2-particle correlations in pp and AA collisions

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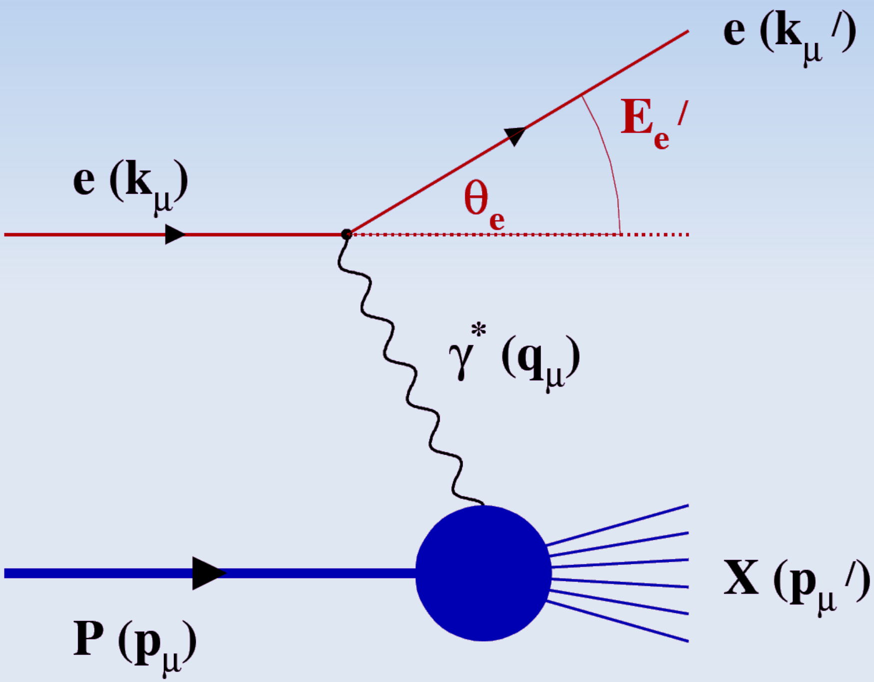
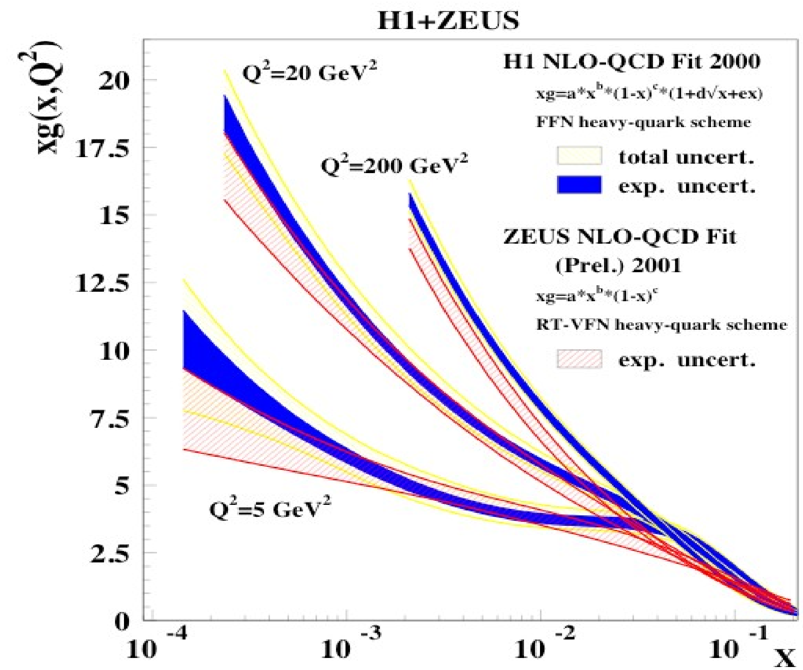
A proton at small x

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





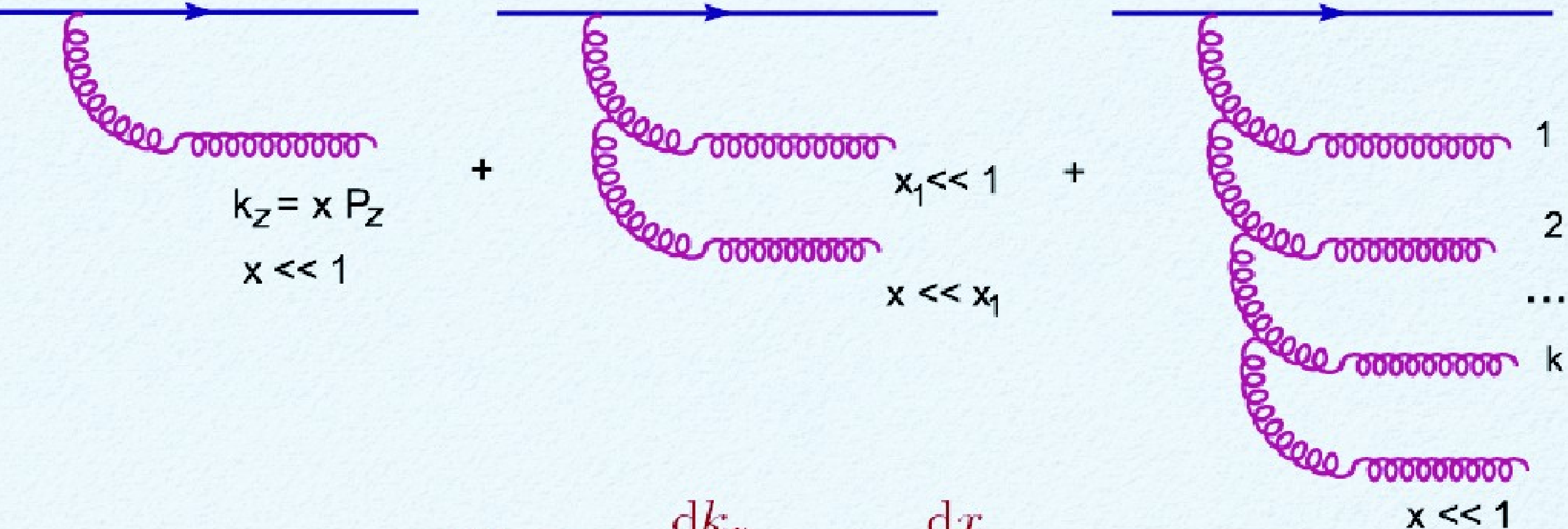
$$x = \frac{p^+}{P^+}$$

is the fraction of hadron energy carried by a parton

there are a lot of gluons at small x

gluon radiation at small x :pQCD

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



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

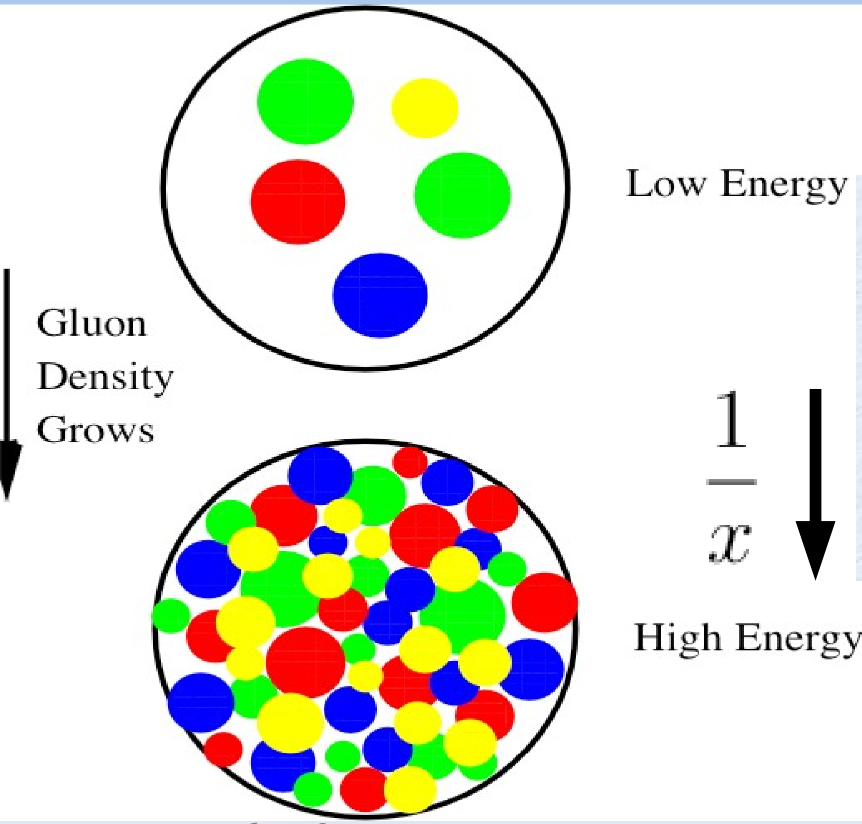
The 'price' of an additional gluon:

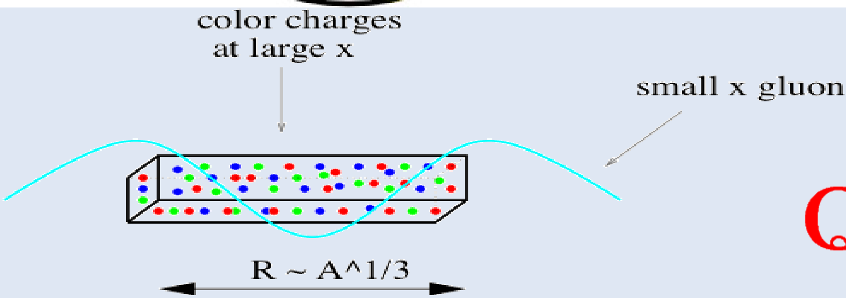
$$\mathcal{P}(1) \propto \alpha_s \int_x^1 \frac{dx_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

number of gluons grows fast

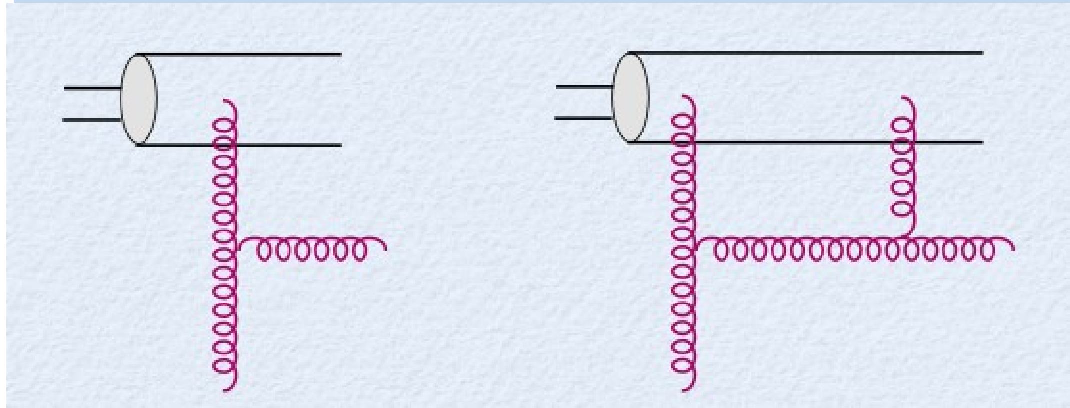
$$n \sim e^{\alpha_s ln 1/x}$$

CGC and gluon saturation





"attractive" bremsstrahlung vs. "repulsive" recombination



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

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

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 $\mathbf{A}^\mu$

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

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

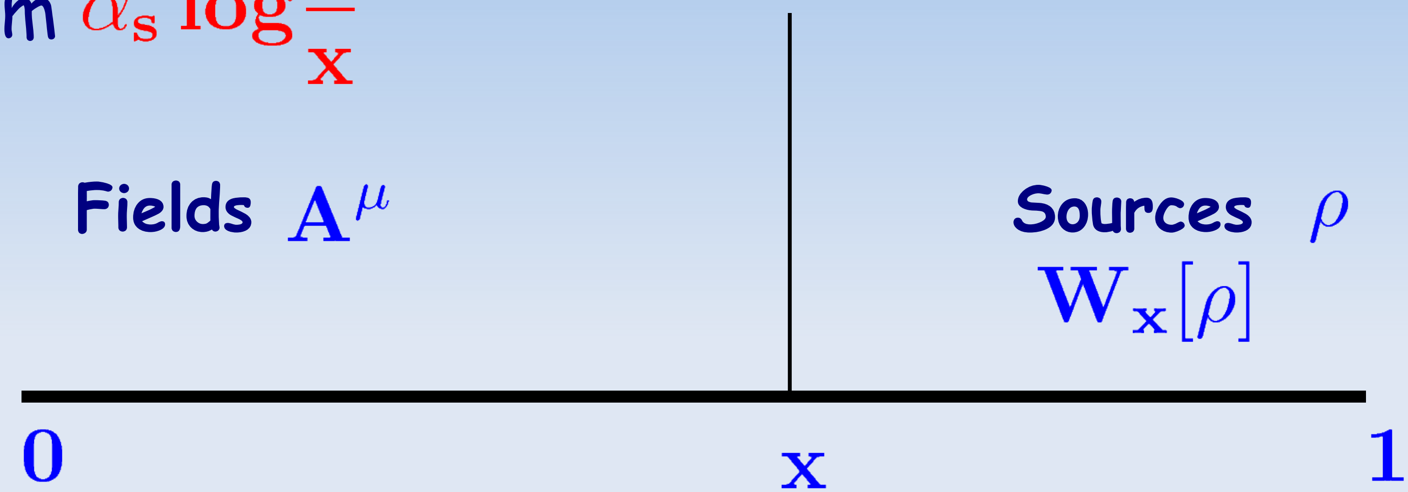
weight functional:

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

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

QCD at High Energy: Wilsonian RG

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



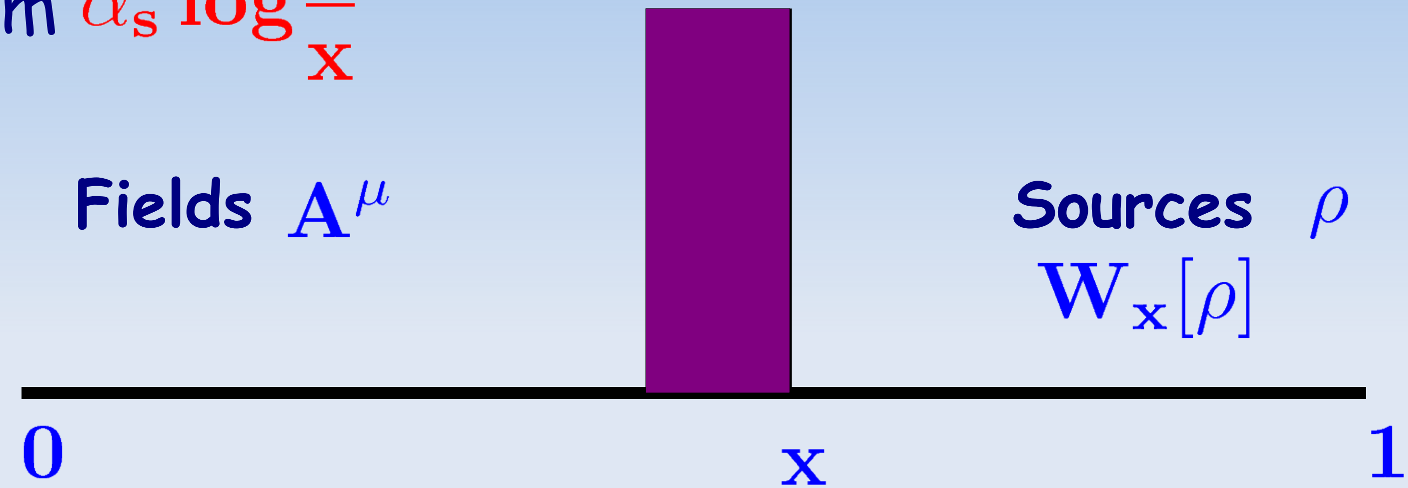
QCD at High Energy: Wilsonian RG

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

Fields A^μ

Sources ρ

$W_x[\rho]$



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

integrate out field fluctuations quadratically

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

QCD at High Energy: Wilsonian RG

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

Fields $\mathbf{A}^{\mu}$

Sources ρ

$\mathbf{W_x}[\rho]$

$\mathbf{0}$ $\mathbf{x}$ $\mathbf{1}$

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

JIMWLK eq. describes x evolution of observables

CGC:QCD at high gluon density

multiple scatterings → **p_t broadening**

"Cronin" effect

evolution with ln (1/x) → **suppression**

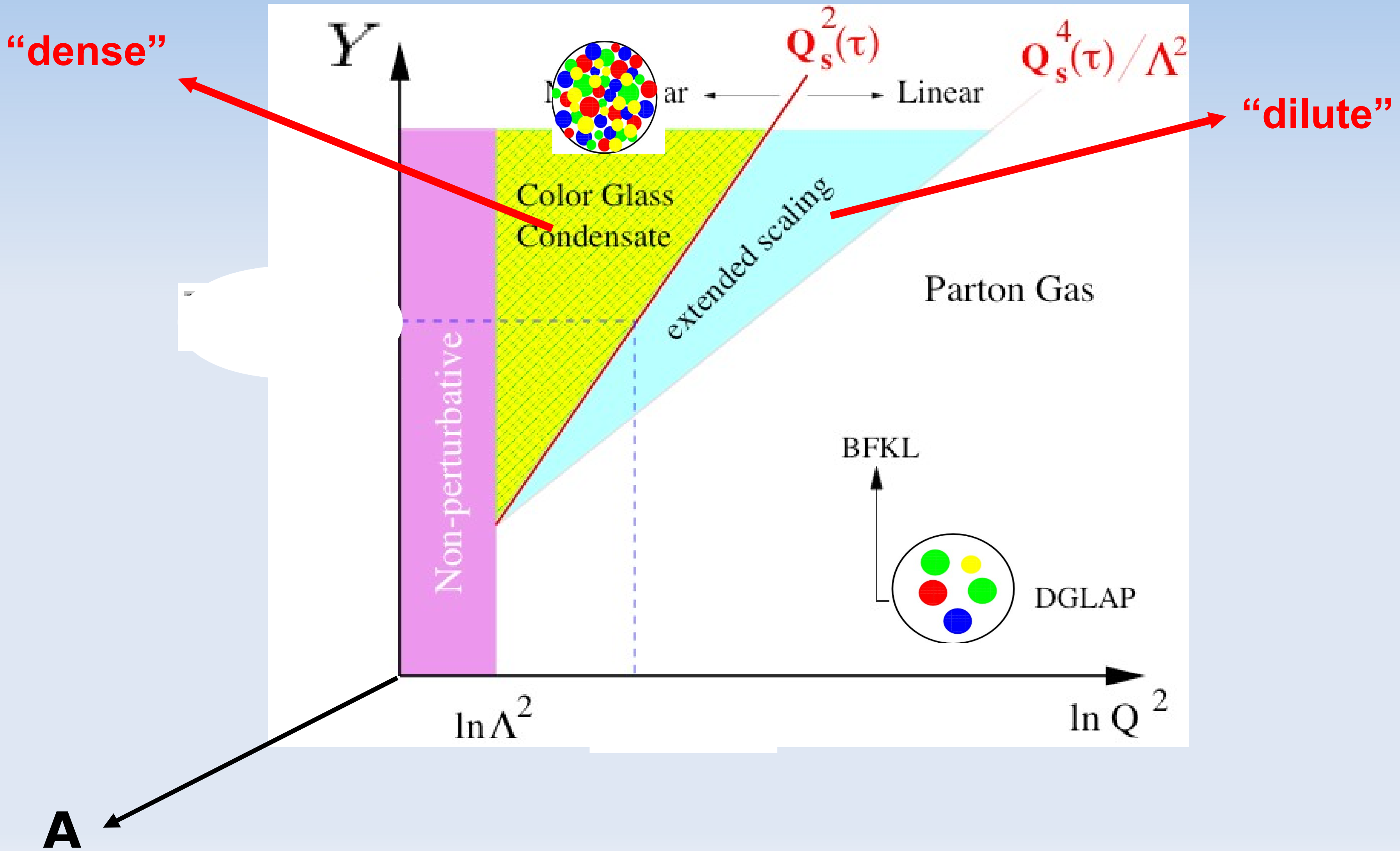
"Leading twist" nuclear shadowing

effective degrees of freedom:
Wilson line $V(x_t)$ re-sums multiple scatterings

CGC observables are expressed in terms of

$$< \mathrm{Tr\,V} \cdots \mathrm{V}^{\dagger} >$$ → *satisfy the JIMWLK equation: Re-sums ln 1/x*

Road Map of QCD Phase Space



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

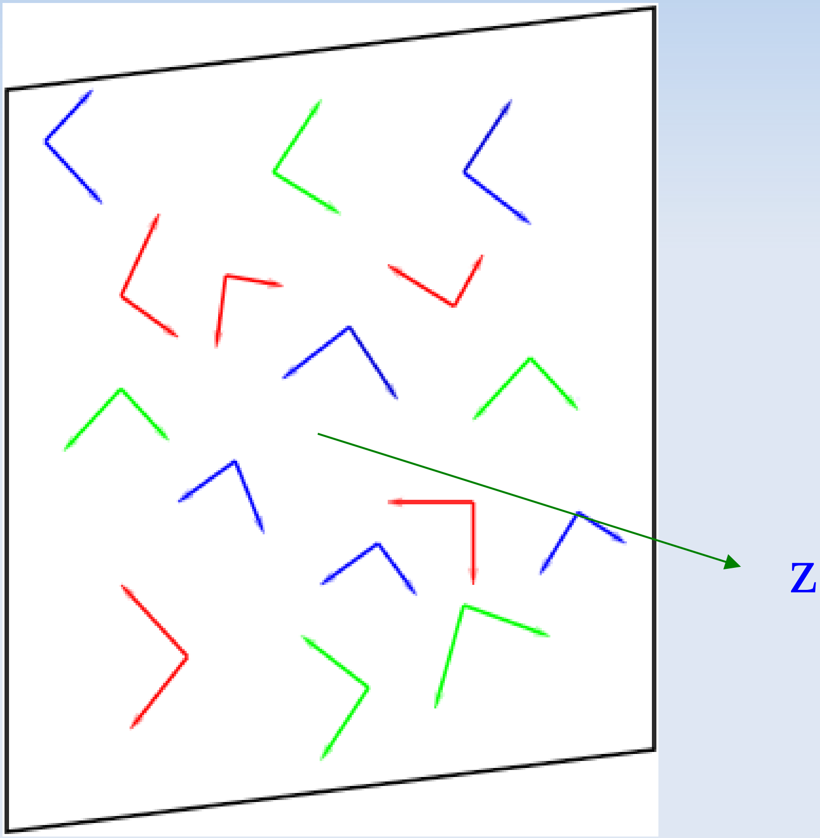
$$\mathbf{A}^+ = \mathbf{0}$$

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

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

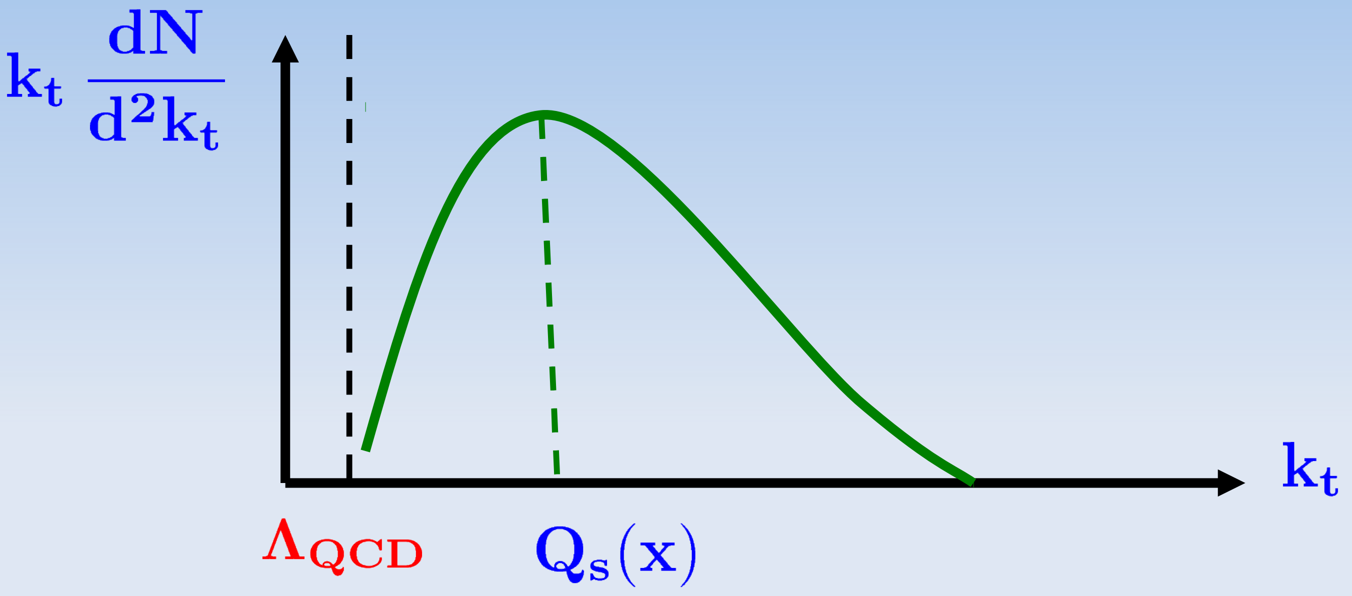
$$\partial^{\mathbf{i}} \, \alpha^{\mathbf{i}}_{\mathbf{a}} = \mathbf{g} \, \rho_{\mathbf{a}}$$

pure (2d) gauge



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

Intrinsic (un-integrated) gluon distribution at small x



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***

Observables

DIS:

structure functions (inclusive and diffractive)
single and double particle production

PA (dilute-dense):

multiplicities
single and double inclusive spectra

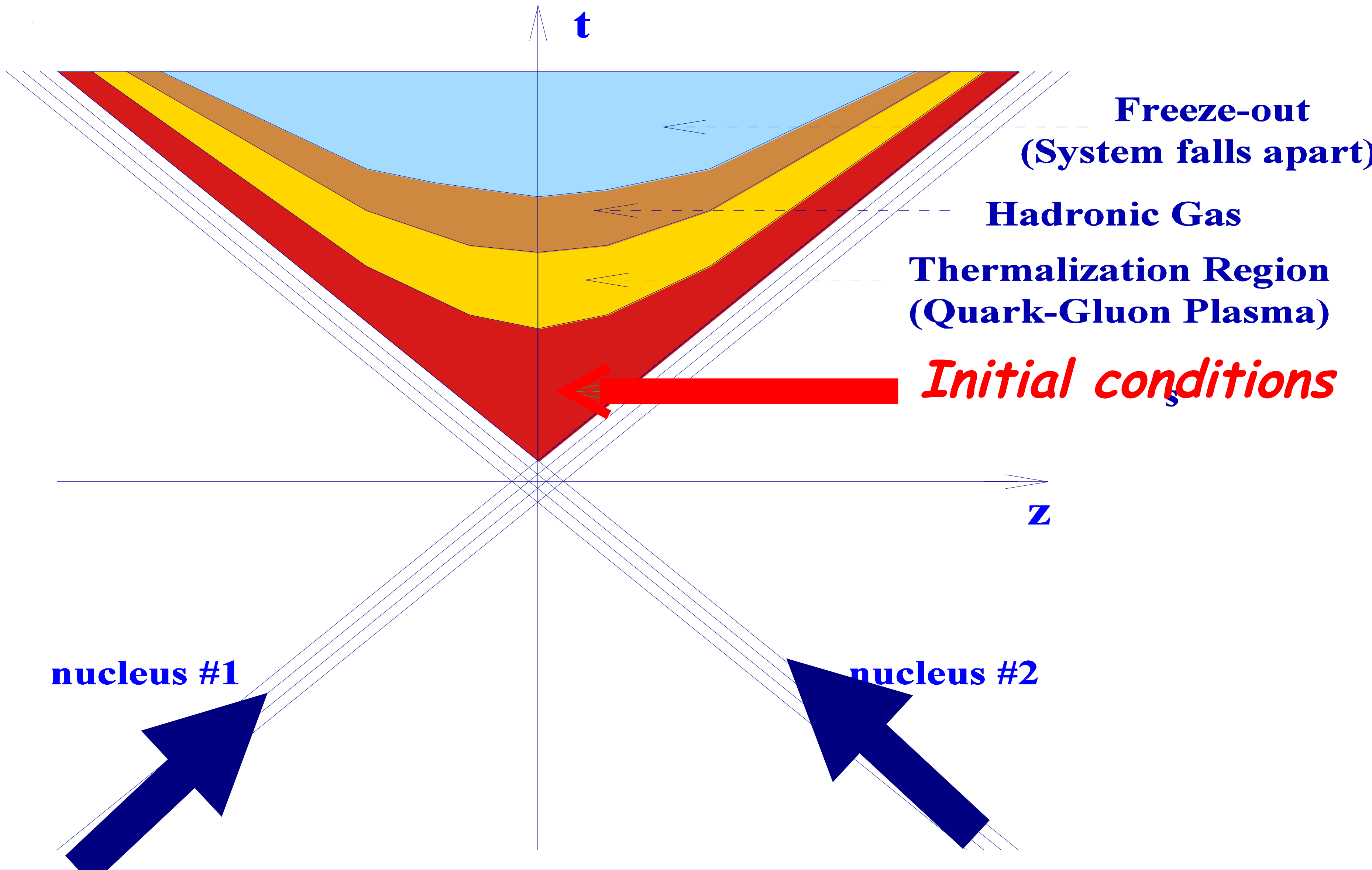
talk by
C. Marquet

AA, pp (dense-dense):

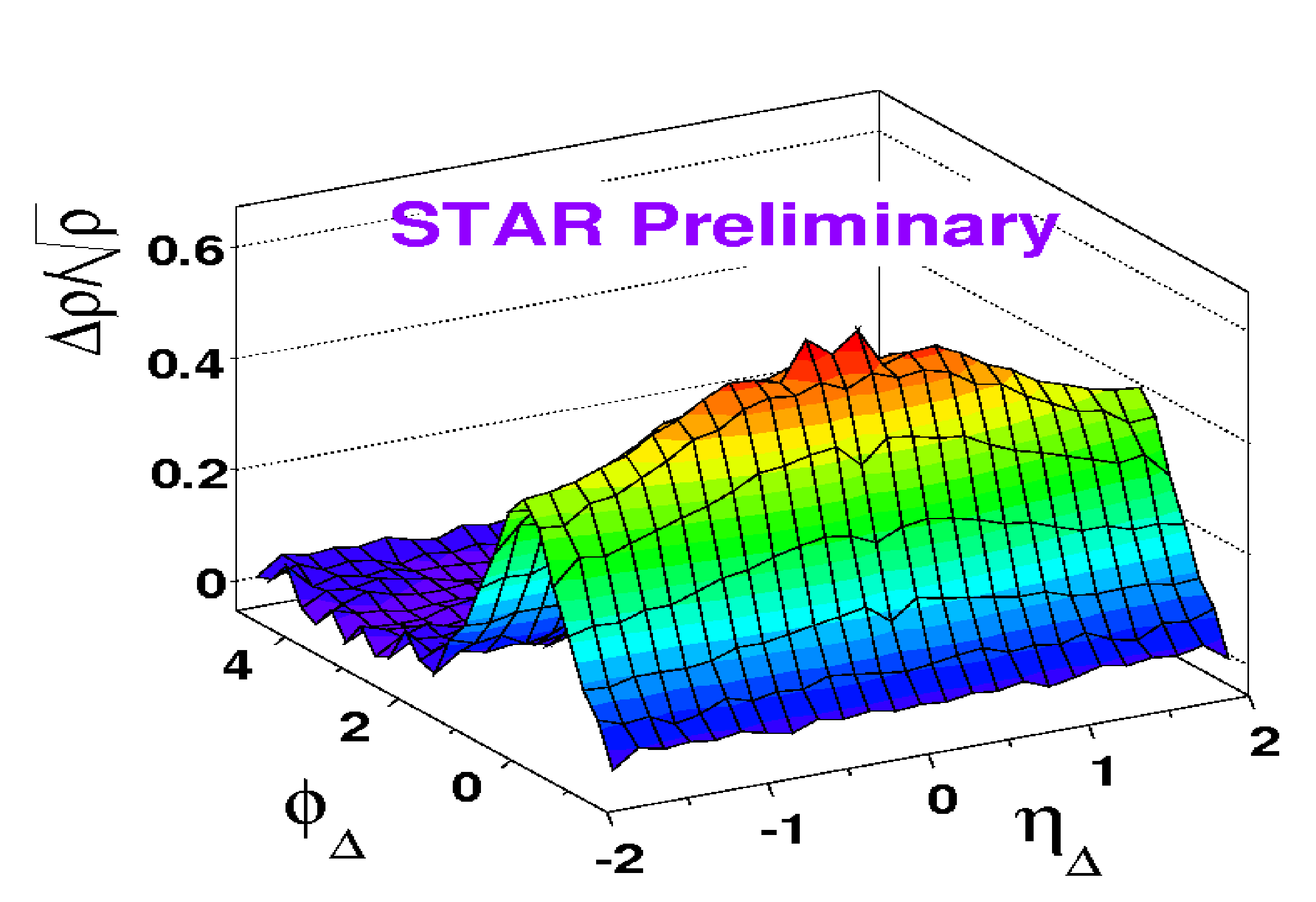
multiplicities, spectra
near-side long range rapidity correlation

RIDGE

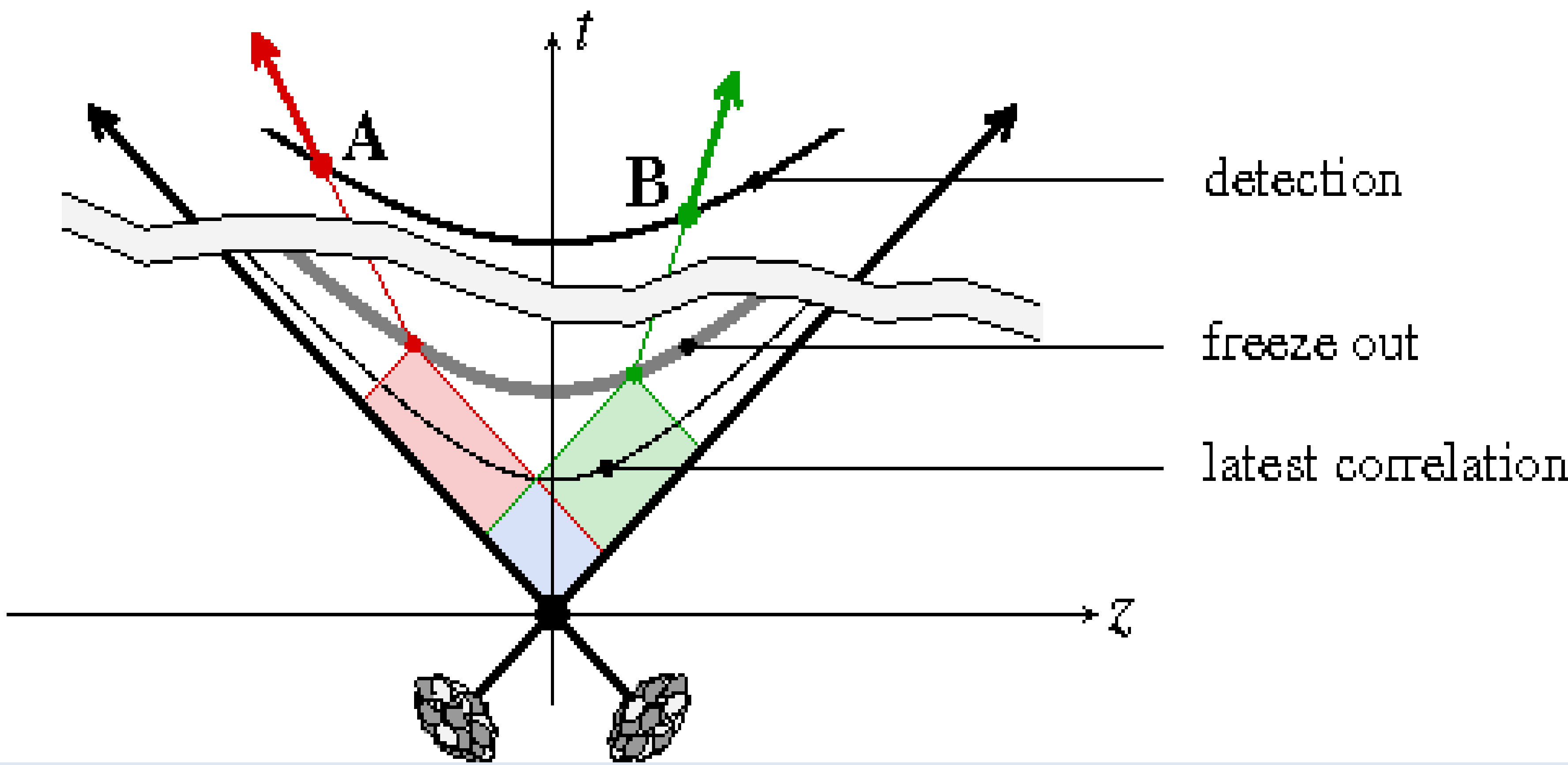
Space-Time History of a Heavy Ion Collision



Ridge in AA
(near-side long-range rapidity correlations)



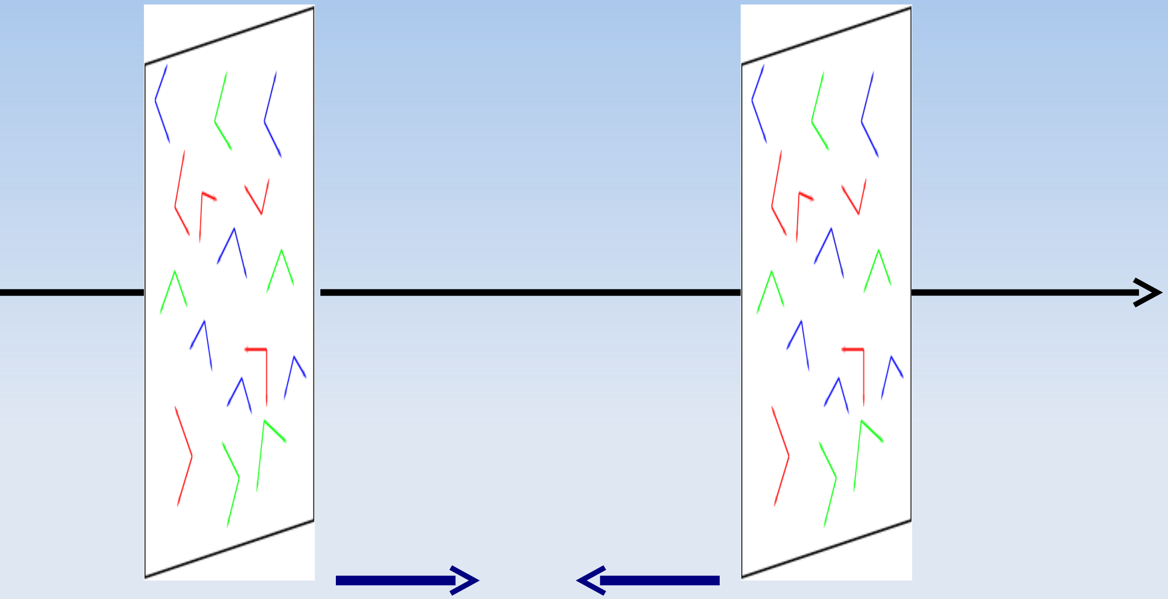
long-range rapidity correlations

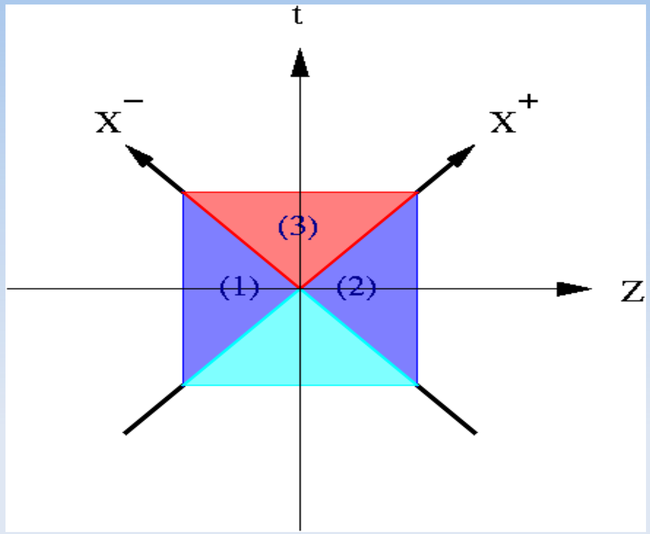


$$\tau \leq \tau_{\mathrm{fo}}\, e^{-\frac{1}{2}|y_A - y_B|}$$

DGMV: NPA810 (2008) 91, DGLV:NPA836 (2010) 159

Colliding Sheets of Color Glass





before the collision:

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

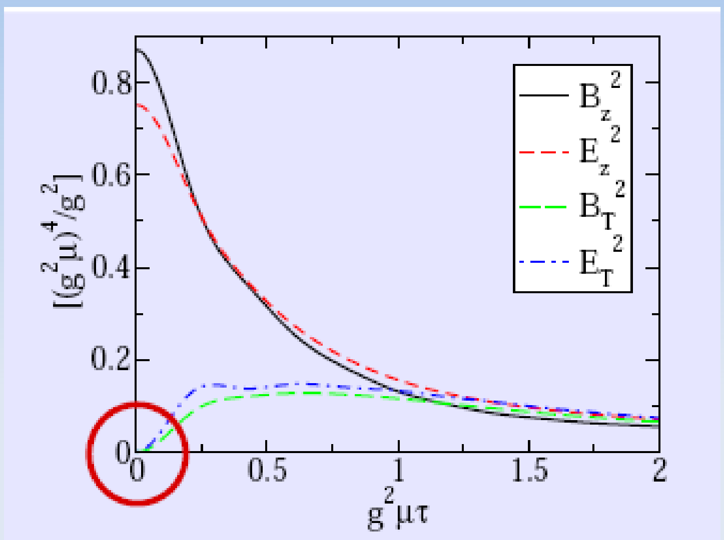
after the collision:

solve for A_μ

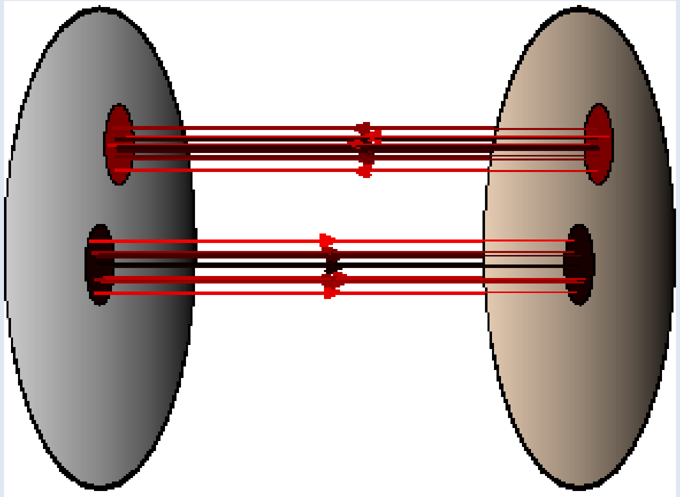
in the forward LC

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 $\sim \frac{1}{Q_s}$

Two-gluon correlation

$$C(p_\perp, q_\perp) = \frac{g^4}{64(2\pi)^6} \left(f_{abc} f_{a'\bar{b}\bar{c}} f_{a\hat{b}\hat{c}} f_{a'\tilde{b}\tilde{c}}\right) \int \prod_{i=1}^{4} \frac{d^2 k_{i\perp}}{(2\pi)^2}$$

$$L_\mu(p_\perp, k_{1\perp}) L^\mu(p_\perp, k_{2\perp}) L_\nu(q_\perp, k_{3\perp}) L^\nu(q_\perp, k_{4\perp})$$

$$\left\langle {\alpha^*}_1^{\hat{b}}(k_{2\perp}) {\alpha^*}_1^{\tilde{b}}(k_{4\perp}) {\alpha_1}^b(k_{1\perp}) {\alpha_1}^{\bar{b}}(k_{3\perp}) \right\rangle$$

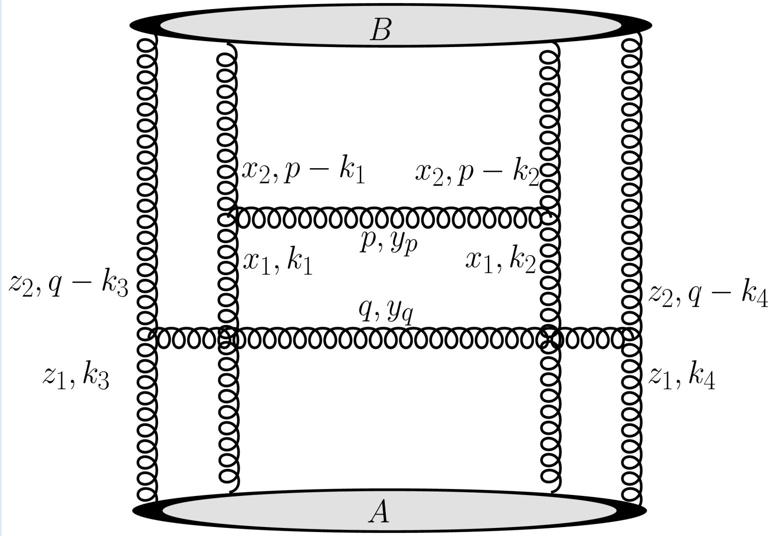
$$\left\langle {\alpha^*}_2^{\hat{c}}(p_\perp - k_{2\perp}) {\alpha^*}_2^{\tilde{c}}(q_\perp - k_{4\perp}) {\alpha_2}^c(p_\perp - k_{1\perp}) {\alpha_2}^{\bar{c}}(q_\perp - k_{3\perp}) \right\rangle$$

dilute region: 4-pt function of gluon fields

Gaussian averaging: $\mathbf{e}^{-\frac{\rho^2}{\mu^2}}$

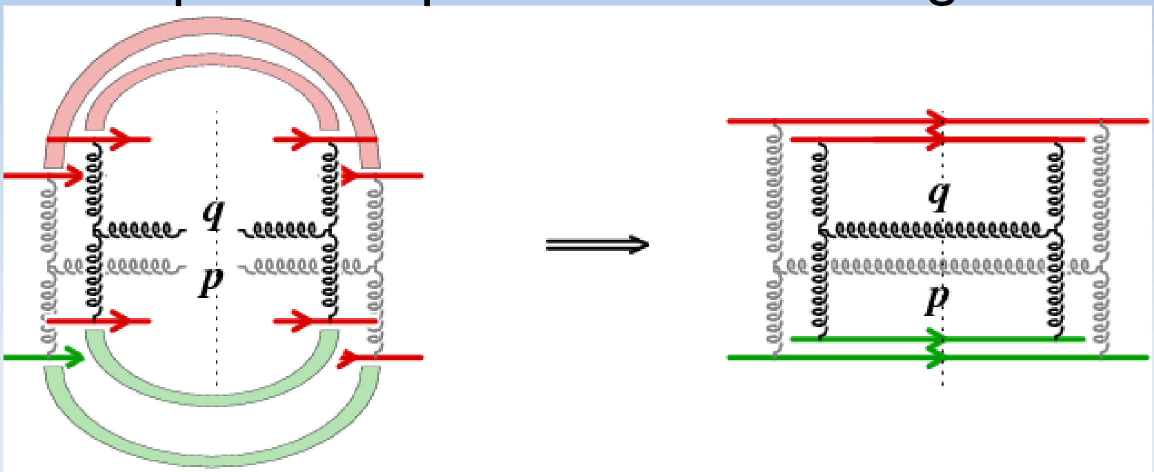
uncorrelated: 1 (single inclusive)^2

correlated: 8, suppressed by $\dfrac{1}{N_c^2 - 1}$



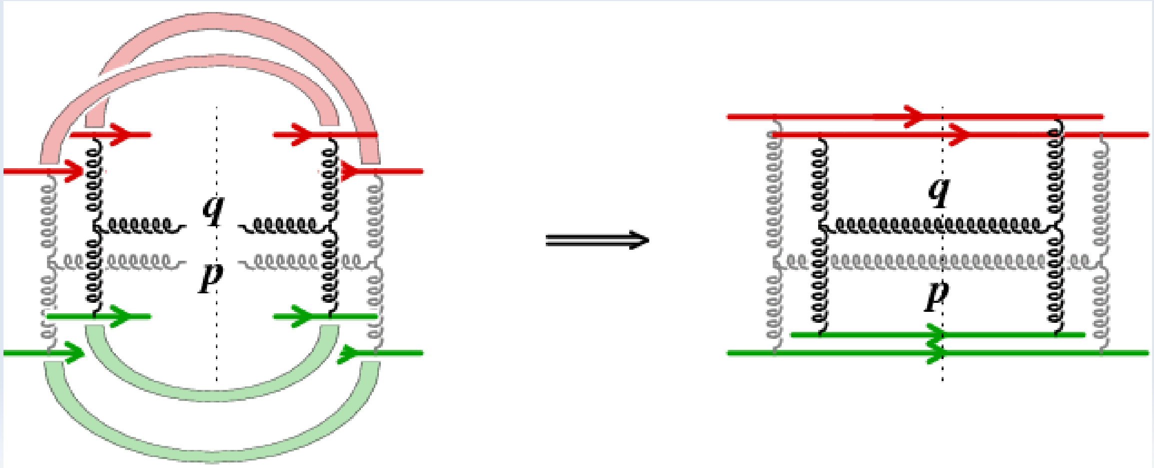
Two-gluon production in AA (pp)

Independent production of two gluons:



PYTHIA:
"independent multi-parton interactions"

Correlated two-gluon production:



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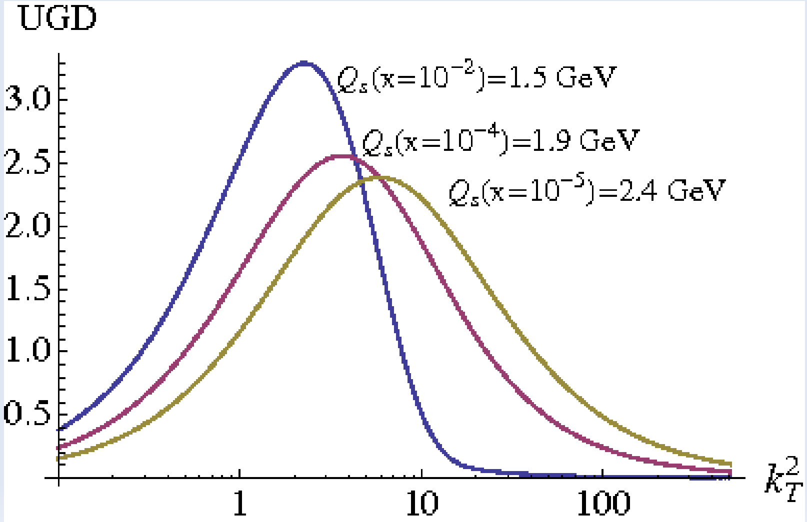
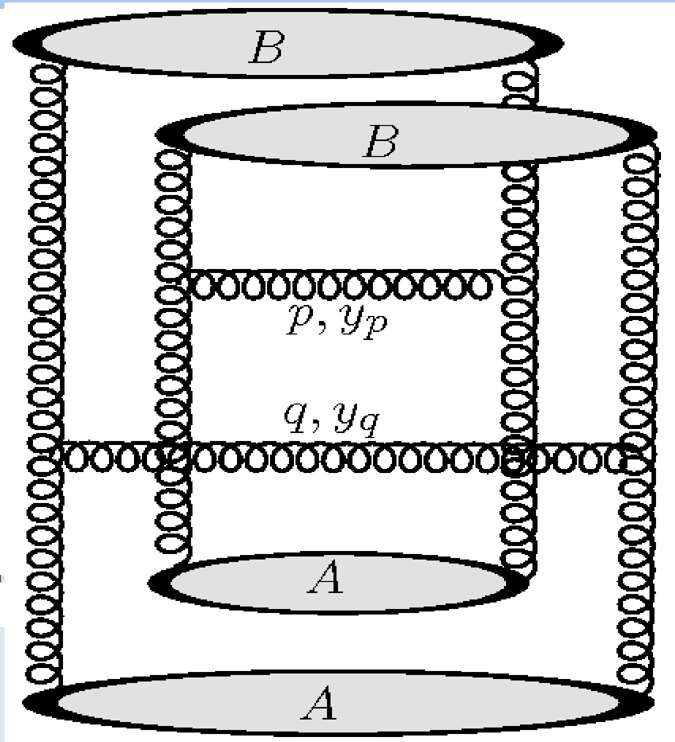
Two-gluon production in AA (pp)

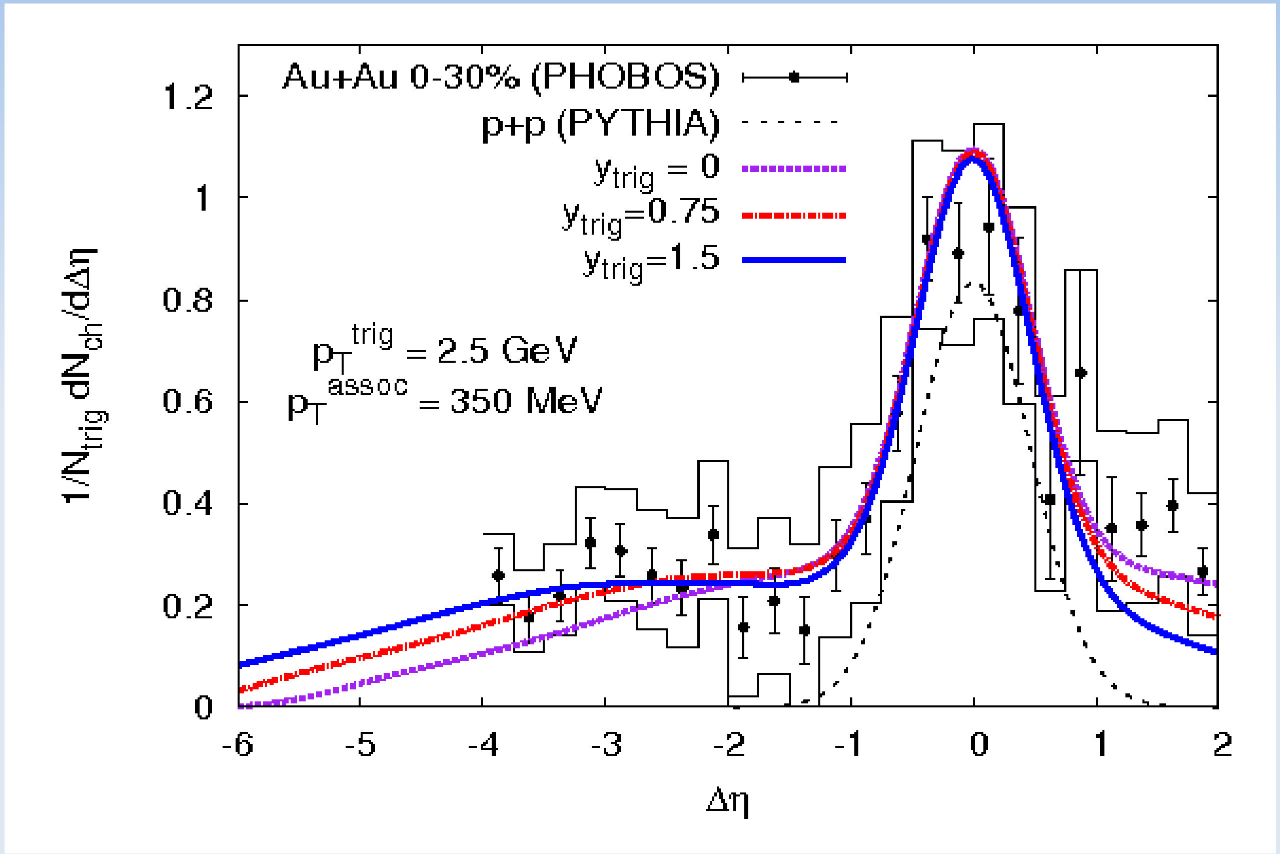
$$\frac{dN_2}{d^2p_\perp dy_p d^2q_\perp dy_q} = \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2 S_\perp}{(N_c^2-1)^3\, p_\perp^2 q_\perp^2}$$
$$\times \int d^2k_\perp \Big\{ \Phi_A^2(y_p, k_\perp)\Phi_B(y_p, p_\perp - k_\perp)$$
$$\times [\Phi_B(y_q, q_\perp + k_\perp) + \Phi_B(y_q, q_\perp - k_\perp)]$$
$$+\Phi_B^2(y_q, k_\perp)\Phi_A(y_p, p_\perp - k_\perp)$$
$$\times [\Phi_A(y_q, q_\perp + k_\perp) + \Phi_A(y_q, q_\perp - k_\perp)] \Big\}$$





solutions of rcBK
angular collimation

Ridge in AA



CGC glasma flux tubes

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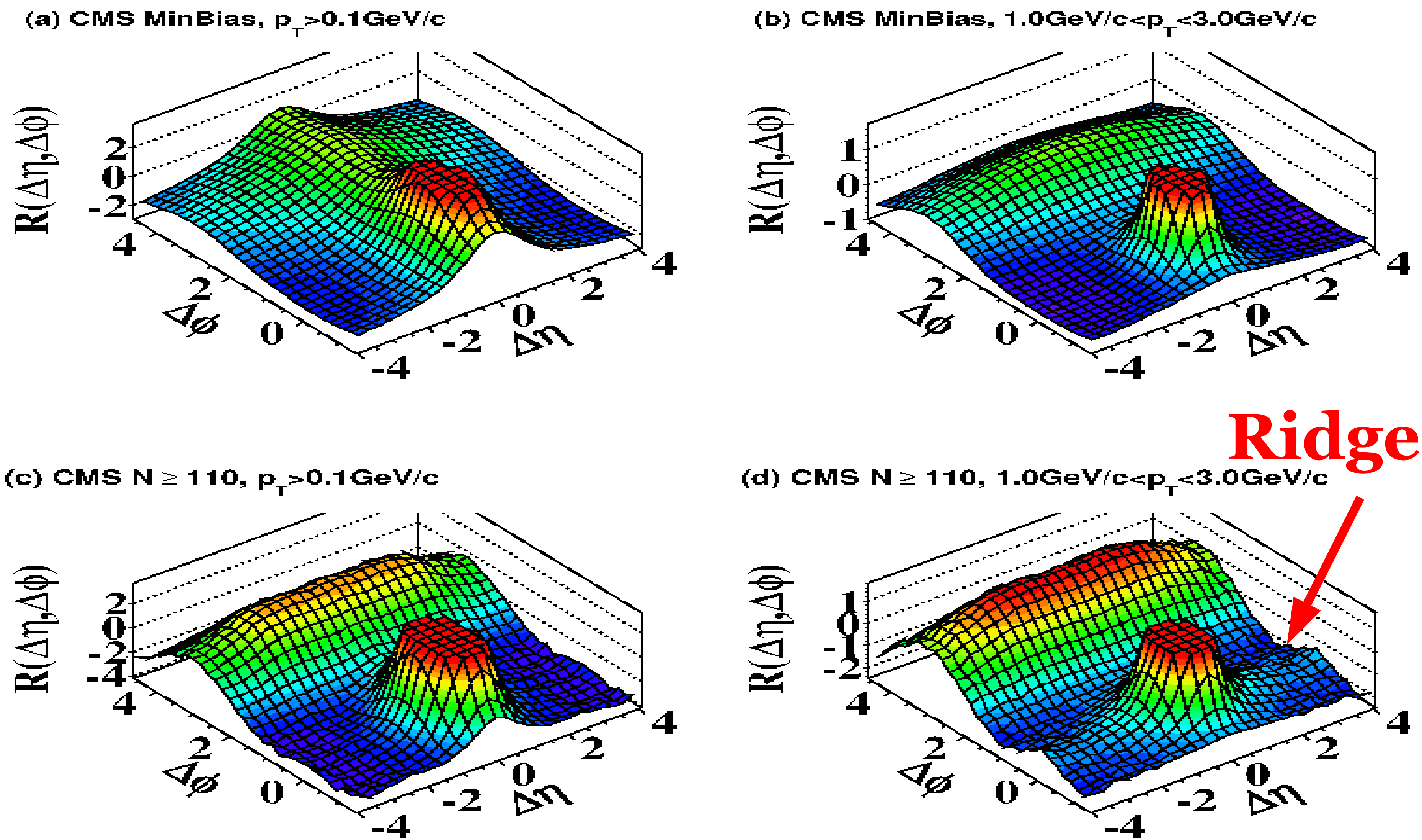
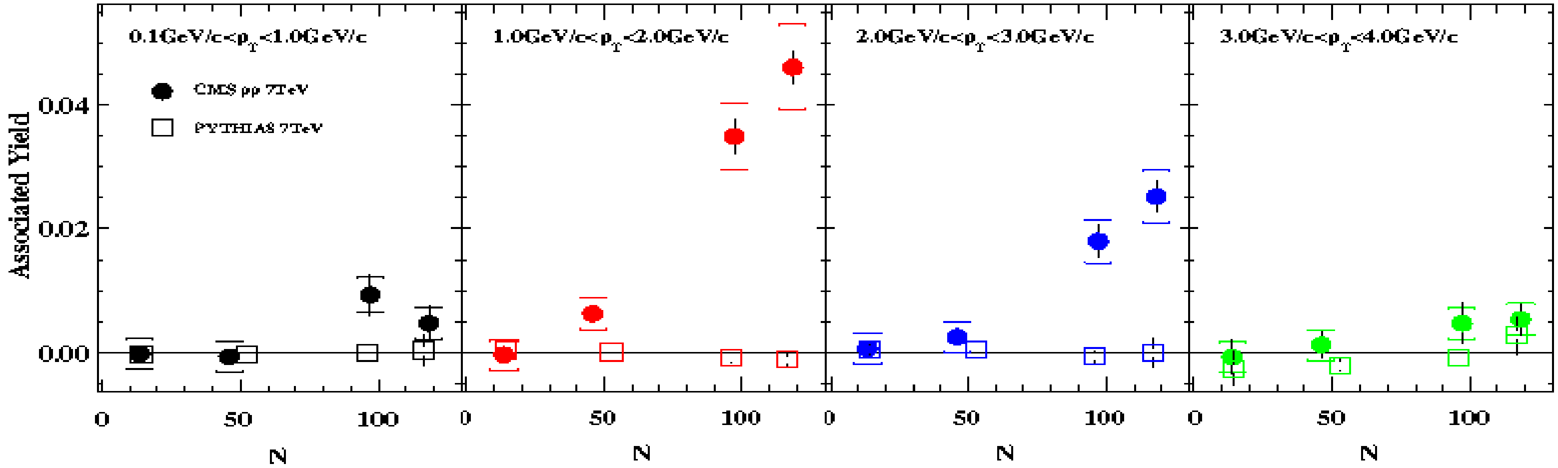
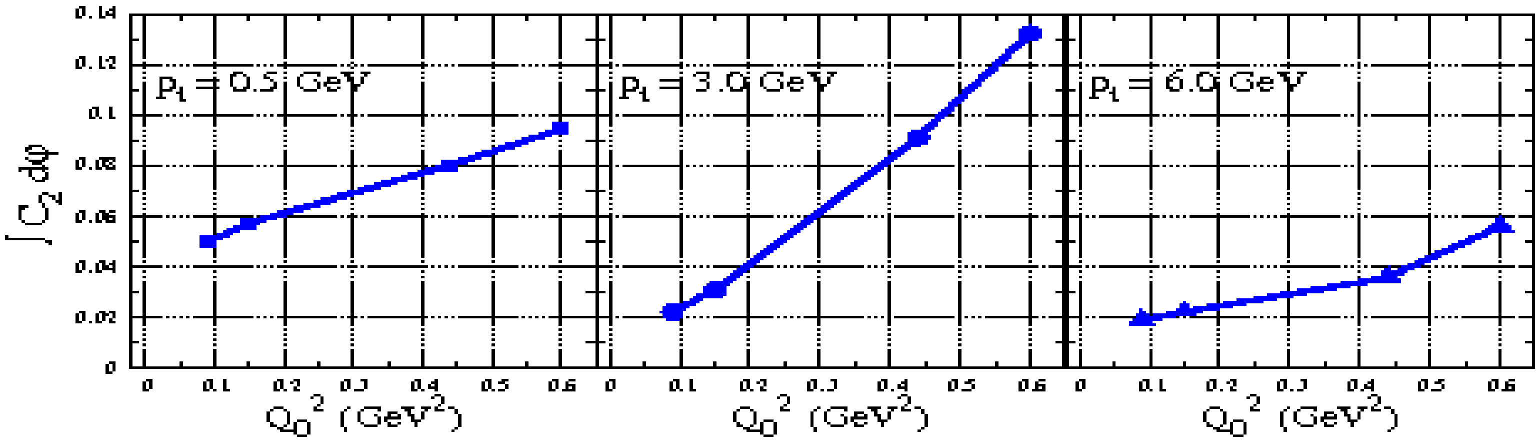
Azimuthal angle dependence <u>enhanced</u> by radial flow in QGP

The CMS ridge at LHC



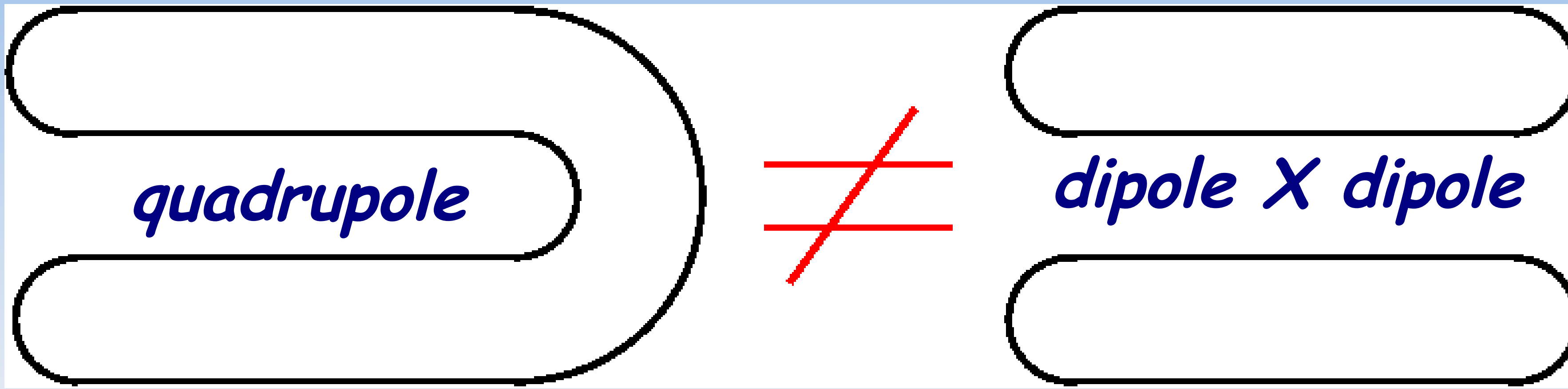
The CMS ridge at LHC



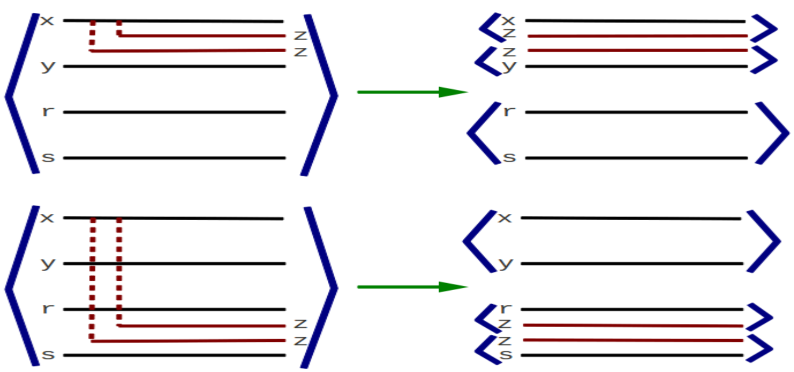


DDGJLV, PLB697 (2011) 21

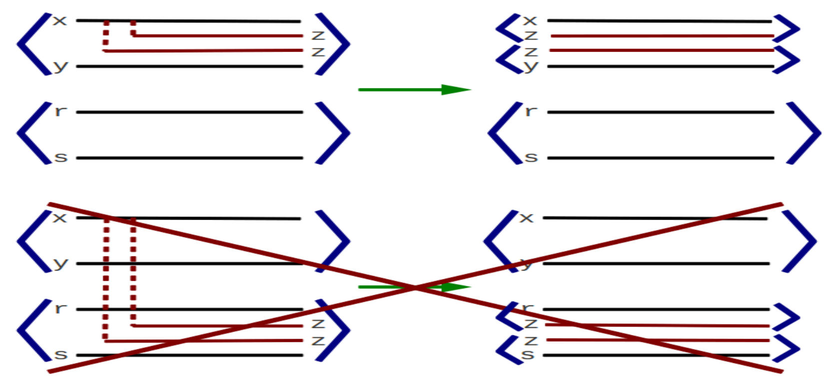
Beyond dipole + large N_c approximation



and they evolve differently even at large N_c



JIMWLK



Dipole approximation

Evolution of gluon 4-pt function

$$\frac{d}{dY}\,\langle\alpha^a_r\alpha^b_{\bar r}\alpha^c_s\alpha^d_{\bar s}\rangle = \frac{g^2N_c}{(2\pi)^3}\int d^2z$$

$$\left\langle \frac{\alpha^a_z\alpha^b_{\bar r}\alpha^c_s\alpha^d_{\bar s}}{(r-z)^2} + \frac{\alpha^a_r\alpha^b_z\alpha^c_s\alpha^d_{\bar s}}{(\bar r-z)^2} + \frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_z\alpha^d_{\bar s}}{(s-z)^2} + \frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_s\alpha^d_z}{(\bar s-z)^2} - 4\,\frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_s\alpha^d_{\bar s}}{z^2}\right\rangle$$

$$+\frac{g^2}{\pi}\int\frac{d^2z}{(2\pi)^2}$$

$$\Big\langle f^{e\kappa a}f^{f\kappa b}\frac{(r-z)\cdot(\bar r-z)}{(r-z)^2(\bar r-z)^2}\left[\alpha^e_r\alpha^f_{\bar r}-\alpha^e_r\alpha^f_z-\alpha^e_z\alpha^f_{\bar r}+\alpha^e_z\alpha^f_z\right]\alpha^c_s\alpha^d_{\bar s}$$

$$+f^{e\kappa a}f^{f\kappa c}\frac{(r-z)\cdot(s-z)}{(r-z)^2(s-z)^2}\left[\alpha^e_r\alpha^f_s-\alpha^e_r\alpha^f_z-\alpha^e_z\alpha^f_s+\alpha^e_z\alpha^f_z\right]\alpha^b_{\bar r}\alpha^d_{\bar s}$$

$$+f^{e\kappa a}f^{f\kappa d}\frac{(r-z)\cdot(\bar s-z)}{(r-z)^2(\bar s-z)^2}\left[\alpha^e_r\alpha^f_{\bar s}-\alpha^e_r\alpha^f_z-\alpha^e_z\alpha^f_{\bar s}+\alpha^e_z\alpha^f_z\right]\alpha^b_{\bar r}\alpha^c_s$$

$$+f^{e\kappa b}f^{f\kappa c}\frac{(\bar r-z)\cdot(s-z)}{(\bar r-z)^2(s-z)^2}\left[\alpha^e_{\bar r}\alpha^f_s-\alpha^e_{\bar r}\alpha^f_z-\alpha^e_z\alpha^f_s+\alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^d_{\bar s}$$

$$+f^{e\kappa b}f^{f\kappa d}\frac{(\bar r-z)\cdot(\bar s-z)}{(\bar r-z)^2(\bar s-z)^2}\left[\alpha^e_{\bar r}\alpha^f_{\bar s}-\alpha^e_{\bar r}\alpha^f_z-\alpha^e_z\alpha^f_{\bar s}+\alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^c_s$$

$$+\,f^{e\kappa c}f^{f\kappa d}\frac{(s-z)\cdot(\bar s-z)}{(s-z)^2(\bar s-z)^2}\left[\alpha^e_s\alpha^f_{\bar s}-\alpha^e_s\alpha^f_z-\alpha^e_z\alpha^f_{\bar s}+\alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^b_{\bar r}\Big\rangle$$

dipole approximation breaks down!

AD-JJM, PRD81:094015 (2010)

JIMWLK: Beyond dipole + large Nc

2-hadron correlations poses new challenges to CGC
but
every challenge can become an opportunity

How large are the terms missed by dipole approximation ?

What is their energy dependence ?

What is the role of non-Gaussian (quartic) initial conditions ?

need to solve JIMWLK equation

Two-hadron correlations

qualitative **agreement with CGC predictions**

A *quantitative* description of two-hadron correlation requires going beyond dipole approximation in CGC framework