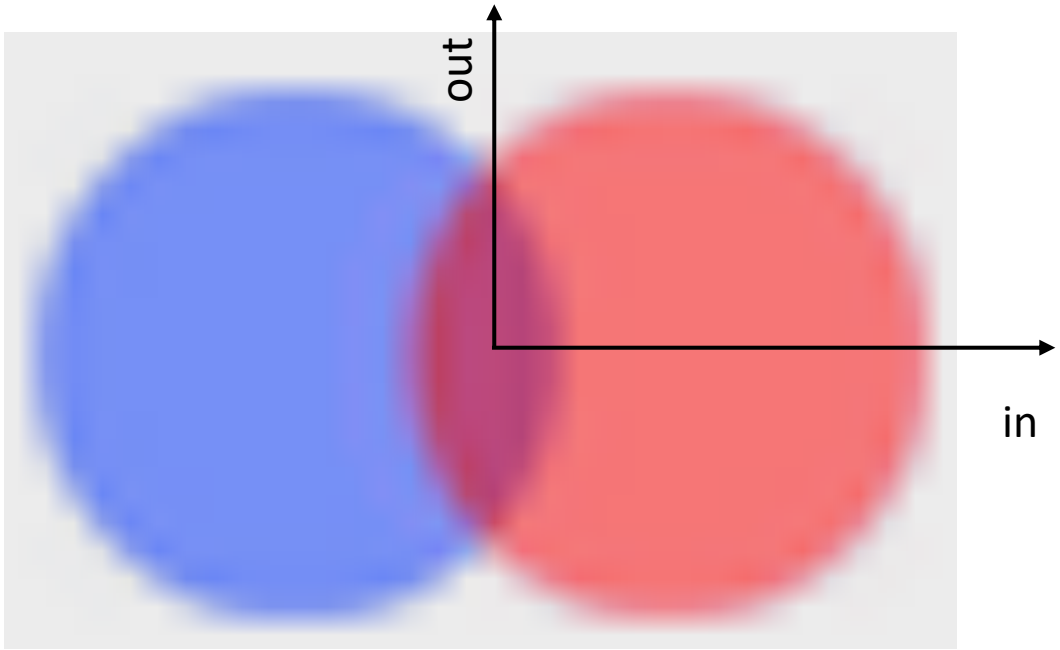
t_{in} : p_T square in the direction of $\vec{b}$

t_{out} : p_T square in the transverse plane perpendicular to $\vec{b}$

Proposal : “Imaging of Heavy Ion Collisions”

- Study of the $|t_{in}|$- and $|t_{out}|$- dependences of coherent J/ψ photo-nuclear production in Pb-Pb at 5 TeV
- Utilization of ψ_1 for discriminating between beam directions?
- Measurement of “heavy ion collision form factor” $F(t_{in},t_{out})$
- High Momentum resolution (1%)
- Image of the heavy ion collision at first stages
- Measuring the role of the overlap region
- Challenge : reach high $|t|$ at least until sqrt(-t) 200-300 MeV/c (femtoscopic resolution)
- Apparatus resolution is crucial : Alice e+e-, LHCb

Formalism to be constructed



Conclusions and perspective

- Excellent results obtained by the ALICE collaboration concerning J/ψ photonuclear production.
- Recently, J/ψ “coherent” photo nuclear is surprisingly observed in semi-central collisions (i.e. 30-50%).
- Understanding “coherent” J/psi photo-production is semi-central heavy ion in a challenge.
- In peripheral collisions large statistics of “coherent” photonuclear J/ψ will become available at the LHC
- Studying J/ψ photo-production with respect to the reaction plane in peripheral collisions should allow to imaging the first stages of the heavy ion collisions via the measurement of the 2D form factor $F(t_{in},t_{out})$
- ALICE e+e- and LHCb are competitive the best for these measurements
- At mid-rapidity, destructive interference between target nuclei will be observed.

Acknowledgements

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Thanks for the invitation to present this topic in this workshop of the GDR QCD.

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$\gamma + A \rightarrow J/\psi + A$ and $A + \gamma \rightarrow J/\psi + A$ Interference

- Parity inversion switches the photon emitter nucleus with the target nucleus
- The parity of the J/ψ is negative
- Amplitudes has a relative phase of π at y=0
- Destructive interference between the J/ψ produced from each nucleus
- For $y_{J/\psi}$=0 and $p_{T,J/\psi}$=0, total destructive interference : $d\sigma/dp_T^2dy(pT=0, y=0)=0$

$$\left\{1 - \cos\left(\vec{p}_{J/\psi}\vec{b}\right)\right\} \qquad p_{J/\psi,T} \sim \frac{1}{b}$$

- For LHC UPC, average b about 50 fm for J/ψ production very low transverse momentum 4 MeV/c

For y≠0 :
- the amplitudes are different : partial destructive interference
- The photon energies are different : relative phase is not necessarily π

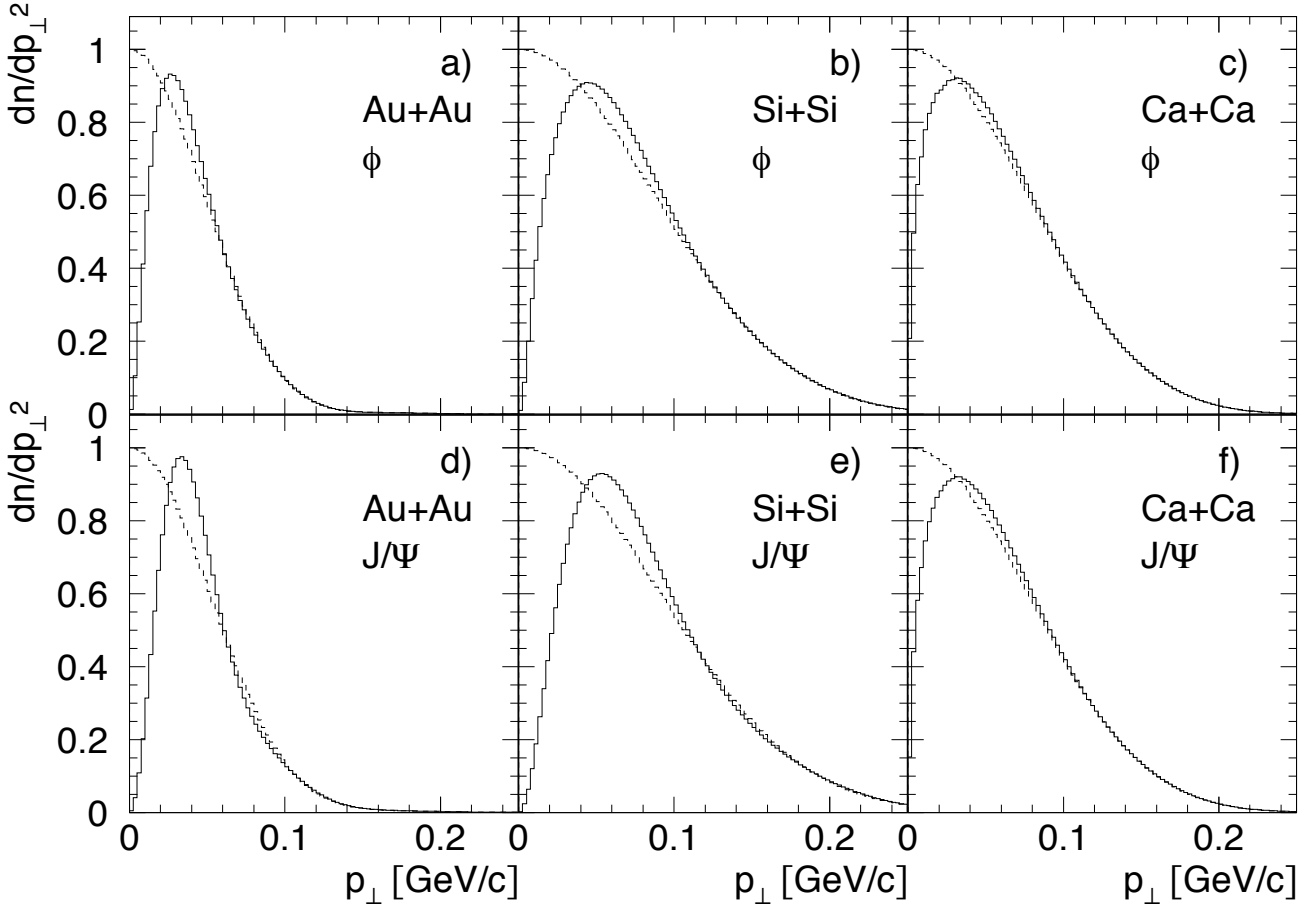
Spencer R. Klein and Joakim Nystrand, Interference in Exclusive Vector Meson Production in Heavy Ion Collisions, Phys. Rev. Lett. 84 (2000) 2330, https://arxiv.org/abs/hep-ph/9909237
Spencer Klein, Private communication

Interference effect

RHIC

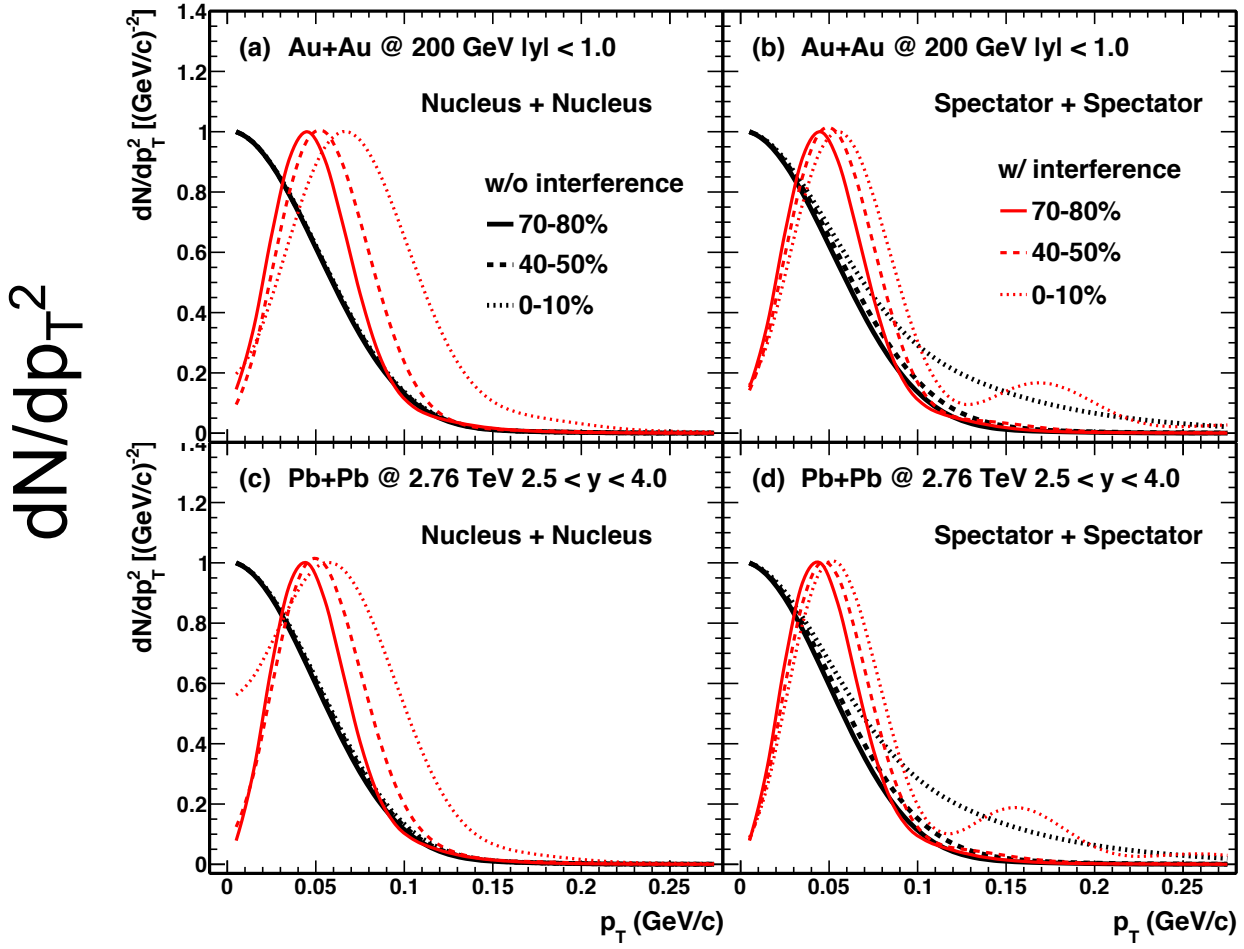
LHC

Solide line : with intereference effect
Dash line : without intereference effect



Spencer R. Klein and Joakim Nystrand, Interference in Exclusive Vector Meson Production in Heavy Ion Collisions, Phys. Rev. Lett. 84 (2000) 2330, https://arxiv.org/abs/hep-ph/9909237

The interference effect in nuclear collisions



- Four different hypothesis of photo-productions
- Small differences in peripheral collisions
- Clear signal of destructive interference at very low p_T (0 – 100 MeV/c^2)
- Tiny effect in the 0-300 MeV/c^2 integrated cross-section

W. Zha, S.R. Klein et al., Coherent J/ψ photoproduction in hadronic heavy-ion collisions, Phys. Rev. C 97 (2018) 044910, https://arxiv.org/abs/1705.01460