Complete NLO Single-Inclusive π^0 Production in Forward pA Collisions

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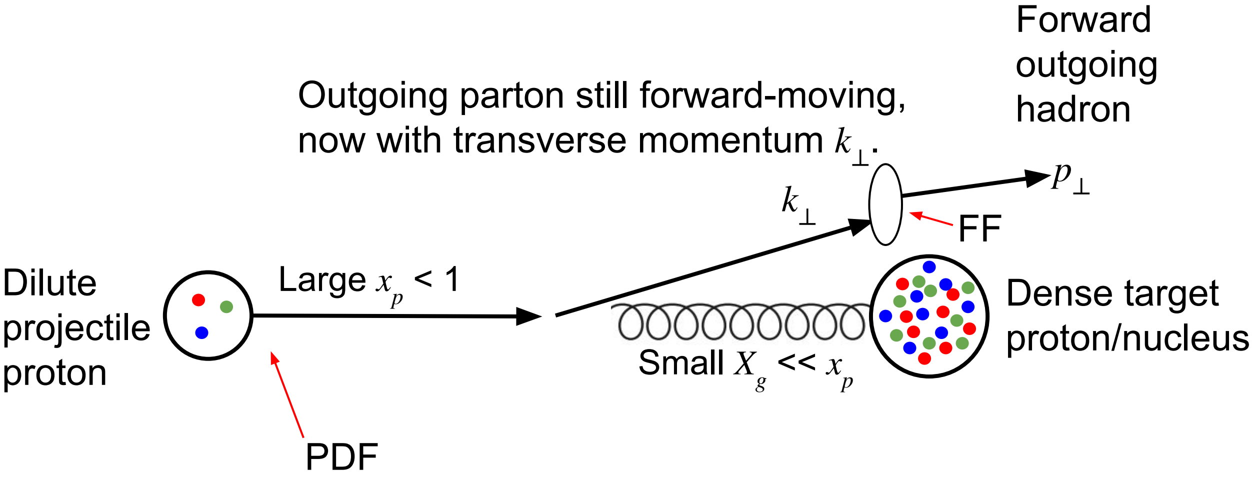
WILHELM UND ELSE HERAEUS-STIFTUNG

CoE QM

Based on: 2310.06640

Motivation

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



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

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

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

Setup

Hard factor

- Momentum space
- LO: Fourier transform of $S_{a,c}$ w.r.t. $k_\perp$.
- NLO: One emission of hard "primary parton"

Soft factor

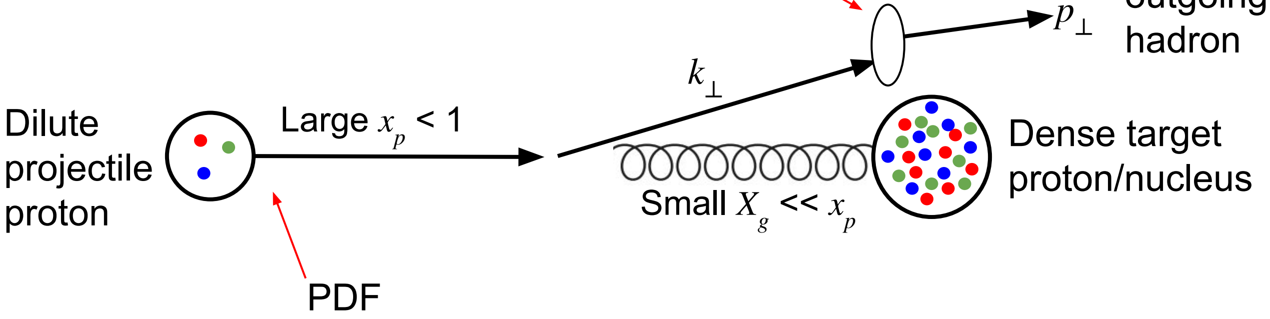
- Mixed space: $(k^+, x_\perp)$.
- Shockwave picture
- Interaction a + A corresponds to a color rotation of the forward parton line, a: "Wilson line"
- |Amplitude|^2: $\left\langle \mathrm{tr}\left[V_{\underline{x}} V_{\underline{y}}^\dagger\right]\right\rangle$
  - "Dipole amplitude"
  - Same d.o.f. as BK equation.

PDF

FF

$$\sigma^{p+\mathrm{A}\to h+X} \to \sum_{a,c} f_a \otimes \mathcal{H}_{a\to c} \otimes S_{a,c} \otimes D_{h,c}$$

Three (anti)quark flavors + gluon



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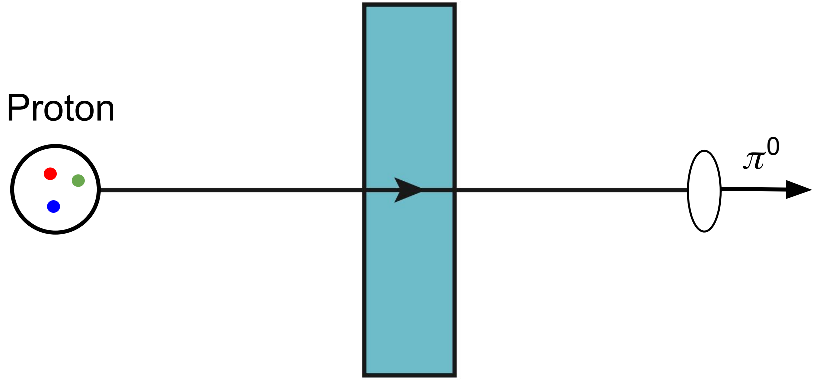
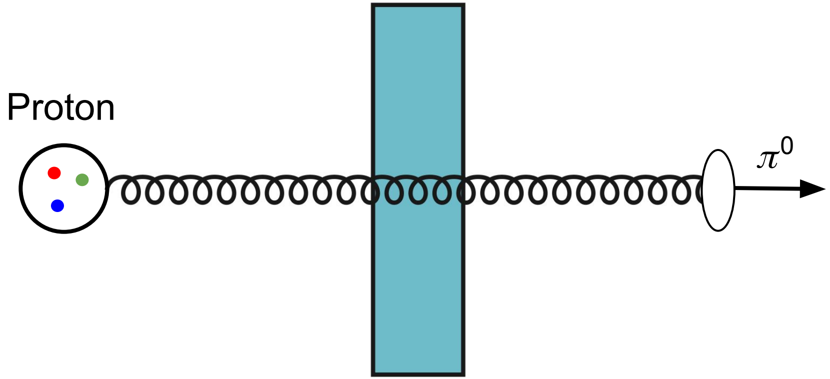
q channel:



g channel:



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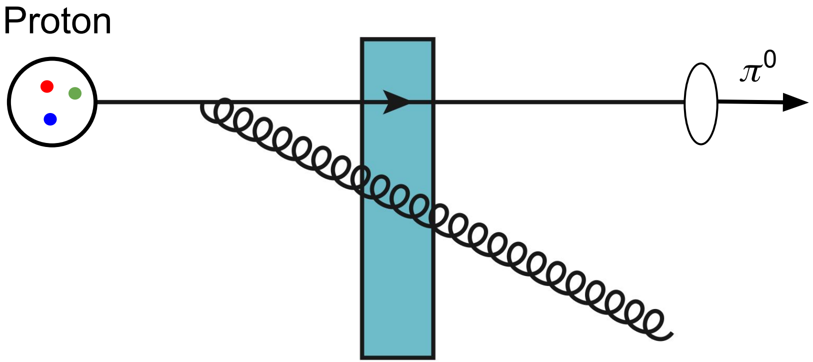

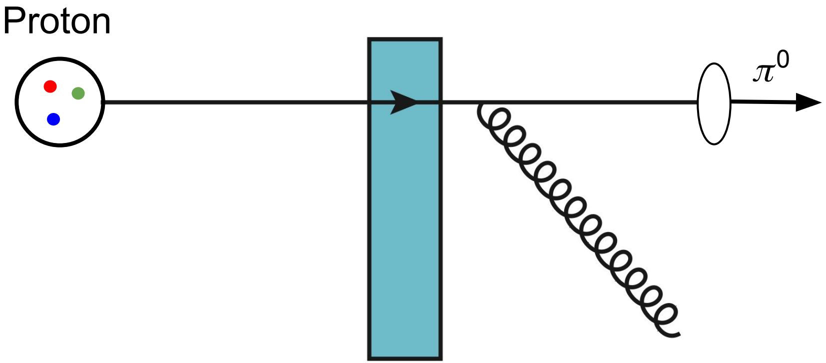

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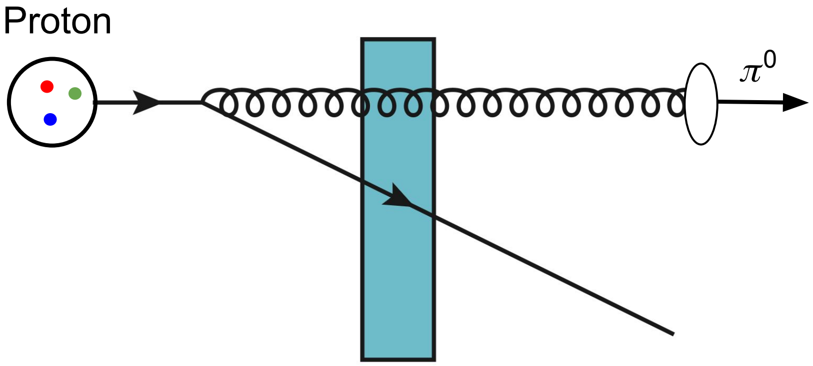

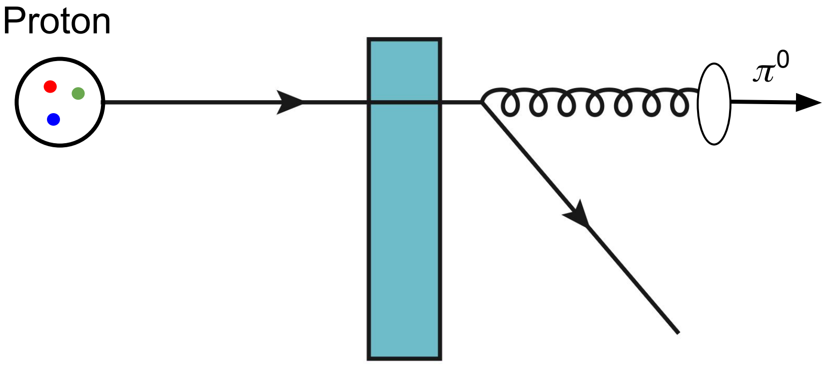

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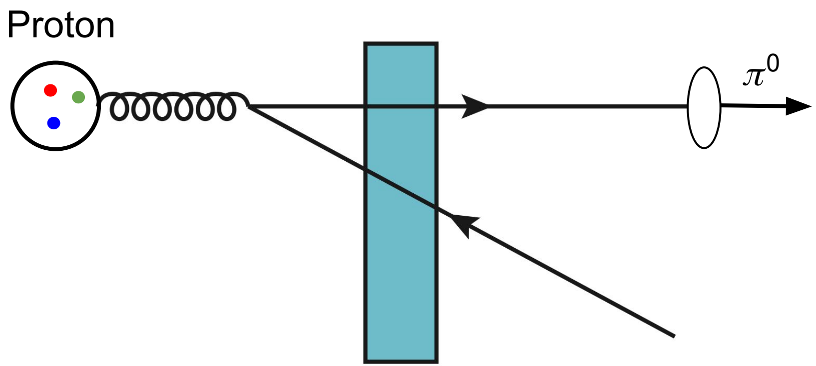

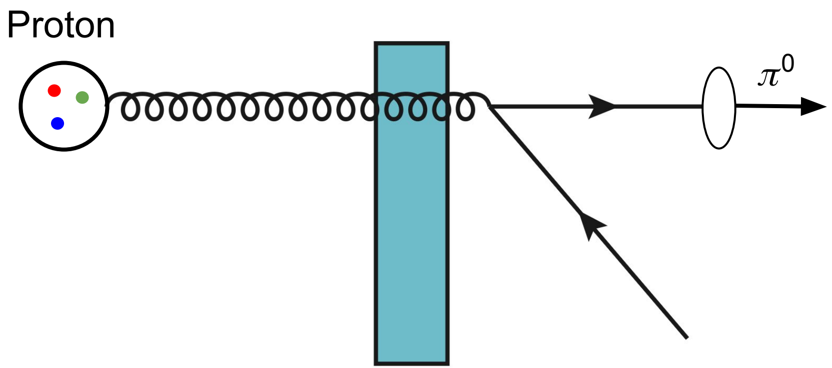

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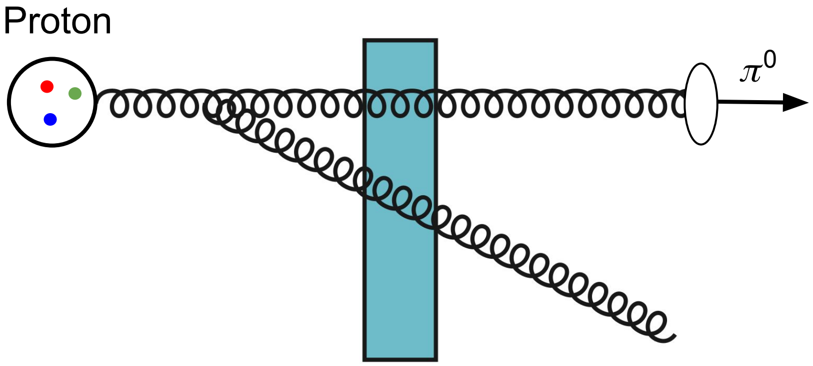
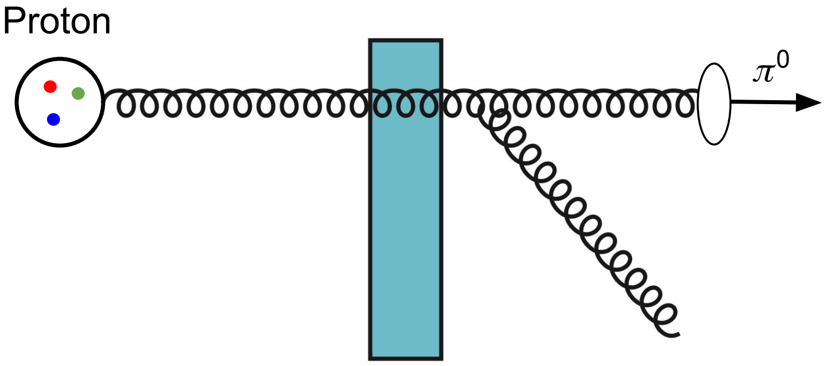
gg channel:





Dipole Amplitude

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- Initial condition generalizes MV model.
  - pp:

$$\exp\left[-\frac{(r_\perp^2 Q_{s,0}^2)^\gamma}{4}\ln\left(\frac{1}{r_\perp \Lambda_{\mathrm{QCD}}}+e\right)\right]$$

Using optical Glauber model to generalize pp to pA.

  - pA:

Nuclear transverse thickness function

$$\exp\left[-\frac{\sigma_0}{2}AT_A(\boldsymbol{b}_\perp)\frac{(r_\perp^2 Q_{s,0}^2)^\gamma}{4}\ln\left(\frac{1}{r_\perp \Lambda_{\mathrm{QCD}}}+e\right)\right]$$

Modify the initial saturation scale for pp to account for the impact-parameter profile of A [Lappi, Mäntysaari, 1309.6963].

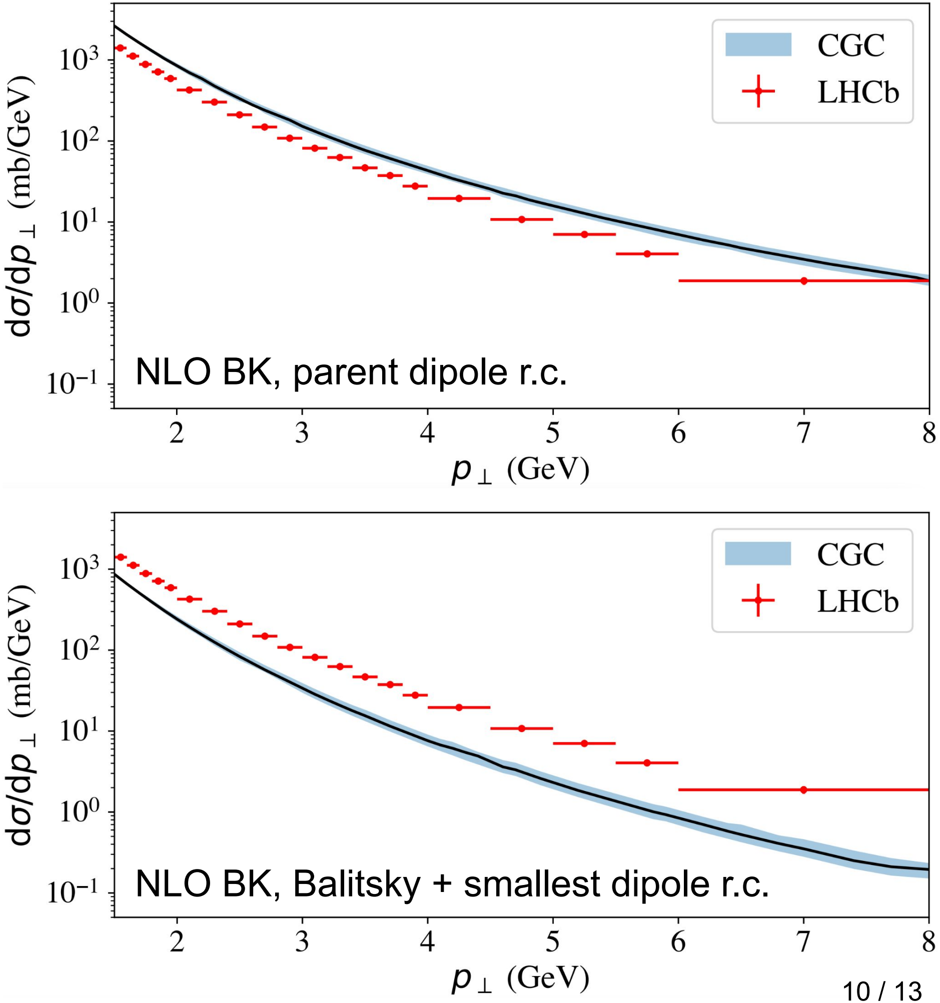
- High-energy (small-x) evolution: Balitsky-Kovchegov (BK) equation
  - For the first time, we include NLO corrections to BK (with running coupling).
  - Parameters γ, $Q_{s,0}$ and σ_0 taken from the fit to HERA data [Beuf et al, 2007.01645]

Neutral Pion Spectra (p+Pb)

<u>Kinematics</u>: y = 3 and $\sqrt{s}$ = 8.16 TeV.

LHCb: $y \in$ [2.5, 3.5] [LHCb, 2204.10608].

- Both: normalization mismatch.
- Balitsky + smallest dipole: falls more steeply than LHCb results.
- Each r.c. has different γ, $Q_{s,0}$ and σ_0 in the IC, such that DIS structure functions come out identical.
- Forward pA collisions put additional constraints on NLO BK parameters.



Nuclear Modification Factor

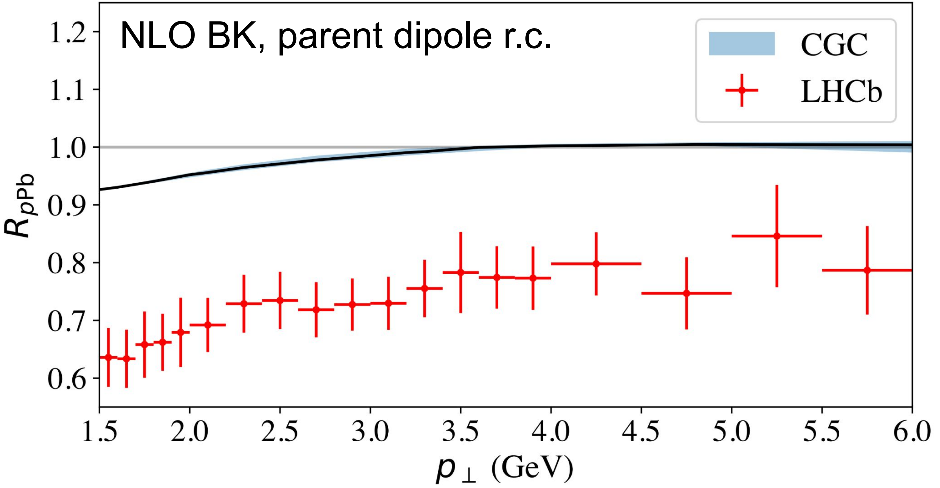
<u>Kinematics</u>: y = 3 and $\sqrt{s}$ = 8.16 TeV.

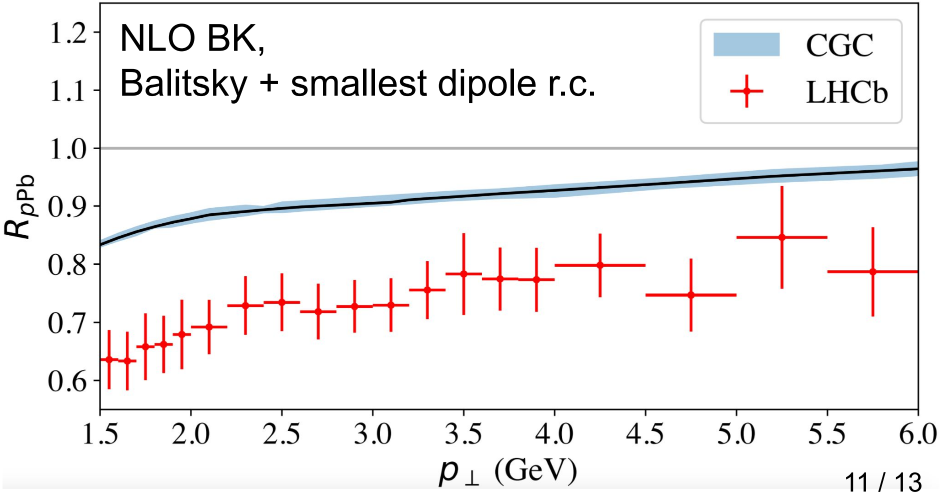
LHCb: $y \in [2.5, 3.5]$ [LHCb, 2204.10608].

$$R_{p\mathrm{Pb}} = \frac{\mathrm{d}\sigma^{pA\to h+X}}{A\,\mathrm{d}\sigma^{pp\to h+X}}$$

Similarly for both cases,

- Weak nuclear suppression at low $p_\perp$.
- $R_{p\mathrm{Pb}} \to 1$ at moderate to high $p_\perp$, overshooting LHCb data.
- Resulted from small σ_0 from the DIS fit, which is mostly sensitive to $\sigma_0 Q^2_{s,0}$.

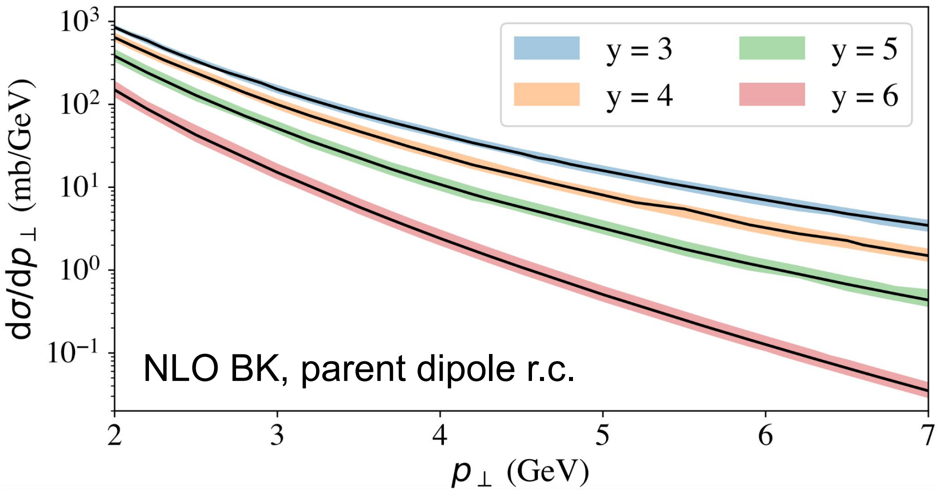


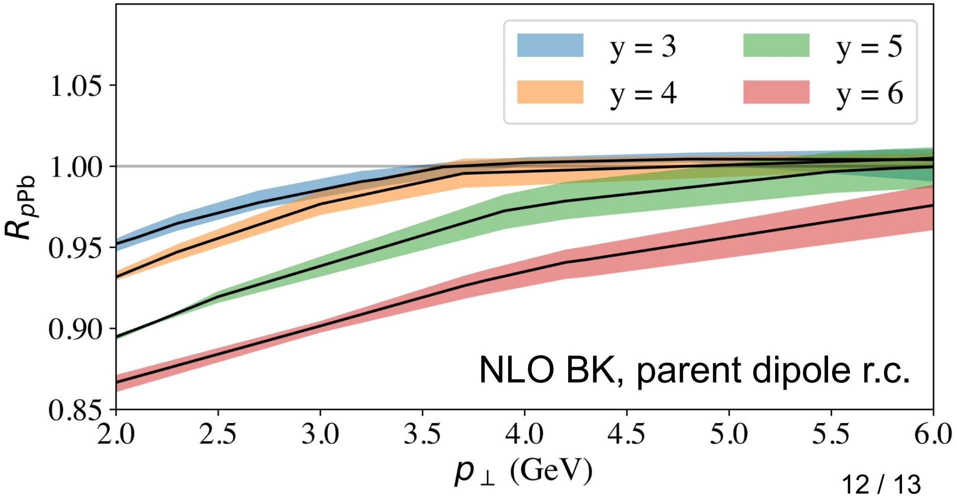


Rapidity Dependence

<u>Kinematics</u>: $\sqrt{s}$ = 8.16 TeV.

- Spectra suppressed as y increases, since PDFs vanish as $x_p \to 1$.
- Stronger low-$p_\perp$ nuclear suppression at larger y because nuclear saturation scale increases.
- Still see $R_{p\mathrm{Pb}} \to 1$ at high $p_\perp$ for all y. Qualitatively consistent with the charged hadron data from LHCb [LHCb, 2108.13115]. Here, we get a slightly weaker y dependence.





Conclusion and Outlook

- For the first time, we compute the forward single inclusive hadron production with NLO hard factor and NLO dipole. The latter employs parameters fitted to HERA structure function data.
- NLO corrections have significant effects on π^0 spectra and $R_{p\mathrm{Pb}}$.
- The spectra qualitatively agree with the LHCb π^0 data, while $R_{p\mathrm{Pb}}$ overestimates LHCb data and approaches 1 at high $p_\perp$.
- **This calls for a comprehensive global analysis of NLO BK evolution, including both DIS and forward pA collision data.**
- Spectra and $R_{p\mathrm{Pb}}$ are suppressed at high rapidities, in qualitative agreement with LHCb charged hadron data.

Backup Slides

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**	**No**