Saturation model in UPCs

Heikki Mäntysaari

University of Jyväskylä, Finland

Open Questions in Photon-Induced Interactions
April 27, 2021

Exclusive vector meson production in UPCs

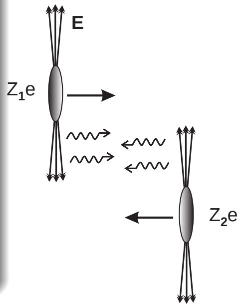
Advantages

- No net color charge transfer: at least two gluon exchange

$$\left.\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t}\right|_{t=0} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{\mathrm{em}} M_V^5} \left[\mathbf{xg(x, Q^2)}\right]^2$$

  In practice connection to PDFs complicated (see Vadim's talk) Ryskin, 1993

- Measure J/ψ p_T = total momentum transfer Δ
  = Fourier conjugate to **b**
  ⇒ Access to spatial structure



UltraPeripheral heavy ion Collisions (UPC)

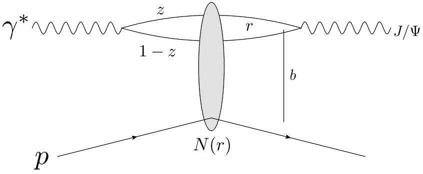
- At $|b_T| > R_1 + R_2$ one nucleus acts as a photon source

High energy (nuclear) DIS before the Electron Ion Collider!

Vector meson production at high energy/small x

High energy factorization:

1. $\gamma \to q\bar{q}$ splitting,
   wave function $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically: $N(r, x, b)$
3. $q\bar{q} \to J/\Psi$,
   wave function $\Psi^V(r, z)$



Diffractive scattering amplitude

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

- $N(r, x, b)$: universal dipole-proton scattering amplitude, resumming multiple scattering
  Convenient degrees of freedom at small x

Phenomenology at the moment: LO (resumming $\alpha_s \ln 1/x$), NLO is coming...
H.M, J. Penttala, arXiv:2104.02349 [hep-ph]

Target shape from coherent diffraction

Coherent cross section: target remains on the same quantum state

Average interaction of states that diagonalize the scattering matrix

- These states are $q\bar{q}$ dipoles with fixed size $\mathbf{r}$, probing fixed target configuration Ω
- Good, Walker, PRD 120, 1960

Coherent cross section

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

- Cross section probes average $\mathbf{b}$ dependence of the scattering amplitude = target geometry

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

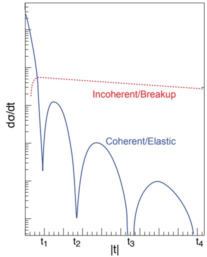
Incoherent diffraction = target dissociation

Incoherent cross section

- Target final state $|f\rangle \neq$ initial state $|i\rangle$
- No net color charge transfer: rapidity gap between J/Ψ and target remnants

$$\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f|\mathcal{A}|i\rangle|^2$$

$$= \sum_f \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$



Miettinen, Pumplin, PRD 18, 1978,

Caldwell, Kowalski, PRC81 (2010) 025203

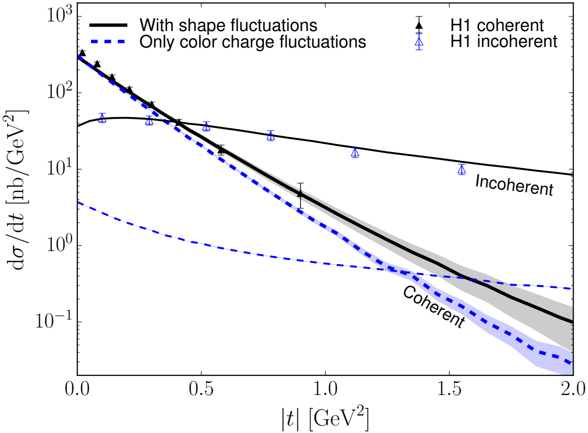
Average over initial states:

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

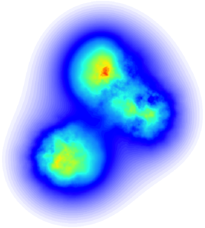
Incoherent cross section = covariance of $\mathcal{A}^{\gamma^* A \to VA}$

- Amount of event-by-event fluctuations in target configurations Ω

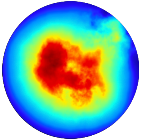
HERA data at small x: $\gamma + p \to J/\psi + p$ at $W = 75$ GeV ($x_{\mathbb{P}} \approx 10^{-3}$)



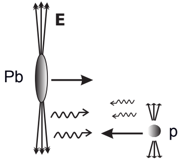
Fluctuations



Round



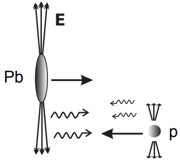
HERA data well understood
(incoherent with fluctuating substructure) H.M, B. Schenke, 1607.01711



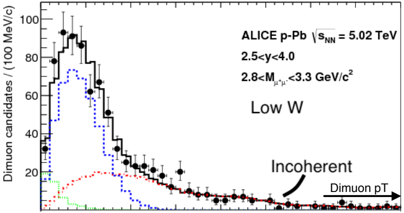
Ultraperipheral collisions in pA

What happens to the incoherent cross section at high W?

Ultraperipheral $p + A$:
Photon flux $\sim Z^2$
$\gamma + p$ dominates



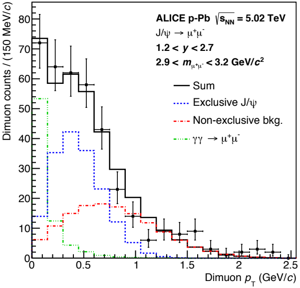
Low energy $\gamma - A$: coherent and incoherent visible ALICE: 1406.7819

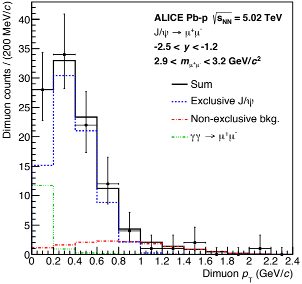


Larger COM energies:
incoherent $\to 0$ (?)
$\Rightarrow$ smoother proton?

ALICE:1809.03235

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





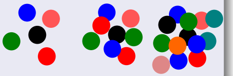
Medium $\to$ high energy

Can we understand the energy dependence?

Approach 1: parametrize the number of hot spots

Small-x gluon emissions increase the number of hot spots Cepila, Contreras, Tapia Takaki, 1608.07559

$$N_{hs}(x) \sim x^{p_1}(1 + p_2\sqrt{x})$$



Approach 2: Solve small-x evolution equations

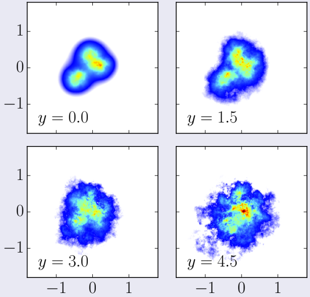
Evolve proton structure by solving evolution perturbatively

- BK eq. with impact parameter

  Berger, Stasto, 1106.5740, Cepila, Contreras, Matas, 1812.02548
- JIMWLK eq. Schlichting, Schenke, 1407.8458, H.M., Schenke, 1806.06783

Fit HERA F_2 and exclusive data. H.M, Schenke, 1806.06783

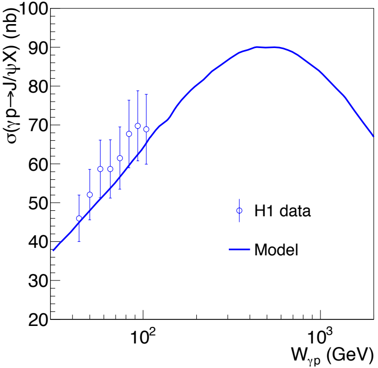
Difficulty: regulating confinement effects

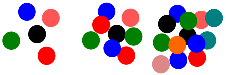


Towards small x: $\gamma + p \to J/\psi + p^*$

Increasing # of hot spots with energy:
Smoother proton, less fluctuations

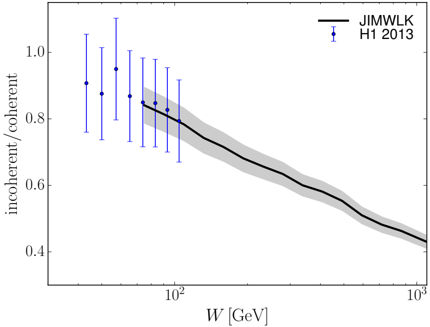
Cepila, Contreras, Tapia Takaki, 1608.07559

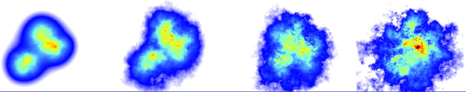




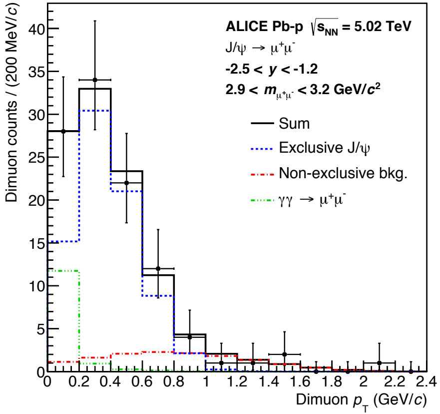
JIMWLK evolution event-by-event
Includes also growing RMS size

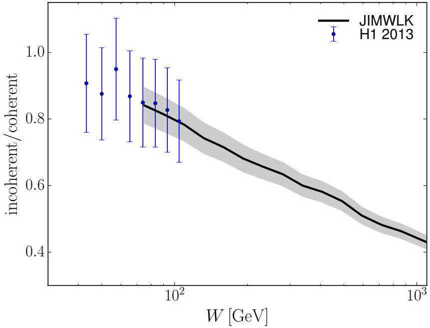
H.M., Schenke, 1806.06783



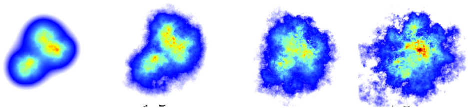


Small x in $\gamma + p \to J/\psi + p^*$





H.M, Schenke, 1806.06783



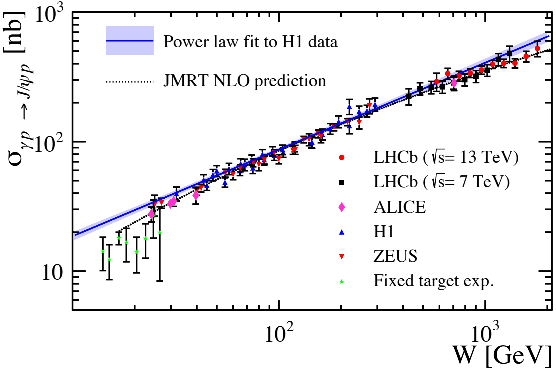
ALICE data qualitatively compatible with e-b-e fluctuating geometry evolution

- Final data at cross section level?
- Are we approaching the black disc limit?

ALICE, 1808.03235

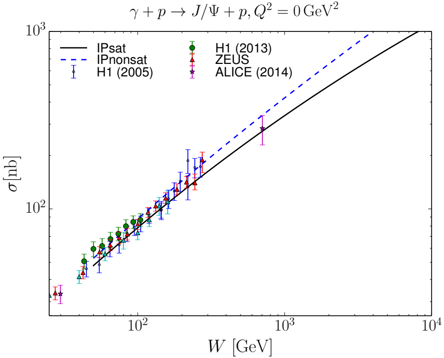
Saturation in $\gamma + p \to J/\psi + p$?

LHCb measurement in ultra peripheral $p + p$
Generically saturation effects $\Rightarrow$ deviations from the $\sigma \sim W^\delta$ behaviour

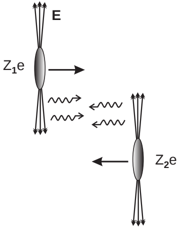


LHCb, 1806.04079

- Small hints at highest W?
- Saturation effects expected to have only a small effect in δ at this W

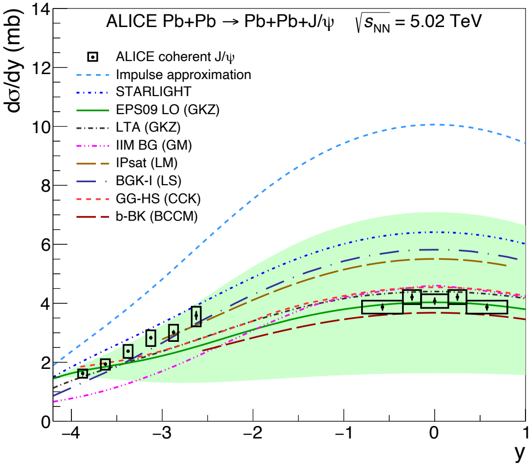


H.M, P. Zurita, 1804.05311



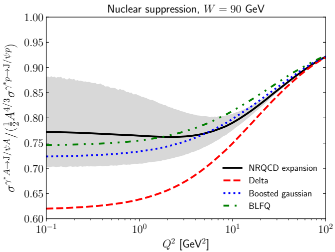
Ultraperipheral collisions in AA

Coherent diffraction today



- Different calculations with saturation effects relatively successful
- Flat(?) rapidity dependence in $-2 < y < 0$???

Also: normalization uncertainty from J/ψ wf, does not completely cancel in nuclear suppression ratio (=ratio to imp. approx.)

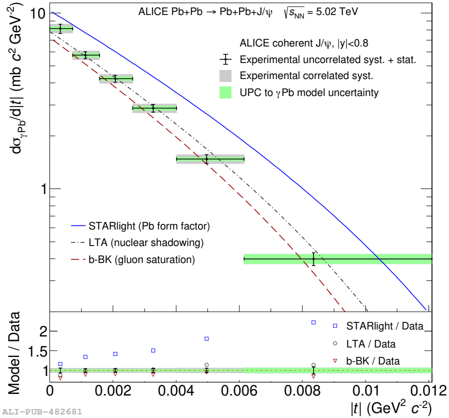


T. Lappi, H. M, J. Penttala, 2006.02830

Measurements not statistic limited anymore

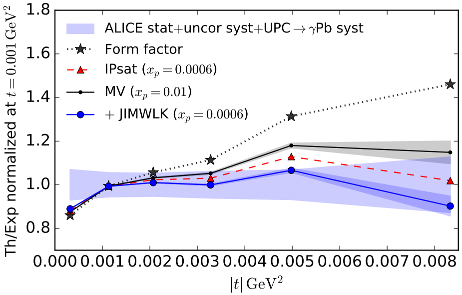
ALICE, 2101.04577

Coherent t spectra



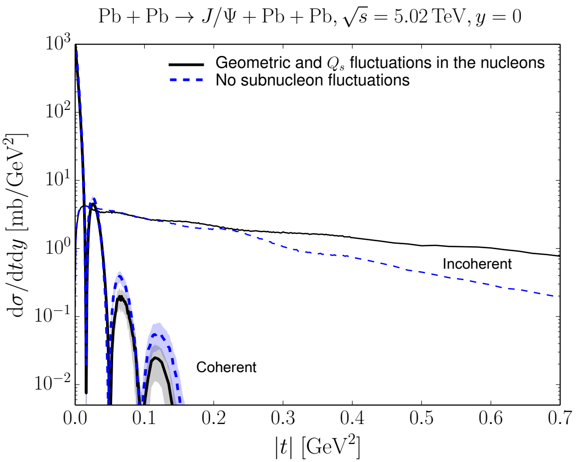
ALICE, 2101.04623

- First t spectra measured!
- (Would be interesting to see coh and incoh)
- Much steeper t spectra than FT of WS
- Steeper slope expected from saturation
- Especially the smallest t bin?



With T. Lappi, F. Salazar and B. Schenke

Accessing fluctuations at different scales

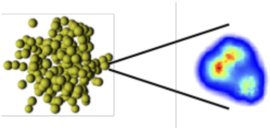


H. M., B. Schenke, arXiv:1703.09256

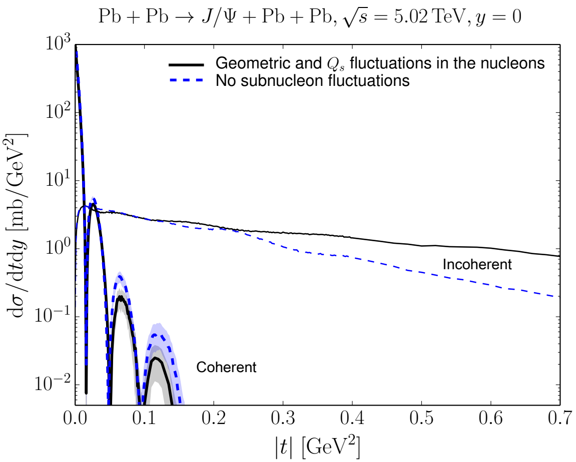
- $\sqrt{|t|}$ is conjugate to b_T
- Small $|t|$: fluctuations of nucleon positions
- Large $|t|$: fluctuations at subnucleon scale
- Incoherent slope changes at

$$|t| \approx 0.25\mathrm{GeV}^2 \sim 0.4\,\mathrm{fm}$$

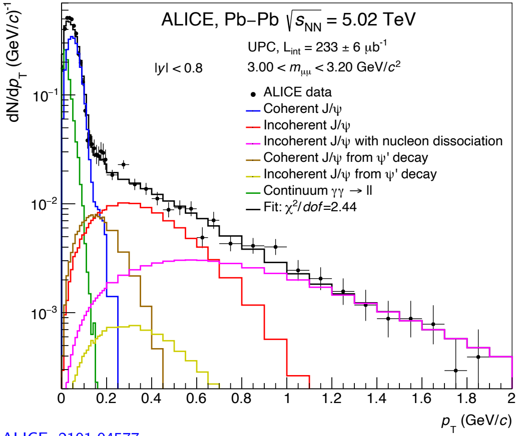
which is the hot spots size from HERA



Accessing fluctuations at different scales



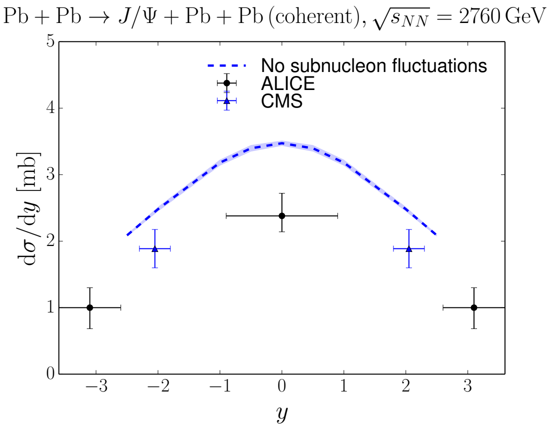
H. M., B. Schenke, arXiv:1703.09256

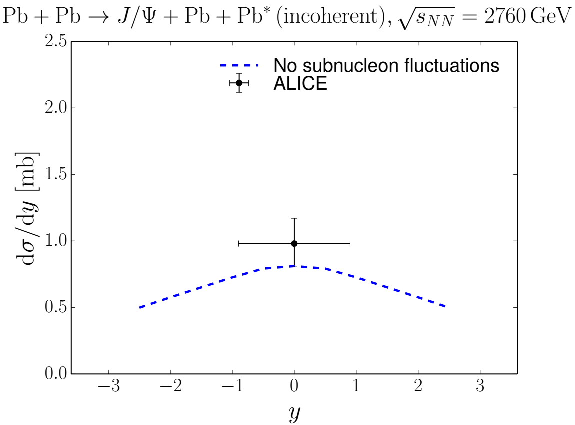


ALICE, 2101.04577

Qualiatively consistent with the ALICE data, but want cross section level spectra!

Comparison to LHC data, no subnucleonic fluctuations

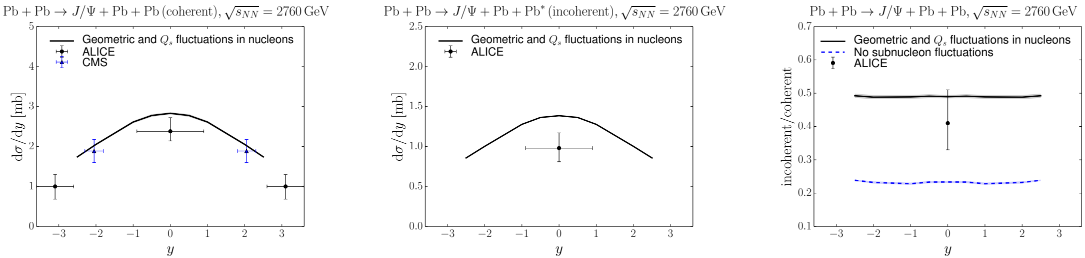




- Only fluctuations of nucleon positions from Woods-Saxon: Coherent cross section overestimated and incoherent underestimated
- Overall normalization uncertainty from the J/Ψ wave function

H.M, B. Schenke, arXiv:1703.09256

Comparison to LHC data, with subnucleon fluctuations



- Calculations with nucleon substructure consistent with the LHC data.
- Dependence on the J/ψ wave function mostly cancels in the ratio
- Note: no W dependent geometry included
- Missing: y and $\sqrt{s}$ dependence of the incoherent cross section
  How does the incoherent cross section and e-b-e fluctuations depend on $x_{\mathbb{P}}$?

H.M, B. Schenke, arXiv:1703.09256

Conclusions

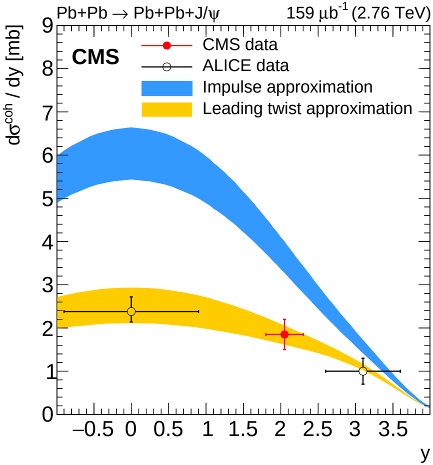
- Vector meson production from HERA relatively well understood
- Lots of precise data from LHC (and RHIC!)
- Interesting observations include
  - Large nuclear suppression compared to impulse approximation
  - Disappearing incoherent cross section in high energy $\gamma + p$??
  - Total $\gamma + p \to \mathrm{J}/\psi + p$ cross section: deviating from W^δ law from HERA???
  - Low-t part of the $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$ spectra????
- Wish list:
  - t spectra in $\gamma + p$ and $\gamma + A$ (coherent+incoherent ok)
  - y and $\sqrt{s}$ dependence of the incoherent cross section
- Clear signatures of non-linear effects, but also need for precision theory
  - NLO (coming, see H.M, J. Penttala, 2104.02349)
  - Vector meson wave function beyond phenomenological models (see T. Lappi, H.M, J. Penttala, 2006.02830; Y. Li, P. Maris, J. Vary, 1704.06968)

Backups

Significant nuclear effects seen in $\gamma + A \to J/\psi + A$

Enhance non-linearities:
$Q_{s,A}^2 \sim A^{1/3} x^{-\lambda}$
(larger A is cheaper than smaller x)

The first UPC measurements:
clear nuclear suppression
Impulse approximation = scaled $\gamma + p$

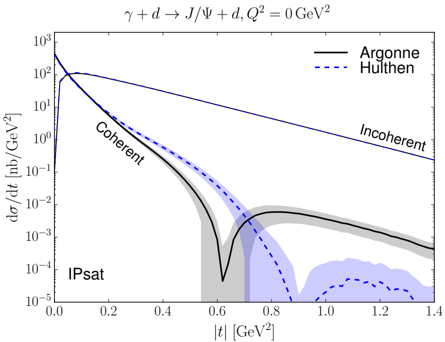


$x_{\mathbb{P}} = M_V e^{\pm y}/\sqrt{s}$

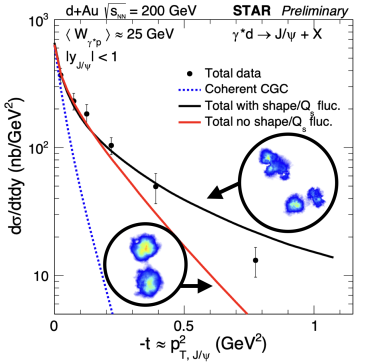
CMS, 1605.06966

Light ions

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



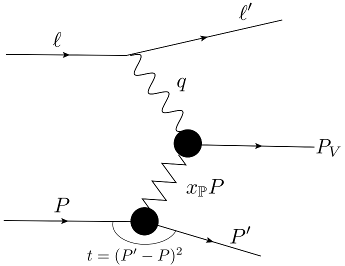
Distribution of small-x gluons in d:
Does it follow nucleon positions?
Details of the deuteron wf at small x



Nucleon substructure fluctuations in d
Preferred by STAR data (coh+incoh)

H.M, Schenke, 1910.03297; STAR 2009.04860

Diffractive scattering

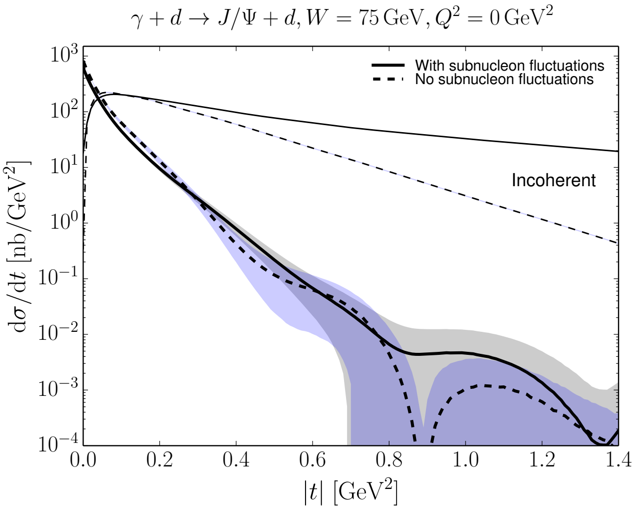


Diffractive events: no exchange of color charge ($\rightarrow$ rapidity gap)

- Target remains intact: *coherent diffraction*, small $|t|$.
  Probes average distribution of gluons.
- Target breaks up: *incoherent diffraction*, larger $|t|$.
  Sensitive to fluctuations.

Target: proton or nucleus

Subnucleon fluctuations in deuteron



Dipole-proton scattering: IPsat model

An impact parameter dependent dipole amplitude

$$N(r,x,b) = 1 - \exp\left[-\frac{\pi^2}{2N_c}\alpha_s xg(x,\mu^2) T_p(b) r^2\right]$$

- Fit to HERA data (F_2): initial condition for the DGLAP evolution of $xg(x,\mu^2)$ (Kowalski, Teaney 2003; Rezaeian et al, 2013, H.M, Zurita, 1804.05311)
- Proton profile T_p: Gaussian, width B_p

$$T_p(b) = -\frac{1}{2\pi B_p} e^{-b^2/2B_p}$$

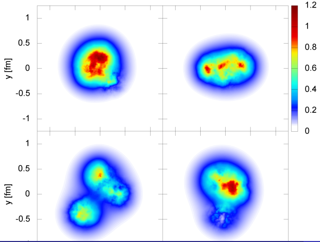
Adding color charge fluctuations: IP-Glasma

- Obtain saturation scale $Q_s(b_T)$ from IPsat (with constituent quarks)
- Sample color charges $\rho(b_T) \sim Q_s(b_T)$
- Solve Yang-Mills equations to obtain Wilson lines

$$V(x_T) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(x^-, x_T)}{\nabla^2 + m^2}\right)$$

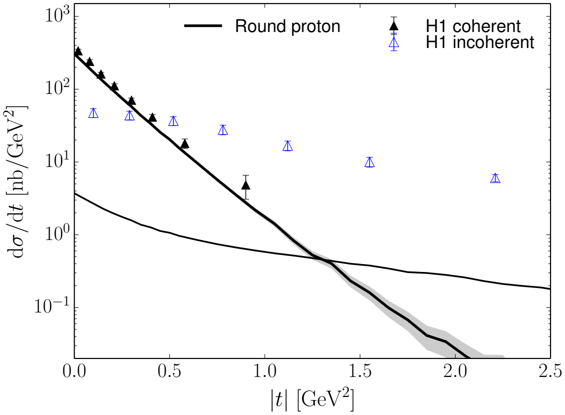
- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr}\, V(x_T) V^\dagger(y_T)/N_c$
- Fix parameters B_{qc}, B_q and m with HERA data

Example configurations:
$1 - \mathrm{Re}(\mathrm{Tr}\, V(x_T))/N_c$



H.M., B. Schenke, arXiv:1603.04349

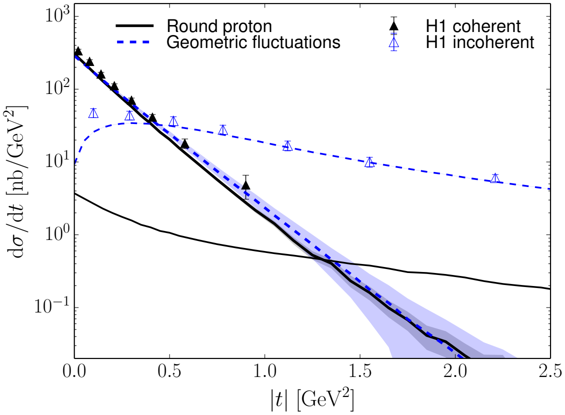
IP-Glasma and HERA data



H.M., B. Schenke, in preparation and arXiv:1603.04349

- Color charge fluctuations alone are not enough

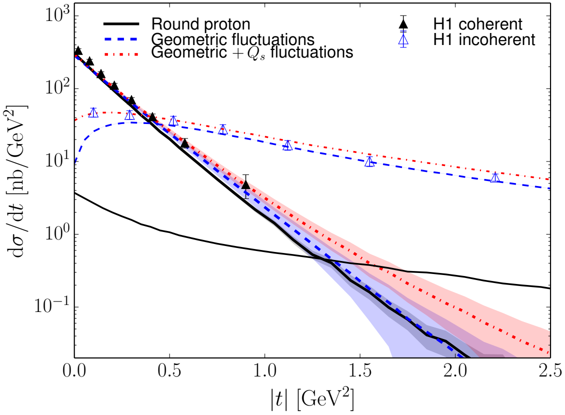
IP-Glasma and HERA data



H.M., B. Schenke, arXiv:1603.04349

- Large geometric fluctuations are needed

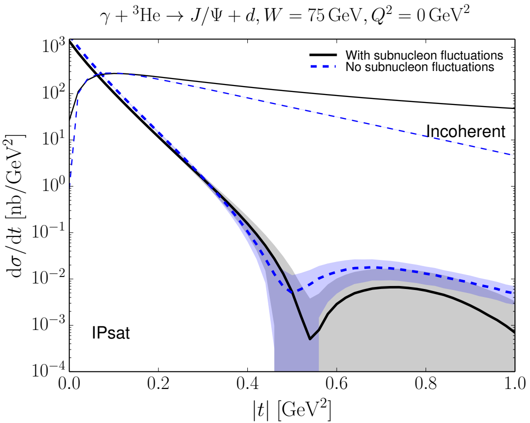
IP-Glasma and HERA data

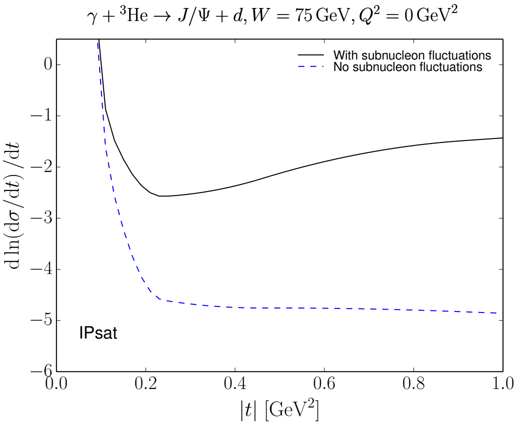


H.M., B. Schenke, arXiv:1603.04349

- Q_s fluctuations improve description at small $|t|$

Similar results for ^{3}He





- Subnucleon fluctuations alter the incoherent $|t|$ slope, and significantly increase the incoherent cross section
- EIC will open a new window to the gluonic structure of light ions, also!