ALICE shines light inside proton and nuclei

Michal Broz
Czech Technical University in Prague

On behalf of the ALICE Collaboration

- Photon-induced processes at LHC
- γ-p: search for saturation
- γ-A: probing gluon shadowing
- Prospects for Run 3 and Run 4

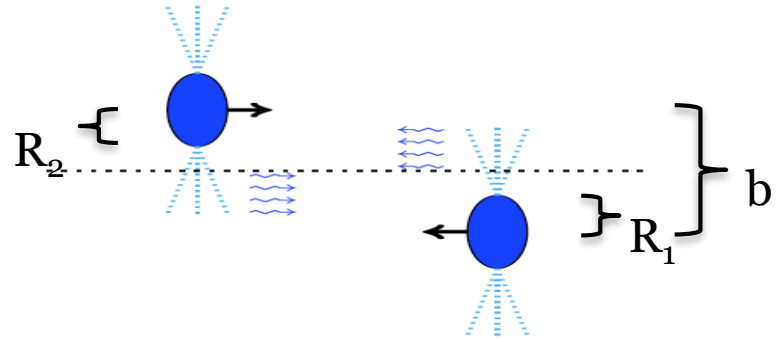
LHC seminar

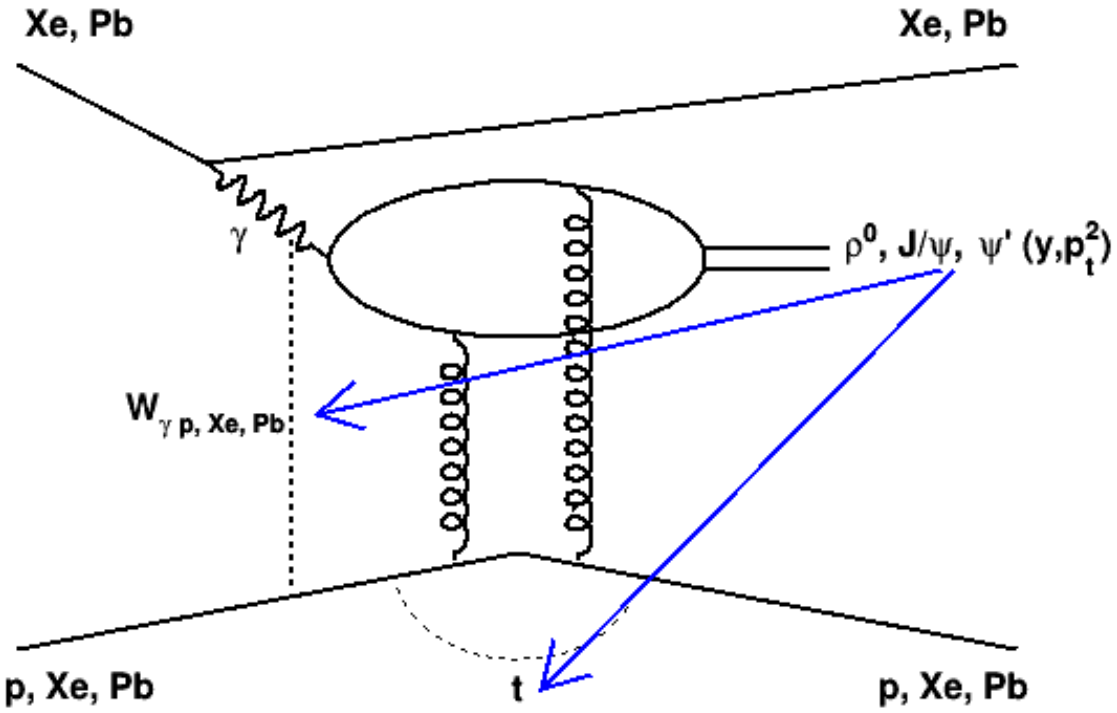
2nd March 2021
CERN

Photon-induced processes at LHC

Ultra-peripheral collisions

- Ultra-peripheral collision = Impact parameter b larger than sum of nuclear radii
- EM field of protons and ions =>beam of quasi real photons (intensity ≈ Z^2)
- Using Pb-Pb and p-Pb data at the LHC it is possible to study γ-Pb, γp and γγ collisions at higher center of mass energies than ever before
- LHC is a photon-hadron collider (Light-Hadron Collider)

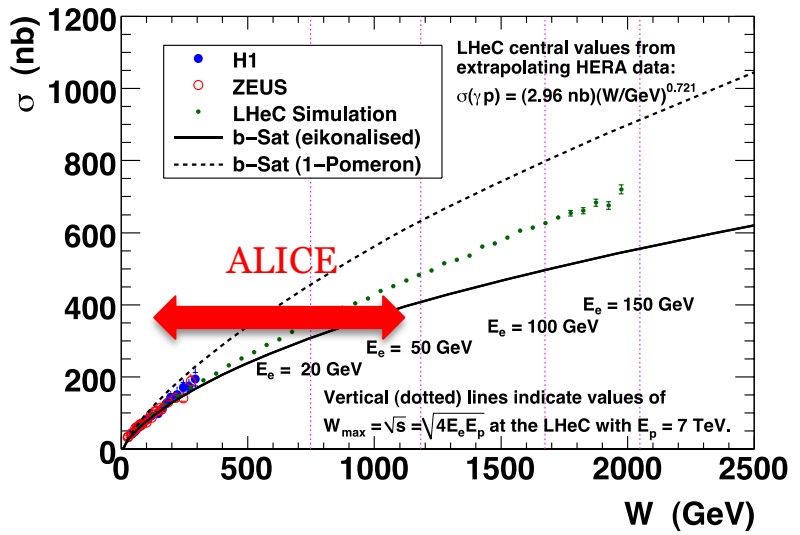


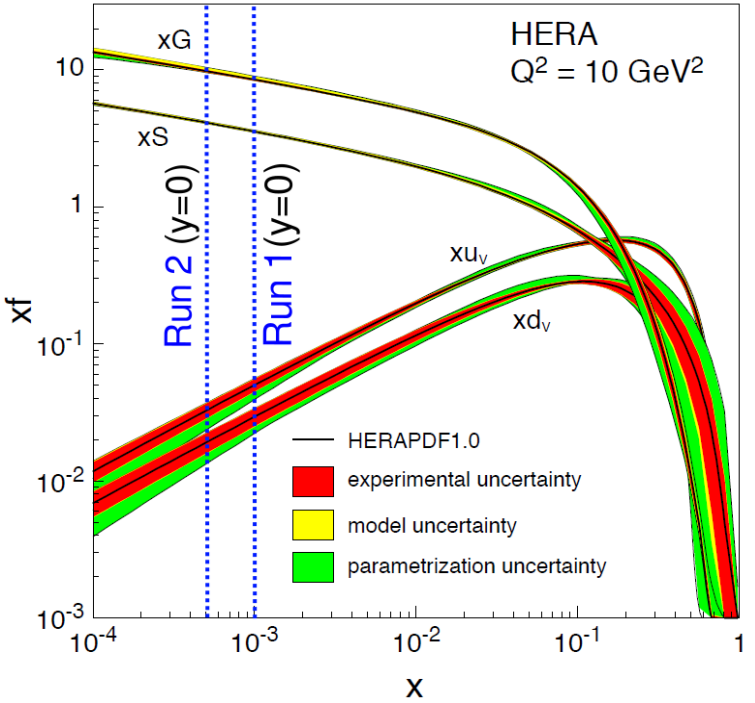


Gluon saturation in γp collisions

- The density of gluons at small x grows rapidly
  - Gluon saturation = mechanism to slow down the growth
  - Important implications in the early stages of ultrarelativistic heavy-ion collisions
- Evidence for gluon saturation = central task for QCD experiments
  - Only hints at HERA, RHIC, CEBAF and LHC so far

LHeC Study group, ArXiv: 1211.4831





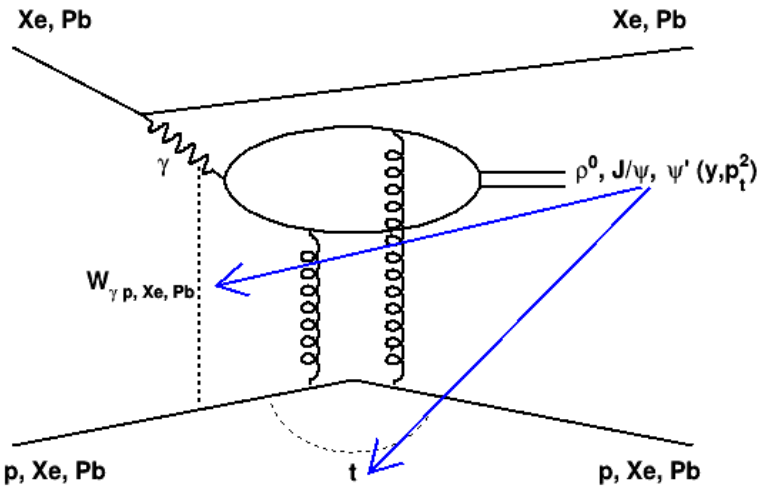
Exclusive vector meson production

- Only vector meson is produced, nothing else
- Photon fluctuates into a quark-antiquark pair
  - Spin 1 and negative parity => fluctuation to vector meson
- Probe the nuclear gluon density at low Bjorken-x

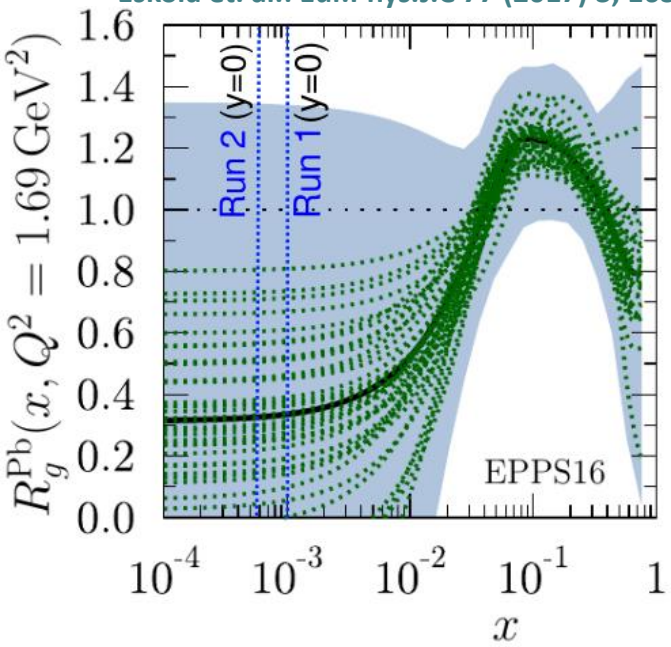
$$x = p_{\text{parton}} / p_{\text{hadron}}$$

$$x = \frac{M_{J/\psi}}{\sqrt{s}} e^{\pm y} \qquad Q^2 \sim \frac{M_{J/\psi}^2}{4}$$

- Constrain the initial state by measuring the nuclear effects on the parton distribution functions (PDFs)
  - Important to control hard probes in Pb-Pb
- Nuclear effects in the gluon PDFs = nuclear shadowing
  - PDFs at small-x are suppressed wrt. free proton

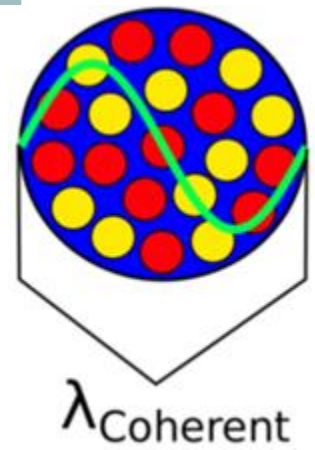


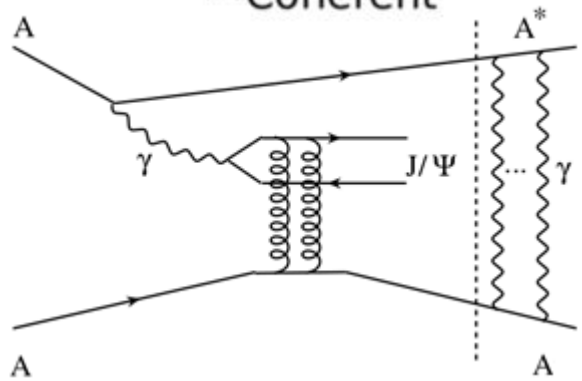
Eskola et. al.: Eur.Phys.J.C 77 (2017) 3, 163

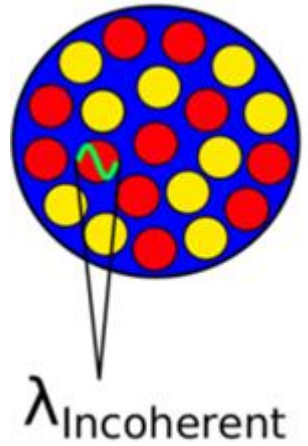


Vector meson photoproduction off nuclei

- Coherent production:
  - Photon interacts with whole nucleus
  - Vector meson $p_T \approx 60$ MeV/c $\sim 1/R_{Pb}$
- Coherent production with nuclear break up:
  - Intense electromagnetic field => independent interaction
  - Excite one/both nuclei => emission of a neutron(s)
- Incoherent production:
  - Photon interacts with single nucleon
  - Vector meson $p_T \approx 300$ MeV/c $\sim 1/R_N$
  - Break up of nuclei => forward neutrons
  - Nucleon may dissociate

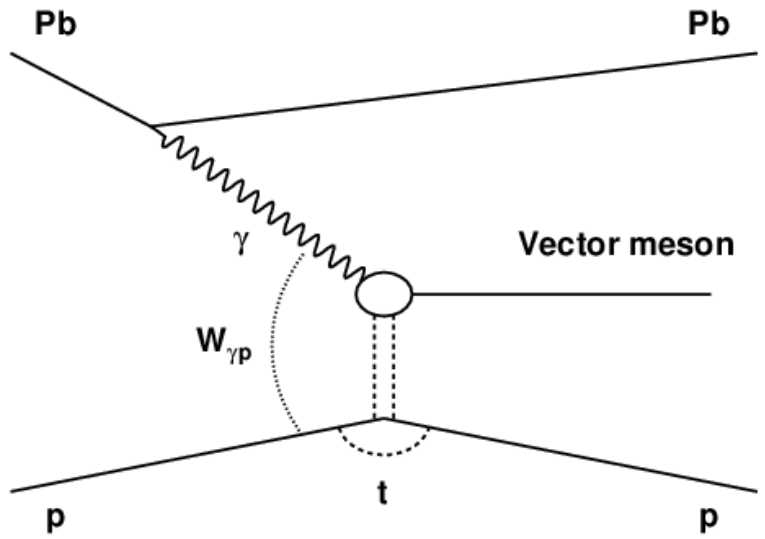




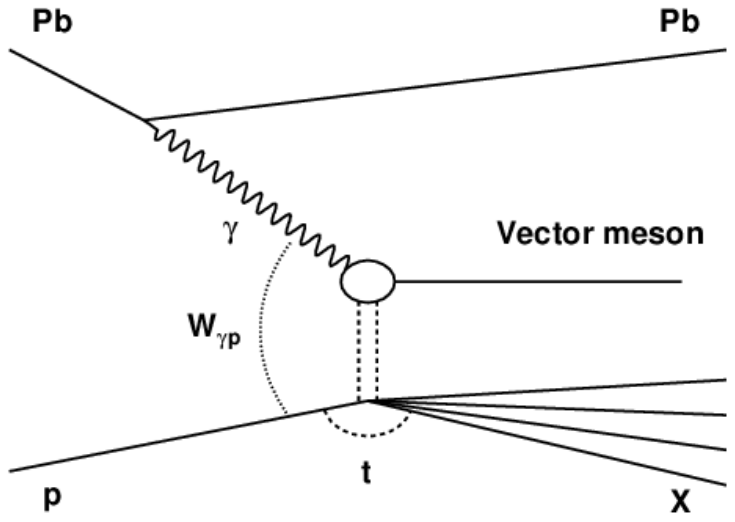


Photoproduction off protons in p-Pb UPCs

- Exclusive production:
  - Photon interacts with the proton without breaking it
  - Vector meson $p_T \approx 300$ MeV/c



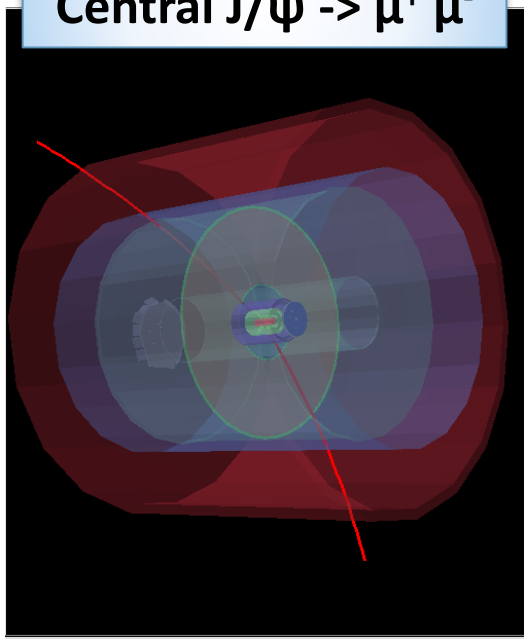
- Dissociative production:
  - Proton is excited and dissociates
  - Vector meson $p_T \approx 1$ GeV/c.



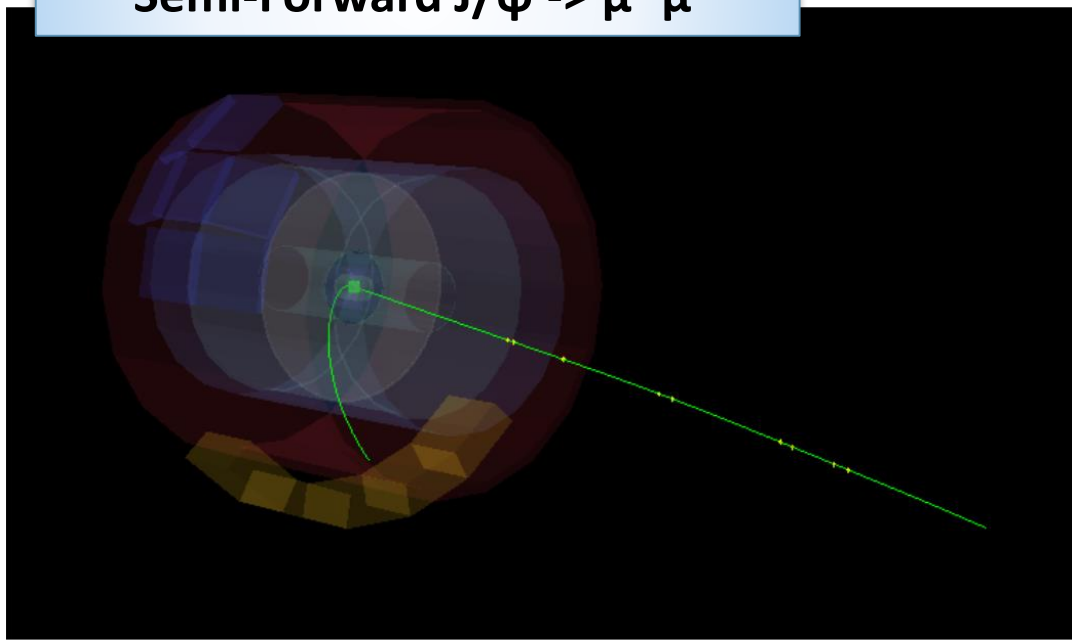
Ultra-peripheral collisions

- Very clean signature - two or four tracks in an otherwise empty detector
- Decay channels:
  - $\rho^0 \rightarrow \pi^+ \pi^-$
  - $J/\psi \rightarrow l^+ l^-$
  - $\psi(2S) \rightarrow l^+ l^-$
  - $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$

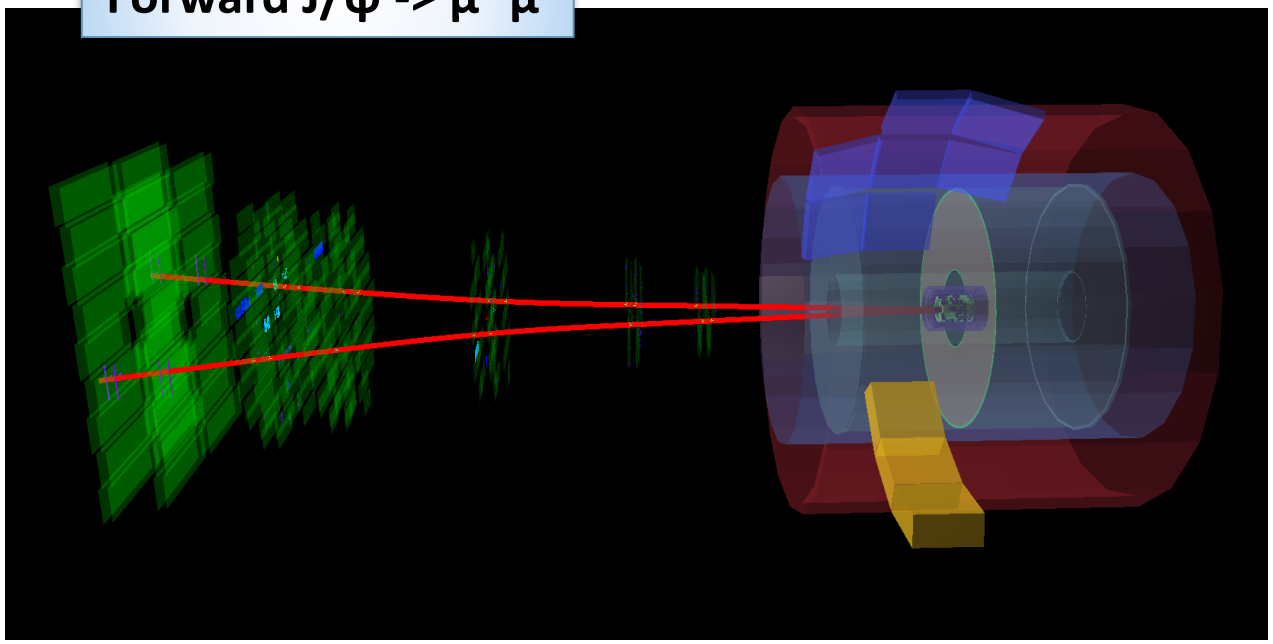
Central $J/\psi \rightarrow \mu^+ \mu^-$

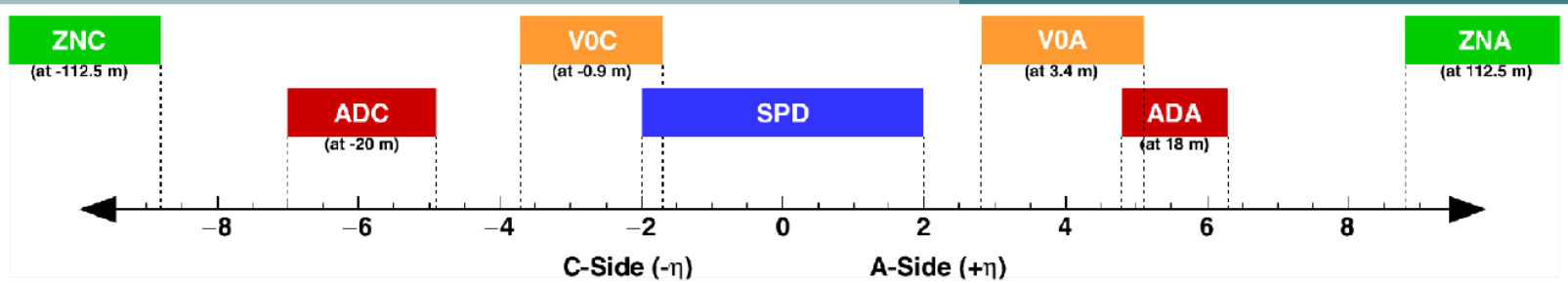


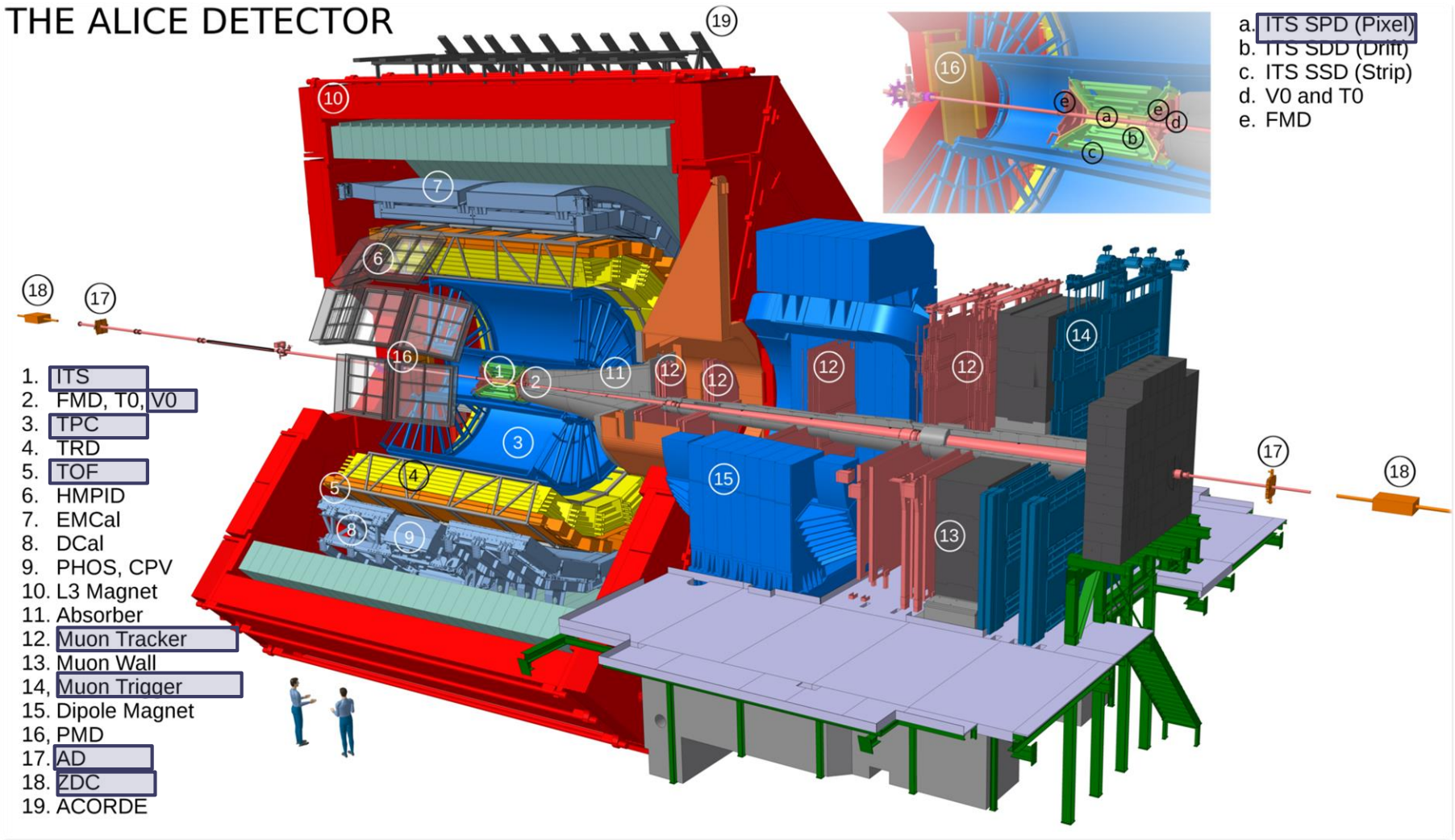
Semi-Forward $J/\psi \rightarrow \mu^+ \mu^-$



Forward $J/\psi \rightarrow \mu^+ \mu^-$




ZNC
(at -112.5 m)
V0C
(at -0.9 m)
V0A
(at 3.4 m)
ZNA
(at 112.5 m)
ADC
(at -20 m)
SPD
ADA
(at 18 m)
−8
−6
−4
−2
0
2
4
6
8
C-Side (-η)
A-Side (+η)


THE ALICE DETECTOR
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

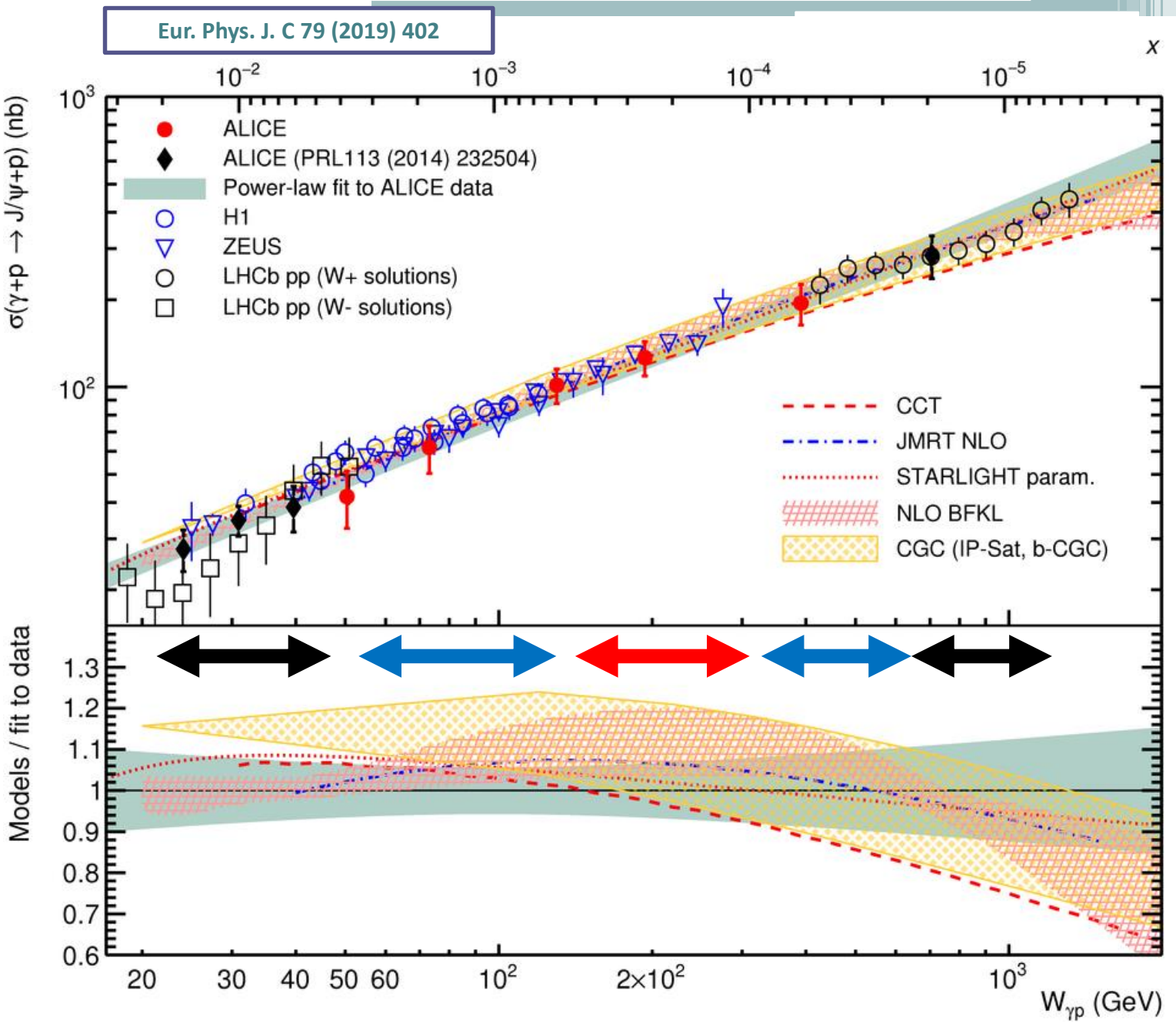
Shining light inside proton
Searching for gluon saturation

Phys. Rev. Lett. 113, 232504 (2014)

Eur. Phys. J. C 79 (2019) 402

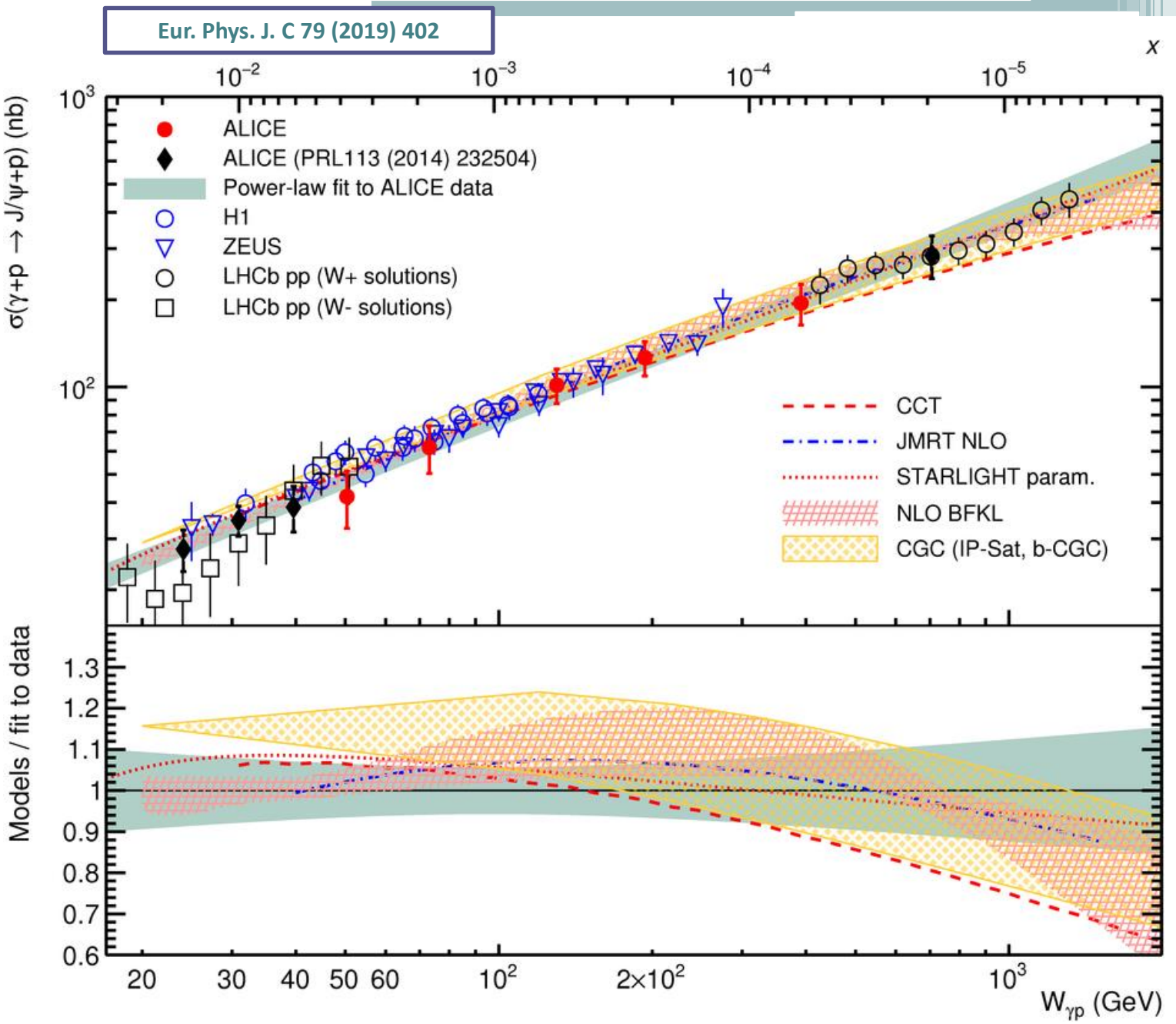
Cross section for J/ψ in γp

- ALICE covers continuously from x=2. 10^{-2} to x= 2. 10^{-5}!
  - **Forward**
  - **Semi-forward**
  - **Central**
- ALICE fits with a **power law** with exponent 0.70 ± 0.05
  - LHCb, H1 (0.67±0.03) and ZEUS (0.69±0.02±0.03) exponents compatible
- No change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC



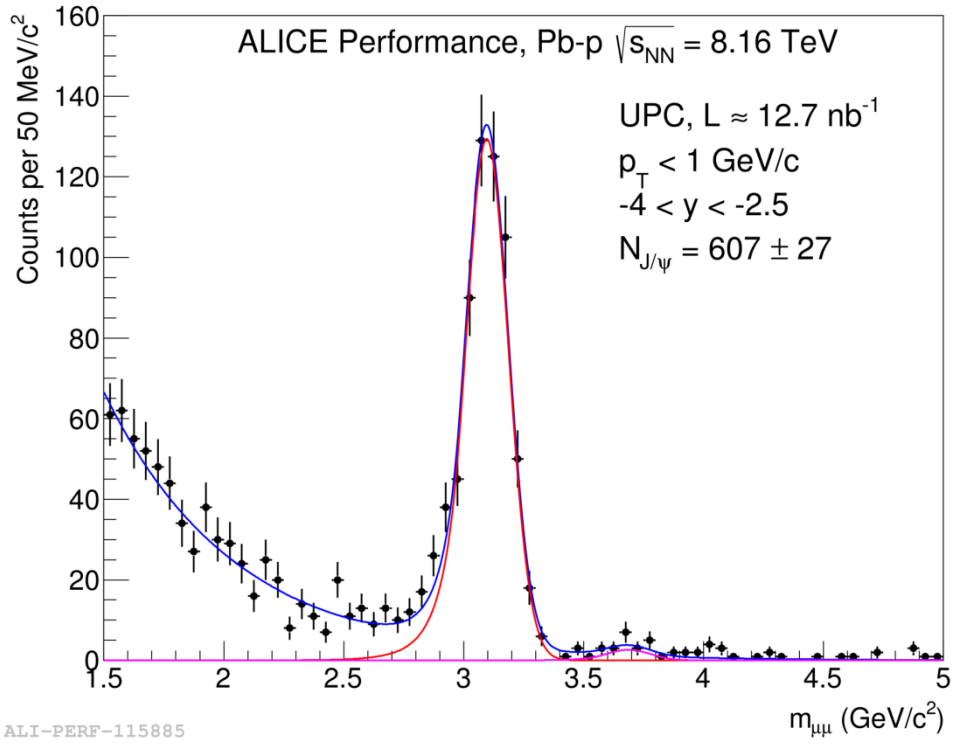
Cross section for J/ψ in γp

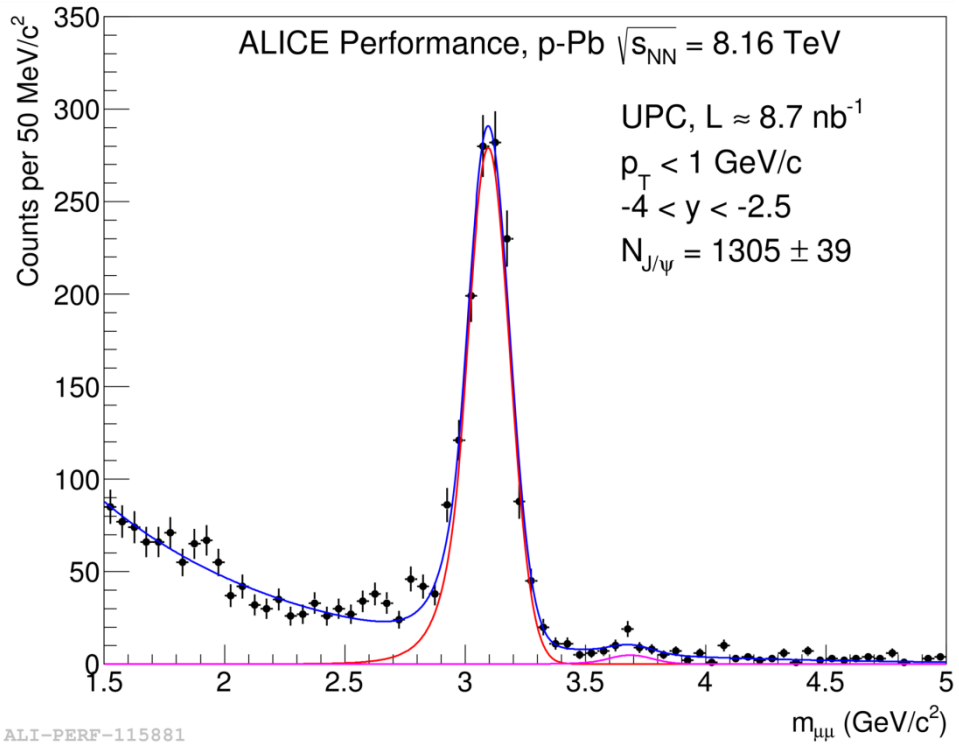
- JMRT NLO: DGLAP formalism with main NLO contributions included
- CCT: Saturation in an energy dependent hot spot model
- CGC: Color dipole model
- NLO BFKL: BFKL evolution of HERA values
- STARLIGHT: Parameterization of HERA and fixed target data
- Good description by all models independently of the inclusion of saturation or subnuclear degrees of freedom



p-Pb at 8.16 TeV

- Data at 5 TeV and 8.16 TeV p-Pb and Pb-p were recorded in Run 2
- Allow us to extend $W_{\gamma p}$ from 700 GeV to **1.4 TeV**
- Search for gluon saturation effects in proton at low x ($5 \cdot 10^{-6}$)
- Study proton-dissociative cross section at high $W_{\gamma p}$ using AD and ZDC





Shining light inside nucleus
Probes of gluon shadowing

Phys.Lett. B798 (2019) 134926

JHEP 06 (2020) 035

arXiv:2101.02581

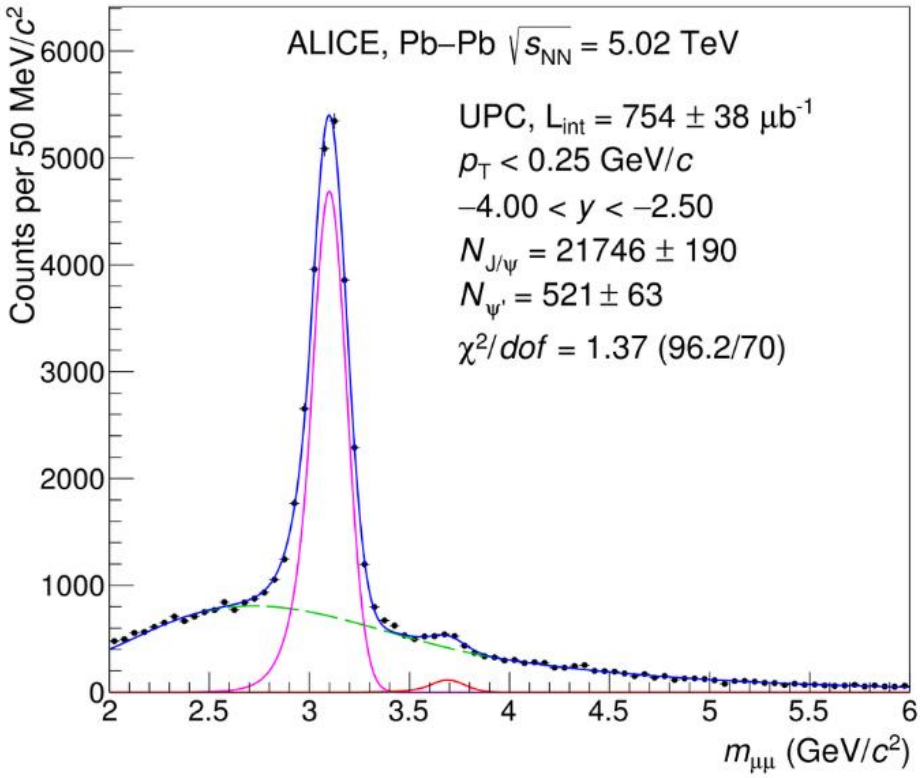
arXiv:2101.04577

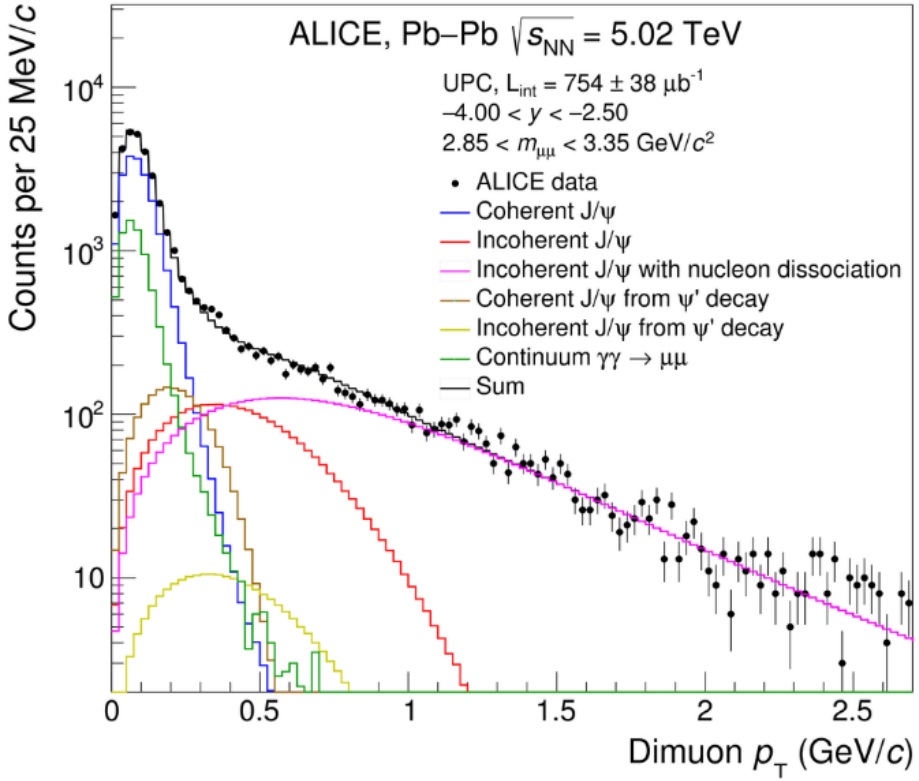
arXiv:2101.04623

Forward rapidity J/ψ

- J/ψ and ψ' fitted by Crystal Ball function
- Background, dominated by γγ->μμ process
- Various p_T templates by STARLIGHT
- High-p_T tail (J/ψ with nucleon dissociation) fitted with H1 parameterization

Phys.Lett. B798 (2019) 134926



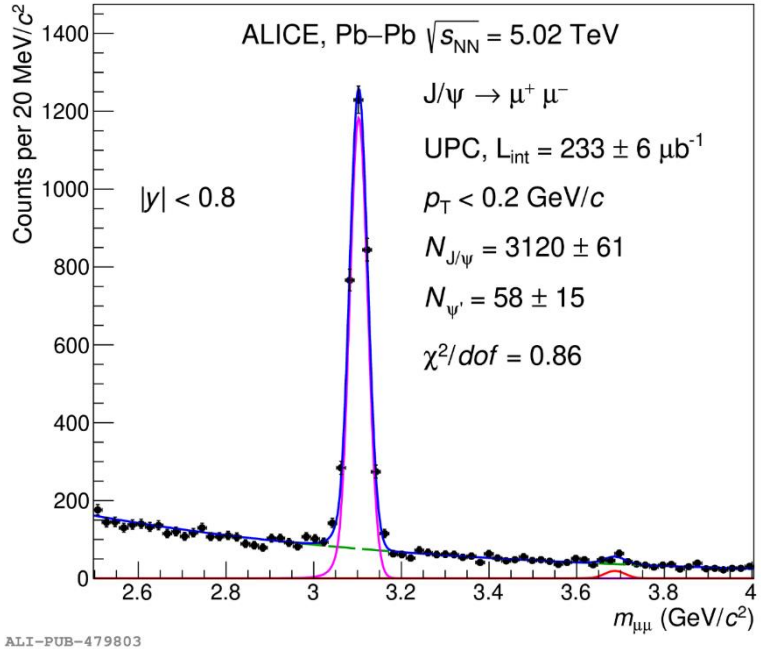


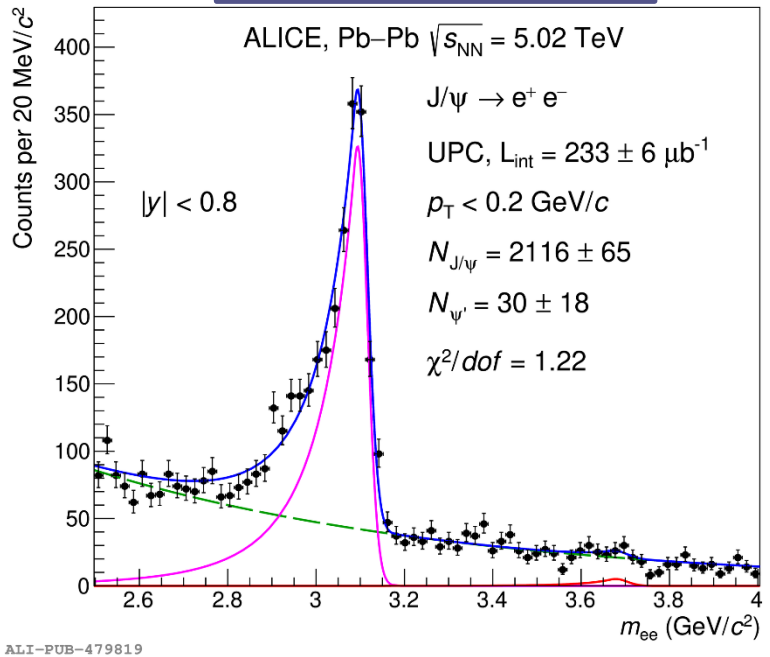
Midrapidity J/ψ and ψ'

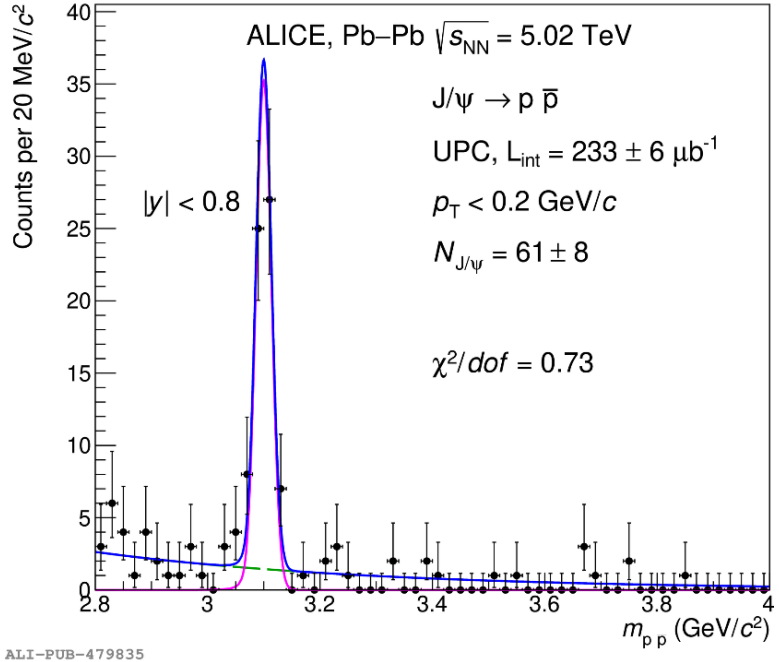
- Analysis based on midrapidity tracks reconstructed in central barrel (ITS,TPC,TOF)
- Particle identification (TPC, TOF) allows us to separate three channels
  - J/ψ -> $\mu^+ \mu^-$
  - J/ψ -> $e^+ e^-$
  - J/ψ -> $p \bar{p}$
- J/ψ and ψ' fitted by Crystal Ball function

Decay channel	Branching ratio
$J/\psi \to \mu^+ + \mu^-$	5.961%±0.033%
$J/\psi \to e^+ + e^-$	5.971%±0.032%
$J/\psi \to p + \bar{p}$	0.2121%±0.0029%

arXiv:2101.04577







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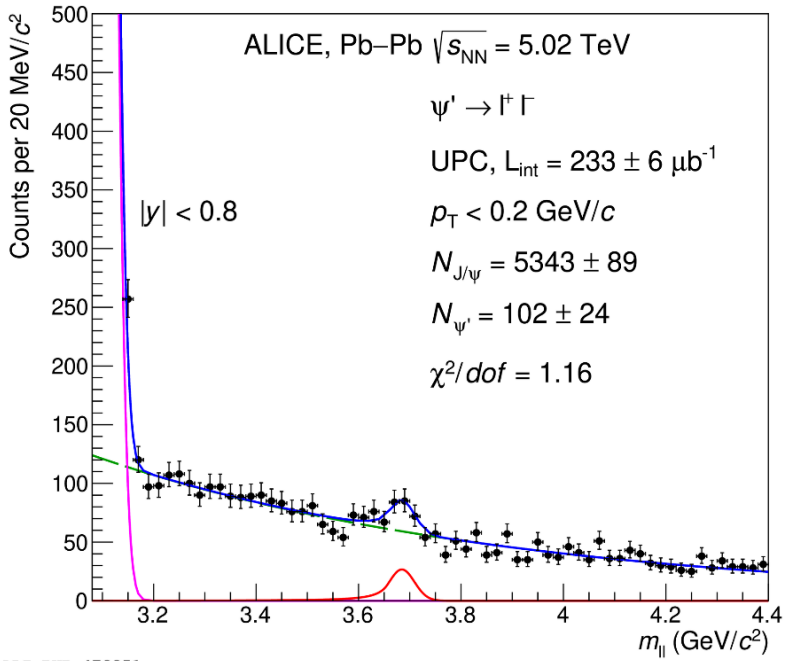
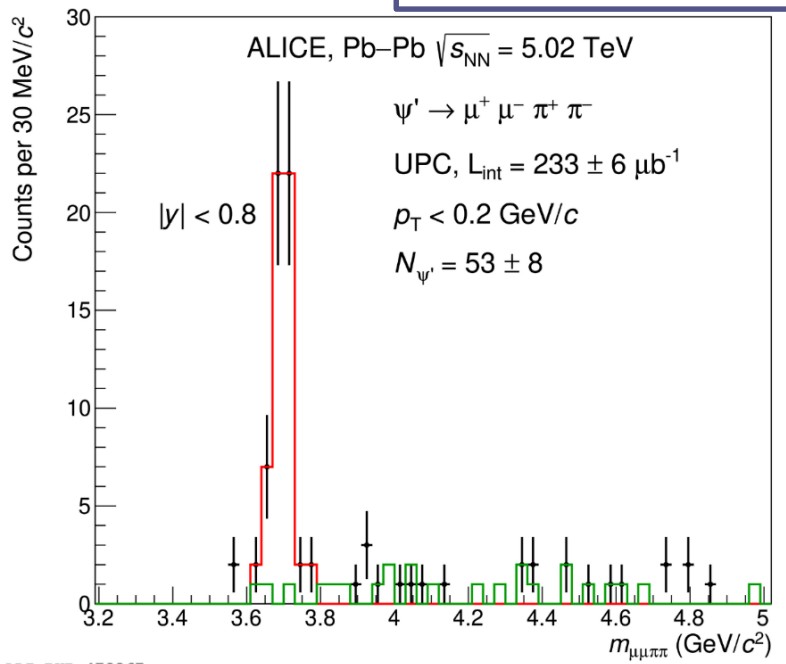
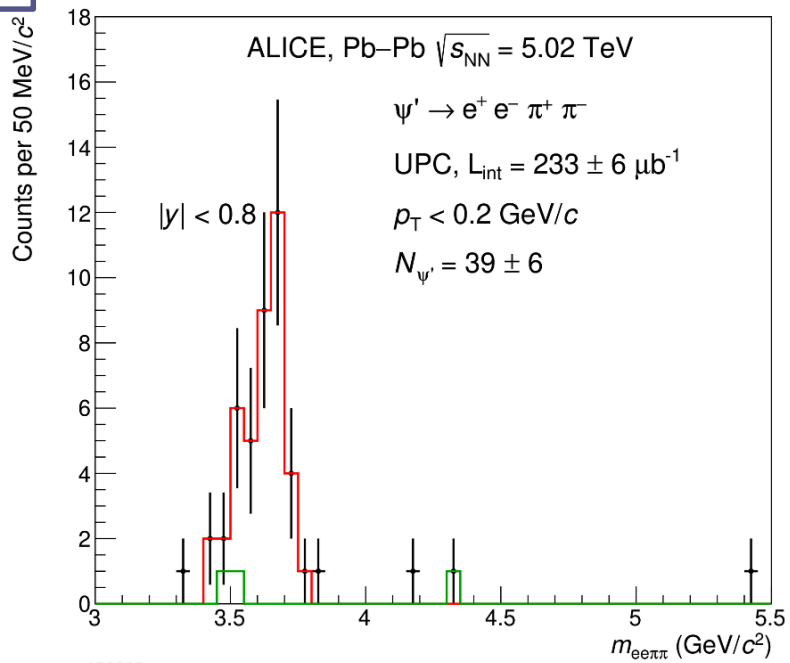
  - ψ' -> $l^+ l^-$
  - ψ' -> J/ψ + $\pi^+ \pi^-$ -> $e^+ e^-$ + $\pi^+ \pi^-$
  - ψ' -> J/ψ + $\pi^+ \pi^-$ -> $\mu^+ \mu^-$ + $\pi^+ \pi^-$
- Four particle final states have very clear signal allowing to extract the yield by simple bin-counting method

Decay channel	Branching ratio
$\psi(2s) \to \mu^+ + \mu^-$	0.8%±0.06%
$\psi(2s) \to e^+ + e^-$	0.793%±0.017%
$\psi(2s) \to J/\psi + \pi^+\pi^-$	34.68%±0.3%
$\psi(2s) \to \mu^+\mu^- + \pi^+\pi^-$	2.07%±0.3%
$\psi(2s) \to e^+e^- + \pi^+\pi^-$	2.07 %±0.3%

arXiv:2101.04577







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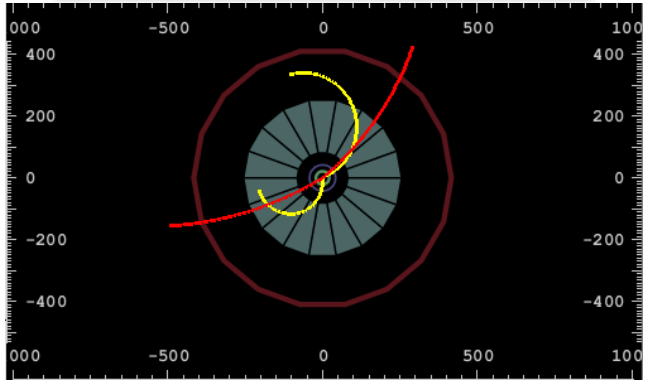
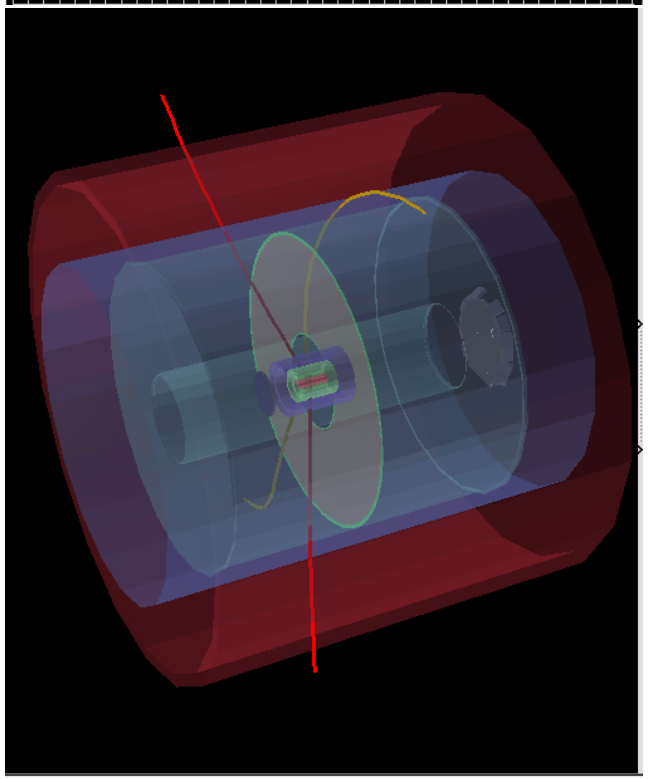
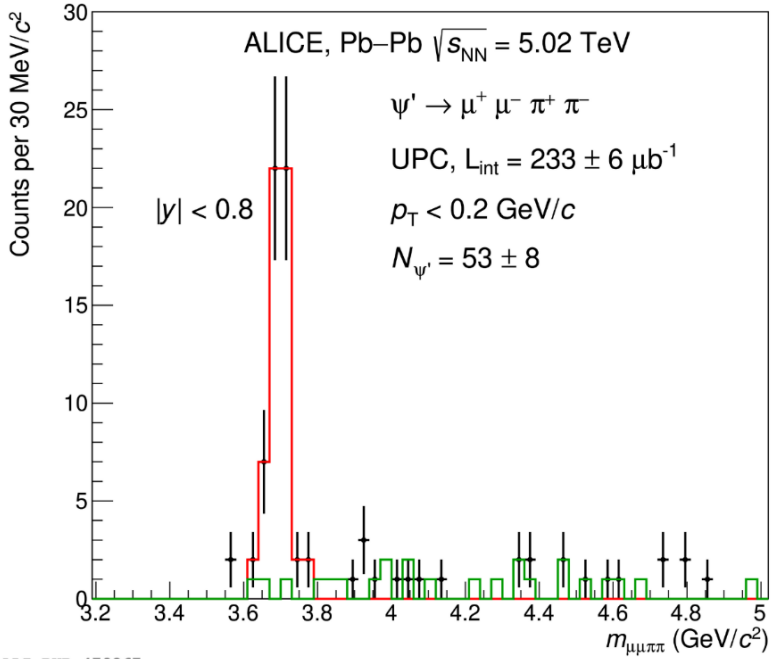
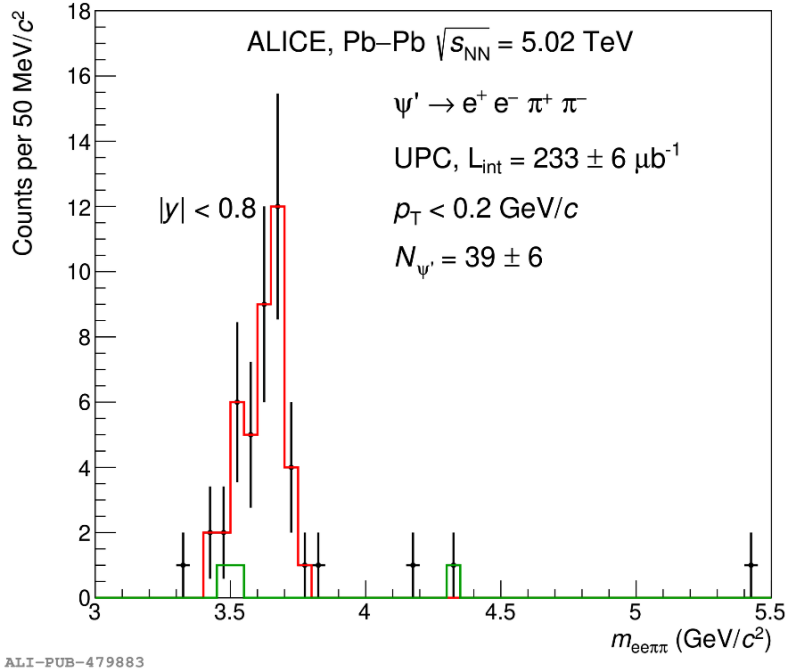
ψ(2s) -> $e^+ e^-$ + $\pi^+ \pi^-$







ALI-PUB-479867

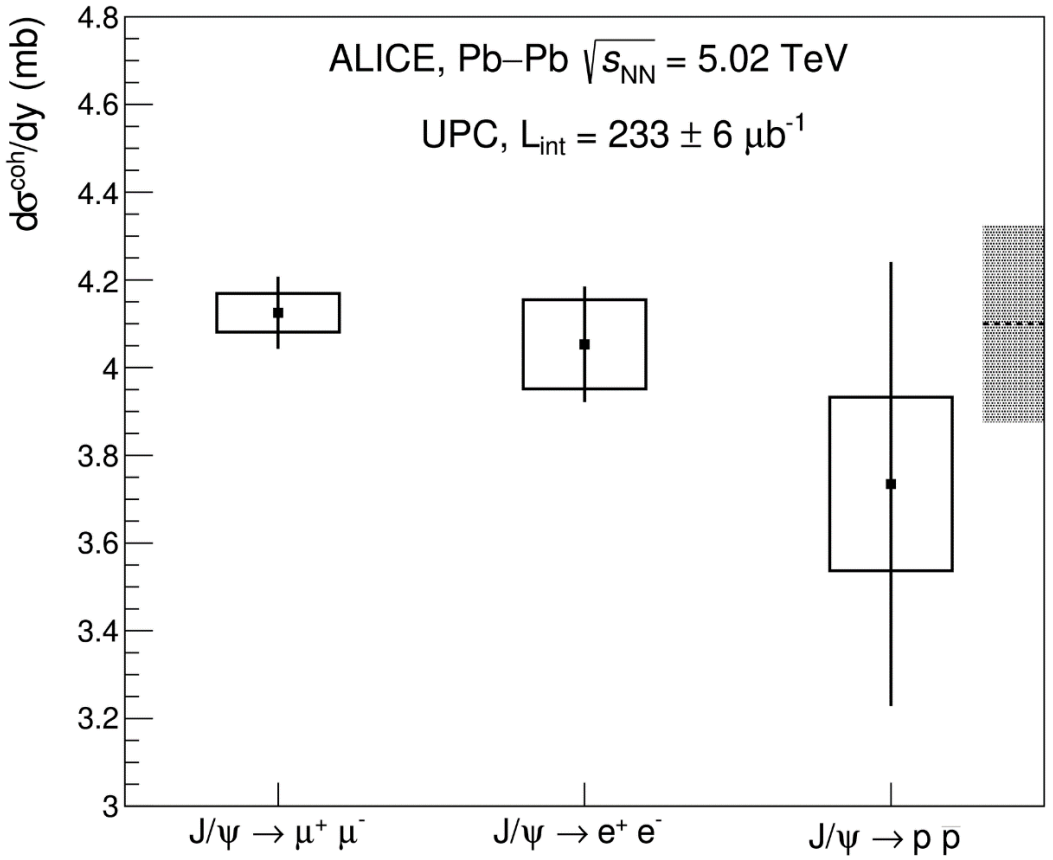


ALI-PUB-479883

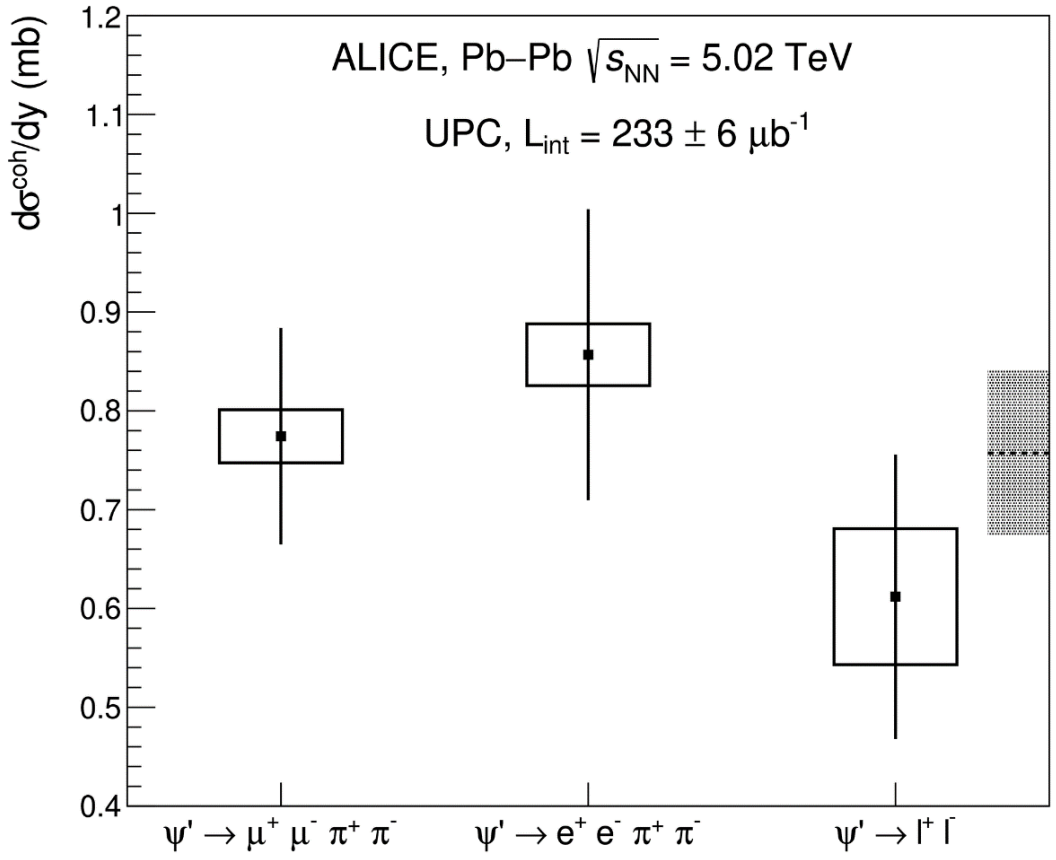
Midrapidity J/ψ and ψ'

- Compatibility between various channels serves as important check of the analysis procedure
- Channels are then combined to final cross section

arXiv:2101.04577



ALI-PUB-479899

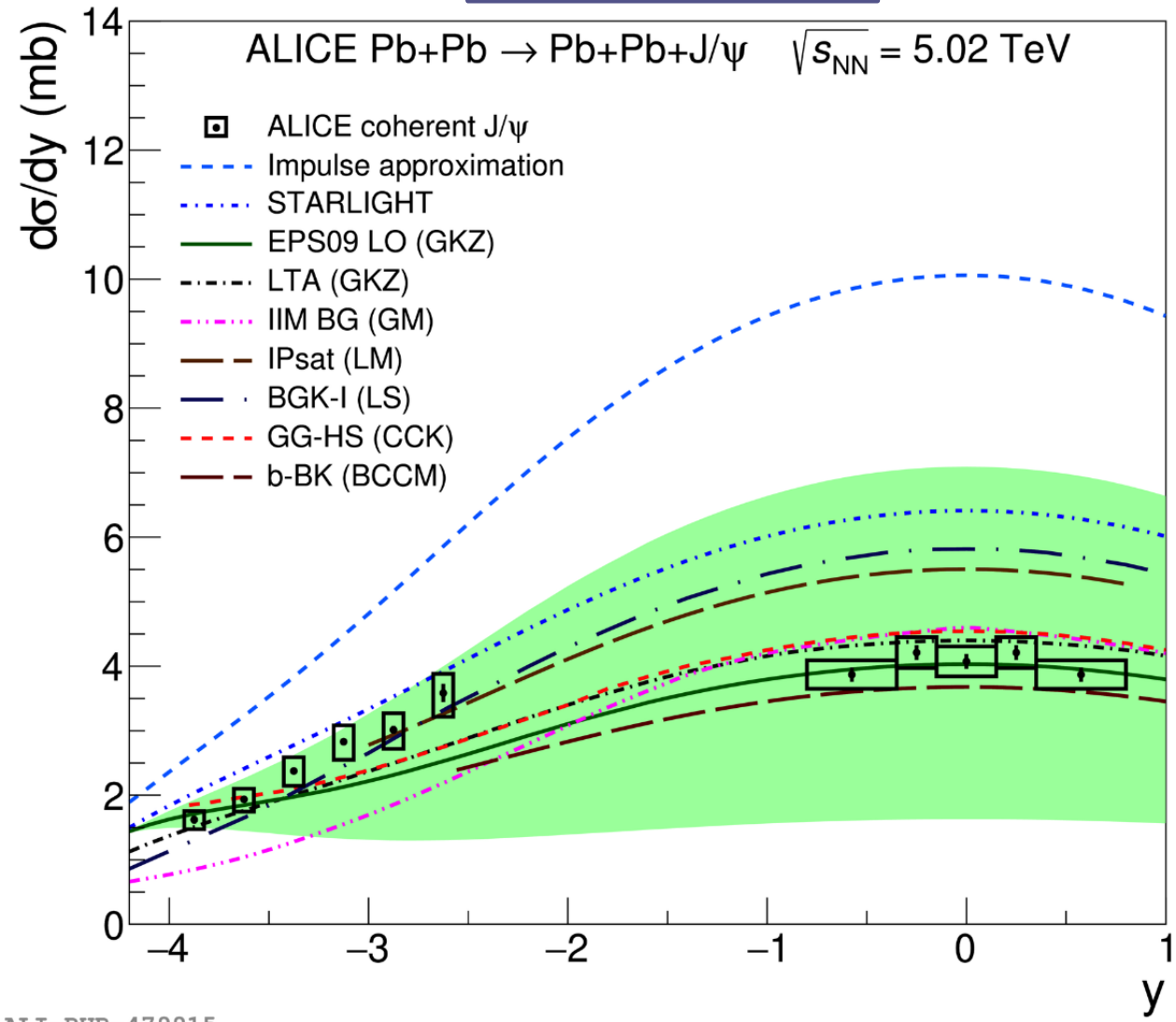


ALI-PUB-479907

UPC J/ψ compared with calculations

- Impulse approximation: Exclusive photoproduction data off protons, neglecting all nuclear effects except coherence.

arXiv:2101.04577



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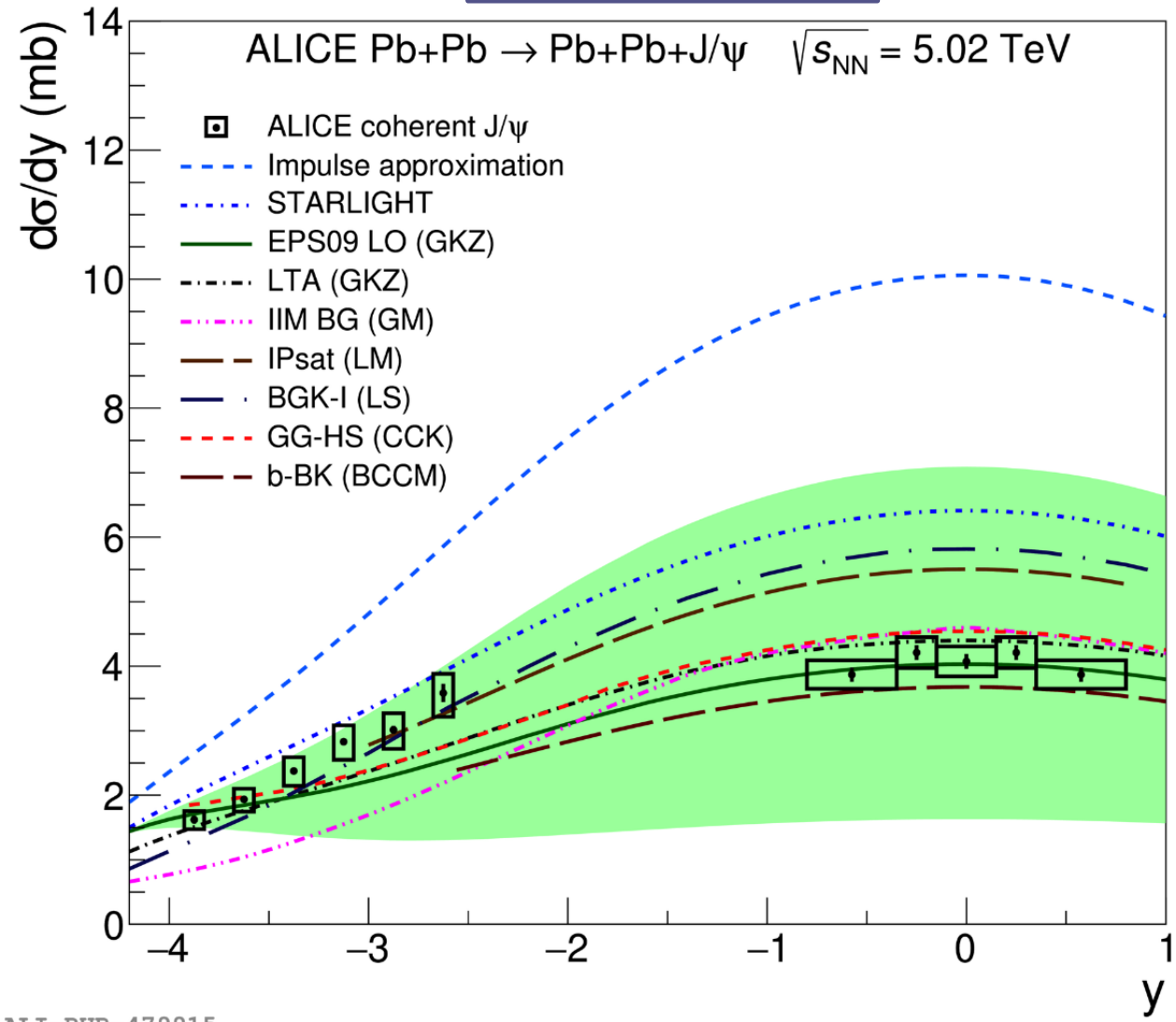
- STARlight: Vector Meson Dominance model with Glauber-like formalism to calculate cross section in Pb-Pb

arXiv:2101.04577



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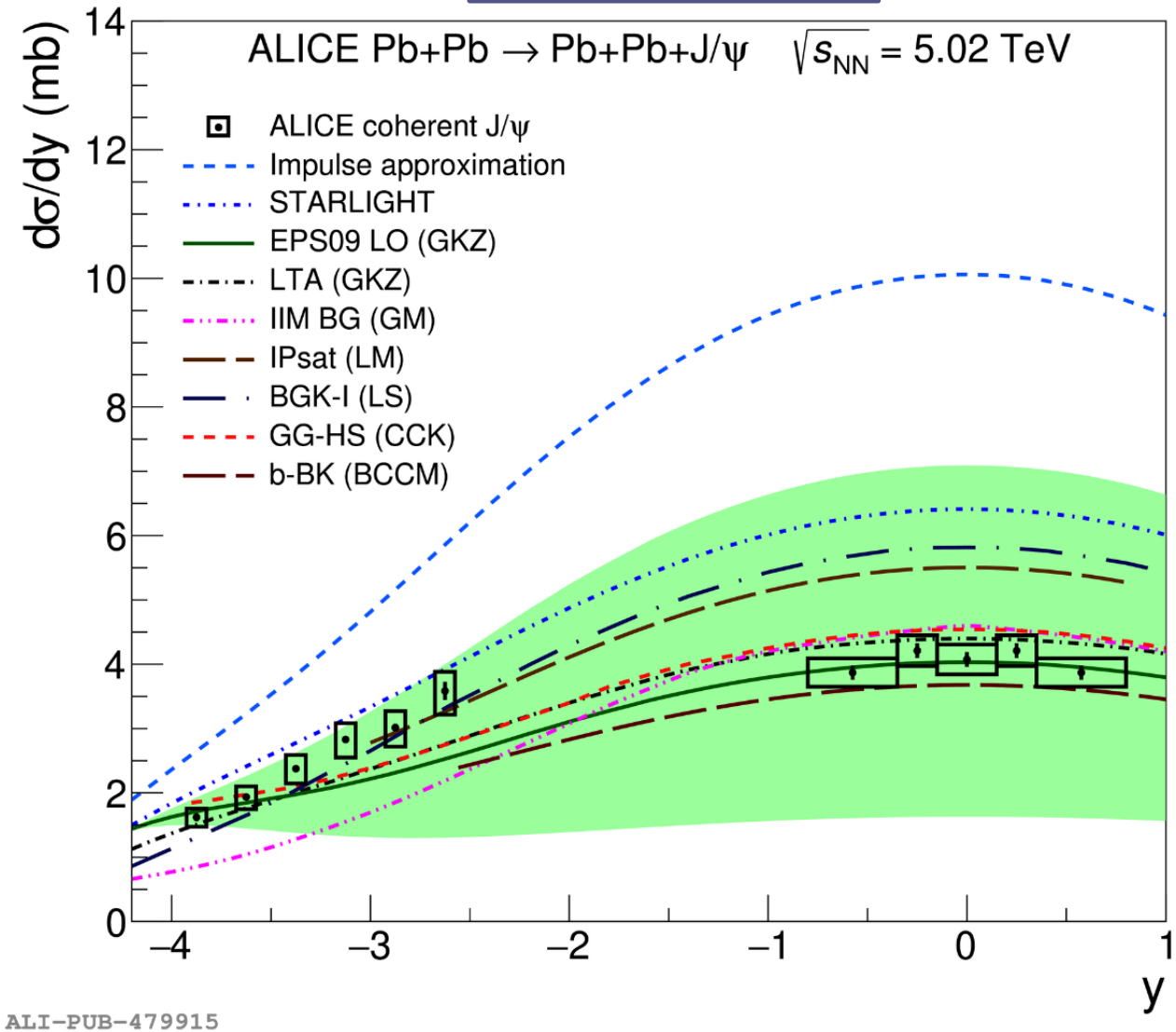
- GKZ: Leading twist approximation (LTA) of nuclear shadowing

arXiv:2101.04577



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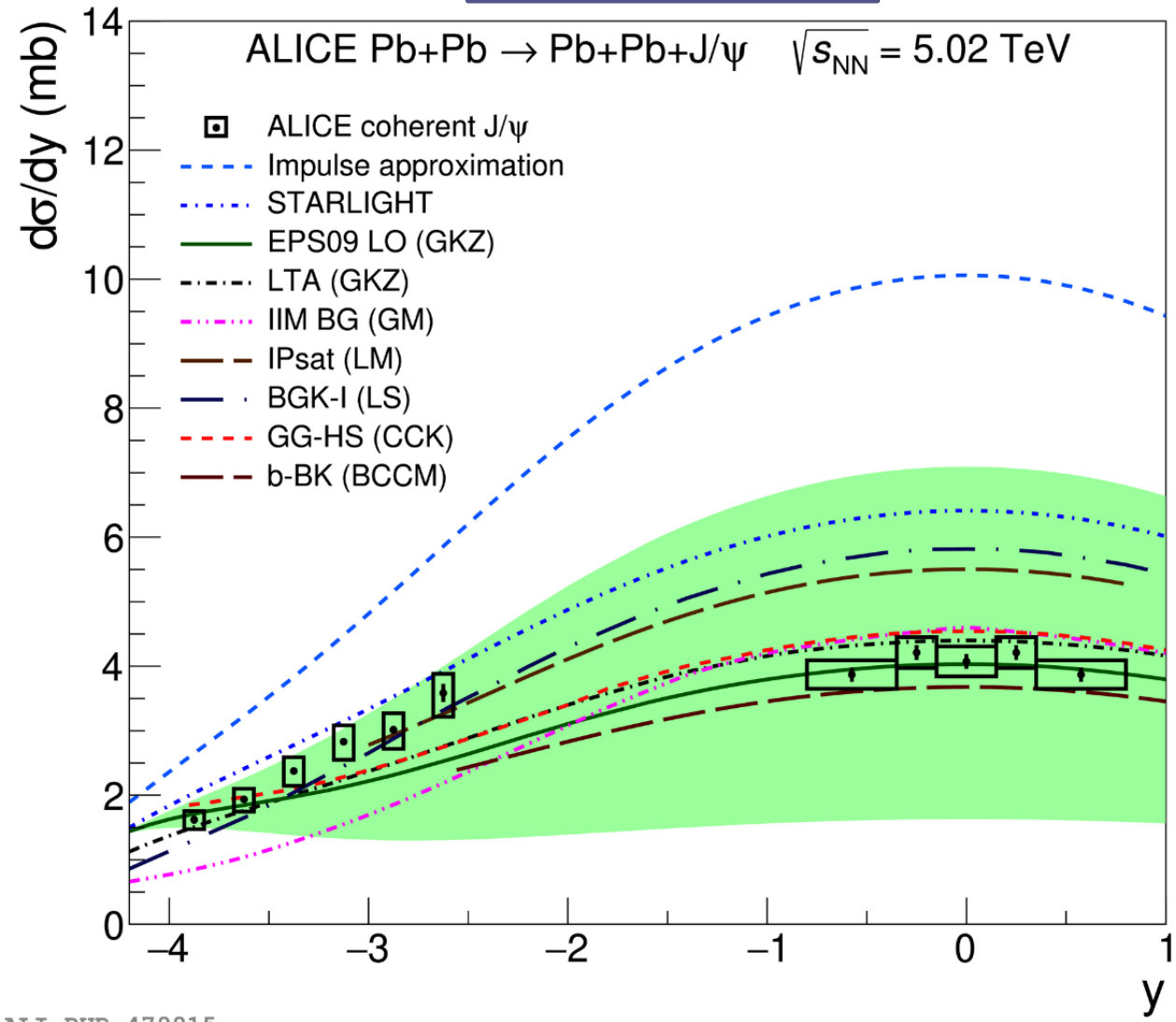
- CCK: Color dipole model with the structure of the nucleon described by the hot spots

arXiv:2101.04577



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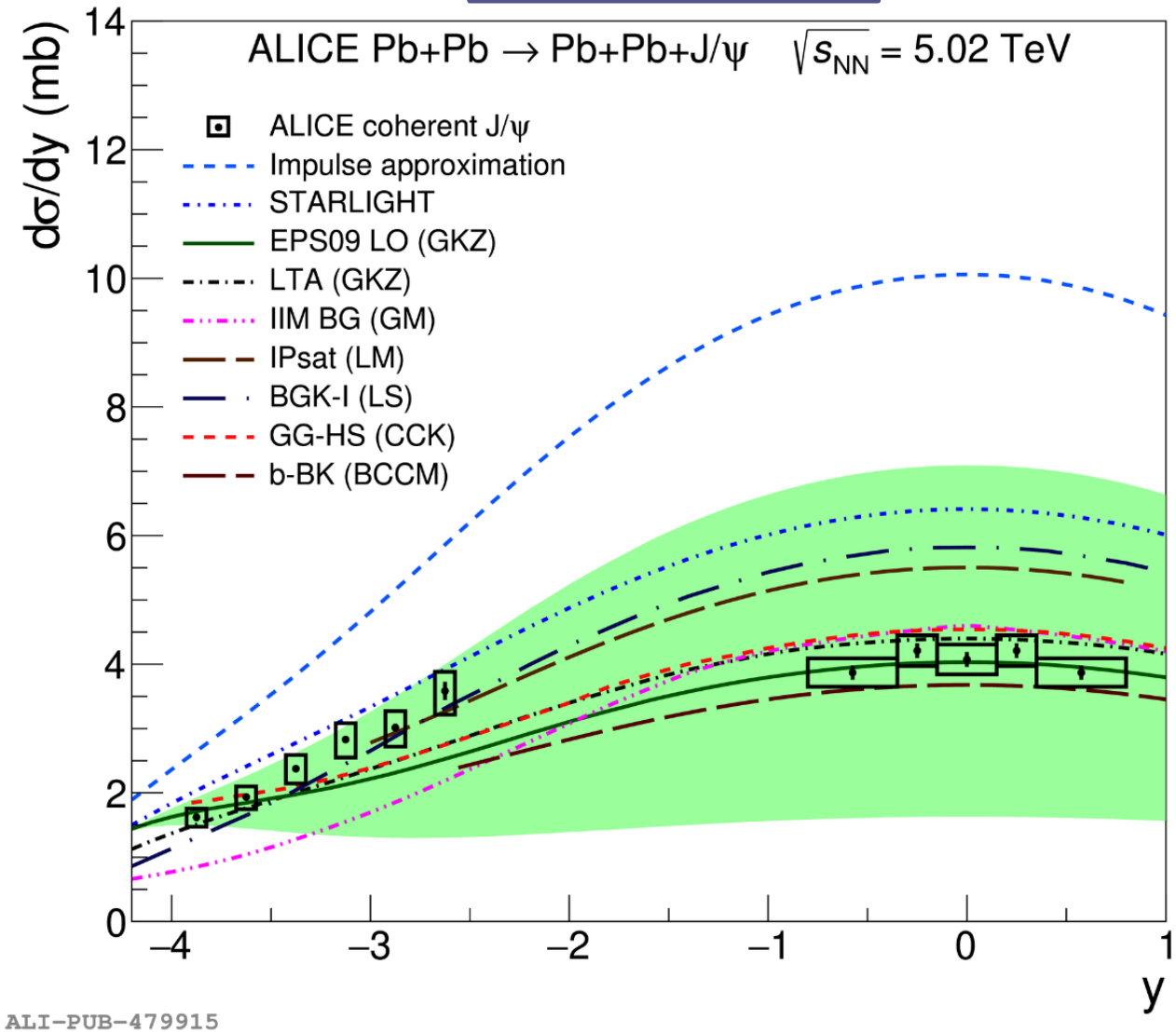
- BCCM: Color dipole approach coupled to the solutions of the Balitsky-Kovchegov equation

arXiv:2101.04577



ALI-PUB-479915

UPC J/ψ compared with calculations

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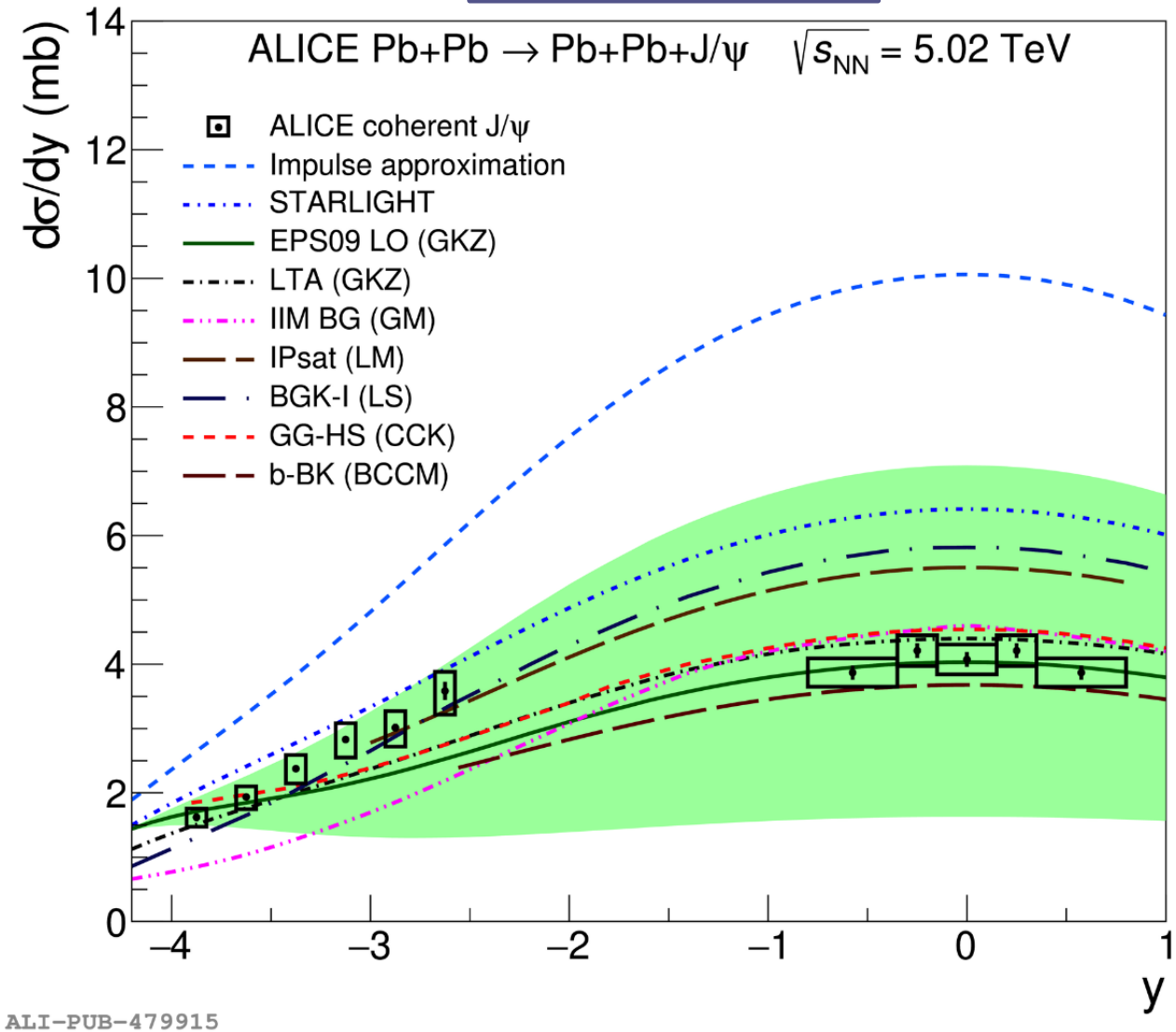
- STARlight: Vector Meson Dominance model with Glauber-like formalism to calculate cross section in Pb-Pb
- GKZ: EPS09 LO parametrization of the nuclear shadowing data
- GKZ: Leading twist approximation (LTA) of nuclear shadowing
- CCK: Color dipole model with the structure of the nucleon described by the hot spots
- BCCM: Color dipole approach coupled to the solutions of the Balitsky-Kovchegov equation
- GM, LM, LS: Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude

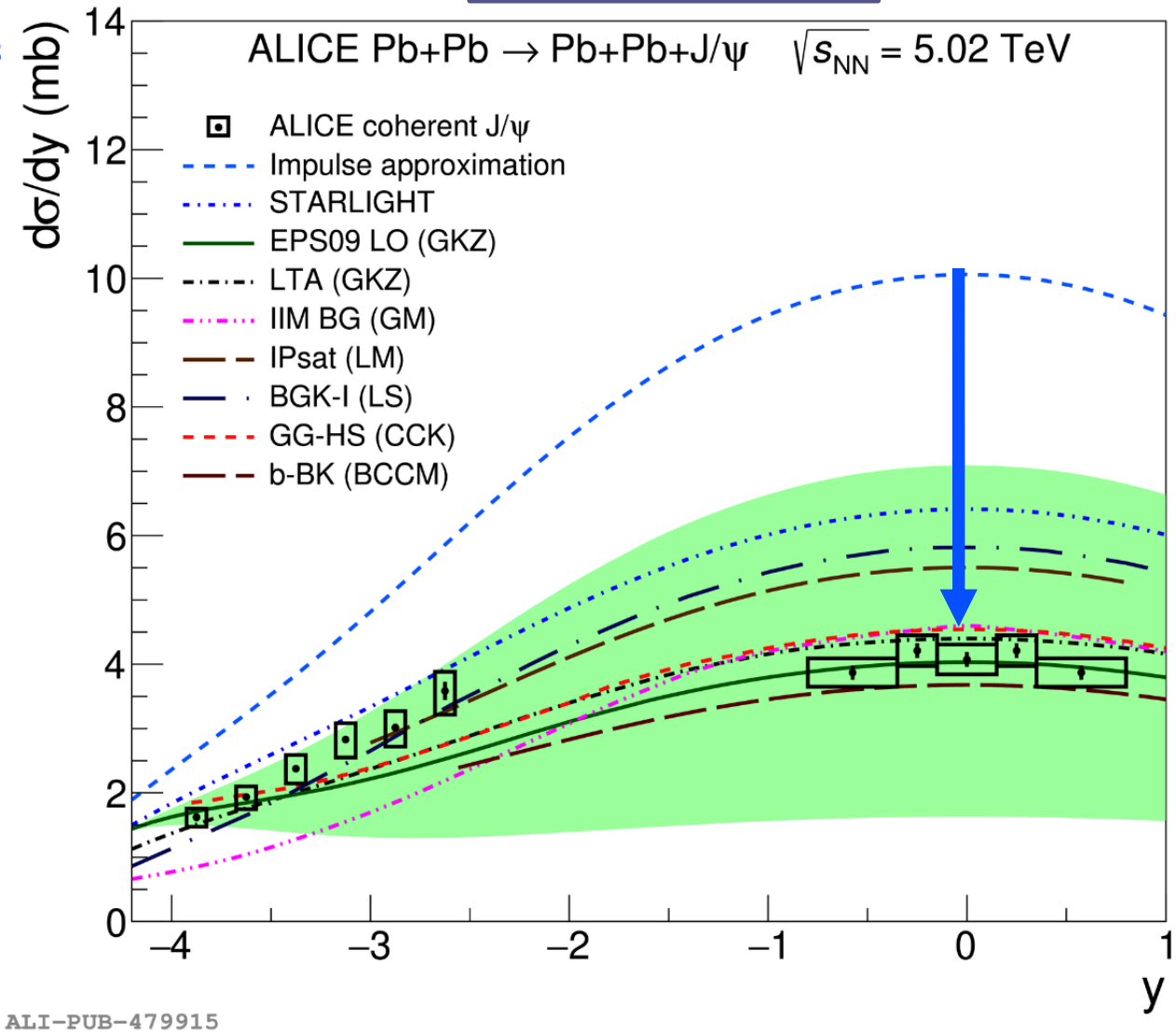
arXiv:2101.04577



UPC J/ψ compared with calculations

- Shadowing 0.65 at Bjorken-$x \in (0.3,1.4) \cdot 10^{-3}$
  - Comparison with the impulse approximation
- No models fully describe the whole rapidity dependence
- Central and most forward rapidities described by:
  - Leading twist approximation
  - EPS09 parameterization
  - Energy-dependent hot-spot model
  - Color dipole approach coupled to b-BK equation
- Color dipole models coupled to the color glass condensate describe either the forward or central rapidity

arXiv:2101.04577



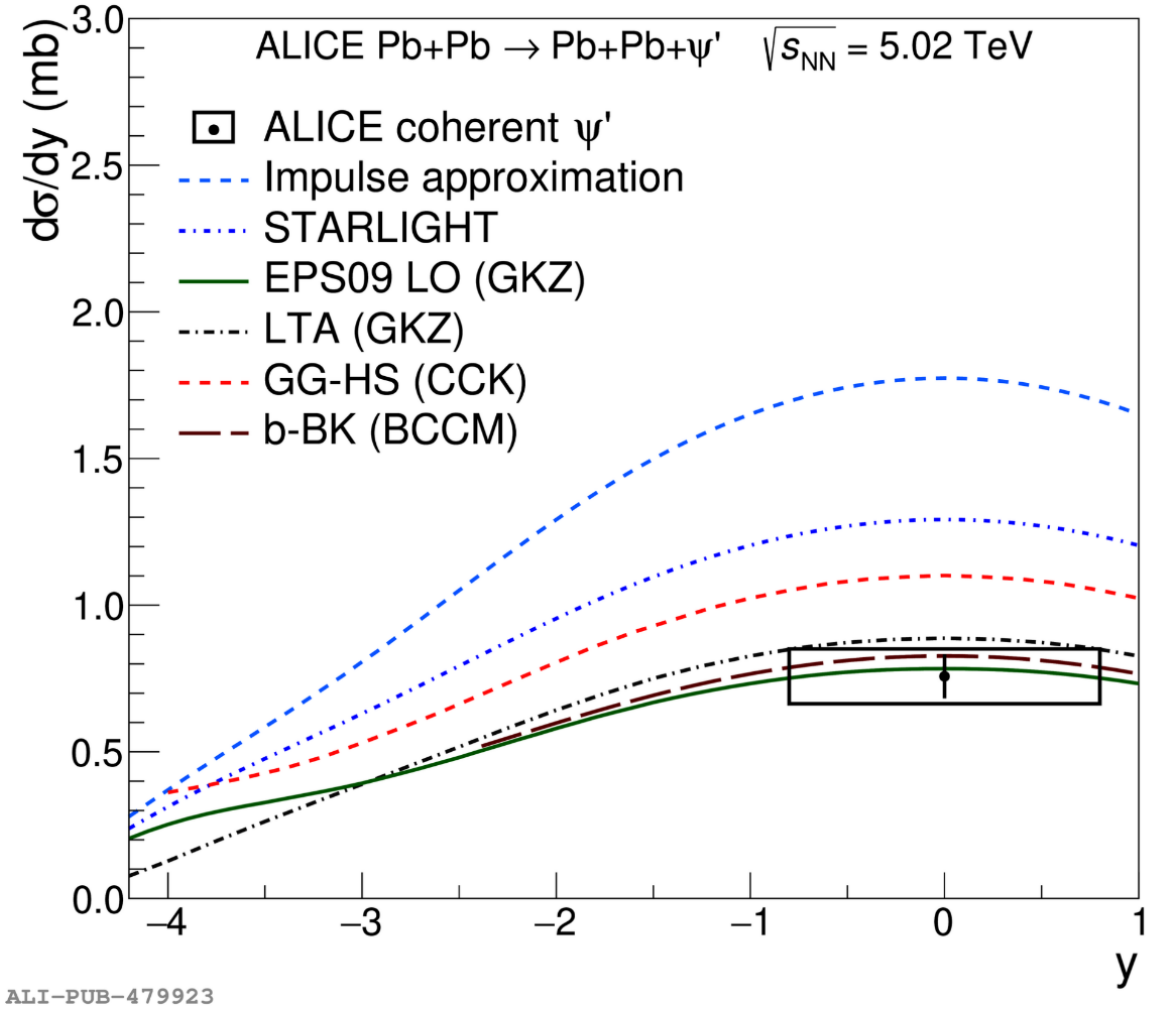
Midrapidity ψ'

- The measured ratio of the ψ' to J/ψ cross section is compatible with the:
  - Exclusive photoproduction cross section ratio measured by the H1 collaboration in ep collisions
  - Ratio measured by the LHCb collaboration in pp collisions
  - Ratio predicted in the leading twist approximation

$$\frac{\frac{\sigma^{coh}_{\psi'}}{dy}}{\frac{\sigma^{coh}_{J/\psi}}{dy}} = 0.18 \pm 0.0185(stat.) \pm 0.028(syst.) \pm 0.005(BR)$$

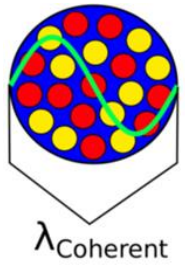
- ψ' well described by models with moderate shadowing

arXiv:2101.04577

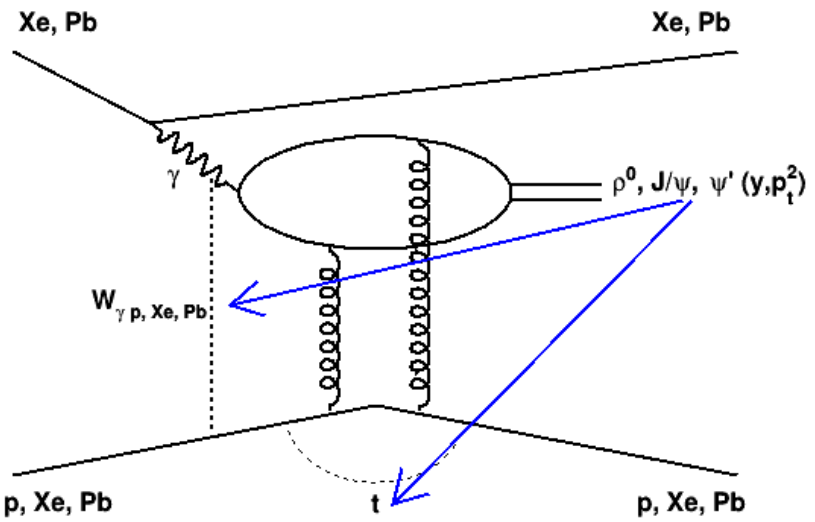


t-dependence of J/ψ cross section

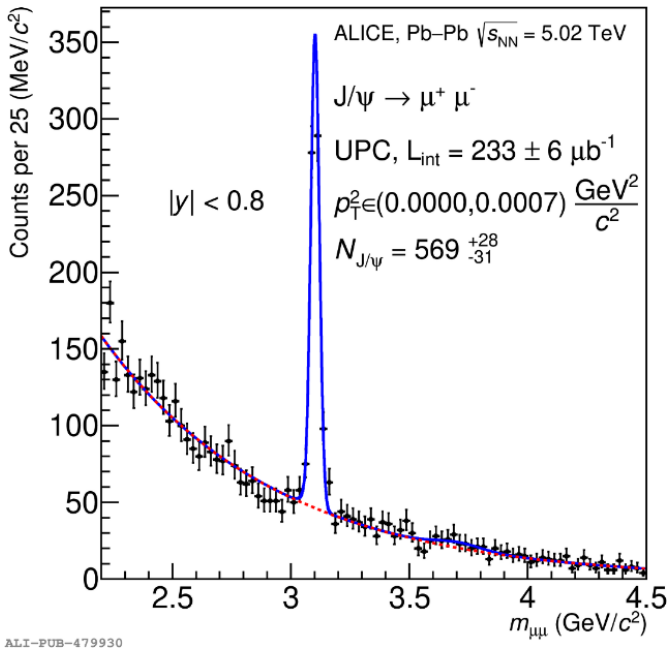
- $|t|$: The square of the momentum transferred between the incoming and outgoing target nucleus
- $|t|$ - dependence related by a 2D Fourier transform to the distribution of gluons in the transverse plane
  - Additional constraint for models
  - Investigate transverse gluonic structure at low Bjorken-x: is shadowing varying in the transverse area?

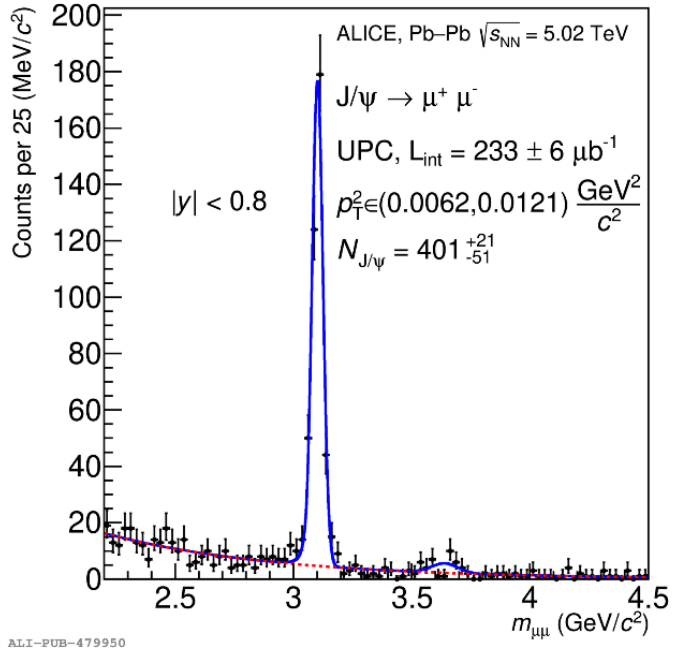


- Measurement done using J/ψ p_T^2
  - Unfolding from p_T^2 to |t| done using response matrix from STARlight with correction for p_T^2 shape



arXiv:2101.04623

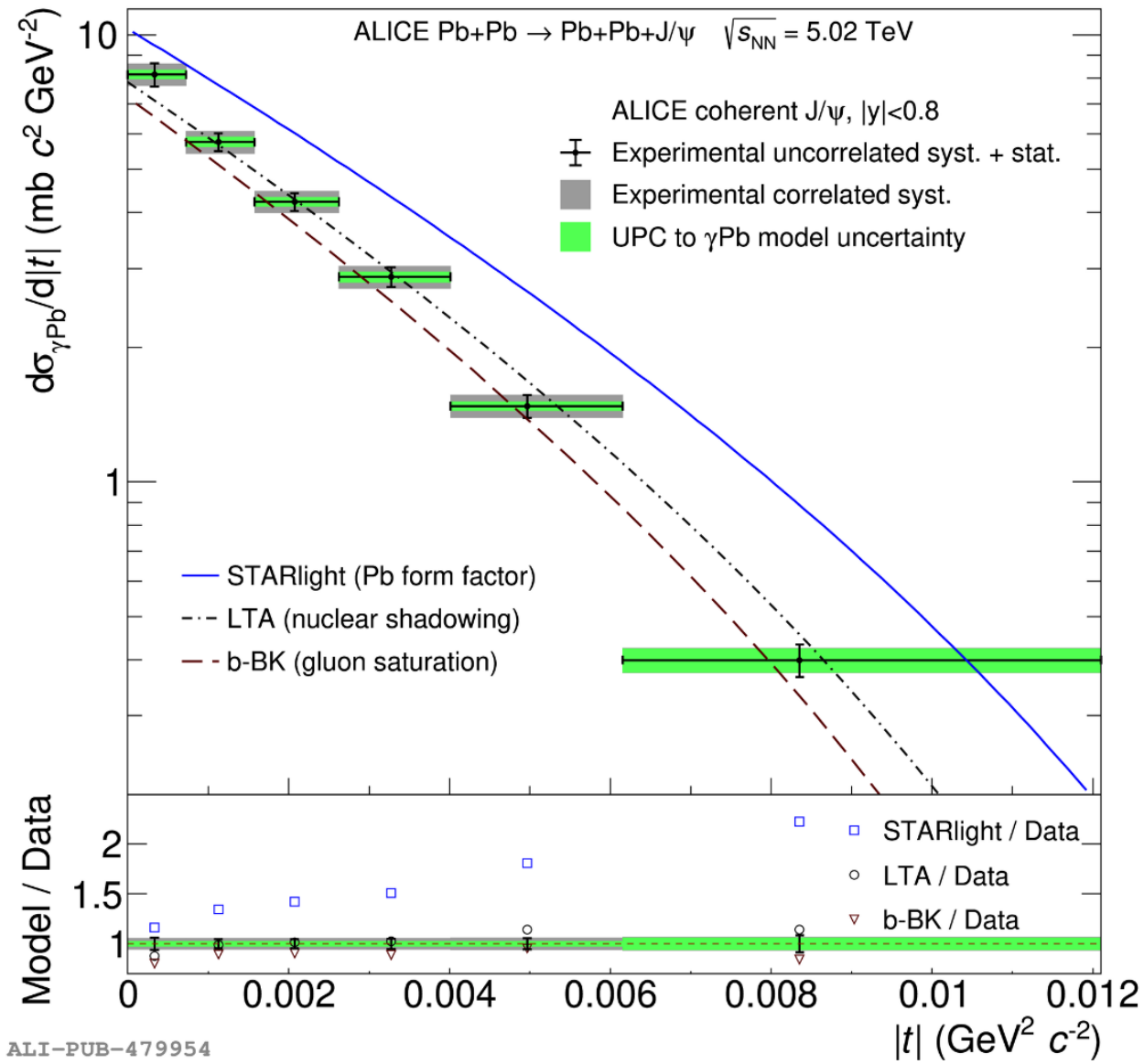




t-dependence of J/ψ cross section

arXiv:2101.04623

- Poor description by STARlight with Pb form factor implies existence of QCD dynamical effects
  - Observables sensitive to the transverse gluonic structure of particles important for understanding of the high-energy limit of QCD
- Models incorporating nuclear shadowing according to LTA or gluon saturation from the impact-parameter dependent Balitsky-Kovchegov (b-BK) describe well the data
  - Difference between the LTA and b-BK models smaller than uncertainties => high precision data in future



Coherent ρ^0 in Pb-Pb

- Provides insight on the hadronic structure of photon
  - $\gamma + p \rightarrow \rho^0 + p$ contributes about 15% of total $\gamma + p$ cross section
  - From nucleon to a nuclear target using the Glauber model
  - For heavy nuclei one may reach the black disk limit of QCD
- Mass distribution described by the model

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

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

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

- Background M from $\gamma\gamma \rightarrow \mu\mu$ fixed using STARlight
- p_T spectrum used for estimation of incoherent contamination
- First and second diffractive peaks clearly visible in the p_T spectrum
- The ratio of nonresonant pion production B/A found at midrapidity is 0.57 ± 0.01 (stat.) ± 0.2 (syst.) $(\mathrm{GeV}/c^2)^{-1/2}$

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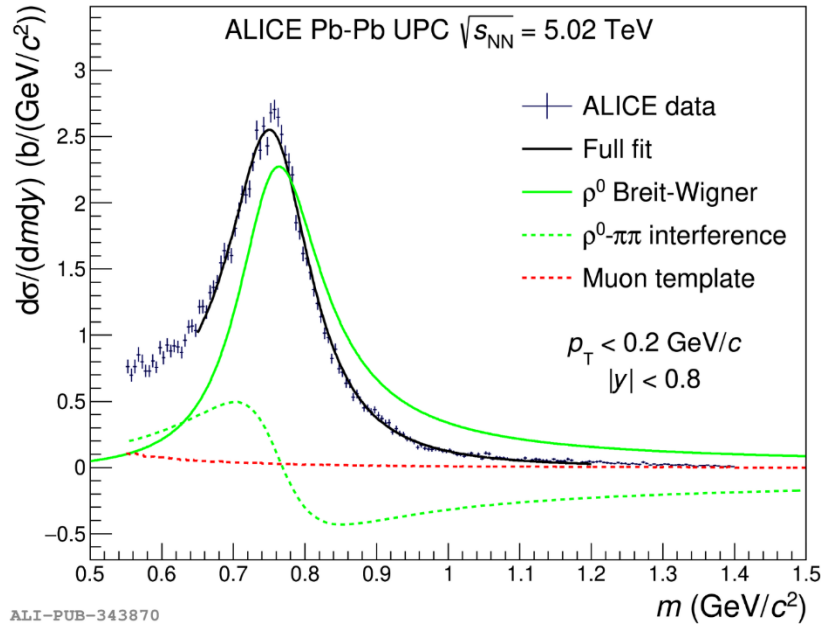

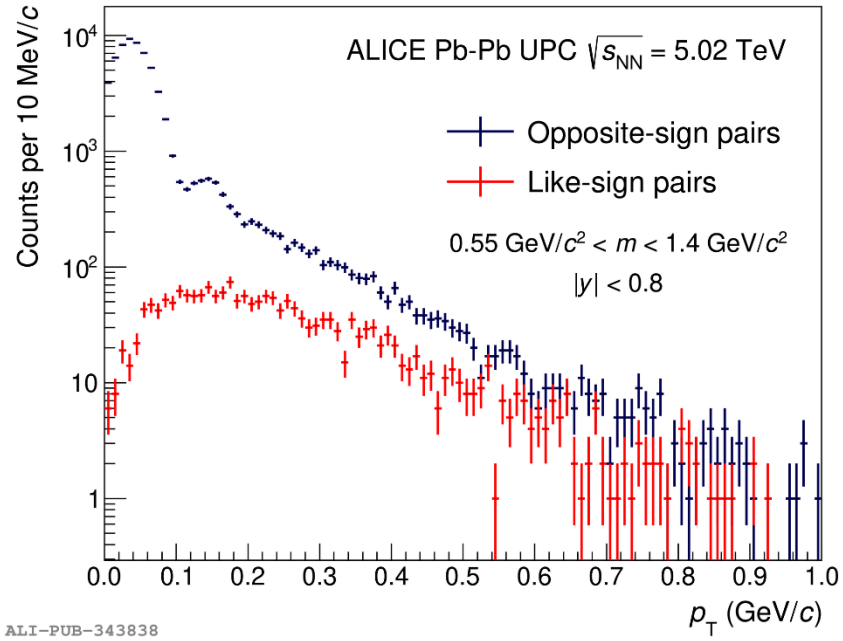

Resonance-like structure

- Resonance-like structure in the region m > 1.2 GeV/c^2.
- The model yields a mass of (1725 ± 17) MeV/c^2 and width (143 ± 21) MeV/c^2
- Very low transverse momentum as a coherent-production
- Such an object is also seen by the STAR/ZEUS/H1 at a similar mass
- This resonance is also compatible with the $\rho_3(1690)$ in the PDG, which has a total angular momentum J = 3

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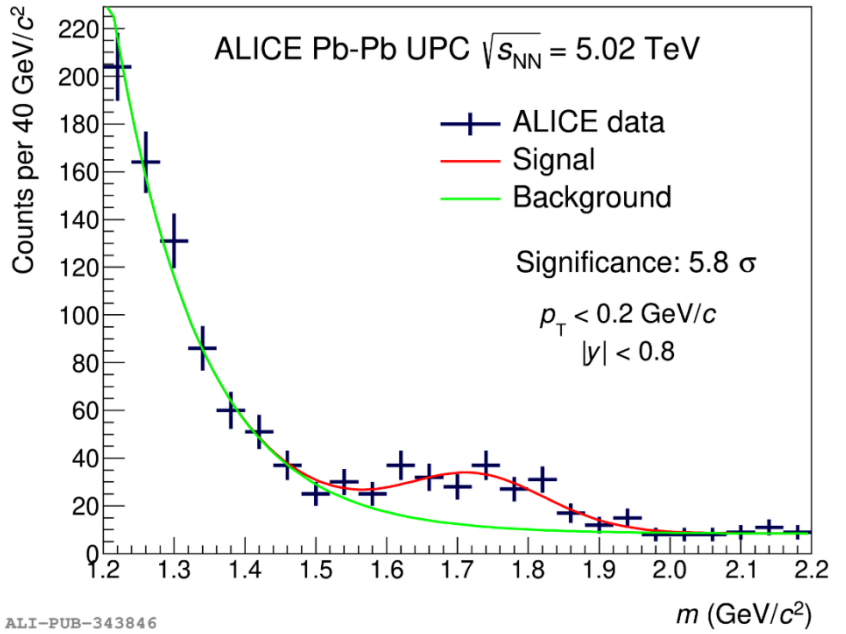
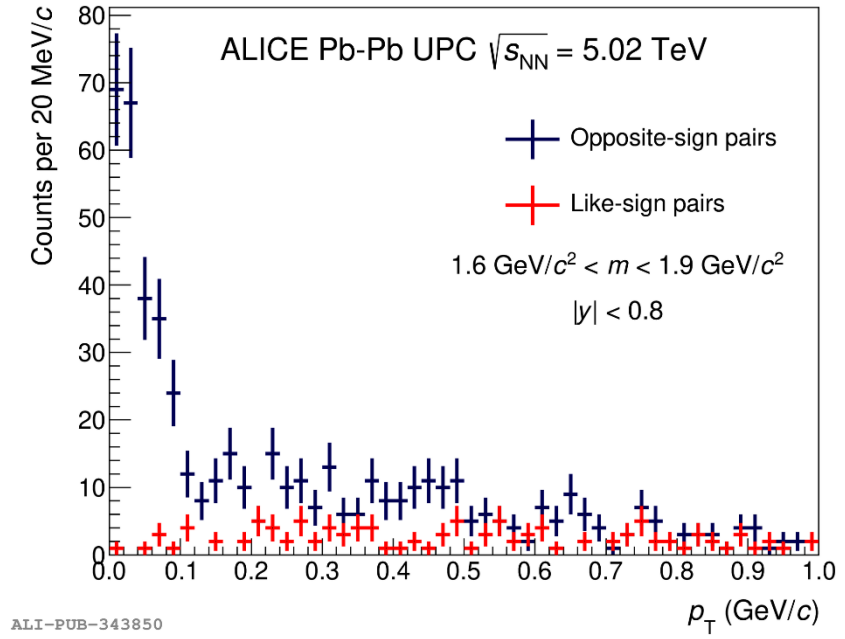
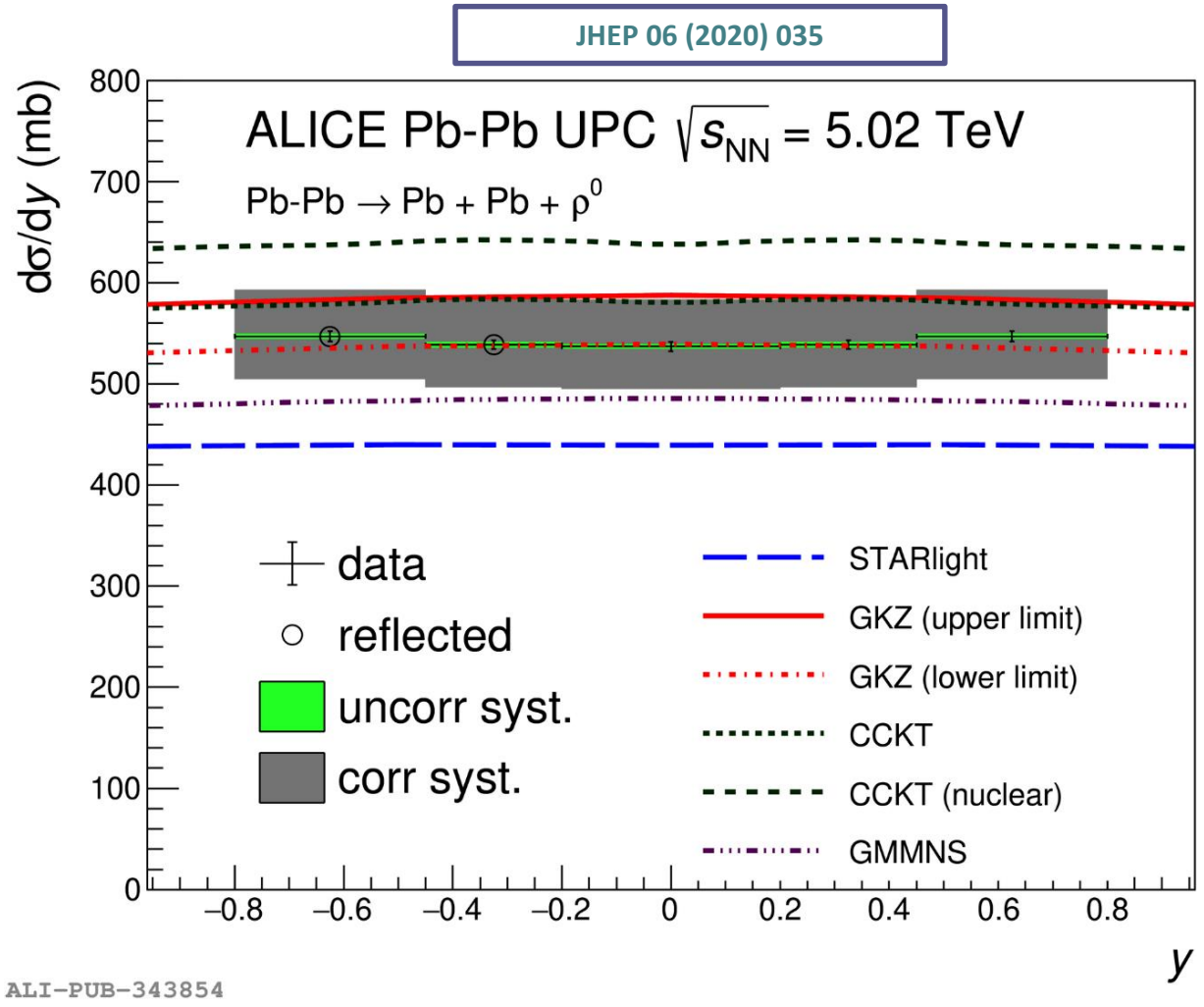




Coherent ρ^0 in Pb-Pb at midrapidity

- STARlight: Vector Meson Dominance model and photoproduction off protons data combined with a Glauber-like approach.
- GKZ: modified Vector Meson Dominance model
- CCKT: Color-Dipole Model with the structure of nucleon described by hot spots
- GMMNS: the IIM implementation of gluon saturation within the Color-Dipole Model
- Good description of the data by GKZ model indicates importance of the Gribov-Glauber approach in describing the hadronic heavy ion collision over plain Glauber model(STARlight, CCKT nuclear)



Ambiguity in photon source

- Vector meson cross section in Pb–Pb UPC = sum of two terms
  - Either of the ions can be photon source:

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

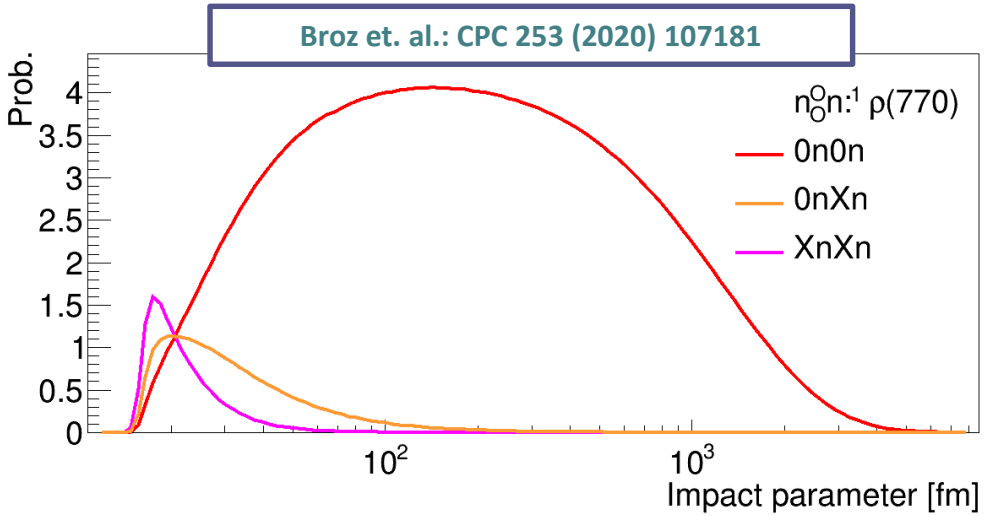
- Photoproduction cross sections $\sigma_{\gamma\mathrm{Pb}}(y)$ $\sigma_{\gamma\mathrm{Pb}}(-y)$ are coupled
  - Cannot be extracted from the measured cross section

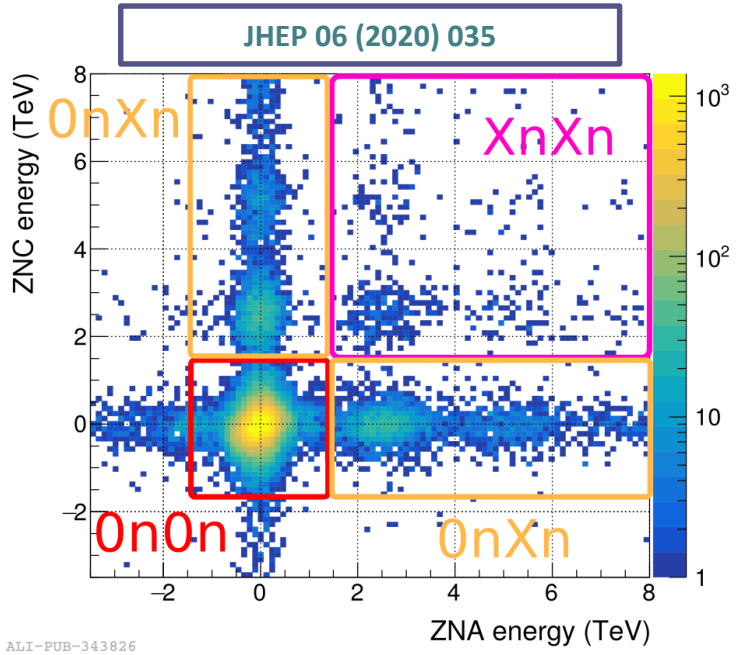
- Can be decoupled by measuring additional neutron activity

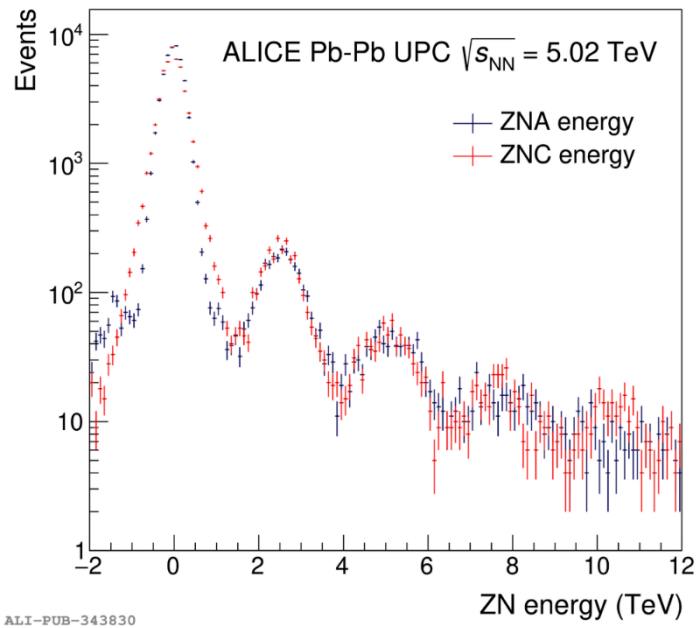
$$\begin{aligned}
\sigma_{0\mathrm{N}0\mathrm{N}}(y) &= n_{0\mathrm{N}0\mathrm{N}}(+y)\sigma_{\gamma\mathrm{Pb}}(+y) + n_{0\mathrm{N}0\mathrm{N}}(-y)\sigma_{\gamma\mathrm{Pb}}(-y), \\
\sigma_{0\mathrm{N}\mathrm{X}\mathrm{N}}(y) &= n_{0\mathrm{N}\mathrm{X}\mathrm{N}}(+y)\sigma_{\gamma\mathrm{Pb}}(+y) + n_{0\mathrm{N}\mathrm{X}\mathrm{N}}(-y)\sigma_{\gamma\mathrm{Pb}}(-y),
\end{aligned}$$

Coherent ρ^0 with neutron emission

- Difficulties to disentangle low and high energy γ-Pb at forward rapidity. Data at midrapidity can test factorisation methods.
- The different nuclear cases allow to access different impact parameters (b).
- XnXn = neutrons in both beam sides ('small' b)
- 0nXn = neutrons in one beam side ('medium' b)
- 0n0n = no neutrons are detected ('large' b)
- Experimental classification based on zero-degree neutral energy (ZNA and ZNC detectors)







Coherent ρ^0 with neutron emission

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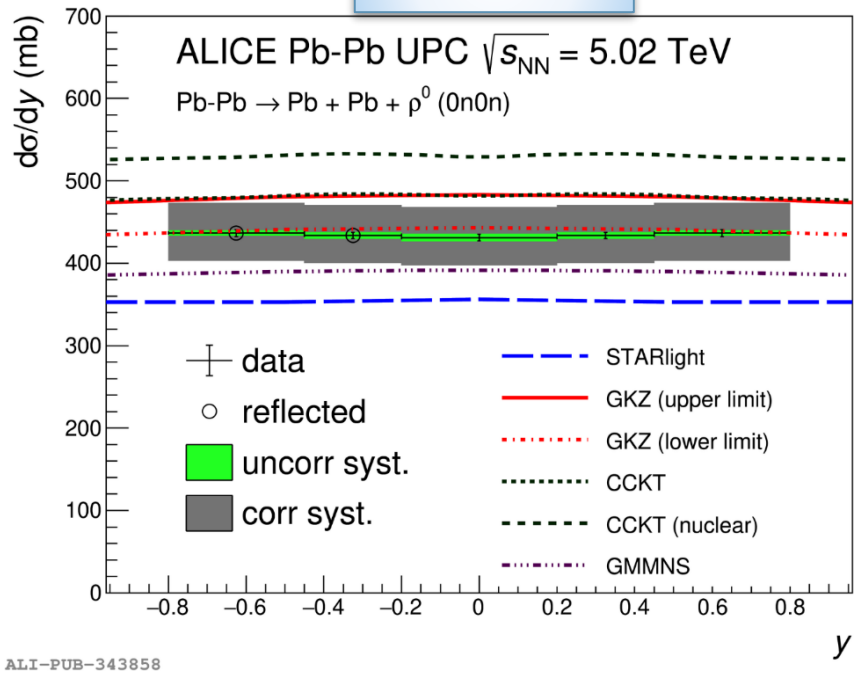
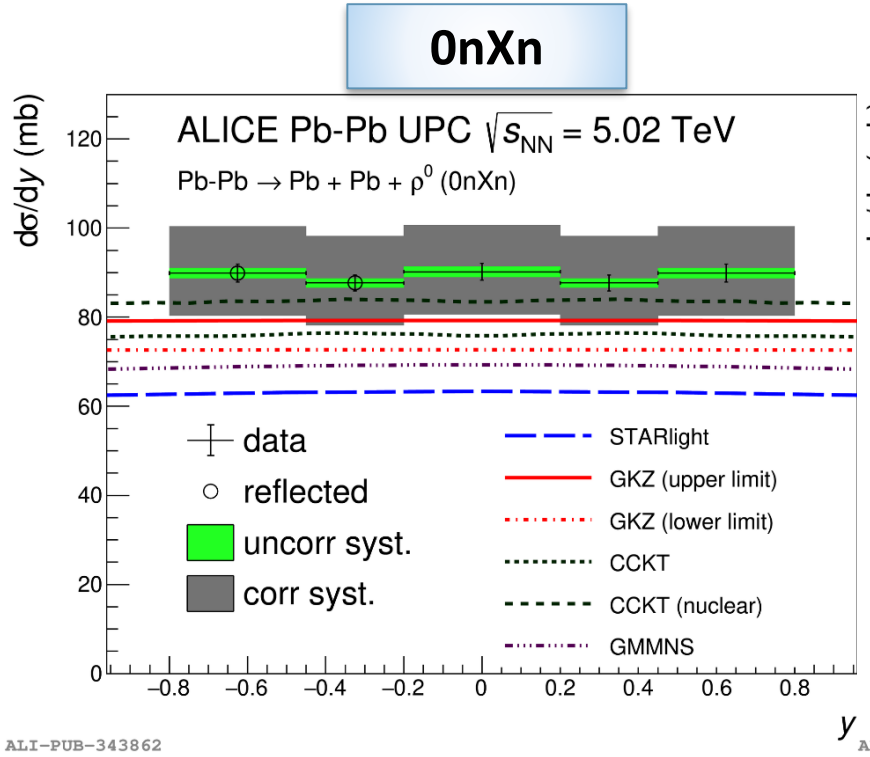
- Large difference in cross sections
- Factorisation of photon fluxes and ρ^0 production works
- We can measure the process at the same rapidity and different impact-parameter ranges -> tool to disentangle low and high energy contributions
- The measured cross section is compatible with all models within around two standard deviations, except for the single neutron emission class (0nXn), where models underestimate data slightly

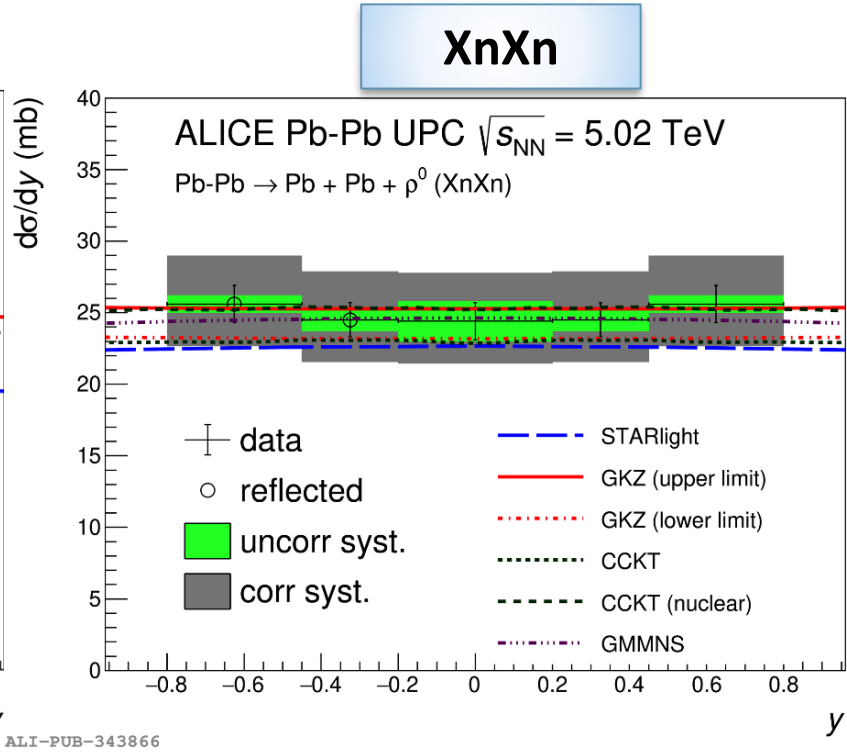
0n0n



0nXn



XnXn

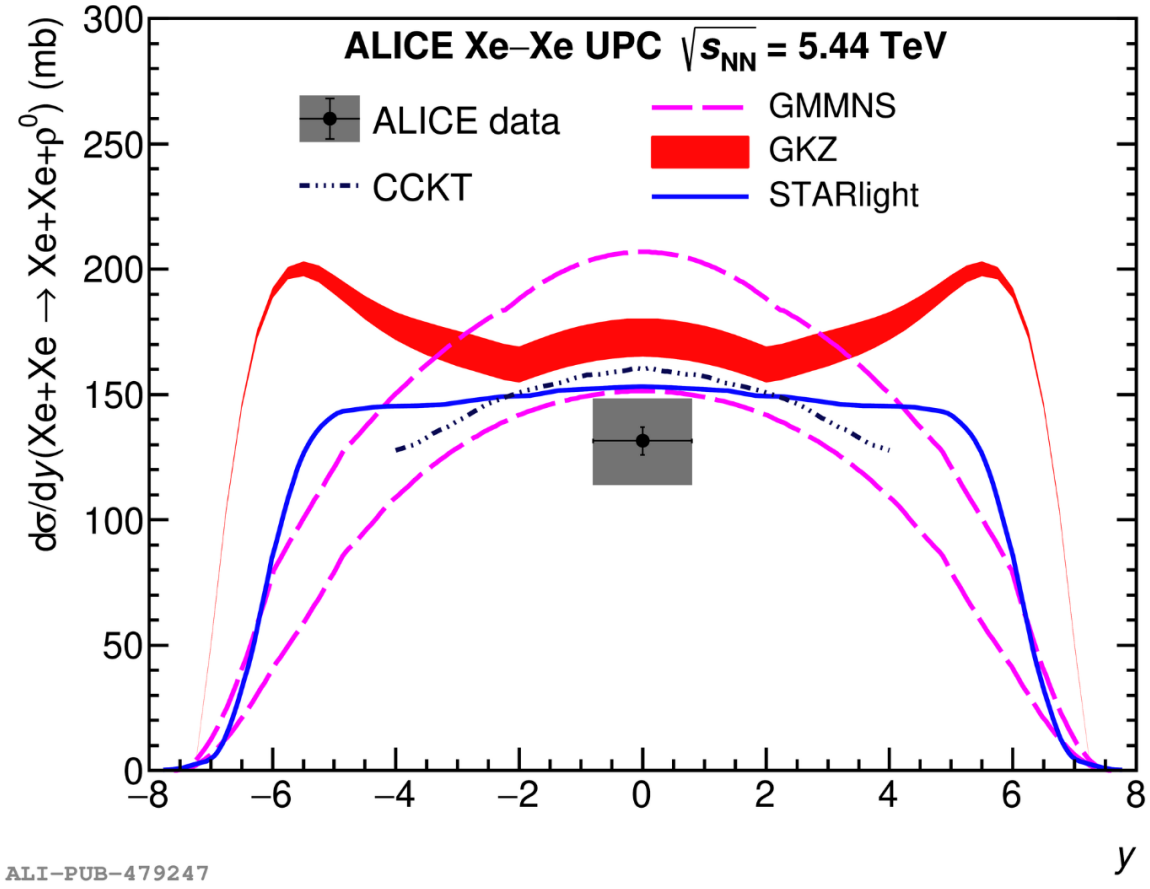


Coherent ρ^0 in Xe-Xe

- First measurement with Xe nucleus -> first study of A dependence
- The theoretical predictions slightly overestimate the measurement
- The fractions of 0n0n, 0nXn, XnXn also measured; compatible with the predictions from $\mathbf{n}^{\mathbf{O}}_{\mathbf{O}}\mathbf{n}$
- The fair agreement between data and predictions suggest that this process is well understood within the current experimental uncertainties

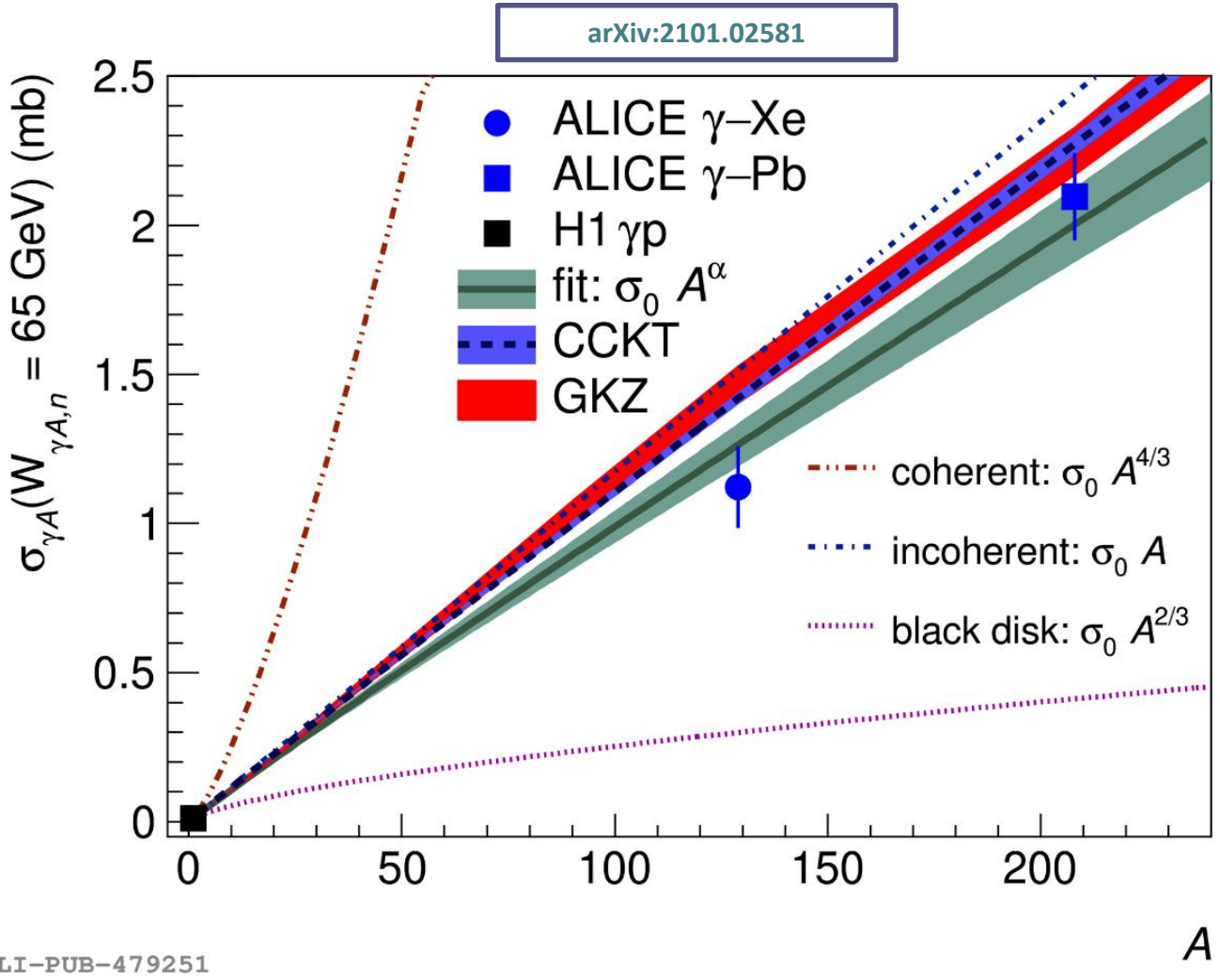
arXiv:2101.02581

Class	Measured fraction	$\mathbf{n}^{\mathbf{O}}_{\mathbf{O}}\mathbf{n}$ prediction
0n0n	$(90.46 \pm 0.70 \pm 0.17 \mp 0.68)\%$	92.4%
0nXn+Xn0n	$(8.48 \pm 0.66 \mp 0.13 \pm 0.64)\%$	6.9%
XnXn	$(1.07 \pm 0.25 \mp 0.04 \pm 0.07)\%$	0.7%



The A dependence of coherent ρ^0

- The dependence of cross sections on A fitted by a power-law
  - With H1 data
  - Parameter = 0.96±0.02
- Significantly bellow 4/3=> important shadowing effects
- Close to unity => not incoherent behavior, just large shadowing suppression
- Black disk limit (cross section proportional to nucleus transverse area) quite distant at $W_{\gamma A}$ = 65 GeV



Coherent J/ψ photonuclear production in peripheral Pb-Pb collisions

- Clear excess at very low p_T in peripheral Pb-Pb collisions with respect to expected hadronic production

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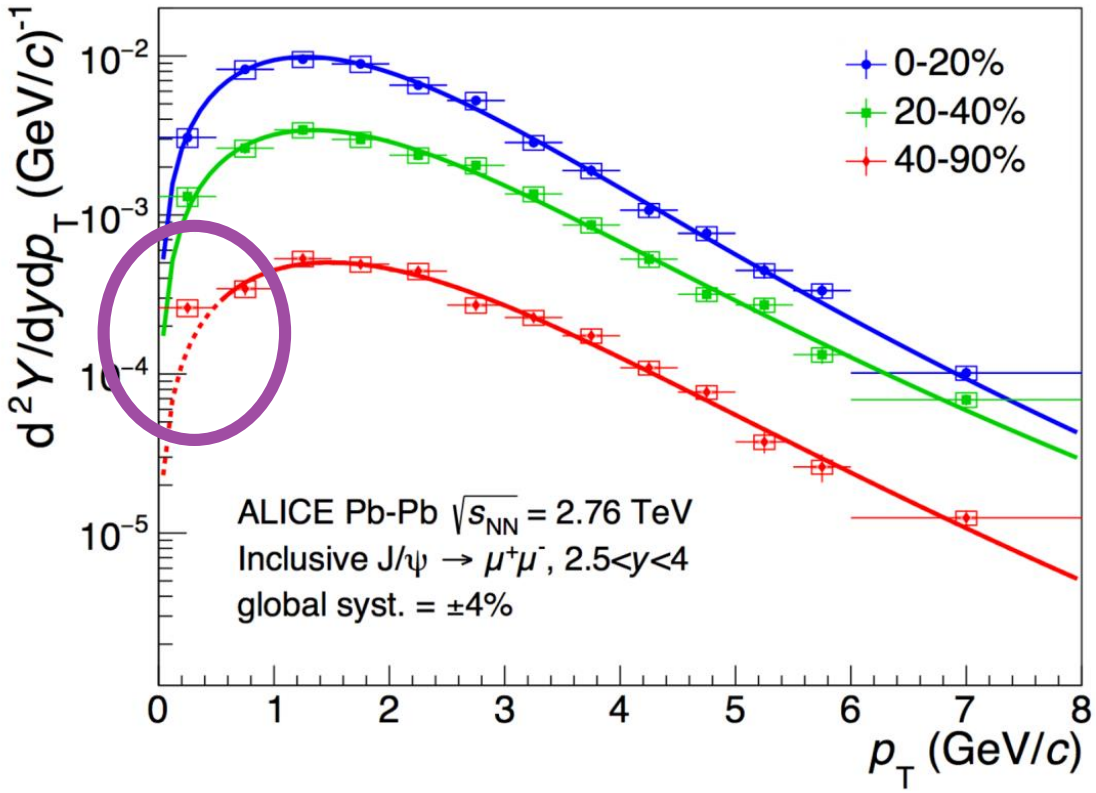
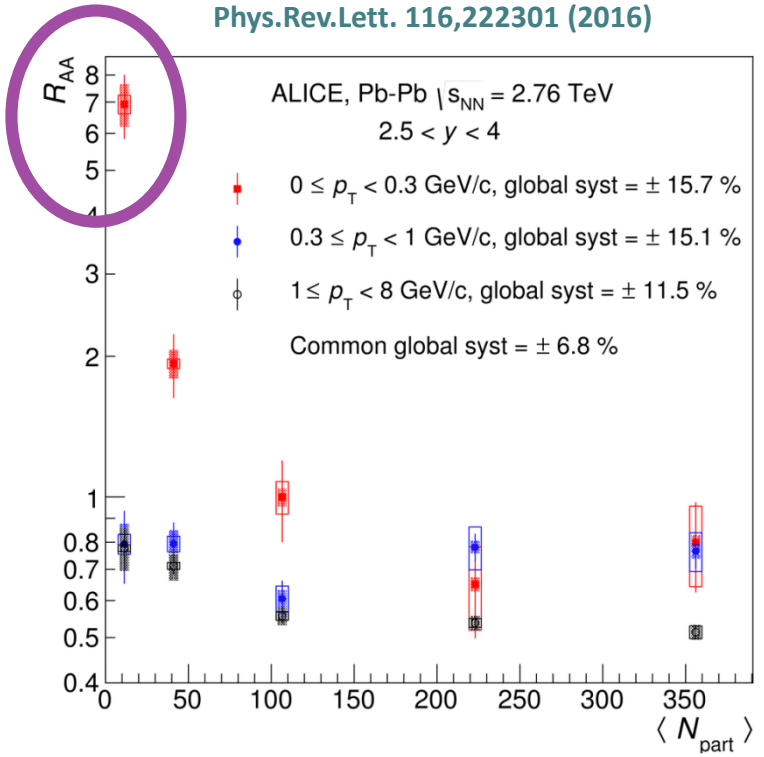


Phys.Rev.Lett. 116,222301 (2016)



$$R_{AA} = \frac{N_{AA}^{J/\psi}}{\langle N_{coll} \rangle \, N_{pp}^{J/\psi}}$$

$= 1 \rightarrow$ No medium effect

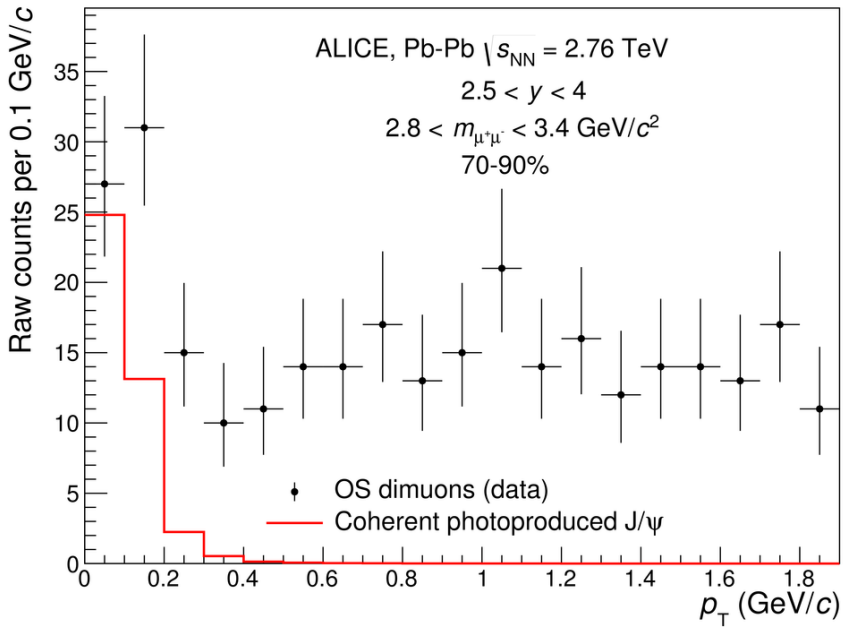
$< 1 \rightarrow$ Suppression

$> 1 \rightarrow$ Enhancement

Coherent J/ψ photonuclear production in peripheral Pb-Pb collisions

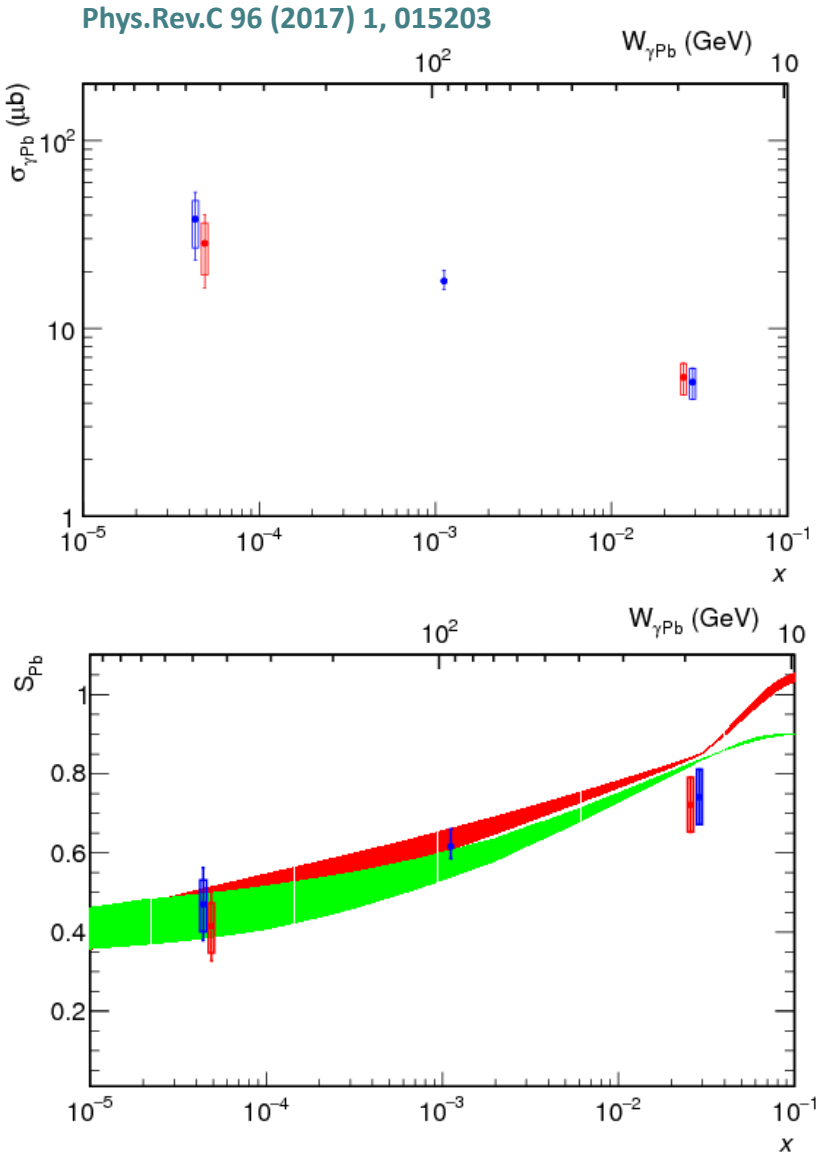
- Clear excess at very low p_T in peripheral Pb-Pb collisions with respect to expected hadronic production
- Remarkably similar to J/ψ photoproduction in ultra-peripheral collisions
- Combining with coherent UPC data photonuclear cross sections and shadowing factor is accesible

Phys.Rev.Lett. 116,222301 (2016)



+ Phys. Lett. B718, 1273 (2013)

Phys.Rev.C 96 (2017) 1, 015203



Prospect for Run 3 and Run 4

arXiv:1812.06772

ALICE UPC in Run 3 and Run 4

- The higher LHC luminosity and experimental upgrades => improved samples of UPC events
- ALICE continuous readout
  - No trigger-based constraints
  - High-efficiency collection of large samples
- The increases in sample sizes larger than by scaling the luminosity
  - Pb-Pb integrated luminosity goal Run 3+4: 13 nb^{-1}

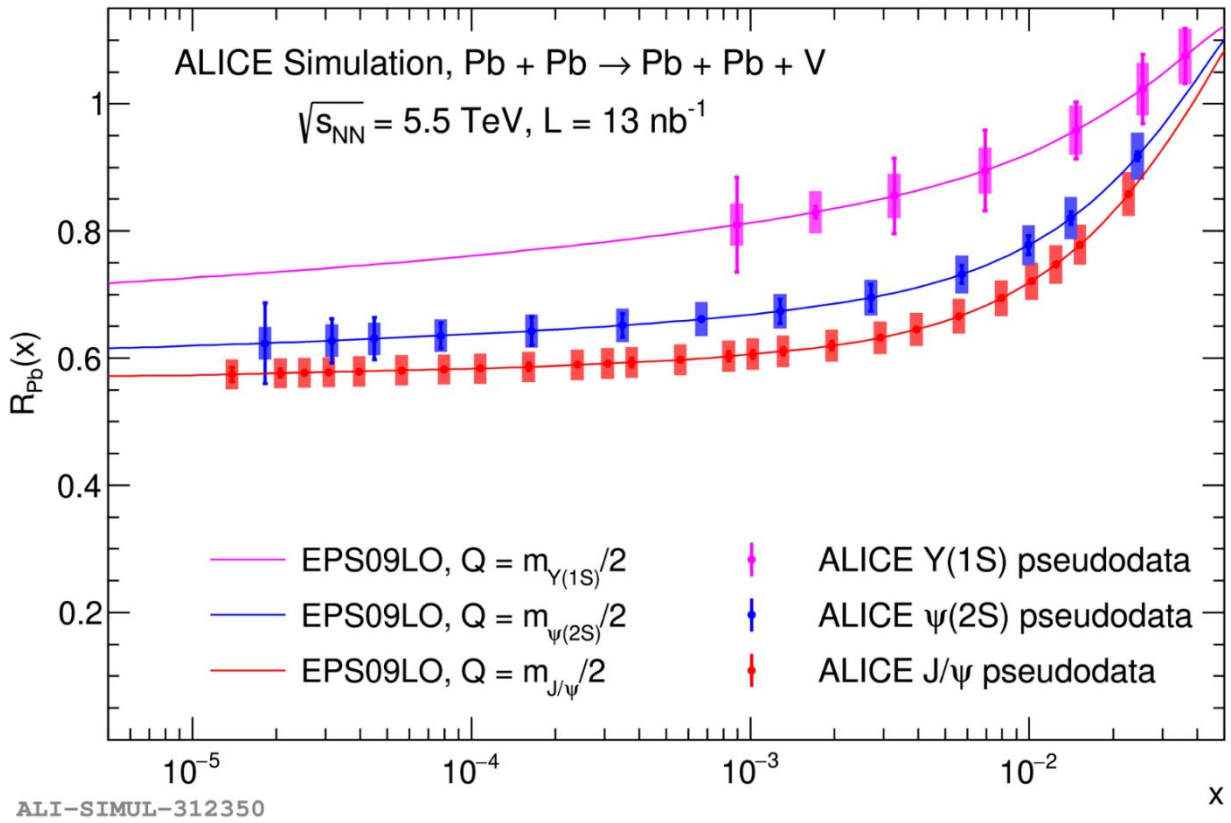
	PbPb			
Meson	σ	All Total	Central 1 Total	Forward 1 Total 1
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	4.9 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	190 M
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	15 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	600 K
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	19 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	880

ALICE UPC in Run 3 and Run 4

- Coherent production of two pions with masses above 1 GeV/c^2
  - Interplay of soft and hard dynamics as a function of mass and p_T
- Heavier 2π, 4π and other resonances on ion targets
  - Search for the photoproduction of exotic mesons
- Double vector mesons photoproduction available
  - By a single ion-ion pair by exchange of two independent photons
- Beyond precise cross section measurements for J/ψ, ψ' and Υ(1S)
  - Allow tomographic measurements
  - Can be used to infer information on the nuclear wave function

ALICE UPC in Run 3 and Run 4

- Extend substantially the x range for coherent J/ψ photoproduction on nuclei
  - Using impact parameter distribution in peripheral and ultra-peripheral collisions
  - Via forward neutron production
- High statistics coherent Υ(1S) production in γp and γA
  - Probe gluon shadowing at a factor of 10 higher Q^2 than in J/ψ production



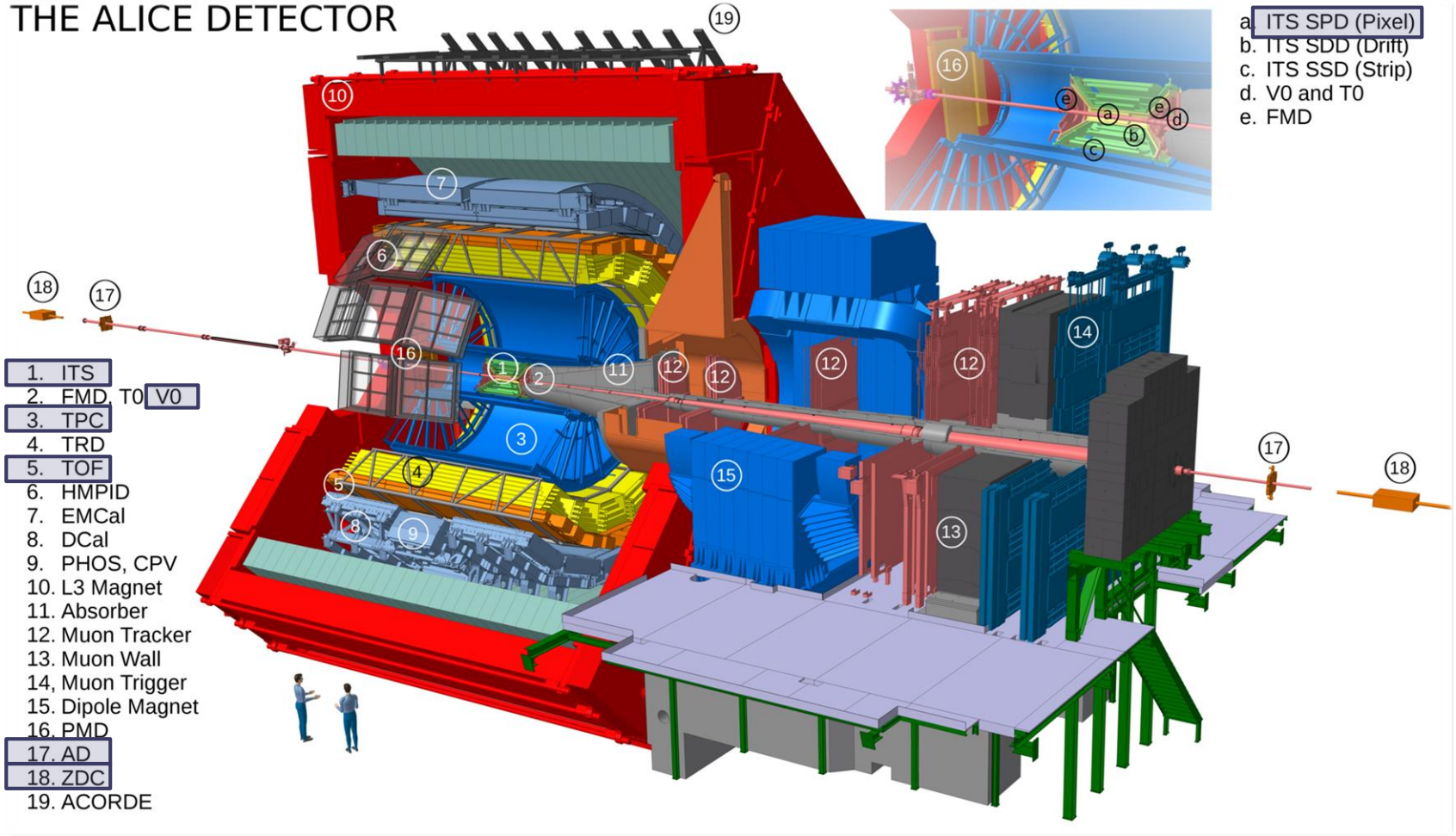
Summary and outlook

- Difference between the J/ψ and ψ' cross section data and impulse approximation is a direct measurement of moderate nuclear shadowing $R_g^{Pb} \sim 0.65$ at $x \sim 10^{-3}$
  - Looking forward to the inclusion of the J/ψ UPC results in nPDF fits
- No indication of saturation of the gluon PDF in the proton between HERA and LHC
- Ongoing with Run 2 data: γ-p with p-Pb 8.16 TeV, J/ψ with forward neutrons, coherent production in peripheral collisions
- Bright prospects for Run 3 and Run 4 – **Stay tuned!**

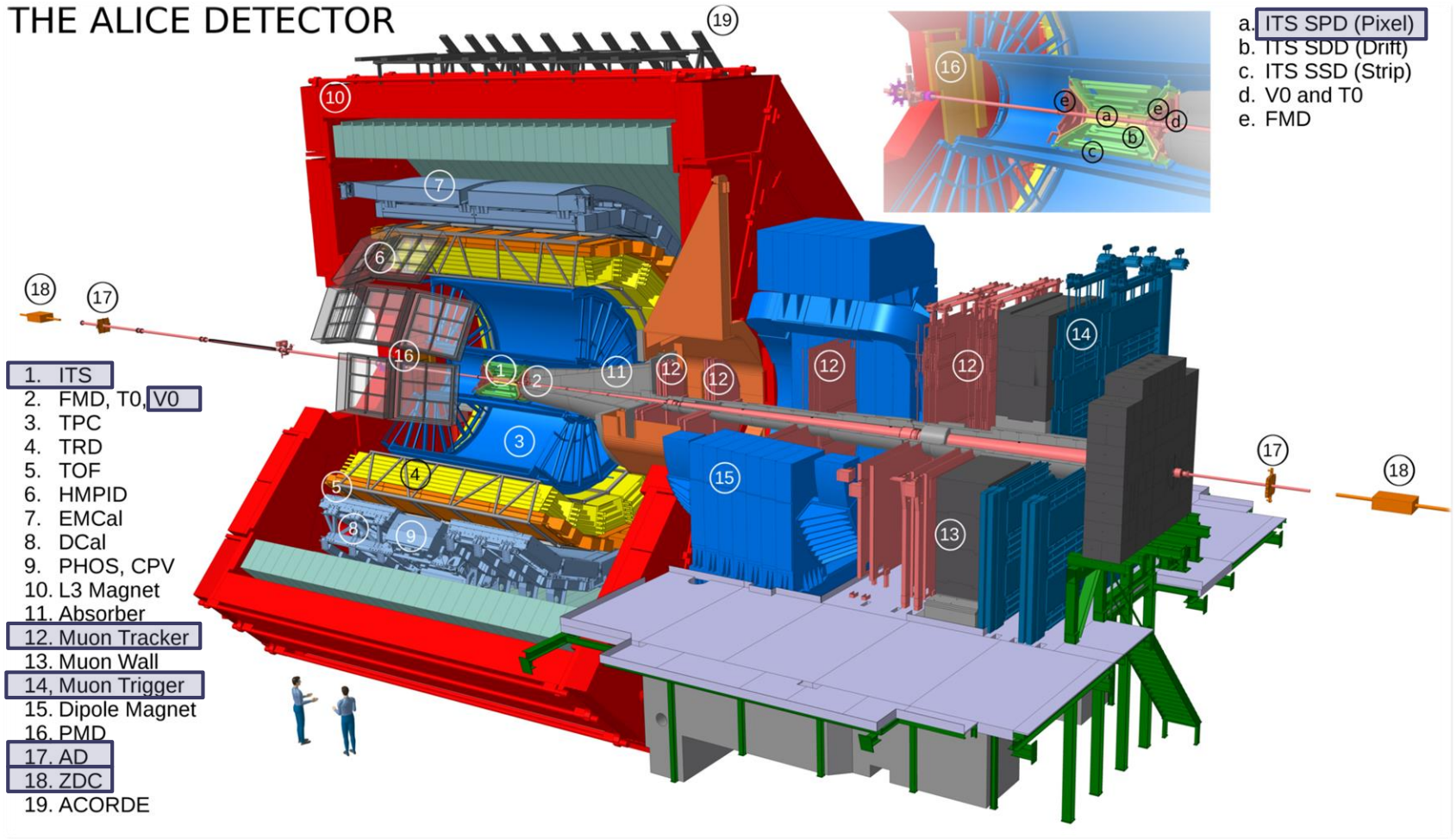
Thank you

Backup

- Central barrel trigger on UPC
  - 2010: veto on V0, hits in SPD ≥ 2 , TOF hits ≥ 2
  - 2011: veto on V0, hits in SPD ≥ 2 , 2 ≤ TOF hits ≤ 6 with back-to-back topology
  - 2013/2015/2018: veto on V0, (veto on AD – Run 2), hits in SPD ≥ 4 with back-to-back topology / 2 ≤ TOF hits ≤ 6 with back-to-back topology



- Forward rapidity trigger on UPC
  - 2011/2016: veto on V0A , hits in V0C , single muon with $p_T > 1$ GeV/c
  - 2013/2016: veto on V0A , hits in V0C , di-muon, each with $p_T > 0.5$ GeV/c
  - 2015/2018: veto on V0A, veto on AD, di-muon, each with $p_T > 1$ GeV/c
- Semi-forward rapidity trigger on UPC
  - 2013/2016: veto on V0A , hits in V0C , hits in SPD ≥ 2, single muon with $p_T > 0.5$ GeV/c



UPC results from Run 1

- Coherent and incoherent J/ψ cross sections were measured in the forward and the central rapidity region.
- Coherent ψ' cross section was measured in the central rapidity region.
- Large spread of predictions before the measurement.
- Data favour moderate nuclear shadowing models at central rapidity.