Particle production at all x:
from proton-nucleus collisions to DIS

(toward a unified evolution equation including both large and small x)

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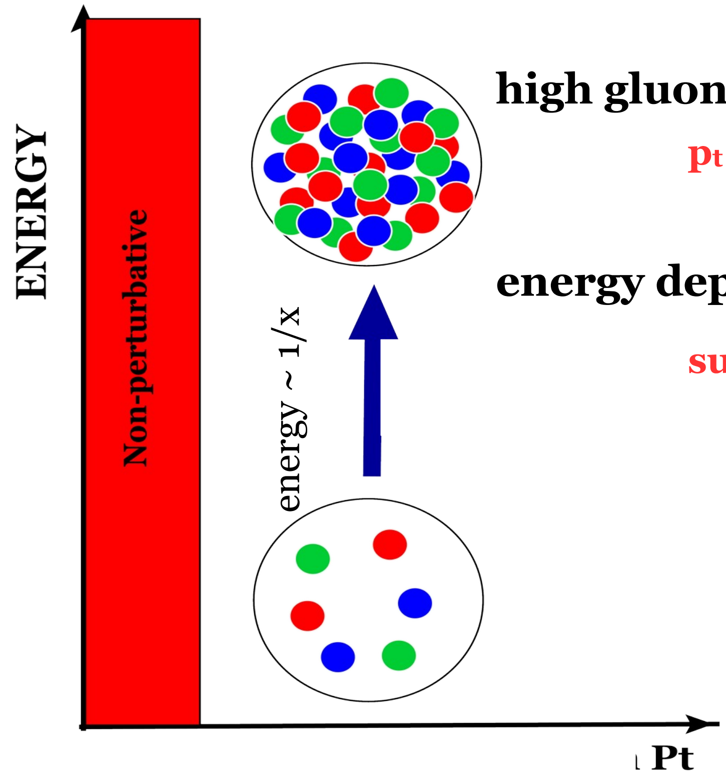
based on:
PRD102 (2020) 1, 014008
PRD99 (2019) 1, 014043
and work in progress

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)

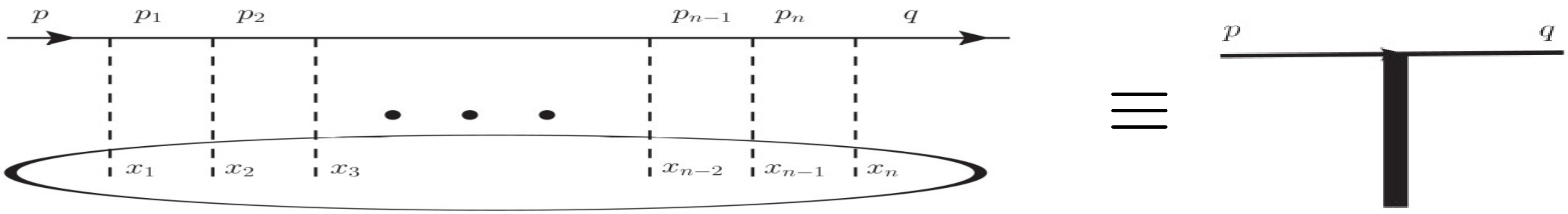
a framework for multi-particle production in QCD at small x/low p_t

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

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

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

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

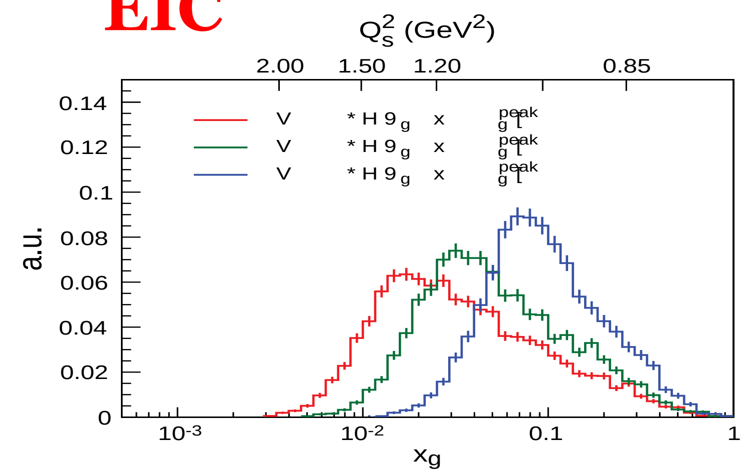
scattering from small x gluons of the target can cause only a ***small angle deflection***

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)

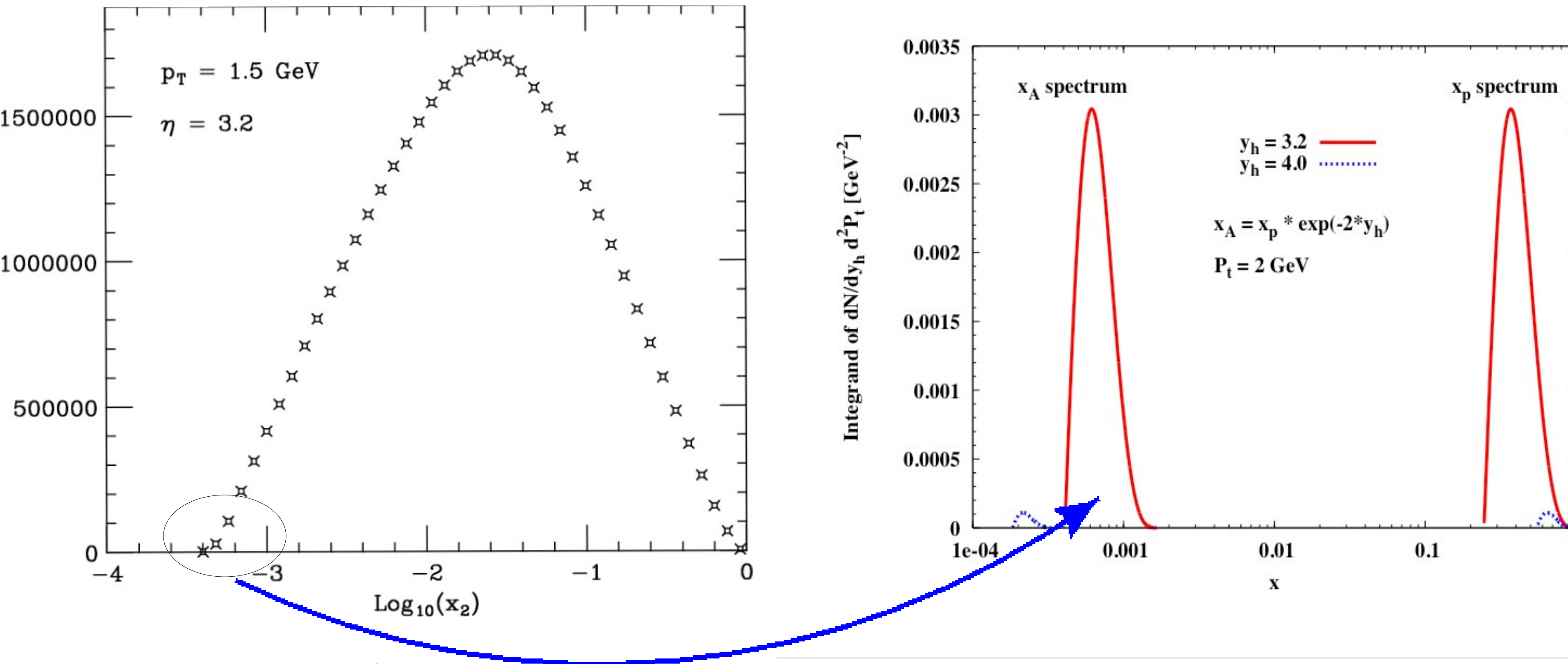
Agostini+Altinoluk+Armesto, EPJC (2019)

....

single inclusive pion production in pp at RHIC

collinear factorization CGC

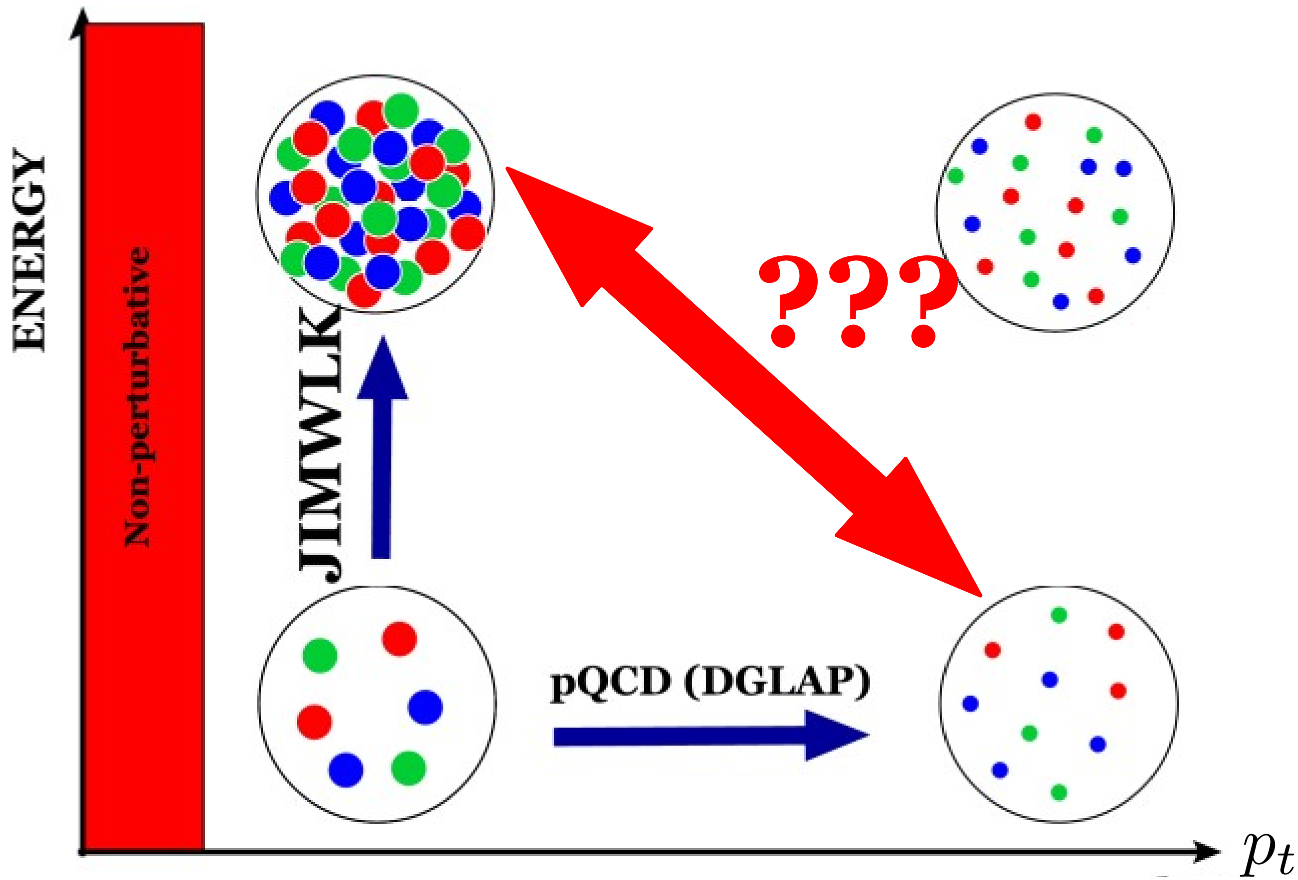
GSV, PLB603 (2004) 173-183 DHJ, NPA765 (2006) 57-70



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

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, ...

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

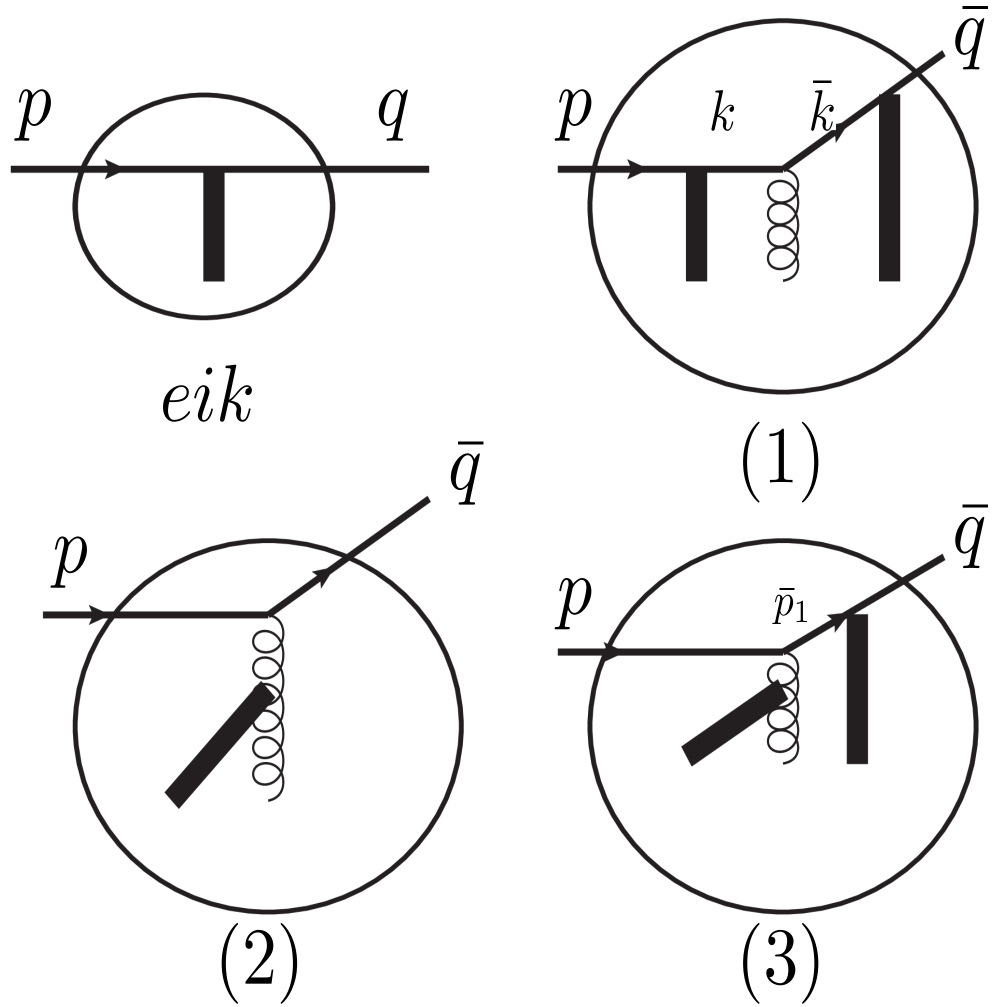
$$\mathcal{A}^\mu = \mathbf{S}^\mu + \mathbf{A}^\mu$$

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

$$\mathbf{S}^\mu$$



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

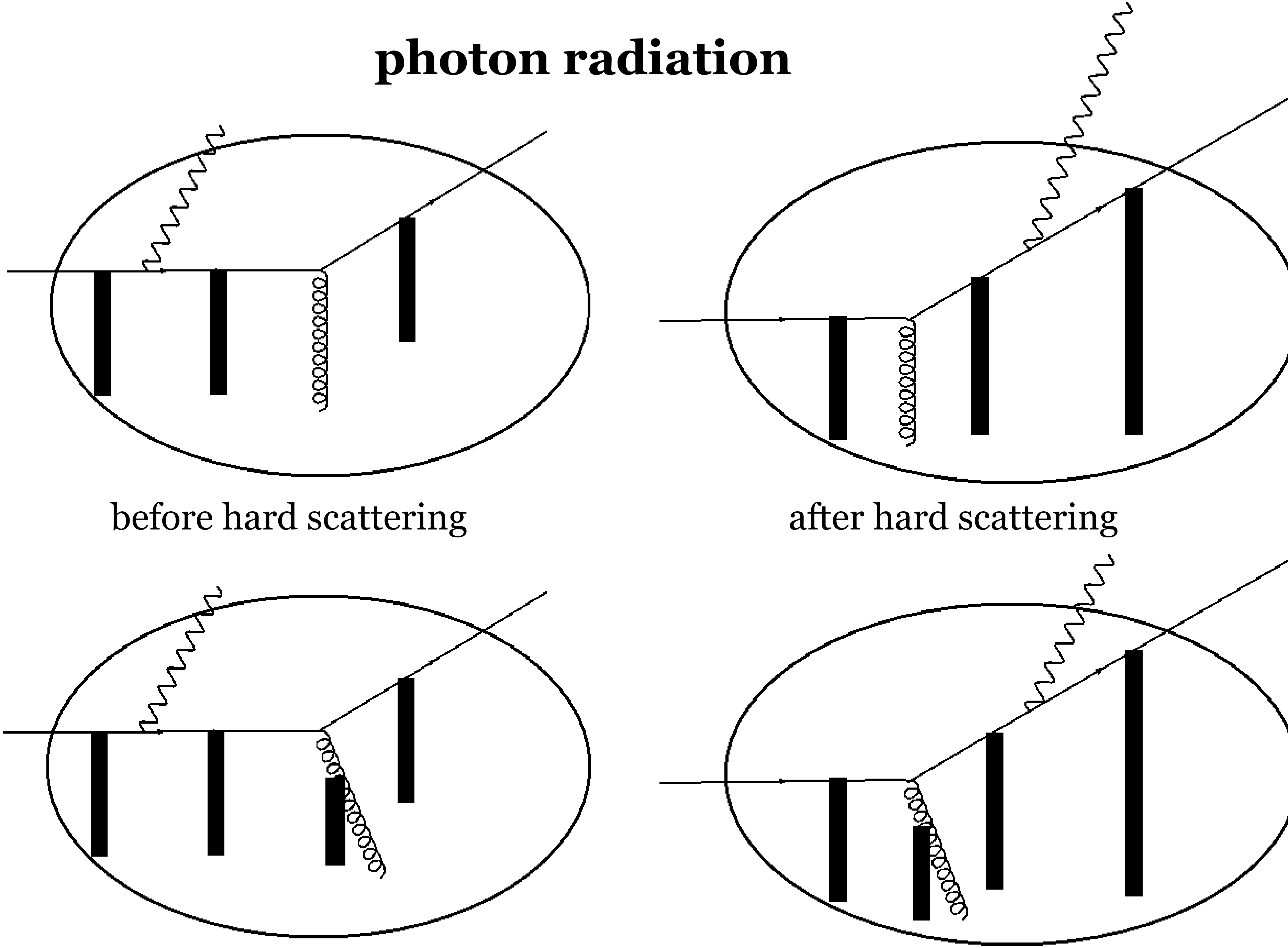
related problem: photon radiation

photon-jet correlations:

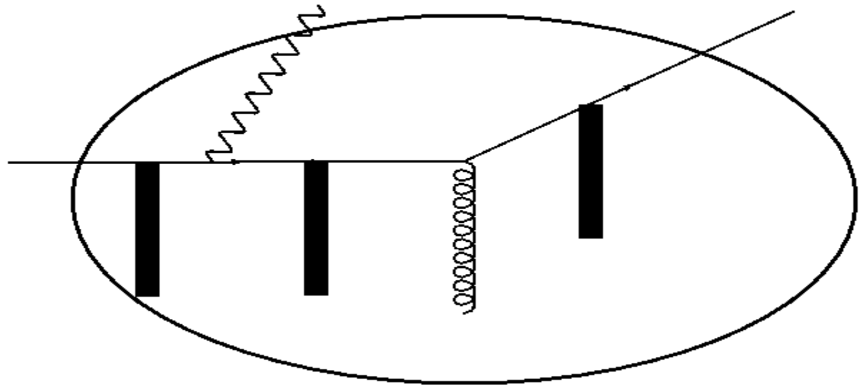
azimuthal angular correlations from low to high p_t

forward-backward rapidity correlations

photon radiation



photon radiation: helicity amplitudes



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

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

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

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

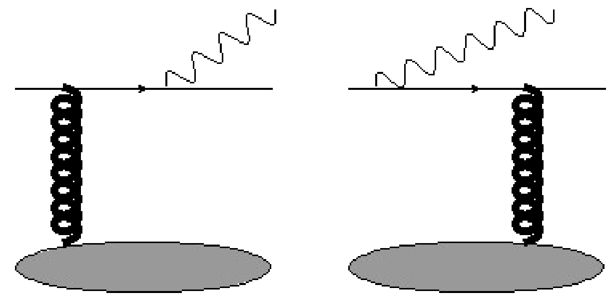
$$\mathcal{N}_{1-1}^{+-} = \left(\mathcal{N}_{1-1}^{-+}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{[n\cdot p\,l_{\perp}\cdot\epsilon_{\perp} - n\cdot l\,k_{1\perp}\cdot\epsilon_{\perp}]}{n\cdot p\,n\cdot l}\,\langle\bar{k}_1^{+}|\not{A}(x)|k_3^{+}\rangle$$

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

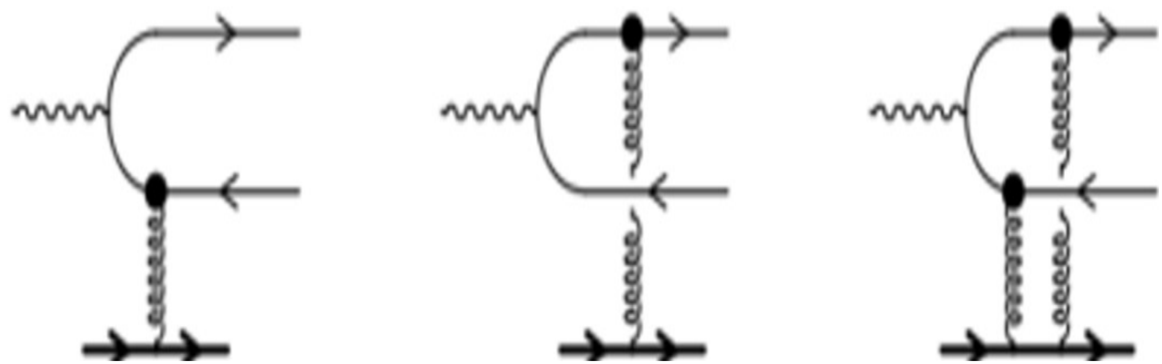
from pA to DIS: crossing symmetry FG+JJM, hep-ph/0211363

recall at small x

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



$$\gamma^{\star}\,\mathbf{T \rightarrow q\,\bar{q}}$$



can do the same crossing here to get to dijets in DIS

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, ...

beyond eikonal approximation:

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