ALICE

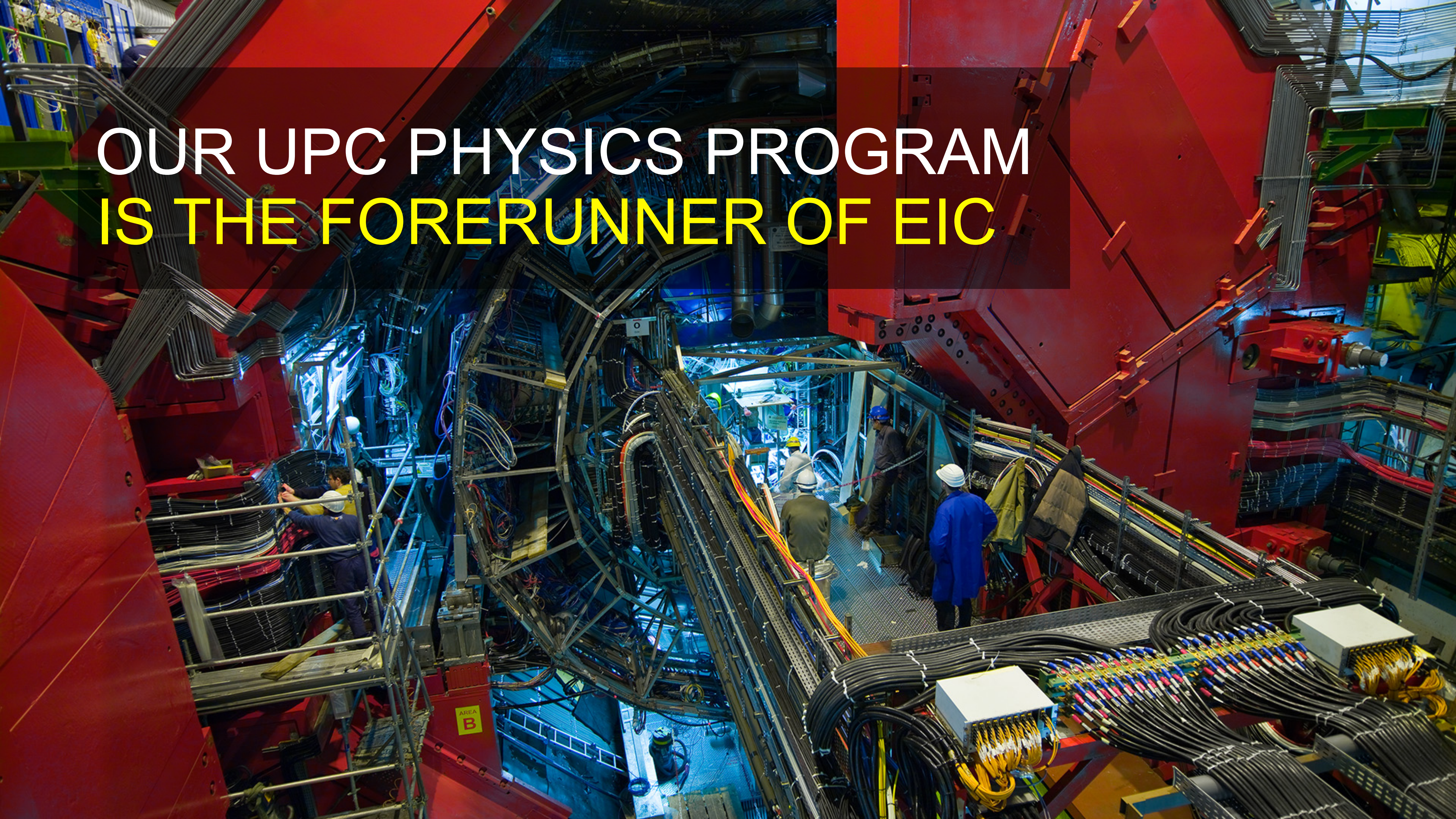
Creighton University

U.S. Department of Energy | Office of Science

Overview of recent UPC results from ALICE with a focus on incoherent measurements

Simone Ragoni

Creighton University, USA


OUR UPC PHYSICS PROGRAM
IS THE FORERUNNER OF EIC

Outline

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

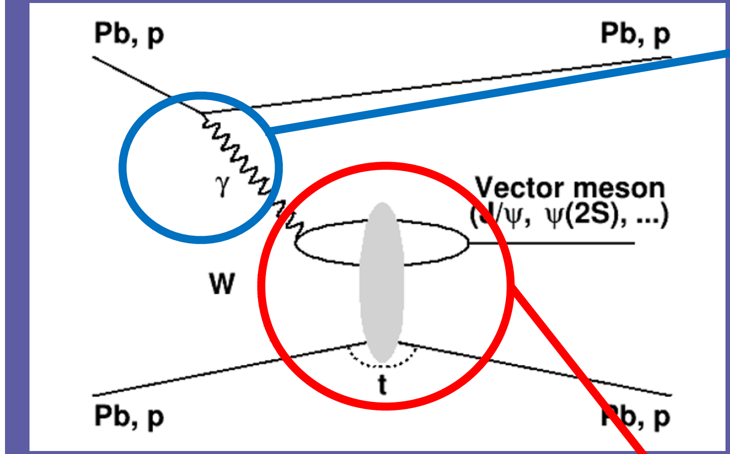
Outline

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

Introduction to ultraperipheral collisions (UPC)

Creighton UNIVERSITY

ALICE



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

Only QED involved at this vertex!

LO

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

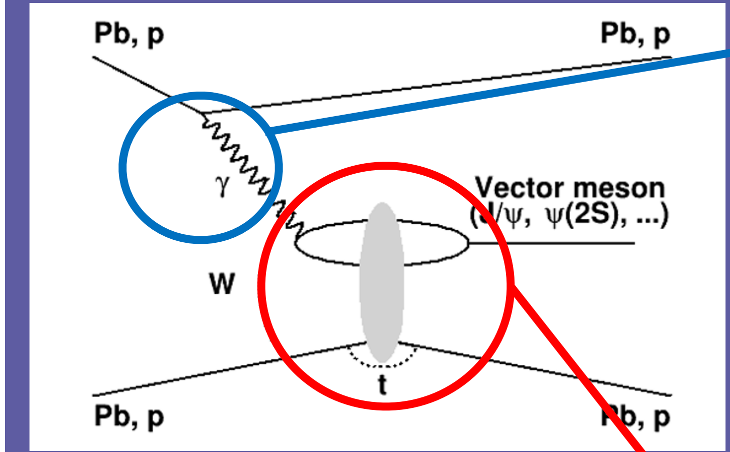
$$= [F_N^{2G}(t)]^2 \frac{\alpha_s{}^2 \Gamma_{ee}^J m_J^3}{3\alpha_{e.m.}} \pi^3 \left[\bar{x} G(\bar{x}, \bar{q}^2) \frac{2\bar{q}^2 - |q_t^J|^2}{(2\bar{q}^2)^3} \right]^2$$

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

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

- *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 ultraperipheral 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 assured by high mass states i.e. $J/\psi,\ \psi(2S)$

- *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

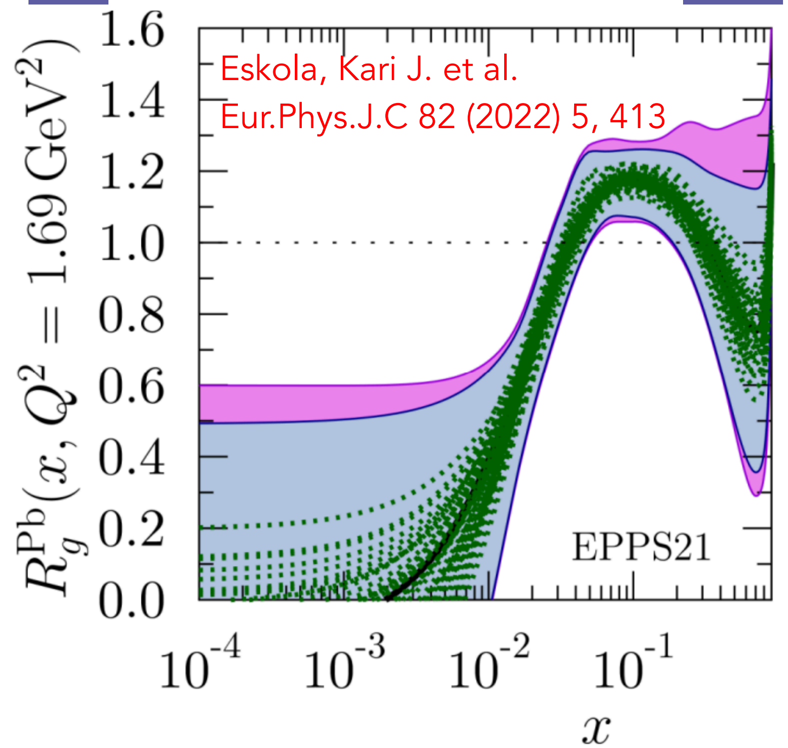
Physics of ultra-peripheral collisions (UPC)

Studying nuclear shadowing

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

Nuclear gluon PDF

Proton gluon PDF



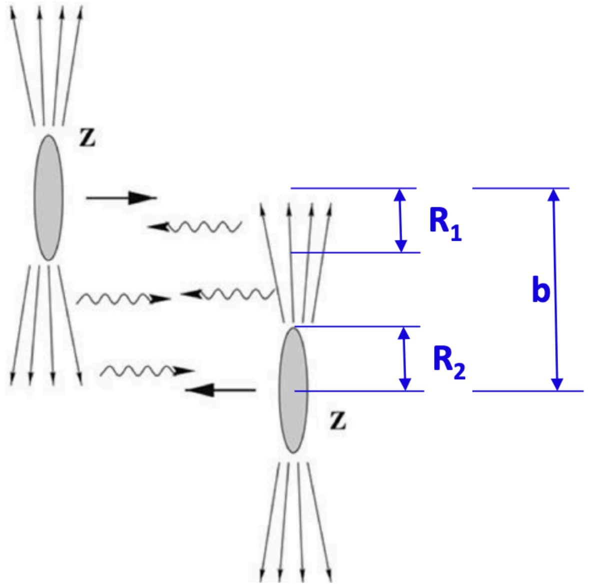
Eskola, Kari J. et al.
Eur.Phys.J.C 82 (2022) 5, 413

LO

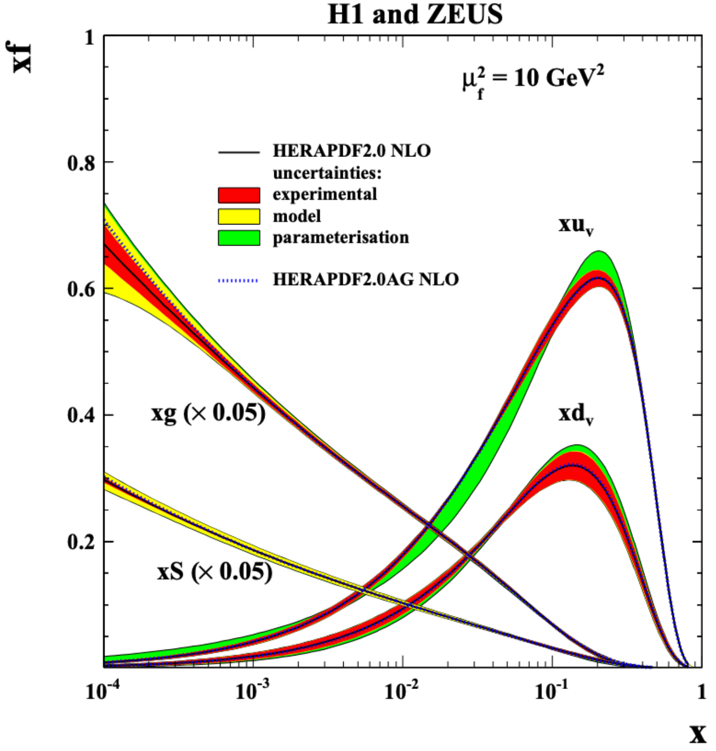
$$\frac{d\sigma^T(\gamma p \to J/\Psi + p)}{dt} = \frac{|M|^2}{16\pi s^2}$$

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

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



Looking for gluon saturation

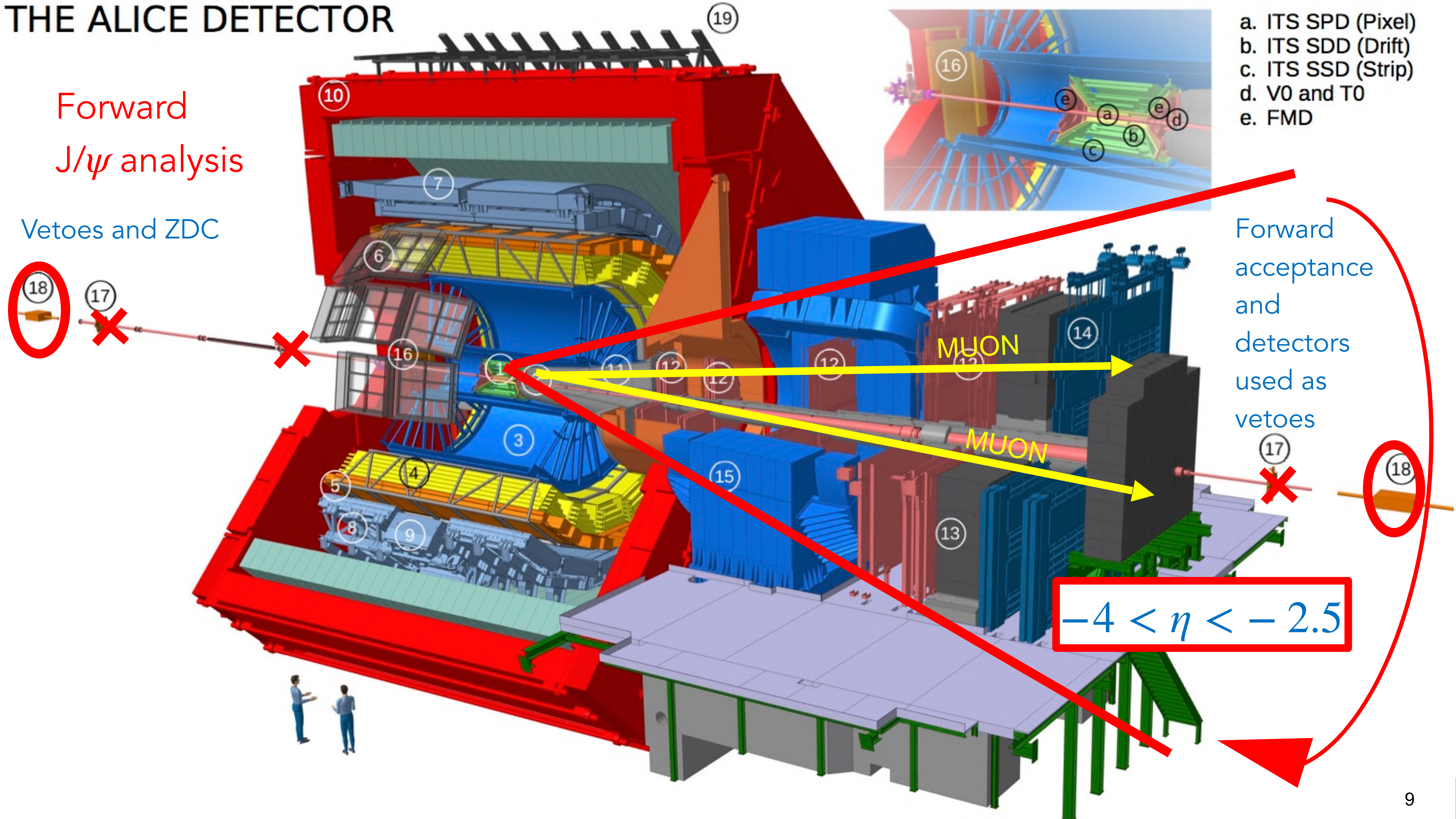


H1 and Zeus, EPCJ 75 (2015) 580

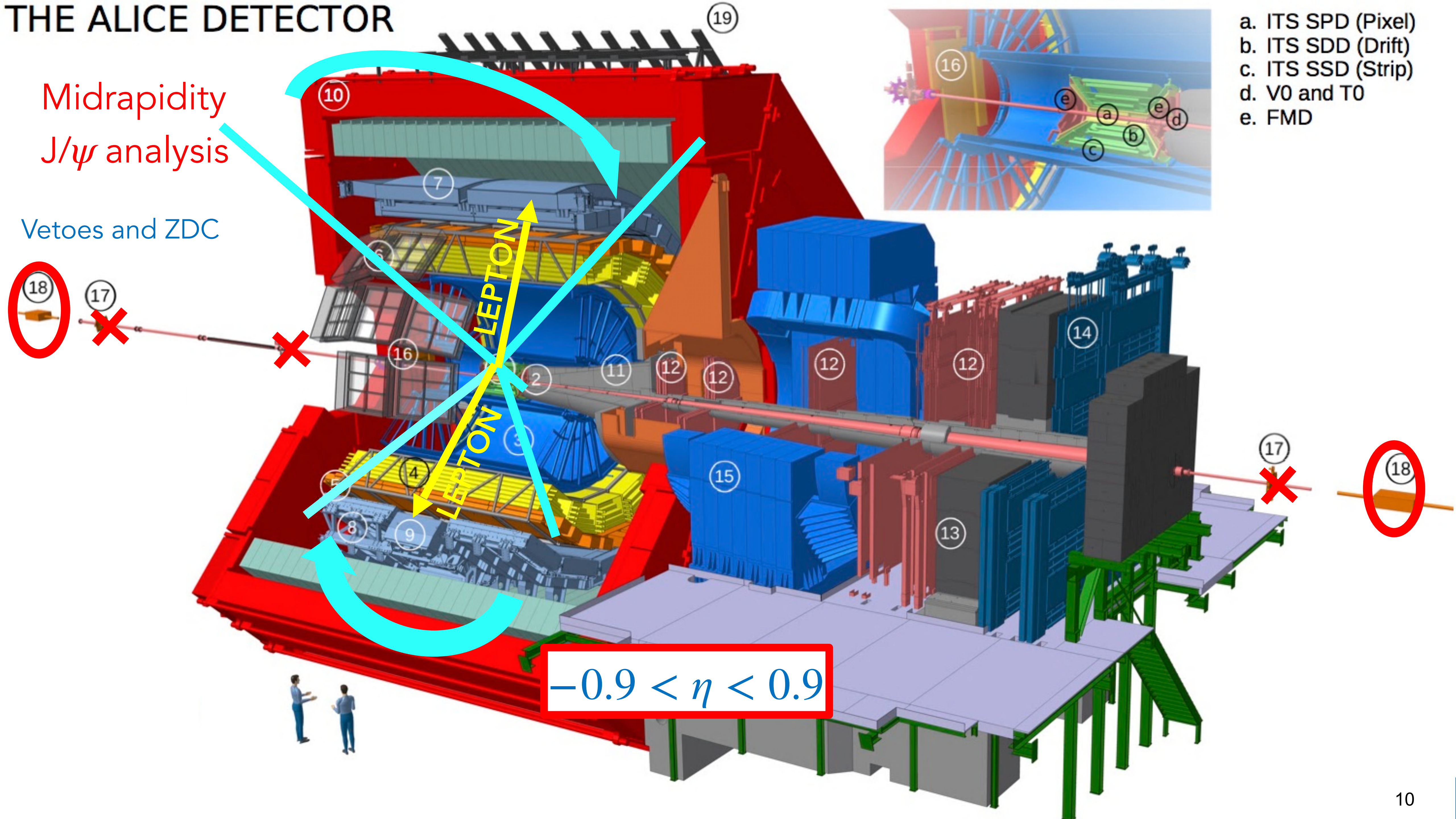
Outline

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

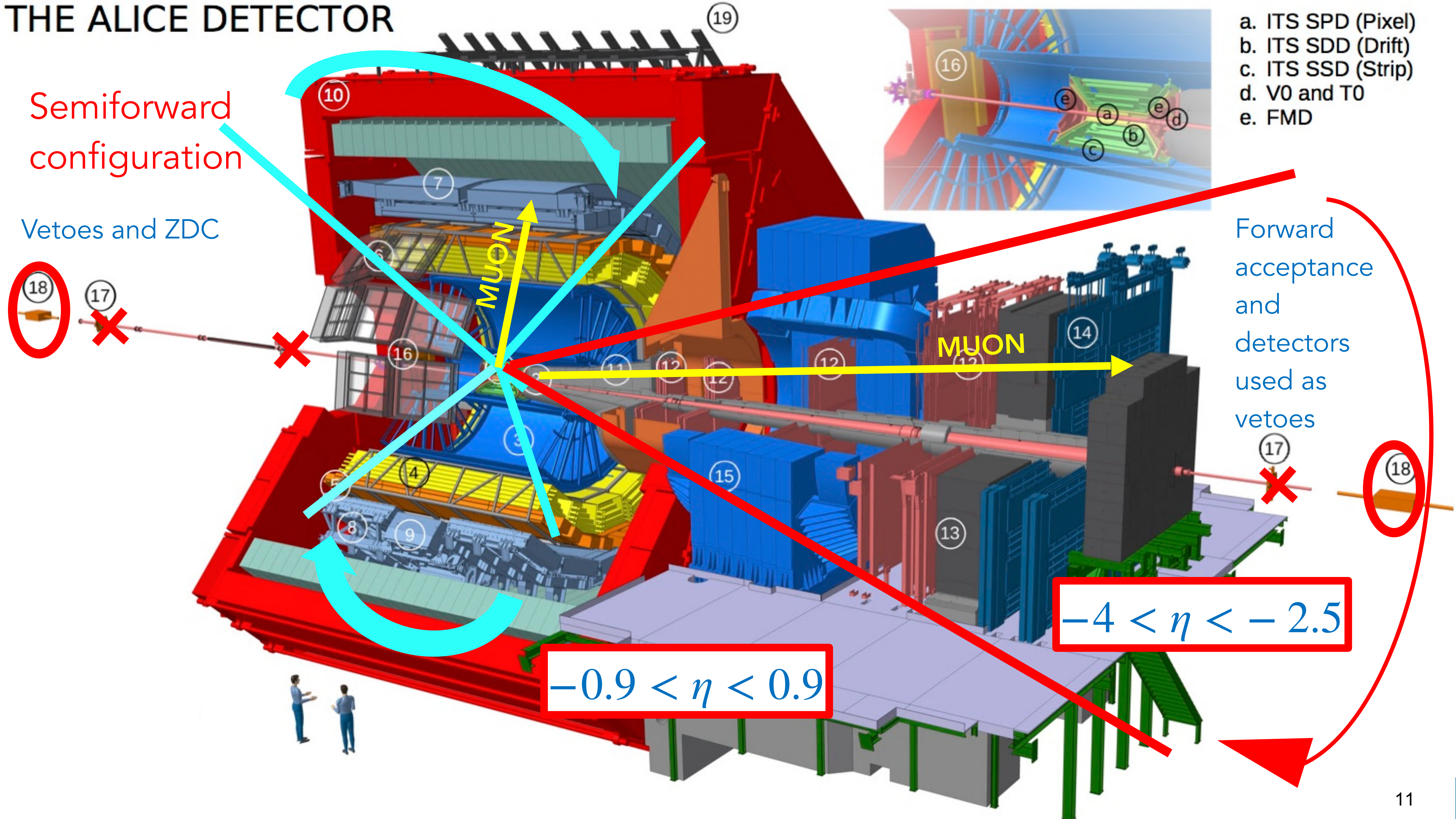
THE ALICE DETECTOR



THE ALICE DETECTOR



THE ALICE DETECTOR



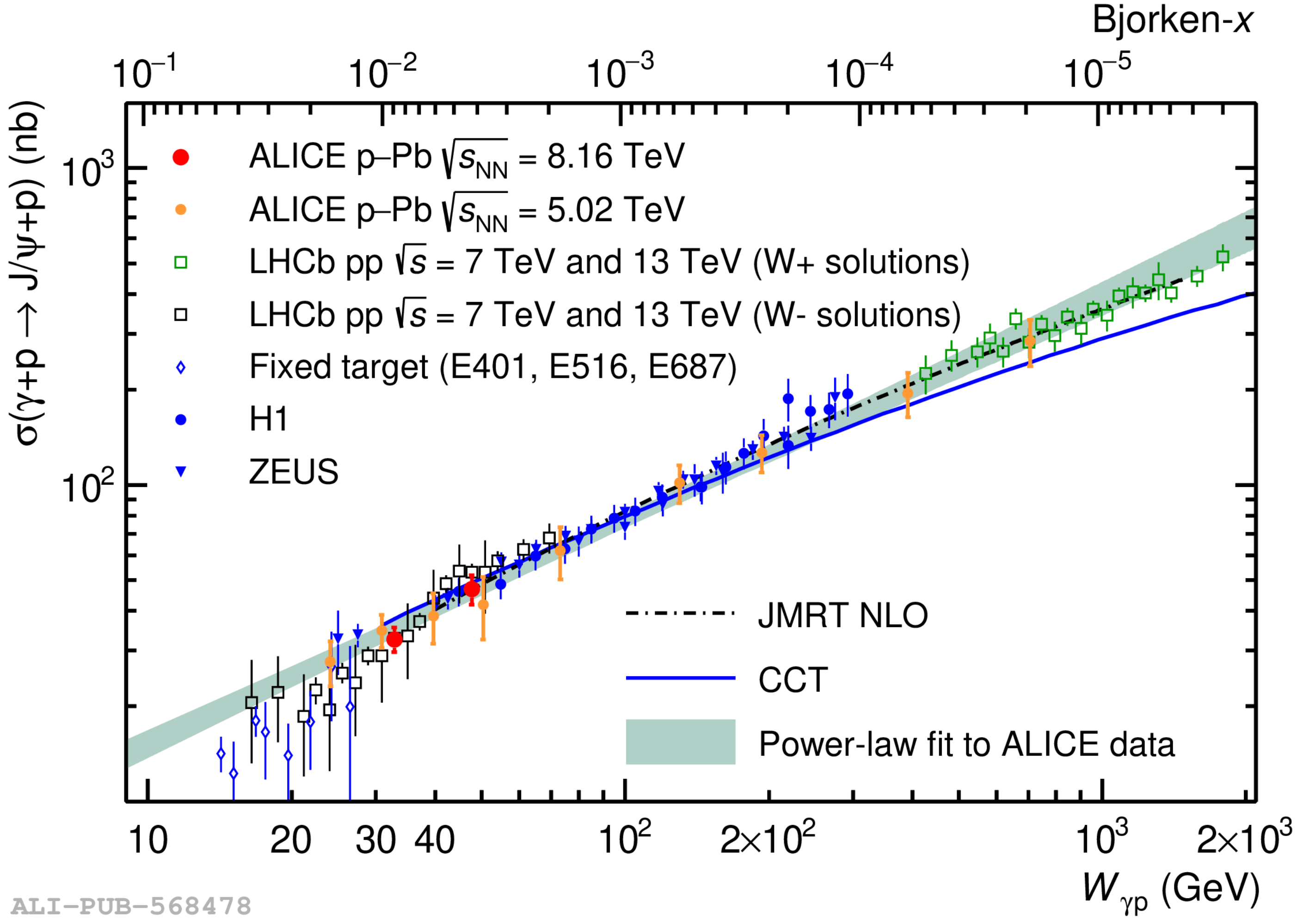
Outline

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

Exclusive J/ψ in p-Pb

- $x = e^{\pm|y|} \frac{M_{J/\psi}}{2E_p}$
- Probing Bjorken-$x \sim 10^{-5}$ with ALICE
- power-law growth of cross-sections → power-law growth of gluon distributions down to $x \sim 10^{-6}$ -> no clear signs of gluon saturation
- 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

ALICE, *Phys.Rev.D* 108 (2023) 11, 112004

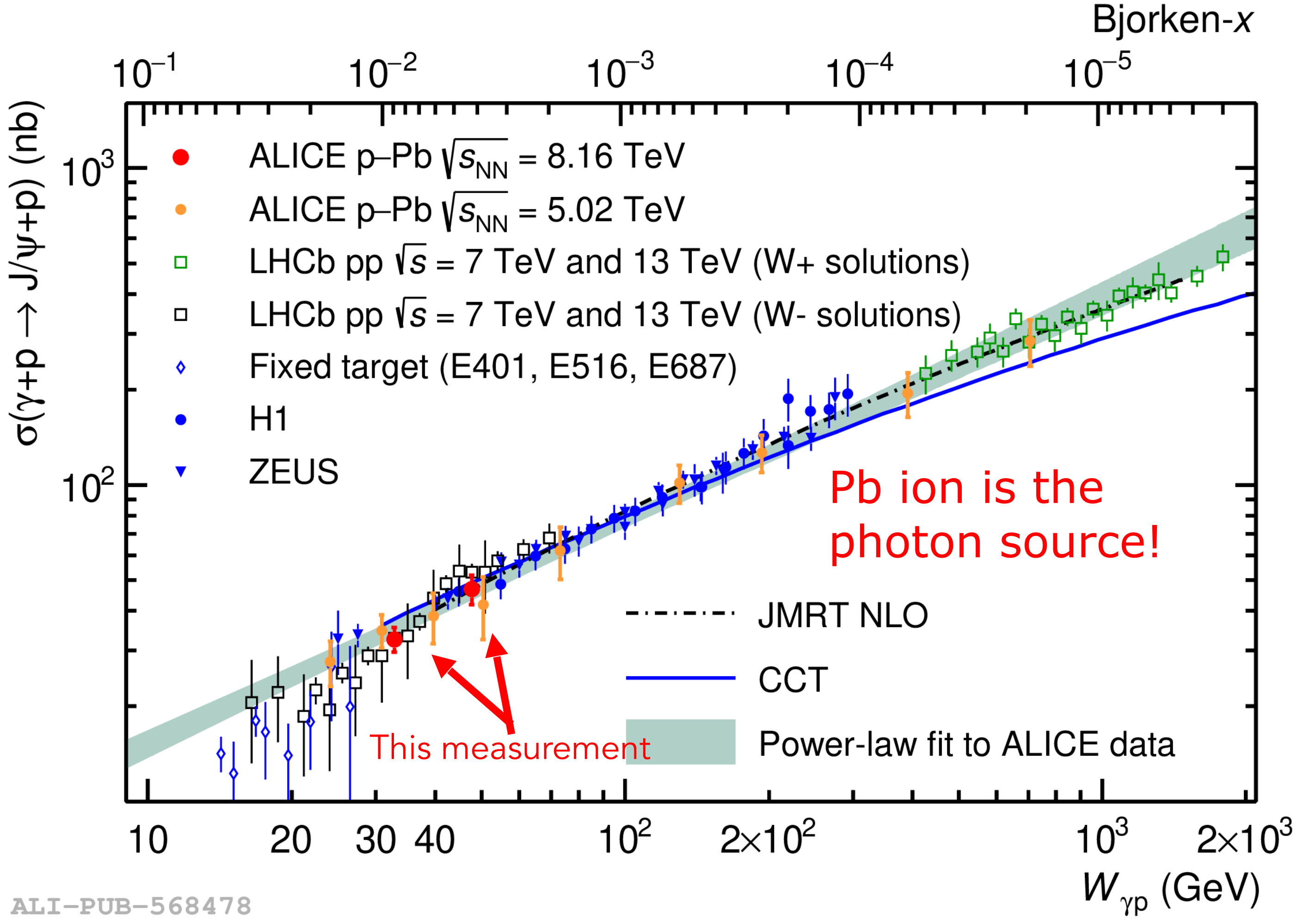


Eur. Phys. J. C (2019) 79: 402 (ALICE midrapidity and semiforward), Phys. Rev. Lett. 113 no. 23, (2014) 232504 (ALICE forward)

Exclusive J/ψ in p-Pb

- $x = e^{\pm|y|} \frac{M_{J/\psi}}{2E_p}$
- Probing Bjorken-$x \sim 10^{-5}$ with ALICE
- power-law growth of cross-sections → power-law growth of gluon distributions down to $x \sim 10^{-6}$ -> no clear signs of gluon saturation
- 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

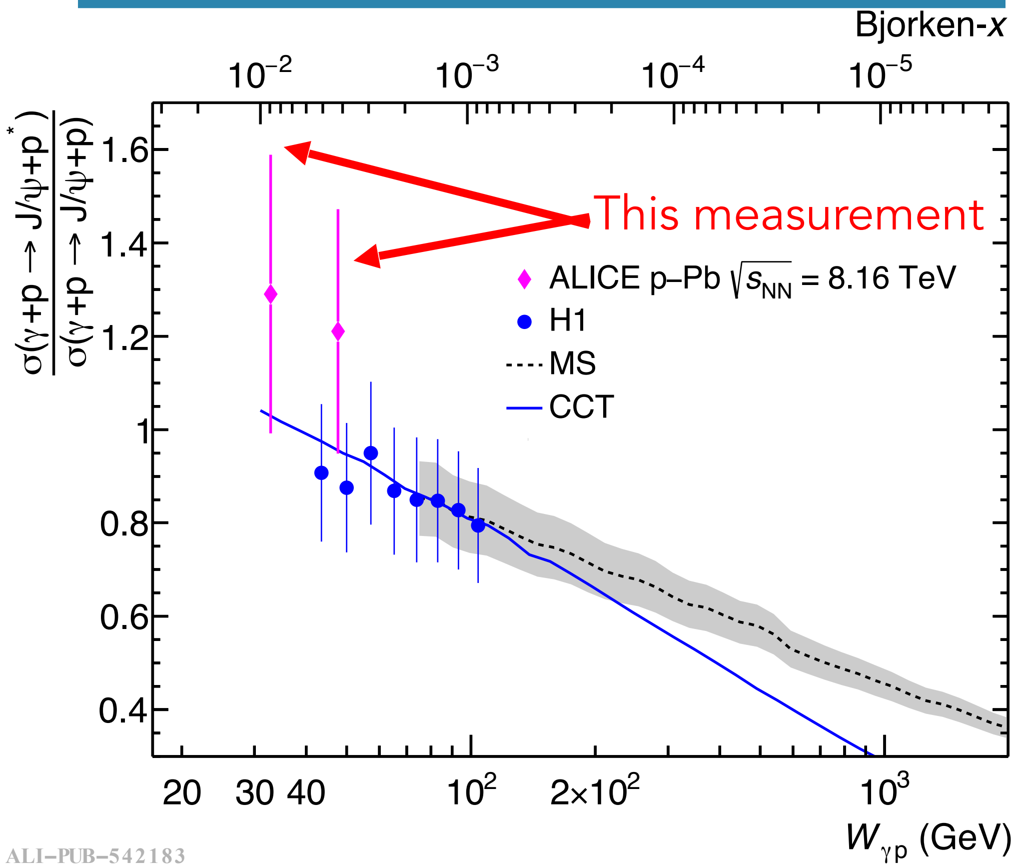
ALICE, *Phys.Rev.D* 108 (2023) 11, 112004



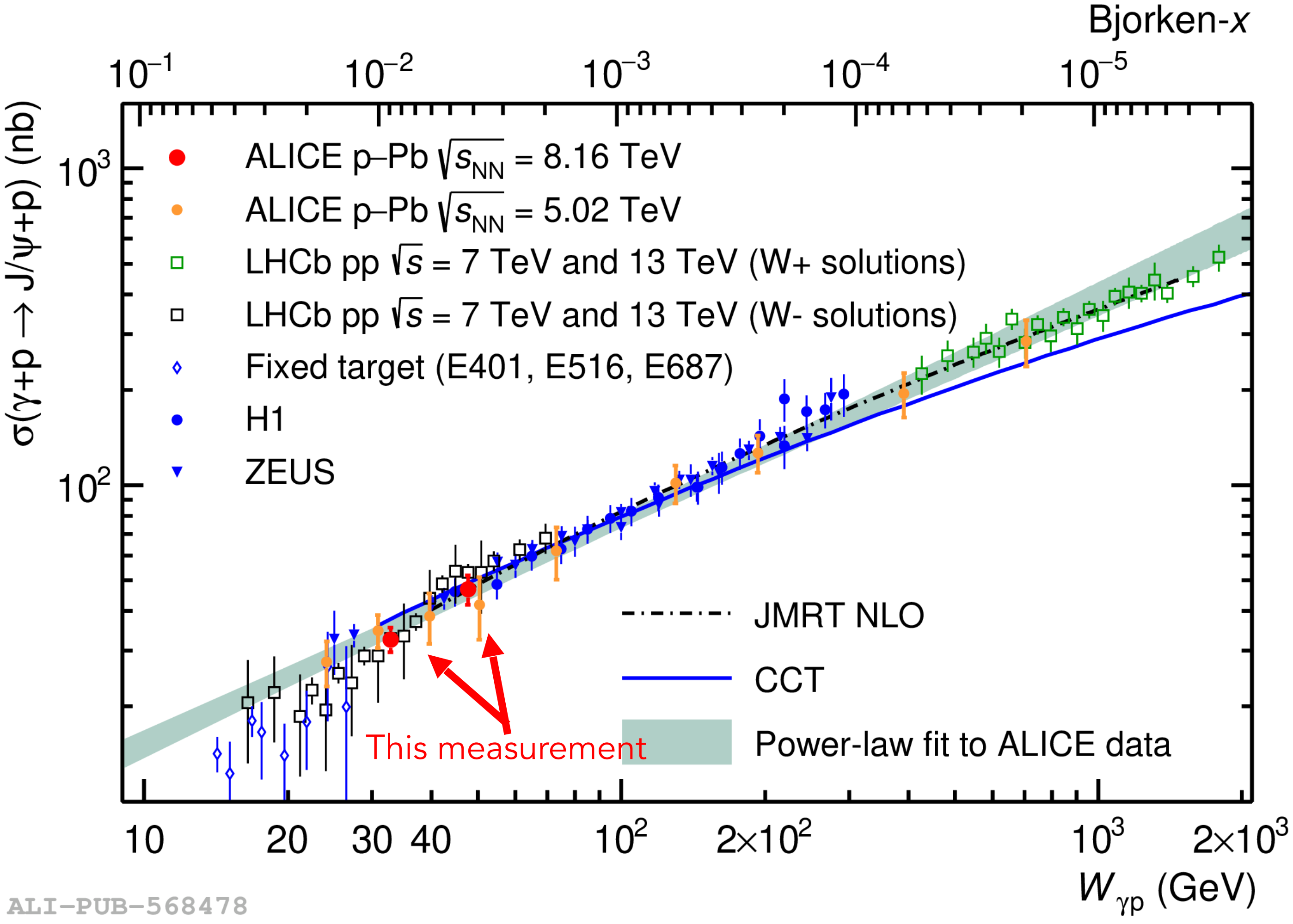
Eur. Phys. J. C (2019) 79: 402 (ALICE midrapidity and semiforward), Phys. Rev. Lett. 113 no. 23, (2014) 232504 (ALICE forward)

Exclusive and dissociative J/ψ in p-Pb

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



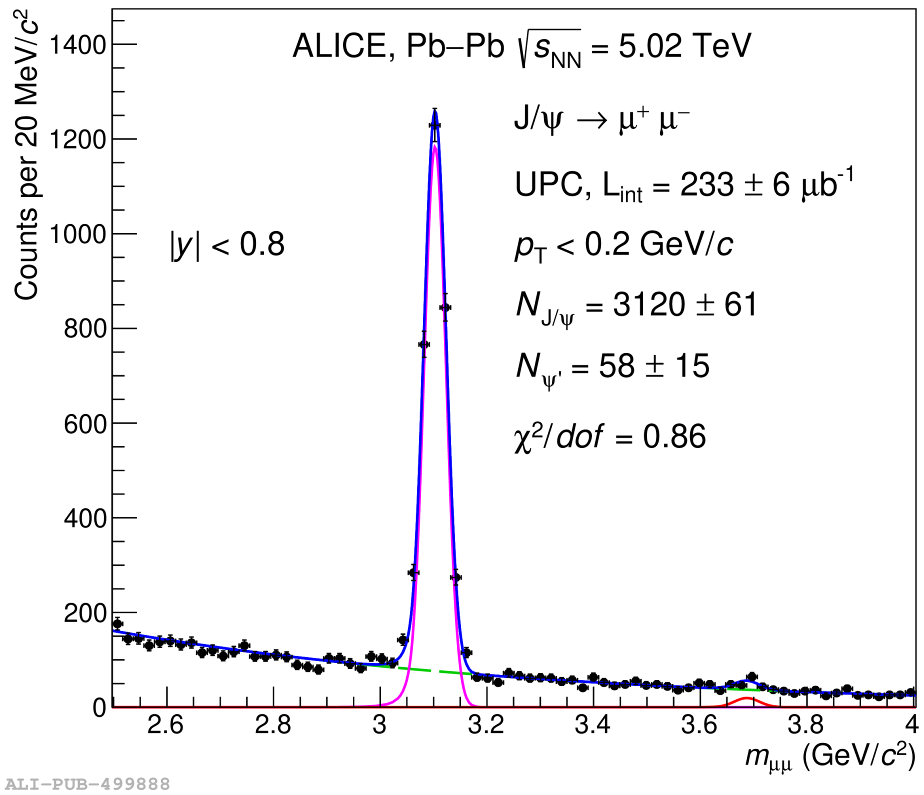
ALICE, *Phys.Rev.D* 108 (2023) 11, 112004

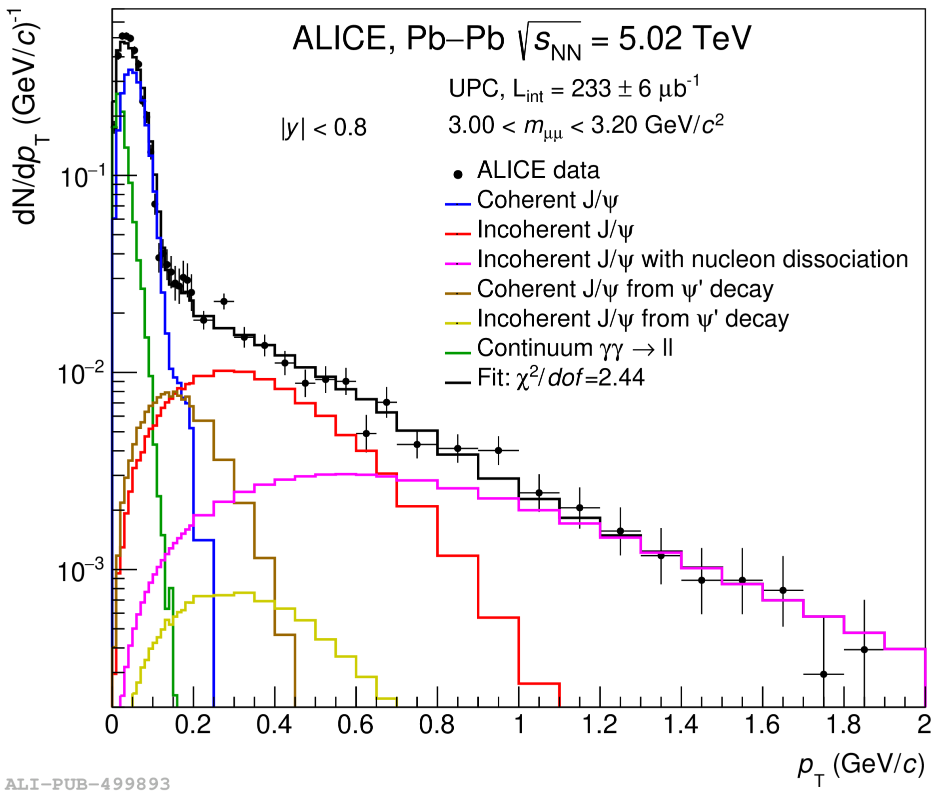


Outline

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

Coherent vs incoherent J/ψ



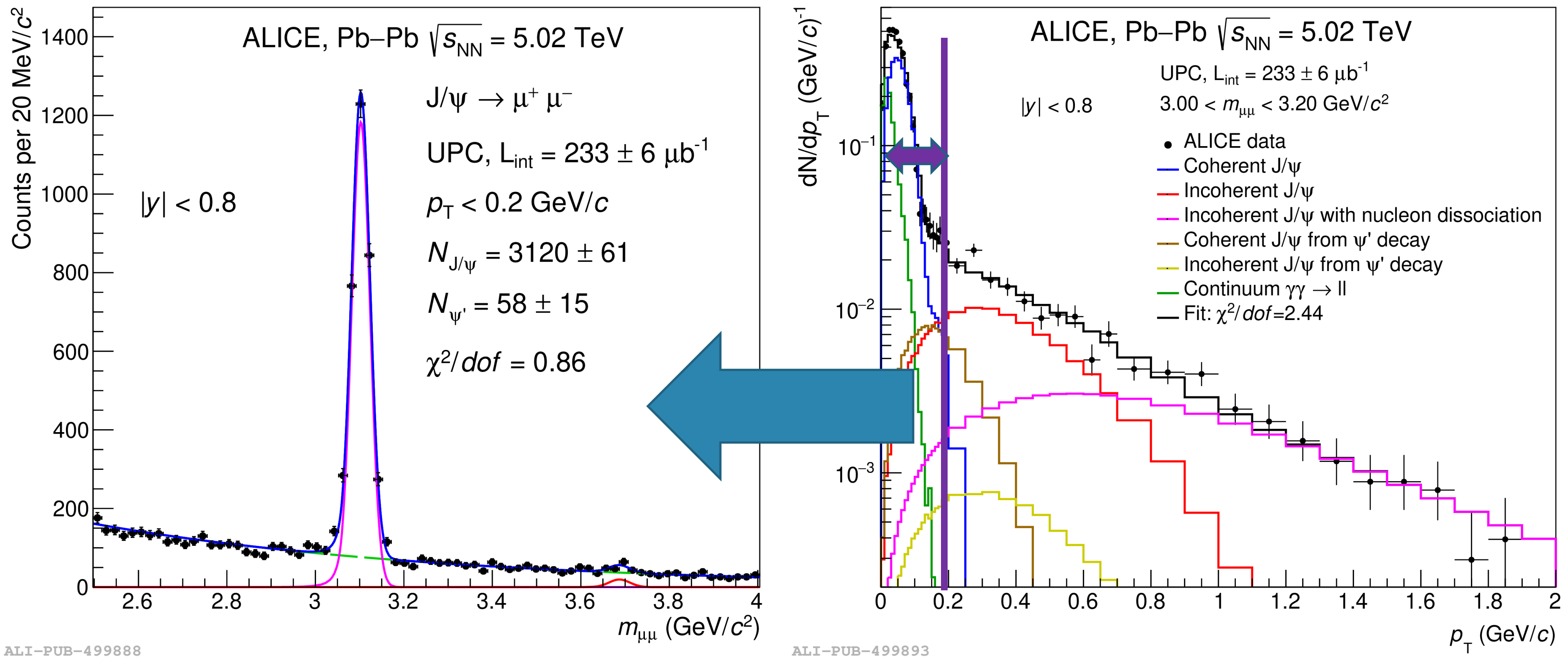


Plots at midrapidity

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

- Coherent (dimuon $p_T < 0.2$ GeV/c) – photon couples to entire nucleus *coherently*
- Incoherent J/ψ features a much wider p_T distribution – photon interacts with a single nucleon of the target nucleus

Coherent vs incoherent J/ψ



Plots at midrapidity

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

- Coherent (dimuon $p_T < 0.2$ GeV/c) – photon couples to entire nucleus *coherently*
- Incoherent J/ψ features a much wider p_T distribution – photon interacts with a single nucleon of the target nucleus

Studying coherent J/ψ in terms of...

1. Angular distributions
2. y
3. p_{T}^2
4. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

Studying coherent J/ψ in terms of…

1. Angular distributions

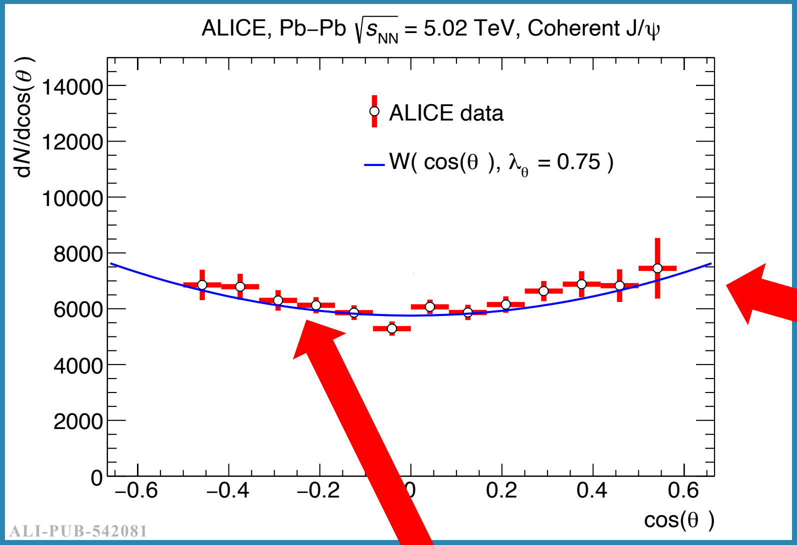
2. y

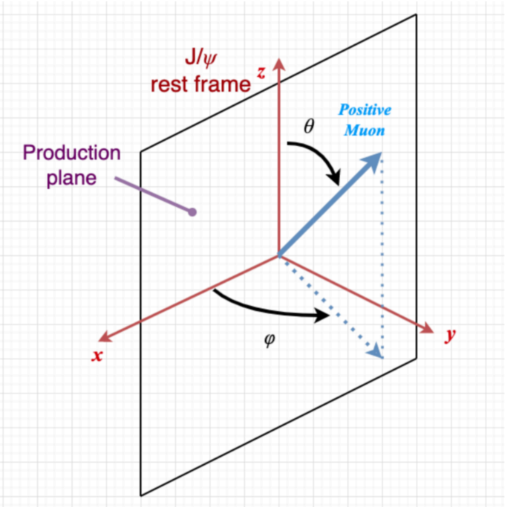
3. p_{T}^{2}

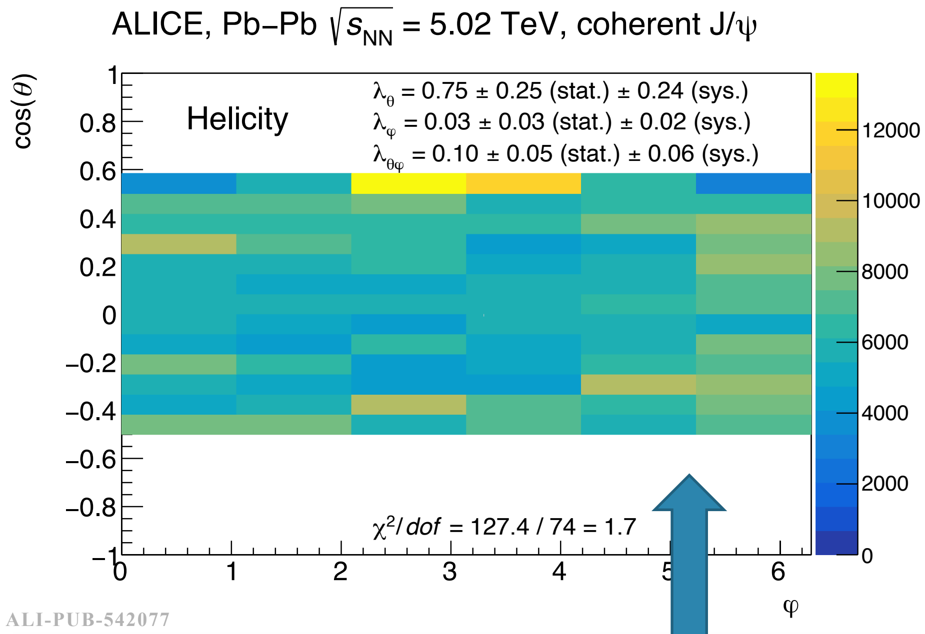
4. $W_{\gamma Pb,n}^{2} = m\sqrt{s_{NN}}e^{-y}$

Coherent J/ψ polarisation

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

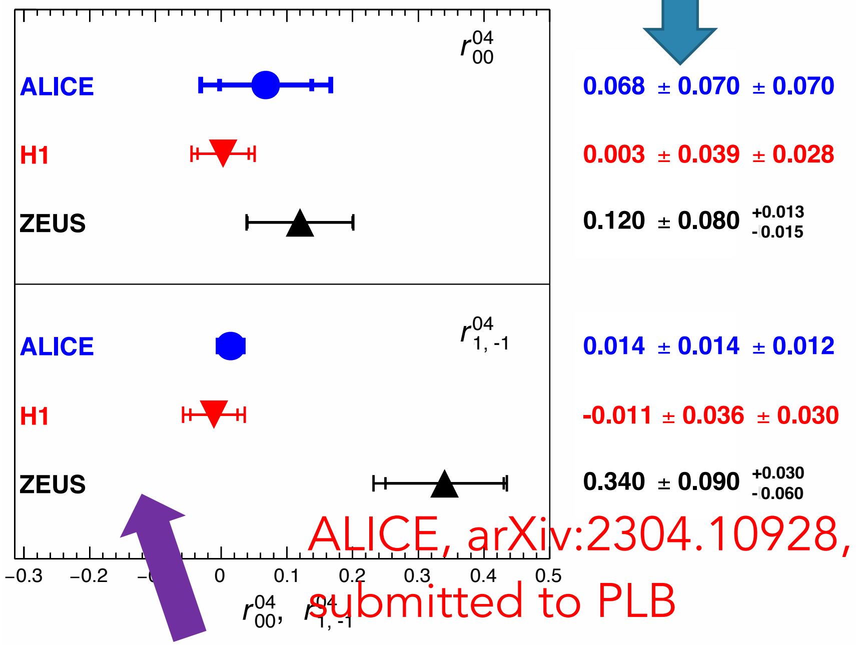






$$r_{00}^{04} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$

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



Upward parabolic shape in $\cos(\theta)$ typical of transverse polarisation

ALICE, arXiv:2304.10928, submitted to PLB

Results with the spin-density matrix elements

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

Studying coherent J/ψ in terms of…

1. Angular distributions

2. y

3. p_{T}^2

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

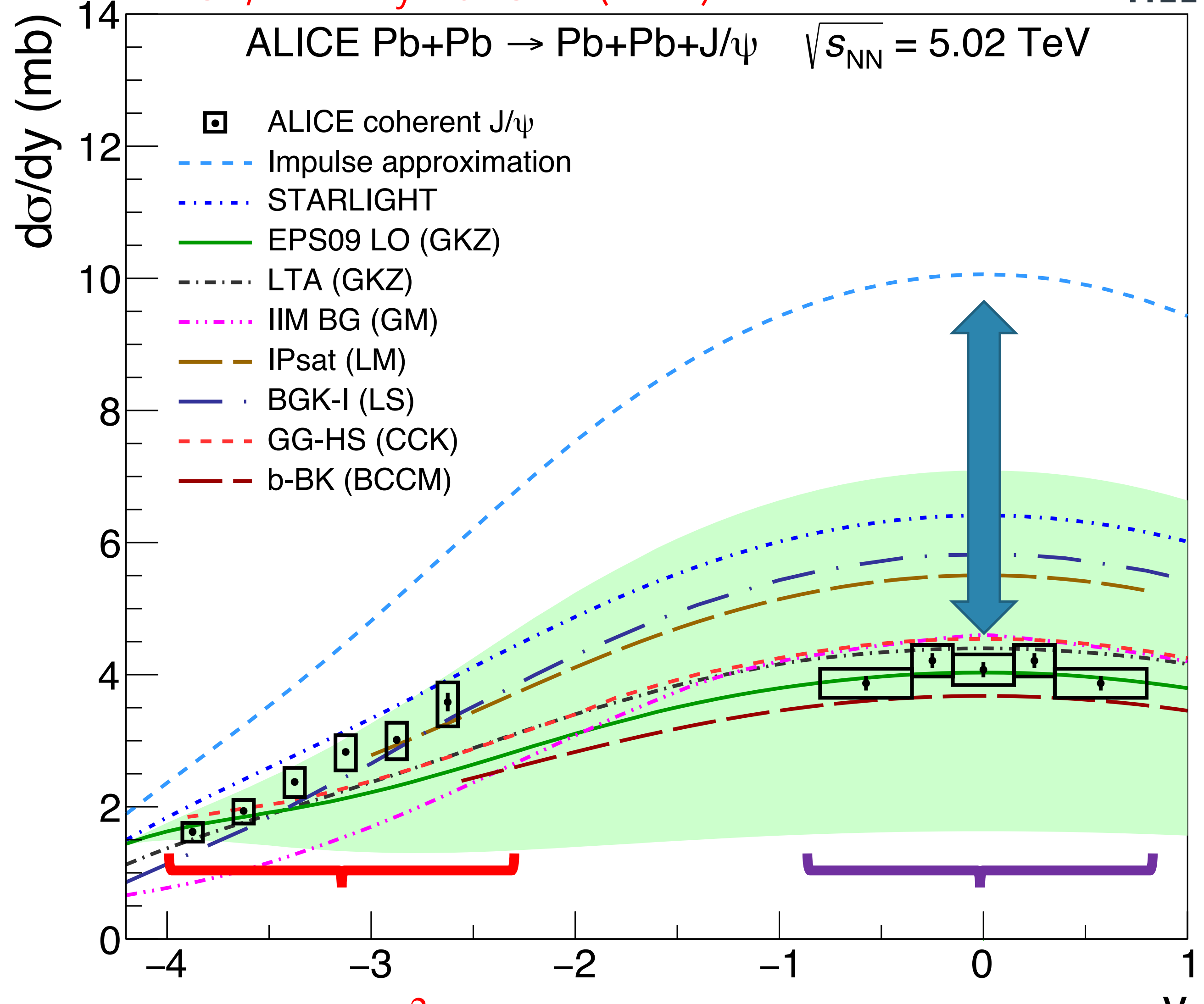
Coherent J/ψ cross section

- ALICE data exhibit moderate nuclear shadowing
- Nuclear suppression factor

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

- 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



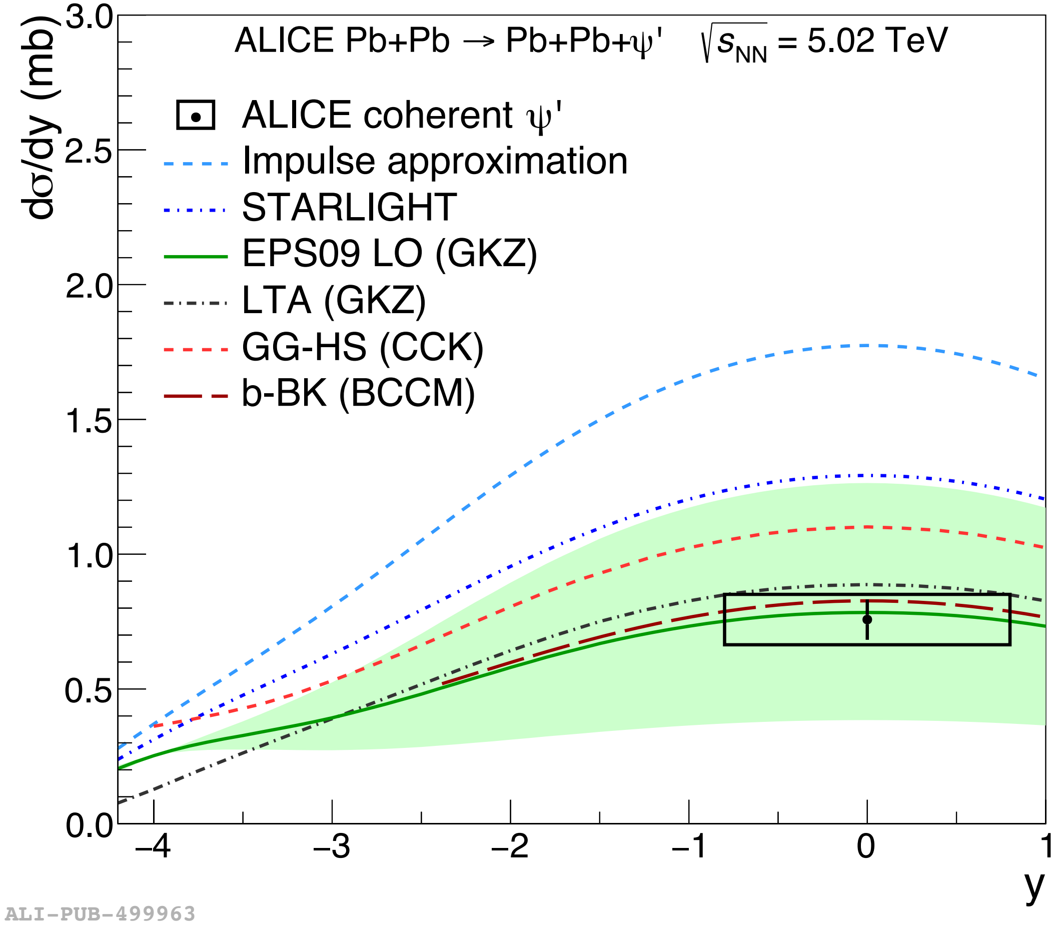
$x \sim 10^{-2}$ (95%)

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

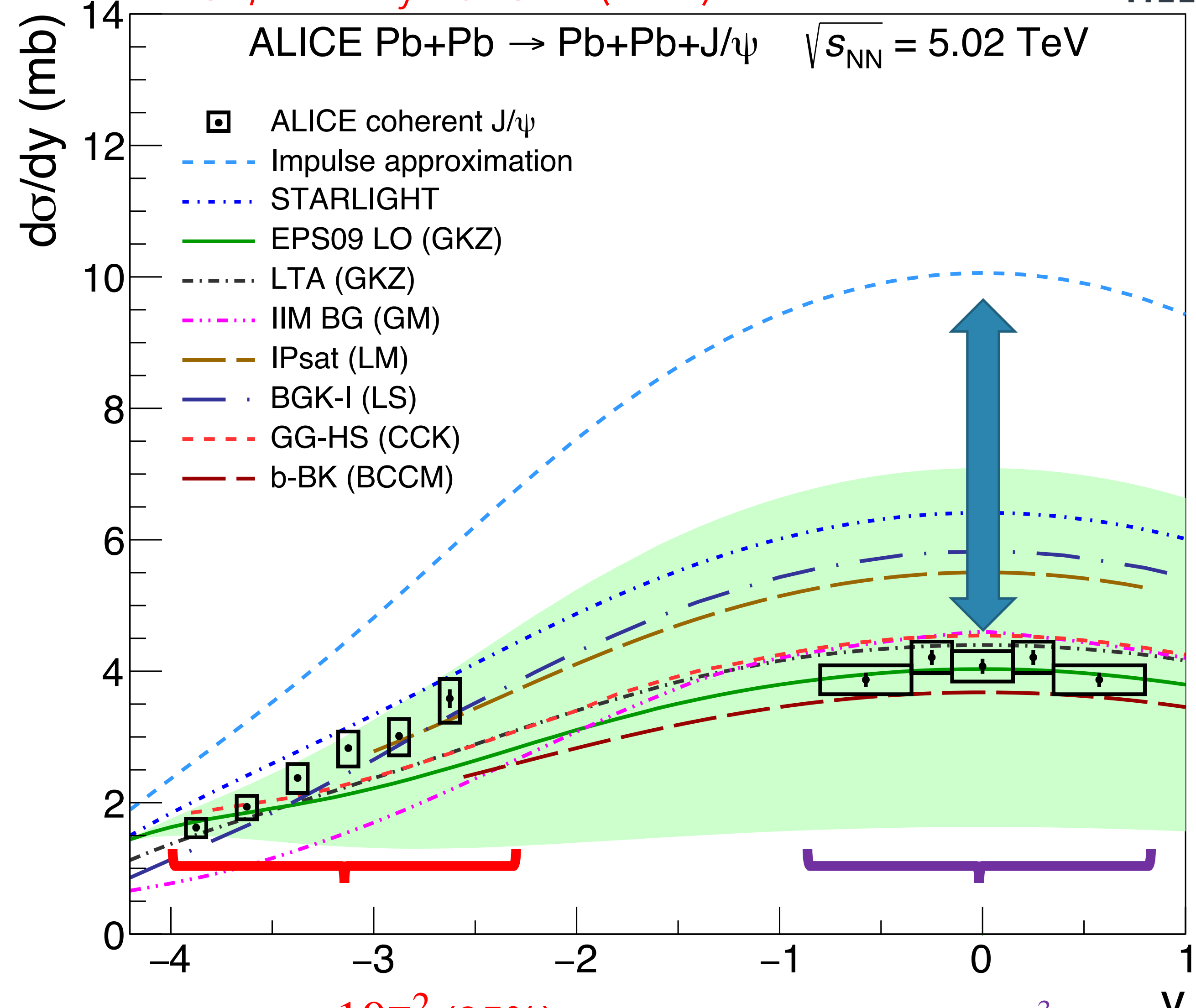
$x \sim 10^{-3}$

Coherent J/ψ and ψ′ cross section

$$S_{Pb}(y \sim 0, \psi') = \sqrt{\frac{d\sigma}{dy}_{data} \Big/ \frac{d\sigma}{dy}_{IA}} = 0.66 \pm 0.06$$



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



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

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

$x \sim 10^{-3}$

Studying coherent J/ψ in terms of...

1. Angular distributions
2. y
3. p_{T}^2
4. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

Coherent J/ψ *t*-dependence

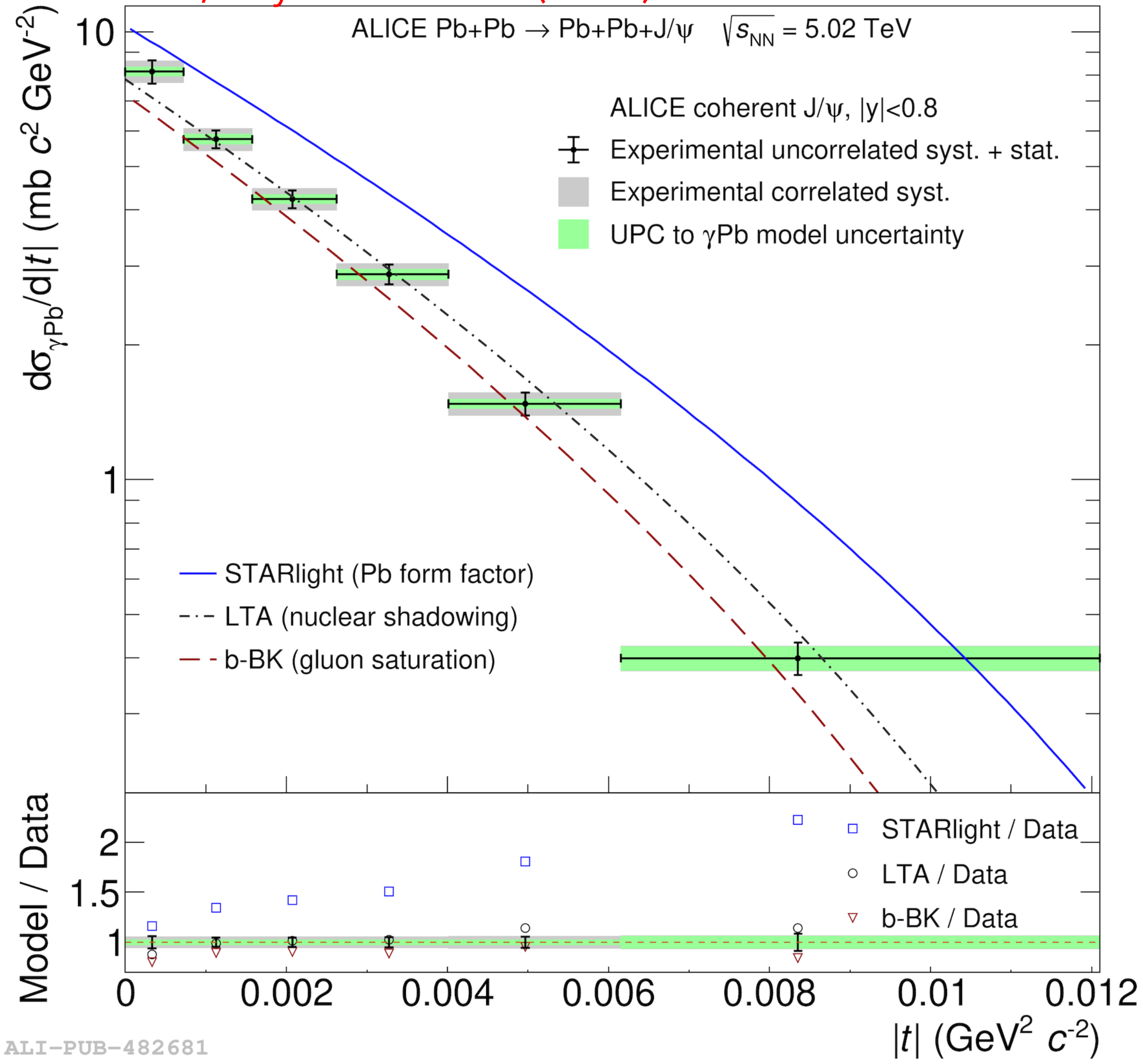
- From p_T^2-dependent photoproduction to $|t|$-dependent photonuclear production

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

- 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
- Run 3 data will also allow to push further in $|t|$

$0 < |t| < 0.012\ \mathrm{GeV}^2$

ALICE, Phys.Lett.B 817 (2021) 13628

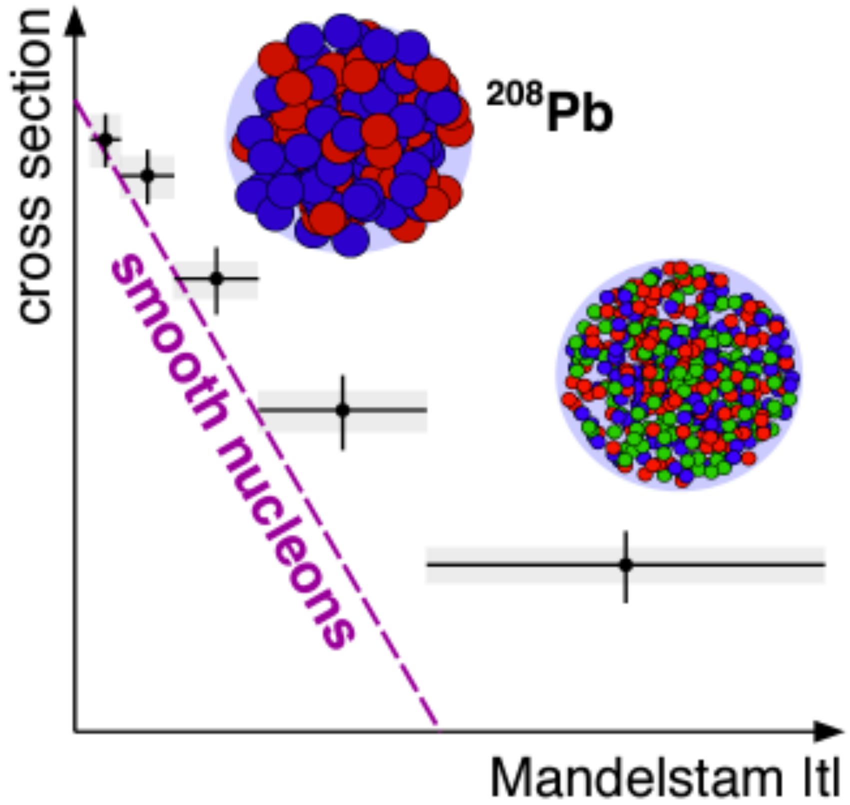


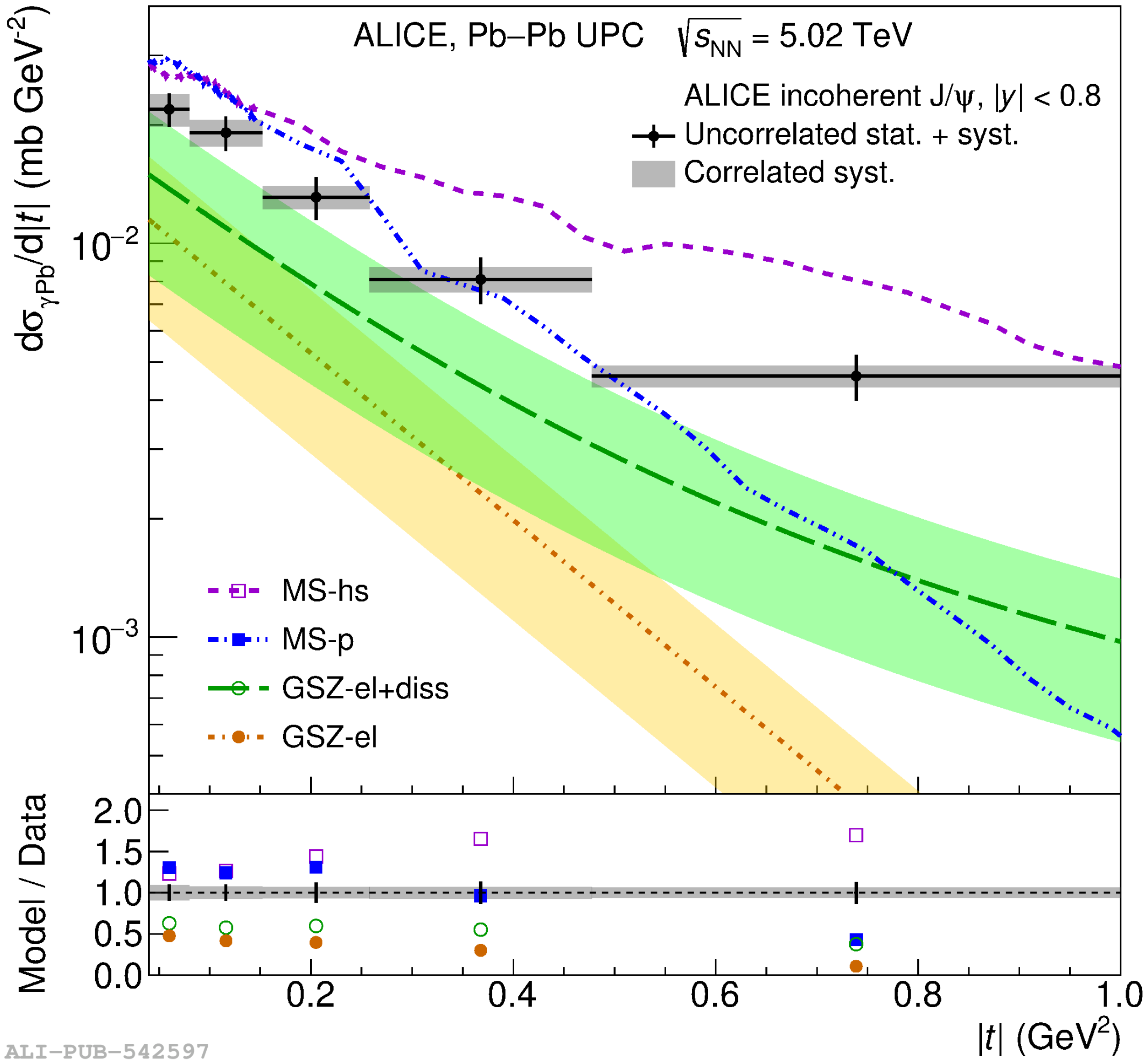
Incoherent J/ψ *t*-dependence

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

ALICE, *PRL* 132 (2024) 16, 162302

- Gluonic subnucleon fluctuations needed to describe the data
- First measurement of this kind ever!
- Models fail to predict normalisation





Complete view of J/ψ *t*-dependence

- The first observation of subnucleonic structure in the Pb target using UPCs
- ALICE covers three orders of magnitude in $|t|$ with a HERA-like accuracy

H. Mäntysaari, B. Schenke / Physics Letters B 772 (2017) 832–838

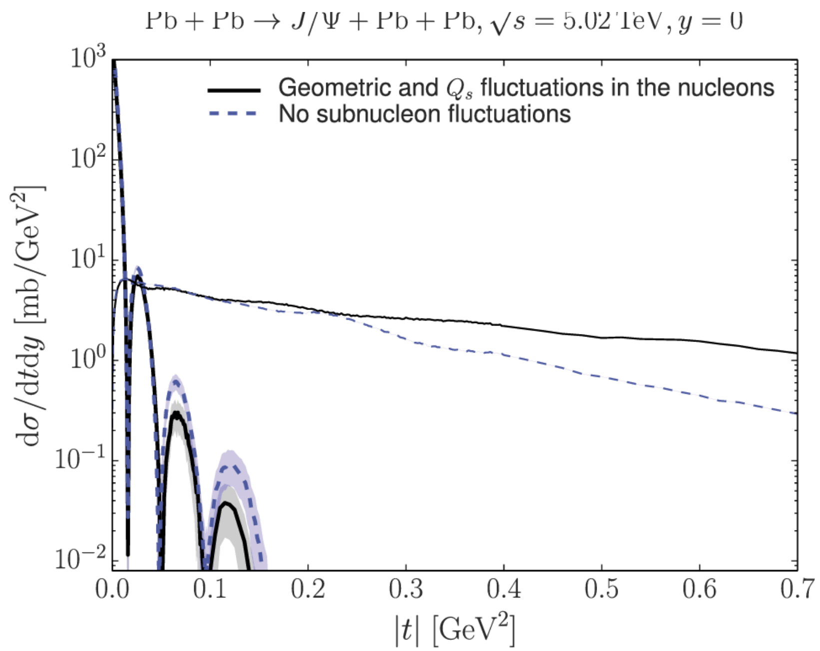
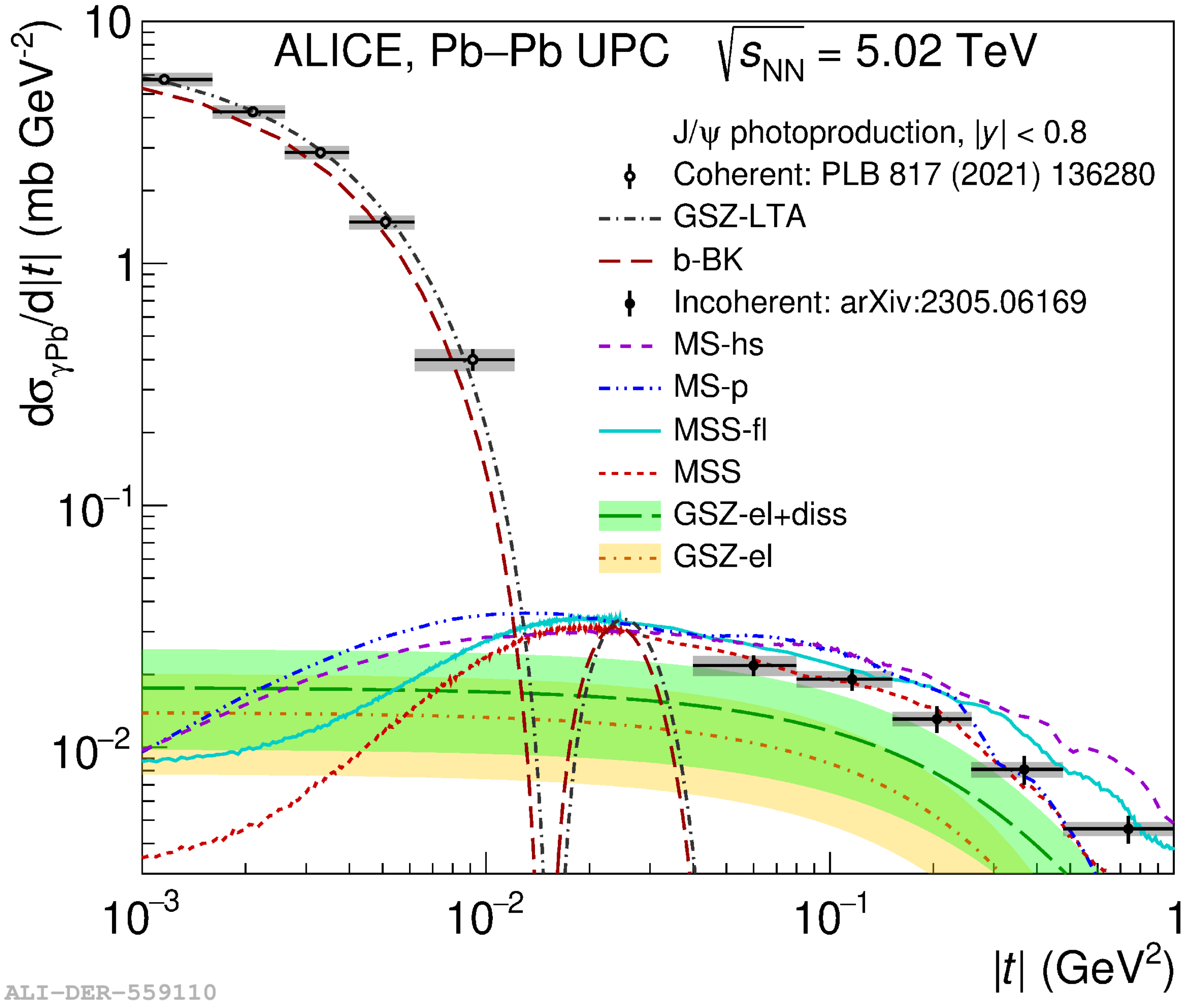


Fig. 1. Coherent (thick) and incoherent (thin lines) diffractive J/Ψ production cross section as a function of t, with (solid lines) and without (dashed lines) subnucleonic fluctuations. The band shows statistical uncertainty of the calculation.



Studying coherent J/ψ in terms of...

1. Angular distributions
2. y
3. p_{T}^2
4. $W_{\gamma Pb,n}^2 = m\sqrt{s_{NN}}e^{-y}$

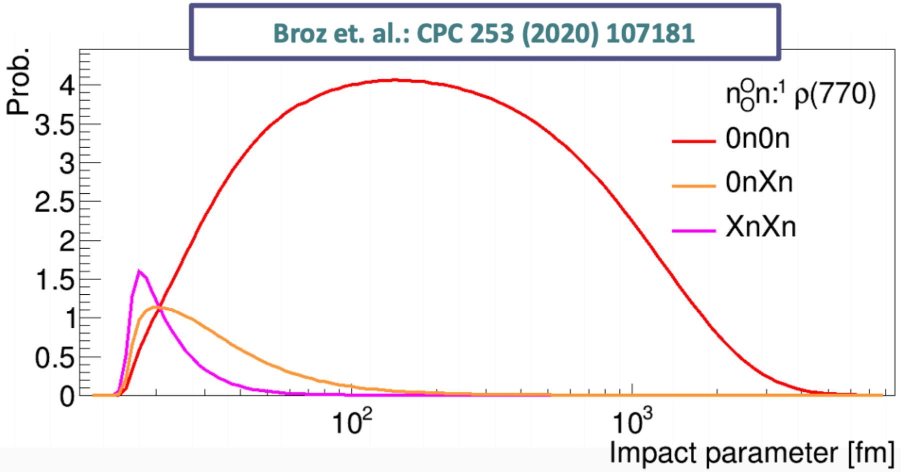
Outline

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

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}



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

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

- Additional photon exchanges may lead to neutron emission

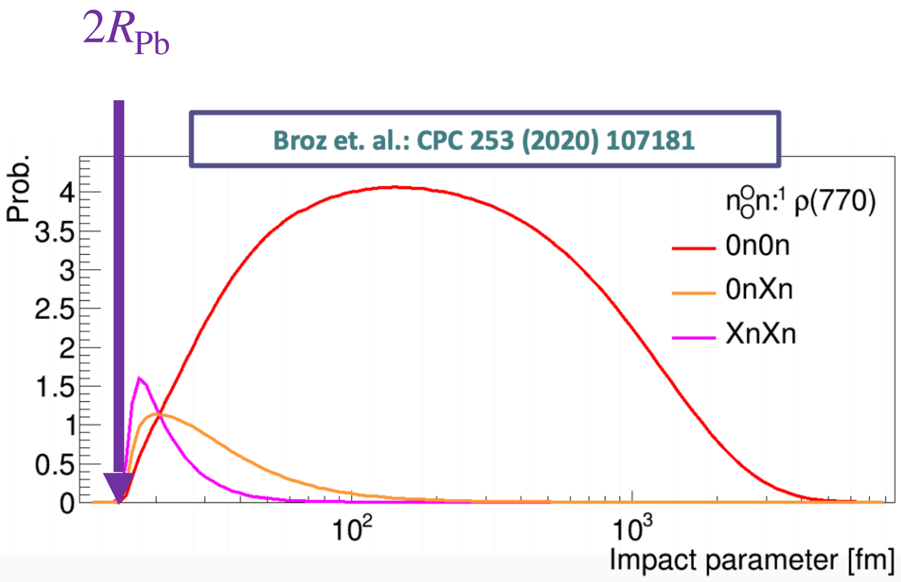
Guzey et al., Eur.Phys.J.C 74 (2014) 7, 2942

- 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}



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

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

- Additional photon exchanges may lead to neutron emission

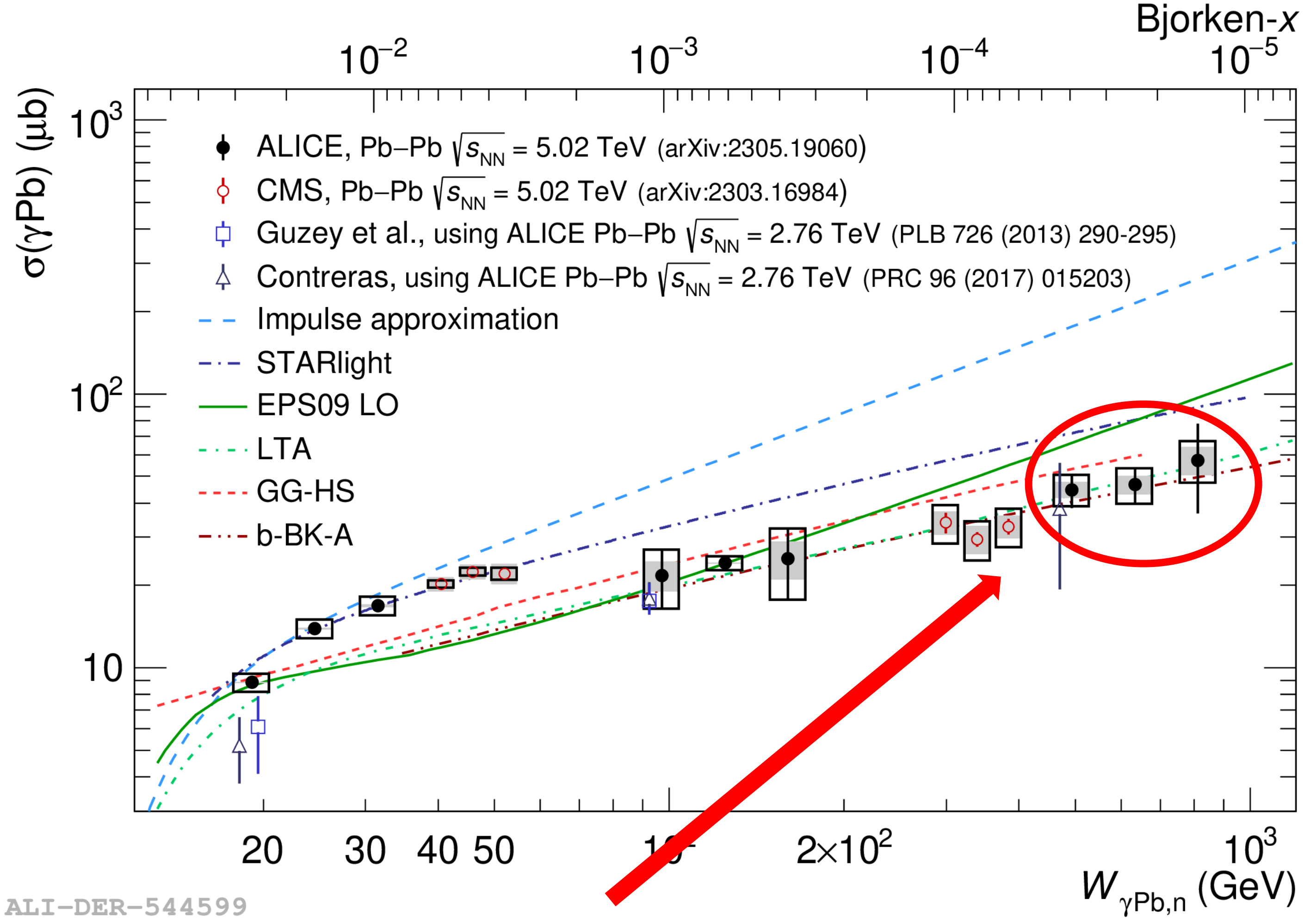
Guzey et al.,
Eur.Phys.J.C 74 (2014) 7, 2942

- 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

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, *JHEP* 10 (2023) 119



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

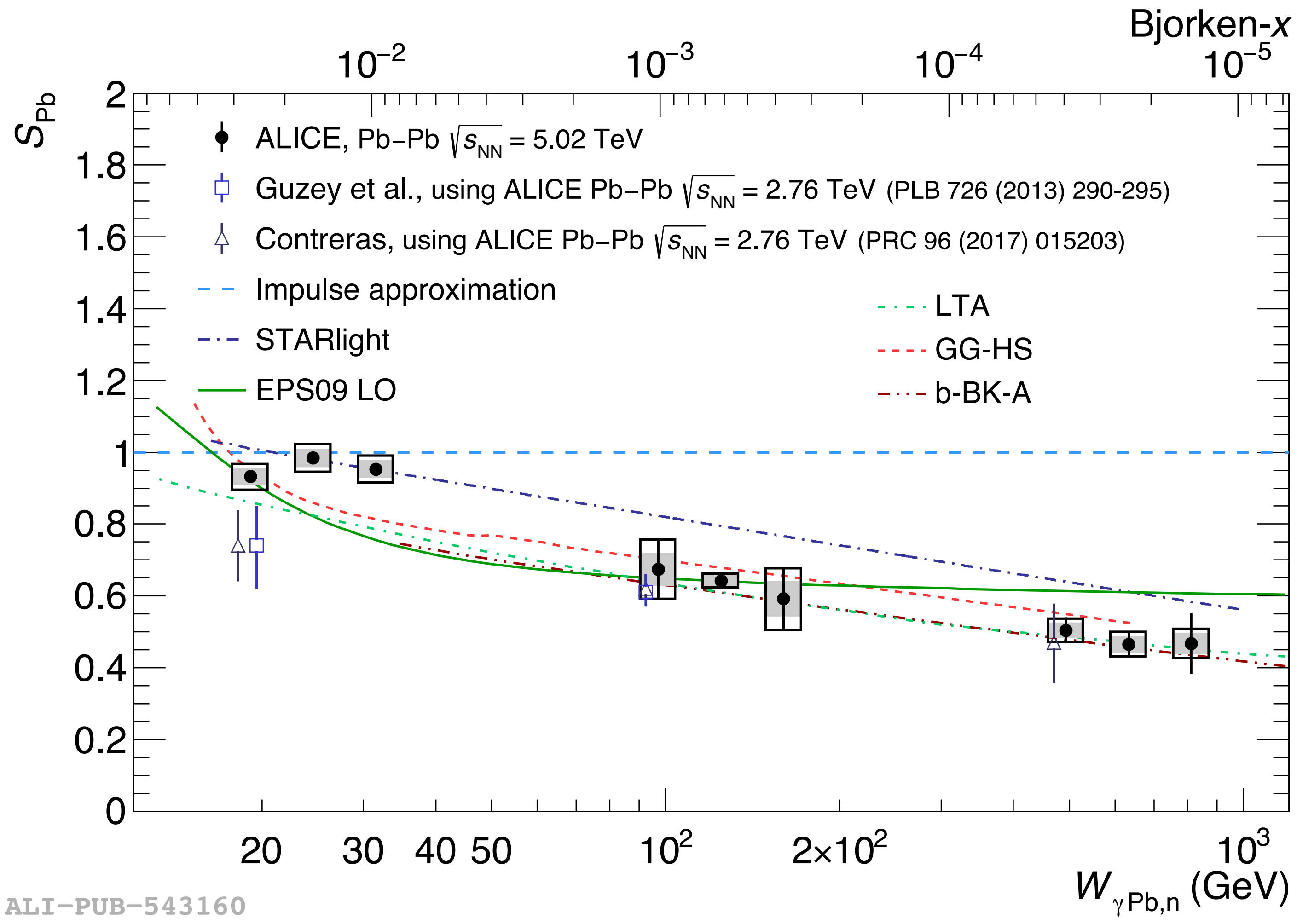
Coherent J/ψ with neutron emission

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

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

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

ALICE, *JHEP* 10 (2023) 119



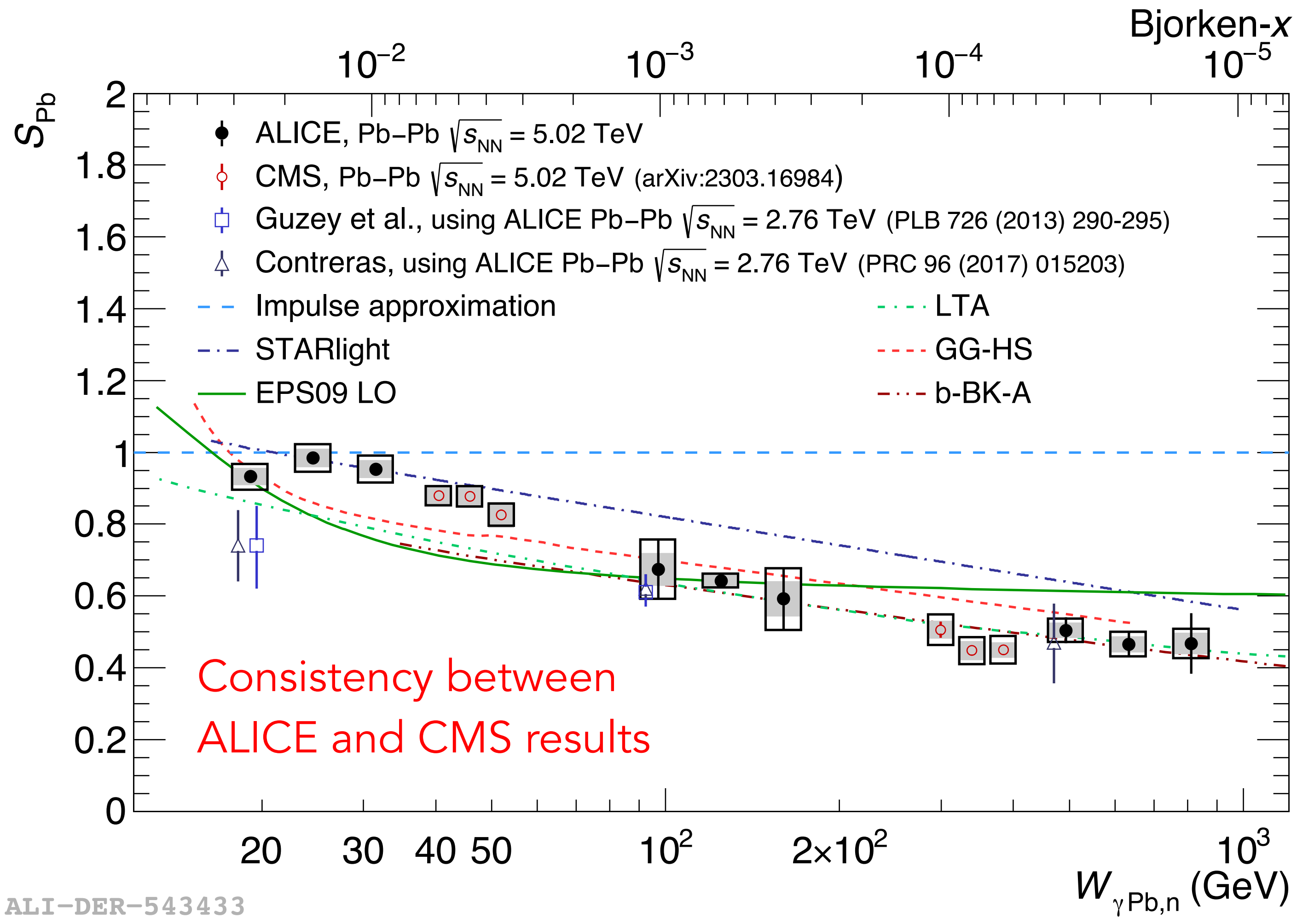
Coherent J/ψ with neutron emission

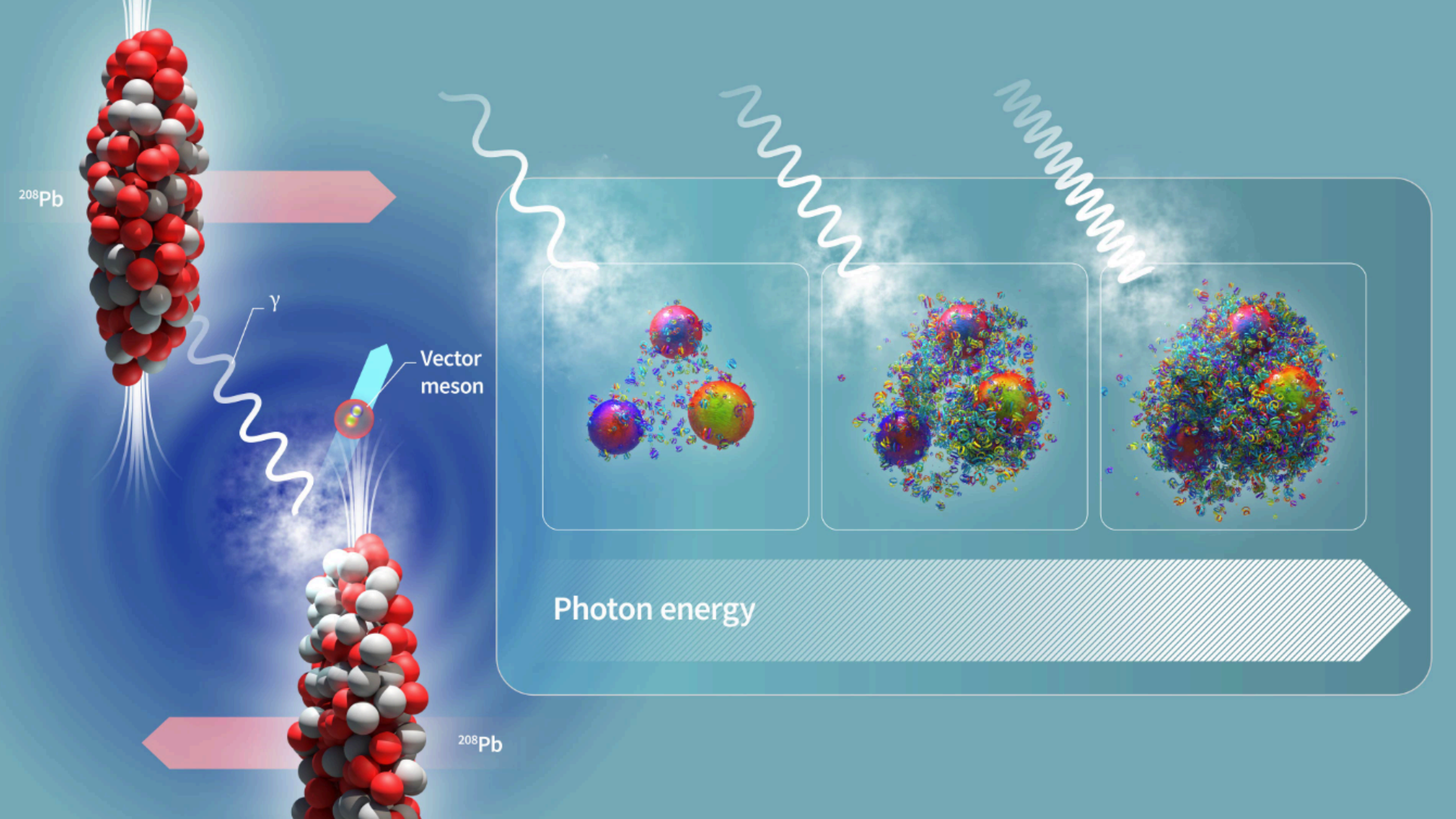
- First measurement of the nuclear suppression factor at Bjorken-$x \sim 10^{-5}$!

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

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

ALICE, *JHEP* 10 (2023) 119

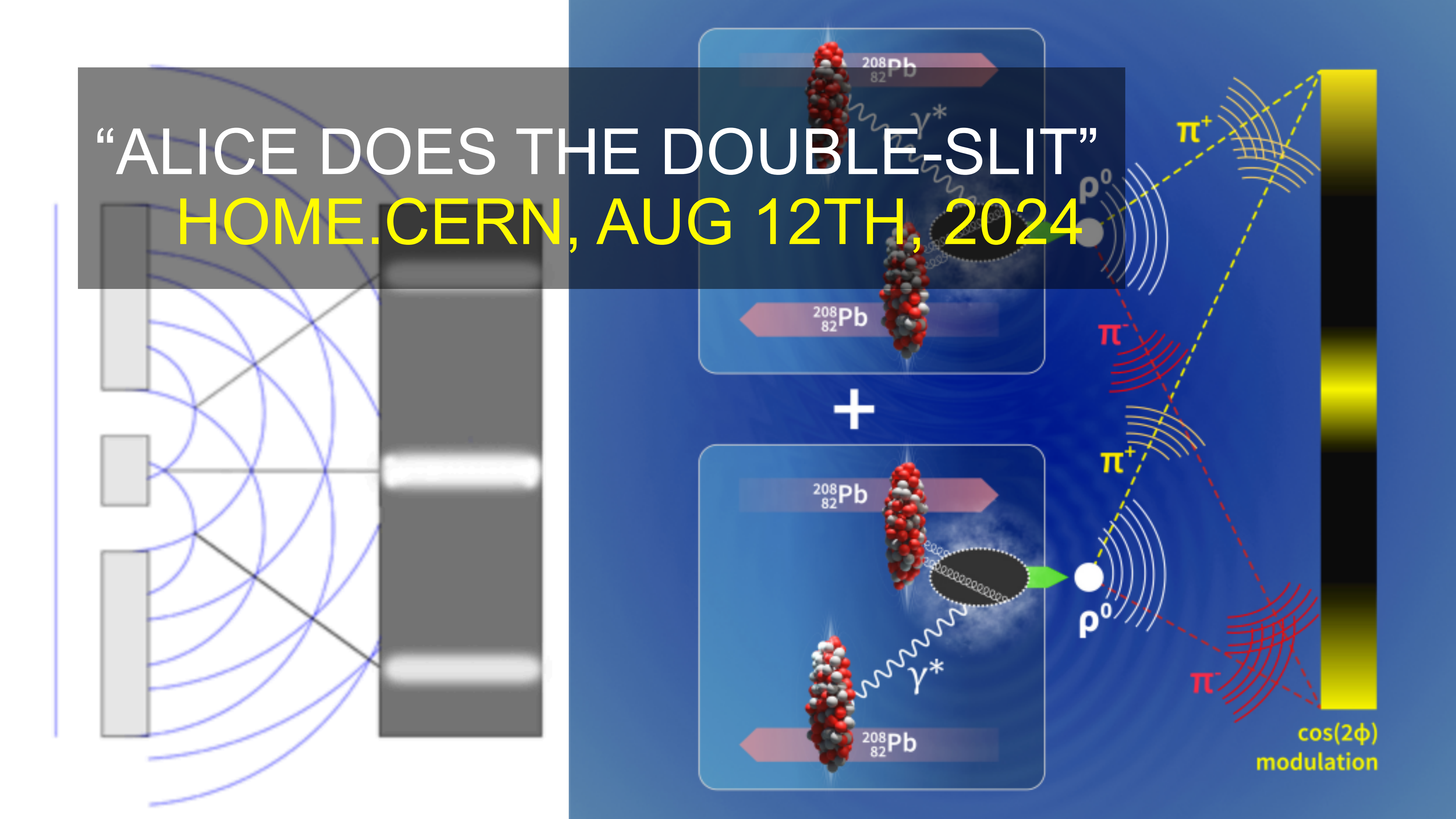




^{208}Pb
γ
Vector meson
Photon energy
^{208}Pb

"ALICE DOES THE DOUBLE-SLIT"

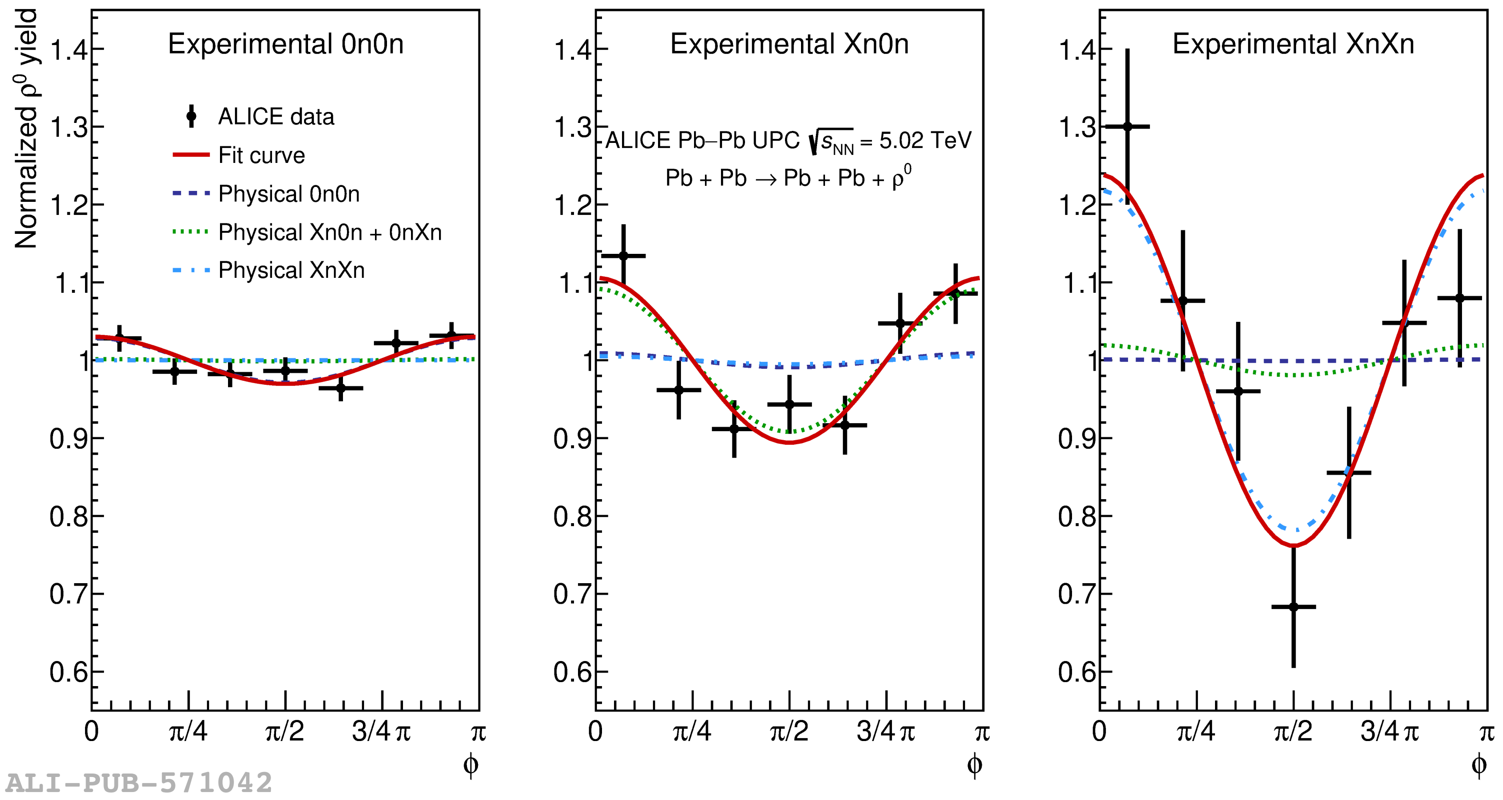
HOME.CERN, AUG 12TH, 2024

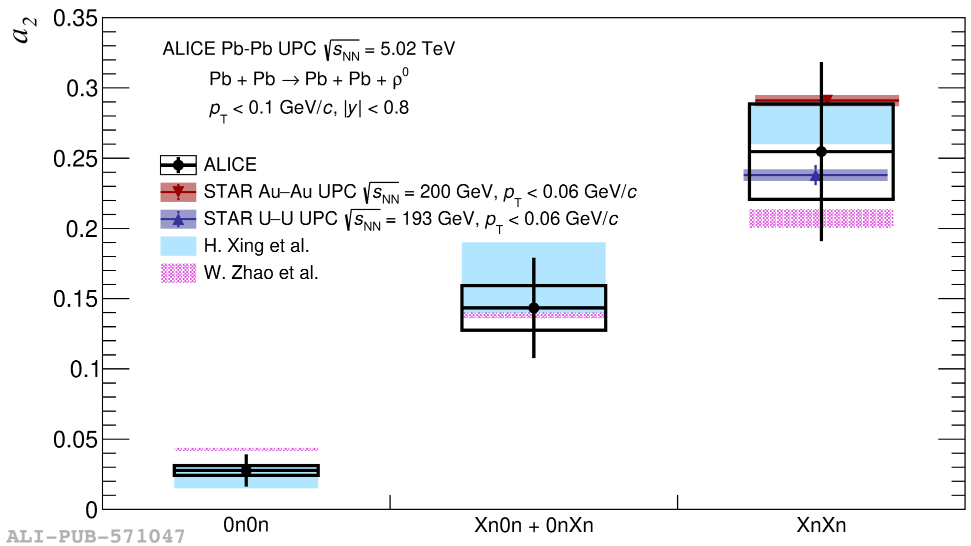


Coherent ρ^0 with neutron emission

ALICE, arXiv:2405.14525 [nucl-ex], submitted to PLB

- Modulation increases as the impact parameter lowers
- ALICE results compatible with both theory and STAR results
- Modulation: linearly polarised photons + quantum interference at the fermi scale





https://home.cern/news/news/physics/alice-does-double-slit

Same technique: neutron emission classes → impact parameter range

ALICE IN THE FUTURE

UPGRADES IN RUN 3 AND 4

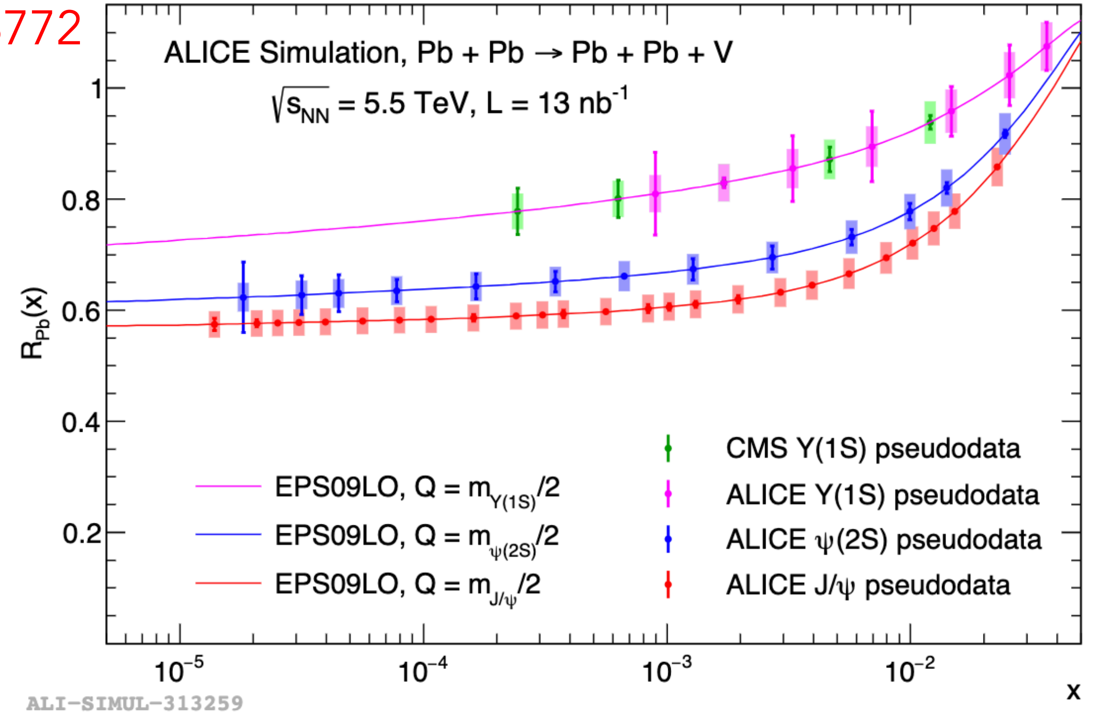
ALICE in Run 3 and 4

- 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	PbPb Central 1 Total	PbPb 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

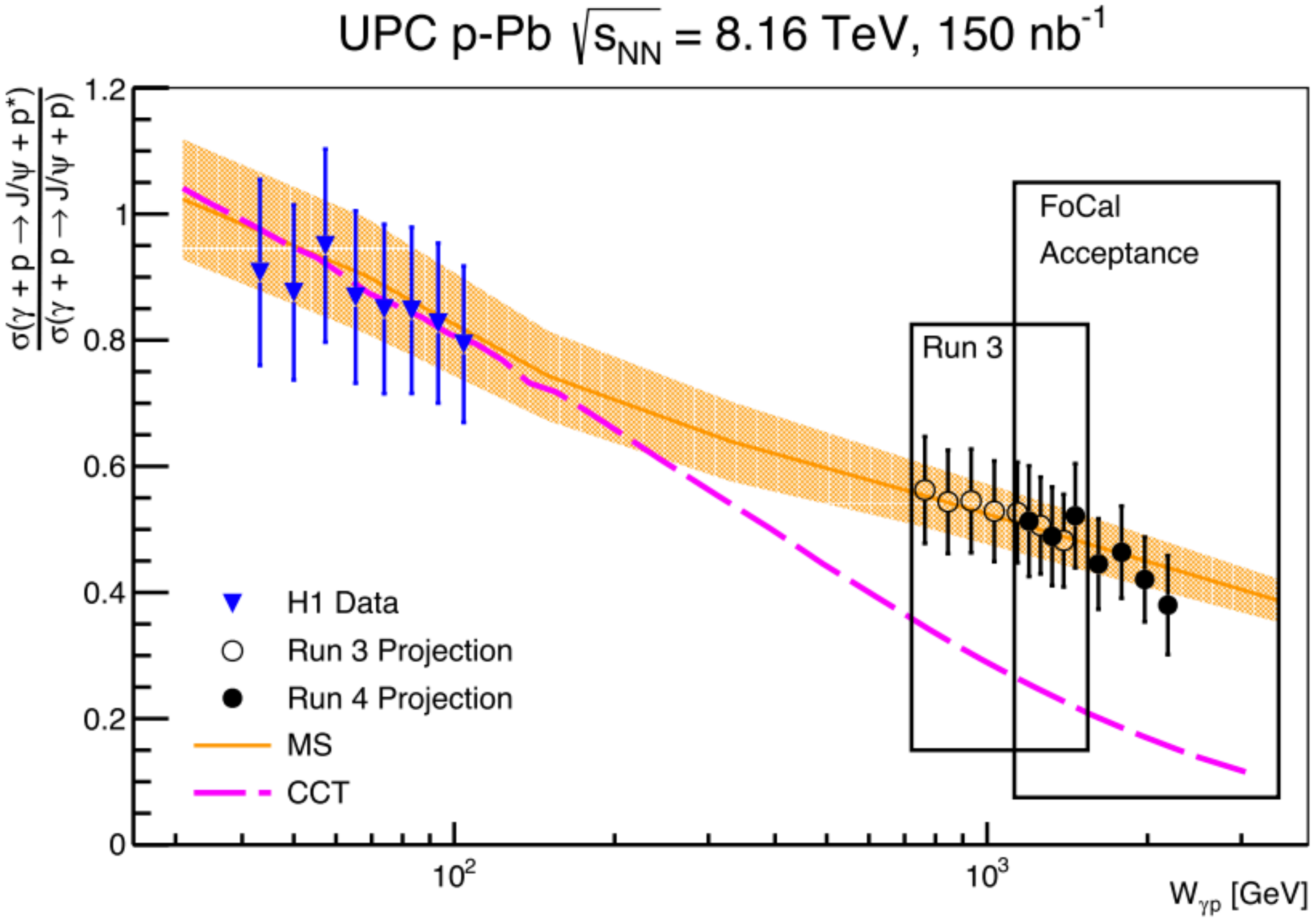
$|y| < 0.9$ $\quad 2.5 < |y| < 4$

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



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

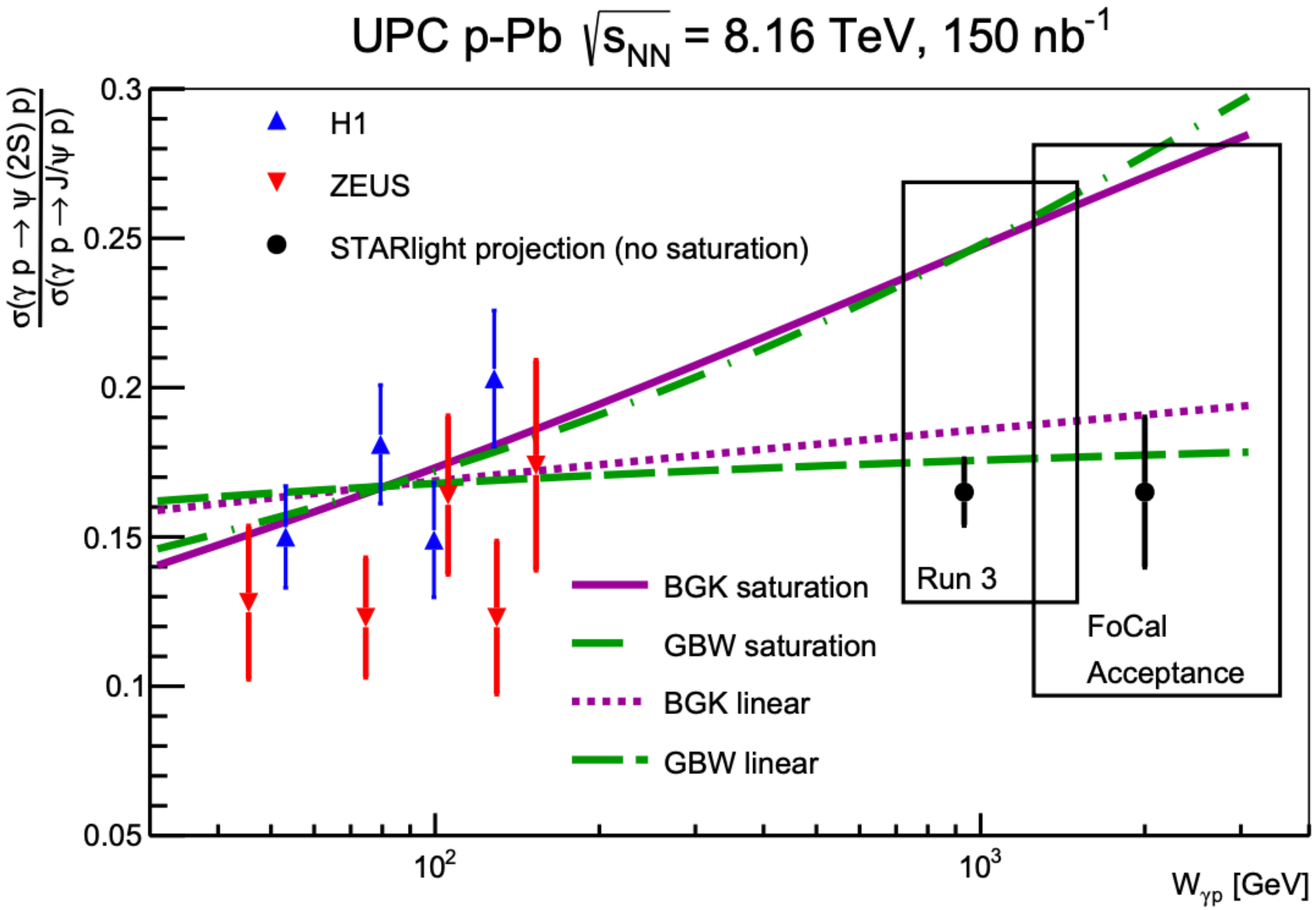
- Already in Run 3, but with FOCAL much easier to measure higher energies (using the channel $J/\psi \longrightarrow ee$)
- CCT model features gluonic hotspots
- Significant reduction at higher energies would imply the onset of the saturation regime



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

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

- The ratio is also a very sensitive observable
- Both Run 3 and 4 are needed to find the onset of the saturation regime



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

Backup slides