Classicalization, Scrambling and Thermalization in QCD at high energies

Raju Venugopalan
Brookhaven National Laboratory

Galileo Institute School, February 27-March 3, 2020

Outline of lectures

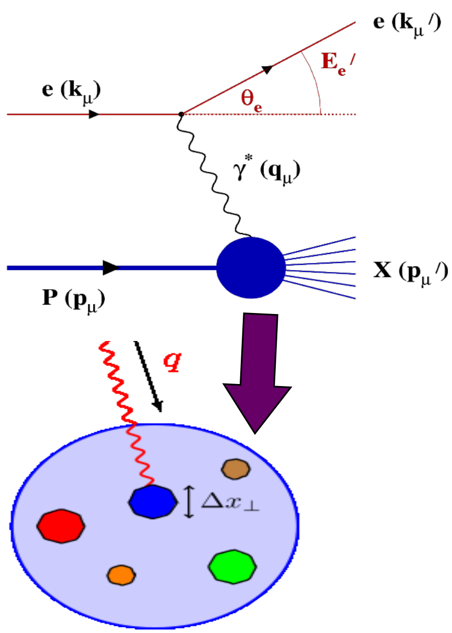
Lecture I: Classicalization: The hadron wavefunction at high energies as a Color Glass Condensate

Lecture II: CGC continued ? Multi-particle production and scrambling in strong fields: the Glasma

Lecture III: Novel features of the Glasma: universal non-thermal fixed points, the Chiral magnetic effect

Lecture IV: Thermalization and interdisciplinary connections

The deeply inelastic scattering (DIS) femtoscope



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Bjorken variable: Measure of momentum fraction of struck quark

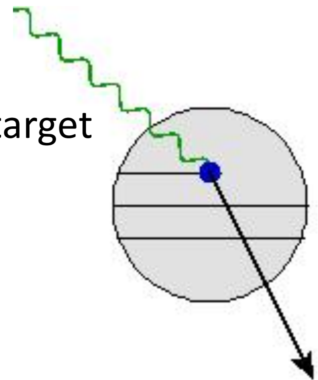
$$\frac{d^2\sigma^{eh\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

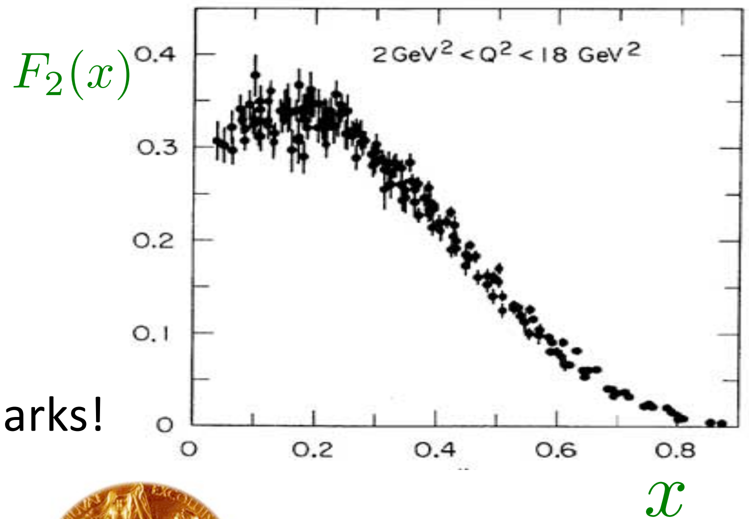
quark+anti-quark momentum distributions

gluon momentum distribution

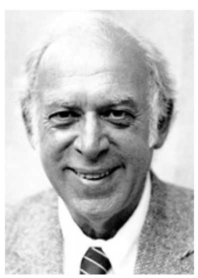
The deeply inelastic scattering (DIS) femtoscope

From SLAC fixed target DIS… (**late 1960s**)

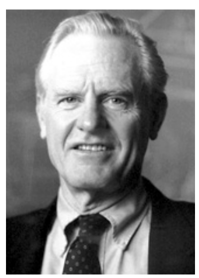




Discovery of quasi-free point-like quarks!



Friedman



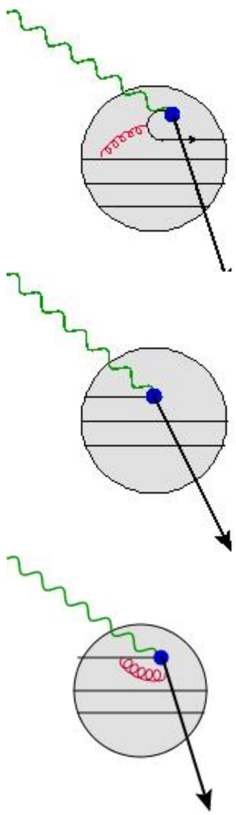
Kendall

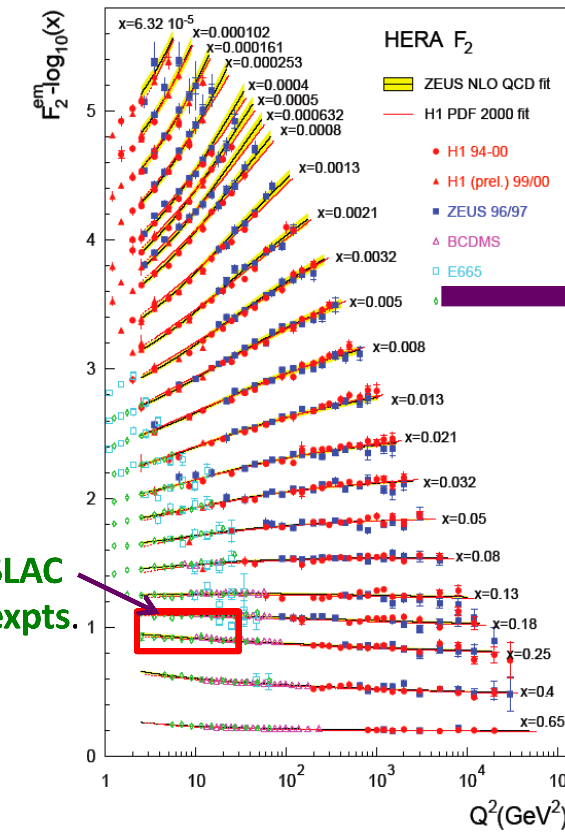
Taylor

(**1990**)

The deeply inelastic scattering (DIS) femtoscope

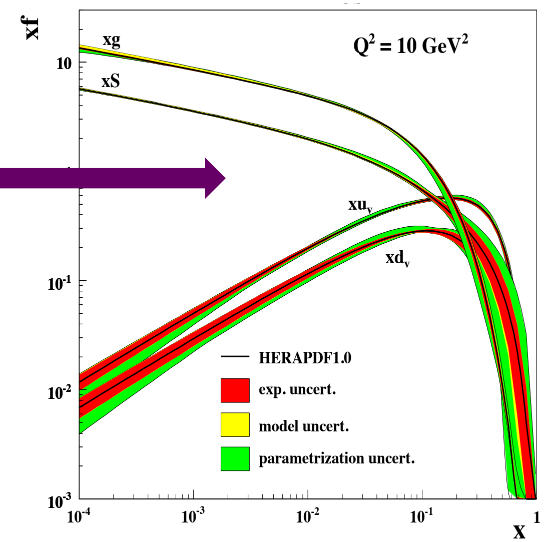
…to the HERA DIS collider (1990s)





SLAC expts.

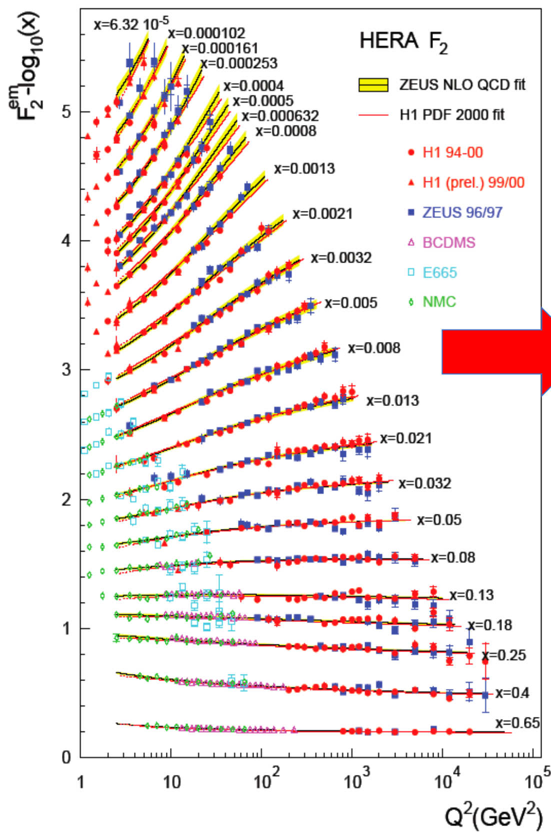
Gluons and "sea" quarks



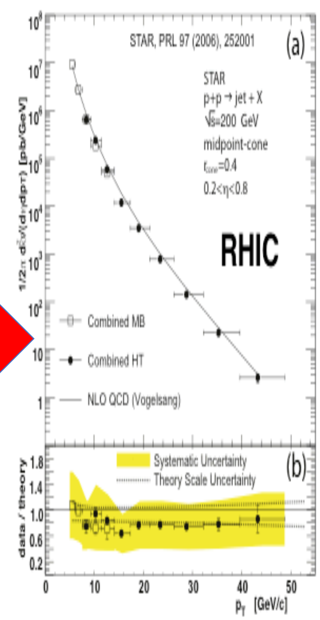
The proton at high energies (small x) is dominated by glue!

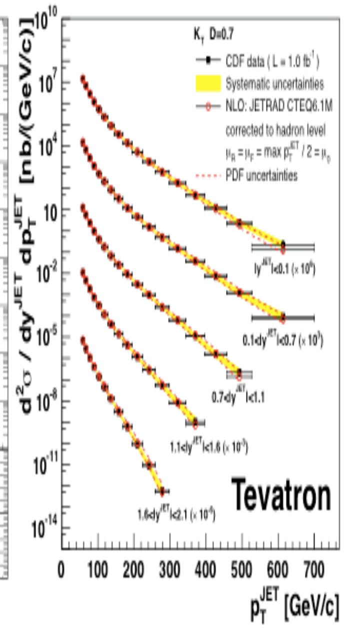
Perturbative QCD: now benchmark for new physics

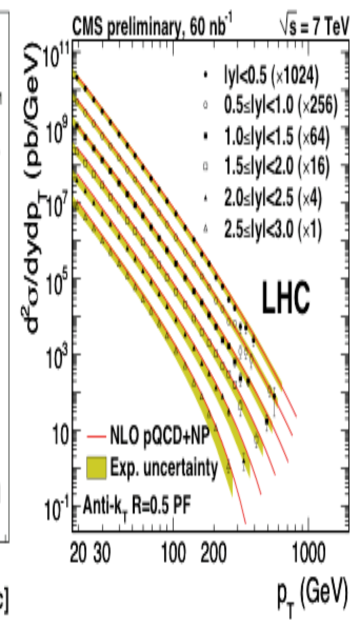
Structure functions measured at HERA electron-proton collider



Jet cross-sections: proton-proton collisions (RHIC &LHC) and proton-antiproton collisions at Fermilab







At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

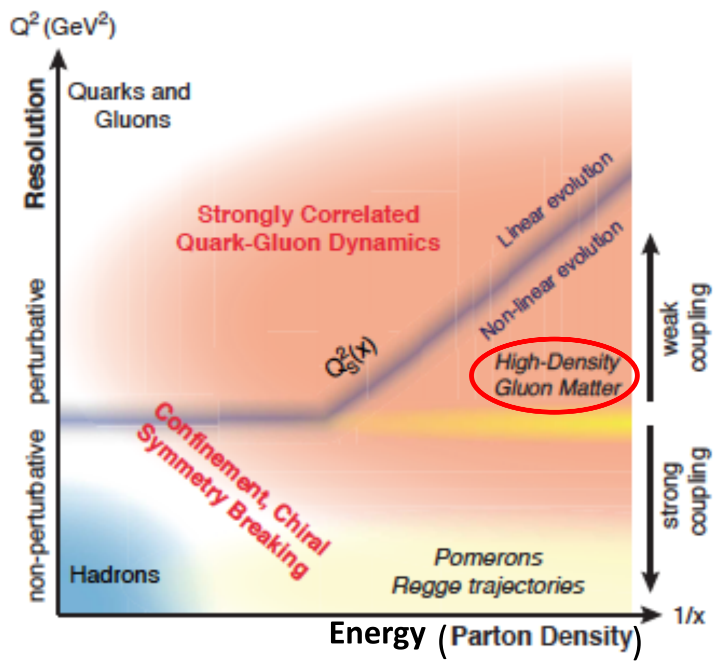
In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

F. Wilczek , "Quarks (and Glue) at the Frontiers of Knowledge"
Talk at Quark Matter 2014

Are we done ?

Scattering in the strong interactions

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



- Perturbative QCD describes only a small part of the total cross-section
- Lattice QCD is of very limited utility in describing scattering
- Effective theories: how do quark and gluon degrees organize themselves to describe the bulk of the cross-section ?

QCD: Known-Unknowns

◆ The bulk of elastic, inelastic and diffractive cross-sections in QCD (sometimes called ``soft" physics – though includes scales of a few GeV).

◆ Fragmentation/hadronization is not understood— though useful and successful parametrizations exist.

◆ *Stringy* models (PYTHIA,DPM,AMPT,EPOS) successfully parametrize a lot of data and loosely capture features of the underlying theory.

◆ However, they *cannot be derived* in any limit from QCD, and require further ad hoc assumptions and numerous tuned parameters when applied in extreme environments

What we need

- An effective theory to describe varied phenomena of multi-particle production in high energy collisions

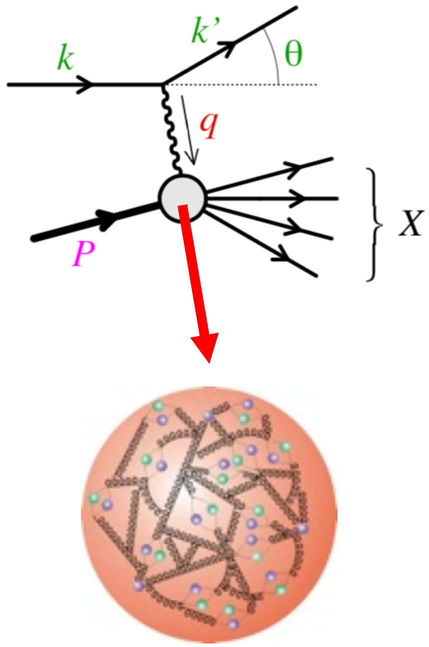
- Smoothly matches to "perturbative" QCD in appropriate kinematic limits

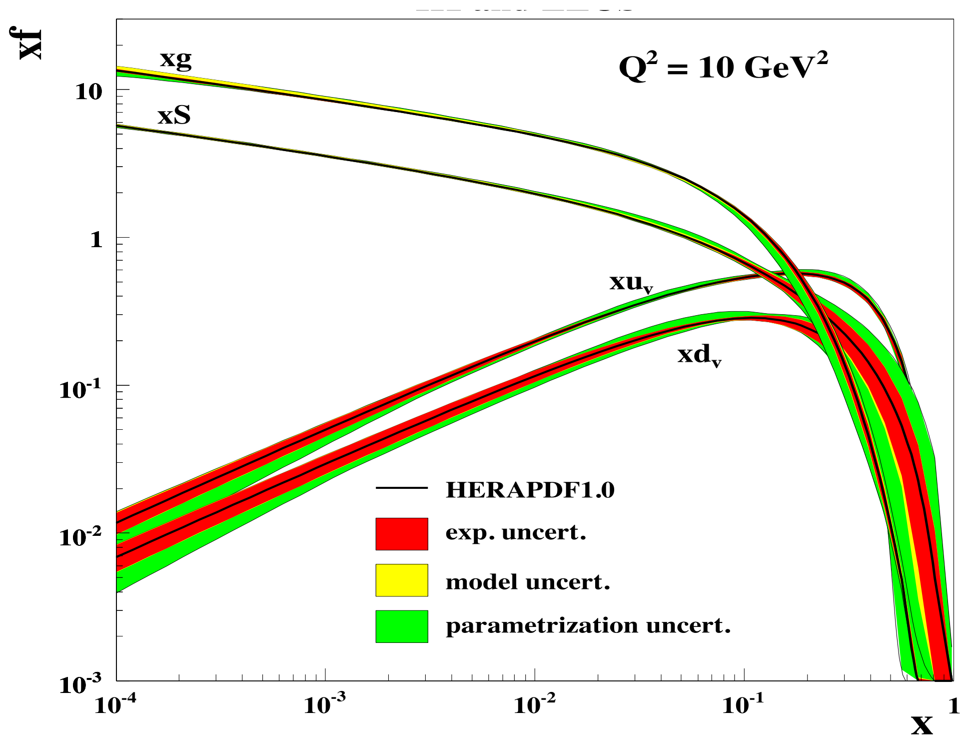
- The rest of my talk will briefly outline the elements of such an effective theory.

- The theory has much predictive power— it provides an efficient and systematic description of *DIS, hadron-hadron and heavy-ion collisions*.

- However, it is least effective when the physics is sensitive to the infrared scales that govern chiral symmetry breaking and confinement.

The proton as a complex many-body system

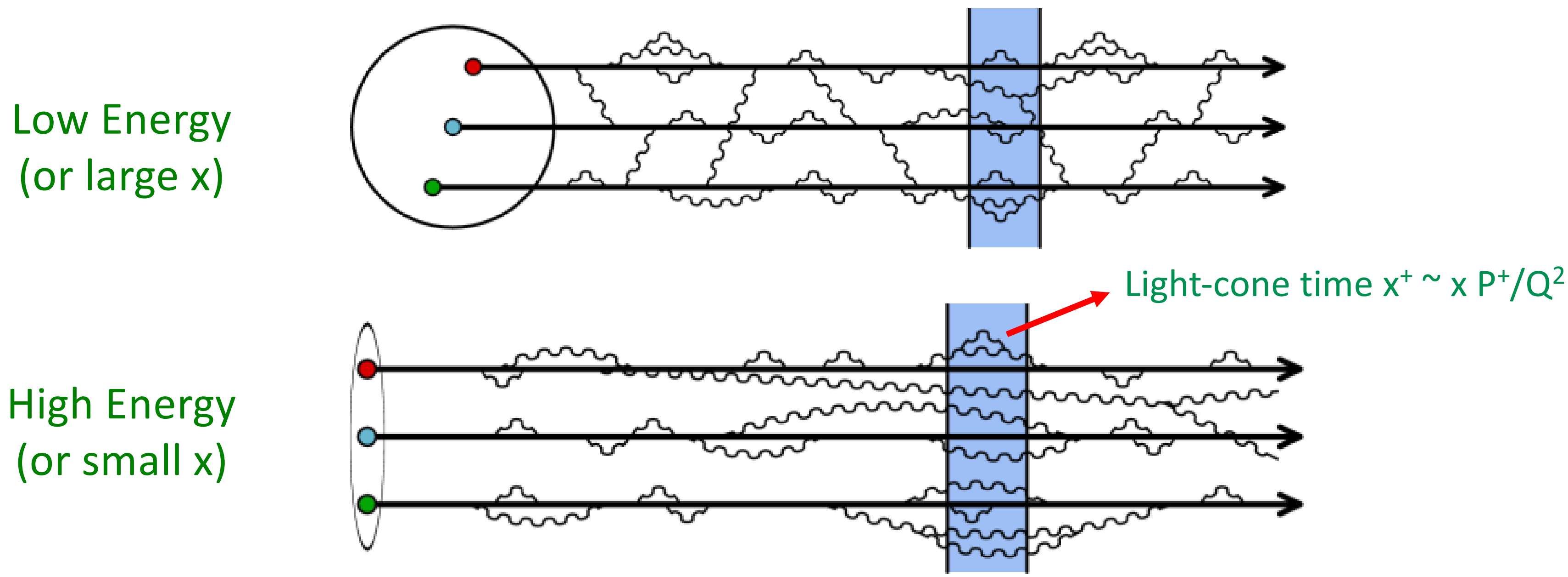




A key lesson from the HERA DIS collider:

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

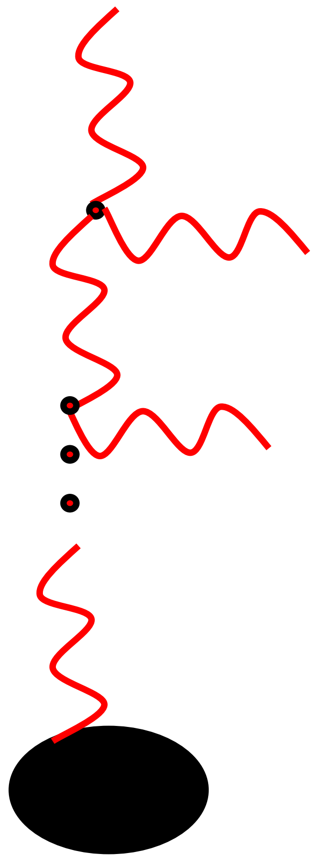
Lifting the veil: boosting the proton uncovers many-body structure



Wee parton fluctuations time dilated on strong interaction time scales.

Long lived gluons radiate further small x gluons…Markovian process
- power law growth of gluon distribution at small x.

Bremsstrahlung in perturbative QCD



Each rung of the ladder gives

$$\alpha_S \int \frac{dk_t^2}{k_t^2} \int \frac{dx}{x} \equiv \alpha_S \ln\left(\frac{x_0}{x}\right) \ln\left(\frac{Q^2}{Q_0^2}\right)$$

If only transverse momenta are ordered from target to projectile:

$$k_{T1}^2 << k_{T2}^2 << \cdots Q^2$$

Sum leading logs in Q^2 (DGLAP evolution)

Conversely, $x_0 >> x_1 \cdots >> x$

Sum leading logs in x (BFKL evolution)

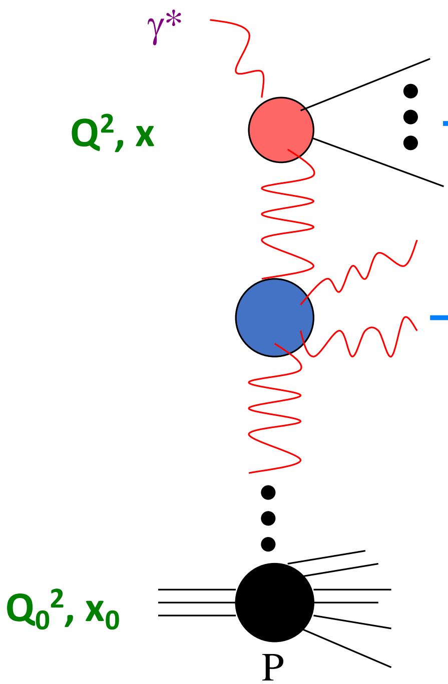
Both DGLAP and BFKL give rapid growth of gluon density at small x

Perturbative computations in the Bjorken limit of QCD

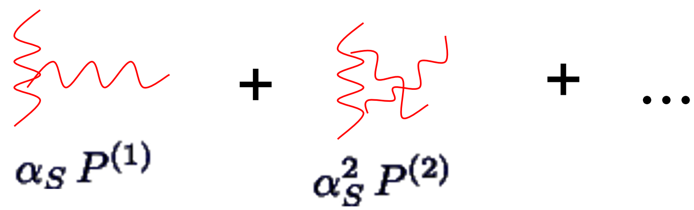
$$Q^2 \to \infty\, ;\, s \to \infty\, ;\, x_{\mathrm{Bj}} \approx \frac{Q^2}{s} = \text{fixed}$$

- Operator product expansion (OPE), factorization theorems, machinery of precision physics in QCD

Structure of higher order perturbative contributions in QCD



$$C_2(x, \alpha_S) = \delta(1-x) + \alpha_S C_2^{(1)}(x) + \alpha_S^2 C_2^{(2)} + \cdots$$

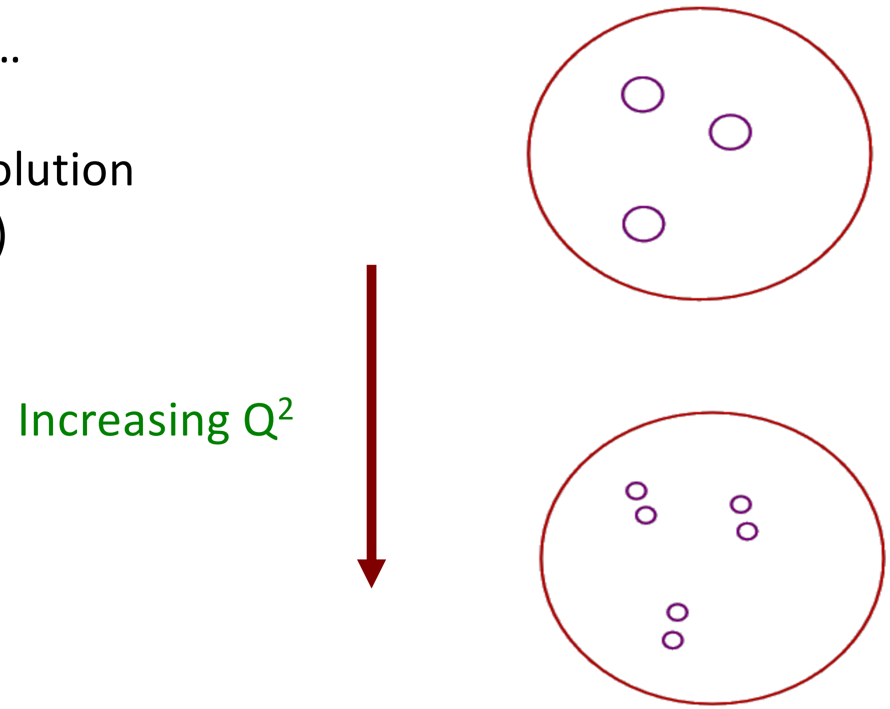


+ higher twist (power suppressed) contributions...

- Coefficient functions C - computed to NNLO for many processes
- Splitting functions P - computed to 3-loops

Resolving the hadron…

Ren.Group-DGLAP evolution
(sums large logs in Q^2)



Phase space density (# partons / area / Q^2) decreases
- the proton becomes more dilute…

The Regge-Gribov Limit

$$x_{\mathrm{Bj}} \to 0\,;\ s \to \infty\,;\ Q^2 (>> \Lambda^2_{\mathrm{QCD}}) = \mathrm{fixed}$$

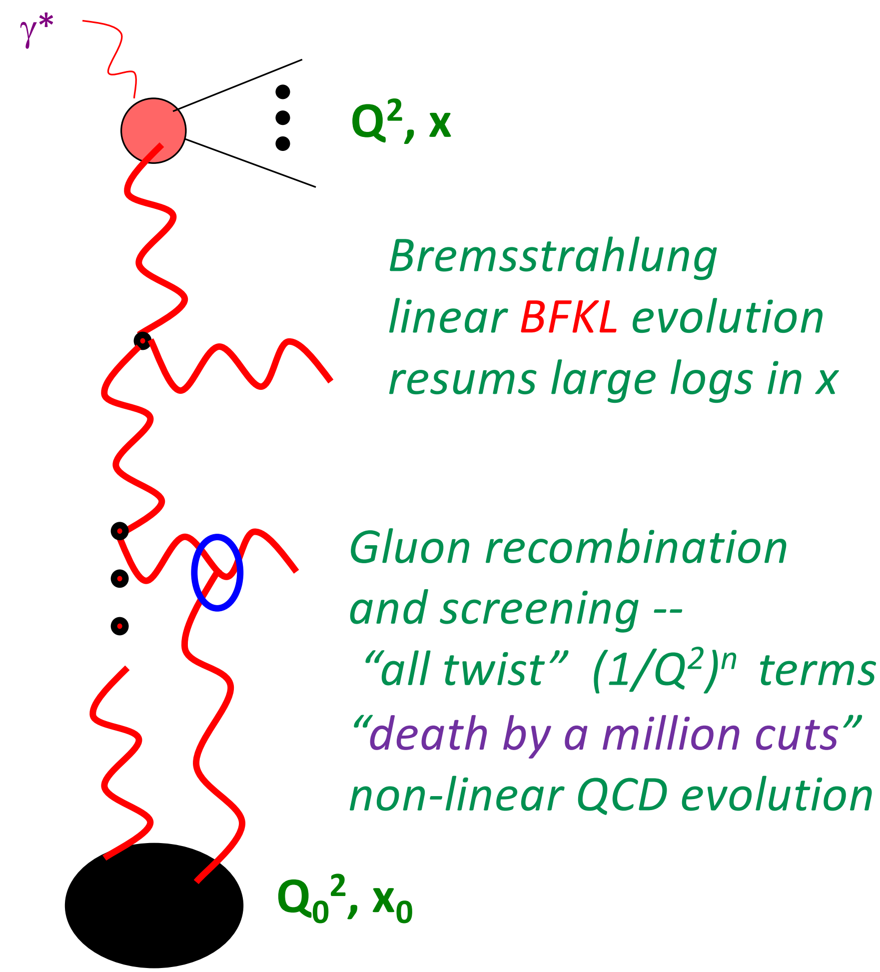
Physics of multi-particle production and strong fields in QCD

Novel universal properties of QCD ?

Generating strong fields by multi-particle production

Multi-particle production in the Regge limit:

$s \to \infty, Q^2 = \text{fixed} \gg \Lambda^2_{QCD} \;\; x \to 0$



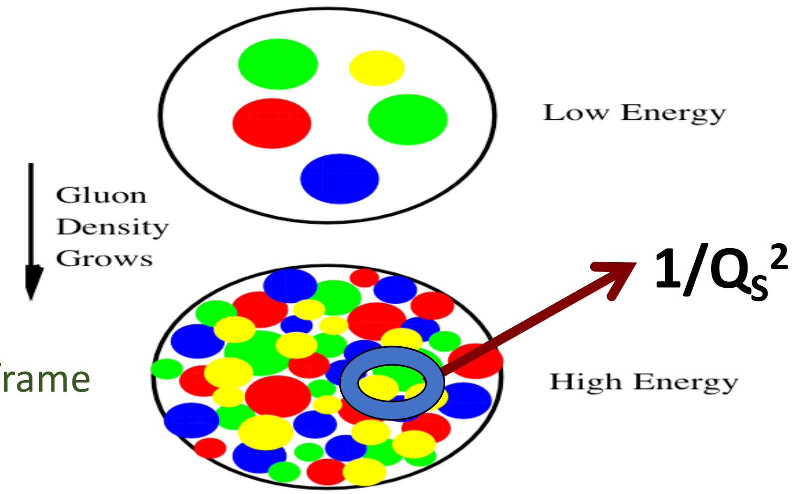
A fascinating equilibrium of splitting and recombination should eventually result. It is a considerable theoretical challenge to calculate this equilibrium in detail…

F. Wilczek, Nature (1999)

The boosted proton: gluon saturation

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

Decoupling of longitudinal
and transverse dynamics
In the hadron infinite momentum frame

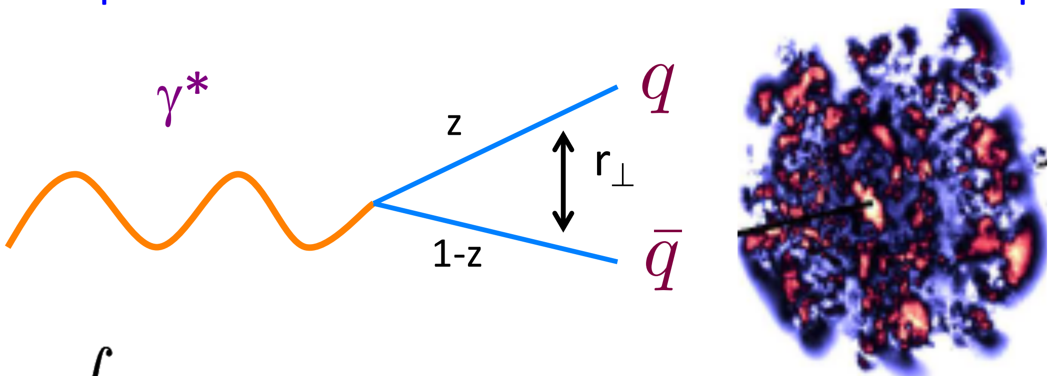


Gluons at maximal phase space occupancy $n \sim 1/\alpha_S$, resist close packing by recombining and screening their color charges -- gluon saturation

Emergent dynamical saturation scale $Q_S(x) \gg \Lambda_{QCD}$

Asymptotic freedom! $\alpha_S(Q_S) \ll 1$ *provides non-pert weak coupling window into infrared*

Saturation as perturbative unitarization: the dipole model



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

QED QCD

Golec-Biernat Wusthoff model

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

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

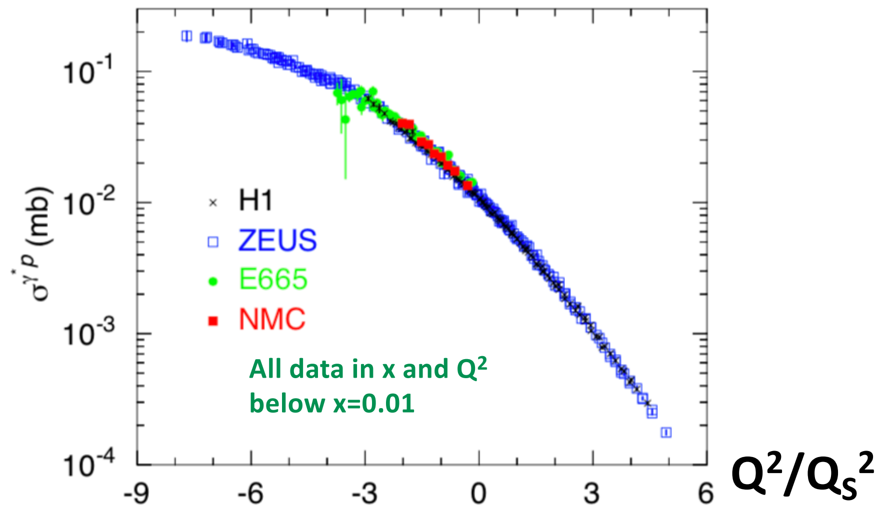
Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

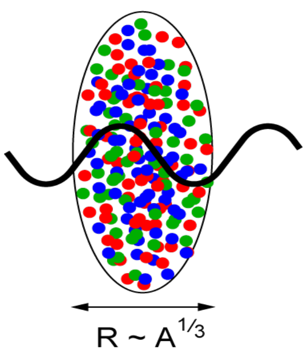
Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

QCD picture of "shadowing"…

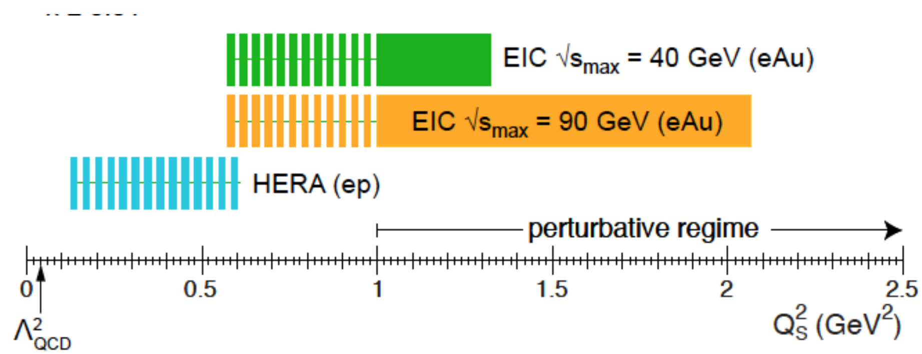
Parameters from HERA fit:
Q_0 = 1 GeV; λ = 0.3;
x_0 = 3* 10^{-4}; σ_0 = 23 mb

Geometrical scaling: evidence for Q_S?

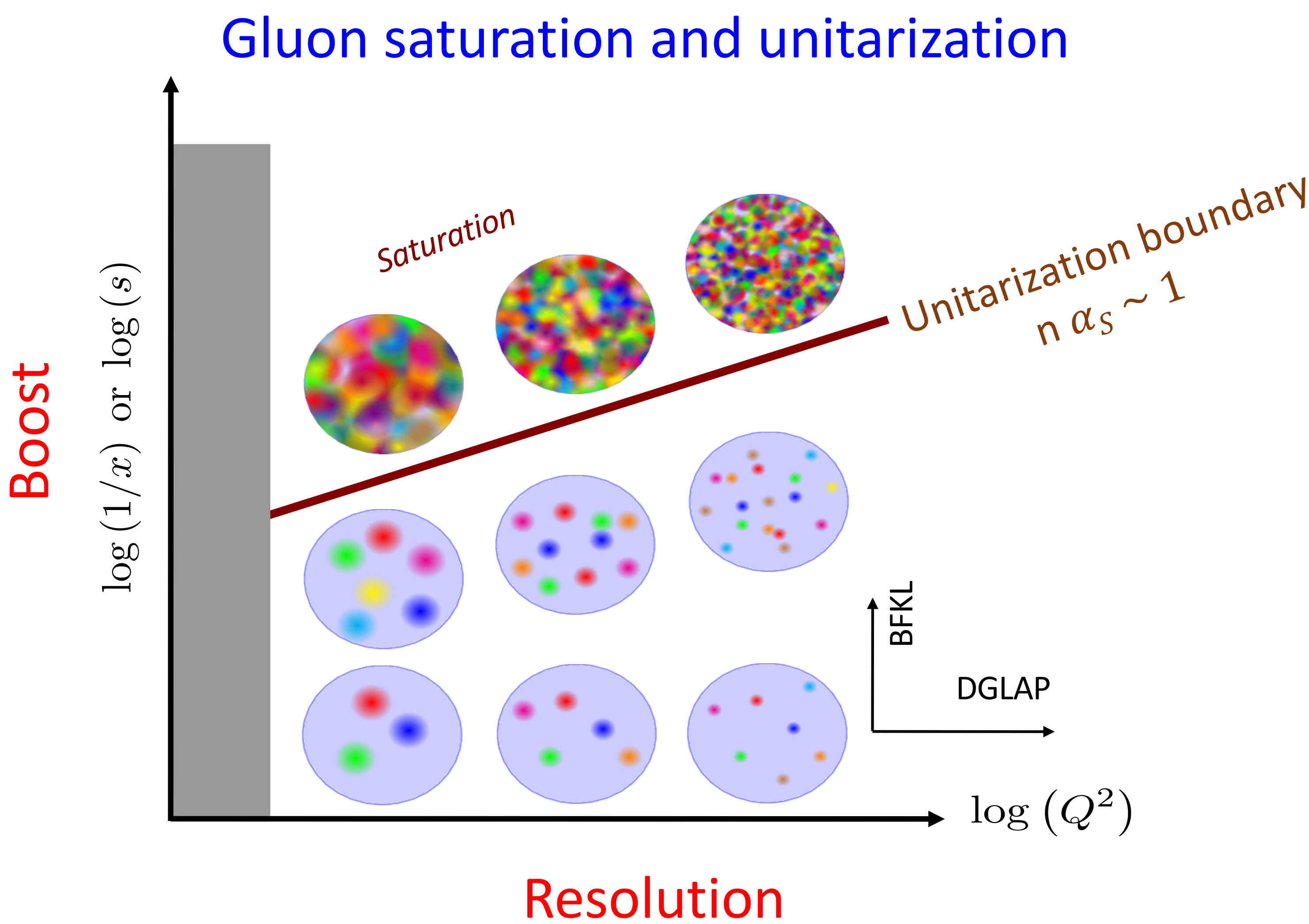




$Q_S^2 \sim A^{1/3}$ since "wee" gluons couple coherently for $x << A^{-1/3}$



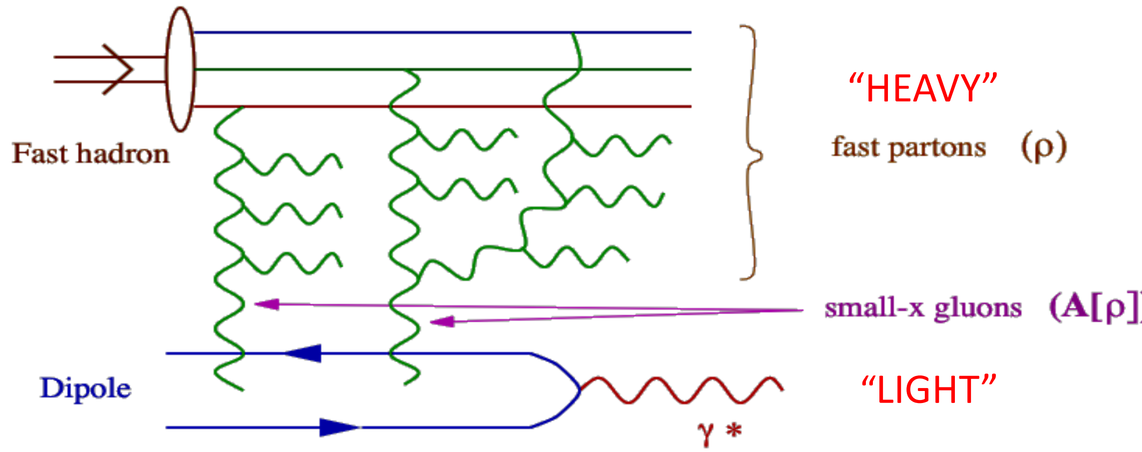
Big nuclear "oomph" at a future Electron-Ion Collider
(late 2020's, approved for construction at BNL !)



Gluon saturation and unitarization
Saturation
Unitarization boundary
n $\alpha_S \sim 1$
Boost
$\log(1/x)$ or $\log(s)$
BFKL
DGLAP
$\log(Q^2)$
Resolution

Classicalization in the Regge limit: the Color Glass Condensate EFT

Born-Oppenheimer separation between fast and slow modes



CGC: Effective Field Theory of classical static quark/gluon sources and dynamical gluon fields

Remarkably, physics of extreme quantum fluctuations becomes classical because of high gluon occupancy…

McLerran, RV (1994)