



U.S. DEPARTMENT OF
ENERGY

Office of
Science



ALICE

Creighton
UNIVERSITY

Recent results on J/ψ photoproduction in ultra-peripheral collisions with ALICE

Simone Ragoni for the ALICE Collaboration

Creighton University, USA

Outline



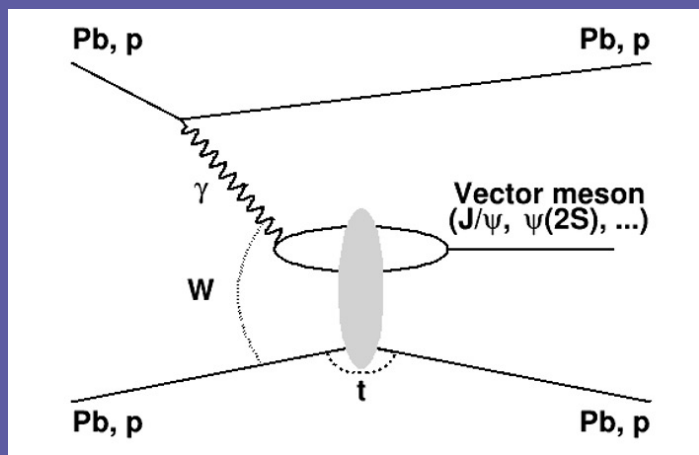
- Introduction to ultra-peripheral collisions (UPC)
- The ALICE detector
- New results on exclusive and dissociative J/ψ in UPC p-Pb
- New results on coherent and incoherent J/ψ in UPC Pb-Pb
- New measurements of the energy dependence of the photonuclear cross sections

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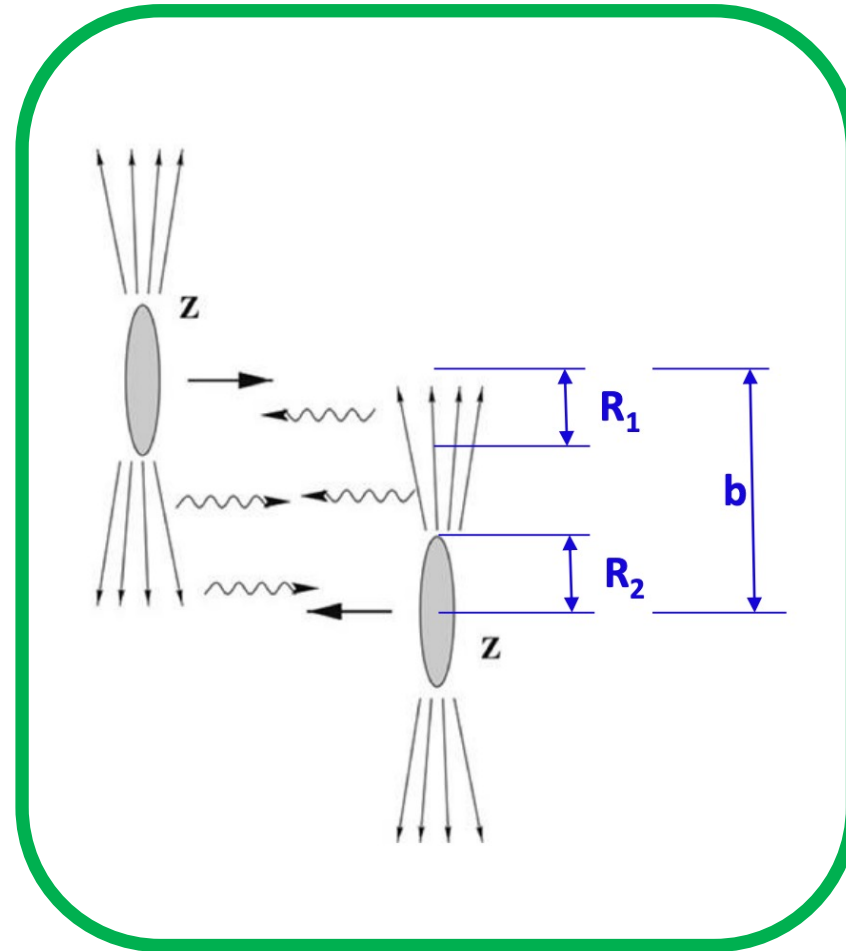


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Introduction to ultra-peripheral collisions (UPC)

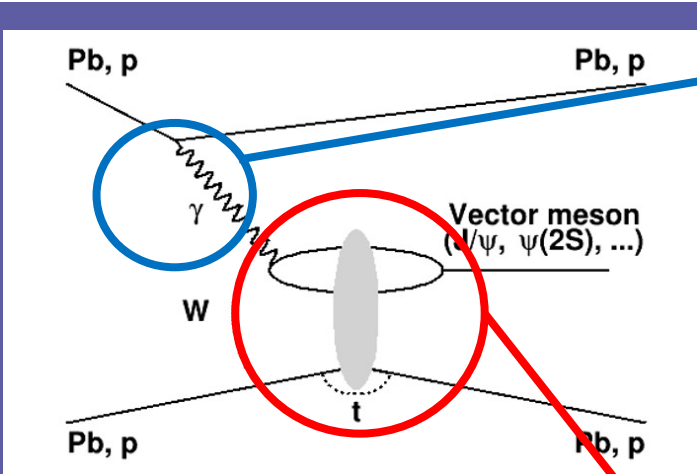


- Large impact parameter (beyond the reach of the strong interaction)
- Vector meson production
- e.g. ρ^0 , J/ψ , $\psi(2S)$



- 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!

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

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

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

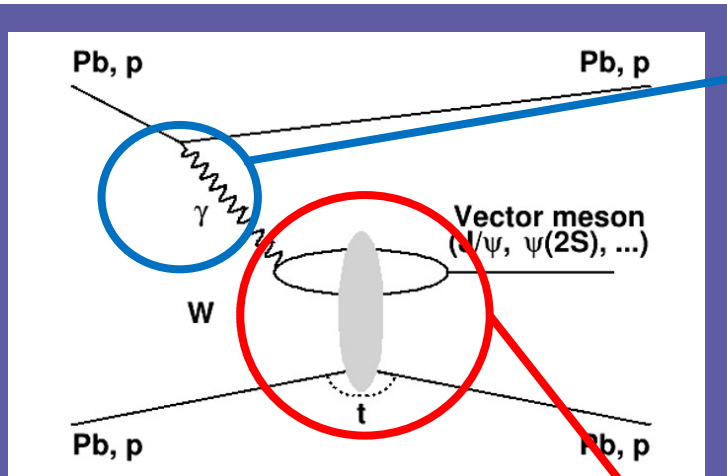
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Hard scale ensured by high mass states i.e. $J/\psi, \psi(2S)$

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

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

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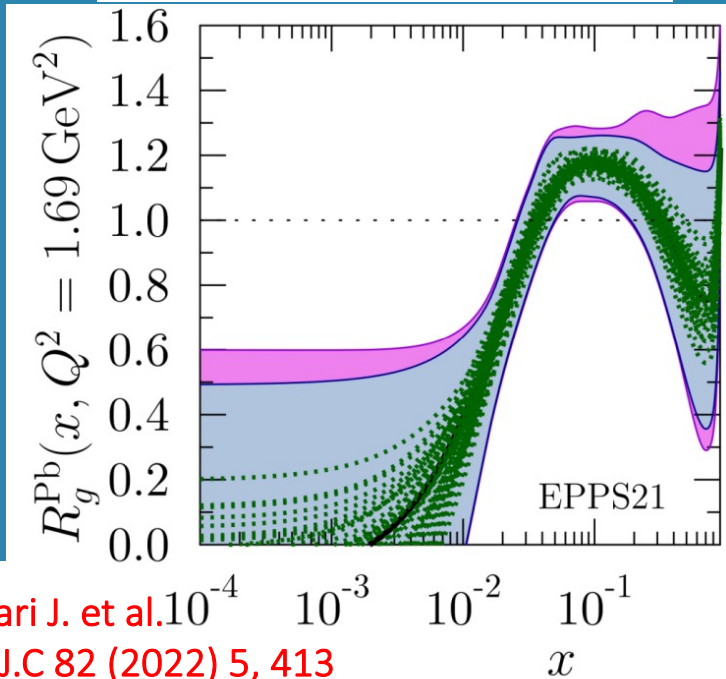
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Nuclear shadowing and gluon saturation

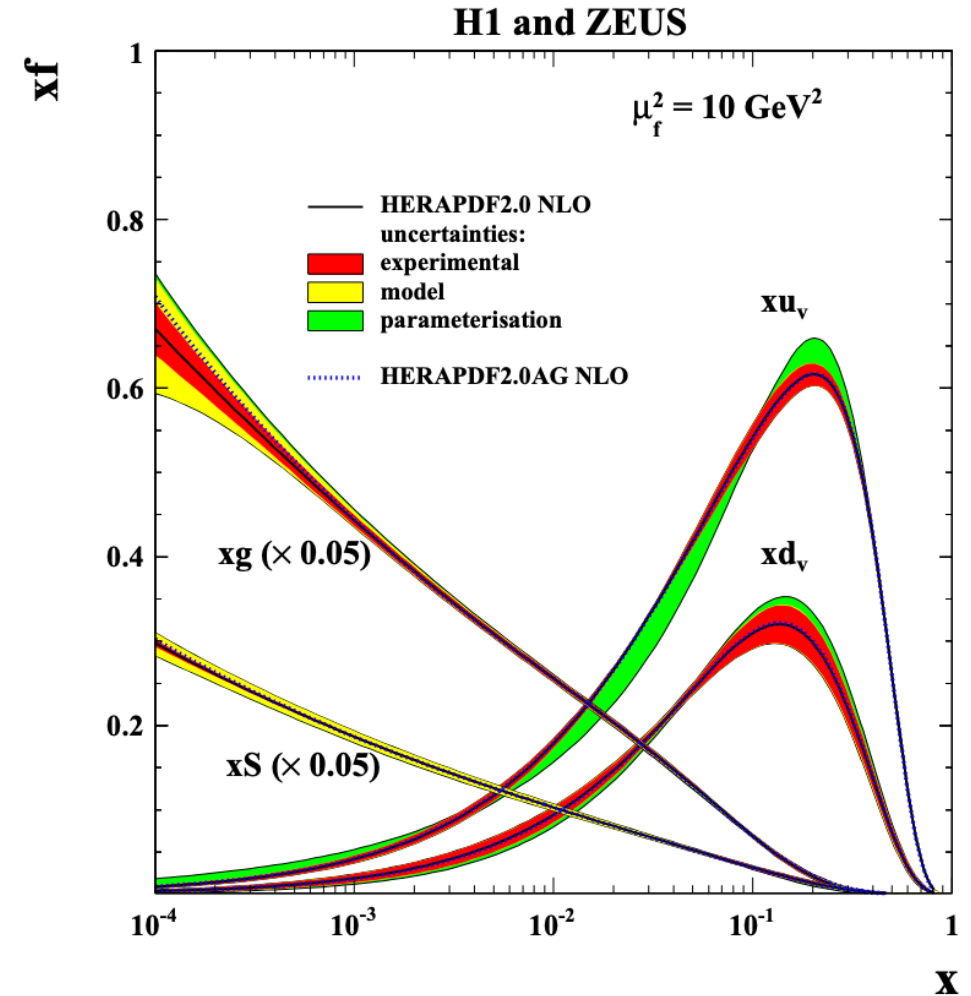
- Nuclear structure functions \neq superposition of nucleons!

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

Nuclear gluon PDF
Proton gluon PDF

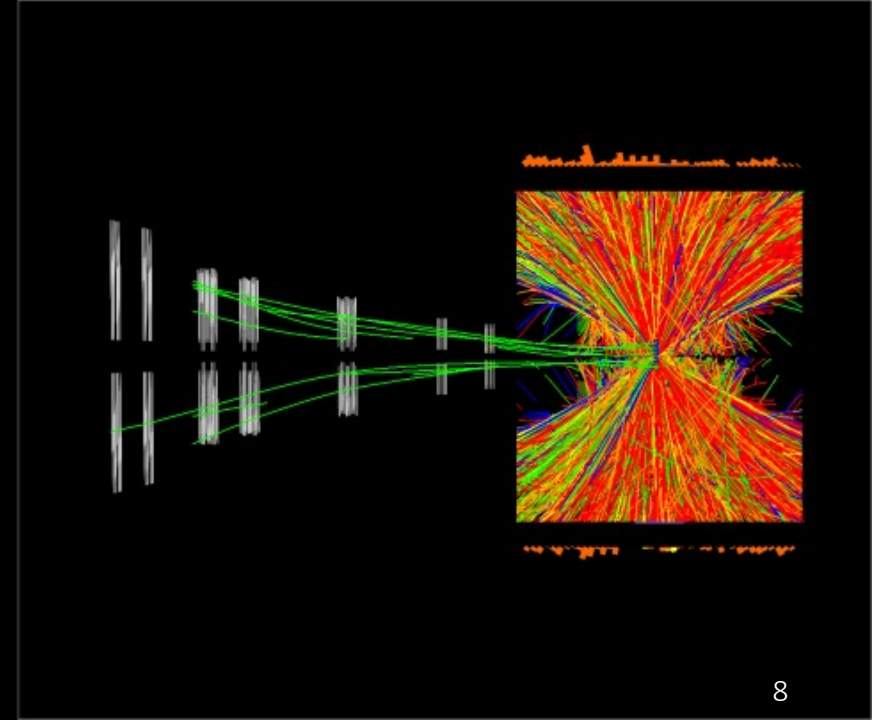
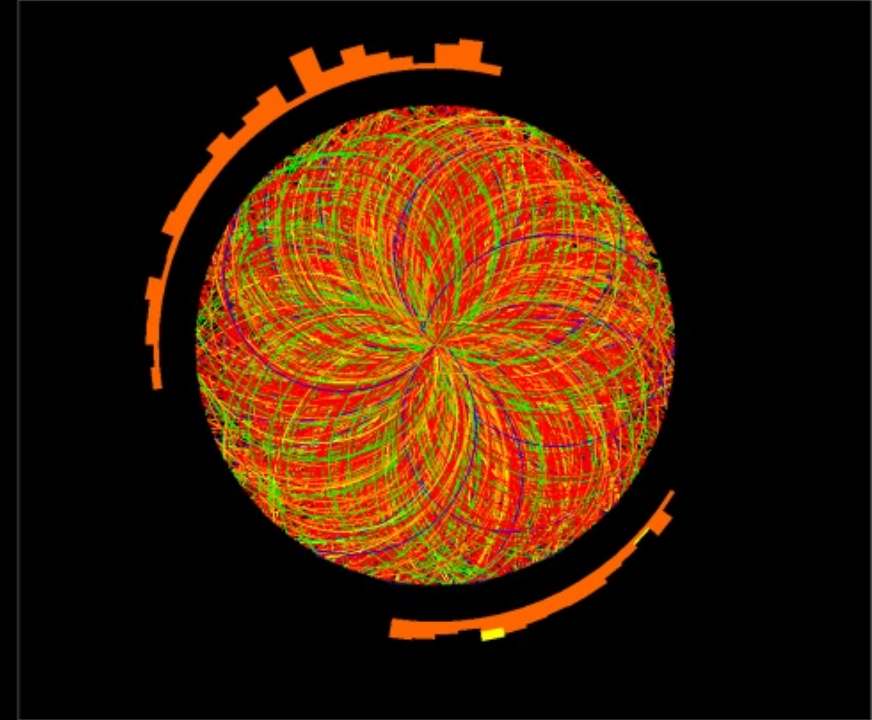
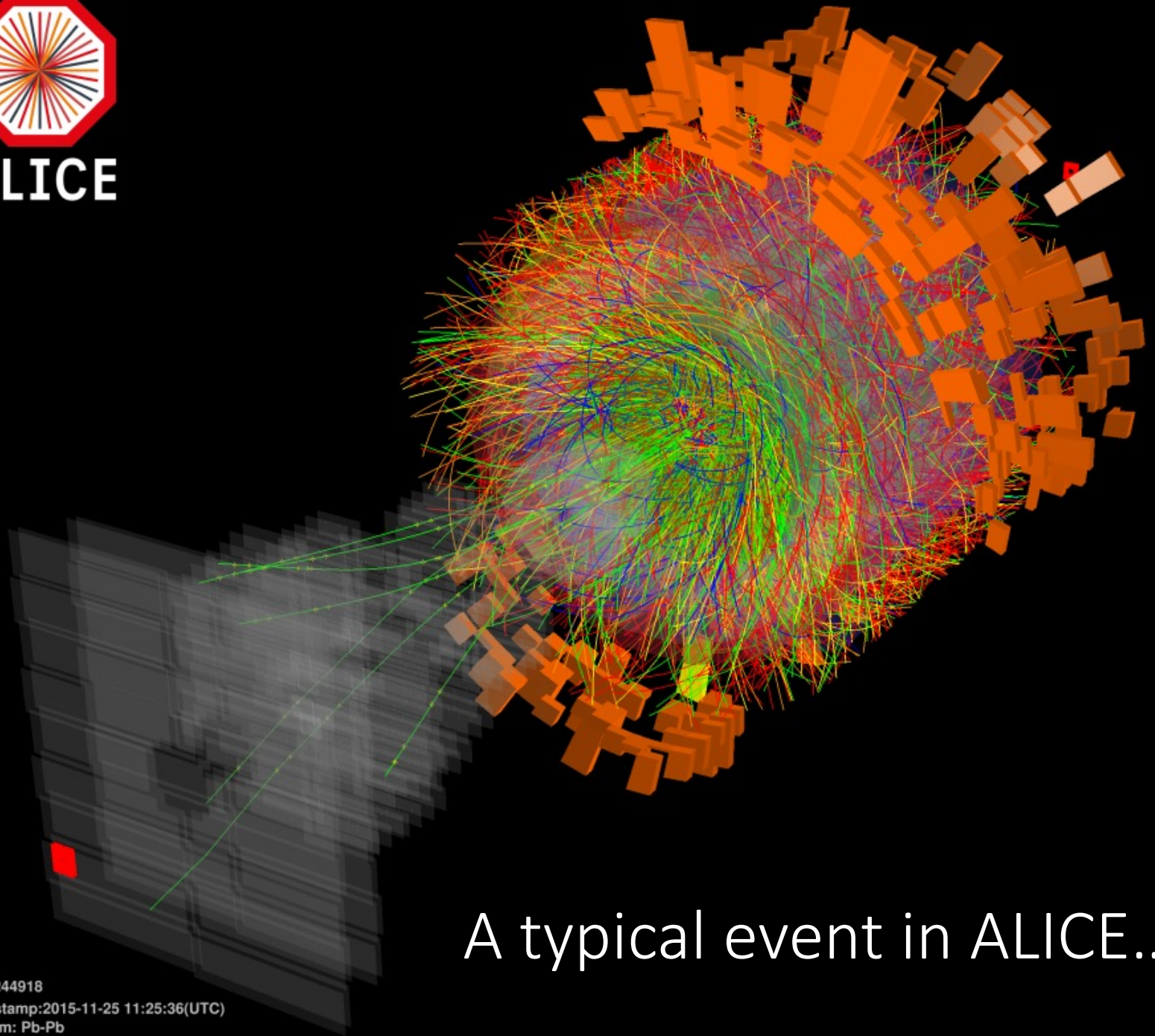


H1 and Zeus, EPCJ 75 (2015) 580





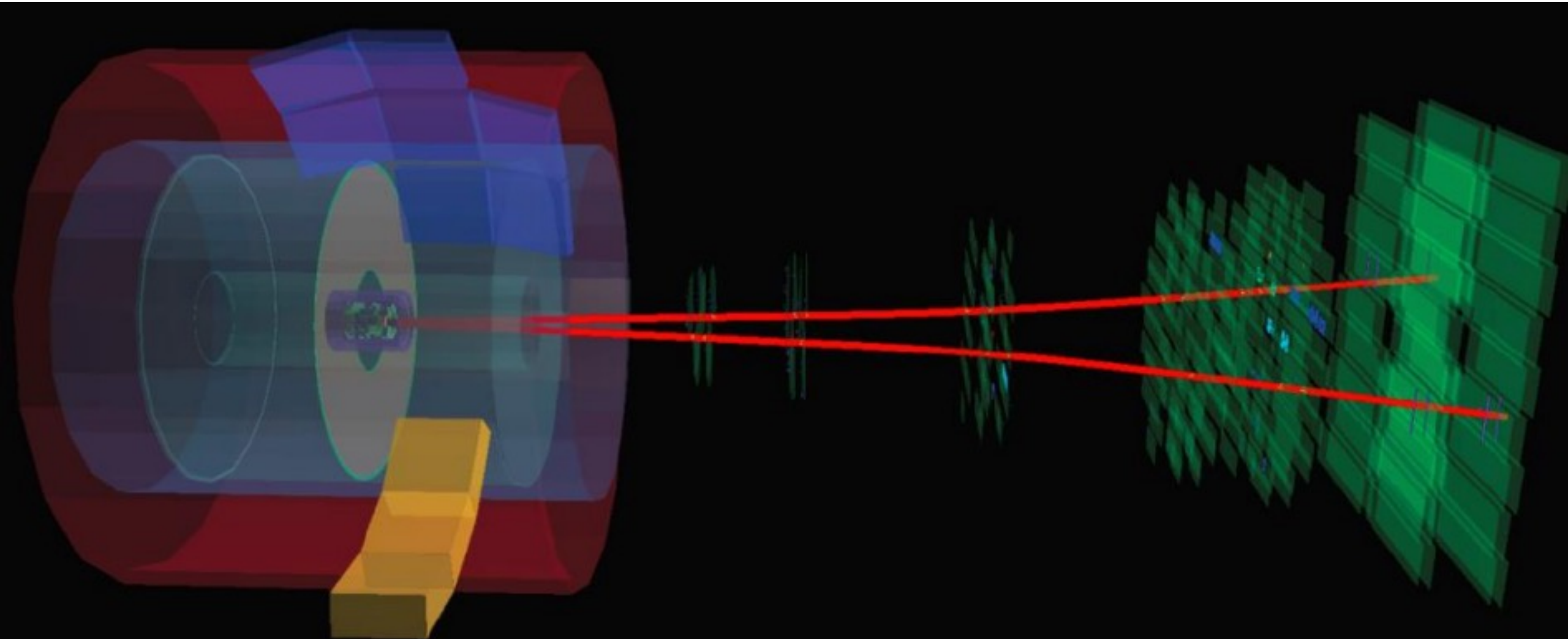
ALICE



A typical event in ALICE...

Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

... and a UPC event!



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THE ALICE DETECTOR

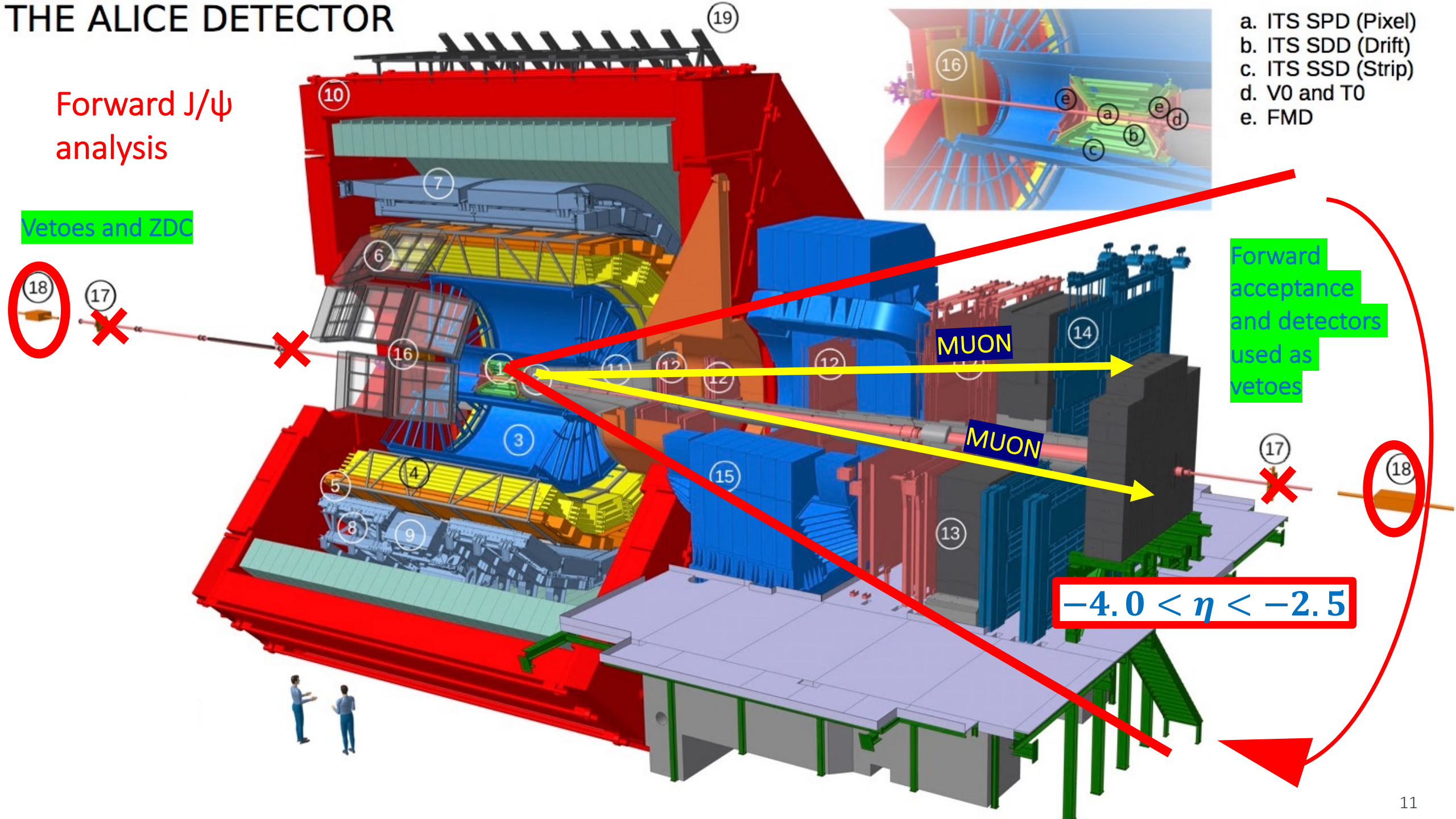
Forward J/ψ
analysis

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

Veto and ZDC

Forward acceptance and detectors used as vetoes

$$-4.0 < \eta < -2.5$$



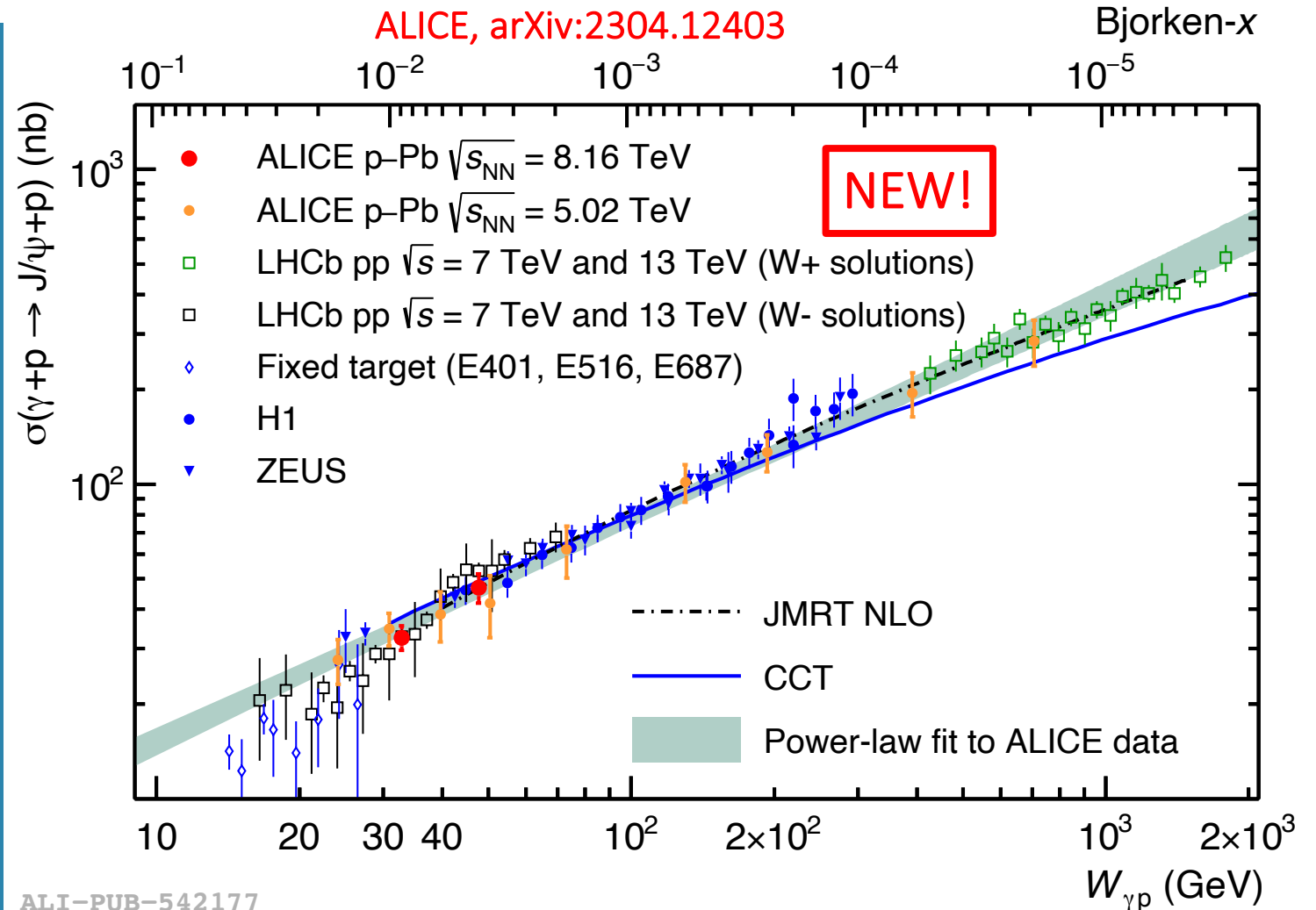
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Exclusive J/ψ in UPC p-Pb

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

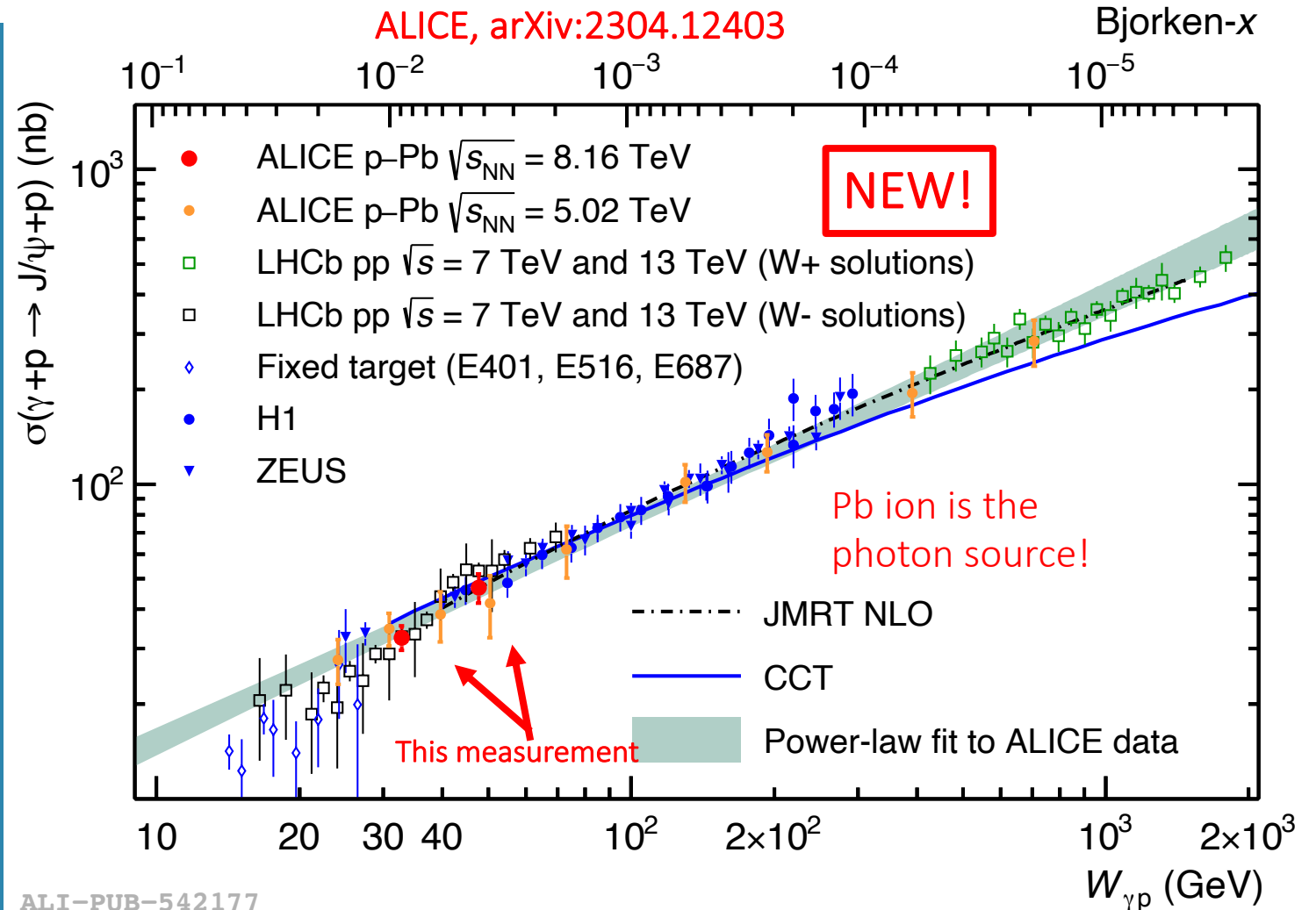


ALI-PUB-542177

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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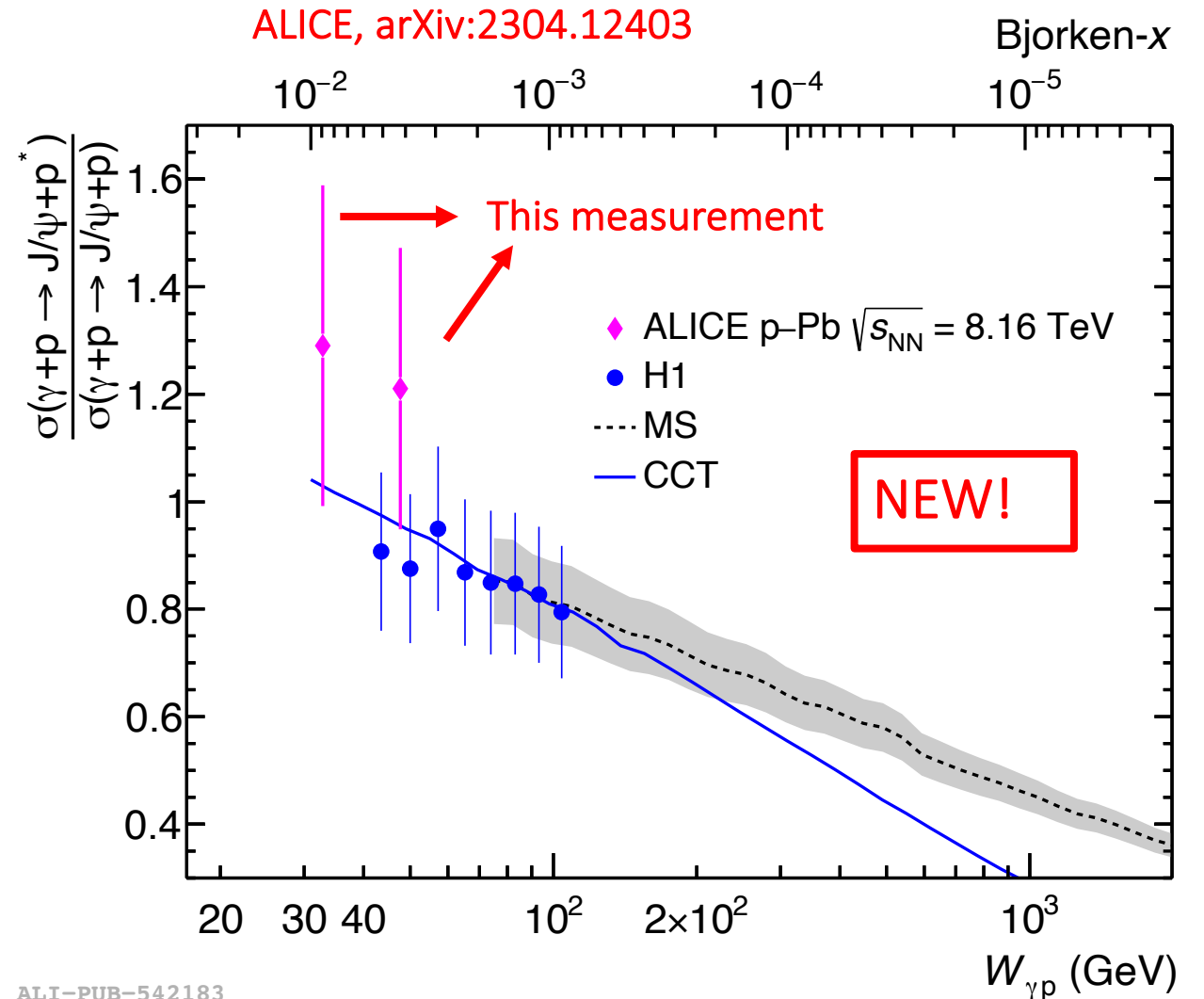
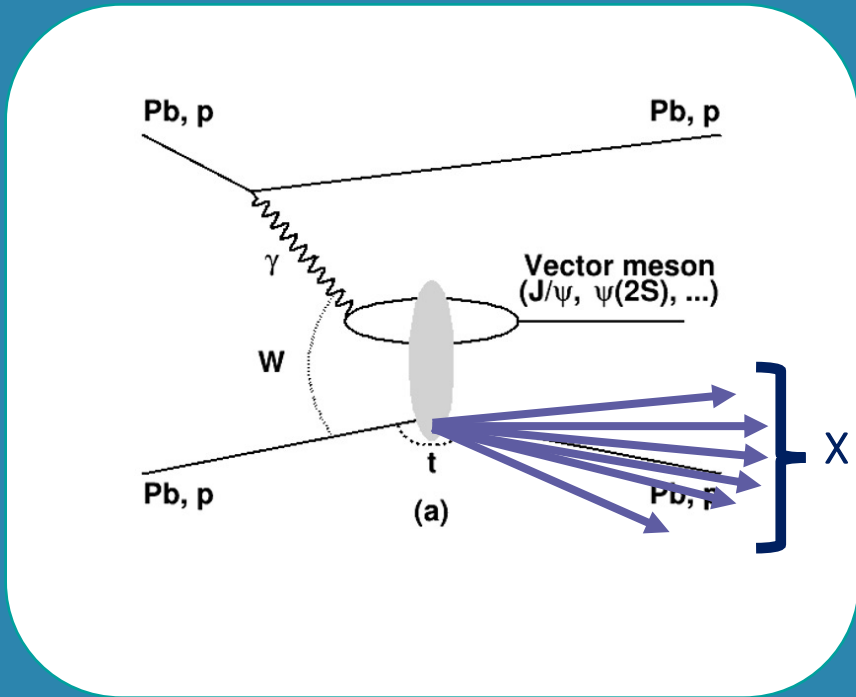


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Exclusive and dissociative J/ψ in p-Pb

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



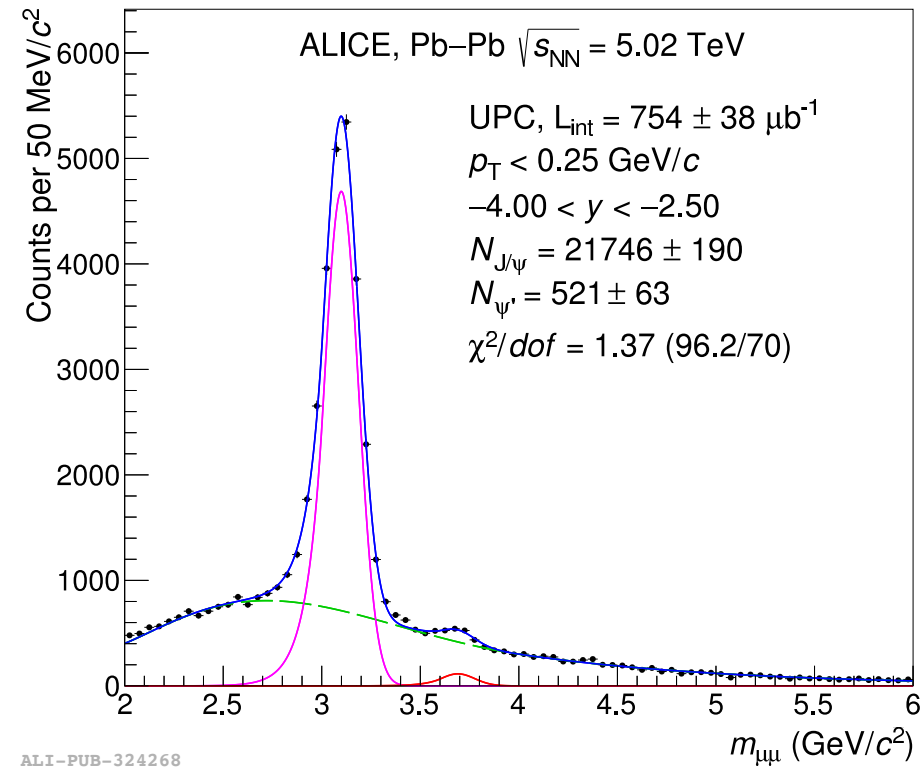
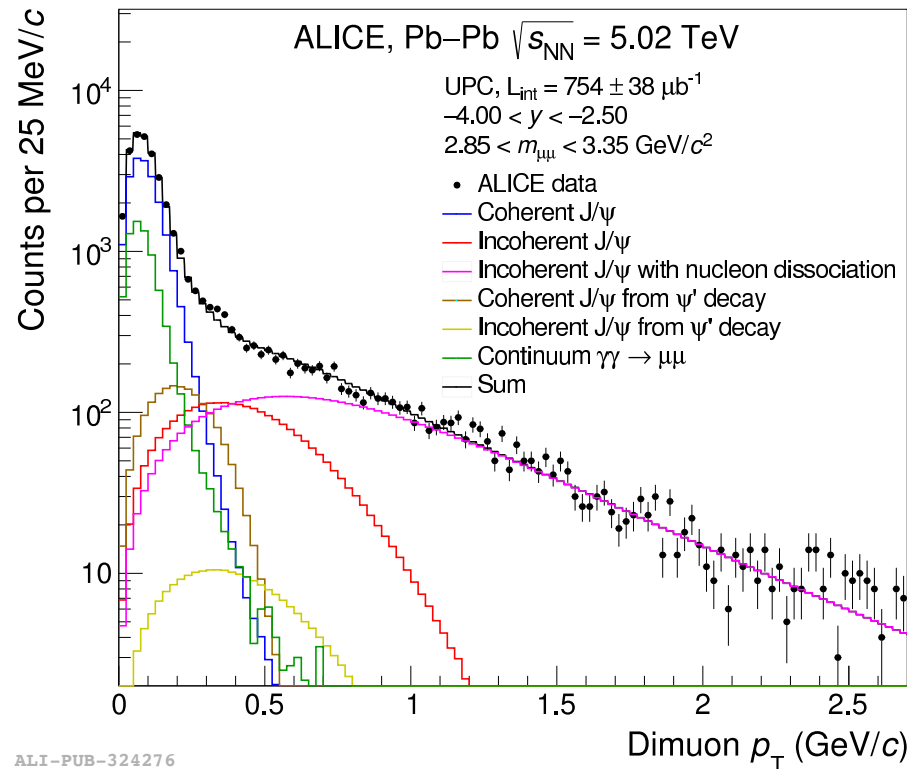
ALI-PUB-542183

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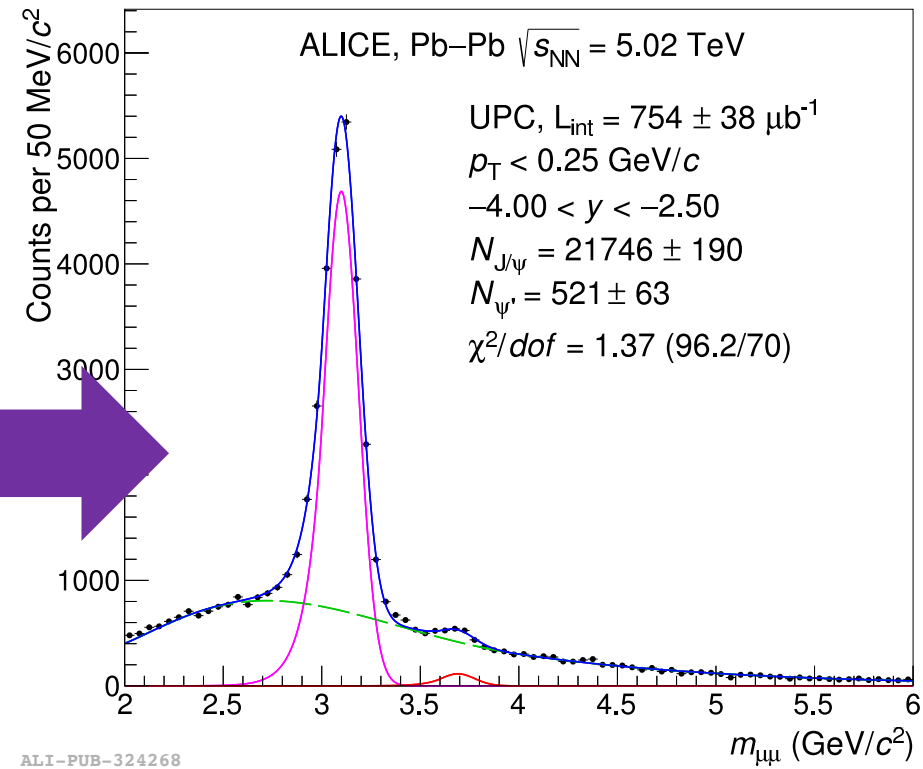
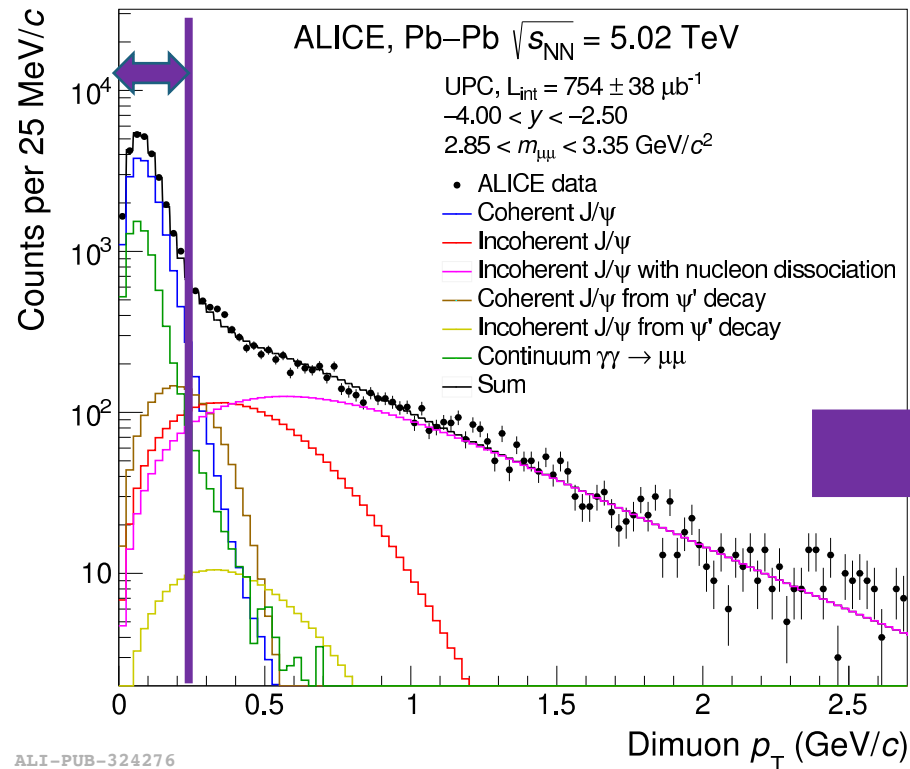
Coherent and incoherent J/ψ



ALICE,
 Phys.Lett. B798
 (2019) 134926

- Coherent J/ψ (dimuon $p_T < 0.25 \text{ GeV}/c$) – photon couples to entire nucleus *coherently*
- Incoherent J/ψ much wider p_T distribution – photon interacts with a single nucleon of the target nucleus

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Studying coherent J/ψ in terms of...

1. y

2. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

3. p_T^2

4. *Angular distributions*

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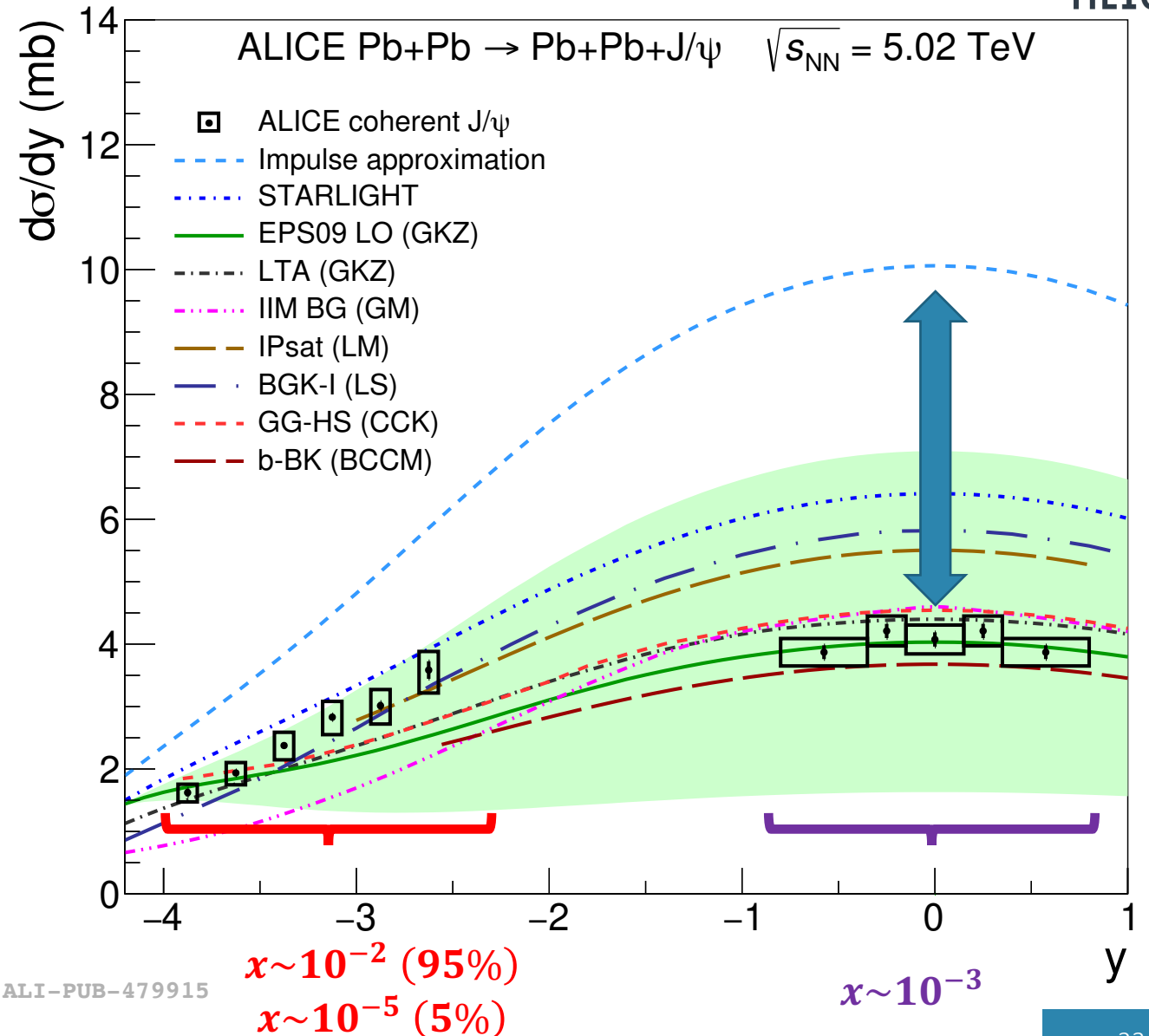
Coherent J/ψ cross section

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

- ALICE data exhibit moderate nuclear shadowing
- Nuclear suppression factor

$$S_{Pb}(y \sim 0) = \sqrt{\frac{d\sigma}{dy}_{data} / \frac{d\sigma}{dy}_{IA}} \sim 0.63$$

- 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

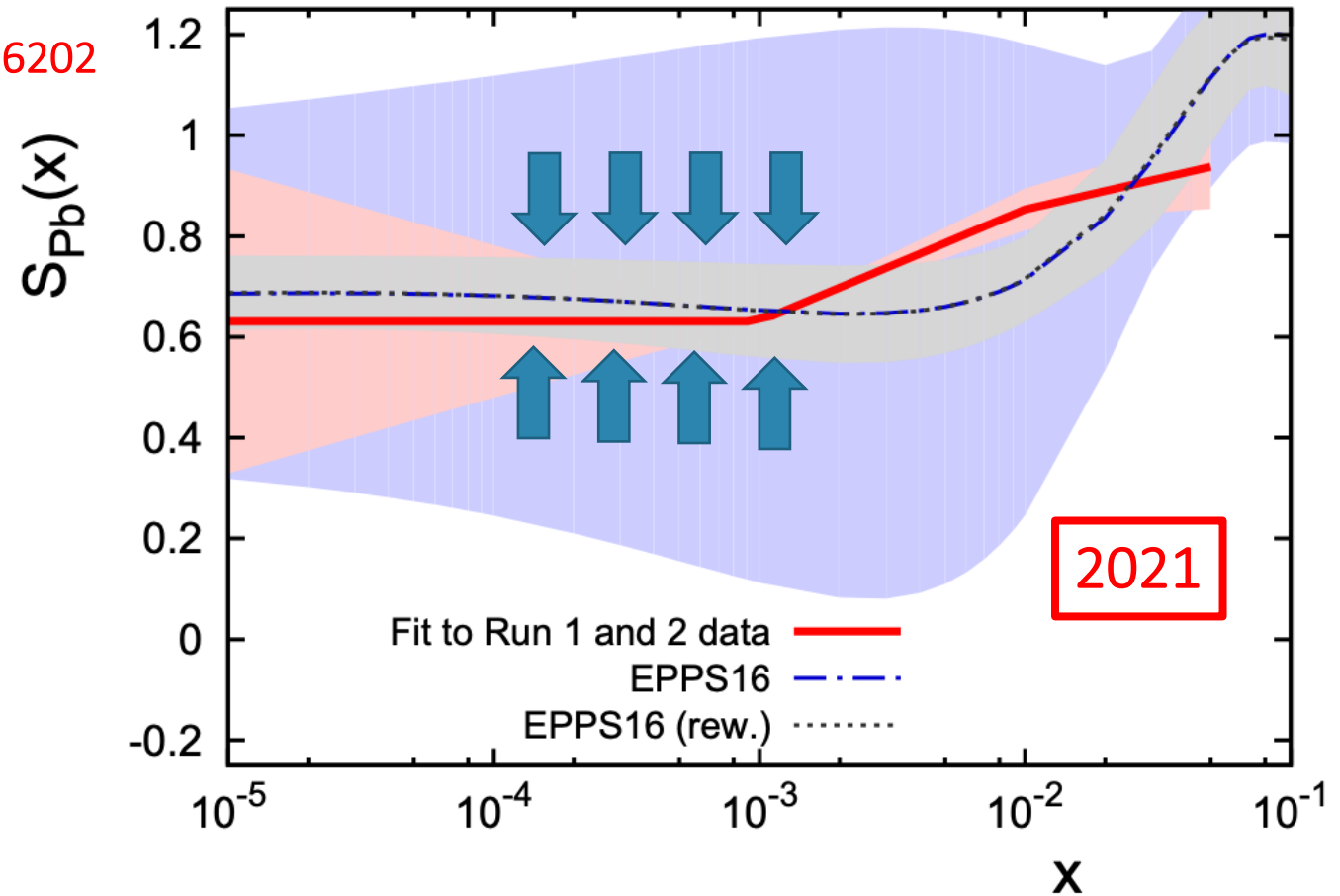


ALI-PUB-479915

Suppression factors with ALICE data

Guzey, Kryshen, Strikman, Zhalov, Phys.Lett.B 816 (2021) 136202

$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb \rightarrow J/\psi Pb}^{\text{exp}}(W_{\gamma p})}{\sigma_{\gamma Pb \rightarrow J/\psi Pb}^{\text{IA}}(W_{\gamma p})} \right]^{1/2}$$



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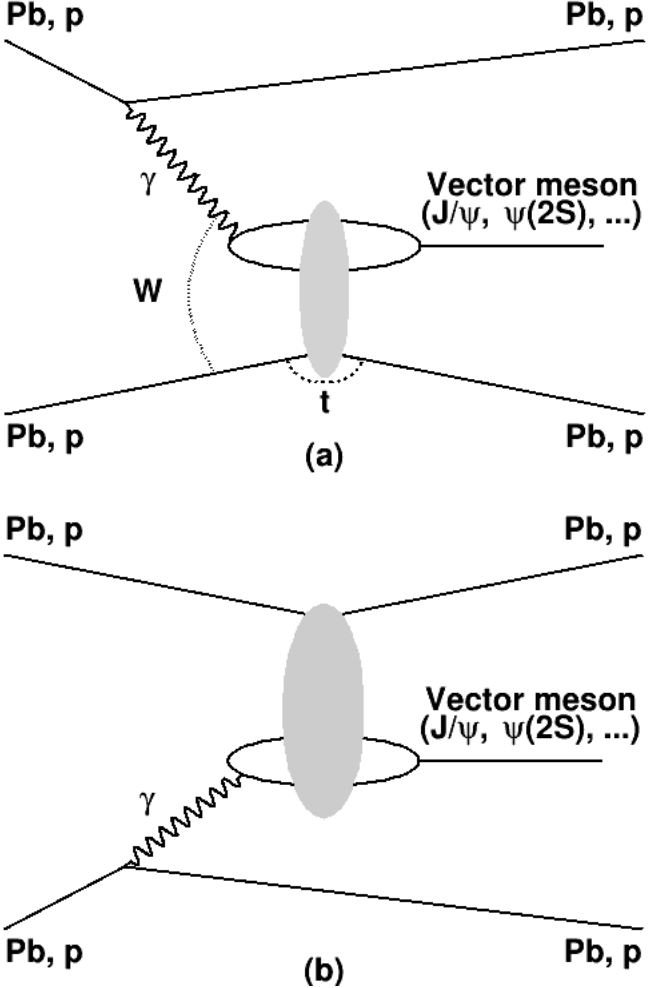
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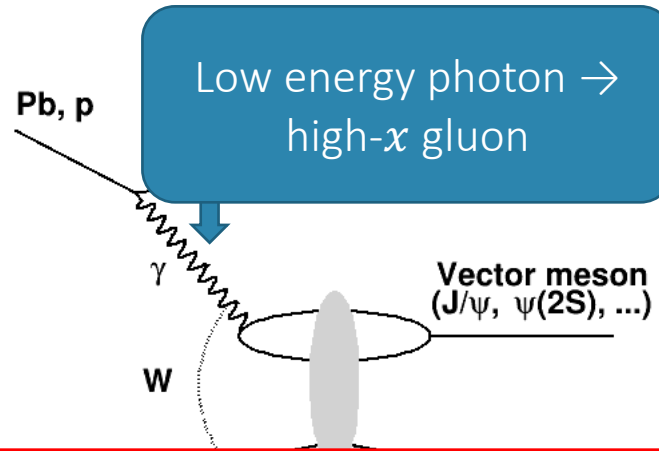
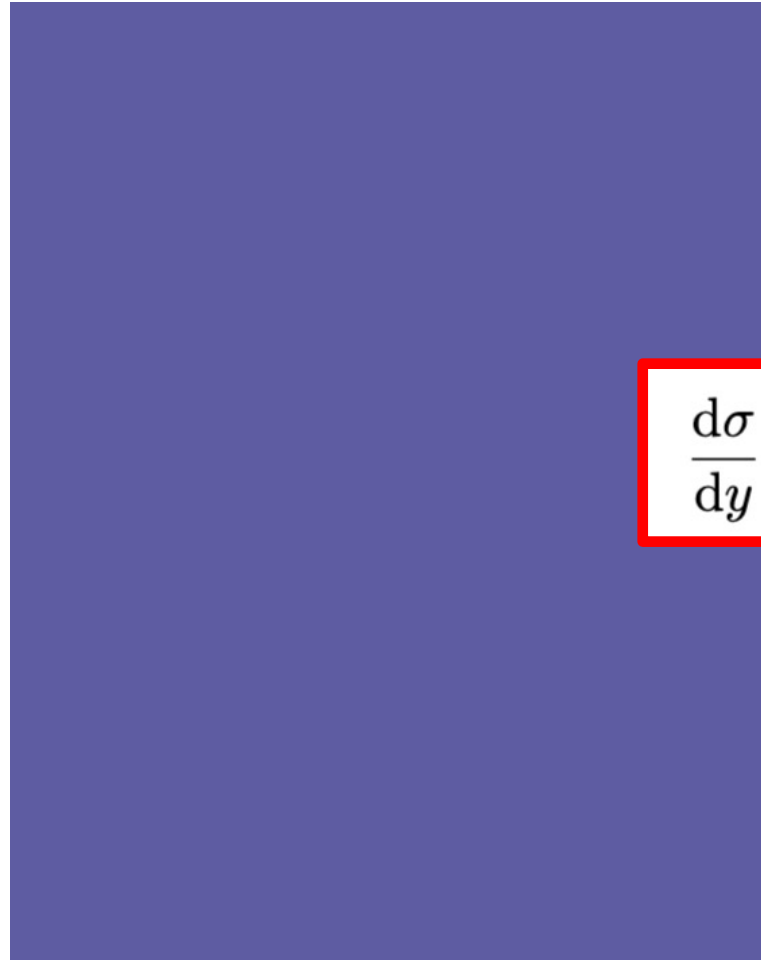


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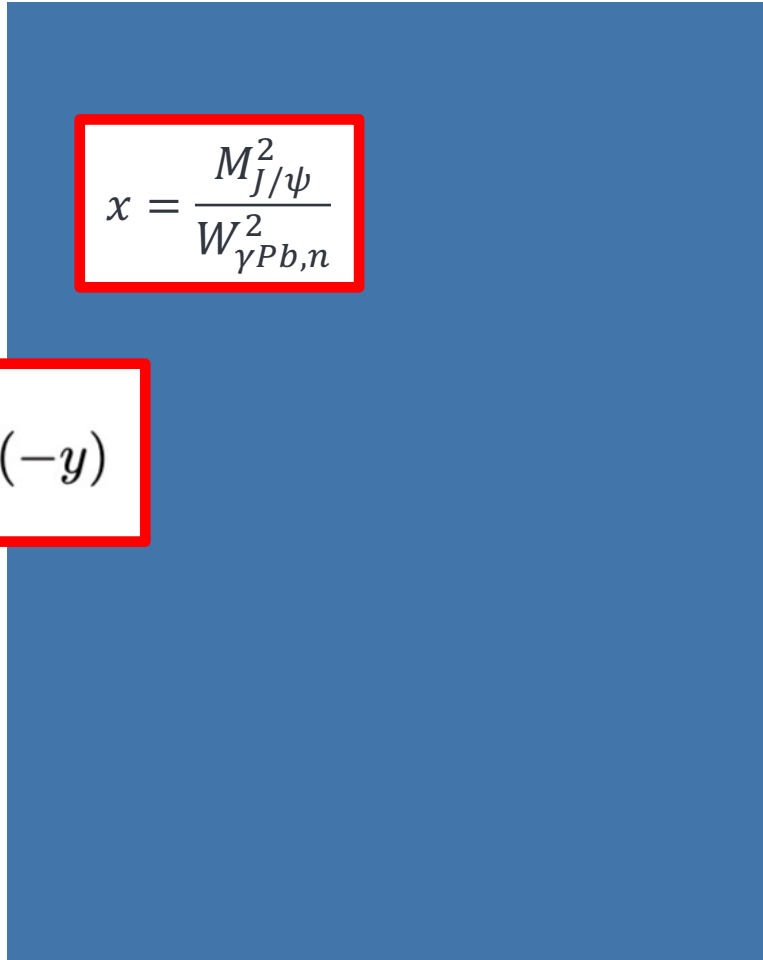
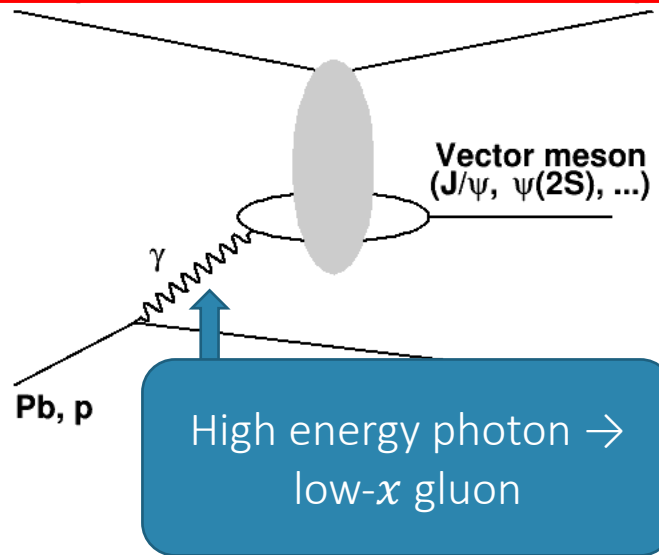
Measuring the energy dependence



Measuring the energy dependence



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



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

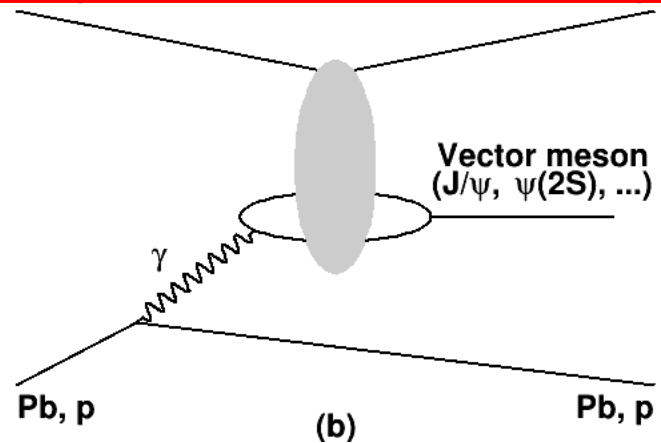
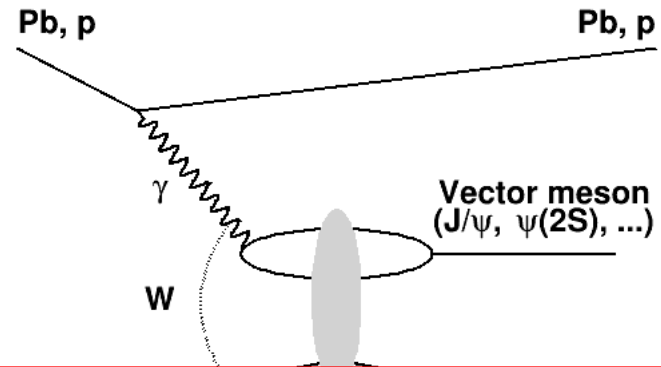
Measuring the energy dependence

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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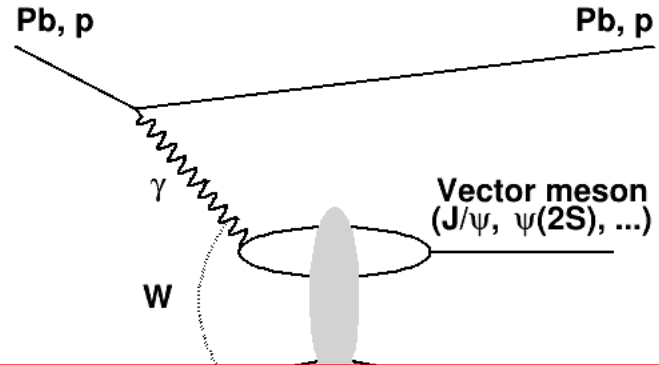


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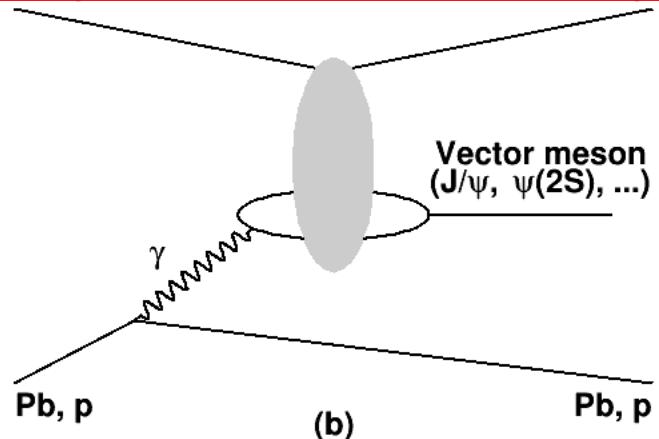
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Coherent J/ψ at forward rapidity:

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

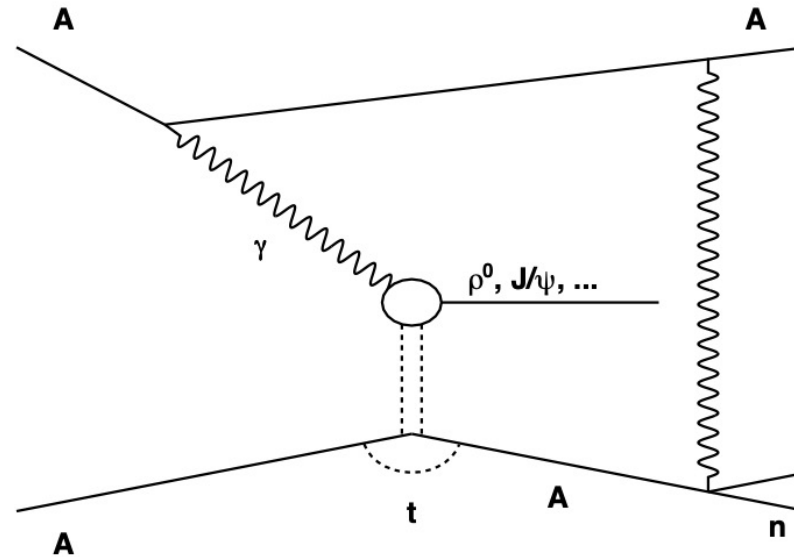
$$\frac{d\sigma}{dy} \simeq n(\gamma)\sigma_{\gamma\text{Pb}}$$

But that remaining 5% is very interesting

Techniques for the photon direction ambiguity

Neutron emission:

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

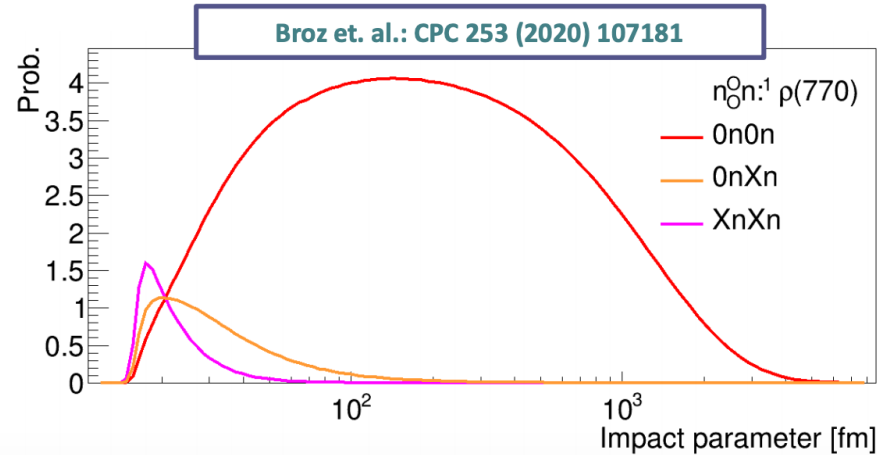


- Using the neutron ZDCs on the A and C side to detect the neutrons!
- E.g. 0N0N: no neutrons on either ZDCs
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$$\frac{d\sigma_{PbPb}^{0N0N}}{dy} = n_{0N0N}(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_{0N0N}(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

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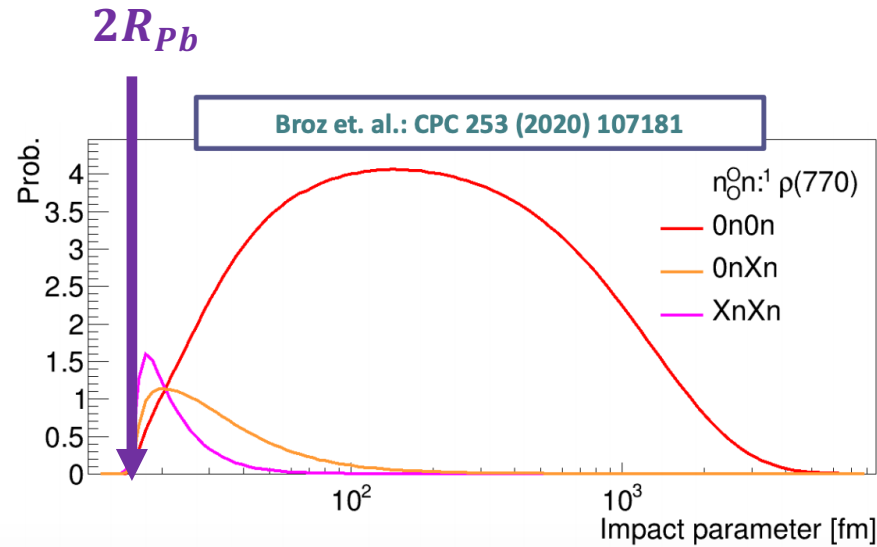
Guzey et al., Eur.Phys.J.C 74 (2014) 7, 2942

- Effectively leveraging on the impact parameter

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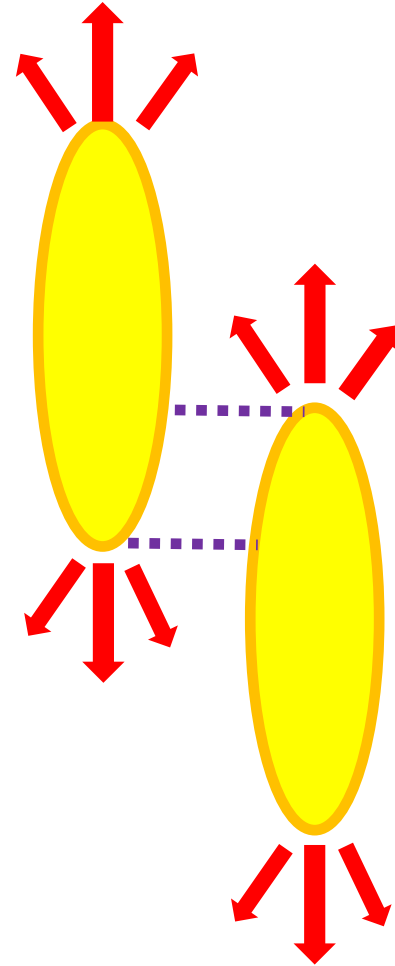
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- Effectively leveraging on the impact parameter

Techniques for the photon direction ambiguity

Peripheral photoproduction:

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



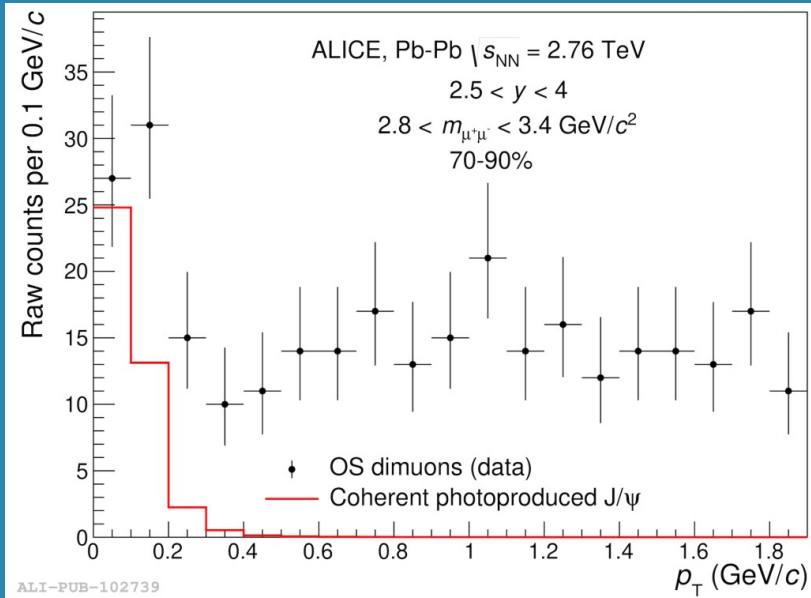
- Simultaneously use UPC and peripheral results to get rid of the ambiguities!

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

J.G. Contreras PRC 96 (2017) 015203

Peripheral J/ψ photoproduction

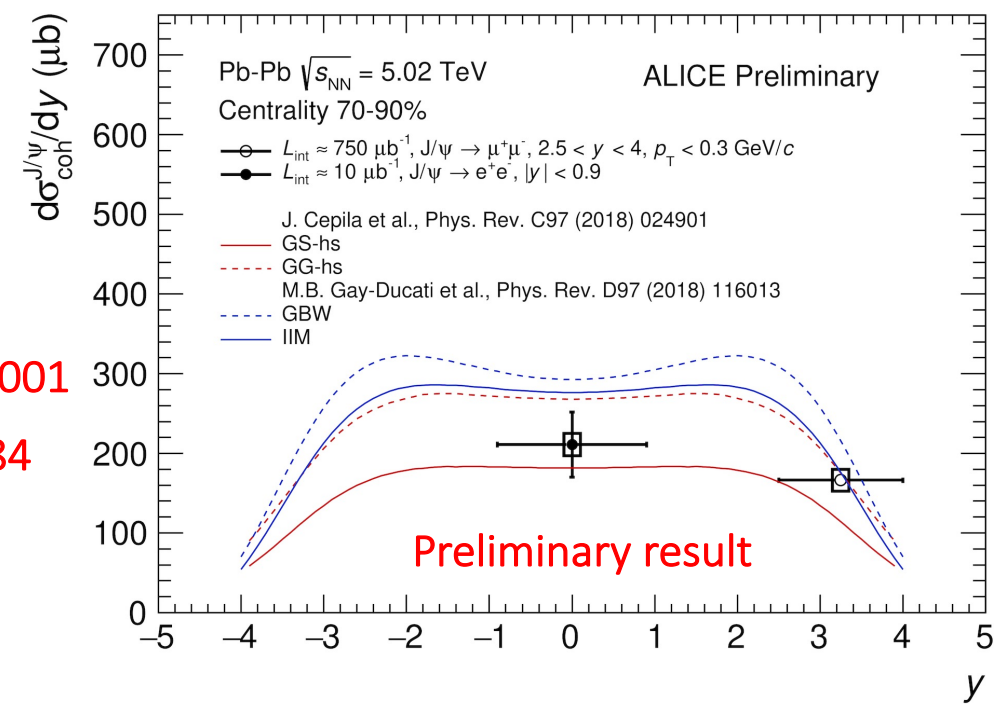
- First observed with Run 1 data by ALICE
- Now confirmed with Run 2 statistics by both ALICE and LHCb. STAR also reports this



ALICE, PRL 116 (2016), 222301

ALICE, EPL 129 (2020) 42001

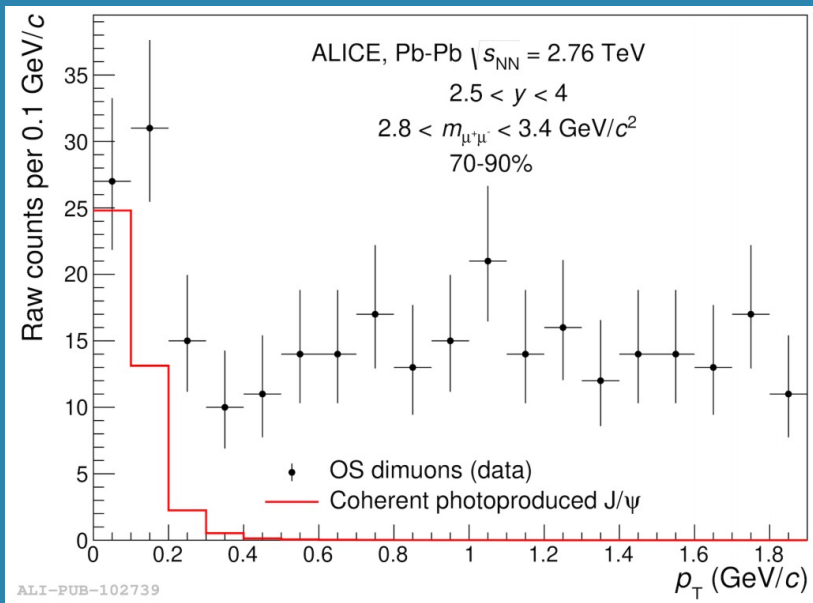
ALICE, arXiv:2204.10684



LHCb, Phys.Rev.C 105 (2022) 3, L032201
 STAR, Phys.Rev.Lett. 123 (2019) 132302

Peripheral J/ψ photoproduction

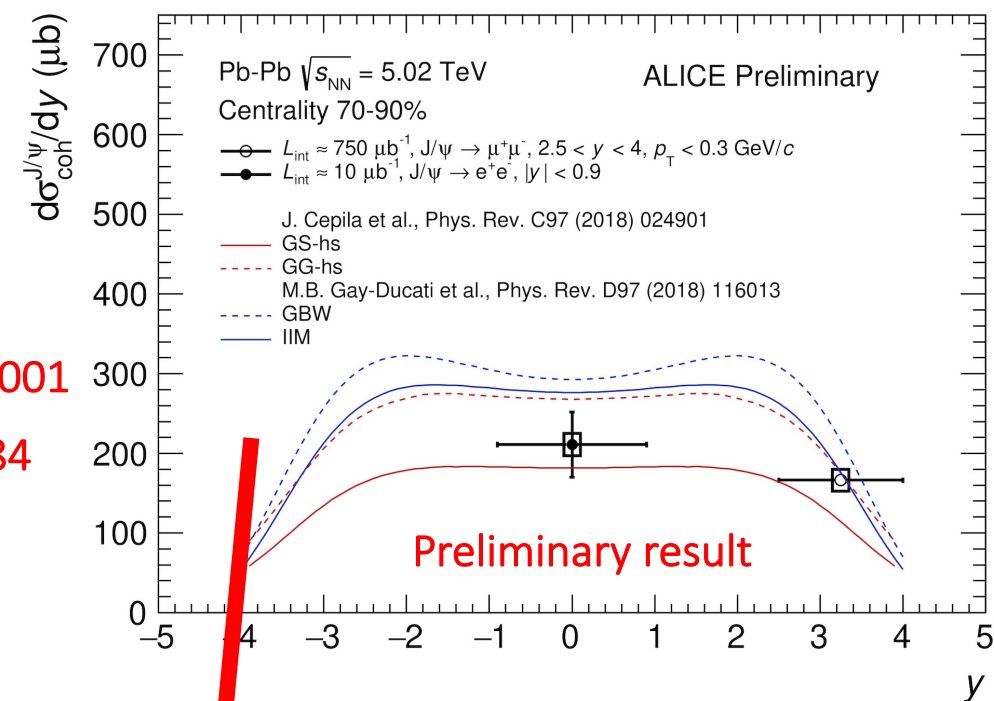
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ALICE, PRL 116 (2016), 222301

ALICE, EPL 129 (2020) 42001

ALICE, arXiv:2204.10684



UPC results

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

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

LHCb, Phys.Rev.C 105 (2022) 3, L032201
 STAR, Phys.Rev.Lett. 123 (2019) 132302

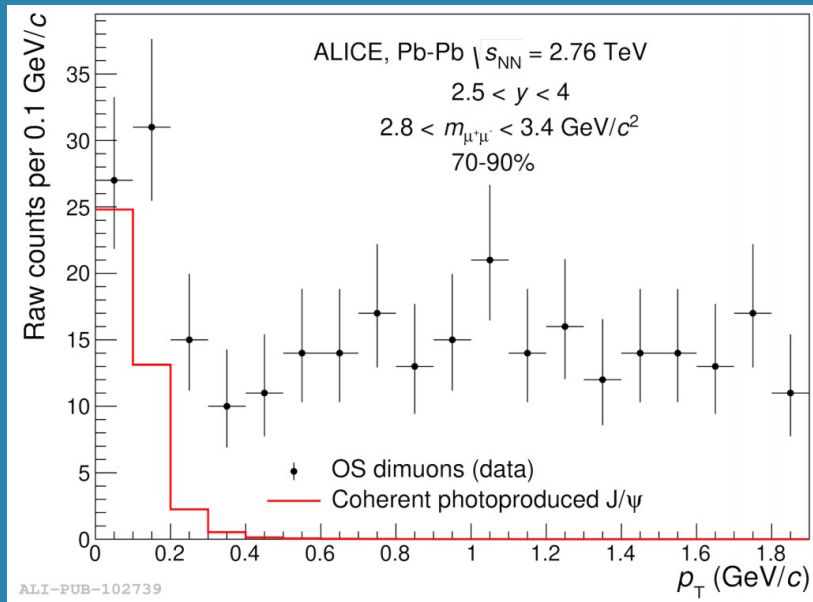
Peripheral J/ψ photoproduction using ALICE Run 1 data

- First extraction of the photonuclear cross sections with Run 1 data

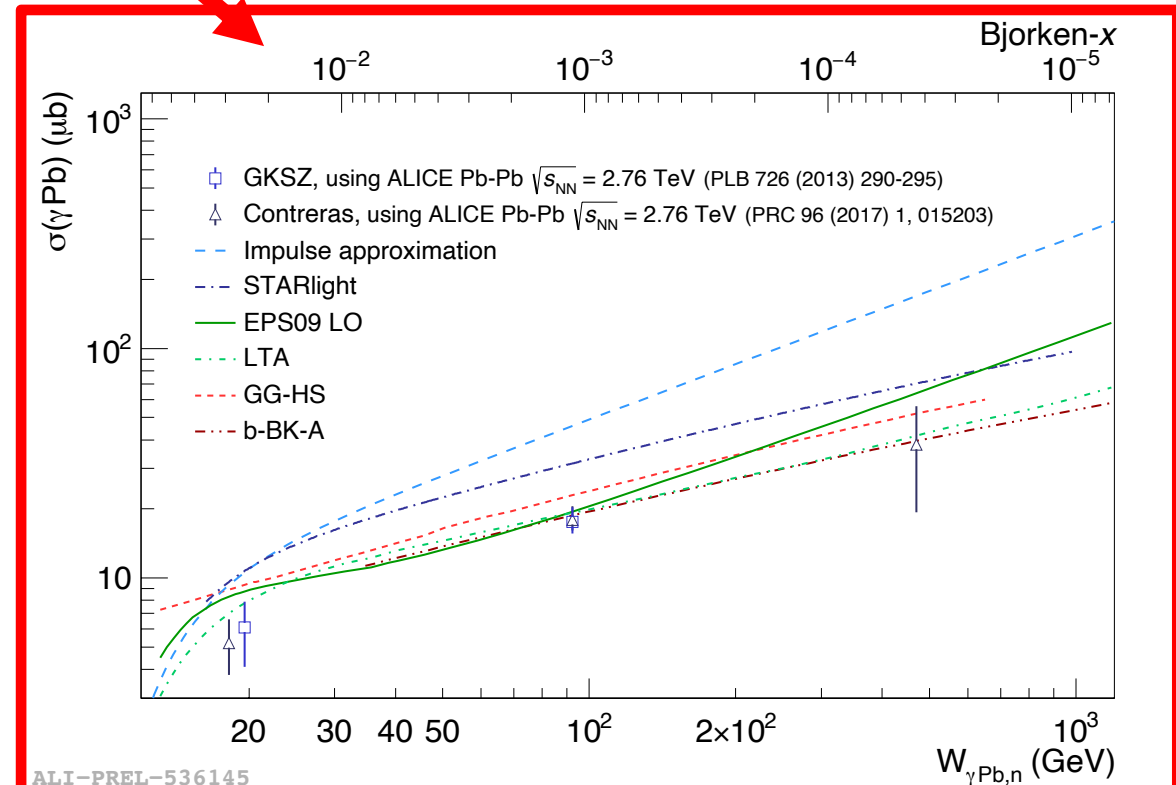
$$\frac{d\sigma_{PbPb}^P}{dy} = n_P(\gamma, +y) \cdot \sigma_{\gamma Pb}(+y) + n_P(\gamma, -y) \cdot \sigma_{\gamma Pb}(-y)$$

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J.G. Contreras PRC 96 (2017) 015203



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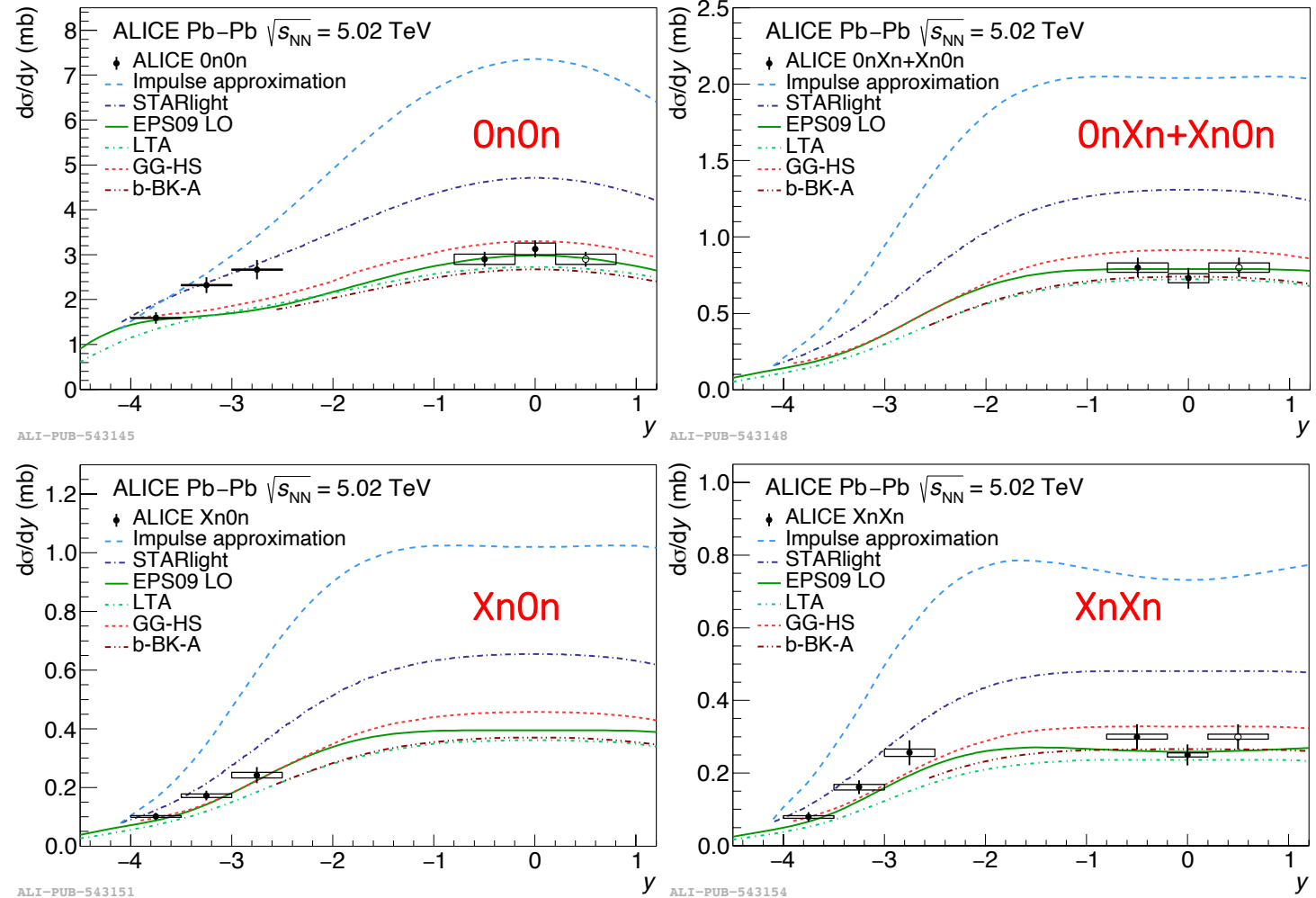


ALI-PREL-536145

Coherent J/ ψ with neutron emission

- Event *migrations*: missed detection of a neutron (i.e. XNON \rightarrow ONON), 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:

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

- 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

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

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

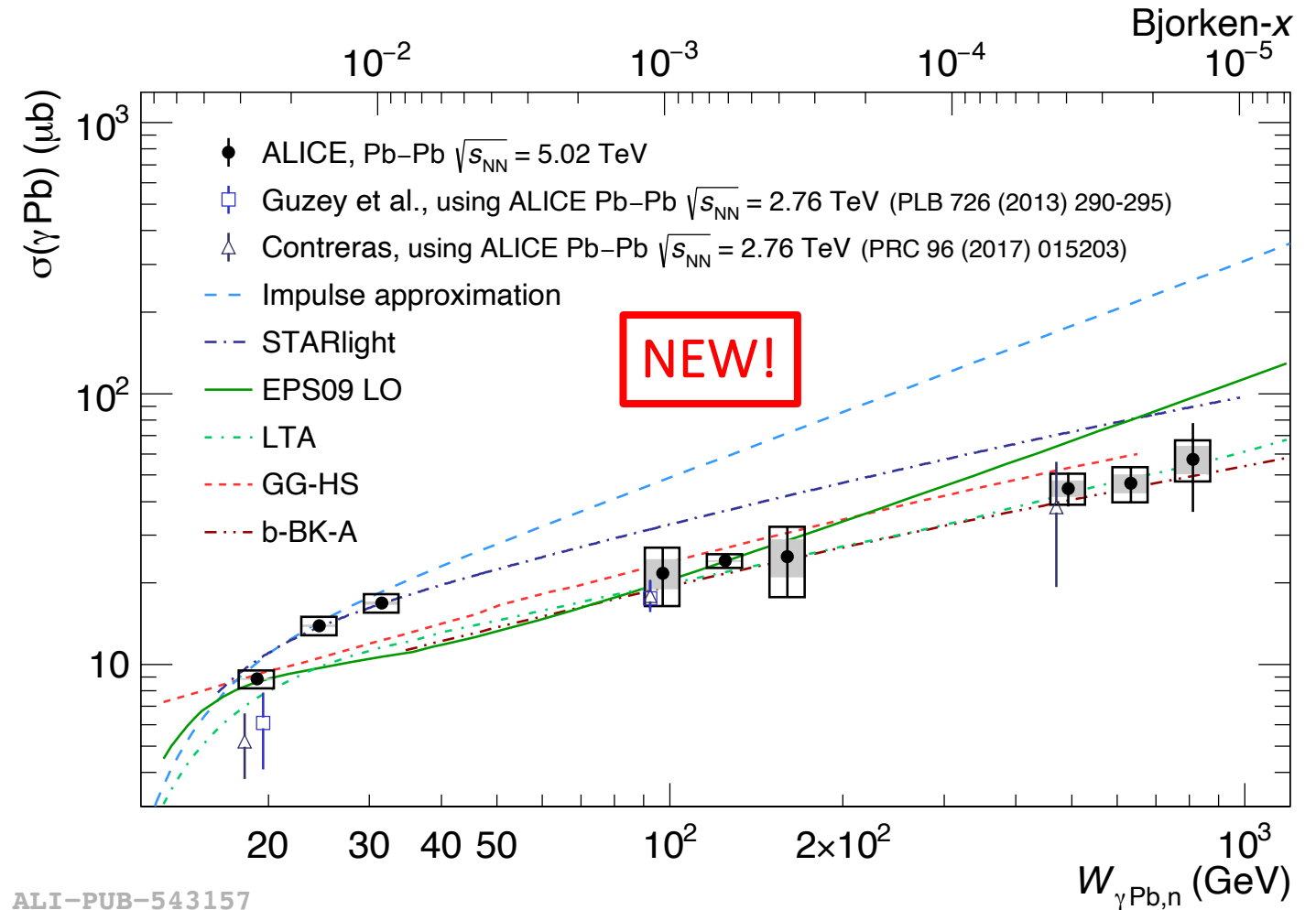
Large difference in weight of the two solutions for the photon fluxes!

y	$n_{\gamma}(0n0n)$	$n_{\gamma}(0nXn+Xn0n)$	$n_{\gamma}(XnXn)$	$\sigma_{\gamma Pb}^{IA} (\mu b)$
$3.5 < y < 4$	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

Coherent J/ ψ with neutron emission

ALICE, arXiv:2305.19060

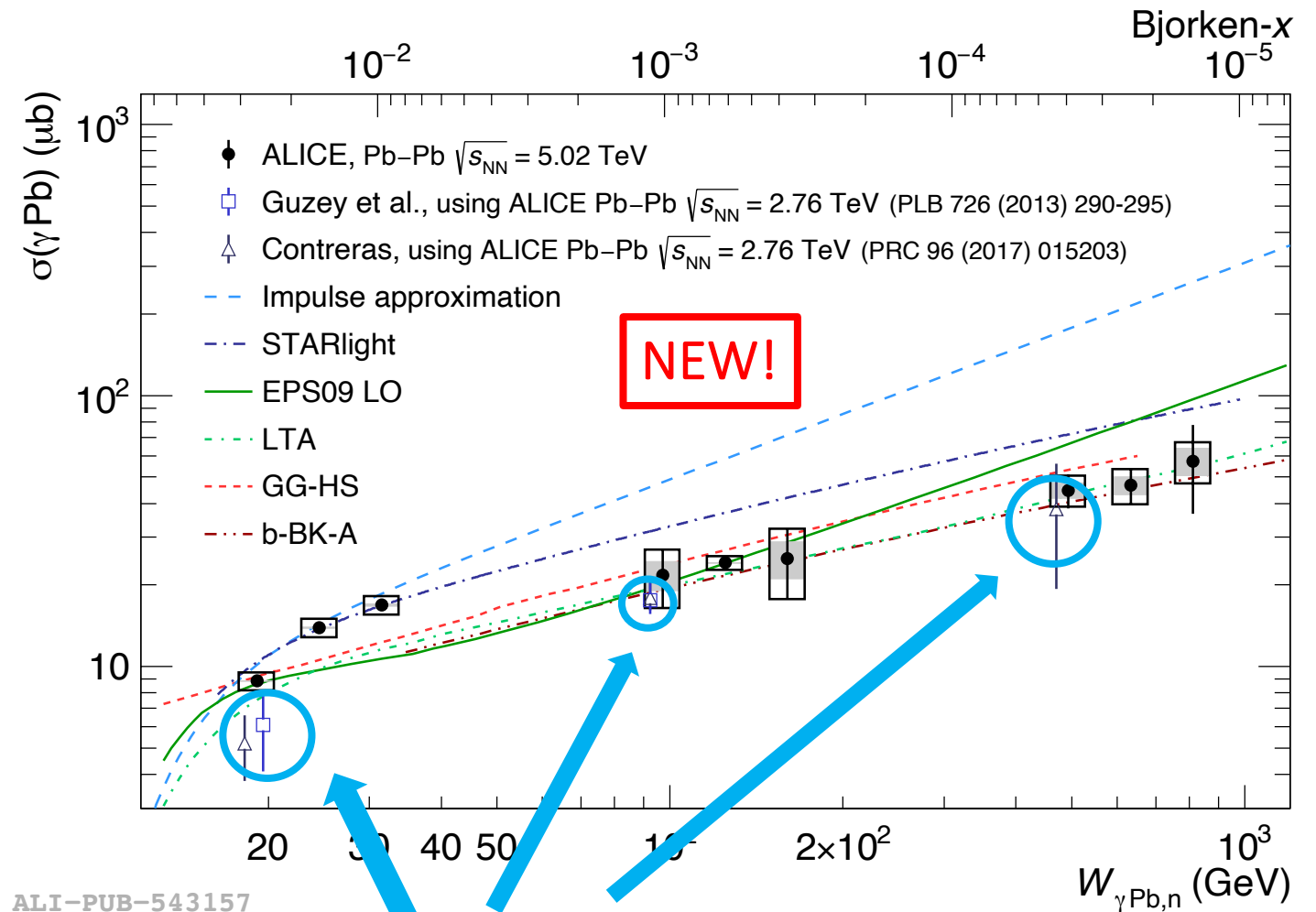
- First measurement of the energy dependence of the photonuclear cross section down to Bjorken- $x \sim 10^{-5}$!
- At low- x data favours both saturation and shadowing models



Coherent J/ ψ with neutron emission

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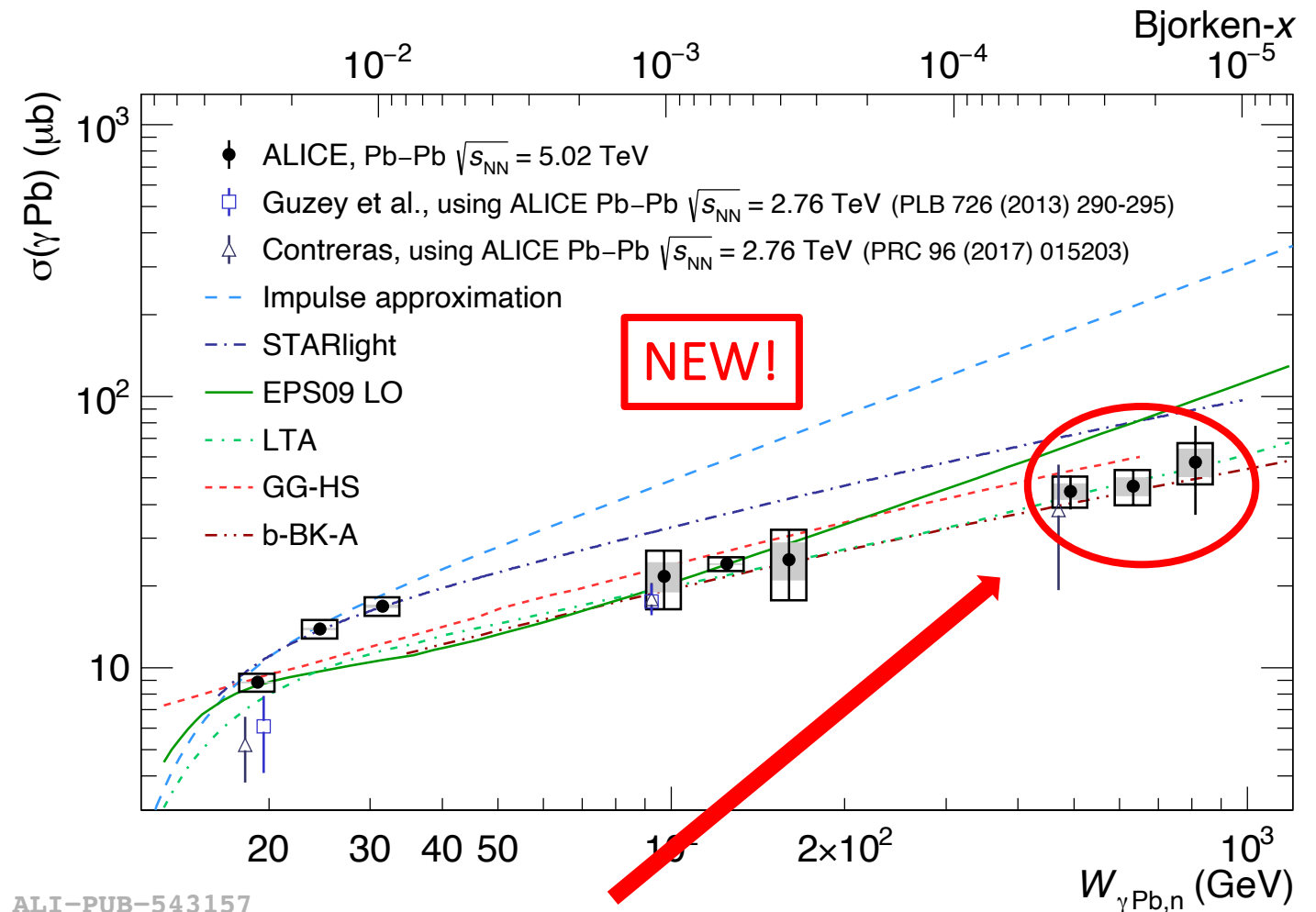


Good agreement between Run 1 peripheral and Run 2 neutron emission measurements!

Coherent J/ ψ with neutron emission

ALICE, arXiv:2305.19060

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- New Run 2 results probe unprecedented Bjorken- x region like no other LHC experiment!



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

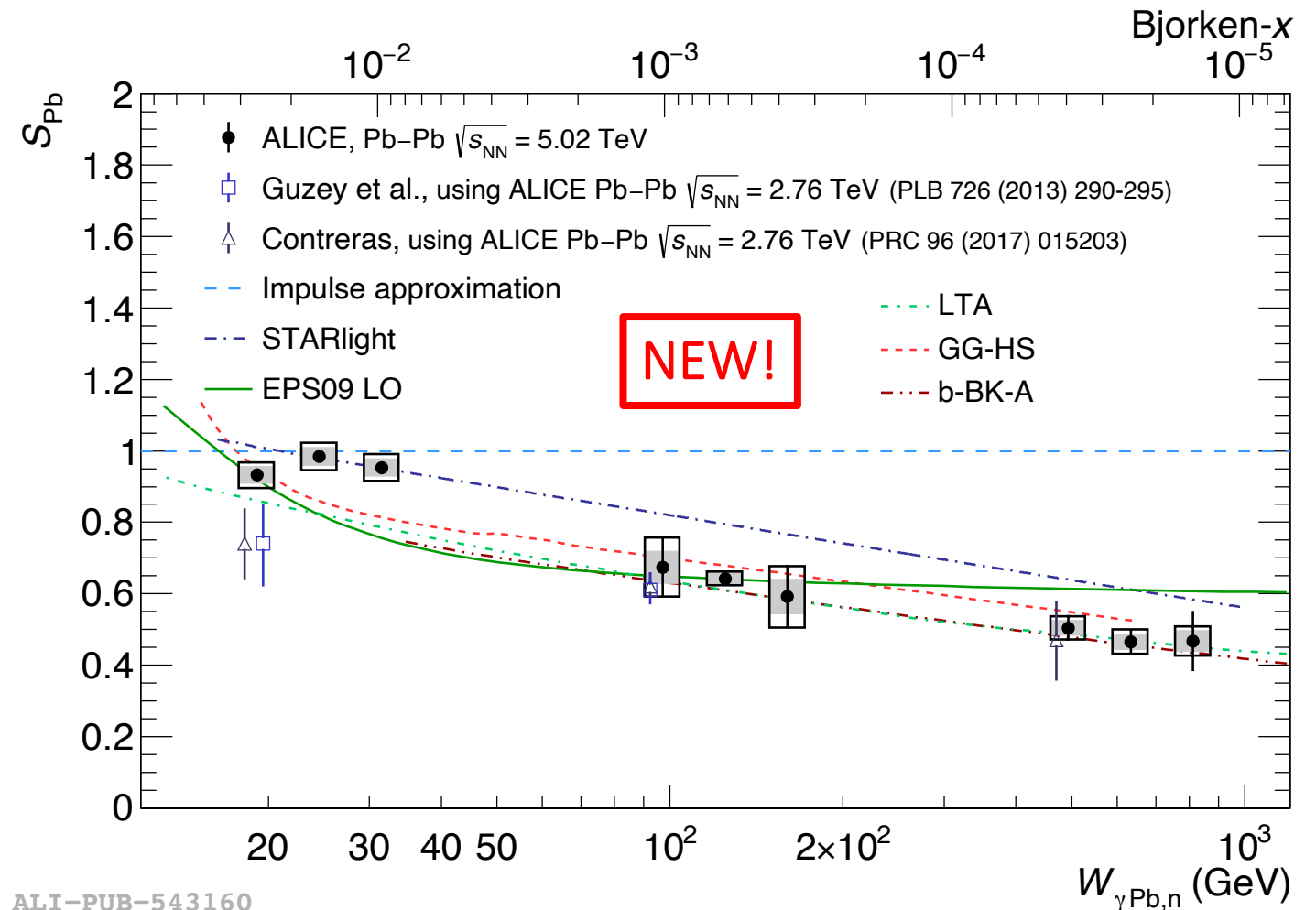
Coherent J/ψ with neutron emission

ALICE, arXiv:2305.19060

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

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

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



ALI-PUB-543160

Studying coherent J/ψ in terms of...

1. y

2. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

3. p_T^2

4. *Angular distributions*

Coherent J/ψ |t|-dependence

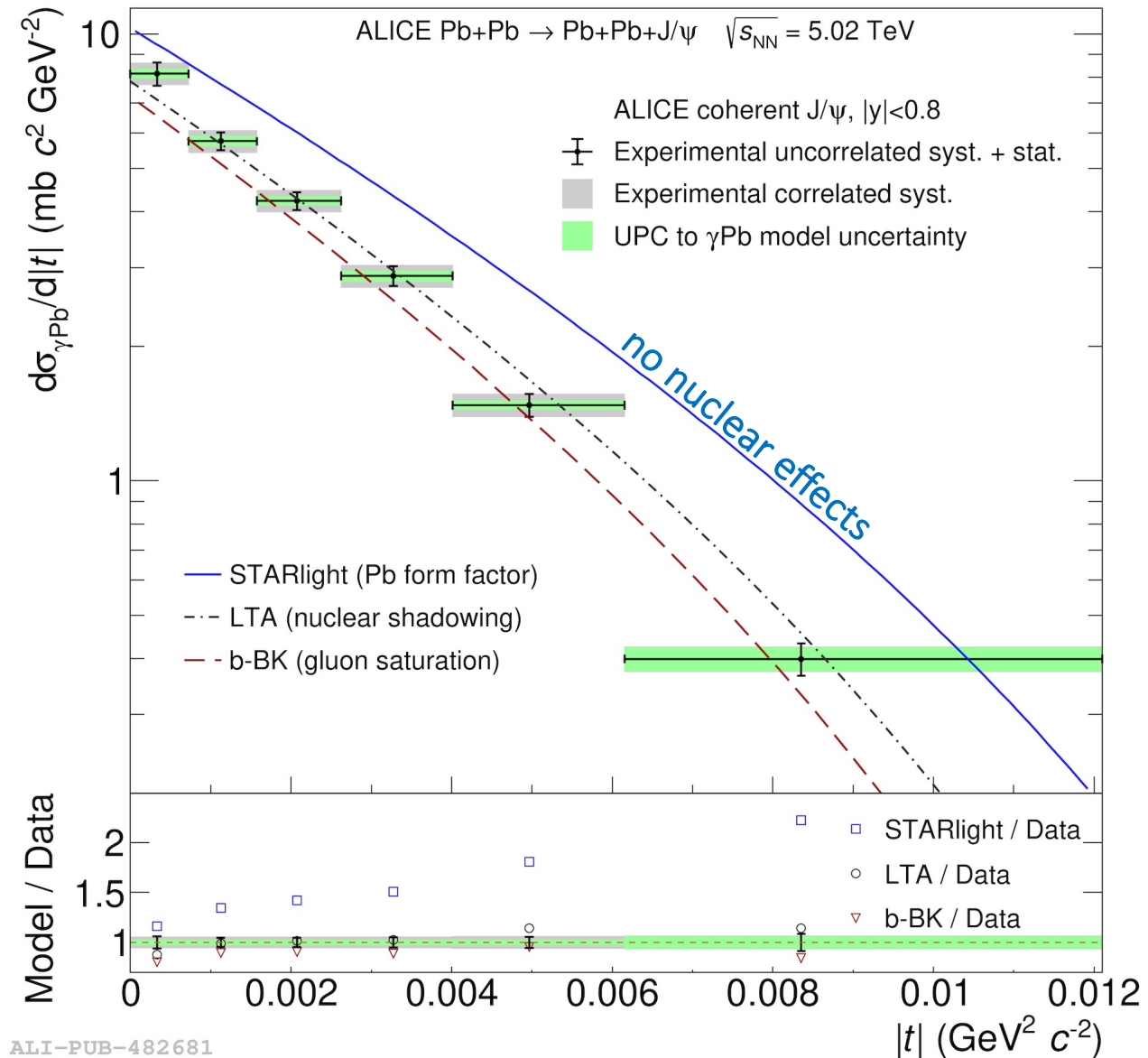
ALICE, Phys.Lett.B 817 (2021) 13628 $0 < |t| < 0.012 \text{ GeV}^2$

- From p_T^2 -dependent photoproduction to $|t|$ -dependent photonuclear production

$$\left. \frac{d^2 \sigma_{J/\psi}^{\text{coh}}}{dy dp_T^2} \right|_{y=0} = 2n_{\gamma\text{Pb}}(y=0) \frac{d\sigma_{\gamma\text{Pb}}}{d|t|}$$

- Transverse momentum of the photon accounted for by unfolding with a response matrix built from p_T^2 - and $|t|$ -distributions
- Probing the transverse gluonic structure of the nucleus at low x
- Models including QCD dynamical effects are favoured

Sensitive to the average spatial distribution of gluons



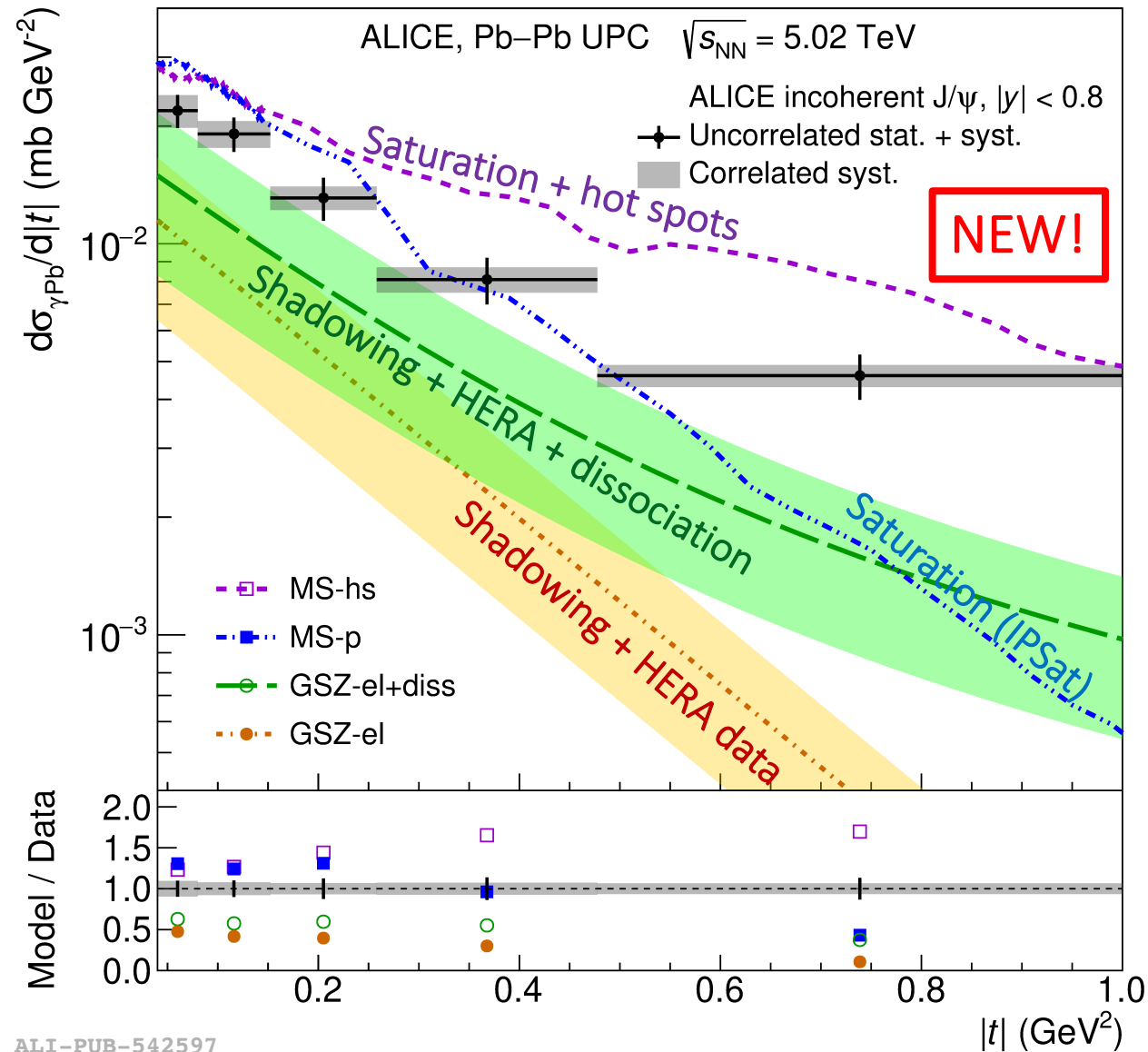
ALI-PUB-482681

Incoherent J/ψ |t|-dependence

ALICE, arXiv:2305.06169

$0.04 < |t| < 1 \text{ GeV}^2$

- Gluonic subnucleon fluctuations needed to describe the data
- First measurement of its kind ever!



Sensitive to the variance of the spatial distribution of gluons

Studying coherent J/ψ in terms of...

1. y

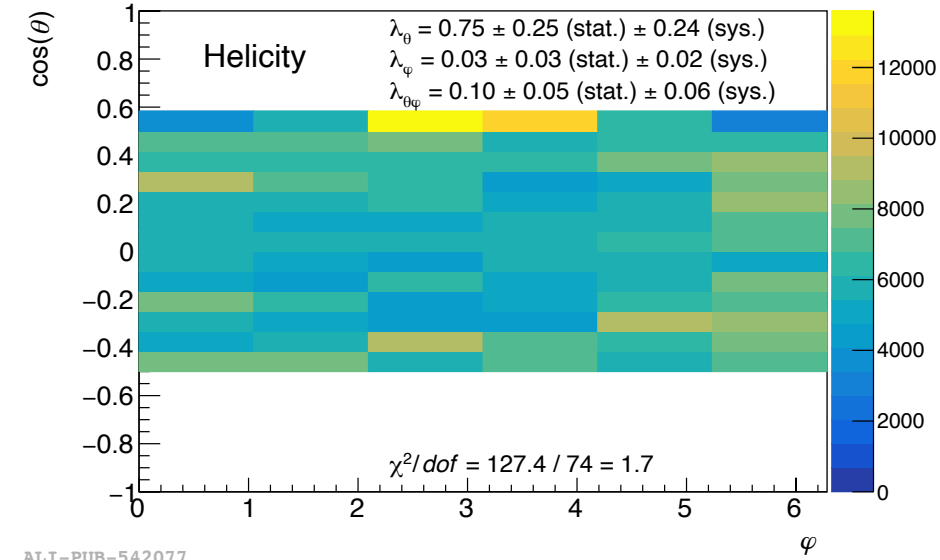
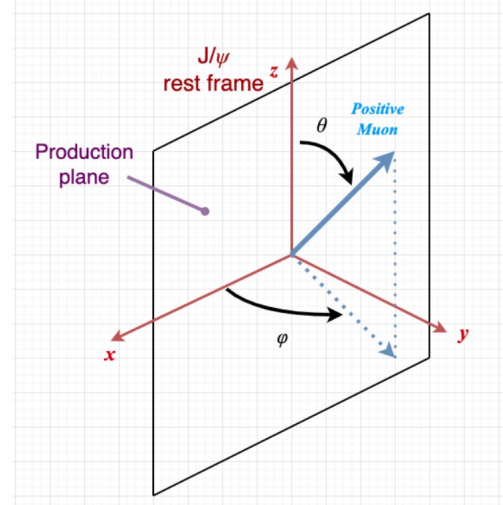
2. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

3. p_T^2

4. *Angular distributions*

Coherent J/ ψ polarisation

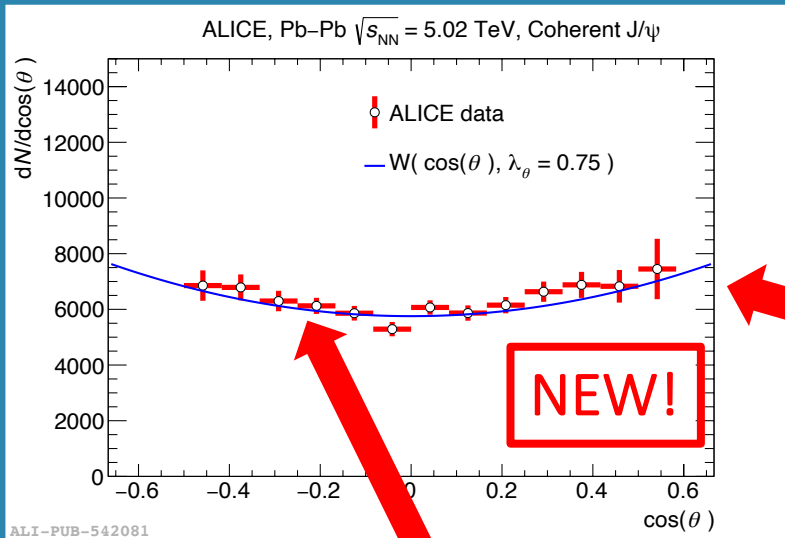
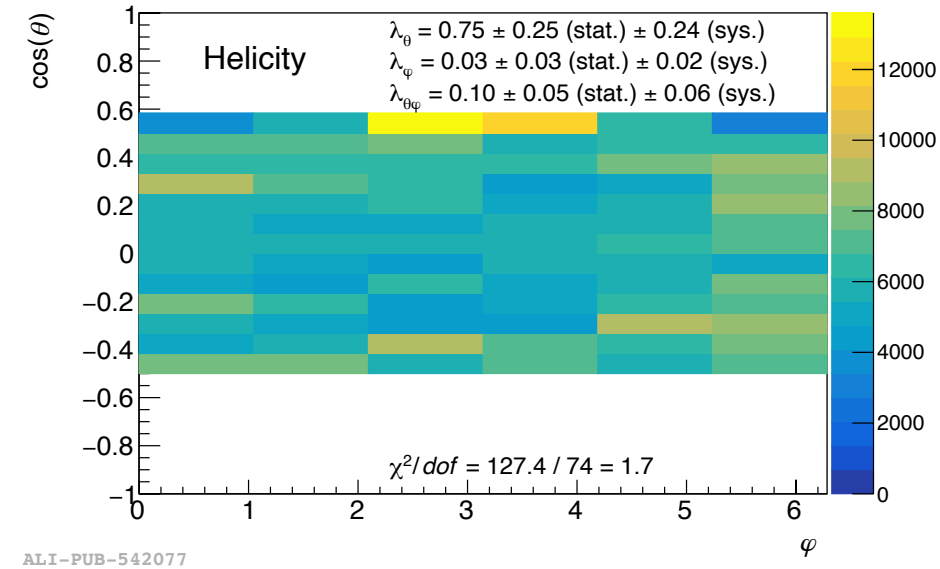
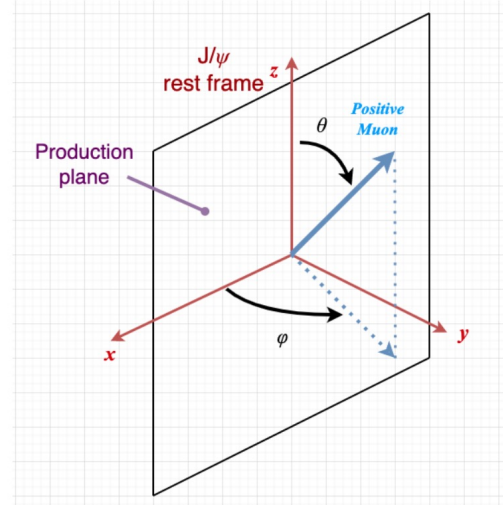
- Quasireal photons ($Q^2 \sim 0$): s-channel helicity conservation suggests transverse polarisation for the vector meson
- Agreement with H1 (photoproduction)
- ZEUS measures electroproduction



$$W(\cos \theta, \varphi) \propto \frac{1}{3 + \lambda_\theta} \cdot [1 + \lambda_\theta \cdot \cos^2 \theta + \lambda_\varphi \cdot \sin^2 \theta \cdot \cos 2\varphi + \lambda_{\theta\varphi} \cdot \sin 2\theta \cos \varphi]$$

Coherent J/ ψ polarisation

- Quasireal photons ($Q^2 \sim 0$): s-channel helicity conservation suggests transverse polarisation for the vector meson
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Upward parabolic shape in $\cos(\theta)$ expected for transverse polarisation

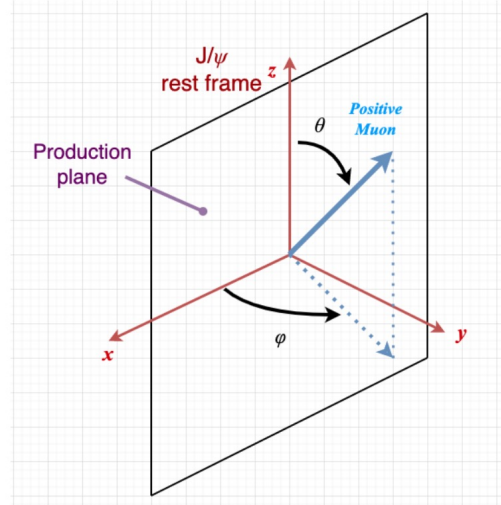
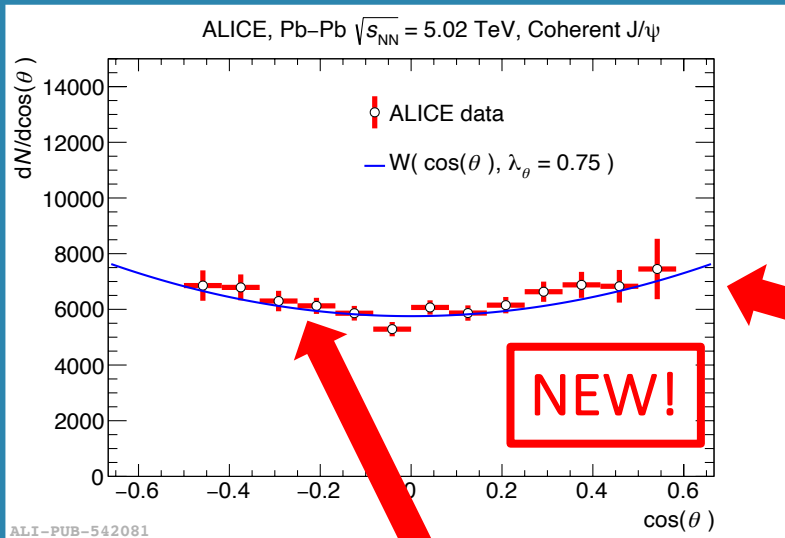
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Coherent J/ψ polarisation

ALICE, arXiv:2304.10928

ALICE, Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, coherent J/ψ

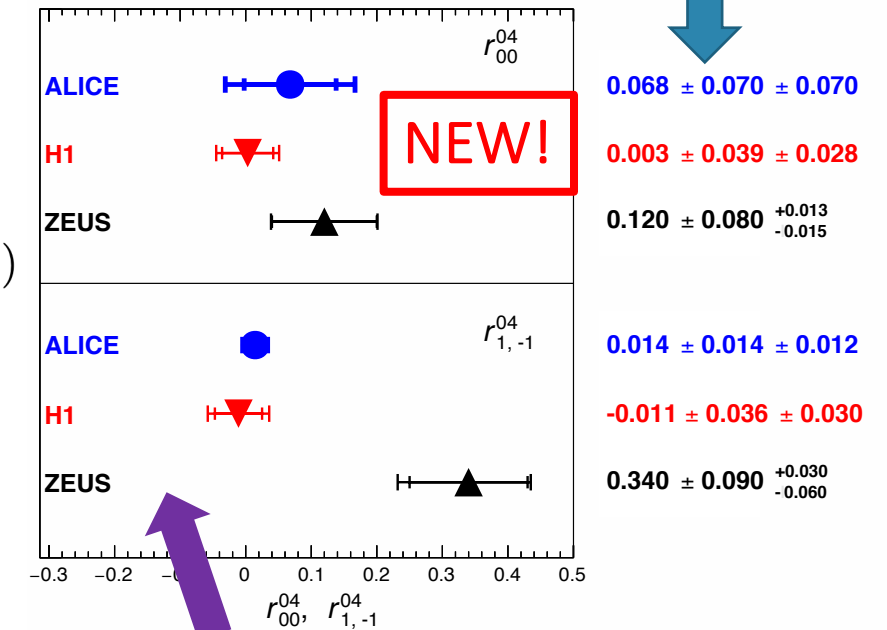
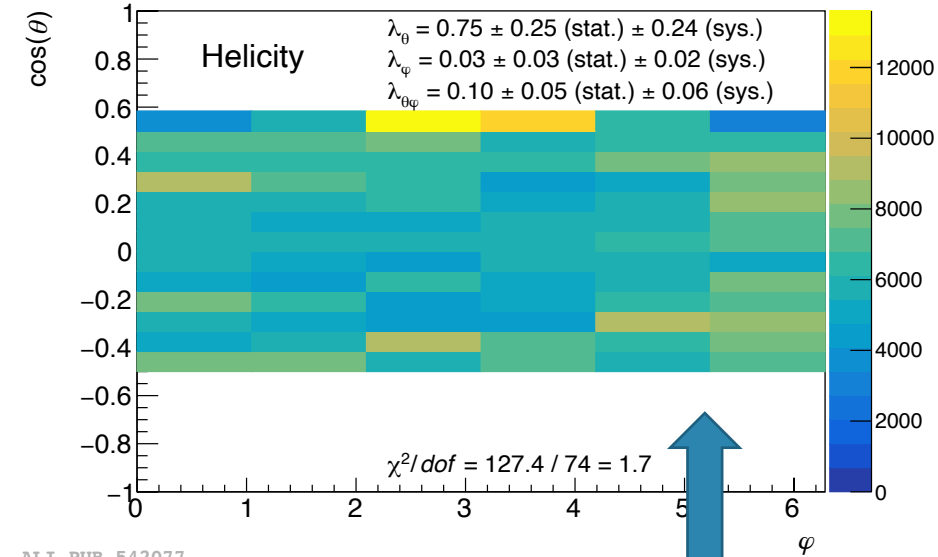
- Quasireal photons ($Q^2 \sim 0$): s-channel helicity conservation suggests transverse polarisation for the vector meson
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$$r_{00}^{04} = \frac{1 - \lambda_\theta}{3 + \lambda_\theta}$$

$$r_{1,-1}^{04} = \frac{\lambda_\varphi}{2} \cdot (1 + r_{00}^{04})$$

Upward parabolic shape in $\cos(\theta)$ expected for transverse polarisation



Results for the spin-density matrix elements

$$W(\cos \theta, \varphi) \propto \frac{1}{3 + \lambda_\theta} \cdot [1 + \lambda_\theta \cdot \cos^2 \theta + \lambda_\varphi \cdot \sin^2 \theta \cdot \cos 2\varphi + \lambda_{\theta\varphi} \cdot \sin 2\theta \cos \varphi]$$

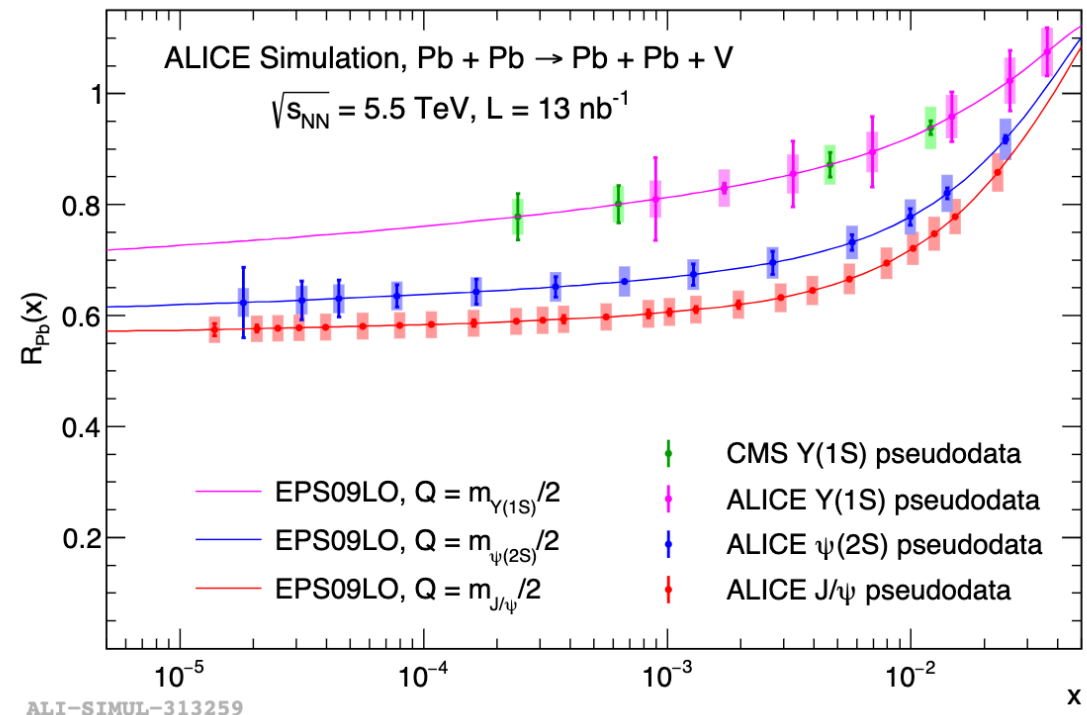
ALICE in Run 3 and 4

- 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
- Double vector meson photoproduction
- Uncertainties for nuclear suppression factor expected to be at the level of 4%
- More differential measurements e.g. in $|t|$
- New measurements e.g. bottomonium states

PbPb			
Meson	σ	Central 1	Forward 1
		Total	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
$\psi(2S) \rightarrow \mu^+ \mu^-$	$30 \mu\text{b}$	35 K	19 K
$Y(1S) \rightarrow \mu^+ \mu^-$	$2.0 \mu\text{b}$	2.8 K	880

CERN Yellow Rep. Monogr. 7 (2019)
1159-1410, arXiv [1812.06772](https://arxiv.org/abs/1812.06772)

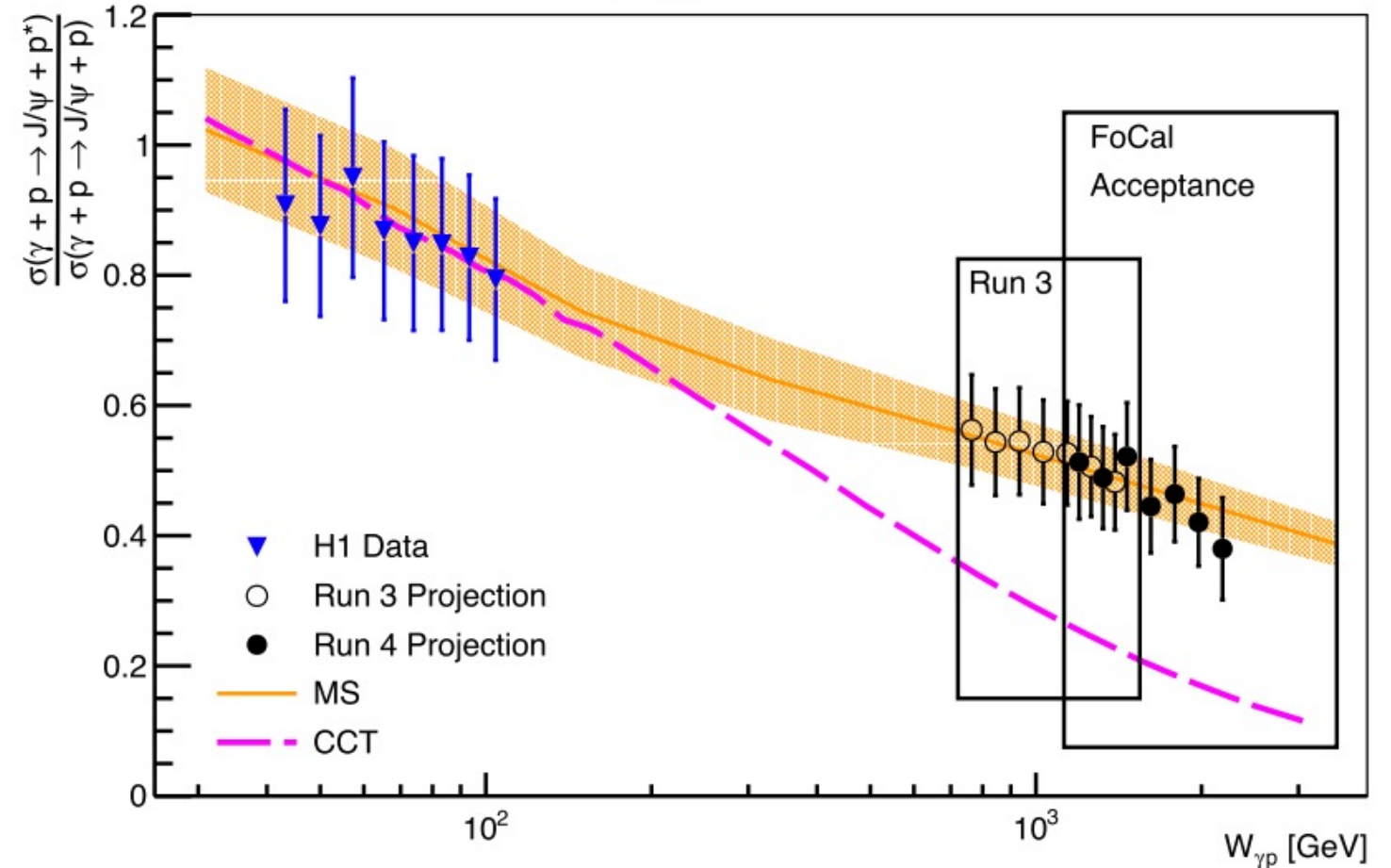
$|y| < 0.9$ $2.5 < |y| < 4$



Dissociative J/ψ in Run 3 (+ Run 4 with FOCAL)

- CCT model features gluonic hotspots
- Significant reduction at higher energies would be a clear signal of the onset of saturation

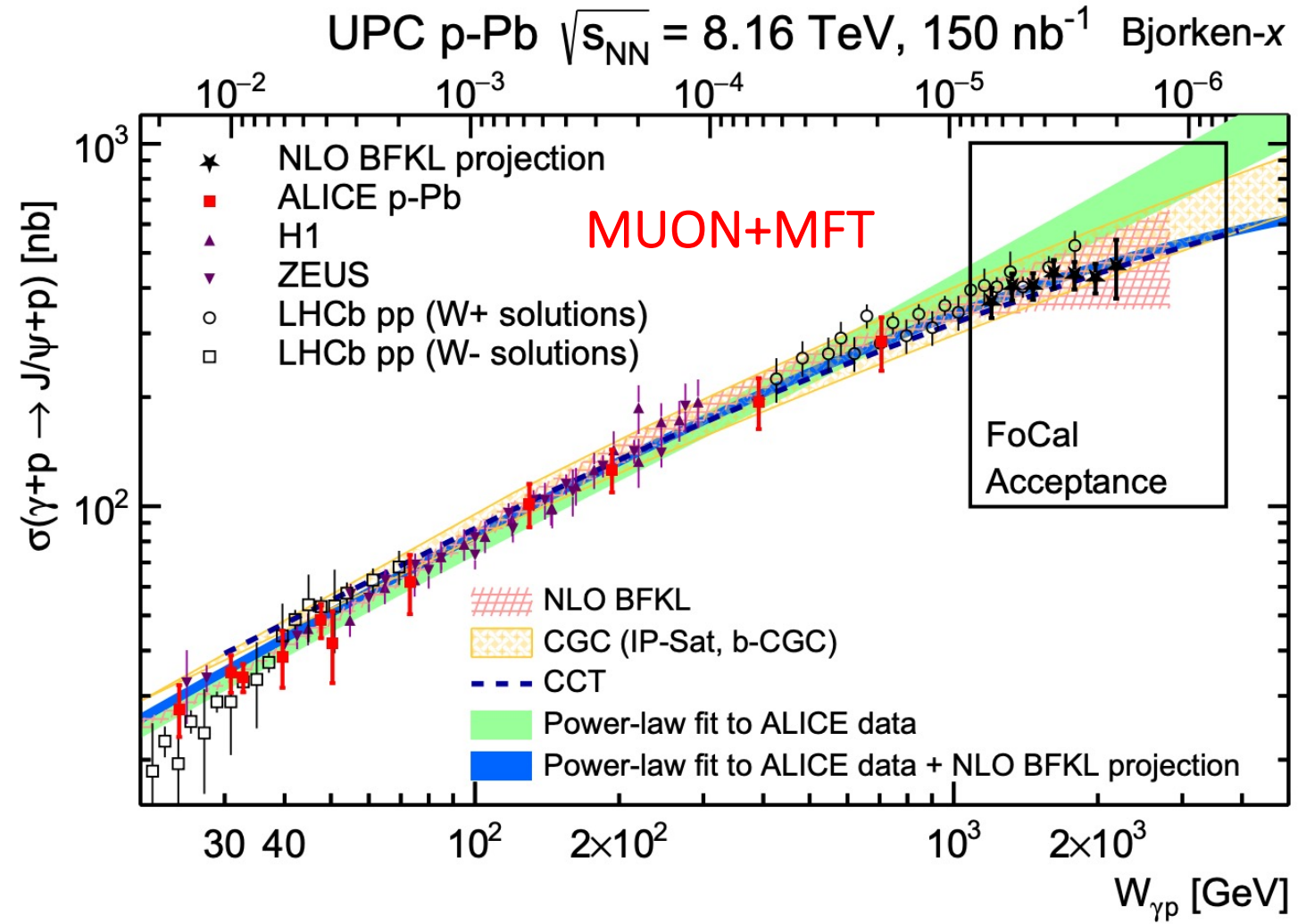
UPC p-Pb $\sqrt{s_{NN}} = 8.16$ TeV, 150 nb^{-1}



A. Bylinkin, J. Nystrand, D. Tapia Takaki, 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 055105

Exclusive J/ψ and ψ' in Run 3 (+ Run 4 with FOCAL)

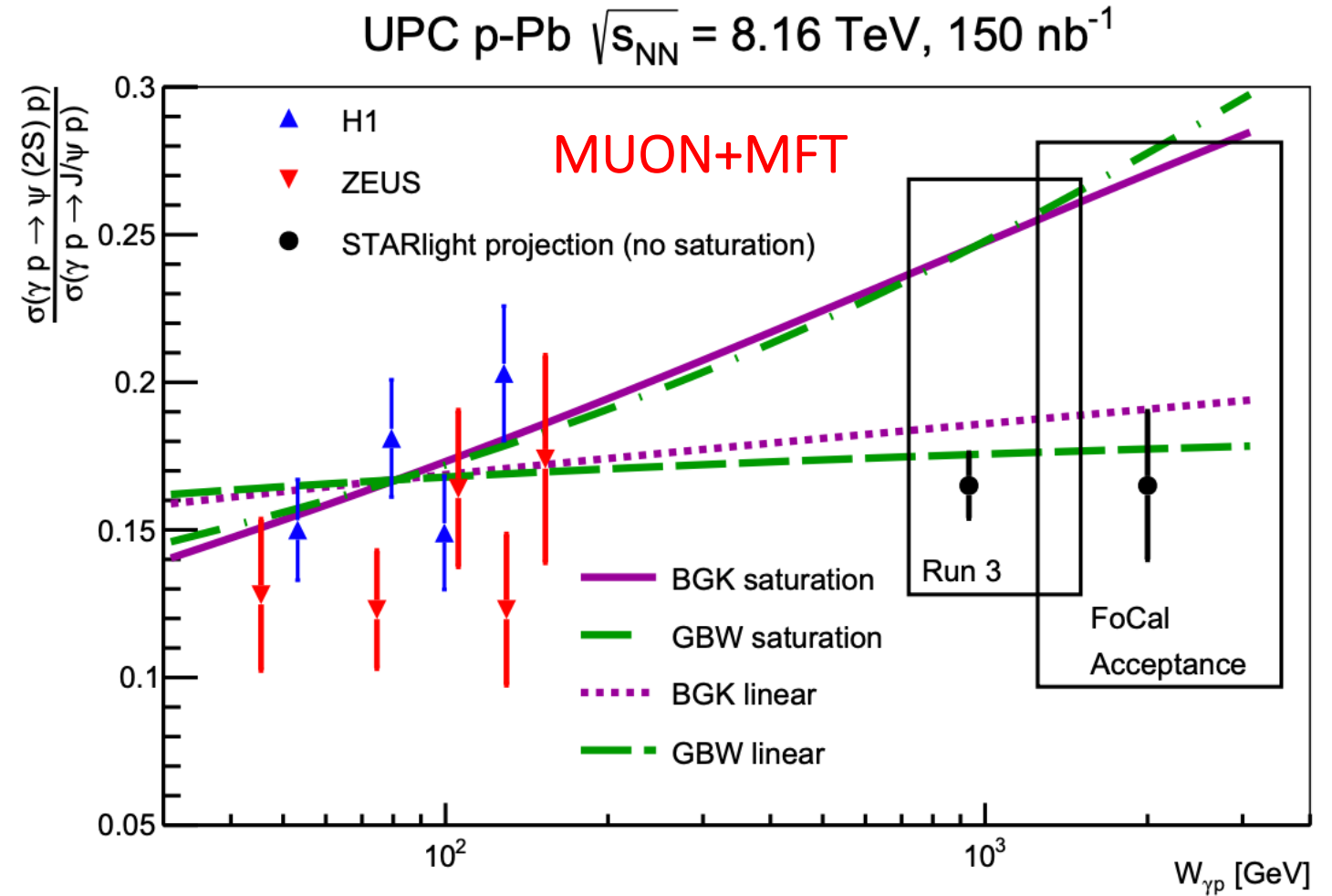
- Expanding the range in Bjorken- x down to 10^{-6}



A. Bylinkin, J. Nystrand, D. Tapia Takaki, 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 055105

Exclusive J/ψ and ψ' in Run 3 (+ Run 4 with FOCAL)

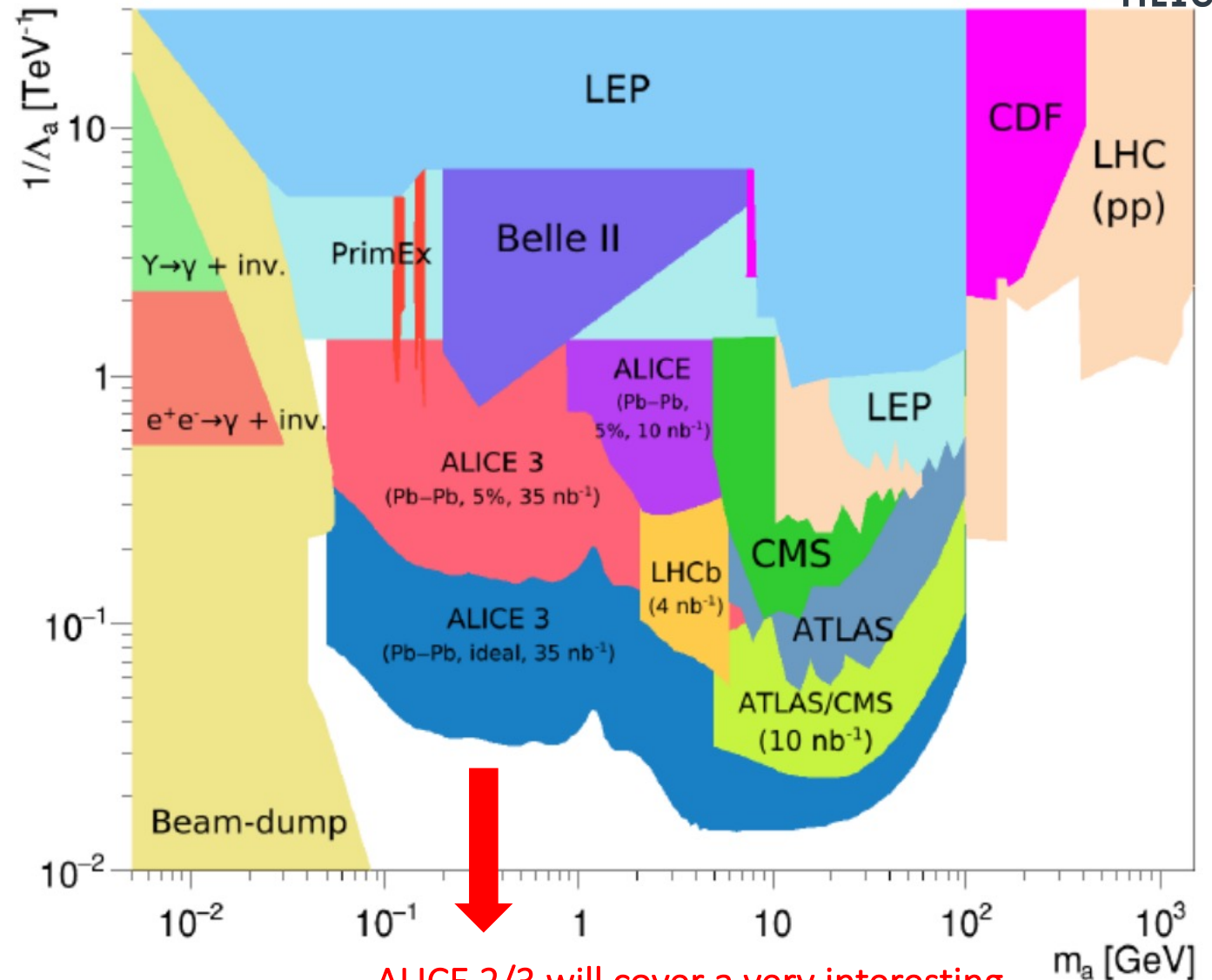
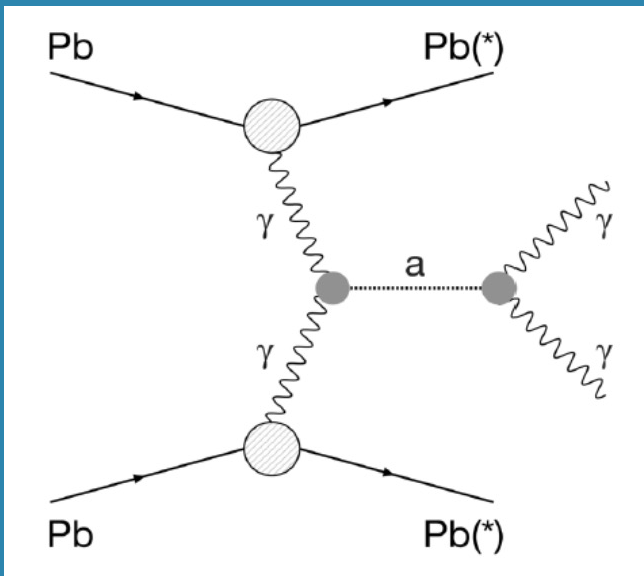
- Ratio more sensitive than the individual cross sections
- Both Run 3 and Run 4 are needed to find hints of saturation or its onset



A. Bylinkin, J. Nystrand, D. Tapia Takaki, 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 055105

Axion-Like Particles (ALPs) with ALICE 3

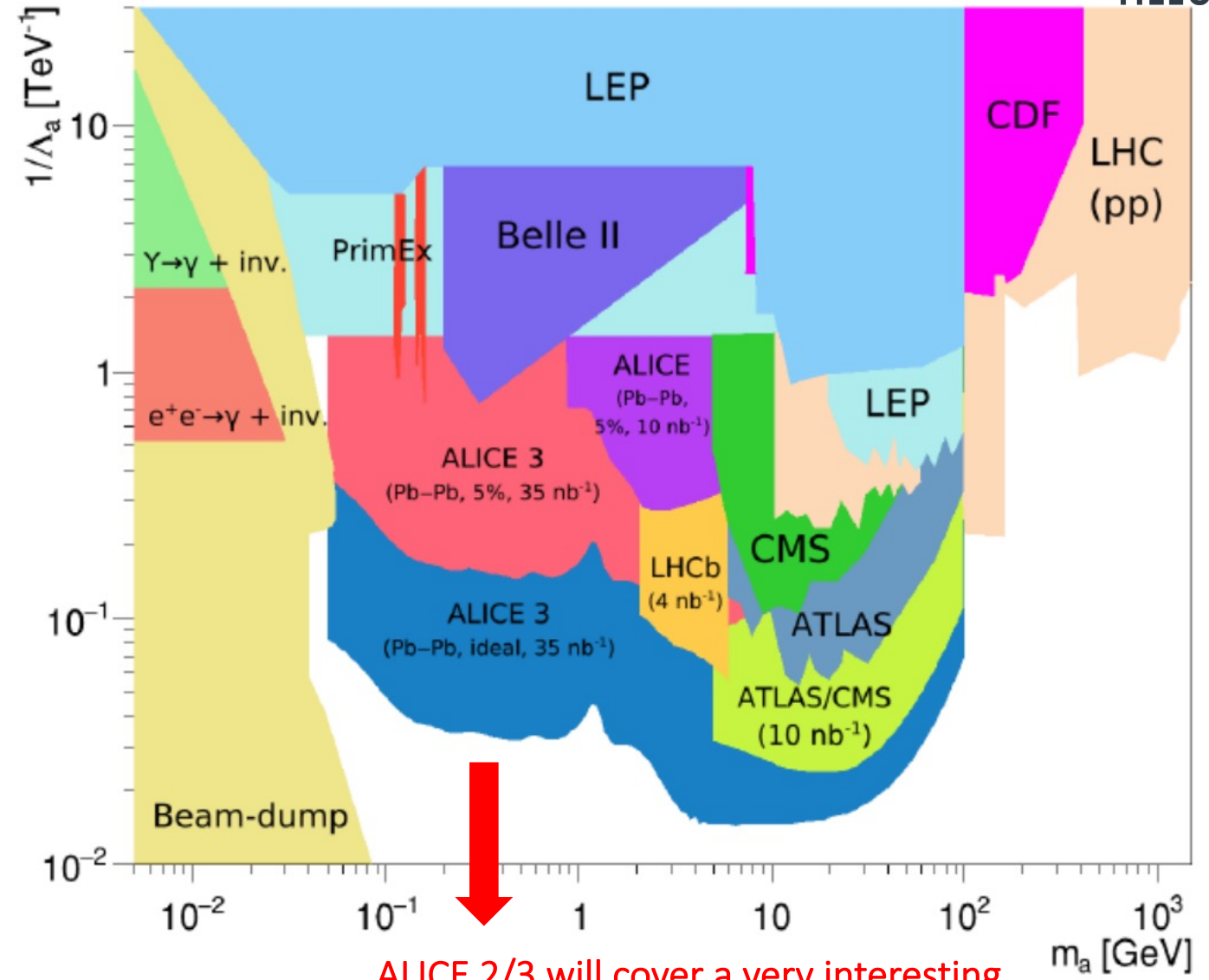
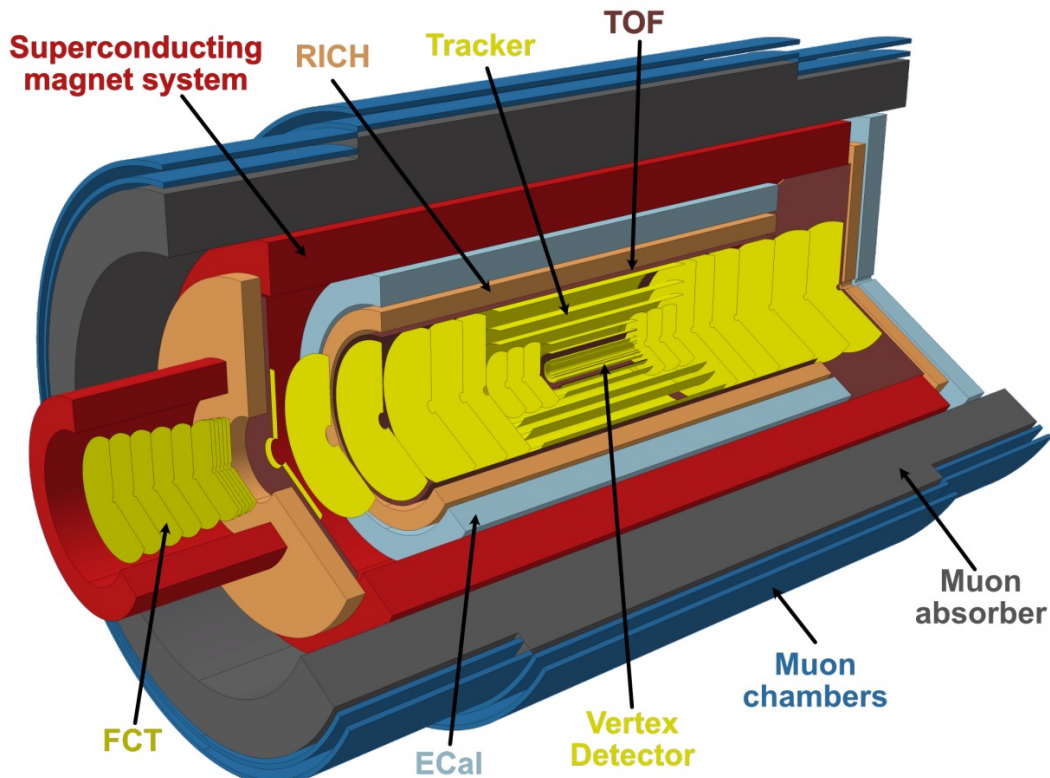
- Measuring light-by-light scattering and looking for resonances in the invariant mass distributions



ALICE 2/3 will cover a very interesting portion of the phase space!

Axion-Like Particles (ALPs) with ALICE 3

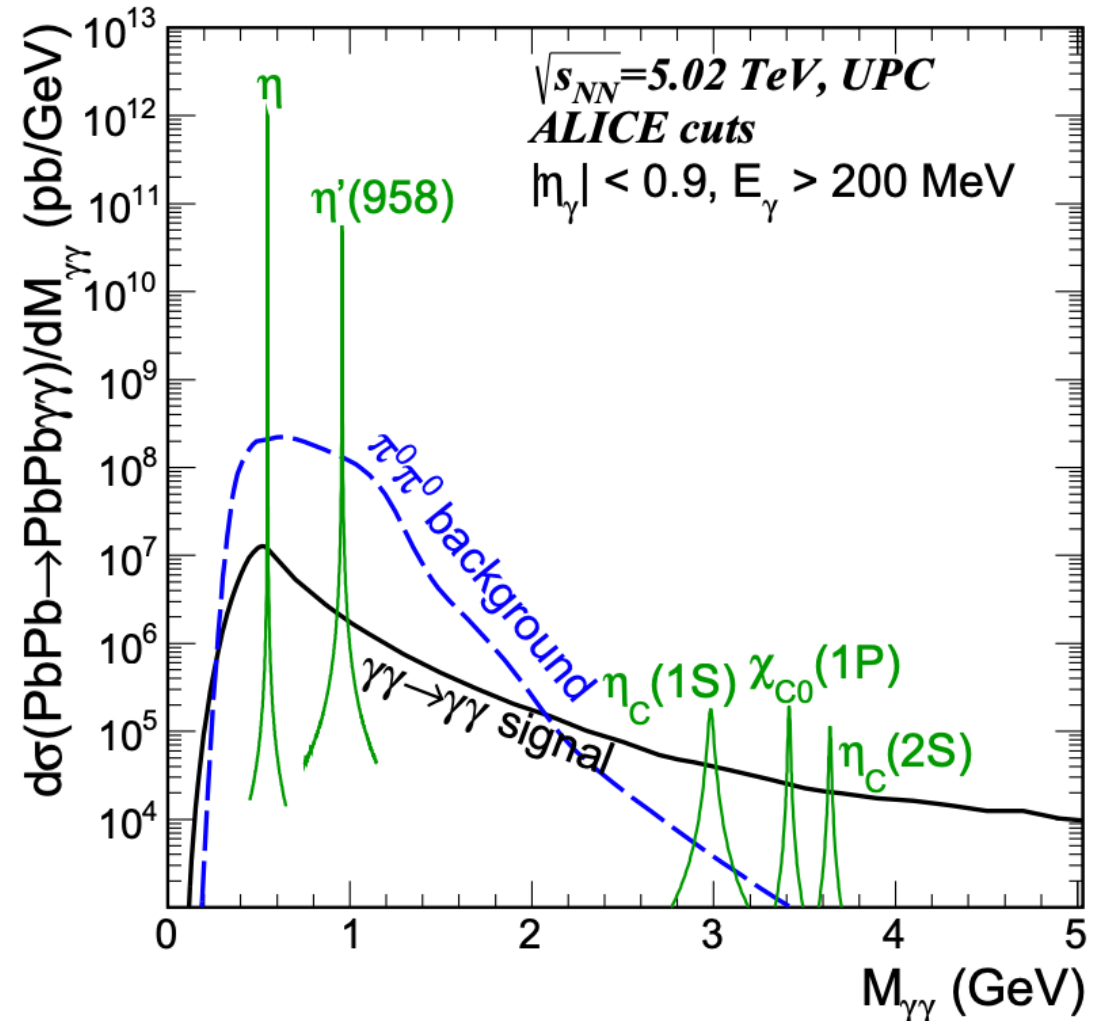
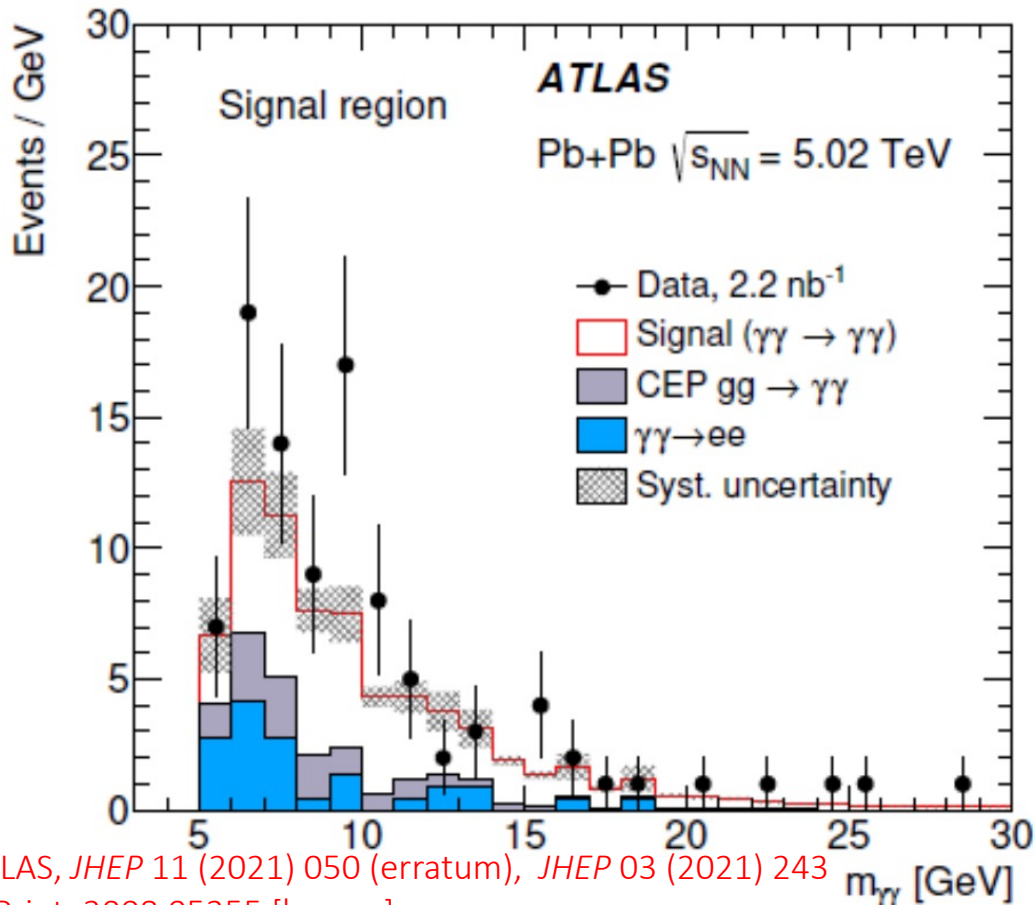
- Measuring light-by-light scattering and looking for resonances in the invariant mass distributions



ALICE 2/3 will cover a very interesting portion of the phase space!

Axion-Like Particles (ALPs) with ALICE 3

- ALICE focus on low invariant masses



Mariola Klusek-Gawenda et al., *Phys. Rev. D* 99 (2019) 9, 093013, e-Print: [1904.01243](https://arxiv.org/abs/1904.01243) [hep-ph]

Summary



- $|t|$ -dependence of incoherent J/ψ demonstrates the importance of subnucleon fluctuations
- First measurement of the nuclear suppression factor at Bjorken- $x \sim 10^{-5}$! Obtained with the neutron emission technique
- Models do not describe the growth of $\sigma_{\gamma Pb}$ at low energies
 - 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
- Transverse polarisation for coherent J/ψ

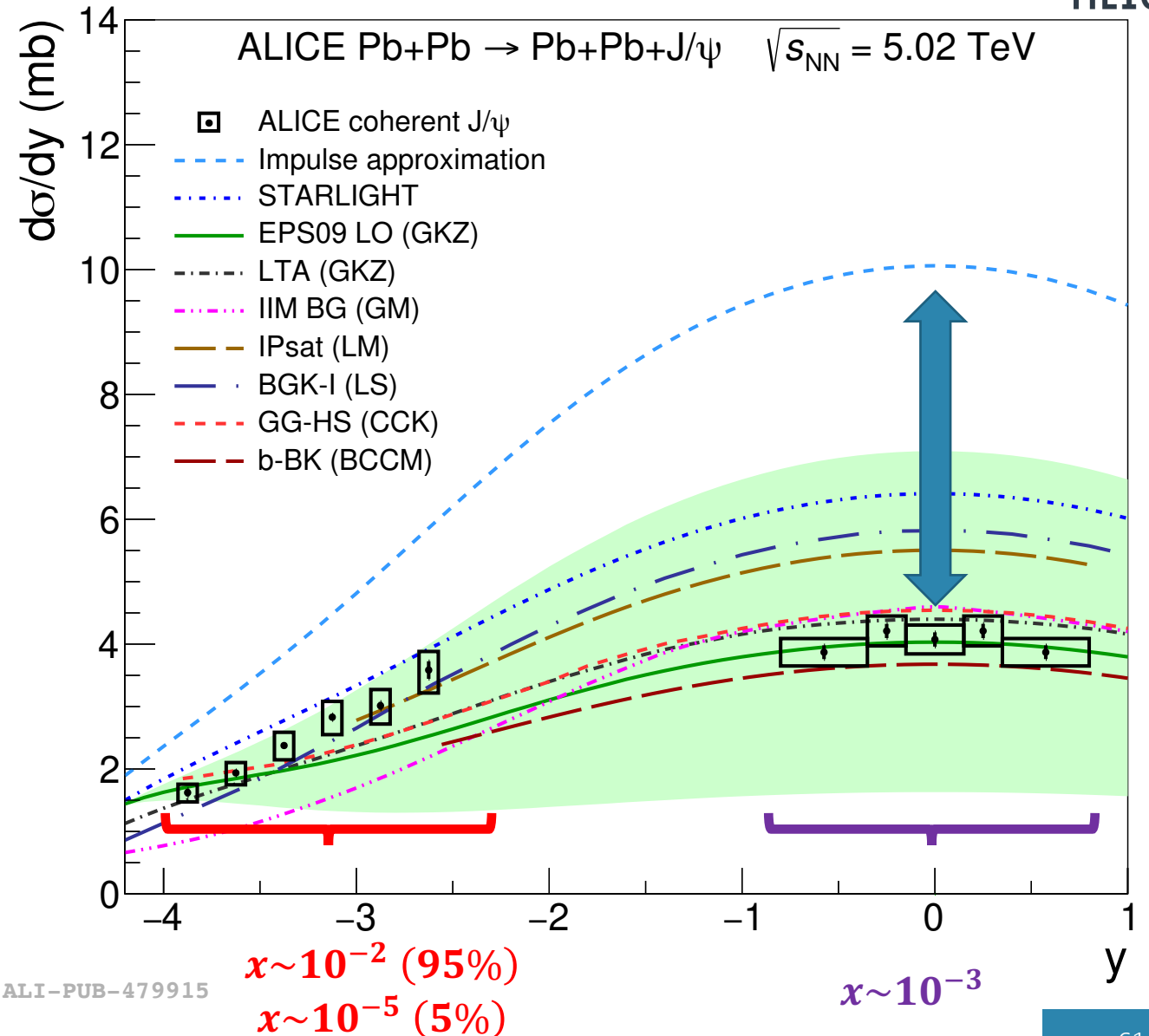


Backup slides

Coherent J/ψ cross section

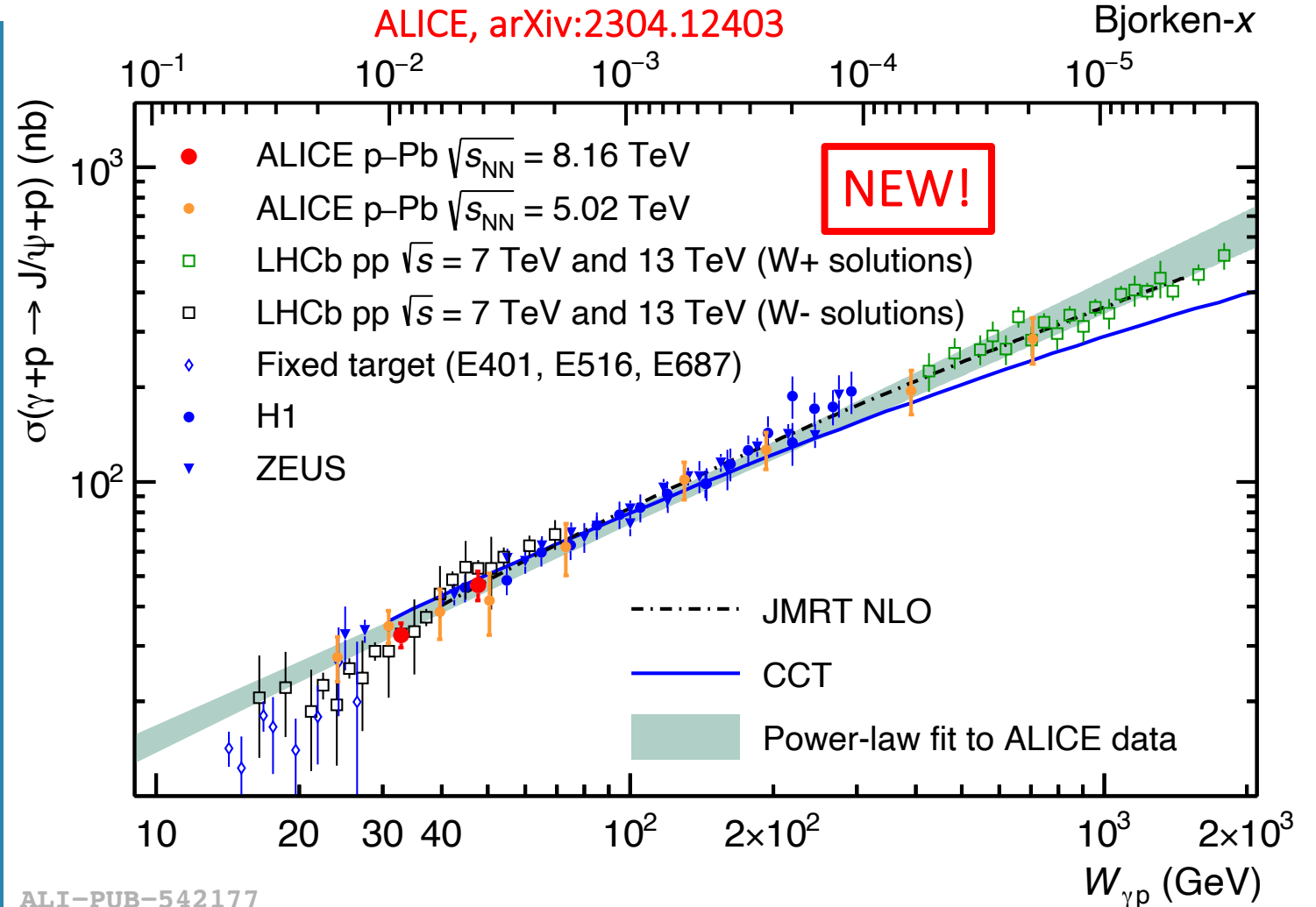
ALICE, Eur. Phys. J. C 81 (2021) 712

- 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 dipole-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 UPC p-Pb

- 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. B 766 (2017) 186–191]

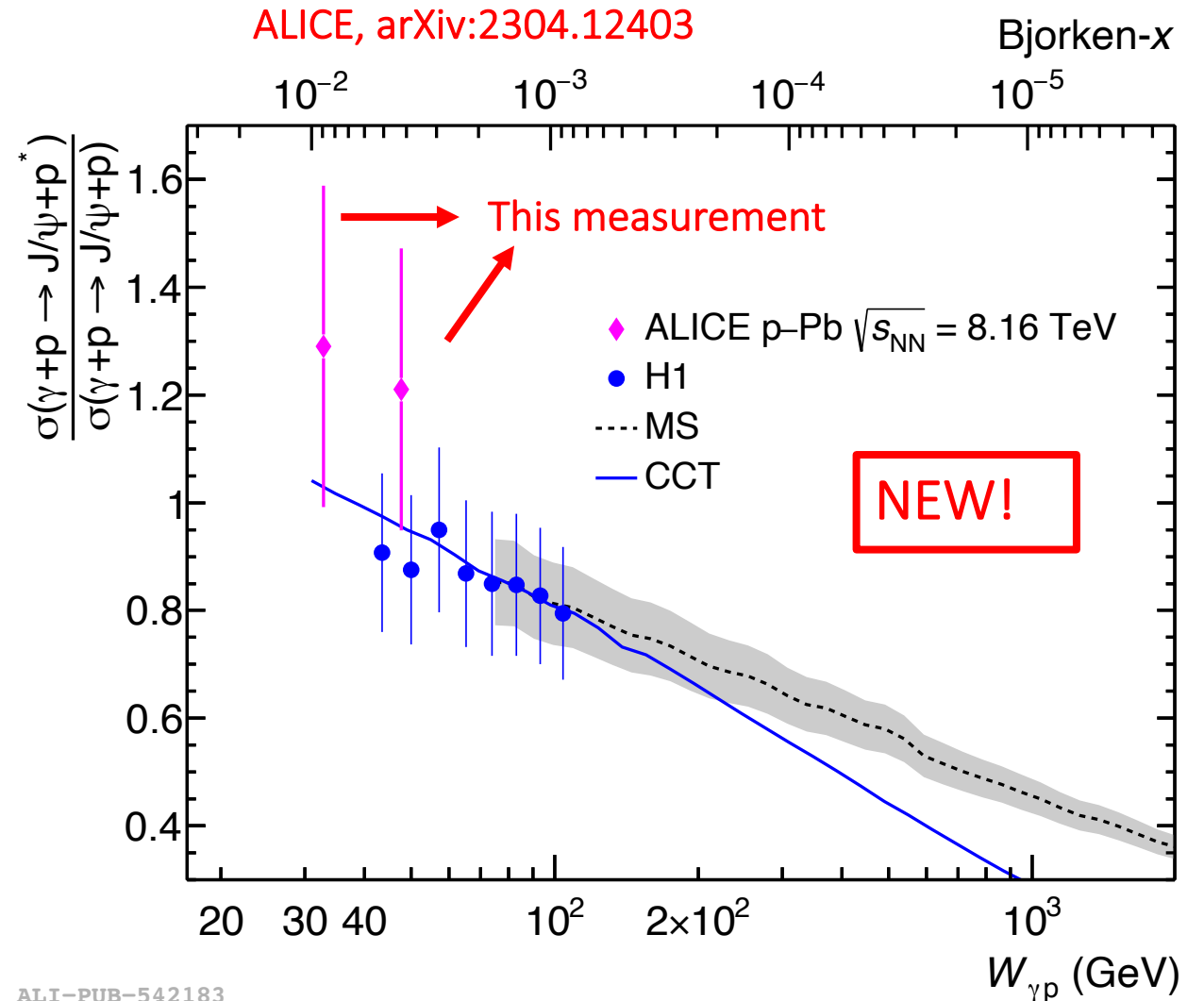


ALI-PUB-542177

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

- 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]



ALI-PUB-542183