Probing high energy QCD via Correlations

Jamal Jalilian-Marian

Baruch College, New York NY

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QCD

Asymptotic freedom

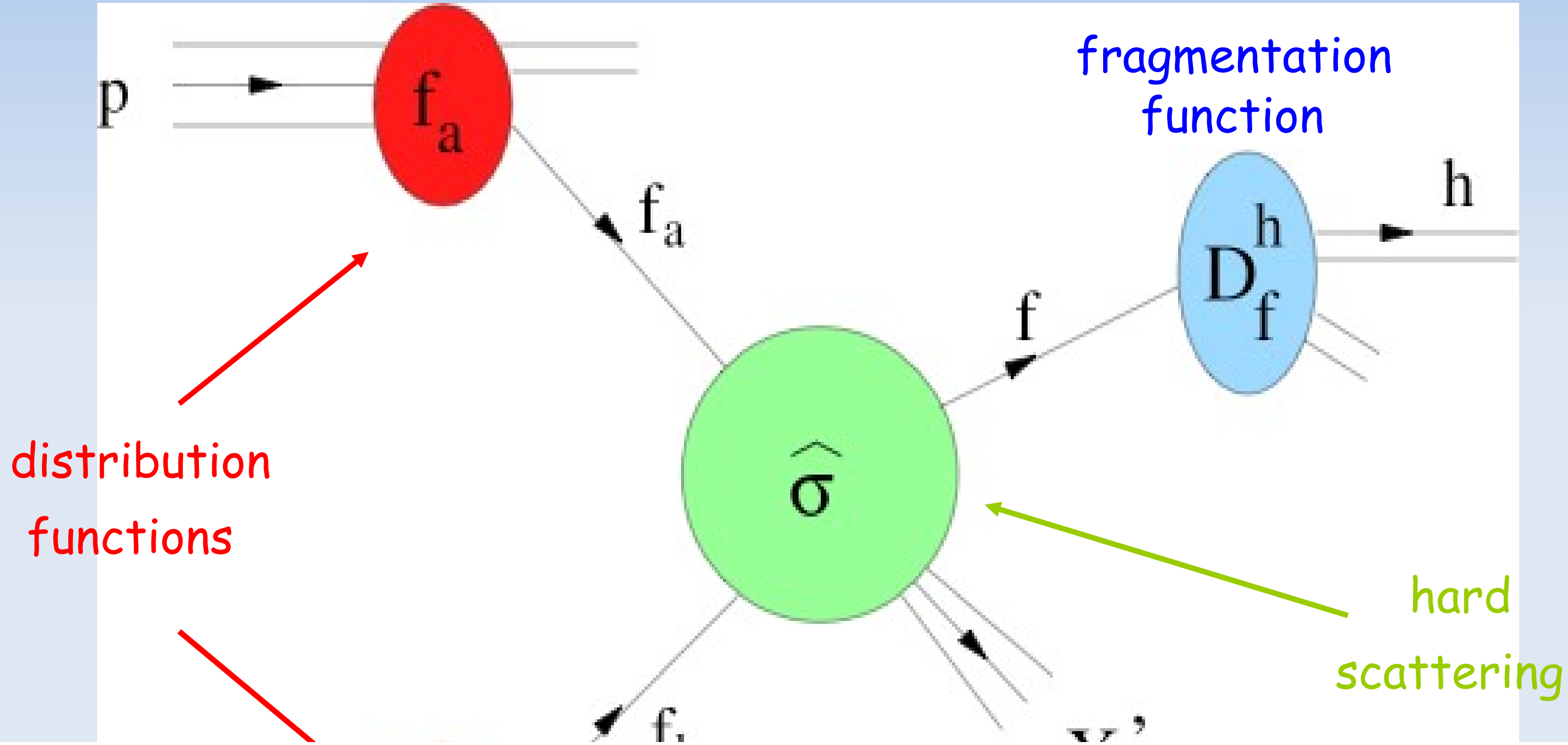
pQCD - collinear factorization

QCD at high energy: ***CGC***

Probes and signatures

pQCD in pp Collisions

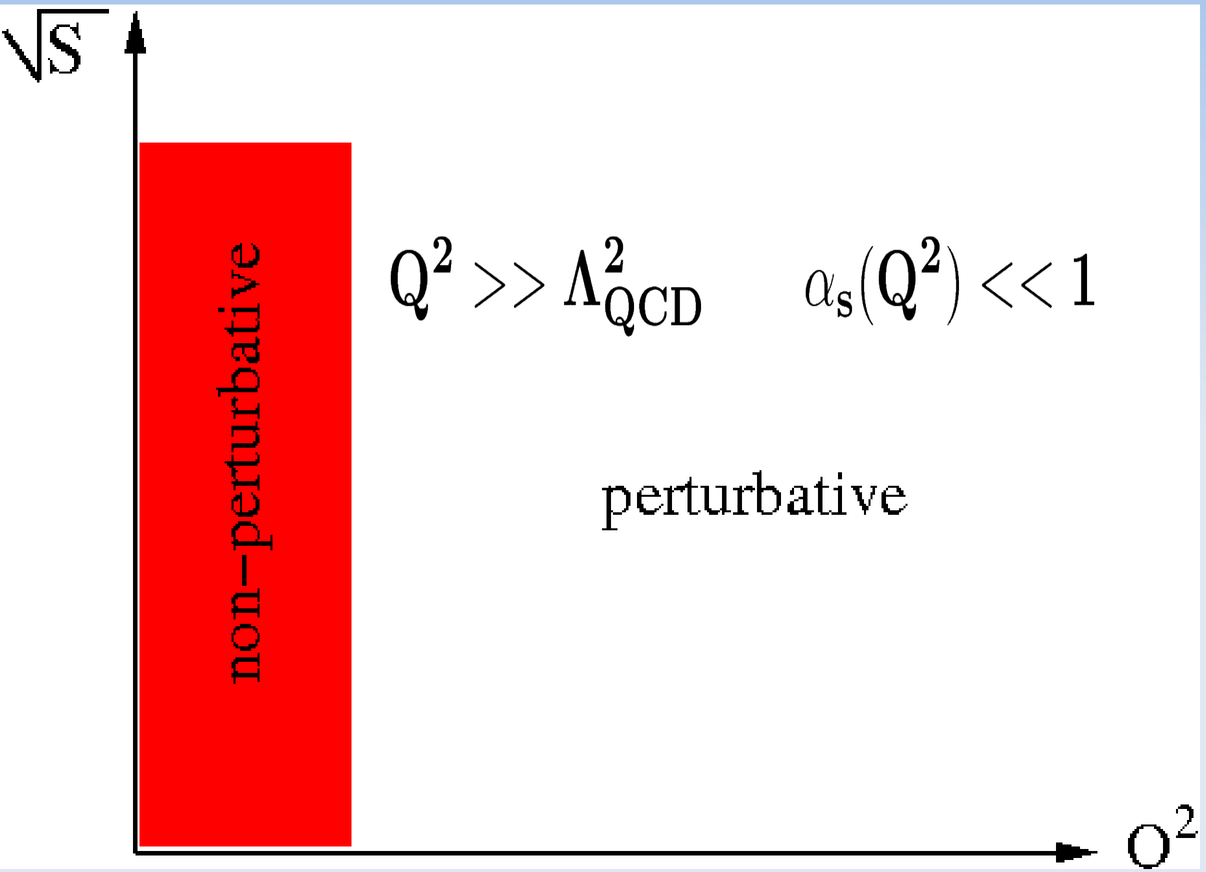
Collinear factorization: separation of long and short distances



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

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

QCD: the old paradigm



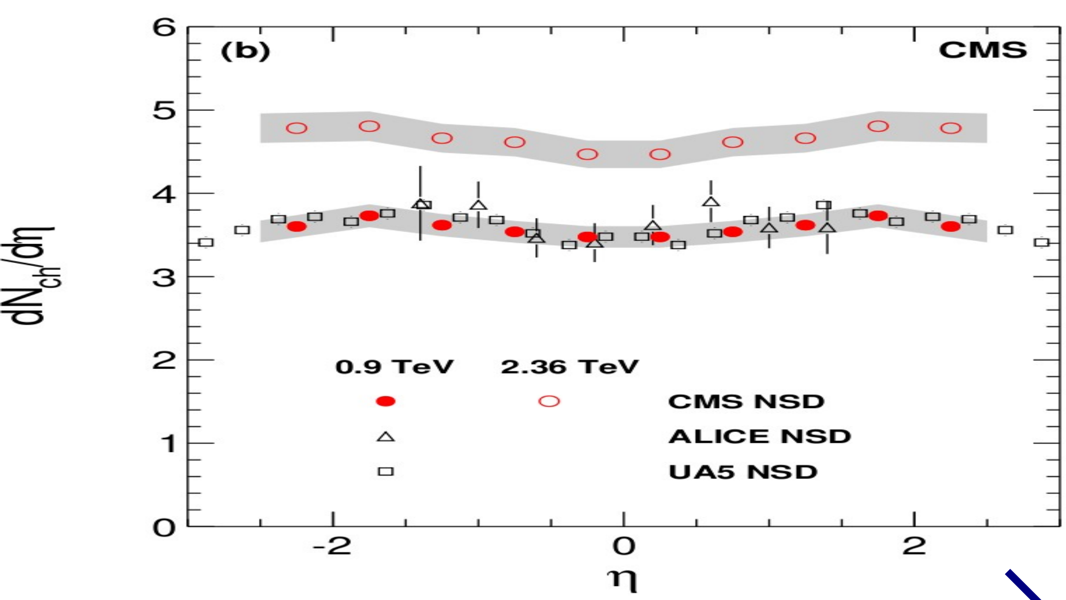
pQCD tools:
twist expansion,
collinear factorization

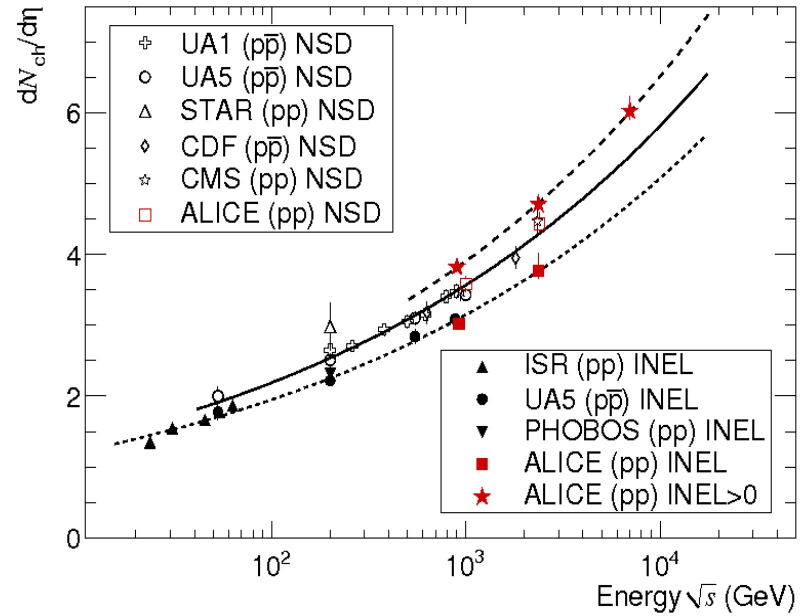
$$\sqrt{S} \to \infty$$

$$Q^2 \to \infty$$

but bulk of QCD phenomena happens at low Q

pp collisions at LHC





$$y \sim \ln \frac{\sqrt{S}}{M_N}$$

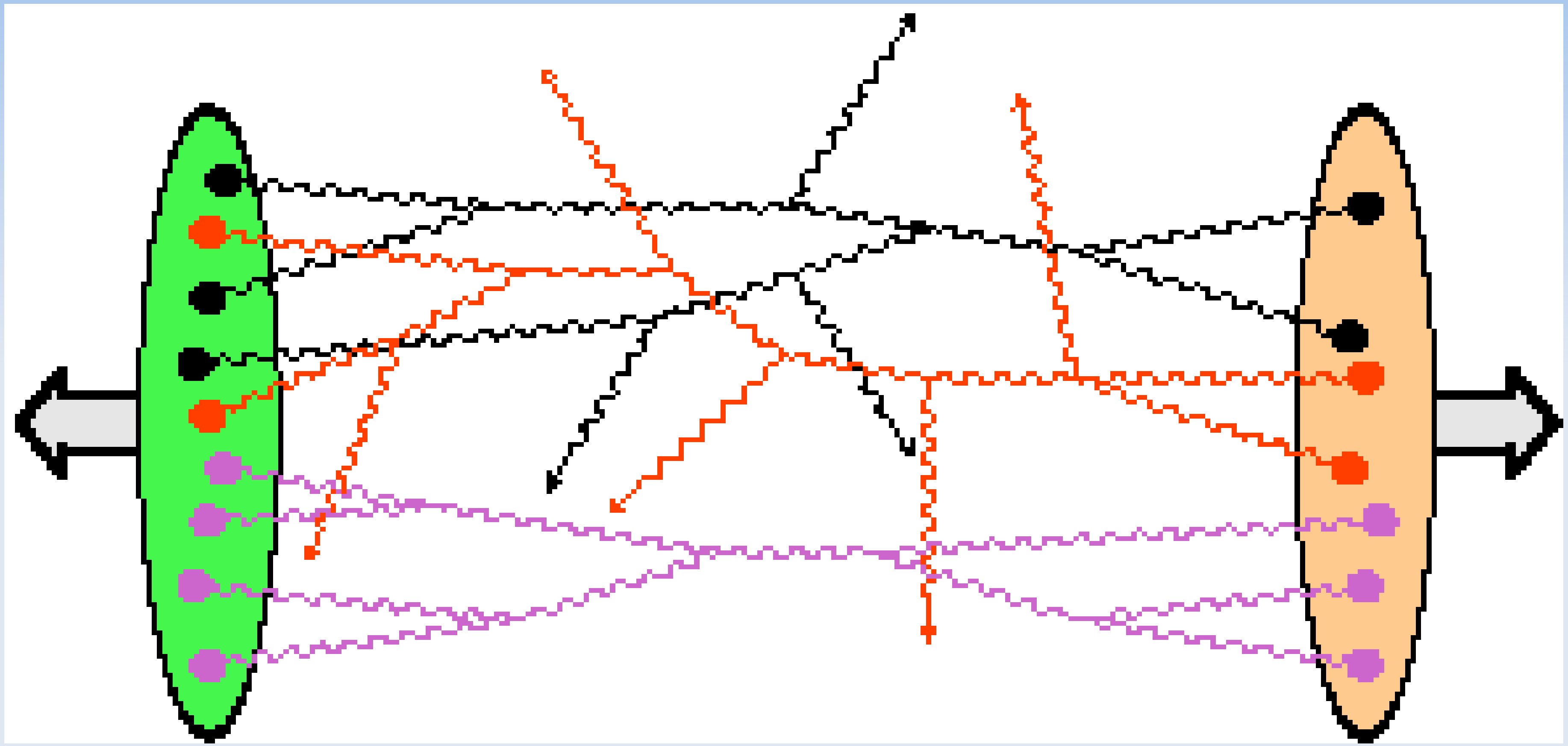
mid-rapidity
$\theta = 90$

forward-rapidity $\theta \to 0$

most particles produced
with p_t ~ 1 GeV

$$x \sim \frac{p_t}{\sqrt{S}} e^{-y} \to 0$$

High energy nucleus- nucleus collisions



most produced particles are soft

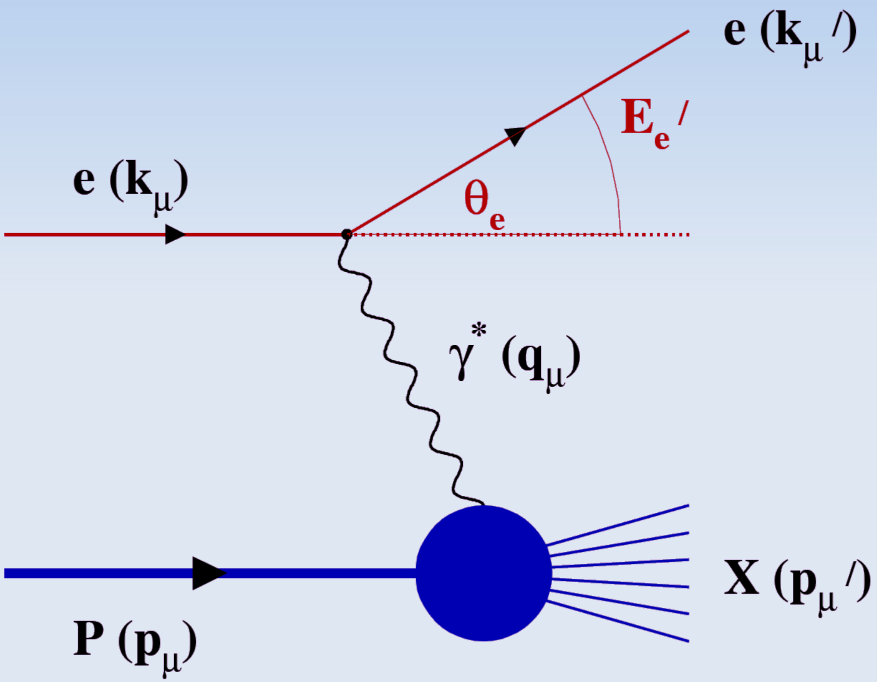
$$\left(\mathbf{x} \sim \frac{\mathbf{p_t}}{\sqrt{\mathbf{S}}} \to \mathbf{0} \right)$$

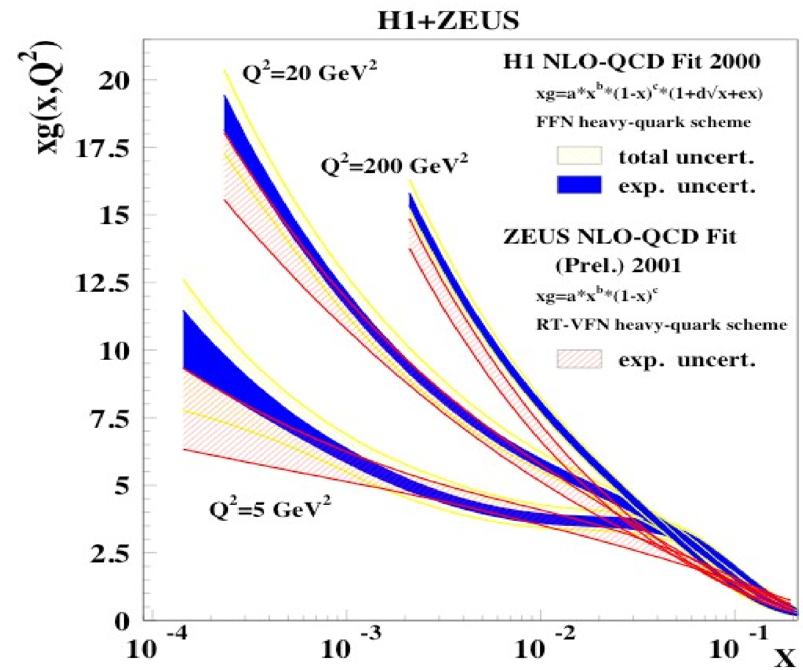
thermalization?

Hadronic collisions at small x

A hadron at small x

DIS: $e\,p \to e\,X$

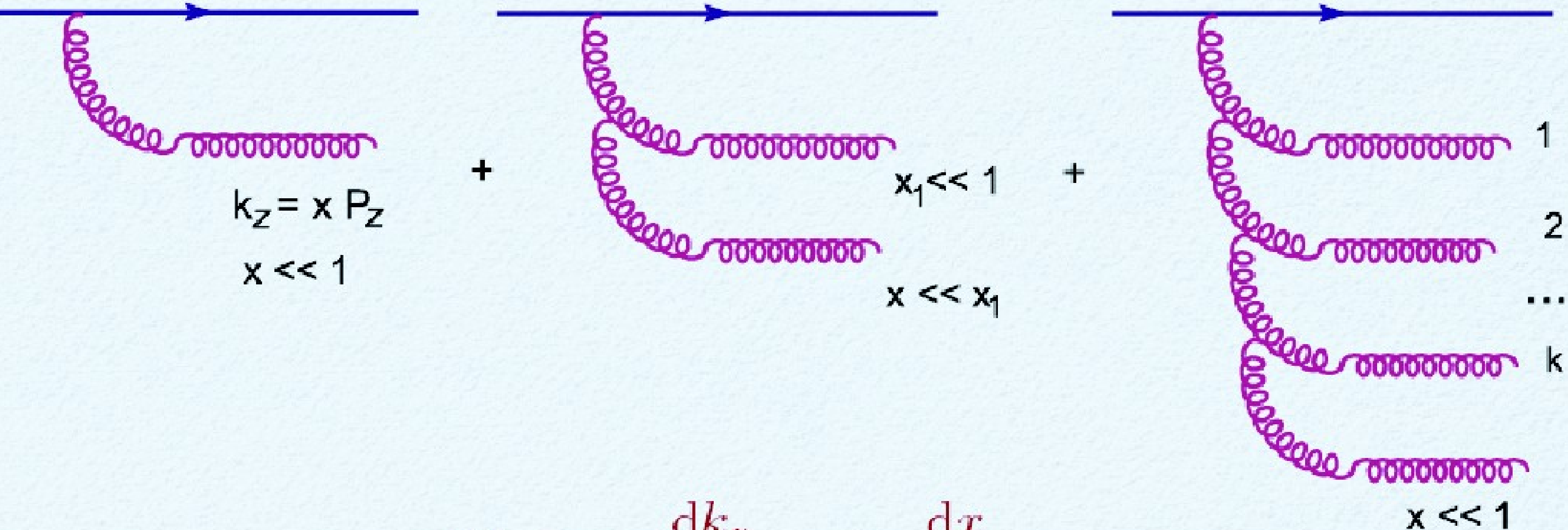




$$x = \frac{p^+}{P^+}$$ is the fraction of hadron energy carried by a parton

gluon radiation at small x :pQCD

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



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

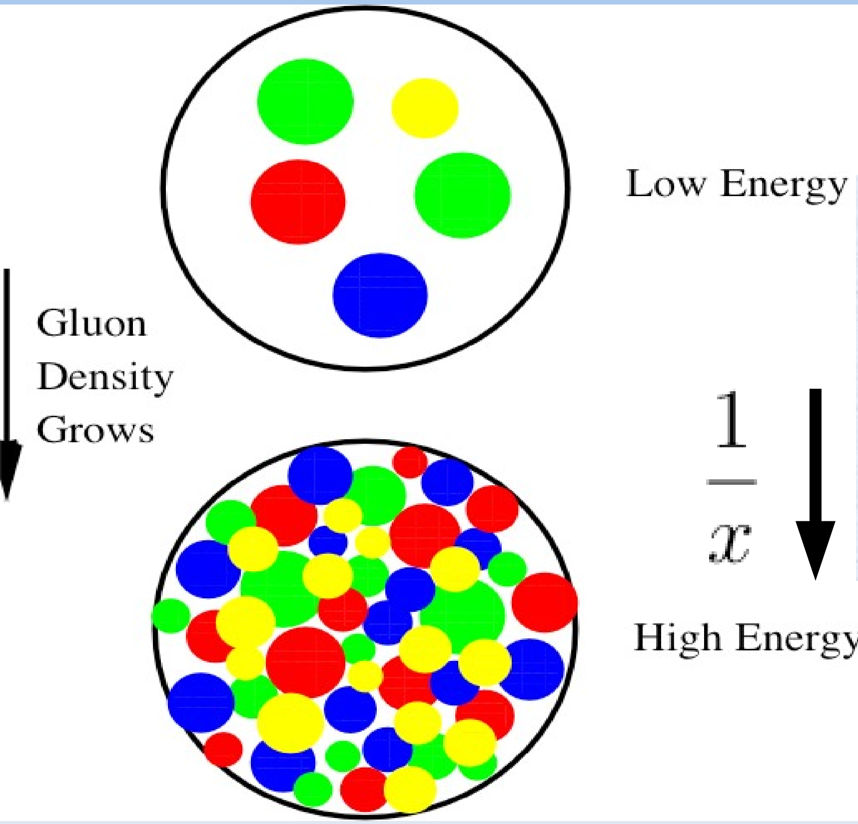
The 'price' of an additional gluon:

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

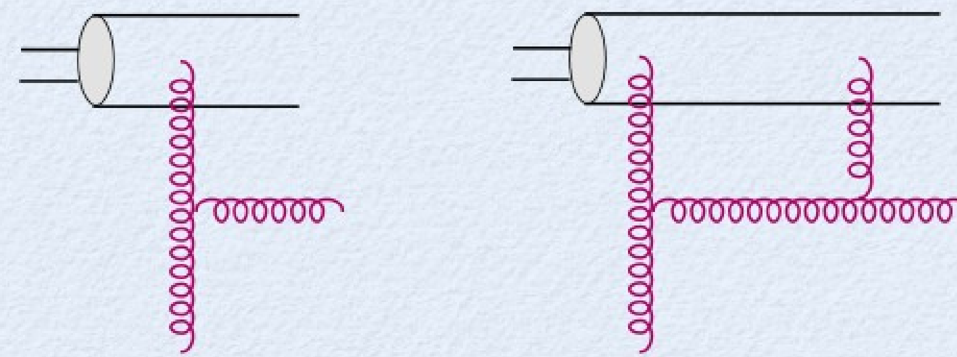
number of gluons grows fast

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

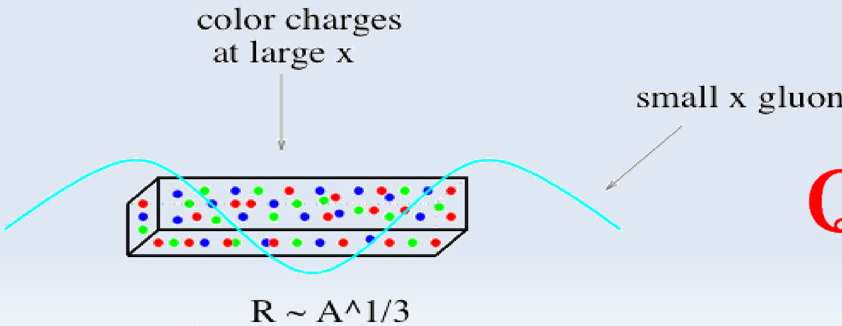
Gluon saturation



"attractive" bremsstrahlung vs. "repulsive" recombination



$$\frac{\alpha_s\, xG(x, b_t, Q^2)}{S_\perp\, Q^2} \sim 1$$



$$Q_s^2(x, b_t, A) \sim A^{1/3}\,(\frac{1}{x})^{0.3}$$

Effective Action + RGE

$$\mathbf{S[A,\rho] = -\frac{1}{4}\int d^4x\, F^2_{\mu\nu} + \frac{i}{N_c}\int d^2x_t\, dx^-\, \delta(x^-)\, Tr[\rho(x_t) U(A^-)]}$$

Large x: color source ρ small x: gluon field $\mathbf{A}^\mu$

$$\mathbf{U(A^-) = \hat{P}\, Exp\left[ig\int dx^+\, A_a^-\, T_a\right]}$$

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

weight functional:

$\mathbf{W}_{\Lambda^+}[\rho]$ probability distribution of color source ρ at longitudinal scale Λ^+

invariance under change of Λ^+ $\longrightarrow$ RGE for $\mathbf{W}_{\Lambda^+}[\rho]$

The Classical Field

saddle point of effective action-> Yang-Mills equations

$$\mathbf{D}_\mu \, \mathbf{F}^{\mu\nu}_{\mathbf{a}} = \delta^{\nu\,+} \delta(\mathbf{x}^-)\, \rho_{\mathbf{a}}(\mathbf{x_t})$$

solutions are non-Abelian
Weizsäcker-Williams fields

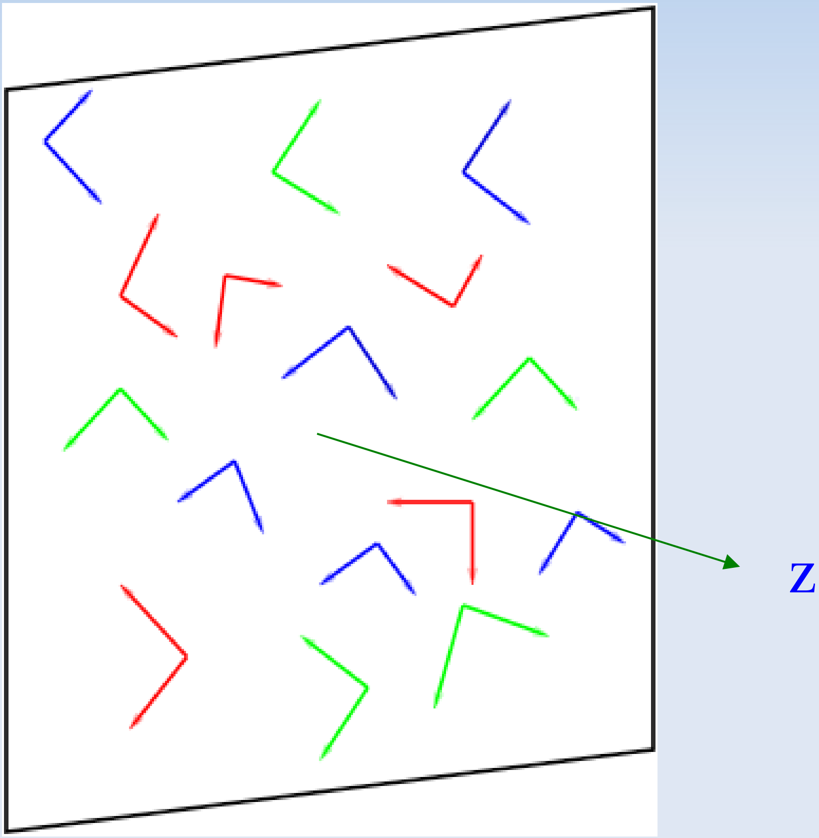
$$\mathbf{A}^+ = \mathbf{0}$$

$$\mathbf{A}^- = \mathbf{0}$$

$$\mathbf{A}^{\mathbf{i}}_{\mathbf{a}} = \theta(\mathbf{x}^-)\, \alpha^{\mathbf{i}}_{\mathbf{a}}(\mathbf{x_t})$$

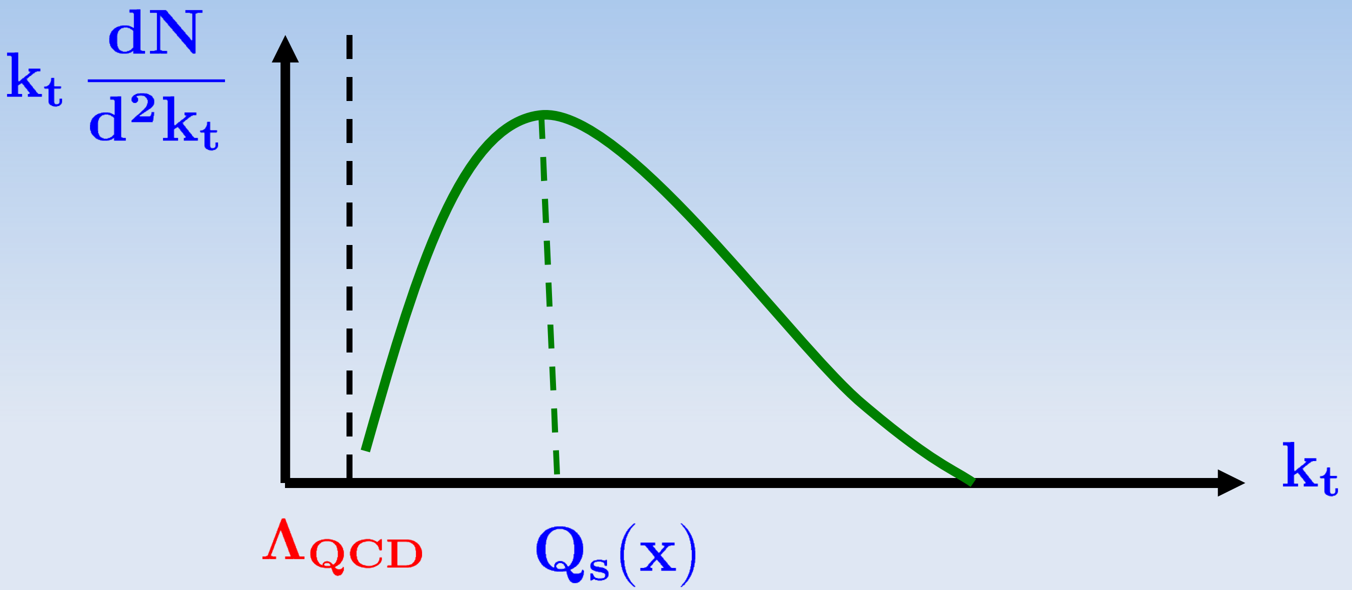
$$\partial^{\mathbf{i}}\, \alpha^{\mathbf{i}}_{\mathbf{a}} = \mathbf{g}\, \rho_{\mathbf{a}}$$

pure (2d) gauge



color $\mathrm{E}_\perp$, $\mathrm{B}_\perp$ fields

A hadron at high energy is a Color Glass Condensate



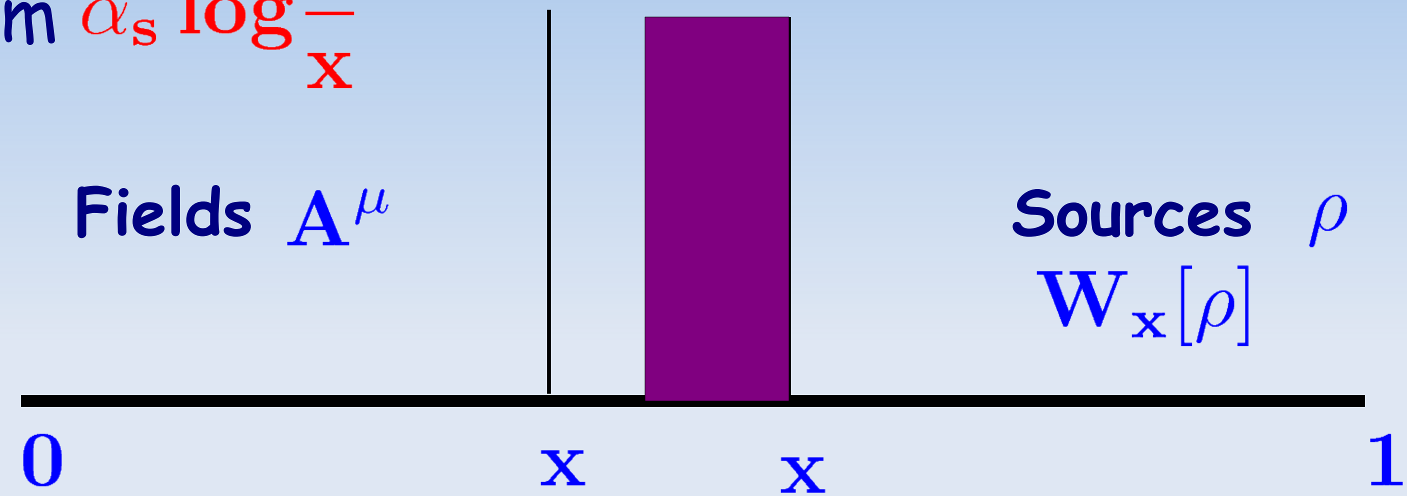
a state with large (gluon) occupation number $O[\frac{1}{\alpha_s}]$

very different time scales between large and small x modes

$Q_s(x, b_t, A)$ ***can provide a <u>hard</u> infrared cutoff***

QCD at High Energy: Wilsonian RG

resum $\alpha_s \log \frac{1}{x}$



$$A^\mu = A^\mu_{class} + \delta A^\mu$$

integrate out field fluctuations quadratically

$$\frac{\partial W[\rho]}{\partial \ln 1/x} = \frac{1}{2}\int_{x_t, y_t} \frac{\delta}{\delta \rho^a(x_t)} \chi^{ab}(x_t, y_t)[\rho] \frac{\delta}{\delta \rho^a(y_t)} W[\rho]$$

$$\rho \to \rho' = \rho + \delta\rho$$

JIMWLK eq. describes x evolution of observables

Evolution of the 2-point function

Basic building block in DIS, pA processes

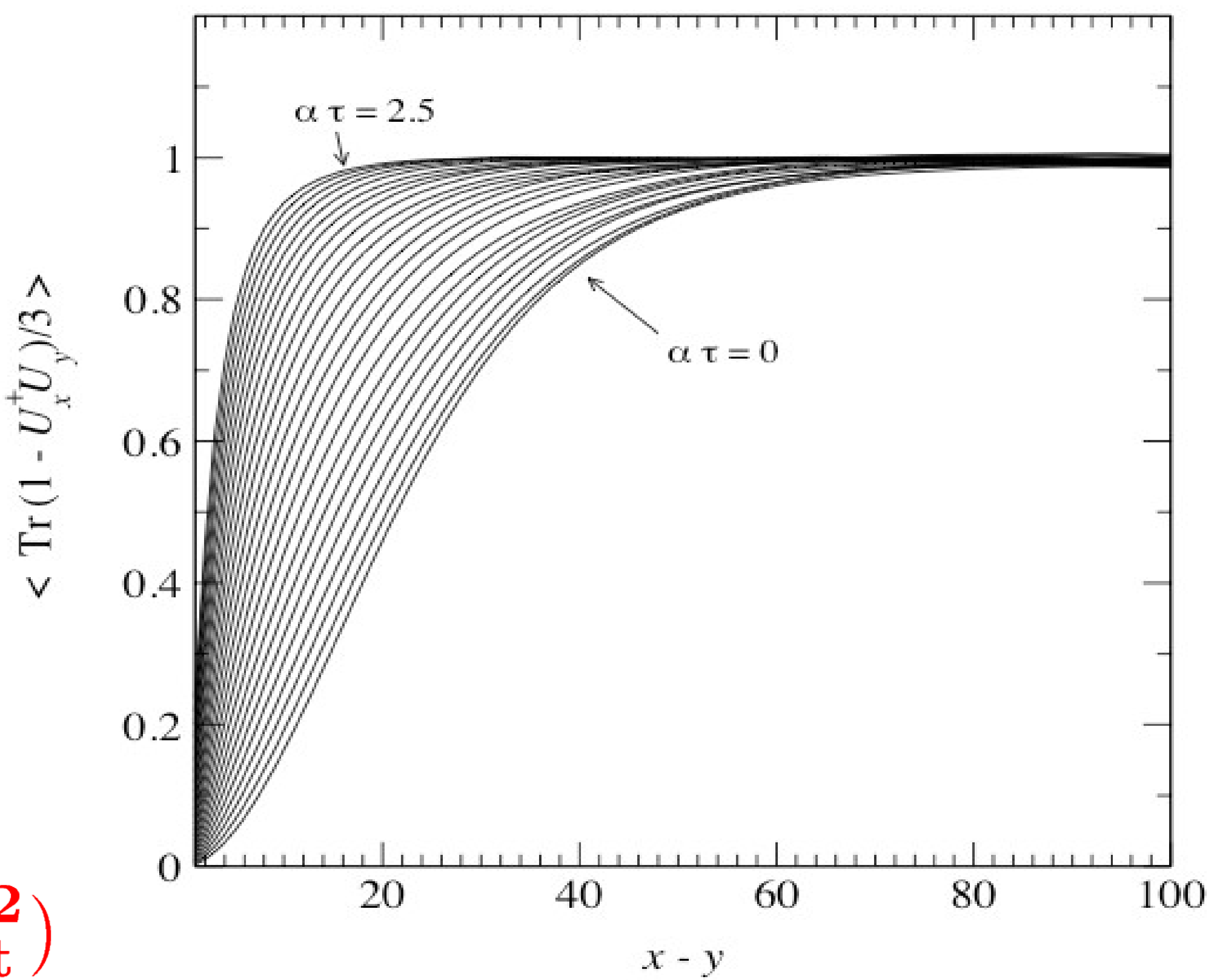
$$\frac{\mathbf{d}}{\mathbf{dy}} < \mathbf{Tr V_x^\dagger V_y} >= -\frac{\bar{\alpha}_s}{2\pi} \int \mathbf{d^2 z} \, \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2 (\mathbf{y}-\mathbf{z})^2} \times \left[< \mathbf{Tr V_x^\dagger V_y} > - \frac{1}{\mathbf{N_c}} < \mathbf{Tr V_x^\dagger V_z \, Tr V_z^\dagger V_y} > \right]$$

Evolution of 2-point function depends on 4-point function

$$\frac{\mathbf{d}}{\mathbf{dy}} < \mathbf{Tr V_x^\dagger V_z \, Tr V_z^\dagger V_y} > \sim \mathbf{V^4} + \cdots$$

Infinitely many coupled equations!

Evolution of the 2-point function



saturation region

dilute region

$\sim [r_t^2 Q_s^2]^\gamma$

pQCD region

$\sim r_t^2 \, xG(x, 1/r_t^2)$

RW, NPA739 (2004) 183

Mean field + large N_c (BK eq.)

$$\frac{d}{dy} < \mathrm{Tr} V^\dagger_x V_y > = -\frac{\bar{\alpha}_s}{2\pi} \int d^2z \, \frac{(x-y)^2}{(x-z)^2 (y-z)^2} \times$$

$$\left[< \mathrm{Tr} V^\dagger_x V_y > - \frac{1}{N_c} < \mathrm{Tr} V^\dagger_x V_z > < \mathrm{Tr} V^\dagger_z V_y > \right]$$

All higher point functions are expressed in terms of the 2-point function

extended scaling region: $< \mathrm{Tr} V^\dagger_x V_y > = F\left[(x-y) Q_s^2\right]$

IIM, NPA708 (2002) 327

NLO: B-KW-G-BC (2007-2008)

Running coupling BK

- Output: Modified evolution kernel:

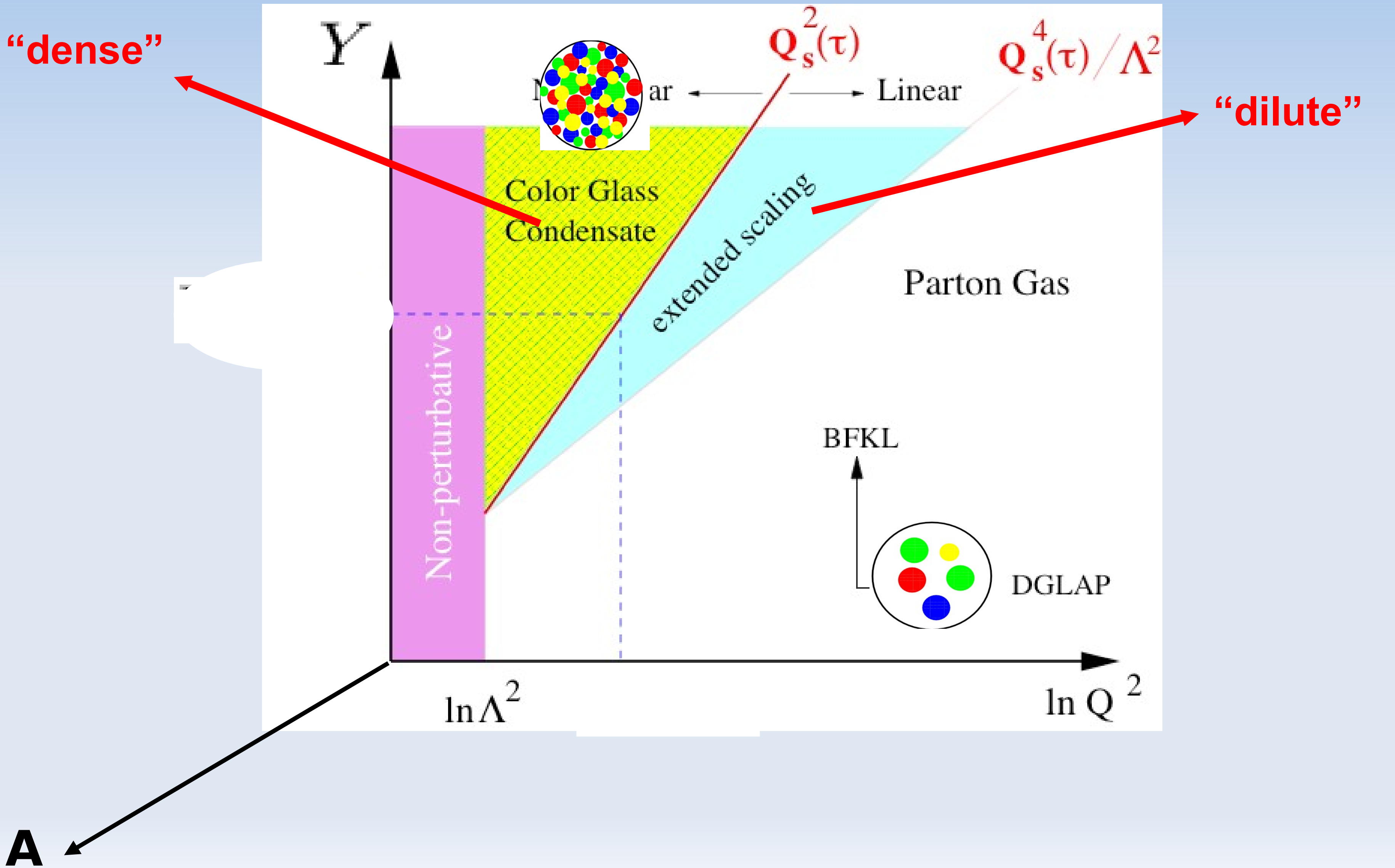
⇒ Leading order: $$\frac{\partial S(\underline{x},\underline{y};Y)}{\partial Y} = \int d^2z\, K^{LO}(\underline{r},\underline{r}_1,\underline{r}_2)\, [S(\underline{x},\underline{z})\, S(\underline{z},\underline{y}) - S(\underline{x},\underline{y})]$$

↓

⇒ Running coupling: $$\frac{\partial S(\underline{x},\underline{y};Y)}{\partial Y} = \int d^2z\, \tilde{K}(\underline{r},\underline{r}_1,\underline{r}_2)\, [S(\underline{x},\underline{z})\, S(\underline{z},\underline{y}) - S(\underline{x},\underline{y})]$$

$$\tilde{K}_{Bal}(\underline{r},\underline{r}_1,\underline{r}_2) = \frac{N_c\, \alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\, r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

Road Map of QCD Phase Space



Probes and Signatures

multiple scatterings $\rightarrow$ **p_t broadening**

effective degrees of freedom: Wilson line $V(x_t)$

evolution with ln (1/x) $\rightarrow$ **suppression**

Nuclear shadowing

Observables

DIS:

structure functions
single and double inclusive spectra

PA (dilute-dense):

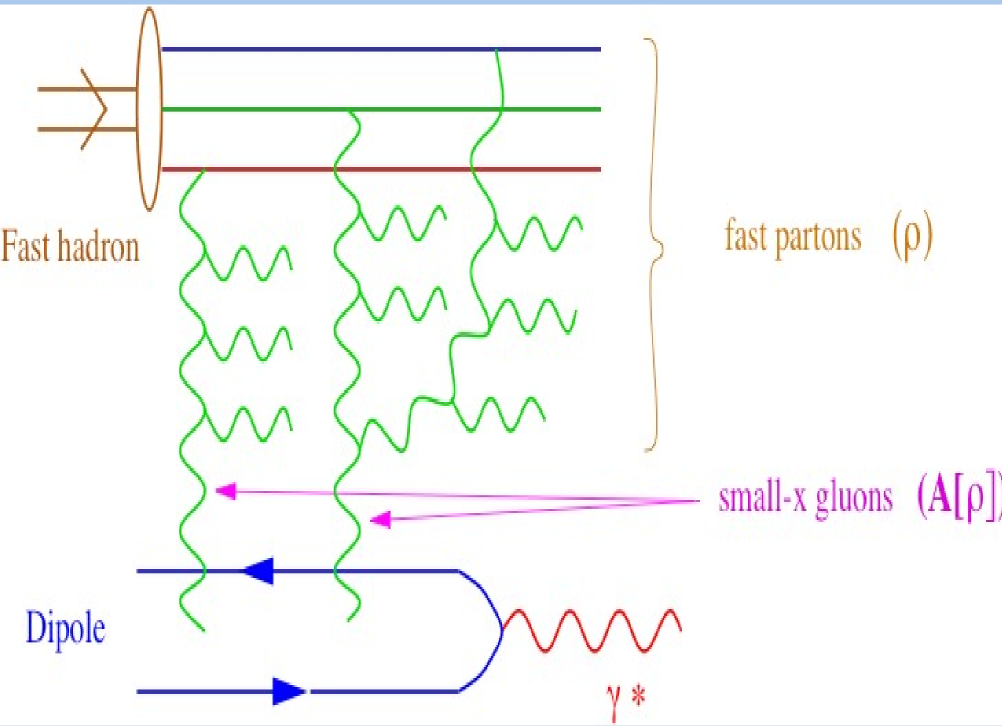
multiplicities
single and double inclusive spectra

AA, pp (dense-dense):

multiplicities, spectra
long range rapidity correlation

RIDGE

DIS



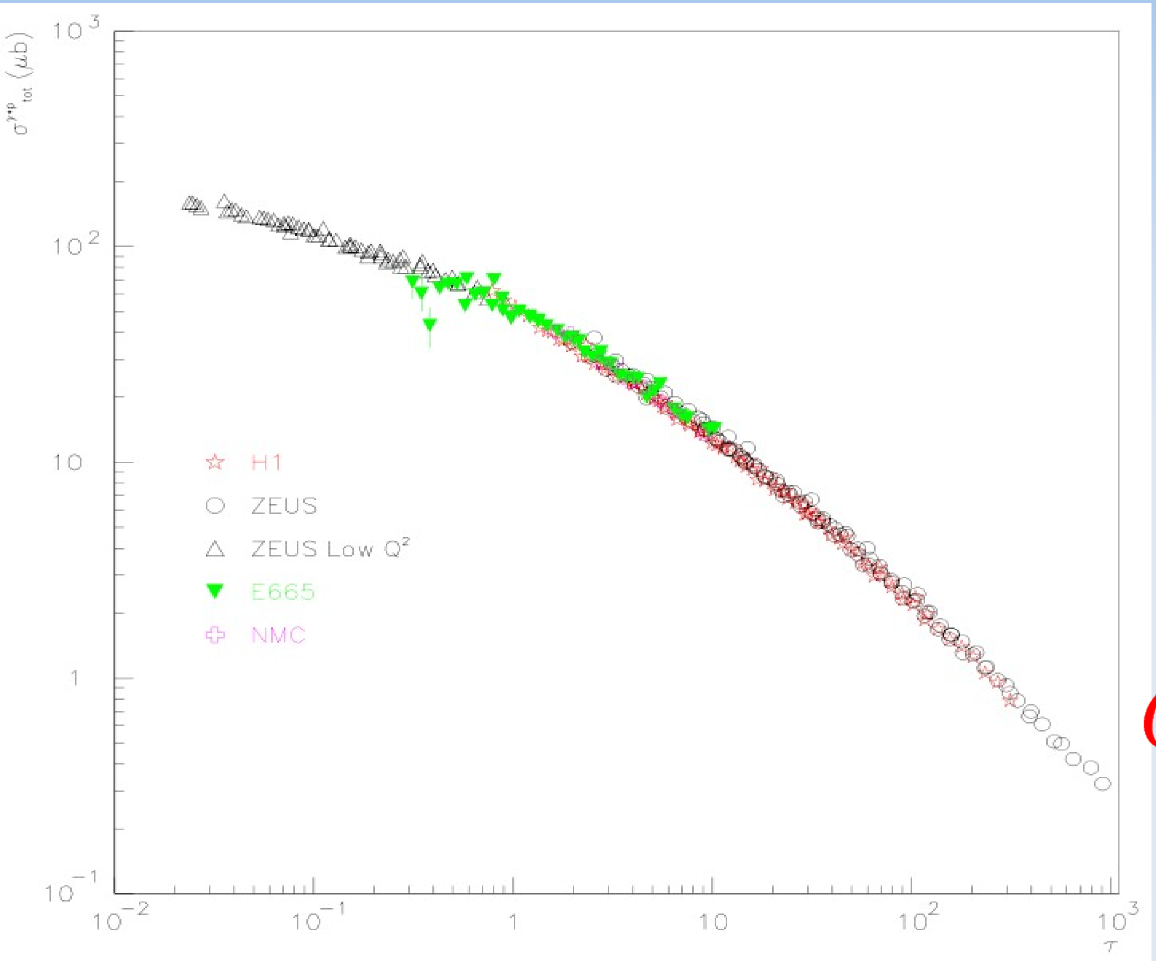
$$\mathbf{e\,p \longrightarrow e\,X}$$

$$\sigma_{\gamma^\star p} = \int_0^1 dz \int d^2 r_t d^2 b_t$$
$$|\Psi(z, r_t, Q^2)|^2\, N(x, r_t, b_t)$$

only the 2-pt function contributes $\quad \mathrm{N} \equiv \frac{1}{\mathrm{N_c}} < \mathrm{Tr}[1 - \mathrm{V}^\dagger(\mathrm{x_t})\mathrm{V}(\mathrm{y_t})] >$

where JIMWLK eqs. determine the x dependence of N

CGC at HERA? Extended scaling



S(G-B)K
PRL86 (2001) 596

Collinear Fact.:

$$\sigma = \sigma(\mathbf{x}, \mathbf{Q^2})$$

CGC:

$$\sigma = \sigma(\mathbf{Q^2}/\mathbf{Q_s^2})$$

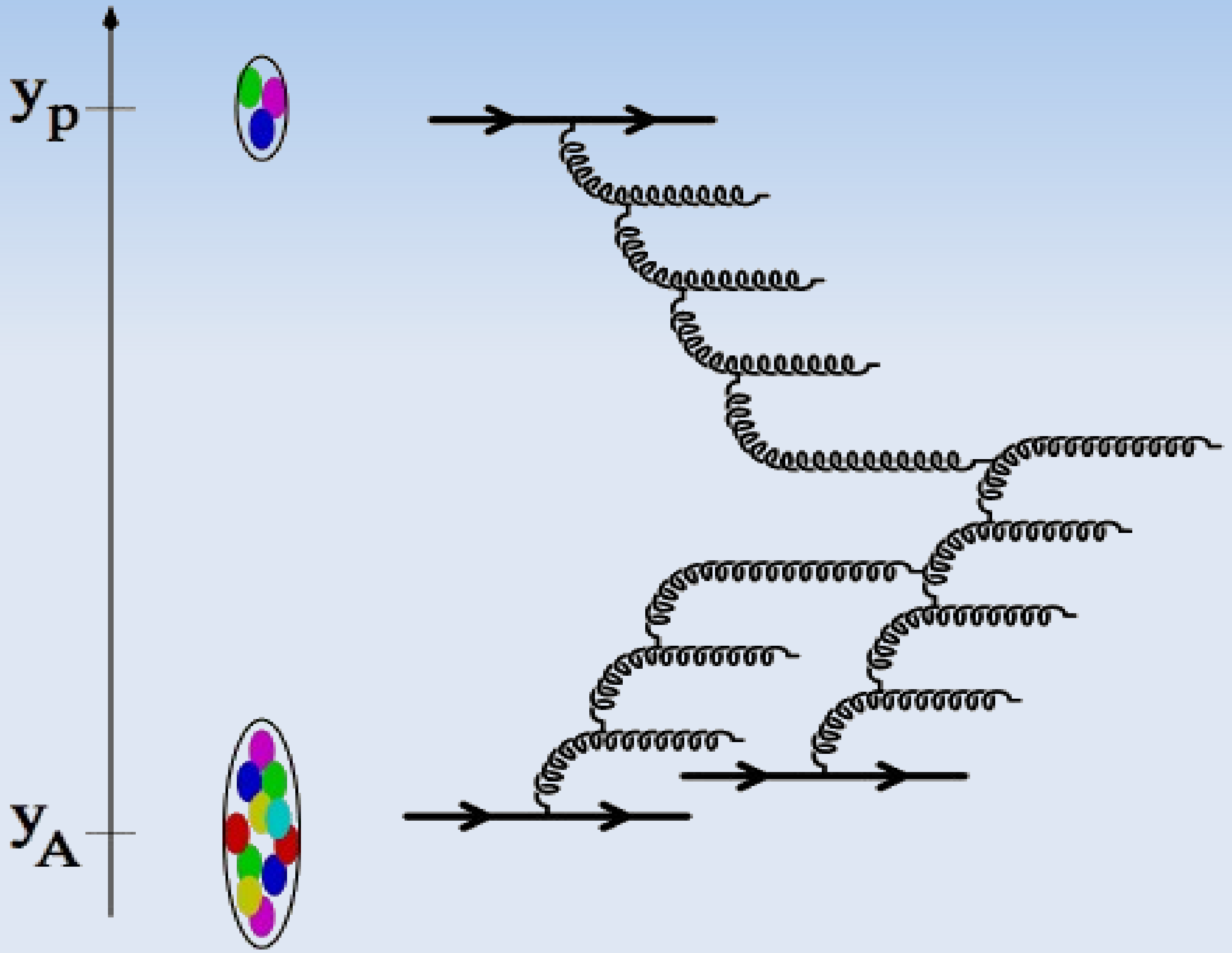
$$Q_s << Q << \frac{Q_s^2}{\Lambda}$$

IIM (2002)

$$\mathbf{Q_s^2} = \mathbf{1\,GeV^2}[\mathbf{x_0}/\mathbf{x}]^{\lambda}$$

$$\mathbf{x_0} = \mathbf{3X10^{-4}}$$

pA (dilute-dense) scattering



Single inclusive hadron production in pA

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

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

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

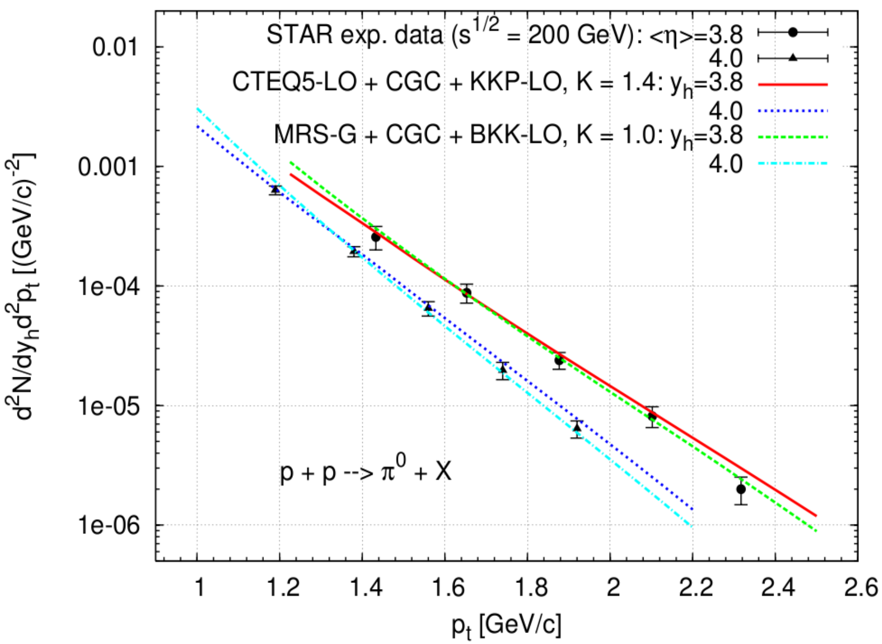
AD and JJM (2004)

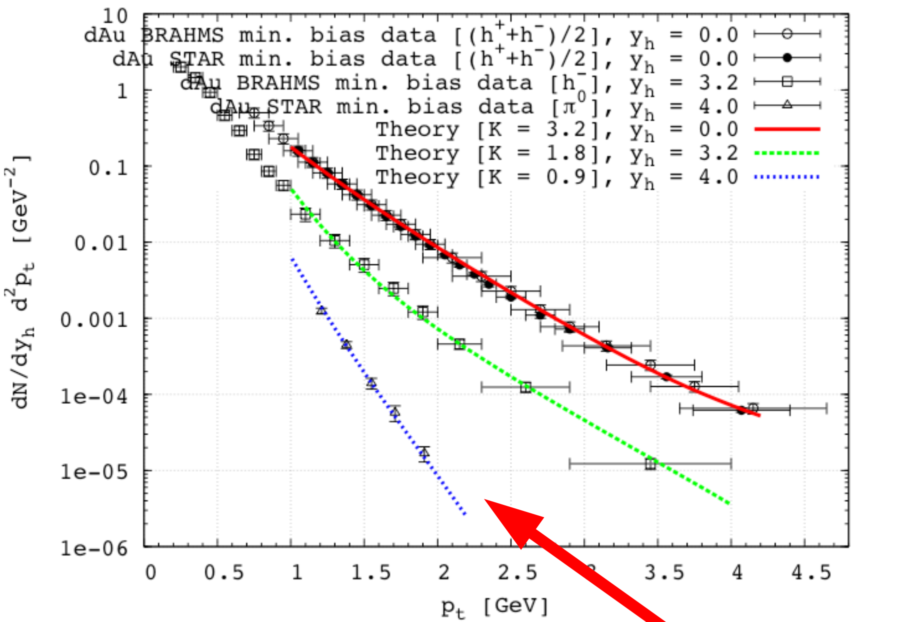
2-point function only: same as in DIS and photon,dilepton production in pA (FG and JJM)

UNIVERSALITY

Single inclusive hadron production

$$\sqrt{S} = 200\,\mathrm{GeV}$$





proton-proton

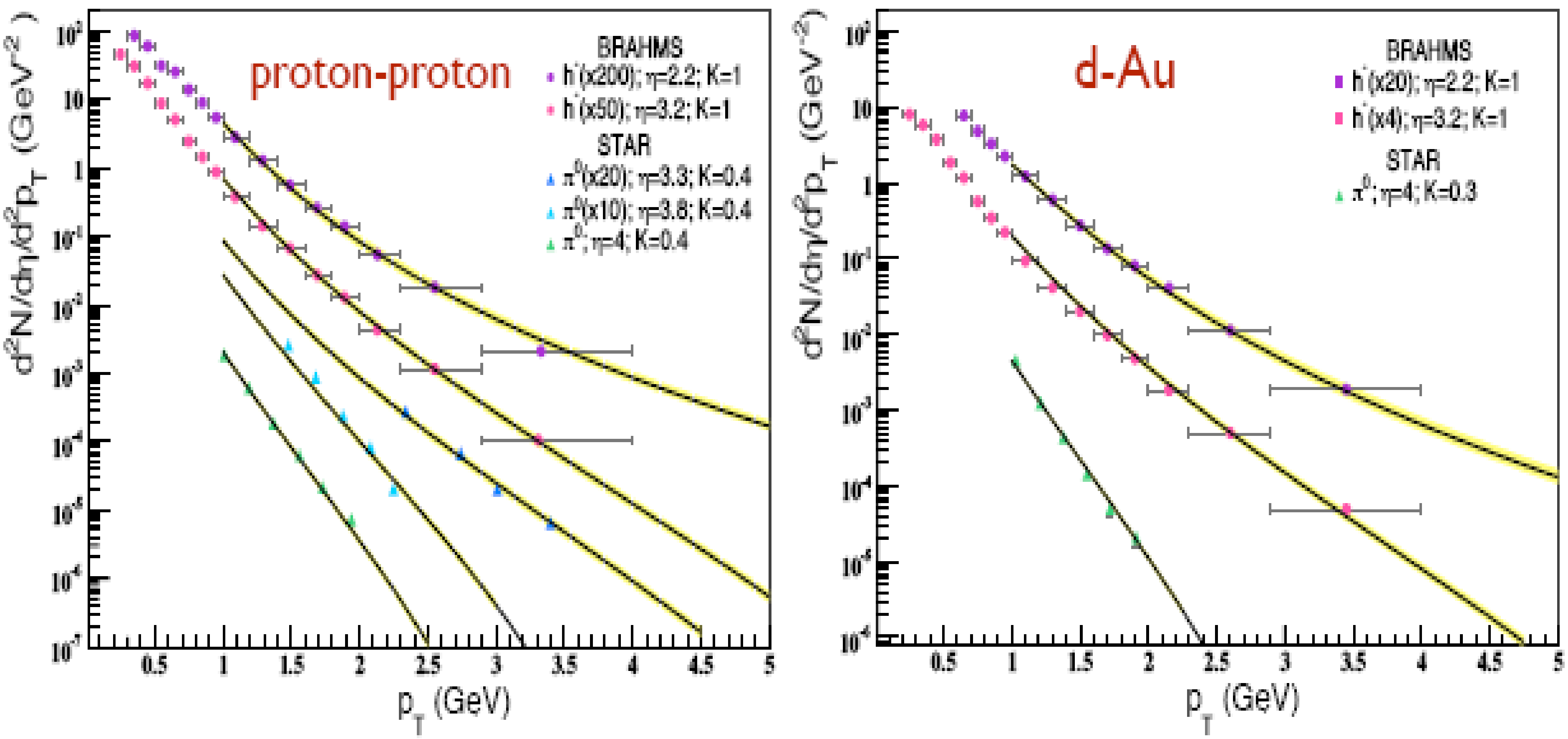
deuteron-gold

true prediction

BDH
PRD74 (2006) 074018

DHJ
NPA770 (2006) 57

dA at RHIC



J. Albacete + C. Marquet with running coupling BK equation

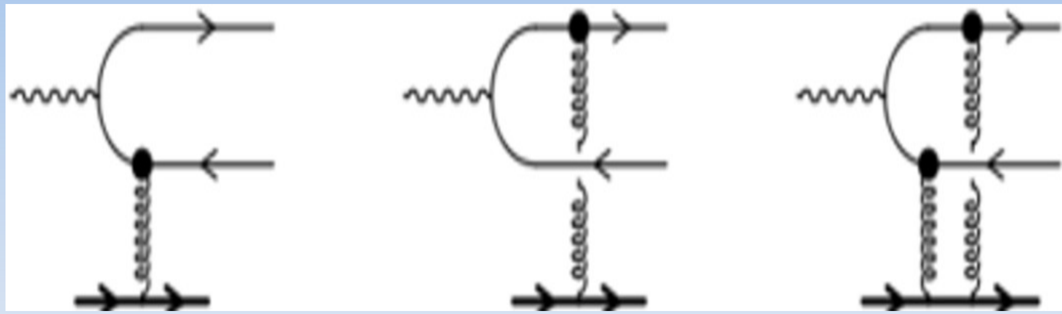
Also, KKT, BUW, RS,........

Two-hadron Correlations

Two hadron correlations: DIS

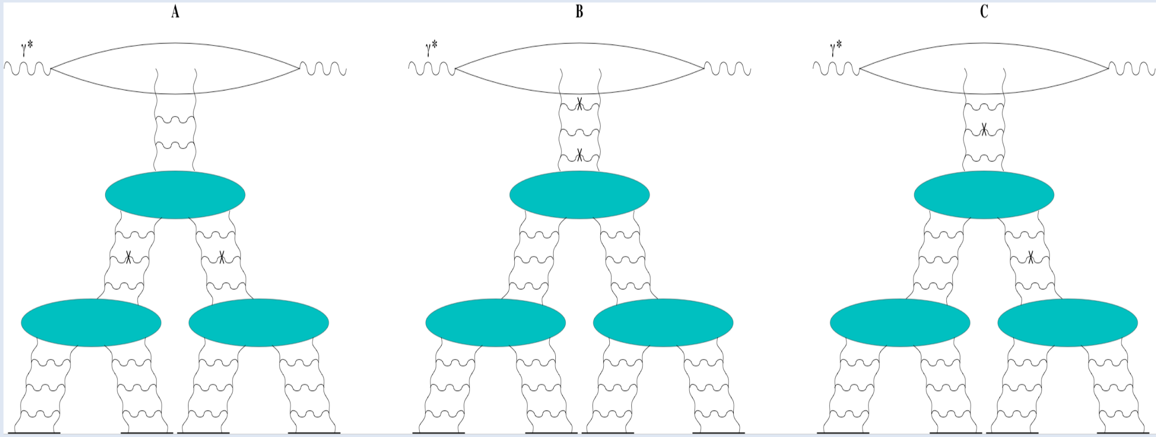
$$\gamma^{\star}\,\mathbf{p}(\mathbf{A}) \rightarrow \mathbf{q}\,\bar{\mathbf{q}}\,\mathbf{X}$$

FG-JJM, PRD67 (2003)



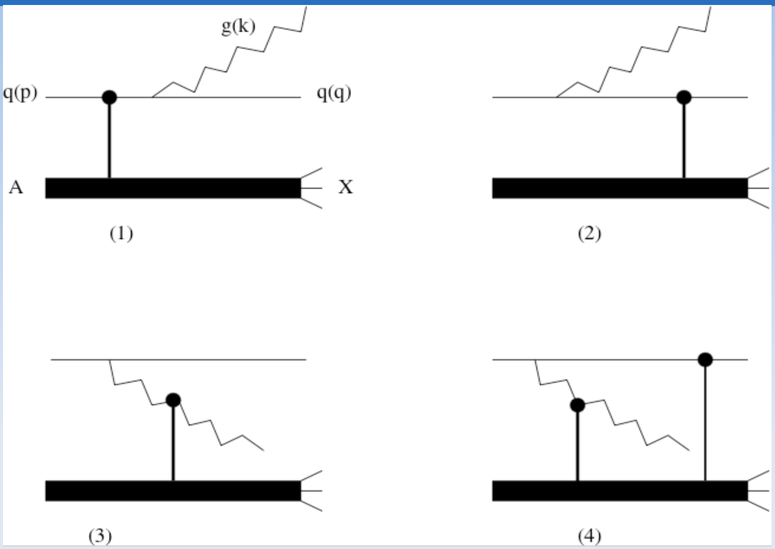
$$\gamma^{\star}\,\mathbf{p}(\mathbf{A}) \rightarrow \mathbf{g}\,\mathbf{g}\,\mathbf{X}$$

JJM-YK, PRD70 (2004)
AK-ML, JHEP (2006)



two hadron production in DIS probes higher point functions

Two hadron correlation: pA



$$\frac{d\sigma^{dA\to q\,g\,X}}{d\,p_t^2\,dy_1\,d\,q_t^2\,dy_2} \sim \int K \otimes$$

$$[< \mathrm{Tr} V^\dagger V > + < \mathrm{Tr} V^\dagger V V^\dagger V >$$

JJM and YK, PRD70 (2004), AK and ML, JHEP (2006), FGV, NPA (2006), CM, NPA796 (2007) , KT, NPA (2010)

two hadron production in pA probes higher point functions (up to 6-pt function)

dA: two hadron production

$$O_2(r,\bar{r}) \equiv TrV_r\,V_{\bar{r}}^{\dagger}$$ **F2 in DIS, single hadron in pA**

$$O_4(r,\bar{r}:s) \equiv \frac{1}{2}\left[TrV_r^{\dagger}\,V_s\;\;TrV_{\bar{r}}\,V_s^{\dagger} - \frac{1}{N_c}TrV_r^{\dagger}\,V_{\bar{r}}\right]$$

$$O_6(r,\bar{r}:s,\bar{s}) \equiv \frac{1}{2}\left[TrV_r\,V_{\bar{r}}^{\dagger}\,V_{\bar{s}}\,V_s^{\dagger}\,TrV_s\,V_{\bar{s}}^{\dagger} - \frac{1}{N_c}TrV_r\,V_{\bar{r}}^{\dagger}\right]$$

Dipole + large N_c approximation:

$$\begin{aligned}
\langle O_4(r,\bar{r}:s)\rangle &\simeq \langle O_2(r-s)\rangle\,\langle O_2(s-\bar{r})\rangle \\
\langle O_6(r,\bar{r}:s,\bar{s})\rangle &\simeq \langle O_2(r-s)\rangle\,\langle O_2(\bar{r}-\bar{s})\rangle\,\langle O_2(s-\bar{s})\rangle \\
&+ \langle O_2(r-\bar{r})\rangle\,\langle O_2(\bar{s}-s)\rangle\,\langle O_2(s-\bar{s})\rangle
\end{aligned}$$

Beyond dipole + large Nc

JIMWLK evolution equation:

$$\frac{d}{dy}\langle O\rangle = \frac{1}{2}\left\langle \int d^2x\, d^2y\, \frac{\delta}{\delta\alpha_x^b}\,\eta_{xy}^{bd}\,\frac{\delta}{\delta\alpha_y^d}\,O\right\rangle$$

$$\eta_{xy}^{bd} = \frac{1}{\pi}\int \frac{d^2z}{(2\pi)^2}\frac{(x-z)\cdot(y-z)}{(x-z)^2(y-z)^2}\left[1+U_x^\dagger U_y - U_x^\dagger U_z - U_z^\dagger U_y\right]^{bd}$$

JIMWLK: Beyond dipole + large Nc

AD-JJM, arXiv:1008.0480

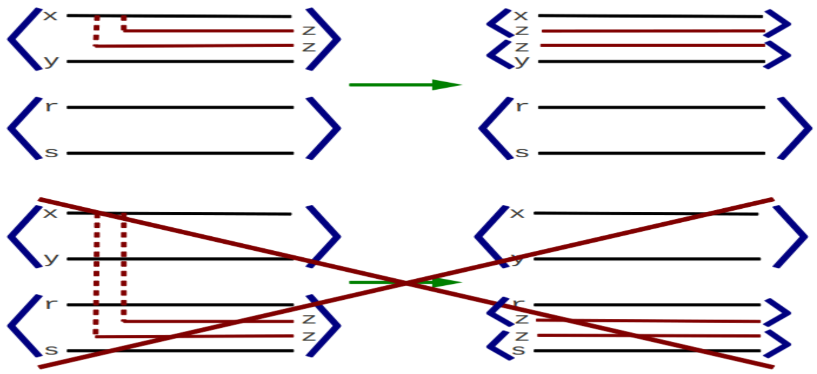
Recall evolution of S2 is sensitive to S4 only

Leading Nc: $$\frac{d}{dy} S_4(r, \bar{r} : s) \simeq \frac{d}{dy} [S_2(s - \bar{r})\, S_2(r - s)]$$

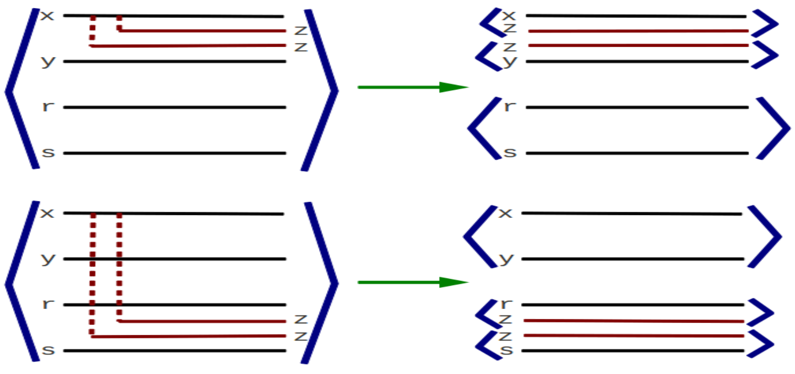
DIS, single inclusive production in pA probe S2

$$\frac{d}{dy} S_6(r, \bar{r} : s, \bar{s}) \simeq \frac{d}{dy} \Big[S(r - s)\; S(\bar{s} - \bar{r})\; S(s - \bar{s})\; + S(r - \bar{r})\; S(s - \bar{s})\; S(s - \bar{s}) \Big] + \textbf{MANY MORE}$$

Beyond dipole + large N_c approximation



Dipole approximation



JIMWLK

Making the dipole approximation before the evolution misses many leading Nc terms

Two hadron production is sensitive to JIMWLK

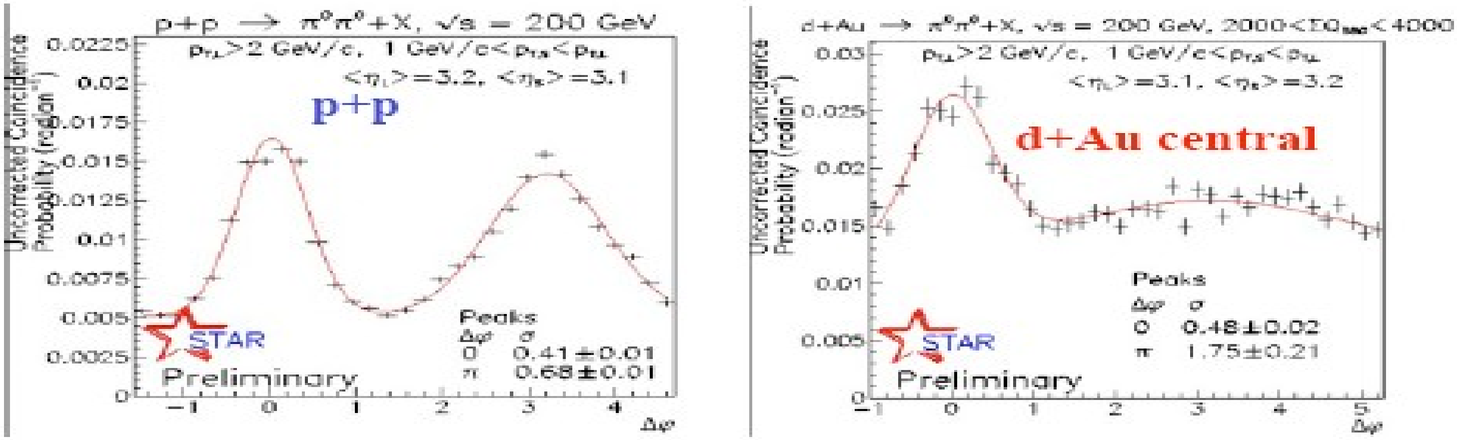
disappearance of back to back jets

Experimental evidence for "monojet" production

- "Coincidence probability" measured by STAR Coll. at forward rapidities:

$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$

- ΔΦ=0 (near side) peak originates from two pion fragments within the same quark jet
- ΔΦ=Π (away side) peak suppressed in central d+Au coll with respect to p+p collisions



theory fits from Albacete + Marquet, PRL (2010)

Photon-Hadron correlations:dA

another process to test CGC formalism

less inclusive than single inclusive particle production

one less hadron fragmentation function

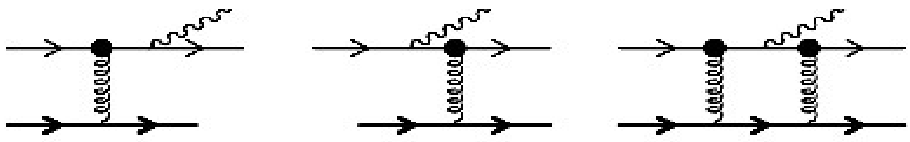
theoretically cleaner: 2-point function only

lower rates compared to two hadron production

photons are hard to measure

will help distinguish between different approaches

$$\mathbf{q(p)\,T \to q(q)\,\gamma(k)\,X}$$



$$\frac{d\sigma^{d\,A\to h\,\gamma\,X}}{d^2b_t\,dq_t^2\,dk_t^2\,dy_\gamma\,dy_h\,d\theta} = a\int_{z_{min}}^{1}\frac{dz}{z^5}\,f_{q/d}(x_p,Q^2)$$

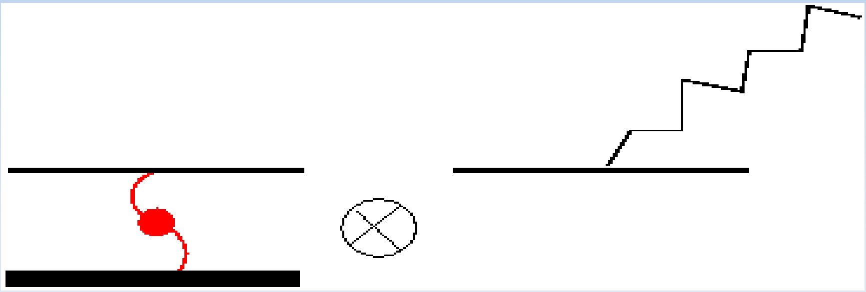
$$D_{h/q}(z,Q^2)[z^2+(\frac{q^-}{q^-+zk^-})^2]\,\frac{(\tilde{q}_t+z\tilde{k}_t)^2}{(k^-\tilde{q}_t-q^-\tilde{k}_t)^2}N_F(|\tilde{q}_t/z+\tilde{k}_t|)$$

FG-JJM, PRD66 (2002) 014021
JJM, EPJC61 (2009) 789

Kopeliovich et al.,
Rezaeian 2010

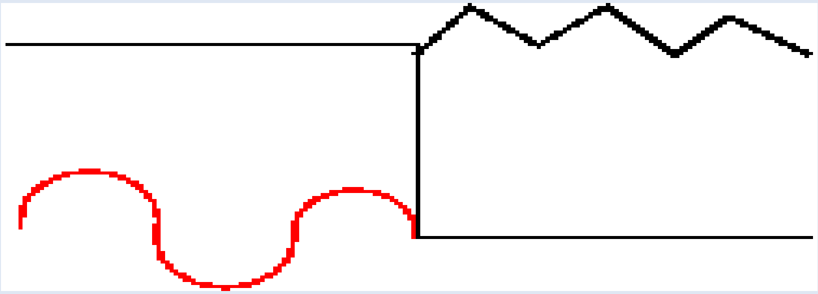
pQCD limit

near side: collinear divergence $\theta \to 0$



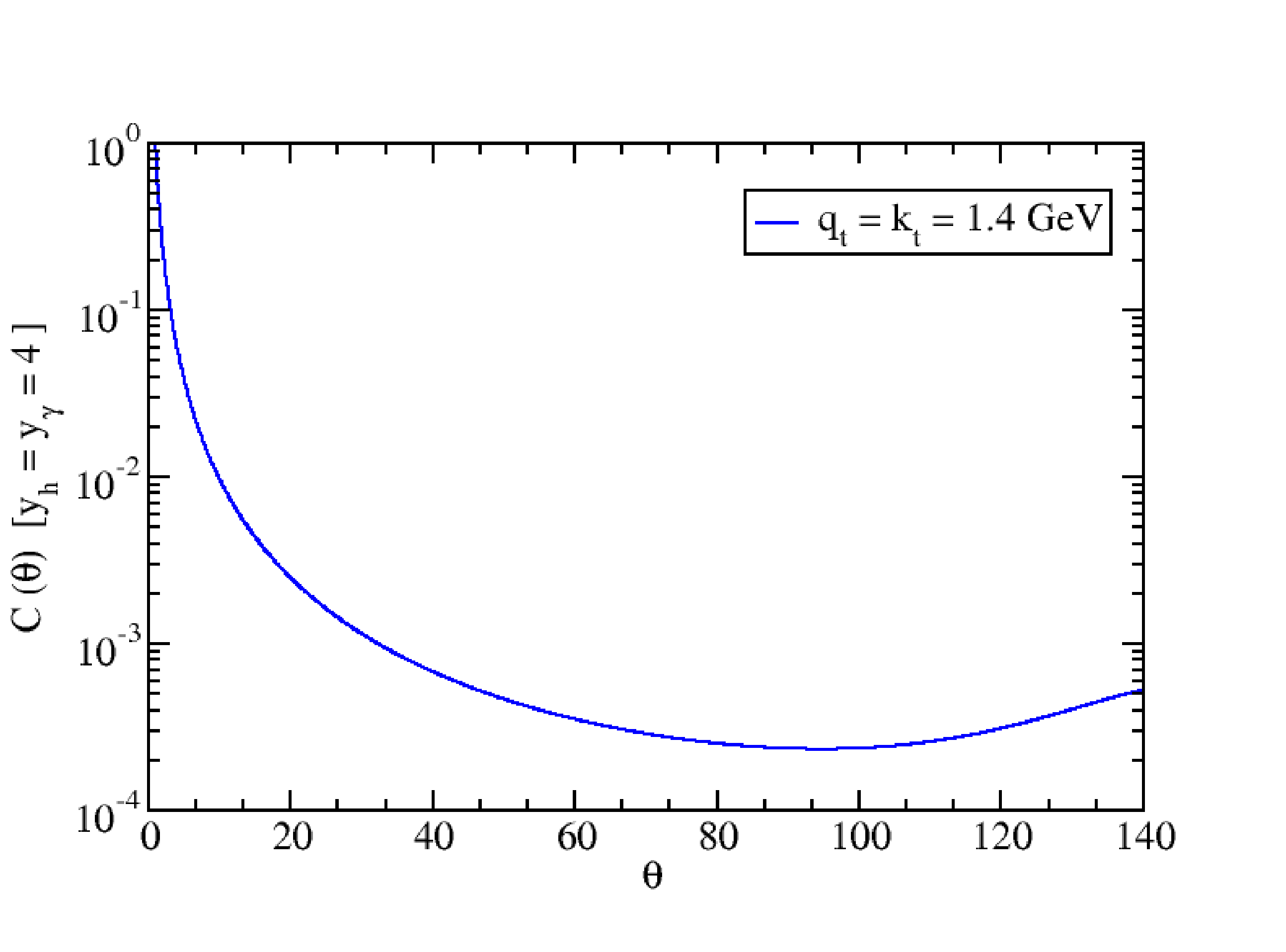
$$N_F \otimes D_{\gamma/q}$$

away side: $\theta \to \pi$



$$p_t >> Q_s$$

Photon-Hadron correlations:dA



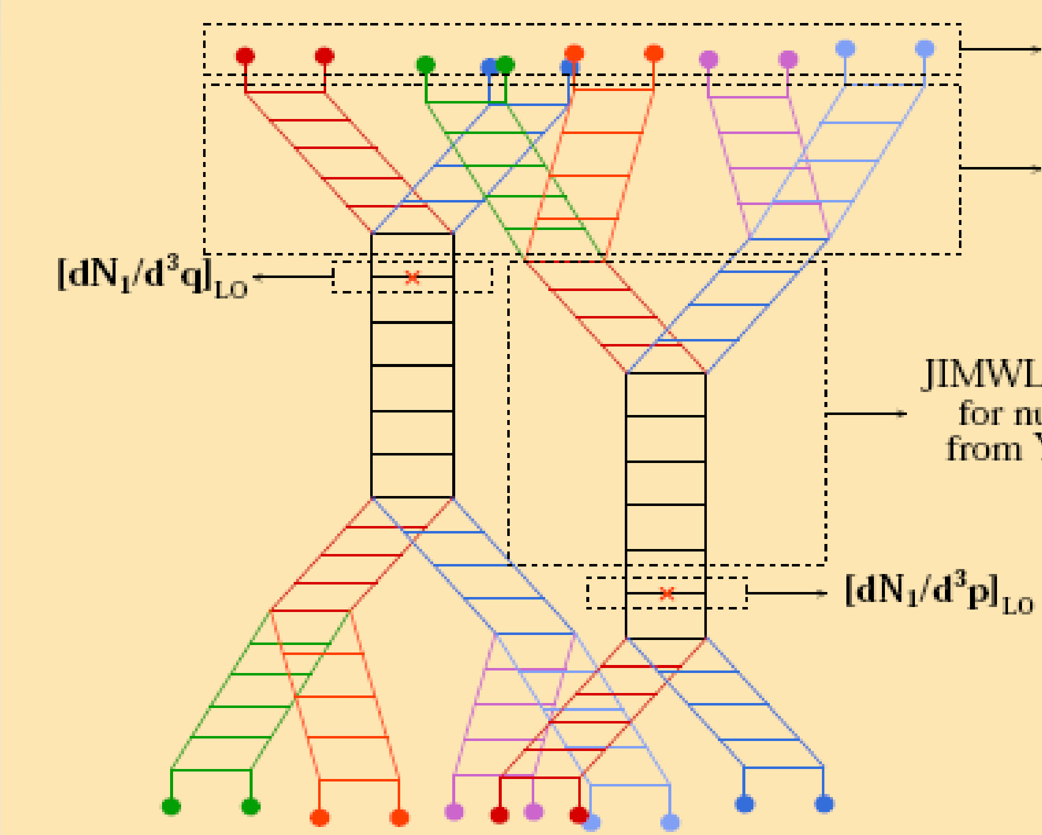
$$\mathbf{C}(\theta) \equiv \frac{\mathbf{d}\sigma}{\mathbf{dq_t^2\, dk_t^2\, dy_h\, dy_\gamma\, d}\theta} \Bigg/ \int \mathbf{d}\theta \frac{\mathbf{d}\sigma}{\mathbf{dq_t^2\, dk_t^2\, dy_h\, dy_\gamma\, d}\theta}$$

AA/pp Collisions at High Energy

Factorization theorems

Gelis, Lappi, Venugopalan

quantum corrections (ln 1/x) absorbed into $\mathbf{W}[\rho]$



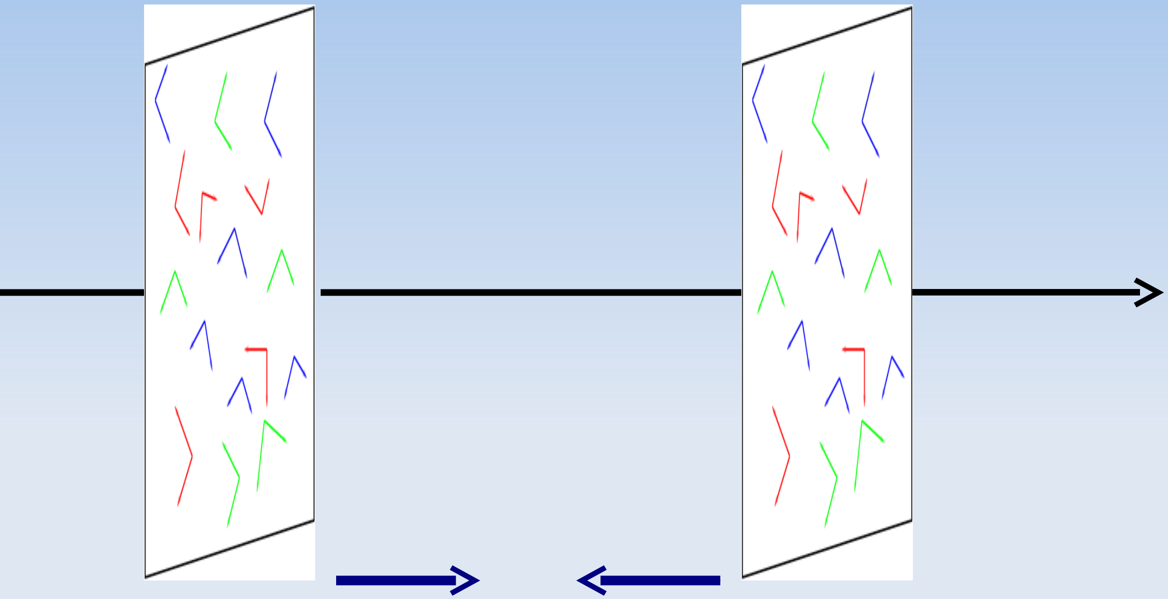
Single gluon

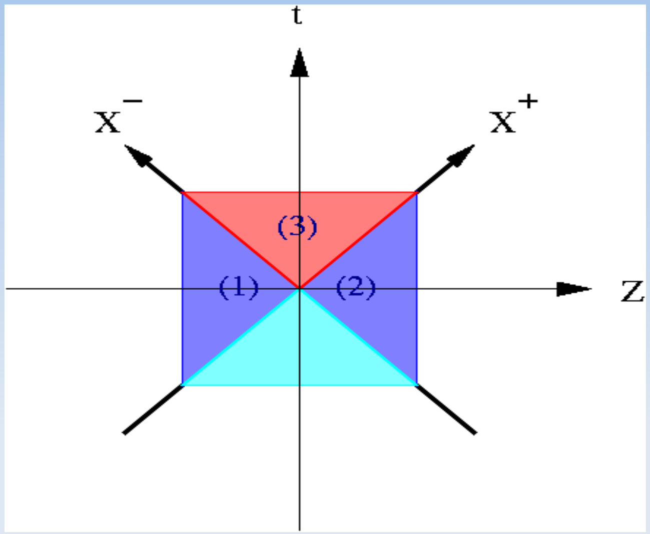
Only $\langle \rho(y)\rho(y) \rangle$

Double gluon

Also $\langle \rho(y_p)\rho(y_q) \rangle$

Colliding Sheets of Color Glass





before the collision:

$$\mathbf{A^+ = A^- = 0}$$
$$\mathbf{A^i = A^i_1 + A^i_2}$$
$$\mathbf{A^i_1} = \theta(\mathbf{x^-})\theta(-\mathbf{x^+})\alpha^{\mathbf{i}}_{\mathbf{1}}$$
$$\mathbf{A^i_2} = \theta(-\mathbf{x^-})\theta(\mathbf{x^+})\alpha^{\mathbf{i}}_{\mathbf{2}}$$

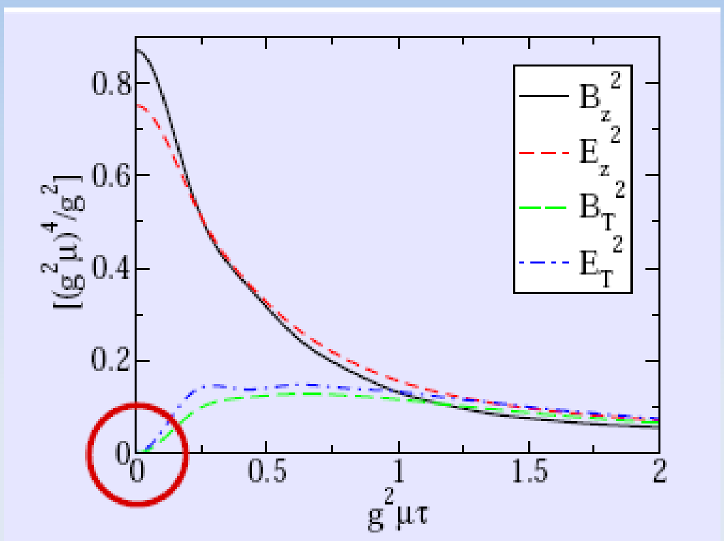
after the collision:

solve for A_μ

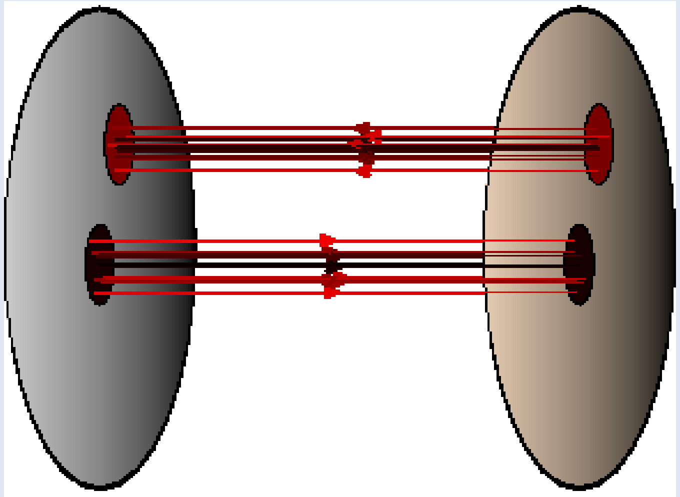
in the forward LC

GLASMA:

gluon fields produced in collision of two sheets of color glass



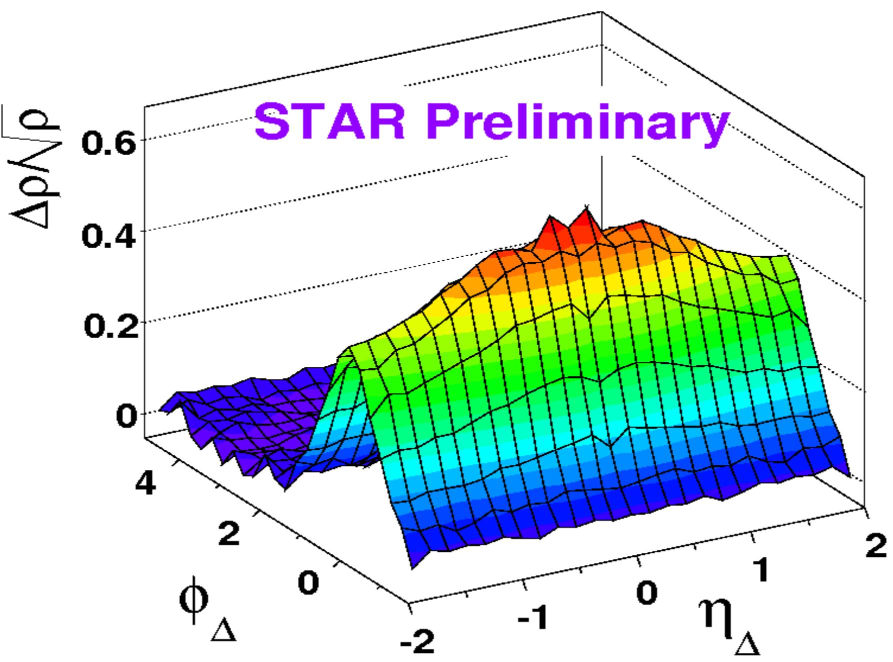
Early on glasma fields (E and B) are longitudinal

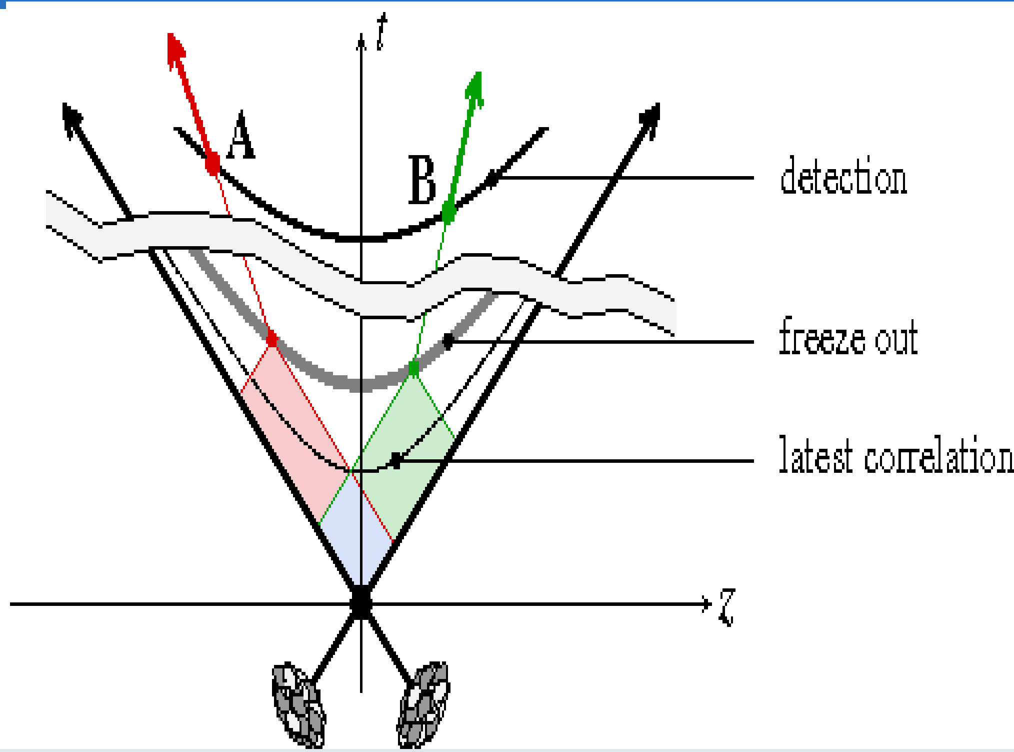


Classical solutions are boost invariant

Transverse size of these flux tubes is $\sim \frac{1}{Q_s}$

Ridge in AA *(long-range rapidity correlations)*





$$\tau \leq \tau_{\mathrm{fo}}\, e^{-\frac{1}{2}|y_A - y_B|}$$

DGMV: NPA810 (2008) 91

Two-gluon production in AA/pp

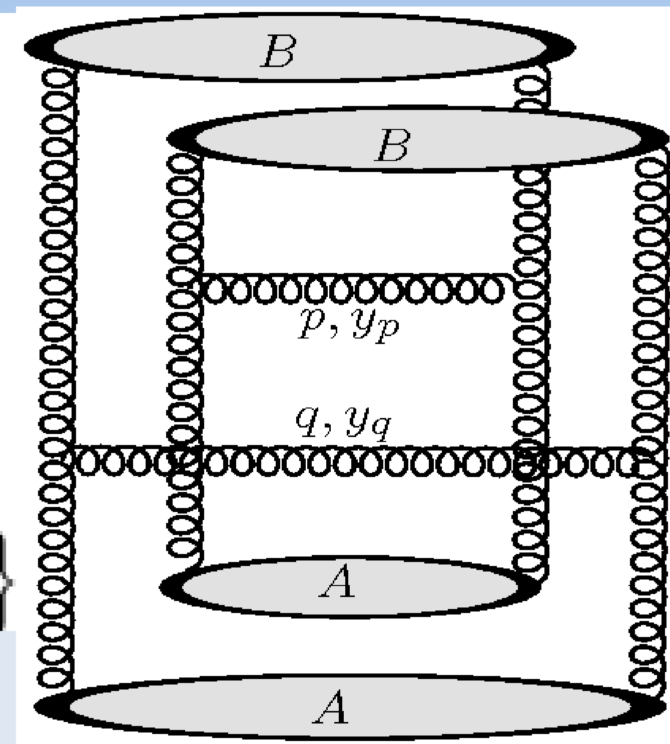
$$\frac{dN_2}{d^2p_\perp dy_p d^2q_\perp dy_q} = \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2 S_\perp}{(N_c^2-1)^3\, p_\perp^2 q_\perp^2}$$

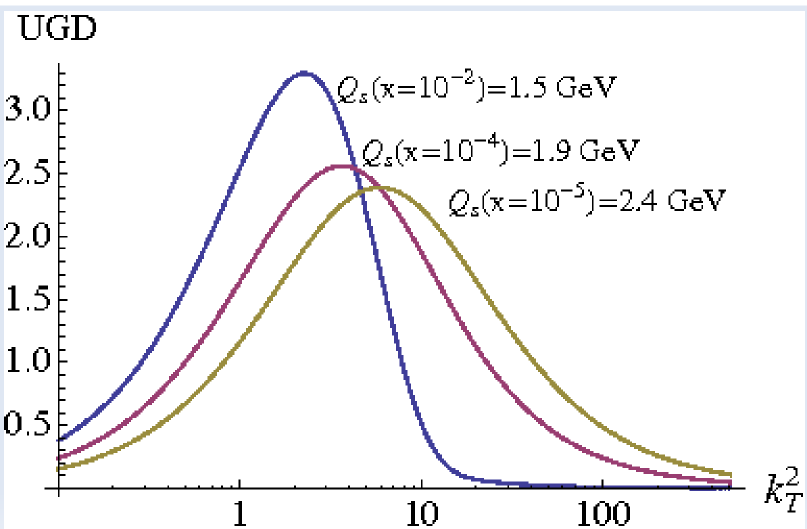
$$\times \int d^2k_\perp \Big\{ \Phi_A^2(y_p, k_\perp)\Phi_B(y_p, p_\perp - k_\perp)$$

$$\times \left[\Phi_B(y_q, q_\perp + k_\perp) + \Phi_B(y_q, q_\perp - k_\perp)\right]$$

$$+\Phi_B^2(y_q, k_\perp)\Phi_A(y_p, p_\perp - k_\perp)$$

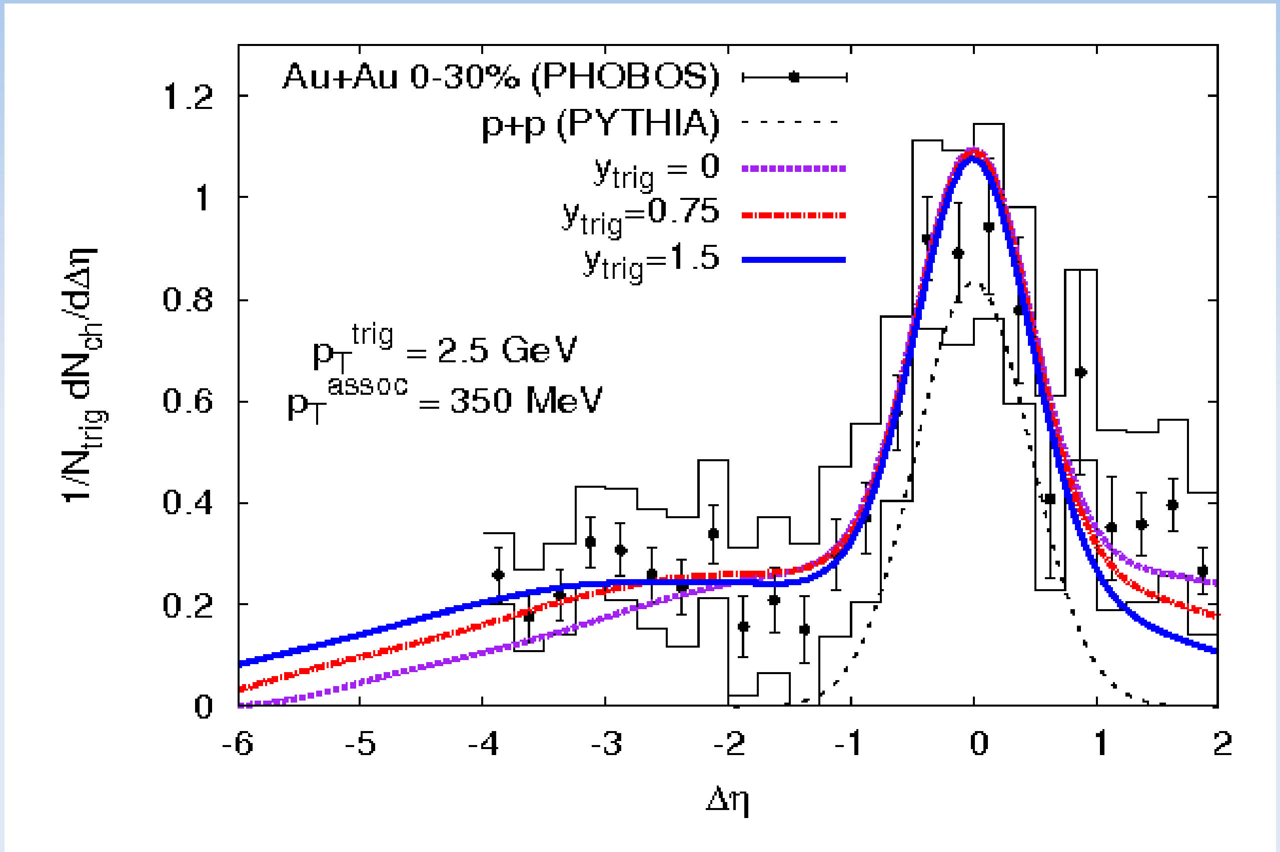
$$\times \left[\Phi_A(y_q, q_\perp + k_\perp) + \Phi_A(y_q, q_\perp - k_\perp)\right]\Big\}$$





solutions of rcBK
angular collimation

Ridge in AA



CGC glasma flux tubes

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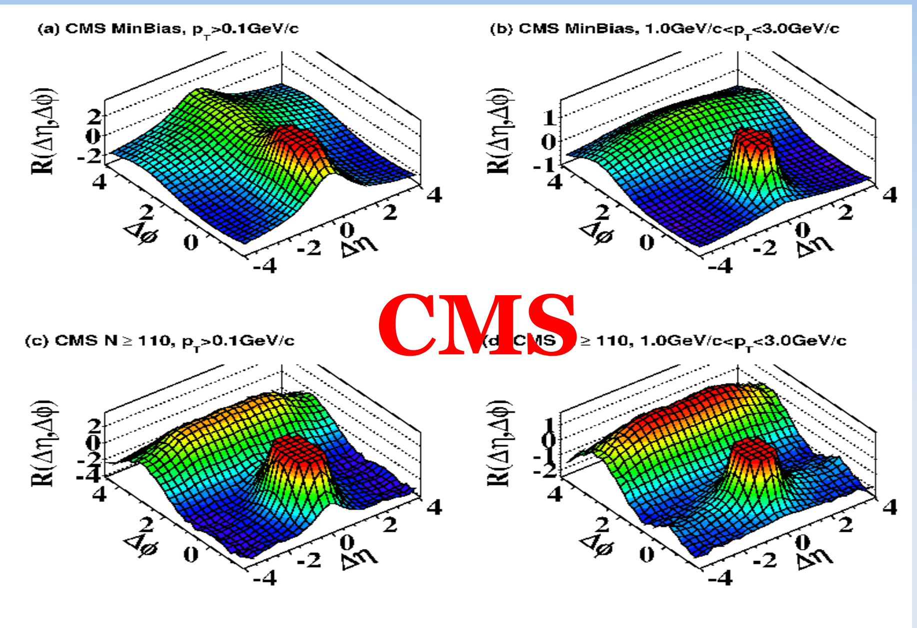
Azimuthal angle dependence enhanced by radial flow in QGP

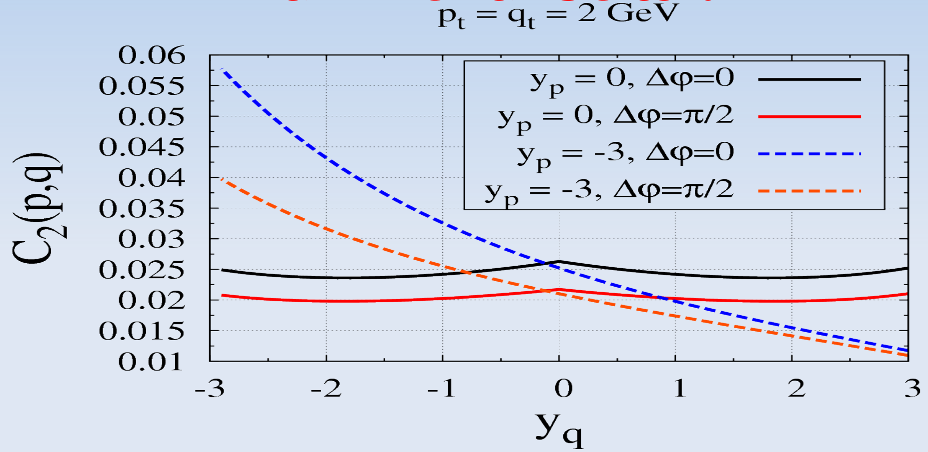
Ridge in pp at LHC

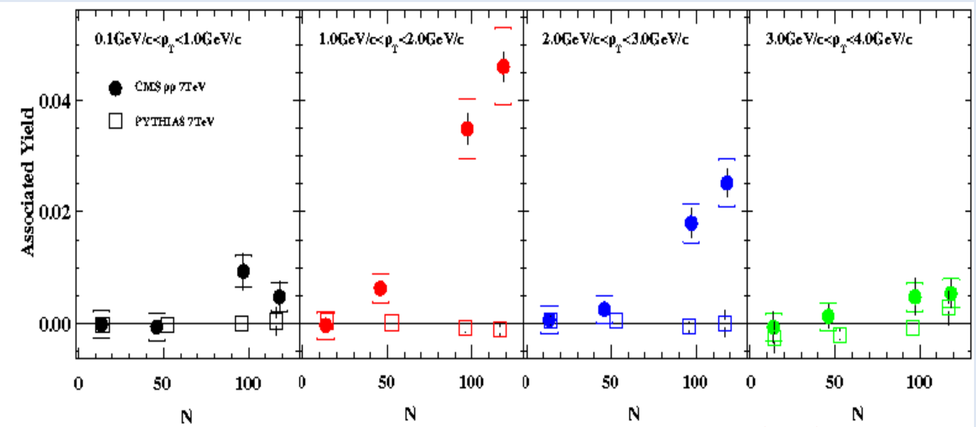


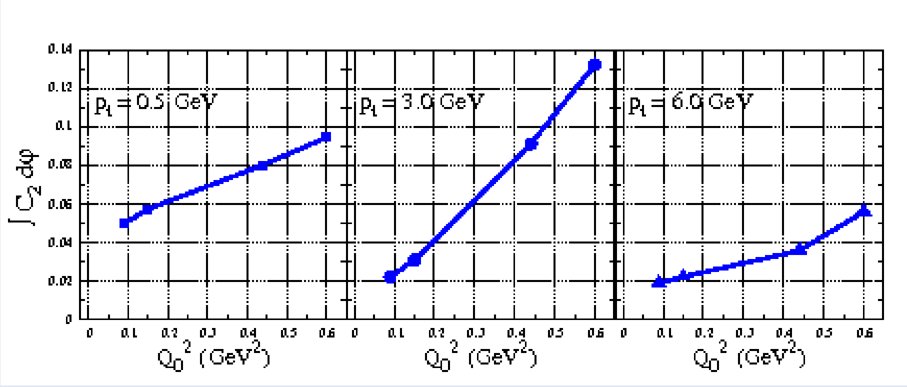
CMS

Arxiv:1009:5295

Dumitru et al.







A. Dumitru, RIKEN-BNL Workshop on "Progress in High pT Physics at RHIC", March 17-19, 2010, RBRC Vol. 45, page 129.

High energy QCD: Color Glass Condensate

A new region of QCD phase space

A systematic approach with controlled approximations

Q_s: a dynamical semi-hard scale

Evidence for CGC at HERA, RHIC soon to be tested at LHC

CMS data on high multiplicity events in pp are in qualitative agreement with CGC predictions