U.S. DEPARTMENT OF ENERGY

Office of Science

Coherent and incoherent J/ψ photoproduction

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for the ALICE Collaboration

APS GHP workshop

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KU THE UNIVERSITY OF KANSAS

Gluonic saturated matter

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

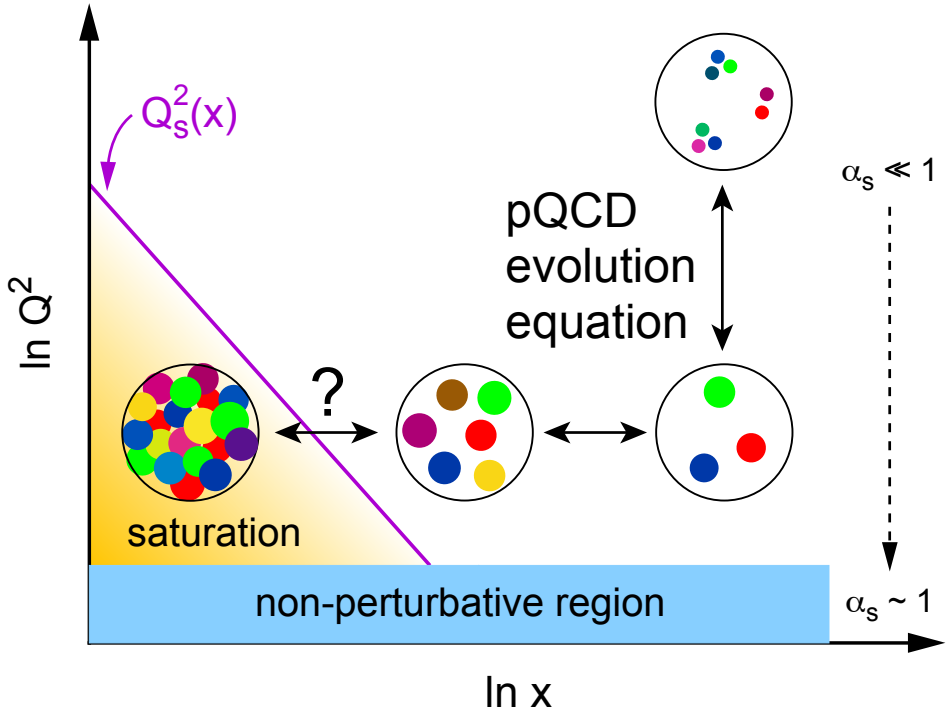
gluon emission

gluon recombination

Dynamical equilibrium of gluon saturation state reached

- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- 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

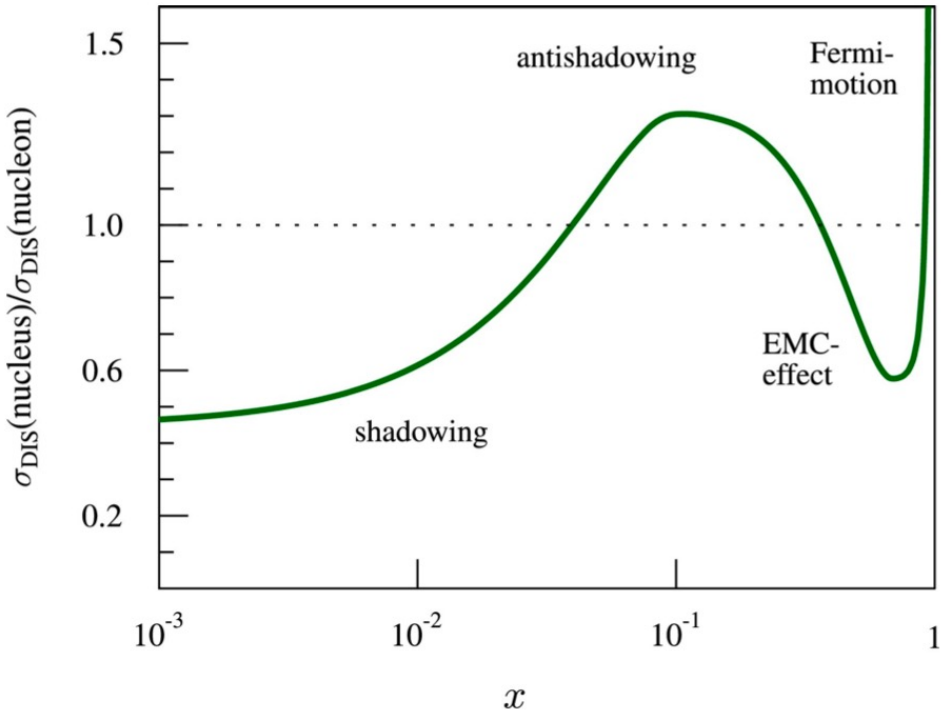


- Experimental observables needed to map out the transition between the dilute and saturation regimes
- For nuclei, the saturation scale is enhanced by a $A^{1/3}$ factor

$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

Nuclear effects at low x 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

The LHC as 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,

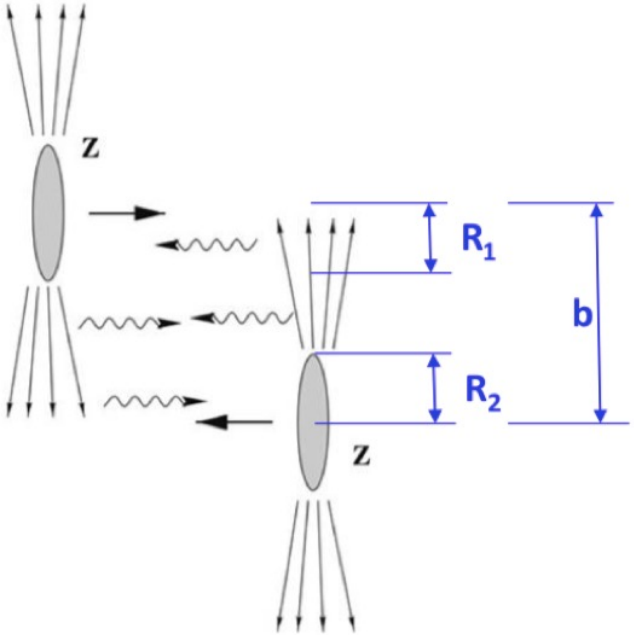
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

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

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

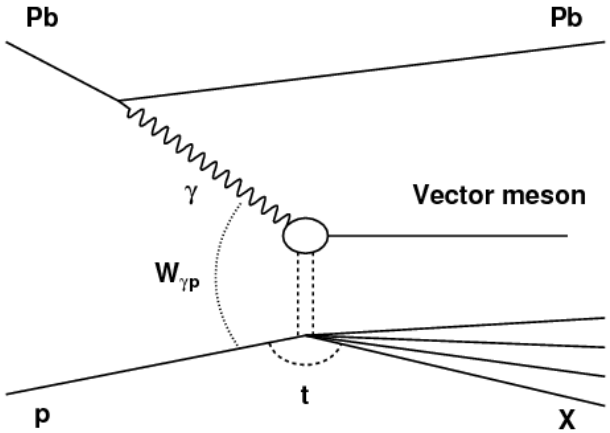
Interactions mediated by the EM interactions

Equivalent photon flux



Vector meson (VM) photoproduction in UPCs

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

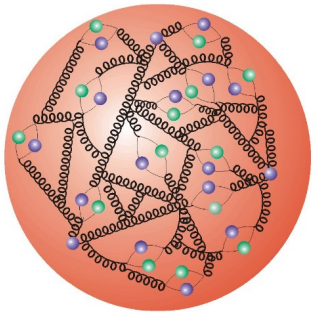


- As in DIS, several reactions are possible in UPCs:

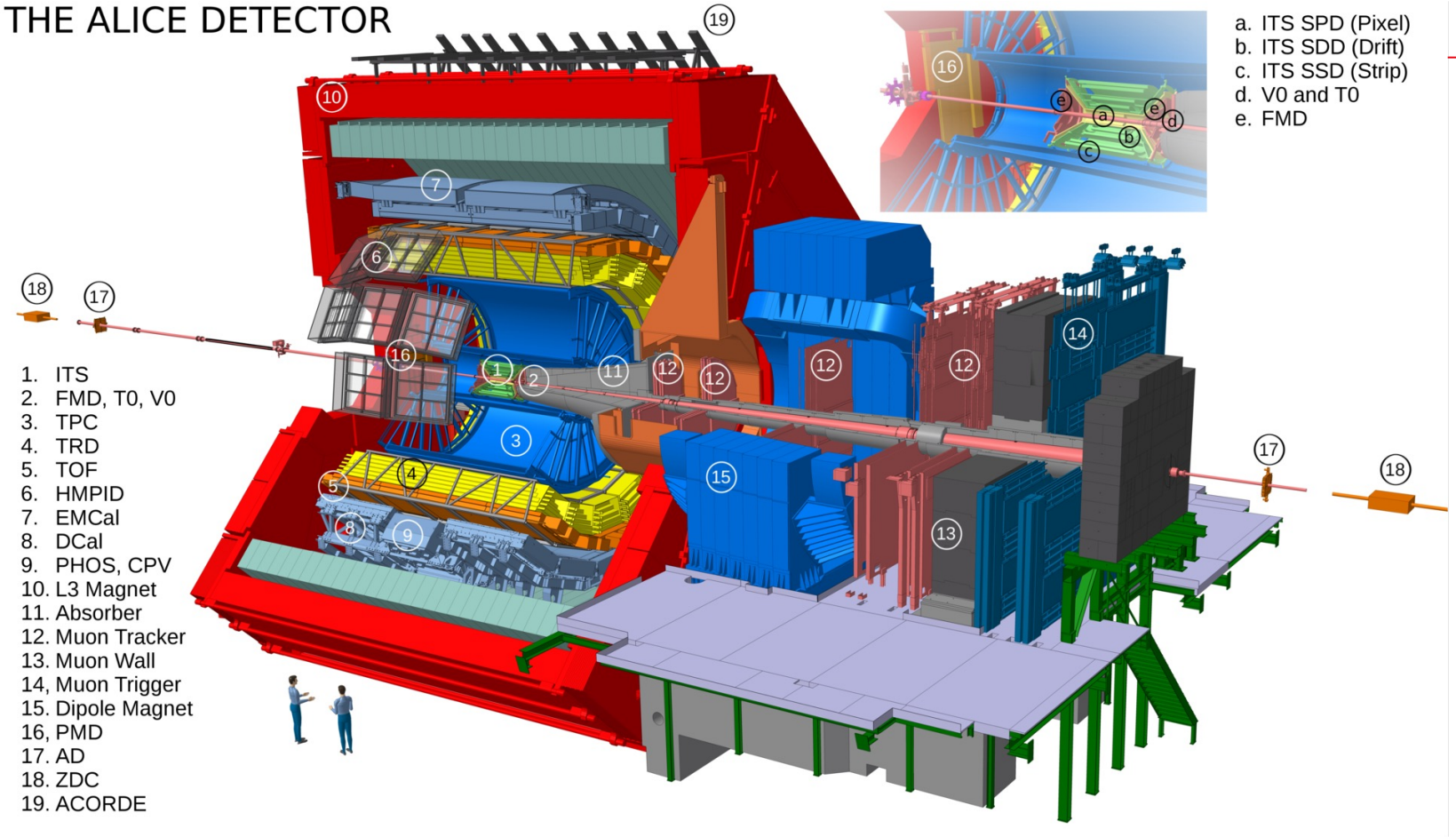
  -Exclusive photoproduction
  -Semi-exclusive photoproduction
  -Inclusive photoproduction

- By studying various VMs, it is possible to probe 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



THE ALICE DETECTOR



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

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

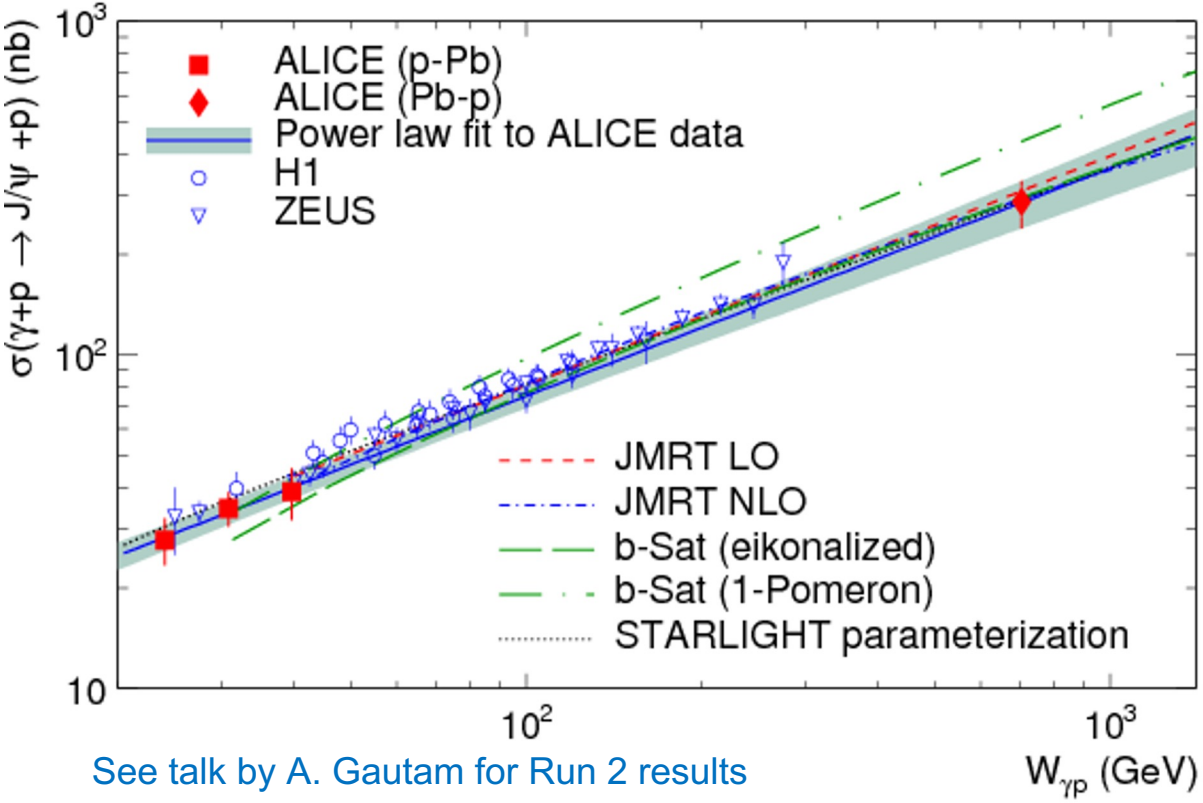
Positive rapidity

Negative rapidity

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

First exclusive J/ψ measurements by ALICE using Run 1 (2013)

Phys. Rev. Lett. 113 (2014) 23, 232504



See talk by A. Gautam for Run 2 results

- No change with respect to HERA power-law growth observed at low energies up to 700 GeV
- UPC pPb collisions have no ambiguity on the photon energy

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

ALICE UPC results using Run 2 data

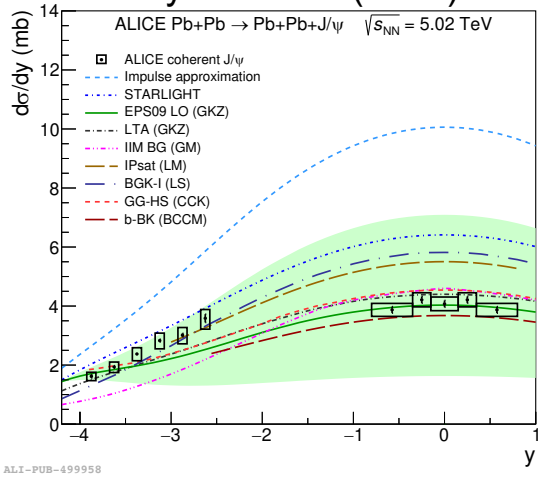
- Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb–Pb collisions at √s = 5.02 TeV
  Phys. Lett. B798 (2019) 134926
- Coherent photoproduction of ρ0 vector mesons in ultra-peripheral Pb–Pb collisions at √s = 5.02 TeV
  JHEP 06 (2020) 035
- Coherent J/ψ and ψ′ photoproduction at midrapidity in ultra-peripheral Pb-Pb collisions at √s = 5.02 TeV
  Eur. Phys. J. C 81 (2021) 712
- First measurement of coherent ρ0 vector mesons in ultra-peripheral Xe–Xe collisions at √s = 5.44 TeV
  Phys. Lett B 820 (2021) 136481
- First measurement of the |t| dependence of coherent J/ψ photonuclear production
  PLB 817 (2021) 136280
- Neutron emission in ultraperipheral Pb–Pb collisions at √s = 5.02 TeV
  arXiv:2209.04250. Accepted by PRC

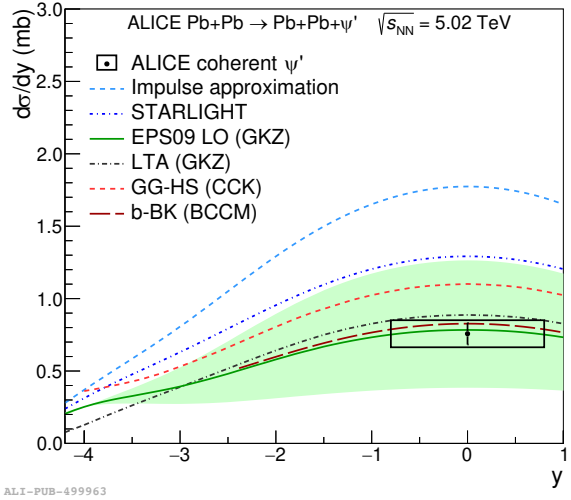
Two new preliminary results presented:

- More on the energy dependence of coherent J/ψ
- t-dependence of incoherent J/ψ

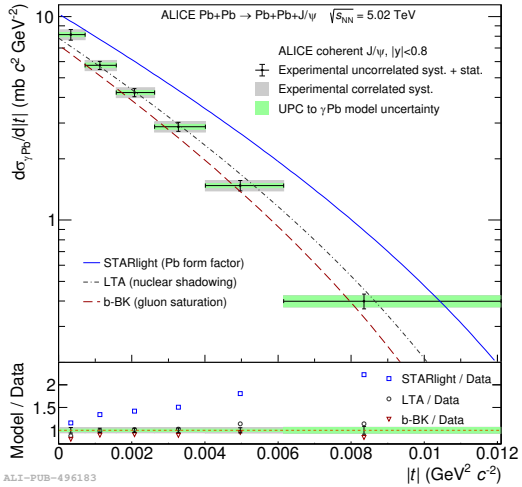
Comprehensive UPC vector meson program at ALICE

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





PLB 817 (2021) 136280



Confirmation of nuclear shadowing with Run 2 data

t-dependence only described by shadowing or gluon saturation model

Coherent J/ψ in UPC Pb-Pb

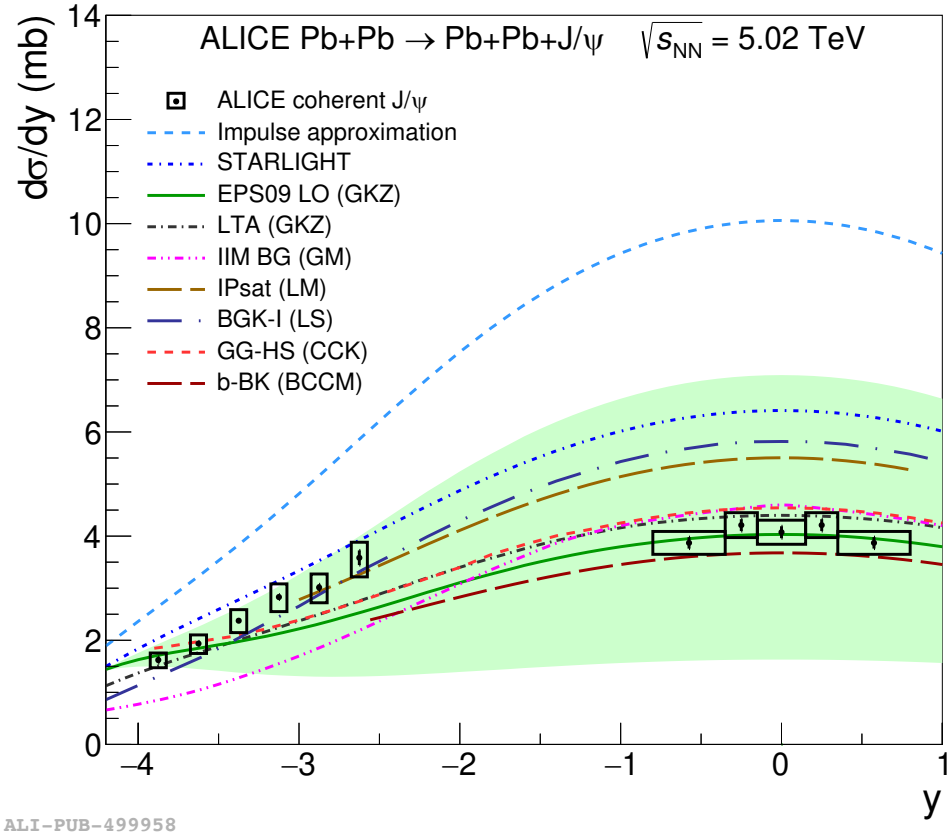
Eur. Phys. J. C 81 (2021) 712

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

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

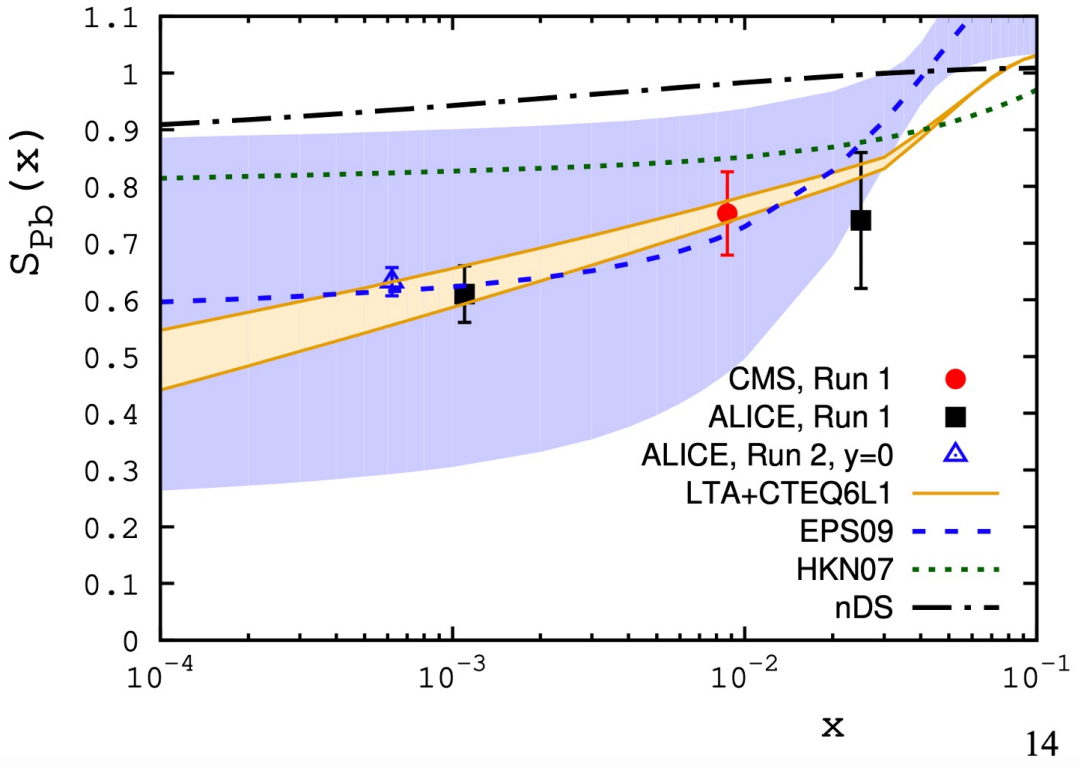
Mid-rapidity x ~10^{-3}

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

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

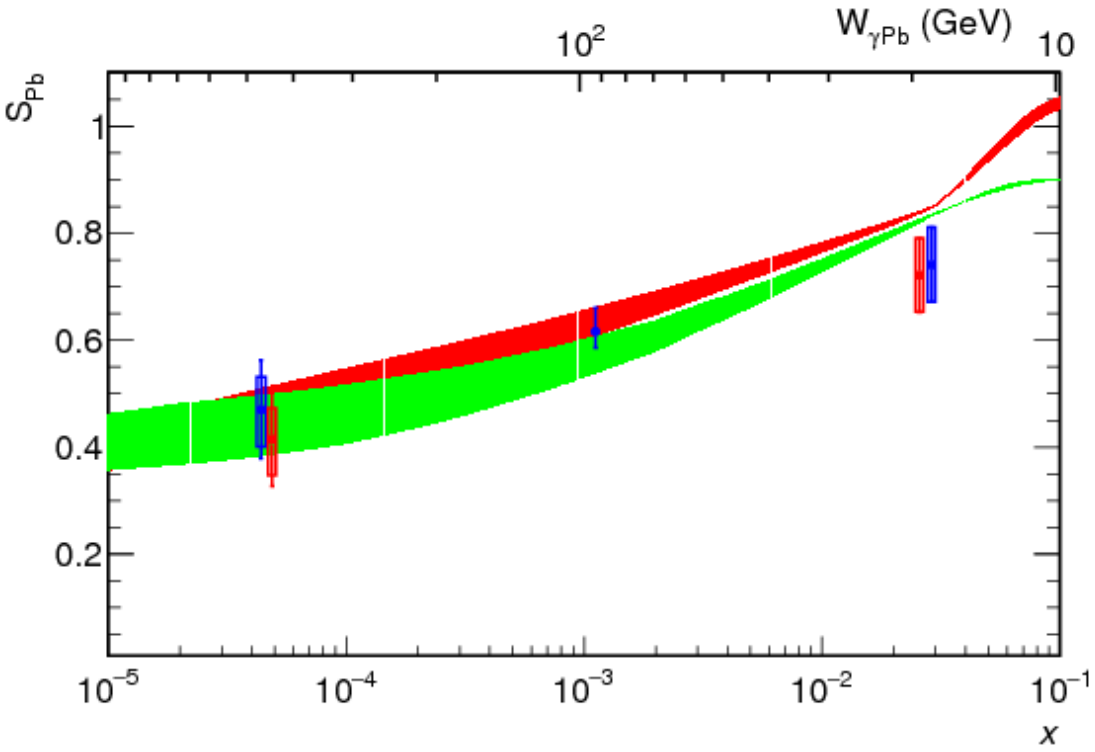
Run 1 data from ALICE was the first at indicating nuclear gluon shadowing at x ~ 10^{-3}

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

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

Analysis using peripheral and UPC J/ψs

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

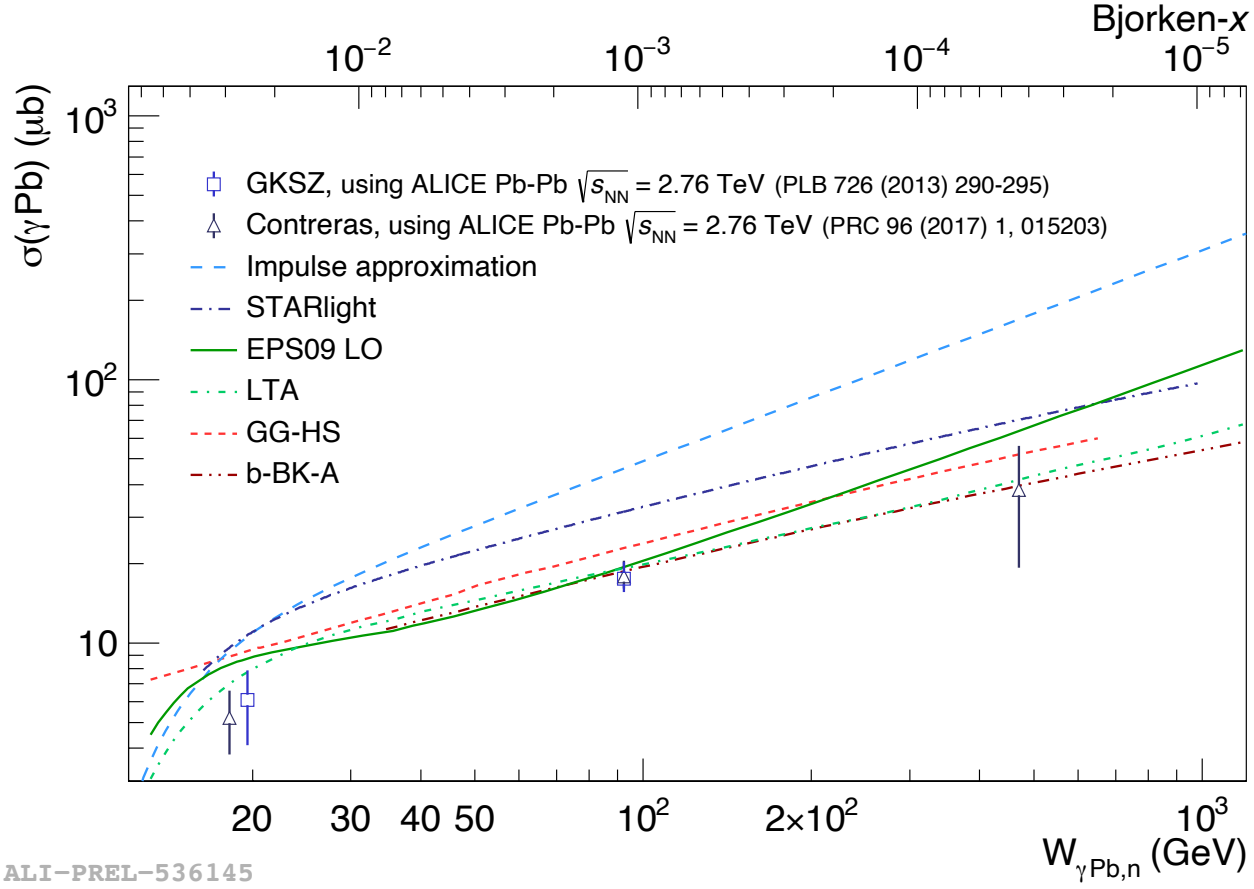


Run 1 data from ALICE observed coherent-like J/ψ from peripheral hadronic PbPb events. Process later confirmed by STAR

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

Sensitivity to x ~ 10^{-5}

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



Compilation of published results based on ALICE Run 1 data, compared to current model calculations

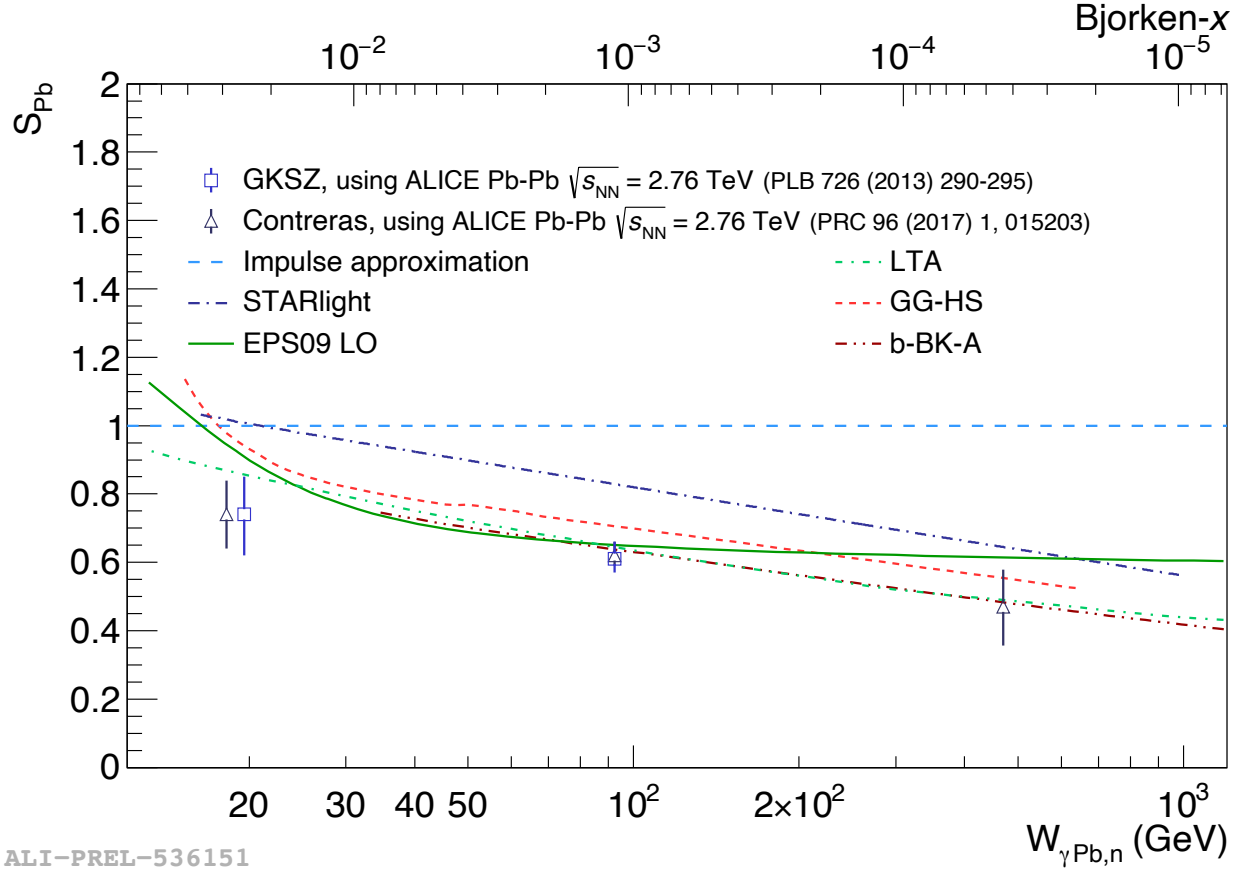
Low x described by shadowing and saturation models

Sensitivity to x ~ 10^{-5}

Nuclear suppression factor – ALICE Run 1 data

Coherent J/ψ in γPb

For x ~ 10^{-5} data favor both shadowing and saturation models



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

$$\frac{d\sigma}{dy} = \frac{d\sigma(0\mathrm{n}0\mathrm{n})}{dy} + 2\frac{d\sigma(0\mathrm{n}\mathrm{X}\mathrm{n})}{dy} + \frac{d\sigma(\mathrm{X}\mathrm{n}\mathrm{X}\mathrm{n})}{dy}$$

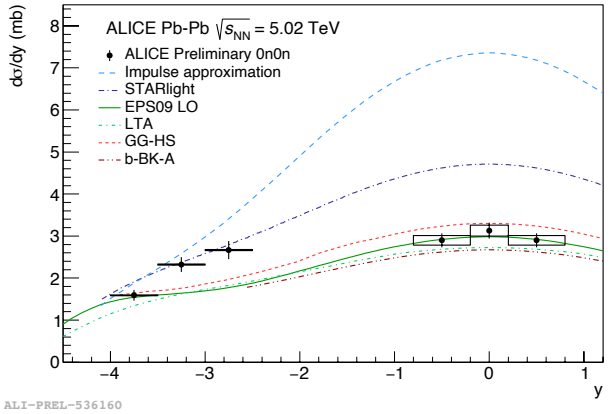
Solving the linear equations resolves the two-fold ambiguity for VMs at y ≠ 0

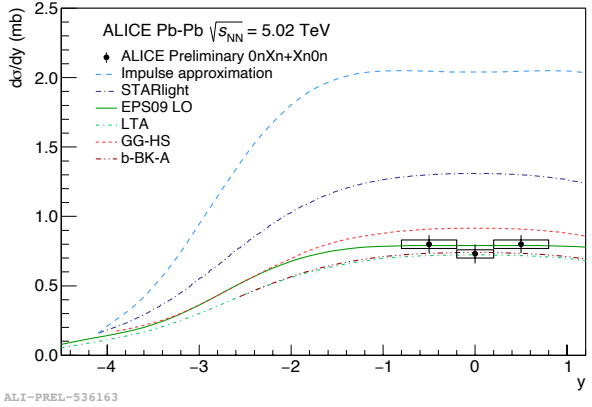
Positive rapidity Negative rapidity

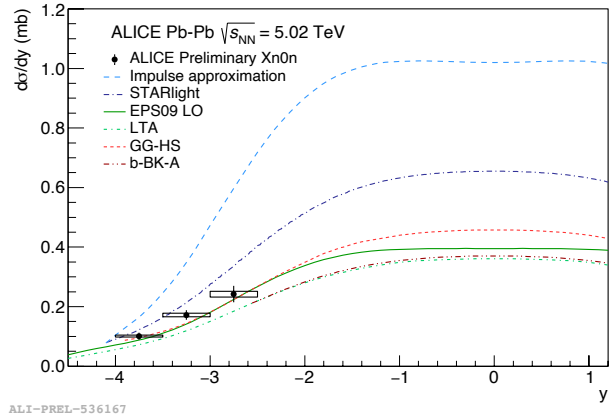
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma\mathrm{p}, +\mathrm{y}) + \mathrm{n}(-\mathrm{y})\sigma(\gamma\mathrm{p}, -\mathrm{y})$$

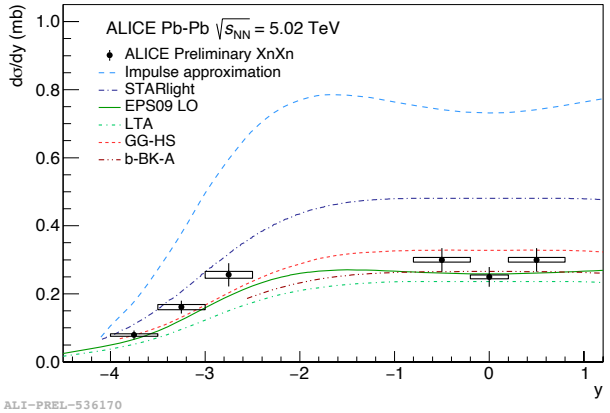
Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

dσ/dy for different neutron configurations









Interesting on its own right

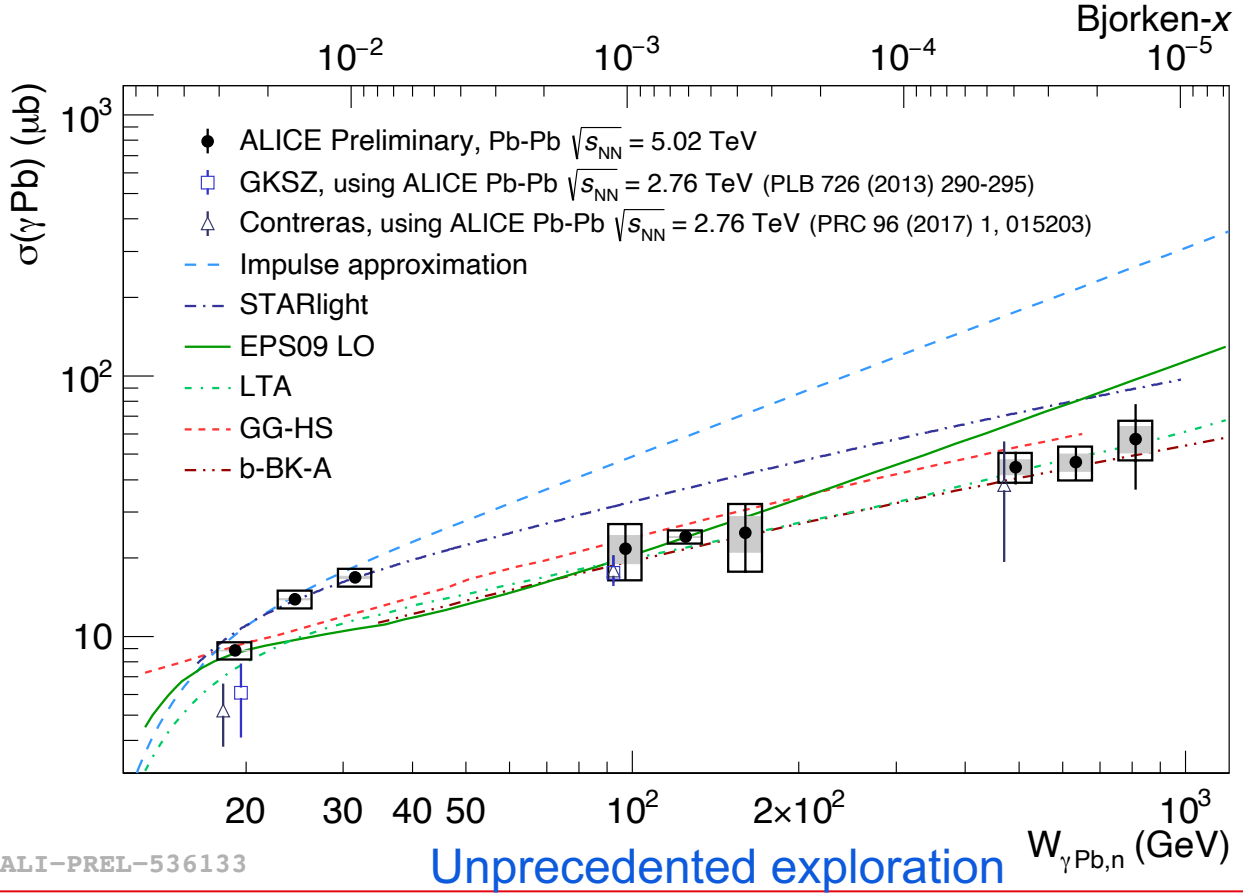
Sensitivity to test theoretical models

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

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

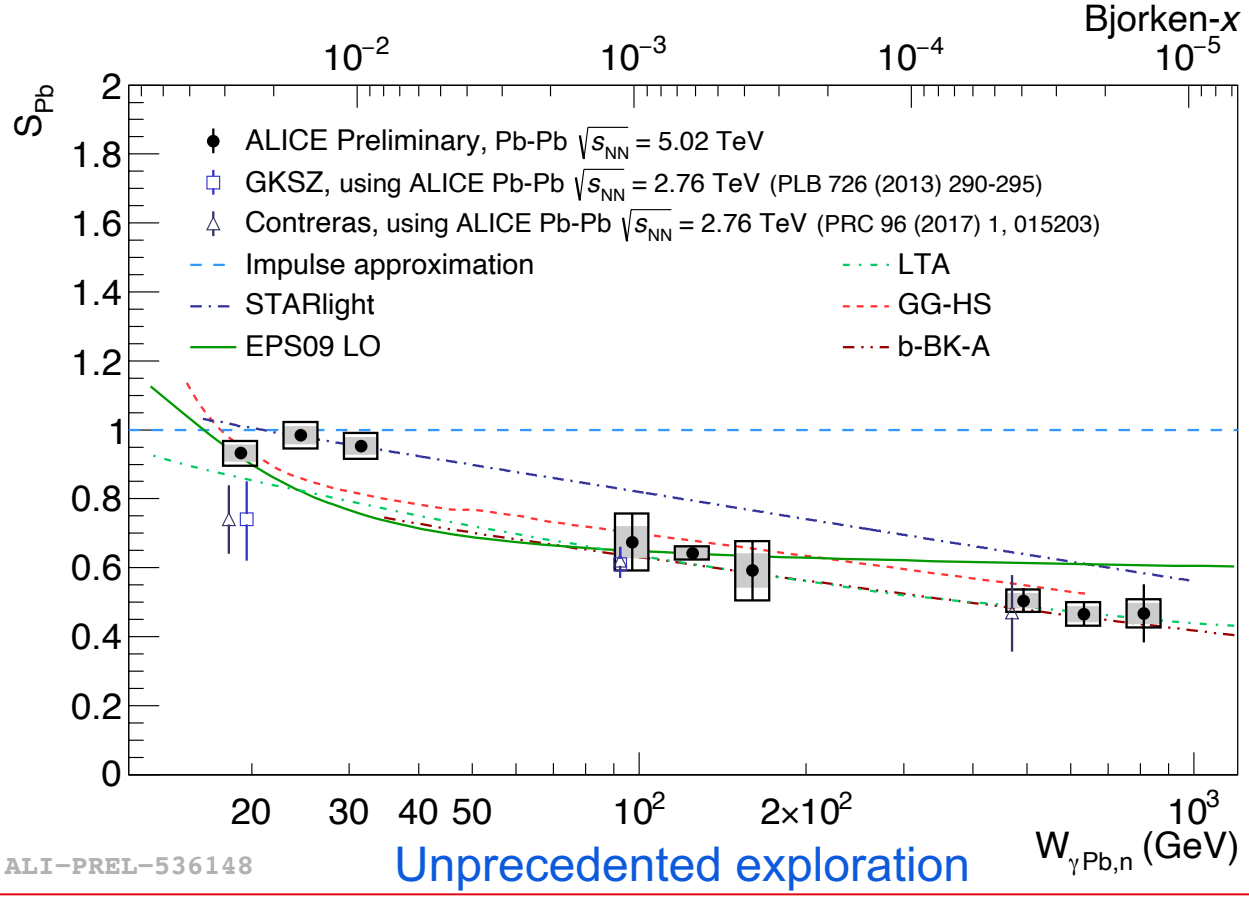
Energy dependence across the whole range not described by models

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



Unprecedented exploration

Nuclear suppression factor – ALICE Run 1 and Run 2 data



Unprecedented exploration

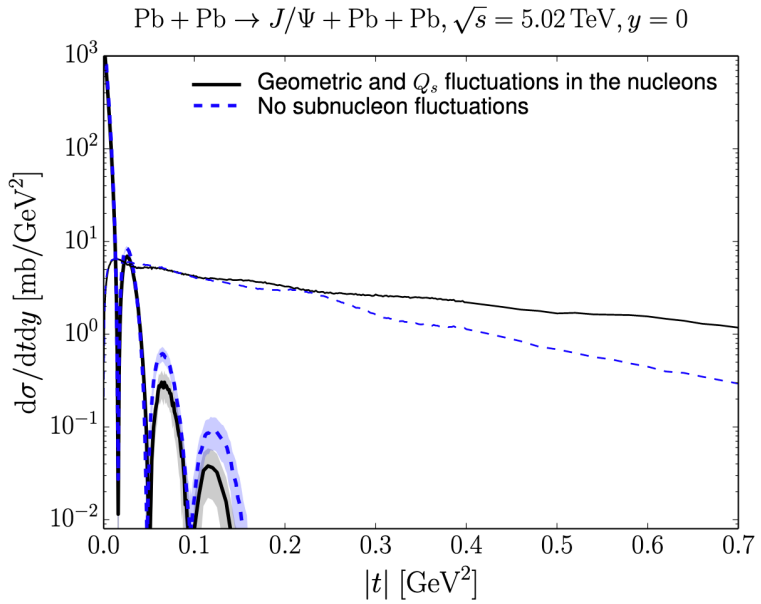
At low x, both shadowing and saturation models describe the data

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 $x = 1.1 \times 10^{-5}$, Run 2

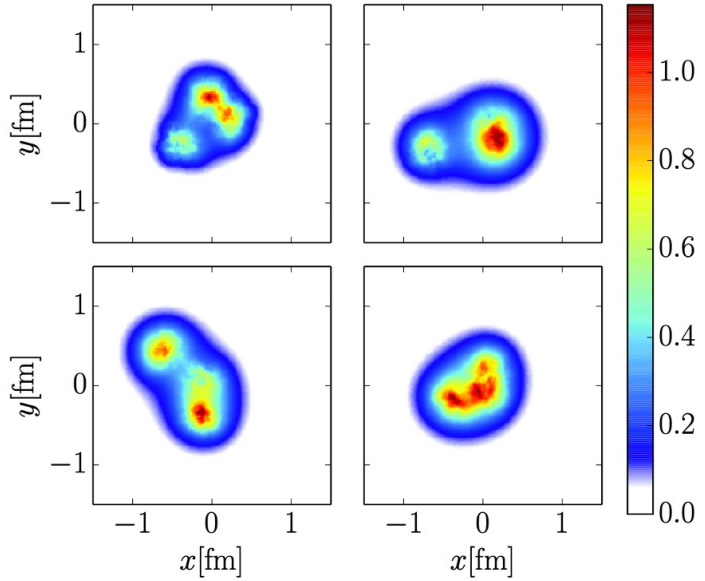
Dissociative/incoherent J/ψ in γp

H. Mantysaari and B. Schenke,
Phys. Lett. B772 (2017) 832



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

Event-by-event fluctuations

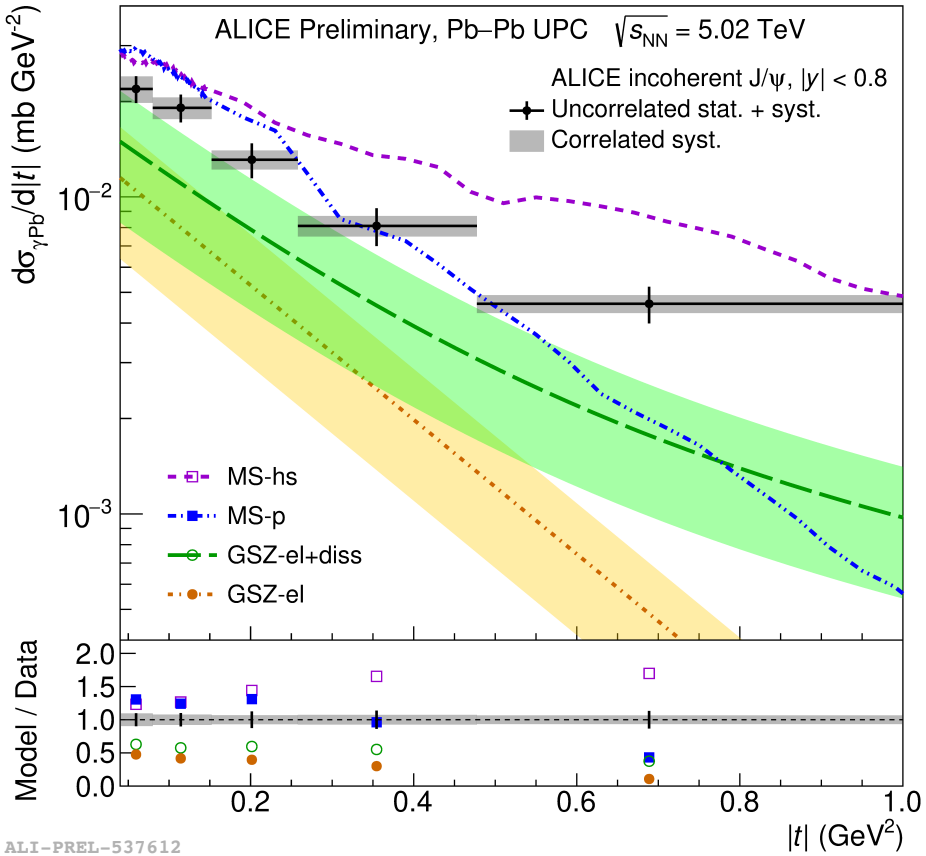


Mantysaari and Schenk, PRD 94, 034042 (2016)
S. Klein arXiv:2301.014018

In the Good-Walker approach, sensitive to subnucleonic fluctuations of the gluon density

$$\frac{d\sigma(\gamma p\to \mathrm{J}/\psi Y)}{dt}=\frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle-\left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

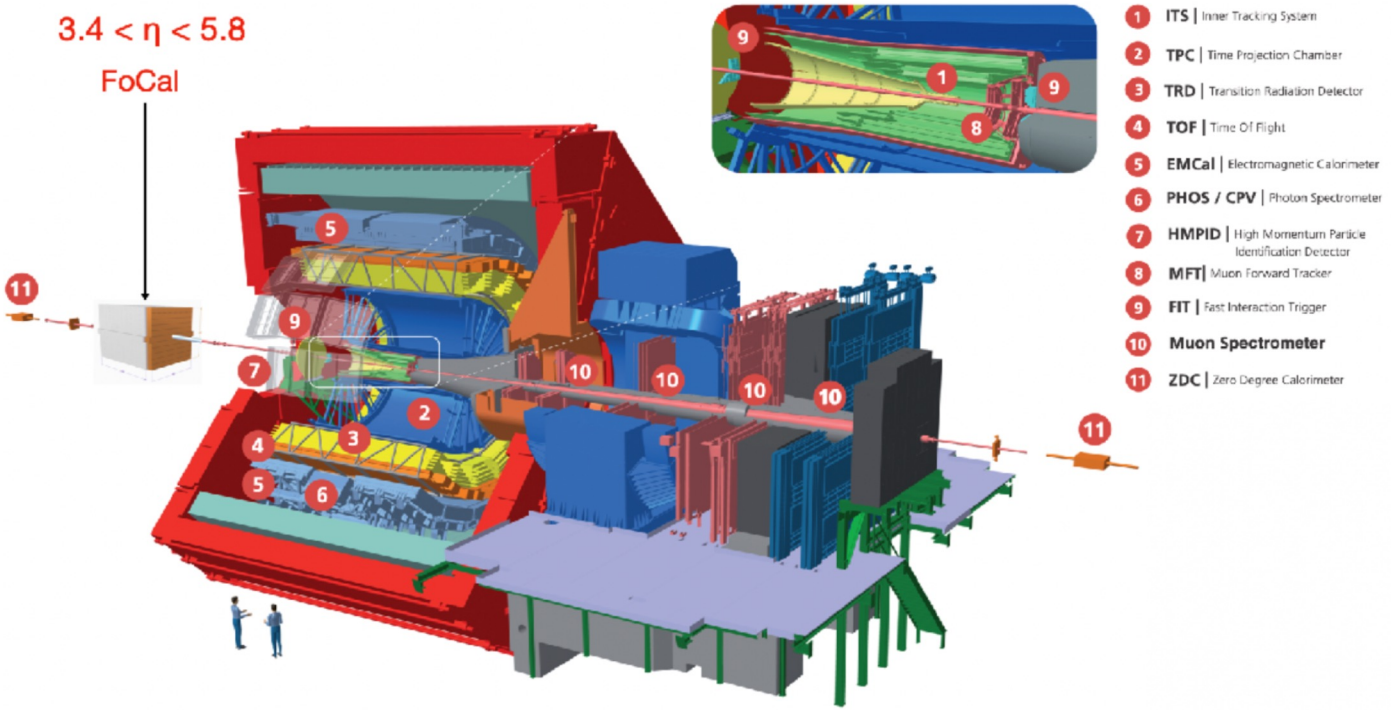
t-dependence of incoherent J/ψ cross section ratio in γPb



Data favor models with subnucleonic degrees of freedom (MS-hs and GSZ el+dis)

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

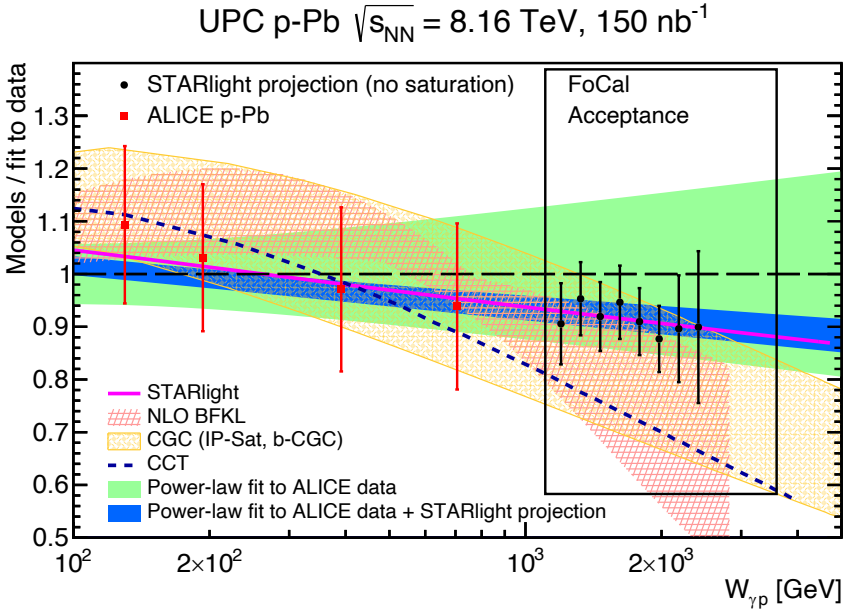
The ALICE FoCal project for Run 4



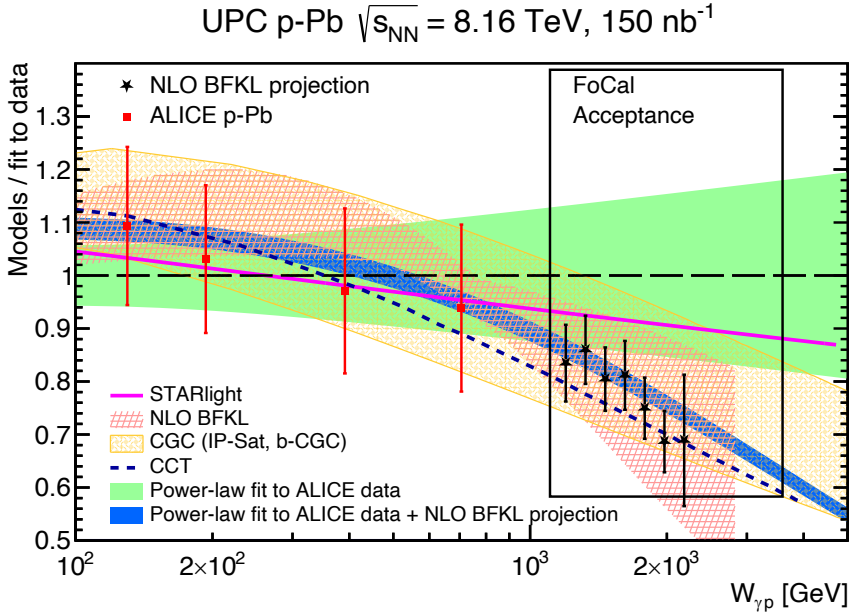
Projections for exclusive J/ψ off protons

A Bylinkin *et al* 2023
J. Phys. G: Nucl. Part. Phys. **50** 055105

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

Summary

- ALICE has provided evidence of strong nuclear gluon effects since Run 1
  Energy dependence of coherent J/ψ has been obtained using four different methods probing down to x ~ 10^{-5} like no other LHC experiment!
  Preliminary results on the neutron-dependent studies were presented

- At the lowest x, data favor both shadowing and saturation models. At high *x*, no model can describe the data. Confirmation that coherent J/ψs in peripheral hadronic events contribute to this physics program

- First measurement of the t-dependence of incoherent J/ψ. Data have strong sensitivity for "gluonic hotspots" fluctuations in Pb

- Exciting program for Run 3: upgraded detectors and the *trigger-less* read out system. For Run 4, FoCal will be a superb detector for UPCs