Extreme QCD at RHIC and LHC

Jamal Jalilian-Marian

Baruch College, New York, NY, USA

OUTLINE

* **QCD at high temperature**
  * *Phase transition: hadrons to partons (**QGP**)*
* **QCD at high energy**
  * *Unitarity: small to large (**CGC**)*
* **RHIC and LHC**

QCD at high T

Hadrons vs. partons: energy density

$$\epsilon = \mathbf{n}\frac{\pi^2}{30}\mathbf{T}^4$$

Hadronic Matter: quarks and gluons confined up to T ~ 200 MeV, 3 pions with spin=0

$$\epsilon = \mathbf{3}\,\frac{\pi^2}{30}\mathbf{T}^4$$

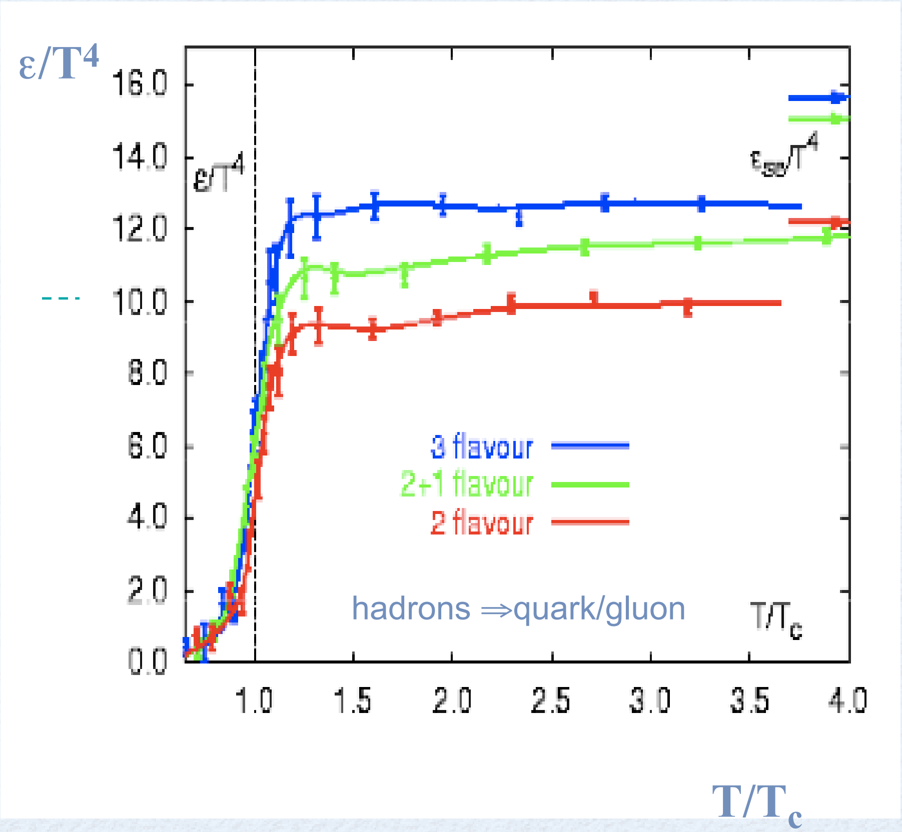
Quark Gluon Matter:
8 gluons; 2 quark flavors, antiquarks, 2 spins, 3 colors

$$\epsilon = \left\{2.8_g + \frac{7}{8}.2_s.2_a.2_f.3_c\right\}\frac{\pi^2}{30}T^4$$

37 >> 3

QGP vs. Hadron Gas

Lattice QCD



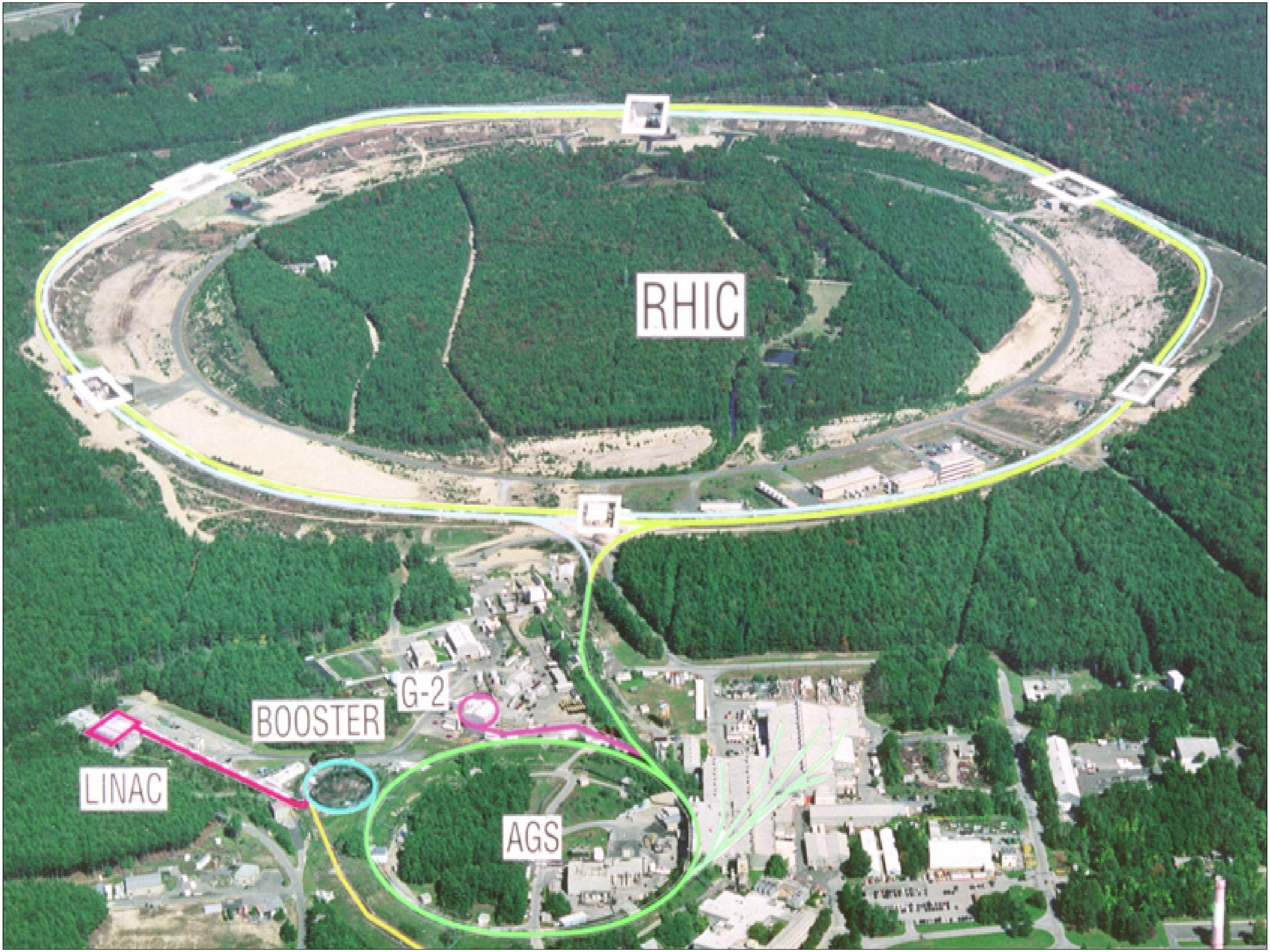
Transition values:

T = 170 MeV

ε_c = 0.8 GeV/fm^3

Assumes thermal system

NEED TO CREATE $\epsilon \gg \epsilon_c$


RHIC
G-2
BOOSTER
LINAC
AGS

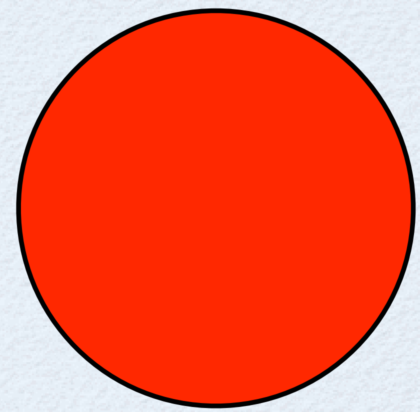
RHIC

Center of mass energy: 20, 60, 130, 200 GeV

Hot nuclear matter:

gold-gold, copper-copper

Central:
maximum overlap

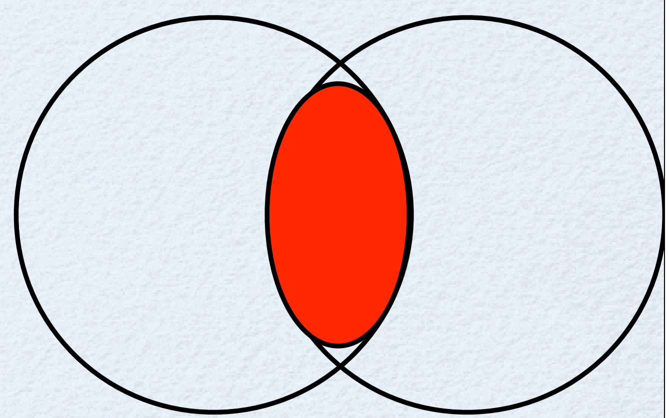


Cold nuclear matter:

deuteron-gold

Baseline:

proton-proton

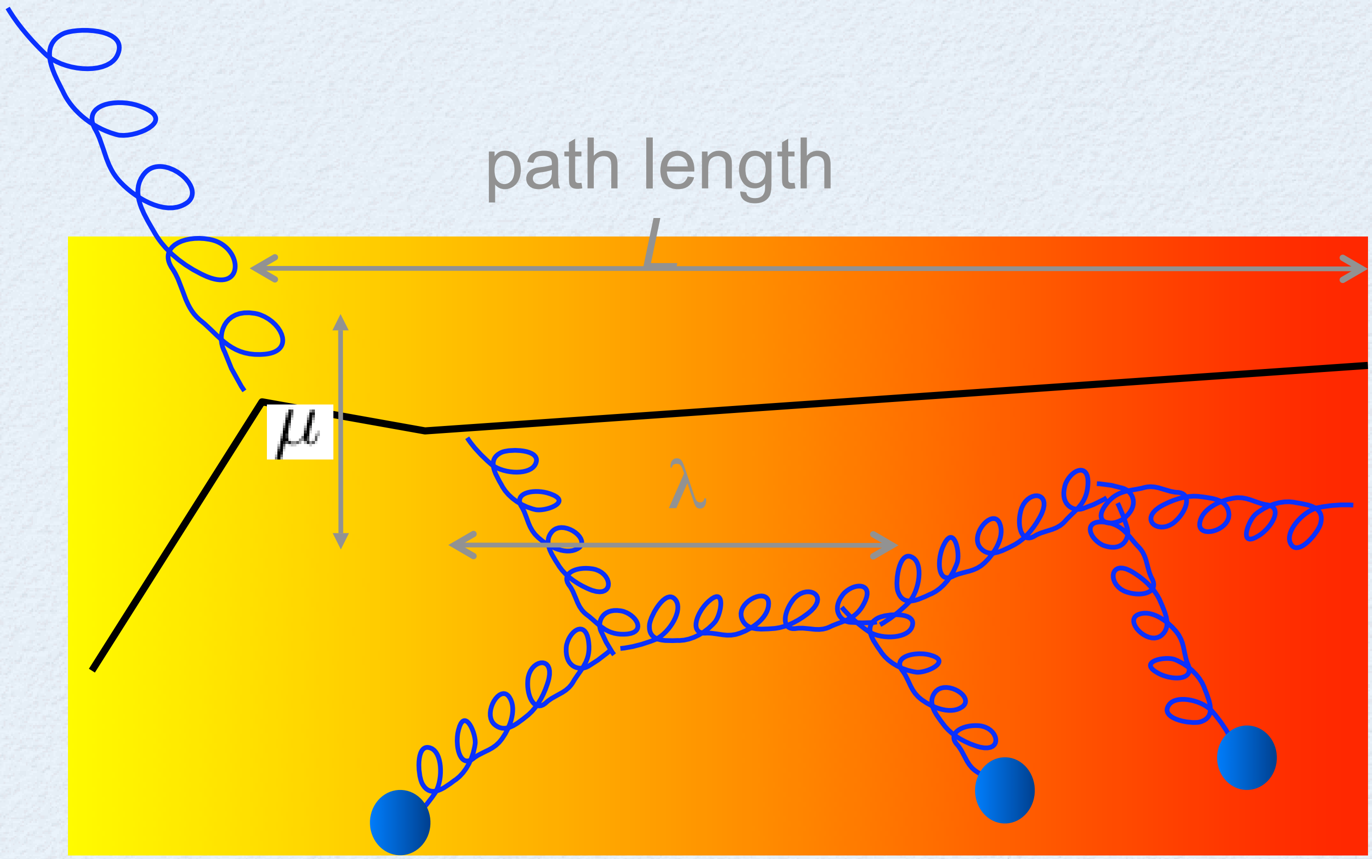


Peripheral:
“Almond” of
overlap region

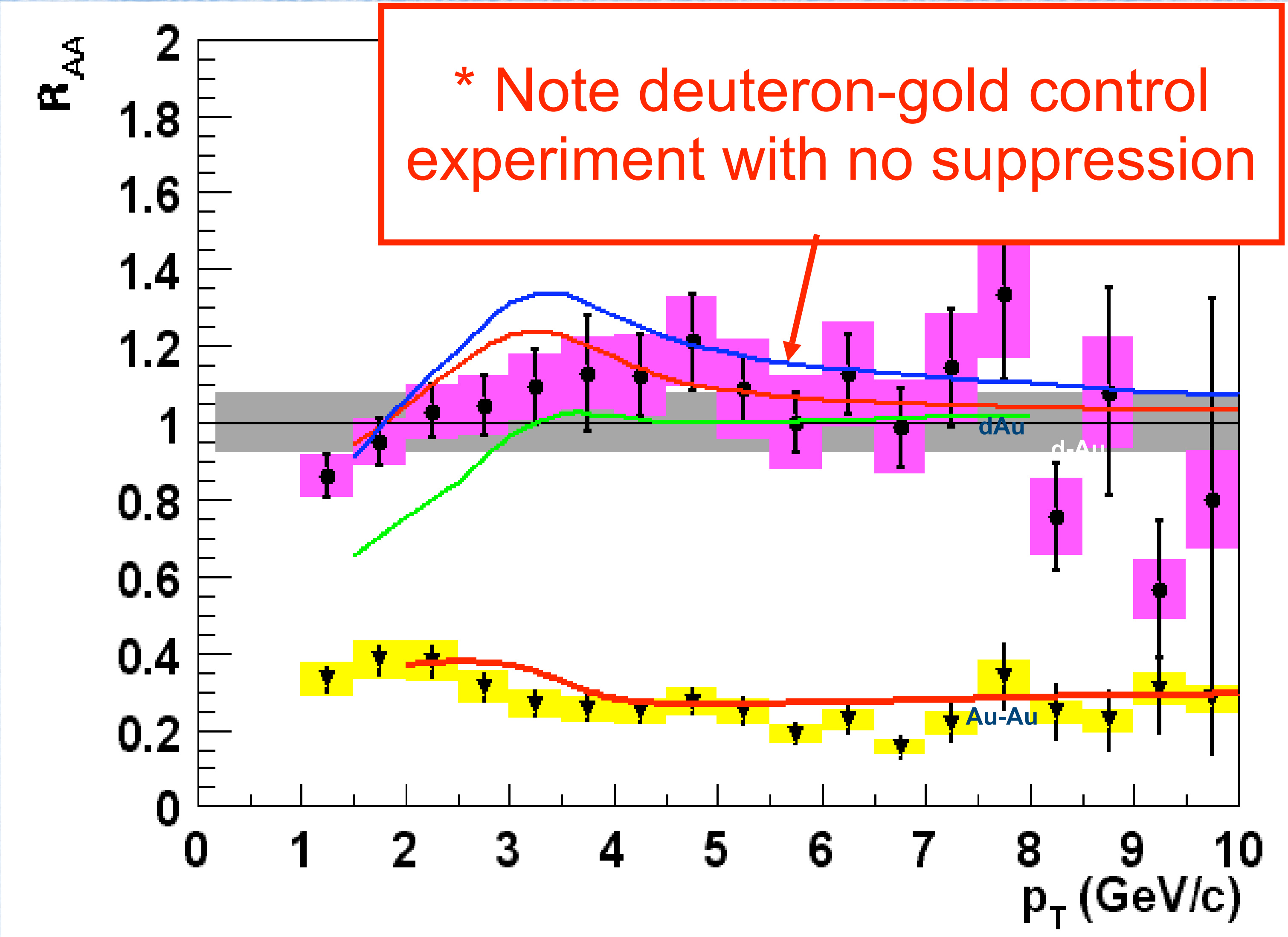
RHIC-II

Colliding heavy ions at high energies

Bjorken: high p_t partons scatter from the medium and "lose energy" (radiate gluons)

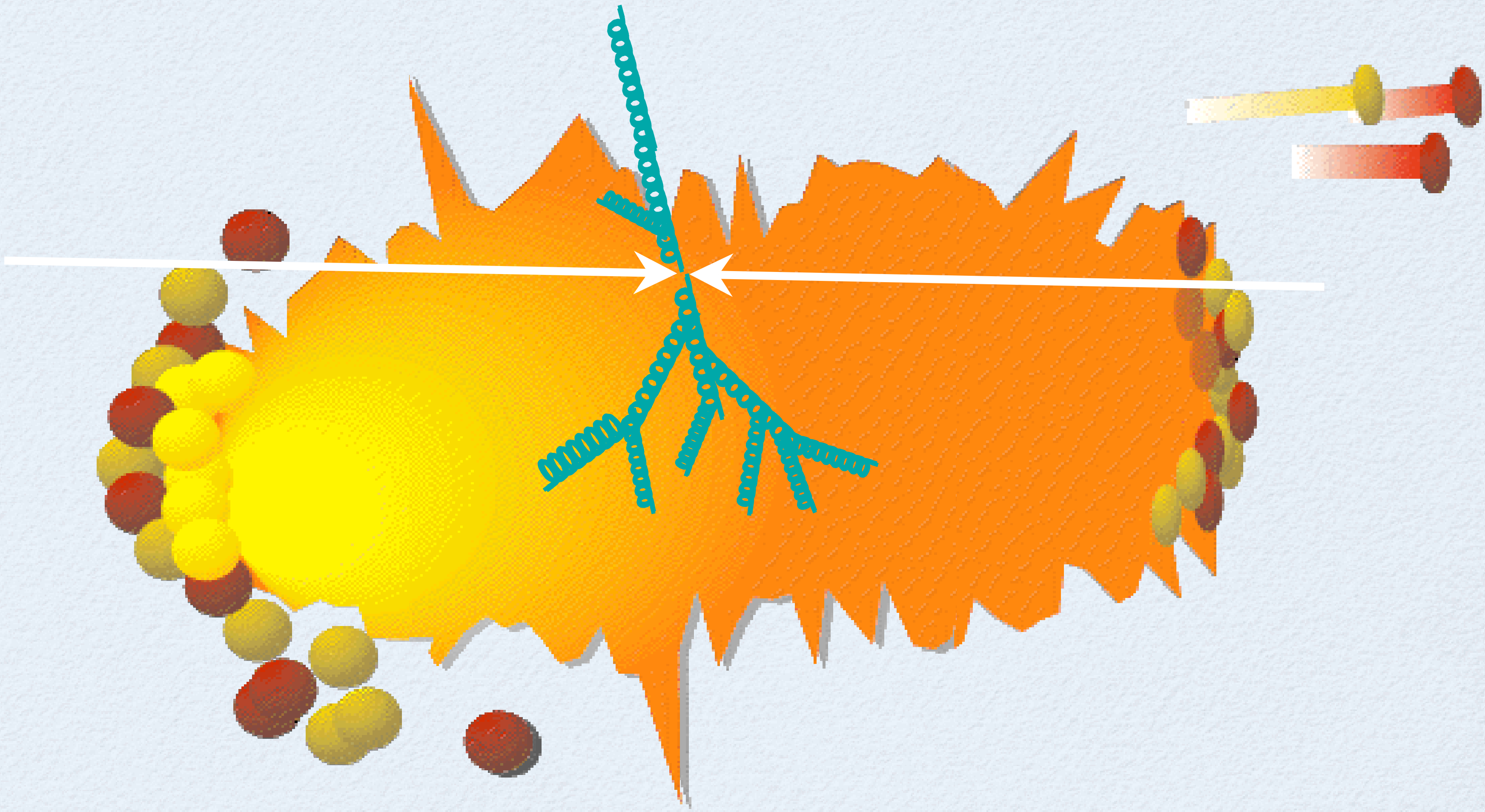


QGP at RHIC

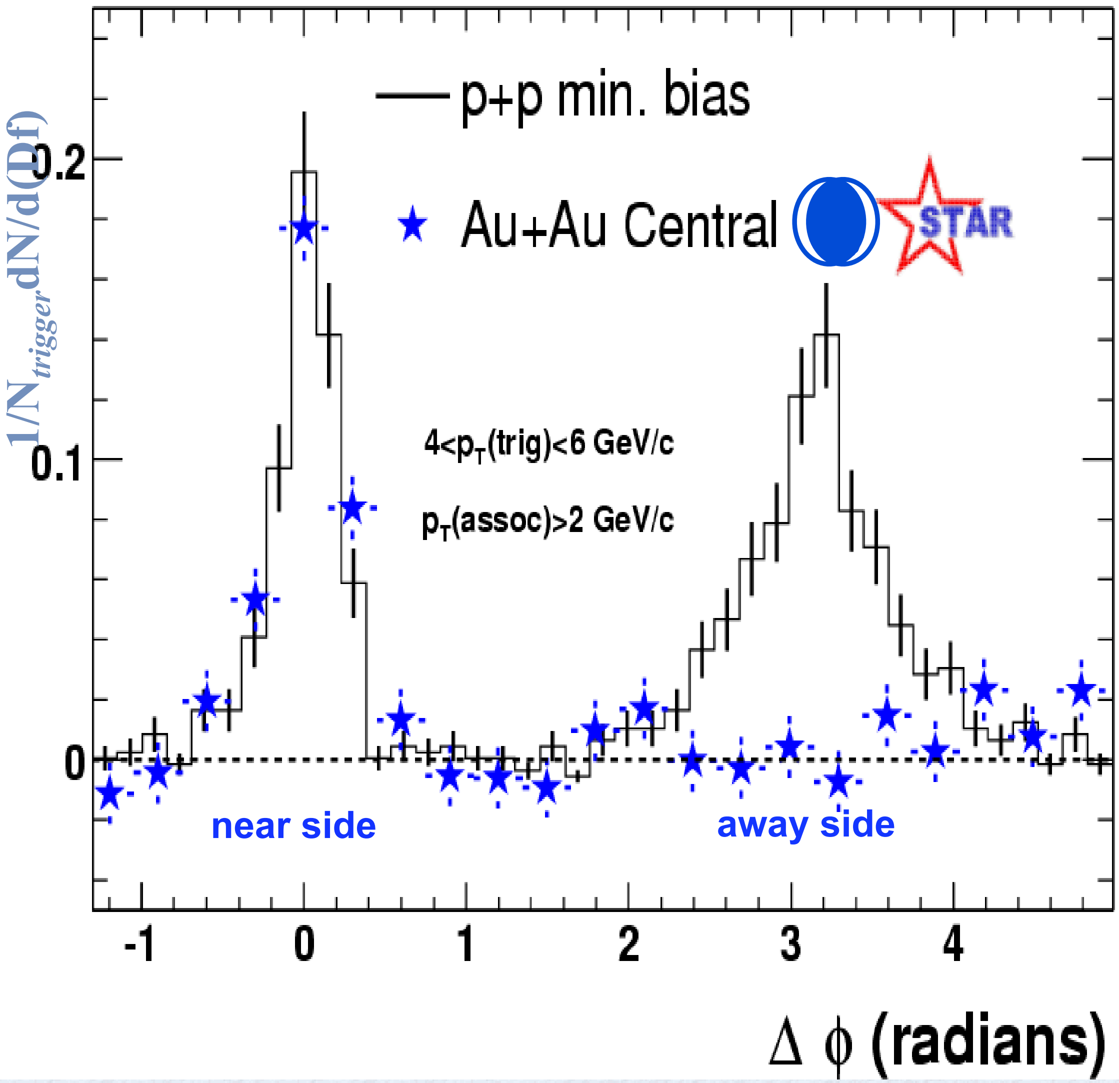


* Note deuteron-gold control experiment with no suppression
R_{AA}
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
dAu
Au-Au
p_T (GeV/c)

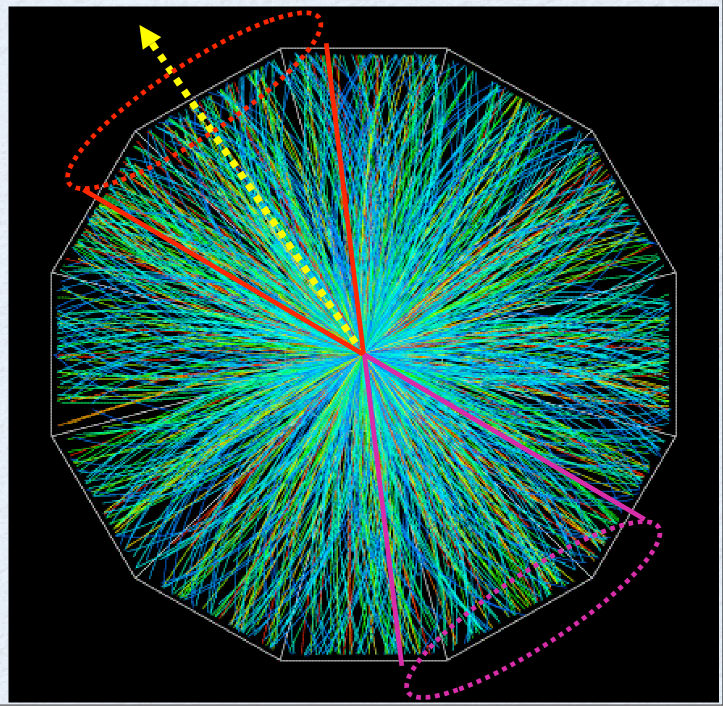
Probing the medium



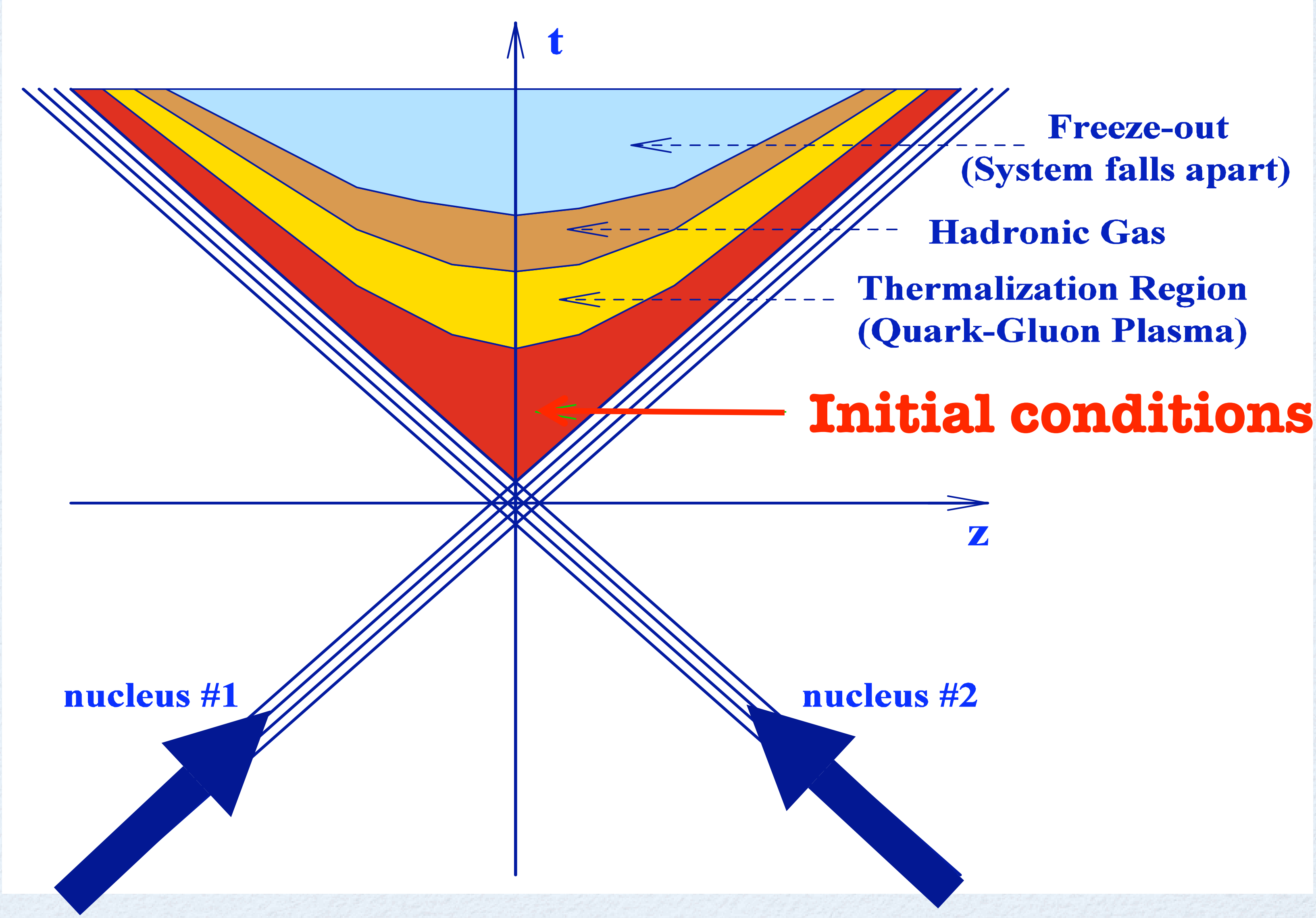
QGP at RHIC



disappearance of back to back jets



From CGC to QGP: Space-Time History of a Heavy Ion Collision



Degrees of Freedom in a Nucleus?

It depends on the scales probed!

A point particle $\lambda >> 10$ fm

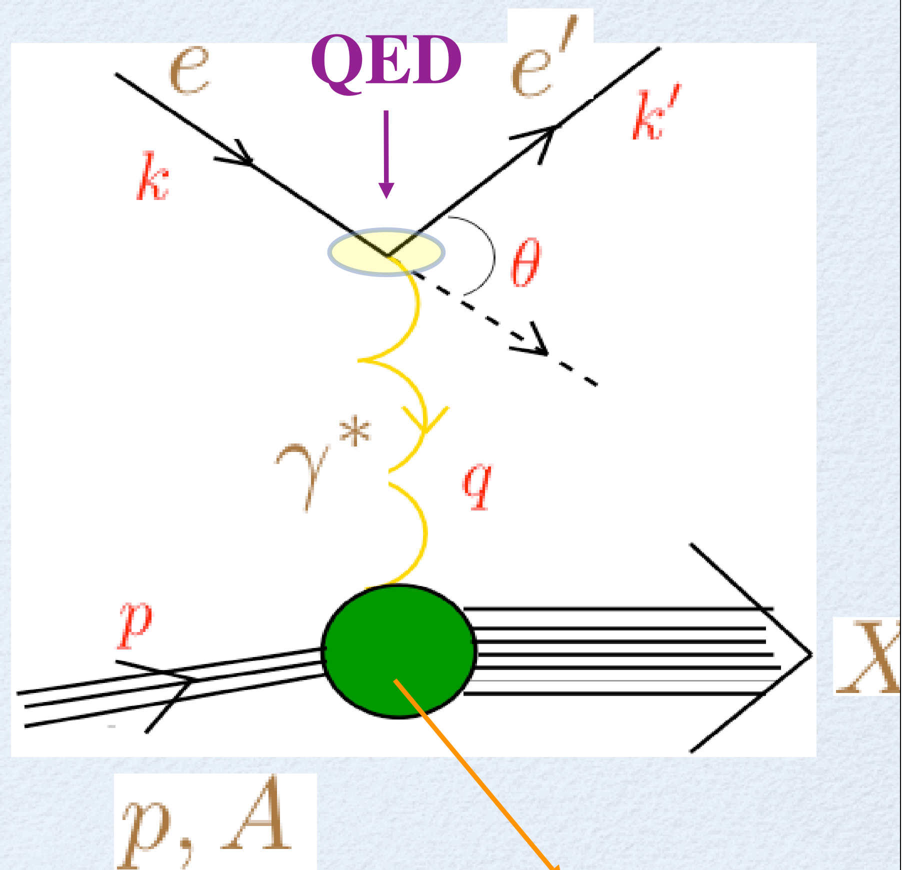
A collection of protons and neutrons $\lambda \sim 1$ fm

A dense system of quarks and gluons $\lambda << 1$ fm

Deeply Inelastic Scattering (DIS)

THE SIMPLEST WAY TO STUDY QCD IN A HADRON/NUCLEUS

e p (A) ---> e X



Kinematic Invariants:

Center of mass energy squared

$$\mathbf{S \equiv (p+q)^2}$$

Momentum resolution squared

$$\mathbf{Q^2 \equiv -q^2}$$

$$\mathbf{x_{bj} \equiv \frac{Q^2}{2\,p\cdot q}}$$

QCD: Structure Functions F_1 , F_2

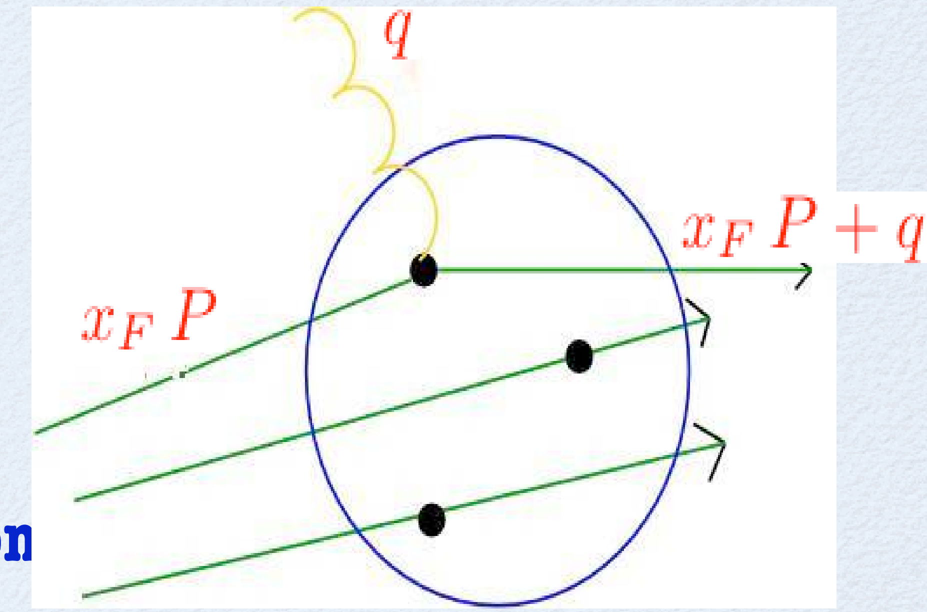
The hadron at high energy

★Bjorken: $\mathbf{Q^2}$, $\nu \to \infty$ but $\frac{\mathbf{Q^2}}{\nu}$ fixed

structure functions F_1, F_2 depend only on x_{bj}

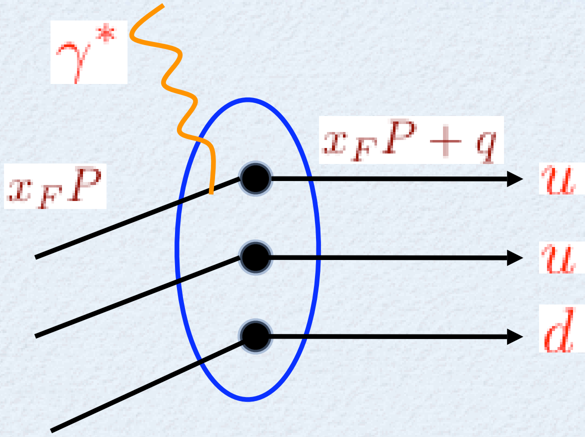
★Feynman:

Parton constituents of proton are "quasi-free" on interaction time scale $1/Q << 1/\Lambda$ (interaction time scale between partons)

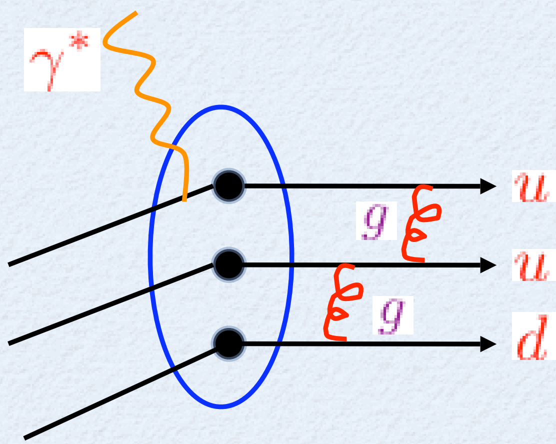


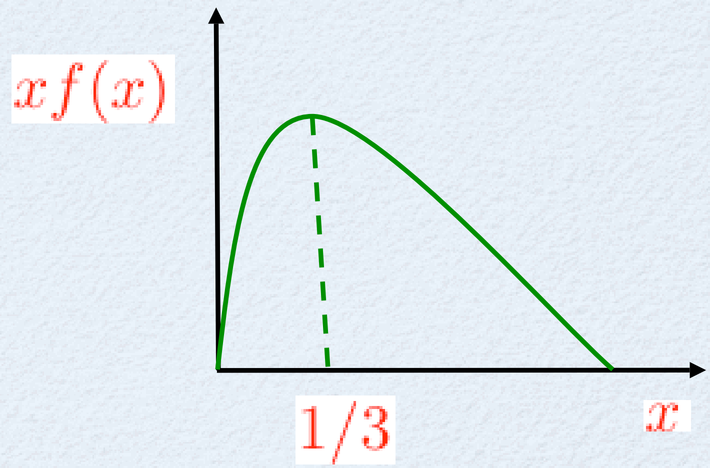
$\mathbf{X_{bj}}$ = *fraction of hadron momentum carried by a parton* = $\mathbf{X_F}$

The hadron at high energy



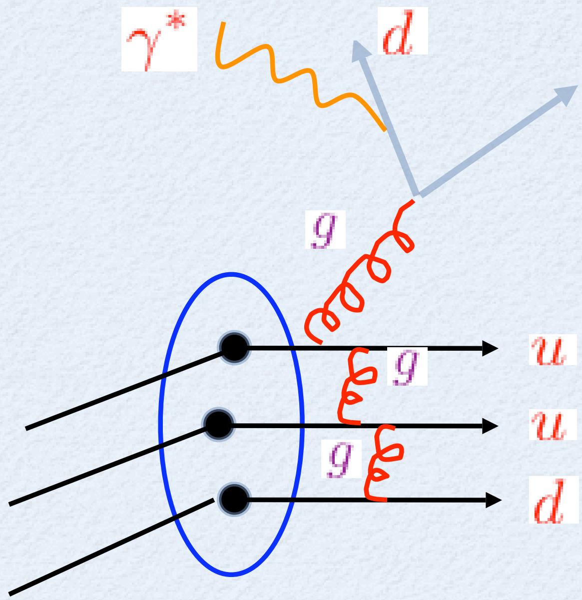
Parton model

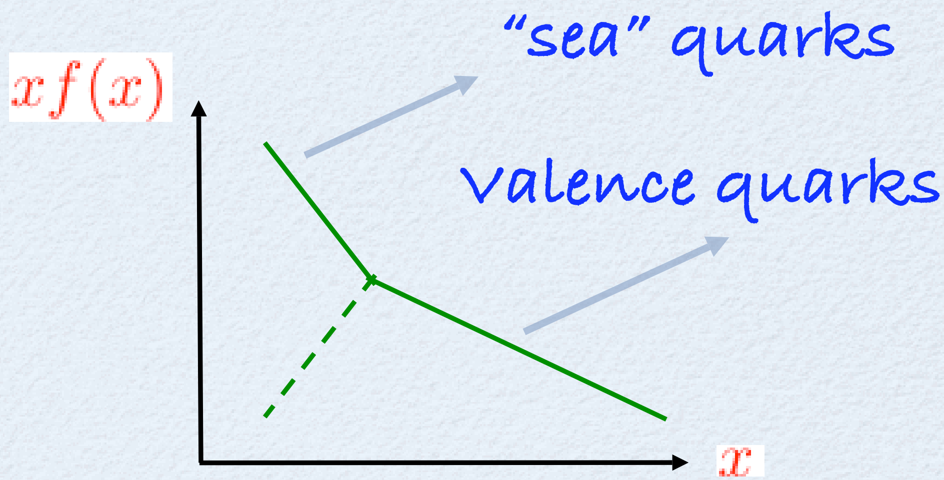




QCD - bound quarks

pQCD--RG evolution (radiation)

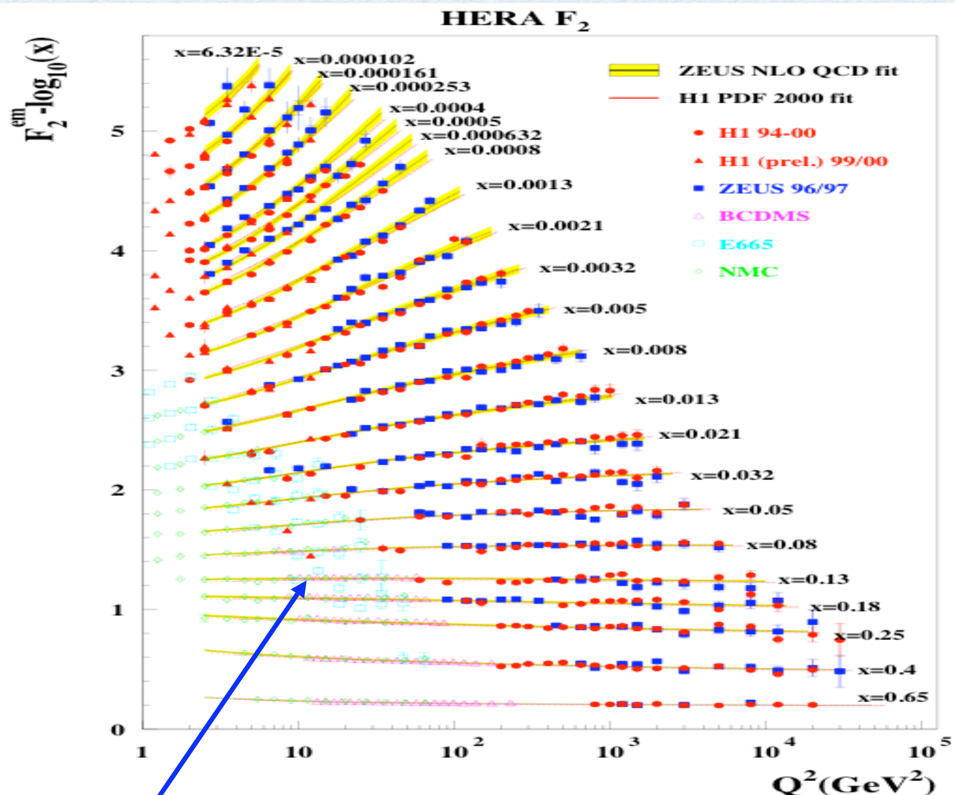




$$\int_0^1 \frac{dx}{x}[xq(x) - x\bar{q}(x)] = 3$$ *# of valence quarks*

$$\int_0^1 \frac{dx}{x}[xq(x) + x\bar{q}(x)] \to \infty$$ *# of quarks ....*

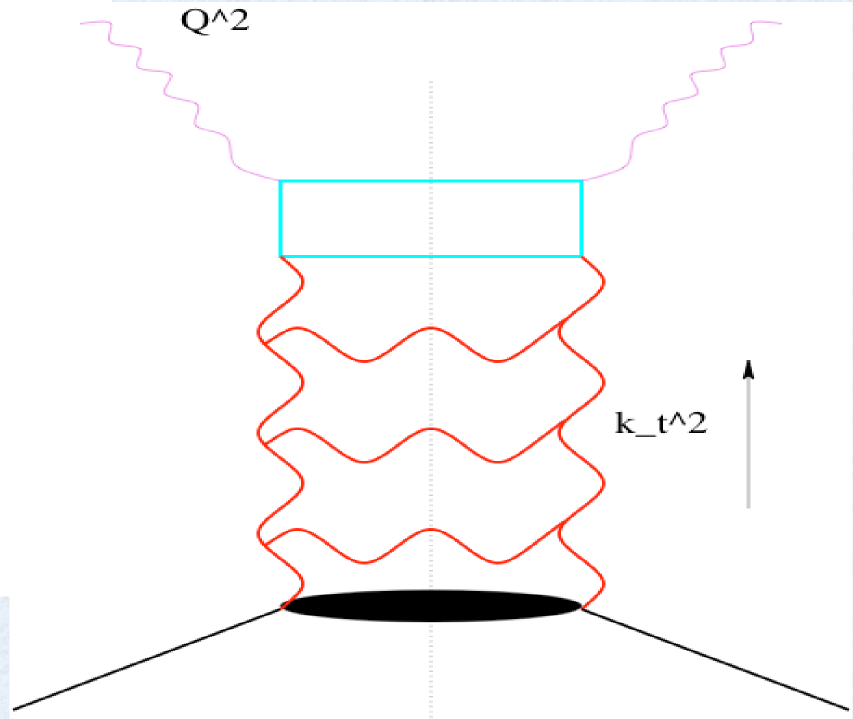
pQCD--RG evolution (radiation)



Bj scaling

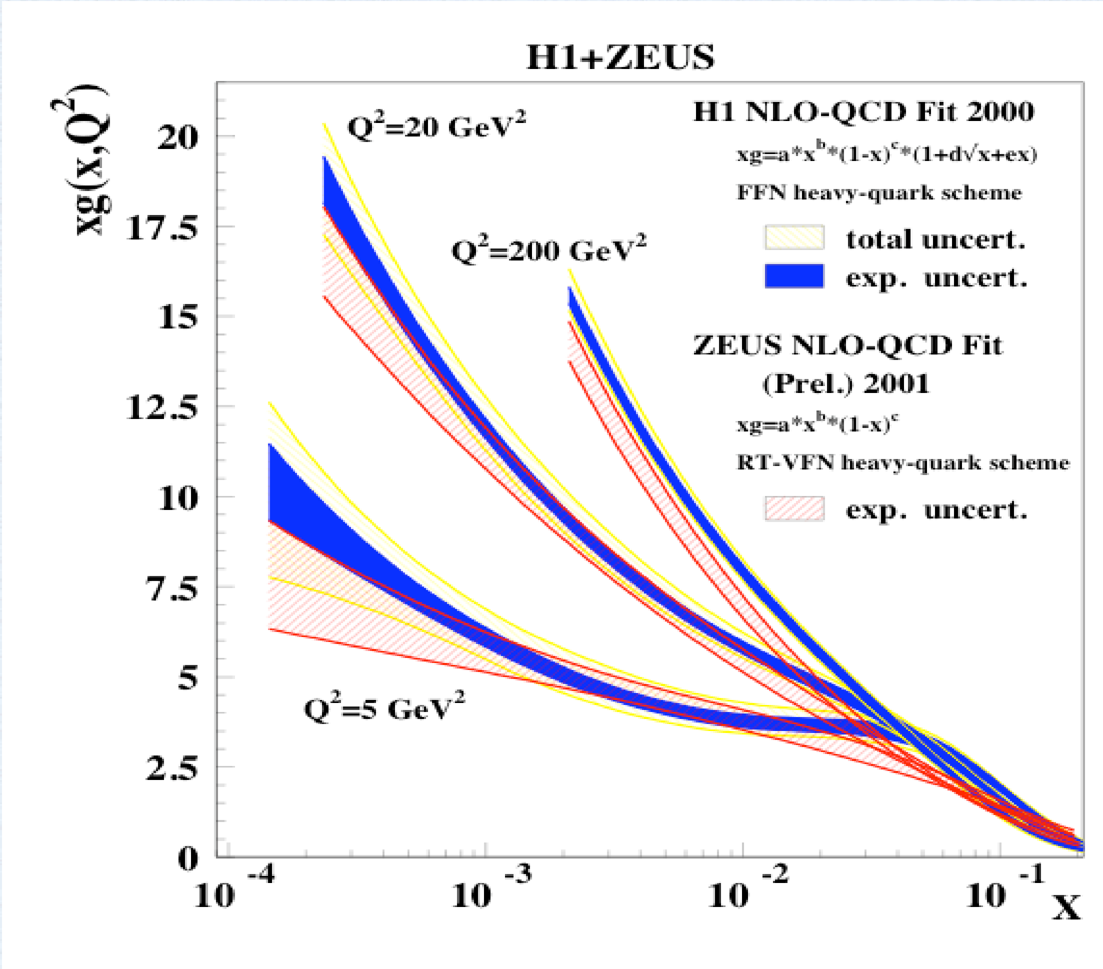
evolution of distribution functions

DGLAP



$$F_2(x, Q^2) = \sum_q e_q^2 \left[x\, q(x, Q^2) + x\, \bar{q}(x, Q^2) \right]$$

pQCD--RG evolution (radiation)

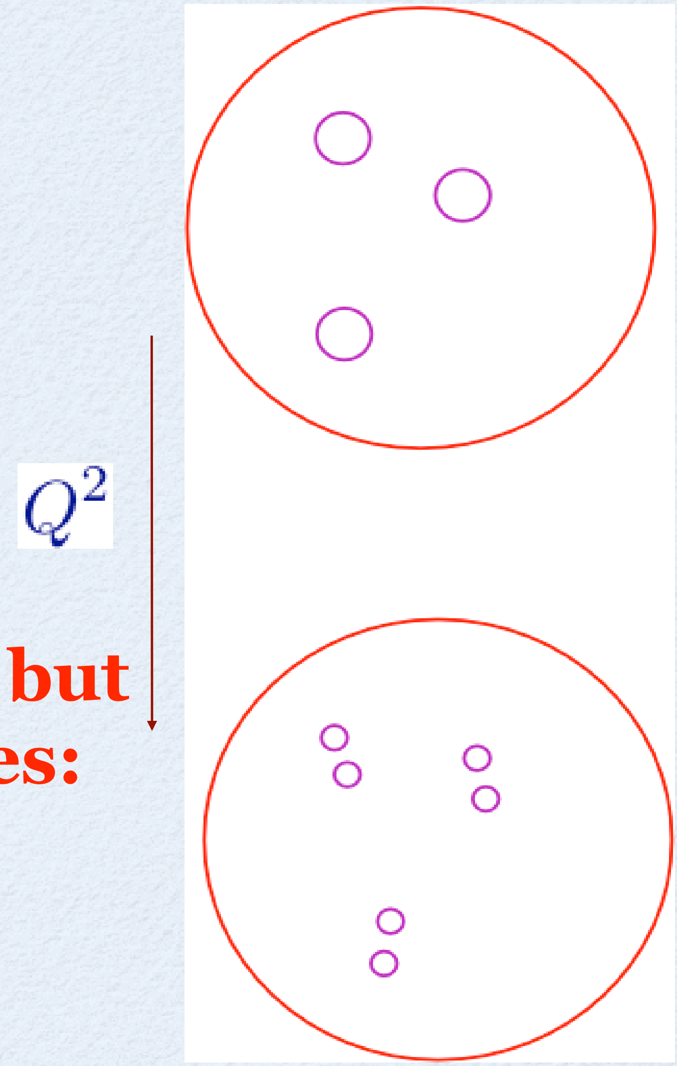


# of gluons grows rapidly at small x…

Resolving the hadron: DGLAP evolution

Radiated gluons have smaller and smaller sizes (~ $1/Q^2$) as Q^2 grows

The number of gluons increases but the phase space density decreases: hadron becomes more dilute



QCD in the Regge-Gribov limit

$$Q^2 \text{ fixed}, \quad S \to \infty$$

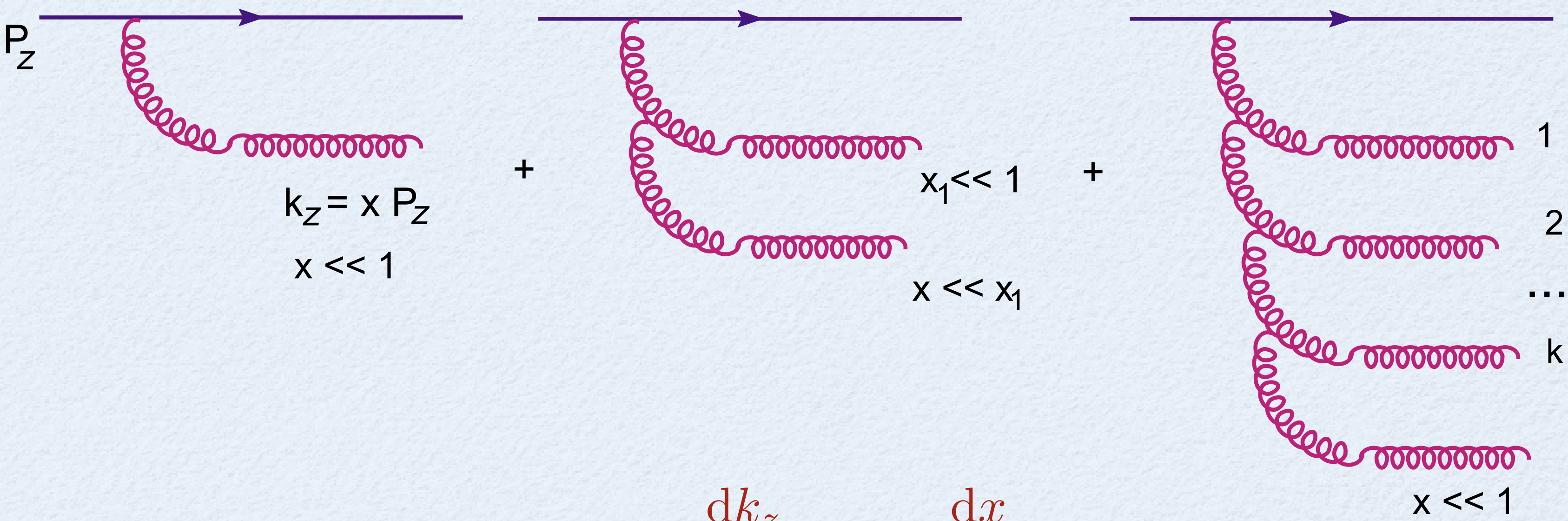
$$X_{bj} \to 0$$

Regge

Gribov

BFKL evolution

- The infrared sensitivity of bremsstrahlung favors the emission of 'soft' (= small–x) gluons



$$d\mathcal{P} \propto \alpha_s \frac{dk_z}{k_z} = \alpha_s \frac{dx}{x}$$

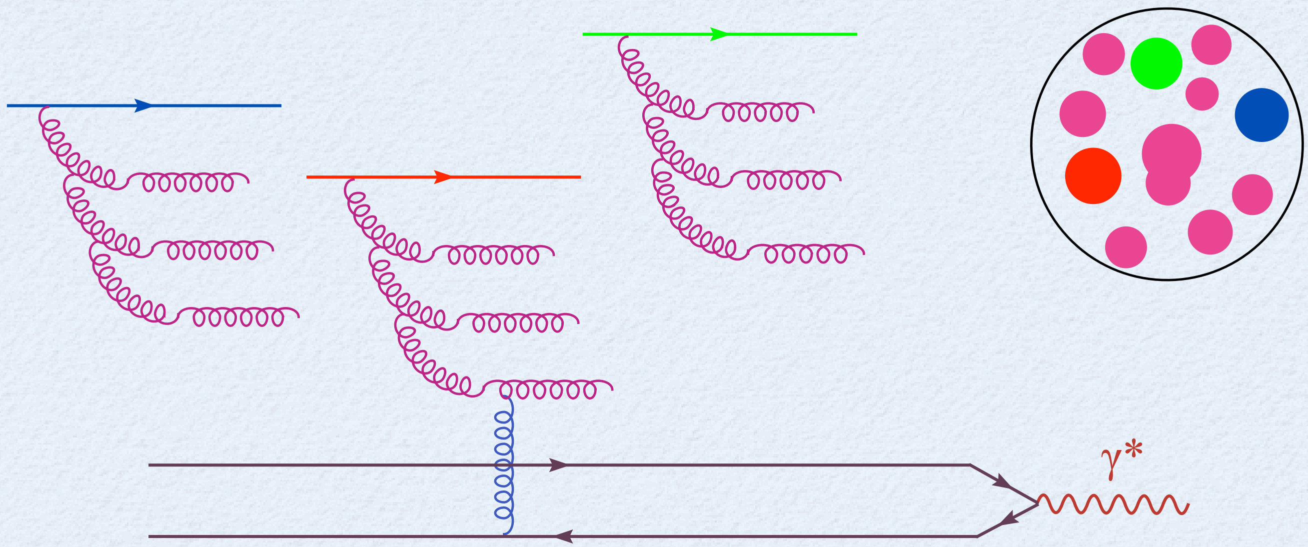
- The 'price' of an additional gluon:

$$\mathcal{P}(1) \propto \alpha_s \int_x^1 \frac{dx_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

BFKL evolution: Unitarity violation

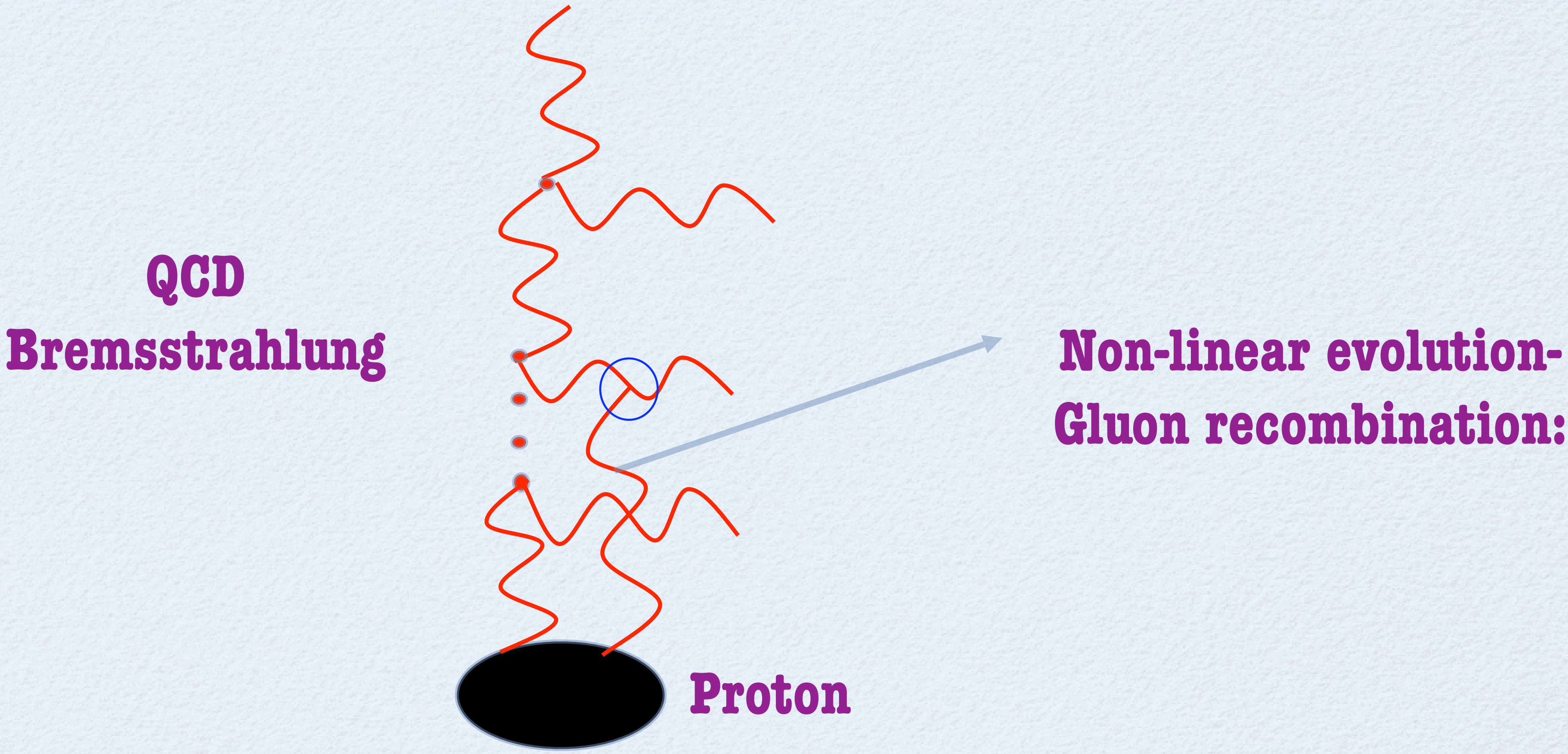
- The 'last' gluon at small x can be emitted off any of the 'fast' gluons with $x' > x$ radiated in the previous steps :

$$\frac{\partial n}{\partial Y} \simeq \alpha_s n \qquad \Longrightarrow \qquad n(Y) \propto \mathrm{e}^{\omega \alpha_s Y}$$



- Dipole scattering amplitude: $T \sim \alpha_s n$
- Unitarity bound : $SS^{\dagger} = 1 \implies T \leq 1$ — violated by BFKL !

The hadron at high energy

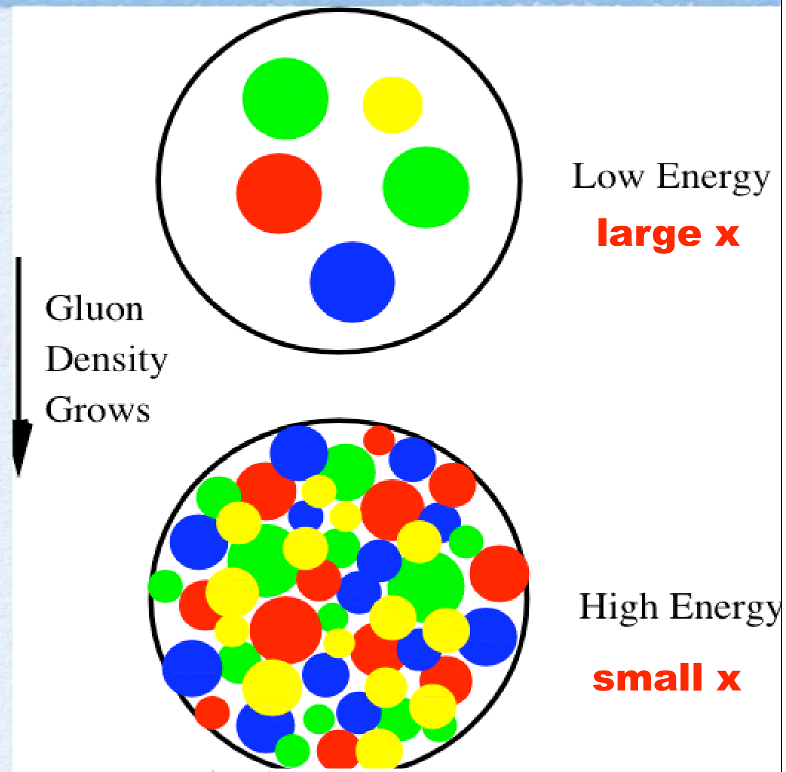


this is essential if proton is a dense object

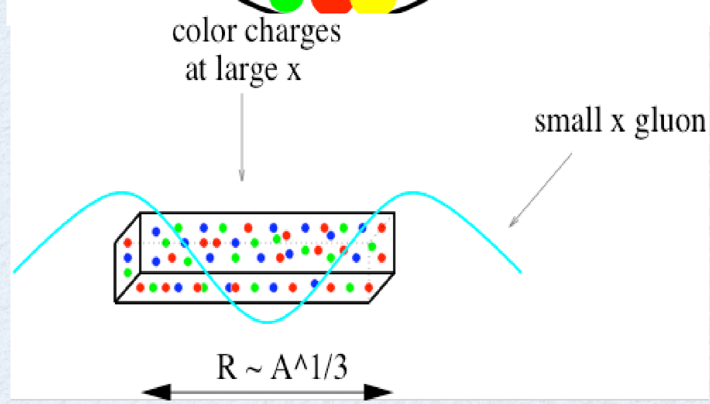
How to achieve high gluon density

Increase the energy

Radiated gluons have the same size ($1/Q^2$) - the number of partons increase due to the increased longitudinal phase space



or/and large nuclei



Parton saturation

Competition between "attractive" bremsstrahlung and "repulsive" recombination effects

maximal phase space density

$$\frac{1}{2(N_c^2-1)}\,\frac{x\,G(x,Q^2)}{\pi R^2\,Q^2} = \frac{1}{\alpha_S(Q^2)}$$

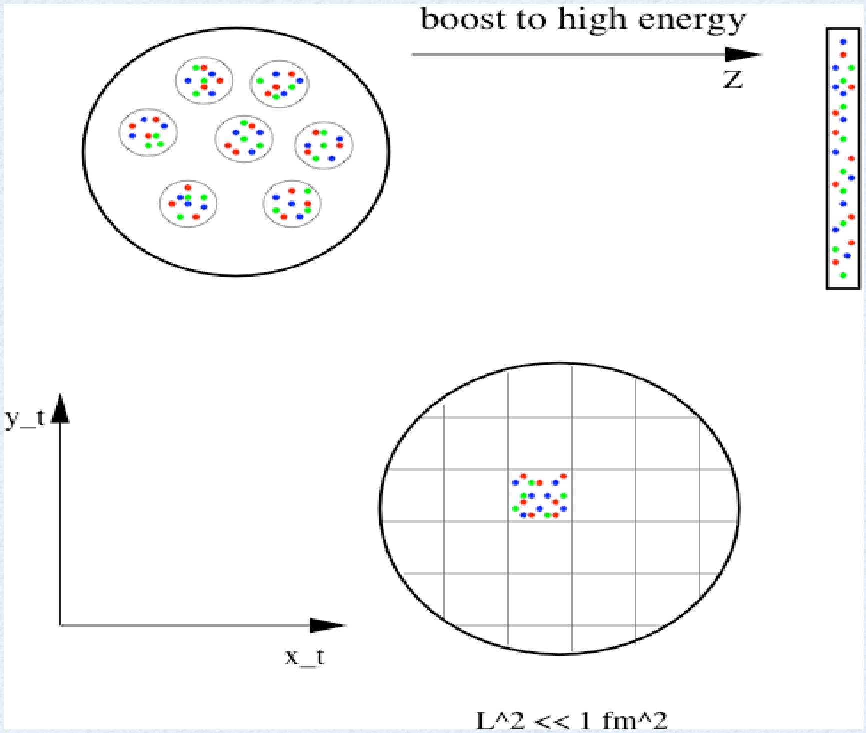
saturated for

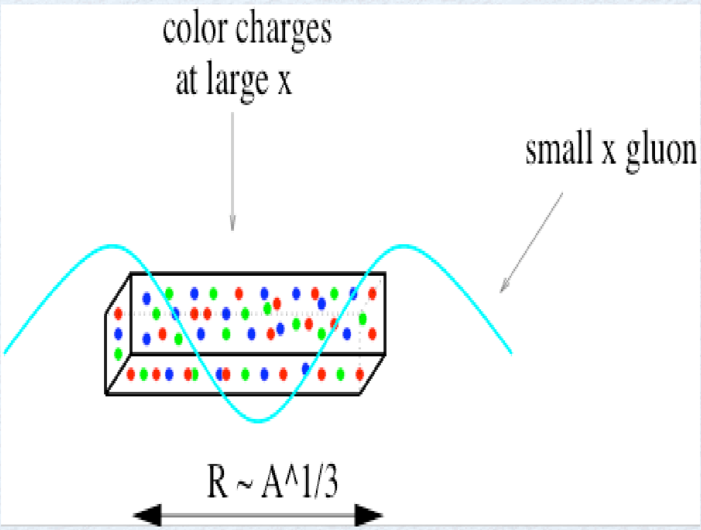
$$\mathbf{Q = Q_s(x) \gg \Lambda_{QCD} \simeq 0.2\,GeV}$$

Classical Effective Theory

McLerran, Venugopalan

Consider a large nucleus in the IMF frame $P^+ \to \infty$

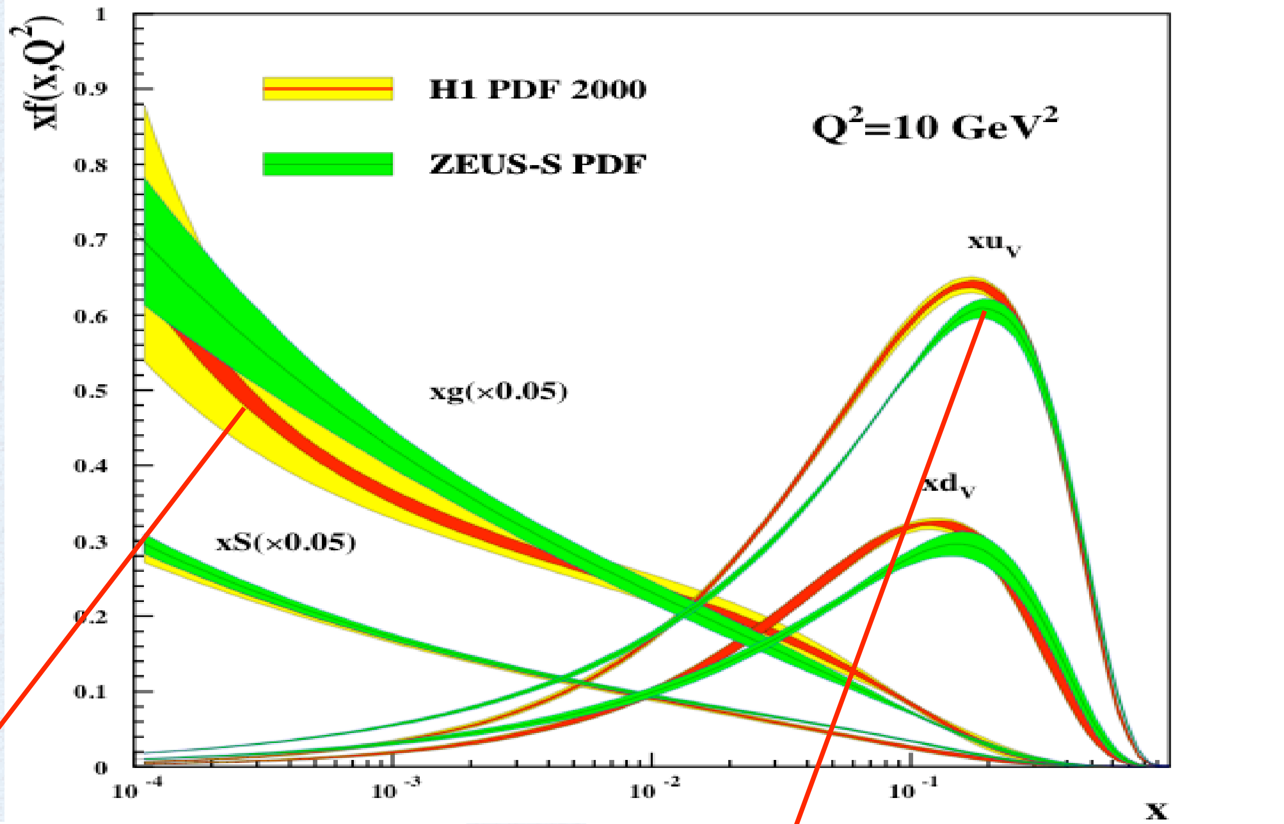




One large component of the current-others suppressed by $\frac{1}{P^+}$

Wee partons see a large density of valence color charges at small transverse resolutions

Born-Oppenheimer: separation of large x and small x modes



$$\tau_{\text{wee}} \sim \frac{1}{k^-} = \frac{2k^+}{k_\perp^2} \equiv \frac{2x\,P^+}{k_\perp^2}$$

$$\tau_{\text{valence}} = \frac{2P^+}{k_\perp^2} >> \tau_{\text{wee}} \text{ for } x << 1$$

Large X partons are static over small X parton life times

The effective action

$$S = -\frac{1}{4}\int d^4x\, G^2 \longrightarrow \text{Yang-Mills}$$

$$+ \frac{i}{N_c}\int d^2x_t\, dx^-\, \delta(x^-)\, \mathrm{tr}\ \rho(x_t)\, U_{-\infty,\infty}[A^-](x^-, x_t)$$

coupling of color charges to gluon fields

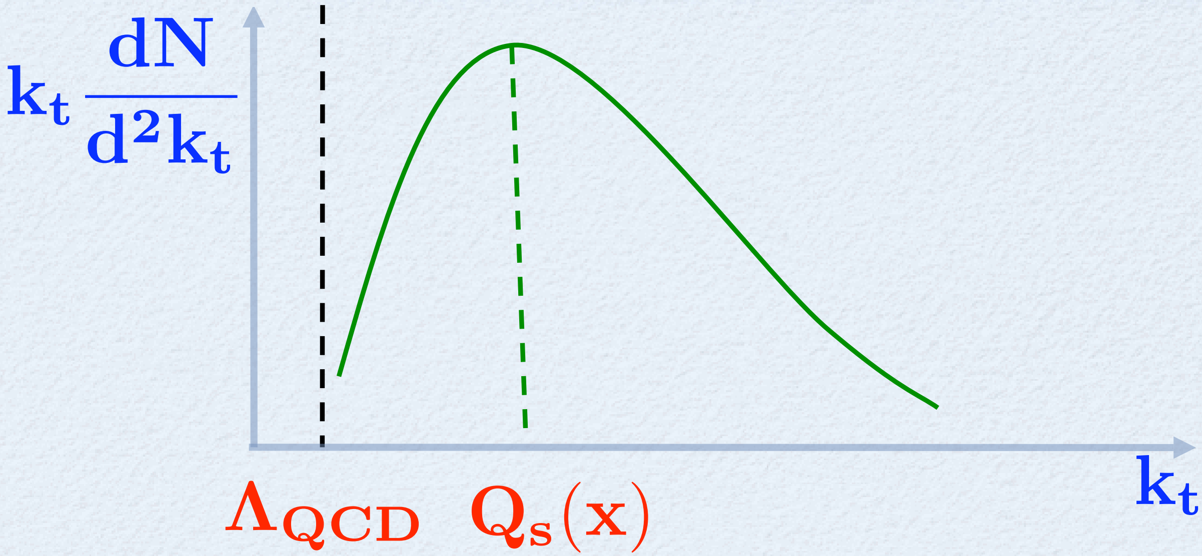
$$+ i\int d^2x_t F[\rho^a(x_t)] \longrightarrow$$

weight function for color charge configurations

where $$U[A^-] \equiv \hat{P}\, e^{-ig\int dx^+\, A^-_a\, T_a}$$

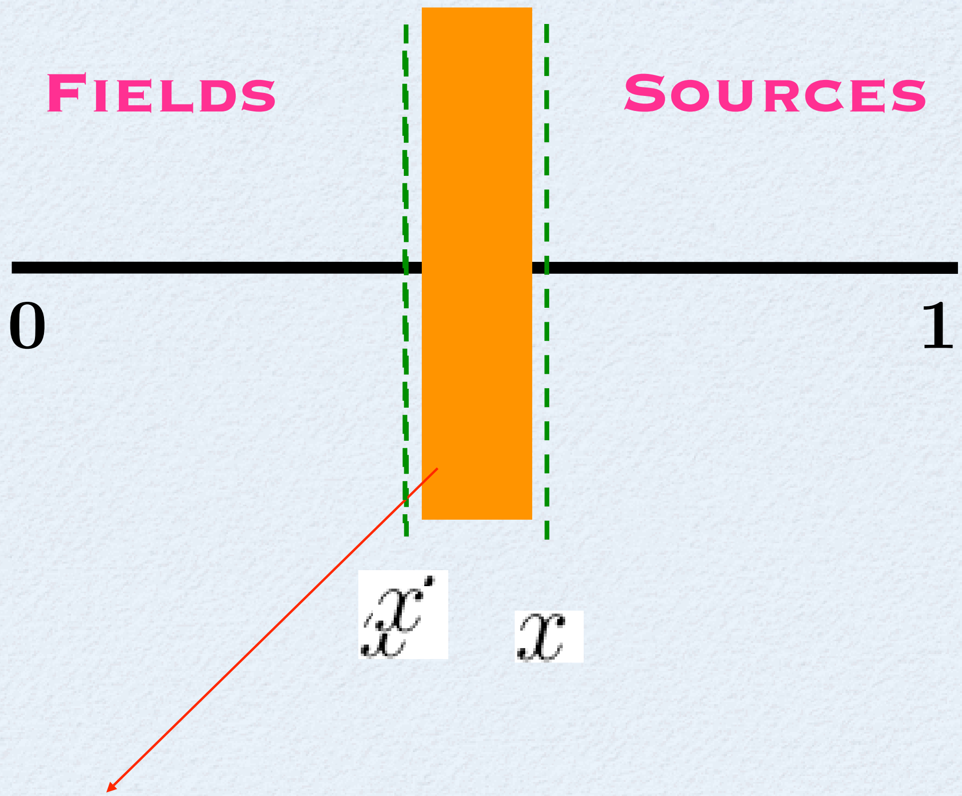
MV: $$F[\rho] \to \frac{\rho^2}{\mu^2} \qquad \mathrm{tr}\,\rho\,\mathrm{U} \to \rho\mathrm{A}^-$$

Hadron/nucleus at high energy is a Color Glass Condensate



- *Gluons are colored*
- *Random sources evolving on time scales much larger than natural time scales - very similar to spin glasses*
- *Bosons with a large occupation number* $n \sim \frac{1}{\alpha_s}$
- *Typical momentum of gluons is* $Q_s(x)$

QCD at High Energy: from classical to quantum (α_s Log 1/x)



Integrate out small fluctuations => Increase color charge of

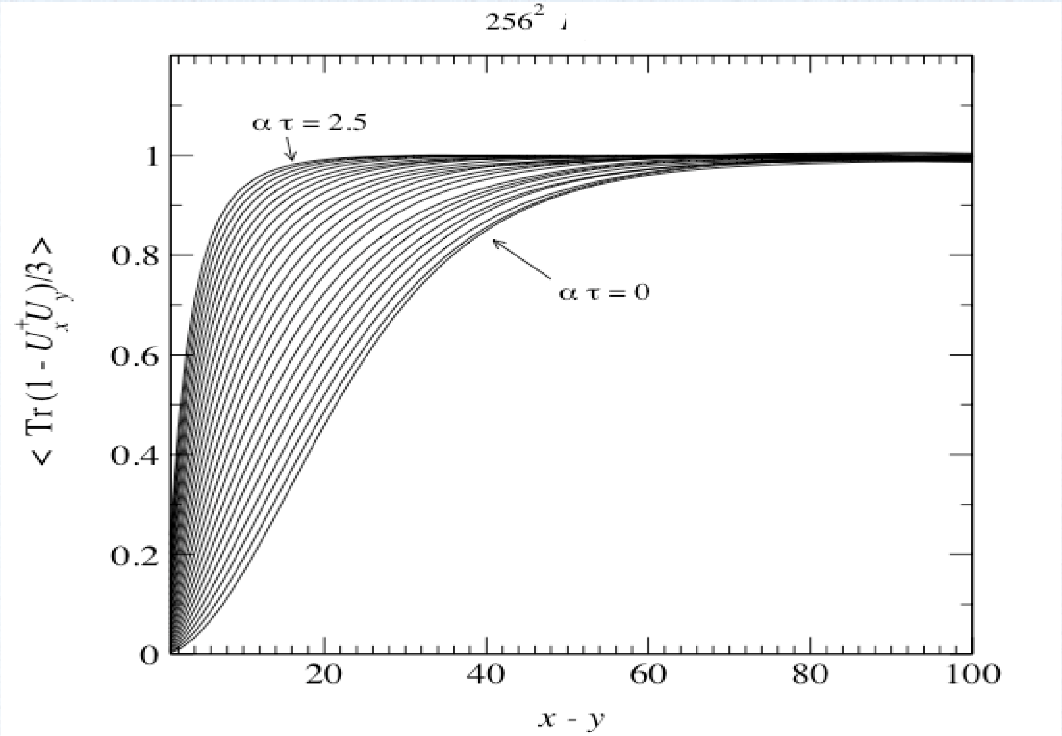
$$\frac{\partial W_x[\rho]}{\partial \ln(1/x)} = \frac{1}{2}\int_{x_\perp, y_\perp} \frac{\delta}{\delta\rho_x^a(x_\perp)} \chi^{ab}(x_\perp, y_\perp)[\rho] \frac{\delta}{\delta\rho_x^b(y_\perp)} W_x[\rho]$$

B-JIMWLK

B-JIMWLK equations describe evolution of all N-point correlation functions with energy

the 2-point function: Tr [1 - $U^{+}(x_t)\, U(y_t)$]

(probability for scattering of a quark-anti-quark dipole on a target)



B-JIMWLK in two limits:

I) Strong field: exact scaling - f (Q^2/Q^2_s) for $Q < Q_s$

II) Weak field: BFKL

BK: mean field + large N_c

A closed form equation

$$\partial_Y \langle T_{\mathbf{xy}} \rangle = \frac{\bar{\alpha}}{2\pi} \int d^2 z \, \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} \left[\langle T_{\mathbf{xz}} \rangle + \langle T_{\mathbf{zy}} \rangle - \langle T_{\mathbf{xy}} \rangle - \langle T_{\mathbf{xz}} \rangle \langle T_{\mathbf{zy}} \rangle \right]$$

The simplest equation to include unitarity: $T < 1$

Exhibits geometric scaling

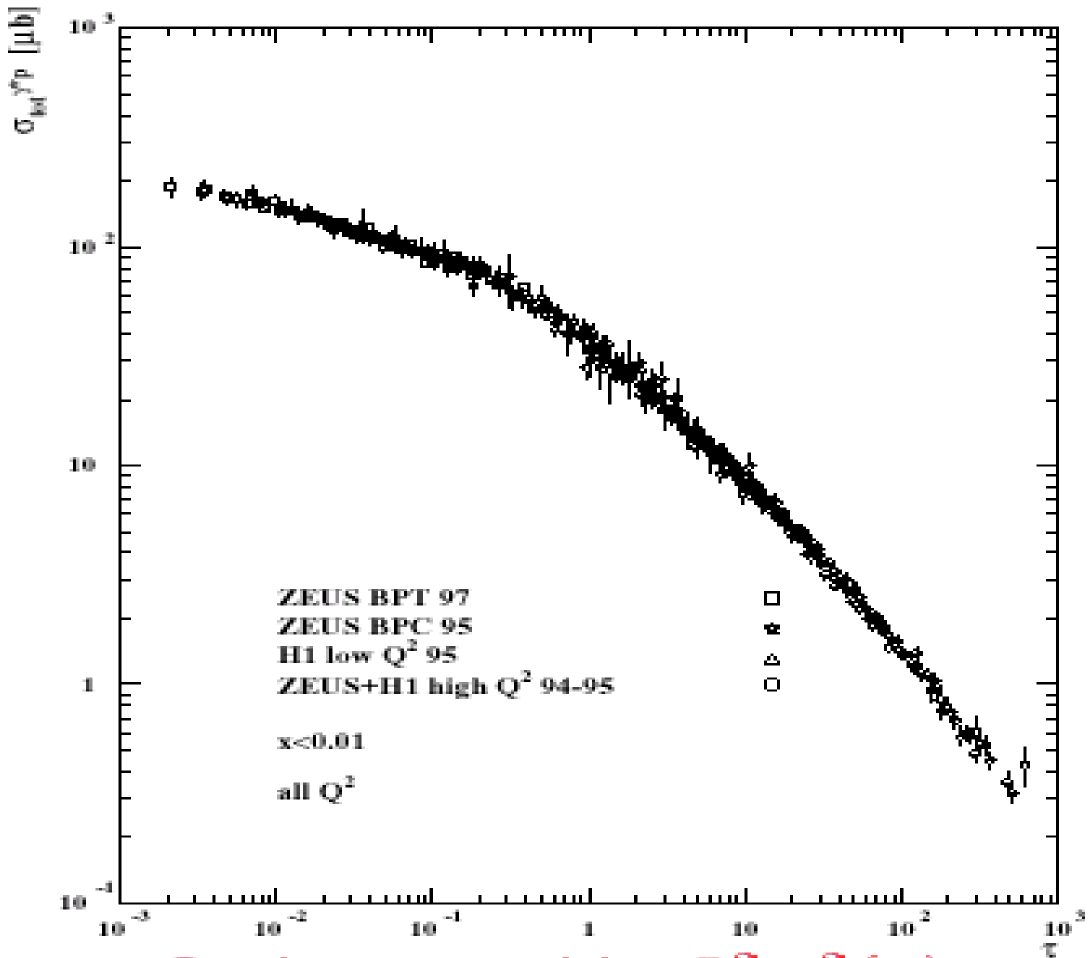
$$\mathbf{T(x, r_t) \rightarrow T[r_t Q_s(x)]}$$

for

$$\mathbf{Q_s < Q < \frac{Q_s^2}{\Lambda_{QCD}}}$$

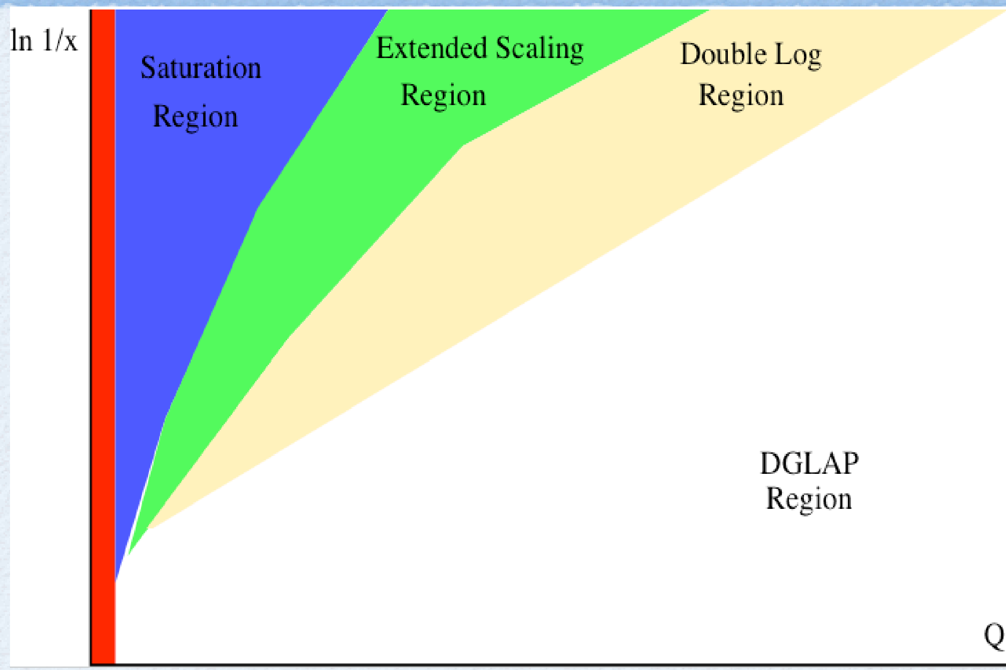
Geomtric scaling at HERA

$x < 0.01, \quad 0.045 < Q^2 < 450\ \mathrm{GeV}^2$



Scaling variable $Q^2 R_0^2(x)$

A New Paradigm of QCD



Saturation region: dense system of gluons

Extended scaling region: dilute system -anomalous dimension

Double Log: BFKL meets DGLAP

DGLAP: collinearly factorized pQCD

Relation to statistical physics

MP

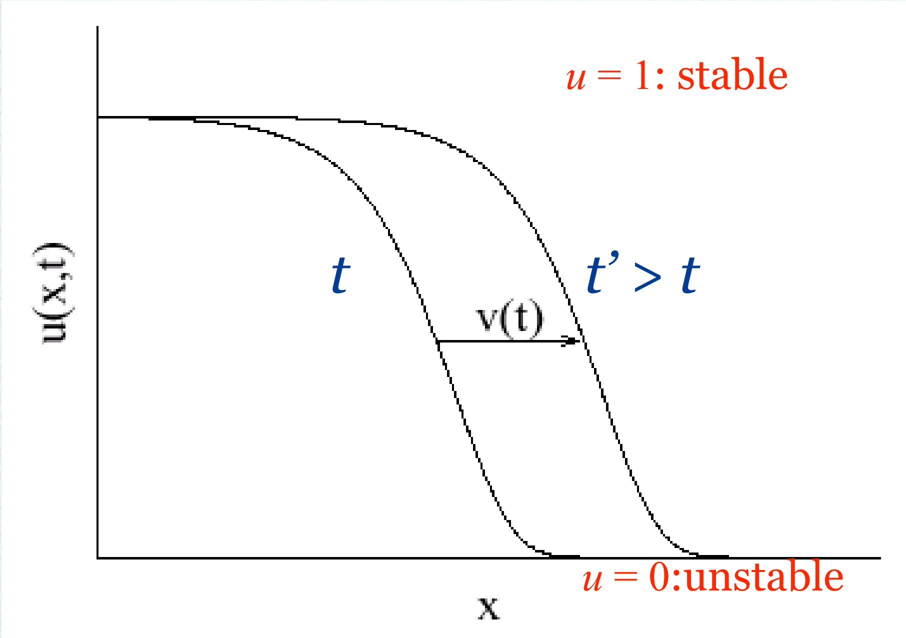
BK in momentum space $\partial_{\mathbf{y}} \mathbf{N} = \bar{\alpha}\, \chi[-\partial_{\mathbf{L}}] \mathbf{N} - \bar{\alpha}\, \mathbf{N}^2$

can be written as with

N --> u, y ---> t,L ---> x

$\partial_{\mathbf{t}} \mathbf{u} = \partial_{\mathbf{x}}^2 \mathbf{u} + \mathbf{u} - \mathbf{u}^2$

traveling wave solution



F-KPP equation in statistical mechanics

with applications in biology, ...

Beyond B-JIMWLK (BK)

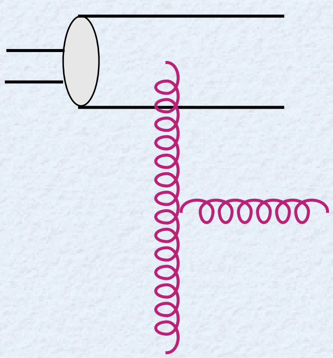
some undesirable features

merging vs. splitting

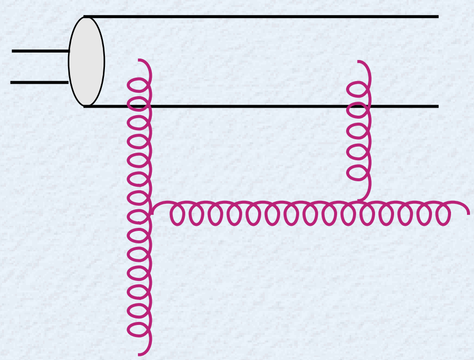
2 --> 1 vs. 1 --> 2

reaction-diffusion in statistical mechanics: sF-KPP

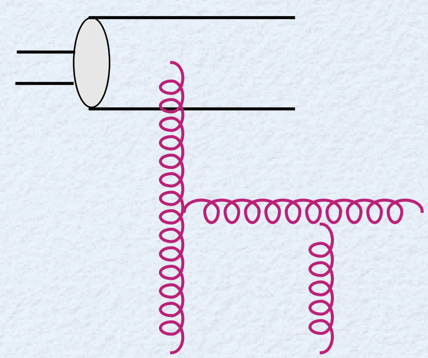
Pomeron loops



BFKL



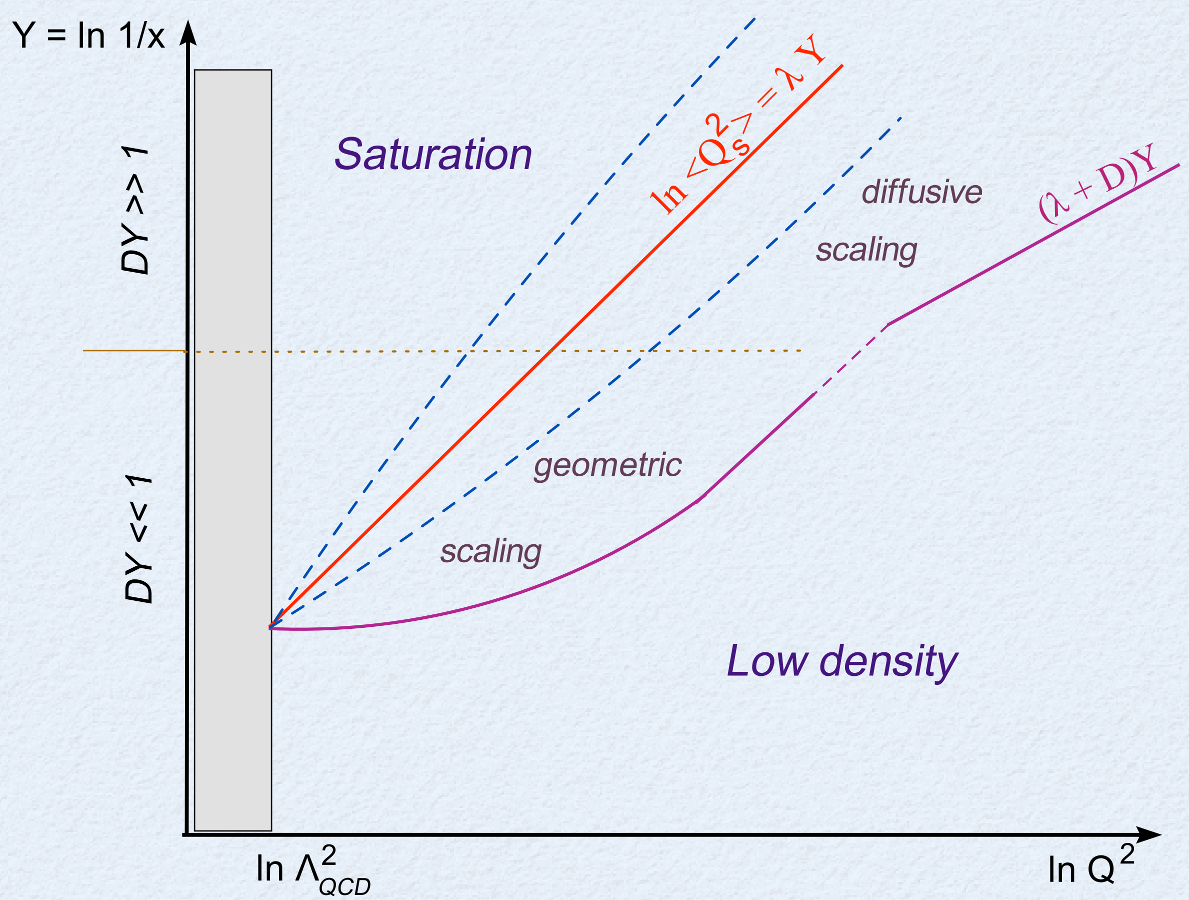
saturation



fluctuation

The new phase diagram

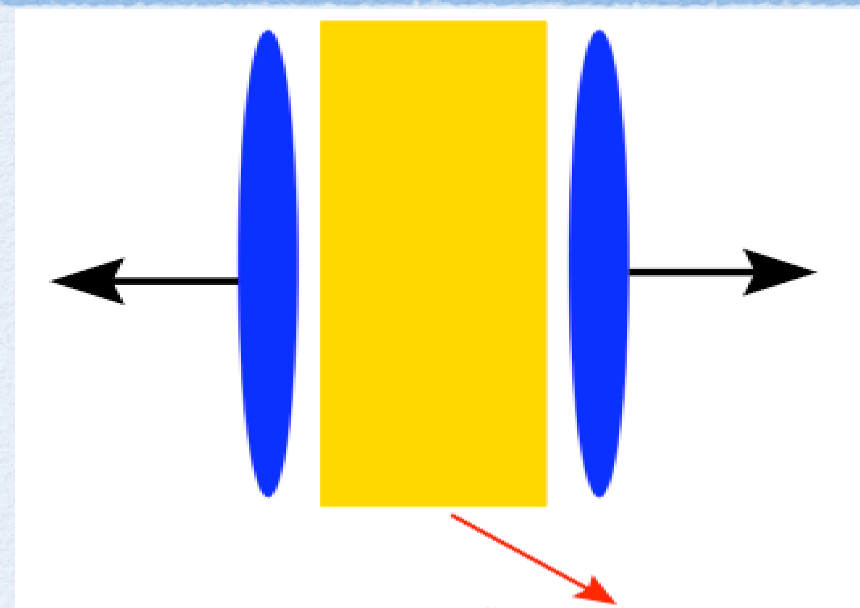
The “phase–diagram” revisited



Applications to RHIC and LHC

Colliding sheets of color glass

solve the classical eqs. of motion in the forward light cone: subject to initial conditions given by one nucleus solution



Classical Fields with occupation # f= $\frac{1}{\alpha_S}$

Initial energy and multiplicity of ***produced*** *gluons depends on* **Q_s**

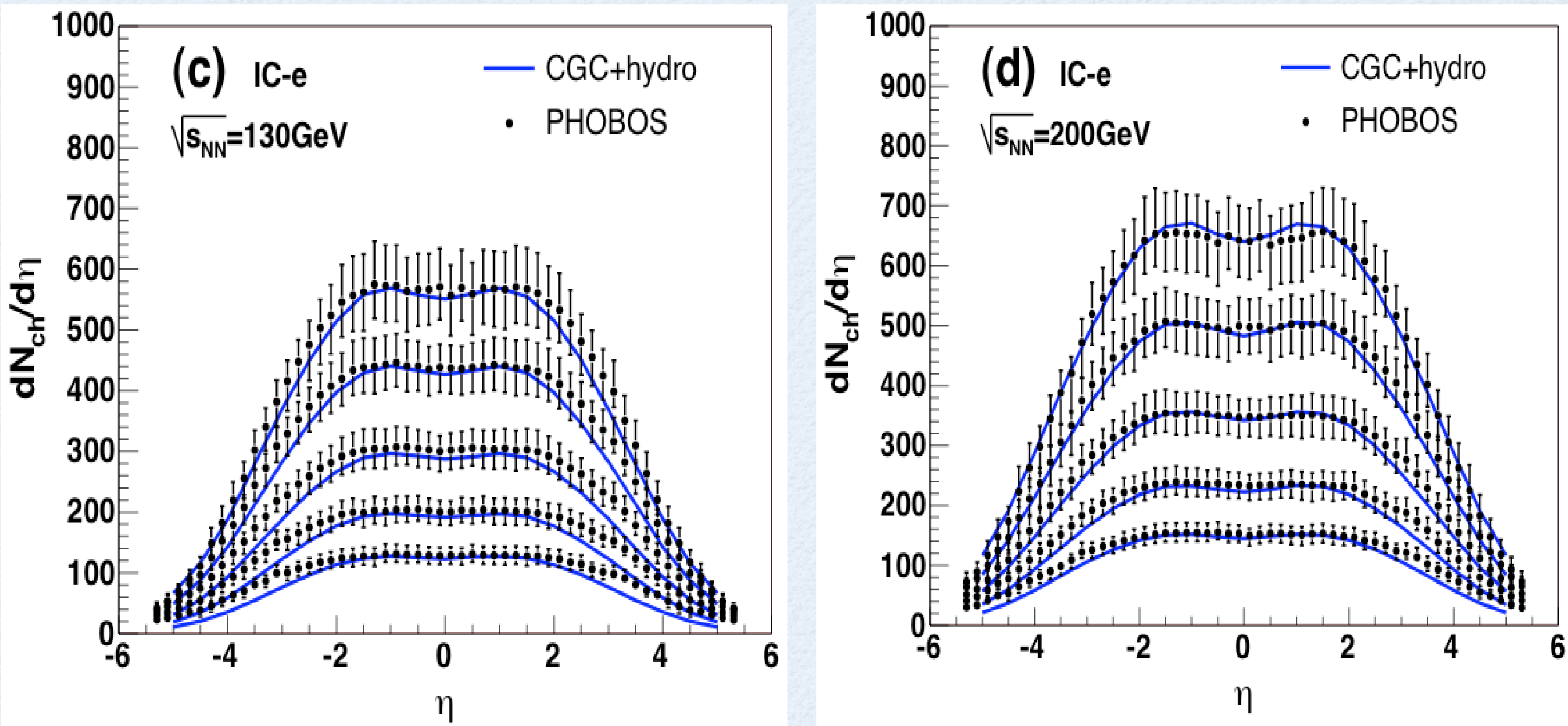
$$\frac{1}{\pi R^2}\frac{dE_\perp}{d\eta} = \frac{0.25}{g^2} Q_s^3$$

$$\frac{1}{\pi R^2}\frac{dN}{d\eta} = \frac{0.3}{g^2} Q_s^2$$

Fermion production (Gelis et al.)

Colliding Sheets of Colored Glass

adding final state effects: hydro, energy loss



Colliding Sheets of Colored Glass

What happens to produced gluons?

Is there thermalization of QCD matter?

Can it be described by weak coupling ?

Bottom up scenario (Baier, Mueller, Schiff, Son)

Production of "hard" gluons: $k \sim Q_s$

Radiation of "soft" gluons: $k << Q_s$

Soft gluons thermalize

Hard gluons thermalize

Thermalization time: $\tau \sim \frac{1}{\alpha_s^{13/5} Q_s}$ $\quad T_{max} \sim \alpha^{2/5} Q_s$

Instabilities? **Fast thermalization?**

Signatures of CGC at RHIC: pA

- Multiplicities (dominated by $p_t < Q_s$):

  energy, rapidity, centrality dependence

- **Single particle production: hadrons, EM**

  rapidity, p_t, centrality dependence

i) Fixed p_t: vary rapidity (evolution in x)

ii) Fixed rapidity: vary p_t (transition from dense to dilute)

- *Two particle production: back to back correlations*

CGC: qualitative expectations

$$R_{pA} \equiv \frac{1}{A} \frac{\frac{d\sigma^{pA \to h\,X}}{dy\, d^2p_t}}{\frac{d\sigma^{pp \to h\,X}}{dy\, d^2p_t}}$$

Classical (multiple elastic scattering):

$p_t \gg Q_s$: enhancement (**Cronin effect**)

$R_{pA} = 1 + (Q_s^2/p_t^2) \log p_t^2/\Lambda^2 + \ldots$

$R_{pA}\ (p_t \sim Q_s) \sim \log A$

position and height of enhancement are increasing with centrality

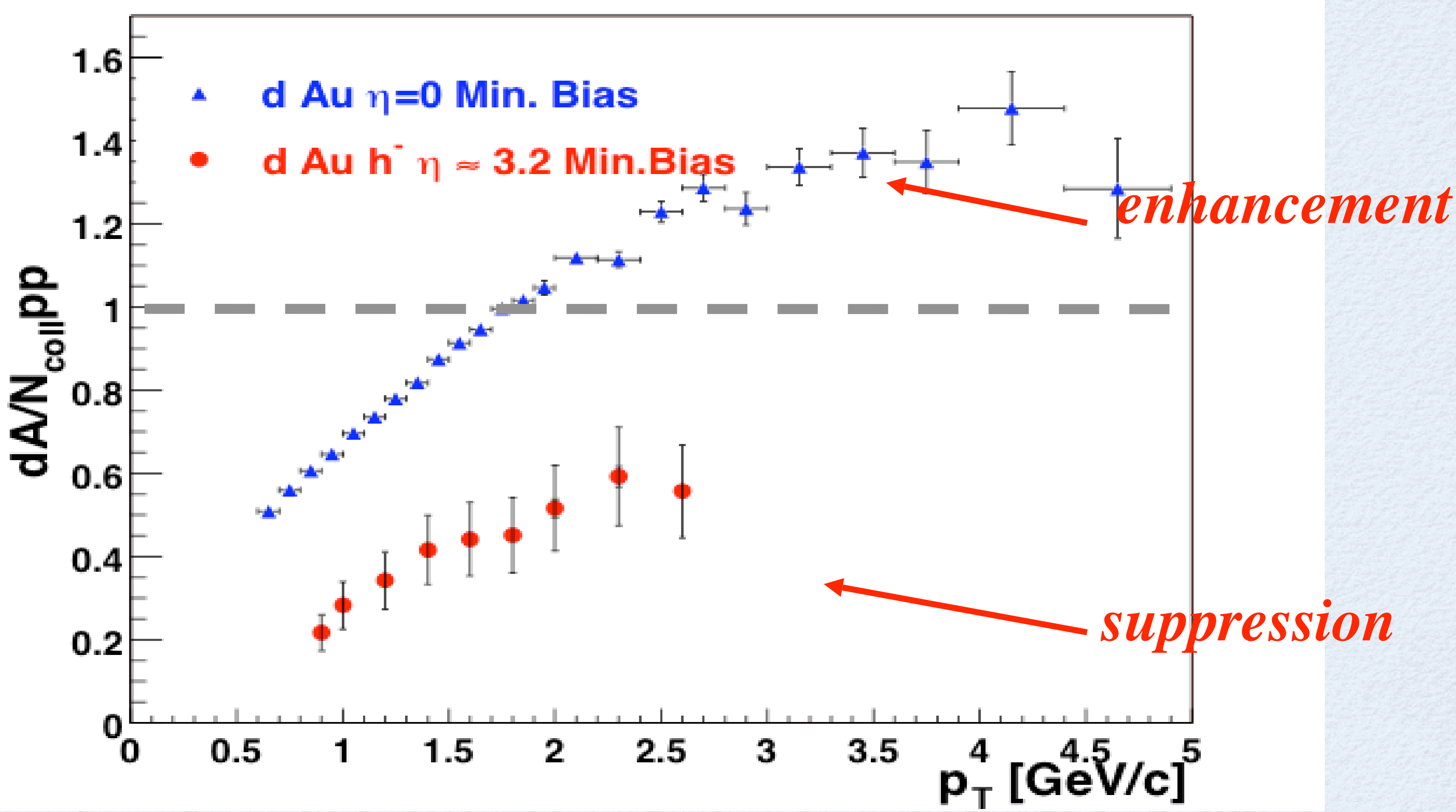
Evolution in x:

can show analytically the peak disappears as energy/rapidity grows

and levels off at $R_{pA} \sim A^{-1/6} < 1$

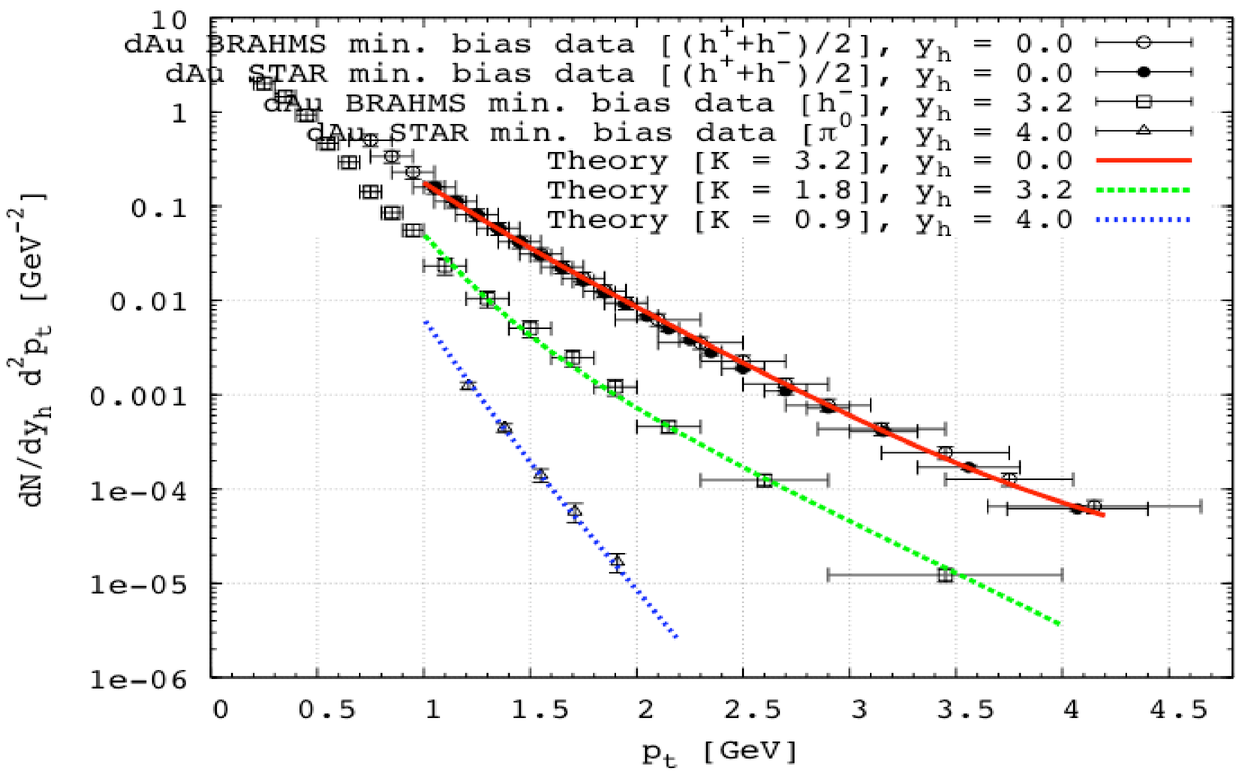
These expectations are confirmed at RHIC

CGC vs. RHIC



BRAHMS

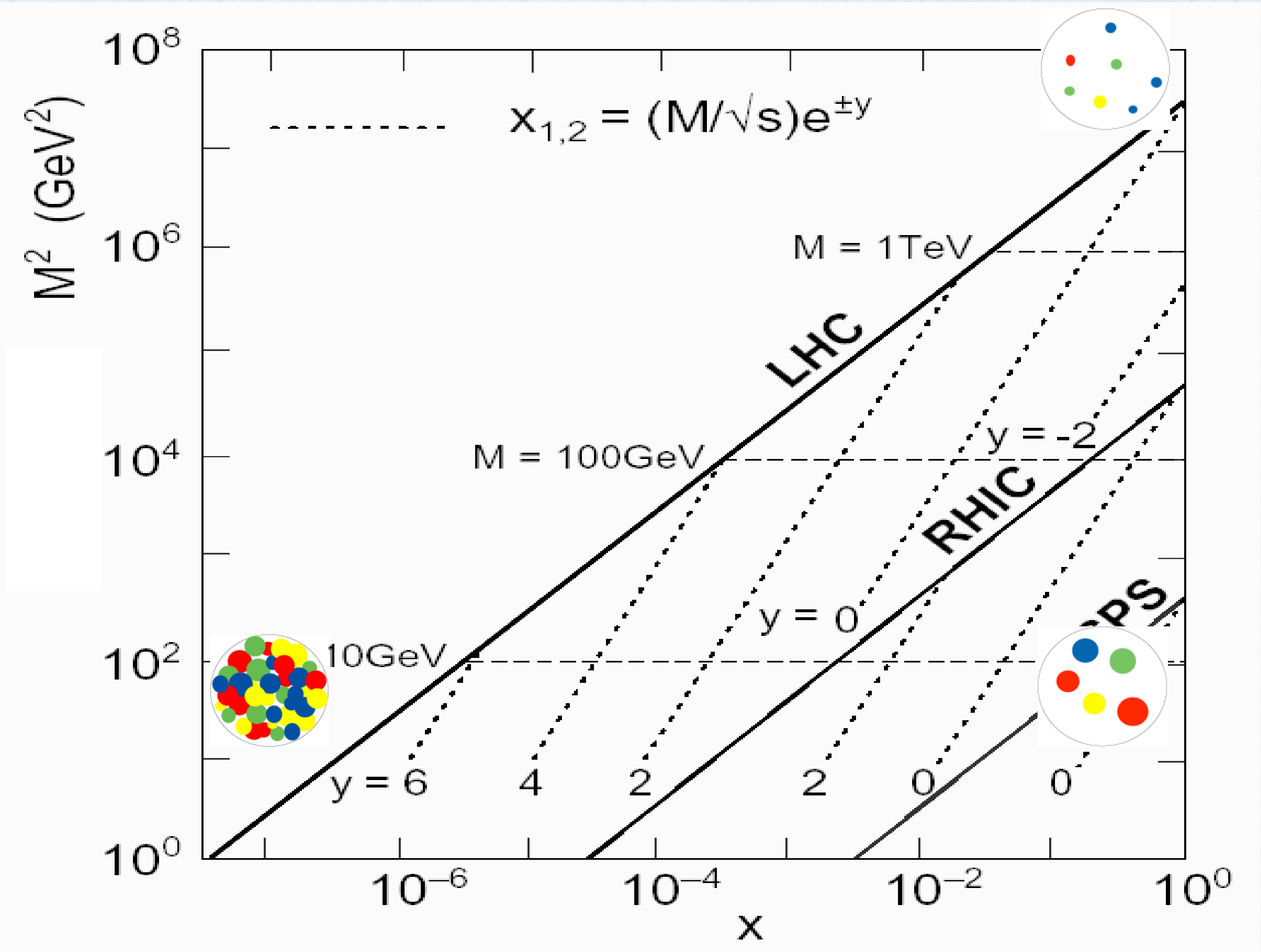
Rapidity and pt dependence



What we see is a transition from DGLAP to BFKL to CGC kinematics

Centrality, flavor, species dependence

The future is promising!



Exciting time in high energy QCD again

- *Frenetic pace of theoretical developments*
- *Hints for CGC from HERA*
- *Strong evidence for CGC from RHIC*

Significant ramifications for strong interaction physics at LHC and eRHIC