

# Diffractive quarkonium production with target break-up at an EIC

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virtual Quarkonia As Tools 2021

Mar 23, 2021

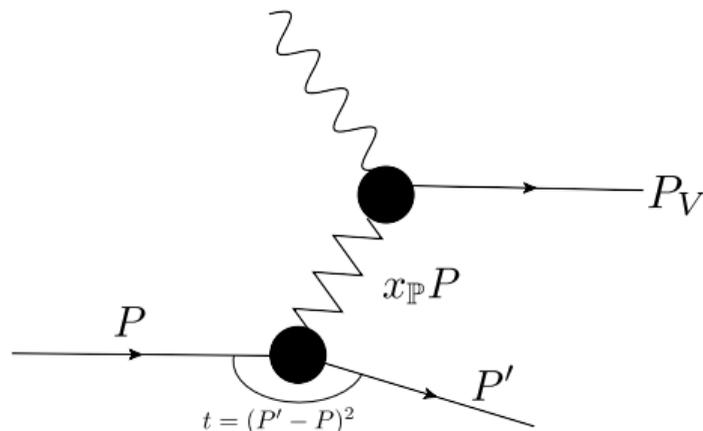
# Why diffraction

Exclusive production of a vector meson/dijet/diffractive system

$$\gamma + A \rightarrow V + A$$

$$\gamma + A \rightarrow \text{jet}_1 + \text{jet}_2 + A$$

$$\gamma + A \rightarrow M_X + A$$

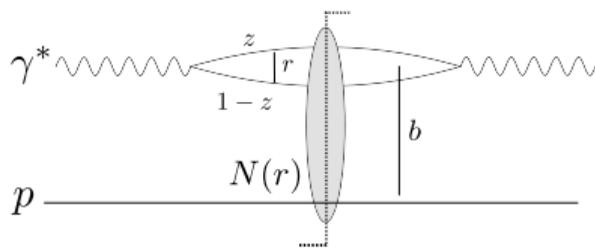


Pocket formula for VM production (2-gluon exchange), [Ryskin 1993]

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

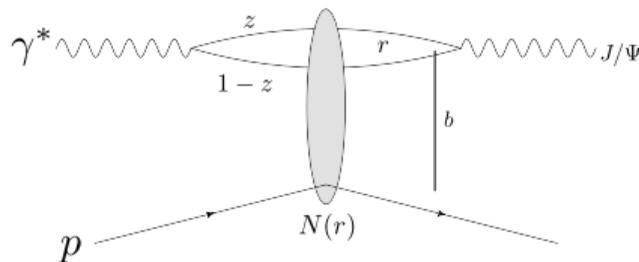
- Diffraction is very sensitive to (small- $x$ ) gluons!
- Measure  $t$  (conjugate to impact parameter)  $\Rightarrow$  access to geometry
- But PDFs are inclusive quantities, this is exclusive...

# Deep inelastic scattering at high energy: dipole picture



Optical theorem:

$$\sigma^{\gamma^* p} \sim \text{dipole amplitude } N$$



$$\sigma^{\gamma^* p \rightarrow V p} \sim |\text{dipole amplitude } N|^2$$

## Universal dipole amplitude

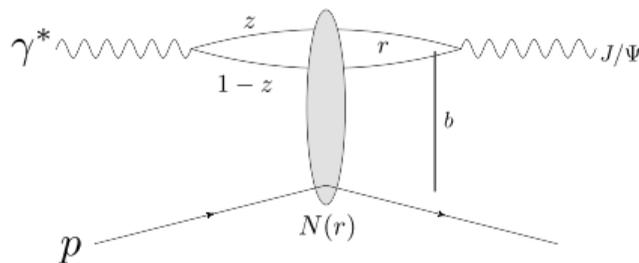
Same universal QCD evolved dipole amplitude  $N = \frac{1}{N_c} \text{Tr}(1 - V(x_T)V^\dagger(y_T))$

- Convenient degrees of freedom at high energy: Wilson lines  $V(x_T)$  and dipole  $N$
- Diffractive cross sections  $\sim \text{gluon}^2 \sim N^2 \Rightarrow$  saturation effects especially in nuclei!
- Perturbative  $x$  evolution (BK, JIMWLK), non-perturbative initial condition: fit HERA  $F_2$

# Probe of the geometry: exclusive $J/\Psi$ production

High energy factorization:

- 1  $\gamma^* \rightarrow q\bar{q}$ :  $\Psi^\gamma(r, Q^2, z)$
- 2  $q\bar{q}$  dipole scatters elastically  
Amplitude  $N$
- 3  $q\bar{q} \rightarrow J/\Psi$ :  $\Psi^V(r, Q^2, z)$



## Diffractive scattering amplitude

$$\mathcal{A}^{\gamma^* p \rightarrow V p} \sim \int d^2 b dz d^2 r \Psi^{\gamma^*} \Psi^V(r, z, Q^2) e^{-i\mathbf{b} \cdot \mathbf{\Delta}} N(r, x_{\mathbb{P}}, \mathbf{b})$$

- Impact parameter is the Fourier conjugate to the momentum transfer  
→ Access to the spatial structure
- $x_{\mathbb{P}}$  = fraction of the target longitudinal momentum

# Classification of diffractive events

## Coherent diffraction:

- Target remains in the same quantum state, e.g.

$$\gamma + p \rightarrow J/\psi + p$$

- Probes average interaction

$$\frac{d\sigma^{\gamma^* A \rightarrow VA}}{dt} \sim |\langle \mathcal{A}^{\gamma^* A \rightarrow VA} \rangle_{\Omega}|^2$$

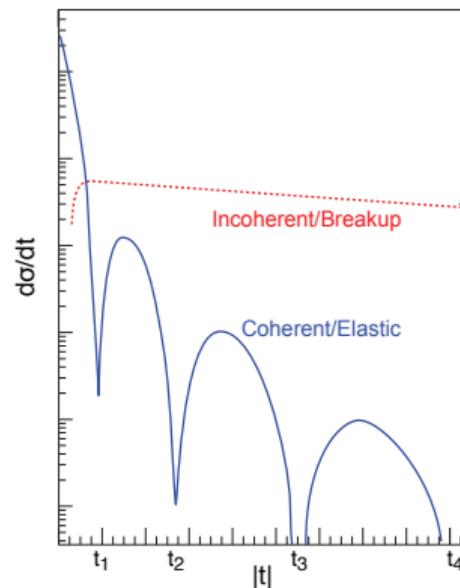
$\langle \rangle_{\Omega}$ : average over target configurations  $\Omega$

Recall:

$$\mathcal{A}^{\gamma^* p \rightarrow Vp} \sim \int d^2 b dz d^2 r \Psi^{\gamma^*} \Psi^V(r, z, Q^2) e^{-i\mathbf{b} \cdot \Delta} N_{\Omega}(r, x_{\mathbb{P}}, \mathbf{b})$$

## Incoherent diffraction:

- E.g.  $\gamma + p \rightarrow J/\psi + p^*$
- Target proton dissociates ( $p^* \rightarrow X$ ).



Good, Walker, PRD 120, 1960  
Miettinen, Pumplin, PRD 18, 1978  
Kovchegov, McLerran, PRD 60, 1999  
Kovner, Wiedemann, PRD 64, 2001

Mäntysaari, Rept. Prog. Phys. 83, 2020

# Incoherent diffraction = target dissociation

## Incoherent cross section

- Target final state  $|f\rangle \neq$  initial state  $|i\rangle$
- Rapidity gap between  $J/\Psi$  and target remnants

$$\begin{aligned}\sigma_{\text{incoherent}} &\sim \sum_{f \neq i} |\langle f | \mathcal{A} | i \rangle|^2 \\ &= \sum_f \langle i | \mathcal{A} | f \rangle^\dagger \langle f | \mathcal{A} | i \rangle - \langle i | \mathcal{A} | i \rangle^\dagger \langle i | \mathcal{A} | i \rangle\end{aligned}$$

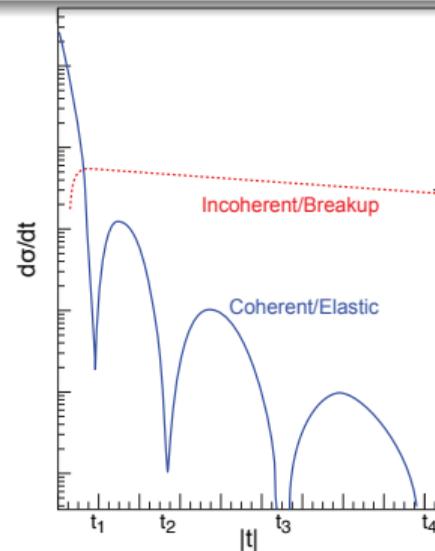
Average over initial states:

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

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

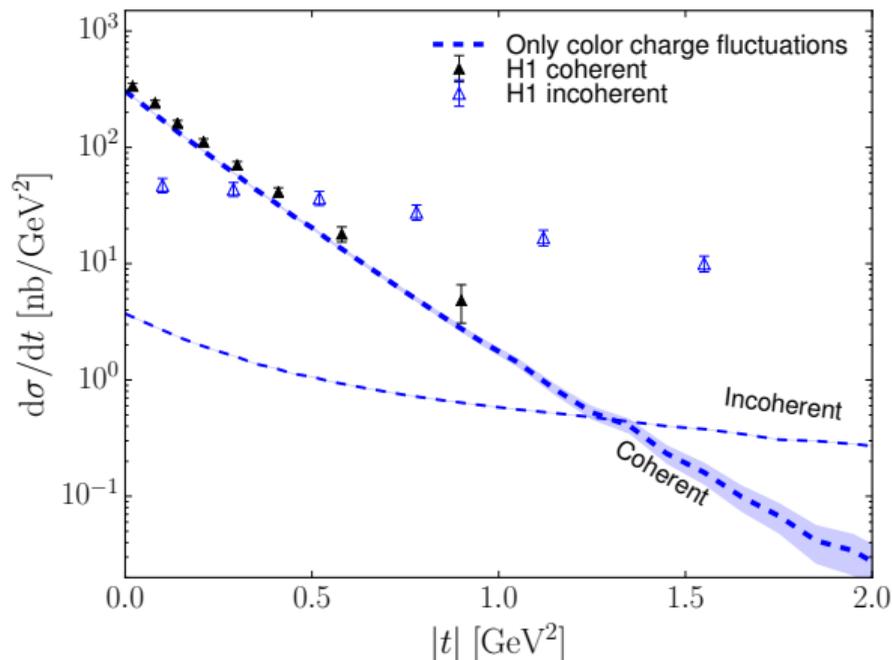
- Amount of event-by-event fluctuations in target configurations  $\Omega$

Miettinen, Pumplin, PRD 18, 1978, Caldwell, Kowalski, Phys.Rev. C81 (2010) 025203, Mäntysaari, Rept. Prog. Phys. 83, 2020

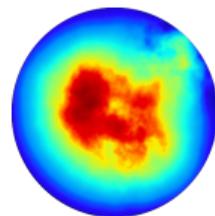


# Proton shape from diffraction: $\gamma + p \rightarrow J/\psi + p$

HERA data with only color charge fluctuations ( $\times \sim 10^{-3}$ )



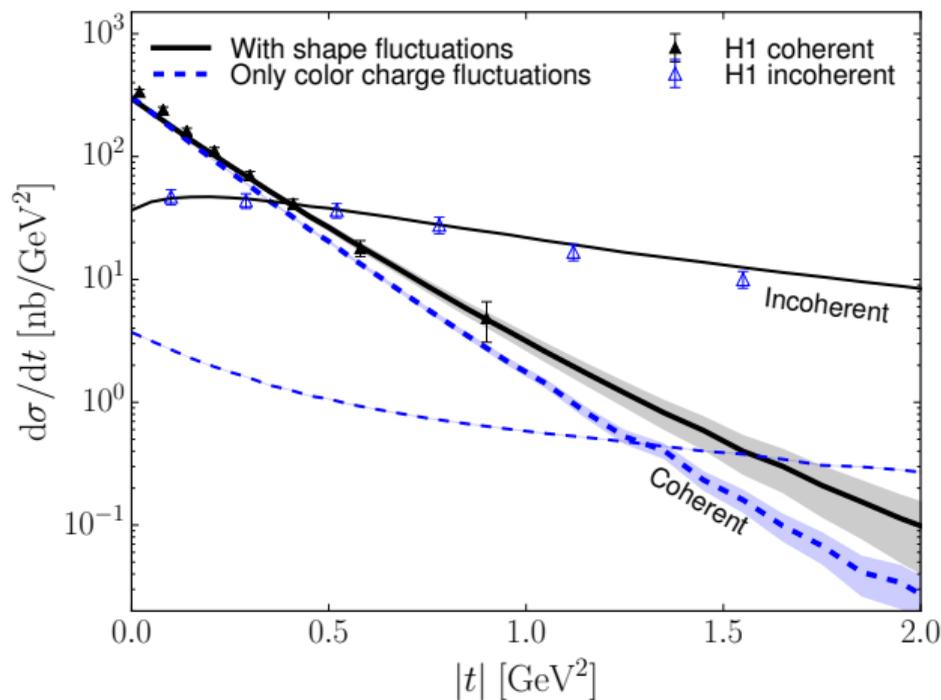
Round  
CGC proton:  
Color charges  
+ Yang-Mills



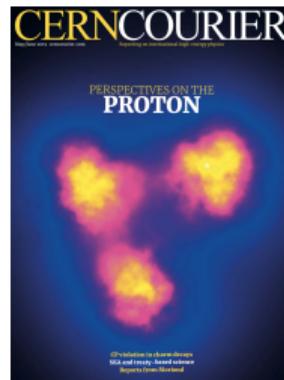
H.M., B. Schenke, 1607.01711,

H1: 1304.5162

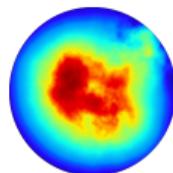
# Constraining proton fluctuations: $\gamma + p \rightarrow J/\psi + p$ at $x_{\mathbb{P}} \sim 10^{-3}$



## Fluctuations



Round



HERA data requires large event-by-event fluctuations [H.M., B. Schenke, 1607.01711](#)

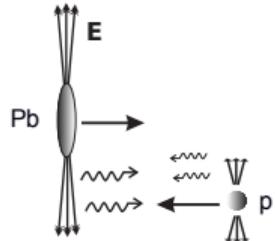
Similar setup e.g. in [Bendova, Cepila, Contreras](#); [Cepila, Contreras, Krelina, Takaki](#); [Traini, Blaizot](#)

# Exclusive $J/\psi$ production at small $x$ at the LHC: UPC

Ultrapерipheral  $p + A$ :

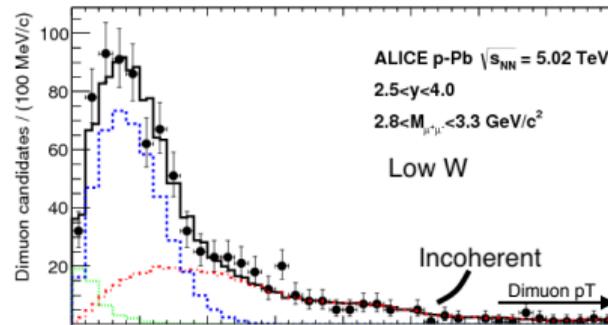
Photon flux  $\sim Z^2$

$\gamma + p$  dominates



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

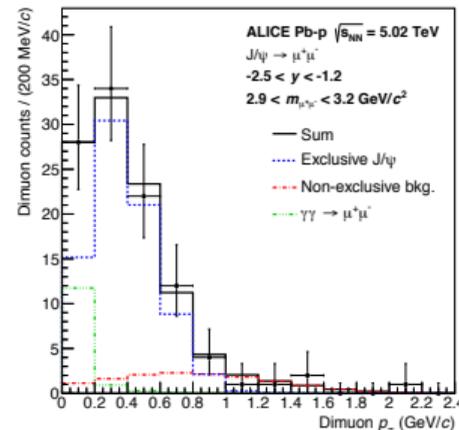
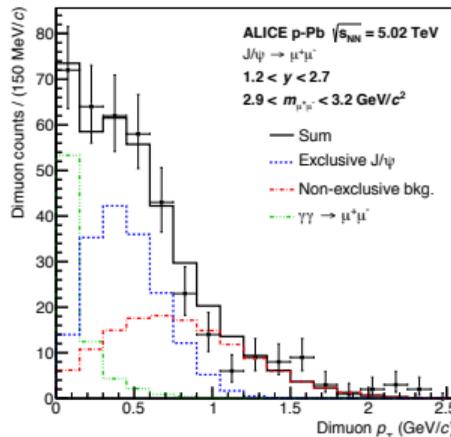
ALICE: 1406.7819



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

ALICE:1809.03235

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



Medium  $\rightarrow$  high  
energy

## 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

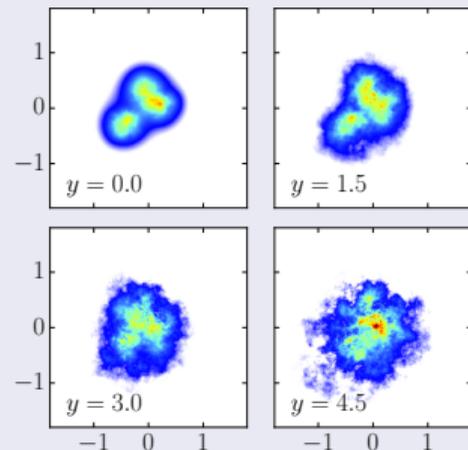
- BK eq. with impact parameter

[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.

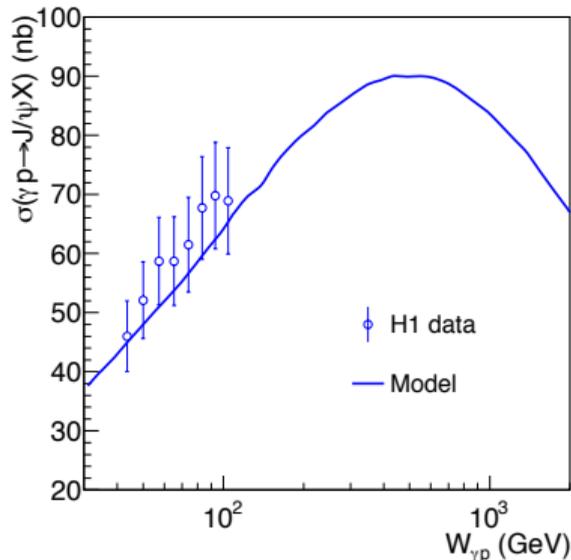
Difficulty: regulating confinement effects



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

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

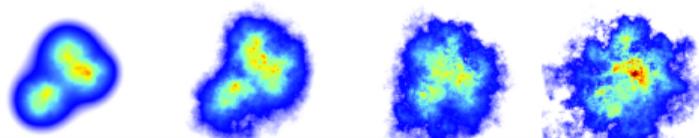
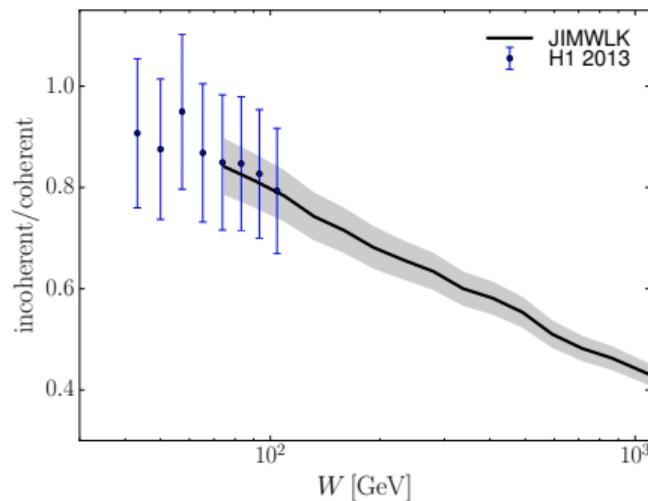
Cepila, Contreras, Tapia Takaki, 1608.07559



Heikki Mäntysaari (JYU)

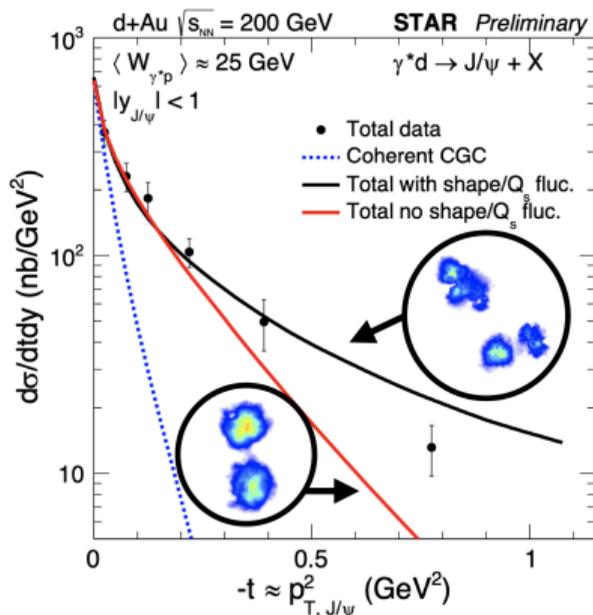
JIMWLK evolution event-by-event  
Includes also growing RMS size

H.M., Schenke, 1806.06783



Incoherent diffraction

$t$  is conjugate to  $b$ : access fluctuations at different length scales

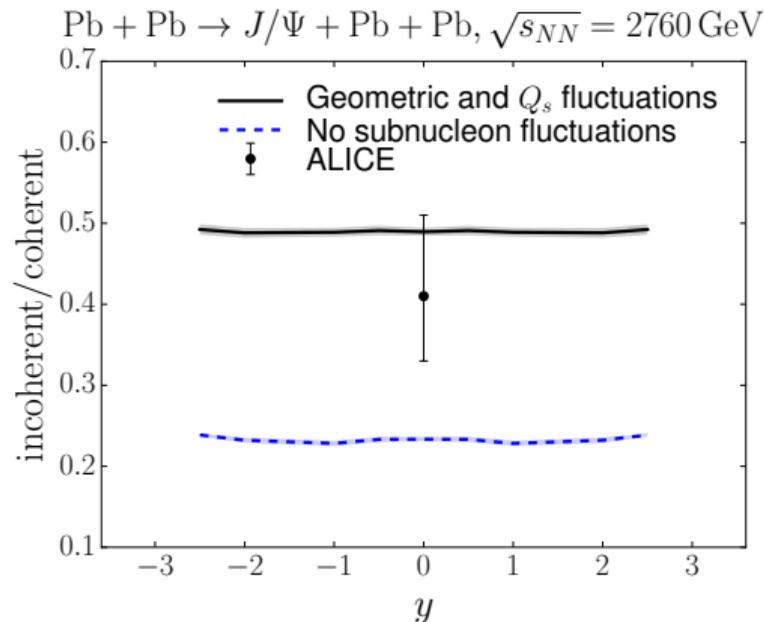
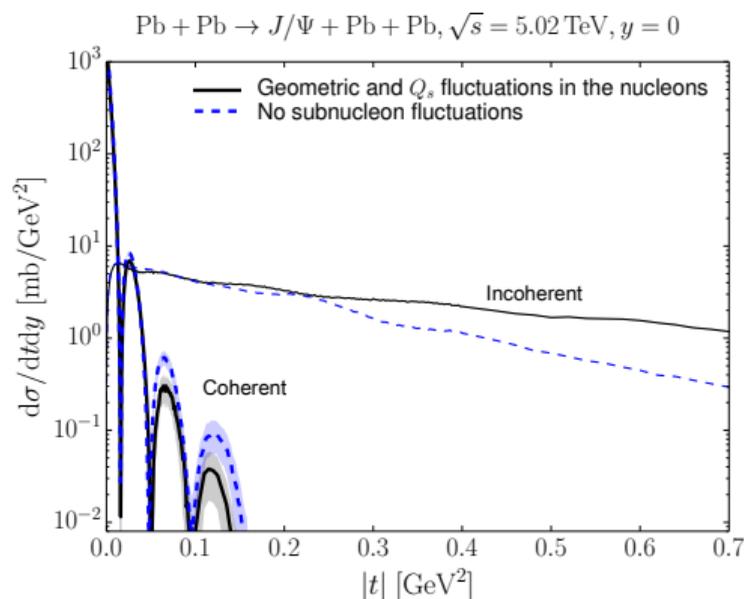


STAR  $\gamma + d \rightarrow J/\psi + d^*$  data at  $x_{\mathbb{P}} \sim 0.01$

- Total (coherent+incoherent) cross section measured
- Experimental challenge: coh and incoh
- Data at high  $|t| \gtrsim 0.25 \text{ GeV}^2$  prefers substructure, no effect at lower  $|t|$
- Nucleon fluctuations from HERA data  
[B. Schenke, H.M, 1910.03297](#)
- Note  $|t| \gtrsim 0.25 \text{ GeV}^2$  corresponds to length  $\lesssim 0.4 \text{ fm}$  = substructure (hot spot radius  $\sim 0.2 \text{ fm}$ )

# Fluctuations in heavy 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



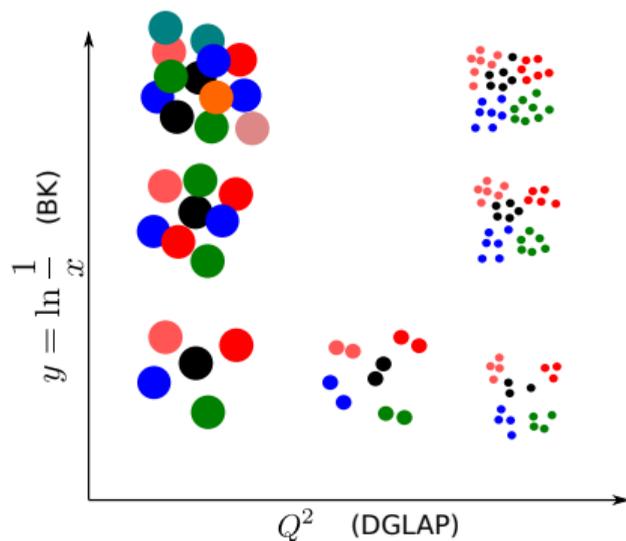
Subnucleon fluctuations preferred by the ALICE data

H.M, B. Schenke, 1703.09256, ALICE: 1305.1467

- Exclusive particle production is a powerful probe of high energy QCD
  - Especially sensitive to gluon structure at small  $x$  and non-linear effects
  - Access to geometry
- Two classes of diffractive events
  - Coherent  $\sim$  average shape
  - Incoherent  $\sim$  event-by-event fluctuations
- HERA  $J/\psi$  data prefers large proton shape fluctuations
- First incoherent data from RHIC and LHC UPC programs:
  - Prefer  $\approx$  similar nucleon e-b-e fluctuations as the HERA data
  - Interesting energy dependence
  - First steps towards the EIC
- Experimental challenge also at the EIC: separate incoh and coh (see intact p/d/He/...?)
- Fluctuating protons in p+A hydro: good description of the LHC data (backup)

BACKUPS

# QCD at high energy: Color Glass Condensate

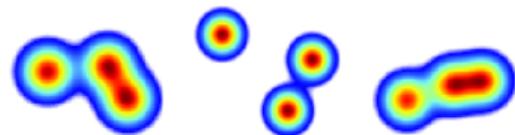


- CGC = QCD at high energies
- $x$  (energy) dependence:  
BK/JIMWLK (perturbative)
- Gluon saturation at small  $x$  at scale  $Q_s^2$
- Non-linear effects enhanced in nuclei  
 $Q_s^2 \sim A^{1/3}$

Natural framework to describe high energy scattering,  
which probes QCD in the non-linear regime

# Constraining proton fluctuations

Simple constituent quark inspired picture:



- Proton density profile is a sum of randomly distributed hot spots
- Hot spot size and distribution controlled by free parameters

Now proton = 3 overlapping hot spots.

$$T_{\text{proton}}(b) = \sum_{i=1}^3 T_q(b - b_i) \quad T_q(b) \sim e^{-b^2/(2B_q)}$$

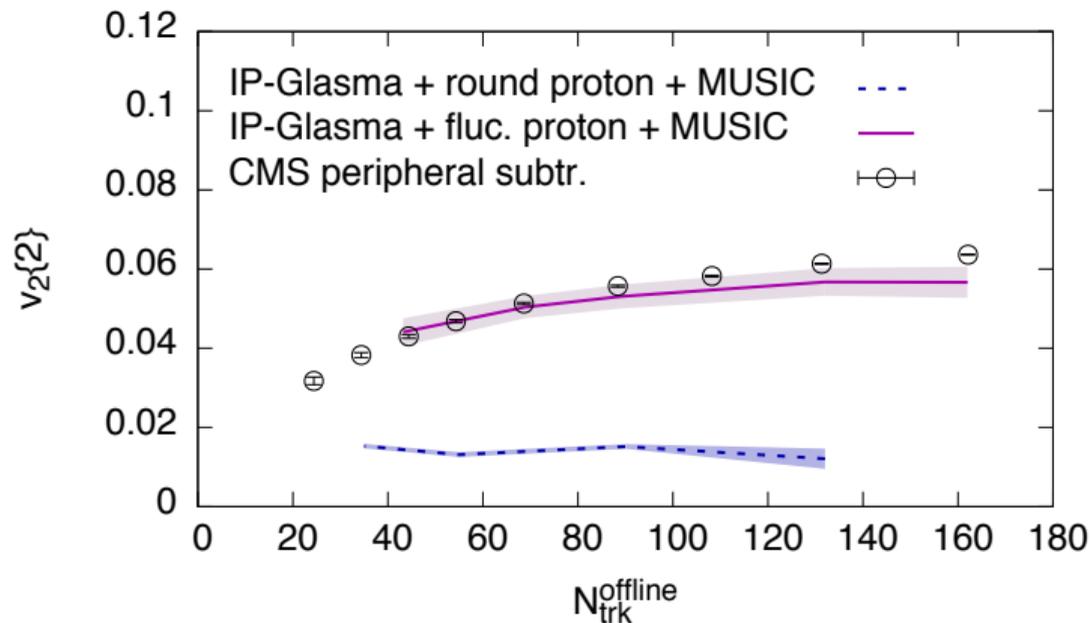
+ density fluctuations for each hot spot

H.M, Schenke, 1607.01711, 1603.04349, also more complicated geometries

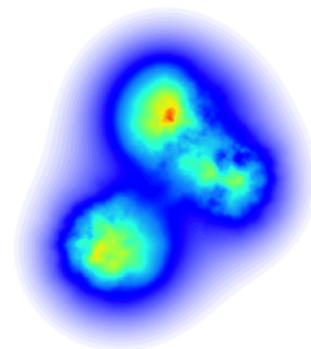
Similar setup e.g. in Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot

# Implications on heavy ion phenomenology: p+A

Hydro + fluctuations from HERA  $J/\psi$  data: success



Fluctuations



H.M, Schenke, Shen, Tribedy, 1705.03177

# High gluon densities in nuclei

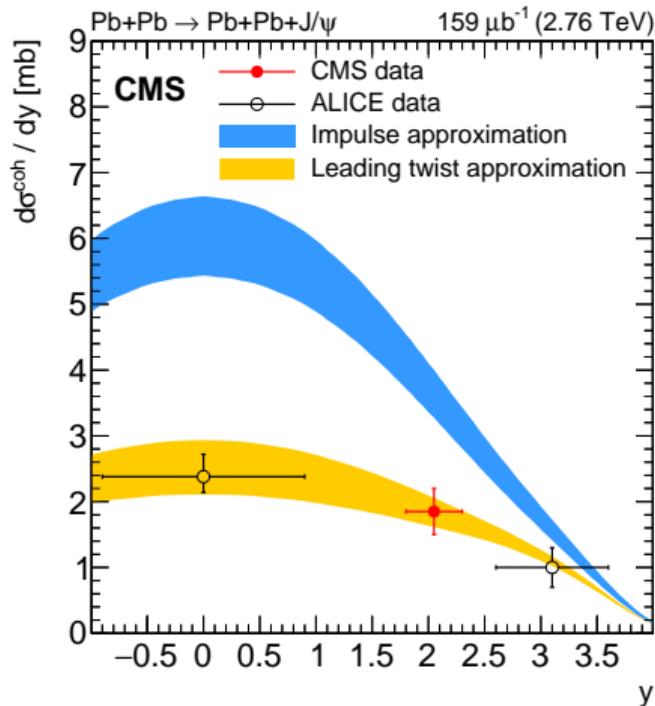
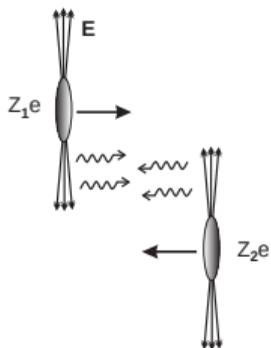
Enhance saturation effects:

$$Q_{s,A}^2 \sim A^{1/3} x^{-\lambda}$$

(larger  $A$  is cheaper than smaller  $x$ )

Already data from UPCs,

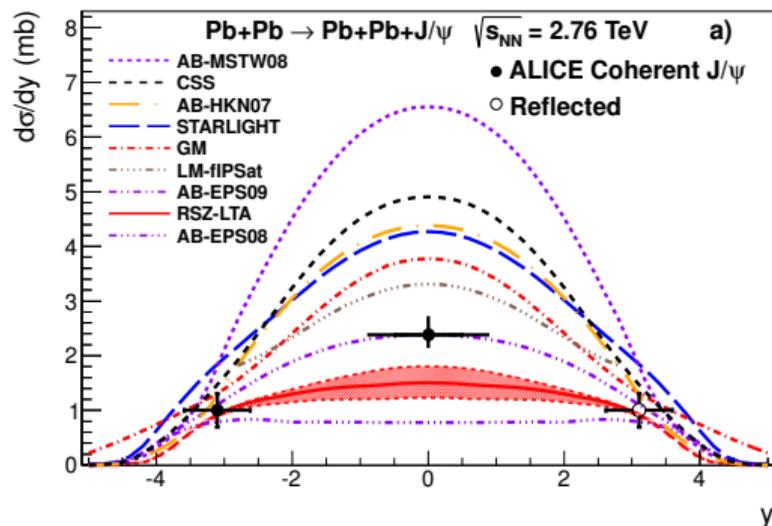
momentum fraction  $x = M_V e^y / \sqrt{s}$



Clear nuclear effects: impulse approximation is scaled  $\gamma + p$

CMS, 1605.06966

# Coherent diffraction, model comparison



ALICE, 1305.1467

Shadowing/saturation needed

- LM-fIPsat (CGC)
- AB-PS09 (nPDF)

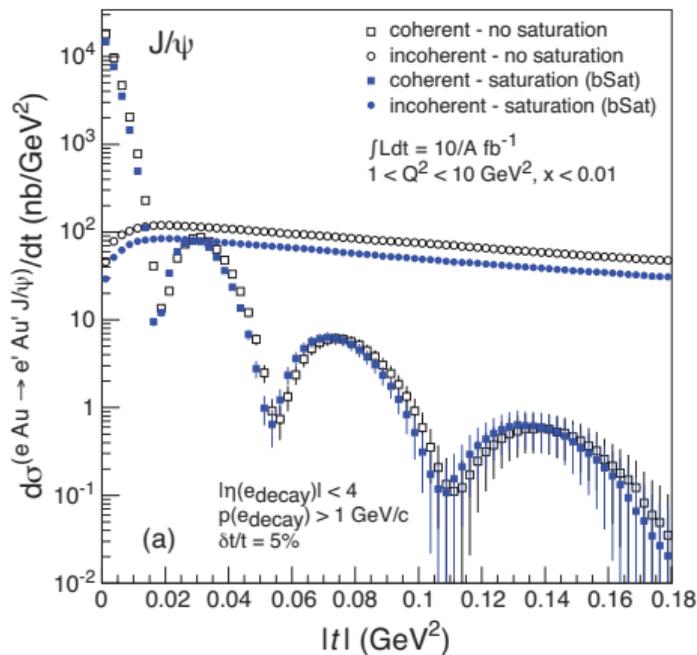
Linear models fail

- AB-MSTW08 (proton PDF)

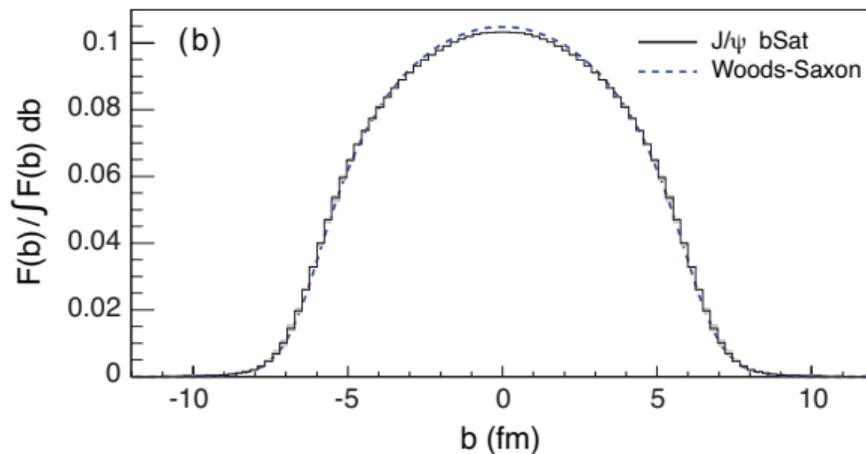
CGC: inclusive and diffractive observables from the same framework (depend on [dipole  \$N\$](#) )  
Exclusive data difficult to include in nPDF fits (PDFs are inclusive)

# Extract nuclear geometry

Full EIC simulation with expected uncertainties in  $\gamma + A \rightarrow J/\psi + A$



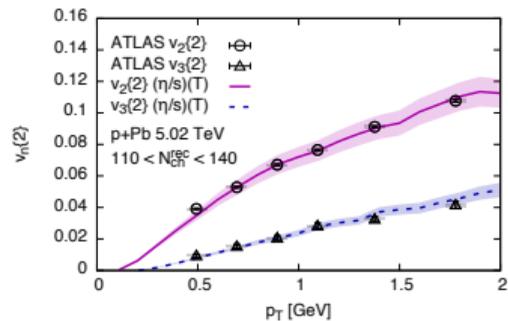
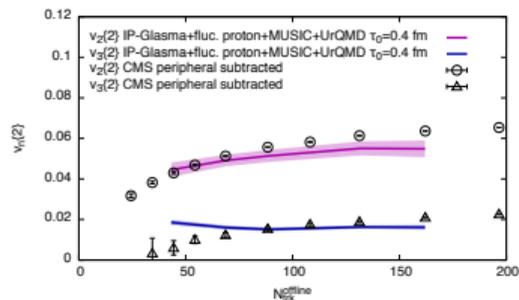
Coherent  $J/\psi$  spectra  $\Rightarrow$  FT  
 $\Rightarrow$  Density profile



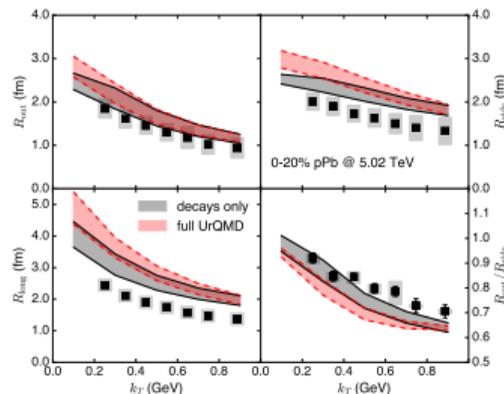
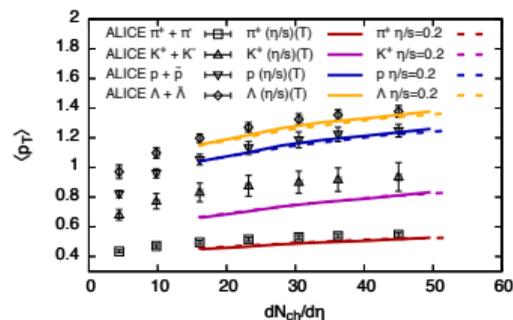
Extract transverse density profile of small-x gluons

# Implications on heavy ion phenomenology: p+A

## Hydro + fluctuations from HERA $J/\psi$ data: success



H.M., Schenke, Shen, Tribedy, 1705.03177

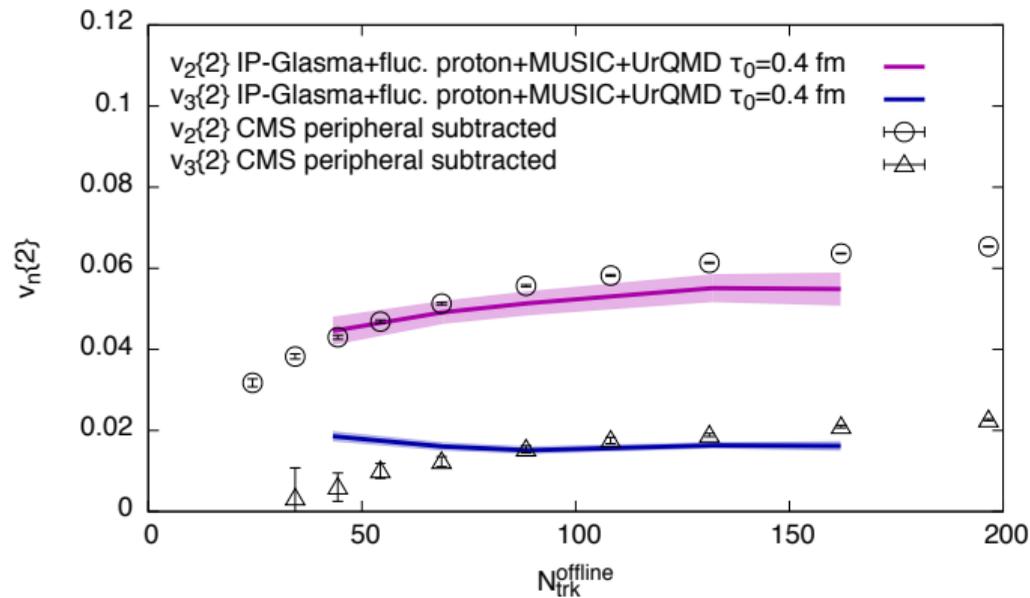


# Fluctuating protons in pA collisions

## Hydro calculations with proton fluctuations from HERA

### Hydro numbers

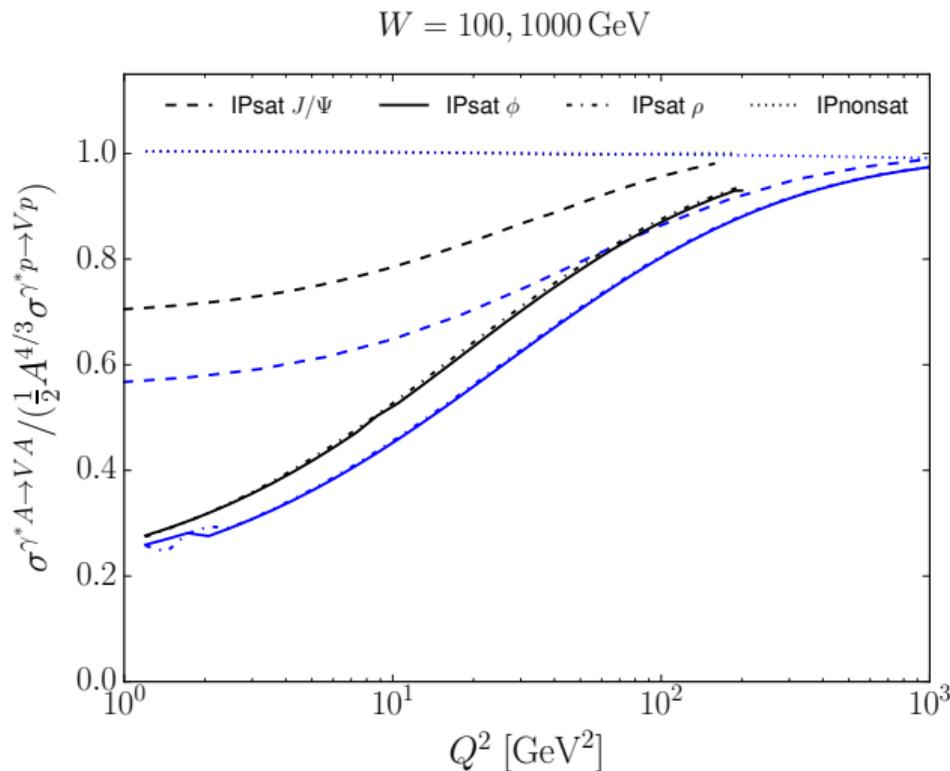
- $\tau_0 = 0.4$  fm
- $T_{fo} = 155$  MeV
- Shear and bulk viscosity
- Initial  $\pi^{\mu\nu}$
- $\eta/s = 0.2$



Large  $v_2$  and  $v_3$  at largest centrality bins reproduced well.

H.M, B. Schenke, C. Shen, P. Tribedy, 1705.03177

# Large nuclear suppression in vector meson production

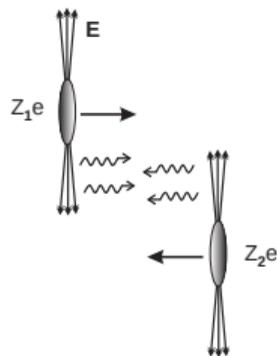


H.M, P. Zurita, 1804.05311

- Especially for heavy mesons expect large nuclear effects

# Ultraperipheral collision as a deep inelastic scattering

$b \gtrsim 2R_A$ : strong interactions are suppressed



J. Nystrand et al, nucl-ex/0502005

- 1 Nucleus creates a (real) photon flux  $n(\omega)$
- 2 Photon-nucleus scattering

$$\sigma^{AA \rightarrow AA+V} \sim n(\omega) \sigma^{\gamma A \rightarrow VA}(\omega)$$

Interesting QCD part: high-energy  $\gamma$ -nucleus or  $\gamma$ -proton scattering.

- Obtain saturation scale  $Q_s(x_T)$  from IPsat (with fluctuations)
- MV-model: Sample color charges, density  $\sim Q_s(x_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

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

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

# Lumpiness matters, not details of the density profile

3 valence quarks that are connected by "color flux tubes" (Gaussian density profile, width  $B_q$ ).  
Also good description of the data

