Photon-hadron/jet production and angular correlations
in
high energy proton-nucleus collisions

(from small to large x: toward a unified formalism)

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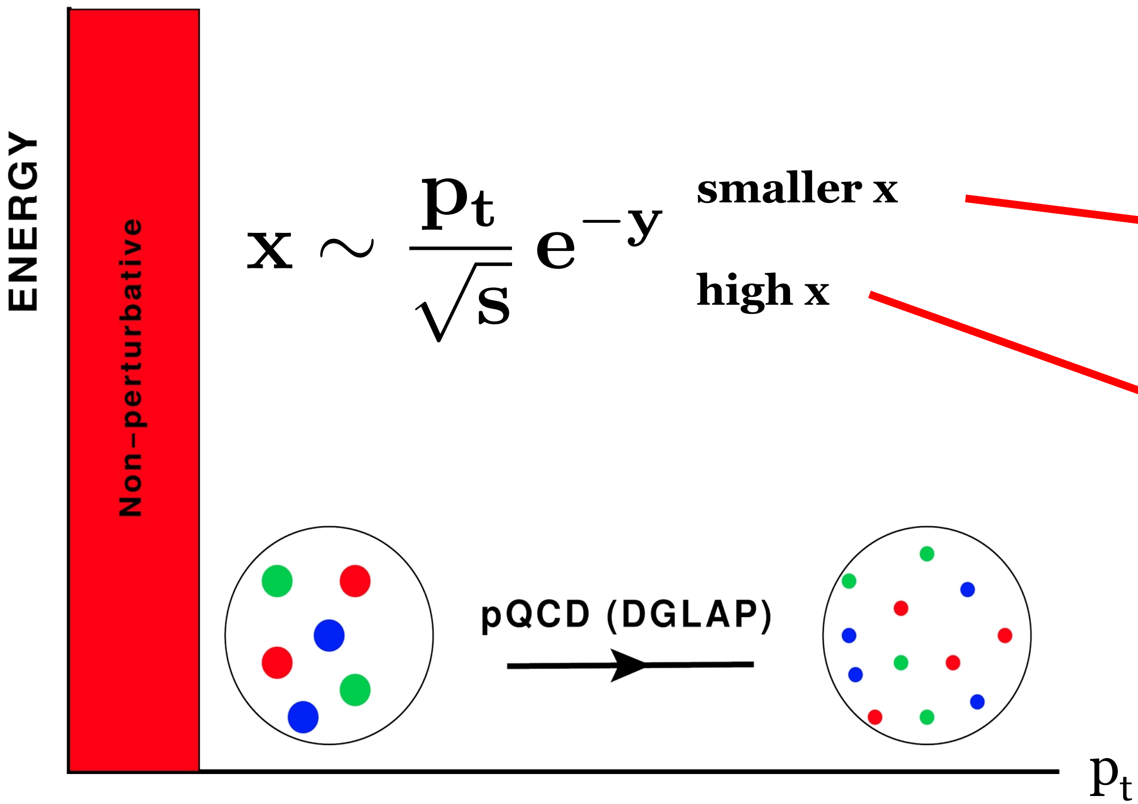
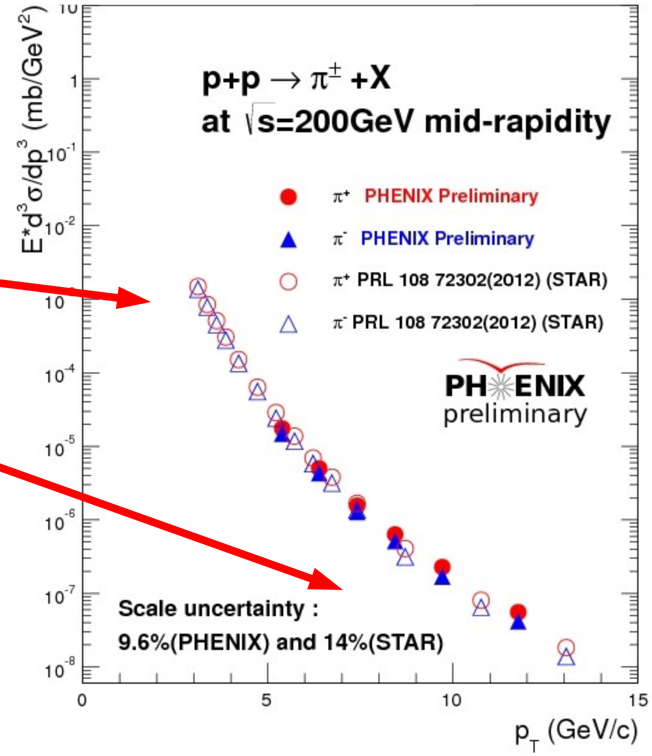
based on:
PRD102 (2020) 1, 014008
PRD99 (2019) 1, 014043
PRD96 (2017) 7, 074020 and work in progress

pQCD: the standard paradigm

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

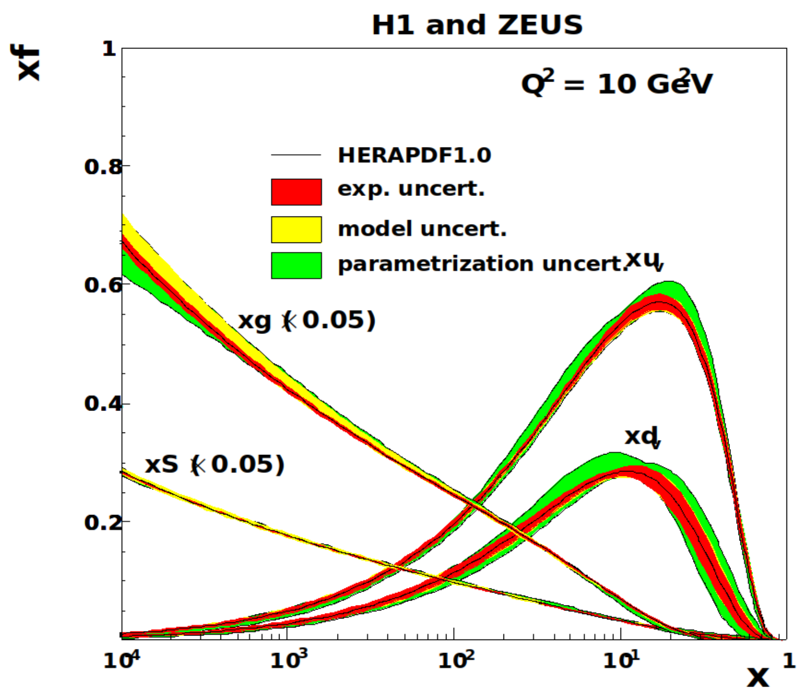
$$x \sim \frac{p_t}{\sqrt{s}}\, e^{-y}$$



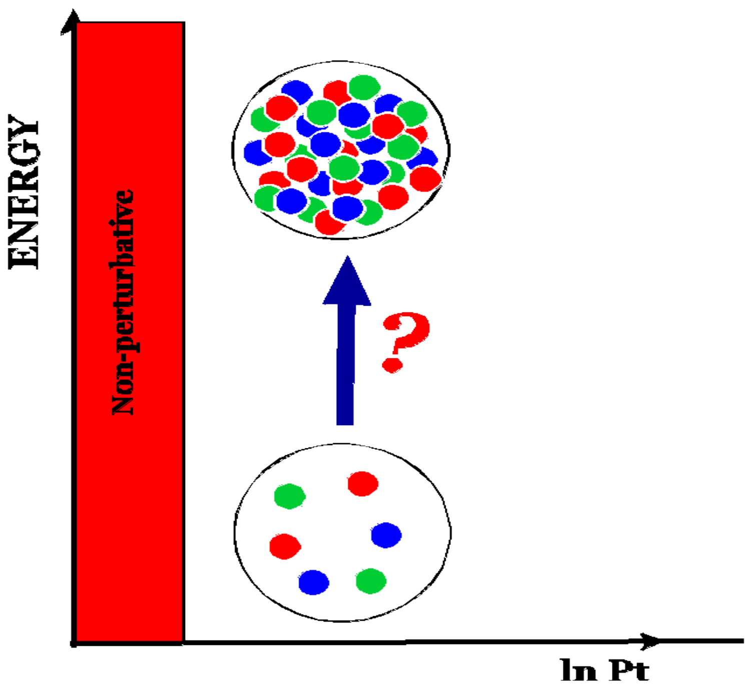


bulk of QCD phenomena happens at low p_t (small x)

dynamics of *universal gluonic matter:*
gluon saturation



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



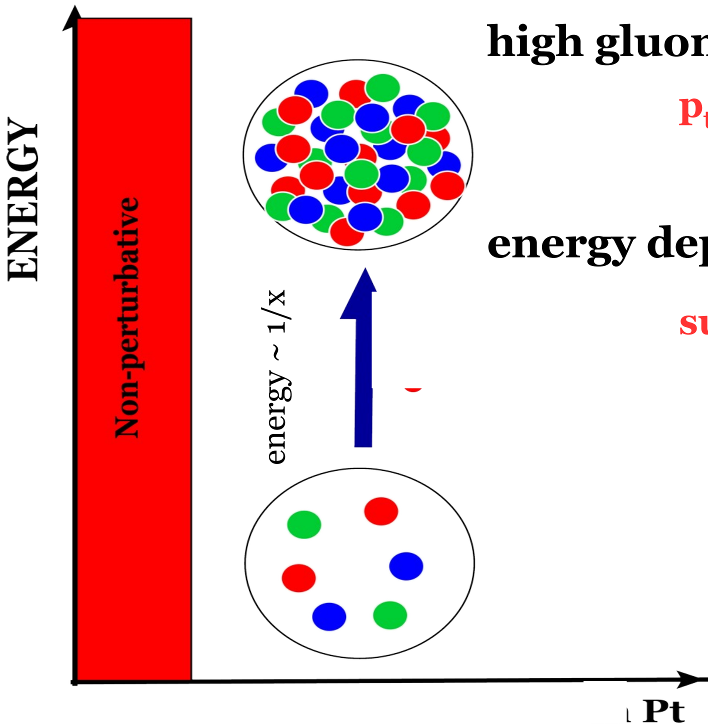
How does this happen ?

How do correlation functions evolve ?

Is there a universal fixed point for the evolution ?

Are there scaling laws ?

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

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

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

for a proton target (quarks)

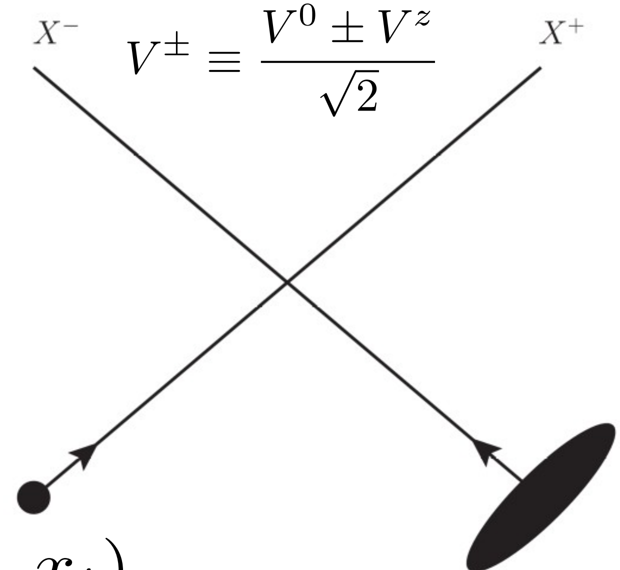
a framework for multi-particle production in QCD at small x/low p_t

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

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

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

Eikonal approximation *(dilute-dense scattering)*



$$J^\mu_a \simeq \delta^{\mu -} \rho_a$$

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

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

does not depend on x^-

EOM:solution $$A^-_a(x^+, x_t) \equiv n^- S_a(x^+, x_t)$$

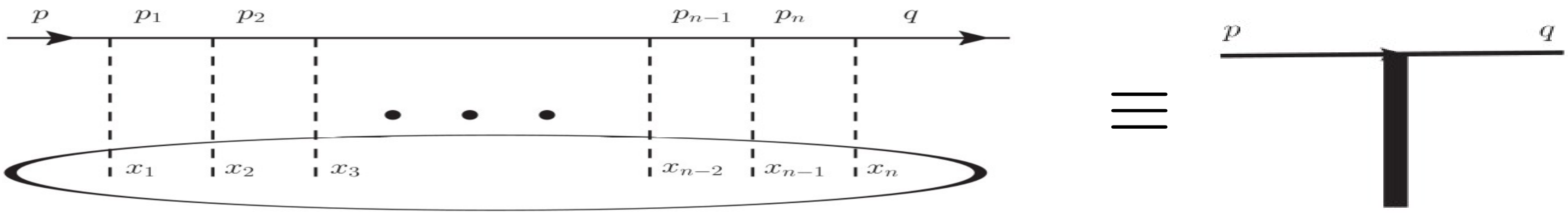
$$n^\mu = (n^+ = 0, n^- = 1, n_t = 0)$$

recall (eikonal approx): $$\bar{u}(q)\gamma^\mu u(p) \to \bar{u}(p)\gamma^\mu u(p) \sim p^\mu$$

$$\bar{u}(q)\not{A}\, u(p) \to p \cdot A \sim p^+ A^-$$

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

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 <u>small x gluons</u> of the target
can cause only a <u>*small angle deflection*</u>

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

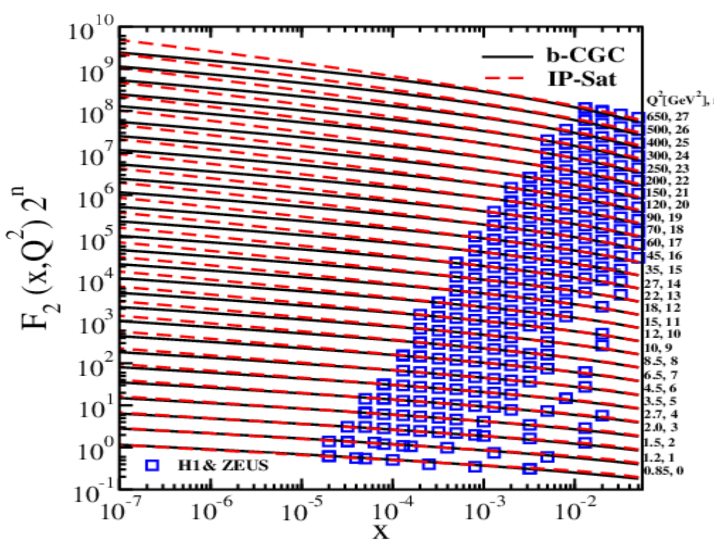
Pre-RHIC: all we know about saturation came from HERA structure function fits

HERA: large kinematic window for x
structure functions: x = x_{bj}

Still debating whether saturation is seen at HERA!

<u>Less-inclusive observables are more discriminatory</u>

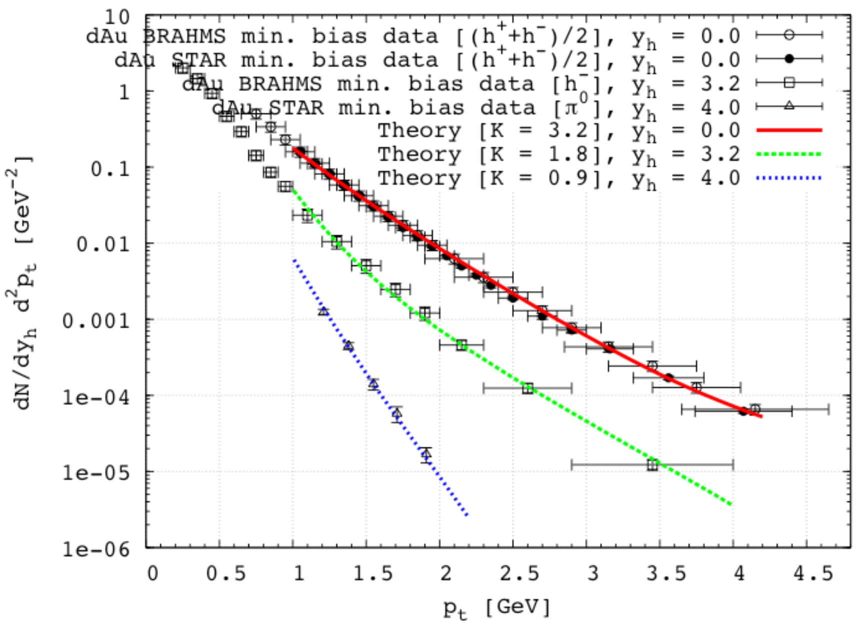
$\mathbf{x \neq x_{bj}}$

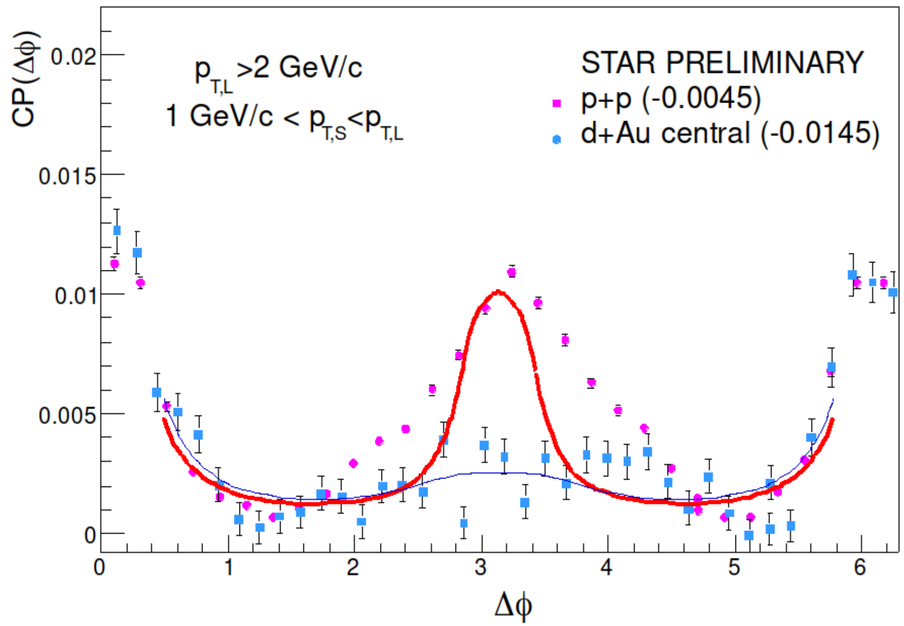


A. Rezaeian and I. Schmidt, PRD88 (2013) 074016

CGC at RHIC

Single and double inclusive hadron production in dA collisions





DHJ, NPA770 (2006) 57

Albacete+Marquet
PRL105 (2010) 162301

convolution over x: is x small enough?

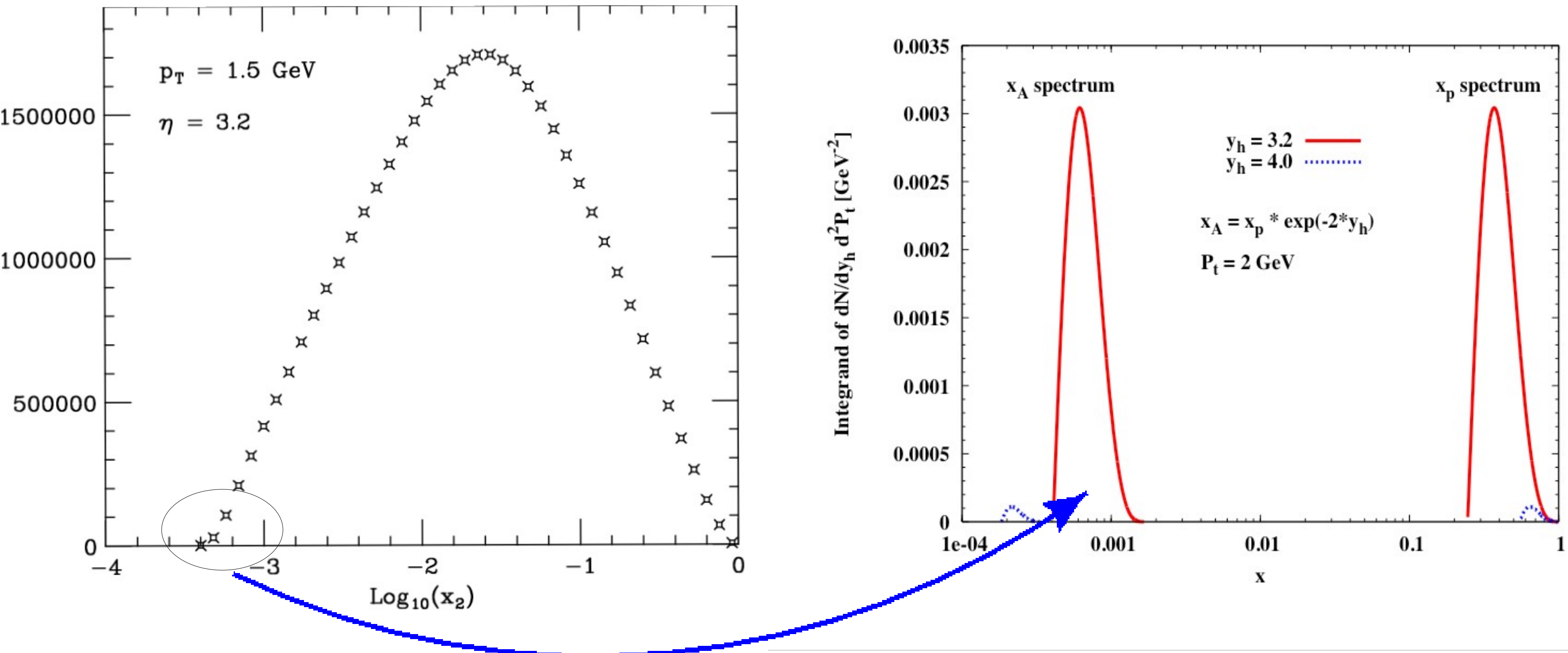
Single inclusive pion production in pp at RHIC

collinear factorization

GSV, PLB603 (2004) 173-183

CGC

DHJ, NPA765 (2006) 57-70

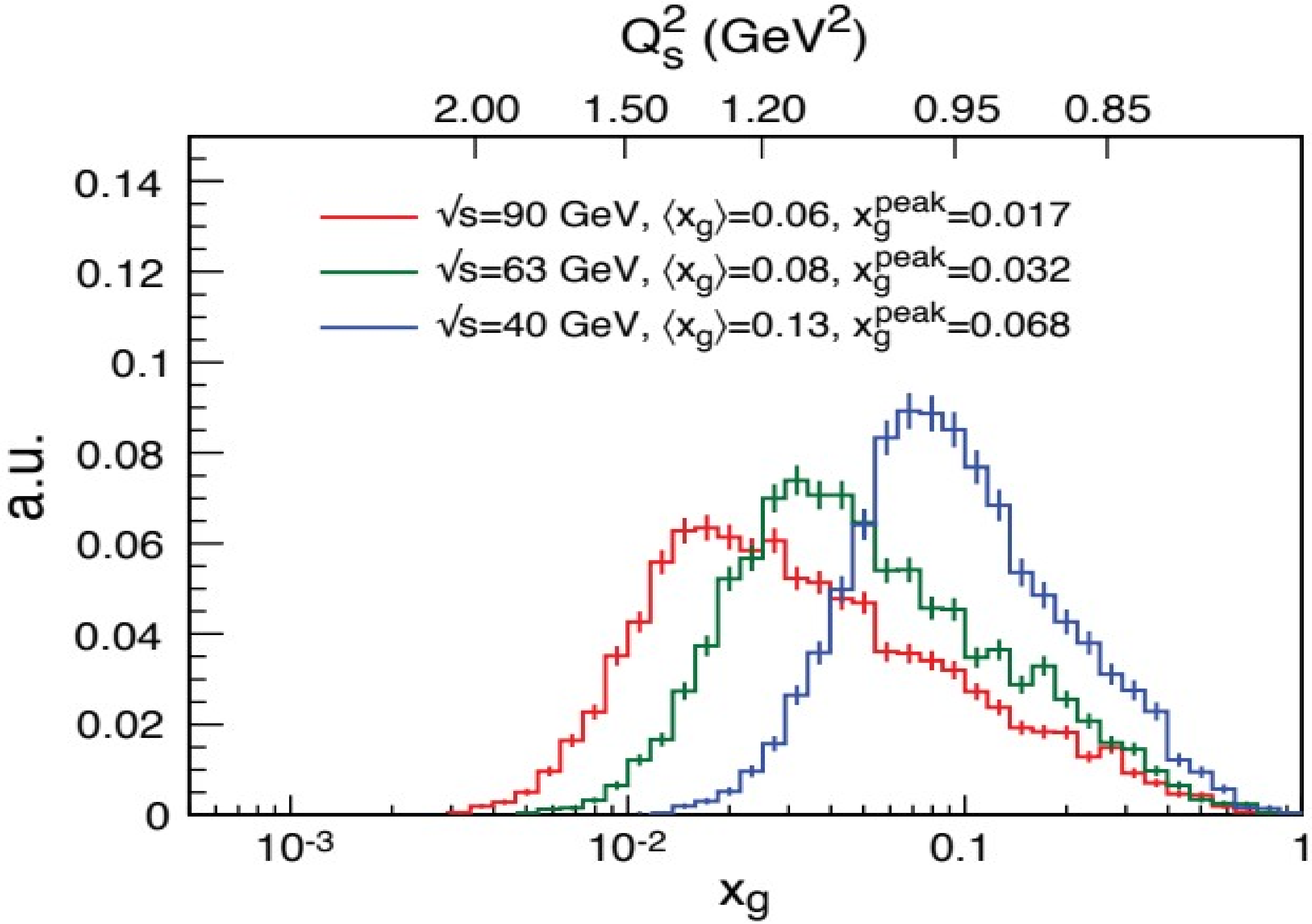


$$\int_{x_{min}}^{1} dx\, xG(x, Q^2) \cdots\cdots \longrightarrow x_{min} G(x_{min}, Q^2) \cdots$$

which kinematics are we in?

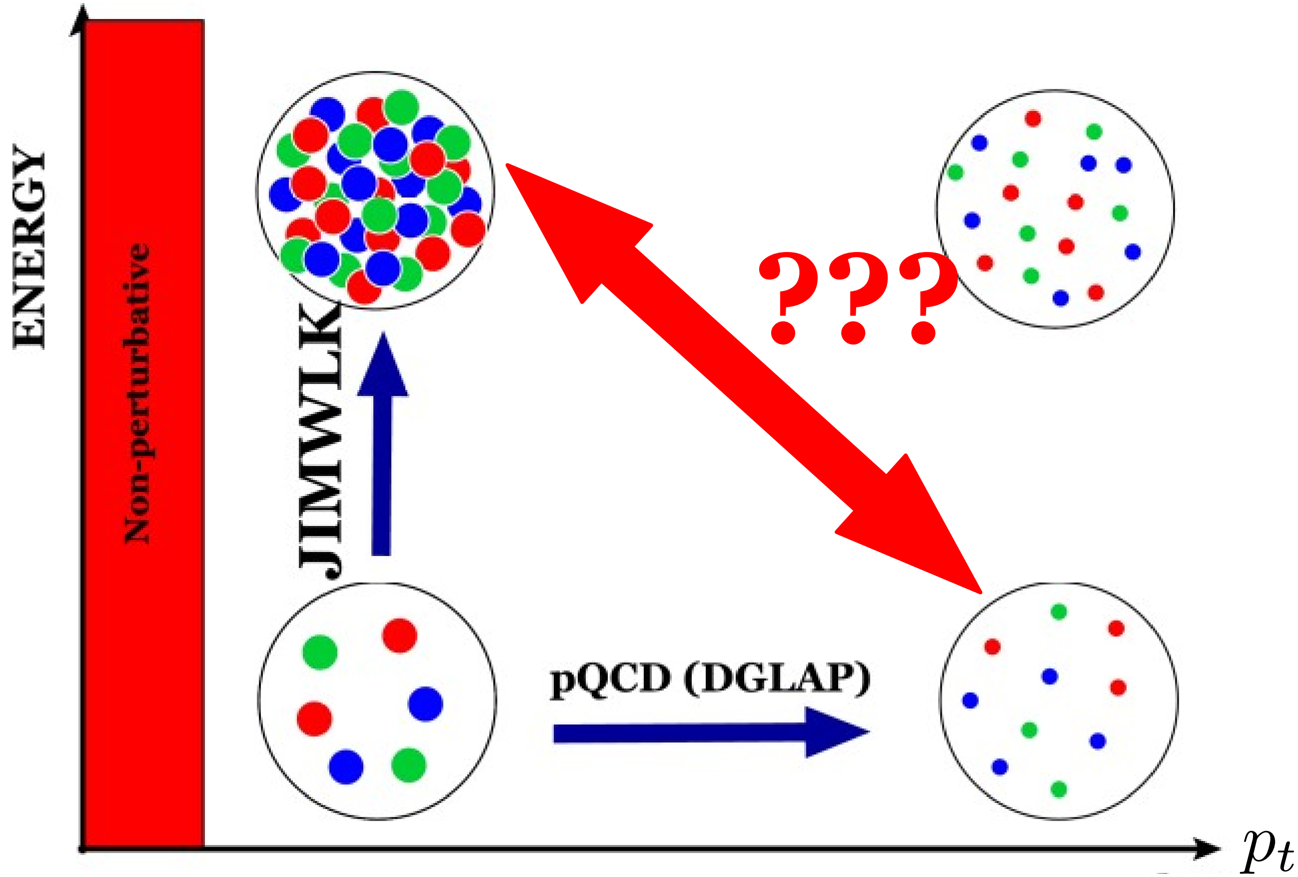
EIC

Kinematics of double inclusive hadron production



Aschenauer et al. arXiv:1708.01527

QCD kinematic phase space



unifying saturation with high p_t (large x) pnysics?

<u>kinematics of saturation: *where is saturation applicable?*</u>
structure functions at all Q^2
high p_t and forward-backward correlations,
spin physics, early time e-loss in heavy ion collisions, ...

Beyond eikonal approximation: longitudinal momentum exchange

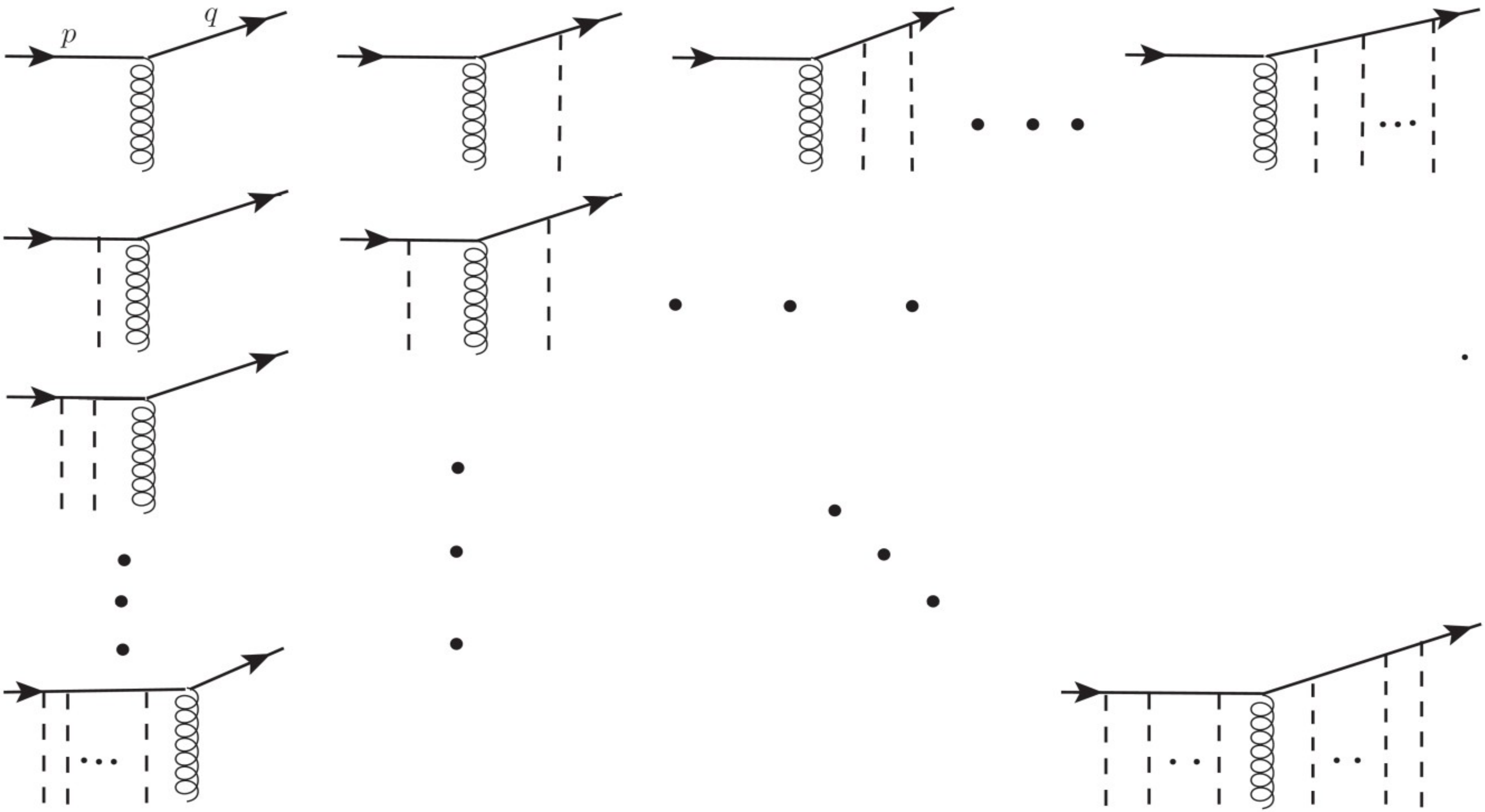
$\mathcal{A}^\mu = \mathbf{S}^\mu + \mathbf{A}^\mu$

single scattering from
large x gluons of target

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

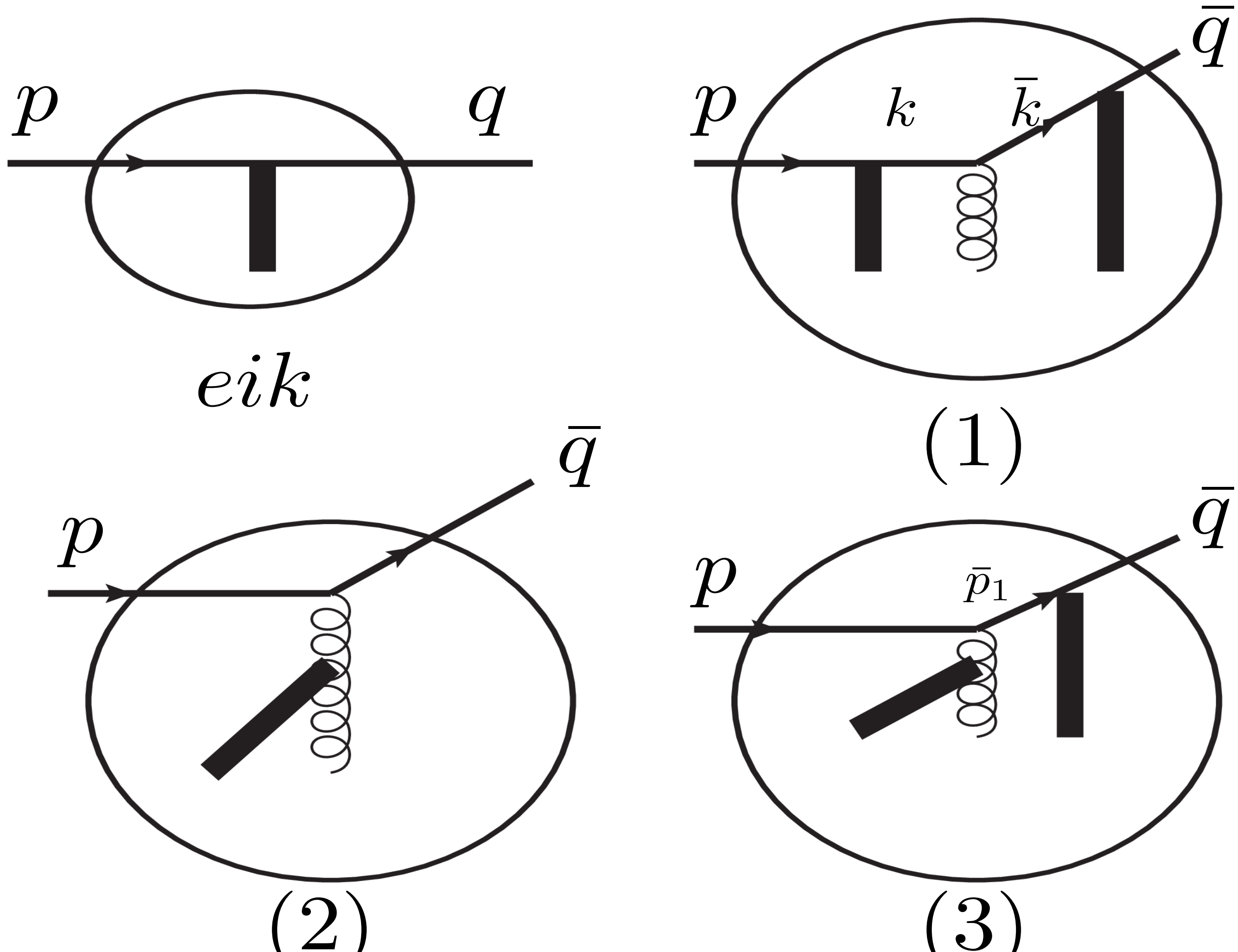
multiple scatterings from
small x gluons of target (CGC)

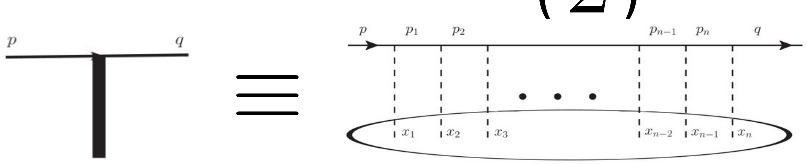
$\mathbf{S}^\mu$



Quark scattering: beyond small x approximation

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





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

use spinor helicity formalism: helicity amplitudes

Including large x partons of the target leads to:

longitudinal double spin asymmetries (A_{LL})

baryon transport (beam rapidity loss), ...

one-loop corrections: factorized cross section at all x (p_t)

gluon radiation

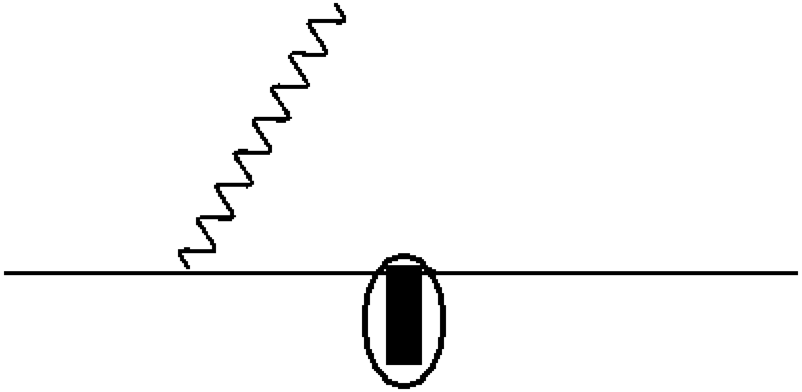
related problem: photon production

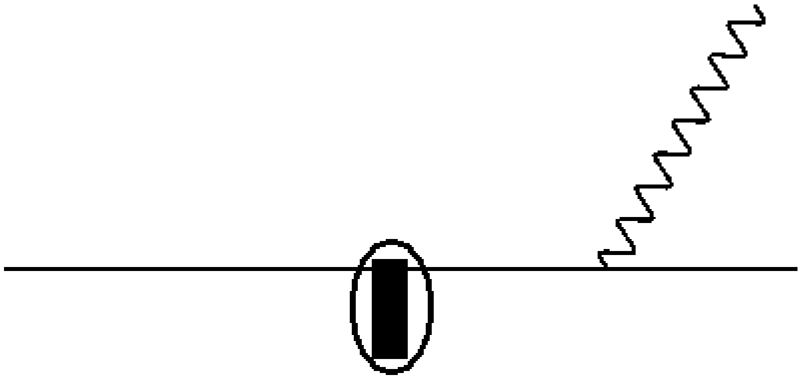
photon-hadron correlations:

azimuthal angular correlations from low to high p_t

forward-backward rapidity correlations

photon radiation: small x (eikonal approximation)



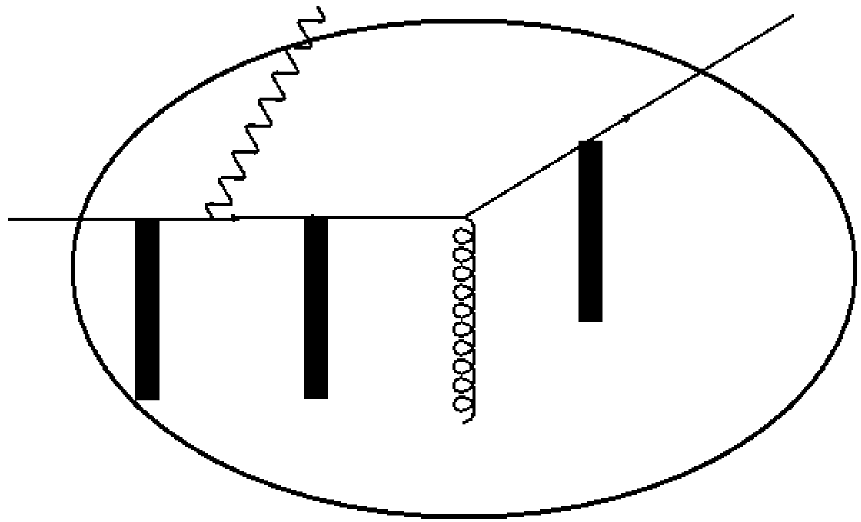


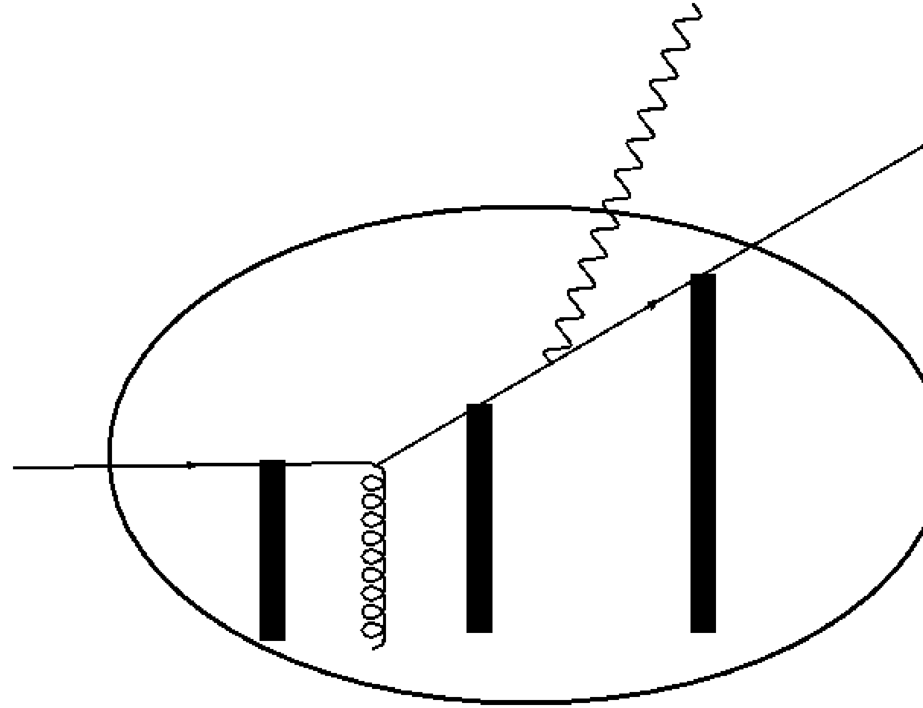
before quark scatters on the target

after quark scatters on the target

No radiation inside the target

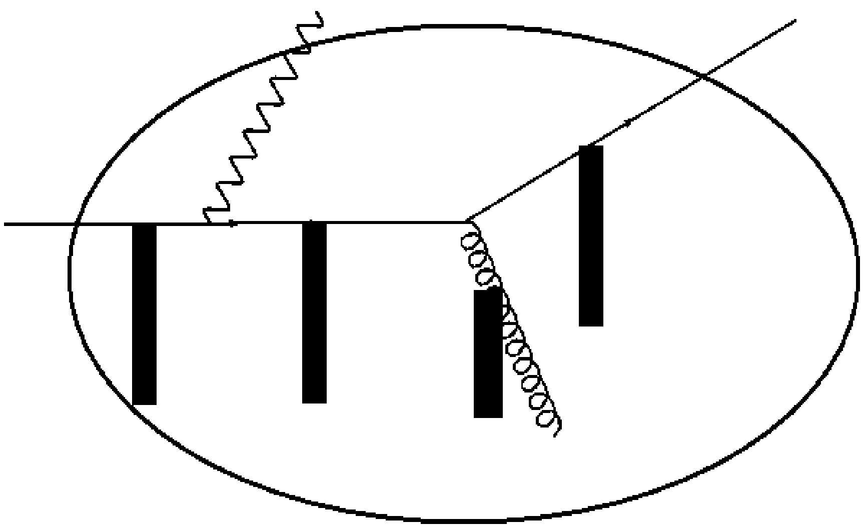
photon radiation: all x

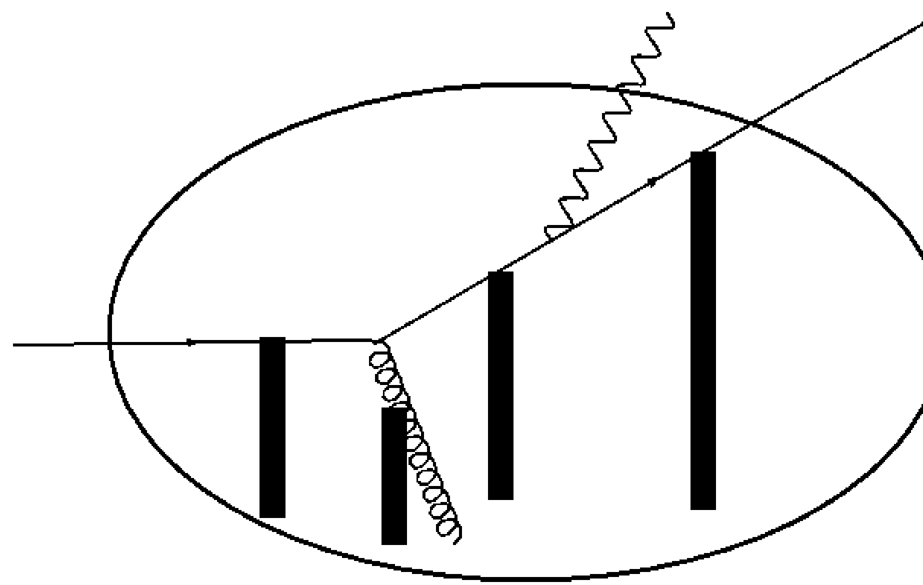




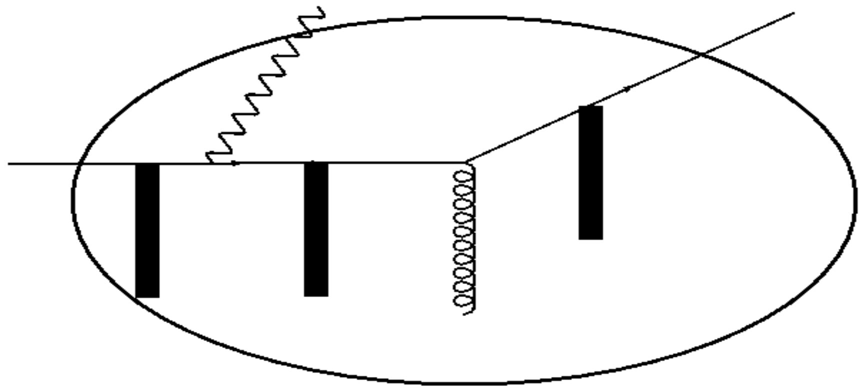
before hard scattering

after hard scattering





photon radiation: all x



$$i\mathcal{M}_1(p,q,l) =$$

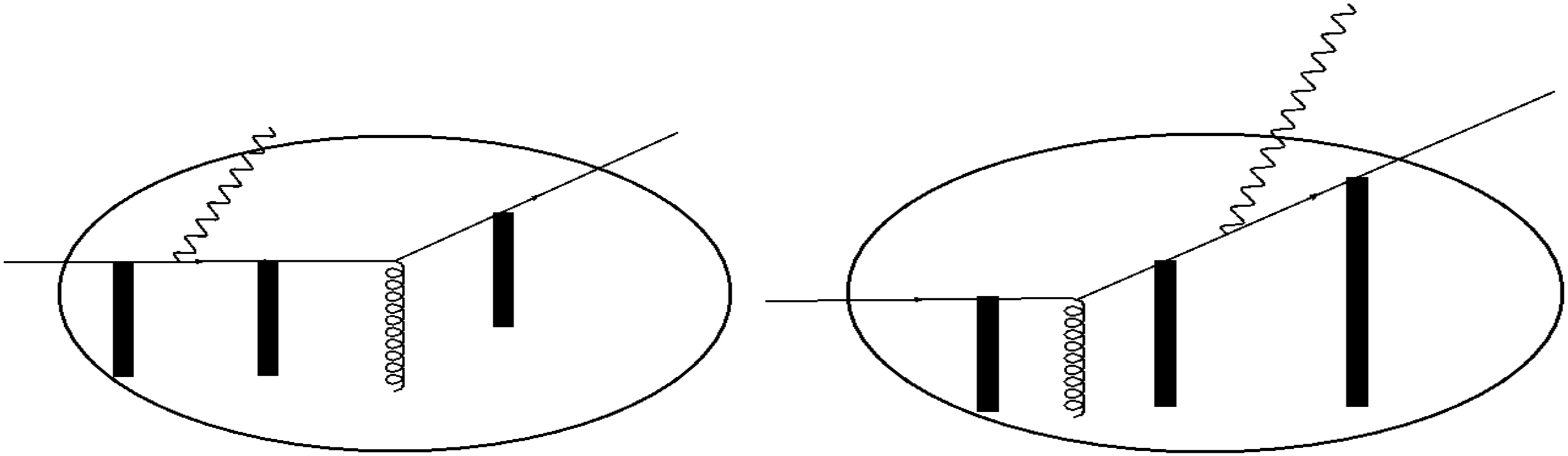
$$eg \int \frac{d^2k_{2t}}{(2\pi)^2}\,\frac{d^2k_{3t}}{(2\pi)^2}\,\frac{d^2\bar{k}_{1t}}{(2\pi)^2} \int d^4x\, d^2y_{1t}\, d^2y_{2t}\, d^2\bar{y}_{1t}\, dz^+\, \theta(x^+ - z^+)\, e^{i(l^+ + \bar{q}^+ - p^+)x^-}$$

$$e^{-i(\bar{q}_t - \bar{k}_{1t})\cdot\bar{y}_{1t}}\, e^{-i(\bar{k}_{1t} - k_{3t})\cdot x_t}\, e^{-i(k_{3t} - k_{2t})\cdot y_{2t}}\, e^{-i(l_t + k_{2t} - p_t)\cdot y_{1t}}\, \bar{u}(\bar{q})\, \overline{V}(\bar{y}_{1t}; x^+, \infty)\, \frac{\not{\bar{n}}\, \not{\bar{k}}_1}{2\bar{n}\cdot\bar{q}}$$

$$\not{A}(x)\, \left[\frac{\not{k}_3}{2n\cdot(p-l)}\, V(y_{2t}; z^+, x^+)\, \frac{\not{n}\, \not{k}_2}{2n\cdot(p-l)} + i\, \frac{\delta(x^+ - z^+)}{2n\cdot(p-l)}\not{n}\right]$$

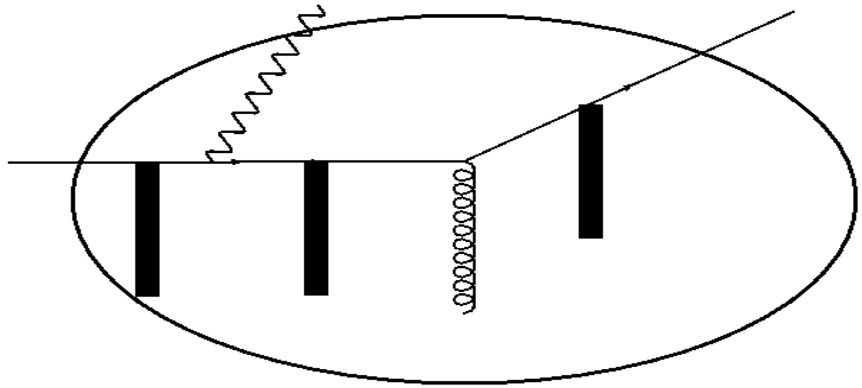
$$\not{\epsilon}(l)\, \frac{\not{k}_1}{2n\cdot p}\, V(y_{1t}; -\infty, z^+)\, \not{n}\, u(p)$$

pQCD limit (single gluon exchange):



V = U = 1

photon radiation: helicity amplitudes



$$\mathcal{N}_{1-1} = \bar{u}(\bar{q})\,\frac{\bar{\not{n}}\,\bar{\not{k}}_1}{2\bar{n}\cdot\bar{q}}\,\not{A}(x)\,\frac{\not{k}_3\,\not{n}\,\not{k}_2\not{\epsilon}(l)\,\not{k}_1\,\not{n}}{2n\cdot p\,2n\cdot(p-l)\,2n\cdot(p-l)}\,u(p)$$

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

$$\mathcal{N}^{++}_{1-1} = \left(\mathcal{N}^{--}_{1-1}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{[n\cdot l\,k_{2\perp}\cdot\epsilon^{\star}_{\perp} - n\cdot(p-l)\,l_{\perp}\cdot\epsilon^{\star}_{\perp}]}{n\cdot l\,n\cdot(p-l)}\,\langle\bar{k}^{+}_1|\not{A}(x)|k^{+}_3\rangle$$

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

$$\mathcal{N}^{+-}_{1-1} = \left(\mathcal{N}^{-+}_{1-1}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{[n\cdot p\,l_{\perp}\cdot\epsilon_{\perp} - n\cdot l\,k_{1\perp}\cdot\epsilon_{\perp}]}{n\cdot p\,n\cdot l}\,\langle\bar{k}^{+}_1|\not{A}(x)|k^{+}_3\rangle$$

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

So far

Classical CGC is generalized by including longitudinal momentum exchange (large angle scattering) with the target

beam rapidity loss

Helicity amplitudes for quark and photon production are evaluated

spin asymmetries

Relevant operators are identified

products of Wilson lines and large x gluon field
computing expectation values?

Toward a factorized cross section at all x (p_t)

gluon radiation

Need to classify/regulate the divergences

Combining with small x

sharp boundary (x = 0.01)?
matching field strengths?

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 inclusion of large x physics:

- *spin asymmetries*
- *beam rapidity loss*
- *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, ...*