Saturation Physics: Probes and Signatures

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Outline

- Perturbative QCD (pQCD)
  - Proton-proton collisions
    - Collinear factorization
    - Distribution functions
- QCD at high energy/large A
  - Color Glass Condensate (***CGC***)
- Proton (deuteron)-nucleus collisions
  - Particle production
  - Signatures of CGC at RHIC
- Outlook

Deeply Inelastic Scattering (DIS)

e p (A) ---> e X

Kinematic Invariants:

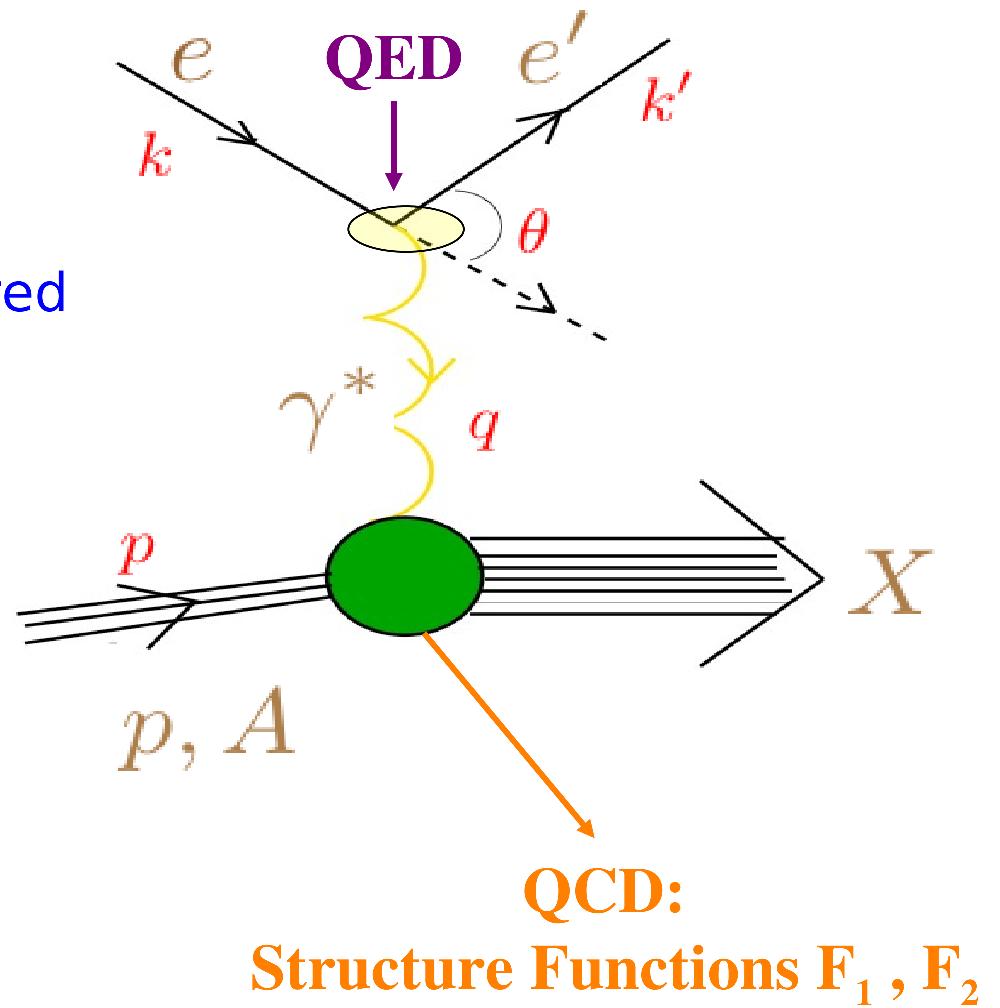
Center of mass energy squared

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

Momentum squared

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

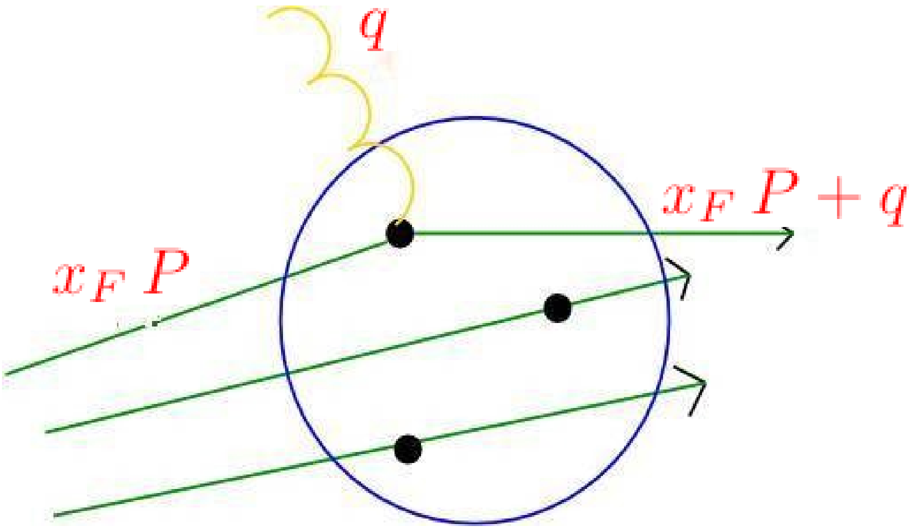
$$\mathbf{x_{bj}} \equiv \frac{\mathbf{Q^2}}{\mathbf{2p \cdot q}}$$



Parton model

- Bjorken: $\mathbf{Q^2}\ ,\ \mathbf{S} \to \infty$ but $x_{Bj}=Q^2/S$ fixed

Structure functions depend only on x_{Bj}

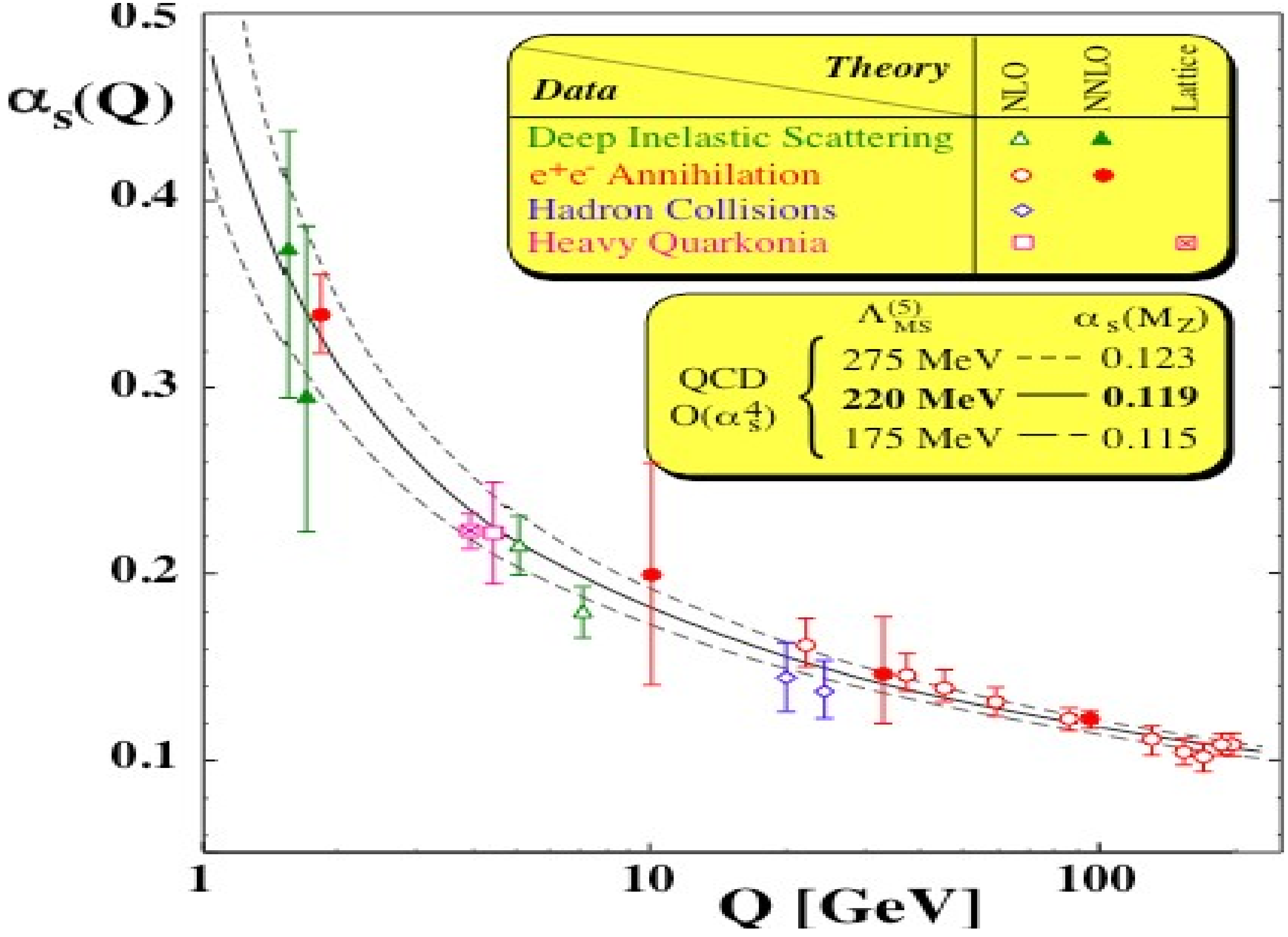


- Feynman:

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

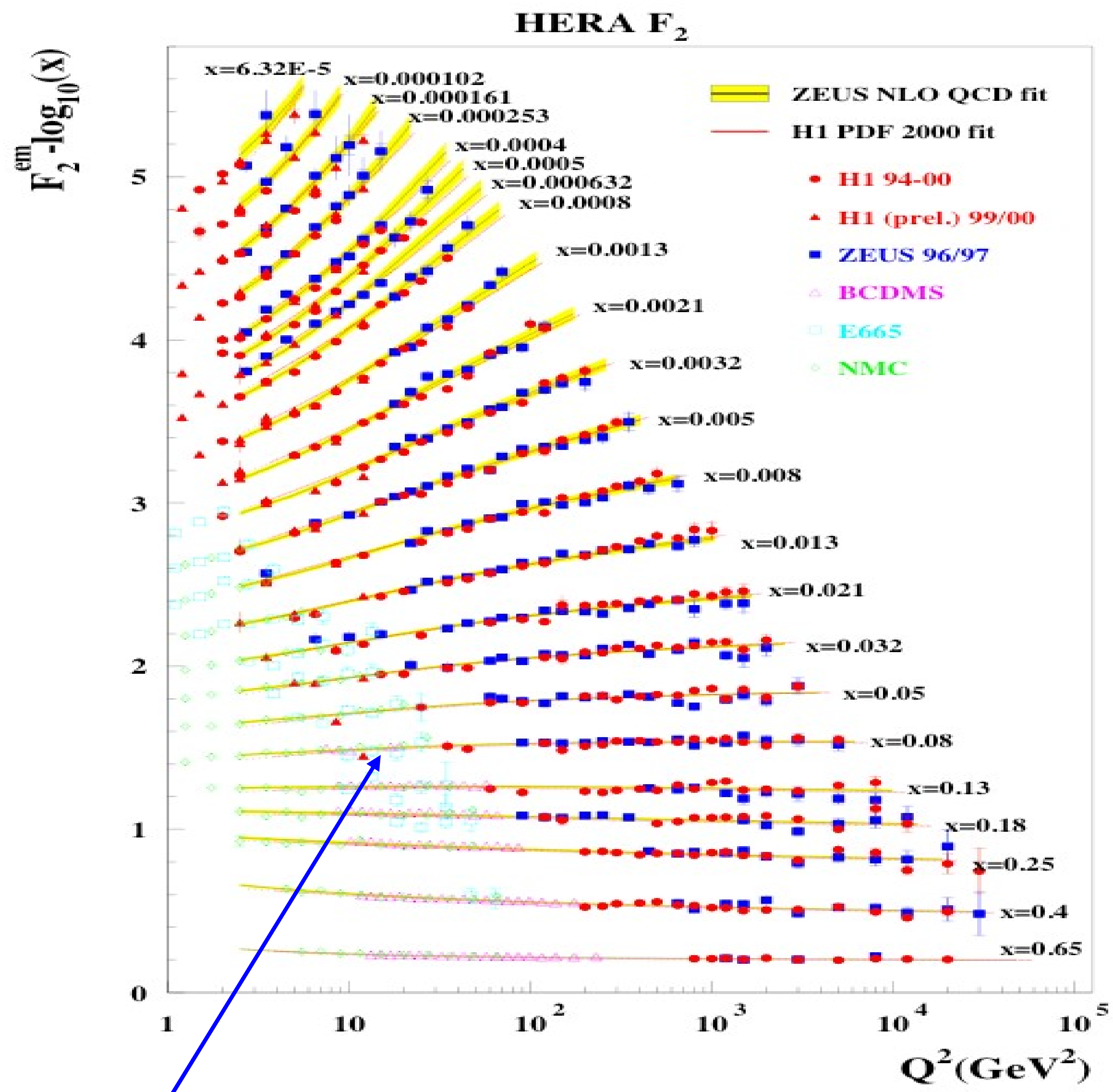
$x_{\mathrm{Bj}} =$ fraction of hadron momentum carried by a parton

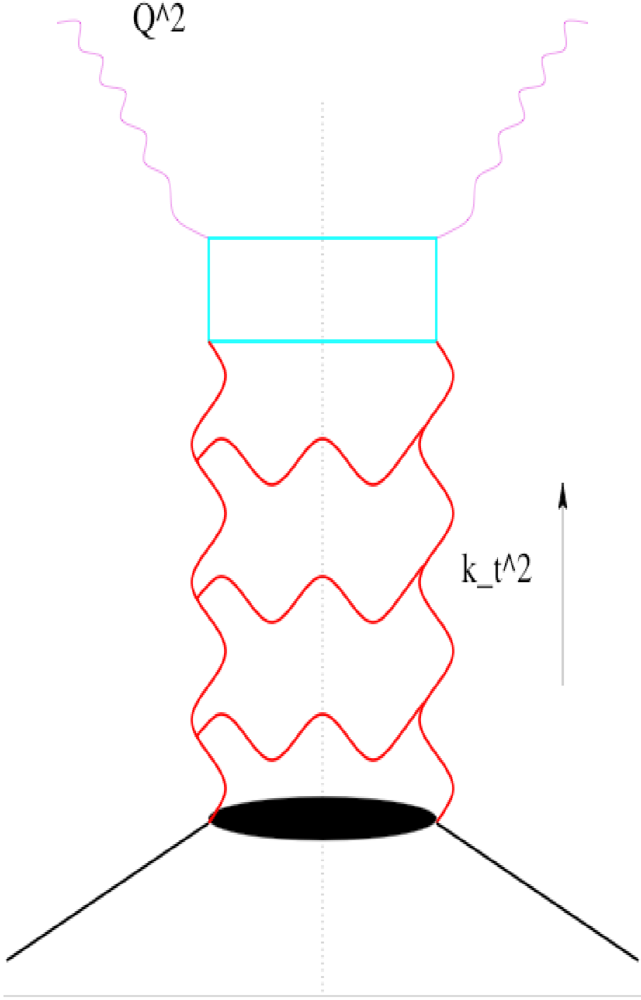
running of the coupling constant



***perturbative QCD**: expansion in the coupling constant*

evolution of
distribution functions



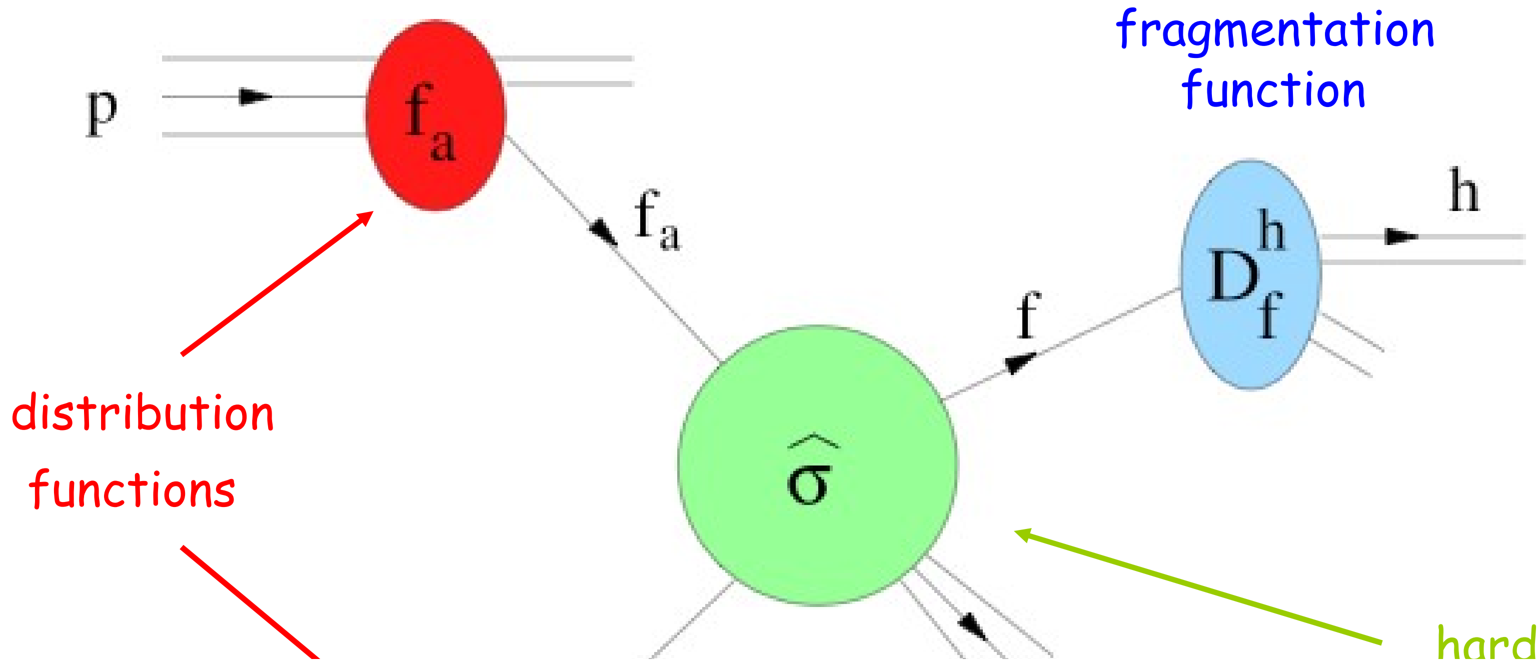


Bj scaling

Dokshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi

pQCD in pp Collisions

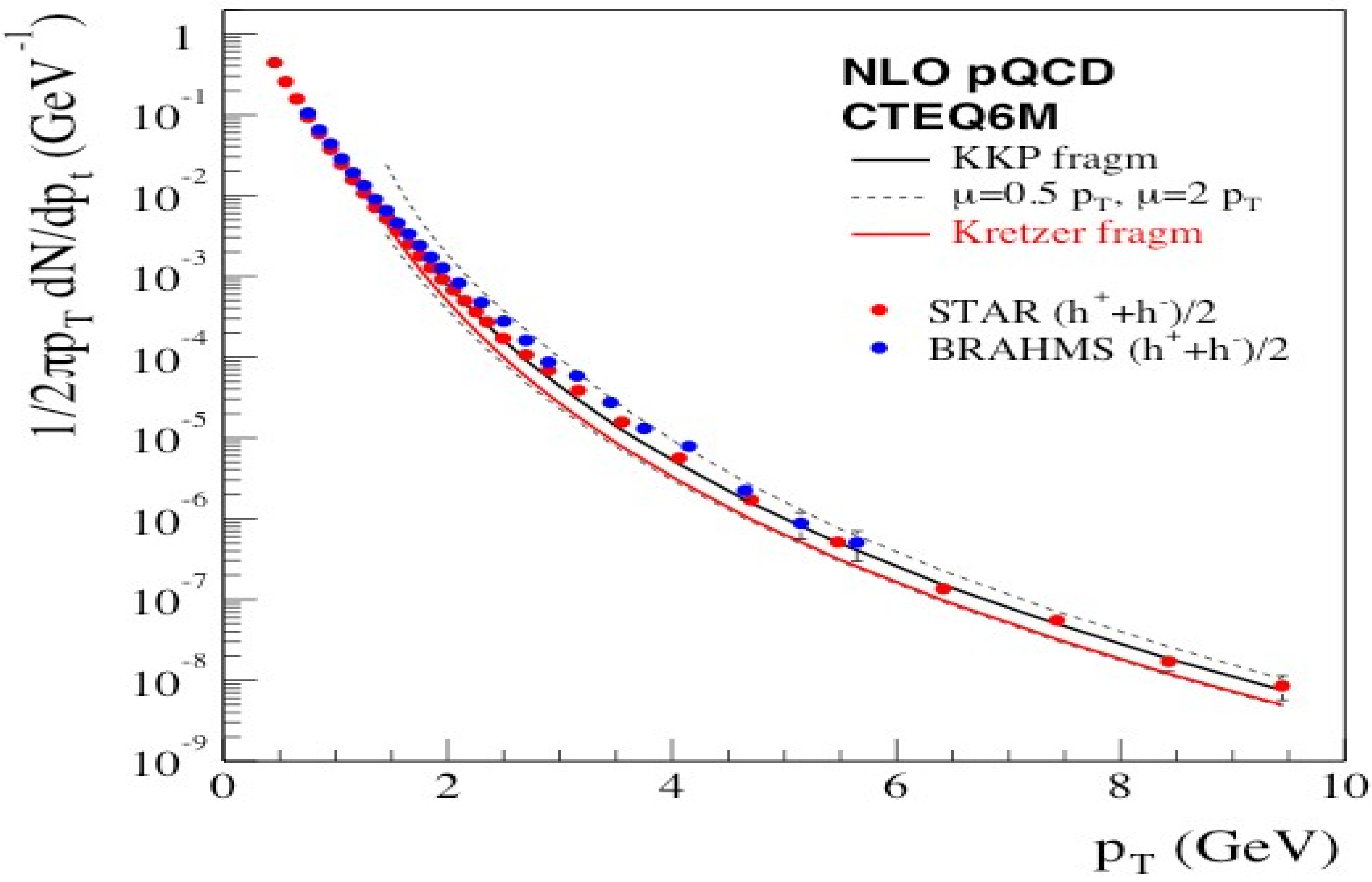
Collinear factorization: separation of long and short distances



$$d\sigma = \int dx_1\, dx_2\, dz\, f_a^{H1}(x_1, M^2)\, f_b^{H2}(x_2, M^2)\, D_c^h(z, M^2)$$

$$\otimes \quad d\hat{\sigma}_{ab}^c(x_1 P_{H1}, x_2 P_{H2}, P_h/z, M^2)$$

pQCD in pp Collisions at RHIC



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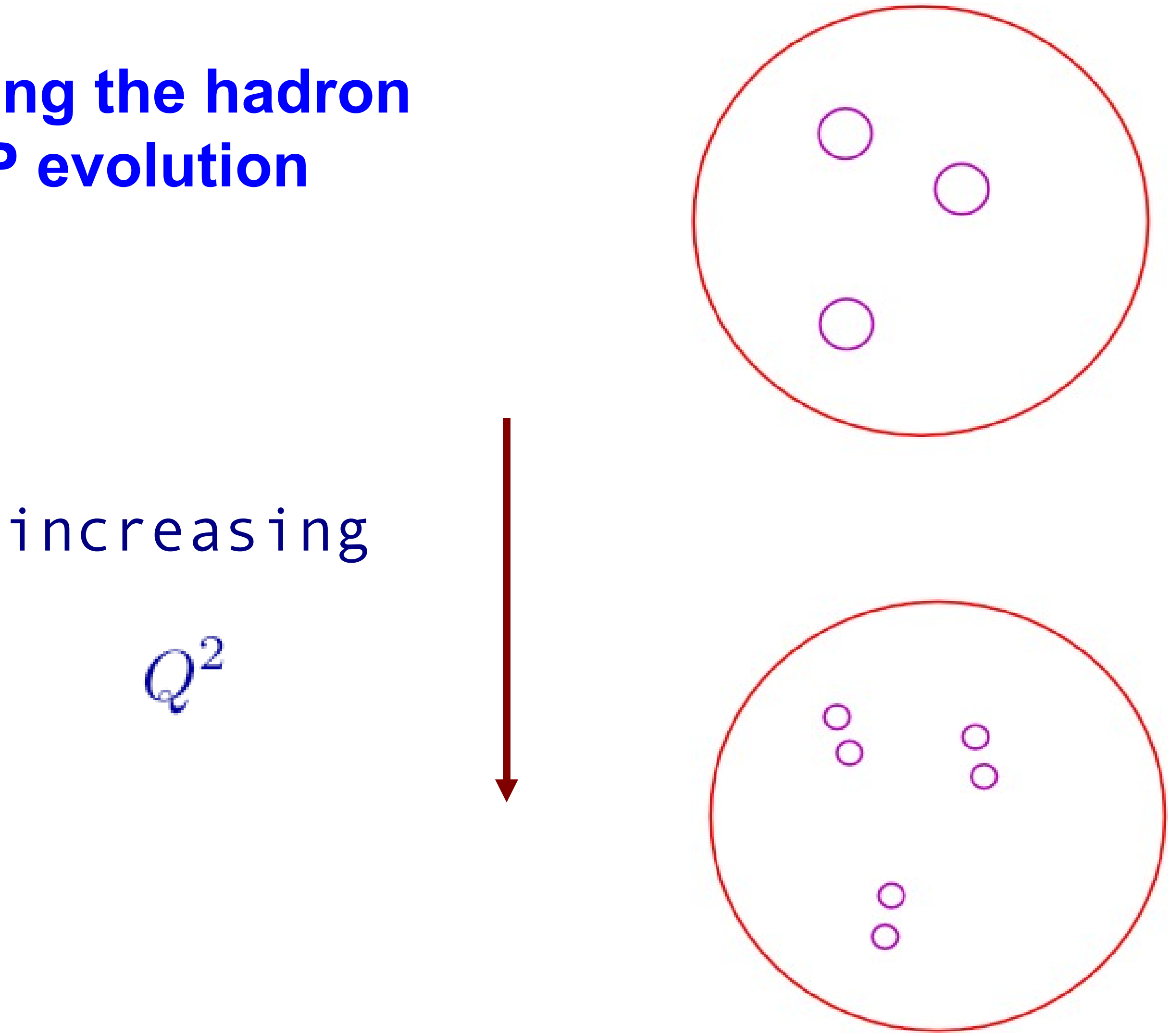
Resolving the hadron
-DGLAP evolution



But… the phase space density decreases
-the proton becomes more dilute

QCD in the Regge-Gribov limit

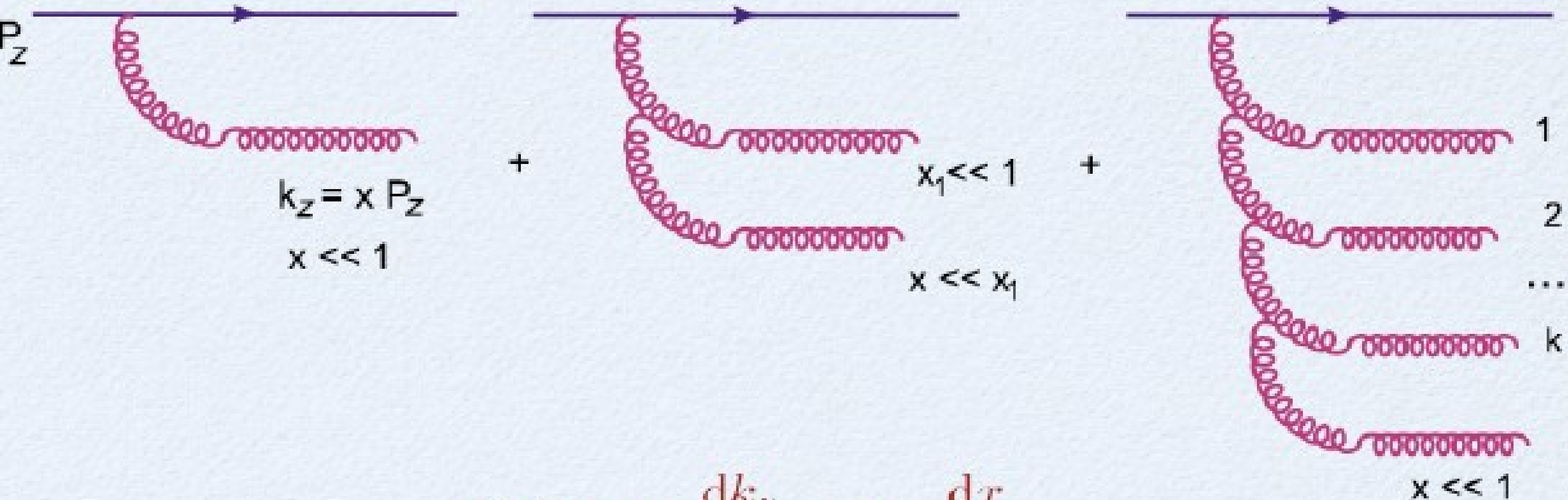
$$\mathbf{S \to \infty\,,\ Q^2\ fixed : x_{Bj} \to 0}$$

Regge

Gribov

gluon radiation at small x

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



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

- The 'price' of an additional gluon:

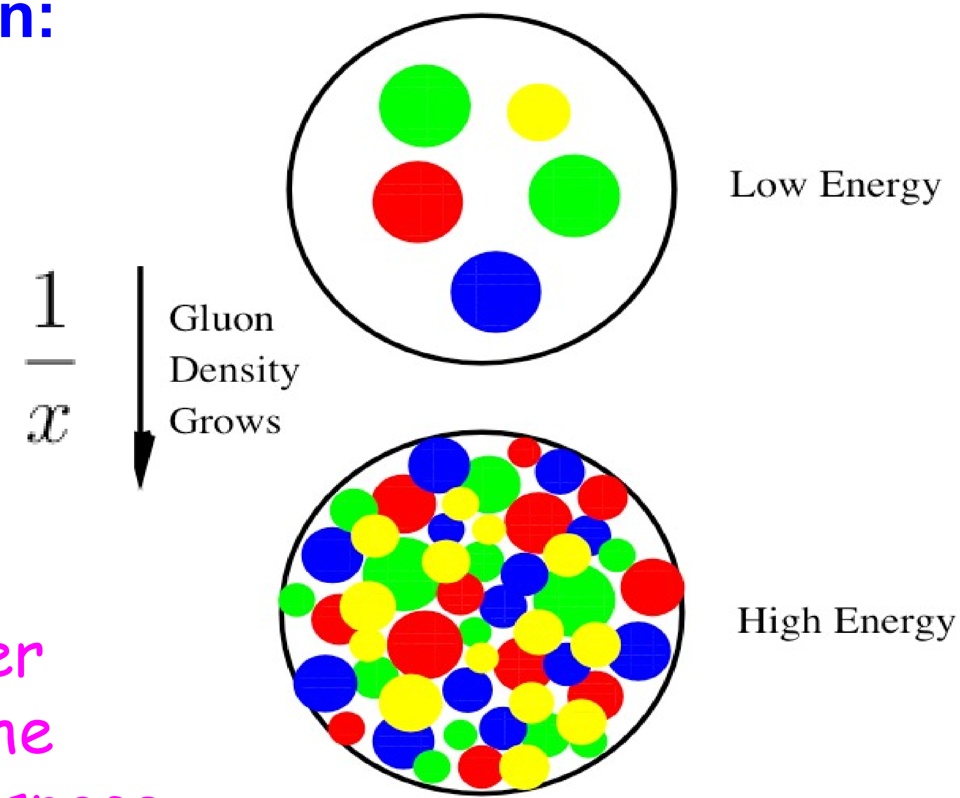
$$\mathcal{P}(1) \propto \alpha_s \int_x^1 \frac{\mathrm{d}x_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

number of gluons grows fast

$$n \sim e^{\alpha_s \ln 1/x}$$

Resolving the nucleus/hadron:

Regge-Gribov limit



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

Physics of strong color fields in QCD, multi-particle production- universal properties of theory in this limit ?

Mechanism for parton saturation

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

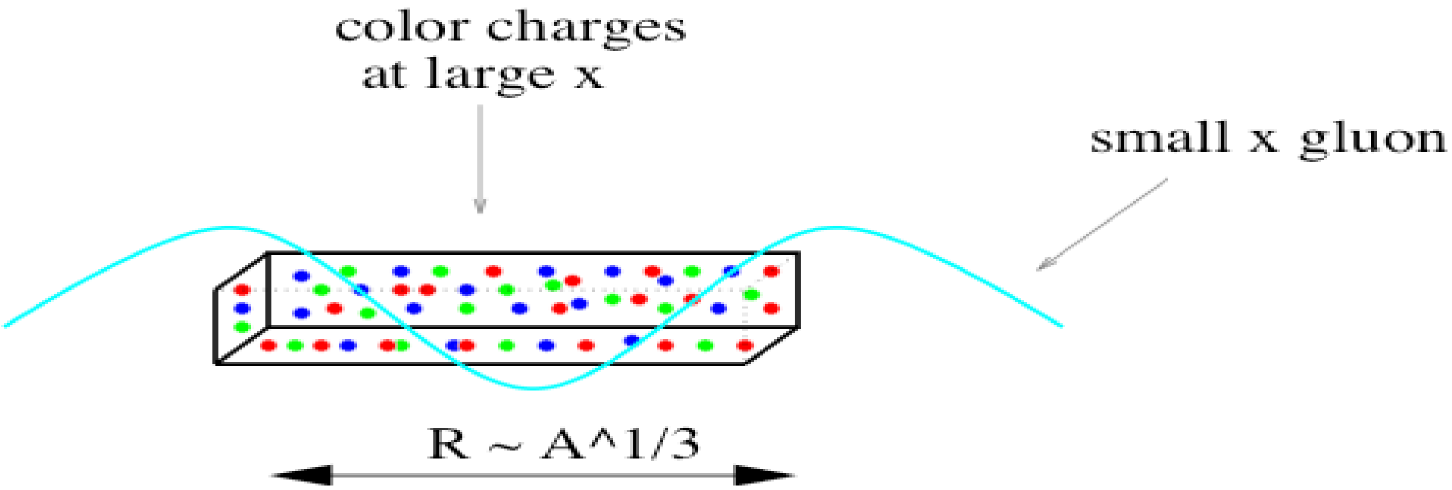
Maximum occupation number =>

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

saturated for

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

The nuclear "oomph" factor

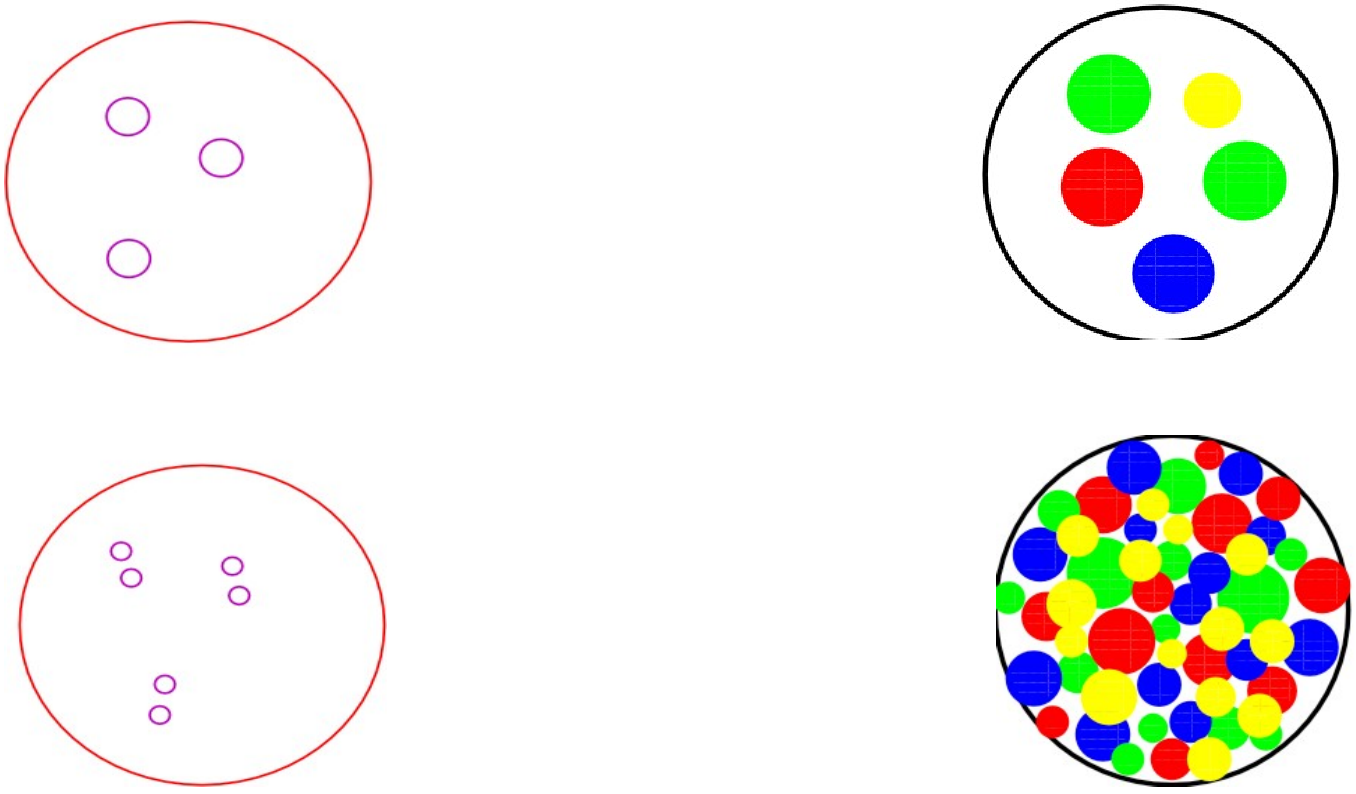


$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^{\delta}}$$

$\delta \sim 0.3$

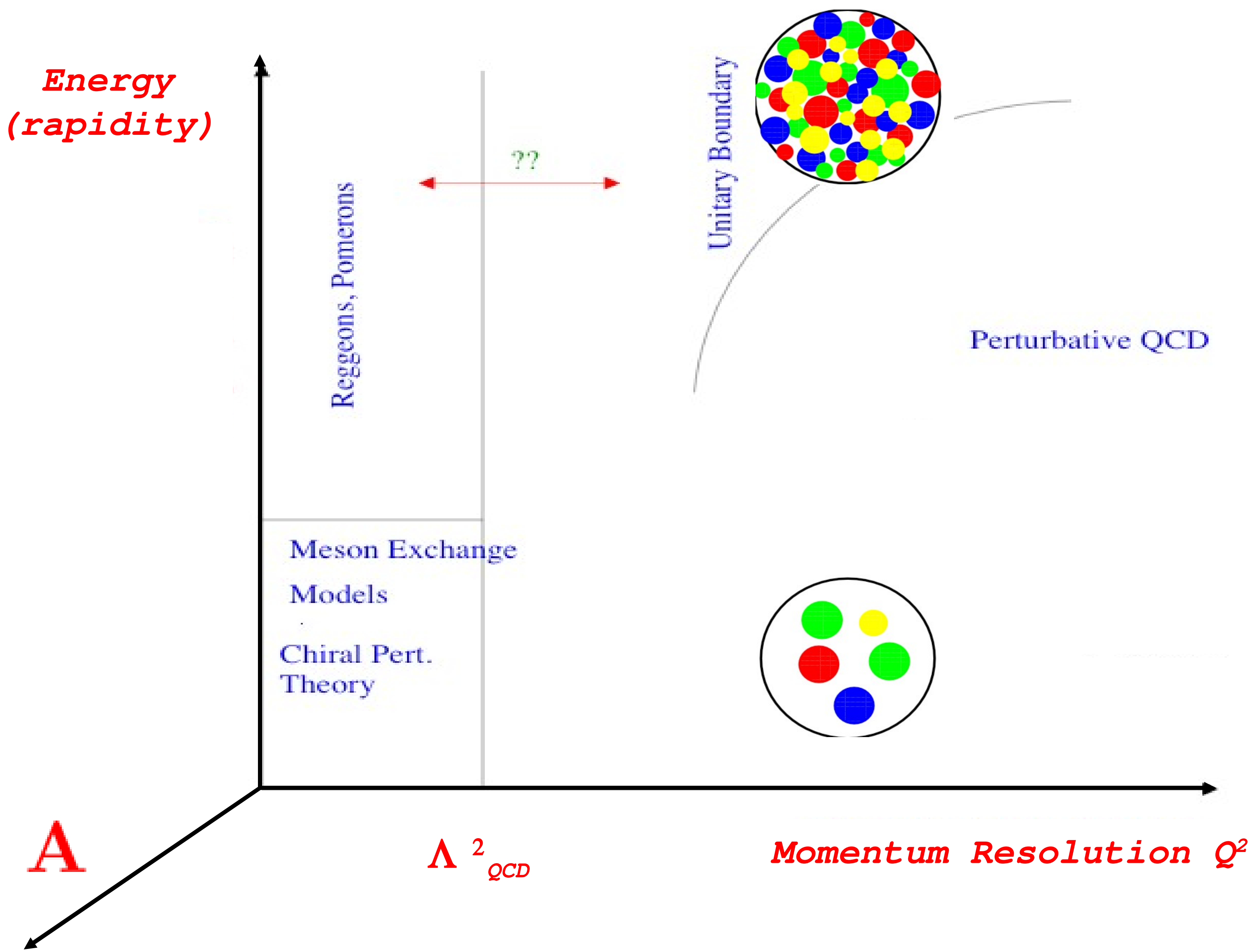
$$\alpha_s(Q_s^2) \ll 1$$

Bjorken/Feynman or Regge/Gribov?



depends on kinematics!

Road map of the strong interactions



QCD in high gluon density regime

Need a new organizing principle to explore this novel regime of high energy QCD

"multiple scattering": classical fields

+

energy (x) dependence: ln (1/x)

The effective action

Scale separating sources and fields

Generating functional:

$$\mathcal{Z}[j] = \int [d\rho]\, W_{\Lambda^+}[\rho] \left\{ \frac{\int^{\Lambda^+} [dA]\, \delta(A^+)\, e^{iS[A,\rho] - \int j\cdot A}}{\int^{\Lambda^+} [dA]\, \delta(A^+)\, e^{iS[A,\rho]}} \right\}$$

Gauge invariant weight functional describing distribution of the sources

$$S[A,\rho] = \frac{-1}{4}\int d^4x\, F_{\mu\nu}^2 + \frac{i}{N_c}\int d^2x_\perp dx^- \delta(x^-) \mathrm{Tr}\left(\rho(x_\perp)\, U_{-\infty,\infty}[A^-]\right)$$

where $U_{-\infty,\infty}[A^-] = \mathcal{P}\exp\left(ig\int dx^+ A^{-,a}T^a\right)$

To lowest order, $= -J^+A^- \text{ with } J^+ = g\,\rho(x_\perp)\,\delta(x^-)$

McLerran,Venugopalan;

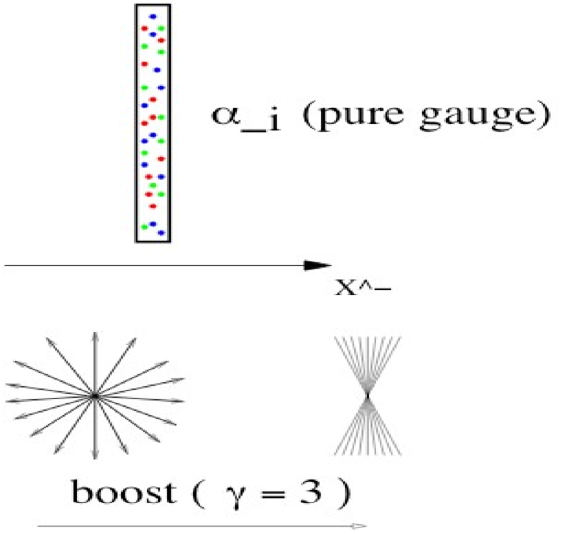
Jalilian-Marian,Kovner,Leonidov,Weigert;

Fukushima

The classical field of the nucleus at high energies

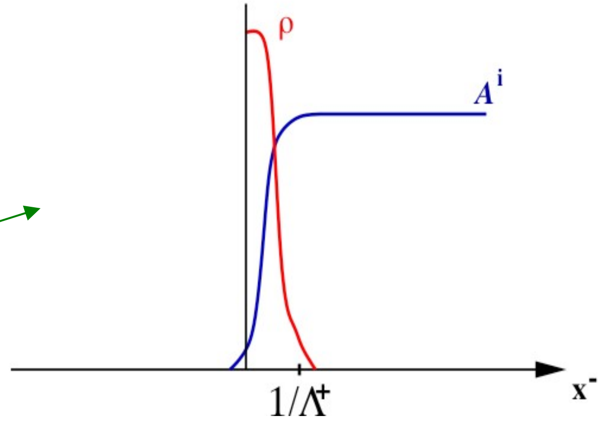
Saddle point of effective action-> Yang-Mills equations

$$D_\mu F^{\mu\nu,a} = \delta^{\nu +}\delta(x^-)\rho^a(x_\perp)$$



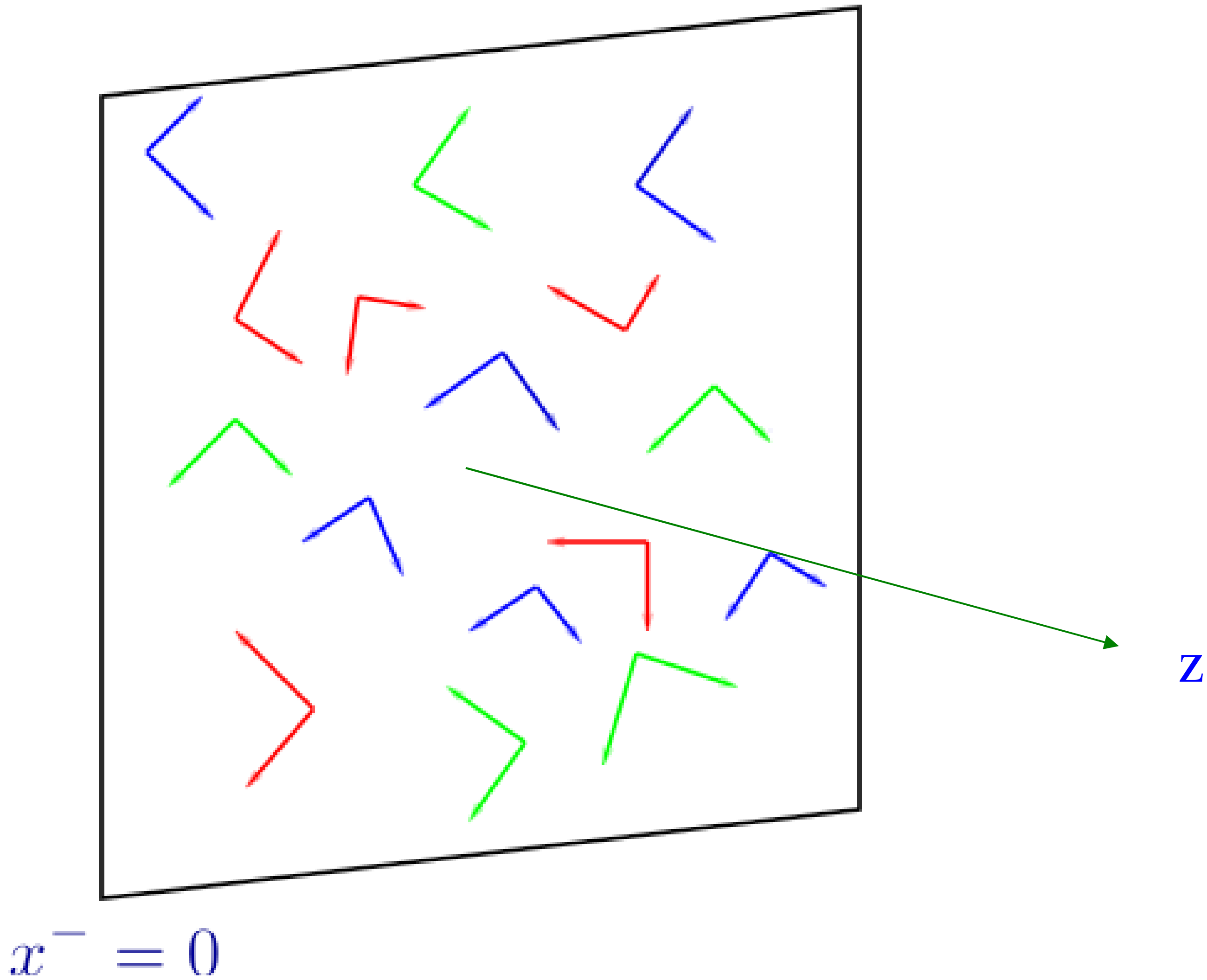
Solutions are non-Abelian Weizsäcker-Williams fields

$$A^+ = A^- = 0\ ;$$
$$F^{ij} = 0 => A^i = \theta(x^-)\alpha^i\,,$$
$$\text{where } \alpha^i = \frac{-1}{ig} U\nabla^i U^\dagger$$
$$\text{and } \nabla\cdot\alpha = g\rho$$

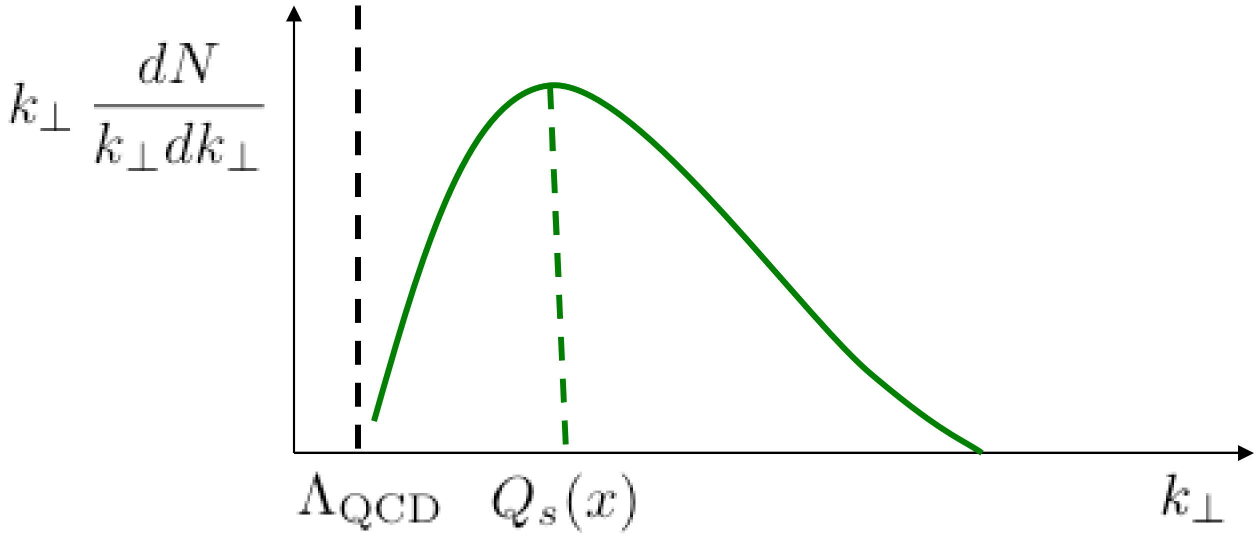


Careful solution requires smearing in x^-

Random Color Electric & Magnetic fields in the plane of the fast moving nucleus

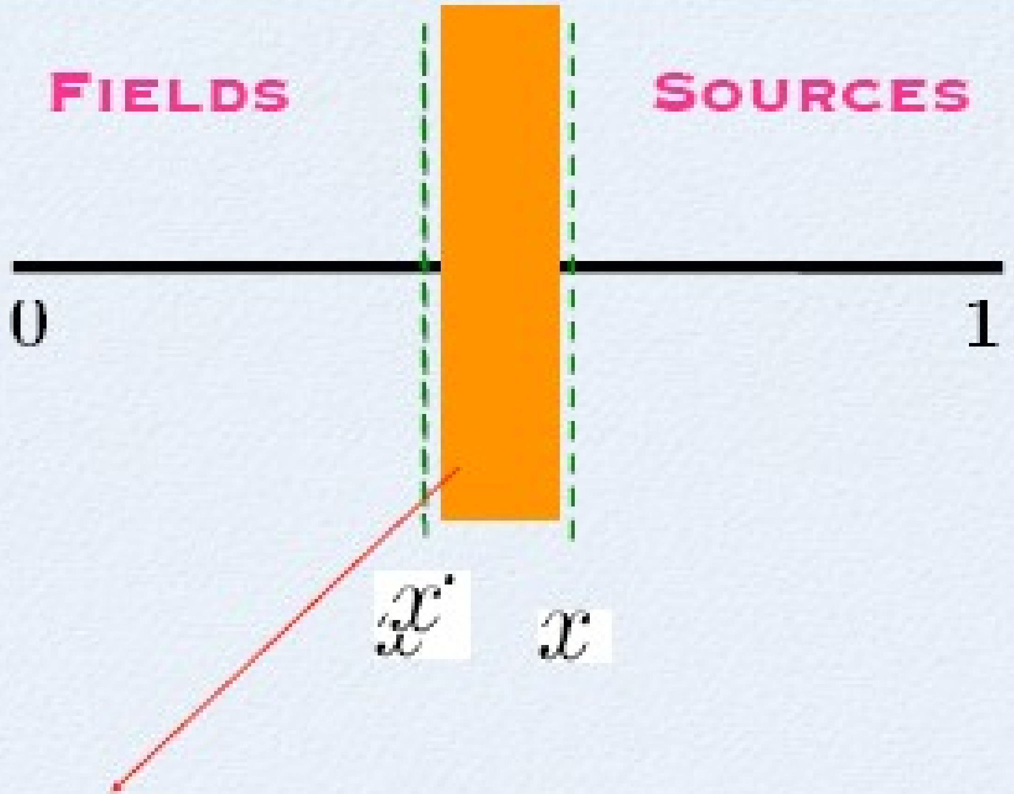


Nucleus/Hadron at high energy is a Color Glass Condensate



- ✓ **Gluons are colored**
- ✓ **Random sources evolving on time scales much larger than natural time scales – very similar to spin glasses**
- ✓ **Bosons with large occupation number ~** $\frac{1}{\alpha_S}$

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



Integrate out small fluctuations => Increase color charge of

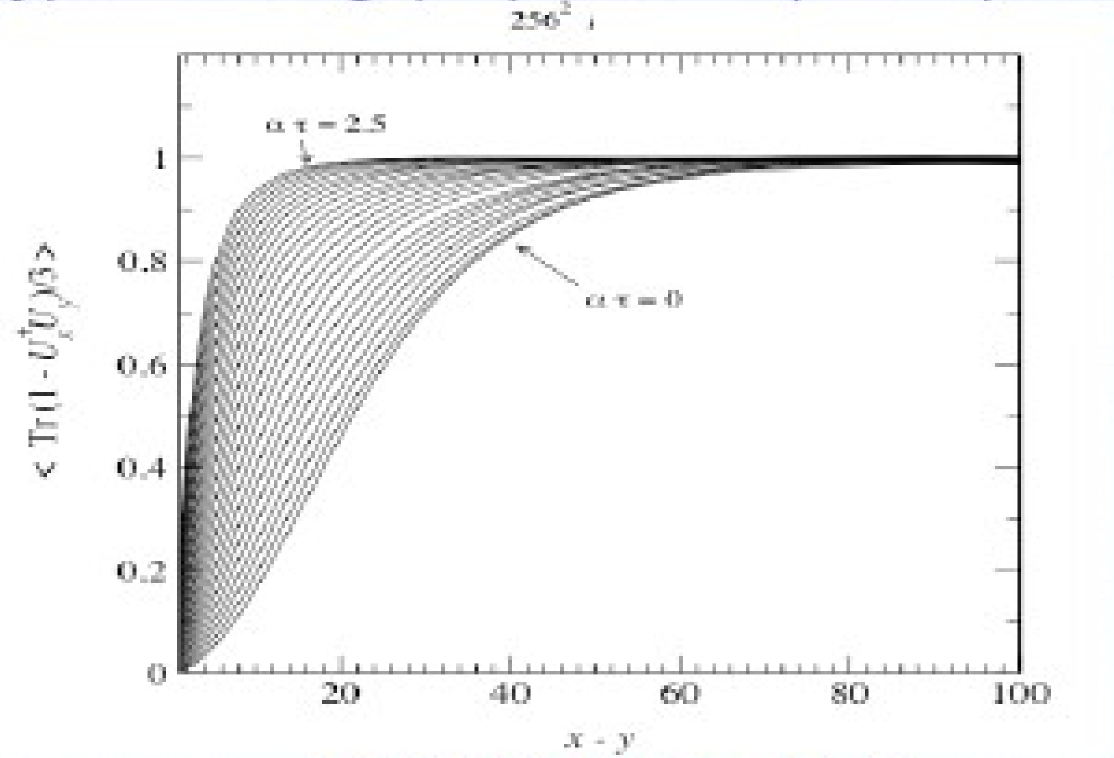
$$\frac{\partial W_x[\rho]}{\partial \ln(1/x)} = \frac{1}{2}\int_{x_\perp, y_\perp} \frac{\delta}{\delta \rho_x^a(x_\perp)} \chi^{ab}(x_\perp, y_\perp)[\rho] \frac{\delta}{\delta \rho_x^b(y_\perp)} W_x[\rho]$$

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: $T < 1$

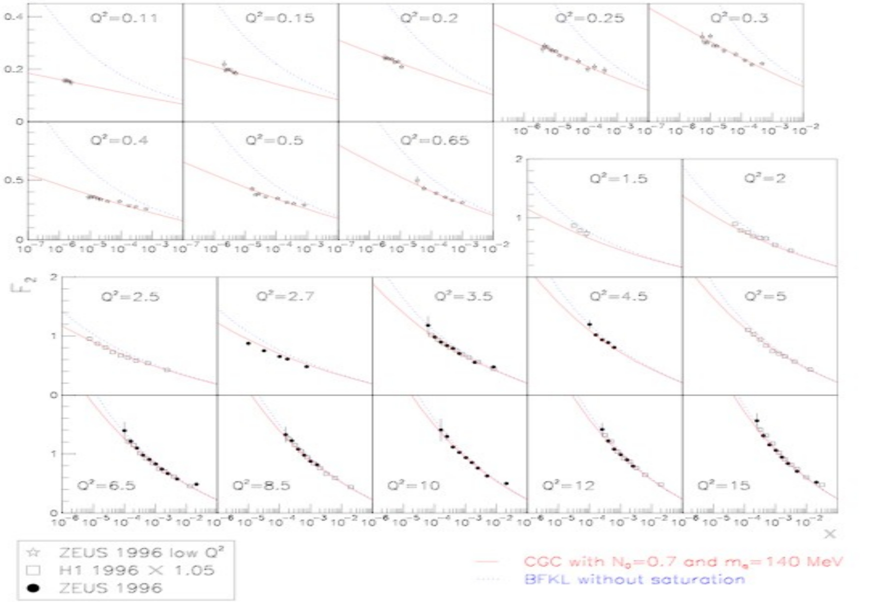
Exhibits geometric scaling

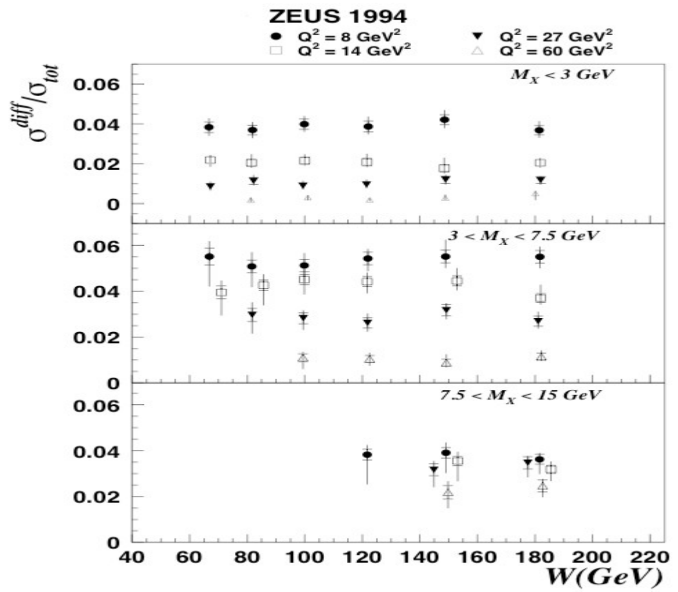
$$\mathbf{T}(\mathbf{x}, \mathbf{r_t}) \rightarrow \mathbf{T}[\mathbf{r_t} \mathbf{Q_s}(\mathbf{x})]$$

for

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

CGC at HERA (ep: $\sqrt{S}$ = 310 GeV)



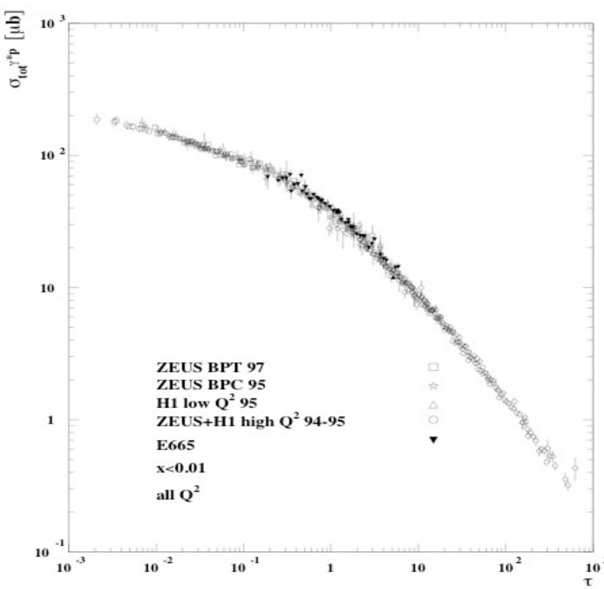


Structure Functions

$\sigma^{diff}/\sigma^{tot}$ energy dependence

Geometric Scaling

ρ , J/ψ production, ….



Signatures of CGC at RHIC/LHC

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

energy, rapidity, centrality dependence

Single particle production: hadrons, photons, dileptons

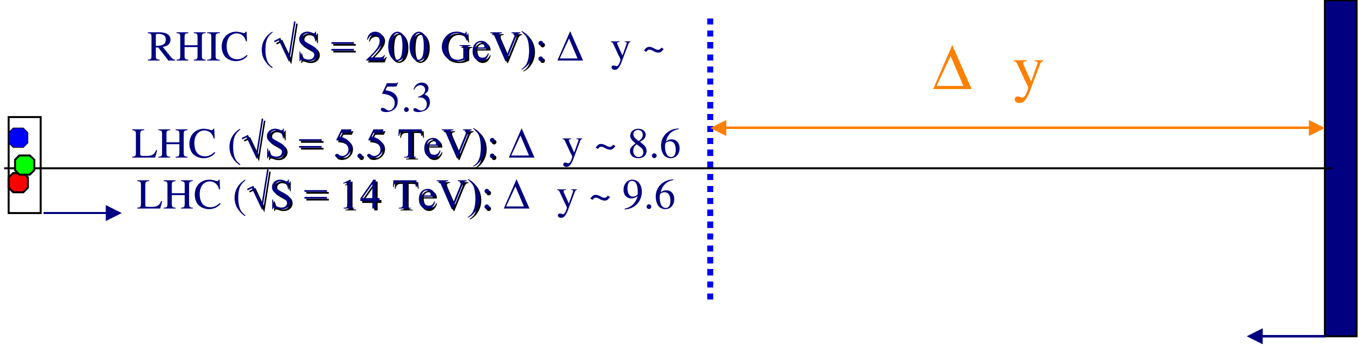
rapidity, p_t, centrality dependence

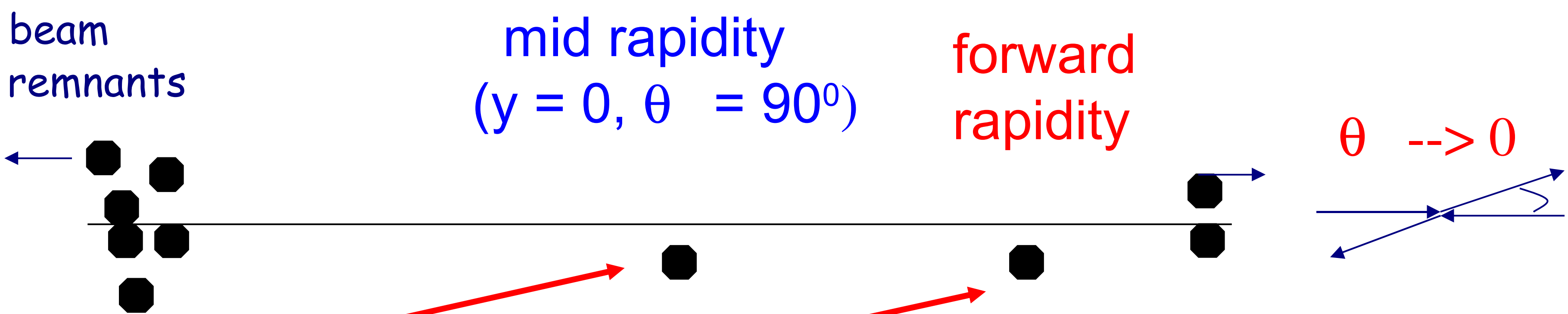
- **Fixed p_t: vary rapidity (evolution in x)**
- **Fixed rapidity: vary p_t (transition from dense to dilute)**

▪ Two particle production:

back to back correlations

Kinematics





y = 0: x_1 = x_2 = 10^{-2}

y ~ 4: x_1~ 0.55, x_2~10^{-4}

(RHIC: for p_t^2 = 4 GeV²)

$$x_{1,2} = \frac{p_t}{\sqrt{S}} e^{\pm y}$$

Q_s^2 (y=0) = 2 GeV²

Q_s^2 (y=4) = 2 $e^{0.3\,y}$ = 6.65 GeV²

two orders of magnitude evolution in x

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

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

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

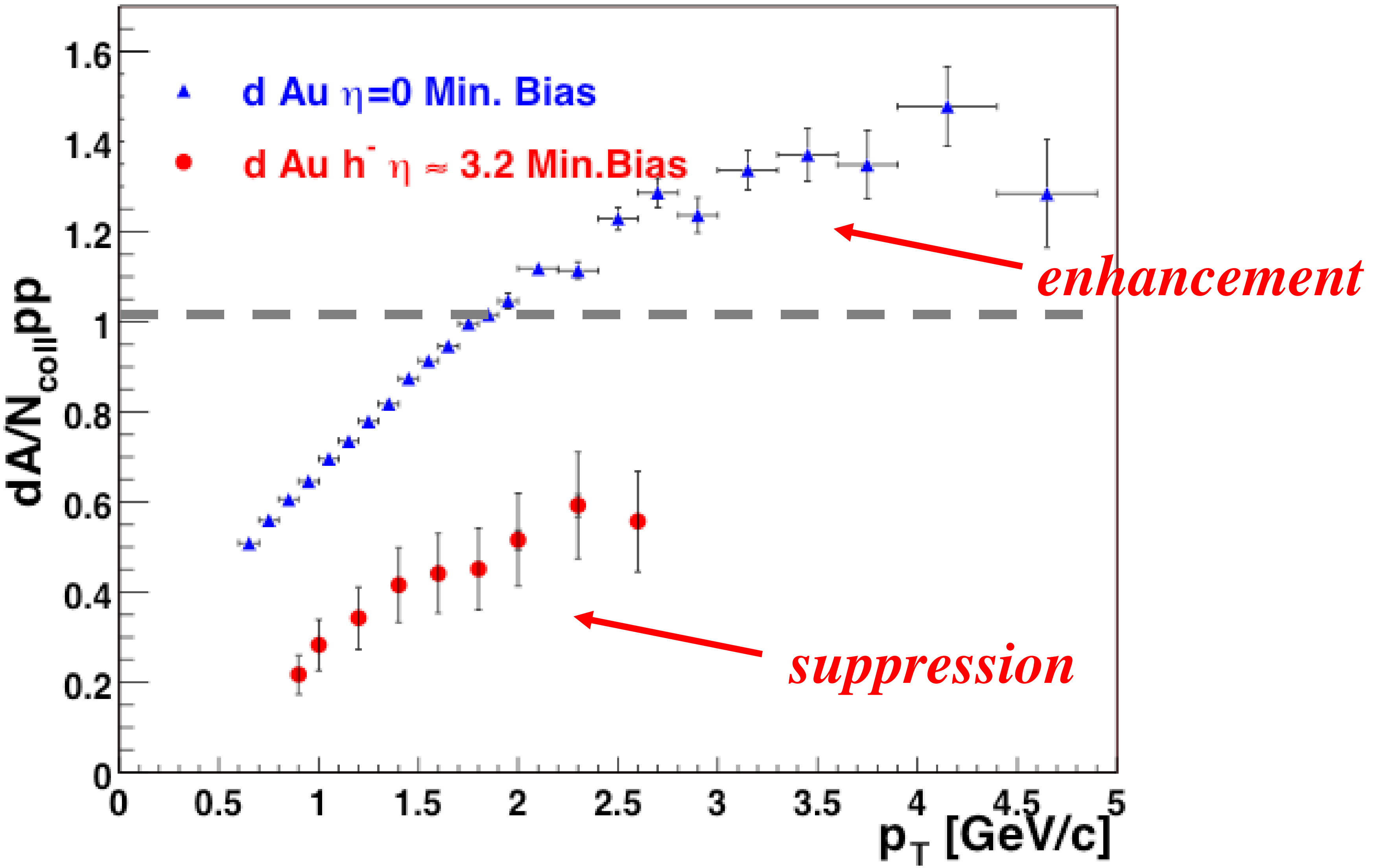
position and height of enhancement are increasing with centrality

Quantum evolution in x: essential as we go to forward rapidity

can show analytically the peak disappears as energy/rapidity grows

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

CGC prediction vs. RHIC



BRAHMS

Single Hadron Production in pA

$$\frac{d\sigma^{pA\to hX}}{dY\, d^2P_t\, d^2b} = \frac{1}{(2\pi)^2}\int_{x_F}^{1} dx\, \frac{x}{x_F}$$

$$\Big\{ f_{q/p}(x,Q^2)\;\; N_F[\frac{x}{x_F}P_t, b, y]\;\; D_{h/q}(\frac{x_F}{x}, Q^2) +$$

$$f_{g/p}(x,Q^2)\;\; N_A[\frac{x}{x_F}P_t, b, y]\;\; D_{h/g}(\frac{x_F}{x}, Q^2) \Big\}$$

N_F, N_A are dipoles in fundamental and adjoint representation and satisfy the <u>JIMWLK</u> evolution equation

Models of the dipole cross section

$$N(x,r) = 1 - \exp\{-\frac{1}{4}(\frac{C_F}{N_c} r^2 Q_s^2)^{\gamma}\}$$

Kharzeev, Kovchegov, Tuchin (2004) KKT

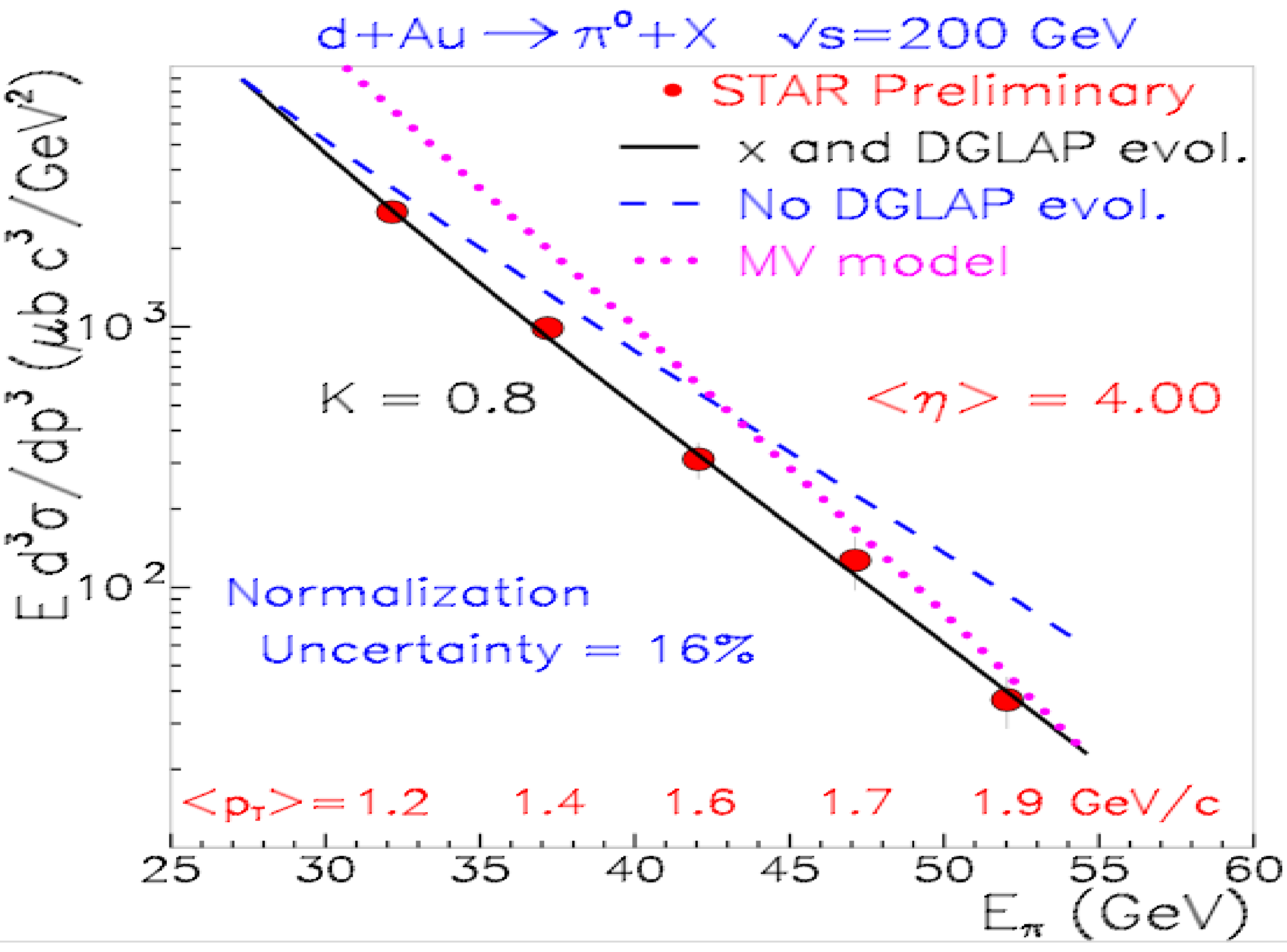
$$\gamma(Y,r) = \frac{1}{2}\left(1 + \frac{\xi(Y,r)}{\xi(Y,r) + \sqrt{2\xi(Y,r)} + 7\zeta(3)c}\right) \qquad \xi = \frac{\ln[1/(r^2 Q_{s0}^2)]}{(\lambda/2)(Y - Y_0)}$$

Dumitru, Hayashigaki, Jalilian-Marian (2006) DHJ

$$\gamma(Y,r) = \gamma_s + (1-\gamma_s)\frac{|\log\frac{1}{r^2 Q_s^2}|}{\lambda Y + |\log\frac{1}{r^2 Q_s^2}| + d\sqrt{Y}}$$

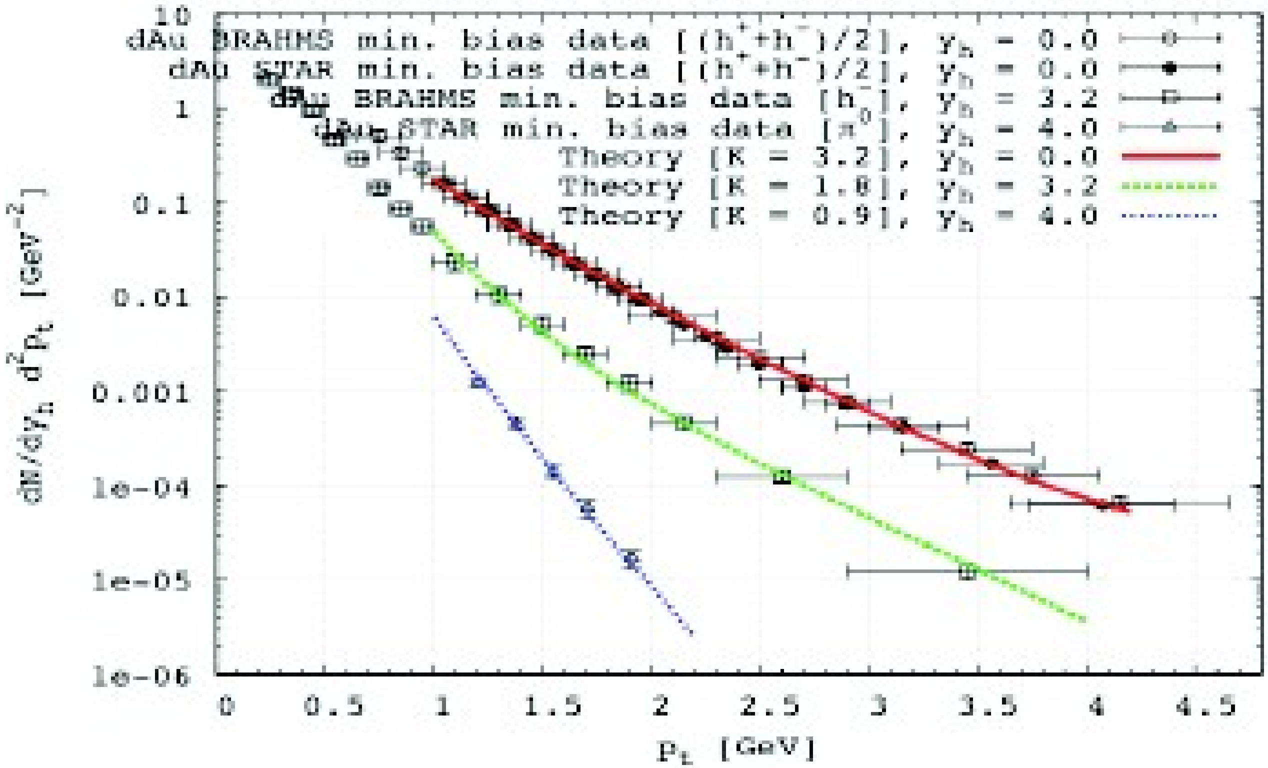
Predictions for dA at RHIC

Dumitru, Hayashigaki, Jalilian-Marian NPA765 (2006) 464



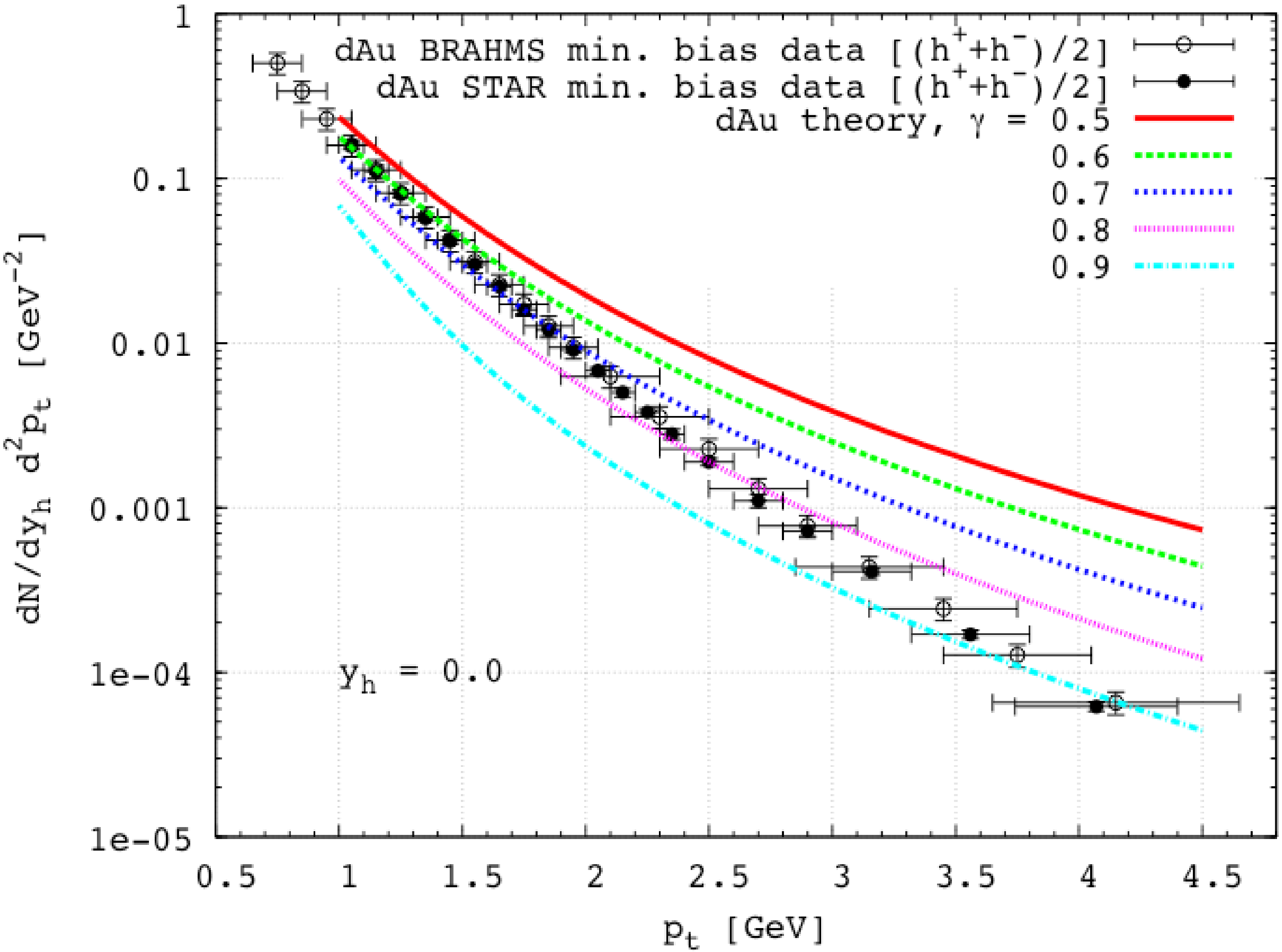
J. Adams et al., PRL97 (2006) 152302

Rapidity and pt dependence



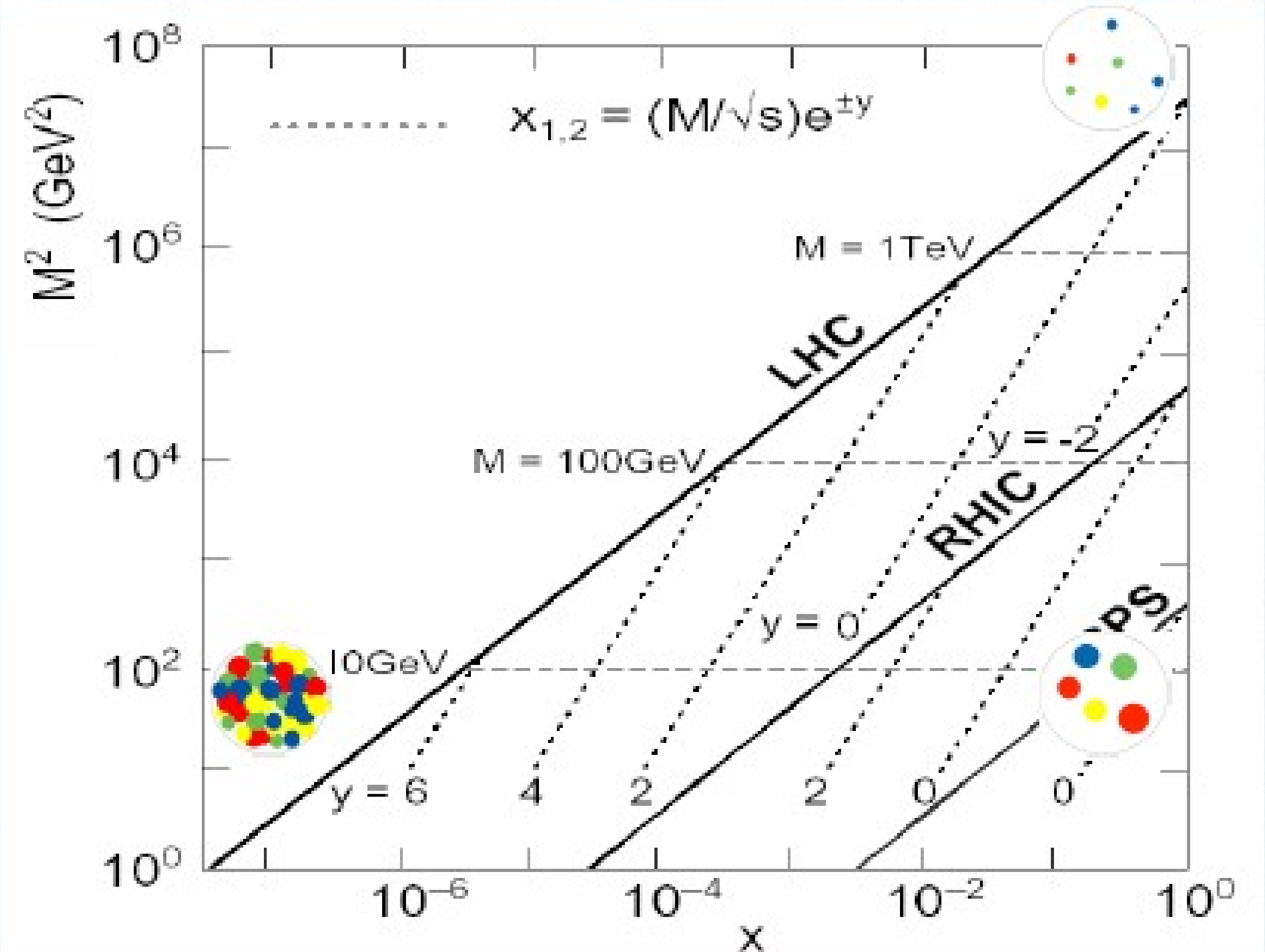
What we see is a transition from DGLAP to BFKL to *CGC* kinematics

Centrality, flavor, **species dependence**



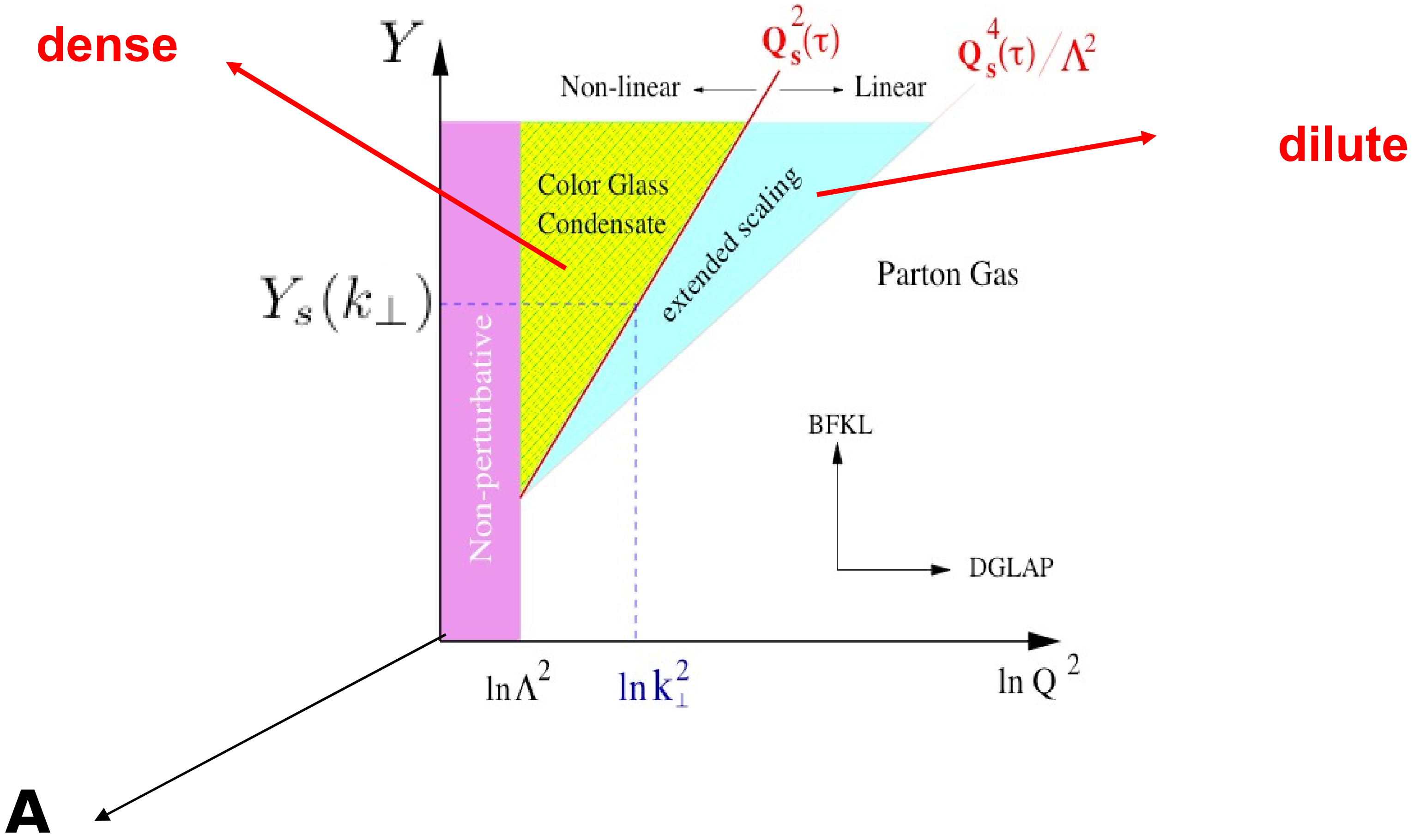
dAu BRAHMS min. bias data [(h++h-)/2]
dAu STAR min. bias data [(h++h-)/2]
dAu theory, γ = 0.5
0.6
0.7
0.8
0.9
y_h = 0.0
dN/dy_h d²p_t [GeV⁻²]
p_t [GeV]
1
0.1
0.01
0.001
1e-04
1e-05
0.5
1
1.5
2
2.5
3
3.5
4
4.5

The future is promising!



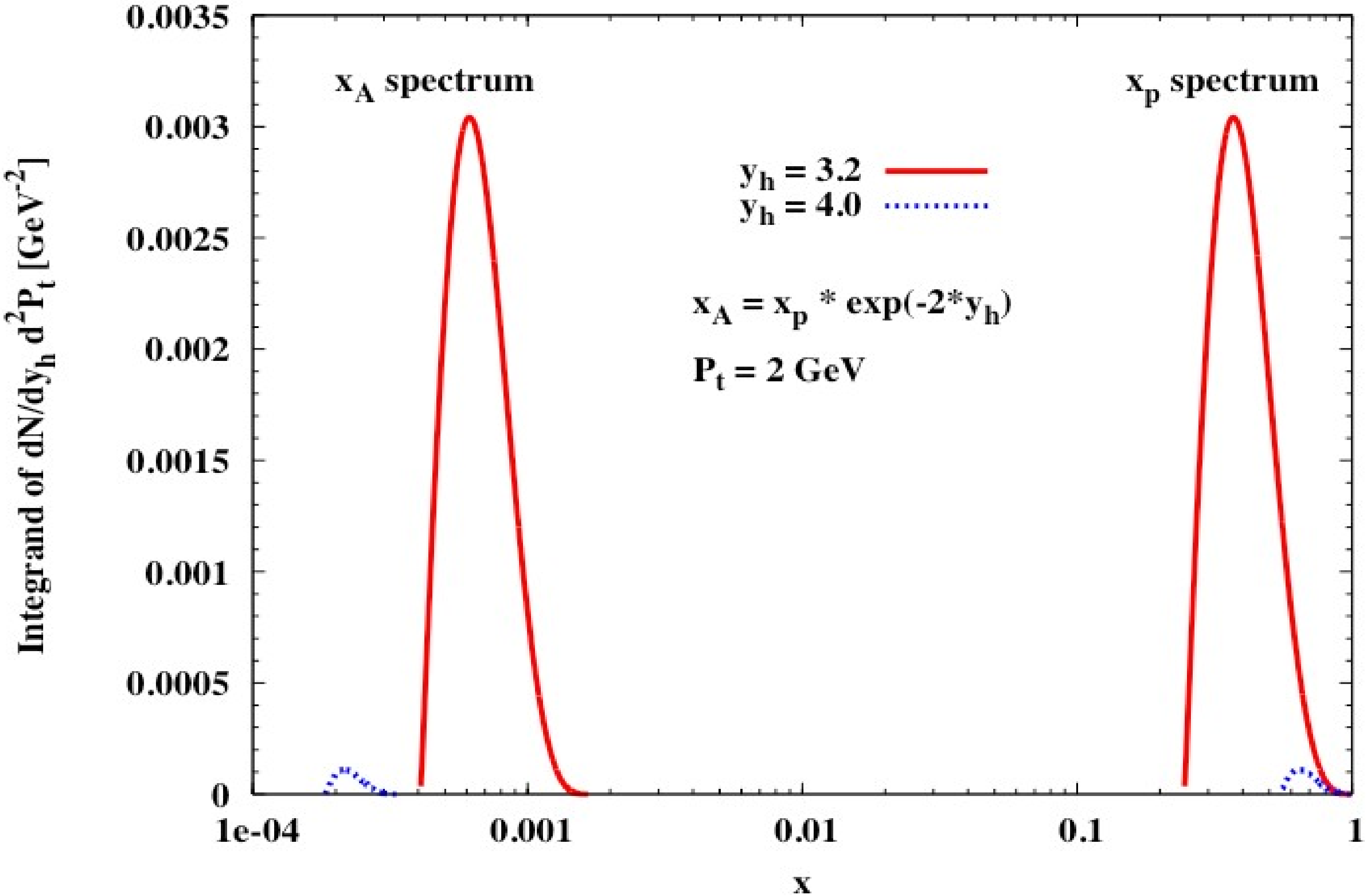
Summary

Exploring QCD phase space by high energy nuclei

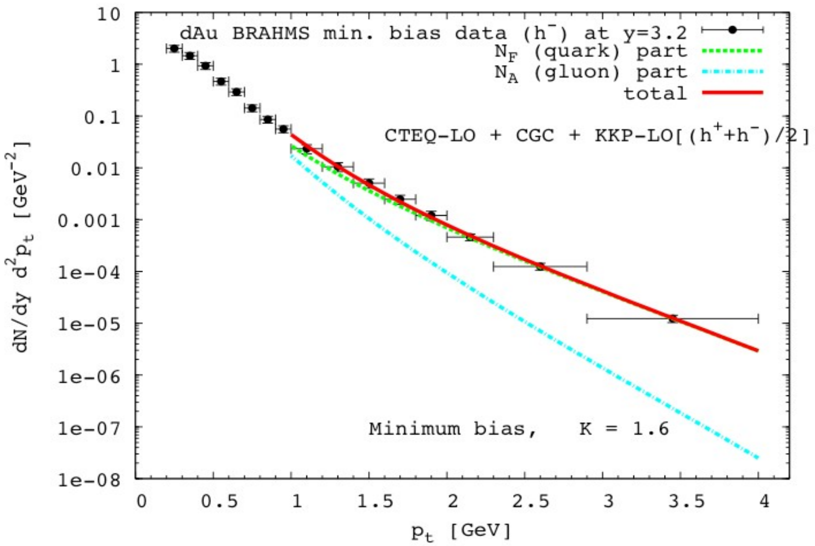


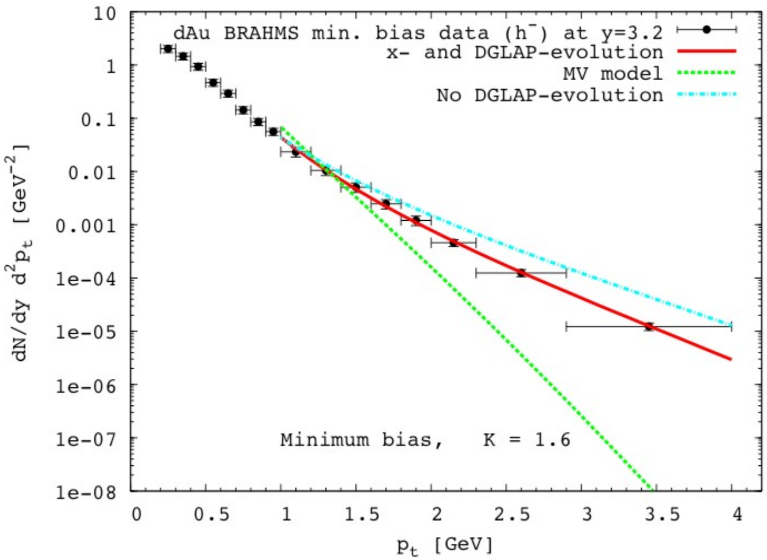
BACK UP SLIDES

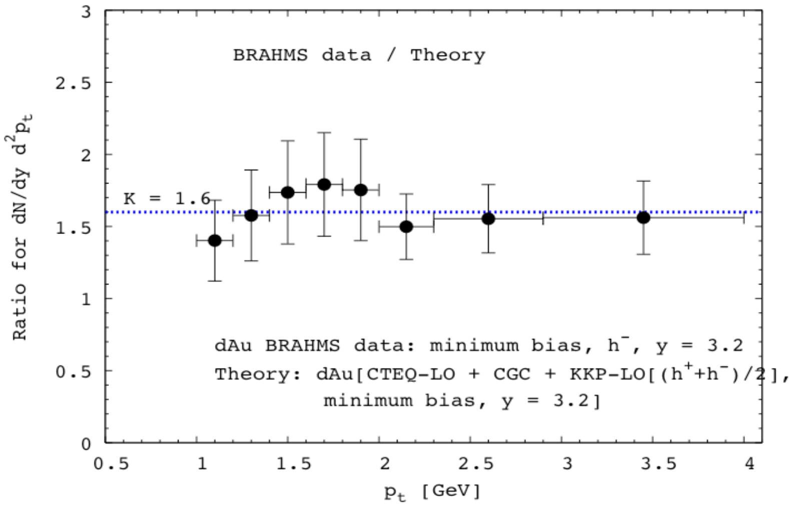
2 ---> 1 Kinematics for dA at RHIC



Application to dA at RHIC







modification of the nuclear structure functions