Full-NLO Forward Single-Inclusive Particle Production in pA Collisions

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Work in progress in collaboration with:
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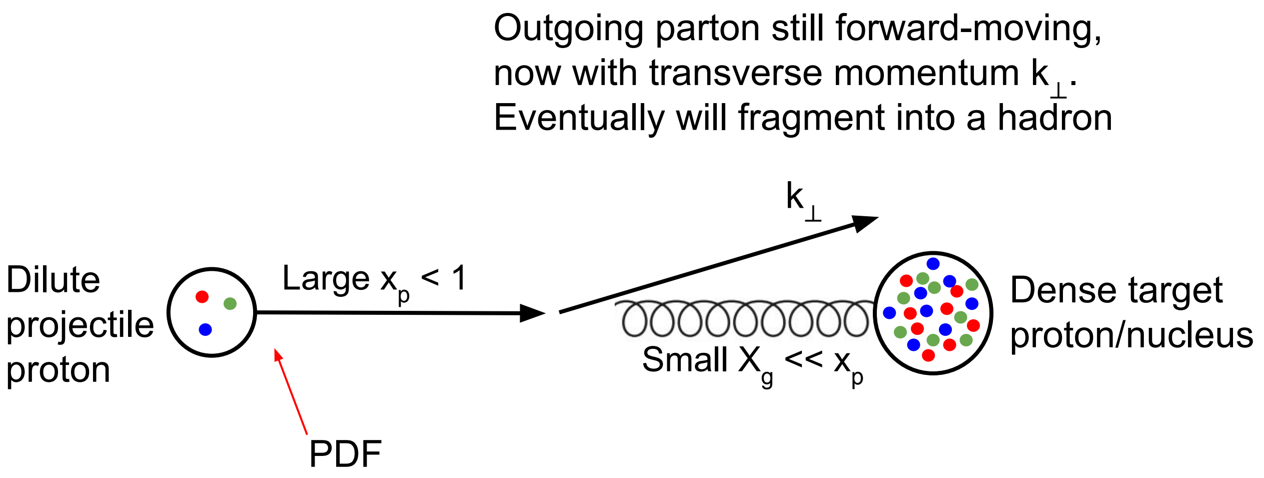
Motivation

- Single-inclusive particle production provides a way to probe heavy nuclei at small x.



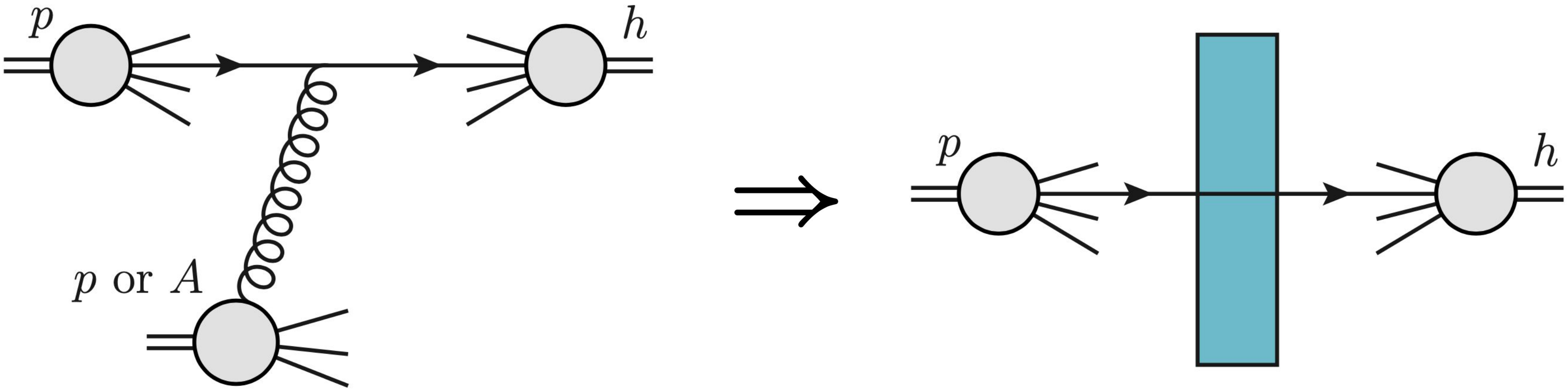
With CM energy s and (large) parton rapidity y,

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

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

Single-inclusive particle production at small x

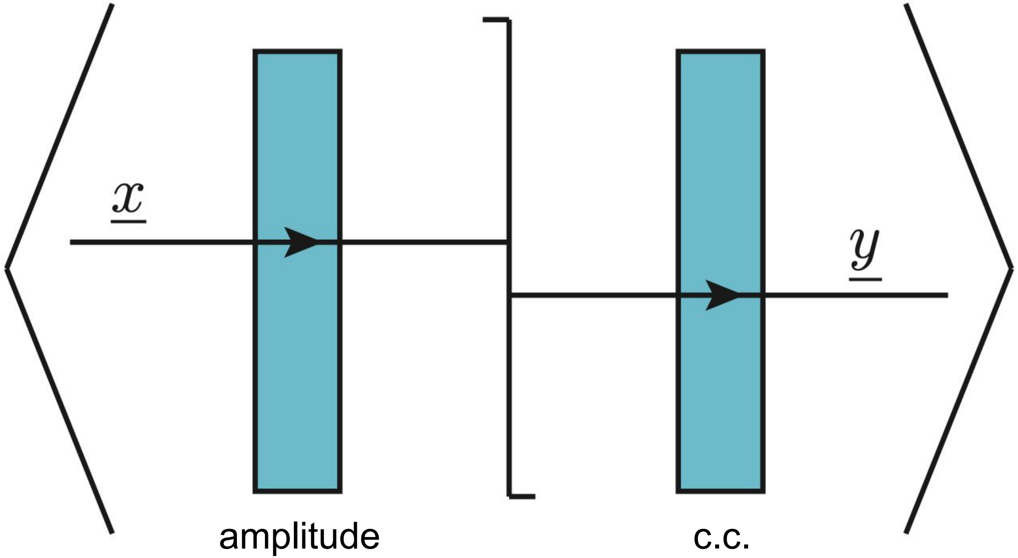
With a dilute projectile (proton) and a dense target (proton or nucleus), we have



Single-inclusive particle production at small x

With a dilute projectile (proton) and a dense target (proton or nucleus), we have

- Describes the interaction with the target
- Obeys BK evolution.
- Convolute with PDF and FF to get the hadron production 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) in impact factor, we have

$$\frac{d\sigma_{pp/pA\to hX}}{d^2p_\perp dy} = \int \frac{dz}{z^2} \int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^2}\, e^{-ik_\perp\cdot(x_\perp - y_\perp)}$$

$$\times \left[\sum_f x_p\, q_f(x_p)\, D_{h/f}(z)\, \frac{1}{N_c} \left\langle \mathrm{tr}\left[V_{\underline{x}} V_{\underline{y}}^\dagger \right] \right\rangle (X_g) \right.$$

$$\left. + x_p\, g(x_p)\, D_{h/g}(z)\, \frac{1}{N_c^2 - 1} \left\langle \mathrm{Tr}\left[U_{\underline{x}} U_{\underline{y}}^\dagger \right] \right\rangle (X_g) \right]$$

q channel: proton → quark → hadron

g channel: proton → gluon → hadron

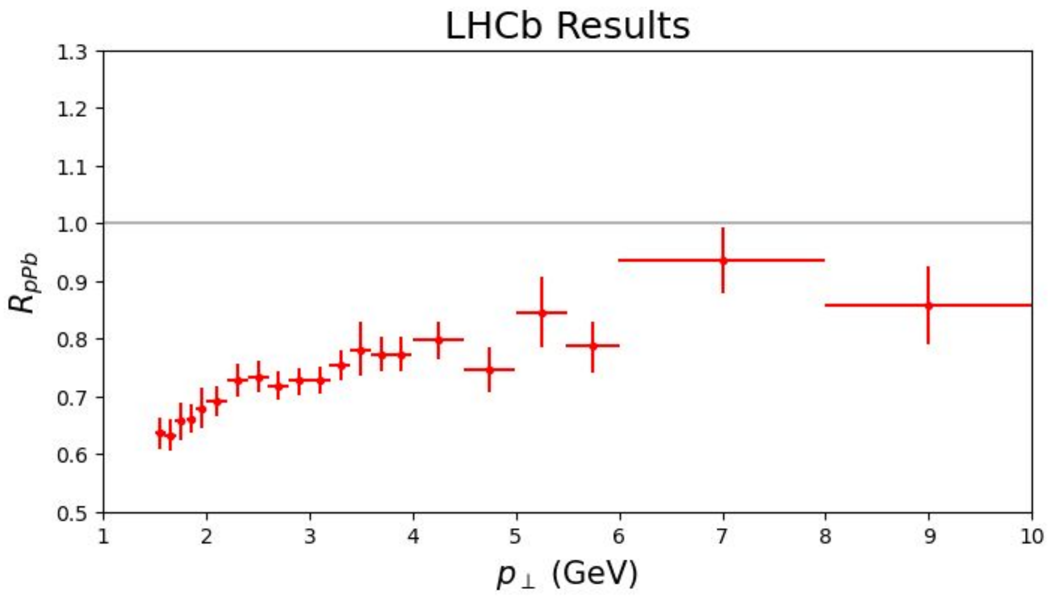
Nuclear Modification Factor (R_{pA})

- Defined by

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

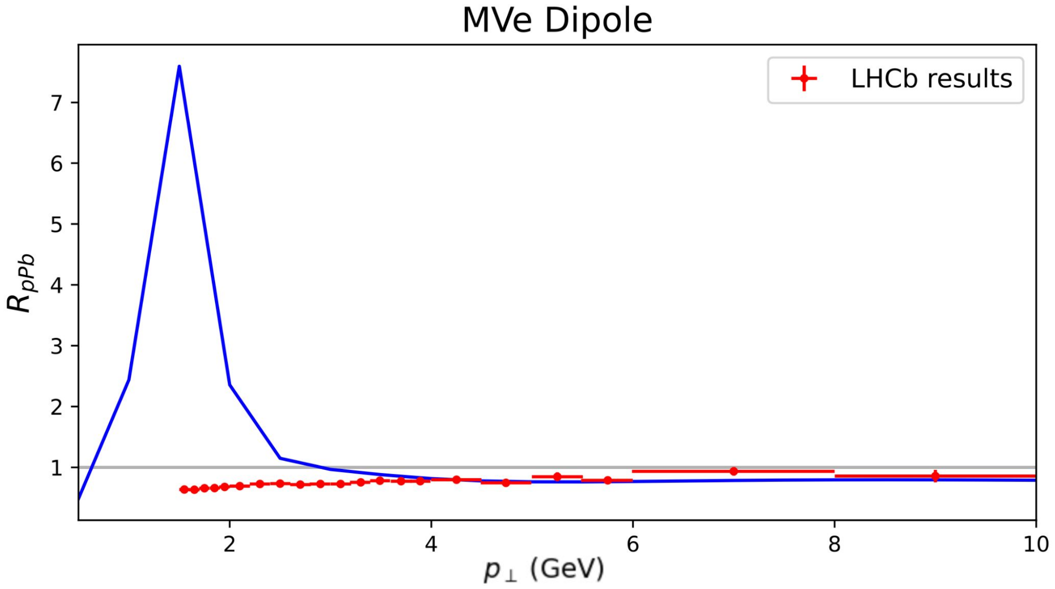
- Compares the pA cross section with pp, adjusted for the number of nucleons.

- The latest LHCb results [LHCb, 2108.13115] with y = 3 and √s = 8.16 TeV show R_{pPb} displayed on the right.



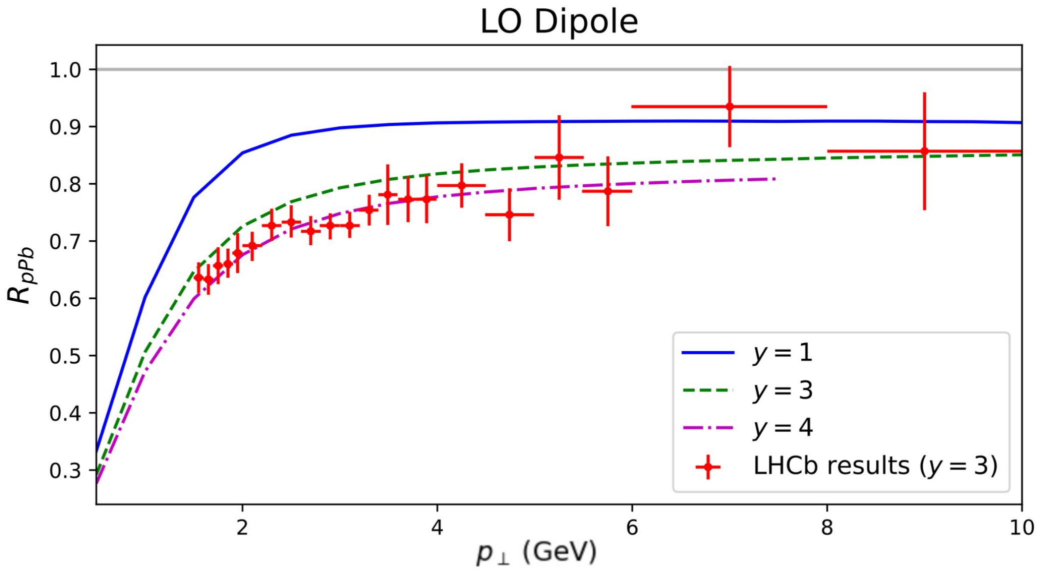
LO Impact Factor x Unevolved Dipole

- Plug the unevolved dipole according to MVe model into the LO impact factor.
- We see the Cronin Effect at low $p_\perp$, which disagrees with the LHCb data.



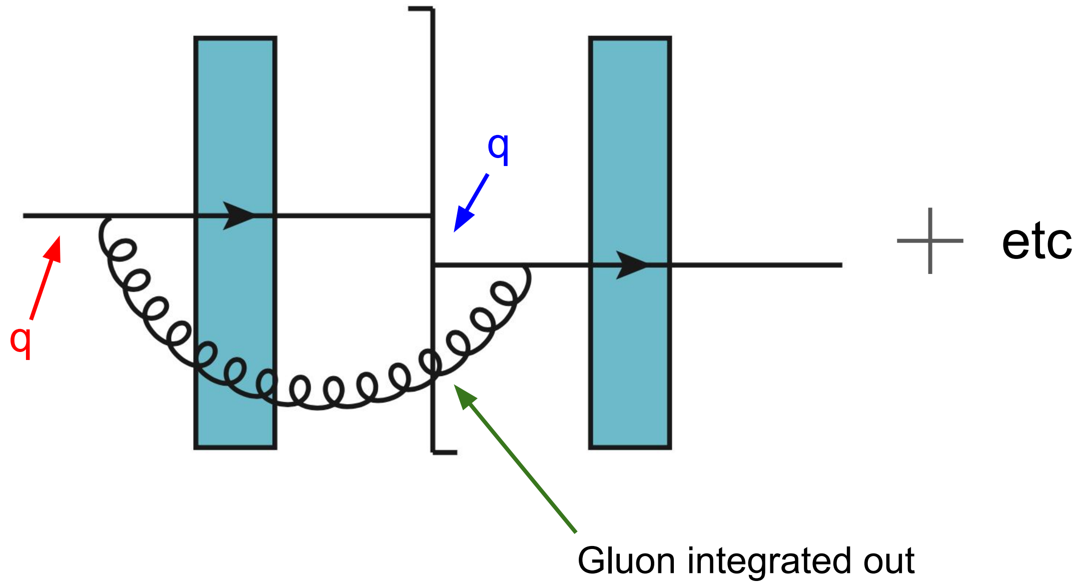
LO Impact Factor x LO Dipole

- Evolve the dipole according to LO BK evolution to rapidity y = 1,3 and 4, then plug the result into the LO impact factor.
- With the BK evolution, the Cronin peak goes away, giving a better agreement with data



NLO Corrections to the Impact Factor

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

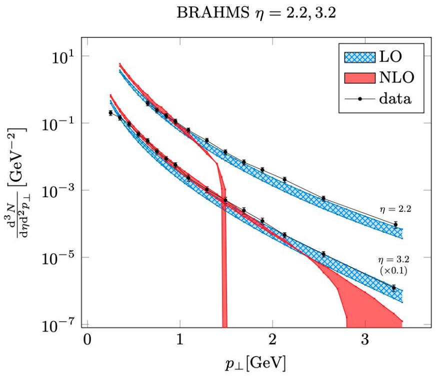


- LHS diagram: qq channel (q from incoming proton; q fragments into hadron.)
- We also have qg, gq and gg channels.
- Cross section is more complicated, but still

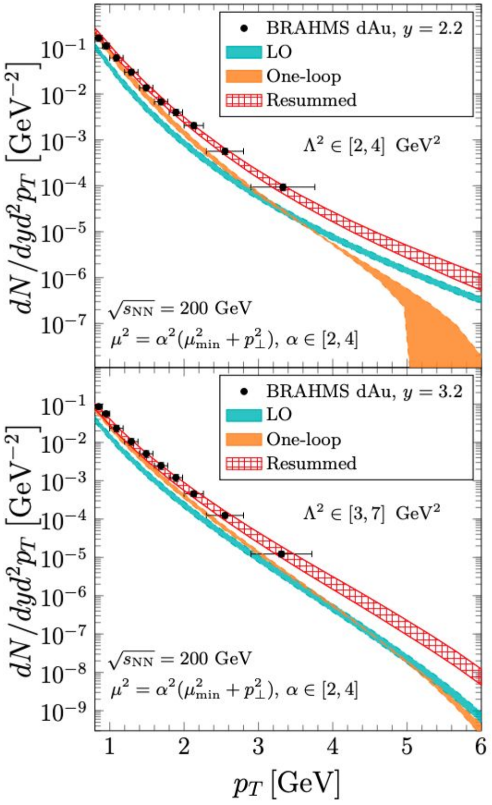
$$\mathrm{PDF} \otimes \sigma_{\mathrm{parton}} \otimes \mathrm{FF}$$

NLO Impact Factor x LO Dipole

- First calculation leads to negative cross section [Stasto et al, 1307.4057].
- Later fixed (for the qq channel) with a proper choice of running coupling and a different rapidity subtraction scheme [Ducloué et al, 1712.07480].
  - This sets up the framework for our current work.
- More recently, [Shi et al, 2112.06975] employs threshold resummation to also get positive cross sections that agree with BRAHMS and LHCb data.



[Stasto et al, 1307.4057]



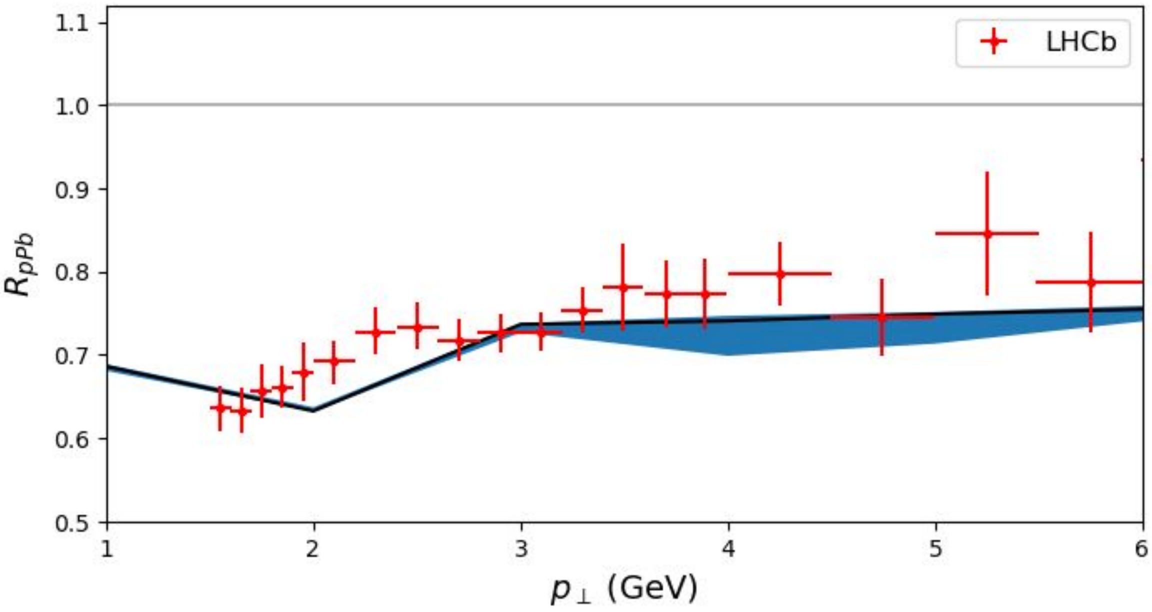
[Shi et al, 2112.06975]

NLO Impact Factor x NLO Dipole

In this work, we calculate the NLO $\boldsymbol{\pi}^0$ R_{pPb}, combining, for the first time:

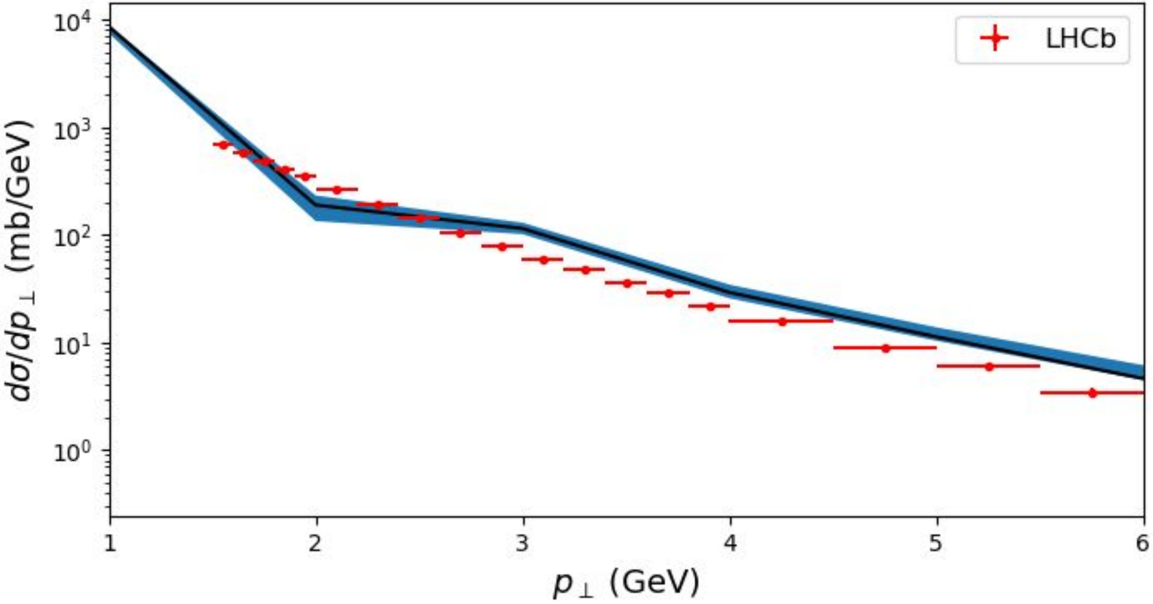
- Dipoles evolved w/ NLO BK eqn, fitted to HERA data in [Beuf et al, 2007.01645].
  - For the NLO BK evolution, we consider the rapidity-local resummed (resumBK) [Iancu et al, 1502.05642] and the kinematically-constrained (KCBK) [Beuf, 1401.0313].
- All parton channels (gluon and 3 light (anti)quarks for incoming/outgoing), in addition to the qq channels considered in [Ducloué et al, 1712.07480].
- Dipole-nucleus amplitude generalized from the dipole-proton case using optical Glauber following [Lappi et al, 1309.6963].

Results: Nuclear Modification Factor



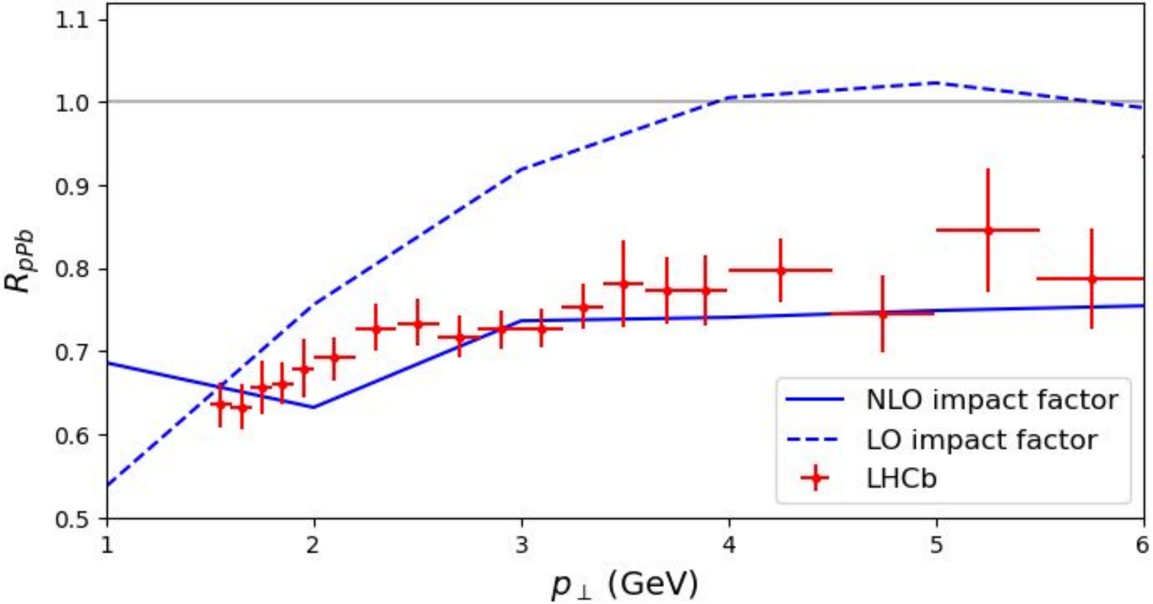
- Our results in LHCb kinematics ($y = 3$ and $\sqrt{s} = 8.16$ TeV)
- **NLO impact factor** convoluted with **NLO BK dipole,** using KCBK evolution with momentum-space coupling.
- Error band generated with different factorization scales: $\mu = 2p_\perp$, $4p_\perp$ and $8p_\perp$.
- Fair agreement with LHCb data with no Cronin effect.

Results: pA Spectra



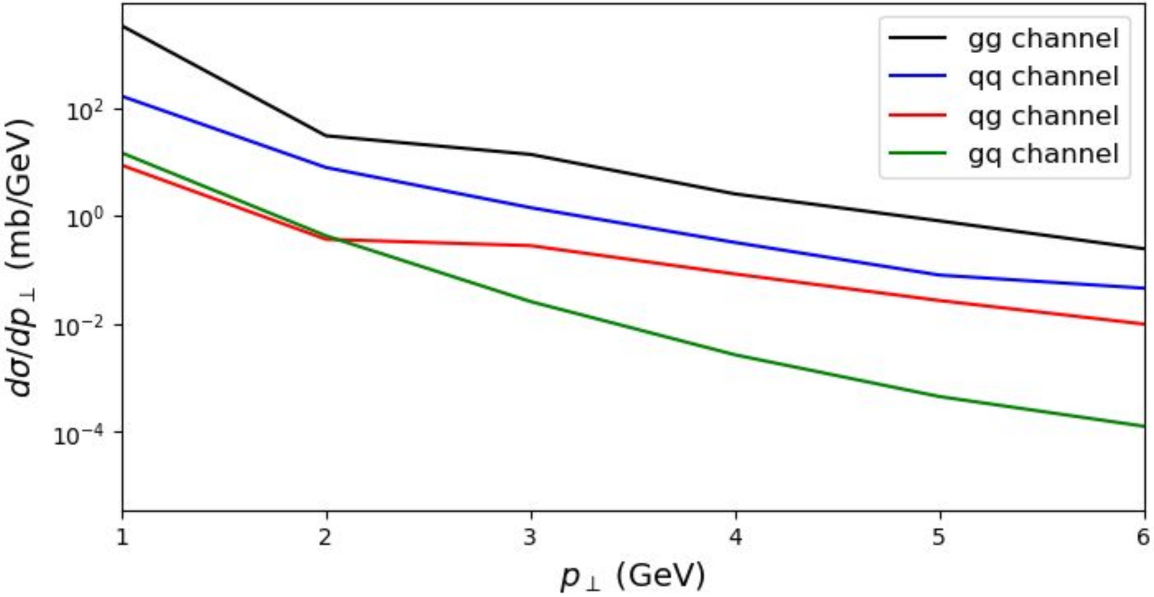
- Our results in LHCb kinematics (y = 3 and $\sqrt{s}$ = 8.16 TeV)
- **NLO impact factor** convoluted with **NLO BK dipole,** using KCBK evolution with momentum-space coupling.
- Error band generated with different factorization scales: $\mu = 2p_\perp$, $4p_\perp$ and $8p_\perp$.
- Agree in slope with LHCb data, with a slight normalization mismatch.

Cronin Effect with NLO Dipole



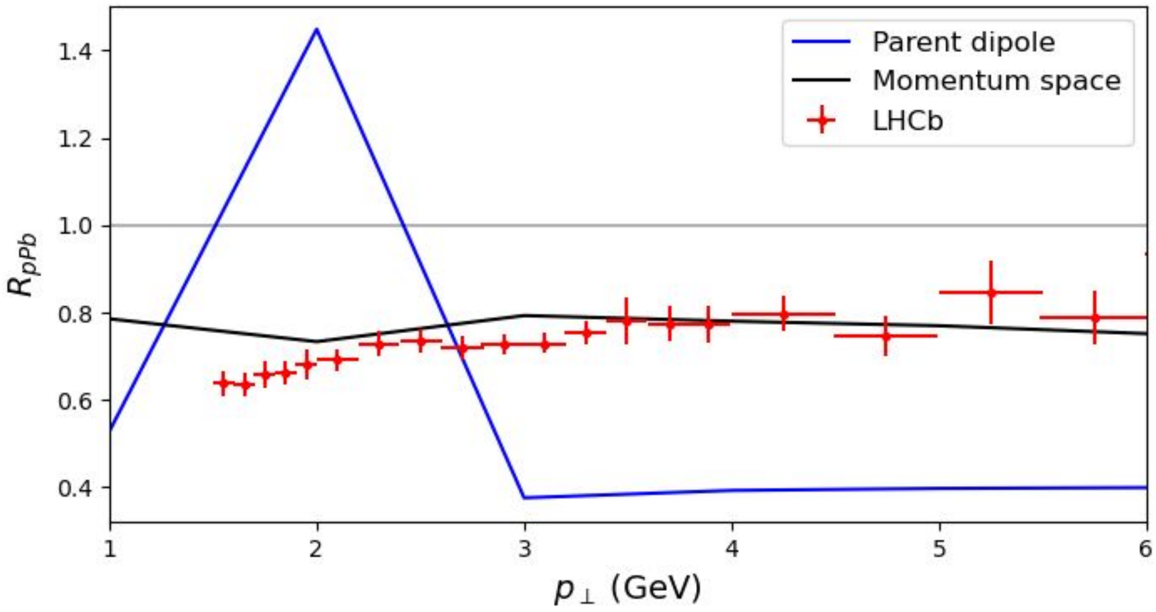
- Our results in LHCb kinematics ($y = 3$ and $\sqrt{s} = 8.16$ TeV)
- LO impact factor x NLO dipole: Cronin peak present at low $p_\perp$, i.e. NLO BK evolution does **not** remove the Cronin peak at IC.
- NLO impact factor x NLO dipole: Cronin peak disappears, leading to a better agreement with data.

Comparison between NLO Channels



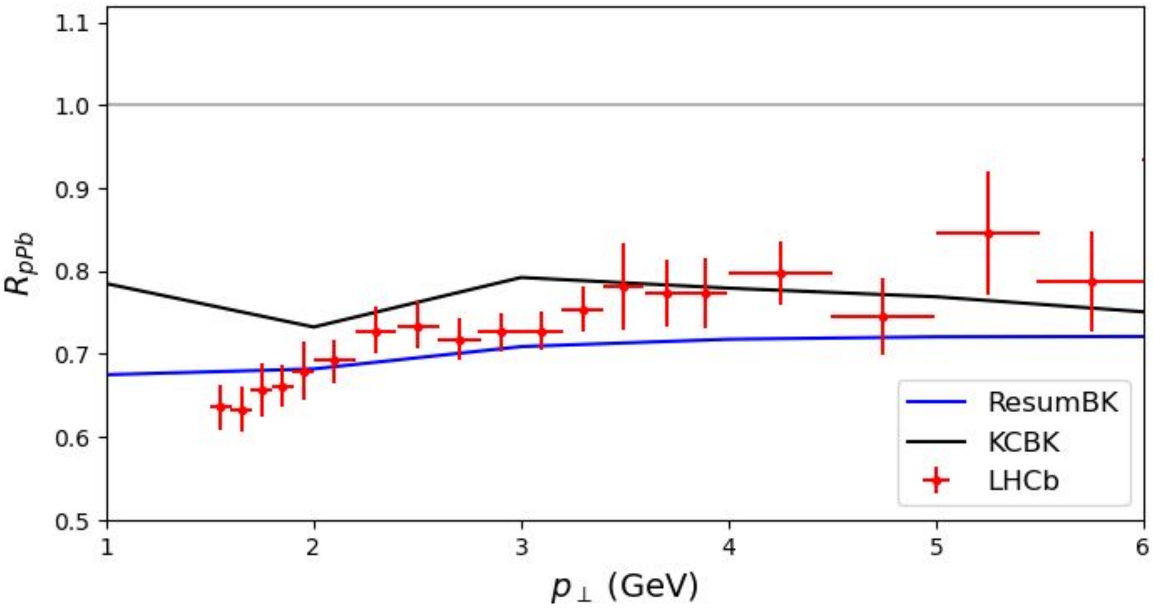
- Our results in LHCb kinematics (y = 3 and √s = 8.16 TeV)
- **NLO impact factor** convoluted with **NLO BK dipole,** using KCBK evolution with momentum-space coupling.
- As expected, gg channel dominates the pA spectra, followed by the qq channel.

Running Coupling Prescription in Impact Factor



- **Theory calculation at b = 0,** full NLO in LHCb kinematics (y = 3 and √s = 8.16 TeV).
- Parent-dipole rc prescription leads to “fake potential,” where the dominant contribution to full-NLO cross section comes from the non-interaction terms in dipole amplitude, c.f. [Ducloué et al, 1712.07480].

BK Resummation Scheme



- **Theory calculation at b = 0,** full NLO in LHCb kinematics (y = 3 and √s = 8.16 TeV).
- Using dipoles from different NLO BK resummation schemes (KCBK [Beuf, 1401.0313] and ResumBK [Iancu et al, 1502.05642]).
- We will also investigate the target momentum fraction (TBK) evolution [Ducloué et al, 1902.06637] in the future.

Conclusion and Outlook

- For the first time, we compute the forward single inclusive hadron production with NLO impact factor and NLO dipole.
- We observe the Cronin peak suppression that agrees with LHCb data in R_{pPb}. The pA spectra agree up to a normalization factor, which we will investigate.
- The parent-dipole rc does not work for the impact factor, confirming the previous “fake potential” results. Best to proceed with momentum-space rc.
- The dependence on NLO BK resummation scheme is suppressed for KCBK and ResumBK. We will also check this for TBK.