NLO corrections to single and double inclusive hadron production in DIS at small x

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Workshop on Resummation, Evolution, Factorization 2022

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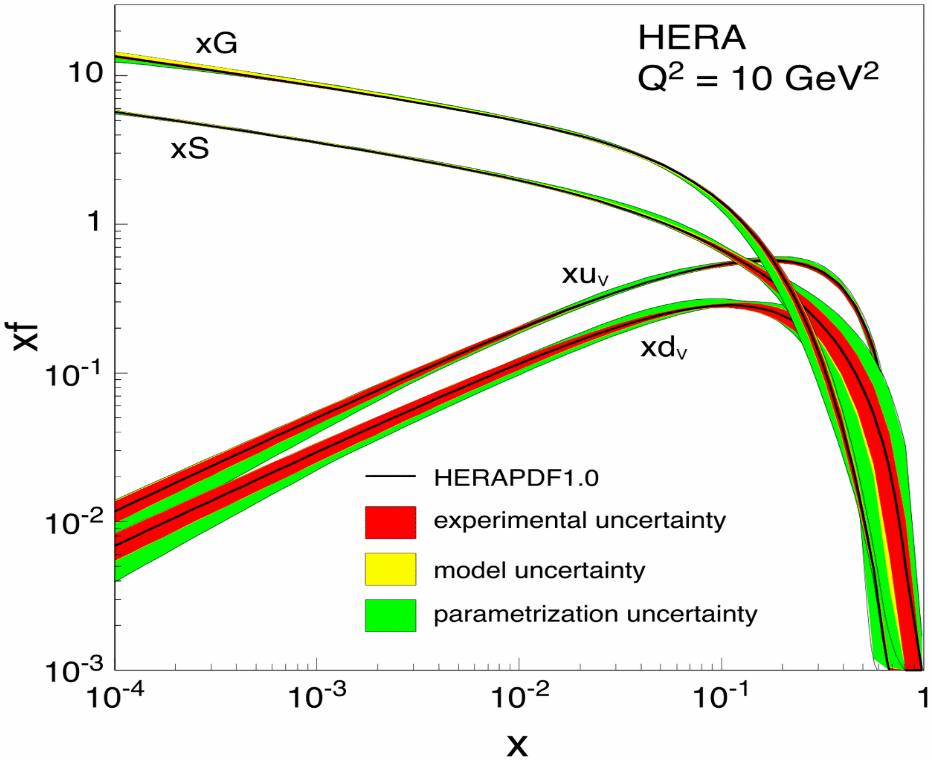
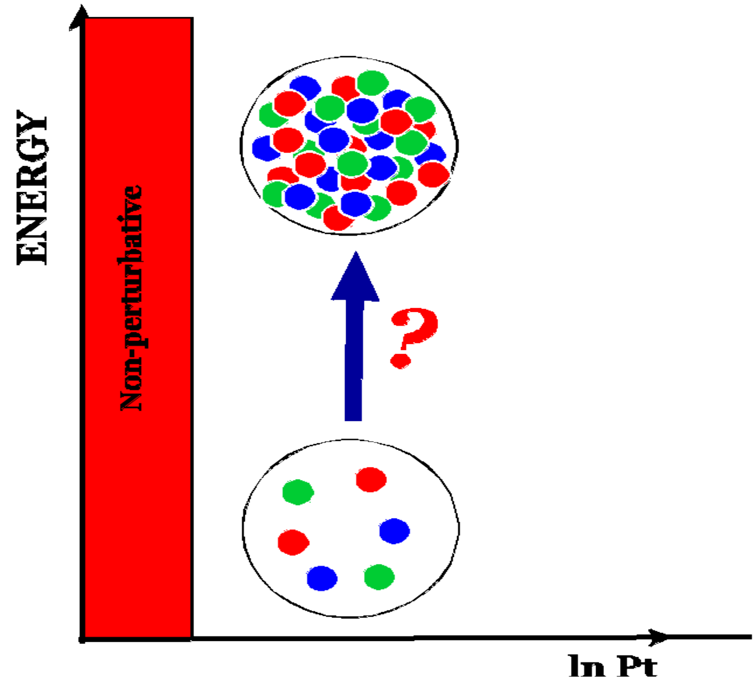
dynamics of *universal gluonic matter:* *gluon saturation*



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



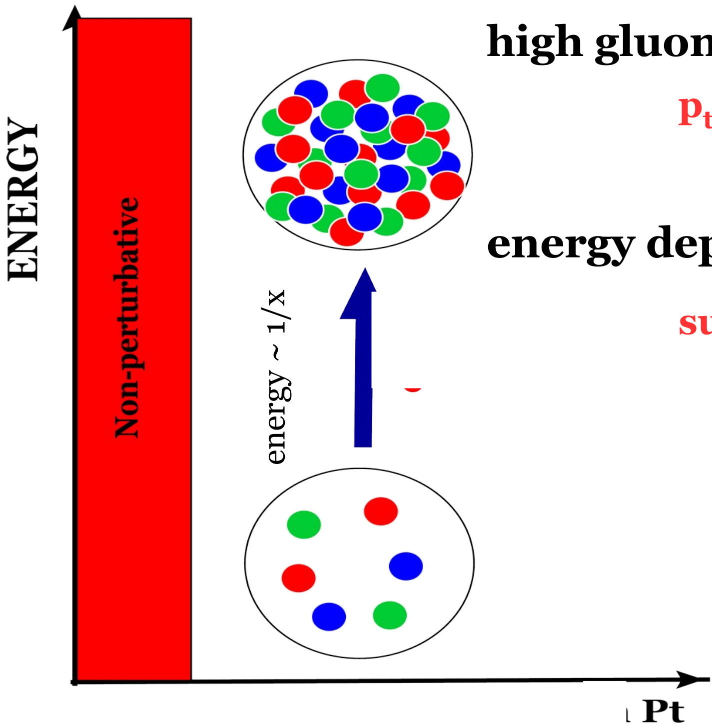
How does this happen ?

How do correlation functions evolve ?

Is there a universal fixed point for the evolution ?

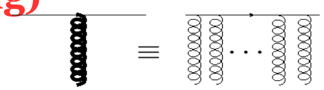
Are there scaling laws ?

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

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

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

for a proton target (quarks)

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

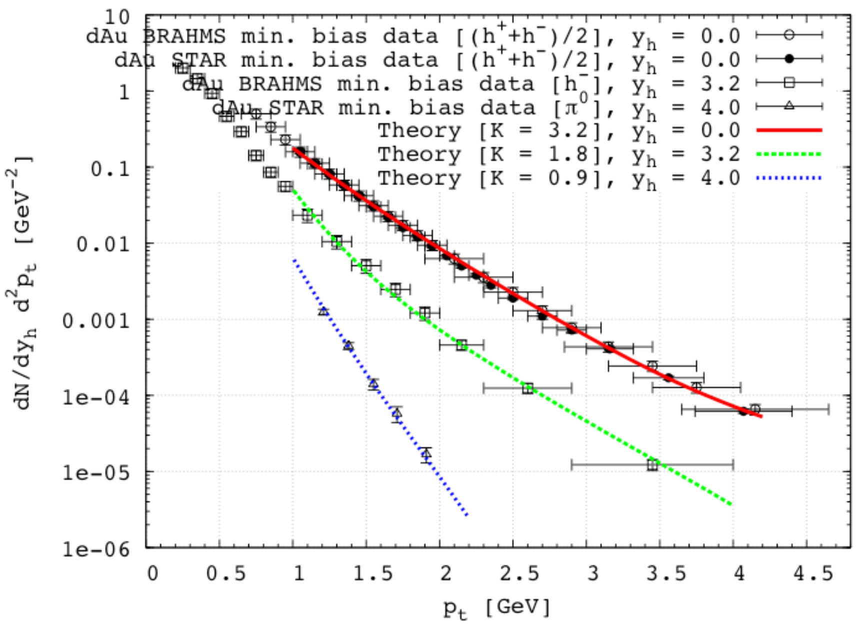
Shadowing/Nuclear modification factor
Azimuthal angular correlations
Long range rapidity correlations (ridge,...)
Initial conditions for hydro
Thermalization (?)

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

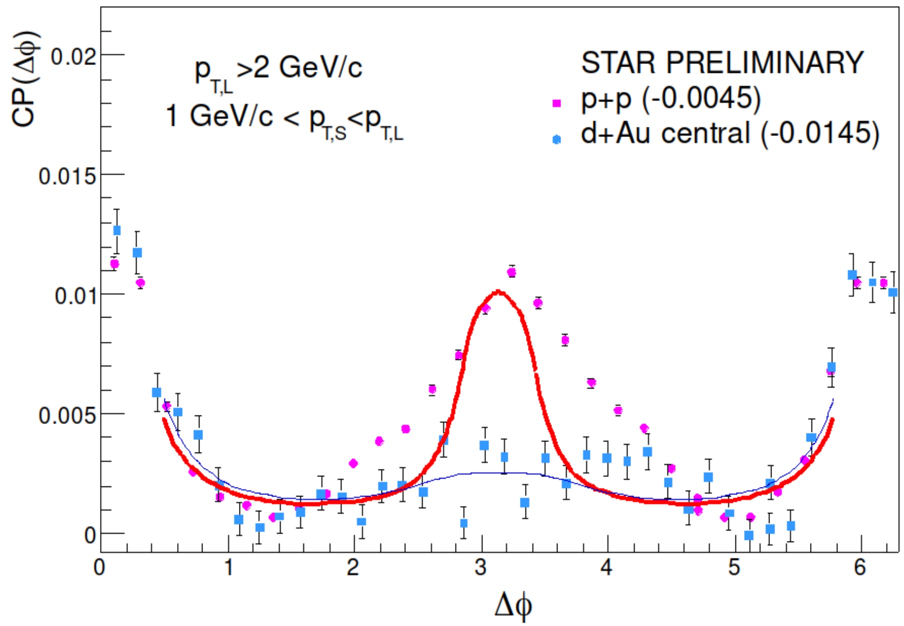
$$\alpha_s \ln{(x_v/x)} \sim 1$$

CGC at RHIC

Single and double inclusive hadron production in dA collisions



Dumitru,Hayashigaki, JJM, NPA770 (2006) 57



Albacete, Marquet, PRL105 (2010) 162301

For more recent work see talks by S. Wei on Wednesday and P. Kotko on Thursday

NLO corrections to inclusive dihadron production in DIS at small x

Based on F. Bergabo and JJM:

NPA 1018 (2022) 122358

PRD 106 (2022) 5, 054035

Closely related talks in this conference:

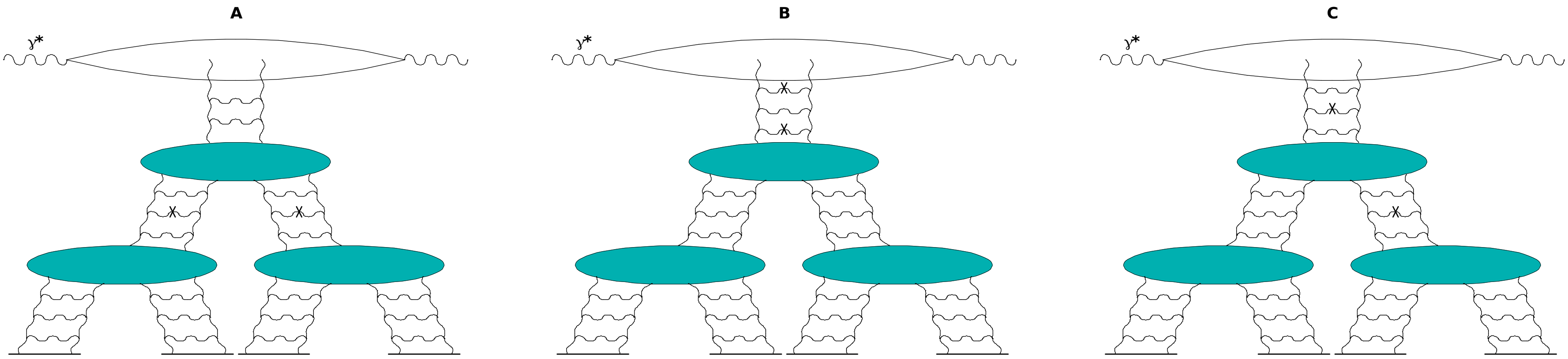
Sudakov effects in dijets: P. Taels, Wednesday

NLO dijets: F. Salazar, Thursday

NLO diffractive dihadrons: E. Li, Thursday

LO: inclusive dihadron production in DIS at small x

JJM, Yu. Kovchegov
PRD70 (2004) 114017



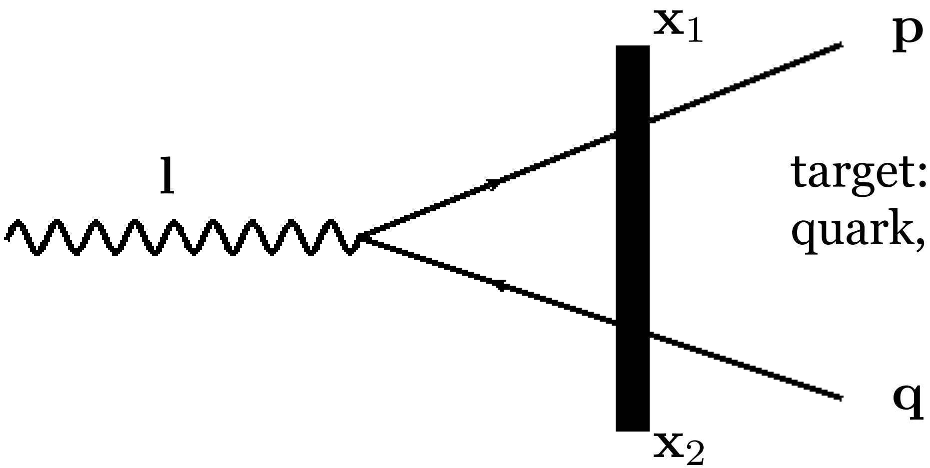
dominant diagrams in the **mid-rapidity** region

target is treated as a classical color field $\mathbf{A}_a^{\mu} = \delta^{\mu -}\, n^{\mu}\, S_a(x^+, \mathbf{x})$

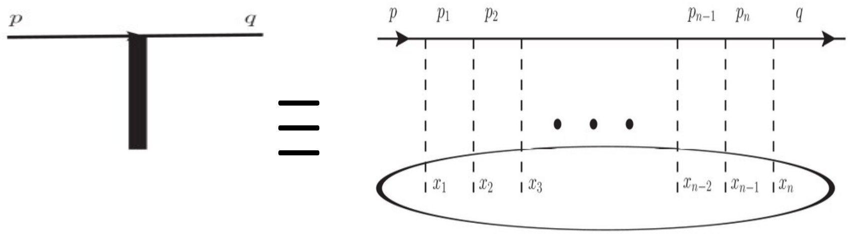
scatterings of gluons on the target encoded in Wilson lines $\mathbf{U}\ (\mathbf{x}_1), U^{\dagger}(\mathbf{x}_2)$

leading log evolution included

LO: inclusive dihadron production in DIS at small x



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



$$\frac{d\sigma^{\gamma^* A\to q\bar{q}X}}{d^2p\, d^2q\, dy_1\, dy_2} = \frac{e^2Q^2(z_1 z_2)^2 N_c}{(2\pi)^7}\delta(1-z_1-z_2)$$

$$\int d^8x_\perp e^{ip\cdot(x_1'-x_1)}e^{iq\cdot(x_2'-x_2)}\left[S_{122'1'}-S_{12}-S_{1'2'}+1\right]$$

$$\Big\{4z_1z_2K_0(|x_{12}|Q_1)K_0(|x_{1'2'}|Q_1)+$$

$$(z_1^2+z_2^2)\,\frac{x_{12}\cdot x_{1'2'}}{|x_{12}||x_{1'2'}|}\,K_1(|x_{12}|Q_1)K_1(|x_{1'2'}|Q_1)\Big\}$$

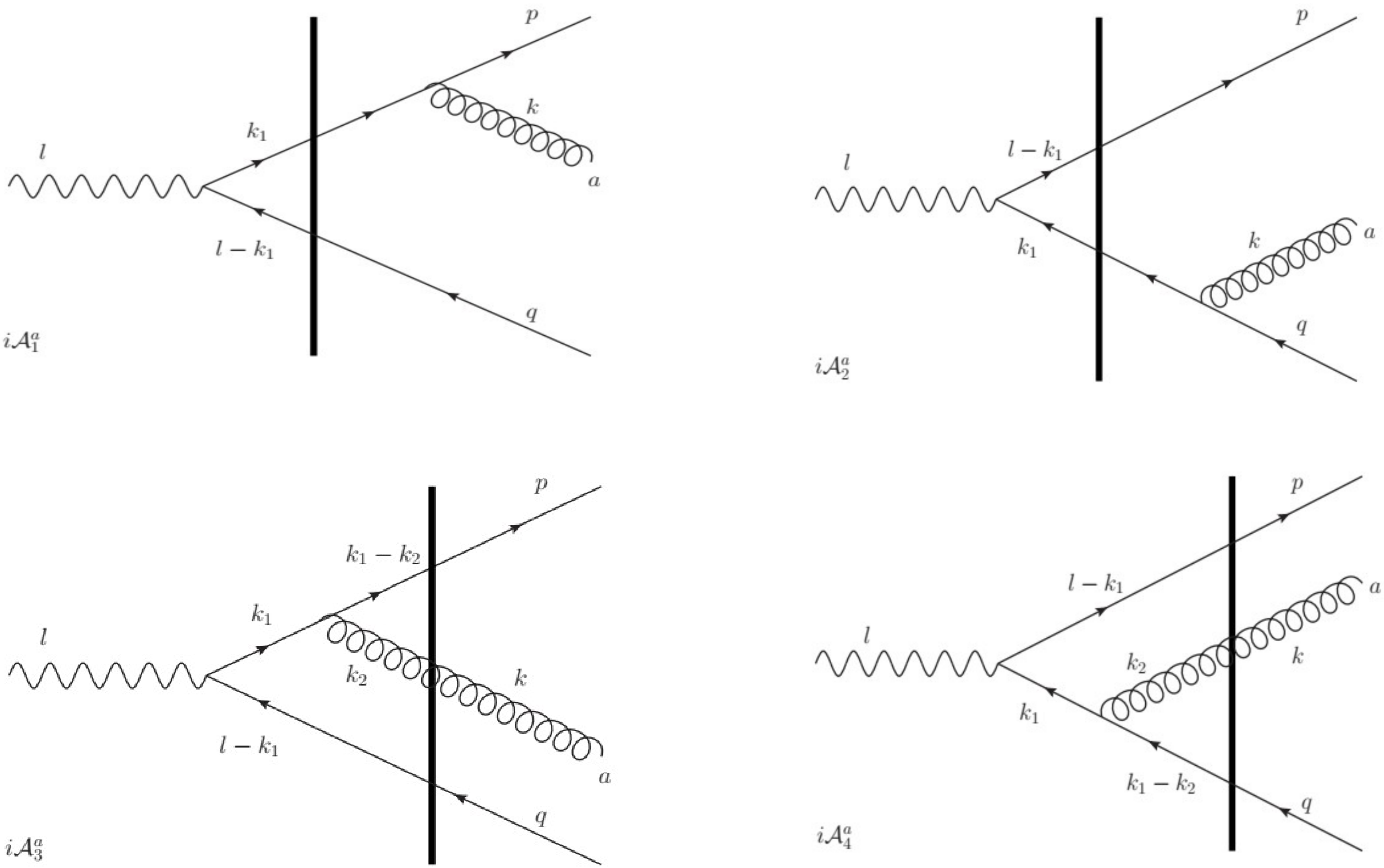
with

$$\mathbf{S}_{12}\equiv\frac{1}{N_c}Tr\,V(x_1)\,V^\dagger(x_2)$$

$$\mathbf{x}_{12}\equiv\mathbf{x}_1-\mathbf{x}_2$$

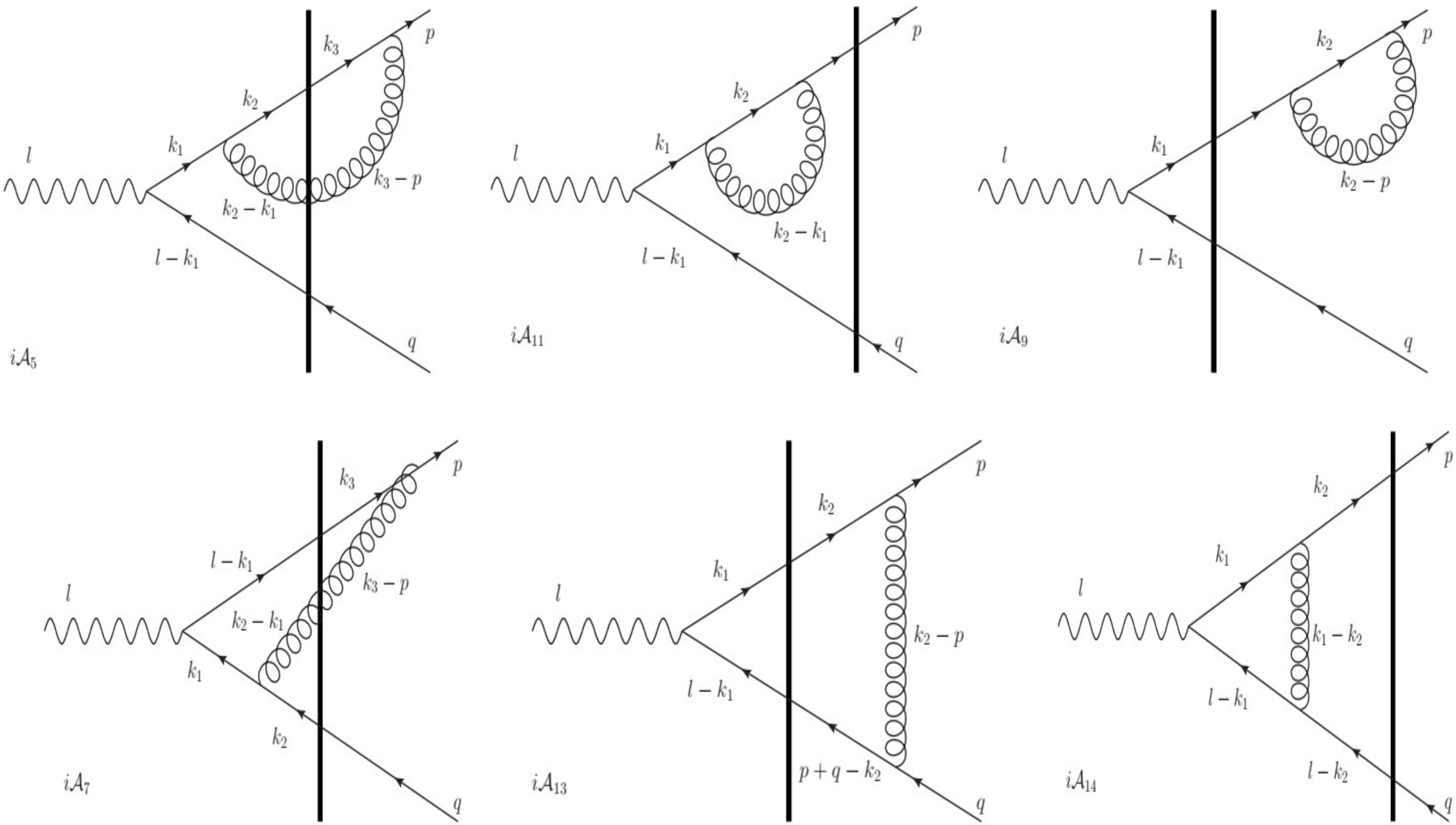
$$\mathrm{S}_{122'1'}\equiv\frac{1}{N_c}Tr\,V(\mathbf{x}_1)\,V^\dagger(\mathbf{x}_2)\,V(\mathbf{x}_{2'})\,V^\dagger(\mathbf{x}_{1'})$$

one loop corrections - real diagrams



3-parton production: Ayala, Hentschinski, JJM, Tejeda-Yeomans
PLB 761 (2016) 229 and NPB 920 (2017) 232

One loop corrections – virtual diagrams

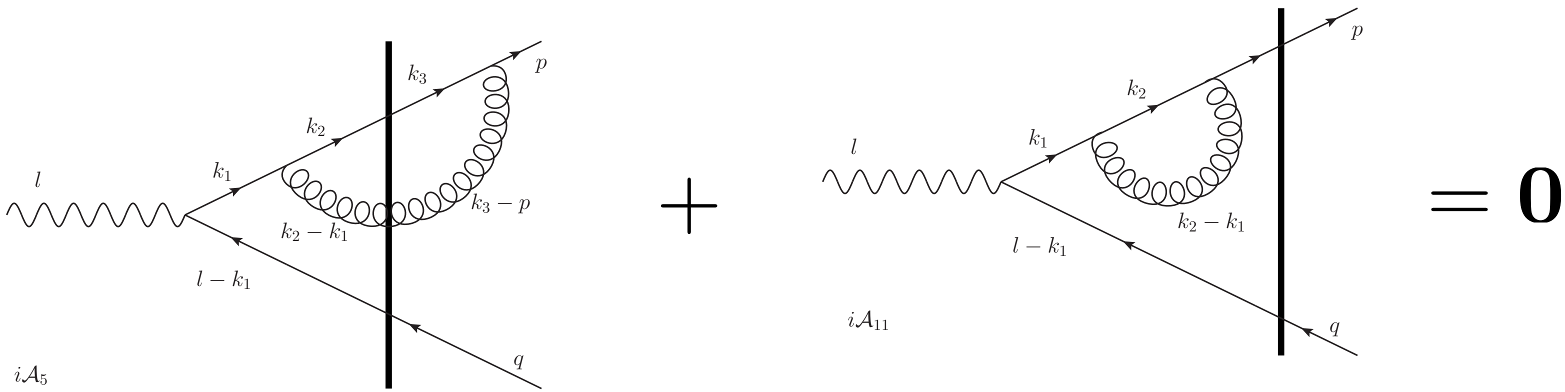


F. Bergabo and JJM, dihadrons, 2207.03606
P. Taels et al., dijets, 2204.11650
P. Caucal et al., dijets, 2108.06347

divergences

- ***Ultraviolet:***

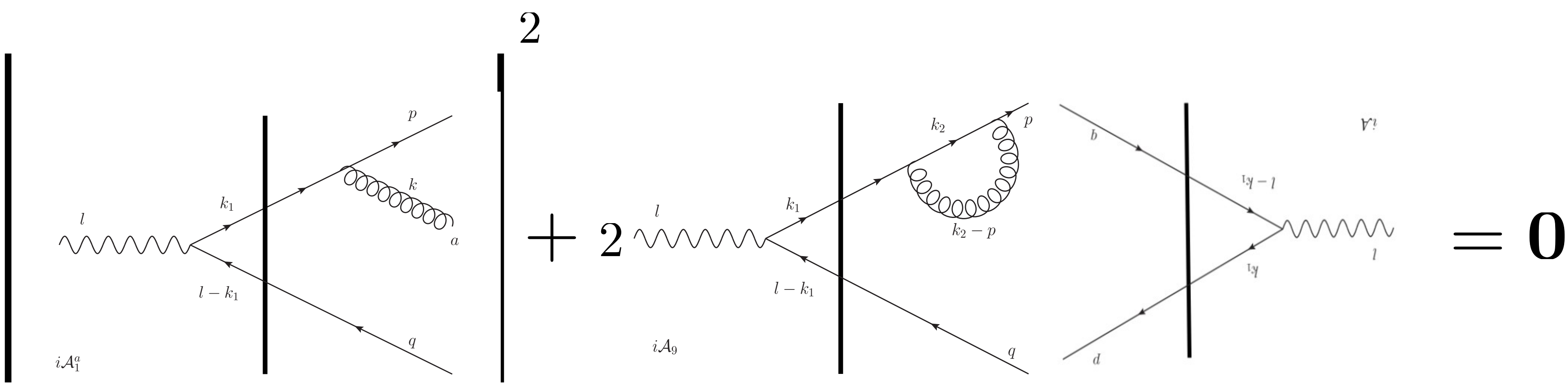
Real corrections are UV finite
UV divergences cancel among virtual corrections



divergences

- ***Soft:***

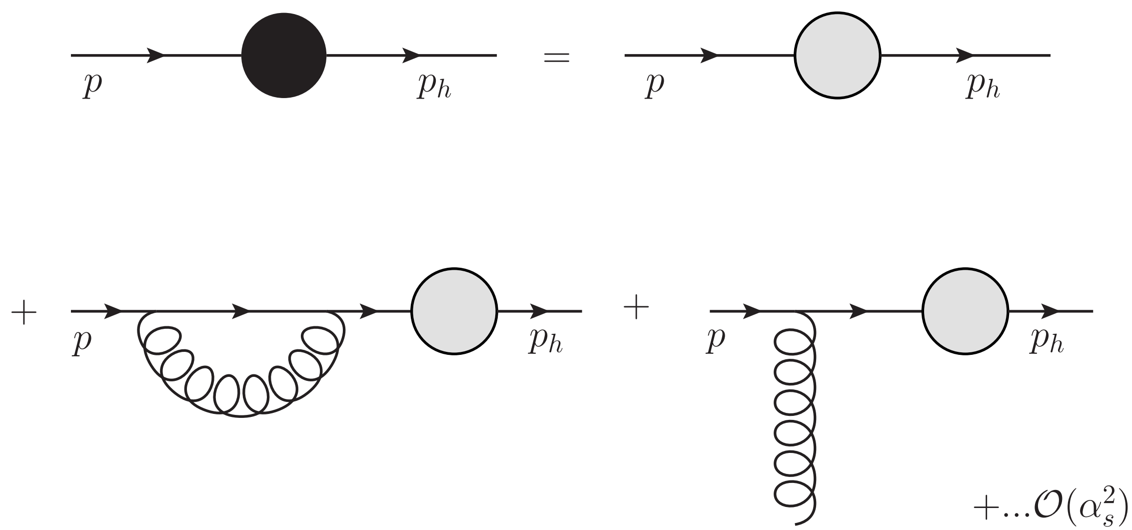
Soft divergences cancel between real and virtual corrections



divergences

- ***Collinear:***

Collinear divergences are absorbed into evolution of parton-hadron fragmentation functions



$$D_{h1/q}(z_{h1}, \mu^2) = \int_{z_{h1}}^{1} \frac{d\xi}{\xi} D^0_{h_1/q}\left(\frac{z_{h1}}{\xi}\right) \left[\delta(1-\xi) + \frac{\alpha_s}{2\pi} P_{qq}(\xi) \, \log\left(\frac{\mu^2}{\Lambda^2}\right)\right]$$

divergences

- ***Rapidity:***

Rapidity divergences are absorbed into JIMWLK evolution of dipoles and quadrupoles

$$\frac{d\sigma^L_{\rm NLO}}{d^2\mathbf{p}\, d^2\mathbf{q}\, dy_1\, y_2} = \frac{2e^2 g^2 Q^2 N_c^2 (z_1 z_2)^3}{(2\pi)^{10}}\, \delta(1 - z_1 - z_2) \int_0^{z_f} \frac{dz}{z} \int d^{10}\mathbf{x}\, K_0(|\mathbf{x}_{12}|Q_1) K_0(|\mathbf{x}_{1'2'}|Q_1)$$

$$e^{i\mathbf{p}\cdot\mathbf{x}_{1'1}} e^{i\mathbf{q}\cdot\mathbf{x}_{2'2}} \Big\{ \left(\tilde\Delta_{12} + \tilde\Delta_{22'} - \tilde\Delta_{12'}\right) S_{132'1'} S_{23} + \left(\tilde\Delta_{1'2'} + \tilde\Delta_{22'} - \tilde\Delta_{21'}\right) S_{1'321} S_{2'3}$$

$$+ \left(\tilde\Delta_{12} + \tilde\Delta_{11'} - \tilde\Delta_{21'}\right) S_{322'1'} S_{13} + \left(\tilde\Delta_{1'2'} + \tilde\Delta_{11'} - \tilde\Delta_{12'}\right) S_{32'21} S_{1'3}$$

$$- \left(\tilde\Delta_{11'} + \tilde\Delta_{22'} + \tilde\Delta_{12} + \tilde\Delta_{1'2'}\right) S_{122'1'} - \left(\tilde\Delta_{12} + \tilde\Delta_{1'2'} - \tilde\Delta_{12'} - \tilde\Delta_{21'}\right) S_{12} S_{1'2'}$$

$$- \left(\tilde\Delta_{11'} + \tilde\Delta_{22'} - \tilde\Delta_{12'} - \tilde\Delta_{21'}\right) S_{11'} S_{22'} - 2\tilde\Delta_{12} \left(S_{13} S_{23} - S_{12}\right) - 2\tilde\Delta_{1'2'} \left(S_{1'3} S_{2'3} - S_{1'2'}\right) \Big\}$$

JIMWLK evolution of quadrupoles

JIMWLK evolution of dipoles

Cancellation of divergences

- ***Ultraviolet:***

Real corrections are UV finite
UV divergences cancel among virtual corrections

- ***Soft:***

Soft divergences cancel between real and virtual corrections

- ***Colinear***

Collinear divergences are absorbed into hadron fragmentation functions

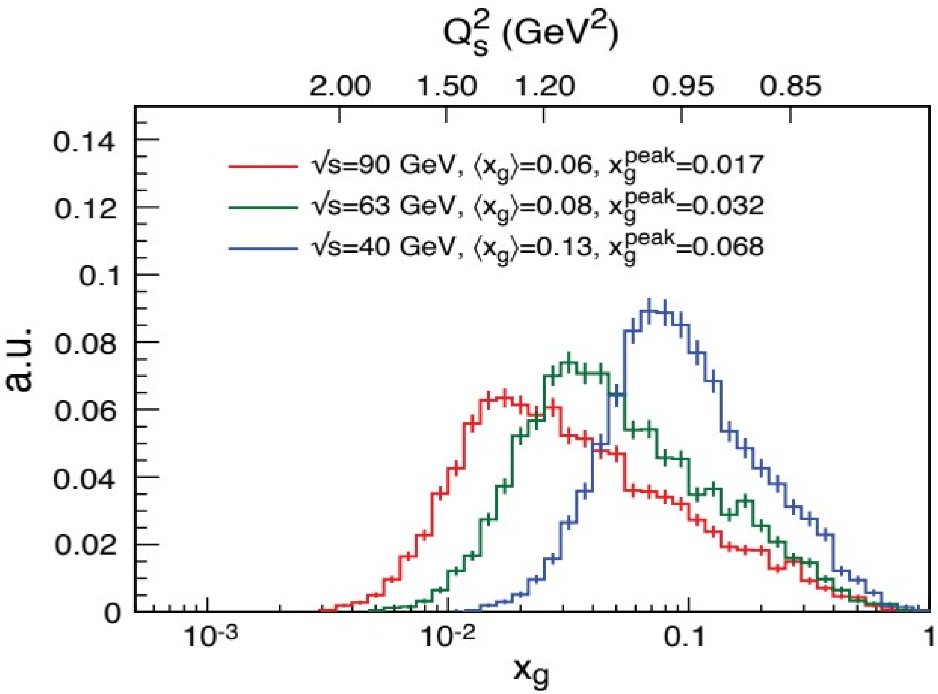
- ***Rapidity***

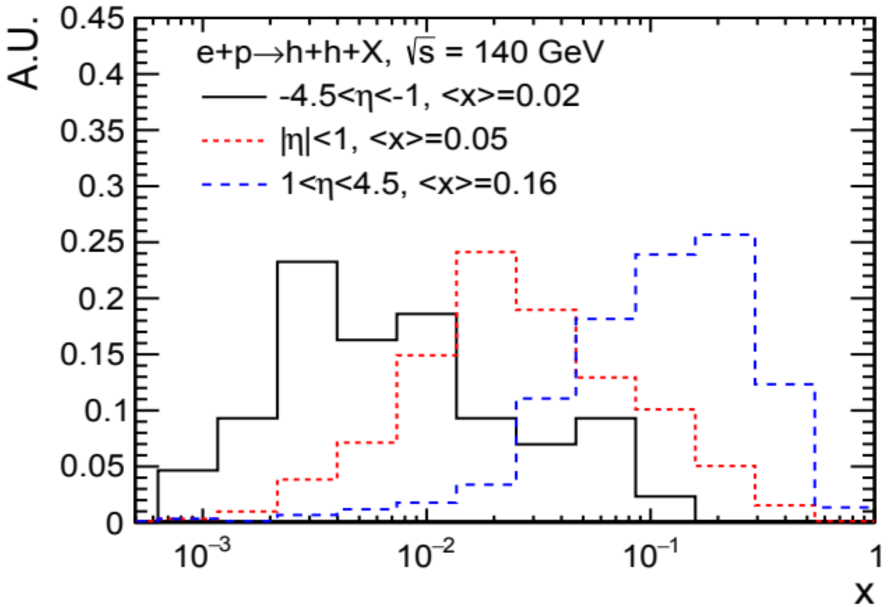
rapidity divergences are absorbed into JIMWLK evolution of dipoles, quadrupoles

$$\sigma^{\gamma^* A\to h_1 h_2 X} = \sigma_{LO} \otimes \mathrm{JIMWLK} + \sigma_{LO} \otimes D_{h_1/q}(z_1,\mu^2) D_{h_2/\bar{q}}(z_2,\mu^2) + \sigma_{NLO}^{\mathrm{finite}}$$

EIC

kinematics of double inclusive hadron production





Aschenauer et al. arXiv:1708.01527

Fig. courtesy of Xiaoxuan Chu

Talk by E. Aschenauer today

NLO corrections to single inclusive hadron production in DIS at small x

Larger kinematic phase space at EIC

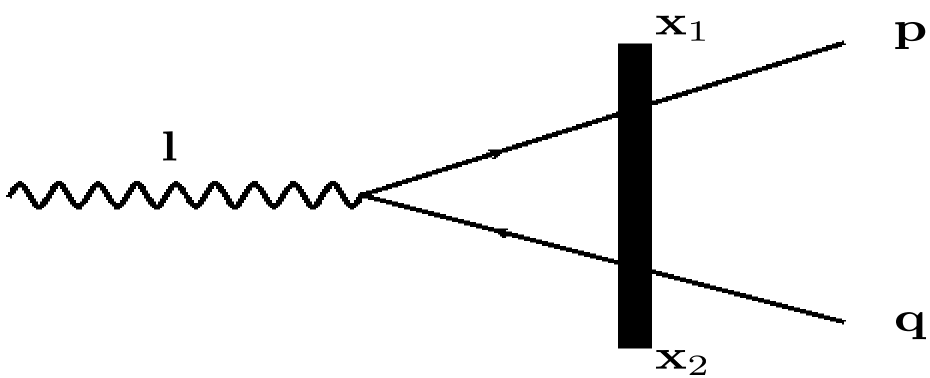
No Sudakov

Dipoles only

Forward rapidity: quark or antiquark production

F. Bergabo and JJM: arXiv:2210.03208

LO: antiquark production in DIS at small x



integrate out quark

$$\frac{d\sigma^{\gamma^* A\to \bar{q}X}}{d^2\mathbf{q}\,dy_2} = \frac{e^2 Q^2 z_2^2(1-z_2)N_c}{(2\pi)^5}\int d^6\mathbf{x}\,[S_{22'} - S_{12} - S_{12'} + 1]$$

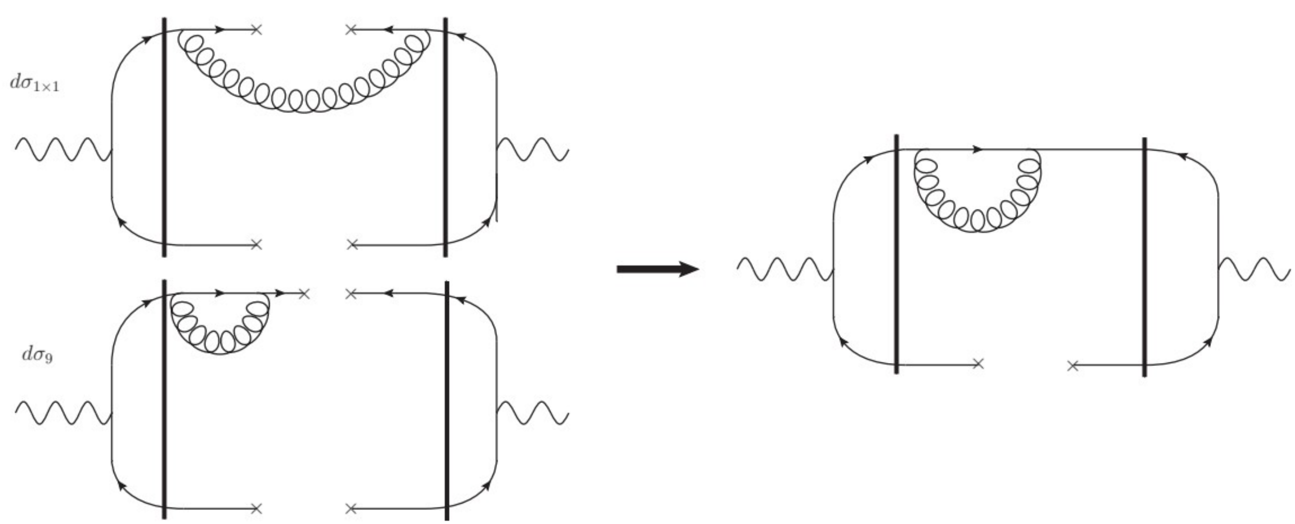
$$e^{i\mathbf{q}\cdot(\mathbf{x}_2' - \mathbf{x}_2)}\Big[4z_2(1-z_2)K_0(|\mathbf{x}_{12}|Q_2)K_0(|\mathbf{x}_{12'}|Q_2) +$$

$$\left[z_2^2 + (1-z_2)^2\right]\,\frac{\mathbf{x}_{12}\cdot\mathbf{x}_{12'}}{|\mathbf{x}_{12}||\mathbf{x}_{12'}|}\,K_1(|\mathbf{x}_{12}|Q_2)K_1(|\mathbf{x}_{12'}|Q_2)\Big]$$

NLO corrections to single inclusive hadron production in DIS at small x

start with NLO corrections to dihadron production and integrate out quark

cancellations among diagrams



NLO corrections to single inclusive hadron production in DIS at small x

all terms with quadrupoles cancel; only dipoles contribute to the cross section

cancellations of divergences as before

$$\sigma^{\gamma^* A \to hX} = \sigma_{LO} \otimes \text{JIMWLK} + \sigma_{LO} \otimes D_{h/\bar{q}}(z_h, \mu^2) + \sigma_{NLO}^{\text{finite}}$$

phenomenology: need to consider hadronization of any of the 3 partons

relation to TMD,...

SUMMARY

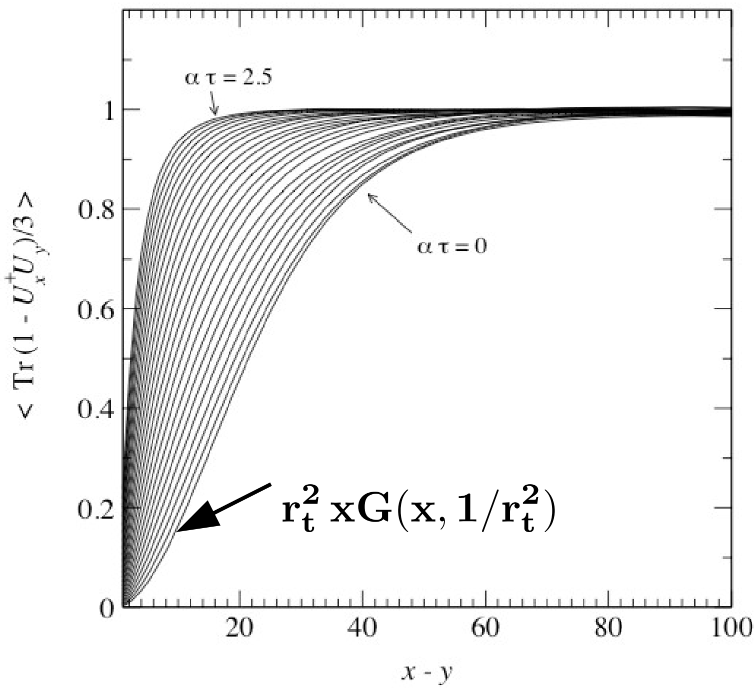
CGC is a systematic approach to high energy collisions

- ***strong hints from RHIC, LHC,...***
- ***to be probed extensively at EIC***
- ***toward precision: NLO, sub-eikonal corrections, ...***
  - ***structure functions***
  - ***SIDIS***
  - ***dihadron/dijet production***

Dipoles at large N_c : BK equation

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

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



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