Confronting JIMWLK evolution with HERA data

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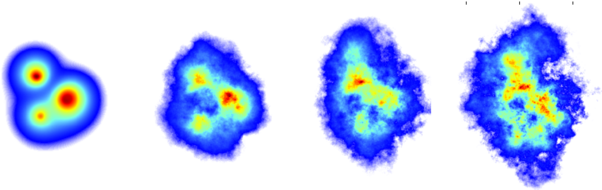


May 21, 2018 / Probing QCD at the high energy frontier

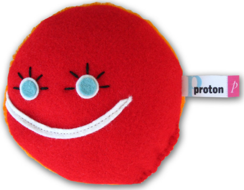
Going beyond a round proton

A fundamental question

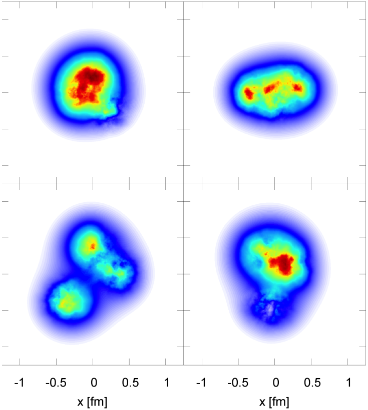
How are small-x gluons distributed spatially inside the proton?

How do the positions fluctuate?

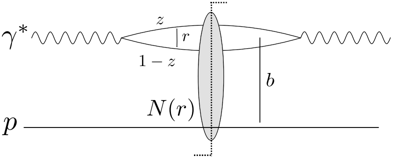
How do these distributions evolve in Bjorken-x?



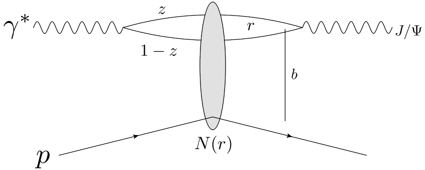
$\Rightarrow$



DIS at high energy: dipole picture



Optical theorem:
$\sigma^{\gamma^* p} \sim$ dipole amplitude



$\sigma^{\gamma^* p \to Vp} \sim |\text{dipole amplitude}|^2$

Universal dipole amplitude

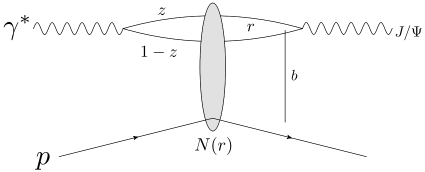
QCD dynamics is included in the dipole amplitude N

- Total cross section $\sim N \sim$ **gluon density**
- Diffraction $\sim N^2 \sim$ **gluon density²**
  $+$ access to spatial structure

Probe of the geometry: exclusive J/Ψ production

High energy factorization:

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



Diffractive scattering amplitude

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

- Impact parameter is the Fourier conjugate of the momentum transfer $\to$ Access to the spatial structure
- No net color charge transfer: at LO 2 gluon exchange, $\sigma \sim$ **gluon^2**

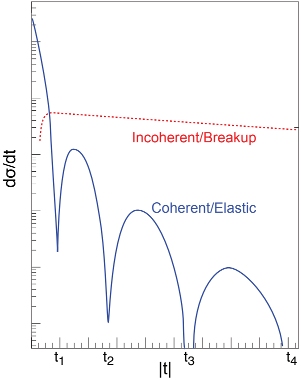
Average over configurations

Coherent diffraction:

Target proton remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$



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

$\langle\,\rangle$: average over target configurations [N(r, **b**)]

Average over configurations

Coherent diffraction:

Target proton remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Incoherent/target dissociation:

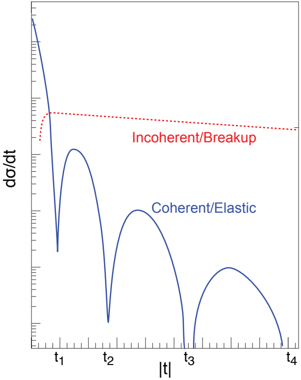
Total diffractive − coherent cross section

Target breaks up

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Variance, measures the amount of fluctuations!

$\langle\,\rangle$: average over target configurations [N(r, **b**)]



Good, Walker, PRD 120, 1960
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Dipole-proton scattering

IP-Glasma

- Parametrize proton geometry, $Q_s^2 \sim T_{\text{proton}}(b_T)$
- MV-model: Sample color charges, density $\sim Q_s(b_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

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

- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr}\, V(x_T) V^\dagger(y_T)/N_c$

Energy evolution: solve JIMWLK equation to get $V(b_T)$ at small x

Schenke, Schlichting, 1407.8458

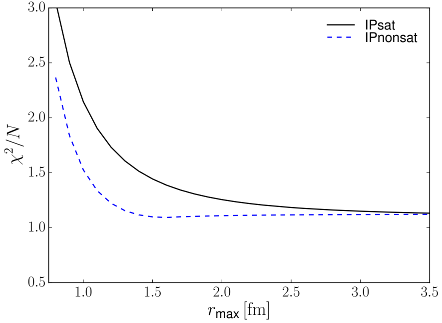
Comparison: IP-sat

- $N(r) \sim 1 - \exp(-r^2 \alpha_s x g(x, \mu^2) T_b(b_T))$
- Parametrized x dependence, match pQCD with DGLAP at high Q^2

Strategy

Multiple constraints for the non-perturbative input

- Structure function data $\sim Q_s^2 \times \sigma_0$
- Transverse size of the proton σ_0 (slope of the J/Ψ spectra)



H.M, P. Zurita, 1804.05311

IPsat fit to HERA data

- Successful phenomenology
- Need dipoles up to ~ 2 fm

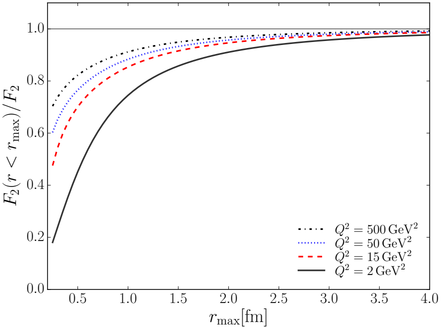
How to include those to IP-Glasma?

- Quarks miss the proton: $N \to 0$
- In IPsat $N(r \gg 1/Q_s(b_T)) \to 1$
- What really happens?
- Avoid by using charm-F_2

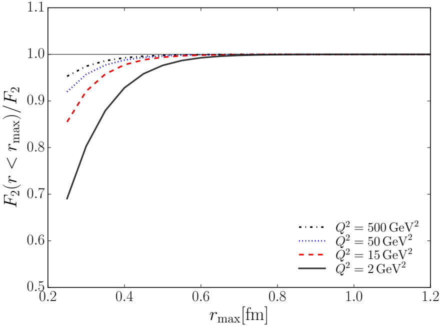
Avoiding large dipoles

IPsat dipole (with $N(r \gg 1/Q_s) = 1$): maximum dipole size dependence

Total F_2



Charm F_2



Charm F_2 doesn not need dipoles larger than ~ 0.4 fm

Note: different x axes

H.M, P. Zurita, 1804.05311

1. Round protons with JIMWLK evolution

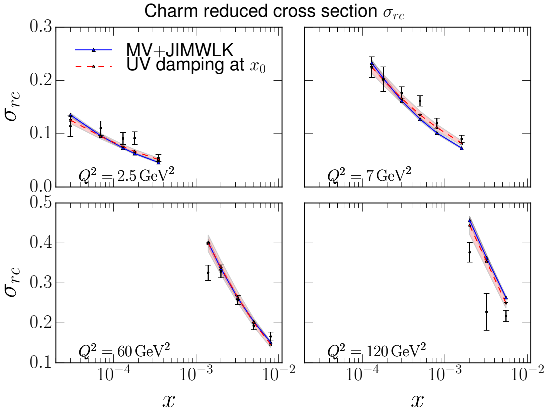
Parameters

- Q_s^2 at initial $x = x_0$
- Proton size at $x = x_0$
- Infrared regulator m
- Fixed α_s or coordinate space Λ_{QCD}

H. M, B. Schenke, in preparation

Initial condition for the JIMWLK evolution (round proton)

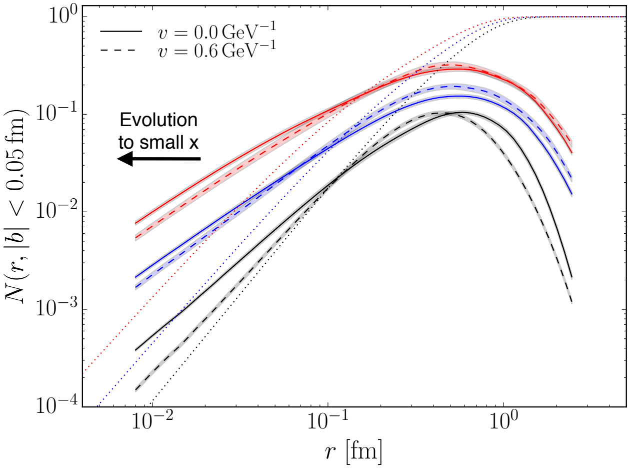
Good description of the charm production data



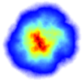
- Too fast Q^2 dependence from MV model
  Fit improves when UV modes are damped at x_0 by $exp(-\#k)$
  ($\chi^2/N : 4.3 \rightarrow 2.5$)

H.M, B. Schenke, in preparation

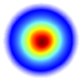
Effect of the UV damping



$x = x_0 = 10^{-2}$:



Solid: MV
Dashed: Damp e^{-vk}
Dotted: IPsat

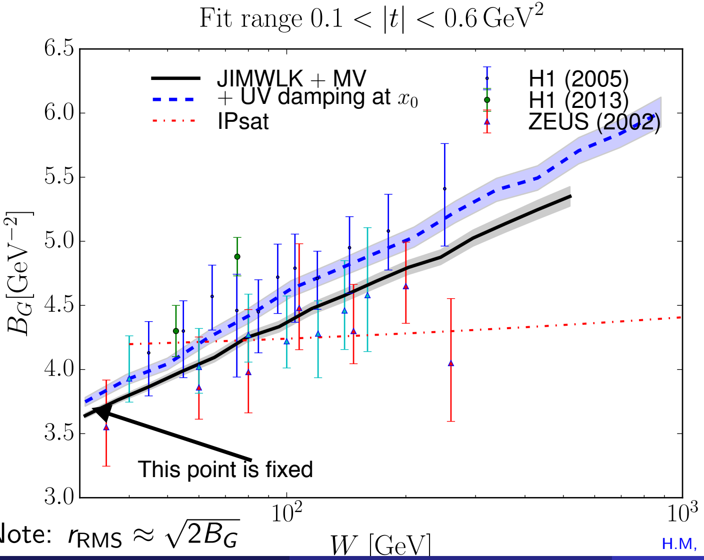


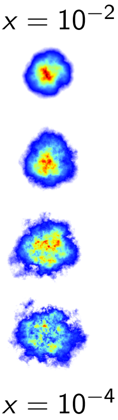
H. M, B. Schenke, in preparation

UV filtering changes the anomalous dimension
Steeper dipole compared to MV preferred by HERA data (e.g. rcBK fits)

Proton size evolution (round proton)

Proton size constrained by the slope of the coherent J/Ψ spectra



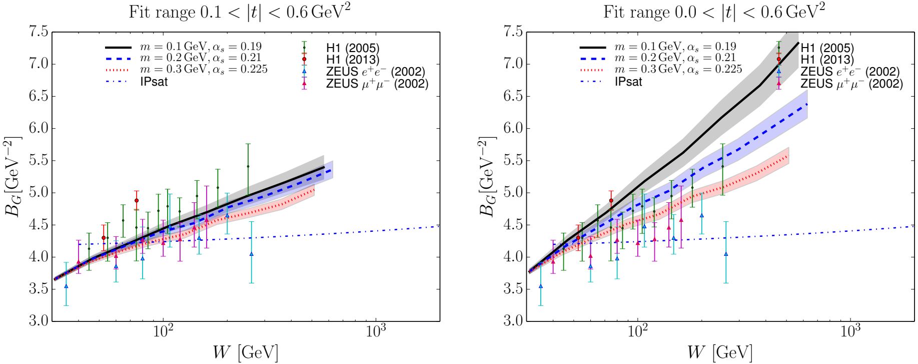


Note: $r_{\mathrm{RMS}} \approx \sqrt{2B_G}$

H.M, B. Schenke, in preparation

Suppress long distance Coulomb tails

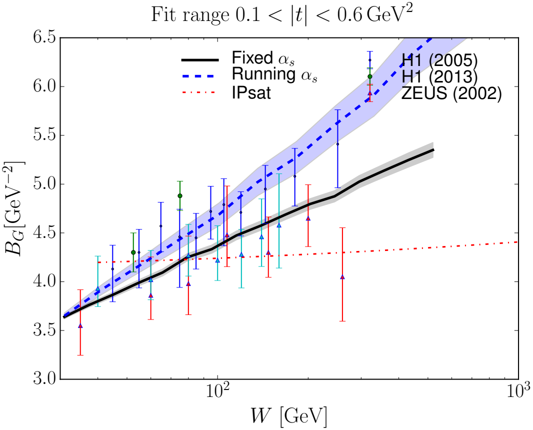
Modified JIMWLK kernel: $K = \frac{x^i}{\mathbf{x}_T^2} \rightarrow m|\mathbf{x}_T|K_1(m|\mathbf{x}_T|)\frac{x^i}{\mathbf{x}_T^2}$



- Small-t part of the spectra is sensitive to long distance evolution
  $\Rightarrow$ Potentially constrain m independently of α_s
- Note: In all cases charm-F_2 works
- $\exp(-B_G|t|)$ fit: t range dependence $\Rightarrow$ small t spectra not Gaussian

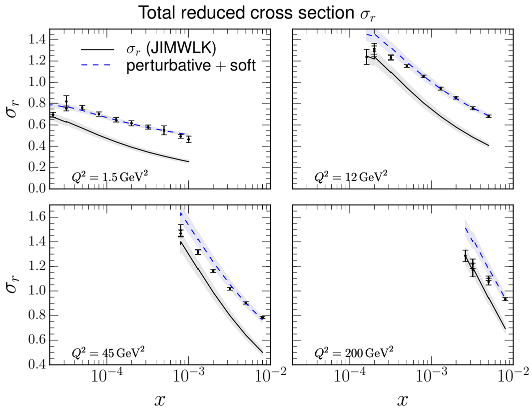
Running coupling effects: J/Ψ photoproduction

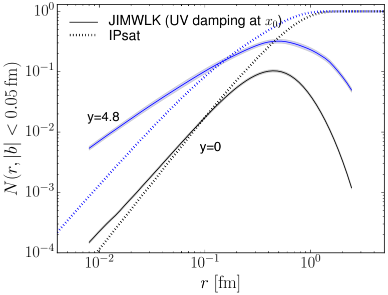
With fixed and running coupling equally good description of the σ_r data.



- Running coupling suppresses evolution of short-wavelength modes
- Faster evolution at long distance scales
- Running coupling: T. Lappi, H.M, 1212.4825

Missing large dipole contribution to F_2 (round proton)



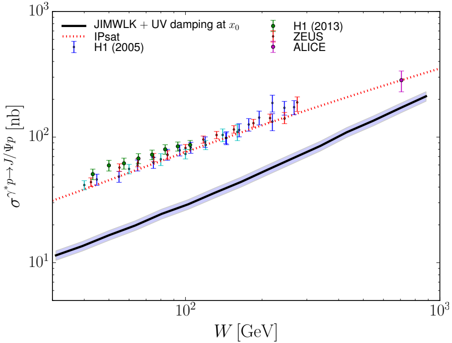


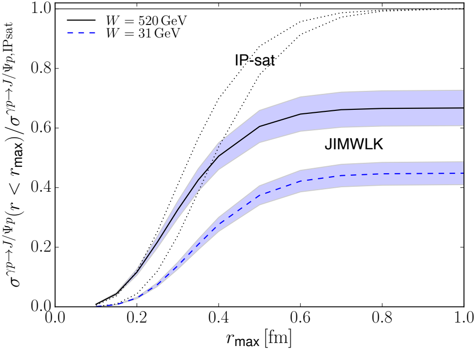
- F_2 is sensitive to large dipoles, but $N(r \gg R_p, b = 0) \to 0$
- Need *non-perturbative* $(N(r > R_p) = 1)$ contribution Berger, Stasto, 1106.5740

Similar results with the MV model initial condition

More about large dipole contributions: H.M, P. Zurita, 1804.05311 H.M, B. Schenke, in preparation

Total diffractive cross section: $\gamma + p \to J/\Psi + p$, $Q^2 = 0$





- Total coherent cross section underestimated at small W
- Note: $\sigma \sim Q_s^4$, so more sensitive to Q_s^2 than F_2
- J/Ψ wave function needs dipoles up to ~ 0.7 fm, how to include?
  Reminder: Charm F_2 only needs up to ~ 0.4 fm
- Contribution from largish dipoles missing?

More about large dipole contributions: H.M, P. Zurita, 1804.05311

H.M, B. Schenke, in preparation

2. Adding proton geometry fluctuations

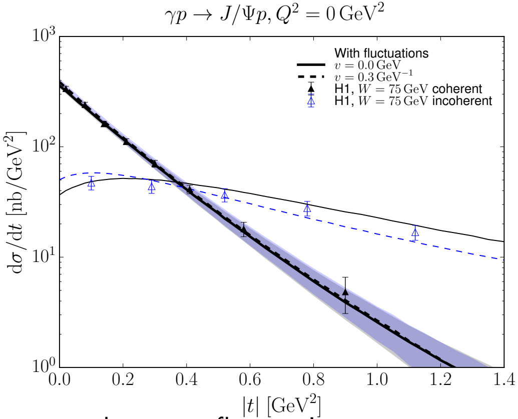
Replace proton width parameter by

- Size of the hot spot at x_0
- Sampling radius for the hot spots at x_0
- Fix Q_s^2 by diffractive data, but use $\alpha_s/\Lambda_{\mathrm{QCD}}$ fixed by charm F_2 data

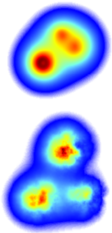
H. M, B. Schenke, in preparation

Fix proton geometry at $W = 75$ GeV (fluctuations)

Implement constituent quark structure $T_{\text{proton}}(b_T) = \sum_{i=1}^{3} T_p(b_T - b_{T,i})$



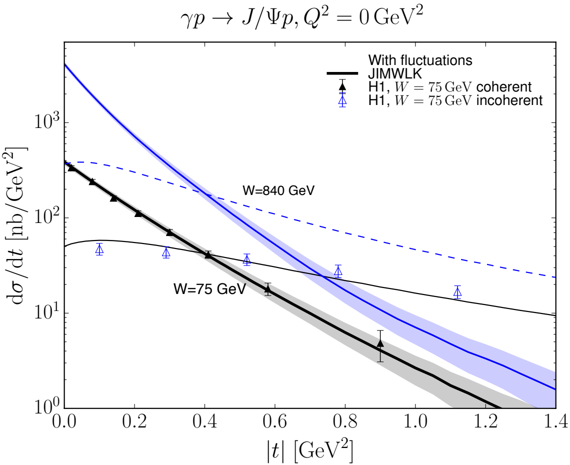
$W = 75$ GeV
$x \sim 10^{-3}$



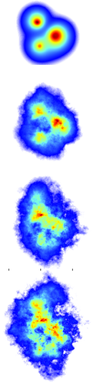
- Large event-by-event fluctuations
- UV damping increases fluctuations at long distance scale
- Need larger Q_s^2 than with charm F_2 data (but use same α_s and m)

H.M, B. Schenke, in preparation

J/Ψ photoproduction evolution from JIMWLK



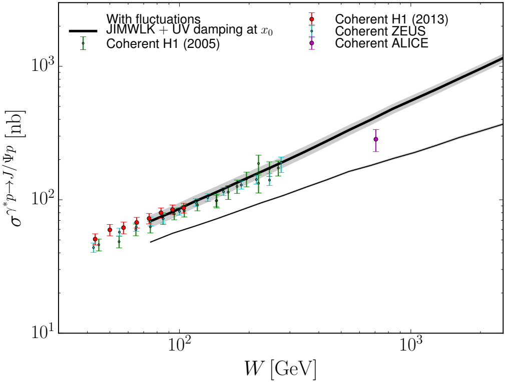
$W = 75$ GeV:



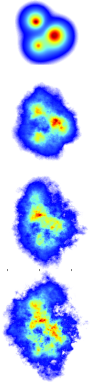
$W = 680$ GeV

- Both coherent and incoherent cross sections grow with W
- Protong gets larger $\Rightarrow$ steeper coherent spectra

Total J/Ψ production cross sections



$W = 75$ GeV:

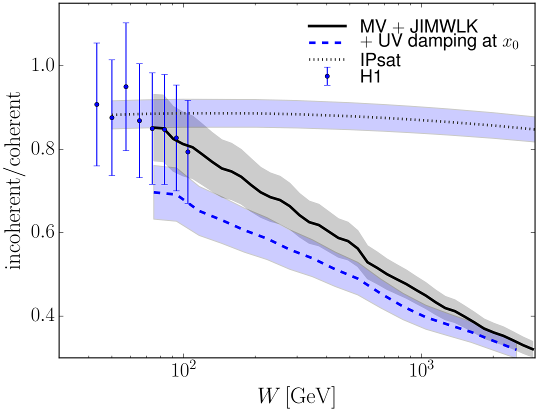


$W = 680$ GeV

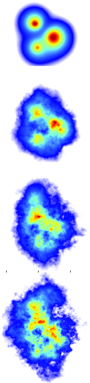
- Coherent (thick) grows much faster than incoherent (thin)
- Initial Q_s^2 fixed to HERA data, charm-F_2 overestimated (x dep. ok)

Evolution of the fluctuations: $\gamma + p \to J/\Psi + p$

Incoherent/coherent cross section ratio compatible with H1 data



$W = 75$ GeV:

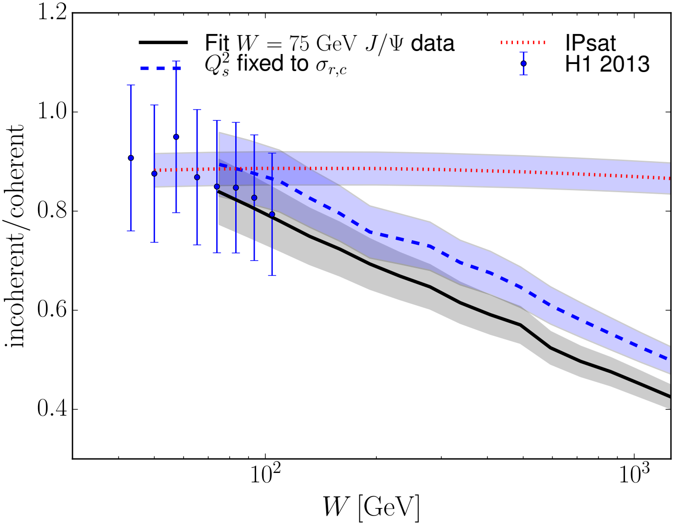


$W = 680$ GeV

Note: parameters fixed at $W = 75$GeV, the rest is prediction.

H.M, B. Schenke, in preparation

Dependence on initial Q_s^2

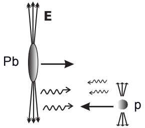


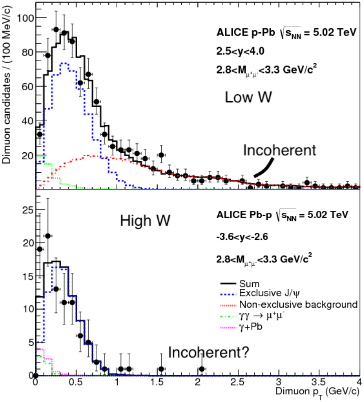
Fix initial Q_s^2 to 1) J/Ψ at $W = 75$ GeV [larger] or 2) charm F_2 [smaller]

- Small effect on cross section ratio (evolution from geometry)

High-energy J/Ψ photoproduction at the LHC

Ultraperipheral $p+A$ at the LHC:
Photon flux $\sim Z^2 \Rightarrow \gamma + p$ dominates





Forward/backward rapidity J/Ψ
High/low W

- Low W: significant coherent and incoherent contributions
- High W: no incoherent
  Qualitatively in agreement with our JIMWLK results
  Note, nucleus: coh $\sim A^2$, incoherent $\sim A$ (edge)

ALICE: 1406.7819

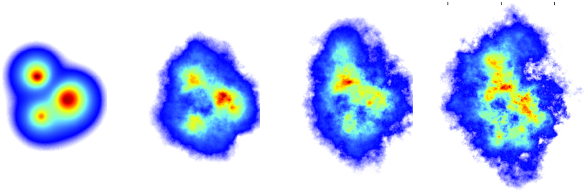
Conclusions

Multi dimensional event-by-event picture of the proton

- Bjorken-x dependence from JIMWLK evolution equation
- Initial condition from HERA data
- Uncertainty: how to describe large dipole - proton scattering?
  - Simultaneous description of F_2, $F_{2,\mathrm{charm}}$ and diffractive data?

Strong hints from HERA and LHC data that

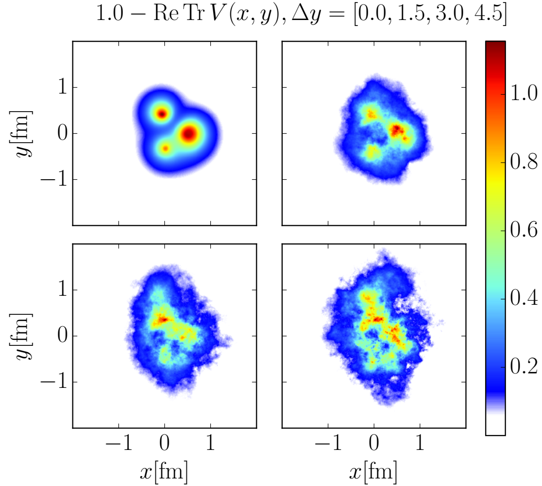
- Proton geometry has large event-by-event fluctuations
- Fluctuations evolve in x



BACKUPS

What does the fluctuating proton look like

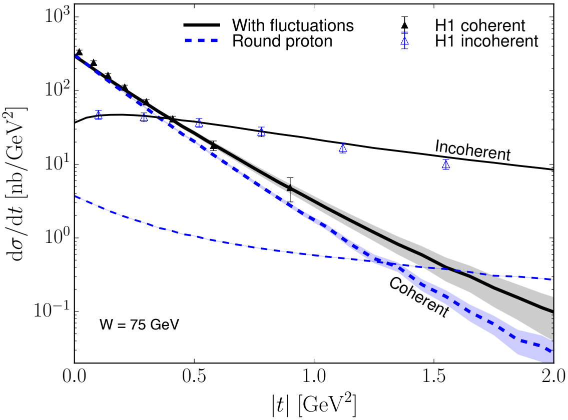
Illustration of the proton shape evolution: trace of a Wilson line



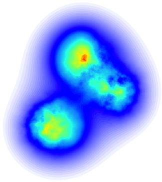
H.M, B. Schenke, in preparation. Also Schenke, Schlichting, 1407.8458

Evidence of fluctuations at HERA: $\gamma + p \to J/\Psi + p$

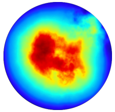
HERA data with only color charge fluctuations



Fluctuations



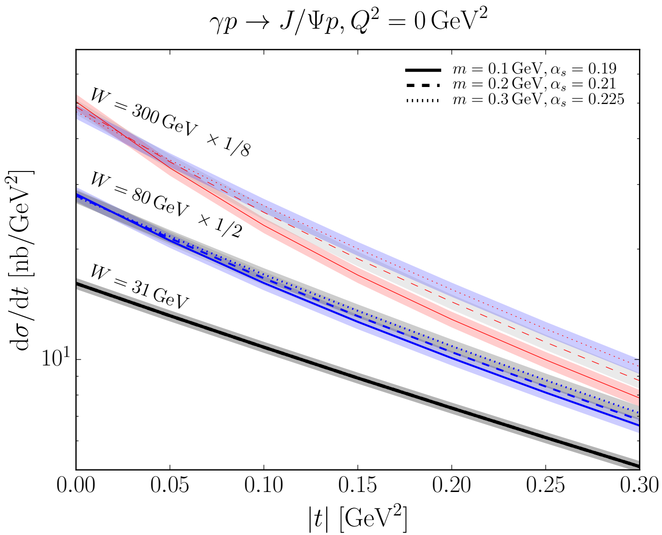
Round



H.M, B. Schenke, 1607.01711, H1: 1304.5162

Problem with the incoherent cross section

m dependence of the spectra evolution

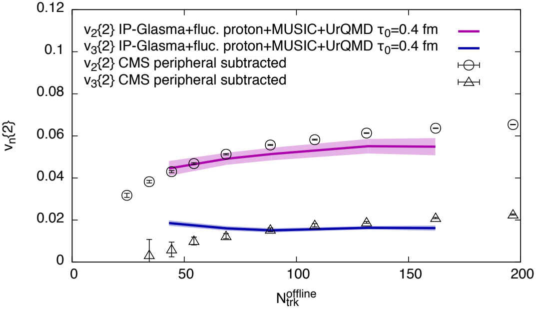


Application I: collectivity in pA collisions

Hydro calculations with proton fluctuations from HERA

Hydro numbers

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



Good description of v_n at high multiplicitiesl.

H.M, B. Schenke, C. Shen, P. Tribedy, arXiv:1704.03177