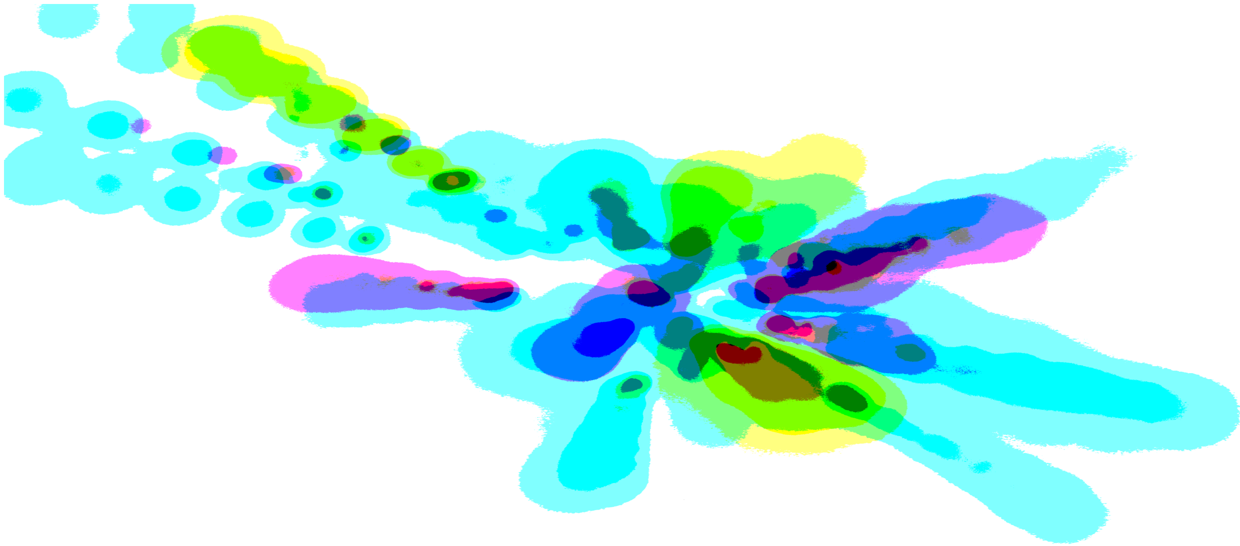
The physics of gluon saturation

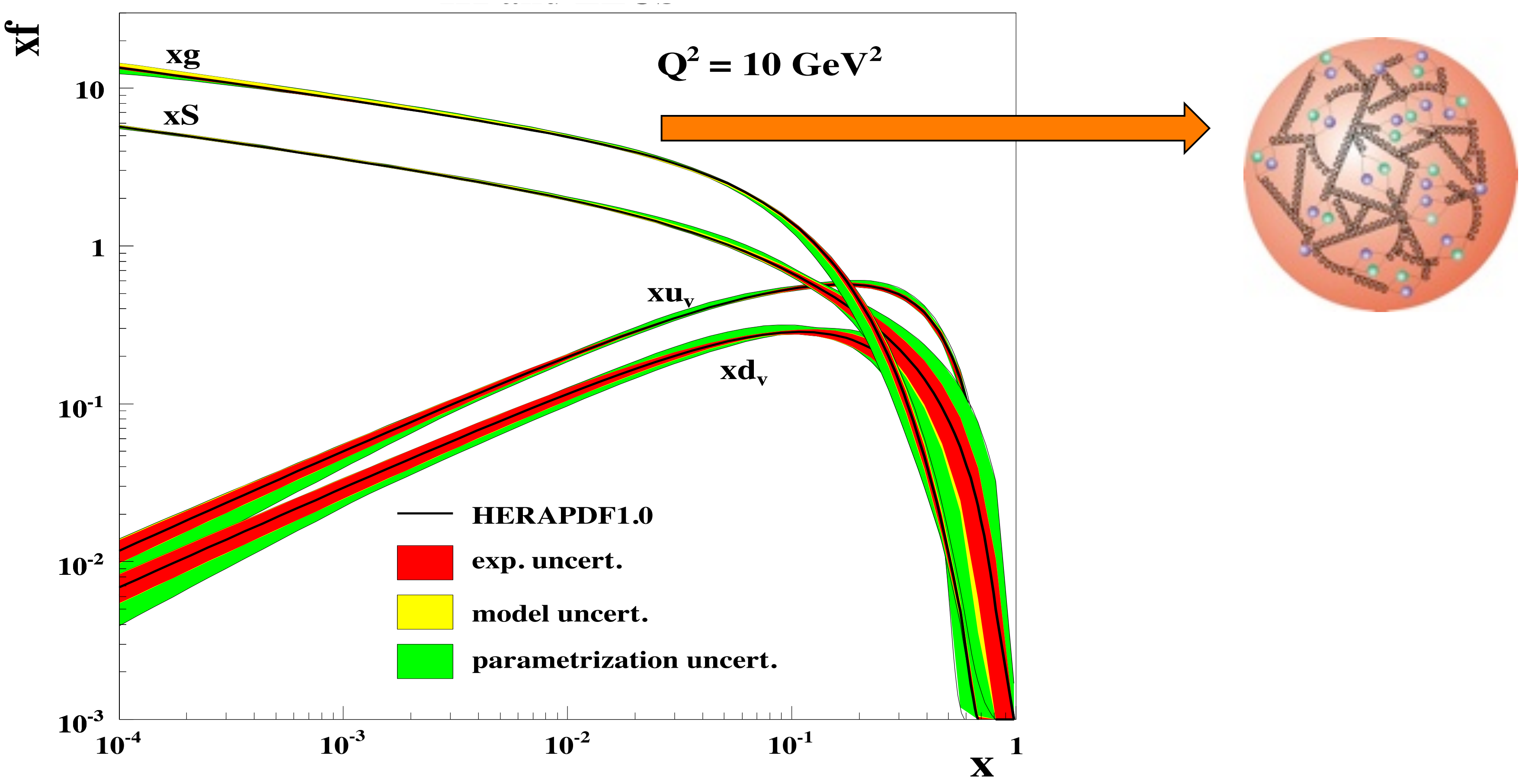


Raju Venugopalan

Brookhaven National Laboratory

EIC Users Group Meeting, Trieste, July 18-22nd, 2017

The proton: a complex many-body system

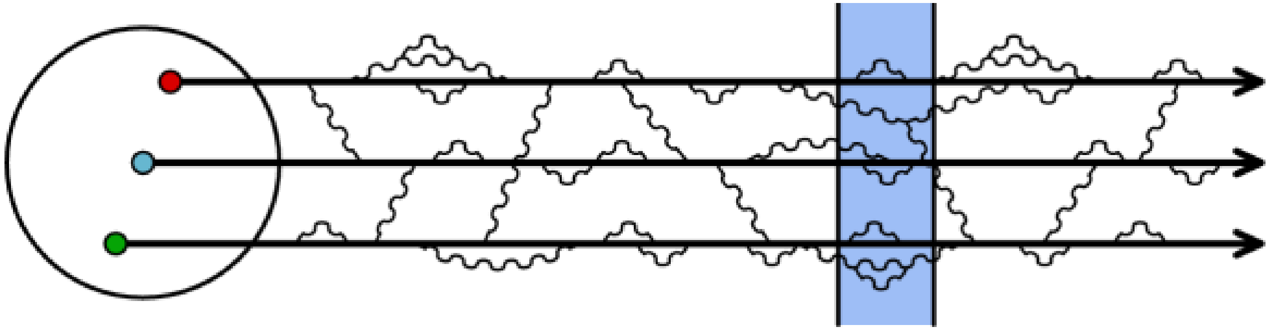


A key lesson from the HERA DIS collider:

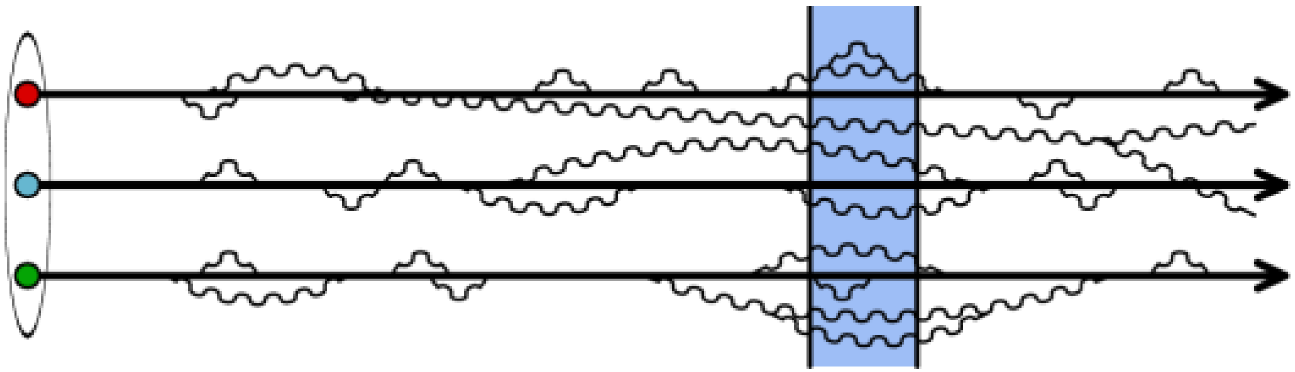
gluons and sea quarks dominate the proton wave-function at high energies

Boosting the proton uncovers many-body structure

Low Energy
(or large x)



High Energy
(or small x)



Wee parton fluctuations time dilated on strong interaction time scales

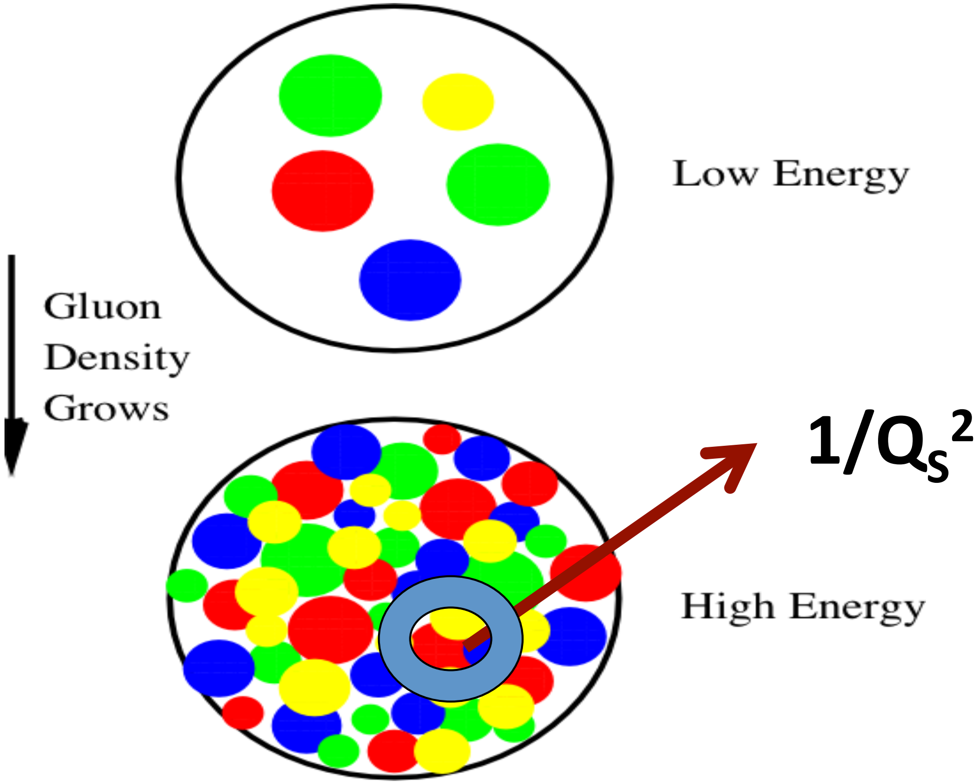
Long lived gluons can radiate further small x gluons…

Is the proton a runaway popcorn machine at high energies ?

The runaway proton…

Nature does not like this!

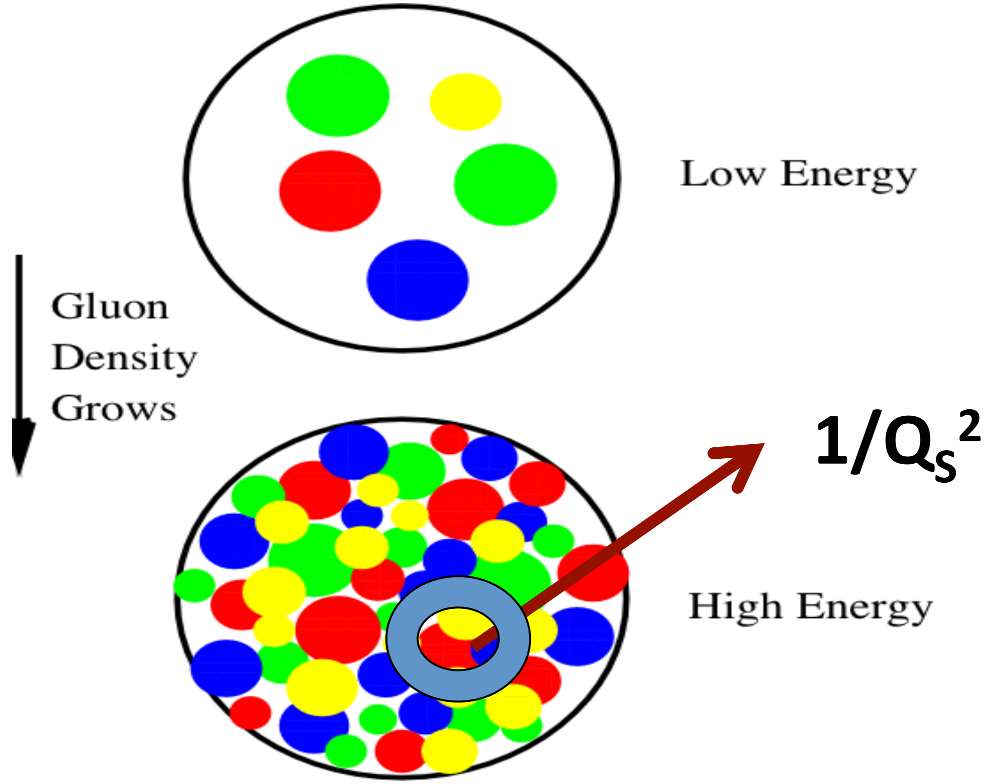
The boosted proton viewed head-on



When their occupancies become very large ~ $1/\alpha_S$,
gluons resist further close packing -- by recombining and screening their color charges -- leading to gluon saturation

Characterized by an emergent scale Q_S
-- rigorous in the Regge-Gribov limit of QCD

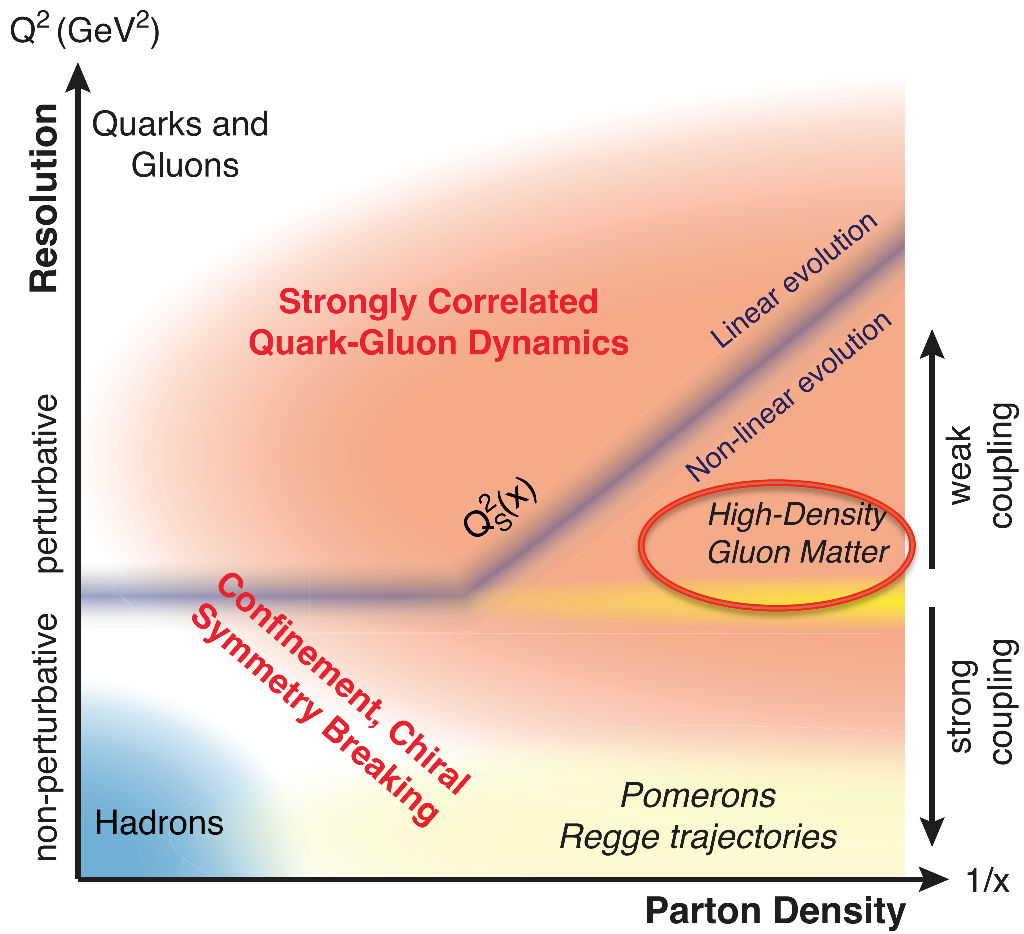
The boosted proton viewed head-on



The corresponding Chromo-Electric and Chromo-Magnetic fields are amongst the strongest in nature

$$E^2 \sim B^2 \sim Q_S^4/\alpha_S$$

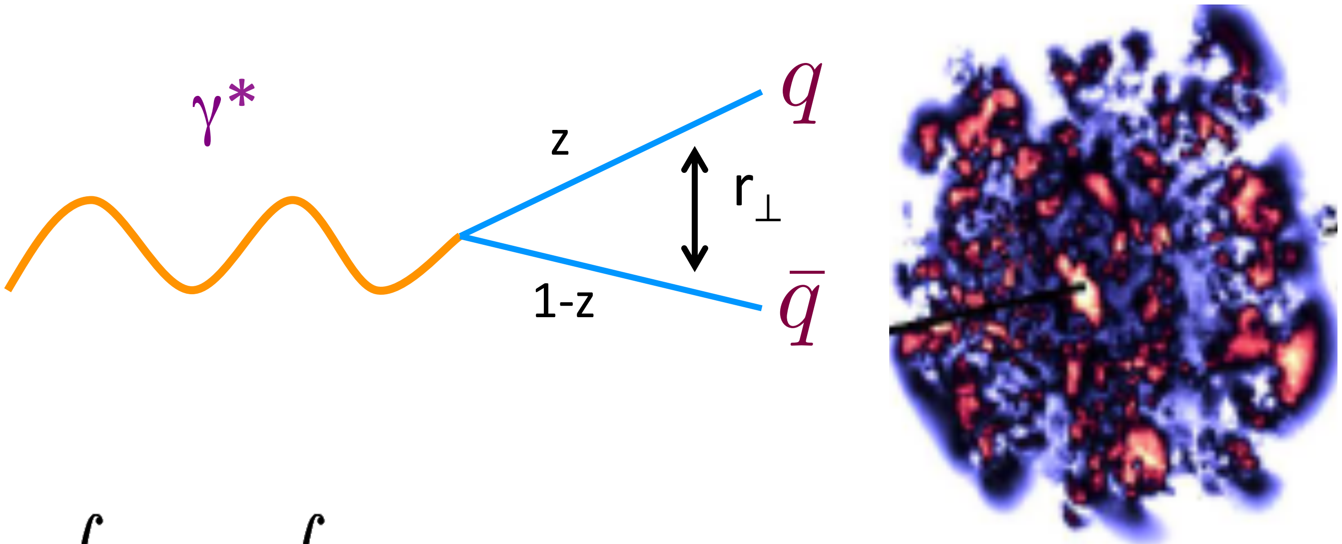
Saturation in the QCD landscape



Unique and controlled *dynamical* exploration of a fully nonlinear regime of quantum field theory

Theory framework: the Color Glass Condensate

Saturation: dipole model formulation in DIS



$$\sigma^{\gamma^*,P}_{\mathrm{T,L}} = \int d^2 r_\perp \int dz \, |\psi_{\mathrm{T,L}}(r_\perp, z, Q^2)|^2 \, \sigma_{q,\bar{q},P}(r_\perp, x)$$

Golec-Biernat Wusthoff model

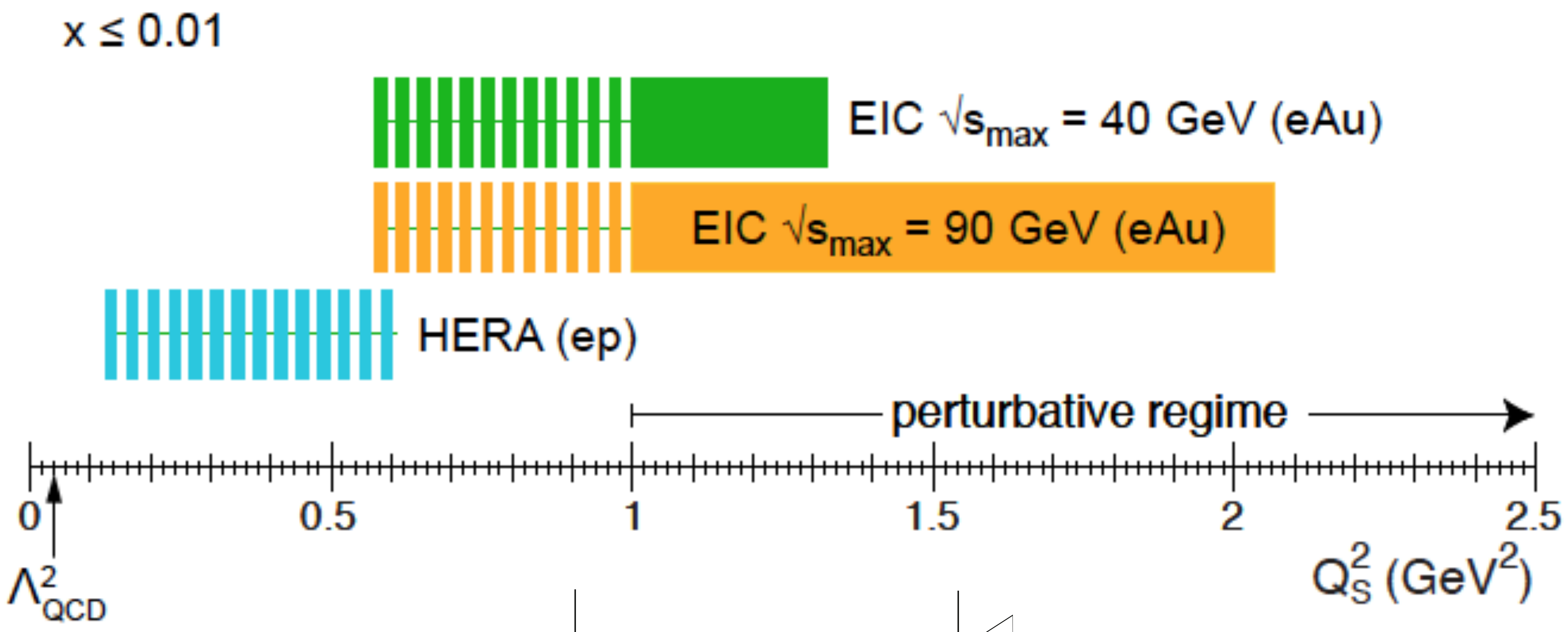
$$\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2 \, Q_s^2(x)\right)\right]$$

$$\boxed{Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda}$$

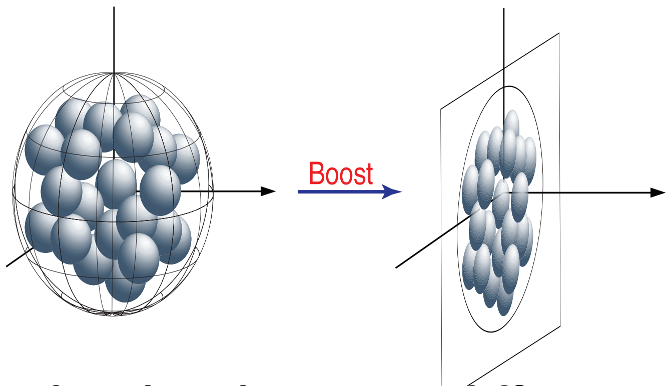
Parameters:
Q_0 = 1 GeV; λ = 0.3;
x_0 = 3* 10^{-4}; σ_0 = 23 mb

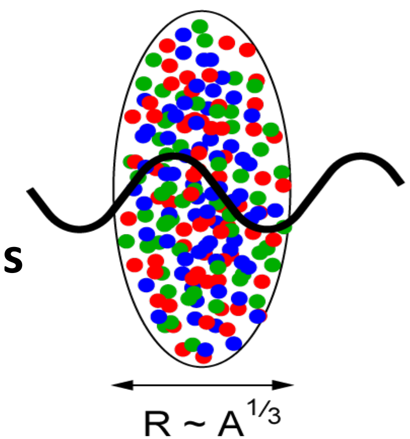
Sophisticated dipole models
give excellent fits to all HERA small x data

Saturation scale from dipole model fits to DIS data



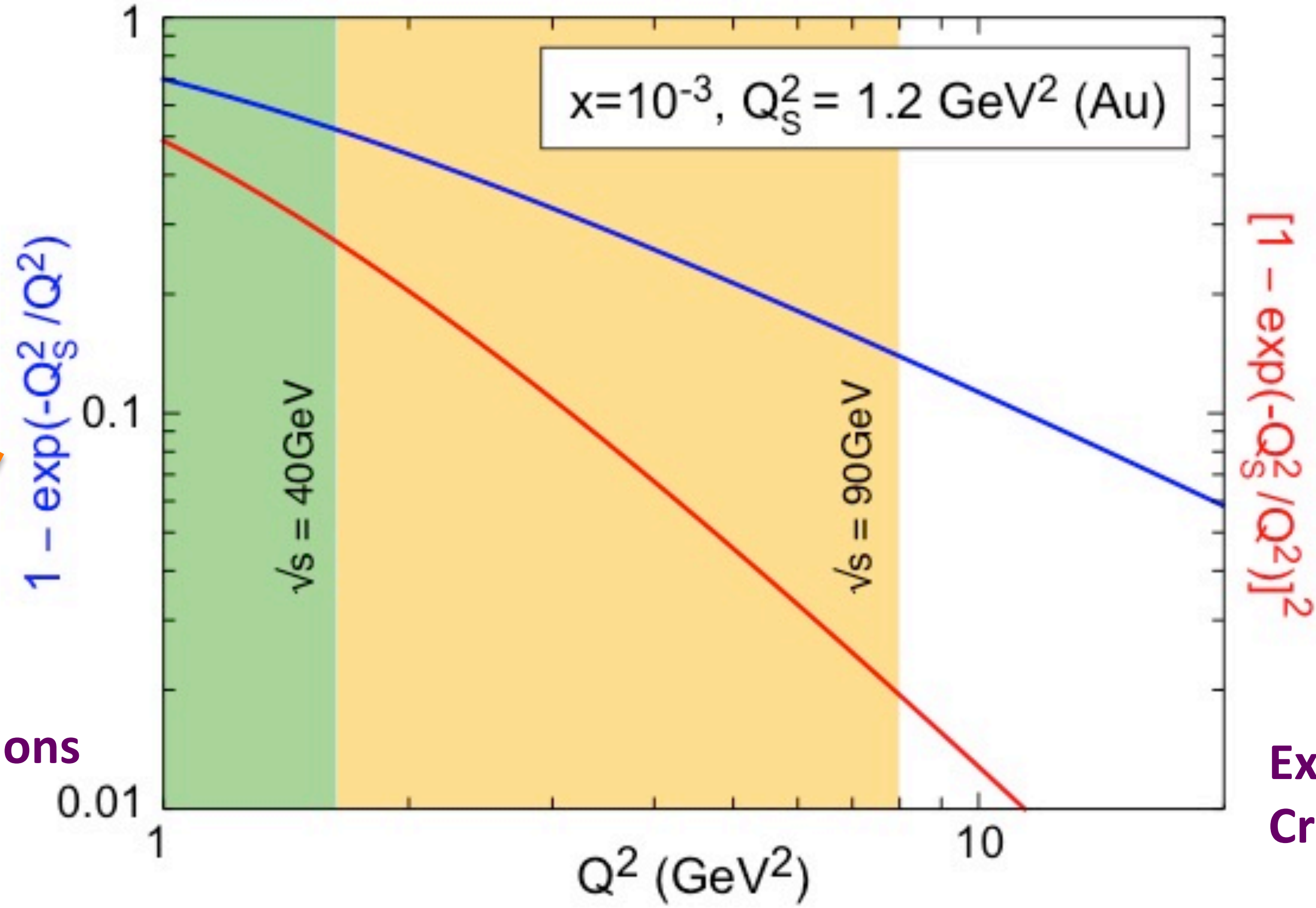
Big nuclear oomph:





dipole couples coherently with color charges in different nucleons in path of its scattering: $Q_S^2 \sim A^{1/3}$

Nonlinear response of saturated matter to probes

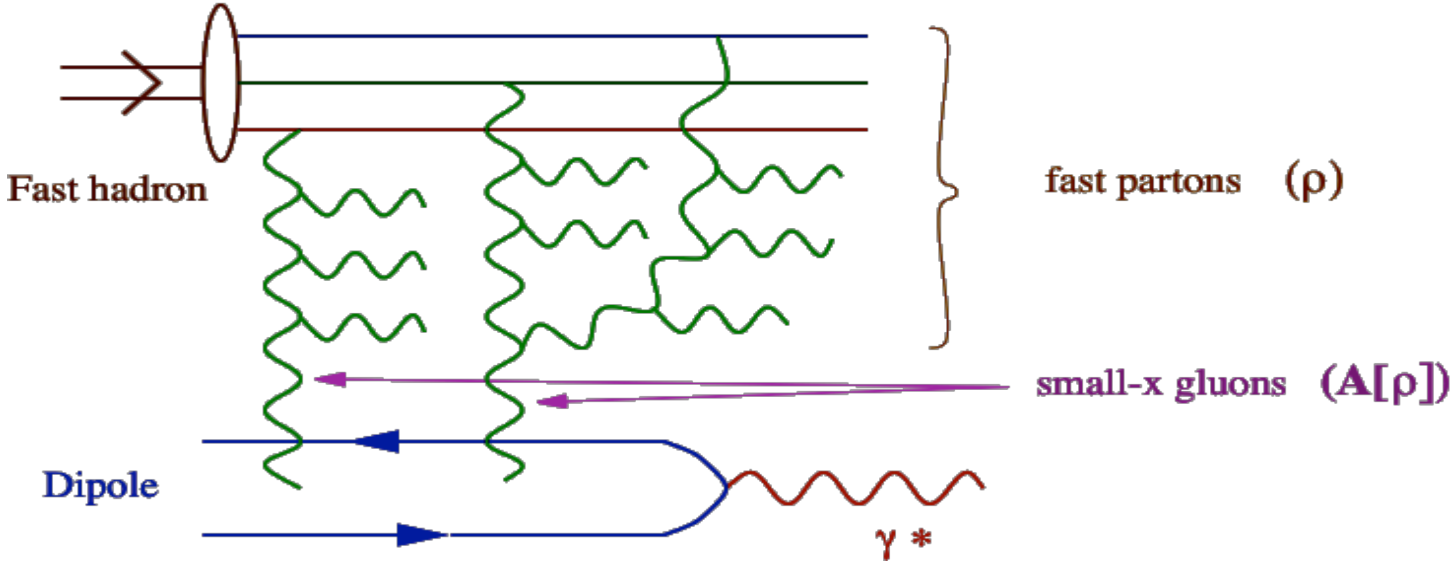


Inclusive Cross-Sections

Exclusive Cross-Sections

Varying both x and Q^2 essential to see nonlinear response of saturated gluons - a clear manifestation of the fully nonlinear character of QCD

CGC Effective Theory:B-JIMWLK hierarchy of many-body correlators



$$\frac{\partial}{\partial Y} < O[\alpha] >_Y = < \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] >_Y$$

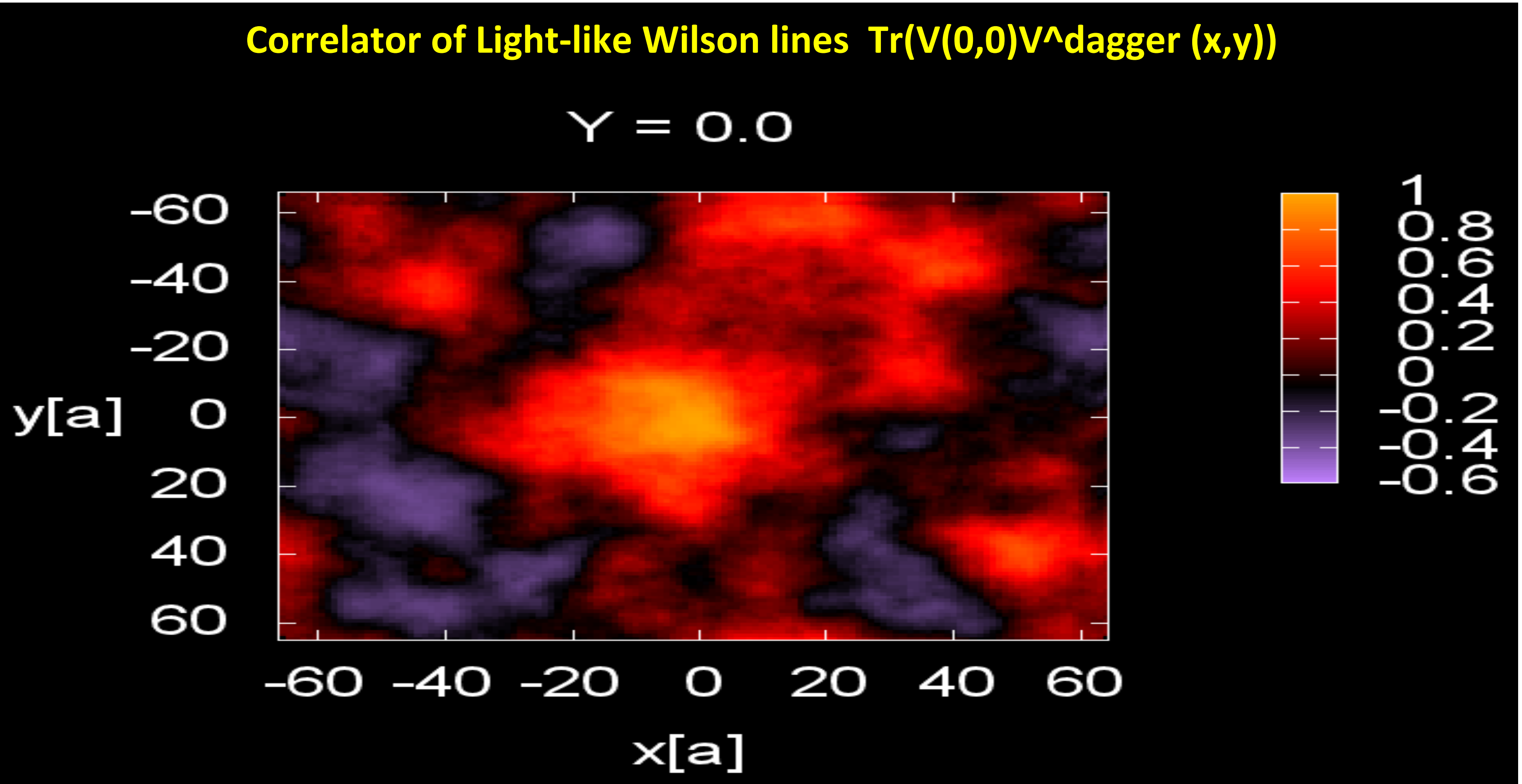
"time"

"diffusion coefficient"

Diffusion of the fuzz of "wee" partons in the functional space of colored fields

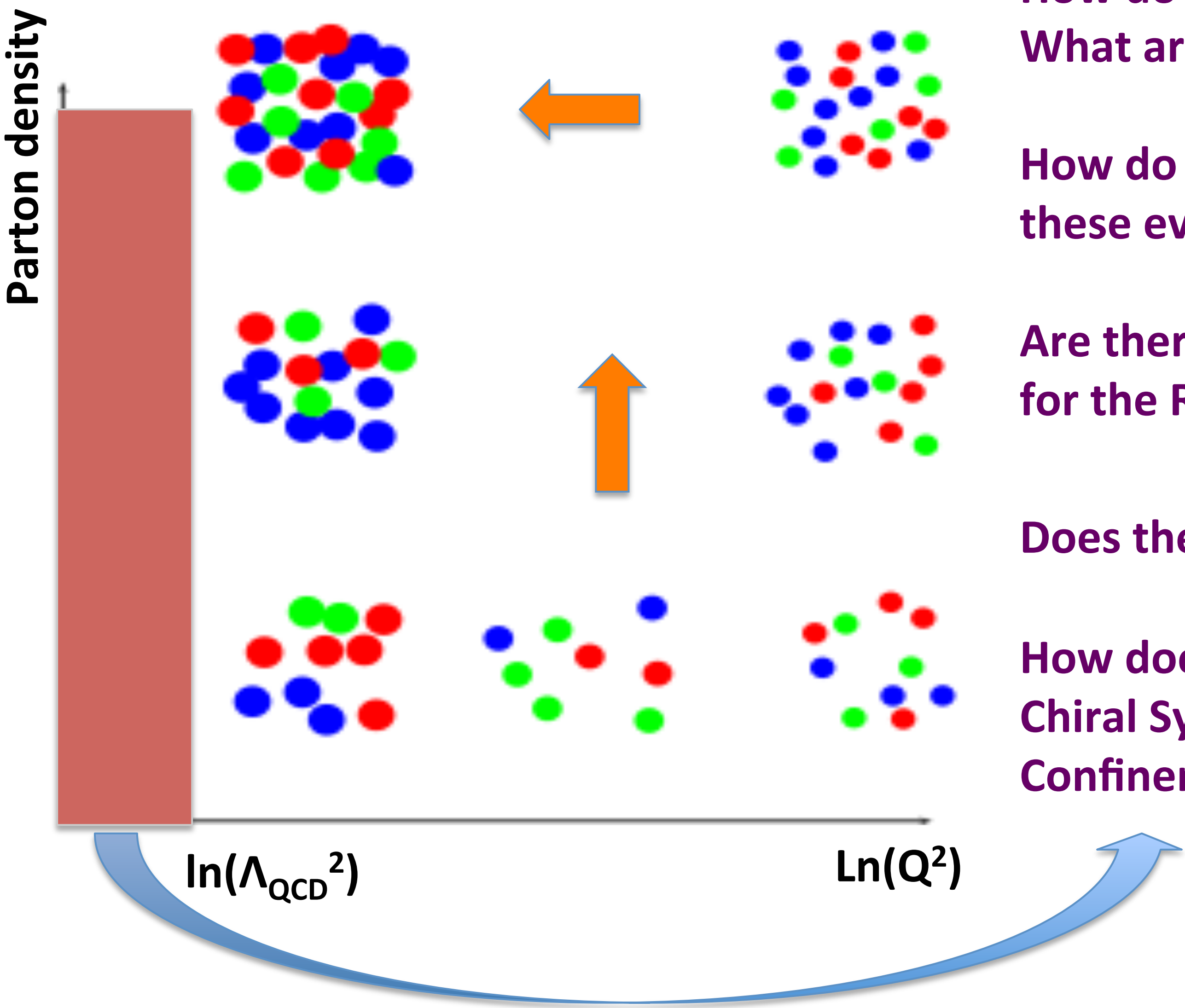
Can be solved numerically to "leading logs in x" accuracy.
Considerable ongoing work at NLO…

Glue probed by the the quark-antiquark femtoscope



Typical size of the blobs at a given time is the inverse saturation scale

Intricate dance of color across the QCD landscape



How do these transitions occur?
What are the degrees of freedom?

How do correlation functions of these evolve?

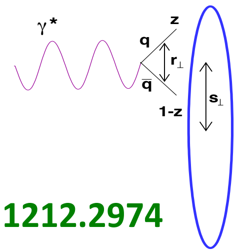
Are there universal fixed points for the RG evolution of d.o.f

Does the coupling run with Q_s^2 ?

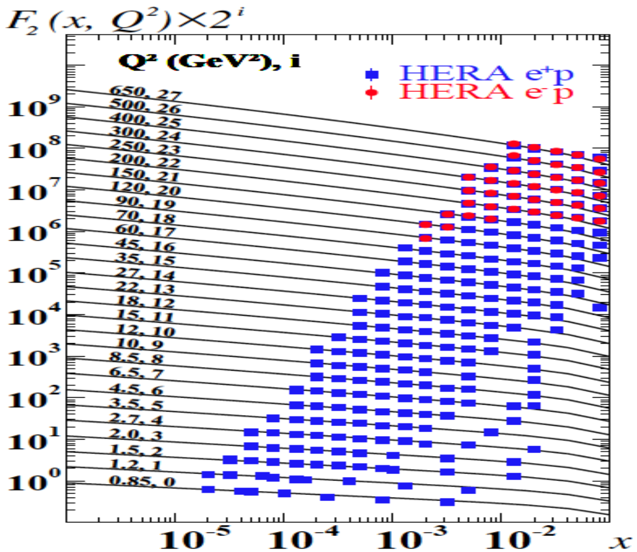
How does saturation transition to Chiral Symmetry Breaking and Confinement?

What is the evidence for gluon saturation?

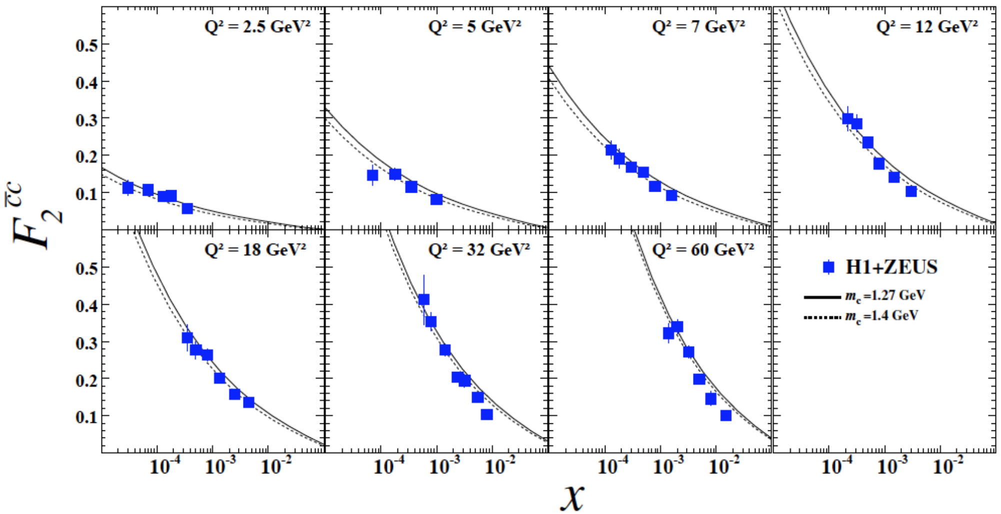
DIS off the proton



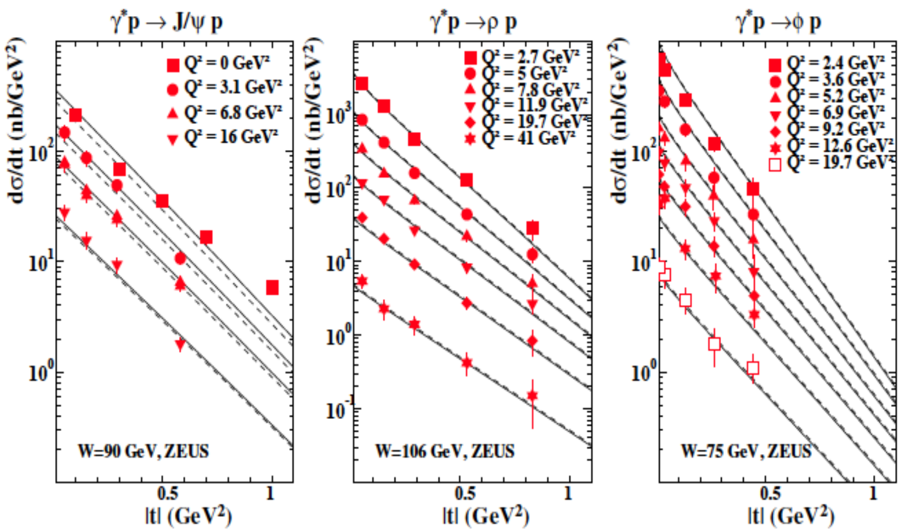
Inclusive distributions

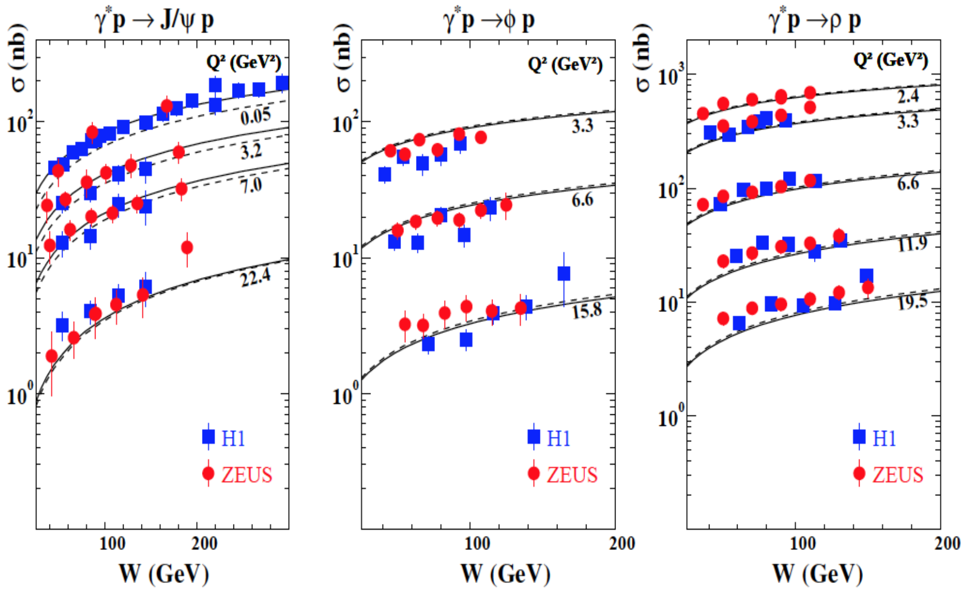


Rezaiean,Siddikov,Van der Klundert,RV:1212.2974

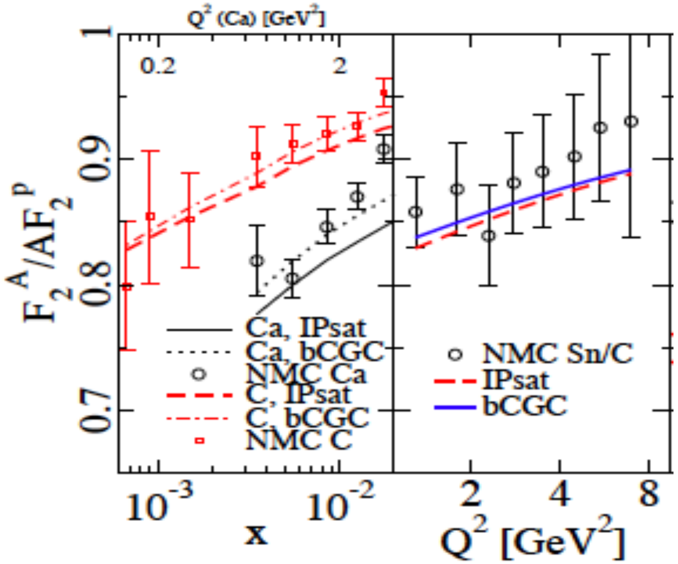


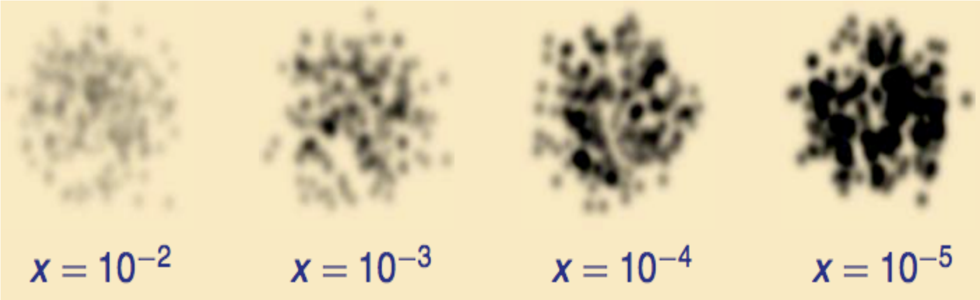
Exclusive distributions





DIS off nuclei

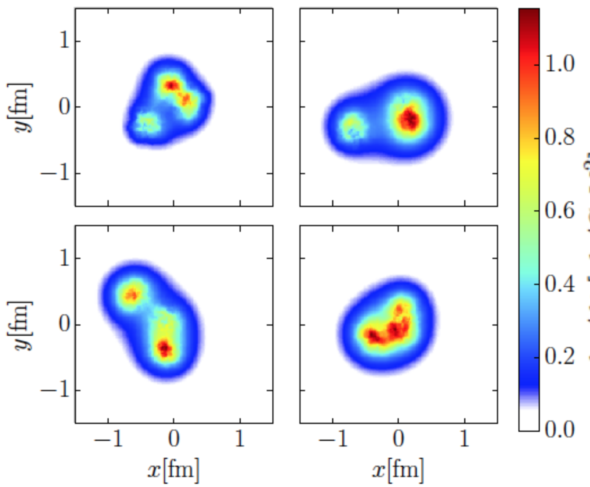


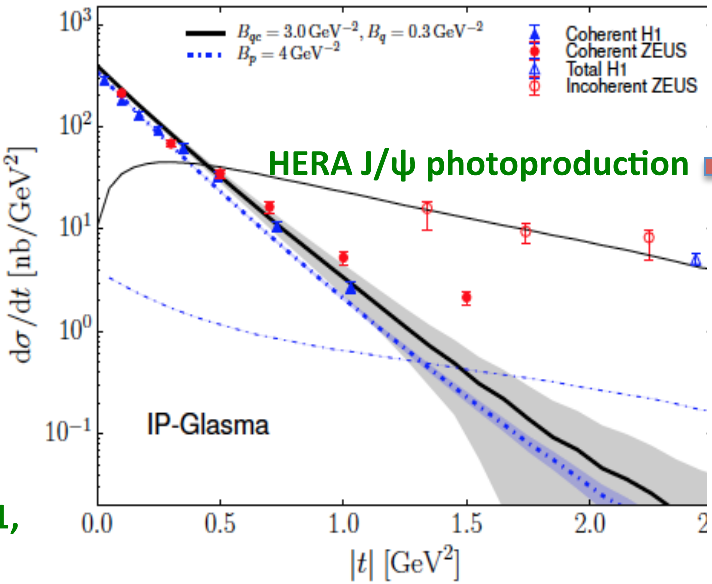


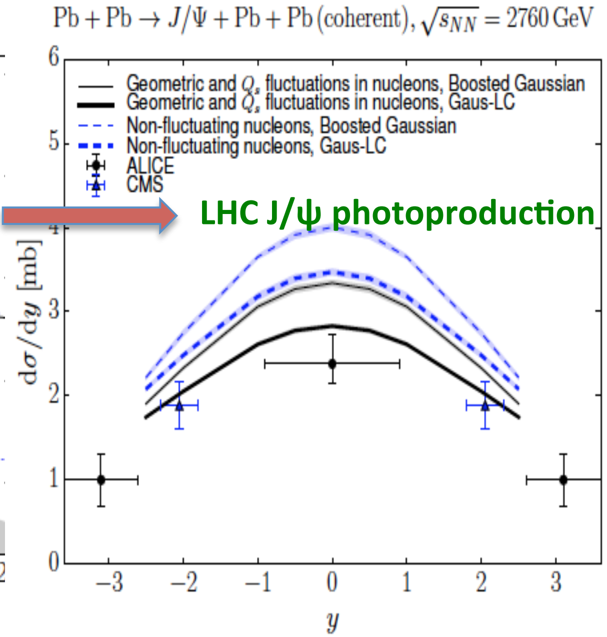
Kowalski,Lappi,RV:0705.3047

Consistent, within limited available data, with shadowing obseved in e+A collisions

Role of gluon shape fluctuations in the proton

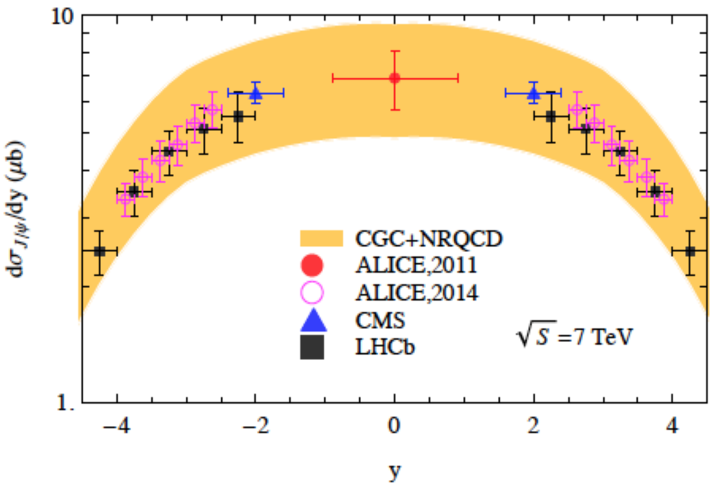


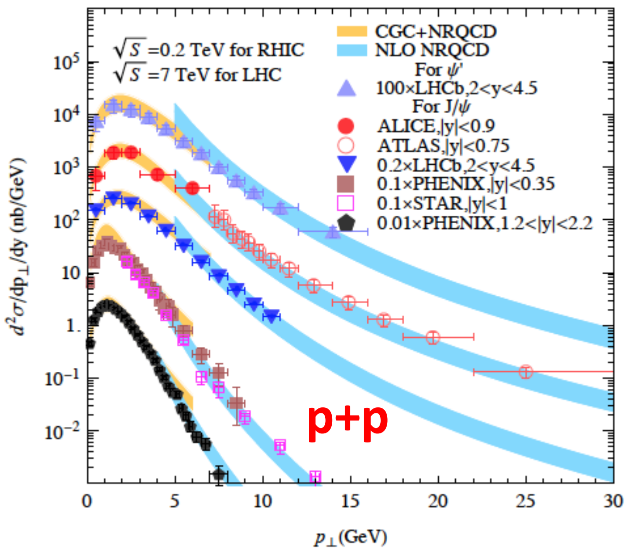


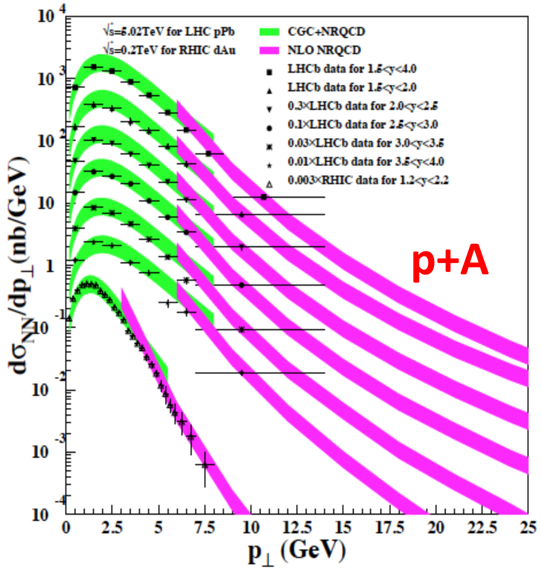


Mantysaari,Schenke,arXiv:1607.01711, arXiv:1703.09257

A sampling of results from p+p & p+A collisions

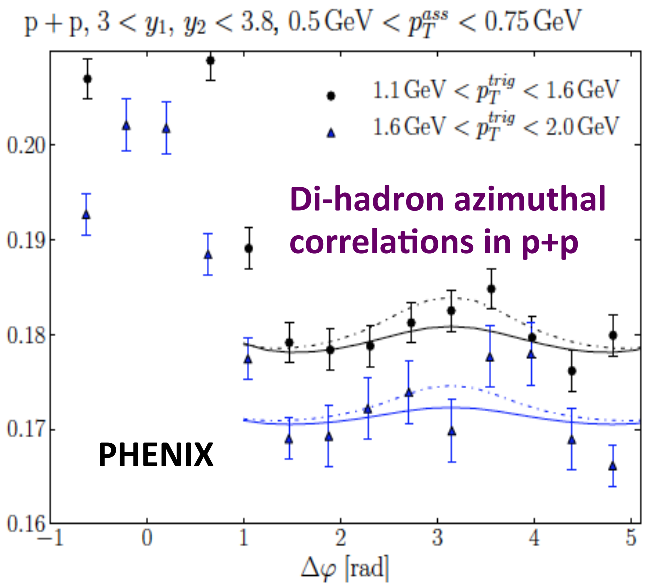


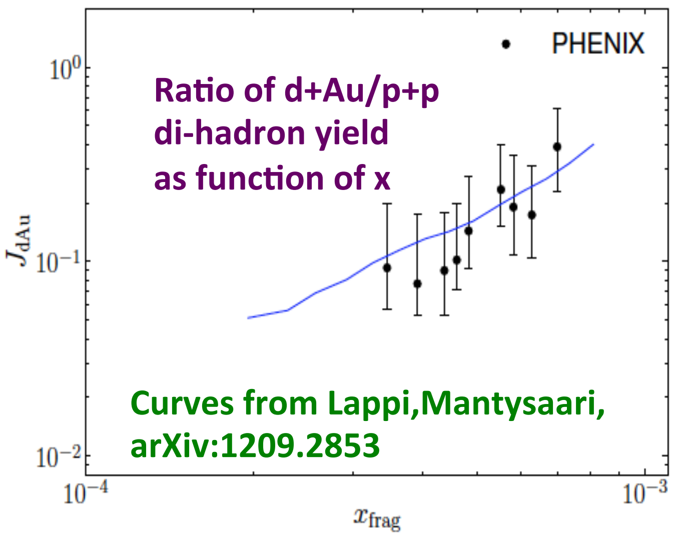


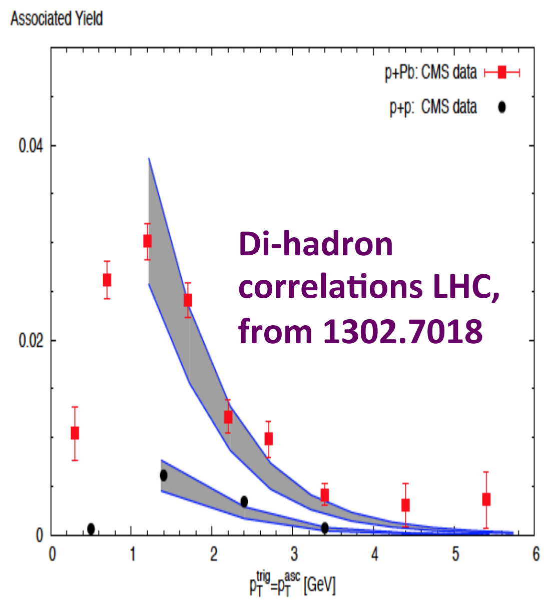


Ma et al., arXiv 1408.4075 & 1503.0772

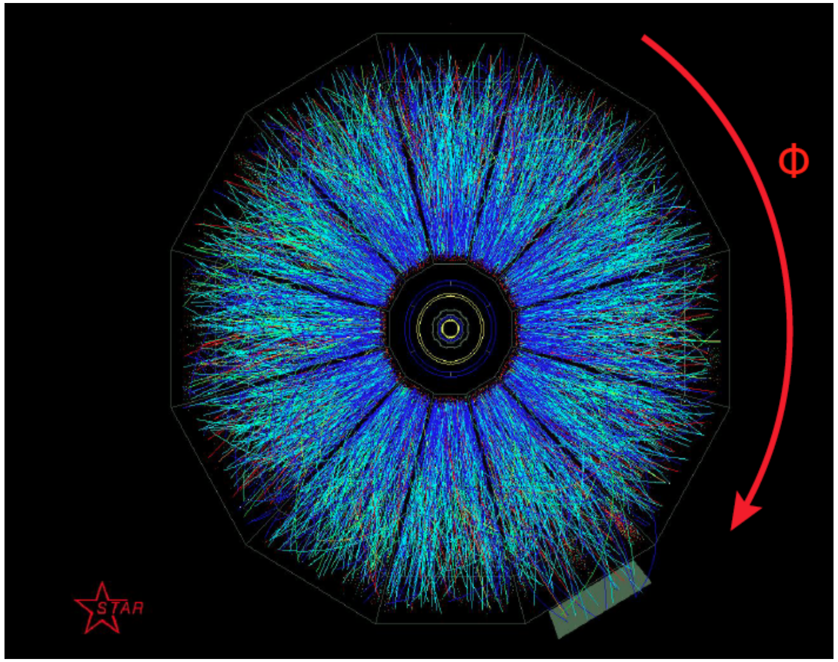
J/ψ rapidity and p_T rapidity distributions in p+p and p+A at RHIC & the LHC

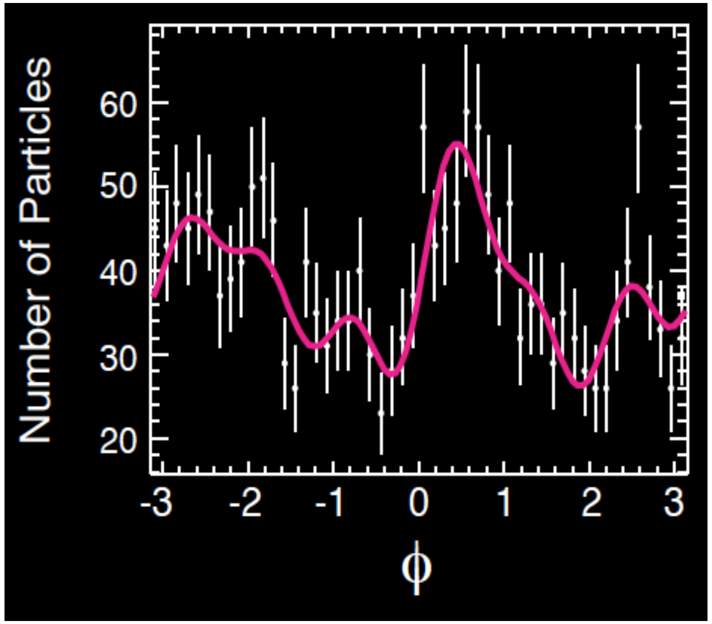


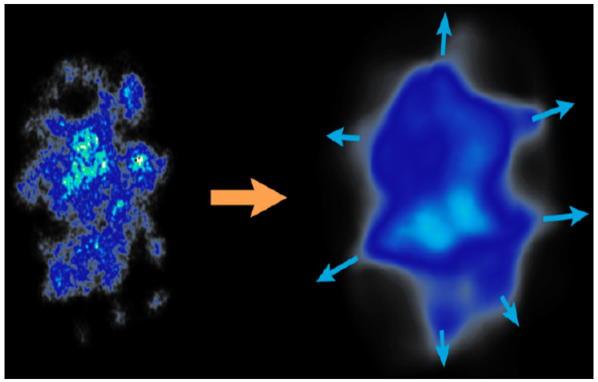




CGC initial conditions key to quantitative description of heavy-ion data



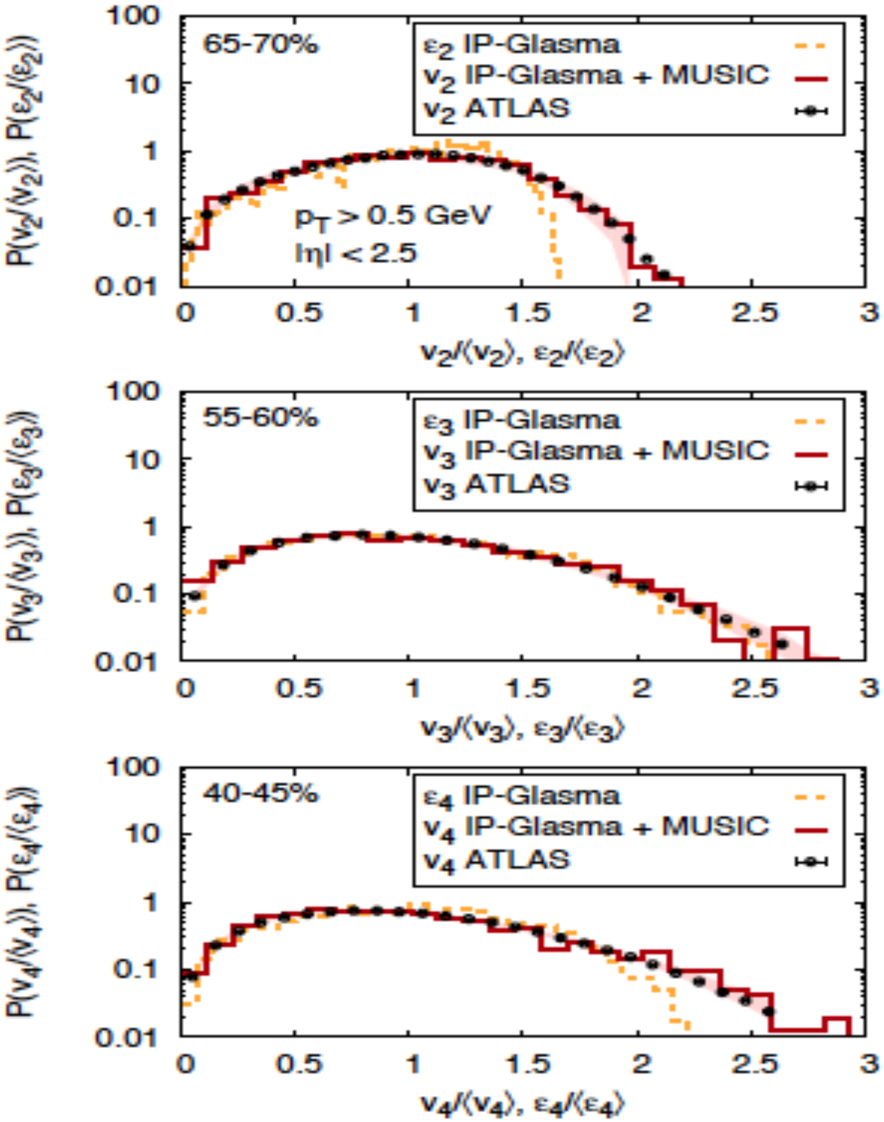


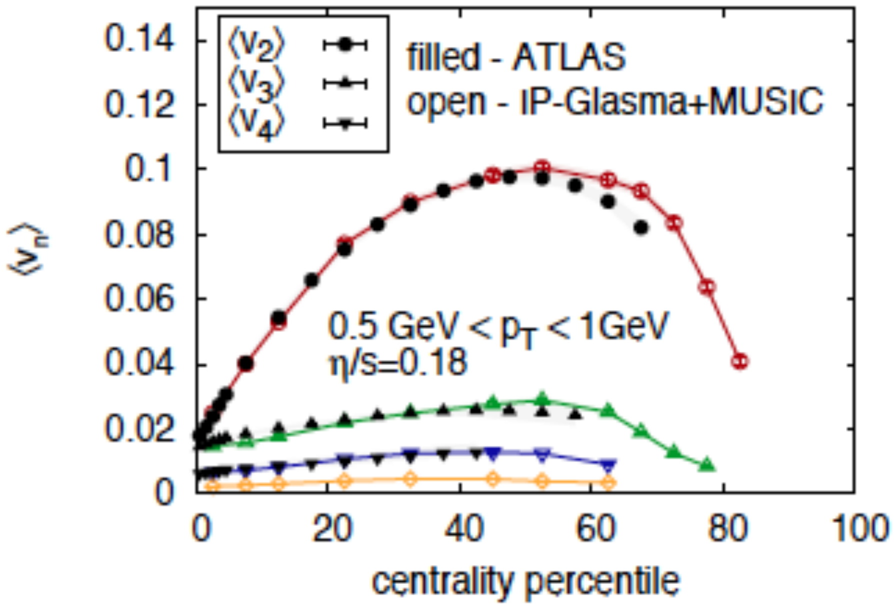


Hydrodynamics converts initial spatial anisotropies of partons into final state momentum anisotropies

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + 2v_4\cos(4\phi) + \cdots\right)$$

CGC initial conditions key to quantitative description of heavy-ion data





IP-Glasma + viscous hydro (MUSIC)
-- excellent description of event by event azimuthal anisotropies V_n

For analog in e+A, see talk by T. Ullrich

Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL (2013) 012302
Schenke, Venugopalan, PRL 113 (2014) 102301

Quo Vadis?

- In e+p DIS, saturation models provide a good *combined* description of inclusive, diffractive, and exclusive final states at small x. However, the Q_S^2 scales extracted are not much larger than the intrinsic QCD scale.

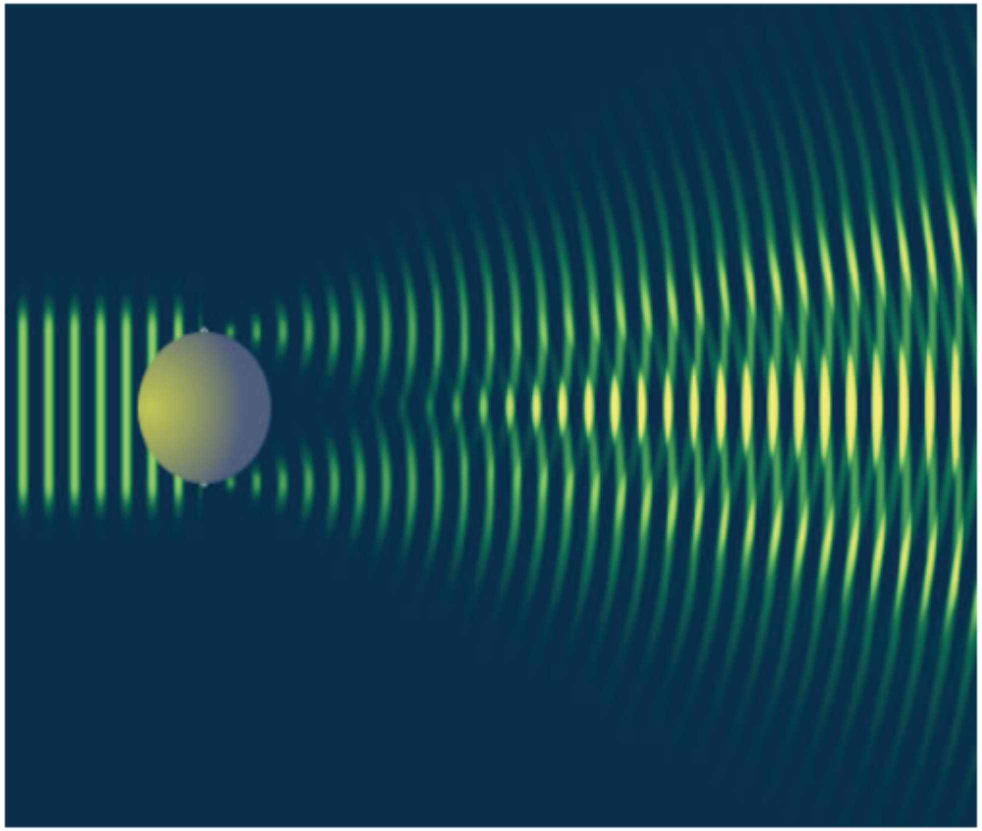
- Data in e+A DIS is very scarce at the small x and for $Q^2 > 1$ GeV^2 where the extraction of gluon distributions is reliable

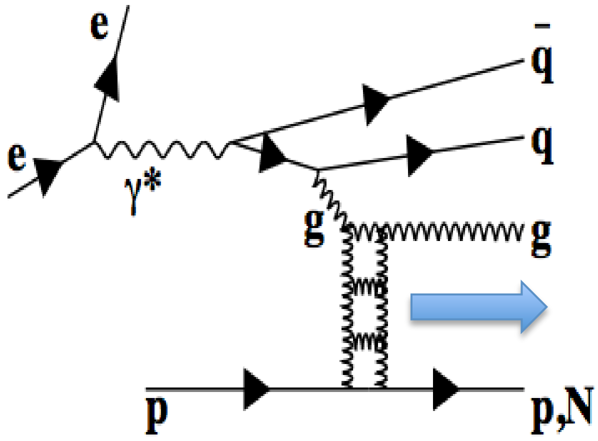
- In hadron-hadron collisions, descriptions of the *initial states* of the colliding protons and nuclei as saturated glue states provide good agreement with data for semi-hard processes. However, *final state interactions* are also strong, and separating the two in an interesting challenge

  – addressing, in their own right, profound questions of quantum vs classical dynamics, the nature of thermalization, and quantum entanglement…

- DIS off nuclei over with large reach, range, light and heavy beams, and high luminosities afford novel opportunities I will outline briefly

Diffraction for the 21st century





M_X

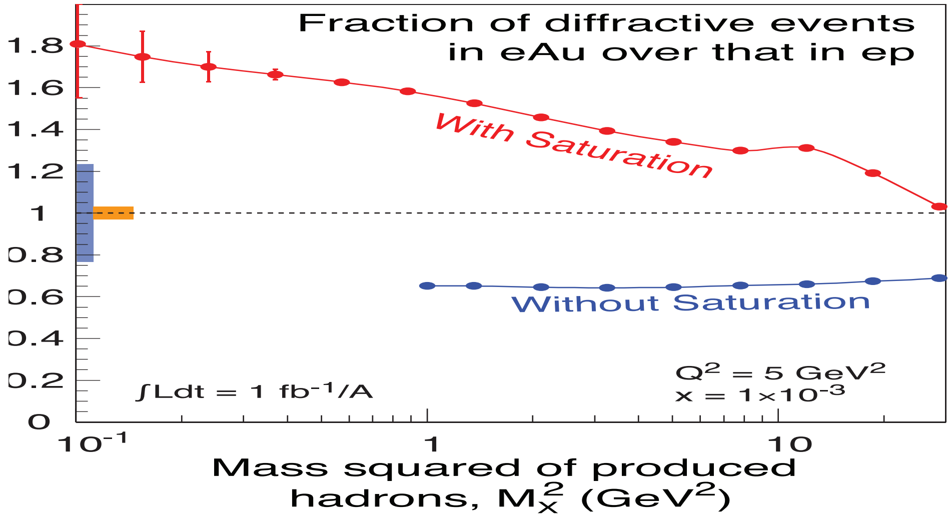
Colorless exchange

$$|e^-\rangle = |e_B\rangle + |e_B\,\gamma^*\rangle + |e_B\,\gamma^*\,q\bar{q}\rangle + |e_B\,\gamma^*\,q\bar{q}\,g\rangle + \cdots$$

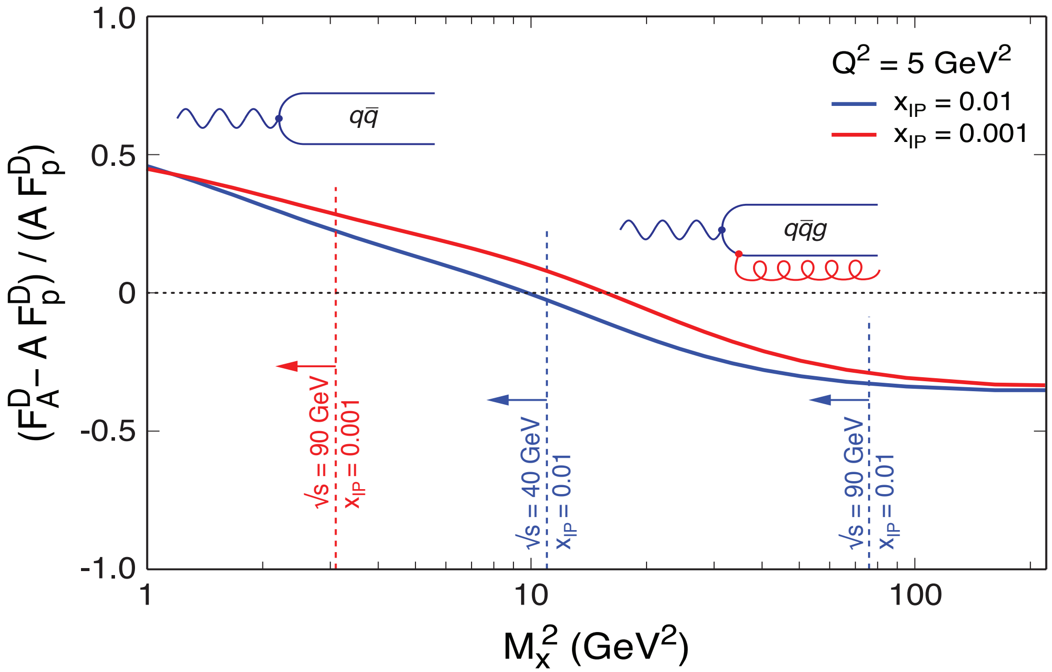
A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

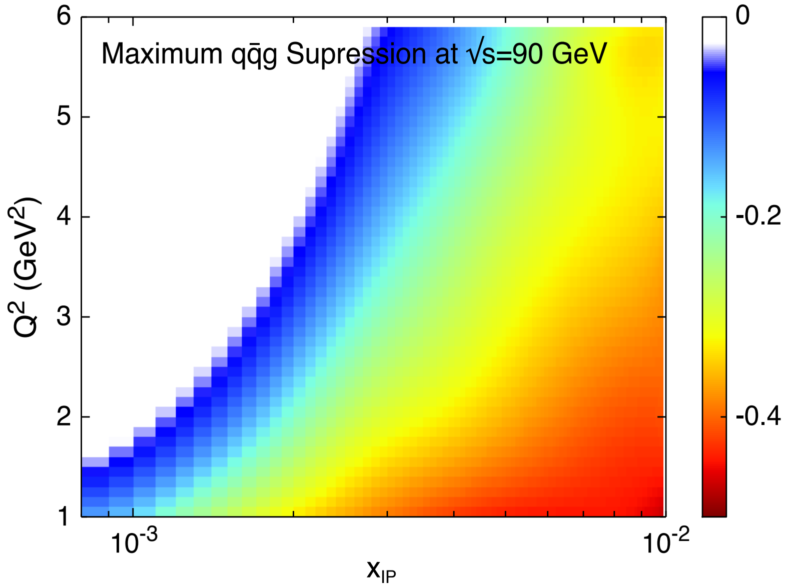
Day 1 prediction: nucleus remains intact in at least 1 in 5 events

Diffraction for the 21st century



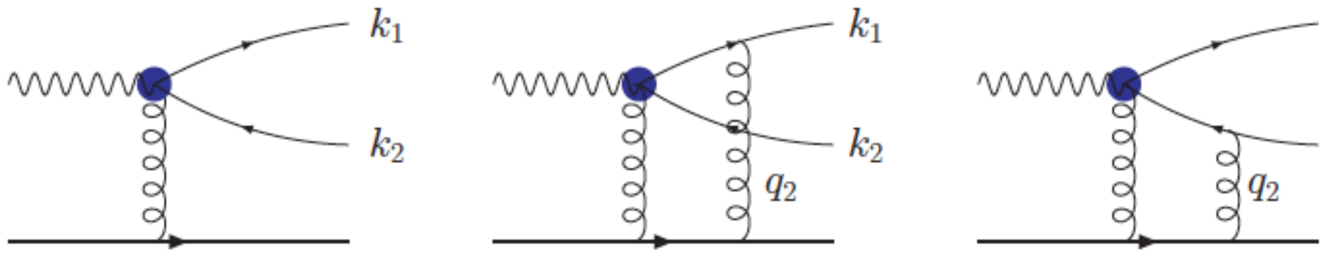
Plot from EIC whitepaper showing qualitatively different predictions for diffractive structure functions

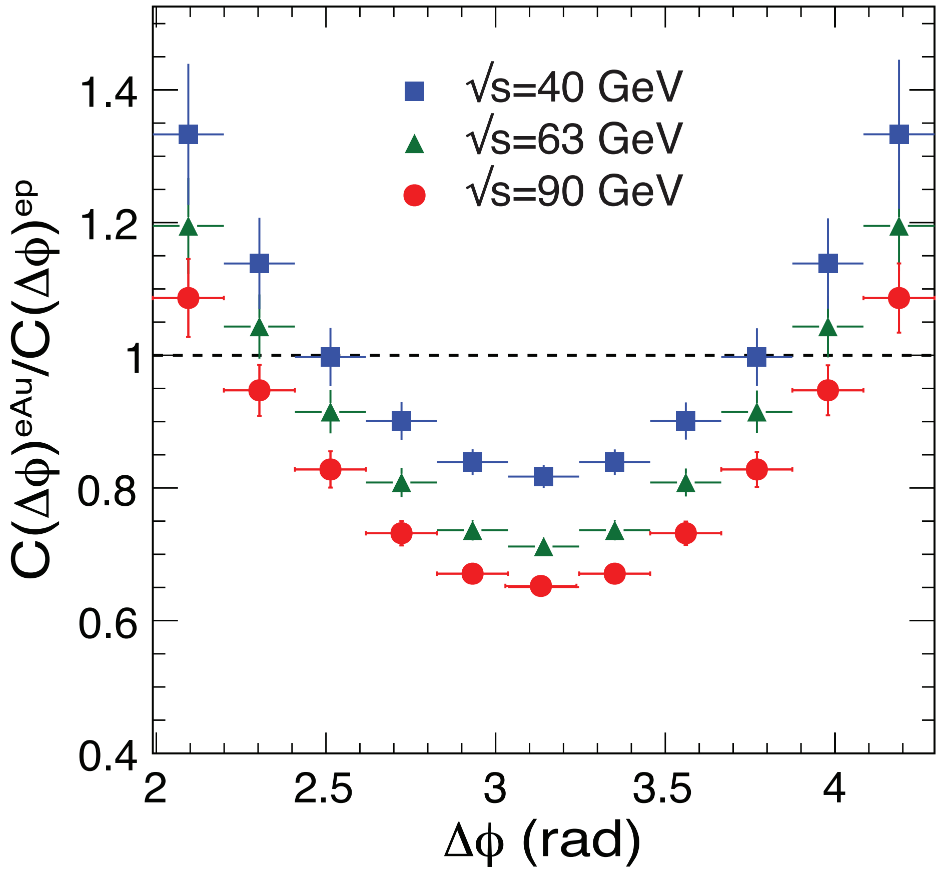


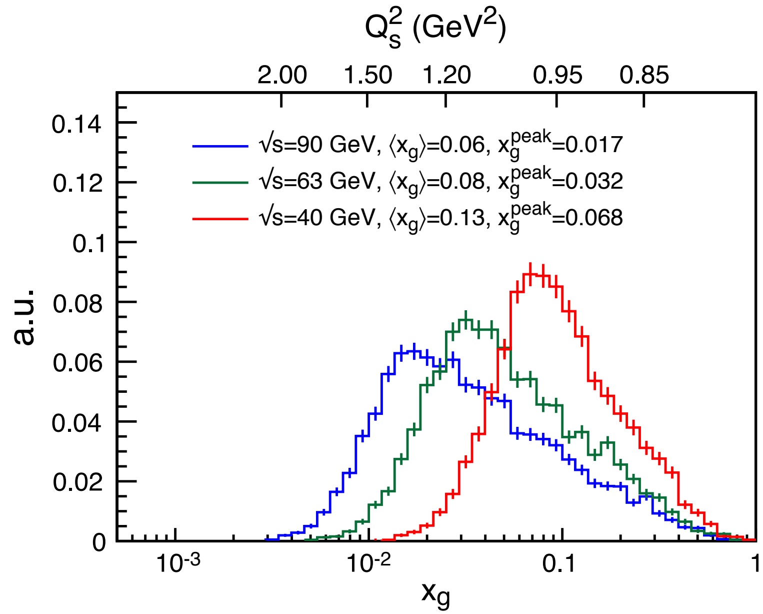


Striking transition from region of color transparency to color opacity (or saturation)

Gluon saturation through di-hadron correlations







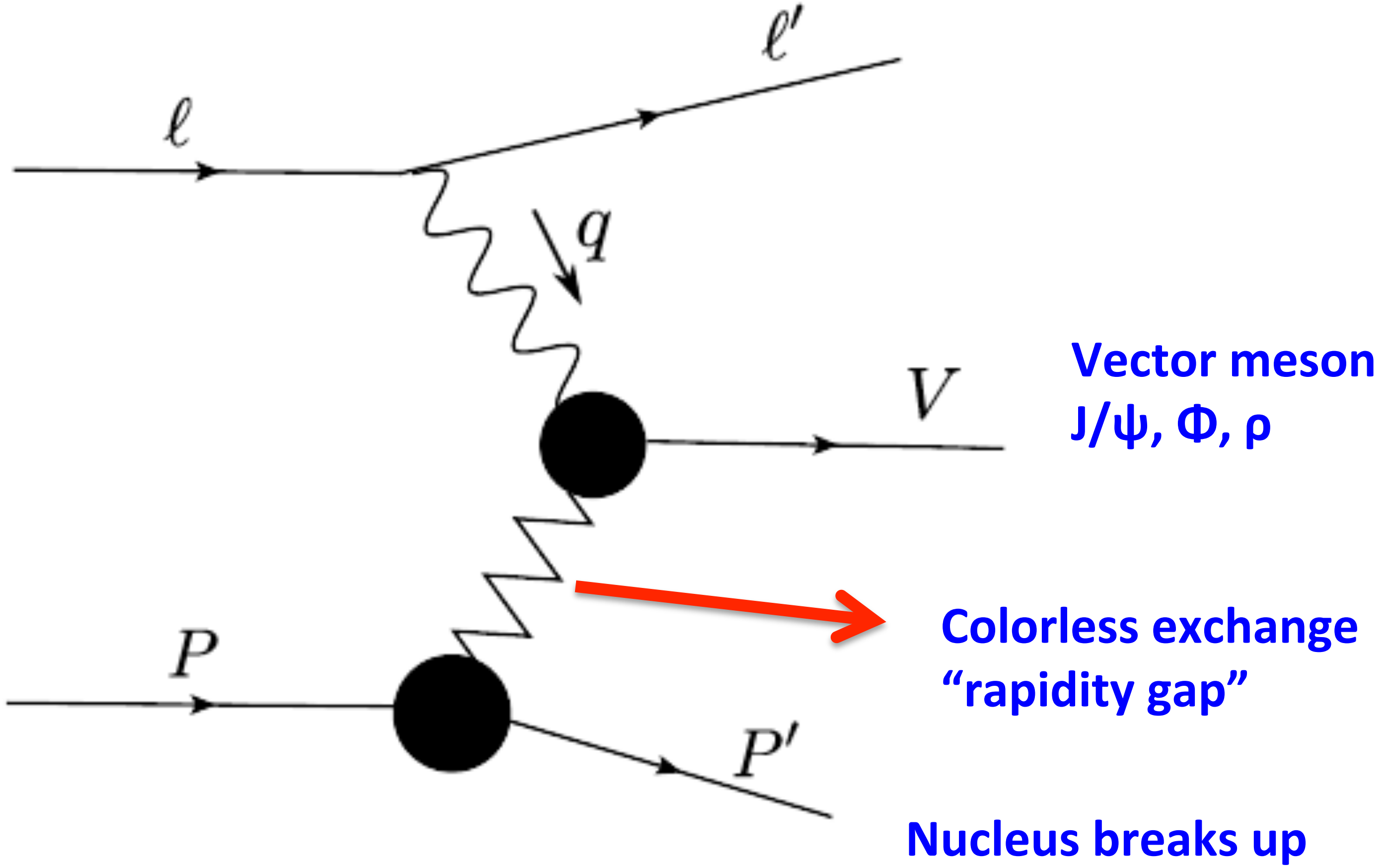
Systematic decorrelation of the di-hadron signal with energy range and with nuclear size −compelling evidence of saturation


EIC whitepaper
New opportunities

Probing rare glue fluctuations with ballistic protons

Lappi,Mantysaari,RV: PRL 114 (2015) 8, 082301

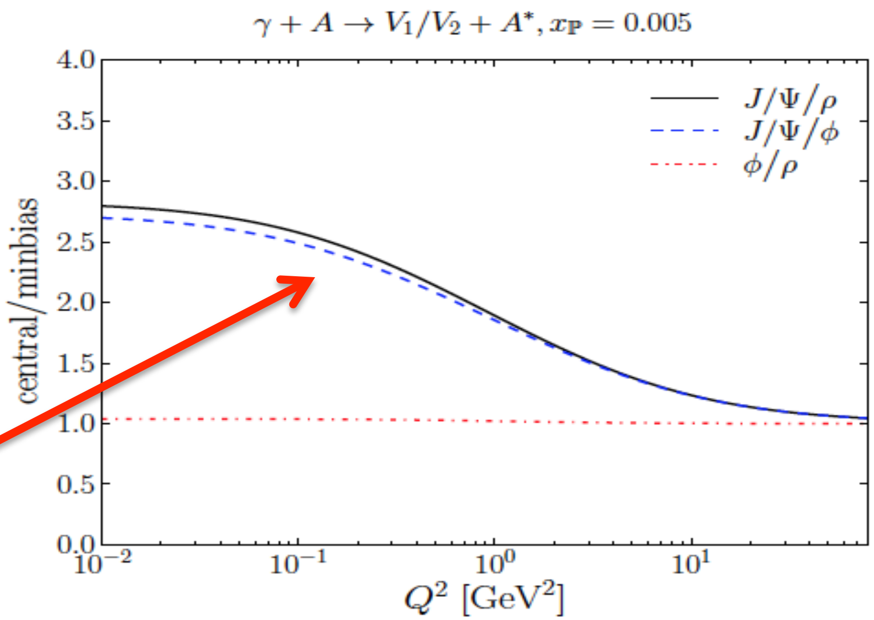
Incoherent diffraction (nucleus breaks up but no color is exchanged)
- directly sensitive to gluon field fluctuations



Probing rare glue fluctuations with ballistic protons

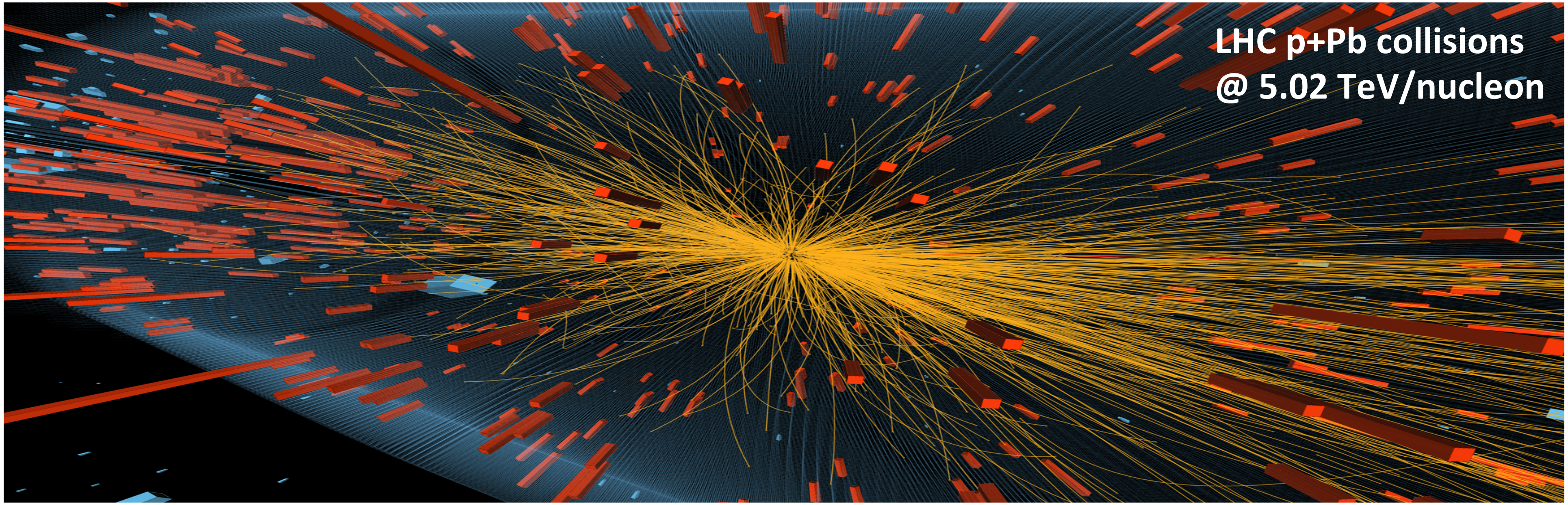
Lappi,Mantysaari,RV: PRL 114 (2015) 8, 082301

Can use "ballistic" protons in Roman pots as a measure of centrality dependence of fluctuations



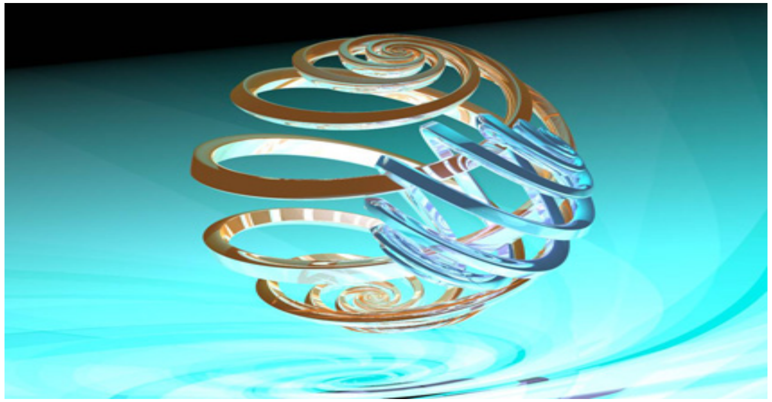
Central/min.bias double ratios very sensitive probe of fluctuations of strong gluon fields

Collectivity in small systems



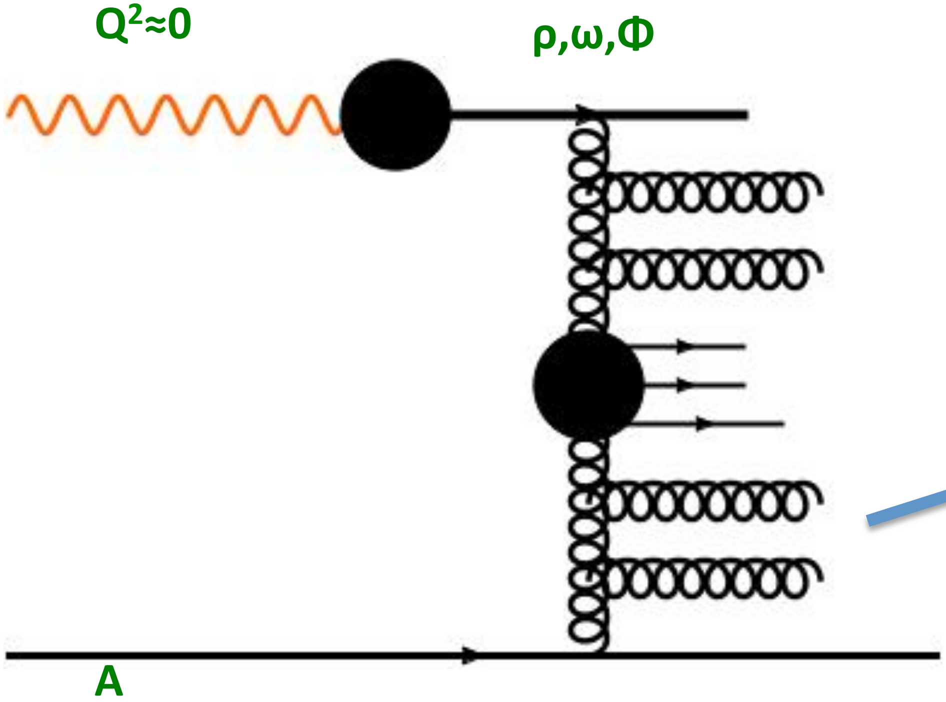
Is the matter created…

…the world's smallest droplet?



…or a novel form of gluon entanglement?

The p+A limit of e+A



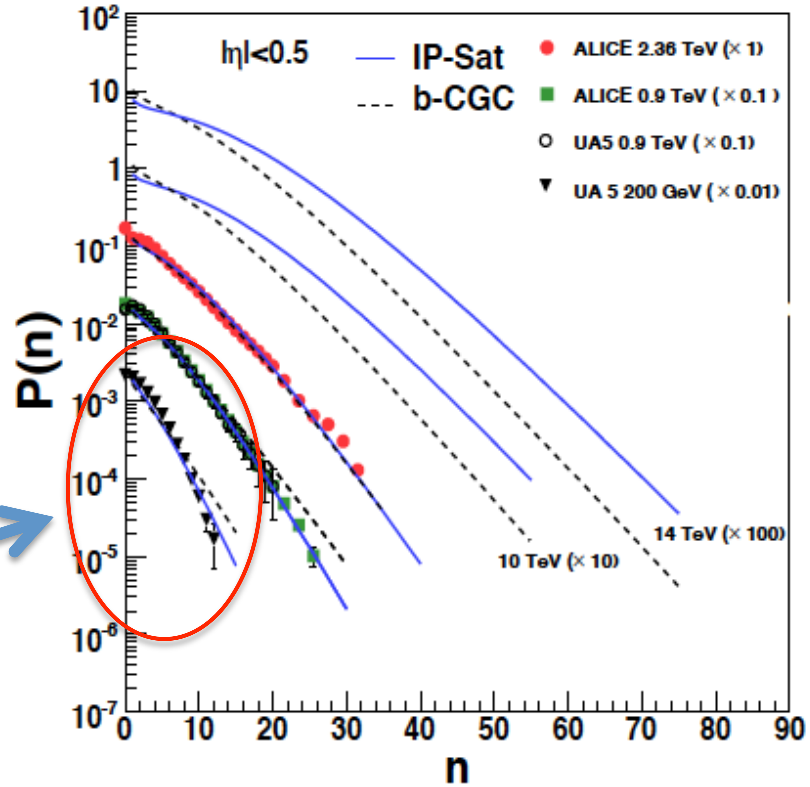


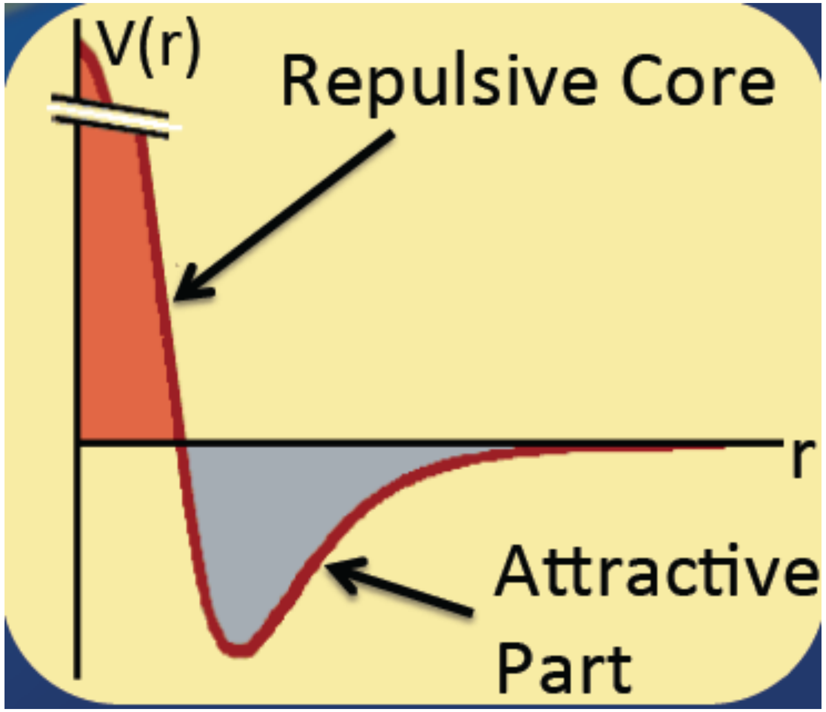
Photo-production in e+A is like p+A collisions – can perform all p+A-like correlation measurements in very rare e+A collisions – can one see the "ridge" in such events ?

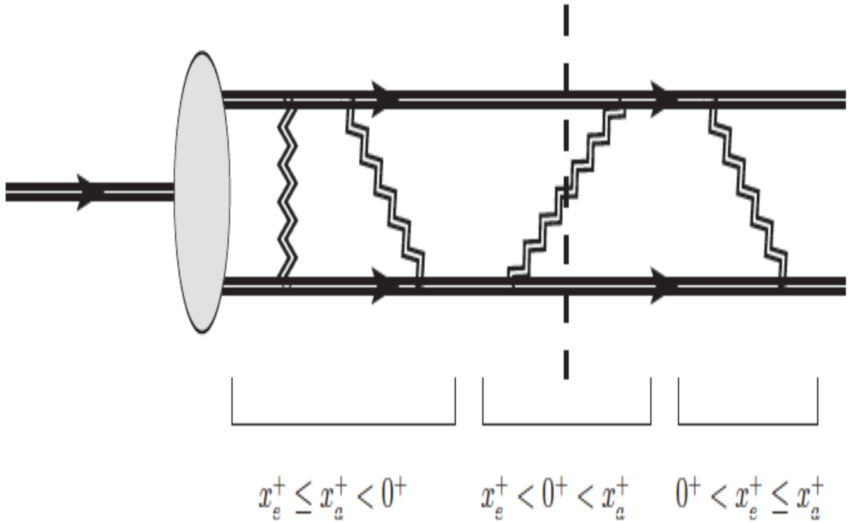
Dial up Q^2 to see how these effects go away…

Exciting possibility: compute the quantum entanglement entropy from long range hadron correlations

Kovner,Lublinsky, PRD92 (2015) 034016
Kharzeev,Levin,PRD95 (2017)114008
Berges,Florchinger, RV, arXiv:1707.05338

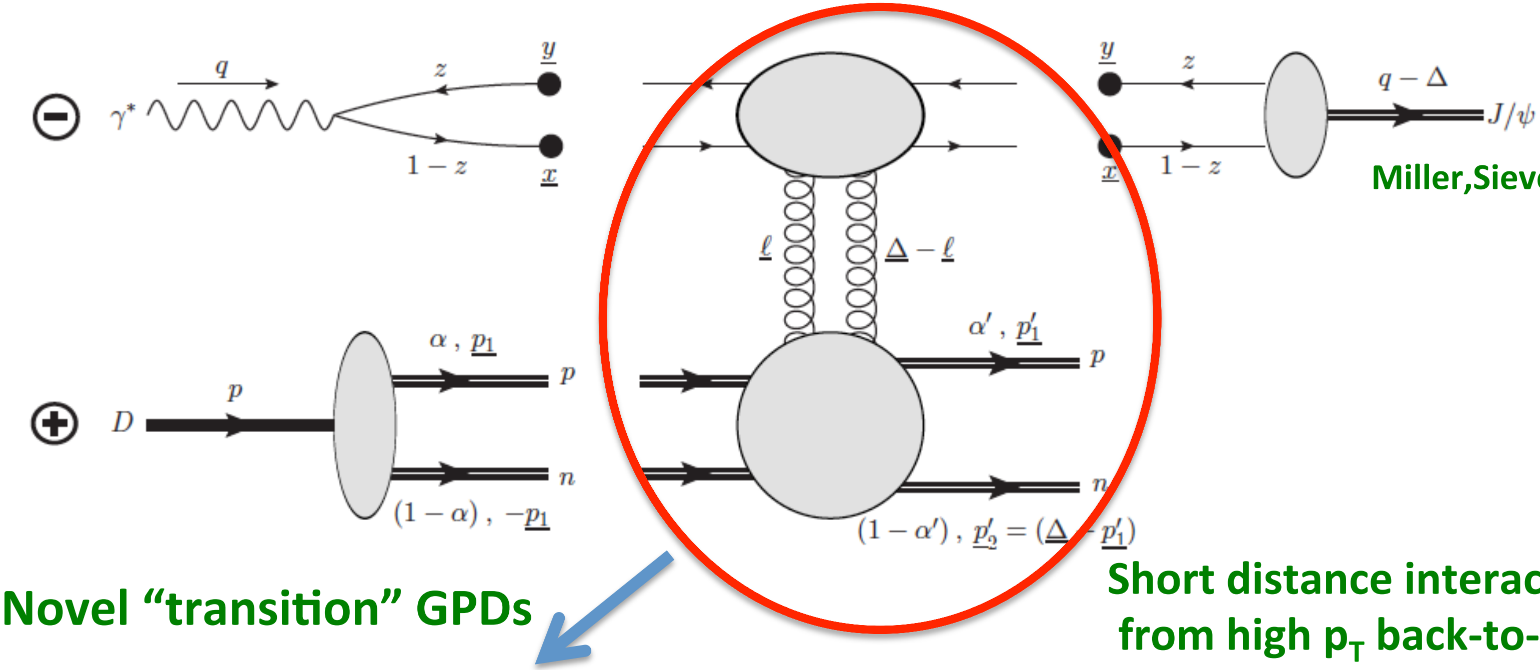
Short-range nucleon-nucleon interactions with EIC





Can EIC provide insight into the short-range gluon contribution to the nucleon-nucleon potential ?

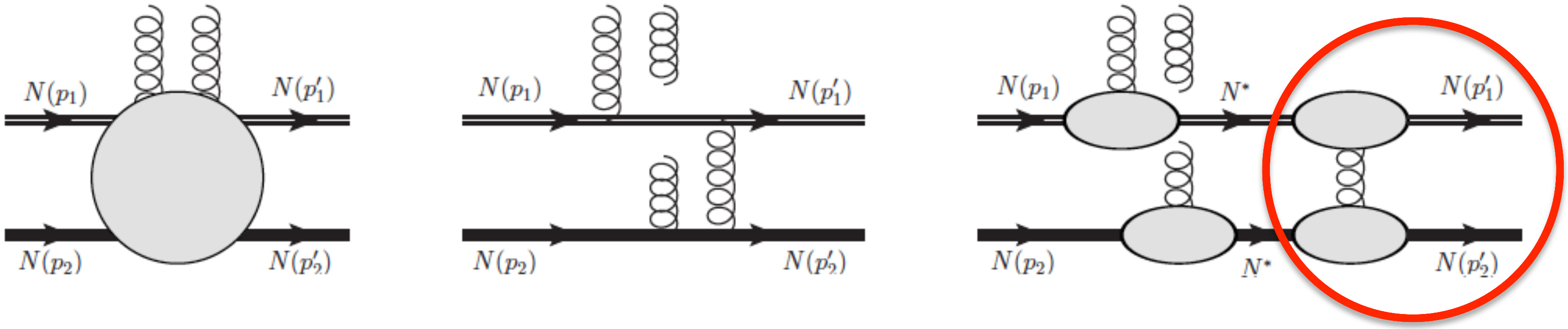
Short-range nucleon-nucleon interactions with EIC



Miller,Sievert,RV,1512.03111

Novel "transition" GPDs

Short distance interactions from high p_T back-to-back nucleons



Preliminary estimate of rates suggest that these measurements are very feasible at EIC with p_T ~ several GeV range

Outlook

- Unique opportunity to study fully nonlinear features of QCD dynamically (and cleanly) in a regime where the coupling is weak
- The interplay of the strong color fields of saturated gluons and those from confining dynamics may provide fundamental insight into both
- Where I am going: a deeper understanding of the interplay of QCD spin and saturation at small x, including possible novel signatures of the chiral anomaly