Exclusive vector meson production

From the saturation physics point of view

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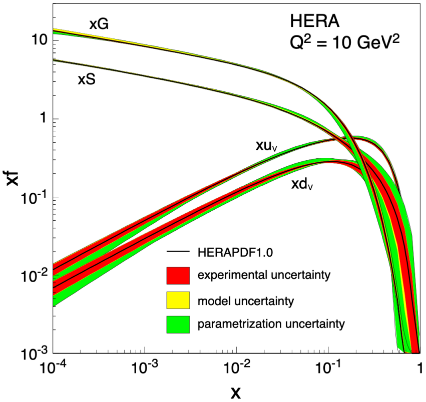
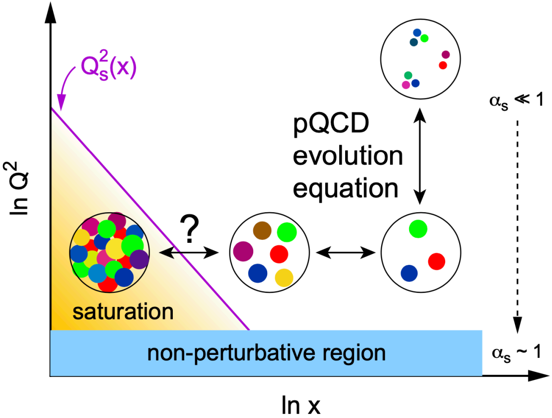
HERA total $\gamma^* + p$ cross section data: parton densities $\sim x^{-\lambda}$, eventually violates unitarity

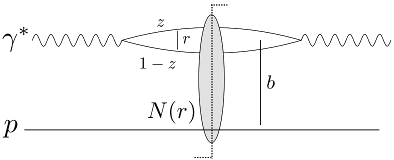


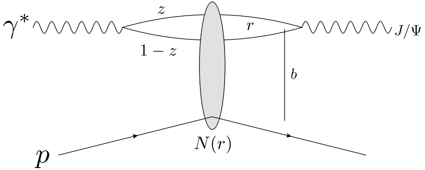


Non-linear QCD effects at small x (e.g. $gg \to g$) should tame this growth

$\Rightarrow$ Saturated state of gluonic matter at small x and moderate Q^2 ($\sim M^2_{J/\Psi}$ $\leftarrow$ focus here)

Probing high density gluonic matter in DIS: CGC and dipole picture





Inclusive cross section

Optical theorem:

$\sigma^{\gamma^* p} \sim \Psi^* \otimes \Psi \otimes N$

$\sim$ dipole N $\sim$ “gluon structure”

Exclusive processes (focus here)

$\mathcal{A} \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} \Psi^* \otimes \Psi_V \otimes N$

$\sigma \sim |\mathcal{F}[\text{dipole}]|^2$

- Very sensitive, and access to geometry

- Dipole picture at high energy: $\gamma^* \to q\bar{q}$ fluctuation has a long lifetime
- Dipole amplitude N: eikonal propagation in the color field, resumming multiple scattering
- Perturbative evolution equations describing the center-of-mass energy dependence of N
  - Non-perturbative initial condition e.g. from F_2 fits
- Here J/ψ production. $e' - J/\psi$ correlations also interesting! HM, Roy, Salazar, Schenke, 2011.02464

Exclusive processes: beyond average structure

Exclusive processes: no net color transfer, rapidity gap around the produced particle

Coherent diffraction:

- Target remains in the same quantum state, e.g.
  $\gamma + p \to J/\Psi + p$
- Probes average interaction

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle_\Omega|^2$$

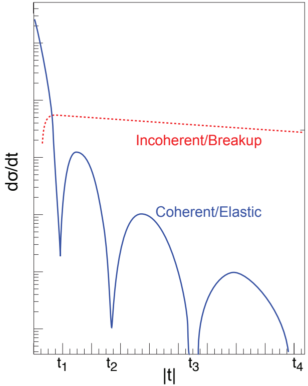
$\langle \, \rangle_\Omega$: average over target configurations Ω

Incoherent diffraction, the remaining events:

- E.g. $\gamma + p \to J/\Psi + p^*$ (+ dissociation $p^* \to X$).
- Total diffractive − coherent

$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

- Variance: sensitive to fluctuations

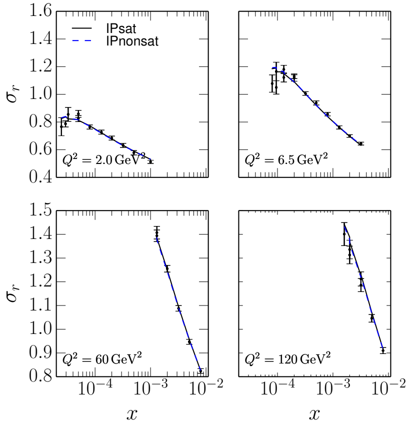


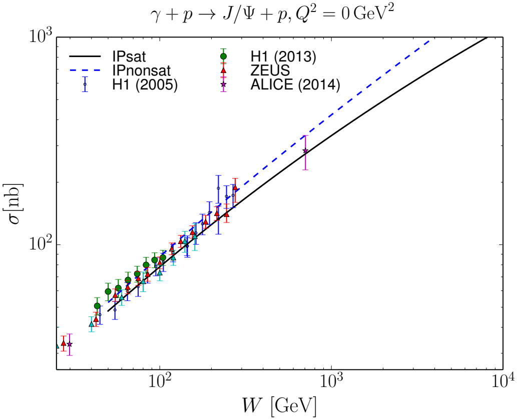
Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Caldwell, Kowalski, PRC 81, 2010

H.M., Rept. Prog. Phys. 83, 2020

1. A few selected lessons from HERA

Successful (LO) CGC phenomenology



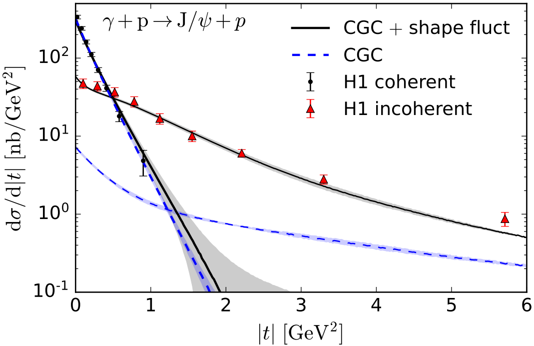


H.M, P. Zurita, 1804.05311

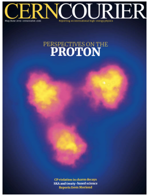
- Simultaneous description of structure function and vector meson production data
  - Caveat: especially F_2 is sensitive to large dipoles..., F_L and $\sigma_{r,c}$ from the EIC! + nuclei
- No clear signal of saturation, linearized calculations also compatible with data

Large geometry fluctuations required by the HERA data ($x_{\mathbb{P}} \approx 0.001$)

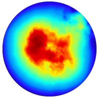
Study simultaneously coherent ($\sim$ average interaction) and incoherent ($\mathcal{A}$ variance)



CGC + shape fluct



“CGC”



- Parametrize e-b-e fluctuating geometry, fit parameters to data
- Construct initial condition for pA collisions $\to$ successful pheno

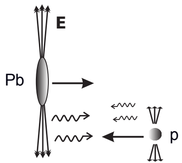
HM, Schenke, Shen, Tribedy, 1705.03177

Orignal: H.M, B. Schenke, 1607.01711 (PRL), recent: 2202.01998 (HM, Schenke, Shen, Zhao), similar setup e.g.: Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot; Kumar, Toll

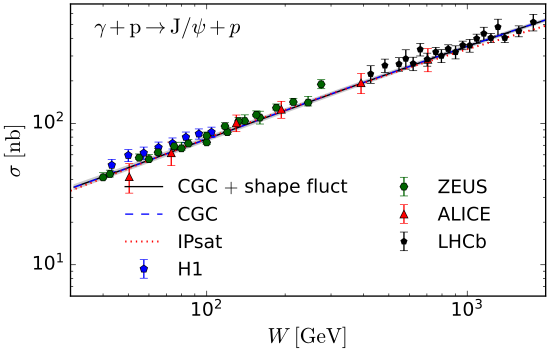
2. UPC in p+A: high energy $\gamma + p$

Ultraperipheral $p + A$:
$\gamma + p$ dominates

Limited to $Q^2 = 0$, but high W



Center-of-mass energy dependence: coherent

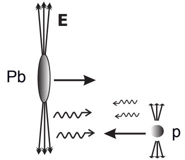


H.M, F. Salazar, B. Schenke, in preparation

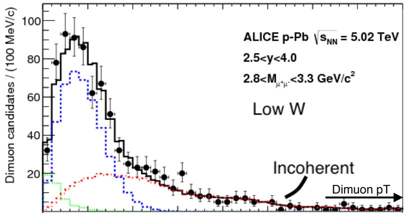
- Coherent cross section measured up to very large W
- No clear deviation from the W^δ extrapolation from HERA energies
- Compatible with CGC calculations, but no clear signal of saturation with proton targets

What happens to the incoherent cross section at high W?

Ultraperipheral $p + A$:
$\gamma + p$ dominates



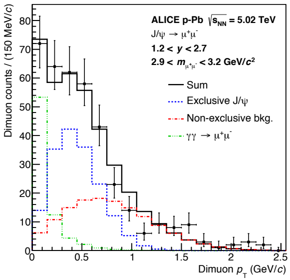
Low energy $\gamma - A$: coherent and incoherent visible ALICE: 1406.7819

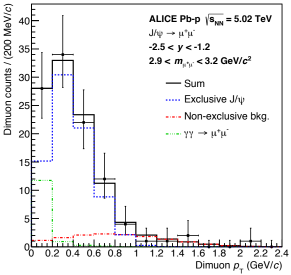


Larger COM energies:
incoherent → 0 (?)
⇒ smoother proton?

ALICE:1809.03235

$x \sim 10^{-2} \to 10^{-5}$





Medium → high energy
(Raw data....)

Towards small x: $\gamma + p \to J/\psi + p^*$

Small-x evolution

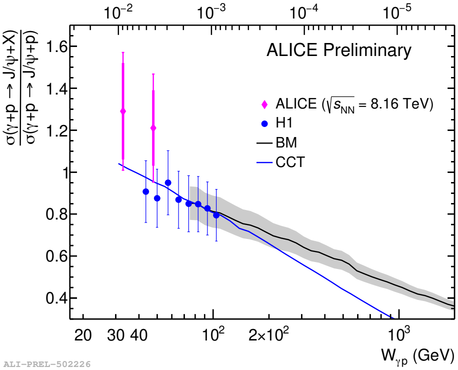
- Evolve proton structure by solving evolution perturbatively (JIMWLK) *BM*

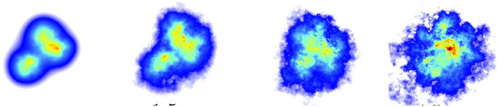
  Schlichting, Schenke, 1407.8458, H.M., Schenke, 1806.06783

- Parametrize the W dependence of the proton density & num. of hot spots *CCT*

  Cepila, Contreras, Takaki, 1608.07559

Constrained by HERA F_2 and J/ψ data.

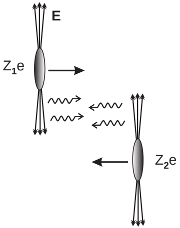




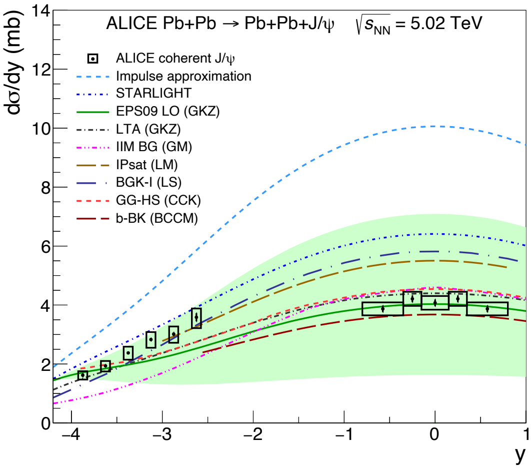
Smoother proton at small x, coherent cross section dominates

Compatible with the high-E ALICE data shown on previous slide. EIC: x, Q^2, A systematics

3. UPC in A+A: nuclear DIS before the EIC



Significant nuclear effects already seen at the LHC (coherent)



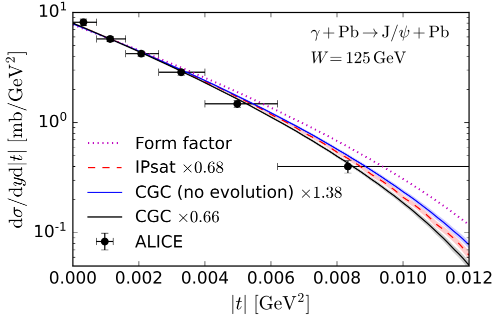
$$x = \frac{M_{J/\Psi}}{\sqrt{s}} e^{\pm y}$$

ALICE: 2101.04577

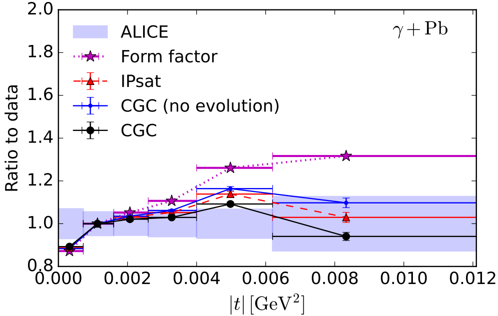
- Extensively studied in UPCs at the LHC by CMS, ALICE, LHCb
- Impulse approximation = scaled $\gamma + p$ from HERA $\Rightarrow$ large nuclear effect
- CGC based calculations (e.g. *IPsat (LM)*) relatively successful
  - But y dependence?
  - Not enough suppression
- EIC advantages:
  - No two-fold ambiquity in kinematics
  - $Q^2, x_{\mathbb{P}}, A$ lever arm

Saturation effects on nuclear geometry

ALICE UPC: extracted $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$ from $\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \mathrm{J}/\psi$



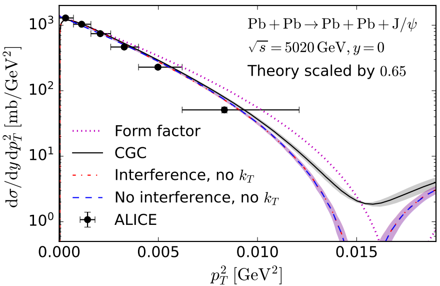
H.M, F. Salazar, B. Schenke, in preparation.

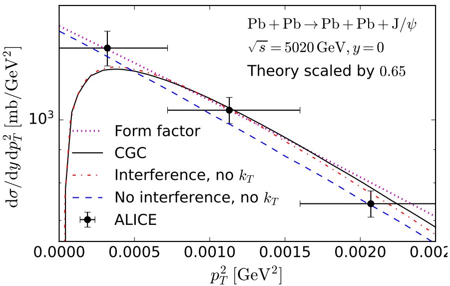


ALICE data: 2101.04623.

- Naive expectation/linearized calculation:
  $\mathrm{d}\sigma/\mathrm{d}t \sim \mathcal{F}$[Woods-Saxon] (*Form factor*), but a steeper t spectrum seen
- Center of the nucleus closer to the black disc limit, stronger nonlinear effects
  $\Rightarrow$ Good description of the data (except lowest $|t|$) + effect on geometry/t spectrum

UPC vs EIC





- UPC: Photon $k_T \lesssim 1/R_A \neq 0$: important around dips, tiny effect on p_T integrated σ
- Interference (both nuclei can emit γ): $\mathrm{d}\sigma/\mathrm{d}p_T^2 \to 0$ when $p_T \to 0$
  Stronger effect predicted than seen in the ALICE data.
- Calculated spectra not steep enough, although the ALICE $\gamma + \mathrm{Pb}$ data was well described
  $\Rightarrow$ Photon k_T effect included differently?
- Need a larger Pb than what we get with standard WS parameters (backup)

H.M, F. Salazar, B. Schenke, in preparation. Photon k_T and interference included following Xing, Zhang, Zhou, Zhou, 2006.06206

4. Theory in the precision era

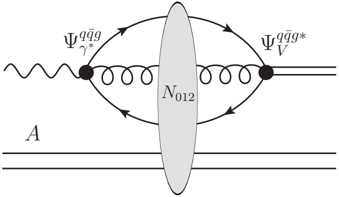
Theory developments: towards NLO

Most of the CGC phenomenology so far: LO (resumming $\alpha_s \ln 1/x$)

Recent progress to calculate exclusive processes at NLO

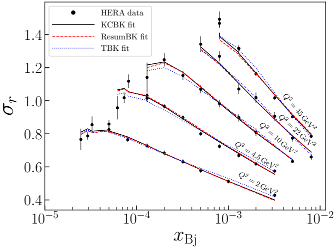
Ingredients

- Photon wave function at NLO Beuf, Hänninen, Paatelainen, Lappi 2018-2022
- Heavy vector meson wave function at NLO Escobedo, Lappi, 1911.01136
- Relativistic corrections to wave function: H.M, Lappi, Penttala, 2104.02349
- Small-x evolution equations Balitsky 0710.4330
- Initial condition fitted to F_2 data Beuf, Hänninen, Lappi, H.M, 2007.01645



Cross sections for exclusive processes

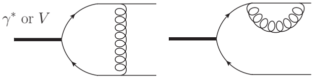
- Light meson at NLO H.M, Penttala, 2203.16911 , Boussarie et al, 1612.08026
- Heavy meson at NLO H.M, Penttala, 2204.14031, 2104.02349



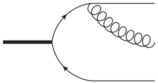
Also much more progress towards NLO not listed here

Heavy vector meson production at NLO

$q\bar{q}$ (virtual corrections):



$q\bar{q}g$ (real corrections):



- Corrections from real and virtual gluons to the γ and J/Ψ wave functions
- UV divergences between the $q\bar{q}$ and $q\bar{q}g$ parts of the calculation cancel
- IR divergences cancel when one takes into account:
  - Renormalization of the leading-order J/Ψ wave function $\phi^{q\bar{q}}$ using Γ_{ee}
  - The energy dependence of the dipole amplitude = BK equation (resum soft gluon emission):

$$\frac{\partial}{\partial \ln 1/x} N(\mathbf{x}_{01}) = \frac{N_c \alpha_s}{2\pi^2} \int \mathrm{d}^2\mathbf{x}_2 \, \frac{\mathbf{x}_{01}^2}{\mathbf{x}_{20}^2 \mathbf{x}_{21}^2} \left[N(\mathbf{x}_{02}) + N(\mathbf{x}_{12}) - N(\mathbf{x}_{01}) - N(\mathbf{x}_{02}) N(\mathbf{x}_{12}) \right]$$

$\Rightarrow$ The total production amplitude is finite and can be numerically evaluated

Final expression

H.M, J. Penttala, arXiv:2104.02349 (L), arXiv:2203.16911 (T)

$$-i\mathcal{A}^L = -Q\sqrt{\Gamma(V \to e^- e^+)\frac{3M_V}{16\pi^2\alpha_{\mathrm{em}}}} \int \mathrm{d}^2\mathbf{x}_{01} \int \mathrm{d}^2\mathbf{b} \left\{ \mathcal{K}^{\mathrm{LO}}_{q\bar{q}}(Y_0) + \frac{\alpha_s C_F}{2\pi} \mathcal{K}^{\mathrm{NLO}}_{q\bar{q}}(Y_{\mathrm{dip}}) + \frac{\alpha_s C_F}{2\pi} \int \mathrm{d}^2\mathbf{x}_{20} \int_{z_{\min}}^{1/2} \mathrm{d}z_2\, \mathcal{K}_{q\bar{q}g}(Y_{\mathrm{qqg}}) \right\}$$

where $\mathcal{K}^{\mathrm{LO}}_{q\bar{q}}(Y_0) = K_0(\zeta) N_{01}(Y_0)$, $\zeta = |\mathbf{x}_{01}|\sqrt{\frac{1}{4}Q^2 + m_q^2}$,

$$\mathcal{K}^{\mathrm{NLO}}_{q\bar{q}}(Y_{\mathrm{dip}}) = \left[\mathcal{K} + \tilde{\mathcal{I}}_{\mathcal{V}}\left(z = \frac{1}{2}, \mathbf{x}_{01}\right) + K_0(\zeta)\left(6 - \frac{\pi^2}{3} + \Omega_{\mathcal{V}}\left(\gamma; z = \frac{1}{2}\right) + L\left(\gamma; z = \frac{1}{2}\right) - 3\log\left(\frac{|\mathbf{x}_{10}| m_q}{2}\right) - 3\gamma_E\right)\right] N_{01}(Y_{\mathrm{dip}})$$

and

$$\mathcal{K}_{q\bar{q}g}(Y_{\mathrm{q\bar{q}g}}) = -32\pi m_q \left\{ \frac{i\mathbf{x}_{20}^i}{|\mathbf{x}_{20}|} K_1(2m_q z_2 |\mathbf{x}_{20}|) \left[\left((1-z_2)^2 + z_2^2\right) \mathcal{I}^i_{(f)} + (2z_2^2 - 1)(1 - 2z_2)\mathcal{I}^i_{(g)}\right] N_{012}(Y_{\mathrm{q\bar{q}g}}) \right.$$
$$\left. + 4 m_q z_2^3 K_1(2m_q z_2 |\mathbf{x}_{20}|) \left[\mathcal{I}_{(f)} - \frac{1-2z_2}{1+2z_2}\mathcal{I}_{(g)}\right] N_{012}(Y_{\mathrm{q\bar{q}g}}) + \frac{1}{8\pi^2}\left((1-z_2)^2 + z_2^2\right) \frac{1}{m_q z_2 |\mathbf{x}_{20}|^2} K_0(\zeta) e^{-\mathbf{x}_{20}^2/(\mathbf{x}_{10}^2 e^{\gamma_E})} N_{01}(Y_{\mathrm{q\bar{q}g}}) \right\}.$$

Equation for transverse production similar but more complicated. Everything finite.

Towards NLO phenomenology

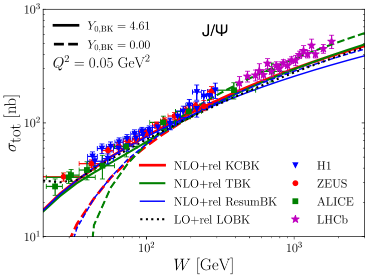
What do we have

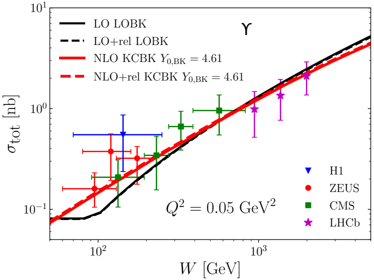
- NLO result for exclusive heavy vector meson production
- Corrections $\sim \alpha_s$ and $\sim v^2$
  Both important in J/Ψ production
  Relativistic $\sim v^2$ correction negligible in Υ production
- Also NLO light meson production at high Q^2
- Codes for numerical evaluation

What is needed for full EIC/LHC phenomenology

- Initial condition for small-x evolution:
  Fit to HERA F_2 data with quark masses at NLO

In progress with Hänninen, Penttala, Paatelainen





Conclusions and outlook

Exclusive vector meson production

- Powerful probe of small-x hadron structure
  - Approximatively $\mathrm{d}\sigma \sim \text{gluon}^2 \Rightarrow$ nonlinear dynamics in eA at the EIC!
  - Access to geometry (and event-by-event fluctuations)

Lessons learnt

- LHC data from Ultra Peripheral Collisions: significant nuclear effects
- Qualitatively described when gluon saturation is included
- Event-by-event fluctuating nucleon geometry required

EIC era

- Precise data + NLO level $\mathcal{O}(\alpha_s \ln 1/x) + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2 \ln 1/x)$ accuracy
- Wide x, Q^2, A coverage $\Rightarrow$ systematic & evolution

Backups

Gluon saturation and the Color Glass Condensate

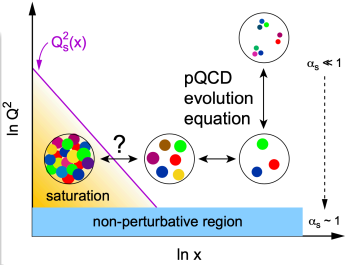
- Very high occupation number $xg(x, Q^2)$, apparent size $1/Q^2$

Non-linear dynamics important when

$$\pi R_p^2 = \alpha_s xg(x, Q^2)\frac{1}{Q^2}$$

Emergent saturation scale $Q^2 = Q_s^2 > \Lambda_{\mathrm{QCD}}^2$
Characterizes the target wave function

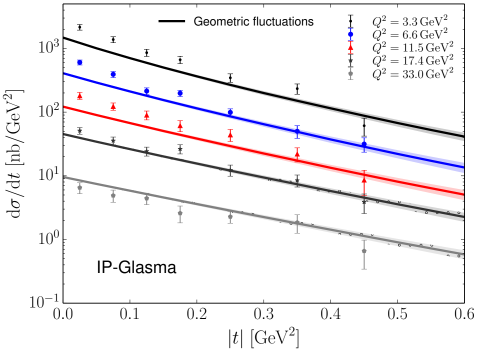
- Exclusive vector meson production at $Q^2 + M_V^2 \sim Q_s^2$: probe transition to saturated region

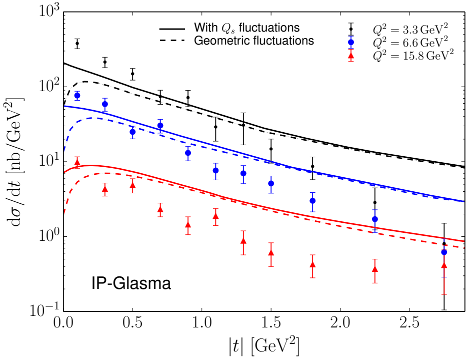


Color Glass Condensate

- Effective theory of QCD in the high energy limit
- Large x: static color charge ρ, small x: classical gluon field A_μ
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$

Light mesons





H.M, B. Schenke, 1806.06783

- OK simultaneous description of light and heavy vector meson production data (Calculations of light meson production at low Q^2 not reliable)
- Proton geometry and geometry fluctuations from J/ψ data
- Same fluctuating geometry: a good description of flow in $p + \mathrm{Pb}$ H.M, Schenke, Shen, Tribedy, 1705.03177

Dipole amplitude from the CGC

Color charge distribution at $x = 0.01$

- Event-by-event random color charge distribution ρ^a
- McLerran-Venugopalan model $\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y})\rangle \sim \delta^{ab}\delta(\mathbf{x}-\mathbf{y})g^4\mu^2$
- $g^4\mu^2 \sim Q_s^2(\mathbf{b}) \sim T_p(\mathbf{b})$ e.g. from HERA data

Small-x evolution

- Perturbative JIMWLK evolution (event-by-event)
- Infrared regulator to suppress gluon emission at long distance

Dipole-target amplitude

- $N(\mathbf{r} = \mathbf{x} - \mathbf{y}) = 1 - \frac{1}{N_\mathrm{c}}\langle V^\dagger(\mathbf{x})V(\mathbf{y})\rangle$
- $V(\mathbf{x}) = P\exp\left(-ig\int \mathrm{d}x^- \frac{\rho(\mathbf{x})}{\nabla^2 - m^2}\right)$

Spatial distribution of nuclear matter at small x

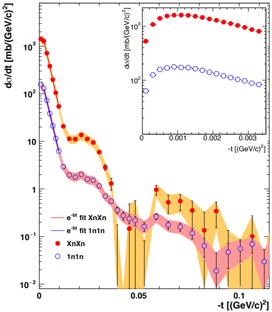
Total momentum transfer t can be measured in exclusive processes!

- By definition $\sqrt{|t|}$ is Fourier conjugate to the impact parameter $\Rightarrow$ access to geometry

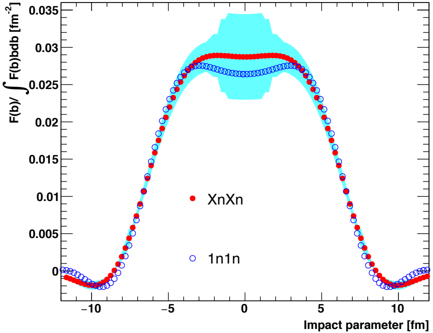
Example: STAR measurement of exclusive $\pi^+\pi^-$ production in Au+Au UPC $\Rightarrow$ b profile

FT: momentum space
$\rightarrow$ coordinate space

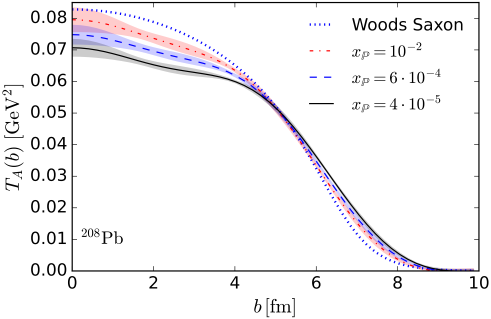
$$F(b) \sim \int \mathrm{d}|\mathbf{k}||\mathbf{k}|J_0(b|\mathbf{k}|)\sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$



STAR: 1702.07705



Saturation effects on nuclear geometry



H.M, F. Salazar, B. Schenke, in preparation.

Normalization: $\int \mathrm{d}^2 b T_A(b) = 1$

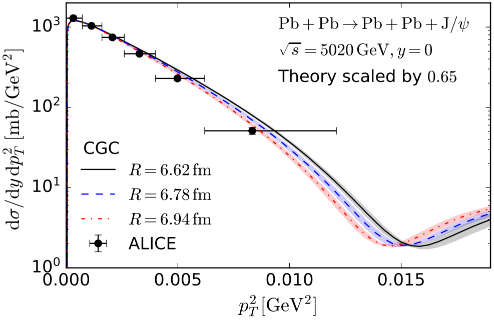
FT: momentum space $\to$ coordinate space

$$F(b) \sim \int \mathrm{d}|\mathbf{p}||\mathbf{p}|(-1)^n J_0(b|\mathbf{p}|)\sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

- CGC setup: nucleon positions sampled from Woods-Saxon at $x = 0.01$
- Perturbative JIMWLK evolution
- Nonlinear dynamics changes the profile close to the center
- Size of the nucleus grows towards small x

n: number of dips before $|\mathbf{p}|$ = sign changes in amplitude

Need for a larger nuclear size

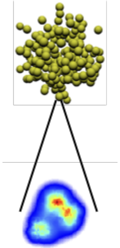


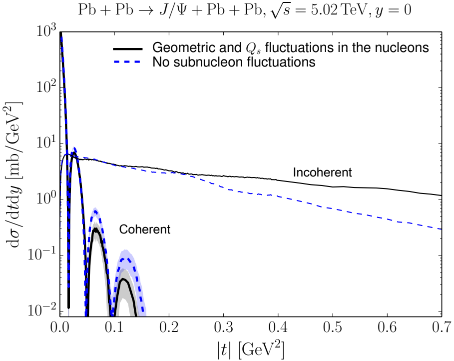
H.M, F. Salazar, B. Schenke, in preparation.

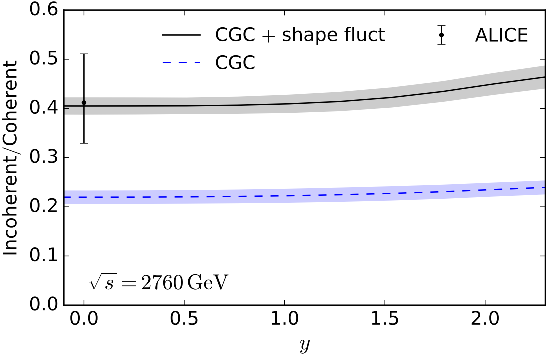
- Steep enough spectrum obtained with a larger nucleus
- Larger Pb needed than the with the standard WS parameters
- But: $\gamma + p$ data suggests that for protons gluonic radius $<$ electromagnetic radius

Event-by-event fluctuations at small-x: nuclei

- Small $|t| \lesssim 0.25\text{GeV}^2$: long length scale, fluctuating nucleon positions
- Large $|t| \gtrsim 0.25\text{GeV}^2$: short length scale, fluctuating nucleon substructure







Subnucleon fluctuations preferred by ALICE data

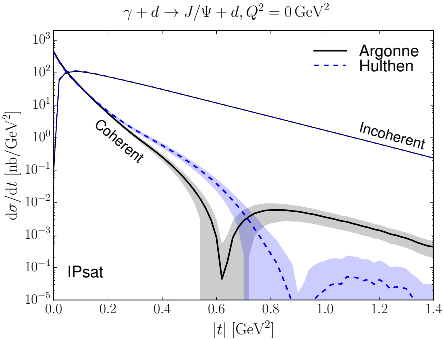
H.M, B. Schenke, 1703.09256 + in preparation w Schenke and Salazar

EIC: nuclear effects on nucleon shape fluctuations as a function of x, A, Q^2

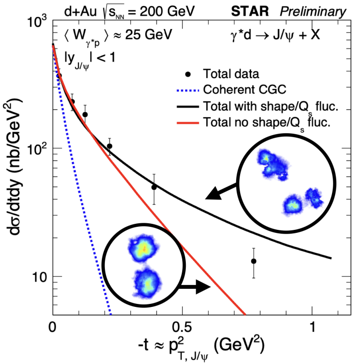
ALICE: 1305.1467

Light ions

RHIC:
UPC in $d + \mathrm{Au}$
(and $^3\mathrm{He} + \mathrm{Au}$)
$x_{\mathbb{P}} \sim 10^{-2}$



Distribution of small-x gluons in d:
Does it follow nucleon positions?
Details of the deuteron wf at small x

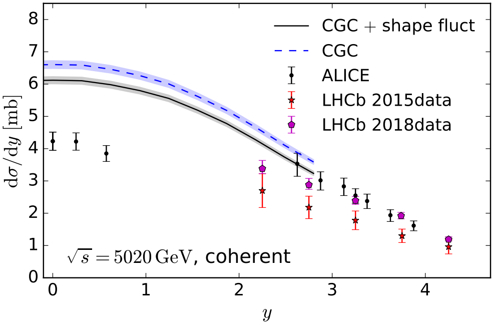


Nucleon substructure fluctuations preferred by STAR data (coh+incoh)

H.M, Schenke, 1910.03297; STAR 2109.07625

Gluon saturation and event-by-event fluctuations

$$\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \mathrm{J}/\psi$$



- Coherent $\sigma \sim$ average interaction, but:
- Substructure $\Rightarrow$ larger saturation effect: Larger local density when hotspots overlap
- Note: $\gamma + p \to \mathrm{J}/\psi + p$ identical with and without substructure by construction
- Still less suppression than in the data

H.M, F. Salazar, B. Schenke, in preparation; ALICE: 2101.04577, 1904.06272, LHCb: 2107.03222, DIS2022