Proton structure fluctuations: constraints from incoherent diffraction and applications to pA collisions

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H.M., B. Schenke, PRL 117 (2016), 052301 and PRD94 (2016), 034042

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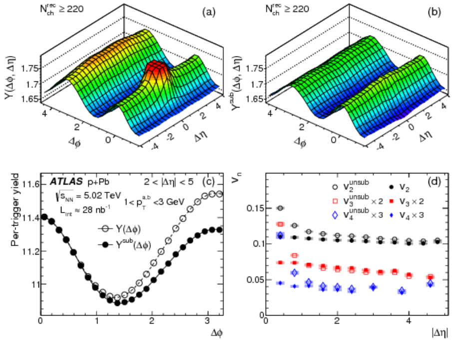
Motivation

A fundamental question

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



ATLAS, arXiv:1409.1792

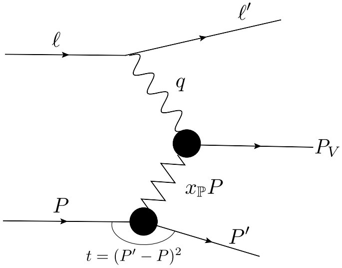
Collective phenomena seen in pp&pA

- Can be caused by initial state geometry
- Initial state geometry is a necessary input for hydrodynamical calculations

Diffractive processes probe

- Spatial density profile
- **Density fluctuations**

Exclusive vector meson production



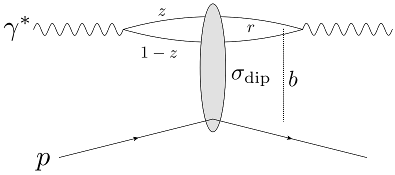
Diffractive events: no exchange of color charge

- 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

Vector mesons from the CGC at high energy

CGC: Dipole-proton cross section
$\sigma_{\text{dip}}(x, r, \Delta) = 2 \int \mathrm{d}^2 b e^{ib\cdot\Delta} N(r, x, b)$
Universal dipole amplitude N



- Exclusive diffraction:

$$\frac{1}{16\pi} \left| \int \mathrm{d}^2 r \mathrm{d}z \Psi^* \Psi^V(Q^2, r, z) \sigma_{\text{dip}}(x, r, \Delta) \right|^2$$

- Total $\gamma^* p$ (DIS):

$$\int \mathrm{d}^2 r \mathrm{d}z |\Psi^\gamma(Q^2, r, z)|^2 \sigma_{\text{dip}}(x, r, \Delta = 0)$$

- Inclusive particle production (pp, pA):

$$\sim xg(x, Q^2) \int \mathrm{d}^2 r e^{ir\cdot p_T} [1 - N(r, x, b)]$$

- $+$ many other processes

Coherent and incoherent diffraction

With event-by-event fluctuations:

- Coherent diffraction: target remains intact

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

- Incoherent, target breaks up: variance

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}(x, Q^2, t)|^2 \rangle - \left| \langle \mathcal{A}(x, Q^2, t) \rangle \right|^2$$

$\langle\rangle$ = Target average.
$\mathcal{A}$ = scattering ampliude for exclusive process

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

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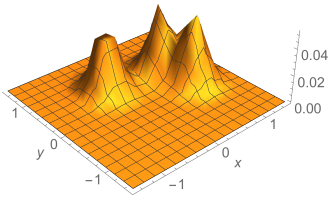
Constraining proton fluctuations

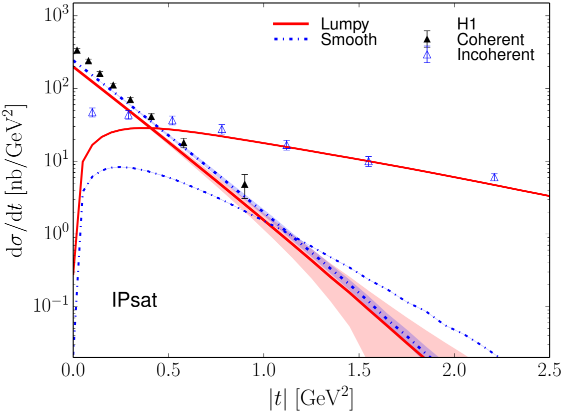
Start with a simple constituent quark inspired picture:

- Small-x gluons are located around the valence quarks (width B_q).
- Sample quark positions from a Gaussian distribution, width B_{qc}
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations

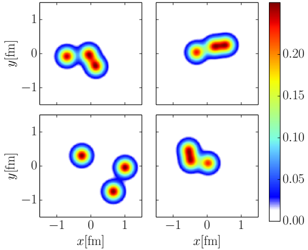
Now proton = 3 overlapping hot spots.



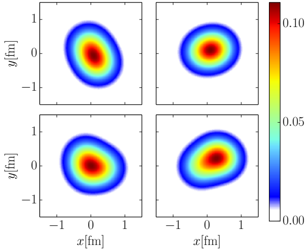
Constraining proton fluctuations in $\gamma + p \to J/\Psi + p^*$



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



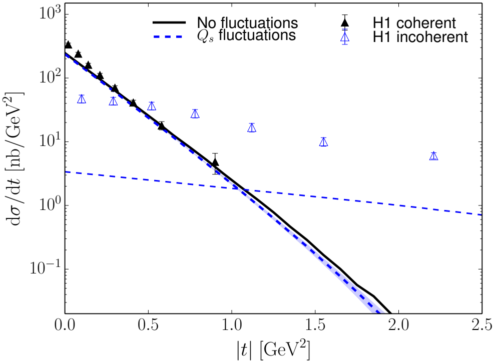
Smooth: $B_{qc} = 1.0$, $B_q = 3.0$



- Incoherent data requires large fluctuations

Saturation scale 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

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 the 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

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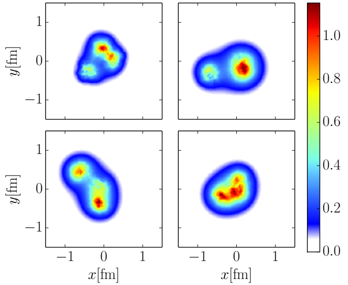
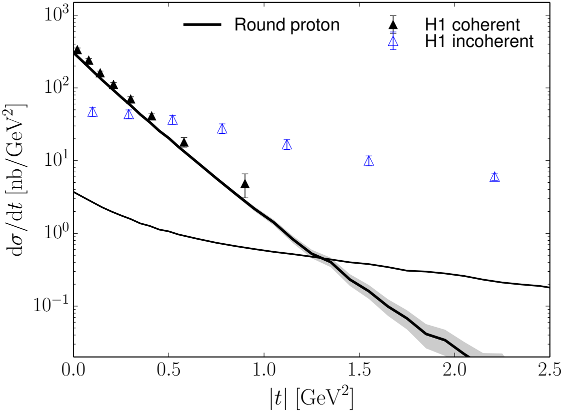
Example configurations:
$1 - \mathrm{Re}(\mathrm{Tr}\, V(x_T))/N_c$



IP-Glasma and HERA data



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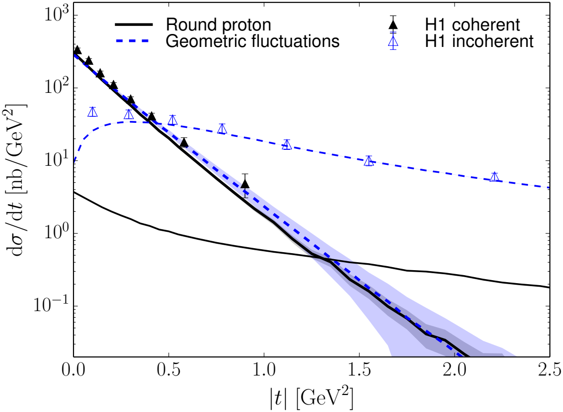
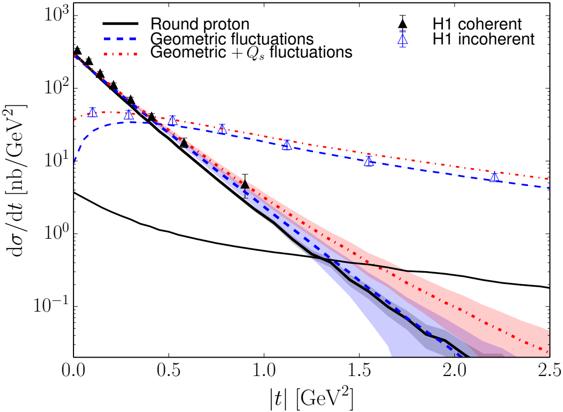


- Large geometric fluctuations are needed



- Large geometric fluctuations are needed
- Q_s fluctuations improve description at small $|t|$

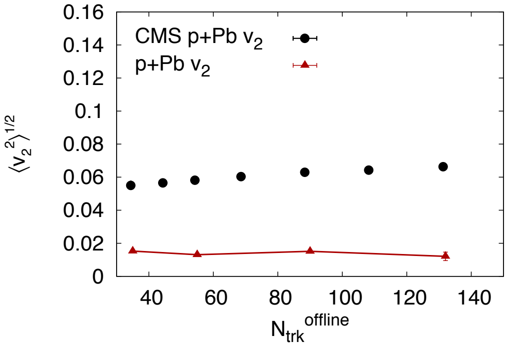
Applications to pA collisions

Large elliptic flow (v_2) seen in pA collisions

IP-Glasma+hydro successfully works 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



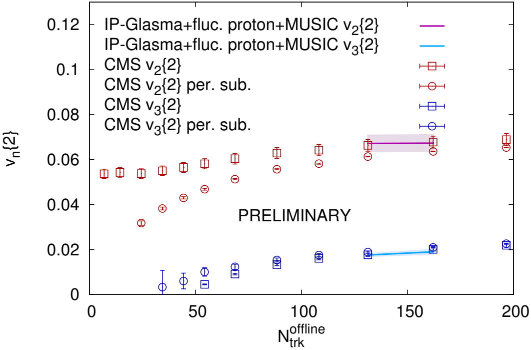
Color charge and Q_s fluctuations in the initial state do not create large enough flow harmonics to the final state

Fluctuating protons in pA collisions

Preliminary hydro calculations with proton fluctuations from HERA

Hydro numbers

- $\tau_0 = 1$ fm
- $T_{fo} = 160$ MeV
- Viscosity as in arXiv:1512.01538

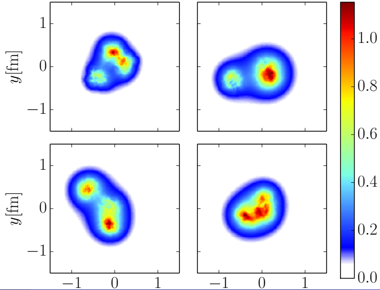


Large v_2 and v_3 at largest centrality bins reproduced well.

Work in progress (centrality dependence, initial $\pi^{\mu\nu}$,...)

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
  - Saturation scale fluctuations improve description at small $|t|$
- Improve description of pA collisions within the IP-Glasma framework (work in progress)



Backups

Saturation scale fluctuations

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

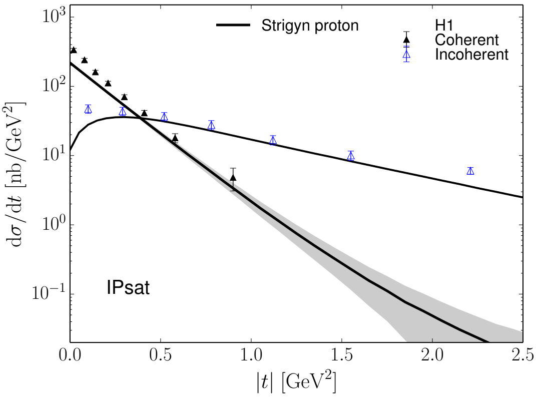
$$P(\ln Q_s^2/\langle Q_s^2\rangle) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\ln^2 Q_s^2/\langle Q_s^2\rangle}{2\sigma^2}\right]$$

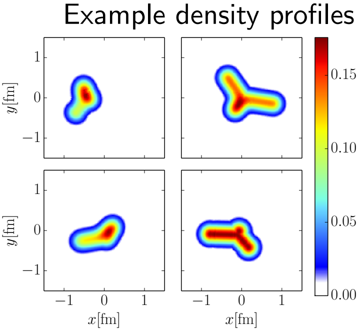
McLerran, Tribedy, arXiv:1508.03292: $p+p$ multiplicity distributions: $\sigma \sim 0.5$

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

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



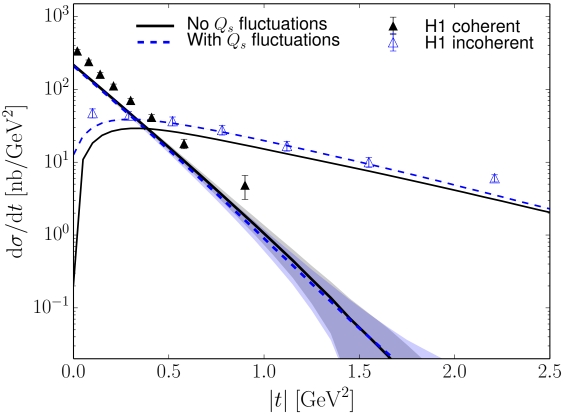


H.M, B. Schenke, PRD94 034042

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

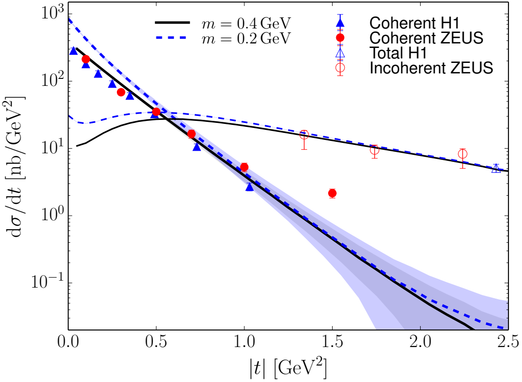
Saturation scale fluctuations + geometric fluctuations

IP-sat



- Q_s fluctuations dominate incoherent cross section at small $|t|$

Insensitivity on infrared cutoff



H.M., B. Schenke, in progress

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

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

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)
- Proton profile T_p: Gaussian, width B_p

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