Vector meson photoproduction in ALICE at the LHC

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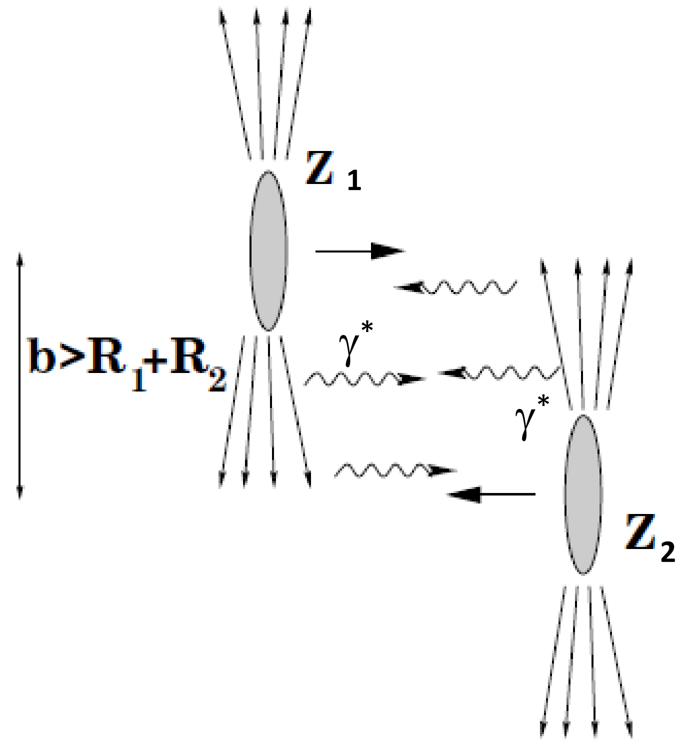
Outline

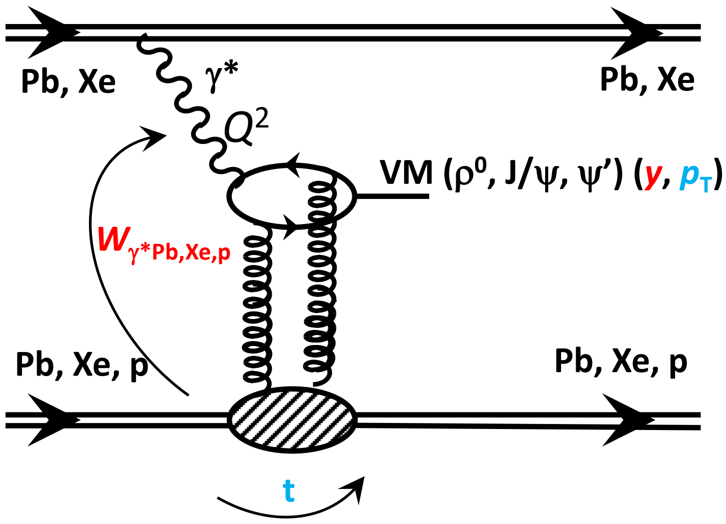
- Introduction
- ALICE detector
- ρ^0 photoproduction in Pb-Pb and Xe-Xe
- J/ψ and ψ' photoproduction in Pb-Pb
- $\mu^+\mu^-$ pair production and J/ψ photoproduction in p-Pb
- Run 3 and beyond perspectives
- Summary

Ultra-peripheral collisions (UPC)



- Photon induced reactions
- Photon flux ~ Z^2 (Z_{Pb} = 82)
- Large γ-induced interaction cross section
- Hadronic interactions suppressed
- Rapidity gap(s)

Photoproduction and main variables



- Vector Meson (VM) quantum numbers:
  - $J^{PC} = 1^{--}$
- Bjorken-*x*

$$x_B = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\pm y}$$

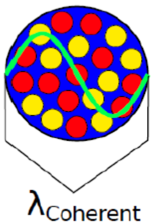
  - ➢ Photoproduction is sensitive to the x_B evolution at LO of the gluon distribution (nPDFs)
- Photon-target centre-of-mass energy

$$W^2_{\gamma^* Pb,Xe,p} = 2E_{Pb,Xe,p} M_{VM} e^{\mp y}$$

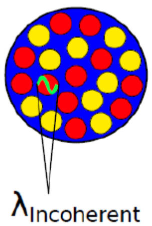
- Transverse plain gluon distribution $|t| \sim p_T^2$
- Photon virtuality $Q^2 \sim M_{VM}^2 / 4$

p_T signature

- **Coherent** Vector Meson (VM) photoproduction:
  - Photon couples coherently to all nucleons (whole nucleus)
  - $\langle p_T^{VM} \rangle \sim 1/R_{Pb} \sim 50$ MeV/c
  - Target ion stays intact



- **Incoherent** VM photoproduction:
  - Photon couples to a single nucleon
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 400$ MeV/c
  - Target ion breaks, nucleon stays intact
  - Usually accompanied by neutron emission

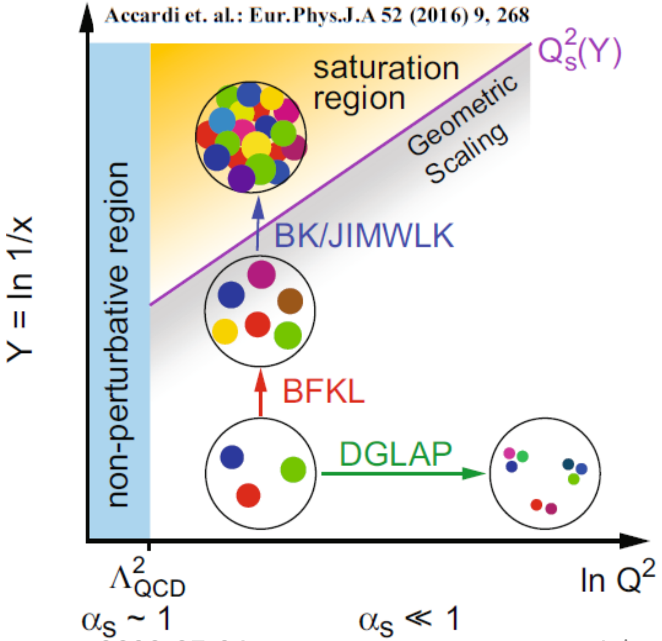


- **Exclusive** VM photoproduction:
  - Photon couples to a single nucleon (proton)
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 400$ MeV/c
  - Target proton stays intact (similar to coherent) in p-Pb case
- **Dissociative** VM photoproduction:
  - Photon interacts with a single nucleon and excites it
  - $\langle p_T^{VM} \rangle \sim 1$ GeV/c
  - Target nucleon and ion break (in heavy ion collision)
  - Target proton breaks (in p-Pb)

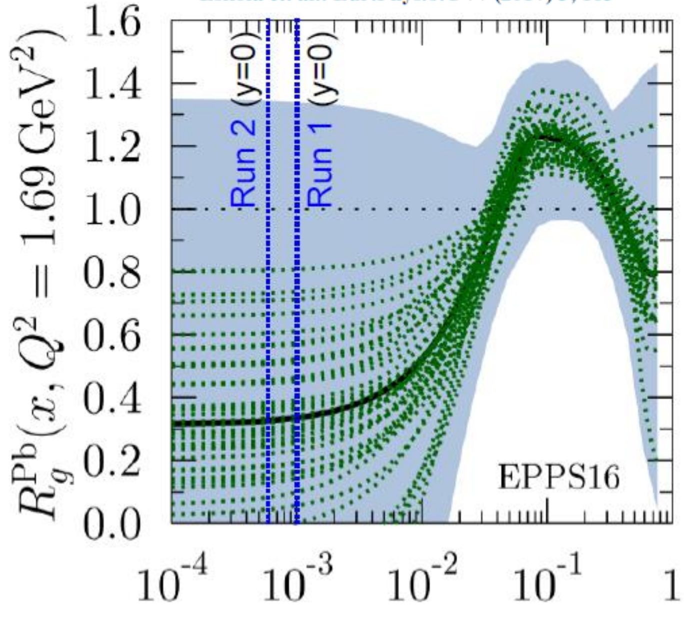
Motivation

- Large photonuclear production cross section of ρ^0 meson allows for studies of black-disk limit of QCD approach
- Coherent vector meson (ρ^0, J/ψ, ψ') photoproduction allows for the study of (gluon) shadowing and atomic number *A* dependence
- Heavy VMs particularly sensitive to gluon shadowing
  - Nuclear gluon shadowing factor $R_g^A(x,Q^2)=g_A(x,Q^2)/Ag_p(x,Q^2) < 1$
  - Saturation may contribute to nuclear shadowing
  - Search for saturation at low x_B
- $|t|$-dependence helps to constrain transverse gluonic structure at low x_B
- Constrain parameters of models

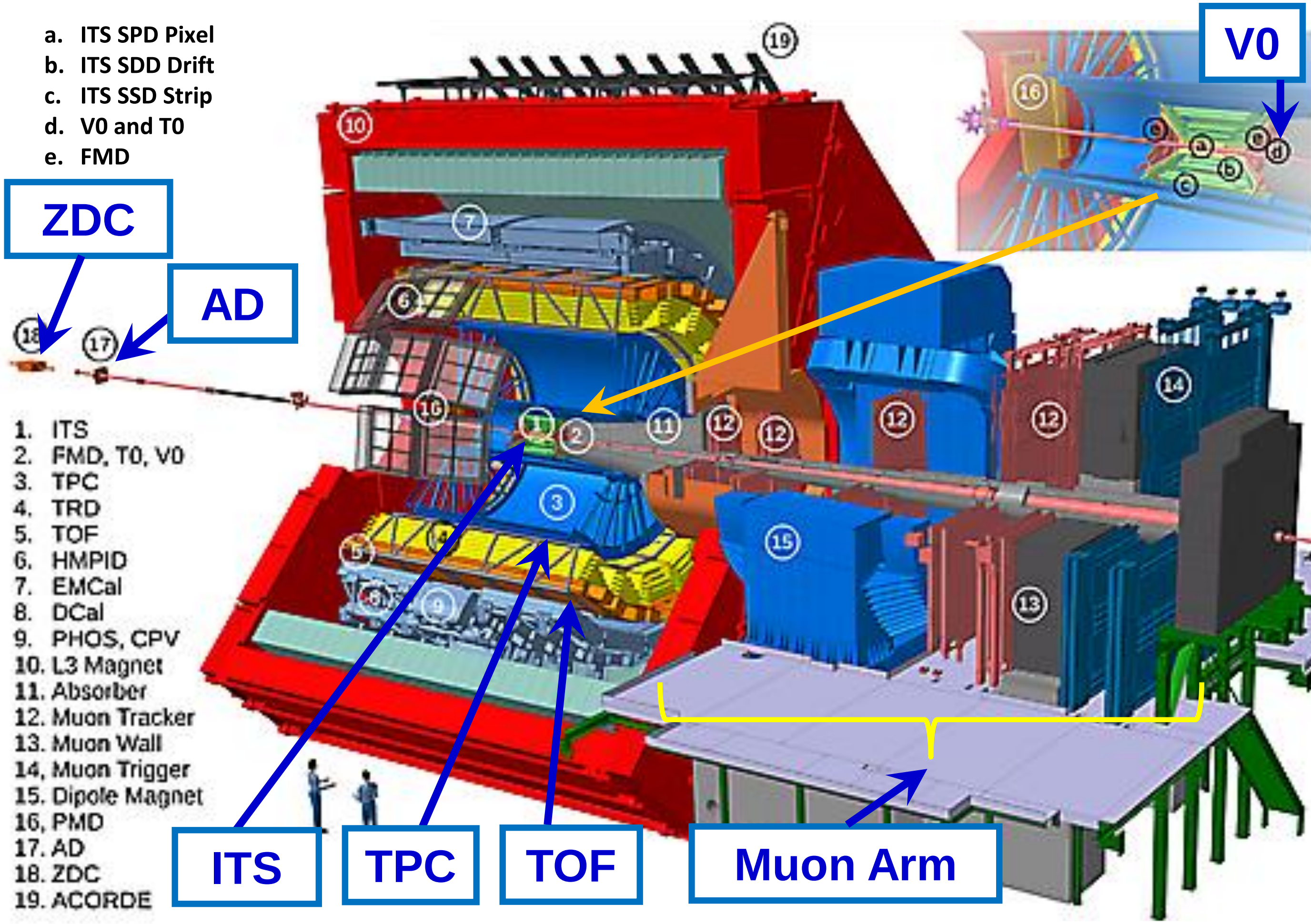
Accardi et. al.: Eur.Phys.J.A 52 (2016) 9, 268



Eskola et. al.: Eur.Phys.J.C 77 (2017) 3, 163



ALICE detector

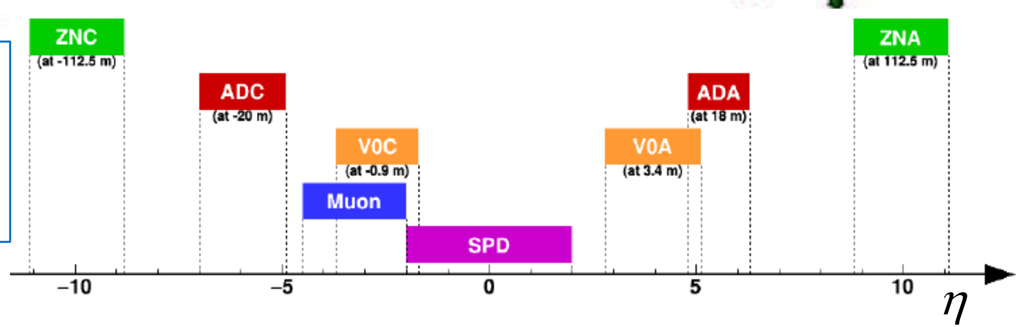


- Central Barrel tracking ($e^{\pm}$, $h^{\pm}$)
  - $|\eta| < 0.9$, $0 < \varphi < 2\pi$
  - ITS - silicon detector
  - TPC - gas drift detector
  - TOF - resistive plate chambers
- Forward tracking ($\mu^{\pm}$)
  - $-4 < \eta < -2.5$
  - Absorber
  - Muon tracker
  - Muon trigger
  - Dipole magnet
- Diffractive detectors
  - AD - scintillator counter
  - V0 - scintillator counter
  - ZDC - sampling calorimeter

Vertex
- Pixel

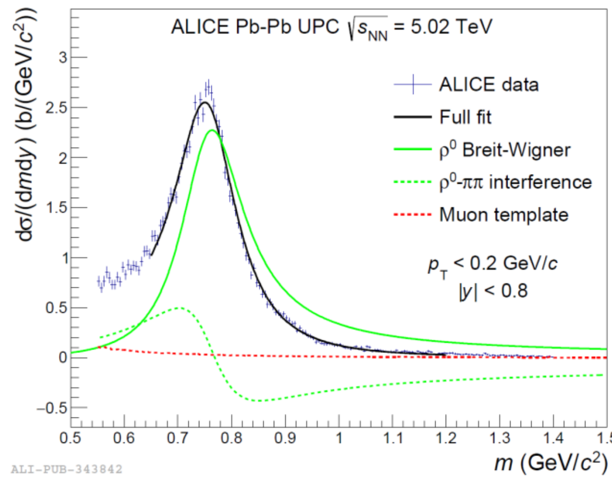
Trigger
- SPD, TOF, AD, V0, Muon

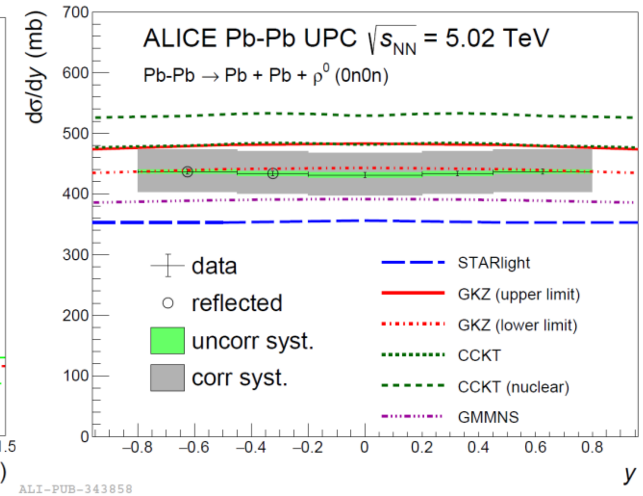
Look at backup slide for a list of vector meson photoproduction publications



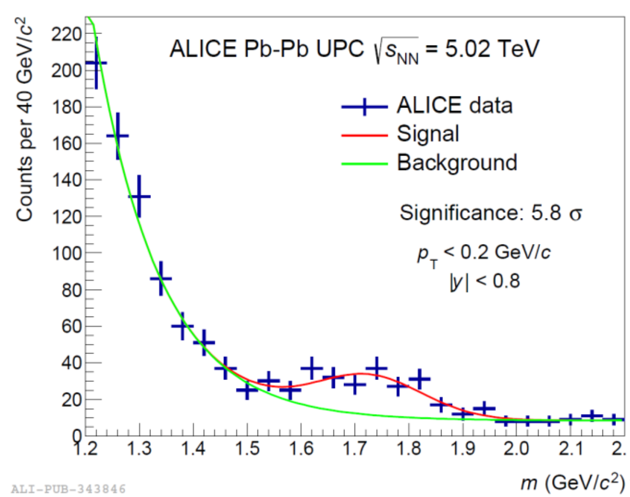
ρ^0 in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

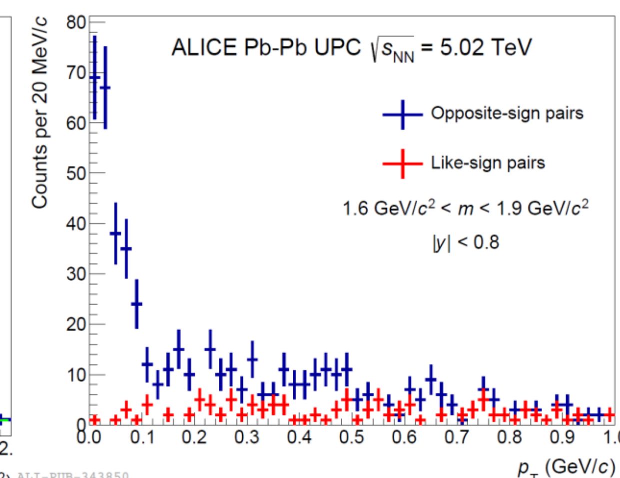
- Coherent $\rho^0 \rightarrow \pi^+ \pi^-$
  - $$\frac{d\sigma}{dm\,dy} = |A \cdot BW_\rho + B|^2 + M,$$
  - Pole mass and width agree with PDG
- Comparisons with models
  - GKZ (nuclear shadowing) gives the best description
  - CCKT (saturation) is slightly worse
  - STARlight and GMMNS (saturation) underestimate
- Resonance-like structure $M^{\pi\pi} \sim 1.7$ GeV/c^2
  - Significance of 4.5 σ
  - Seen also by STAR, ZEUS, H1





JHEP 06 (2020) 035

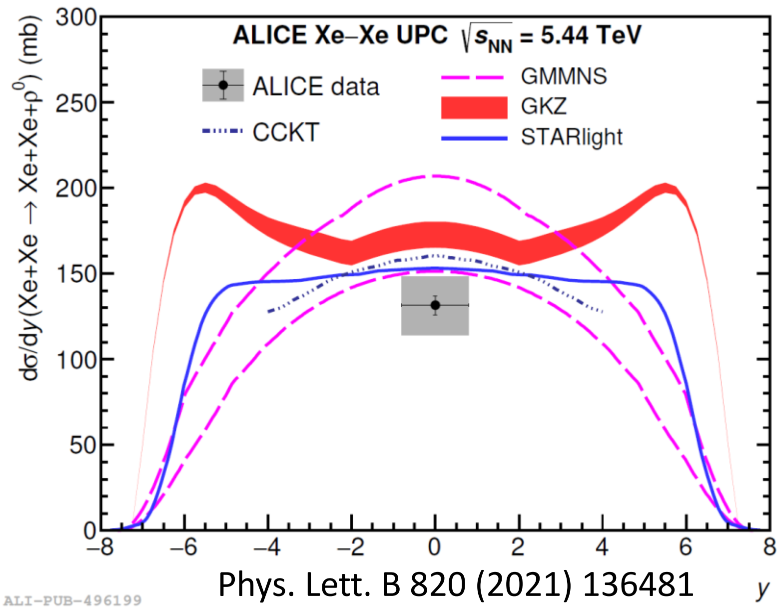




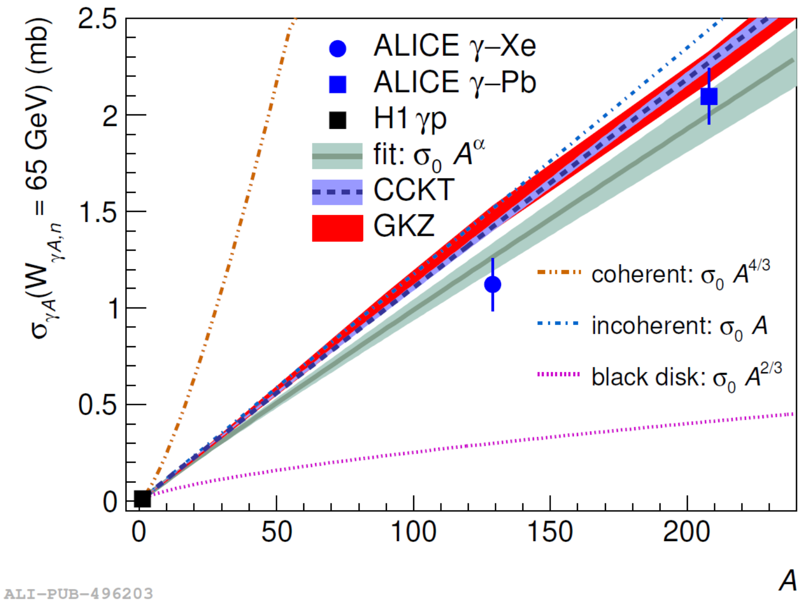
ρ^0 in Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV

- $d\sigma/dy = 131.5 \pm 5.6^{st}\, {}^{+17.5}_{-16.9}{}^{sy}$ mb
- All models relatively close to data

- $W_{\gamma A,n}$ = 65 GeV
- $\sigma(\gamma A \rightarrow \rho^0 A) \sim A^{\alpha}$ with a slope $\alpha = 0.96 \pm 0.02^{sy}$
  - ⇒ Signals important shadowing effect
  - – Far from black disk limit
  - – Slope close to 1 by coincidence
- Fair description of data by models CCKT (saturation) and GKZ (shadowing)



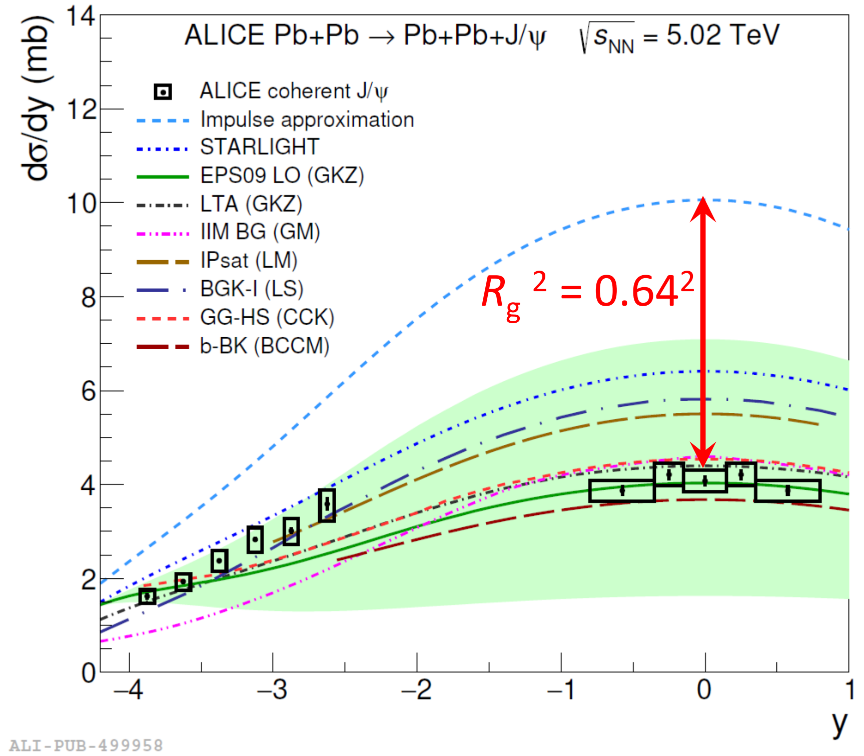
Phys. Lett. B 820 (2021) 136481



J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- Forward region:
  - $J/\psi \rightarrow \mu^+\mu^-$
- Central region:
  - $J/\psi \rightarrow \mu^+ \mu^-, e^+ e^-, p\bar{p}$
- Nuclear gluon shadowing factor $R_g = 0.64 \pm 0.04$ for $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
- No model describes the full rapidity dependence
  - Models with nuclear shadowing (EPS09 LO, LTA) or saturation (GG-HS) describe central and very forward data but tensions in semiforward region
  - Other models describe either forward or central rapidity region

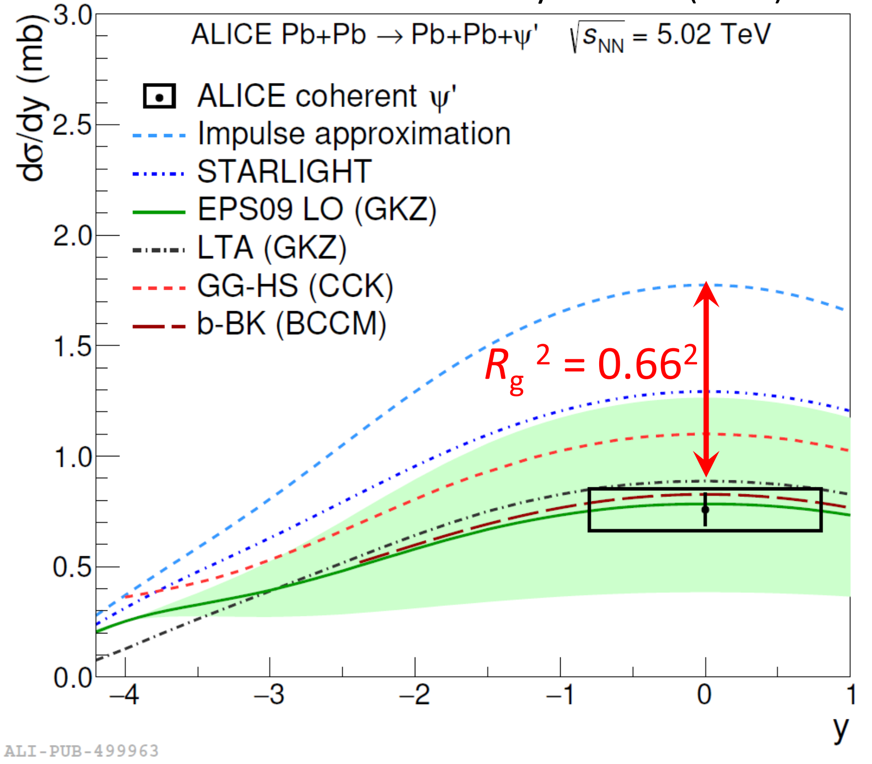
Eur. Phys. J. C 81 (2021) 712



ψ' in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- $\psi' \rightarrow \mu^+\mu^-\pi^+\pi^-$, $e^+e^-\pi^+\pi^-$, l^+l^-
- Nuclear gluon shadowing factor
  - $R_g = 0.66 \pm 0.06$ for $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
  - Consistent with J/ψ result
- Good agreement of models with shadowing (EPS09 LO, LTA)
- Good agreement of model BCCM with saturation
- Other models overpredict data

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



J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

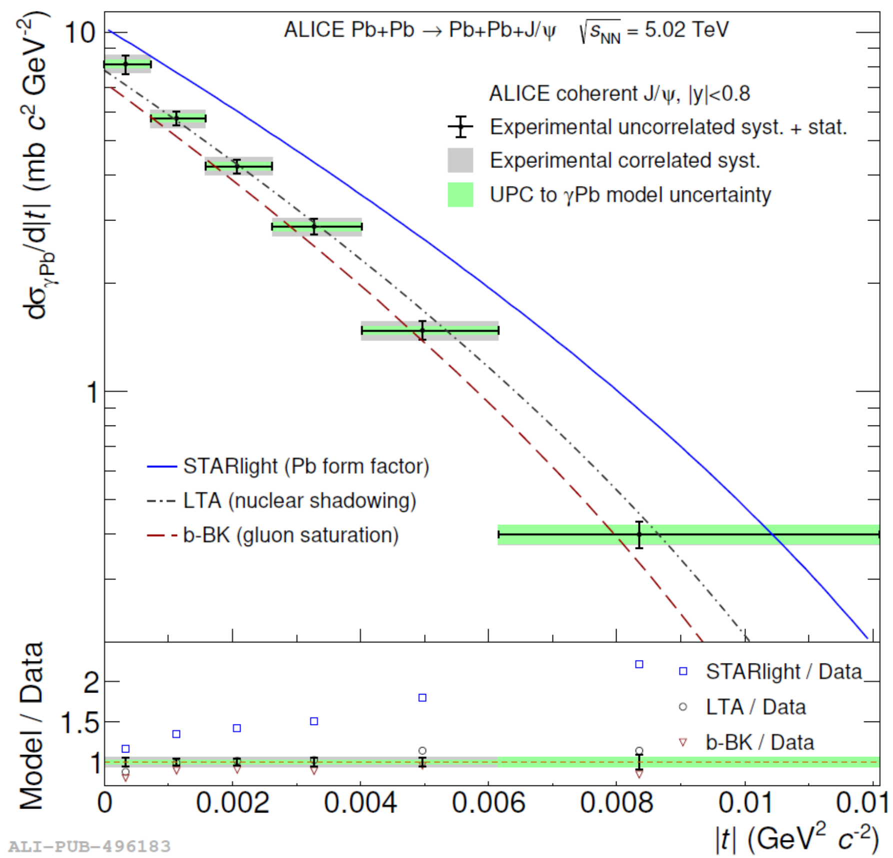
- Central region
  - $J/\psi \rightarrow \mu^+\mu^-$
- $|t|$ dependence is sensitive to spatial gluon distribution
- Bayesian and SVD unfolding used to transform $p_T^2 \rightarrow |t|$
- Transition from UPC to photonuclear cross section

Photon flux

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

- Comparison to models:
  - STARlight does not contain explicitly shadowing – do not describe shape nor magnitude
  - LTA contains nuclear shadowing – agrees with data
  - b-BK based on gluon saturation – agrees with data

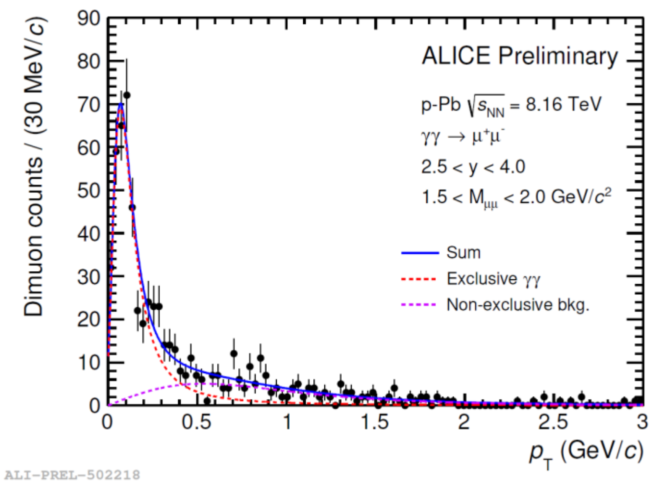
PLB 817 (2021) 136280

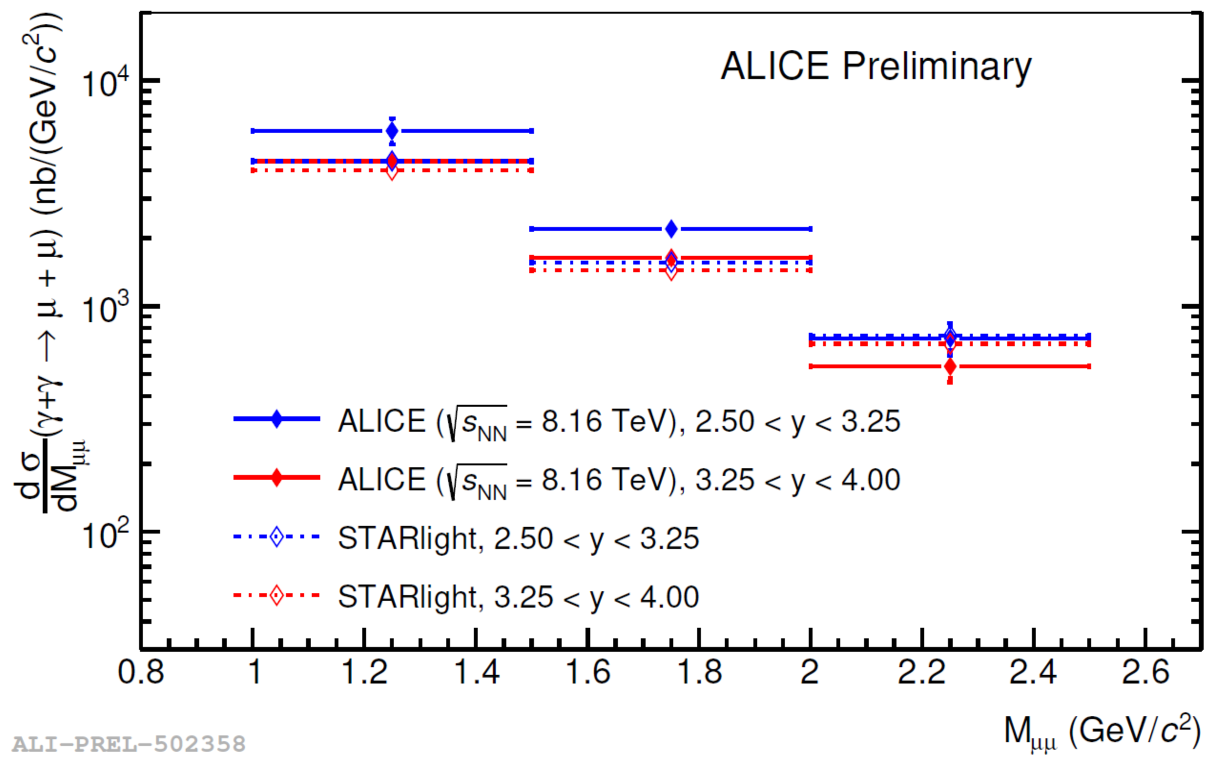


⇒ Reflects effects of QCD dynamics at small $x_B \sim 10^{-3}$

$\gamma\gamma \to \mu\mu$ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

- **$\gamma\gamma \to \mu\mu$ cross section**
- Good agreement of simulation and data
- Comparison with STARlight (LO QED, no FSR) shows slight excess in data
- Important background for other UPC processes
- Constrain theoretical models

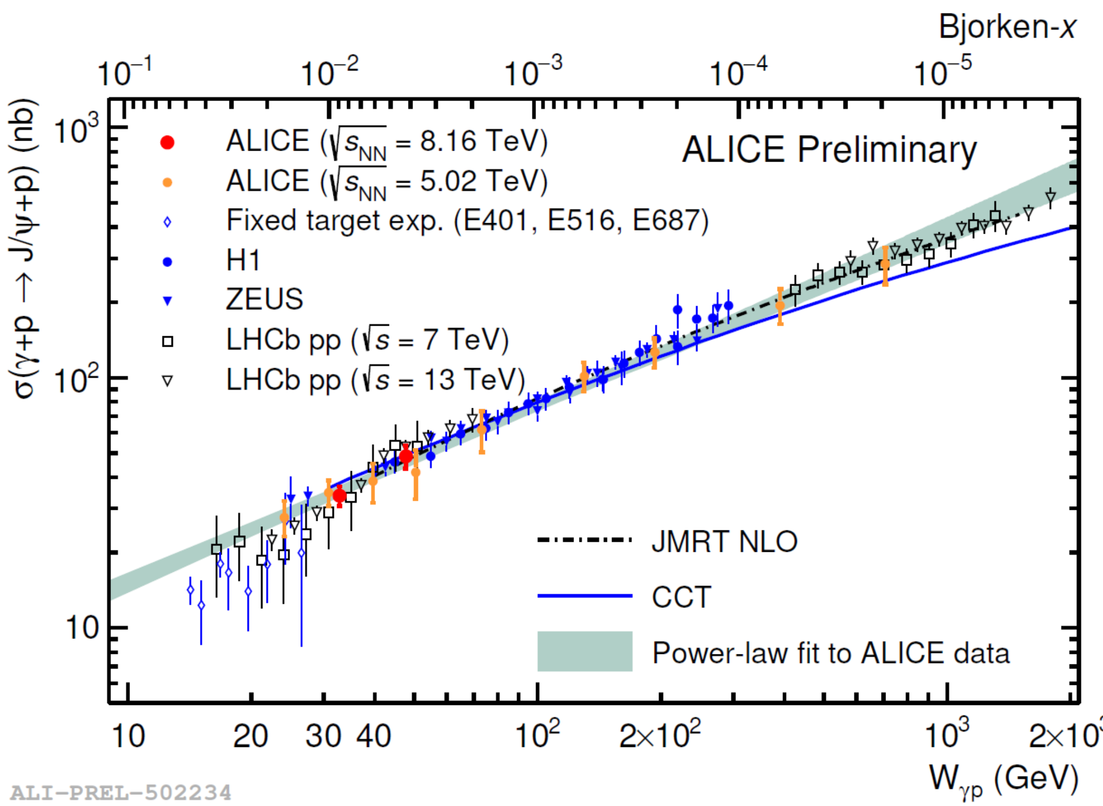




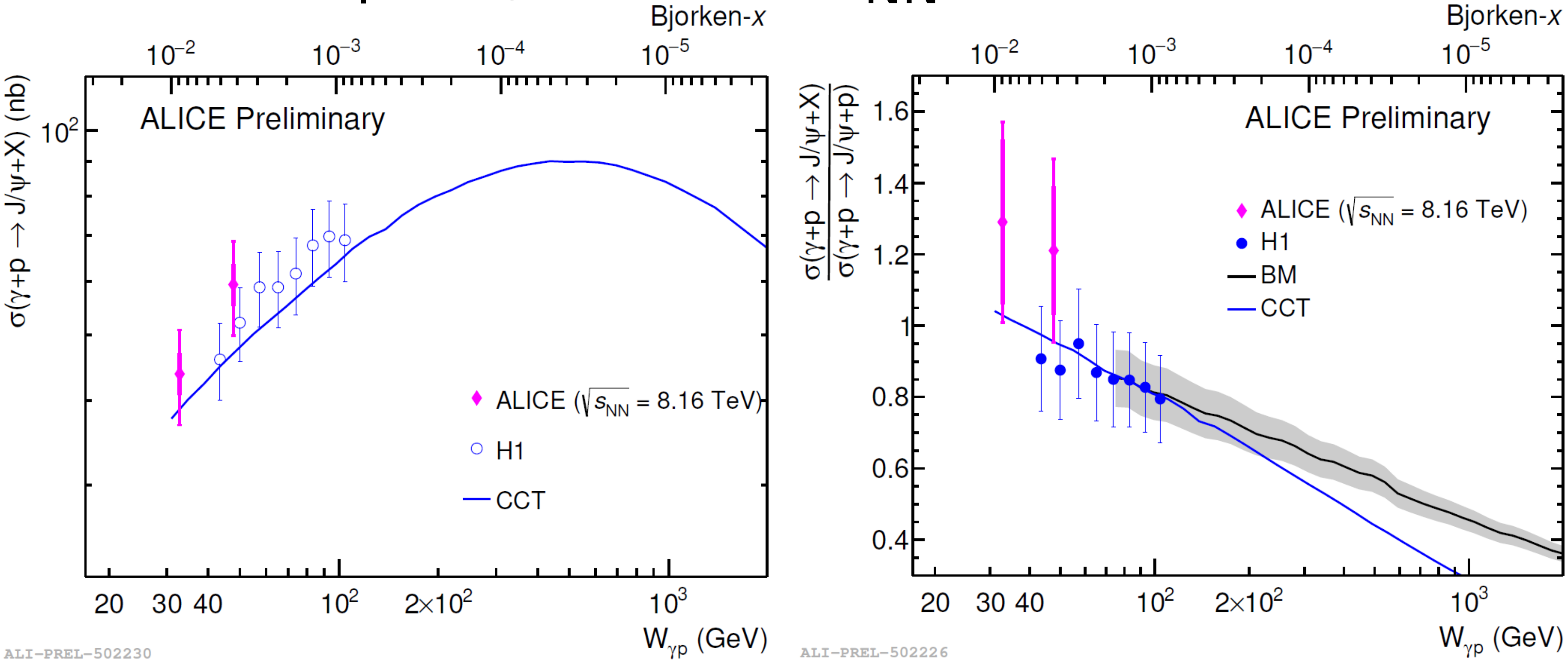
J/ψ in p-Pb at $\sqrt{s_{NN}} = 8.16$ TeV

- Gluon distribution at HERA energies follows power law at low x_B
  $\Rightarrow$ similar trend in $W_{\gamma p}$
- **Exclusive J/ψ cross section** fits well into trend of photo nuclear energy dependence
- A deviation from trend $\rightarrow$ a change in the evolution of the gluon PDF
  $\Rightarrow$ expected at the onset of saturation

- Power law fit to ALICE data $\sigma \sim W_{\gamma p}{}^{\delta}$ with $\delta = 0.7 \pm 0.04$
  $\Rightarrow$ agreement LHC and HERA
  $\Rightarrow$ agreement ALICE and LHCb
- Models show agreement
  - JMRT NLO: based on DGLAP evolution with dominant NLO contribution
    - valid to $x_B \sim 2 \times 10^{-5}$
  - CCT: Saturation in an energy dependent hot spot model



J/ψ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV



- **First measurement** of the dissociative cross section at the LHC
- Energy dependent **dissociative J/ψ cross section** ($x_B \sim (0.5,2) \times 10^{-2}$)
- Agreement with HERA results
- CCT model with saturation agrees with data
  - Predicted maximum at $W_{\gamma p}$ ~ 500 GeV to be checked in Run 3
- BM: perturbative JIMWLK evolution with parameters constrained to H1 data to be checked in Run 3

Run 3 and beyond

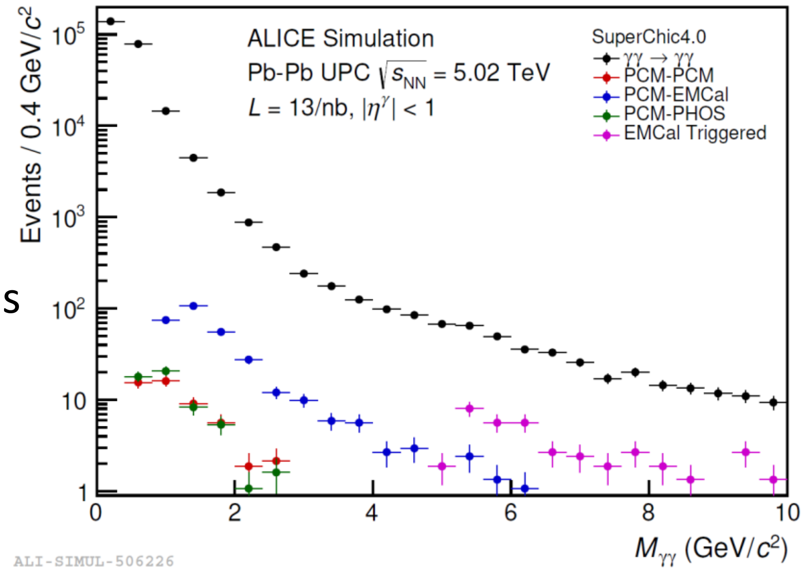
- Luminosity increase
- Detector upgrade and continous readout

  $\Rightarrow$ More than 10^4 data with respect to Run 2!

- Precise and new measurements in VM sector
- Light-by-light scattering
- τ anomalous magnetic moment

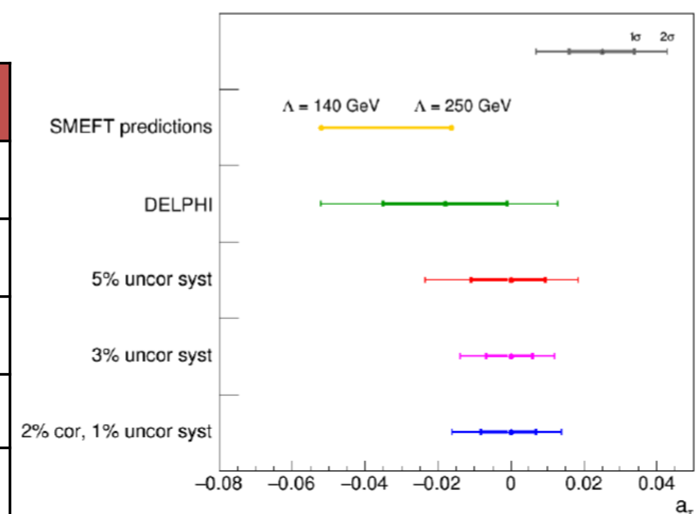
+ BSM searches (Light-by-light scattering, τ anomalous magnetic moment)

Period	Run 2	Run 3	Run 4	Run 5 per year
$L^{\text{Pb-Pb}}$	1/nb	6/nb	7/nb	5.6/nb



CERN Yellow Rep.Monogr. 7 (2019) 1159

Meson, channel	$\sigma^{\text{Pb-Pb}}$	N^{Tot}	$N^{\|\eta\| < 0.9}$	$N^{-4 < \eta < -2.5}$
$\rho^0 \rightarrow \pi^+ \pi^-$	5.2 b	68×10^9	5.5×10^9	-
$\rho' \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	730 mb	9.5×10^9	210×10^6	-
$\phi \rightarrow K^+ K^-$	0.22 b	2.9×10^9	82×10^6	-
$J/\psi \rightarrow \mu^+ \mu^-$	1.0 mb	14×10^6	1.1×10^6	600×10^3
$\psi(2S) \rightarrow \mu^+ \mu^-$	30 μb	400×10^3	35×10^3	19×10^3
$\Upsilon(1S) \rightarrow \mu^+ \mu^-$	2.0 μb	26×10^3	2.8×10^3	880



Burmasov et al., arXiv:2203.00990 (2022)

Summary

- Light VM photoproduction signals large shadowing effects
  - No model describes all the breakup classes (0nXn is the most difficult)
- Resonance-like structure at $M^{\pi\pi}$ ~ 1.7 GeV/c^2
- Nuclear gluon structure probed with J/ψ at $x_B \sim 10^{-3}$
  - Nuclear gluon shadowing factor $R_g \sim 0.65$
  - Models with shadowing or saturation describe data the best
  - No model describe all the rapidity points
  - |t|dependence is sensitive to spatial gluon distribution
- Proton gluon structure probed at $x_B \sim 10^{-2}$
  - Agreement of exclusive and dissociative J/ψ photoproduction with saturation models
  - Agreement with previous results
  - First measurement of the dissociative cross section at the LHC
- Analyses of data coming from Run 3 and beyond will provide new exciting results

Backup

Coverage

- V0A: $2.8 < \eta < 5.1$, z = 3.4 m
- V0C: $-3.7 < \eta < -1.7$, z = -0.9 m
- ADA: $4.7 < \eta < 6.3$, z = 16.9 m
- ADC: $-6.9 < \eta < -4.9$, z = -19.5 m
- ZDC: z = $\pm$ 112.5 m, $|\eta| > 8.8$

Triggers

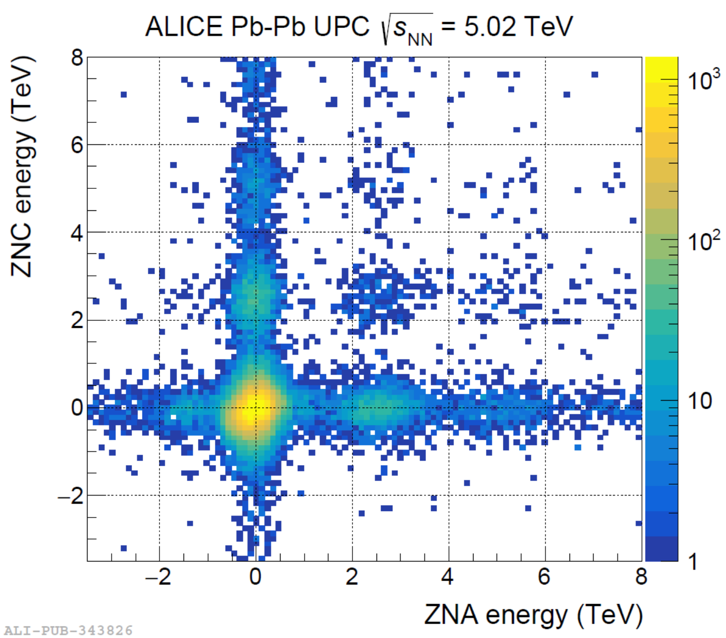
- Central barrel trigger
  - ρ^0 in Pb-Pb — $L = 485 \pm 24$ mb^{-1}
    - Veto in AD and V0
    - SPD topology $\Delta\varphi > 153°$
  - ρ^0 in Xe-Xe — $L = 279.5 \pm 29.9$ mb^{-1}
    - Veto in V0
    - SPD and TOF signal
  - J/ψ, ψ' in Pb-Pb — $L^{\mathrm{Central}} = 233$ μb^{-1}
    - Veto in AD, V0
    - SPD and TOF topology $\Delta\varphi > 153°$
    - Signal in central barrel ITS, TPC, TOF

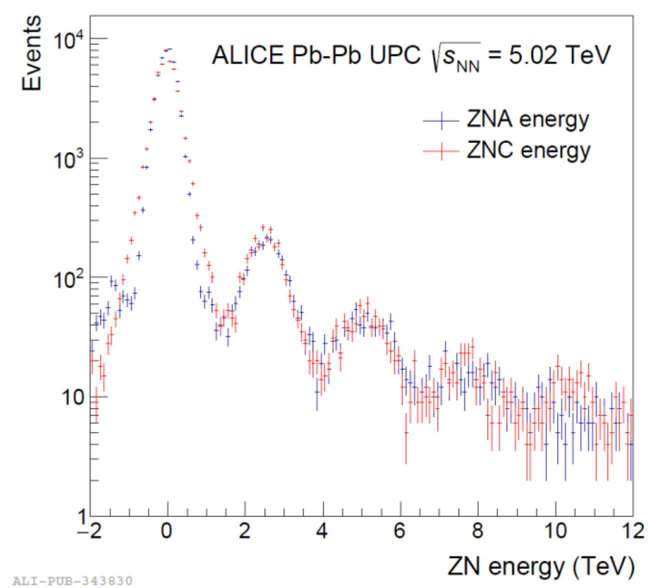
- Forward trigger
  - J/ψ, ψ' in Pb-Pb — $L^{\mathrm{Forward}} = 754 \pm 38$ μb^{-1}
    - Veto in SPD, AD, V0
    - Signal in muon spectrometer
  - J/ψ in p-Pb — $L = 7.62 \pm 0.14$ nb^{-1}
    - Veto in AD, V0
    - Signal in muon spectrometer

VM photoproduction publications

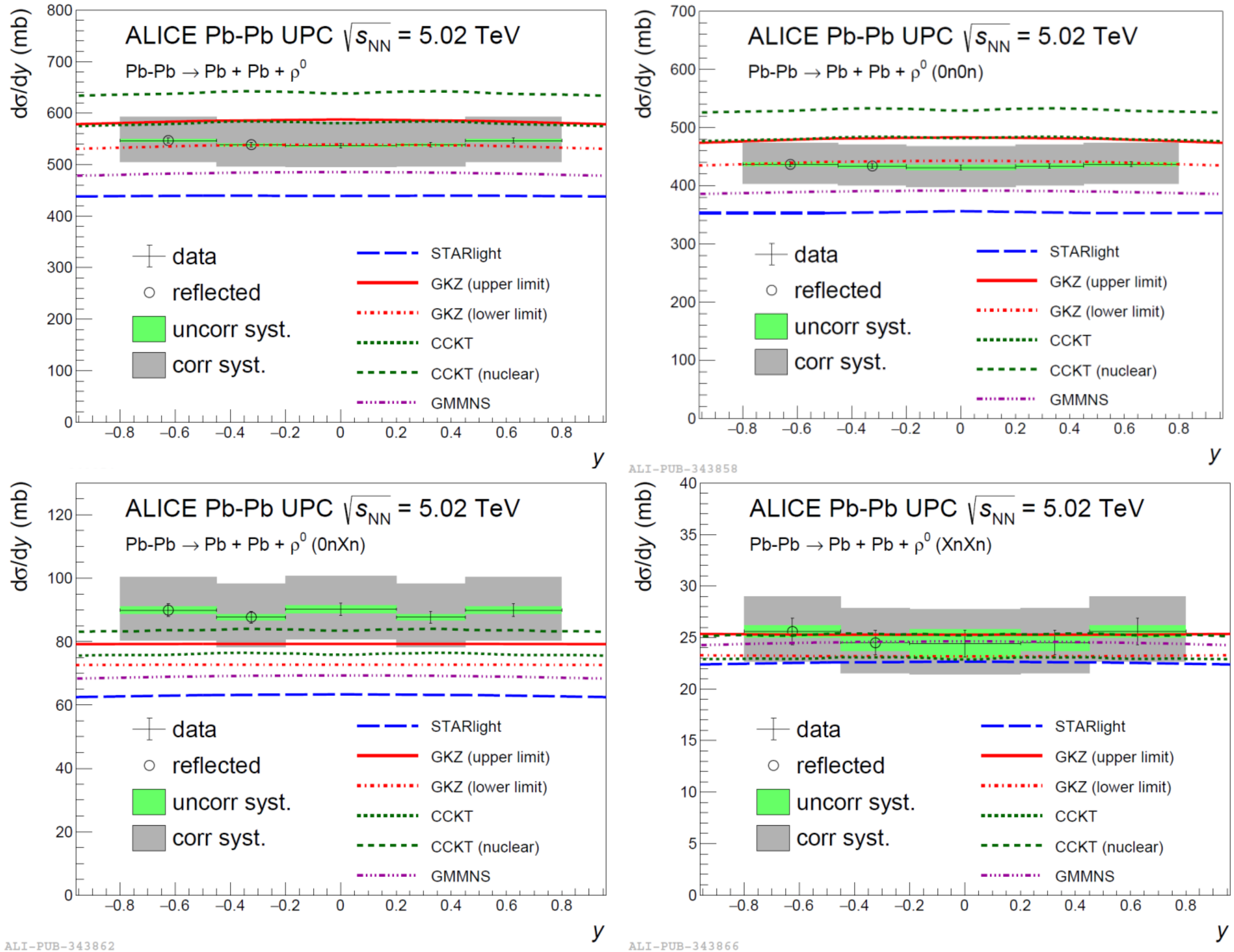
- Coherent photoproduction of ρ^0 vector mesons in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, JHEP 06 (2020) 035.
- First measurement of coherent ρ^0 photoproduction in ultra-peripheral Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV, Phys. Lett. B 820 (2021) 136481.
- Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys.Lett. B798 (2019) 134926.
- Coherent J/ψ and ψ′ photoproduction at midrapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C 81 (2021) 712.
- First measurement of the |t|-dependence of coherent J/ψ photonuclear production, PLB 817 (2021) 136280.
- Energy dependence of exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C (2019) 79: 402.

ρ^0 – ZDC energy

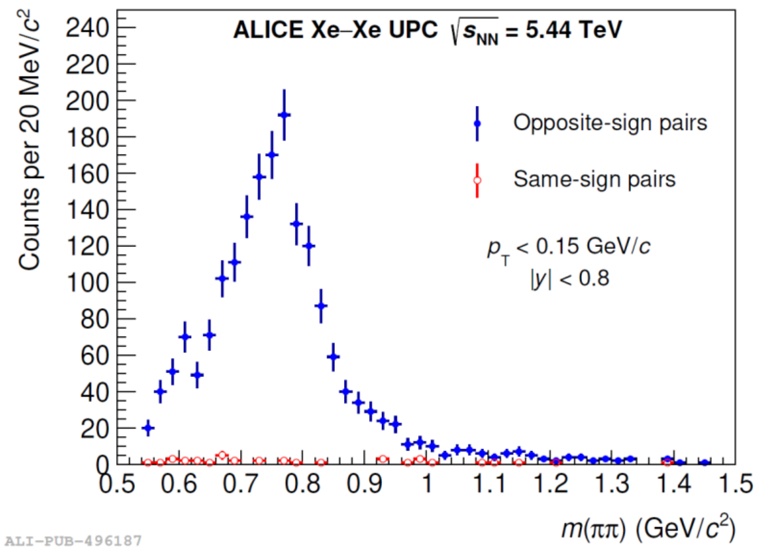


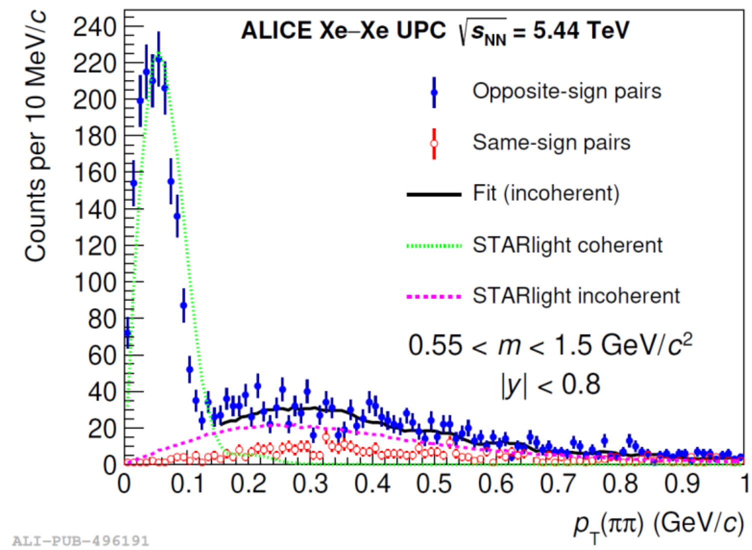


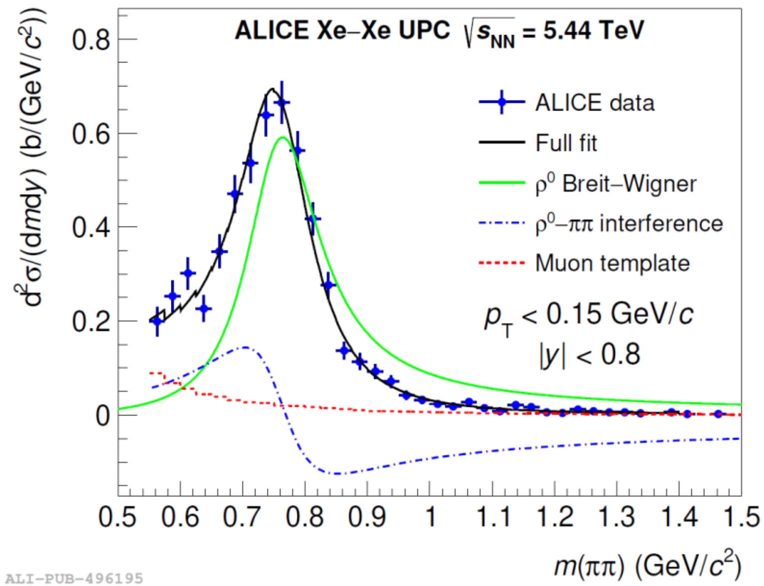
ρ^0 in Pb-Pb – nuclear breakup classes



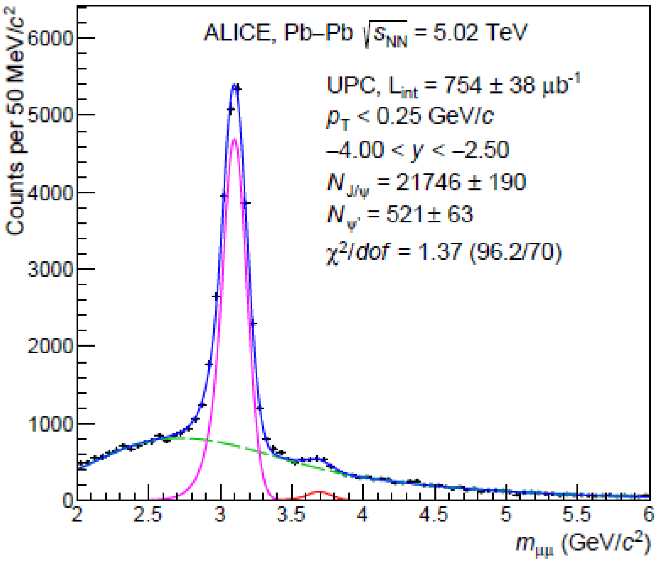
ρ^0 in Xe-Xe

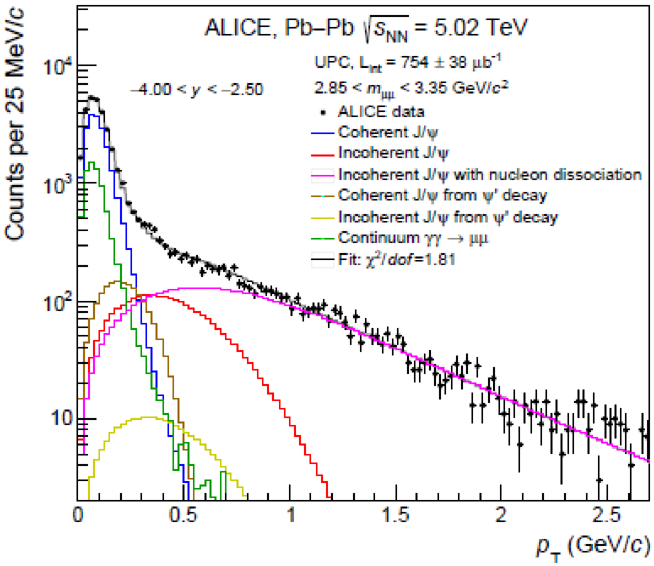

ALICE Xe–Xe UPC $\sqrt{s_{NN}}$ = 5.44 TeV
Opposite-sign pairs
Same-sign pairs
p_T < 0.15 GeV/c
|y| < 0.8
Counts per 20 MeV/c^2
$m(\pi\pi)$ (GeV/c^2)
ALI-PUB-496187


ALICE Xe–Xe UPC $\sqrt{s_{NN}}$ = 5.44 TeV
Opposite-sign pairs
Same-sign pairs
Fit (incoherent)
STARlight coherent
STARlight incoherent
0.55 < m < 1.5 GeV/c^2
|y| < 0.8
Counts per 10 MeV/c
$p_T(\pi\pi)$ (GeV/c)
ALI-PUB-496191

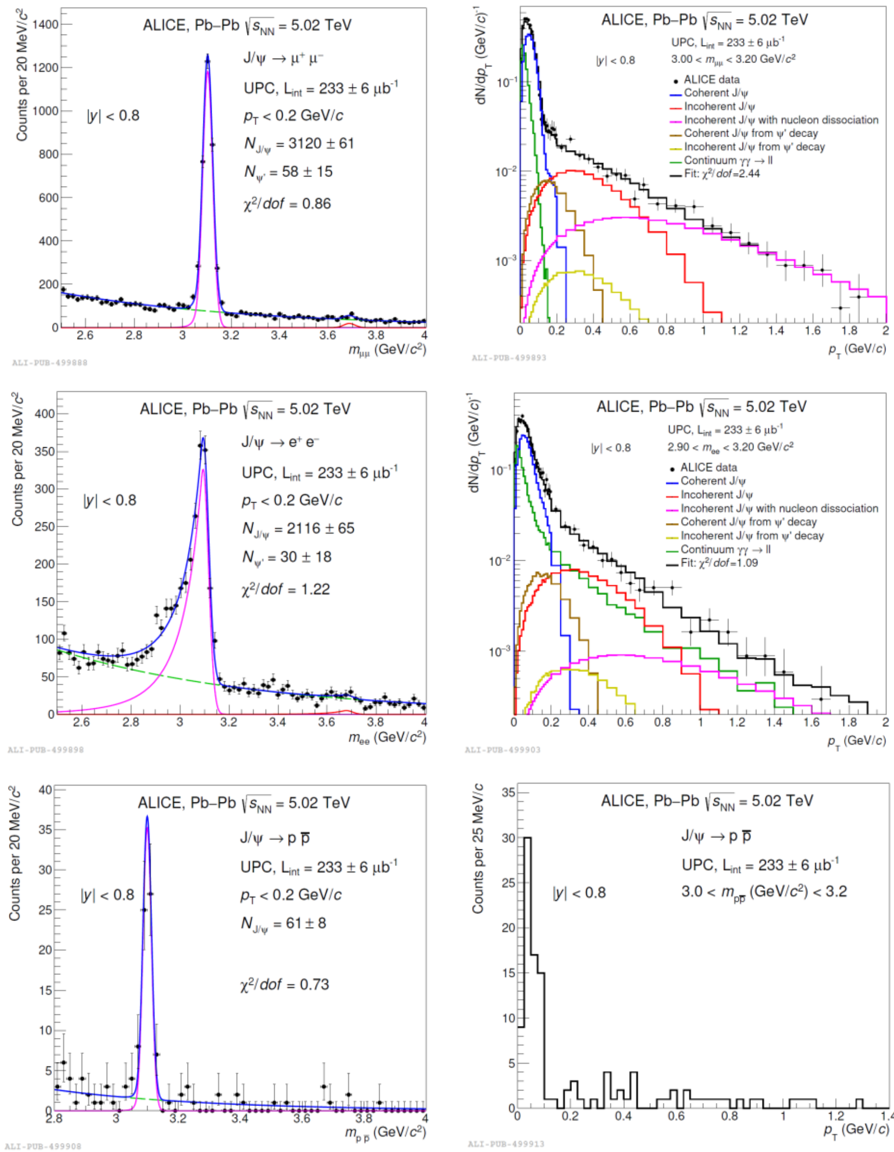

ALICE Xe–Xe UPC $\sqrt{s_{NN}}$ = 5.44 TeV
ALICE data
Full fit
ρ^0 Breit–Wigner
ρ^0–$\pi\pi$ interference
Muon template
p_T < 0.15 GeV/c
|y| < 0.8
$d^2\sigma/(dmdy)$ (b/(GeV/c^2))
$m(\pi\pi)$ (GeV/c^2)
ALI-PUB-496195

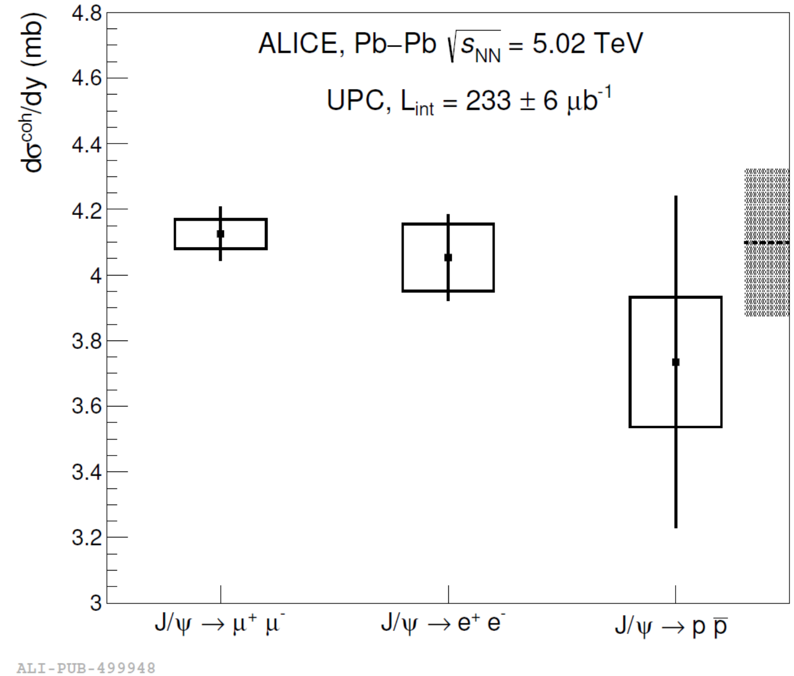
J/ψ in Pb-Pb – forward



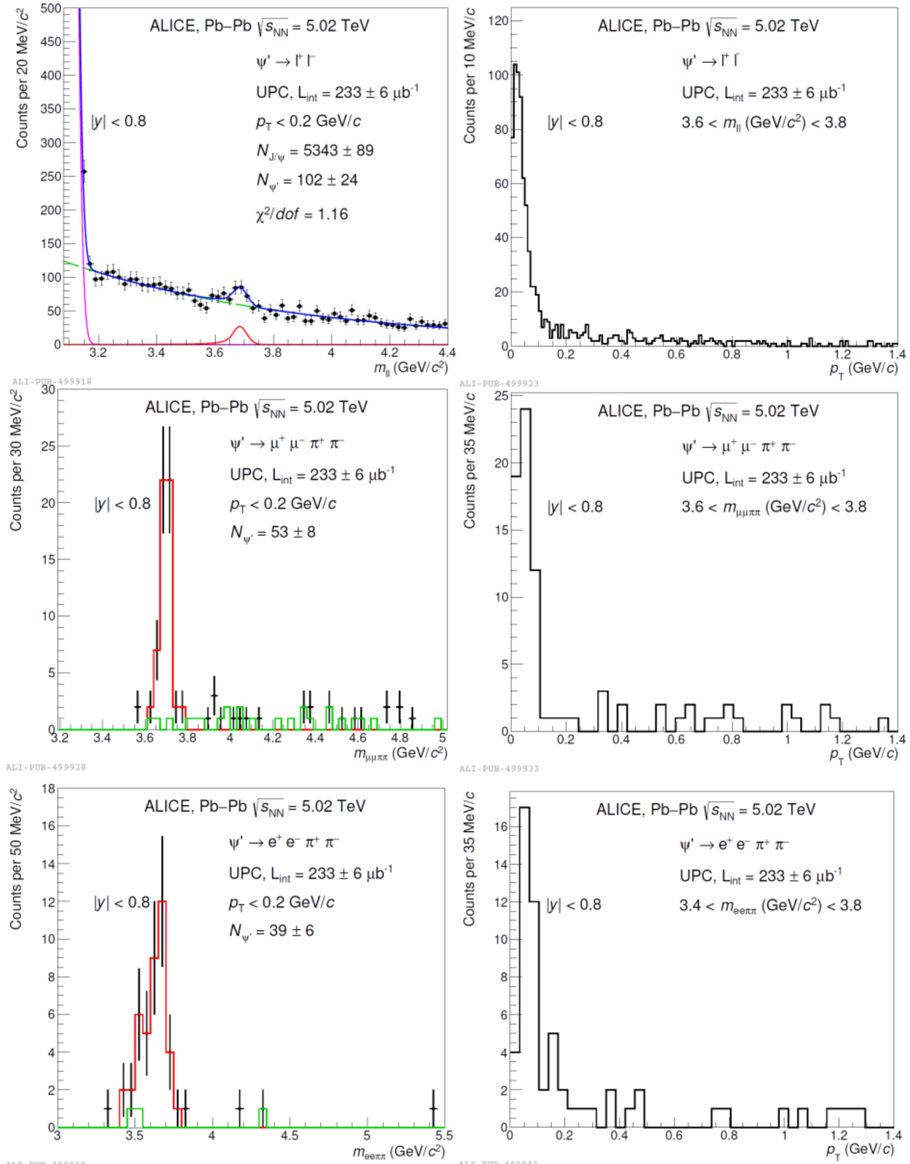


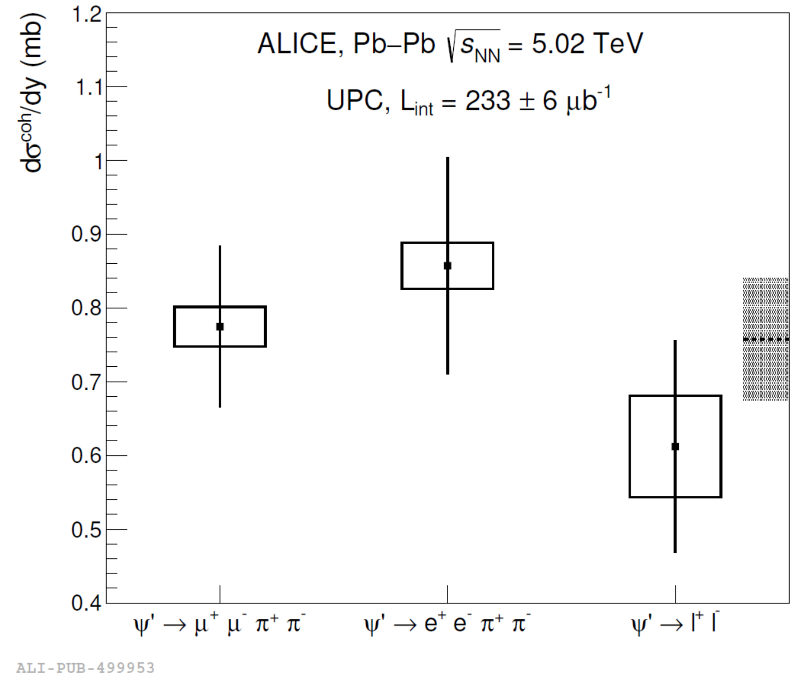
J/ψ in Pb-Pb – central barrel



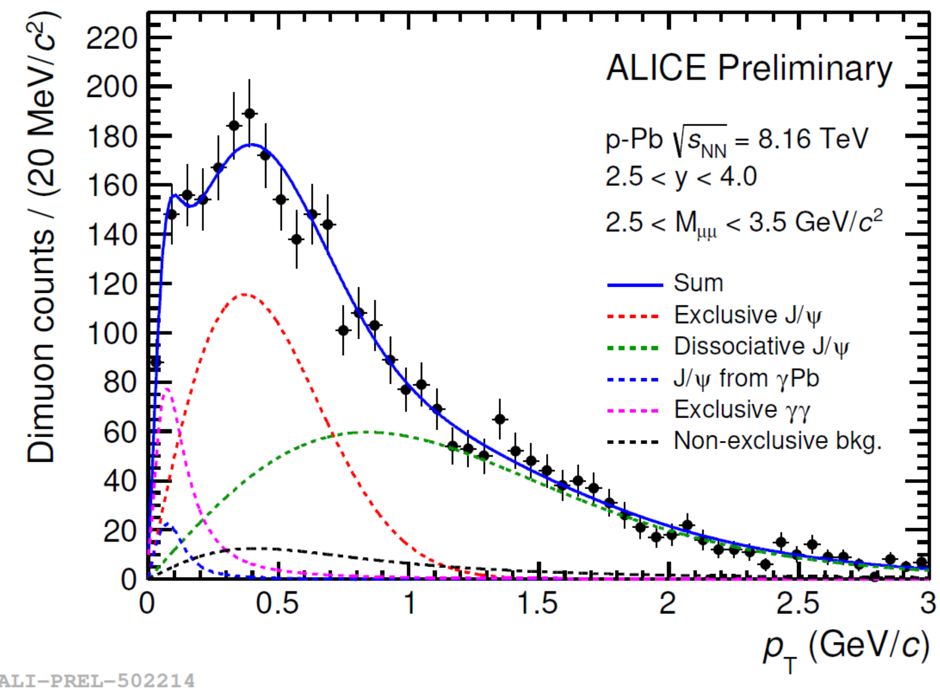


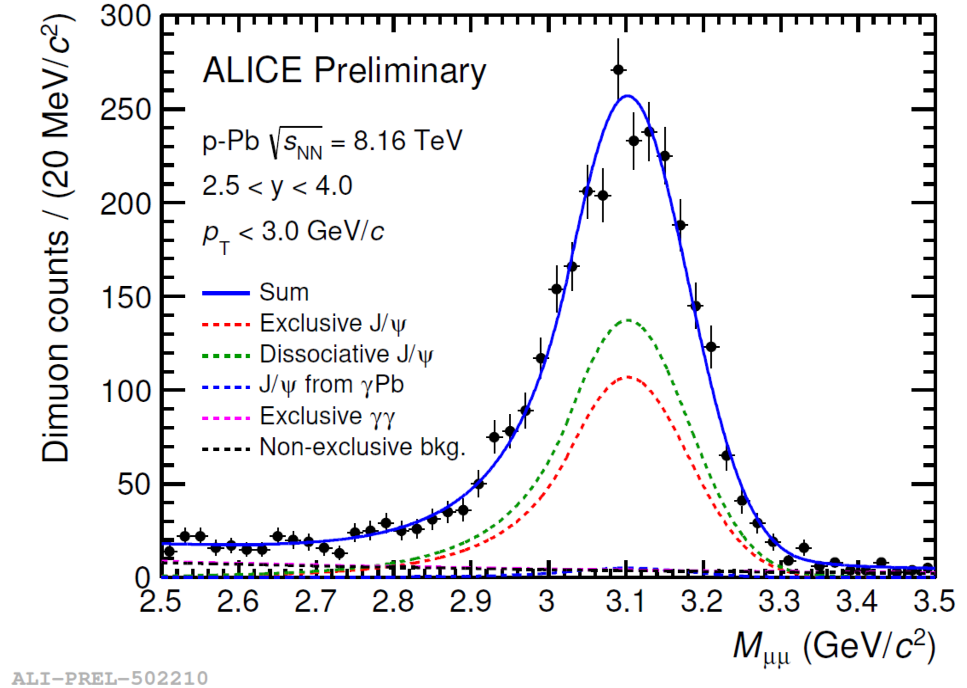
ψ’ in Pb-Pb – central barrel





Exclusive J/ψ in p-Pb





Cross section parameterization

$$\frac{d\sigma}{dm\,dy} = |A \cdot BW_\rho + B|^2 + M,$$

$$BW_\rho = \frac{\sqrt{m \cdot m_{\rho^0} \cdot \Gamma(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \cdot \Gamma(m)}$$

$$\Gamma(m) = \Gamma(m_{\rho^0}) \cdot \frac{m_{\rho^0}}{m} \cdot \left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - m_\pi^2} \right)^{3/2}$$

Soding formula

- A – normalization
- B – non resonsnt amplitude
- M – other background
- BW_ρ – Breit-Wigner function
- Γ(m) – mass dependent width
- $m_{\rho 0}$ – pole mass
- m_π - pion mass

ρ_3(1690) with angular momrentum J = 3

$$\frac{dN_{\pi\pi}}{dm} = P_1 \cdot \exp(-P_2 \cdot (m - 1.2\,\mathrm{GeV}/c^2)) + P_3 + P_4 \cdot \exp(-(m - M_x)^2/\Gamma_x^2)$$

VM cross section

$$\frac{\mathrm{d}\sigma_{\mathrm{VM}}^{\mathrm{coh}}}{\mathrm{dy}} = \frac{N_{\mathrm{VM}}^{\mathrm{coh}}}{\varepsilon_{\mathrm{VM}} \times \varepsilon_{\mathrm{veto}}^{\mathrm{pileup}} \times \varepsilon_{\mathrm{veto}}^{\mathrm{EMD}} \times \mathrm{BR} \times \mathscr{L}_{\mathrm{int}} \times \Delta\mathrm{y}}$$

$$N_{J/\psi}^{\mathrm{coh}} = \frac{N_{\mathrm{yield}}}{1 + f_{\mathrm{I}} + f_{\mathrm{D}}}$$

$$N_{\psi'}^{\mathrm{coh}} = \frac{N_{\mathrm{yield}}}{1 + f_{\mathrm{I}}}.$$

- N_{yield} – J/ψ or ψ' raw yield,
- ε_{VM} - reconstruction efficiency
- f_I – incoherent contamination fraction
- f_D – feed down contamination fraction
- L_{int} – integrated luminosity
- Δy – rapidity interval
- BR – branching ratio of the Decay
- $\varepsilon^{pileup}{}_{veto}$ – pileup veto efficiency
- $\varepsilon^{EMD}{}_{veto}$ – electromagnetic dissociation veto efficiency

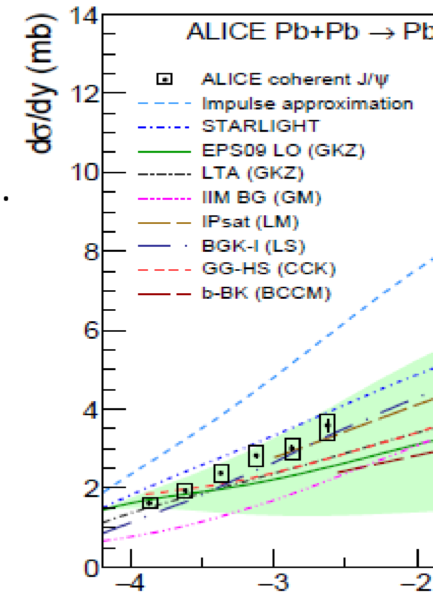
Shadowing and saturation

- Shadowing – the experimental fact that the nuclear structure functions are suppressed compared to the superposition of those of their constituent nucleons.
  - N. Armesto, “Nuclear shadowing”, J. Phys. G 32 (2006) R367–R394.
- Saturation – a dynamic equilibrium between gluon radiation and recombination.
  - J. L. Albacete and C. Marquet, “Gluon saturation and initial conditions for relativistic heavy ion collisions”, Prog. Part. Nucl. Phys. 76 (2014) 1–42.

Models

- **Black disk limit:**
  - Frankfurt, Strikman, Zhalov, *Phys. Lett.* B537 (2002) 51–61.
  - total cross section of the interaction is equal to $2\pi R_A^2$.
- **STARlight:**
  - Klein, Nystrand, Seger, Gorbunov, Butterworth, Comput. Phys. Commun. 212 (2017) 258–268; Klein and Nystrand, Phys. Rev. C 60 (1999) 014903.
  - Based on a phenomenological description of the exclusive production of VM off nucleons, the optical theorem, and a Glauber-like eikonal formalism, does not take into account the elastic part of the elementary VM–nucleon cross section.
  - Includes multiple scattering, **no gluon shadowing**.
- **GKZ (Guzey, Kryshen and Zhalov):**
  - Guzey, Kryshen, Zhalov, Phys. Rev. C93 (2016) 055206; Frankfurt, Guzey, Strikman, Zhalov, Phys. Lett. B752 (2016) 51–58.
  - Based on a modified **vector dominance model**, in which the hadronic fluctuations of the photon interact with the nucleons in the nucleus according to the Gribov-Glauber model of **nuclear shadowing**
- **GMMNS (Goncalves, Machado, Morerira, Navarra and dos Santos):**
  - Gonçalves, Machado, Moreira, Navarra, dos Santos, Phys. Rev. D96 (2017) 094027; Iancu, Itakura, Munier, Phys. Lett. B590 (2004) 199–208,
  - Based on the Iancu-Itakura-Munier (IIM) implementation of **gluon saturation** within the **colour dipole model** coupled to a boosted-Gaussian description of the wave function of the vector meson.
- **CCKT (Cepila, Contreras, Krelina and Tapia):**
  - Cepila, Contreras, Tapia Takaki, Phys. Lett. B766 (2017) 186–191; Cepila, Contreras, Krelina, Tapia Takaki, Nucl. Phys. B934 (2018) 330–340; N. Armesto, Eur. Phys. J. C26 (2002) 35–43
  - Based on the **colour dipole model** with the structure of the nucleon in the transverse plane described by so-called **hot spots**, regions of high gluonic density, whose number increases with increasing energy. The nuclear effects are implemented along the ideas of the Glauber model. Version without hot spots (named *nuclear*) and including them.
  - Indicates **gluon saturation**.

Models



- **Impulse approximation:**
  - Exclusive photoproduction off protons, neglects all nuclear effects but coherence.
  - Based on STARlight.
- **EPS09 LO:**
  - GKZ model with parameterization of **nuclear shadowing** data.
  - Eskola, Paukkunen, Salgado, JHEP 04 (2009) 065.
- **LTA:**
  - GKZ model based on Leading Twist Approximation of **nuclear shadowing**.
  - Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255–393.
- **IIM BG, IPsat, BGK-I:**
  - **Color dipole** approach coupled to the Color Glass Condensate (CGC) formalism with different assumptions on the dipole-proton scattering amplitudę.
  - Gonçalves, Moreira, Navarra, Phys. Rev. C 90 (2014) 015203; dos Santos, Machado, J. Phys. G 42 no. 10, (2015) 105001. (saturation)
  - Lappi, Mäntysaari, Phys. Rev. C 83 (2011) 065202; Lappi, Mäntysaari, Phys. Rev. C 87 (2013) 032201. (saturation)
  - A. Łuszczak, Schäfer, Phys. Rev. C 99 no. 4, (2019) 044905. (shadowing)
- **GG-HS**:
  - CCK **color dipol model** with **hot spots** nucleon structure with Glauber-Gribov formalism
  - Cepila, Contreras, Krelina, Phys. Rev. C 97 no. 2, (2018) 024901; Cepila, Contreras, Tapia Takaki, Phys. Lett. B766 (2017) 186–191.
- **b-BK:**
  - Bendova, Cepila, Contreras, Matas (BCCM) model based on the **color dipole** approach coupled to the impact-parameter dependent Balitsky-Kovchegov equation with initial conditions based on the Woods-Saxon shape of the Pb nucleus.
  - Bendova, Cepila, Contreras, Matas, Physics Letters B 817 (2021) 136306.

Models

- noon:
  - Broz, Contreras, Tapia Takaki, “A generator of forward neutrons for ultra-peripheral collisions: nOOn”, Comput. Phys. Commun. (2020) 107181.
- JMRT NLO:
  - next-to-leading-order calculations
  - Jones, Martin, Ryskin, Teubner, J. Phys. G 44 no. 3, (2017) 03LT01; JHEP 11 (2013) 085.
- BM:
  - Perturbative JIMWLK evolution based on HERA data
  - Mantysaari, Schenke, Phys. Rev. D 98 no. 3, (2018) 034013

Systematic uncertainty

ρ^0 in Pb-Pb

Source	Uncertainty
Variations to the fit procedure	0.4–5.9 %
Ross-Stodolsky fit model	+3.5%
Track selection	±1.5%
Track matching	±4.0%
Acceptance and efficiency	±1.0%
Muon background ($\gamma\gamma \rightarrow \mu^+\mu^-$)	±0.3%
Incoherent contribution	±0.5%
Trigger efficiency of SPD chips	±1.0%
Pile-up	±3.8%
Luminosity	±5.0%
Total	$^{+(8.5-10.3)}_{-(7.8-9.7)}$ %

ρ^0 in Xe-Xe

Source	Uncertainty
Variations to the fit procedure	±2.5%
Ross–Stodolsky fit model	+3.5%
Acceptance and efficiency	±0.5%
Track selection	±3.0%
Track ITS–TPC matching	±4.0%
SPD trigger-to-track matching	±2.0%
TOF trigger efficiencies	±2.8%
Vertex selection	±1.5%
Incoherent contribution	±2.0%
Pile-up	±1.0%
Muon background ($\gamma\gamma \rightarrow \mu^+\mu^-$)	$^{+(0.5)}_{-(0.2)}$ %
Electromagnetic dissociation	±0.2%
Luminosity	±10.7%
Total	$^{+(13.3)}_{-(12.8)}$ %