U.S. DEPARTMENT OF ENERGY

Office of Science

Experimental overview of recent studies of (cold nuclear matter) with UPCs

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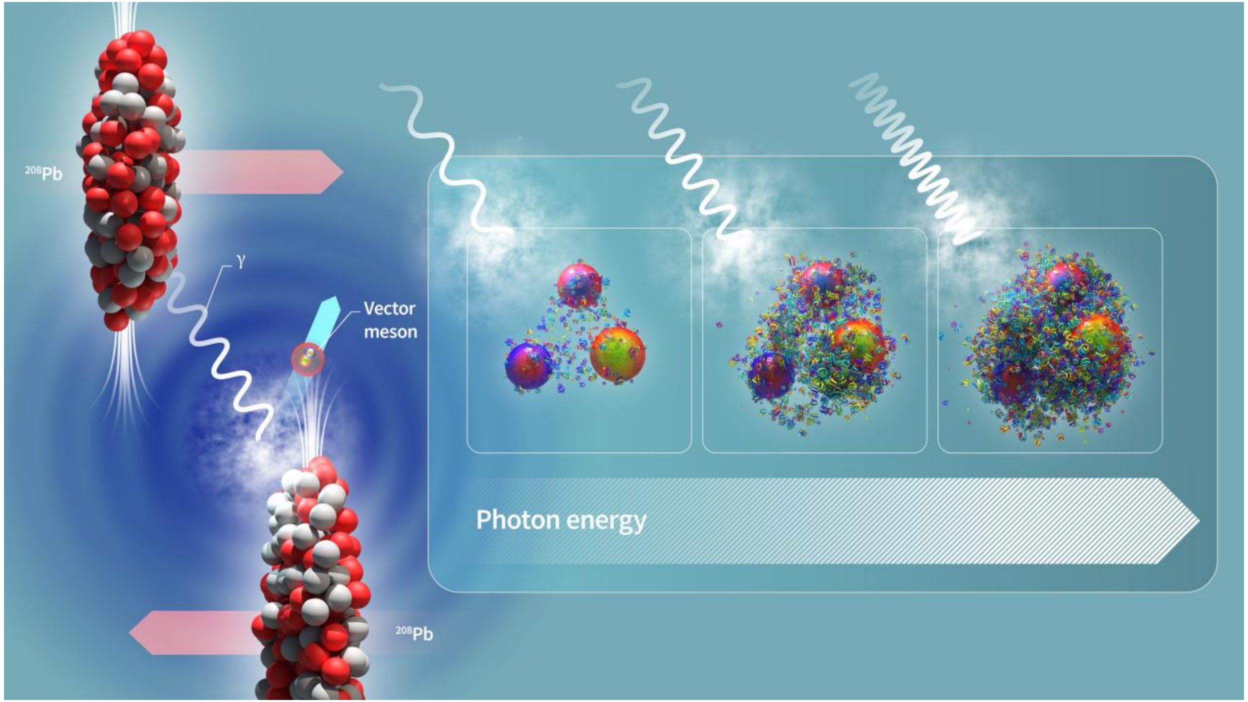
Towards improved hadron femtography with hard exclusive reactions, edition IV

JLab

July 29, 2025

KU THE UNIVERSITY OF KANSAS

Ultra peripheral collisions (UPC)

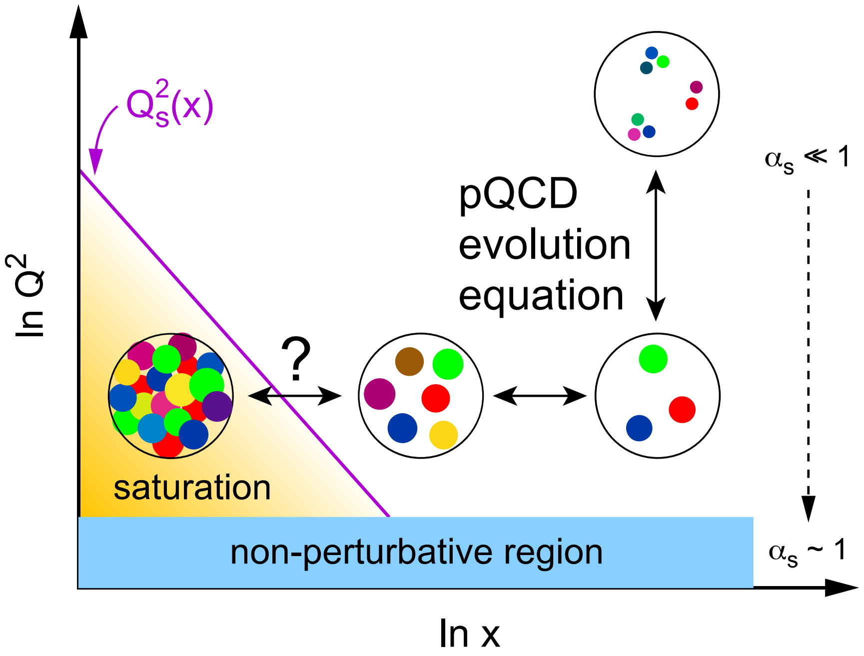


UPC studies offer insight into fundamental aspects of matter

Gluon dynamics, saturation effects, and nuclear structure phenomena like hotspots and shadowing are essential to understanding the origin of the visible mass in the universe

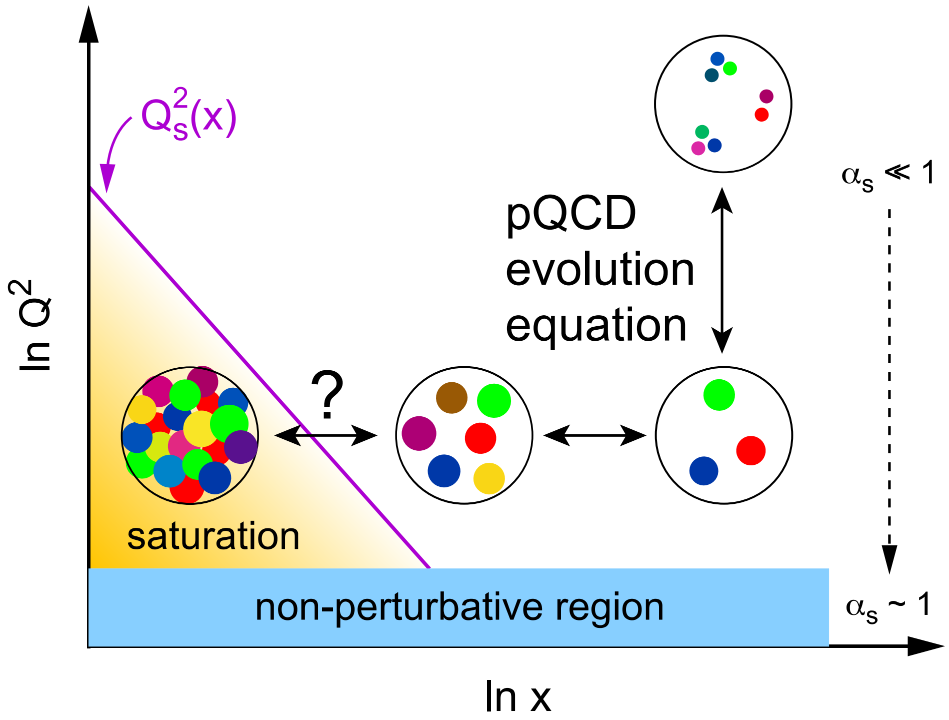
Gluon saturation matters

At high energies, or for heavy nuclei at lower energies, gluon saturation is predicted



- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Experimental observables needed to map out the transition between the dilute and saturation regimes. The onset of saturation
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter formed by gluon saturated matter with universal properties?

Evolution of the hadronic structure with Bjorken-*x* and Q^2

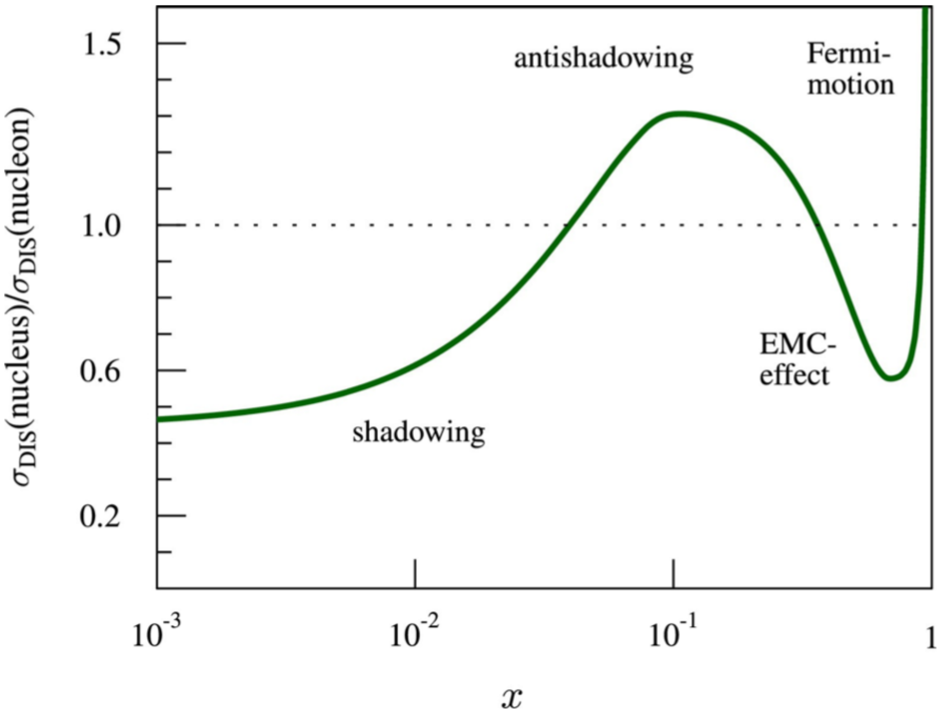


- Experimental observables needed to map out the transition between the dilute and saturation regimes
- For nuclei, the saturation scale is enhanced by a $A^{1/3}$ factor

$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

Nuclear shadowing experimentally confirmed, but not fully understood

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$



- Experimental observation that parton distributions are different for protons and nuclei
- What's the mechanism responsible for shadowing? How is gluon saturation related?
- The knowledge of the initial state of nuclei also needed for understanding the QGP evolution

- **Ultra Peripheral Collisions (UPC)** can explore a wide range of energies using almost real photons

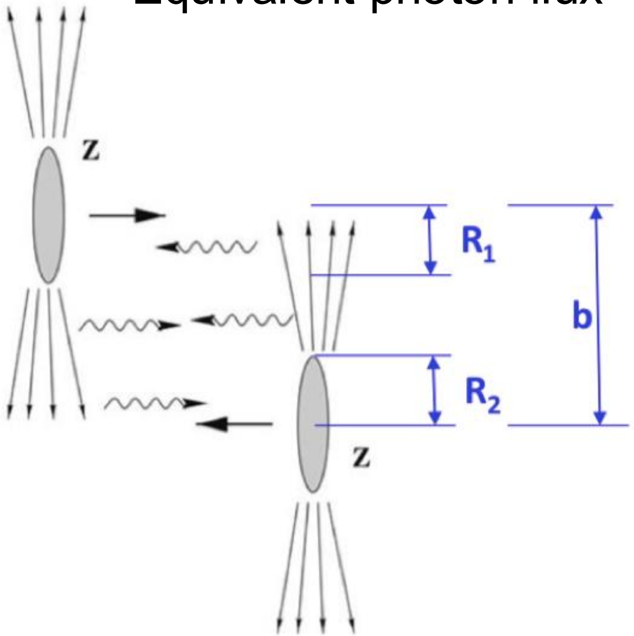
  $k = \gamma M_V \exp(\pm,y)$
  Up to several TeV in γp
  Up to ~ 700 GeV/nucleon in γA
  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- UPCs at the LHC probe the hadronic structure over broad and unique Bjoren *x* region, yet the precision not compatible to DIS machines like the EIC

  $x = M_V/\gamma m_p \exp(\pm,y)$

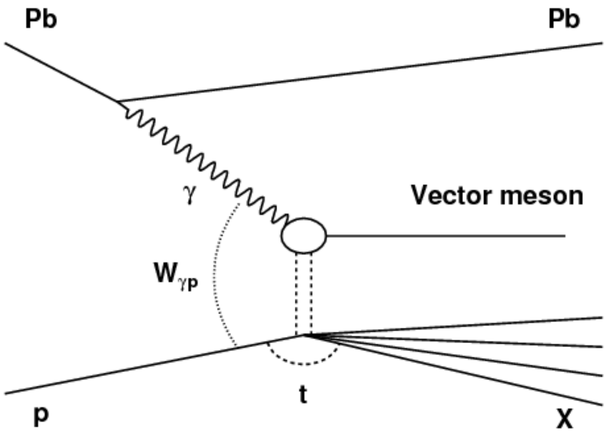
Interactions mediated by the EM interactions

Equivalent photon flux



Vector meson (VM) photoproduction in UPCs

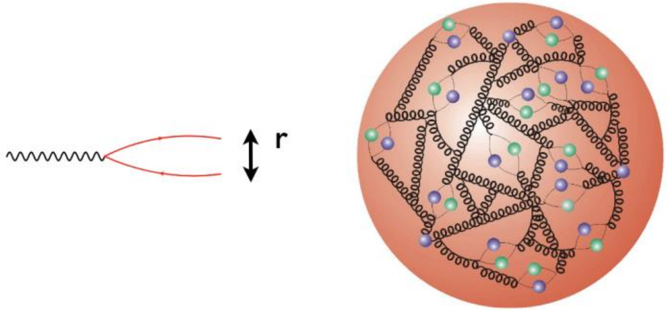
$$W_{\gamma p}^2 = 2E_p M_{J/\psi} e^{\pm y}$$



- As in DIS, several reactions are possible in UPCs:
  - -Exclusive photoproduction
  - -Semi-exclusive photoproduction
  - -Inclusive photoproduction

- By studying various VMs, it is possible to study the Q^2 dependence

- In the dipole approach, the light VMs (ϕ, ρ^0) are more sensitive to saturation because of the larger dipole, but pQCD methods not applicable

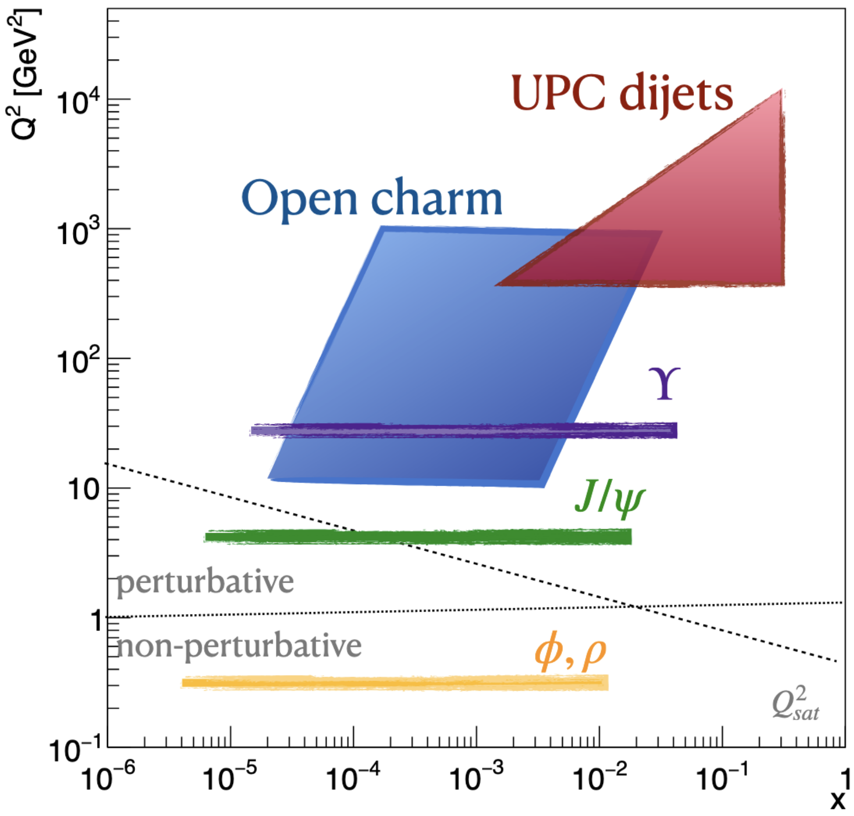


Various processes

Fig. from A. Ogrodnik

- By studying various processes, it is possible to explore both the Bjorken *x* and Q^2 dependence

- Transition between the dilute and dense QCD region, and from the perturbative and non-perturbative QCD regime



Two-fold ambiguity on the photon direction in symmetric systems

$$\mathrm{W}^2_{\gamma\mathrm{p}} = 2\mathrm{E_p}\mathrm{M}_{\mathrm{J}/\psi}\mathrm{e}^{\pm\mathrm{y}}$$

Symmetric systems (pp, A-A) suffer from the two-fold ambiguity on the photon direction

Positive rapidity — Negative rapidity

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

Only UPC asymmetric systems (p-Pb) analyses provide a model independent way of the energy dependence of $\sigma(\gamma p)$

Coherent J/ψ in UPC Pb-Pb

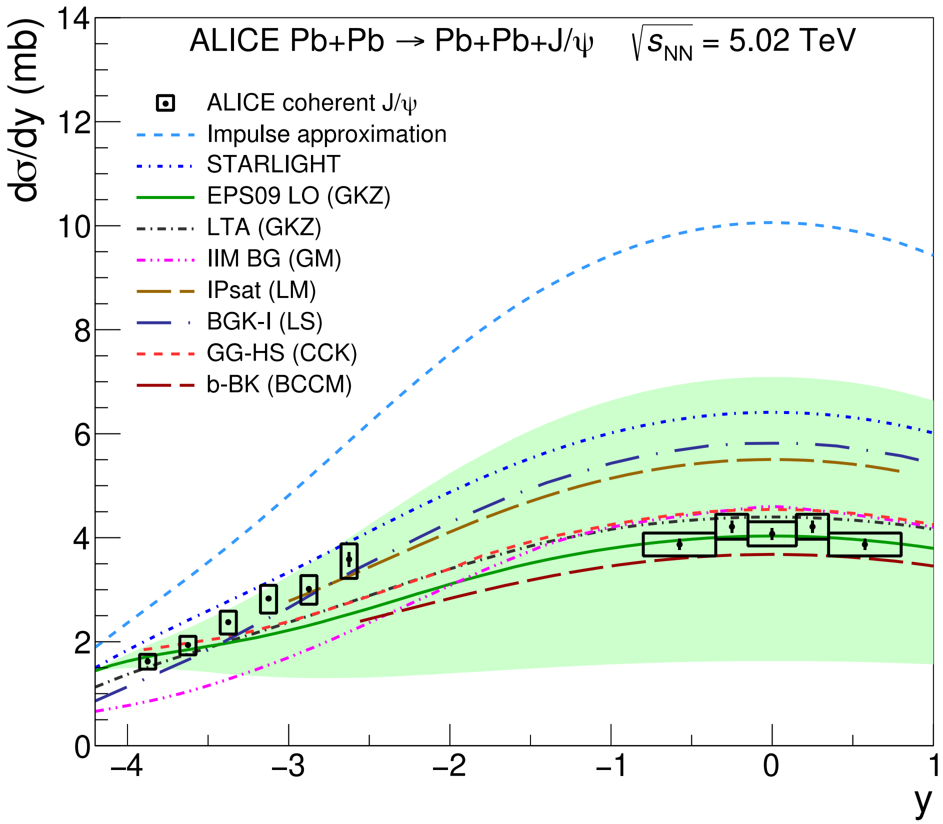
Eur. Phys. J. C 81 (2021) 712

- Confirmation of nuclear shadowing with Run 2 data
- No model can describe the rapidity dependence

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

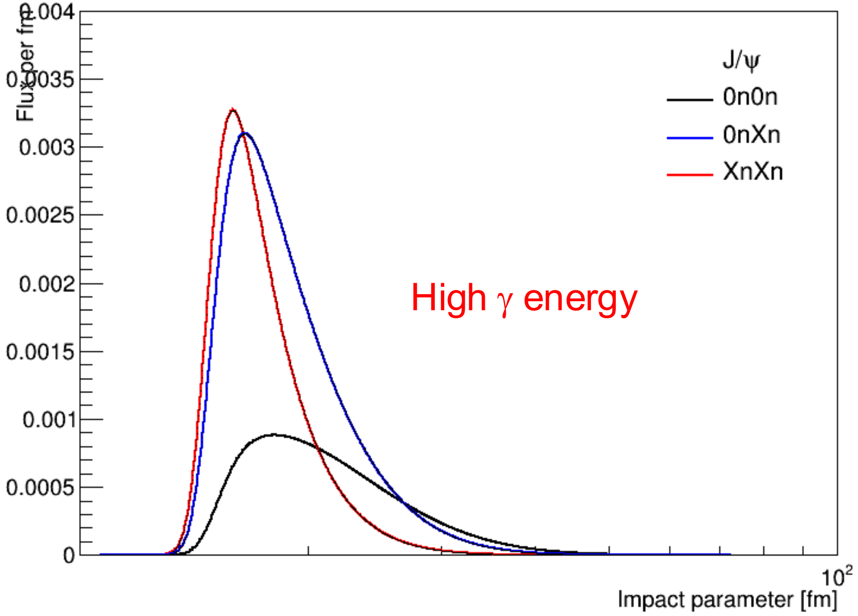
Mid-rapidity x ~10^{-3}

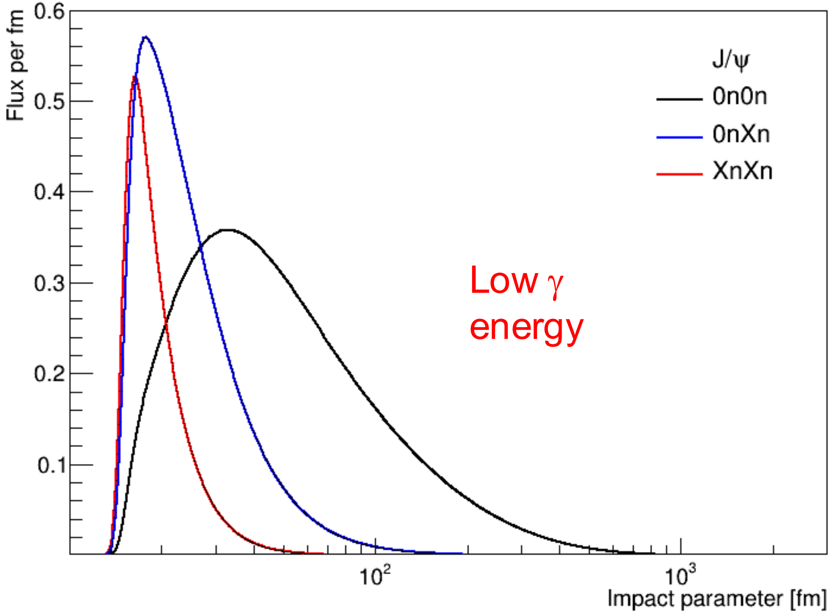
Forward rapidity 95% at x ~ 10^{-2}
5% at x ~ 10^{-5}



Impact parameter flux profile

Broz, Contreras and DTT, CPC 235 (2020) 107181





Neutron-dependence of coherent J/ψ in UPC Pb-Pb

The photon flux (n) depends on the impact parameter

Decomposed in terms of neutron configurations emitted in the forward region

$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

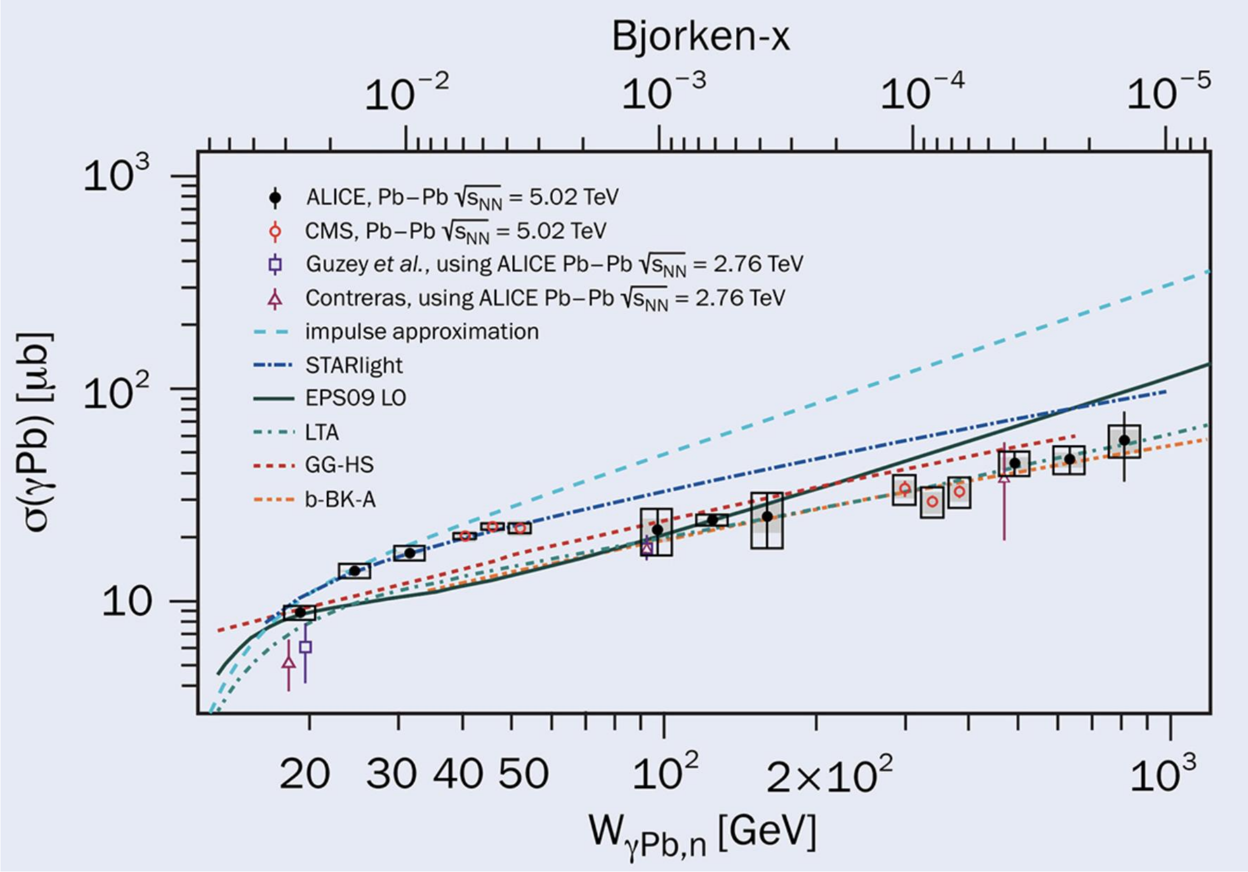
Solving the linear equations resolves the two-fold ambiguity for VMs at y ≠ 0

Positive rapidity   Negative rapidity

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

Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

Energy dependence of coherent J/ψ in γPb



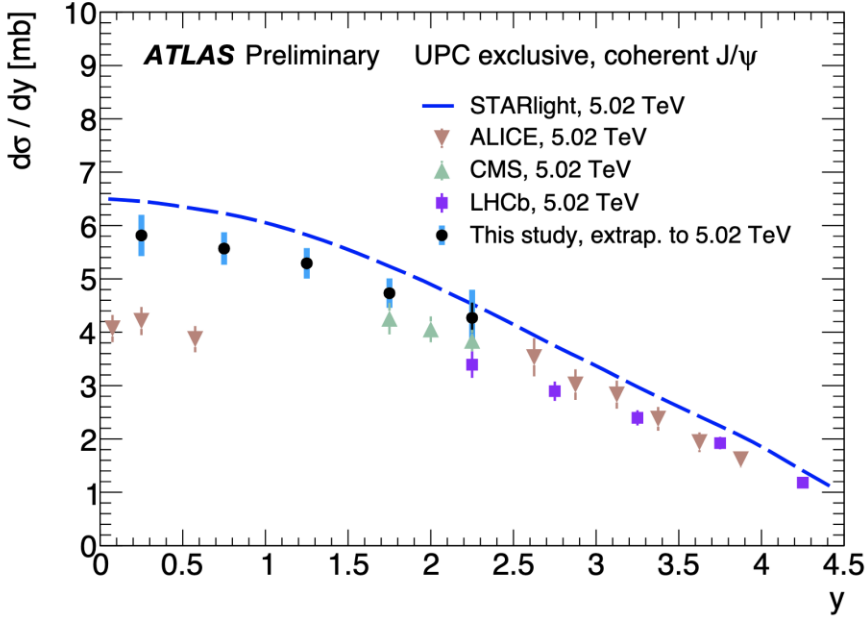
JHEP 10 (2023) 119
PRL 131 (2023) 26, 262301

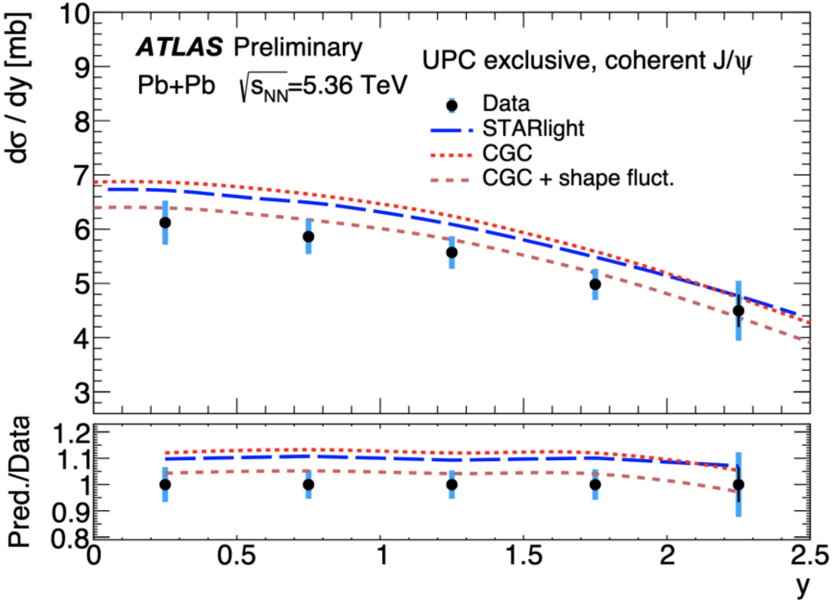
Both gluon saturation and shadowing describe the data at high energies

At low energies the data cannot be described by these models

Coherent J/ψ in γPb with Run 3 data

ATLAS-CONF-2025-003





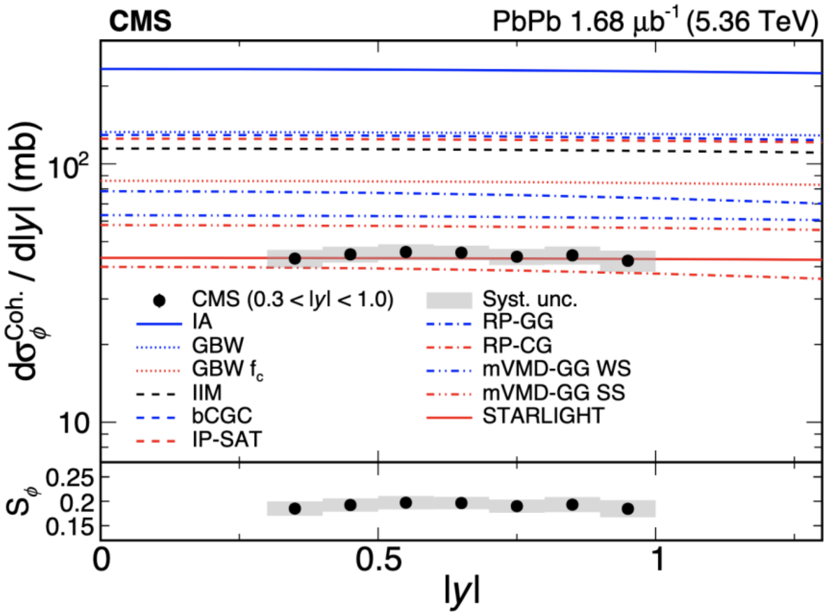
ATLAS preliminary data thanks to new trigger in Run 3

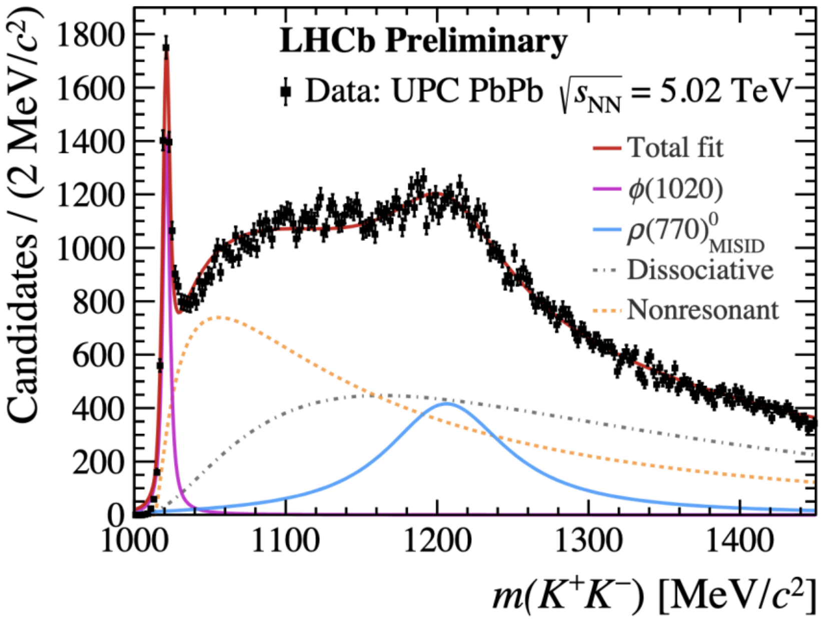
Stronger suppression than seen by mid-rapidity ALICE data. No shadowing?

Coherent $\phi(1020)$ in γPb

CERN-EP-2025-051

CERN-LHCb-CONF-2024-006



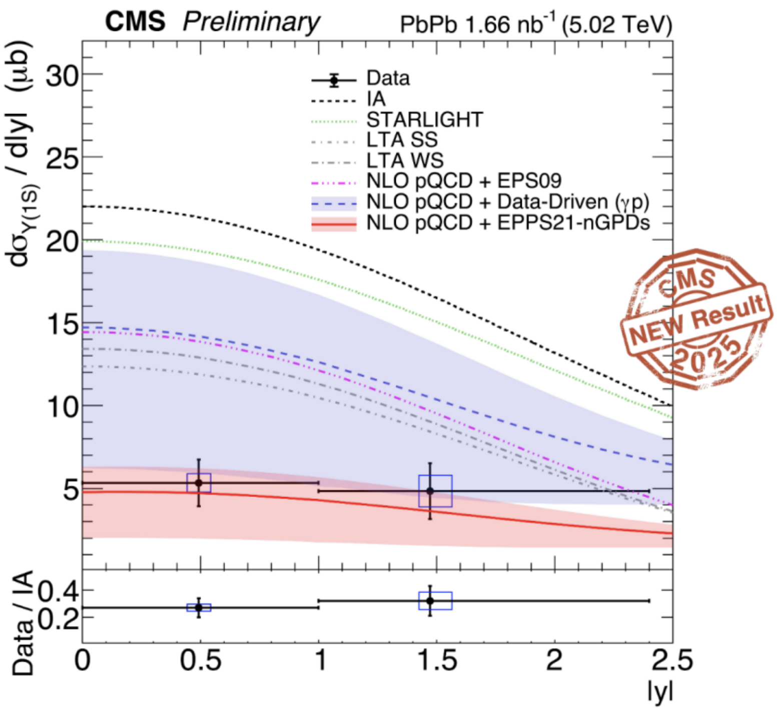


CMS data on $\phi(1020)$ data described by shadowing model

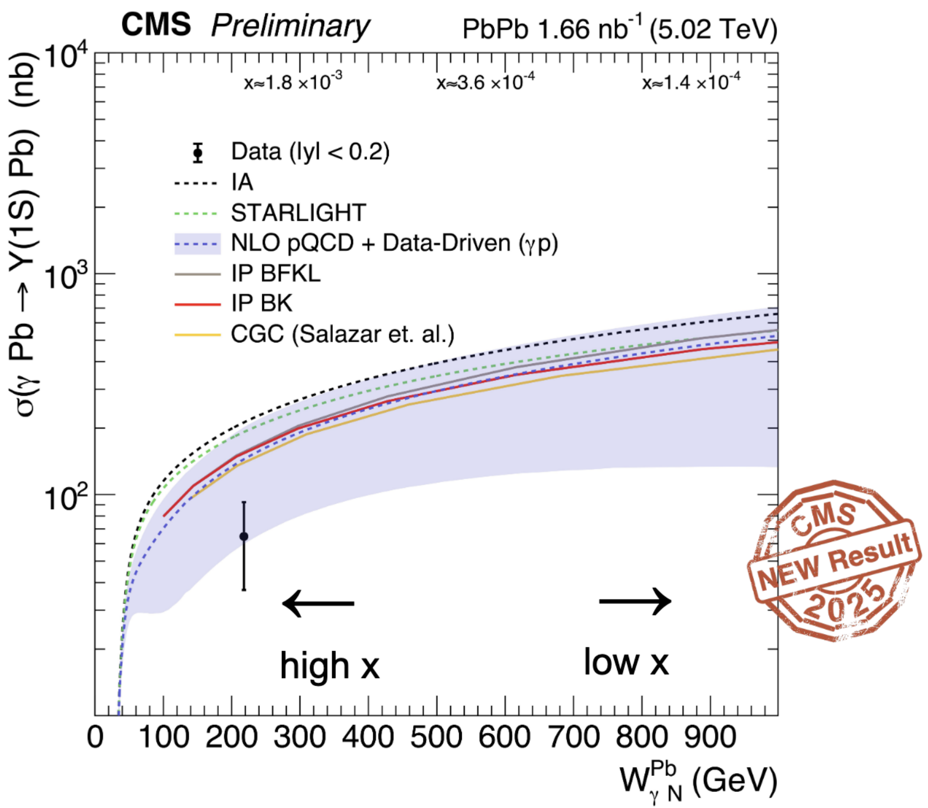
CGC calculations not applicable, though

Coherent Upsilon in γPb

CMS-PAS-HIN-24-013



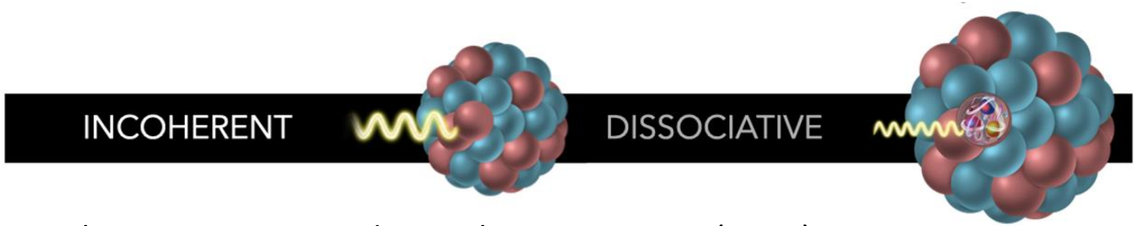
Rapidity differential cross-section

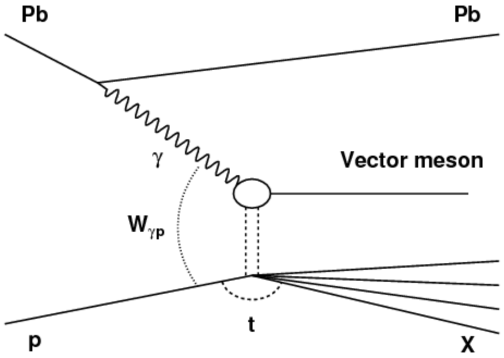


Stronger suppression than predicted by theory

Incoherent J/ψ in UPC

$$\left.\frac{d\sigma^{\gamma^* H \to VH}}{d|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} |\langle \mathcal{A}_{T,L} \rangle|^2$$





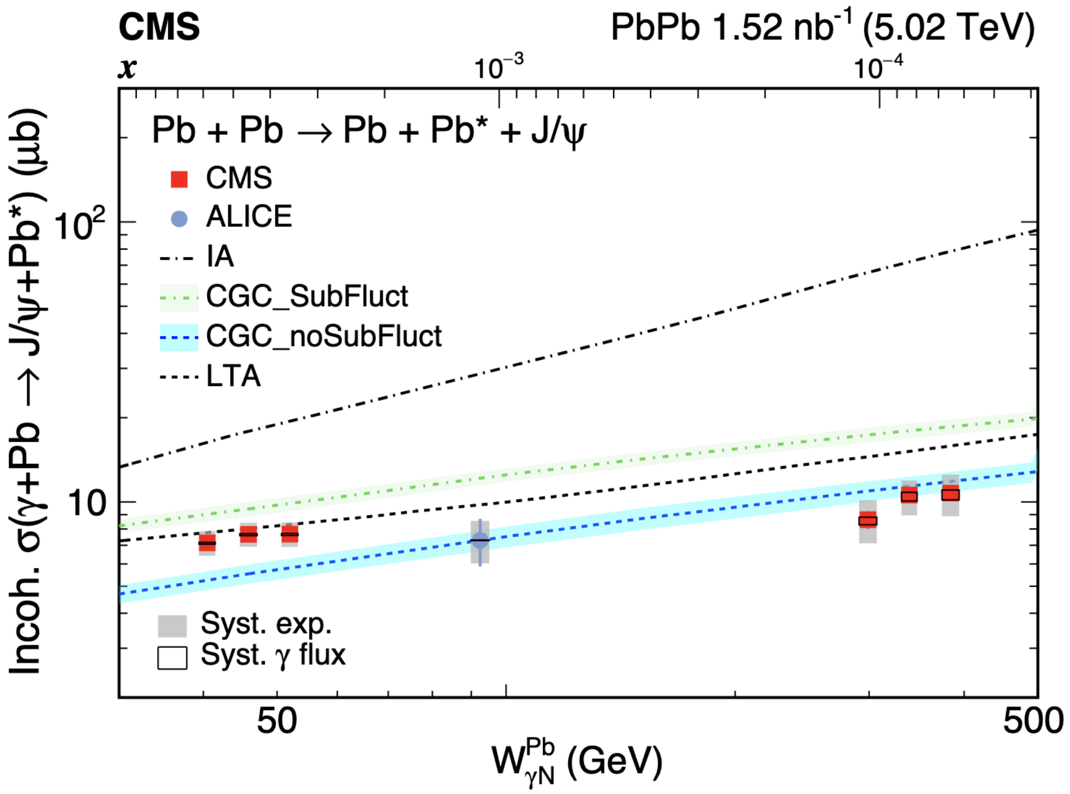
J. Cepila, G. Contreras and DTT Phys. Lett. B 766 (2017) 186-191

In the hot spot model, the increase in gluon distribution with decreasing Bjorken-*x* is described by the energy-dependent evolution of the number of hot spots

$$\left.\frac{d\sigma^{\gamma^* p \to VY}}{d|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} \left(\langle |\mathcal{A}_{T,L}|^2 \rangle - |\langle \mathcal{A}_{T,L} \rangle|^2 \right)$$

Incoherent J/ψ in γPb

CERN-EP-2025-030

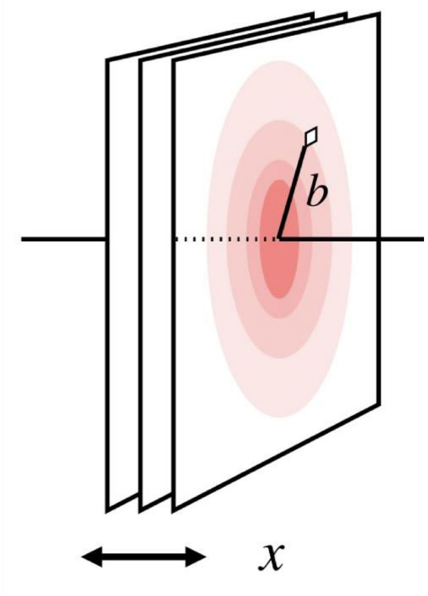


Shadowing disfavored at high energies

At high energies, good agreement with a saturation model without subnucleon fluctuations.

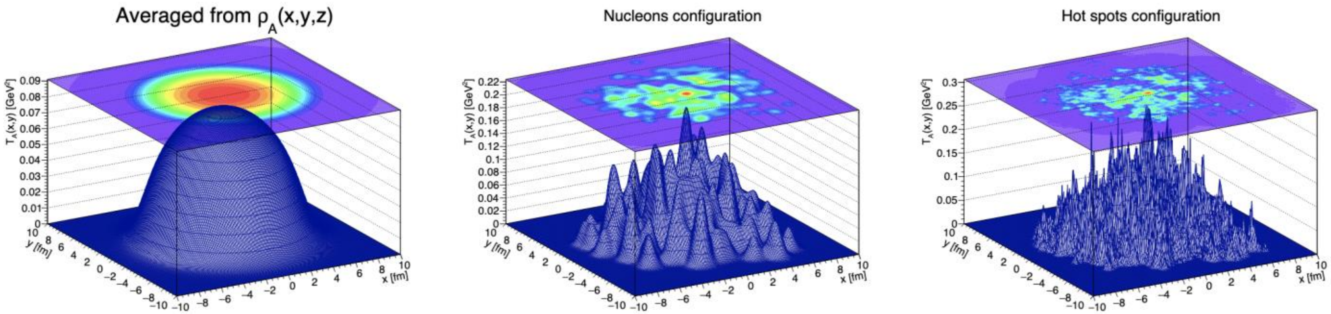
Strong quantum fluctuations expected at high |t|

Transverse profile of the target



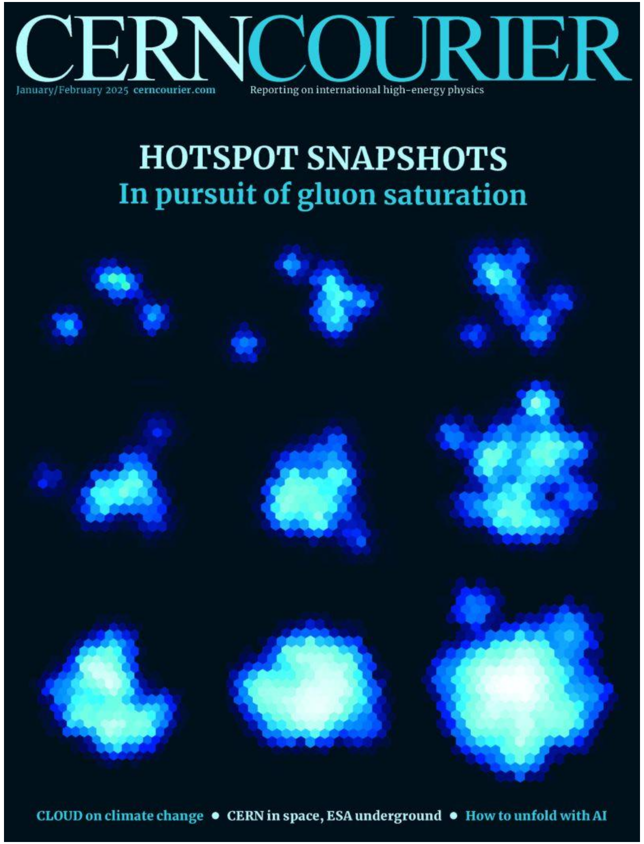
UPCs can probe the transverse profile of the target!

Appearance and location of diffractive dips can be signatures of gluon saturation



Gluonic hot spots

- https://cerncourier.com/a/the-other-99/


CERNCOURIER

January/February 2025 cerncourier.com

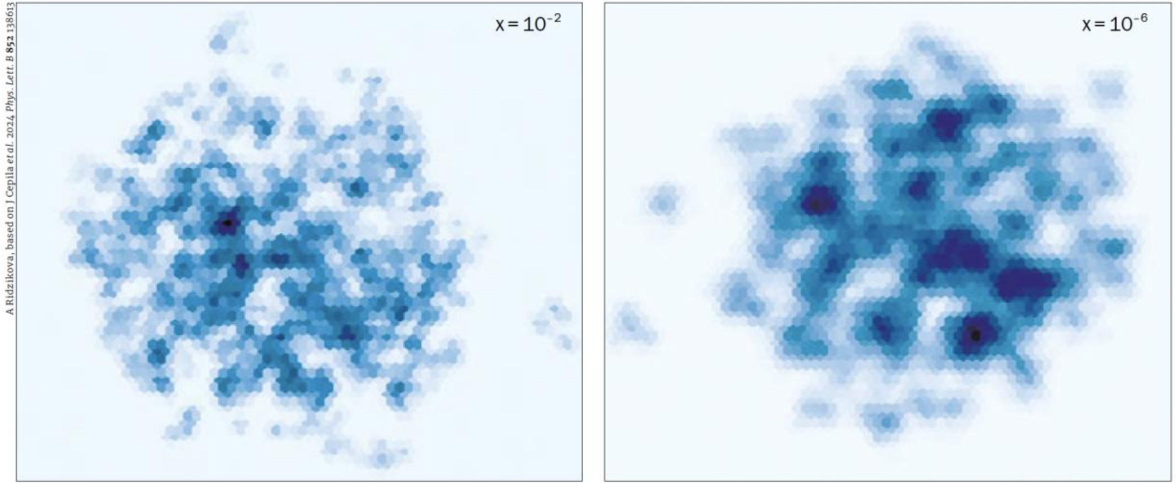
Reporting on international high-energy physics

HOTSPOT SNAPSHOTS

In pursuit of gluon saturation

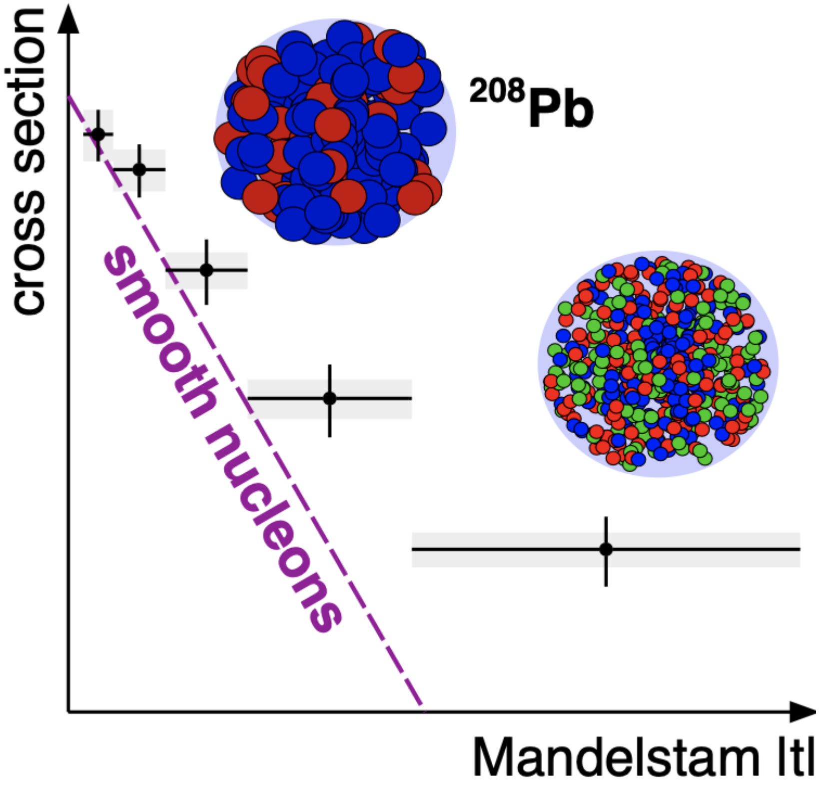
CLOUD on climate change • CERN in space, ESA underground • How to unfold with AI

Large Bjorken-x Low Bjorken-x



Hotspot snapshots *Simulations of the transverse density of gluons in lead nuclei at Bjorken x of 10^{-2} (left) and 10^{-6} (right). The distributions are 10 times broader than for protons and span almost 15 fm. The number of gluonic hotspots increases from 1,400 to 12,000 as x drops by a factor of 10,000, from left to right.*

t-dependence of incoherent J/ψ in UPC Pb-Pb

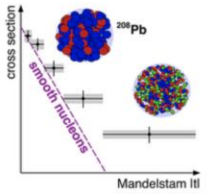


Editors' Suggestion

First Measurement of the $|t|$ Dependence of Incoherent J/ψ Photonuclear Production

S. Acharya *et al.* (ALICE Collaboration)

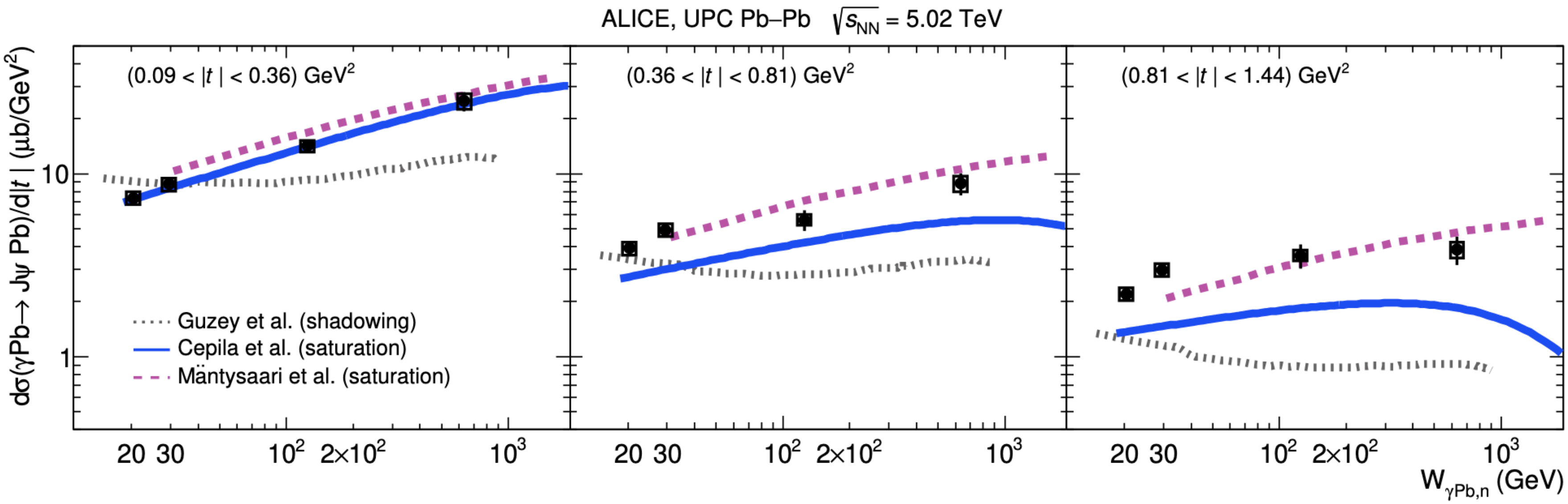
Phys. Rev. Lett. **132**, 162302 (2024) – Published 19 April 2024



The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

Show Abstract +

Evidence of incoherent J/ψ suppression in γPb CERN-EP-2025-057



Shadowing model is disfavored across all measurements

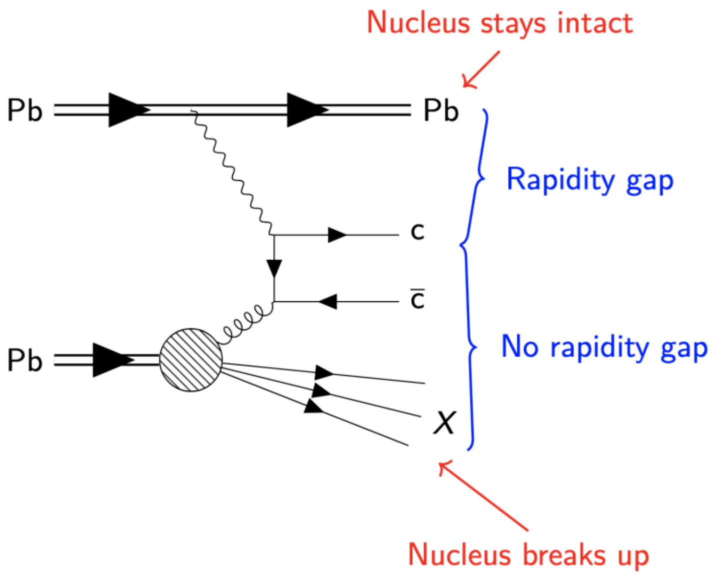
The field is now ready for a global analysis of UPC data on coherent and incoherent photoproduction

Inelastic γ+Pb -> X events

Experimental signatures for inelastic photonuclear interactions:

1) There is a rapidity gap on the side of the photon-emitting nucleus → main experimental signature

2) The photon energy << beam energy → particle production is shifted in rapidity to the side of the target nucleus



Phys. Rev C 66 (2002) 044906

Total cross sections in Pb+Pb @ √s = 5.5 TeV

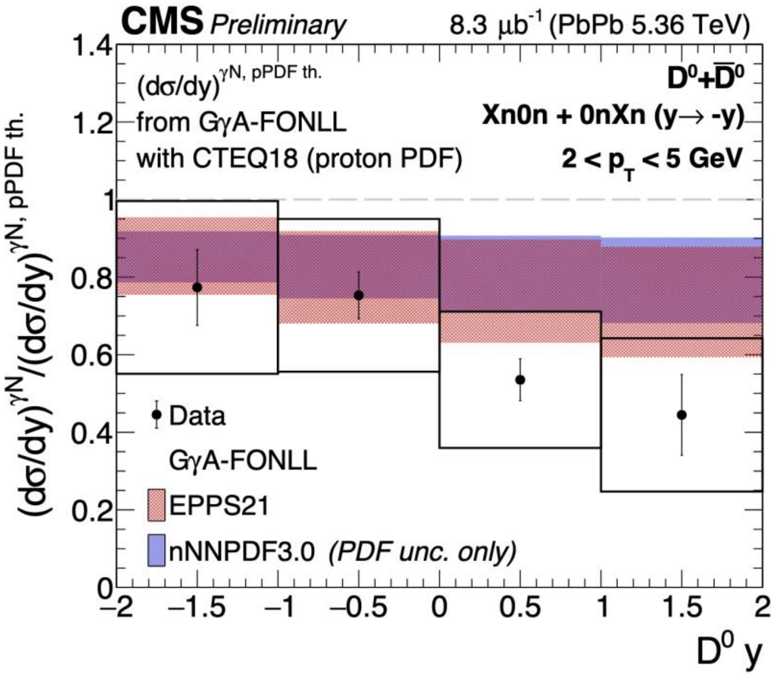
σ(Pb+Pb → Pb+ccbar+X) = 2b

σ(Pb+Pb → Pb + bbbar +X) = 830 μb

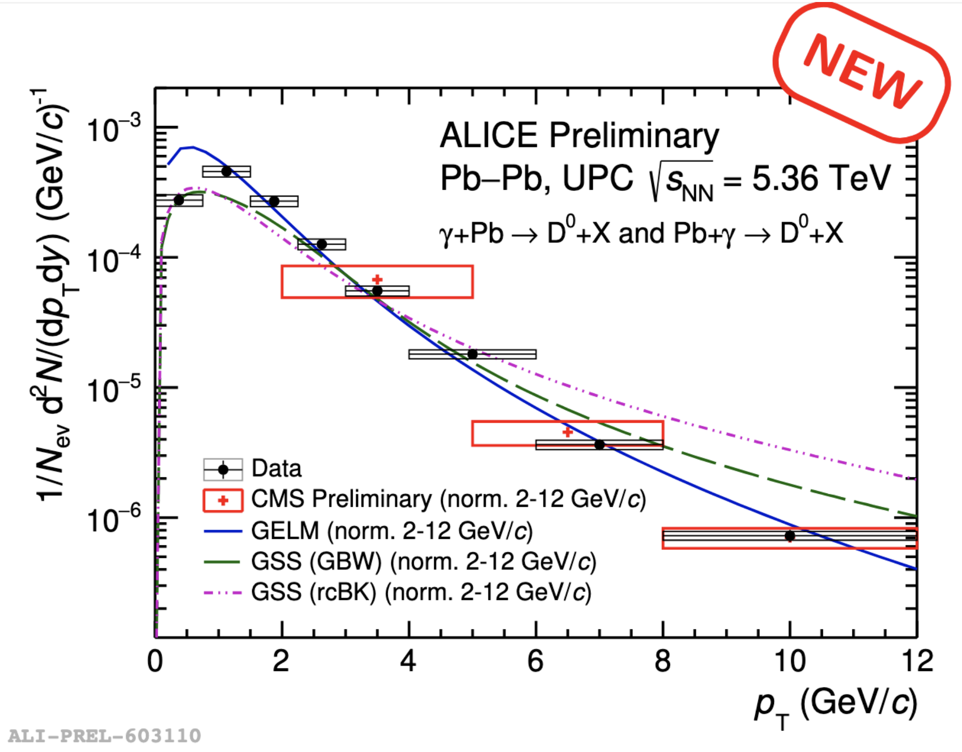
Direct production: a bare photon interacts with a parton in the target

Resolved production: the photon fluctuates to vector meson which interacts inelastically with the target

First open flavor measurements in inelastic γPb



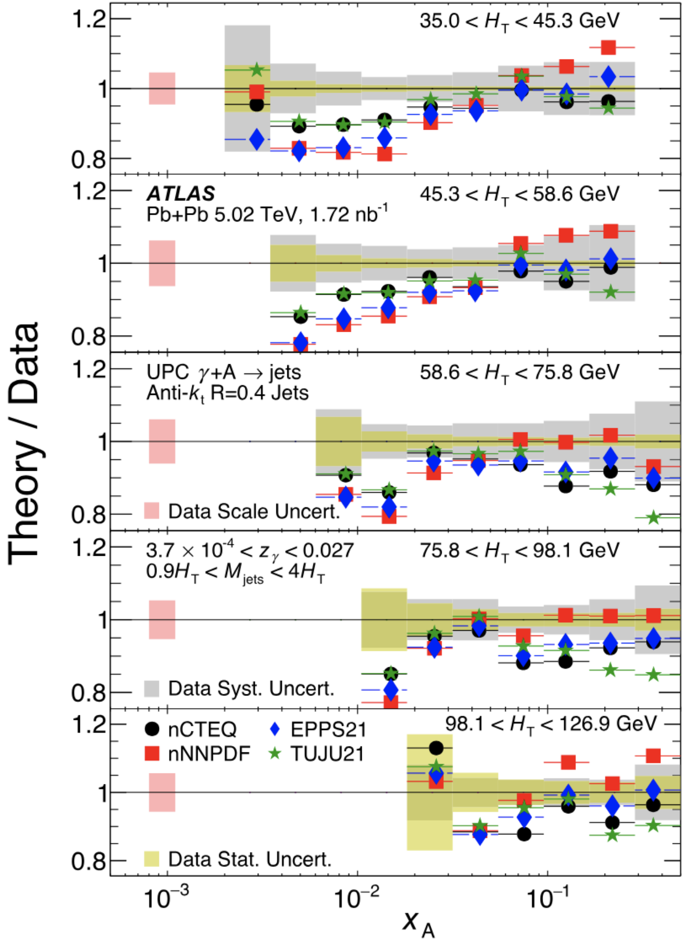
CMS-PAS-HIN-25-002
CMS-PAS-HIN-24-003

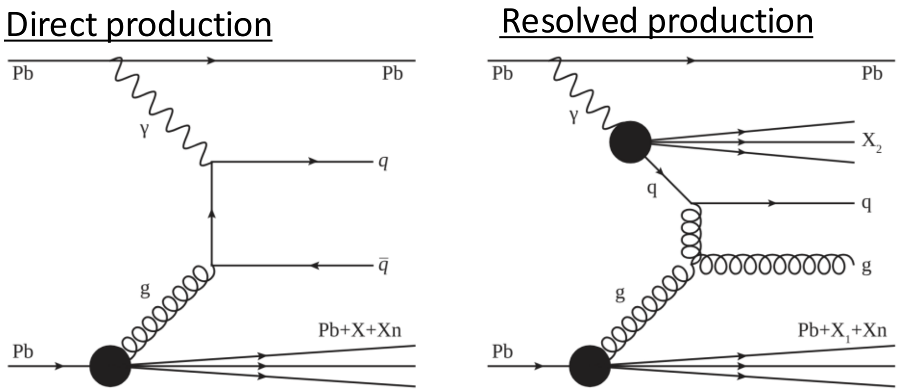


Measurements crucial for exploring different regions in Q^2 and x, and different type of theory uncertainties

Photonuclear dijets in UPCs

Phys. Rev.D 111 (2025) 5, 052006



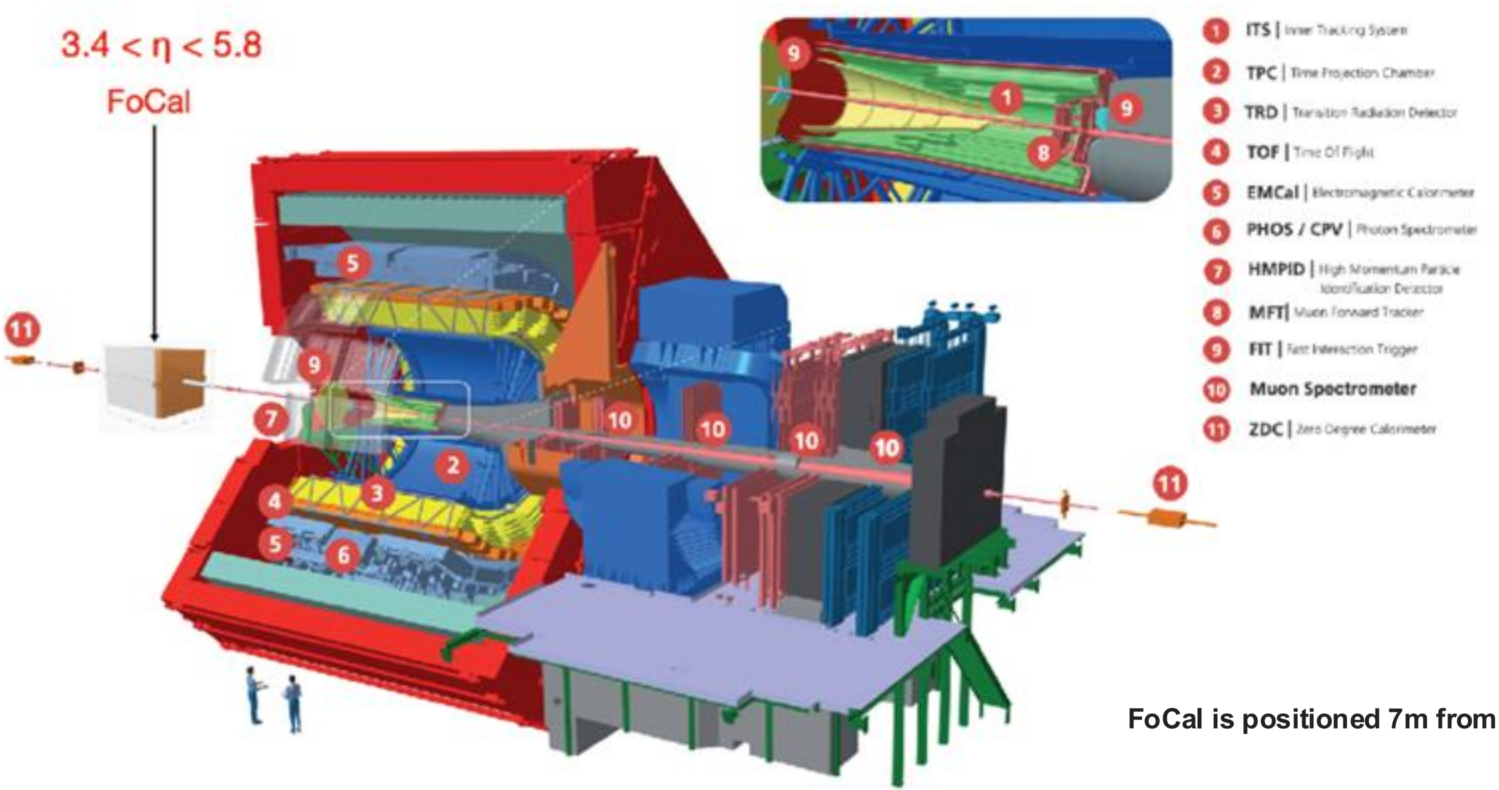


Triple differential cross sections!

LO PYTHIA8 predictions underpredict the data in the shadowing region, OK in the antishadowing/EMC regions.

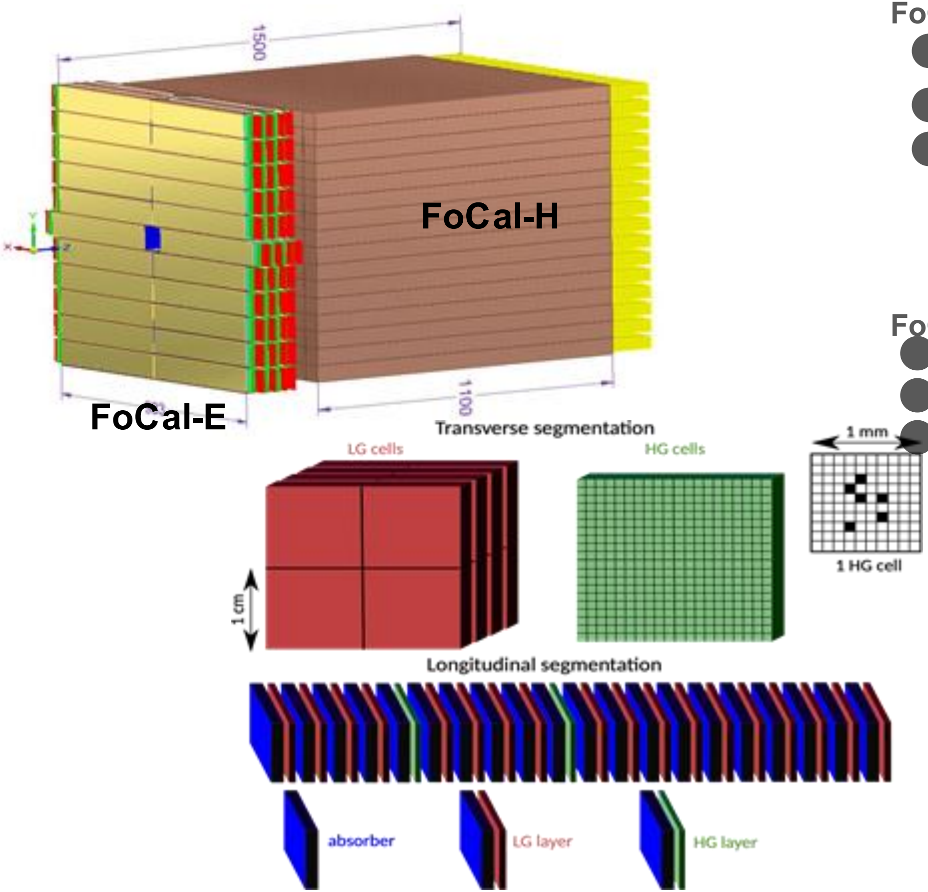
Data useful for nPDF fits with ever more precise NLO pQCD calculations

The ALICE FoCal project for Run 4



FoCal is positioned 7m from IP2 (A-side)

The ALICE FoCal project for Run 4



FoCal-E

- 20 Layers (LG + HG Si detectors + W absorbers). Tot (~ 20 X0)
- Dimensions ~ 90cm x 98cm x 20cm
- Designed for:
  - measurement of direct photons
  - Measurement of high pt neutral pions (Pb-Pb vs p-p)
  - Granularity optimized to enable photons separation (~ 5mm distance)

FoCal-H

- Transversally segmented calorimeter Tot thickness ~ 6 λhad
- located behind FoCal-E (reduce shower blow-up)
- Designed for:
  - Studying the dynamics of hadronic matter with photons and jets (isolation capabilities (single hadron res ~ 20-25%))

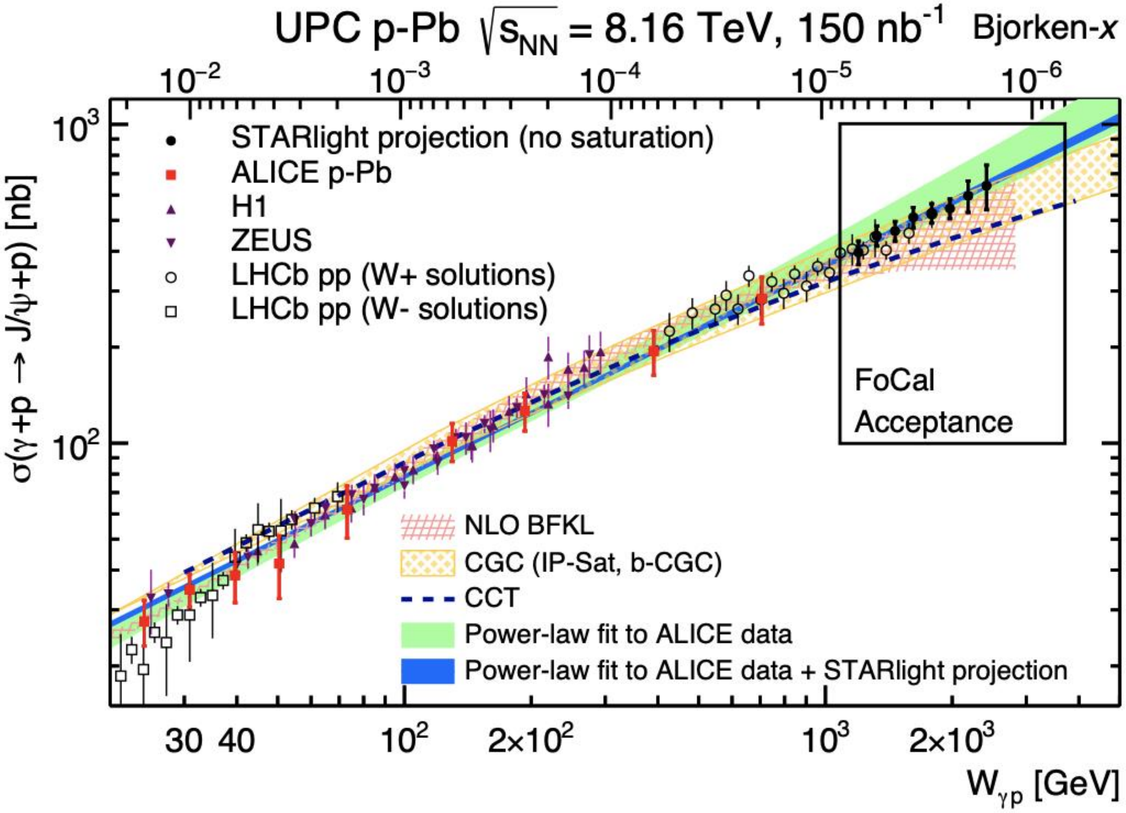
FoCal is positioned 7m from IP2 (A-side)

UPC VM projections for FoCal

A. Bylinkin, J. Nystrand and DTT *J. Phys. G* 50 (2023) 055105, 5

VM	$\sigma(\mathrm{p+Pb \to p+Pb+VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
		$\mathrm{p \to FoCal}$	$\mathrm{p \to FoCal}$
ρ^0	35 mb	140 nb	21,000
ϕ	1.7 mb	51 nb	7,700
J/ψ	98 μb	400 nb	60,000
$\psi(2S)$	16 μb	8.9 nb	1,300
$\Upsilon(1S)$	220 nb	0.38 nb	60
		$\mathrm{Pb \to FoCal}$	$\mathrm{Pb \to FoCal}$
ρ^0	35 mb	17 nb	2,600
ϕ	1.7 mb	5.3 nb	800
J/ψ	98 μb	36 nb	5,400
$\psi(2S)$	16 μb	0.53 nb	80
$\Upsilon(1S)$	220 nb	0.67 pb	~ 0

Projections for exclusive J/ψ off protons



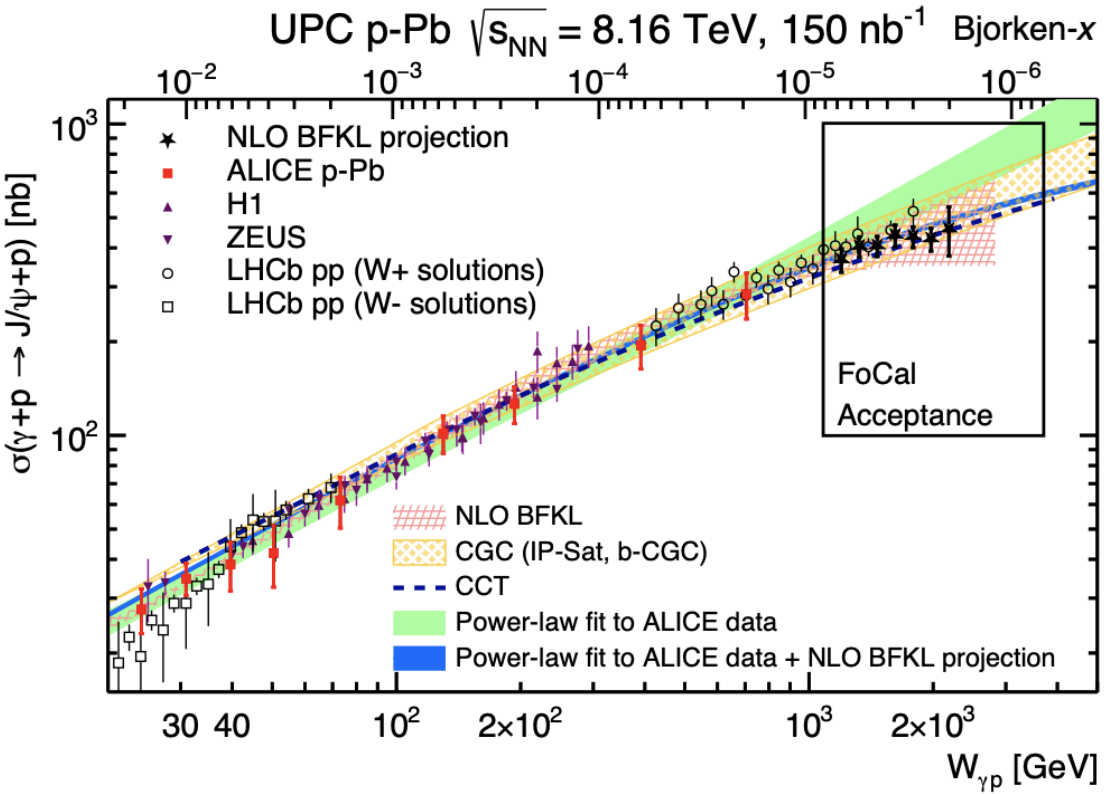
- Deviations from a power-law trend should signal non-linear QCD dynamics

- Here, projections based on STARlight which uses a parametrization based on HERA data

$$\sigma_0 (W_{\gamma p}/W_0)^{\delta}$$

- For all figures, 60% efficiency. Conservative assumption after acceptance selection

Projections for exclusive J/ψ off protons



- Projections assuming a broken power-law
- Projected points based on NLO BFKL calculation

$$\sigma(\gamma p) \approx \frac{\sigma_0}{\frac{1}{W_{\gamma p}^{\delta}} + A}$$

Neutron-dependence of coherent J/ψ in γPb

Decomposed in terms of neutron configurations emitted in the forward region

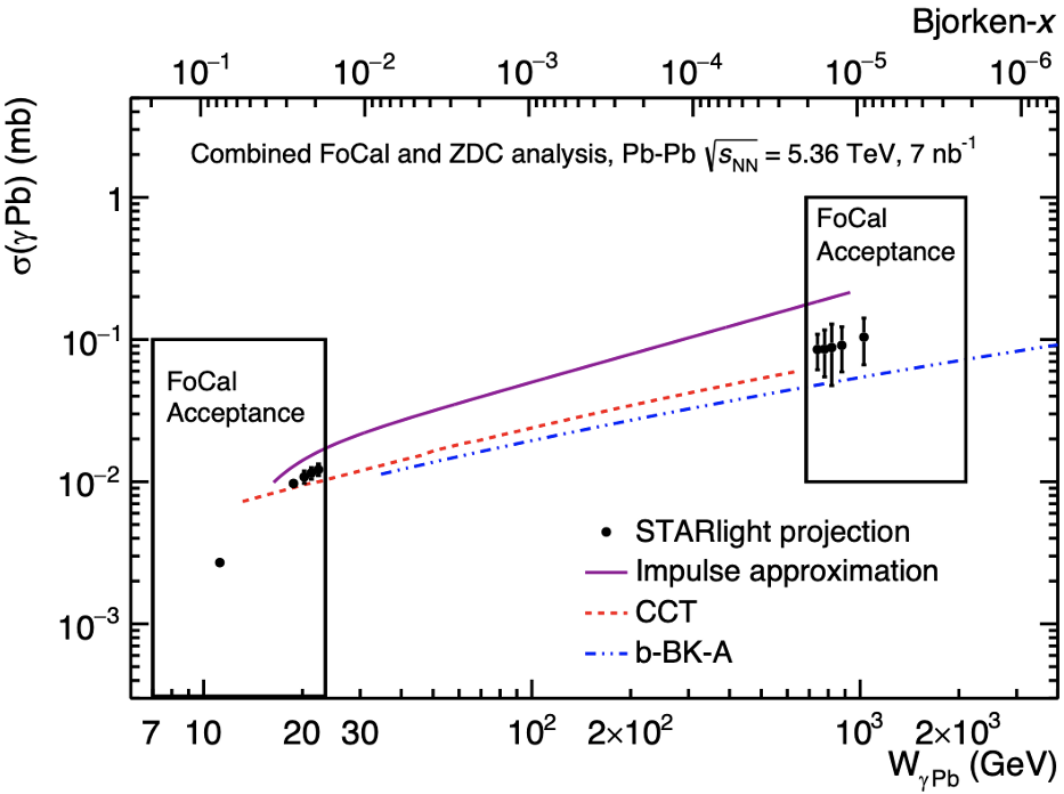
$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

Neutron configuration	$\sigma(\mathrm{Pb+Pb} \to \mathrm{J}/\psi + \mathrm{Pb+Pb})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
0n0n	28.8 mb	47 μb	329,000
0nXn + Xn0n	7.3 mb	5.0 μb	35,000
XnXn	3.0 mb	2.0 μb	14,000

Solving the linear equations resolves the two-photon ambiguity for VMs at y ≠ 0

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

Projections for Neutron-dependence of coherent J/ψ in γPb



- Neutrons measured with Zero Degree Calorimeters
- Projections based on STARlight
- ALICE will be the only detector capable of explore $x \sim 10^{-6}$ in Pb thanks to FoCal

Summary

- The UPC (Ultra-Peripheral Collision) program investigates the high-density regime of Quantum Chromodynamics (QCD), focusing on the initial states of protons and ions at high energies.

- Recent results from ALICE, ATLAS, CMS, and LHCb cover coherent and incoherent photoproduction, as well as inelastic photonuclear processes.

- New and increasingly multidifferential measurements are opening unexplored kinematic territories. Incoherent data challenge existing models of nuclear shadowing, while recent studies on photonuclear dijets and open heavy flavor probe new and interesting kinematic regions

- Very promising future with the complete Run 3 dataset analysis and Run 4 data in the coming years!

Thanks!

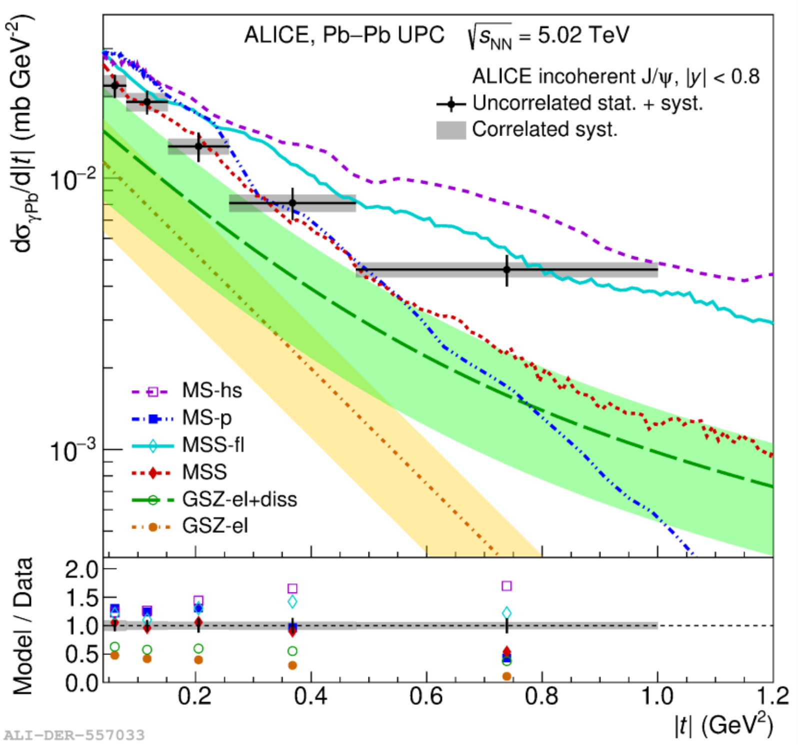
Additional slides

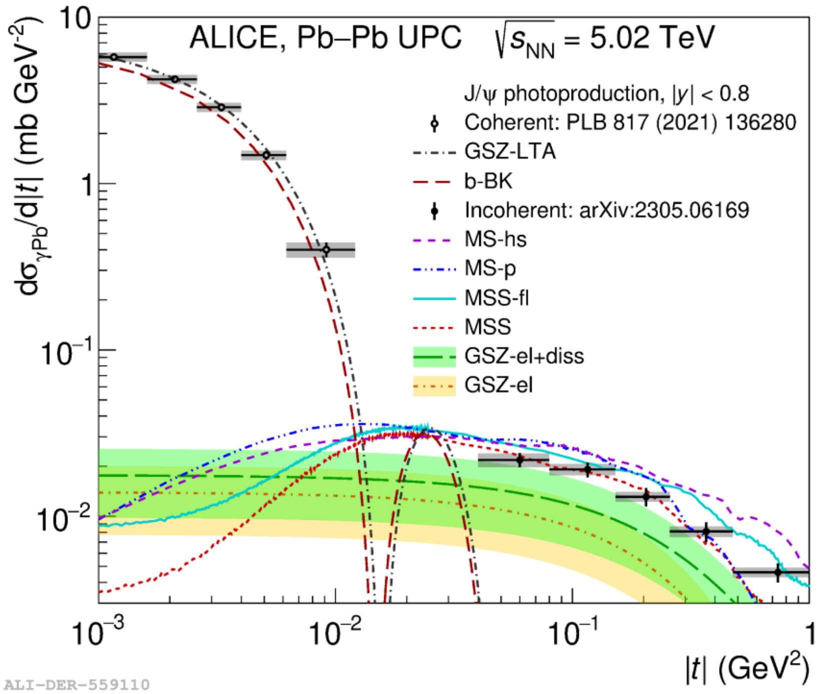
t-dependence of coherent and incoherent J/ψ in UPC Pb-Pb

First measurement of the |t|-dependence of incoherent J/ψ photonuclear production

Phys.Rev.Lett. 132 (2024) 16, 162302

Probing for gluonic ”hot spots” in Pb using UPCs for the first time!

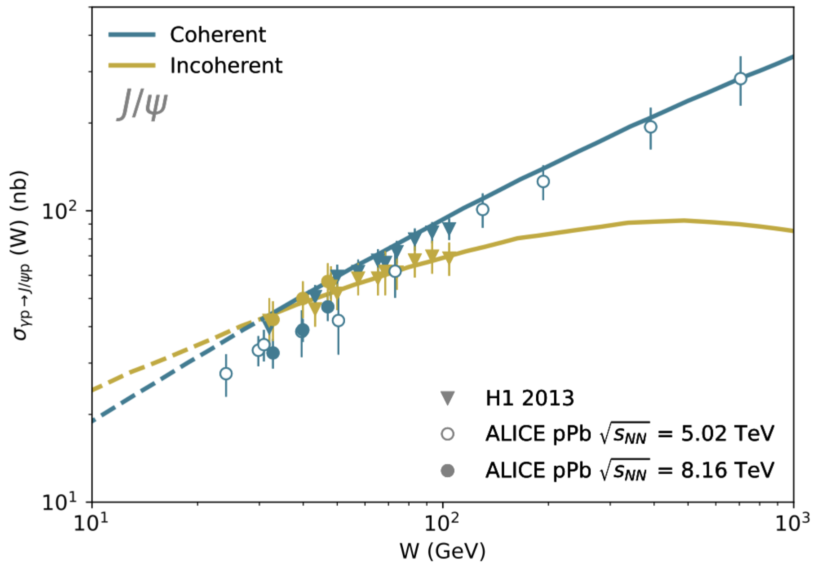


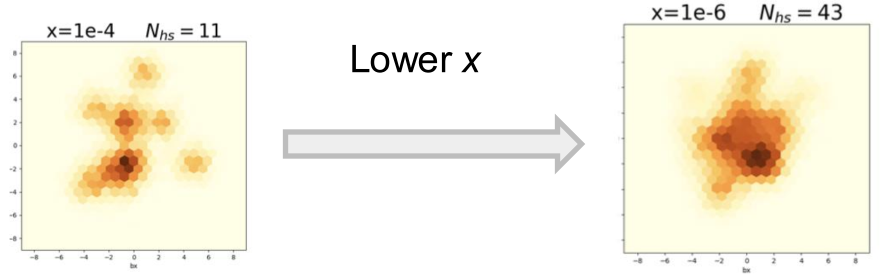


Gluon saturation and dissociative J/ψ in UPC

See talk by A. Ridzikova at DIS'24
Her figures

Phys. Lett. B 852 (2024) 138613





$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p \to VY}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{\mathrm{T,L}}|^2\rangle - |\langle\mathcal{A}_{\mathrm{T,L}}\rangle|^2\right)$$

In the hot spot model, the increase of large hot spots within the proton reaches a point of significant overlap, and the resulting uniformity reduces both the variance and the dissociative cross section

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