Multi-Reggeon exchanges at high pt from gluon saturation

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based on arXiv:1407.3080
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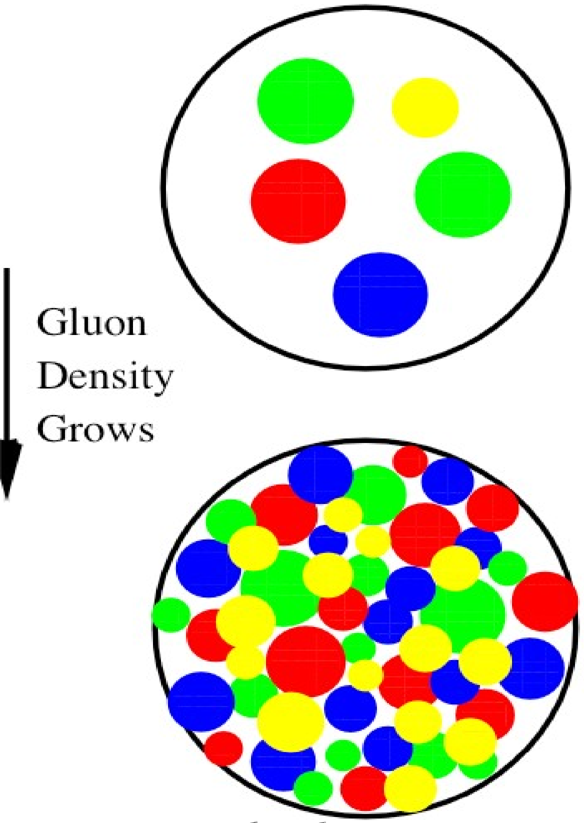
Nantes, France

Gluon saturation/CGC

$$\mathbf{S \to \infty, \quad Q^2 \ \ fixed, \quad x_{Bj} \equiv \frac{Q^2}{S} \to 0}$$

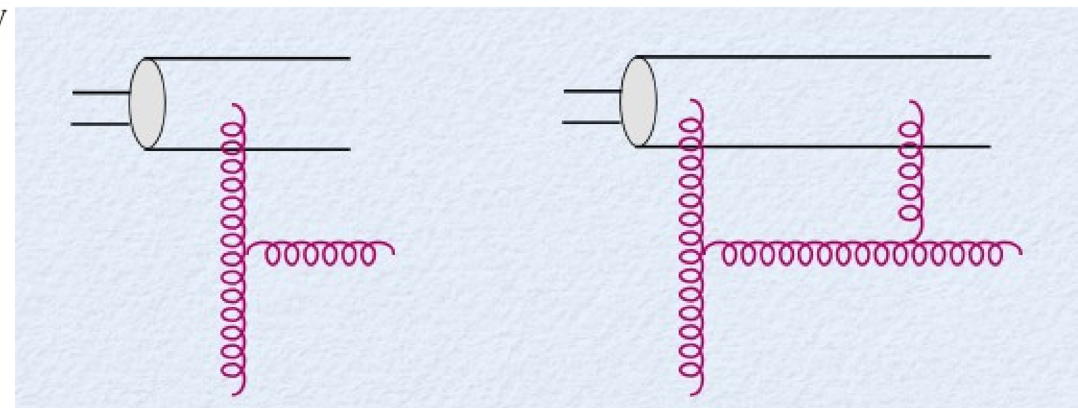
Gribov-Levin-Ryskin
Mueller-Qiu

“attractive” bremsstrahlung
vs. “repulsive” recombination



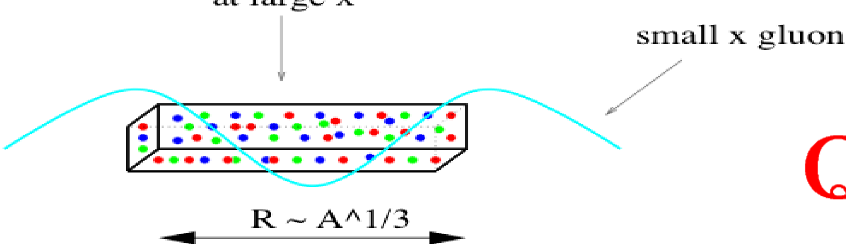
Low Energy

$\frac{1}{x}$



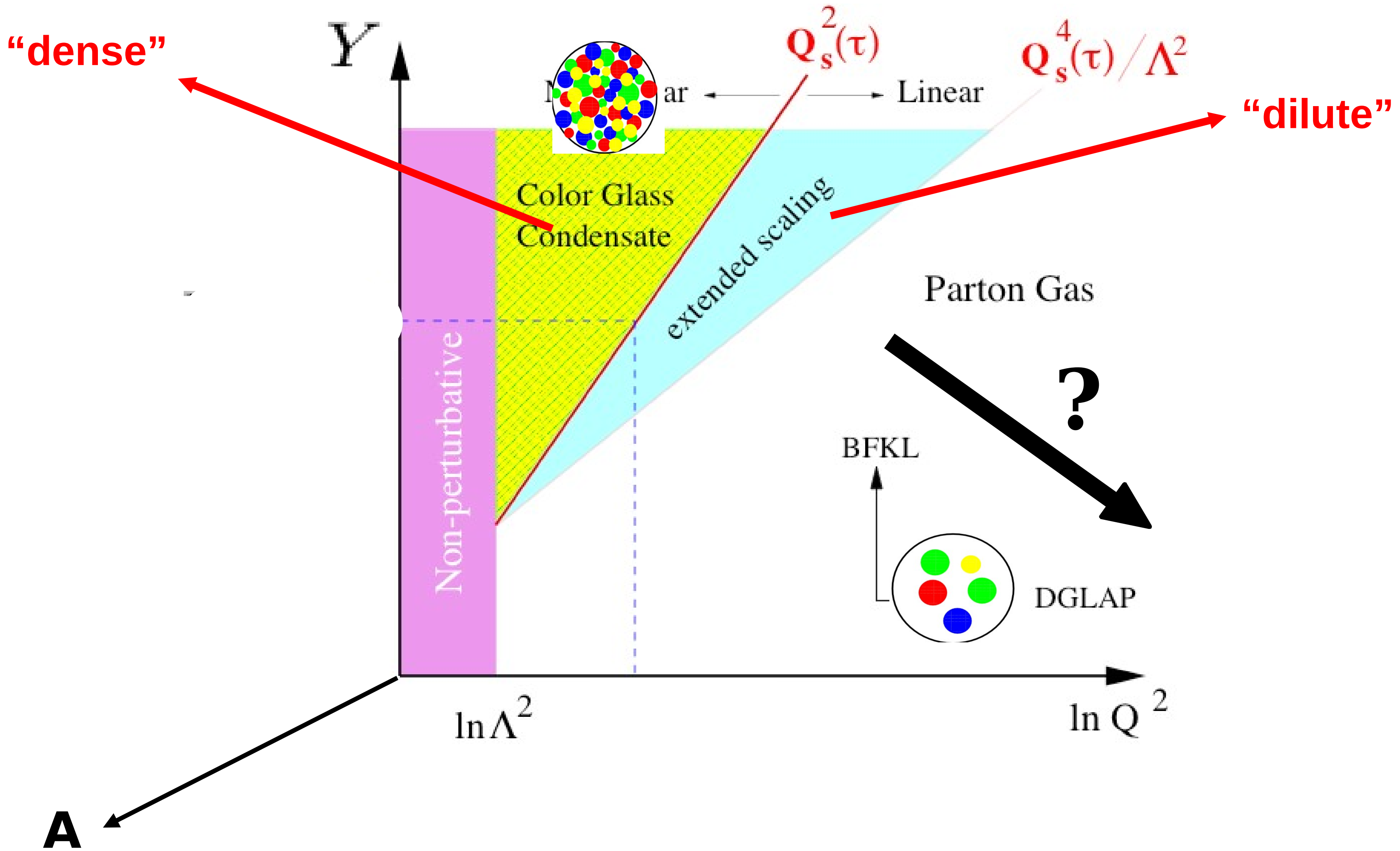
High Energy

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



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

Road Map of QCD Phase Space



QCD at low x: CGC

(a high gluon density environment)

two main effects:

“multiple scatterings”

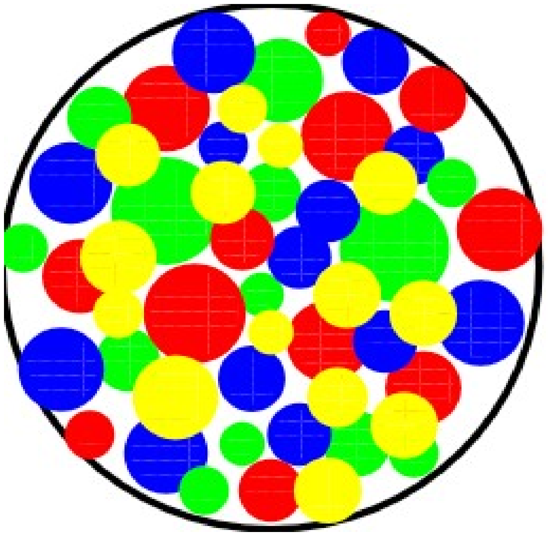
evolution with ln (1/x)

pQCD with collinear factorization:

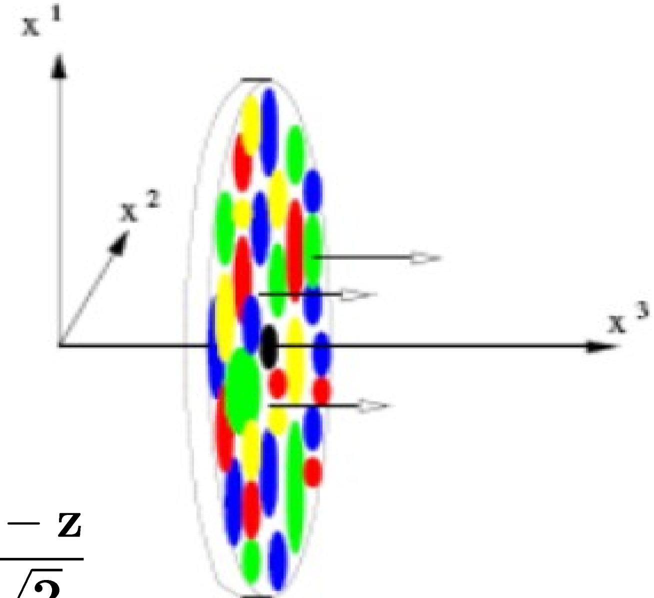
single scattering

evolution with ln Q^2

MV model of nuclei at high energy



boost

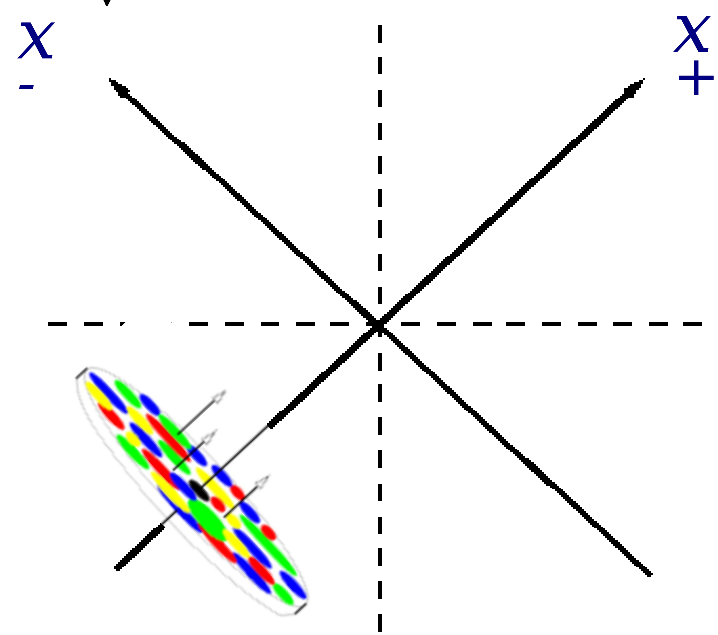


$$\mathbf{x}^+ \equiv \frac{\mathbf{t}+\mathbf{z}}{\sqrt{2}} \qquad \mathbf{x}^- \equiv \frac{\mathbf{t}-\mathbf{z}}{\sqrt{2}}$$

sheet of color charge moving along x^+ and sitting at $x^- = 0$

$$\boxed{\mathbf{J}^\mu_\mathbf{a}(\mathbf{x}) \equiv \delta^{\mu\,+}\,\delta(\mathbf{x}^-)\,\rho_\mathbf{a}(\mathbf{x_t})}$$

color current *color charge*



current has only one large component

Classical Field: $\alpha^{\mathbf{a}}(\mathbf{k_t})$

$$\mathbf{A}^{\mu}_{\mathbf{a}}(\mathbf{x_t}, \mathbf{x}^-) \sim \delta^{\mu +}\,\delta(\mathbf{x}^-)\,\alpha_{\mathbf{a}}(\mathbf{x_t})$$

where the classical field $\boldsymbol{\alpha}$ *and the color charge density* $\boldsymbol{\rho}$
are related via equations of motion

$$\alpha^{\mathbf{a}}(\mathbf{k_t}) = \mathbf{g}\,\rho^{\mathbf{a}}(\mathbf{k_t})/\mathbf{k_t^2}$$

unintegrated gluon distribution: $\phi(\mathbf{x}, \mathbf{k_t^2}) \sim < \rho^{\star}_{\mathbf{a}}(\mathbf{k_t})\,\rho_{\mathbf{a}}(\mathbf{k_t}) >$

gluon distribution: $\quad \mathbf{xG}(\mathbf{x}, \mathbf{Q^2}) \sim \int^{\mathbf{Q^2}} \frac{\mathbf{d^2k_t}}{\mathbf{k_t^2}}\,\phi(\mathbf{x}, \mathbf{k_t})$

Quantum corrections:
non-linear evolution equation

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

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

U is a Wilson line in adjoint representation

CGC observables:

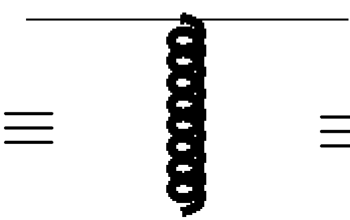
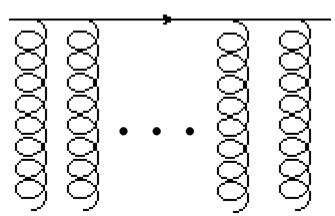
DIS

Particle production in pA,.....

involves propagation of a parton from the projectile in the background color field of the target

$$\mathbf{V(x_t) = \hat{P} e^{ig \int dx^- \, A_a^+ \, t_a}}$$

Wilson line encodes multiple scatterings on the target

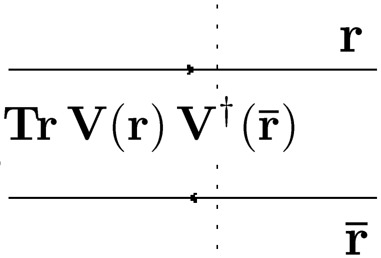
$\mathbf{V} \equiv$  $\equiv$  $\sim \mathbf{1 + O(g\,\rho) + O(g^2\,\rho^2)}$

observables are given in terms of Wilson line correlators $\quad < \mathbf{Tr\, V \cdots \cdots V^\dagger} >$

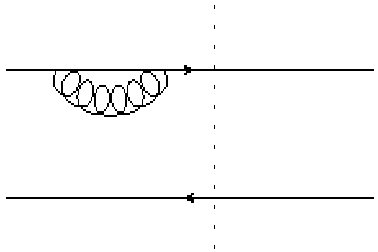
Evolution (energy dependence) of the 2-point function (dipole): DIS, single inclusive production

BK equation (known to NLO)

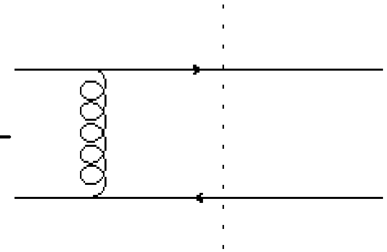
$$\frac{\mathbf{d}}{\mathbf{dy}}\mathbf{Tr\,V(r)\,V^{\dagger}(\bar{r})}$$



$$=$$

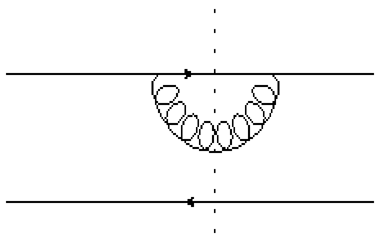


$$+$$

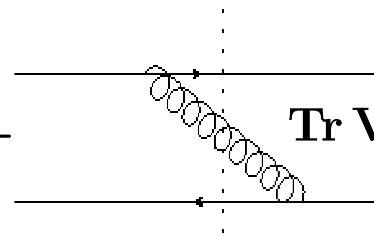


$$\mathbf{Tr\,V(r)\,V^{\dagger}(\bar{r})}$$

$$+$$



$$+$$



$$\mathbf{Tr\,V(r)\,V^{\dagger}(z)\,Tr\,V(z)\,V^{\dagger}(r)}$$

$$\frac{\mathbf{1}}{\mathbf{(r-z)^2}} \qquad \frac{\mathbf{(r-z)\cdot(\bar{r}-z)}}{\mathbf{(r-z)^2(\bar{r}-z)^2}}$$

$$\frac{\mathbf{d}}{\mathbf{dy}}\mathbf{T(r-\bar{r})} = \frac{\bar{\alpha}_{\mathbf{s}}}{\mathbf{2}\pi}\int \mathbf{d^2z}\,\frac{\mathbf{(r-\bar{r})^2}}{\mathbf{(r-z)^2(\bar{r}-z)^2}} \otimes$$

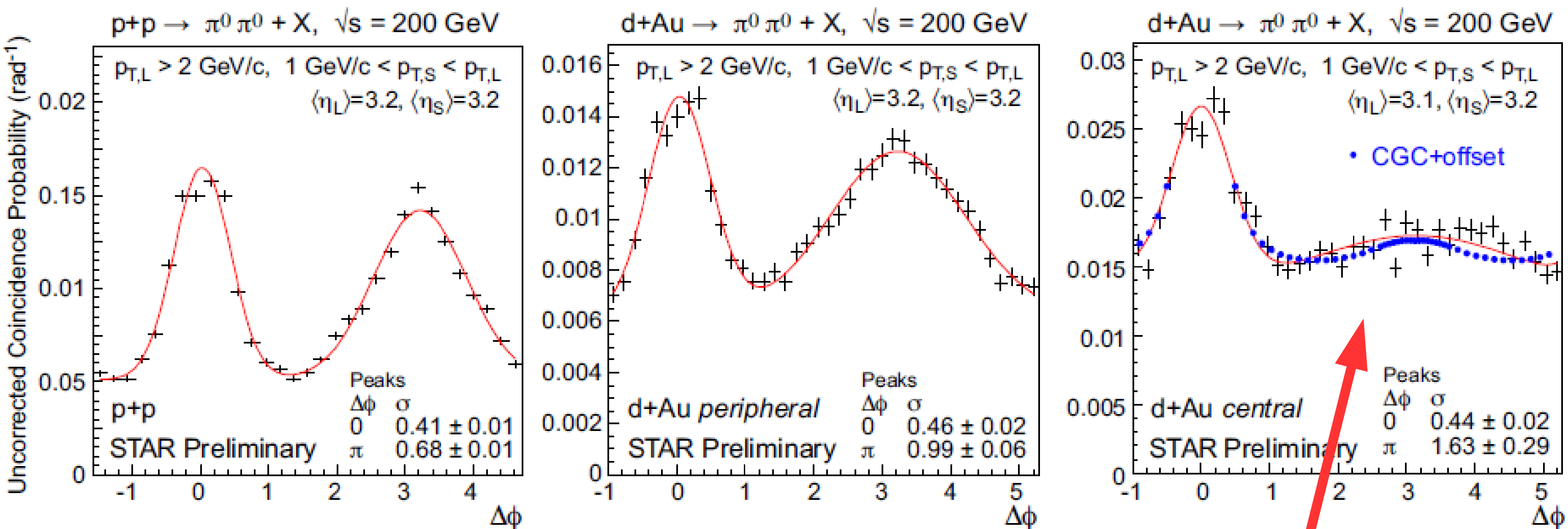
non-linear term

$$\Big[\mathbf{T(}\underbrace{\mathbf{r-z)+T(z-\bar{r})-T(r-}}_{\text{Linear (BFKL)}}\mathbf{\bar{r})} - \color{red}{\mathbf{T(r-z)T(\bar{r}-z)}}\Big]$$

disappearance of back to back hadrons

C. Marquet, NPA796 (2007) 41

Recent STAR measurement (arXiv:1008.3989v1):



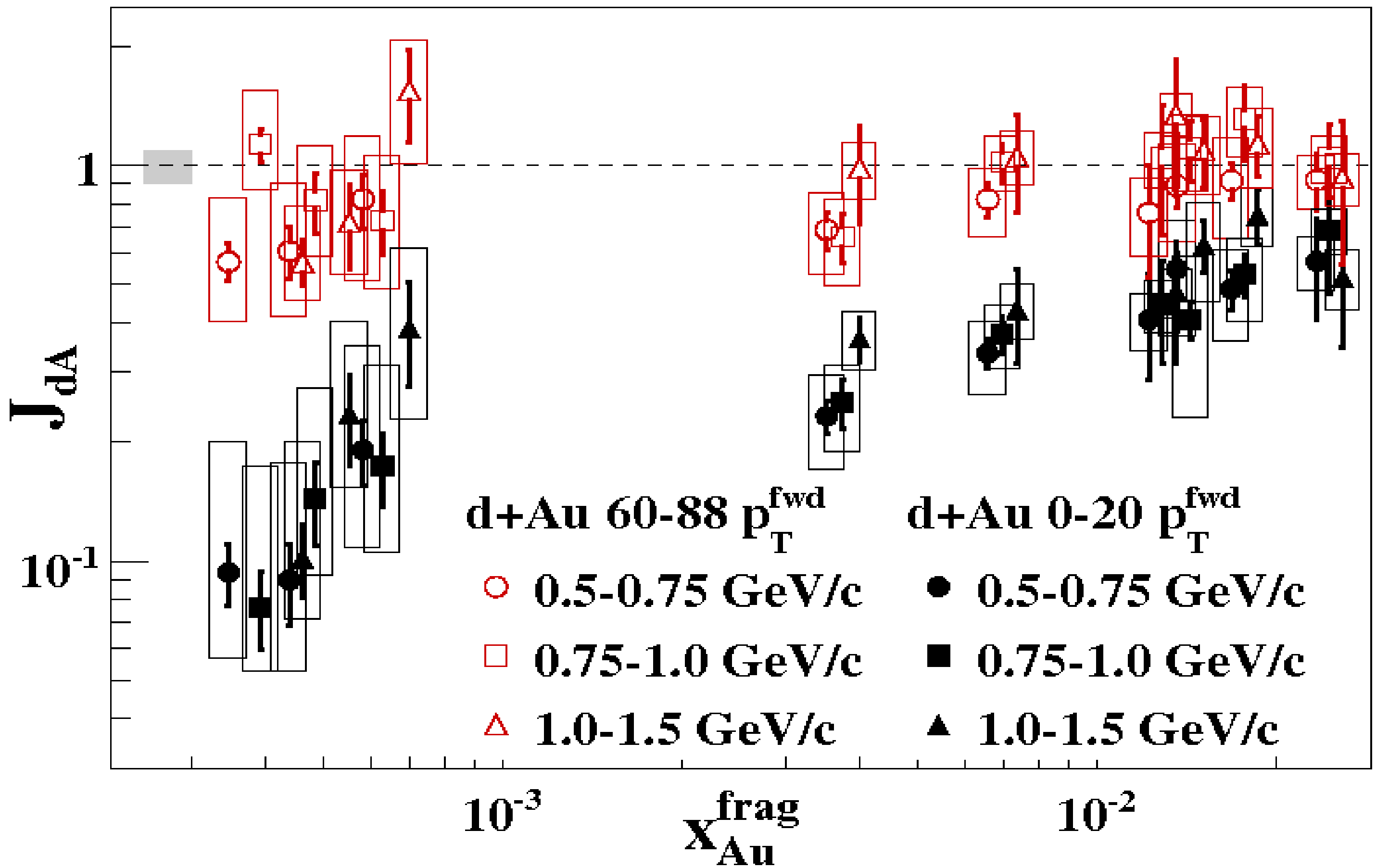
CGC fit from Albacete + Marquet, PRL (2010)
Tuchin, NPA846 (2010)
A. Stasto, B-W. Xiao, F. Yuan, PLB716 (2012)
T. Lappi, H. Mantysaari, NPA908 (2013)

multiple scatterings de-correlate the hadrons

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

disappearance of back to back jets

$$J_{dA} \sim \frac{N_{dAu}^{\text{back-to-back}} \,/\, N_{\text{N-N-collision}}}{N_{pp}^{\text{back-to-back}}}$$



Peripheral d-Au collisions

Central d-Au collisions

A. Adare, et al., PRL 107 (2011) 172301

QCD at high energy

Two distinct approaches:

1) CGC

McLerran-Venugopalan effective action
JIMWLK-BK evolution

2) Reggeized-gluon exchange

BJKP equation
triple,... pomeron vertex

Is there a connection between CGC and BJKP + multi-pomeron vertices

arXiv:1407.3080
A. Ayala, E. Cazaroto, L. Hernandez, J. Jalilian-Marian, M.E. Tejeda-Yeomans

CGC vs. BJKP

<u>BJKP</u> equation describes evolution of n-Reggeized gluons (in a singlet state) in t channel

conserves the number of exchanged gluons

<u>CGC</u>: JIMWLK evolution equation for 2n Wilson lines

linearize the equation

expand in powers of α/p_t

the linear regime

$\mathbf{O}(\alpha^{\mathbf{2}})$: 2-gluon (BFKL **Pomeron**) exchange

$\mathbf{O}(\alpha^{\mathbf{3}})$: 3-gluon (**odderon**) exchange

dipole odderon: *Kovchegov, Szymanowski, Wallon*

baryonic odderon: *Hatta, Iancu, Itakura, McLerran*

$\mathbf{O}(\alpha^{\mathbf{4}})$: 4-gluon (**quadrupole**) exchange

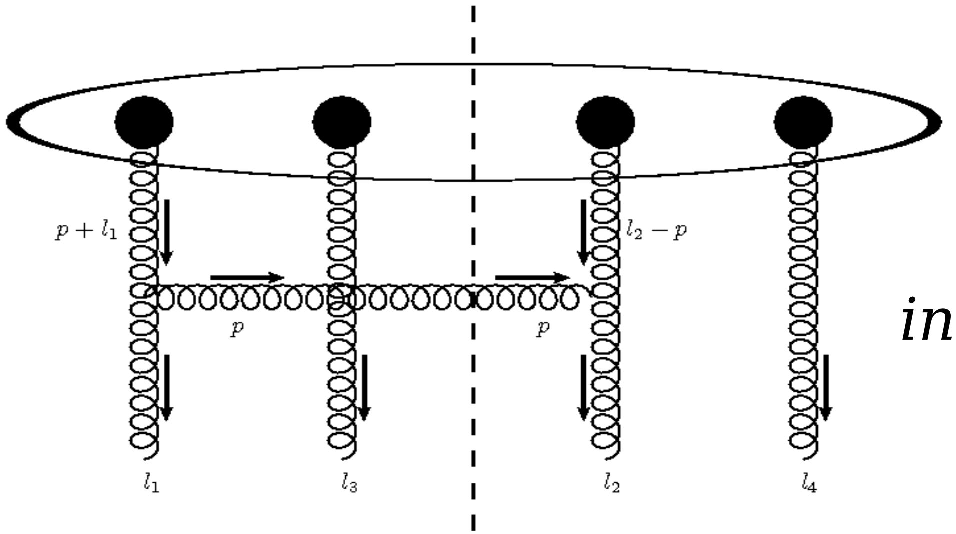
Dominguez, Mueller, Munier, Xiao
J. Jalilian-Marian
D. Triantafyllopoulos

quadrupole evolution: <u>linear regime</u>

BJKP equation

$\mathrm{O}(\alpha^4)$: 4-gluon exchange

J. Jalilian-Marian, PRD85 (2012) 014037



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> di-jets at high $p_t > Q_s$

2n-Wilson line evolution: linear regime

$\mathbf{O}\left(\alpha^{\mathbf{2n}}\right)$: 2n-gluon exchange

$$
\begin{aligned}
& \frac{d}{dY} T^{(2n)}_{\left(\prod_{k=1}^{2n} l_k\right)} = - \frac{\bar{\alpha}}{2\pi} \sum_{j=1}^{2n} \int d^2 p_t \left[\frac{l_j^2}{p_t^2 \left[p_t^2 + (p_t - l_j)^2 \right]} \right] T^{(2n)}_{\left(\prod_{k=1}^{2n} l_k\right)} \\
+ \quad & \frac{\bar{\alpha}}{4\pi} \int d^2 p_t \left[\frac{l_1^2}{p_t^2 \, (p_t + l_1)^2} + \frac{l_{2n}^2}{p_t^2 \, (p_t - l_{2n})^2} - \frac{(l_1 + l_{2n})^2}{(p_t + l_1)^2 \, (p_t - l_{2n})^2} \right] T^{(2n)}_{(l_1 + p_t) \left(\prod_{k=2}^{2n-1} l_k\right) (l_{2n} - p_t)} \\
+ \quad & \frac{\bar{\alpha}}{4\pi} \sum_{j=2}^{2n} \int d^2 p_t \left[\frac{l_{j-1}^2}{p_t^2 \, (p_t + l_{j-1})^2} + \frac{l_j^2}{p_t^2 \, (p_t - l_j)^2} - \frac{(l_{j-1} + l_j)^2}{(p_t + l_{j-1})^2 \, (p_t - l_j)^2} \right] T^{(2n)}_{\left(\prod_{k=1}^{j-2} l_k\right) (l_{j-1} + p_t) (l_j - p_t) \left(\prod_{k=j+1}^{2n} l_k\right)} .
\end{aligned}
$$

A Mathematica program that gives the equation can be downloaded from

faculty.baruch.cuny.edu/naturalscience/physics/Jalilian-Marian/

paginas.fisica.uson.mx/elena.tejeda/code.nb

Non-linear regime: triple pomeron vertex

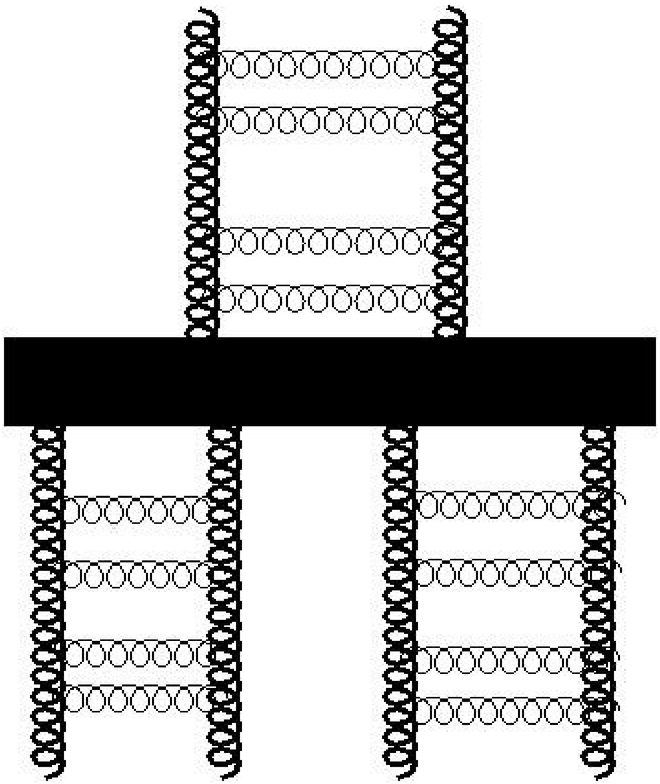
Chirilli, Szymanowski, Wallon PRD83 (2011) 014020

start with the dipole evolution equation

$$\frac{\mathbf{d}}{\mathbf{dy}}\mathbf{T}(\mathbf{r}-\bar{\mathbf{r}}) \;=\; \frac{\bar{\alpha}_{\mathbf{s}}}{\mathbf{2}\pi}\int \mathbf{d}^{\mathbf{2}}\mathbf{z}\,\frac{(\mathbf{r}-\bar{\mathbf{r}})^{\mathbf{2}}}{(\mathbf{r}-\mathbf{z})^{\mathbf{2}}(\bar{\mathbf{r}}-\mathbf{z})^{\mathbf{2}}}\otimes$$

$$\Big[\mathbf{T}(\mathbf{r}-\mathbf{z})+\mathbf{T}(\mathbf{z}-\bar{\mathbf{r}})-\mathbf{T}(\mathbf{r}-\bar{\mathbf{r}})-\mathbf{T}(\mathbf{r}-\mathbf{z})\mathbf{T}(\bar{\mathbf{r}}-\mathbf{z})\Big]$$

non-linear term



recall $\quad \mathbf{T}(\mathbf{r}-\bar{\mathbf{r}}) \;\equiv\; \mathbf{1}-\frac{\mathbf{1}}{\mathbf{N_c}}\mathbf{Tr}\,\mathbf{V}(\mathbf{r_t})\,\mathbf{V}^{\dagger}(\bar{\mathbf{r}}_{\mathbf{t}})$

with $\quad \mathbf{V}(\mathbf{r_t})=\hat{\mathbf{P}}\,\mathbf{exp}\Big\{-\mathbf{ig}\int_{-\infty}^{\infty}\mathbf{dz}^{-}\,\alpha(\mathbf{z}^{-},\mathbf{r_t})\Big\}$

Triple pomeron-vertex from O (α^4) terms in the expansion of the non-linear term

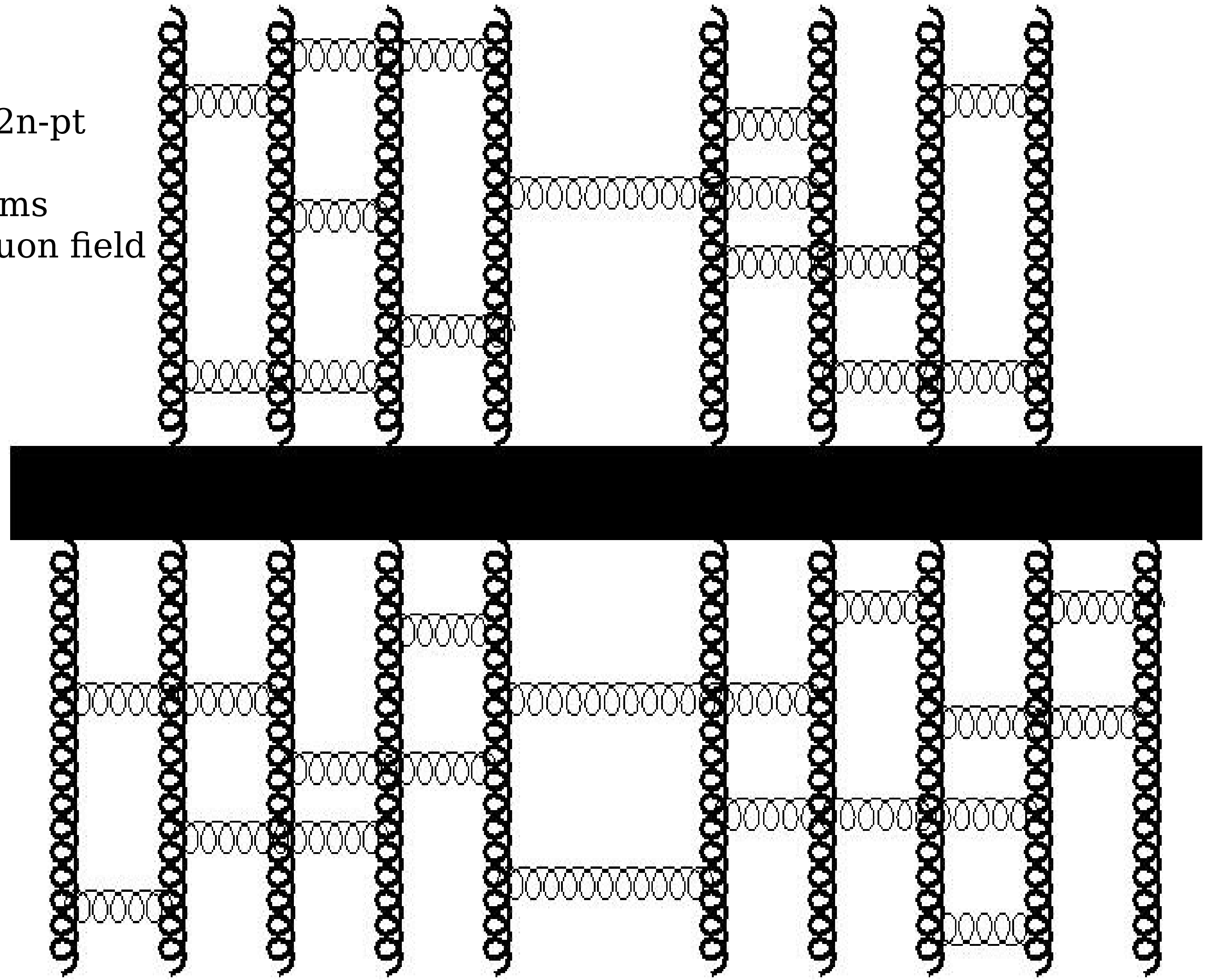
<u>agrees with Reggeized gluon exchange results of Bartles et al.</u>

Non-linear regime: n ----> n+1 pomeron vertex

A. Ayala, E. Cazaroto, L. Hernadez, J. Jalilian-Marian, M.E. Tejeda-Yeomans, in progress

Follow the same strategy:

- Evolution equation for 2n-pt function
- Keep the non-linear terms
- Expand in powers of gluon field
- Extract the vertex



First case:
2 ---> 3 vertex
(first high density correction)

SUMMARY

JIMWLK evolution equation for 2n Wilson lines in the linear regime is equivalent to the BJKP equation for evolution of a singlet state of 2n Reggeized gluons

It appears possible to extract the vertex for any n to n+1 "Pomeron" vertex

Can one make a saturation based effective theory of diffraction in proton-proton collisions?