What wee partons reveal about hadron structure at high energies and the dynamics of confinement-I

Raju Venugopalan

Brookhaven National Laboratory

Midsummer school, Saariselka, Finland, June 25-27, 2024

Quantum Chromodynamics (QCD)

QCD - “nearly perfect” fundamental quantum theory of quark and gluon fields F.Wilczek, hep-ph/9907340

Theory is rich in symmetries: “Symmetries dictate interactions” – C.N Yang

$$\underbrace{SU(3)_c}_{\textbf{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\textbf{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\textbf{iii}}$$

i) Gauge “color” symmetry: unbroken but confined
ii) Global “chiral” symmetry: exact for massless quarks
iii) Baryon number and axial charge (m=0) are conserved
iv) Scale invariance of quark (m=0) and gluon fields
v) Discrete C,P & T symmetries

Chiral, Axial, Scale and (in principle) C, P &T broken by vacuum/quantum effects - ”emergent” phenomena

Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

Fundamental feature of QCD: Yang-Mills Theory

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

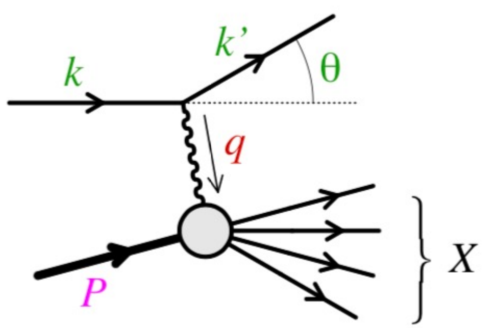
C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

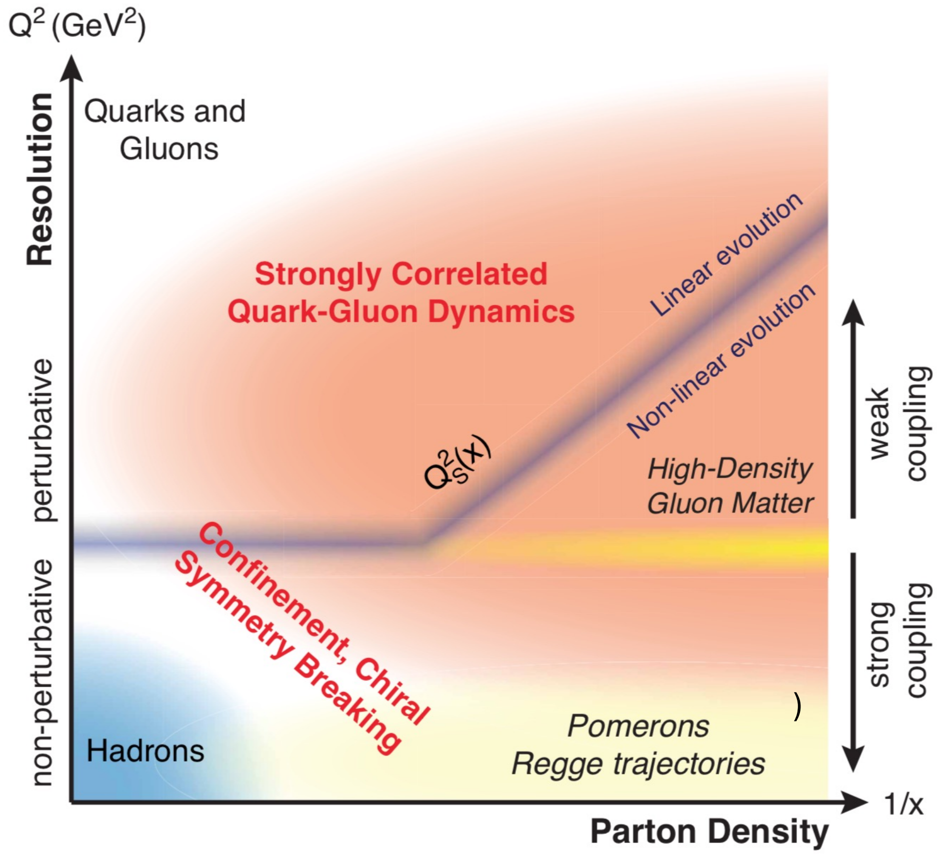
Possibly the most important paper from BNL

Landscape of the strong interaction

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

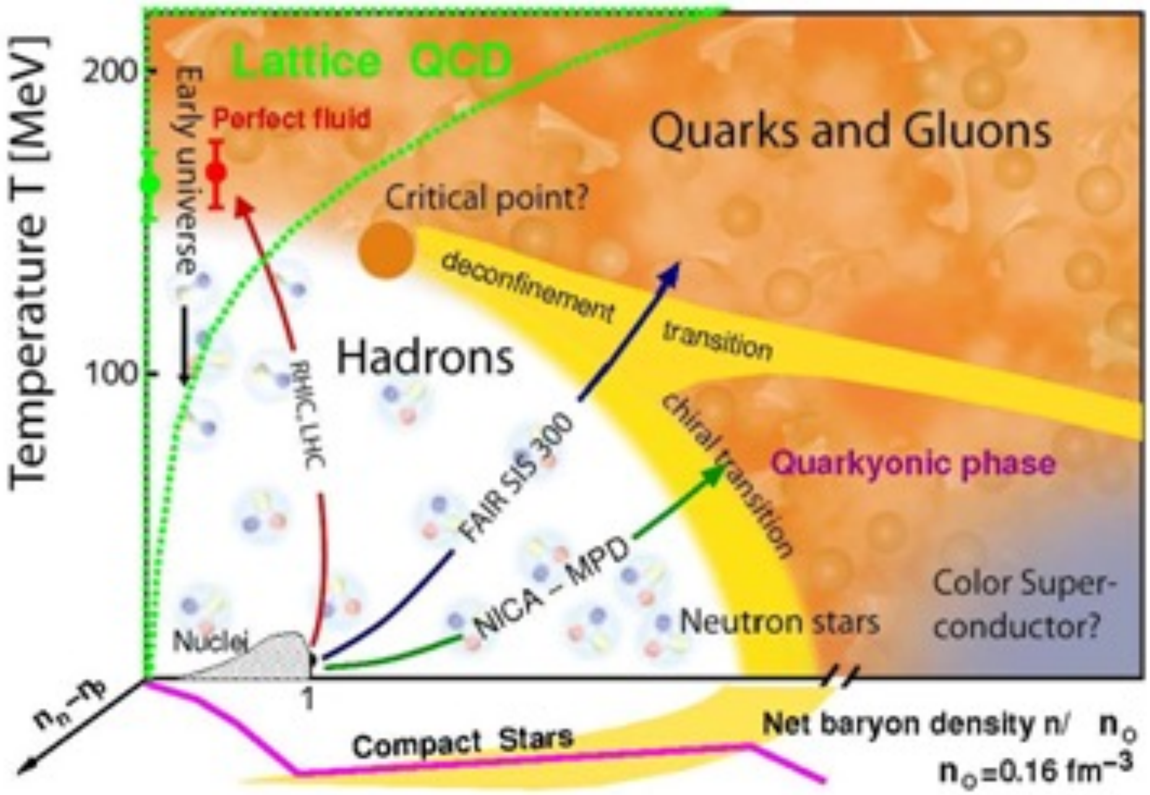


Deeply inelastic scattering



Many open questions: 3-D structure of quark-gluon structure of protons & nuclei, spin and orbital dynamics, many-body correlations, multi-particle production...

The QCD phase diagram



From lattice QCD: cross-over temperature
from hadron gas to quark-gluon plasma = 156.5 $\pm$1.5 MeV (approx. 2 trillion Kelvin!)

The elephant in the room: quark and gluon confinement

Clay Millenial Prize Problem:

Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on R^4 and has a mass gap $\Delta > 0$

Existence include establishing axiomatic properties at least as strong as those cited in Streater & Wightman (1964),[19] Osterwalder & Schrader (1973),[20] and Osterwalder & Schrader (1975).[21]

Arthur Jaffe and Ed Witten, courtesy Wikipedia

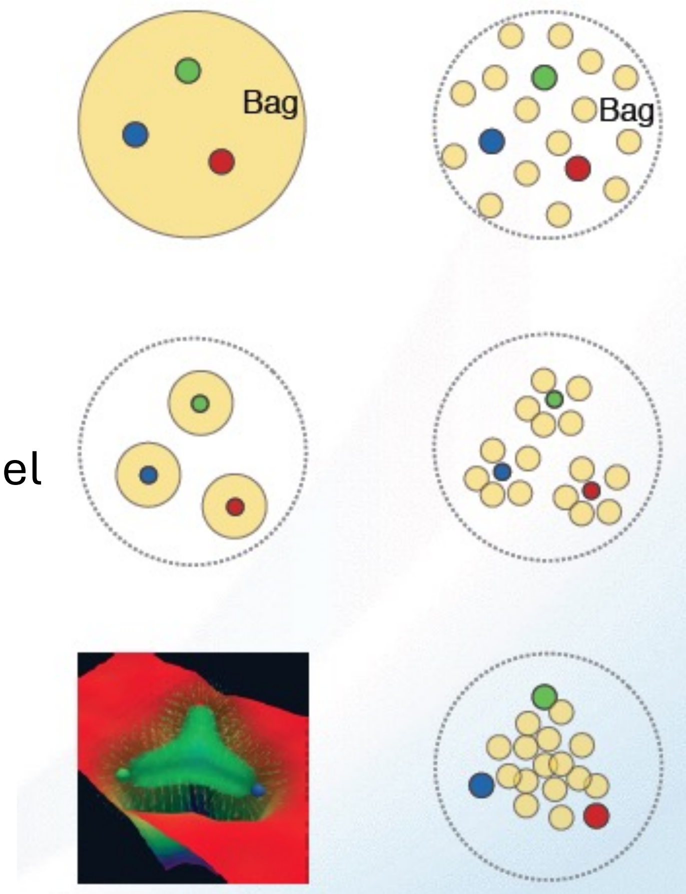
Dynamical confinement: an enduring puzzle

Static pictures | Boosted proton

Bag Model

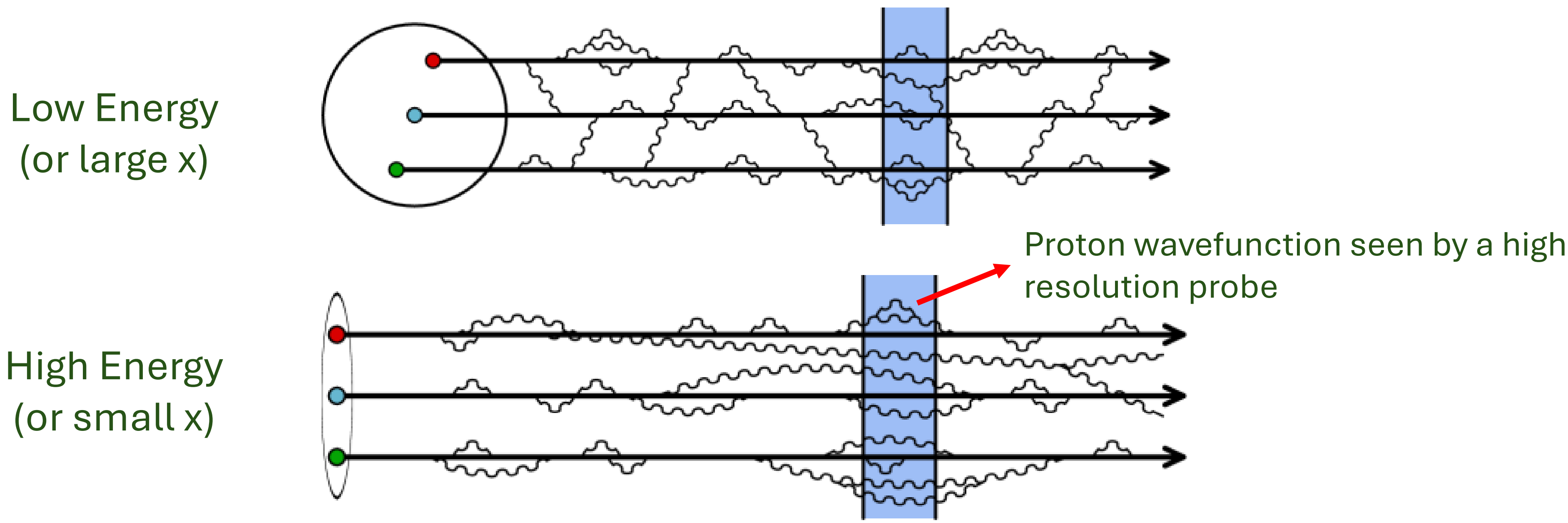
Constituent Quark Model

Lattice Gauge Theory



Fresh insight from the buzz of wee partons ?

Lifting the veil: boosting the proton uncovers many-body structure

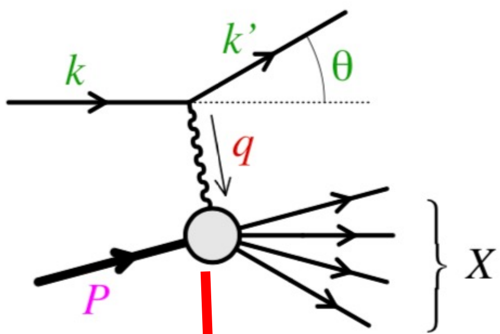


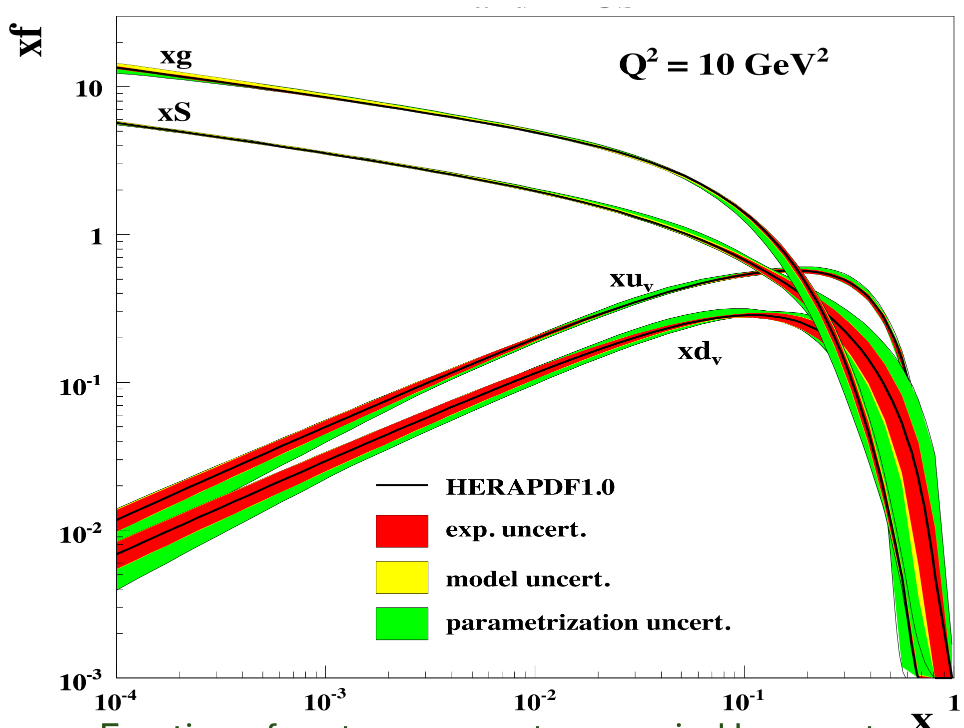
“Wee” parton fluctuations carrying a fraction x << 1 of proton’s moment are time dilated on strong interaction time scales.

Long lived (large x) gluons radiate shorter lived (small x) gluons…and so on, in a “Markovian”
Exponential growth of gluon multiplicity

The proton as a complex many-body system

Deeply Inelastic Scattering (DIS)





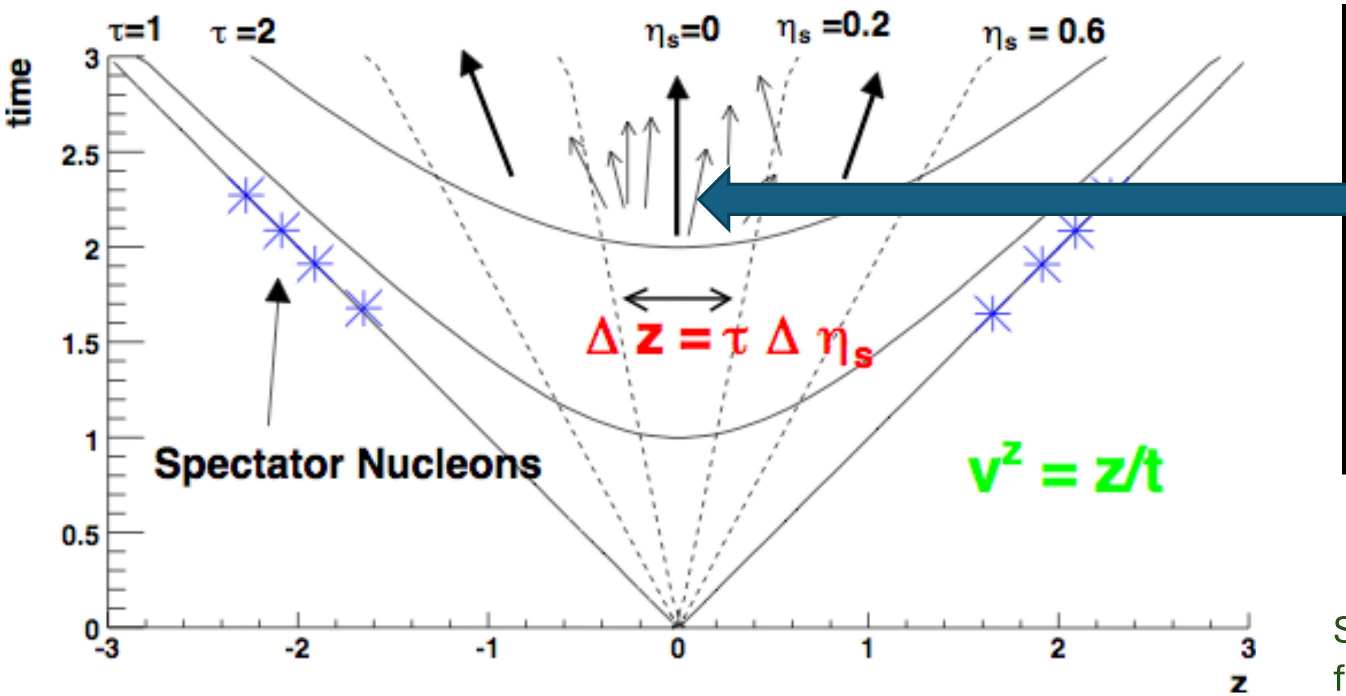
Fraction of proton momentum carried by a parton

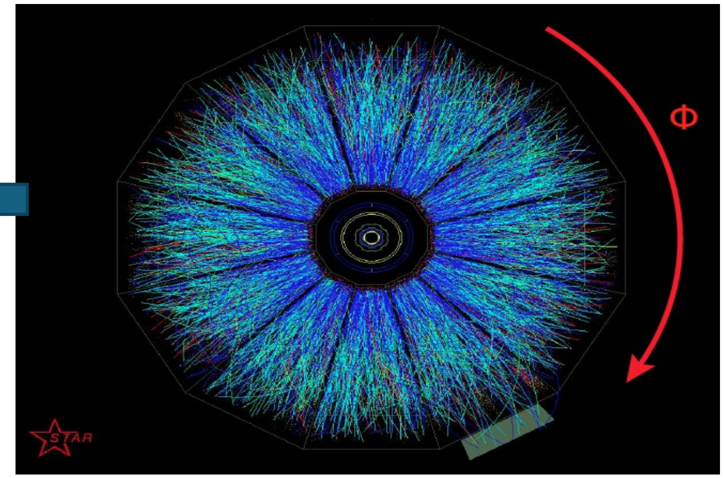
A key lesson from the HERA DIS collider:

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

The boosted proton

Spacetime picture of a high energy hadron-hadron collision





$$\eta_s = \frac{1}{2}\,\mathrm{Ln}\,\left(\frac{t+z}{t-z}\right) \approx Y$$

Spacetime rapidity ≈ momentum rapidity for ultrarelativistic particles

Fast “valence” partons populate fragmentation regions at large rapidities – “leading particle” effect

Slow “wee” partons populate central rapidities (mostly gluons and sea-quark pairs)

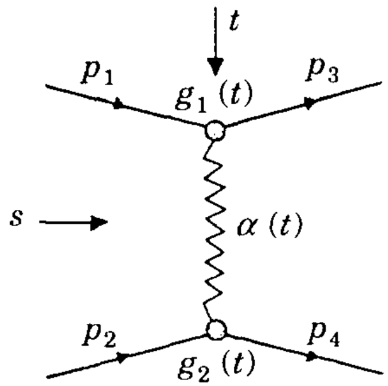
Other interdisciplinary connections of QCD at small x

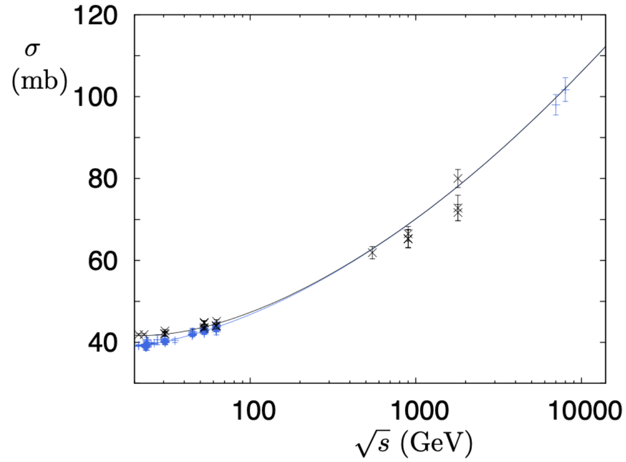
Overoccupied ultracold atomic gases

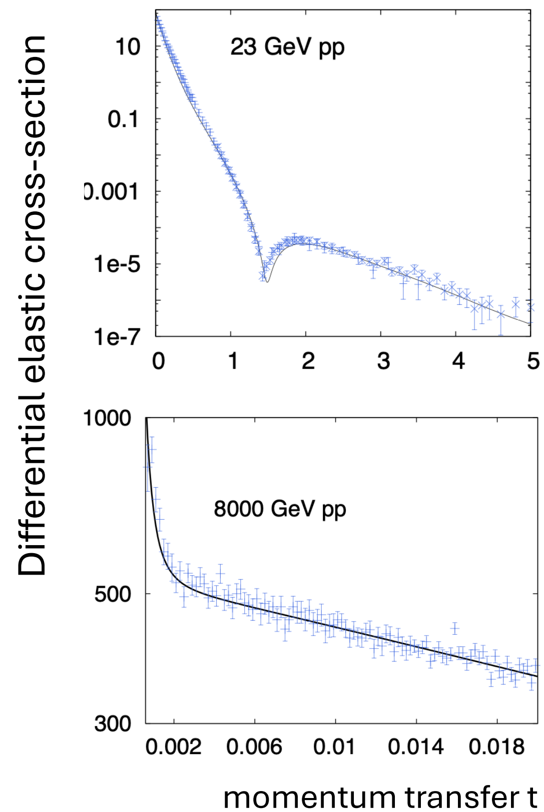
Inflationary dynamics and sphaleron transitions in the early universe

Black Holes and quantum information science

High energy cross-sections: the Pomeron







Total cross-sections across three orders of magnitude in energy (SPS -> LHC) simply described in terms of Pomeron and Reggeon trajectories:

Scattering amplitude $A(s,t) = s^{\alpha(t)}$ with $\alpha(t) = 1 + \varepsilon + \alpha' t$

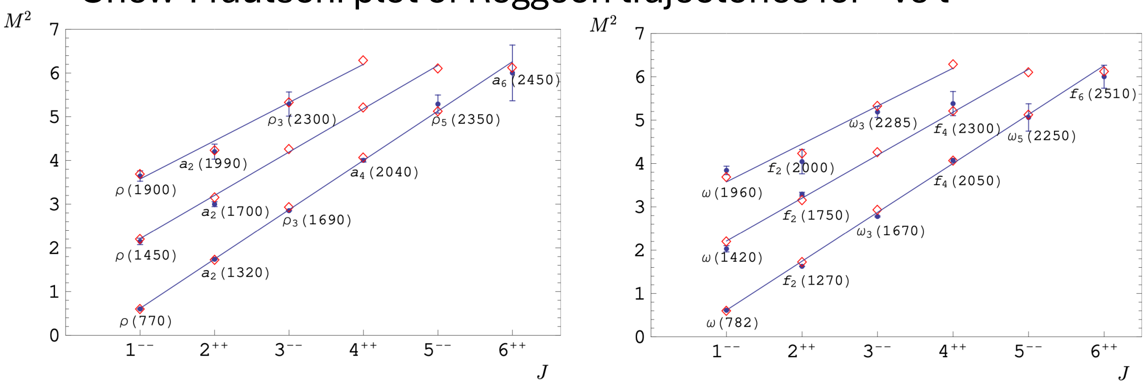
Pomeron: t-channel exchange (corresponding to a pole in the t-j plane) with vacuum quantum numbers dominates total hadron-hadron cross-sections

Intercept ε_P= 0.11 String tension α'= 0.165 GeV^{-2}

Donnachie, Landshoff, Phys. Lett. B750 (2015) 669

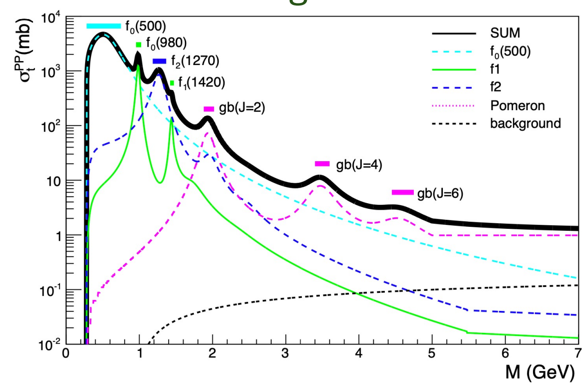
High energy cross-sections: Pomerons+Reggeons

Chew-Frautschi plot of Reggeon trajectories for +ve t



Ebert et al.,arXiv:0903.5183

Pomeron glueball candidates



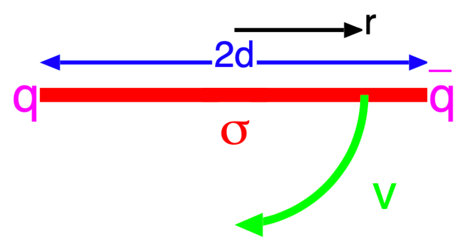
Schiker et al., arXiv:1910.02494

$J(M^2) = \alpha(0) + \alpha' M^2$

$$\alpha' = \frac{1}{2\pi\sigma}$$

trajectory	$\sqrt{\sigma}$/MeV	ΔJ
$\pi, b_1, \ldots$	469(6)	0.06
$\rho, a_2, \ldots$	429(2)	0.03
$\omega, f_2, \ldots$	436(8)	0.12
$\phi, f_2', \ldots$	437(5)	0.06
$K, K_1, \ldots$	480(4)	0.04
$K^*, K_2^*, \ldots$	424(5)	0.07

Bali, hep-ph/0001312

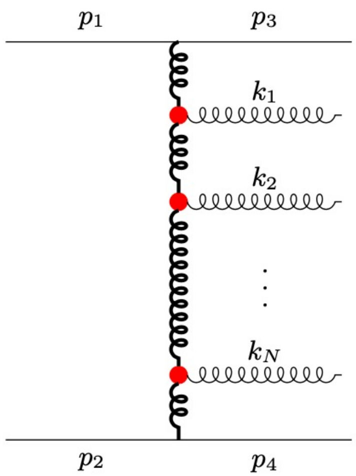


Relativistic quark model

Reggeon field theory:
Veneziano dual resonance model relating s and t channel S-matrix unitarity provided much of the powerful initial (pre+post-QCD) motivation for string theory and incipient relativistic quark model for confinement

Veneziano, Nuovo Cim. 57, 190 (1968)

The BFKL Pomeron: 2→ N QCD amplitudes in Regge asymptotics*



Compute multiparticle in multi-Regge kinematics of QCD:

$$y_0^+ \gg y_1^+ \gg y_2^+ \gg \cdots \gg y_N^+ \gg y_{N+1}^+ \qquad \text{with} \qquad \boldsymbol{k}_i \simeq \boldsymbol{k}$$

BFKL ladder is ordered in rapidity . Produced partons are wee in longitudinal momentum(` `slow") but hard in transverse momentum – weak coupling Regge regime

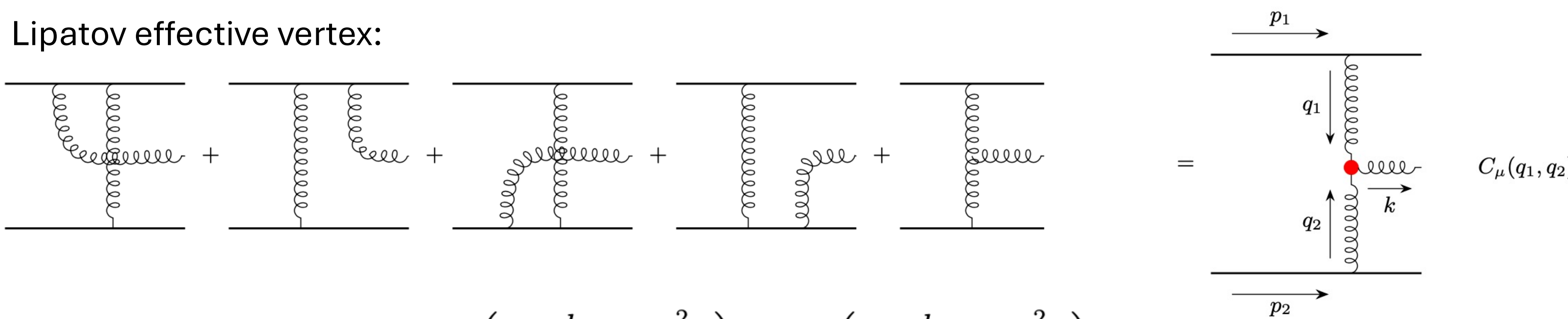
RG description rapidity of evolution given by the BFKL Hamiltonian
Very rapid growth of the amplitude with energy

A(s,t) = $s^{\alpha(t)}$ with $\alpha(t) = \alpha_0 + \alpha' \, |t|$ BFKL pomeron

* Asymptotics is the calculus of approximations. It is used to solve hard problems that cannot be solved exactly and to provide simpler forms of complicated results

BFKL: Building blocks

Lipatov effective vertex:

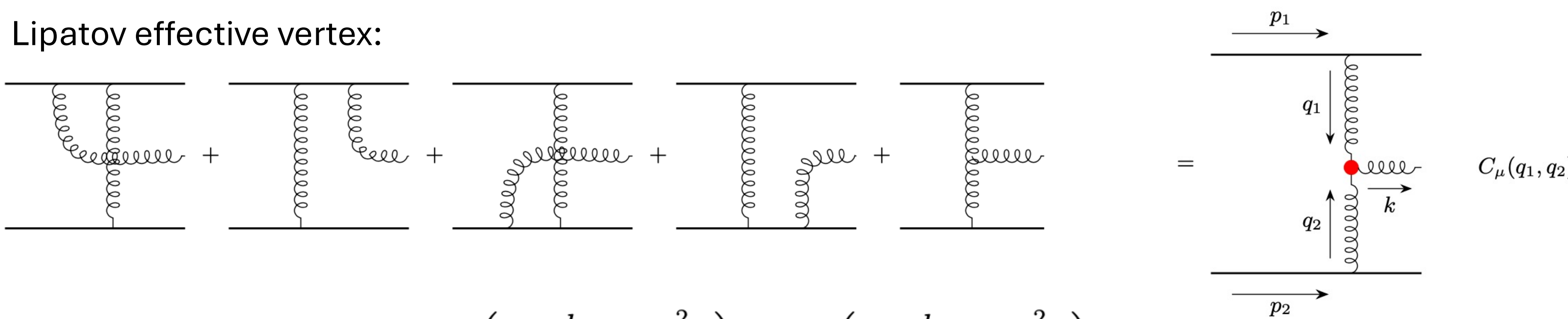


$$C_\mu(\boldsymbol{q}_1, \boldsymbol{q}_2) \simeq -\boldsymbol{q}_{1\mu} + \boldsymbol{q}_{2\mu} + p_{1\mu}\left(\frac{p_2 \cdot k}{p_1 \cdot p_2} - \frac{\boldsymbol{q}_1^2}{p_1 \cdot k}\right) - p_{2\mu}\left(\frac{p_1 \cdot k}{p_1 \cdot p_2} - \frac{\boldsymbol{q}_2^2}{p_2 \cdot k}\right)$$

Gauge covariant, satisfies $k_\mu\, C^\mu$ =0

BFKL: Building blocks

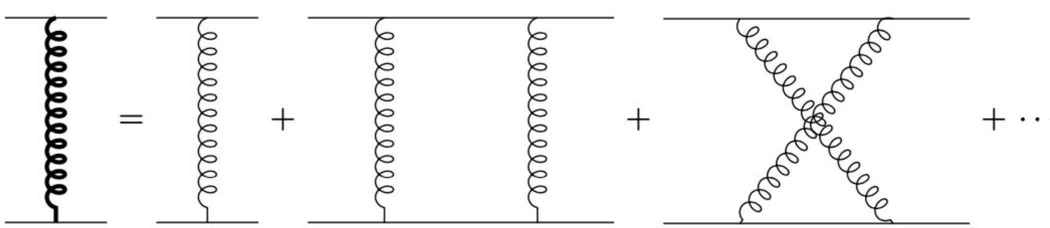
Lipatov effective vertex:



$$C_\mu(\boldsymbol{q}_1, \boldsymbol{q}_2) \simeq -\boldsymbol{q}_{1\mu} + \boldsymbol{q}_{2\mu} + p_{1\mu}\left(\frac{p_2 \cdot k}{p_1 \cdot p_2} - \frac{\boldsymbol{q}_1^2}{p_1 \cdot k}\right) - p_{2\mu}\left(\frac{p_1 \cdot k}{p_1 \cdot p_2} - \frac{\boldsymbol{q}_2^2}{p_2 \cdot k}\right)$$

Gauge covariant, satisfies $k_\mu\, C^\mu$ =0

Reggeized gluon:

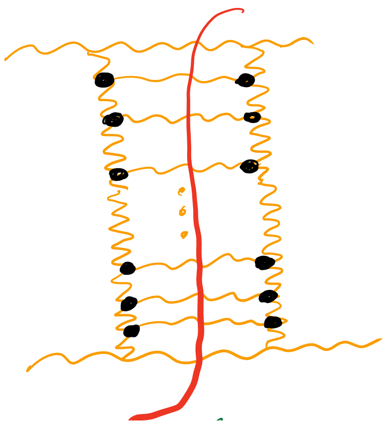


$$\frac{1}{t_i} \to \frac{1}{t_i} e^{\alpha(t_i)(y_{i-1} - y_i)}$$

$$\alpha(t) = \alpha_s N_c\, t \int \frac{d\boldsymbol{k}}{(2\pi)^2} \frac{1}{\boldsymbol{k}^2 (\boldsymbol{q} - \boldsymbol{k})^2}\,, \qquad t = -\boldsymbol{q}^2$$

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

BFKL Pomeron: compound color singlet state of two reggeized gluons



$$\mathrm{Im}\, A(s,t) \propto \sum_{n=0}^{\infty} (\alpha_s C_T)^{n+2}$$

C_T is color factor

$$\times \int \prod_{i=1}^{n} \frac{dy_i}{4\pi} \prod_{j=1}^{n+1} \frac{d^2 q_{jl}}{(2\pi)^2}$$

Phase space factors

$$\times\ 2is \prod_{l=1}^{n+1} \frac{1}{t_l t_{l'}} e^{(y_{l-1}-y_l)[\alpha(t_l)+\alpha(t_l')]}$$

→ Reggeized propagators on both sides of cut

$$\times \prod_{m=1}^{n} (C_\mu C^\mu)[q_m, q_{m+1}]$$

→ Product of Lipatov vertices

$$\sigma_{tot} = 2\,\mathrm{Im}\, A(s,t=0)$$

$$= s^{\lambda} \text{ with } \lambda = \frac{4\alpha_s N_c \ln 2}{\pi}$$

$$\simeq 0.5 \text{ for } \alpha_s = 0.2$$

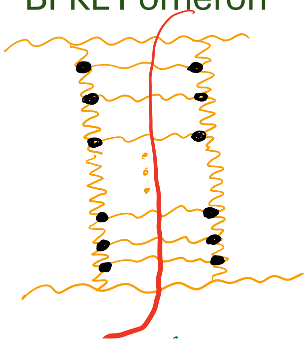
Real and virtual corrections combine to cancel infrared divergence !

Strongly violates Froissart bound

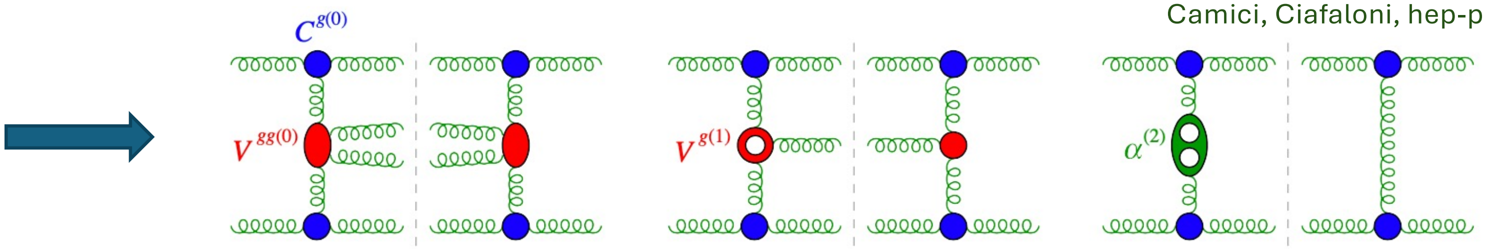
Resummed NLO BFKL : $\lambda \approx 0.3$

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

BFKL Pomeron



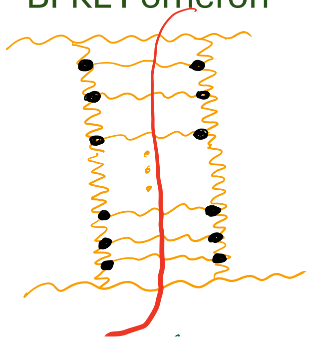
Fadin, Lipatov, hep-ph/9802290
Camici, Ciafaloni, hep-ph/8903389



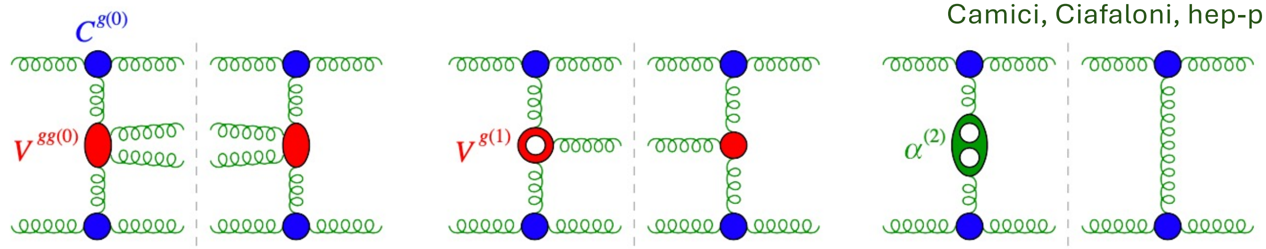
Regge factorization at NLL $[(\alpha_S \, \mathrm{Ln}(s/t))^n]$: Includes one loop corrections to the Lipatov vertex ($V^{g(1)}$) and two loop corrections to the Regge trajectory ($\alpha^{(2)}$)

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

BFKL Pomeron

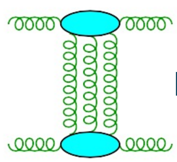


Fadin, Lipatov, hep-ph/9802290
Camici, Ciafaloni, hep-ph/8903389



Regge factorization at NLL [$(\alpha_S \text{ Ln}(s/t))^n$]: Includes one loop corrections to the Lipatov vertex ($V^{g(1)}$) and two loop corrections to the Regge trajectory ($\alpha^{(2)}$)

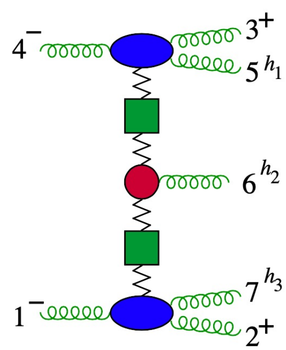
Beyond NLL:



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

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



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

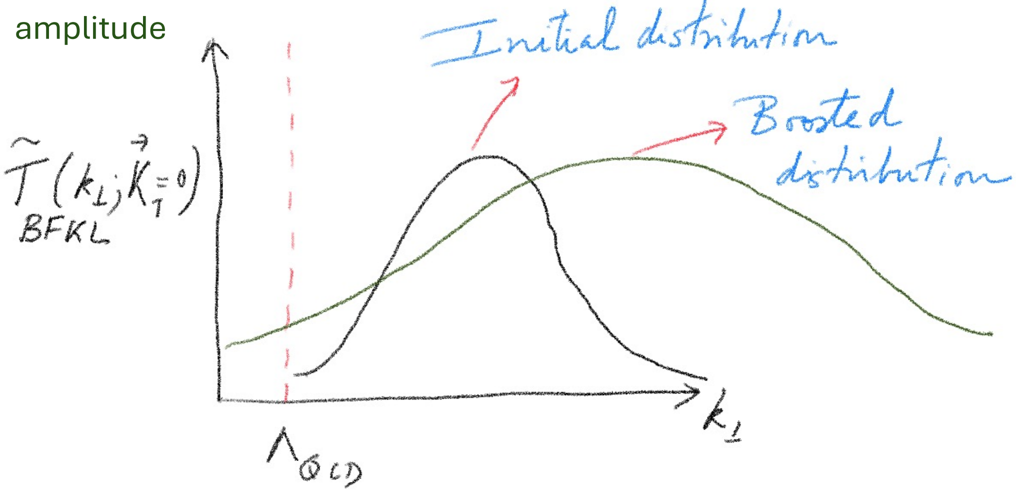
Dual conformal tranformations → BDS ansatz; rich mathematical structure of MHV amplitudes in MRK kinematics

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

Figures from excellent review of state-of-the art:
Del Duca, Dixon, arXiv:2203.13026

BFKL: infrared diffusion and gluon saturation

BFKL forward amplitude



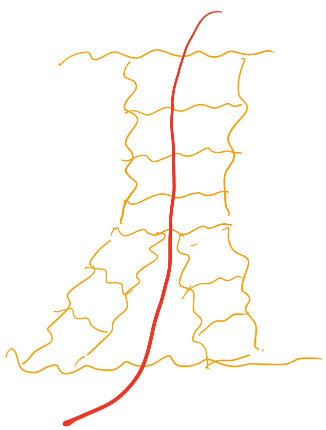
For a fixed large Q^2 there is an $x_0(Q^2)$ such that below x_0 the OPE breaks down…

significant nonperturbative corrections in the leading twist coefficient and anomalous dimension functions due to diffusion of gluons to small values of transverse momentum.

A. H. Mueller, PLB 396 (1997) 251

NLL BFKL does not cure infrared diffusion

Gluon saturation cures infrared diffusion



+ other higher twist cuts of O(1) when gluon occupancy $N \equiv \frac{xG_A(x,Q_S^2)}{2(N_c^2-1)\pi R_A^2 Q_S^2} = \frac{1}{\alpha_S(Q_S)}$

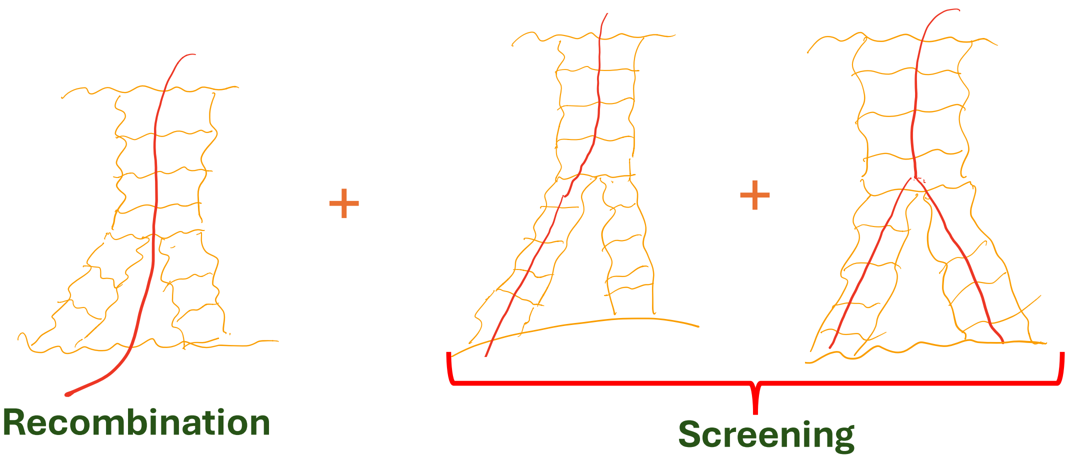
Classicalization when $\alpha_S(Q_S) \ll 1$ for saturation scale $Q_S \gg \Lambda_{QCD}$

Breakdown of OPE: Multi-Pomeron and Reggeon exchange

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

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

Partons recombine and screen – many-body "shadowing"



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

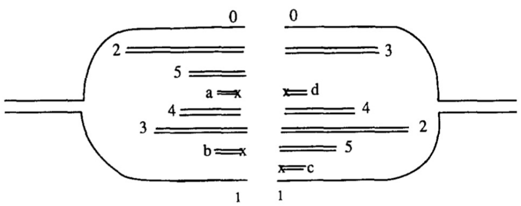
All-twist power suppressed contributions
{"death by a million cuts" equally important for $N \equiv \frac{xG_A(x,Q_S^2)}{2(N_c^2-1)\pi R_A^2 Q_S^2} = \frac{1}{\alpha_S(Q_S)}$

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

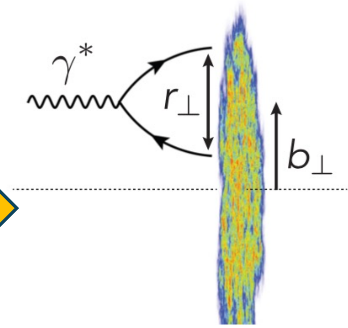
Gluon saturation: classicalization and perturbative unitarization

s-channel "dipole" scattering picture
– more convenient for multi-pomeron interactions

Mueller, NPB415 (1994) 373
Mueller, Patel, hep-ph/9403256



Boosted projectile



Boosted target

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

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

Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

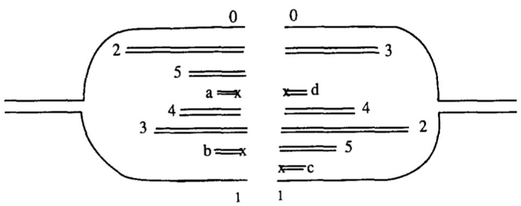
Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

QCD picture of observed "shadowing" at small x

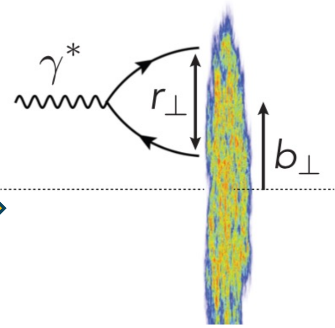
Gluon saturation: classicalization and perturbative unitarization

s-channel "dipole" scattering picture
– more convenient for multi-pomeron interactions

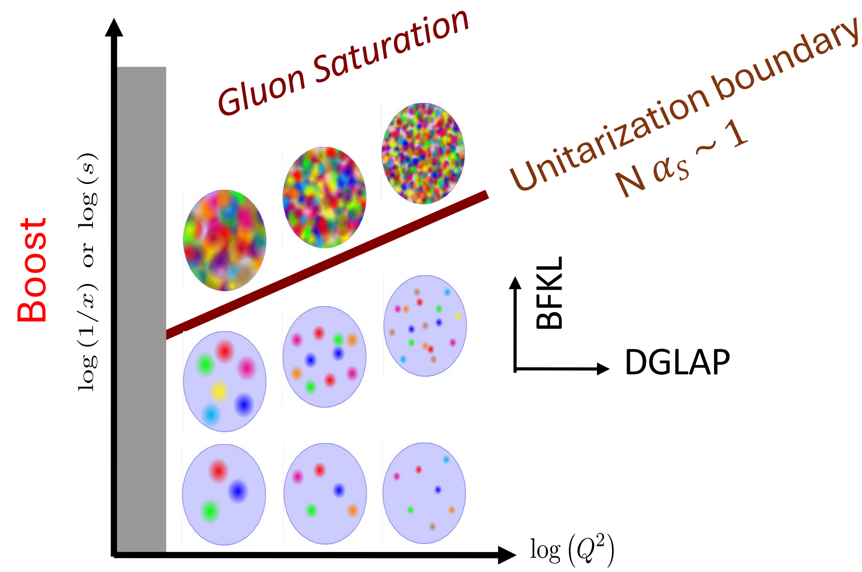
Mueller, NPB415 (1994) 373
Mueller, Patel, hep-ph/9403256



Boosted projectile



Boosted target



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

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

Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

QCD picture of observed "shadowing" at small x