New ALICE results on the energy dependence of coherent photoproduction of J/ψ in ultra-peripheral Pb-Pb collisions

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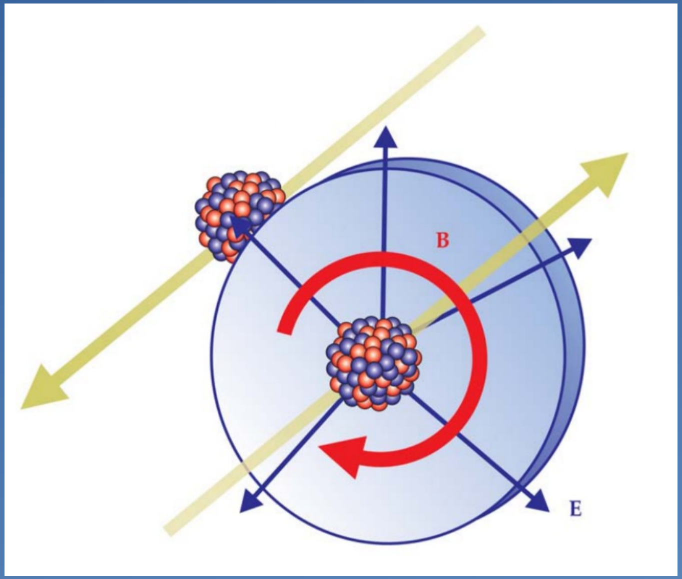
for the ALICE collaboration

What are ultra-peripheral collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.



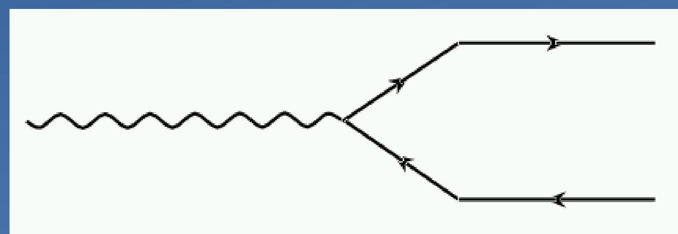
The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

UPCs represent the energy frontier for electromagnetic and electroweak interactions.

Photonuclear interactions in UPC

A variety of photonuclear and two-photon interactions may occur in an ultra-peripheral collision at the LHC.

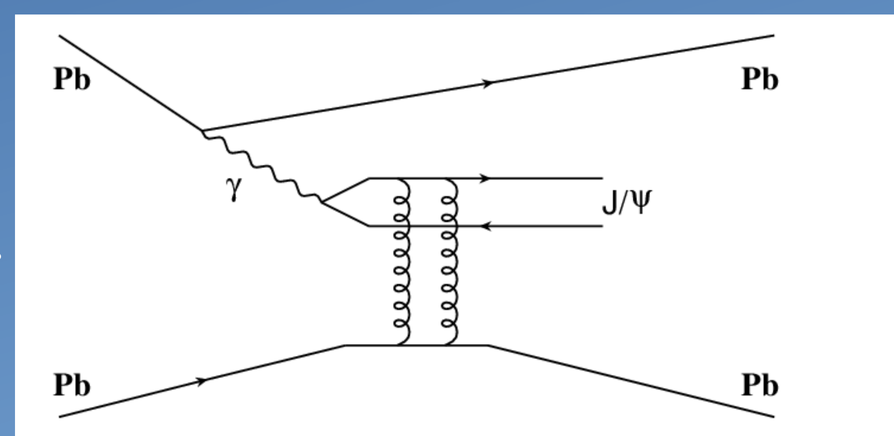
Vector meson dominance (VMD): Quantum numbers of the photon $J^{PC} = 1^{--} \Rightarrow$ High probability for fluctuation to vector neson.



While in the vector meson state, it will interact strongly.
The virtual qq-pair is knocked on mass shell by scattering off the target nucleus.

Target remains intact ⇨
Color-neutral exchange particle.

2-gluon or ”Pomeron” exchange.



Photonuclear interactions in UPC

Early, leading-order calculation related the cross section to the gluon distribution.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993
(Z. Phys. 57 (1993) 89)

Attempts have been made to incorporate NLO effects[1,2]:

EFGLP: Strong sensitivity to choice of scale, surprisingly large contribution from quarks.

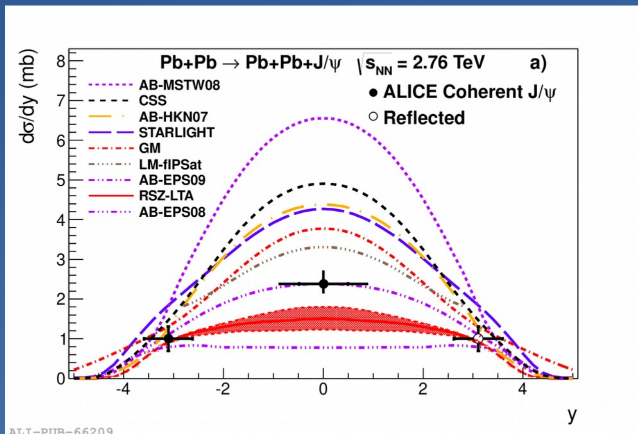
But one is able to find a good description of the measured cross section over the full rapidity range and for two different collision energies with a certain choice of scale.

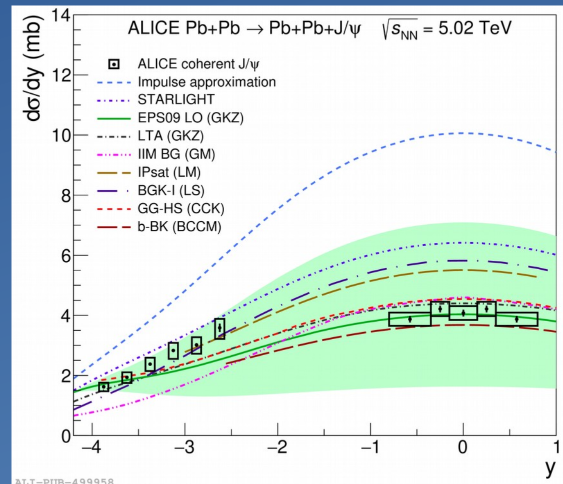
Scale uncertainty reduced if one considers the ratio σ(Pb-Pb)/σ(O-O).

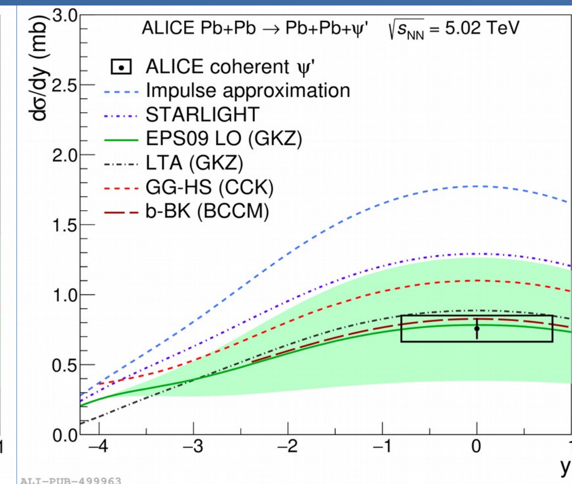
[1]Jones, Martin, Ryskin, Teubner, J. Phys. G 43 (2016) 035002;
[2]Eskola, Flett, Guzey, Löytäinen, Paukkunen, Phys. Rev. C 106 (2022) 035202; 107 (2023) 044912. ==> Talk by K. Eskola Wed. 12:00.

Photonuclear interactions in UPC

Exclusive J/ψ and ψ(2S) photoproduction has been studied by ALICE in Run 1 and 2.







ALICE Collaboration, PLB 718 (2013) 1273; EPJC 73 (2013) 2617; EPJC 82 (2021) 712.

Midrapidity results consistent with models which include a moderate amount of shadowing, probed down to Bjorken $x \sim 10^{-3}$.

Photonuclear interactions in UPC

Summary of recently submitted papers on UPC from ALICE:

- First measurement of the |*t*|-dependence of incoherent J/ψ photonuclear production, https://arxiv.org/abs/2305.06169. ⇐ See poster by David Grund.

- Exclusive and dissociative J/ψ photoproduction, and exclusive dimuon production, in p−Pb collisions at 8.16 TeV, https://arxiv.org/abs/2304.12403.

- First polarisation measurement of coherently photoproduced J/ψ in ultra-peripheral Pb−Pb collisions at 5.02 TeV, https://arxiv.org/abs/2304.10928.

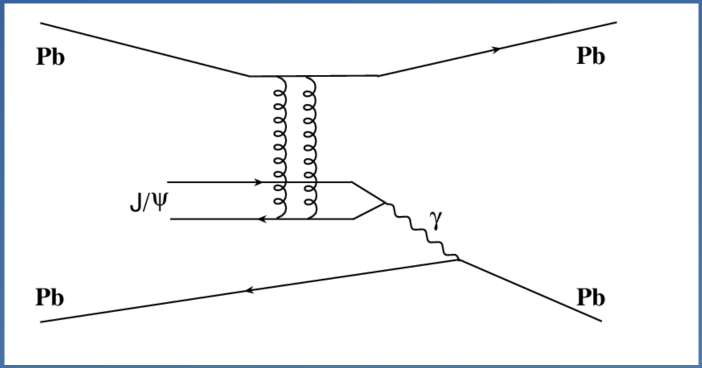
- Energy dependence of coherent photonuclear production of J/ψ mesons in ultra-peripheral Pb-Pb collisions at 5.02 TeV, https://arxiv.org/abs/2305.19060.

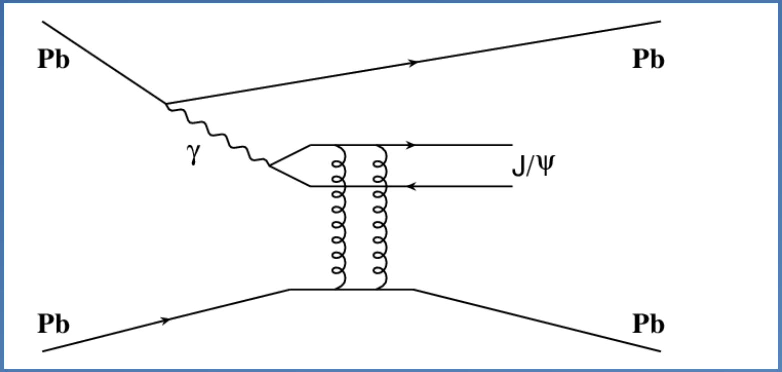
Focus of this talk: Energy dependence of coherent photonuclear production of J/ψ mesons in ultra-peripheral Pb-Pb collisions at 5.02 TeV.

Photonuclear interactions in UPC

Exclusive J/ψ photoproduction away from midrapidity has so far mostly probed the high-*x* region.

In a Pb-Pb collision, both nuclei can emit photons and act as targets.





Kinematics: A vector meson produced at a rapidity $y \neq 0$ will have contributions from two different photon energies, k_1 and k_2, and these correspond to two different γ-p CM energies, $W_{\gamma p,1}$ and $W_{\gamma p,2}$.

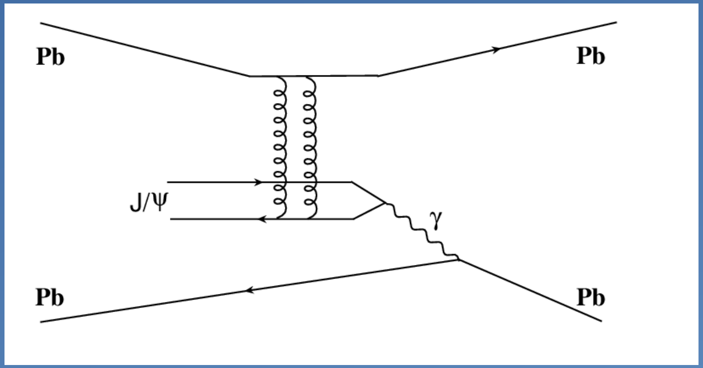
$$\frac{d\sigma}{dy} = n(k_1)\sigma_{\gamma A}(W_{\gamma p,1}) + n(k_2)\sigma_{\gamma A}(W_{\gamma p,2})$$

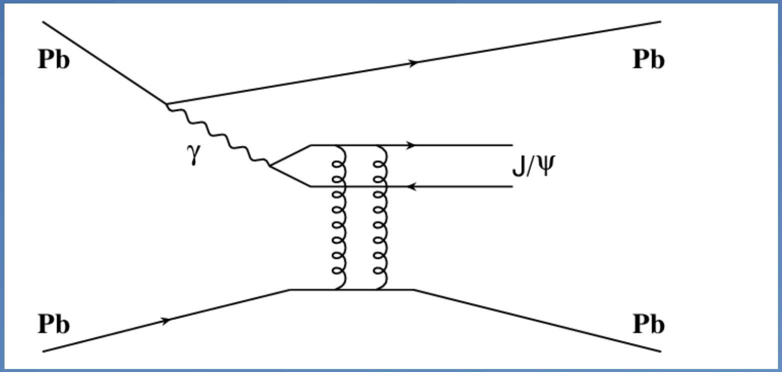
Photonuclear interactions in UPC

A J/ψ produced at rapidity y =3 in a Pb+Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV will have contributions corresponding to $W_{\gamma p,1}$ = 28 GeV and $W_{\gamma p,2}$ = 560 GeV.

$x = (m_V/W_{\gamma p})^2 \Rightarrow$ Bjorken x-values of $1.2\cdot10^{-2}$ and $3.1\cdot10^{-5}$.

STARLight[1]: Low energy photons contribute 83% of the cross section and the high energy photons only 17%.



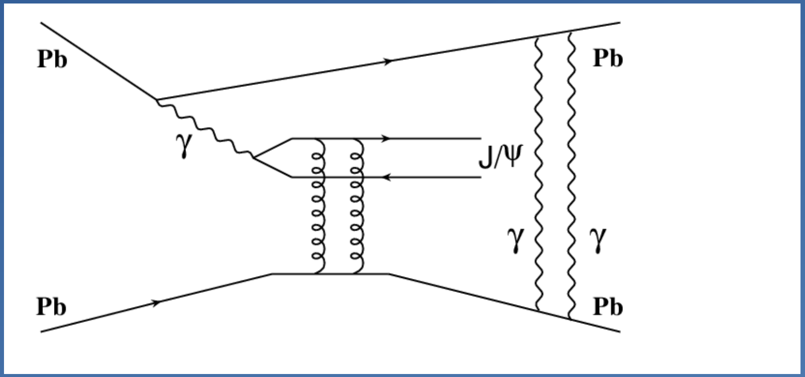


[1]S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comput. Phys. Commun. 212 (2017) 258.

Photonuclear interactions in UPC

How can one separate the low-x and high-x contributions for a given rapidity?

Exchange of multiple photons!



Can divide events into breakup classes:

0n0n – no neutrons emitted.

0nXn – neutrons emitted in one direction but not in the other.

XnXn – neutrons emitted in both directions.

Strong EM fields ==> High probability to exchange one or more additional photons in a UPC.

Typically low energy photons.

Dominating interaction for heavy nuclei: Excitation into a giant dipole resonance (GDR).

Leads to breakup of the nucleus.

Neutrons emitted in the forward direction.

Photonuclear interactions in UPC

The probability to emit additional photons is assumed to factorize in impact parameter space ⇒ modified impact parameter distributions for different breakup classes ⇒ modified photon spectrum (Baltz, Klein, Nystrand, PRL 89 (2002) 012301).

One can write the cross sections

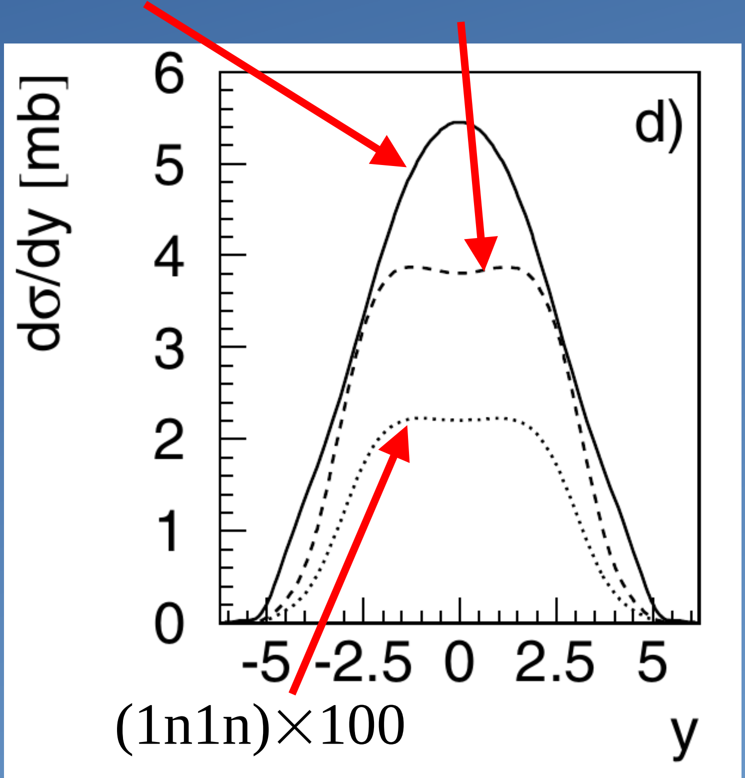
$$\frac{d\sigma_{0n0n}}{dy} = n_{0n0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{0n0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

$$\frac{d\sigma_{Xn0n}}{dy} = n_{Xn0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{Xn0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

$$\frac{d\sigma_{XnXn}}{dy} = n_{XnXn}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{XnXn}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

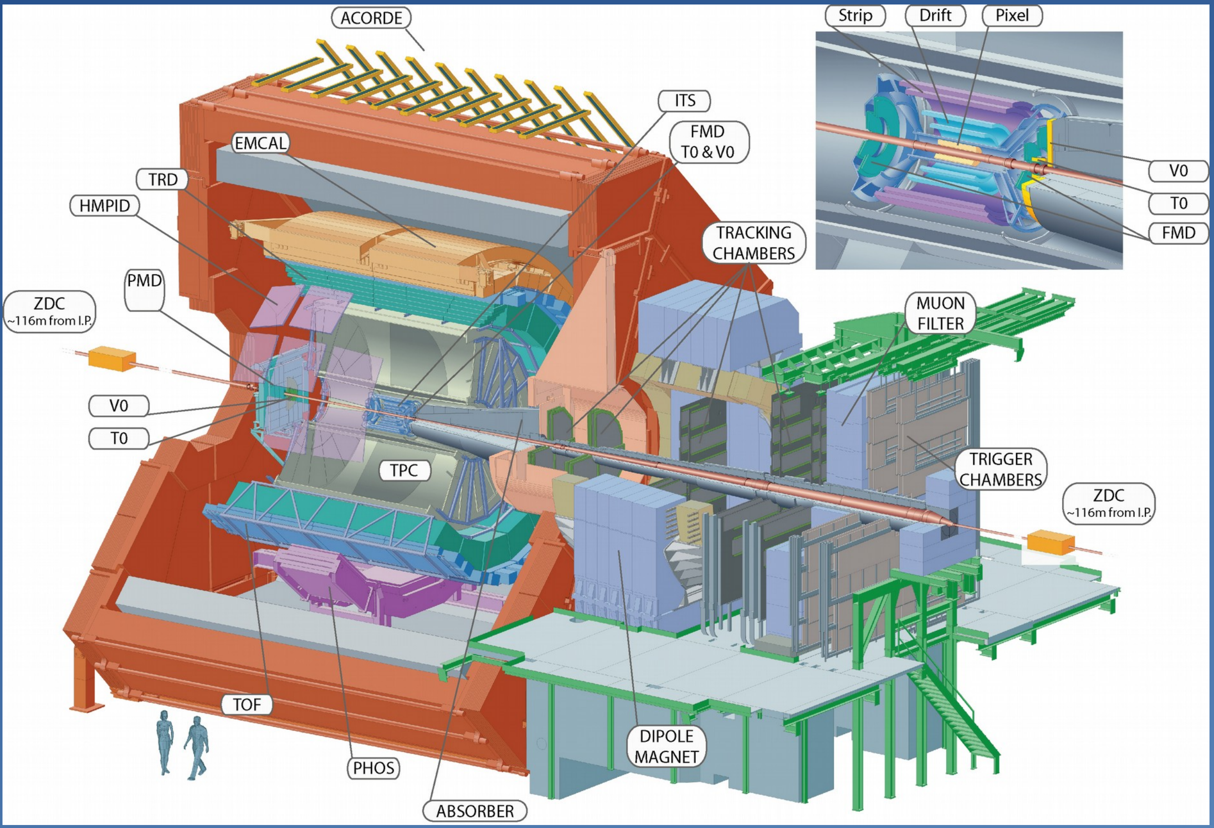
A system of equations which can be solved to extract $\sigma_{\gamma A}(W_{\gamma p1})$ and $\sigma_{\gamma A}(W_{\gamma p2})$.

Guzey, Strikman, Zhalov, EPJC 74 (2014) 2942.



Pb+Pb → Pb*+Pb*+J/ψ
PRL 89 (2002) 012301.

The ALICE Experiment Run 1 and 2



A central tracking system with particle identification.

Acceptance $|\eta| \leq 0.9$, $p_T > 100$ MeV/c.

Trigger from SPD and TOF.

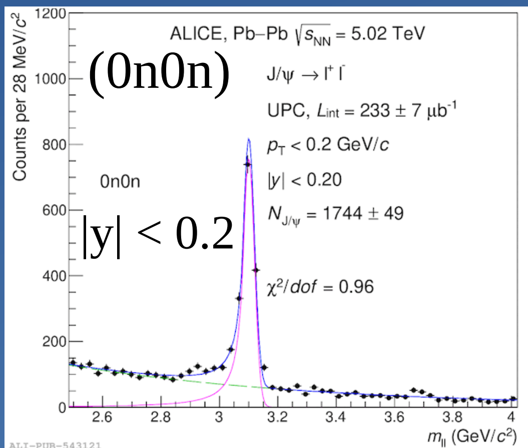
- A muon arm at forward rapidities $-4.0 < \eta < -2.5$. Triggering, tracking and identification of muons.

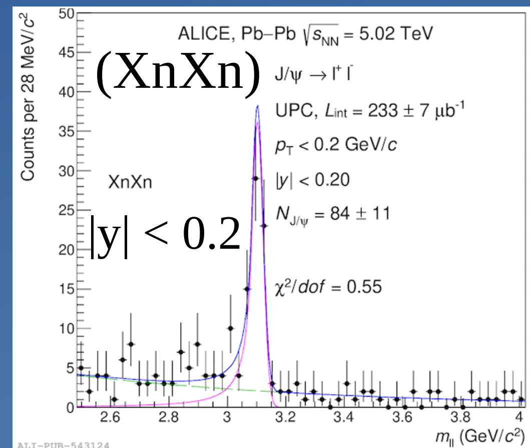
- VZERO counters for triggering; used here as veto detectors to define rapidity gaps ($-3.7 < \eta < -1.7$) and ($2.8 < \eta < 5.1$)

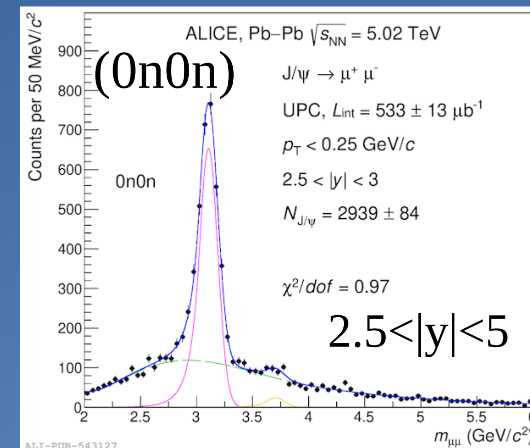
- Zero Degree Calorimeters (ZDC) – detects neutrons from nuclear breakup.

Exclusive photoproduction of J/ψ

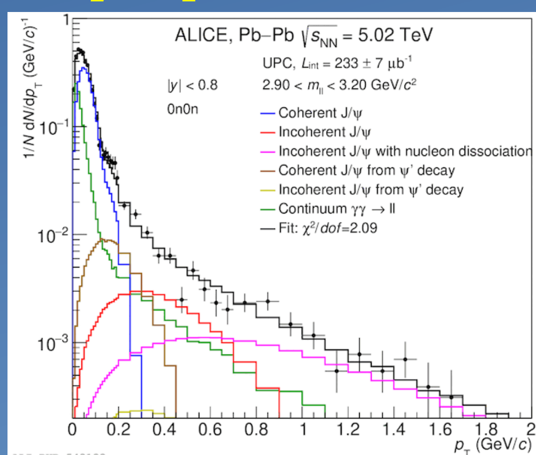
Exclusive photoproduction of J/ψ can be measured in the dilepton decay channel at mid- and forward rapidities divided in breakup classes (0n0n), (Xn0n), and (XnXn): ALICE Collaboration arXiv:2305.19060

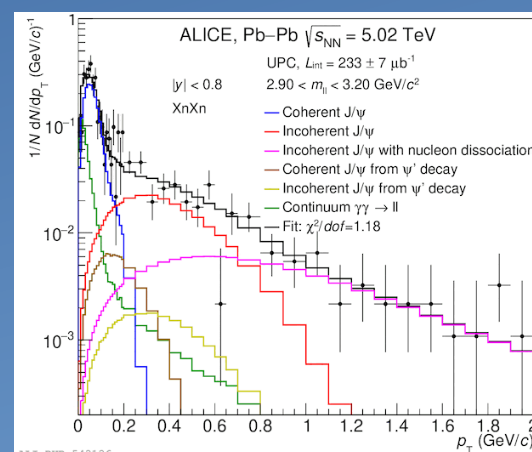


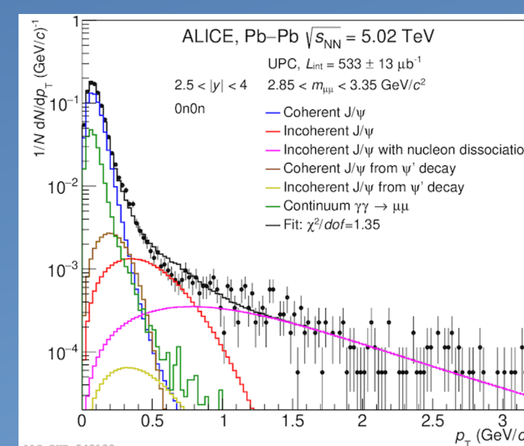




The p_T spectra show a clear coherent peak.

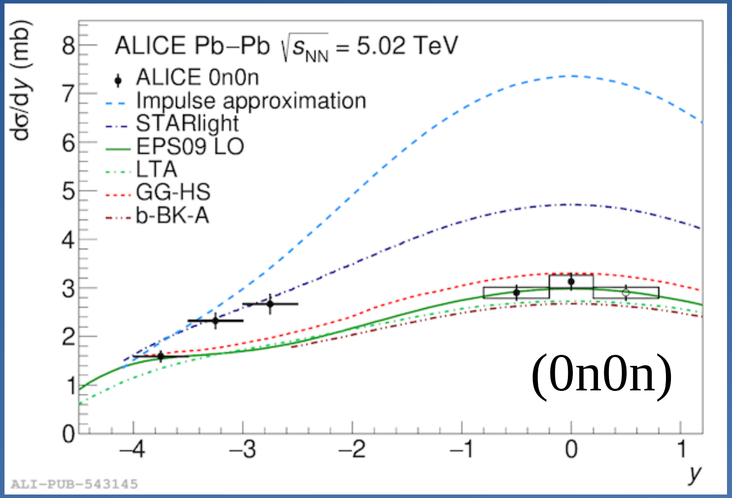


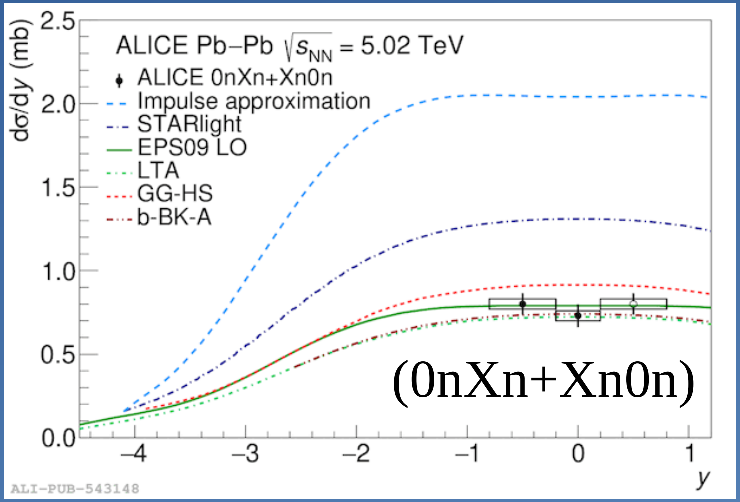


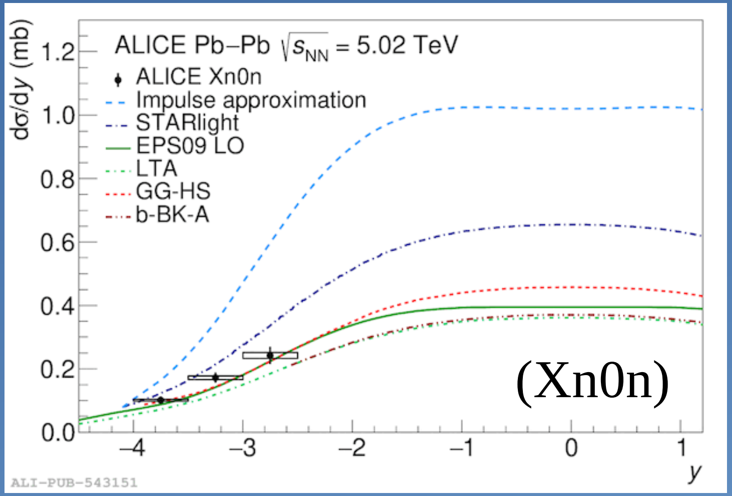


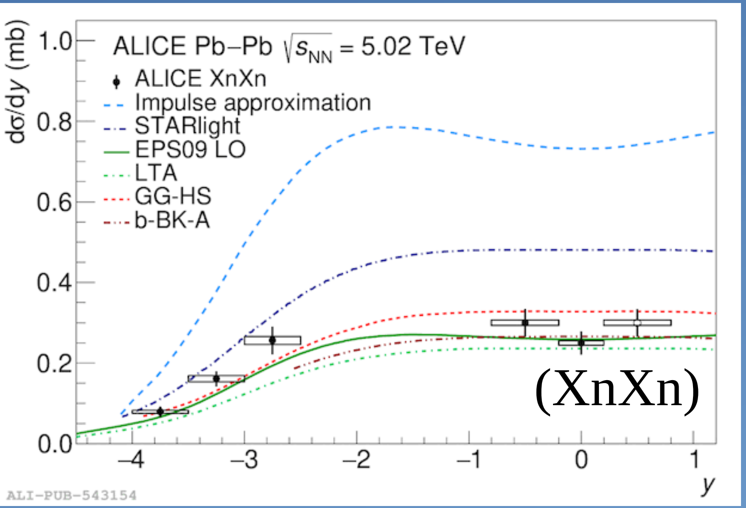
Exclusive photoproduction of J/ψ

The J/ψ cross section has been measured in 6 rapidity bins.









ALICE Collaboration arXiv:2305.19060

Extracting the photonuclear J/ψ cross section

The system of equations is solved from these measurements using a χ^2 minimization technique which takes into account the correlated uncertainties.

$$\frac{d\sigma_{0n0n}}{dy} = n_{0n0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{0n0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

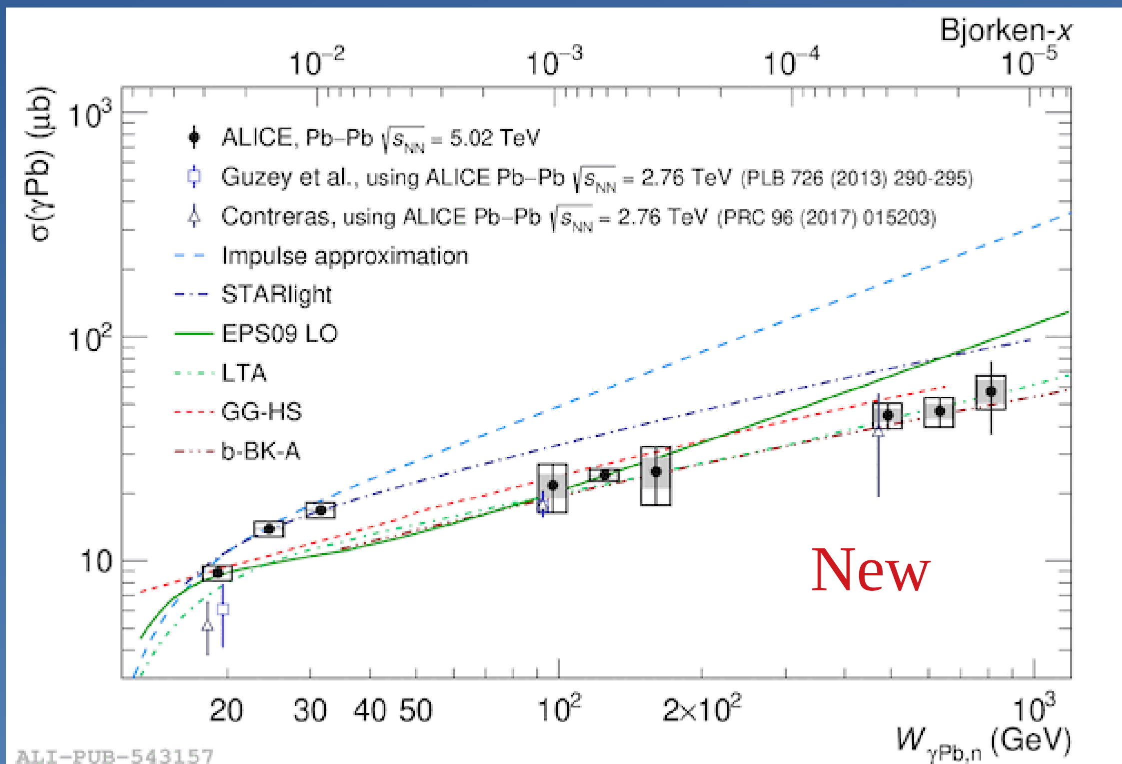
$$\frac{d\sigma_{Xn0n}}{dy} = n_{Xn0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{Xn0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

$$\frac{d\sigma_{XnXn}}{dy} = n_{XnXn}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{XnXn}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

The photon spectra are calculated from the n00n Monte Carlo (Broz, Contreras, Tapia Takaki, Comput. Phys. Commun. (2020) 107181).

Extracting the photonuclear J/ψ cross section

The cross section $\sigma(\gamma + A \rightarrow J/\psi + A)$ can then be measured over the energy range 20 GeV $\leq \mathbf{W}_{\gamma p} \leq$ 800 GeV in a single experiment! This corresponds to $10^{-5} \leq x \leq 10^{-2}$.



ALICE Collaboration arXiv:2305.19060

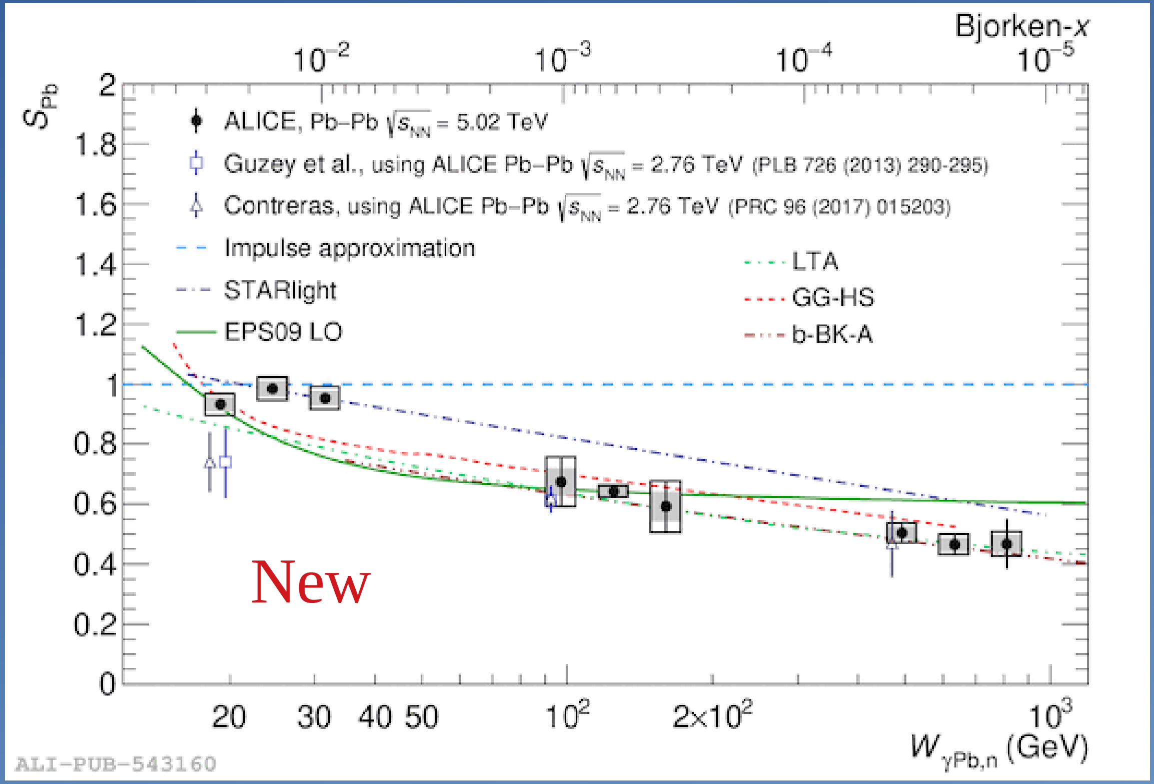
Guzey et al. and Contreras based on ALICE Run 1 data.

Data in agreement with STARLight (hadron based) and impulse approximation in the $x \approx 10^{-2}$ range, while for lower x a suppression is observed, indicating the onset of nuclear shadowing.

Extracting the photonuclear J/ψ cross section

The suppression can be quantified by taking the ratio of the measured cross section to the cross section in the impulse approximation:

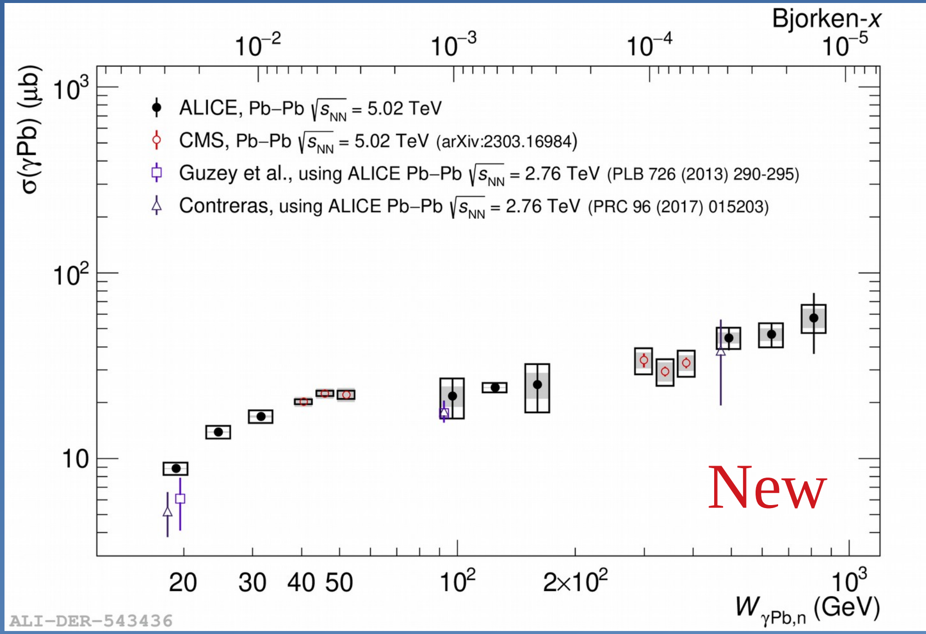
$$S_{\mathrm{Pb}}(W_{\gamma \mathrm{Pb,n}}) = \sqrt{\frac{\sigma_{\gamma \mathrm{Pb}}}{\sigma_{\gamma \mathrm{Pb}}^{\mathrm{IA}}}}$$

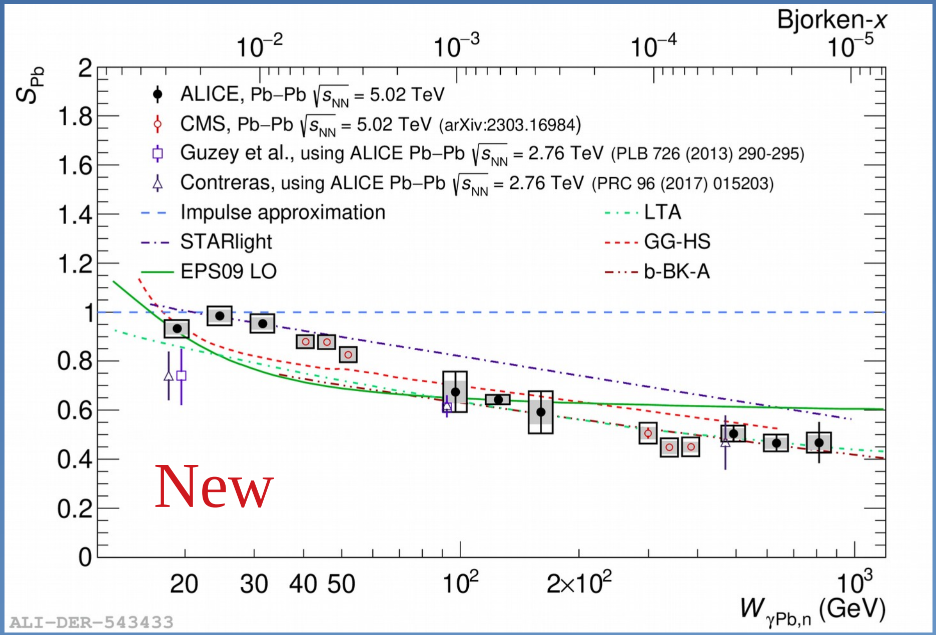


Extracting the photonuclear J/ψ cross section

Recently, the CMS experiment has performed a similar measurement in a narrower $W_{\gamma p}$ interval (CMS Coll. arXiv:2303.16984).

The combined data sets show a consistent picture of onset of nuclear shadowing below $x \approx 10^{-2}$.



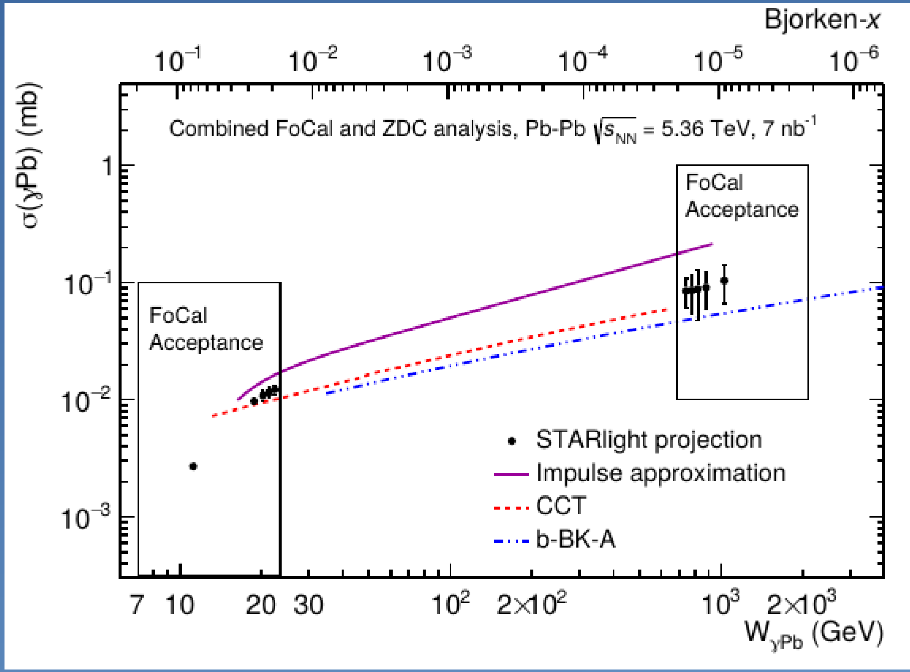


Extracting the photonuclear J/ψ cross section

There are plans to install a Forward Calorimeter (FoCal) in ALICE in Run 4 ("Physics of the ALICE Forward Calorimeter upgrade", ALICE-PUBLIC-2023-001).

See talks by P. Jacobs and M. Rauch later in this session today.

It would extend the range for J/ψ reconstruction to $3.4 < \eta < 5.8$, corresponding to $W_{\gamma p} > 1$ TeV and $x < 10^{-5}$.



The black circles show the cross section from starlight and the error bars represent the expected statistical and systematic errors.

Bylinkin, Nystrand, Tapia Takaki,
J. Phys. G 50 (2023) 055105.

Summary

- The first extraction of the photonuclear cross section $\sigma(\gamma+A \rightarrow J/\psi+A)$ over the energy range 20 GeV $\leq W_{\gamma p} \leq$ 800 GeV has been presented.

- Extends the previous measurements at midrapidity $\Leftrightarrow x\sim10^{-3}$ to $x\sim10^{-5}$.

- The measured cross section show a suppression for Bjorken-*x* values $x < \approx 10^{-2}$ relative to the impulse approximation, indicating the onset of nuclear shadowing.

- The energy dependence not described by any model.

Backup Slide

Extracting the photonuclear J/ψ cross section

The measured fraction of events in different breakup classes for coherent ρ^0 photoproduction compared with calculations from the STARLight (A.J. Baltz, S.R. Klein, J. Nystrand, PRL 89 (2002) 012310; S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comput. Phys. Commun. 212 (2017) 258) and GDL (V. Rebyakova, M. Strikman, M. Zhalov, Phys. Lett. B 710 (2012) 647) models.

Selection	Number of events	Fraction	STARLIGHT	GDL
All events	7293	100 %		
0n0n	6175	$84.7 \pm 0.4(\text{stat.})^{+0.4}_{-1.9}(\text{syst.})$ %	79 %	80 %
Xn	1174	$16.1 \pm 0.4(\text{stat.})^{+2.2}_{-0.5}(\text{syst.})$ %	21 %	20 %
0nXn	958	$13.1 \pm 0.4(\text{stat.})^{+0.9}_{-0.3}(\text{syst.})$ %	16 %	15 %
XnXn	231	$3.2 \pm 0.2(\text{stat.})^{+0.4}_{-0.1}(\text{syst.})$ %	5.2 %	4.5 %

ALICE Collaboration, JHEP 09 (2015) 095.