Particle production from CGC – photons, hadrons,dihadrons,...

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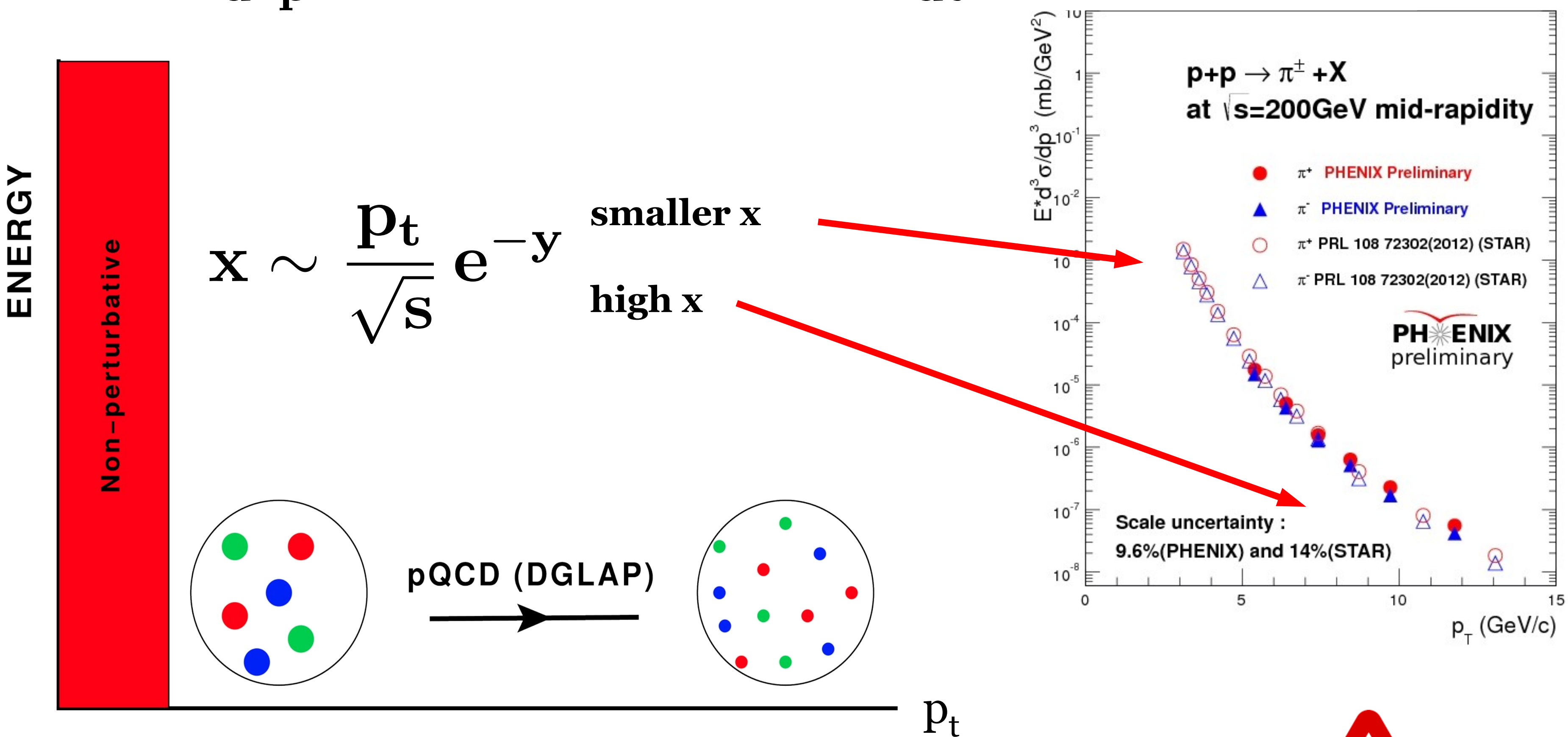
Workshop on Exploration of small-x structure of nuclei and signals of saturation in forward measurements at the LHC, CERN, June 22nd, 2022

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)

pQCD: the standard paradigm

DGLAP evolution of partons

number of partons increases with Q^2

effective size of partons decrease

hadron becomes more dilute

Excellent tool for high Q^2 inclusive observables

higher twists become important at low Q^2

Not designed to treat collective phenomena:

diffraction

multiple scattering

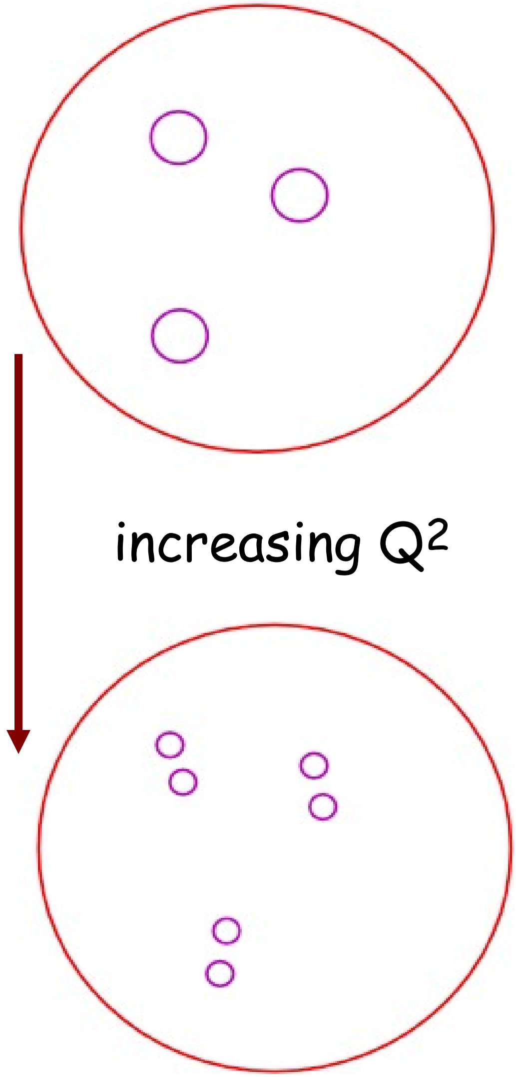
impact parameter dependence

shadowing

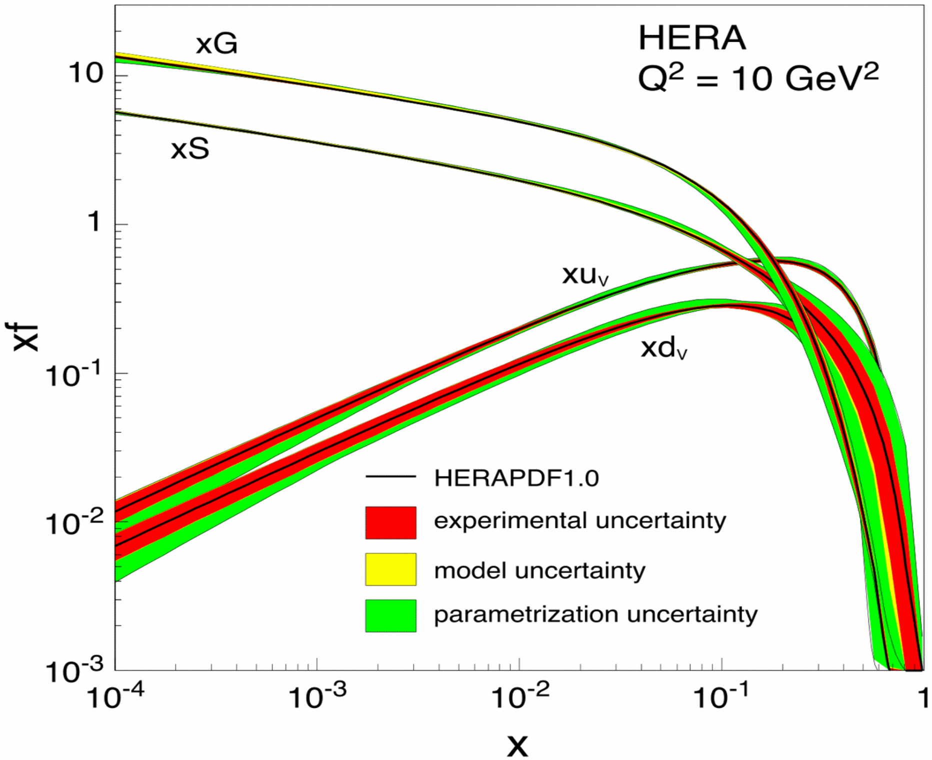
....

Extension beyond leading twist is very difficult

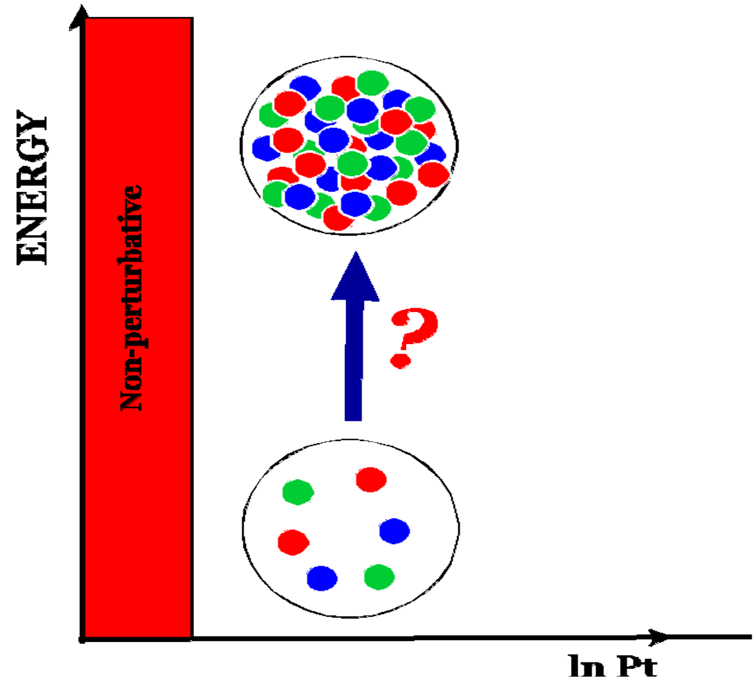
many-body dynamics hidden in parameters



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



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



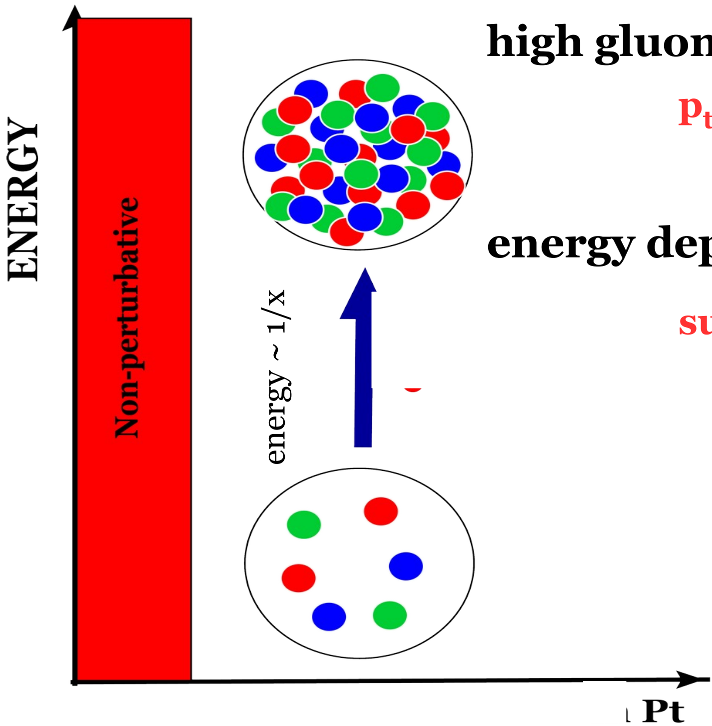
How does this happen ?

How do correlation functions evolve ?

Is there a universal fixed point for the evolution ?

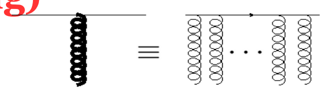
Are there scaling laws ?

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

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

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

for a proton target (quarks)

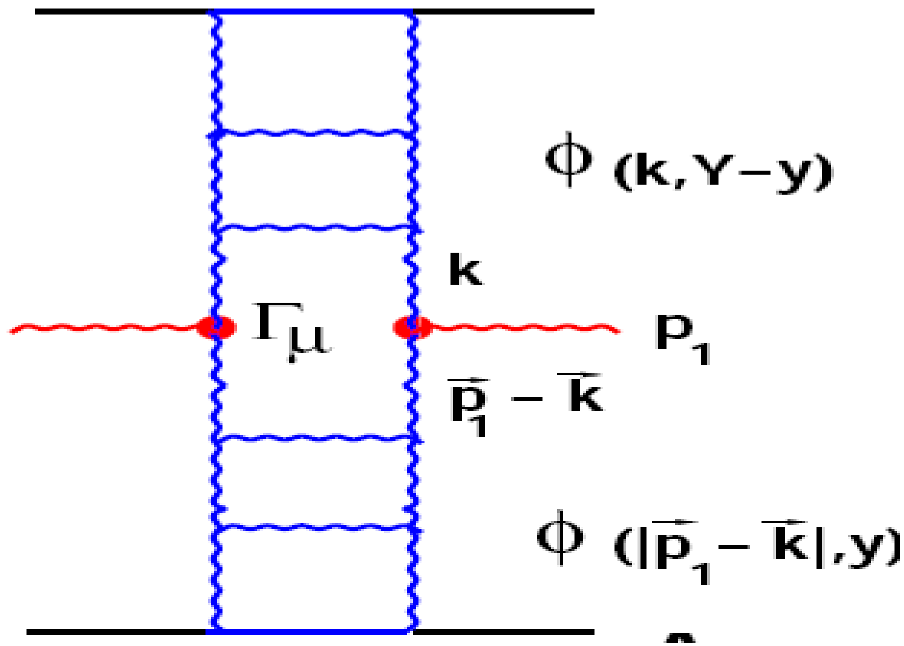
a framework for multi-particle production in QCD at small x/low p_t

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

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

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

particle production in midrapidity: “kt” factorization



$$\frac{d\sigma}{d^2p_t\,dy} \sim \int d^2k_t\,\phi(k_t,y)\,\phi(p_t-k_t,y)$$

Φ : intrinsic gluon distribution satisfies small x evolution equation

forward rapidity: hybrid factorization

$$\frac{d\sigma^{pA\to hX}}{dY\, d^2P_t\, d^2b} = \frac{1}{(2\pi)^2}\int_{x_F}^{1} dx\, \frac{x}{x_F}$$

$$\Big\{ f_{q/p}(x,Q^2)\;\; N_F[\frac{x}{x_F}P_t, b, y]\;\; D_{h/q}(\frac{x_F}{x}, Q^2) +$$

$$f_{g/p}(x,Q^2)\;\; N_A[\frac{x}{x_F}P_t, b, y]\;\; D_{h/g}(\frac{x_F}{x}, Q^2) \Big\}$$

Sensitive to dipoles only $\mathrm{N}_F \equiv \frac{1}{N_c} Tr\, \left(1 - V(x_1)\, V^\dagger(x_2)\right)$

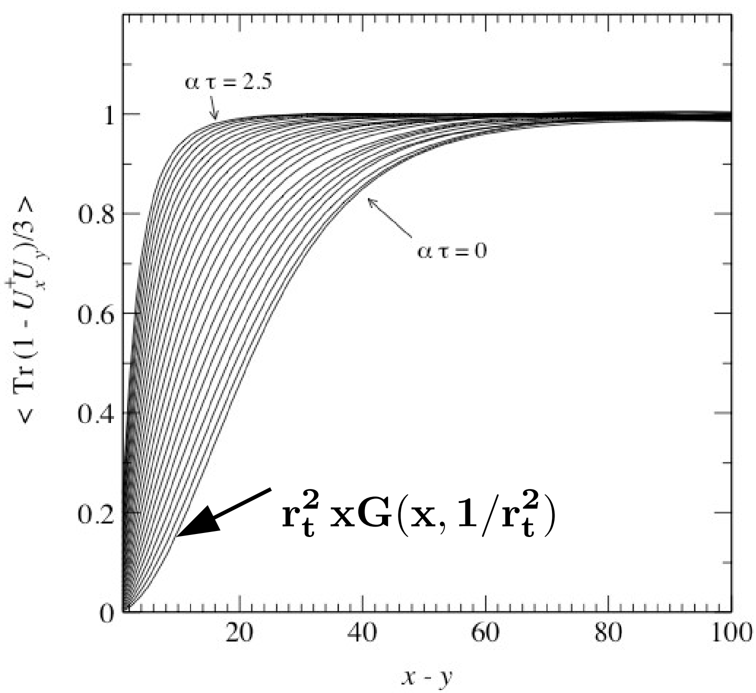
Same as in DIS and photon, dilepton production

NLO: Chrilli, Xiao, Yuan, arXiv:1112.1061,....

Dipoles at large N_c : BK equation

$$\frac{d}{dy}T(x_t - y_t) = \frac{\bar{\alpha}_s}{2\pi}\int d^2 z_t \,\frac{(x_t - y_t)^2}{(x_t - z_t)^2 (y_t - z_t)^2}\left[T(x_t - z_t) + T(z_t - y_t) - T(x_t - y_t) - T(x_t - z_t)T(z_t - y_t)\right]$$

$$T(x_t, y_t) \equiv 1 - S(x_t, y_t) = \frac{1}{N_c}\mathrm{Tr}\left\langle 1 - V(x_t)V^\dagger(y_t)\right\rangle$$



$\tilde{T}(p_t) \to \log\left[\frac{Q_s^2}{p_t^2}\right]$ **saturation region**

$\tilde{T}(p_t) \to \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right]^\gamma$ **extended scaling region**

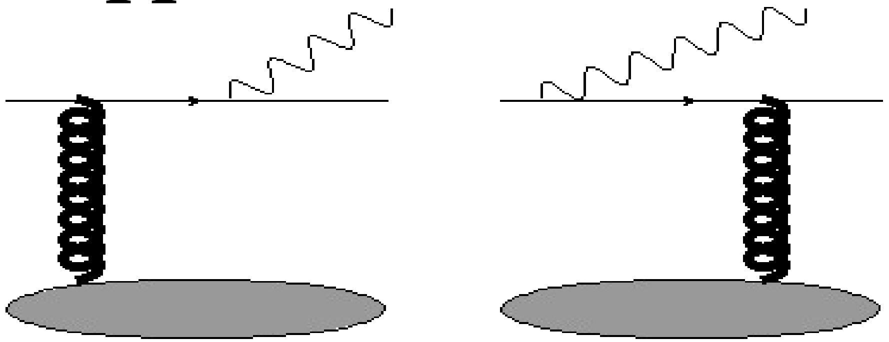
$\tilde{T}(p_t) \to \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right]$ **pQCD region**

Rummukainen-Weigert, *NPA739 (2004) 183*

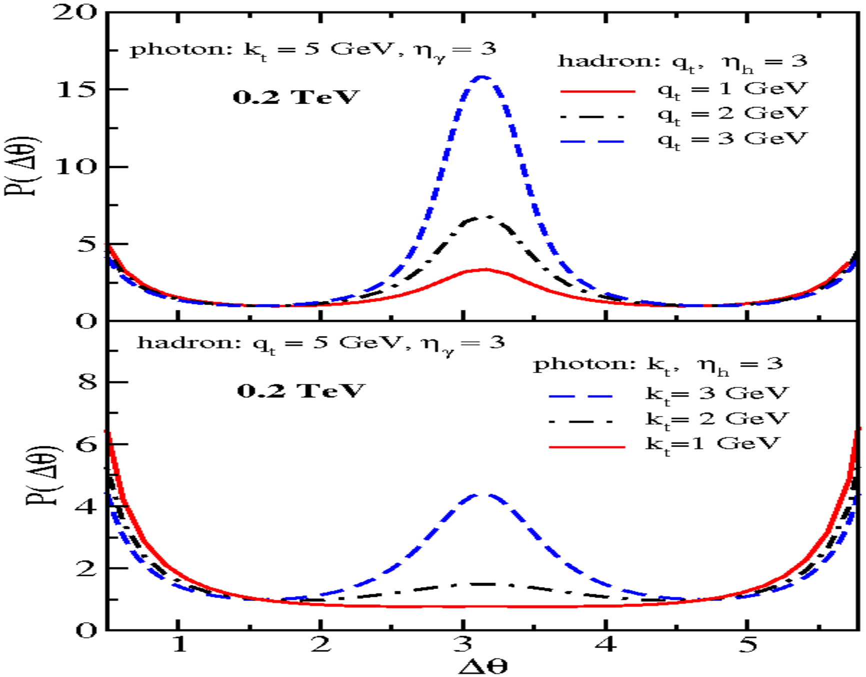
NLO: *Balitsky-Kovchegov-Weigert-Gardi-Chirilli (2007-2008)*

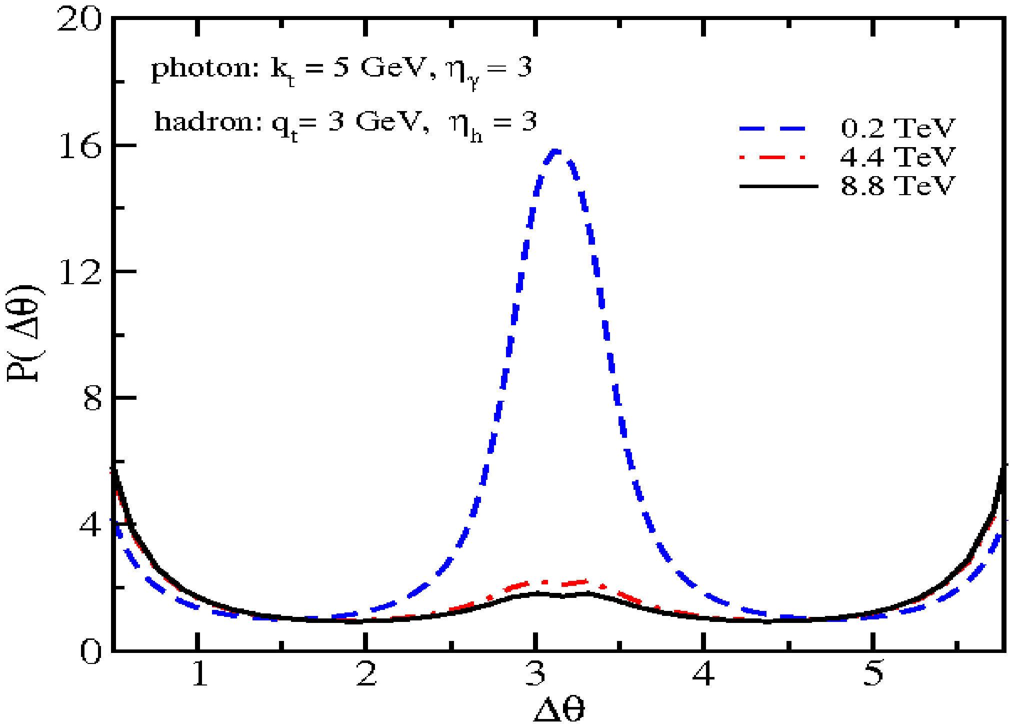
Photon radiation: eikonal approximation

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



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

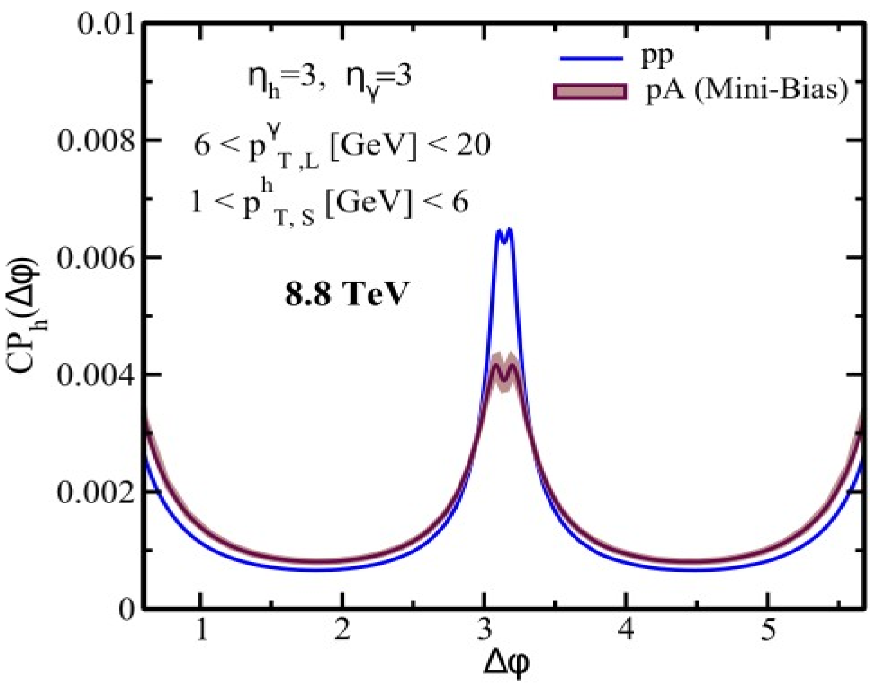


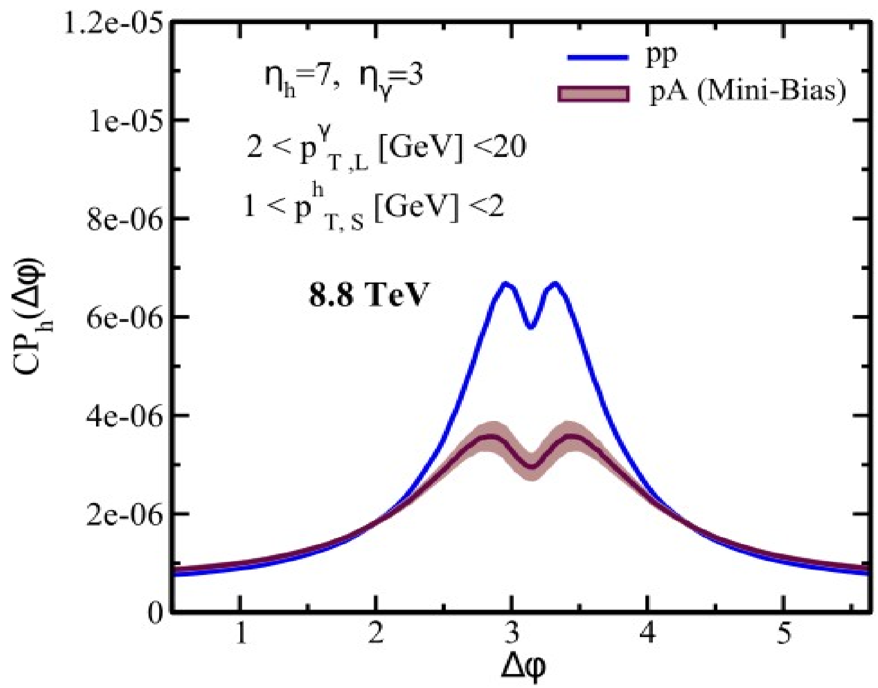


Particle in production in forward rapidity

Single inclusive photon, hadron production photon-hadron angular correlations in forward rapidity involve only dipoles

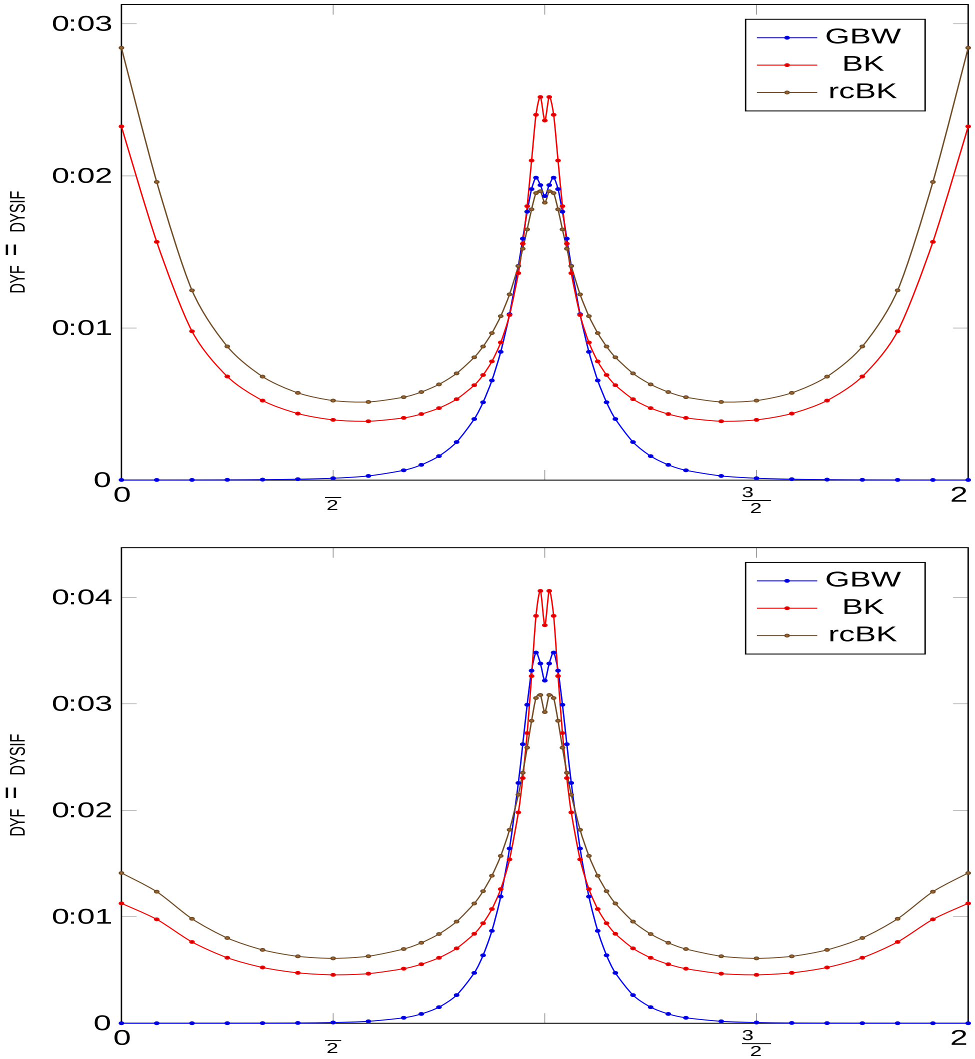
photons can be real or virtual





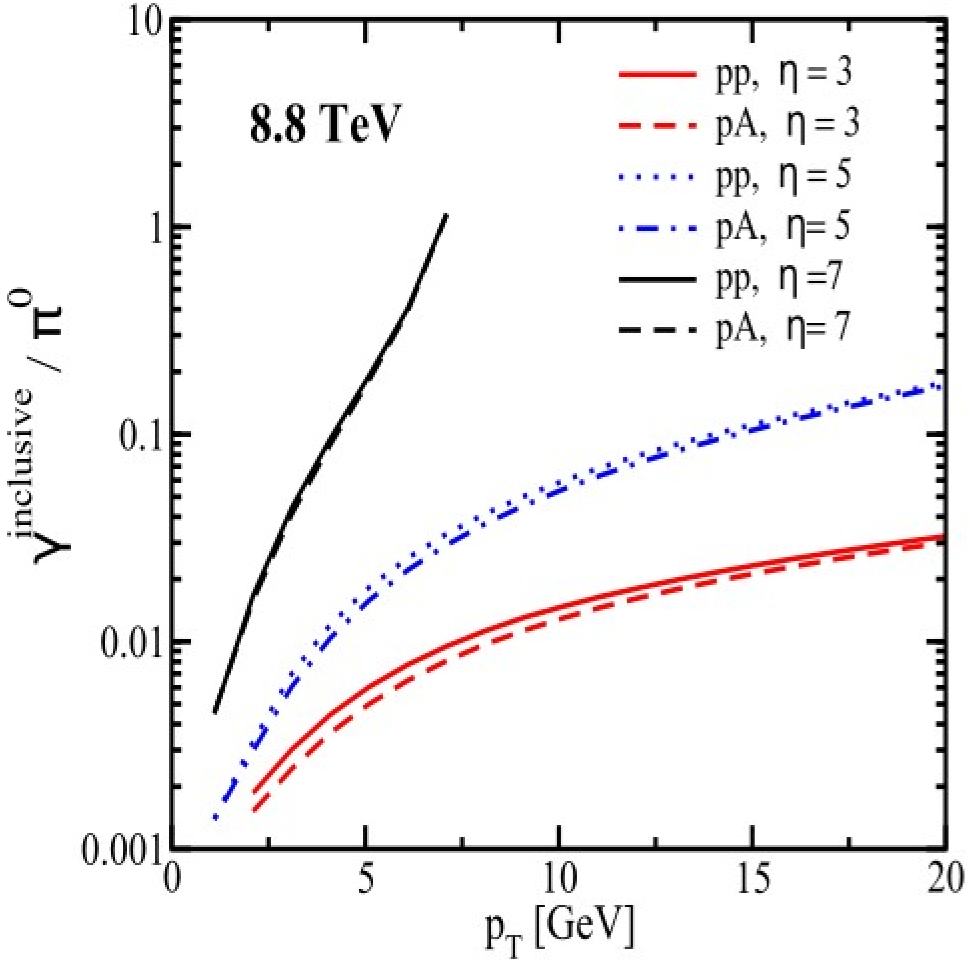
A. Rezaeian, arXiv:1209.0478

Dilepton-hadron angular correlations



Stasto, Xiao, Zaslavsky, arXiv:1204.4861

Photon to pion ratio



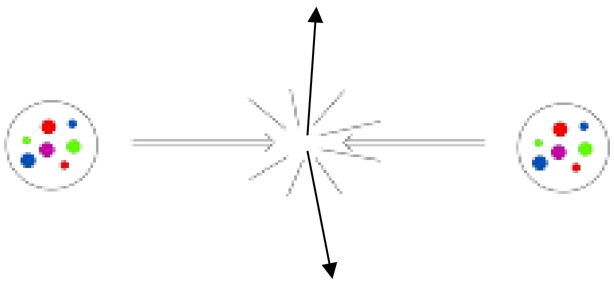
A. Rezaeian, arXiv:1209.0478

Dihadron production in pA at small x

production in forward rapidity: hybrid factorization

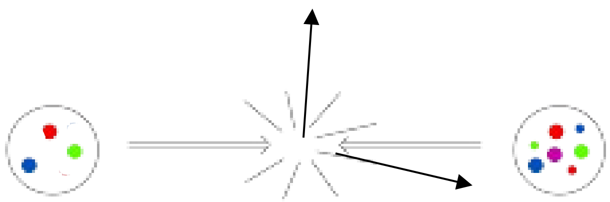
produced partons: $k_1, y_1 \qquad k_2, y_2$ $\qquad x_p = \dfrac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \dfrac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$

scanning the wave-functions (RHIC) $\quad k_1 \sim k_2 \sim k \sim 2\, GeV$



mid-mid correlations
probe moderate x

$$x_p \sim x_A \sim \frac{k}{\sqrt{S}} \sim 10^{-2}$$



mid-forward

$$x_p \sim \frac{k}{\sqrt{S}}\, e^{y_1} \to 1 \quad x_A \sim \frac{k}{\sqrt{S}} \sim 10^{-2}$$

forward-forward $\quad x_p \sim \dfrac{k}{\sqrt{S}}\, e^{y_1} \to 1 \quad x_A \sim \dfrac{k}{\sqrt{S}}\, e^{-y_2} \sim 10^{-4}$

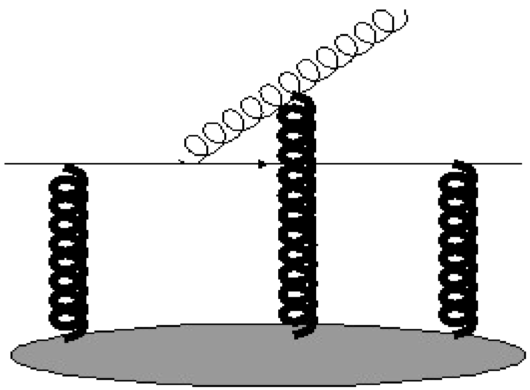
Slide made by C. Marquet

Di-jet production: pA

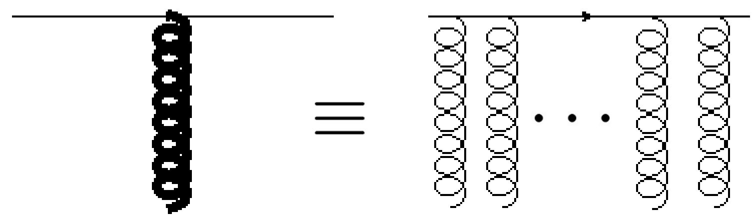
J. Jalilian-Marian, Y. Kovchegov
PRD70 (2004) 114017

$$\mathbf{q(p)\,T \rightarrow q(q)\,g(k)\,X}$$

target: a classical color field
quark, gluon multiply scatter on the target



with



$$\frac{d\sigma^{p\,A \rightarrow q\,g\,X}}{d^2p\,d^2q\,dy_1\,dy_2} \sim \color{red}{S_{122'1'}\ ,\ S_{12}}$$

$$\mathrm{S}_{122'1'} \equiv \frac{1}{N_c} Tr\, V(\mathbf{x}_1)\, V^\dagger(\mathbf{x}_2)\, V(\mathbf{x}_{2'})\, V^\dagger(\mathbf{x}_{1'})$$

$$\mathrm{S}_{12} \equiv \frac{1}{N_c} Tr\, V(\mathbf{x}_1)\, V^\dagger(\mathbf{x}_2)$$

quadrupole: limits

$$< Q(r,\bar{r},\bar{s},s) > \equiv \frac{1}{N_c} < Tr\, V(r)\, V^\dagger(\bar{r})\, V(\bar{s})\, V^\dagger(s) >$$

line config.: $r=\bar{s},\ \bar{r}=s,\ z\equiv r-\bar{r}$

square config.: $r-\bar{s}=\bar{r}-s=r-\bar{r}=\cdots\equiv z$

"naive" Gaussian: $Q=S^2$

Gaussian $Q_|(z)\approx\frac{N_c+1}{2}[S(z)]^{2\frac{N_c+2}{N_c+1}}-\frac{N_c-1}{2}[S(z)]^{2\frac{N_c-2}{N_c-1}}$

$$Q_{sq}(z)=[S(z)]^2\left[\frac{N_c+1}{2}\left(\frac{S(z)}{S(\sqrt{2}z)}\right)^{\frac{2}{N_c+1}}-\frac{N_c-1}{2}\left(\frac{S(\sqrt{2}z)}{S(z)}\right)^{\frac{2}{N_c-1}}\right]$$

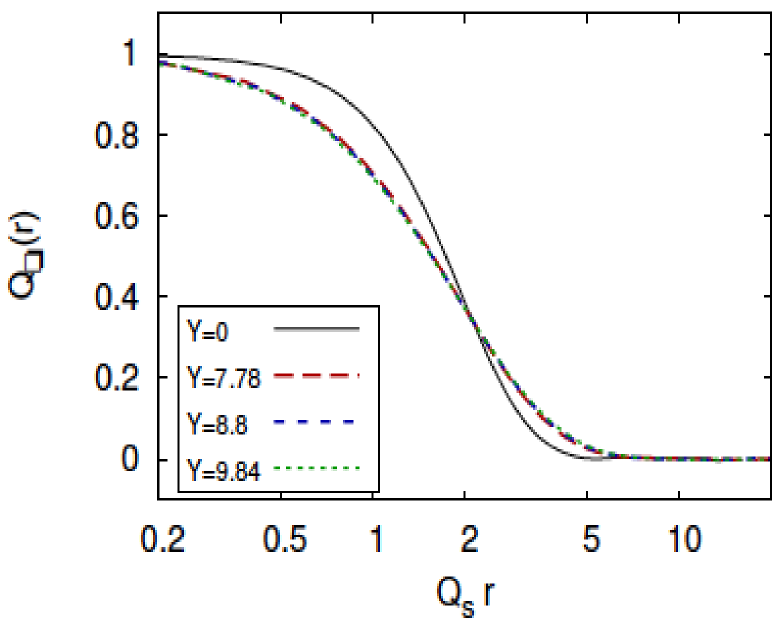
Gaussian + large Nc $Q_|(z)\rightarrow S^2(z)[1+2\,log[S(z)]]$

$$Q_{sq}(z)=S^2(z)\left[1+2\ln\left(\frac{S(z)}{S(\sqrt{2}z)}\right)\right]$$

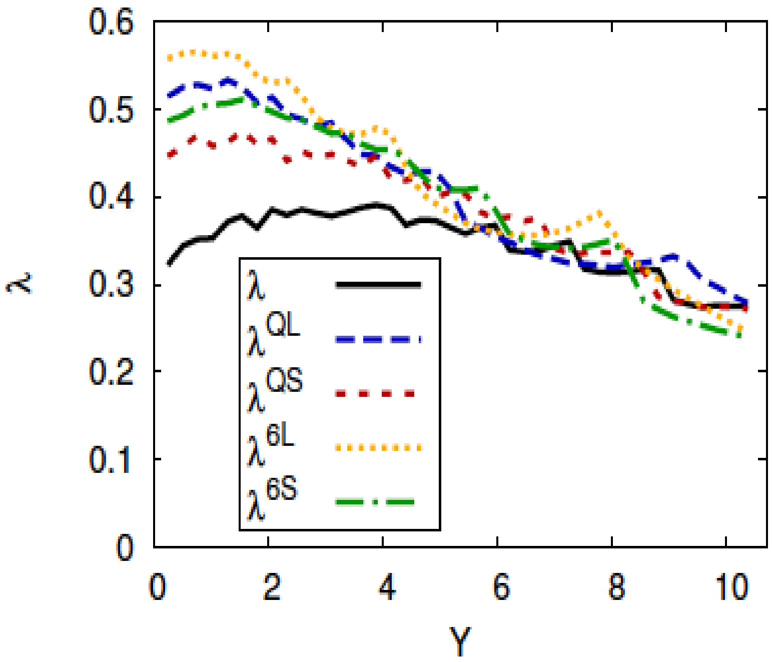
Quadrupole evolution

Dumitru-Jalilian-Marian-Lappi-Schenke-Venugopalan: PLB706 (2011) 219

$$< Q(r,\bar{r},\bar{s},s) >\equiv \frac{1}{N_c} < Tr\, V(r)\, V^\dagger(\bar{r})\, V(\bar{s})\, V^\dagger(s) >$$



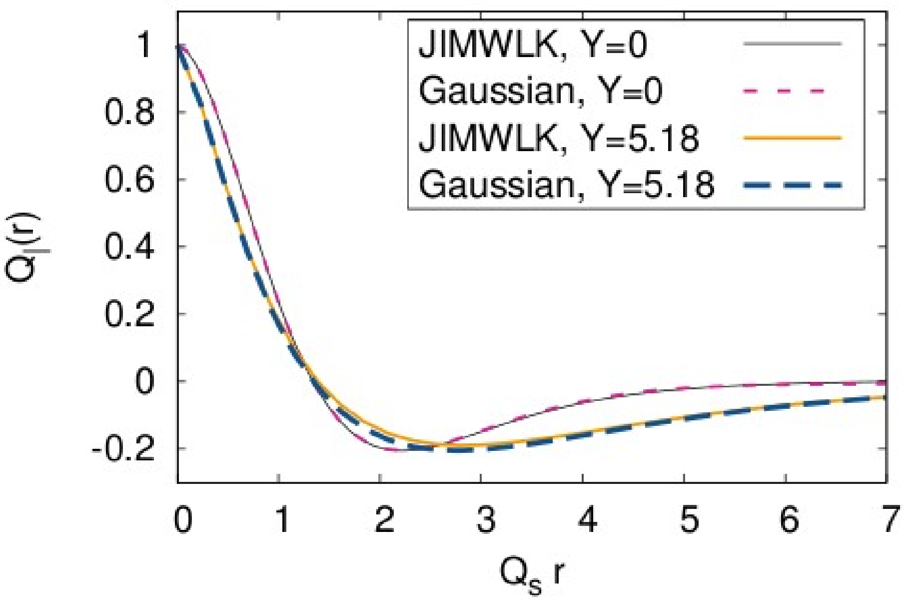
scaling

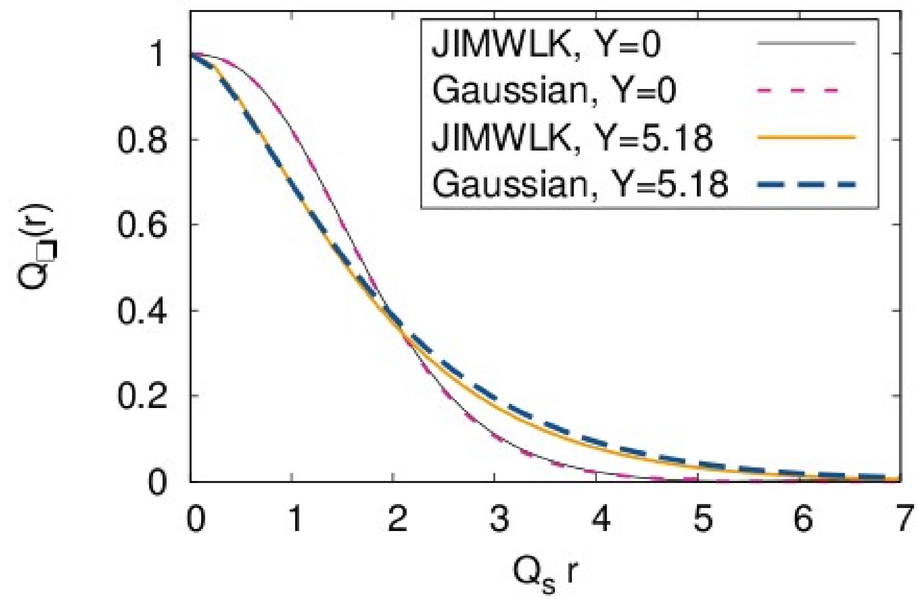


energy dependence

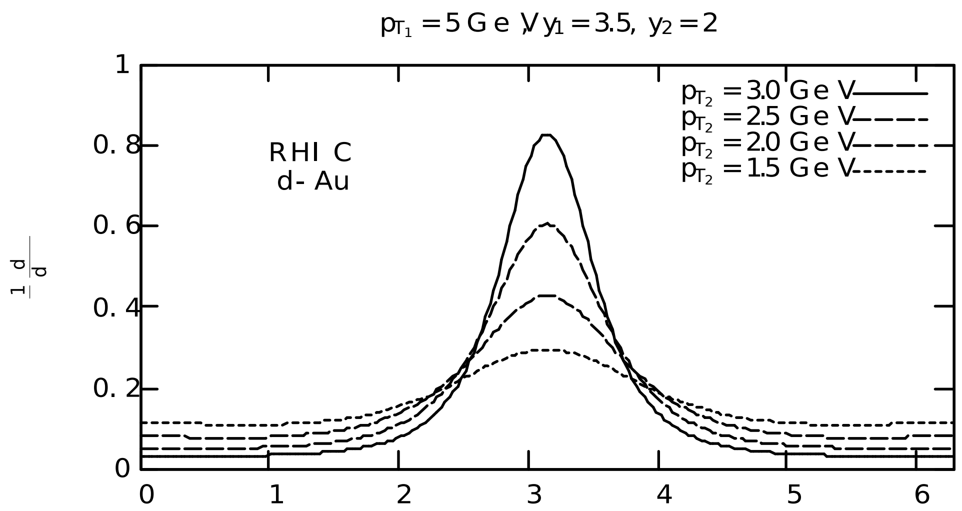
Quadrupole evolution

comparing with Gaussian model





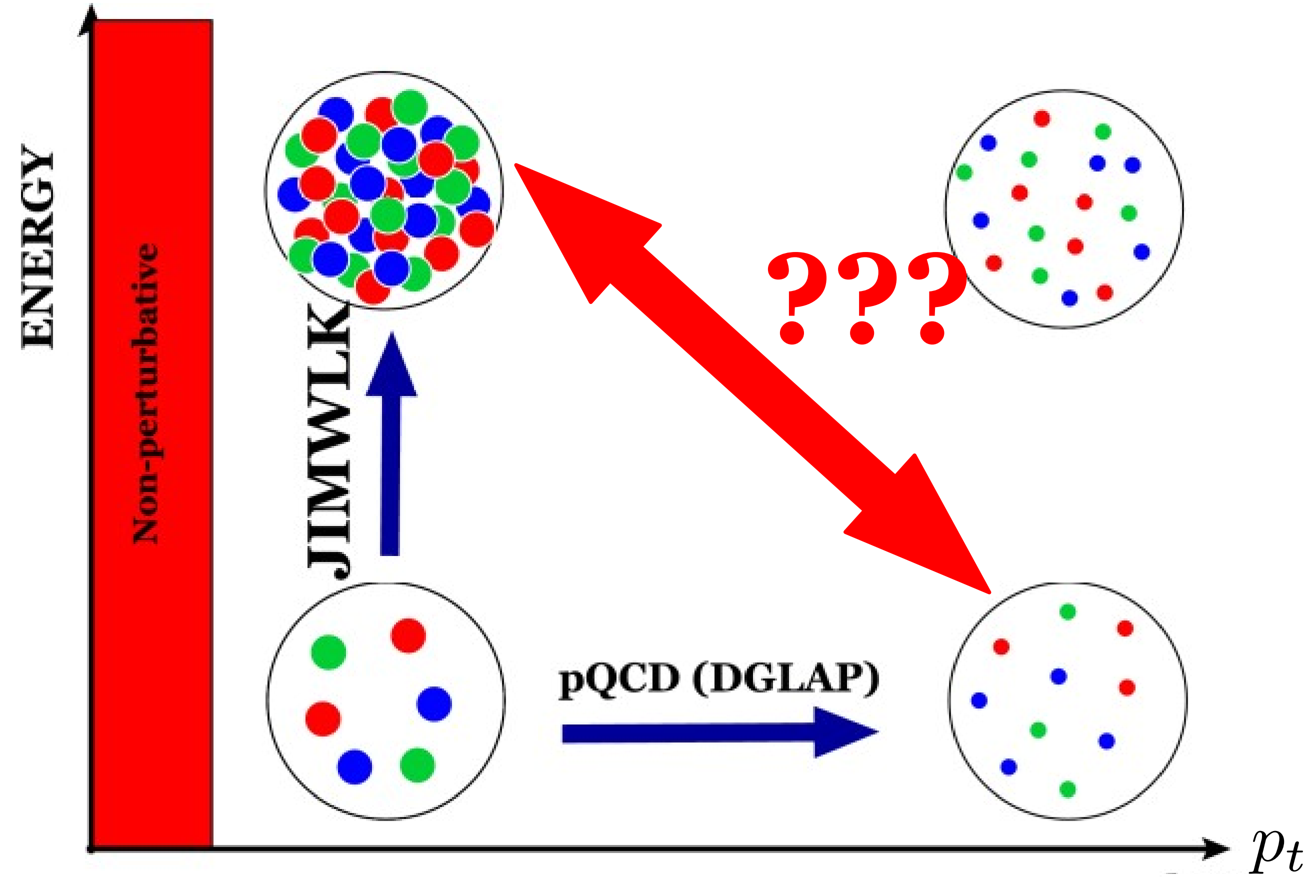
CGC predictions for di-hadron angular correlations: p(d)A



C. Marquet, NPA796 (2007) 41

And much more recent work: more sophisticated fits, NLO,…

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, …….

Including large x partons of the target leads to:

longitudinal double spin asymmetries (A_{LL})

baryon transport (beam rapidity loss), ...

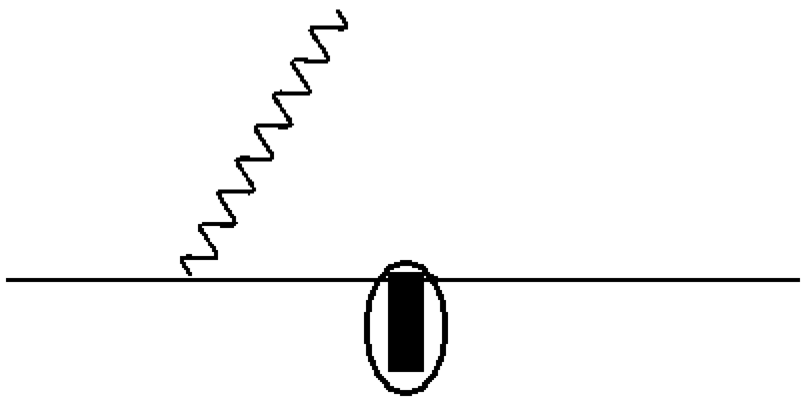
Photon production at all x

photon-hadron correlations:

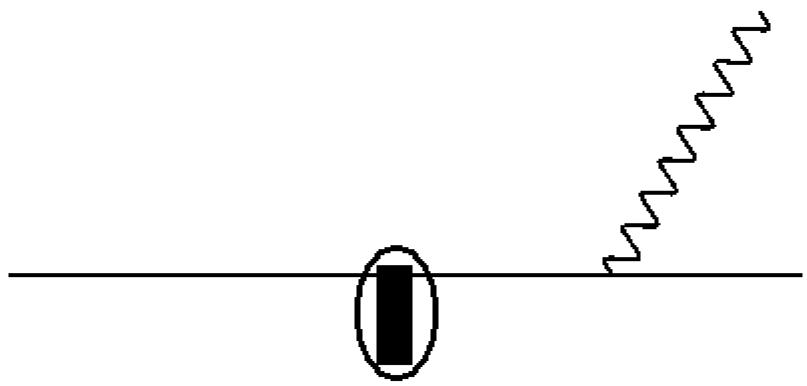
azimuthal angular correlations from low to high p_t

forward-backward rapidity correlations

photon production: small x



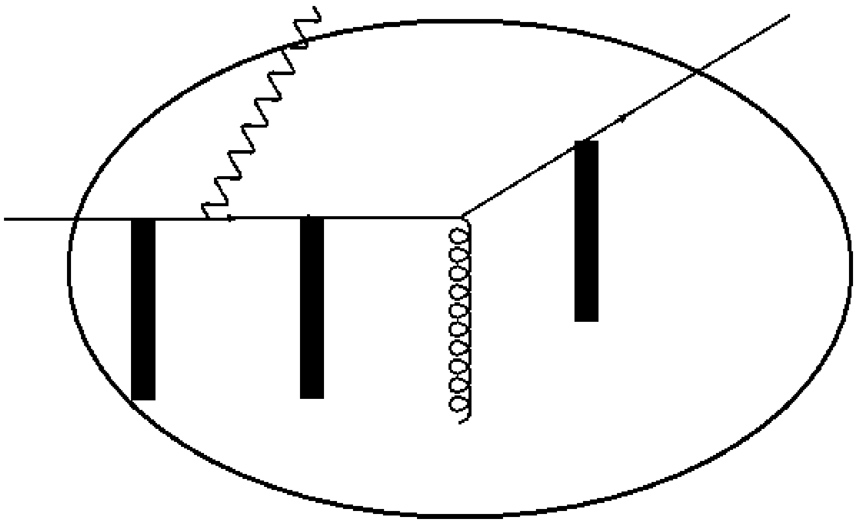
before quark scatters on the target

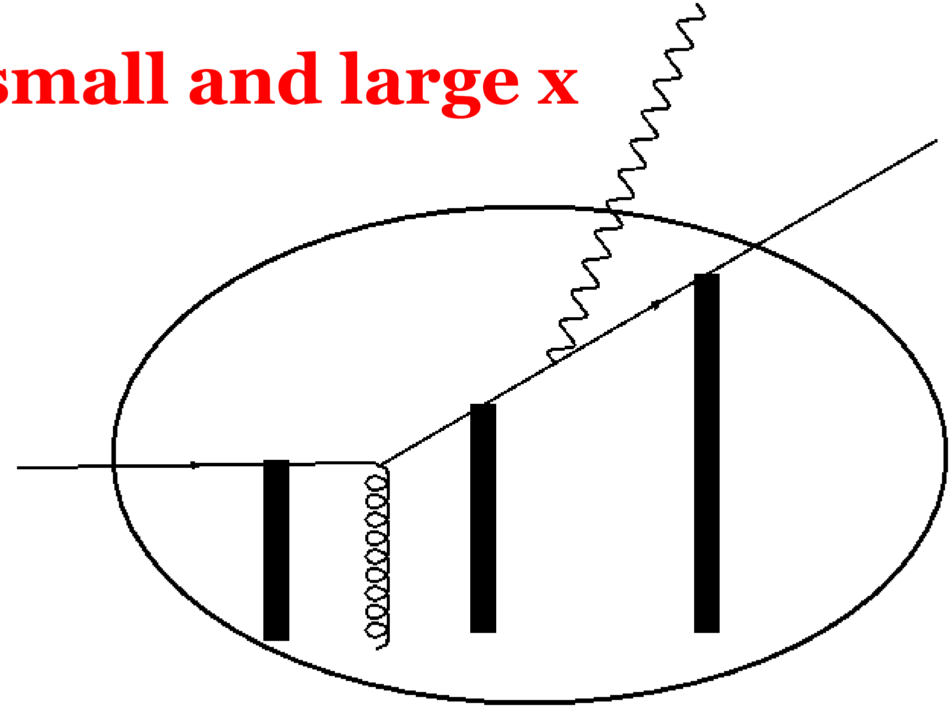


after quark scatters on the target

No radiation inside the target

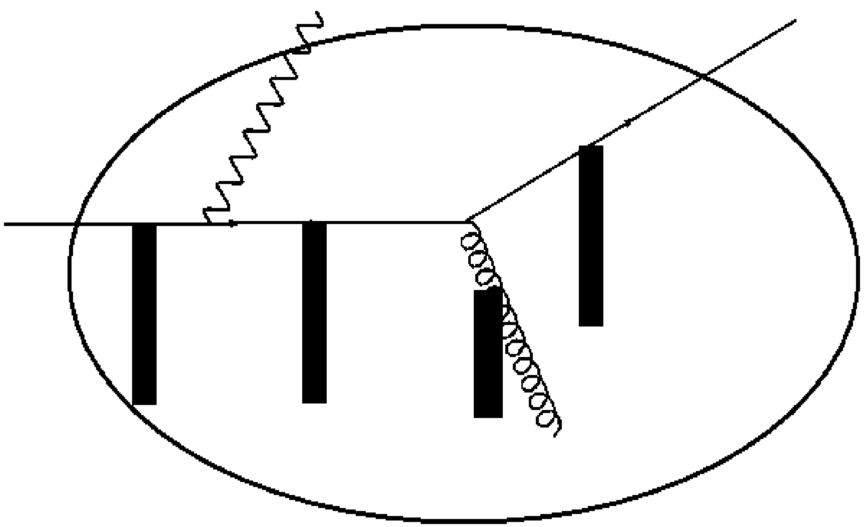
photon production: both small and large x

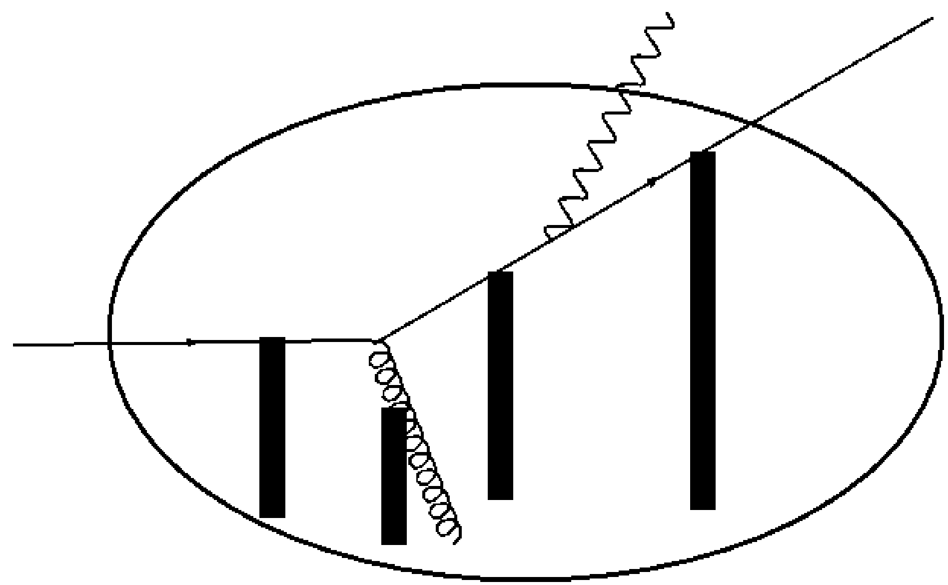




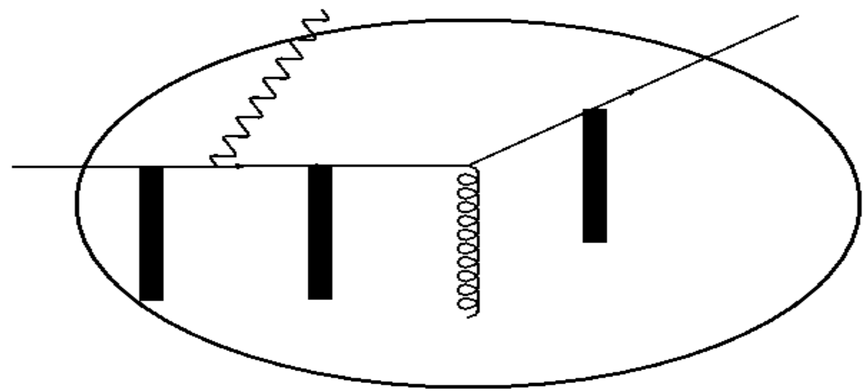
before hard scattering

after hard scattering





photon production: both small and large x



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

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

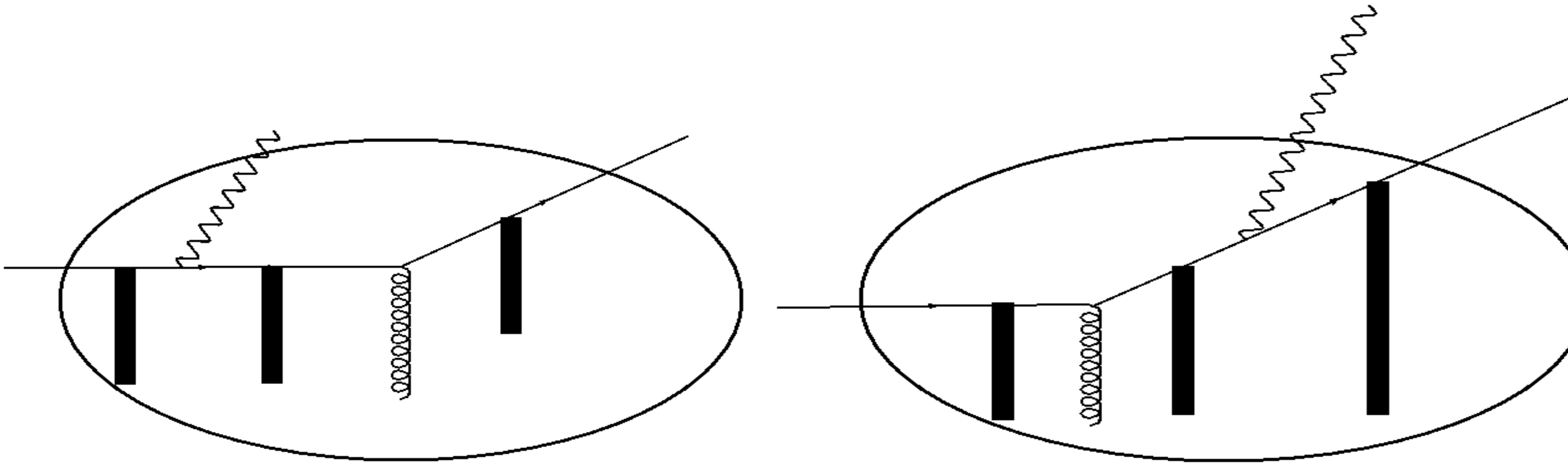
$$\mathcal{N}^{++}_{1-1} = \left(\mathcal{N}^{--}_{1-1}\right)^{\star} = -\sqrt{\frac{n\cdot p}{n\cdot(p-l)}}\,\frac{\left[n\cdot l\,k_{2\perp}\cdot\epsilon^{\star}_{\perp} - n\cdot(p-l)\,l_{\perp}\cdot\epsilon^{\star}_{\perp}\right]}{n\cdot l\,n\cdot(p-l)}\,\langle\bar{k}^{+}_1|\not{A}(x)|k^{+}_3\rangle$$

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

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

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

pQCD limit (large x: gluon PDF X partonic cross section):



V = U = 1

SUMMARY

CGC is a systematic approach to high energy collisions

strong hints from RHIC, LHC,...

to be probed extensively at EIC

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

Forward rapidity at LHC: smallest x

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 (pQCD) to small x (CGC)

Toward inclusion of large x physics:

particle production in both small and large p_t kinematics

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