Single and double inclusive hadron production in Ultra-Peripheral Collisions:

NLO corrections

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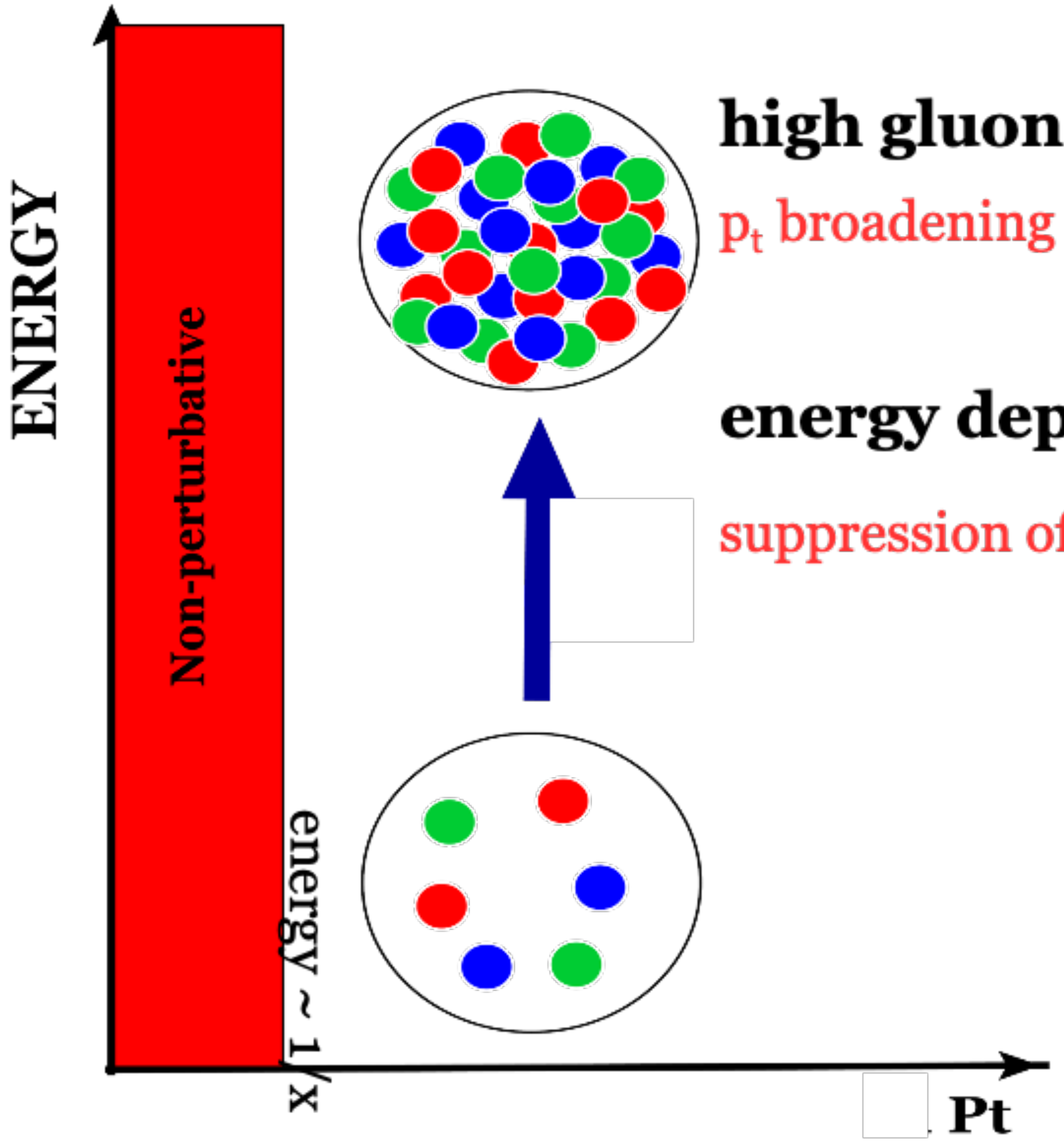
QCD at high energy: gluon saturation



high gluon density: Eikonal multiple scattering

p_t broadening

energy dependence: x-evolution via JIMWLK/BK

suppression of spectra/away side peaks

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

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

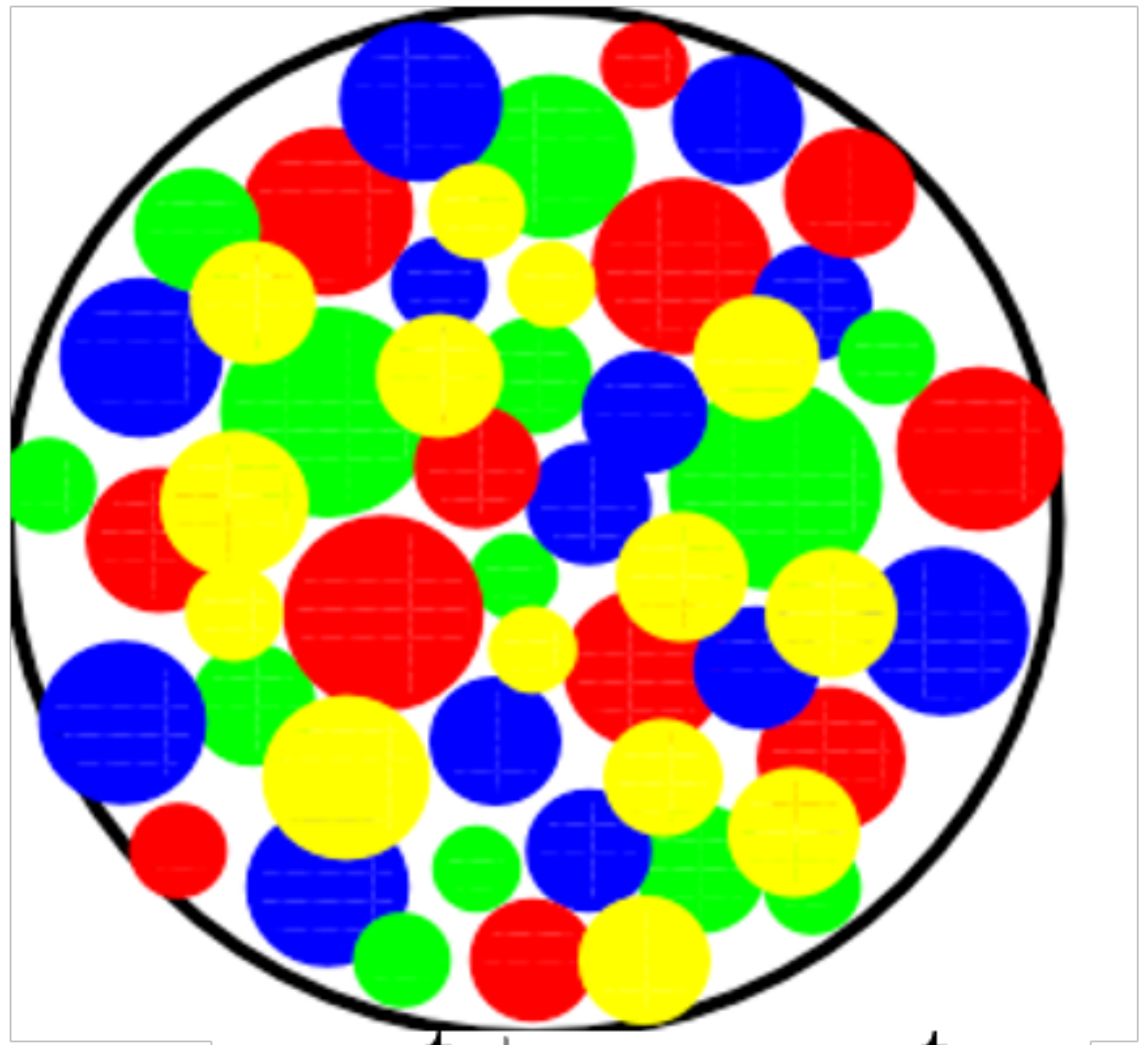
for a proton target (quarks)

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

Shadowing/Nuclear modification factor
Azimuthal angular correlations (dihadrons/dijets,...)
Long range rapidity correlations (ridge,...)
Connections to TMDs,...

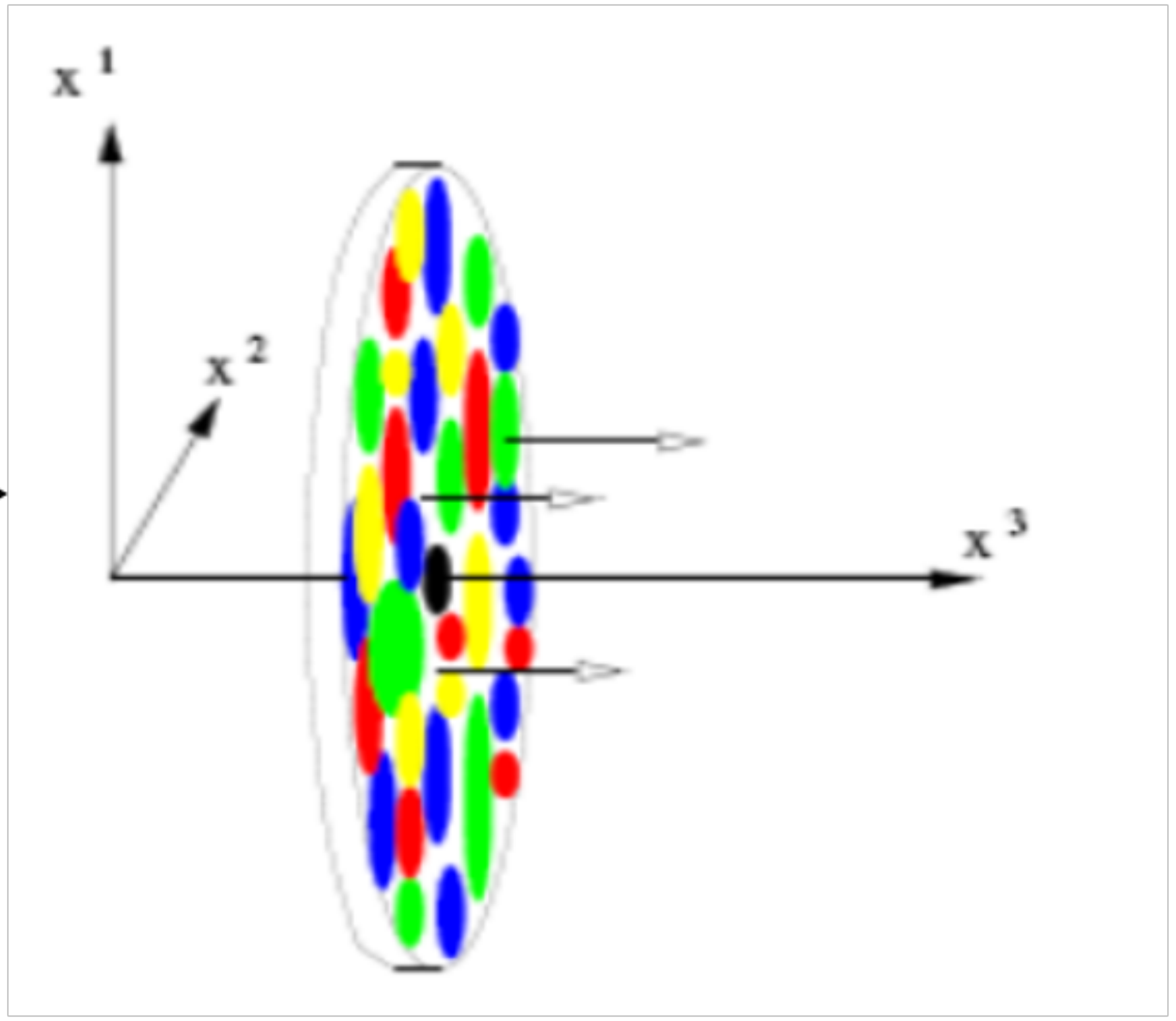
$$\mathbf{x \leq 0.01}$$

A very large nucleus at high energy: MV model

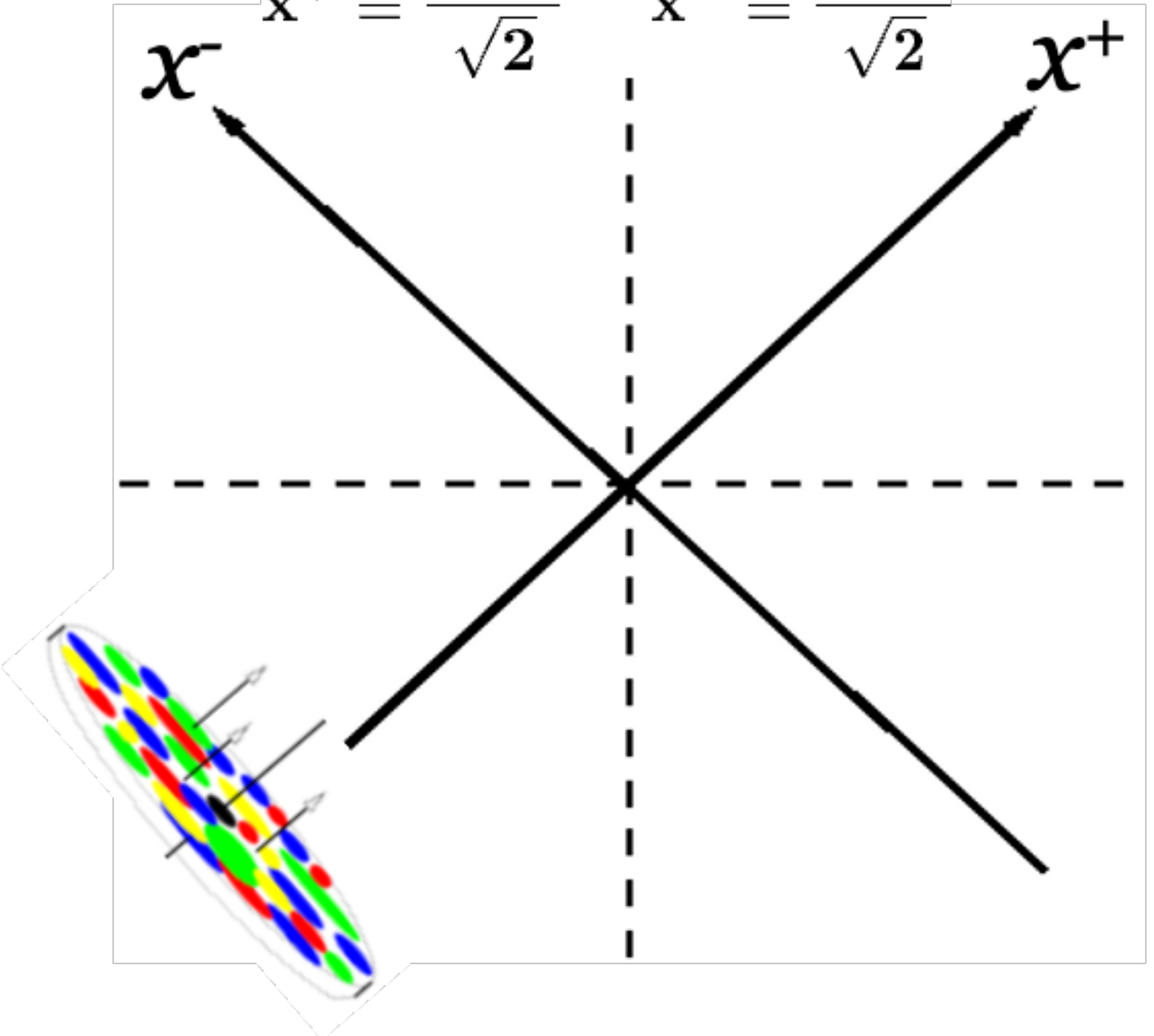


boost

R	$\rightarrow$	$\frac{R}{\gamma}$	
γ	$\sim$	100	RHIC
γ	$\sim$	2500	LHC



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



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

$$\boxed{\mathbf{J^\mu_a(x) \equiv \delta^{\mu\,+}\,\delta(x^-)\,\rho_a(x_t)}}$$

color current *color charge*

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

with $\partial_i\,\alpha^a_i = g\,\rho^a$

Dense proton/nucleus: multiple eikonal scatterings

sum over all scatterings $$i\mathcal{M} = \sum_n i\,\mathcal{M}_n$$

$$i\mathcal{M}(p,q) = 2\pi\delta(p^+ - q^+)\,\bar{u}(q)\,\not{n}\int d^2x_t\, e^{-i(q_t-p_t)\cdot x_t}\,\left[V(x_t) - 1\right]\,u(p)$$

with

$$V(x_t) \equiv \hat{P}\,\exp\left\{ig\int_{-\infty}^{+\infty} dx^+\, n^-\, S_a(x^+, x_t)\, t_a\right\}$$

Wilson lines: effective degrees of freedom that contain all the target information

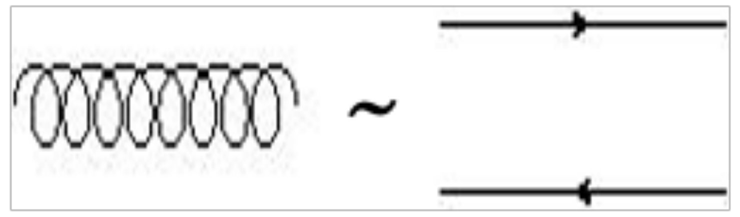
$$\frac{d\,\sigma^{q\,T\to q\,X}}{d^2p_t\,dy} \sim |i\mathcal{M}|^2 \sim F.T. < Tr\,V(x_t)\,V^\dagger(y_t) >$$

dipole

One-loop corrections: BK-JIMWLK eq.

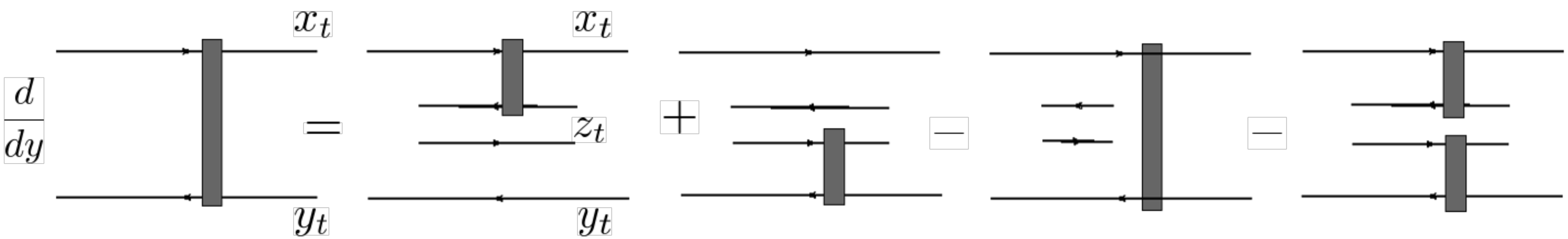
at large N_c

$3 \otimes \bar{3} = 8 \oplus 1 \simeq 8$



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

$$T \equiv 1 - S$$



$$\tilde{T}(p_t) \sim \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right] \qquad Q_s^2 \ll p_t^2$$

$$\tilde{T}(p_t) \sim \log\left[\frac{Q_s^2}{p_t^2}\right] \qquad Q_s^2 \gg p_t^2$$

$$\tilde{T}(p_t) \sim \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right]^{\gamma} \qquad Q_s^2 < p_t^2$$

nuclear modification factor

$$R_{pA} \equiv \frac{\frac{d\sigma^{pA}}{d^2 p_t \, dy}}{A^{1/3}\,\frac{d\sigma^{pp}}{d^2 p_t \, dy}}$$

nuclear shadowing

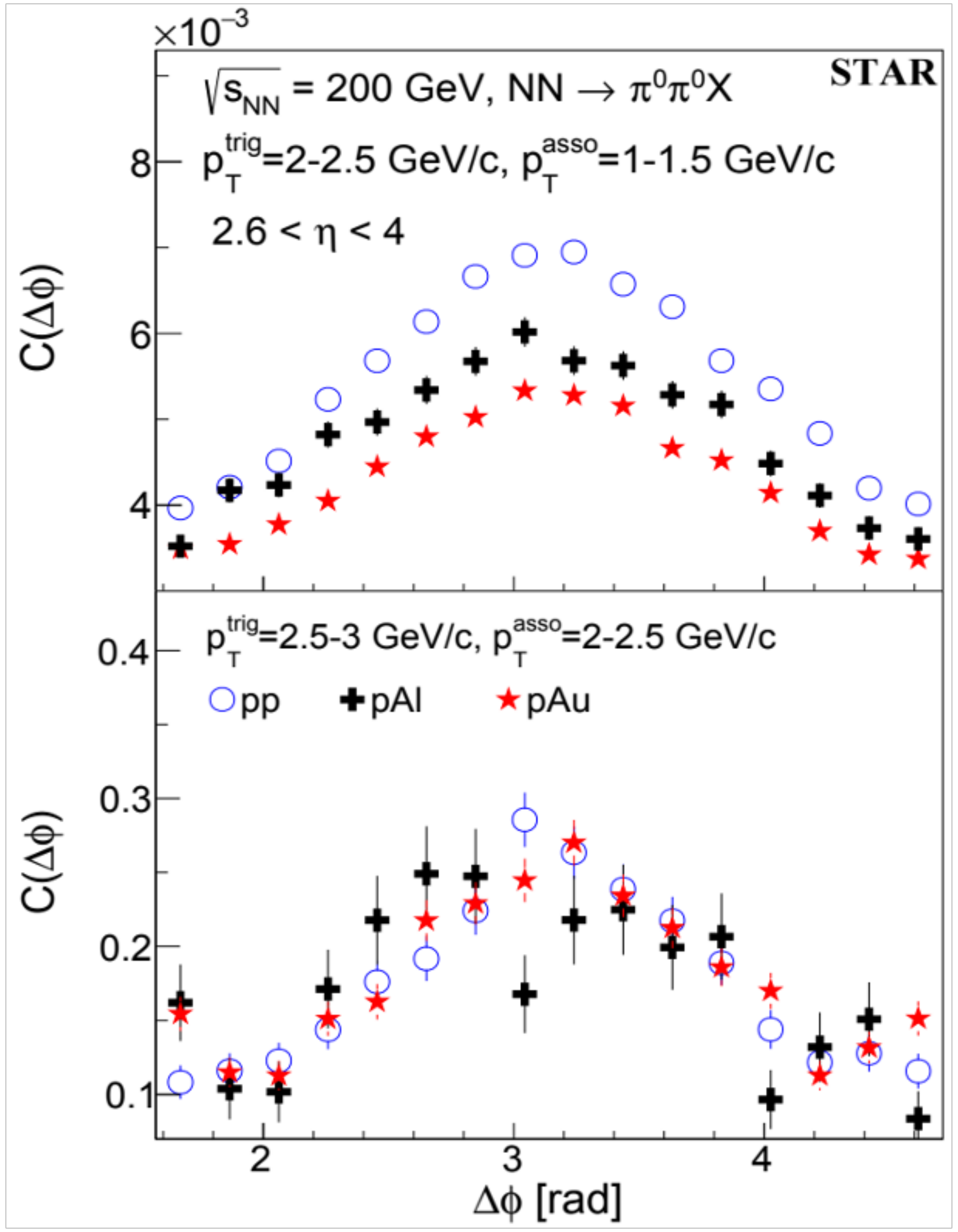
suppression of p_t spectra

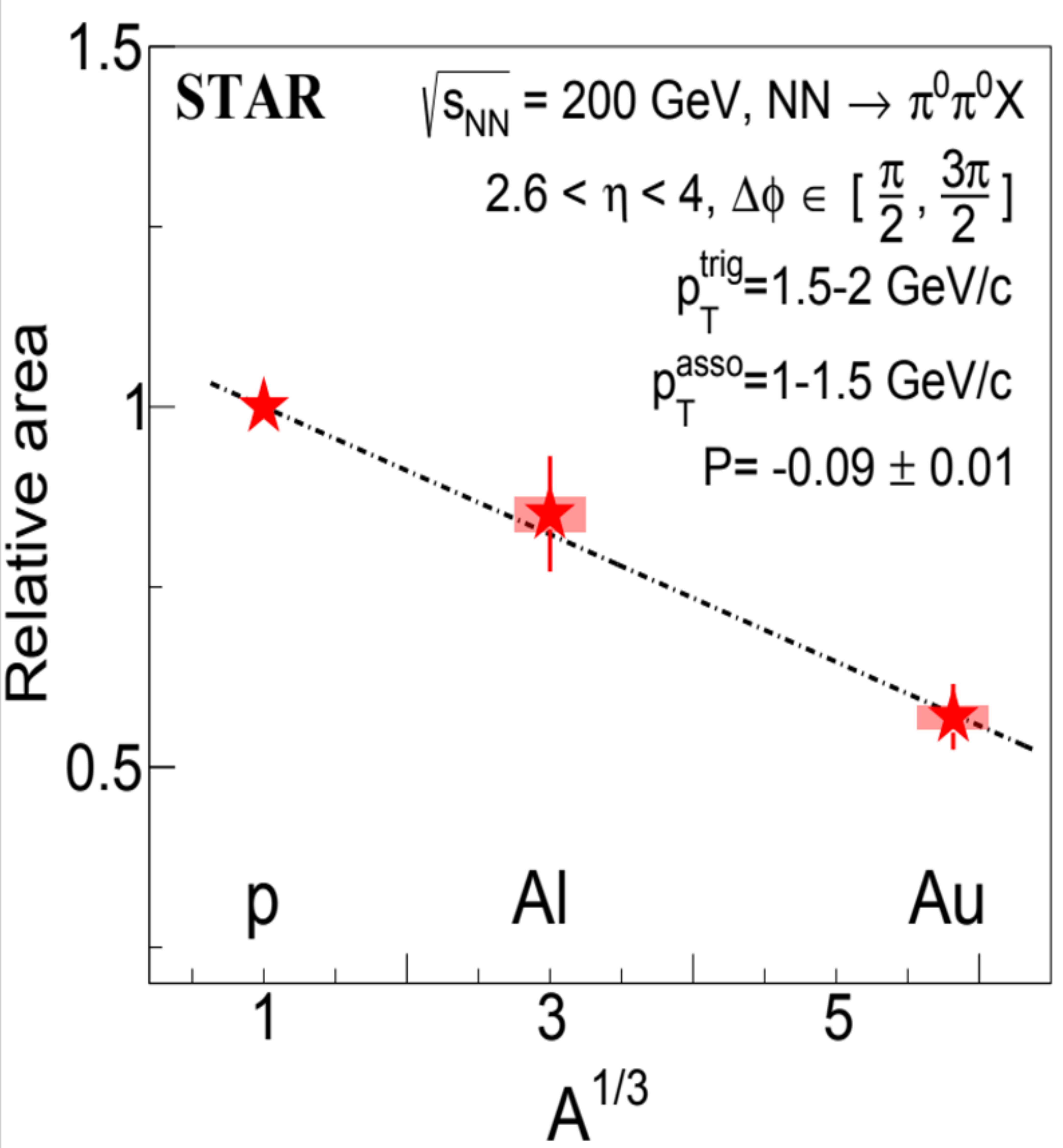
disappearance of back to back peaks

....

Back to back hadron production in pA collisions: forward rapidity

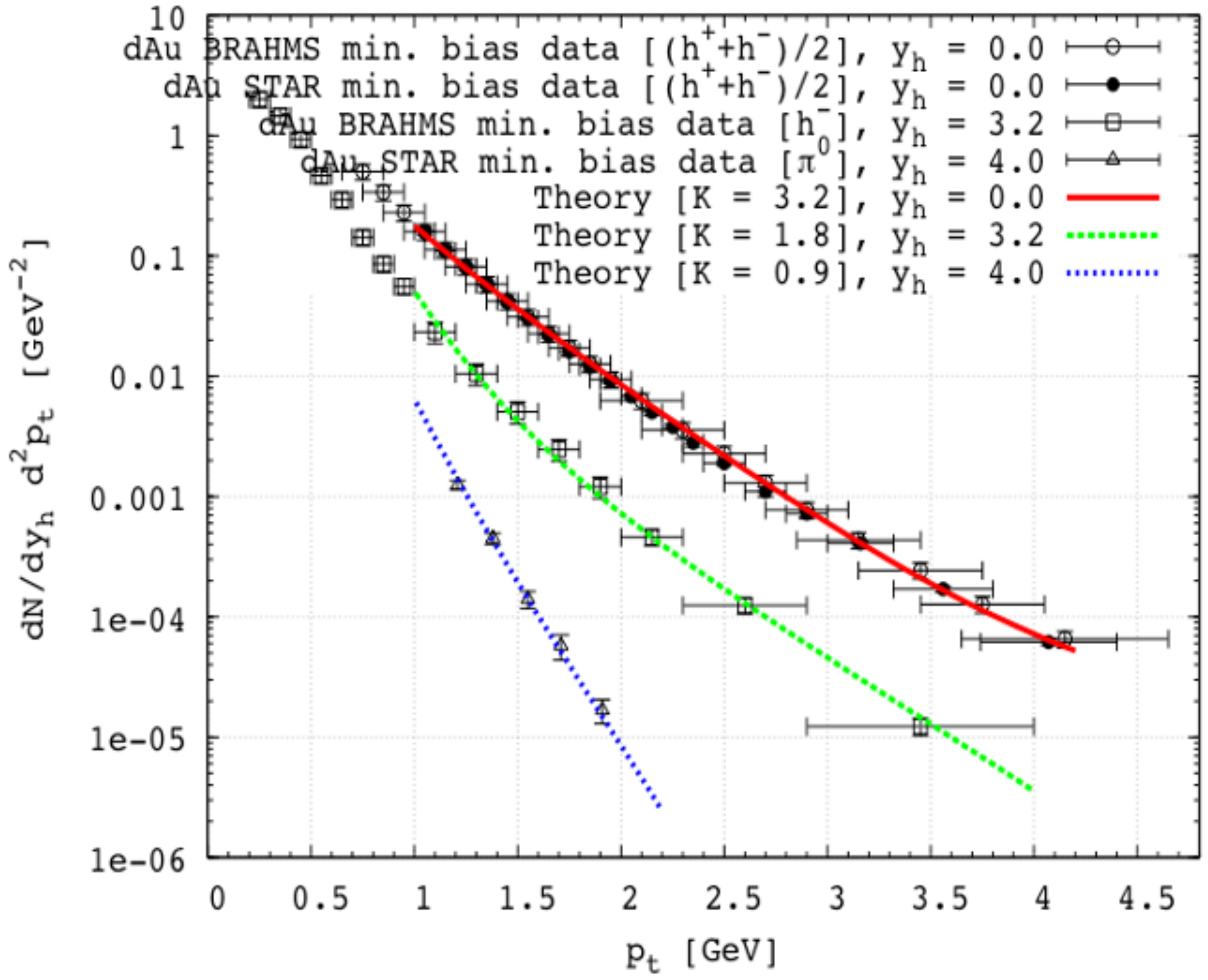
STAR collaboration(2021)
arXiv:2111.10396



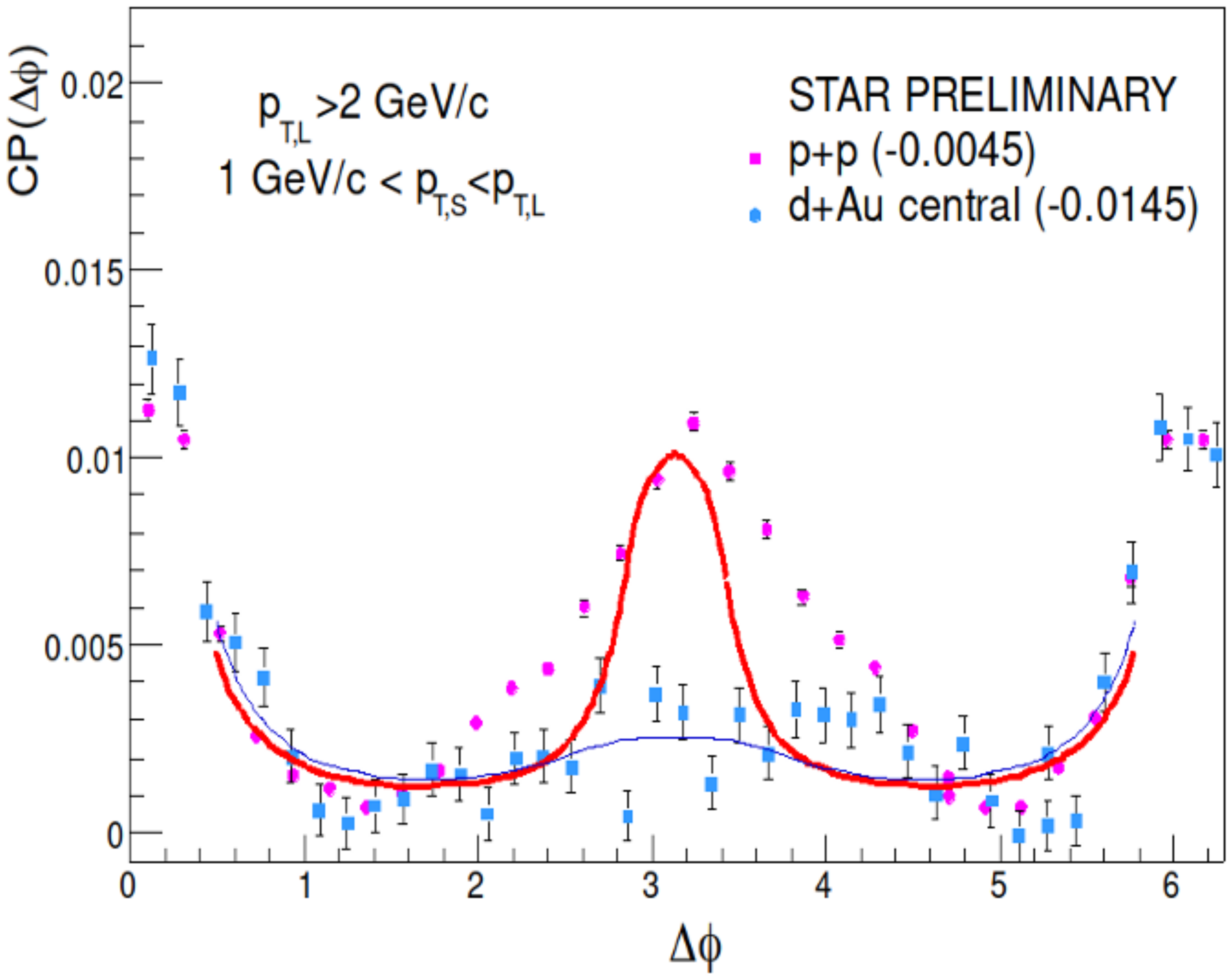


CGC at RHIC

Single and double inclusive hadron production in dA collisions



Dumitru,Hayashigaki, JJM, NPA770 (2006) 57



Albacete, Marquet, PRL105 (2010) 162301

Toward precision CGC: inclusive DIS

NLO BK/JIMWLK evolution equations

Kovner, Lublinsky, Mulian (2013)

Balitsky, Chirilli (2007)

NLO corrections to structure functions

Beuf, Lappi, Paatelainen (2022)

Beuf (2017)

NLO corrections to SIDIS

Bergabo, JJM (2023)

NLO corrections to dihadron/dijets

Bergabo, JJM (2022, 2023)

Iancu, Mulian (2023)

Caucal, Salazar, Schenke, Stebel, Venugopalan (2023)

Caucal, Salazar, Schenke, Venugopalan (2022)

Taels, Altinoluk, Beuf, Marquet (2022)

Caucal, Salazar, Venugopalan (2021)

Ayala, Hentschinski, JJM, Tejeda-Yeomans (2016-2017)

Toward precision CGC: diffractive/exclusive DIS

NLO corrections to diffractive structure functions:

Beuf, Hanninen, Lappi, Mulian, Mantysaari (2022)

……………….

NLO corrections to diffractive dijet (+) production:

Boussarie, Grabovsky, Szymanowski, Wallon (2016)

Iancu, Mueller, Triantafyllopoulos (2021, 2022)

…………….

NLO corrections to exclusive light/heavy vector meson production:

Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon (2016)

Mantysaari, Penttala (2021, 2022)

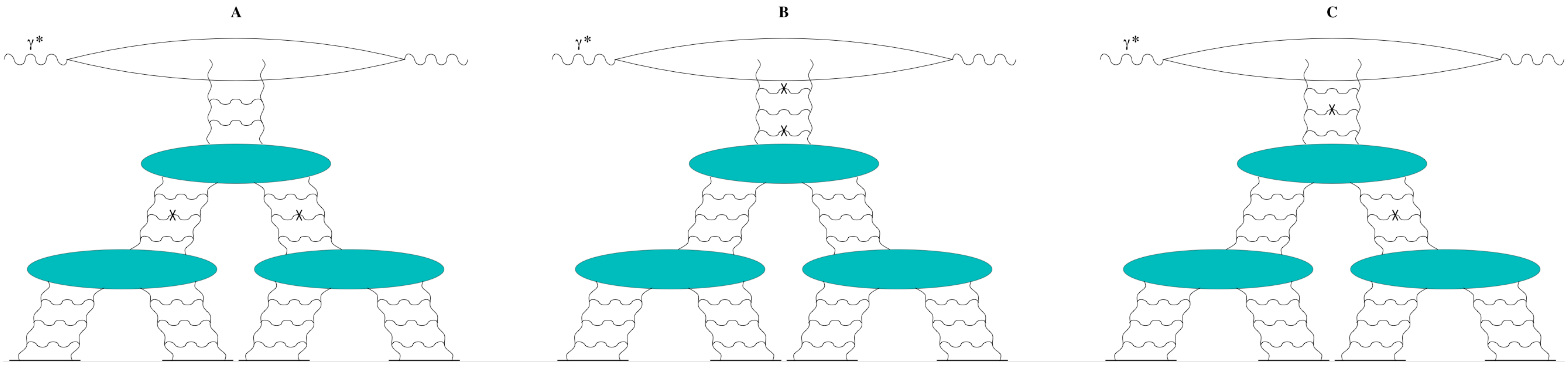
………….

Inclusive dihadron production in DIS at small x:

central vs forward rapidity

Inclusive dihadron production in midrapidity: LO

JJM, Yu. Kovchegov
PRD70 (2004) 114017



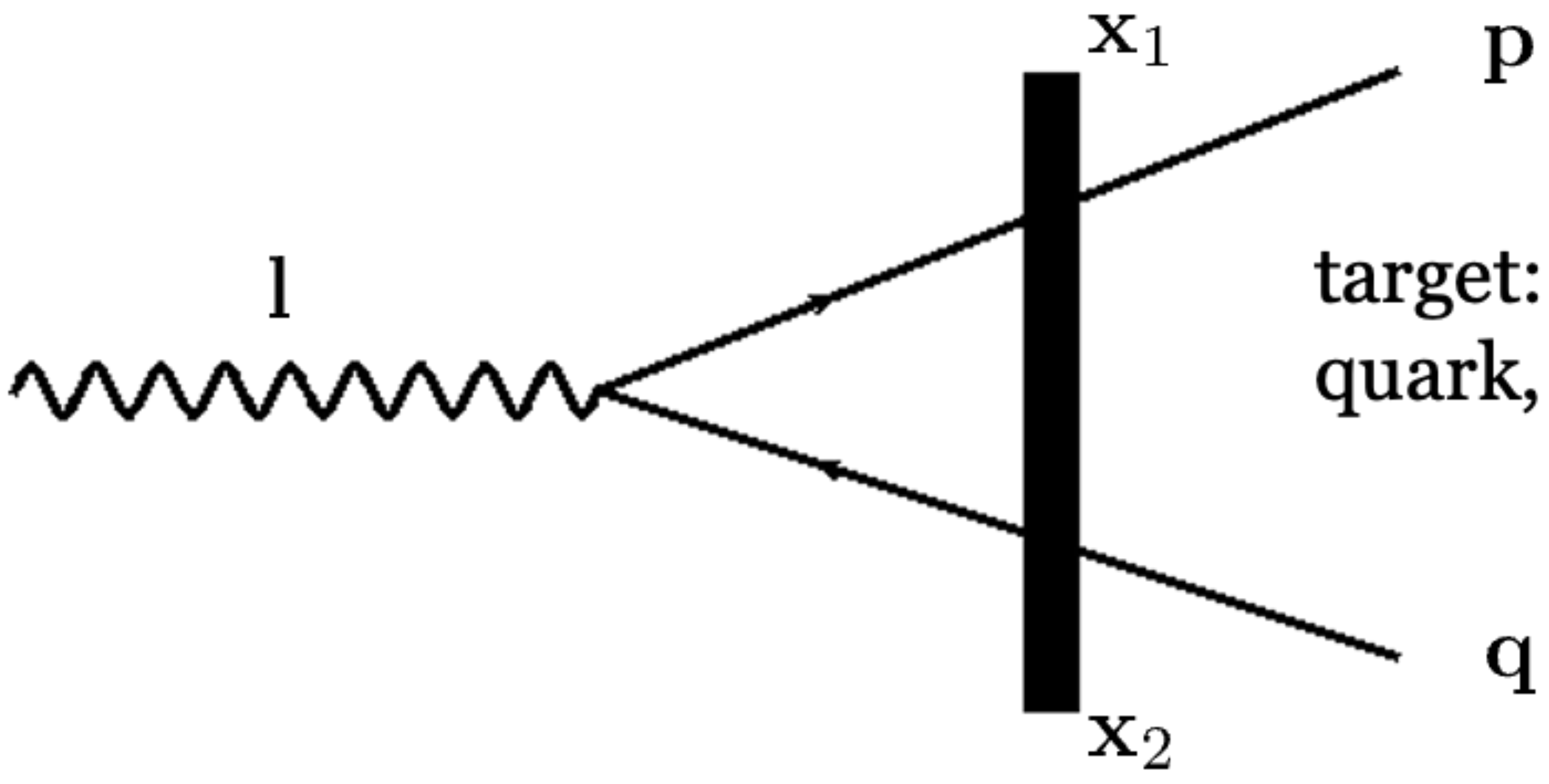
need a very large rapidity window

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

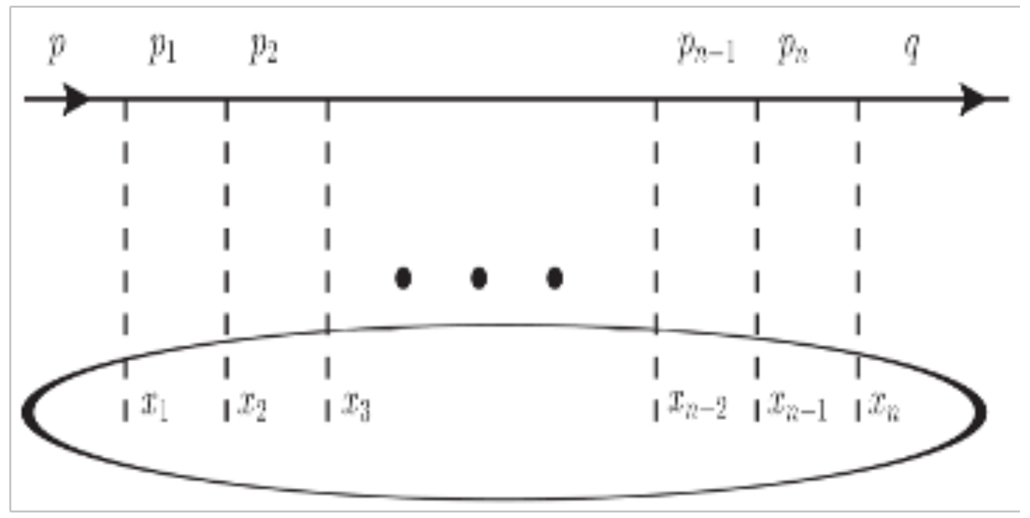
scatterings of gluons on the target encoded in Wilson lines $\mathbf{U}\ (\mathbf{x}_1), U^\dagger(\mathbf{x}_2)$

leading log evolution included

Inclusive dihadron production in <u>forward rapidity</u>: LO



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



$$\frac{d\sigma^{\gamma^* A\to q\bar{q}X}}{d^2p\, d^2q\, dy_1\, dy_2} = \frac{e^2Q^2(z_1z_2)^2N_c}{(2\pi)^7}\delta(1-z_1-z_2)$$

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

with

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

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

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

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

quadrupole

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

Only dipoles and quadrupoles contribute: DMXY, PRD 83 (2011) 105005

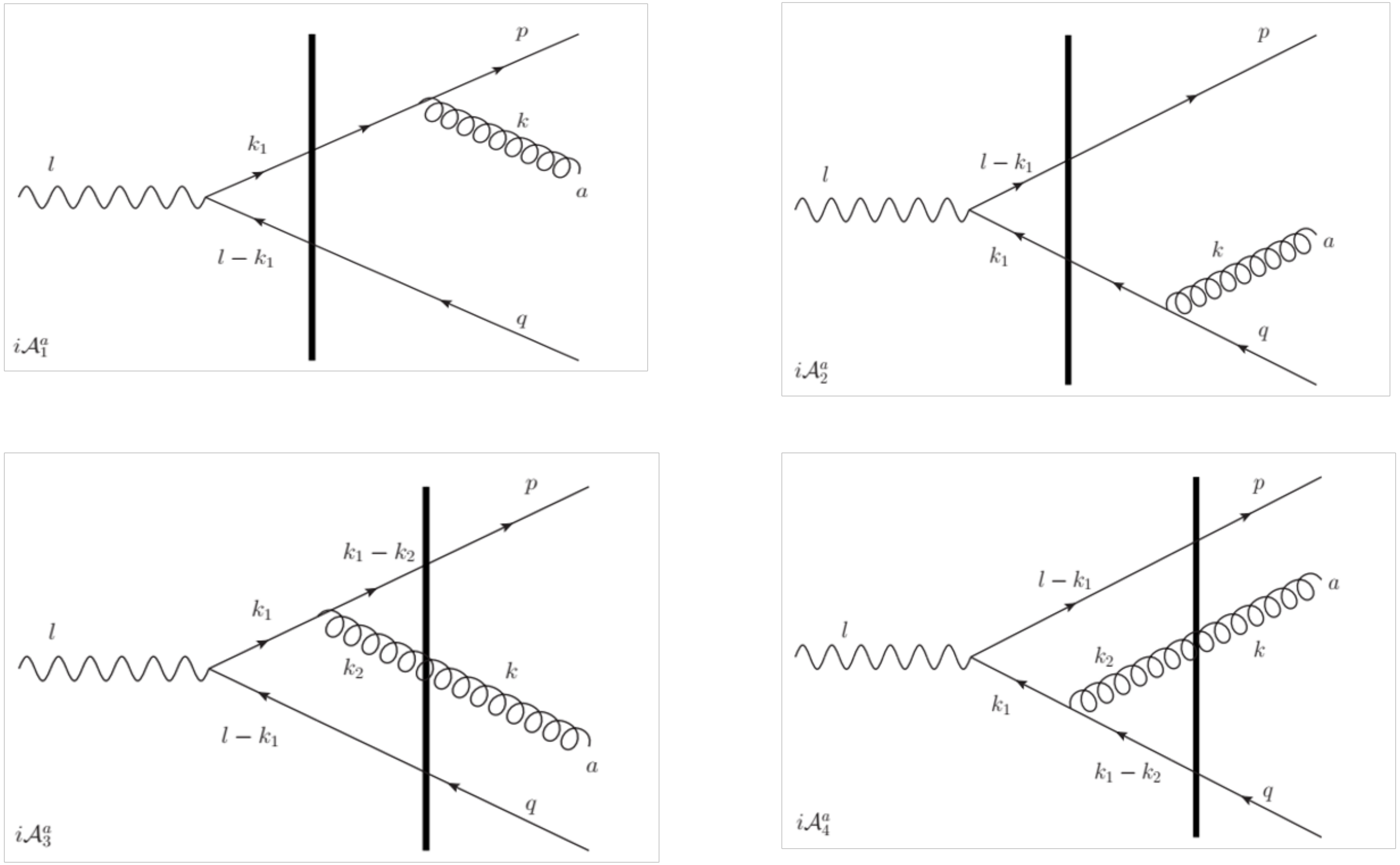
Toward precision: NLO corrections to inclusive observables in DIS at small x

Based on F. Bergabo and JJM:

PRD 107 (2023) 5, 054036 (dihadrons: transverse photon)
JHEP 01 (2023) 095 (single inclusive hadrons: longitudinal photon)
PRD 106 (2022) 5, 054035 (dihadrons: longitudinal photon)
NPA 1018 (2022) 122358 (coherent e-loss in dihadron production)

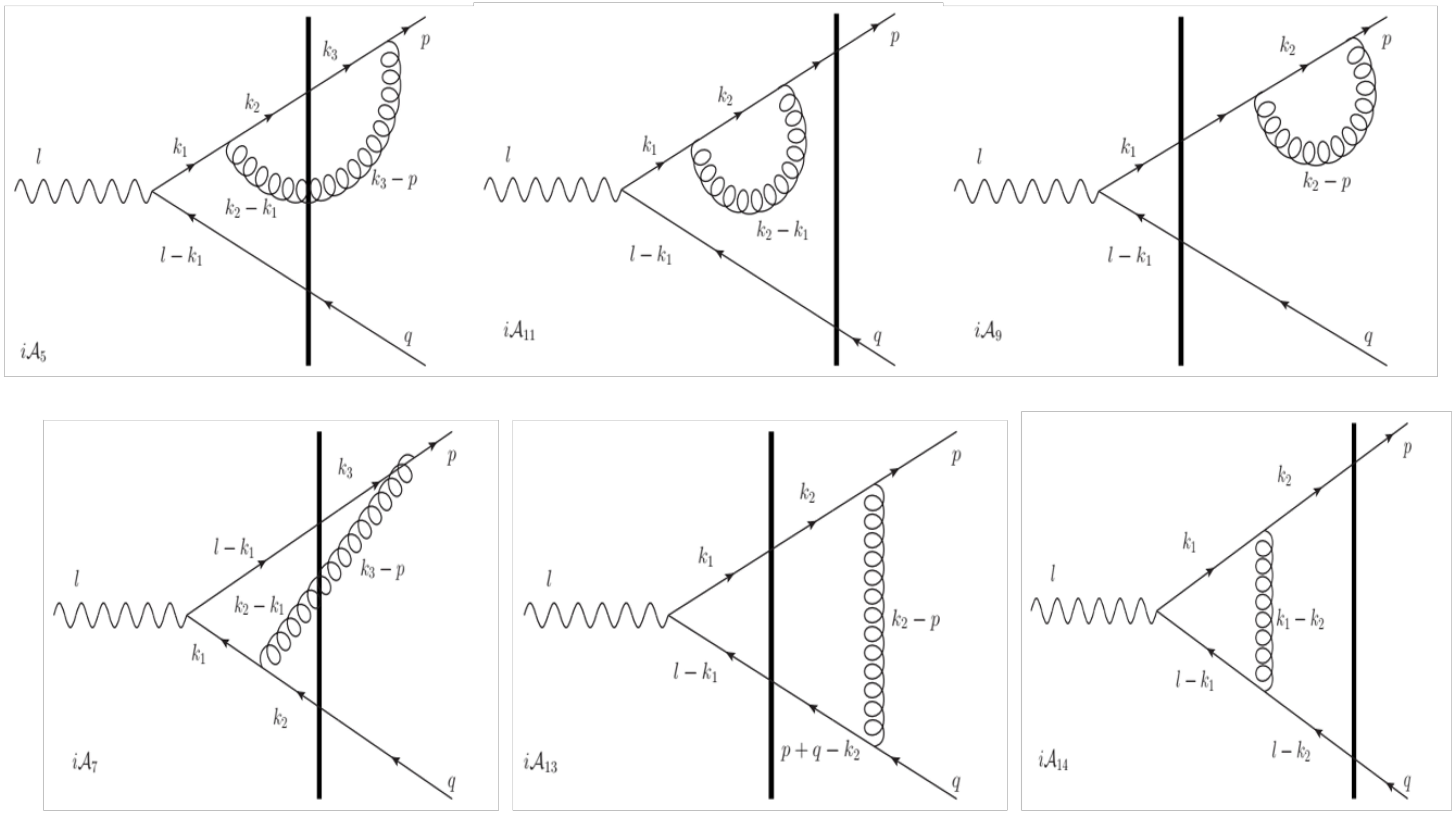
and work in progress (JJM)

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

Spinor helicity formalism: helicity amplitudes

Numerator	$\lambda_\gamma; \lambda_q, \lambda_g$	$N_i^{\lambda_\gamma;\lambda_q,\lambda_g}$
	$L;+,+$	$-Q(z_1z_2)^{3/2}(1-z_2)\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}$
	$L;+,-$	$-Q(z_2)^{3/2}\sqrt{z_1}(1-z_2)^2\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}$
N_1	$+;+,+$	$-(z_1)^{3/2}\sqrt{z_2}(1-z_2)\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+;+,-$	$-\sqrt{z_1z_2}(1-z_2)^2\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon^*]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+;-,+$	$(z_2)^{3/2}\sqrt{z_1}(1-z_2)\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+,-,-$	$(z_1z_2)^{3/2}\frac{[(z_1\mathbf{k}-z_3\mathbf{p})\cdot\epsilon^*]}{(z_1\mathbf{k}-z_3\mathbf{p})^2}(\mathbf{k}_1\cdot\epsilon)$
	$L;+,+$	$Q(z_1)^{3/2}\sqrt{z_2}(1-z_1)^2\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}$
	$L;+,-$	$Q(z_1z_2)^{3/2}(1-z_1)\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon^*]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}$
N_2	$+;+,+$	$-(z_1)^{3/2}\sqrt{z_2}(1-z_1)\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+;+,-$	$-(z_1z_2)^{3/2}\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon^*]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+;-,+$	$(z_2)^{3/2}\sqrt{z_1}(1-z_1)\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}(\mathbf{k}_1\cdot\epsilon)$
	$+,-,-$	$\sqrt{z_1z_2}(1-z_1)^2\frac{[(z_2\mathbf{k}-z_3\mathbf{q})\cdot\epsilon^*]}{(z_2\mathbf{k}-z_3\mathbf{q})^2}(\mathbf{k}_1\cdot\epsilon)$
	$L;+,+$	$Q(z_1z_2)^{3/2}(1-z_2)\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_2}\right)$
	$L;+,-$	$Q(z_2)^{3/2}\sqrt{z_1}(1-z_2)^2\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{1-z_2}\right)$
N_3	$+;+,+$	$(z_1)^{3/2}\sqrt{z_2}(1-z_2)\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_2}\right)\mathbf{k}_1\cdot\epsilon$
	$+;+,-$	$\sqrt{z_1z_2}(1-z_2)^2\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{1-z_2}\right)\mathbf{k}_1\cdot\epsilon$
	$+;-,+$	$-(z_2)^{3/2}\sqrt{z_1}(1-z_2)\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_2}\right)\mathbf{k}_1\cdot\epsilon$
	$+,-,-$	$-(z_1z_2)^{3/2}\left[\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{(1-z_2)}\right)\mathbf{k}_1\cdot\epsilon+\frac{\mathbf{k}_1^2+z_2(1-z_2)Q^2}{2z_2(1-z_2)}\right]$
	$L;+,+$	$-Q(z_1)^{3/2}\sqrt{z_2}(1-z_1)^2\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_1}\right)$
	$L;+,-$	$-Q(z_1z_2)^{3/2}(1-z_1)\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{1-z_1}\right)$
N_4	$+;+,+$	$(z_1)^{3/2}\sqrt{z_2}(1-z_1)\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_1}\right)\mathbf{k}_1\cdot\epsilon$
	$+;+,-$	$(z_1z_2)^{3/2}\left[\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{(1-z_1)}\right)\mathbf{k}_1\cdot\epsilon+\frac{\mathbf{k}_1^2+z_1(1-z_1)Q^2}{2z_1(1-z_1)}\right]$
	$+;-,+$	$-(z_2)^{3/2}\sqrt{z_1}(1-z_1)\left(\frac{\mathbf{k}_2\cdot\epsilon}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon}{1-z_1}\right)\mathbf{k}_1\cdot\epsilon$
	$+,-,-$	$-\sqrt{z_1z_2}(1-z_1)^2\left(\frac{\mathbf{k}_2\cdot\epsilon^*}{z_3}-\frac{\mathbf{k}_1\cdot\epsilon^*}{1-z_1}\right)\mathbf{k}_1\cdot\epsilon$

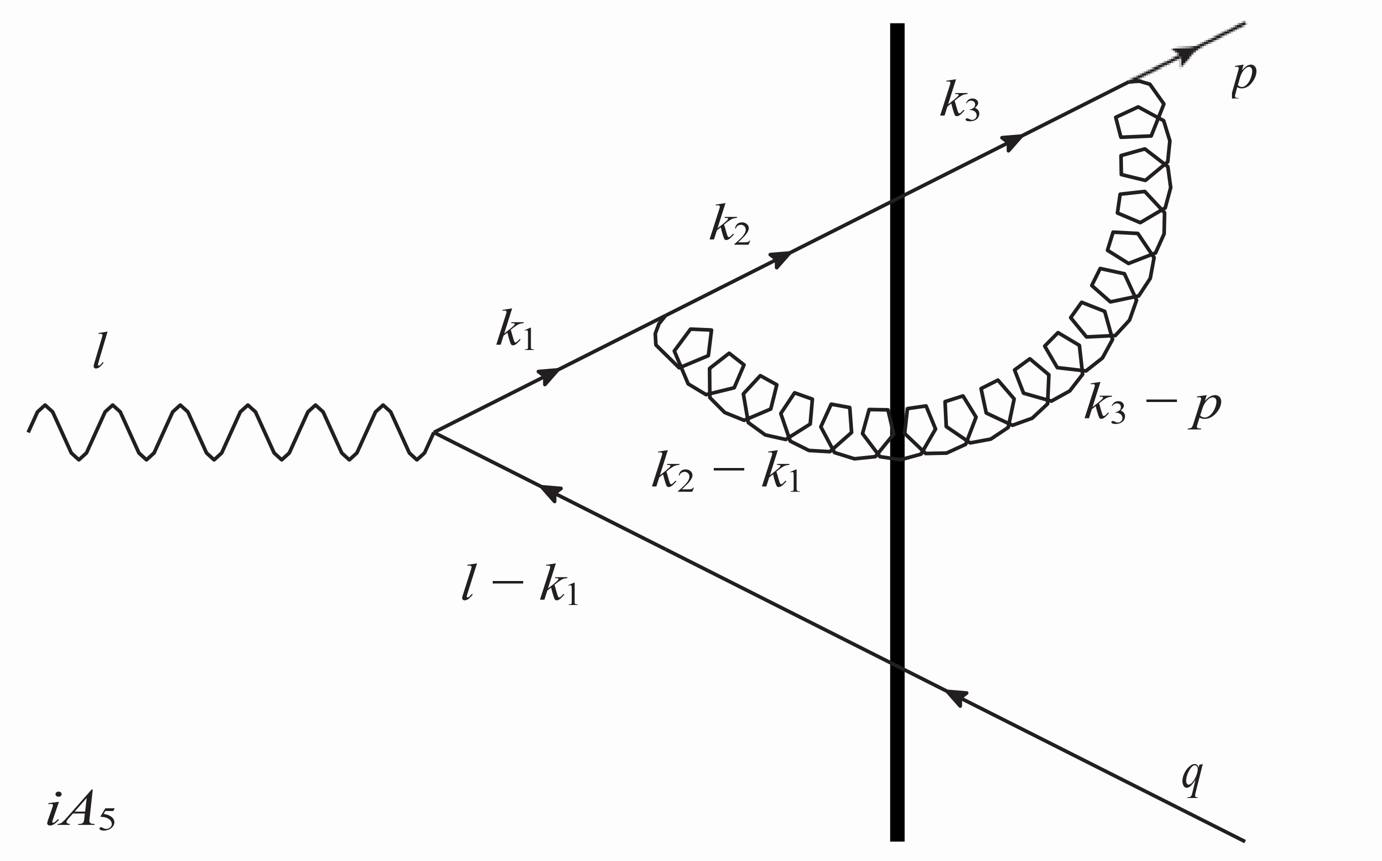
divergences

- ***Ultraviolet:***

Real corrections are UV finite

UV divergences cancel among virtual corrections $\mathbf{k} \to \infty$ **or** $\mathbf{x_3} \to \mathbf{x_i}$

$$\left(d\sigma_5 + d\sigma_{11}\right)_{UV} = 0$$
$$\left(d\sigma_6 + d\sigma_{12}\right)_{UV} = 0$$
$$\left(d\sigma_9 + d\sigma_{10} + d\sigma_{14(1)} + d\sigma_{14(2)}\right)_{UV} = 0$$



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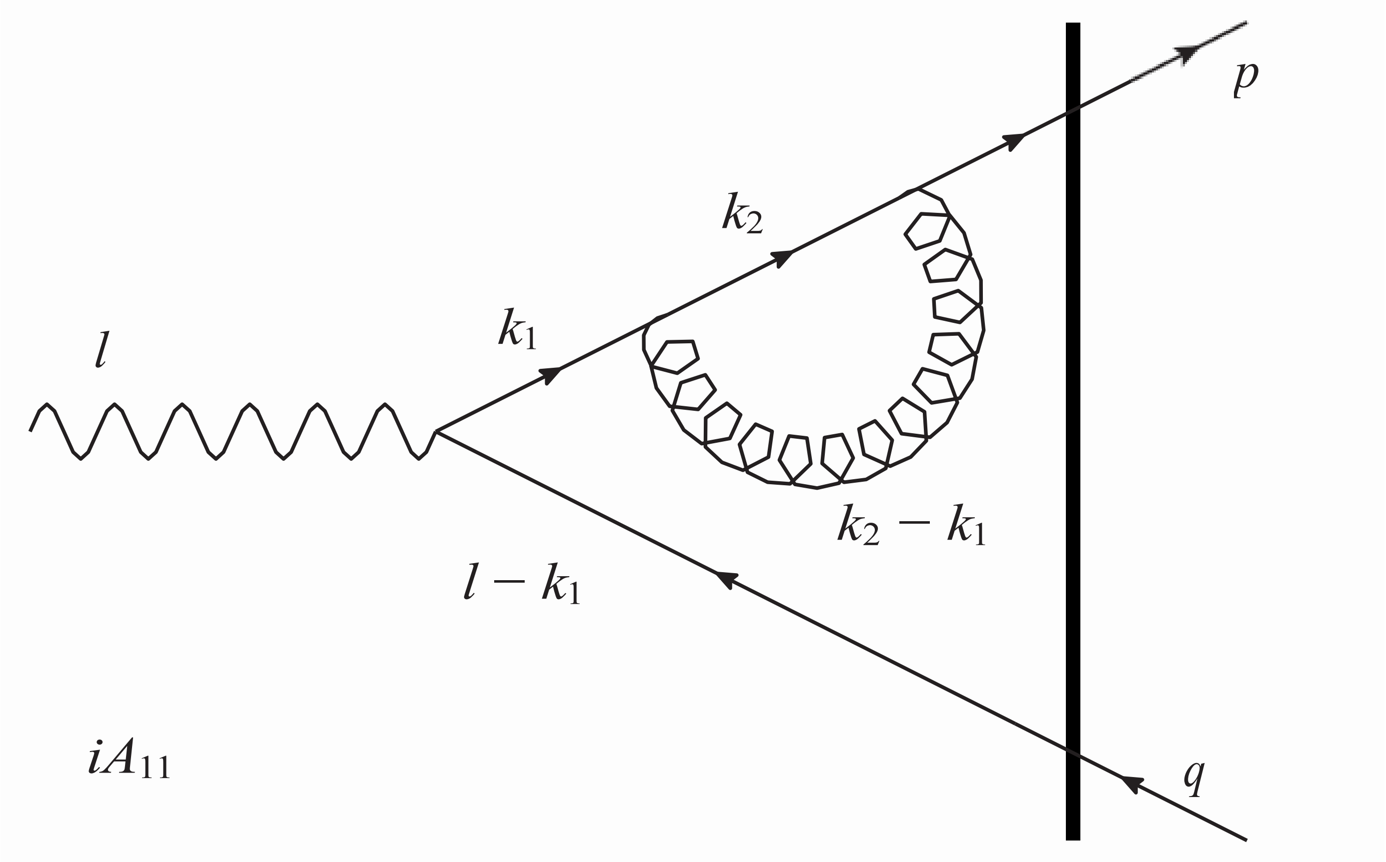


$= \mathbf{0}$

divergences

- ***Soft:*** $\mathbf{k}^{\mu} \rightarrow \mathbf{0}\ \ (\mathbf{x_3} \rightarrow \infty\ \ \ \mathbf{AND}\ \ \ \mathbf{z} \rightarrow \mathbf{0})$

Soft divergences cancel between real and virtual corrections

$$(d\sigma_{1-1} + d\sigma_9)_{soft} = 0,$$

$$\left(d\sigma_{1-2} + d\sigma_{13}^{(1)} + d\sigma_{13}^{(2)}\right)_{soft} = 0$$

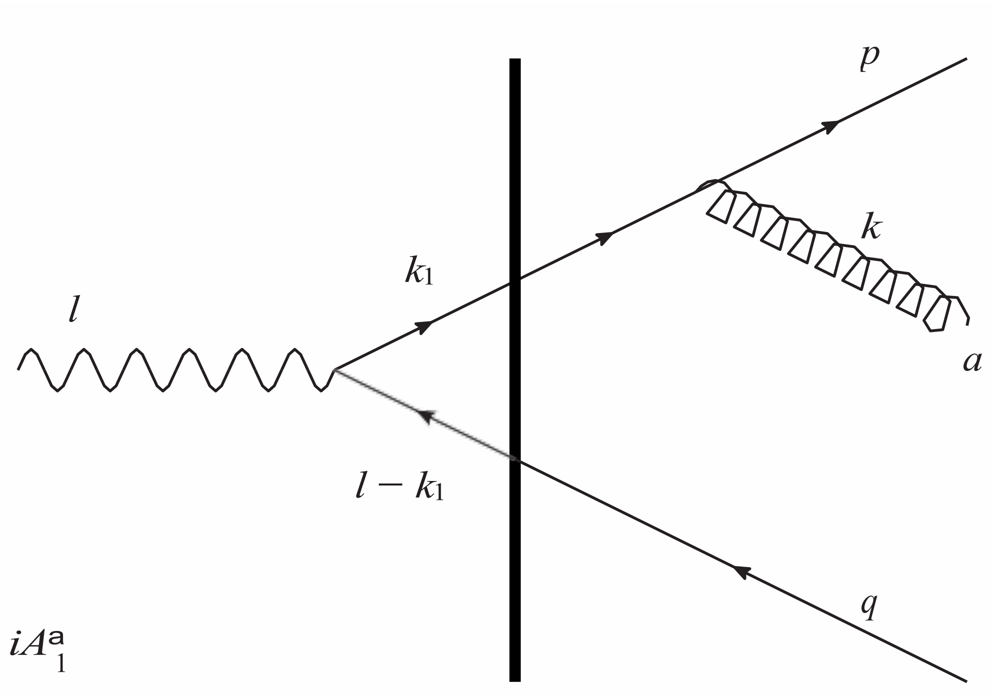
$$(d\sigma_{3-3} + d\sigma_{4-4} + d\sigma_{3-4})_{soft} = 0$$

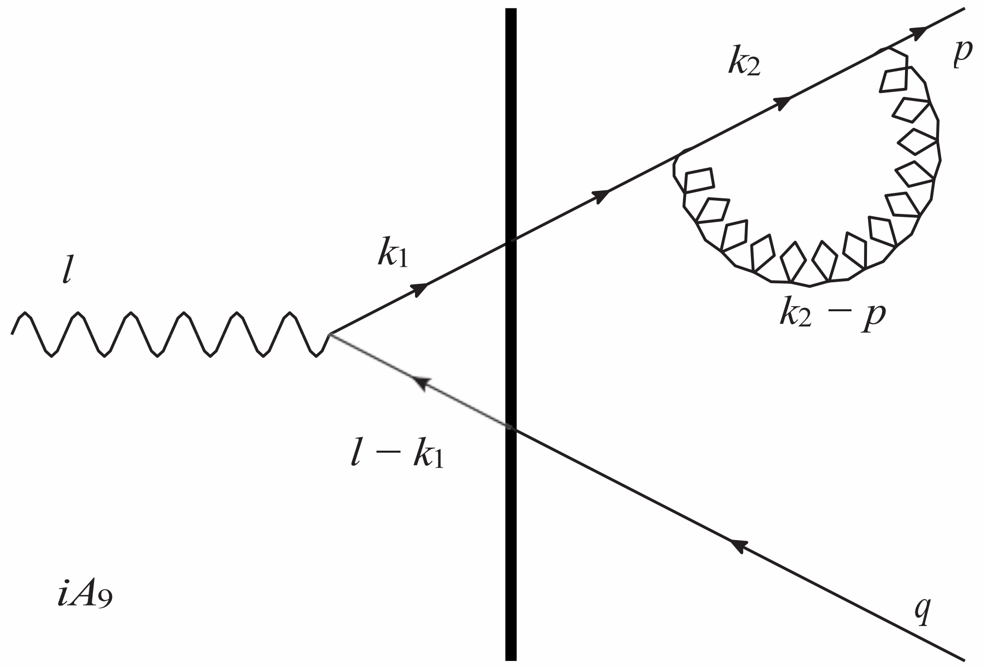
$$(d\sigma_{1-3} + d\sigma_{1-4})_{soft} = 0$$

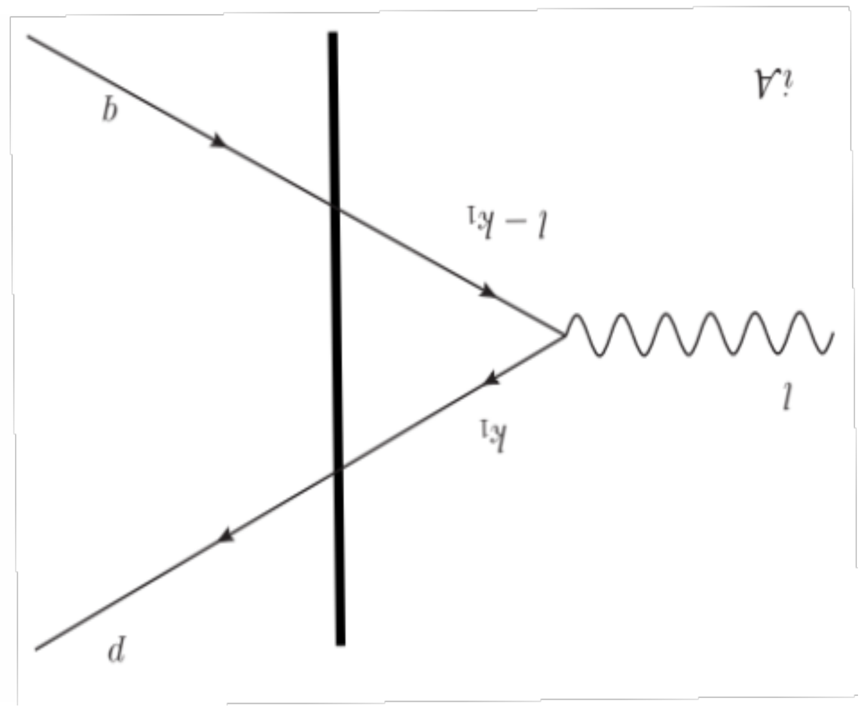
$$(d\sigma_{2-3} + d\sigma_{2-4})_{soft} = 0$$

$$(d\sigma_5 + d\sigma_7)_{soft} = 0$$

$$\left(d\sigma_{11} + d\sigma_{14}^{(1)}\right)_{soft} = 0$$

$\Big|$  $\Big|^2$

$+\ 2$ 



$= \mathbf{0}$

divergences

- ***Rapidity:*** $\mathbf{z \to 0}$ ***, but finite*** $\boldsymbol{k_t}$

$$\int_0^1 \frac{dz}{z} = \int_0^{z_f} \frac{dz}{z} + \int_{z_f}^1 \frac{dz}{z}$$

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

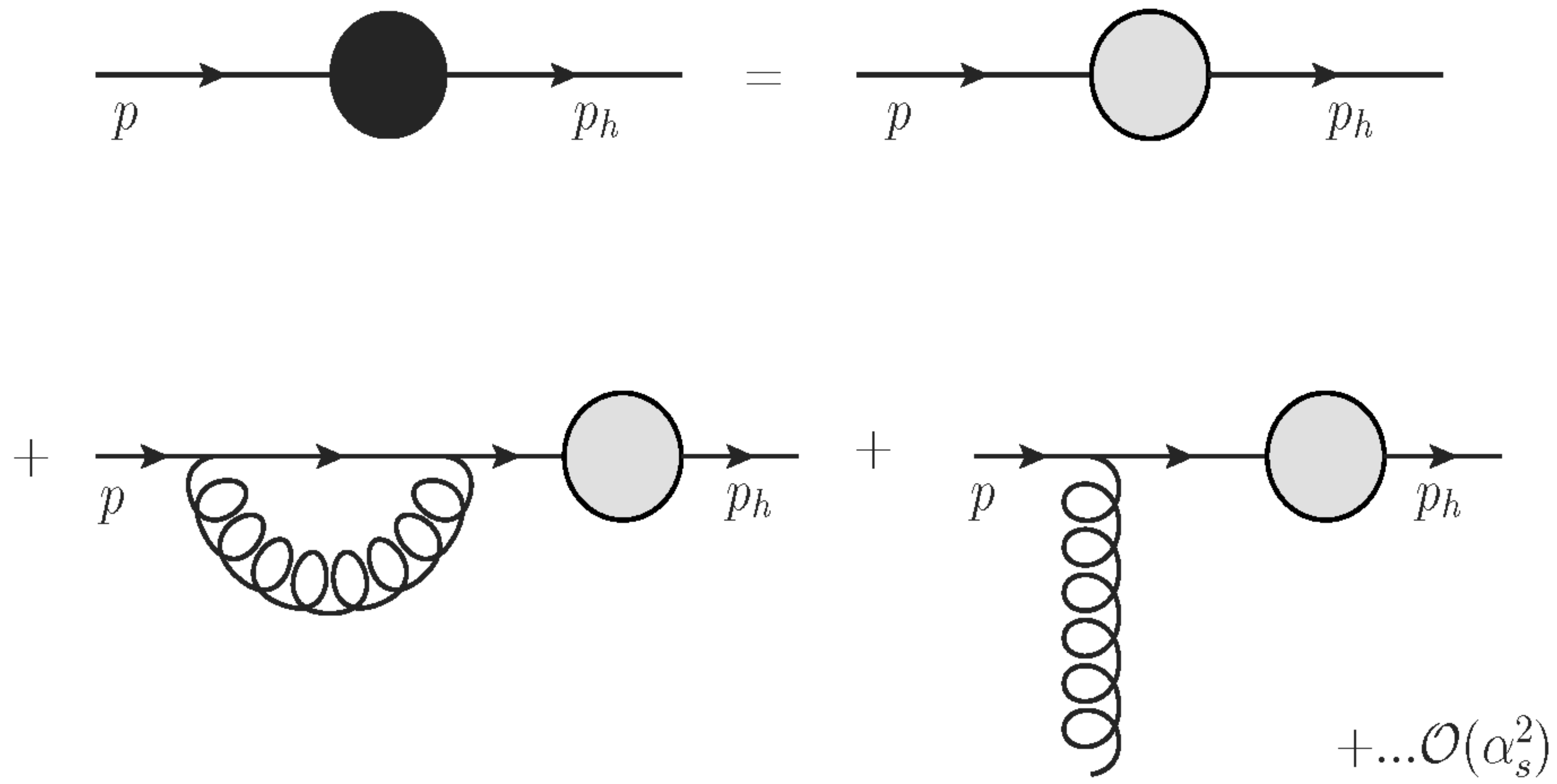
JIMWLK evolution of dipoles

$$\tilde{\boldsymbol{\Delta}}_{\mathbf{12}} \equiv \frac{(\mathbf{x_1} - \mathbf{x_2})^2}{(\mathbf{x_1} - \mathbf{x_3})^2 (\mathbf{x_2} - \mathbf{x_3})^2}$$

divergences

- ***Collinear:*** $$\frac{1}{(p+k)^2} = \frac{1}{|\vec{p}||\vec{k}|(1-cos\,\theta)} \longrightarrow \infty \quad as \quad \theta \to 0$$

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



collinear divergences

real corrections

$$\frac{d\sigma_{LO+1-1}^{\gamma^* A\to h_1 h_2 X}}{d^2\mathbf{p}_h\, d^2\mathbf{q}_h\, dy_1\, dy_2} = \int_0^1 dz_{h_1} \int_0^1 dz_{h_2} \frac{4e^2 Q^2 N_c (z_1 z_2)^3}{(2\pi)^7 (z_{h_1} z_{h_2})^2} H\left(\mathbf{p}, \mathbf{q}, z_2\right) D^0_{h_1/q}(z_{h_1}) D^0_{h_2/\bar{q}}(z_{h_2})$$

$$\int \frac{d\xi_1}{\xi_1^3} \delta(1 - z_2 - z_1/\xi_1) \left[\delta(1-\xi_1) + 2\alpha_s\, P_{qq}(\xi_1) \int d^2\mathbf{k} \frac{e^{i\mathbf{k}\cdot(\mathbf{x}_1' - \mathbf{x}_1)}}{\left(\xi_1 \mathbf{k} - (1-\xi_1)\mathbf{p}\right)^2}\right]$$

with $$P_{qq}(\xi_1) = C_F \frac{(1+\xi_1^2)}{(1-\xi_1)}$$

virtual corrections

$$\frac{d\sigma_9^{\gamma^* A\to h_1 h_2 X}}{d^2\mathbf{p}_h\, d^2\mathbf{q}_h\, dy_1\, dy_2} = -\int_0^1 dz_{h_1} \int_0^1 dz_{h_2} \frac{4e^2 Q^2 (z_1 z_2)^3 N_c}{(2\pi)^7 (z_{h_1} z_{h_2})^2} H(\mathbf{p}, \mathbf{q}, z_2) D^0_{h_1/q}(z_{h_1}) D^0_{h_2/\bar{q}}(z_{h_2})$$

$$\times\, \alpha_s \int_0^1 d\xi\, P_{qq}(\xi) \int d^2\mathbf{k} \frac{1}{\left(\mathbf{k} - (1-\xi)\mathbf{p}\right)^2} \delta(1 - z_1 - z_2)$$

these are combined into DGLAP evolution of fragmentation functions

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

Divergences

- Ultraviolet

  real corrections are UV finite

  UV divergences cancel among virtual diagrams

- Soft

  soft divergences cancel Soft

  soft divergences cancel between real and virtual diagrams real and virtual diagrams

- Collinear

  collinear divergences are absorbed into fragmentation functions

- Rapidity

  Rapidity divergences are absorbed into JIMWLK evolution of dipoles and quadrupoles

$$\sigma^{\gamma^* A \to h_1 h_2 X} = \sigma_{LO} \otimes \mathrm{JIMWLK} + \sigma_{LO} \otimes D_{h/q}(z_h, \mu^2) \otimes D^{(0)}_{h/q}(z_h) + \sigma^{\mathrm{finite}}_{NLO}$$

Back to back limit: deep connections to physics of TMDs, Sudakov effect,....

UPC,.....

talk by C. Marquet, today

Single inclusive hadron production in DIS at small x: NLO

F. Bergabo, JJM, JHEP 01 (2023) 095 (longitudinal photon)

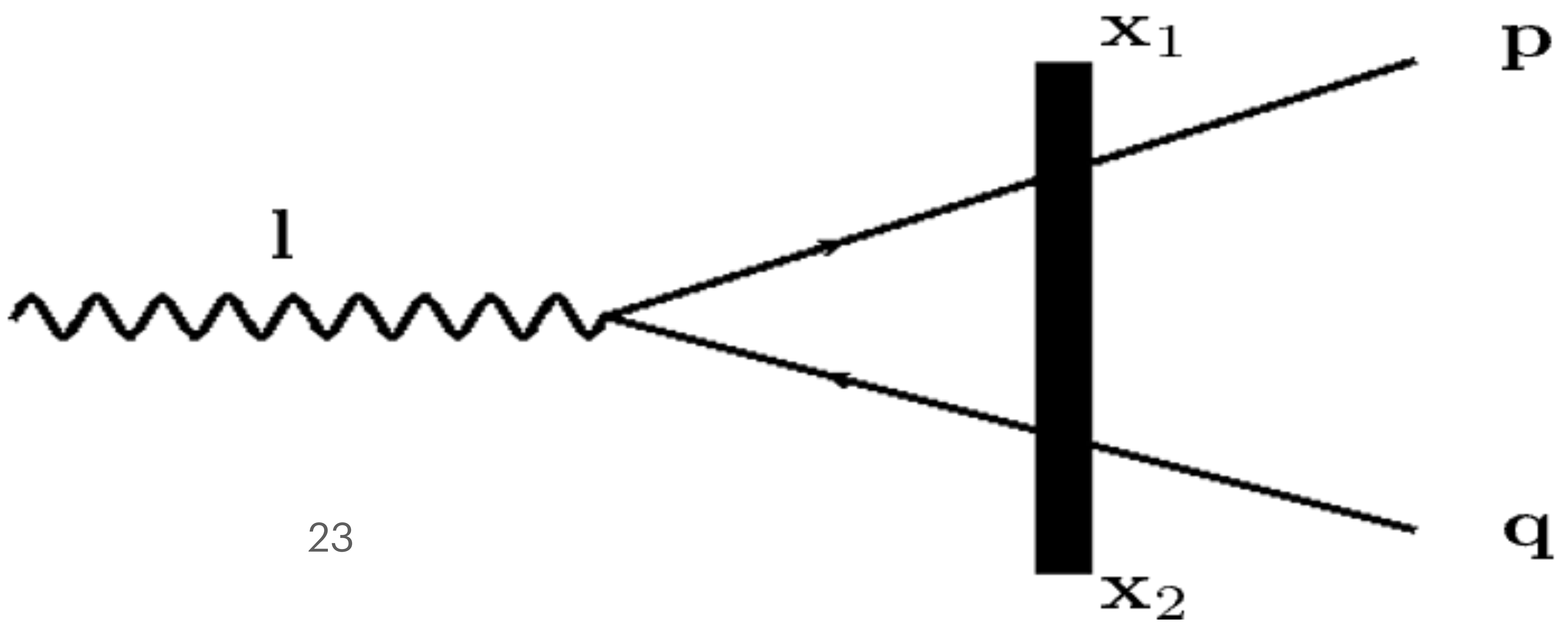
Larger kinematic phase space at EIC

Sudakov (can it be avoided?)

Dipoles only

Forward rapidity: quark or antiquark production

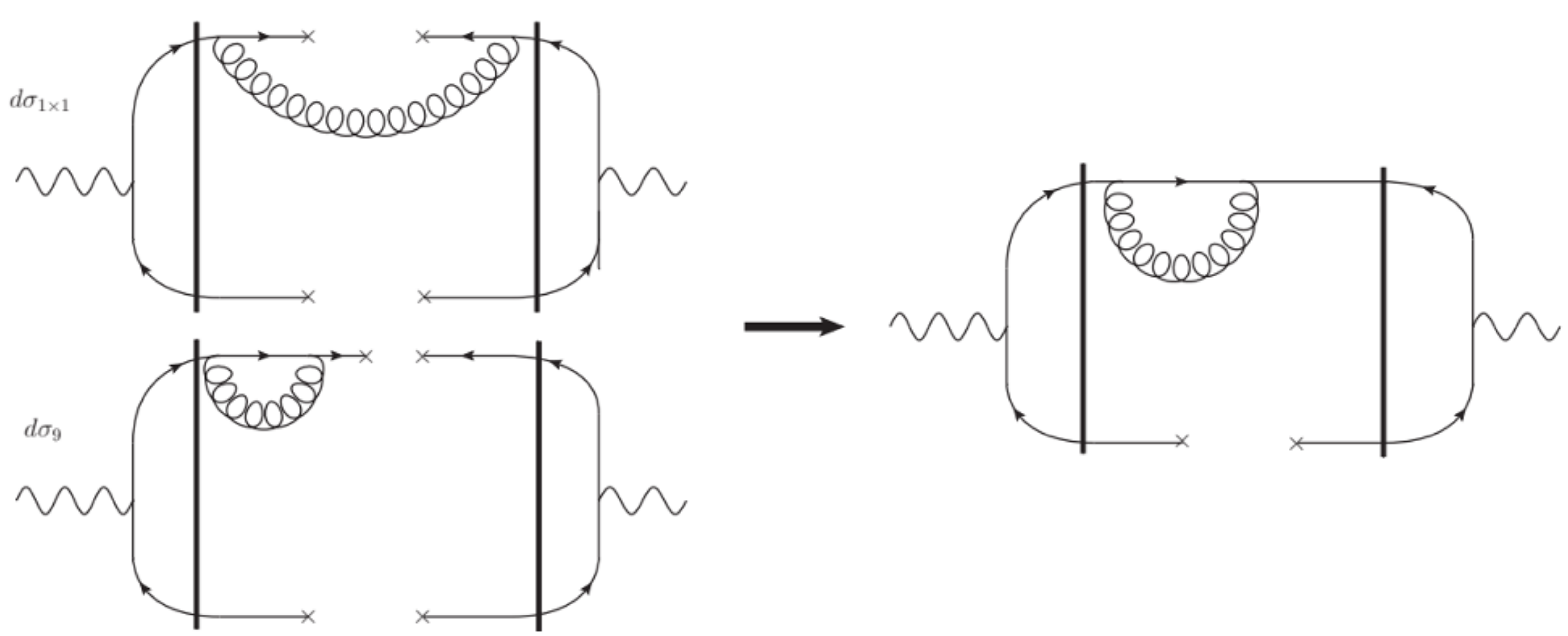
LO: integrate out quark



Single inclusive hadron production in DIS at small x: NLO

start with NLO corrections to dihadron production and integrate out quark

cancellations among diagrams



Single inclusive hadron production in DIS at small x: NLO

all terms with quadrupoles cancel; only <u>dipoles</u> contribute to the cross section

cancellations of divergences as before

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

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

consider hadronization of the gluon

Gluon production

finite N_c corrections included

integrate out both quark and antiquark

$$\frac{\mathrm{d}\sigma^L_{1\times 1}}{\mathrm{d}^2\mathbf{k}\,\mathrm{d}y} = 4\frac{e^2Q^2g^2N_c}{(2\pi)^6}\,C_F\int \mathrm{d}z_1\mathrm{d}z_2\,\delta(1-z_1-z_2-z)\,z_2^2(1-z_2)^2\left[z_1^2+(1-z_2)^2\right]$$
$$\int \mathrm{d}^6\,\mathbf{x}e^{i\mathbf{k}\cdot\mathbf{x}_{1'1}}\,K_0(|\mathbf{x}_{12}|Q_2)K_0(|\mathbf{x}_{1'2}|Q_2)\;[S_{11'}-S_{12}-S_{1'2}+1]\int\frac{\mathrm{d}^2\mathbf{p}}{(2\pi)^2}\frac{e^{i\mathbf{p}\cdot\mathbf{x}_{1'1}}}{[z\mathbf{p}-z_1\mathbf{k}]^2}$$

$$\frac{\mathrm{d}\sigma^L_{2\times 2}}{\mathrm{d}^2\mathbf{k}\,\mathrm{d}y} = 4\frac{e^2Q^2g^2N_c}{(2\pi)^6}\,C_F\int \mathrm{d}z_1\mathrm{d}z_2\,\delta(1-z_1-z_2-z)\,z_1^2(1-z_1)^2\left[z_2^2+(1-z_1)^2\right]$$
$$\int \mathrm{d}^6\mathbf{x}\,e^{i\mathbf{k}\cdot\mathbf{x}_{22'}}\,K_0(|\mathbf{x}_{12}|Q_1)K_0(|\mathbf{x}_{12'}|Q_1)\;[S_{22'}-S_{12}-S_{12'}+1]\int\frac{\mathrm{d}^2\mathbf{q}}{(2\pi)^2}\frac{e^{i\mathbf{q}\cdot\mathbf{x}_{22'}}}{[z\mathbf{q}-z_2\mathbf{k}]^2}$$

$\ldots\ldots$

$\ldots\ldots$

$$\frac{\mathrm{d}\sigma^L_{3\times 3}}{\mathrm{d}^2\mathbf{k}\,\mathrm{d}y} = 4\frac{e^2Q^2g^2N_c}{(2\pi)^6}\int \mathrm{d}z_1\mathrm{d}z_2\,\delta(1-z_1-z_2-z)\,z_2^2\left[z_1^2+(1-z_2)^2\right]$$
$$\frac{1}{(2\pi)^2}\int \mathrm{d}^8\mathbf{x}\,\frac{\mathbf{x}_{31}\cdot\mathbf{x}_{3'1}}{\mathbf{x}_{31}^2\mathbf{x}_{3'1}^2}\;\left[K_0(QX)\,K_0(QX')\right]_{1'=1\,,\,2'=2}\;e^{i\mathbf{k}\cdot\mathbf{x}_{3'3}}$$
$$\left\{\frac{N_c}{2}\left[S_{33'}S_{33'}-S_{13}S_{23}-S_{13'}S_{23'}\right]+C_F-\frac{1}{2N_c}\left[1-2S_{12}\right]\right\}$$

$\ldots\ldots$

$\ldots\ldots$

Gluon hadronizing

$$k_h^+ \frac{\mathrm{d}\sigma}{\mathrm{d}^2\mathbf{k}_h\,\mathrm{d}k_h^+} = \frac{8e^2Q^2N_c}{(2\pi)^5}\int\frac{\mathrm{d}z_h}{z_h^2}\,z^3(1-z)^2\int\mathrm{d}^6\,\mathbf{x}\,K_0(|\mathbf{x}_{12}|Q_2)K_0(|\mathbf{x}_{12'}|Q_2)\;[S_{22'}-S_{12}-S_{12'}+1]$$

$$e^{i\frac{\mathbf{k}_h}{z_h}\cdot\mathbf{x}_{22'}}\int\frac{\mathrm{d}\xi}{\xi}\,D^{(0)}_{h/g}(\frac{z_h}{\xi})\,C_F\,\frac{\alpha_s}{\pi}\,P_{gq}(\xi)\,\log\frac{\mu^2}{\Lambda^2}$$

$$+ \quad \cdots\cdots$$

with $z \equiv \frac{k_h^+}{z_h l^+}$ and $P_{gq}(\xi) = \frac{1+(1-\xi)}{\xi}$

this can be combined with quark hadronizing contributions

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

so far: SIDIS for longitudinal photons

work on transverse photons is almost complete: **UPC**!

Summary

QCD at high energy

dense hadron: gluon saturation, strong color fields - CGC

strong hints from RHIC, LHC,...

to be probed precisely at EIC

toward precision: NLO, sub-eikonal corrections, ...

CGC is limited to small x (low p_t)

EIC is several years away

UPC is a excellent environment in which to probe aspects of saturation