Single and double inclusive hadron production in DIS at small x: Next to Leading Order corrections

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QCD Evolution workshop

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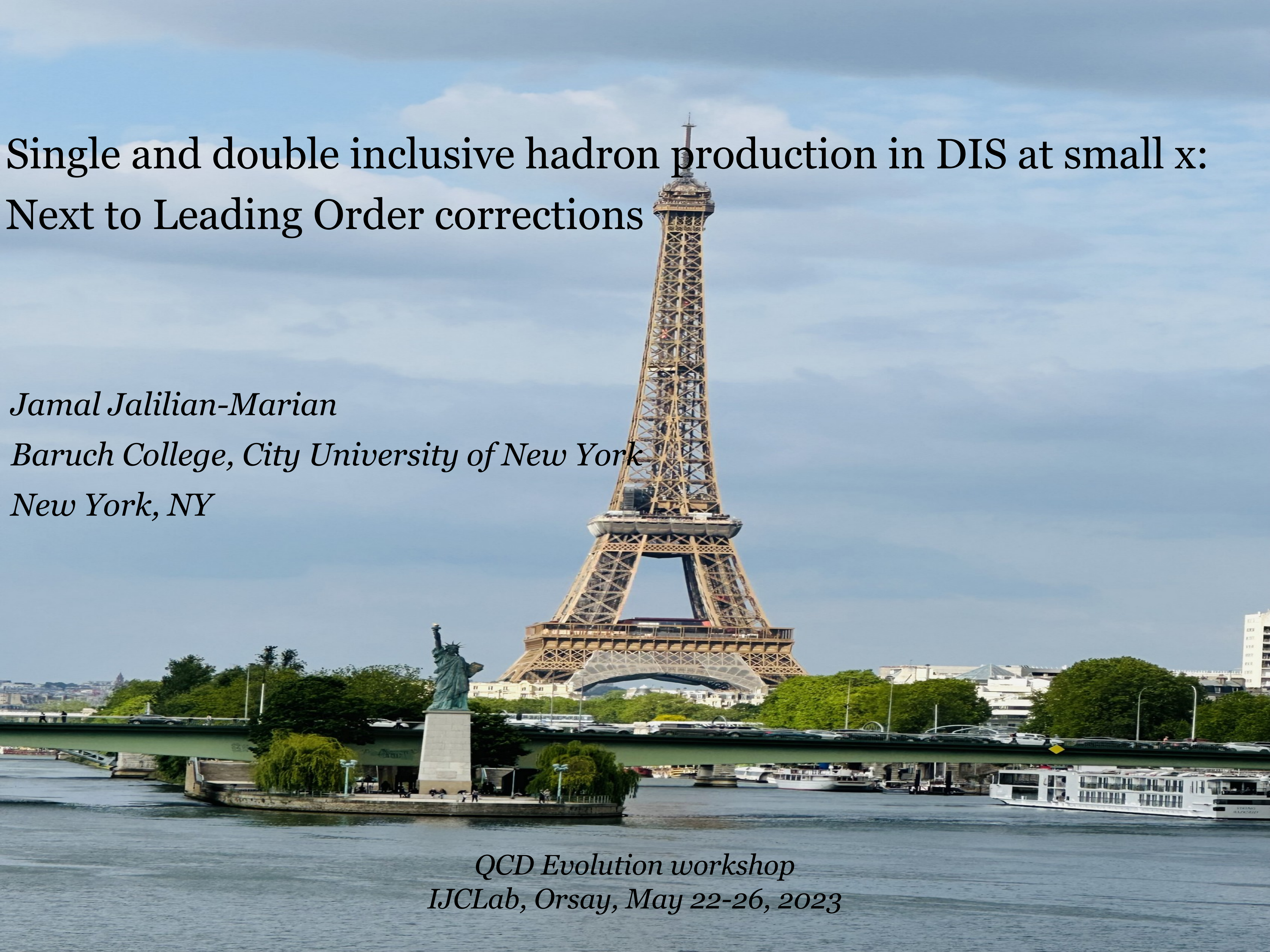
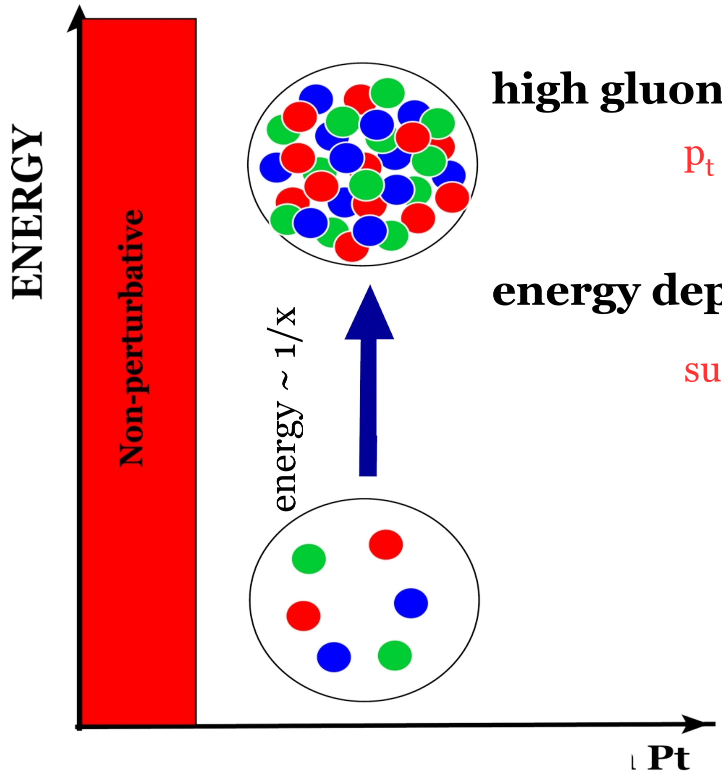


QCD at high energy: gluon saturation



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)

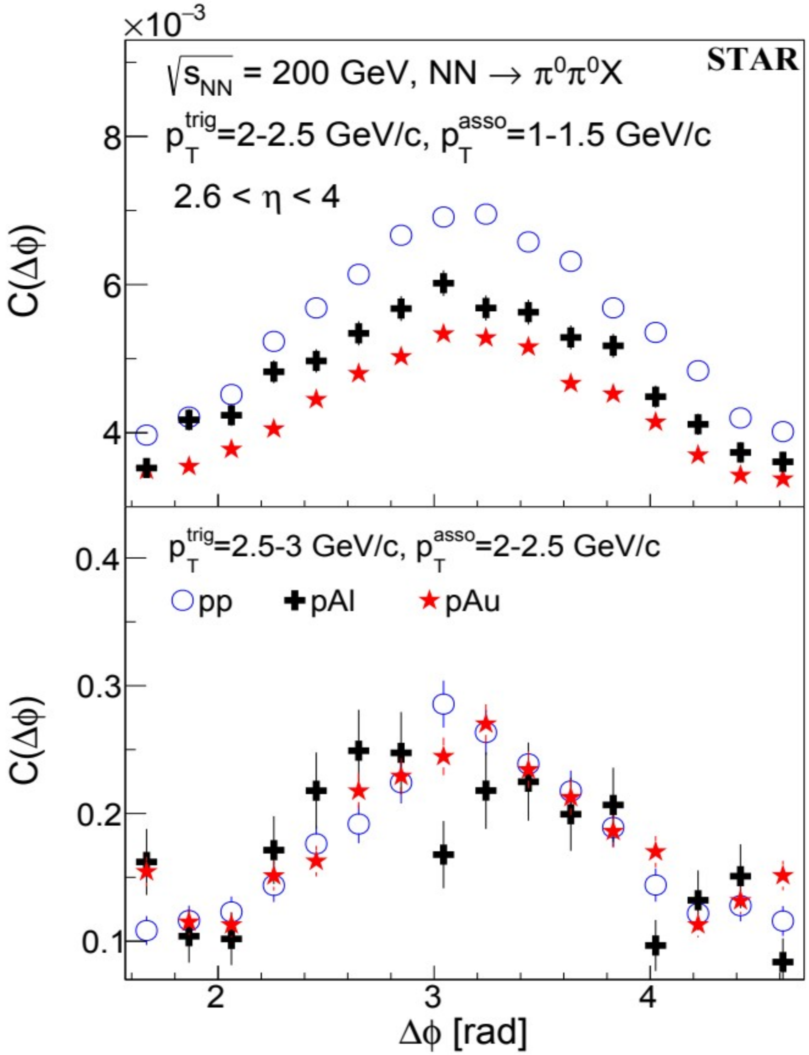
a framework for multi-particle production in QCD at small x/low p_t

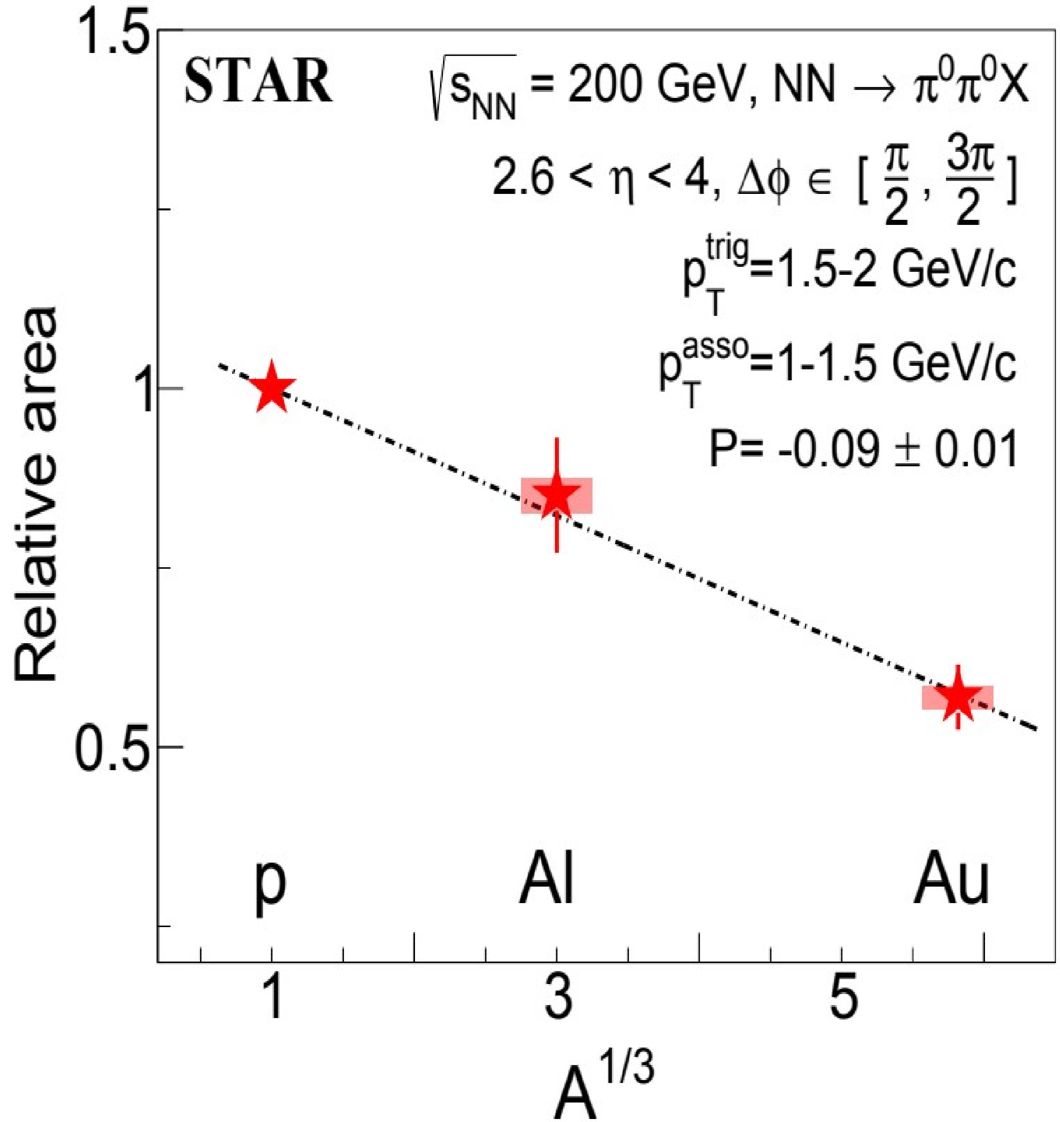
Shadowing/Nuclear modification factor
Azimuthal angular correlations (dihadrons/dijets,...)
Long range rapidity correlations (ridge,...)
Connections to TMDs,...

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

Back to back hadron production in pA collisions: forward rapidity

STAR collaboration(2021)
arXiv:2111.10396





Toward precision CGC at small x: inclusive DIS

NLO corrections to DIS structure functions:

Beuf (2017)
Beuf, Lappi, Paatelainen (2022)
....

NLO corrections to single inclusive hadron production in DIS:

Bergabo, JJM (2023)

NLO corrections to inclusive two-particle production in DIS:

Bergabo, JJM (2022, 2023)
Taels, Altinoluk, Beuf, Marquet (2022)
Caucal, Salazar, Schenke, Venugopalan (2022)
Caucal, Salazar, Venugopalan (2021)
....

DIS: sub-eikonal corrections at small x

Altinoluk, Armesto, Beuf (2023)
Altinoluk, Beuf, Czajka, Tymowska (2021, 2022)
....

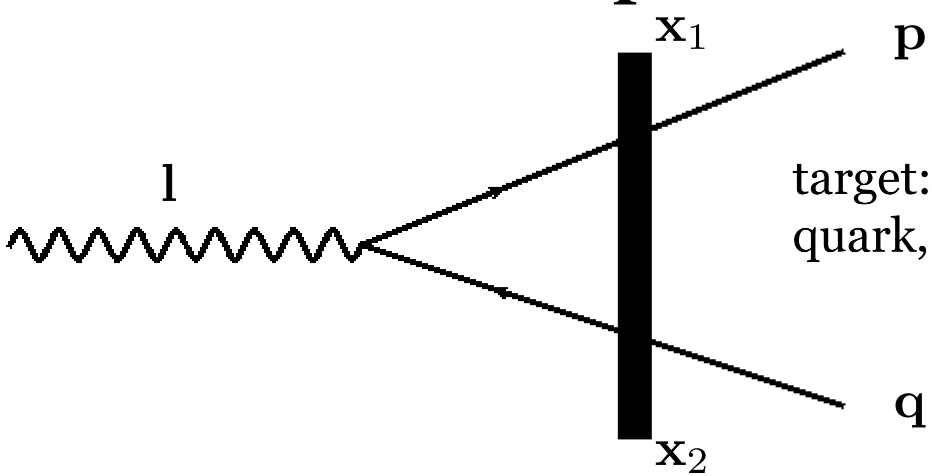
Significant work on exclusive production, diffraction, spin,TMDs,...

Inclusive dihadron production in DIS at small x:

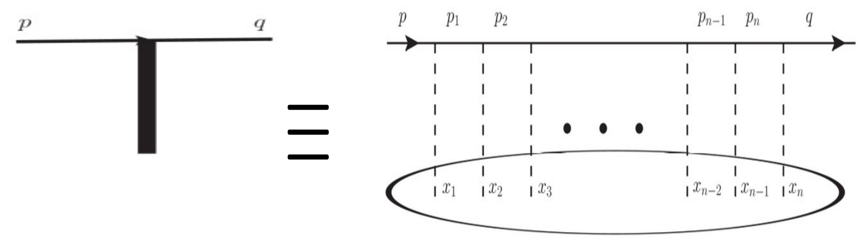
central vs forward rapidity

Diffractive production: next talk by E. Li

Inclusive dihadron production in forward rapidity: LO



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



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

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

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

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

with

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

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

Dominguez,Marquet,Xiao,Yuan, PRD 83 (2011) 105005

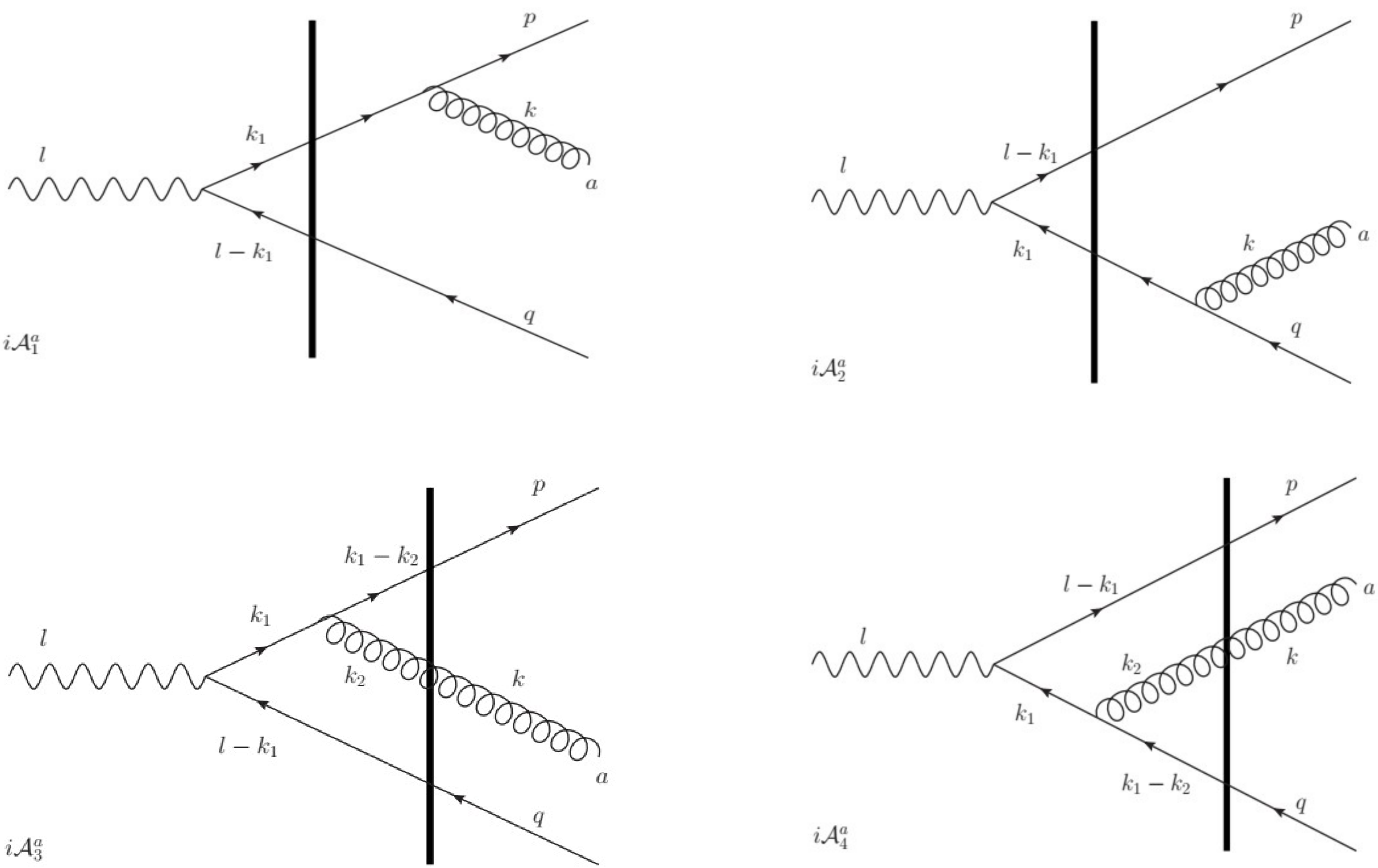
Inclusive dihadron production in forward rapidity: NLO

Based on F. Bergabo and JJM:

PRD 107 (2023) 5, 054036
JHEP 01 (2023) 095
NPA 1018 (2022) 122358
PRD 106 (2022) 5, 054035

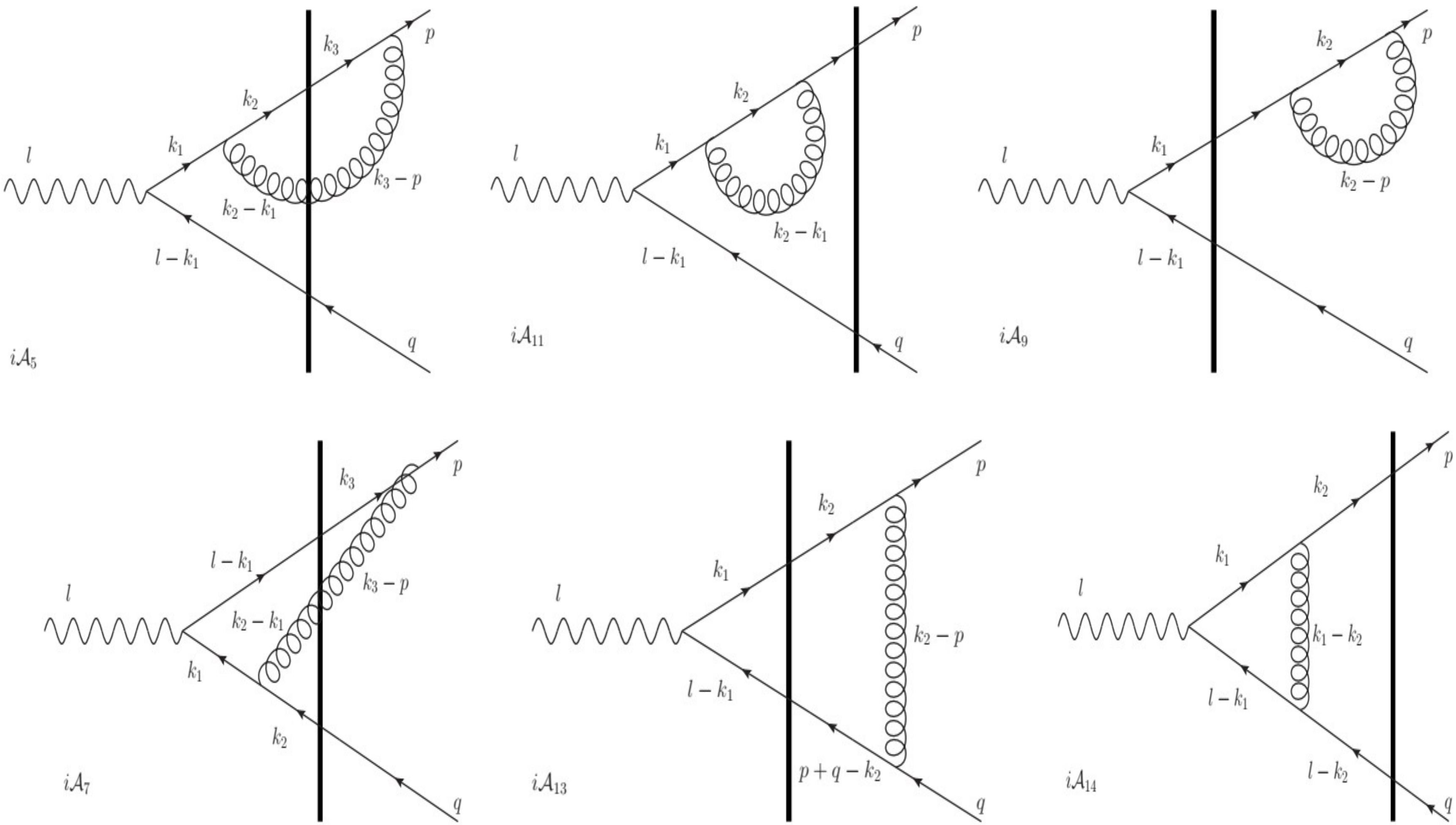
NLO dijets +Sudakov + connection to TMD,..., P. Caucal, Tuesday

NLO corrections - real diagrams (3-jet production)



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

NLO corrections – virtual diagrams



F. Bergabo and JJM, dihadrons, 2207.03606, 2301.03117

P. Taels et al., dijets, 2204.11650

P. Caucal et al., dijets, 2108.06347,…….

$$\frac{\sigma_{1-1}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_2^3(1-z_2)^2(z_1^2+(1-z_2)^2)}{(2\pi)^{10}z_1}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(|\mathbf{x}_{12}|Q_2)K_0(|\mathbf{x}_{1'2'}|Q_2)\Delta_{11'}^{(3)}$$
$$[S_{122'1'}-S_{12}-S_{1'2'}+1]\,e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_1}\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{2-2}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_1^3(1-z_1)^2(z_2^2+(1-z_1)^2)}{(2\pi)^{10}z_2}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(|\mathbf{x}_{12}|Q_1)K_0(|\mathbf{x}_{1'2'}|Q_1)\Delta_{22'}^{(3)}$$
$$[S_{122'1'}-S_{12}-S_{1'2'}+1]e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\frac{z}{z_2}\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{1-2}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{-2e^2g^2Q^2N_c^2z_1z_2(1-z_1)(1-z_2)(z_1(1-z_1)+z_2(1-z_2))}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(|\mathbf{x}_{12}|Q_2)K_0(|\mathbf{x}_{1'2'}|Q_1)$$
$$\Delta_{12'}^{(3)}[S_{12}S_{1'2'}-S_{12}-S_{1'2'}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_1}\mathbf{p}\cdot(\mathbf{x}_2'-\mathbf{x}_3)}e^{i\frac{z}{z_2}\mathbf{q}\cdot(\mathbf{x}_3-\mathbf{x}_1)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{3-3}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_1z_2^3(z_1^2+(1-z_2)^2)}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(QX)K_0(QX')\Delta_{11'}^{(3)}$$
$$[S_{11'}S_{22'}-S_{13}S_{23}-S_{1'3}S_{2'3}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{4-4}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_1^3z_2(z_2^2+(1-z_1)^2)}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(QX)K_0(QX')\Delta_{22'}^{(3)}$$
$$[S_{11'}S_{22'}-S_{13}S_{23}-S_{1'3}S_{2'3}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{3-4}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{-2e^2g^2Q^2N_c^2z_1^2z_2^2(z_1(1-z_1)+z_2(1-z_2))}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(QX)K_0(QX')\Delta_{12'}^{(3)}$$
$$[S_{11'}S_{22'}-S_{13}S_{23}-S_{1'3}S_{2'3}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{1-3}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{-2e^2g^2Q^2N_c^2z_2^3(1-z_2)(z_1^2+(1-z_2)^2)}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}\,K_0(|\mathbf{x}_{12}|Q_2)K_0(QX')\Delta_{11'}^{(3)}$$
$$[S_{122'3}S_{1'3}-S_{1'3}S_{2'3}-S_{12}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_1}\mathbf{p}\cdot(\mathbf{x}_3-\mathbf{x}_1)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{1-4}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_1z_2^2(1-z_2)(z_1(1-z_1)+z_2(1-z_2))}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}K_0(|\mathbf{x}_{12}|Q_2)K_0(QX')\Delta_{12'}^{(3)}$$
$$[S_{122'3}S_{1'3}-S_{1'3}S_{2'3}-S_{12}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_1}\mathbf{p}\cdot(\mathbf{x}_3-\mathbf{x}_1)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{2-3}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{2e^2g^2Q^2N_c^2z_1^2z_2(1-z_1)(z_1(1-z_1)+z_2(1-z_2))}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}K_0(|\mathbf{x}_{12}|Q_1)K_0(QX')\Delta_{21'}^{(3)}$$
$$[S_{1231'}S_{2'3}-S_{1'3}S_{2'3}-S_{12}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_2}\mathbf{q}\cdot(\mathbf{x}_3-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$
$$\frac{\sigma_{2-4}^{\mathrm{Real},L}}{d^2\mathbf{p}\,d^2\mathbf{q}\,dy_1\,dy_2} = \frac{-2e^2g^2Q^2N_c^2z_1^3(1-z_1)(z_2^2+(1-z_1)^2)}{(2\pi)^{10}}\int\frac{z}{z}\int d^{10}\mathbf{x}K_0(|\mathbf{x}_{12}|Q_1)K_0(QX')\Delta_{22'}^{(3)}$$
$$[S_{1231'}S_{2'3}-S_{1'3}S_{2'3}-S_{12}+1]e^{i\mathbf{p}\cdot(\mathbf{x}_1'-\mathbf{x}_1)}e^{i\mathbf{q}\cdot(\mathbf{x}_2'-\mathbf{x}_2)}e^{i\frac{z}{z_2}\mathbf{q}\cdot(\mathbf{x}_3-\mathbf{x}_2)}\delta(1-z_1-z_2-z).$$

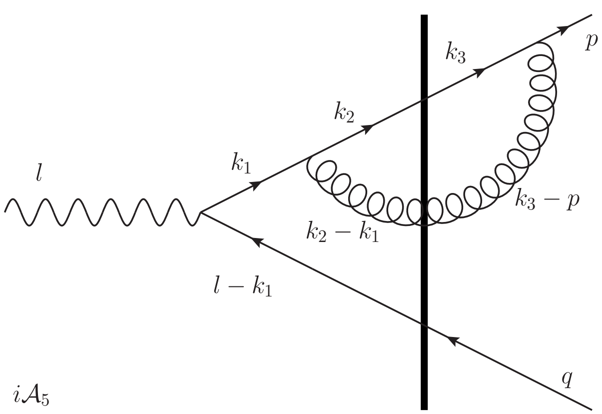
divergences

- ***Ultraviolet:***

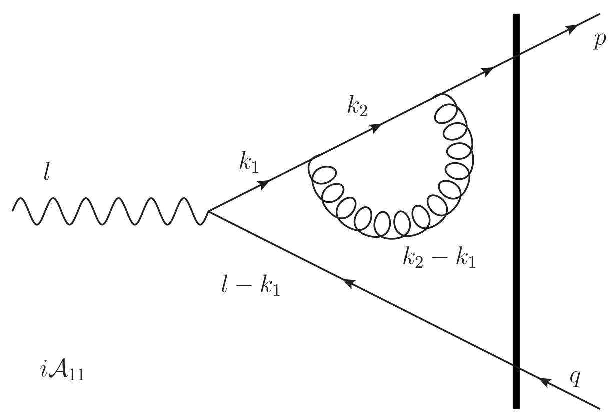
Real corrections are UV finite

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

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



$+$



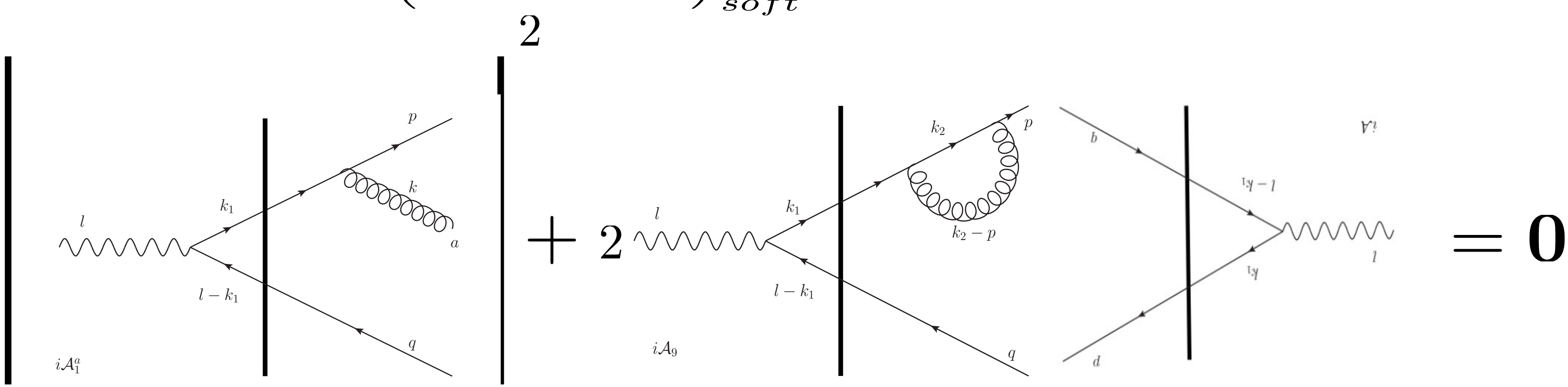
$= \mathbf{0}$

divergences

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

Soft divergences cancel between real and virtual corrections

$$
\begin{aligned}
&(d\sigma_{1-1} + d\sigma_9)_{soft} = 0, \\
&\left(d\sigma_{1-2} + d\sigma_{13}^{(1)} + d\sigma_{13}^{(2)}\right)_{soft} = 0 \\
&(d\sigma_{3-3} + d\sigma_{4-4} + d\sigma_{3-4})_{soft} = 0 \\
&(d\sigma_{1-3} + d\sigma_{1-4})_{soft} = 0 \\
&(d\sigma_{2-3} + d\sigma_{2-4})_{soft} = 0 \\
&(d\sigma_5 + d\sigma_7)_{soft} = 0 \\
&\left(d\sigma_{11} + d\sigma_{14}^{(1)}\right)_{soft} = 0
\end{aligned}
$$



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

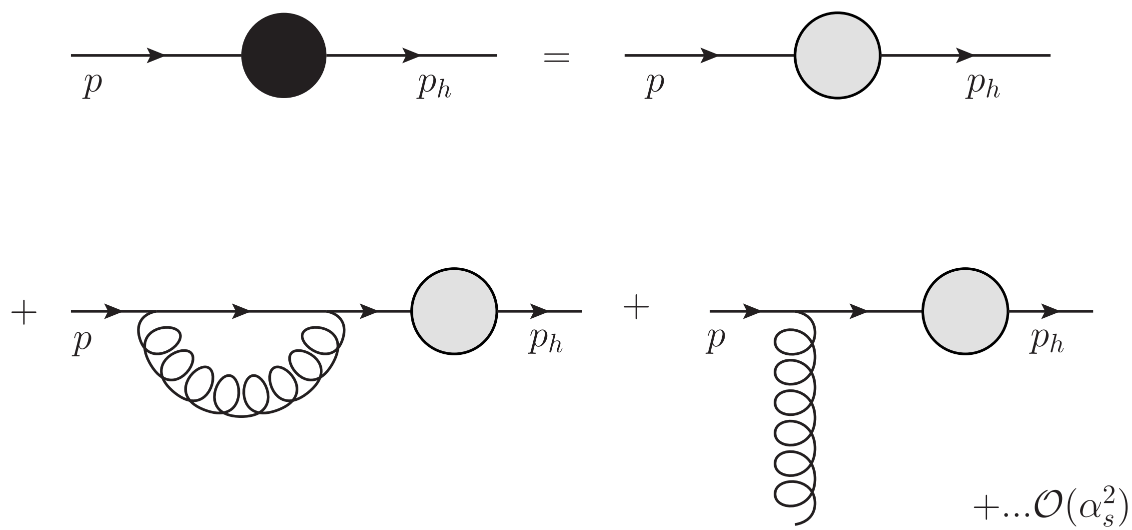
$$\tilde{\boldsymbol{\Delta}}_{\mathbf{12}} \equiv \frac{(\mathbf{x_1} - \mathbf{x_2})^2}{(\mathbf{x_1} - \mathbf{x_3})^2 (\mathbf{x_2} - \mathbf{x_3})^2}$$

divergences

- ***Collinear:***

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

Collinear divergences are absorbed into evolution of parton-hadron 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 corrections

•*Soft*

Soft divergences cancel between real and virtual corrections

•*Collinear*

Collinear divergences are absorbed into hadron fragmentation functions

•*Rapidity*

rapidity divergences are absorbed into JIMWLK evolution of dipoles, quadrupoles

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

phenomenology: EIC, UPC at the LHC,...

Single inclusive hadron production in DIS at small x: NLO

F. Bergabo and JJM: arXiv:2210.03208

larger kinematic phase space at EIC; 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: EIC, UPC at the LHC,...

DIS structure functions at small x: NLO

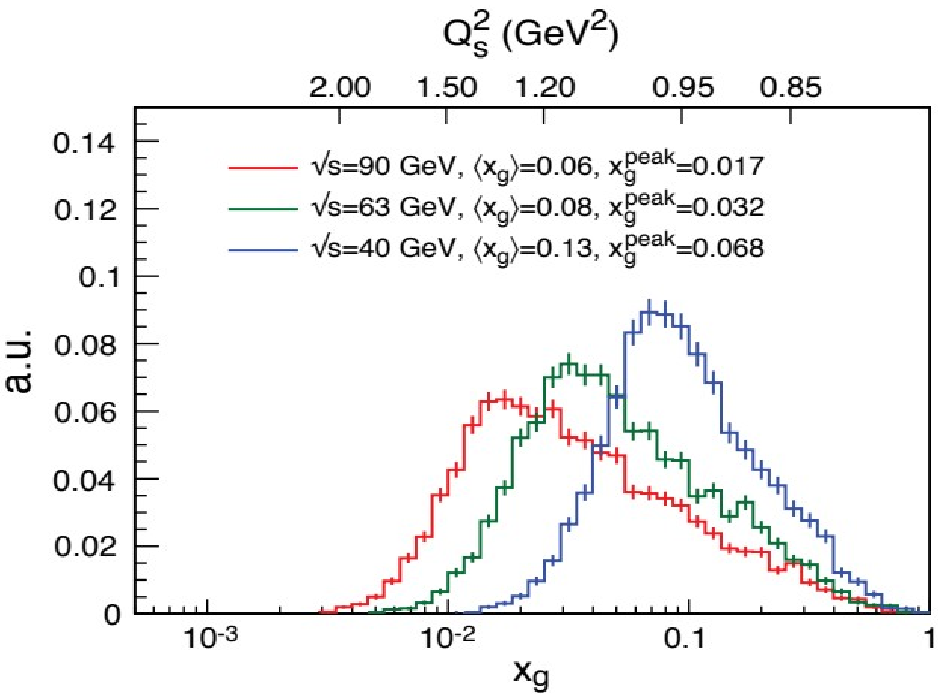
integrate out all produced partons

compare with results derived using LC perturbation theory

G. Beuf, arXiv:1708.06557
Beuf, Lappi, Paatelainen, arXiv:2112.03158

EIC

kinematics of inclusive dihadron production



Aschenauer et al. arXiv:1708.01527

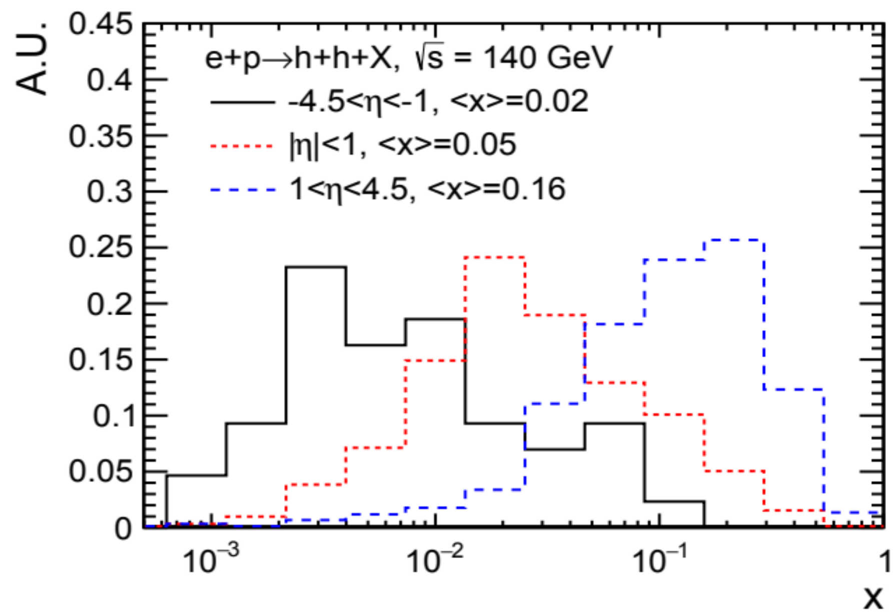
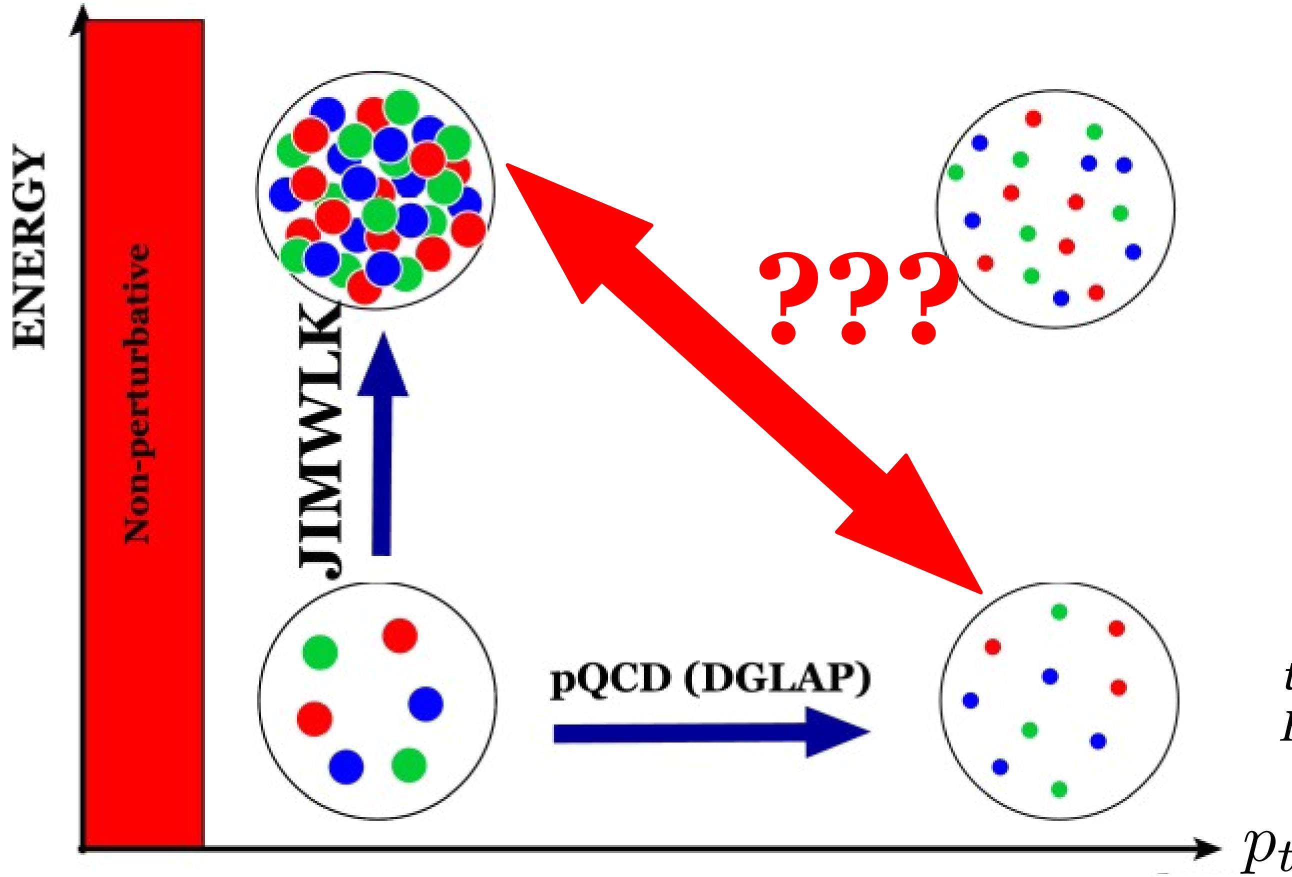


Fig. courtesy of Xiaoxuan Chu

transition region: from large x to small x

QCD kinematic phase space



twist expansion:
H. Xing, Tuesday

Unifying saturation with large x (collinear factorization) physics?

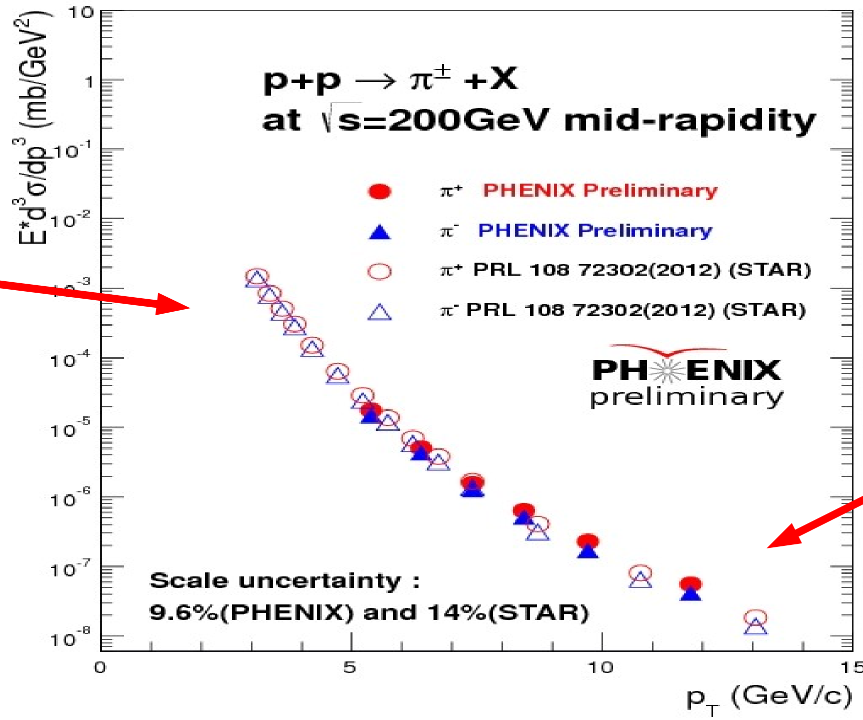
related talk by Y. Mehtar-Tani, Thursday

Bjorken vs Regge limit

$Q^2 \sim S \to \infty \quad X_{Bj} < 1$

$S \to \infty\,,\; Q^2 \text{ fixed} : X_{Bj} \to 0$

smaller x



high x

experiments are run at high but fixed energy!

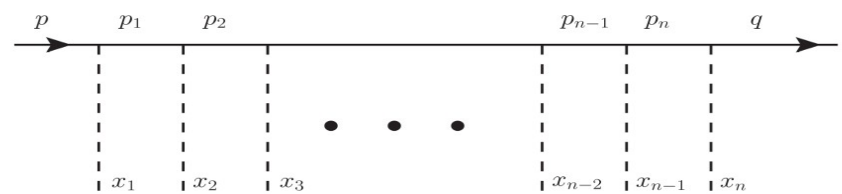
in pp, pA, AA collisions x and p_t are correlated!

x may be a more useful expansion parameter than S!

Including large x gluons of the target in dilute-dense collisions ("tree level")

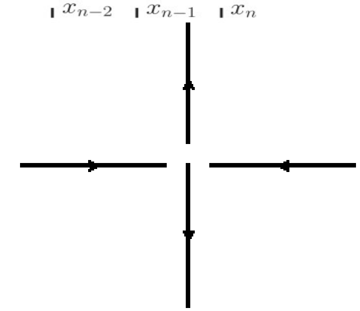
scattering from small x modes of the target field $A^- \equiv n^- S$ involves only small transverse momenta exchange (small angle deflection)

$$
\begin{aligned}
p^\mu &= (p^+ \sim \sqrt{s},\, p^- = 0, p_t = 0) \\
S &= S(p^+ \sim 0, p^-/P^- \ll 1, p_t)
\end{aligned}
$$

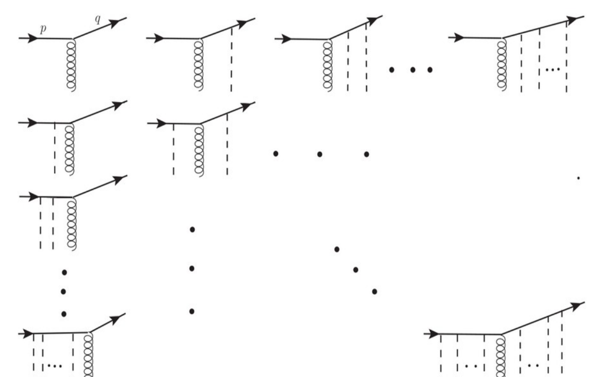


include one hard scattering so that projectile parton can get deflected by a large angle

$A_a^\mu(x^+, x^-, x_t)$

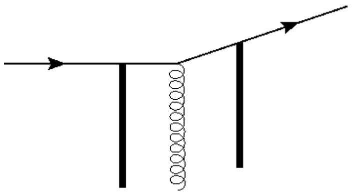


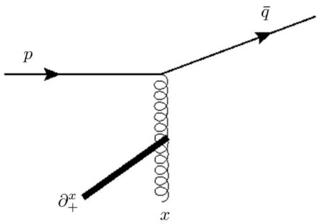
include eikonal multiple scattering before and after (along a different direction) the hard scattering

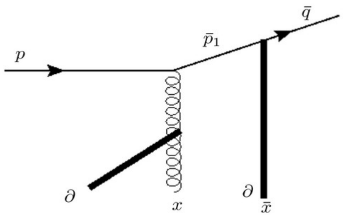


JJM, PRD96 (2017), PRD99 (2019), PRD102 (2020) cross section: $|\mathbf{i}\mathcal{M}|^2 = |\mathbf{i}\mathcal{M}_{\mathbf{eik}} + \mathbf{i}\mathcal{M}_{\mathbf{1}} + \mathbf{i}\mathcal{M}_{\mathbf{2}} + \mathbf{i}\mathcal{M}_{\mathbf{3}}|^2$

soft (eikonal) limit: $i\mathcal{M} \longrightarrow i\mathcal{M}_{eik}$







<u>spin asymmetries</u>

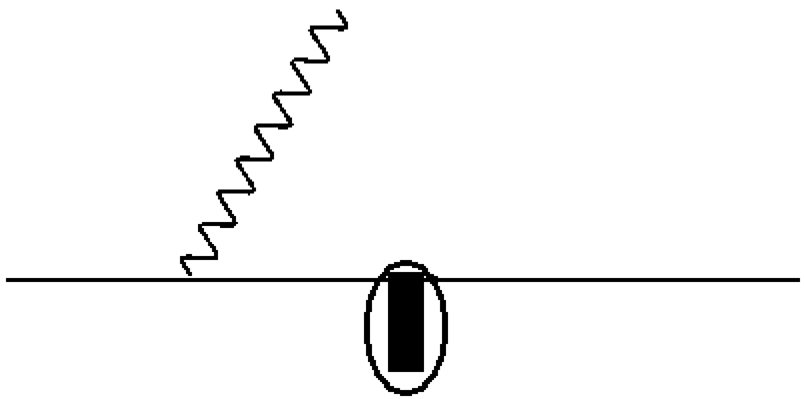
$$|i\mathcal{M}_2^+|^2 \sim g^2 \frac{q^+}{p^+} \frac{1}{q_\perp^4} \int d^4x\, d^4y\, e^{i(q^+ - p^+)(x^- - y^-)}\, e^{-i(q_t - p_t)\cdot(x_t - y_t)}$$
$$\Big\{ \Big[(p^+ - q^+)^2\, q_\perp^2\, A_\perp^b(x) \cdot A_\perp^c(y) + 4\, p^+ q^+\, q_\perp \cdot A_\perp^b(x)\, q_\perp \cdot A_\perp^c(y) \Big]$$
$$+\, \mathbf{i}\, \epsilon^{ij}\, [(p^+)^2 - (q^+)^2] \Big[q_i\, A_j^b(x)\, q_\perp \cdot A_\perp^c(y) - q_i\, A_j^c(y)\, q_\perp \cdot A_\perp^b(x) \Big] \Big\}$$
$$[\partial_{y^+}\, U_{AP}]^{ca}\, [\partial_{x^+}\, U_{AP}^\dagger]^{ab}$$

$$|i\mathcal{M}_2^-|^2 = \left(|i\mathcal{M}_2^+|^2\right)^\star \longrightarrow \mathbf{d}\sigma^{++} - \mathbf{d}\sigma^{+-} \neq \mathbf{0}$$

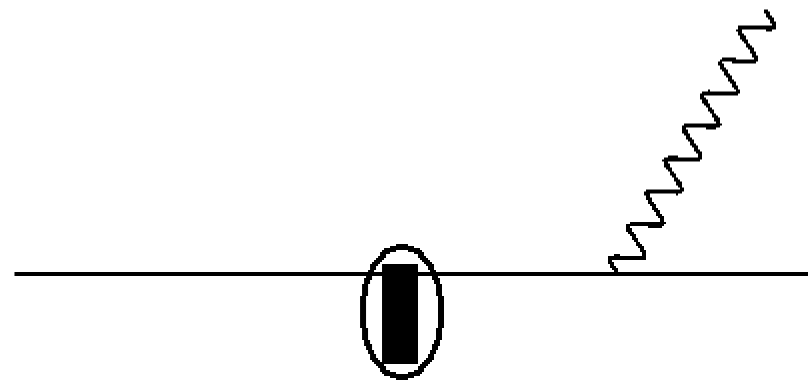
this is zero in (eikonal) CGC

<u>rapidity loss</u>

photon production at small x: eikonal approx.



before quark scatters on the target

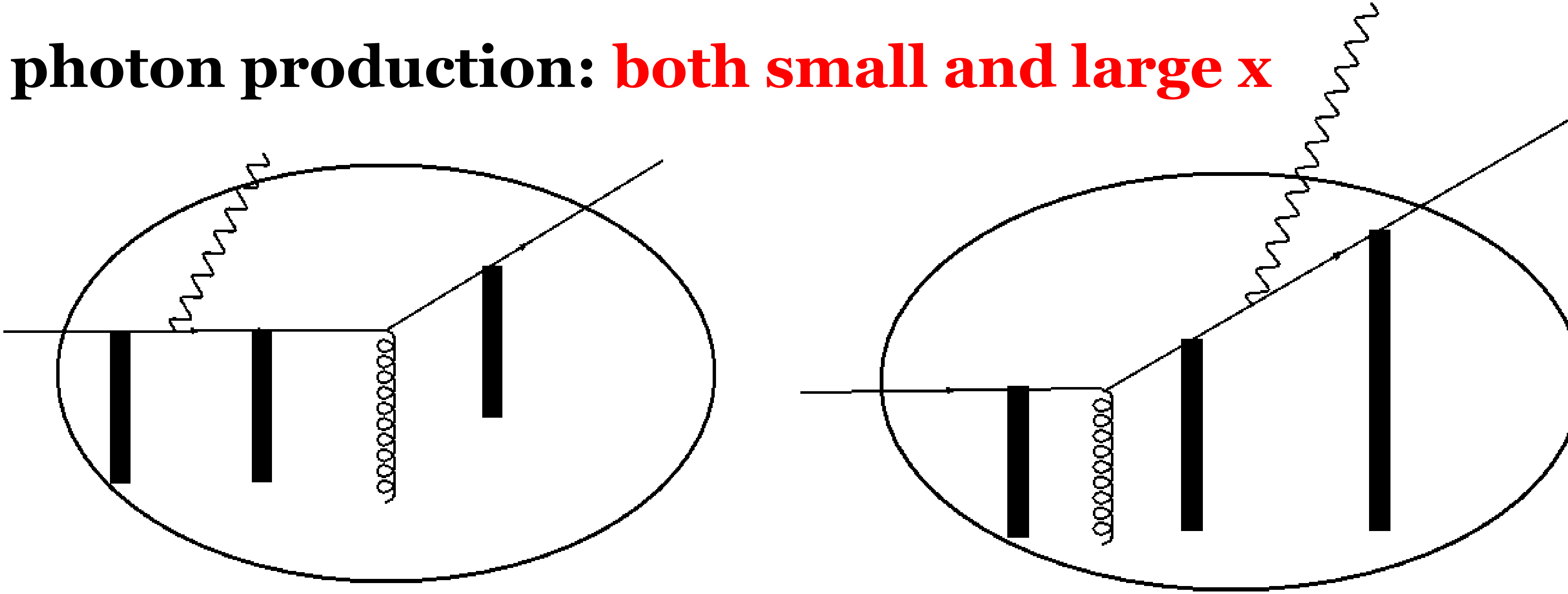


after quark scatters on the target

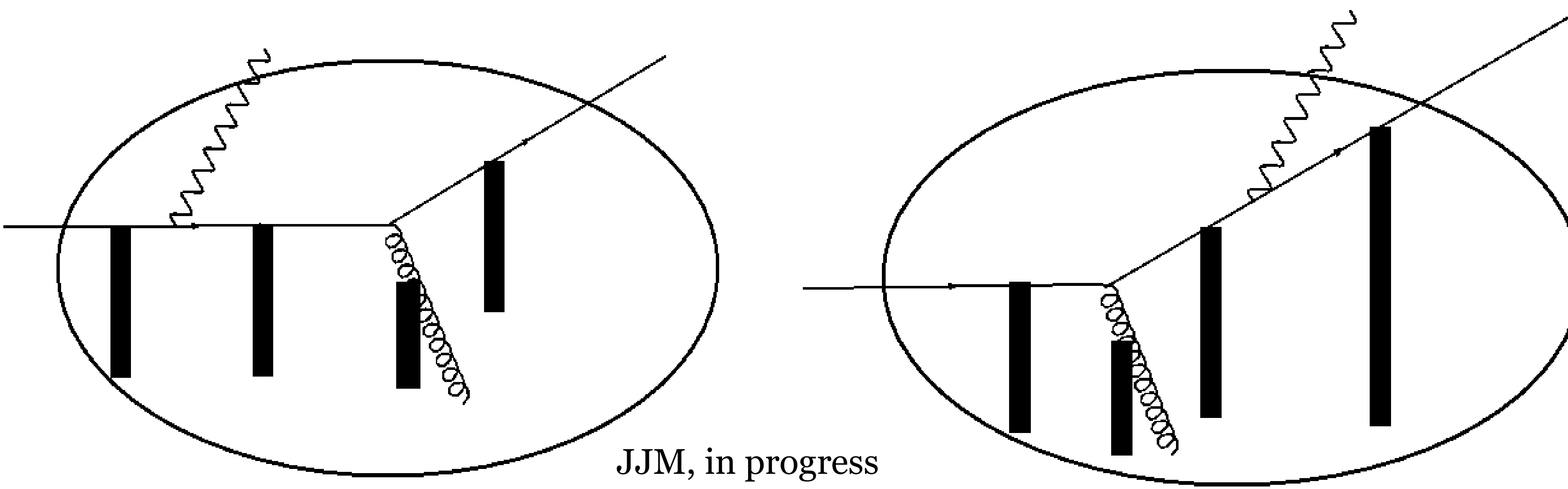
Eikonal approximation: no radiation inside the target

B. Kopeliovich, Tarasov, Schafer, hep-ph/9808378
F. Gelis, JJM, hep-ph/0205037

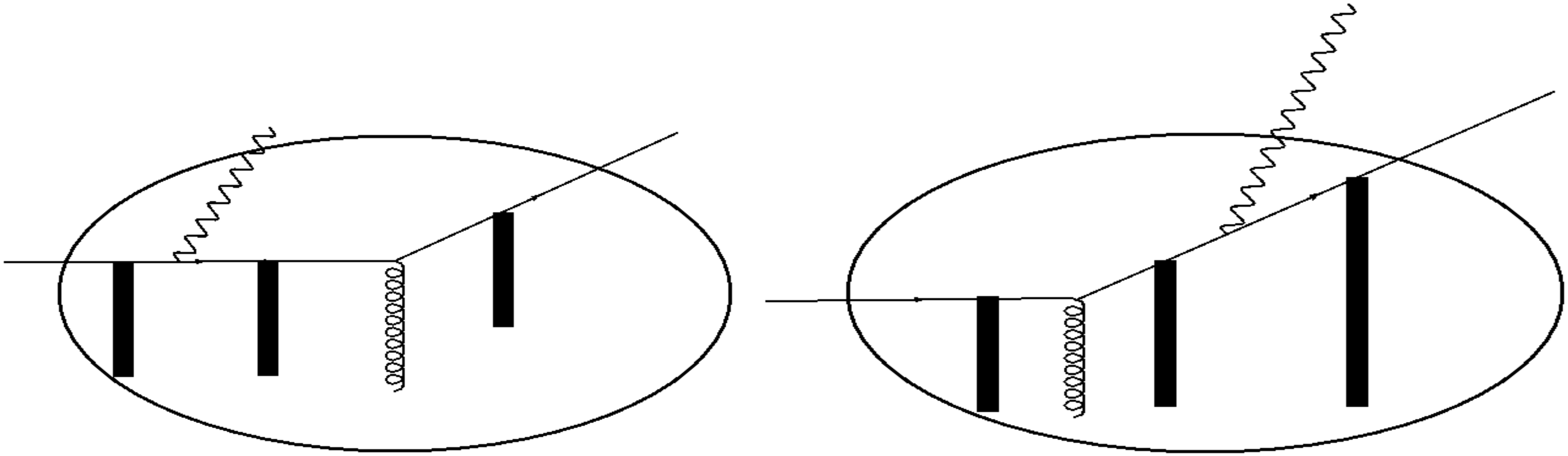
photon production: both small and large x



before hard scattering after hard scattering



pQCD limit (large x: gluon PDF X partonic cross section):



V = U = 1

tree level so far, how about quantum corrections (evolution)?

SUMMARY

pQCD and collinear factorization at high p_t

breaks down at small x (low p_t)

CGC is a systematic approach to high energy collisions

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)

Transition from large x physics (pQCD) to small x (CGC)

a significant part of EIC/RHIC/LHC phase space is at large x

Toward inclusion of large x physics:

spin asymmetries

beam rapidity loss

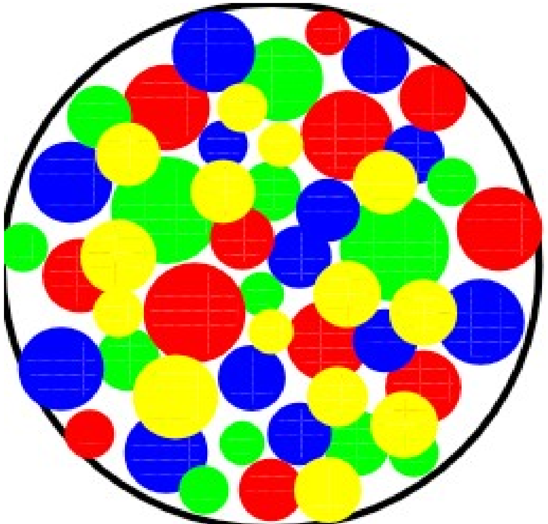
particle production in both small and large p_t kinematics

two-particle correlations: from forward-forward to forward-backward

one-loop correction: both collinear and CGC factorization limits

need to clarify/understand: gauge invariance, initial conditions, ...

A very large nucleus at high energy: MV model

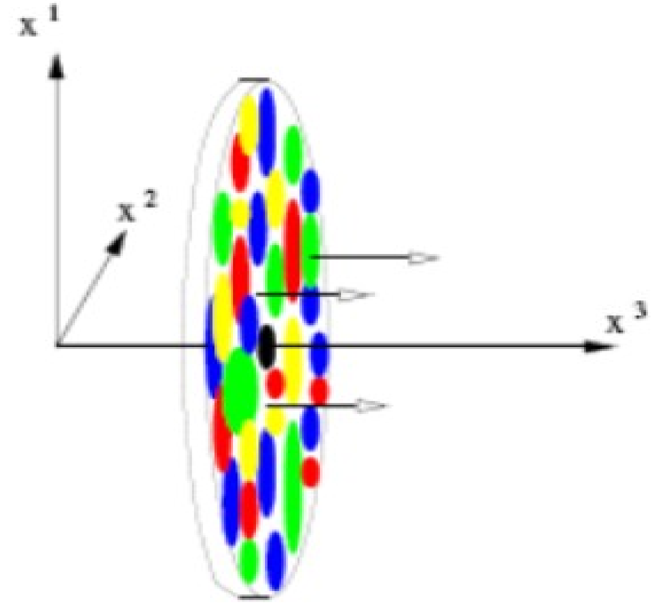


boost

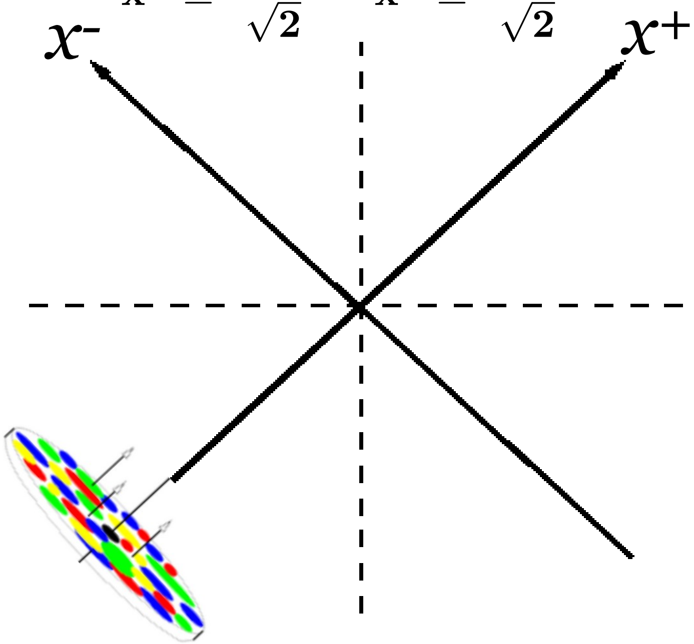
$$R \to \frac{R}{\gamma}$$

$\gamma \sim 100$ RHIC

$\gamma \sim 2500$ 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

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

color current *color charge*

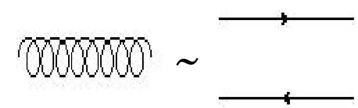
$$\mathbf{A^a_i(x^-, x_t) = \theta(x^-)\,\alpha^a_i(x_t)}$$

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

One-loop corrections: BK-JIMWLK eq.

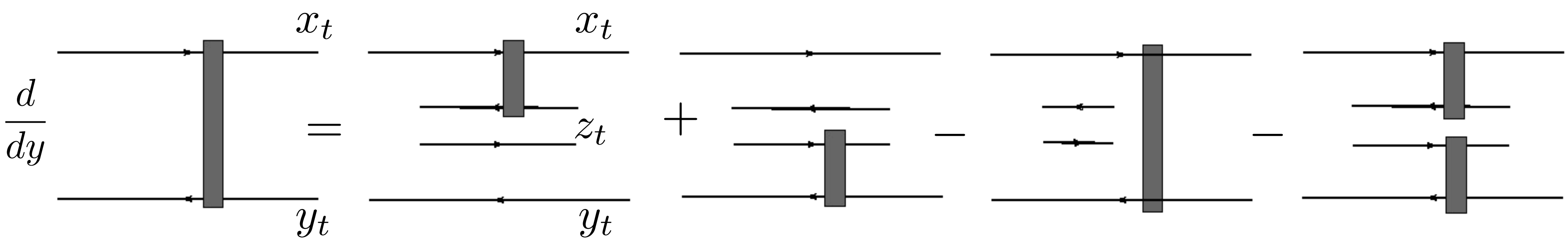
at large N_c

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



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

$$T \equiv 1 - S$$



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

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

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

nuclear modification factor

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

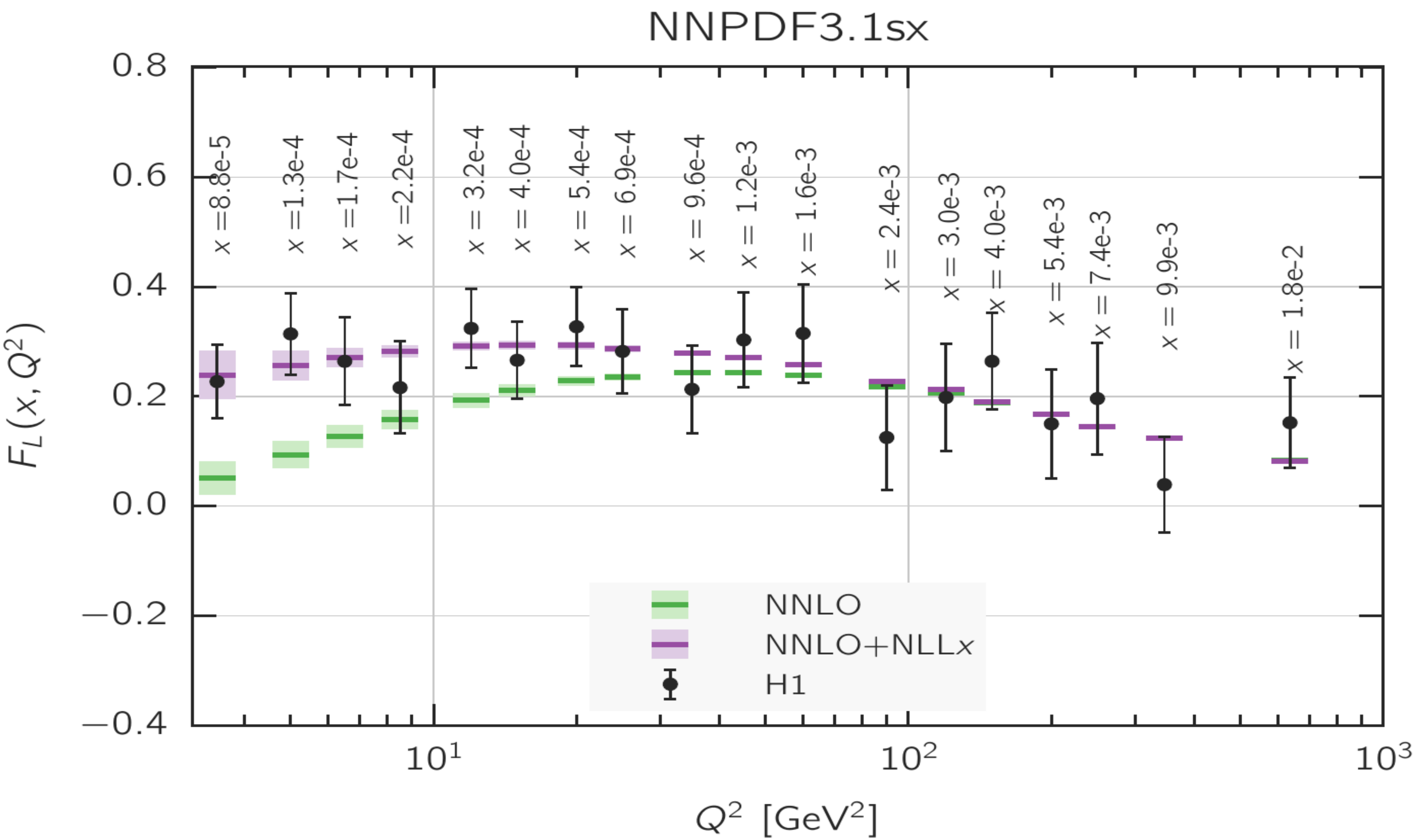
nuclear shadowing

suppression of p_t spectra

disappearance of back to back peaks

....

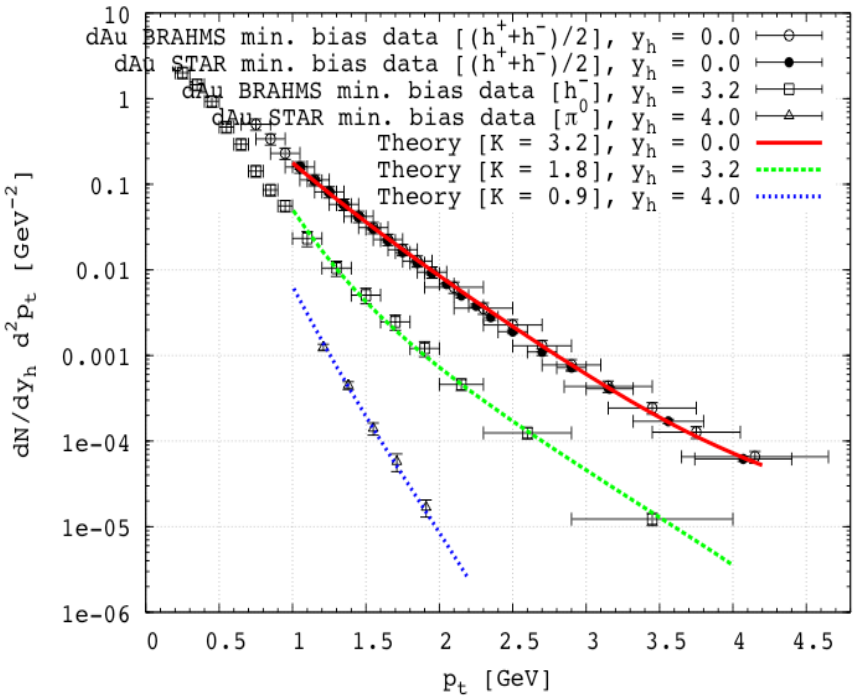
F_L at HERA



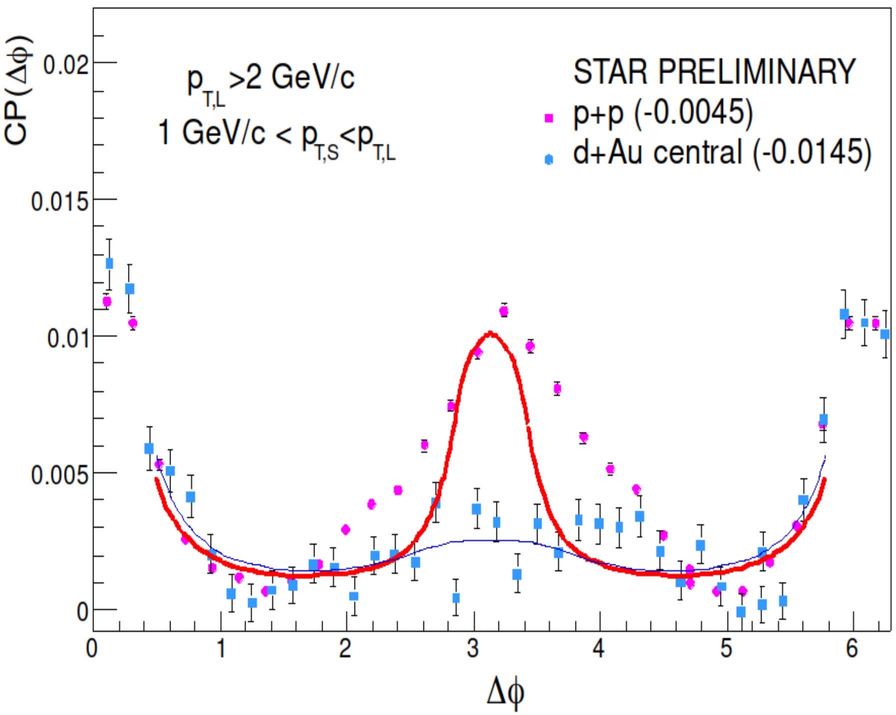
arXiv:1710.05935

CGC at RHIC

Single and double inclusive hadron production in dA collisions



Dumitru,Hayashigaki, JJM, NPA770 (2006) 57

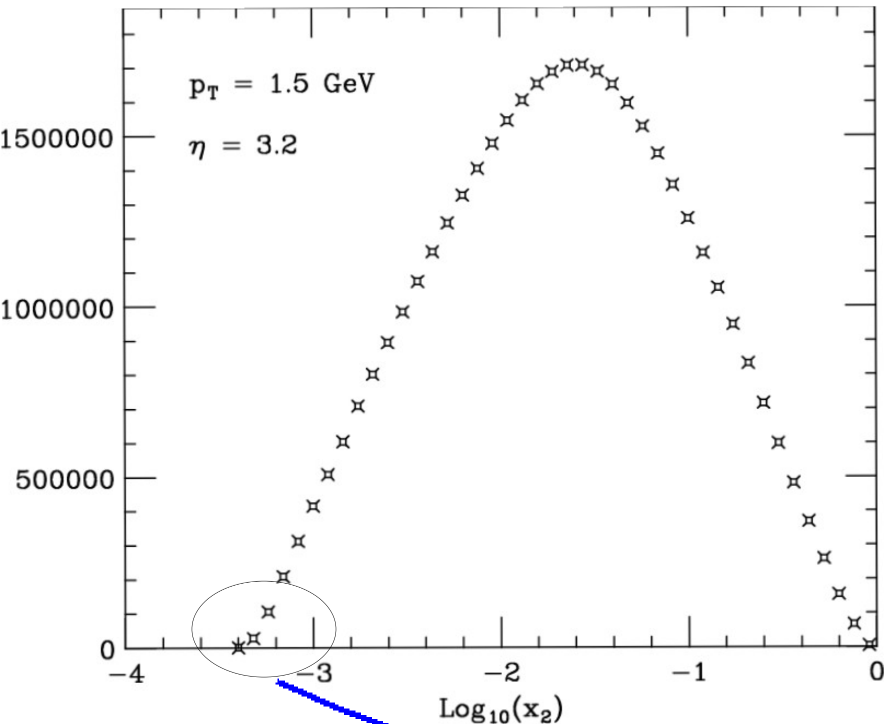


Albacete, Marquet, PRL105 (2010) 162301

Single inclusive pion production in pp at RHIC

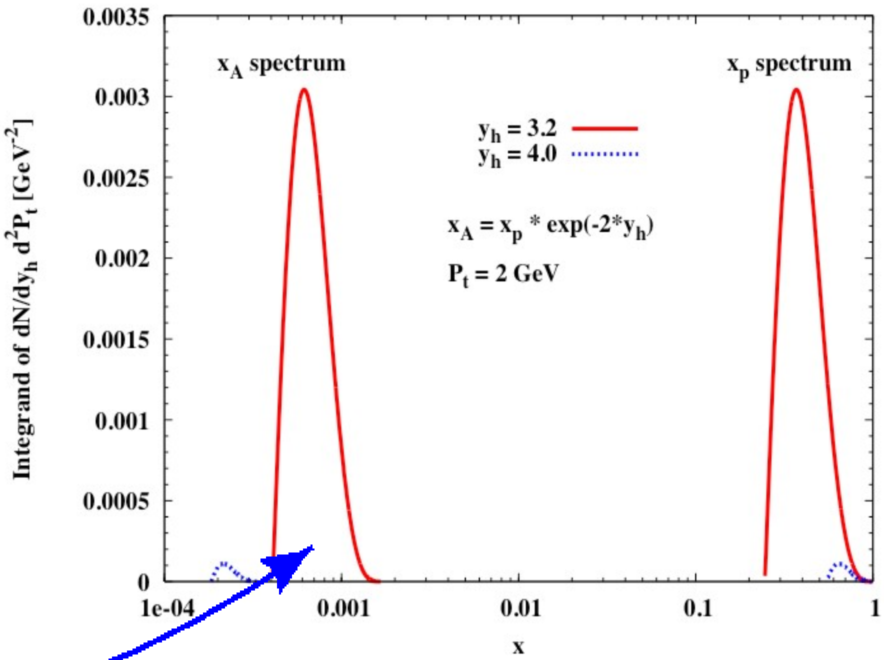
collinear factorization

GSV, PLB603 (2004) 173-183



CGC

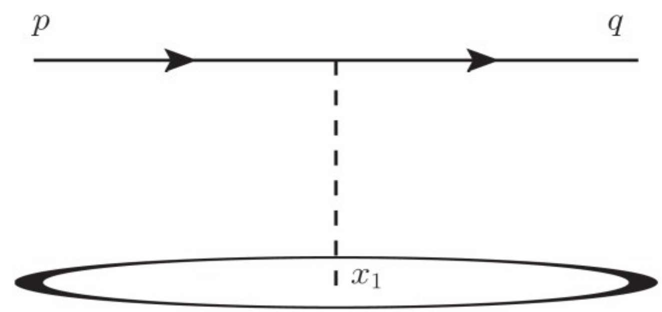
DHJ, NPA765 (2006) 57-70



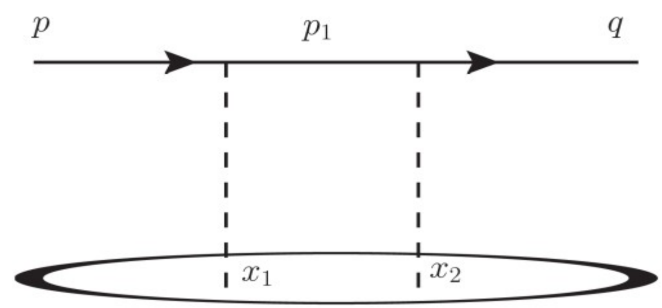
$$\int_{x_{min}}^{1} dx\, xG(x, Q^2) \cdots\cdots \longrightarrow x_{min} G(x_{min}, Q^2) \cdots$$

which kinematics are we in?

$$iM_1 = (ig)\int d^4x_1\, e^{i(q-p)x_1}\, \bar{u}(q)\, \left[\not{n}\, S(x_1)\right]\, u(p)$$
$$= (ig)(2\pi)\delta(p^+ - q^+)\int d^2x_{1t}\, dx_1^+\, e^{i(q^- - p^-)x_1^+}\, e^{-i(q_t - p_t)x_{1t}}$$
$$\bar{u}(q)\left[\not{n}\, S(x_1^+, x_{1t})\right] u(p)$$



$$iM_2 = (ig)^2\int d^4x_1\, d^4x_2 \int \frac{d^4p_1}{(2\pi)^4}\, e^{i(p_1-p)x_1}\, e^{i(q-p_1)x_2}$$
$$\bar{u}(q)\left[\not{n}\, S(x_2)\, \frac{i\not{p}_1}{p_1^2 + i\epsilon}\, \not{n}\, S(x_1)\right] u(p)$$



$$\int \frac{dp_1^-}{(2\pi)} \frac{e^{ip_1^-(x_1^+ - x_2^+)}}{2p^+\left[p_1^- - \frac{p_{1t}^2 - i\epsilon}{2p^+}\right]} = \frac{-i}{2p^+}\,\theta(x_2^+ - x_1^+)\, e^{i\frac{p_{1t}^2}{2p^+}(x_1^+ - x_2^+)}$$

contour integration over the pole leads to path ordering of scattering

ignore all terms: $O(\frac{p_t}{p^+}, \frac{q_t}{q^+})$ and use $\not{n}\, \frac{\not{p}_1}{2n\cdot p}\, \not{n} = \not{n}$

$$iM_2 = (ig)^2\,(-i)(i)\, 2\pi\delta(p^+ - q^+) \int dx_1^+\, dx_2^+\, \theta(x_2^+ - x_1^+) \int d^2x_{1t}\, e^{-i(q_t - p_t)\cdot x_{1t}}$$
$$\bar{u}(q)\left[S(x_2^+, x_{1t})\, \not{n}\, S(x_1^+, x_{1t})\right] u(p)$$