



U. S. DEPARTMENT OF
ENERGY

Office of
Science



Creighton
UNIVERSITY

First global study of super dense gluonic matter with UPCs in **ALICE**

Simone Ragoni for the ALICE Collaboration
Creighton University, USA

Outline

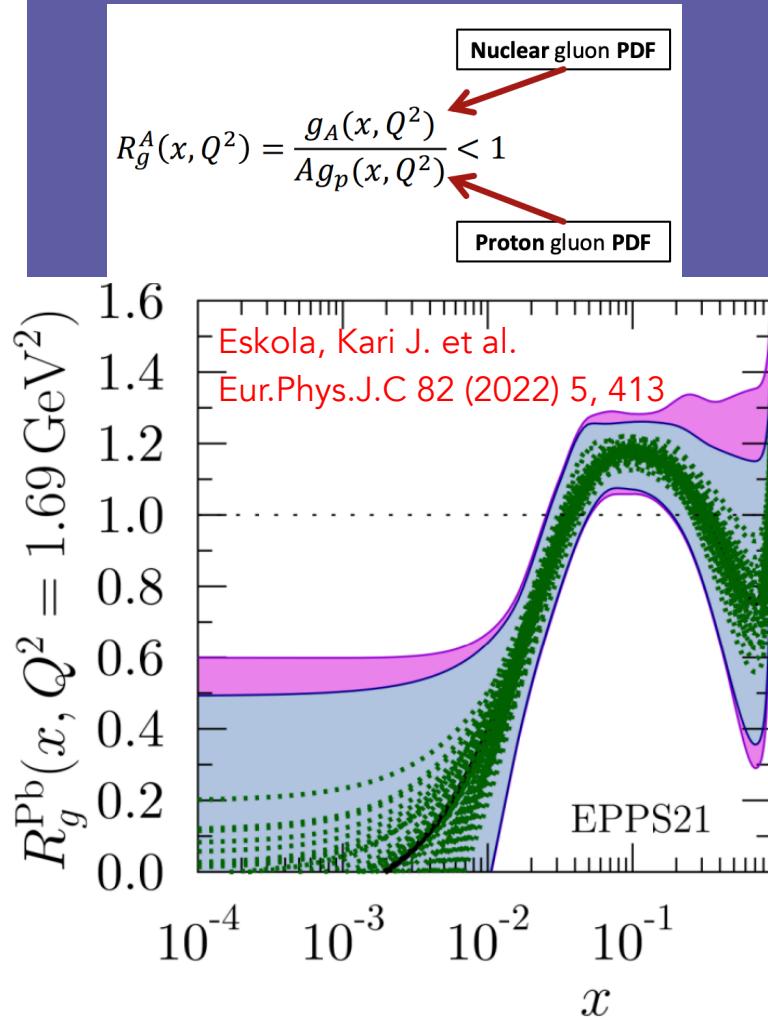
- Physics of ultra-peripheral collisions (UPC)
- The ALICE detector
- Results on exclusive J/ψ in p-Pb UPC
- Measurements of the energy dependence of the photonuclear cross sections

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Physics of ultra-peripheral collisions (UPC)

Studying nuclear shadowing

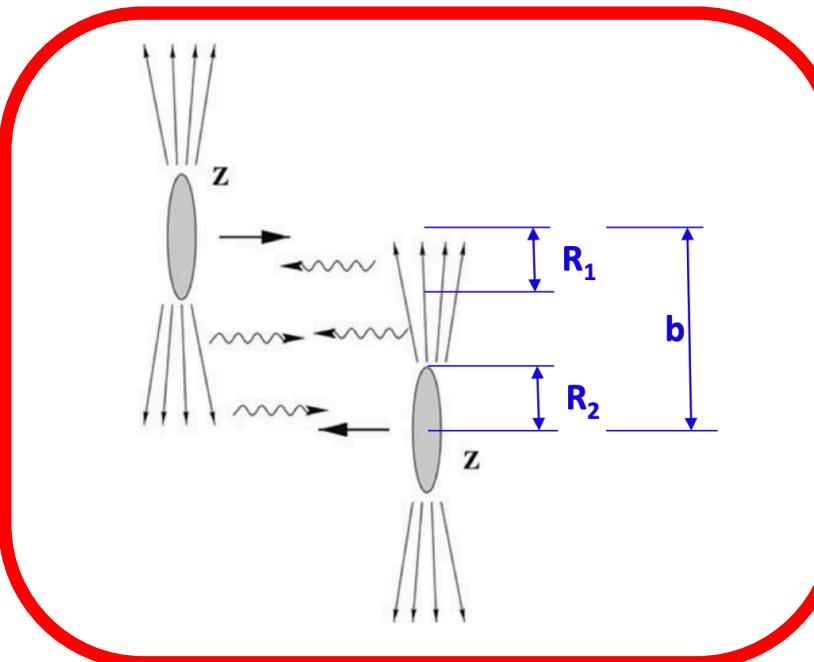


LO

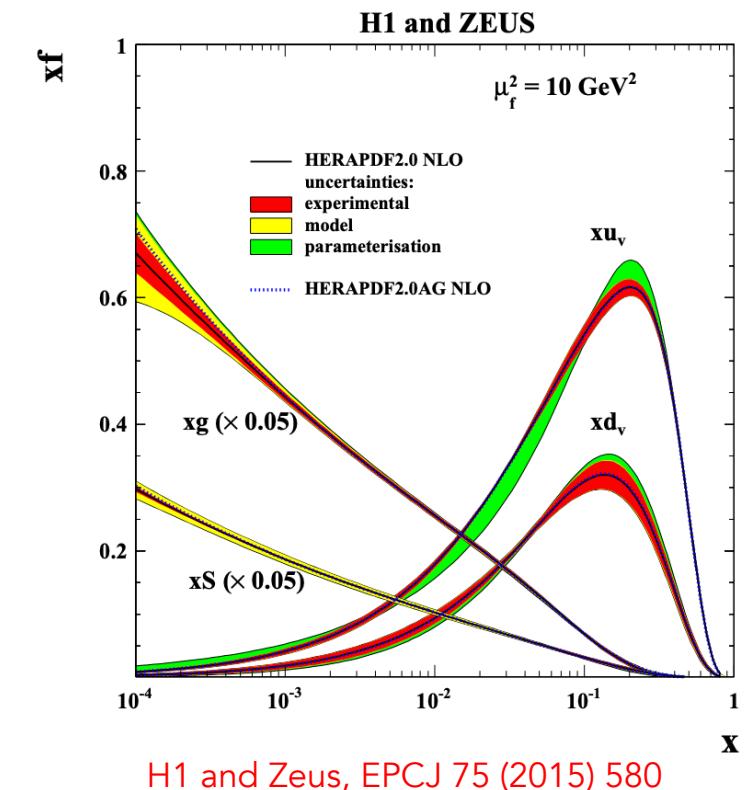
$$\frac{d\sigma^T(\gamma p \rightarrow J/\Psi + p)}{dt} = \frac{|M|^2}{16\pi s^2}$$

$$= [F_N^{2G}(t)]^2 \frac{\alpha_s^2 \Gamma_{ee}^J m_J^3}{3\alpha_{e.m.}} \pi^3 \left[\bar{x} G(\bar{x}, \bar{q}^2) \frac{2\bar{q}^2 - |q_t^J|^2}{(2\bar{q}^2)^3} \right]^2$$

Ryskin: Z. Phys. C 57, 89-92 (1993)



Looking for gluon saturation



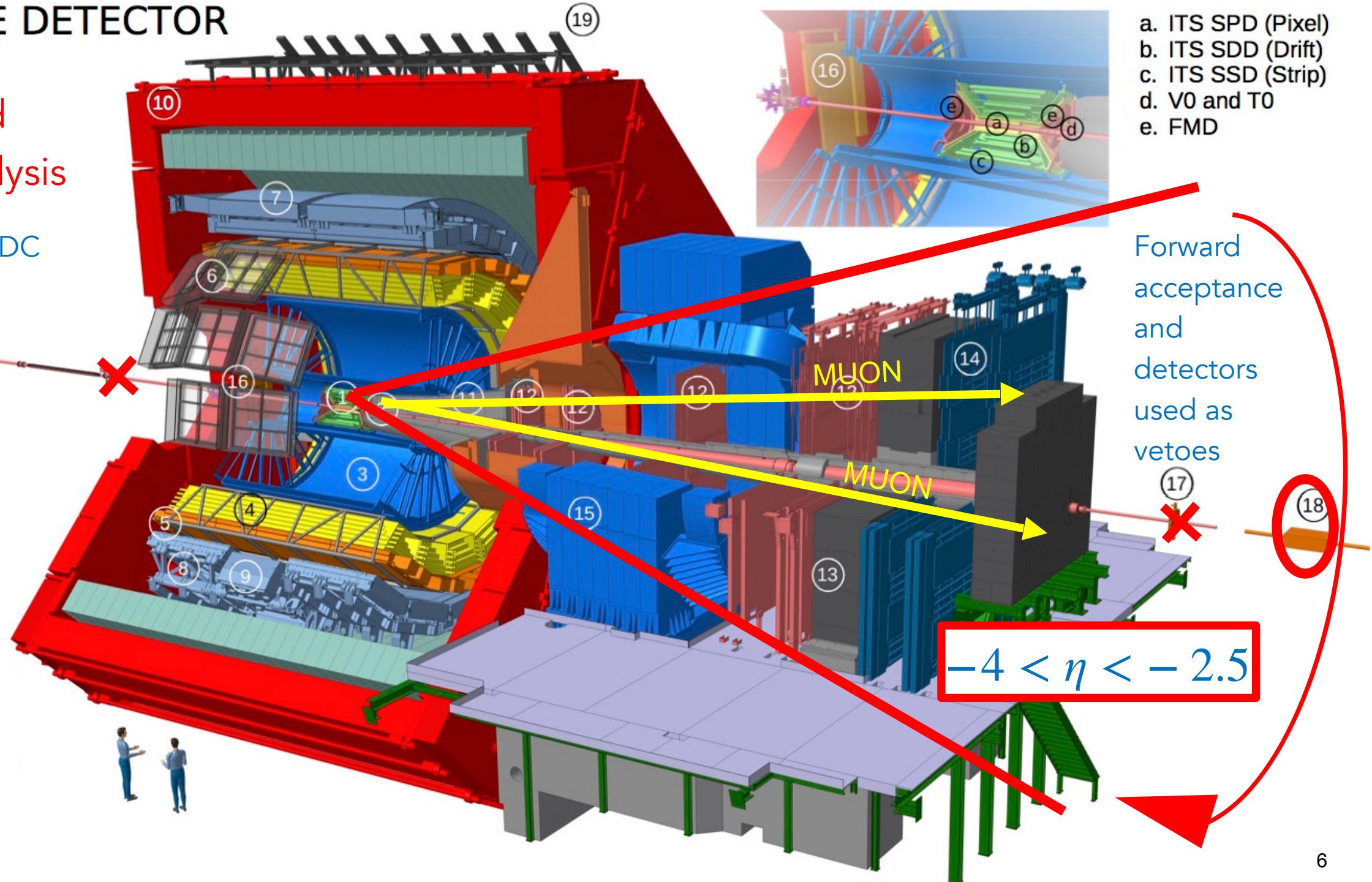
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THE ALICE DETECTOR

Forward
 J/ψ analysis

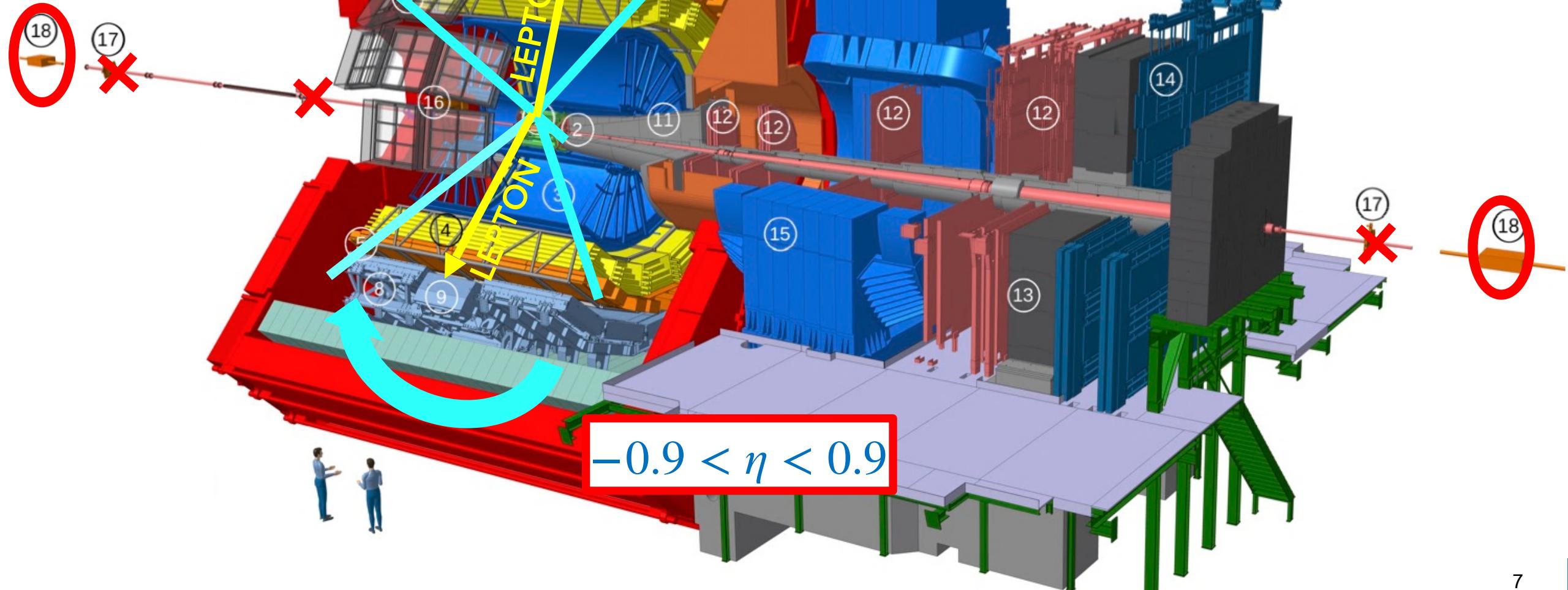
Vetoes and ZDC



THE ALICE DETECTOR

Midrapidity
 J/ψ analysis

Vetoes and ZDC

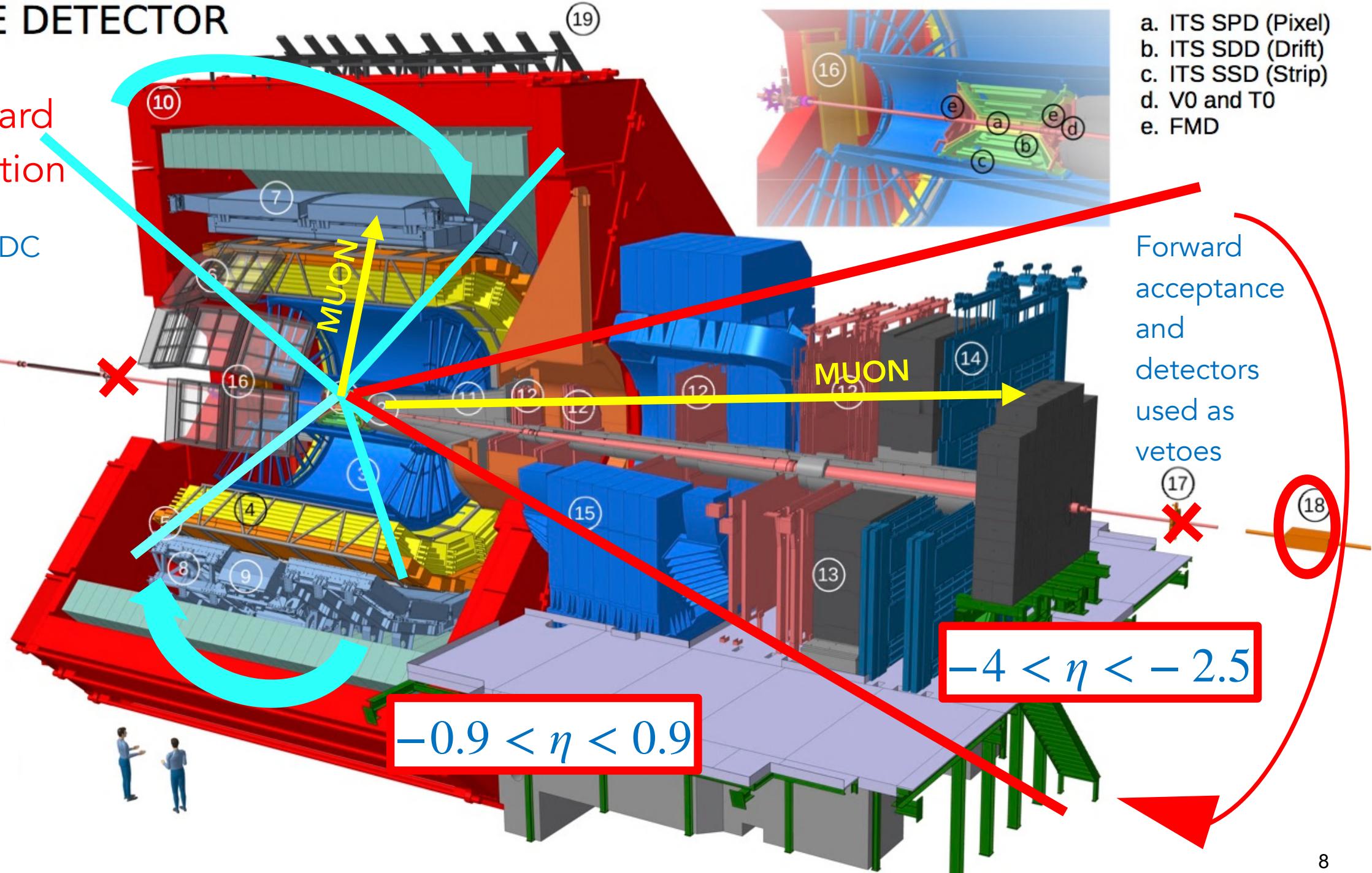


- a. ITS SPD (Pixel)
- b. ITS SDD (Drift)
- c. ITS SSD (Strip)
- d. V0 and T0
- e. FMD

THE ALICE DETECTOR

Semiforward
configuration

Vetoes and ZDC

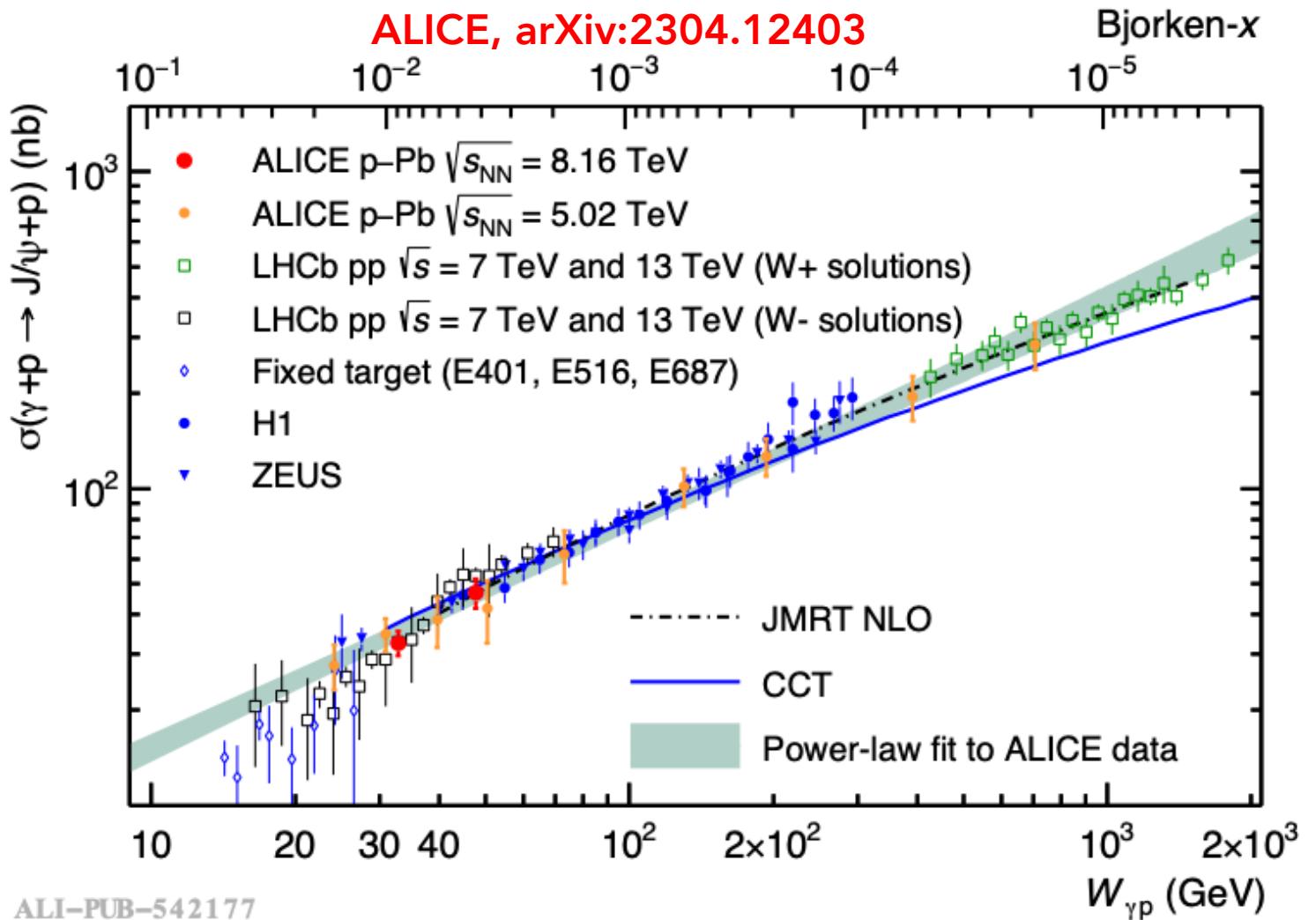


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Exclusive J/ ψ in p-Pb UPC

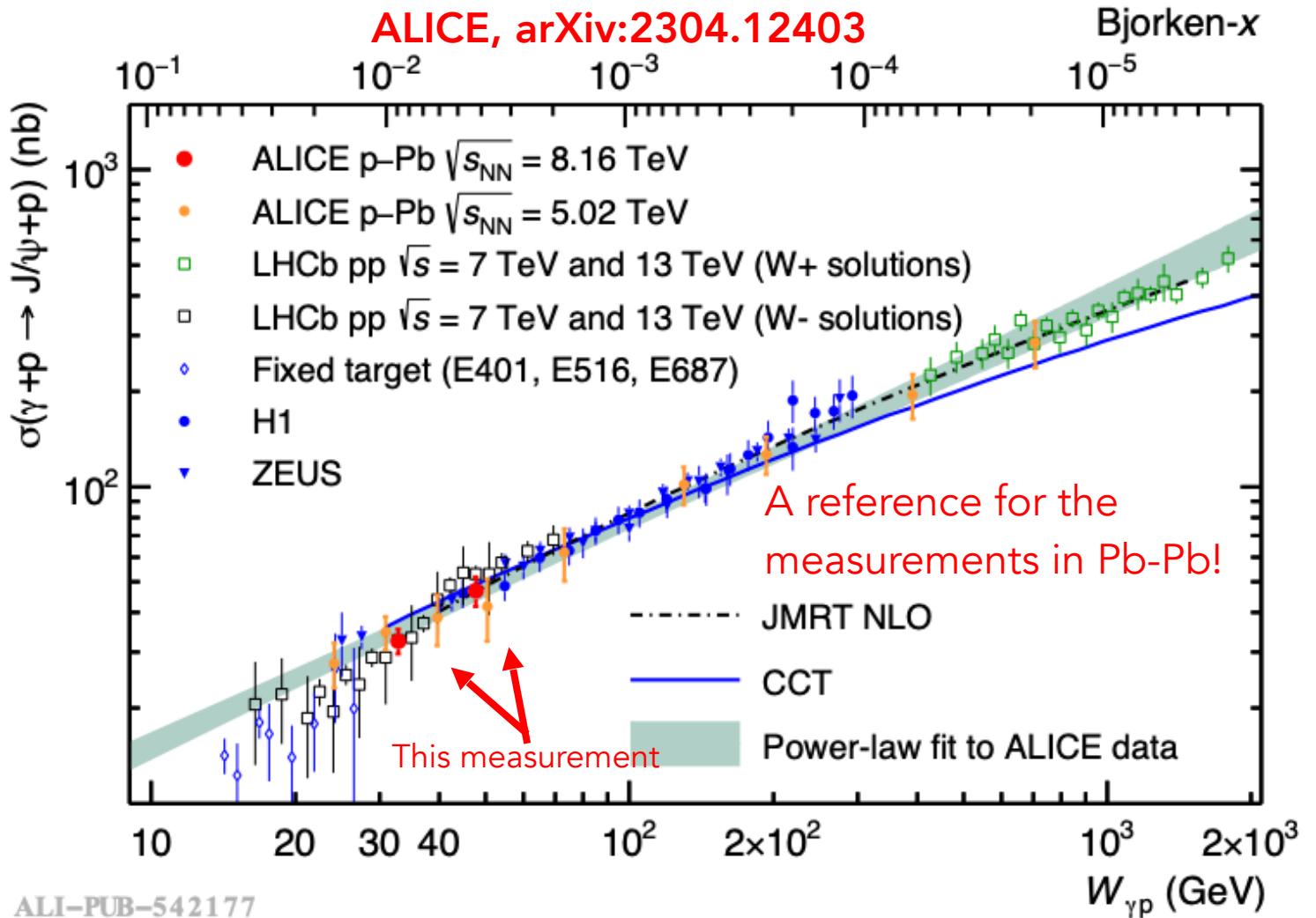
- $x = e^{\pm|y|} M_{J/\psi} / 2E_p$
- Probing Bjorken- $x \sim 10^{-5}$ with ALICE data
- power-law growth of cross sections observed -> no change in the behaviour of the gluon PDF in the proton between HERA and LHC energies
- ALICE points: forward, semiforward and midrapidity configurations
 - Forward: two muons in the spectrometer
 - Semiforward: one in the spectrometer, one in the central barrel
 - Midrapidity: two muons/ electrons in the central barrel



Eur. Phys. J. C (2019) 79: 402 (ALICE midrapidity and semiforward)
 Phys. Rev. Lett. 113 no. 23, (2014) 232504 (ALICE forward)

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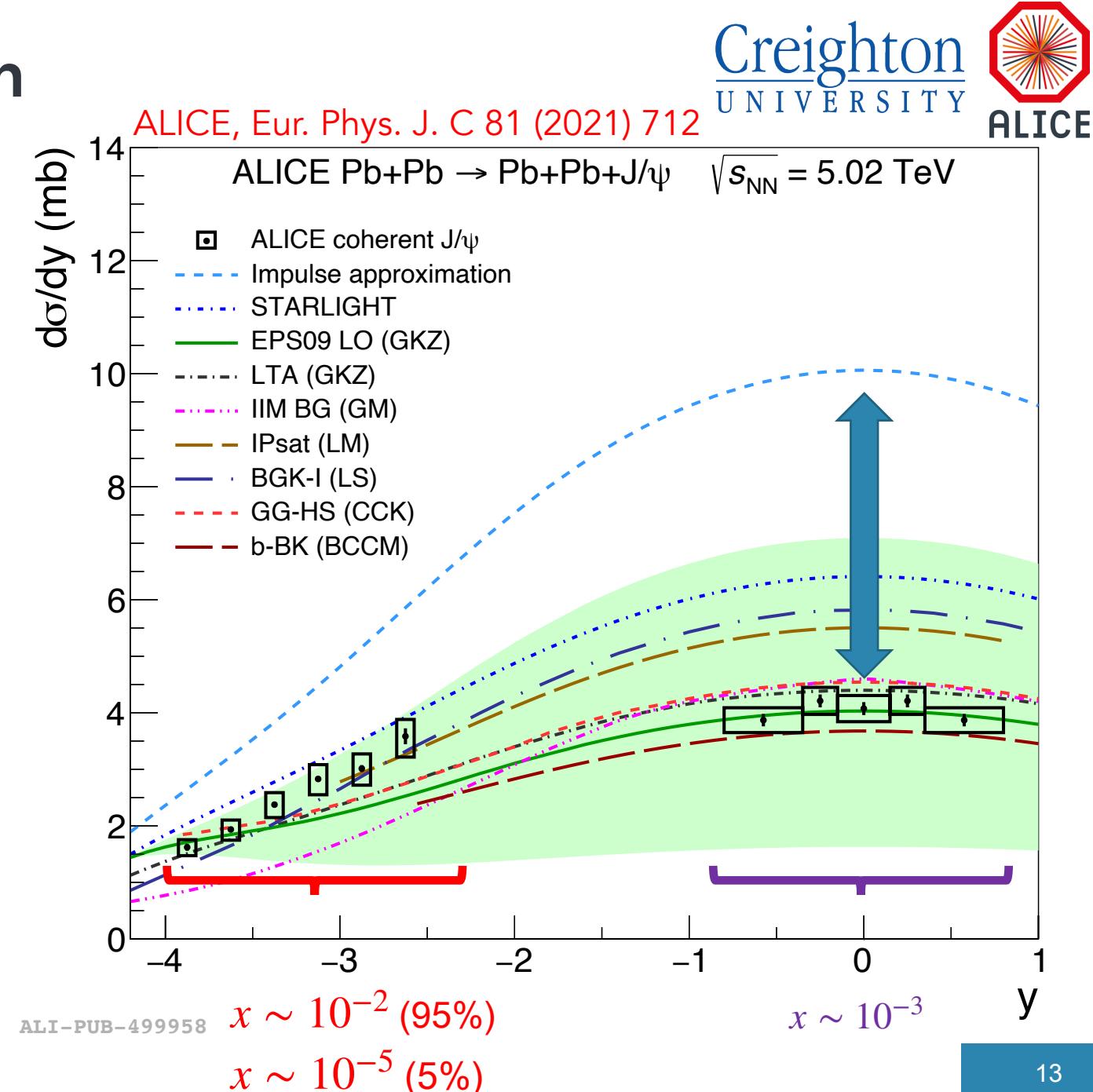
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Coherent J/ ψ cross section

- ALICE data exhibit moderate nuclear shadowing
- Nuclear suppression factor

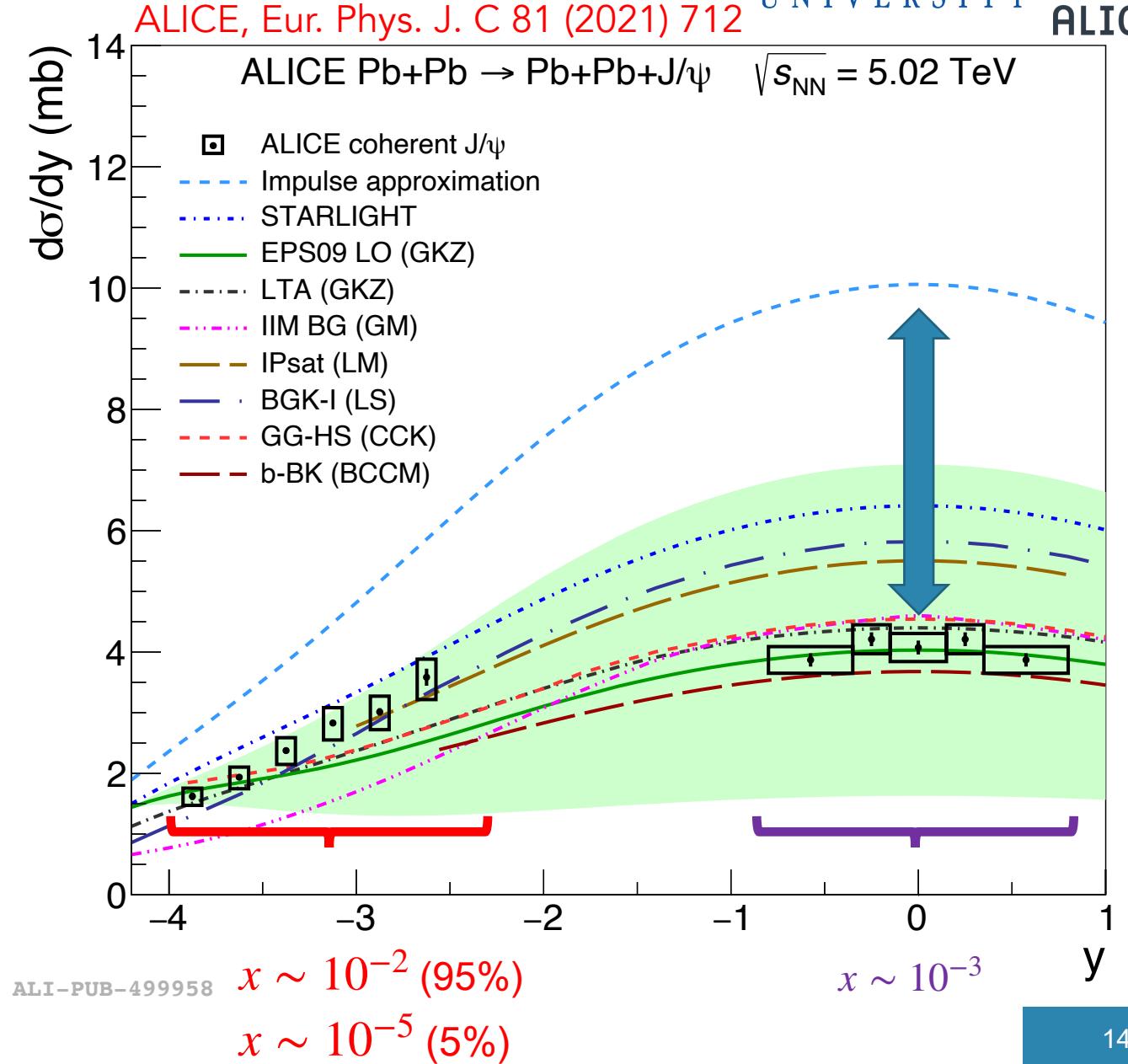
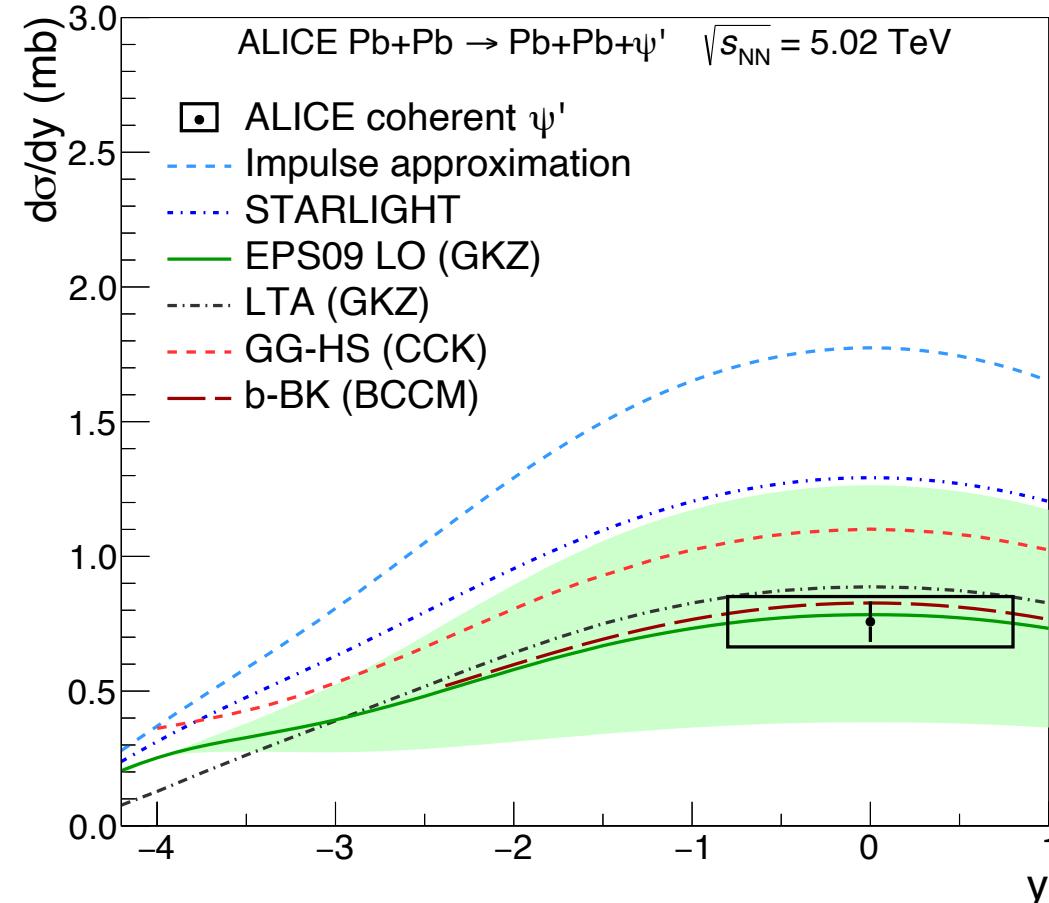
$$S_{\text{Pb}}(y \sim 0) = \sqrt{\frac{d\sigma}{dy}_{\text{data}} / \frac{d\sigma}{dy}_{IA}} = 0.64 \pm 0.04$$

- IA = impulse approximation (no nuclear effects)
- $S(W_{\gamma p})$ - nuclear suppression factor - provides a way to test the consistency of the data with the available nuclear and nucleon PDFs and to measure the nuclear shadowing factor

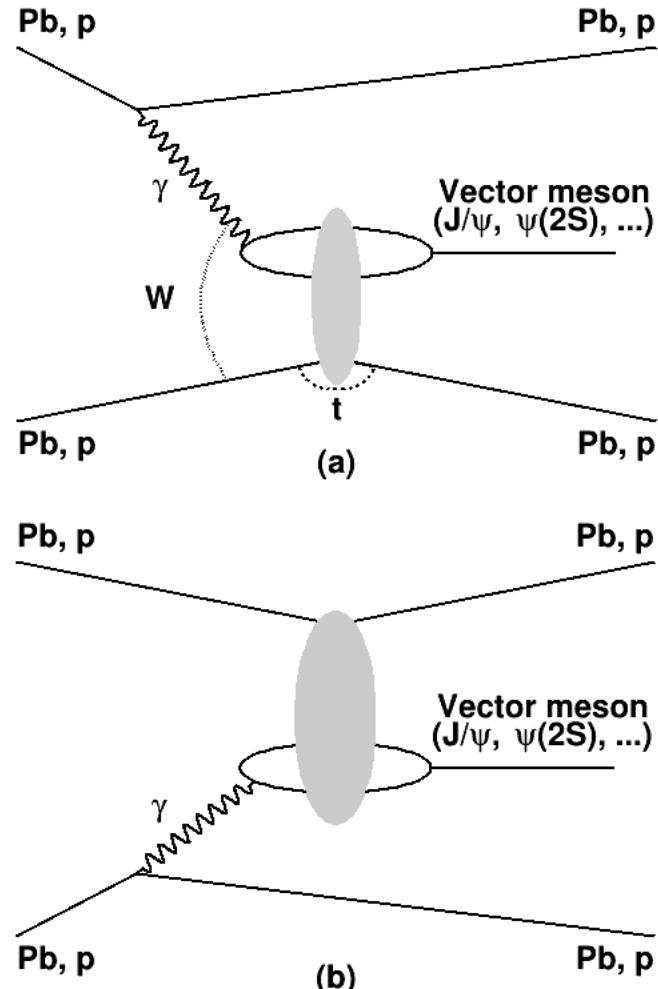


Coherent J/ ψ and ψ' cross section

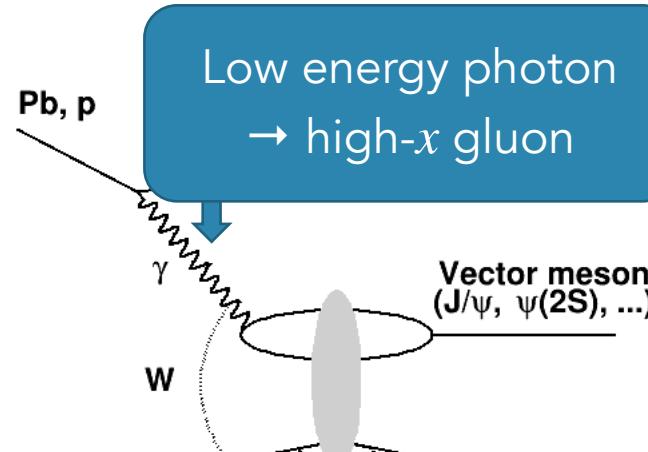
$$S_{\text{Pb}}(y \sim 0, \psi') = \sqrt{\frac{d\sigma}{dy}_{\text{data}} / \frac{d\sigma}{dy}_{IA}} = 0.66 \pm 0.6$$



Measuring the energy dependence

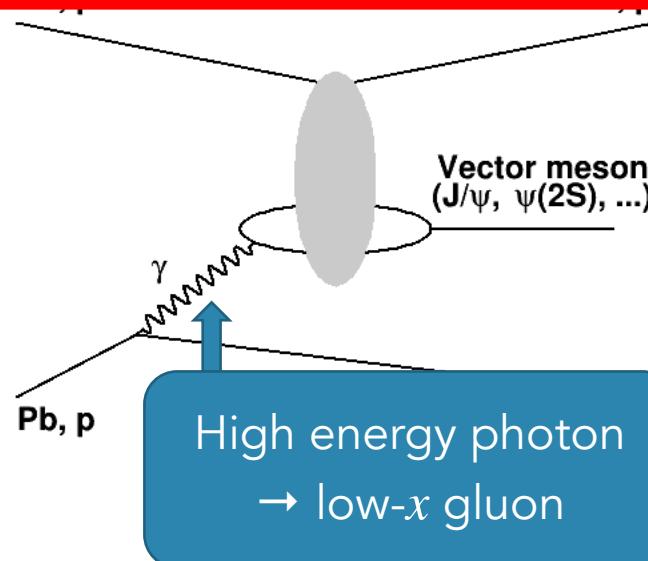


Measuring the energy dependence



$$x = \frac{M_{J/\psi}^2}{W_{\gamma Pb,n}^2}$$

$$\frac{d\sigma}{dy} = n(\gamma, +y)\sigma_{\gamma Pb}(+y) + n(\gamma, -y)\sigma_{\gamma Pb}(-y)$$



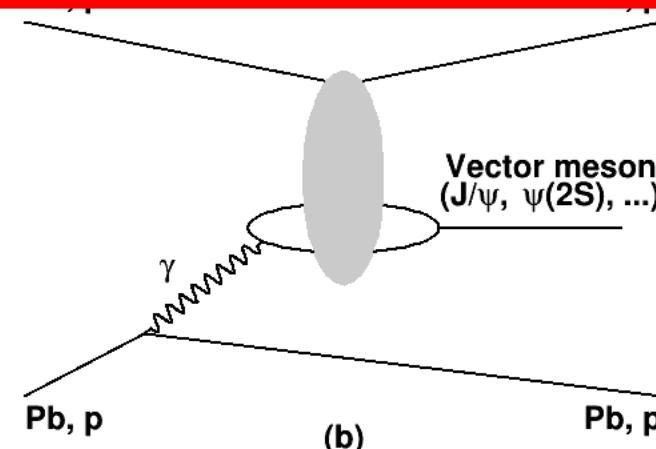
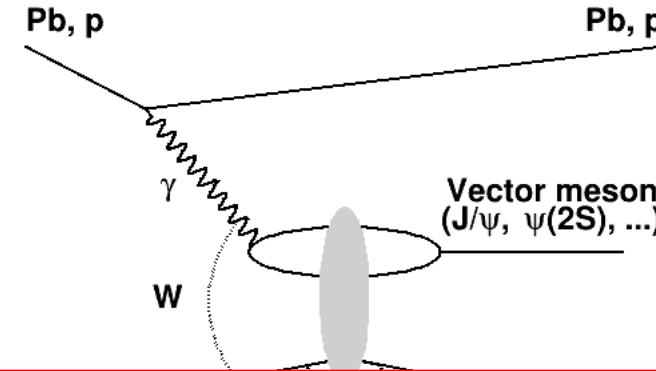
Measuring the energy dependence

Coherent J/ ψ at midrapidity:

- UPC cross sections can be linked directly to the photonuclear cross section

$$\frac{d\sigma}{dy} = 2n(\gamma)\sigma_{\gamma Pb}$$

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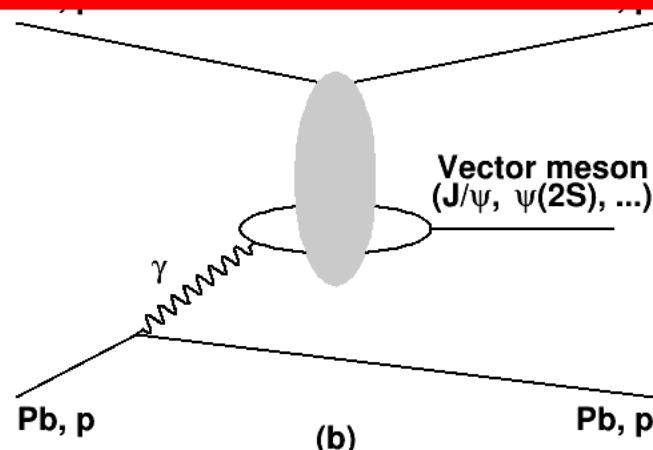
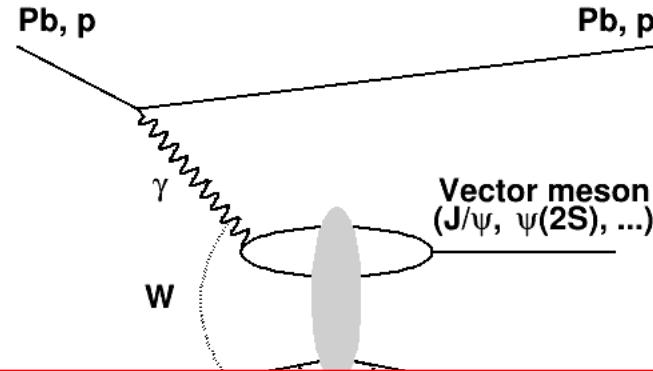
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Coherent J/ ψ at forward rapidity:

- 95% of the cross section originates from the low-energy photon

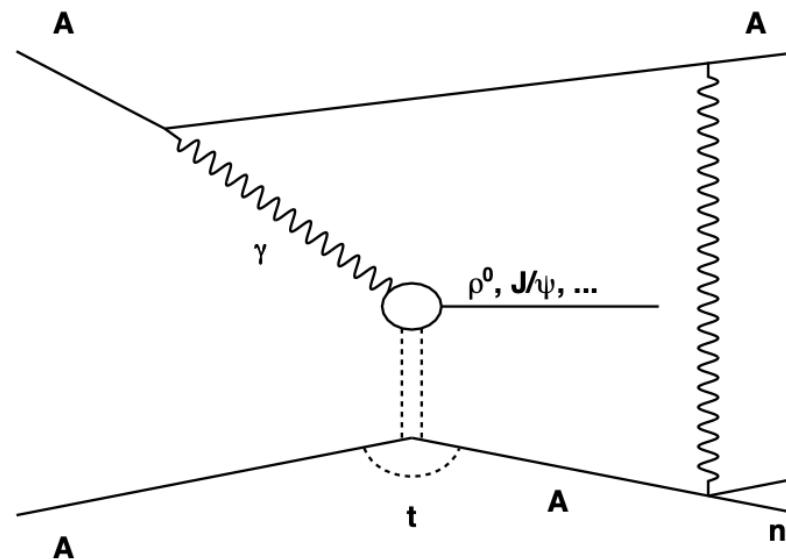
$$\frac{d\sigma}{dy} \simeq n(\gamma)\sigma_{\gamma Pb}$$

But that remaining 5% is very interesting

Techniques for the photon direction ambiguity

Neutron emission:

- $x = \frac{M_{\text{VM}}}{\sqrt{s_{\text{NN}}}} \cdot e^{\pm y}$
- Ambiguity due to sign in the rapidity of the photon emitter $\rightarrow 10^{-2}, 10^{-5}$
- Additional photon exchanges may lead to neutron emission

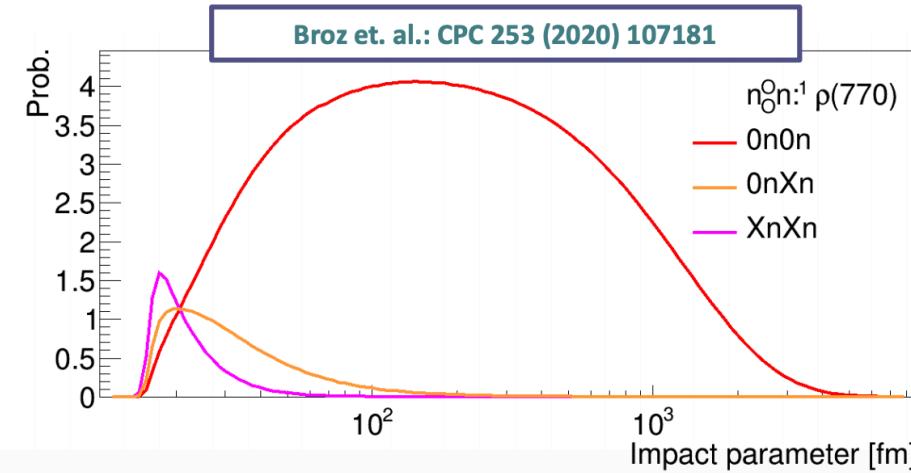


- Using the neutron ZDCs on the A and C side to detect the neutrons!
- E.g. 0N0N: no neutrons on either ZDCs
- E.g. 0NXN: neutrons only on one side

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$$\frac{d\sigma_{PbPb}^{0N0N}}{dy} = n_{0N0N}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0N0N}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$
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Guzey et al.,
Eur.Phys.J.C 74 (2014) 7, 2942

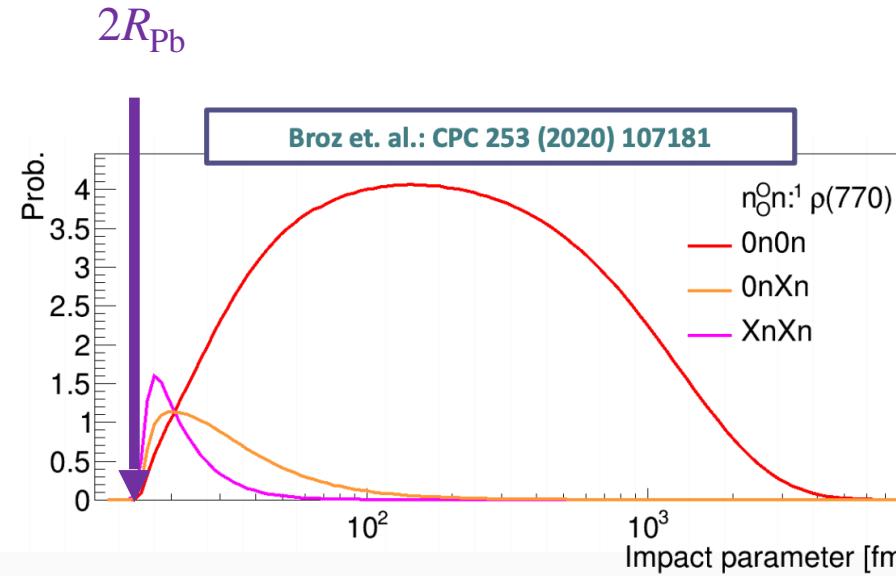
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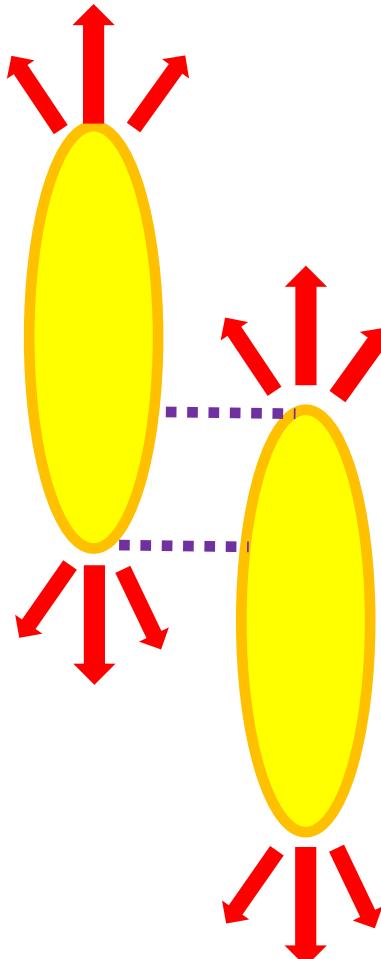
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Techniques for the photon direction ambiguity

Peripheral
photoproduction:

- $b < R_1 + R_2$
- Hadronic interactions + photoproduction



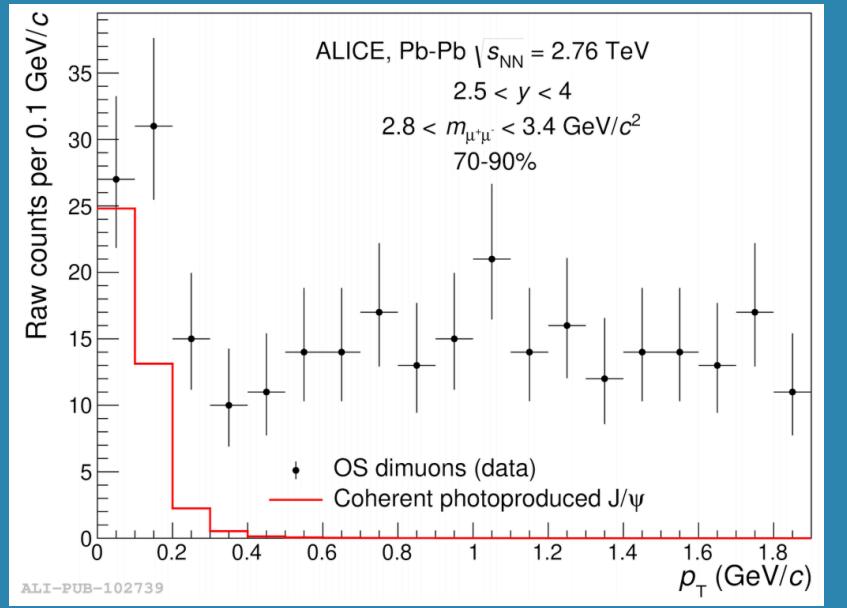
- Simultaneously use UPC and peripheral results to get rid of the ambiguities!

$$\frac{d\sigma_{PbPb}^P}{dy} = n_P(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_P(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$
$$\frac{d\sigma_{PbPb}^U}{dy} = n_U(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_U(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

J.G. Contreras PRC 96 (2017) 015203

Peripheral J/ ψ photoproduction using ALICE Run 1 data

- First observed with Run 1 data by ALICE, then with Run 2 statistics by both ALICE and LHCb, and by STAR
- First extraction of the photonuclear cross sections with Run 1 data

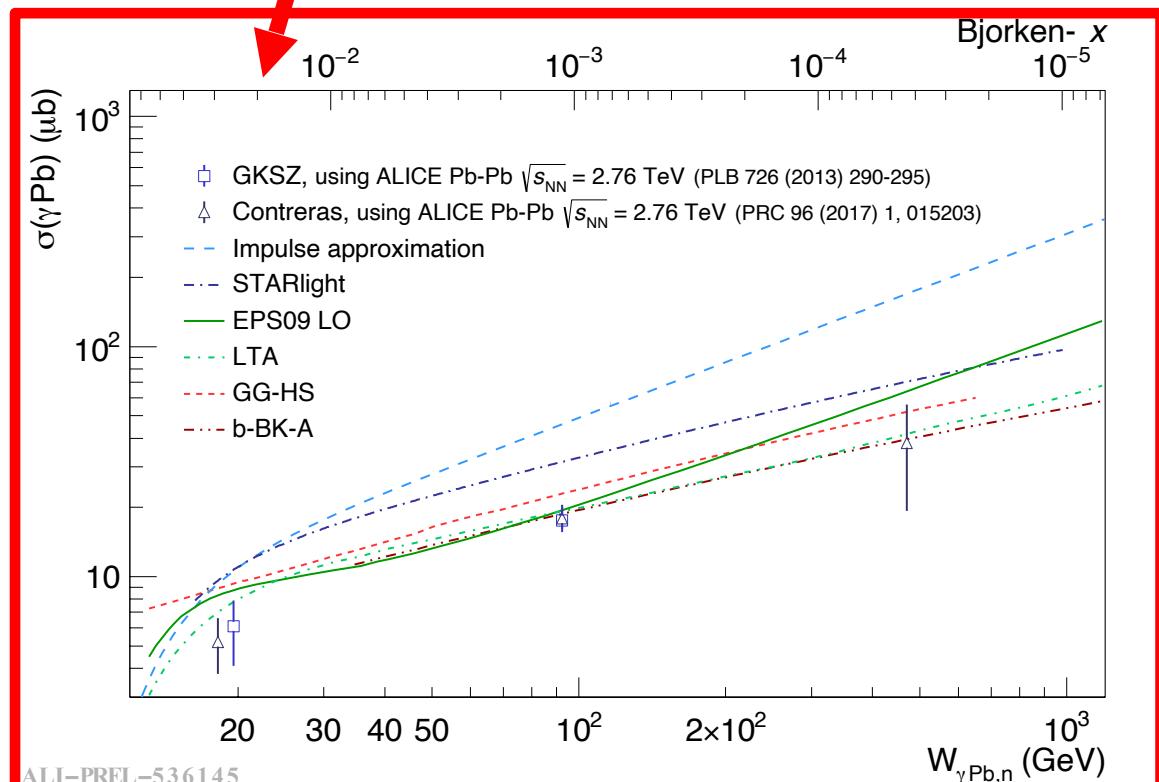


ALICE, PRL 116 (2016), 222301 LHCb, Phys.Rev.C 105 (2022) 3, L032201
ALICE, arXiv:2204.10684 STAR, Phys.Rev.Lett. 123 (2019) 132302

Peripheral results →
$$\frac{d\sigma_{PbPb}^P}{dy} = n_P(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_P(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

UPC results →
$$\frac{d\sigma_{PbPb}^U}{dy} = n_U(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_U(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

J.G. Contreras PRC 96 (2017) 015203



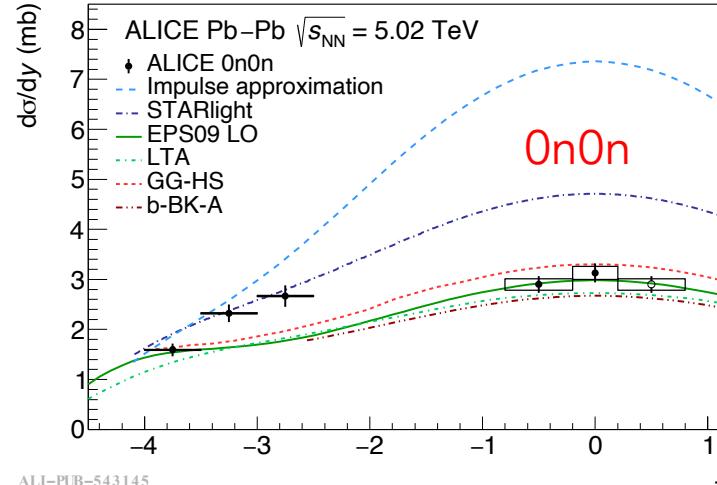
Coherent J/ ψ with neutron emission

$$\frac{d\sigma_{PbPb}^{0N0N}}{dy} = n_{0N0N}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0N0N}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

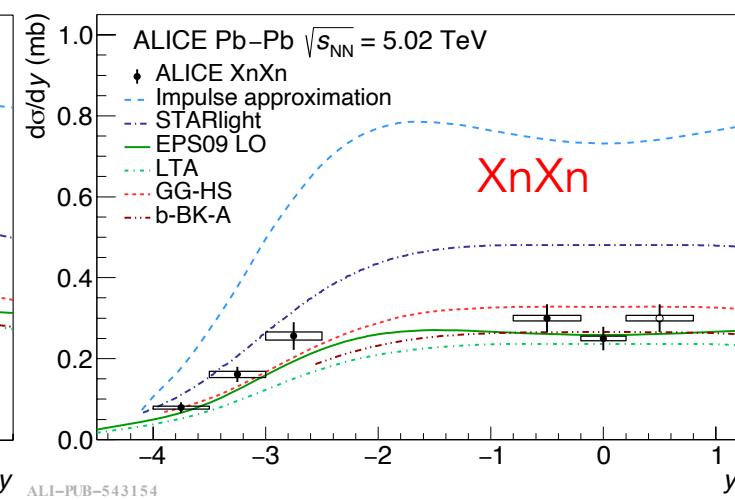
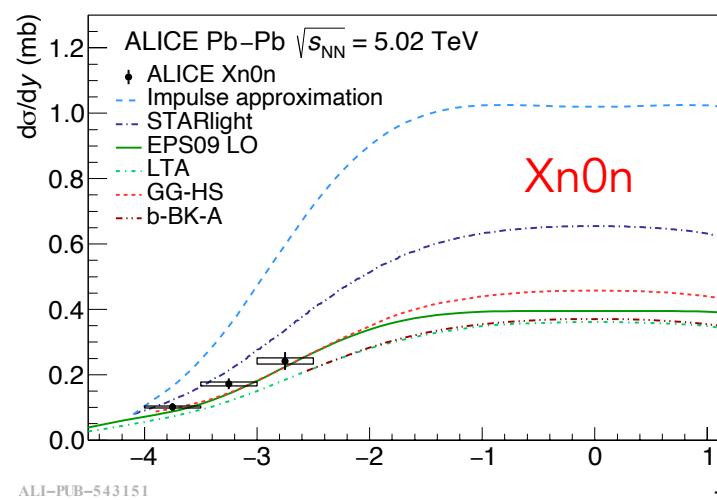
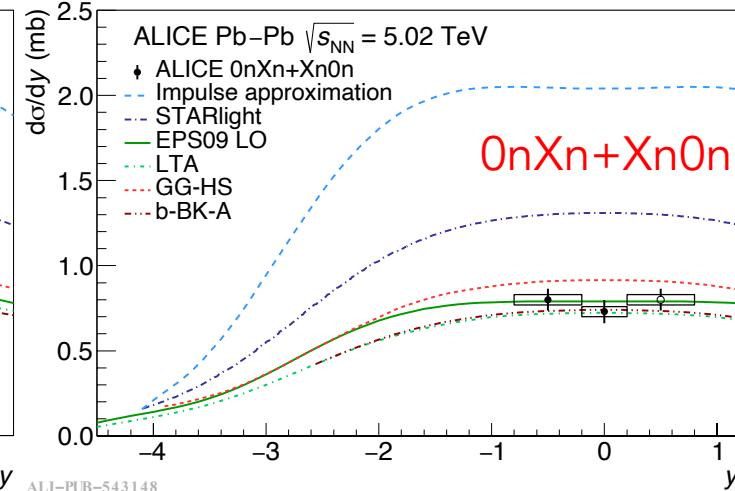
$$\frac{d\sigma_{PbPb}^{0NXN}}{dy} = n_{0NXN}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0NXN}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$



y	$n_\gamma(0n0n)$	$n_\gamma(0nXn+Xn0n)$	$n_\gamma(XnXn)$	$\sigma_{\gamma Pb}^{\text{IA}} (\mu\text{b})$
$3.5 < y < 4$	178.51	18.18	6.34	10
$3 < y < 3.5$	162.99	18.19	6.34	14
$2.5 < y < 3$	147.46	18.19	6.34	19
$0.2 < y < 0.8$	77.88	17.88	6.33	48
$-0.2 < y < 0.2$	62.86	17.47	6.27	58
$-0.8 < y < -0.2$	48.31	16.75	6.18	71
$-3 < y < -2.5$	3.91	4.97	2.78	176
$-3.5 < y < -3$	1.22	2.15	1.42	215
$-4 < y < -3.5$	0.26	0.61	0.48	262

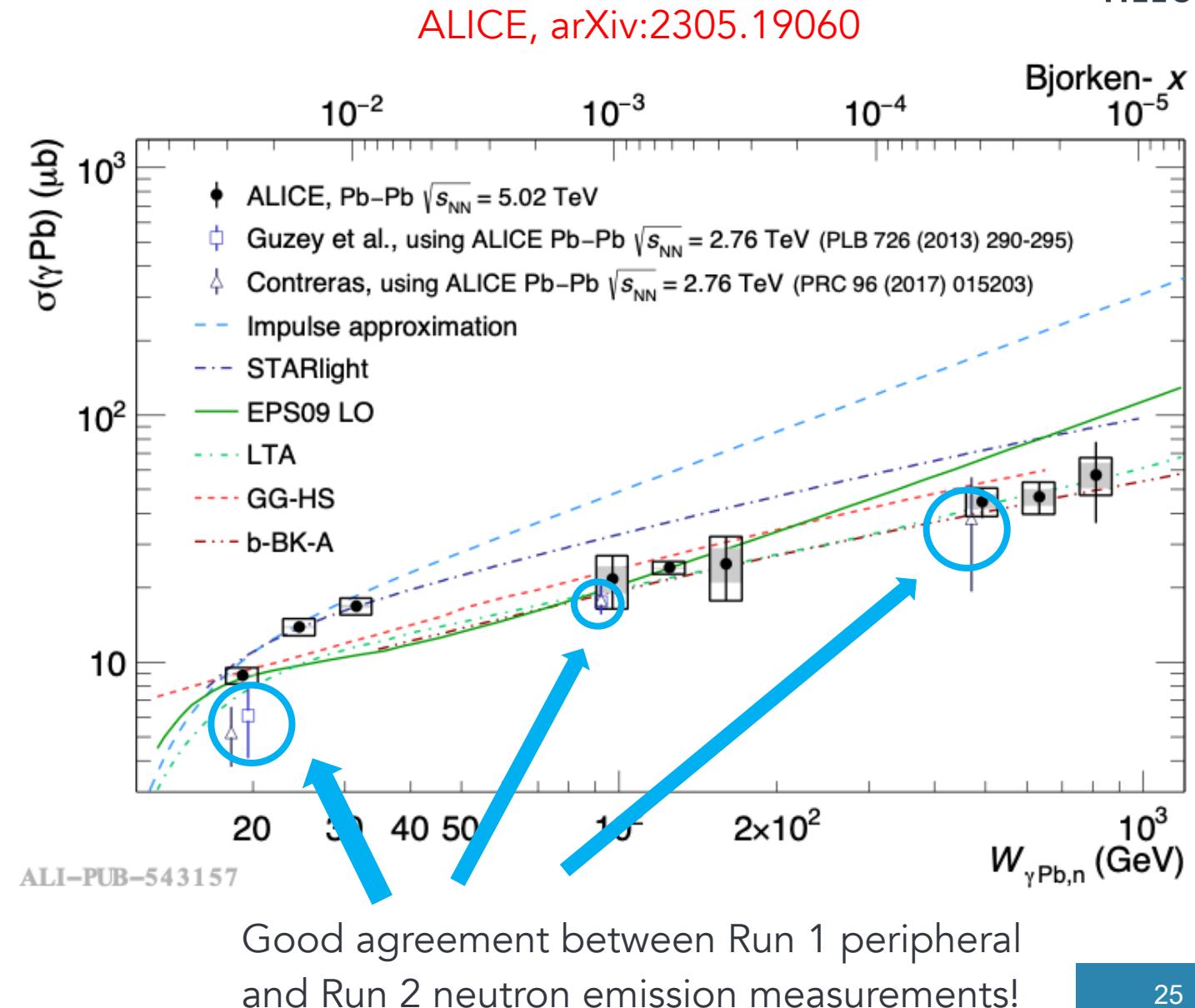


ALICE, arXiv:2305.19060



Coherent J/ ψ with neutron emission

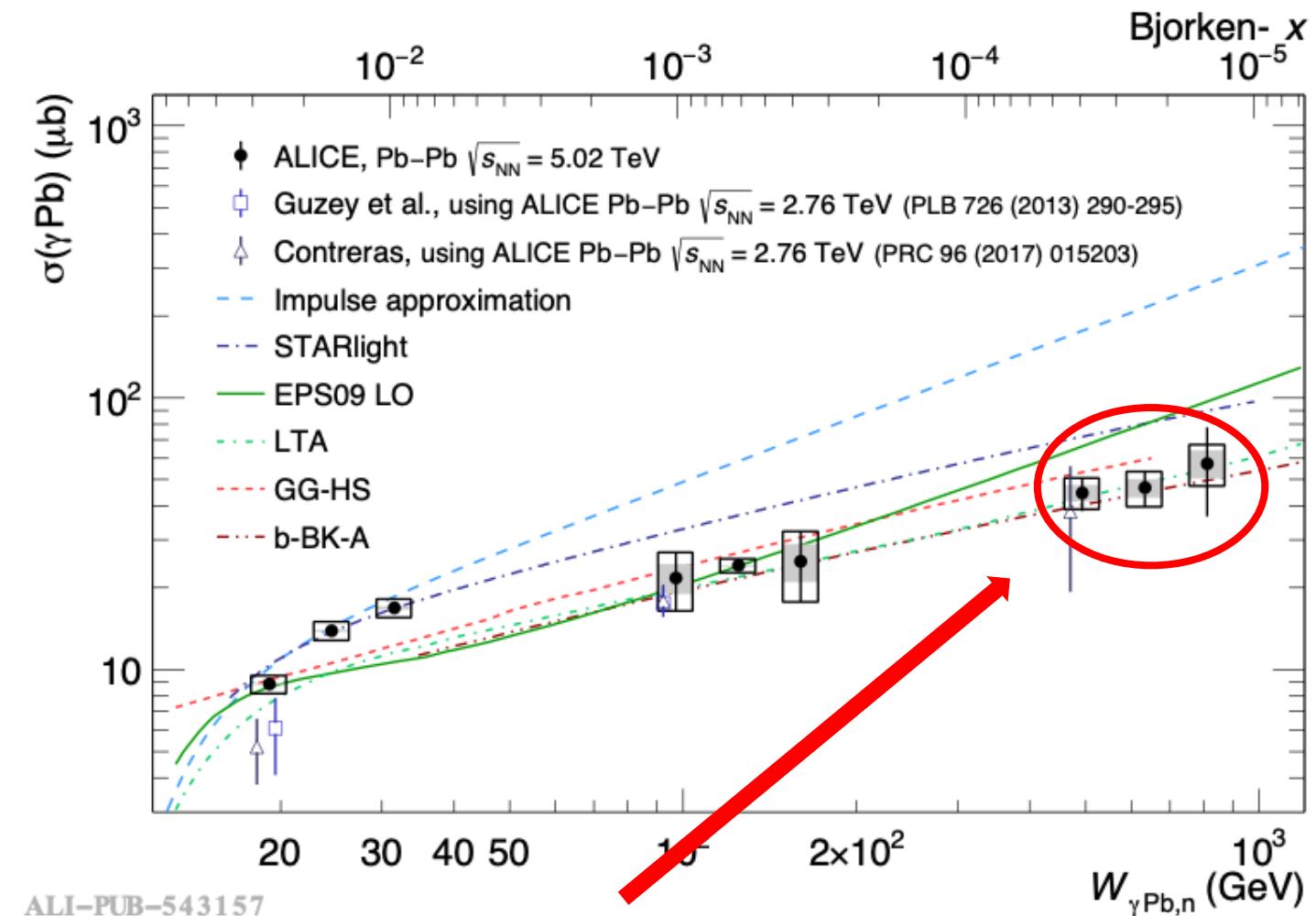
- First measurement of the energy dependence of the photonuclear cross section down to Bjorken- $x \sim 10^{-5}$!
- At low- x data favours both saturation and shadowing models



Coherent J/ ψ with neutron emission

- First measurement of the energy dependence of the photonuclear cross section down to Bjorken- $x \sim 10^{-5}$!
- At low- x data favours both saturation and shadowing models
- New Run 2 results probe unprecedented Bjorken- x region like no other LHC experiment!

ALICE, arXiv:2305.19060



ALI-PUB-543157

Neutron emission extends the range in energy being explored by about 300 GeV!

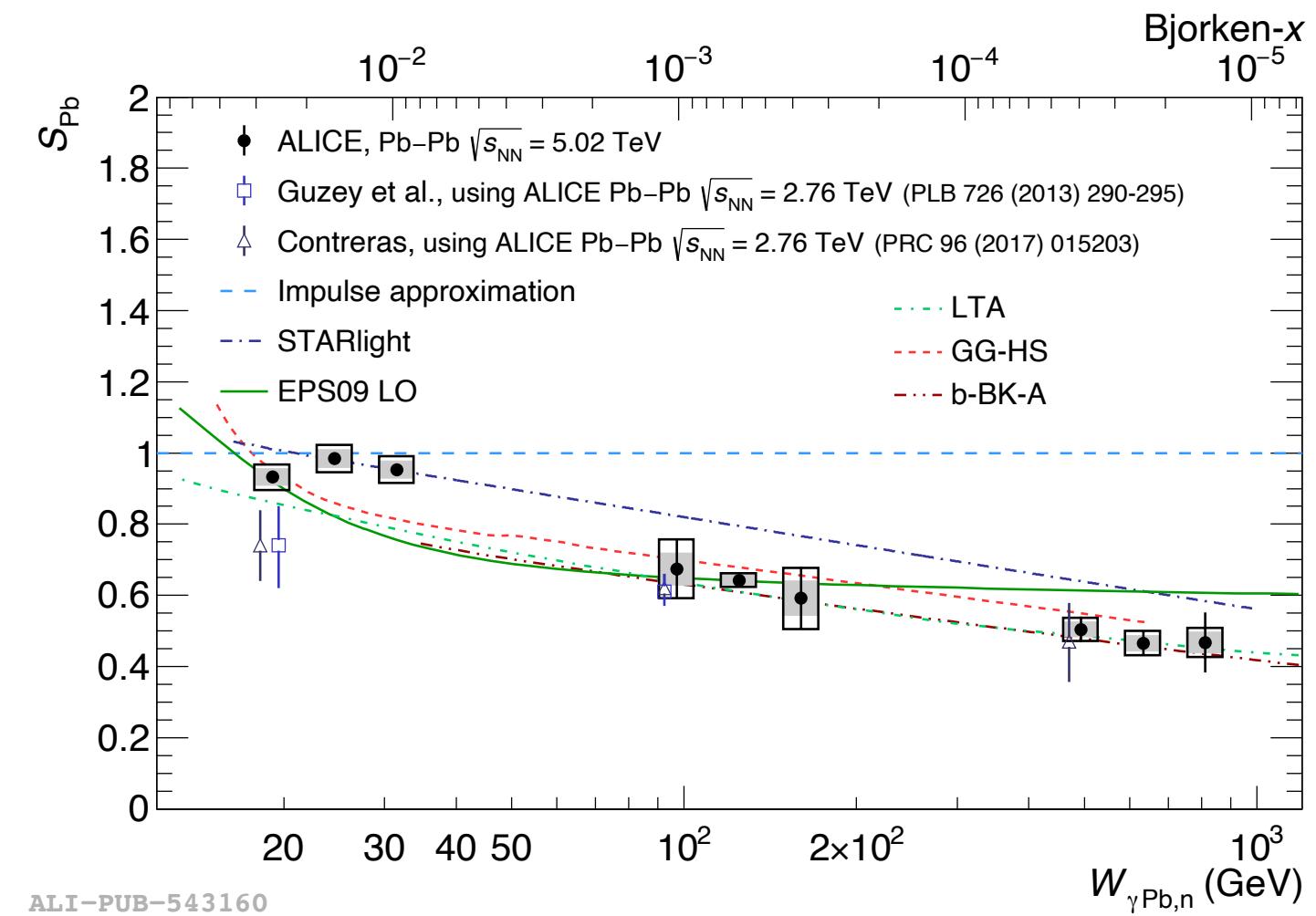
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$$S_{\text{Pb}}(y) = \sqrt{\frac{d\sigma}{dy}_{\text{data}} / \frac{d\sigma}{dy}_{IA}}$$

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- Additional theoretical uncertainty from impulse approximation \rightarrow dominates at low energies

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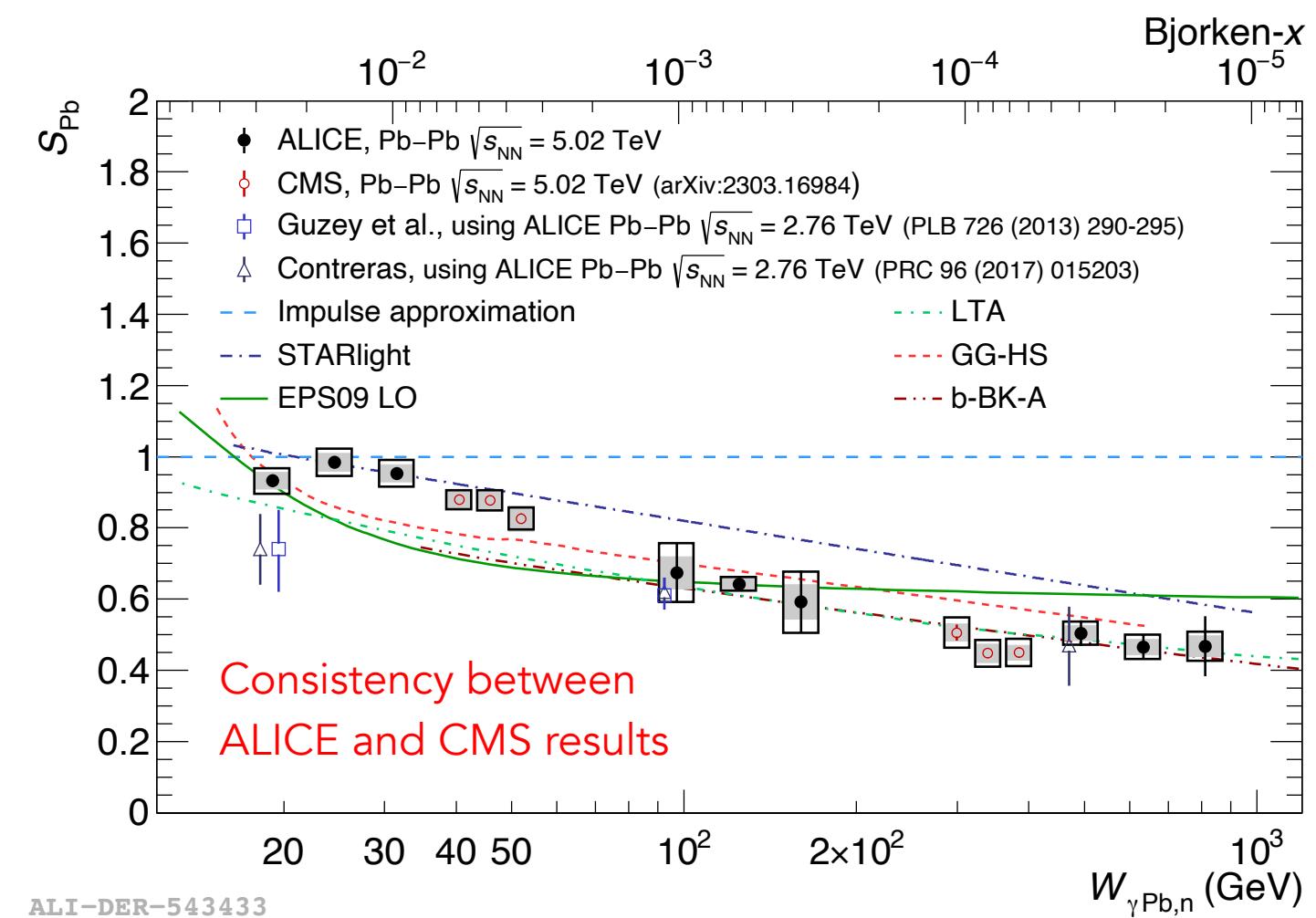
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ALICE, arXiv:2305.19060



ALICE in Run 3 and 4

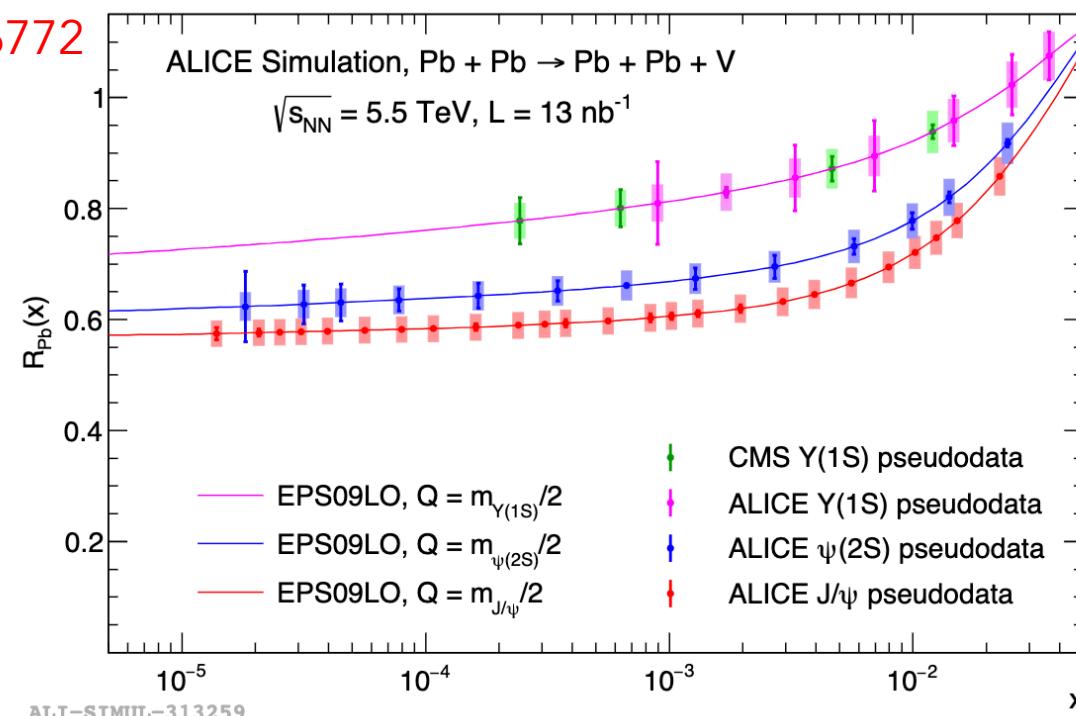
- Significant increase in integrated lumi from 1 nb^{-1} for Run 2 to 13 nb^{-1} for Run 3 and Run 4 together
- Great increase in statistics with continuous readout
- Uncertainties for nuclear suppression factor expected to be at the level of 4%
 - Nuclear shadowing studied as a function of x and Q^2
- New measurements e.g. bottomonium states
- MFT in Run 3, FoCal in Run 4!

Meson	σ	Central 1 Total	Forward 1 Total 1
$\rho \rightarrow \pi^+ \pi^-$	5.2b	5.5 B	4.9 B
$\rho' \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	730 mb	210 M	190 M
$\phi \rightarrow K^+ K^-$	0.22b	82 M	15 M
$J/\psi \rightarrow \mu^+ \mu^-$	1.0 mb	1.1 M	600 K
$\psi(2S) \rightarrow \mu^+ \mu^-$	30 μb	35 K	19 K
$Y(1S) \rightarrow \mu^+ \mu^-$	2.0 μb	2.8 K	880

CERN Yellow Rep. Monogr. 7
(2019) 1159-1410, arXiv

1812.06772

$|y| < 0.9$ $2.5 < |y| < 4$



Summary

- First measurement of the nuclear suppression factor at Bjorken- $x \sim 10^{-5}$! Obtained with the neutron emission technique
- At high- x , models fail to describe the data
- At low- x , nuclear shadowing and saturation consistent with the data
- Peripheral and neutron emission techniques in good agreement

Other ALICE photoproduction contributions in QM 2023



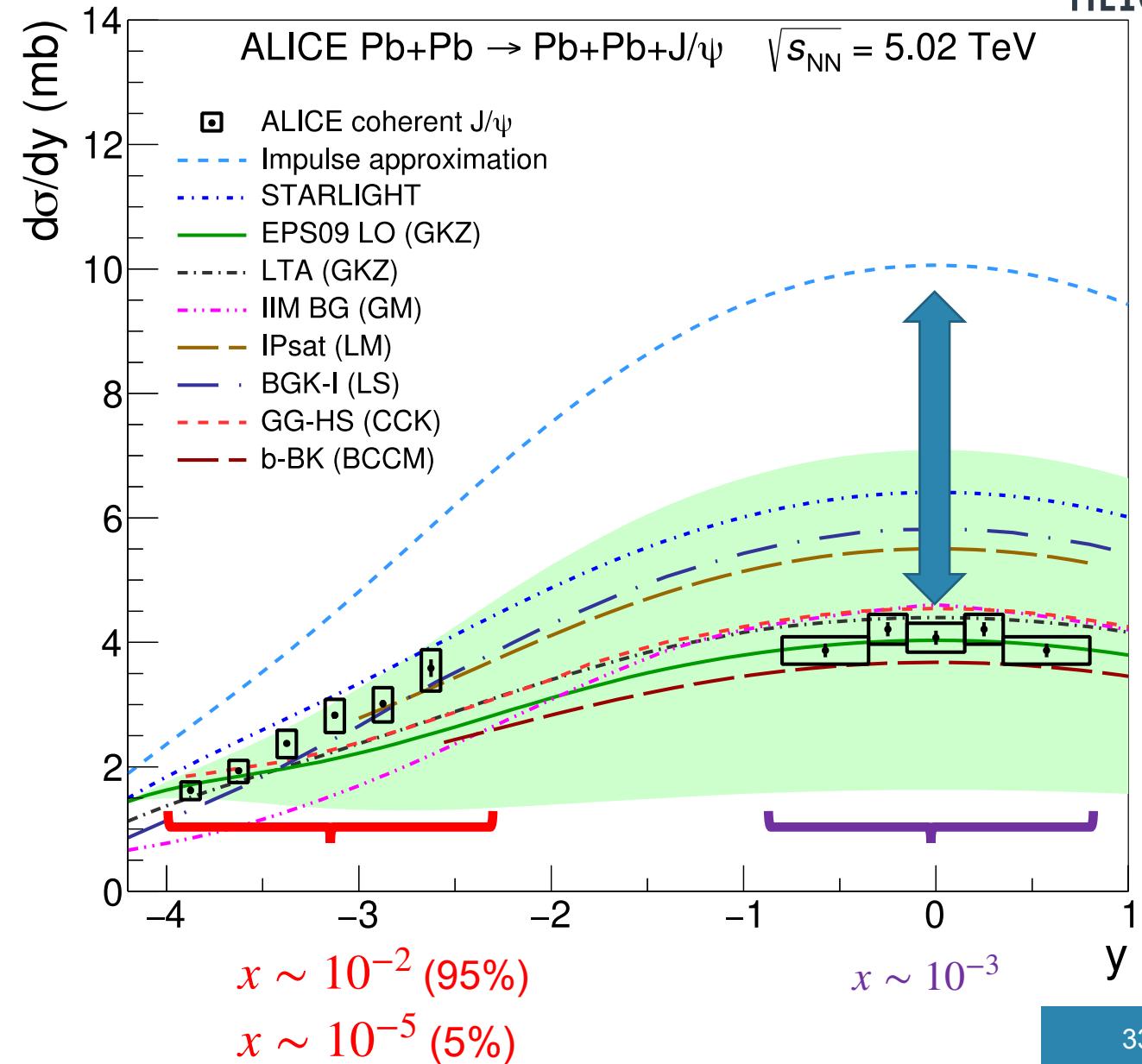
- *First study of the initial gluonic fluctuations using UPCs with ALICE* (talk), Adam Matyja, <https://indico.cern.ch/event/1139644/contributions/5540962/>
- *Coherent J/ ψ photoproduction and polarization in peripheral Pb-Pb collisions with ALICE* (talk), Afnan Shatat, <https://indico.cern.ch/event/1139644/contributions/5540081/>
- *Exploring light hadrons in UPCs with ALICE* (poster), Alexander Bylinkin, <https://indico.cern.ch/event/1139644/contributions/5491649/>
- *Physics prospects of central exclusive production in pp collisions with ALICE Run 3 data* (poster), Minjung Kim, <https://indico.cern.ch/event/1139644/contributions/5456343/>
- *Studying the nucleus via angular correlations in UPCs with ALICE* (poster), Andrea Giovanni Riffero, <https://indico.cern.ch/event/1139644/contributions/5456343/>



Backup slides

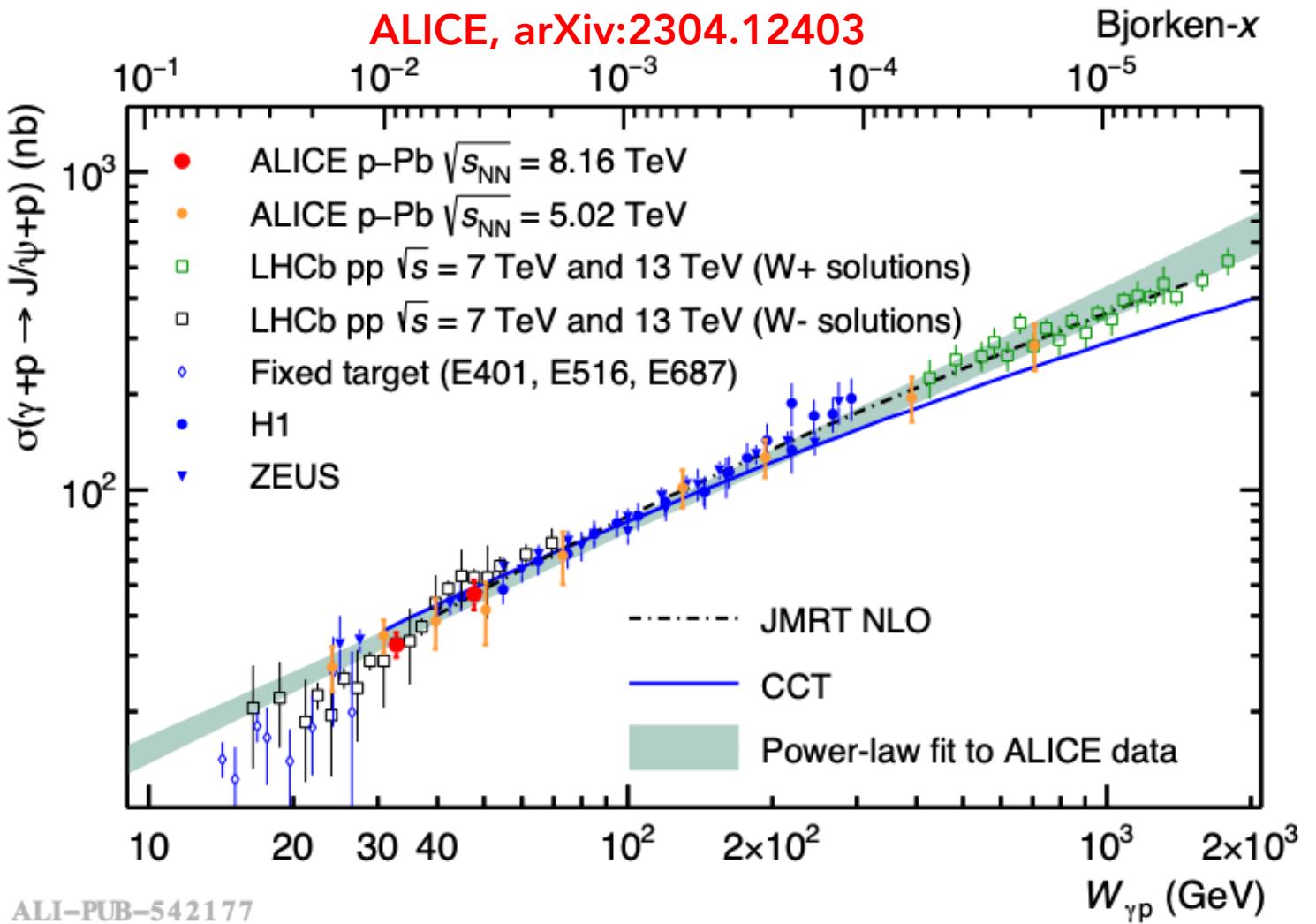
Coherent J/ ψ cross section

- Impulse approximation: Photoproduction data from protons, does not include nuclear effects except coherence
- STARlight: Photoproduction data from protons + Vector Meson Dominance model, includes multiple scattering but no gluon shadowing [Klein, Nystrand et al: Comput. Phys. Commun. 212 (2017) 258]
- EPS09: parametrization of nuclear shadowing data [Guzey, Kryshen, Zhalov, PRC93 (2016) 055206]
- LTA: nuclear shadowing [Guzey, Kryshen, Zhalov, PRC93 (2016) 055206]
- IIM BG, IPsat, BGK-I: Color dipol-based approaches [Goncalves, Machado et al.: PRC 90 (2014) 015203, JPG 42 (2015) 105001], [T. Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201]
- GG-HS: Color dipole + hot spots [Cepila, Contreras et al. PRC97 (2018) 024901]
- LS: Color dipole model [Luszczak, Schafer: PRC 99, 044905 (2019)]
- b-BK: Color dipole + Balitsky-Kovchegov equation



Exclusive J/ ψ in p-Pb UPC

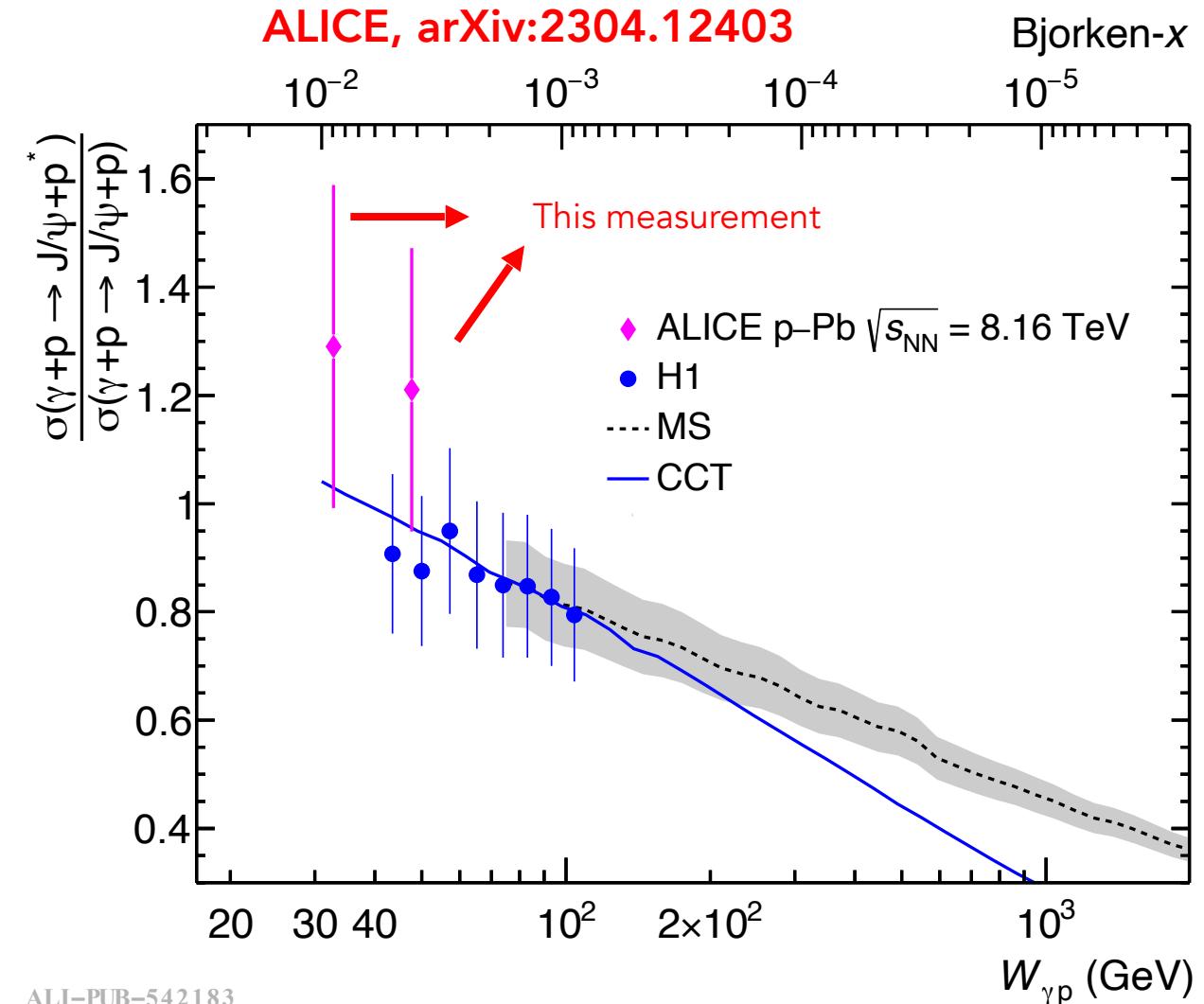
- JMRT NLO: DGLAP formalism with main NLO contributions [Jones et al. JHEP 11 (2013) 085, J. Phys. G 44 (2017) 03LT01, Phys. Rev. D 97 (2018) 116013]
- CCT: colour dipole + energy dependent hot spot model [Cepila et al., Phys. Lett. B766 (2017) 186–191]



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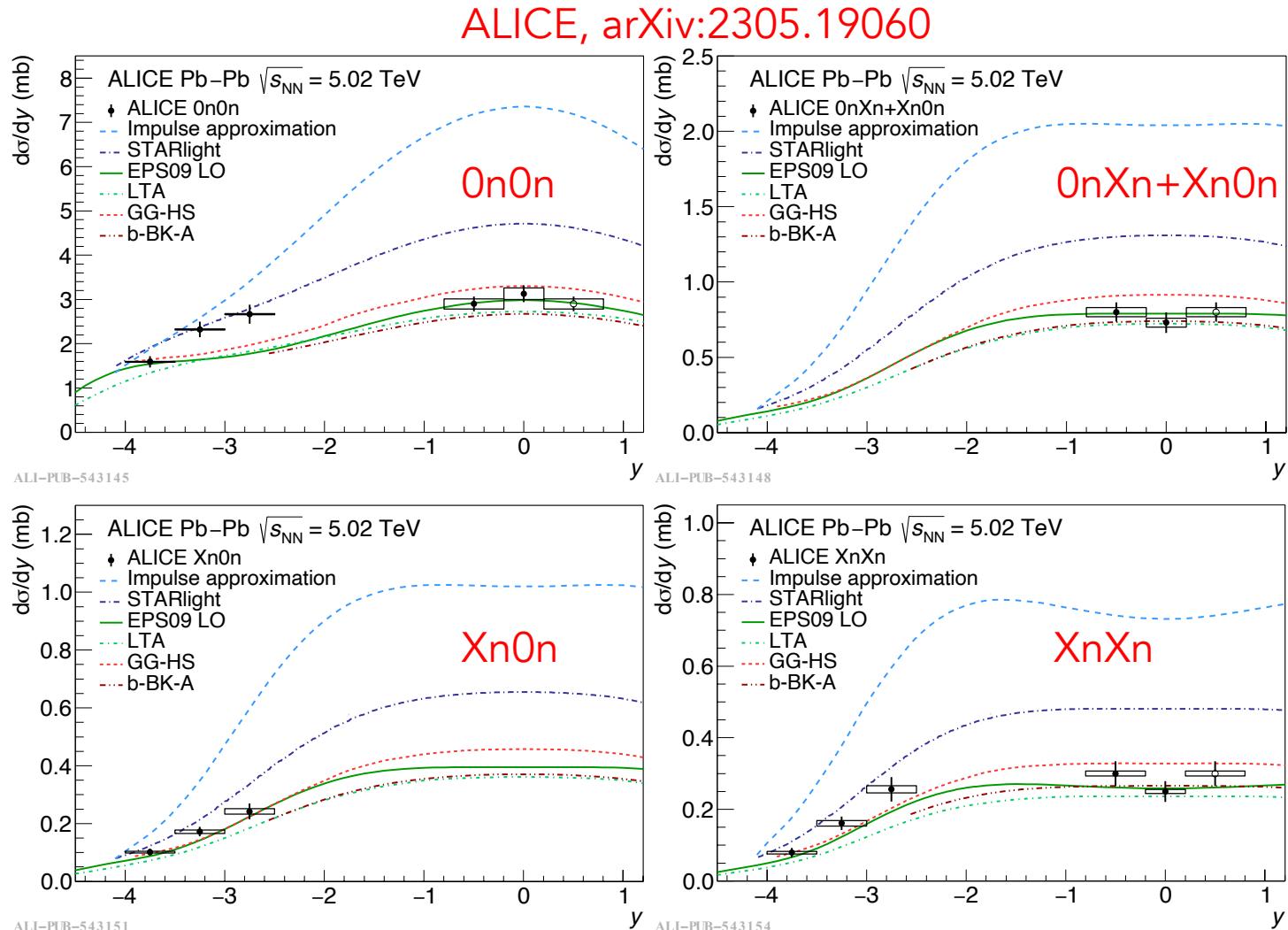
Exclusive and dissociative J/ ψ in p-Pb

- CCT: colour dipole + energy dependent hot spot model [Cepila et al., Phys. Lett. B766 (2017) 186–191]
- MS: JIMWLK + constrains from fits to H1 data [Mäntysaari, Schenke, Phys. Rev. D 98 (2018) 034013]



Coherent J/ ψ with neutron emission

- Event migrations: missed detection of a neutron (i.e. XN0N->0N0N), and neutrons from pile-up events
- $\epsilon_A = \epsilon_C = 0.933 \pm 0.017$
- $p_A = 0.0237 \pm 0.0005$
- Events are collected for pile-up, with $\epsilon_{pu} = 0.920 \pm 0.002$ and 0.962 ± 0.001 for mid and forward rapidity respectively
- Further correction for charged particles produced at beam rapidities by the dissociation of either nuclei, ϵ_{emd}



Systematics relevant to the extraction
of the UPC cross section, i.e. $d\sigma/dy$

Coherent J/ ψ with neutron emission

- Photon flux used as weights in a χ^2 minimisation:

$$\chi_{\text{exp}}^2(\vec{m}, \vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma_j^i m^i b_j - \mu^i\right)^2}{\delta_{i,\text{stat}}^2 \mu^i \left(m^i - \sum_j \gamma_j^i m^i b_j + (\delta_{i,\text{uncor}} m^i)^2\right)} + \sum_j b_j^2.$$

- Two types of uncertainty on the photon flux:
 - Total flux, obtained by varying the nuclear radius according to nuclear skin measurements
 - Fraction of the flux to each neutron class

$$\frac{d\sigma_{PbPb}^{0N0N}}{dy} = n_{0N0N}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0N0N}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

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Large difference in weight of the two solutions for the photon fluxes!



y	$n_\gamma(0n0n)$	$n_\gamma(0nXn+Xn0n)$	$n_\gamma(XnXn)$	$\sigma_{\gamma Pb}^{\text{IA}} (\mu\text{b})$
$3.5 < y < 4$	178.51	18.18	6.34	10
$3 < y < 3.5$	162.99	18.19	6.34	14
$2.5 < y < 3$	147.46	18.19	6.34	19
$0.2 < y < 0.8$	77.88	17.88	6.33	48
$-0.2 < y < 0.2$	62.86	17.47	6.27	58
$-0.8 < y < -0.2$	48.31	16.75	6.18	71
$-3 < y < -2.5$	3.91	4.97	2.78	176
$-3.5 < y < -3$	1.22	2.15	1.42	215
$-4 < y < -3.5$	0.26	0.61	0.48	262

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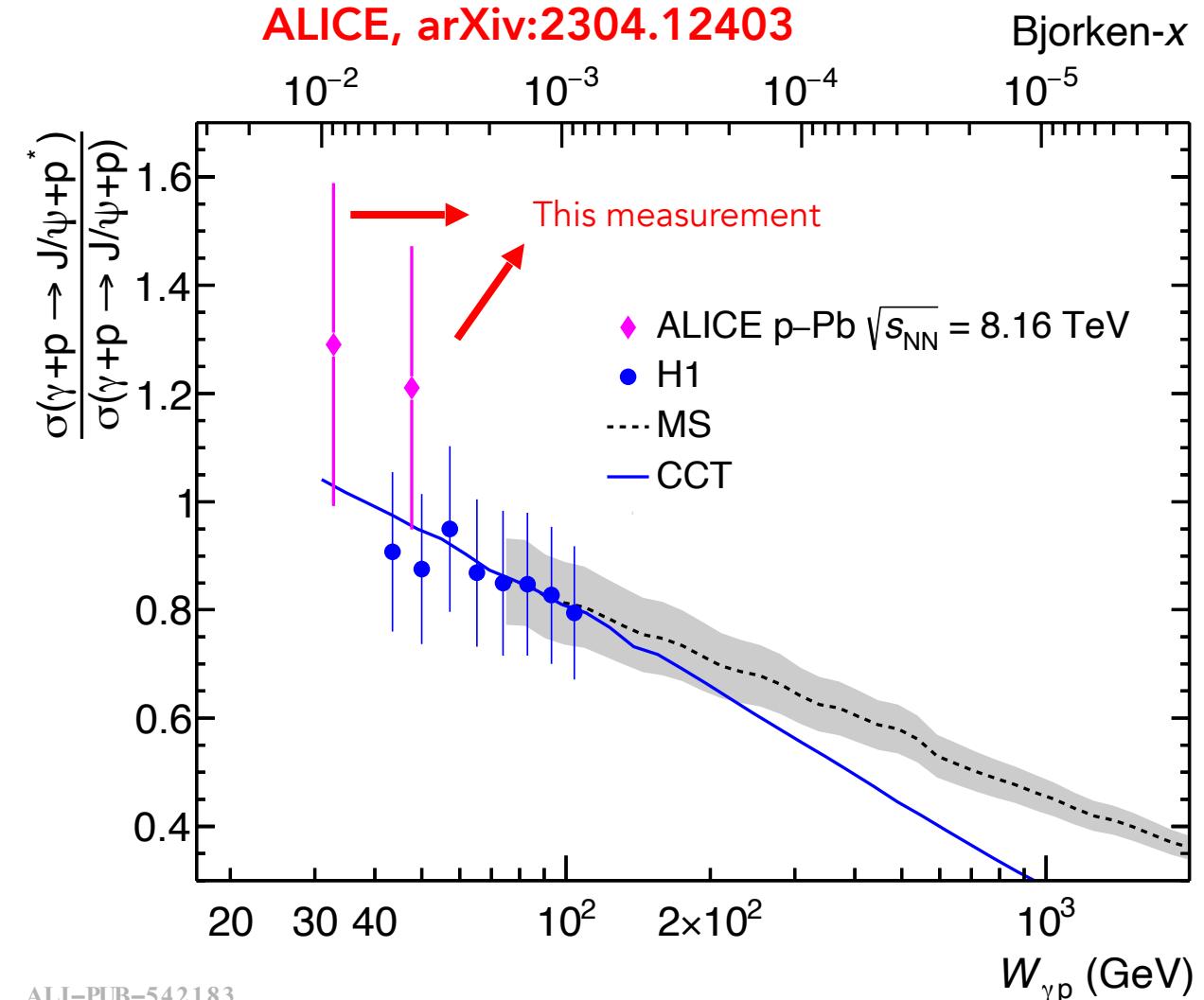
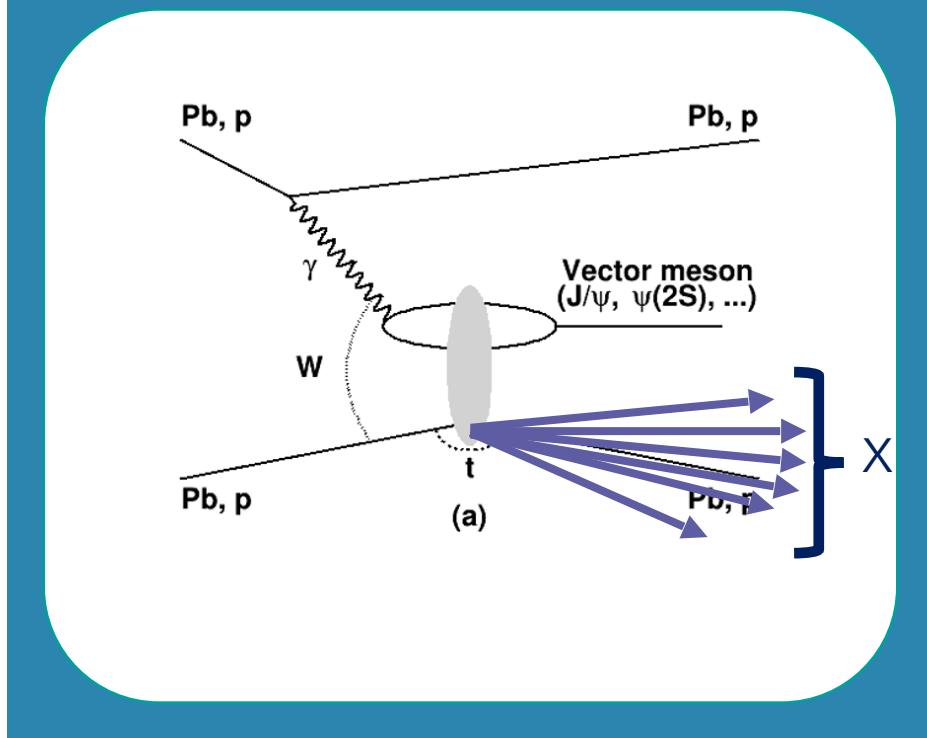
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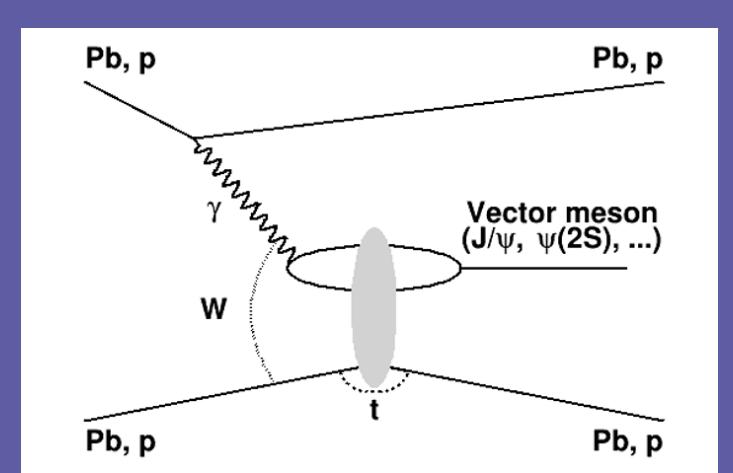
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Exclusive and dissociative J/ ψ in p-Pb

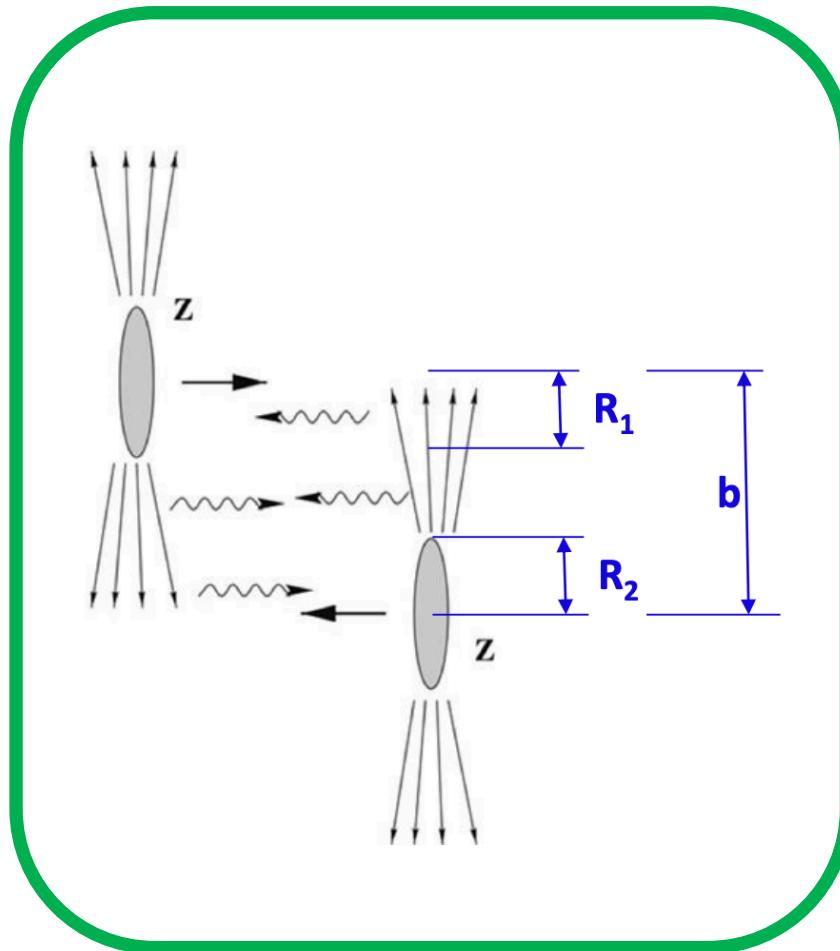
- First result at the LHC of the measurement of dissociative J/ ψ



Physics of ultra-peripheral collisions (UPC)

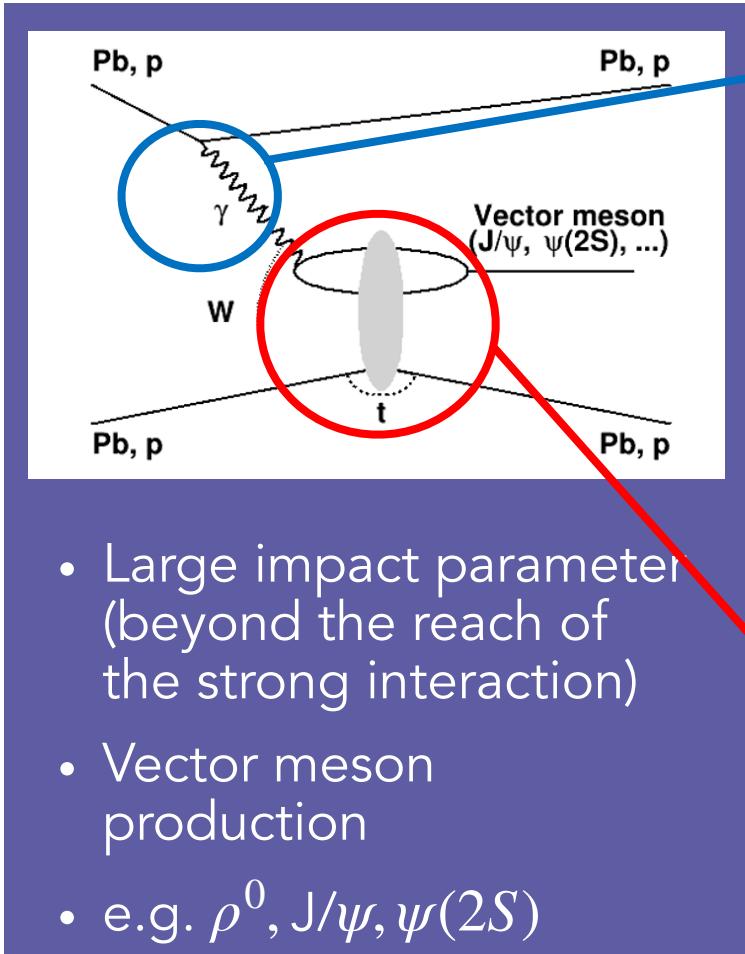


- Large impact parameter (beyond the reach of the strong interaction)
- Vector meson production
- e.g. ρ^0 , J/ ψ , $\psi(2S)$



- High photon flux
- Described in Weizsäcker-Williams approach of quasireal photons
- Flux proportional to Z^2

Introduction to ultra-peripheral collisions (UPC)



- Only QED involved at this vertex!
- $|t|$ the square of the momentum transferred between the incoming and outgoing target nucleus
- W the centre-of-mass energy of the photon-target system
- Hard scale ensured by high mass states i.e. $J/\psi, \psi(2S)$
- Semi-hard scale for ρ^0

- *Coherent photoproduction:* photon couples with the **entire nucleus**
- *Incoherent photoproduction:* photon couples with a **single nucleon** only
- Different average p_T of the vector mesons for the two processes