



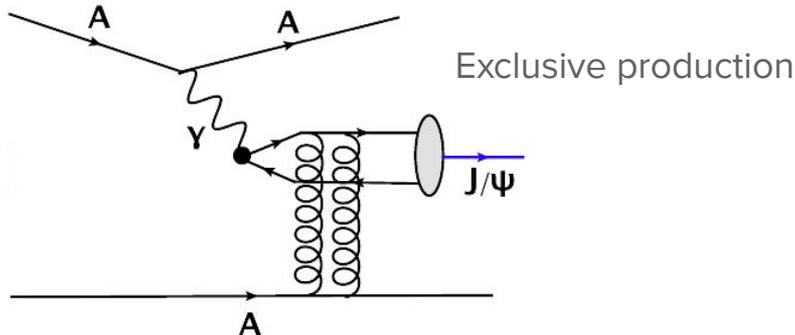
Photoproduction of J/ψ in heavy-ion collisions with nuclear overlap and J/ψ polarization

Afnan SHATAT
Quarkonia as tools workshop
Aussois, France
11 Jan. 2022

J/ψ production mechanisms in heavy ion collisions

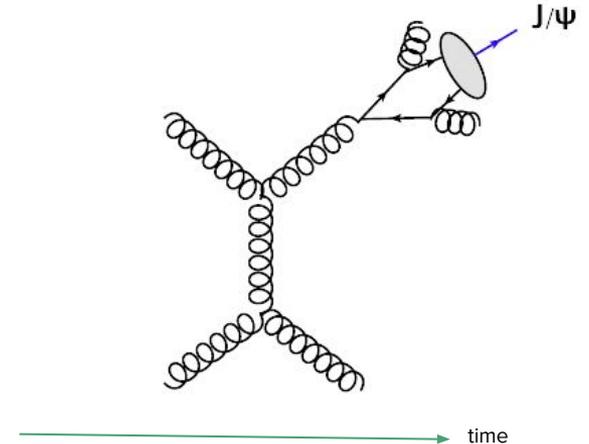
❖ Photoproduction

- ◇ Ultrarelativistic Pb ions are strong EM field emitter
- ◇ Photoproduction could be
 - Coherent: photon sees the whole target nucleus → nucleus doesn't break → small transferred momentum
→ low p_T J/ψ (≈ 60 MeV/c).
 - Incoherent: photon sees one nucleon → larger momentum transfer
→ slightly larger p_T J/ψ (≈ 500 MeV/c).



❖ Inclusive hadronic production

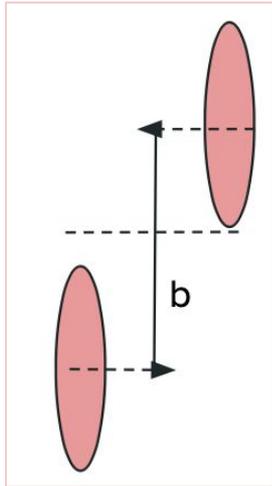
- prompt {
 - ◇ Direct J/ψ:
(dominated by gluon fusion at high energies).
 - ◇ Indirect feed down:
e.g., $\psi(2S) \rightarrow J/\psi$
- ◇ Non prompt: b hadrons → J/ψ



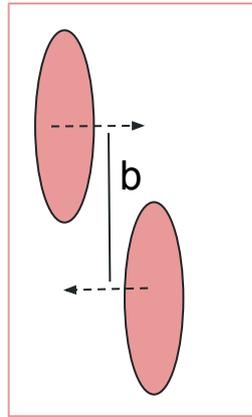
Centrality terminology in heavy ion collisions

- b : impact parameter: the distance between the center of the colliding nuclei in the transverse plane of the collision.

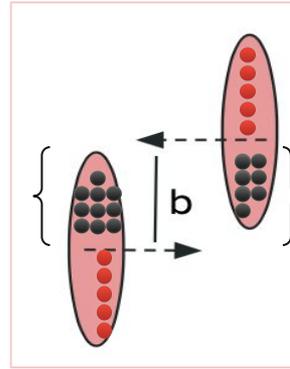
Longitudinal view



Ultra-peripheral collision
UPC

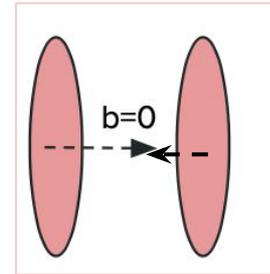


Peripheral collision
PC



Semi-central collision

N_{part} : Number of participant nucleons.
 N_{spect} : Number of spectator nucleons.



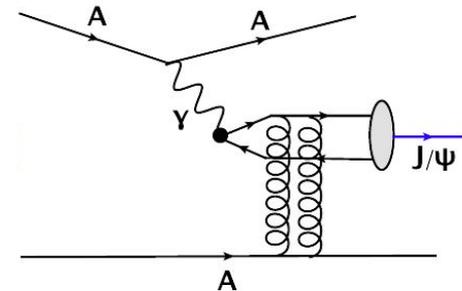
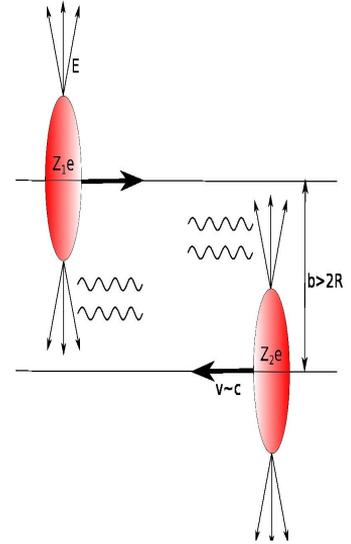
Central collision

90%

0% Centrality

J/ψ photoproduction in ultraperipheral collisions UPC

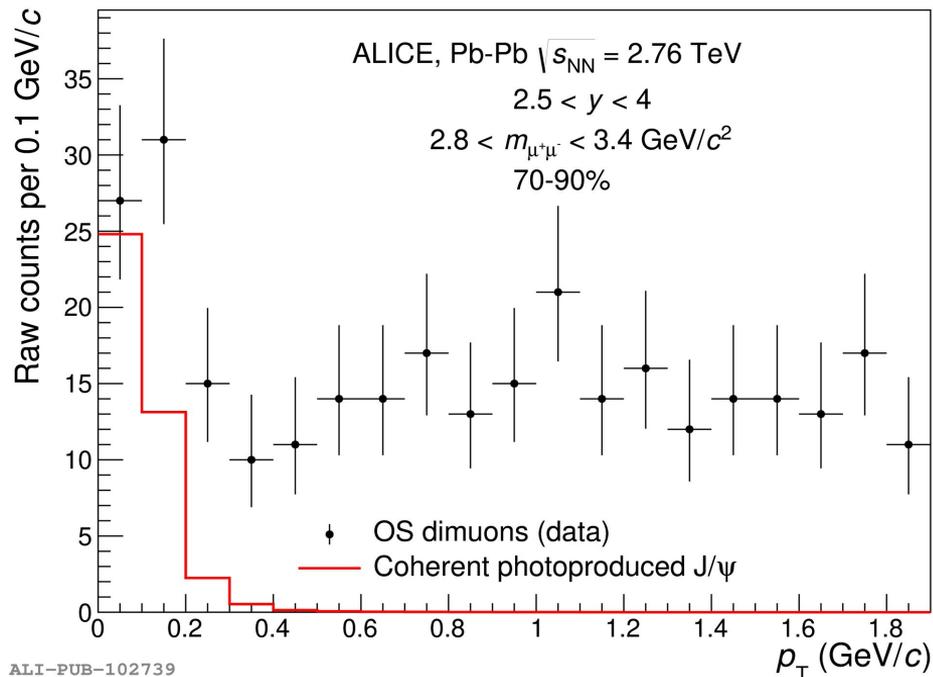
- ❖ Ultraperipheral collisions (UPC)
 - ◇ Since $b > (R_1 + R_2)$
 - ◇ → Suppressed hadronic interactions
 - Allow to study the photo-nuclear interaction & photon-photon interactions.
- ❖ J/ψ photoproduction in heavy ion collisions is well studied in UPC, e.g.
 - ◇ **PHENIX** in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, [PLB 679 (2009) 321–329]
 - ◇ **ALICE** in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, [PLB 718 (2013) 1273–1283]
 - ◇ **CMS** in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, [PLB 772 (2017) 489–511]
 - ◇ ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, [PLB 798 (2019), 134926]
- ❖ Physics of interest with J/ψ photoproduction in UPC
 - ◇ **Probe of the gluon distributions in the target nuclei $g(x_g, Q^2)$,** where x_g is the fraction of the nucleon longitudinal momentum carried by the gluon, Q^2 is the transferred momentum in the process.



Excess yield of J/ψ at low p_T at forward rapidity in Pb-Pb PC

- **ALICE** reported the first observation of an **excess in the yield of J/ψ over the expected hadronic yield at low $p_T < 0.3$ GeV/c** at $\sqrt{s_{NN}} = 2.76$ TeV in Pb-Pb collisions in the centrality class (70-90)% at forward rapidity.
[Phys. Rev. Lett. 116 (2016) 222301].
- Interpreted as a coherent photoproduction of J/ψ .

ALICE Collaboration, Phys. Rev. Lett. 116 (2016) 222301

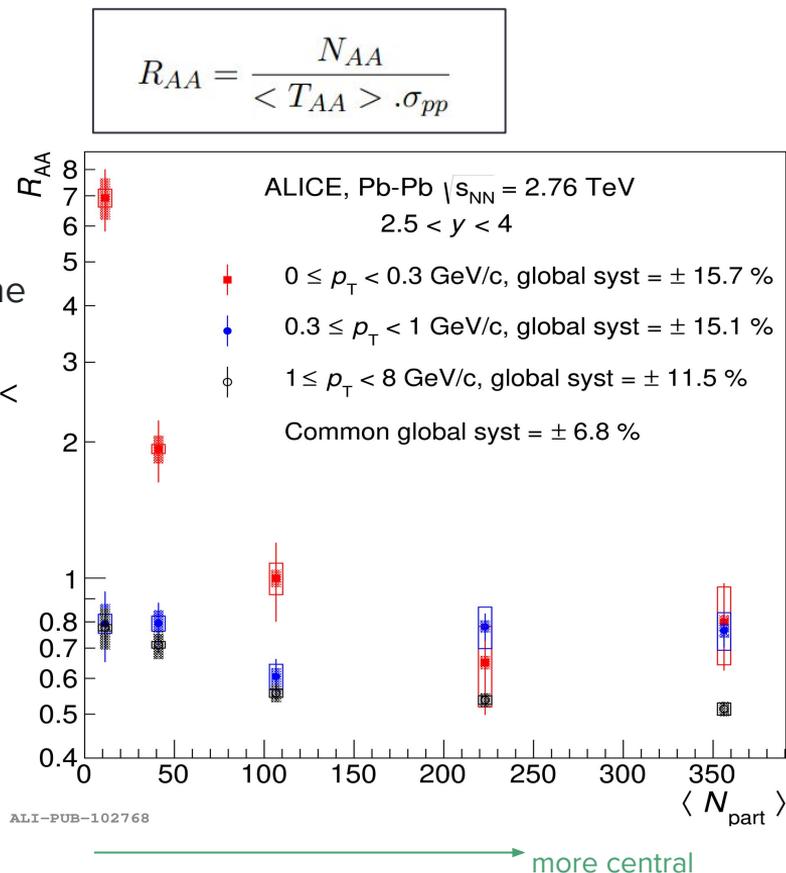


ALI-PUB-102739

p_T distribution of the dimuon yield in the J/ψ mass window.

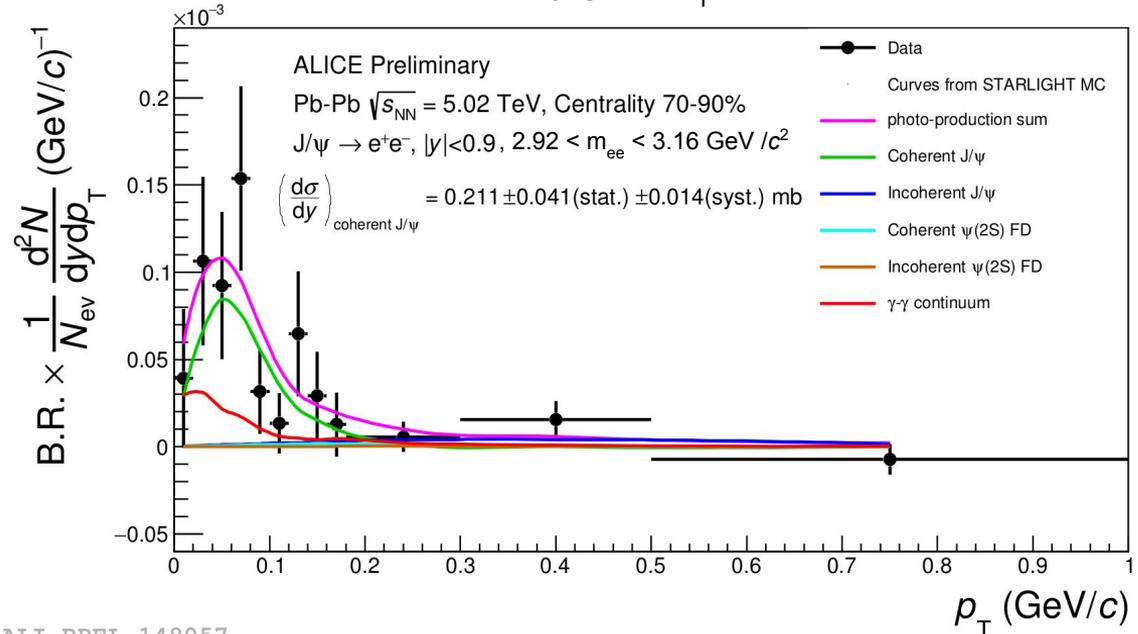
Nuclear modification factor R_{AA} in Pb-Pb PC

- Account for the nuclear matter effects in A-A collisions
- The proton-proton collisions is used as a reference
- T_{AA} : the probability/unit area of a nucleon to be in the overlap region between the colliding nuclei.
- Hadronic production yield of J/ψ is expected to be suppressed in the heavy ion collisions with respect to the pp collisions.
- ALICE reported a dramatic increase in the J/ψ R_{AA} at $p_T < 0.3$ GeV/c in Pb-Pb collisions in the centrality classes (70-90)% and (50-70)% at $\sqrt{s_{NN}} = 2.76$ TeV [[Phys. Rev. Lett. 116 \(2016\) 222301](#)].
- A production mechanism other than the hadronic mechanism is expected \Rightarrow supporting the photoproduction hypothesis along with the previous excess yield p_T shape.



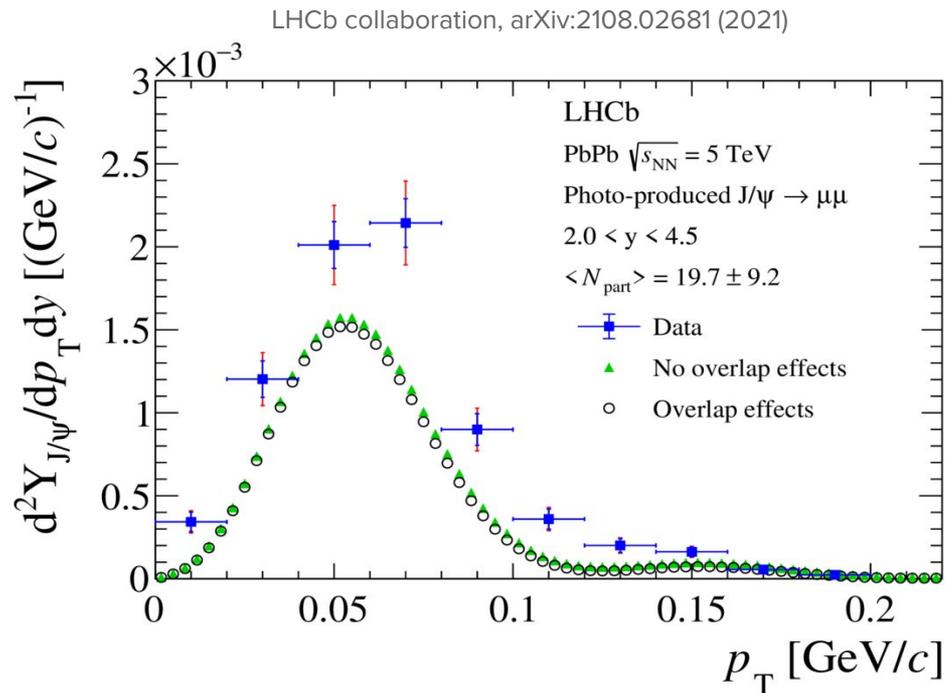
Coherent J/ψ photoproduction at low p_T at mid rapidity in Pb-Pb PC

- **ALICE has reported also an excess in the yield of J/ψ at low p_T at mid rapidity $|y| < 0.9$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the centrality class (70-90)% via the decay channel of $J/\psi \rightarrow e^+e^-$.**
- The excess was fitted by a MC simulation cocktail of STARLIGHT, in which the coherent J/ψ photoproduction is one of the main contributions.
- The p_T distribution of the J/ψ excess is extracted thanks to the very good p_T resolution of ALICE central barrel.



Coherent J/ψ photoproduction at forward rapidity in PC in LHCb

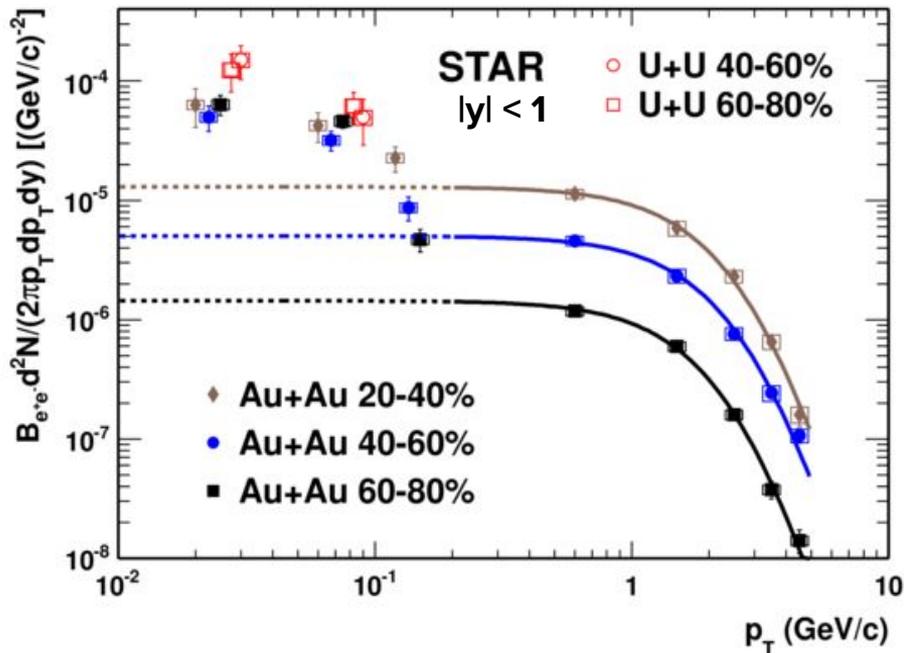
- LHCb collaboration has reported the J/ψ photoproduction at the low p_T region at forward rapidity in peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [[arXiv:2108.02681 \(2021\)](https://arxiv.org/abs/2108.02681)].
- The p_T distribution of the J/ψ excess is extracted thanks to the very fine p_T resolution of LHCb detectors.
- Comparison with models: the effect of the violent hadronic interactions on the interference of the two amplitudes of the photoproduced J/ψ is accounted for (overlap effects).



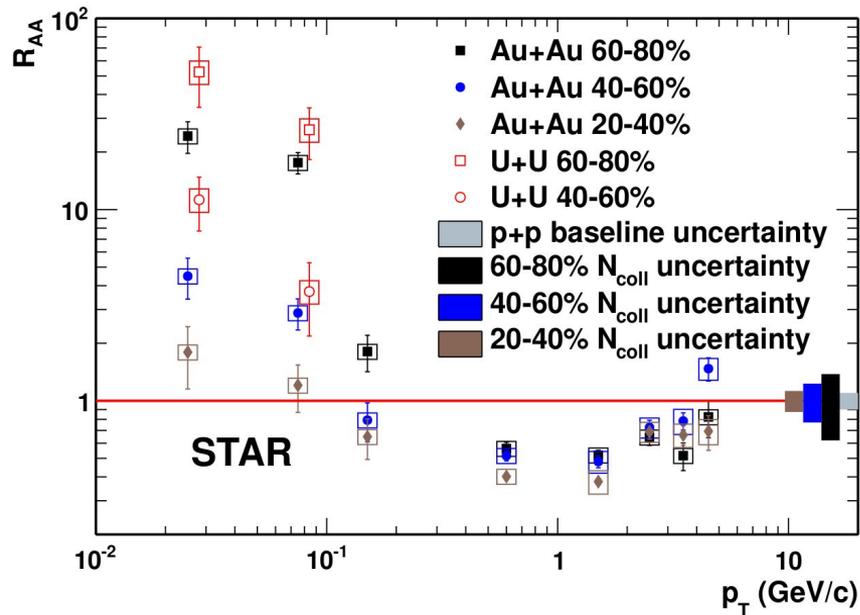
Coherent J/ψ photoproduction observation in PC in STAR

- Observation of an excess in the yield of J/ψ over the expected hadronic J/ψ at low $p_T < 0.2$ GeV/c at mid rapidity peripheral and semi-central Au-Au and U-U collisions at $\sqrt{s_{NN}} = 200$ and $\sqrt{s_{NN}} = 193$ GeV respectively.
- Interpreted as a coherent J/ψ photoproduction over the hadronic production.

STAR Collaboration, Phys. Rev. Lett. 123, 132302 (2019)

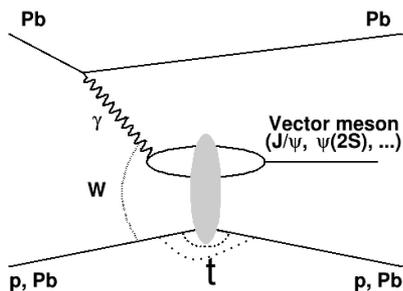


STAR Collaboration, Phys. Rev. Lett. 123, 132302 (2019)



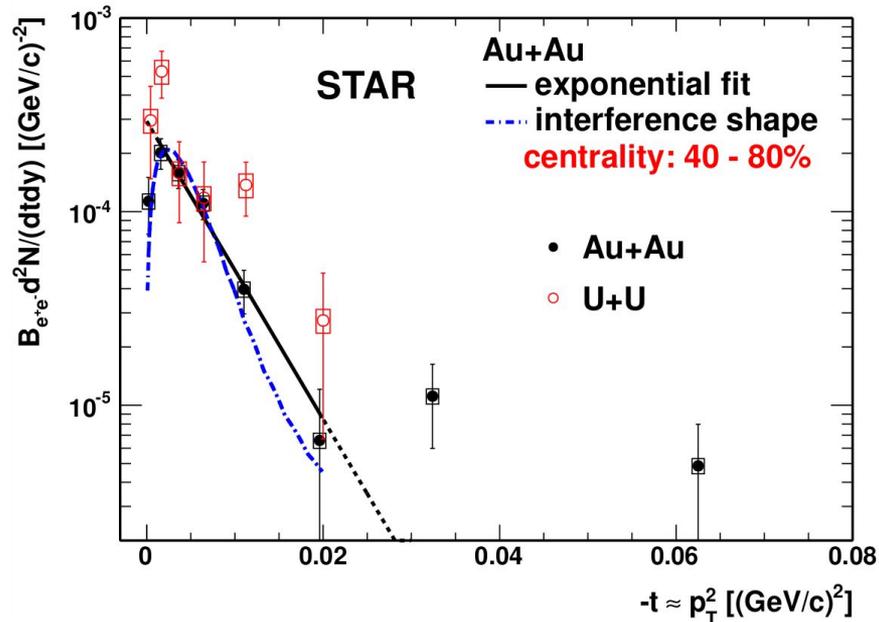
First p_T^2 measurement of the coherent J/ψ photoproduction in PC

- STAR has reported the first measurement of the p_T^2 shape of the corresponding J/ψ excess yield in Au-Au and U-U PC and semi-central collisions [Phys. Rev. Lett. 123, 132302 (2019)].
- For J/ψ photoproduction, Mandelstam variable $t = (p_\gamma - p_{J/\psi})^2 = -p_{T,J/\psi}^2$.



- The shape is very similar to the UPC shape.
- In UPC, the dN/dt distribution is related to the interaction sites in the target and closely related to the parton distribution in the nucleus.

[STAR Collaboration, Phys. Rev. Lett. 123, 132302 (2019)]



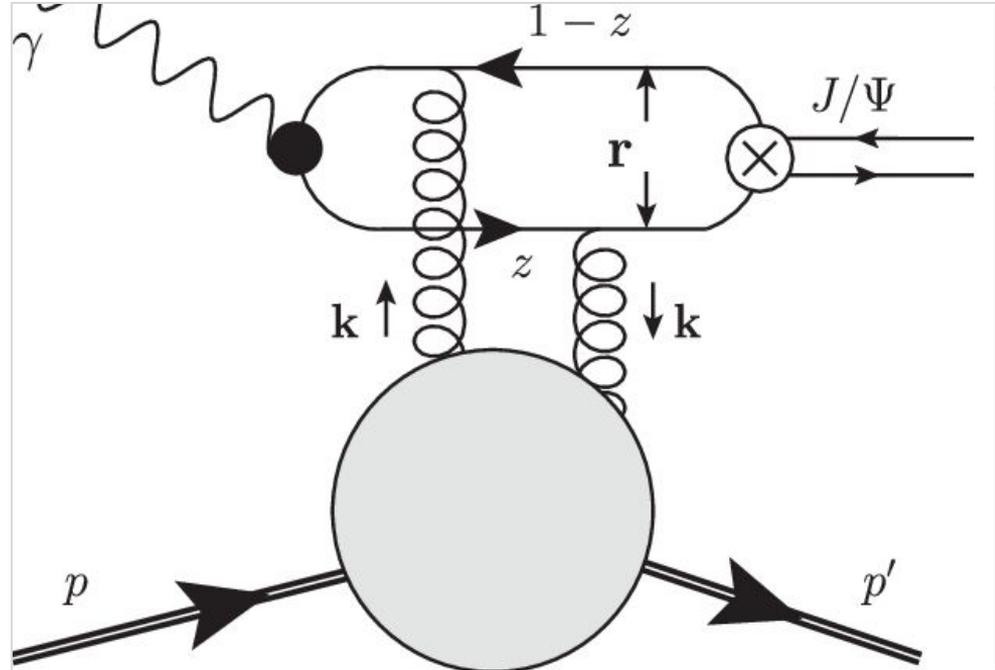
- The extracted position of the interaction site within the target, using the slope of the exponential fit = $177 \pm 23 (GeV/c)^{-2}$, is consistent with what is expected for Au nucleus ($199 (GeV/c)^{-2}$).

Theoretical models of the coherent J/ψ photoproduction in heavy ion collisions

J/ψ photoproduction in the photon dipole picture

γ - target A scattering is 3 steps process:

- γ fluctuate to quark and anti-quark pair, called dipole.
- The dipole-target interaction, modeled via a Pomeron (as an equivalent to two gluons in the perturbative QCD).
- Then the quark & the anti-quark recombine into the vector meson, e.g. J/ψ .



[M. Hentschinski and E. P. Molina, Phys. Rev. D 103, 074008 (2021)]

Theoretical models of the coherent J/ψ photoproduction

- ❖ In the hot spot models (GG-hs & GS-hs), Golec-Biernat and Wusthoff (GBW) and Iancu-Itakura-Munier (IIM) dipole models
 - ◇ The coherent J/ψ photoproduction cross section is factorized into the photon flux and the photo-nucleus cross section.
 - ◇ The γ -flux is extended from the known flux, the Weizsacker-Williams virtual photon spectra, in UPC \Rightarrow PC, considering the fact that there is a nuclear overlap.
- ❖ In the hot spot model [J. Cepila, J. G. Contreras, and M. Krelina, Phys. Rev. C 97, 024901 (2018)]
 - ◇ The proton structure in the b plane is an energy dependent hot spot profile; regions of high-gluon density.
 - ◇ To calculate the photo-nucleus cross section, it is interpolated from the γp case to γA case by two approaches: standard Glauber-Gribov(GG) formalism and Geometrical Scaling (GS).
 - ◇ Both uses the GBW dipole-proton cross section.
 - ◇ GG uses the proton saturation scale while GS calculates a nuclear saturation scale.
- ❖ In the Golec-Biernat and Wusthoff (GBW) and Iancu-Itakura-Munier (IIM) dipole models [M.B. Gay Ducati and S. Martins, Phys. Rev. D 97, 116013 (2018)]
 - ◇ To calculate the photo-nucleus cross section, the color dipole formalism is considered.
 - ◇ IIM model is based on a Color-Glass-Condensate approach.
 - ◇ GBW model implemented two scenarios, one includes modified γA cross section and one does not. The model we are comparing to in this presentation does not include the modification.

Interference effect in J/ψ photoproduction

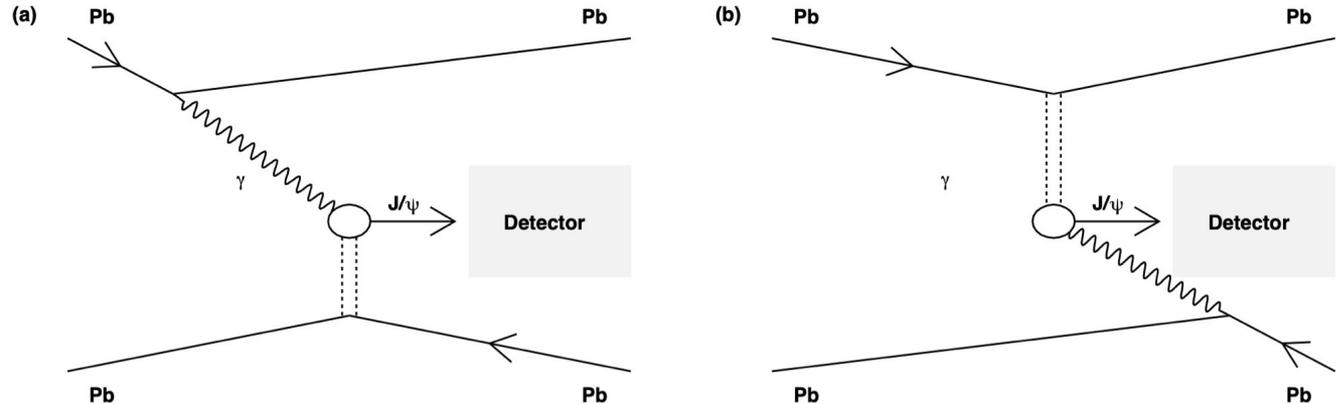
- The cross section of coherent J/ψ photoproduction via photon-pomeron fusion, can be as follows:

$$\sigma(AA \rightarrow AAJ/\psi) = \int d\omega_\gamma \frac{dN_\gamma(\omega_\gamma)}{d\omega_\gamma} \sigma(\gamma A \rightarrow J/\psi A)$$

$$\sigma(p_T, y, b) = A^2(p_T, y, b) + A^2(p_T, -y, b) - 2A(p_T, y, b)A(p_T, -y, b) \times \cos(\vec{p}_T \cdot \vec{b})$$

Interference term

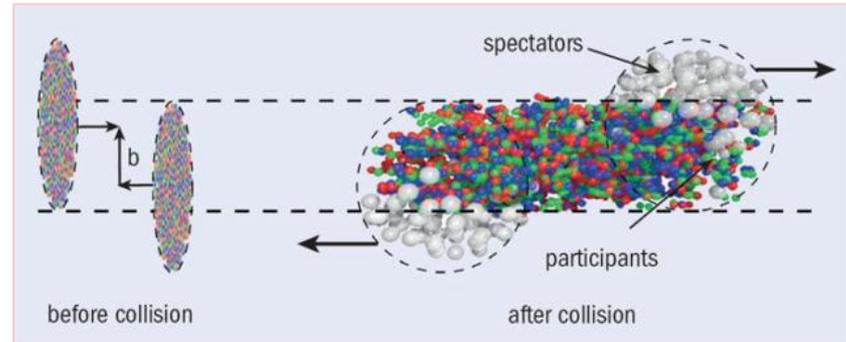
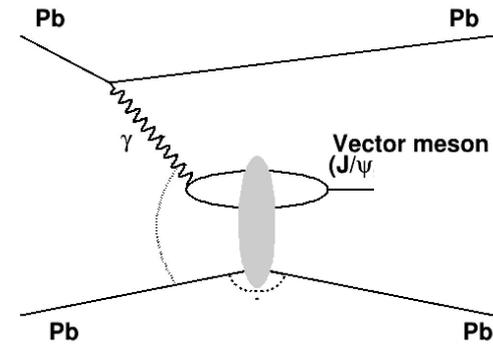
- Interference between J/ψ photoproduction amplitudes on ions moving in opposite directions.



Photon-pomeron fusion model [W. Zha et al., Phys. Rev. C 97, 044910 (2018)]

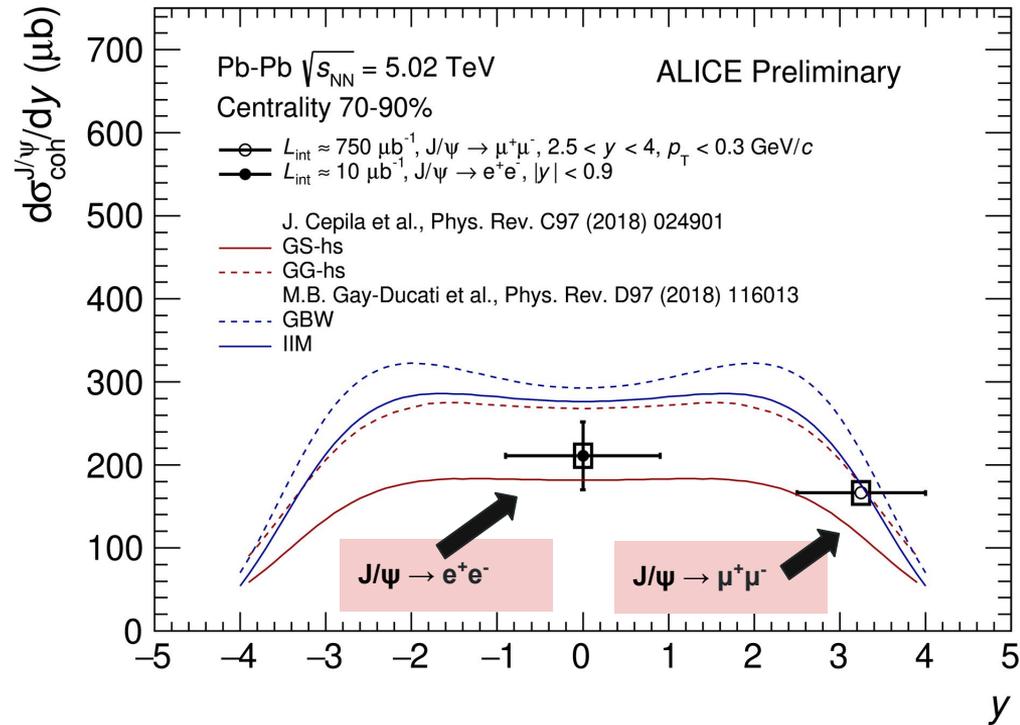
- The coherent J/ψ photoproduction cross section is convolution of the photon flux and the photo-nucleus cross section.
- The γ -flux is extended from UPC \rightarrow PC by including the hadronic interactions.
- The $(\gamma-A)$ cross section is extended from UPC \rightarrow PC
 - Use the $(\gamma-p)$ cross section as an input from parametrization.
 - Includes a destructive interference effect.
 - considers the hadronic interactions effect using the spectators as emitters instead of the whole nucleus.
- Photon emitter-Pomeron emitter coupling scenarios with interference:

- Nucleus+Nucleus
- - - Nucleus+Spectator
- · - · Spectator+Nucleus
- · · · Spectator+Spectator



Coherent J/ψ photoproduction in Pb-Pb peripheral collisions (PC)

- Coherent J/ψ photoproduction cross section measurement by ALICE in PbPb peripheral collisions at low $p_T < 0.3$ GeV/c at both mid and forward rapidity at $\sqrt{s_{NN}} = 5.02$ TeV.
- The models reproduce qualitatively the data.
- More precise and differential measurements are needed to distinguish the best describing model of the coherent J/ψ photoproduction mechanism.

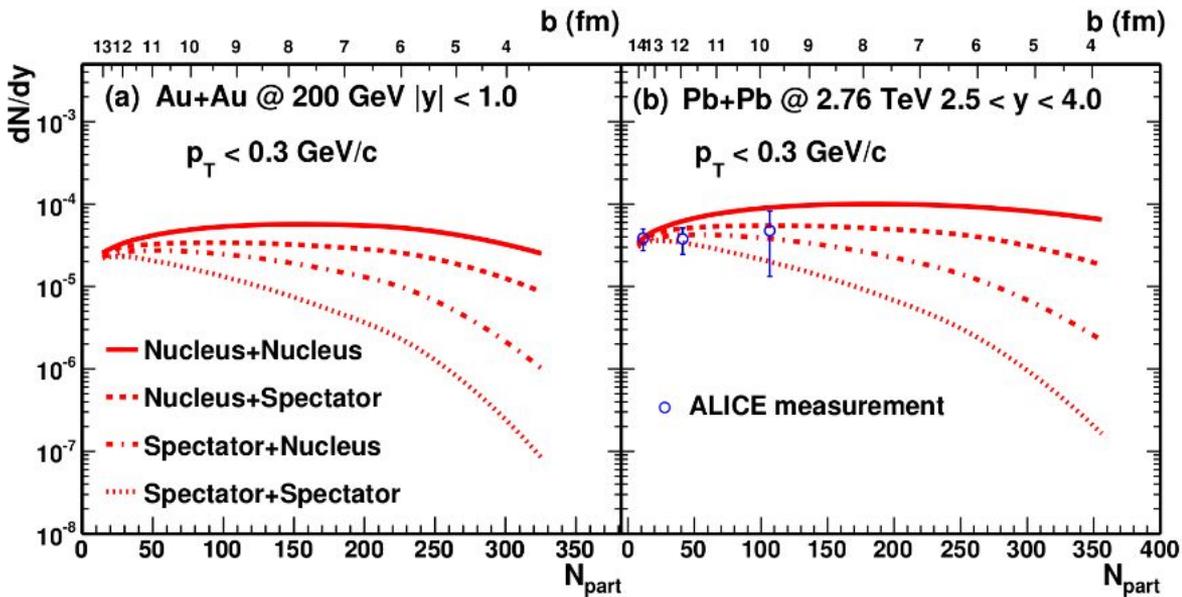


ALI-PREL-367210

Coherent J/ψ photoproduction scenarios via photon-pomeron coupling at ALICE

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

- All scenarios can describe ALICE data.
- Perspectives:
 - Precision measurement is needed toward more central collisions.
 - Cold medium effects and hot medium effects are to be included in the model calculations, e.g. the color screening.

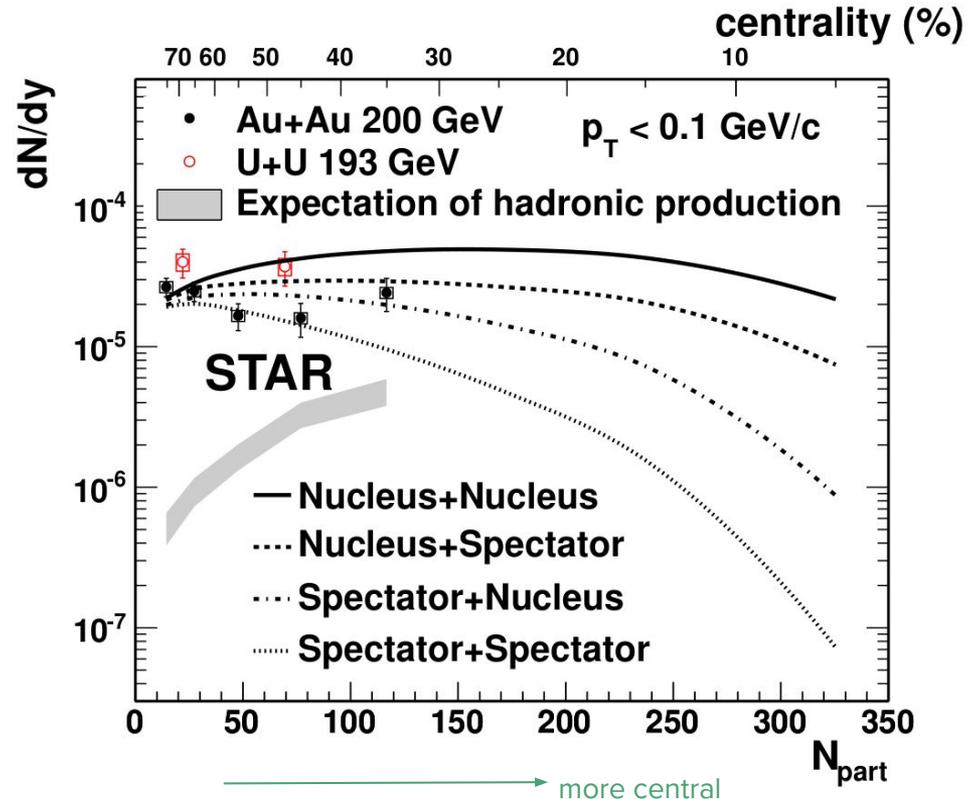


→ more central

Coherent J/ψ photoproduction scenarios via photon-pomeron coupling at STAR

[STAR Collaboration, Phys. Rev. Lett. 123, 132302 (2019)]

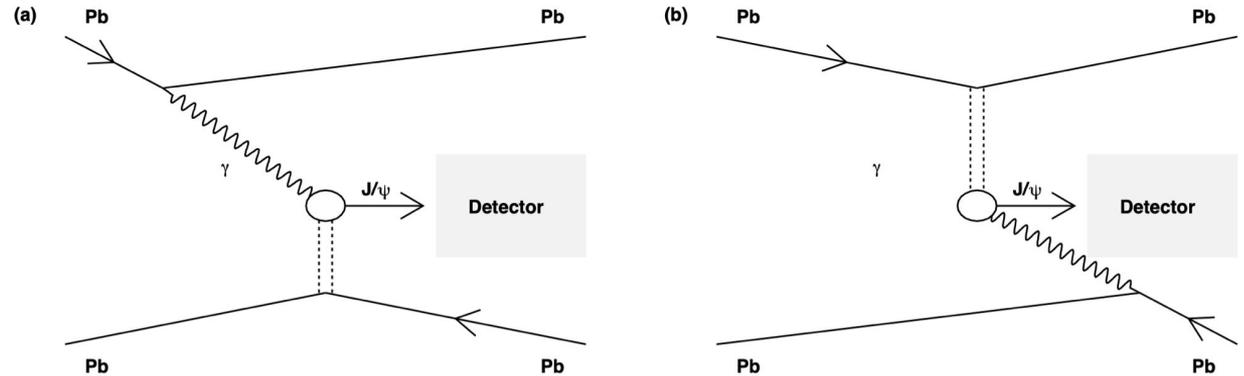
- All scenarios can describe the data in the most peripheral collisions (60-80)%
- Semi-central data seems to favor the scenario N+ S or S+ N, as expected from the hadronic interactions effect.
- The N+ N scenario overestimates the data when going toward more central collisions.
- Perspectives:
 - More measurements toward central region are needed.
 - Cold medium effects and hot medium effects are to be included in the model calculations, e.g. the color screening.



Ideas with coherent J/ψ photoproduction in heavy ion collisions

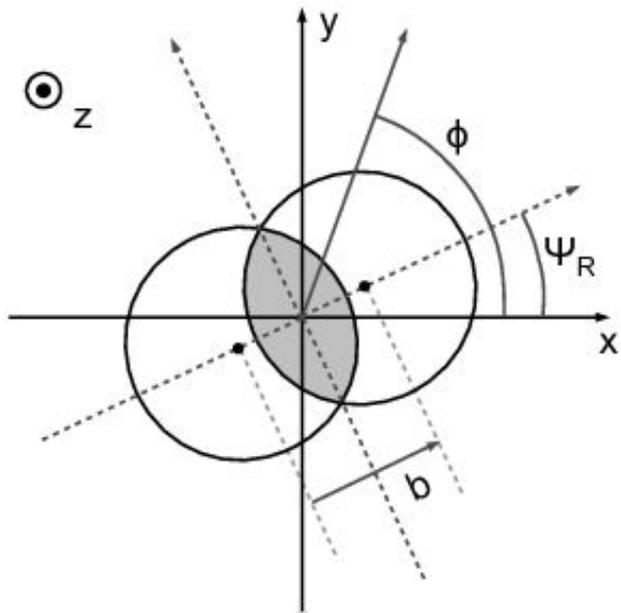
An idea to disentangling the low and high x_g contributions in J/ψ photoproduction

- ◆ Each colliding nucleus could serve as a photon emitter, the other acts as a target (+/- y)
 - ◇ Contribution from low/ high x_g $x_g = (M_{J/\psi}/\sqrt{S_{NN}}) e^{\pm y}$
 - ◇ Proposed solution by [[J. G. Contreras, PRC 96, 015203 \(2017\)](#)]: use PC measurement with the previous UPC measurement to disentangle the contribution from the low and high energy photon-nucleus interaction.
 - ◇ Caveat: this suggestion considers the photon-nucleus cross sections in both PC and UPC to be the same.



Anisotropy in the coherent J/ψ photoproduction yield in PC: Definition of the reaction plane

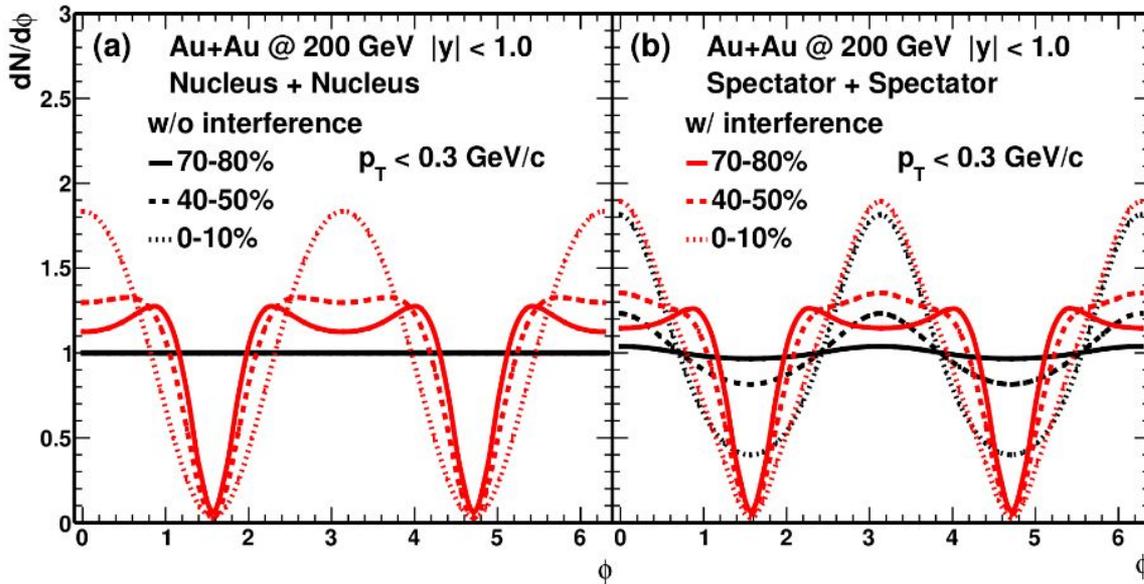
- A schematic diagram of a noncentral nucleus-nucleus collision viewed in the plane orthogonal to the beam.
- The reaction plane: contains the impact parameter vector b and the beam axis.
- Ψ_R is the reaction plane angle .



Anisotropy in the coherent J/ψ photoproduction yield in PC

- $dN/d\phi$: the angular distributions of the coherent J/ψ with respect to the reaction plane.
- The initial collision geometry induced anisotropy vanishes in more central collisions and at low p_T region.

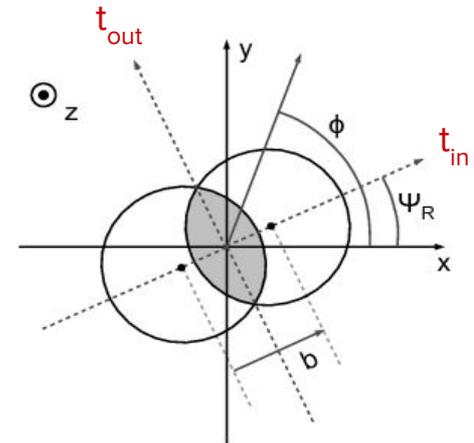
[W. Zha et al., Phys. Rev. C 97, 044910 (2018)]



- An anisotropy is predicted for the coherent J/ψ photoproduction at mid rapidity $|y| < 1$ and at low p_T region, to originate from an asymmetric density profiles of the emitters considering the destructive interference effects.
- Using the angular distribution \Rightarrow It is expected to distinguish the coherently photoproduced J/ψ from hadronic production.

Imaging heavy-ion collisions in peripheral Pb-Pb collisions

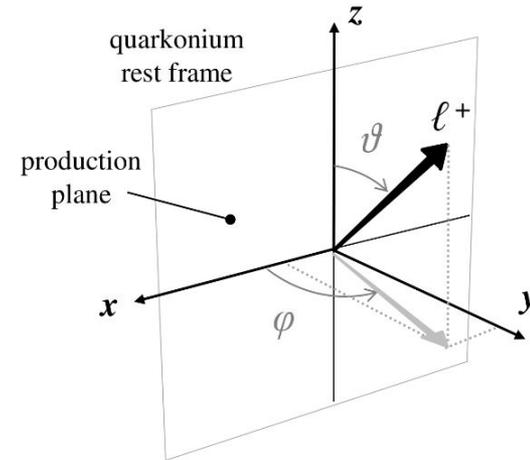
- Proposal of imaging the heavy ion collision via the study of $|t_{in}|$ and $|t_{out}|$ dependence of the J/ψ photoproduction cross section, where:
 - $|t_{in}|$ (in plane): p_T^2 in the direction of the impact parameter vector b .
 - $|t_{out}|$ (out of plane): p_T^2 in the transverse plane perpendicular to the b vector
- Peripheral collision \rightarrow overlapping region \rightarrow charged particles production \rightarrow determination of the event plane \rightarrow should allow to extract the form factor distributions.
- The J/ψ mid rapidity region has the maximum destructive interference effect, so the interference effect could be seen in the image via $J/\psi \rightarrow e^+e^-$ channel in ALICE thanks to the very good central barrel resolution in Run 3.



J/ψ Polarization in heavy ion collisions

J/ψ Polarization in heavy ion collisions

- J/ψ ($J^{PC} = 1^{-}$), so $|J, J_z\rangle_{J/\psi} = b_{-1}|1, -1\rangle + b_0|1, 0\rangle + b_{+1}|1, +1\rangle$
- Possible states:
 - longitudinal polarization: $b_0 = 1, b_{\pm 1} = 0$.
 - Transverse polarization: $b_0 = 0, |b_{+1}|^2 + |b_{-1}|^2 = 1$
- Polarization of hadroproduced J/ψ in heavy ion collisions is expected to be different from the polarization in pp collisions, due to nuclear medium effects.
- Photoproduced J/ψ is expected to have a different polarization from the hadroproduced J/ψ as it originates from a different mechanism.
- Coherent photoproduced J/ψ are expected to have a transverse polarization.
- ALICE had the first measurement of polarization of hadroproduced J/ψ in heavy-ion collisions [[PLB 815 \(2021\) 136146](#)].
- The polarization parameters are extracted from the dimuon decay angular distribution information in the J/ψ rest frame relative to a chosen reference frame.



[Eur. Phys. J. C (2010) 69; 657-673]

Angular variables definition for the J/ψ polarization determination

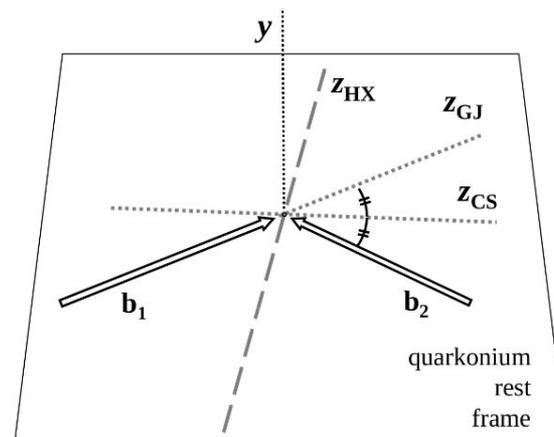
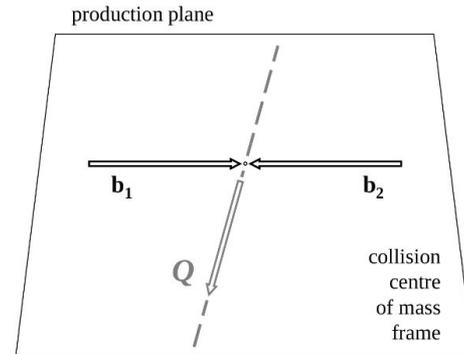
- The polarization axis definition in the chosen reference frame:
 - Helicity (denoted HX): is the J/ψ direction in the lab frame
 - Collins-Soper (denoted CS): is the bisector of the angle between the beam and the opposite of the other beam in the J/ψ rest frame.

- By measuring the angular distributions of the dimuon $W(\theta, \Phi)$ relative to the chosen axis in the J/ψ rest frame, the polarization parameters $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ are extracted

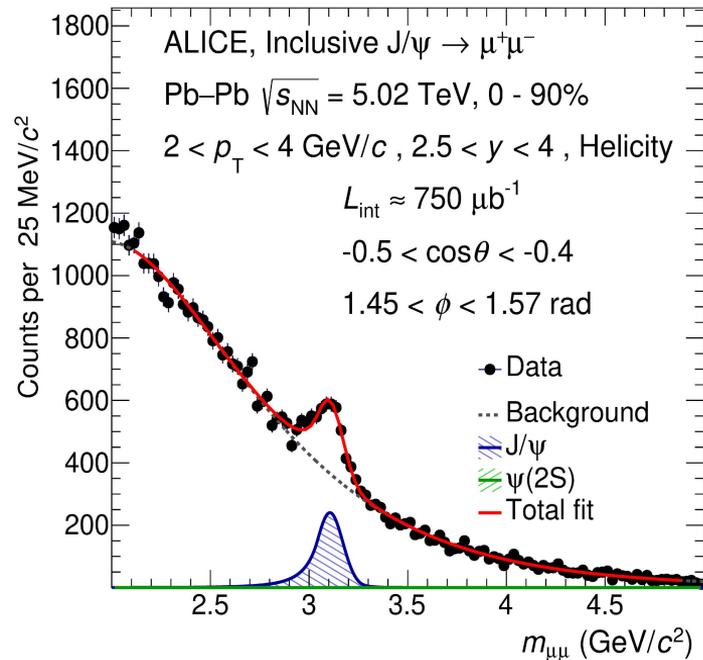
$$W(\theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \times \left(1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi \right)$$

- The J/ψ polarization is strongly related to the parameters $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$, that are combinations of elements of the J/ψ production spin matrix density :

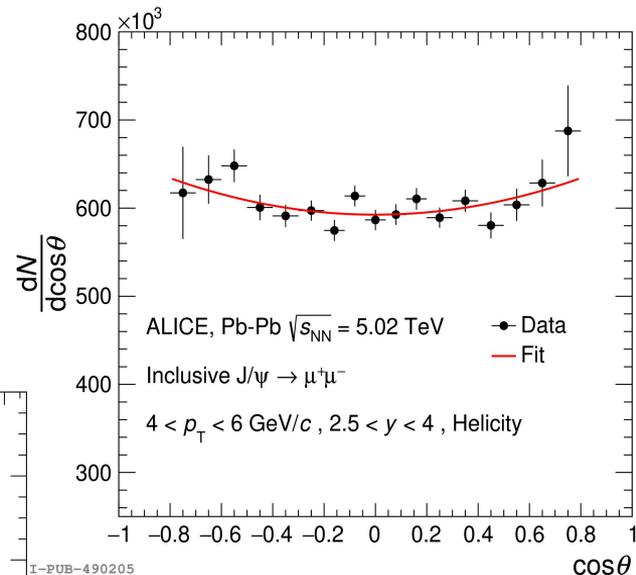
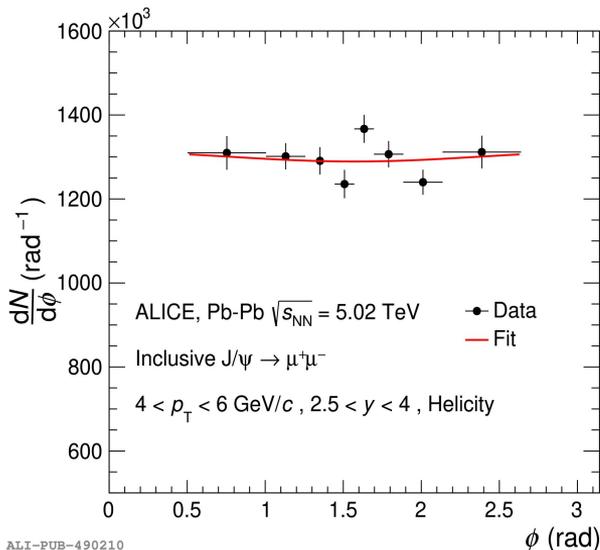
- $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0)$ if no polarization
- $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0)$ if longitudinal polarization
- $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1, 0, 0)$ if transverse polarization



Polarization measurement of inclusive J/ψ at forward rapidity in Pb-Pb collisions



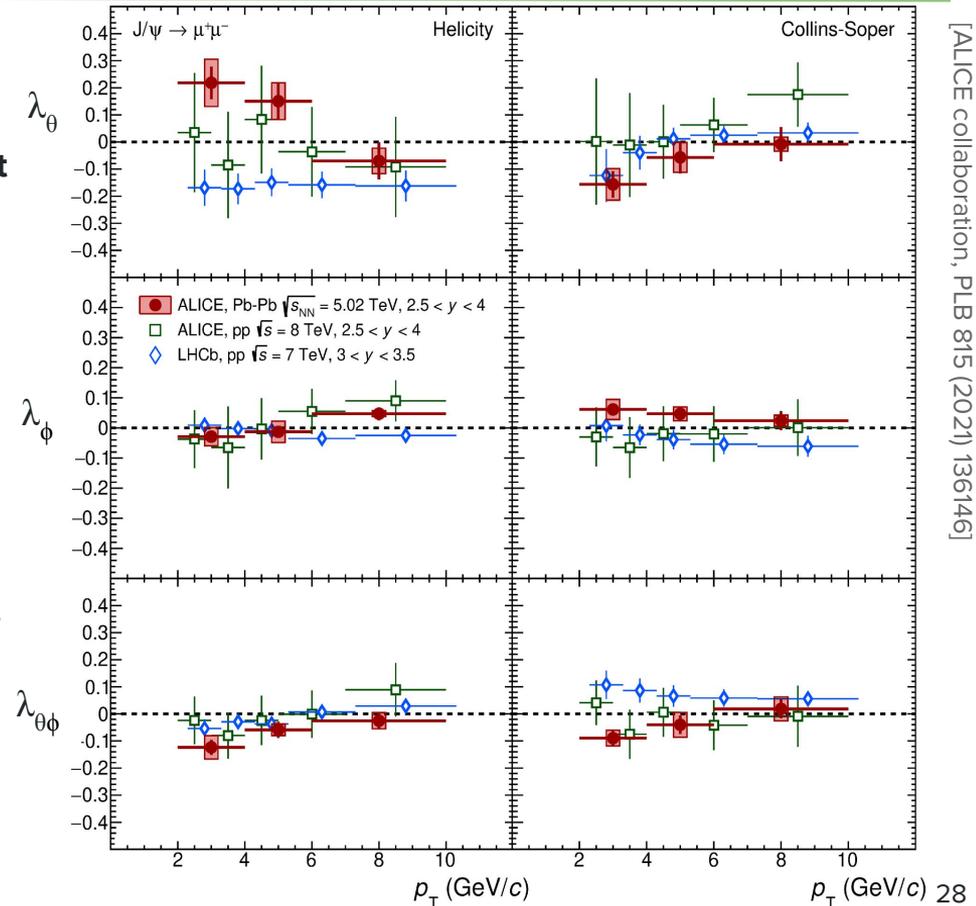
- Via the decay channel J/ψ ($J^{PC} = 1^{--}$) $\rightarrow \mu^+\mu^-$



[ALICE collaboration, PLB 815 (2021) 136146]

Polarization of inclusive J/ψ at forward rapidity in Pb-Pb collisions

- In $2.5 < y < 4$, at $\sqrt{s_{NN}} = 5.02$ TeV in Pb-Pb collisions of centrality (0-90)% \Rightarrow Polarization parameters of the J/ψ are consistent with zero in $2 < p_T < 10$ GeV/c, within a maximum deviation of 2σ for low p_T .
- ALICE measurement in Pb-Pb is compatible with the one in pp within uncertainties.
- An Interesting feature at low p_T , ALICE data in PbPb collisions indicates within 2σ a small transverse polarization in helicity frame, while the LHCb result in pp collisions, that is more precise, at higher energy in similar kinematic region in the same frame indicates to a longitudinal polarization!
- A production mechanism effect ?



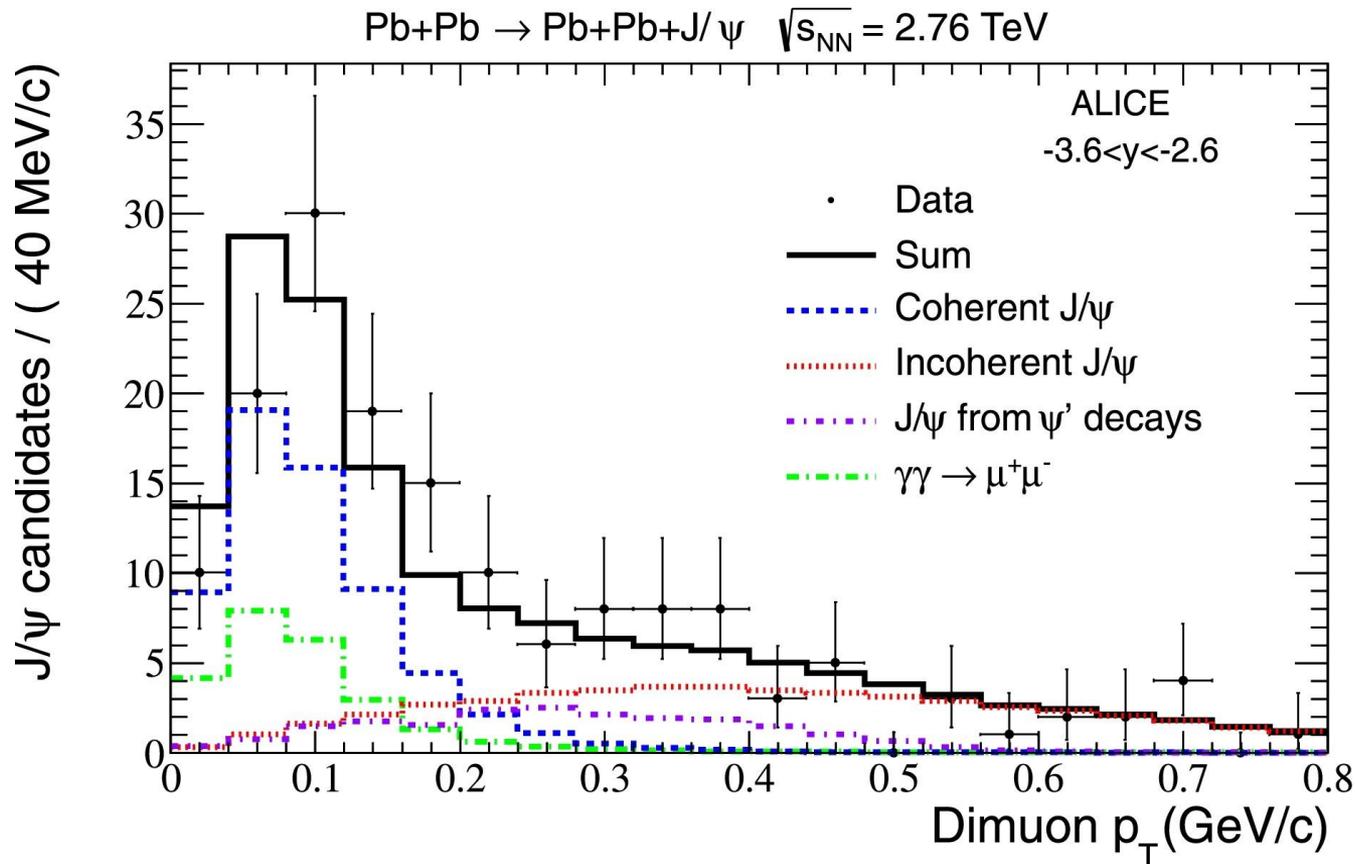
Summary and perspectives

- ★ **Coherent photoproduction of J/ψ was observed by ALICE, STAR and LHCb in peripheral and semicentral heavy ion collisions of Pb-Pb, Au-Au and U-U systems at different energies.**
- ★ **Many theoretical models were successful to reproduce the order of magnitude of the measured coherent J/ψ photoproduction cross section, such as the hot spot model, GBW and IIM dipole models.**
- ★ **Four possible scenarios for coherent J/ψ photoproduction via photon- pomeron fusion were proposed and are consistent with data within uncertainties.**
- ★ A measurement we would like to do in ALICE Run 3 (2022) is the polarization of the coherent J/ψ photoproduction in Pb-Pb PC.
- ★ More precise and differential measurement in rapidity toward more central collisions are needed.
- ★ Many theoretical developments are needed to include the cold, hot nuclear matter effects and interference effect in their calculations.
- ★ Coherent J/ψ photoproduction in PC could provide an image of the heavy ion collision producing the J/ψ .
- ★ **The inclusive hadroproduction of J/ψ is consistent with zero.**
- ★ Photoproduction of J/ψ is hoped to be a novel probe of the QGP and the gluon distributions inside nuclei.

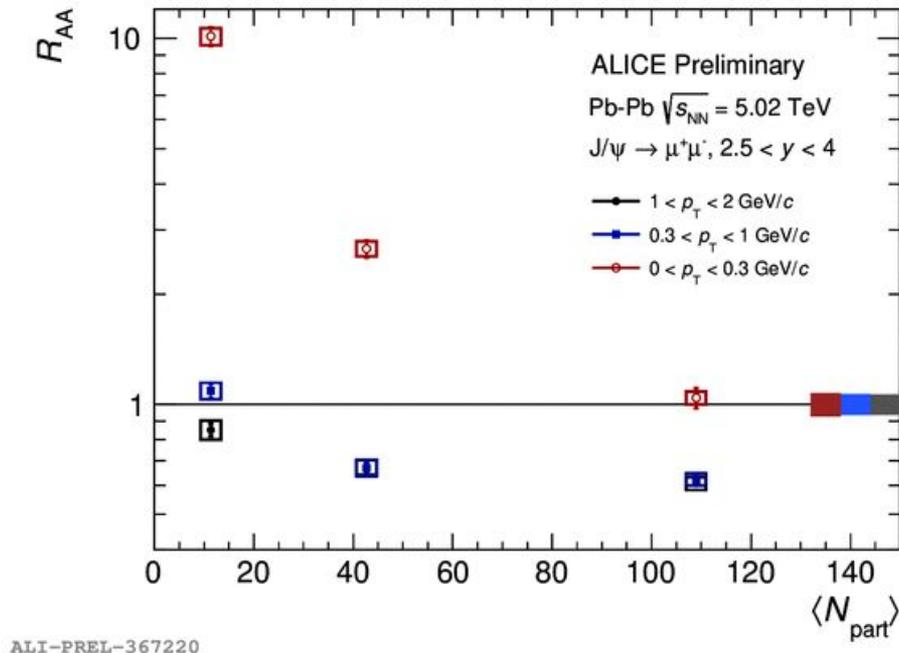
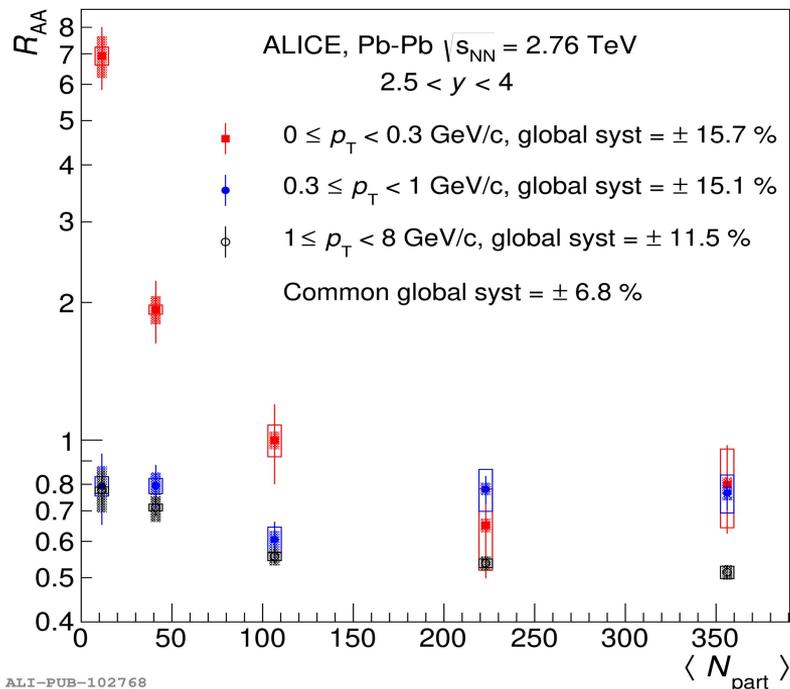
Thank you !

Backup

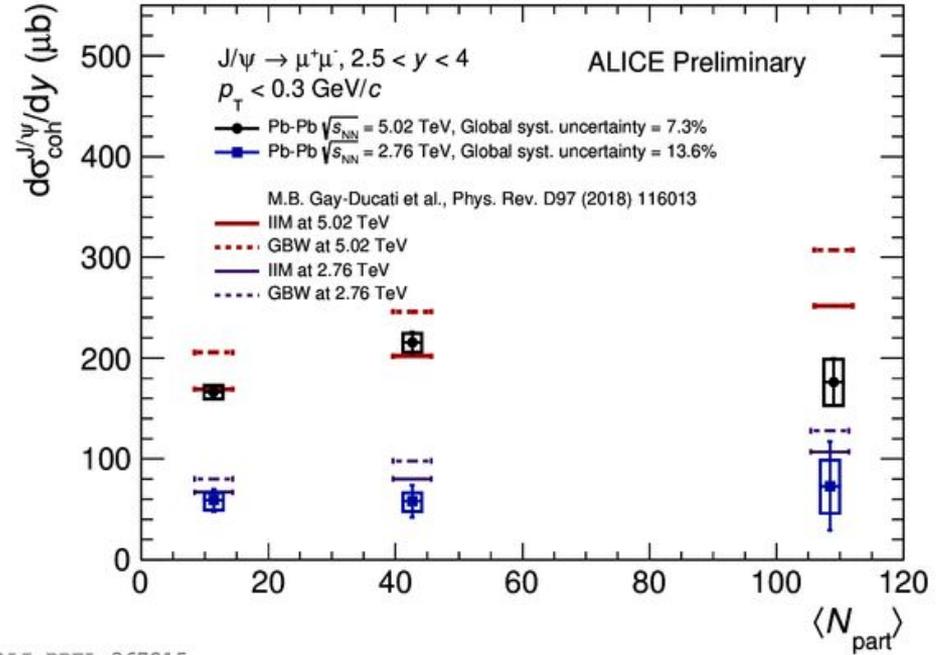
UPC: p_T spectrum of J/ψ candidates from various contributions



R_{AA} Vs. Centrality



Coherent J/ψ photoproduction cross section Vs. Centrality



ALI-PREL-367215