Recent results on J/ψ photoproduction in UPCs with ALICE

Sasha Bylinkin
On behalf of the ALICE Collaboration

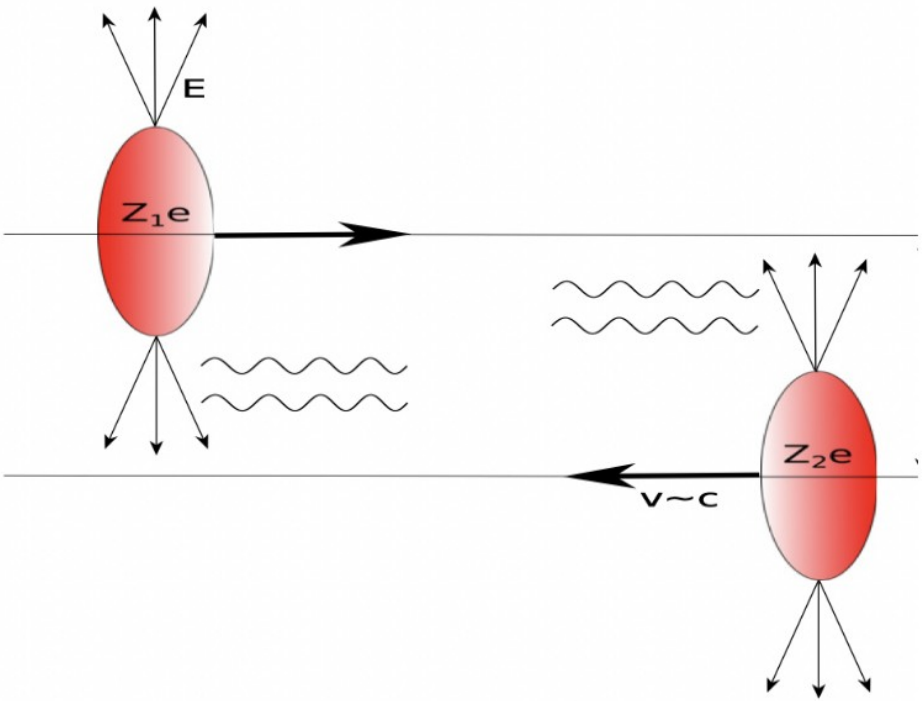
Diffraction and gluon saturation at the LHC and the EIC,
10-14th June 2024, Trento, Italy

Outline

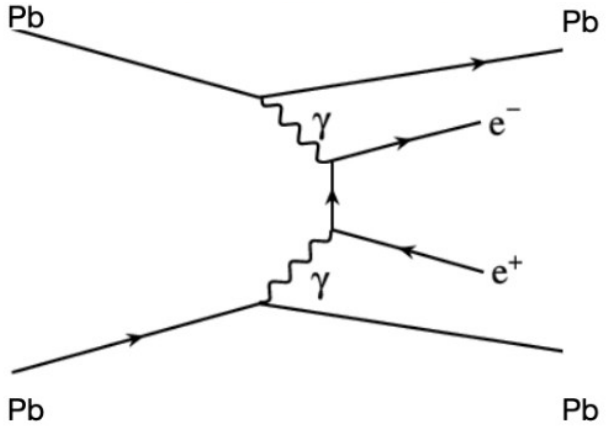
- Motivation
- ALICE Detector
- J/ψ photoproduction in p-Pb UPCs
- J/ψ photoproduction in Pb-Pb UPCs
  - Coherent and incoherent J/ψ photoproduction
  - Energy dependence
- Summary

Photon induced processes in heavy ion collisions

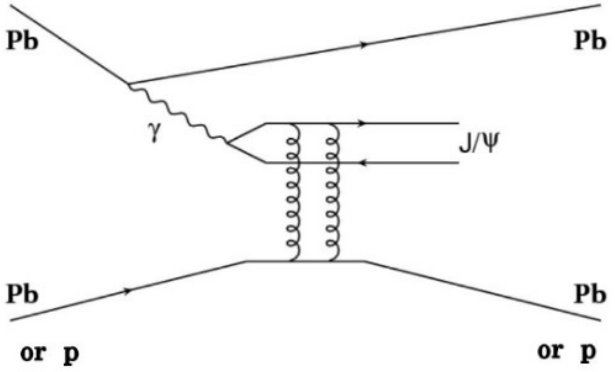
- Nuclei “miss” each other (b > 2R)
- Electromagnetic interaction dominates over strong
- Photon flux grows with the square of the charge, Z^2



Dilepton production

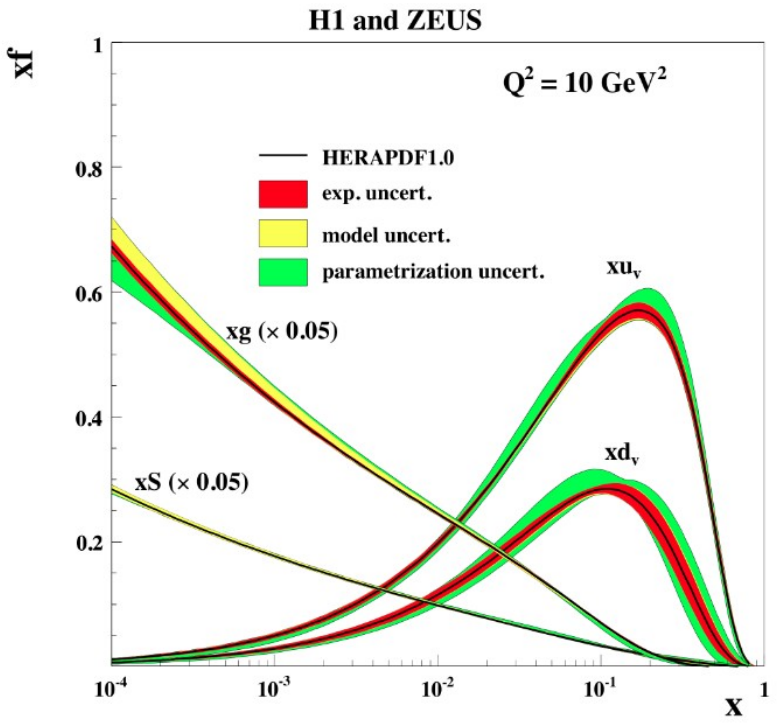


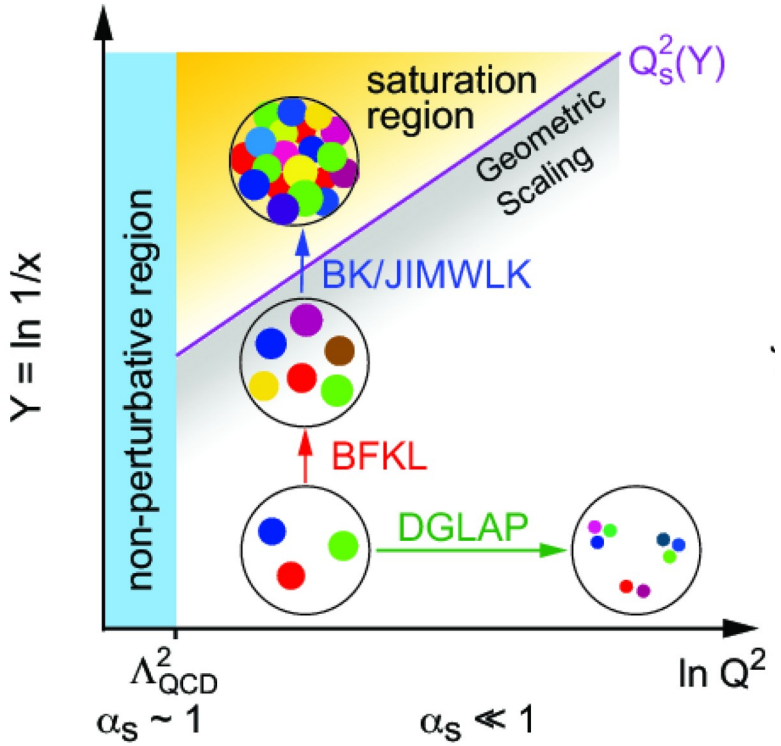
Vector meson production



Probes of nuclei in UPC

- UPCs at LHC: the most energetic photon-nuclei interactions
- Low-x physics and search for the nonlinear parton dynamics (saturation regime)





Exclusive vector meson photoproduction

- Photoproduction is sensitive to the gluon density at LO (NLO calculations are already available)

$$\left.\frac{d\sigma_{\gamma p,A\to V p,A}}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xG(x,Q^2)]^2$$

K.J. Eskola et. al
Phys. Rev. C 106 (2022) 035202

$$\sigma_{\gamma p\to VMp} = \frac{1}{b}\left.\frac{d\sigma_{\gamma p,A\to VM\,p,A}}{dt}\right|_{t=0}$$

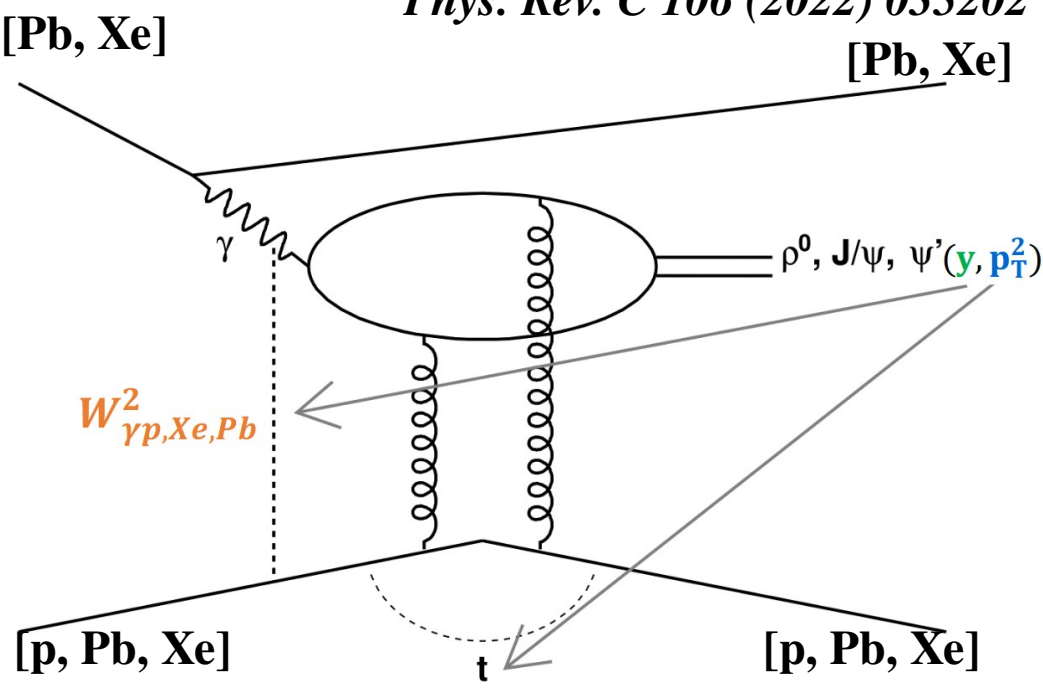
- Energy of the γp collision

$$W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y)$$

E_p – proton beam energy
M_{VM} – mass of the vector meson
y – rapidity of the vector meson

- Probe gluon distributions in the proton as a function of Bjorken-x

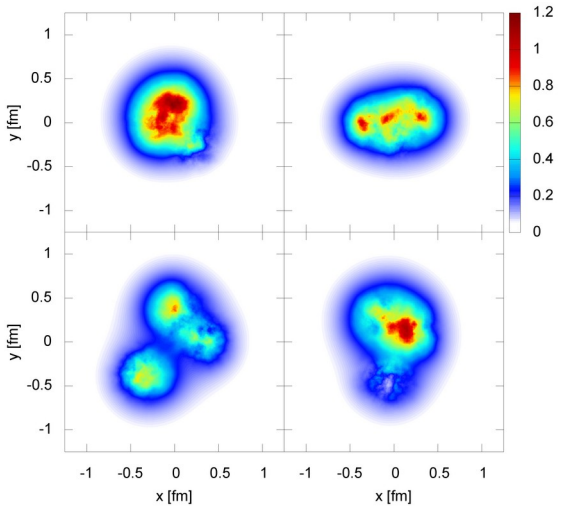
$$x = (M_{VM}/W_{\gamma p})^2$$



Probing gluonic structure in the transverse plane

- The impact parameter b and the VM transverse momentum p_T are Fourier conjugates.
- |t| dependence ↔ color distribution in the transverse plane

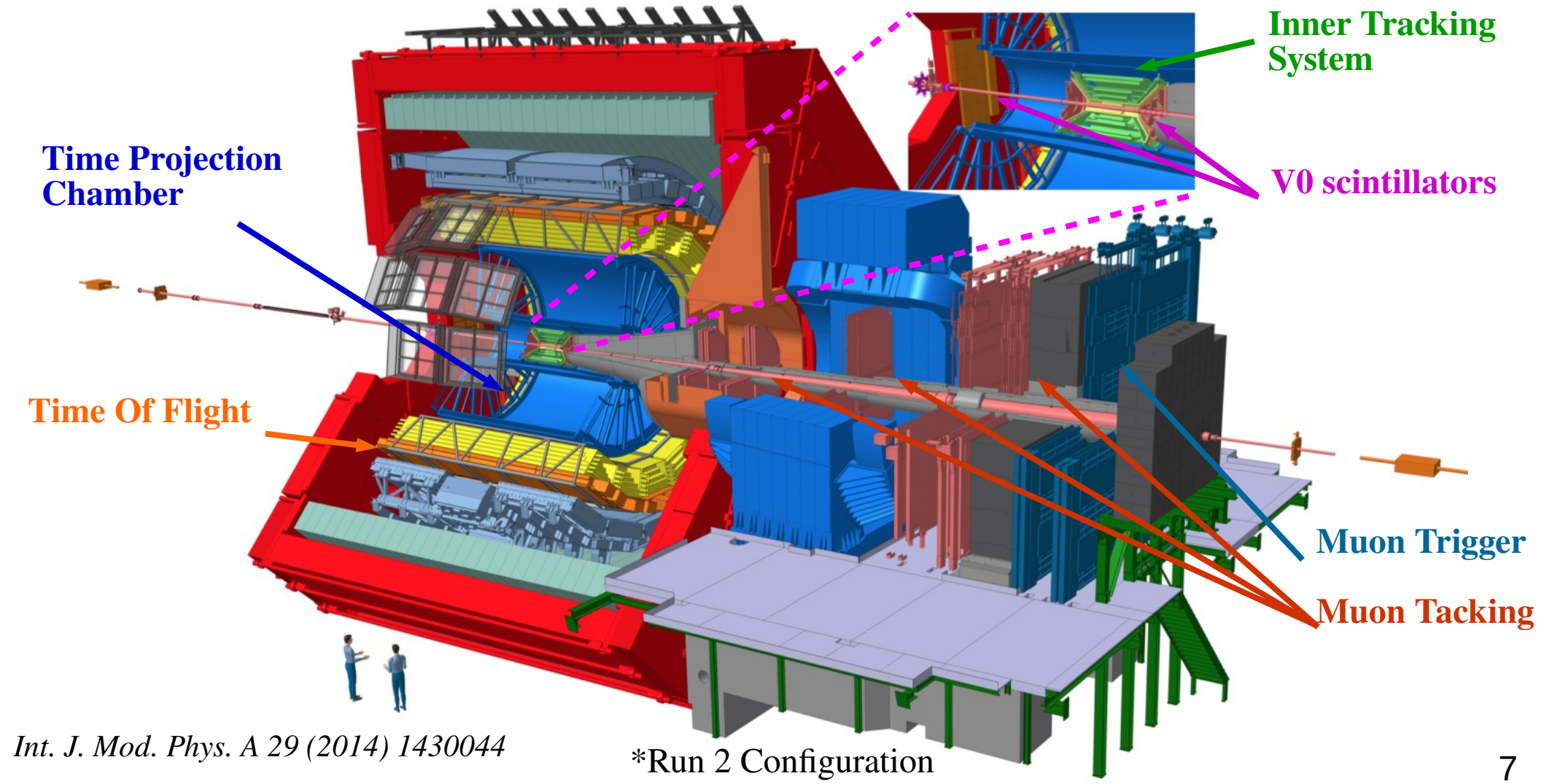
Process	γ interacts with	In the Good-Walker model*, $\sigma_{\gamma A}$ is sensitive to	$\langle \lvert t \rvert \rangle$ (GeV^2)
Coherent	The whole nucleus	The **average**	$\lesssim 0.01$
Incoherent	A single nucleon	The **variance (fluctuations)**	~ 0.1
Incoherent dissociative	Subnucleonic structure		~ 1



Significant fluctuations of gluon fields at the subfemtometer scale enhance the incoherent cross section at $|t| \sim 1$ GeV^2

Heikki Mäntysaari and Björn Schenke
PRL 117 (2016) 5, 052301

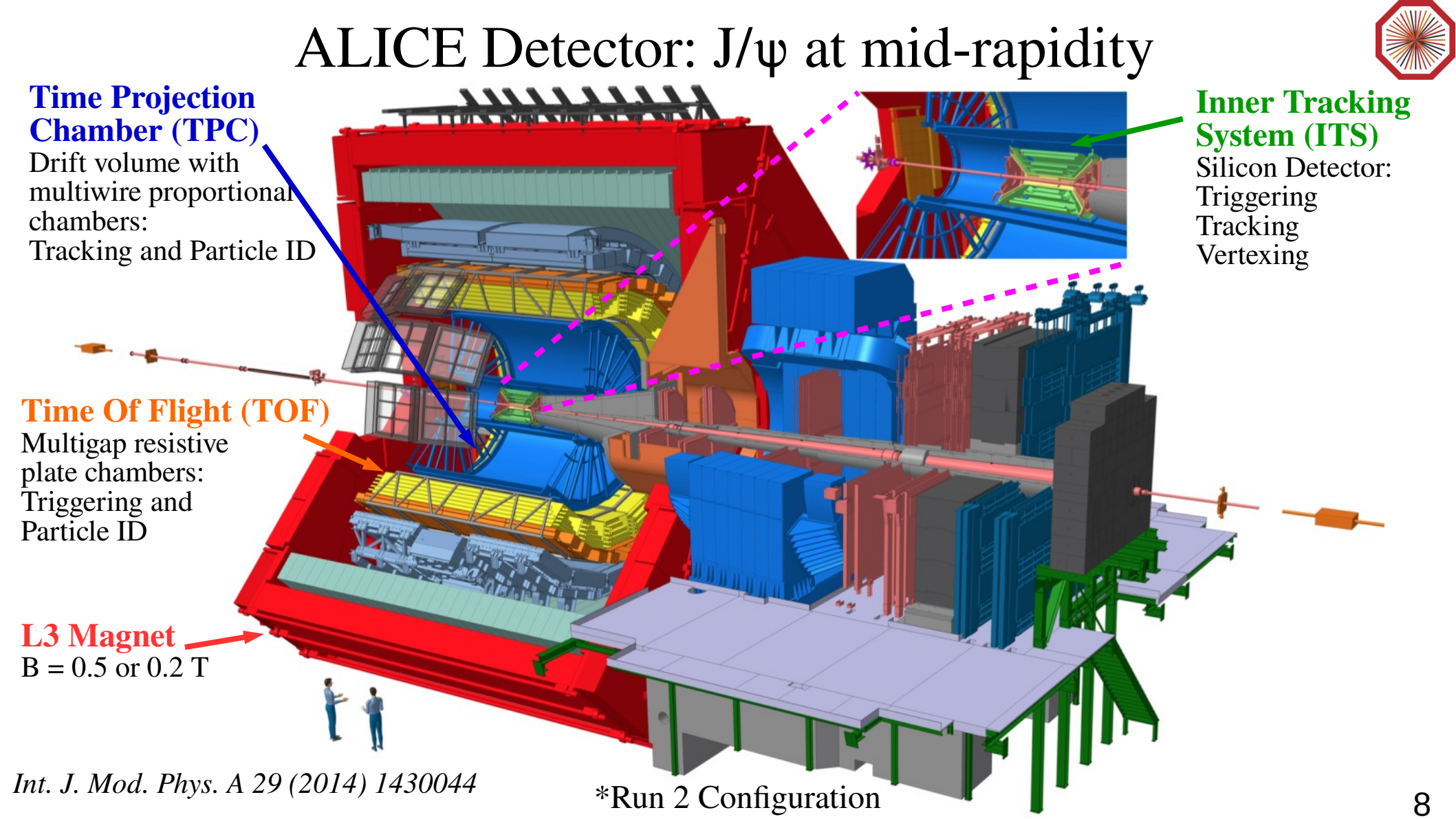
ALICE (A Large Ion Collider Experiment)



Int. J. Mod. Phys. A 29 (2014) 1430044

*Run 2 Configuration

ALICE Detector: J/ψ at mid-rapidity



Time Projection Chamber (TPC)
Drift volume with multiwire proportional chambers:
Tracking and Particle ID

Inner Tracking System (ITS)
Silicon Detector:
Triggering
Tracking
Vertexing

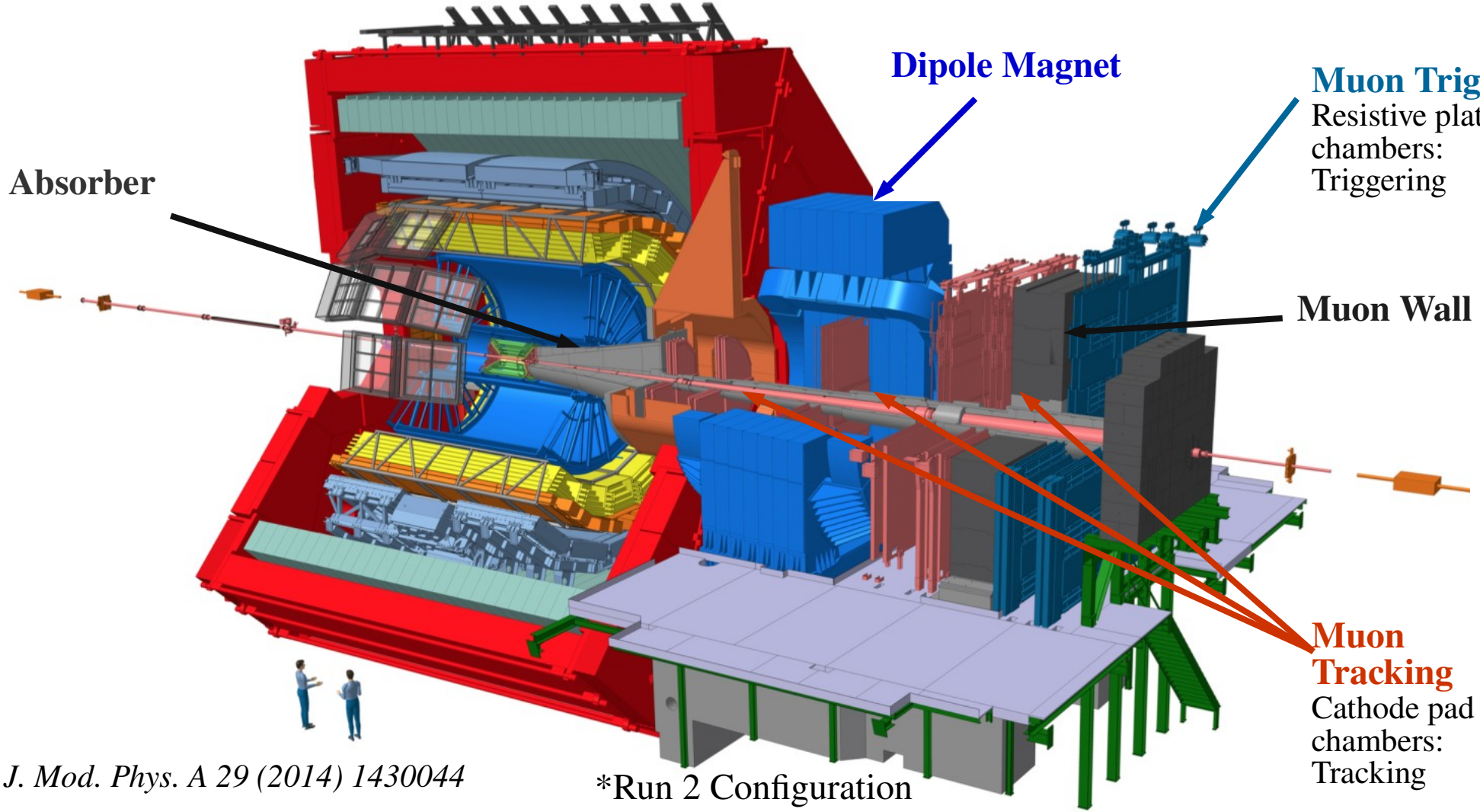
Time Of Flight (TOF)
Multigap resistive plate chambers:
Triggering and Particle ID

L3 Magnet
B = 0.5 or 0.2 T

Int. J. Mod. Phys. A 29 (2014) 1430044

*Run 2 Configuration

ALICE Detector: J/ψ at forward rapidity



Int. J. Mod. Phys. A 29 (2014) 1430044

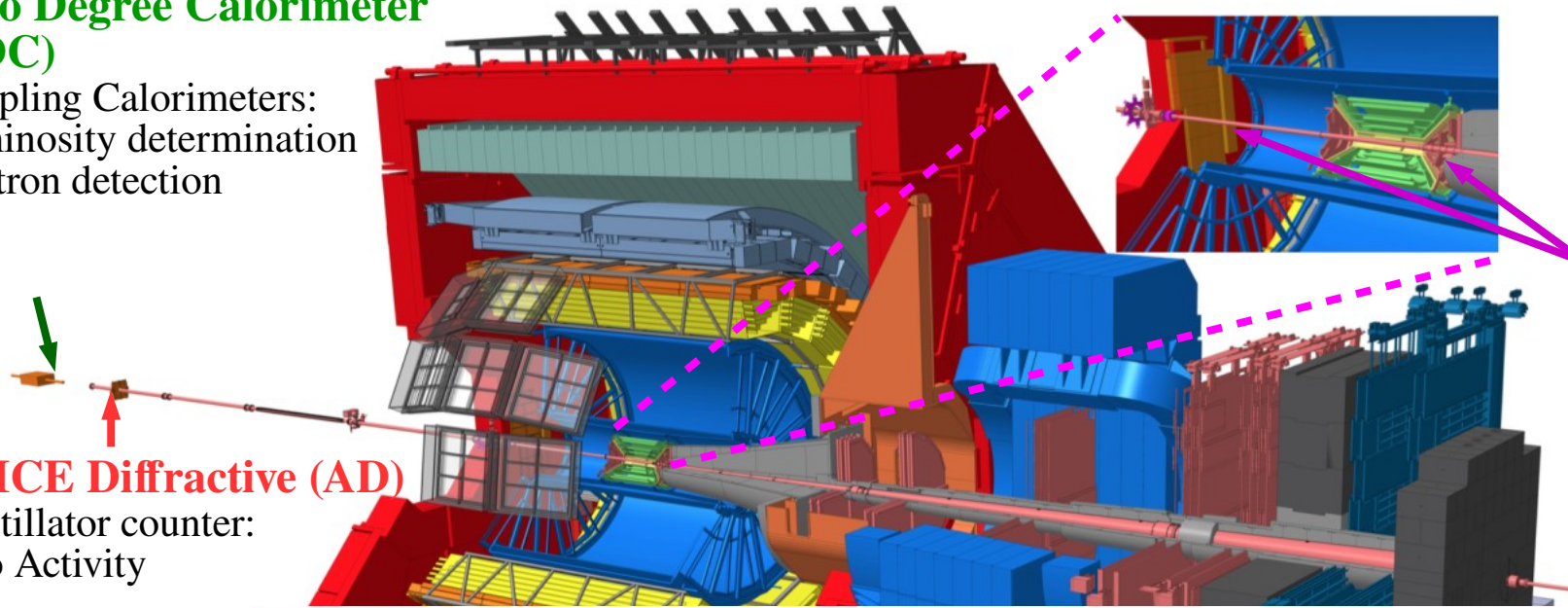
*Run 2 Configuration

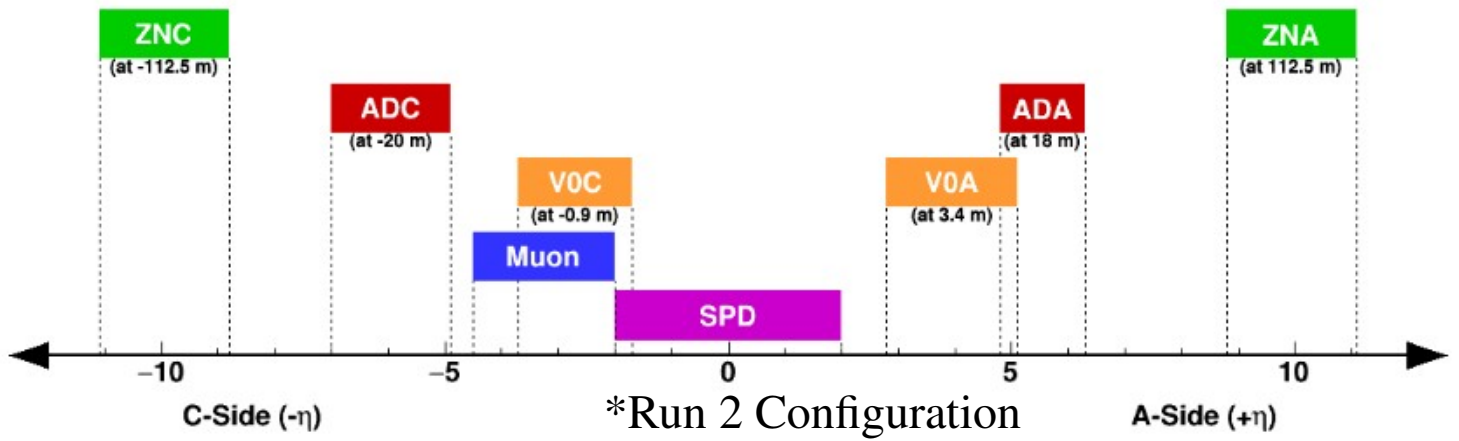
ALICE Detector: exclusivity condition

Zero Degree Calorimeter (ZDC)
Sampling Calorimeters:
Luminosity determination
Neutron detection

V0 scintillators
Scintillator counter:
Veto activity
Luminosity

ALICE Diffractive (AD)
Scintillator counter:
Veto Activity





*Run 2 Configuration

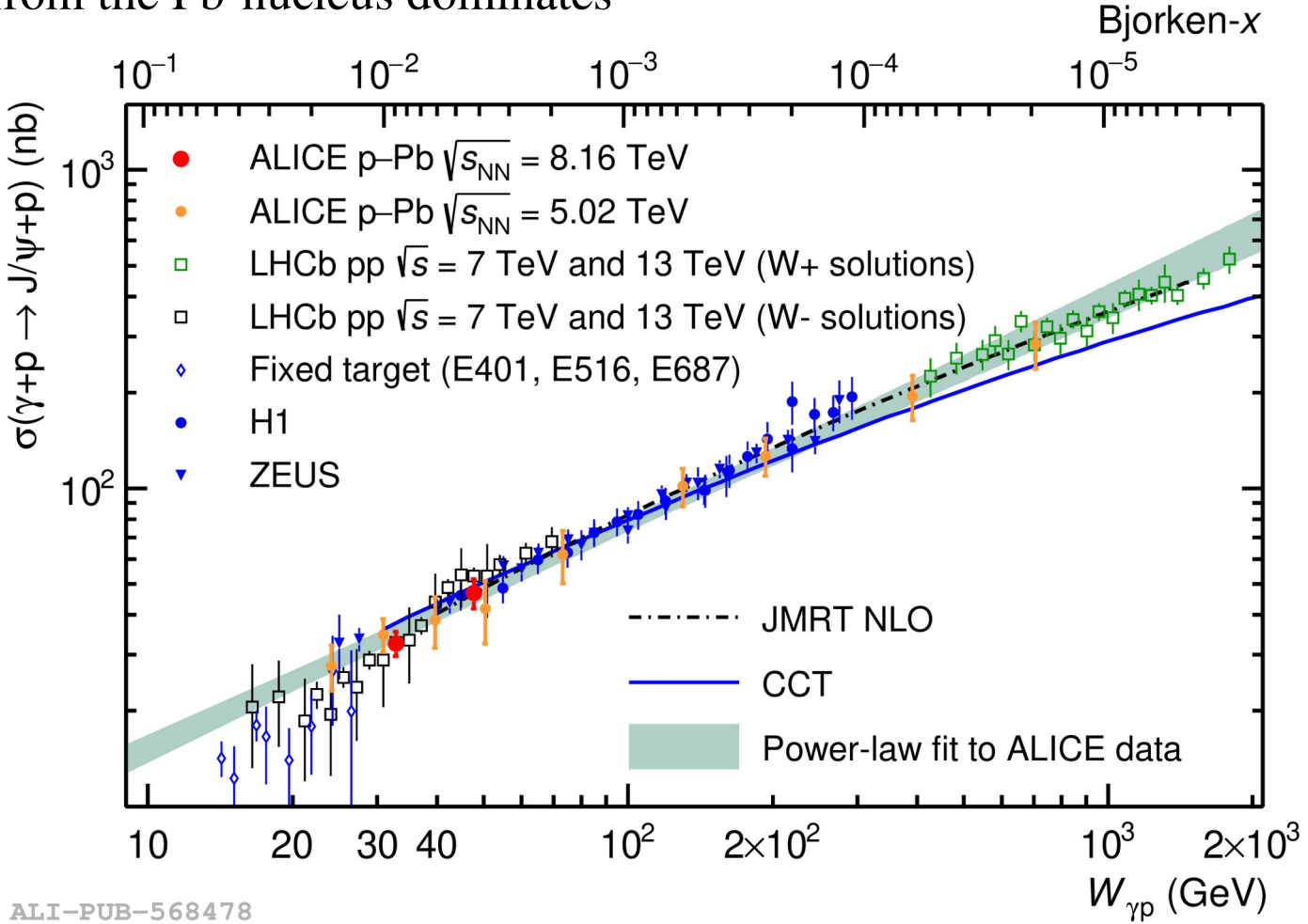
J/ψ photoproduction in p-Pb UPC

- The cross section of J/ψ photoproduction as a function of photon-proton c.m.s. energy allows the comparison with other experiments and extends the energy range reachable at HERA.
- Dissociative photoproduction allows to study the proton structure.

Exclusive J/ψ cross section: energy dependence

- In p-Pb UPCs the photon flux from the Pb-nucleus dominates
  → access to γp interactions
- Power law fit to ALICE data
  Exponent: δ = 0.70 ±0.04
- The same trend as observed at HERA and LHCb

- Agreement with models:
  - **JMRT NLO**:
    DGLAP formalism with main NLO contributions
  - **CCT**:
    Saturation in an energy dependent hot spot model

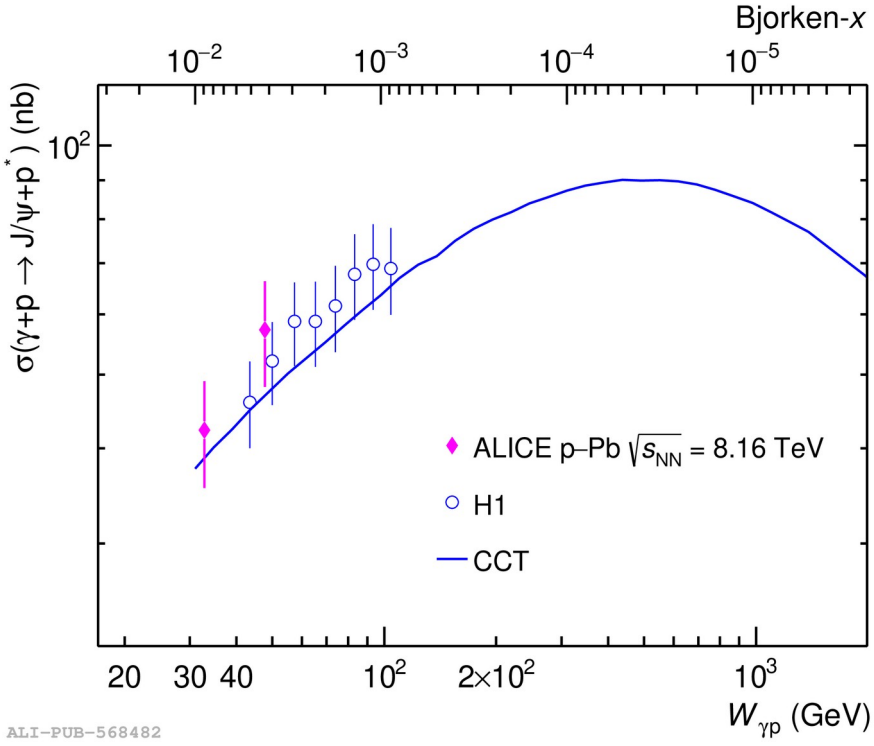


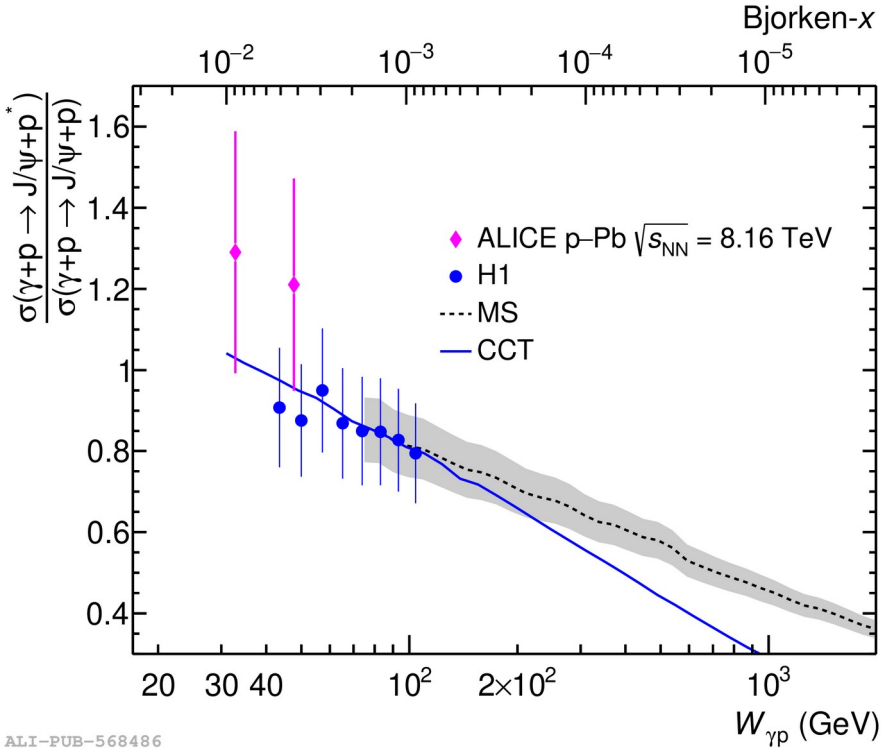
ALICE, PRD 108, 112004 (2023)

ALI-PUB-568478

Dissociative J/ψ cross section: energy dependence

First measurement of the dissociative cross section (with the proton break up) at the LHC!





ALICE, PRD 108, 112004 (2023)

- Compatible with HERA measurements
- Well described by CCT, *J. Cepila, J. G. Contreras and J. D. Tapia Takaki Phys.Lett. B766 (2017) 186*
- Run 4 data will give access to ~1 TeV region

Coherent and incoherent J/ψ photoproduction

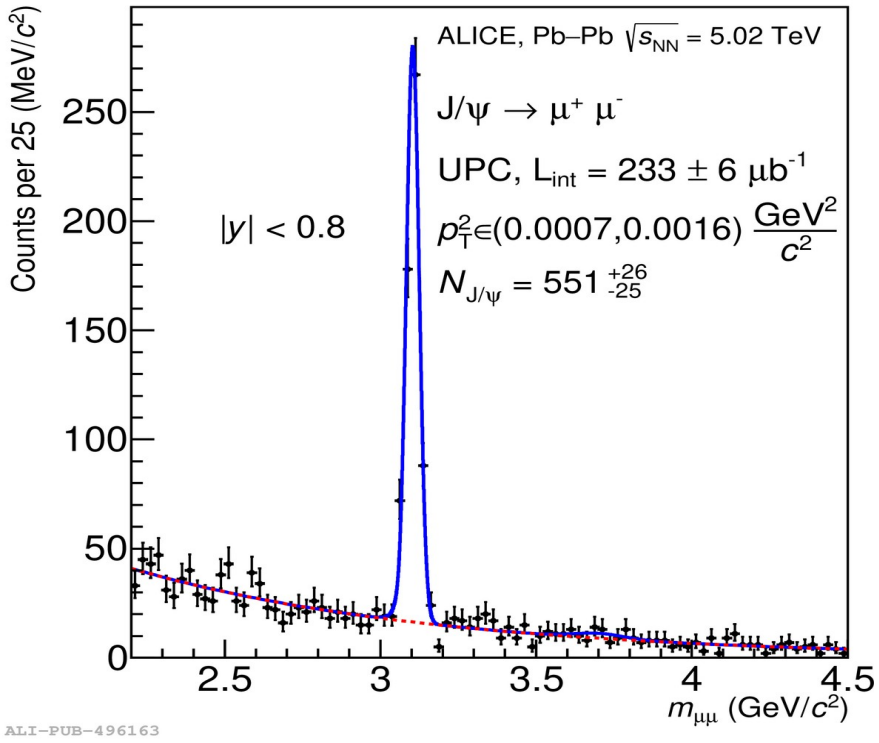
The cross section of coherent J/ψ photoproduction as a function of $|t|$ can probe the nuclear shadowing and saturation effects in the transverse plane.

Coherent and incoherent J/ψ production

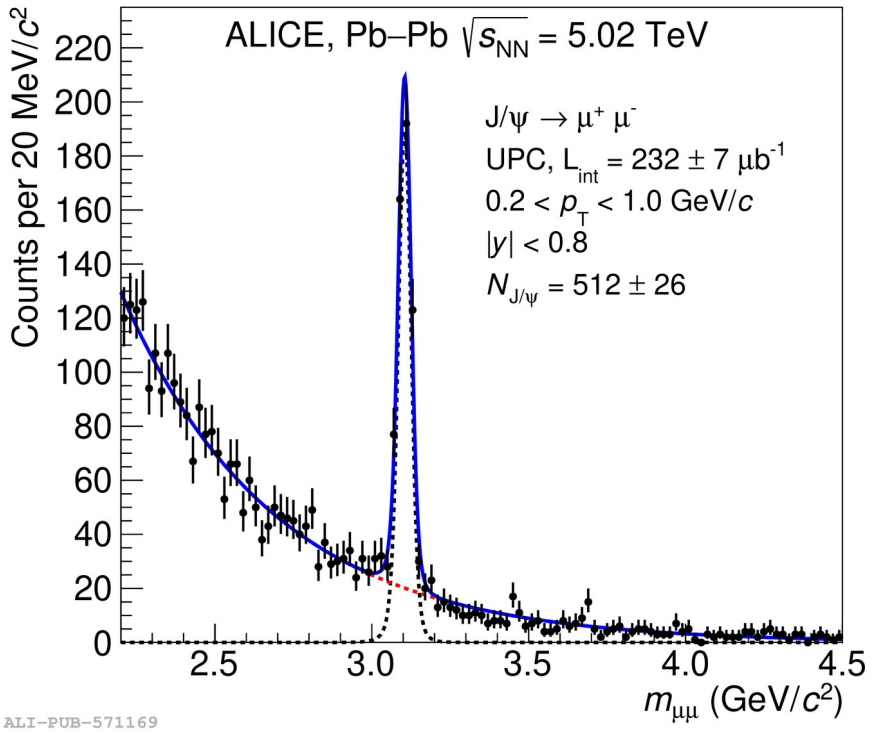
Photon flux used to calculate the photonuclear cross sections from the UPCs

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

Yields of J/ψ candidates from fits to the invariant mass distribution:



ALICE, PLB 817 (2021) 136280



ALICE, PRL 132 (2024) 162302

Coherent and 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

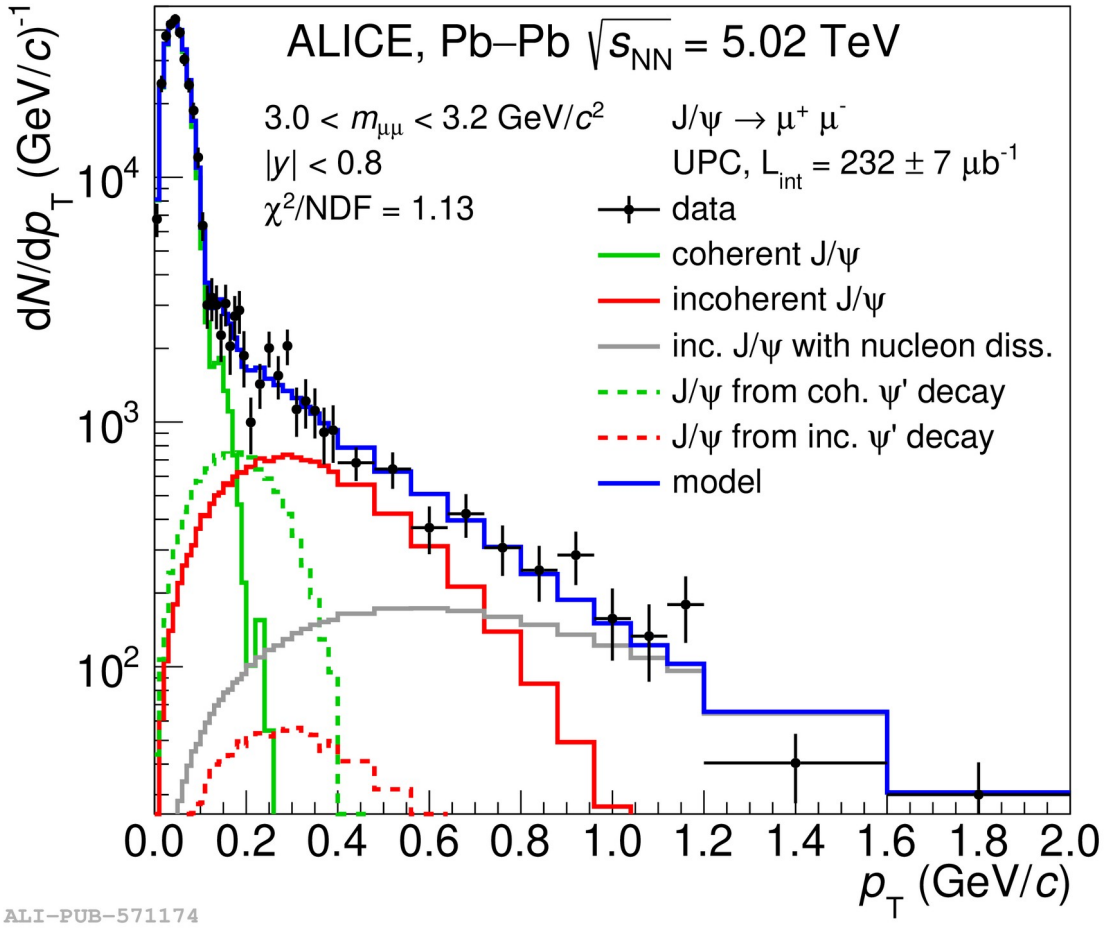
• Templates created using the STARlight MC generator + GEANT 3.21

• Nucleon dissociation: H1 parametrization

• Additional corrections:

→ Coherent J/ψ measurement
- Unfolding to account for p_T migration (detector resolution effects)
- $p_T^2 \rightarrow |t|$ unfolding (photon k_T)

→ Incoherent J/ψ measurement
- p_T migration negligible
- k_T negligible ⇒ $|t| = p_T^2$



ALICE, PRL 132 (2024) 162302

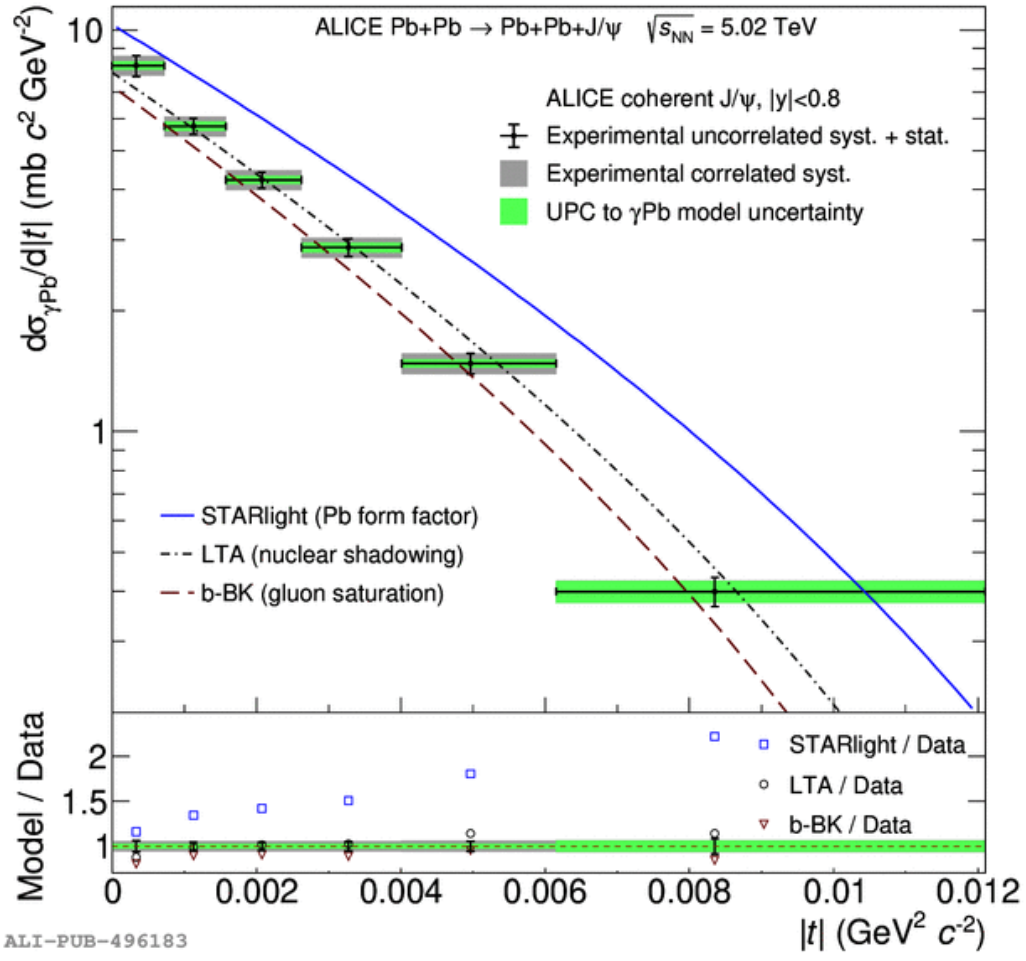
Results: coherent J/ψ production

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)

Run 3 measurement would allow to distinguish between these models.



ALICE, PLB 817 (2021) 136280

Results: incoherent J/ψ production

• 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:

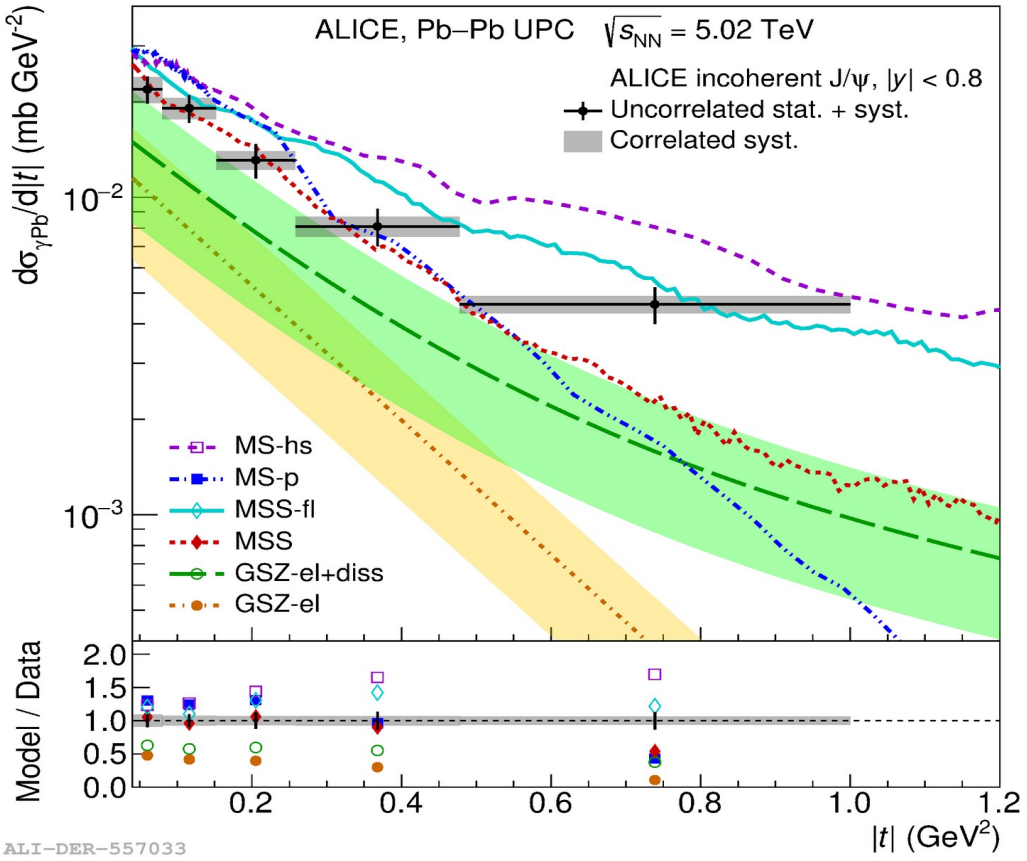
– **MS-hs**: IPsat (hot spots + fluctuations in the saturation scale)

– **MSS-fl**: CGC-based, JIMWLK solution

– **GSZ-el+diss**: extra dissociative component

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

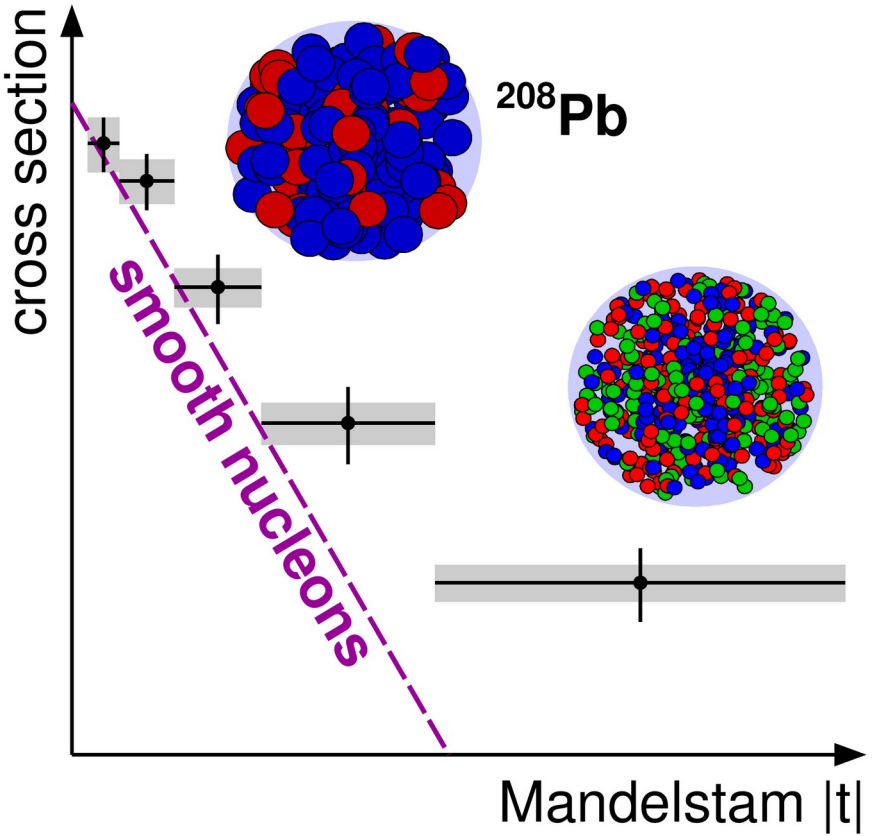
• The models generally fail to describe the normalization (scaling from the proton to nuclear targets)

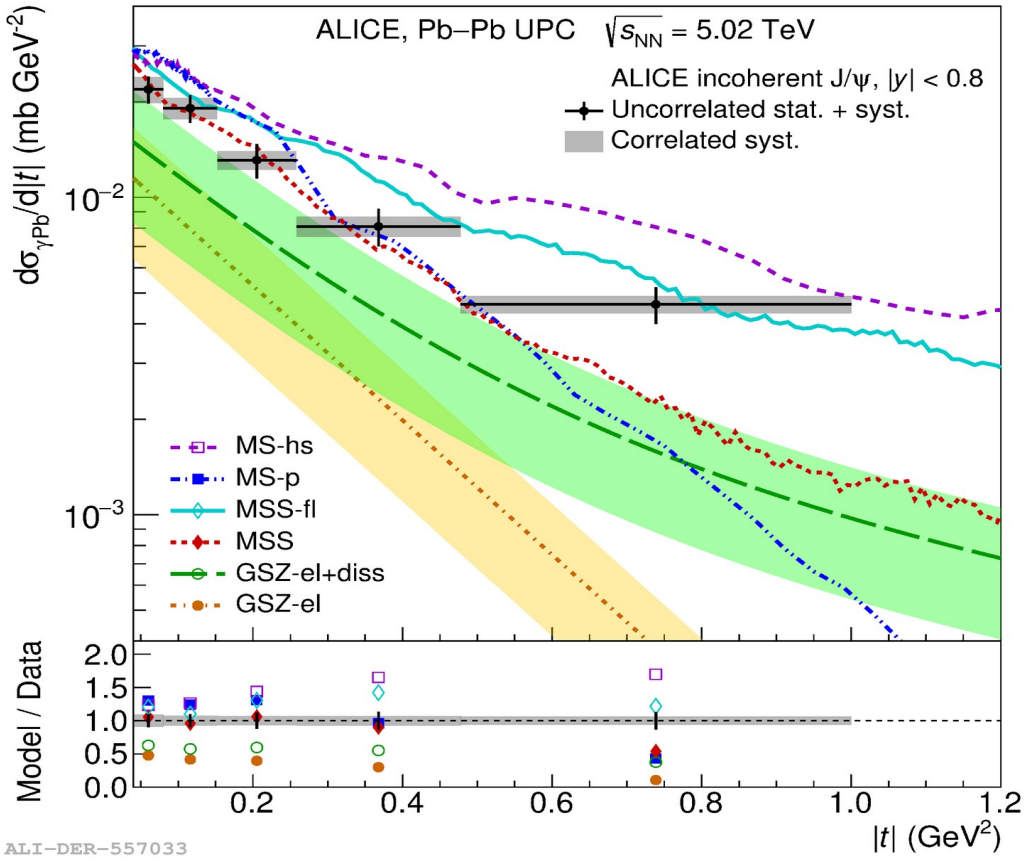


ALICE, PRL 132 (2024) 162302

Results: incoherent J/ψ production

• The slope is sensitive to **fluctuations** in the transverse profile of the target

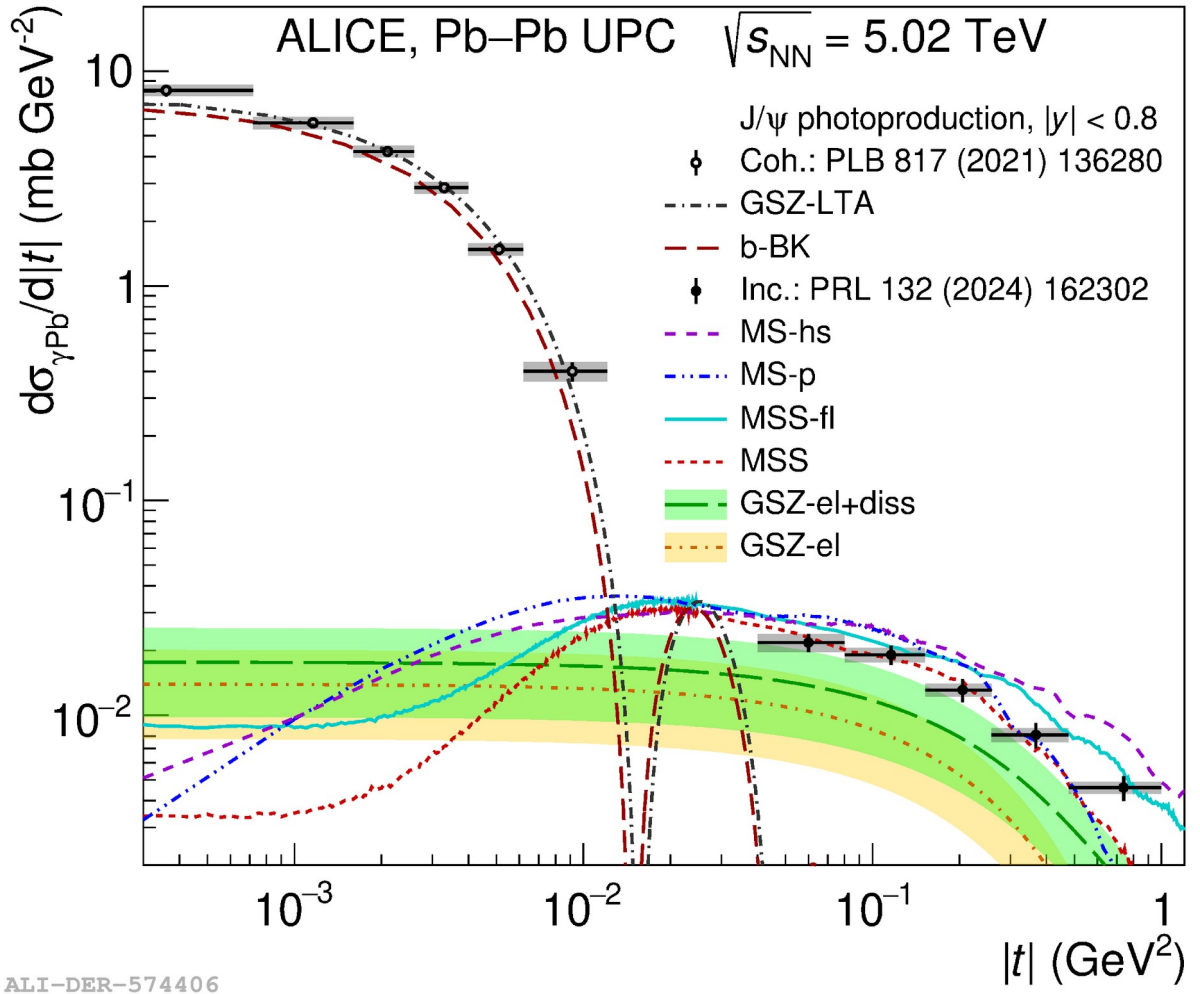




ALICE, PRL 132 (2024) 162302

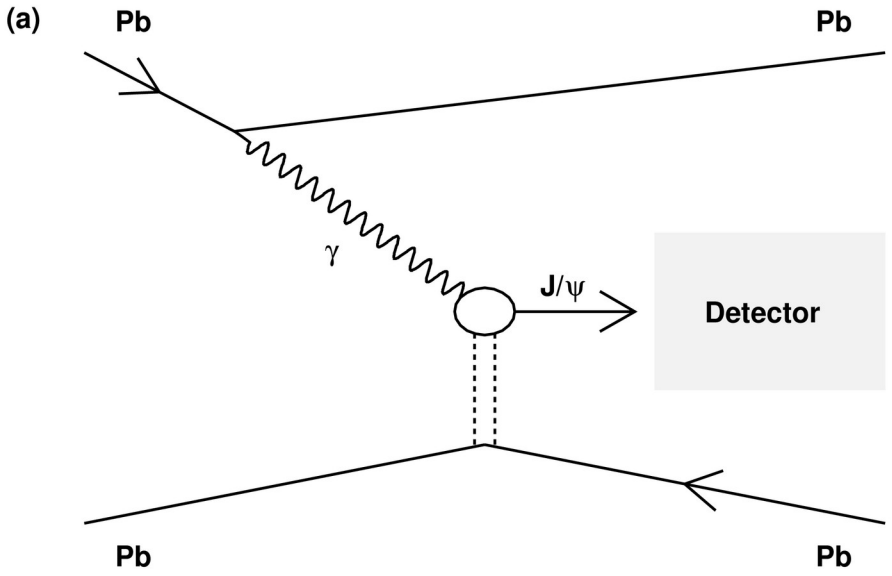
Results: full |t|-dependence

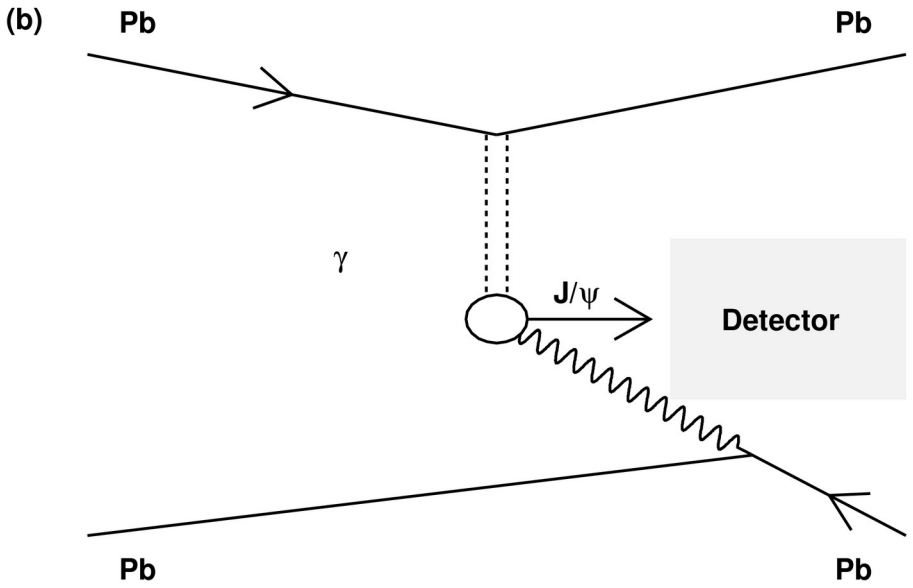
- The first observation of subnucleonic structure in the Pb target using UPCs
- ALICE covers three orders of magnitude in |t| with a HERA-like accuracy



Energy dependence of J/ψ photoproduction

Two-fold ambiguity





Positive rapidity	**Negative rapidity**
High energy γ	Low energy γ
Small photon flux	Large photon flux
Large W	Small W
Small x	Large x

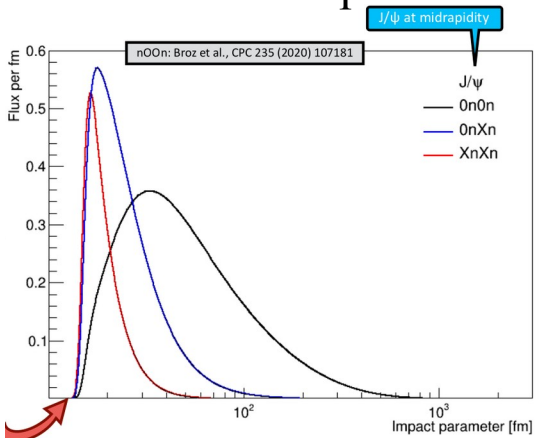
Positive rapidity: VM is aligned with the Pb-beam emitting photon.

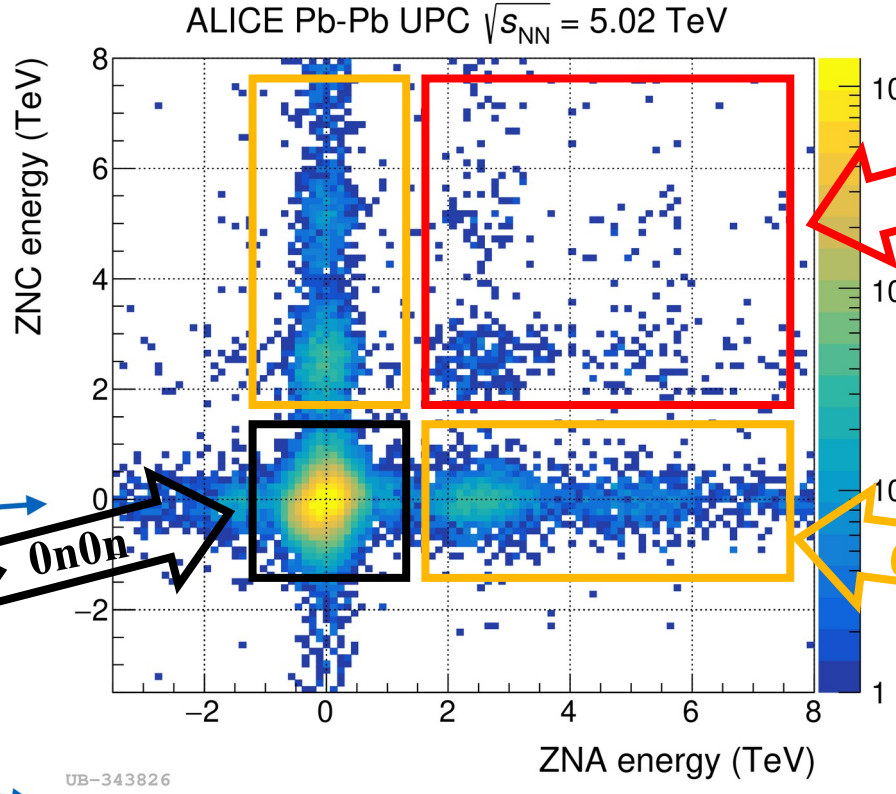
Both processes contribute to the measured cross section:

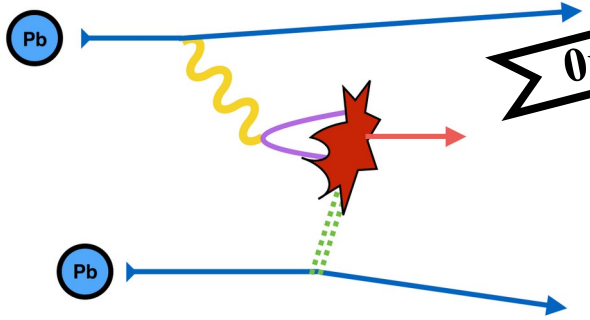
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

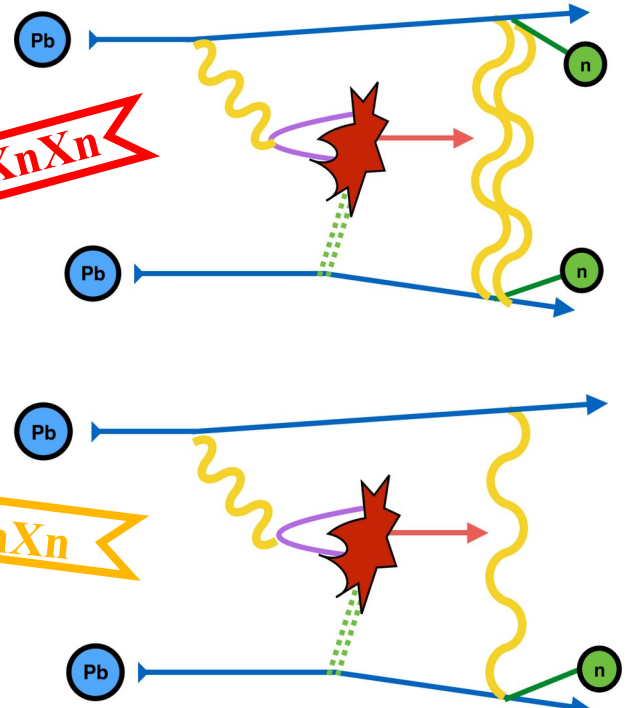
Independent measurements using EMD

It is possible to cleanly separate the different event topologies, using the ZDC







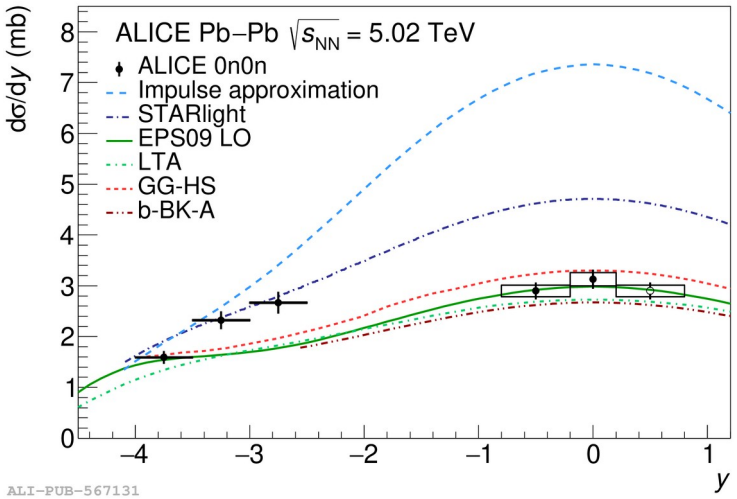


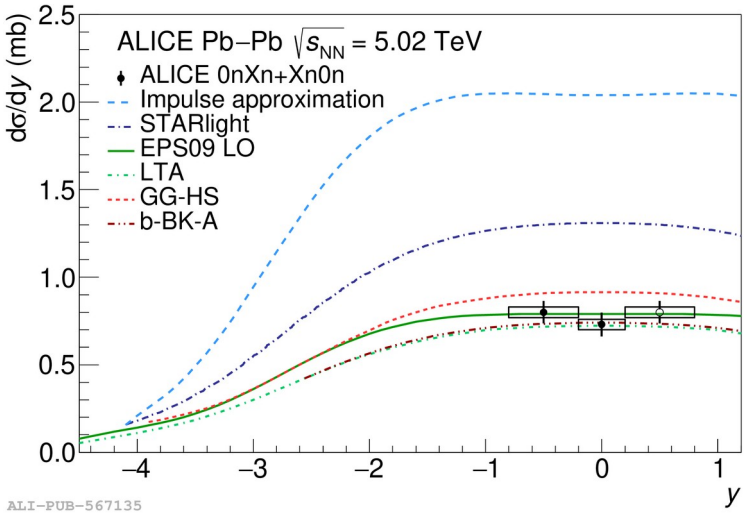
ALICE, JHEP 06 (2020) 035

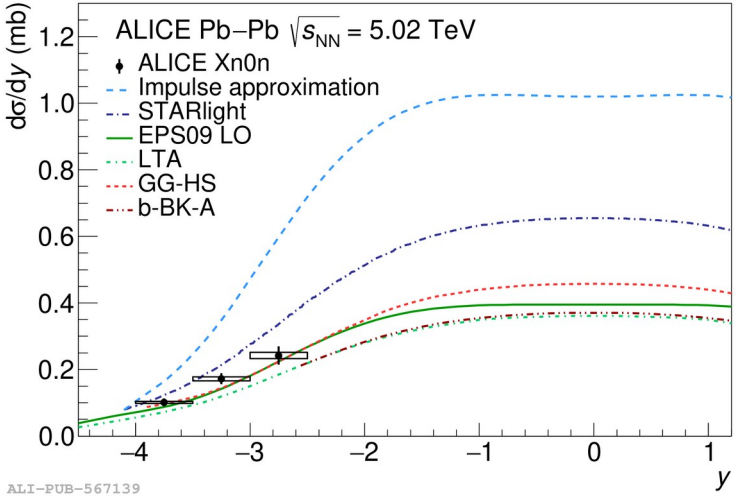
Neutron dependence

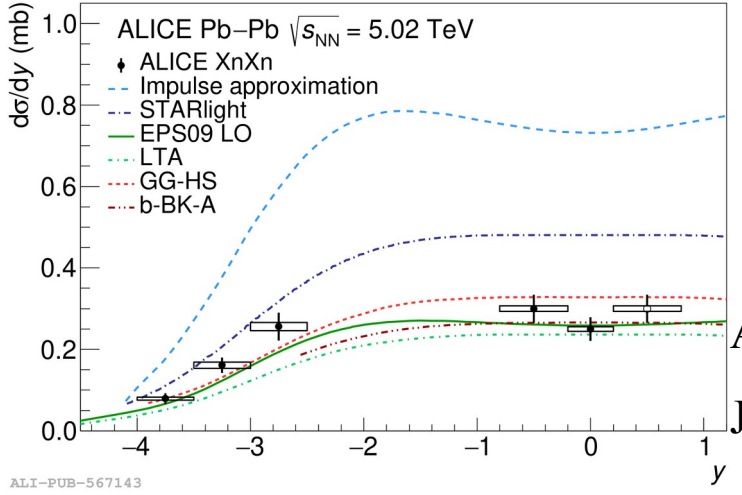
$$d\sigma(\text{total})/dy = d\sigma(0\text{n}0\text{n})/dy + 2d\sigma(0\text{n}\text{Xn})/dy + d\sigma(\text{Xn}\text{Xn})/dy$$

Rapidity dependence of J/ψ coherent production in EMD classes







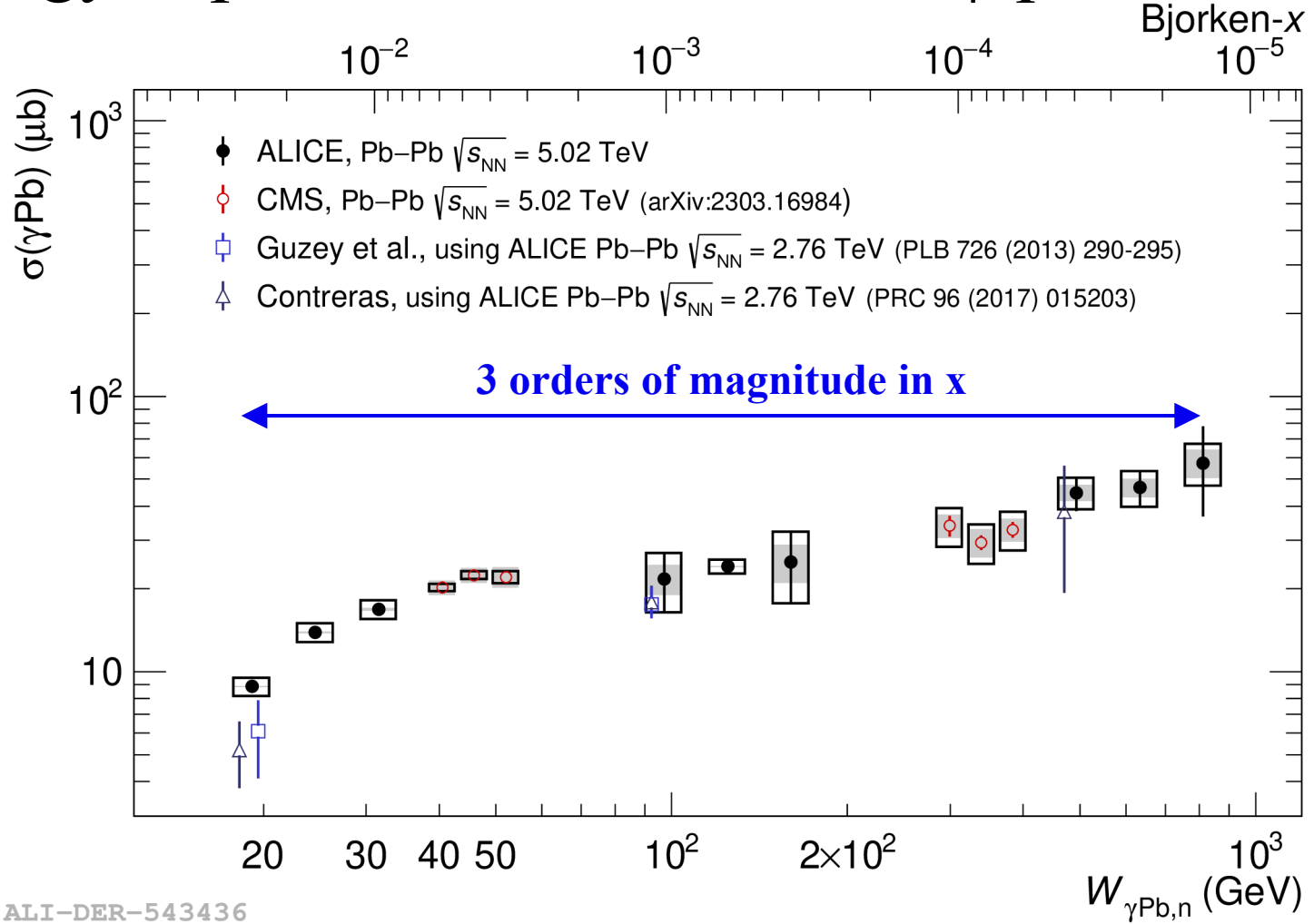


ALICE,

JHEP 10 (2023) 119

Several UPC measurements for each rapidity range → We can extract the photonuclear cross sections!

Energy dependence of coherent J/ψ production



ALICE, JHEP 10 (2023) 119 **Extracted cross sections are consistent with Run 1 and CMS results**

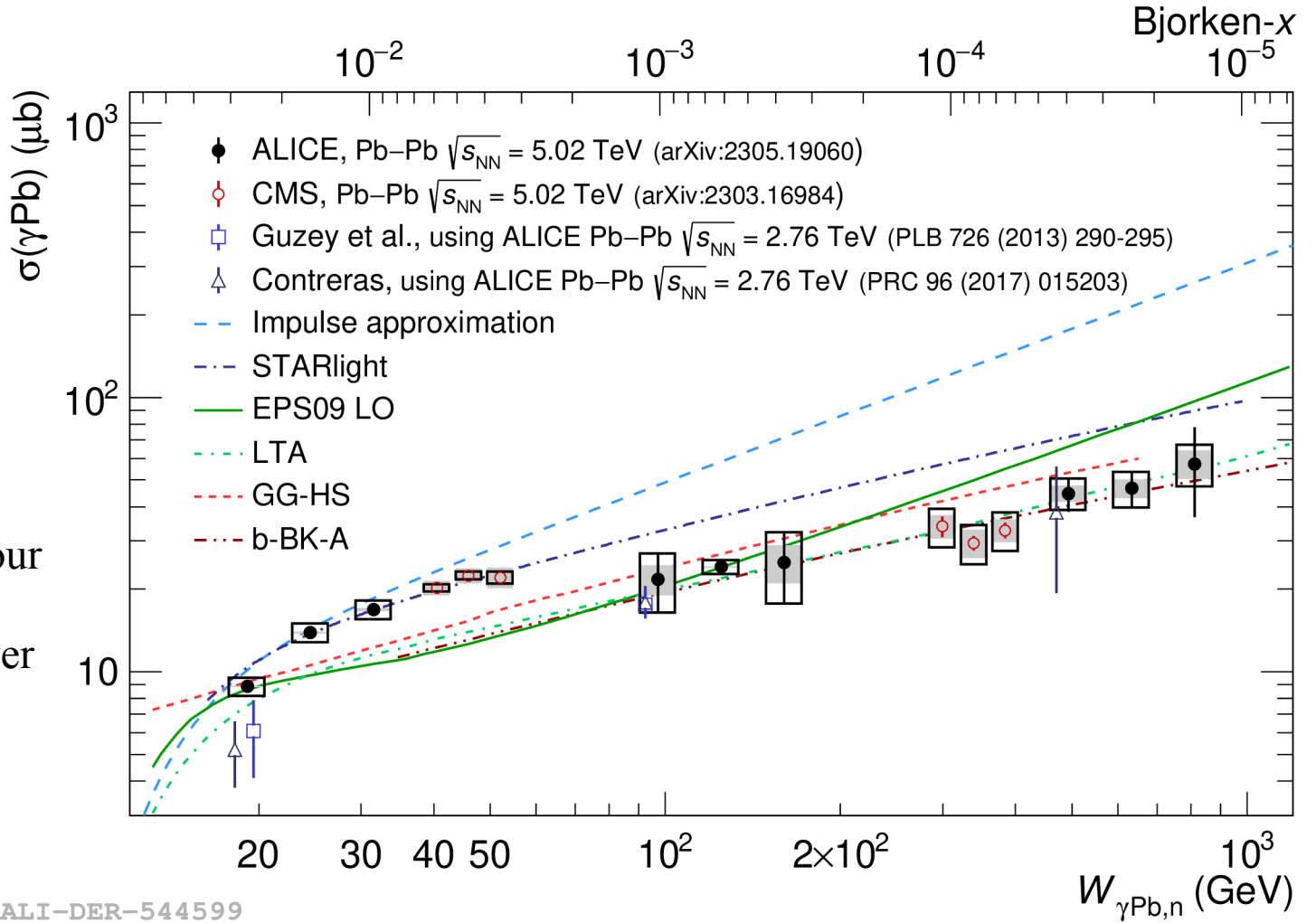
Energy dependence of coherent J/ψ production

✗ **Impulse approximation** above data
→ strong QCD dynamic effects

✔ **LTA** describes the high energy behaviour

✔ Models including saturation (**hot spots**, and **b-BK**) also describe the high energy behaviour

✗ But they have problems at lower energies, where **STARlight** describes data



ALI-DER-544599

ALICE: JHEP 10 (2023) 119

CMS: PRL 131, 262301 (2023)

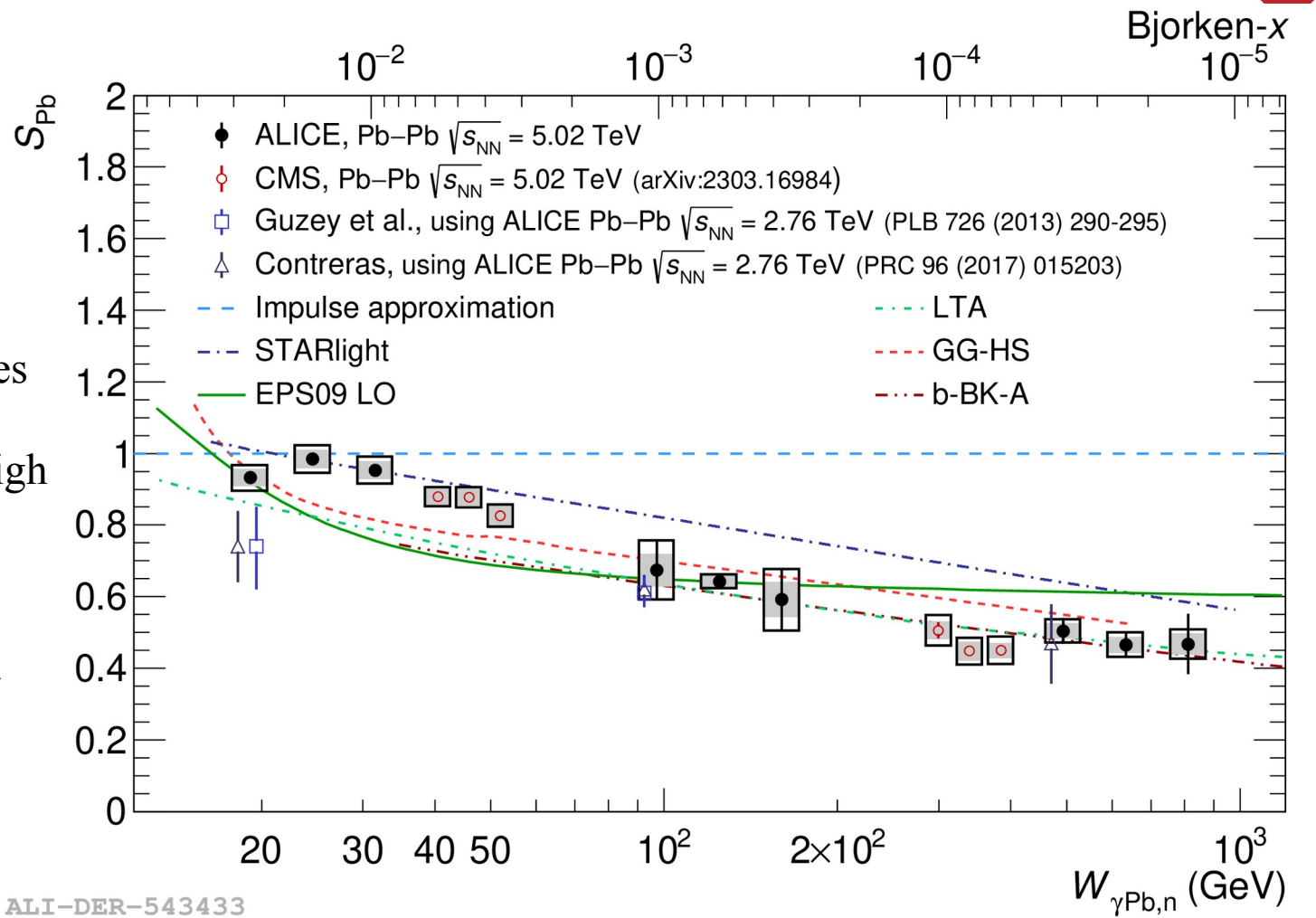
Energy dependence: nuclear suppression factor

$$S_{\mathrm{Pb}} = \sqrt{\frac{\sigma_{\gamma\mathrm{Pb}}}{\sigma^{\mathrm{IA}}_{\gamma\mathrm{Pb}}}}$$

✗ No suppression at low energies

✔ Flatenning of suppresion at high energies

✔ **Saturation** and **shadowing** models can described the data in the low-x region

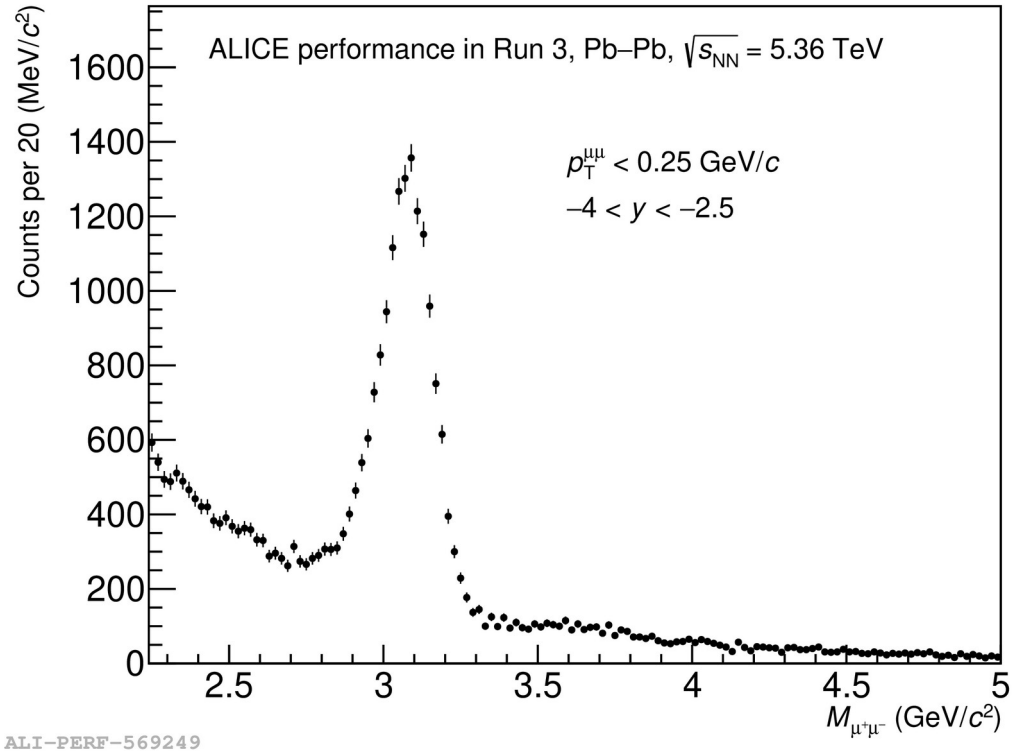


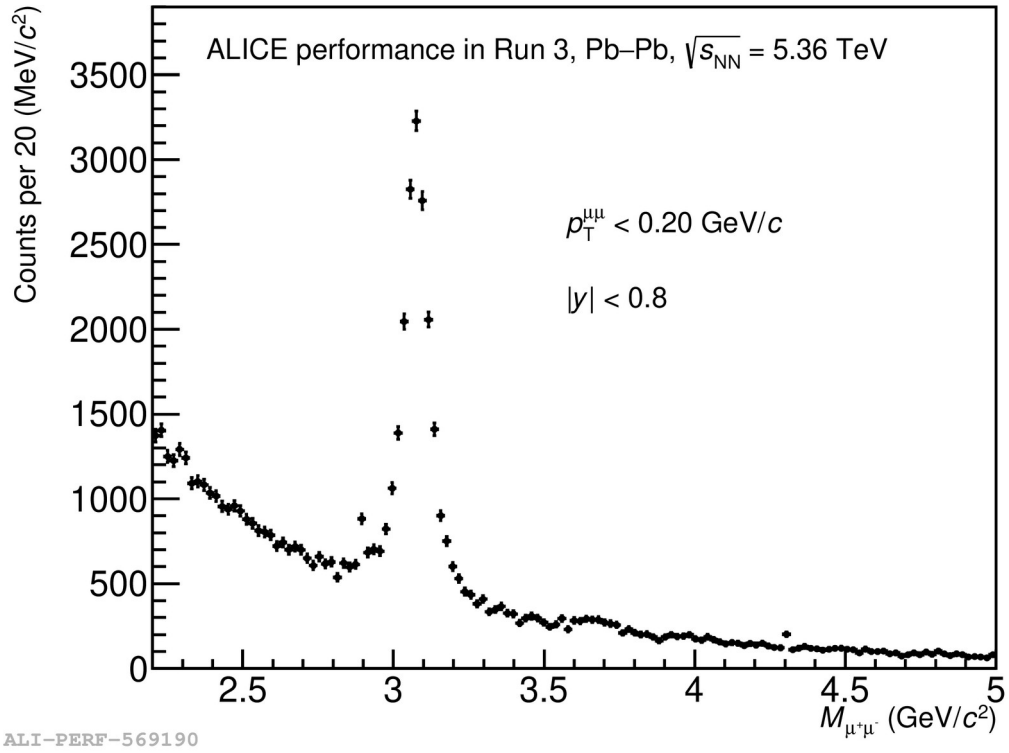
ALI-DER-543433

ALICE: JHEP 10 (2023) 119

CMS: PRL 131, 262301 (2023)

Run 3 performance





Continuous readout and ALICE detector upgrades will allow more precise measurements of J/ψ photoproduction!

Summary

- 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

- |t|-dependence has been measured for both coherent and incoherent J/ψ photoproduction in Pb-Pb UPCs at 5.02 TeV
  → Saturation or shadowing effects needed to describe the data
  → Subnucleonic fluctuations of the gluon fields (e.g. via the hot spot picture)

- Energy dependence of coherent J/ψ production measured across 3 orders of magnitude in c.m.s. energy $W_{\gamma Pb}$ (20-900 GeV) and Bjorken-x (10^{-2} to 10^{-5})
  → Consistent with ALICE Run 1 and with CMS Run 2 results
  → The data can be described by both saturation and shadowing in the low x region

- ALICE will be able to perform more systematic studies and reduce the uncertainties of current measurements with the new data… STAY TUNED!

Thank you very much for your attention!