U.S. DEPARTMENT OF ENERGY
Office of Science

Synergies between the UPC and EIC program

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POETIC

Miami, Florida

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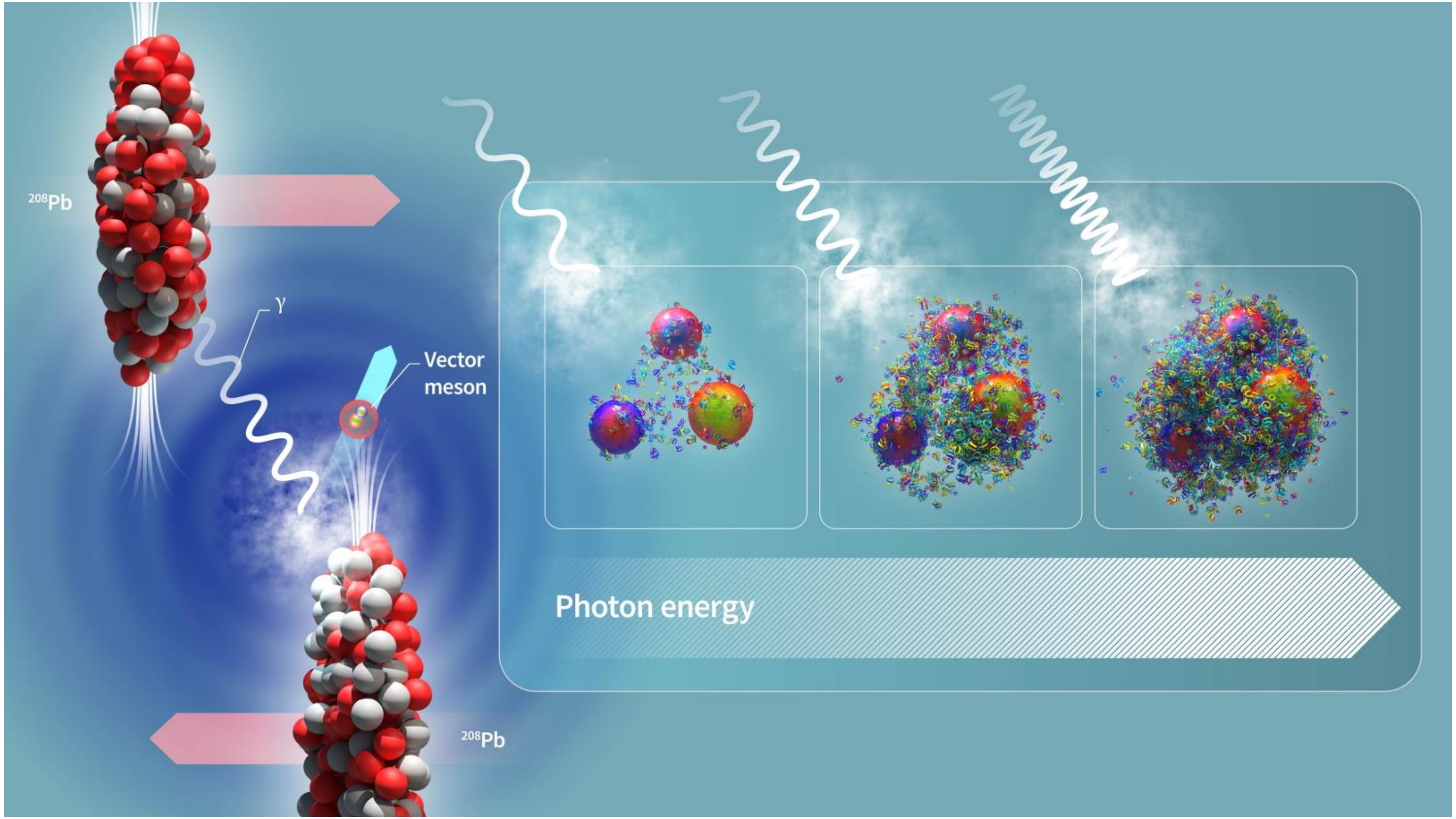
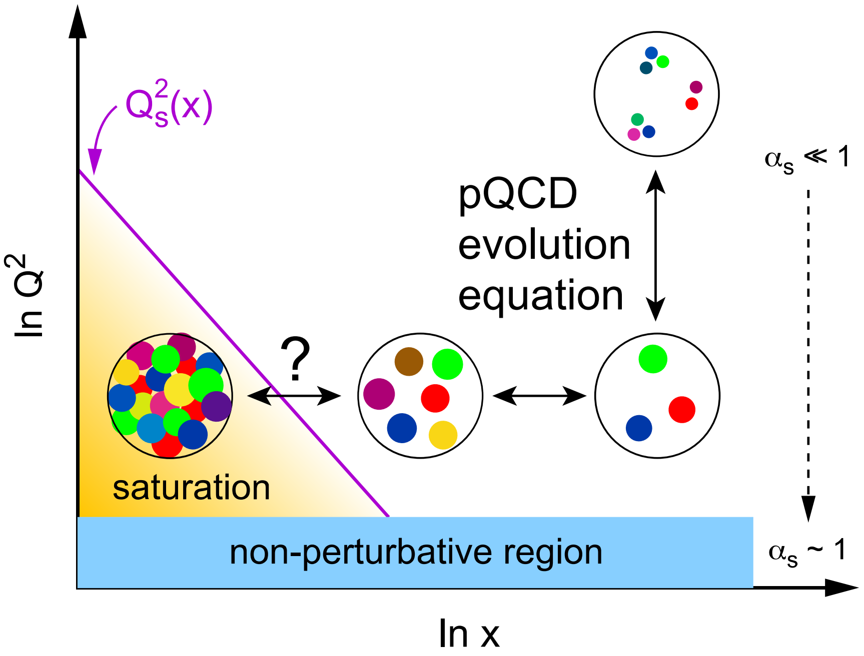
Ultra peripheral collisions (UPC)



Gluon saturation matters

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

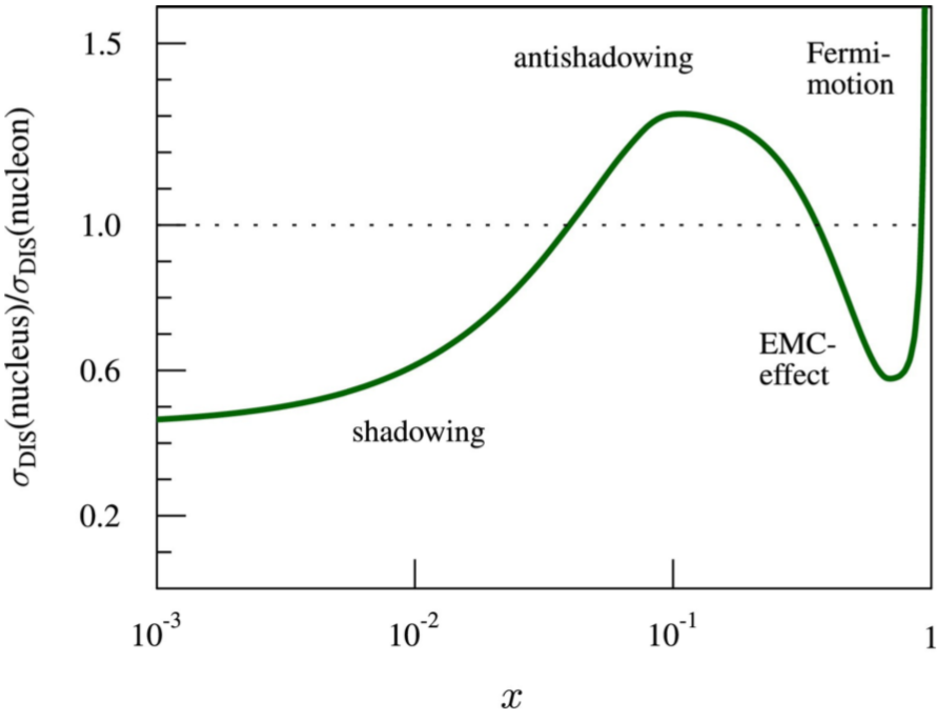


$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

- 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?

Nuclear shadowing experimentally confirmed, but not fully understood

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

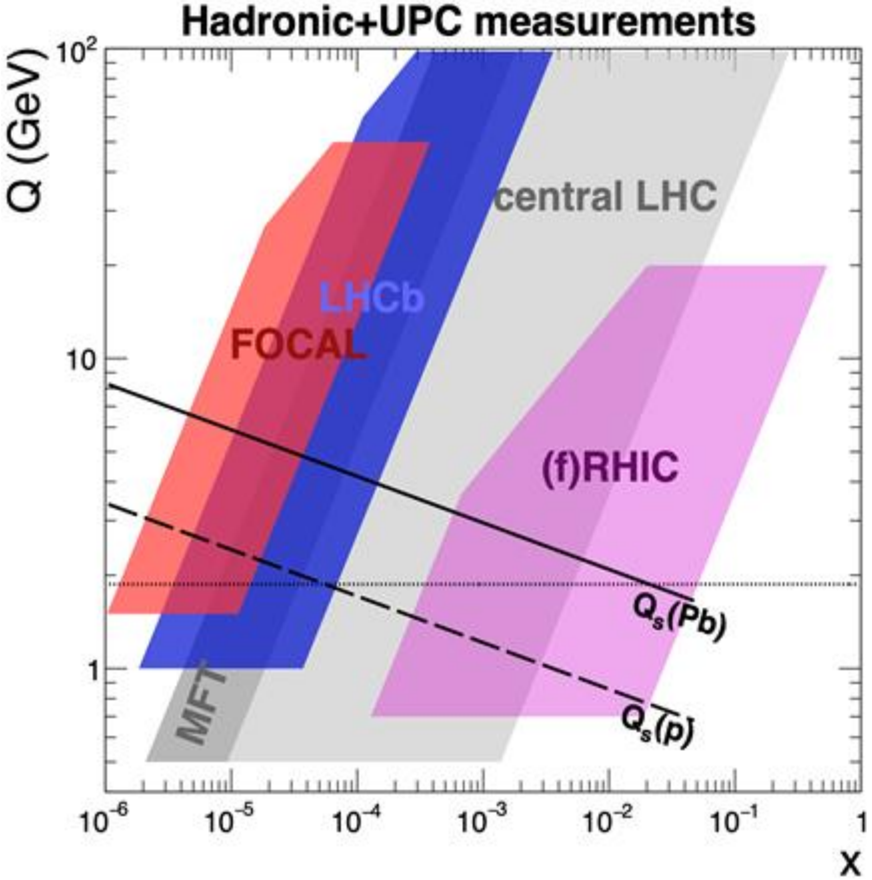


- Experimental observation that parton distributions are different for protons and nuclei
- What's the mechanism responsible for shadowing? <u>How is gluon saturation related?</u>
- The knowledge of the initial state of nuclei also needed for understanding the QGP evolution

Experimental program

- The Electron-Ion Collider will be a dedicated QCD machine with the **precision and control** capabilities for studying gluon saturation and shadowing in a systematic way like never before.

- The LHC explores the **high energy domain** for both hadronic and photon-induced reactions



The LHC is the Large Photon Collider

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

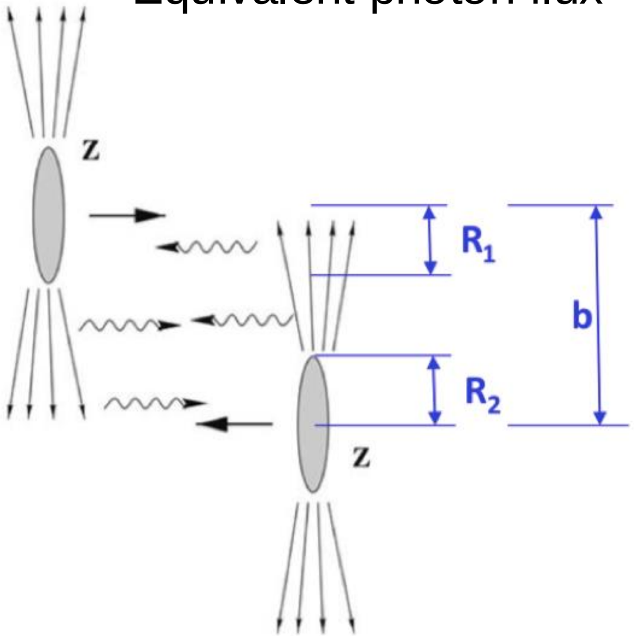
  $k = \gamma M_V \exp(\pm,y)$
  Up to several TeV in γp
  Up to ~ 700 GeV/nucleon in γA
  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- 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

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

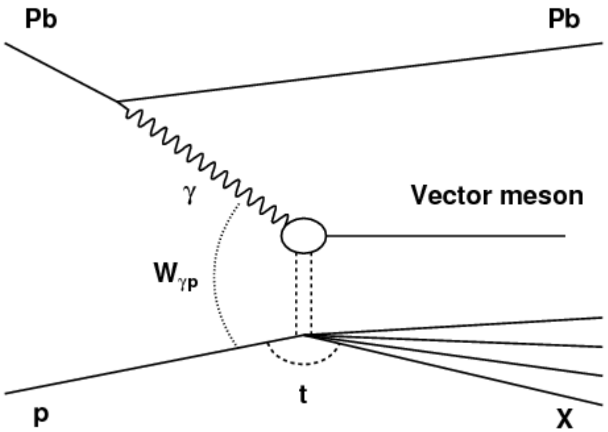
Interactions mediated by the EM interactions

Equivalent photon flux



Vector meson (VM) photoproduction in UPCs

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

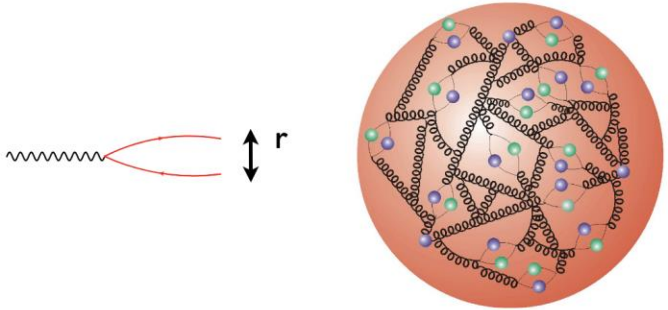


- As in DIS, several reactions are possible in UPCs:

  -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



Two-fold ambiguity on the photon direction in symmetric systems

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

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

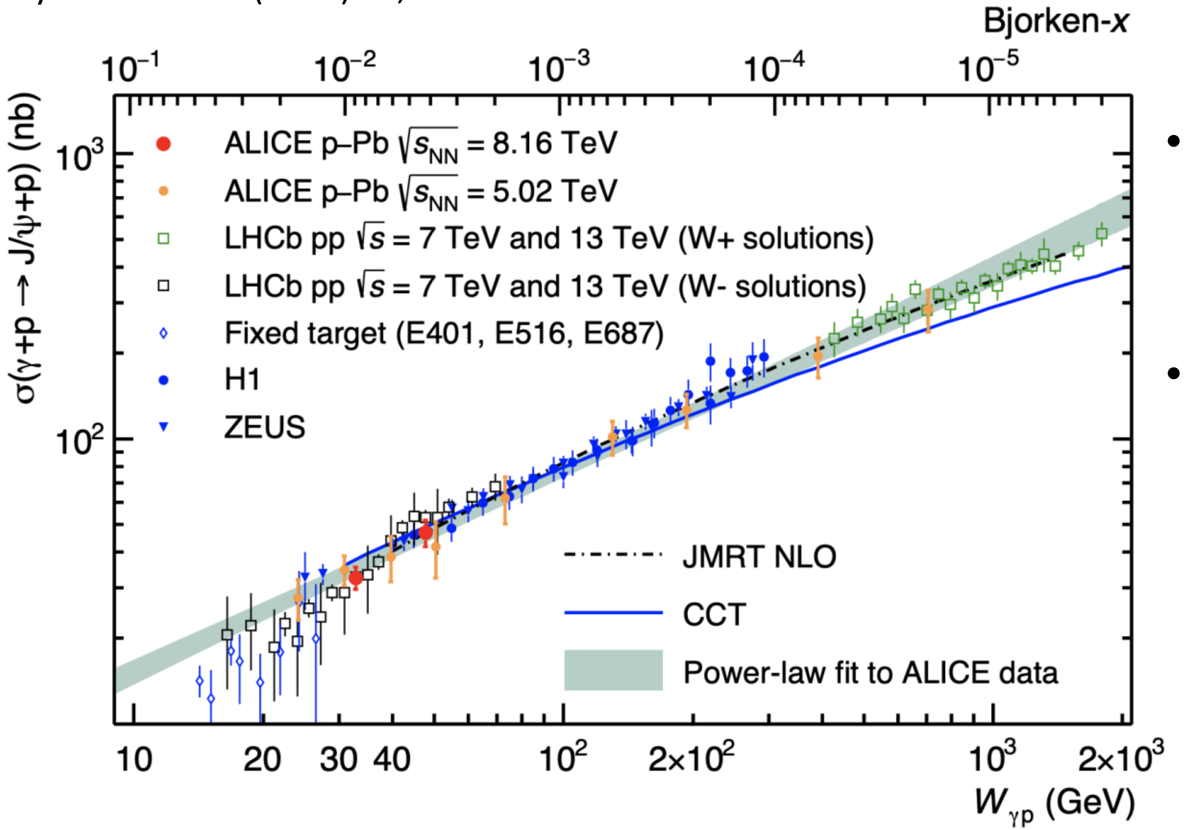
Positive rapidity | Negative rapidity

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

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

Exclusive J/ψ in UPC p-Pb (2023)

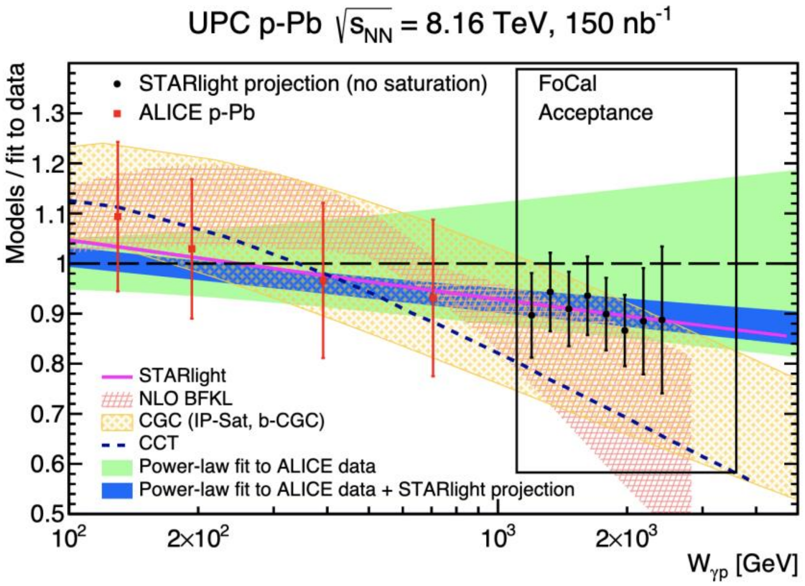
Phys. Rev. D 108 (2023) 11, 112004



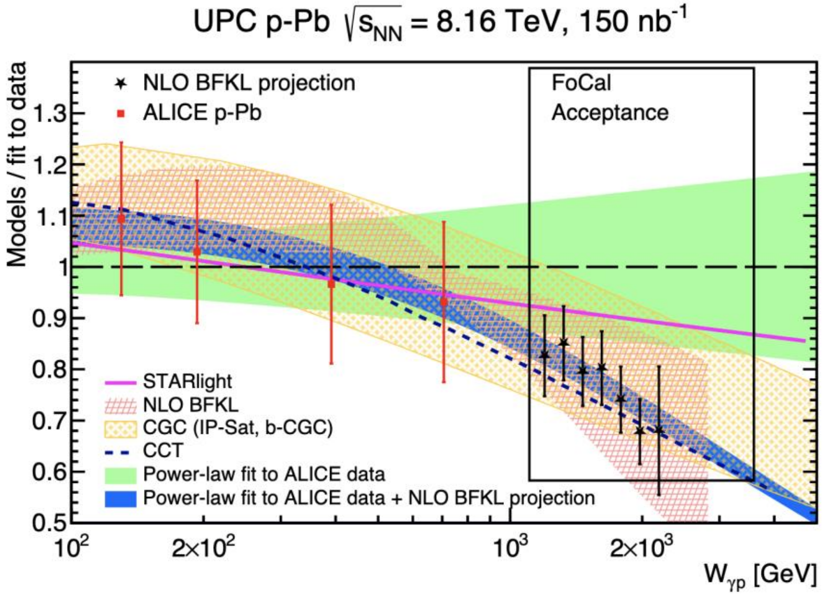
- No change in the behavior observed between HERA and LHC energies
- The highest energy point measured in a model-independent way is only up to 700 GeV in UPC p-Pb by ALICE

Projections for exclusive J/ψ off protons

Power-law behavior (STARlight)

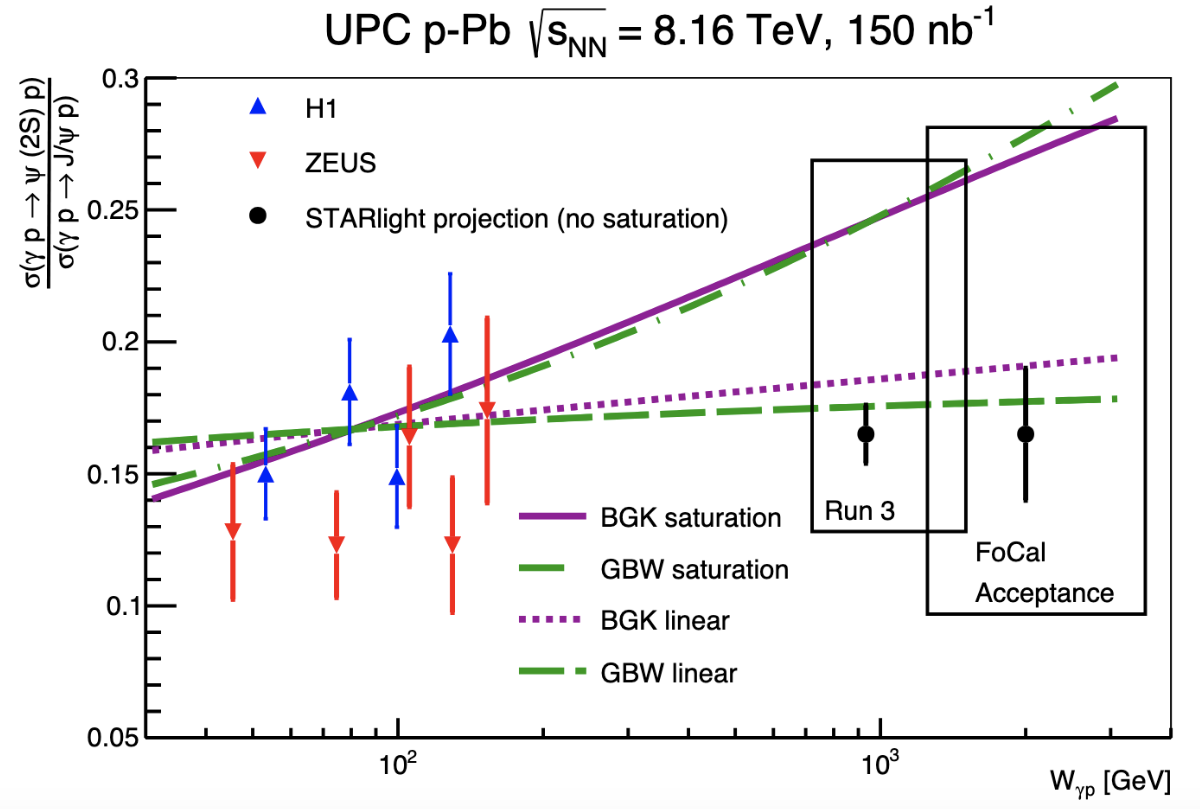


Broken power-law behavior (NLO BFKL)



FoCal measurement would be sufficient to observe a deviation from a power law behavior, if exists

Projections for exclusive ψ(2S) and J/ψ cross section ratio in γp



- Different wave functions and dipole sizes evolution result in great sensitivity to non-linear QCD effects
- No sensitivity at HERA, but expected at the LHC
- Projections here based on STARlight

Coherent J/ψ in UPC Pb-Pb

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

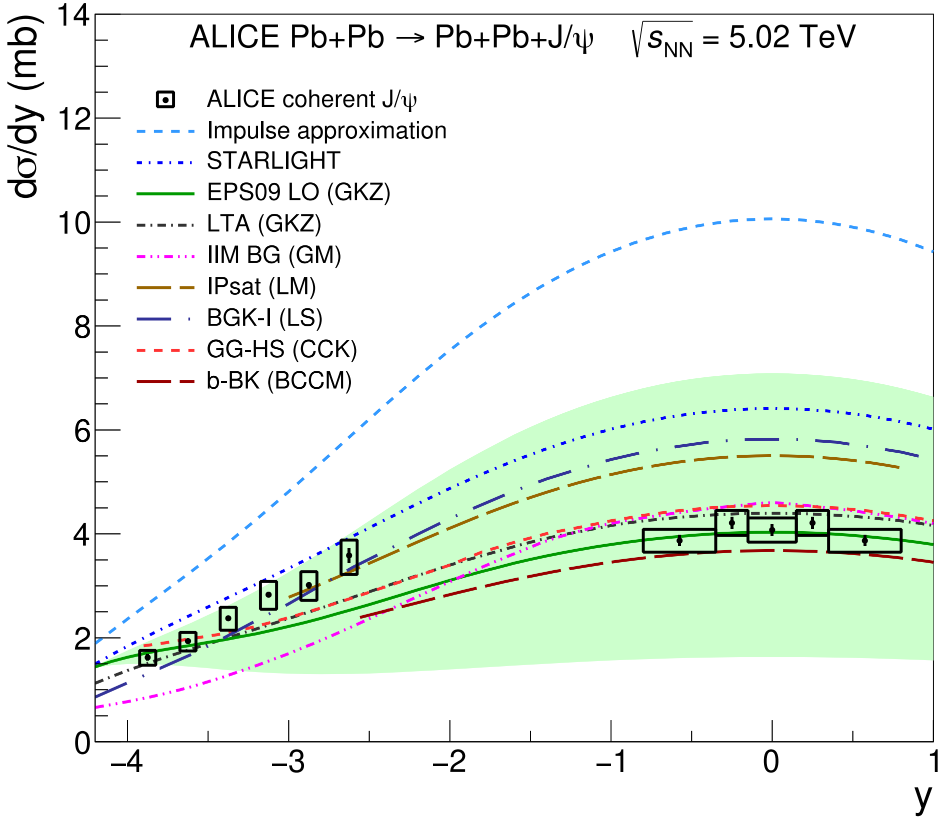
- Confirmation of nuclear shadowing with Run 2 data

- No model can describe the rapidity dependence

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

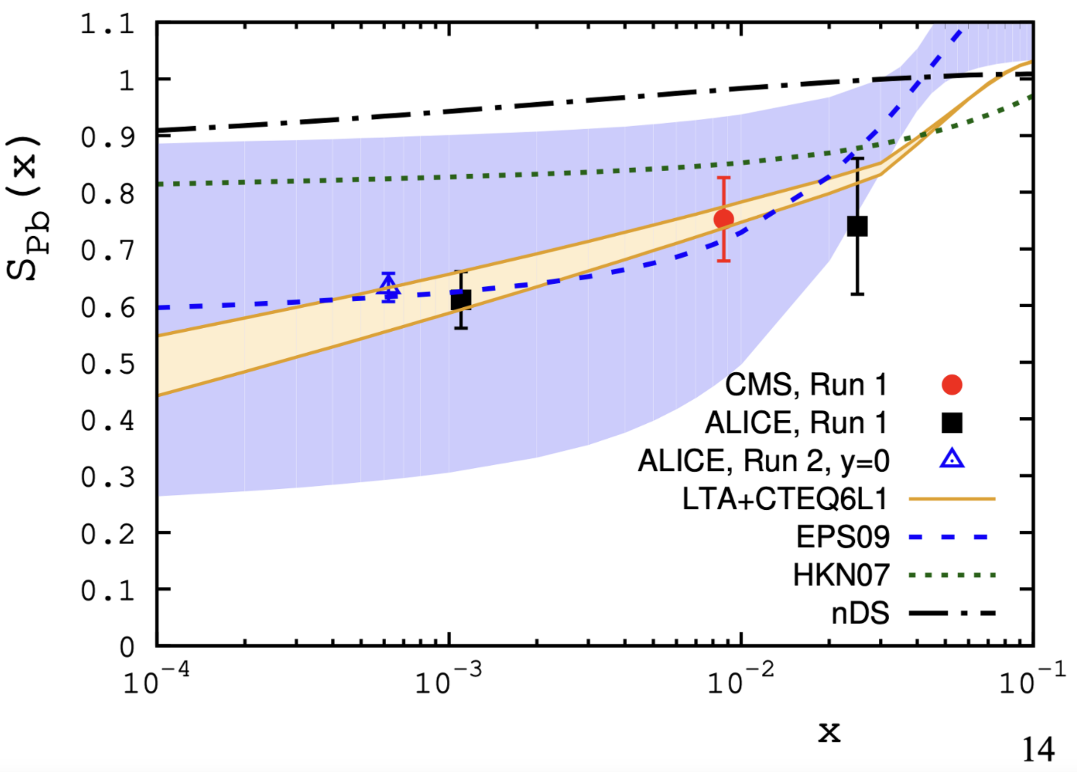
Mid-rapidity x ~10^{-3}

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



Nuclear suppression factor for UPC J/ψ: Comparing γPb to γp

V. Guzey et al. PLB 726 (2013)



An experimental definition, which can be linked to PDFs at LO

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A \to J/\psi A}(W_{\gamma p})}{\sigma^{IA}_{\gamma A \to J/\psi A}(W_{\gamma p})}} = \kappa_{A/N} \frac{x g_A(x,\mu^2)}{A x g_N(x,\mu^2)}$$

Run 1 data from ALICE was the first at indicating nuclear gluon shadowing at x ~ 10^{-3}

Large scale NLO uncertainties should cancel in the $S_{Pb}(x)$ ratio

ALICE results at y=0 have no ambiguity on the photon energy

Two-fold ambiguity on the photon direction in symmetric systems

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

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

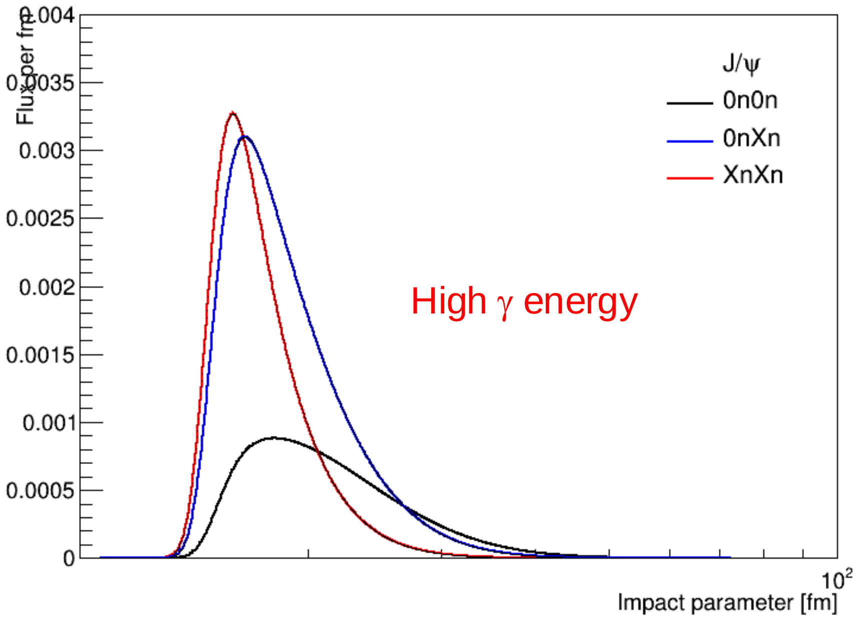
Positive rapidity — Negative rapidity

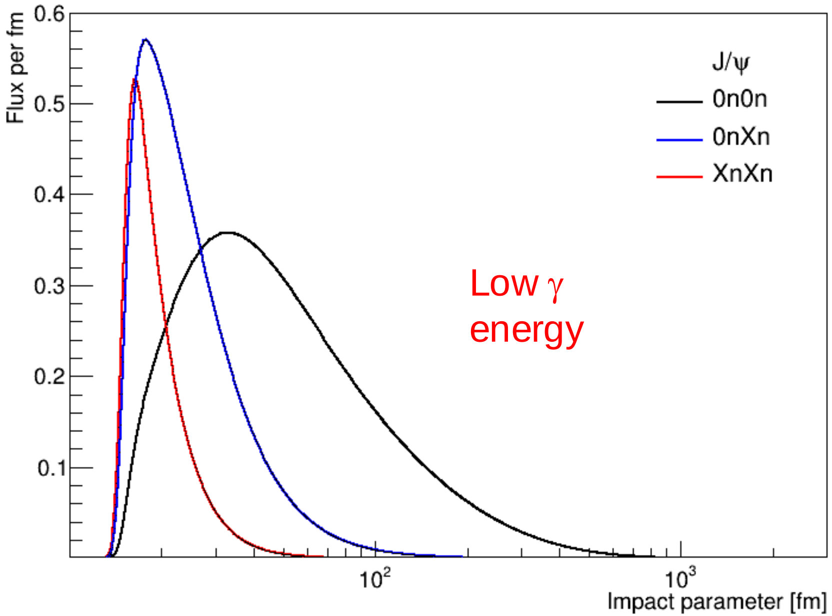
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

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

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 $y \neq 0$

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

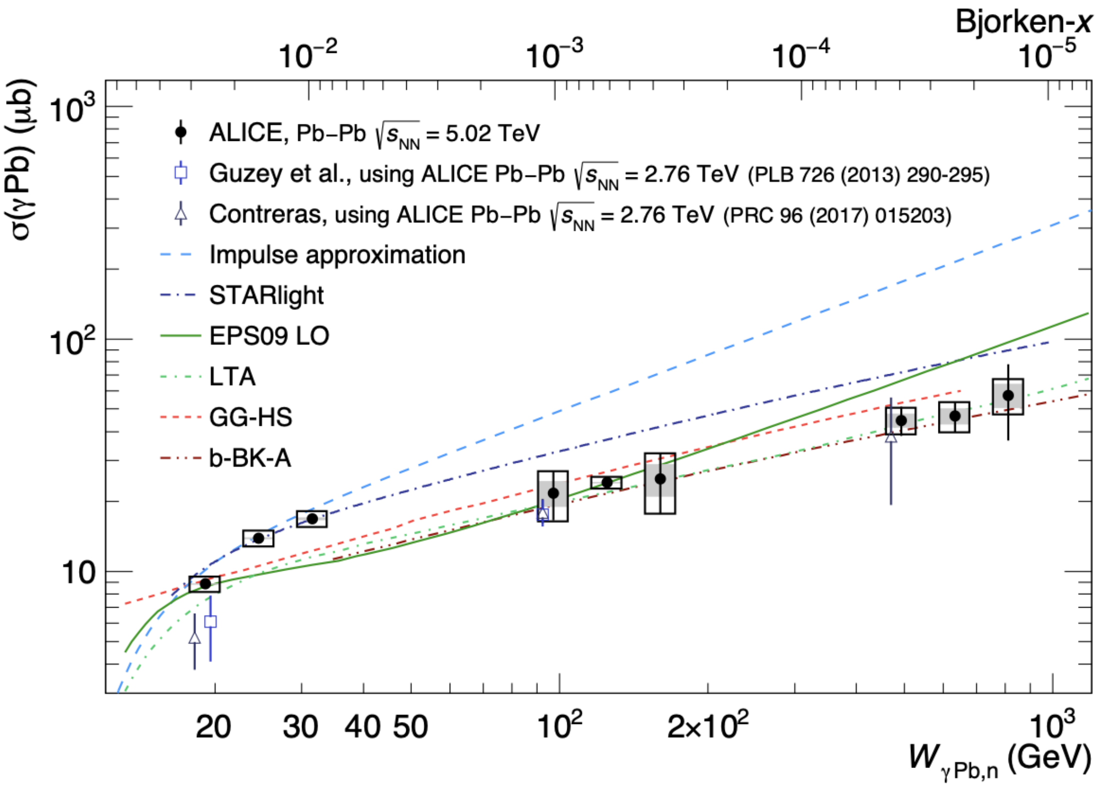
Energy dependence of coherent J/ψ in γPb – ALICE Run 1 and Run 2 data

JHEP 10 (2023) 119

Confirmed Run 1 results. At low x, both shadowing and saturation models describe the data

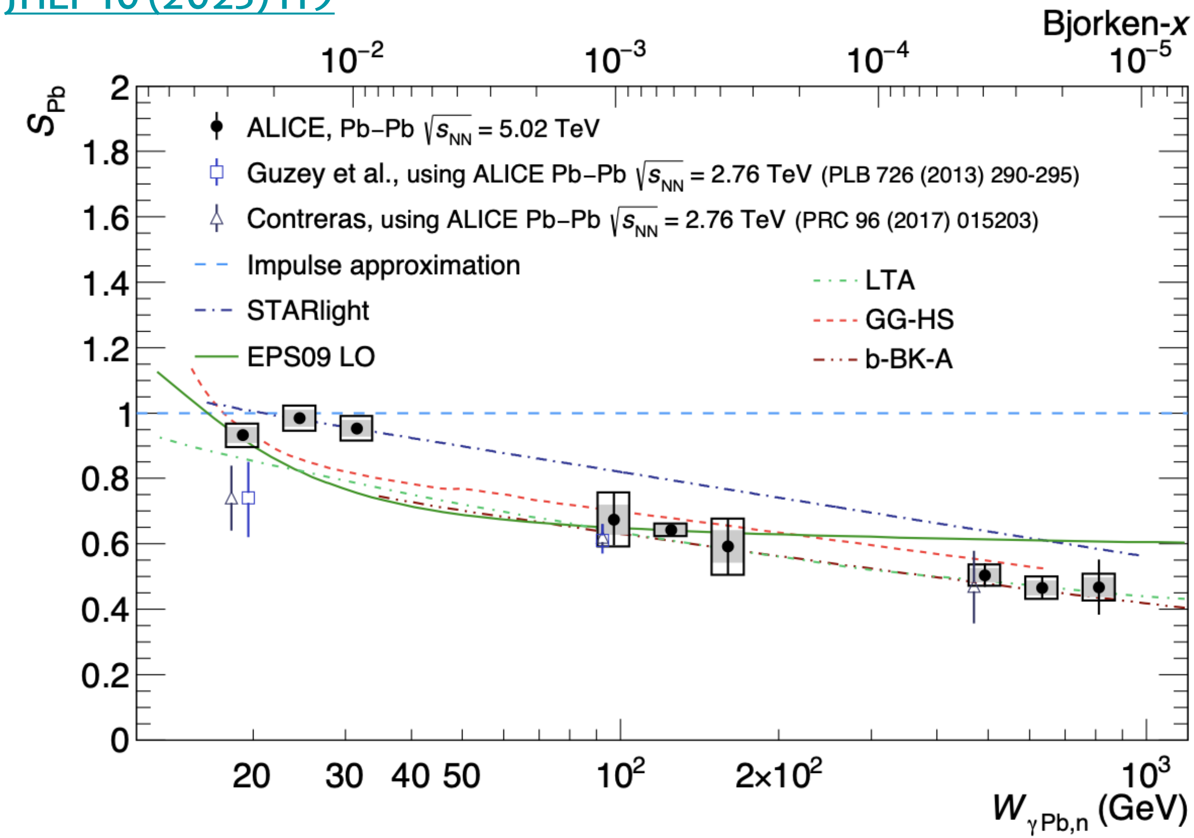
Energy dependence across the whole range not described by models

In a single experiment exploring (20,800) GeV in $W_{\gamma Pb}$ and x from 10^{-2} to 10^{-5}



Nuclear suppression factor – ALICE Run 1 and Run 2 data

JHEP 10 (2023) 119

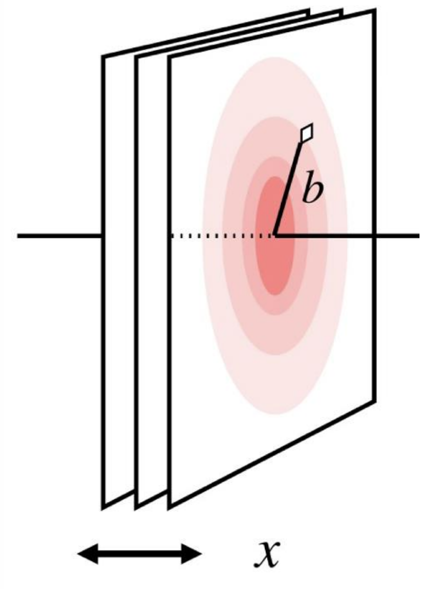


At low x, both shadowing and saturation models describe the data

Confirmation that peripheral hadronic events can be used to extract the energy dependence. Already explored down to $x = 4.4 \times 10^{-5}$ using Run 1 data

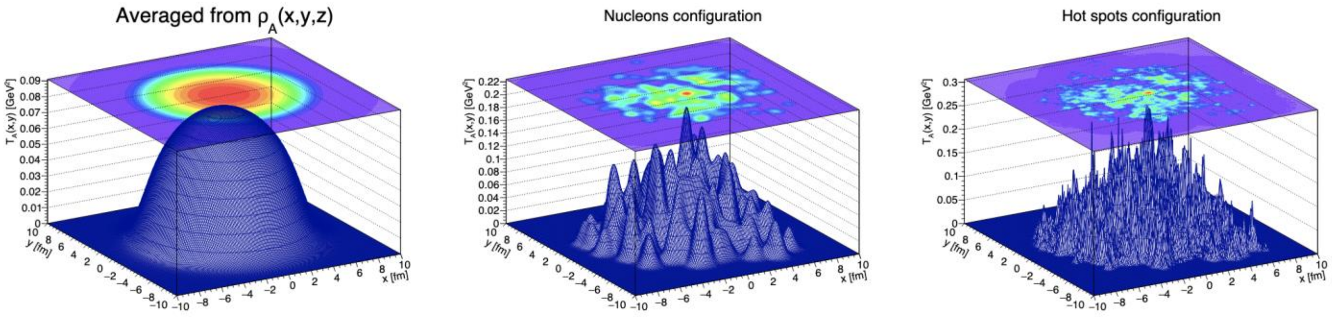
With the neutron-dependent analysis using Run 2 data, down to $x = 1.1\times10^{-5}$, Run 2

Transverse profile of the target



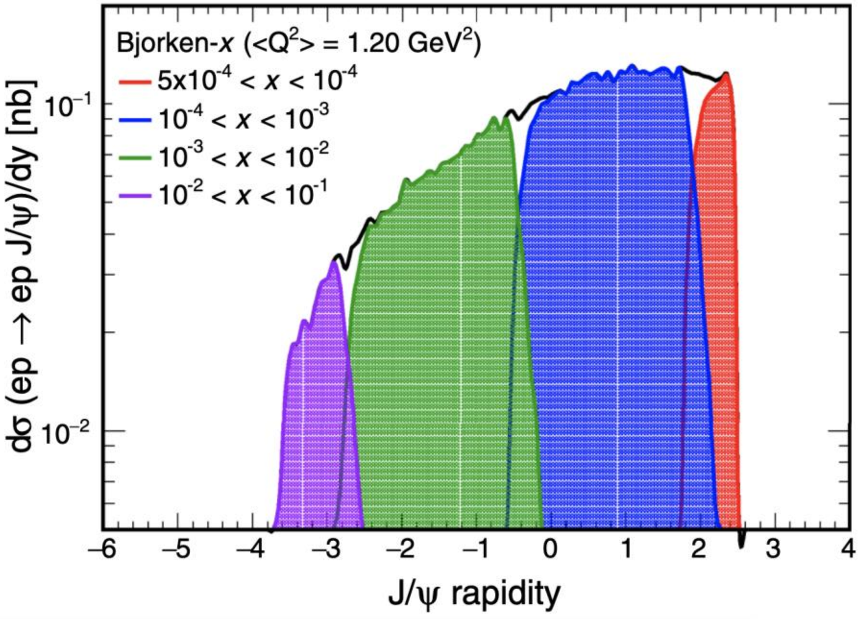
UPCs can probe the transverse profile of the target!

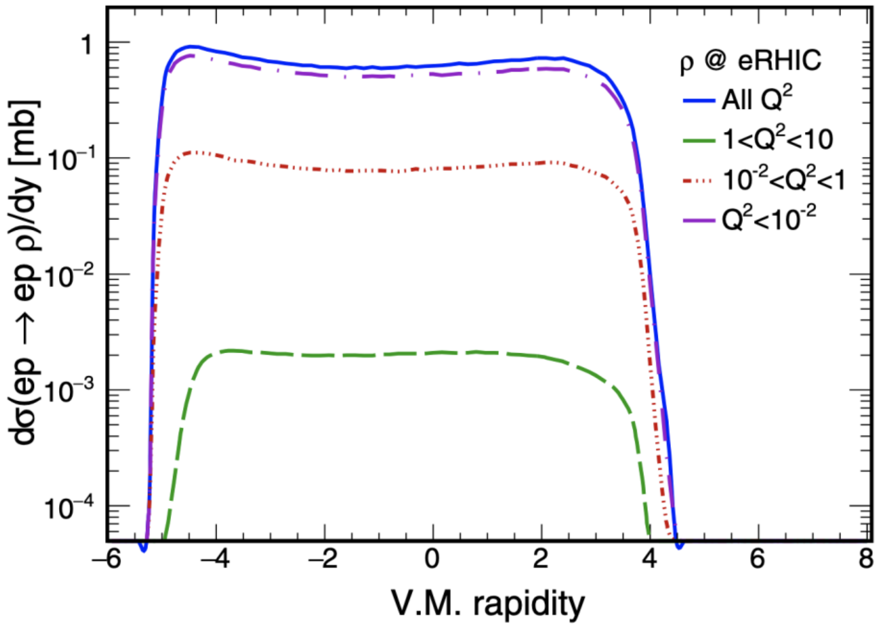
Appearance and location of diffractive dips can be signatures of gluon saturation



Exclusive VM at the acceptance

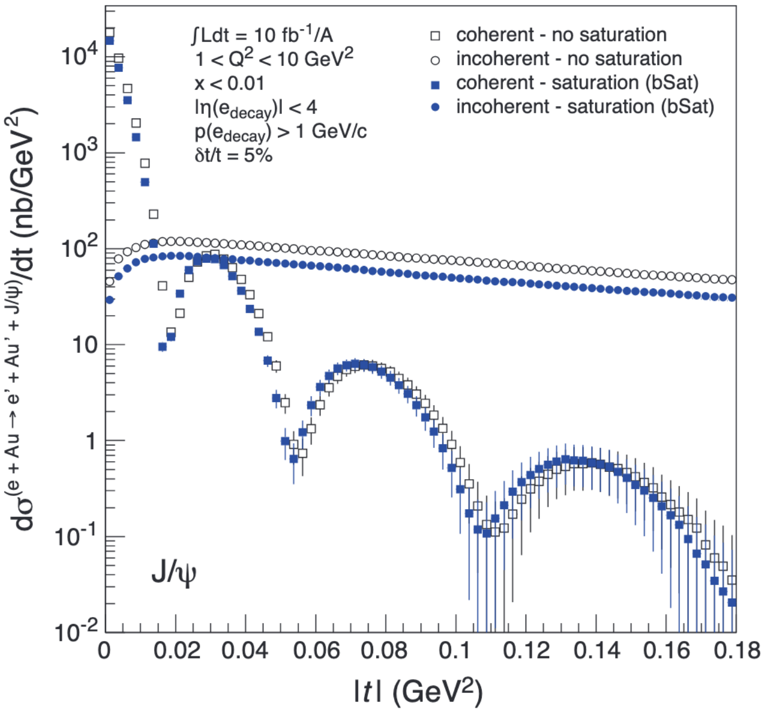
S. Klein and M. Lomnitz
Phys. Rev. C **99**, 105203 (2019)



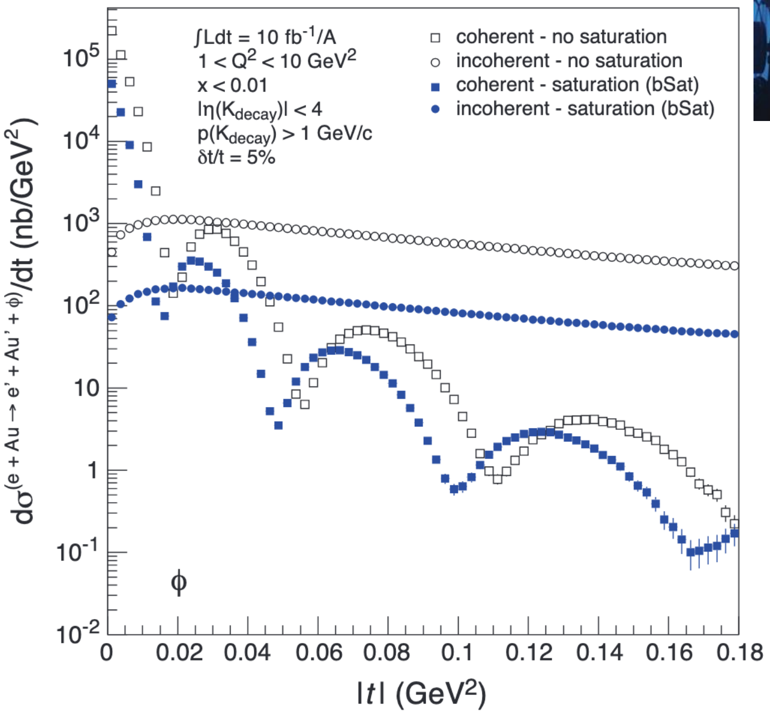


Flipped rapidity convention used

EIC 2012



∫Ldt = 10 fb⁻¹/A
1 < Q² < 10 GeV²
x < 0.01
|η(e_decay)| < 4
p(e_decay) > 1 GeV/c
δt/t = 5%
coherent - no saturation
incoherent - no saturation
coherent - saturation (bSat)
incoherent - saturation (bSat)
J/ψ
dσ^(e + Au → e' + Au' + J/ψ)/dt (nb/GeV²)
|t| (GeV²)



∫Ldt = 10 fb⁻¹/A
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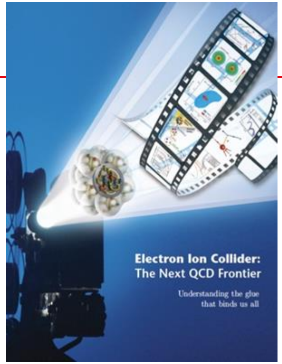
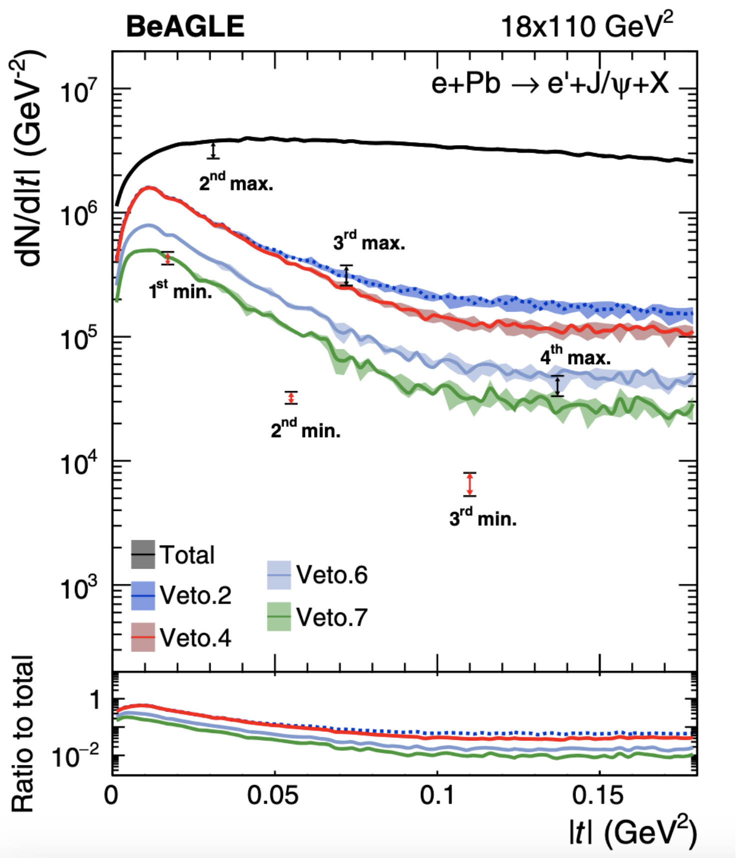
|η(K_decay)| < 4
p(K_decay) > 1 GeV/c
δt/t = 5%
coherent - no saturation
incoherent - no saturation
coherent - saturation (bSat)
incoherent - saturation (bSat)
φ
dσ^(e + Au → e' + Au' + φ)/dt (nb/GeV²)
|t| (GeV²)

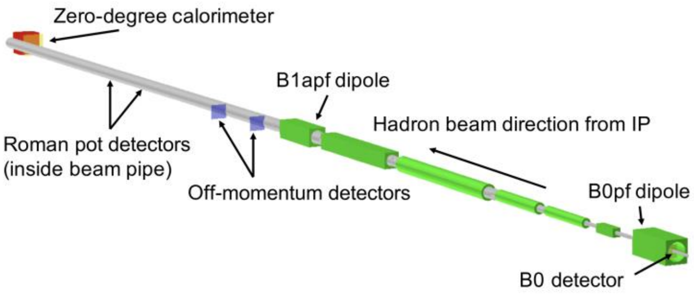


Electron Ion Collider:
The Next QCD Frontier
Understanding the glue that binds us all

Coherent J/ψ selection at ePIC, vetoing incoherent production

W. Chang *et al.*, Phys. Rev. D **104**, 114030 (2021)

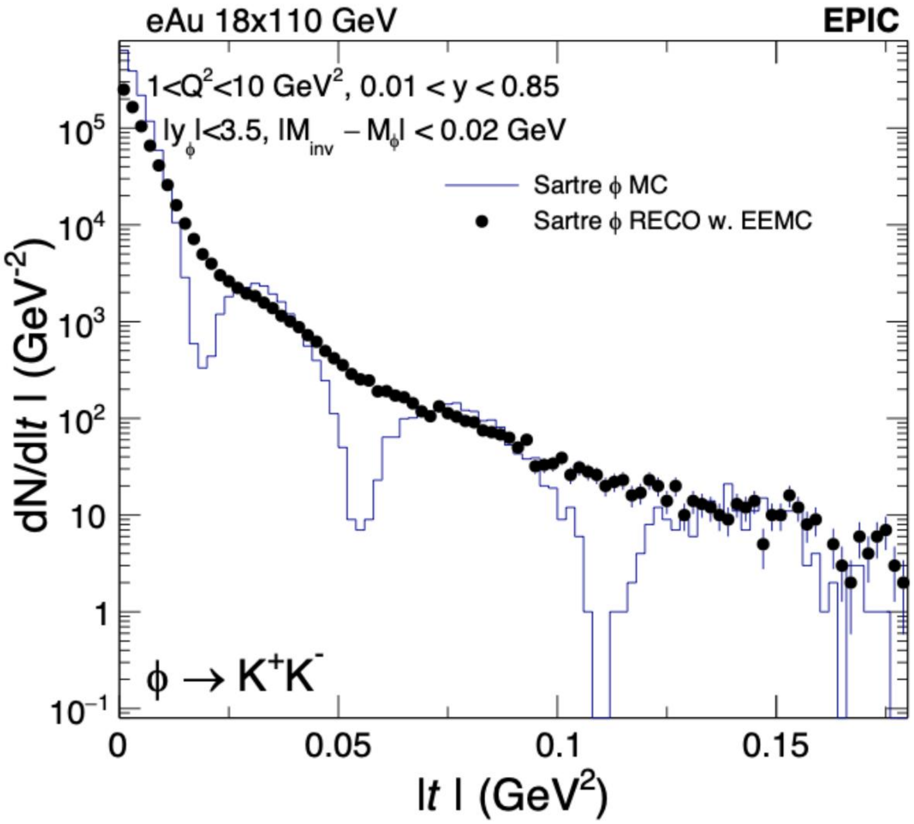




(a) Veto.1: no activity other than e^- and J/ψ in the main detector ($|\eta| < 4.0$ and $p_T > 100$ MeV$/c$).
(b) Veto.2: veto.1 and no neutron in ZDC.
(c) Veto.3: veto.2 and no proton in RP.
(d) Veto.4: veto.3 and no proton in OMDs.
(e) Veto.5: veto.4 and no proton in B0.
(f) Veto.6: veto.5 and no photon in B0.
(g) Veto.7: veto.6 and no photon with $E > 50$ MeV in ZDC.

Forward instrumentation and modeling crucial

Coherent ϕ(1020) electroproduction

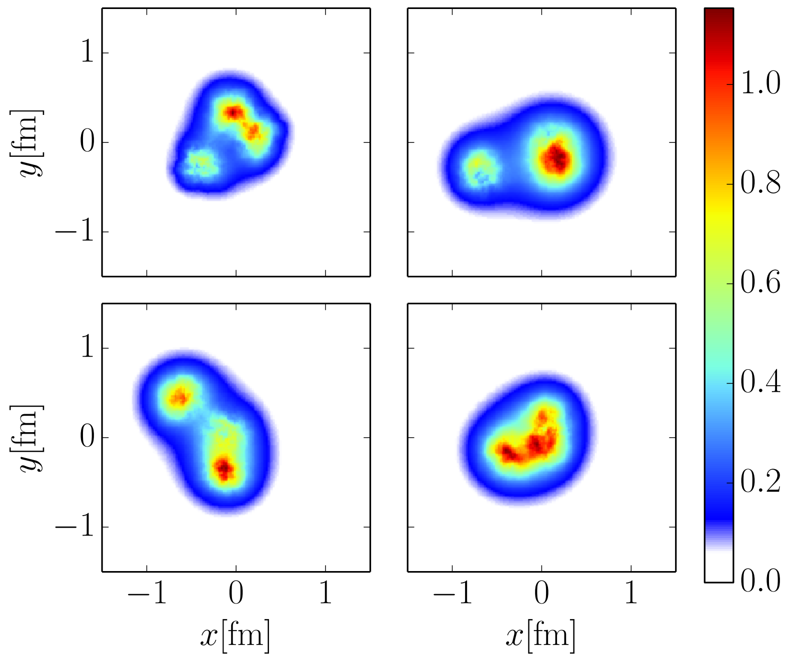


Sensitivity to gluon saturation

FF instrumentation and modeling crucial

Incoherent J/ψ and comparison to HERA data

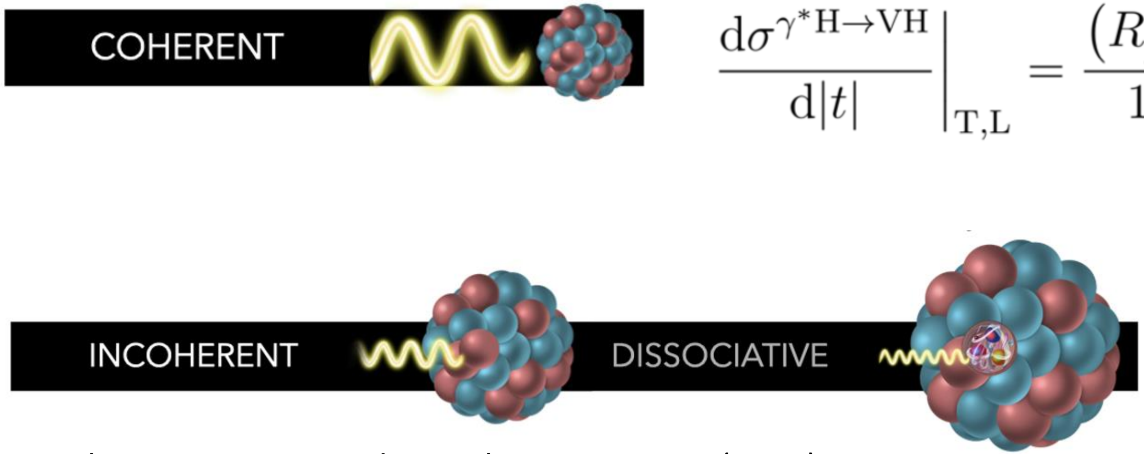
H. Mäntysaari & B. Schenke



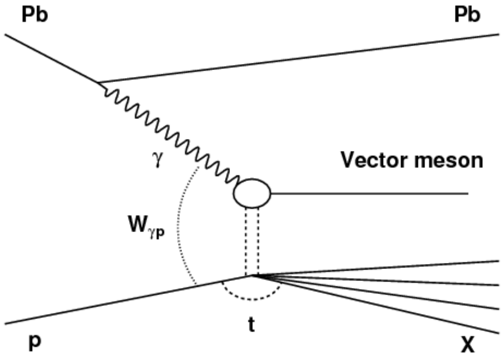
Examples of proton density profiles at x ~ 10^{-3}

Dissociative J/ψ in UPC

See talk by A. Ridzikova at DIS'24
Figures from her



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



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

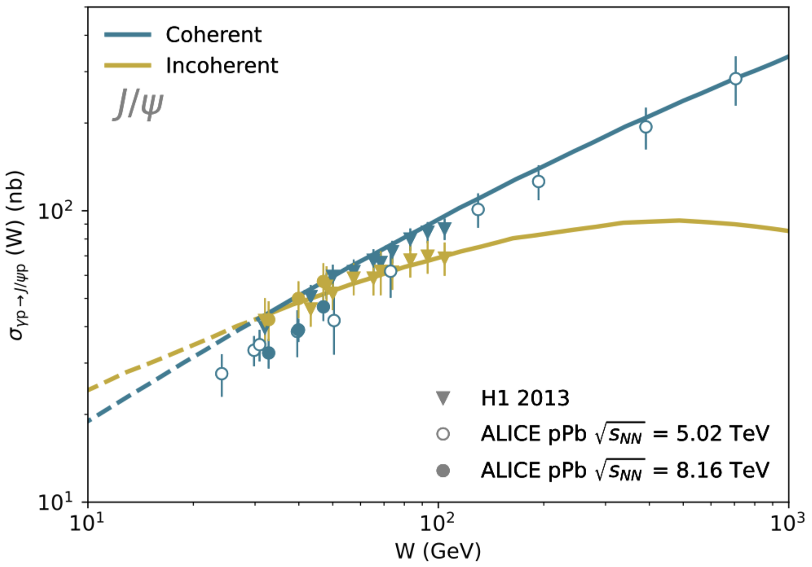
In the hot spot model, the increase in gluon distribution with decreasing Bjorken-*x* is described by the energy-dependent evolution of the number of hot spots

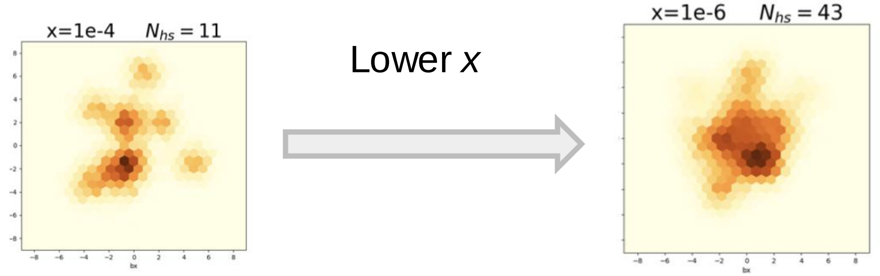
$$\frac{d\sigma^{\gamma^* p \to VY}}{d|t|}\bigg|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} \left(\langle |\mathcal{A}_{T,L}|^2 \rangle - |\langle \mathcal{A}_{T,L} \rangle|^2\right)$$

Gluon saturation and dissociative J/ψ in UPC

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

Phys. Lett. B 852 (2024) 138613





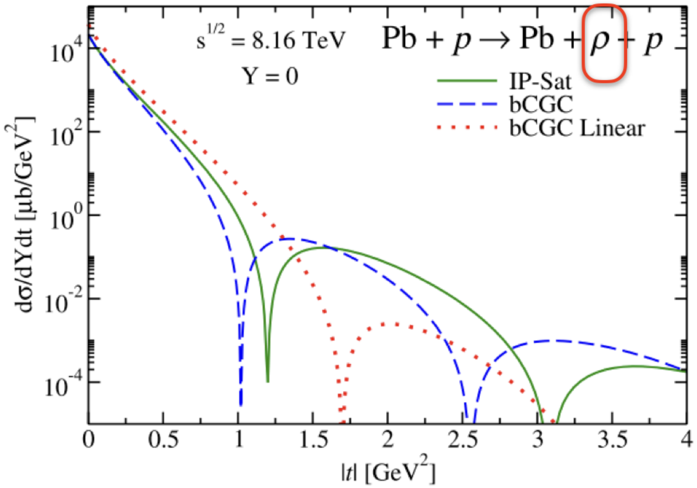
$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p \to VY}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{\mathrm{T,L}}|^2\rangle - |\langle\mathcal{A}_{\mathrm{T,L}}\rangle|^2\right)$$

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

Phys. Lett. B 766 (2017) 186-191

Transverse profile of the target

V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304

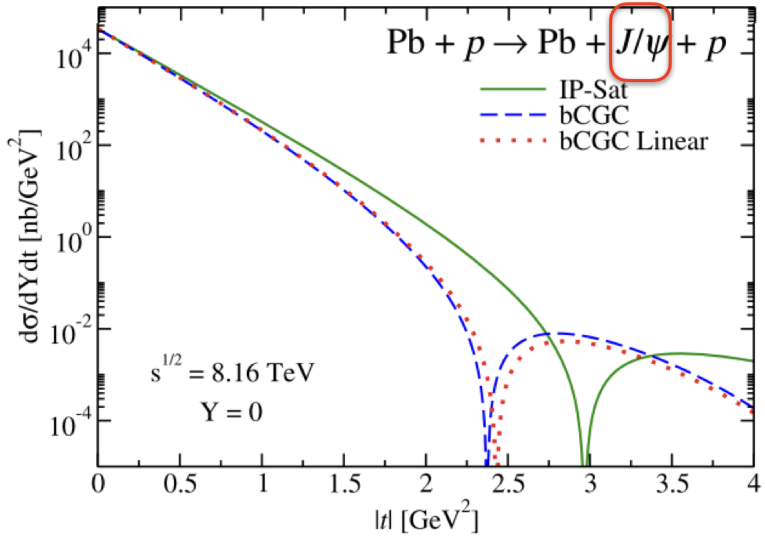


Location of the Diffractive dips:
Different for IP-Sat and bCGC

Energy dependence of the t-distribution: onset of gluon saturation

Signature of gluon saturation

Study of ρ^0 is very promising since diffractive dips expected at lower t values

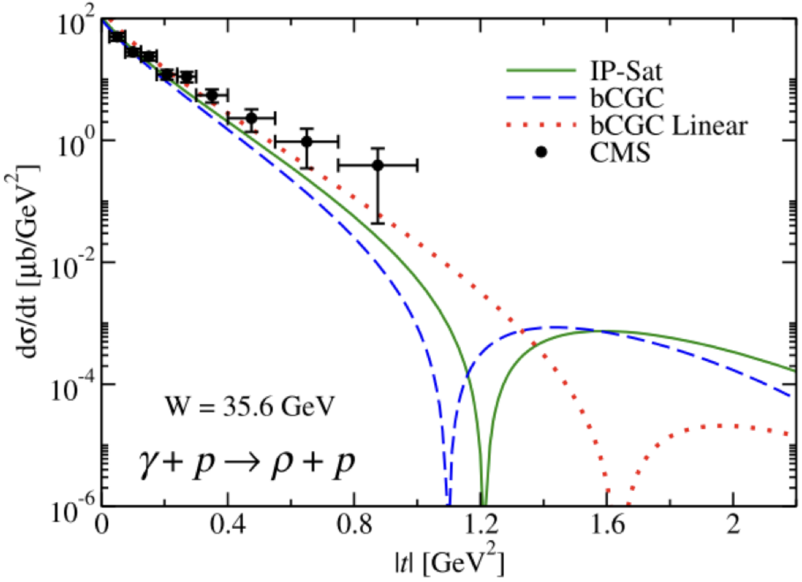


t-dependence measurement of UPC ρ^0

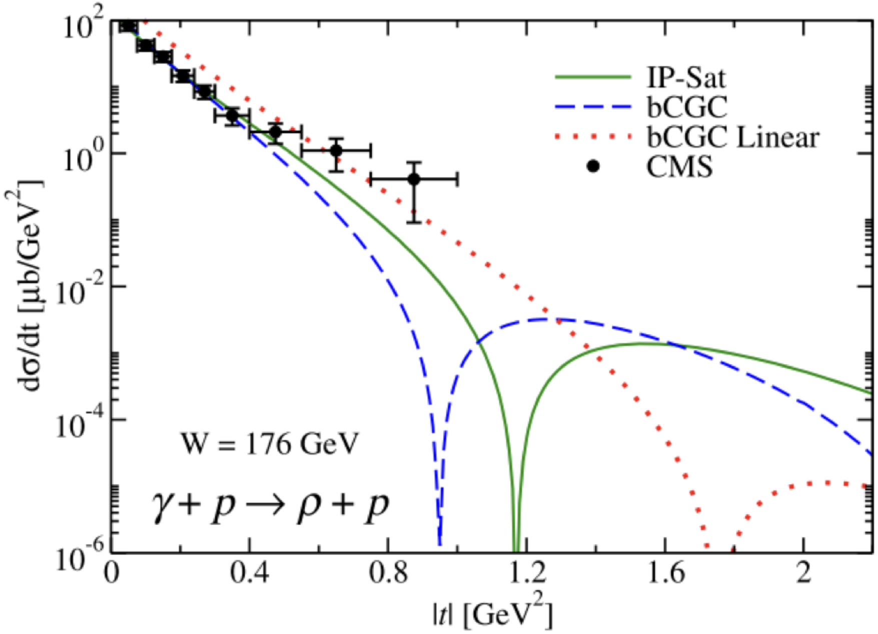
V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304

Similar studies could also be done for Pb targets, but energies are lower and also challenging in UPCs

36 Gev



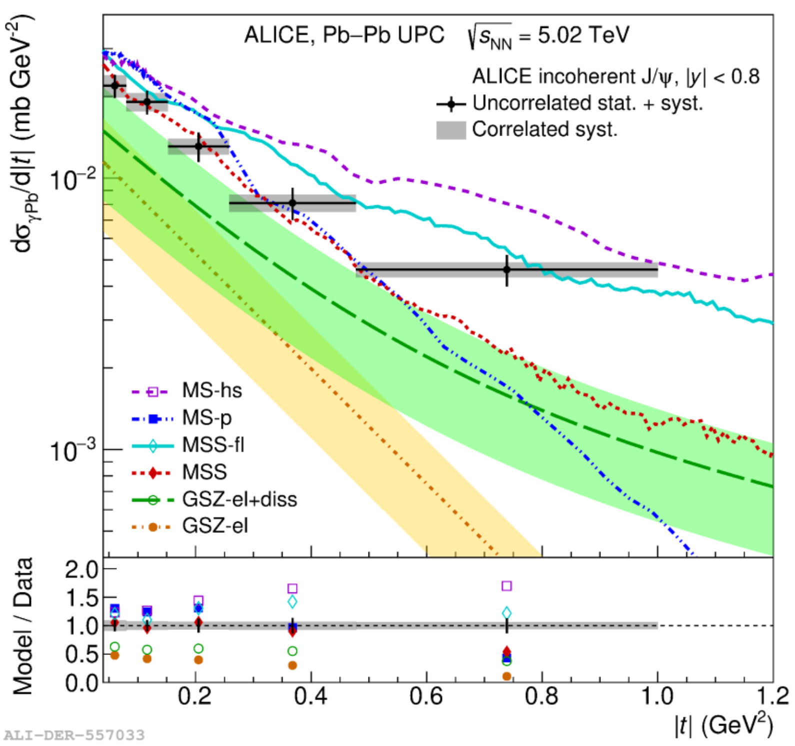
176 Gev



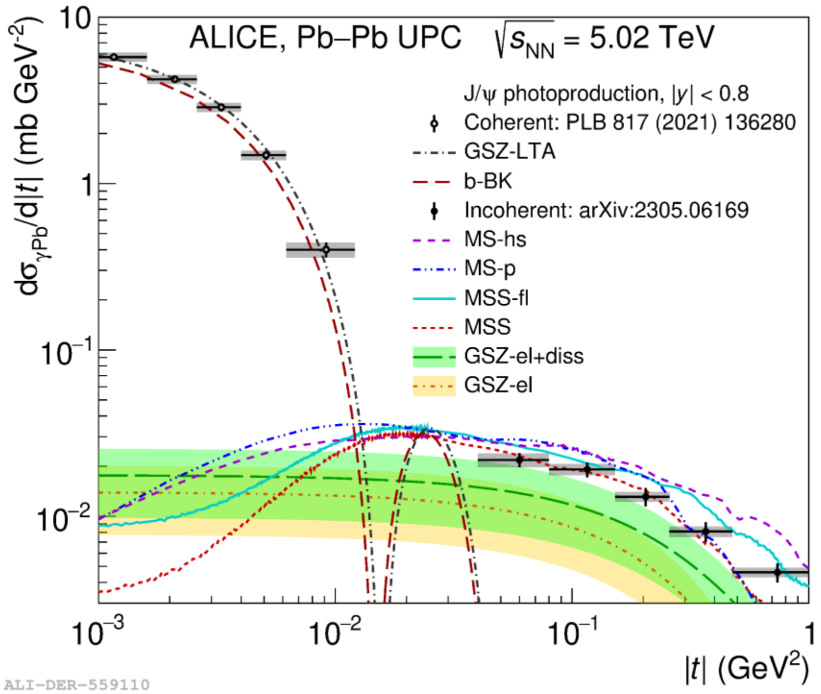
t-dependence of coherent and incoherent J/ψ in UPC Pb-Pb

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

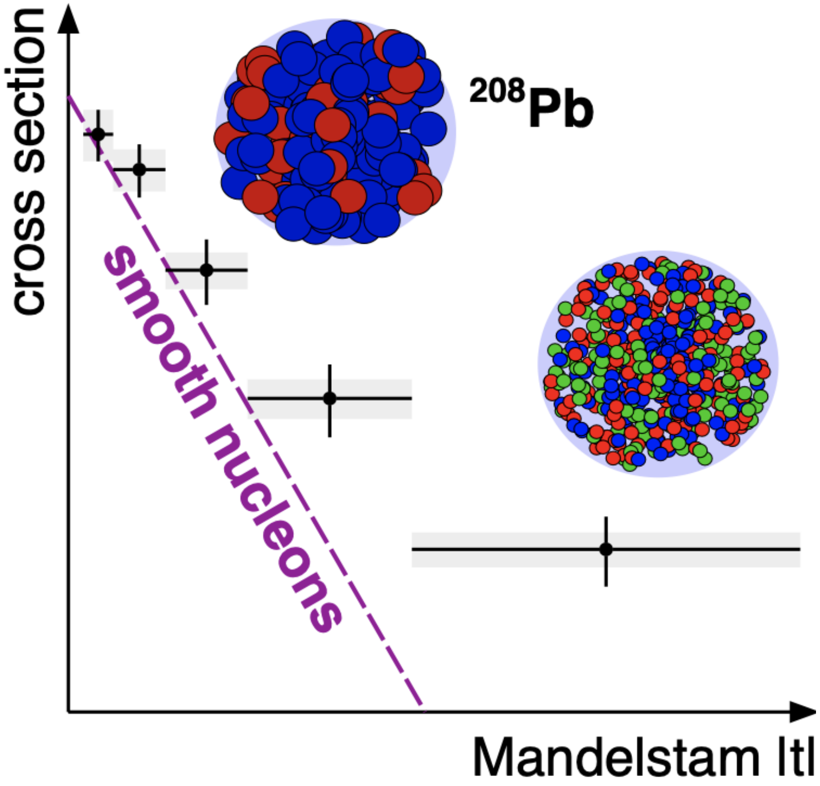
Phys.Rev.Lett. 132 (2024) 16, 162302



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



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

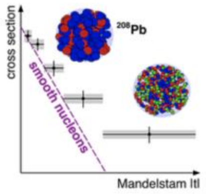


Editors' Suggestion

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

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

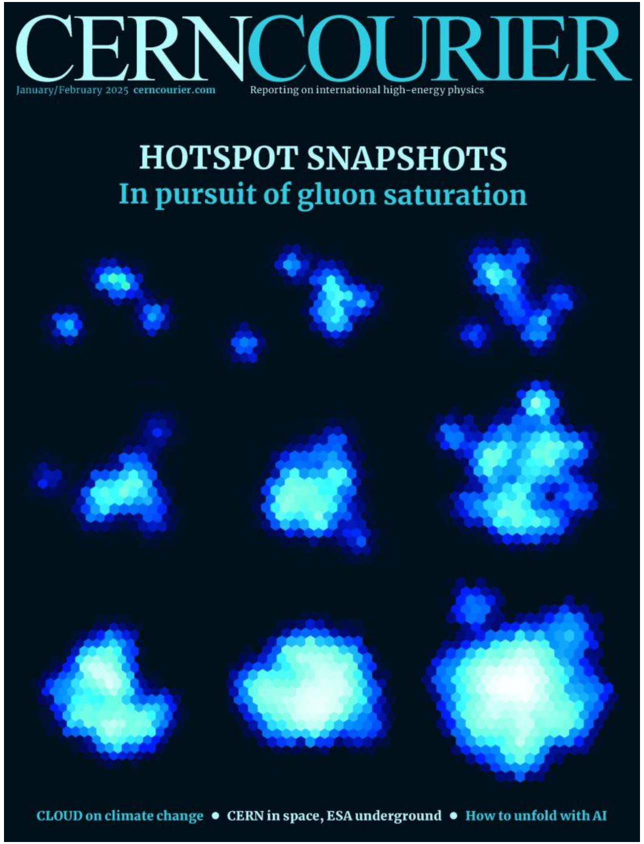
Phys. Rev. Lett. **132**, 162302 (2024) – Published 19 April 2024



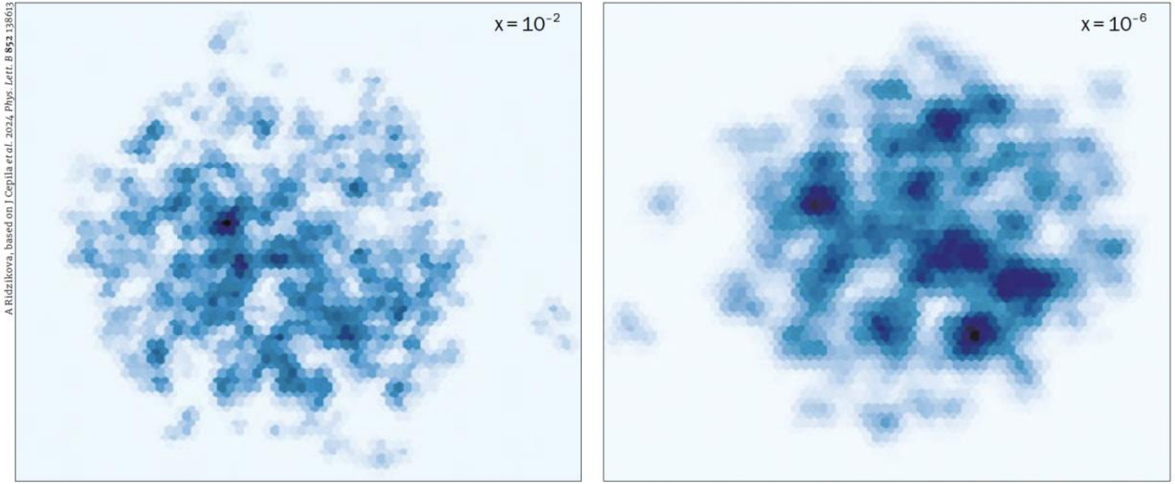
The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

Show Abstract +

Gluonic hot spots

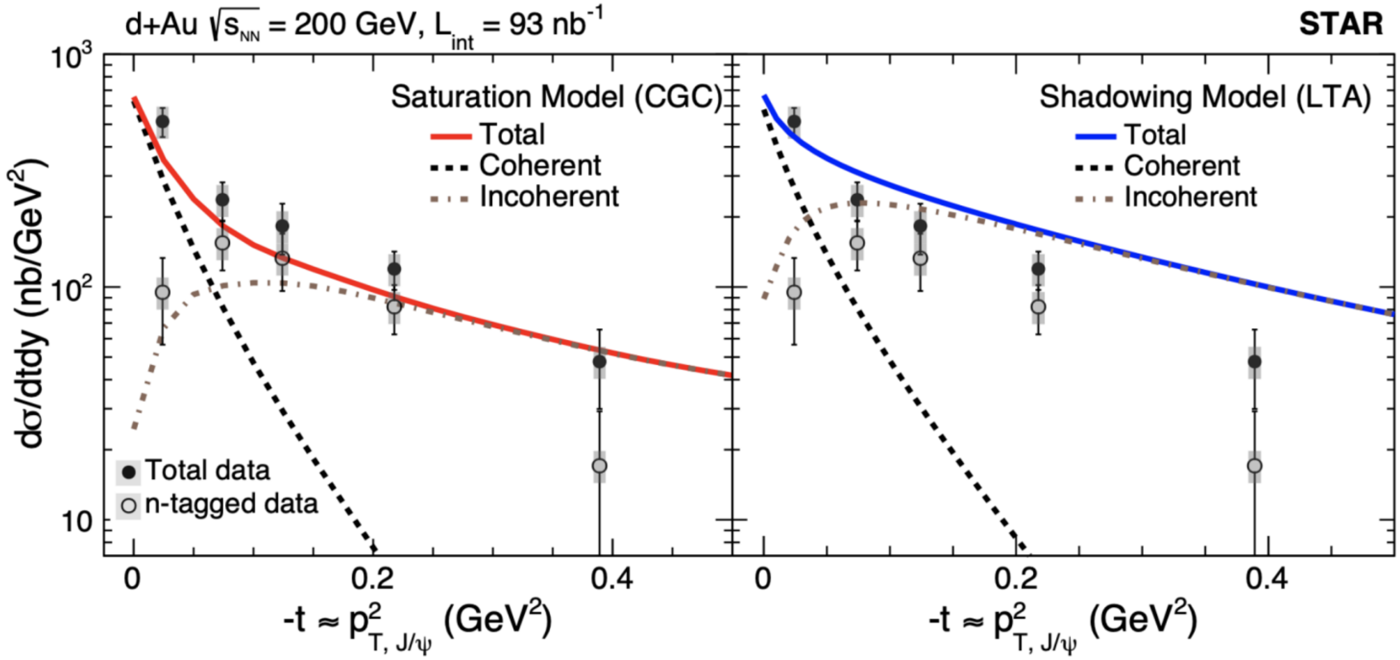


J. Cepila et al. 2024 Phys. Lett. B 852 138613



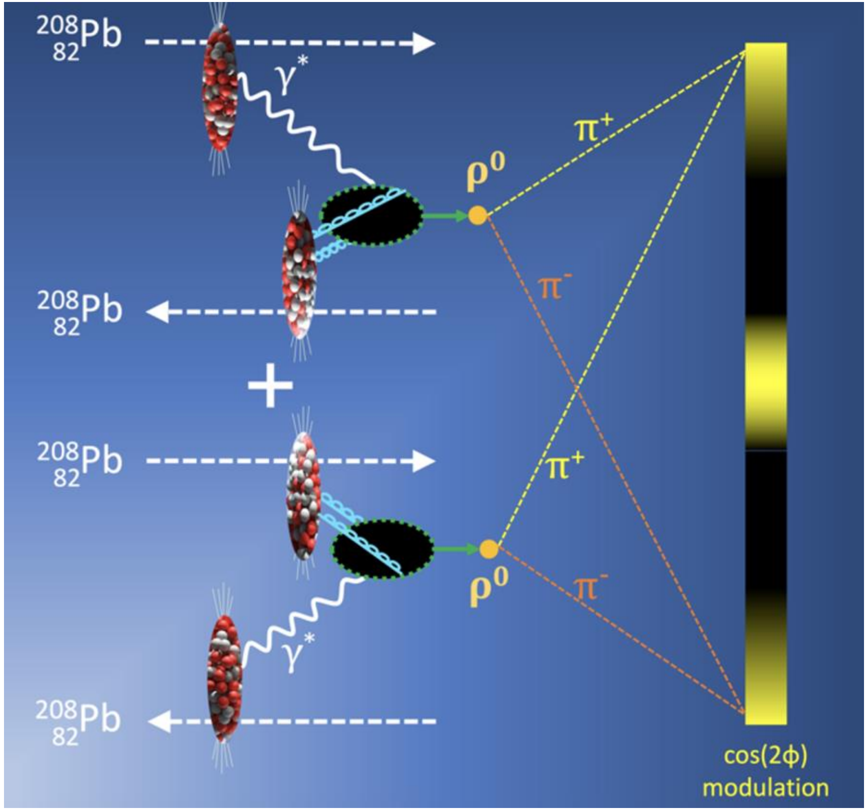
Hotspot snapshots *Simulations of the transverse density of gluons in lead nuclei at Bjorken x of 10^{-2} (left) and 10^{-6} (right). The distributions are 10 times broader than for protons and span almost 15 fm. The number of gluonic hotspots increases from 1,400 to 12,000 as x drops by a factor of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

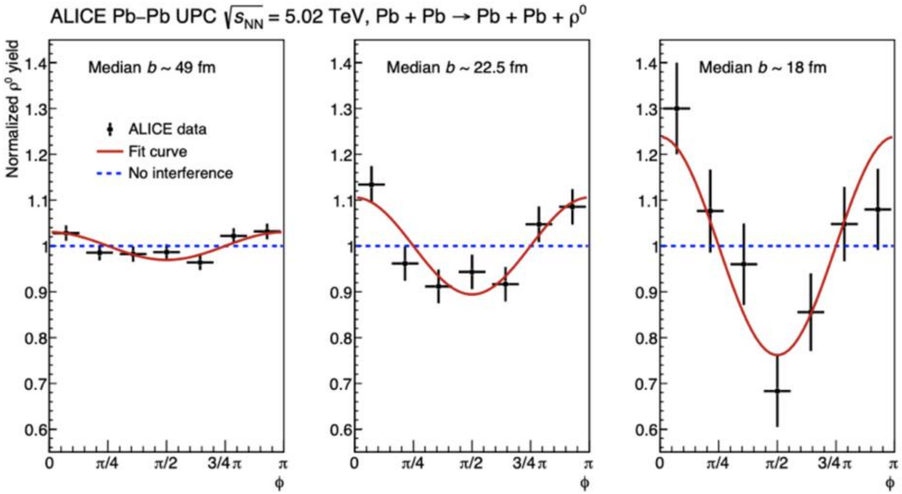
Incoherent J/ψ in UPC d+Au



As expected, no additional component expected at lower energies with limited luminosities.
At the EIC the high high luminosities is very promising

A femtometer scale double-slit experiment

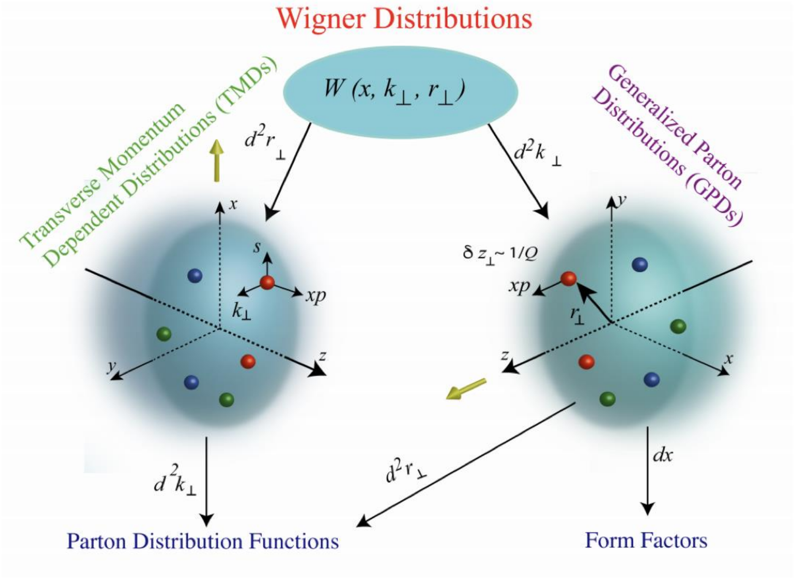




STAR has an active program here.

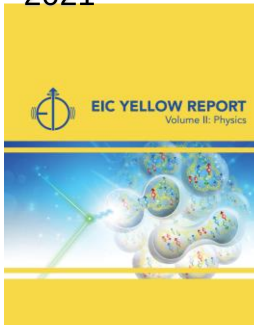
In ALICE, first measurement in terms of impact parameter dependence

Diffractive dijets

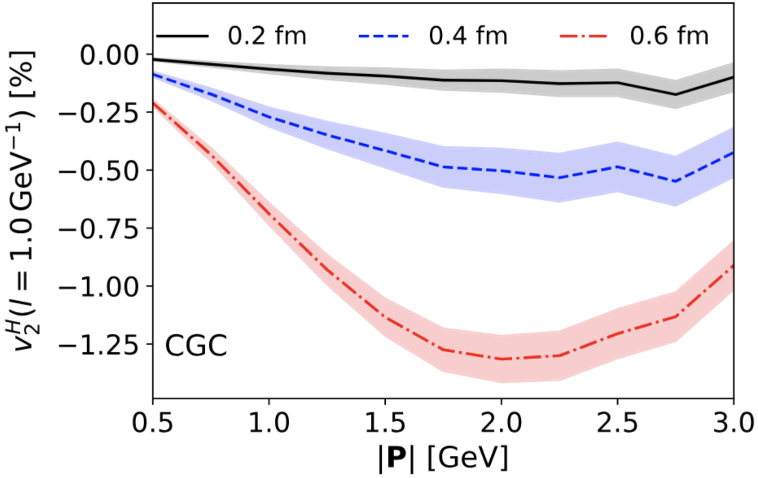


H. Mantysaari, N. Mueller, B. Schenke
Phys. Rev. D 99 (7) (2019) 074004

2021



Original ideal the effect was a percent level. Several theory groups studied it

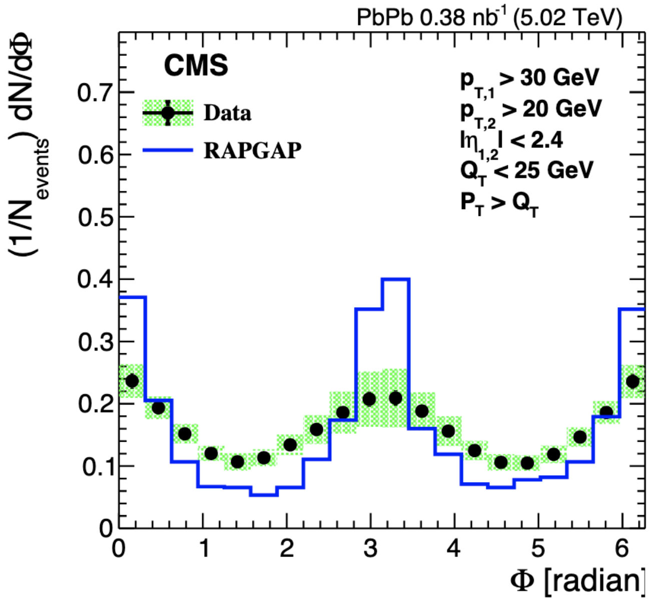


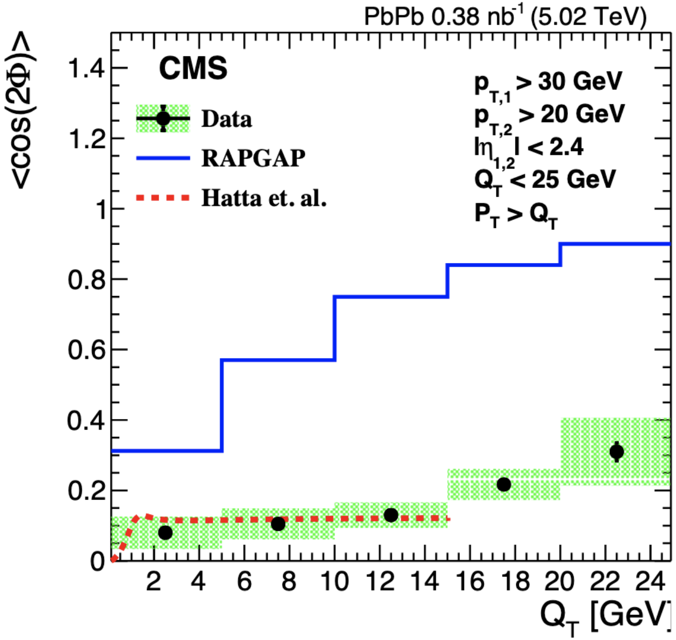
Azimuthal correlations of exclusive dijets

Another example of synergies with EIC,
testing and strengthening the science opportunities

Several new theory ideas for the EIC resulted from this work

CMS Collaboration
Phys. Rev. Lett. 131 (2023) 5, 051901





Summary

- The UPC program and the EIC have strong synergies, offering complementary insights into fundamental physics.

- While UPCs probe the energy frontier, the EIC focuses on the luminosity and precision frontier.

- Existing synergies between the two programs demonstrate mutual benefits, with improved modeling, playing a crucial role in refining high-luminosity EIC measurements.

- These connections are also valuable for shaping discussions on the early science goals of the EIC.

- Additionally, a "multi-messenger program" may be necessary to fully explore certain observables.

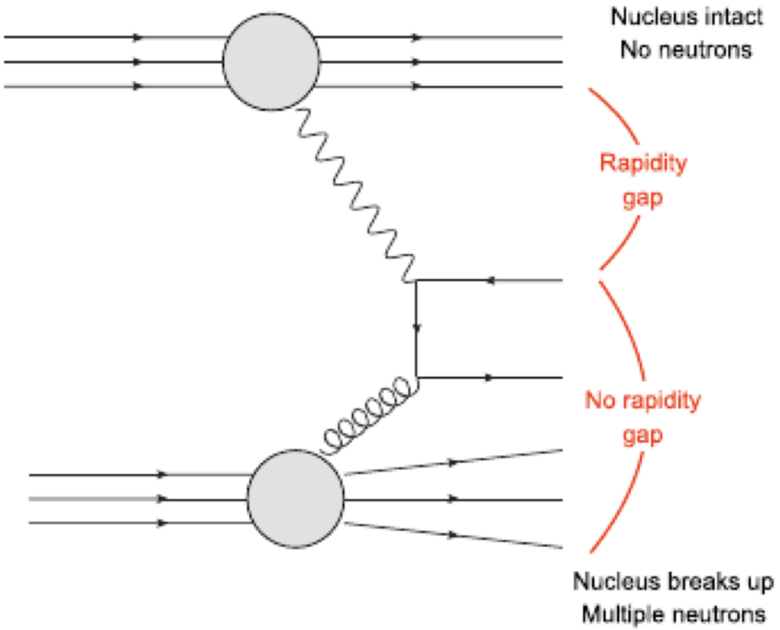
Thanks!

Run 3 data analysis: 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

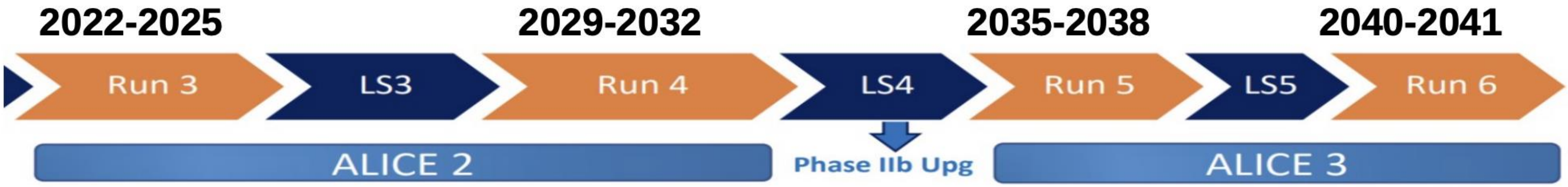
σ(Pb+Pb → Pb+ccbar+X) = 2b

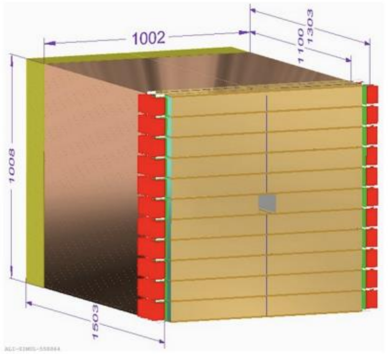
σ(Pb+Pb → Pb + bbbar +X) = 830 μb

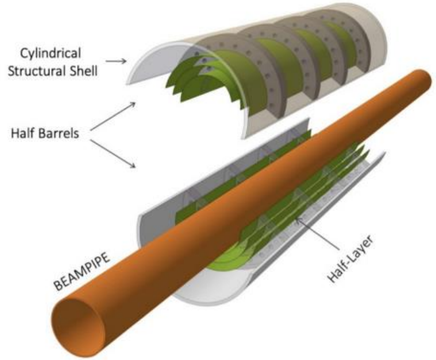
Direct production: a bare photon interacts with a parton in the target

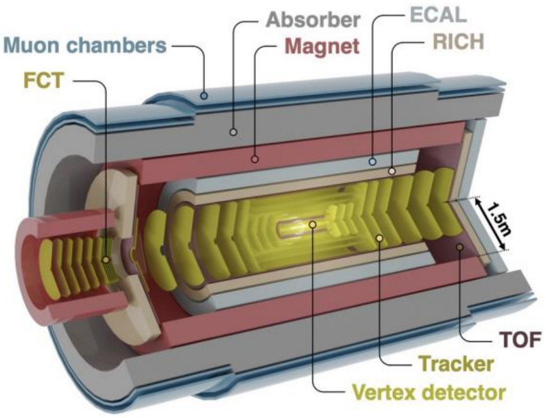
Resolved production: the photon fluctuates to vector meson which interacts inelastically with the target

CERN LHC and ALICE timeline







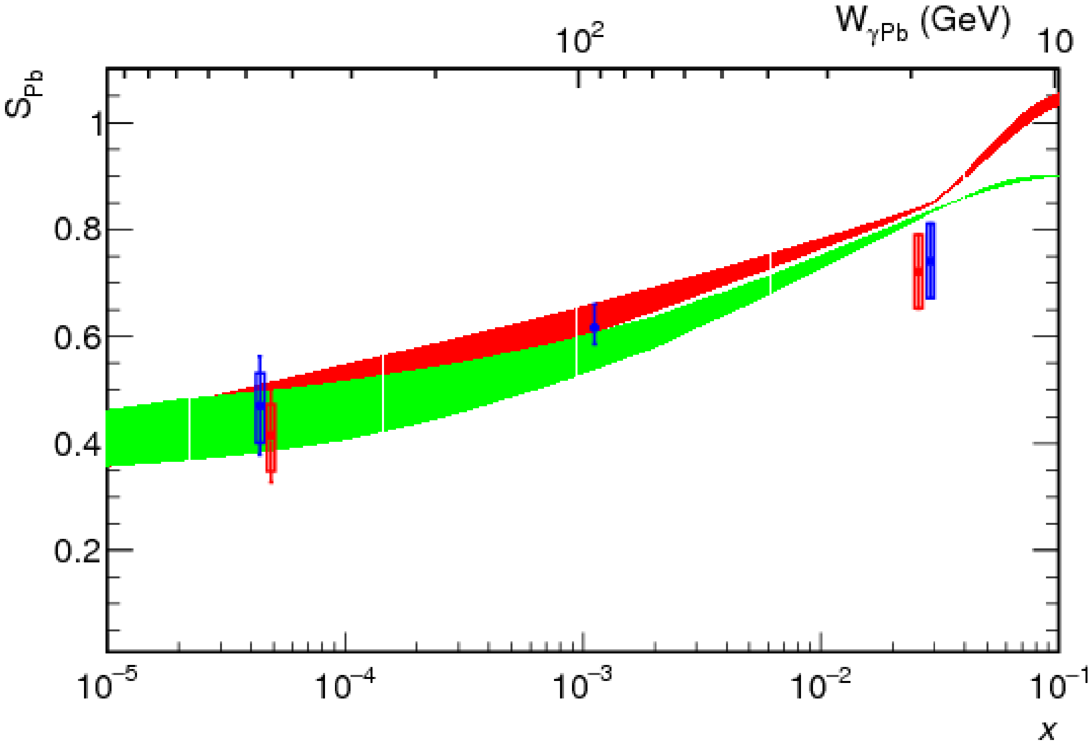


FoCal and ITS3

ALICE3

Nuclear suppression factor for peripheral (not UPC) J/ψ

J.G. Contreras, *Phys. Rev .C* 96 (2017) 1, 015203



Run 1 data from ALICE observed Coherent-like J/ψ from peripheral hadronic PbPb events. Process later confirmed by STAR

The photon flux depends on the impact parameter, these peripheral J/ψ explore γP energies beyond coherent J/ψ at the same y interval at the same cms energy

Sensitivity to x ~ 10^{-5}