

Effective theories for nuclei at high energies

Sören Schlichting | Universität Bielefeld



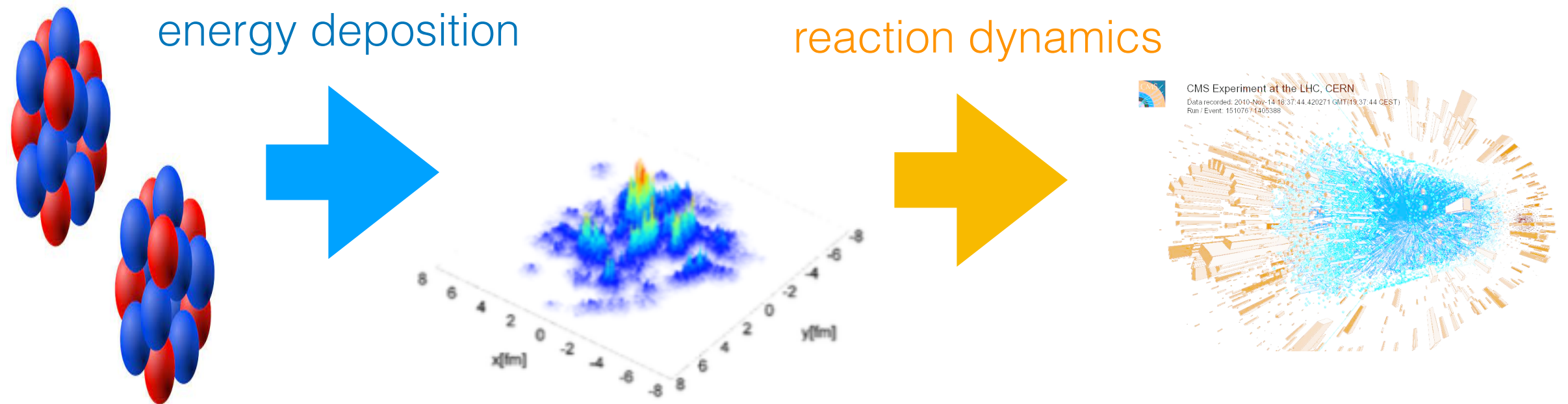
ESNT Workshop

CEA Saclay Sept 2022

Deciphering nuclear phenomenology across energy scales

Motivation

Nuclear structure manifests itself in the initial energy deposition of a heavy-ion collisions



Experimental Heavy-Ion measurements rely on final state observables
accessing nuclear structure with Heavy-Ion collisions relies on our ability
to describe initial state energy deposition & reaction dynamics

will describe theoretical framework underlying energy deposition

High-Energy Scattering

High-energy scattering experiments of nuclei and nucleons probe the partonic QCD content of nuclei

degrees of freedom are quarks/gluons inside nuclei

a priori no connection to low energy nuclear structure

Generally quantified in terms of QCD correlation functions of hadrons nuclei (coll. PDFs, TMDs, GPDs, Wigner-Distribution)

$$f_{g/A}(x, \mu) = \frac{1}{2\pi x P^+} \int dy^- e^{-ixP^+ y^-} \langle P^+, \vec{0}_T | F_a(0, y^-, \vec{0}_T)^{+\nu} \mathcal{O}_{ab} F_b(0, 0, \vec{0}_T)_{\nu}^+ | P^+, \vec{0}_T \rangle_{\overline{\text{MS}}}$$

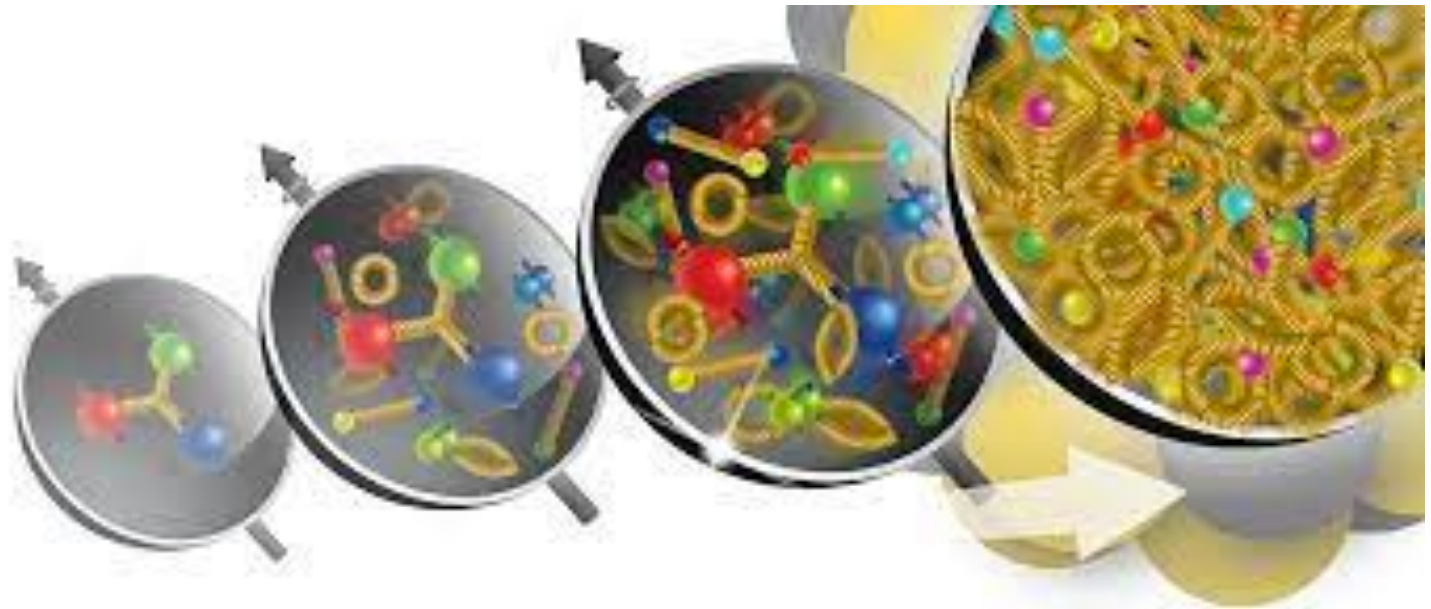
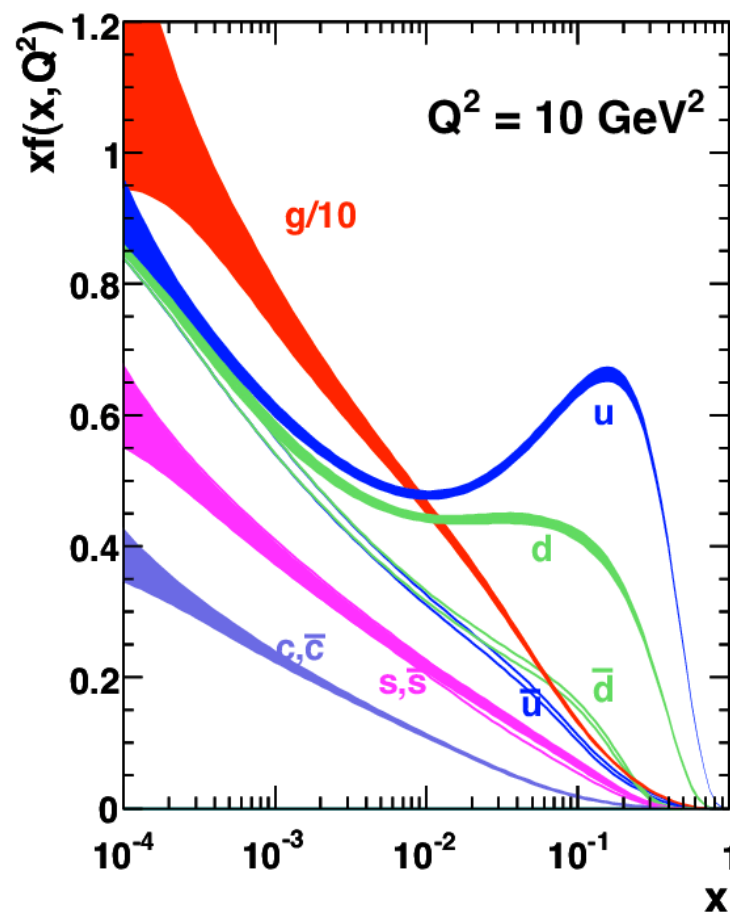
Evidence from modeling of hadronic collisions (HICs) suggests that transverse spatial distribution of quarks & gluons remains confined inside nucleons at present energies

Nucleon/nucleus structure

Knowledge of PDFs historically from fit to Experiments (DIS) and nowadays with clever tricks also from Lattice QCD

$x \sim$ energy/momentum fraction carried by parton

$Q^2 \sim$ resolution scale



valence
regime

many-body
regime

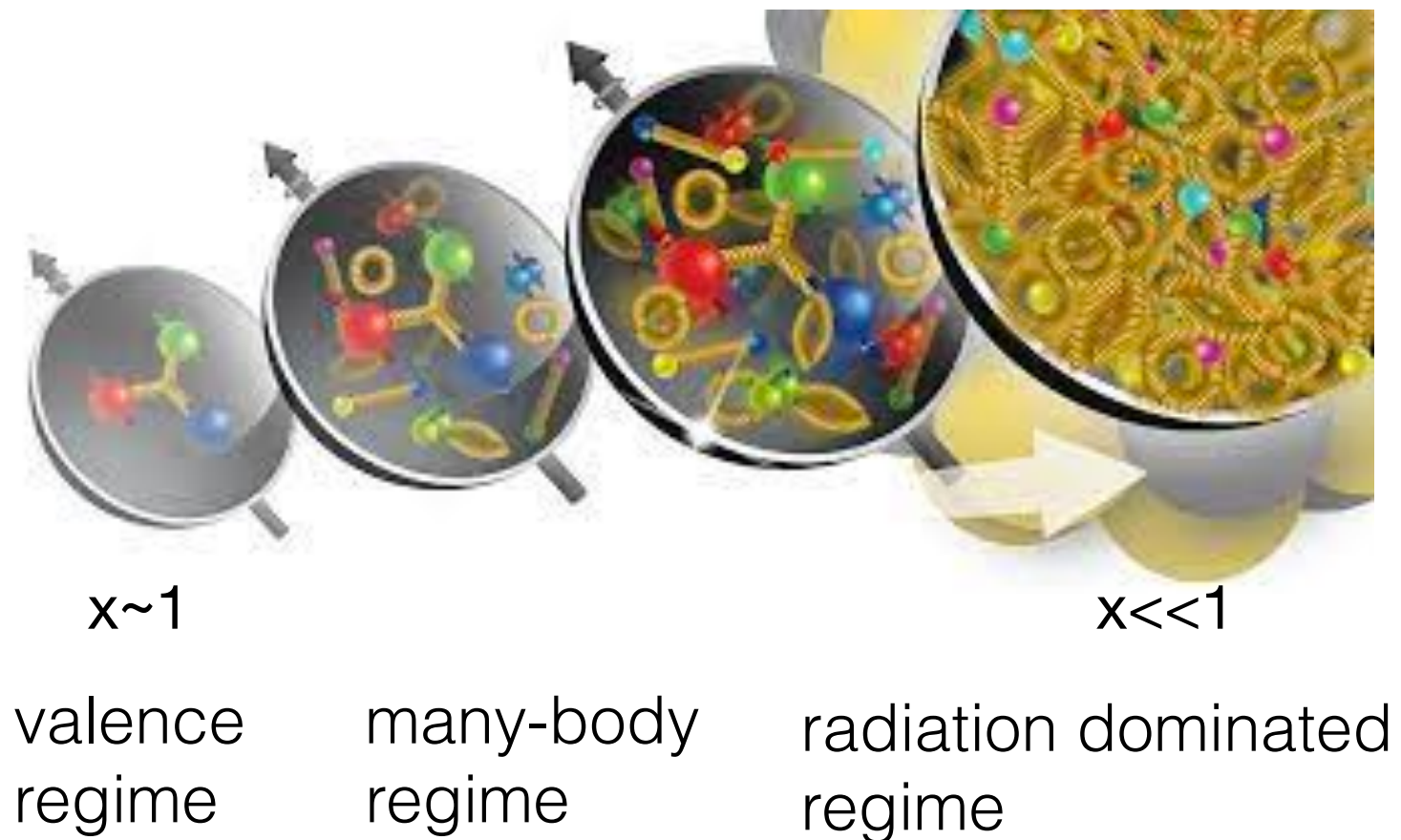
radiation dominated
regime

Nucleon/nucleus structure

What regime is accessed depends on kinematics of experiment

Generally for fixed c.o.m. energy smaller energy of the probe probes smaller x

Generally for fixed energy of the probe (e.g. Z -Boson) higher c.o.m. energy probes smaller x



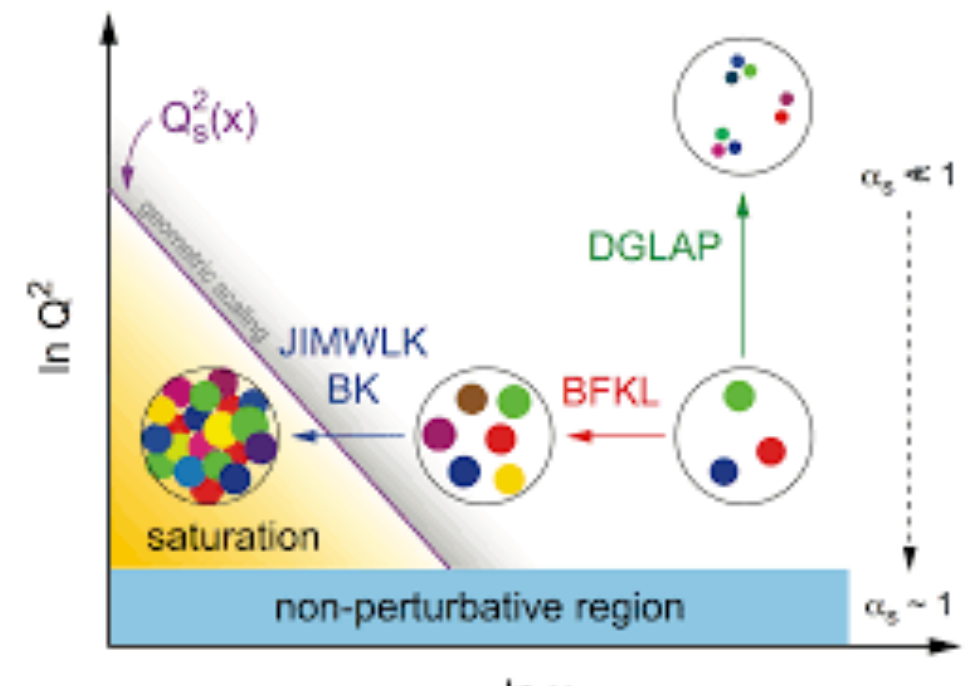
Different theoretical formalism/expansion schemes in QCD

- traditional pQCD aimed at precision physics for single (few) hard scattering physics at large/moderate x
- effective theories for QCD aim to describe dynamics in small x regime

Gluon saturation

Eventually in the radiation dominated regime, gluons densely populate the available phase-space

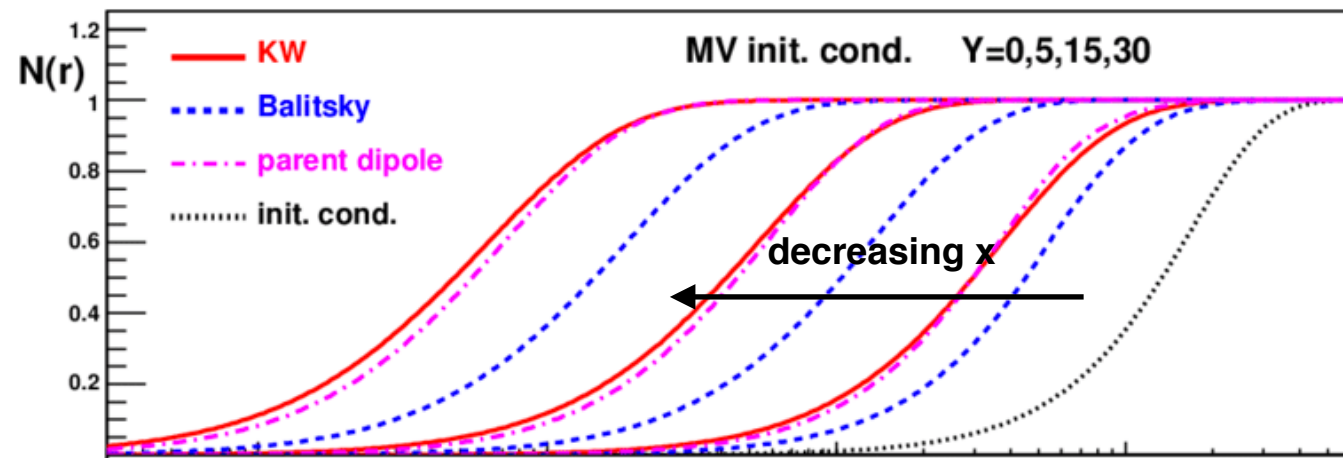
Need to non-linear evolution that includes recombination processes



$$\partial_y N(r_T) = \frac{\bar{\alpha}_s}{2\pi} \int d^2 r'_T \frac{r_T^2}{r_T'^2 (r_T - r'_T)^2} \times [N(r'_T) + N(r_T - r'_T) - N(r_T) - N(r'_T)N(r_T - r'_T)]$$

Balance between gluon emission and recombination leads to saturation of the gluon density (black disk limit $N \sim 1$)

Gluon saturation



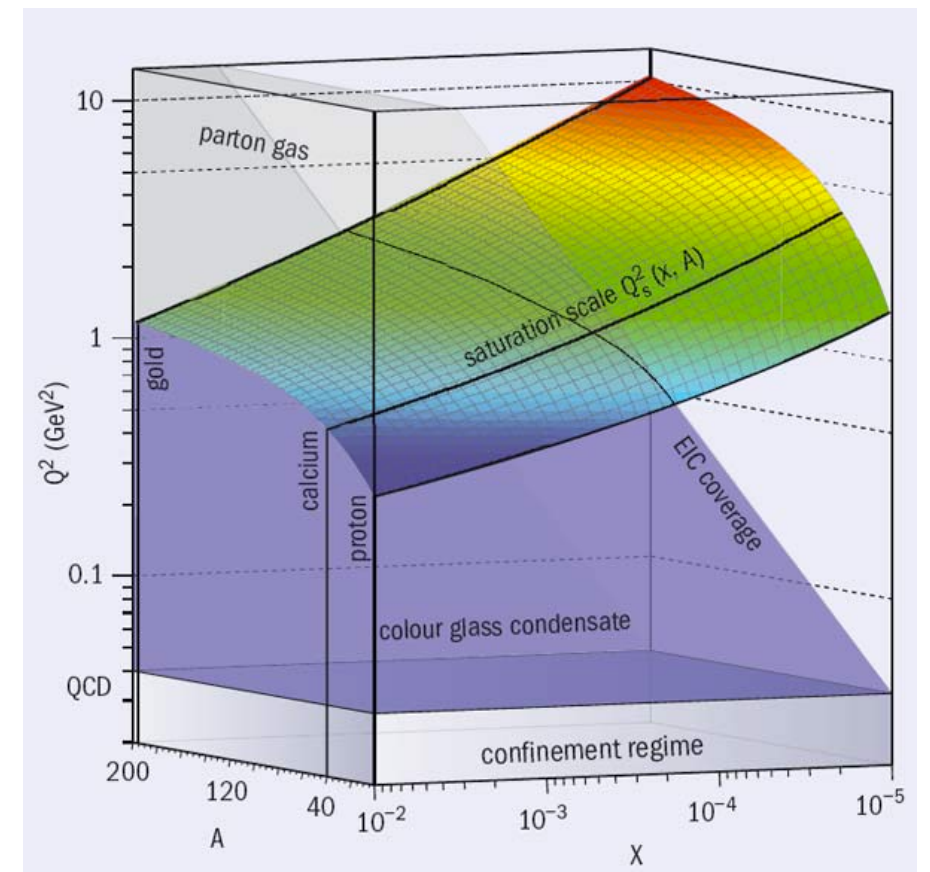
Gluon distribution saturates for $kT < Q_s$ additional radiation fills up large kT tail of gluon distribution

Emergence of a semi-hard(?) saturation scale Q_s , such that for transverse momenta $kT < Q_s$ gluon distribution is saturated

Saturation scale grows with

decreasing x : $Q_s^2(x) \sim x^{-\lambda}$

increasing atomic number A : $Q_s^2(A) \sim A^{1/3}$

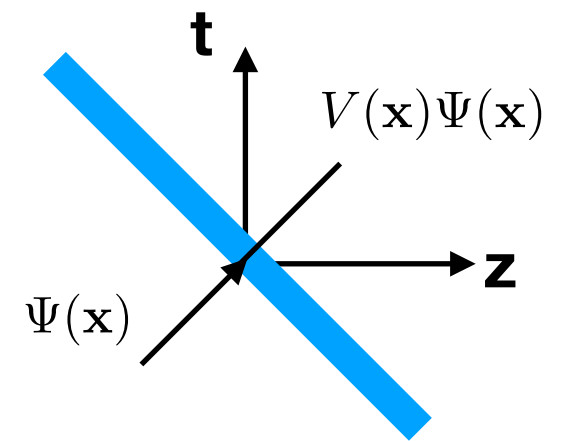


Effective theory for high-energy scattering

High-energy scattering described by eikonal propagation of color charges

Described by light-like Wilson lines (with appr. gauge)

$$V(\mathbf{x}) = \mathcal{P}_+ \exp \left[ig \int_{-\infty}^{\infty} dz^+ \int d^2\mathbf{z} G(\mathbf{x} - \mathbf{z}) \rho_a(z^+, \mathbf{z}) t^a \right].$$



which contains multiple scattering inside nuclear target

Color-Glass Condensate is an effective theory for high-energy scattering based on light-like Wilson lines

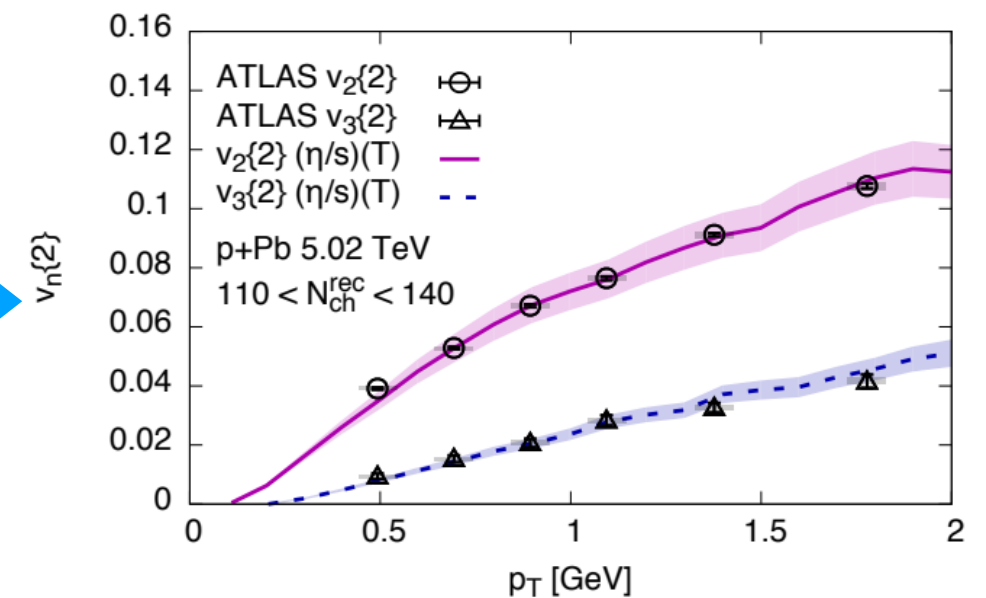
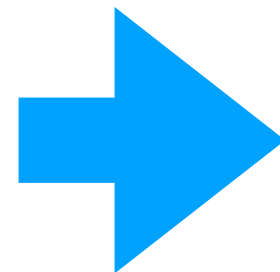
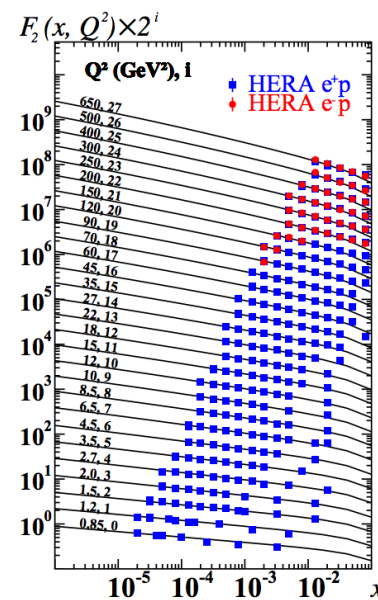
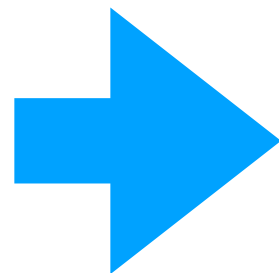
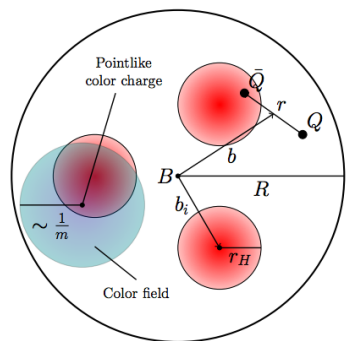
$$\langle \mathcal{O} \rangle_x = \int DV \mathcal{W}_x[V] \mathcal{O}[V]$$

Universality of CGC weight function provides description of different high-energy scattering experiments including DIS & hadronic collisions

General strategy

Generally weight function not known, though evolution with decreasing x described by small- x equation (JIMLWK)

Develop model typically at $x \sim 0.1$ and constrain parameters from fits to DIS



apply description to other collision systems such as forward p+A, A+A

IP-Sat Model

Nucleons distributed inside nucleus according to Nuclear Structure input (positions of ALL nucleons frozen during high-energy scattering)

Each nucleon contains fluctuating color-charge density concentrated around

N_q hot spots

Size of hot-spot r_H (Gaussian)

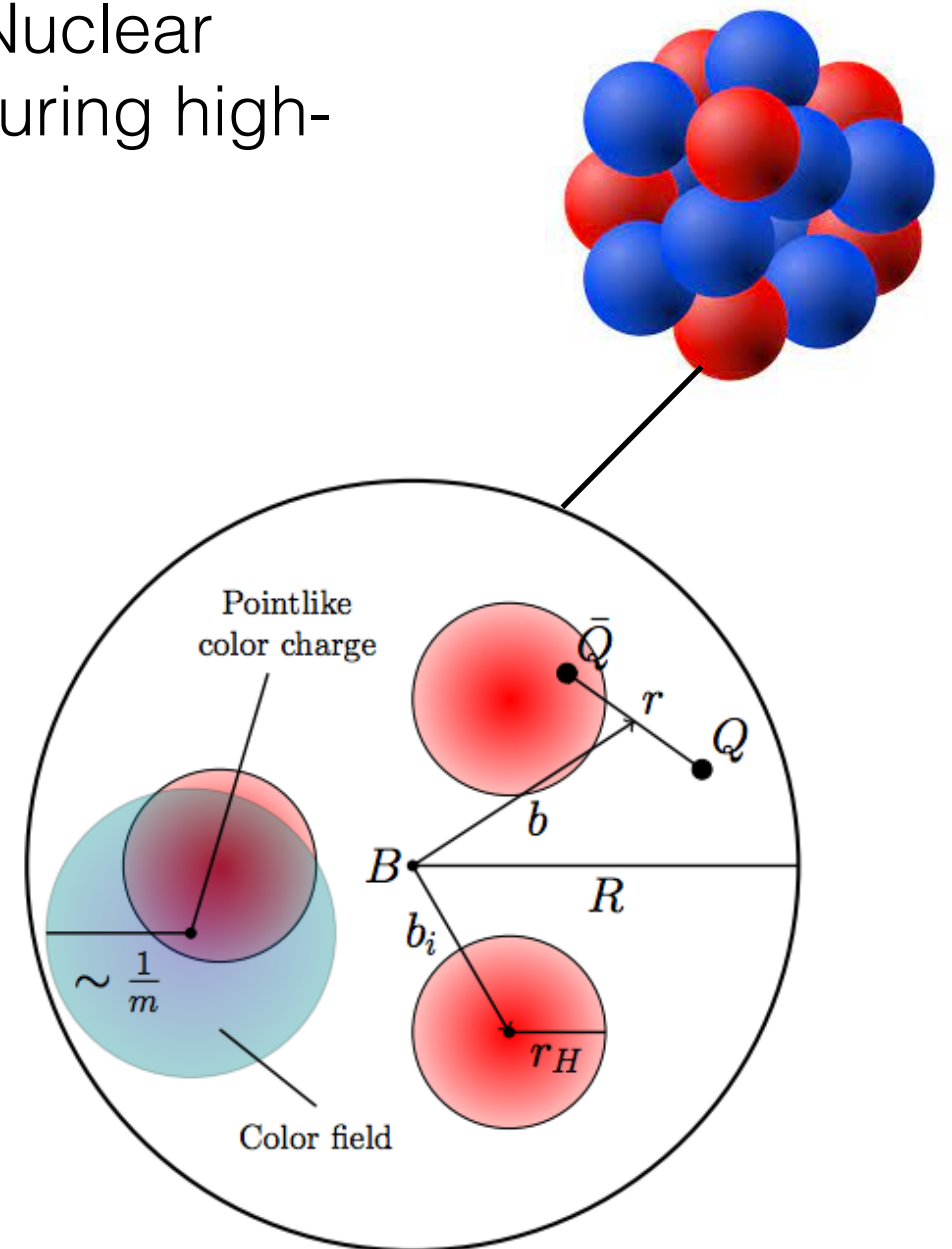
color field of each charge extends up to

IR regulator $1/m$

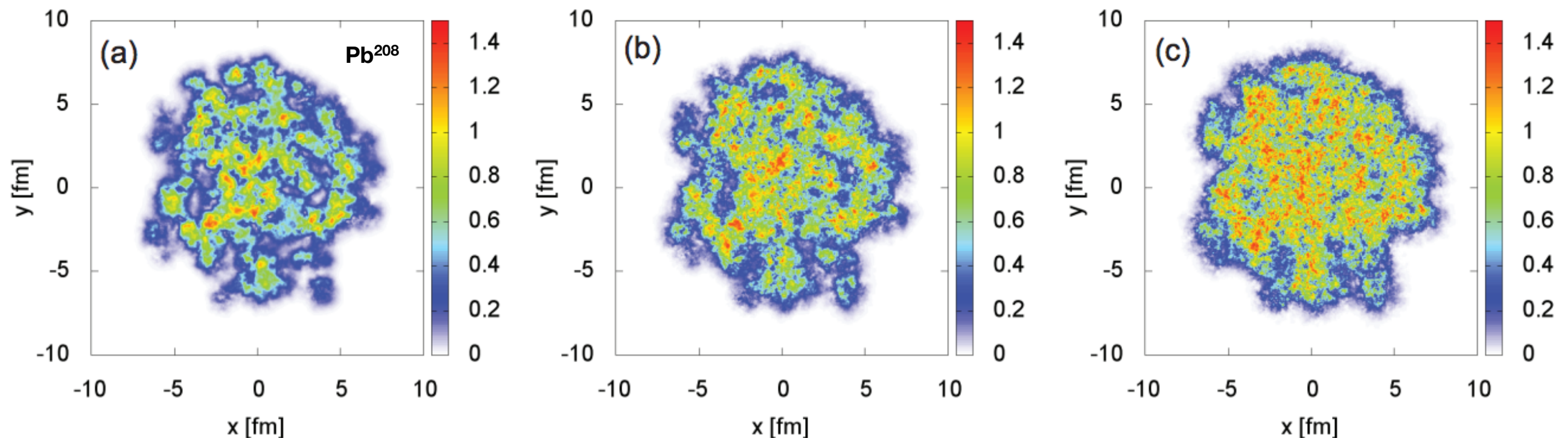
Individual hot-spots distributed within

Size R of proton (Gaussian)

different hot-spots uncorrelated, except for center-of-mass constraint



Evolution towards smaller x



Schenke, SS Phys.Rev.C 94 (2016) 4, 044907

Increase of saturation scale (“small scale structure”) perturbatively calculable

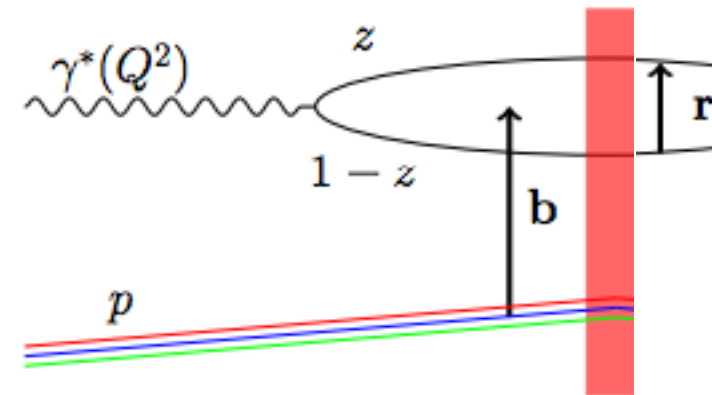
Growth of hadron/nucleus and change “large scale structure” due to Gribov diffusion, but requires modeling non-perturbative physics

Change in large scale nuclear structure observable in very forward/very high energy experiments?

Inclusive DIS

Deep inelastic scattering
of electrons off protons/nuclei

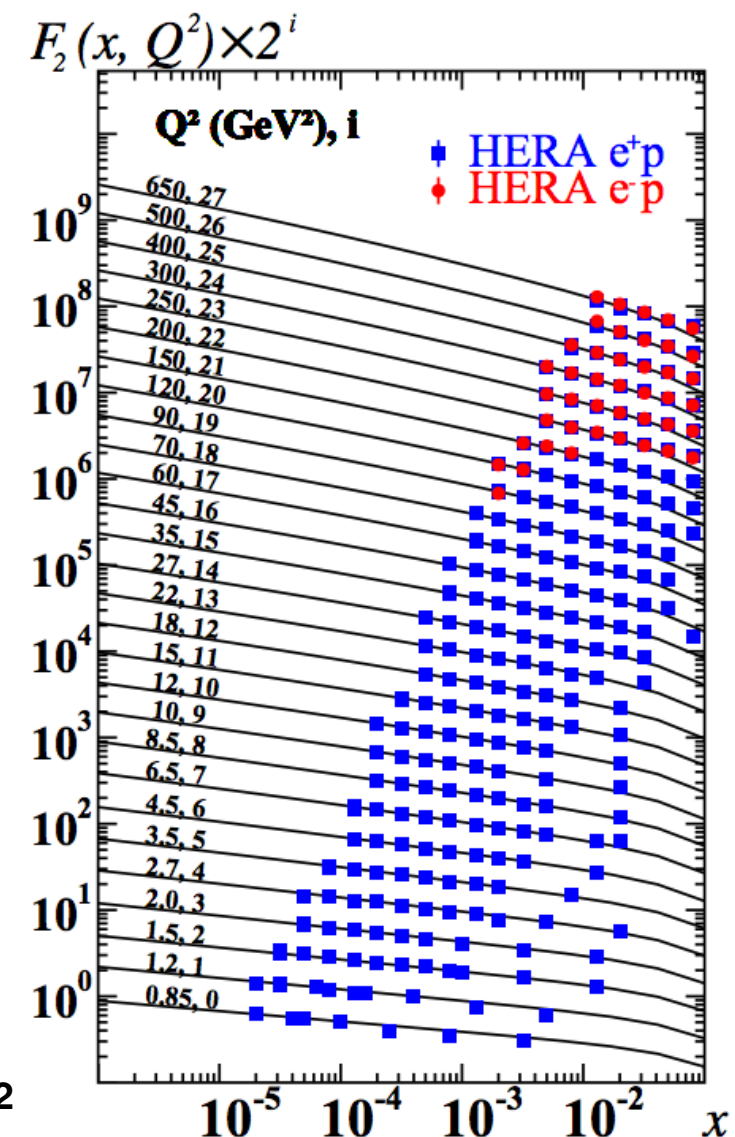
Cross-section determined by
convolution of QED part and
color dipole cross-section



$$\sigma_{L,T}^{\gamma^*p}(Q^2, x) = 2 \sum_f \int \int d^2b d^2r \int_0^1 dz |\Psi_{L,T}^{(f)}(r, z; Q^2)|^2$$

$$\frac{1}{N_c} \text{tr} [1 - V(\mathbf{b} + \mathbf{r}/2) V^\dagger(\mathbf{b} - \mathbf{r}/2)]$$

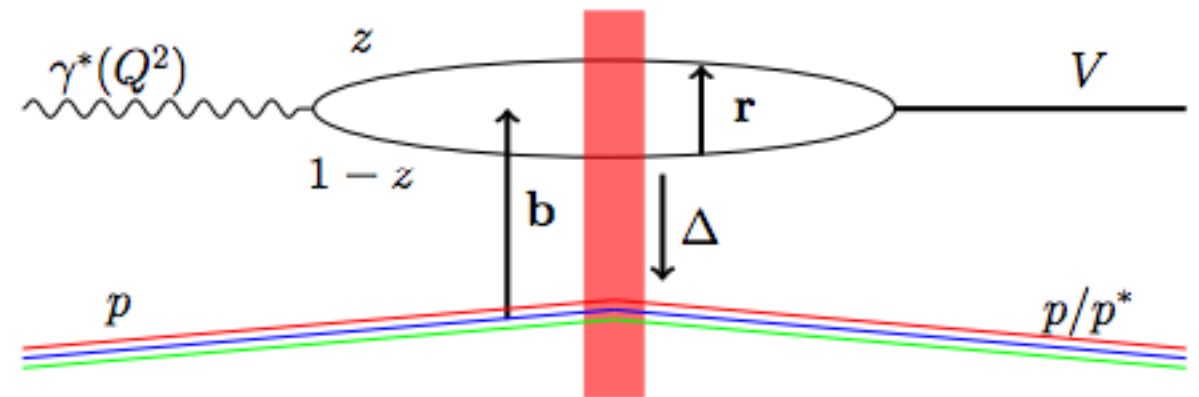
But no information on spatial geometry &
(non-perturbatively) large dipoles provide
large contribution to cross-section



Exclusive Vector-Meson production in DIS

Exclusive production of QQ
vector meson in $\gamma^* + p \rightarrow J/\psi + p^{(*)}$

Scattering amplitude at LO
in small-x limit given by



$$\mathcal{A}_{T,L}^{\gamma^* p \rightarrow V p}(Q^2, \Delta) = i \int d^2 \mathbf{r} \int d^2 \mathbf{b} \int \frac{dz}{4\pi} (\Psi^* \Psi_V)_{T,L}(Q^2, \mathbf{r}, z) \exp \left\{ -i \left[\mathbf{b} + \left(\frac{1}{2} - z \right) \mathbf{r} \right] \cdot \Delta \right\} \frac{d\sigma_{\text{dip}}^p}{d^2 \mathbf{b}}(\mathbf{b}, \mathbf{r}).$$

Distinguish **coherent**/**incoherent** production $\frac{d\sigma_{\text{dip}}^p}{d^2 \mathbf{b}}(\mathbf{b}, \mathbf{r}) = 2 \frac{1}{N_c} \text{tr} [1 - V(\mathbf{b} + \mathbf{r}/2) V^\dagger(\mathbf{b} - \mathbf{r}/2)]$

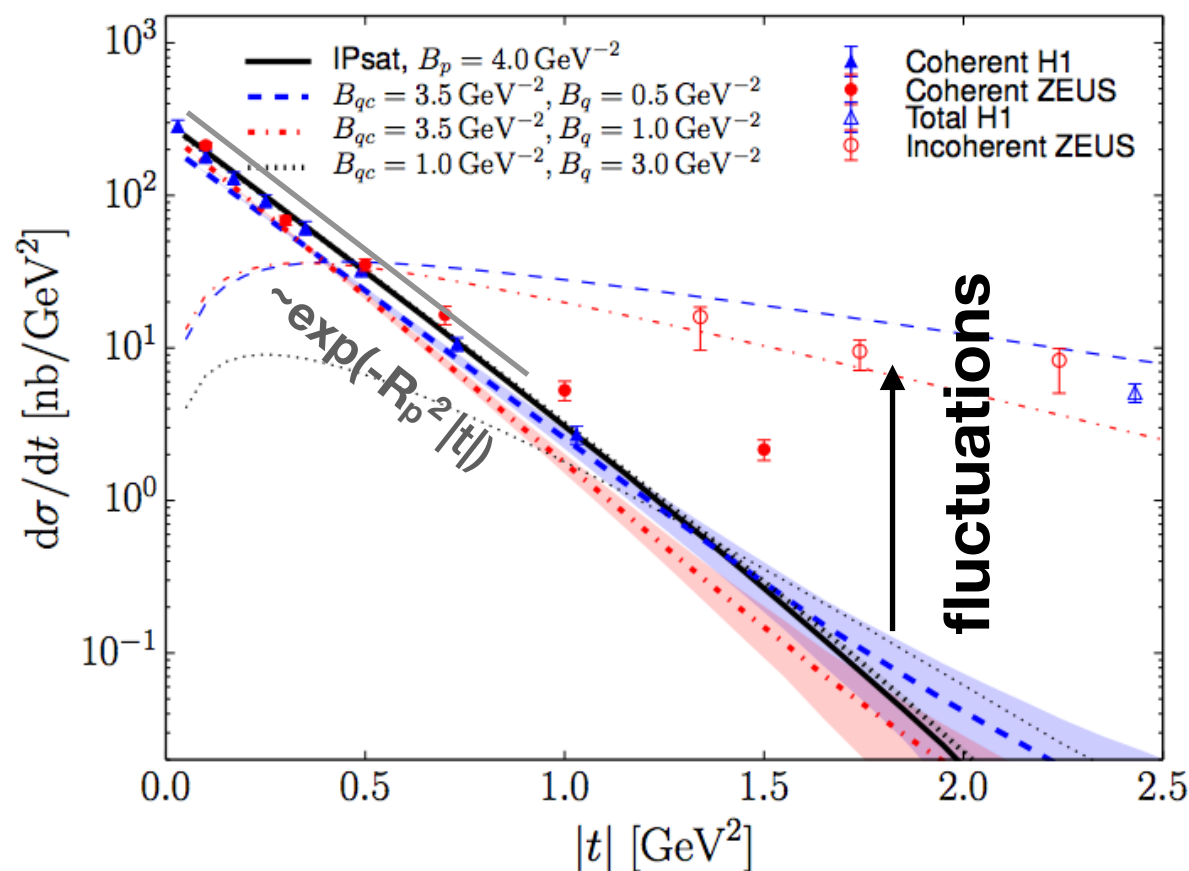
$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow V p}}{dt} = \frac{1}{16\pi} |\langle \langle \mathcal{A}_{T,L}^{\gamma^* p \rightarrow V p}(Q^2, \Delta) \rangle \rangle|^2$$

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow V p^*}}{dt} = \frac{1}{16\pi} \left(\langle \langle |\mathcal{A}_{T,L}^{\gamma^* p \rightarrow V p}(Q^2, \Delta)|^2 \rangle \rangle - |\langle \langle \mathcal{A}_{T,L}^{\gamma^* p \rightarrow V p}(Q^2, \Delta) \rangle \rangle|^2 \right).$$

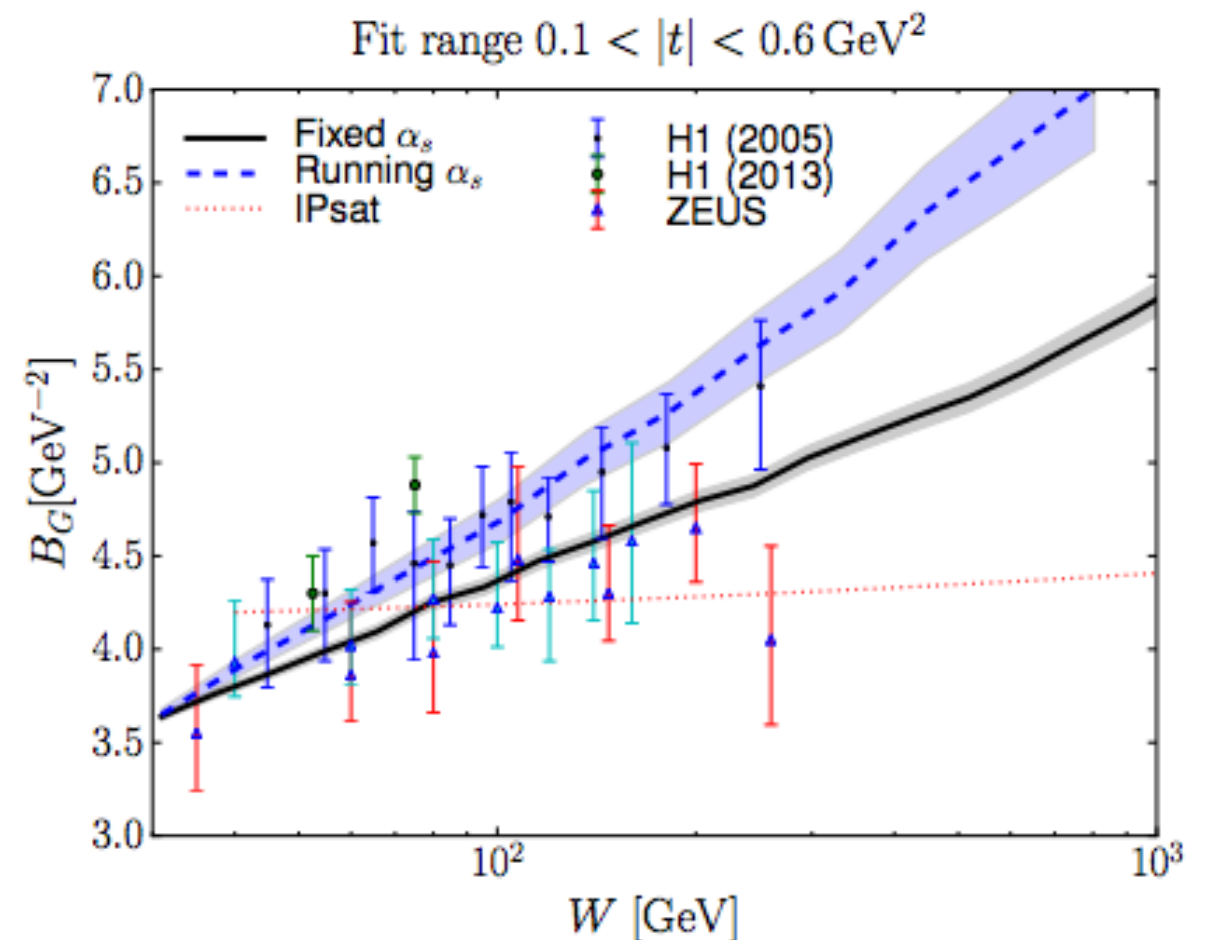
which probe directly **average**/**fluctuations** of dipole cross section

Exclusive Vector-Meson production in DIS

Explored for protons with DIS (HERA, future EIC) and UPCs at RHIC and LHC



Mäntysaari, Schenke Phys.Rev.Lett. 117 (2016) 5, 052301

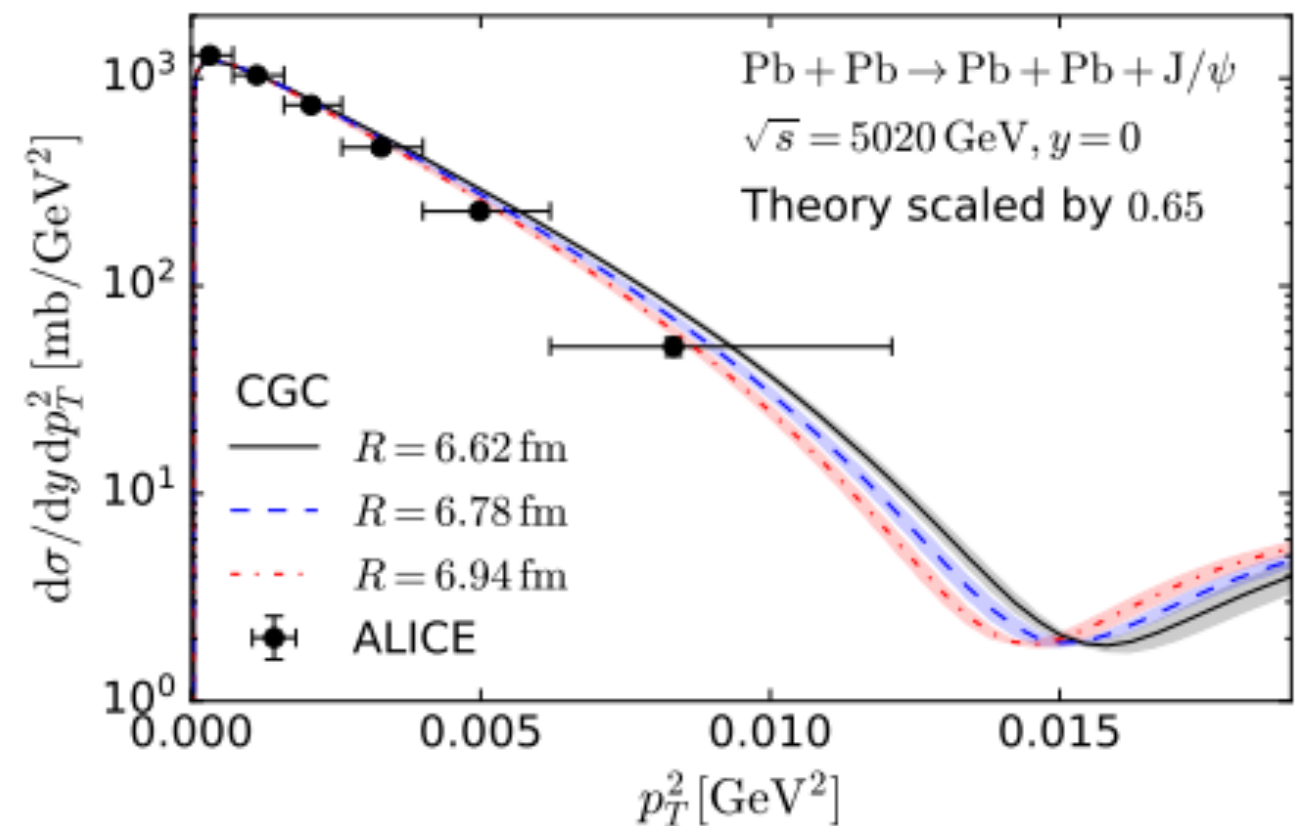
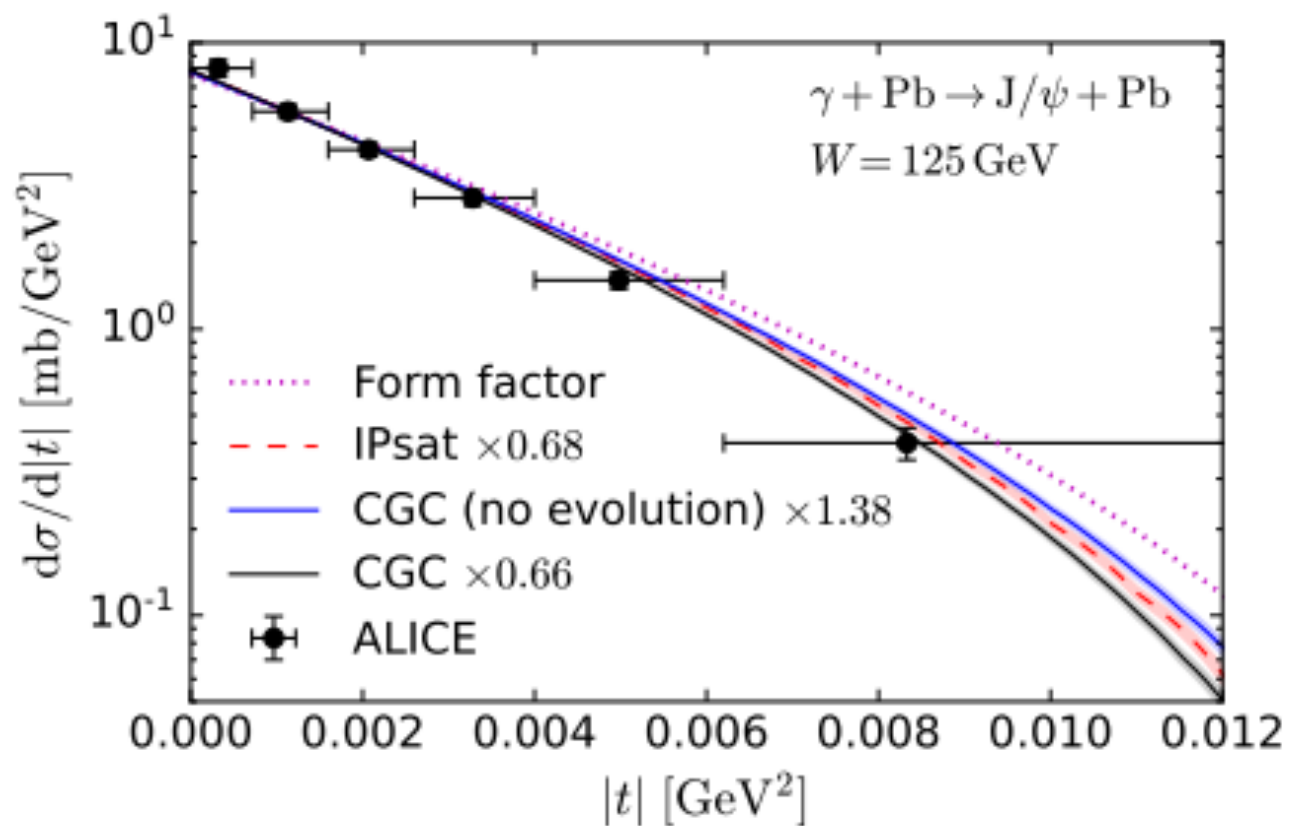


Mäntysaari, Schenke Phys.Rev.D 98 (2018) 3, 034013

Size of proton tightly constrained from coherent data; Shape fluctuations of the proton essential to describe incoherent cross-section; Hints at energy dependence of proton size due to small-x evolution

Exclusive Vector-Meson production in DIS

Explored for nuclei within UPCs at RHIC and LHC

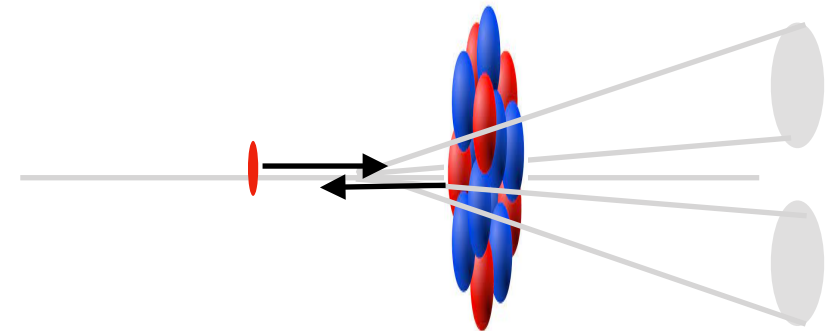


Mäntysaari, Salazar, Schenke arXiv:2207.03712

Effect of nuclear deformation in exclusive J/Psi in e+A scattering at EIC?

Hybrid factorization in forw. p+A collisions

Small x in nucleus accessed by forward di-jet production in p+A collisions

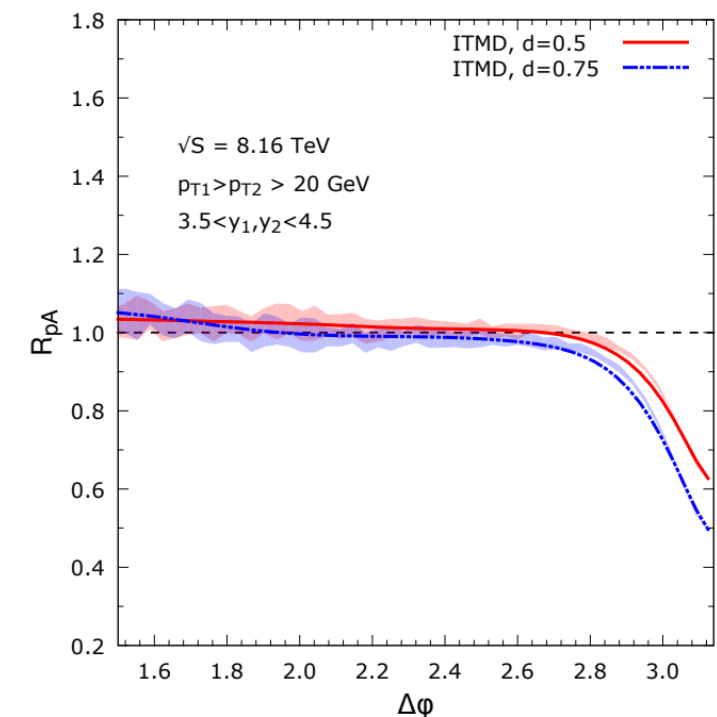


Hybrid factorization

Dumitru, Jalilian-Marian PLB 89 (2002) 022301

$$\frac{d\sigma^{pA \rightarrow hX}}{dy d^2k_t d^2b} = \int dx \frac{dz}{z^2} q(x, Q_f^2) \frac{d\sigma_{qA}^{tot}}{dy_q d^2q_t d^2b} D_{q/h}(z, Q_f^2) .$$

De-correlation of back-to-back dijets due to multiple scattering in the nucleus, in addition to hard production process



Marquette NPA 796 (2007); Lappi, Mäntysaari NPA 908 (2013) 51-72

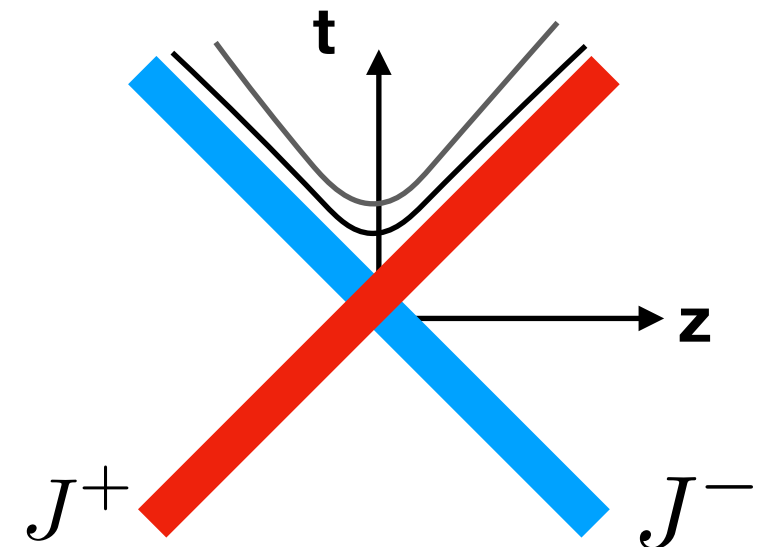
v. Hameren, Kotko, Kotko, Kutak, Marquet, Petreska, JHEP 12 (2016) 034, JHEP 02 (2019) 158 (erratum)

So far studies average over all impact parameters not including multiplicity selection, which could be handled within same framework to enhance nuclear effects

Heavy-Ion collisions

Described at LO by solving classical Yang-Mills equations in the presence of eikonal color currents of two nuclei

$$D_\mu F^{\mu\nu} = J^\nu$$



Energy deposition directly after the collision proportional to product of parton fluxes

Lappi, SS, PRD 97 (2018) 3, 034034

$$e(\mathbf{x}) \sim Q_A^2(\mathbf{x})Q_B^2(\mathbf{x}) \sim T_A(\mathbf{x})T_B(\mathbf{x})$$

Changes during formation time (e.g. in GBW model)

$$e_0(\mathbf{x}) \sim \frac{Q_{s,A}^2 Q_{s,B}^2}{(Q_{s,A}^2 + Q_{s,B}^2)^{5/2}} [2Q_{s,A}^4 + 7Q_{s,A}^2 Q_{s,B}^2 + 2Q_{s,B}^4]$$

Borghini, Borrell, Feld, Roch, SS, Werthmann arXiv:2209.01176

Early-time dynamics of equilibration changes profile

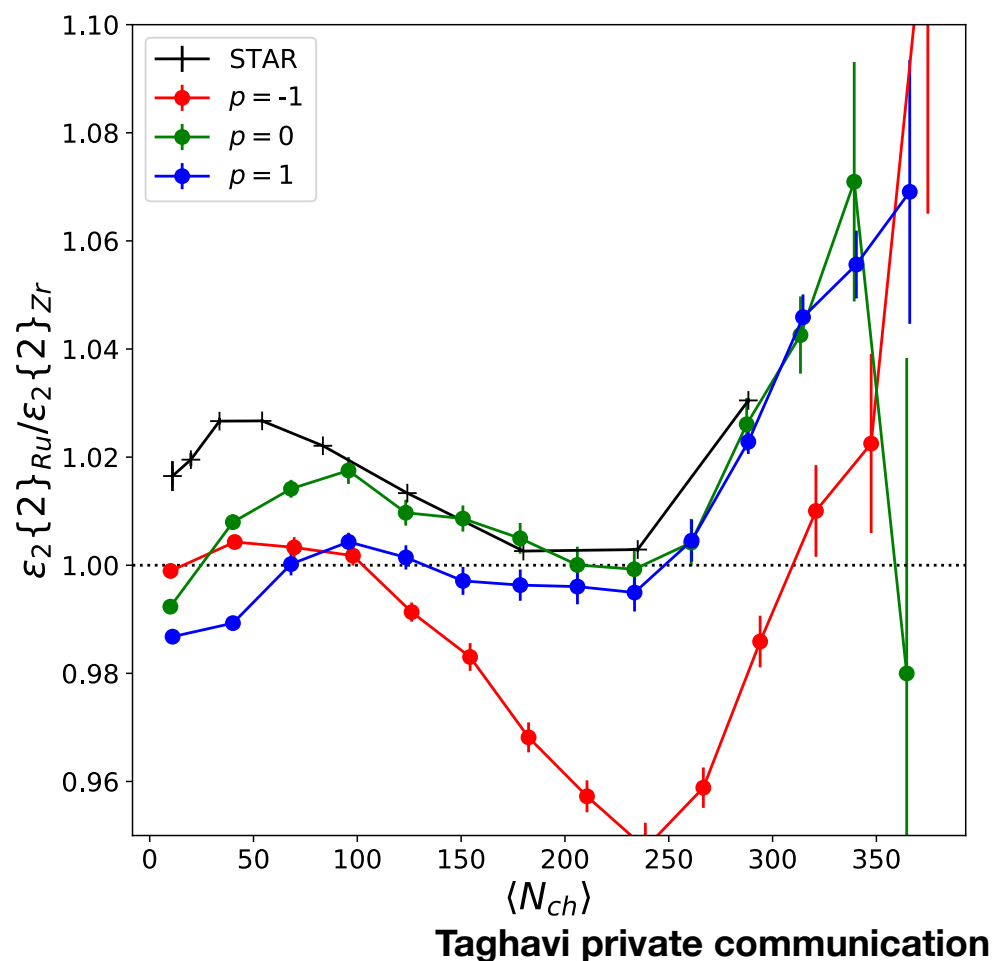
$$e_{\text{Hydro}}(\mathbf{x}) \sim e_0(\mathbf{x})^{8/9}$$

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

provides initial conditions for subsequent hydrodynamic evolution

Heavy-Ion collisions

Note that many Heavy-Ion models do not make use of theoretical formalism but instead choose to parametrize initial energy deposition

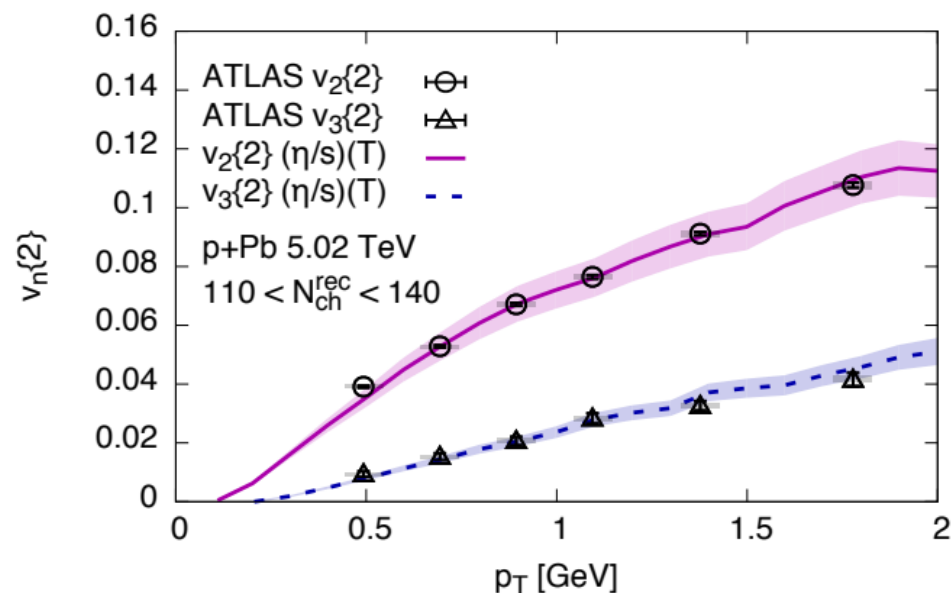


TrENTo parametrization

$$\epsilon(\mathbf{x}) \sim \left(\frac{T_A^p(\mathbf{x}) + T_B^p(\mathbf{x})}{2} \right)^{1/p}$$

Energy deposition formula has an effect on relative geometry of isobaric collisions

Heavy-Ion collisions

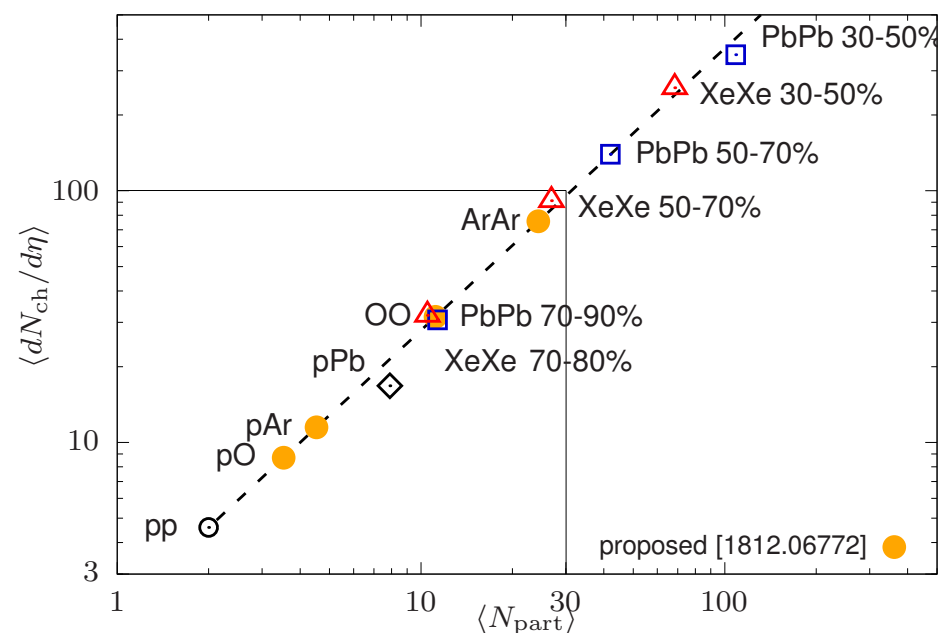


Mäntysaari, Schenke, Shen, Tribedy, PLB 772 (2017) 681-686

Effects of non-trivial proton geometry essential for description of flown p+A collision

Not clear if Hydrodynamics quantitatively accurate for p+A

Heavy-Ion phenomenology can not properly distinguish geometry (e_2) and magnitude of response ($v_2 \sim k_{22} e_2$)



Mazeliauskas talk at Initial State 2021

Crucial test in upcoming $O_{16}+O_{16}$ where medium properties are similar to high mult. p+A but geometry is (well?) constrained from nuclear structure