Photoproduction results from ALICE in ultra-peripheral collisions at the LHC

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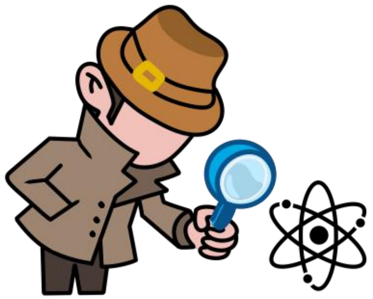
Kruger National Park, South Africa

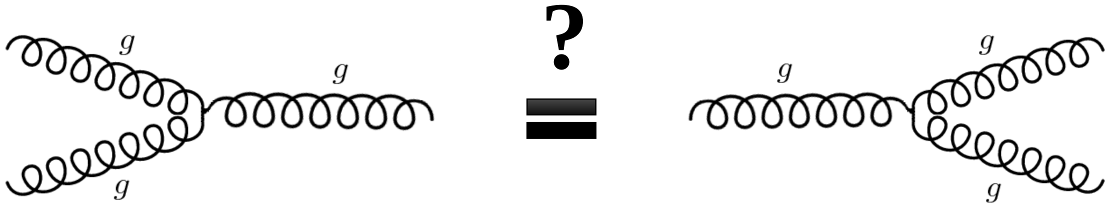
Introduction

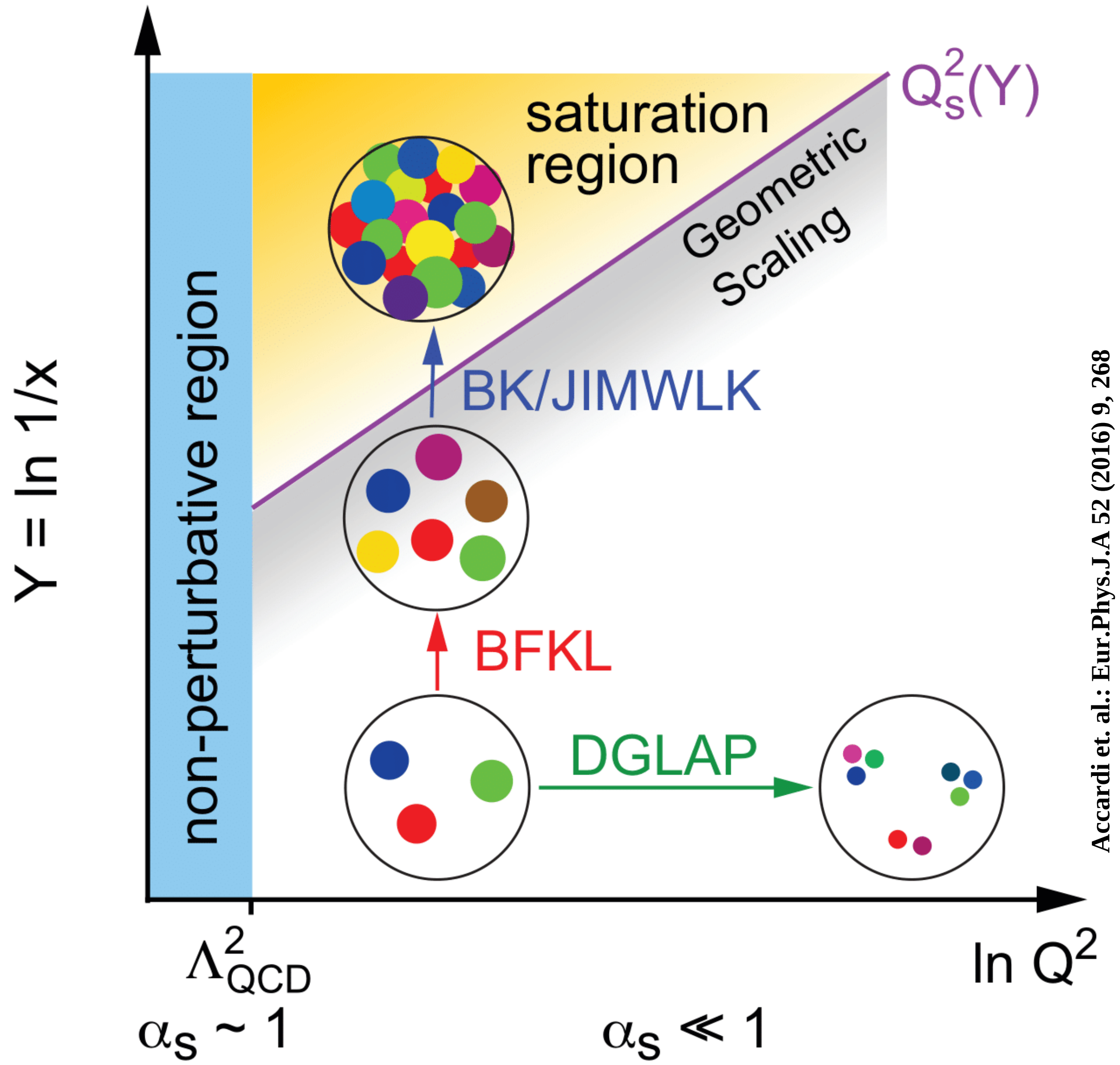
Proton structure

- Active search for **saturation** at **low *x***!



- New measurements are needed



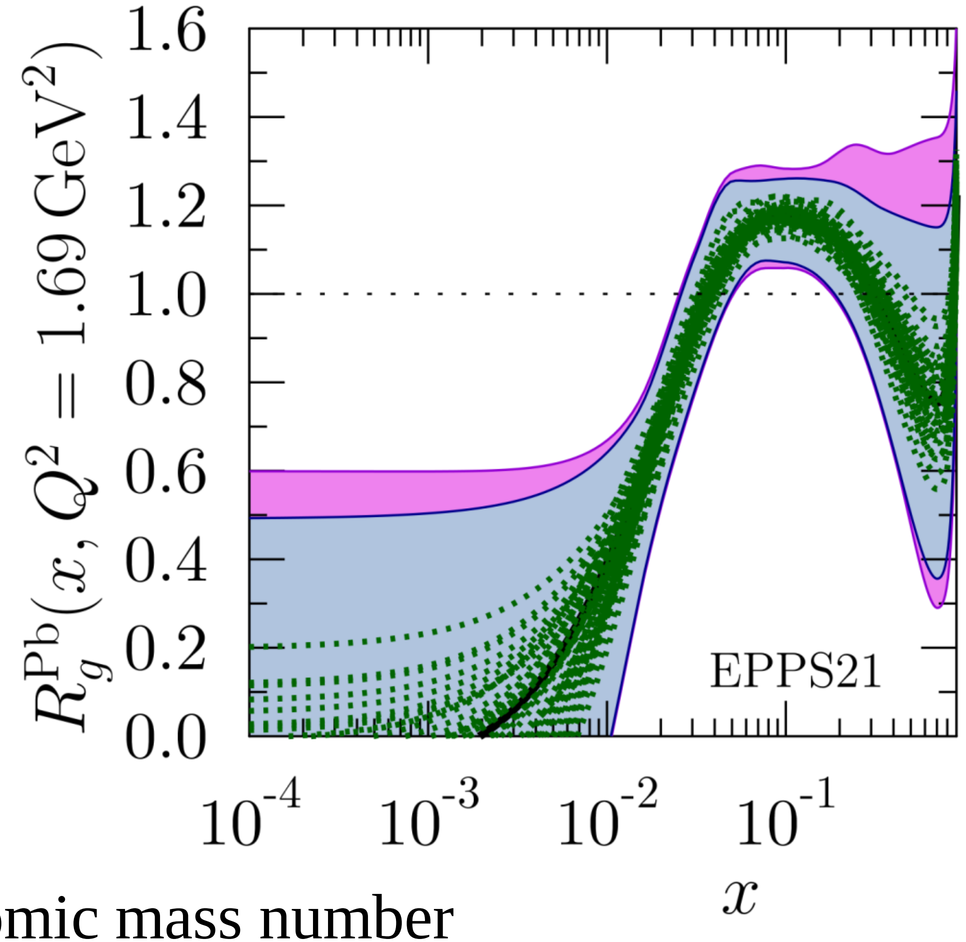


Accardi et. al.: Eur.Phys.J.A 52 (2016) 9, 268

Nuclear structure

- **Nuclear shadowing effects** on gluon PDFs **at low *x***

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



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

- Onset of saturation is expected to depend on the atomic mass number

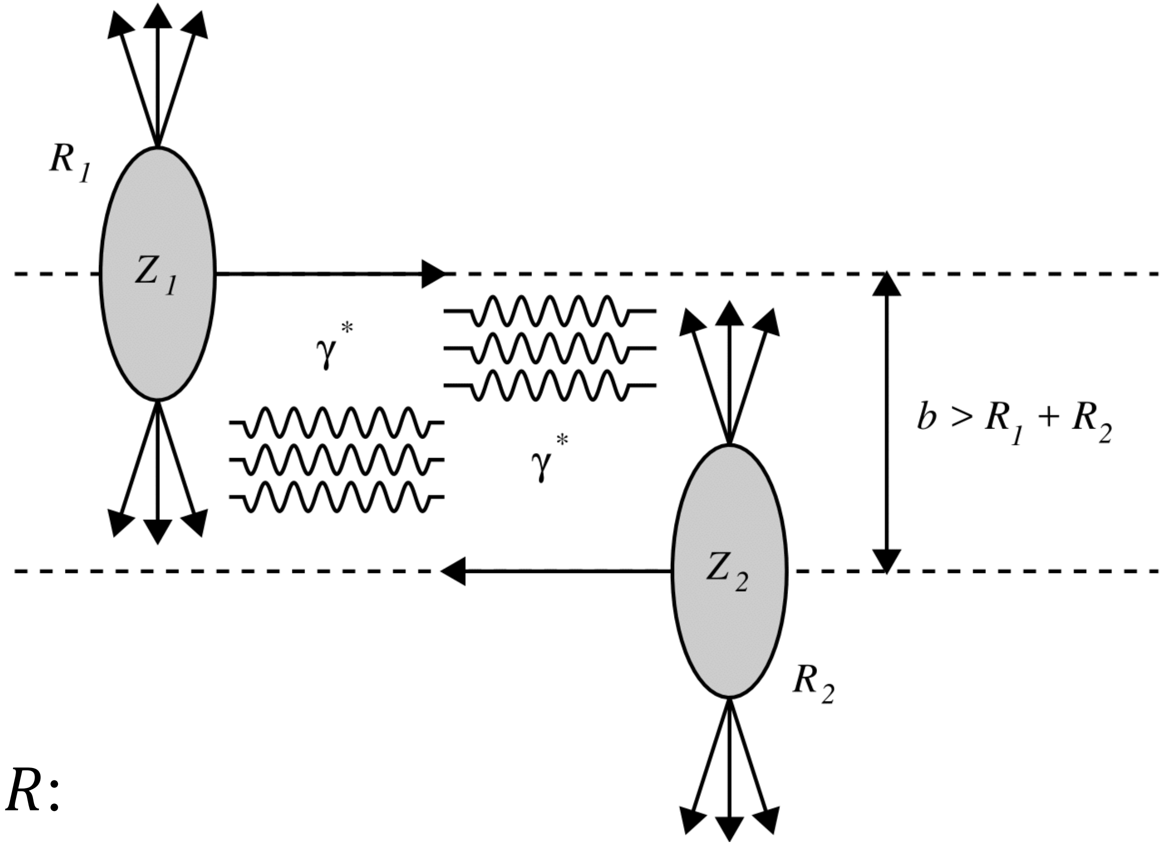
→ **Saturation may contribute to nuclear shadowing!**

Ultra-peripheral collisions

- Hadronic interactions are suppressed

→ **Photon-induced reactions**

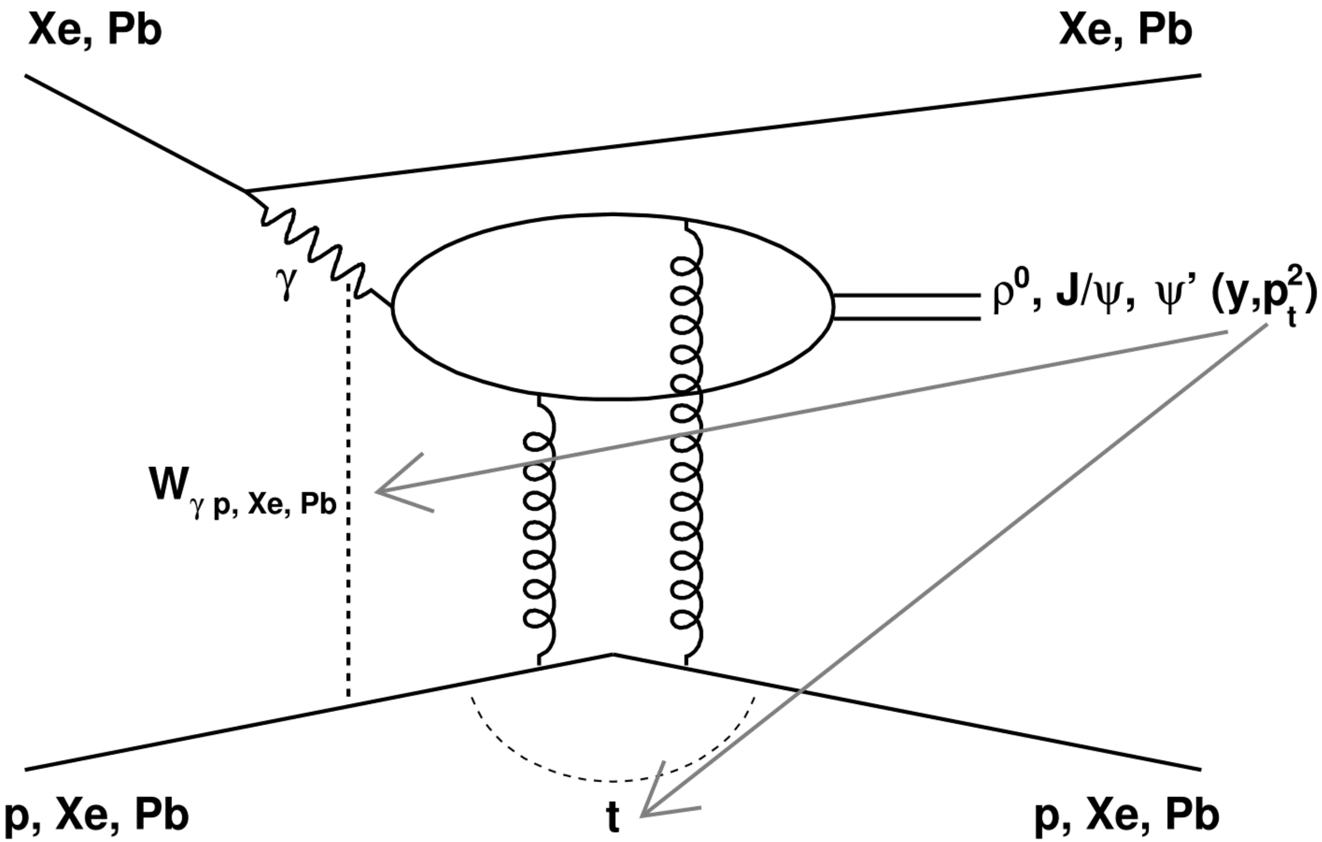
can be measured at the LHC!



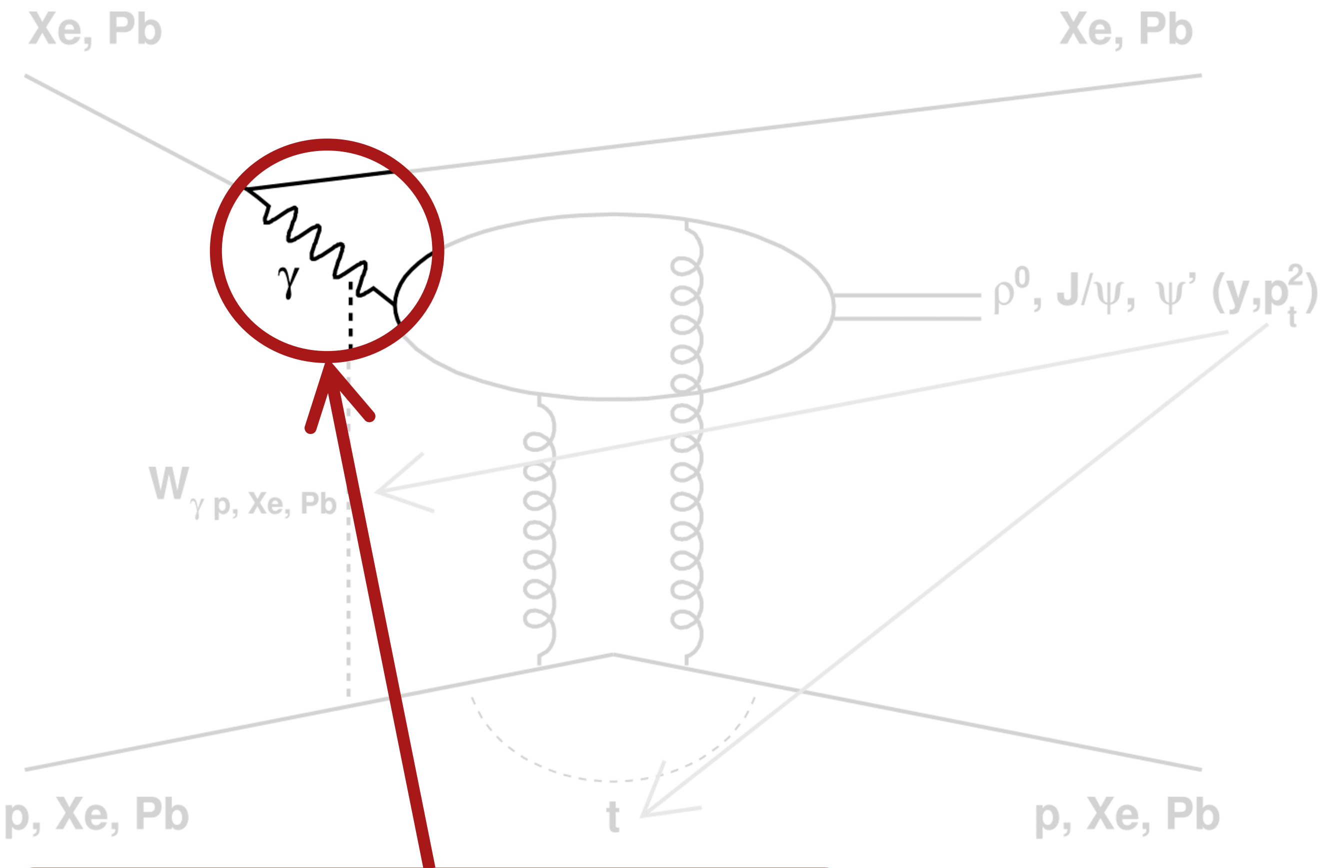
- Photon-induced reactions also contribute at $b < 2R$:
  - J/ψ excess at very low p_{T} – ALICE[1,3]
  - Dielectron excess at very low p_{T} – ALICE[2]

[1] ALICE: Phys. Rev. Lett. 116 (2016) 222301, [2] ALICE: CERN-EP-2022-068 , [3] ALICE: CERN-EP-2022-071

Photoproduction



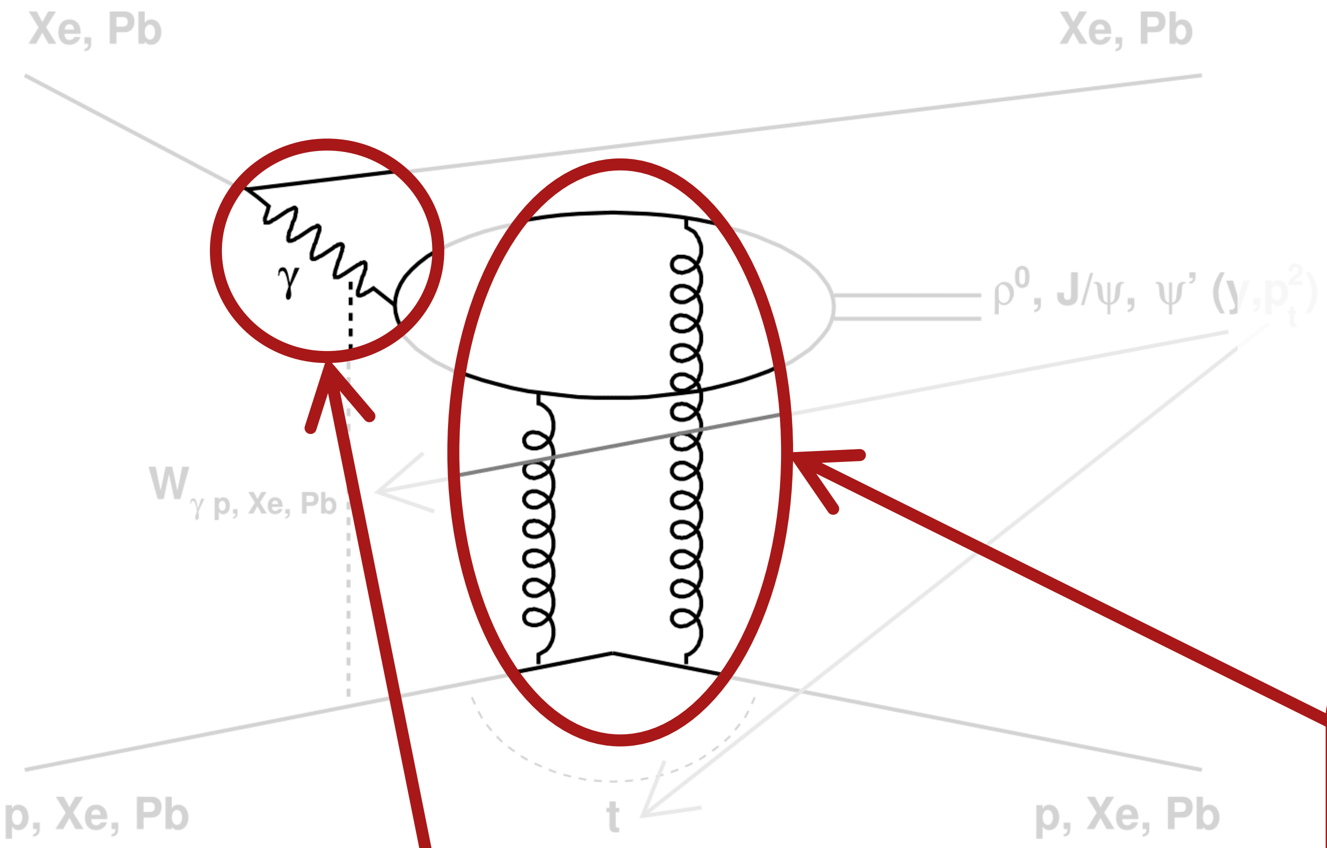
Photoproduction



Photon emission

- Flux **intensity** ~ Z^2
- Photon **energy** given by Pb **boost**

Photoproduction



Photon emission

- Flux **intensity** ~ $\boldsymbol{Z^2}$
- Photon **energy** given by Pb **boost**

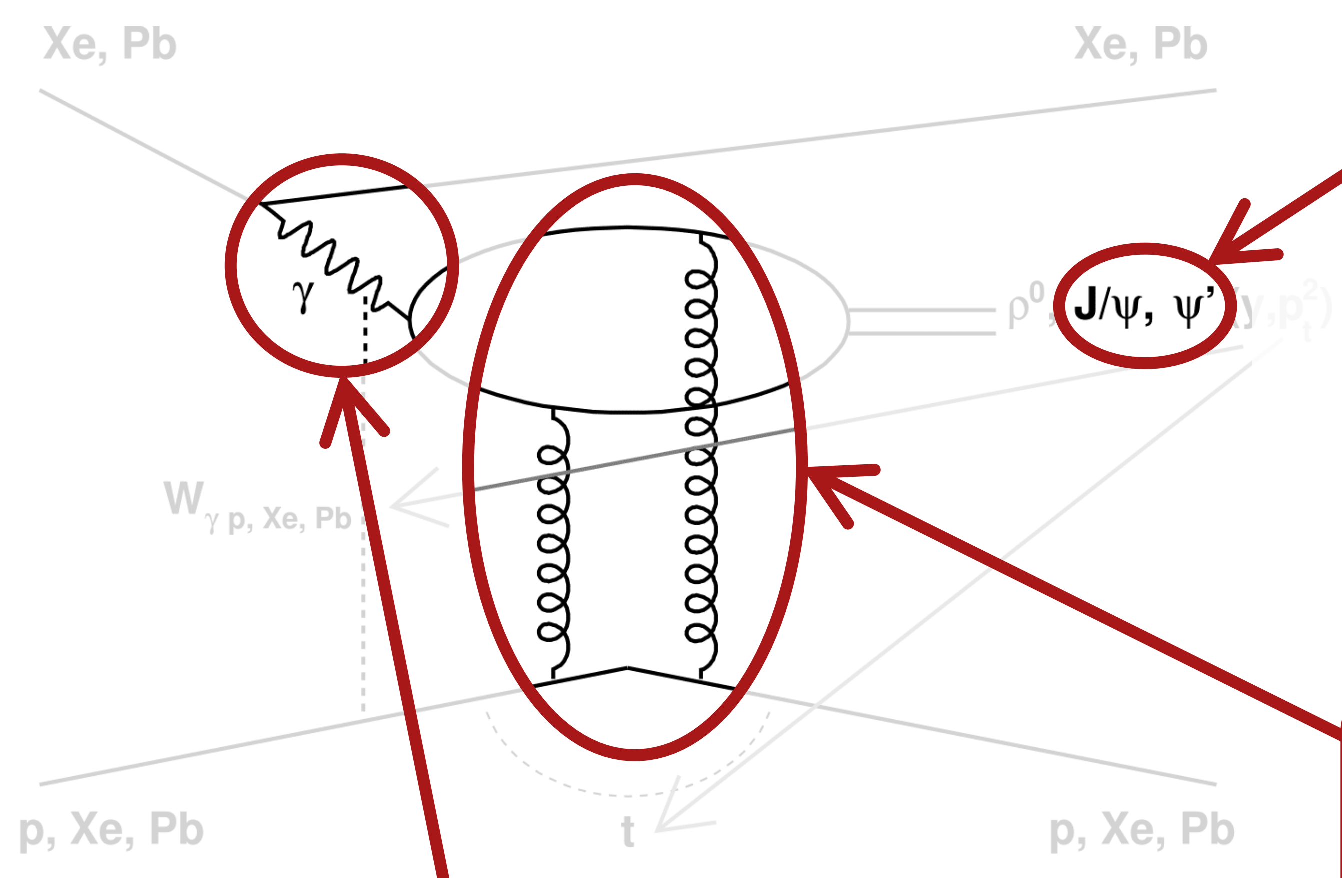
Photon target interaction

- In LO collinear pQCD:

$$\left.\frac{\mathrm{d}\sigma_{\gamma+A\rightarrow J/\psi+A}}{\mathrm{d}t}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s(Q^2)}{48\alpha_{\mathrm{em}}Q^8}\left[xg_A(x,Q^2)\right]^2$$

M.G. Ryskin, Z.Phys. C57 (1993) 89-92

Photoproduction



J/ψ, ψ'

- **Perturbative QCD** $Q^2 \sim \frac{M^2}{4}$
- **Clear** experimental **signal:**
  - Large lepton branching ratios
  - Small decay width
  - Exclusive production

Photon emission

- Flux **intensity** ~ $\boldsymbol{Z^2}$
- Photon **energy** given by Pb **boost**

Photon target interaction

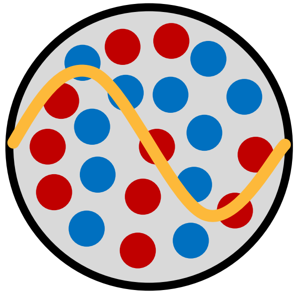
- In LO collinear pQCD:

$$\left.\frac{d\sigma_{\gamma+A\to J/\psi+A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s(Q^2)}{48\alpha_{em} Q^8} \left[x g_A(x, Q^2)\right]^2$$

M.G. Ryskin, Z.Phys. C57 (1993) 89-92

Photoproduction p_T signature

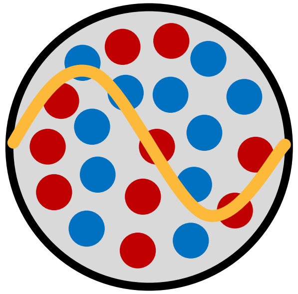
- Photon interacts with the **whole nucleus**: $p_T \approx 60$ MeV/c ~ 1/R$_{Pb}$
  - **Coherent** (Pb-Pb) - Target ion stays intact



Coherent

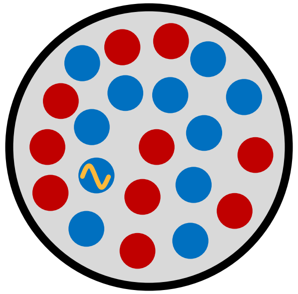
Photoproduction p_T signature

- Photon interacts with the **whole nucleus**: $p_T \approx 60$ MeV/c ~ $1/R_{Pb}$
  - **Coherent** (Pb-Pb) - Target ion stays intact
- Photon interacts with **single nucleon**: $p_T \approx 300$ MeV/c ~ $1/R_N$
  - **Incoherent** (Pb-Pb) - Target ion breaks, nucleon stays intact
  - **Exclusive** (p-Pb) - Target proton stays intact



Coherent

Exclusive



Incoherent

Photoproduction p_T signature

- Photon interacts with the **whole nucleus**: $p_T \approx 60$ MeV/c ~ 1/R$_{Pb}$
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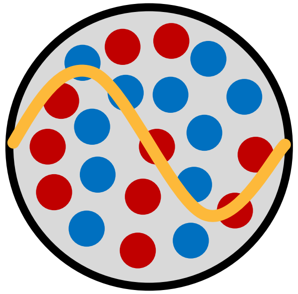
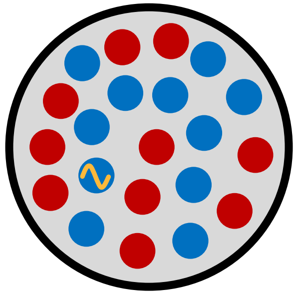


Coherent

- Photon interacts with **single nucleon**: $p_T \approx 300$ MeV/c ~ 1/R$_N$
  - **Incoherent** (Pb-Pb) - Target ion breaks, nucleon stays intact
  - **Exclusive** (p-Pb) - Target proton stays intact

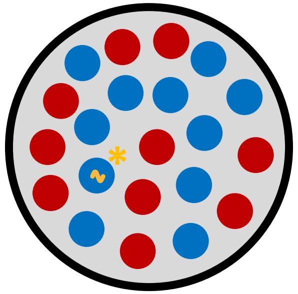
Exclusive



Incoherent

- Photon interacts with **single nucleon and excites it**: $p_T \approx 1$ GeV/c
  - **Dissociative** (p-Pb) - Target proton breaks
  - **Dissociative** (Pb-Pb) - Target nucleon breaks as well as the ion

Dissociative



Dissociative

Photoproduction kinematics

- LHC is a **Light-Hadron Collider** at the highest available energies
- Many photoproduction processes can be studied in ALICE → Vector meson production
- Bjorken-x evolution of the parton distribution

$$\rightarrow \quad x = \frac{M_{\mathrm{VM}}}{\sqrt{s_{\mathrm{NN}}}} e^{\pm y}$$

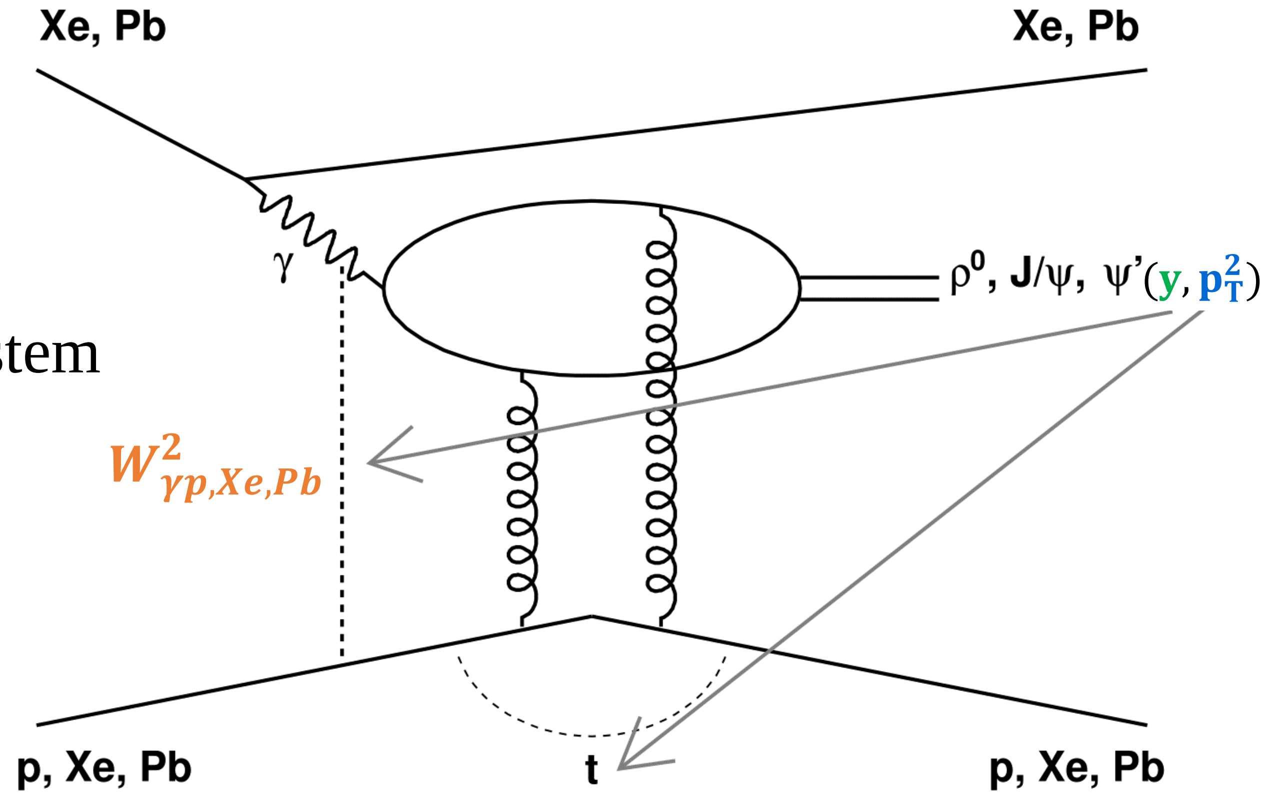
- Centre-of-mass energy of the photon–target system

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

- Transverse-plane distribution of the partons

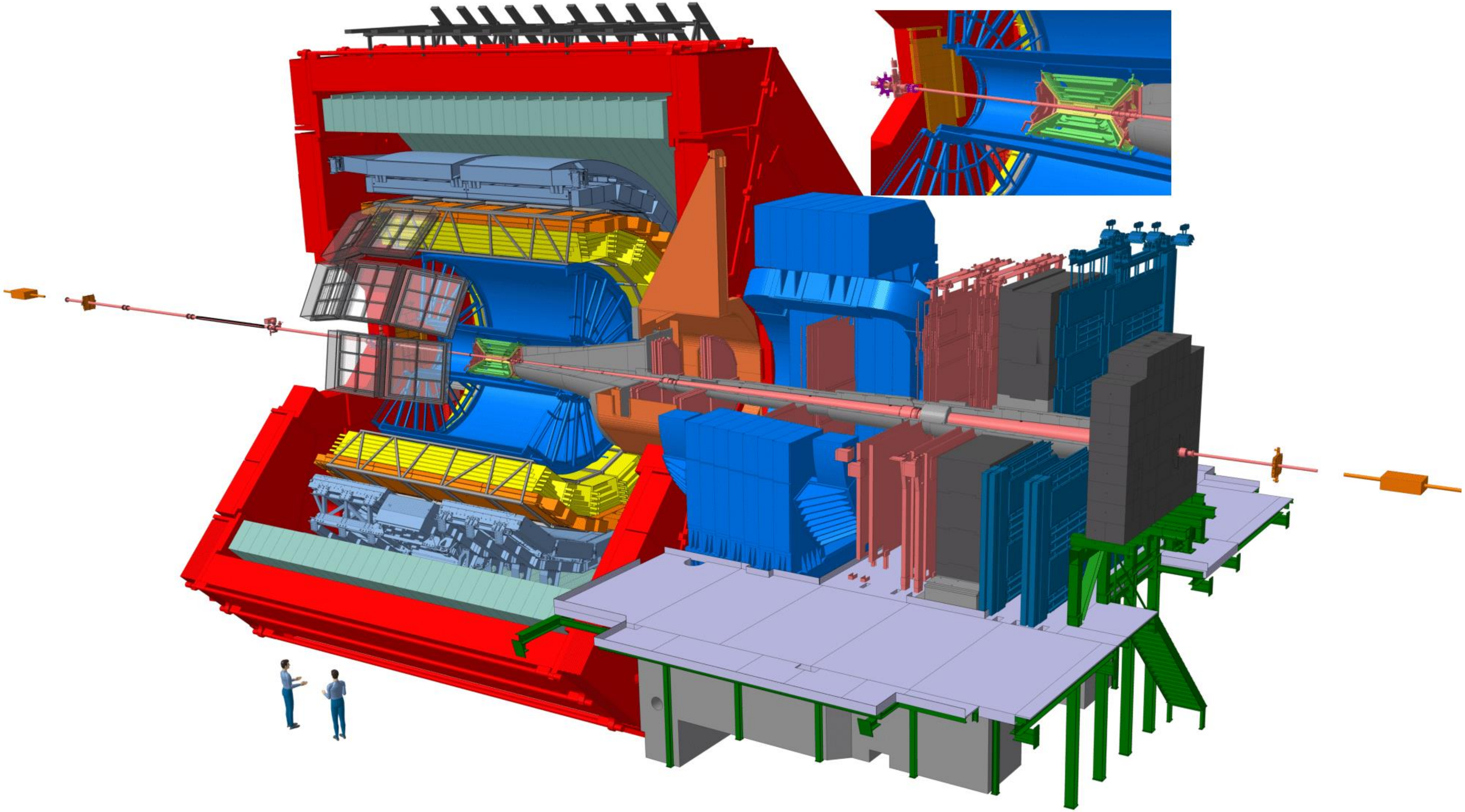
→ **2D Fourier** transform

to the $|t|$ ($\sim p_{\mathrm{T}}^2$) **dependence**

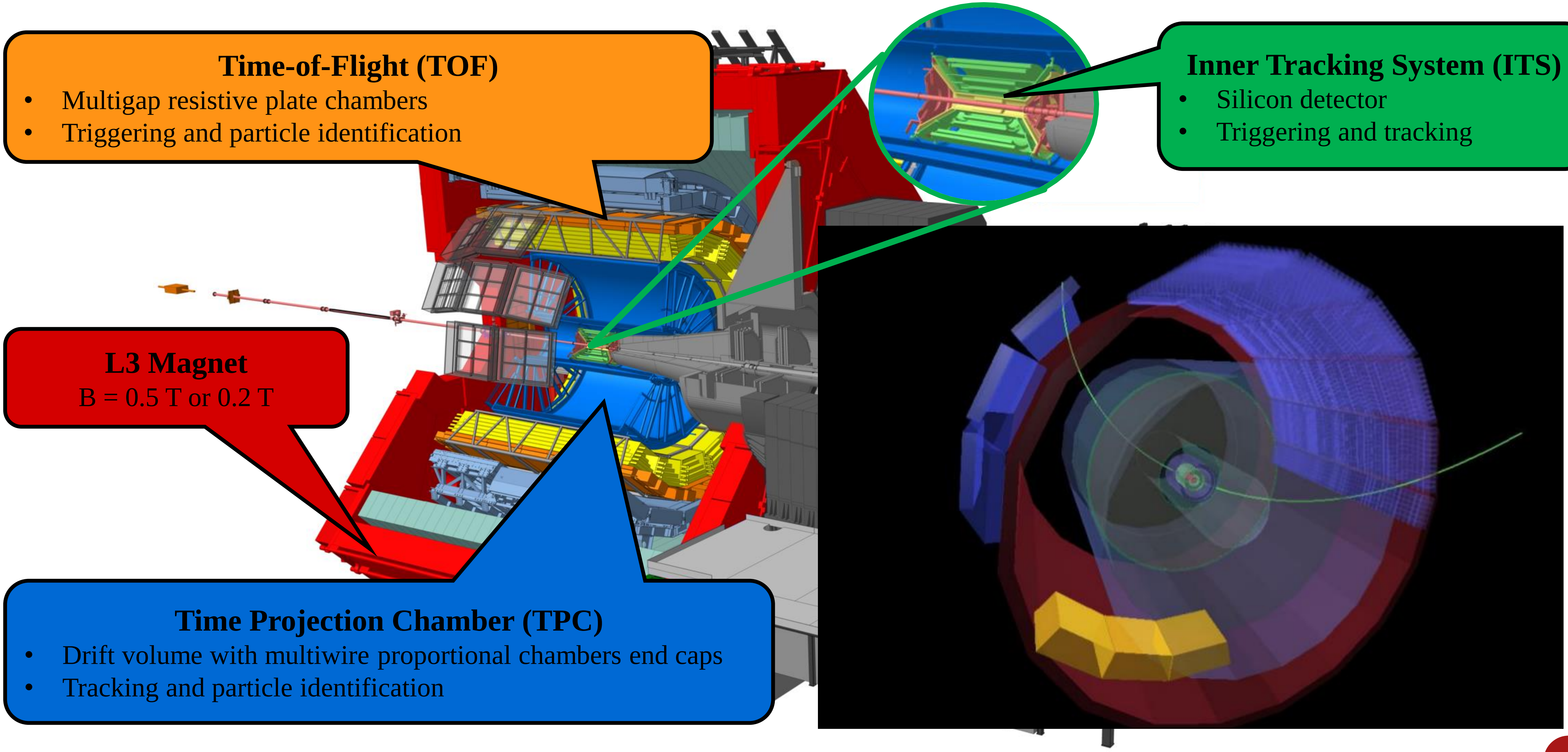


ALICE detector in Run 2

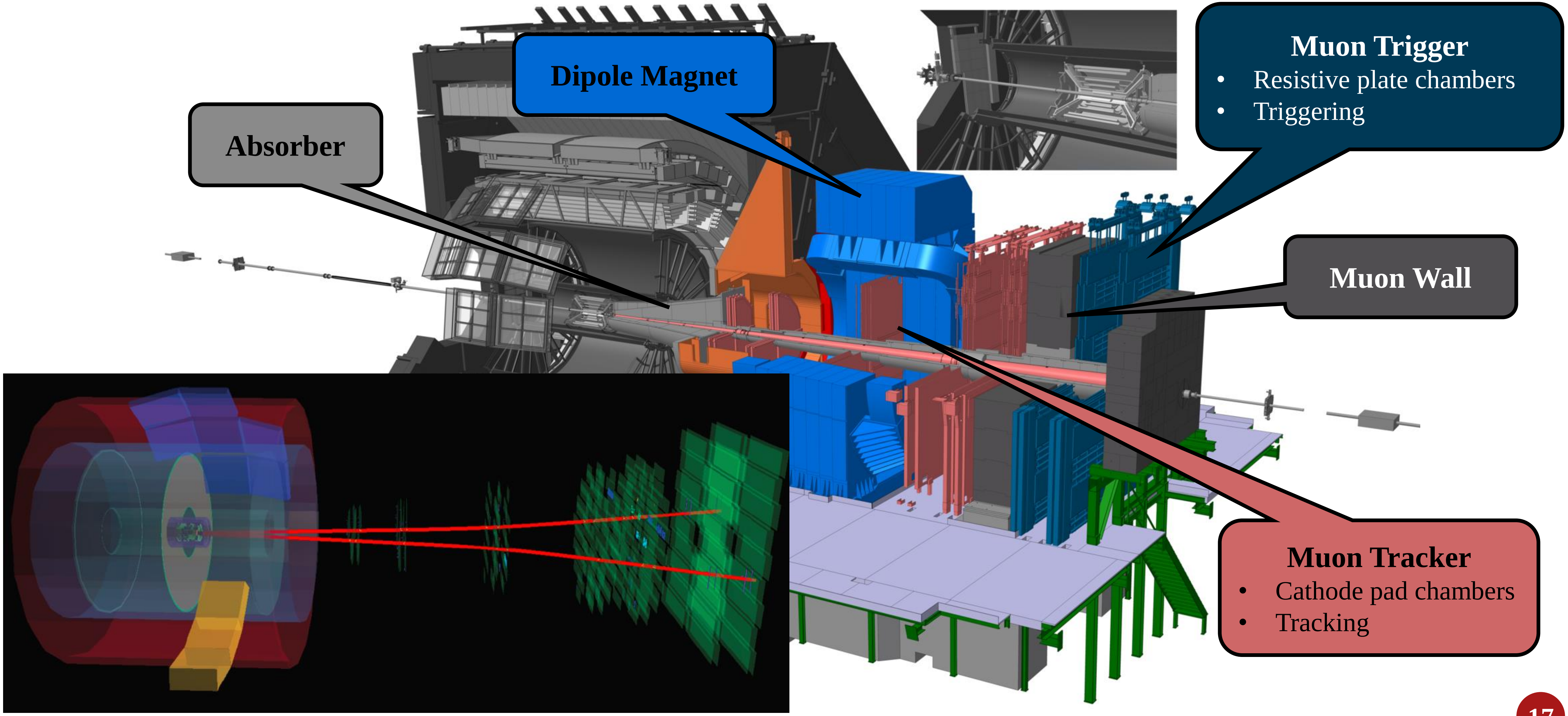
ALICE in Run 2



ALICE: J/ψ measurement at midrapidity



ALICE: J/ψ measurement at forward rapidity

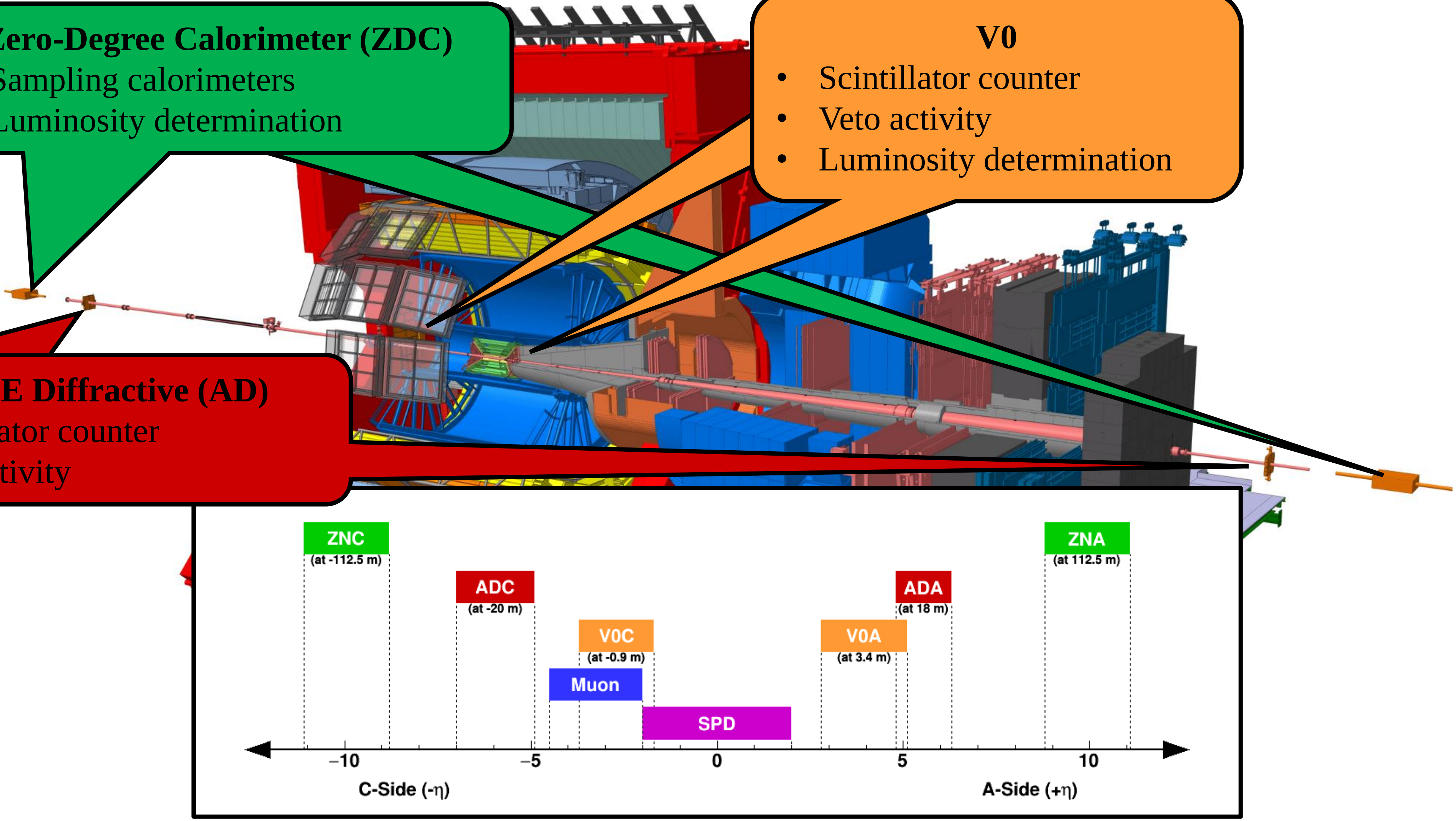


ALICE: Vetoes to enforce exclusivity condition

Zero-Degree Calorimeter (ZDC)
- Sampling calorimeters
- Luminosity determination

V0
- Scintillator counter
- Veto activity
- Luminosity determination

ALICE Diffractive (AD)
- Scintillator counter
- Veto activity



Pb-Pb UPC Results

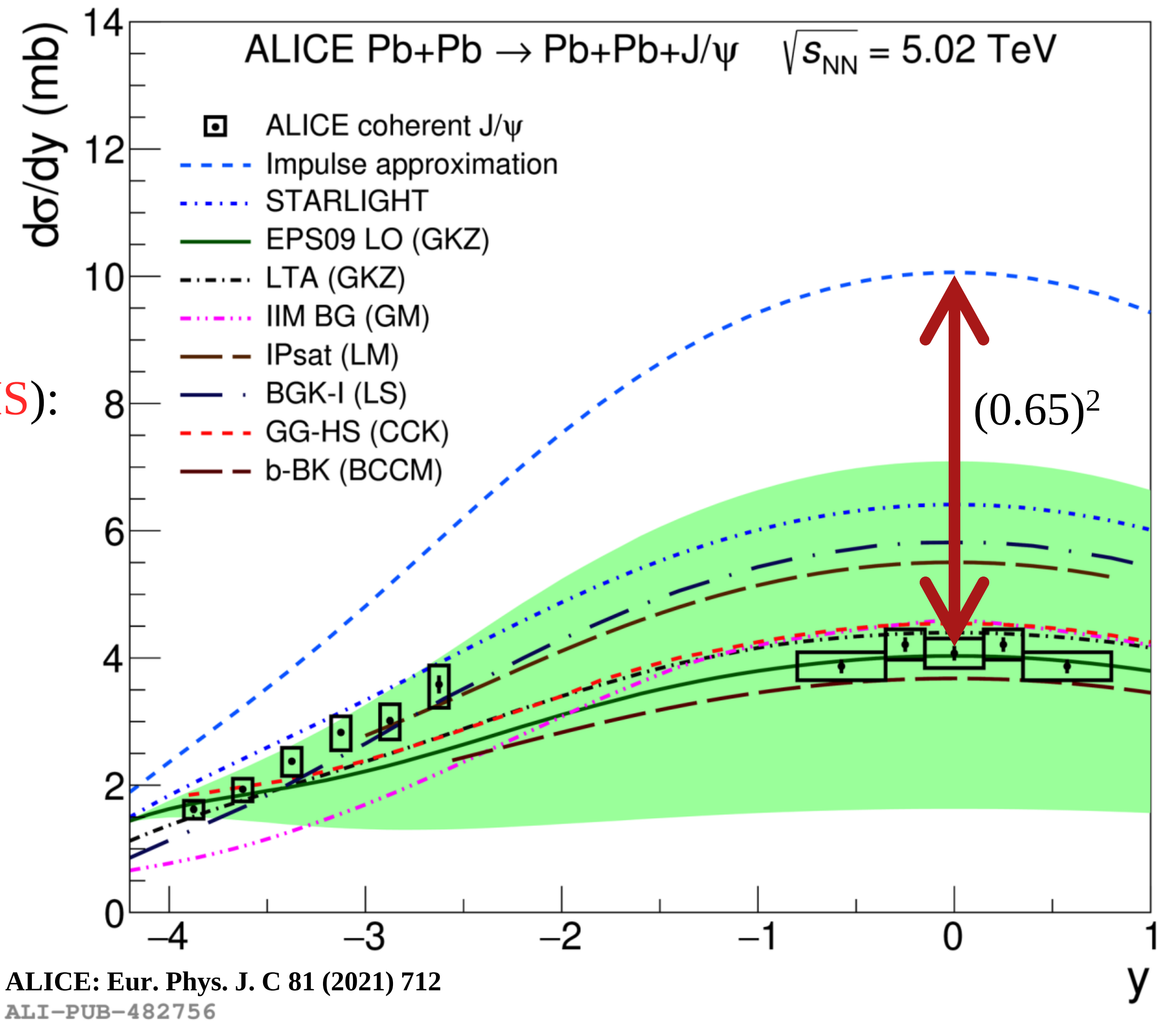
Coherent J/ψ cross section: y - dependence

- **Nuclear suppression factor:** for $x \in (0.3,1.4) \cdot 10^{-3}$

$$S_{\mathrm{Pb}} = \sqrt{\left(\frac{d\sigma}{dy}\right)_{\mathrm{data}} \Big/ \left(\frac{d\sigma}{dy}\right)_{\mathrm{IA}}} = \mathbf{0.65 \pm 0.03}$$

- Models with **shadowing** (EPS09, LTA) and **saturation** (GG-HS):
  - Describe central and forward data
  - Underestimate semi-forward data
- Other models describe either the central or the forward rapidity region

→ **No model describes the full rapidity dependence**



ALICE: Eur. Phys. J. C 81 (2021) 712
ALI−PUB−482756

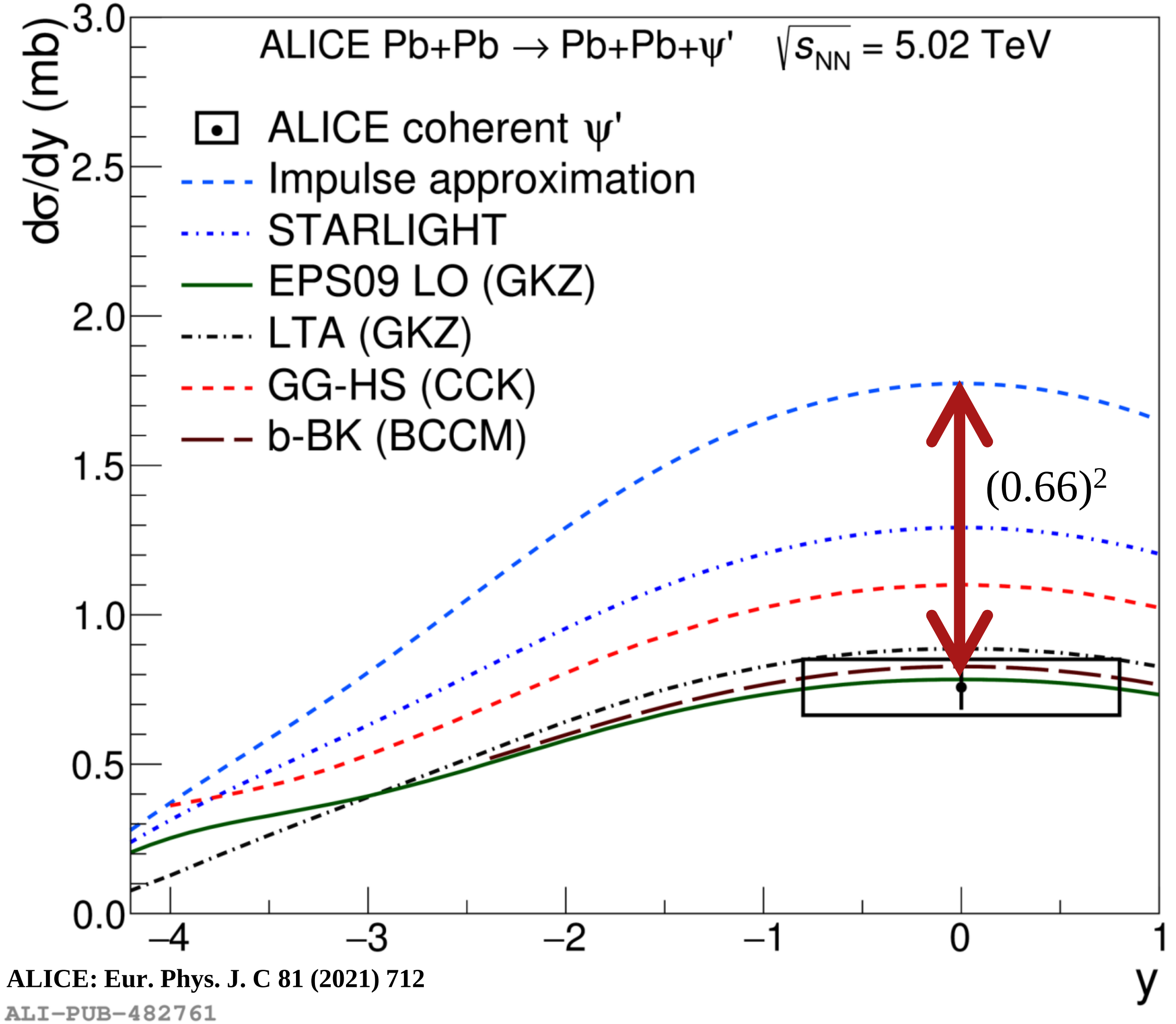
Coherent ψ' cross section: y - dependence

- **Nuclear suppression factor:** for $x \in (0.3, 1.6) \cdot 10^{-3}$

$$\boldsymbol{S_{\mathrm{Pb}} = 0.66 \pm 0.06}$$

Consistent with the J/ψ result

- Models with **shadowing:**
  - EPS09 - agrees
  - LTA - agrees
- Models with **saturation:**
  - b-BK - agrees
  - GG-HS - overpredicts
- Other models overpredict the results



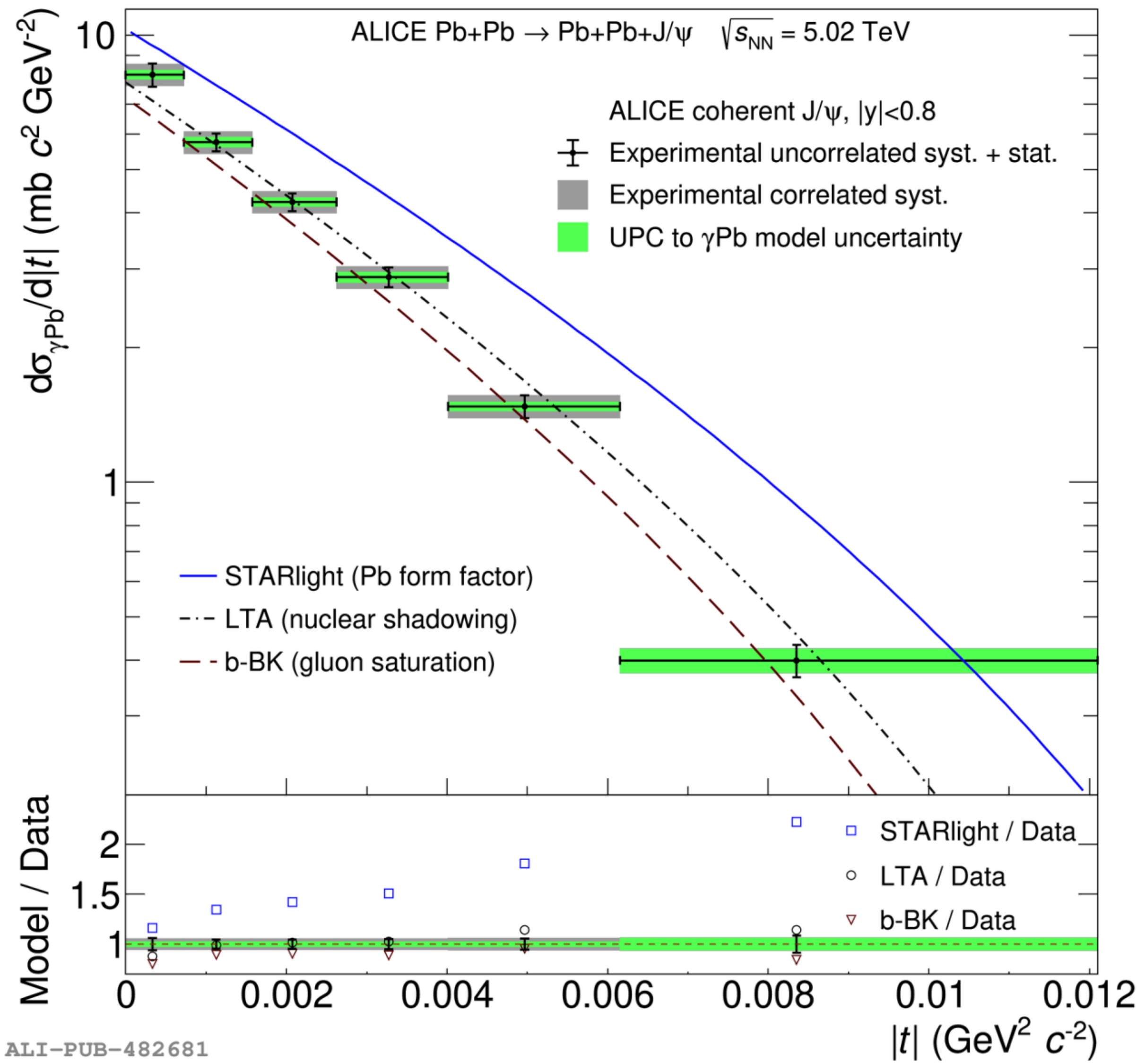
ALICE: Eur. Phys. J. C 81 (2021) 712
ALI-PUB-482761

Coherent J/ψ cross section: $|t|$- dependence

- From p_{T}^2-dependent photoproduction to $|t|$-dependent photonuclear production:
  - p_{T}^2 to $|t|$ transition with two different unfolding methods
  - Correction on interference of photon sources
  - From UPC to photonuclear cross section using the photon flux

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

⟶ **Probing the transverse partonic structure of the nucleus at low *x*!**



ALI-PUB-482681

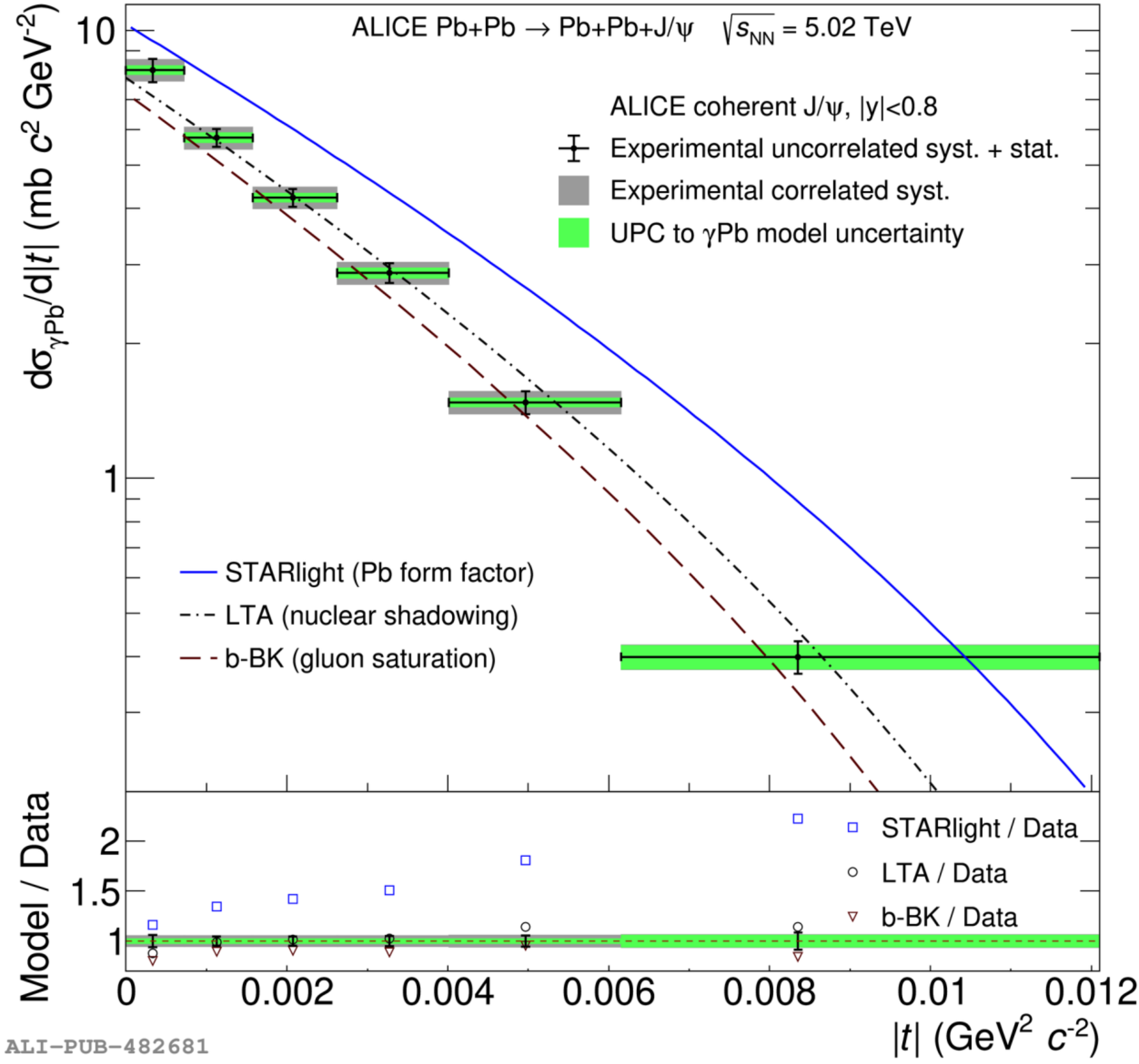
ALICE: Phys. Lett. B 817 (2021) 136280

Coherent J/ψ cross section: $|t|$ - dependence

- Measurement down to **very low $|t|$** approaching **HERA-like precision!**
- Difference from STARlight (driven by the nuclear form factor) in shape and magnitude

→ **$|t|$ dependent QCD dynamical effects!**

- Models based on pQCD describe data within current uncertainties:
  - Nuclear **shadowing** (LTA)
  - Gluon **saturation** (b-BK)
- Future measurements should allow to distinguish between the predictions



ALI-PUB-482681

ALICE: Phys. Lett. B 817 (2021) 136280

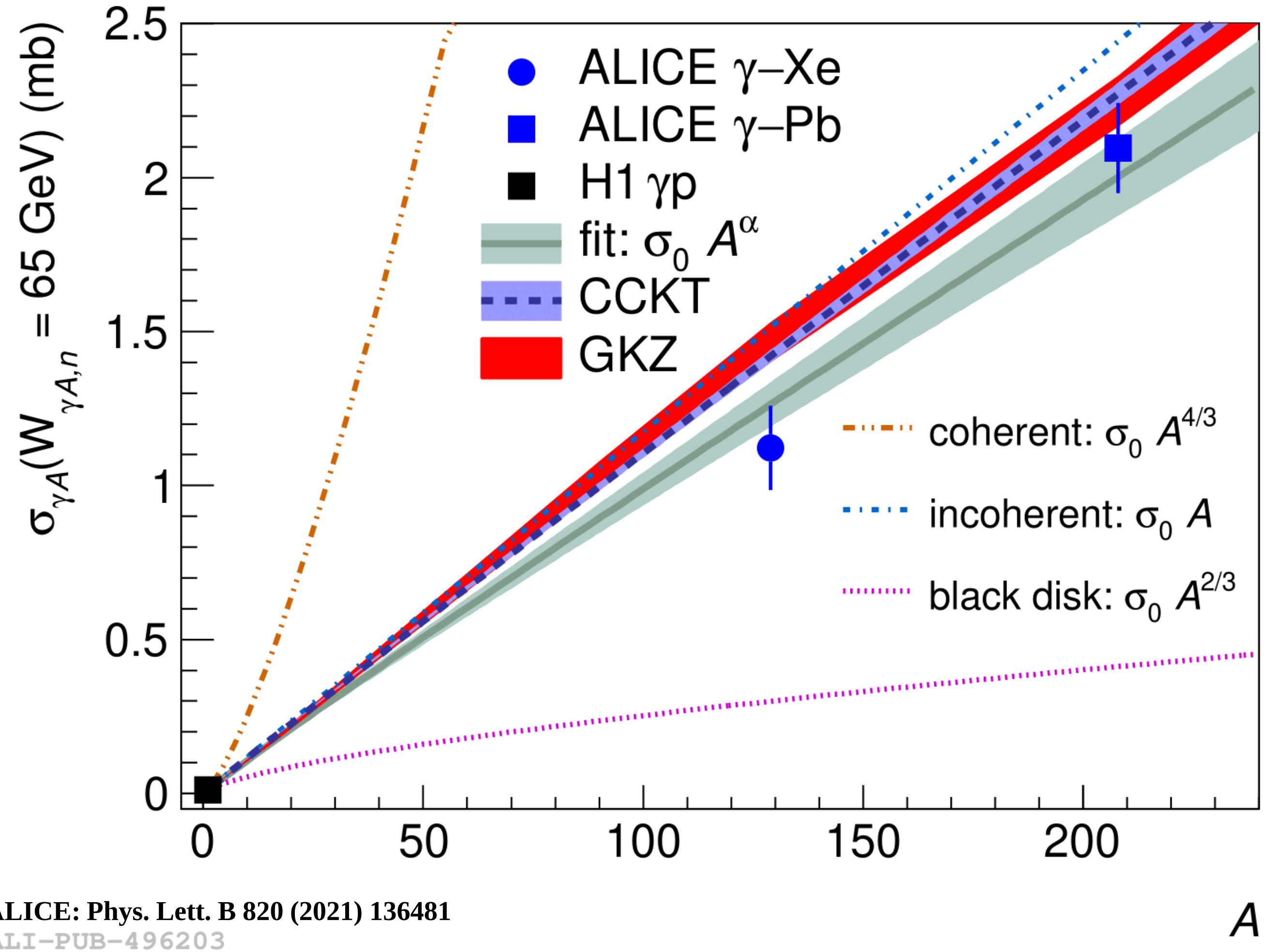
Xe-Xe UPC Results

Coherent ρ^0 cross section: A - dependence

- Measurement with Pb and Xe collisions ⟶ **Study of the A dependence!**

- Power-law fit: $\alpha = 0.96 \pm 0.02$
  - Below coherent ⟶ **Shadowing**
  - Value close to incoherent is a coincidence caused by large shadowing effect
  - Black-disc limit distant at $W_{\gamma A}$ = 65 GeV

- Models **agree** with the data:
  - GKZ - **shadowing**
  - CCKT - **saturation**



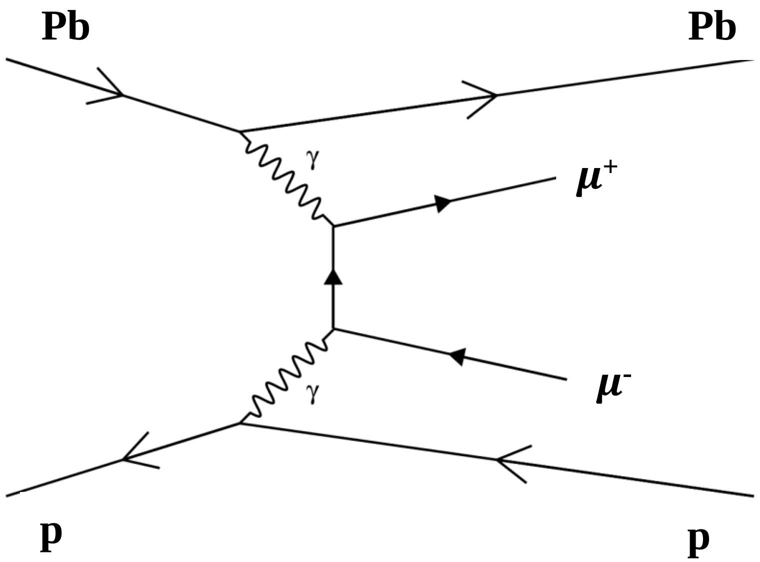
ALICE: Phys. Lett. B 820 (2021) 136481

ALI-PUB-496203

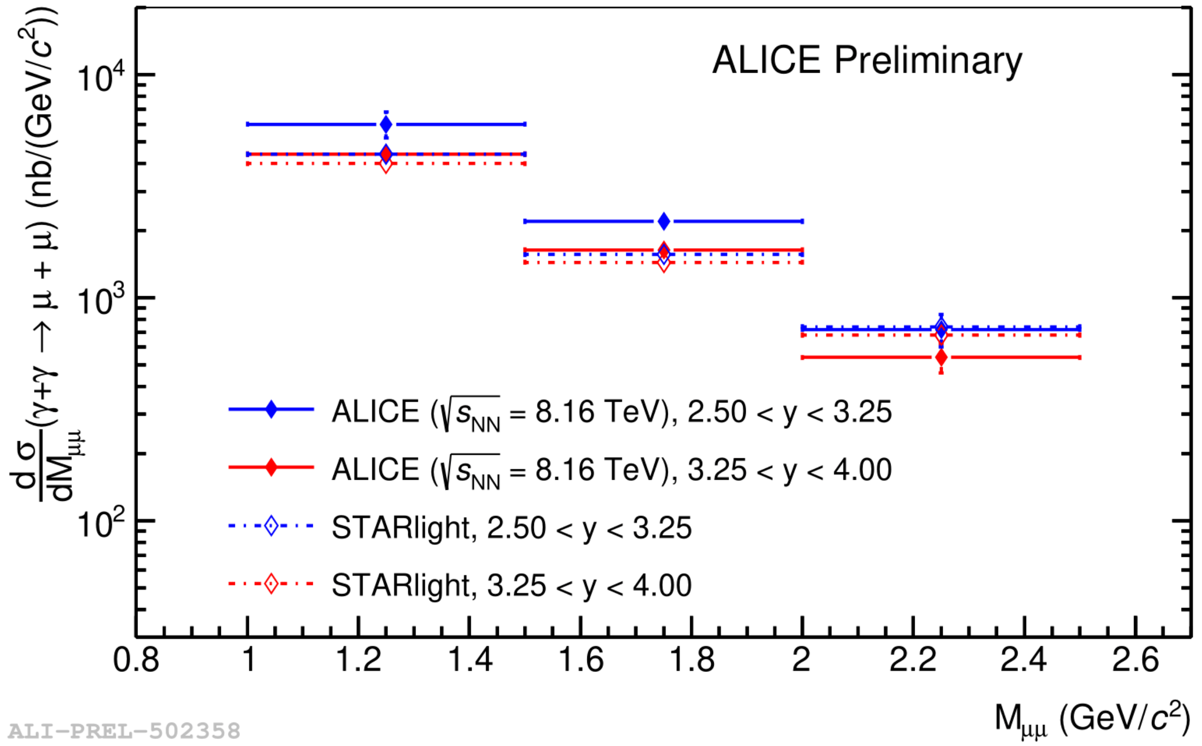
p-Pb UPC Results

$\gamma\gamma \rightarrow \mu\mu$ cross section

- $\gamma\gamma \rightarrow \mu\mu$ cross section in the **low mass** region!
- STARlight:
  - LO QED without final-state radiation or other NLO effects
  - No interactions within the radius of the targets



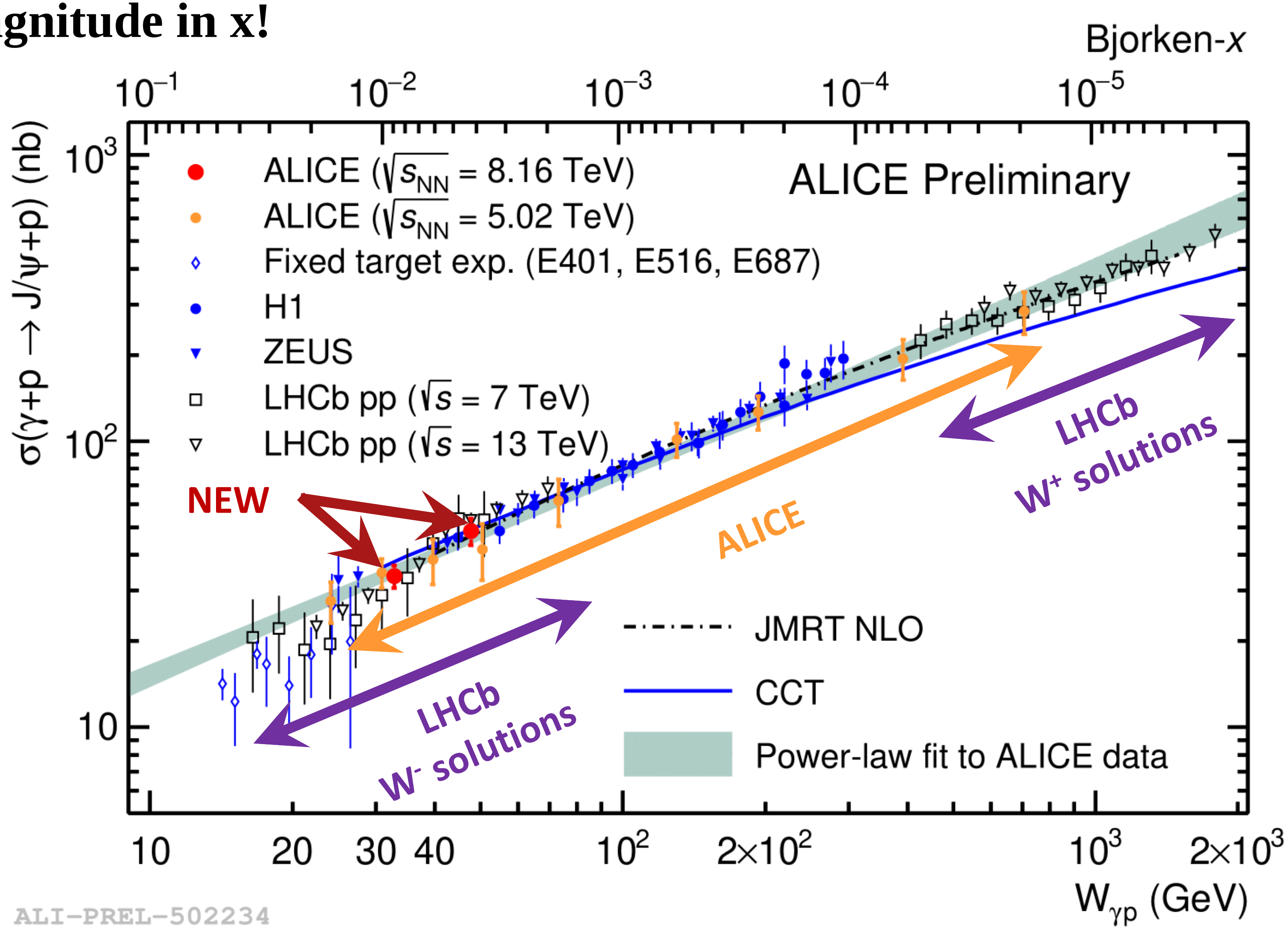
→ **Slight excess in data**
agreement within 3 sigma



- Can be used to improve current models
  - **Fix background** for VM or jet **photoproduction**
  - Improve predictions for **light-by-light scattering**

Energy dependence: Exclusive J/ψ cross section

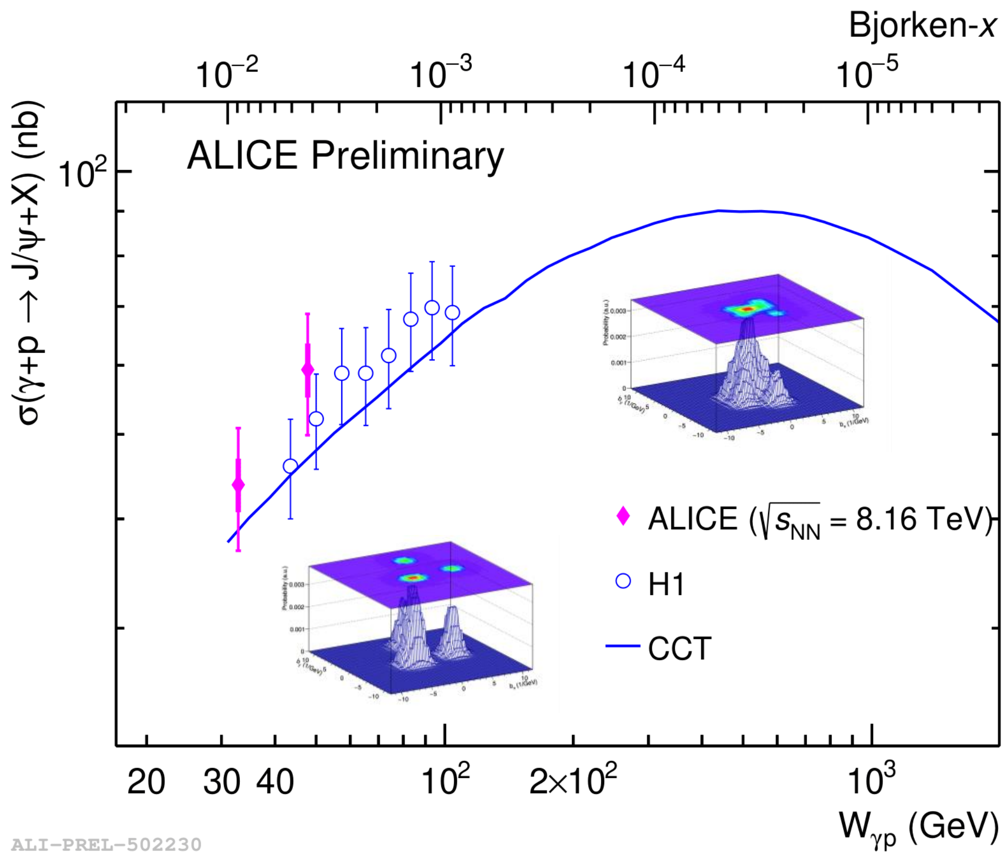
- **ALICE** data covers **three orders of magnitude in x!**
- Power law fit to ALICE data
  - Exponent: $\delta = 0.70 \pm 0.04$
  - **No change** between **HERA** and **LHC**
- **ALICE** and **LHCb** are **compatible**
- **Agreement** with models:
  - **JMRT NLO**: DGLAP formalism with main NLO contributions
  - **CCT**: Saturation in an energy dependent hot spot model

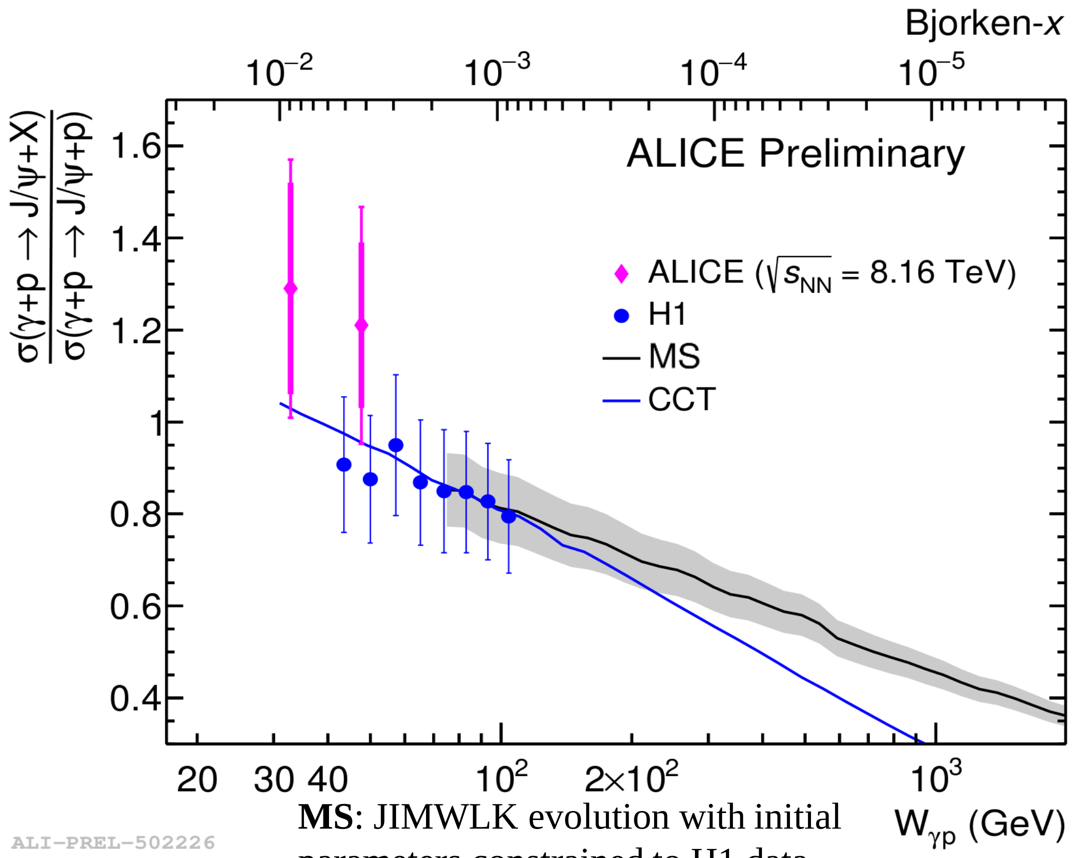


Energy dependence: Dissociative J/ψ cross section

- **First measurement of the dissociative cross section at the LHC!**
  - Agreement with HERA results
  - Agreement with **CCT**, predicts maximum at $W_{\gamma p} \approx 500$ GeV

Energies ≈ 1 TeV to be available in Run 3!





MS: JIMWLK evolution with initial parameters constrained to H1 data

Outlook

Outlook: LHC Runs 3 & 4

- $\mathcal{L}$ **increase -** 1 nb^{-1} (Run 2) → 13 nb^{-1} (Runs 3+4)
- **Continuous readout** → higher data collection efficiency
- Significant **detector upgrades**
- Proposed **O-O run** → new system size

→ **Many more collisions to be recorded by ALICE!**

	PbPb					
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

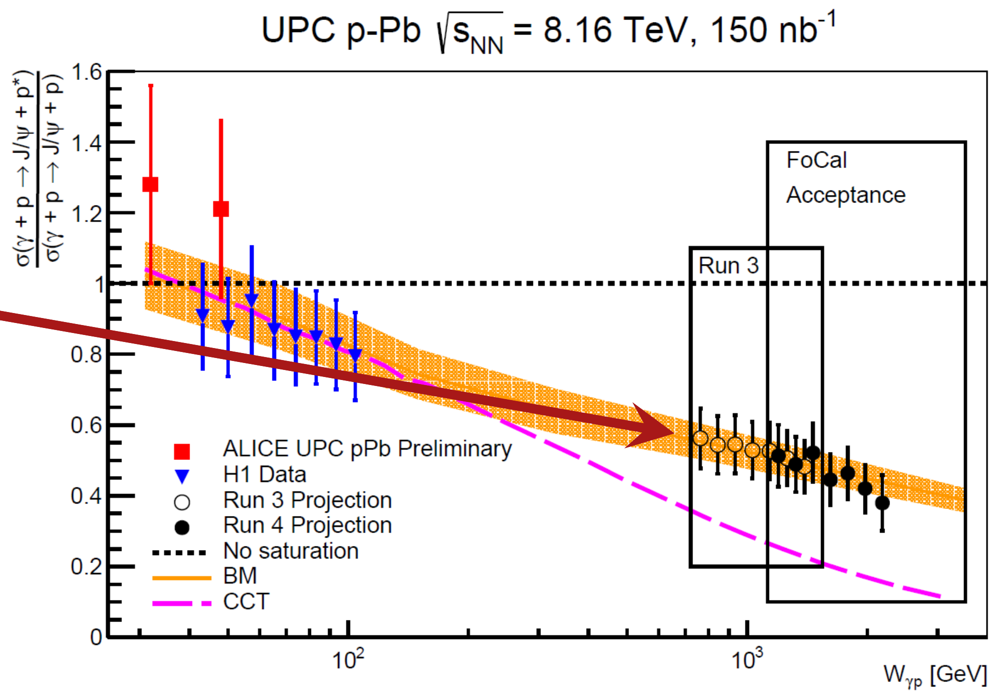
CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

	pPb - lead shine, γp								
Meson	σ	All Total	Ctl. 1 Total	Ctl. 2 Total	FW 1 Total	FW 2 Toal	BW 1 Total	BW 2 Total
$\rho \to \pi^+\pi^-$	35 mb	70 B	3.9 B	15 B	2.0 B	5.5 B	850 M	2.0 B
$\phi \to K^+K^-$	870 μb	1.7 B	65 M	290 M	22 M	120 M	9.7 M	52 M
$J/\psi \to \mu^+\mu^-$	6.2 μb	12 M	1.0 M	5.2 M	260 K	800 K	180 K	430 K
$\psi(2S) \to \mu^+\mu^-$	134 nb	270 K	22 K	110 K	6.0 K	18 K	3.2 K	7.7 K
$\Upsilon(1S) \to \mu^+\mu^-$	5.74 nb	11 K	1.1 K	5.4 K	310	880	41	100

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

Outlook: LHC Runs 3 & 4

- **Improvements** of all **previous measurements**
- **More differential** measurements:
  - $\frac{d^2\sigma}{dy\,d|t|}$
  - Angular dependences between l^+l^-
  - Coherent ρ^0 evolution with A in O-O …
- **New** measurements:
  - Υ(1S) - Q^2 factor 10 larger than J/ψ
  - Interference effects
  - Open charm photoproduction
  - Incoherent ρ^0 production …



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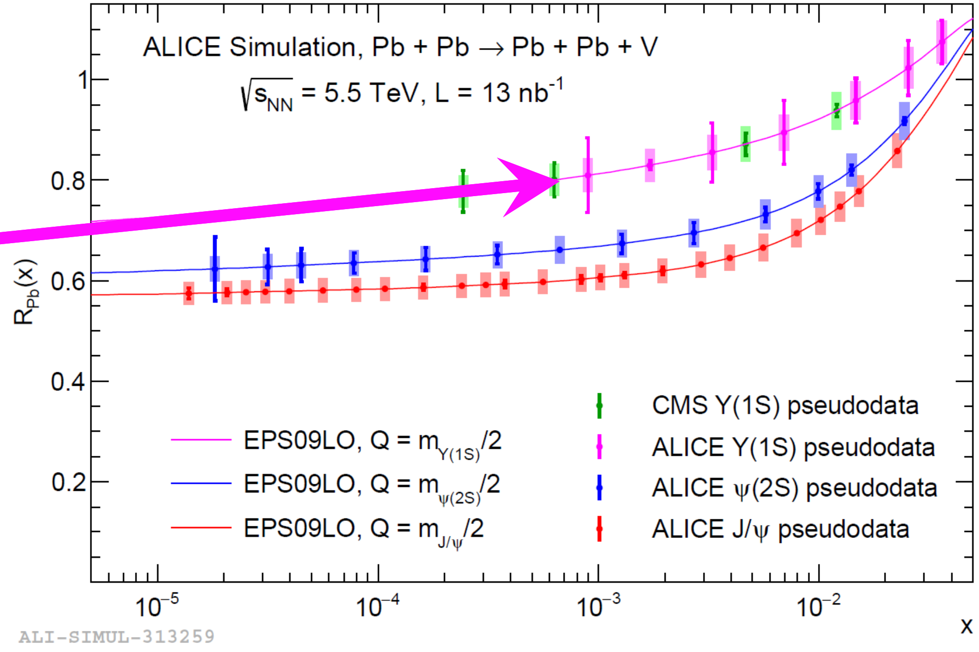


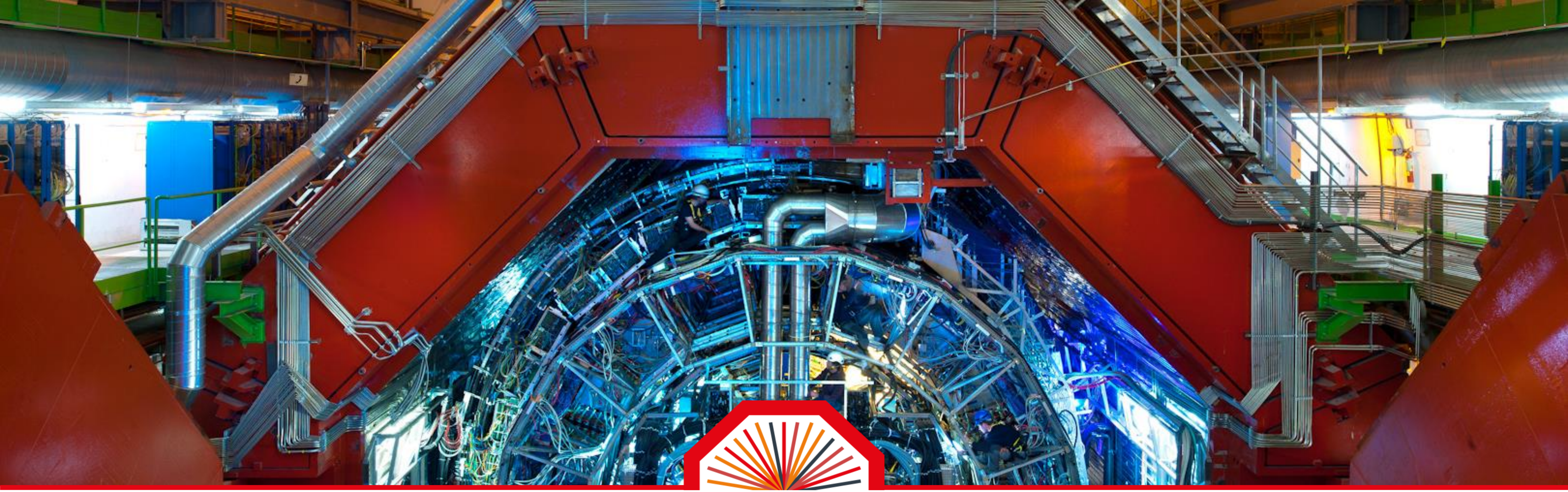
A. Bylinkin, J. Nystrand, D. T. Takaki: arXiv:2211.16107

Conclusion

Conclusion

- Nuclear parton structure at Bjorken $x \in (0.3, 1.4) \cdot 10^{-3}$:
  - $S_{\mathrm{Pb}} \approx 0.65$
  - $|t|$ **dependence** sensitive to parton distribution in the transverse plane
  - Models with **shadowing** or **saturation** describe data within uncertainties
- Proton parton structure at Bjorken $x \in (0.5, 2) \cdot 10^{-2}$:
  - Exclusive cross section agrees with previous results
  - **For the first time at the LHC - dissociative J/ψ** production off protons!
  - $\gamma\gamma \rightarrow \mu\mu$ production at low masses in pPb collisions
- Major improvements for Runs 3 & 4:

→ **Plenty of new results anticipated!**

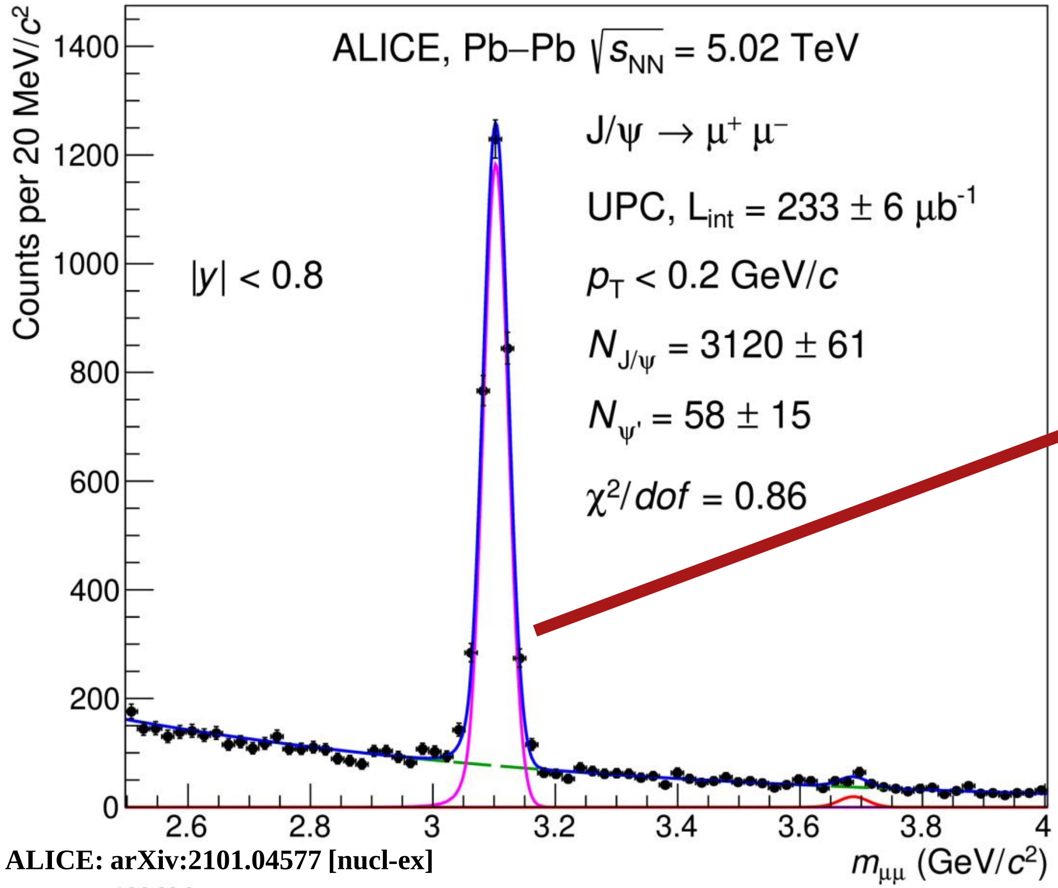


Thank you for your attention!

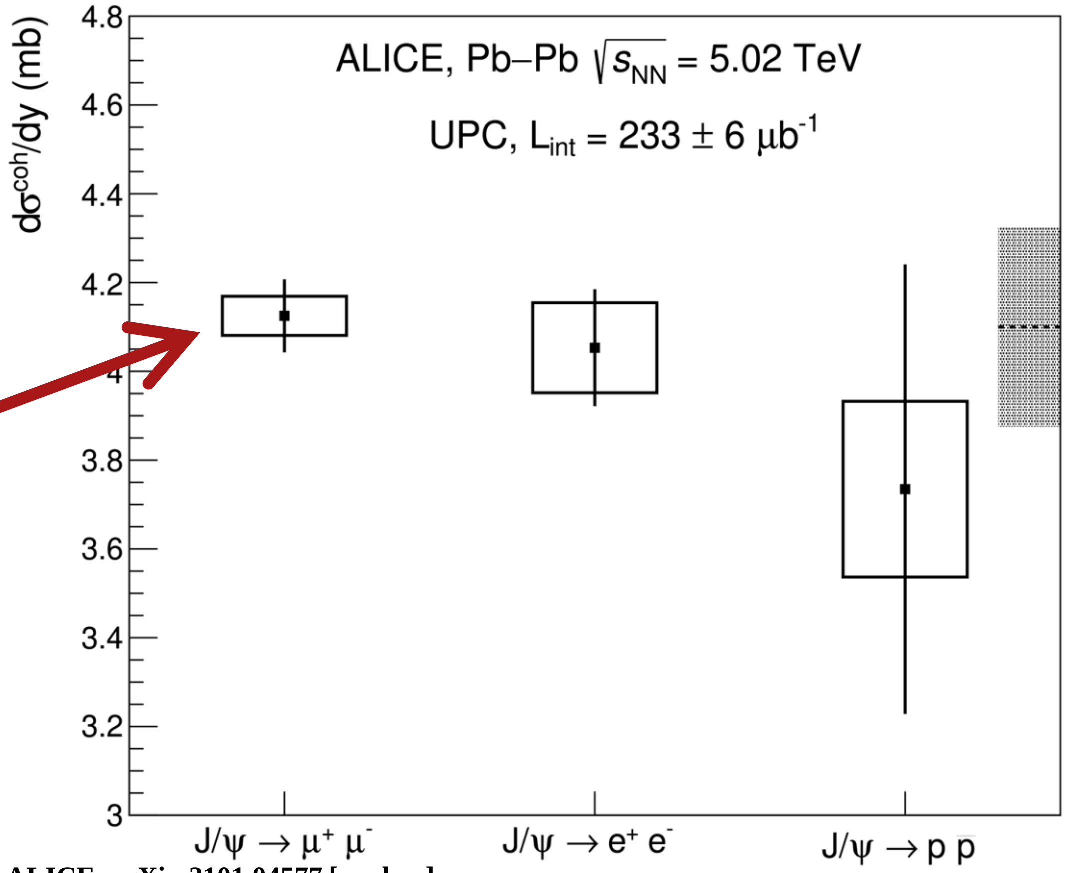
Backup

Coherent J/ψ cross section

- Very clear signal
- Measured in 3 decay channels: $\mu^+\mu^-, e^+e^-, p\bar{p}$



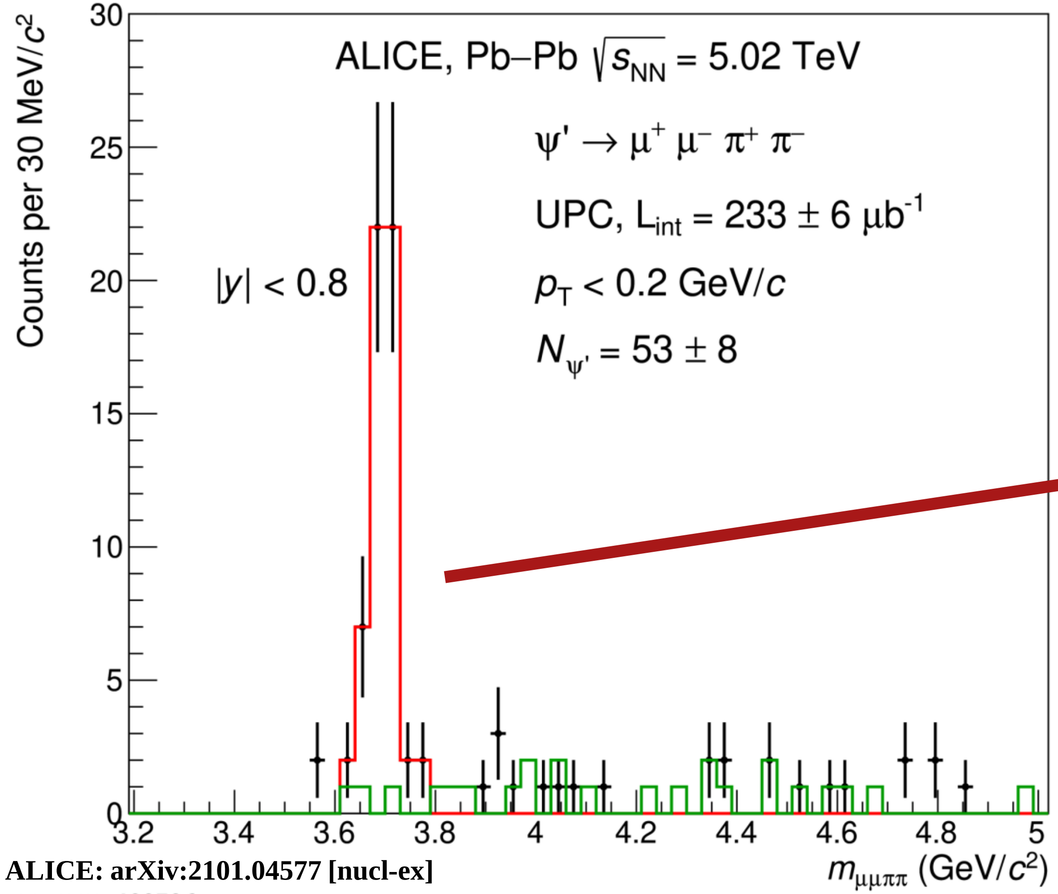
ALICE: arXiv:2101.04577 [nucl-ex]
ALI-PUB-482686



ALICE: arXiv:2101.04577 [nucl-ex]
ALI-PUB-482746

Coherent ψ' cross section

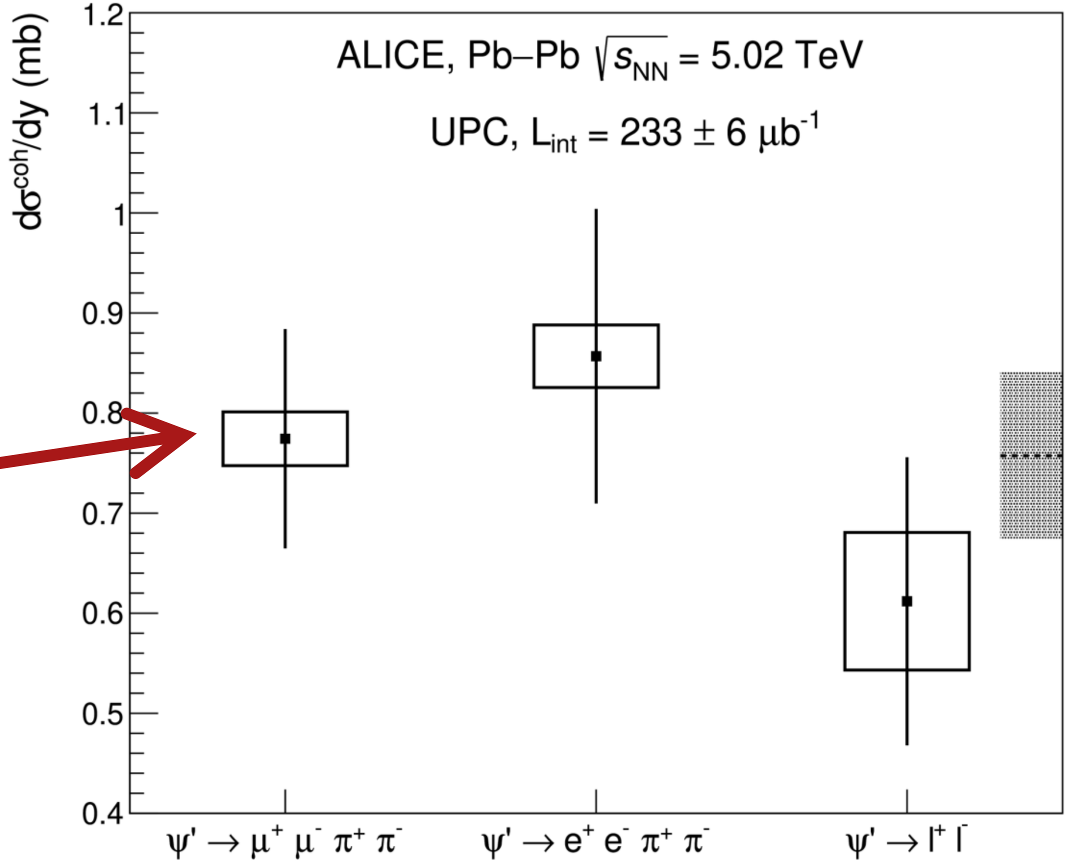
- Clear signal even with less events



ALICE: arXiv:2101.04577 [nucl-ex]

ALI-PUB-482726

- Measured in 3 decay channels: $\mu^+\mu^-\pi^+\pi^-, e^+e^-\pi^+\pi^-, l^+l^-$

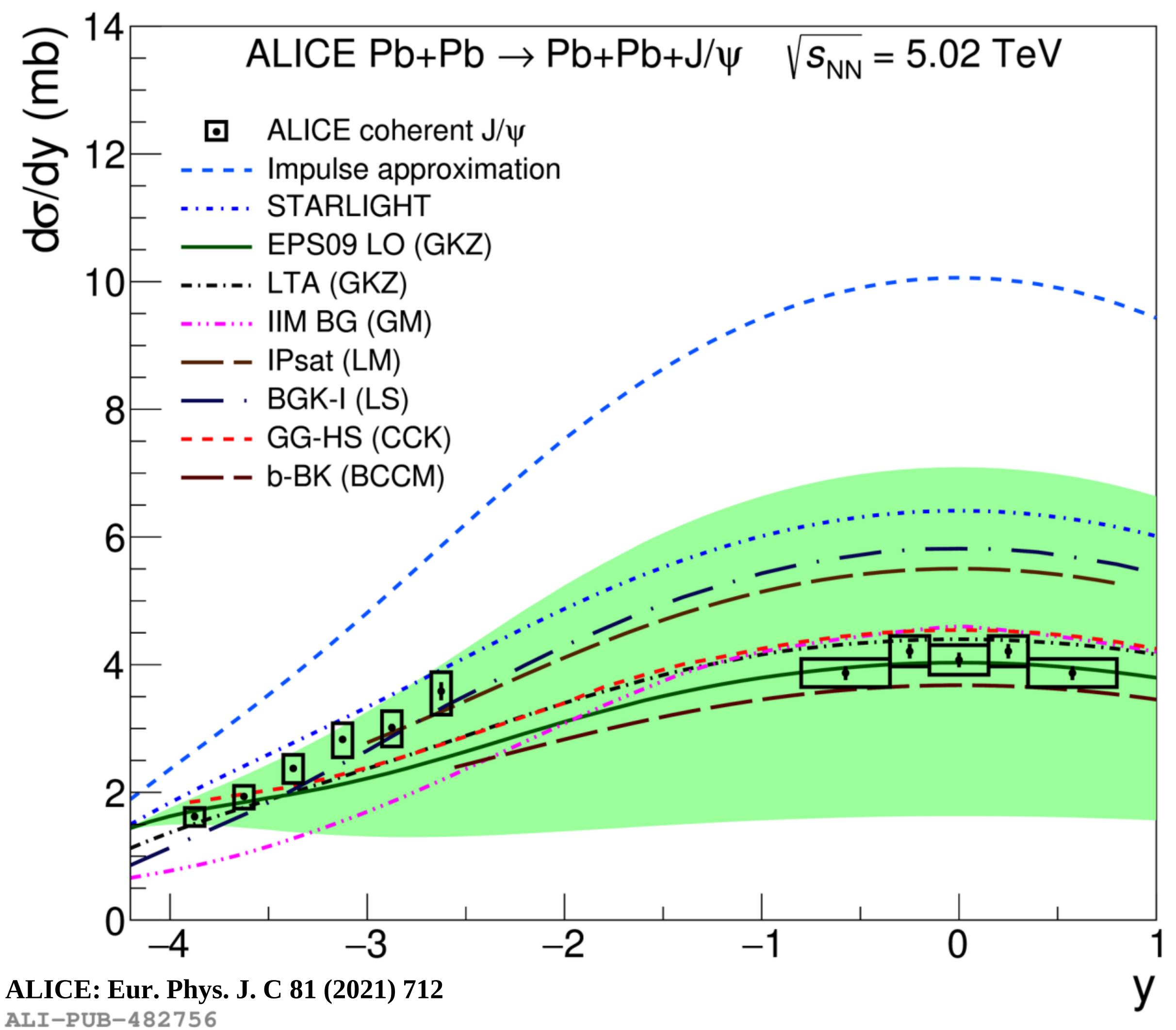


ALICE: arXiv:2101.04577 [nucl-ex]

ALI-PUB-482751

Coherent J/ψ cross section: y - dependence

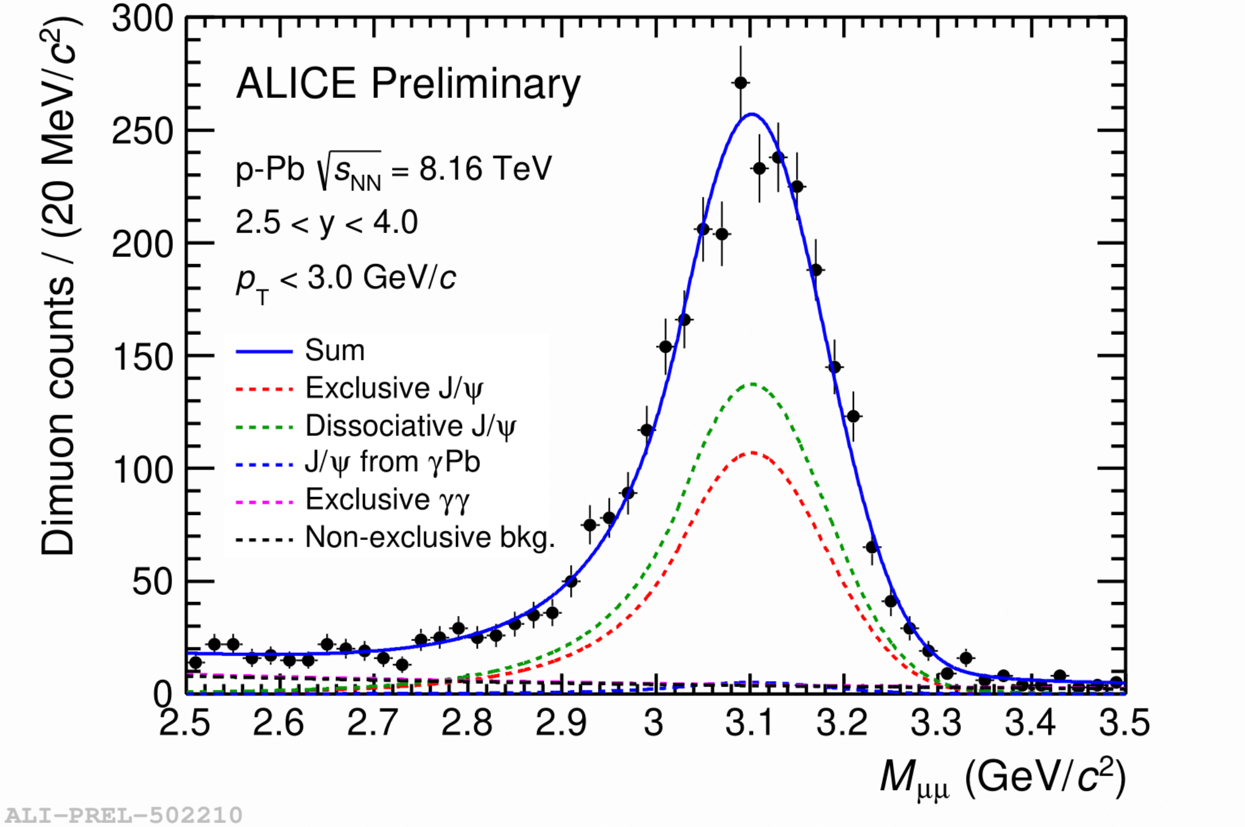
- **Impulse approximation (IA):** Photoproduction data from protons, does not include nuclear effects except coherence
- **STARlight:** Photoproduction data from protons + Vector Meson Dominance model, includes multiple scattering but no gluon shadowing
- **EPS09 LO:** parametrization of nuclear shadowing data
- **LTA:** Leading Twist Approximation of nuclear shadowing
- **IIM BG**, **IPsat**, **BGK-I:** Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude
- **GG-HS:** Color dipole model with hot spots nucleon structure
- **b-BK:** Color dipole approach coupled with impact-parameter dependent Balitsky-Kovchegov equation

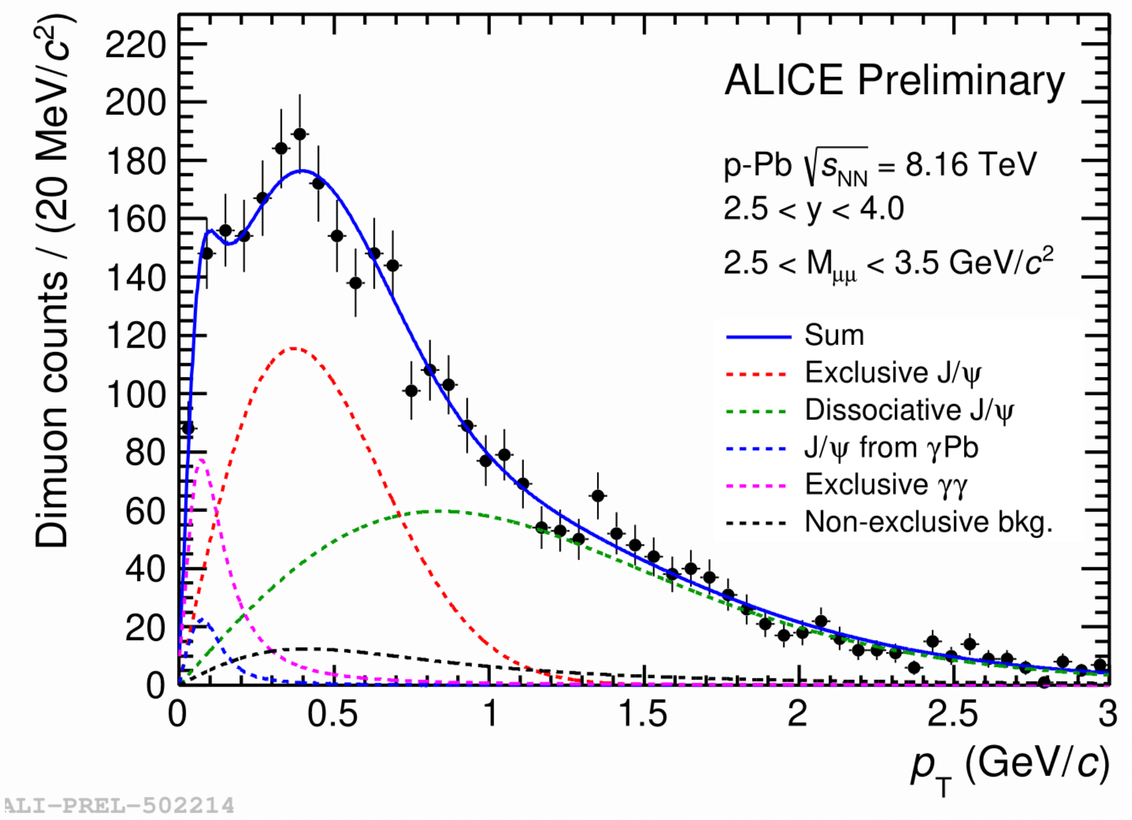


ALICE: Eur. Phys. J. C 81 (2021) 712
ALI-PUB-482756

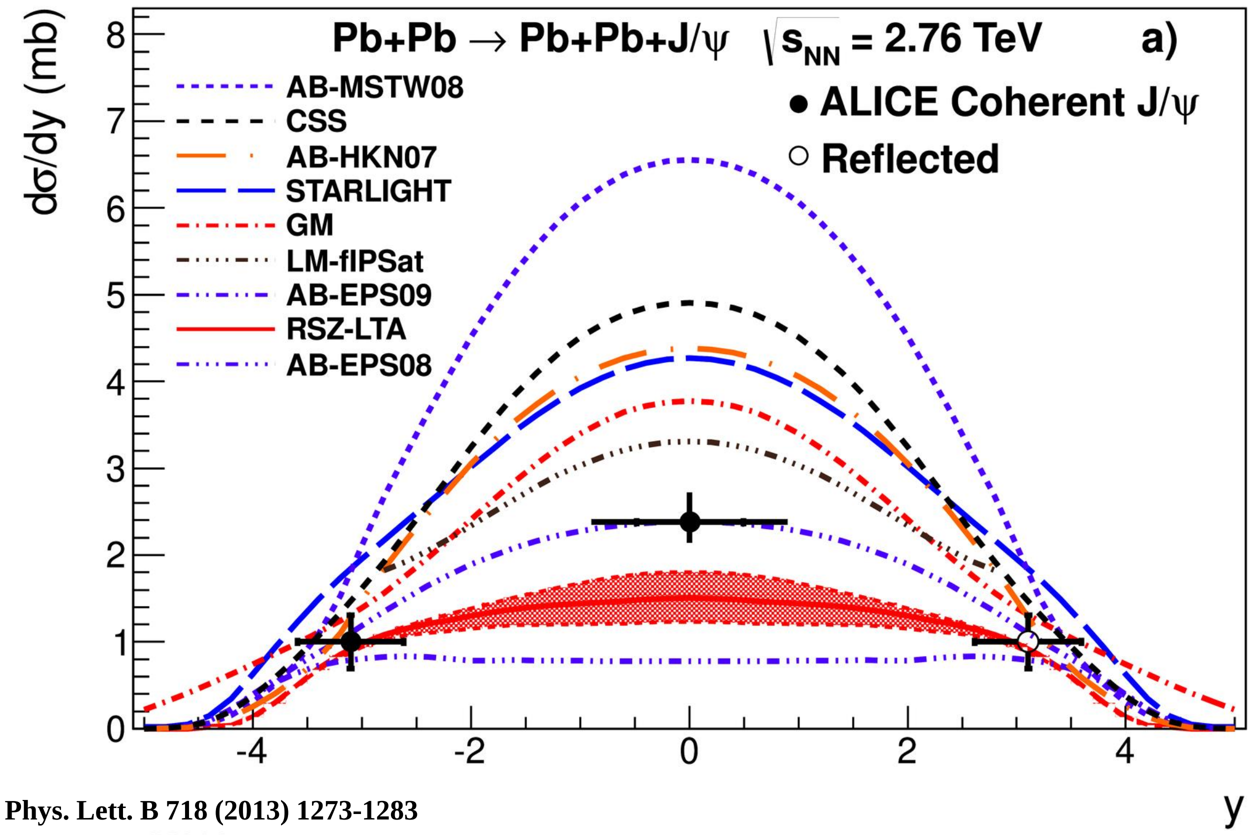
Exclusive and Dissociative J/ψ signal extraction

- Simultaneous unbinned fit of mass and p_{T} spectra of $\mu^+\mu^-$ pairs





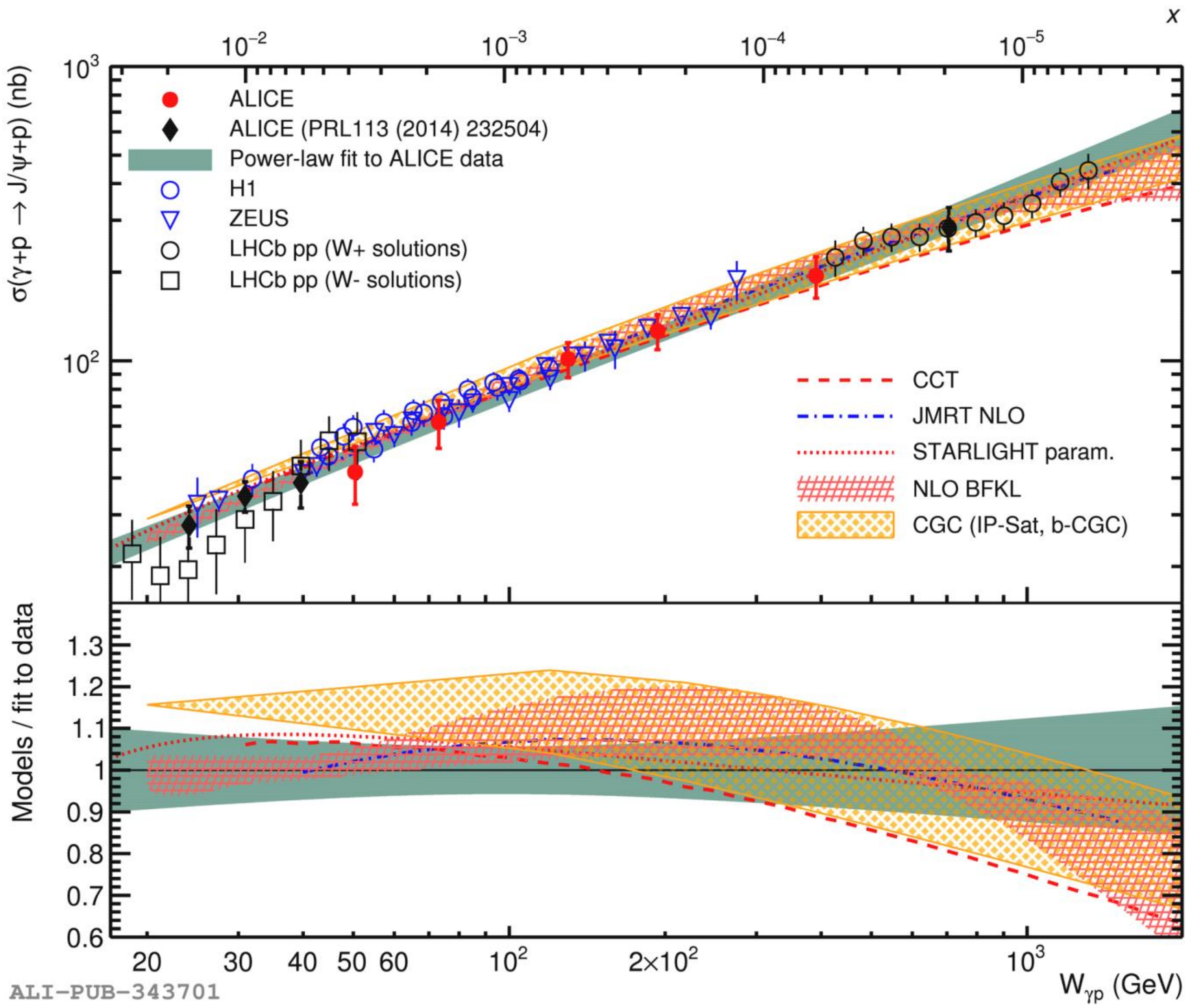
Run 1 ALICE Pb-Pb UPC at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV



Phys. Lett. B 718 (2013) 1273-1283

ALI-PUB-66209

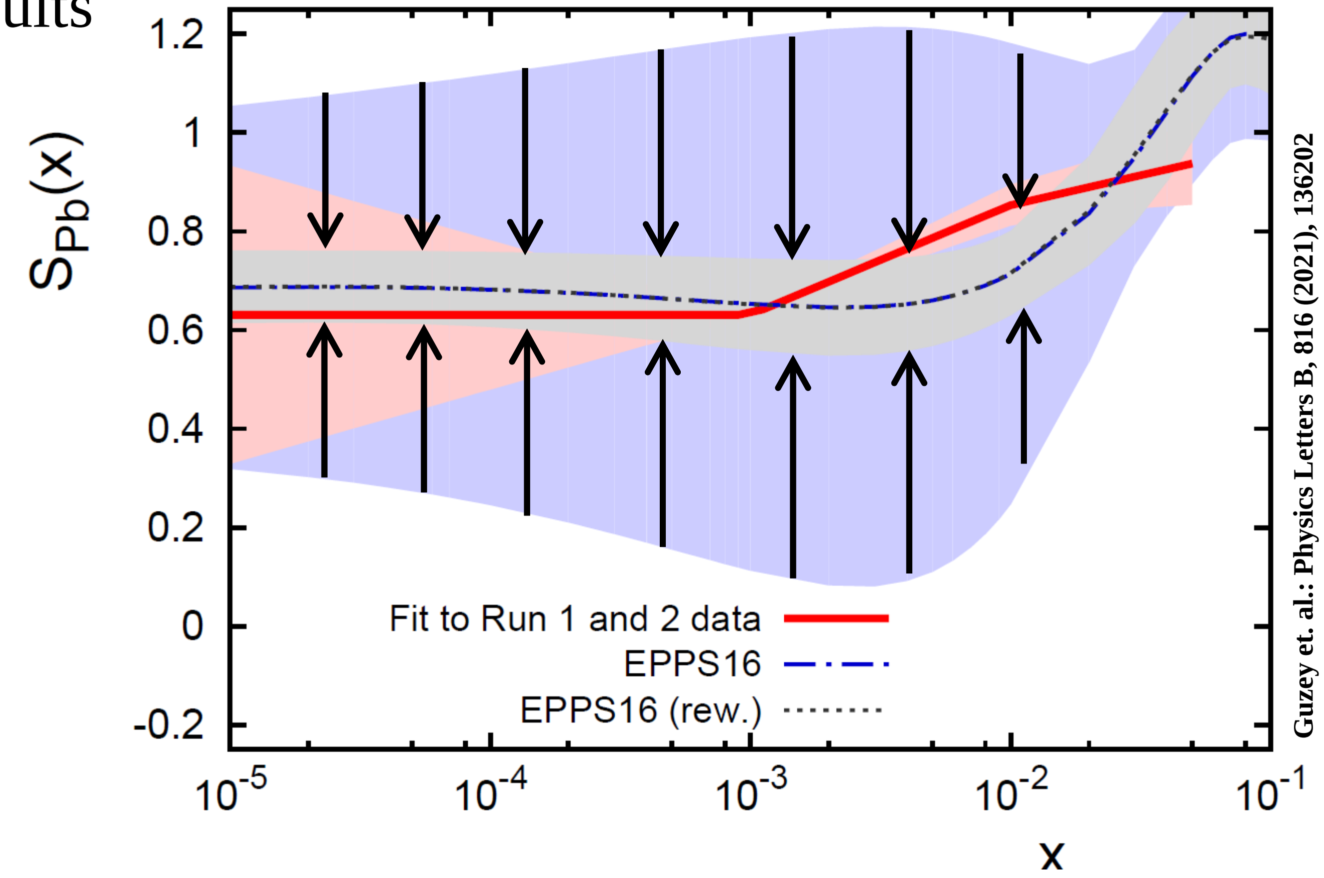
Run 1 ALICE p-Pb UPC at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



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

Outlook: Impact of ALICE and LHC UPC results

- Reweighted EPPS16 nPDFs with LHC results
  - **Run 2**: **ALICE** + **LHCb**
  - **Run 1**: **ALICE** + **CMS**



Guzey et. al.: Physics Letters B, 816 (2021), 136202

→ **Decrease in EPPS16 uncertainties!**