Phenomenology for forward particle production in pA collisions in CGC framework

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work in preparation

2023 EIC User Group Early Career Workshop, July,23-24, 2023

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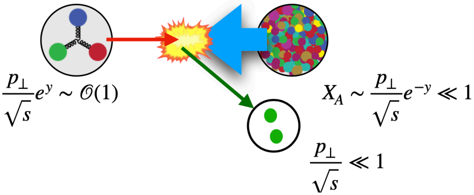
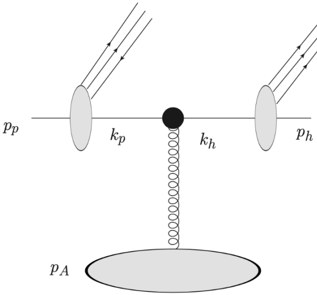
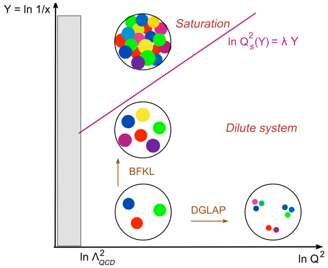
The purpose and meaning of the study

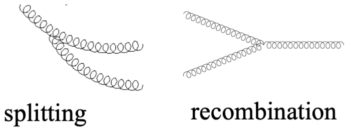




- small-x collider phenomenology is a part of QCD application.
- Single inclusive forward hadron production in high energy pA collisions is a key observable in searching for gluon saturation.

The purpose and meaning of the study

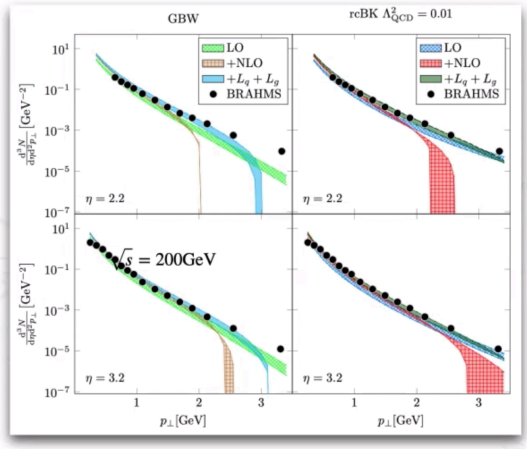




- CGC(Color Glass Condensate) effective theory is the appropriate theory for saturation physics(also called small-x physics).

Inclusive Hadron production in pA collision at small-x

[watanabe,xiao,yuan and zaslavsky arXiv:1505.05183]

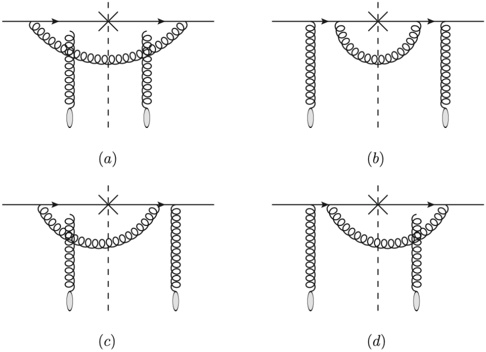


- Negative cross section problem
- Solution:threshold resummation

Inclusive Hadron production in pA collision at small-x

- qq Channel NLO Real Feynman Diagram

[A.Ghirilli,xiao and yuan arXiv:1203.6139]



Inclusive Hadron production in pA collision at small-x [Kang and Liu arXiv:1910.10166v2]

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}y_h\,\mathrm{d}^2p_{h\perp}} &= \frac{1}{4\pi^2}\int \frac{\mathrm{d}\xi}{\xi^2}\frac{\mathrm{d}x}{x} z x f_{q/P}(x,\mu) D_{h/q}(\xi,\mu) \\ &\times \int \mathrm{d}^2b_\perp \mathrm{d}^2b'_\perp \mathrm{d}^2x_\perp e^{ip'_\perp\cdot r_\perp}\left\langle S_w^{(2)}\left(b_\perp,x_\perp\right)S_w^{(2)}\left(x_\perp,b'_\perp\right)\right\rangle_\nu \\ &\times\left(\mathcal{I}_\delta^{(3)}\left(z,b_\perp,b'_\perp,\mu\right)\mathcal{S}_\delta^{(3)}\left(b_\perp,b'_\perp\right)\delta^{(2)}\left(x_\perp-b_\perp\right)\right. \\ &\left.+\mathcal{I}^{(3)}\left(z,b_\perp,b'_\perp,x_\perp,\nu\right)+\mathcal{S}^{(3)}\left(b_\perp,b'_\perp,x_\perp,\nu\right)\right)+\mathcal{O}\left(\alpha_s^2\right)\end{aligned} \tag{1}$$

where:

$$S_w^{(2)}\left(b_\perp,b'_\perp\right)=\frac{1}{N_c}\mathrm{Tr}\left[W\left(b_\perp\right)W^\dagger\left(b'_\perp\right)\right] \tag{2}$$

$$z=\tau/x\xi \tag{3}$$

$$\tau=\bar{n}\cdot p_h/\bar{n}\cdot p_P=p_{h\perp}e^{y_h}/\sqrt{s} \tag{4}$$

- Introduce η regulator [J.-y. Chiu, A. Jain, D. Neill, and I. Z. Rothstein;arXiv:1104.0881,arXiv:1202.0814v2]

$$\frac{1}{(1-z)^{1+\eta}}\left(\frac{\nu}{\bar{n}\cdot p}\right)^{\eta}$$

- in which the rapidity scale ν is introduced and one will expands around $\eta=0$ before doing the ϵ-expansion in the dimensional regularization

$$-\frac{\alpha_s N_c}{2\pi\eta}\left[\frac{\nu}{\bar{n}\cdot p}\right]^{\eta}\frac{1}{\pi}\left[\frac{r_\perp^2}{r_\perp'^2 r_\perp''^2}\right]_+ \left\langle S_w^{(2)} S_w^{(2)}\right\rangle_\nu \delta(1-z) \tag{5}$$

$$-\frac{\alpha_s C_F}{2\pi\epsilon}\mathcal{P}_{qq}(z)\left[1+\frac{1}{z^2}e^{i\frac{1-z}{z}p'_\perp\cdot r_\perp}\right]\left\langle S_w^{(2)}\left(b_\perp, b'_\perp\right)\right\rangle_\nu \tag{6}$$

$$\mathcal{I}^{(3)}_{\delta,fin.} = \delta(1-z) - \frac{\alpha_s}{\pi}C_F\left[\mathcal{P}_{qq}(z)\ln\frac{r_\perp^2\mu^2}{c_0^2} - (1-z) + \left(-\frac{3}{2}\ln\frac{r_\perp^2 {p'_\perp}^2}{c_0^2}+\frac{1}{2}\right)\delta(1-z)\right]\frac{1}{2}\left(1+\frac{1}{z^2}e^{i\frac{1-z}{z}p'_\perp\cdot r_\perp}\right)$$
$$-\frac{\alpha_s}{\pi}\left(C_F-\frac{N_c}{2}\right)\left[\frac{1+z^2}{(1-z)_+}\tilde{I}_{21}(z) - 2\left((1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)\right)_+\right],$$

$$r_\perp = b'_\perp - b_\perp \qquad r''_\perp = x_\perp - b'_\perp \qquad r'_\perp = b_\perp - x_\perp$$

$$c_0 = 2e^{-\gamma_E} \tag{7}$$

$$\begin{aligned}\mathcal{I}_{fin.}^{(3)} = \frac{\alpha_s}{\pi}\frac{N_c}{2}\frac{1}{\pi}\Bigg[\frac{1+z^2}{(1-z)_+}\frac{1}{z}e^{i\frac{1-z}{z}p'_\perp\cdot r'_\perp}\frac{r'_\perp\cdot r''_\perp}{r'^2_\perp r''^2_\perp} \\ + \int_0^1 \mathrm{d}\xi\frac{1+\xi^2}{(1-\xi)_+}e^{i\xi p'_\perp\cdot r'_\perp}\left[\frac{e^{-ip'_\perp\cdot r'_\perp}}{r'_\perp 2}\right]_+\delta(1-z)\Bigg]\end{aligned} \tag{8}$$

$$\begin{aligned}\tilde{I}_{21} = \int\frac{\mathrm{d}^2x_\perp}{\pi}\Bigg[e^{-i(1-z)p'_\perp\cdot x_\perp}\left(\frac{x_\perp\cdot(zx_\perp-r_\perp)}{x_\perp^2(zx_\perp-r_\perp)^2}-\frac{1}{x_\perp^2}\right) \\ +e^{-ip'_\perp\cdot x_\perp}\left(\frac{1}{x_\perp^2}\right)\Bigg]\end{aligned} \tag{9}$$

The n-th order corrections to the partonic cross section possess the logarithmic structure in the large Nc limit

$$\hat{\sigma}^{(n)} \supset \sum_{k=0}^{n-1}\alpha_s^n\left(\frac{\ln^k(1-z)}{1-z}\right)_+ \tag{10}$$

Numerical Part

- change to Momentum space [Liu,Ma,Chao; Phys. Rev. D 100, 071503 (2019),arXiv:1909.02370]

$$\frac{d\sigma_{q\to q}}{d^2p_{h\perp}dy_h}$$
$$= \int_\tau^1 \frac{dz}{z^2} D_{h/q}(z) \left\{ x_p f(x_p) \left[\mathcal{F}_F(k_{h\perp}; X_f) - \frac{\alpha_s N_c}{\pi^2} \ln\left(\frac{\bar{X}}{X_f}\right) I_{\rm BK}(k_{h\perp}, X_f) - \frac{\alpha_s N_c}{\pi^2} J_{\rm BK}(k_{h\perp}, X_f) \right] \right.$$
$$+ \frac{\alpha_s}{2\pi^2}\frac{N_c}{2} \left\{ \int_{\frac{\tau}{z}}^1 d\xi \frac{x_p}{\xi} f\left(\frac{x_p}{\xi}\right) \frac{2(1+\xi^2)}{(1-\xi)_+} I_{\rm rBK}(k_{h\perp}, X_f, \xi) + \int_0^1 d\xi x_p f(x_p) \frac{2(1+\xi^2)}{(1-\xi)_+} I_{\rm vBK}(k_{h\perp}, X_f, \xi) \right.$$
$$+ \int_{\frac{\tau}{z}}^1 d\xi \frac{x_p}{\xi} f\left(\frac{x_p}{\xi}\right) \pi \frac{1+\xi^2}{(1-\xi)_+} \left[\mathcal{F}_F(k_{h\perp}; X_f) \ln\frac{k_{h\perp}^2}{\mu^2} + \frac{1}{\xi^2}\mathcal{F}_F\left(\frac{k_{h\perp}}{\xi}; X_f\right) \ln\frac{k_{h\perp}^2}{\xi^2\mu^2} \right]$$
$$- \int_0^1 d\xi x_p f(x_p) \pi \frac{2(1+\xi^2)}{(1-\xi)_+} \mathcal{F}_F(k_{h\perp}; X_f) \ln\frac{k_{h\perp}^2}{\mu^2}$$
$$+\pi \int_{\frac{\tau}{z}}^1 d\xi \frac{x_p}{\xi} f\left(\frac{x_p}{\xi}\right) (1-\xi) \left[\mathcal{F}_F(k_{h\perp}; X_f) + \frac{1}{\xi^2}\mathcal{F}_F\left(\frac{k_{h\perp}}{\xi}; X_f\right) \right] - \pi \int_0^1 d\xi x_p f(x_p) 2(1-\xi) \mathcal{F}_F(k_{h\perp}; X_f \tag{11}$$

$$\text{where } \bar{X} = k_{h\perp}^2 / \left(\frac{\tau}{z} s\right), I_{\rm BK}(k_\perp, X_f) = I_{\rm rBK}(k_\perp, X_f, 1) + I_{\rm vBK}(k_\perp, X_f, 1) \tag{12}$$

X_f is the CGC factorization scale

Numerical Part set up

- use NLO CT18PDF set in LHAPDF
- for different particle, use different fragmentation function(for charged hadron use NLO DSS FFs[arXiv:hep-ph/0703242]; for pi0 use NLO DSS FFs[arXiv:1410.6027] D0 use KKKS08 FF[arXiv:0712.0481])
- BK equation initial condition, whose form is[arXiv:1304.2221]

$$S_{x_0}^{(2)}\left(\vec{r}_t\right)=\exp\left[-\frac{\left(r_t^2 Q_{s0}^2\right)^{\gamma}}{4}\ln\left(\frac{1}{\Lambda r_t}+e\right)\right]$$

the parameters we choose is

$$x_0=0.01, \gamma=1.119, \Lambda=0.241\text{GeV}, Q_{s0,A}^2\left(x_0\right)=A^{1/3}Q_{s0,p}^2\left(x_0\right)=6Q_{s0,p}^2$$

$$\text{where } Q_{s0,p}^2=0.168\text{GeV}^2$$

For Lead nucleus,

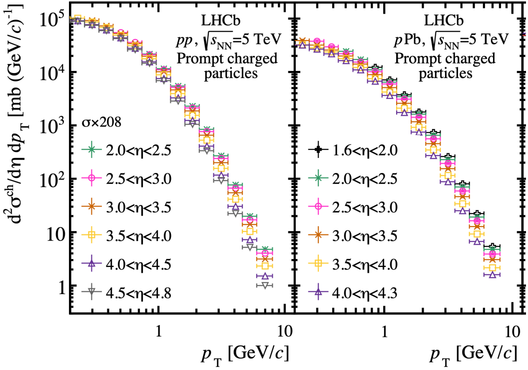
$$A=208$$

Numerical Part set up

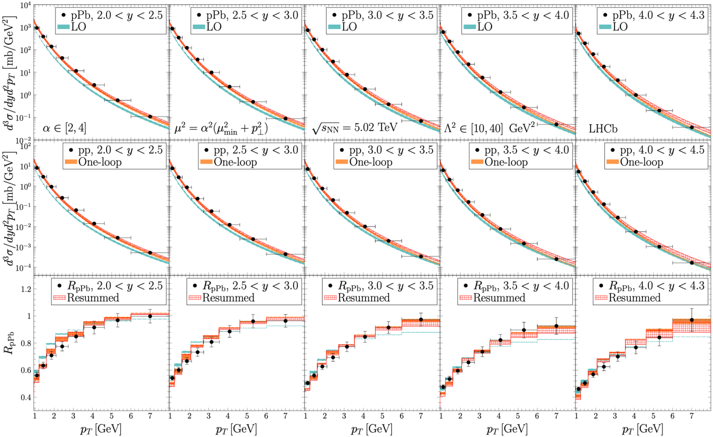
- For threshold resummation part, we follow the idea and procedure of article [arXiv:2004.11990]
  to determine the central rapidity scale by scanning through Xf numerically to find the value that minimizes the exponent.
- For theoretical uncertainty introduced by CGC factorization, estimate it through changing Xf from $0.5Xf$ to $2Xf$ for fixed kinematics.
- For running coupling α_s,we take the PDG α_s NLO form;
- $S_\perp$ can be interpreted as transverse area of the target nucleus or nucleon. Through out our numerical calculation, we take $S = \sigma 0/2 = 16.36mb$ for proton in pp collisions come from HERA data fit [Heikki Mantysaari,Hannu Paukkunen;arXiv:1910.13116] , so $S_\perp = 208^{2/3} * 16.36 \simeq 574$mb for Lead nucleus in pA collisions.

Numerical Part

- study object 1:pA->hX cross section :Here h refers to charged hadron. [LHCb collaboration; Phys.Rev.Lett. 128 (2022), 142004, arXiv:2108.13115v2]

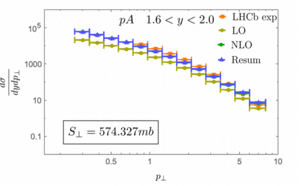


- article [Shi,Wang,Wei,Xiao; Phys. Rev. Lett. 128, 202302, arXiv:2112.06975v2] Numerical result:

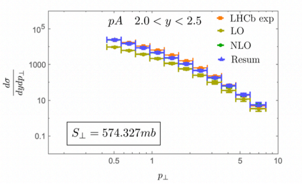


Numerical Part

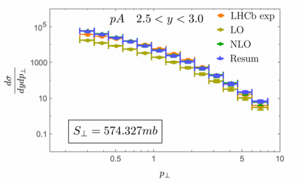
- Our Numerical result [pA result]



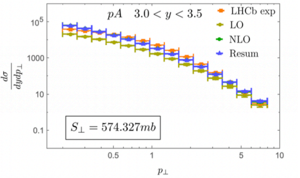
(a)pic1



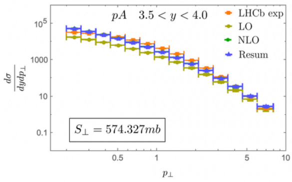
(b)pic2



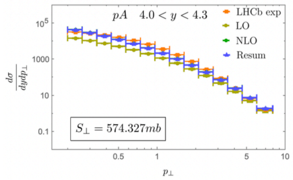
(c)pic3



(d)pic4.

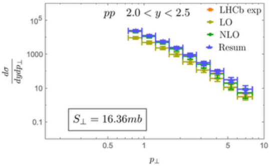


(e)pic5.

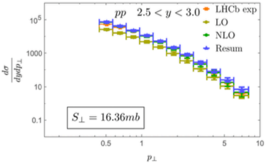


(f)pic6

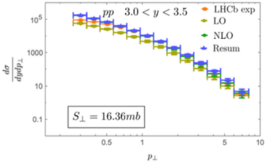
- Our Numerical result [pp result]



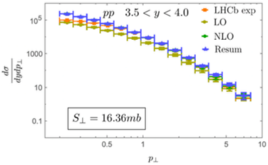
(a)pic1.



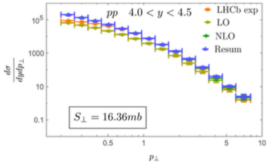
(b)pic2.



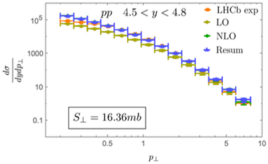
(c)pic3



(d)pic4



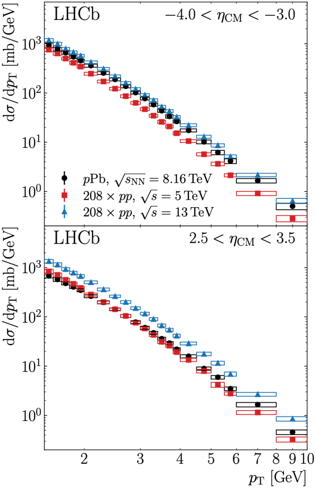
(e)pic5



(f)pic6.

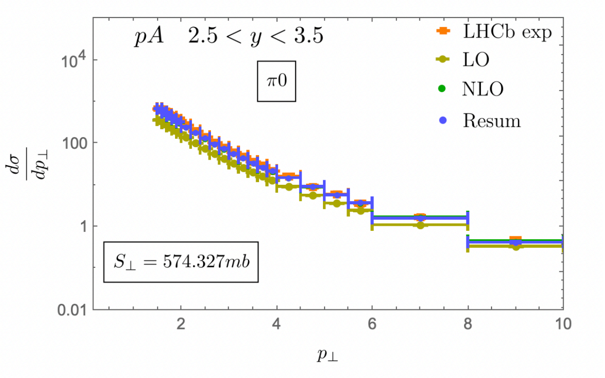
Numerical part

- study object 2:pA->hX cross section :Here h refers to pi0. [arXiv:2204.10608v1]



Numerical result

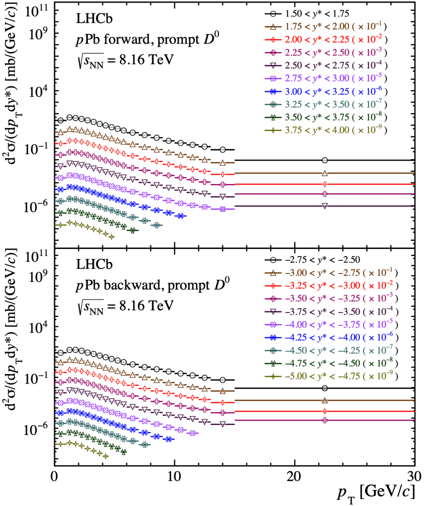
- preliminary numerical result



1. only include numerical error at the moment;
2. theory NLO and threshold resummation result all agree exp data better in numerical error range.

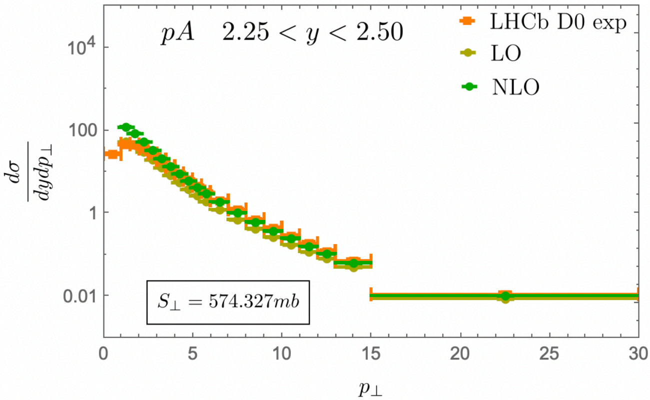
Numerical part

- study object 3:pA->hX cross section :Here h refers to D0 meson. [arXiv:2205.03936v2].



Numerical result

- preliminary numerical result

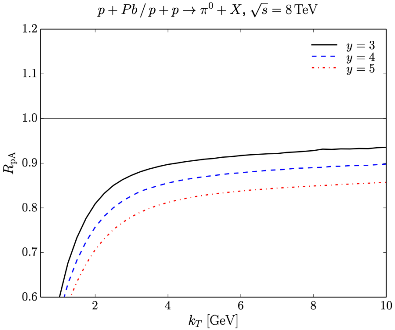


1. (a) use KKKS08 fragmentation function (b)have not consider charm quark mass effect
2. Our theoretical NLO result have good agreement with exp data.

Numerical part

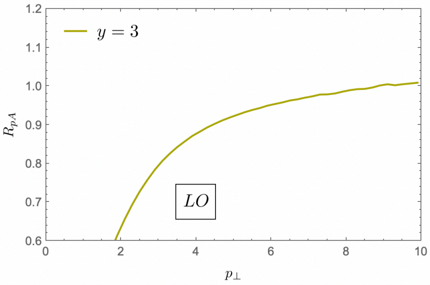
- study object 4:Nuclear modification factor: [arXiv:1710.02206].

$$R_{pA} \equiv \frac{d\sigma^{pA}/dy\, d^2p_\perp}{N_{coll}\, d\sigma^{pp}/dy\, d^2p_\perp}$$

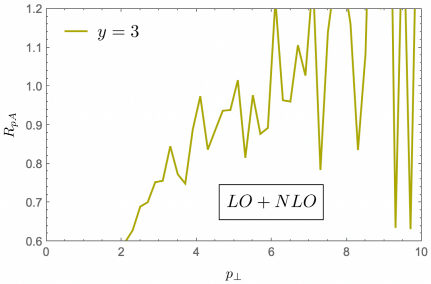


Numerical result

- Our preliminary numerical result



(a)LO Result



(b) NLO Result

1. R_{pA} approach 1 reveals the saturation effect.
2. Our theoretical LO result is agree well with article [arXiv:1710.02206].
3. The LO result is some different with other article result[arXiv:2307.04831],because the parameters we choose is different.

Summary and Outlook

- Summary
  - we did phenomenology study about several forward particle production (include neutral pion charged hadron and D0) in pA collisions in CGC framework use our parameters, and we conclude our theoretical result is good agreement with experimental data and the parameter we choose is proper.
  - Negative cross section problem come from the threshold region in forward hadron production in small x could solved by threshold resummation method.
  - At low pt region in LHCb, threshold resummation effect is not obvious.
- Outlook
  - pA ->hX numerical part will consider μ scale variation
  - do more Phenomenology study about pA collisions

Thanks for your attention!