Azimuthal angular correlations in high energy processes in QCD

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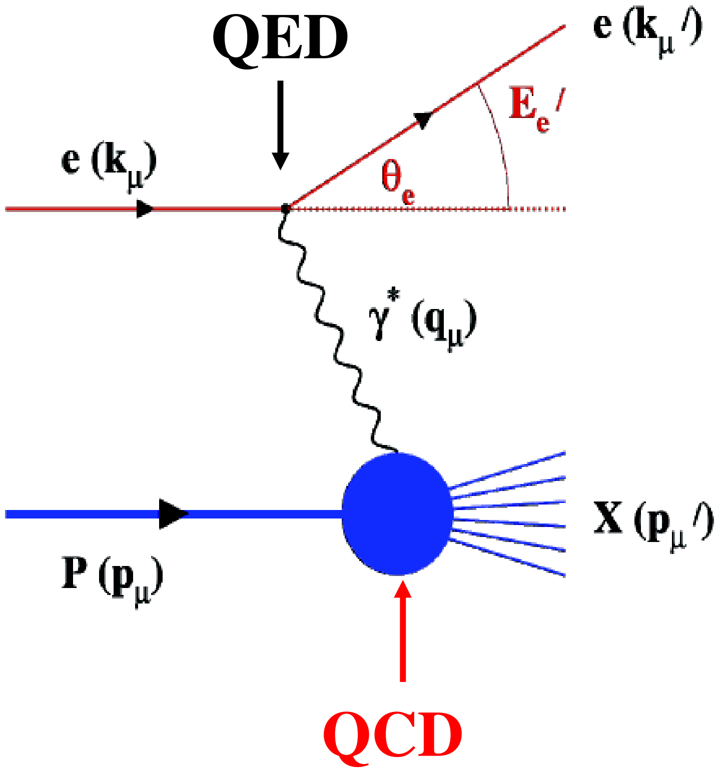
Deeply Inelastic Scattering (DIS)

probing hadron structure



(F₁, F₂ structure functions)

Kinematic Invariants

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

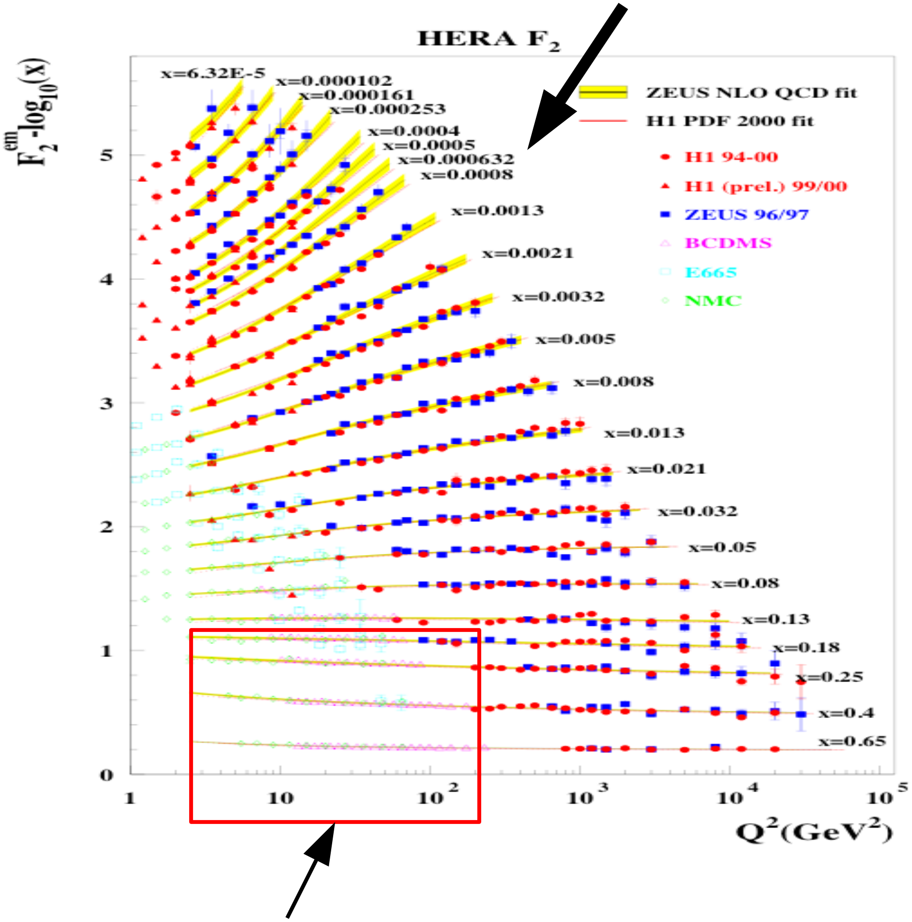
Measure of momentum fraction of struck quark

$$\mathbf{s} \equiv (\mathbf{p} + \mathbf{k})^2$$

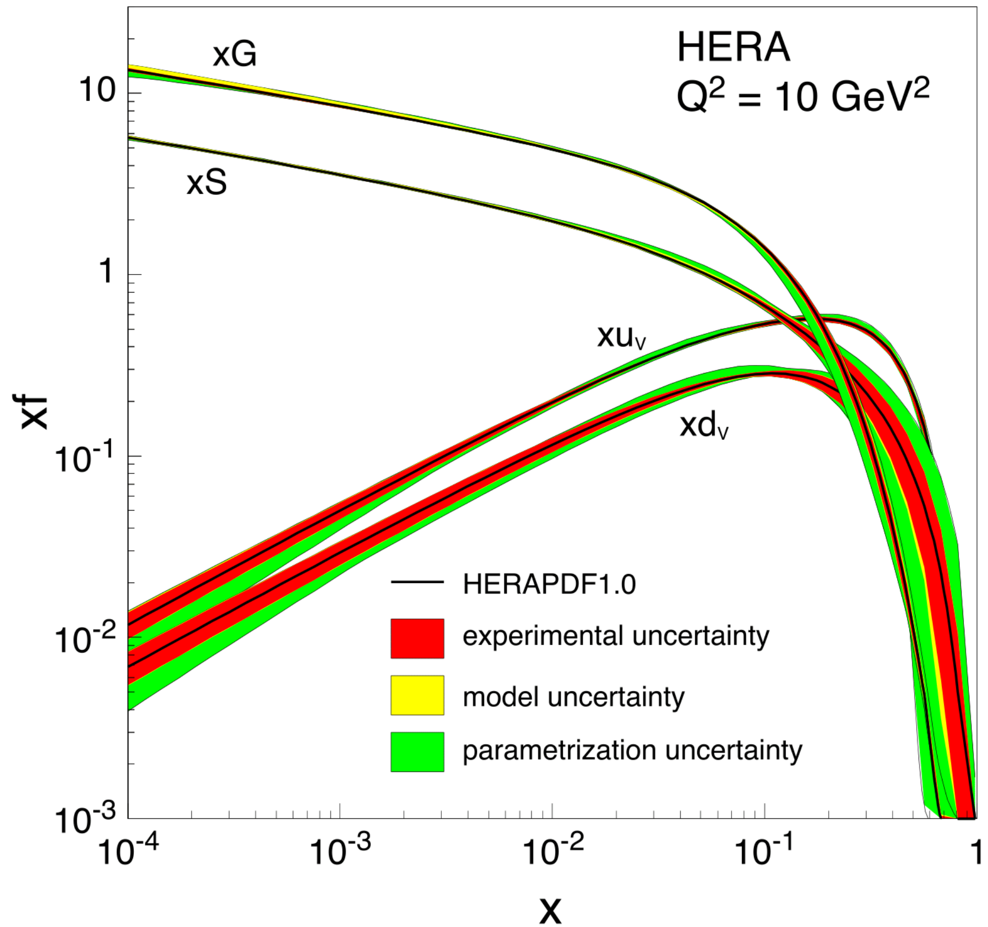
Deep Inelastic Scattering

$$F_2 \equiv \sum_{f=q,\bar{q}} e_f^2 \, xq(x, Q^2)$$

QCD: scaling violations



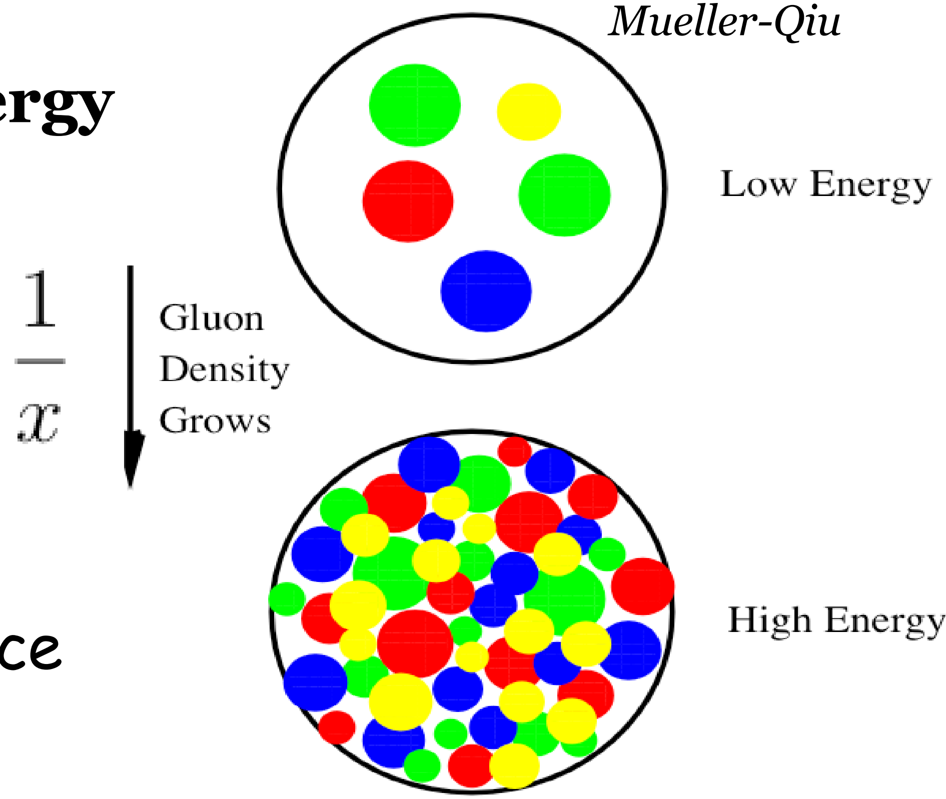
early experiments (SLAC,...):
scale invariance of hadron structure



large number of gluons at small x

Gribov-Levin-Ryskin
Mueller-Qiu

Hadron/nucleus at high energy



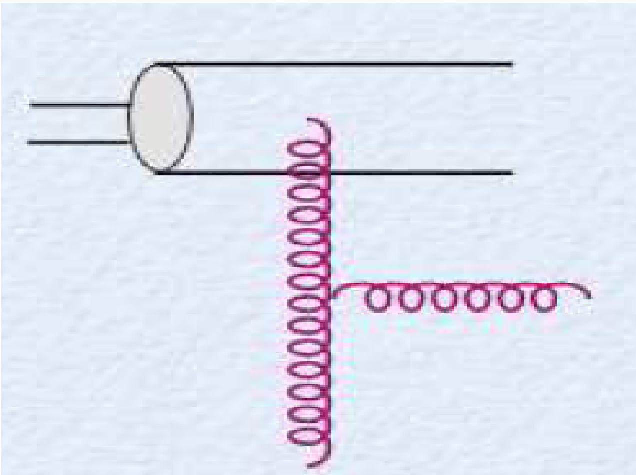
radiated gluons have the same size ($1/Q^2$) - the number of partons increase due to the increased longitudinal phase space

hadron/nucleus becomes a dense system of gluons:
gluon saturation

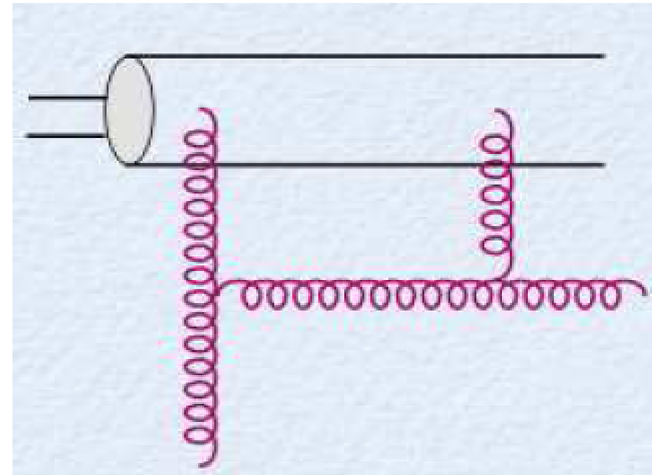
Physics of strong color fields in QCD, multi-particle production- possibly discover novel universal properties of theory in this limit

Perturbative QCD breaks down at small x

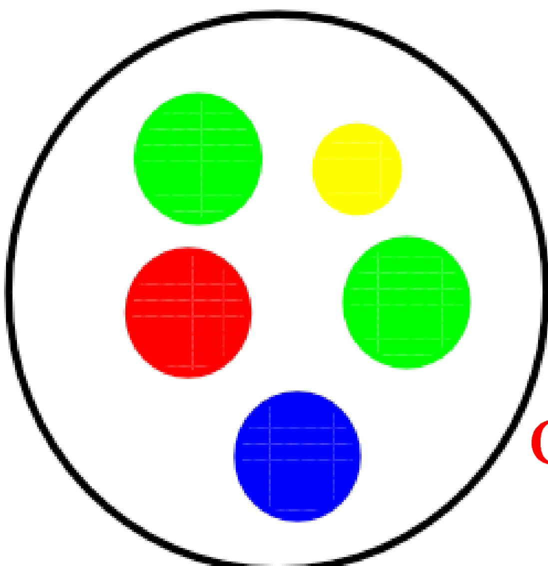
“attractive” bremsstrahlung *vs.* *“repulsive” recombination*



included in pQCD



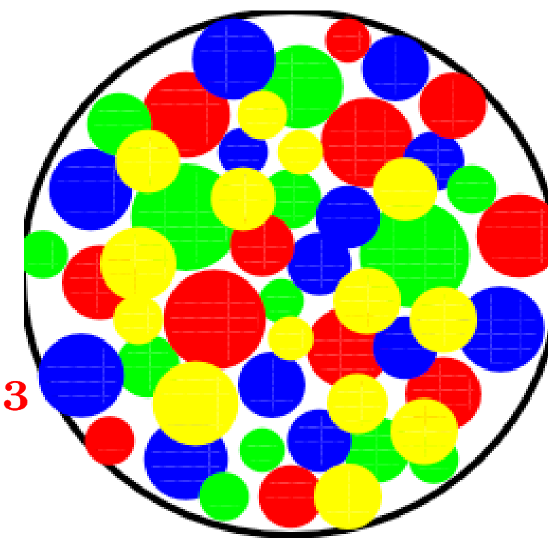
not included in pQCD
(collinear factorization)



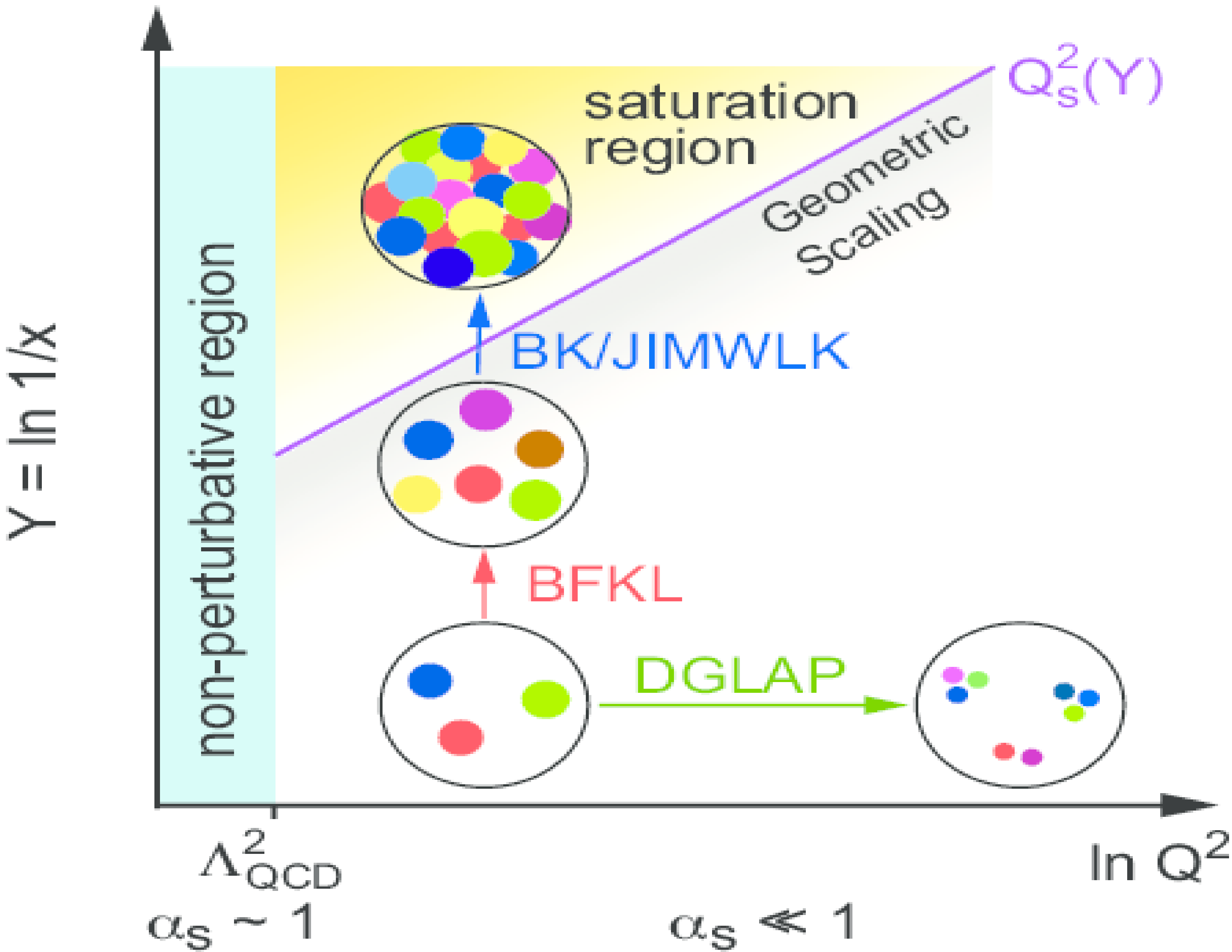
energy ~ 1/x

$$\frac{\alpha_s}{Q^2}\,\frac{xG(x,Q^2)}{\pi r^2} \sim 1$$

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



QCD at high energy: *saturation*



Probing saturation in high energy collisions

"nucleus-nucleus" (dense-dense)

initial multiplicity/energy density

need quite a bit of modeling

"proton-nucleus" (dilute-dense)

production spectra, correlations

<u>DIS</u>

structure functions (diffraction)

<u>NLO</u> di-hadron/jet correlations

<u>3-hadron/jet angular correlations</u>

much less modeling

Probing saturation via correlations

polar angle (long-range rapidity correlations)

azimuthal angle (back to back)

signatures in production spectra

multiple scattering via Wilson lines:

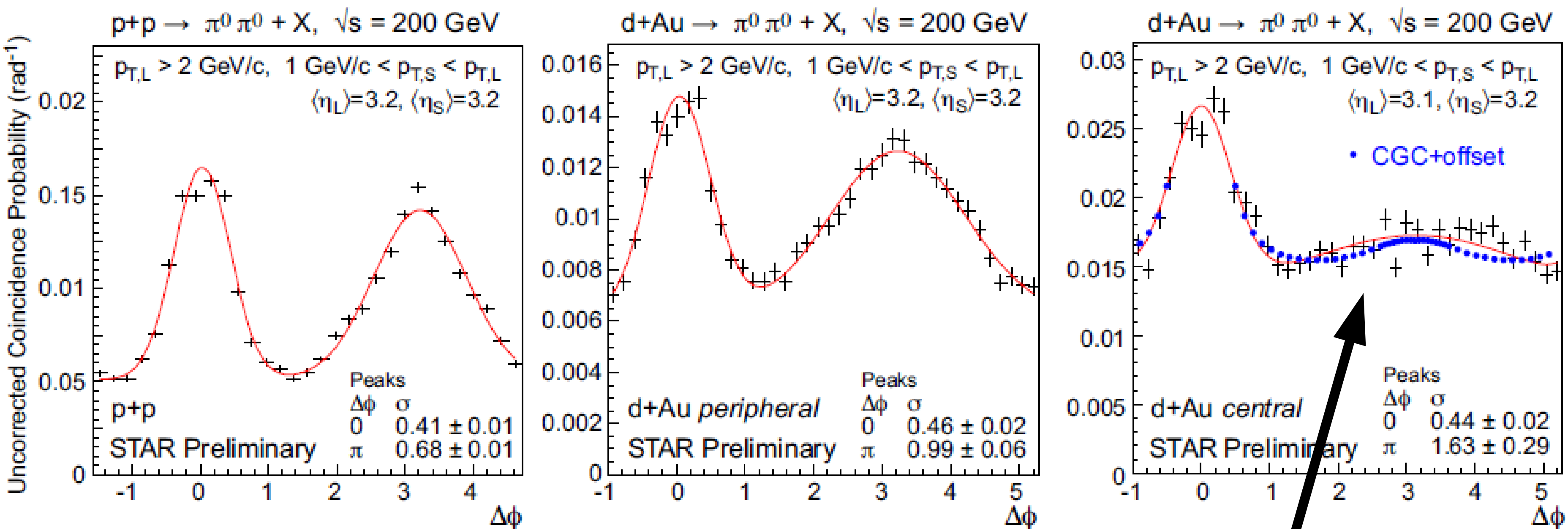
p_t broadening

x-evolution via JIMWLK:

suppression of spectra/away side peaks

di-hadron correlations in dA at RHIC

Recent STAR measurement (arXiv:1008.3989v1):



signature of gluon saturation?

Marquet, NPA (2007), Albacete + Marquet, PRL (2010)
Tuchin, NPA846 (2010)
A. Stasto + B-W. Xiao + F. Yuan, PLB716 (2012)
T. Lappi + H. Mantysaari, NPA908 (2013)

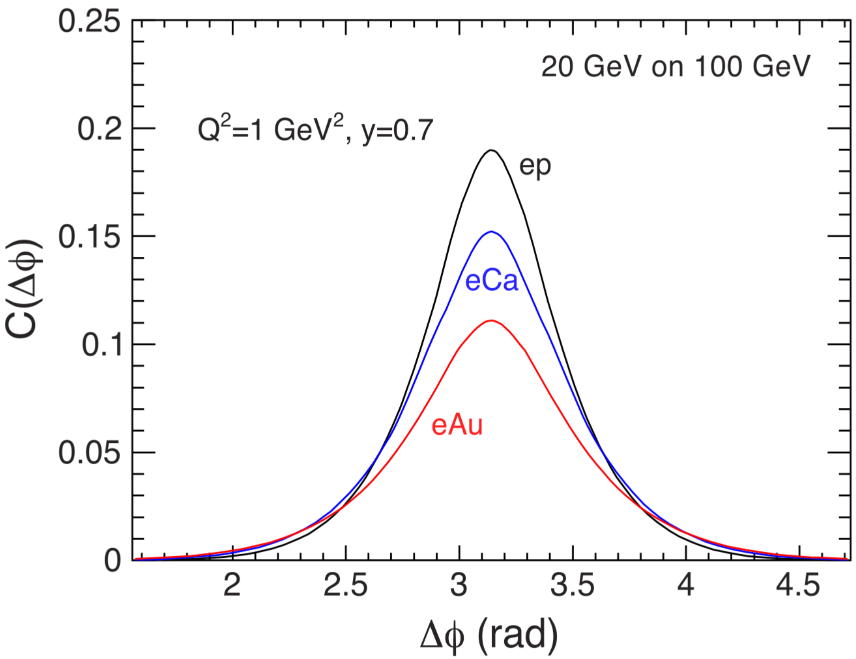
shadowing+energy loss?
Z. Kang, I. Vitev, H. Xing, PRD85 (2012) 054024

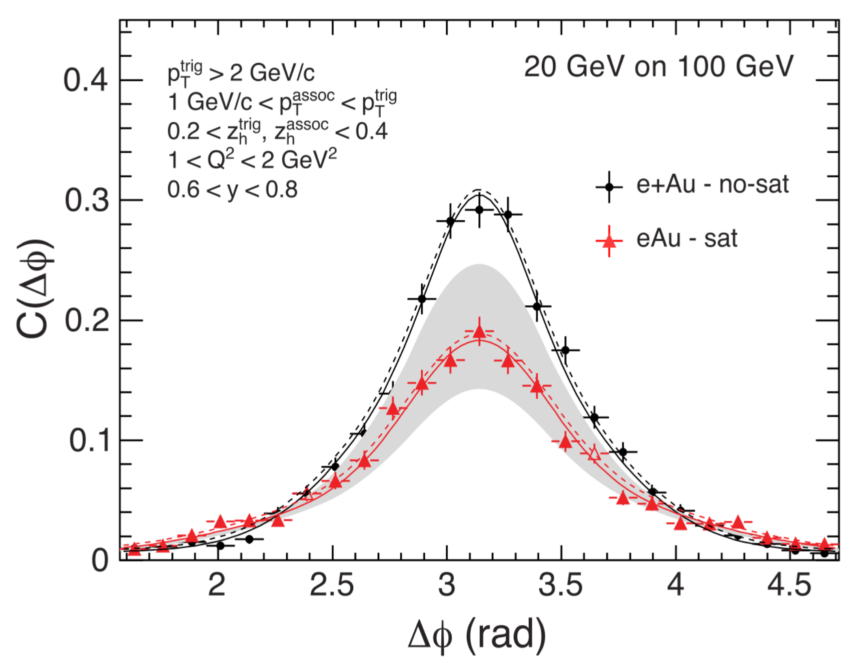
Azimuthal angular correlations

in

DIS

Di-hadron azimuthal correlations in DIS



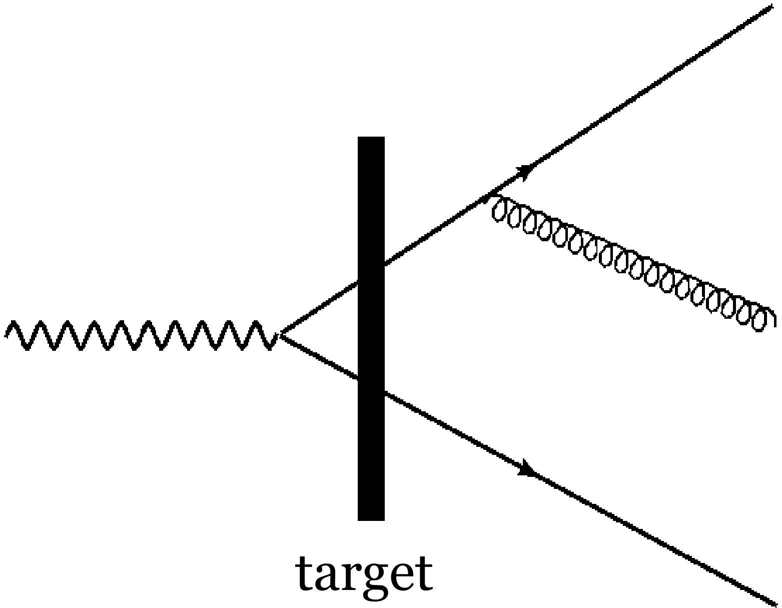


Electron Ion Collider...., A. Accardi et al., arXiv:1212.1701

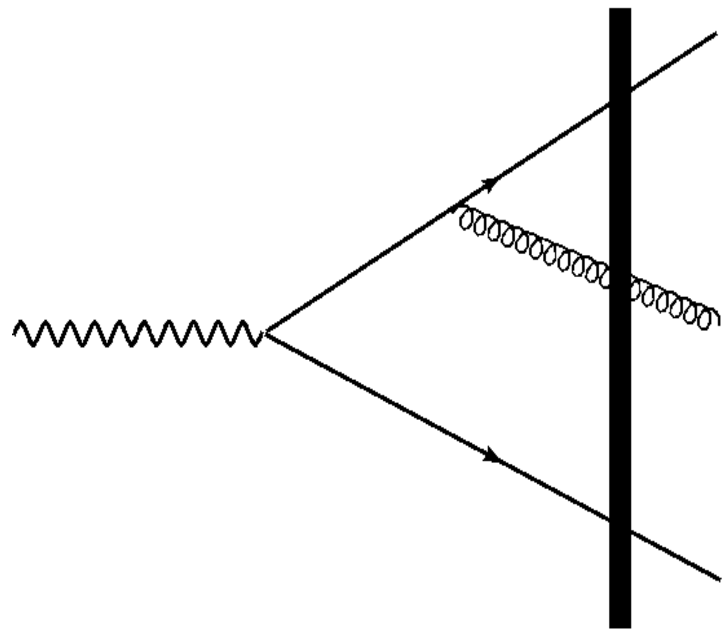
Zheng-Aschenauer-Lee-Xiao, PRD89 (2014)7, 074037

3-parton production in DIS

$$\gamma^\star \mathbf{T} \to \mathbf{q}\,\bar{\mathbf{q}}\,\mathbf{g}\,\mathbf{X}$$



+

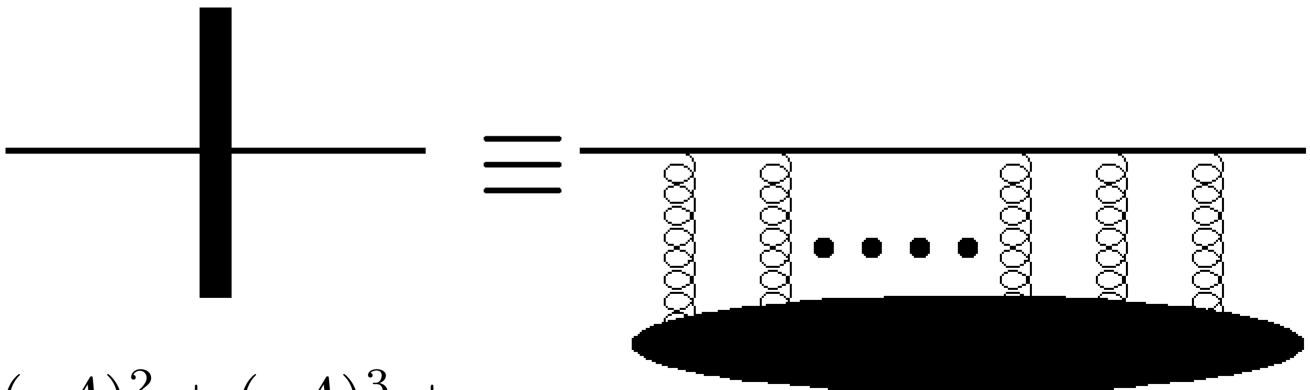


+ radiation from anti-quark

Ayala, Hentschinski , Jalilian-Marian, Tejeda-Yeomans
PLB761 (2016) 229
NPB920 (2017) 232

scattering of a quark from the target

target (proton, nucleus) as a classical color field
quark propagator in the background color field: Wilson line V



$$\sim gA + (gA)^2 + (gA)^3 + \cdots$$

$$\mathrm{S}_F(q,p) \equiv (2\pi)^4 \underbrace{\delta^4(p-q)\, S_F^0(p)}_{\text{no interaction}} + S_F^0(q)\, \underbrace{\tau_f(q,p)}_{\text{interaction}}\, S_F^0(p) \qquad \text{with} \qquad S_F^0(p) = \frac{i}{\not{p} + i\epsilon}$$

$$\begin{aligned} \tau_f(q,p) \quad &\equiv \quad (2\pi)\delta(p^+ - q^+)\,\gamma^+ \int d^2x_t\, e^{i(q_t - p_t)\cdot x_t} \\ &\quad \left\{\theta(p^+)[V(x_t) - 1] - \theta(-p^+)[V^\dagger(x_t) - 1]\right\} \end{aligned}$$

$$\mathrm{V}(\mathrm{x}_t) = \hat{p}\, e^{ig\int dz^+\, A^-(z^+, x_t)}$$

similar for gluon propagator

spinor helicity methods

Review:
L. Dixon, hep-ph/9601359

massless quarks: helicity eigenstates

$$u_\pm(k) \equiv \frac{1}{2}(1 \pm \gamma_5)\, u(k) \qquad \overline{u_\pm(k)} \equiv \overline{u(k)}\,\frac{1}{2}(1 \mp \gamma_5)$$

$$v_\mp(k) \equiv \frac{1}{2}(1 \pm \gamma_5)\, v(k) \qquad \overline{v_\mp(k)} \equiv \overline{v(k)}\,\frac{1}{2}(1 \mp \gamma_5)$$

helicity operator

$$\mathrm{h} \equiv \vec{\Sigma}\cdot\hat{p} = \begin{pmatrix} \vec{\sigma}\cdot\hat{p} & 0 \\ 0 & \vec{\sigma}\cdot\hat{p} \end{pmatrix}$$

$$\begin{aligned} \vec{\Sigma}\cdot\hat{p}\, u_\pm(p) &= \pm u_\pm(p) \\ -\vec{\Sigma}\cdot\hat{p}\, v_\pm(p) &= \pm v_\pm(p) \end{aligned}$$

$$u_+(k) = v_-(k) = \frac{1}{2^{1/4}} \begin{bmatrix} \sqrt{k^+} \\ \sqrt{k^-}e^{i\phi_k} \\ \sqrt{k^+} \\ \sqrt{k^-}e^{i\phi_k} \end{bmatrix} \qquad u_-(k) = v_+(k) = \frac{1}{2^{1/4}} \begin{bmatrix} \sqrt{k^-}e^{-i\phi_k} \\ -\sqrt{k^+} \\ -\sqrt{k^-}e^{-i\phi_k} \\ \sqrt{k^+} \end{bmatrix}$$

with $e^{\pm i\phi_k} \equiv \dfrac{k_x \pm i k_y}{\sqrt{2k^+\,k^-}} = \sqrt{2}\,\dfrac{k_t\cdot\epsilon_\pm}{k_t}$ and

$$\begin{aligned} k^\pm &= \frac{E \pm k_z}{\sqrt{2}} \\ \epsilon_\pm &= \frac{1}{\sqrt{2}}(1, \pm i) \end{aligned}$$

$$\begin{aligned} n^\mu &= (n^+ = 0, n^- = 1, n_\perp = 0) \\ \bar{n}^\mu &= (\bar{n}^+ = 1, \bar{n}^- = 0, \bar{n}_\perp = 0) \end{aligned}$$

spinor helicity methods

notation:

$$|i^{\pm}>\equiv|k_i^{\pm}>\equiv u_{\pm}(k_i)=v_{\mp}(k_i) \qquad <i^{\pm}|\equiv<k_i^{\pm}|\equiv\overline{u}_{\pm}(k_i)=\overline{v}_{\mp}(k_i)$$

basic spinor products:

$$<i\,j> \;\equiv\; <i^-|j^+>=\overline{u}_-(k_i)\,u_+(k_j) \;=\; \sqrt{|s_{ij}|}e^{i\phi_{ij}} \qquad \cos\phi_{ij} \;=\; \frac{k_i^x k_j^+ - k_j^x k_i^+}{\sqrt{|s_{ij}|k_i^+ k_j^+}}$$

$$[i\,j] \;\equiv\; <i^+|j^->=\overline{u}_+(k_i)\,u_-(k_j) \;=\; -\sqrt{|s_{ij}|}e^{-i\phi_{ij}} \qquad \sin\phi_{ij} \;=\; \frac{k_i^y k_j^+ - k_j^y k_i^+}{\sqrt{|s_{ij}|k_i^+ k_j^+}}$$

with

$$\begin{aligned} s_{ij} &= (k_i+k_j)^2 = 2k_i\cdot k_j \\ &= -<ij>[ij] \end{aligned}$$

and

$$\begin{aligned} <ii> &= [ii]=0 \\ <ij] &= [ij>=0 \end{aligned}$$

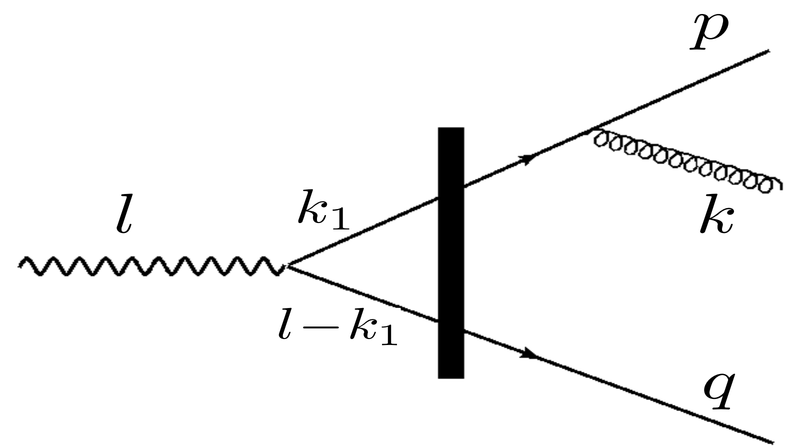
charge conjugation $\quad <i^+|\gamma^\mu|j^+>=<j^-|\gamma^\mu|i^->$

Fierz identity $\quad <i^+|\gamma^\mu|j^+><k^+|\gamma^\mu|l^+>=2[ik]\;<lj>$

any off-shell momentum $\quad k^\mu\equiv\bar{k}^\mu+\dfrac{k^2}{2k^+}n^\mu \quad$ where $\bar{k}^\mu$ is on-shell $\quad \bar{k}^2=0$

any on-shell momentum $\quad \not{p}=|p^+><p^+|+|p^-><p^-|$

Diagram A1



Numerator: Dirac Algebra

$$a_1 \equiv \overline{u}(p)\,(k)\,(\not{p}+\not{k})\;\not{k}_1\;(l)\,(\not{k}_1-\not{l})\;v(q)$$

longitudinal photons

quark anti-quark gluon helicity: + - +

$$\not{l} = l^+\not{\overline{n}} - \frac{Q^2}{2l^+}\not{n}$$

$$a_1^{L;+-+} \;=\; -\frac{\sqrt{2}}{[n\,k]}\frac{Q}{l^+}\,[n\,p] < k\,p > [n\,p] < n\,\overline{k}_1 > \left[n\,\overline{k}_1\right] < n\,q >$$

$$\left(< n\,\overline{k}_1 > \left[n\,\overline{k}_1\right] - l^+ < n\,\overline{n} > [n\,\overline{n}]\right)$$

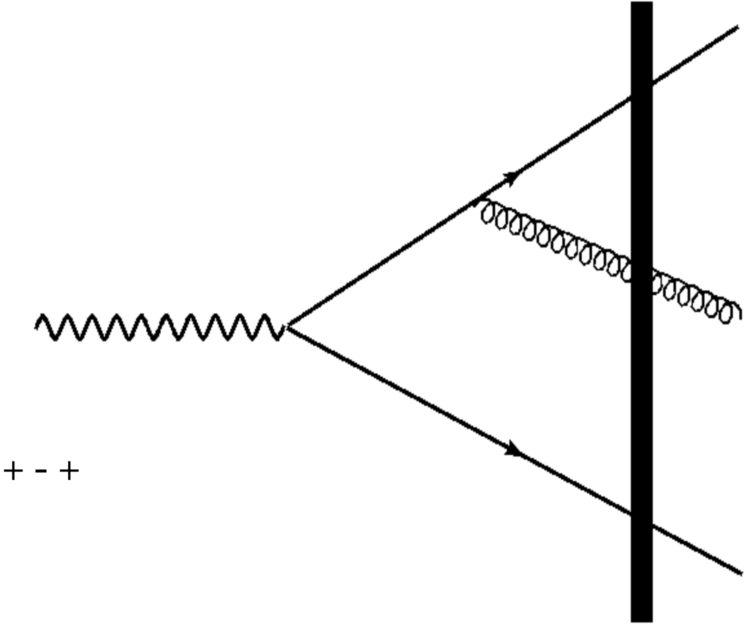
with

$$< np >= -[np] = \sqrt{2p^+}$$

transverse photons: +

$$a_1^{\perp=+;+-+} = -\frac{\sqrt{2}}{[nk]}[pn] < kp > [pn] < nk_1 > [k_1 n] < \bar{n}k_1 > [k_1 n] < nq >$$

Diagram A3



Numerator: Dirac Algebra

longitudinal photons

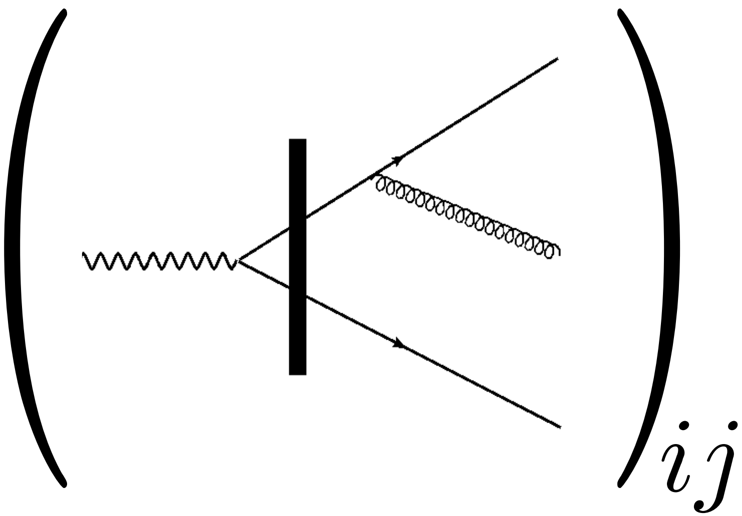
quark anti-quark gluon helicity: + - +

$$
\begin{aligned}
a_3^{L;+-+} &= \frac{\sqrt{2}Q}{l^+\,[n\bar{k}_2]}[pn]\left(< n\bar{k}_1 > [\bar{k}_1 n] - < n\bar{k}_2 > [\bar{k}_2 n]\right) < \bar{k}_2\bar{k}_1 > [\bar{k}_1 n] \\
&\quad \left(< n\bar{k}_1 > [\bar{k}_1 n] - l^+ < n\bar{n} > [\bar{n}n]\right) < nq > \\
&= -2^4 Q(l^+)^2\,\frac{(z_1 z_2)^{3/2}}{z_3}\,\left[z_3\, k_{1\,t}\cdot\epsilon - (z_1+z_3)k_{2\,t}\cdot\epsilon\right]
\end{aligned}
$$

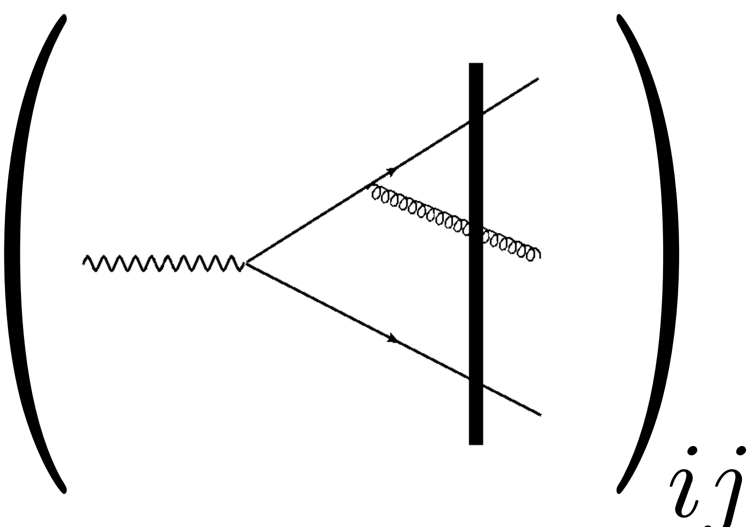
the rest is some standard integrals, <u>we know how to compute the numerators efficiently</u>

add up the amplitudes, add, square.. : **get (trace of) products of Wilson lines**

structure of Wilson lines: amplitude



$$= \left[V^\dagger(y_t)\, V(x_t)\, t^a\right]_{ij}$$

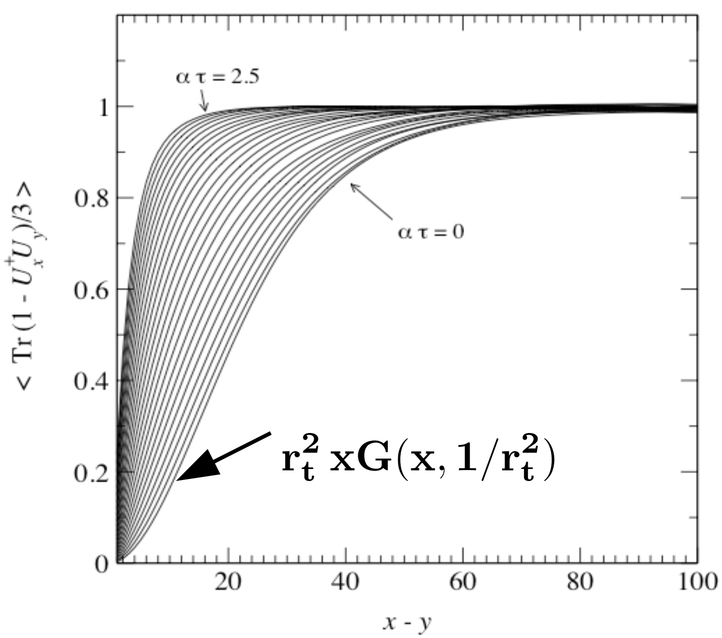


$$= \left[V^\dagger(y_t)\, t^b\, V(x_t)\right]_{ij}\; U^{ba}(z_t)$$

Dipoles at large N_c : Balitsky-Kovchegov eq $\quad T \equiv 1 - S$

$$\frac{\mathbf{d}}{\mathbf{dy}}\mathbf{T}(\mathbf{x_t}-\mathbf{y_t}) = \frac{\bar{\alpha}_s}{2\pi}\int \mathbf{d^2 z_t}\,\frac{(\mathbf{x_t}-\mathbf{y_t})^2}{(\mathbf{x_t}-\mathbf{z_t})^2(\mathbf{y_t}-\mathbf{z_t})^2}\times$$

$$\left[\mathbf{T}(\mathbf{x_t}-\mathbf{z_t})+\mathbf{T}(\mathbf{z_t}-\mathbf{y_t})-\mathbf{T}(\mathbf{x_t}-\mathbf{y_t})-\mathbf{T}(\mathbf{x_t}-\mathbf{z_t})\mathbf{T}(\mathbf{z_t}-\mathbf{y_t})\right]$$



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

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

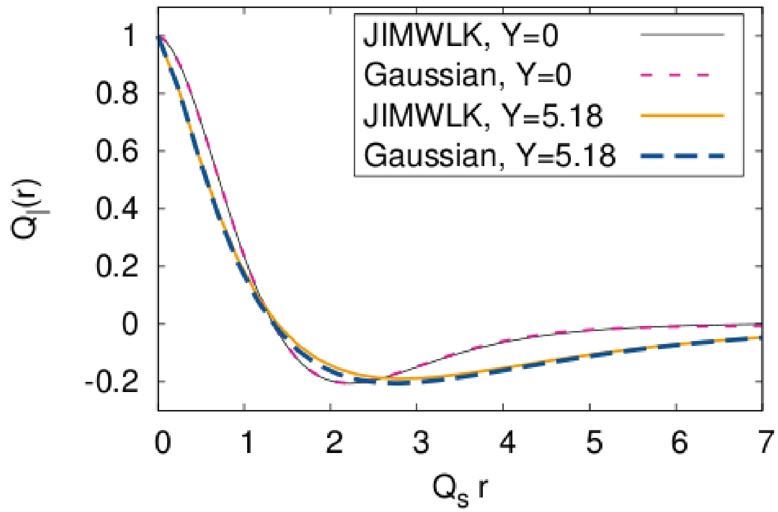
$$\tilde{\mathbf{T}}(\mathbf{p_t}) \to \frac{\mathbf{1}}{\mathbf{p_t^2}}\left[\frac{\mathbf{Q_s^2}}{\mathbf{p_t^2}}\right]$$ **pQCD region**

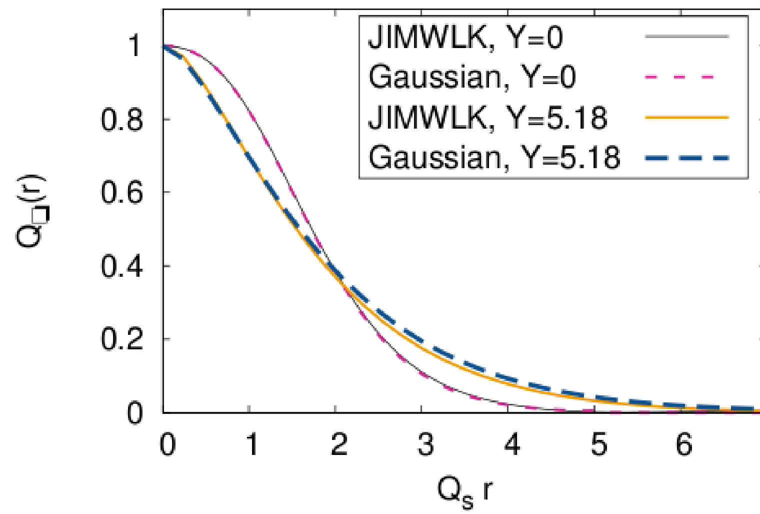
***Rummukainen-Weigert**, NPA739 (2004) 183*

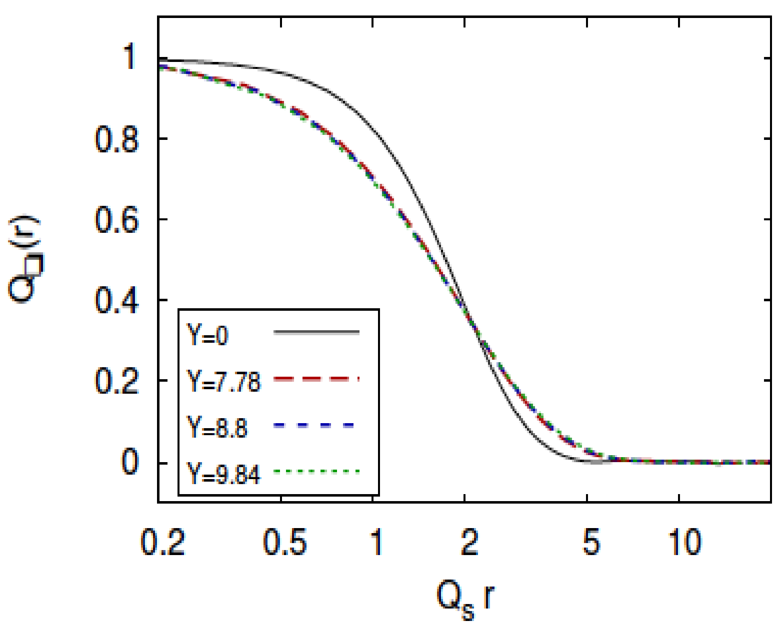
***NLO:** Balitsky-Kovchegov-Weigert-Gardi-Chirilli (2007-2008)*

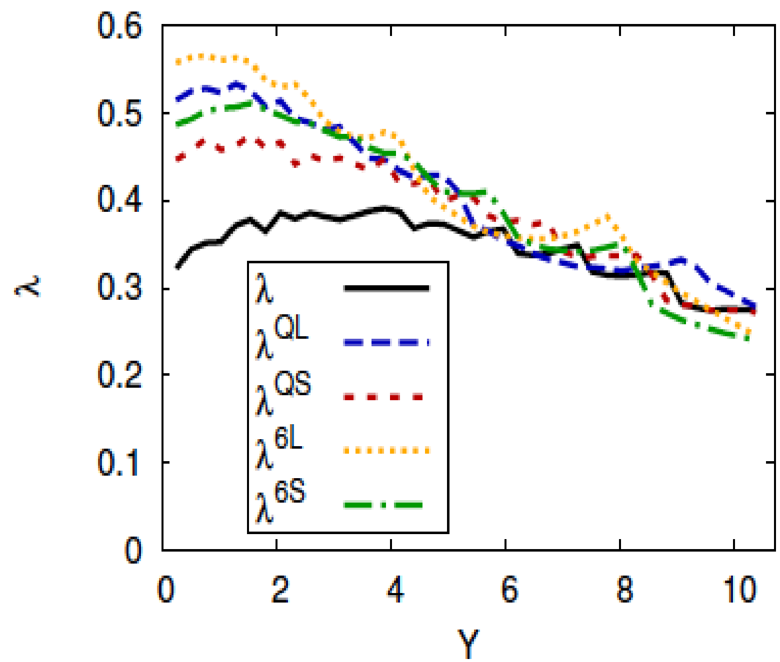
Quadrupole: $Q(r,\bar{r},\bar{s},s) \equiv \frac{1}{N_c} < Tr\, V(r)\, V^\dagger(\bar{r})\, V(\bar{s})\, V^\dagger(s) >$

Dumitru-Jalilian-Marian-<u>Lappi-Schenke</u>-Venugopalan:PLB706 (2011) 219

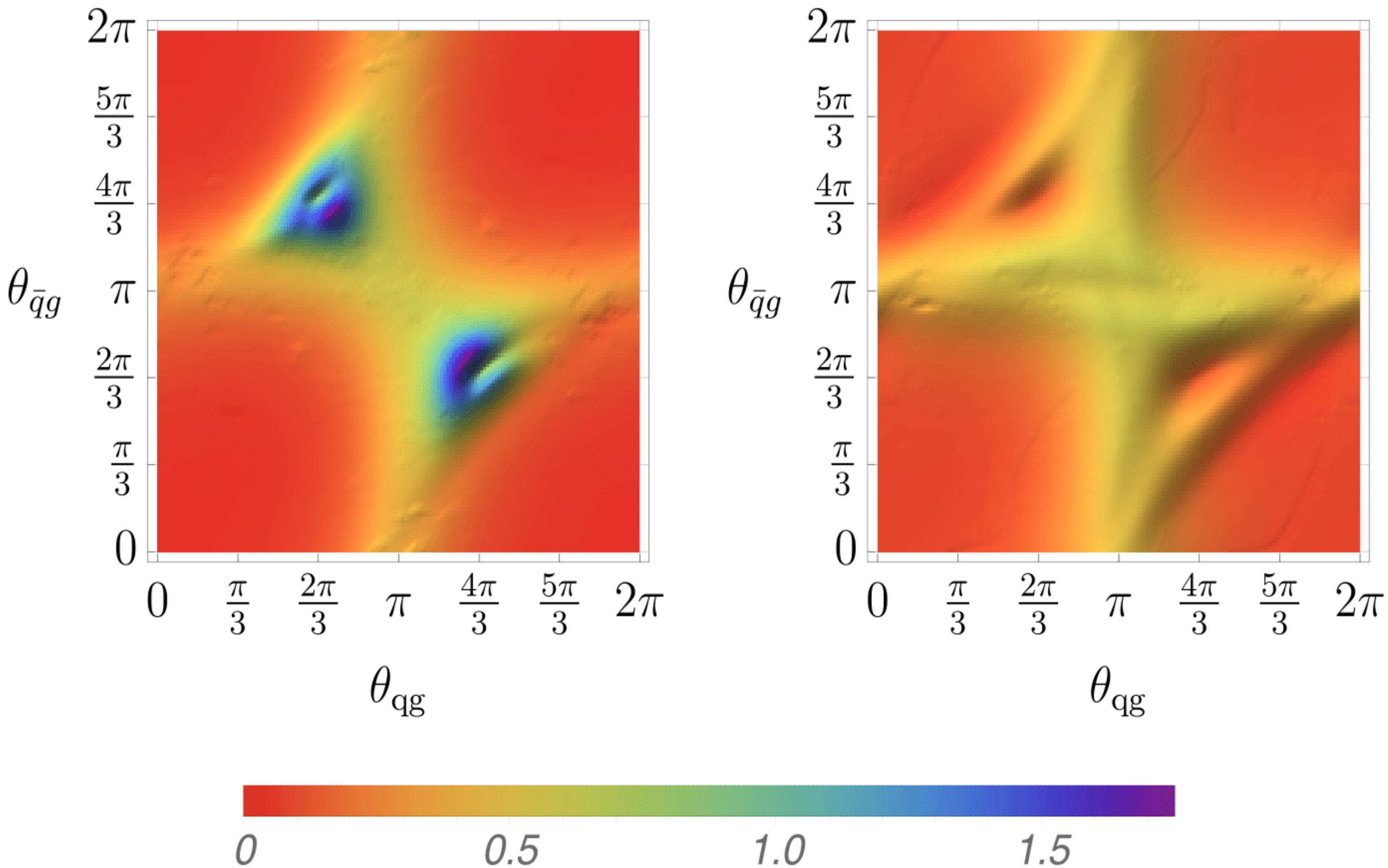








3-parton azimuthal angular correlations



multiple scattering:

broadening of the peak

x-evolution:

reduction of magnitude

some thoughts/ideas/......

cold matter energy loss

how important is cold matter Eloss in single inclusive production in the forward rapidity region?

cold matter energy loss?
Kopeliovich, Frankfurt and Strikman
Neufeld,Vitev,Zhang, PLB704 (2011) 590

Munier, Peigne, Petreska, arXiv:1603.01028

$$z\frac{dI}{dz} \equiv \frac{\frac{d\sigma^{a+A\to a+g+X}}{dydy'd^2p_t}}{\frac{d\sigma^{a+A\to a+X}}{dyd^2p_t}}$$

the difference between a nuclear target and a proton target is the medium induced energy loss

used to estimate the energy loss in single inclusive processes in the forward kinematics at RHIC and the LHC

can also do this for di-jets in DIS

(3-parton production/2-parton production)

SUMMARY

CGC is a systematic approach to high energy collisions

high gluon density: re-sum multiple soft scatterings

high energy: re-sum large logs of energy (rapidity or log 1/x)

Leading Log CGC works (too) well

it has been used to fit a wealth of data; ep, eA, pp, pA, AA

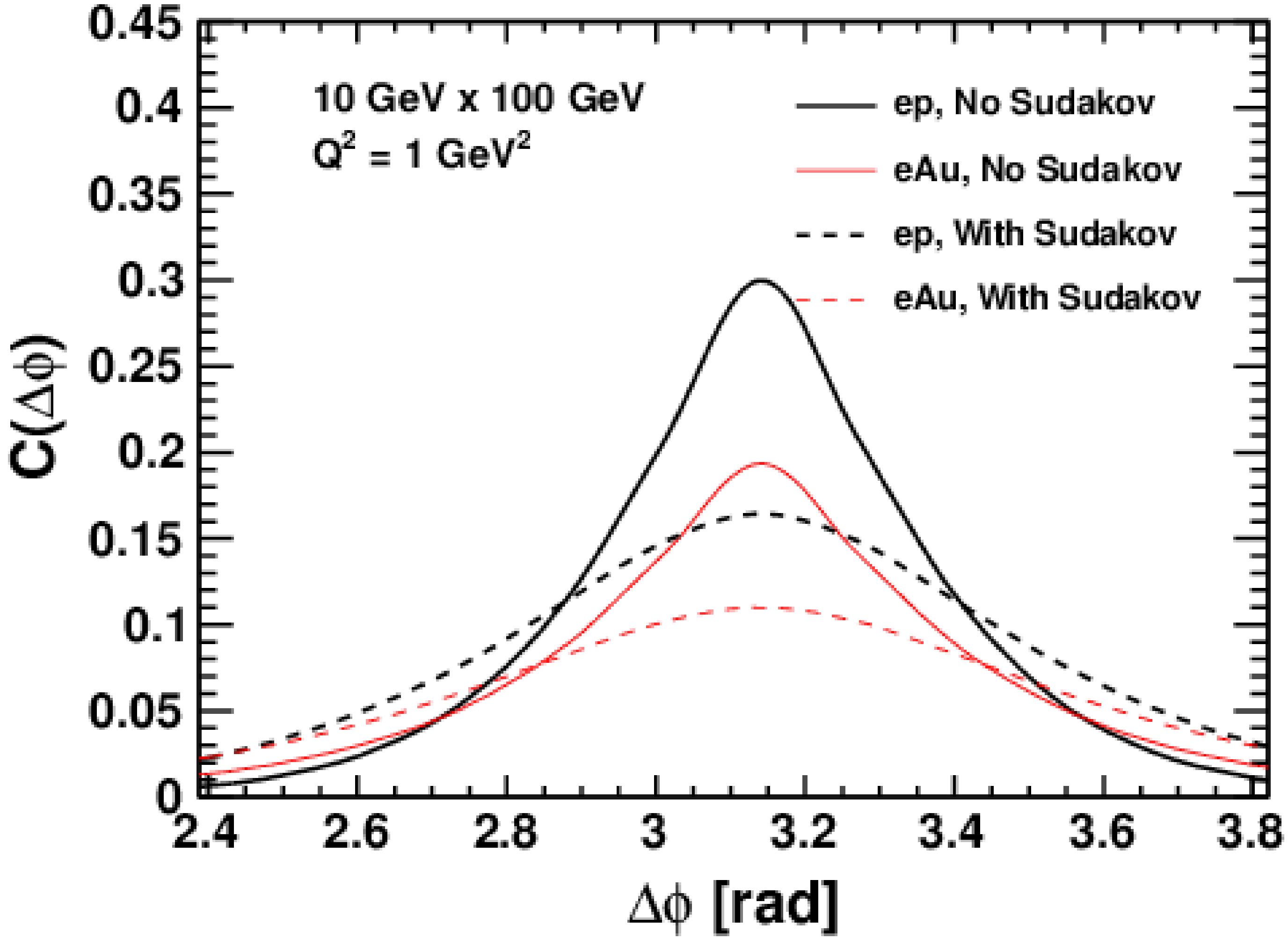
Precision (NLO) studies are needed

available for DIS, single inclusive forward production in pp, pA

Azimuthal angular correlations offer a unique probe of CGC

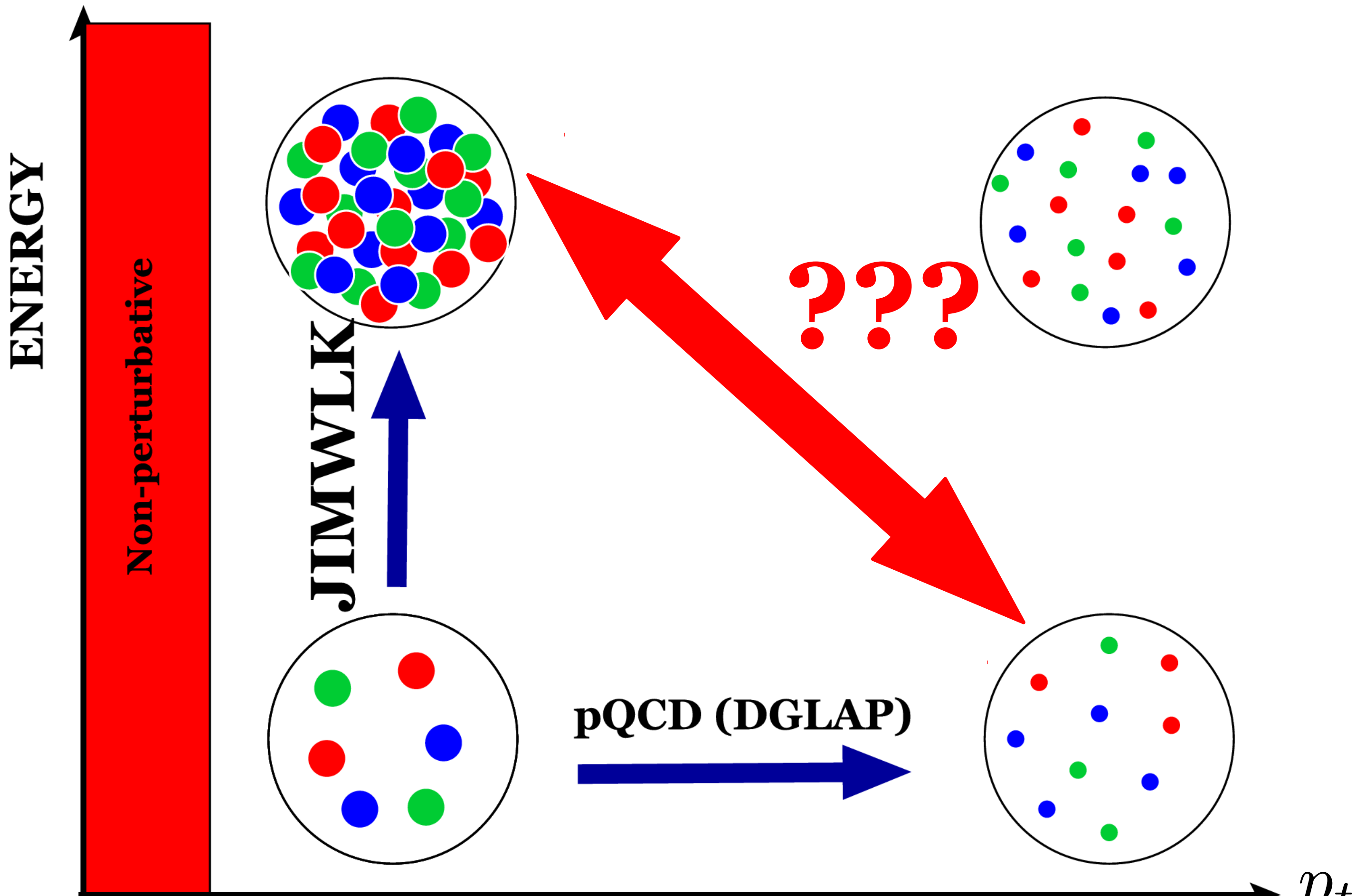
3-hadron/jet correlations should be even more discriminatory

Azimuthal correlations in DIS



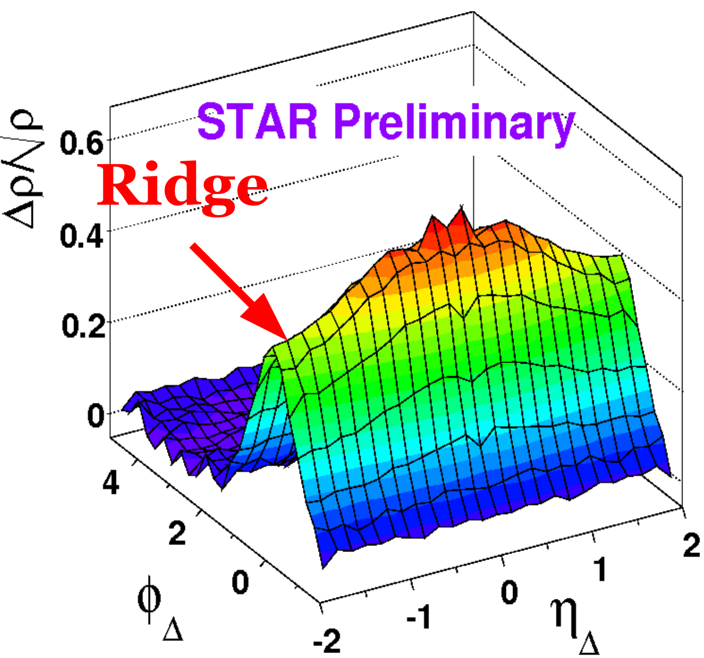
Zheng + Aschenauer + Lee + Xiao, PRD89 (2014)7, 074037

QCD phase space

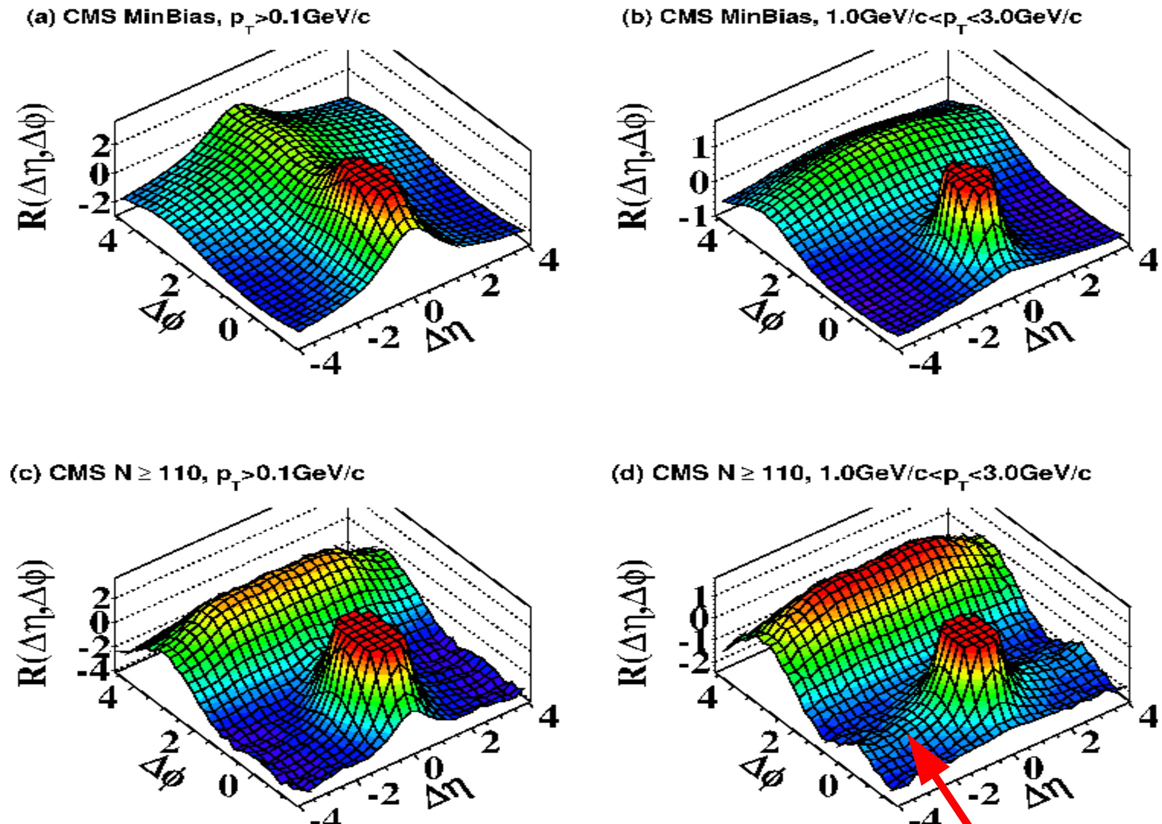


a general formalism for all x, Q^2:
toward unifying JIMWLK with DGLAP?

long-range rapidity correlations: the ridge



AA at RHIC



PP at LHC

Ridge

Initial state vs final state ?

if final state, early or late times?

The quadrupole

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

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: $Q = S^2$ $\qquad S(r,\bar{r}) \equiv \frac{1}{N_c} < Tr\, V(r)\, V^\dagger(\bar{r}) >$

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

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

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

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