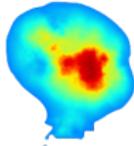
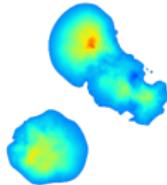
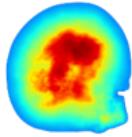


Hadron shape fluctuations and its relation to DIS

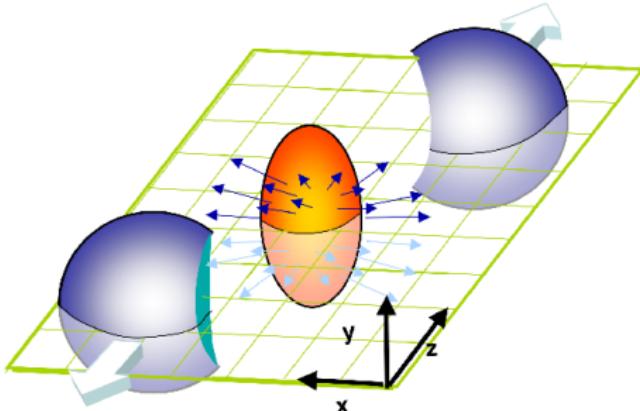
Heikki Mäntysaari

University of Jyväskylä, Department of Physics
Finland

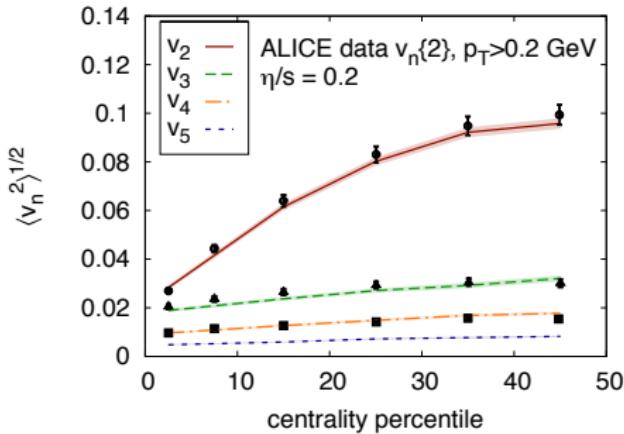


Proton geometry from heavy ion physics point of view

Heavy ion collisions: Initial spatial anisotropy \Rightarrow momentum anisotropy.
Pb + Pb data well described by relativistic hydrodynamics (collectivity)



Heinz, 0810.05529



Fourier harmonics \mathbf{v}_n

$$\frac{dN}{d\phi} \sim N_0(1 + 2\mathbf{v}_2 \cos(2\phi) + \dots)$$

Gale et al, 1209.6330

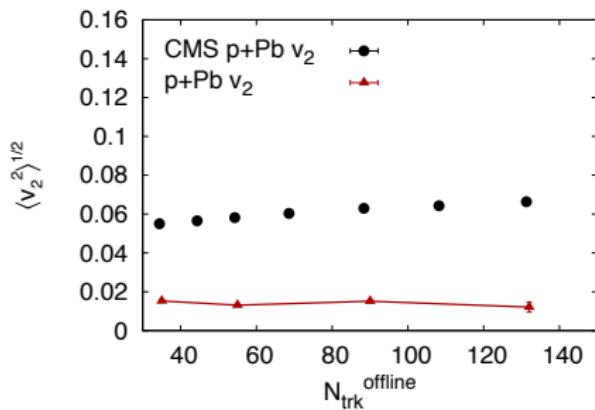
Proton geometry from heavy ion physics point of view

LHC surprise

Large elliptic flow v_2 seen in proton-lead collisions!

Something causes collectivity, again hydrodynamically evolving QGP?

Same hydro framework
fails with the LHC p+Pb data:



Schenke, Venugopalan, 1405.3605

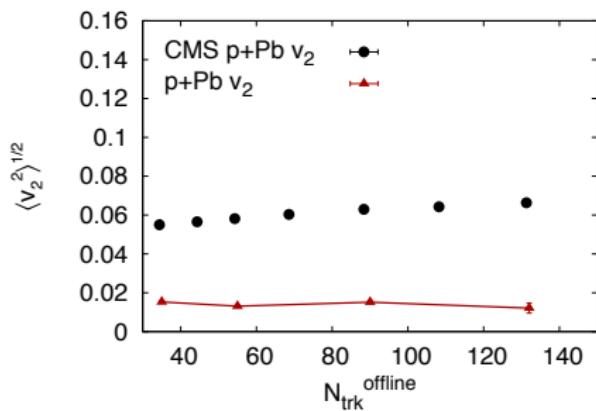
Proton geometry from heavy ion physics point of view

LHC surprise

Large elliptic flow v_2 seen in proton-lead collisions!

Something causes collectivity, again hydrodynamically evolving QGP?

Same hydro framework
fails with the LHC p+Pb data:



But a round proton was assumed!



particlezoo.net

And nature is quantum mechanical
(more complicated)

Schenke, Venugopalan, 1405.3605

Going beyond round proton

A fundamental question

How are quarks and gluons distributed spatially inside the proton?
How do the positions fluctuate?

Practical applications to for example

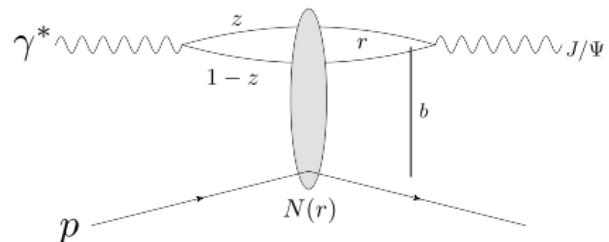
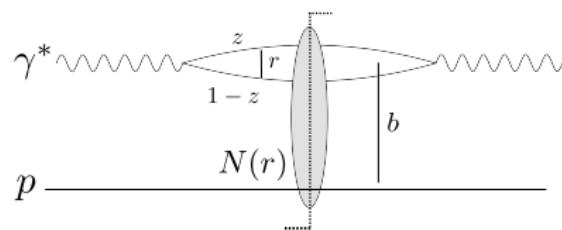
Collective phenomena in $p + A$ and $p + p$ Mäntysaari, Schenke, Shen, Tribedy, Heinz,
Singer, Welsh, Moreland, Bernhard, Ke, Bass, Albacete, Petersen, Soto-Ontoso
Exclusive scattering processes Mäntysaari, Schenke, Cepila, Contreras, Takaki, Krelina
Elastic $p + p$ and *hollowness* effect Albacete, Soto-Ontoso

This talk: use exclusive scattering in $e + p$ to constrain the fluctuations
Applications to heavy ion phenomenology

Also other approaches

Deep Inelastic Scattering as a probe of the proton structure

DIS at high energy: dipole picture



Optical theorem:

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

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

Universal dipole amplitude

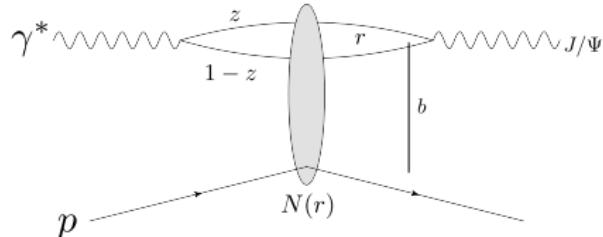
QCD dynamics is included in the **dipole amplitude N**

- Total cross section $\sim N \sim \text{gluon density}$
- Diffraction $\sim N^2 \sim \text{gluon density}^2$
 - + access to spatial structure

Diffractive vector meson production

High energy factorization:

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



Diffractive scattering amplitude

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

- Impact parameter is the Fourier conjugate of the momentum transfer
→ Access to the spatial structure

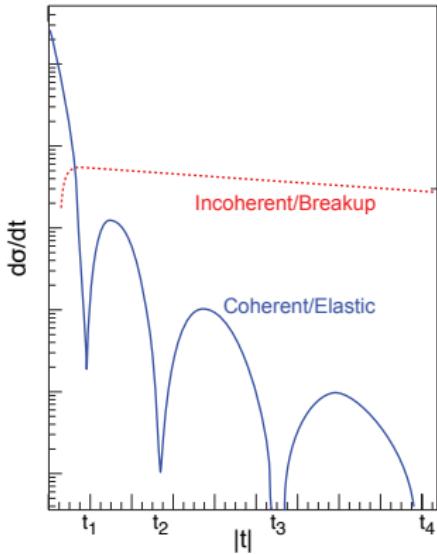
Average over configurations

Coherent diffraction:

Target proton remains in the same quantum state

Probes average density

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} \sim |\langle \mathcal{A}^{\gamma^* p \rightarrow Vp} \rangle|^2$$



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

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} \sim |\langle \mathcal{A}^{\gamma^* p \rightarrow Vp} \rangle|^2$$

Incoherent/target dissociation:

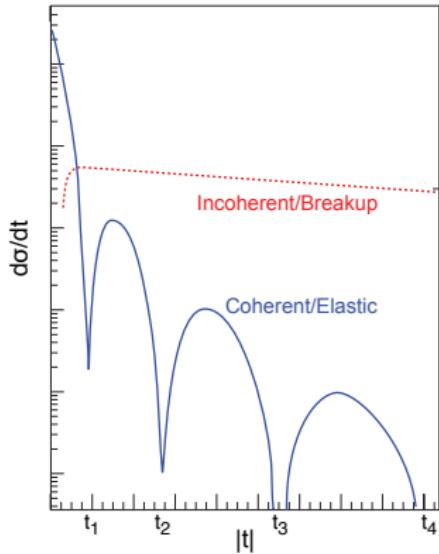
Total diffractive – coherent cross section

Target breaks up

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

Variance, measures the amount of fluctuations!

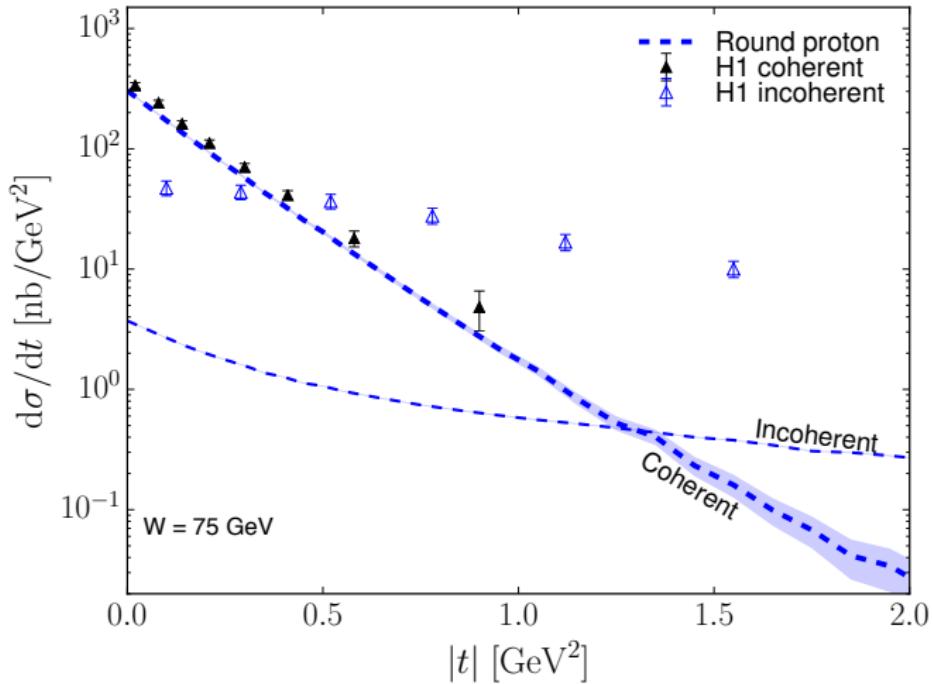
$\langle \rangle$: average over target configurations $[N(r, b)]$



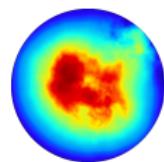
Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

Constraining proton fluctuations: $\gamma + p \rightarrow J/\Psi + p$

HERA data with only color charge fluctuations



Round
IP-Glasma
proton:
Color charges
+Yang-Mills

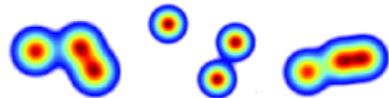


H.M, B. Schenke, 1607.01711, H1: 1304.5162

Problem with the incoherent cross section

Constraining proton fluctuations

Simple constituent quark inspired picture:



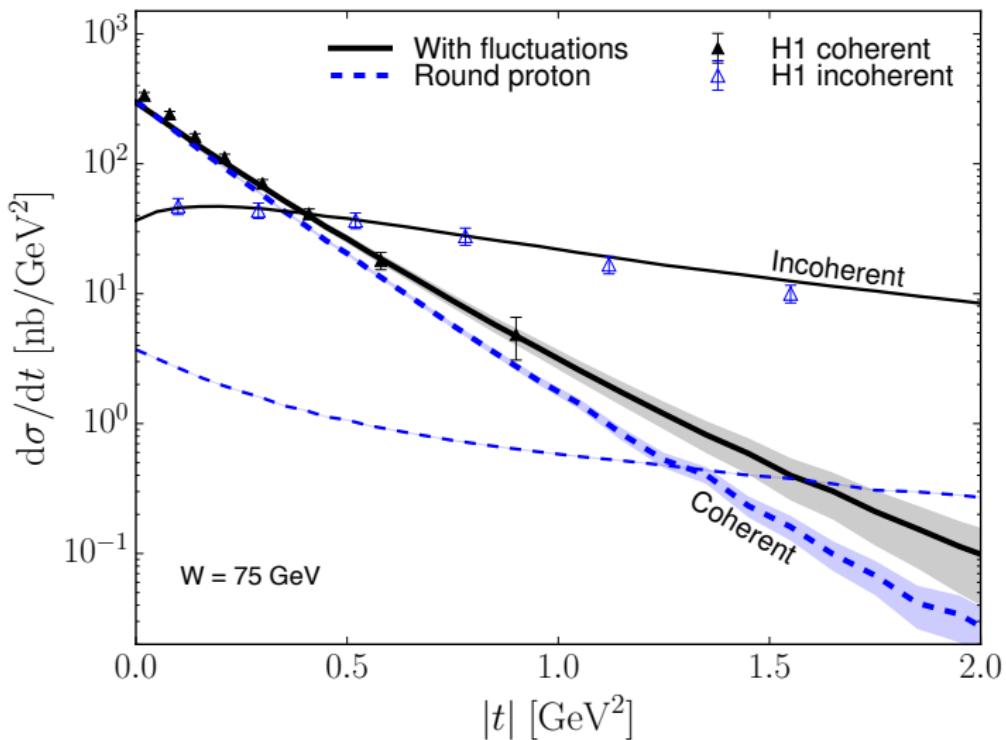
- Sample quark positions from a Gaussian distribution (width B_{qc})
- Small- x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations

Now proton = 3 overlapping hot spots.

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

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

Constraining proton fluctuations: $\gamma + p \rightarrow J/\Psi + p$

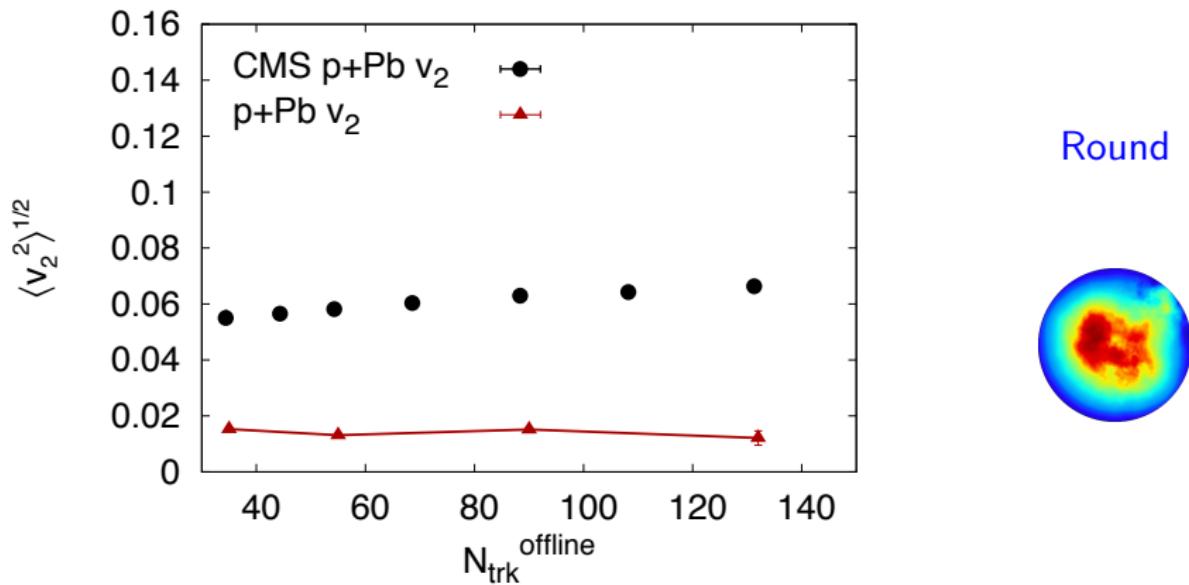


H.M, B. Schenke, 1607.01711

Large event-by-event fluctuations are needed

Implications on heavy ion phenomenology: p+A

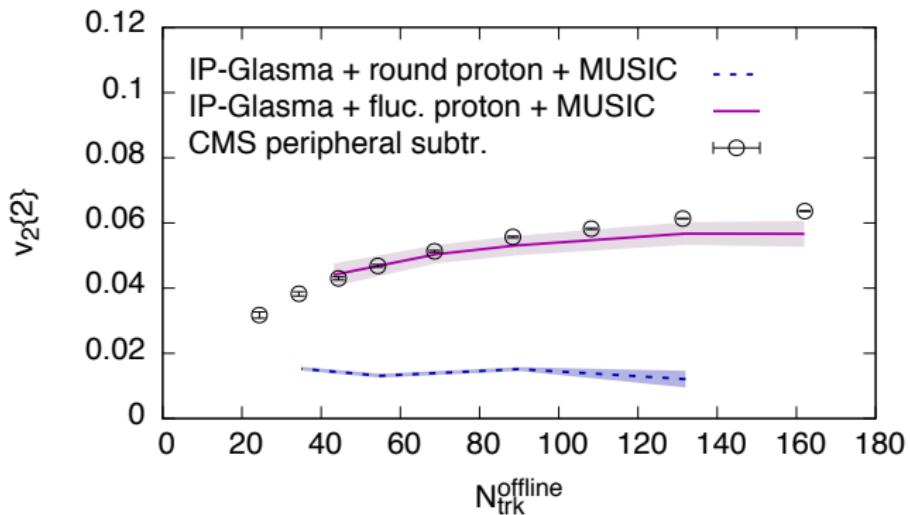
Round protons: hydro simulations failed to describe v_2 in $p + Pb$ collisions



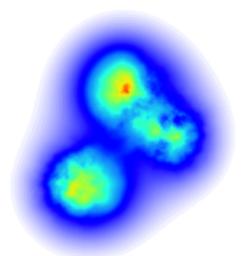
Schenke, Venugopalan, 1405.3605

Implications on heavy ion phenomenology: p+A

Hydro + fluctuations from HERA J/ψ data: success



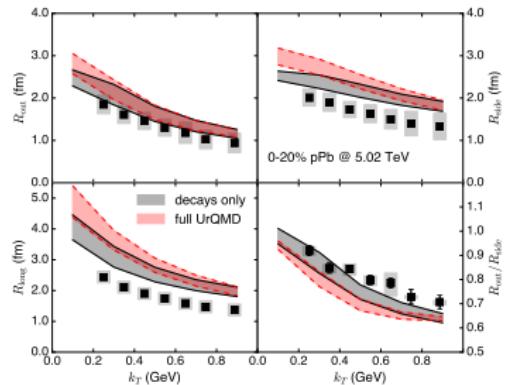
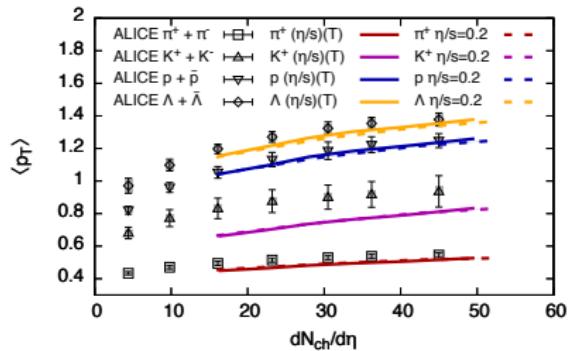
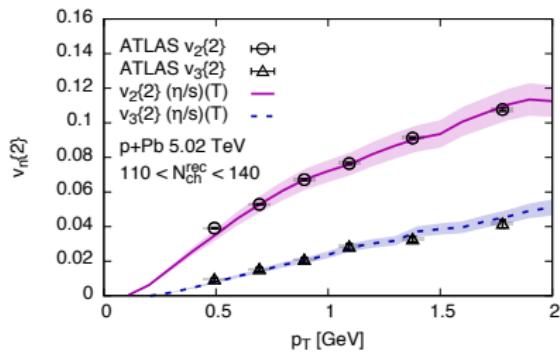
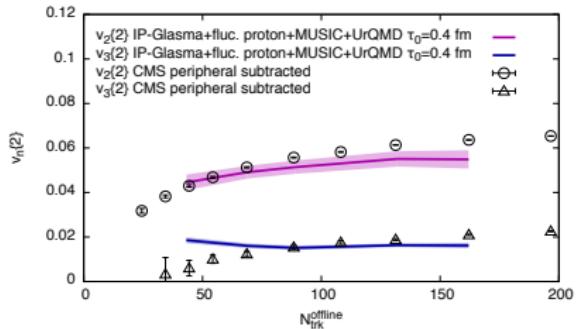
Fluctuations



H.M, Schenke, Shen, Tribedy, 1705.03177

Implications on heavy ion phenomenology: p+A

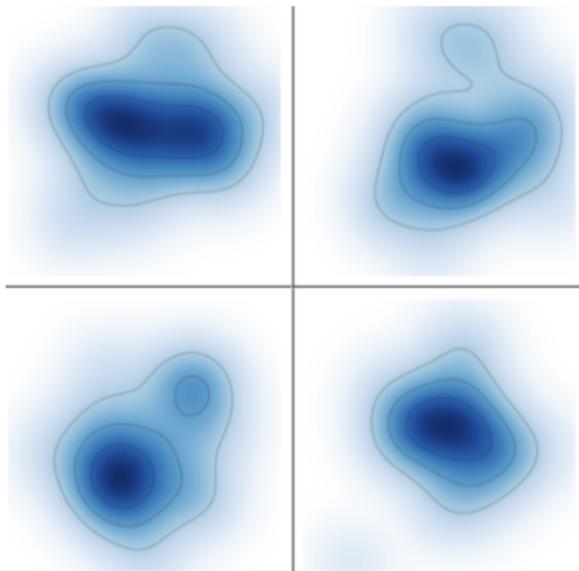
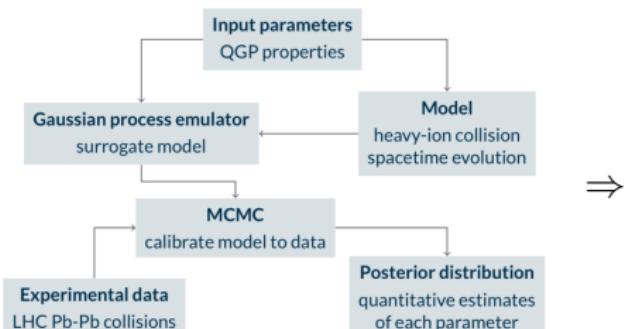
Hydro + fluctuations from HERA J/ψ data: success



H.M. Schenke, Shen, Tribedy, 1705.03177

Alternative approach: fluctuations from $p + A$ data

Extract proton shape parameters from hydro simulations of $p + Pb$ data by applying Bayesian methodology, similar results



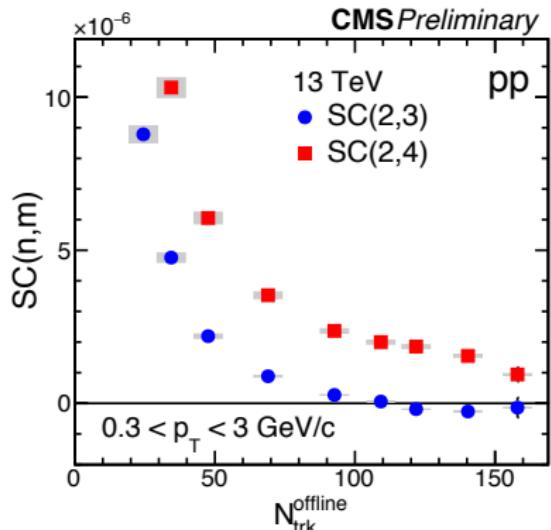
Proton thickness function

Moreland, Bernhard, Ke, Bass, QM2017 and 1704.04486

Alternative approach 2: symmetric cumulants in $p + p$

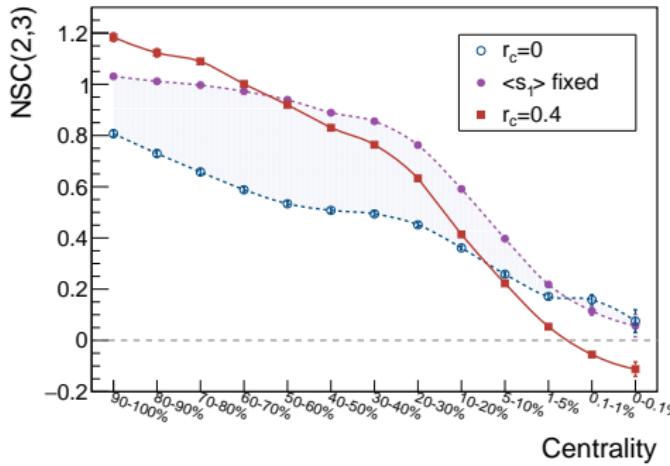
CMS: in central $p + p$ correlation between v_2 and v_3 becomes negative
Explained: fluctuating hot spots + short range repulsive correlations

CMS: $SC(2,3) < 0$ in central $p + p$



CMS-PAS-HIN-16-022

Sign change with 3 hot spots
+ nonzero repulsive distance r_c



Albacete, Petersen, Soto-Ontoso, 1707.05592

Diffraction in ultraperipheral collisions

Beyond HERA

A and x dependence from the LHC

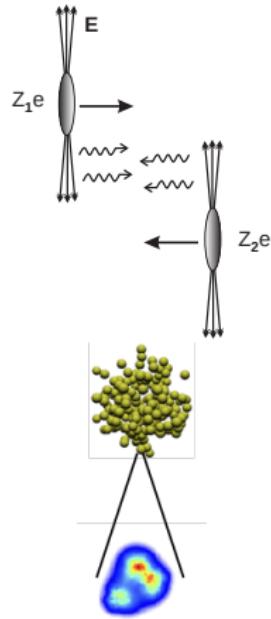
Ultra Peripheral heavy ion Collisions (UPC):
access to photonuclear reactions

- At $|b_T| > 2R_A$ one nucleus acts as a photon source

Two sources of fluctuations:

- Nucleon positions from Woods-Saxon
- Constituent quark structure for each nucleon

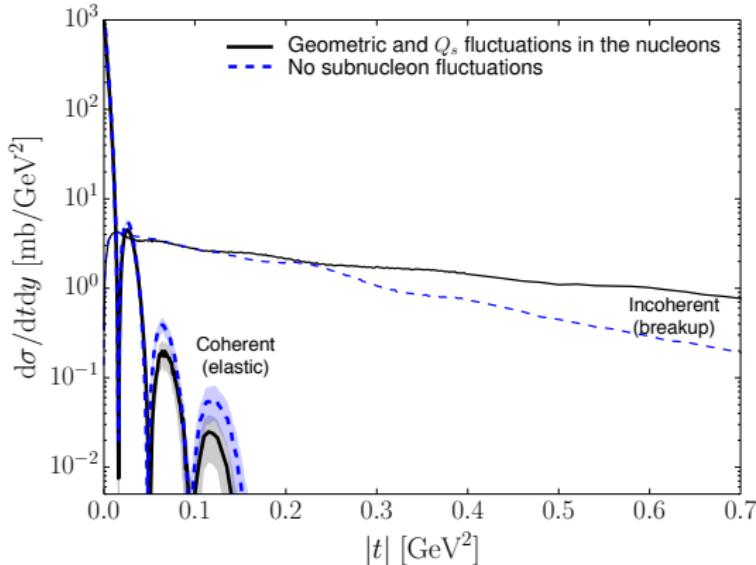
Exclusive J/Ψ production: probe both components



Accessing fluctuations at different scales

LHC: Access nuclear gluon at very small x , midrapidity $x_p \approx 6 \cdot 10^{-4}$

$\text{Pb} + \text{Pb} \rightarrow J/\Psi + \text{Pb} + \text{Pb}, \sqrt{s} = 5.02 \text{ TeV}, y = 0$



Generically

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

LHC: see nucleon scale fluctuations in Pb

H.M. Schenke, 1703.09256; Cepila, Contreras, Krelina, 1711.01855;

ALICE UPC data (1406.7819) seems to prefer subnucleon fluctuations

Bjorken-x dependence

Approach 1: parametrize number of hot spots

Small- x gluon emissions increase the number of hot spots

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

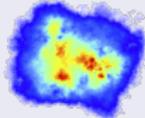
[Cepila, Contreras, Tapia Takaki, 1608.07559](#)



Approach 2: Solve small- x evolution equations

Evolve proton structure by solving

- BK evolution with impact parameter [Berger, Stasto, 1106.5740](#)
- JIMWLK evolution [Schlichting, Schenke, 1407.8458](#), [H.M., Schenke, 18xx.xxxx](#)

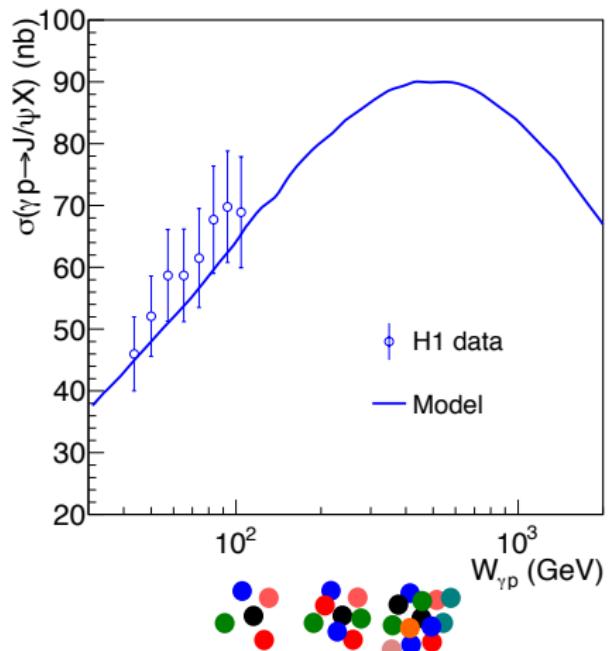


Fit HERA F_2 and exclusive data.

Difficulty: regulating confinement effects

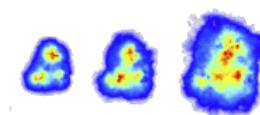
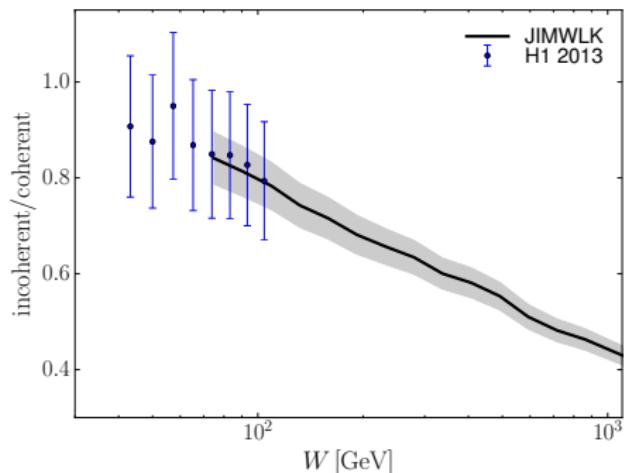
Towards small x : $\gamma + p \rightarrow J/\Psi + p^*$

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



Cepila, Contreras, Tapia Takaki, 1608.07559

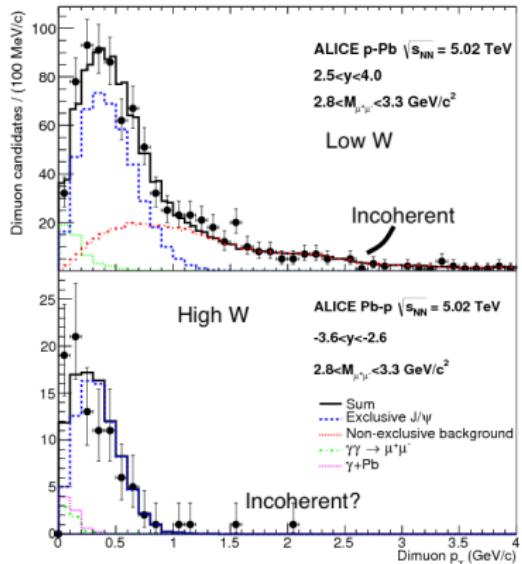
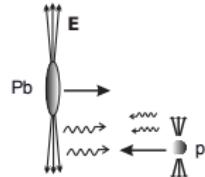
JIMWLK evolution
event-by-event



H.M, Schenke, in progress

Exclusive J/Ψ production at small x 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

- No incoherent at high W
 \Rightarrow smoother proton(?)

ALICE: 1406.7819

Conclusions

Multi dimensional event-by-event picture of the proton

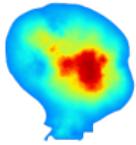
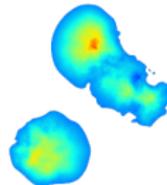
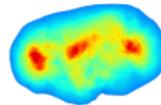
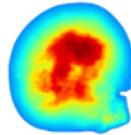
- Input from (diffractive) DIS, applications on heavy ion phenomenology
- Or vice versa...

Strong hints from HERA and LHC data that

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

New interesting data coming

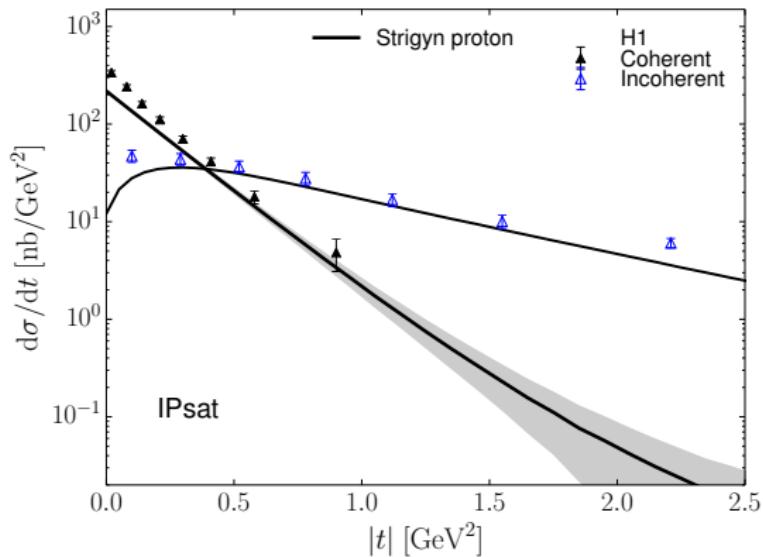
- Ultraperipheral collisions at the LHC
- Electron Ion Collider



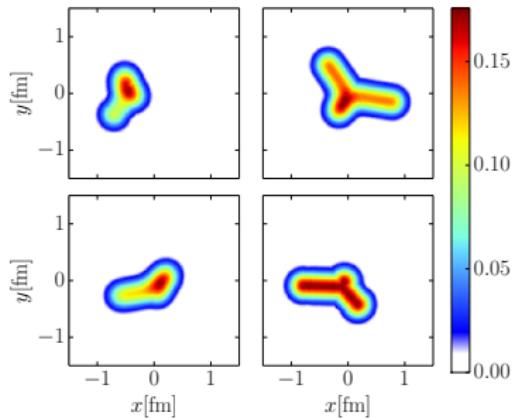
BACKUPS

Lumpiness matters, not details of the density profile

Example: 3 valence quarks that are connected by "color flux tubes":
Also a good description of the data with large fluctuations



Example density profiles



Here using IP-sat model to describe
dipole-proton scattering

H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911