First study of initial gluonic fluctuations using UPCs with **ALICE**

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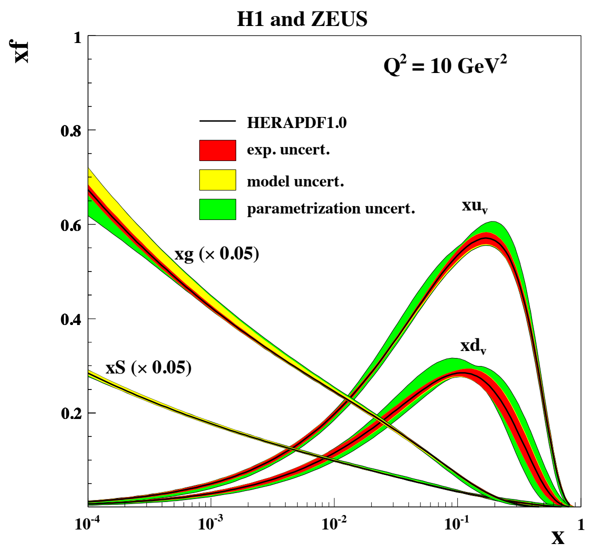
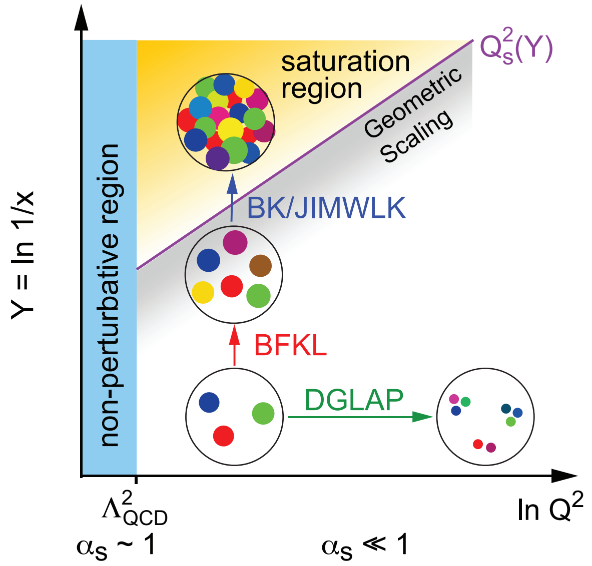
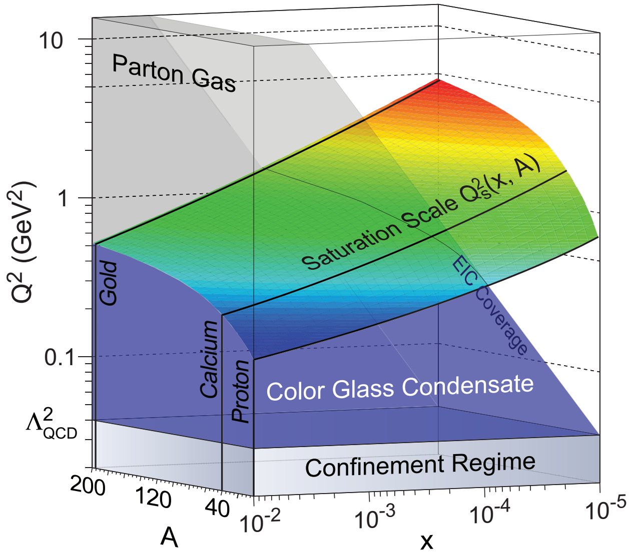
Studying the structure of nucleons and nuclei

- At high energies (low Bjorken x) the **gluon contribution** is dominant and continues to rise
- At some point, gluon splitting should be balanced by annihilation ⇒ **saturation**
- For heavy nuclei, saturation is expected at higher x
- Various aspects of the structure can be studied to **determine the onset of saturation**:
  - The average gluon density
  - Event-by-event fluctuations
- **Photon-induced processes** are an excellent experimental probe



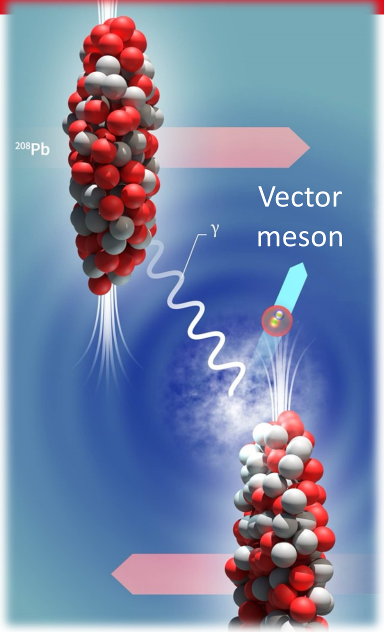
JHEP 01 (2010) 109





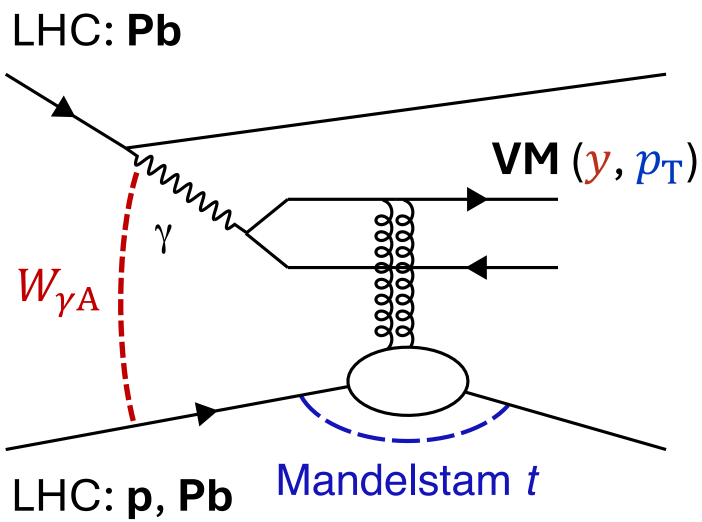
EPJA 52 (2016) 9, 268

Vector meson diffractive photoproduction



- **Ultra-peripheral collisions** (UPCs) at hadron colliders:
  - $b > 2R$, so that pure hadronic interactions are suppressed
  - EM fields of ultra-relativistic ions act as beams of low-virtuality photons
  - Photon flux $\propto Z^2$
- The photon fluctuates into a **color dipole** that scatters off a nucleus/nucleon and a vector meson is formed
- The **photonuclear cross section** $\sigma_{\gamma A}$ is sensitive to the gluon distribution in the target
- The VM rapidity traces back the energy evolution
- Let's focus on J/ψ:
  - $Q^2 \sim M_{\mathrm{VM}}^2/4 \Rightarrow$ hard scale, pQCD
  - Can be reconstructed using ALICE with high precision

Clear experimental signature: for **J/ψ → l⁺l⁻** there are two lepton tracks in an otherwise empty detector



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

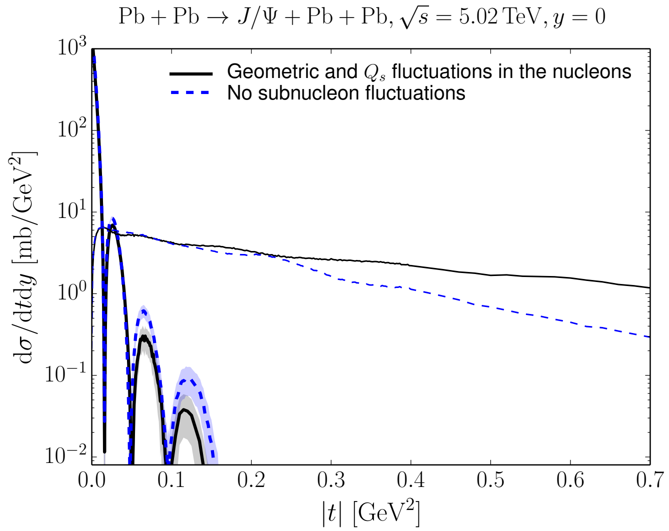
$$t \approx -p_{\mathrm{T}}^2$$

Probing gluonic structure in the transverse plane

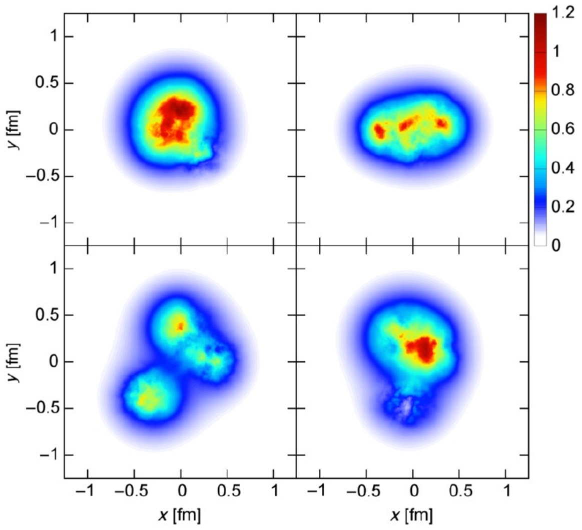
- The impact parameter b and the VM transverse momentum p_{T} are **Fourier conjugates**
- $|t|$-dependence of $\sigma_{\gamma\mathrm{Pb}} \xleftrightarrow{\textbf{Fourier tr.}}$ color distribution in the transverse plane

Process	γ interacts with	In the Good-Walker model*, $\sigma_{\gamma A}$ is sensitive to	$\langle\lvert t\rvert\rangle$ (GeV²)
Coherent	The whole nucleus	The **average**	$\lesssim 0.01$
Incoherent	A single nucleon	The **variance (fluctuations)**	~ 0.1
Incoherent dissociative	Subnucleonic structure		~ 1

PLB 772 (2017) 832-838



PRL 117 (2016) 5, 052301



In such models, significant **fluctuations** of **gluon fields** at the subfemtometer scale enhance the incoherent cross section at $|t| \sim 1$ GeV²

*See e.g. *PLB 772 (2017) 832-838*
but note also *PRC* 107 (2023) 5, 055203

How ALICE detects UPCs

JINST 3 (2008) S08002

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

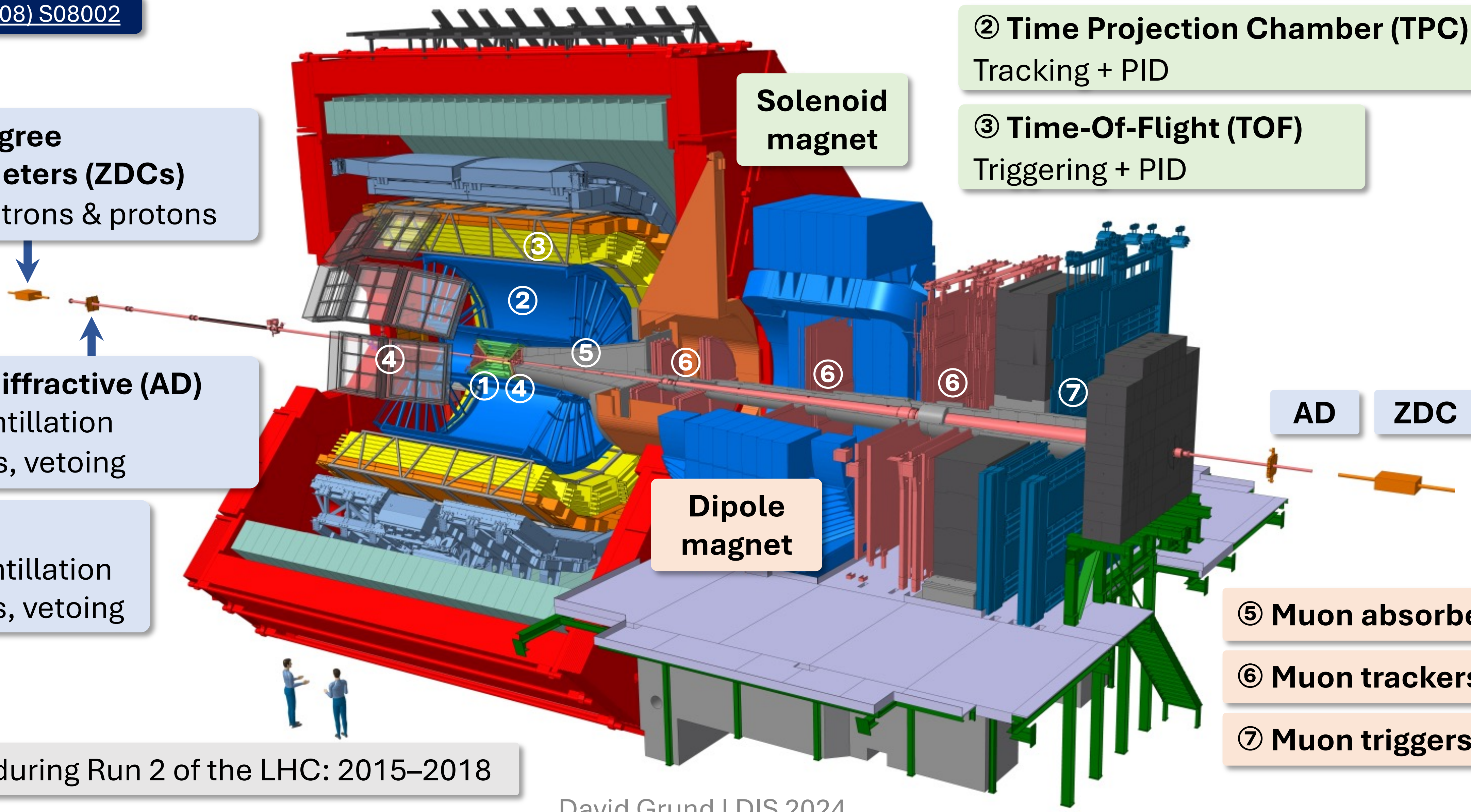
② **Time Projection Chamber (TPC)**
Tracking + PID

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

Zero Degree Calorimeters (ZDCs)
Fwd neutrons & protons

ALICE Diffractive (AD)
Fwd scintillation counters, vetoing

④ **V0**
Fwd scintillation counters, vetoing



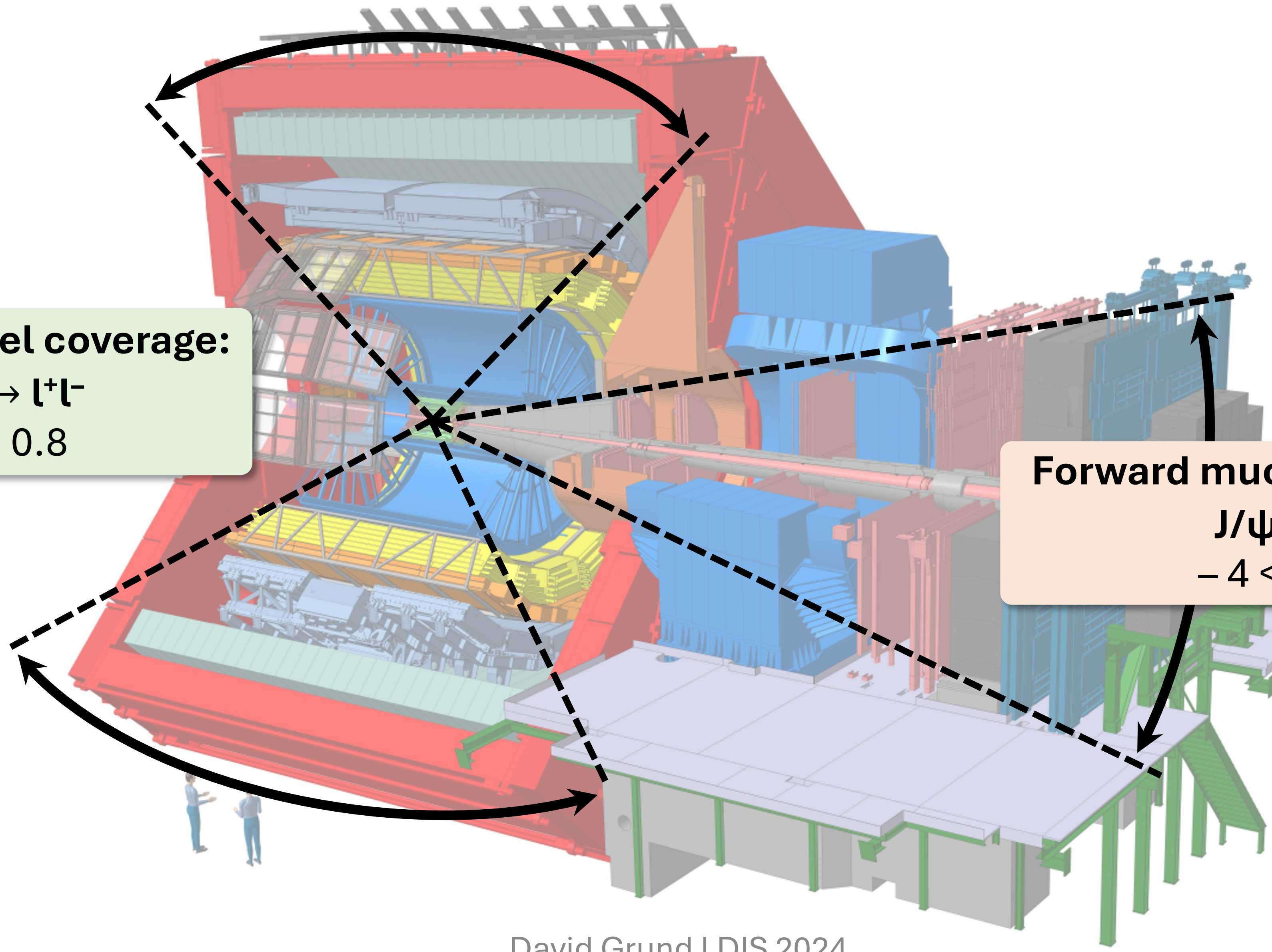
⑤ **Muon absorber**

⑥ **Muon trackers**

⑦ **Muon triggers**

Status during Run 2 of the LHC: 2015–2018

How ALICE detects UPCs



Central barrel coverage:
J/ψ → l^+l^-
$|y| < 0.8$

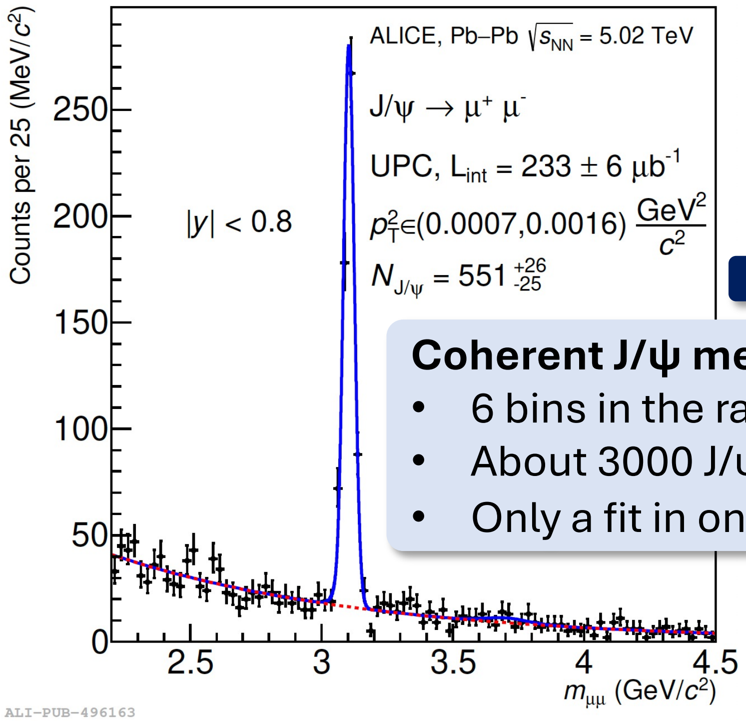
Forward muon arm coverage:
J/ψ → $\mu^+\mu^-$
$-4 < y < -2.5$

Coherent & incoherent J/ψ production

- Using Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, ALICE measured for the first time the dependence of both **coherent** and **incoherent** J/ψ photonuclear production on Mandelstam |*t*|
- J/ψ → μμ at midrapidity ⇒ $x \in (0.3, 1.4) \times 10^{-3}$
- Yields of J/ψ candidates from fits to the invariant mass distribution:

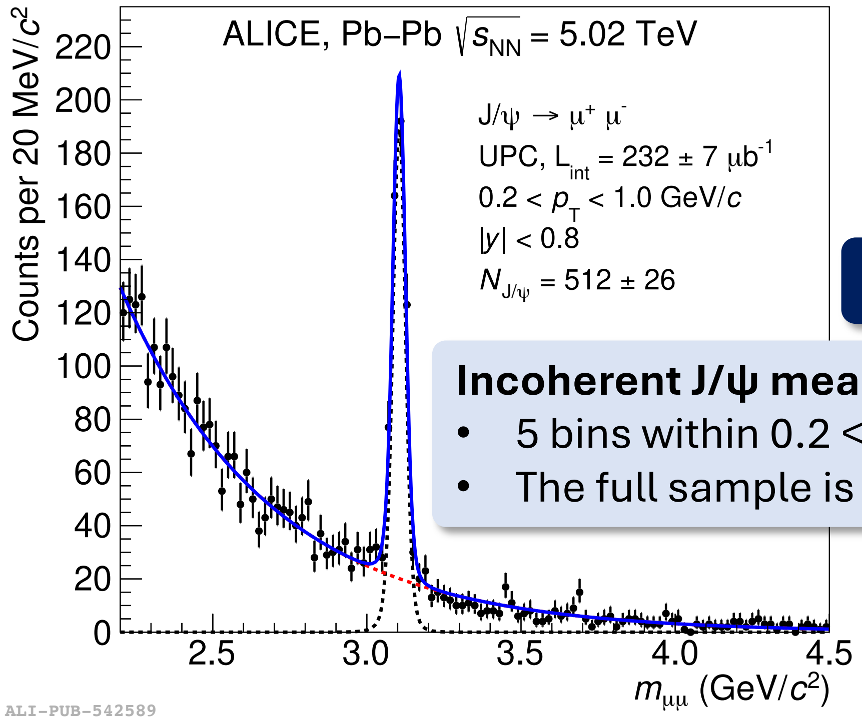
UPC cross section (measured) **photon flux** (calculated) **photonuclear cross section** (extracted)

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



PLB 817 (2021) 136280

Coherent J/ψ measurement:
- 6 bins in the range p_{T} < 0.11 GeV/*c*
- About 3000 J/ψ candidates
- Only a fit in one p_{T} interval is shown



arXiv:2305.06169 (accepted by PRL)

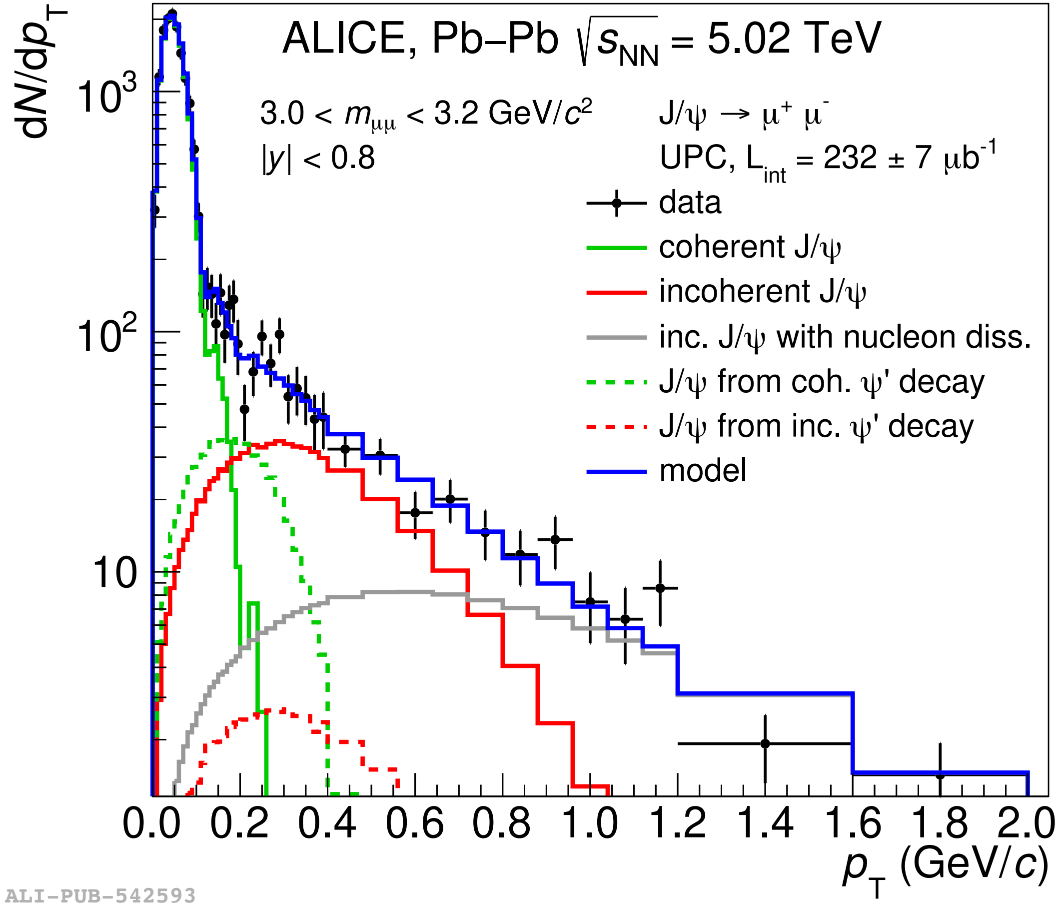
Incoherent J/ψ measurement:
- 5 bins within 0.2 < p_{T} < 1 GeV/*c*
- The full sample is shown

Coherent & incoherent J/ψ production

- Corrections for feed-down and contamination from incoherent/coherent production from fits to the transverse momentum distribution of muon pairs with $3.0 < m_{\mu\mu} < 3.2$ GeV/c^2
  - Templates created using the STARlight MC generator + GEANT 3.21
  - Nucleon dissociation: H1 parametrization
- Additional corrections:

Coherent J/ψ measurement
- Unfolding to account for p_{T} migration (detector resolution effects)
- $p_{\mathrm{T}}^2 \rightarrow |t|$ unfolding (photon k_{T})

Incoherent J/ψ measurement
- p_{T} migration negligible
- k_{T} negligible $\Rightarrow |t| = p_{\mathrm{T}}^2$



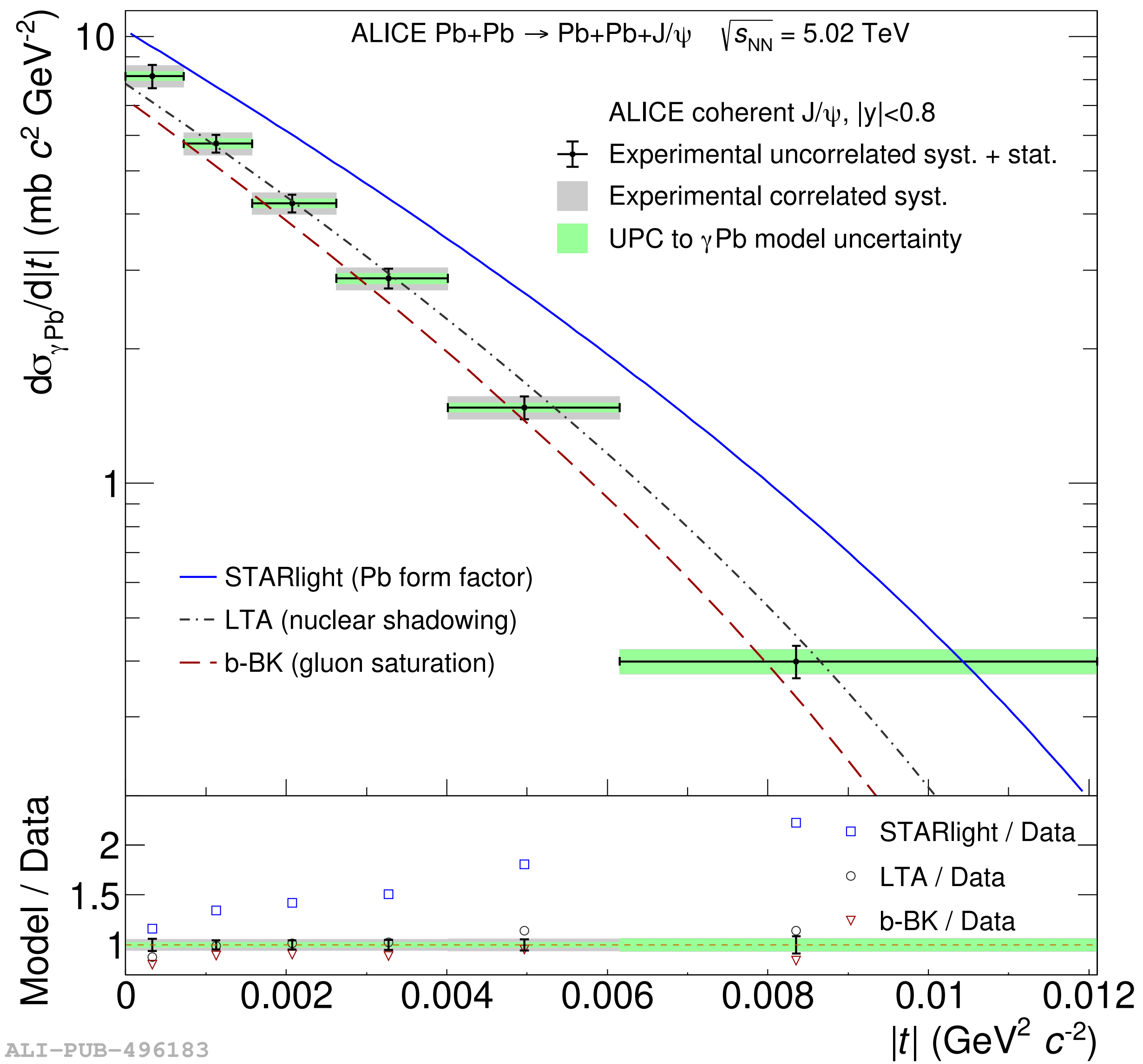
ALI-PUB-542593

arXiv:2305.06169 (accepted by PRL)

Results – coherent J/ψ

- The cross section is sensitive to the **average** of the gluon spatial distribution in the transverse plane
- **STARlight** – hadronic model based on a Glauber calculation
  - Predicts 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**
  - **b-BK** – color dipole approach, solution to the b-dependent BK equation (saturation effects)

Thanks to detector upgrades and expected sizes of data samples, data from **Run 3** should help us distinguish which pQCD prediction is better



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Results – incoherent J/ψ

- The slope is sensitive to **fluctuations** in the transverse profile of the target
- Each theory group provides two predictions:

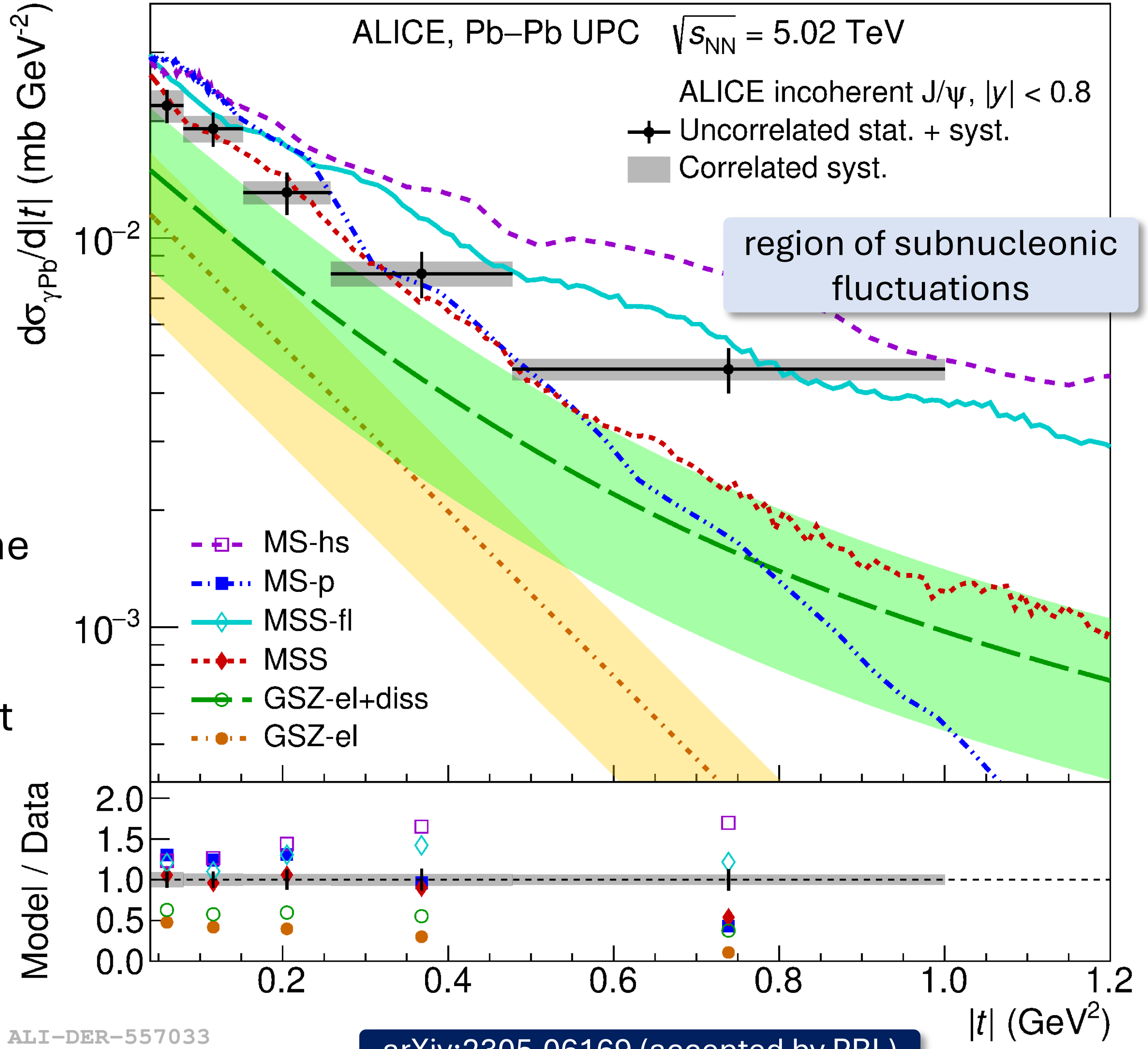
  1) Elastic scattering on a **full nucleon** (**MS-p**, **MSS**, **GSZ-el**)

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

  2) **Subnucleonic degrees of freedom**:
     - **MS-hs**: IPsat (**hot spots** + fluctuations in the saturation scale)
     - **MSS-fl**: CGC-based, JIMWLK solution
     - **GSZ-el+diss**: extra dissociative component

  These models are **favored by the data** at higher $|t|$

- The models generally fail to describe the **normalization** (scaling from the proton to nuclear targets)



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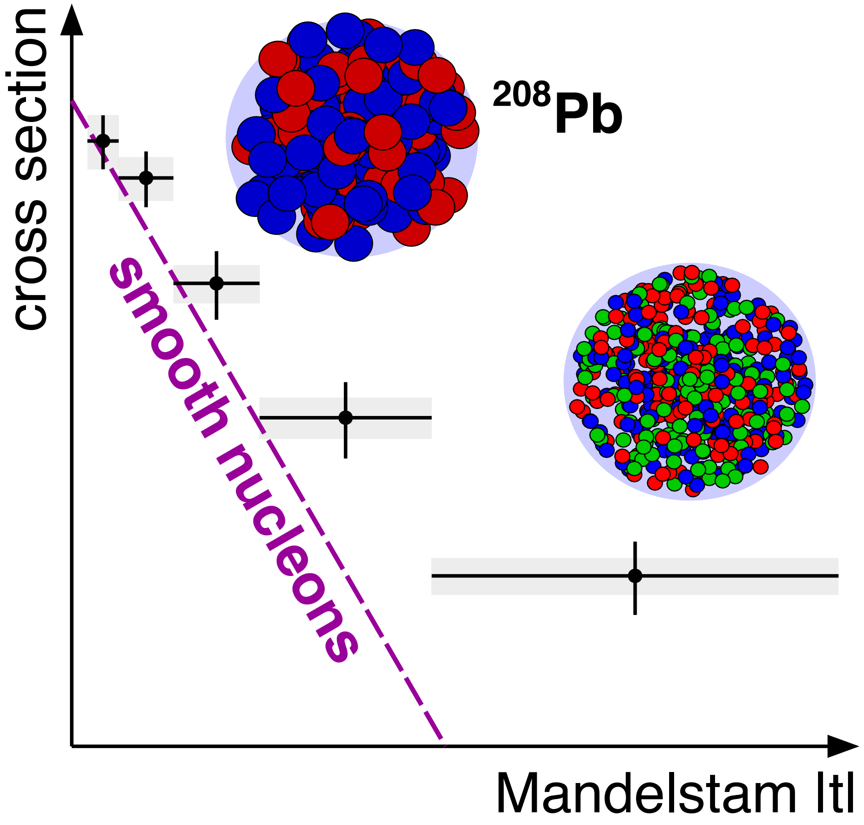

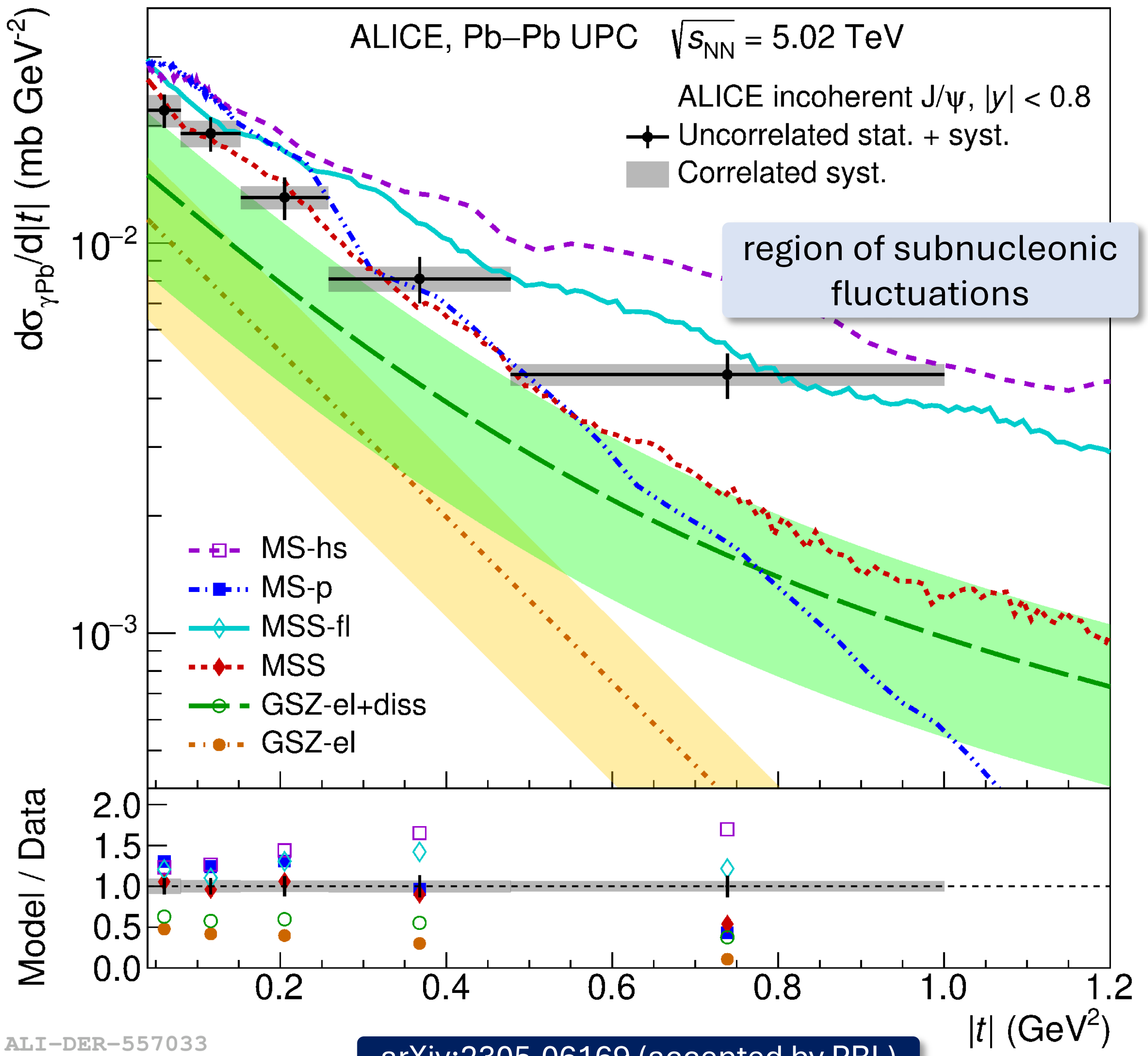

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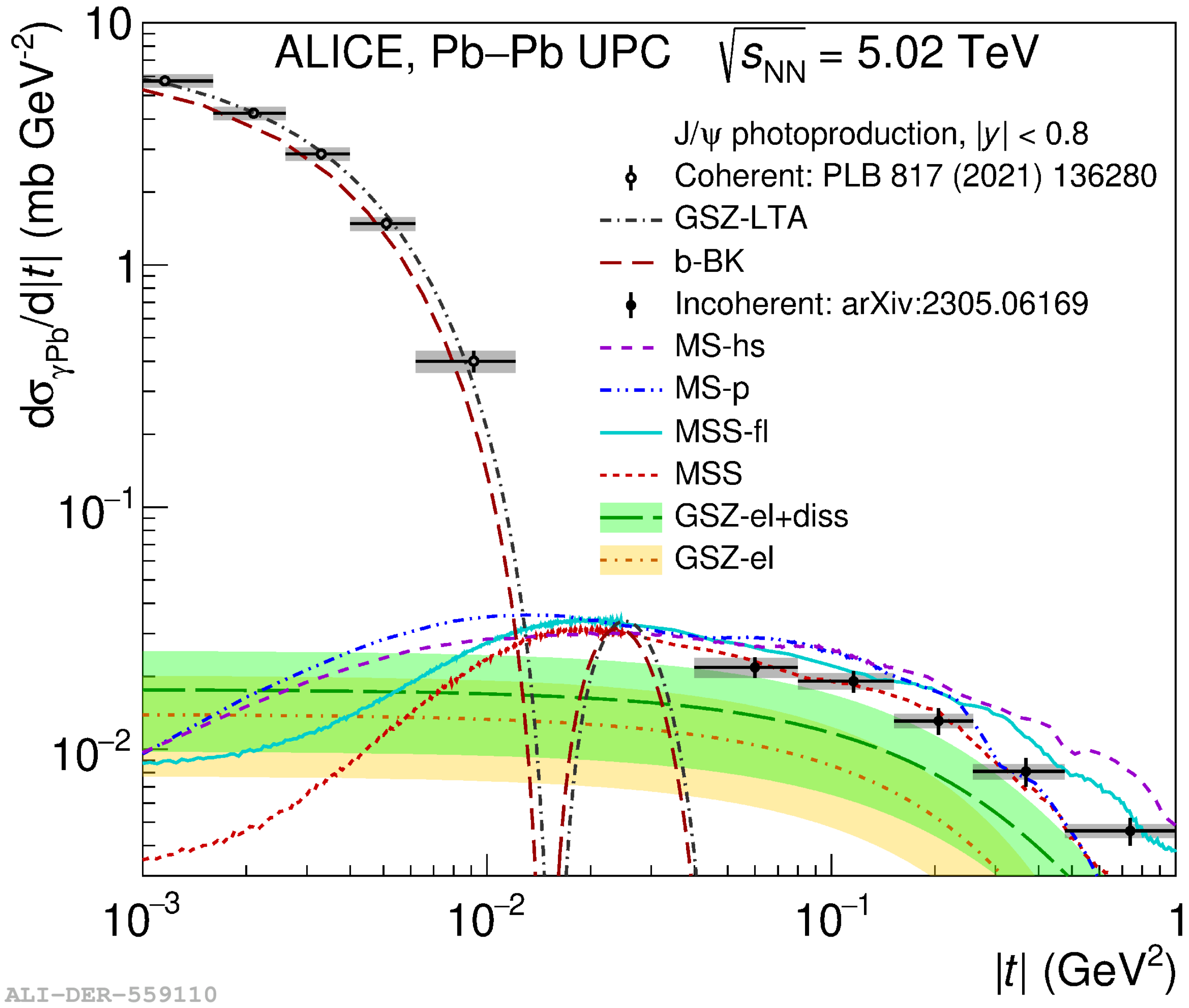
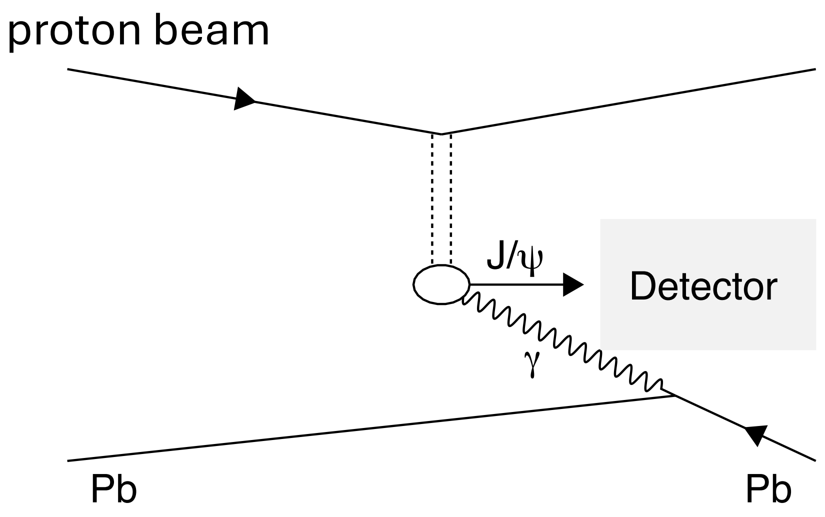
Results – full |t|-dependence

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



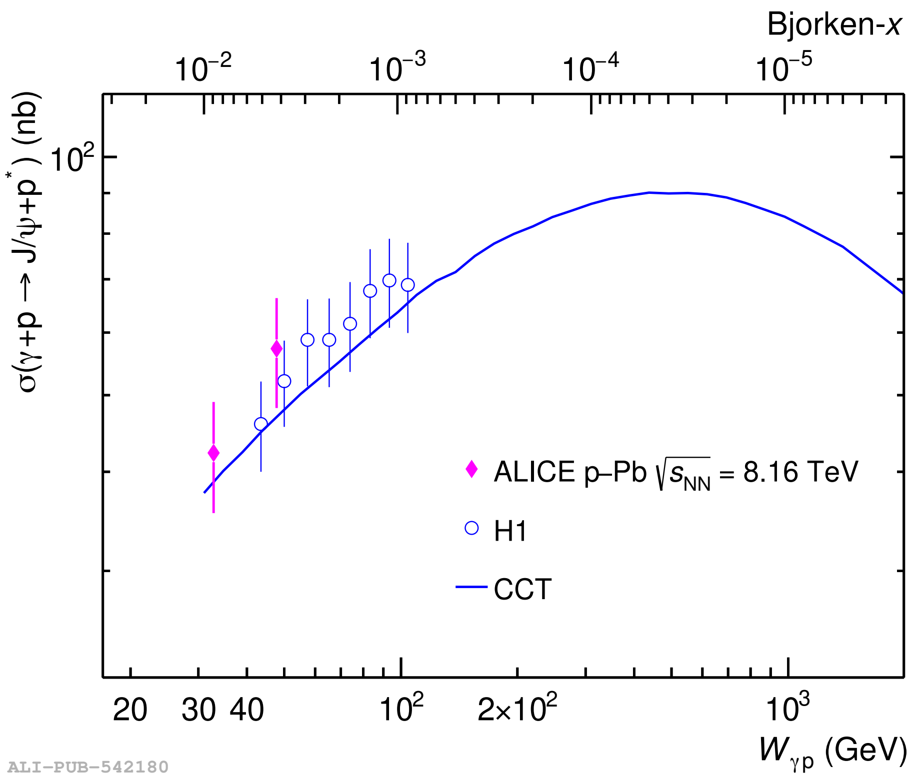
Energy dependence of dissociative J/ψ production

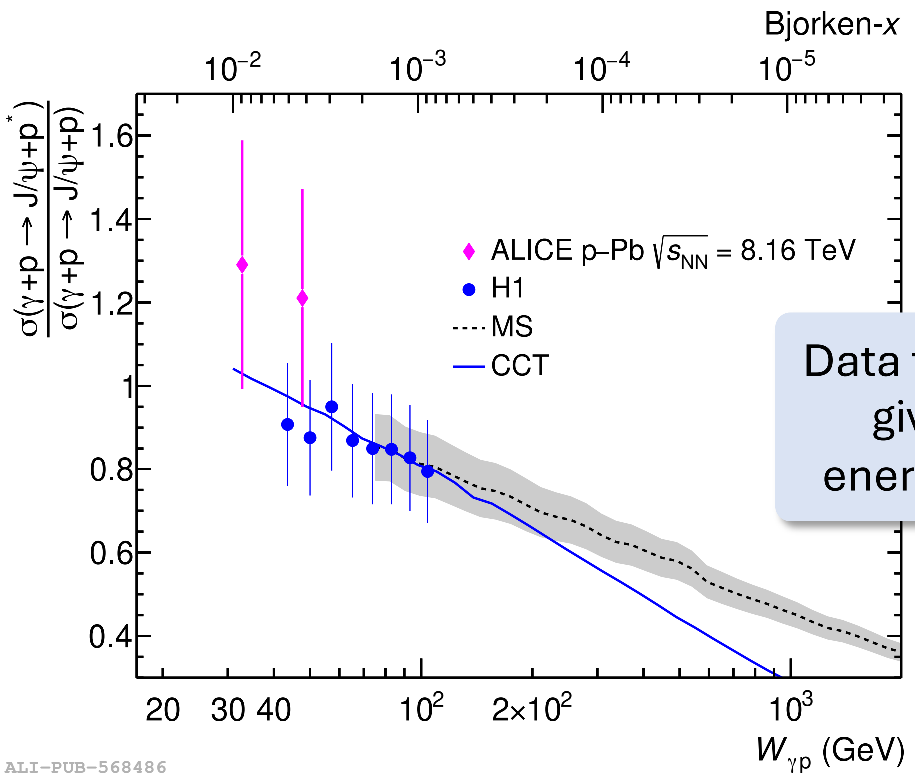
- Using Run 2 data, ALICE also measured the energy dependence of J/ψ photoproduction off protons accompanied by proton dissociation
- p–Pb UPCs at 8.16 TeV; energy range **27 < $W_{\gamma p}$ < 57 GeV**
- The first such measurement at a hadron collider
- **J/ψ** → **μμ** decays reconstructed using the muon spectrometer
- The asymmetric p–Pb system avoids the ambiguity in the center-of-mass energy $W_{\gamma p}$
- The beam configuration corresponded to the "low-energy" photon emitted from the Pb nucleus:



Results – energy dependence of dissociative J/ψ production

PRD 108 (2023) 11, 112004





Data from **Run 4** should give us access to energies up to ~ 1 TeV

- The measurement is compatible with H1 results
- The first probe to fluctuations of subnucleonic structures inside the proton using UPCs

The **CCT model** (hot spots) predicts that the cross section has a maximum at $W_{\gamma p} \simeq 500$ GeV (approaching black disk limit)

Conclusions and outlook

- ALICE measured the dependence of the cross section for **coherent** and **incoherent J/ψ photoproduction** on Mandelstam $|t|$ using Pb–Pb UPCs at 5.02 TeV
- At LHC energies, these processes probe the behavior of the **gluon distribution** and the related high-energy QCD effects
- To obtain a reasonable description of the data, the models need to take into account:
    - **Saturation** or **shadowing** effects
    - **Subnucleonic fluctuations of the gluon fields** (e.g. via the **hot spot picture**)
- For the first time at a hadron collider, ALICE used p–Pb UPCs at 8.16 TeV to measure the **energy dependence of dissociative J/ψ photoproduction** off protons

- With data from Run 3 and beyond, ALICE will soon be able to perform more complex studies and reduce the uncertainties of current measurements … **STAY TUNED**!

Thank you for your attention!

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