Photon-jet angular correlations in high energy proton-nucleus collisions:

from low to high transverse momenta

(or why is large x physics needed to establish saturation at small x)

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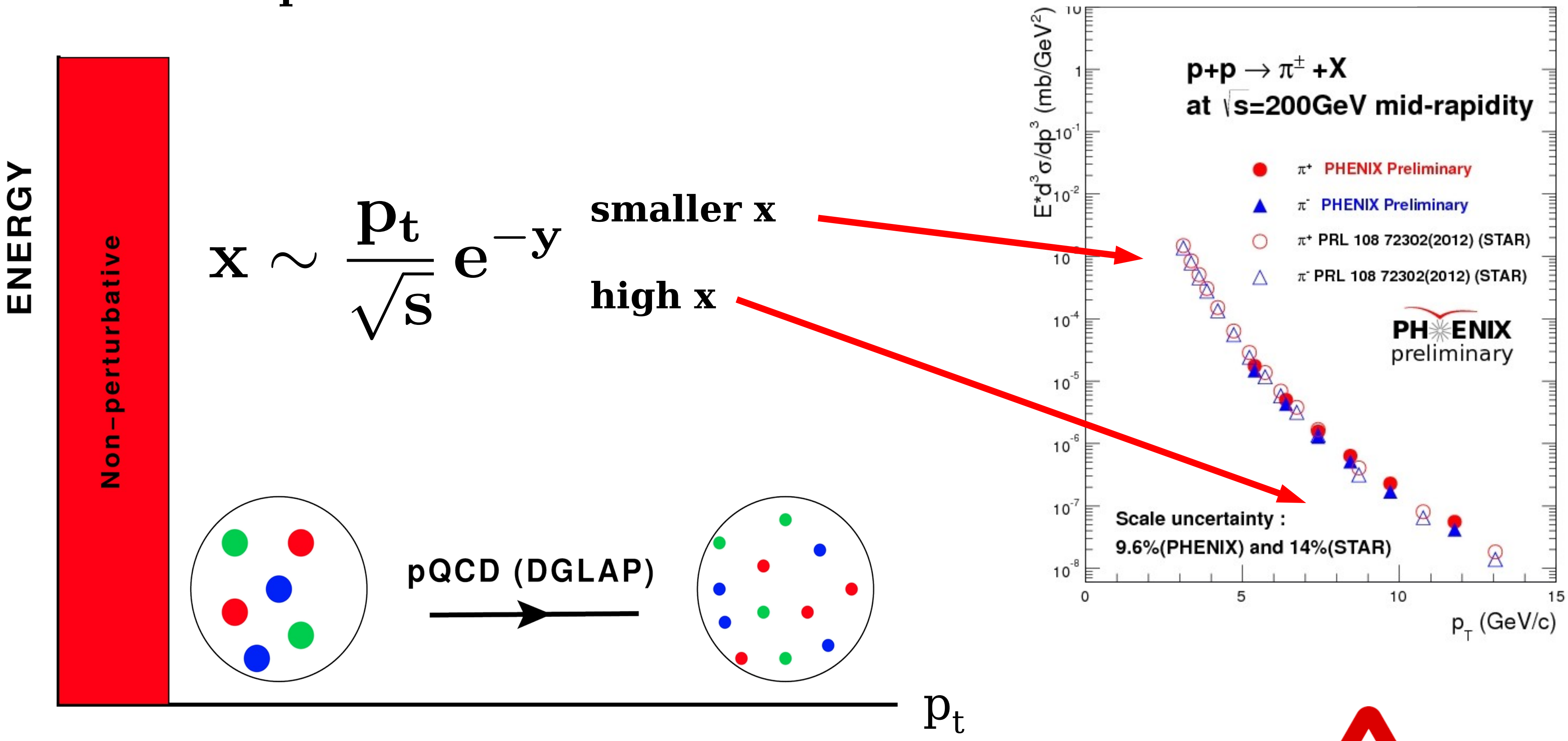
pQCD: the standard paradigm

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

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



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

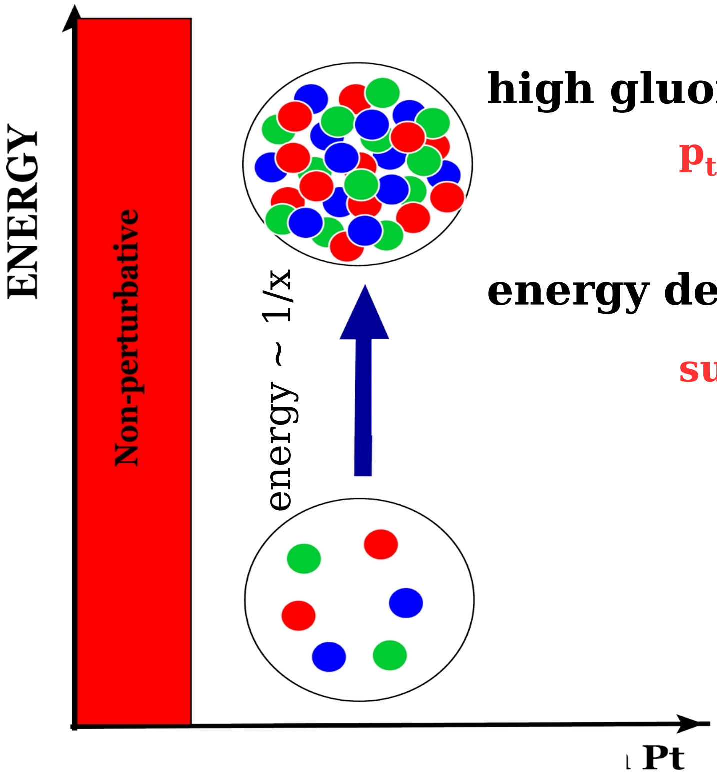
QCD in the Regge-Gribov limit

$$\sqrt{\mathbf{S}} \to \infty \qquad \mathbf{Q^2} \sim \mathbf{const.} \qquad \mathbf{x} \sim \frac{\mathbf{Q^2}}{\mathbf{S}} \to \mathbf{0}$$

$$\log 1/x \gg \log Q^2 \qquad \alpha_s \log 1/x \sim 1$$

QCD at high energy: gluon saturation

Tue. plenary talk
by M. Sievert



high gluon density: Eikonal multiple scattering

p_t broadening (generic to multiple scattering)

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

suppression of spectra/away side peaks

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

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

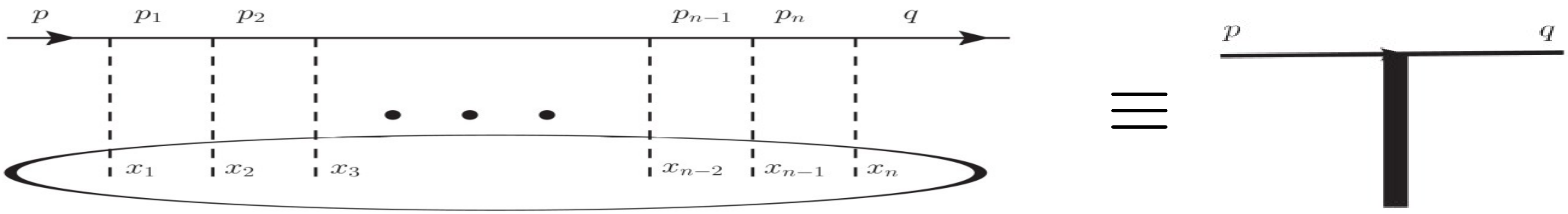
for a proton target (quarks)

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

Shadowing/Nuclear modification factor
Azimuthal angular correlations (di-jets,...)
Long range rapidity correlations (ridge,...)
Initial conditions for hydro
Thermalization (?)

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

CGC: tree level (eikonal approximation)



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

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*

$$S_a^-(k^+ \sim 0, k^-/\sqrt{s} \ll 1, k_t \sim Q_s)$$

Dipole: DIS, proton-nucleus collisions $\quad < Tr\, V(x_\perp)\, V^\dagger(y_\perp) >$

toward precision:

NLO corrections:

Chirilli+Xiao+Yuan, PRL (2012)

Balitsky+Chirilli, PRD88 (2013)

....

sub-eikonal corrections:

Kovchegov+Pitonyak+Sievert, JHEP (2017)

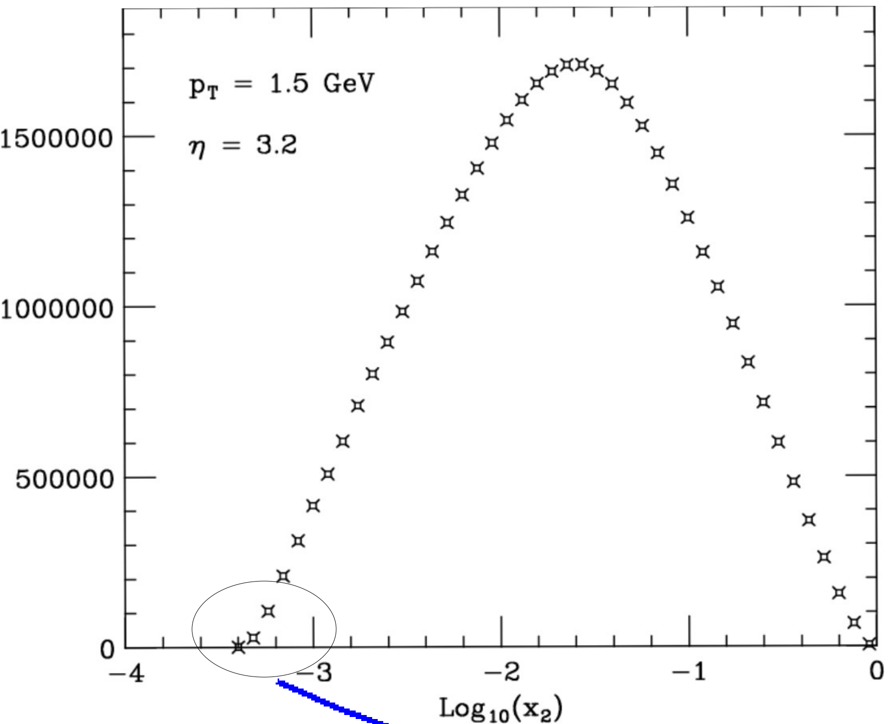
Agostini+Altinoluk+Armesto, EPJC (2019)

....

Not all is well: single inclusive pion production in pp at RHIC

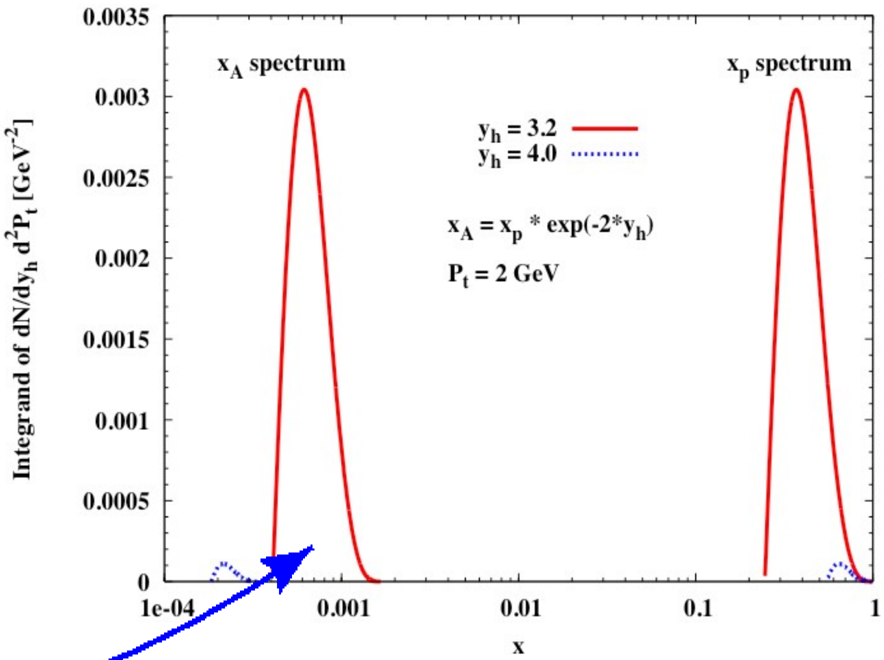
collinear factorization

GSV, PLB603 (2004) 173-183



CGC

DHJ, NPA765 (2006) 57-70

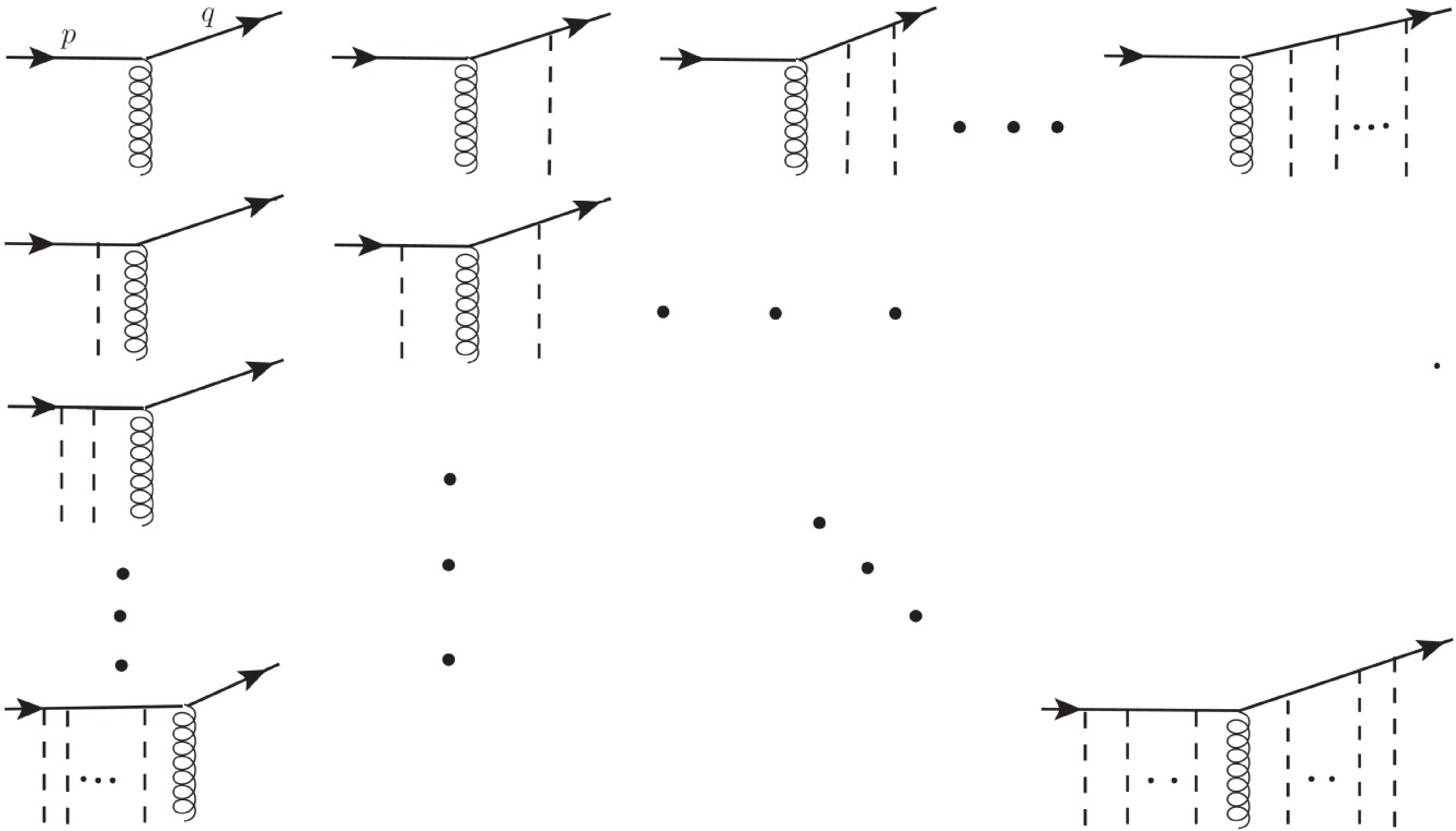


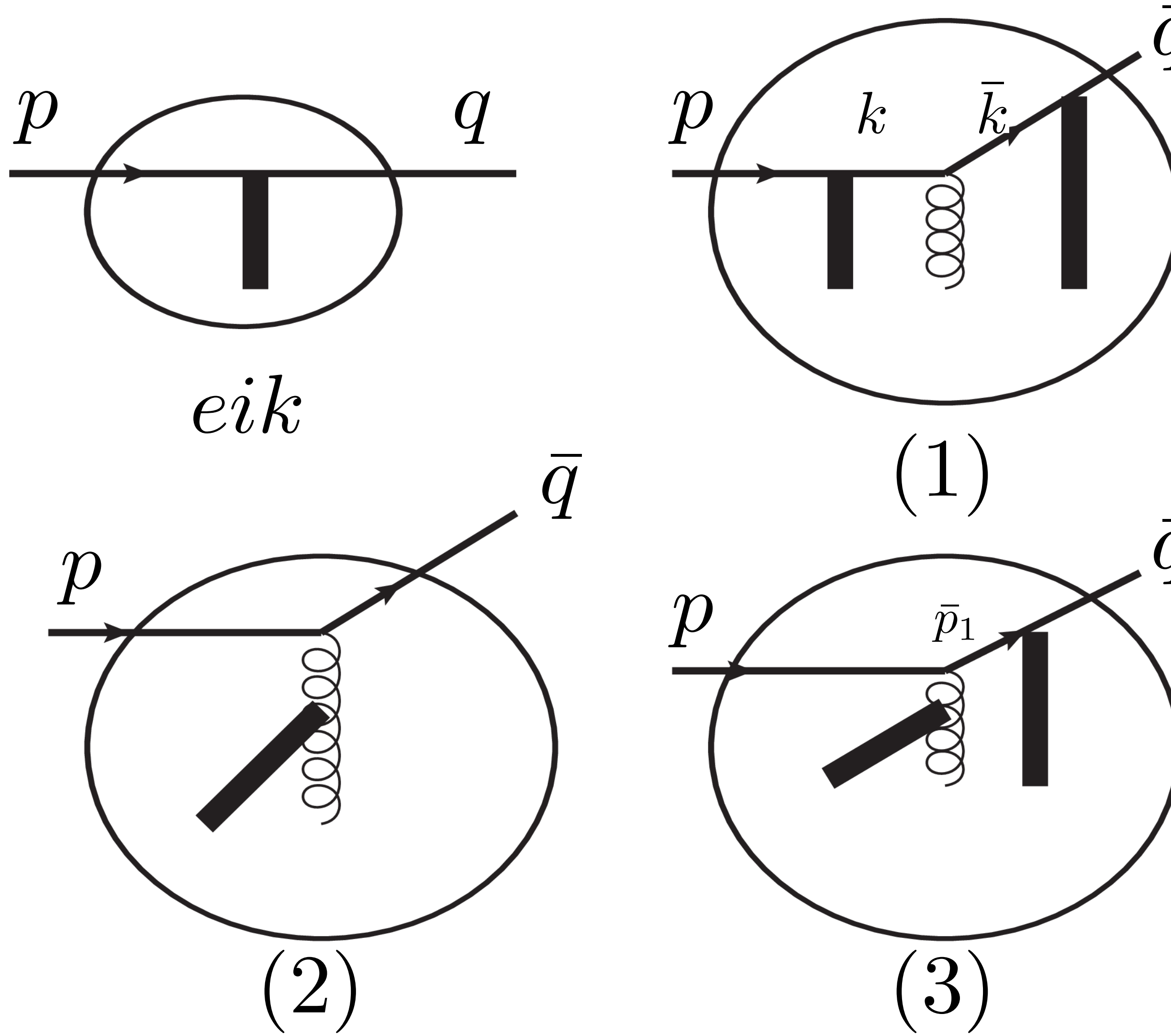
$$\int_{x_{min}}^{1} dx\, xG(x,Q^2) \cdots\cdots \longrightarrow x_{min} G(x_{min},Q^2) \cdots$$

which kinematics are we in?

beyond eikonal approximation:

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




p
q
eik
p
k
$\bar{k}$
$\bar{q}$
(1)
p
$\bar{q}$
(2)
p
$\bar{p}_1$
$\bar{q}$
(3)

$$
\begin{aligned}
i\mathcal{M}_{eik}(p,q) &= 2\pi\delta(p^+ - q^+) \int d^2x_t\, e^{-i(q_t-p_t)\cdot x_t}\ [V(x_t)-1]\,\mathcal{N}_{eik} \\
i\mathcal{M}_1(p,q) &= \int d^4x\, d^2z_t\, d^2\bar{z}_t \int \frac{d^2k_t}{(2\pi)^2}\,\frac{d^2\bar{k}_t}{(2\pi)^2}\, e^{i(\bar{k}-k)x}\, e^{-i(\bar{q}_t-\bar{k}_t)\cdot\bar{z}_t}\, e^{-i(k_t-p_t)\cdot z_t} \\
&\quad \overline{V}(x^+,\bar{z}_t)\,(ig\,t^b)\,V(z_t,x^+)\,\mathcal{N}_1^b \\
i\mathcal{M}_2(p,q) &= 2\,i \int d^4x\, e^{i(\bar{q}^+-p^+)x^- - i(\bar{q}_t-p_t)\cdot x_t}\,(ig\,t^a)\ \left[\partial_{x^+}U^\dagger(x_t,x^+)\right]^{ab}\mathcal{N}_2^b \\
i\mathcal{M}_3(p,q) &= -2\,i \int d^4x\, d^2\bar{x}_t\, d\bar{x}^+\,\frac{d^2\bar{p}_{1t}}{(2\pi)^2}\, e^{i(\bar{p}_1^+-p^+)x^-}\, e^{-i(\bar{p}_{1t}-p_t)\cdot x_t}\, e^{-i(\bar{q}_t-\bar{p}_{1t})\cdot\bar{x}_t} \\
&\quad \left[\partial_{\bar{x}^+}\overline{V}(\bar{x}^+,\bar{x}_t)\right]\ (ig\,t^a)\ \left[\partial_{x^+}U^\dagger(x_t,x^+)\right]^{ab}\mathcal{N}_3^b
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{N}_{eik} &= \bar{u}(q)\,\not{n}\,u(p) \\
\mathcal{N}_1^b &= \frac{1}{2k^+}\,\frac{1}{2\bar{k}^+}\,\bar{u}(\bar{q})\ \left[\not{\bar{n}}\,\not{\bar{k}}\not{A}^b(x)\,\not{k}\,\not{n}\right]\,u(p) \\
\mathcal{N}_2^b &= \frac{1}{(p-\bar{q})^2}\bar{u}(\bar{q})\ \left[n\cdot(p-\bar{q})\not{A}^b(x)-(p-\bar{q})\cdot A^b(x)\,\not{n}\right]\ \Big]\,u(p) \\
\mathcal{N}_3^b &= \frac{1}{2\bar{n}\cdot\bar{p}_1(p-\bar{p}_1)^2}\bar{u}(\bar{q})\left[\not{\bar{n}}\,\not{\bar{p}}_1\left(n\cdot(p-\bar{p}_1)\not{A}^b(x)-(p-\bar{p}_1)\cdot A^b(x)\,\not{n}\right)\right]u(p)
\end{aligned}
$$

cross section: $|\mathbf{i}\mathcal{M}|^{\mathbf{2}} = |\mathbf{i}\mathcal{M}_{\mathbf{eik}} + \mathbf{i}\mathcal{M}_{\mathbf{1}} + \mathbf{i}\mathcal{M}_{\mathbf{2}} + \mathbf{i}\mathcal{M}_{\mathbf{3}}|^{\mathbf{2}}$

soft (eikonal) limit: $i\mathcal{M} \longrightarrow i\mathcal{M}_{eik}$

spinor helicity formalism: light-front spinors

<u>longitudinal double spin asymmetries</u>

<u>angular asymmetries</u>

<u>beam rapidity loss</u>

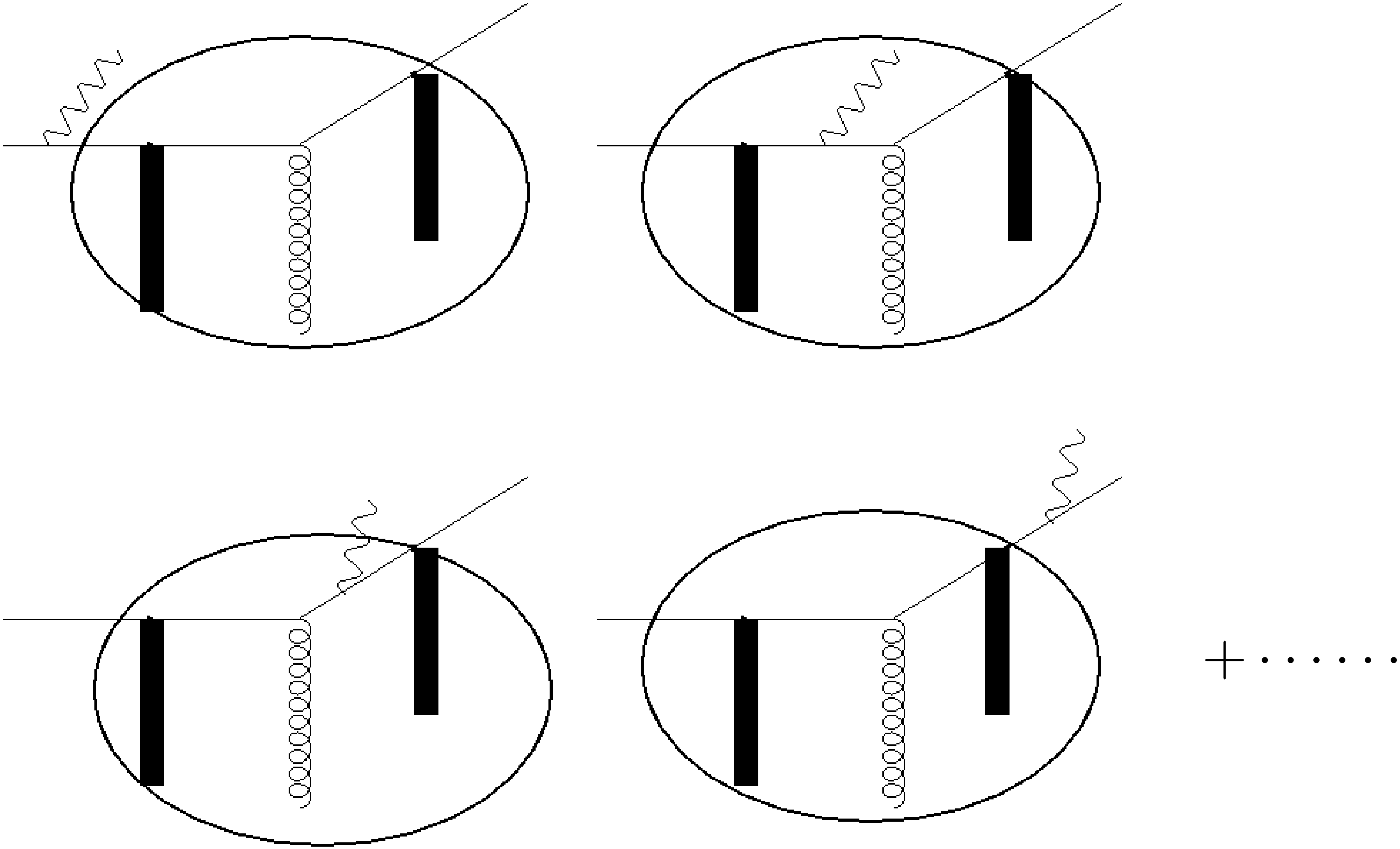
<u>....................</u>

toward one-loop corrections: leading log evolution

gluon radiation

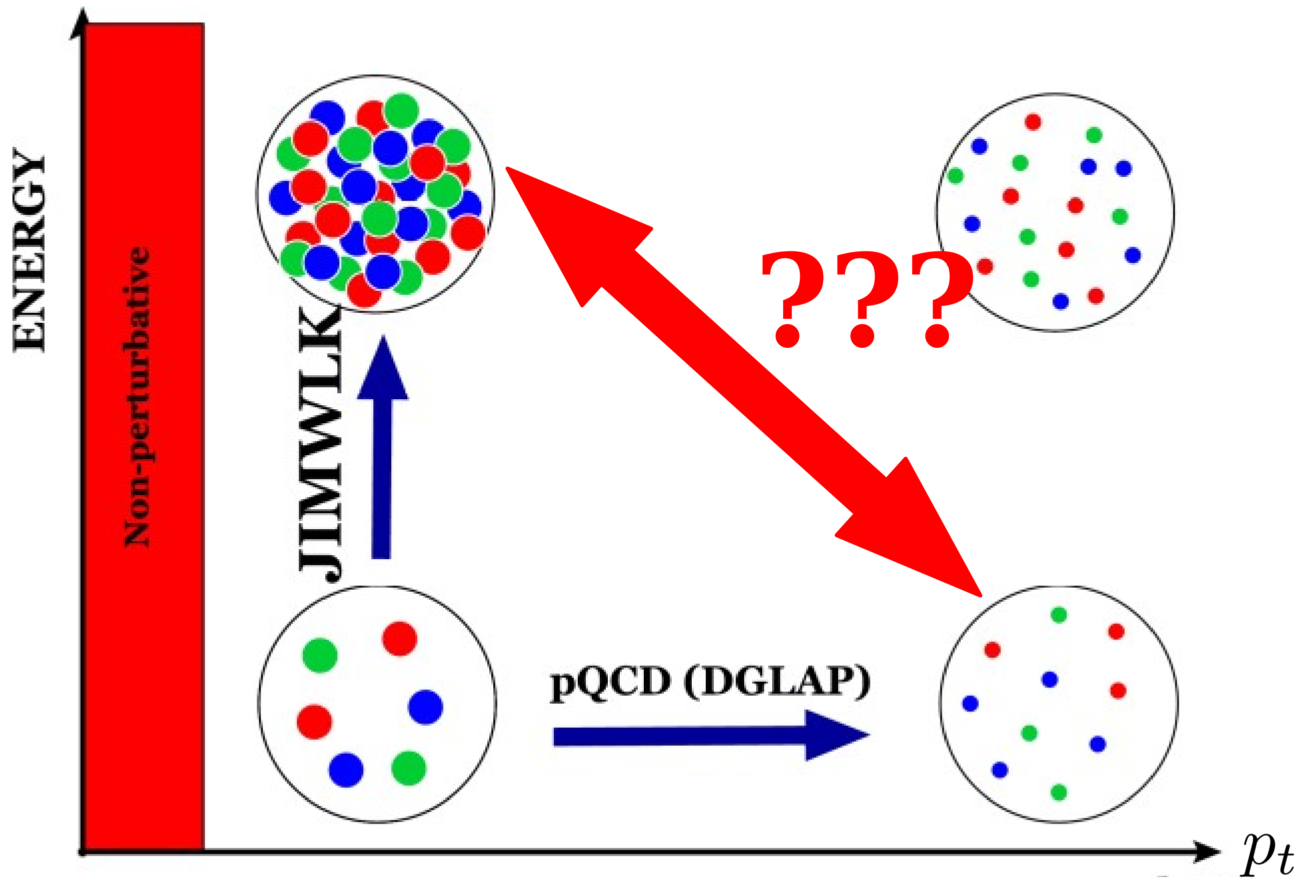
a warm up problem: photon radiation

photon-jet correlations from low to high p_t



work in progress

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 (polar and azimuthal) angular correlations

cold matter energy loss, spin physics, …….

SUMMARY

CGC is a systematic approach to high energy collisions

strong hints from RHIC, LHC,...

connections to TMD,...

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

CGC breaks down at large x (high p_t)

a significant portion of EIC phase space is at large x

transition from DGLAP physics to CGC

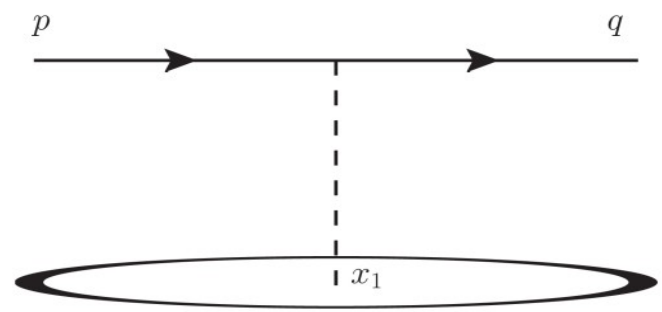
Toward a unified formalism:

particle production in both small and large x (p_t) kinematics

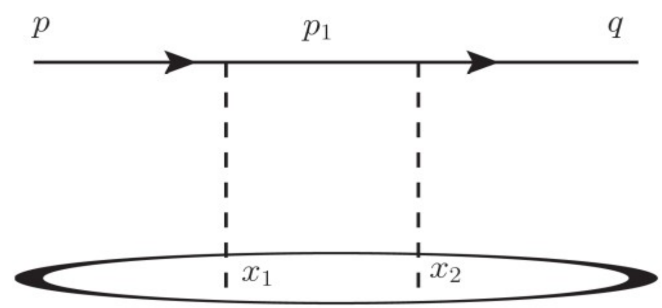
one-loop correction to cross section: from JIMWLK to DGLAP ?

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

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



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



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

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 $\not{n}\, \frac{\not{p}_1}{2n\cdot p}\, \not{n} = \not{n}$

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