Vector meson probes of gluon saturation at the 2nd detector

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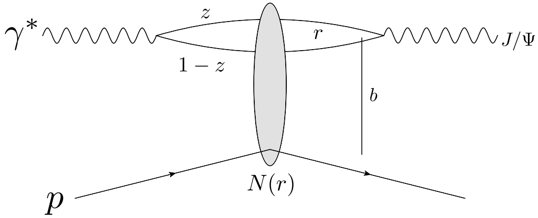
Vector meson production at high energy

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



Lowest order in perturbation theory:

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

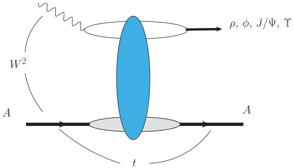
1. $\gamma^* \to q\bar{q}$: photon wave function Ψ (QED)
2. $q\bar{q}$-target interaction: dipole amplitude N_Ω
3. $q\bar{q} \to \mathrm{J}/\psi$: J/ψ wave function $\Psi_{\mathrm{J}/\psi}$ (models)

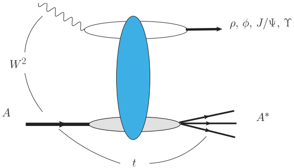
H.M, Salazar, Schenke, 2207.03712

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

Coherent and incoherent vector meson production

Coherent





Incoherent

Figure: 2007.13625

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

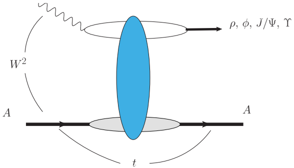
Good, Walker, Phys. Rev. 1960:

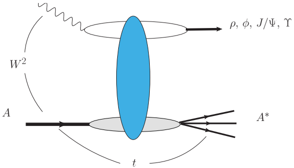
$$\frac{\mathrm{d}\sigma^{\text{coherent}}}{\mathrm{d}t} \sim |\langle \mathcal{A} \rangle_\Omega|^2$$

⇒ Probe average interaction ⇒ average geometry

Coherent and incoherent vector meson production

Coherent





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

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

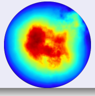
Dipole-target scattering in CGC: $N_\Omega(\mathbf{x}_\perp, \mathbf{y}_\perp) = 1 - \frac{1}{N_c} \mathrm{Tr}\{V^\dagger(\mathbf{x}_\perp) V(\mathbf{y}_\perp)\}$

Same d.o.f. as in the IP-Glasma heavy ion initial state

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 $\tilde{m}$
- $g^2 \mu \sim c Q_s(\mathbf{b}_\perp)$ with $Q_s^2 \sim T_p(\mathbf{b}_\perp)$ from IPsat fit to HERA σ_r data

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



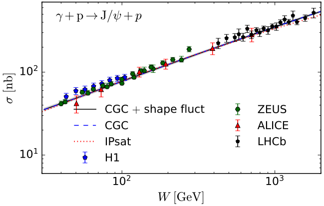
Small-x evolution

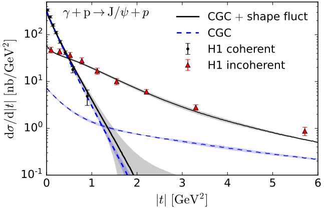
- Perturbative JIMWLK evolution (event-by-event), gluon emission kernel regulated in IR: $K_{\mathbf{x}_\perp} = \frac{x^i}{\mathbf{x}_\perp{}^2} \to m_{\mathrm{JIMWLK}} |\mathbf{x}_\perp| K_1(m_{\mathrm{JIMWLK}} |\mathbf{x}_\perp|) \frac{x^i}{\mathbf{x}_\perp{}^2}$

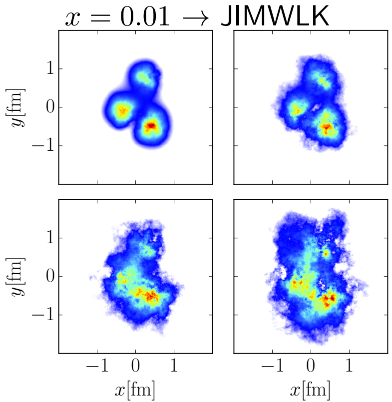
Nucleus: sample nucleon positions from e.g. Woods-Saxon, sum $T_i(\mathbf{b}_\perp)$ – no free parameters

Initial condition + perturbative evolution

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



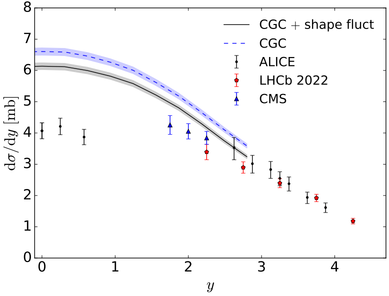


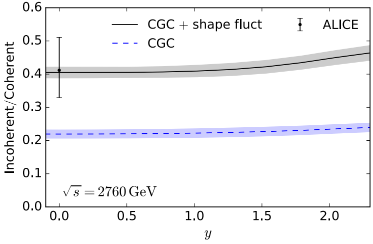


Large e-b-e fluctuations in proton geometry.

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

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





Two setups

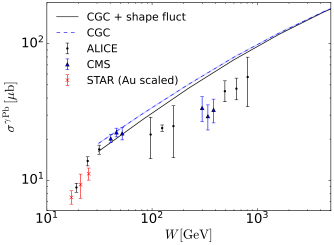
- "CGC+shape fluct": include nucleon substructure
  - Slightly stronger suppresssion
- "CGC": spherical nucleons
  - Much less fluctuations, smaller $\sigma^{\mathrm{incoherent}}$

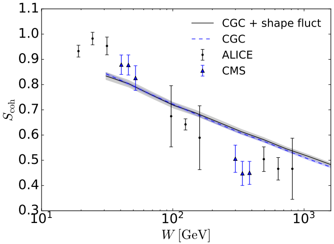
Lessons from UPC (before QM2025 – more soon)

- Midrapidity LHC data ($W \sim 125\,\mathrm{GeV}$) overestimated $\Rightarrow$ surprisingly strong suppression
- Forward data (sensitive to low-W) well described
- Some model uncertainties (e.g. non-perturbative meson wave function) partially cancel in ratios

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
- Nuclear suppression factor

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

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

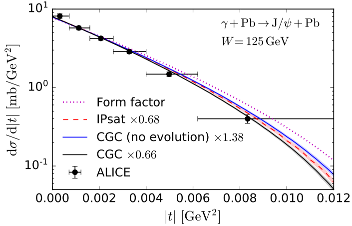
No free parameters when moving $p \to A$: genuine prediction

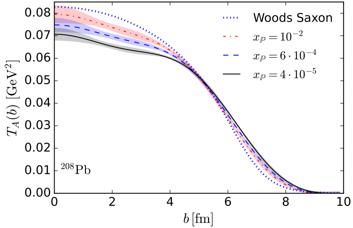
EIC wishlist

- W-dependent cross section for differet A, Q^2
- No uncertainties from two-fold ambiquity

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: $x = 6 \cdot 10^{-4}$

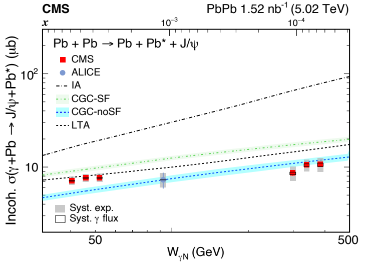
- Coherent $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$
- No saturation: geometry = Woods-Saxon
  $\Rightarrow$ not compatible with ALICE data
- Saturation: nucleus $\approx$ black disc at the center
  $\Rightarrow$ modifies nuclear geometry

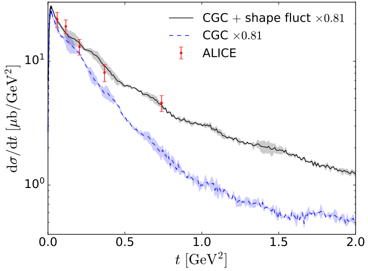
EIC wishlist

- t spectra for different $A, Q^2, x_{\mathbb{P}}$
  - Preferably with good coh-incoh separation
- Photon-k_T under better control than in UPCs

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

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





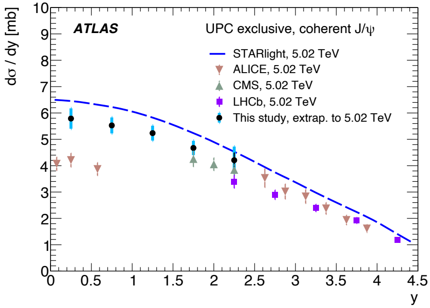
- Proton e-b-e fluctuating geometry tuned to HERA data
- Smoother proton at small-x $\Rightarrow$ reduced fluctuations, incoherent cross section suppressed
- Access $x_{\mathbb{P}}$ dependent geometry fluctuations (recall: $t \sim 1/$ distance scale)
- High-W incoherent cross section overestimated
- ALICE t spectra: compatible with no modification to nucleon substructure in nuclei at $x_{\mathbb{P}} \sim 10^{-3}$

EIC wishlist

- Coherent-incoherent separation & t-spectra

CMS, 2503.08903; H.M, Salazar, Schenke, 2312.04194

Exclusivity is tricky – status after QM2025



ATLAS, 2509.04135

- ATLAS also measured exclusive J/ψ around $y \sim 0$
- Large tension between ATLAS and ALICE

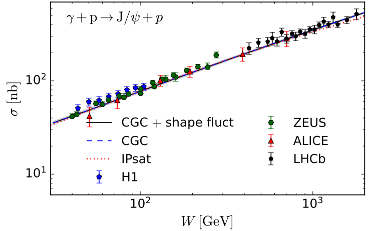
P. Steinberg, IS2025:

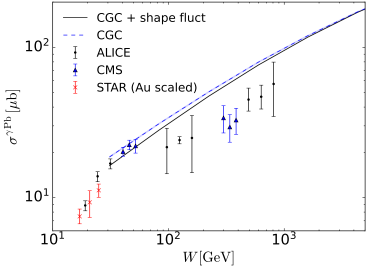
- **ALICE mid-rapidity data requires veto on forward counters (V0 and AD, both in regions well beyond ATLAS acceptance)**
  - ALICE publications raise concern that simultaneous forward e+e- pairs (assumed to be pileup) could lead to self-veto
  - Correct for pileup using veto rate measured in an unbiased beam-crossing trigger
- **ALICE forward results do not apply this selection**

EIC wishlist

- Lessons to be learnt: ensure exclusivity?

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





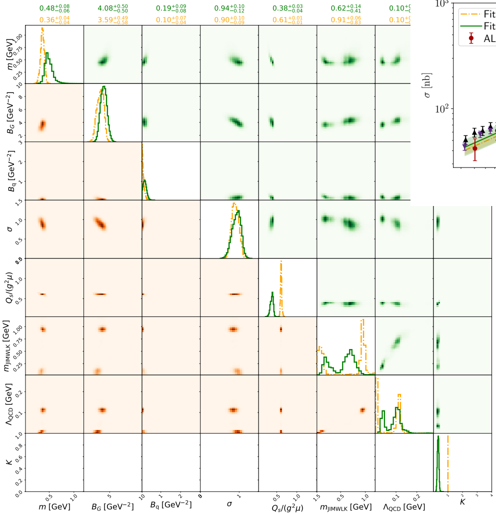
Global analysis

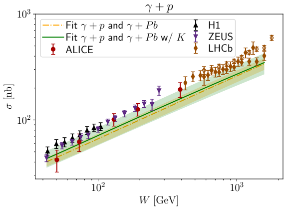
- This talk so far: fix parameters to $\gamma + p$, predict $\gamma + \mathrm{Pb}$
- Next: global Bayesian analysis including $\gamma + p$ and $\gamma + \mathrm{Pb}$ data
- Parameters: proton geometry at $x = 0.01$, coordinate space α_s scale, IR regulators
- $+$ normalization factor (K), parametrize e.g. missing higher order or VM wave function uncertainty

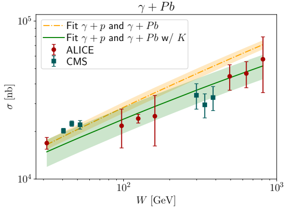
Data

- 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



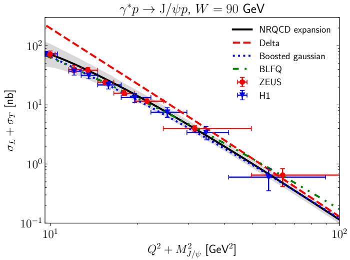


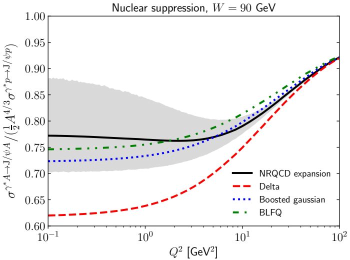


- With $\gamma + \mathrm{Pb}$ data: same conclusion, $\gamma + \mathrm{Pb}$ prefers slower W-dependence
- Fit with K a free parameter:
  - $K \sim 0.3$ preferred
  - Large $Q_s^2 \Rightarrow$ slower evolution with Pb (large saturation effect)
- Possible to describe world data, theory developments needed

H.M, Roch, Salazar, Schenke, Shen, Zhao, 2507.14087

Wave function uncertainty





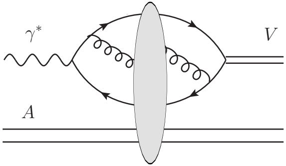
- J/ψ wave function non-perturbative, need to be modelled
- J/ψ photoproduction in $\gamma + p$: up to $\sim 50\%$ uncertainty
- Wave function uncertainty does not cancel in Pb/p ratio
- Systematic approach based on NRQCD:
  Lappi, H.M, Penttala, 2006.02830

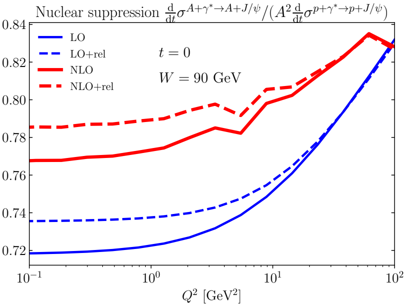
EIC/theory wishlist

- x, Q^2, A, t dependence from EIC/HERA/LHC
- Include wave function uncertainty in global analyses with VM production and other observables

What about NLO?

$$e + A \to M_X + A$$





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

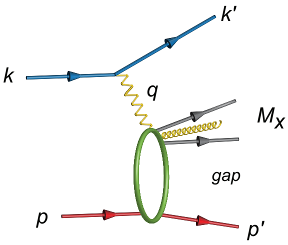
Lappi, H.M, Penttala, 2106.12825:

- 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)

Other relevant probes: diffractive structure function

Potentially more powerful than vector meson production



EIC WP

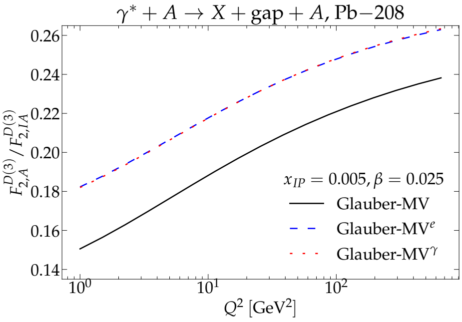
Why diffraction

- No net color transfer ⇒ at least 2 gluons ⇒ sensitivity
- IR-safe, no dependence on e.g. jet algorithm or fragmentation function
- Genuine saturation prediction:

$$\frac{\sigma_{\text{diffractive}}}{\sigma_{\text{total}}} \to \frac{1}{2}$$

  for large Q_s^2, i.e. large A and/or small-x
- A and x dependencies dynamical, i.e. computable from CGC
- Same degrees of freedom as e.g. inclusive DIS

CGC predictions for F_2^D



Dung Le, H.M, Lappi, 2307.16486

- $\sim$ total diffractive cross section
- Predicted nuclear modification factor $\sim \mathbf{0.2}$
- Impulse approximation $F_{2,IA}^D$:
  - $\gamma + p$ scaled to nuclei
  - Use nuclear form factor
  - Neglect saturation: $F_2^D = F_{2,IA}^D$

EIC wishlist

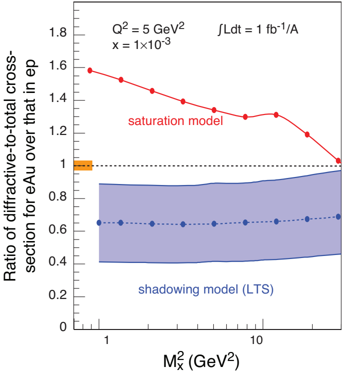
Similar to VM production

- Coherent-incoherent separation
- Diffractive vs. non-diffractive
- Systematics: $A, Q^2, x_{\mathbb{P}}, t$

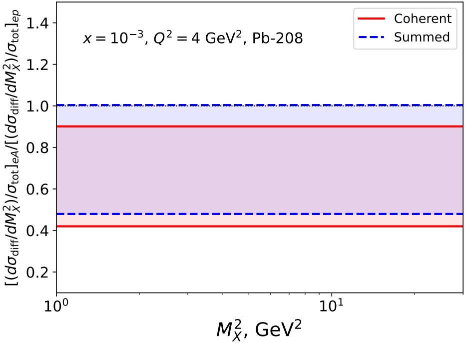
Most promising(?) "smoking gun" for saturation effects: diffractive DIS

If I have to pick one, although there may not be any

EIC White Paper (2012)



State-of-the-art LTS Guzey, Strikman, 2403.08342



Qualitative difference (suppression vs enhancement)

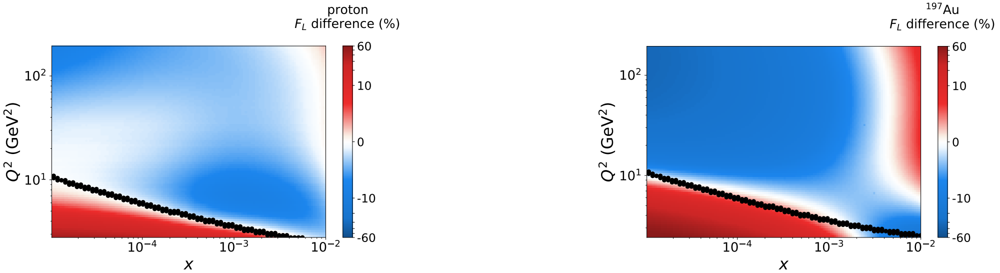
EIC: A, x, Q^2, M_X^2 dependence

Note: Not a genuine DGLAP prediction, diffractive PDFs can fit data with enhancement!

Baseline matters – look for deviations and tensions

Example: total DIS cross section, compare linear (DGLAP) and non-linear (BK) evolution

Tevio et al, 2203.05846: DGLAP and BK match at $Q^2 = 10Q_s(x)^2$ & quantify differences



$\frac{\mathrm{BK}-\mathrm{DGLAP}}{\mathrm{DGLAP}}$ for $F_{2,L}$ $\Rightarrow$ measurable differences especially for F_L and heavy-A

Also Marquet et al, 1702.00839

EIC wishlist

Precision

Conclusions and outlook

- Vector meson data from UPCs: strong saturation signals
  - Even stronger than predicted...
- Experimental challenges
  - What is an exlcusive event?
  - Coherent-incoherent separation
  - t from vector meson p_T (coherent: $t \lesssim 1/R_A^2$)
- My favourite EIC observables: vector meson production & diffractive structure functions
- Need precision and $A, Q^2, x_{\mathbb{P}}, t$ systematics for various observables from the EIC

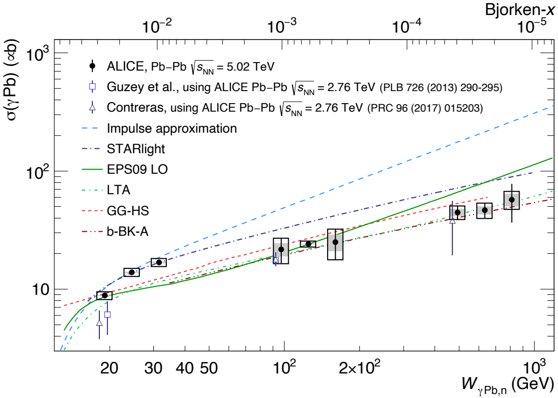
Backups

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

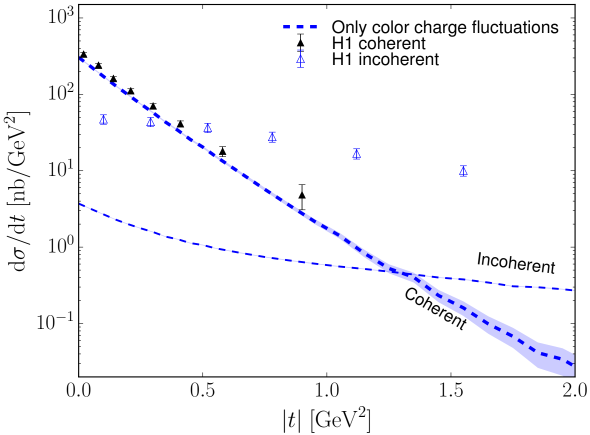


Access VM production at very small x
Confront CGC calculations with this data!

ALICE, 2305.19060

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

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

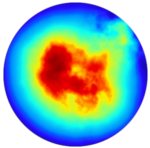


H.M, B. Schenke, PRL 117, 052301 (2016), PRD 94, 034042, H1: EPJC73, 2466

Round proton:

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

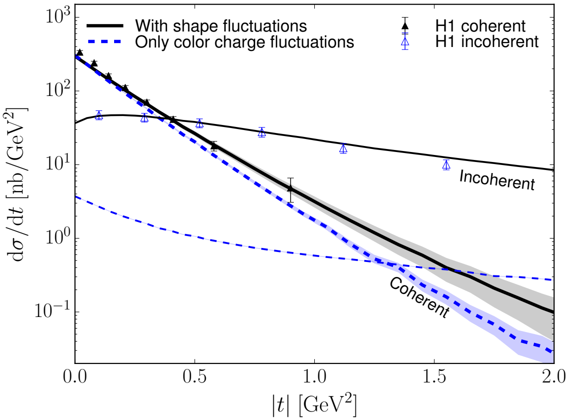
Note EM radius 0.88 fm



Average geometry (coherent) ✓

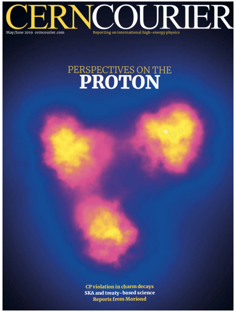
Fluctuations (incoherent) ✗

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

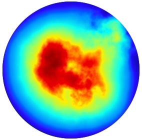


Parametrize e-b-e fluctuating geometry, fit data

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

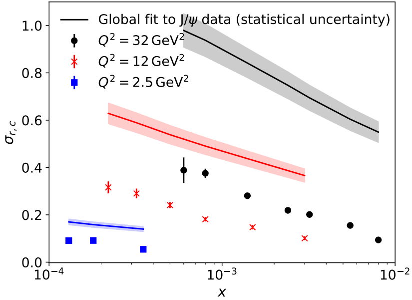
STAR suppression factor data

H.M, Salazar, Schenke, 2312.04194:

Channel	STAR	CGC + shape fluct	CGC
S_{coh}	0.846 ± 0.063	0.89	0.90
S_{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_{coh} obtained with and without nucleon substructure fluctuations are compatible with each other within the numerical accuracy.

Structure function data



H.M, Roch, Salazar, Schenke, Shen, Zhao, 2507.14087

- 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