

Proton structure fluctuations: constraints from diffraction and applications to $p+A$ collisions

Heikki Mäntysaari

Brookhaven National Laboratory

Quark Matter 2017

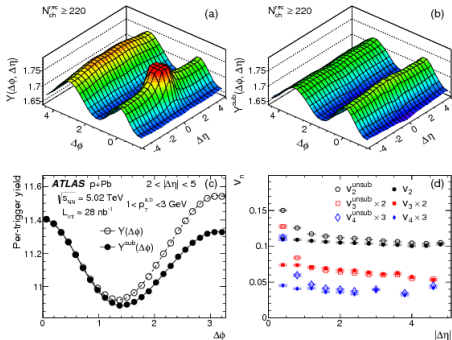
Based on: H.M., B. Schenke, PRL 117 (2016), 052301 and PRD 94 (2016), 034042
and work in progress with B. Schenke, P. Tribedy and C. Shen.

A fundamental question

How are the quarks and gluons distributed in space inside the nucleon?

Practical applications

Initial state geometry is a necessary input for hydrodynamical simulations



ATLAS, arXiv:1409.1792

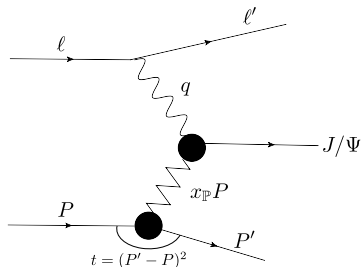
Collective phenomena seen in pp&pA

- Initial state geometry
⇒ final state collectivity

Diffraction processes probe

- Spatial density profile
- **Density fluctuations**

Exclusive vector meson production in DIS



Diffractive events: no exchange of color charge

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

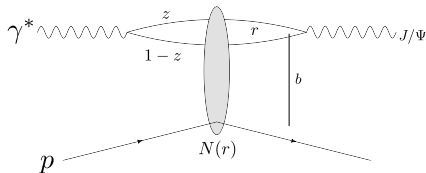
Target: proton or nucleus

Diffractive vector meson production in dipole picture

① $\gamma^* \rightarrow q\bar{q}$ splitting: $\Psi^\gamma(r, Q^2, z)$

② $q\bar{q}$ dipole scatters elastically:
 $N(r, x, b)$

③ $q\bar{q} \rightarrow J/\Psi$: $\Psi^V(r, Q^2, z)$



Diffractive scattering amplitude

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

- Fourier transfer from impact parameter to transverse momentum Δ
→ access to spatial structure
- Δ = transverse momentum of the vector meson
- N is universal dipole-proton scattering amplitude (here: IPsat)

Coherent diffraction = target remains intact

Target is at the same quantum state before and after the scattering:

$\langle \rangle$ = target average (Miettinen, Pumplin, PRD 18, 1978, ...)

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} \sim |\langle \mathcal{A}(x, Q^2, t) \rangle|^2$$

with

$$\mathcal{A} \sim \int d^2b dz d^2r \Psi^* \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b)$$

- Coherent $t = -\Delta^2$ spectra is Fourier transfer of the **average density**

Incoherent diffraction = target breaks up

Total diffractive cross section – coherent cross section → target breaks up

$$\frac{d\sigma^{\gamma^* p \rightarrow V p^*}}{dt} \sim \langle |\mathcal{A}(x, Q^2, t)|^2 \rangle - |\langle \mathcal{A}(x, Q^2, t) \rangle|^2$$

with

$$\mathcal{A} \sim \int d^2 b dz d^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b)$$

- Incoherent cross section is variance \Leftrightarrow sensitive to fluctuations

Incoherent diffraction = target breaks up

Total diffractive cross section – coherent cross section → target breaks up

$$\frac{d\sigma^{\gamma^* p \rightarrow V p^*}}{dt} \sim \langle |\mathcal{A}(x, Q^2, t)|^2 \rangle - |\langle \mathcal{A}(x, Q^2, t) \rangle|^2$$

with

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

- Incoherent cross section is variance \Leftrightarrow sensitive to fluctuations

Constraints

Simultaneous description of coherent and incoherent data allows us to constrain the average shape and the amount of fluctuations

Constraining proton fluctuations

Start with a simple constituent quark inspired picture:

- Sample quark positions from a Gaussian distribution, width B_{qc}
- Small- x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations
- Dipole-target scattering: IPsat model fitted to F_2 data

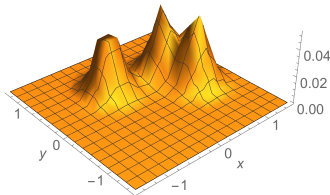
Constraining proton fluctuations

Start with a simple constituent quark inspired picture:

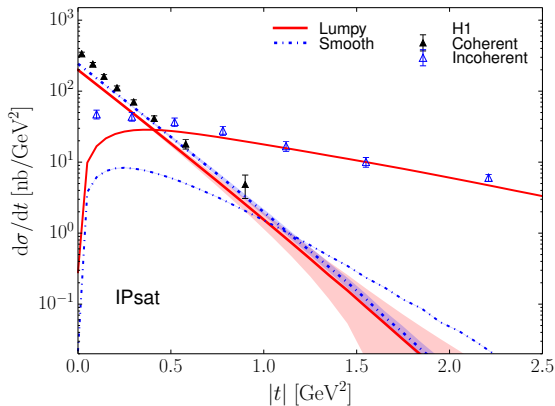
- Sample quark positions from a Gaussian distribution, width B_{qc}
- Small- x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations
- Dipole-target scattering: IPsat model fitted to F_2 data

Now proton = 3 overlapping hot spots.

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

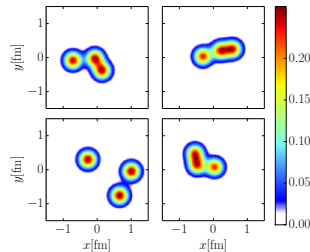


Constraining proton fluctuations in $\gamma + p \rightarrow J/\psi + p^*$

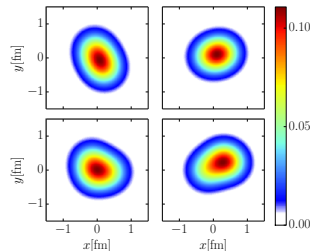


- H1 incoherent data requires large fluctuations
- Proton-photon center-of-mass energy $W = 75\text{GeV}$, probing $x \approx 10^{-3}$

Lumpy: $B_{qc} = 3.3, B_q = 0.7$



Smooth: $B_{qc} = 1.0, B_q = 3.0$



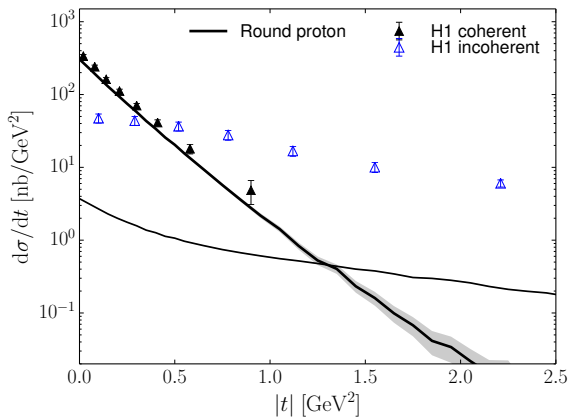
Units: GeV^{-2}

- 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

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

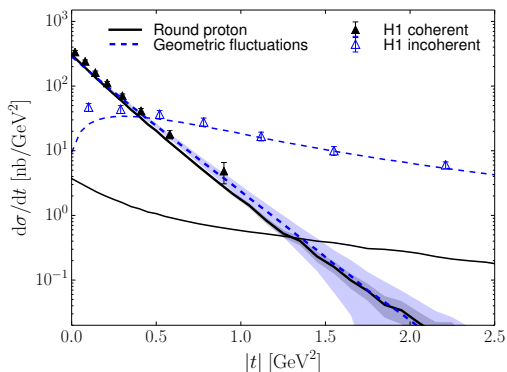
- Dipole amplitude: $N(x_T, y_T) = 1 - \text{Tr} V(x_T) V^\dagger(y_T) / N_c$
- Fix parameters B_{qc} , B_q and m with HERA data

IP-Glasma and HERA data



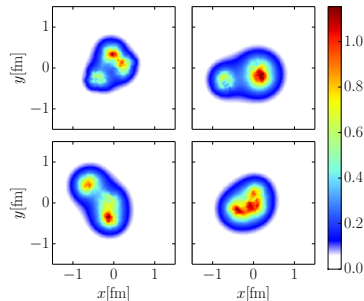
- Color charge fluctuations alone are not enough

IP-Glasma and HERA data



- Large geometric fluctuations are needed

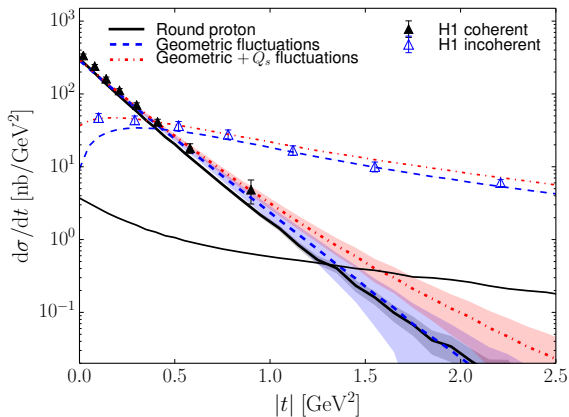
Parameters fitted to H1 data



H.M., B. Schenke, PRD94 (2016), 034042

IP-Glasma and HERA data, add Q_s fluctuations

- Allow Q_s of each constituent quark to fluctuate
- Constrained by pp multiplicity data (McLerran, Tribedy, arXiv:1508.03292)



- Q_s fluctuations improve description at small $|t| \sim$ large distance

Applications to pA collisions

Large elliptic flow (v_2) seen in pA collisions

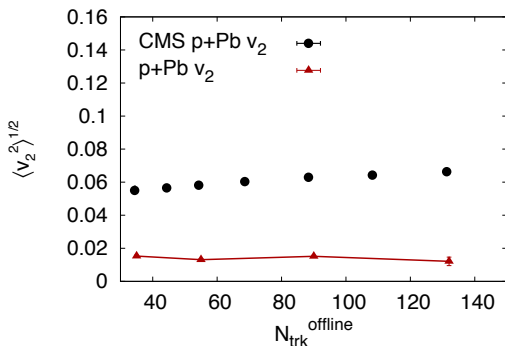
IP-Glasma with hydro works well with the AA data, apply to pA

Does it work?

First approach: round proton
with only color charge
fluctuations

B. Schenke, R. Venugopalan,

PRL113 (2014) 102301

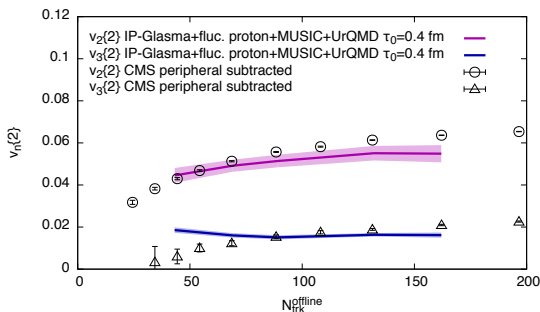


Color charge and Q_s fluctuations in the initial state do not create large enough flow harmonics to the final state

Hydro calculations with proton fluctuations from HERA

Hydro numbers

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

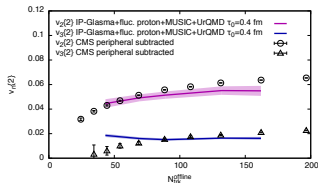
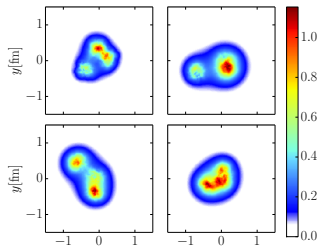


Large v_2 and v_3 at largest centrality bins reproduced well.

In preparation with B. Schenke, C. Shen, P. Tribedy

Conclusions

- Coherent and incoherent diffraction combined probe proton
 - Density profile
 - Event-by-event density fluctuations
- Color charge fluctuations alone are not enough to describe HERA incoherent J/ψ production data
 - Large geometric fluctuations of the proton density are needed
 - Can not constrain exact shape
- Structure fluctuations constrained by HERA data
 - pA hydro calculations compatible with LHC v_n data
- **Next step:** include small- x evolution in terms of JIMWLK equation



Saturation scale fluctuations

Saturation scale fluctuations ($p + p$ multiplicity distributions: $\sigma \sim 0.5$)

$$P(\ln Q_s^2 / \langle Q_s^2 \rangle) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{\ln^2 Q_s^2 / \langle Q_s^2 \rangle}{2\sigma^2} \right]$$

McLerran, Tribedy, arXiv:1508.03292: $p + p$ multiplicity distributions:
 $\sigma \sim 0.5$

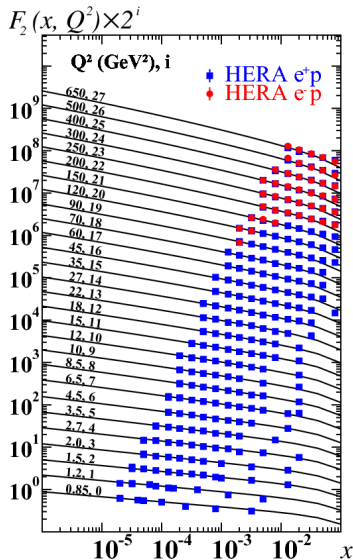
- Shifted to keep average Q_s unchanged
- Allow Q_s^2 of each constituent quark to fluctuate
- If no geometric fluctuations, divide transverse space to $\sim 1/Q_s^2$ cells where Q_s^2 fluctuates

Dipole-target scattering: IPsat

Impact Parameter dependent saturation model for the dipole amplitude

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

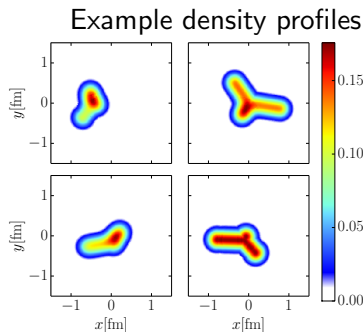
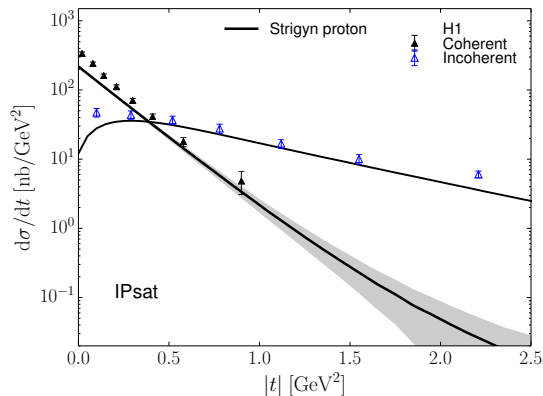
- $T_p(b)$ is transverse proton density function (Gaussian)
- xg is DGLAP evolved gluon density
- Free parameters fitted to HERA F_2 data (Kowalski, Teaney 2003; Rezaeian et al, 2013)



Lumpiness matters, not details of the density profile

3 valence quarks that are connected by "color flux tubes":

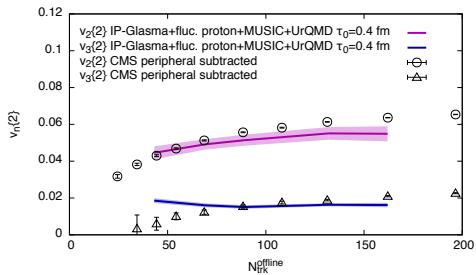
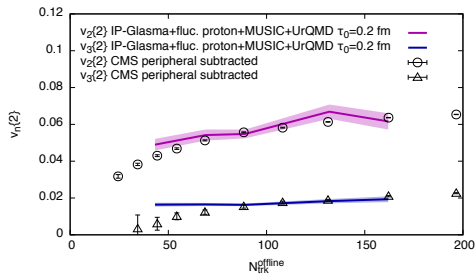
Gaussian tubes connecting quarks. Also good description of the data



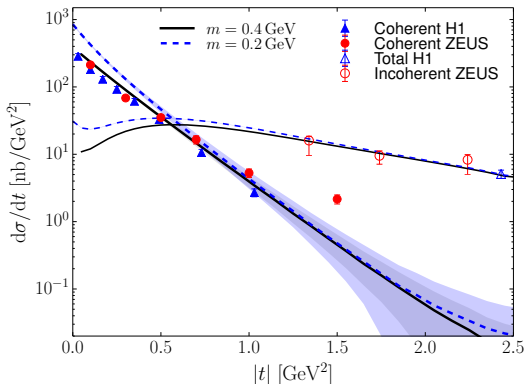
H.M., B. Schenke, PRD94 034042

Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911

Dependence on τ_0



Insensitivity on infrared cutoff



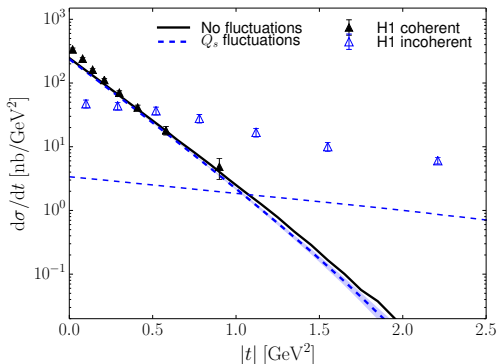
IP-Glasma: IR cutoff $m \sim \Lambda_{\text{QCD}}$ to regulates long distance coulomb tails

- Proton size depends on m
- No sensitivity at large $|t|$

Saturation scale fluctuations w/o geometric fluctuations

Allow Q_s^2 to fluctuate, $P(\ln Q_s^2 / \langle Q_s^2 \rangle) \sim \exp(-[\ln^2 Q_s^2 / \langle Q_s^2 \rangle] / 2\sigma)$

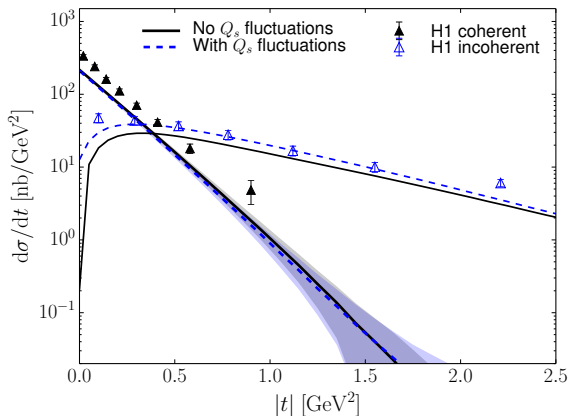
Constrained by pp multiplicity fluctuations (McLerran, Tribedy, arXiv:1508.03292)



- Q_s fluctuations alone are not enough

Saturation scale fluctuations + geometric fluctuations

Allow Q_s of each constituent quark to fluctuate separately (IPsat):



- Q_s fluctuations dominate incoherent cross section at small $|t|$ (\sim large distance)