Photon-jet production and angular correlations in proton-nucleus collisions

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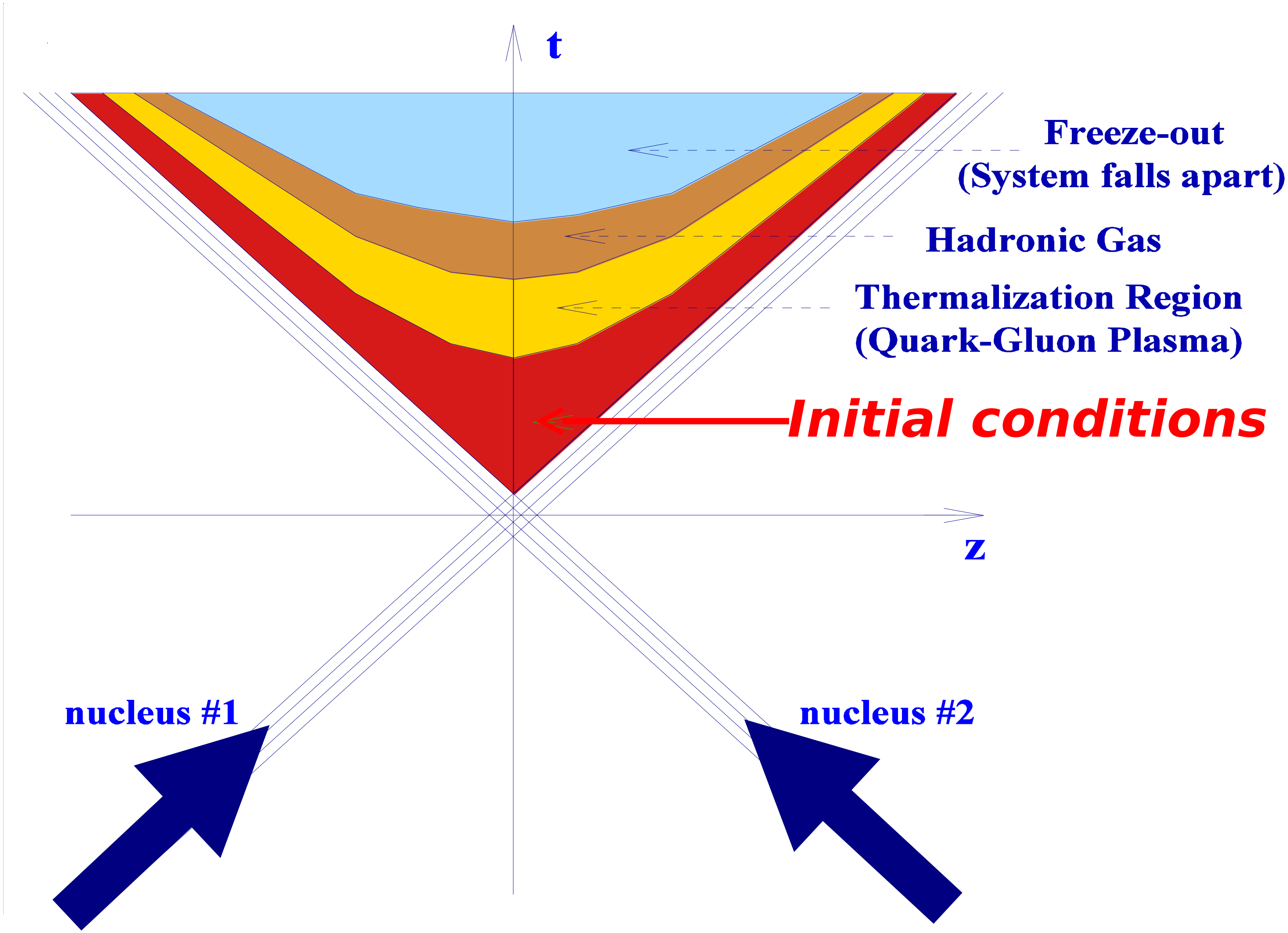
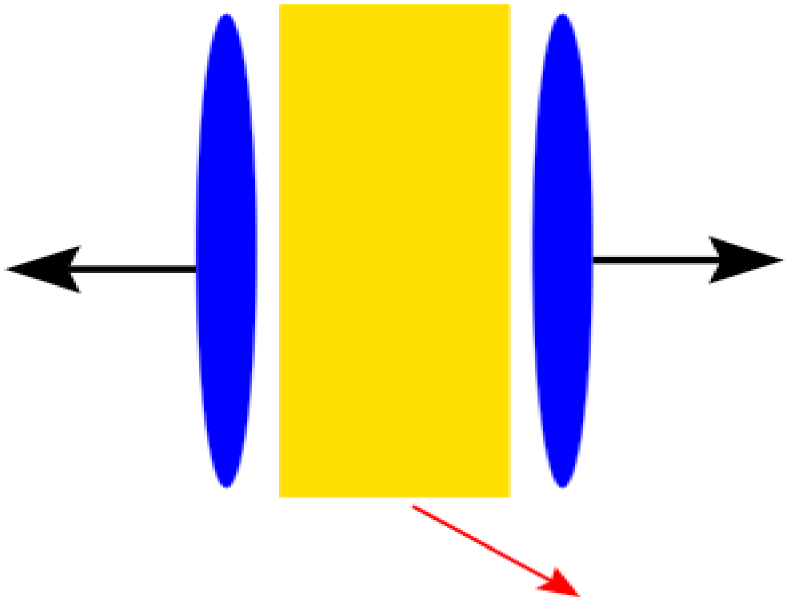
Space-Time History of a Heavy Ion Collision



Colliding sheets of CGC at high energies



Initial energy density and multiplicity of produced gluons

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

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

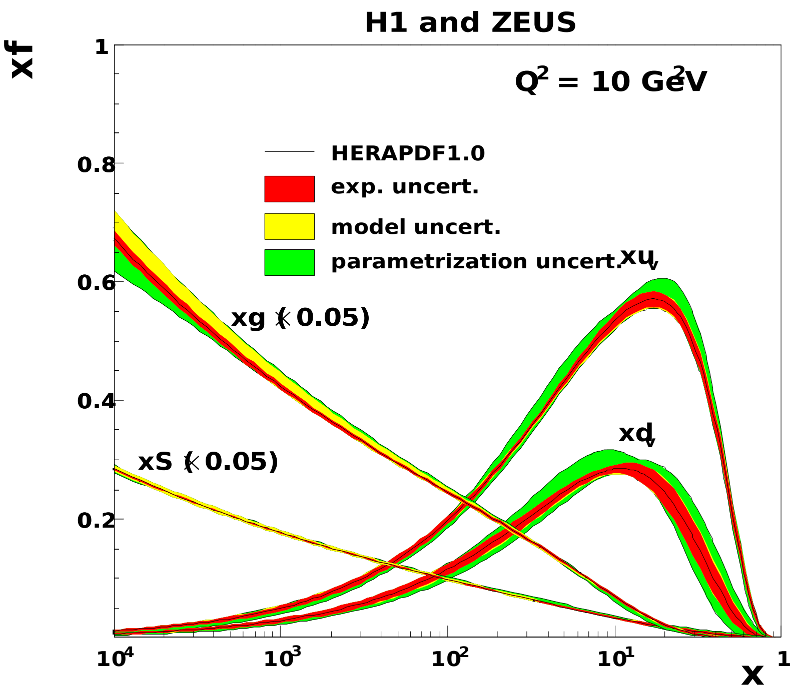
Thermalization? Instabilities, ...

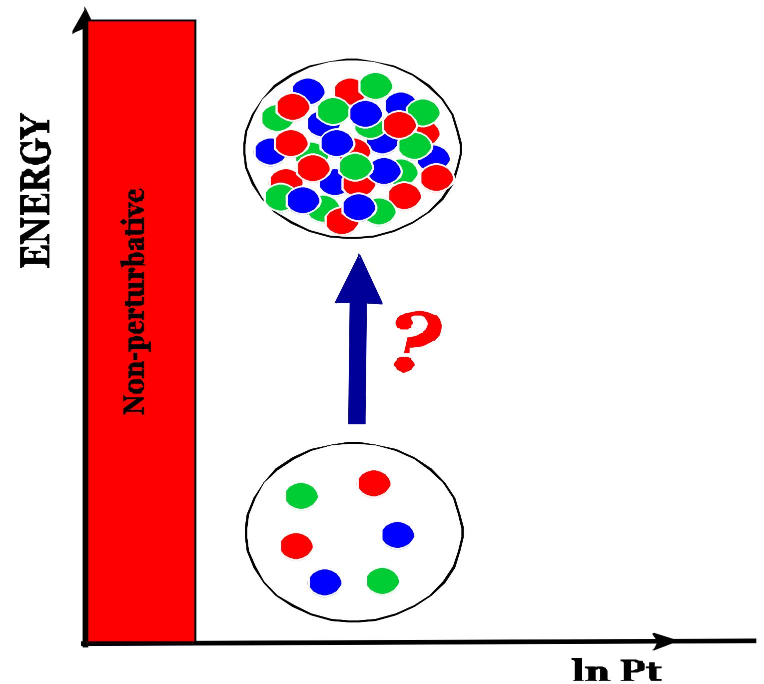
Initial Conditions

Color Glass Condensate (CGC) formalism is a weak-coupling approach that allows a first-principle understanding of the initial conditions of a high energy heavy ion collision

What is CGC and how to probe it?

dynamics of *universal gluonic matter:* *gluon saturation*





$$P_{gg} \sim P_{gq} \sim \frac{1}{x}$$

How does this happen ?

How do correlation functions evolve ?

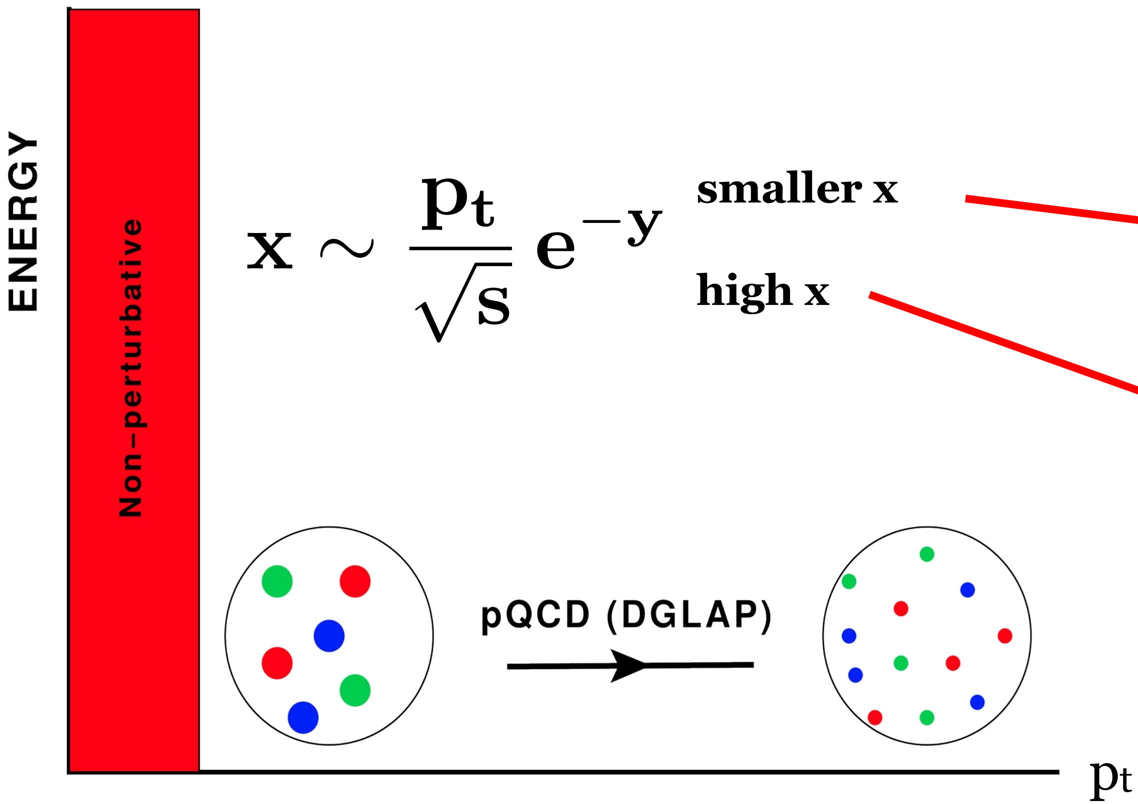
Is there a universal fixed point for the evolution ?

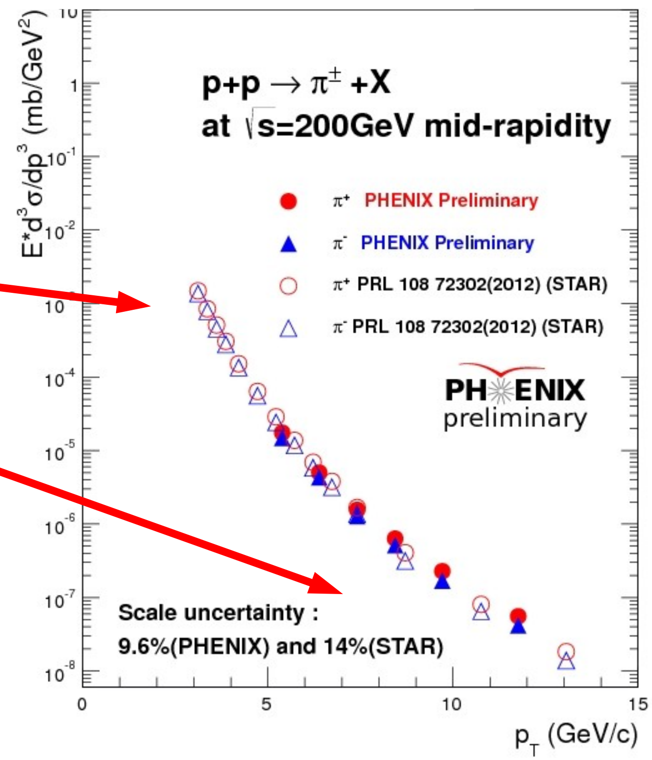
Are there scaling laws ?

pQCD: the standard paradigm

$$E\frac{d\sigma}{d^3p} \sim f_1(x, p_t^2) \otimes f_2(x, p_t^2) \otimes \frac{d\sigma}{dt} \otimes D(z, p_t^2) + \cdots\cdots$$

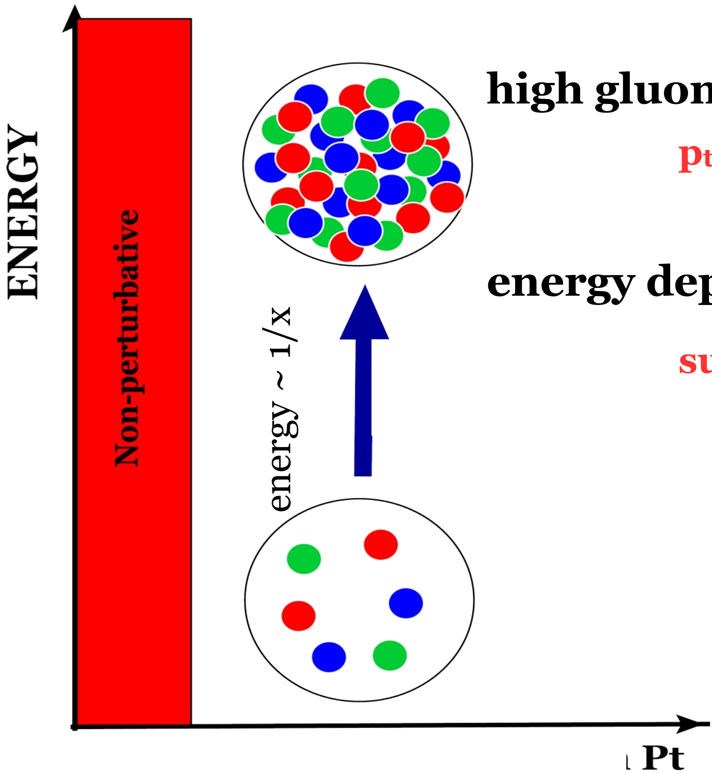
$$x \sim \frac{p_t}{\sqrt{s}} e^{-y}$$





bulk of QCD phenomena happens at low p_t (small x)

QCD at high energy/small x: gluon saturation



high gluon density: <u>Eikonal multiple scattering</u>

p_t broadening (generic to multiple scattering)

energy dependence: <u>x-evolution via JIMWLK/BK</u>

suppression of spectra/away side peaks

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

$$Q_s^2(x = 3\times 10^{-4}) \sim 1\,GeV^2$$

for a proton target (quarks)

a framework for multi-particle production in QCD at small x/low p_t

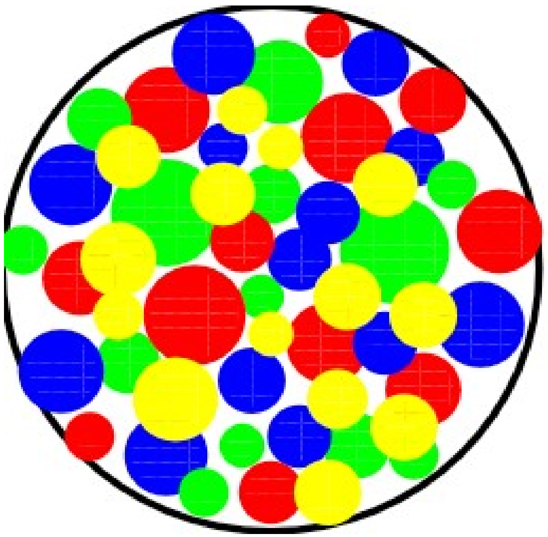
Shadowing/Nuclear modification factor
<u>Azimuthal angular correlations (photon-jet,...)</u>
Long range rapidity correlations (ridge,...)
Initial conditions for hydro
Thermalization (?)

$$\mathbf{x \leq 0.01}$$

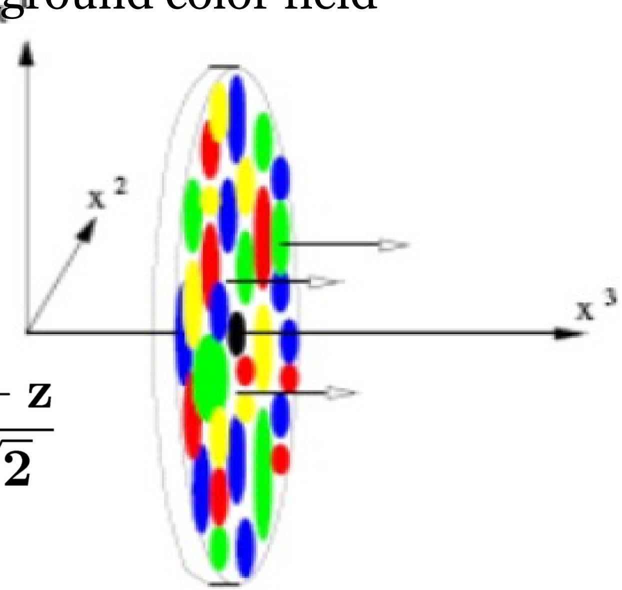
$$\alpha_s \ln{(x_v/x)} \sim 1$$

Dilute-dense (pA) collisions: eikonal approximation

dense target (proton/nucleus) as a background color field



boost



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

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

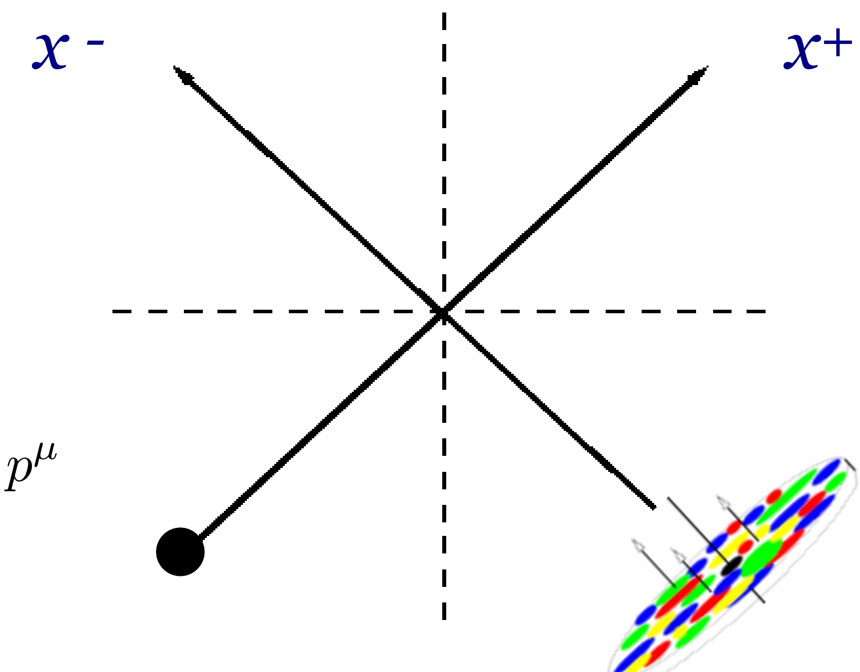
$$\boxed{\mathbf{J^\mu_a(x) \equiv \delta^{\mu\,+}\,\delta(x^-)\,\rho_a(x_t)}}$$

color current *color charge*

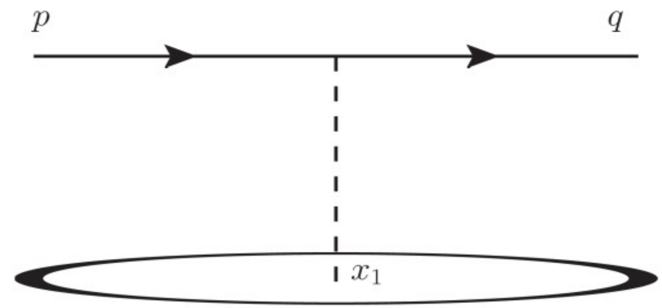
$$\mathbf{A^+_a(z^-, z_t) = \delta(z^-)\,\alpha_a(z_t)}$$

recall eikonal limit

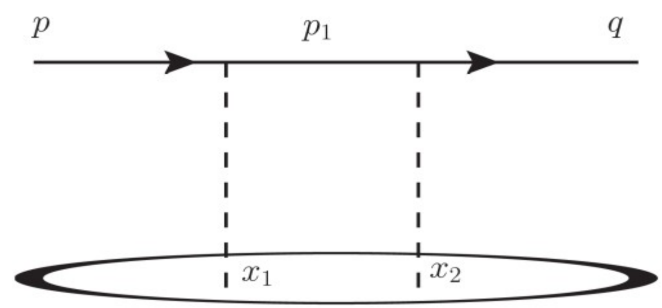
$$\bar{u}(q)\gamma^\mu u(p) \quad \rightarrow \quad \bar{u}(p)\gamma^\mu\, u(p) \sim p^\mu$$
$$\bar{u}(q)\not{A}\, u(p) \quad \rightarrow \quad p \cdot A \sim p^+ A^-$$



$$i\mathcal{M}_1 = (ig)\int d^4x_1\, e^{i(q-p)x_1}\, \bar{u}(q)\, \left[\not{n}\, S(x_1)\right]\, u(p)$$
$$= (ig)(2\pi)\delta(p^+ - q^+)\int d^2x_{1t}\, dx_1^+\, e^{i(q^- - p^-)x_1^+}\, e^{-i(q_t - p_t)x_{1t}}$$
$$\bar{u}(q)\left[\not{n}\, S(x_1^+, x_{1t})\right] u(p)$$



$$i\mathcal{M}_2 = (ig)^2\int d^4x_1\, d^4x_2 \int \frac{d^4p_1}{(2\pi)^4}\, e^{i(p_1-p)x_1}\, e^{i(q-p_1)x_2}$$
$$\bar{u}(q)\, \left[\not{n}\, S(x_2)\, \frac{i\not{p}_1}{p_1^2 + i\epsilon}\, \not{n}\, S(x_1)\right]\, u(p)$$

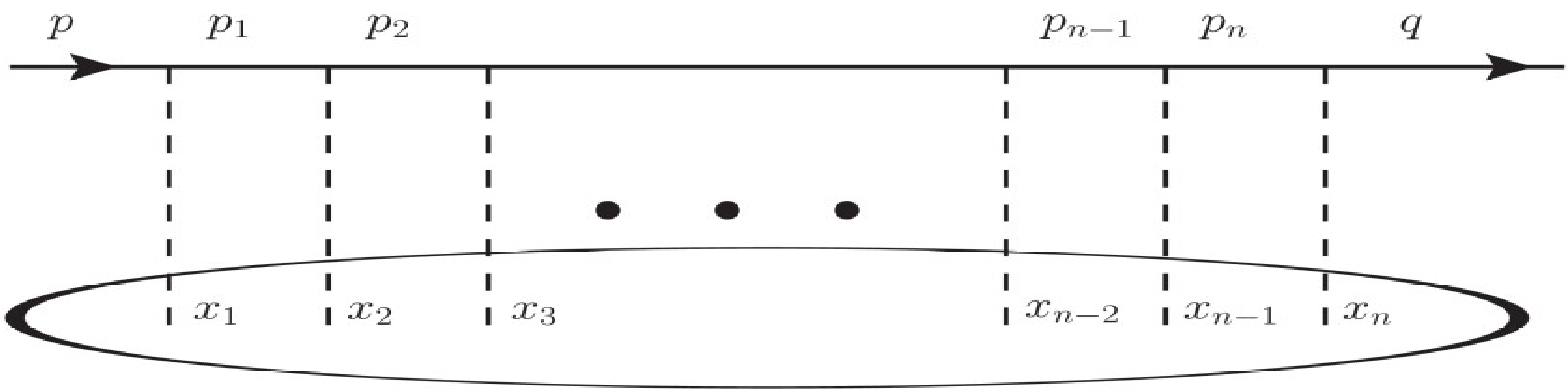


$$\int \frac{dp_1^-}{(2\pi)} \frac{e^{ip_1^-(x_1^+ - x_2^+)}}{2p^+\left[p_1^- - \frac{p_{1t}^2 - i\epsilon}{2p^+}\right]} = \frac{-i}{2p^+}\, \theta(x_2^+ - x_1^+)\, e^{i\frac{p_{1t}^2}{2p^+}(x_1^+ - x_2^+)}$$

contour integration over the pole leads to path ordering of scattering

ignore all terms: $O(\frac{p_t}{p^+}, \frac{q_t}{q^+})$ and use $\not{n}\, \frac{\not{p}_1}{2n\cdot p}\, \not{n} = \not{n}$

$$i\mathcal{M}_2 = (ig)^2\, (-i)(i)\, 2\pi\delta(p^+ - q^+) \int dx_1^+\, dx_2^+\, \theta(x_2^+ - x_1^+) \int d^2x_{1t}\, e^{-i(q_t - p_t)\cdot x_{1t}}$$
$$\bar{u}(q)\, \left[S(x_2^+, x_{1t})\, \not{n}\, S(x_1^+, x_{1t})\right]\, u(p)$$

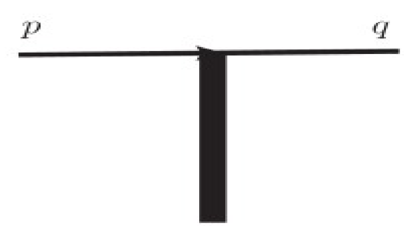


$$
\begin{aligned}
i\mathcal{M}_n \;=\; & 2\pi\delta(p^+ - q^+)\,\bar{u}(q)\,\not{n} \int d^2x_t\, e^{-i(q_t - p_t)\cdot x_t} \\
& \Big\{ (ig)^n\,(-i)^n (i)^n \int dx_1^+\, dx_2^+ \cdots dx_n^+\, \theta(x_n^+ - x_{n-1}^+) \cdots \theta(x_2^+ - x_1^+) \\
& \big[S(x_n^+, x_t)\, S(x_{n-1}^+, x_t) \cdots S(x_2^+, x_t) S(x_1^+, x_t) \big] \Big\}\, u(p)
\end{aligned}
$$

sum over all scatterings $\quad i\mathcal{M} = \sum_n i\,\mathcal{M}_n$

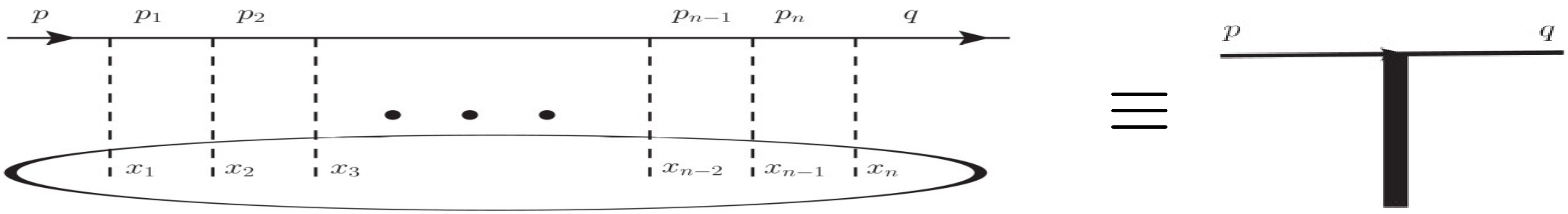
$$
i\mathcal{M}(p,q) = 2\pi\delta(p^+ - q^+)\,\bar{u}(q)\,\not{n} \int d^2x_t\, e^{-i(q_t - p_t)\cdot x_t}\, \left[V(x_t) - 1\right]\, u(p)
$$

with $V(x_t) \equiv \hat{P}\, \exp\left\{ ig \int_{-\infty}^{+\infty} dx^+\, n^-\, S_a(x^+, x_t)\, t_a \right\}$



$$
\frac{d\,\sigma^{q\,T \to q\,X}}{d^2p_t\, dy} \sim |i\mathcal{M}|^2 \sim F.T. \; < Tr\, V(x_t)\, V^\dagger(y_t) >
$$

CGC: eikonal approximation (tree level)



$$i\mathcal{M}(p,q) = 2\pi\delta(p^+ - q^+)\bar{u}(q)\not{n}\int d^2x_t\, e^{-i(q_t-p_t)\cdot x_t}\,[V(x_t)-1]\,u(p)$$

with $\quad V(x_t) \equiv \hat{P}\exp\left\{ig\int_{-\infty}^{+\infty} dx^+ S_a^-(x^+, x_t)t_a\right\}$

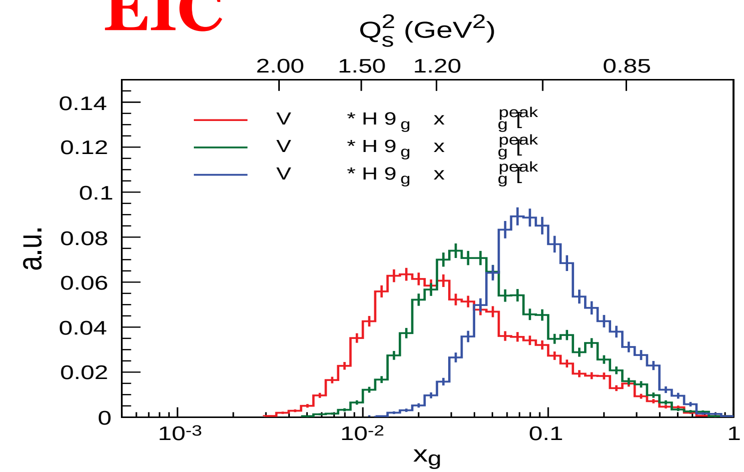
scattering from small x gluons of the target can cause only a *small angle deflection*

Dipole: DIS, proton-nucleus collisions

x dependence from JIMWLK/BK evolution equation

$$< Tr\, V(x_\perp)\, V^\dagger(y_\perp) >$$

EIC



Aschenauer et al. ArXiv:1708.01527

toward precision at small x:

NLO corrections:

Chirilli+Xiao+Yuan, PRL (2012)

Balitsky+Chirilli, PRD88 (2013)

....

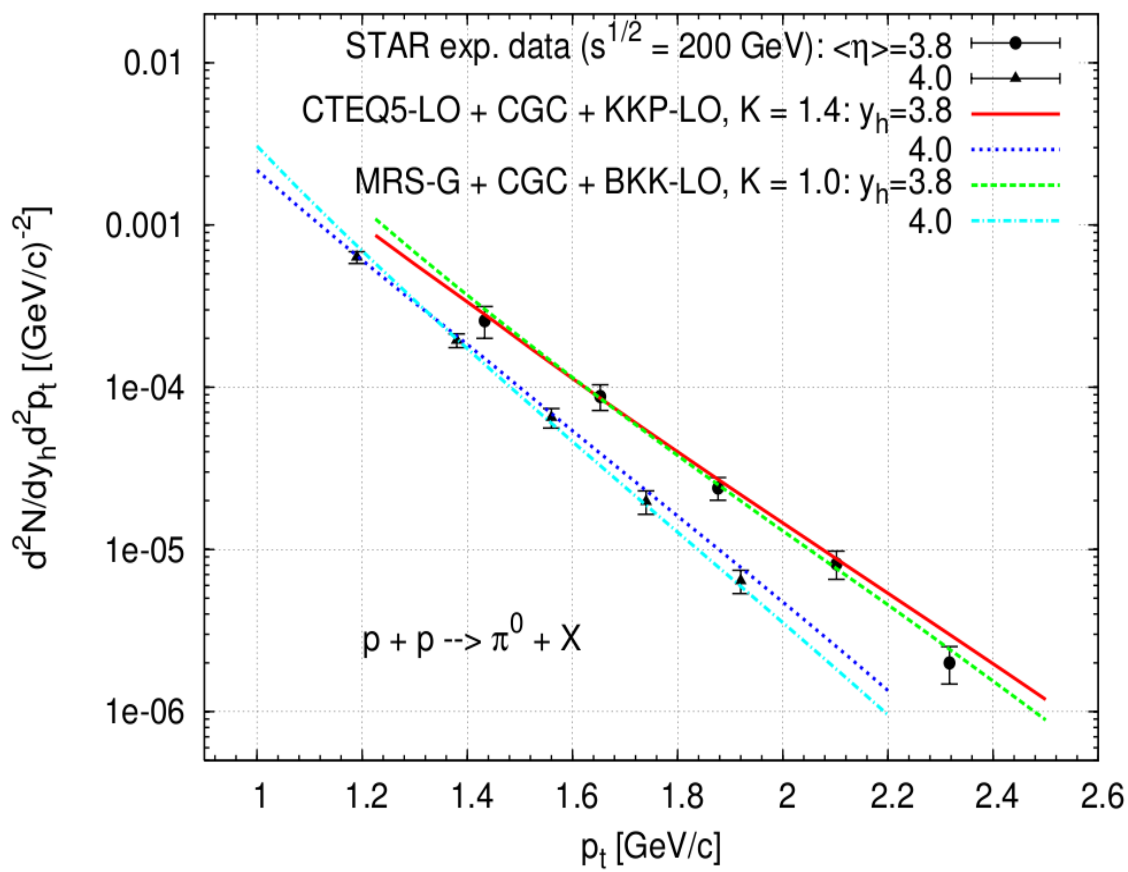
sub-eikonal corrections:

Kovchegov+Pitonyak+Sievert, JHEP (2017)

Agostini+Altinoluk+Armesto, EPJC (2019)

....

Single inclusive pion production in pp at RHIC

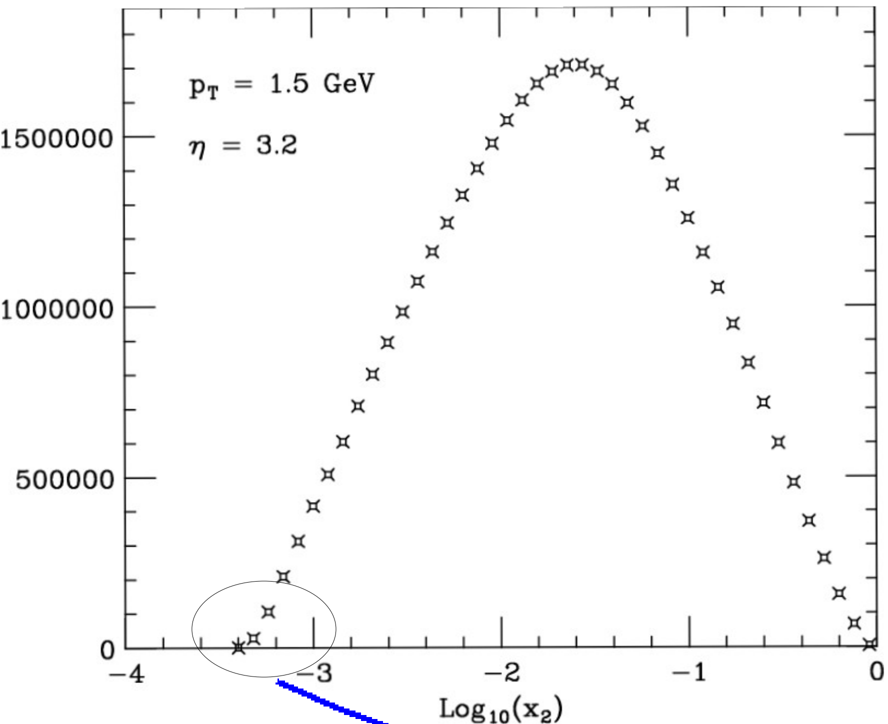


DHJ, NPA765 (2006) 57-70

Single inclusive pion production in pp at RHIC

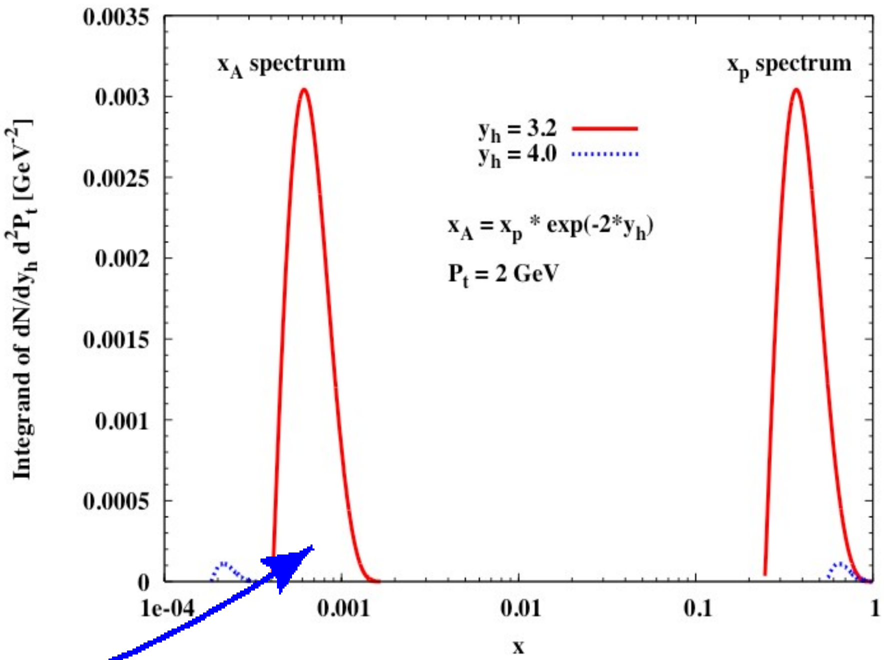
collinear factorization

GSV, PLB603 (2004) 173-183



CGC

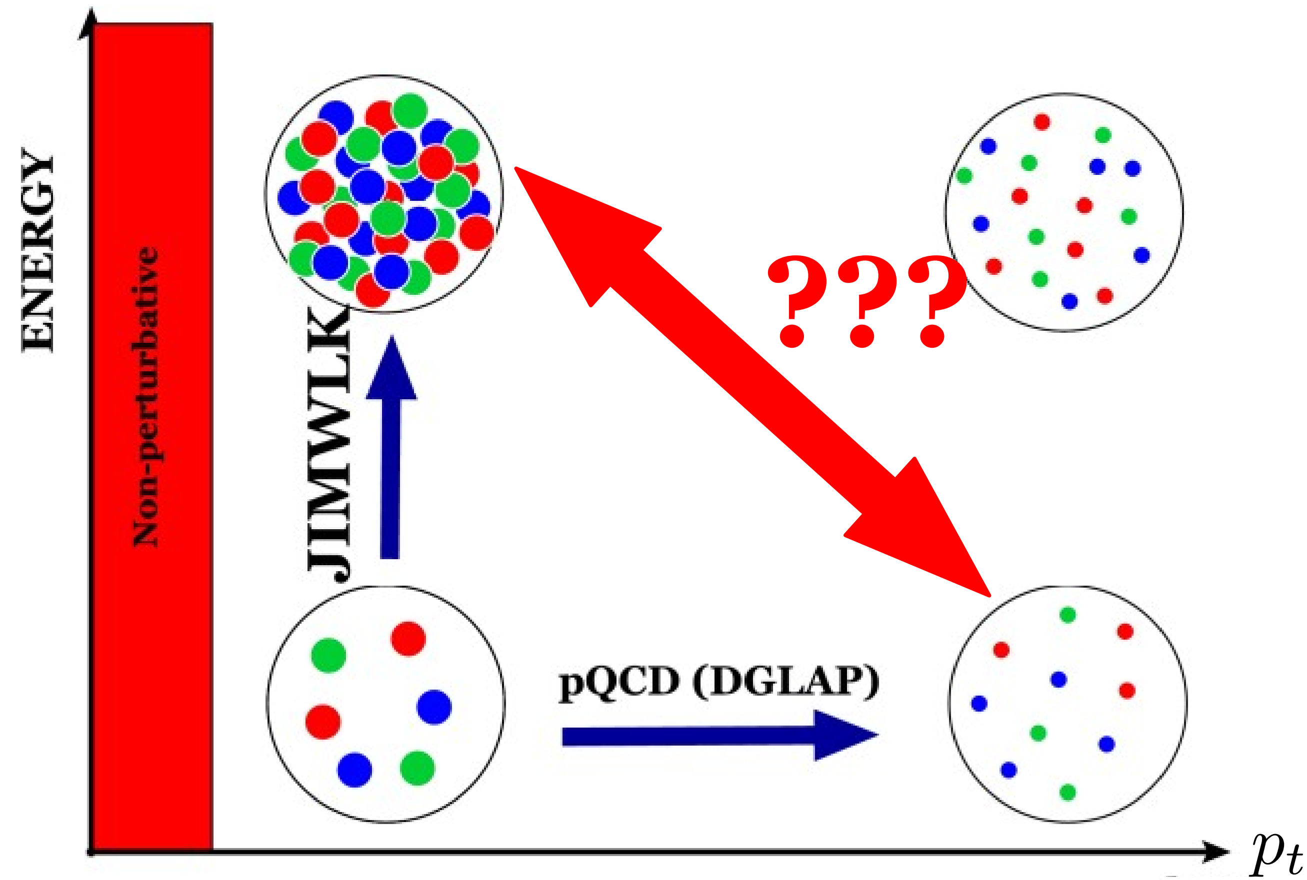
DHJ, NPA765 (2006) 57-70



$$\int_{x_{min}}^{1} dx\, xG(x, Q^2) \cdots\cdots \longrightarrow x_{min} G(x_{min}, Q^2) \cdots$$

which kinematics are we in?

QCD kinematic phase space



unifying saturation with high p_t (large x) physics?

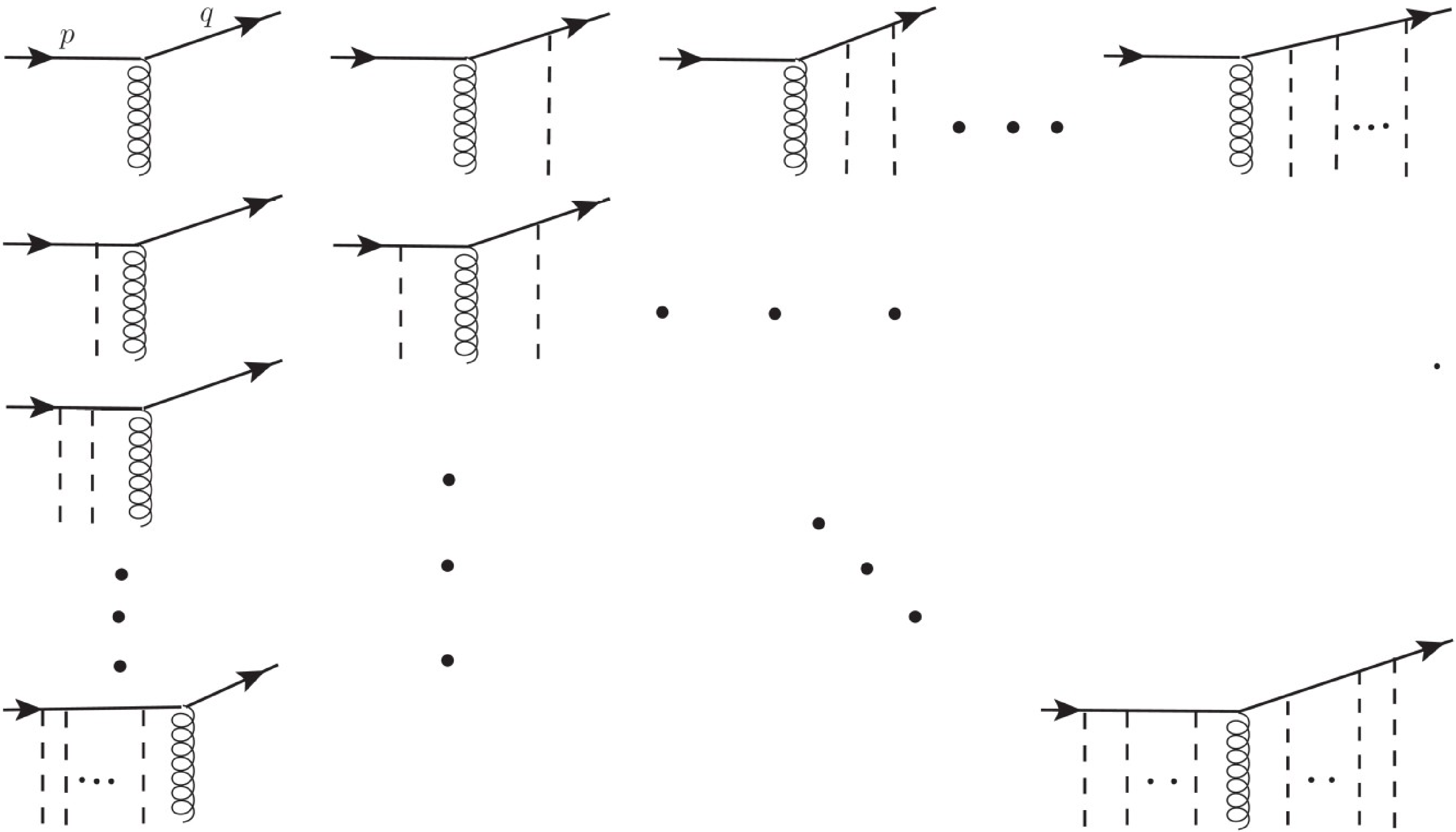
<u>kinematics of saturation: *where is saturation applicable?*</u>

jet physics, high p_t and forward-backward correlations,

spin physics, early time e-loss in heavy ion collisions, …….

Beyond eikonal approximation:

large x partons of target can cause a large-angle deflection of the quark



Quark scattering: beyond small x approximation

large x partons of target can cause a <u>large-angle deflection</u> of the quark

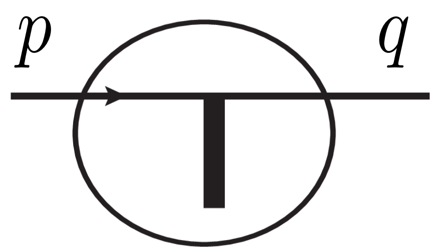
target gluon field

$$\mathcal{A}^\mu = \mathbf{S}^\mu + \mathbf{A}^\mu$$

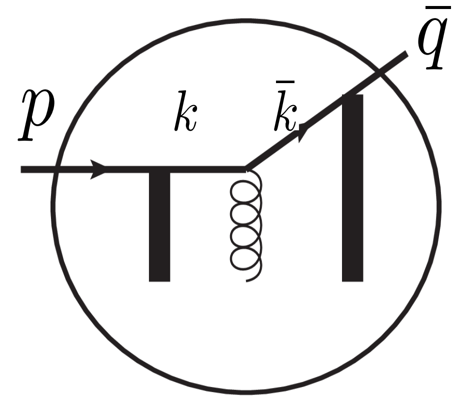
single scattering from large x gluons of target

$$\mathbf{A}^\mu = (\mathcal{A}^\mu - \mathbf{S}^\mu)$$

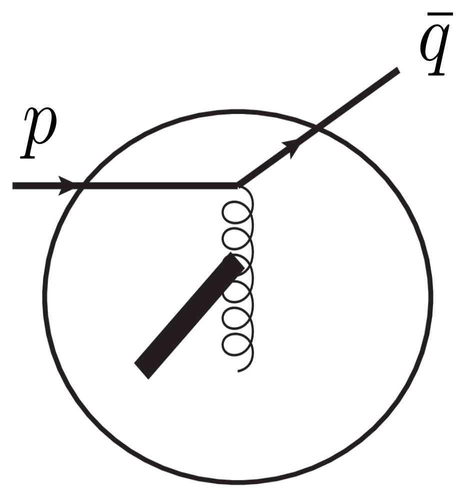
multiple scatterings from small x gluons of target $\mathbf{S}^\mu$



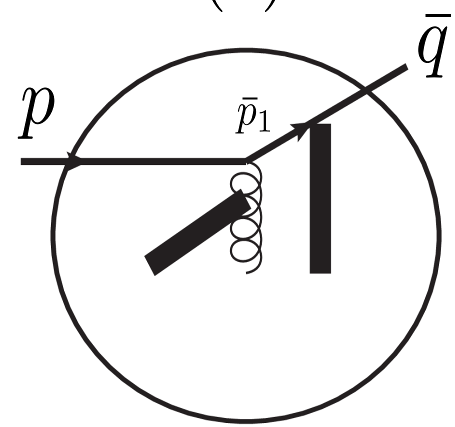
eik



(1)



(2)



(3)

JJM, PRD102 (2020) 1, 014008; PRD99 (2019) 1, 014043 soft (eikonal) limit: $i\mathcal{M} \longrightarrow i\mathcal{M}_{eik}$

use spinor helicity formalism: helicity amplitudes

Including large x gluons of the target leads to:

longitudinal double spin asymmetries (A_{LL})

baryon transport (beam rapidity loss), ...

toward one-loop corrections: leading log evolution

gluon radiation

related problem: photon radiation

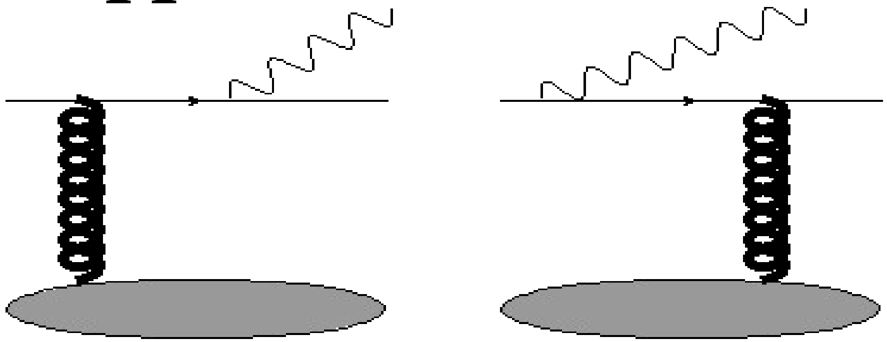
photon-jet correlations:

azimuthal angular correlations from low to high p_t

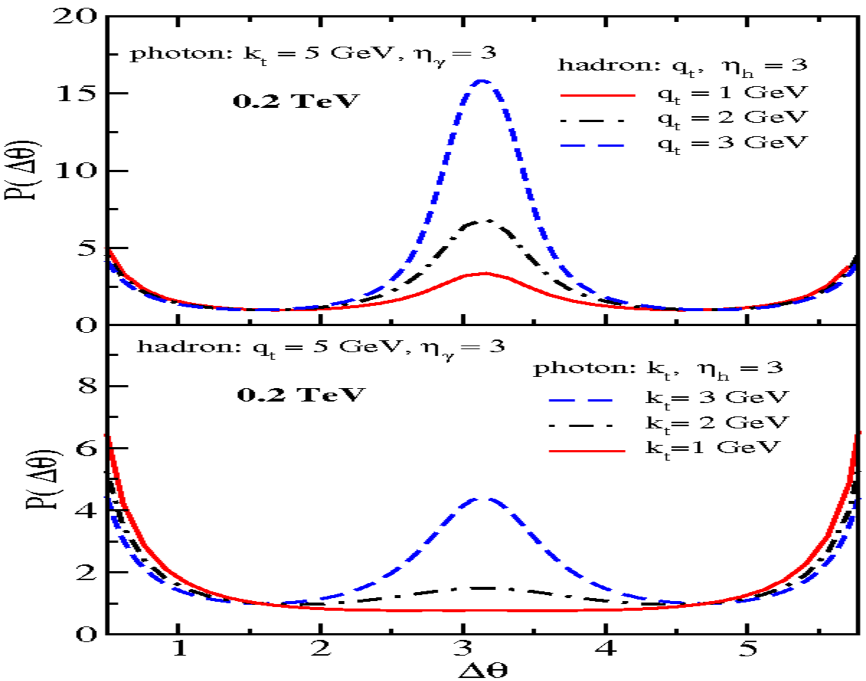
forward-backward rapidity correlations

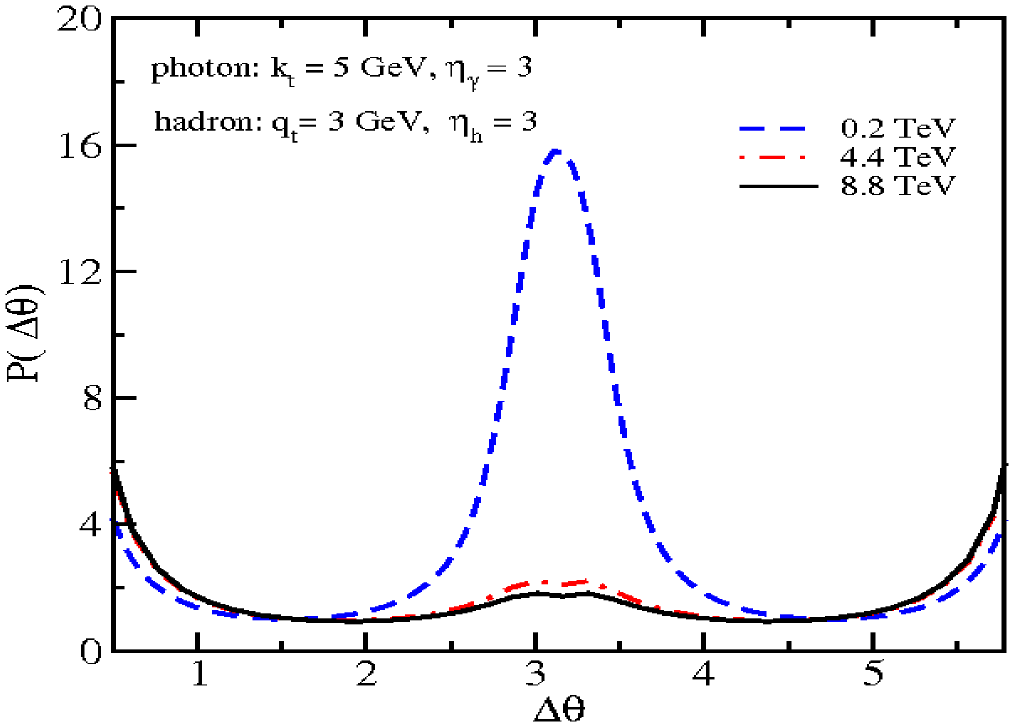
Photon radiation: eikonal approximation

$$\mathbf{q\,T \rightarrow q\,\gamma^{(\star)}\,X}$$

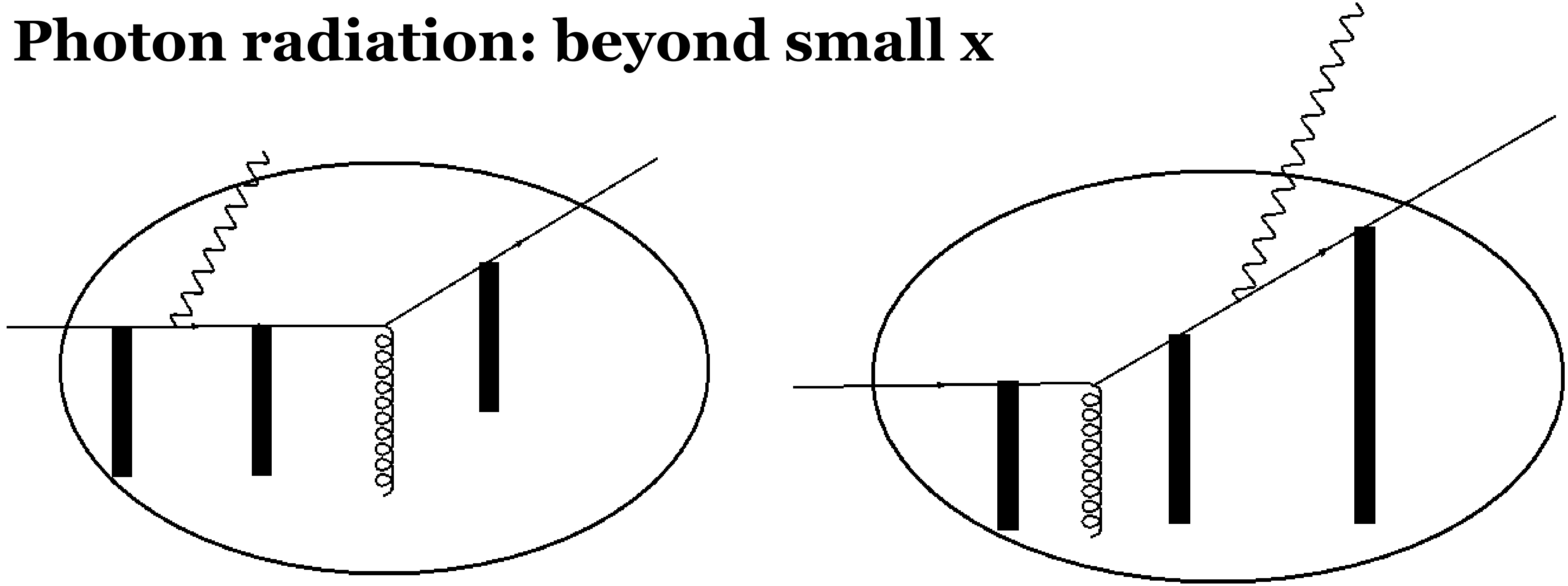


photon-hadron azimuthal correlations: JJM+AR, PRD86, 2012, 034016



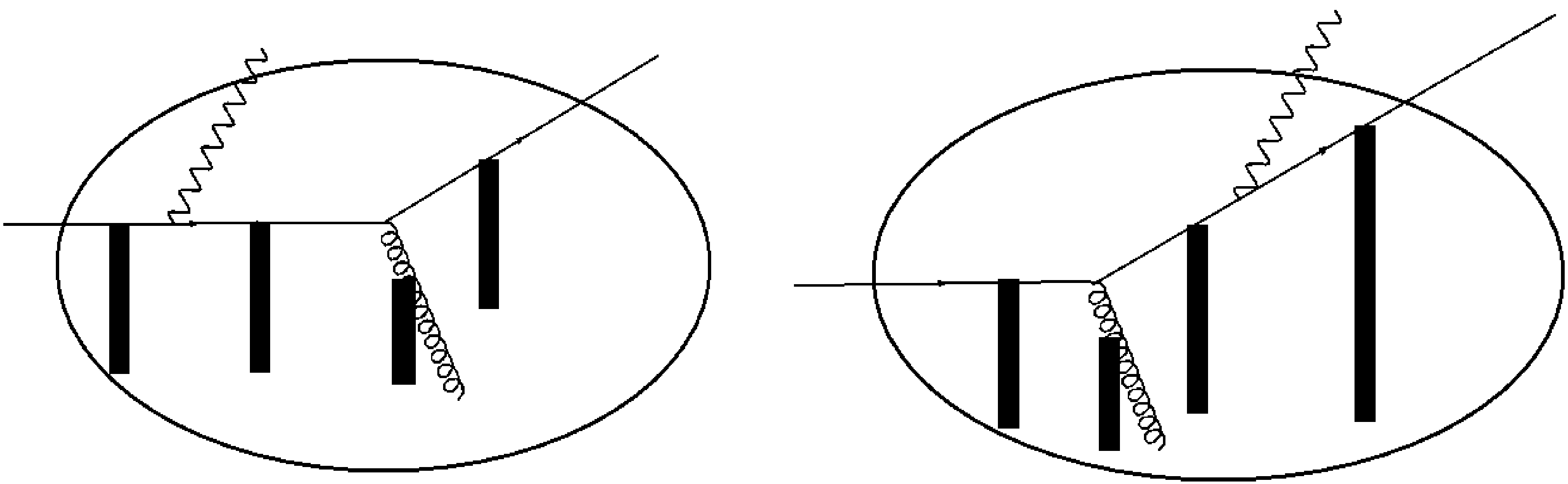


Photon radiation: beyond small x

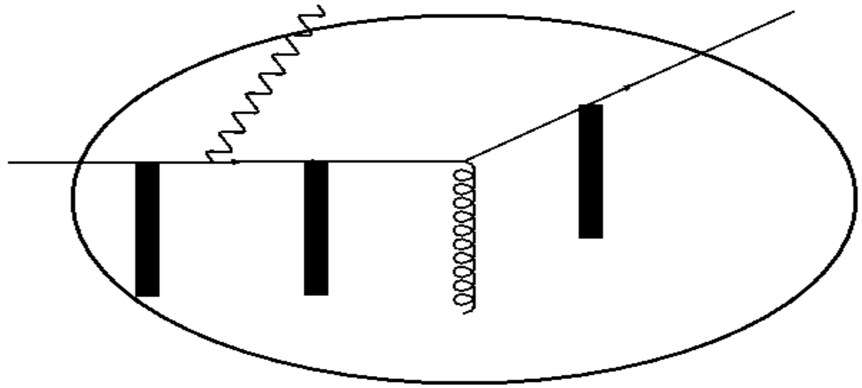


before hard scattering

after hard scattering



photon radiation: helicity amplitudes



$$\mathcal{N}_{1-1} = \bar{u}(\bar{q})\,\frac{\bar{\not{n}}}{2\bar{n}\cdot\bar{q}}\,\not{A}(x)\,\frac{\not{n}\,\not{\epsilon}(l)\,\not{k}_1\,\not{n}}{2n\cdot p\,2n\cdot(p-l)\,2n\cdot(p-l)}\,u(p)$$

$$\mathcal{N}_{1-2} = \bar{u}(\bar{q})\,\frac{\bar{\not{n}}}{2\bar{n}\cdot\bar{q}}\,\not{A}(x)\,\frac{\not{n}\,\not{\epsilon}(l)\,\not{k}_1\,\not{n}}{2n\cdot p\,2n\cdot(p-l)}\,u(p)$$

$$\mathcal{N}_{1-1}^{++} = \left(\mathcal{N}_{1-1}^{--}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{\left[n\cdot l\,k_{2\perp}\cdot\epsilon_{\perp}^{\star} - n\cdot(p-l)\,l_{\perp}\cdot\epsilon_{\perp}^{\star}\right]}{n\cdot l\,n\cdot(p-l)}\,\langle\bar{k}_1^{+}|\not{A}(x)|k_3^{+}\rangle$$

$$\mathcal{N}_{1-2}^{++} = \left(\mathcal{N}_{1-2}^{--}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\langle\bar{k}_1^{+}|\not{A}(x)|n^{+}\rangle$$

$$\mathcal{N}_{1-1}^{+-} = \left(\mathcal{N}_{1-1}^{-+}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{\left[n\cdot p\,l_{\perp}\cdot\epsilon_{\perp} - n\cdot l\,k_{1\perp}\cdot\epsilon_{\perp}\right]}{n\cdot p\,n\cdot l}\,\langle\bar{k}_1^{+}|\not{A}(x)|k_3^{+}\rangle$$

$$\mathcal{N}_{1-2}^{+-} = \mathcal{N}_{1-2}^{-+} = 0$$

So far

Classical CGC is generalized by including large angle scattering from the target

beam rapidity loss

Helicity amplitudes for quark and photon production are evaluated

spin asymmetries

Relevant operators are identified

expectation values?

Need to classify/regulate the divergences

Toward a factorized cross section at all x

gluon radiation

SUMMARY

CGC is a systematic approach to high energy collisions

strong hints from RHIC, LHC,...

toward precision: NLO, sub-eikonal corrections, ...

CGC breaks down at large x (high p_t)

a significant part of EIC/RHIC/LHC phase space is at large x

transition from large x physics to CGC (kinematics?)

Toward a unified formalism:

particle production in both small and large p_t kinematics

two-particle correlations: from forward-forward to forward-backward

one-loop correction: both collinear and CGC factorization limits

need to clarify/understand: gauge invariance, initial conditions, ...