From DIS to pA at small x:

Azimuthal angular correlations

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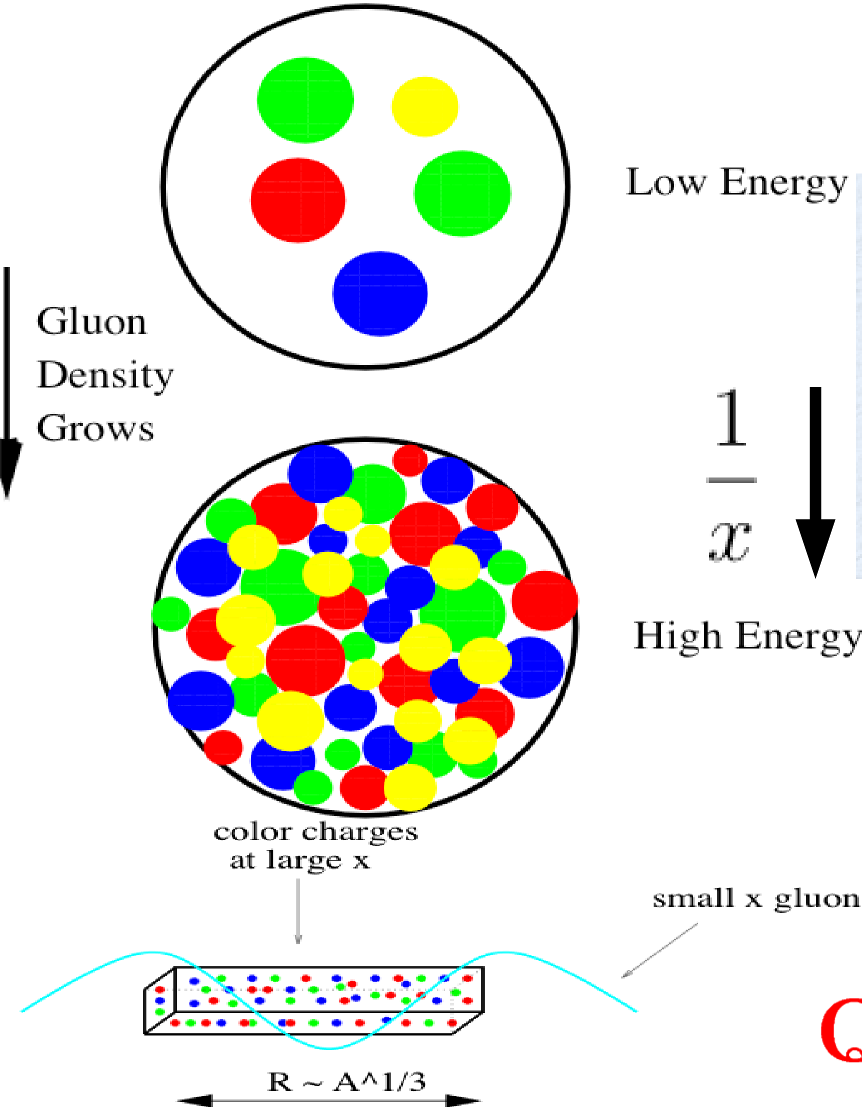
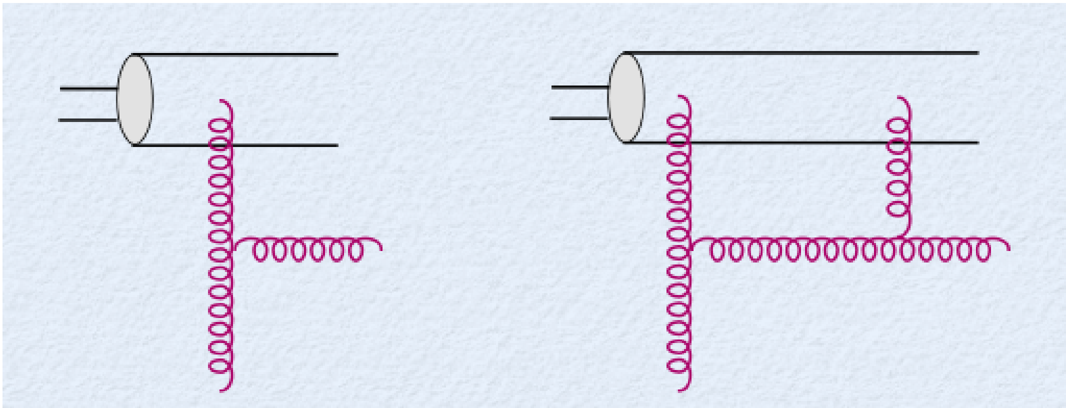
GDR QCD 2016
8-10 November, IPN Orsay

Gluon saturation

Gribov-Levin-Ryskin
Mueller-Qiu

"attractive" bremsstrahlung vs.
"repulsive" recombination

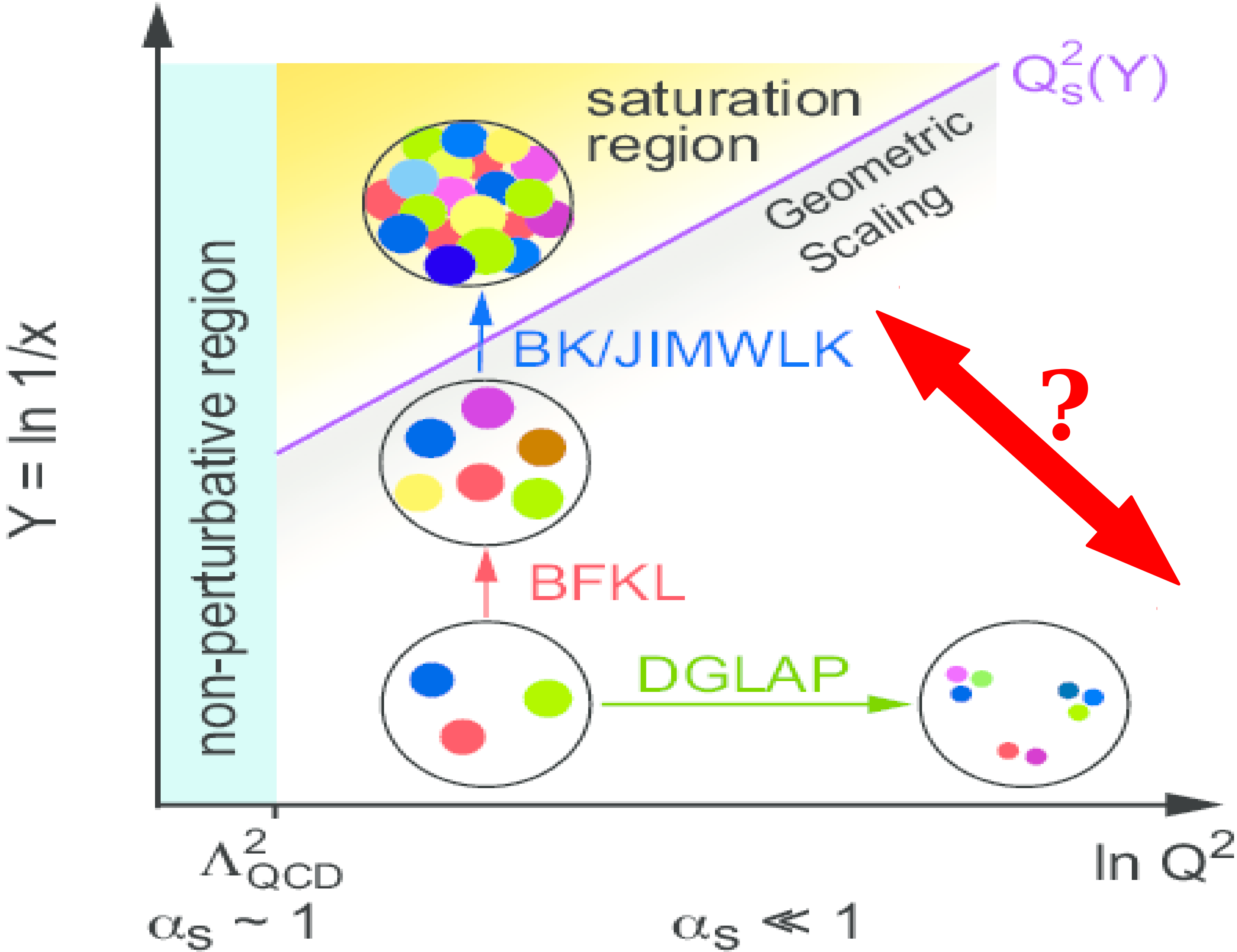




$$\frac{\alpha_s}{Q^2}\,\frac{xG(x, b_t, Q^2)}{S_\perp} \sim 1$$

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

QCD at high energy: *saturation*

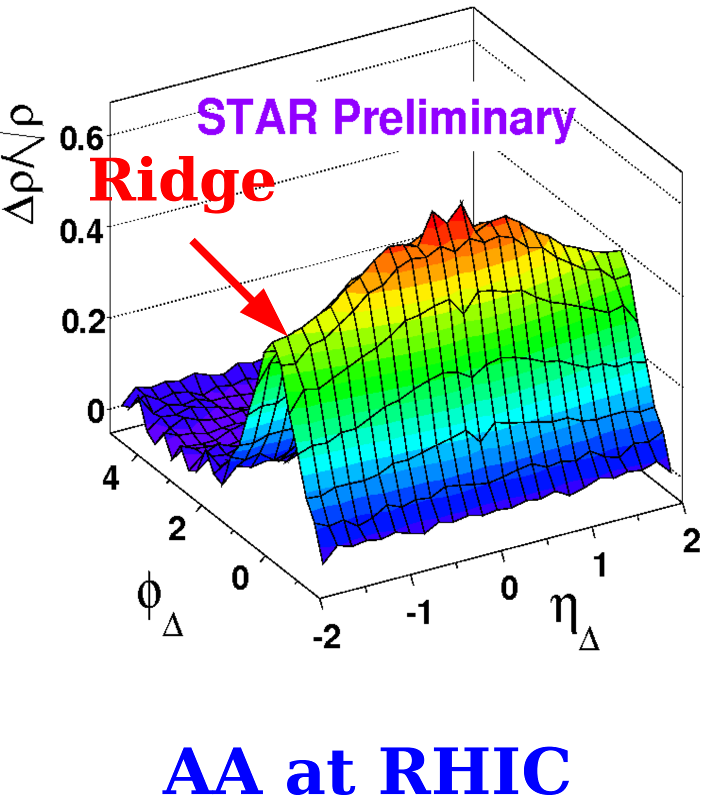


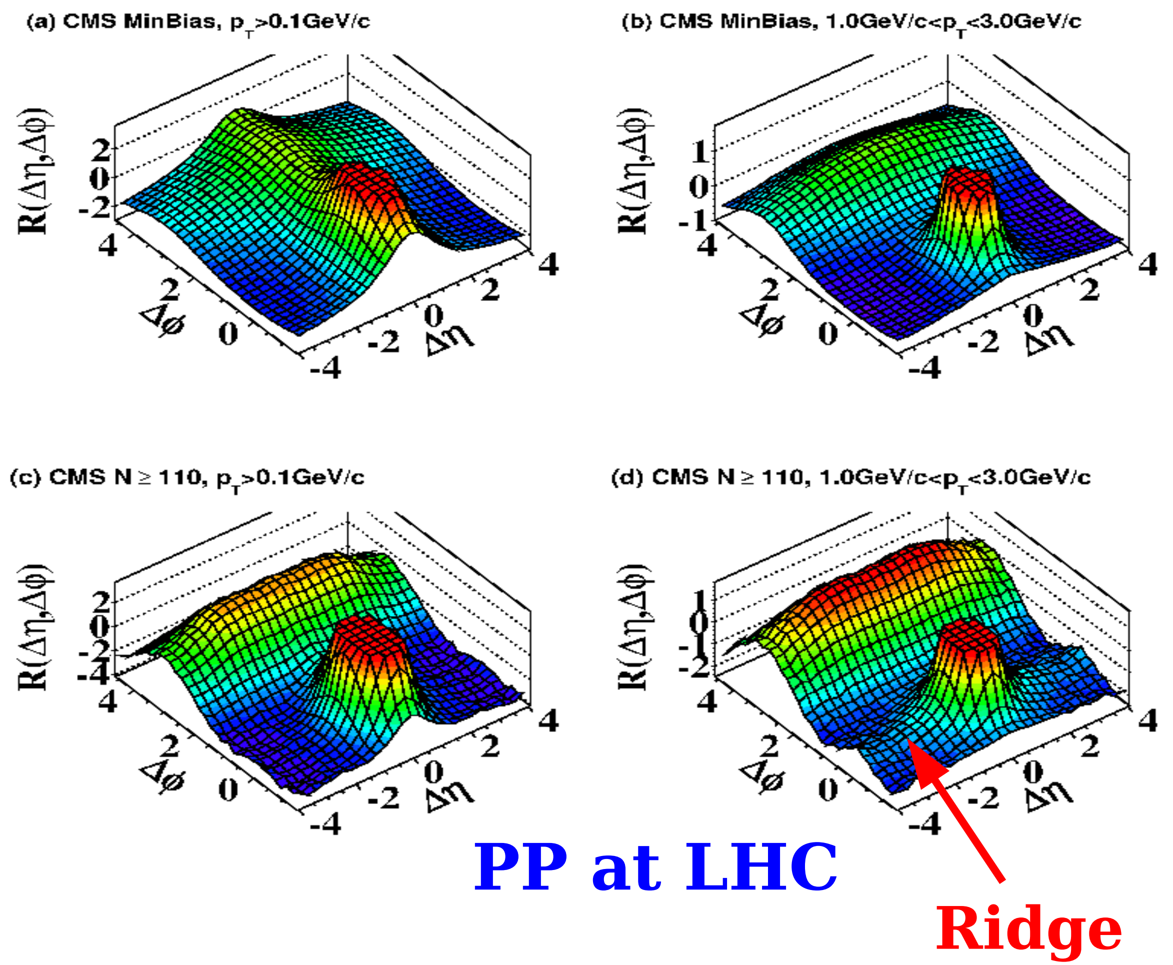
Probing saturation: di-hadron correlations

polar angle (rapidity correlations)

azimuthal angle (back to back)

long-range rapidity correlations: the ridge



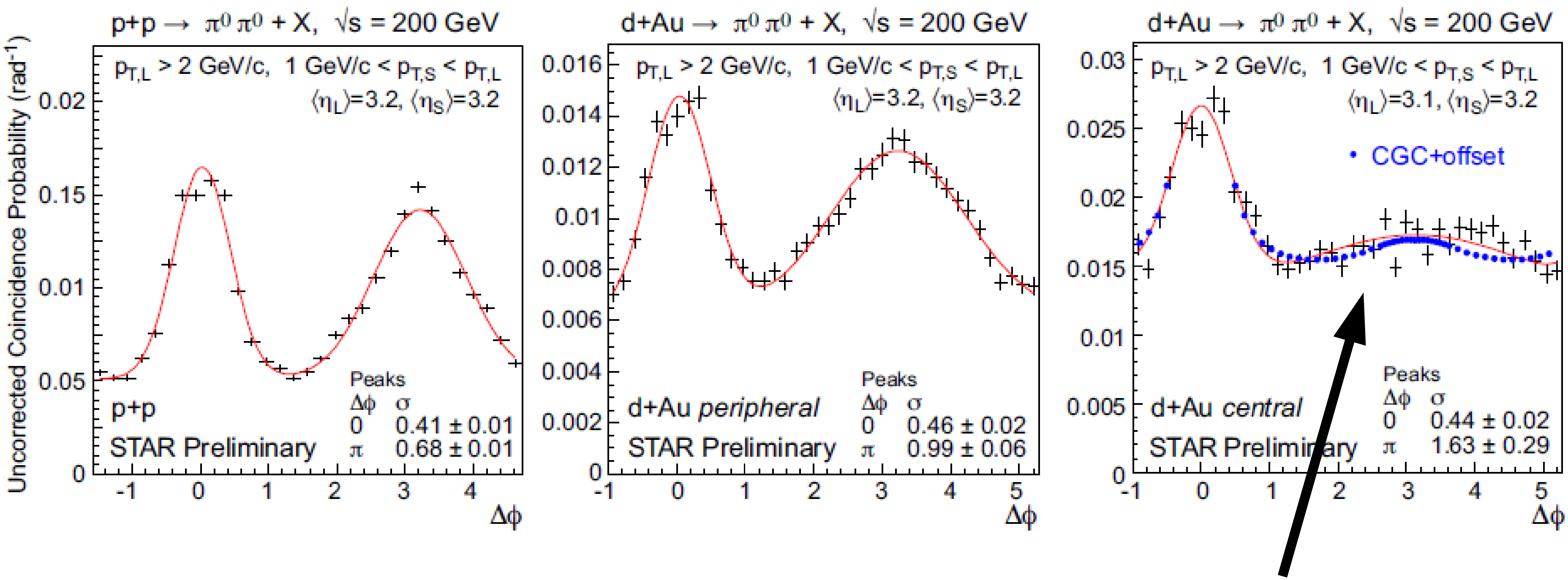


Initial state vs final state ?

if final state, early or late times?

di-hadron correlations in pA

Recent STAR measurement (arXiv:1008.3989v1):



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)

saturation effects de-correlate the hadrons

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

DIS $\longleftrightarrow$ **pA**

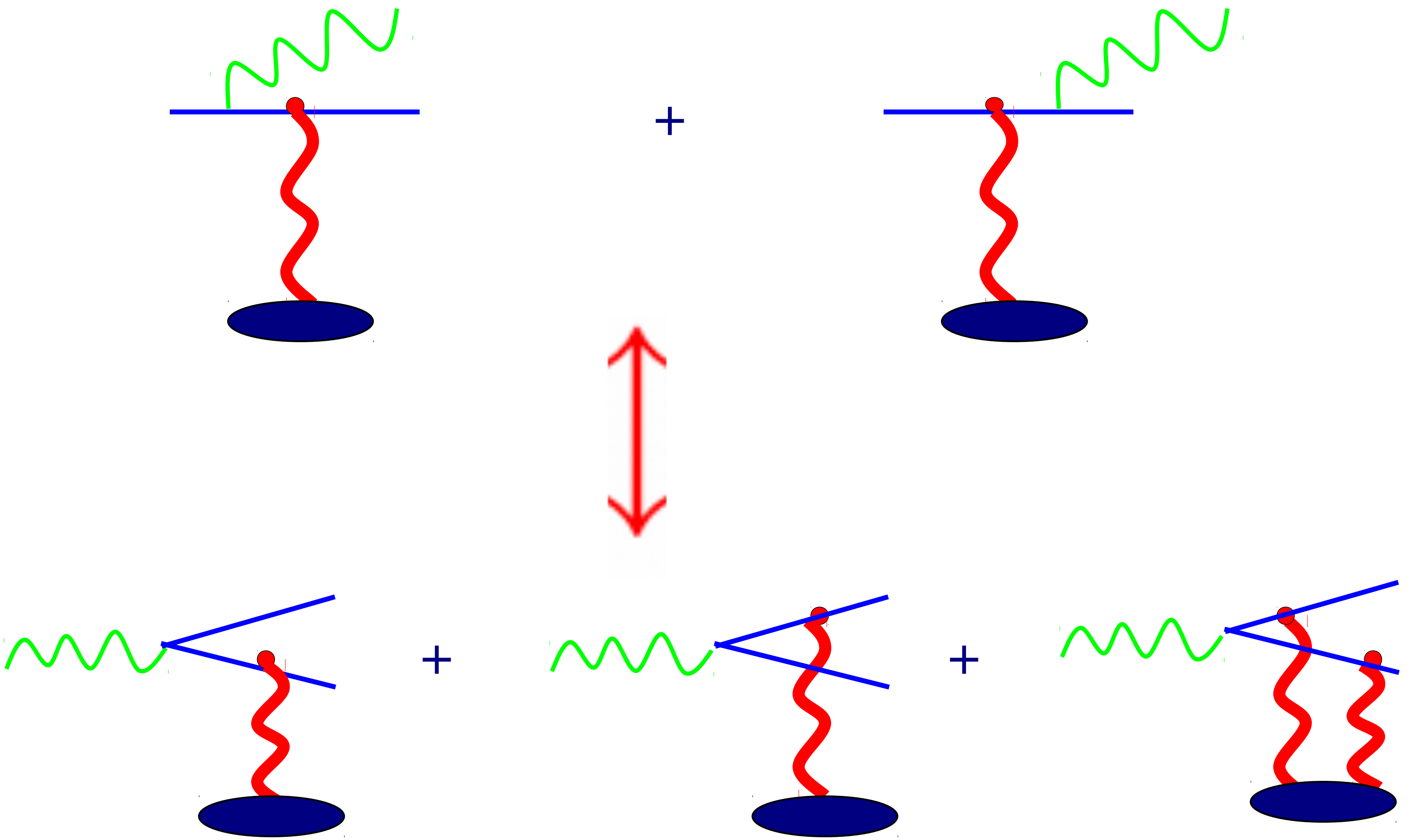
crossing symmetry

From DIS to DY: crossing symmetry (LO)

$$\gamma^\star \mathbf{A} \to \mathbf{q}\,\bar{\mathbf{q}}\,\mathbf{X} \quad \leftrightarrow \quad \mathbf{q}\,\mathbf{A} \to \mathbf{q}\,\gamma^\star\,\mathbf{X}$$

qA:

DIS:

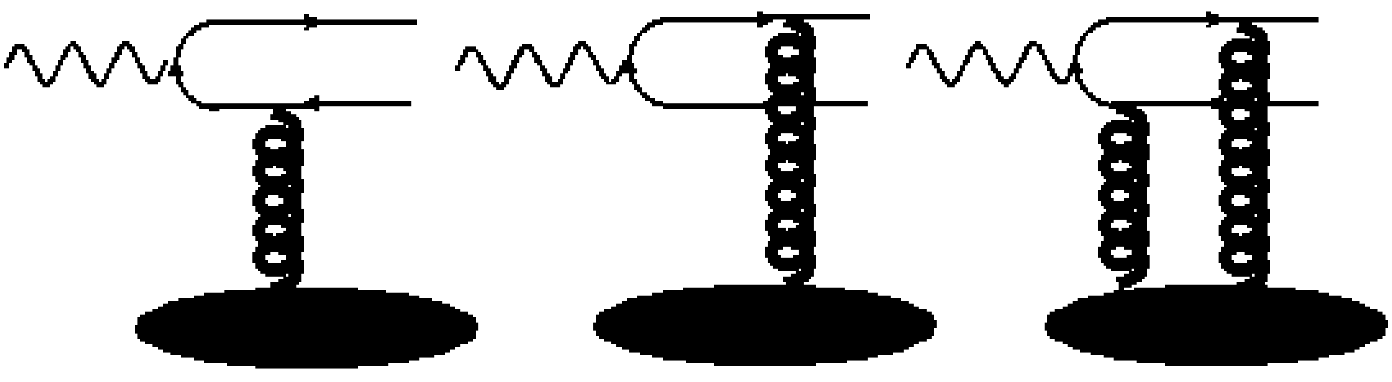


di-hadron (azimuthal) angular correlations in DIS

DIS total cross section (F_L, F_2): ***dipoles*** $< \mathbf{Tr}\, \mathbf{V}\, \mathbf{V}^{\dagger} >$

di-jet production in DIS: ***quadrupoles*** $< \mathbf{Tr}\, \mathbf{V}\, \mathbf{V}^{\dagger}\, \mathbf{V}\, \mathbf{V}^{\dagger} >$

$$\mathrm{LO:} \qquad \gamma^{\star} T \rightarrow q\, \bar{q}\, X$$



di-hadron production in DIS

$$\gamma^\star(\mathbf{k})\,\mathbf{p} \to \mathbf{q}(\mathbf{p})\,\bar{\mathbf{q}}(\mathbf{q})\,\mathbf{X}$$

$$\mathcal{A}^\mu(k,q,p) = \frac{i}{2}\int \frac{d^2 l_\perp}{(2\pi)^2} d^2x_\perp d^2y_\perp\, e^{i(p_\perp + q_\perp - k_\perp - l_\perp)\cdot y_\perp}$$
$$e^{i l_\perp \cdot x_\perp}\, \overline{u}(q)\, \Gamma^\mu(k^\pm, k_\perp, q^-, p^-, q_\perp - l_\perp)\, v(p)$$
$$\left[V(x_\perp)V^\dagger(y_\perp) - 1\right]$$

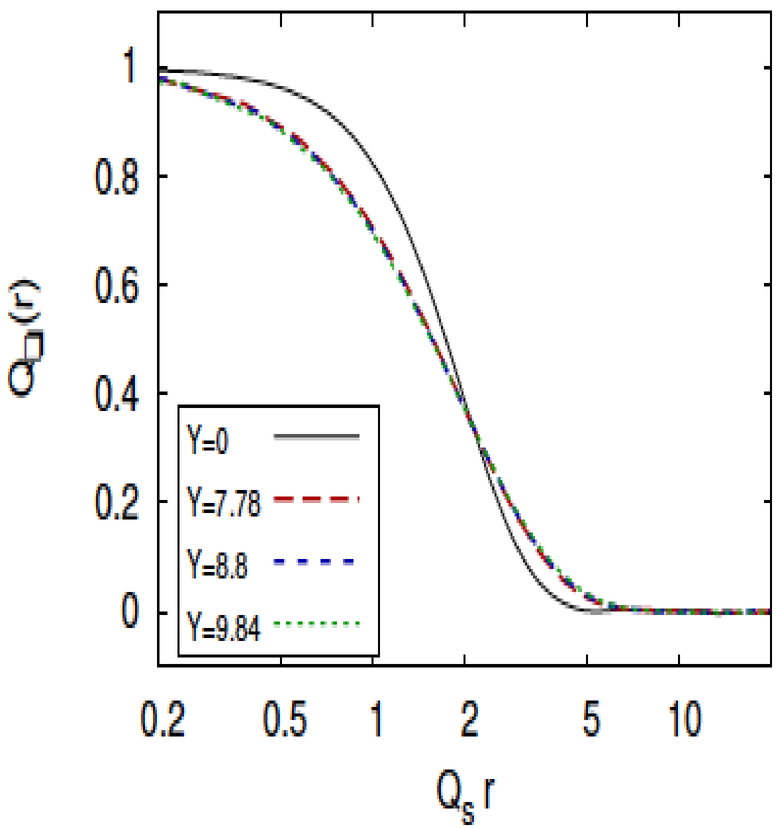
with

$$\Gamma^\mu \equiv$$
$$\frac{\gamma^-(\not{q} - \not{l} + m)\gamma^\mu(\not{q} - \not{k} - \not{l} + m)\gamma^-}{p^-[(q_\perp - l_\perp)^2 + m^2 - 2q^-k^+] + q^-[(q_\perp - k_\perp - l_\perp)^2 + m^2]}$$

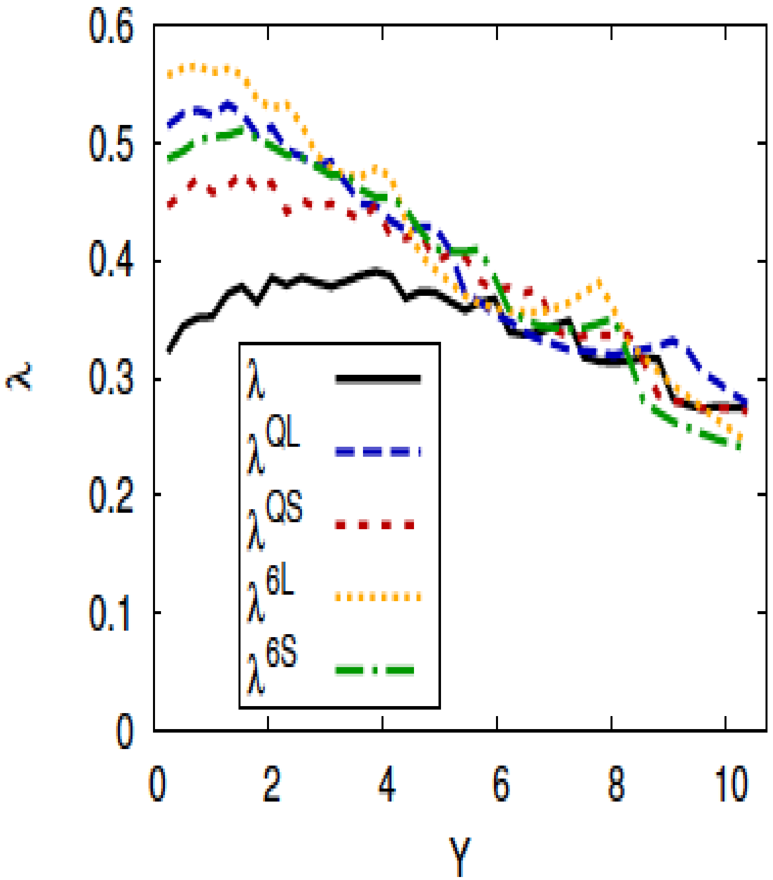
F. Gelis and J. Jalilian-Marian, PRD67 (2003) 074019

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

Quadrupole evolution: JIMWLK



Geometric scaling also present in quadrupoles



Energy dependence of saturation scale

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

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: $Q = S^2$

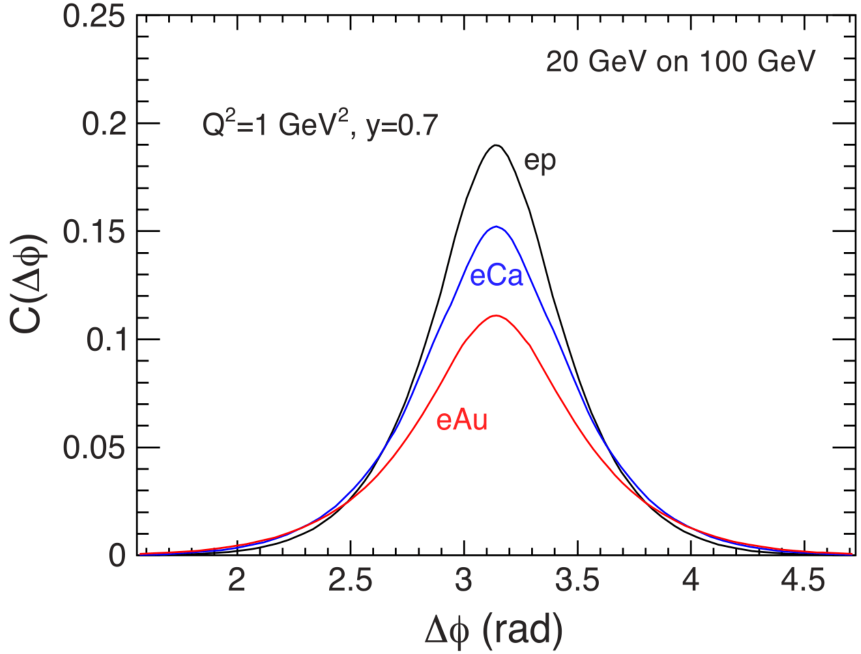
Gaussian $Q_|(z) \approx \frac{N_c+1}{2}[S(z)]^{2\frac{N_c+2}{N_c+1}} - \frac{N_c-1}{2}[S(z)]^{2\frac{N_c-2}{N_c-1}}$

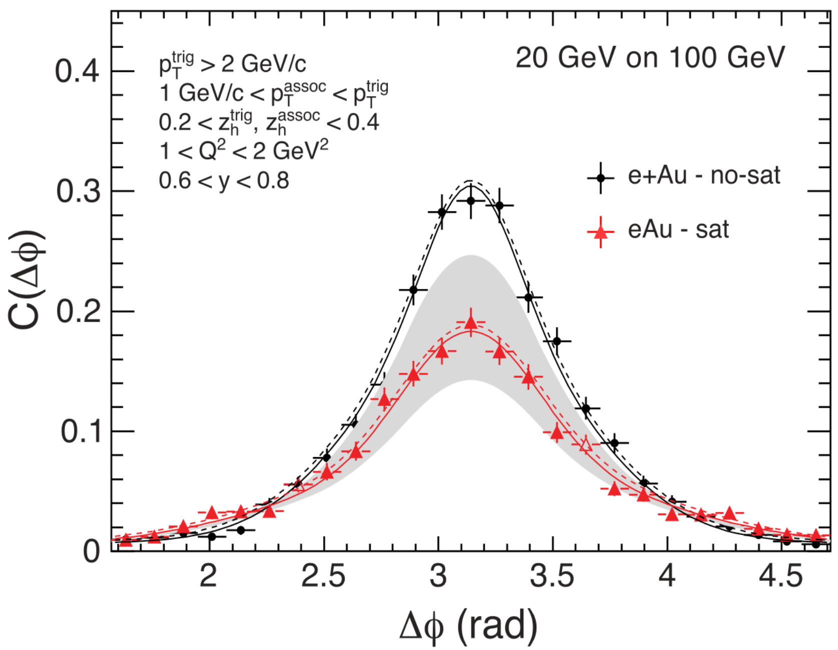
$$Q_{sq}(z) = [S(z)]^2 \left[\frac{N_c+1}{2} \left(\frac{S(z)}{S(\sqrt{2}z)} \right)^{\frac{2}{N_c+1}} - \frac{N_c-1}{2} \left(\frac{S(\sqrt{2}z)}{S(z)} \right)^{\frac{2}{N_c-1}} \right]$$

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

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

Di-hadron azimuthal correlations in DIS

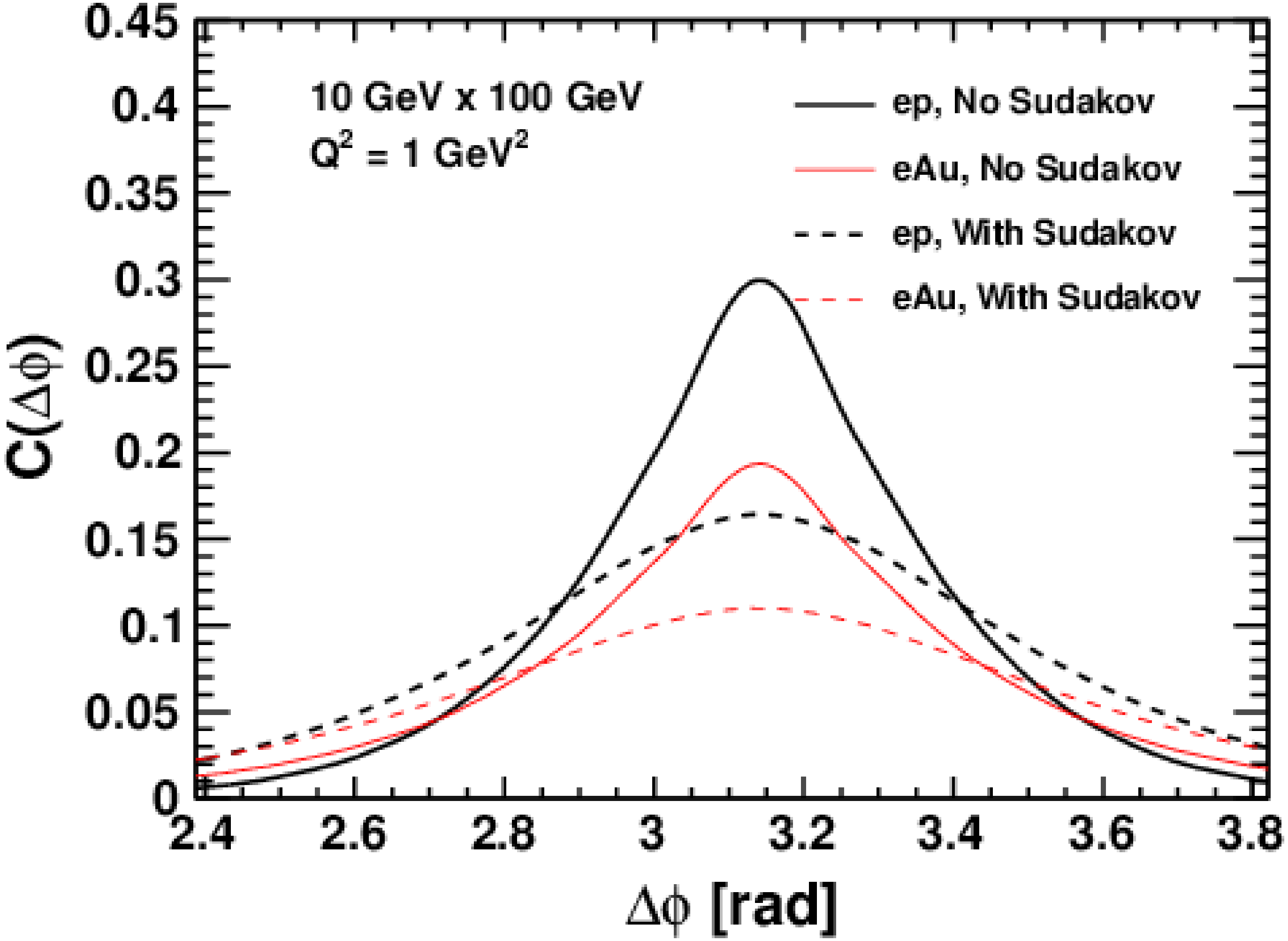




Electron Ion Collider…., A. Accardi et al., arXiv:1212.1701

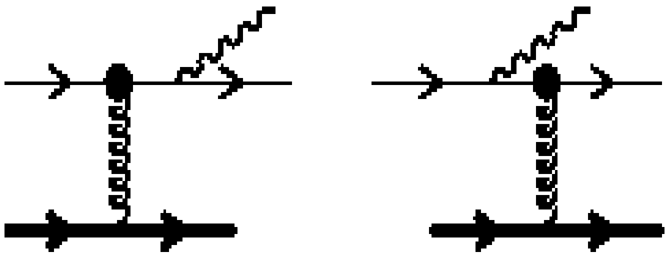
Zheng-Aschenauer-Lee-Xiao, PRD89 (2014)7, 074037

Azimuthal correlations in DIS



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

DY in pA



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

$$\mathbf{M^\mu(p;k,q) = i \int d^2x_t e^{i(q_t+k_t-p_t)\cdot x_t}\,\bar{u}(q)\,\bar{\Gamma}^\mu(k;q,p)\,u(p)\;[V(x_t)-1]}$$

$$= \frac{i}{2}\int \frac{d^2l_t}{(2\pi)^2}\, d^2x_t d^2y_t e^{il_t\cdot x_t} e^{i(q_t+k_t-p_t-l_t)\cdot y_t}\,\bar{u}(q)\,\Gamma^\mu(-k;q,-p)\,u(p)$$
$$\left[V(x_t)\,V^\dagger(y_t)-1\right]\;V(y_t)$$

extra: unitary matrix

same as DIS

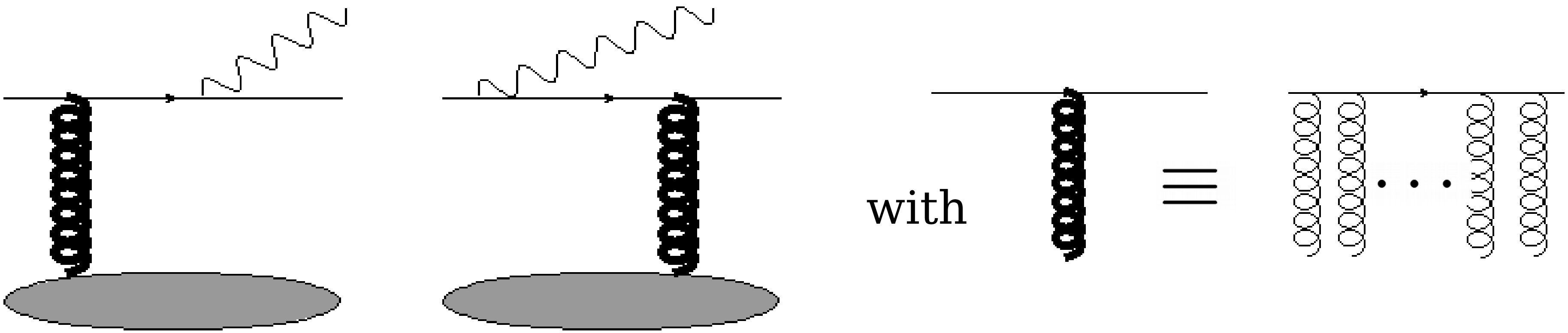
cross section

$$\frac{d\sigma}{dz\,d^2k_t\,d\log M^2\,d^2b_t} = \frac{2\alpha_{em}^2}{3\pi}\int\frac{d^2l_t}{(2\pi)^4}\,d^2r_t e^{il_t\cdot r_t}\,T(x_g,b_t,r_t)\Bigg\{ \left[\frac{1+(1-z)^2}{z}\right]\frac{z^2\,l_t^2}{[k_t^2+(1-z)M^2][(k_t-zl_t)^2+(1-z)M^2]}$$
$$- \; z(1-z)M^2\left[\frac{1}{[k_t^2+(1-z)M^2]}-\frac{1}{[(k_t-zl_t)^2+(1-z)M^2]}\right]^2\Bigg\}$$

Gelis,Jalilian-Marian
PRD66 (2002) 094014

Photon-hadron correlation in p(d)A

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



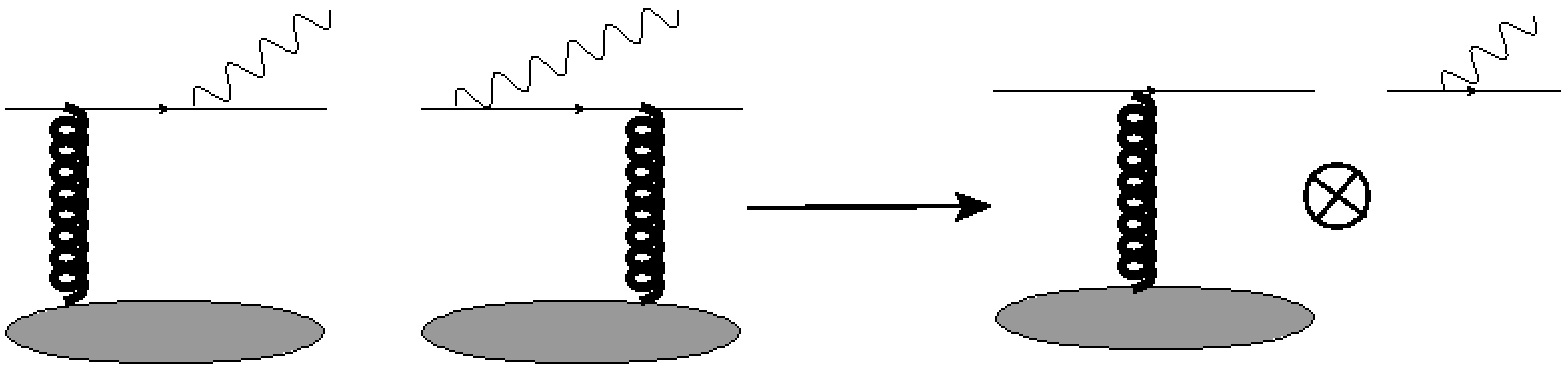
$$\frac{d\sigma^{q(p)\,T\rightarrow q(l)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dl_t^2\,dy_\gamma\,dy_l\,d\theta} = \frac{e_q^2\,\alpha_{em}}{\sqrt{2}(2\pi)^3}\,\frac{k^-}{k_t^2\sqrt{S}}\,\frac{1+(\frac{l^-}{p^-})^2}{[k^-\,\vec{l_t}-l^-\vec{k_t}]^2}$$

$$\delta[x_q - \frac{l_t}{\sqrt{S}}e^{y_l} - \frac{k_t}{\sqrt{S}}e^{y_\gamma}]\left[2l^-k^-\,\vec{l_t}\cdot\vec{k_t} + k^-(p^- - k^-)\,l_t^2 + l^-(p^- - l^-)\,k_t^2\right]$$

$$\int d^2\vec{r_t}\,e^{i(\vec{l_t}+\vec{k_t})\cdot\vec{r_t}}\,N_F(b_t, r_t, x_g)$$

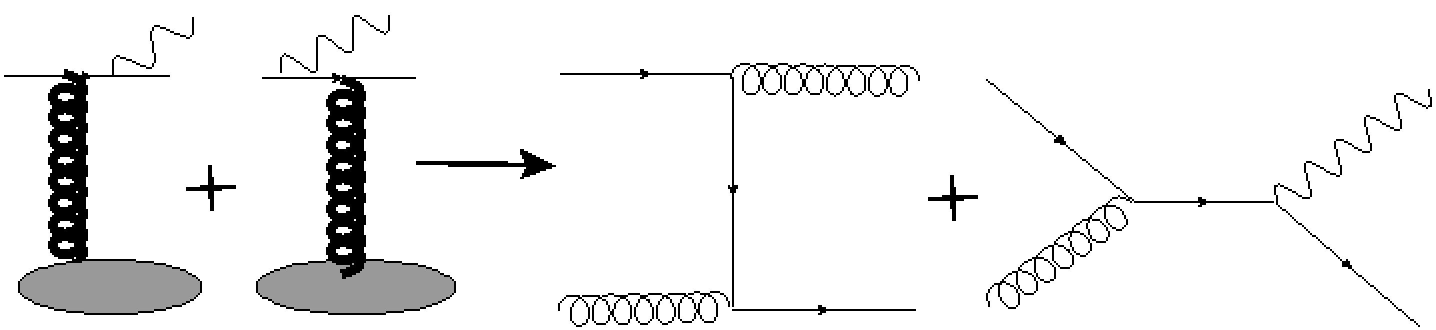
pQCD limits

near side: collinear divergence $\theta \rightarrow 0$



$$\sigma_{\mathbf{dipole}} \otimes \mathbf{D}_{\gamma/\mathbf{q}}$$

away side: $\theta \rightarrow \pi$

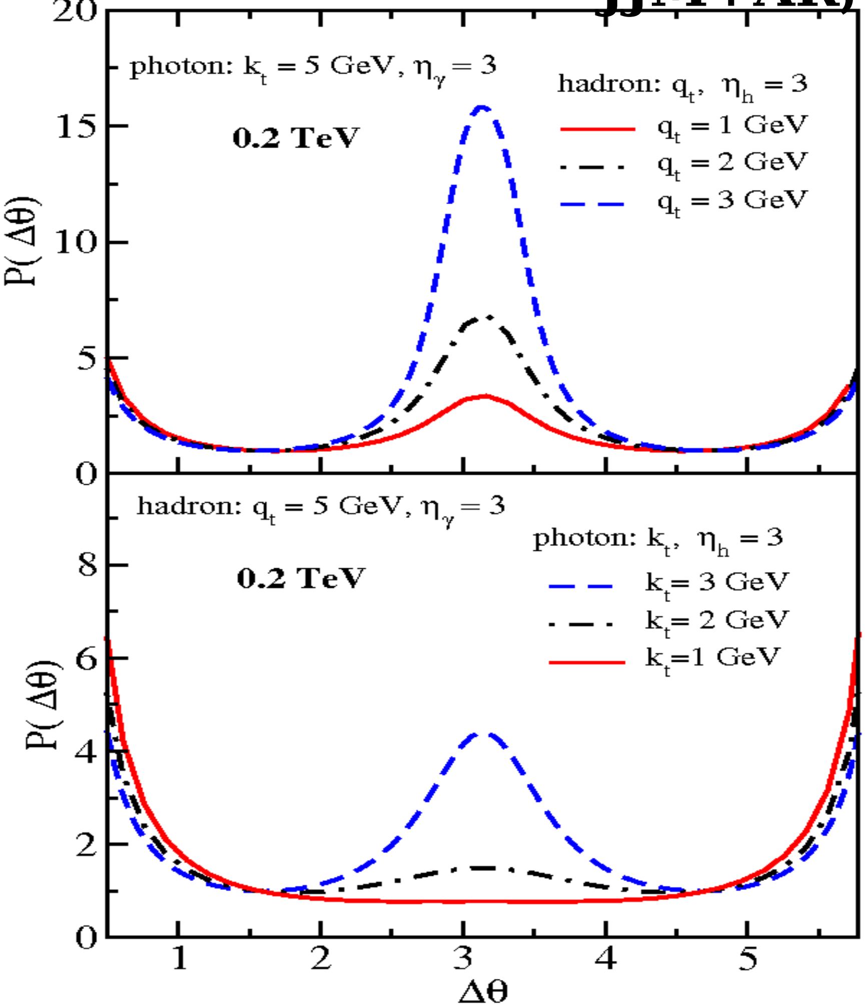


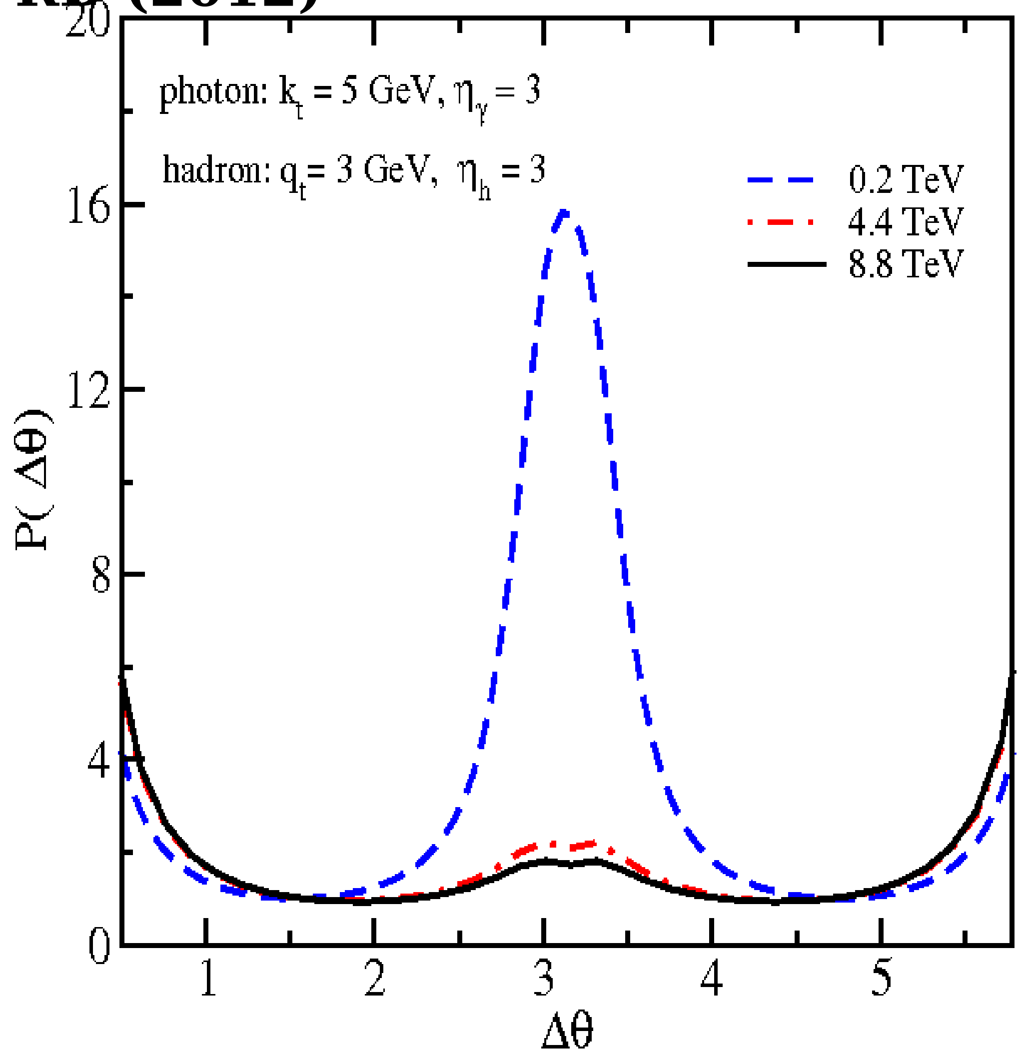
$$\mathbf{p_t >> Q_s}$$

photon-hadron azimuthal correlations

$$P(\Delta\theta) = \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dq_t^2\,dy_\gamma\,dy_l\,d\theta}[\Delta\theta] / \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dq_t^2\,dy_\gamma\,dy_l\,d\theta}[\theta = \theta_c]$$

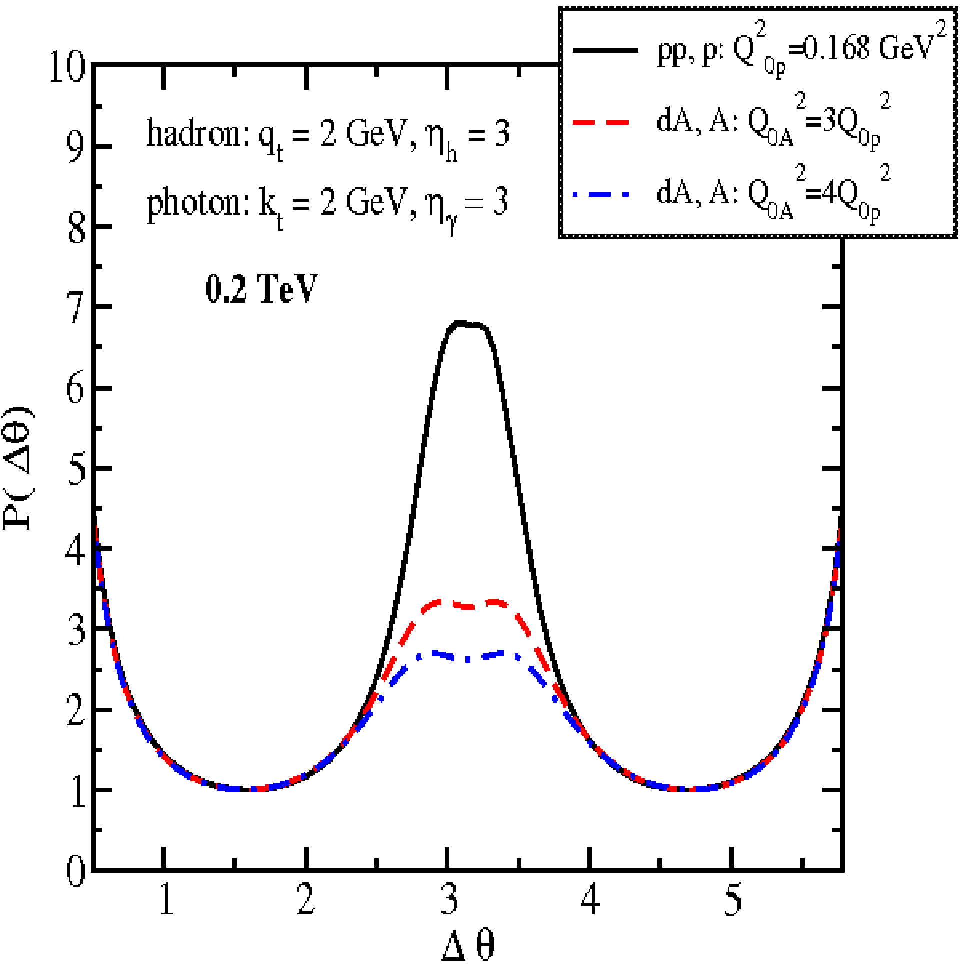
JJM+AR, PRD (2012)

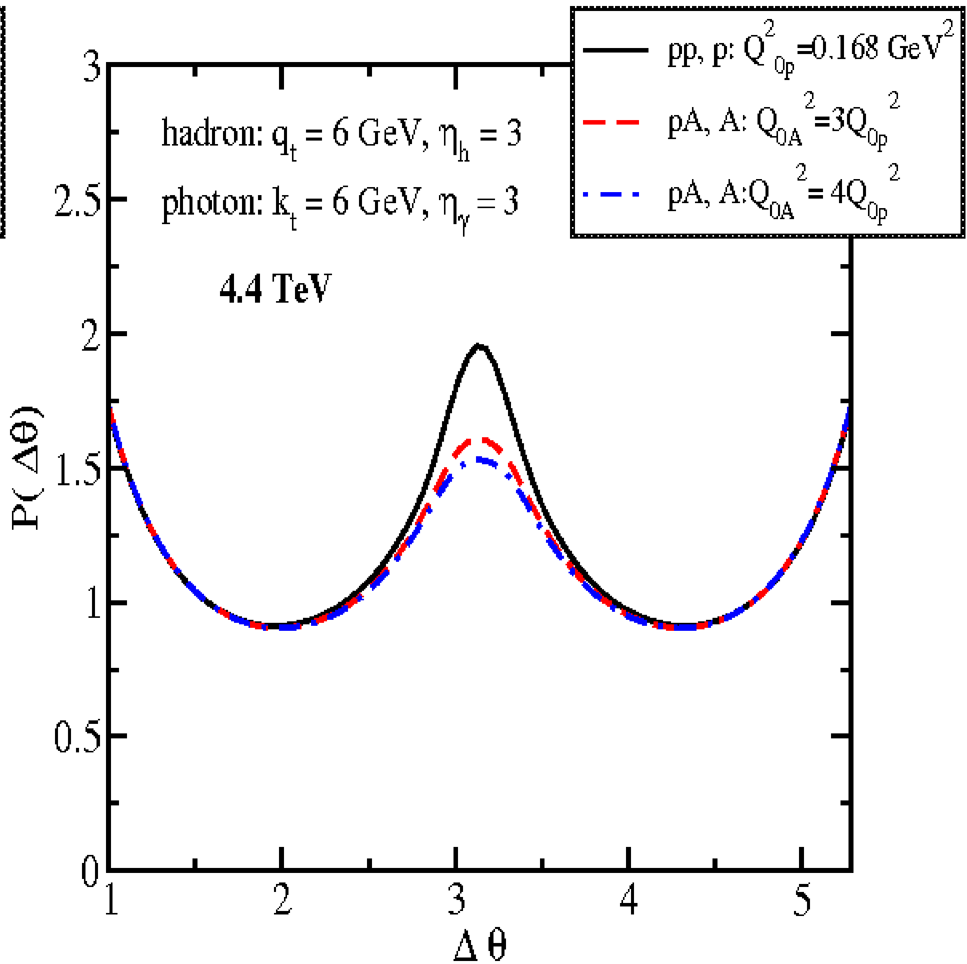




Centrality dependence

$$P(\Delta\theta) = \frac{d\sigma^{p(d)\,T\rightarrow h(q)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dq_t^2\,dy_\gamma\,dy_l\,d\theta}[\Delta\theta] / \frac{d\sigma^{p(d)\,T\rightarrow h(q)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dq_t^2\,dy_\gamma\,dy_l\,d\theta}[\theta=\theta_c]$$





Photon-hadron correlations

new processes to probe the dynamics of high energy QCD

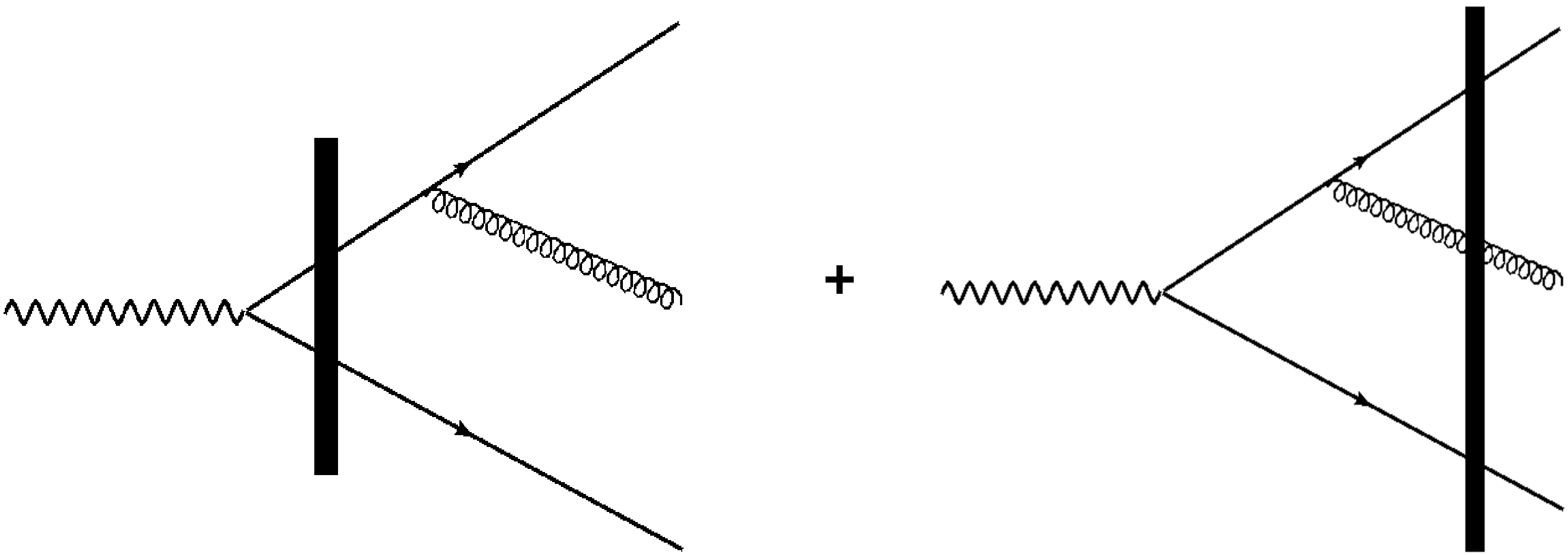
suppression of prompt photon spectrum in forward rapidity in p(d)A

disappearance of the away side peak in photon-hadron azimuthal correlations in p(d)A

need to measure these at RHIC/LHC

<u>3-parton</u> 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

crossing symmetry

3-jet production in DIS

$$\gamma^{(\star)} \longrightarrow q\,\bar{q}\,g \quad \Longleftrightarrow \quad \left\{ \begin{array}{l} q \longrightarrow q\,g\,\gamma^{(\star)} \\ \bar{q} \longrightarrow \bar{q}\,g\,\gamma^{(\star)} \\ g \longrightarrow q\,\bar{q}\,\gamma^{(\star)} \end{array} \right\}$$

2-jet + photon/DY production in pA collisions

(collinear factorization in proton?)

$$pA \longrightarrow h_1\,h_2\,\gamma^{(\star)}\,X$$

MPI (in proton)

SUMMARY

Azimuthal angular correlations offer a unique probe of CGC

Di-hadrons, hadron-photon/dilepton, 3-hadrons,...

Forward-forward correlations probe small x

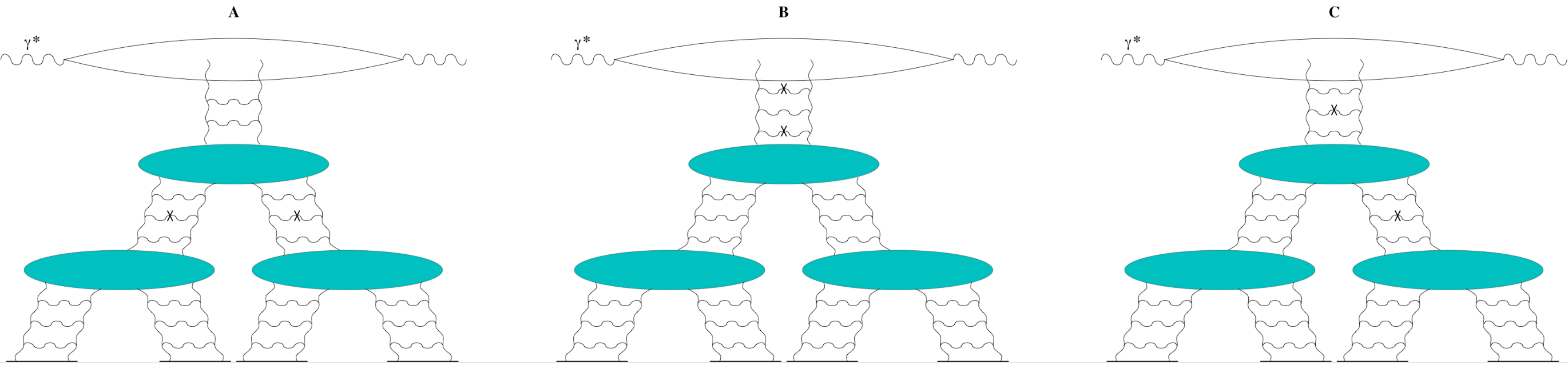
Vary nuclei, transverse momentum, rapidity,...

Azimuthal correlations in DIS

di-jet production in DIS: ***quadrupoles*** $< \mathbf{Tr\, V\, V^\dagger\, V\, V^\dagger} >$

LO: $\gamma^\star \mathbf{T} \rightarrow \mathbf{g\, g\, X}$ JJM+ Y. Kovchegov, PRD (2004)

gluons widely separated in rapidity



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 $h \equiv \vec{\Sigma} \cdot \hat{p}$

$$\vec{\Sigma} \cdot \hat{p}\, U_\pm(p) = \pm U_\pm(p)$$

$$-\vec{\Sigma} \cdot \hat{p}\, V_\pm(p) = \pm V_\pm(p)$$

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

with $e^{\pm i\phi_k} \equiv \dfrac{k_x \pm i k_y}{\sqrt{k^+ k^-}}$ and $k^\pm = \dfrac{E \pm k_z}{\sqrt{2}}$

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

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

and

$$< ii > = [ii] = 0$$
$$< ij] = [ij> = 0$$

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

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

work with a given helicity state