CGC and Two-particle correlations at the LHC

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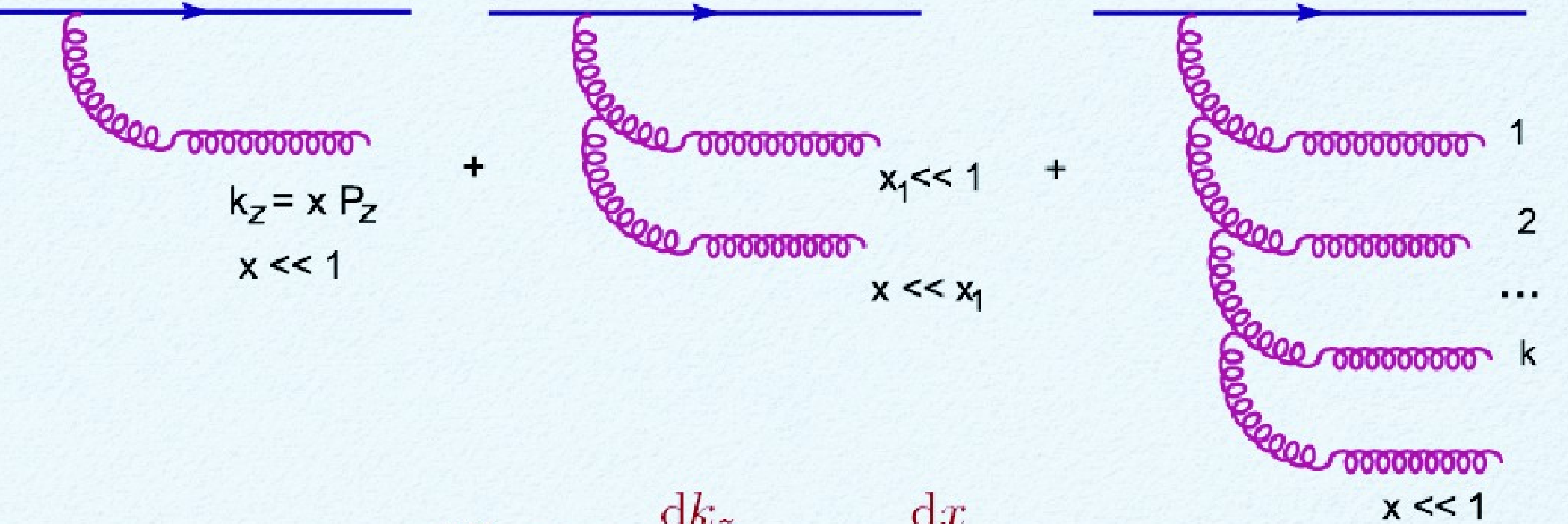
gluon radiation at small x :pQCD

The infrared sensitivity of bremsstrahlung favors the emission of 'soft' (= small–x) gluons



$$d\mathcal{P} \propto \alpha_s \frac{dk_z}{k_z} = \alpha_s \frac{dx}{x}$$

The 'price' of an additional gluon:

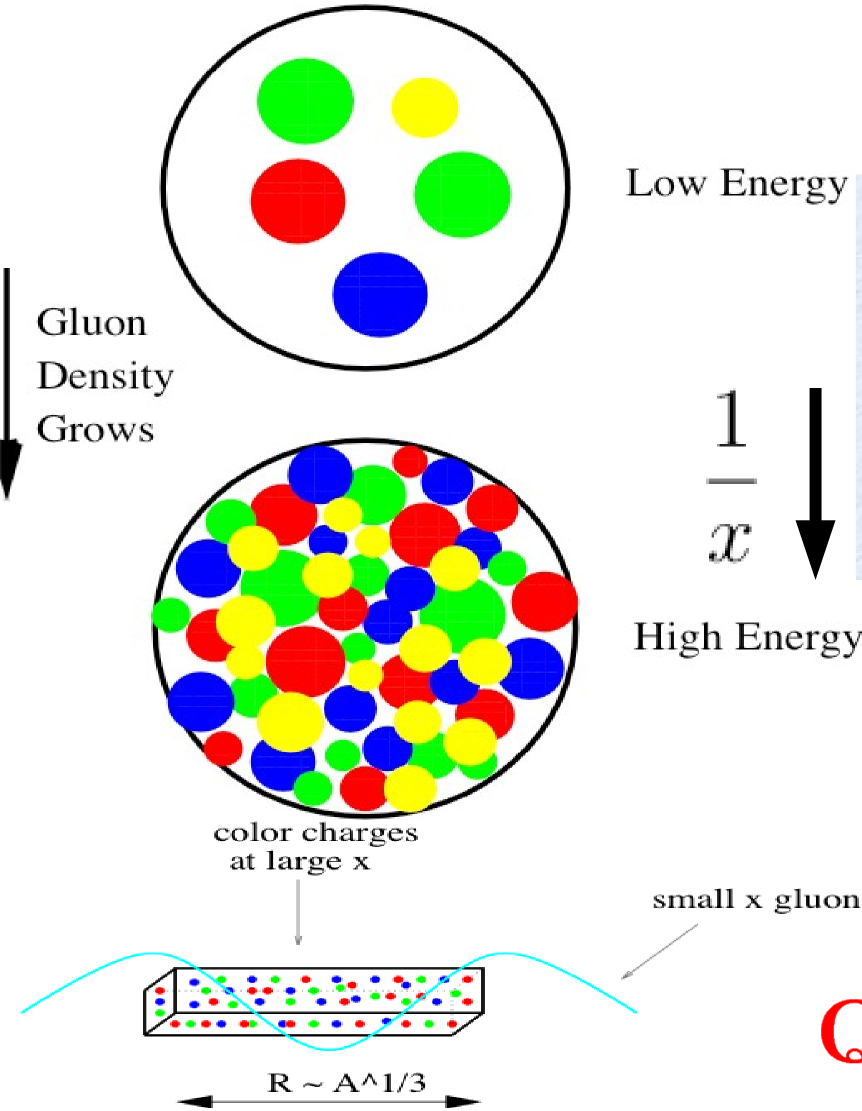
number of gluons grows fast

$$\mathcal{P}(1) \propto \alpha_s \int_x^1 \frac{dx_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

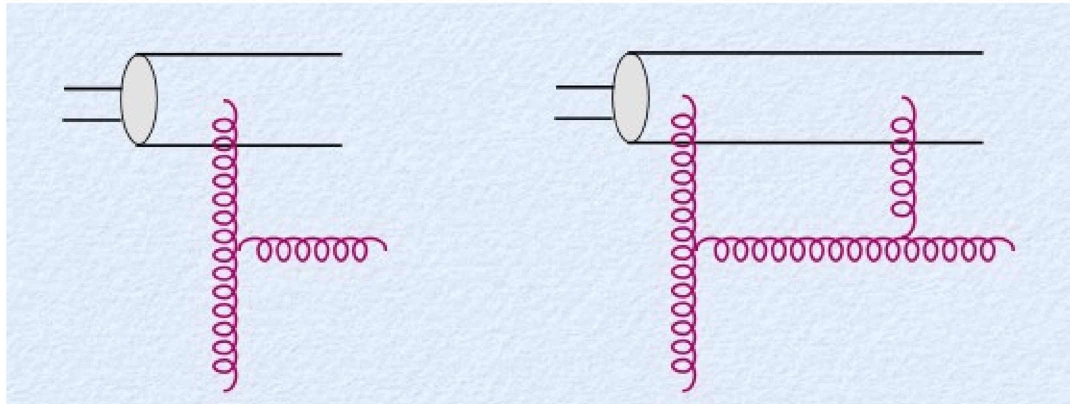
$$n \sim e^{\alpha_s \, ln 1/x}$$

Gluon saturation

Gribov-Levin-Ryskin
Mueller-Qiu



"attractive" bremsstrahlung vs. "repulsive" recombination



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

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

MV effective Action + RGE

$$\mathbf{S[A,\rho] = -\frac{1}{4}\int d^4x\, F^2_{\mu\nu} + \frac{i}{N_c}\int d^2x_t dx^- \, \delta(x^-) Tr[\rho(x_t) U(A^-)]}$$

Large x: color source ρ small x: gluon field $\mathbf{A}^\mu$

$$\mathbf{U(A^-) = \hat{P}\, Exp\left[ig\int dx^+ \, A_a^- \, T_a\right]}$$

$$\mathbf{Z[j] = \int [D\rho]\, W_{\Lambda^+}[\rho]\left[\frac{\int^{\Lambda^+}[DA]\delta(A^+)e^{iS[A,\rho]-\int j\cdot A}}{\int^{\Lambda^+}[DA]\delta(A^+)e^{iS[A,\rho]}}\right]}$$

weight functional:

$\mathbf{W}_{\Lambda^+}[\rho]$ probability distribution of color source ρ at longitudinal scale Λ^+

invariance under change of $\Lambda^+ \longrightarrow$ RGE for $\mathbf{W}_{\Lambda^+}[\rho]$

The Classical Field

saddle point of effective action-> Yang-Mills equations

$$\mathbf{D}_\mu \, \mathbf{F}^{\mu\nu}_{\mathbf{a}} = \delta^{\nu\,+} \delta(\mathbf{x}^-) \, \rho_{\mathbf{a}}(\mathbf{x_t})$$

solutions are non-Abelian Weizsäcker-Williams fields

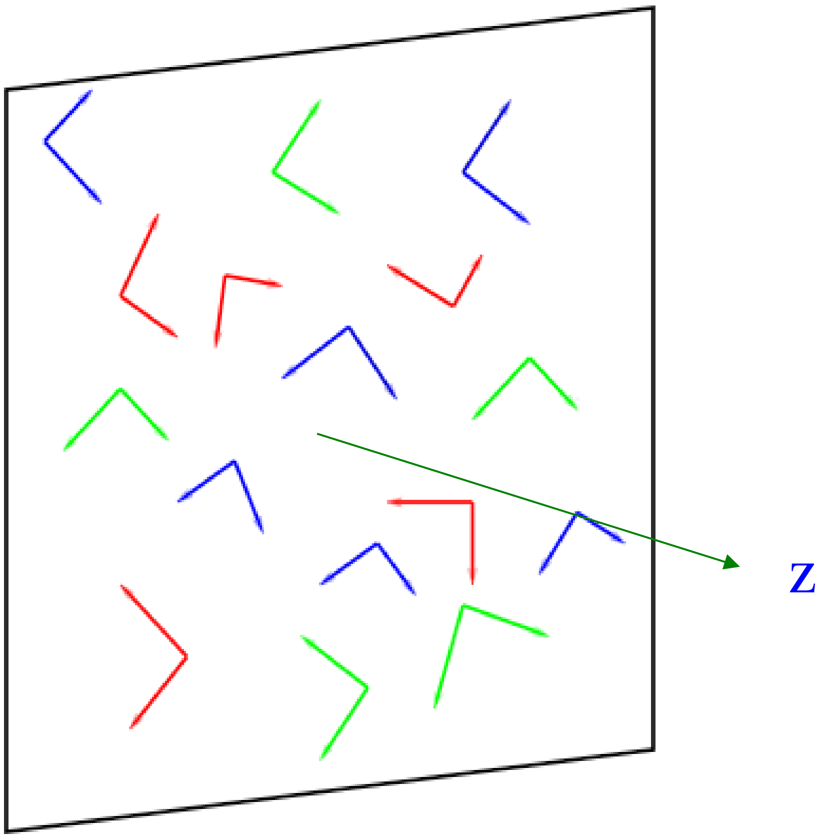
$$\mathbf{A}^+ = \mathbf{0}$$

$$\mathbf{A}^- = \mathbf{0}$$

$$\mathbf{A}^{\mathbf{i}}_{\mathbf{a}} = \theta(\mathbf{x}^-) \, \alpha^{\mathbf{i}}_{\mathbf{a}}(\mathbf{x_t})$$

$$\partial^{\mathbf{i}} \, \alpha^{\mathbf{i}}_{\mathbf{a}} = \mathbf{g} \, \rho_{\mathbf{a}}$$

pure (2d) gauge



color $\mathbf{E}_\perp$, $\mathbf{B}_\perp$ fields

Energy (x) dependence

JIMWLK-BK evolution equation

$$\frac{d}{dy}\langle O\rangle = \frac{1}{2}\left\langle \int d^2x\, d^2y\, \frac{\delta}{\delta\alpha_x^b}\, \eta_{xy}^{bd}\, \frac{\delta}{\delta\alpha_y^d}\, O \right\rangle$$

$$\eta_{xy}^{bd} = \frac{1}{\pi}\int \frac{d^2z}{(2\pi)^2}\frac{(x-z)\cdot(y-z)}{(x-z)^2(y-z)^2}\left[1 + U_x^\dagger U_y - U_x^\dagger U_z - U_z^\dagger U_y\right]^{bd}$$

U is a Wilson line in adjoint representation

CGC: QCD at high gluon density

effective degrees of freedom: Wilson line $V(x_t)$

CGC observables: $< \mathrm{Tr}\, V \cdots\cdots V^\dagger >$ with $\mathbf{V(x_t) = \hat{P} e^{ig\int dx^- A_a^+ t_a}}$

$$\mathbf{A^\mu_a(x_t, x^-) \sim \delta^{\mu +}\, \delta(x^-)\, \alpha_a(x_t)} \qquad \mathbf{\alpha^a(k_t) = g\, \rho^a(k_t)/k_t^2}$$

gluon distribution: $\mathbf{xG(x, Q^2) \sim \int^{Q^2} \frac{d^2k_t}{k_t^2}\, \phi(x, k_t)}$ with $\mathbf{\phi(x, k_t^2) \sim < \rho_a^\star(k_t)\, \rho_a(k_t) >}$

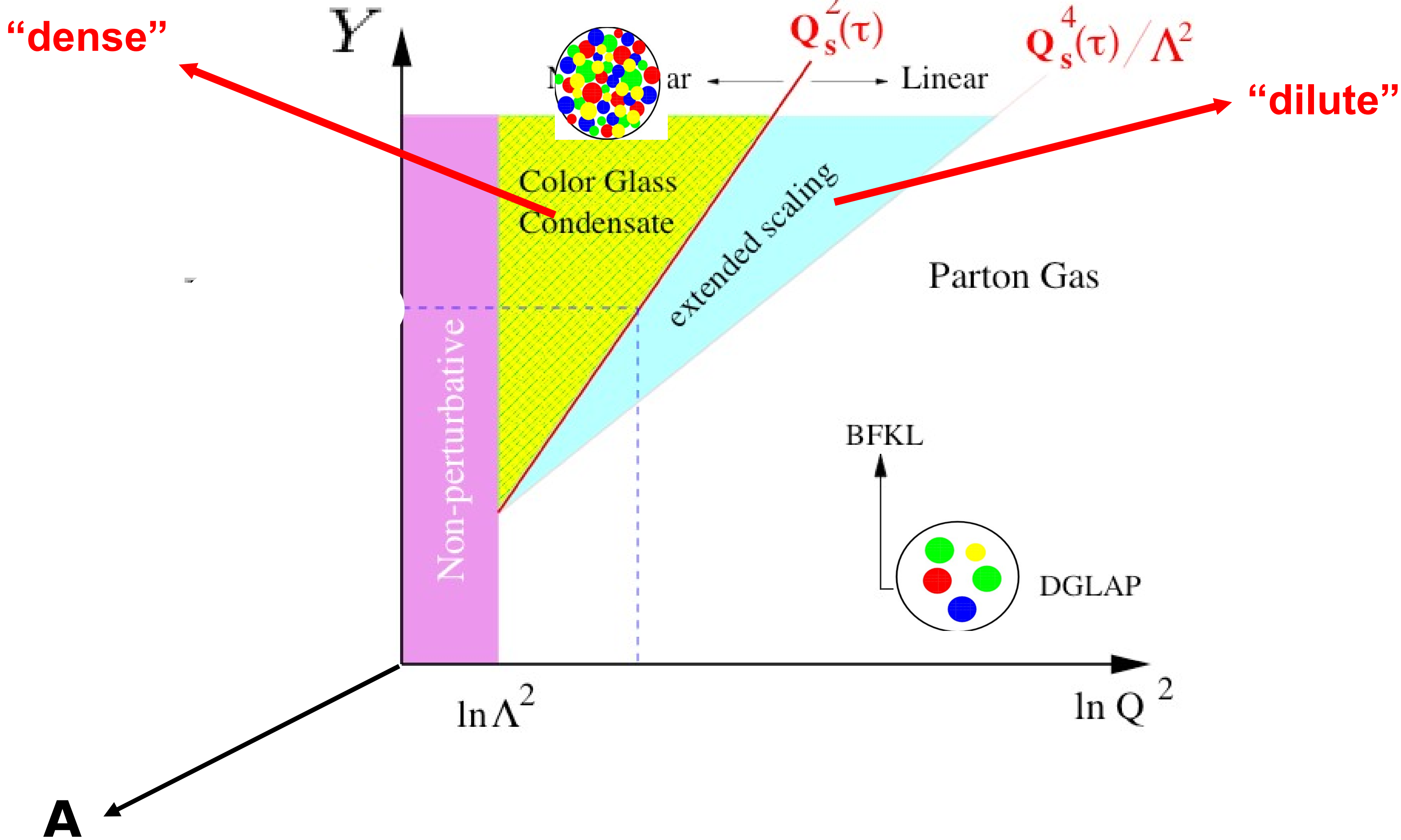
two main effects:

multiple scatterings $\longrightarrow$ **p_t broadening, *Cronin effect***

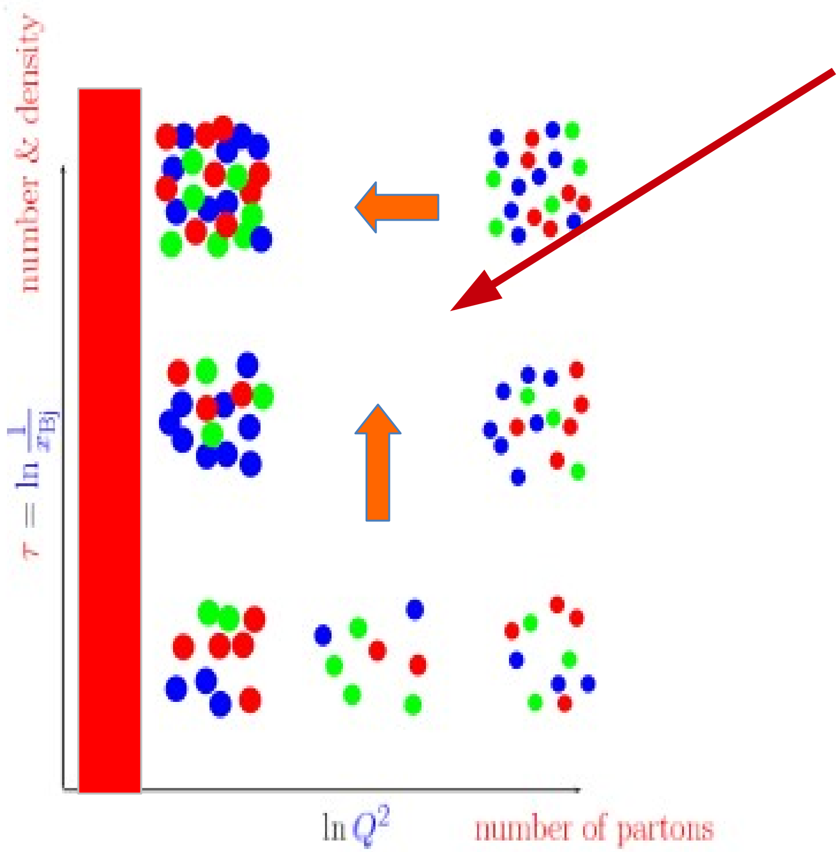
evolution with ln (1/x) $\longrightarrow$ **suppression**

"Leading twist" nuclear shadowing

Road Map of QCD Phase Space



Many-body dynamics of universal gluonic matter



How does this happen ?

How do correlation functions of these evolve ?

Is there a universal fixed point for the RG evolution of d.o.f

How does the coupling run ?

Pre-equilibrium stage of HI collisions: thermalization, ...

Color Glass Condensate

Advantages:

A systematic, first-principle approach to high energy scattering in QCD

Controlled approximations

Same formalism can describe a wide range of phenomena

Disadvantages:

Applicable only at low x (high x, Q2 missing)

Observables

DIS:

structure functions
particle production

dilute-dense (pA, forward pp) collisions:

multiplicities
single inclusive spectra
2-particle correlations

dense-dense (AA, pp) collisions:

multiplicities, spectra
long range rapidity correlations

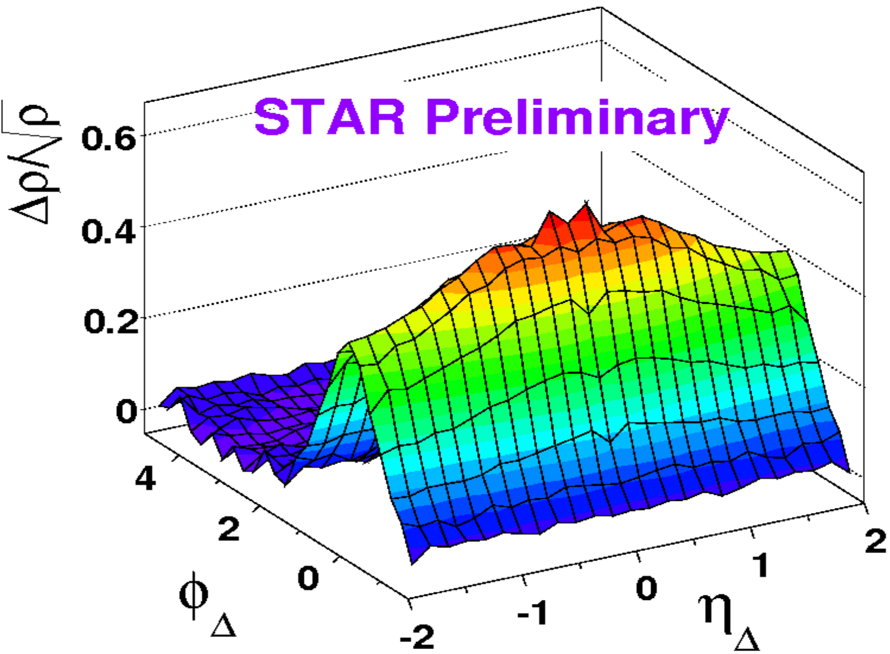
Spin asymmetries

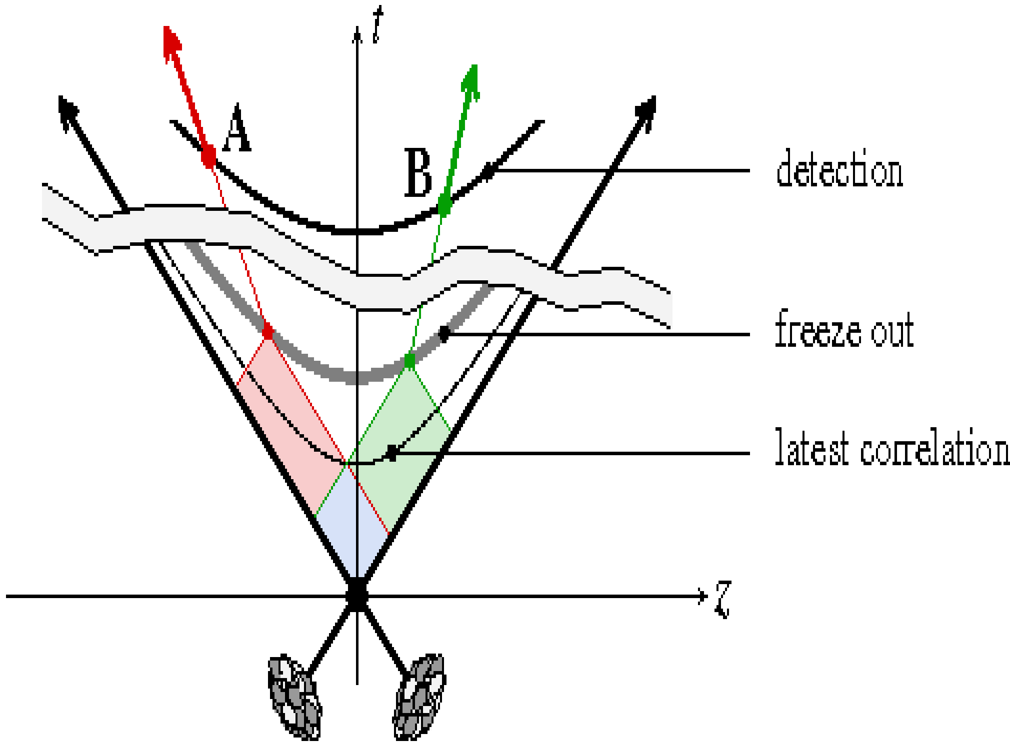
Two-hadron correlations

near-side long-range rapidity correlations: the Ridge

away-side correlations in dA: forward rapidity

Ridge in AA



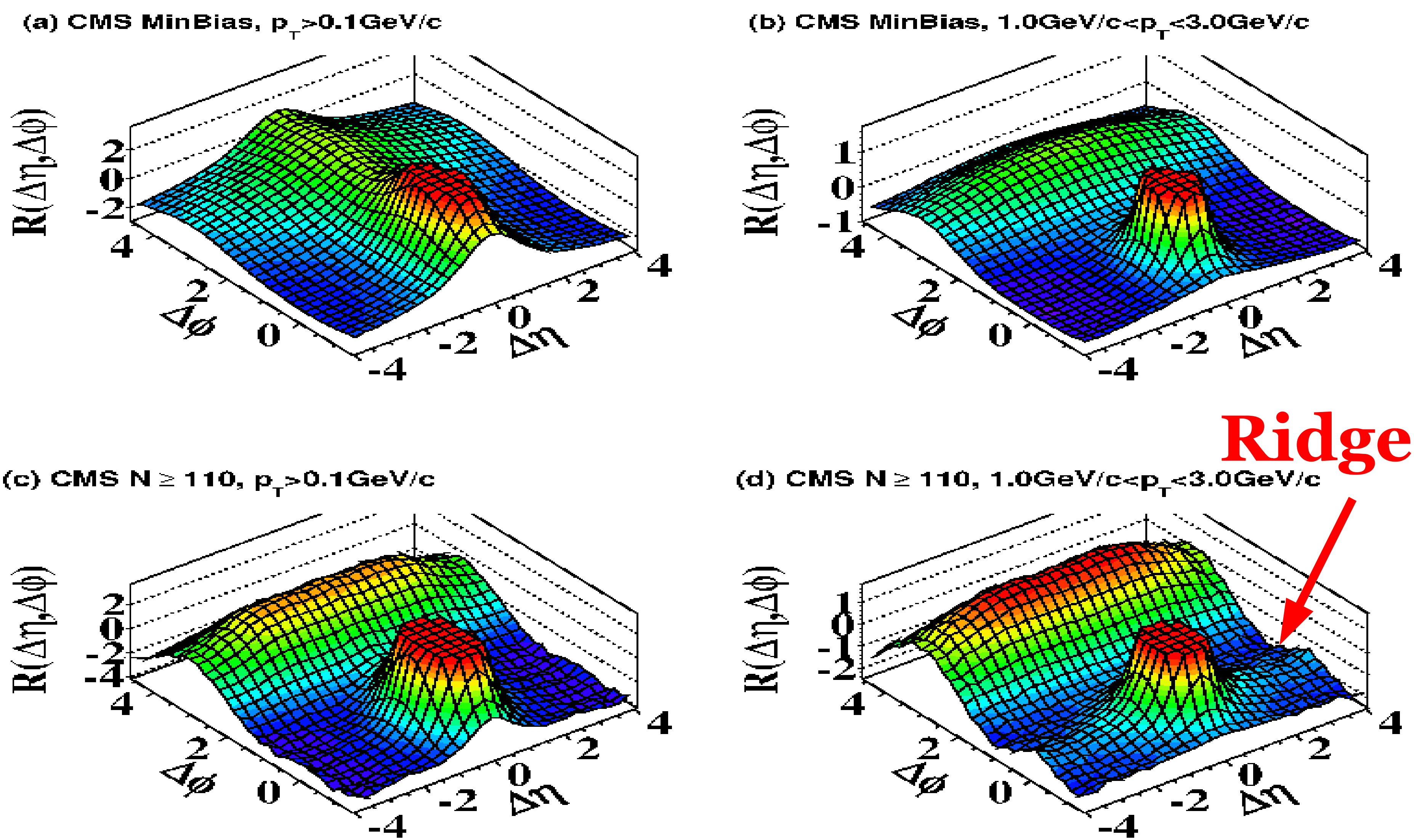


$$\tau \leq \tau_{\mathbf{fo}}\, \mathbf{e}^{-\frac{1}{2}|\mathbf{y_A}-\mathbf{y_B}|}$$

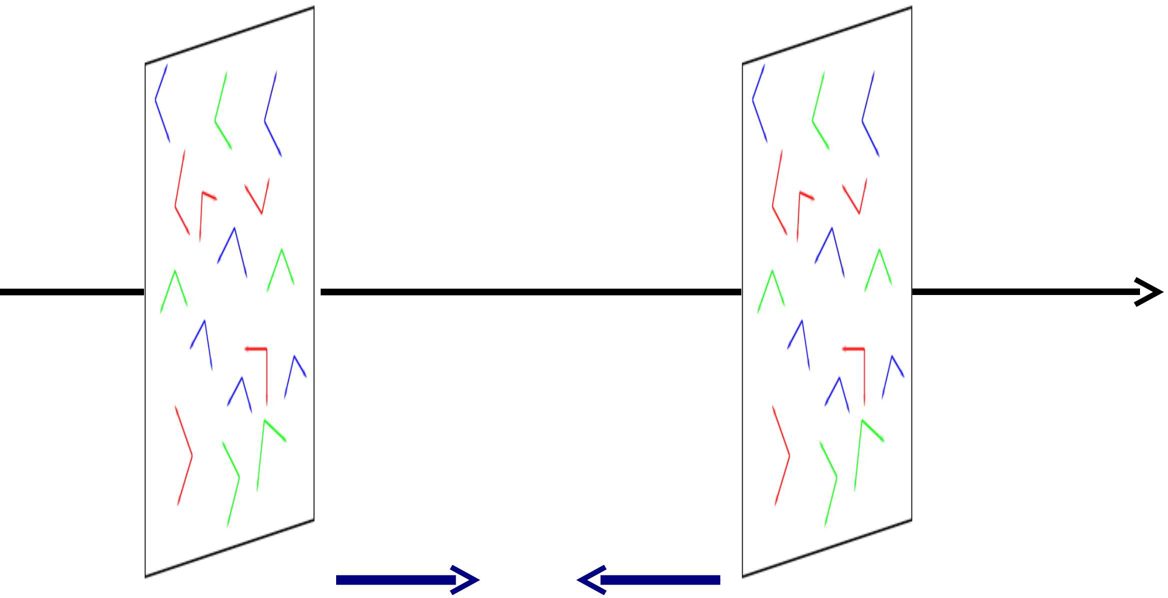
DGMV: NPA810 (2008) 91

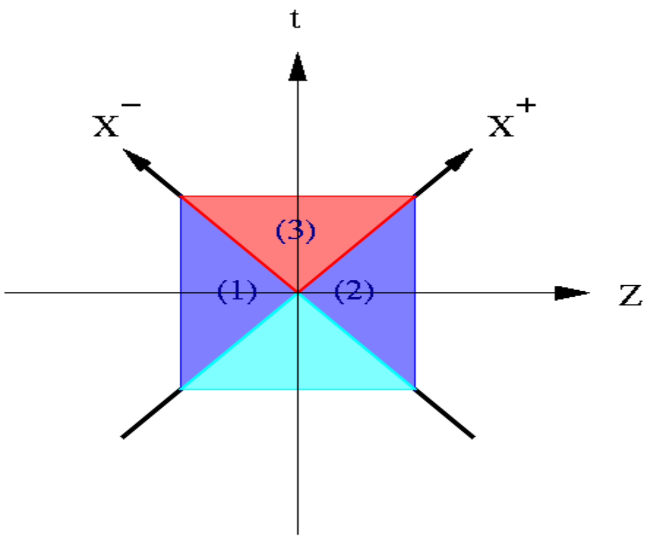
late time interactions can not affect long-range rapidity correlations

The CMS ridge at LHC



Colliding Sheets of Color Glass





before the collision:

$$\mathbf{A}^{+} = \mathbf{A}^{-} = \mathbf{0}$$
$$\mathbf{A}^{\mathbf{i}} = \mathbf{A}^{\mathbf{i}}_{\mathbf{1}} + \mathbf{A}^{\mathbf{i}}_{\mathbf{2}}$$
$$\mathbf{A}^{\mathbf{i}}_{\mathbf{1}} = \theta(\mathbf{x}^{-})\theta(-\mathbf{x}^{+})\alpha^{\mathbf{i}}_{\mathbf{1}}$$
$$\mathbf{A}^{\mathbf{i}}_{\mathbf{2}} = \theta(-\mathbf{x}^{-})\theta(\mathbf{x}^{+})\alpha^{\mathbf{i}}_{\mathbf{2}}$$

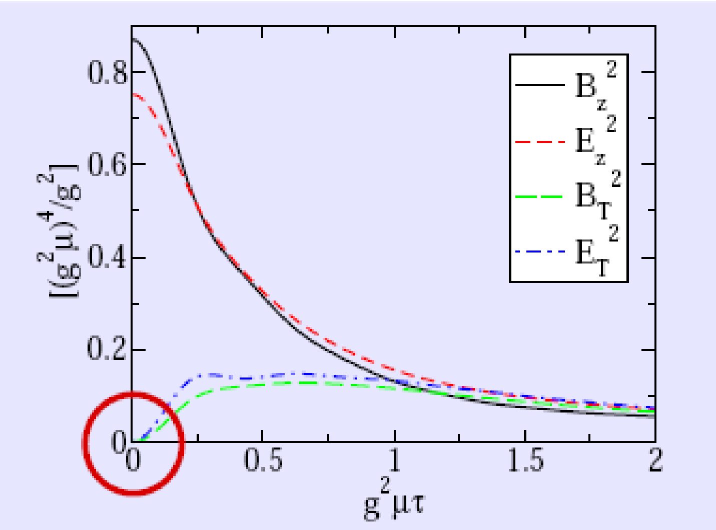
after the collision:

solve for A_{μ}

in the forward LC

GLASMA:

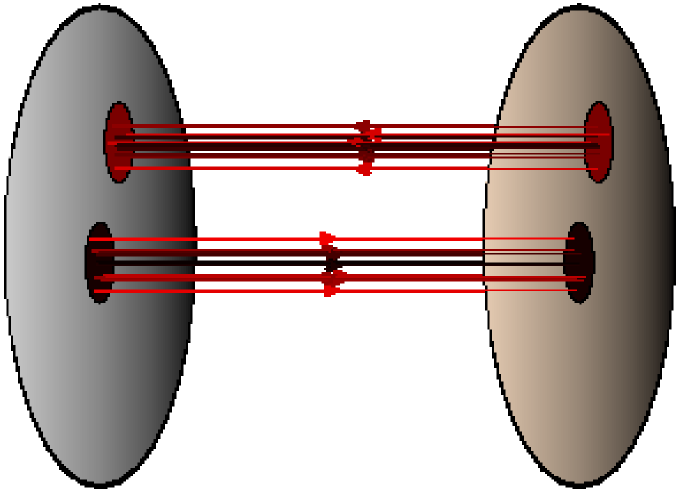
gluon fields produced in collision of two sheets of color glass



Early on glasma fields (E and B) are longitudinal

Lappi+McLerran. NPA772 (2006) 200

Classical solutions are boost invariant



Transverse size of these flux tubes is $\sim \frac{1}{Q_s}$

can be solved numerically

Two-gluon correlation: dilute region

DGMV, NPA810 (2008) 91

$$C(p_\perp, q_\perp) = \frac{g^{12}}{64(2\pi)^6} \left(f_{abc} f_{a'\bar{b}\bar{c}} f_{a\hat{b}\hat{c}} f_{a'\tilde{b}\tilde{c}}\right) \int \prod_{i=1}^{4} \frac{d^2 k_{i\perp}}{(2\pi)^2 k_{i\perp}^2}$$

$$\times \frac{L_\mu(p_\perp, k_{1\perp}) L^\mu(p_\perp, k_{2\perp})}{(p_\perp - k_{1\perp})^2 (p_\perp - k_{2\perp})^2} \frac{L_\nu(q_\perp, k_{3\perp}) L^\nu(q_\perp, k_{4\perp})}{(q_\perp - k_{3\perp})^2 (q_\perp - k_{4\perp})^2}$$

$$\times \left\langle {\rho^*}_1^{\hat{b}}(k_{2\perp}) {\rho^*}_1^{\tilde{b}}(k_{4\perp}) {\rho_1}^b(k_{1\perp}) {\rho_1}^{\bar{b}}(k_{3\perp}) \right\rangle$$

$$\times \left\langle {\rho^*}_2^{\hat{c}}(p_\perp - k_{2\perp}) {\rho^*}_2^{\tilde{c}}(q_\perp - k_{4\perp}) {\rho_2}^c(p_\perp - k_{1\perp}) {\rho_2}^{\bar{c}}(q_\perp - k_{3\perp}) \right\rangle$$

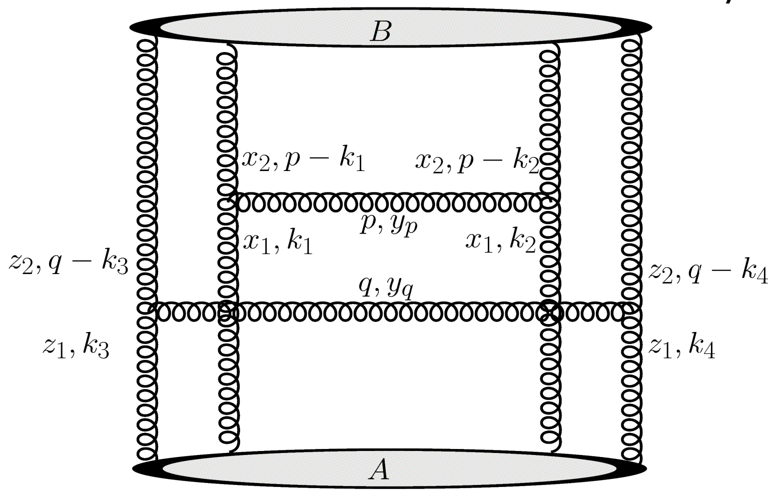
Gaussian averaging

assume ***Gaussian factorization***

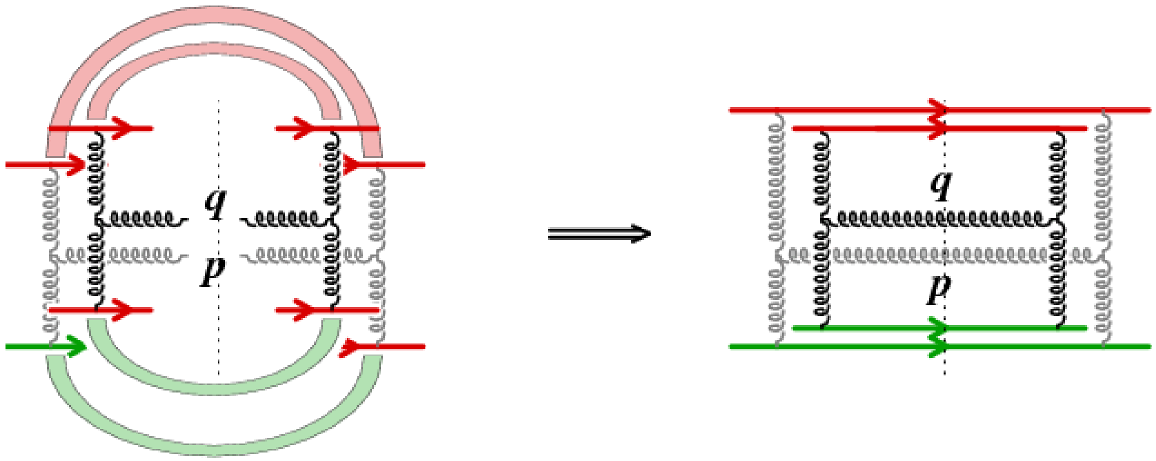
$$< \rho \cdots\cdots \rho > \sim < \boldsymbol{\rho^2} > \cdots < \boldsymbol{\rho^2} >$$

un-integrated gluon distribution

$$\phi(\mathbf{x}, \mathbf{k_t^2}) \sim < \boldsymbol{\rho^2} >$$

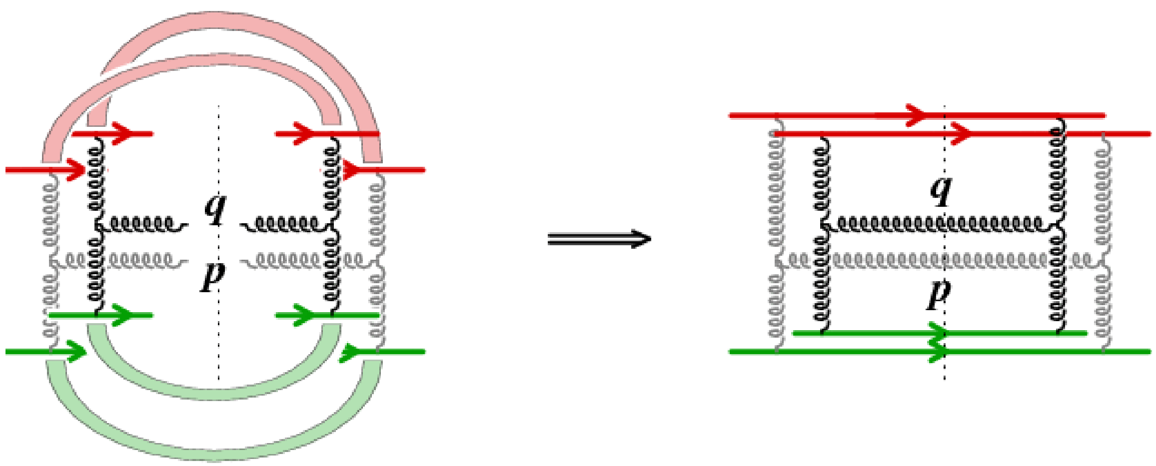


Independent production of two gluons (*subtracted*):



$\sim \mathbf{N_c^2(N_c^2-1)^2}$

Correlated two-gluon production:

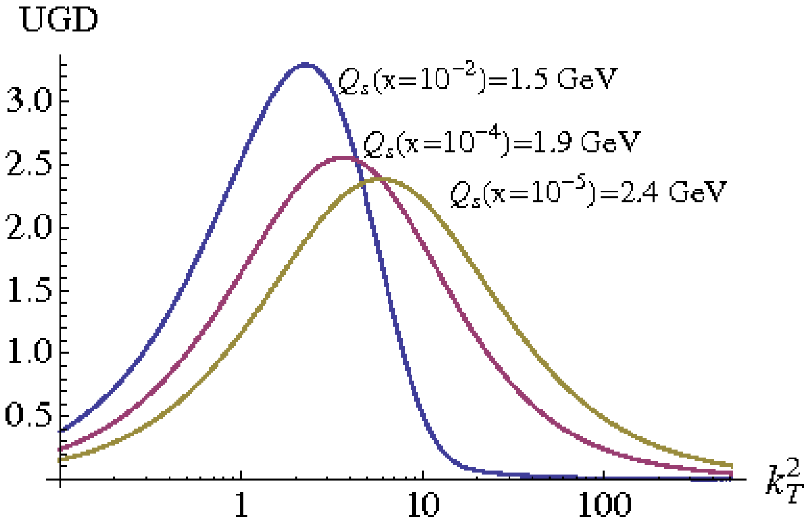


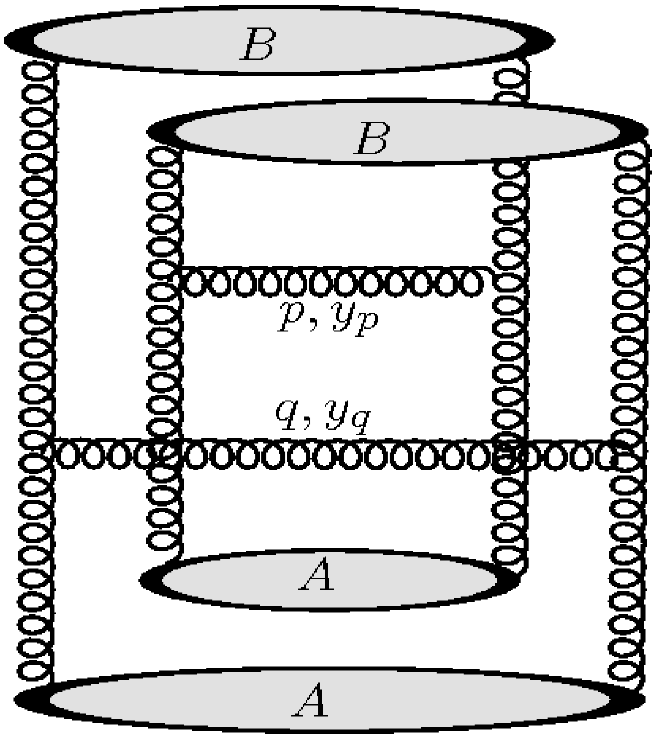
$\sim \mathbf{N_c^2(N_c^2-1)}$

Correlated production is suppressed by N_c^2

Two-gluon production in AA/pp

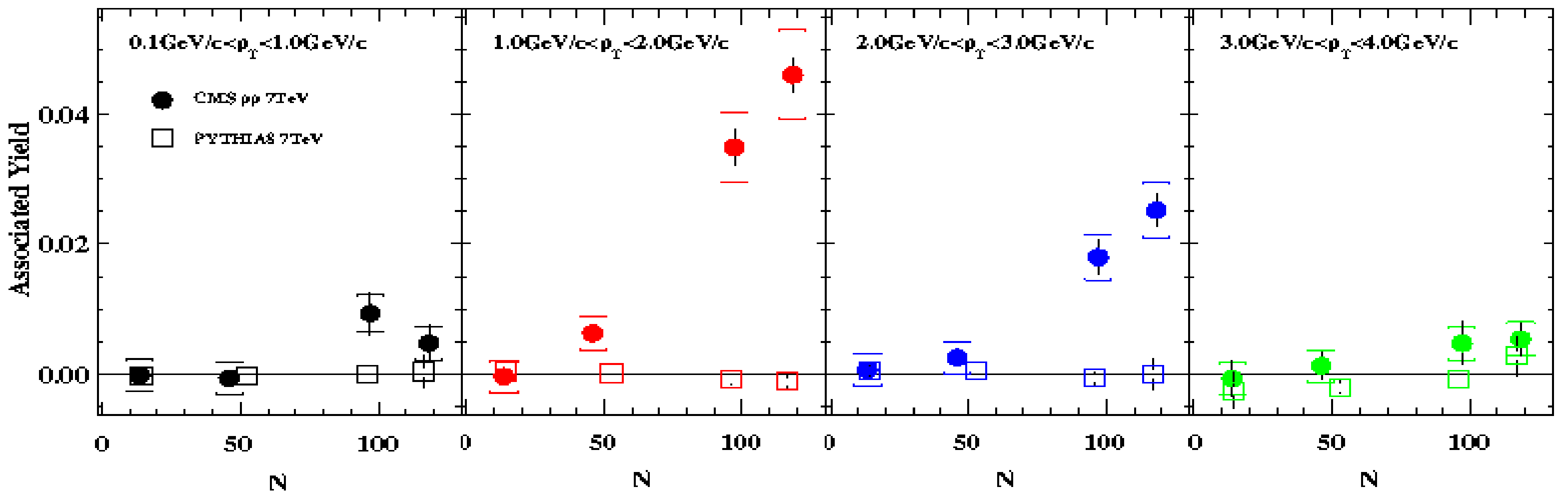
$$\frac{\mathrm{d}N_2}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y_p \mathrm{d}^2\mathbf{q}_\perp \mathrm{d}y_q} = \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2 S_\perp}{(N_c^2-1)^3\, \mathbf{p}_\perp^2 \mathbf{q}_\perp^2}$$
$$\times \int \mathrm{d}^2\mathbf{k}_\perp \Big\{ \Phi_A^2(y_p, \mathbf{k}_\perp)\Phi_B(y_p, \mathbf{p}_\perp - \mathbf{k}_\perp)$$
$$\times [\Phi_B(y_q, \mathbf{q}_\perp + \mathbf{k}_\perp) + \Phi_B(y_q, \mathbf{q}_\perp - \mathbf{k}_\perp)]$$
$$+\Phi_B^2(y_q, \mathbf{k}_\perp)\Phi_A(y_p, \mathbf{p}_\perp - \mathbf{k}_\perp)$$
$$\times [\Phi_A(y_q, \mathbf{q}_\perp + \mathbf{k}_\perp) + \Phi_A(y_q, \mathbf{q}_\perp - \mathbf{k}_\perp)] \Big\}$$

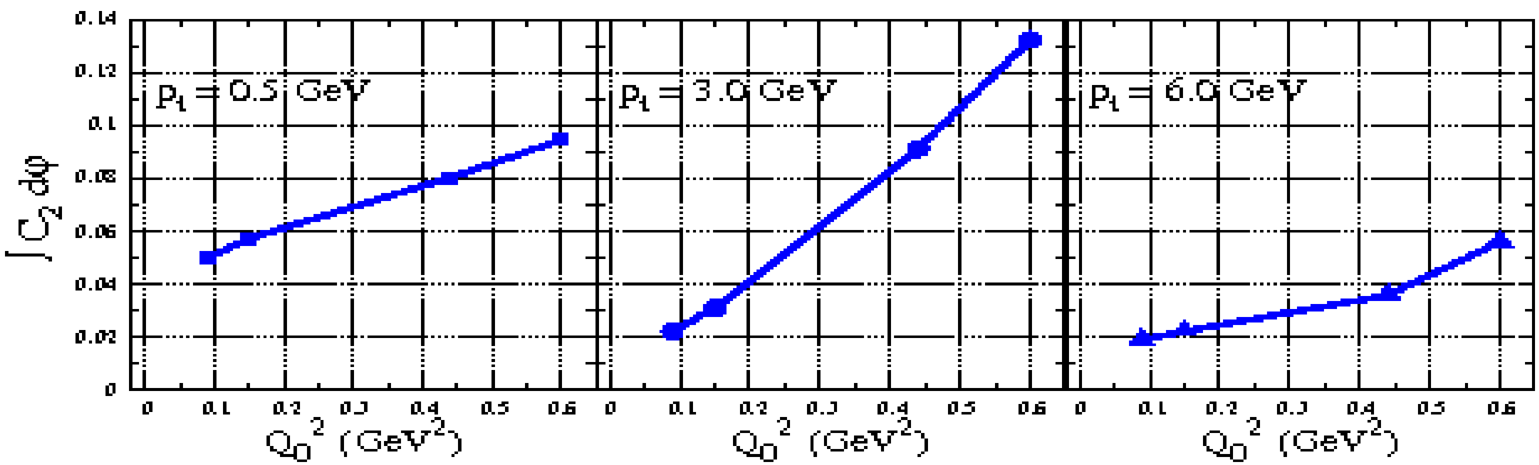




solutions of rcBK
angular collimation

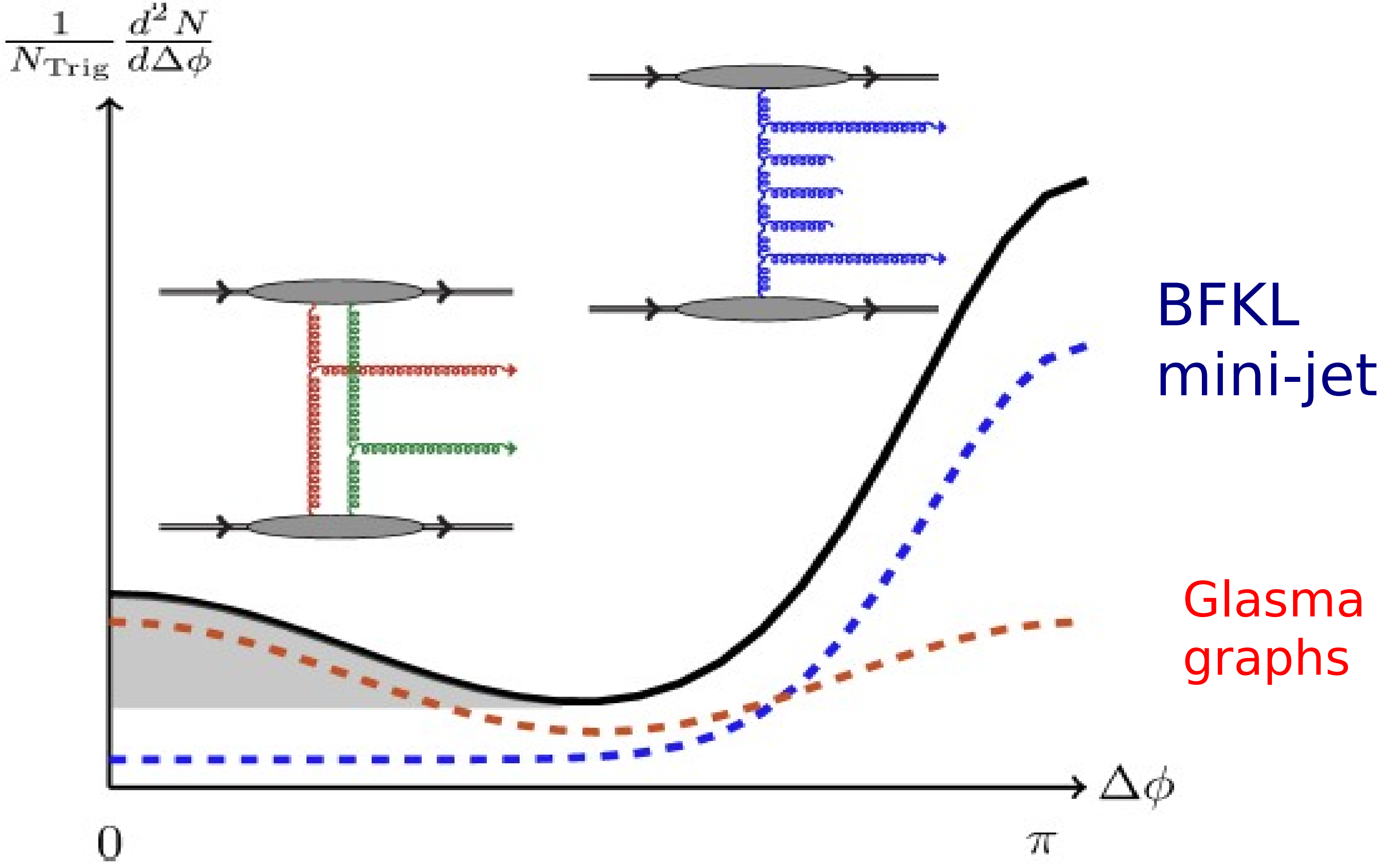
The CMS ridge at LHC





Dumitru et al.,PLB697 (2011) 21

Anatomy of long range di-hadron collimation



Extensive phenomenology, K. Dusling+R. Venugopalan, arXiv:1302.7018

CGC vs. hydro

Two-particle correlations in pA (forward-forward)

away-side correlations:

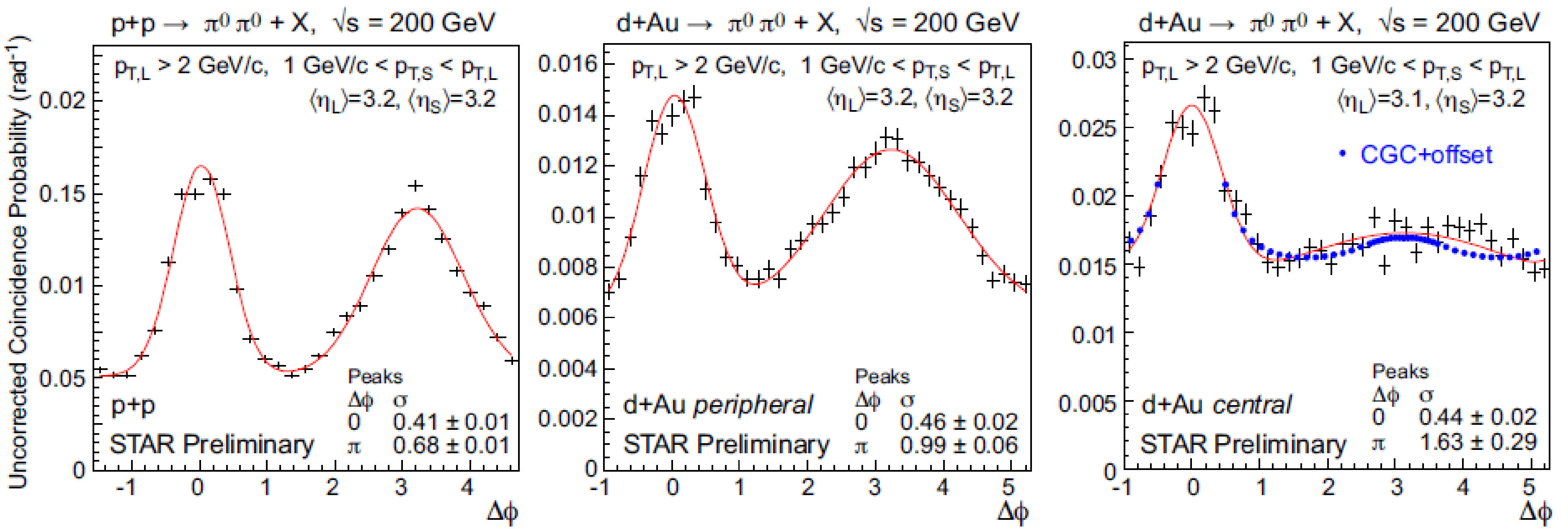
di-hadron

photon-hadron

disappearance of back to back jets

Prediction by C. Marquet using CGC (2007)

Recent STAR measurement (arXiv:1008.3989v1):



CGC fit from Albacete, Marquet, PRL (2010)
K. Tuchin, NPA846 (2010)
A. Stasto, B-W. Xiao, F. Yuan, PLB (2012)
T. Lappi, H. Mantyssari, NPA (2013)

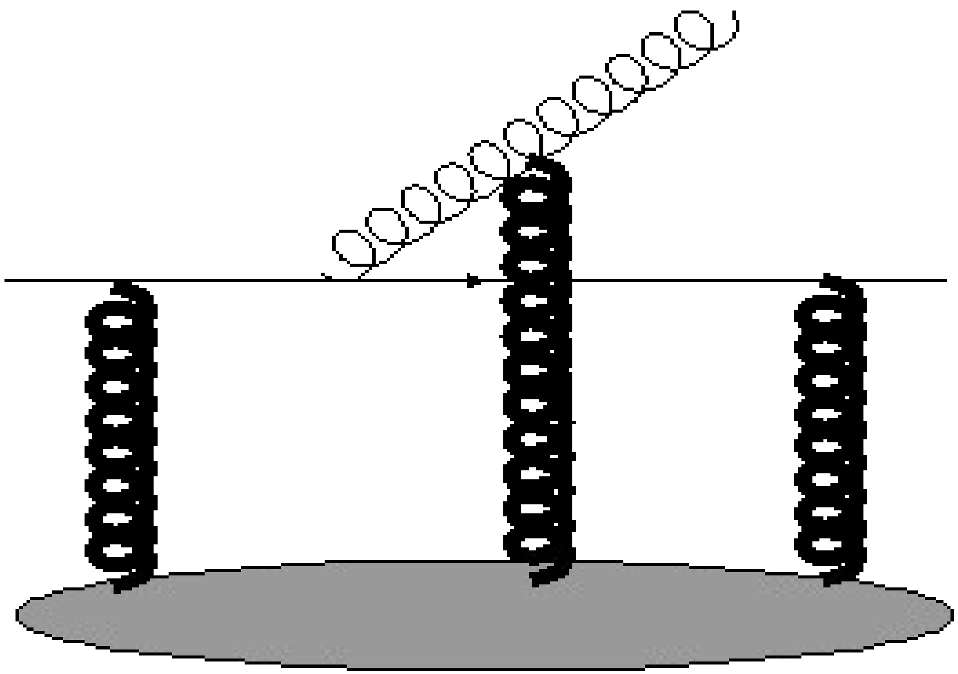
another idea: shadowing + energy loss (M. Strikman et al.)
Z. Kang, I. Vitev and H. Xing, PRD85 (2012) 054024

Di-jet production: pA

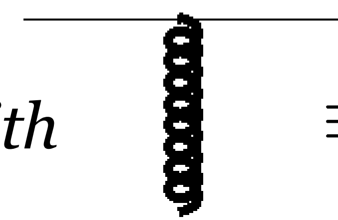
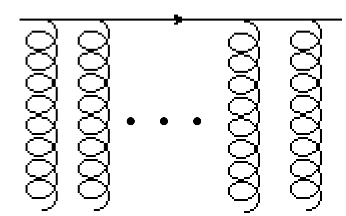
DIS, single inclusive production in pA: ***dipoles*** $< \mathrm{Tr}\, V\, V^{\dagger} >$

di-jet production in pA (and DIS): ***quadrupoles***

$< \mathrm{Tr}\, V\, V^{\dagger}\, V\, V^{\dagger} >$



J. Jalilian-Marian, Y. Kovchegov
PRD (2004)

with  $\equiv$ 

large Nc: quadrupoles at most
Dominguez, Marquet, Stasto, Xiao,
PRD (2013)

quadrupole evolution: limits

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

can be calculated in a Gaussian model DMXY

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

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

quadrupole evolution: limits

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

Gaussian

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

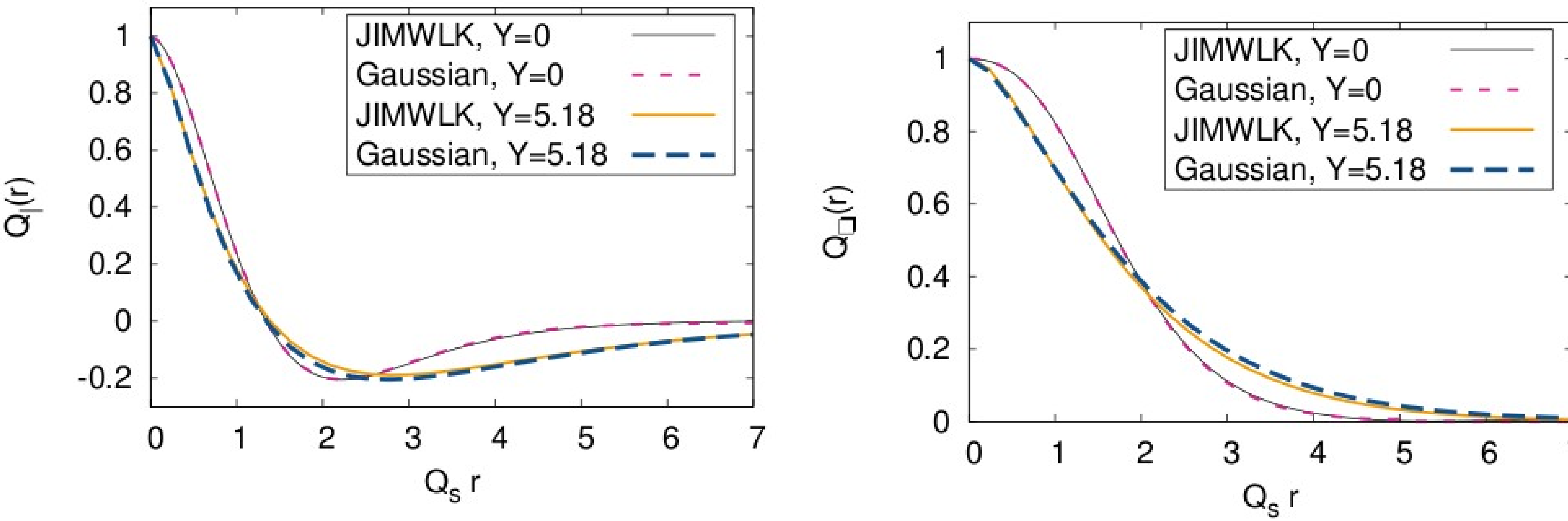
Gaussian + large N_c

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

EI+DT, JHEP (2012): Gaussian approx. is good

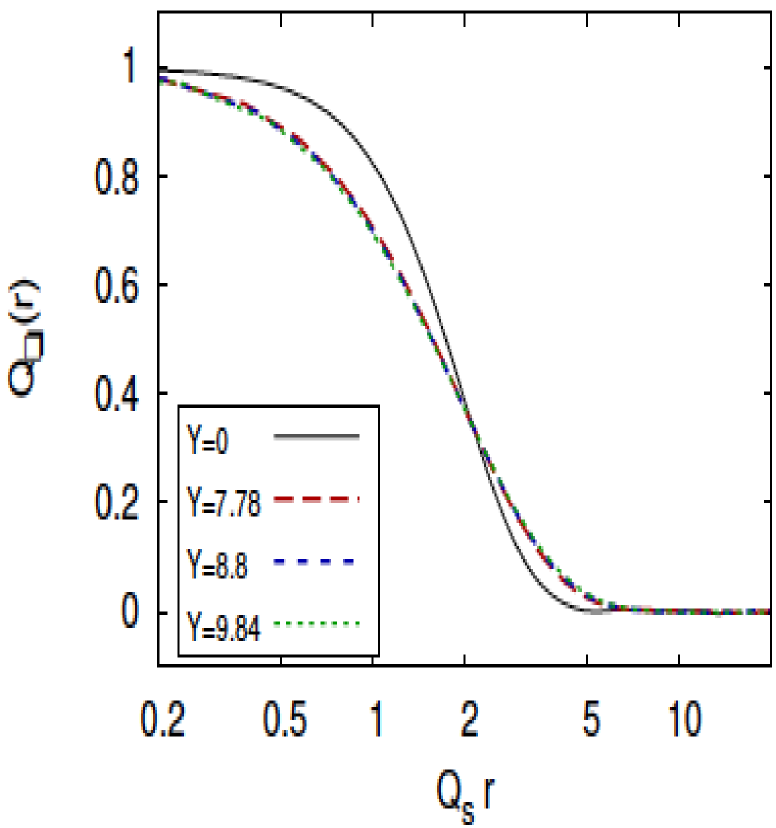
Quadrupole evolution

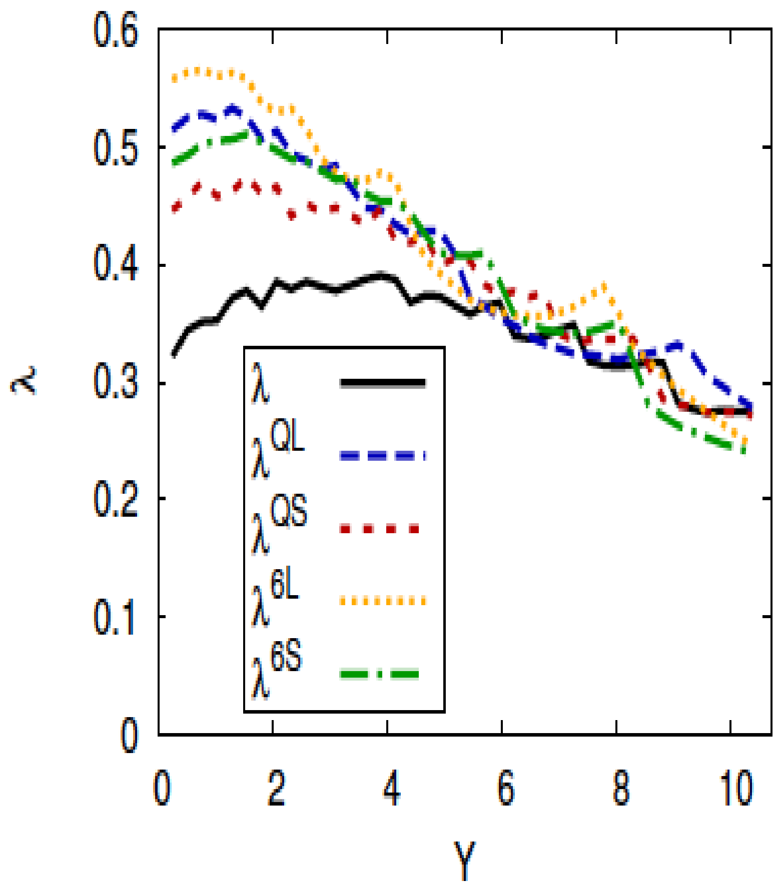
comparing with Gaussian



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

Quadrupole evolution





Geometric scaling also present in quadrupoles

Growth of the saturation scale

di-hadron correlations in the high p_t limit

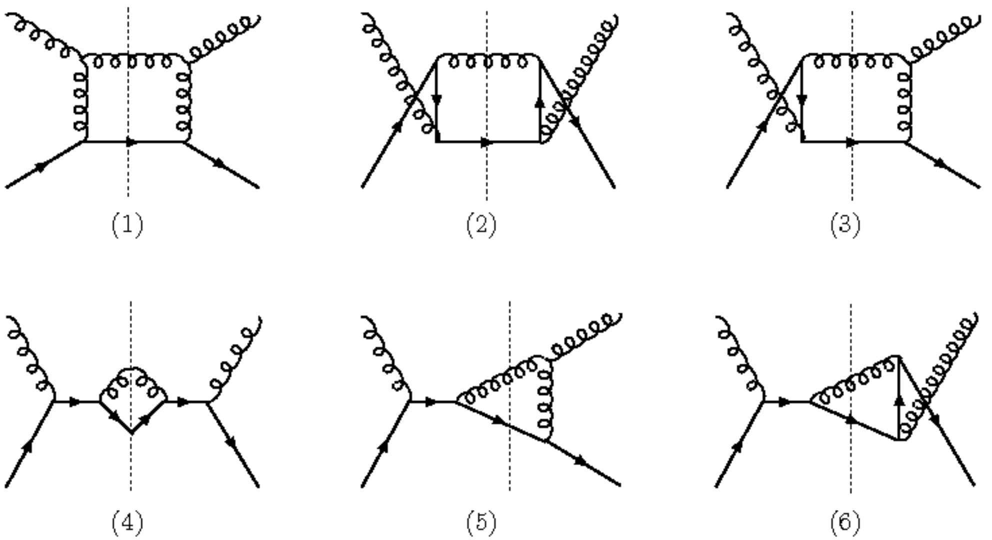
$\mathbf{O}(\alpha^{\mathbf{2}})$

Dominguez, Marquet, Xiao, Yuan (2011)
Dominguez, Xiao, Yuan (2011)

factorization of target distribution functions and hard scattering matrix element

$$\mathbf{d}\sigma \sim \mathbf{\Phi} \otimes \frac{\mathbf{d}\sigma}{\mathbf{dt}}^{\mathbf{2}\to\mathbf{2}}$$

$$\frac{d\sigma}{dt}^{q\,g\to q\,g} \sim \frac{1}{s^2}\left[\frac{4}{9}\frac{s^2+u^2}{-s\,u} + \frac{s^2+u^2}{t^2}\right]$$

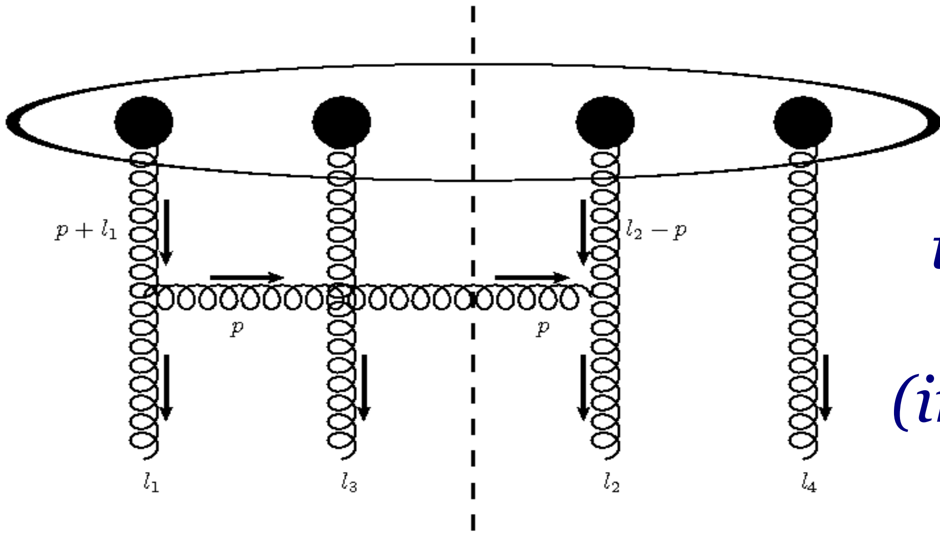


partons are back to back

quadrupole evolution in the linear regime

BJKP equation $\mathbf{O}(\alpha^4)$: 4-gluon exchange

J. Jalilian-Marian, PRD85 (2012) 014037



the color structure is identical on both sides of this eq. (independent of color averaging)

$$\frac{d}{dy}\hat{T}_4(l_1, l_2, l_3, l_4) = \frac{N_c\,\alpha_s}{\pi^2}\int d^2p_t\left[\frac{p^i}{p_t^2} - \frac{(p^i - l_1^i)}{(p_t + l_1)^2}\right]\cdot\left[\frac{p^i}{p_t^2} - \frac{(p^i - l_2^i)}{(p_t + l_2)^2}\right]$$
$$\hat{T}_4(p_t + l_1, l_2 - p_t, l_3, l_4) + \cdots$$
$$- \frac{N_c\,\alpha_s}{(2\pi)^2}\int d^2p_t\left[\frac{l_1^2}{p_t^2(l_1 - p_t)^2} + \{l_1 \to l_2, l_3, l_4\}\right]\hat{T}_4(l_1, l_2, l_3, l_4)$$

this will <u>de-correlate</u> the produced partons at high $p_t > Q_s$

Two-hadron angular correlations

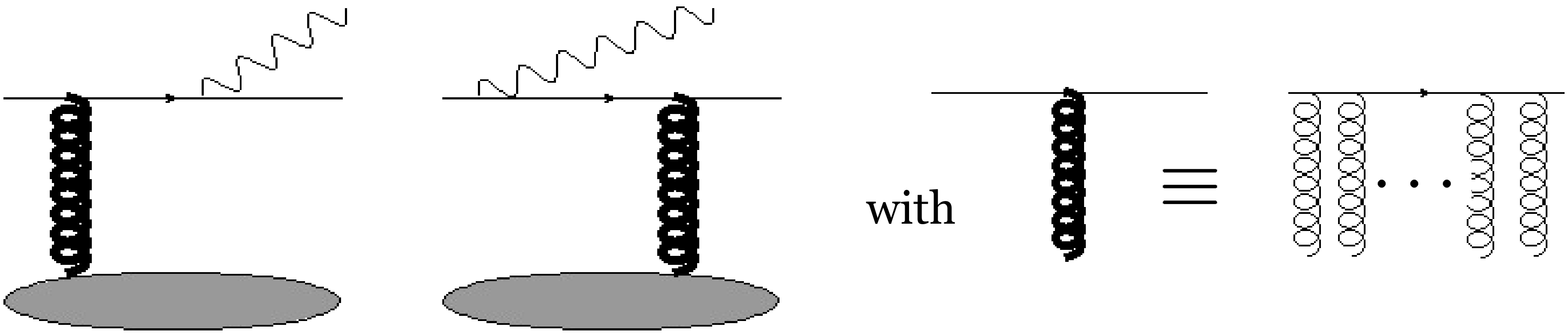
<u>Quadrupoles: a unique window to dynamics of high energy QCD</u>

Connection to pomerons, odderons, triple (and more) pomeron vertex

A simpler correlation to probe CGC:
photon-hadron azimuthal correlation

Photon-hadron correlation in p(d)A

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



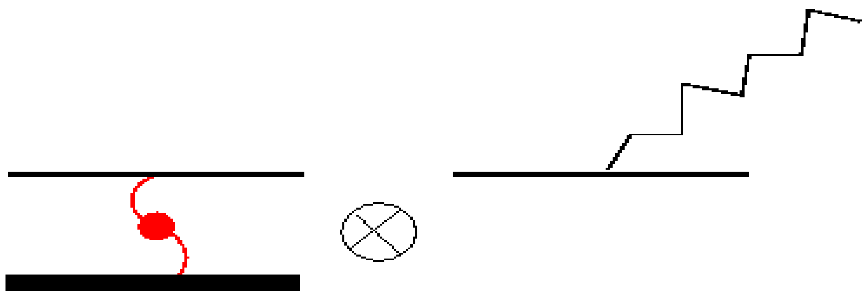
$$\frac{d\sigma^{q(p)\,T\rightarrow q(l)\,\gamma(k)\,X}}{d^2\vec{b_t}\,dk_t^2\,dl_t^2\,dy_\gamma\,dy_l\,d\theta} = \frac{e_q^2\,\alpha_{em}}{\sqrt{2}(2\pi)^3}\,\frac{k^-}{k_t^2\sqrt{S}}\,\frac{1+(\frac{l^-}{p^-})^2}{[k^-\,\vec{l_t}-l^-\vec{k_t}]^2}$$

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

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

pQCD limit

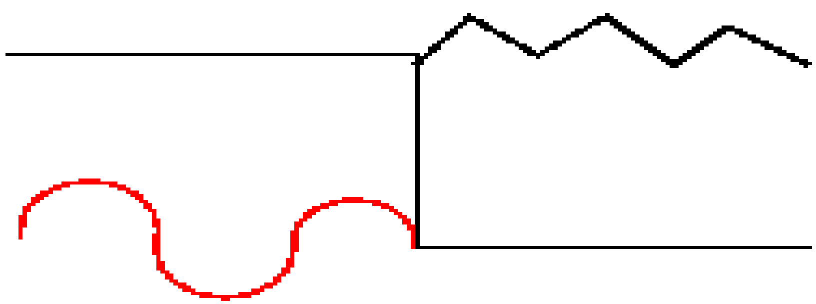
near side: collinear divergence $\theta \to 0$



$$N_F \otimes D_{\gamma/q}$$

away side: $\theta \to \pi$

Baier,Mueller, Schiff,
NPA (2004)

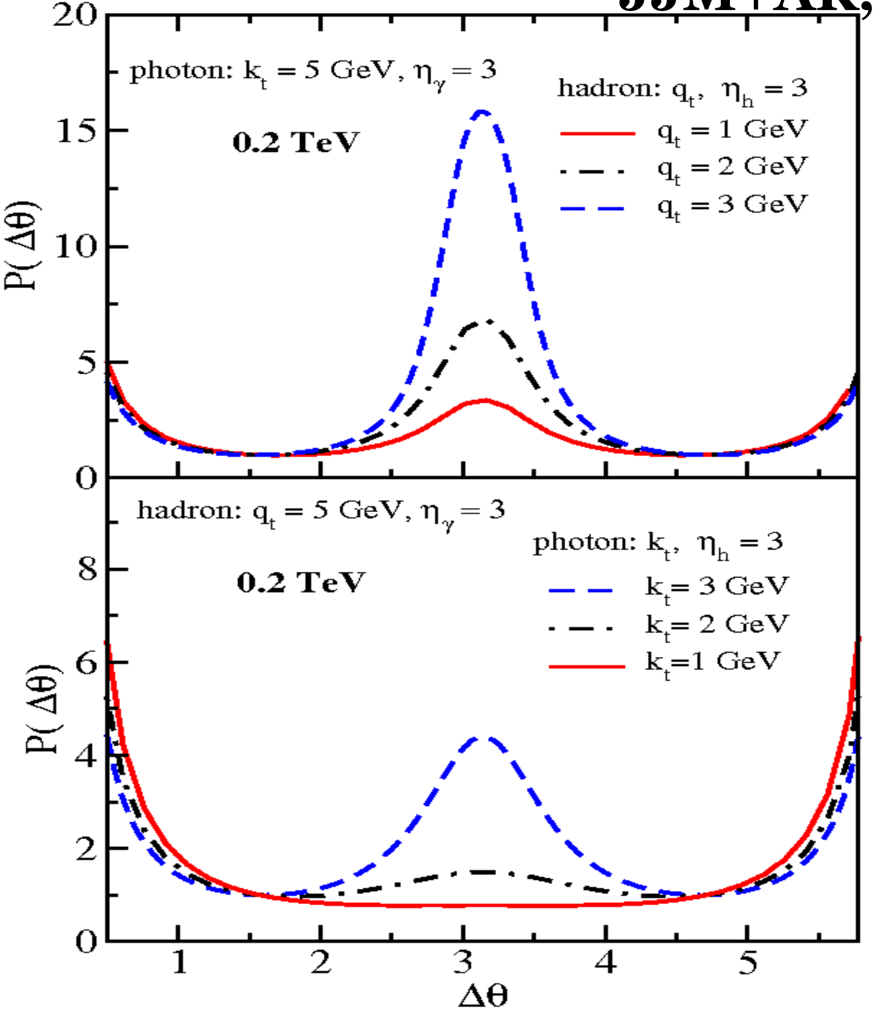


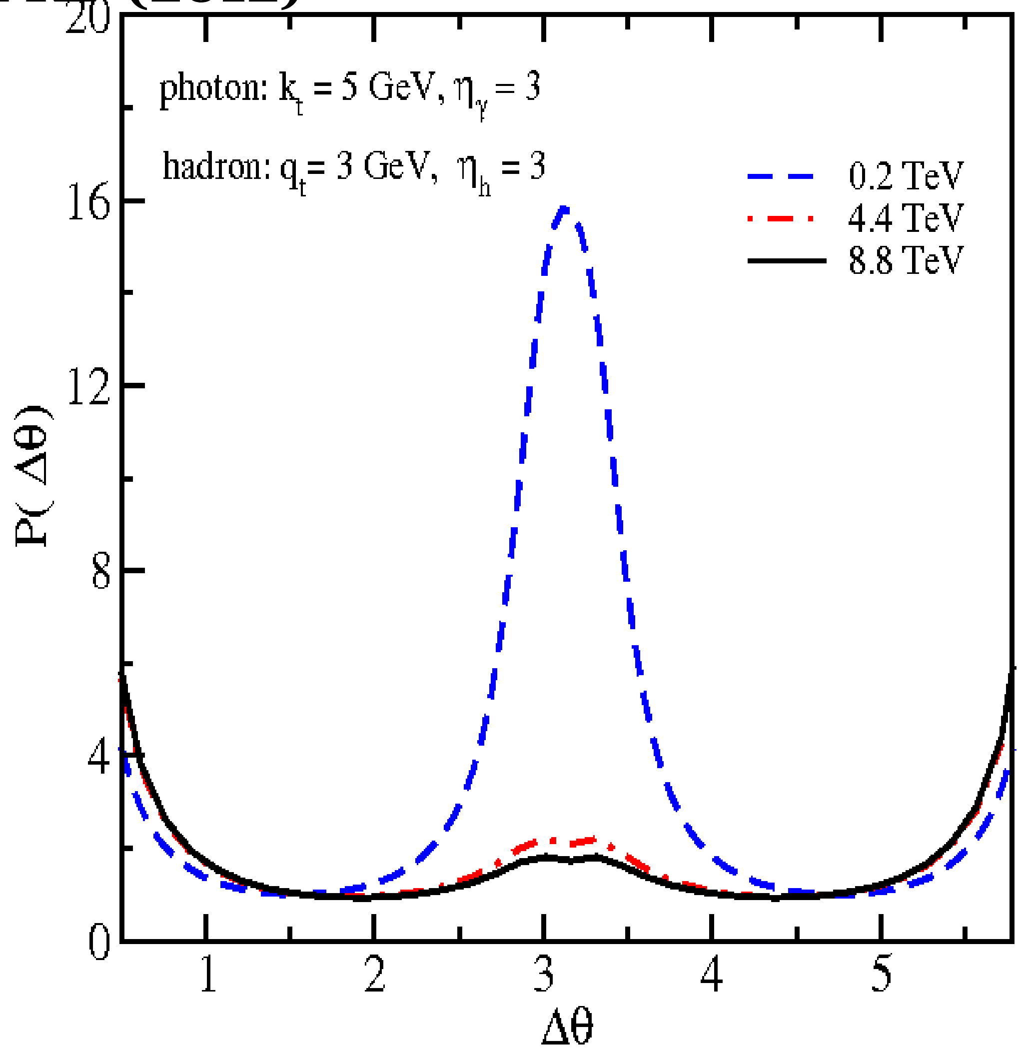
$$p_t >> Q_s$$

photon-hadron azimuthal correlations

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

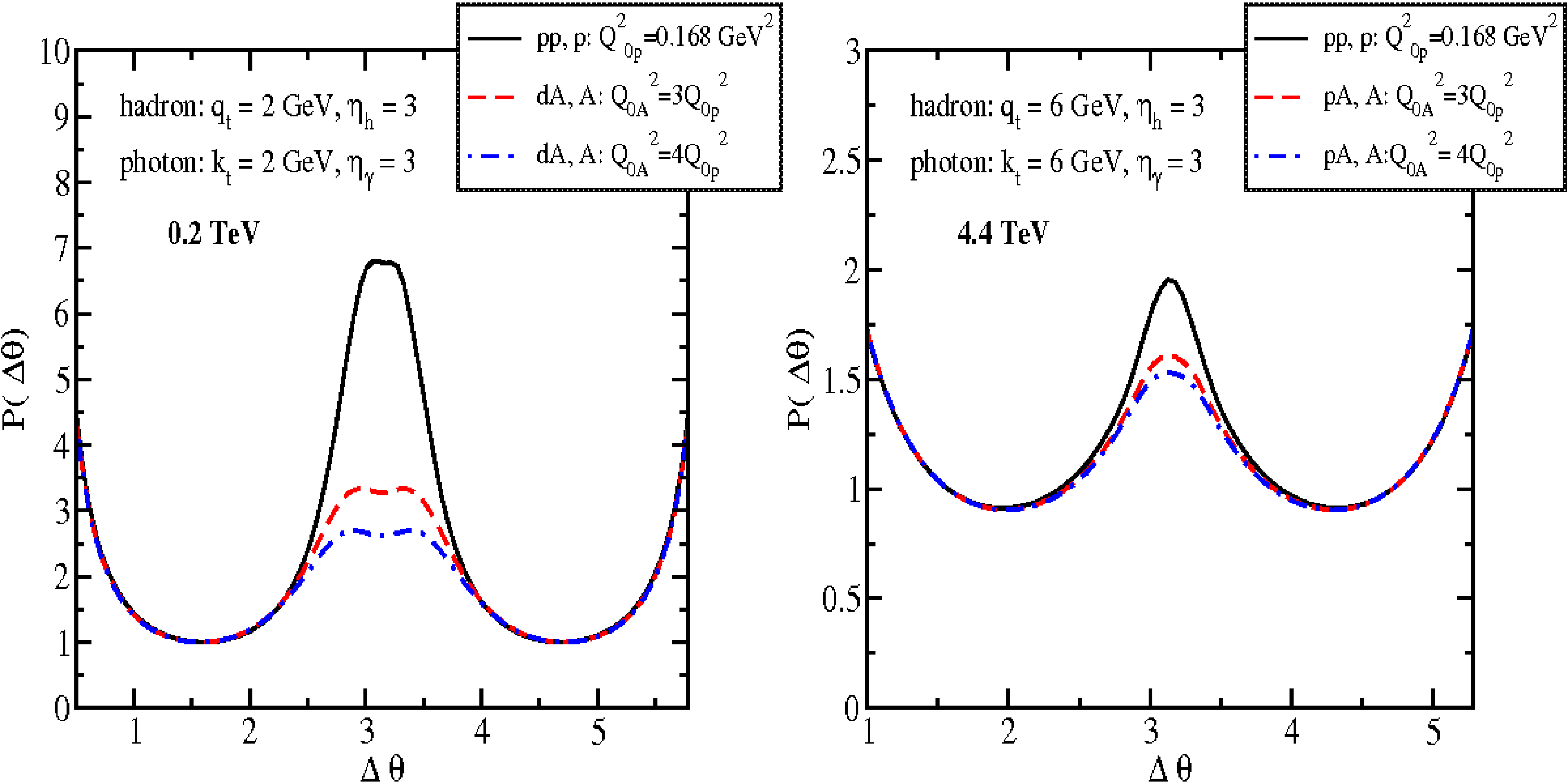
JJM+AR, PRD (2012)





Centrality dependence

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



Photon-hadron correlations

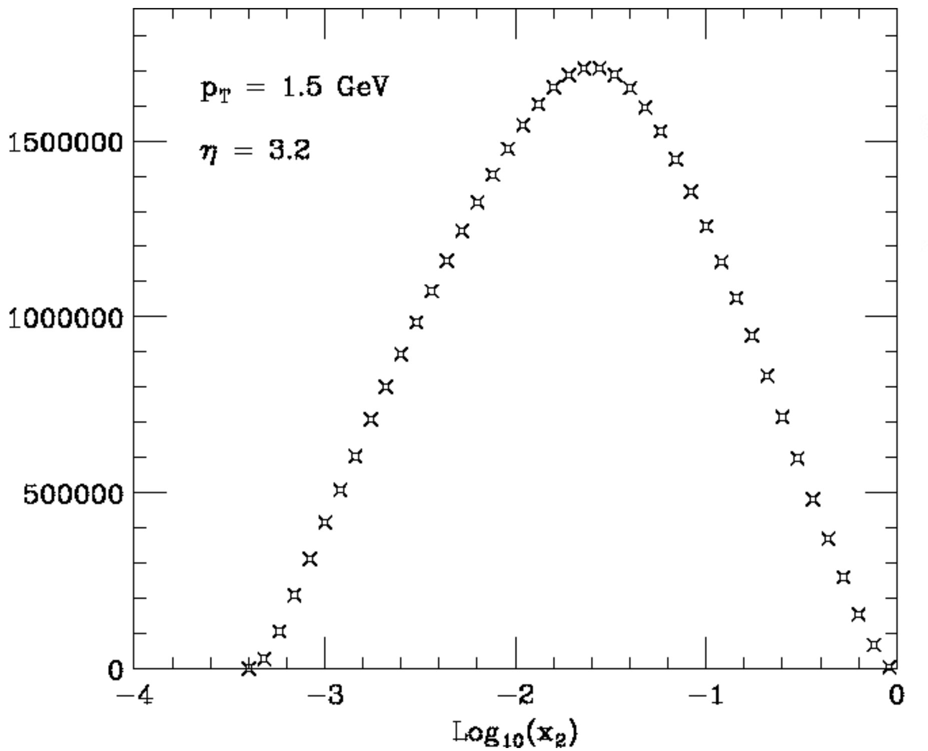
<u>new processes to probe the dynamics of high energy QCD</u>

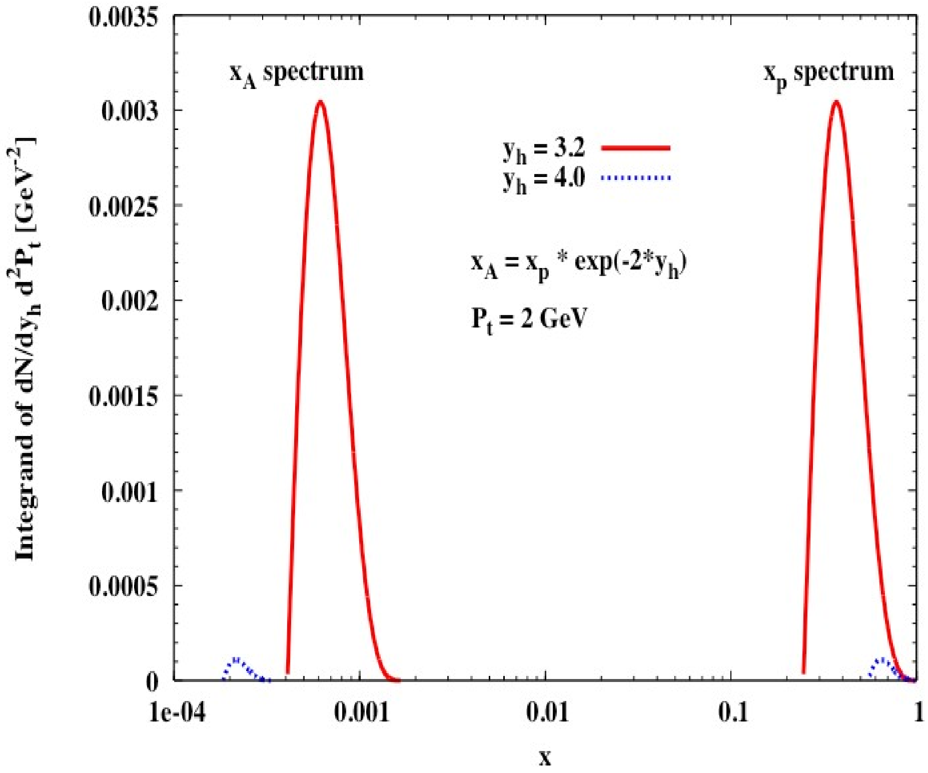
suppression of prompt photon spectrum in forward rapidity in p(d)A

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

<u>need to measure these at RHIC/LHC</u>

2 → 2 vs. 2 → 1





GSV

DHJ