Particle production in high energy collisions: from high to low p_t and back

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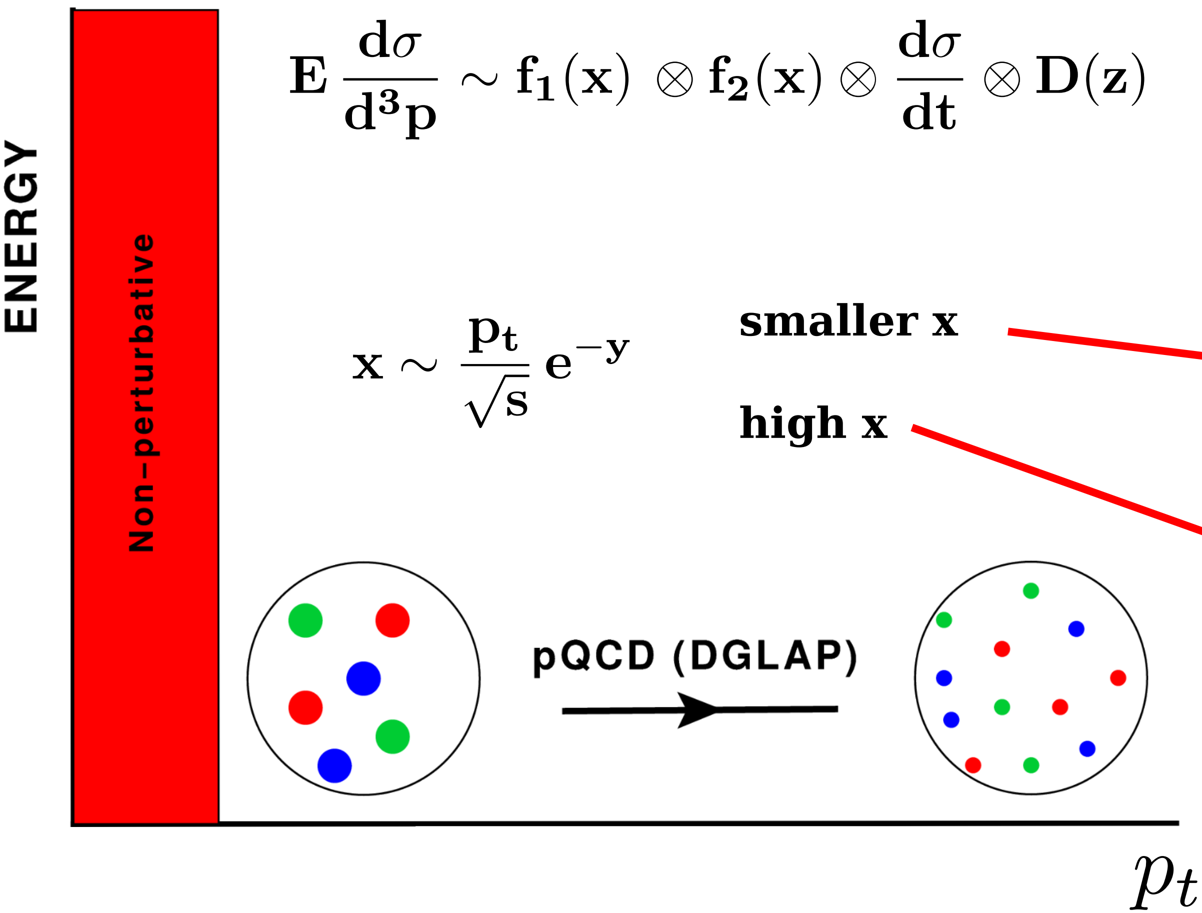
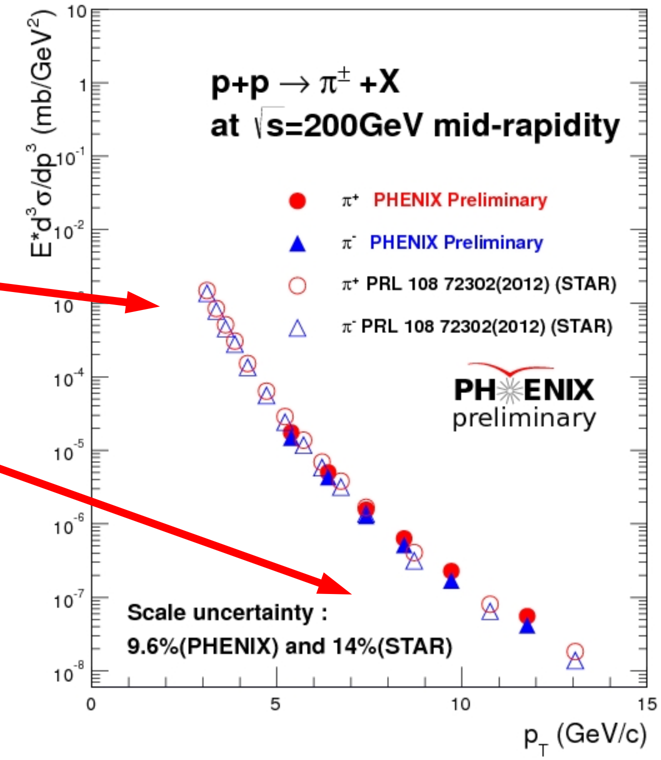
pQCD: the standard paradigm

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

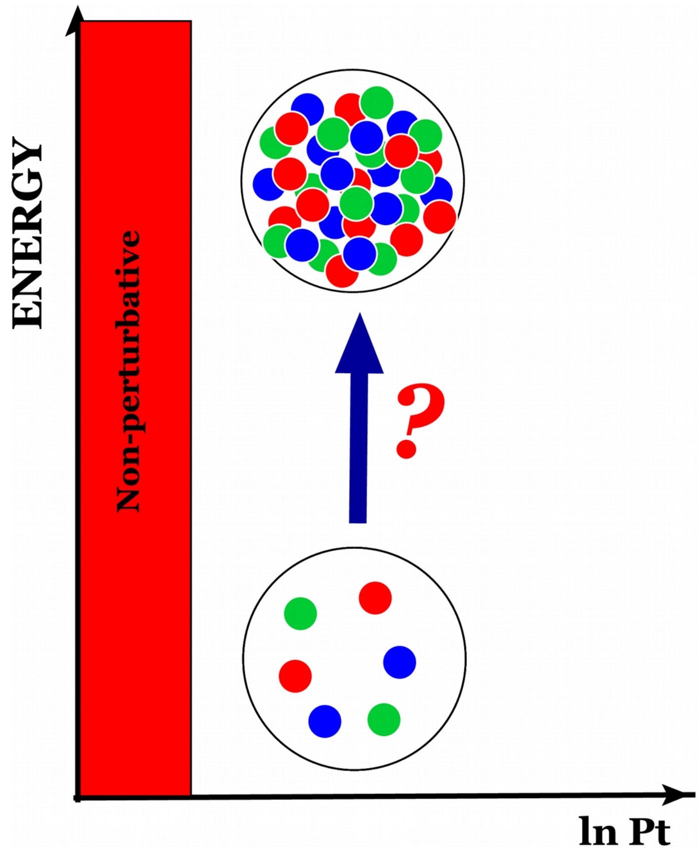
$$x \sim \frac{p_t}{\sqrt{s}}\, e^{-y}$$





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

A hadron/nucleus at high energy: gluon saturation



$$\frac{\partial \mathbf{W_E}[\mathbf{A}]}{\partial \mathbf{E}} = \mathcal{H}\, \mathbf{W_E}[\mathbf{A}]$$

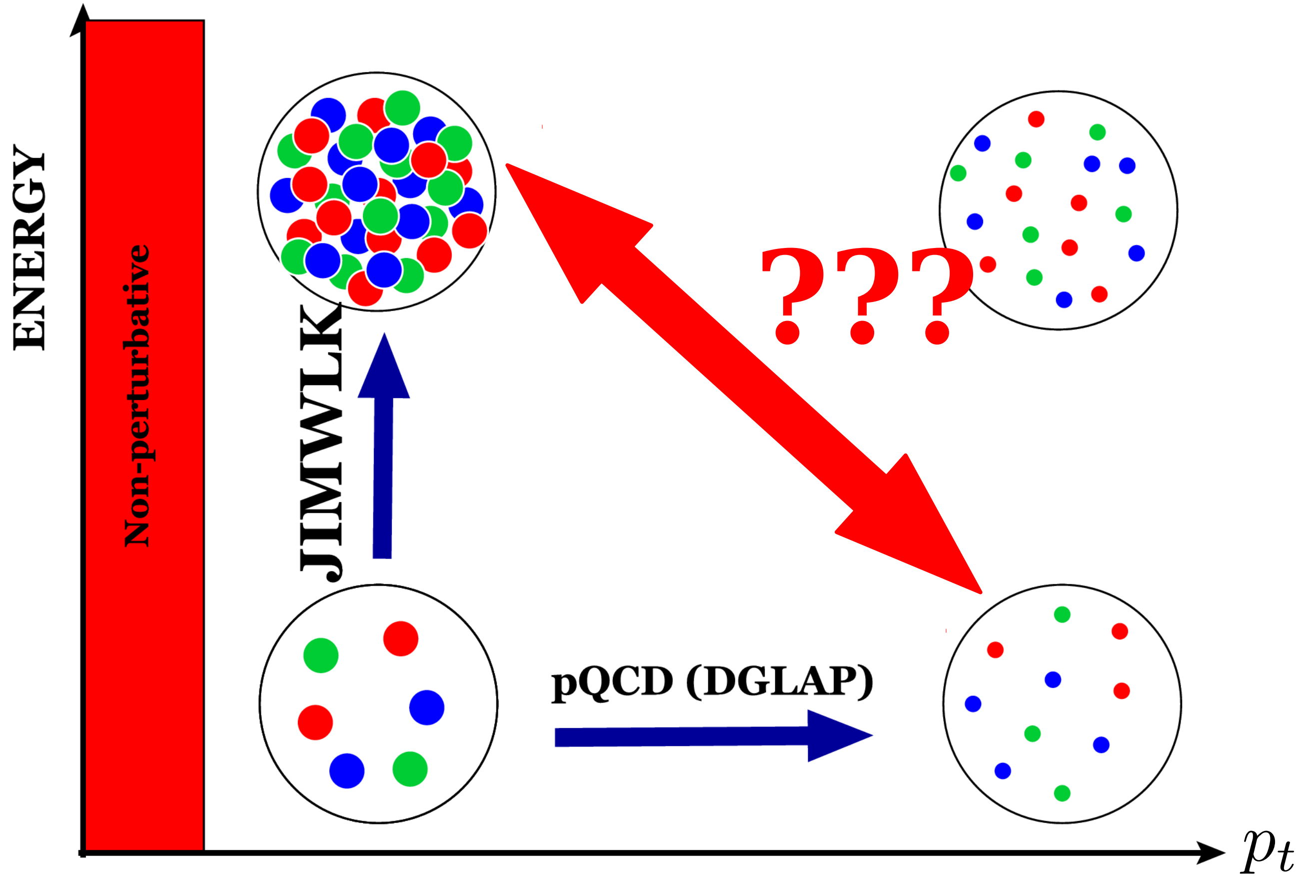
JIMWLK eq.

dynamics of universal gluonic matter

a framework for multi-particle production in QCD

not applicable at high x/high p_t

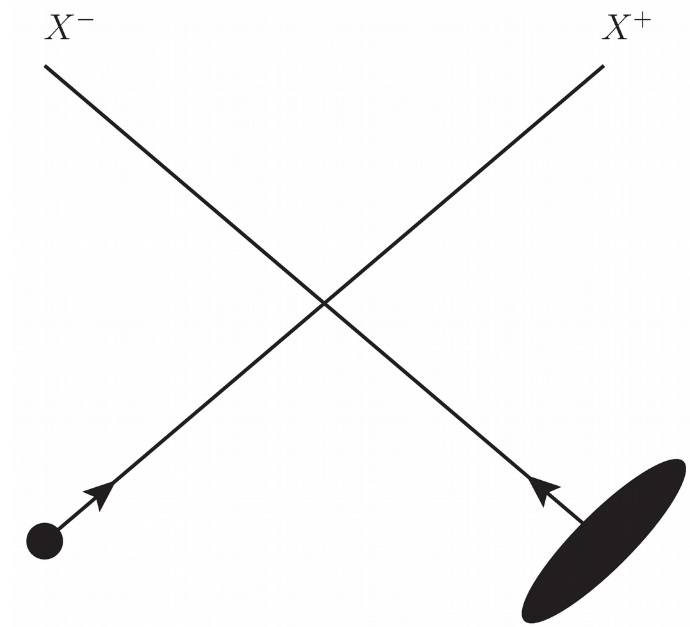
QCD kinematic phase space



connecting JIMWLK with pQCD?

jet physics
partially/fully coherent energy loss
interactions of UHE neutrinos, ...

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



$$J_a^\mu \simeq \delta^{\mu -} \rho_a$$

$$D_\mu\, J^\mu \quad = \quad D_-\, J^- = 0$$

$$\partial_- J^- \quad = \quad 0$$ (in A+ = 0 gauge)

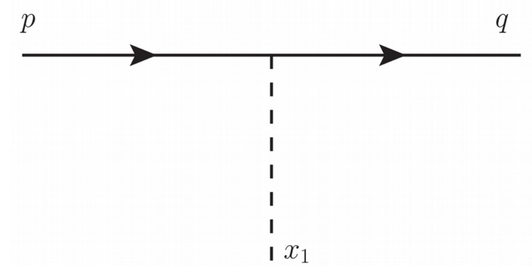
does not depend on x$^-$

solution to classical EOM:

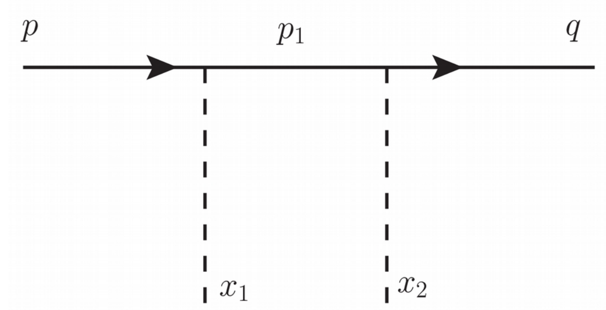
$$A_a^-(x^+, x_t) \equiv n^-\, S_a(x^+, x_t)$$

scattering of a quark from background color field $A_a^-(x^+, x_t)$

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



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

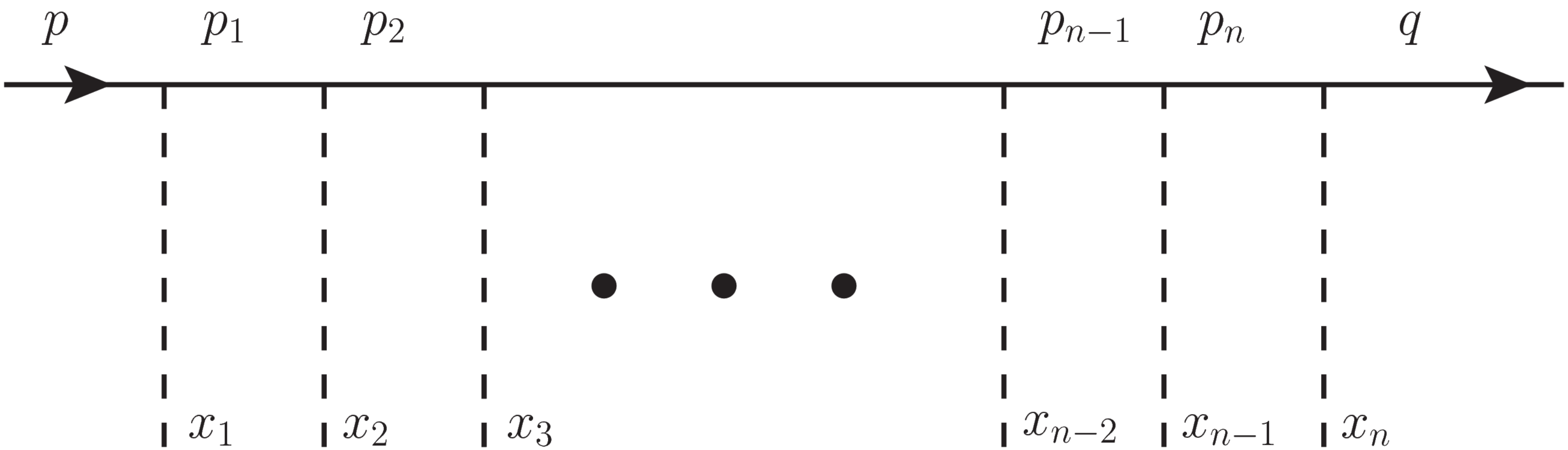


$$
\int \frac{dp_1^-}{(2\pi)}\frac{e^{ip_1^-(x_1^+ - x_2^+)}}{2p^+\left[p_1^- - \frac{p_{1t}^2 - i\epsilon}{2p^+}\right]} = \frac{-i}{2p^+}\,\theta(x_2^+ - x_1^+)\, e^{i\frac{p_{1t}^2}{2p^+}(x_1^+ - x_2^+)}
$$

contour integration over the pole leads to time ordering of scattering

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

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



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

sum over all scatterings gives (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 $\quad V(x_t) \equiv \hat{P}\, \exp\left\{ ig \int_{-\infty}^{+\infty} dx^+\, n^-\, S_a(x^+, x_t)\, t_a \right\}$

including propagation “backward” gives $V^\dagger$

toward unifying small and large x (multiple scattering)

scattering from small x modes of the target field S involves only small transverse momenta exchange (small angle deflection)

$$
\begin{aligned}
p^\mu &= (p^+ \sim \sqrt{s},\, p^- = 0, p_t = 0) \\
S &= S(p^+ \sim 0, p^-/P^- \ll 1, p_t)
\end{aligned}
$$

allow hard scattering by including one all x field during which there is large momenta exchanged and quark can get deflected by a large angle.

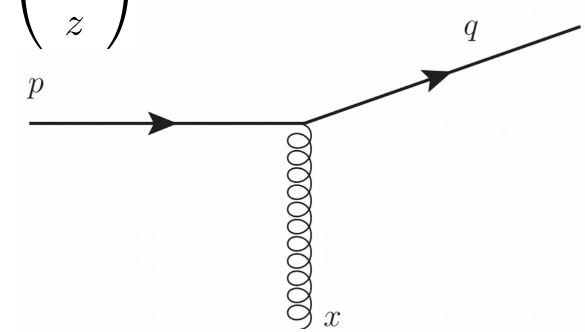
$$A_a^\mu(x^+, x^-, x_t)$$

include Eikonal multiple scattering before and after (along a different direction) the hard scattering

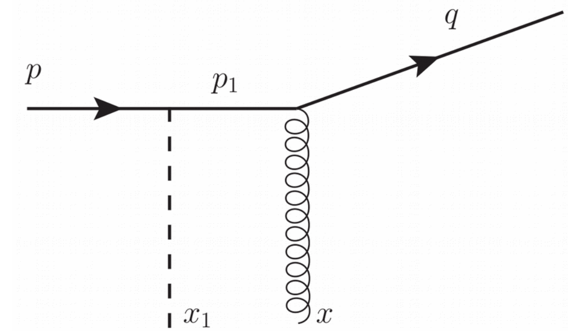
hard scattering: large deflection
scattered quark travels in the new “z” direction: $\bar{z}$

$$\begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix} = \mathcal{O} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

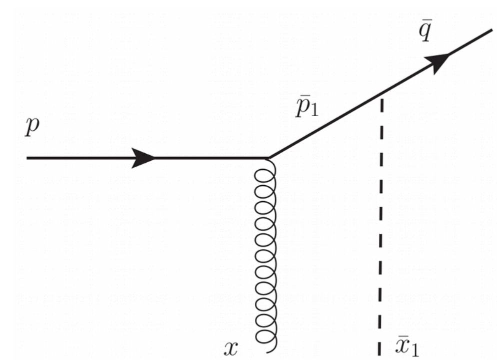
$$i\mathcal{M}_1 = (ig) \int d^4x\, e^{i(\bar{q}-p)x}\, \bar{u}(\bar{q})\, \left[\not{A}(x)\right]\, u(p)$$



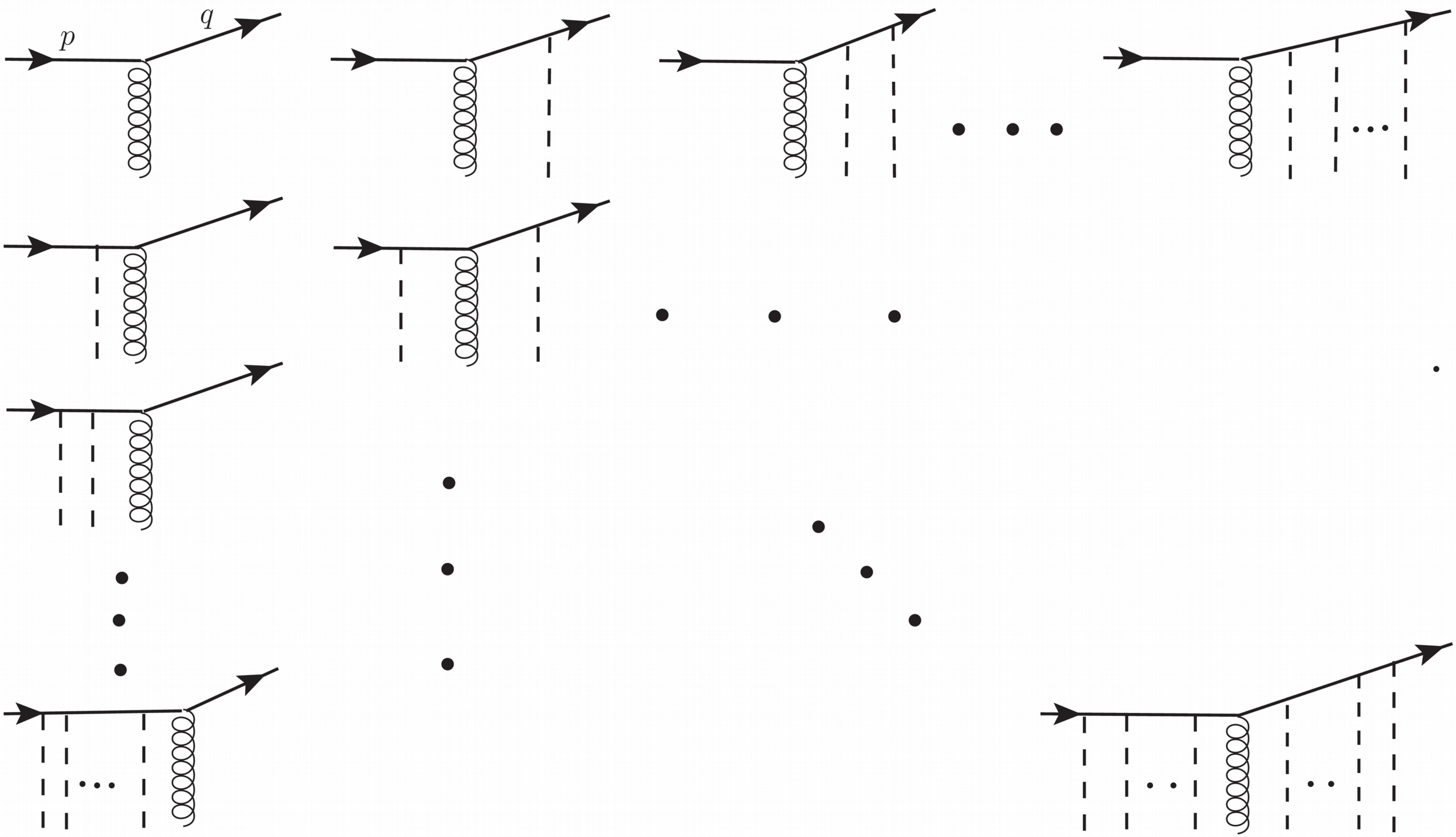
$$\begin{aligned} i\mathcal{M}_2 \quad &= \quad (ig)^2 \int d^4x\, d^4x_1 \int \frac{d^4p_1}{(2\pi)^4}\, e^{i(p_1-p)x_1}\, e^{i(\bar{q}-p_1)x} \\ &\quad\ \bar{u}(\bar{q})\, \left[\not{A}(x)\, \frac{i\not{p}_1}{p_1^2 + i\epsilon}\, \not{n}\, S(x_1)\right]\, u(p) \end{aligned}$$



$$\begin{aligned} i\mathcal{M}_2 \quad &= \quad (ig)^2 \int d^4x\, d^4\bar{x}_1 \int \frac{d^4\bar{p}_1}{(2\pi)^4}\, e^{i(\bar{p}_1-p)x}\, e^{i(\bar{q}-\bar{p}_1)\bar{x}_1} \\ &\quad\ \bar{u}(\bar{q})\, \left[\bar{\not{n}}\, \bar{S}(\bar{x}_1)\, \frac{i\bar{\not{p}}_1}{\bar{p}_1^2 + i\epsilon}\, \not{A}(x)\right]\, u(p) \end{aligned}$$



with $\quad \bar{S}^\mu = \Lambda^\mu_{\ \nu}\, S^\nu$


p
q

$$S_F(p,\bar{q}) = (2\pi)^4 \delta^4(p-\bar{q})\, S_F^0(p) + S_F^0(p)\, \tau_{hard}(p,\bar{q})\, S_F^0(\bar{q})$$

$$\begin{aligned}
\tau_{hard}(p,\bar{q}) \;\;\equiv\;\; & (ig)\int d^4x \int \frac{d^2k_t}{(2\pi)^2}\,\frac{d^2\bar{k}_t}{(2\pi)^2}\, d^2z_t\, d^2\bar{z}_t\, e^{i(\bar{k}-k)x}\, e^{-i(\bar{q}_t-\bar{k}_t)\cdot\bar{z}_t}\, e^{-i(k_t-p_t)\cdot z_t} \\
& \Big\{\theta(p^+)\,\theta(\bar{q}^+)\, V(z_t,x^+)\, \not{n}\, \frac{\not{k}}{2k^+} \not{A}(x)\, \frac{\not{\bar{k}}}{2\bar{k}^+}\, \not{\bar{n}}\, \overline{V}(x^+,\bar{z}_t) - \\
& \theta(-p^+)\,\theta(-\bar{q}^+)\, V^\dagger(z_t,x^+)\, \not{n}\, \frac{\not{k}}{2k^+} \not{A}(x)\, \frac{\not{\bar{k}}}{2\bar{k}^+}\, \not{\bar{n}}\, \overline{V}^\dagger(x^+,\bar{z}_t)\Big\}
\end{aligned}$$

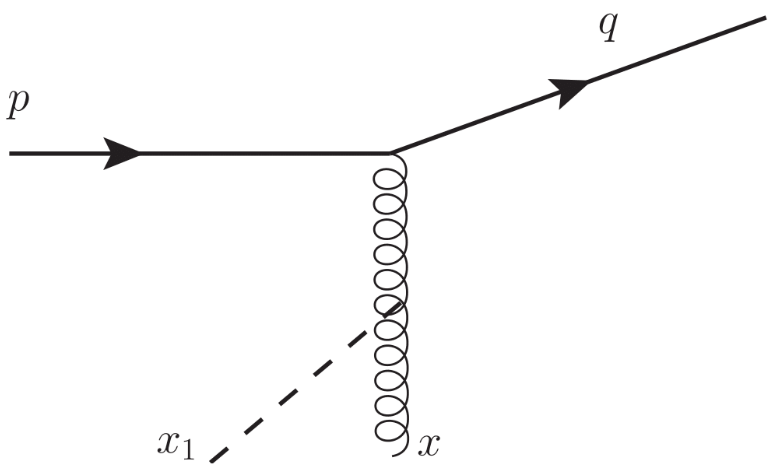
with

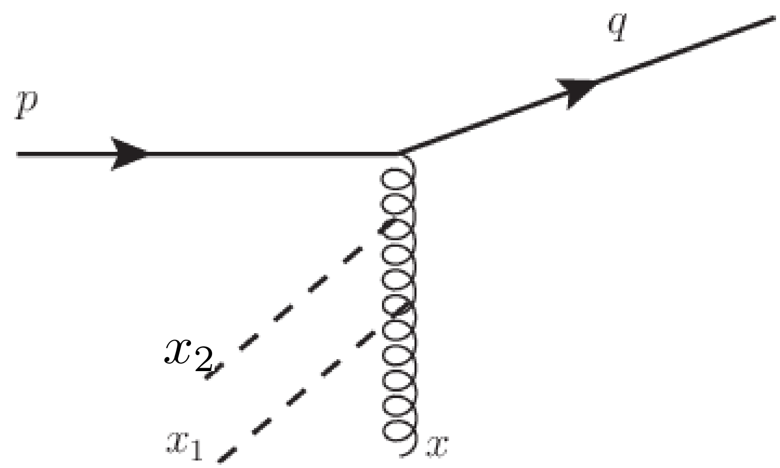
$$\overline{V}(x^+,\bar{z}_t) \equiv \hat{P}\, \exp\left\{ig\int_{x^+}^{+\infty} d\bar{z}^+\, \bar{S}_a(\bar{z}^+,\bar{z}_t)\, t_a\right\}$$

all “bar-ed” quantities are in a rotated frame where quark’s new direction of propagation (after a hard scattering) is $\bar{z}$

this quark propagator is the building block for DIS structure functions, single inclusive particle production in pA,....

but there is more to do: interactions of large and small x modes





in progress

SUMMARY

CGC is a systematic approach to high energy collisions

CGC breaks down at large x (high pt)

Toward a unified formalism:

- ***quark propagator in the background of small and large x fields***
- ***QCD structure functions at both small and large x***
- ***particle production in pp, pA in both small and large p_t regions***