Recent results on ultra-peripheral collisions with the **ALICE** experiment

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UPC 2023, Playa del Carmen

FJFI

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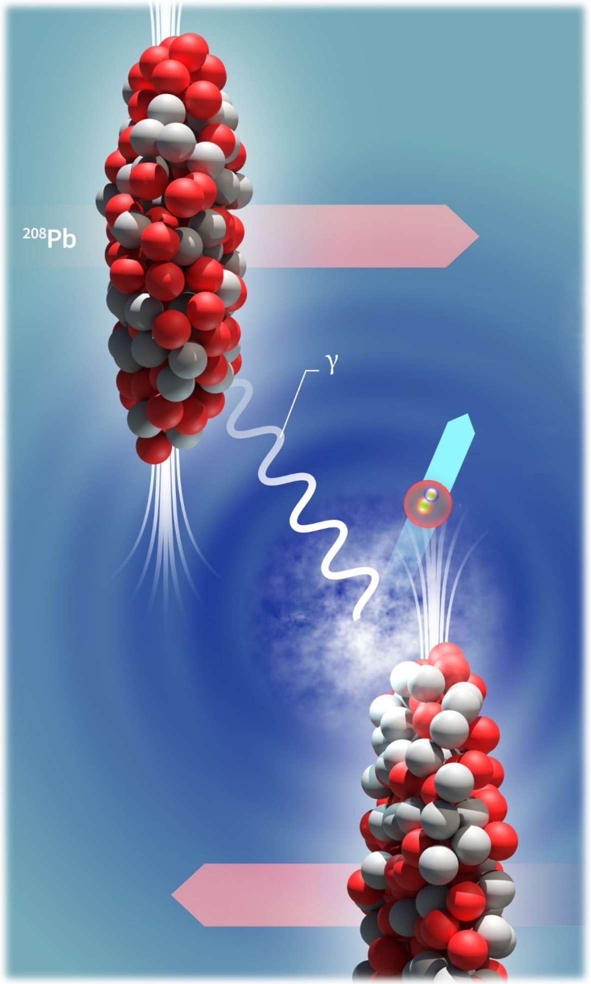
ALICE

Outline

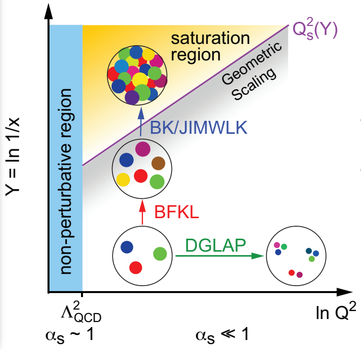
- Introduction to UPC physics & diffractive photoproduction
- How ALICE detects UPCs
- Measurement of **energy dependence of J/ψ photoproduction**
  - Coherent (γPb)
  - Exclusive + dissociative (γp)
- Measurement of **|*t*|-dependence of J/ψ photoproduction**
  - Coherent
  - Incoherent
- **J/ψ polarization**
- Invitation to **more ALICE UPC talks**

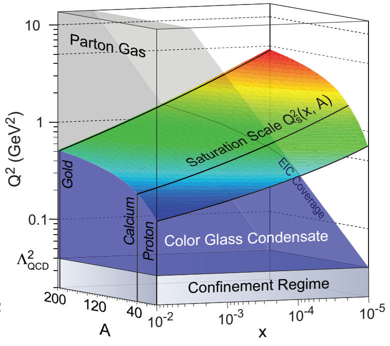


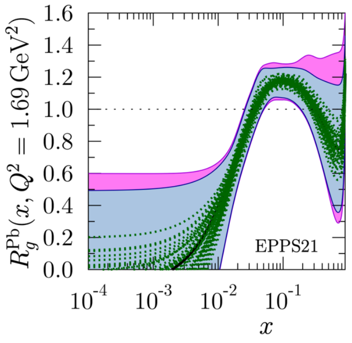
Physics of ultra-peripheral collisions

Eur.Phys.J.A 52 (2016) 9, 268
Eur.Phys.J.C 82 (2022) 5, 413

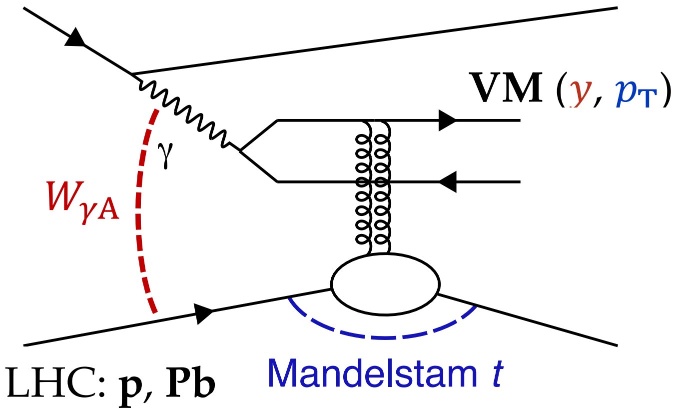
Search for **gluon saturation**, study of nuclear effects such as **shadowing** of gluon PDFs







Vector meson diffractive production in UPCs



$$W_{\gamma A}^2 = \sqrt{s}\, M_{VM}\, e^{\mp y}$$

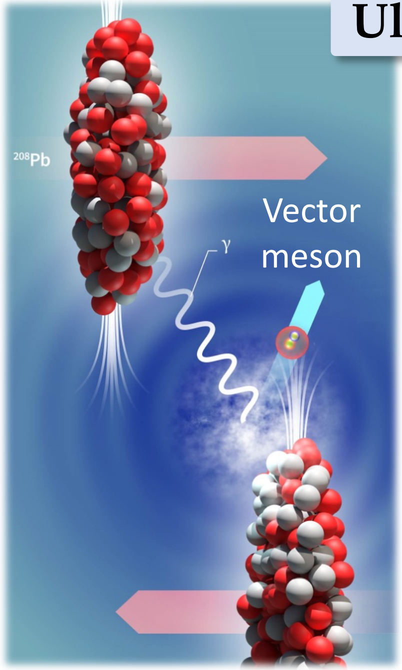
$$x = \frac{M_{VM}^2}{W_{\gamma A}^2} = \frac{M_{VM}}{\sqrt{s}} e^{\pm y}$$

$$t \approx -p_T^2$$

- VM rapidity traces back the energy evolution
- **Clear experimental signature**, e.g. J/ψ → $l^+ l^-$ ⇒ two lepton tracks in an otherwise empty detector (except in a very forward direction)

System	Process	$\langle p_T \rangle$
Pb–Pb	Coherent	$\sim 1/R_{nucleus} \sim 50$ MeV
	Incoherent	$\sim 1/R_{nucleon} \sim 400$ MeV
p–Pb	Exclusive	$\sim 1/R_{proton} \sim 400$ MeV
	Dissociative	~ 1 GeV

Ultra-peripheral collisions (UPCs)



- $b > 2R_A$ ⇒ pure hadronic interactions suppressed
- Photon-induced reactions with sizeable cross sections
- Flux ∝ Z^2; low virtuality Q^2

LO pQCD: *Z.Phys.C 57 (1993) 89-92*

$$\left.\frac{d\sigma(\gamma + \mathrm{Pb} \to \mathrm{VM} + \mathrm{Pb})}{dt}\right|_{t=0} \propto [x g_A(x, Q^2)]^2$$

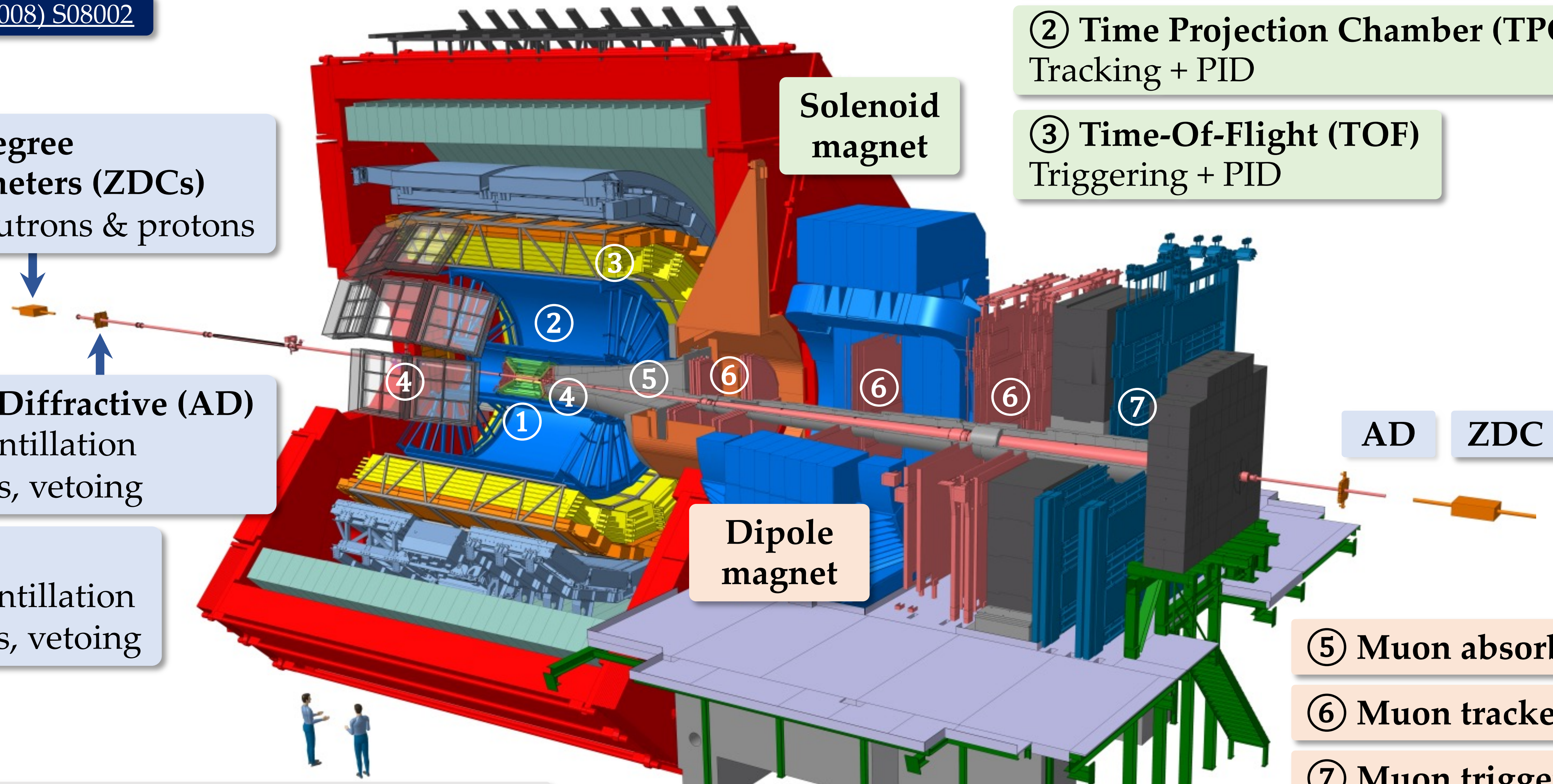
How ALICE detects UPCs

JINST 3 (2008) S08002

Zero Degree Calorimeters (ZDCs)
Fwd neutrons & protons

ALICE Diffractive (AD)
Fwd scintillation counters, vetoing

④ V0
Fwd scintillation counters, vetoing



① Silicon Pixel Detector (SPD)
Tracking, triggering, vertexing

② Time Projection Chamber (TPC)
Tracking + PID

③ Time-Of-Flight (TOF)
Triggering + PID

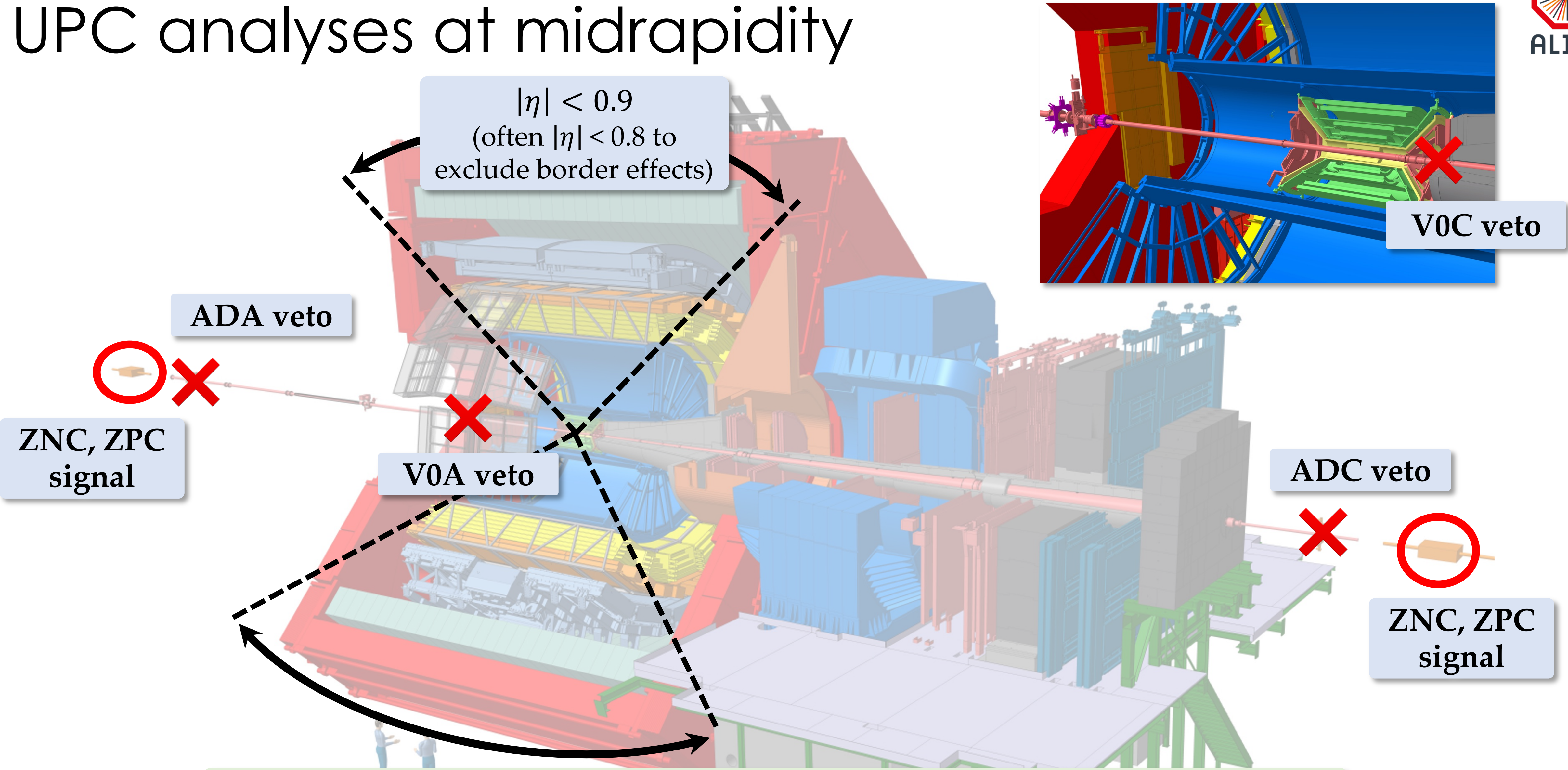
⑤ Muon absorber

⑥ Muon trackers

⑦ Muon triggers

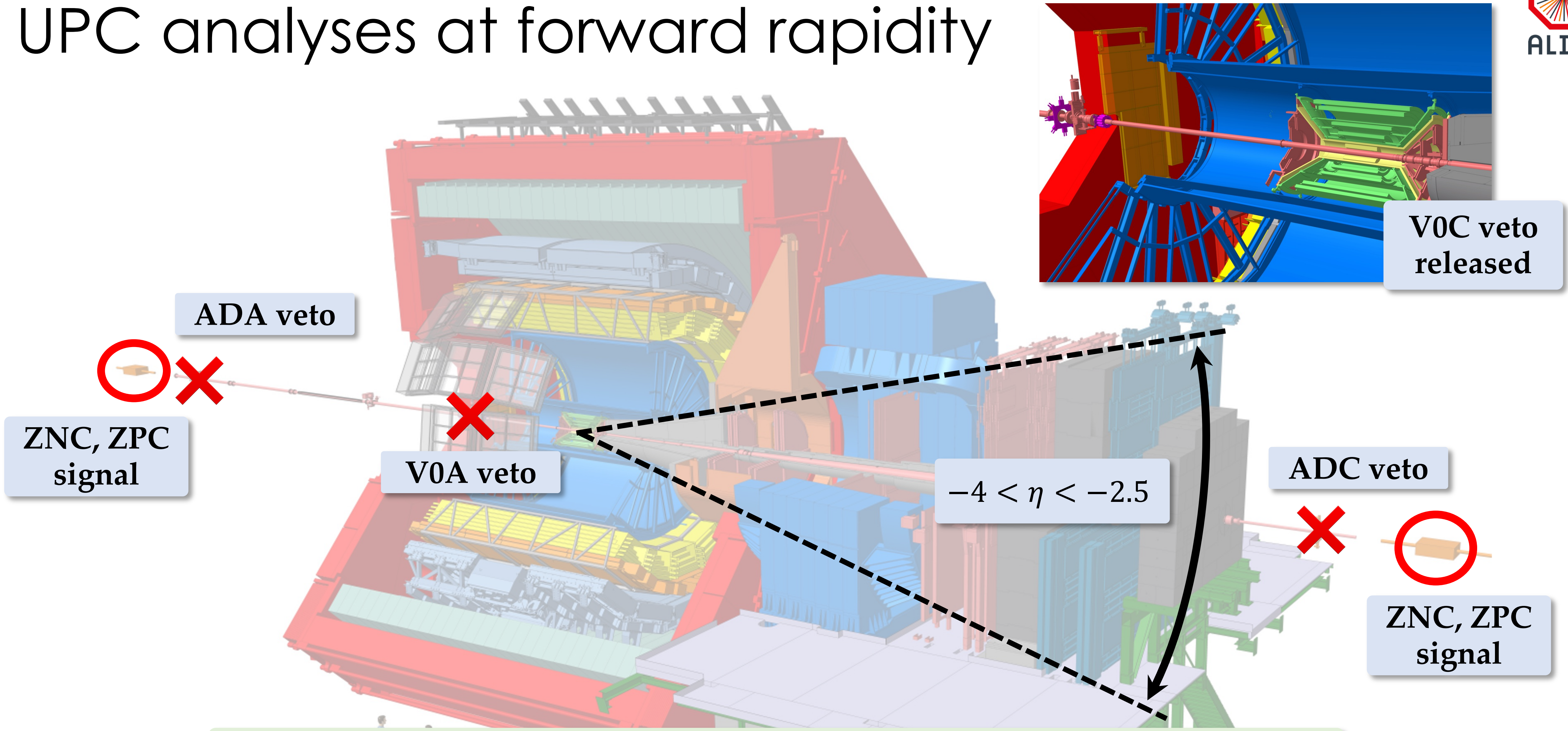
Status during Run 2 of the LHC: 2015–2018

UPC analyses at midrapidity



J/ψ in Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: $|y| < 0.8$ translates to $x \in (0.3, 1.4)\times10^{-3}$

UPC analyses at forward rapidity

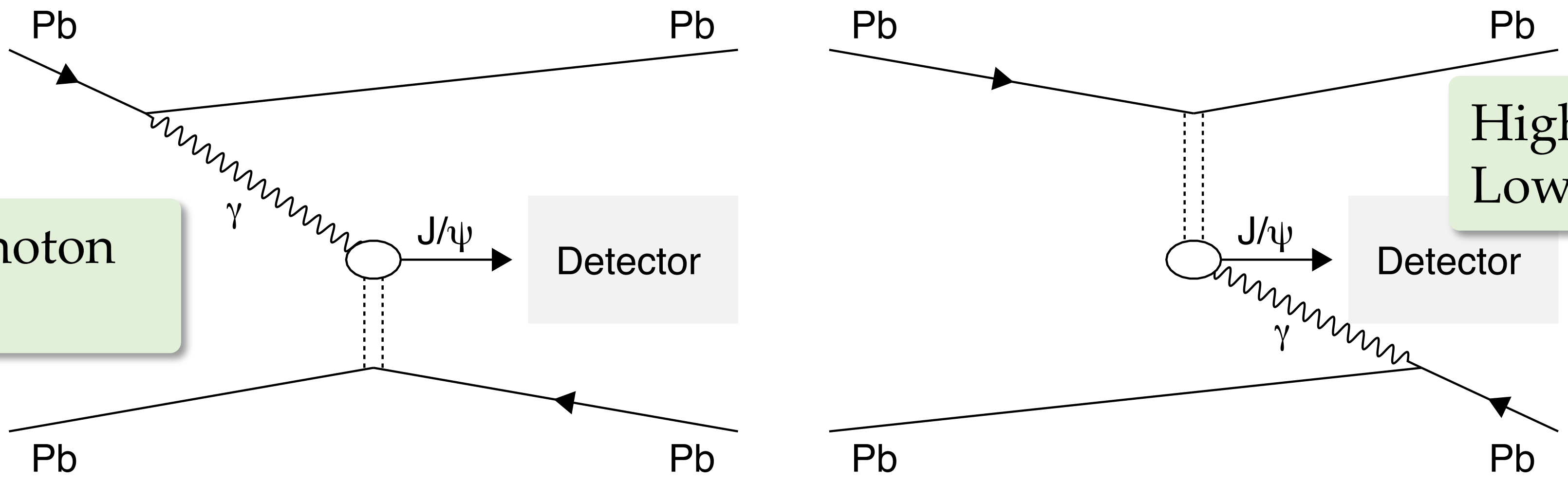


J/ψ in Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: $-4.5 < y < -2.5$ translates to either $x \in (1.1, 5.1)\times10^{-5}$ or $x \in (0.7, 3.3)\times10^{-2}$

Energy dependence of coherent, exclusive and dissociative J/ψ production

- Energy dependence of coherent photonuclear production of J/ψ mesons in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, *JHEP* 10 (2023) 119 **NEW!**
- Exclusive and dissociative J/ψ photoproduction, and exclusive dimuon production, in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV, arXiv:2304.12403 (accepted by PRD) **NEW!**

UPC cross section for photoproduction



Low-energy photon
High-x gluon

High-energy photon
Low-x gluon

QED **QCD enters here!**

- UPC cross section = sum of the two contributions (photon flux × photonuclear cross section):

$$\frac{d\sigma_{\mathrm{PbPb}}}{dy} = n_\gamma(y, \{b\})\sigma_{\gamma\mathrm{Pb}}(y) + n_\gamma(-y, \{b\})\sigma_{\gamma\mathrm{Pb}}(-y)$$

Forward Pb–Pb: how to disentangle the contributions?
$n_\gamma = n_\gamma(b) \Rightarrow$ one needs to measure at the **same rapidity** but using **different impact parameters ranges**: $\{b\}_1$ and $\{b\}_2$

Midrapidity in Pb–Pb:

$$\frac{d\sigma_{\mathrm{PbPb}}}{dy} = 2n_\gamma(y, \{b\})\sigma_{\gamma\mathrm{Pb}}(y)$$

p–Pb:

$$\frac{d\sigma_{\mathrm{pPb}}}{dy} = n_\gamma(y, \{b\})\sigma_{\gamma\mathrm{p}}(y)$$

Solving the photon direction ambiguity puzzle

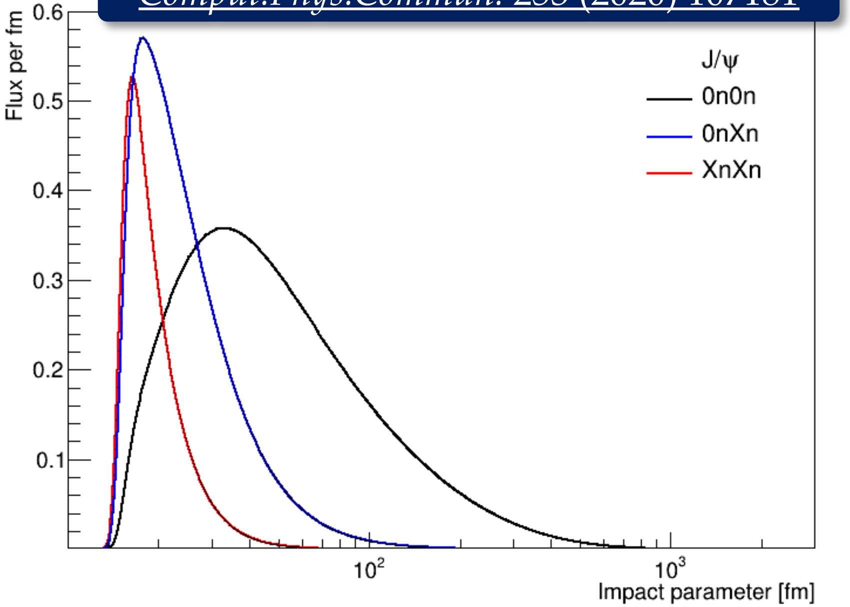
$$\frac{d\sigma^{\{b\}_1}_{PbPb}}{dy} = n_\gamma(y,\{b\}_1)\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\}_1)\sigma_{\gamma Pb}(-y)$$

$$\frac{d\sigma^{\{b\}_2}_{PbPb}}{dy} = n_\gamma(y,\{b\}_2)\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\}_2)\sigma_{\gamma Pb}(-y)$$

We can measure $d\sigma/dy$, calculate the photon fluxes, and then simply solve the system of linear equations (e.g. using a χ^2-minimization)…

- Two possible approaches:
  1) combining results from **UPCs** and **peripheral collisions** ($b < 2R$)
  2) event tagging using **forward neutrons** [1] – an independent photon exchange may lead to electromagnetic dissociation (EMD) of a nucleus
- Event classification:
  - **0n0n**: no neutrons on either side
  - **0nXn** + **Xn0n**: neutrons on one side only
  - **XnXn**: forward neutrons on both sides
- Photon spectra corresponding to these fragmentation scenarios can be calculated [2]

Comput.Phys.Commun. 253 (2020) 107181



[1] Eur.Phys.J.C 74 (2014) 7, 2942
[2] Phys.Rev.Lett. 89 (2002) 012301

Energy dependence of coherent J/ψ production

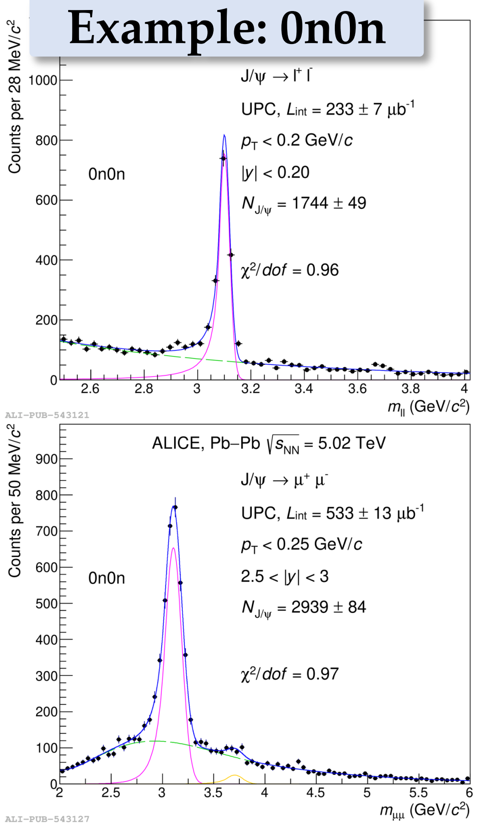
- Simultaneos analysis of mid- and forward-rapidity data
- **Neutron classes** ⇒ extraction of the dependence on $W_{\gamma\text{Pb}}$ + the nuclear shadowing factor $S_{\gamma\text{Pb}}$

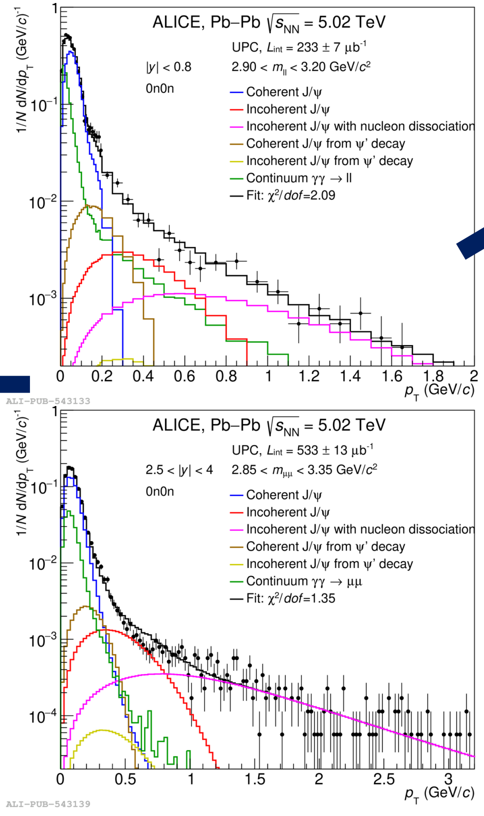
Three bins at $-4 < y < -2.5$

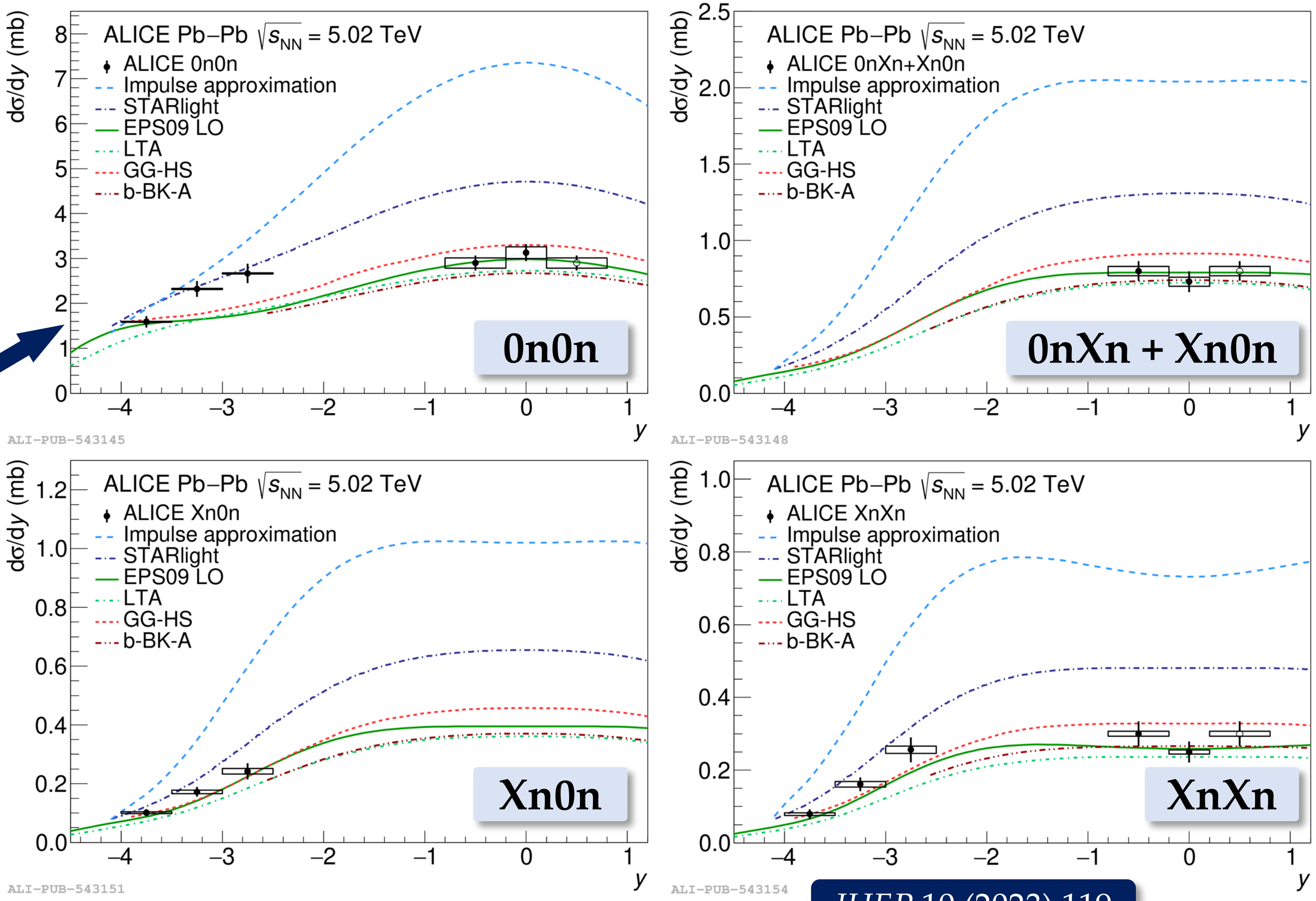
Two bins at $|y| < 0.8$

Five $W_{\gamma\text{Pb}}$ values: **17 to 920 GeV!**
Bjorken-x range: 1×10^{-5} to 3×10^{-2}

Example: 0n0n



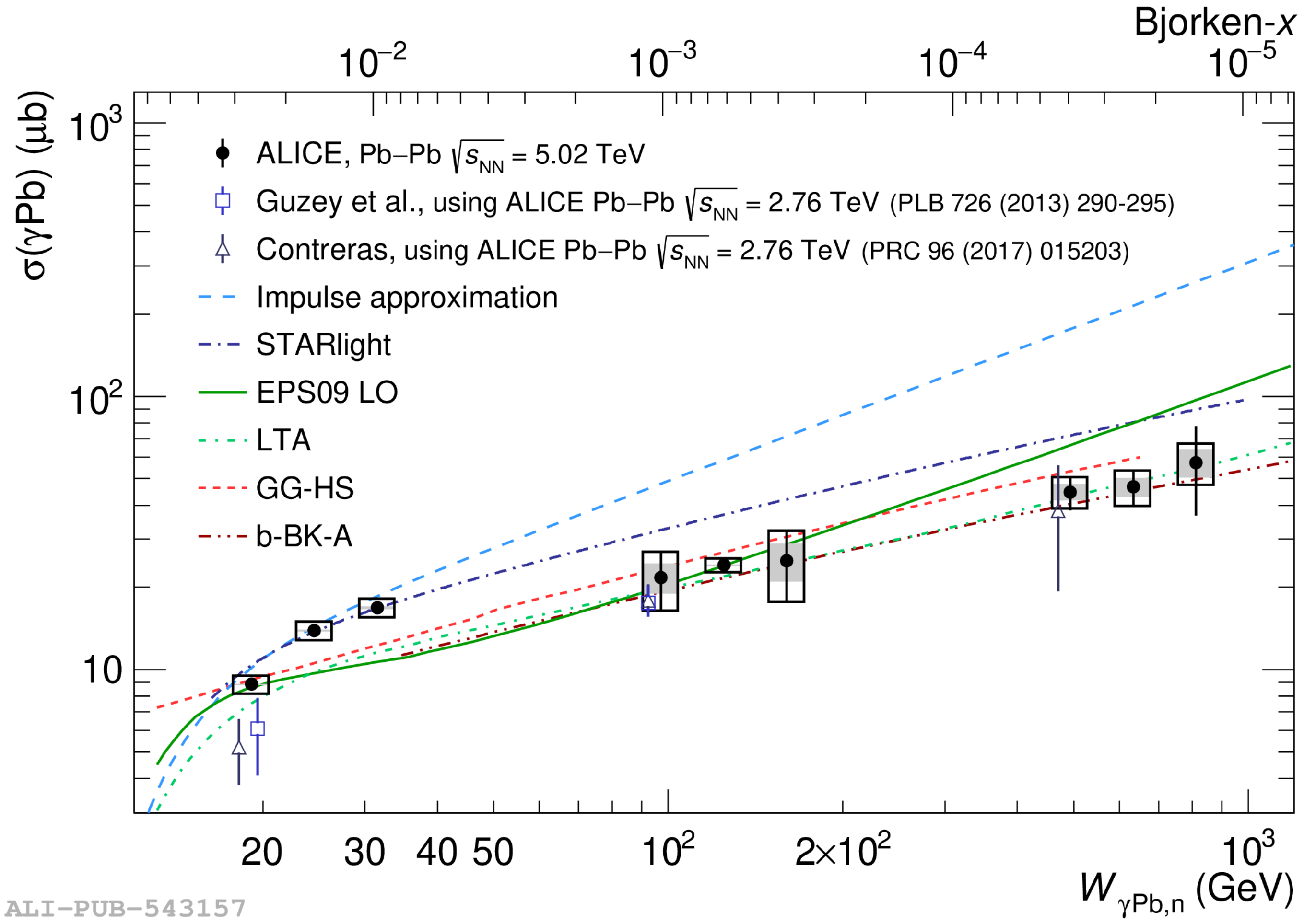




JHEP 10 (2023) 119

Energy dependence

- **Unprecedented range** with the ALICE data
- Agreement with Run-1 ALICE results (UPC + peripheral)
- Good description of the **low-energy data**:
  - **Impulse approximation**
  - **STARlight**
- Good description of the **high-energy data**:
  - **GSZ**: **EPS09-LO** parametrization of nuclear parton functions or leading twist approximation (**LTA**) of gluon shadowing
  - **GG-HS**: colour-dipole approach, gluon saturation (hot spots)
  - **b-BK-A**: solution to the impact-parameter dependent BK equation
- IA significantly above the data at low x ⇒ onset of **nuclear shadowing**

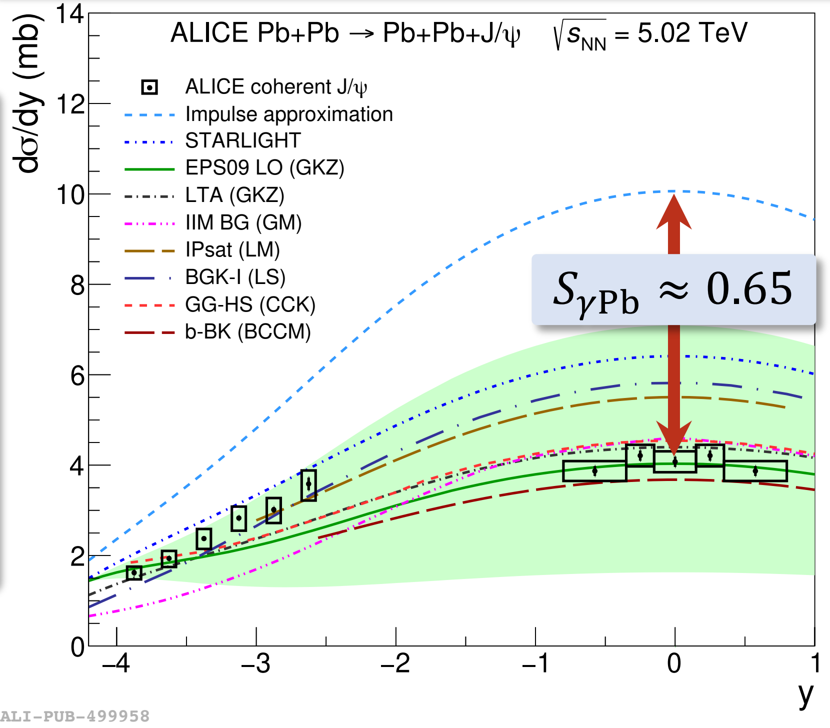


Nuclear suppression factor

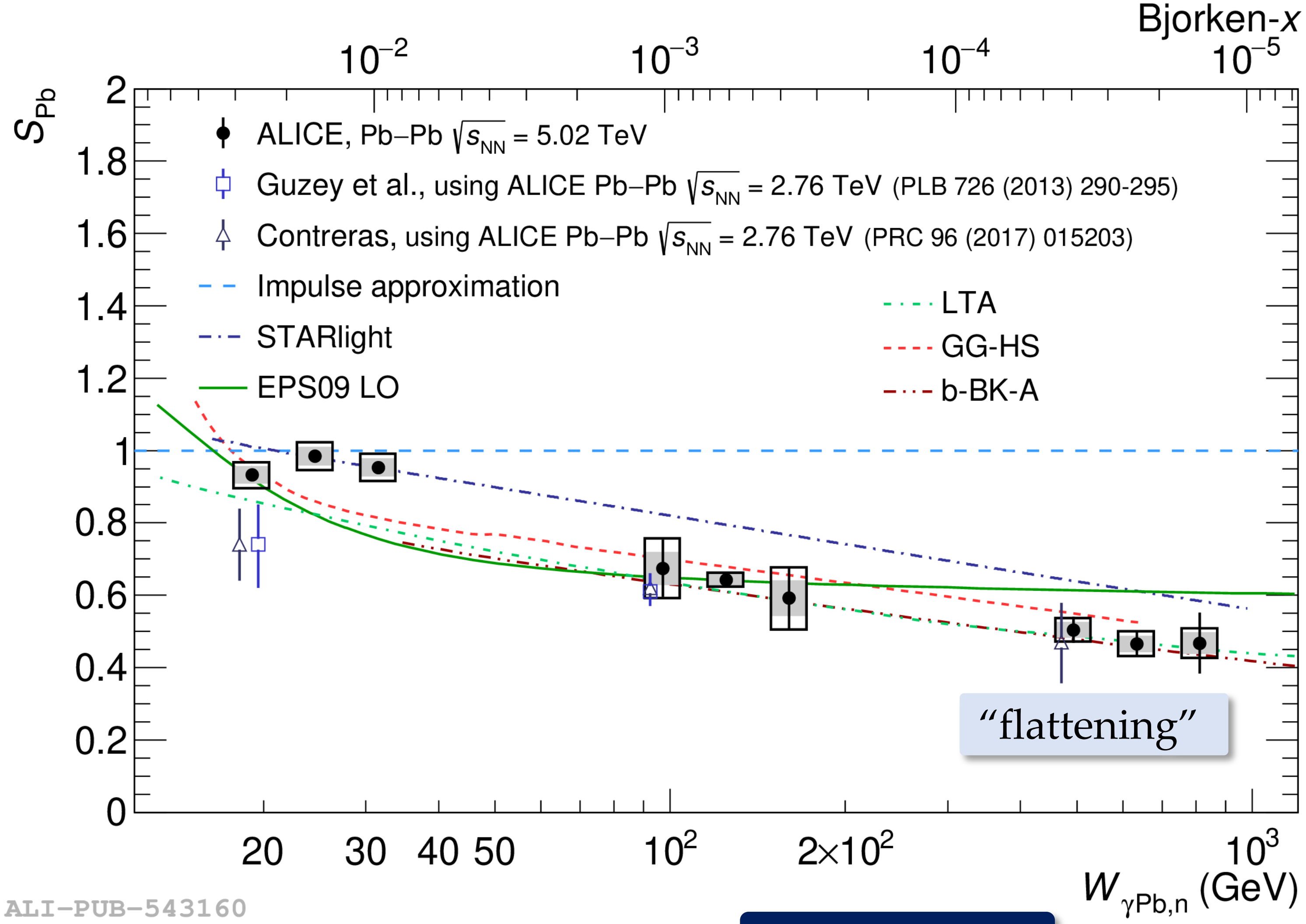
$$S_{Pb}(W_{\gamma Pb,n}) = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}}$$

- A quantitative measure of nuclear gluon shadowing
- $S_{\gamma Pb} \approx 0.95$ at low energies, then a **large gluon depletion** (down to 0.5) at high energies

Cross-check with the previous ALICE Run-2 results at midrapidity:



Eur.Phys.J.C 81 (2021) 8, 712



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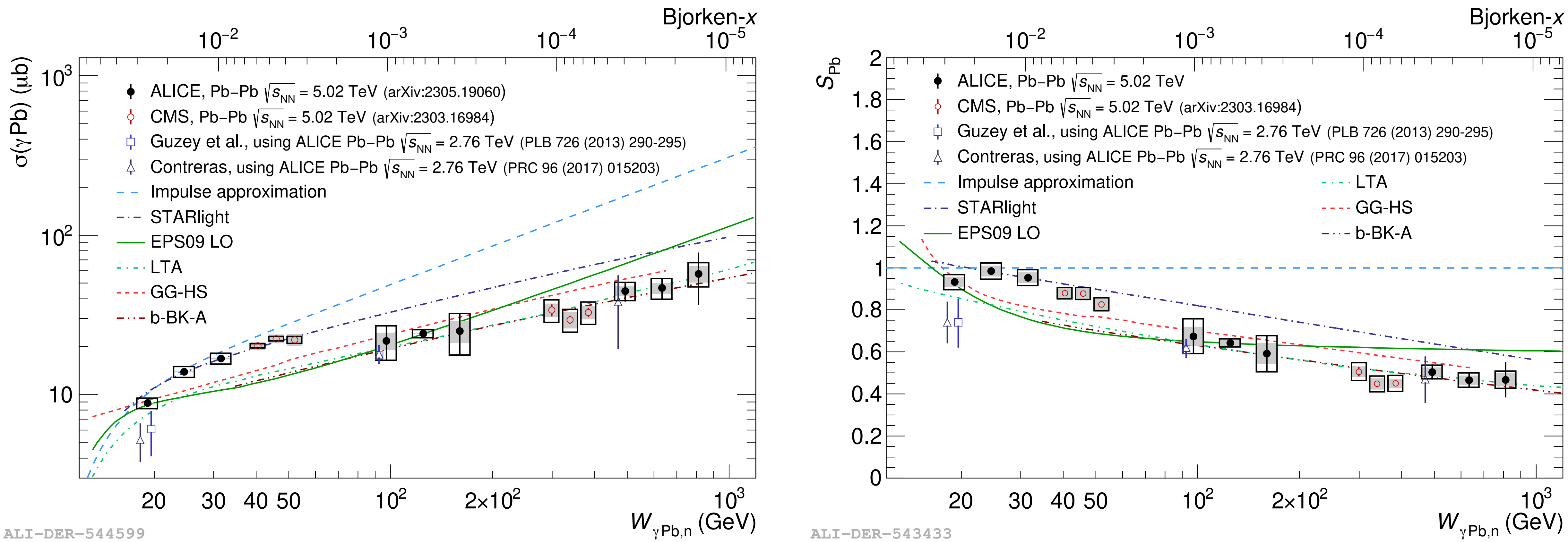
Energy dependence of the photonuclear cross section



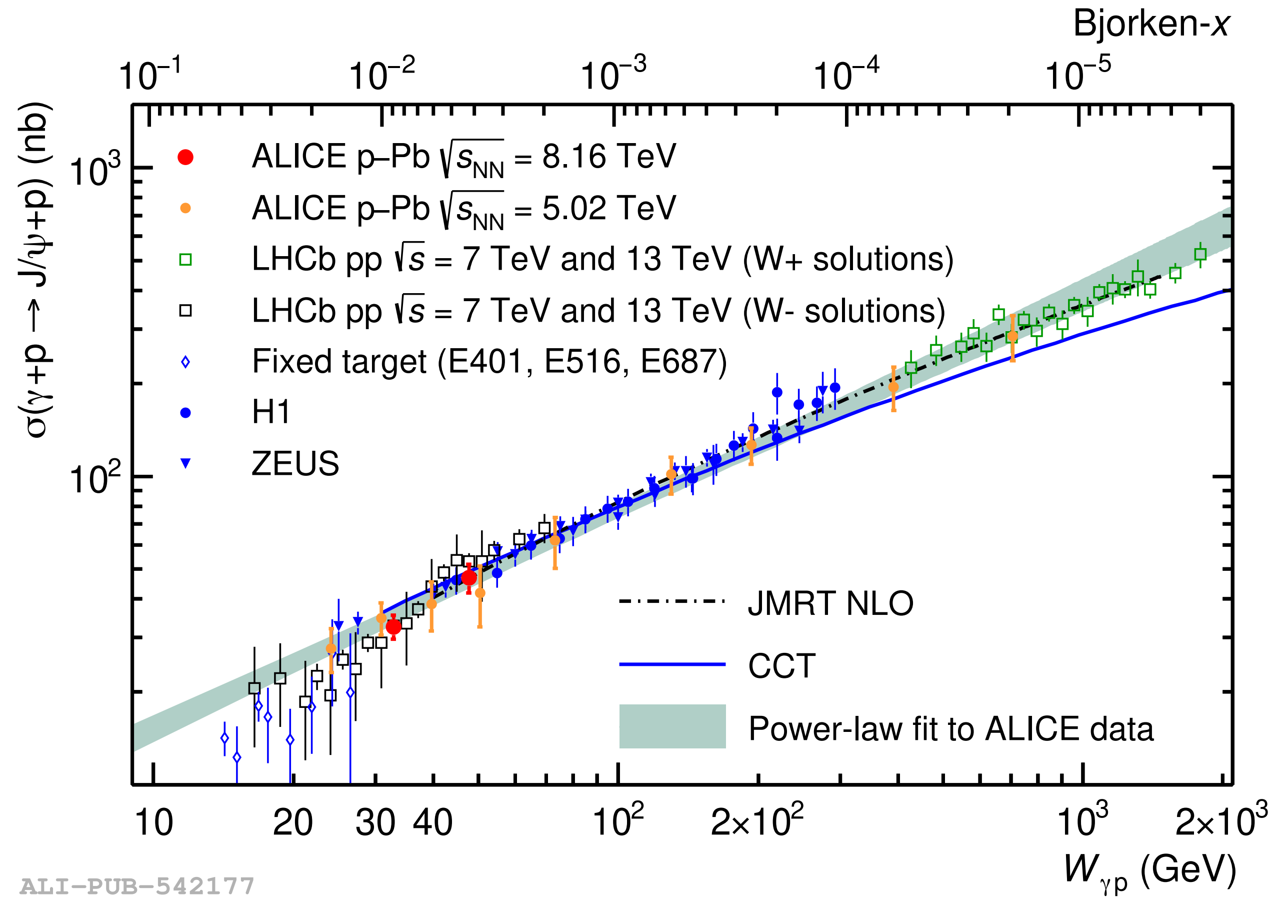
ALICE alone explores $(20, 900)$ GeV in $W_{\gamma Pb}$ and x from 10^{-2} down to 10^{-5}
Recently, CMS performed a similar measurement in a narrower interval

CMS: arXiv:2303.16984 (accepted by PRL)

ALICE: *JHEP 10 (2023) 119*

Energy dependence of exclusive J/ψ production

- Asymmetric **p–Pb** system ⇒ photon can be assigned to the source ✓
- Beam configuration corresponds to the "low-energy" photon emitted from the nucleus



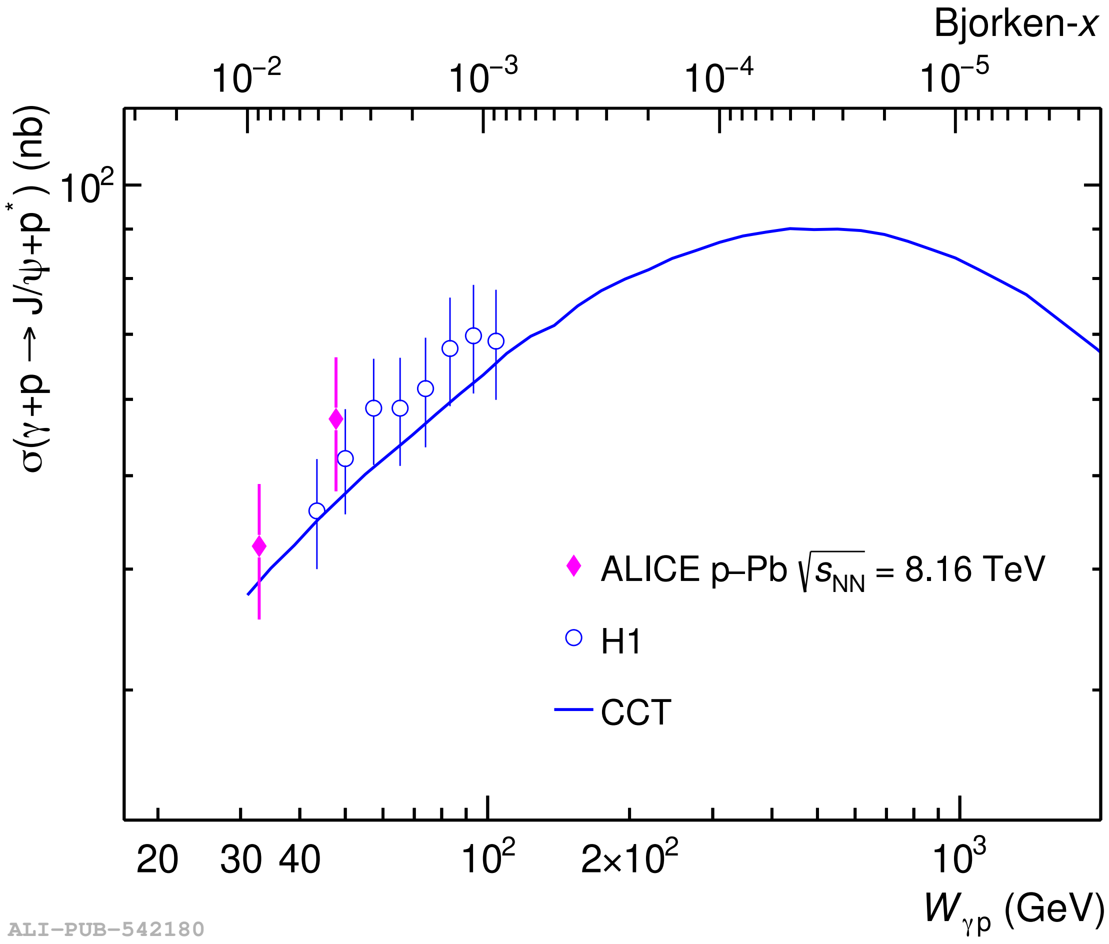
- Two bins within $-4 < y < -2.5$
  ⇒ two $W_{\gamma\mathrm{Pb}}$ values: **27 and 57 GeV**

A power-law fit to the ALICE data: $\delta = 0.70 \pm 0.04$

arXiv:2304.12403 (accepted by PRD)

Energy dependence of dissociative J/ψ production

- First measurement of this process at a hadron collider
- The measurement is compatible with H1 results



The **CCT model** (hot spots) predicts maximum of the cross section at ≃ 500 GeV ("phase-space saturation")

Probe to fluctuations of sub-nucleon structures inside the proton!

See the talk by **Michael Winn**: Monday at 16:30

arXiv:2304.12403 (accepted by PRD)

Distribution of nuclear (Pb) matter in the transverse plane

- First measurement of the $|t|$-dependence of coherent J/ψ photonuclear production, *Phys.Lett.B* 817 (2021) 136280
- First measurement of the $|t|$-dependence of incoherent J/ψ photonuclear production, arXiv:2305.06169 **NEW!**

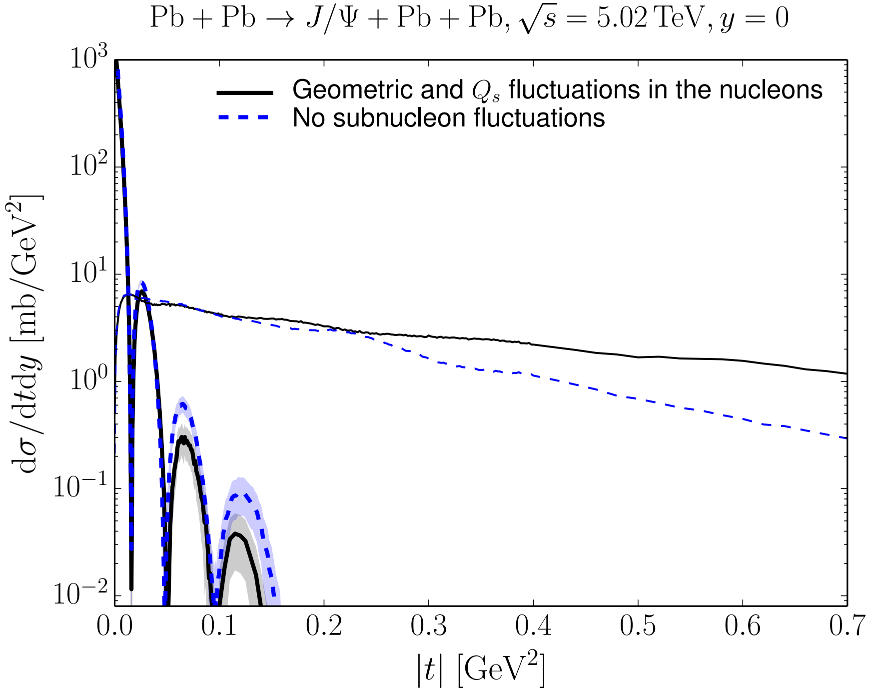
Why to measure $|t|$-dependencies?

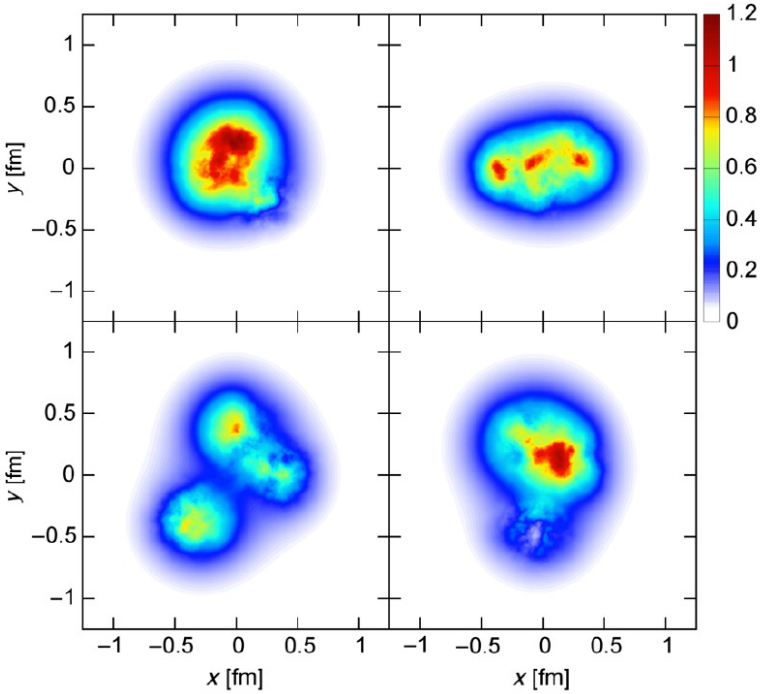
- Impact parameter b and the VM transverse momentum p_{T} are **Fourier conjugates**
- $|t|$-dependence of $\sigma_{\gamma\mathrm{Pb}} \xleftrightarrow{\textbf{Fourier tr.}}$ matter distribution in the transverse plane

<u>Good-Walker approach</u>:
coherent ↔ **average**
incoherent ↔ **variation** (quantum fluctuations)

- Larger $|t|$ ⇔ smaller scattering centers
- At $|t| \sim 1\ \mathrm{GeV}^2$ we probe fluctuations at a sub-femtometer scale ⇒ **gluons**!

Phys.Lett.B 772 (2017) 832-838





Phys.Rev.Lett. 117 (2016) 5, 052301

Photonuclear cross section extraction

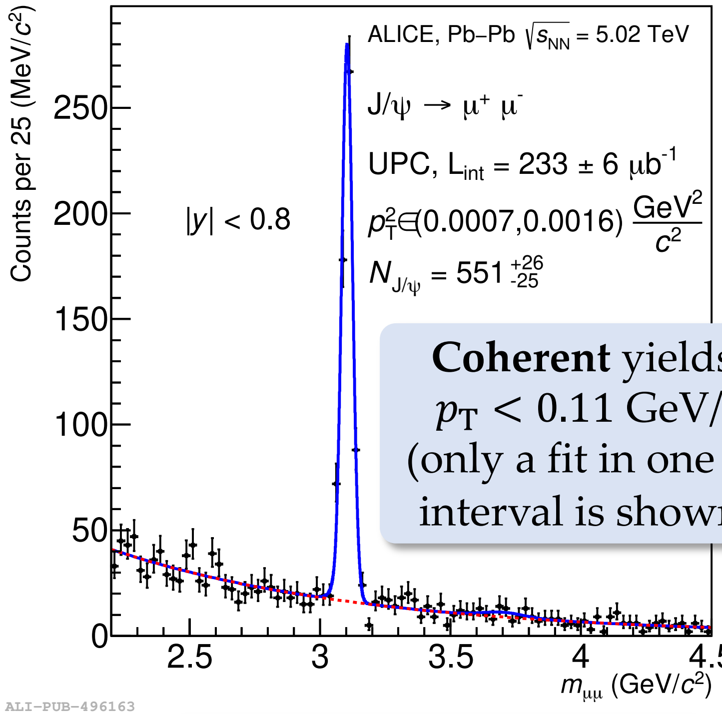
- $J/\psi \to \mu\mu$ at midrapidity $\Rightarrow x \in (0.3, 1.4) \times 10^{-3}$
- Very clean J/ψ signal over a relatively small background

Coherent measurement
- unfolding to account for p_{T} migration
- $p_{\mathrm{T}}^2 \to |t|$ unfolding (photon k_{T})

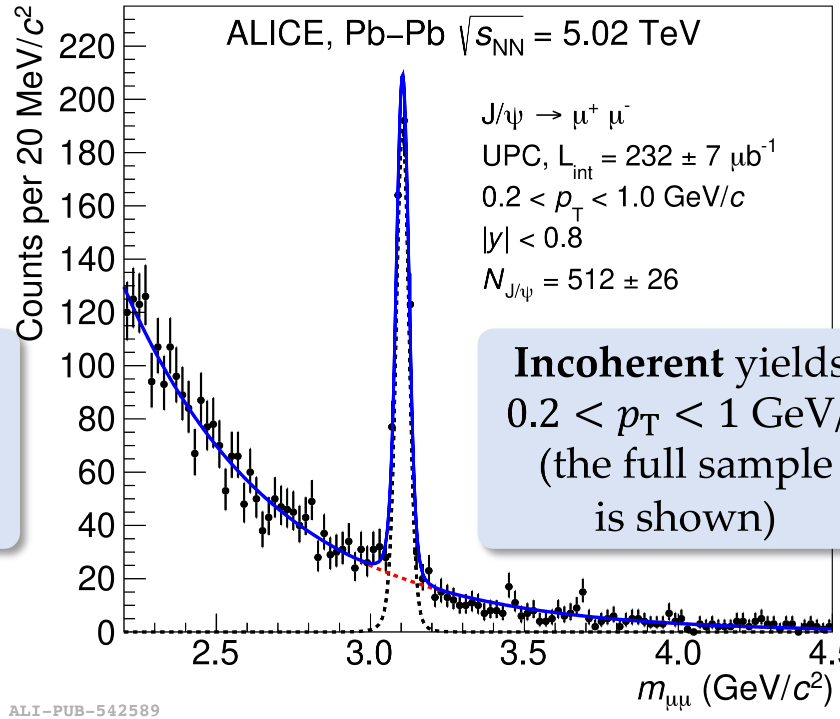
Incoherent measurement
- p_{T} migration negligible
- $|t| = p_{\mathrm{T}}^2$ (large transferred momentum)

UPC cross section (measured) — photon flux (calculated) — photonuclear cross section (extracted)

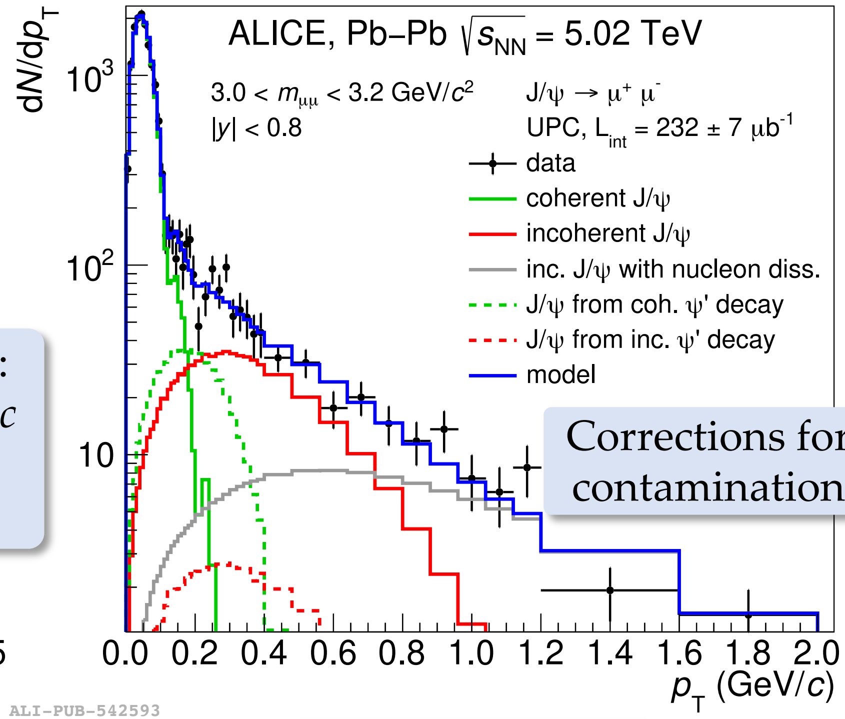
$$\left.\frac{d^2\sigma_{J/\psi}}{dy\,dp_{\mathrm{T}}^2}\right|_{y=0} = 2n_\gamma(y=0)\,\frac{d\sigma_{\gamma\mathrm{Pb}}}{d|t|}$$



Coherent yields: $p_{\mathrm{T}} < 0.11$ GeV/c (only a fit in one p_{T} interval is shown)



Incoherent yields: $0.2 < p_{\mathrm{T}} < 1$ GeV/c (the full sample is shown)



Corrections for contamination

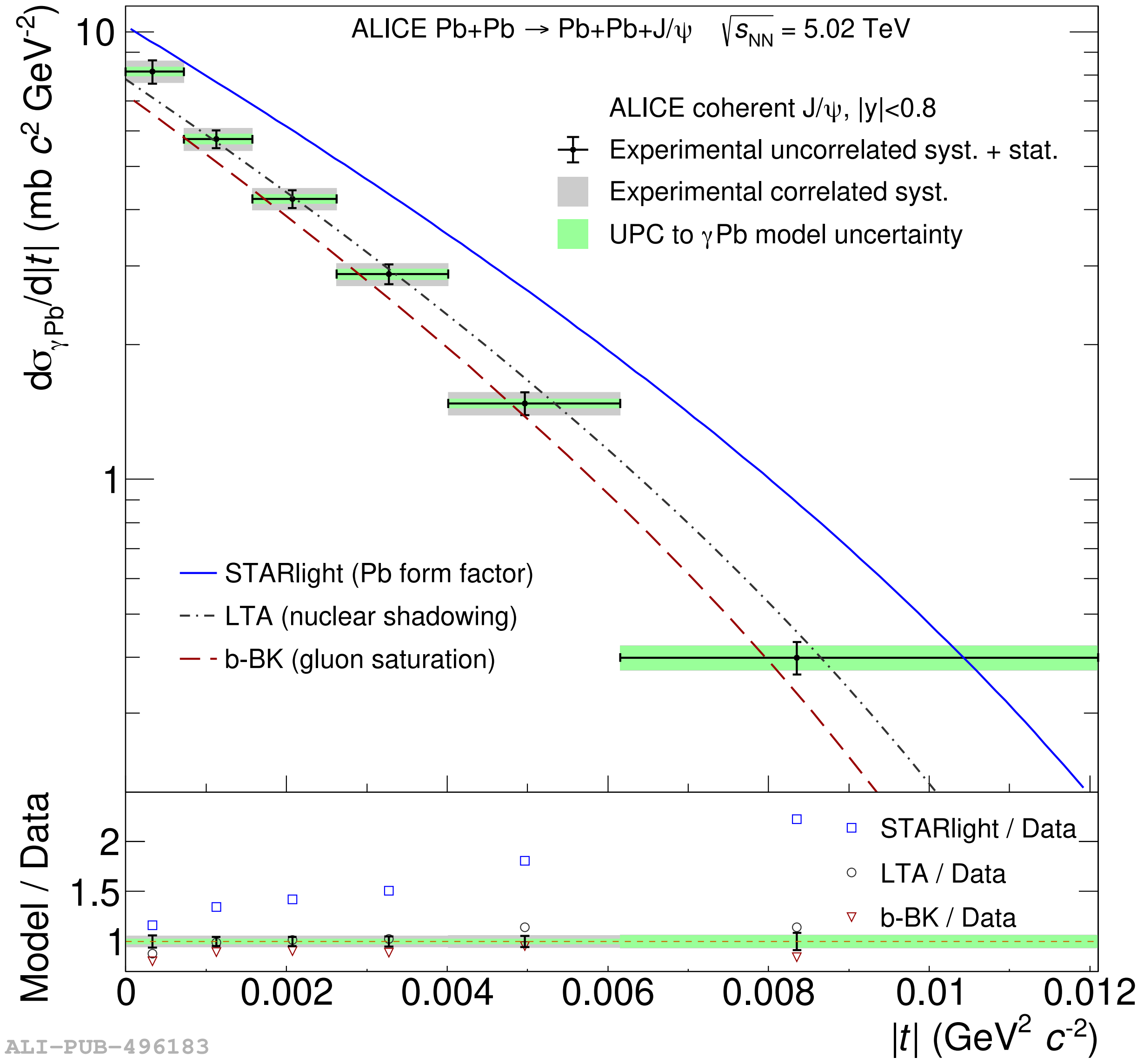
Phys.Lett.B 817 (2021) 136280

arXiv:2305.06169

Coherent J/ψ

- Sensitive to the **average** of the target spatial distribution in the transverse plane
- **STARlight** – hadronic model based on the Glauber calculation
  - Gives a too high cross section
  - The p_T spectrum determined from the nuclear (Pb) form factor
- **Dynamic effects from QCD important**:
  - **LTA** – leading twist approximation of nuclear shadowing ("low" prediction)
  - **b-BK** – color dipole approach, solution to the *b*-dependent BK equation (saturation effects)

New ALICE **Run-3 data** + improved tracking should help us distinguish which pQCD prediction is doing better!



[Phys.Lett.B 817 (2021) 136280]

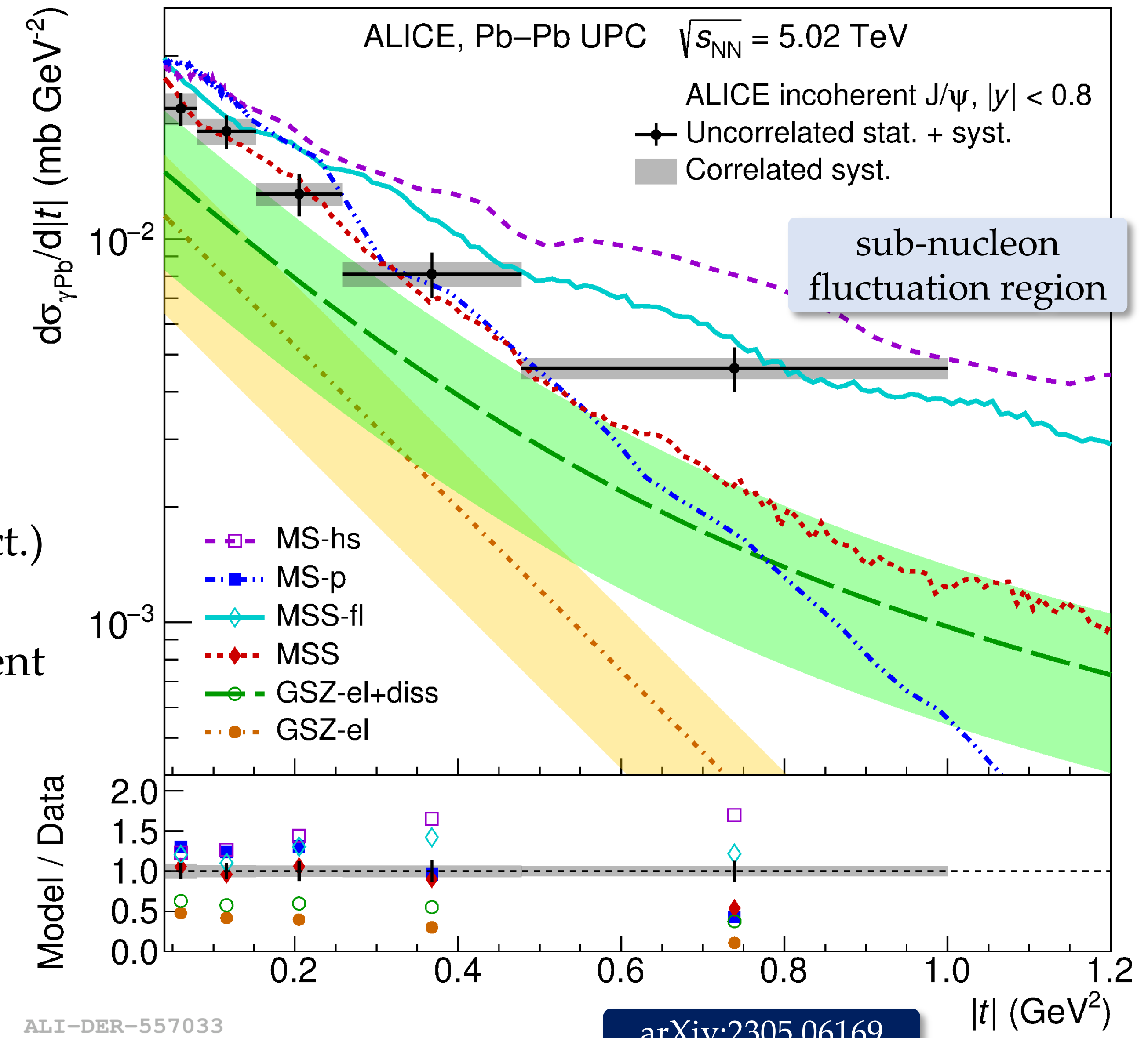
Incoherent J/ψ

- The slope sensitive to **fluctuations** of the target transverse profile
- Each theory group provides two predictions:
  1) Elastic scattering on a **full nucleon** (**MS-p**, **MSS**, **GSZ-el**)

     These models predict **steeper slopes** than in the data…

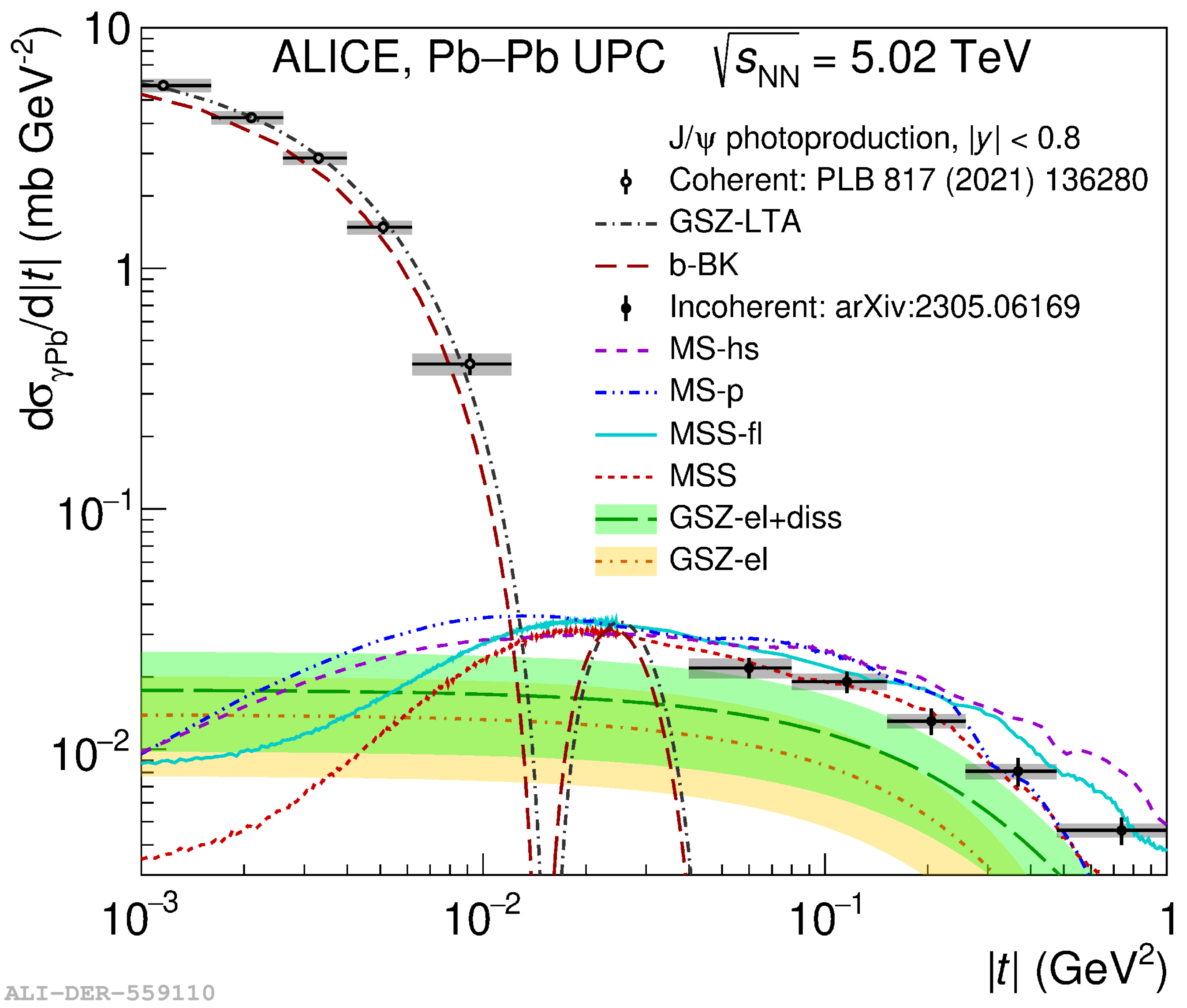
  2) **Sub-nucleon degrees of freedom**:
     - **MS-hs**: IPsat (hot spots + satur. scale fluct.)
     - **MSS-fl**: CGC-based, JIMWLK solution
     - **GSZ-el+diss**: extra dissociative component

     These models are **favored by the data** at higher $|t|$
- The models fail to describe the **normalization** (scaling from proton to nuclear targets)



arXiv:2305.06169

Putting together coherent & incoherent data points



Three orders of magnitude in $|t|$ covered with a **HERA-like accuracy**!

arXiv:2305.06169

Phys.Lett.B 817 (2021) 136280

Other recent ALICE UPC results…

NEW!

- First polarisation measurement of coherently photoproduced J/ψ in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV arXiv:2304.10928
- Photoproduction of K^+K^- pairs in ultra-peripheral collisions, arXiv:2311.11792
- Measurement of the impact-parameter dependent azimuthal anisotropy in coherent ρ^0 photoproduction (preliminary)
- Exclusive four pion photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (preliminary)

See the next slide…

See the talk by **Minjung Kim:** Monday at 18:45

See the talk by **Andrea Riffero:** Tuesday at 10:15

J/ψ polarization

- Angular distribution of J/ψ yields was unfolded in φ, corrected for $A\times\varepsilon$, and fitted to (λ are polarization parameters):

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

- **Helicity frame** used (z axis ∥ J/ψ momentum)

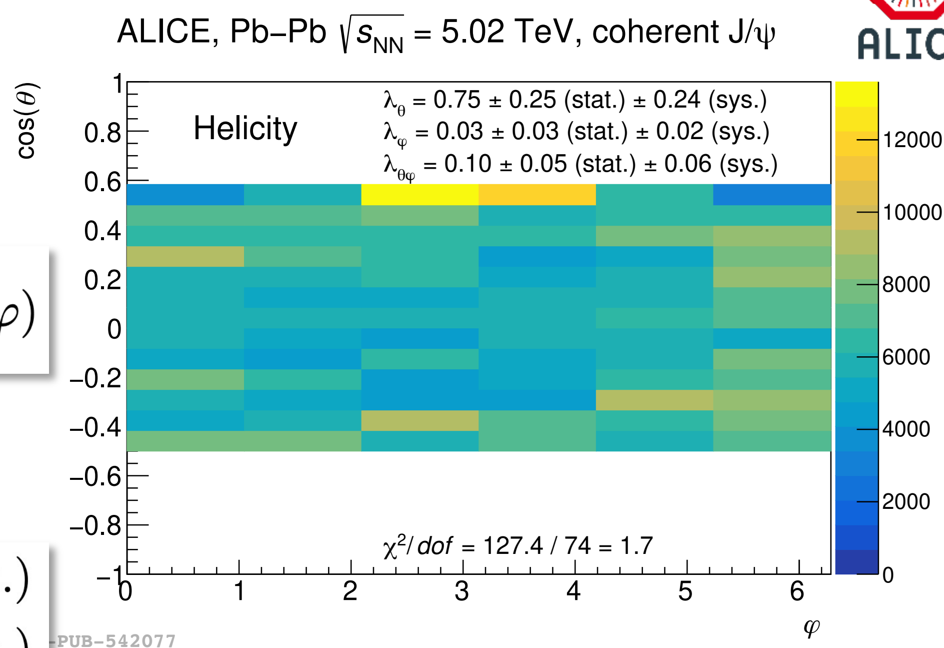
Results compatible with **transverse polarization**: $(\lambda_\theta,\lambda_\varphi,\lambda_{\theta\varphi}) = (1,0,0)$

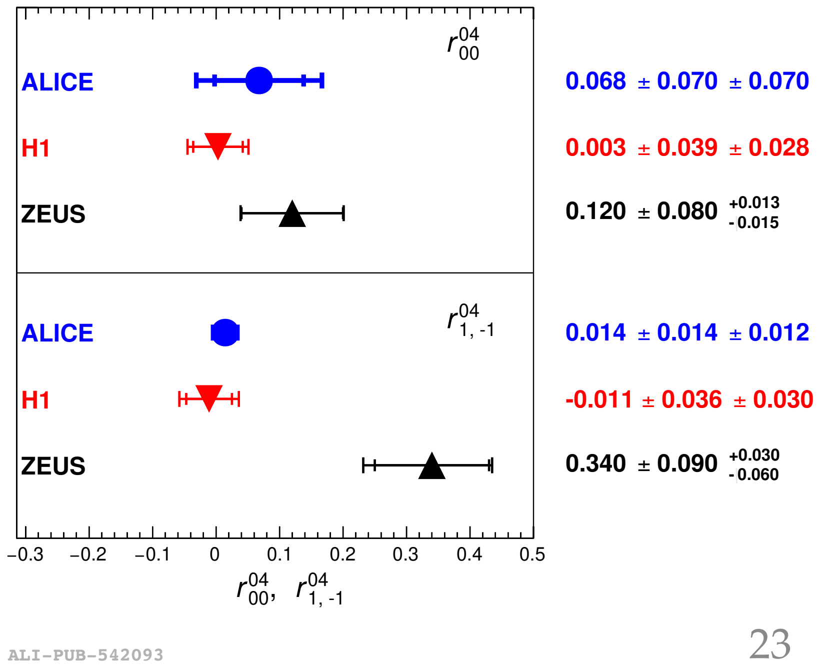
$$\lambda_\theta = 0.75 \pm 0.25\ (\text{stat.}) \pm 0.24\ (\text{syst.})$$
$$\lambda_\varphi = 0.03 \pm 0.03\ (\text{stat.}) \pm 0.02\ (\text{syst.})$$
$$\lambda_{\theta\varphi} = 0.10 \pm 0.05\ (\text{stat.}) \pm 0.06\ (\text{syst.})$$

- First experimental evidence for the s-channel helicity conservation (SCHC) hypothesis in J/ψ photoproduction off lead nuclei
- Spin-density matrix elements extracted & compared with HERA results:

$$r^{04}_{00} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$
$$r^{04}_{1,-1} = \frac{\lambda_\varphi}{2}(1+r^{04}_{00})$$

arXiv:2304.10928





Summary

Using data from Run 2 of the LHC, ALICE has recently presented **many UPC measurements**:

- Energy dependence of coherent, exclusive and dissociative J/ψ production
- Dependence of coherent and incoherent J/ψ production on $|t|$
- J/ψ polarization
- K^+K^- and exclusive four pion photoproduction
- Azimuthal anisotropies in ρ^0 production

Some of these are, especially through comparison with phenomenological models, **a probe into important effects in high-energy QCD**:

- Gluon saturation
- Nuclear shadowing
- Fluctuations at sub-nucleon scale

See the talk by **Anisa Khatun:** Friday at 18:00

With **new data to come in Run 3 & 4**, and thanks to detector upgrades, ALICE will be able improve the precision and conduct even more detailed measurements…

STAY TUNED!

Reminder of ALICE contributions at UPC 2023

ALICE

- Energy dependence of J/ψ in UPCs at the LHC
  Michael Winn, **Monday** at **16:30**
- K^+K^- photoproduction in ultra-peripheral Pb–Pb collisions with ALICE
  Minjung Kim, **Monday** at **18:45**
- Measurement of the impact-parameter dependent azimuthal anisotropy in coherent ρ^0 photoproduction with ALICE
  Andrea Riffero, **Tuesday** at **10:15**
- Photoproduction of J/ψ and dileptons in events with nuclear overlap with ALICE
  Nicolas Bizé, **Thursday** at **17:30**
- A Forward Calorimeter in ALICE
  Ionut Cristian Arsene, **Friday** at **16:30**
- UPC physics with ALICE in Run 3
  Anisa Khatun, **Friday** at **18:00**

Thank you for your attention!