Single-Inclusive Particle Production from pA Collision at Next-to-Leading Order

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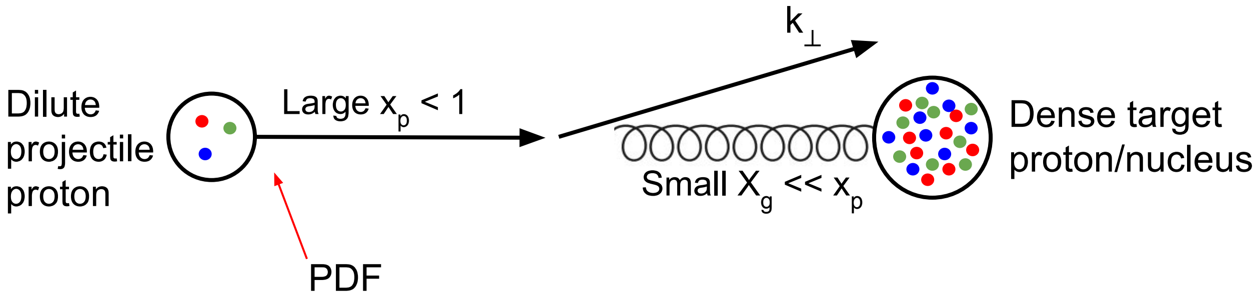
Motivation

- Single-inclusive particle production provides a way to test the CGC formalism against available data, e.g. [LHCb, 2108.13115].

Outgoing parton still forward-moving, now with transverse momentum $k_\perp$. Eventually will fragment into a hadron



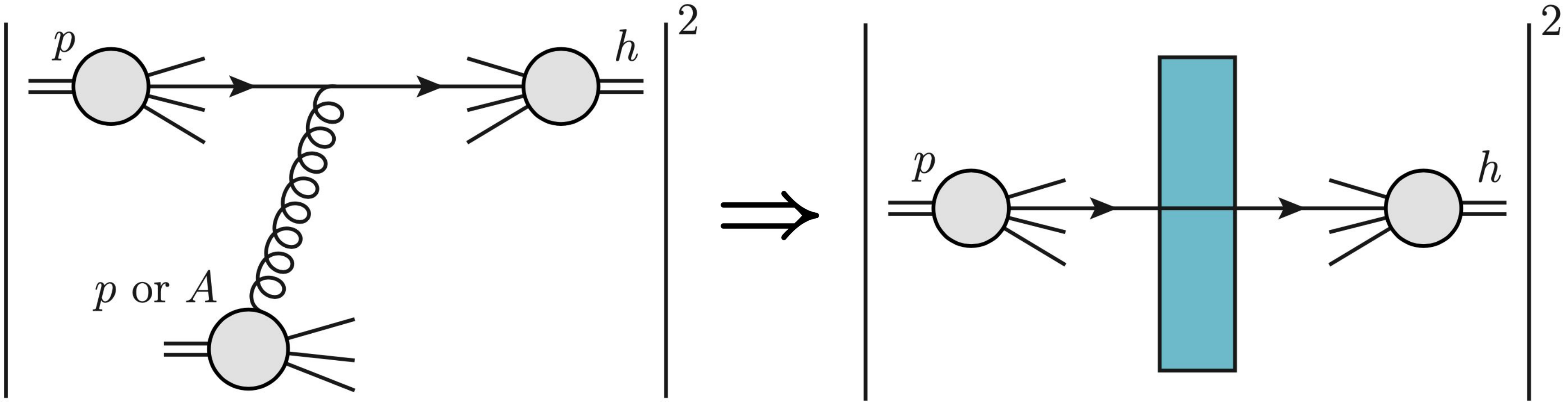
With CM energy s and (large) parton rapidity y,

$$x_p = \frac{k_\perp}{\sqrt{s}} e^y$$

$$X_g = \frac{k_\perp}{\sqrt{s}} e^{-y}$$

Single-inclusive particle production at small x

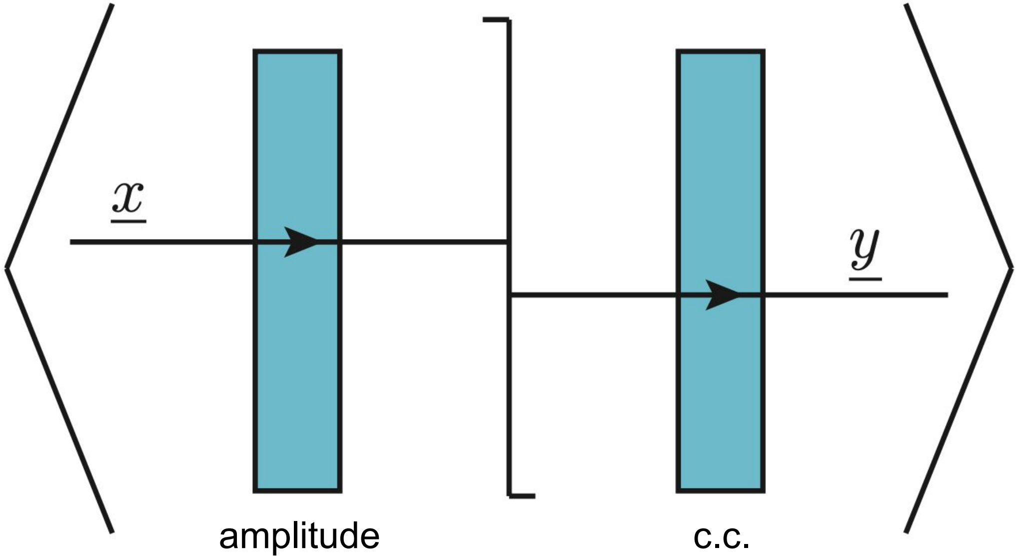
With a dilute projectile (proton) and a dense target (proton or nucleus), at leading order (LO), we have



Single-inclusive particle production at small x

With a dilute projectile (proton) and a dense target (proton or nucleus), at leading order (LO), we have

- This is the **impact factor.**
- Describes the interaction with the target
- Obeys Balitsky-Kovchegov (BK) evolution.
- Convolute with PDF and FF to get the full cross section.



$$\sim \left\langle \mathrm{tr}\left[V_{\underline{x}} V_{\underline{y}}^{\dagger}\right]\right\rangle (X_g)$$

Single-inclusive particle production at small x

With a dilute projectile (proton) and a dense target (proton or nucleus), at leading order (LO), we have

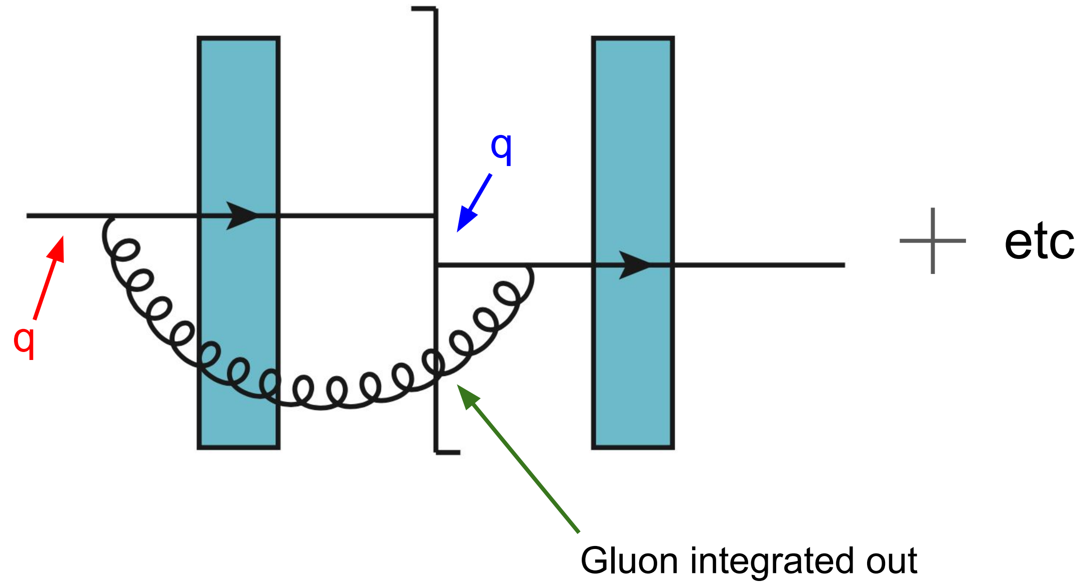
$$\frac{d\sigma_{pp/pA\to hX}}{d^2p_\perp dy} = \int \frac{dz}{z^2} \int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^2} e^{-ik_\perp\cdot(x_\perp - y_\perp)}$$
$$\times \Bigg[\sum_f x_p\, q_f(x_p)\, D_{h/f}(z)\, \frac{1}{N_c} \left\langle \mathrm{tr}\left[V_{\underline{x}} V_{\underline{y}}^\dagger \right] \right\rangle (X_g)$$
$$+ x_p\, g(x_p)\, D_{h/g}(z)\, \frac{1}{N_c^2 - 1} \left\langle \mathrm{Tr}\left[U_{\underline{x}} U_{\underline{y}}^\dagger \right] \right\rangle (X_g) \Bigg]$$

q channel: proton → quark → hadron

g channel: proton → gluon → hadron

NLO Corrections

At NLO, we include an additional splitting of **primary parton** [CXY, 1203.6139].



- LHS diagram: qq channel (q from incoming proton; q fragments into hadron.)
- At NLO, we also have qg, gq and gg channels.
- Cross section is more complicated, but still

$$\mathrm{PDF} \otimes \sigma_{\mathrm{parton}} \otimes \mathrm{FF}$$

NLO Corrections

- First calculation leads to negative cross section [Stasto et al, 1307.4057].
- Later fixed by a proper choice of running coupling [Ducloué et al, 1712.07480].
- Rapidity divergence can be absorbed into the BK evolution of dipole at LO.
  - **Unsubtracted scheme:** LO with unevolved dipole + full NLO kernel
  - **Subtracted scheme:** LO with evolved dipole + regulated NLO kernel
- Collinear divergence is removed through DGLAP evolutions of PDF and FF.
- At NLO, the dipole is BK-evolved based on available rapidity interval.

Recent Developments

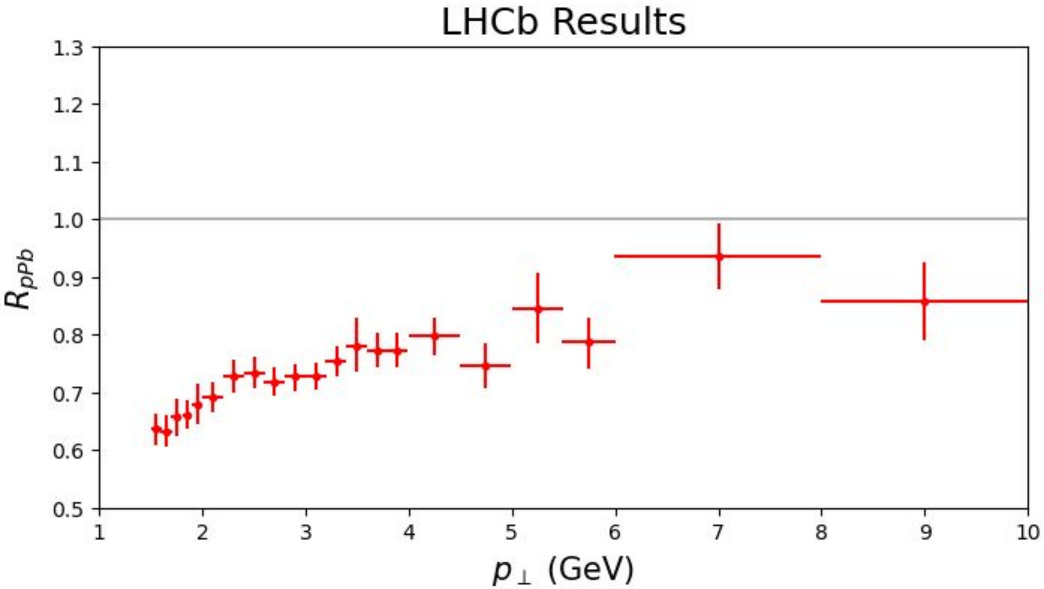
Work	Dipole BK evolution	Impact factor
[Kharzeev et al, 0307037] [Albacete et al, 0307179]	Initial condition	LO
	LO	LO
[Shi, Wang, Wei, Xiao, 2112.06975]	LO with running coupling	NLO
This work	NLO	LO
	NLO	NLO

Nuclear Modification Factor (R_{pA})

- Defined by

$$R_{\mathrm{pA}} = \frac{\frac{d\sigma_{pA\to hX}}{d^2 p_\perp dy}}{A \, \frac{d\sigma_{pp\to hX}}{d^2 p_\perp dy}}$$

- Compares the pA cross section with pp, adjusted for the number of nucleons.
- The latest LHCb results [LHCb, 2108.13115] with y = 3 and $\sqrt{s}$ = 8.16 TeV show R_{pPb} displayed on the right.

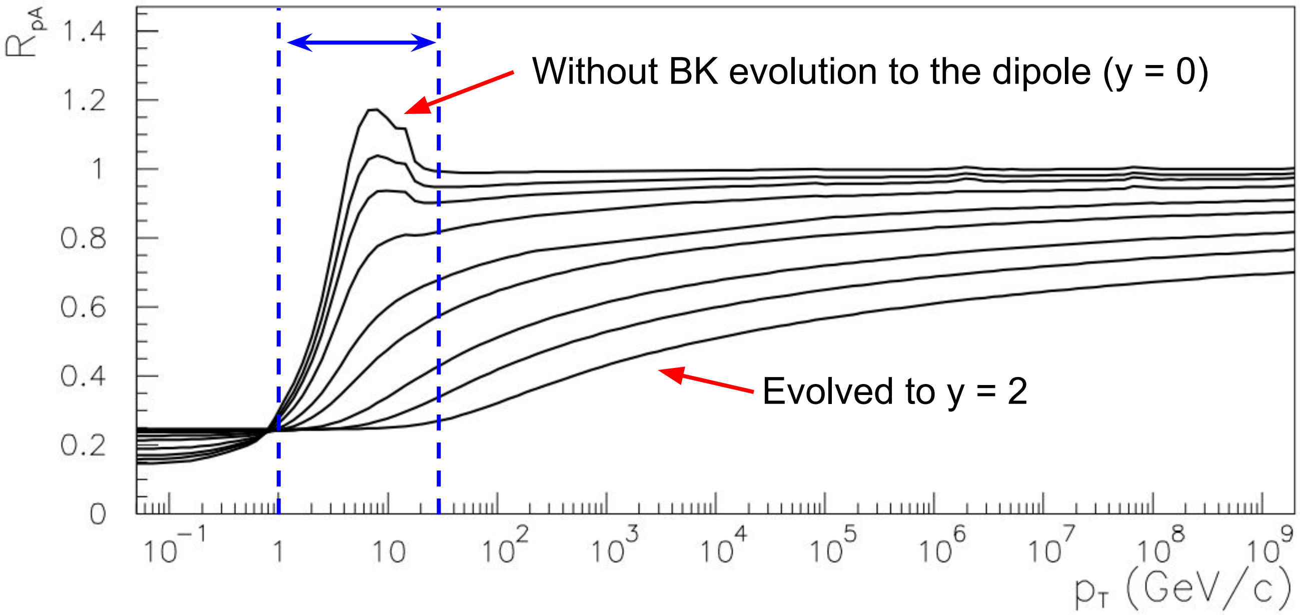


Our Ingredients

In this work, we calculate the NLO π^0 R_{pPb}, combining, for the first time:

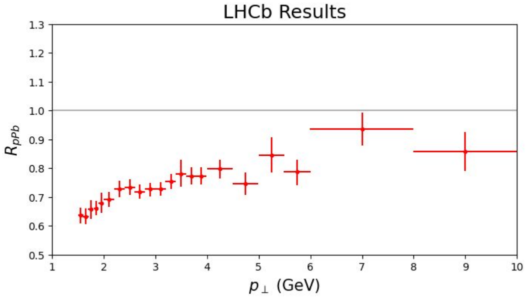
- Dipoles evolved using NLO BK eqn, fitted to HERA in [Beuf et al, 2007.01645].
  - For the NLO BK evolution, we consider the rapidity-local resummed (resumBK) [Iancu et al, 1502.05642] and the kinematically-constrained (KCBK) [Beuf, 1401.0313].
- All parton channels (gluon and 3 light (anti)quarks for incoming/outgoing), in addition to the qq channels considered in [Ducloué et al, 1712.07480].
- State-of-the-art dipole-nucleus amplitude with impact parameter dependence [Lappi et al, 1309.6963].
- Convolution with NLO PDF and NLO FF

Cronin Peak at LO

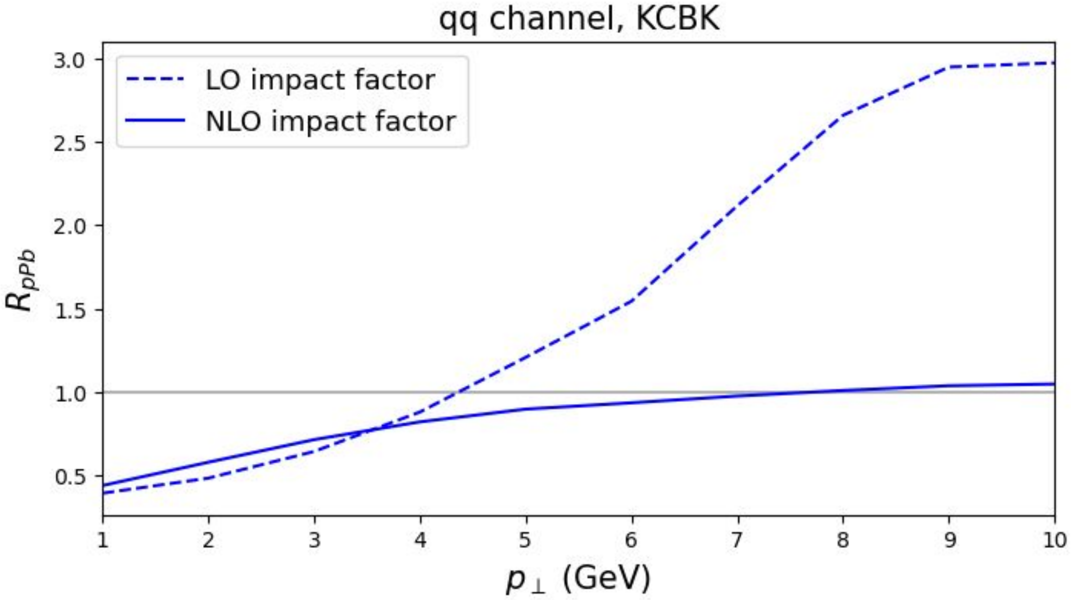


With LO impact factor, dipole evolved with LOBK to y = 0, 0.05, 0.1, 0.2, 0.4, 0.6, 1, 1.4 and 2 (top to bottom curves) [Albacete et al, 0307179].

With LO impact factor, LOBK evolution suppresses the Cronin peak present at IC [Kharzeev et al, 0307037] [Albacete et al, 0307179].



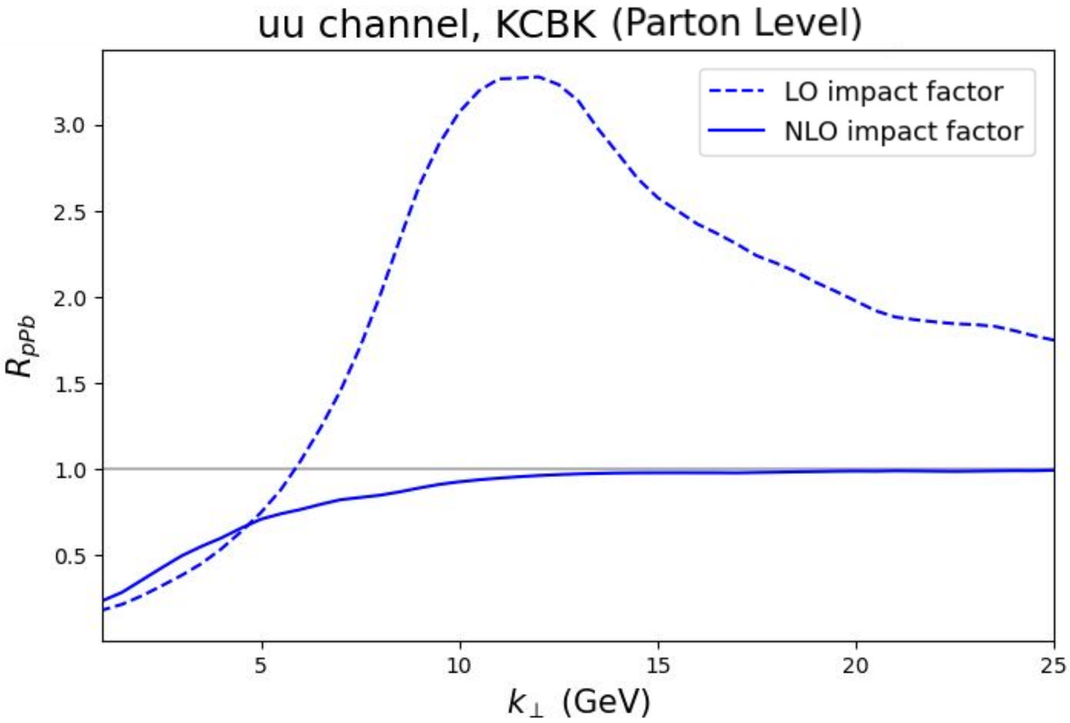
Cronin Peak in qq Channel



qq-channel contribution to π^0 R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics). Dipole evolved with KCBK (NLO). PDF and FF at NLO. Impact factor at LO/NLO.

- Cronin peak is large with LO impact factor, while NLO impact factor suppresses it significantly.
- LHCb data [LHCb, 2204.10608] show no Cronin peak at hadron level.

Cronin Peak in qq Channel



Parton-level uu-channel R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics), central collision (b=0). Dipole evolved with KCBK (NLO). PDF at NLO. Impact factor at LO/NLO.

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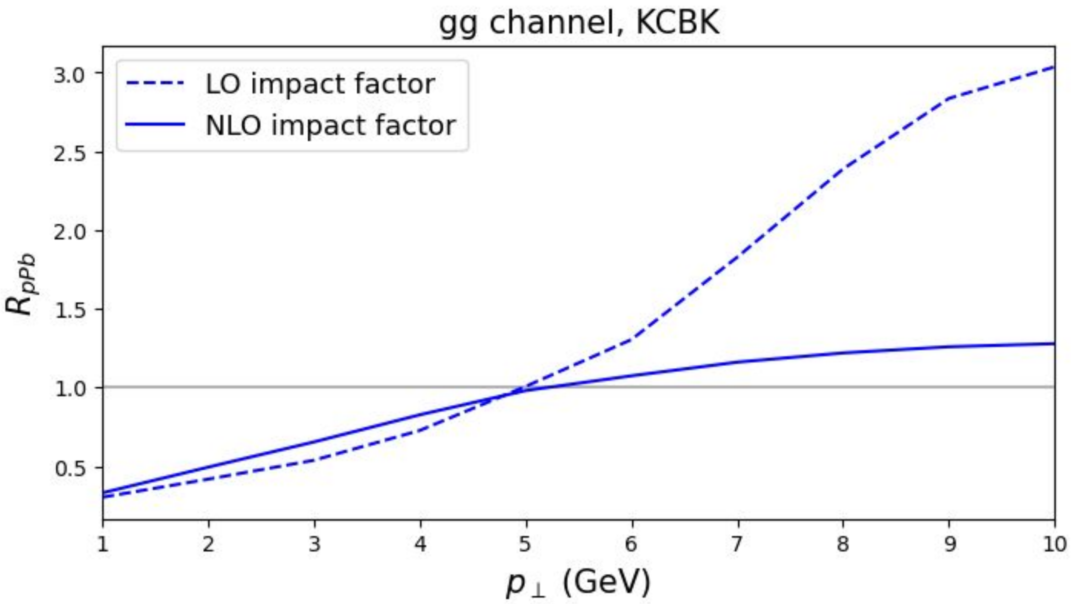
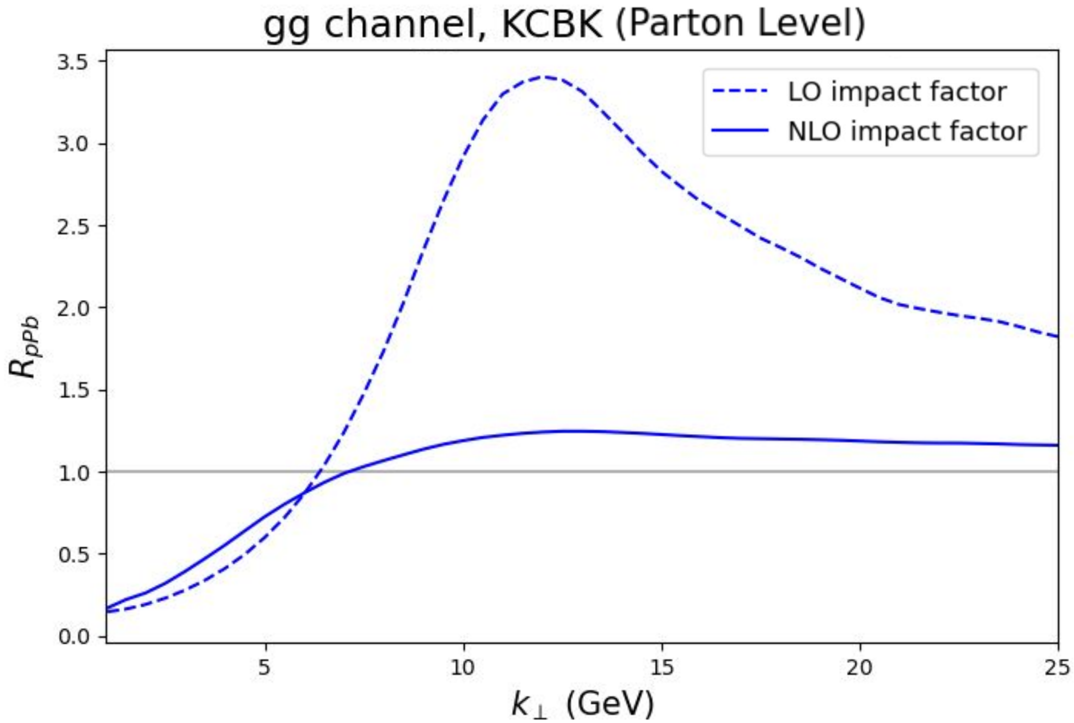
Cronin Peak in gg Channel



gg-channel contribution to π^0 R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics). Dipole evolved with KCBK (NLO). PDF and FF at NLO. Impact factor at LO/NLO.

- In contrast to the uu channel, the Cronin peak does not entirely disappear at NLO, but still significantly suppressed.

Cronin Peak in gg Channel



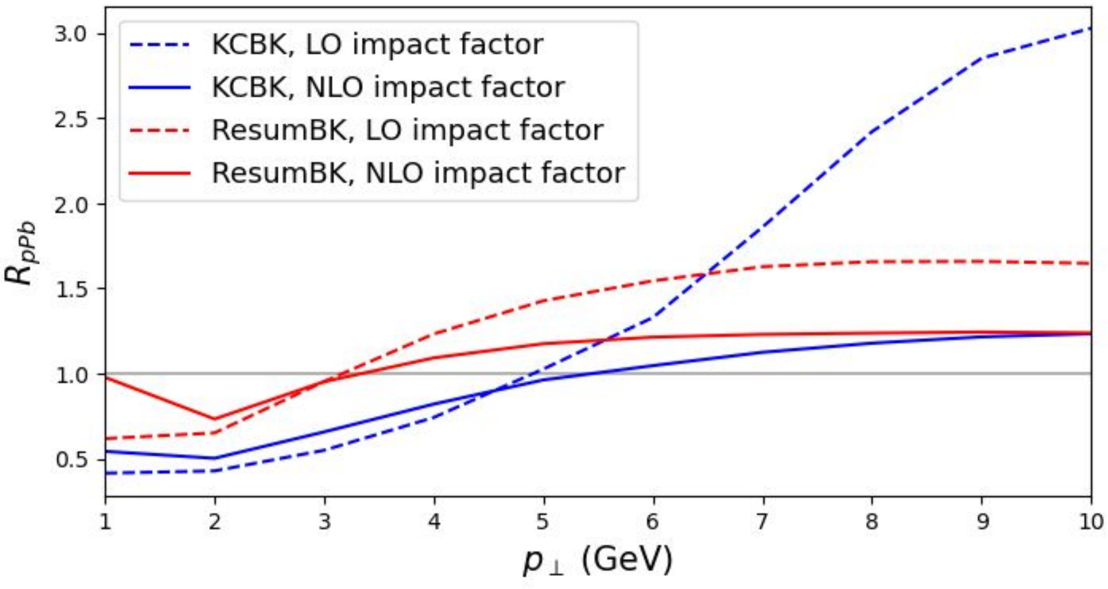
Parton-level gg-channel R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics), central collision (b=0). Dipole evolved with KCBK (NLO). PDF at NLO. Impact factor at LO/NLO.

- In contrast to the uu channel, the Cronin peak does not entirely disappear at NLO, but still significantly suppressed.

Recap: Cronin Peak in LHCb Kinematics

Work	Dipole BK evolution	Impact factor	Cronin peak
[Kharzeev et al, 0307037] [Albacete et al, 0307179]	Initial condition	LO	Yes
	LO	LO	No
[Shi, Wang, Wei, Xiao, 2112.06975]	LO with running coupling	NLO	No
This work	NLO	LO	Yes
	NLO	NLO	Suppressed

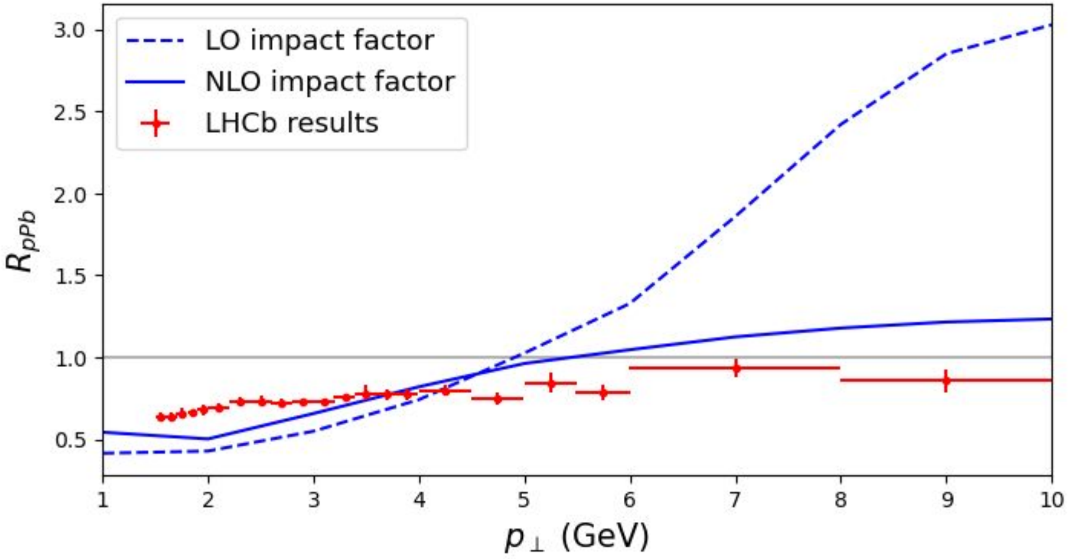
Resummation Scheme Dependence in BK Evolution



π^0 R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics), b=0. Dipole evolved with NLO BK. PDF and FF at NLO. Impact factor at LO/NLO.

- Cronin peak at LO gets removed at NLO, regardless of the evolution's resummation scheme.
- The difference is more pronounced at LO.
- We will also investigate the target momentum fraction (TBK) evolution [Ducloué et al, 1902.06637] in the future.

Comparison with LHCb Results



π^0 R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics). Dipole evolved with KCBK. PDF and FF at NLO. Impact factor at LO/NLO. LHCb data are taken from [LHCb, 2108.13115].

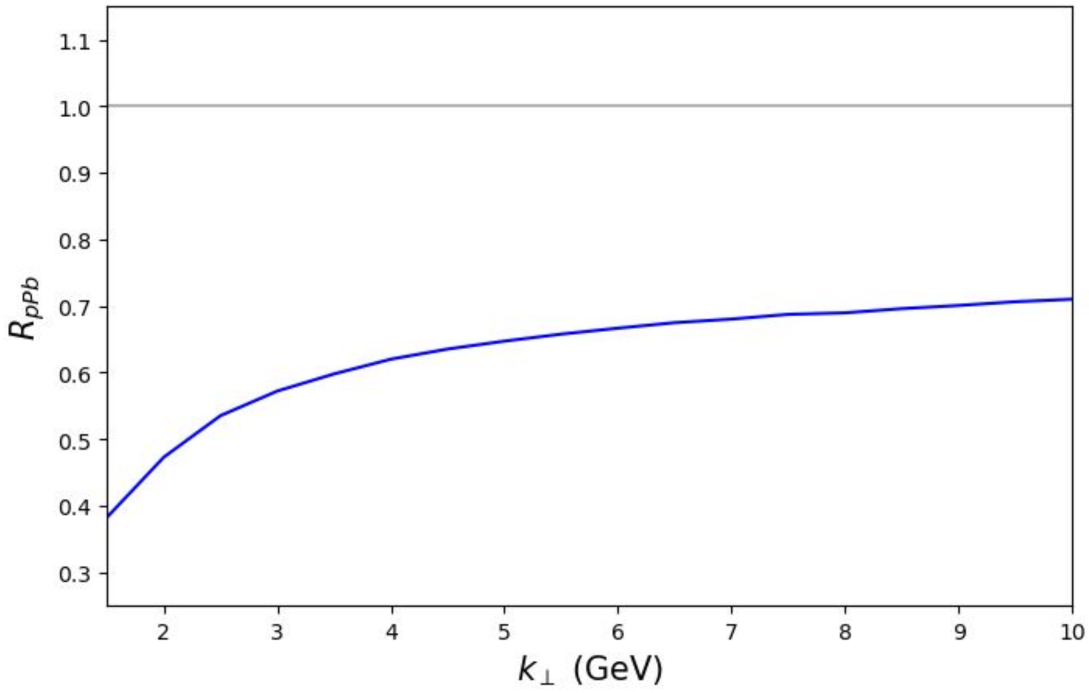
- NLO impact factor is an important correction at hadron level.
- Still a work in progress. We will investigate the source of NLO enhancement at $p_\perp \geq 5$ GeV.

Conclusion and Outlook

- We compute the single inclusive hadron production with NLO impact factor, using NLO dipole, PDF and FF.
- We observe the Cronin peak suppression by the NLO impact factor compared to LO.
- The dependence on NLO BK resummation scheme is suppressed with NLO impact factor. We will also check this for TBK.
- The R_{pPb} has an enhancement at high transverse momentum that we will investigate.

Backup Slides

Cronin Peak at LO: Crosscheck

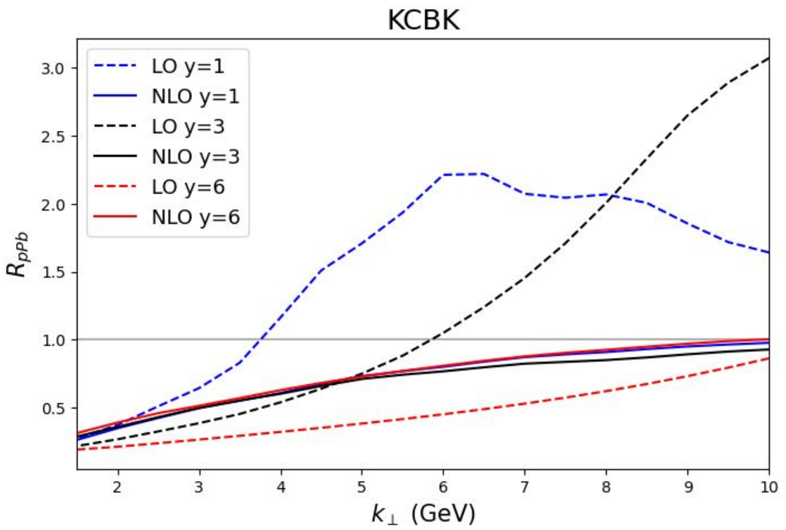


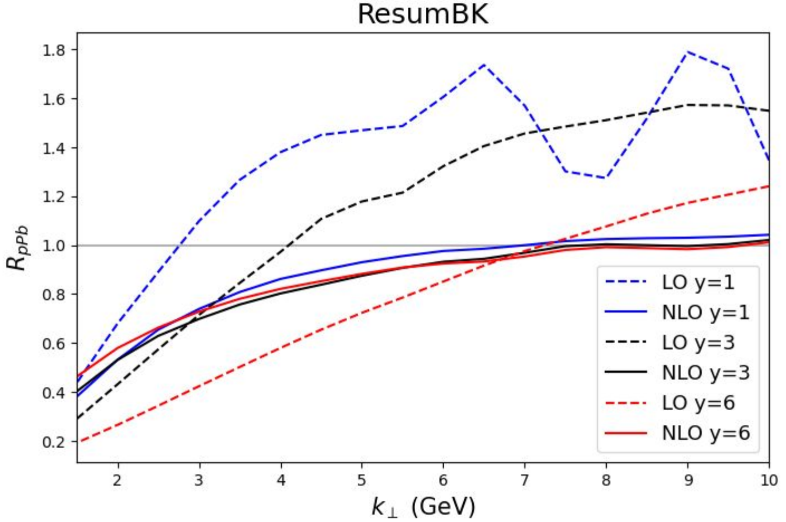
uu-channel R_{pPb} at y = 3, √s = 8.16 TeV, central collision (b=0). Dipole evolved with LOBK. PDF and impact factor at LO.

- This plot qualitatively agrees with the results by [Kharzeev et al, 0307037] [Albacete et al, 0307179], that LOBK evolution suppresses the Cronin peak.
- Note: this plot is only at parton level (not including FF convolution yet)

Results: Dependence on Rapidity

- Once we turn on the NLO impact factor, the dependence on rapidity, y, seems to be significantly suppressed, both with the KCBK and the resumBK evolutions.
- Understanding its cause is a work in progress.





uu-channel R_{pPb} at y = 1,3,6, $\sqrt{s}$ = 8.16 TeV, b=0. Dipole evolved with NLO BK. PDF at NLO. Impact factor at LO/NLO.