Probing gluon saturation in exclusive vector meson production

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with F. Salazar, B. Schenke, C. Shen, W. Zhao

arXiv:2312.04194 & in preparation

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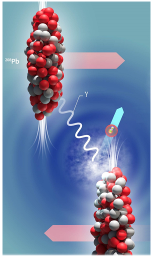
ECT*, June 12, 2024

Introduction: vector mesons in UPCs, $A + A \to J/\psi + A + A$

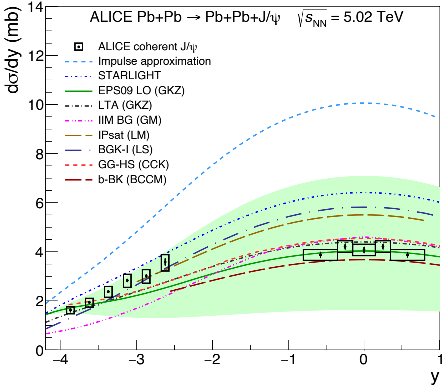


D. Grund, UPC2023

Two-fold ambiguity:

$$x_A = \frac{M_V}{\sqrt{s}} e^{\pm y}$$

$$\sigma \sim n_\gamma(+y)\sigma(+y) + n_\gamma(-y)\sigma(-y)$$



In principle UPCs provide access to very small-x nuclear structure, but high-x_A component dominates at large $|y|$

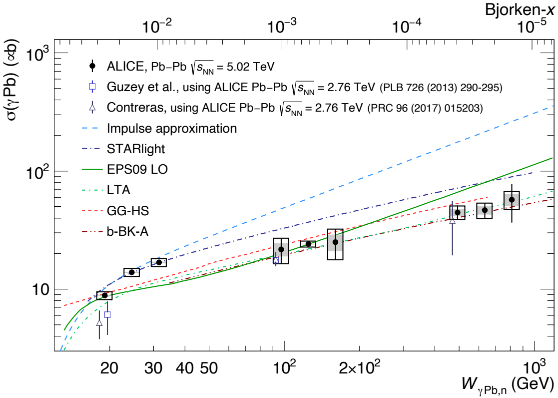
ALICE, 2101.04577

Recent development: extract individual $\gamma + A \to J/\psi + A$ contributions

$$\frac{d\sigma_{AA}^{\{b_1\}}}{dy} = n_\gamma(y, \{b\}_1)\sigma_{\gamma A}(y) + n_\gamma(-y, \{b\}_1)\sigma_{\gamma A}(-y)$$

$$\frac{d\sigma_{AA}^{\{b_2\}}}{dy} = n_\gamma(y, \{b\}_2)\sigma_{\gamma A}(y) + n_\gamma(-y, \{b\}_2)\sigma_{\gamma A}(-y)$$

Forward neutron classes $\Rightarrow$ impact parmeter range $\{b_i\}$ $\Rightarrow$ different flux n_γ
$\Rightarrow$ solve for $\sigma_{\gamma A}$ Method: Guzey et al, 1312.6486
See previous talk

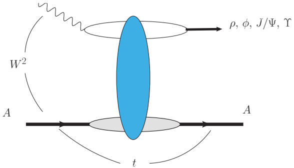


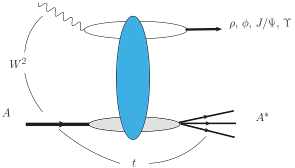
Access VM production at very small x
Confront CGC calculations with this data!

ALICE, 2305.19060

Coherent and incoherent vector meson production

Coherent





Incoherent

Figure: 2007.13625

Coherent: target remains intact, initial state $|i\rangle$ = final state $|f\rangle$.

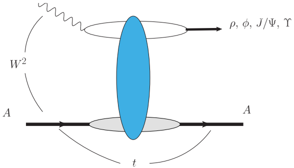
Good, Walker, Phys. Rev. 1960:

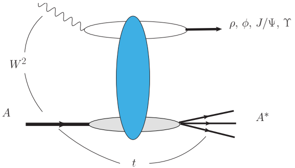
$$\frac{\mathrm{d}\sigma^{\mathrm{coherent}}}{\mathrm{d}t} \sim |\langle \mathcal{A} \rangle_\Omega|^2$$

$\Rightarrow$ Probe average interaction $\Rightarrow$ average geometry

Coherent and incoherent vector meson production

Coherent





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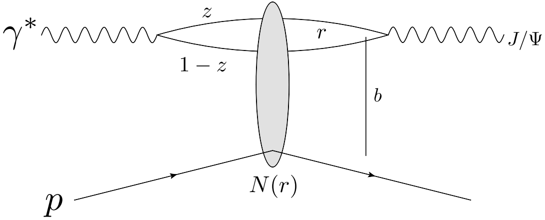
Incoherent: $|i\rangle \neq |f\rangle$: target breaks up:

$$\frac{\mathrm{d}\sigma^{\text{incoh}}}{\mathrm{d}t} = \frac{\mathrm{d}\sigma^{\text{total diff}}}{\mathrm{d}t} - \frac{\mathrm{d}\sigma^{\text{coherent}}}{\mathrm{d}t} \sim \left\langle |\mathcal{A}|^2 \right\rangle_\Omega - \left| \left\langle \mathcal{A} \right\rangle_\Omega \right|^2$$

Variance $\Rightarrow$ access to event-by-event fluctuations in the target structure

Vector meson production at high energy

$$\gamma + A \to (\mathrm{J}/\psi, \rho, \dots) + A$$



Lowest order in perturbation theory:

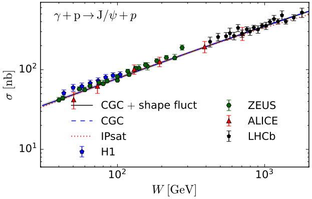
$$\mathcal{A}_\Omega \sim i \int \mathrm{d}^2\mathbf{b}_\perp\, e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}} \Psi^* \otimes \Psi_{\mathrm{J}/\psi} \otimes N_\Omega$$

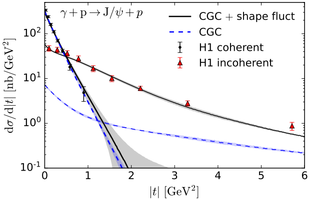
1. $\gamma^* \to q\bar{q}$: photon wave function Ψ (QED)
2. $q\bar{q}$-target interaction: dipole amplitude N_Ω
3. $q\bar{q} \to \mathrm{J}/\psi$: J/ψ wave function $\Psi_{\mathrm{J}/\psi}$

H.M, Salazar, Schenke, 2207.03712

MV model + JIMWLK evolution

constrained by HERA data, details soon





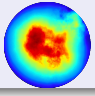
No net color charge transfer ("diffractive"), Ω=target configuration

Dipole-target scattering in CGC: $N_\Omega(\mathbf{x}_\perp, \mathbf{y}_\perp) = 1 - \frac{1}{N_c} \mathrm{Tr}\{V^\dagger(\mathbf{x}_\perp) V(\mathbf{y}_\perp)\}$

Color charge distribution at $x = 0.01$

- Event-by-event random color charge distribution ρ^a
- MV model: $g^2 \langle \rho^a(\mathbf{x}_\perp, x^-) \rho^b(\mathbf{y}_\perp, y^-) \rangle \sim \delta^{ab} \delta(\mathbf{x}_\perp - \mathbf{y}_\perp) \delta(x^- - y^-) g^4 \mu^2$ $+$ an IR regulator $\tilde{m}$
- $g^2\mu \sim cQ_s(\mathbf{b}_\perp)$ with $Q_s^2 \sim T_p(\mathbf{b}_\perp)$ from IPsat fit to HERA σ_r data

$$V(\mathbf{x}_\perp) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(\mathbf{x}_\perp)}{\nabla^2 - \tilde{m}^2}\right)$$



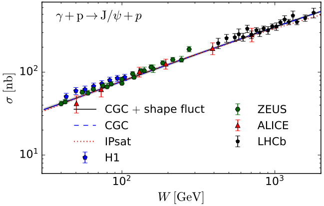
Small-x evolution

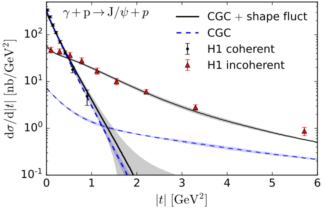
- Perturbative JIMWLK evolution (event-by-event)
- Gluon emission kernel regulated in IR:
  $K_{\mathbf{x}_\perp} = \frac{x^i}{\mathbf{x}_\perp{}^2} \to m_{\mathrm{JIMWLK}} |\mathbf{x}_\perp| K_1(m_{\mathrm{JIMWLK}} |\mathbf{x}_\perp|) \frac{x^i}{\mathbf{x}_\perp{}^2}$

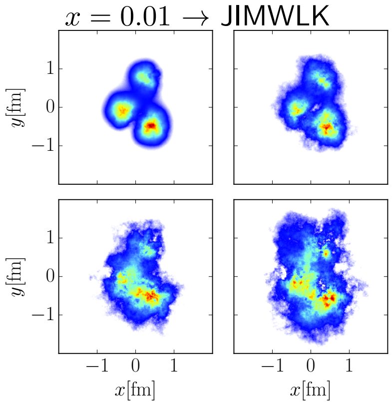
Nucleus: sample nucleon positions from Woods-Saxon, sum $T_i(\mathbf{b}_\perp)$ – no free parameters

Initial condition + perturbative evolution

Dipole: MV model + JIMWLK evolution
constrained by $\gamma + p \to J/\psi + p$ data



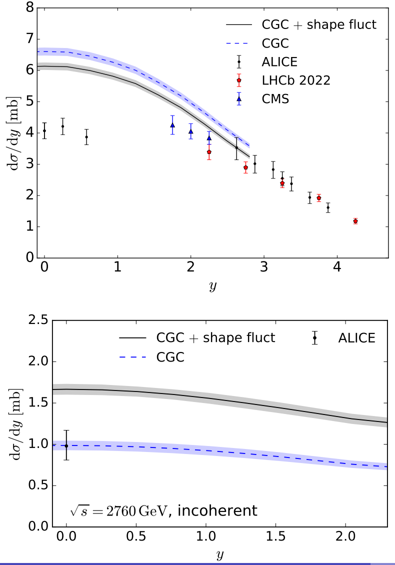




Large e-b-e fluctuations in proton geometry.

H.M, Schenke, 1806.06783, H.M, Salazar, Schenke, 2207.03712

UPC data comparison: $A + A \to J/\psi + A + A$



Two setups

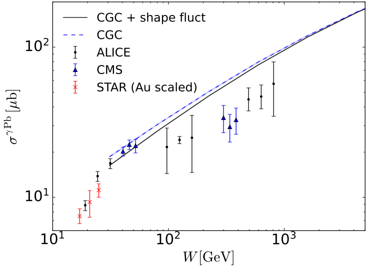
- "CGC+shape fluct": include nucleon substructure
  - Slightly stronger suppresssion
- "CGC": spherical nucleons
  - Much less fluctuations, smaller $\sigma^{\mathrm{incoherent}}$

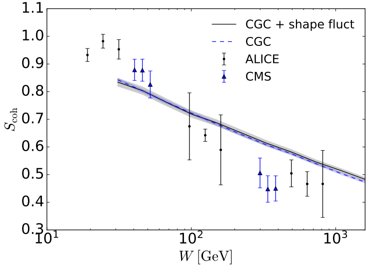
Lessons from UPC data with two-fold ambiguity

- Midrapidity LHC data ($W \sim 125\,\mathrm{GeV}$) overstimated
- Forward data (sensitive to low-W) well described

H.M, F. Salazar, B. Schenke, 2207.03712

Saturation in coherent production: $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$





- Challenging to describe the W dependence of $\sigma^{\gamma\mathrm{Pb}}$
  - LHC data well reproduced at moderate $W \lesssim 100$ GeV
  - Energy dependence well reproduced at higher W, but overestimate overall cross section
- Nuclear suppression factor

$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma\mathrm{Pb}}}{\sigma_{\mathrm{IA}}}}, \quad \sigma_{\mathrm{IA}} = \frac{\mathrm{d}\sigma^{\gamma p}}{\mathrm{d}t}\bigg|_{t=0} \int \mathrm{d}t \, |F(t)|^2$$

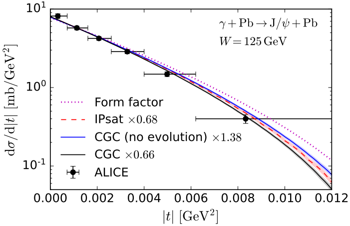
  - General trend captured. . .
  - . . . but data would prefer a stronger W dependence

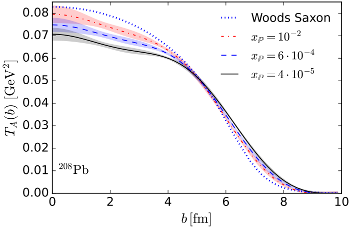
No free parameters when moving $p \to A$: genuine prediction
Recall: parameters fit to $\gamma + p \to \mathrm{J}/\psi + p$ only, more soon

H.M, Salazar, Schenke, 2312.04194

Saturation effect on nuclear geometry: $A + A \to A + A + \mathrm{J}/\psi$

$\gamma + \mathrm{Pb}$ at the LHC: very high density, saturation can modify the nuclear geometry



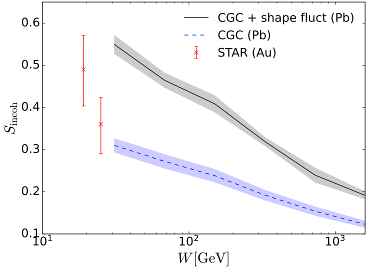


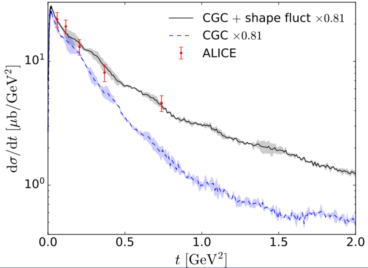
UPC data from LHC: $x = 6 \cdot 10^{-4}$

- Coherent $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$
- No saturation: geometry = Woods-Saxon
  $\Rightarrow$ not compatible with ALICE data
- Saturation: nucleus $\approx$ black disc at the center
  $\Rightarrow$ modifies nuclear geometry
  $\Rightarrow$ J/ψ spectra compatible with ALICE measurements
  (But can't describe UPC spectra, photon k_T handled differently?)

H.M, Schenke, Salazar, PRD106 (2022), ALICE: PLB817 (2021)

Saturation in incoherent production: $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}^*$





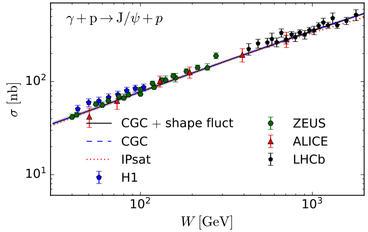
- Proton e-b-e fluctuating geometry tuned to HERA data
- Smoother proton at small-x $\Rightarrow$ reduced fluctuations, incoherent cross section suppressed
- Lower-energy measurement from STAR for the suppression factor

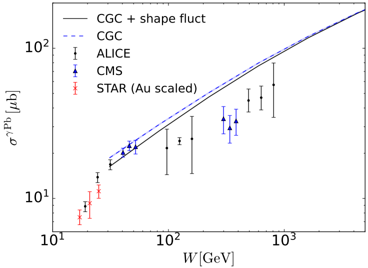
$$S_{\rm incoh} = \frac{\sigma^{\gamma+\mathrm{Pb}\to \mathrm{J}/\psi+\mathrm{Pb}^*}}{A(\sigma^{\gamma+p\to \mathrm{J}/\psi+p} + \sigma^{\gamma+p\to \mathrm{J}/\psi+p^*})}$$

- LHC data can probe $x_{\mathbb{P}}$ dependent geometry fluctuations
- ALICE t spectra: compatible with no modification to nucleon substructure in nuclei at $x_{\mathbb{P}} \sim 10^{-3}$

H.M, Salazar, Schenke, 2312.04194

Simultaneous description of $\gamma + p$ and $\gamma + \mathrm{Pb}$?





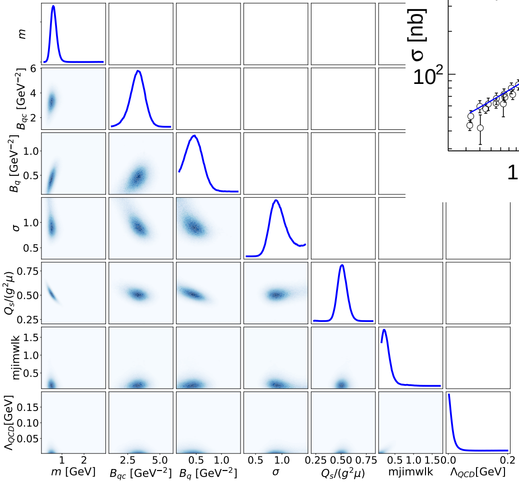
Model parameters, initial condition at $x = 0.01$

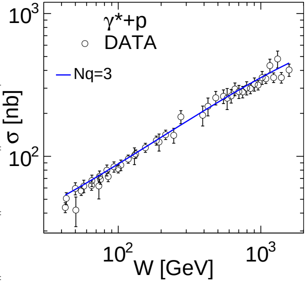
- Proton Q_s (QsmuRatio)
- Proton width (B_G)
- Hot spot size (B_q) (fix: 3 hot spots)
- Magnitude of Q_s fluctuations (smearQsWidth)
- IR regulator in the MV model (m)
- IR regulator in the JIMWLK kernel (m_{JIMWLK})
- Running coupling scale in JIMWLK (Λ)

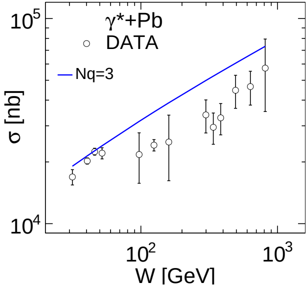
Data

- W dependent $\gamma + p \to \mathrm{J}/\psi + p$ (HERA+LHC)
- W dependent $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$
- $\mathrm{d}\sigma/\mathrm{d}t(\gamma + p \to \mathrm{J}/\psi + p$, coh+incoh, $W = 75\,\mathrm{GeV})$

Globan analysis result



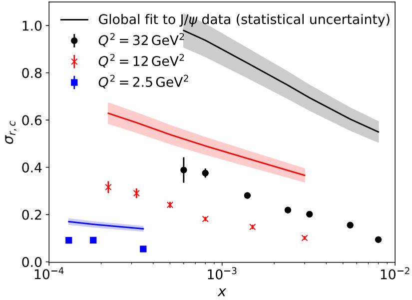




- Even with $\gamma + \mathrm{Pb}$ data included in the fit, the W dependence is still not captured
  - Tension remains at high $W \gtrsim 100\,\mathrm{GeV}$
  - Would need slower evolution in $\gamma + \mathrm{Pb}$
- Wave function uncertainty not included
  - Affects Q_s and as such $\alpha_s(Q_s)$
  - More on that soon

In preparation with Salazar, Schenke, Shen, Zhao

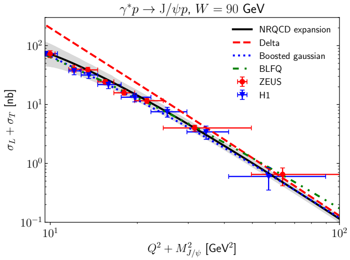
Structure function data

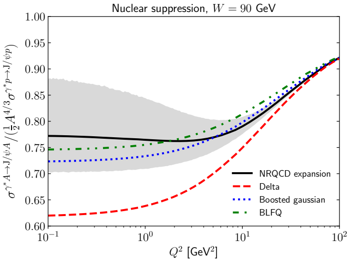


H.M, Salazar, Schenke, Shen, Zhao, in preparation

- Parameters fit to J/ψ photoproduction data: Charm production overestimated
- Similar conclusion as H.M, Schenke, 1806.06783
- IPsat-parmaterization based fits manage to describe all data
  - E.g. Rezaeian et al, 1212.2974
  - But with $\sim 1.5 \times 1.1$ skewedenss&real part corrections for VM production not included here
  - Would get smaller Q_s, weaker suppression
- Note: as we fit J/ψ data, the wave function uncertainty affects these results strongly

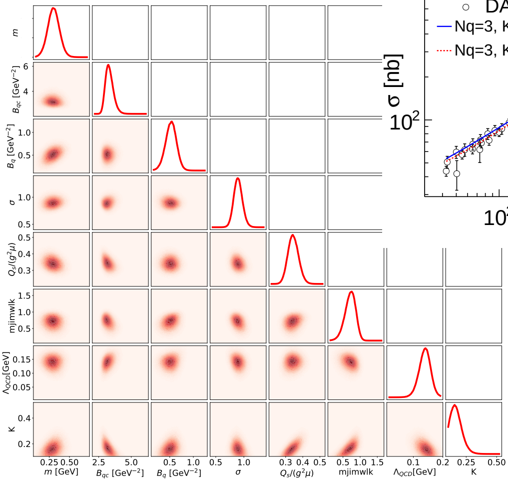
Wave function uncertainty

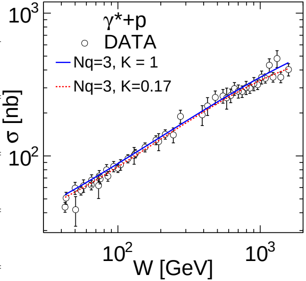


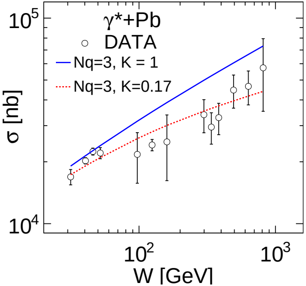


- J/ψ wave function non-perturbative, need to be modelled
- J/ψ photoproduction in $\gamma + p$: up to $\sim 50\%$ uncertainty
- Wave function uncertainty does not cancel in Pb/p ratio
- Systematic approach based on NRQCD:
  Lappi, H.M, Penttala, 2006.02830
- This work: assume that the uncertainty mostly affects normalization, introduce a K factor:
  $\Psi^* \otimes \Psi_{\mathrm{J}/\psi} \to K \Psi^* \otimes \Psi_{\mathrm{J}/\psi}$
  - Idea: e.g. $K < 1$ needs to be compensated by larger Q_s
    $\Rightarrow$ slower evolution speed especially in Pb
    $\Rightarrow$ stronger suppression in $\gamma + \mathrm{Pb}$

Globan analysis with wave function uncertainty



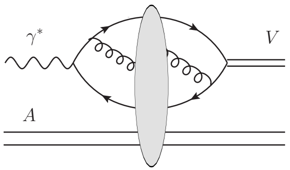


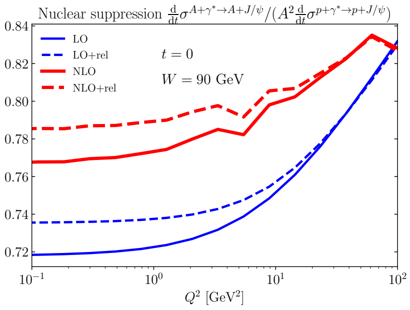


- Very small $K \sim 0.2$ preferred
- Large nuclear suppression at high W
- $\sim$ ok description of data
- But this large Q_s would result in even large overestimation of $\sigma_{r,c}$

In preparation with Salazar, Schenke, Zhao, Shen

What about NLO?





T. Lappi, H.M, Penttala, 2106.12825

NLO calculations exist

- Heavy meson in non-relativistic limit
- Light meson at high-Q^2

H.M, Penttala, 2104.02349, 2204.14031, 2203.16911

First NLO calculations

Lappi, H.M, Penttala, 2106.12825:

- Slightly less suppression at NLO
- NLO corrections mostly cancel in A/p ratio

However, still large uncertainties (resummation scheme in evolution, initial condition, here b-indep evolution [See Jani's talk], ...)

Conclusions and outlook

- $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$ data from UPCs: probe saturation in the TeV range
- Nuclear suppression factors & p_T^2 spectra: signatures of strong saturation effects
  - Stronger than we can naturally describe
  - Tension between the $\gamma + p \to \mathrm{J}/\psi + p$ and $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + p$ data can be reduced by taking into account wave function uncertainty
- Future measurements of incoherent $\gamma + \mathrm{Pb} \to \mathrm{J}/\Psi + \mathrm{Pb}^*$ provide further constraints + probe energy evolution of substructure fluctuations

The 2nd workshop on the physics of Ultra Peripheral Collisions

Ultra Peripheral location for UPC physics

- Lapland, Finland, 9.-13.6.2025 (24h daylight!), TBC
- https://indico.cern.ch/event/1378275/

Local organizing committee chairs

- Ilkka Helenius and Heikki Mäntysaari

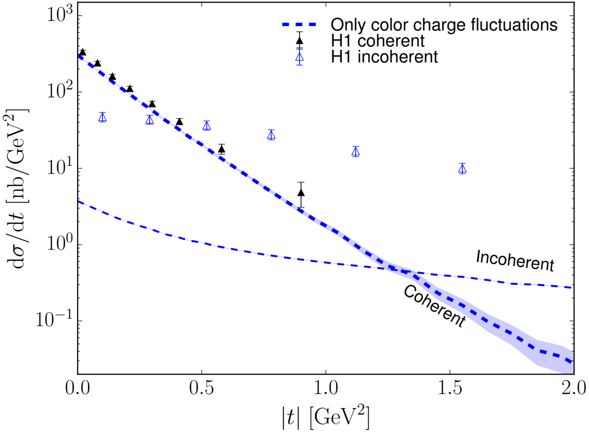
Travel

- International flight to Helsinki + domestic connection

Backups

Example with protons: proton shape from $\gamma + p \to J/\Psi + p$

Comparison to HERA data including color charge fluctuations ($x \sim 10^{-3}$)

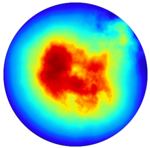


H.M, B. Schenke, PRL 117, 052301 (2016), PRD 94, 034042, H1: EPJC73, 2466

Round proton:

Fit proton size: (gluonic) radius $r_p \sim 0.6$ fm

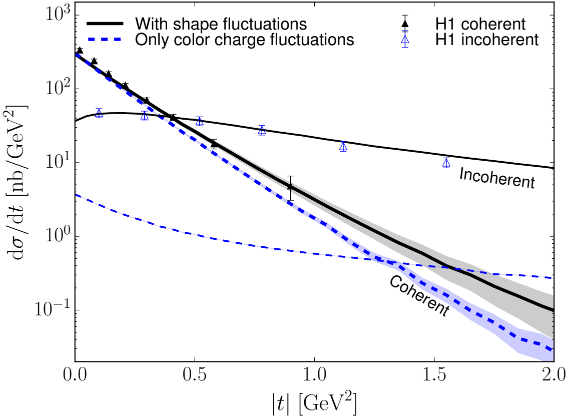
Note EM radius 0.88 fm



Average geometry (coherent) ✓

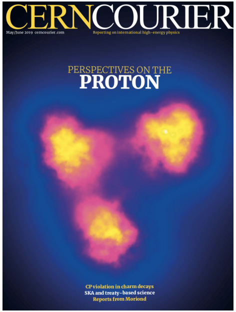
Fluctuations (incoherent) ✗

Constraining proton fluctuations: $\gamma + p \to J/\Psi + p$

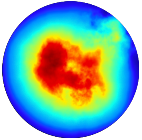


Parametrize e-b-e fluctuating geometry, fit data

Fluctuations



Round



HERA data can be described with large event-by-event fluctuations in the proton geometry

H.M, B. Schenke, PRL 117, 052301 (2016), PRD 94, 034042, H1: EPJC73, 2466

STAR suppression factor data

H.M, Salazar, Schenke, 2312.04194:

Channel	STAR	CGC + shape fluct	CGC
$S_{\rm coh}$	0.846 ± 0.063	0.89	0.90
$S_{\rm incoh}$	$0.36^{+0.06}_{-0.07}$	0.58	0.32

Table: Nuclear modification factors for J/ψ photoproduction in $\gamma + \mathrm{Au}$ collisions. The CGC predictions are calculated at $x_{\mathbb{P}} = 0.01$ and the STAR measurements are performed at $x_{\mathbb{P}} = 0.015$. The coherent suppression factors $S_{\rm coh}$ obtained with and without nucleon substructure fluctuations are compatible with each other within the numerical accuracy.

Slower evolution speed in nuclei