Multi(3)-particle production in DIS at small x

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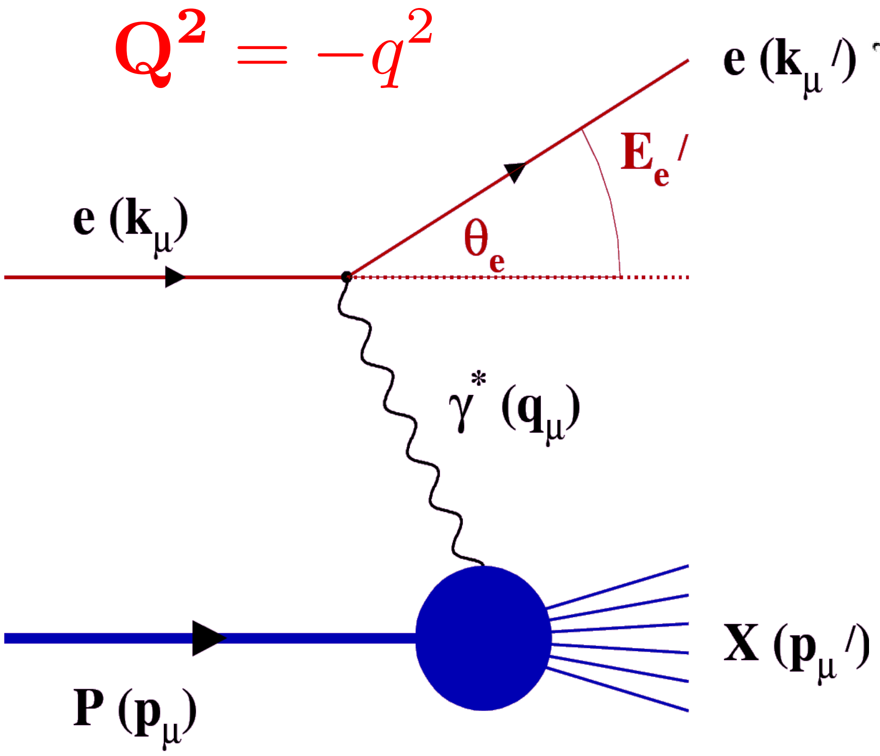
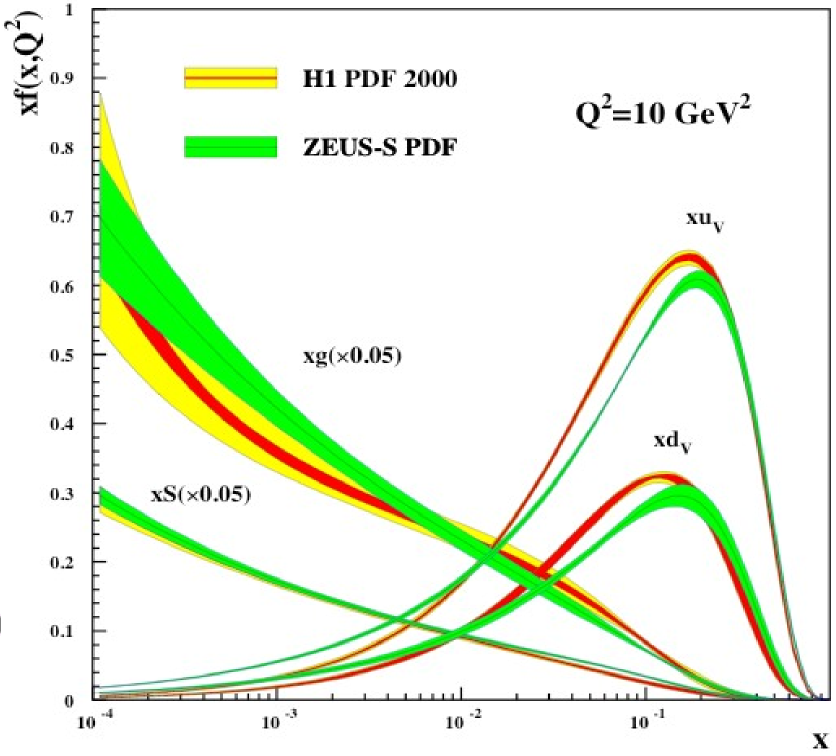
DIS at HERA: parton distributions



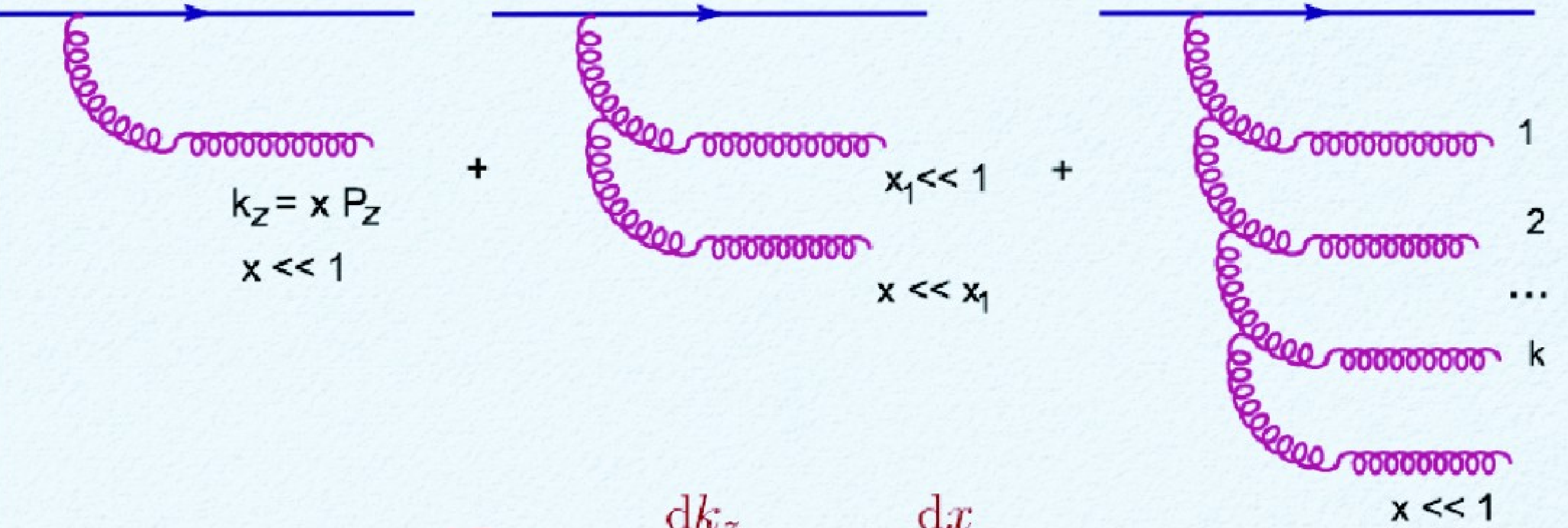


power-like growth of gluon and sea quark distributions with x

new QCD dynamics at small x?

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:

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

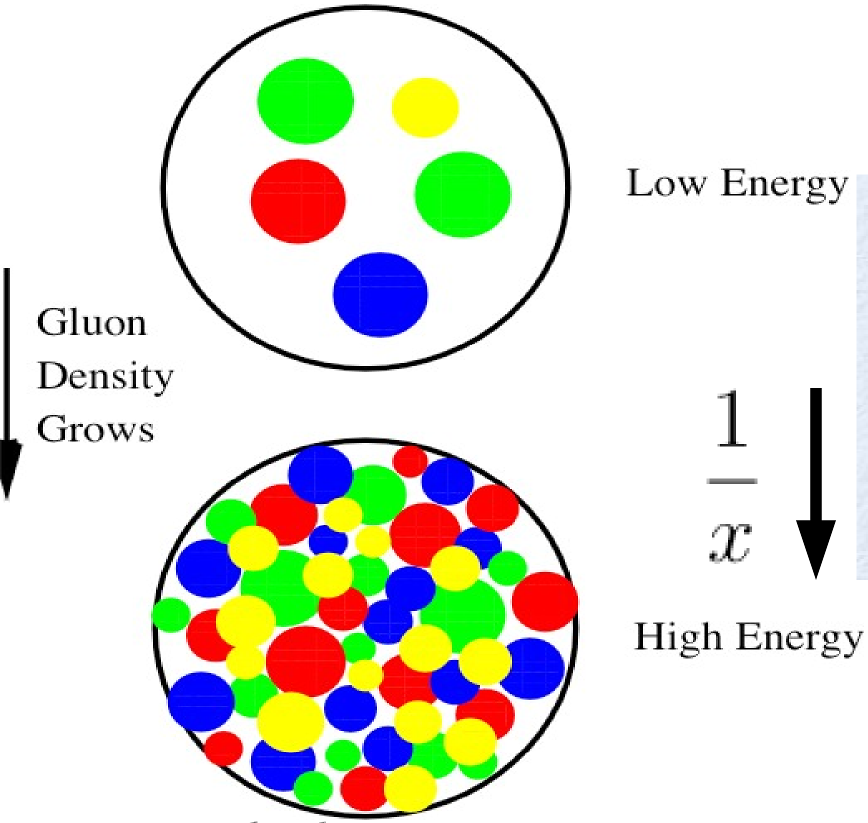
number of gluons grows fast

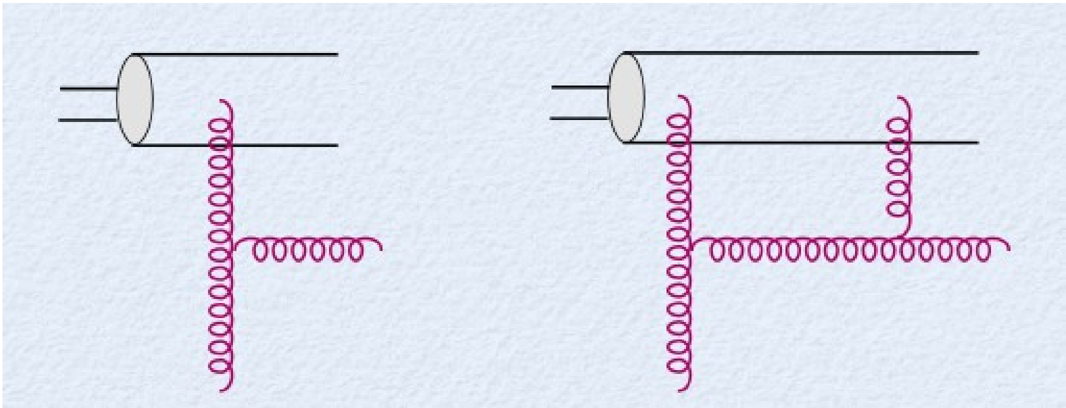
$$n \sim e^{\alpha_s ln 1/x}$$

Gluon saturation

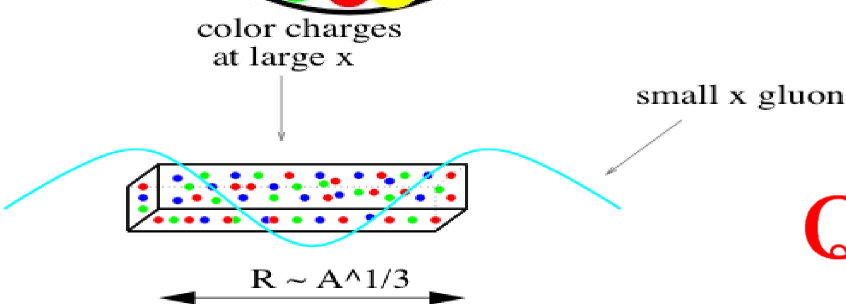
Gribov-Levin-Ryskin
Mueller-Qiu

"attractive" bremsstrahlung vs.
"repulsive" recombination



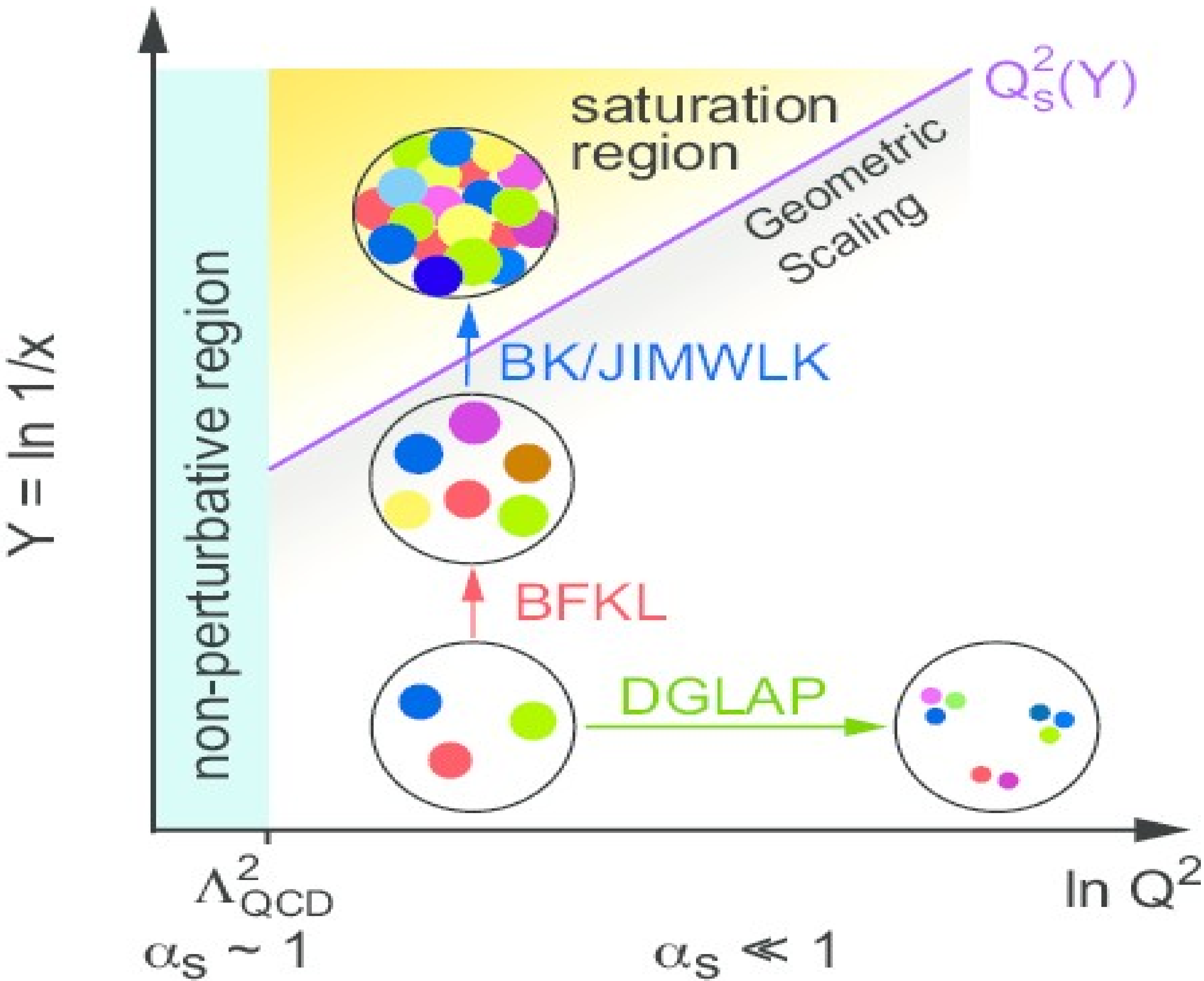


$$\frac{\alpha_s}{Q^2}\,\frac{xG(x, b_t, Q^2)}{S_\perp} \sim 1$$

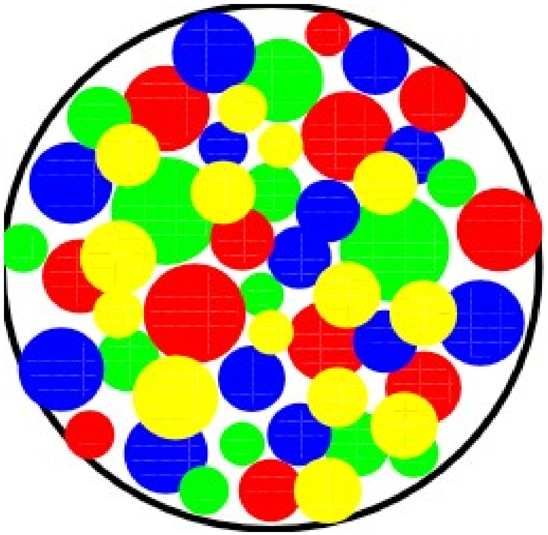


$$Q_s^2(x, b_t, A) \sim A^{1/3}\,\left(\frac{1}{x}\right)^{0.3}$$

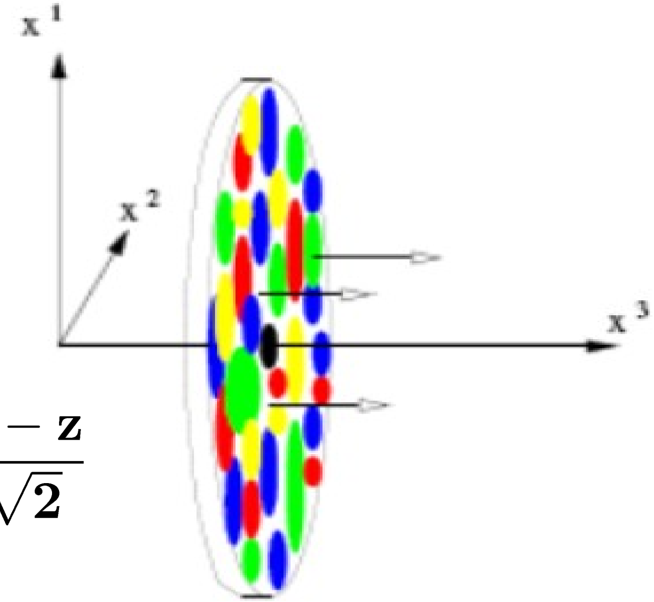
A proton at high energy: saturation



Large A is cheaper than high energy



boost



$$\mathbf{x}^+ \equiv \frac{\mathbf{t+z}}{\sqrt{\mathbf{2}}} \qquad \mathbf{x}^- \equiv \frac{\mathbf{t-z}}{\sqrt{\mathbf{2}}}$$

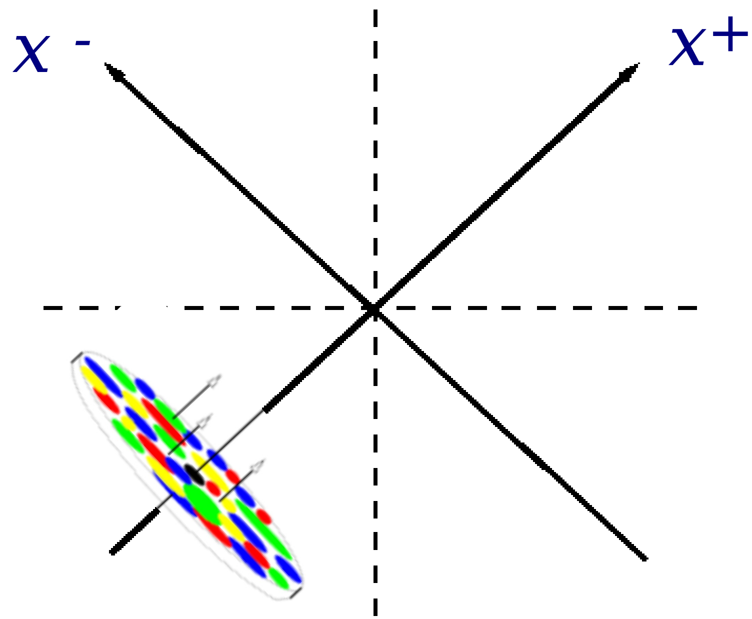
sheet of color charge moving along x^+ and sitting at $x^- = 0$

$$\mathbf{J}^{\mu}_{\mathbf{a}}(\mathbf{x}) \equiv \delta^{\mu\,+}\,\delta(\mathbf{x}^-)\,\rho_{\mathbf{a}}(\mathbf{x_t})$$

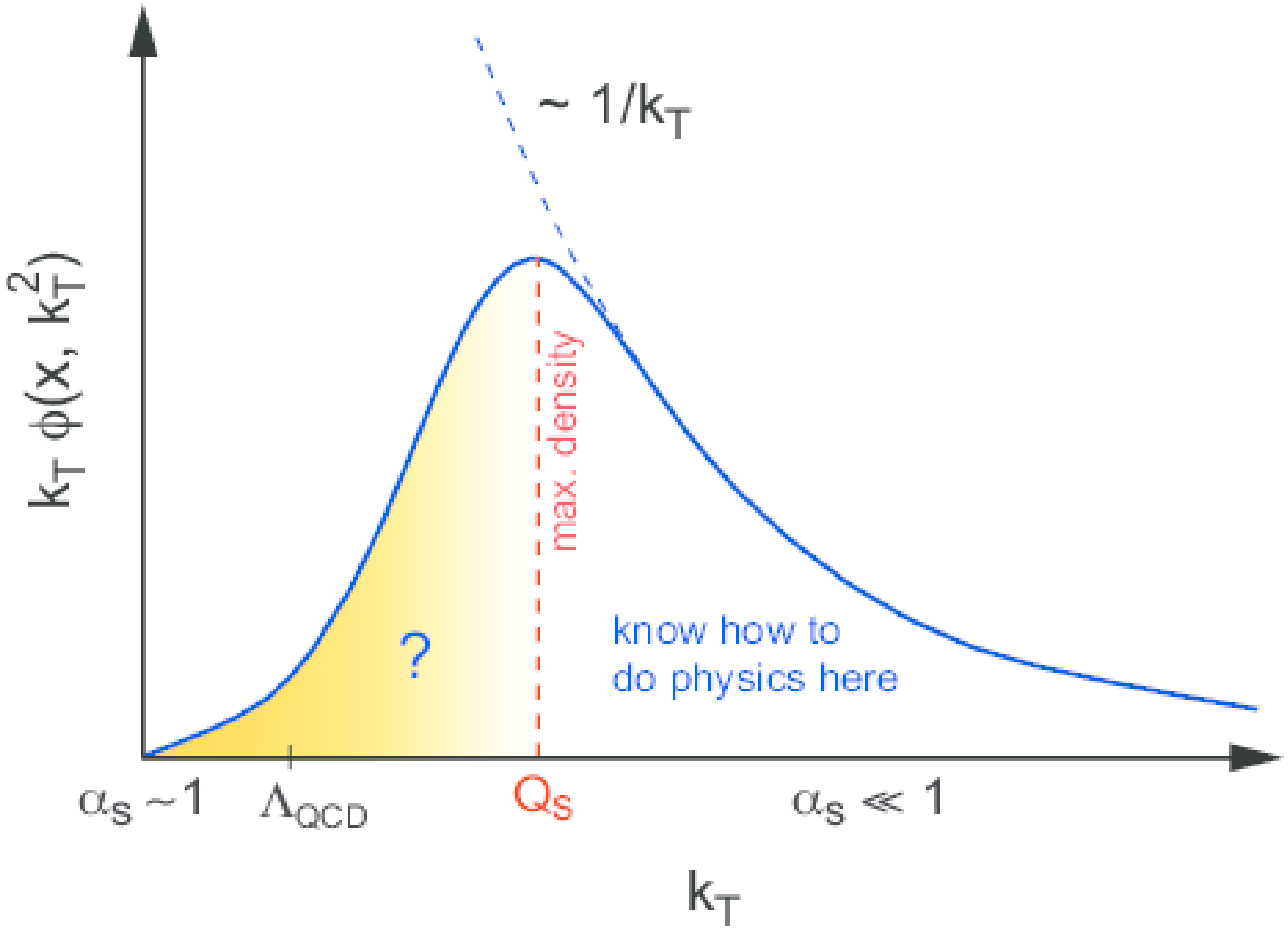
color current *color charge*

$$\mathbf{A}^{+}_{\mathbf{a}}(\mathbf{z}^-, \mathbf{z_t}) = \delta(\mathbf{z}^-)\,\alpha_{\mathbf{a}}(\mathbf{z_t})$$

with $\partial_t^2\,\alpha_a(z_t) = g\rho_a(z_t)$



typical momentum of small x gluons: Q_s^2



one can compute parton multiplicities

low x QCD in a background field: CGC

(a high gluon density environment)

two main effects:

*"multiple scatterings" encoded in classical field (**p_t broadening**)*

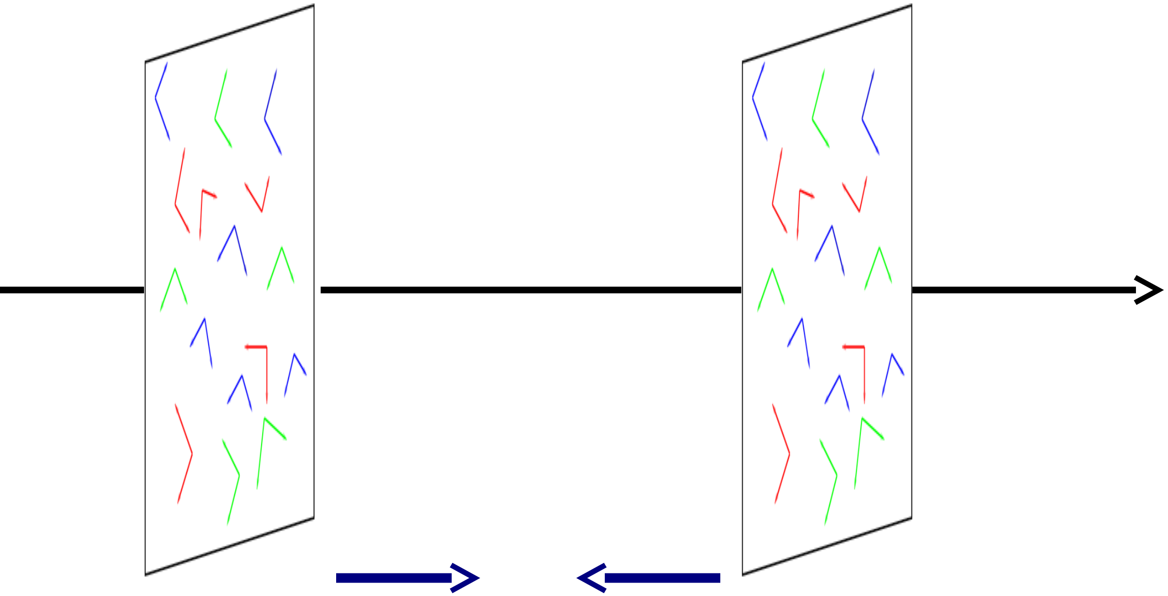
*evolution with ln (1/x) a la BK/JIMWLK equation (**suppression**)*

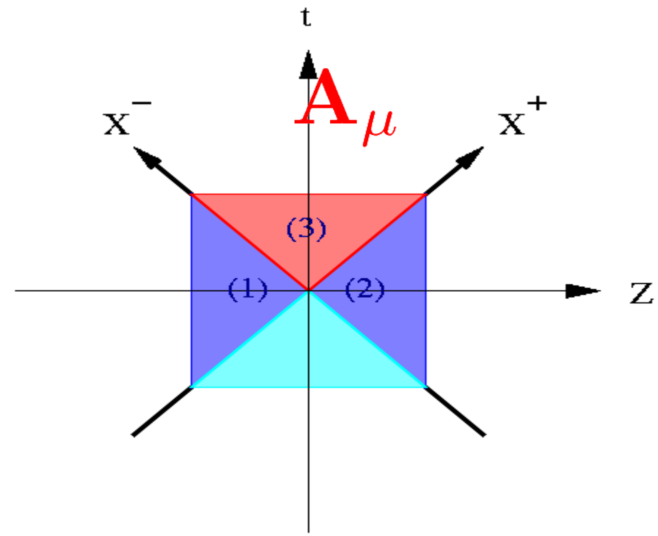
LT pQCD with collinear factorization:

single scattering

evolution with ln Q^2

High energy collisions:
colliding Sheets of Color Glass Condensates





before the collision:

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

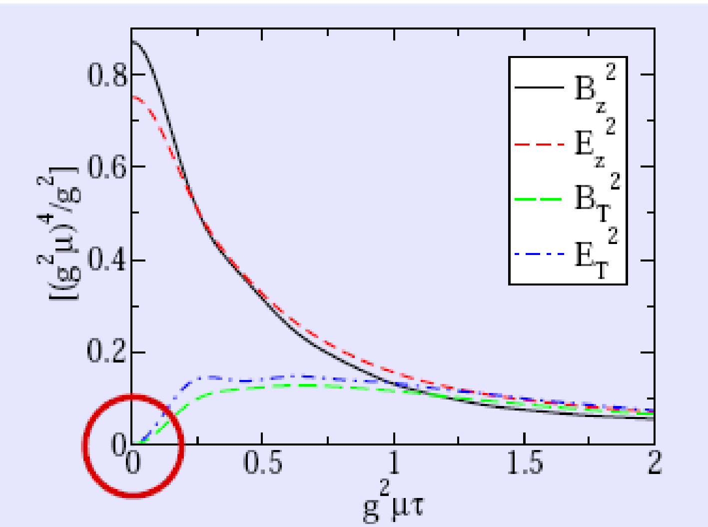
after the collision:

solve for $\mathbf{A}_\mu$

in the forward LC

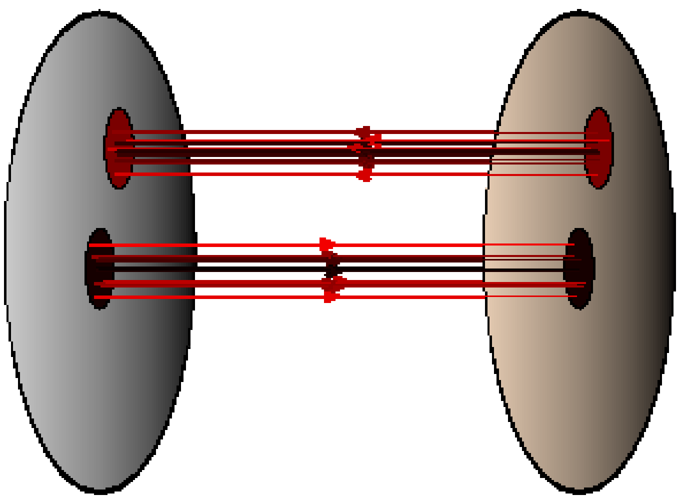
GLASMA:

gluon fields produced in collision of two sheets of color glass



early on fields (E,B) are longitudinal

classical solutions are boost invariant

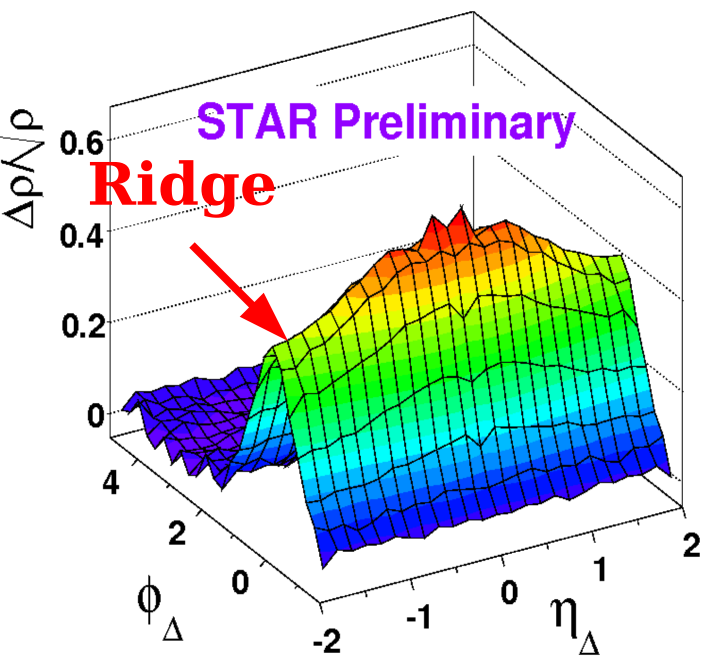


transverse size of these flux tubes is $\sim \frac{1}{Q_s}$

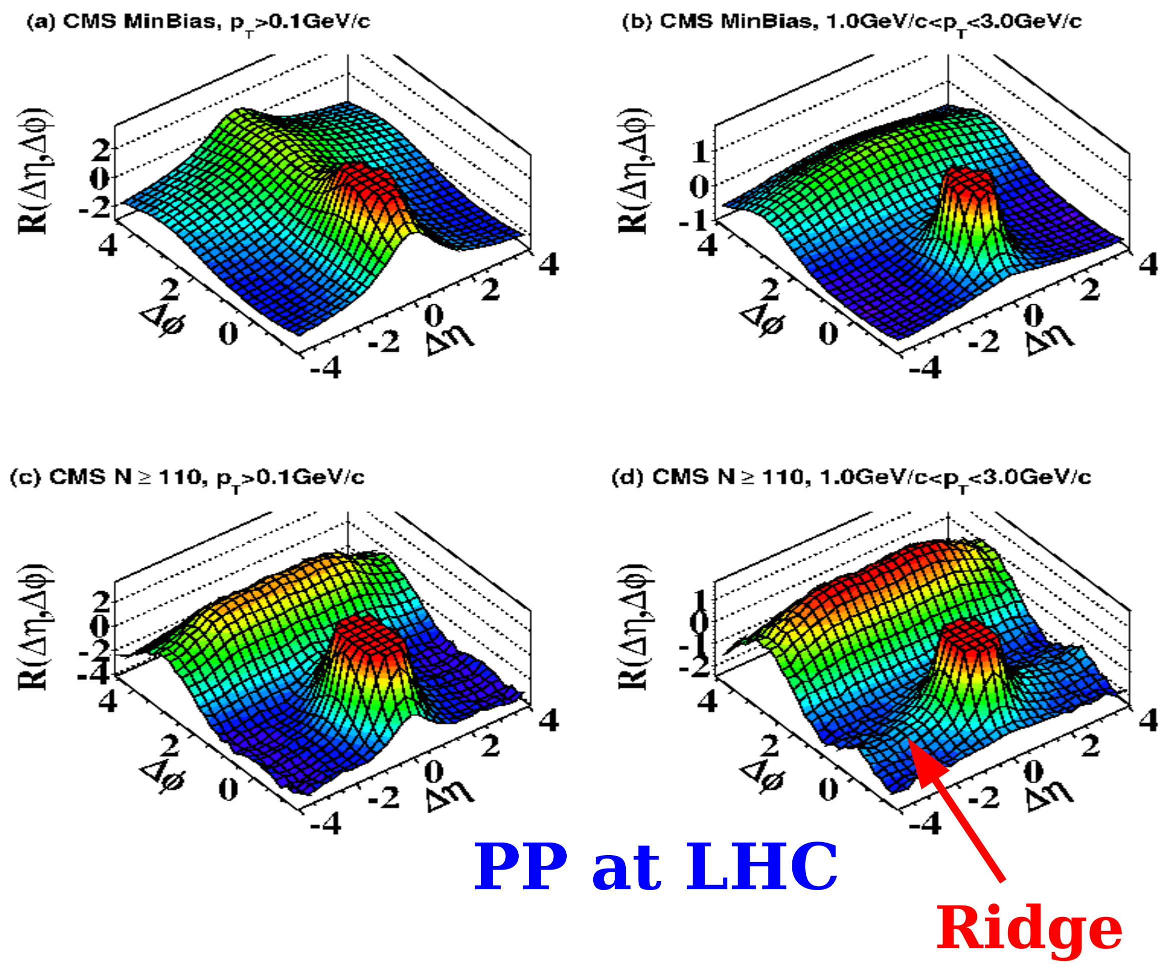
$$\frac{1}{A_\perp}\frac{dN}{d\eta} = \frac{0.3}{g^2}Q_s^2$$

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

long-range rapidity correlations: <u>the ridge</u>



AA at RHIC

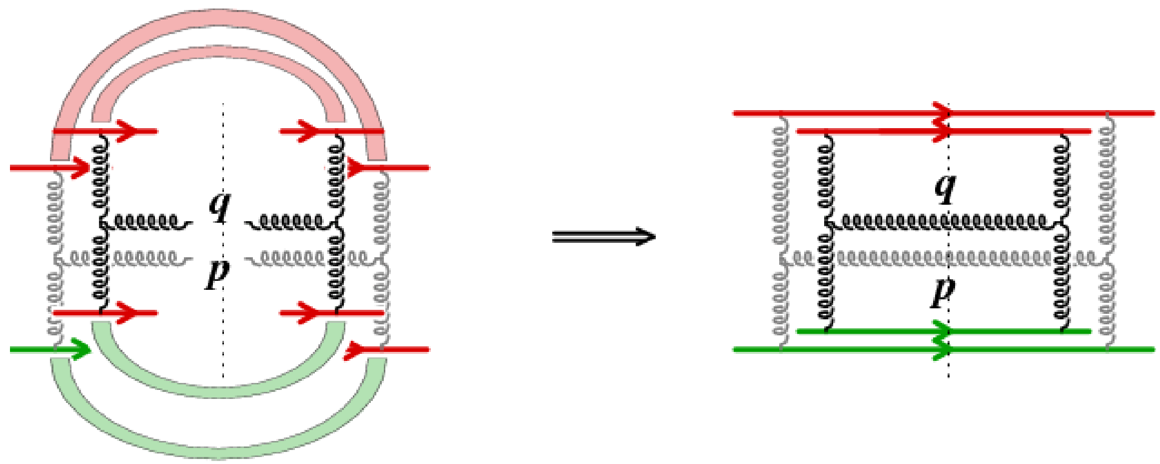


multi-gluon correlations:

<u>need to go beyond single parton distributions</u>

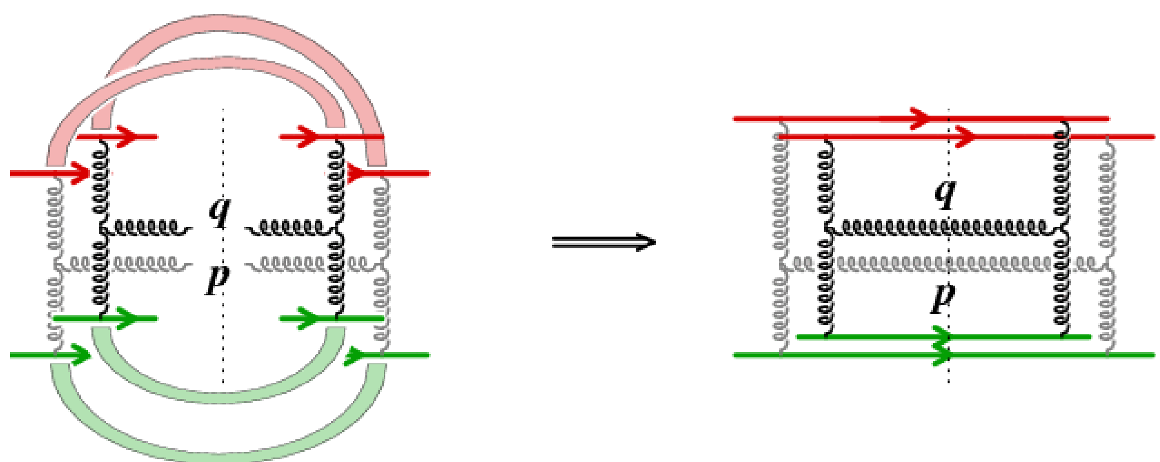
two-gluon production

Independent production of two gluons:



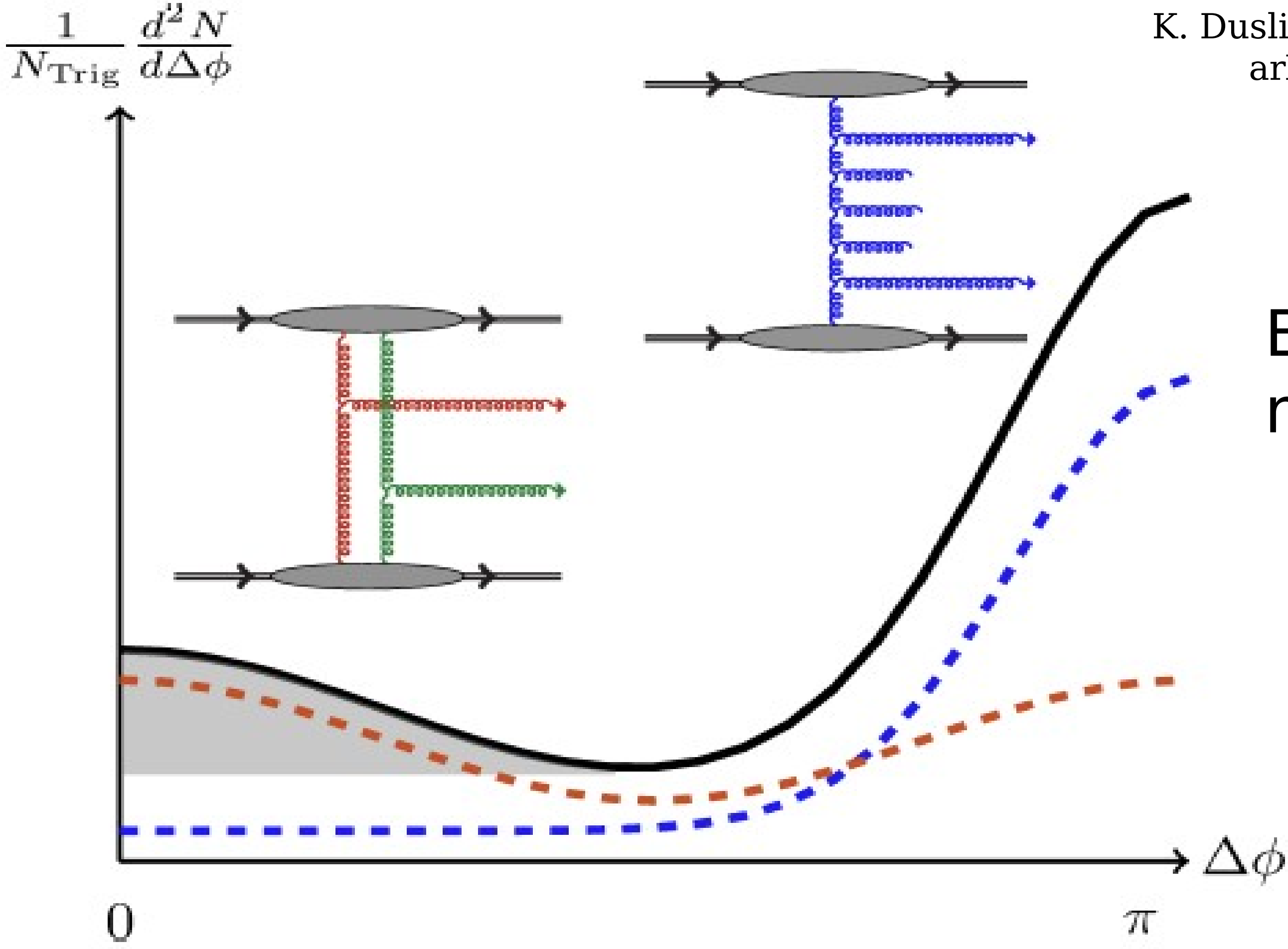
correlated two-gluon production:

DGMV:
NPA810 (2008) 91



Anatomy of long range di-hadron collimation

K. Dusling+R. Venugopalan
arXiv:1302.7018



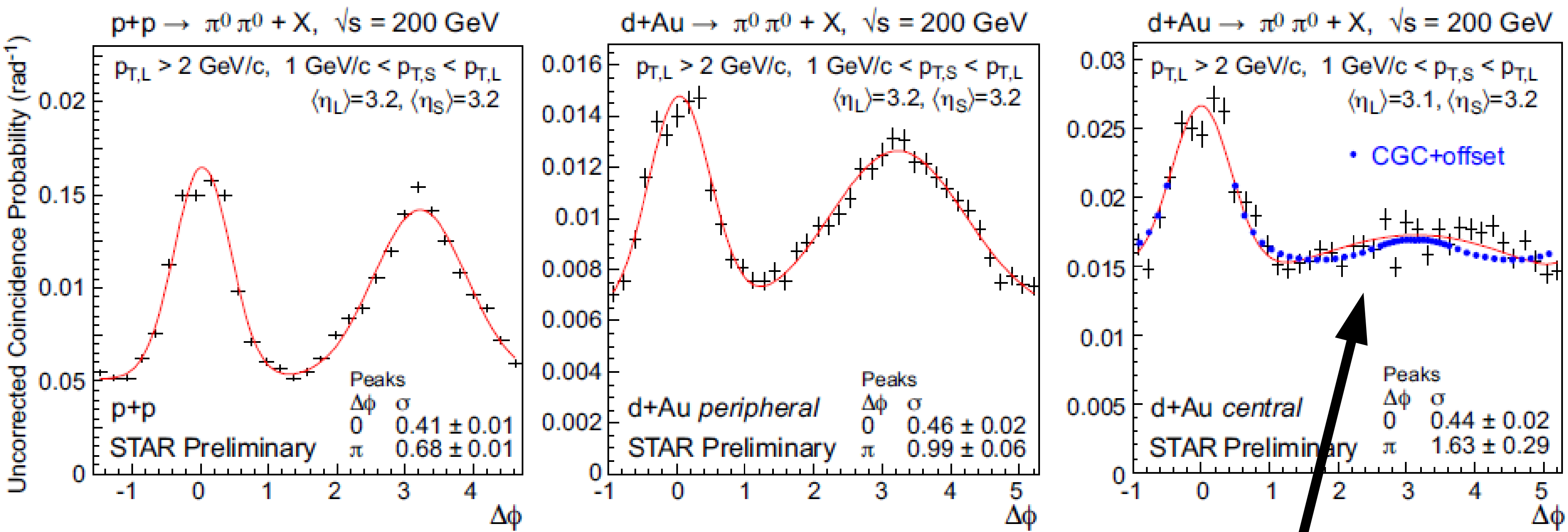
<u>**Talk by P. Tribedy**</u>

late time/medium effects?

A “simpler” system: di-hadron correlations in pA

Talk by E. Petreska

Recent STAR measurement (arXiv:1008.3989v1):



Marquet, NPA (2007), Albacete + Marquet, PRL (2010)
Tuchin, NPA846 (2010)
A. Stasto + B-W. Xiao + F. Yuan, PLB716 (2012)
T. Lappi + H. Mantysaari, NPA908 (2013)

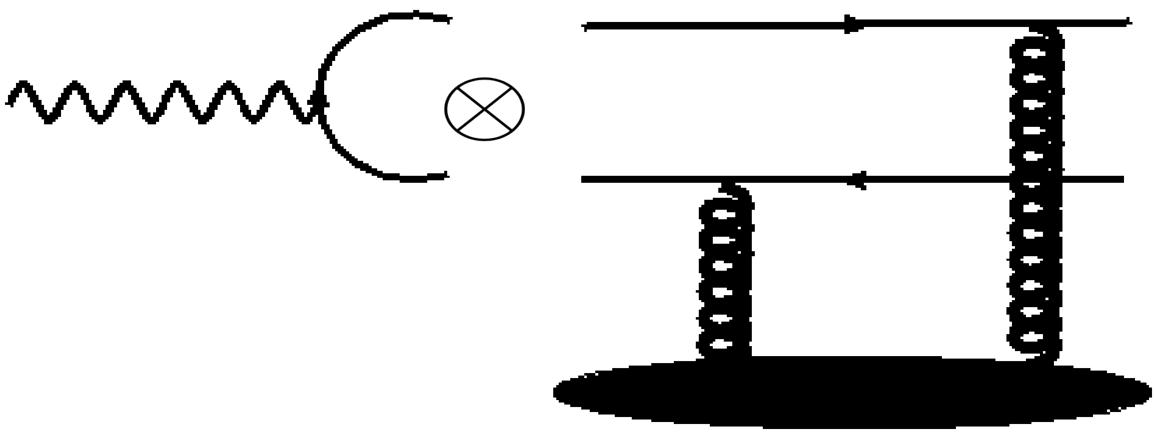
saturation effects de-correlate the hadrons

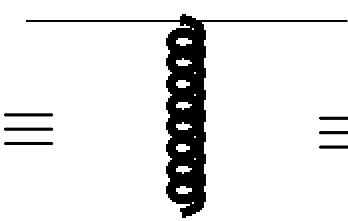
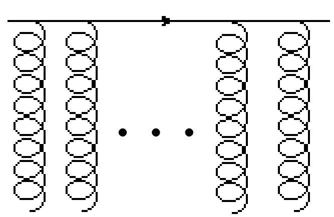
shadowing+energy loss: Z. Kang, I. Vitev, H. Xing, PRD85 (2012) 054024

DIS total cross section

$$\sigma_{\rm DIS}^{\rm total} = 2\int_0^1 dz \int d^2x_t\, d^2y_t \,\left|\Psi(k^{\pm}, k_t | z, x_t, y_t)\right|^2 T(x_t, y_t)$$

$$T(x_t, y_t) \equiv \frac{1}{N_c} \mathrm{Tr} \left\langle 1 - V(x_t) V^{\dagger}(y_t) \right\rangle$$



$V \equiv$  $\equiv$  $\sim 1 + O(g\,A) + O(g^2\,A^2)$

Wilson line encodes multiple scatterings from the color field of the target

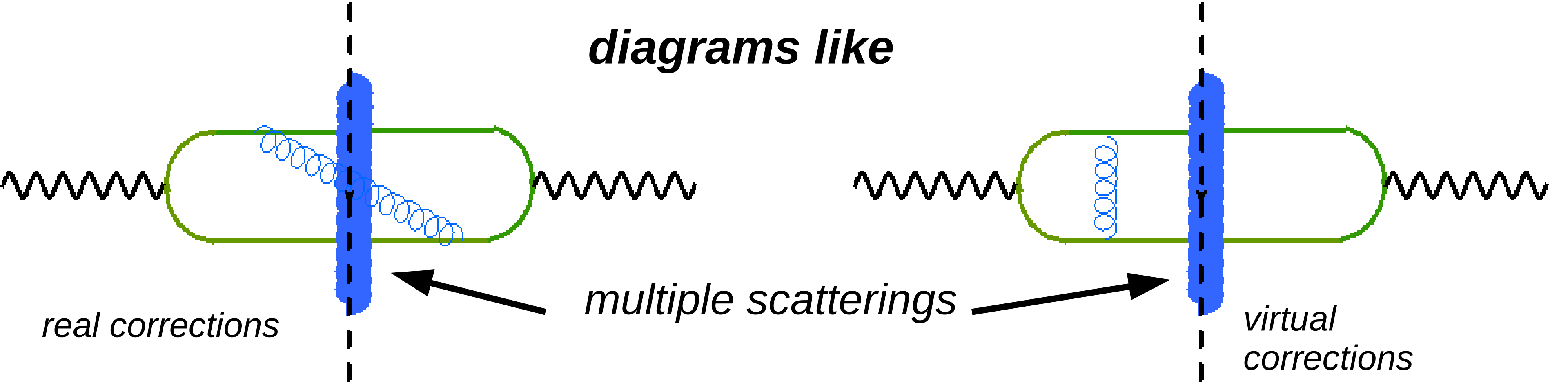
DIS total cross section: energy (x) dependence

recall the parton model was scale invariant, scaling violation (dependence on Q^2) came after quantum corrections - $O(\alpha_s)$

what we have done so far is to include high gluon density effects but no energy dependence yet

to include the energy dependence, need quantum corrections - $O(\alpha_s)$

diagrams like



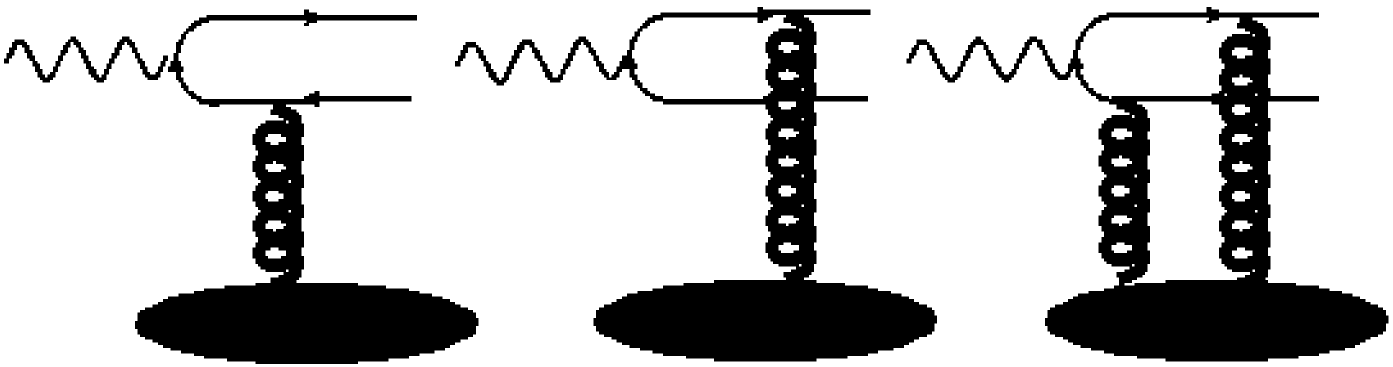
x dependence of dipole cross section:
BK/JIMWLK evolution equation

NLO corrections recently computed

Extensive phenomenology at HERA

something with more discriminating power:
di-hadron correlations in DIS

LO: $\gamma^{\star}\mathrm{T} \rightarrow \mathrm{q}\,\bar{\mathrm{q}}\,\mathrm{X}$

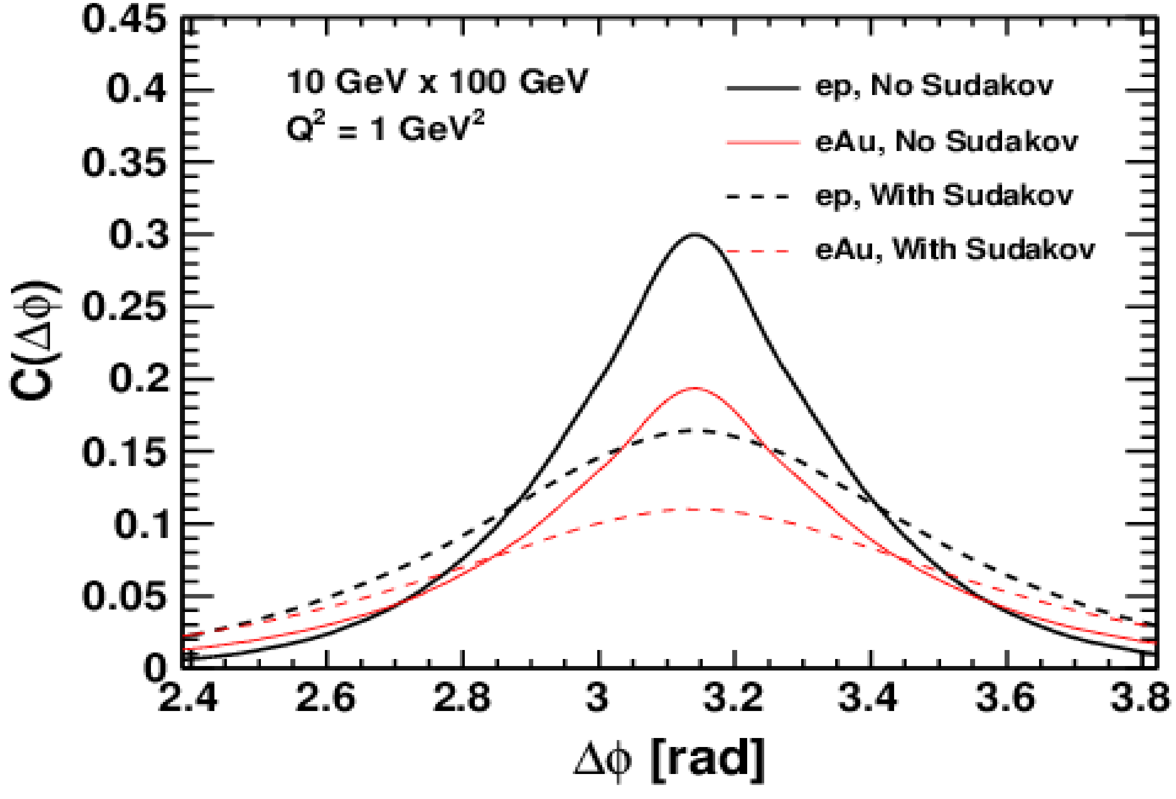


propagator in the background color field

$$\mathrm{S}_F(q,p) \equiv (2\pi)^4\delta^4(p-q)\,S_F^0(p) + S_F^0(q)\,\tau_f(q,p)\,S_F^0(p)$$

$$\tau_f(q,p) \equiv (2\pi)\delta(p^- - q^-)\,\gamma^- \int d^2x_t\, e^{i(q_t-p_t)\cdot x_t}$$
$$\left\{\theta(p^-)[V(x_t)-1] - \theta(-p^-)[V^\dagger(x_t)-1]\right\}$$

Azimuthal correlations in DIS



Zheng + Aschenauer + Lee + Xiao, PRD89 (2014)7, 074037

Toward precision CGC:
NLO corrections

DIS total cross section:

photon impact factor
evolution equations

pA collisions:

Single inclusive particle production

NLO di-jet production in DIS

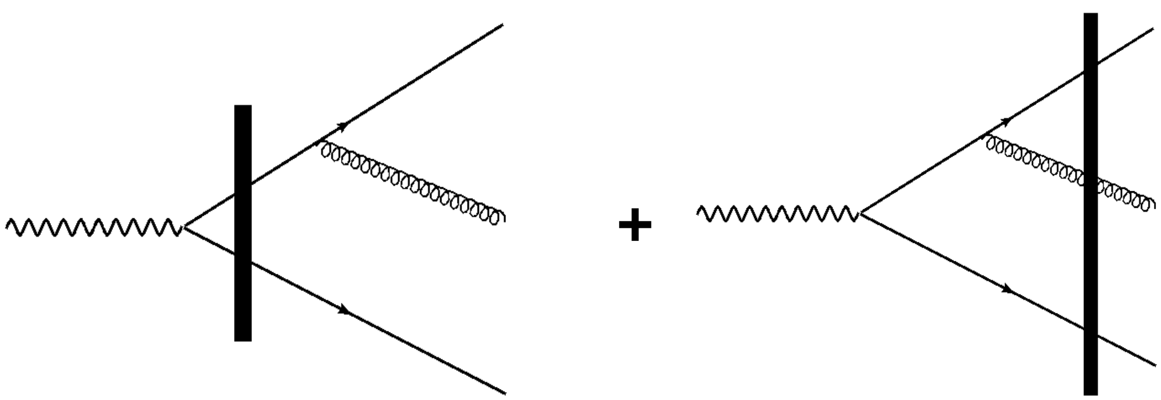
LO 3-jet production

Azimuthal correlations in DIS

*di-jet production in DIS: **NLO***

real contributions: $$\gamma^{\star}\mathbf{T} \rightarrow \mathbf{q}\,\bar{\mathbf{q}}\,\mathbf{g}\,\mathbf{X}$$

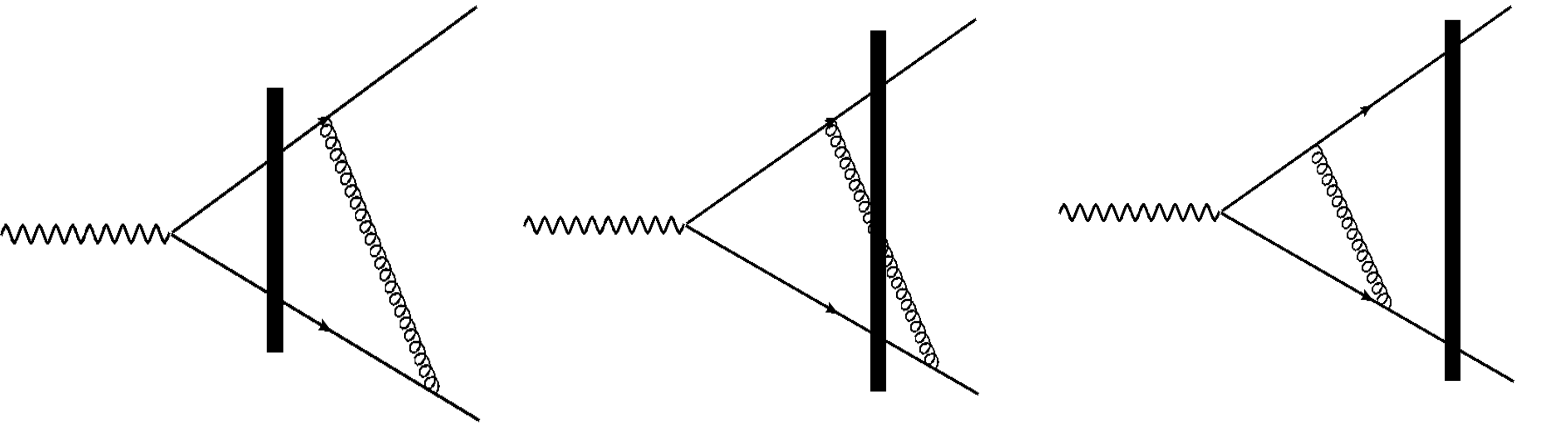
integrate out one of the produced partons



work in progress: Ayala, Hentschinski , Jalilian-Marian, Tejeda-Yeomans

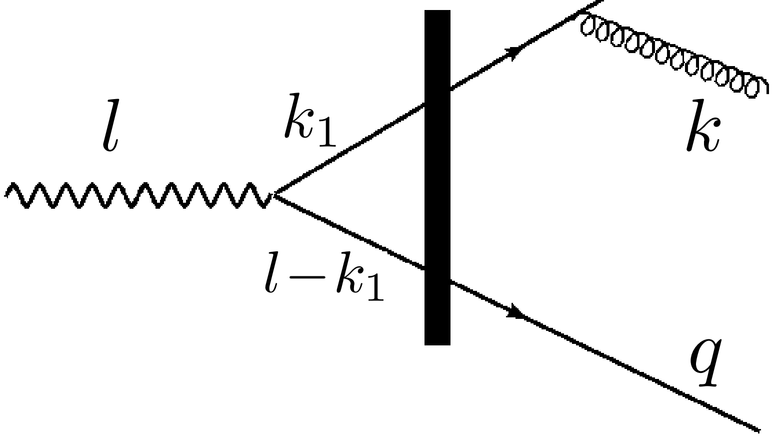
di-jet azimuthal correlations in DIS

virtual contributions: $\gamma^{\star}\mathbf{T} \rightarrow \mathbf{q}\,\bar{\mathbf{q}}\,\mathbf{X}$



+ *"self-energy" diagrams*

$$\mathcal{A} \equiv -eg\,\bar{u}(p)\,[A]^{\mu\nu}\,v(q)\,\epsilon_\mu\,(k)\epsilon^*_\nu(l)$$

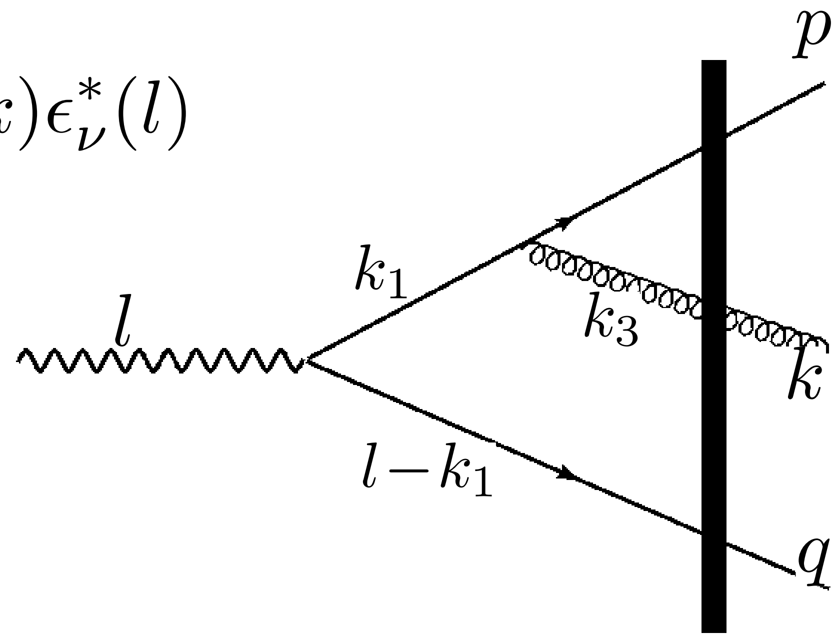


$$A_1^{\mu\nu} = \gamma^\mu\,t^a\,S_F^0(p+k)\,\tau_F(p+k,k_1)\,S_F^0(k_1)\,\gamma^\nu\,S_F^0(l-k_1)\,\tau_F(l-k_1,q)\,\frac{d^4k_1}{(2\pi)^4}$$

with interactions given by

$$\tau_F(p,q) \equiv (2\pi)\delta(p^- - q^-)\gamma^- \int d^2z_t\, e^{-i(p_t-q_t)z_t}\left[\theta(p^-)V(z_t) - \theta(-p^-)V^\dagger(z_t)\right]$$

$$\mathcal{A} \equiv -eg\,\bar{u}(p)\,[A]^{\mu\nu}\,v(q)\,\epsilon_\mu\,(k)\epsilon^*_\nu(l)$$



$$A_2^{\mu\nu} = \tau_F(p, k_1 - k_3)\, S_F^0(k_1 - k_3)\gamma^\mu\, t^a\, S_F^0(k_1)\,\gamma^\nu\, S_F^0(l - k_1)\,\tau_F(l - k_1, q)$$
$$G^{0\,\lambda}_{\mu}(k_3)\,\tau_g^{ac}(k_3, k)\frac{d^4k_1}{(2\pi)^4}\,\frac{d^4k_3}{(2\pi)^4}$$

Two different ways of evaluating these:

1: Use the 1-d delta function, do k^+ integration using contour integration, reduced to 2-d transverse integration over k_t

2: promote all to 4-d, use “standard” momentum space techniques

A 1-loop example

$$I(p_1,p_2)=\int\frac{d^dk_1}{i\pi^{d/2}}\frac{1}{[k_1^2][(l-k_1)^2]}e^{iz_t\cdot(k_{1,t}-p_{1,t})}e^{-iy_t\cdot(k_{1,t}+p_{2,t})}(2\pi)^2\delta(p_1^- - k_1^-)\delta(l^- - k_1^- - p_2^-)$$

complete it to 4-d

$$I(p_1,p_2)=2\pi\delta(l^- - p_1^- - p_2^-)e^{-iy_t\cdot(p_{1,t}+p_{2,t})}\int dr^+\int dr^-\delta(r^+)\int\frac{d^dk_1}{i\pi^{d/2}}\frac{1}{[k_1^2][(l-k_1)^2]}e^{ir\cdot k_1}$$

use Schwinger parameters

$$\left(\frac{i}{k^2-m^2+i0}\right)^\lambda=\frac{1}{\Gamma(\lambda)}\int_0^\infty d\alpha\,\alpha^{\lambda-1}e^{i\alpha(k^2-m^2+i0)}$$

complete the square, Gaussian integration, ...

$$I(p_1,p_2)=8\pi^2\delta(l^- - p_1^- - p_2^-)\frac{e^{-iz_t\cdot p_{1,t}}}{l^-}e^{-iy_t\cdot p_{2,t}}K_0\left(\sqrt{\alpha(1-\alpha)Q^2(x-y)^2}\right),\quad \alpha=p_1^-/l^-$$

we are developing a Mathematica package to do this

di-jet azimuthal correlations in DIS

$$\text{NLO: } \gamma^\star \mathbf{T} \to \mathbf{h}\,\mathbf{h}\,\mathbf{X}$$

integrate out one of the produced partons - there are divergences:

rapidity divergences: JIMWLK evolution of n-point functions

colinear divergences: DGLAP evolution of fragmentation functions

infrared divergences cancel

the finite pieces are written as a factorized cross section

work in progress: Ayala, Hentschinski , Jalilian-Marian, Tejeda-Yeomans

related work by:

Boussarie, Grabovsky, Szymanowski, Wallon, JHEP1409, 026 (2014)
Balitsky, Chirilli, PRD83 (2011) 031502, PRD88 (2013) 111501
Beuf, PRD85, (2012) 034039

SUMMARY

CGC is a systematic approach to high energy collisions

it has been used to fit a wealth of data; ep, eA, pp, pA, AA

Leading Log CGC works (too) well for a qualitative/semi-quantitative description of data, NLO is needed

Need to eliminate/minimize late time/hadronization effects

Di-jet angular correlations offer a unique probe of CGC

3-hadron/jet correlations should be even more discriminatory

an EIC is needed for precision CGC studies