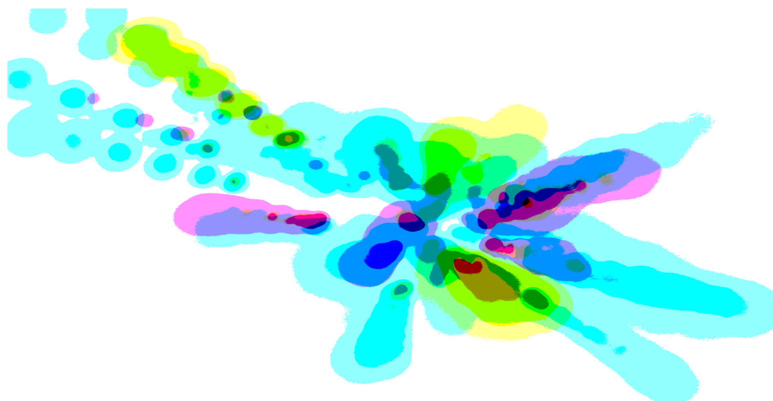
Exploring QCD at small x with the Electron-Ion Collider



Raju Venugopalan
Brookhaven National Laboratory

EIC Theory meeting, MIT, September 20-22, 2022

A long and winding road…

1st eRHIC workshop, BNL Dec. 3-4, 1999

(Garvey,Ludlam,McLerran, Strikman,Venugopalan)

EIC CD0 Dec. 19, 2019

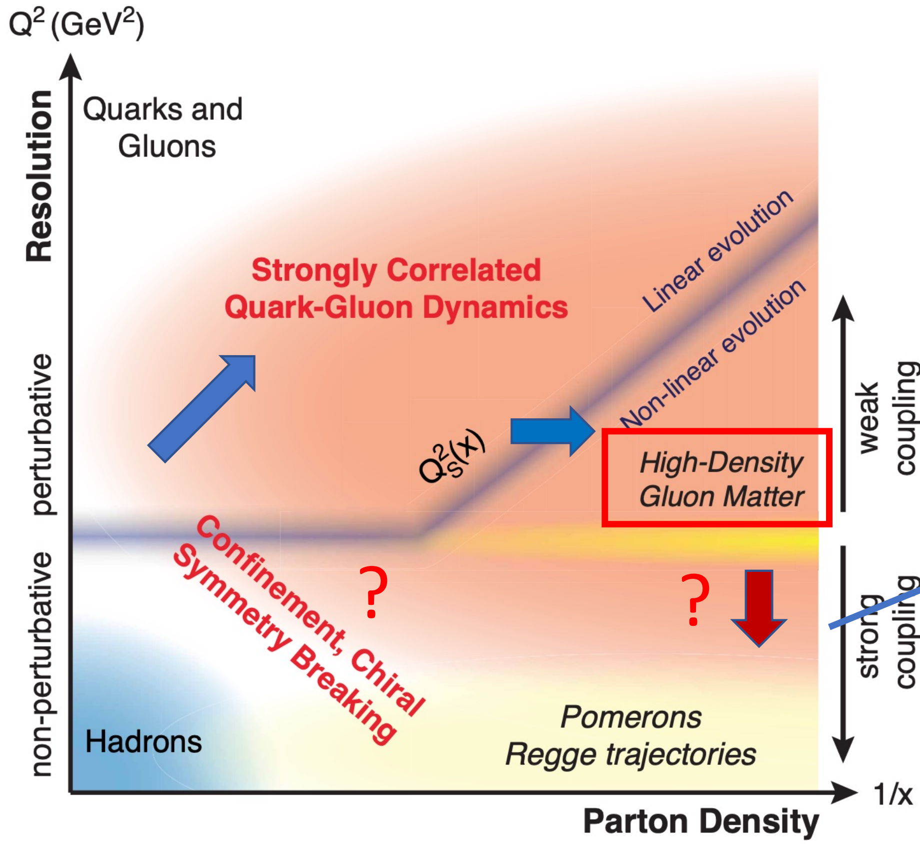
A long and winding road to first collisions…NT theory input crucial

It gets easier the second time."

Critical Decision process → Developing science case (LRP,…), novel theory ideas, simulations & input into detector design community outreach, training, mentorship (incl. DEI)

Landscape of the strong interaction

Aschenauer et al., arXiv:1708.01527
Rep.Prog. Phys. 82, 024301 (2019)

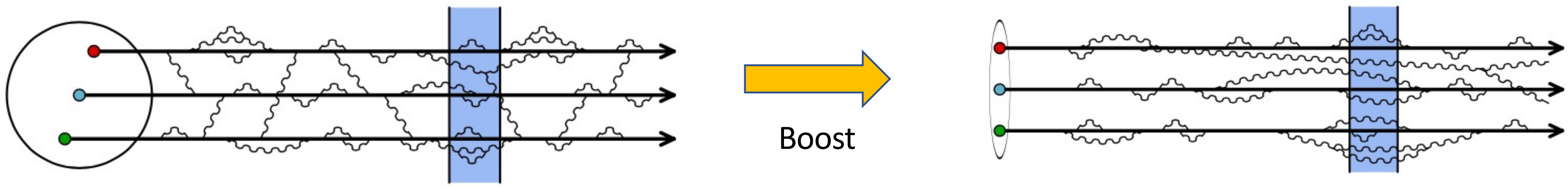


(increasing energy)

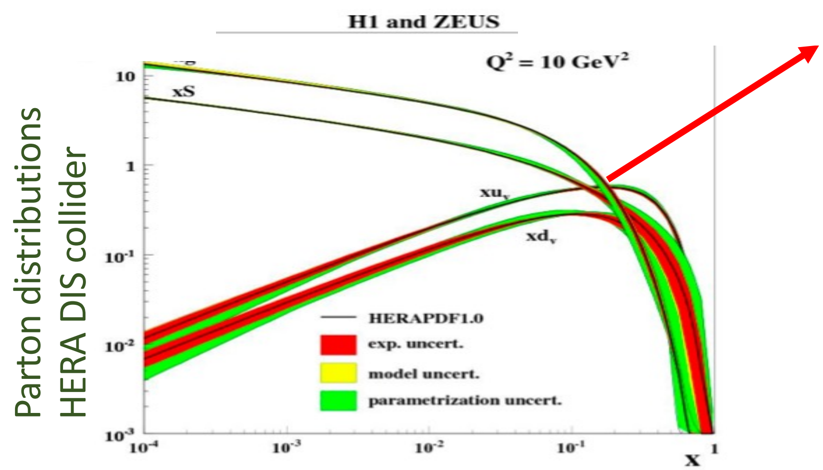
Dominant region of QCD cross-sections!

The EIC is a QCD machine so our quest for ”precision” should match the questions on many-body correlations and dynamics we wish to address: I will address primarily “synergies”

QCD evolution at small x



Parton model picture: from arXiv:0708.0047



Glue and sea quarks begin to dominate already at x$\sim$0.1

Very rapid growth violating asymptotic expectations from Froissart bound

Is the physics universal?

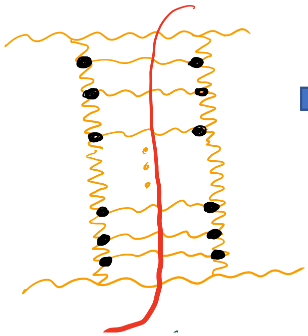
“Small x physics:: when $\alpha_S \mathrm{Ln}(\frac{x_0}{x}) \sim 1 \geq \alpha_S \mathrm{Ln}(\frac{Q_0^2}{Q^2})$

BFKL equation (1976-1978)

BFKL Pomeron: color singlet compound state of 2 reggeized gluons interacting via non-local “Lipatov vertices”
BKP Odderon: color singlet compound state of 3 reggeized gluons ($\propto pp - p\bar{p}$: TOTEM+D0 discovery claim)

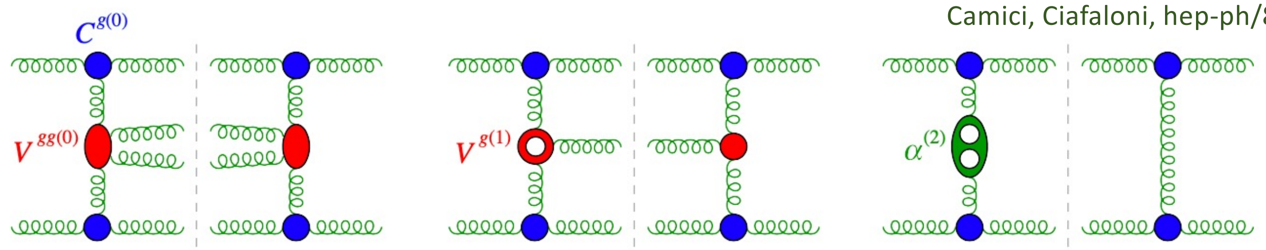
$2 \to N + 2$ amplitude in the Regge limit: the NLL BFKL equation

BFKL Pomeron



NLL

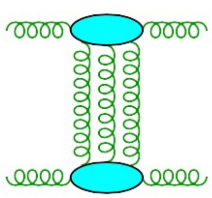
Fadin, Lipatov, hep-ph/9802290
Camici, Ciafaloni, hep-ph/8903389



Figures from arXiv:2203.13026

Regge factorization at NLL $[\alpha_S(\alpha_S \,\mathrm{Ln}(\frac{x_0}{x}))^n]$: Includes one loop corrections to the Lipatov vertex ($V^{g(1)}$) and two loop corrections to the Regge trajectory ($\alpha^{(2)}$)

Beyond NLL:



Breaking of Regge factorization

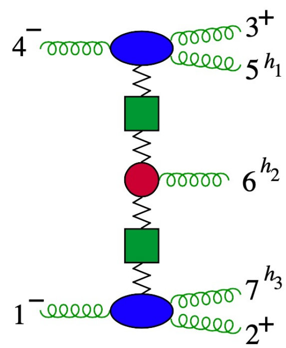
Three reggeized gluon exchange corresponds to Regge cut in angular momentum plane – this can be computed

Falcioni et al., arXiv: 2111.10664, arXIv:2112.11098

$2 \rightarrow \mathrm{N} + 2$ amplitude in the Regge limit: the NLL BFKL equation

Rich mathematical structure of Regge amplitudes in QCD and QCD-like theories.

Multi-Regge limit of planar $\mathrm{SYM}\ \mathcal{N} = 4$:



Excellent review of state-of-the art:
V. Del Duca, L. Dixon, arXiv:2203.13026

At large t'Hooft coupling, AdS/CFT duality between amplitudes and minimal area surfaces with closed light-like polygon boundaries

Dual conformal tranformations $\rightarrow$ BDS ansatz; rich mathematical structure of MHV amplitudes in MRK kinematics

BDS: Bern, Dixon, Smirnov
See for example, Dixon, Liu, Miczajka, arXiv:2110.11388

MHV: Maximally helicity violating
MRK: Multi-Regge kinematics

Significant "particle/string theory amplitudes community" working on this topic - in addition to portions of SCET community – engagement with this larger community would be very beneficial all around

Breakdown of the OPE: Multi-Pomeron and Reggeon exchange

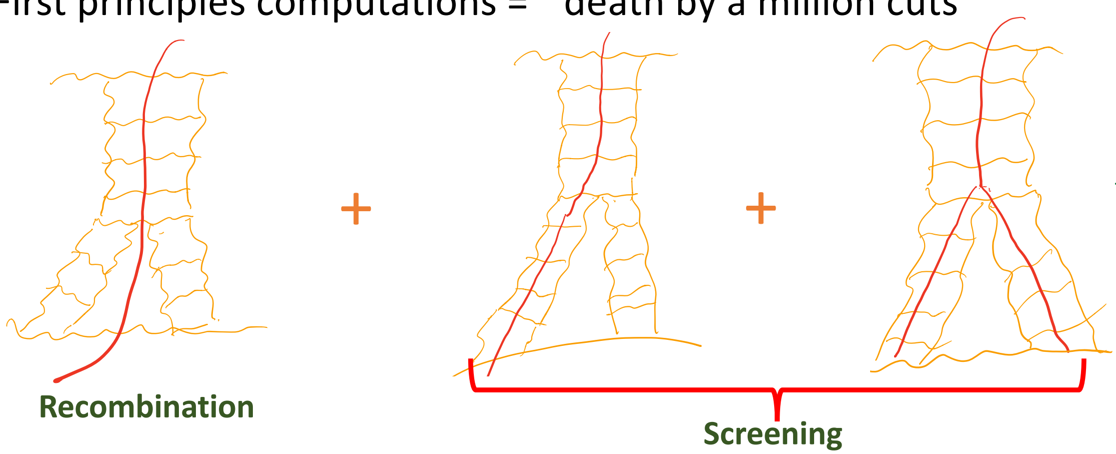
One consequence of BFKL evolution (not cured at NLL) is infrared diffusion of distributions
– this leads to a breakdown of the Operator Product Expansion

Mueller (1996)

Further, rapid BFKL growth leads to large phase-space occupancy N at high energies
→ novel many-body gluodynamics

Partons recombine and screen – many-body "shadowing"
First principles computations = ``death by a million cuts"

Gribov,Levin,Ryskin (1983)
Mueller, Qiu (1986)

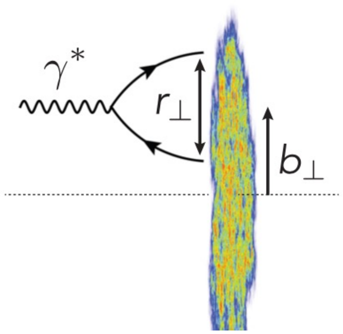


$$= - \frac{\left[\alpha_s G(x,Q^2)\right]^2}{Q^2 R^2}$$

All-twist power suppressed contributions equally important for $N \equiv \frac{xG_A(x,Q_S^2)}{2(N_c^2-1)\pi R_A^2 Q_S^2} = \frac{1}{\alpha_S(Q_S)}$

$$N \rightarrow \frac{1}{\alpha_S} = \text{classicalization!}$$

Gluon saturation: classicalization and perturbative unitarization

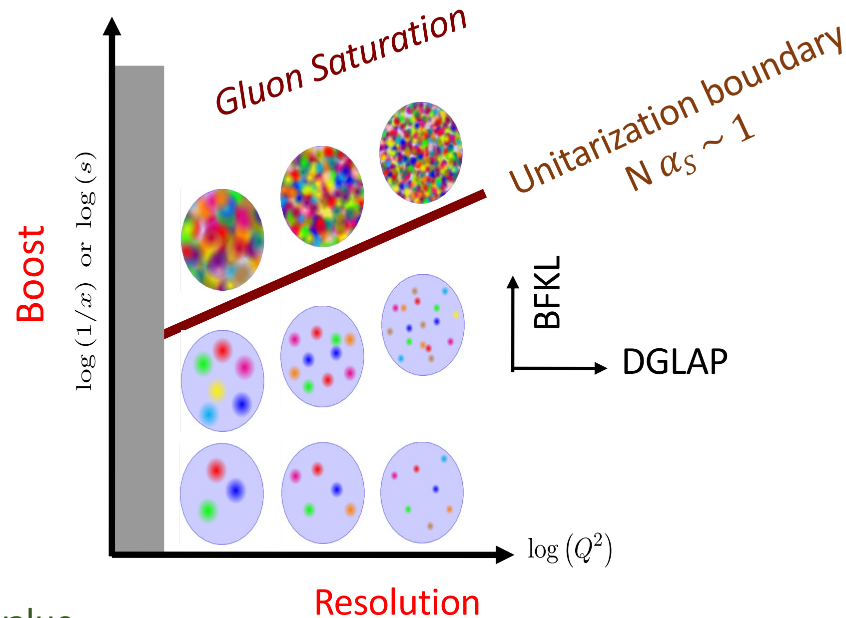


Simple GBW model:

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

Emergent semi-hard scale $\quad Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$

BFKL eigenvalue



Emergent scale suggests that intrinsically non-perturbative dynamics can be studied in weak coupling

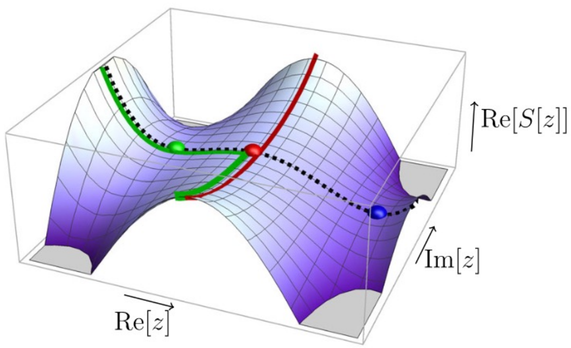
Similarities to dynamics at the Event Horizon of a Black Hole or Pair-Production in very strong Laser fields

A relevant example of such synergy: The ISOQUANT Collaborative Research Center at Heidelberg
https://www.isoquant-heidelberg.de

Classical lumps in $2 \to N$ scattering and unitarity

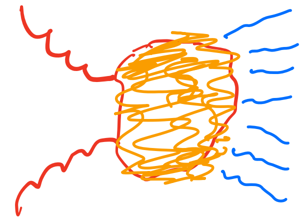
Generic problem: High orders in perturbation theory

False vacuum decay of field configurations $\phi(z)$



Langer; Coleman; …
Fig. from Andreassen,Frost,Schwartz, PRD97 (2018)

$2 \to N$



$P_{2\to N} \sim e^{S} \alpha_s^N N!$

If $N \sim \frac{1}{\alpha_s}$

$P_{2\to N} \sim e^{S} \cancel{\alpha_s^N} \cancel{\left(\frac{1}{\alpha_s}\right)^N} e^{-1/\alpha_s}$

Exponential suppression of high occupancy states (classical lumps) unless

$S \sim 1/\alpha_s \sim N$

$\boxed{\Rightarrow P_{2\to N} \sim O(1)}$

Are such small x configurations maximally entangled states in hadrons?

Kharzeev, Levin,Skokov, Kovner, Lublinsky, Dumitru, Armesto, Kutak …

Satisfy an area law saturating the Bekenstein bound

Dvali,RV

Can features of scattering amplitudes at small x be understood in the language of quantum information?
What are the possible consequences – can these guide experiments?

Quantum computing and quantum information science

Novel thrust in high-energy nuclear physics since last long-range plan:

Some key relevant questions for cold QCD:
Can one devise entanglement measures to characterize the information content of DIS measurements complementary to pdfs and fragmentation functions ?

Can one perform meaningful quantum simulations of high energy scattering on NISQ era quantum computers?
Long-term holy grail: First principles understanding of QCD at small x

Active on-going research on these open questions

C²QA
Co-design Center for Quantum Advantage

One of 5 DOE suported National Quantum Information Research Centers
with a particular focus on theory problems in cold QCD + synergies to CMP and quantum chemistry

Theory sub-thrust lead is Robert Pisarski (BNL)
Co-PI's include
Taku Izubuchi, Raju Venugopalan (BNL)
Robert Edwards, Jianwei Qiu, Kostas Originos (Jlab)
Phiala Shanahan, Jesse Thaler (MIT)
Dima Kharzeev (BNL/Stony Brook)

Promote Research, Mentorship and Outreach
in the cold & hot QCD communities

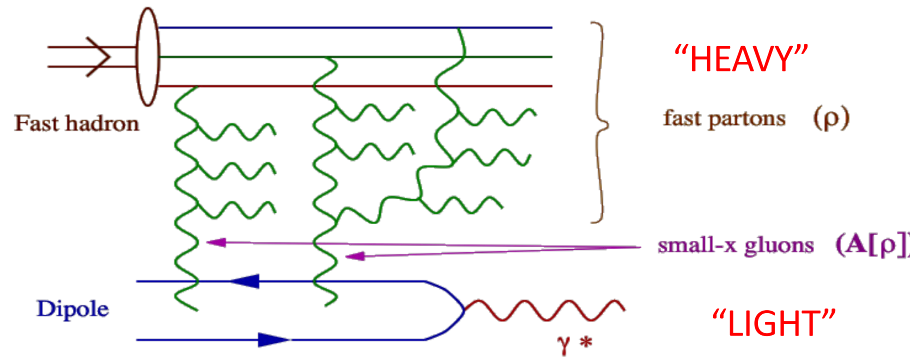
Classicalization in the Regge limit: the Color Glass Condensate EFT

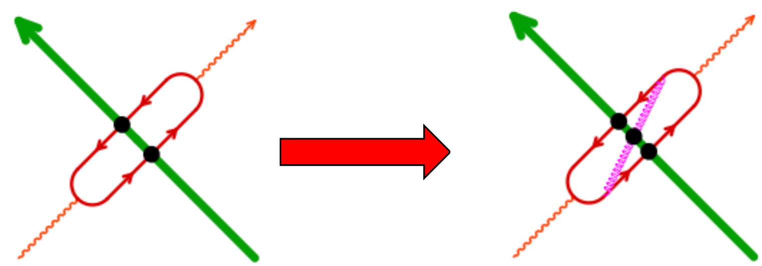
CGC EFT: Systematic semi-classical weak coupling expansion in strong field ($1/g_{YM}$) background

Effective separation of longitudinal and transverse degrees of freedom

Wilsonian RG resums large small x logs:
JIMWLK hierarchy of n-point 2+1-D Wilson line correlators (dipole, quadrupole,…) describes evolution of wee parton dynamics with increasing boost (rapidity)

BK equation is a closed form non-linear evolution equation for the 2-point dipole correlator;
reduces to linear BFKL equation at low parton densities





QCD evolution in shockwave background

CGC state-of-the-art: LO+LLx to NLO+NLLx

Small x evolution:

NLO BFKL: Fadin, Lipatov (1998)

NLO JIMWLK: Balitsky, Chirilli, arXiv:1309.7644, Grabovsky, arXiv:1307.5414 Caron-Huot, arXiv:1309.6521, Kovner,Lublinsky,Mulian, arXiv:1310.0378, Lublinsky, Mulian, arXiv:1610.03453

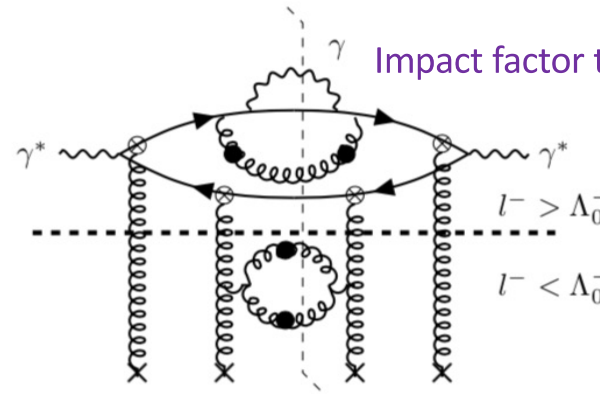
NNLO BK (SYM): Caron-Huot, Herranen (2018)

Resummed NLLx:

Salam (1999); Ciafaloni,Colferai,Salam,Stasto (1999-2004)

Ducloue,Iancu,Madrigal,Mueller,Soyez,Triantaffyllopoulos (2015-2019)

Impact factor to NLO:



Evolution to NLLx:

$O(\alpha_S^2 \ \mathrm{Ln}(\frac{1}{\mathrm{x}}))$

NLO impact factors:

Inclusive DIS: Balitsky,Chirilli (2013)

Diffractive DIS: Boussarie,Szymanowski,Wallon (2016)

Massive quarks: Beuf,Lappi,Paatelainen (2021); Mantysaari,Penttala (2022)

p+A forward di-jets: Iancu,Mulian (2021)

Photon+di-jet in DIS: Roy,RV (2020)

DIS di-jets/di-hadrons: Caucal,Salazar,Venugopalan (2021-2022);

Taels, Altinoluk,Beuf, Marquet, arXiv:2204.11650;

Bergabo, Jalilian-Marian, arXiv:2207.03606

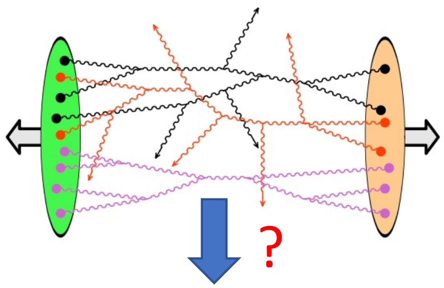
Diffraction: Iancu,Mueller,Triantafyllopolous; Hatta,Xiao,Yuan (2022)

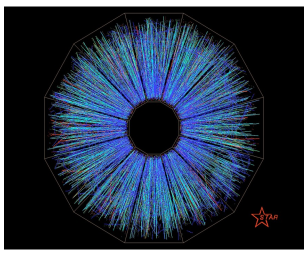
Multipole correlators are universal to e+A and p+A:

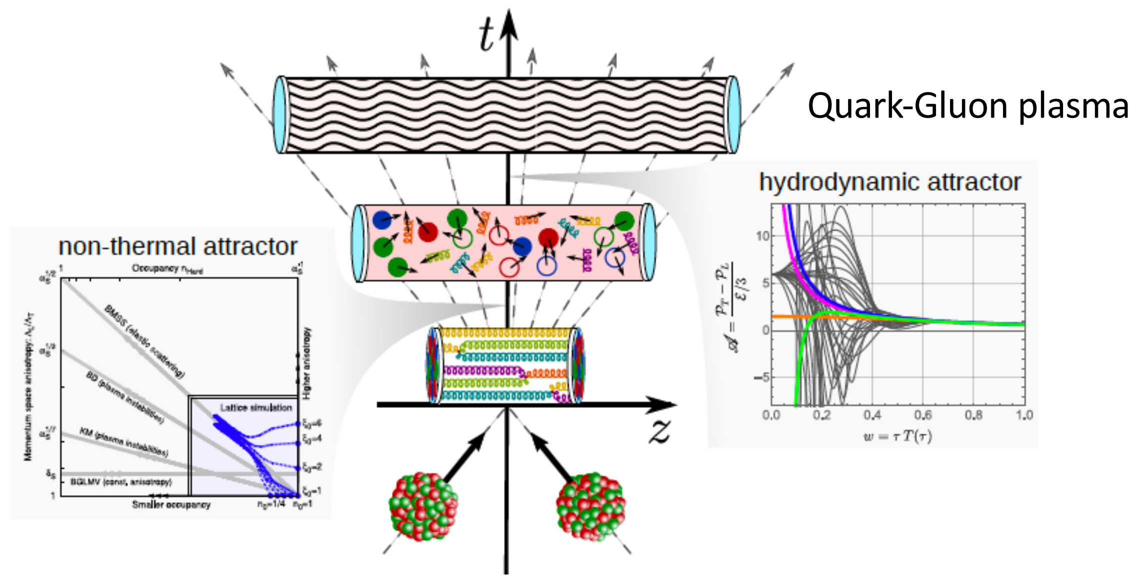
Fully NLO+NLLx computations in p+A are challenging but essential for novel global analysis

A robust continuing p+A experimental program at RHIC and the LHC is likewise very important

Colliding gluon shockwaves in a heavy-ion collision







Colliding Color Glass Condensates

Berges, Heller, Mazeliauskas, Venugopalan, Rev. Mod. Phys. **93**, (2021) 035003

Ab initio description in the CGC

Thermalized soft bath of gluons at $\tau > \frac{1}{\alpha_S^{5/2}} \frac{1}{Q_S}$

Thermalization temperature: $T_i = \alpha_S^{2/5} Q_S$

$$\tau_{\mathrm{therm}} \propto \frac{(\log Q_S)^{2.5}}{Q_S} \to 0 \text{ for } Q_S \to \infty$$

Uncovering early-time dynamics of QGP important focus of RHIC & LHC experiments (Eg., collimated long-range “ridge” correlations) : strong tie in of TMD/GPD/small x physics at EIC to Initial Conditions for high multiplicity hadron-hadron collisions

Dedicated conference series: “Initial Stages” ~ 150-200 participants. Next Edition: Copenhagen, June 19-24, 2023

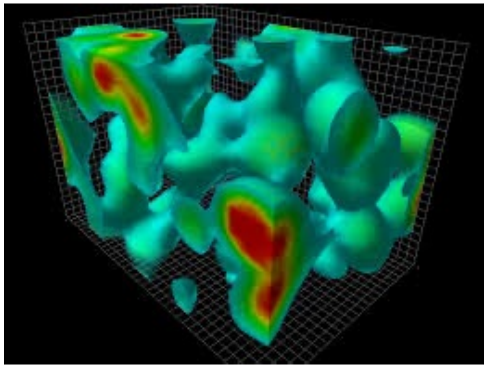
The interplay of gluon saturation and QCD spin

Proton helicity: $S^{\mu}\,\Delta\Sigma \;=\; \langle P,S\,|\,\bar{\psi}\,\gamma^{\mu}\gamma_5\,\psi\,|\,P,S\rangle \;\equiv\; \langle P,S\,|\,j_5^{\mu}\,|\,P,S\rangle$

Sensitive to the topology of the QCD vacuum
from the anomaly equation

$$\partial_\mu J_5^\mu = 2n_f \partial_\mu K^\mu + \sum_{i=1}^{n_f} 2im_i \bar{q}_i \gamma_5 q_i$$

with Chern-Simons current $K_\mu = \frac{g^2}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\left[A_a^\nu\left(\partial^\rho A_a^\sigma - \frac{1}{3} g f_{abc} A_b^\rho A_c^\sigma\right)\right]$

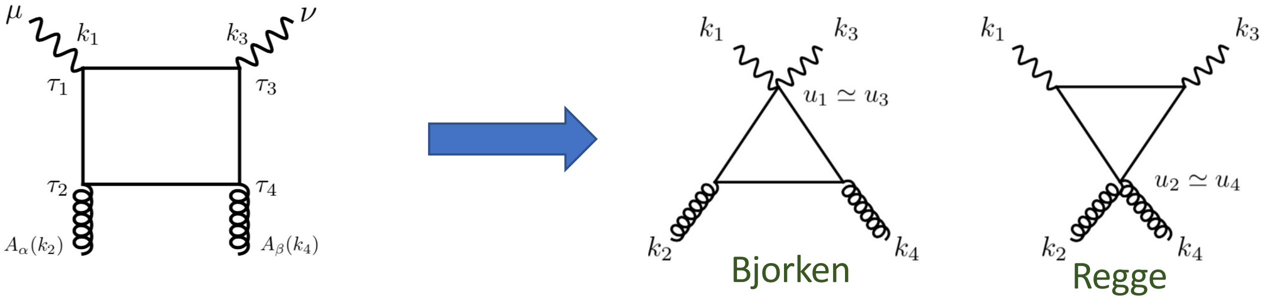


Visualization of topological gauge configurations
D. Leinweber

Considerable work on small x QCD evolution of polarized distributions – see talk by Kovchegov at Town Hall

Novel observation: The chiral anomaly dominates in both Bjorken and Regge asymptotics of the box diagram

Tarasov, Venugopalan
arXiv:2108.08104, PRD (2021)



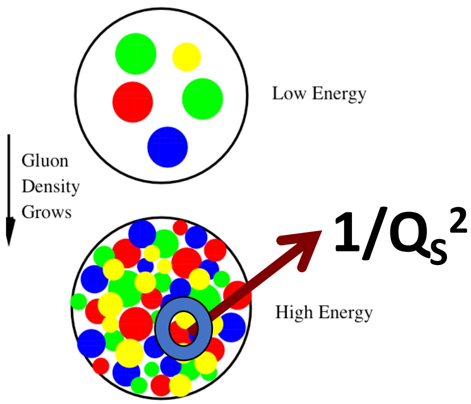
The interplay of gluon saturation and QCD spin

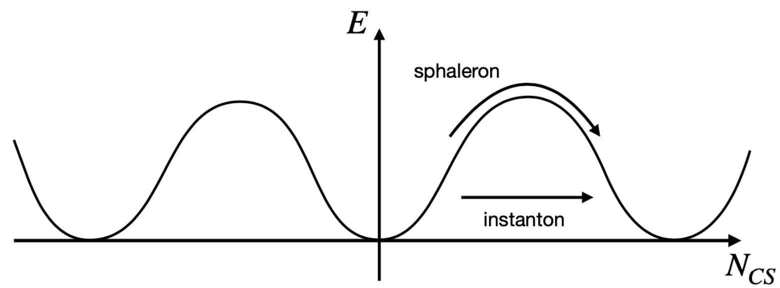
30 year old observation by Shore and Veneziano:
Key role of $\bar{\eta}$ WZW term

$$\Sigma(Q^2) = \sqrt{\frac{2}{3}}\,\frac{2n_f}{M_N}\,g_{\eta_0 NN}\sqrt{\chi'(0)}$$

Derivative of QCD topological susceptibility in forward limit

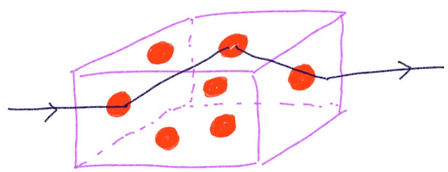
At small x,





Diffusion of topological charge by sphaleron-like transitions at small x: $\Gamma_{sphaleron} \propto Q_S{}^4$

By the Atiyah-Singer Index Theorem:
rapid quenching of helicity in topologically disorderd media

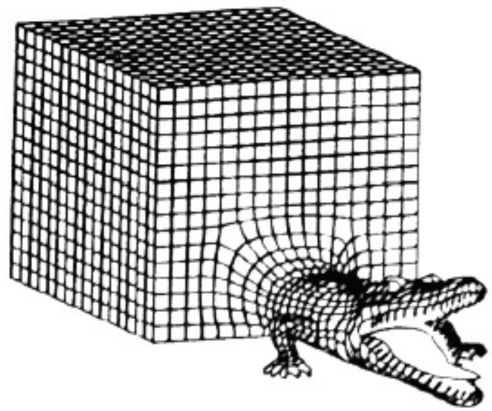


$$g_1^{\mathrm{Regge}}(x_B, Q^2) \propto F(x_B) \times \frac{Q_S^2 m_{\eta'}^2}{F_{\bar{\eta}}^3 M_N} \exp\left(-4\,n_f C\,\frac{Q_S^2}{F_{\bar{\eta}}^2}\right)$$

Exciting possibility of first clear observation at EIC of sphaleron-like topological transitions in nature

Tarasov, RV, arXiv:2109.10370, PRD (2022)

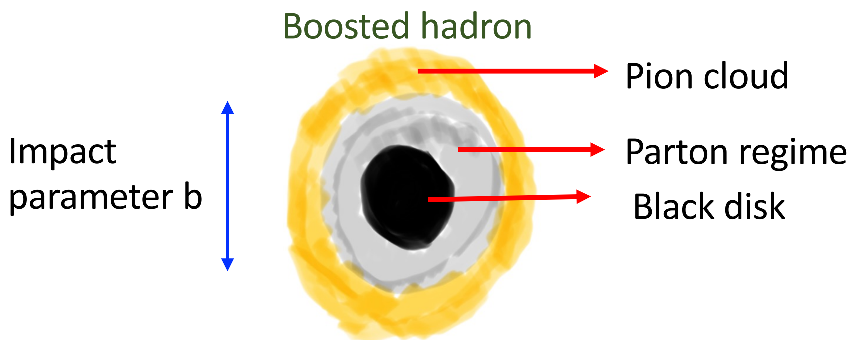
Grand challenge for EIC theory: QCD at small x from first principles



Don’t try (yet) on the lattice…despite some progress, needs new ideas for “deep Minkowski” region of theory:

My bet with Xiangdong Ji (witness Yuri Kovchegov) :
Will Lattice QCD (Ji) or Quantum Computing (RV) first address a concrete small x problem before EIC data

Small x and confinement/χSB: thinking broadly beyond GPDs



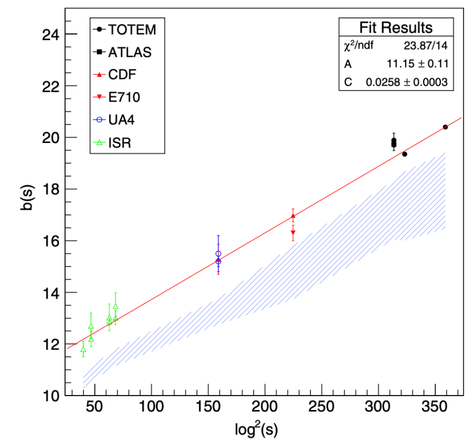


Fig. from A. Nayak,J.Maharana, PRD102 (2020)034018

Evolution kernel contains a Coulomb tail at large b – violates the Froissart bound

Outstanding question: map BFKL/BK dynamics to strong coupling physics at large b?

Important related issue: what sets scale of coefficient of $\mathrm{Ln}^2 s$ term in the Froissart bound.
Fits to data suggest that this scale is $\sim 10\, m_\pi$ consistent with lightest glueball mass/chiral scale ($4\pi f_\pi$)

For an interesting discussion, see S. Nussinov, arXiv:0805.1540

One possible path forward: Focus on gluodynamics combined with large N analytic methods (some inspired by holography)

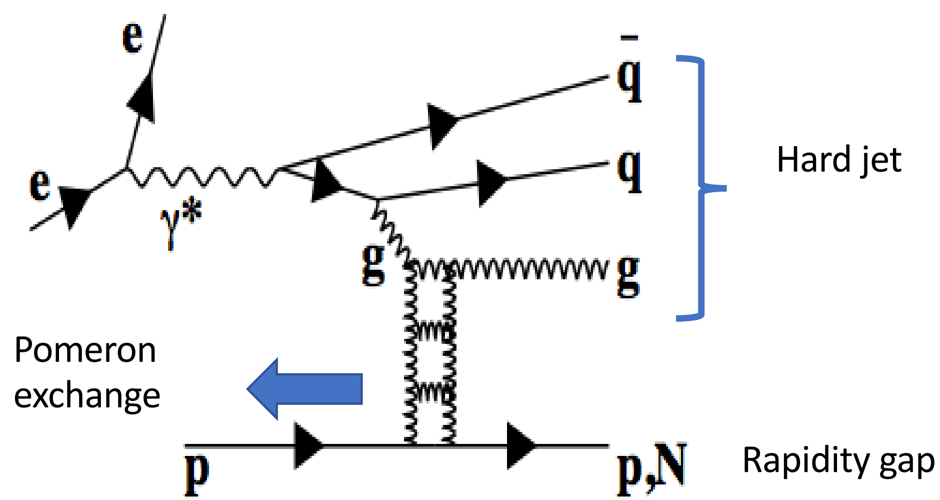
Simons Foundation Collaboration on Confinement and QCD Strings

Director: Igor Klebanov (Princeton)
NP PI's: Aleksey Cherman (Minn.), Phiala Shanahan (MIT), RV (BNL)

https://simonsconfinementcollaboration.org

Thank you for your attention !

Precision studies of the structure of the Pomeron at the EIC



EIC will have 1000 times the luminosity of HERA
- clean, highly differential studies of pomeron dynamics
Also, first such studies in hard DIS off nuclei – is the pomeron flux universal?