Diffractive vector meson production and dips

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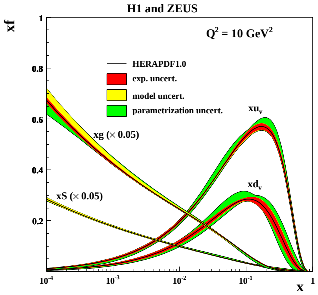
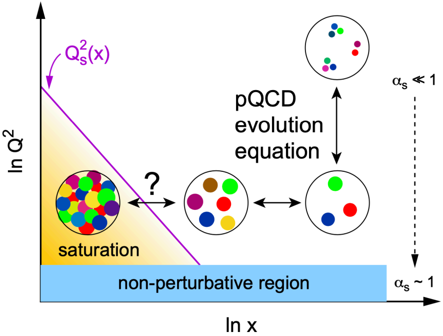
Standard introduction

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



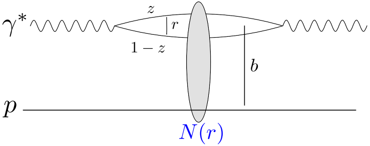


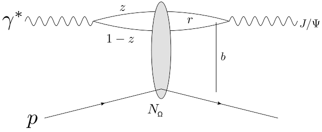
Non-linear QCD effects at small x (e.g. $gg \to g$) should tame this growth

$\Rightarrow$ Saturated state of gluonic matter at small x and moderate Q^2 or M_X^2

Color Glass Condensate: effective theory of QCD in the high-density region

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





Inclusive cross section

Optical theorem:

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

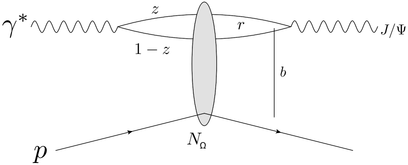
$\sim$ dipole N $\sim$ "gluon structure"

Diffractive processes

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

- Dipole picture at high energy: $\gamma^* \to q\bar{q}$ fluctuation has a long lifetime $\Rightarrow$ factorization
- Dipole amplitude N: eikonal propagation in the color field, resumming multiple scattering
  Center-of-mass energy dependence perturbative: BK/JIMWLK

Vector meson production: $\gamma^* + p \to \mathrm{J}/\psi + p$



- Need at least 2 gluons for exclusivity, very sensitive probe
- Momentum transfer measurable, conjugate to geometry
- Coherent cross section $\sim$ average spatial distribution of gluons at small x

Scattering amplitude in dipole picture

$$-i\mathcal{A}^{\gamma^* A \to VA} \sim \int \mathrm{d}^2\mathbf{b}\,\mathrm{d}^2\mathbf{r}\,\frac{\mathrm{d}z}{4\pi} e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} \Psi_{\gamma^*}^{q\bar{q}}(\mathbf{r}, z) N_\Omega(\mathbf{r}, \mathbf{b}, Y) \Psi_V^{q\bar{q}*}(\mathbf{r}, z)$$

$$\frac{\mathrm{d}\sigma^{\text{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \langle \mathcal{A}^{\gamma^* A \to VA} \rangle_\Omega \right|^2$$

A particular advantage of the dipole picture:
simultaneous descrpition of inclusive and diffractive observables
using the same degrees of freedom

Coherent and incoherent diffraction

Coherent

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

- Proton stays intact

Probes the average interaction
$\Rightarrow$ average shape

Incoherent

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

- Proton dissociates

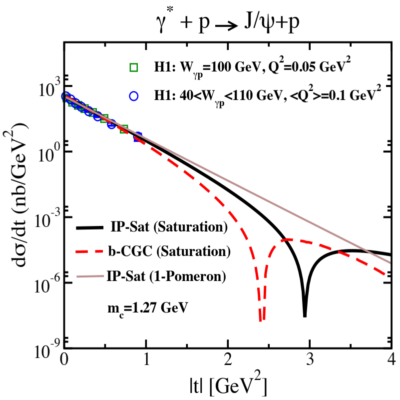
Event-by-event fluctuations in the amplitude $\sim$ proton geometry

- Experimental signature: rapidity gap
- Theoretically: no net color transfer
- Average over target configurations Ω at amplitude/cross section level

$$\mathcal{A}^{\gamma^* p \to Vp} \sim \int \mathrm{d}^2\mathbf{b}\,\mathrm{d}z\,\mathrm{d}^2\mathbf{r}\,\Psi^{\gamma^*}\Psi^{V}(|\mathbf{r}|, z, Q^2) e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} N(|\mathbf{r}|, x, \mathbf{b}, \Omega)$$

Miettinen, Pumplin, PRD 18, 1978; Caldwell, Kowalski, 0909.1254; H.M, Schenke, 1603.04349; H.M, 2001.10705

Why diffractive minima



Armesto, Rezaeian, 1402.4831

Get diffractive minima when
$\langle \mathcal{A}^{\gamma^* A \to VA} \rangle \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} N(\mathbf{r}, \mathbf{b}) = 0$

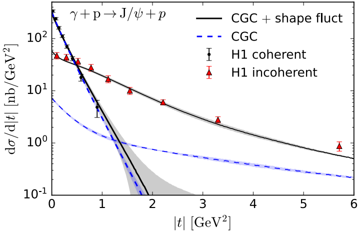
Protons:

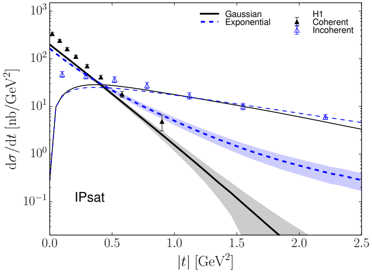
- Hard sphere: $N(r, b) \sim \theta(b - R_p)$: diffractive minima when $J_1(R_p\sqrt{|t|}) = 0$ (first around $|t| \sim 1\ \mathrm{GeV}^2$)
- Gaussian&linear: $N(r, b) \sim e^{-\mathbf{b}^2/(2B)}$: FT Gaussian
- Gaussian&non-linear: $N(\mathbf{r}, \mathbf{b}) \sim 1 - \exp\left(-e^{-\mathbf{b}^2/(2B)}\right)$: dips at large $|t|$

Whether there are diffractive dips depends on

- Actual density profile
- Non-linear dynamics

Accessing proton dips



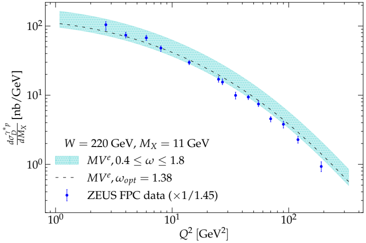


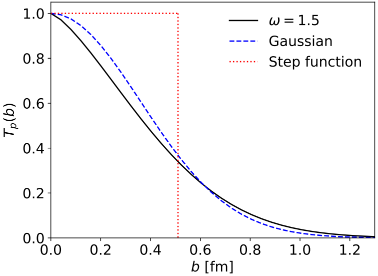
- Incoherent (proton dissociates) dominates at $|t| \gtrsim 1\,\mathrm{GeV}^2$
- Observing dips requires one to suppress incoherent background by $2 \ldots 3$ orders of magnitude
- In principle detecting the forward proton that receives quite high p_T kick is feasible?
- Even if can't see the dips, pushing coherent spectra measurements towards high $|t|$ important: probe potential deviations from the Gaussian profile

H.M, Schenke, 1607.01711; H.M, Salazar, Schenke, 2207.03712

Here CGC = MV model with $Q_s^2(\mathbf{b})$ from IPsat + JIMWLK

Complementary channel: diffractive structure functions





- Structure functions $\sim$ proton area
- Diffractive structure functions $\sim \int \mathrm{d}^2\mathbf{b} |T(\mathbf{b})|^2$
- Inclusive and diffractive data simultaneously: complementary method to constrain the proton shape, non-Gaussian form preferred

$$T_p(b) = \frac{\Gamma\left(\frac{1}{\omega}, \frac{b^2}{R_p^2 \omega}\right)}{\Gamma\left(\frac{1}{\omega}\right)},$$

- FT with $\omega > 1$: no dips
- Band: $0.4 < \omega < 1.7$

Lappi, Le, H.M, in preparation

Light ions: deuteron

How are the small-x gluons distributed in deuteron?

Deuteron, proton-neutron separation $d_{\rm pn}$

Use two different wave functions with same RMS size

- Hulthen: Miller *et al*, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205

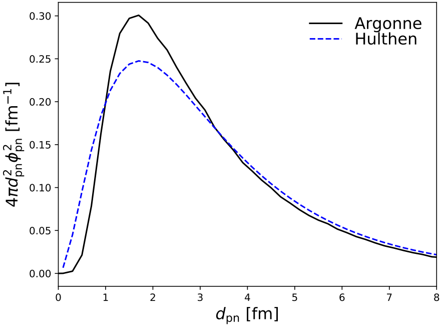
$$\phi(d_{\rm pn}) \sim \frac{e^{-ad_{\rm pn}} - e^{-bd_{\rm pn}}}{d_{\rm pn}}$$

- Argonne V18 two-nucleon potential

  Wiringa, Stoks, Schiavilla, phy.anl.gov/theory/research/density2

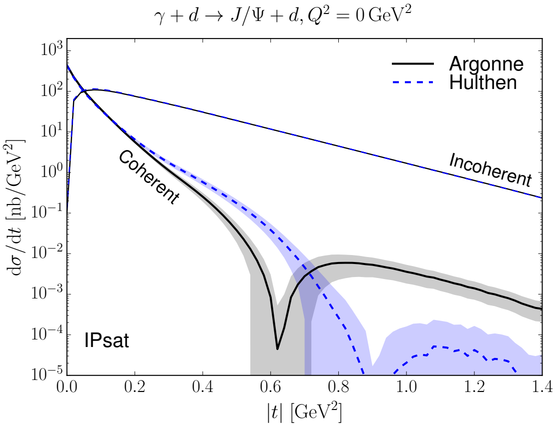
  Includes repulsive short range correlations

Constrained by low-energy data!
EIC: how about small-x?



- Short range correlations have a significant effect in deuteron
- Can affect exclusive spectra at large $|t|$ (small distance)

Predictions for the EIC: deuteron wave function



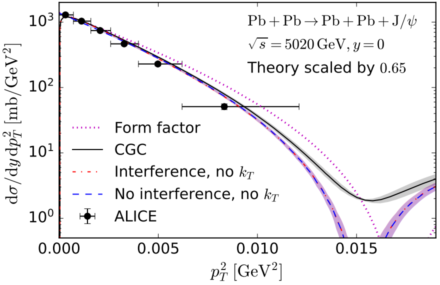
H.M, Schenke, 1910.03297

Hulthen vs Argonnev18 wave functions:

- Coherent spectra at $|t| \gtrsim 0.3\mathrm{GeV}^{-2}$ sensitive to short range correlations in WF
- Difference similar also after the JIMWLK evolution, but dips $\to$ smaller $|t|$
- Note: same RMS sizes, dip position differs due to different shapes
- Tiny effect on the incoherent cross section
- Observing the dip would require a huge reduction of the incoherent background

Heavy nuclei

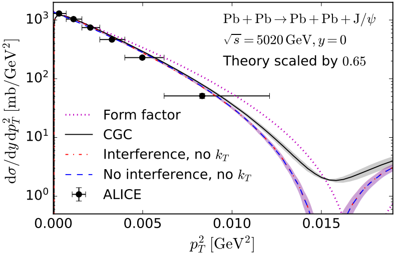
LHC data $\approx \gamma + \mathrm{Pb}$

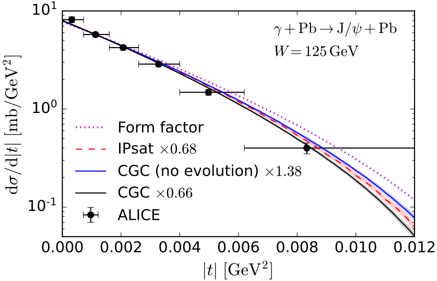


H.M, Salazar, Schenke, 2207.03712

- Large A: dips are at very small t
- ALICE, LHCb have measured in this t range
- Non-linear dynamics important ($x_{\mathbb{P}} \approx 0.0006$): *Form factor* = linearized calculation
- Saturation effects modify the t spectra – including the dip location
  - Extreme black disck limit: step function
- Here non-zero photont k_T washes out the dip
  Also small interference effect at $p_T^2 \approx 0$
- EIC: in principle can remove the photon k_T by measuring the outgoing electron.
  How accurately in practice?

Photon k_T effect





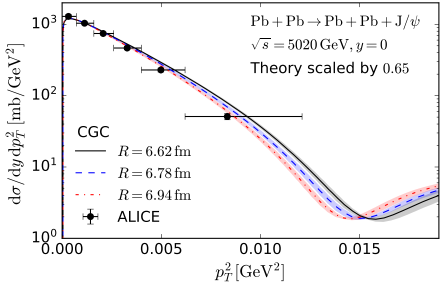
- UPC: Not possible to separately determine the photon $k_T \sim Q$
- ALICE: extract $\gamma + \mathrm{Pb}$ cross section from $\mathrm{Pb} + \mathrm{Pb}$ using Monte Carlos
- CGC calculation: good agreement with $\gamma + \mathrm{Pb}$ data except at smallest $|t|$, but too hard spectrum in $\mathrm{Pb} + \mathrm{Pb}$
- ALICE: steeper spectrum in $\mathrm{Pb} + \mathrm{Pb}$ with photon k_T Opposite systematics in our theory calculation

Important advantage at the EIC: measure outgoint electron $\Rightarrow$ photon k_T

H.M, Salazar, Schenke, 2207.03712

Gluonic size of heavy nuclei

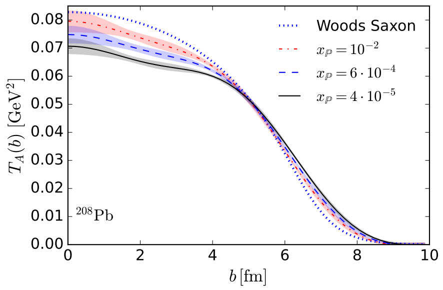
LHC data $\approx \gamma + \mathrm{Pb}$



H.M, Salazar, Schenke, 2207.03712

- As seen on previous slide: ALICE data is more steeply falling than the CGC calculation
- Seems that in addition to non-linear effects would need a larger Pb
- Also larger Au compared to standard value observed in UPCs at STAR 2204.01625
- Differences small in the ALICE kinematics, but grow rapidly when approaching the first dip
- Here photon k_T smoothens the dip, at the EIC it will be sharp(er)

Distribution of small-x gluons from spectra



H.M, Salazar, Schenke, 2207.03712

Normalization

$$\int \mathrm{d}^2\mathbf{b}\, T_A(\mathbf{b}) = A$$

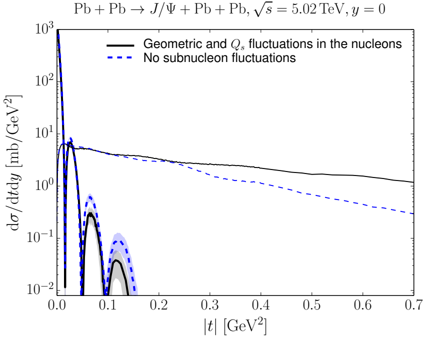
- **b** is Fourier conjugate to impact parameter

$$T_A(\mathbf{b}) \sim \int \mathrm{d}\Delta\, \Delta J_0(b\Delta)(-1)^n \sqrt{\frac{\mathrm{d}\sigma^{\gamma^*+\mathrm{Pb}\to \mathrm{J}/\psi+\mathrm{Pb}}}{\mathrm{d}|t|}}$$

- Here: Woods-Saxon input at $x_{\mathbb{P}} = 0.01$ + JIMWLK Non-linear dynamics included
- Transition towards a black disc profile at the center
- Larger nuclei at small-x after JIMWLK evolution

Does the incoherent process dominate?

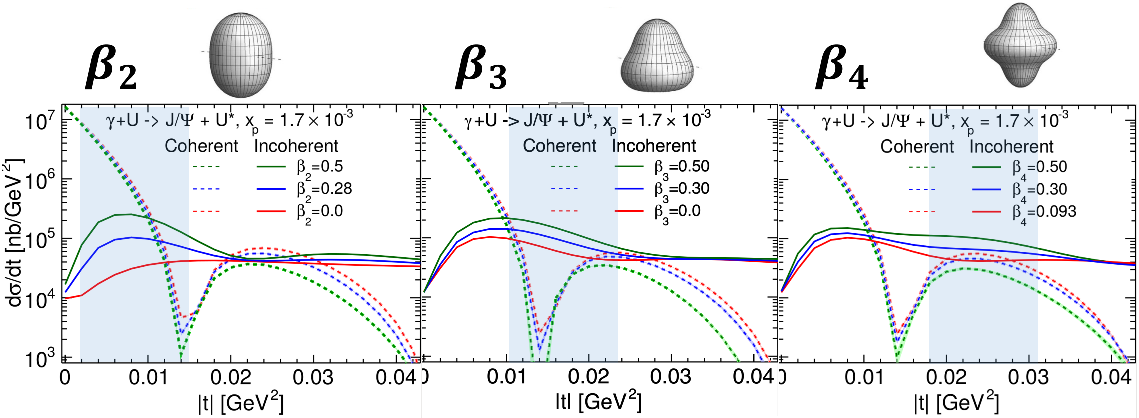
UPC $\approx \gamma + \mathrm{Pb}$



H.M, Schenke, 1703.09256

- In order to see more diffractive dips a large suppression of incoherent contribution is necessary
- Chang, Aschenauer et al, 2108.01694: *can resolve at least the first minimum of the coherent diffractive distribution*
- Still 10 years to tune analysis techniques...
- Nucleon substructure fluctuations enhanced incoherent cross section at $|t| \gtrsim 0.2\,\mathrm{GeV}^2$, no effect in the region or the first few dips

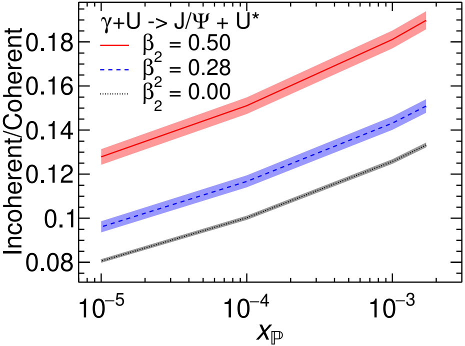
Accessing defomred structure of the uranium at the EIC



- Diffractive dips insensitive to potential deformations at small-x
- Non-spherical structure increases incoherent cross section at low $|t|$ and limits how well coherent spectra can be measured

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

Deformations survive to small-x



$|t| < 0.5\,\mathrm{GeV}^2$

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

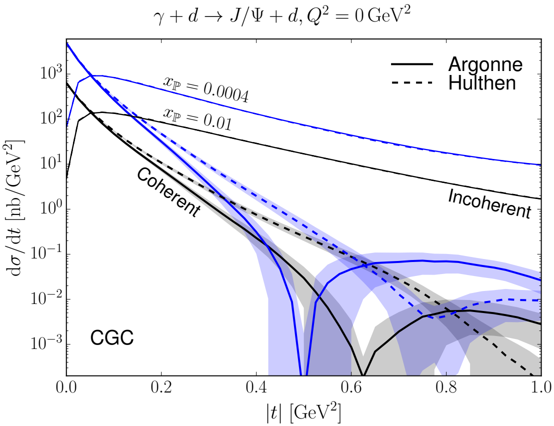
- Deformed uranium shape at initial $x_{\mathbb{P}} = 1.7 \cdot 10^{-3}$
- JIMWLK evolution towards small $x_{\mathbb{P}}$
  Constrained by HERA data
- Cross section ratio sensitive to β_2 even after 2 orders of magnitude $x_{\mathbb{P}}$ evolution

Conclusions

- Coherent spectra sensitive to details of the
  - Proton/nuclear spatial density profile
  - Non-linear dynamic
  - These two are tightly connected!
- Important: precision and as wide $|t|$ range as possible
- Proton: not sure if there are dips, potential to extract e.g. possibly non-Gaussian shape
- Light ions: deviations from low-energy structure, short range correlations, nuclear structure physics at high energies (alpha clustering, . . .)
- Heavy ions: strong non-linear effects expected
- Deformations: connecting low- and high-energy nuclear physcis at the EIC

Backups

Energy dependence of the deuteron structure



H.M, Schenke, 1910.03297