Studying photonuclear cross sections with UPCs in ALICE

Simone Ragoni for the ALICE Collaboration

Creighton University, USA

Outline

- Physics of ultra-peripheral collisions (UPC)
- The ALICE detector
- Measurements of the energy dependence of the photonuclear cross sections
    - Rapidity-differential measurements
    - Peripheral photoproduction
    - Neutron emission

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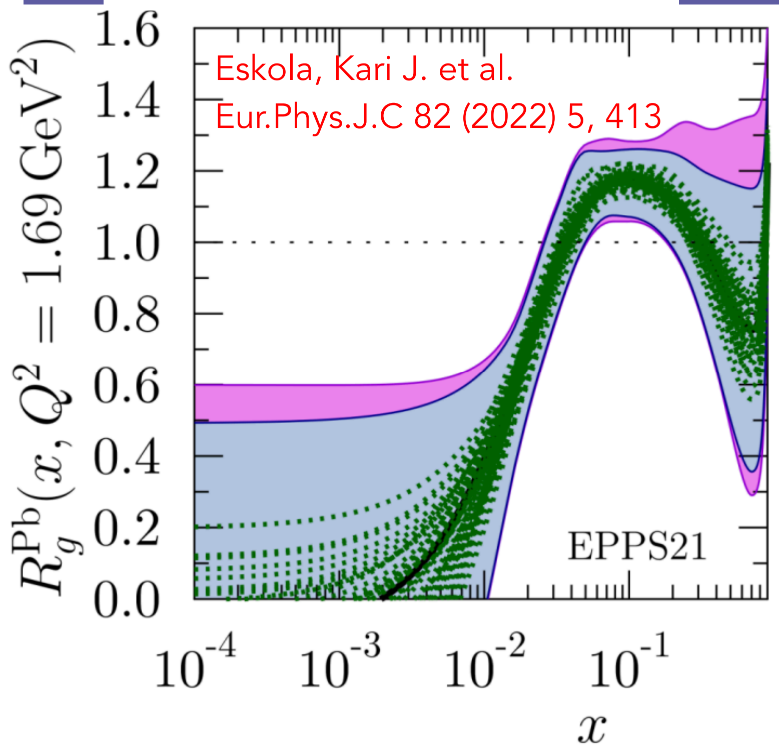
Physics of ultra-peripheral collisions (UPC)

Studying nuclear shadowing

Nuclear gluon PDF

$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)} < 1$$

Proton gluon PDF

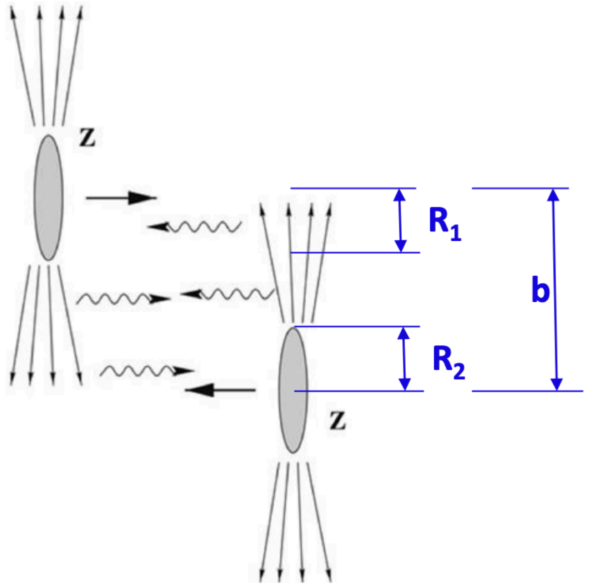


LO

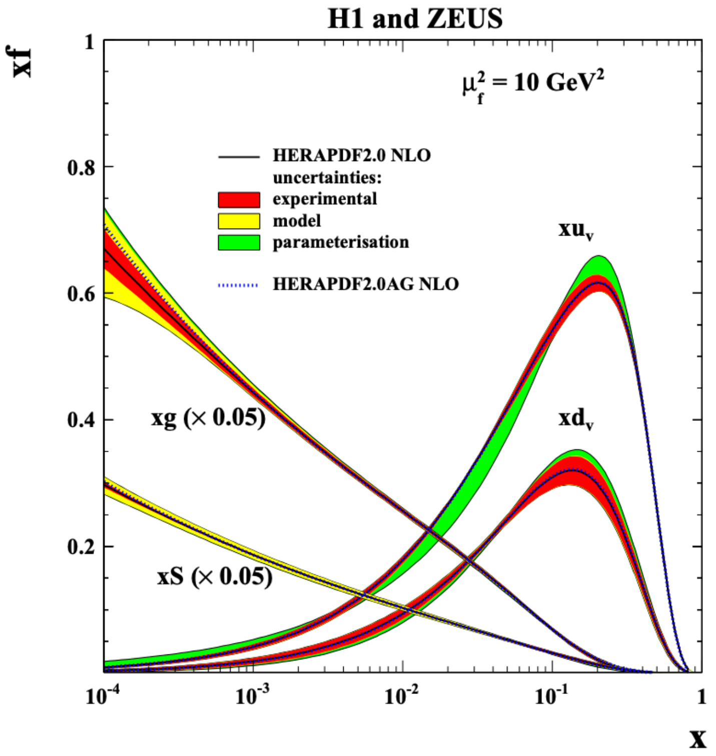
$$\frac{d\sigma^T(\gamma p \to J/\Psi + p)}{dt} = \frac{|M|^2}{16\pi s^2}$$

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

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



Looking for gluon saturation



H1 and Zeus, EPCJ 75 (2015) 580

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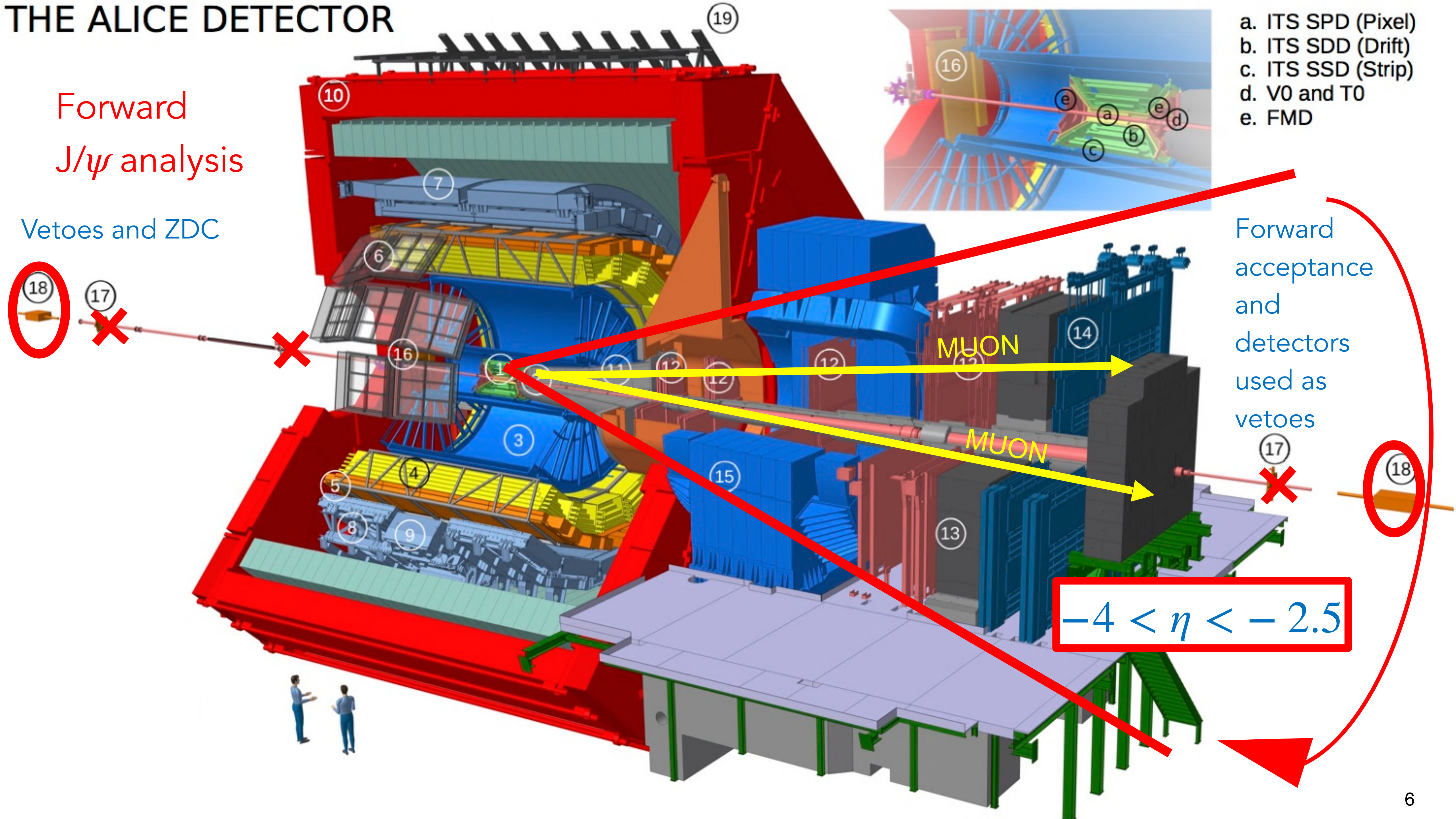
THE ALICE DETECTOR

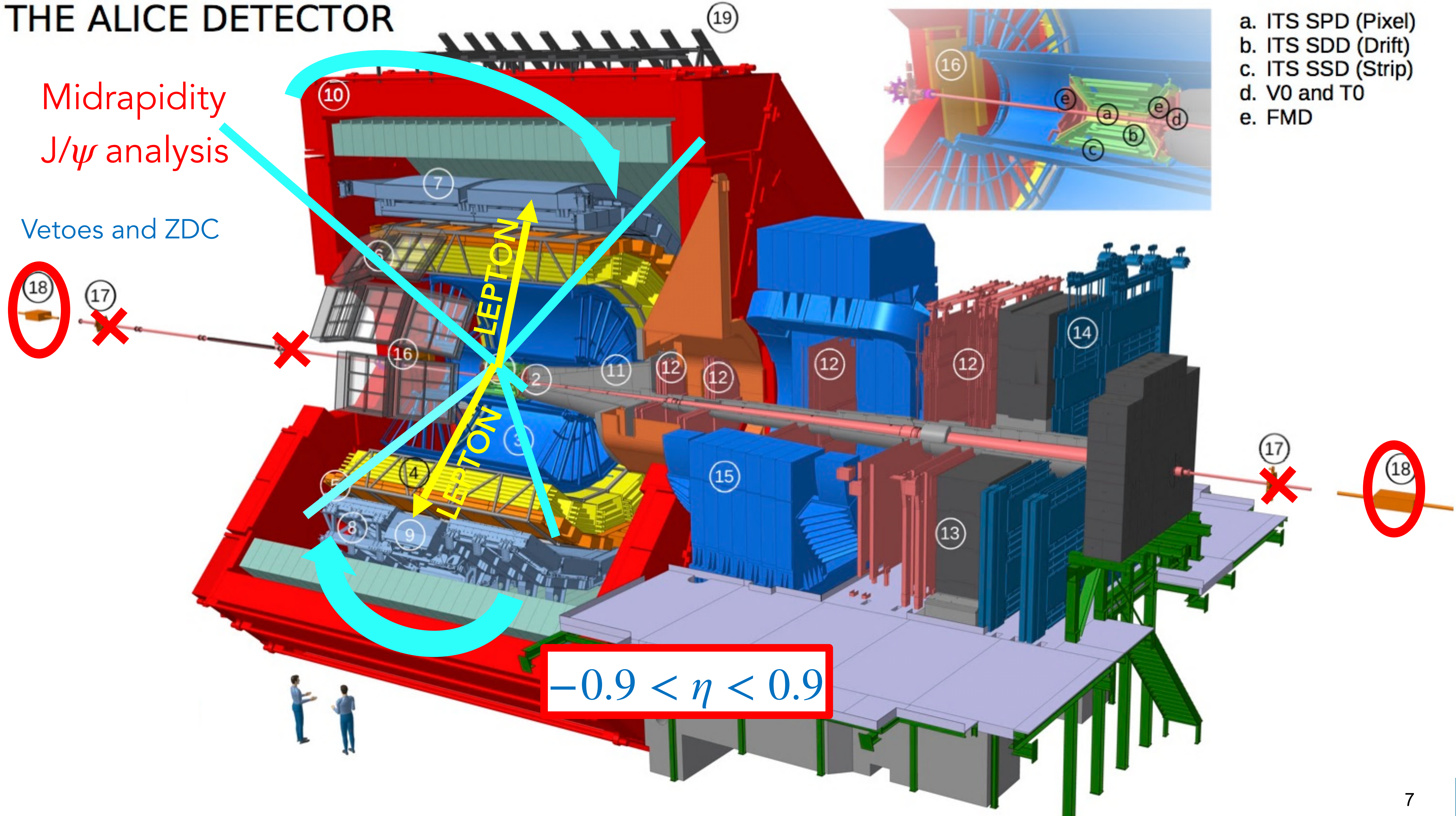
Forward

J/ψ analysis

Vetoes and ZDC



THE ALICE DETECTOR



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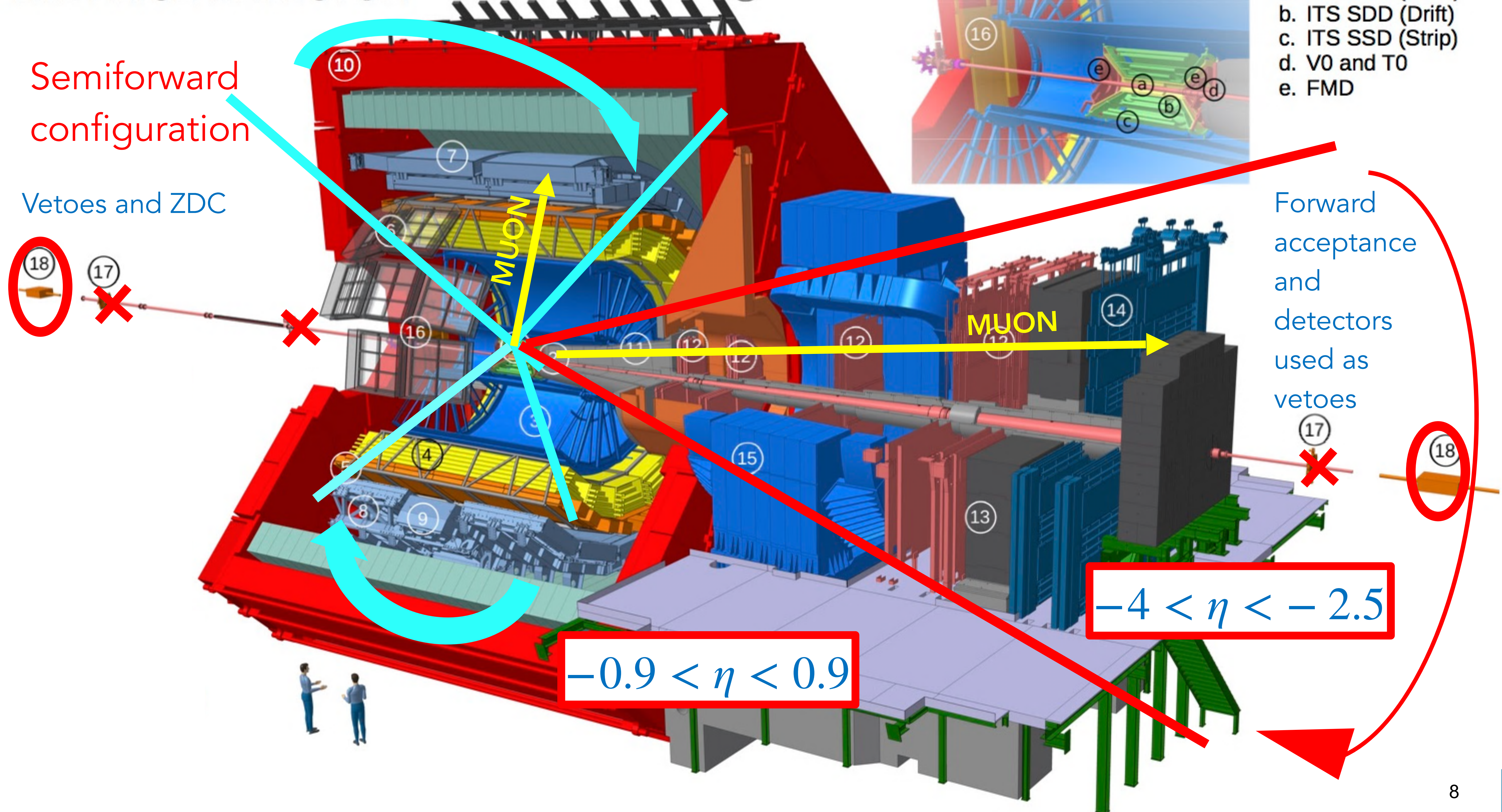

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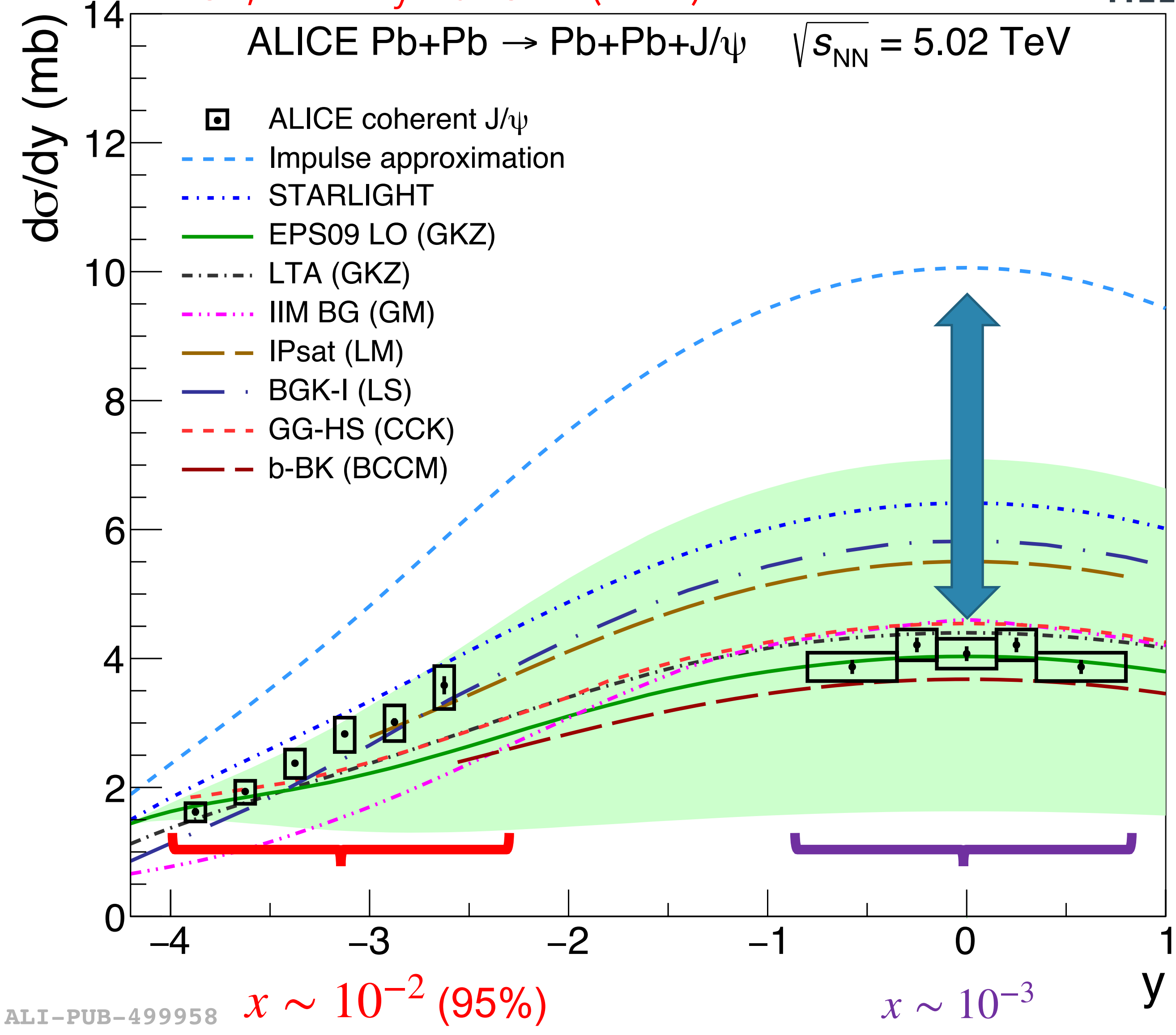
Coherent J/ψ cross section

- ALICE data exhibit moderate nuclear shadowing
- Nuclear suppression factor

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

- 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

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



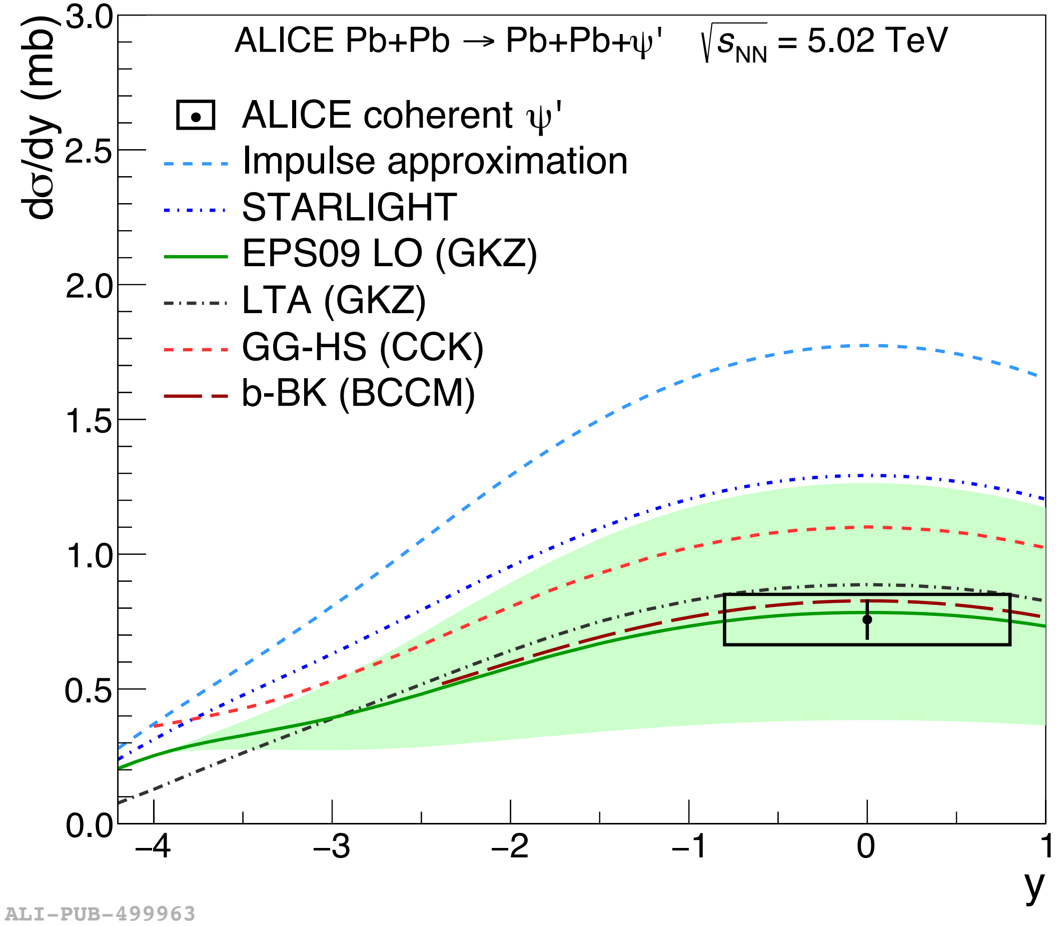
$x \sim 10^{-2}$ (95%)

$x \sim 10^{-5}$ (5%)

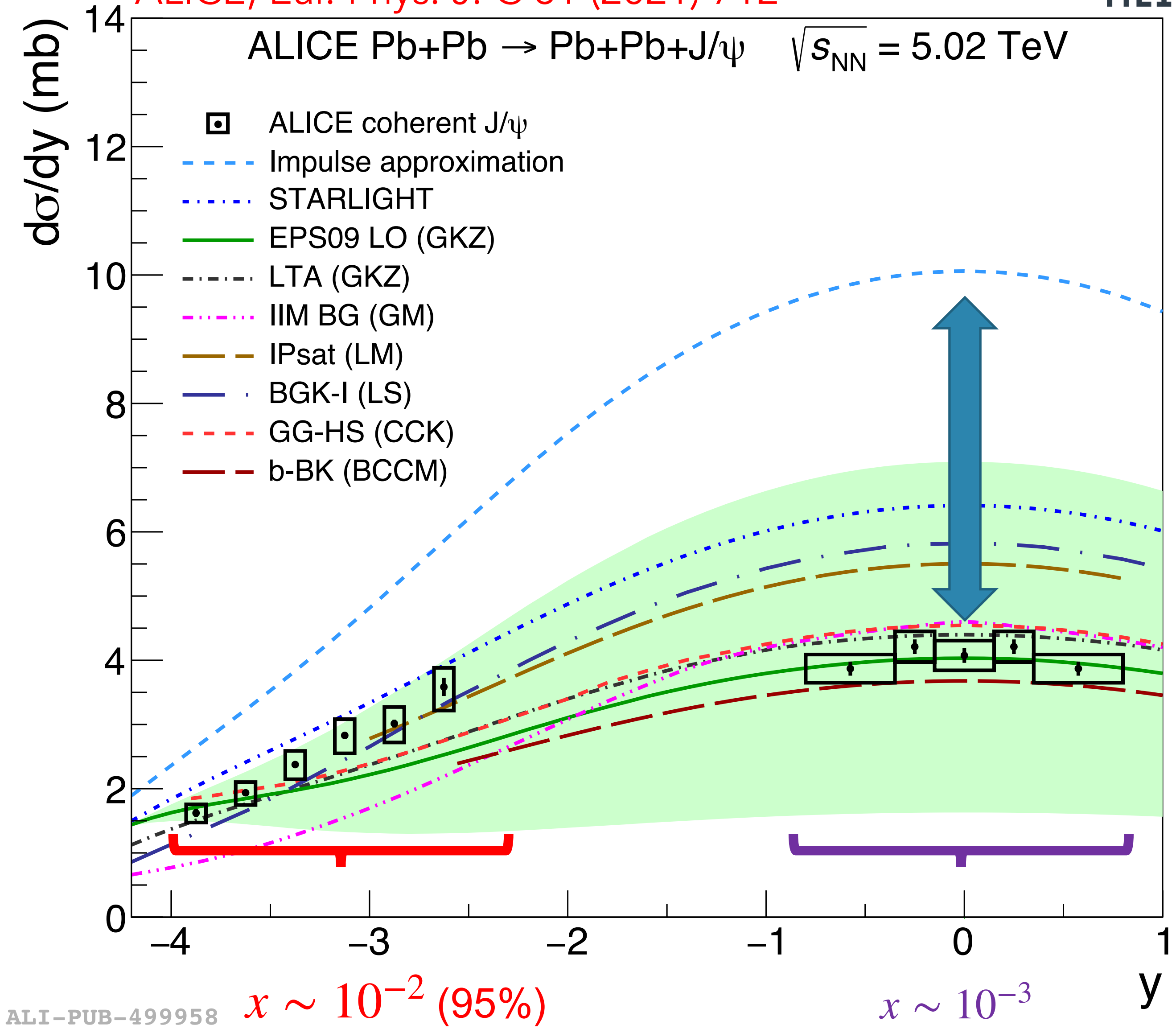
$x \sim 10^{-3}$

Coherent J/ψ and ψ′ cross section

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



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



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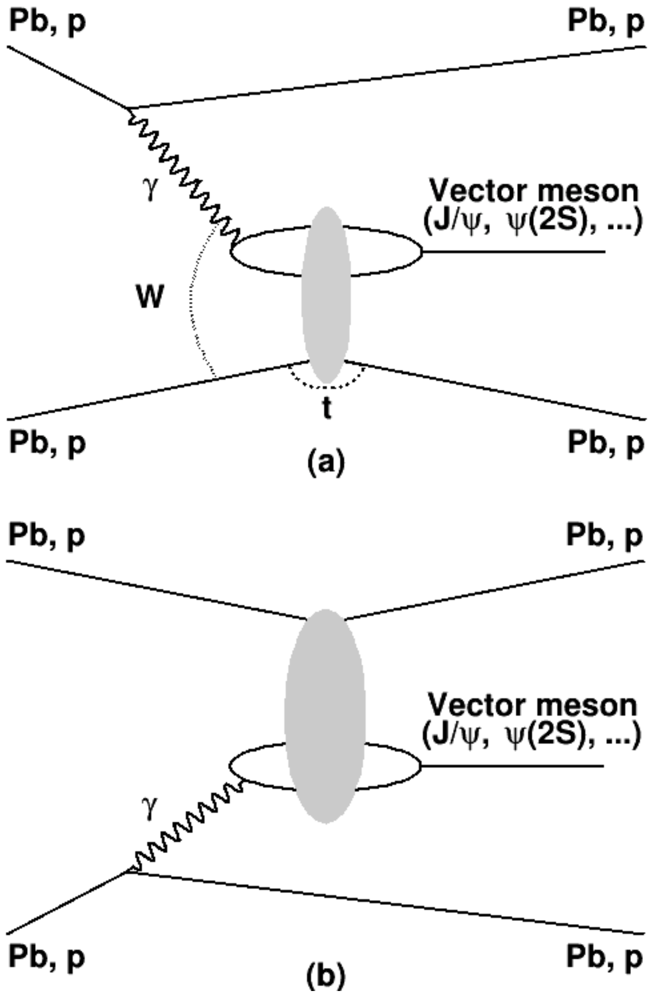
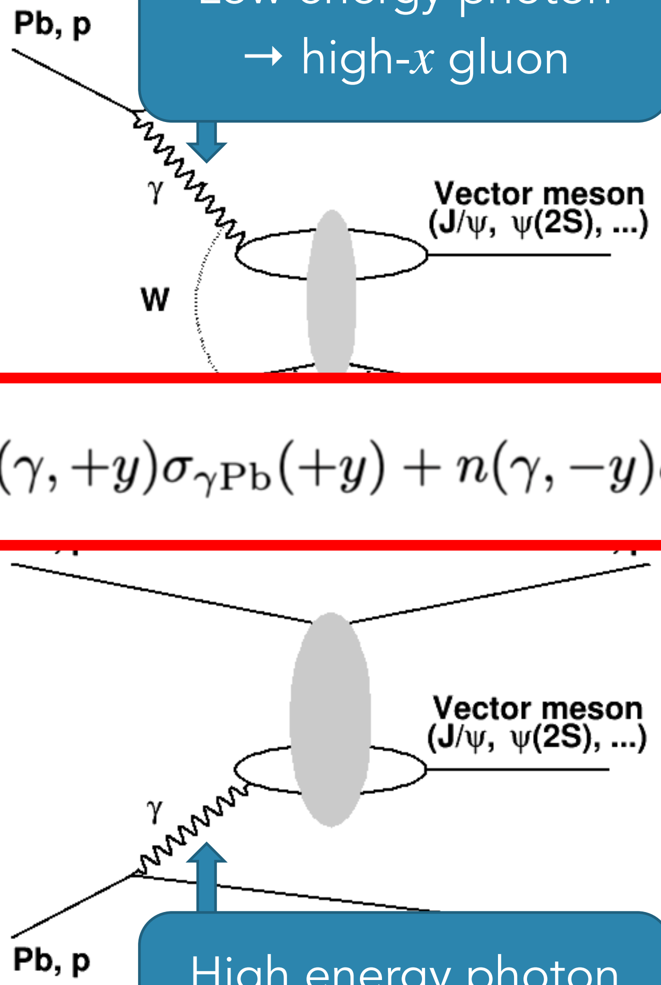
Measuring the energy dependence



Measuring the energy dependence

Low energy photon
→ high-x gluon



$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma Pb,n}}$$

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

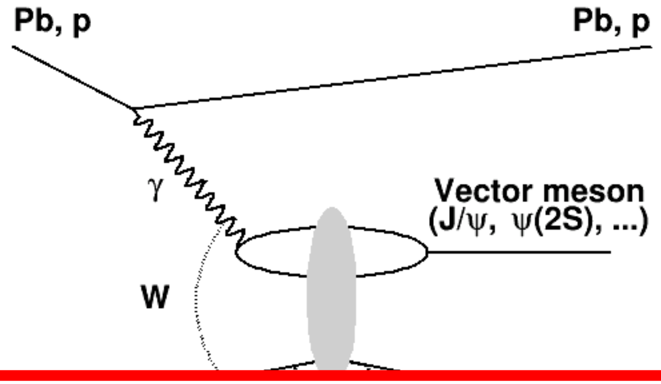
High energy photon
→ low-x gluon

Measuring the energy dependence

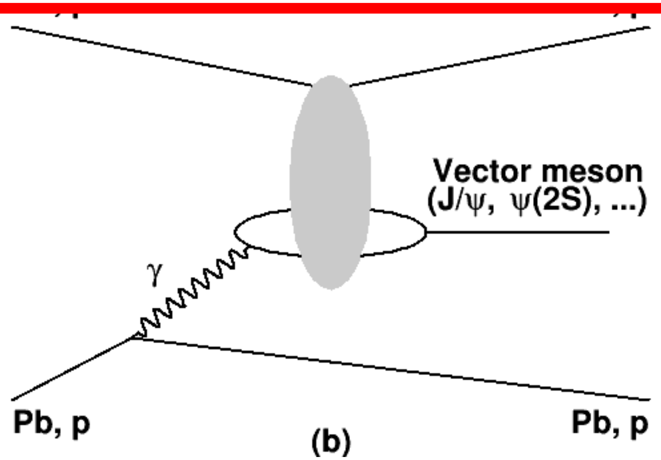
Coherent J/ψ at midrapidity:

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

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



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



Measuring the energy dependence

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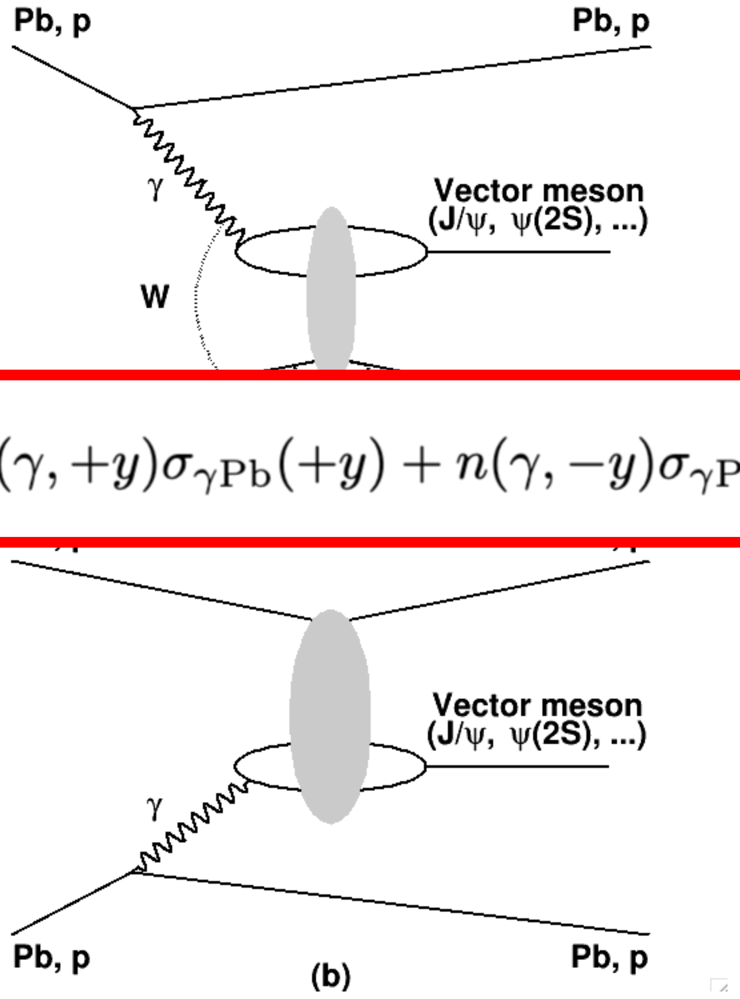


$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = n(\gamma,+y)\sigma_{\gamma\mathrm{Pb}}(+y) + n(\gamma,-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

Coherent J/ψ at forward rapidity:

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

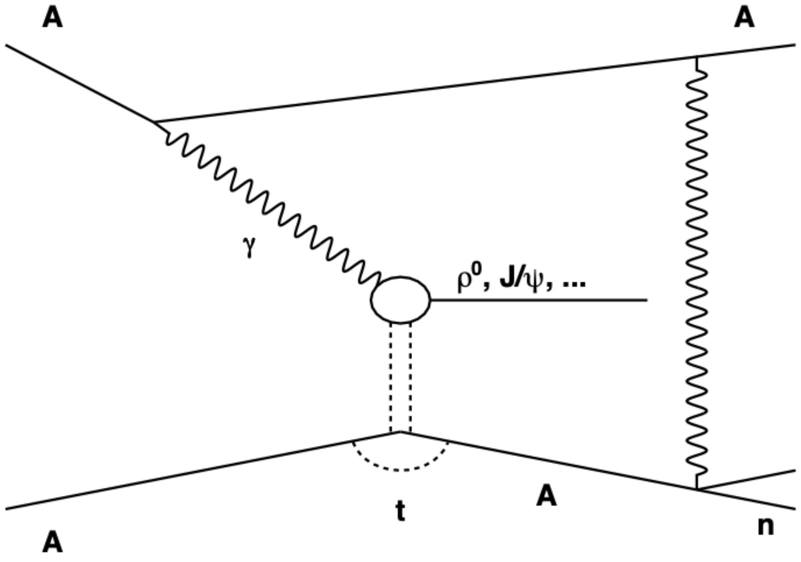
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} \simeq n(\gamma)\sigma_{\gamma\mathrm{Pb}}$$

But that remaining 5% is very interesting

Techniques for the photon direction ambiguity

Neutron emission:

- $x = \frac{M_{\mathrm{VM}}}{\sqrt{s_{\mathrm{NN}}}} \cdot e^{\pm y}$
- Ambiguity due to sign in the rapidity of the photon emitter → 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

Techniques for the photon direction ambiguity

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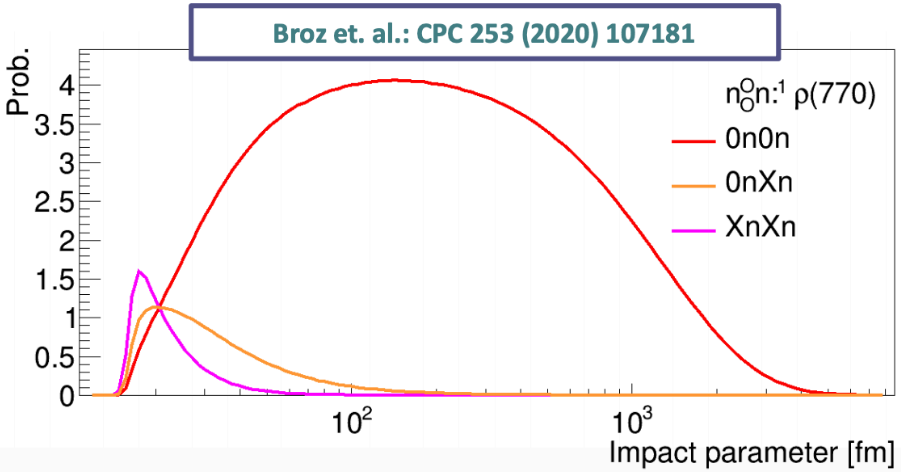


$$\frac{d\sigma^{0N0N}_{PbPb}}{dy} = n_{0N0N}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0N0N}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

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

Guzey et al., Eur.Phys.J.C 74 (2014) 7, 2942

- Additional photon exchanges may lead to neutron emission

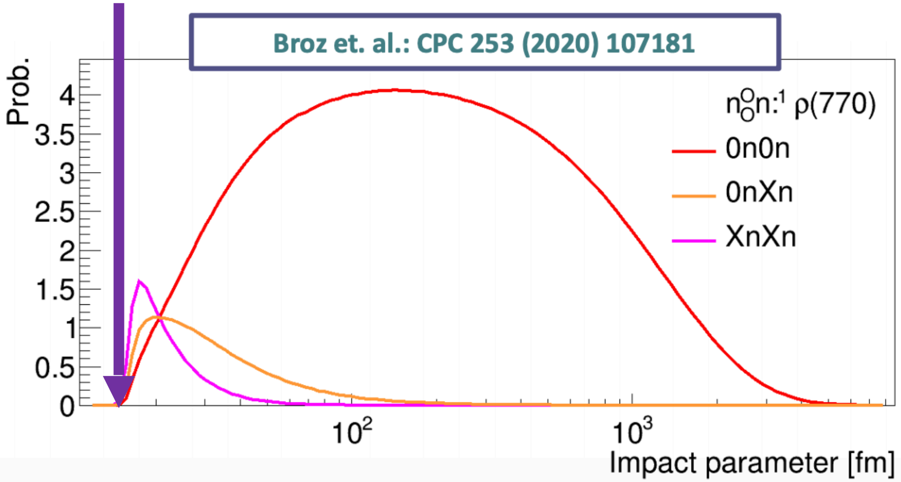
- Using the neutron ZDCs on the A and C side to detect the neutrons!
- E.g. 0N0N: no neutrons on either ZDCs
- E.g. 0NXN: neutrons only on one side
- Effectively leveraging on the impact parameter

Techniques for the photon direction ambiguity

Neutron emission:

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

$2R_{\mathrm{Pb}}$



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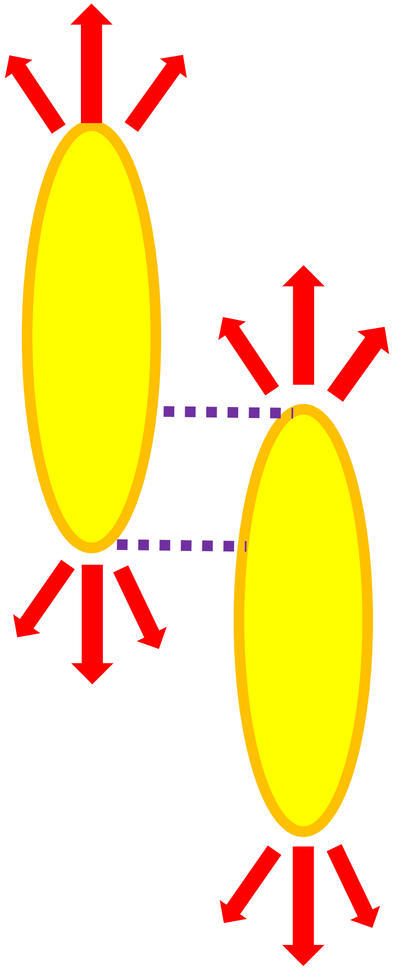
Techniques for the photon direction ambiguity

Peripheral photoproduction:

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



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

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

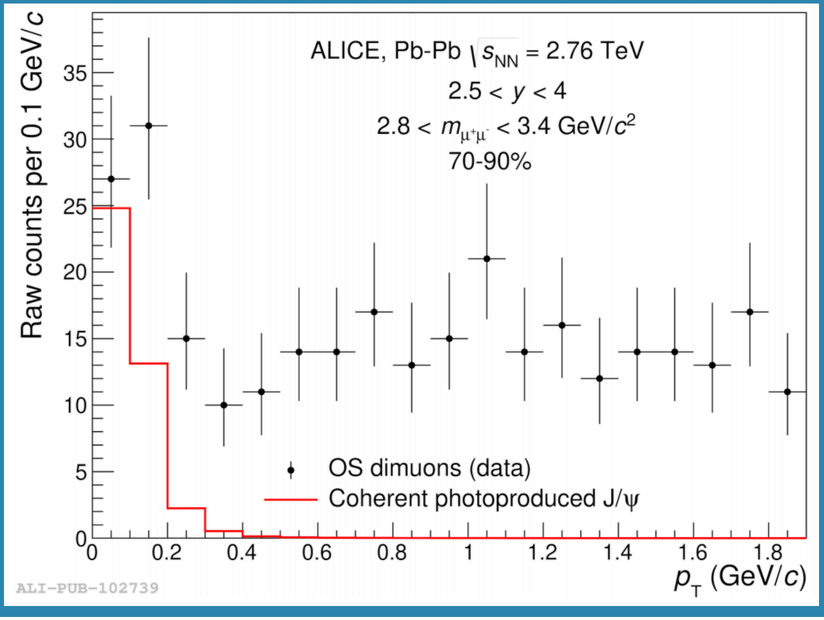
$$\frac{d\sigma^{U}_{PbPb}}{dy} = n_U(\gamma,+y)\cdot\sigma_{\gamma Pb}(+y) + n_U(\gamma,-y)\cdot\sigma_{\gamma Pb}(-y)$$

J.G. Contreras PRC 96 (2017) 015203

Peripheral J/ψ photoproduction using ALICE Run 1 data

ALICE

- 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
ALICE, arXiv:2204.10684
LHCb, *Phys.Rev.C* 105 (2022) 3, L032201
STAR, *Phys.Rev.*Lett. 123 (2019) 132302

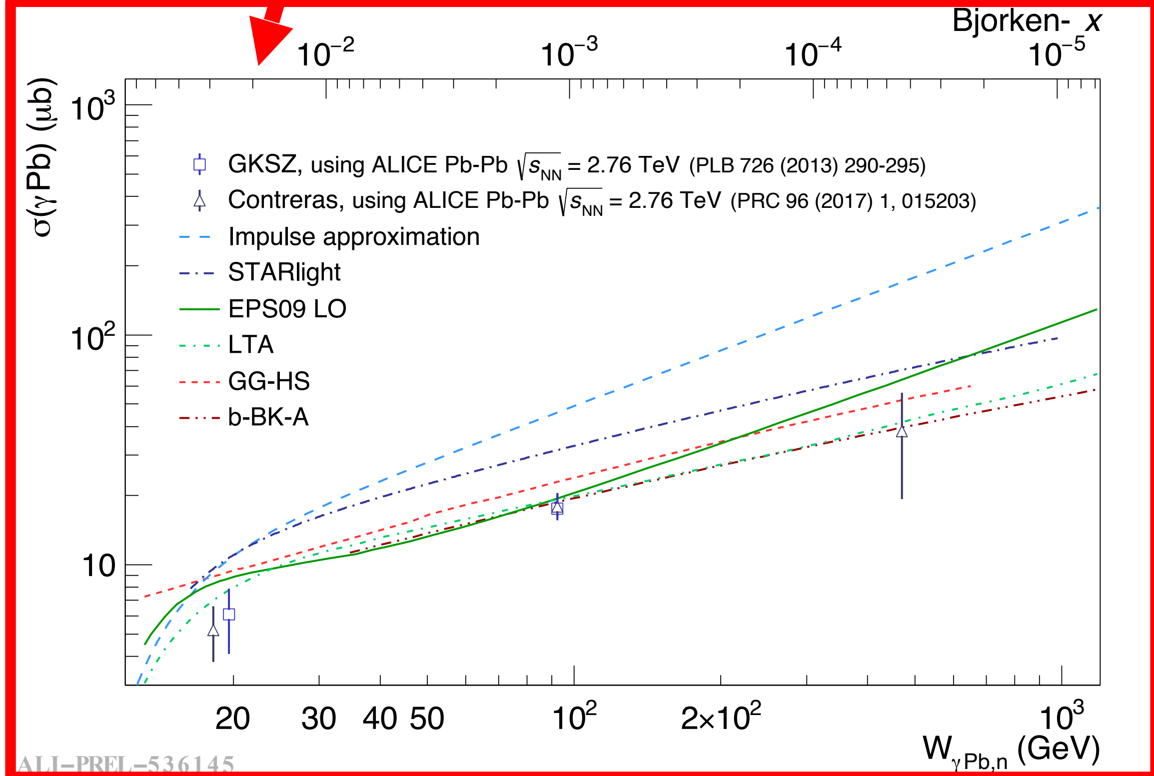
Peripheral results

UPC results

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

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

J.G. Contreras PRC 96 (2017) 015203



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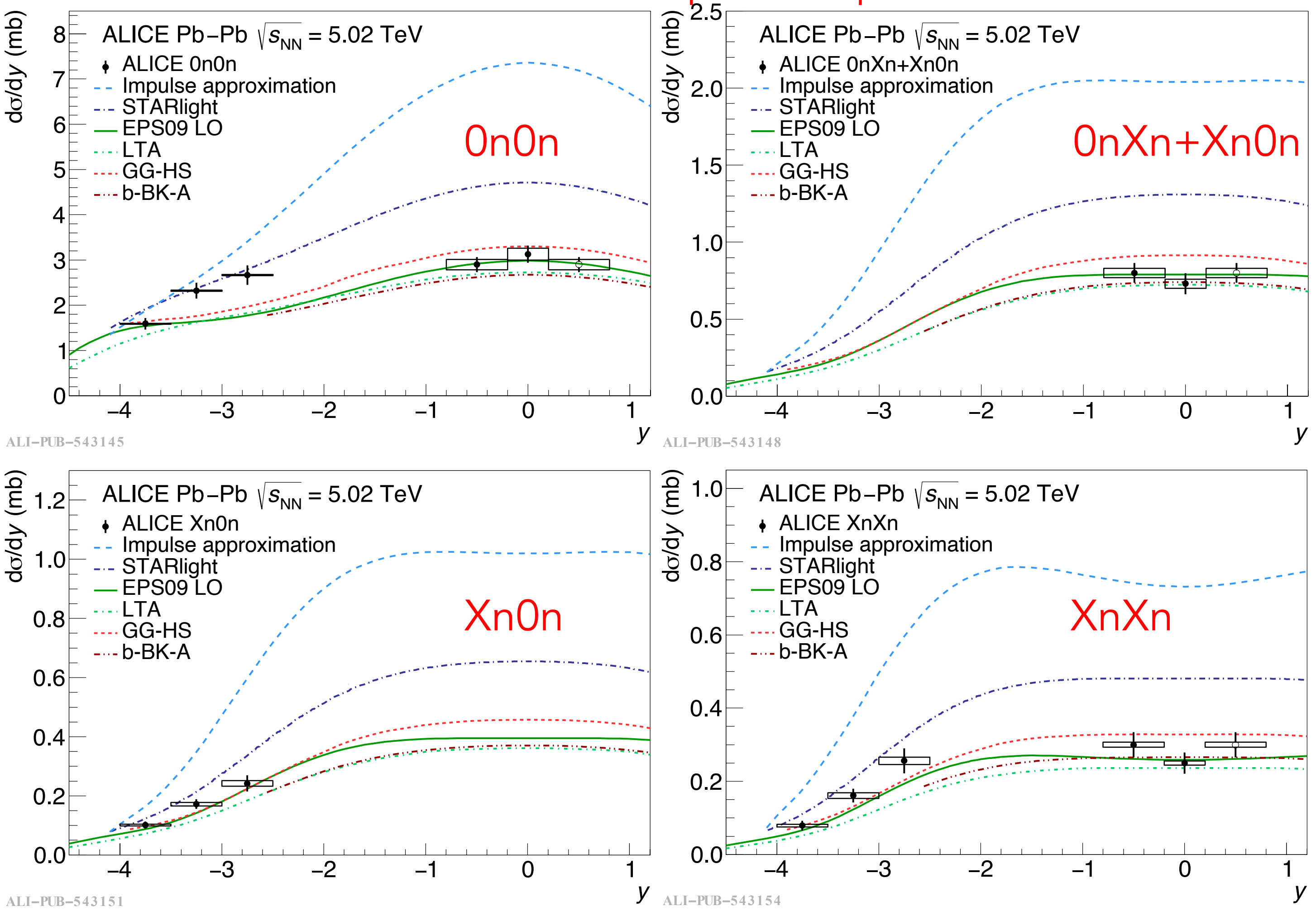
Coherent J/ψ with neutron emission

ALICE, arXiv:2305.19060, accepted for publication in JHEP

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

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

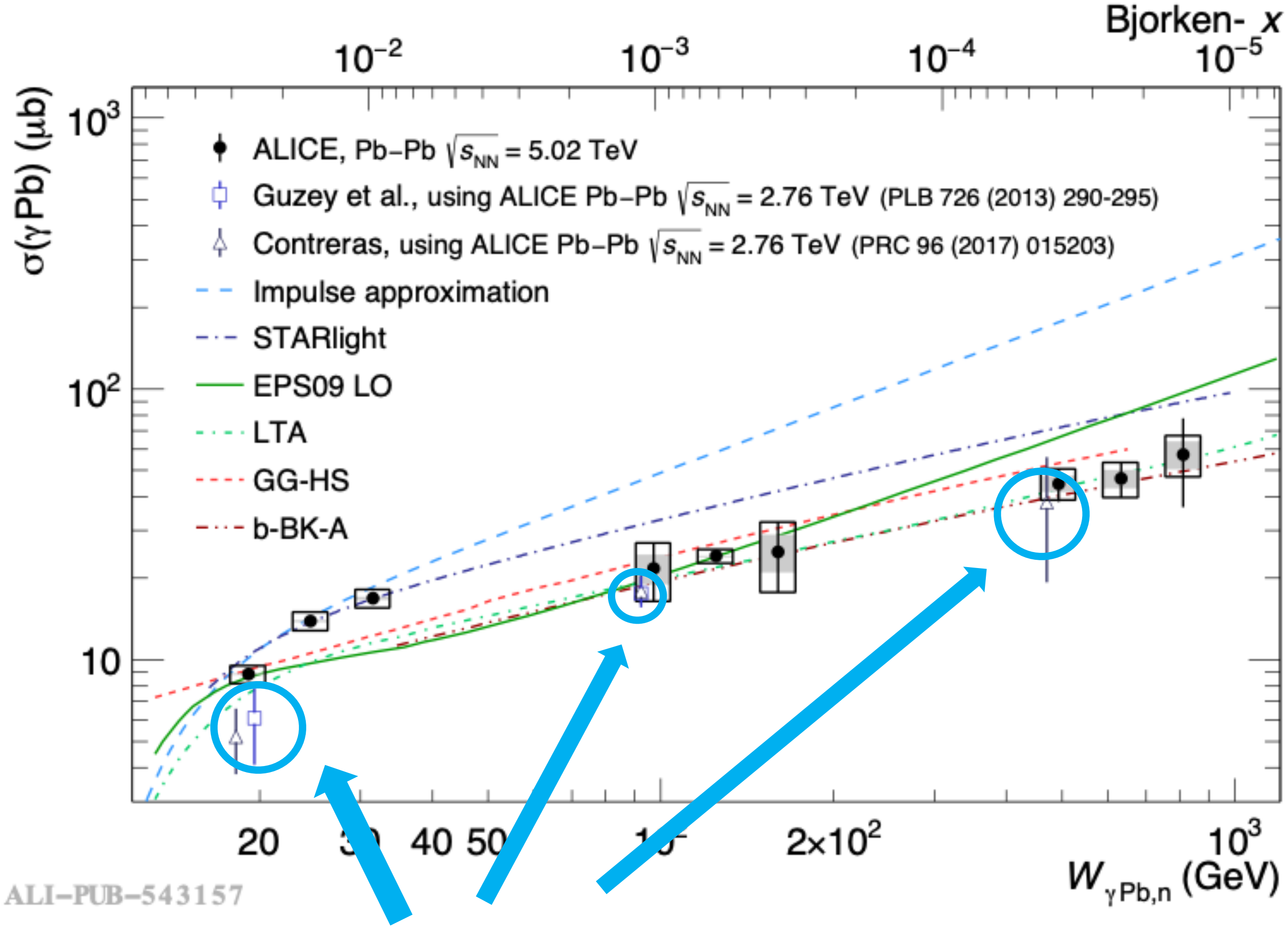
y	n_γ(0n0n)	n_γ(0nXn+Xn0n)	n_γ(XnXn)	$\sigma^{IA}_{\gamma Pb}$ (μb)
$3.5 < y < 4$	178.51	18.18	6.34	10
$3 < y < 3.5$	162.99	18.19	6.34	14
$2.5 < y < 3$	147.46	18.19	6.34	19
$0.2 < y < 0.8$	77.88	17.88	6.33	48
$-0.2 < y < 0.2$	62.86	17.47	6.27	58
$-0.8 < y < -0.2$	48.31	16.75	6.18	71
$-3 < y < -2.5$	3.91	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



Coherent J/ψ with neutron emission

ALICE, arXiv:2305.19060, accepted for publication in JHEP

- 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

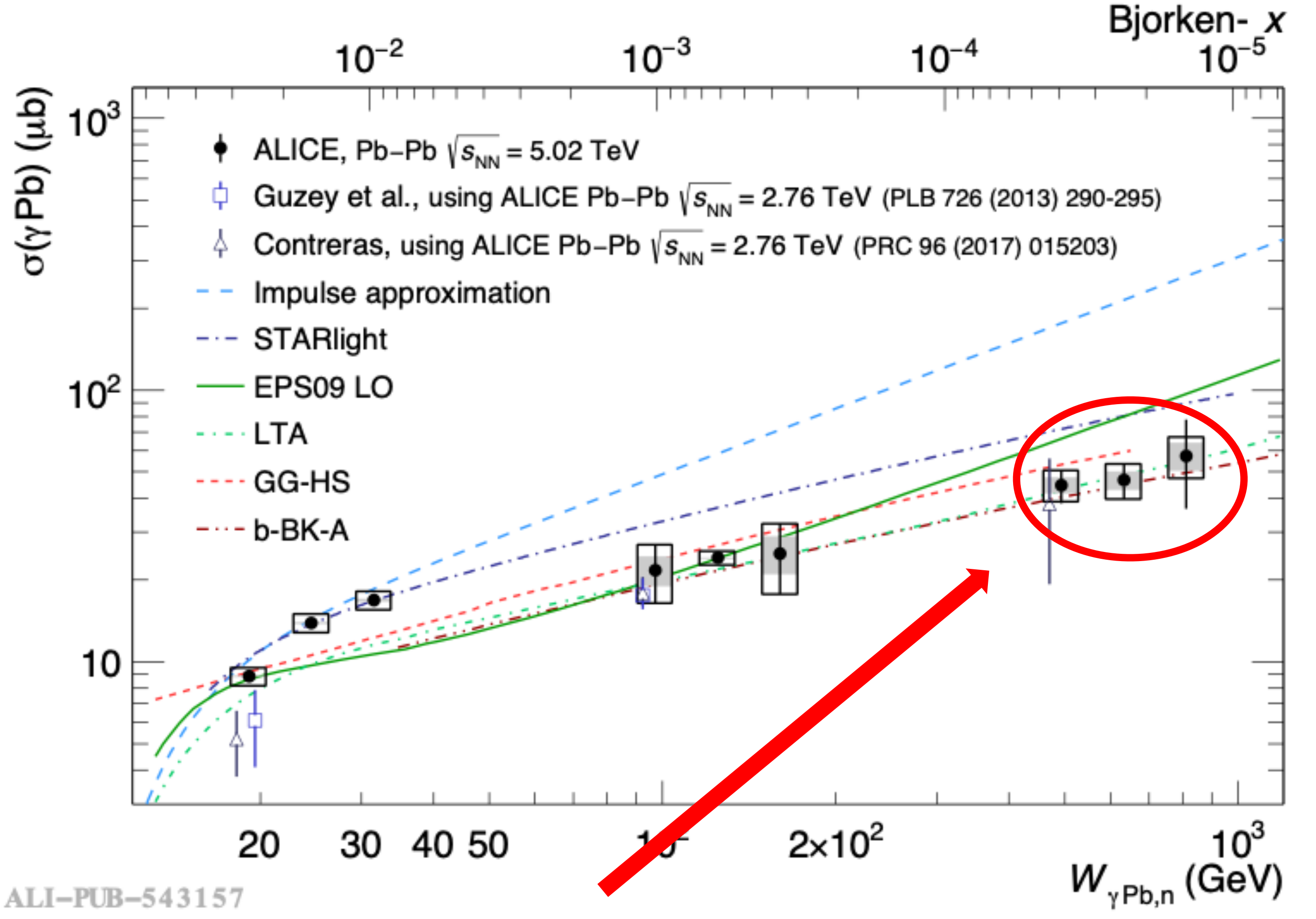


Good agreement between Run 1 peripheral and Run 2 neutron emission measurements!

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, accepted for publication in JHEP



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

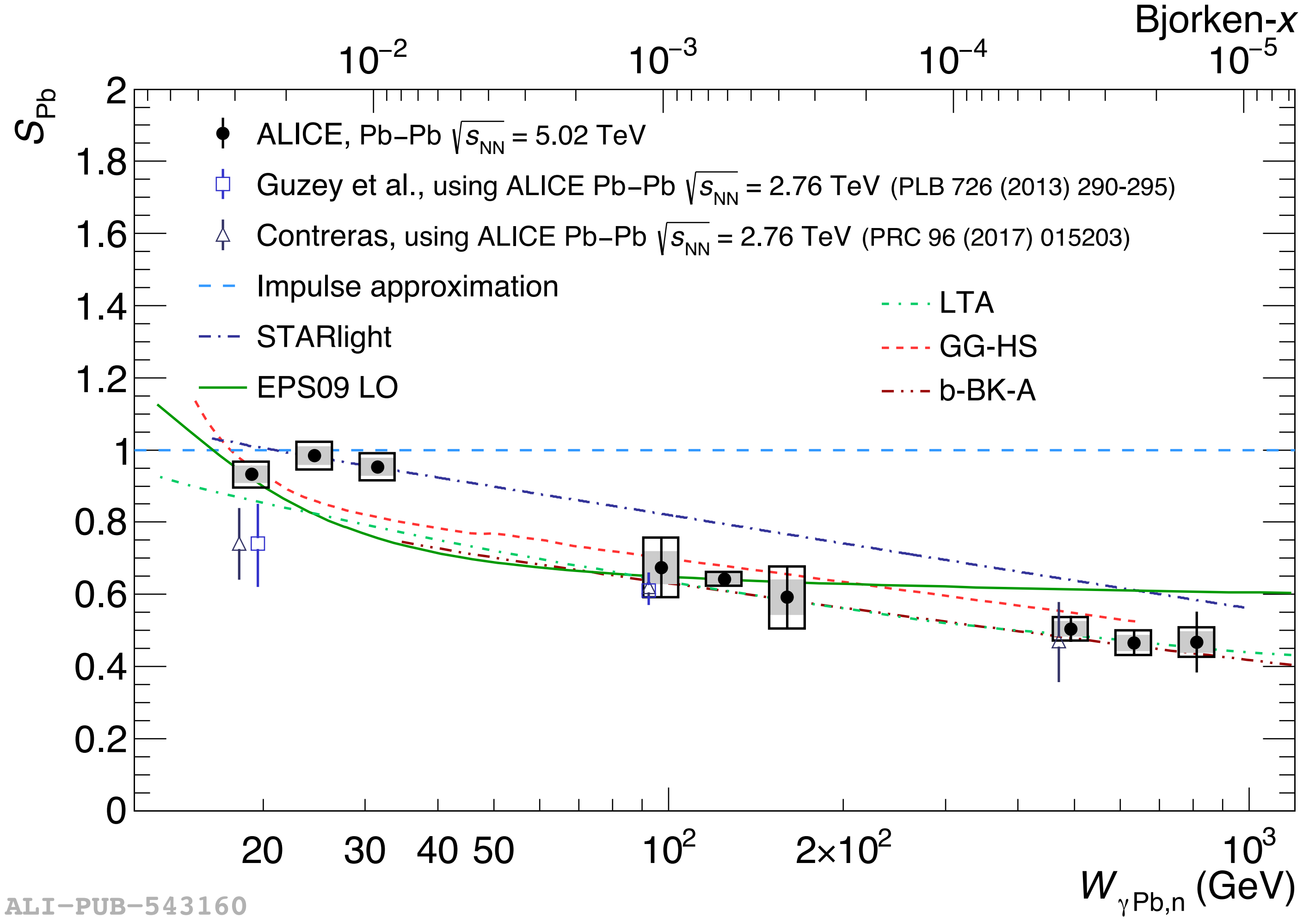
Coherent J/ψ with neutron emission

- First measurement of the nuclear suppression factor at Bjorken-$x \sim 10^{-5}$!

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

- At low-x data favours both saturation and shadowing models
- Additional theoretical uncertainty from impulse approximation → dominates at low energies

ALICE, arXiv:2305.19060, accepted for publication in JHEP



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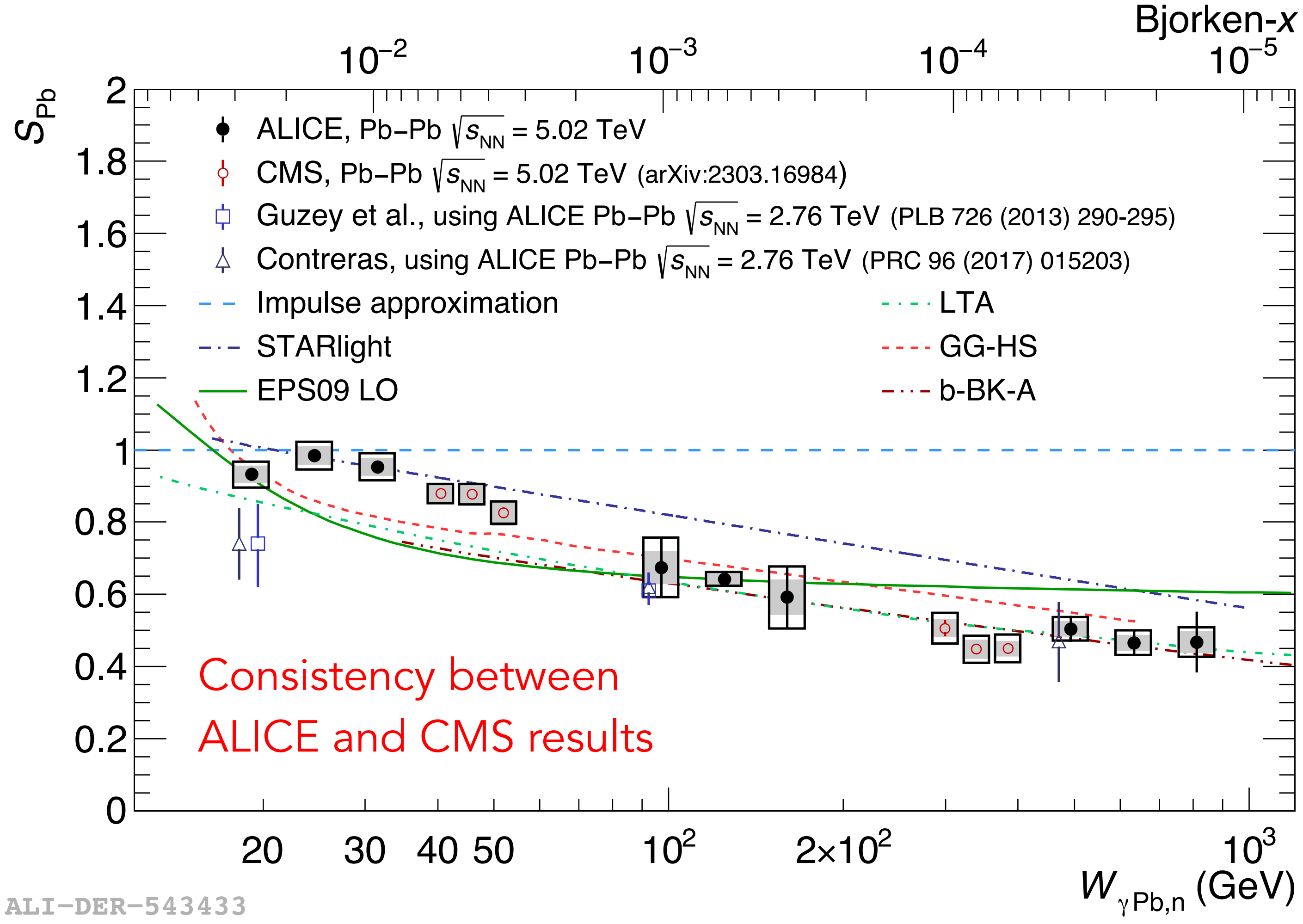


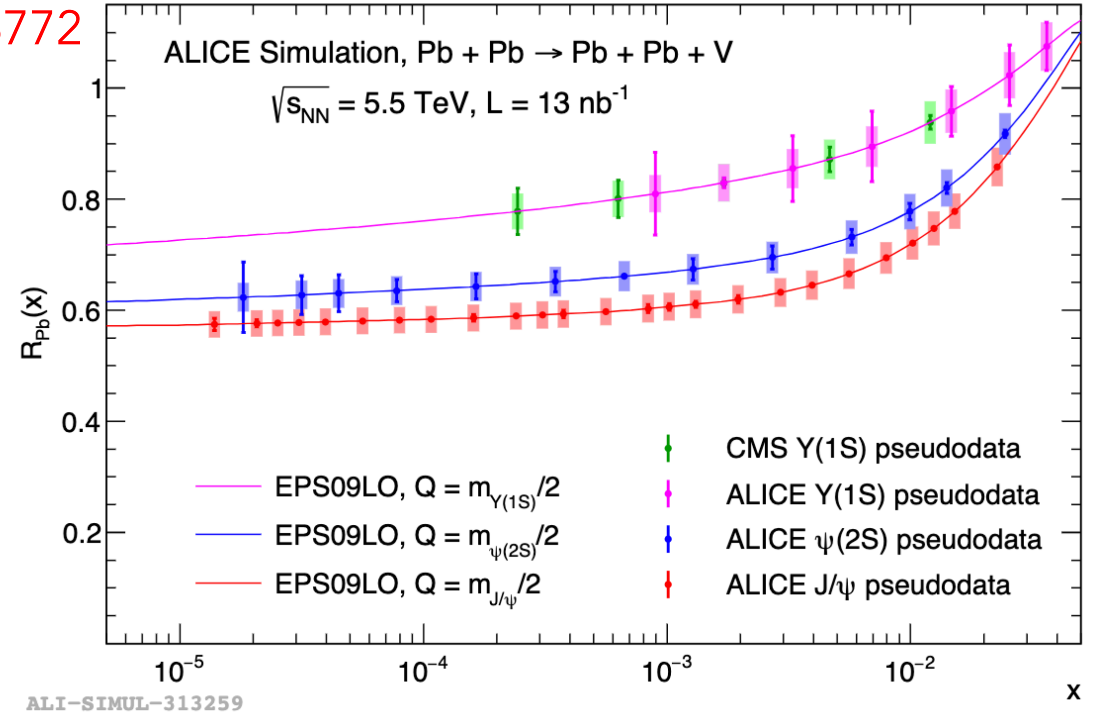
ALICE in Run 3 and 4

- 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!

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

$|y| < 0.9$ $\quad 2.5 < |y| < 4$

CERN Yellow Rep. Monogr. 7 (2019) 1159-1410, arXiv 1812.06772



Summary

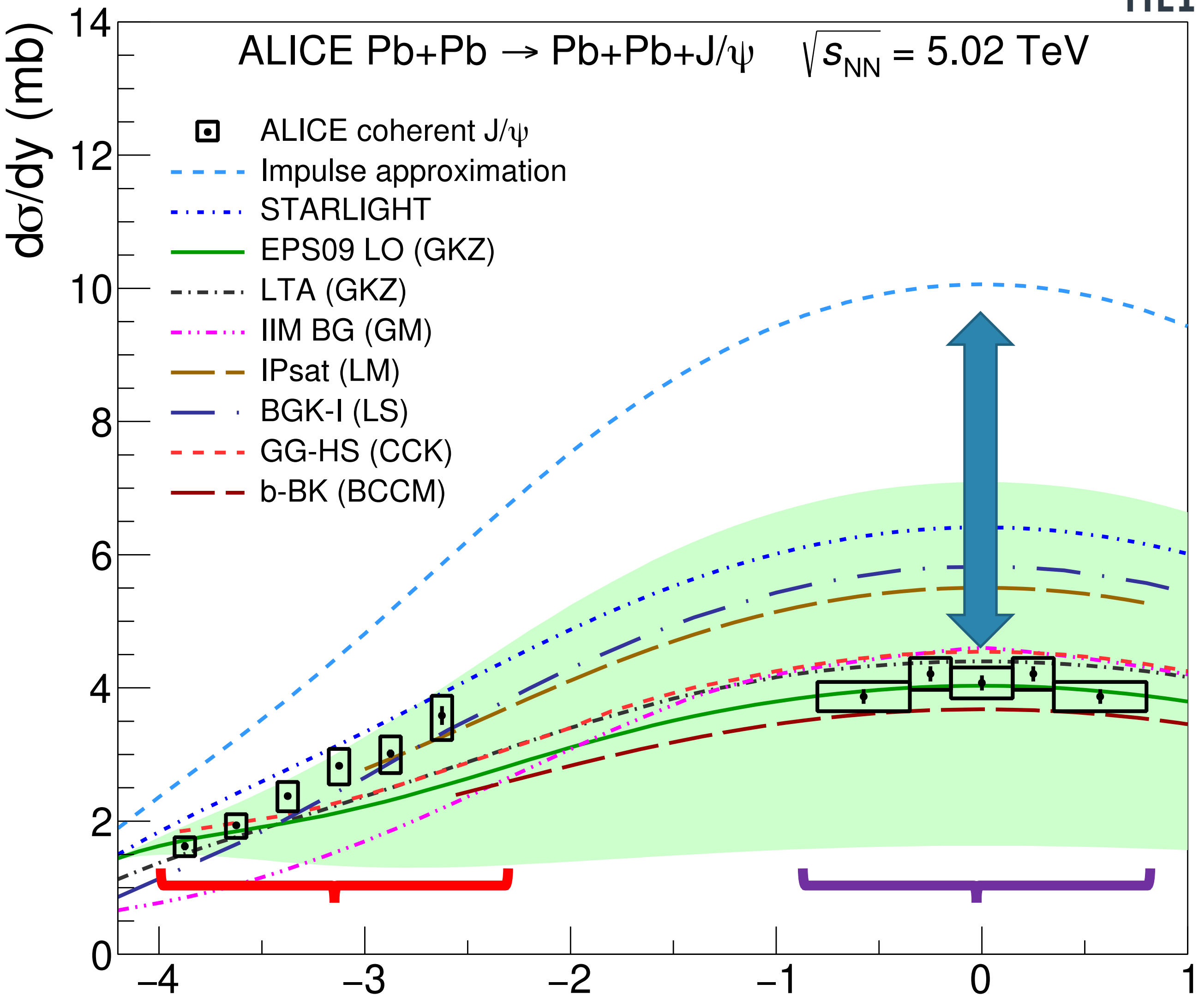
- First measurement of the nuclear suppression factor at Bjorken-$x \sim 10^{-5}$! Obtained with the neutron emission technique
- At high-x, models fail to describe the data
- At low-x, nuclear shadowing and saturation consistent with the data
- Peripheral and neutron emission techniques in good agreement

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

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

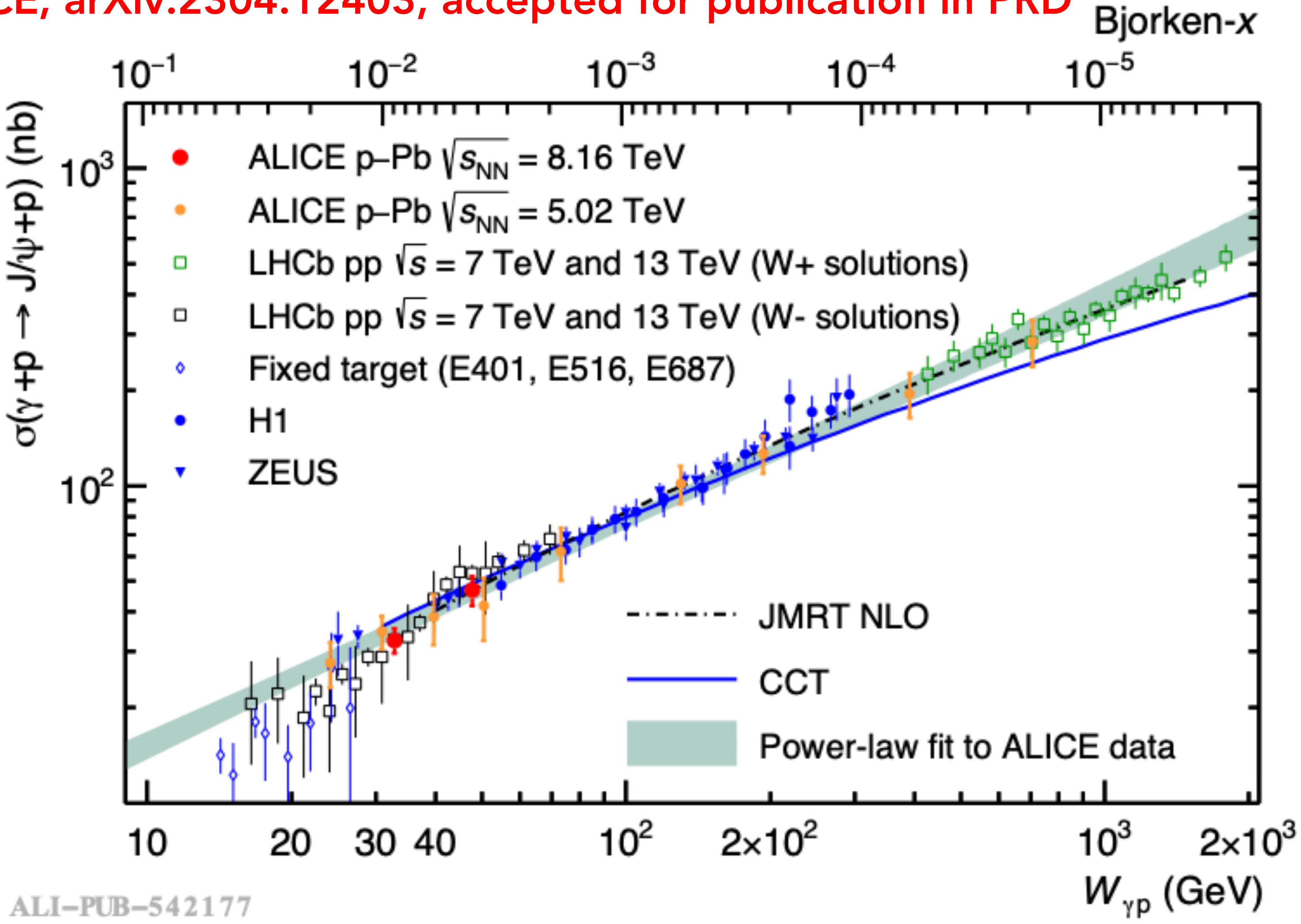


$x \sim 10^{-2}$ (95%)
$x \sim 10^{-5}$ (5%)
$x \sim 10^{-3}$

Exclusive J/ψ in p-Pb UPC

ALICE, arXiv:2304.12403, accepted for publication in PRD

- 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]

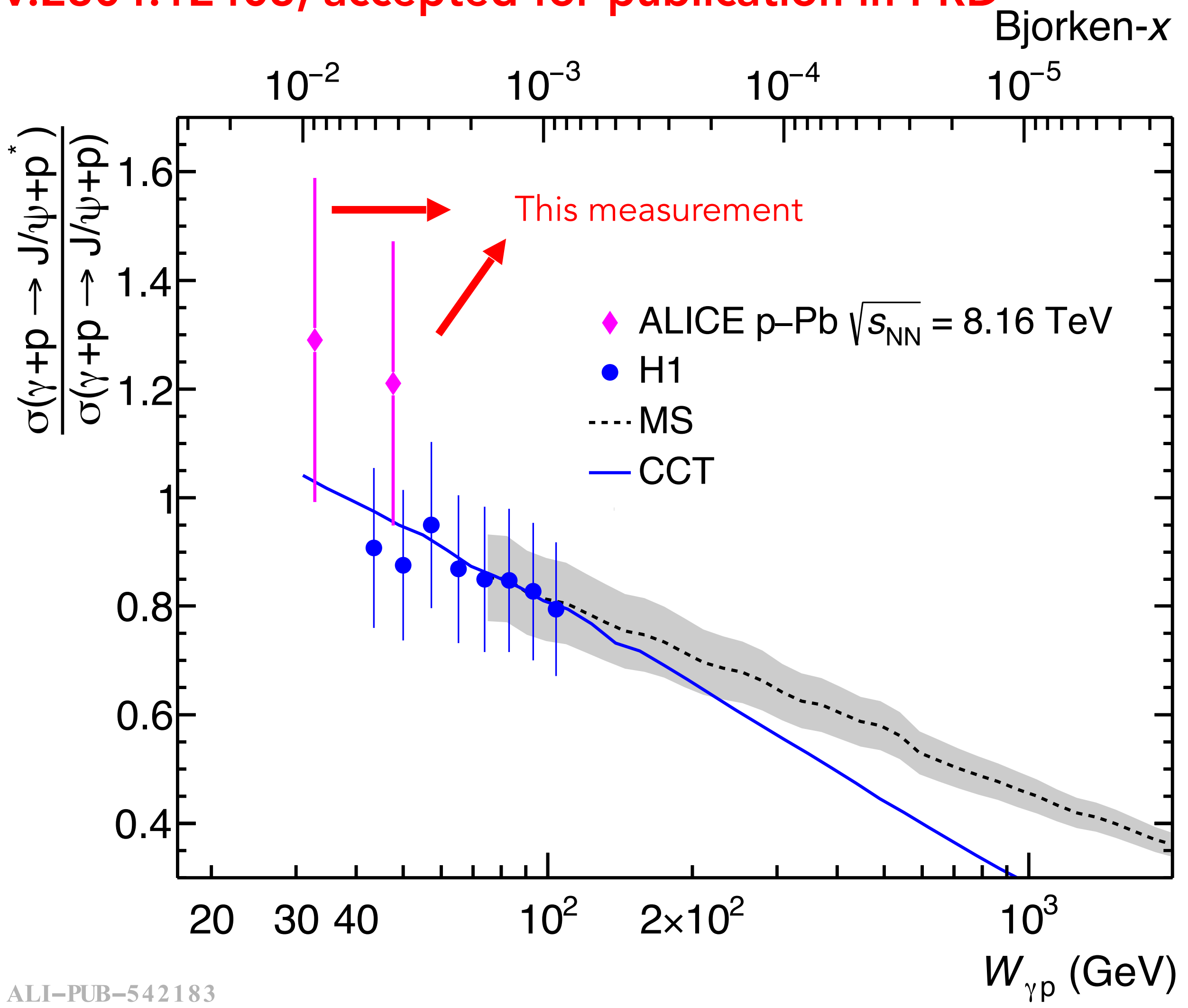


Eur. Phys. J. C (2019) 79: 402 (ALICE midrapidity and semiforward)
Phys. Rev. Lett. 113 no. 23, (2014) 232504 (ALICE forward)

Exclusive and dissociative J/ψ in p-Pb

ALICE, arXiv:2304.12403, accepted for publication in PRD

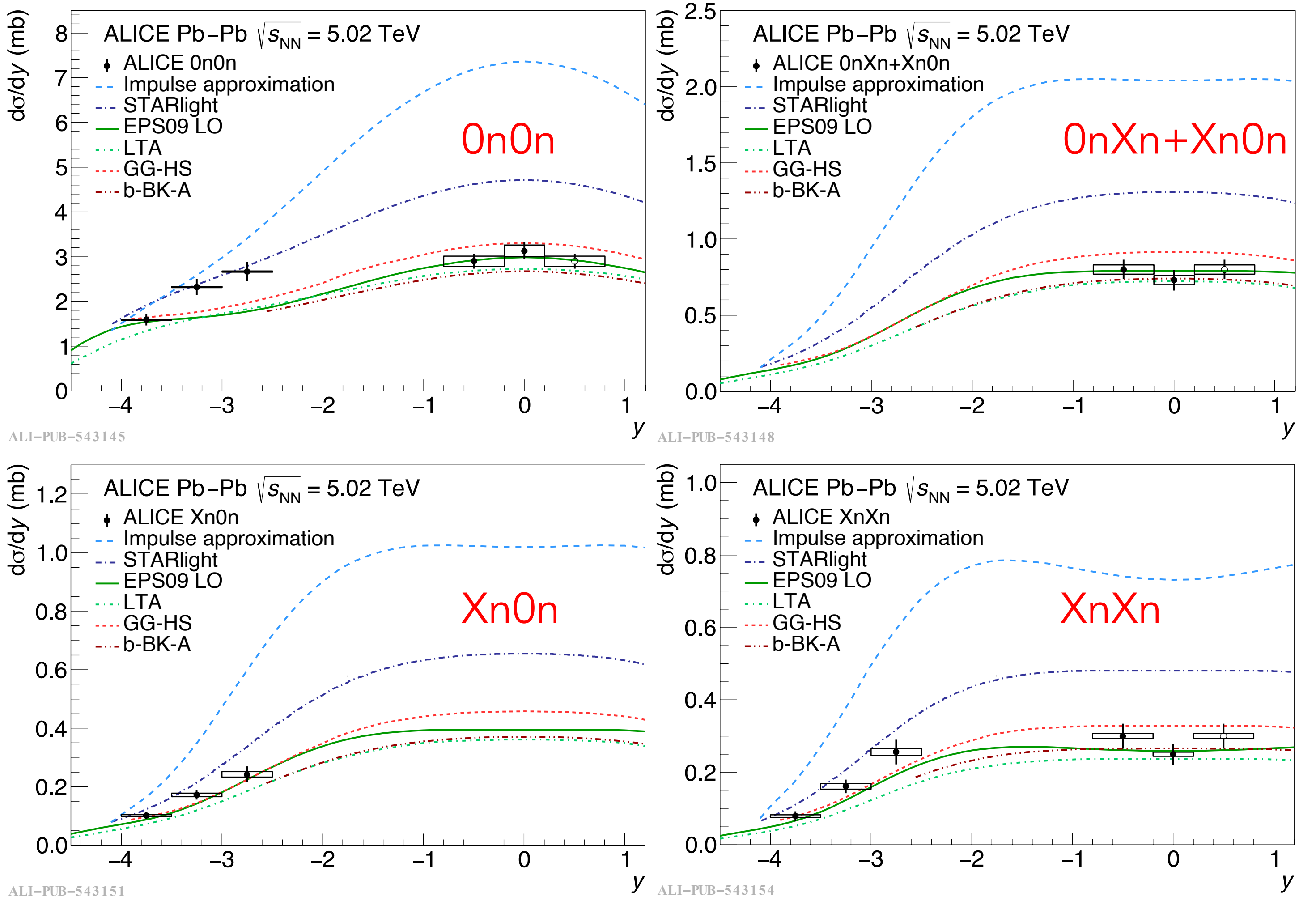
- CCT: colour dipole + energy dependent hot spot model [Cepila et al., Phys. Lett. B766 (2017) 186–191
- MS: JIMWLK + constrains from fits to H1 data [Mäntysaari, Schenke, Phys. Rev. D 98 (2018) 034013]



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}

ALICE, arXiv:2305.19060



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:

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

- 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

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

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

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

y	n_γ(0n0n)	n_γ(0nXn+Xn0n)	n_γ(XnXn)	$\sigma^{\text{IA}}_{\gamma\text{Pb}}$ (μb)
$3.5 < y < 4$	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

Coherent J/ψ with neutron emission

Creighton UNIVERSITY ALICE

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

$$\chi^2_{\exp}\left(\vec{m},\vec{b}\right)=\sum_i \frac{\left(m^i-\sum_j \gamma^i_j m^i b_j-\mu^i\right)^2}{\delta^2_{i,\mathrm{stat}}\mu^i\left(m^i-\sum_j \gamma^i_j m^i b_j\right)+\left(\delta_{i,\mathrm{uncor}}m^i\right)^2}+\sum_j b_j^2.$$

- 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

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

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

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

y	n_γ(0n0n)	n_γ(0nXn+Xn0n)	n_γ(XnXn)	$\sigma^{IA}_{\gamma Pb}$ (μb)
$3.5<y<4$	178.51	18.18	6.34	10
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$-0.2<y<0.2$	62.86	17.47	6.27	58
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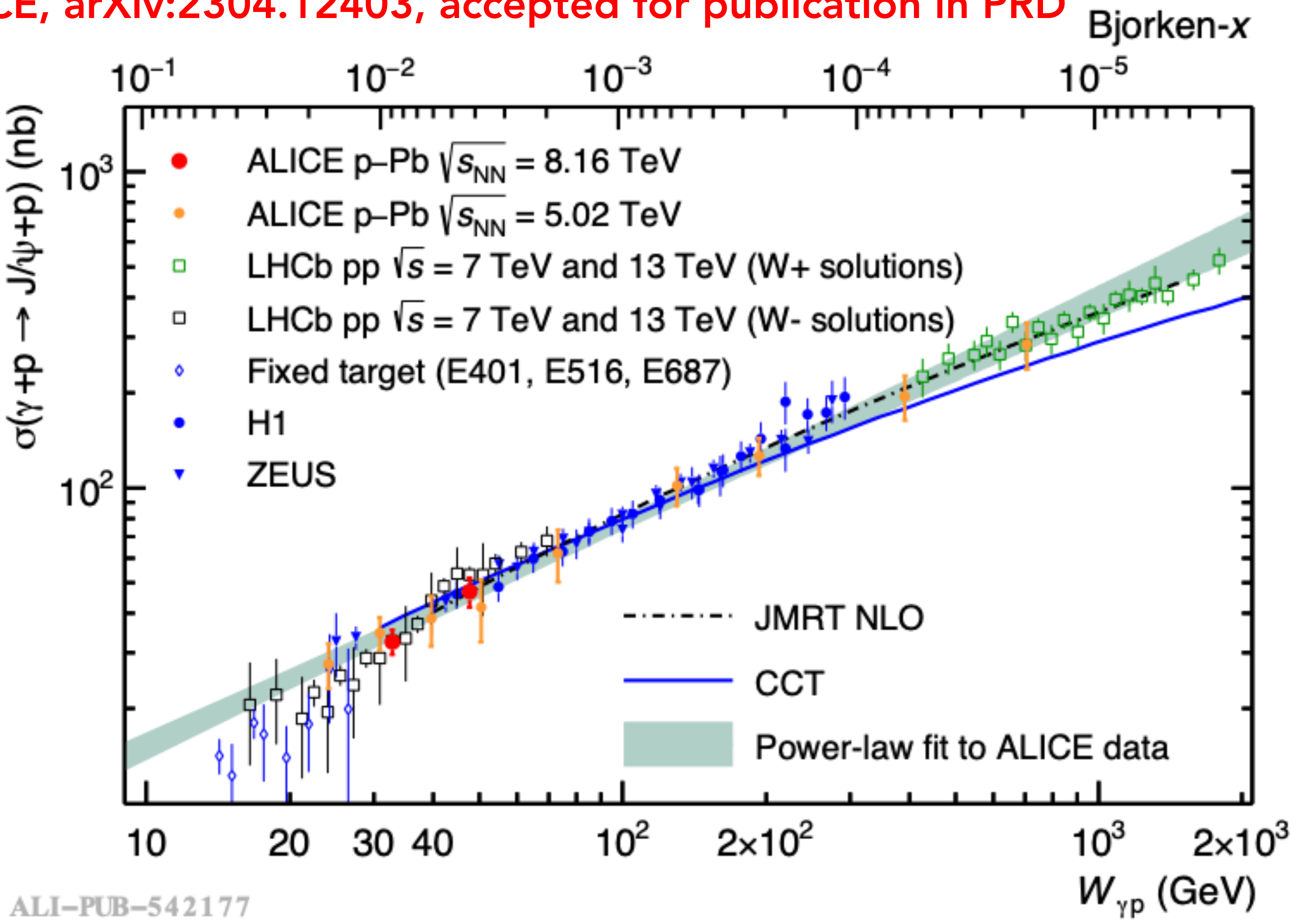
Exclusive J/ψ in p-Pb UPC

ALICE, arXiv:2304.12403, accepted for publication in PRD

- $x = e^{\pm|y|} M_{J/\psi} / 2E_{p}$
- 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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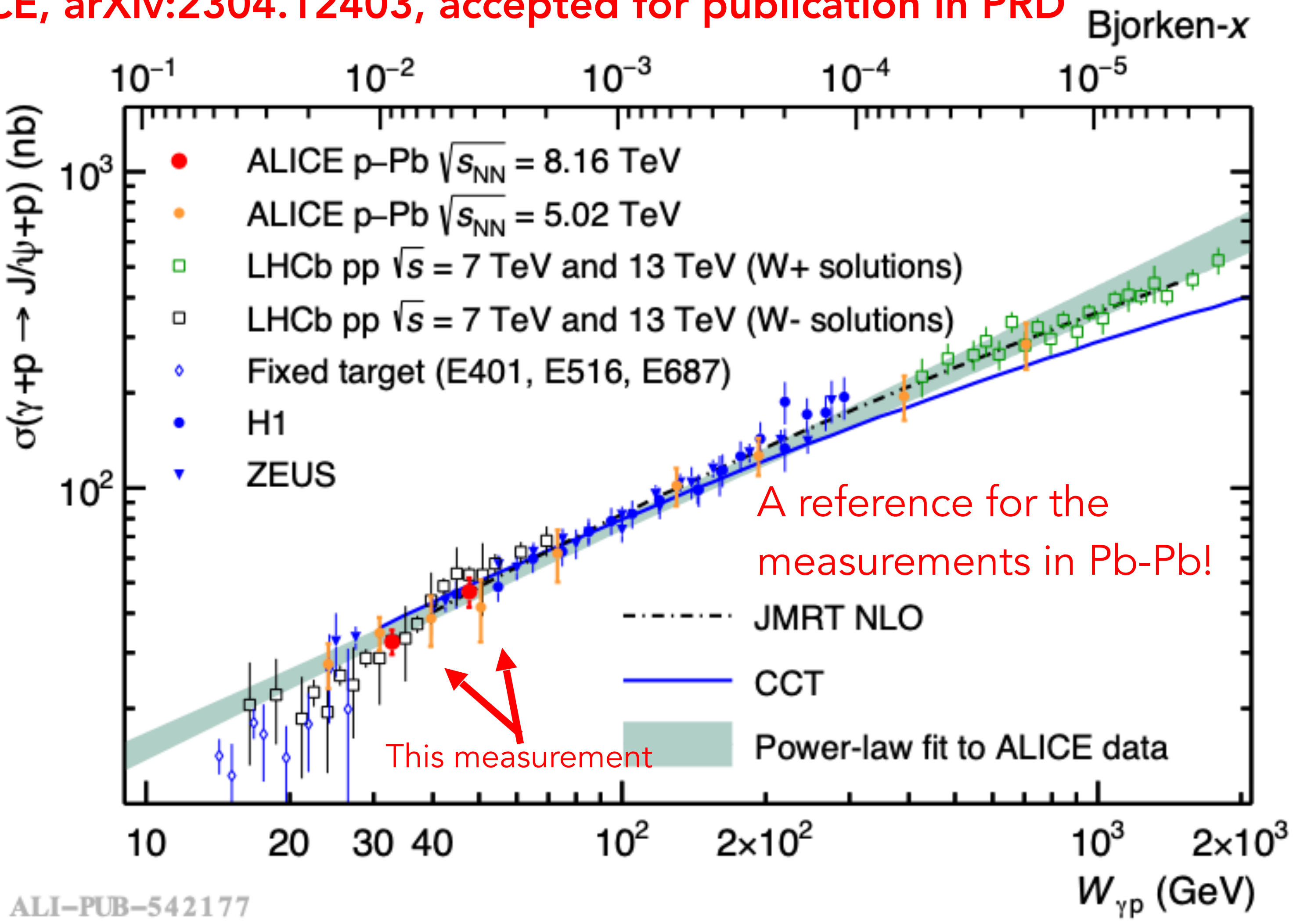
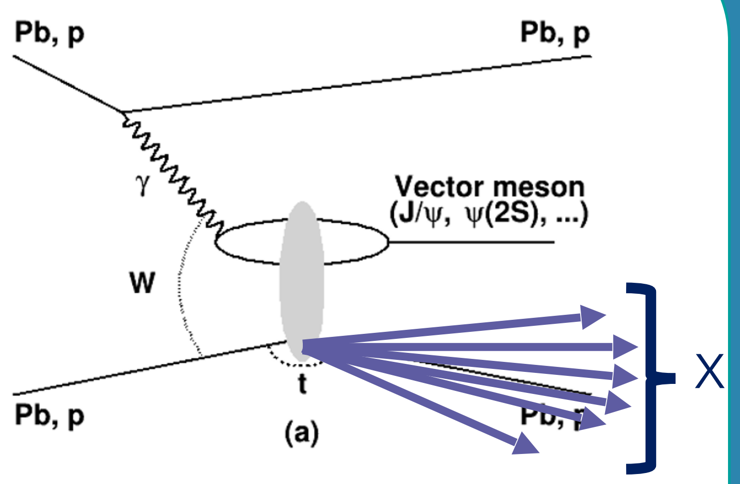


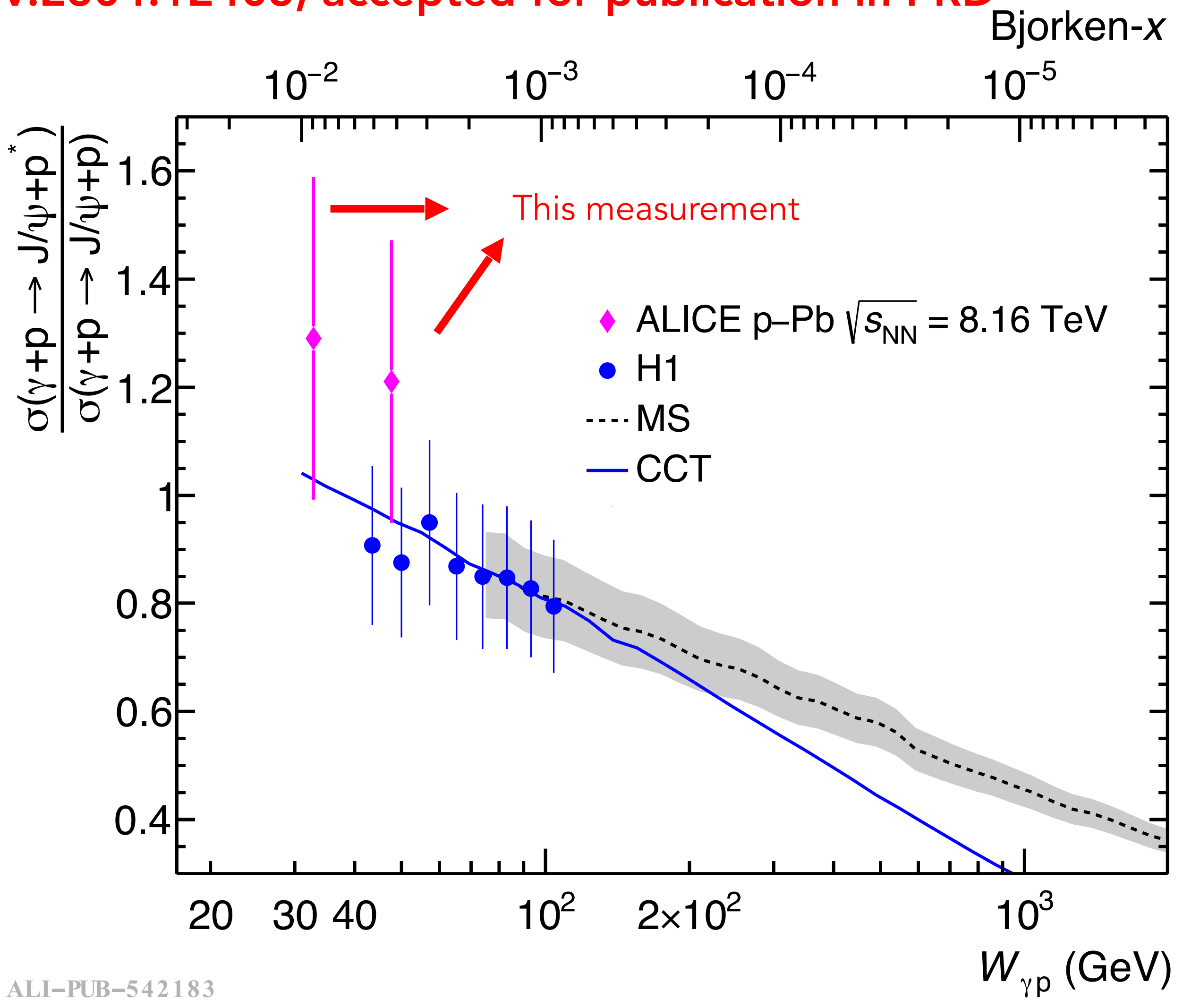
Eur. Phys. J. C (2019) 79: 402 (ALICE midrapidity and semiforward)
Phys. Rev. Lett. 113 no. 23, (2014) 232504 (ALICE forward)

Exclusive and dissociative J/ψ in p-Pb

ALICE, arXiv:2304.12403, accepted for publication in PRD

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

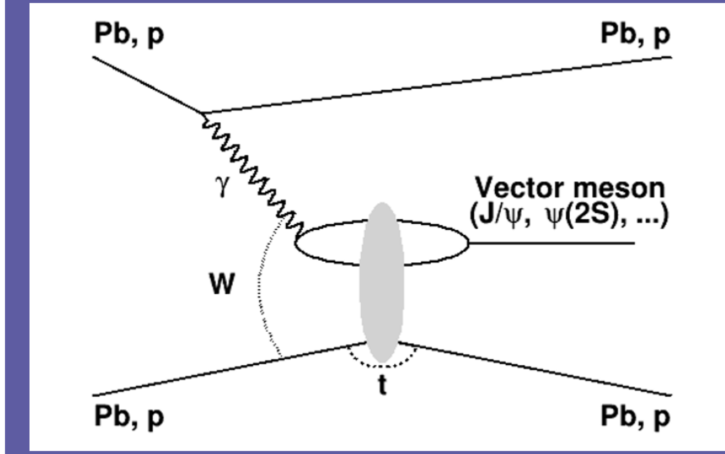




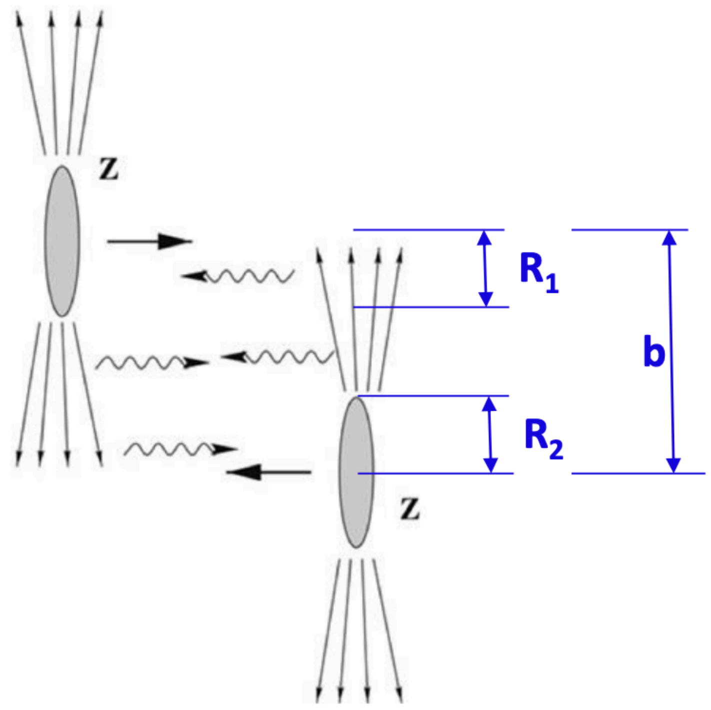
Physics of ultra-peripheral collisions (UPC)

Creighton UNIVERSITY

ALICE

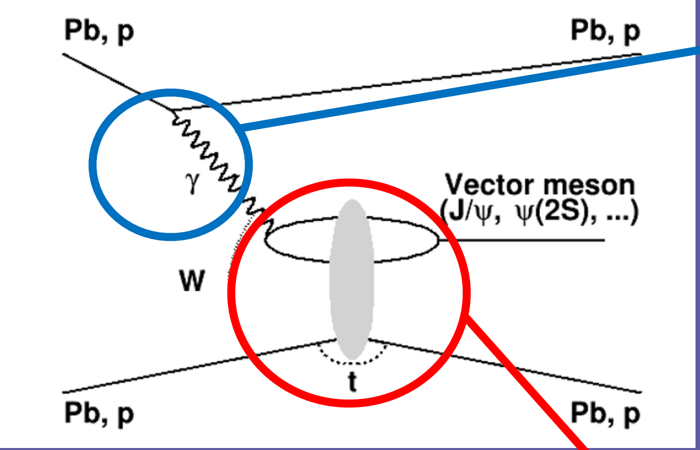


- Large impact parameter (beyond the reach of the strong interaction)
- Vector meson production
- e.g. $\rho^0, J/\psi, \psi(2S)$



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

Introduction to ultra-peripheral collisions (UPC)



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

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