Ultra-forward particle production from CGC+Lund fragmentation

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in collaboration with

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'Heavy Ion Meeting'
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Saclay

ugr Universidad de Granada

Outline

1. **Introduction**
   - Forward production in the Color Glass Condensate: Hybrid formalism

2. **The Monte-Carlo event generator**
   - Perturbative parton production: implementation of DHJ formula
   - Multiple scattering: eikonal model
   - Hadronization: Lund fragmentation model

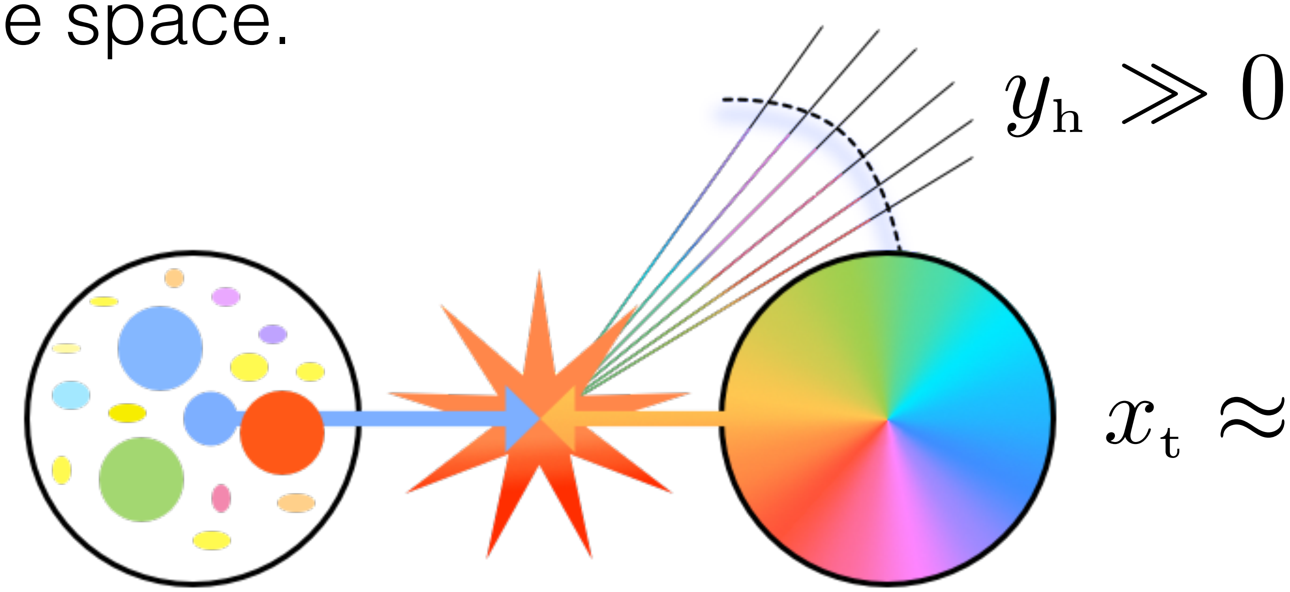
3. **Results:**
   - RHIC: d-Au @ 200 GeV
   - LHCf: p-p @ 7 TeV
   - LHCf: p-Pb @ 5.02 TeV
   - LHCf: nuclear modification factor $R_{\mathrm{p\text{-}Pb}}$ @ 5.02 TeV

4. **Conclusions, future prospects**

1. Introduction

- The analysis of the very forward region of particle production in high-energy collisions gives us access to the wave functions of colliding objects in the extreme limits of phase space.

$$x_{\mathrm{p}} \approx \frac{p_t}{\sqrt{s}} e^{y_{\mathrm{h}}}$$



$$x_{\mathrm{t}} \approx \frac{p_t}{\sqrt{s}} e^{-y_{\mathrm{h}}}$$

Forward particle production in the Color Glass Condensate

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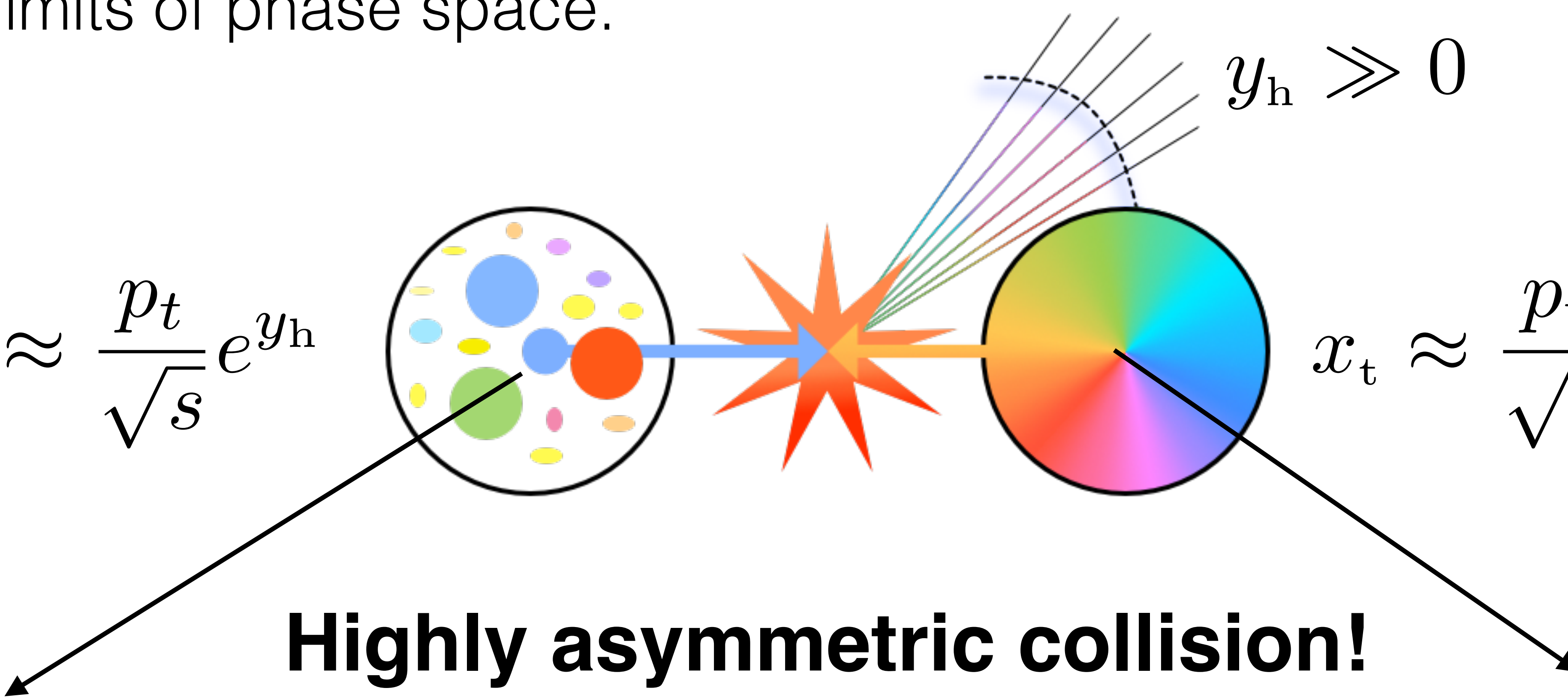


Highly asymmetric collision!

Dilute ensemble of fast valence quarks

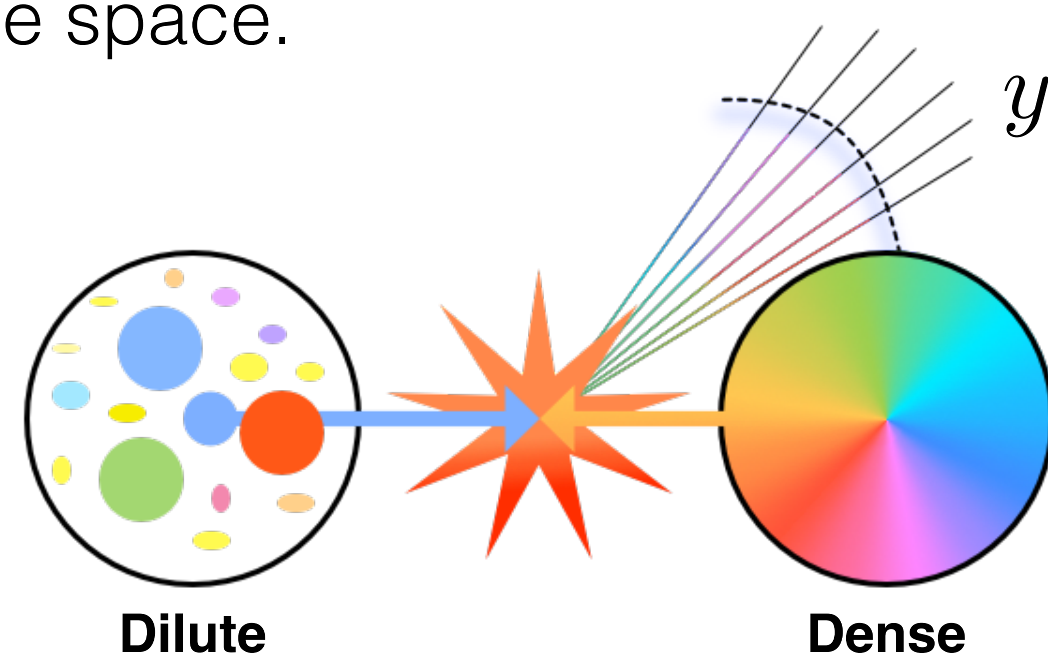
Dense pack of ‘slow’ radiated gluons

Forward particle production in the Color Glass Condensate

- The analysis of the very forward region of particle production in high-energy collisions gives us access to the wave functions of colliding objects in the extreme limits of phase space.

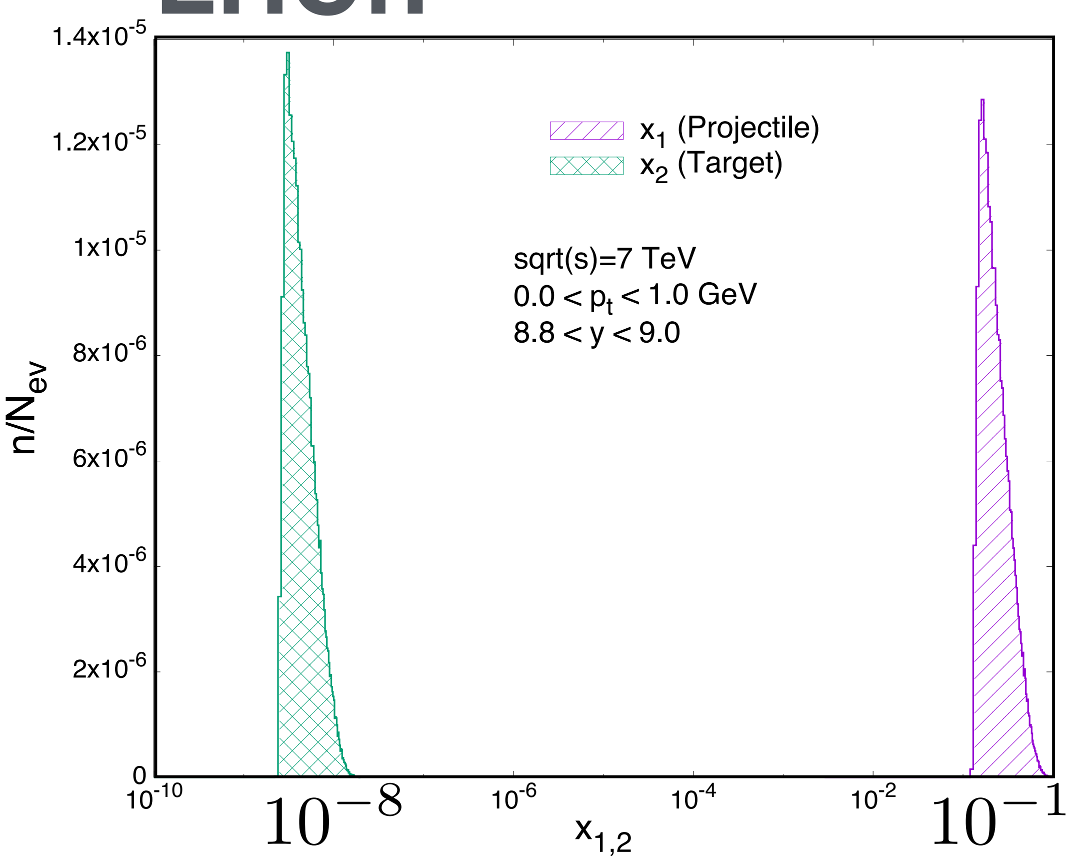
$$y_{\mathrm{h}} \gg 0$$

$$x_{\mathrm{p}} \approx \frac{p_t}{\sqrt{s}} e^{y_{\mathrm{h}}}$$



$$x_{\mathrm{t}} \approx \frac{p_t}{\sqrt{s}} e^{-y_{\mathrm{h}}}$$

LHCf:



$$\sqrt{s} = 7\ \mathrm{TeV}$$

$$p_t \lesssim 1\ \mathrm{GeV}$$

$$8.8 \leq y \leq 9.0$$

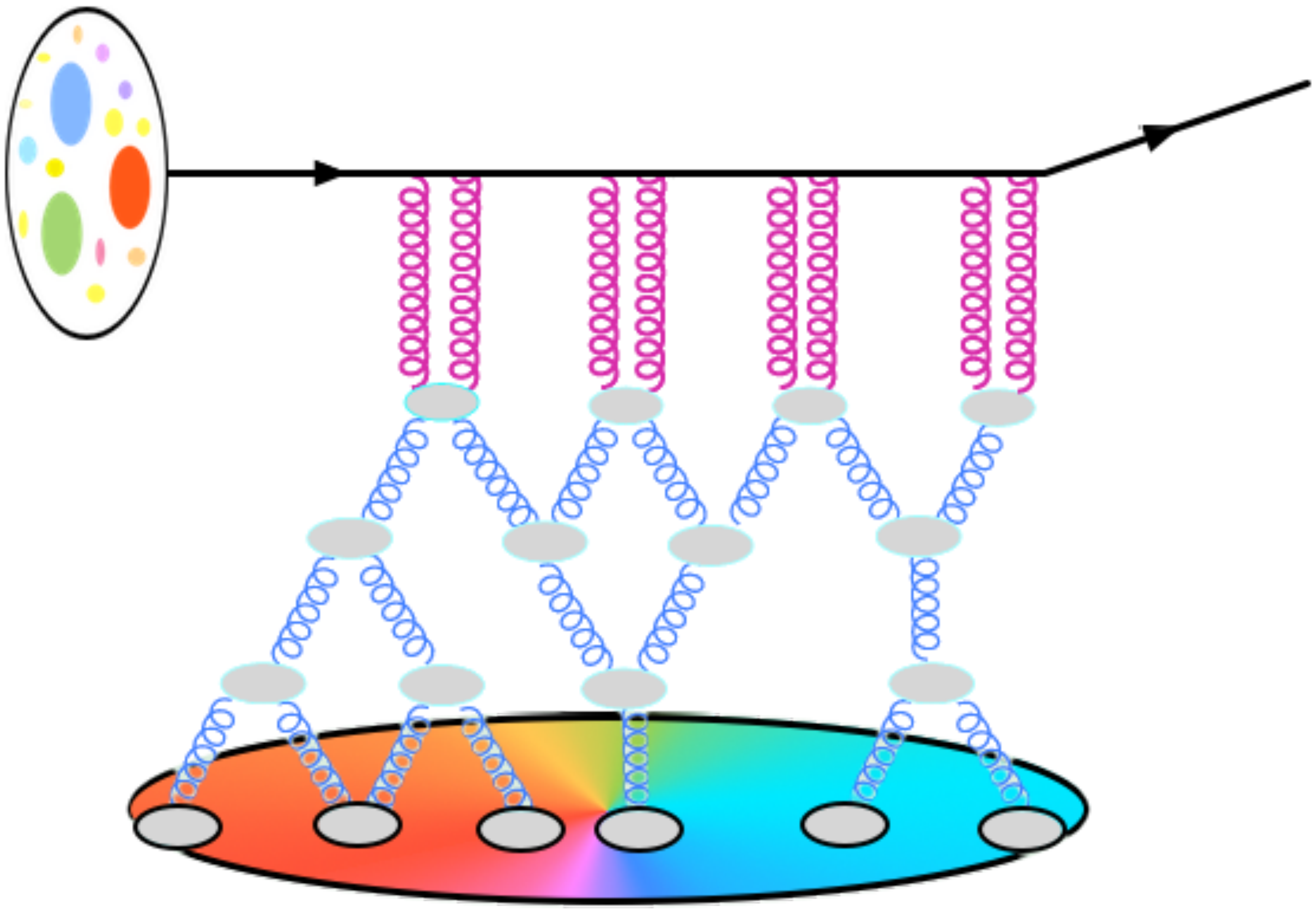
$$x_p \sim 10^{-1} \div 1$$
$$x_t \sim 10^{-8} \div 10^{-9}$$

Smallest *x* values observed yet

Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions (A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, Nucl. Phys. A765 (2006) 464):

$$\frac{d\sigma}{dy d^2 k_\perp} \sim \mathrm{pdf}(x_p, \mu^2) \times \mathrm{uGD}(x_t, k_\perp^2)$$



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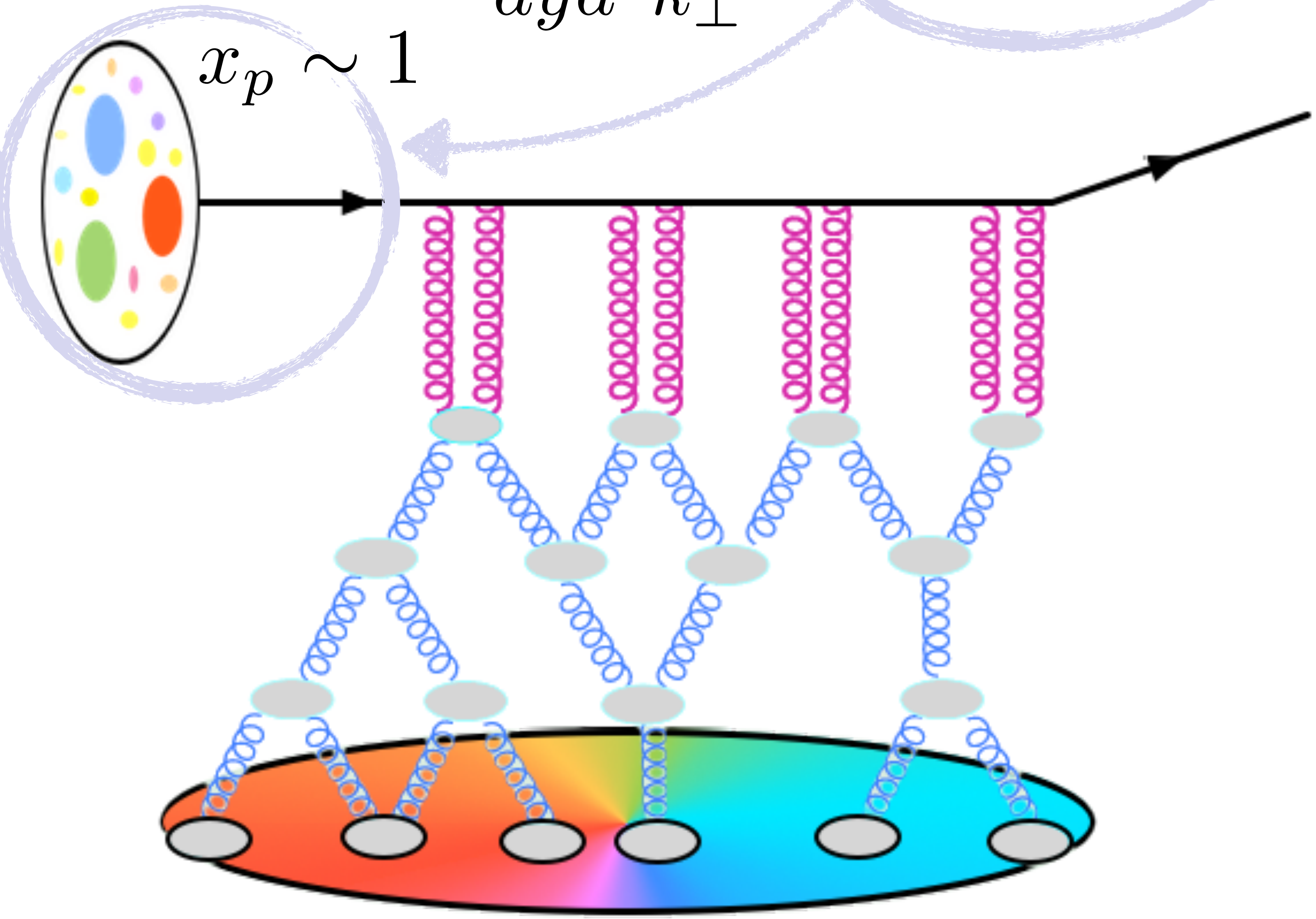

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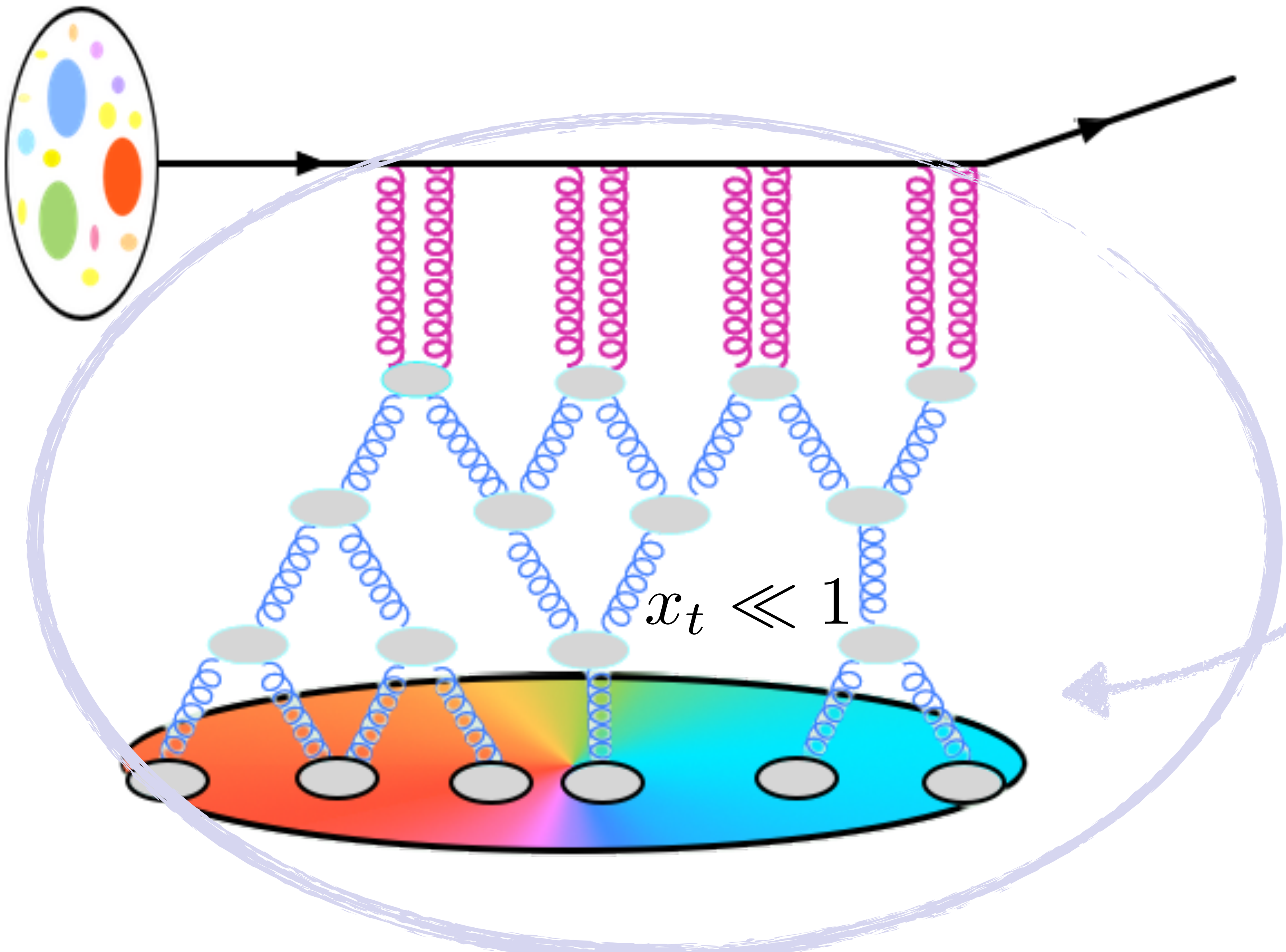

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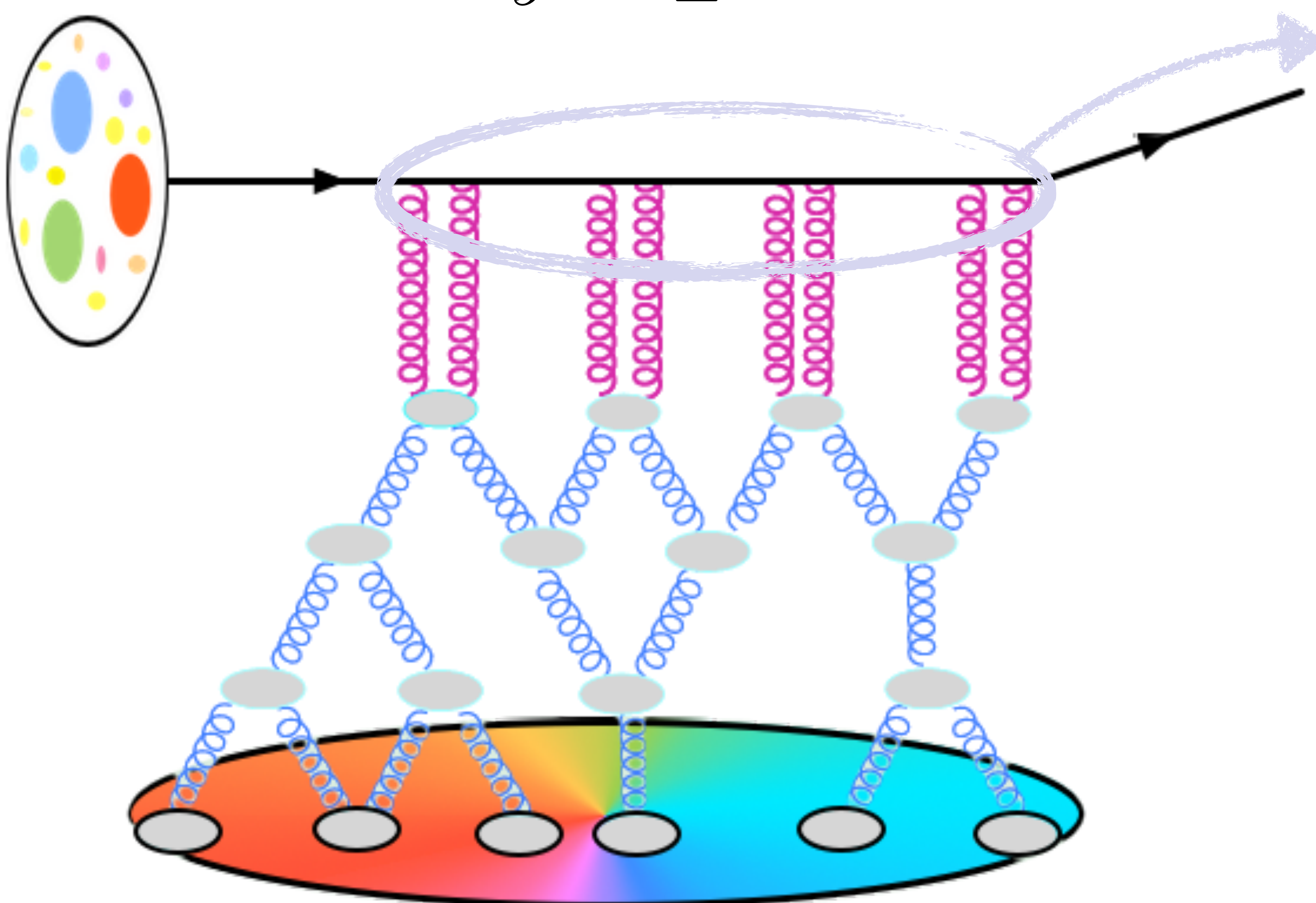

Multiple scattering: All terms of order $g\mathcal{A}(x) \sim \mathcal{O}(1)$ must be resummed.

Strong color field: $\mathcal{A}(x) \sim \frac{1}{g}$

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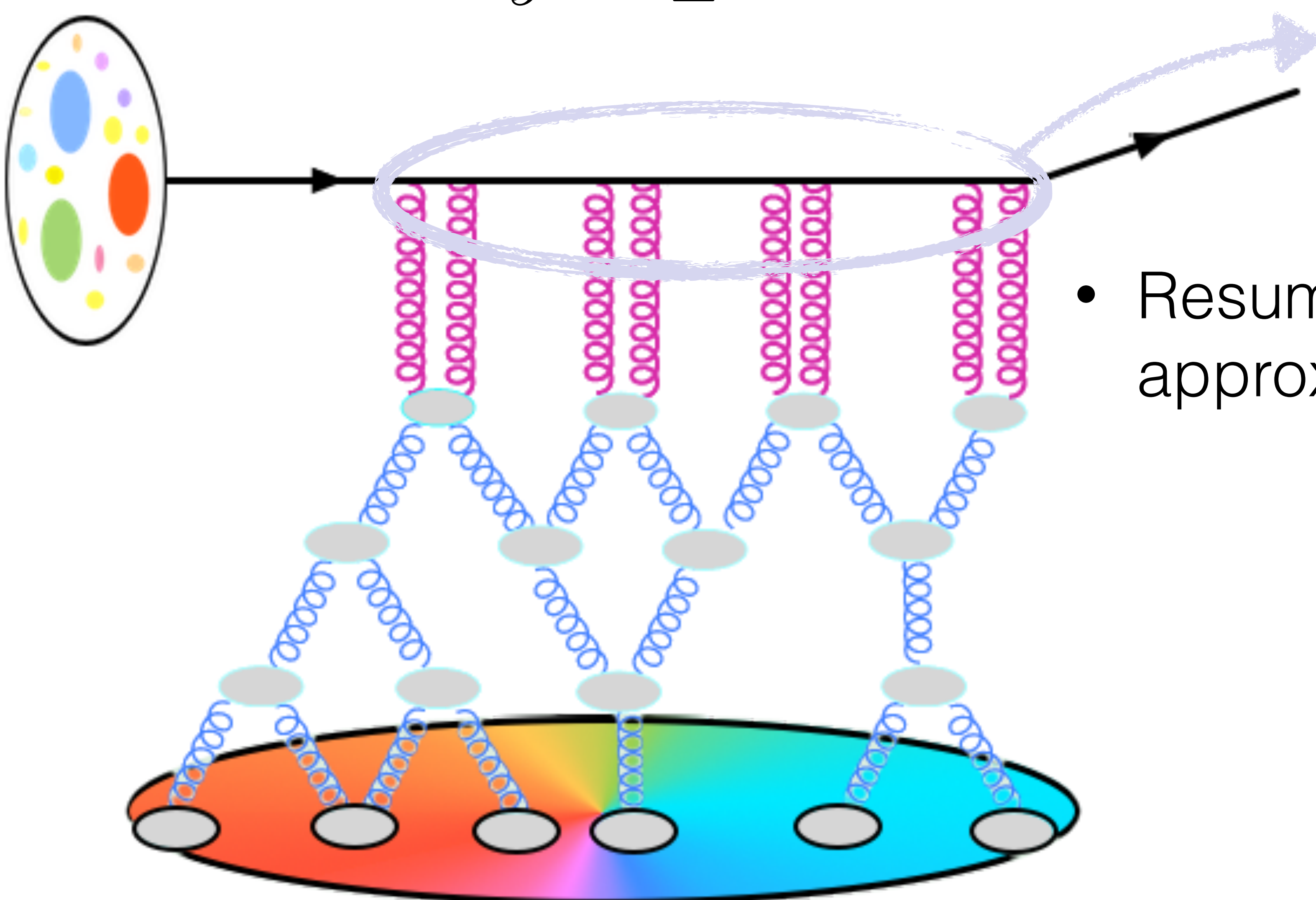

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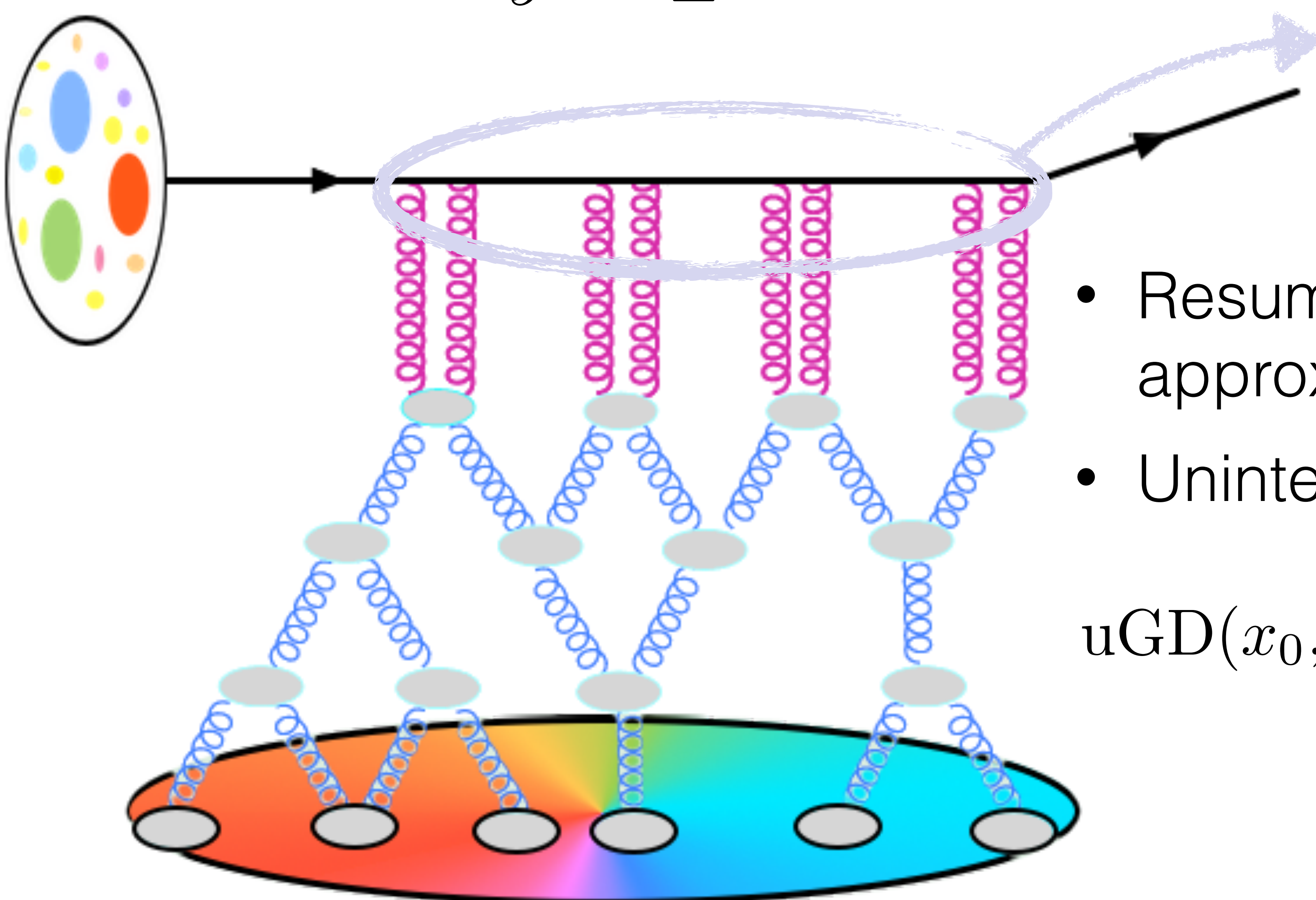

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- Resummation to all orders + eikonal approximation: Wilson line $U(z_\perp)$
- Unintegrated gluon distribution:

$$\mathrm{uGD}(x_0, k_t) = \mathrm{FT}\left[1 - \frac{1}{N_c}\underbrace{\langle \mathrm{tr}(UU^\dagger)\rangle_{x_0}}\right]$$

Dipole scattering amplitude

Strong color field: $\mathcal{A}(x) \sim \frac{1}{g}$

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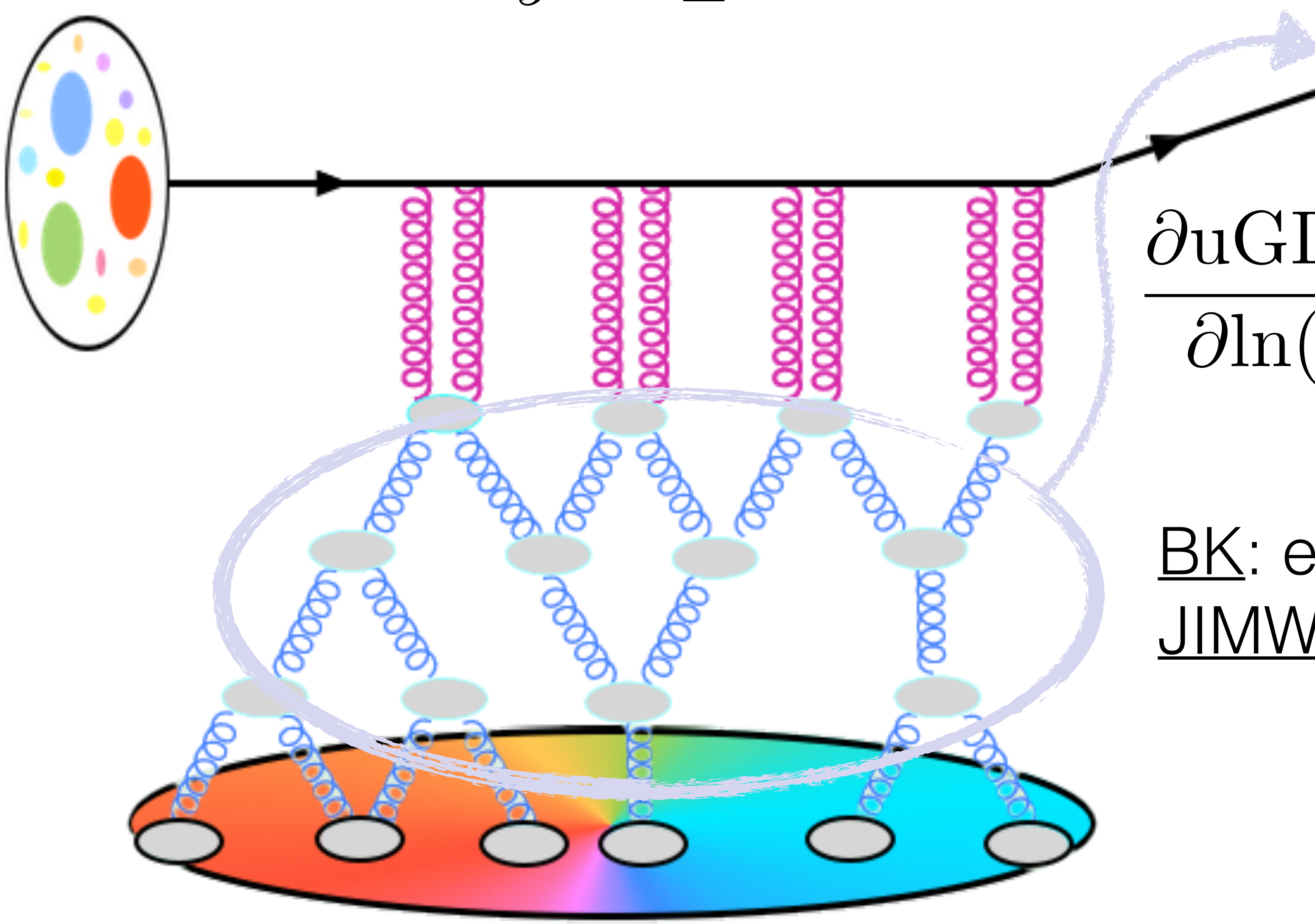

Non-linear small-x evolution:
BK-JIMWLK equations:

$$\frac{\partial \mathrm{uGD}(x, k_t)}{\partial \ln(x_0/x)} \sim \underbrace{\mathcal{K} \otimes \mathrm{uGD}}_{\text{Radiation}} - \underbrace{\mathrm{uGD}^2}_{\text{Recombination}}$$

BK: evolution of 2-point function
JIMWLK: (coupled) evolution of all n-point functions

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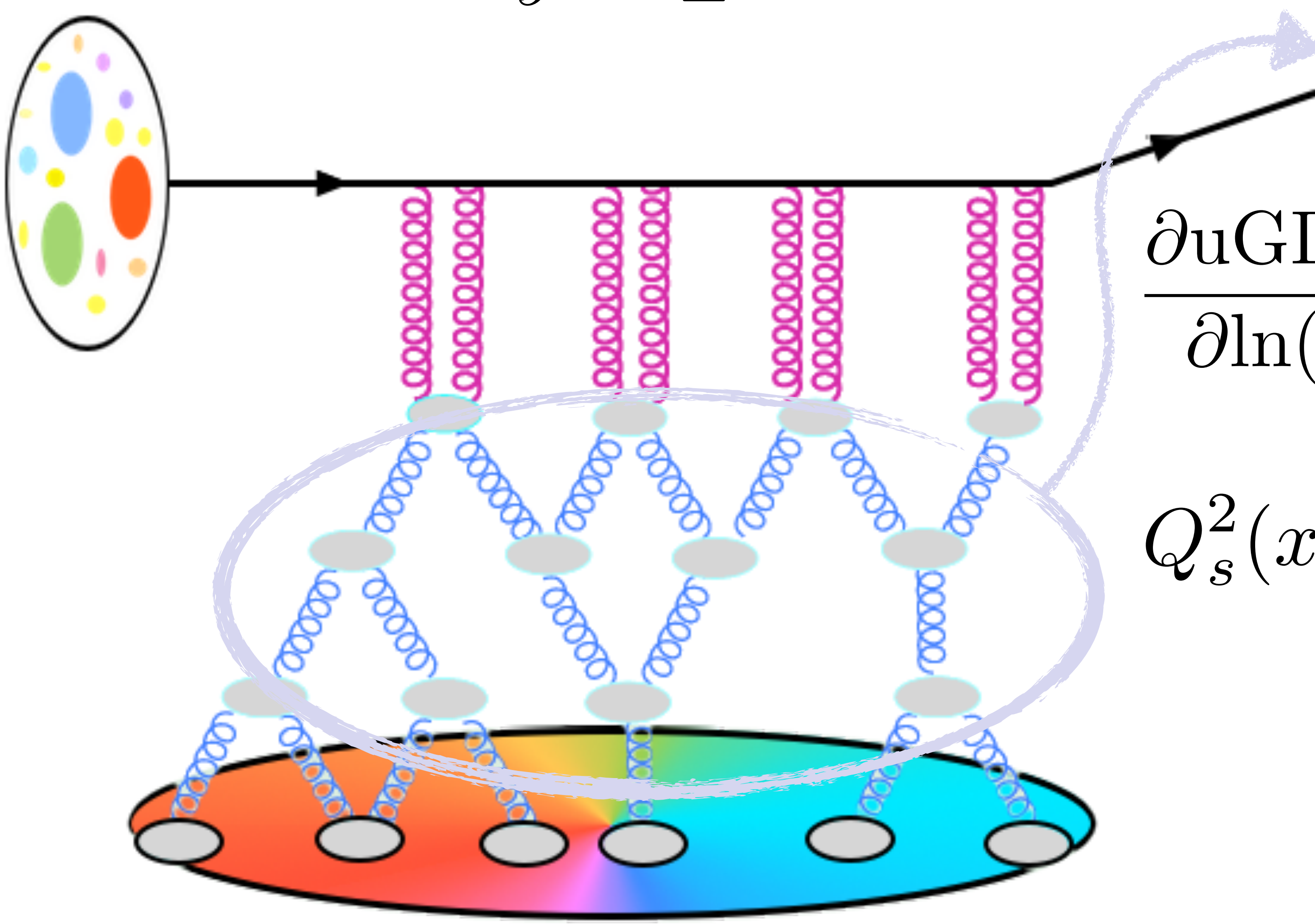

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$Q_s^2(x)$: **Signals when radiation and recombination terms become parametrically of the same order**

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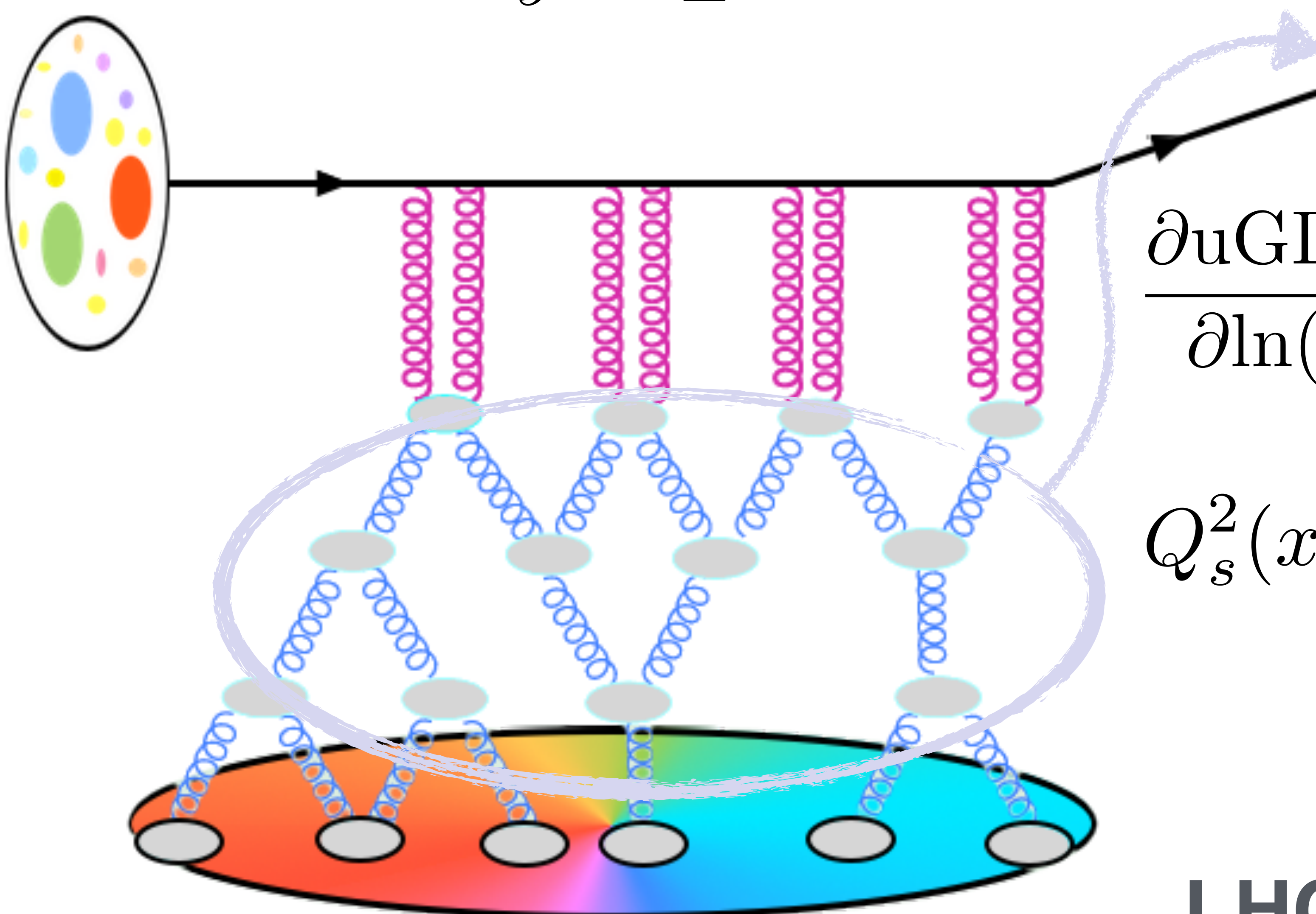

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$Q_s^2(x)$: **Signals when radiation and recombination terms become parametrically of the same order**

LHCf: (p-p)

$$Q_s \gtrsim 1 \text{ GeV}$$

2. The Monte-Carlo event generator

Perturbative parton production: implementation of DHJ formula

- Hybrid formalism (A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, Nucl. Phys. A765 (2006) 464):

$$\frac{d\sigma^{h_1 h_2 \to (q/g)X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f_{(q/g)/h_1}(x_p, \mu^2) N_{(F/A),h_2}(x_t, k_t^2)$$

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  - Proton PDF: CTEQ6 LO set (J. Pumplin et. al., JHEP 07 (2002) 012)
  - Default factorization scale:

LHCf: $\mu = \max\{k_t, Q_s\}$

RHIC (forward): $Q_s < 1\,\text{GeV}$ → $\mu = 1\,\text{GeV}$

(LHCf data description insensitive to cutoff)

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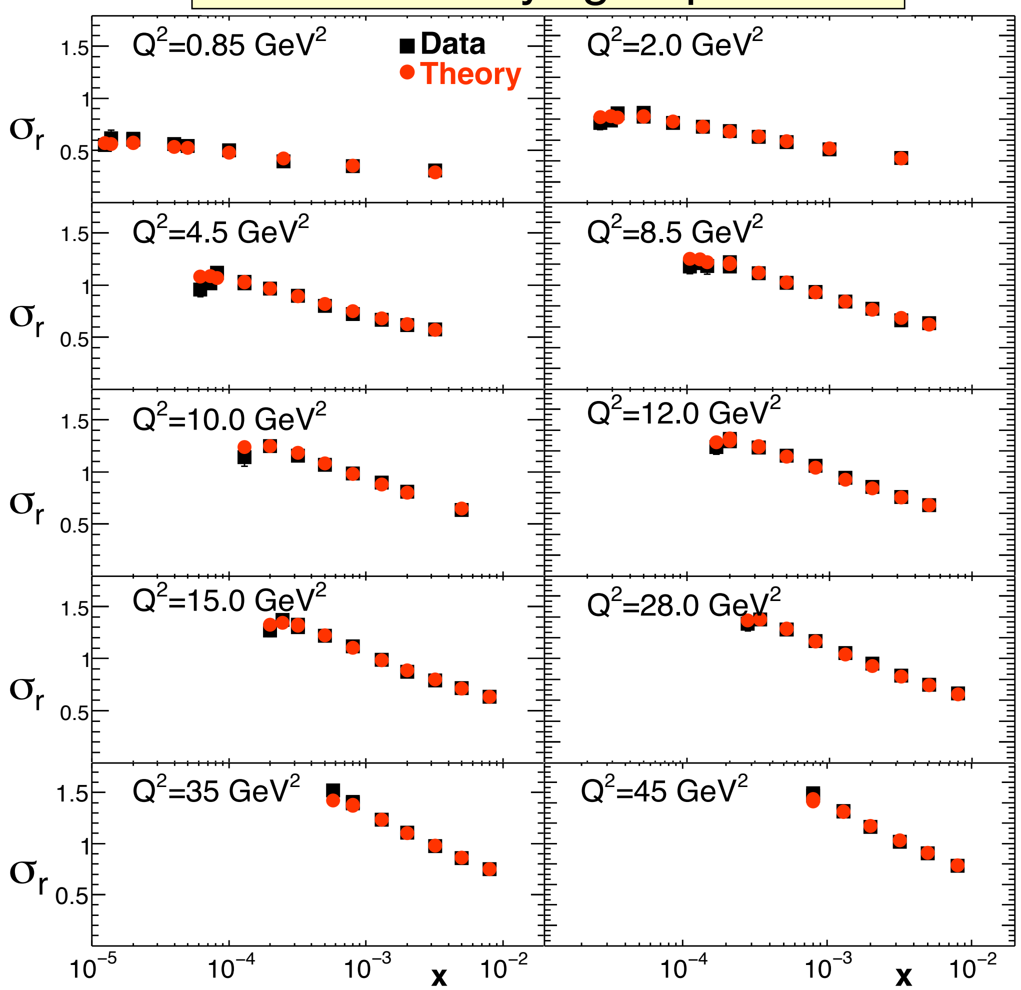
- uGD's: Fourier transforms of dipole scattering amplitudes.

$$N_{F(A)}(x, k_t) = \int d^2\mathbf{r}\; e^{-i\mathbf{k_t}\cdot\mathbf{r}} \left[1 - \mathcal{N}_{F(A)}(x, r)\right].$$

- Small-x evolution: We take parametrization of $\mathcal{N}_{F(A)}(x, r)$ from the *AAMQS* fits to data on the structure functions measured in e+p scattering at HERA:

rc-BK evolution

Fit with only light quarks



J. L. Albacete, N. Armesto, J. G. Milhano and C. A. Salgado, Phys. Rev. D80 (2009) 034031.
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rc-BK evolution

- Initial conditions for evolution:

$$\mathcal{N}_F(x_0, r) = 1 - \exp\left[-\frac{\left(r^2 Q_{s0}^2\right)^\gamma}{4} \log\left(\frac{1}{\Lambda r} + e\right)\right]$$

$$x_0 = 10^{-2} \quad \gamma = 1.101 \quad Q_{s0}^2 = 0.157\,\mathrm{GeV}^2$$

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- uGD's for nuclear target:

$$Q_{s0,nucleus}^2 = A^{1/3} Q_{s0,proton}^2$$

↑ *Oomph* factor

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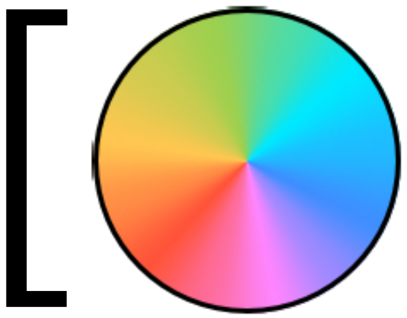
  - Implicit integration in impact parameter $\vec{b}$: $\sigma_0/2$

Free fit parameter of *AAMQS* fits:

$$\boxed{\frac{\sigma_0}{2} = 16.5 \text{ mb}}$$



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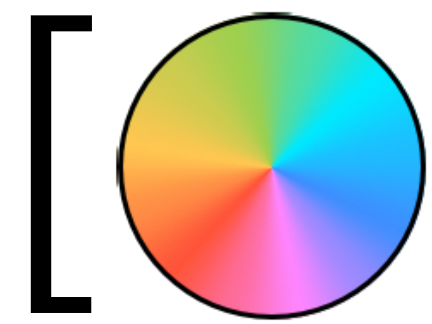
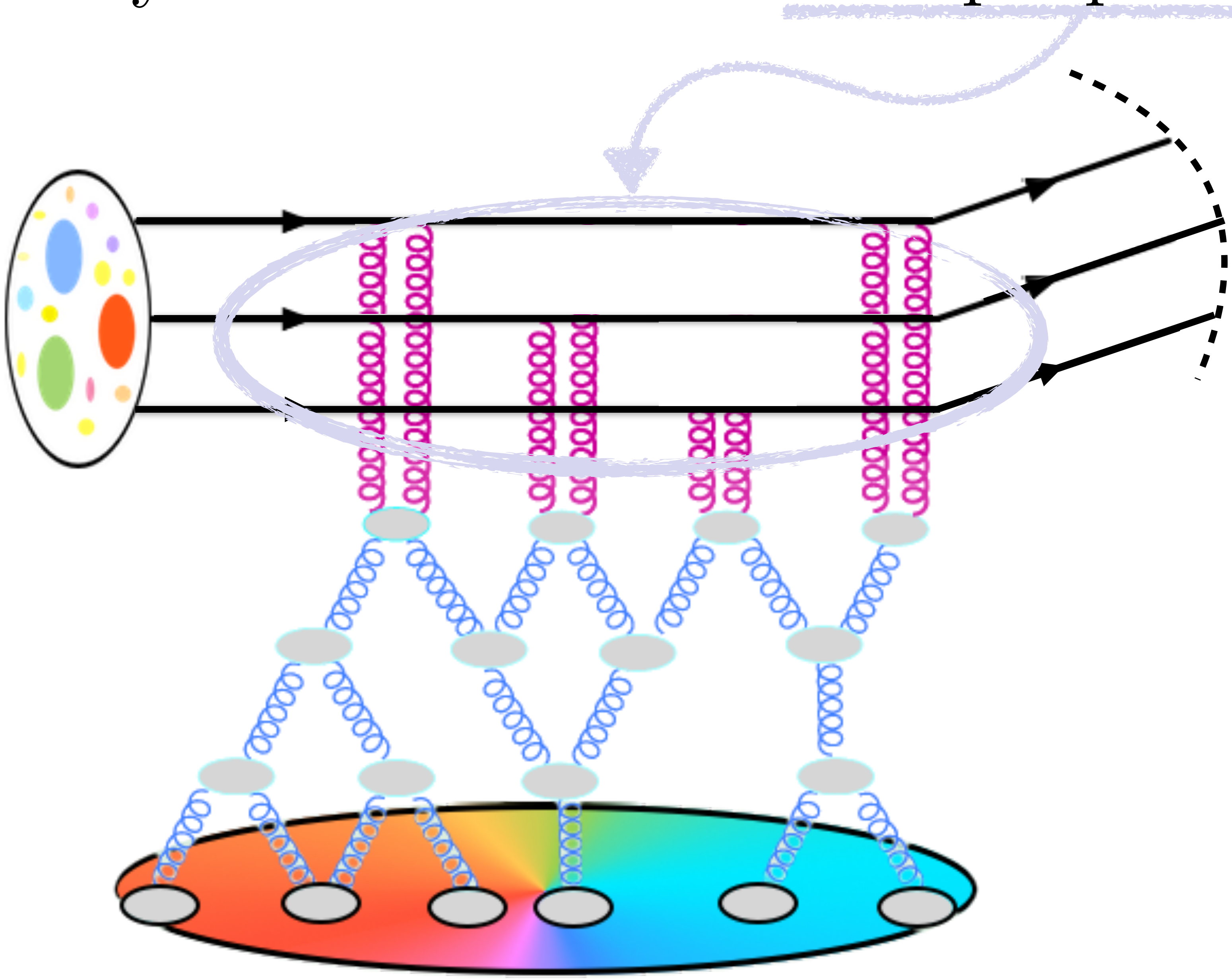


- K-factor: not the result of any calculation. May account for:
  - Higher order corrections
  - Non-perturbative effects
  - (...)

Multiple scattering: eikonal model

- Our approach:
  Monte-Carlo implementation of

$$\text{Hybrid formalism } + \text{Multiple parton scattering}$$



Multiple scattering: eikonal model

- Number of **independent** hard scatterings according to Poisson probability distribution of mean n, where:

$$n(b, s) = T_{\rm pp}(b)\sigma_{\rm DHJ}(s)$$

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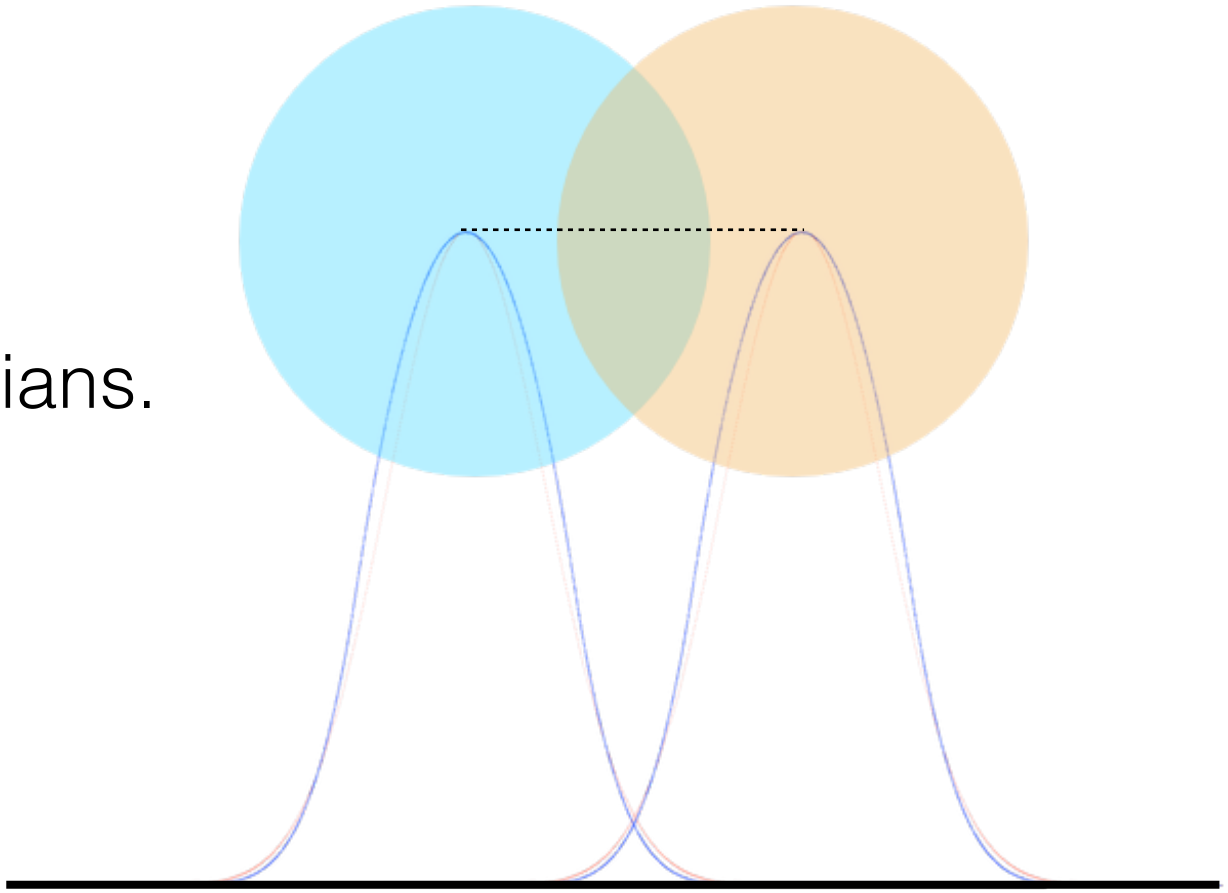
$$n(b,s) = T_{\rm pp}(b)\sigma_{\rm DHJ}(s)$$

- b randomly generated between 0 and b_{max}:

$$b_{max} = \sqrt{\frac{\sigma_{nd}}{\pi}}$$

- Spatial overlap: convolution of two Gaussians.

$$T_{\rm pp}(b) = \frac{1}{4\pi B}\exp\left(-\frac{b^2}{4B}\right)$$



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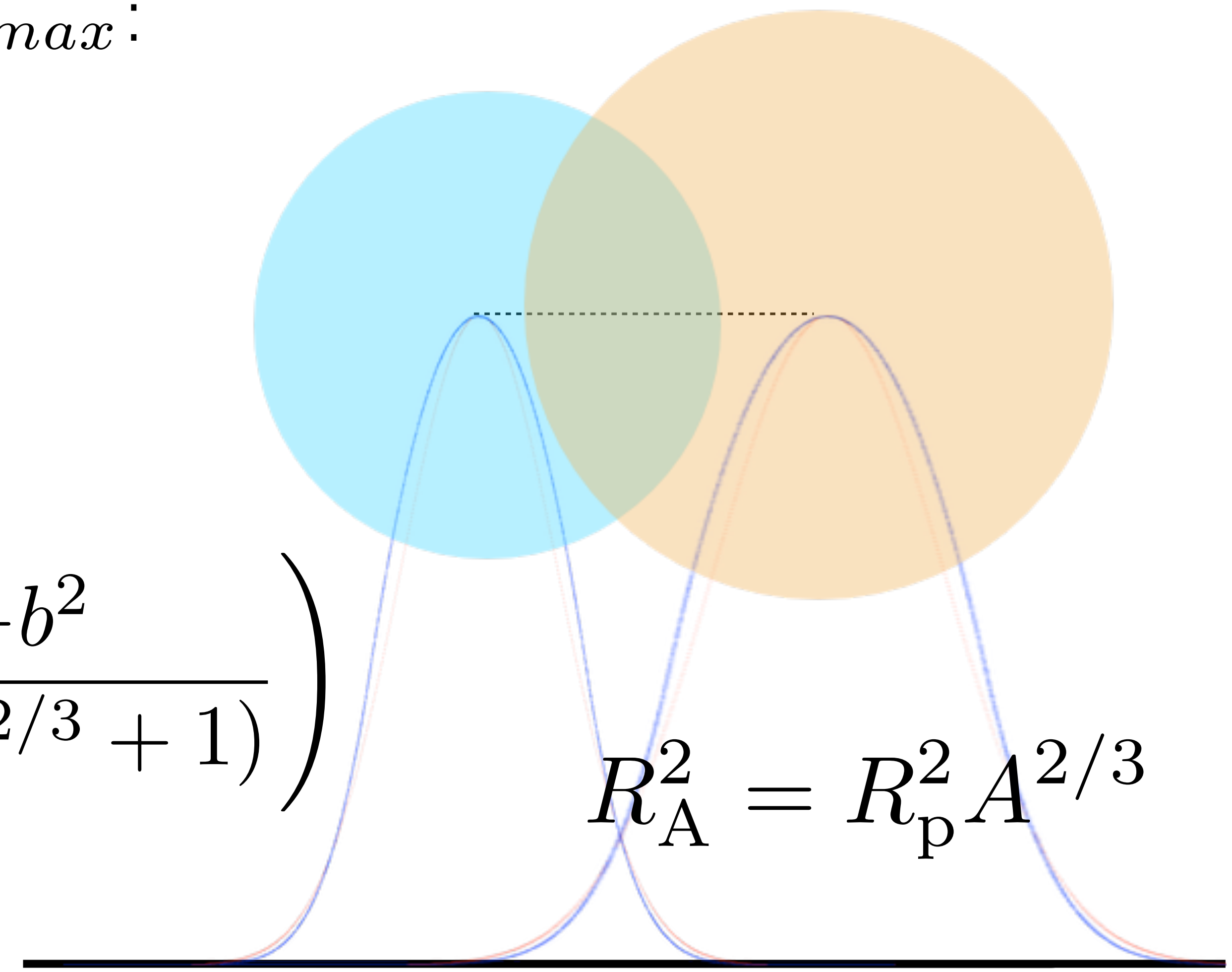
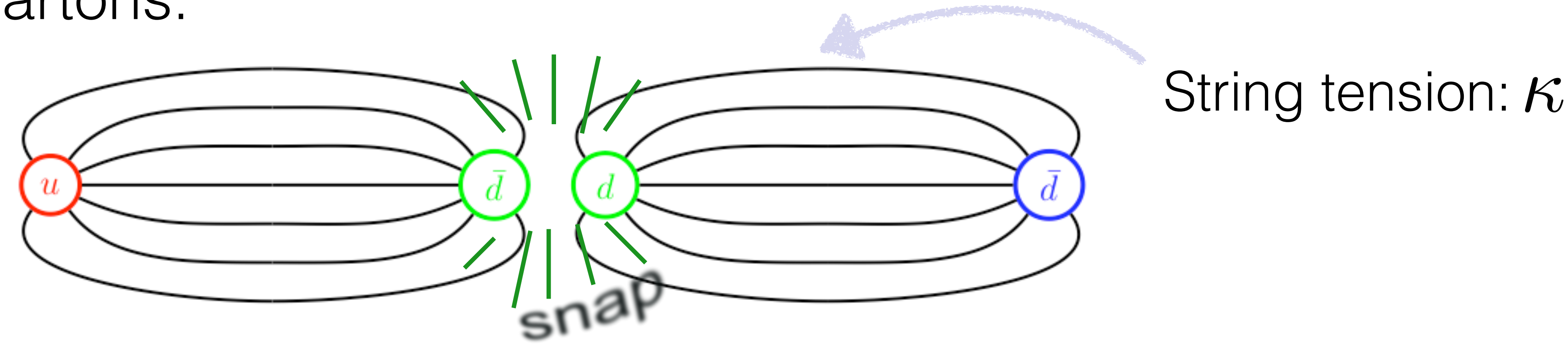
- For a nuclear target of mass number A:

$$T_{\mathrm{pA}}(b) = \frac{1}{\pi R_{\mathrm{p}}^2(A^{2/3}+1)} \exp\left(\frac{-b^2}{R_{\mathrm{p}}^2(A^{2/3}+1)}\right)$$



Hadronization: Lund fragmentation model

- Simple but powerful picture of hadron production based on the breaking of strings between partons:



- Probability of string breaking by quark pair with $m_\perp^2 = m_q^2 + p_{\perp q}^2$:

$$\mathrm{Prob}(m_q^2, p_{\perp q}^2) \;\propto\; \exp\left(\frac{-\pi m_q^2}{\kappa}\right) \exp\left(\frac{-\pi p_{\perp q}^2}{\kappa}\right)$$

As implemented in: **PYTHIA 8**

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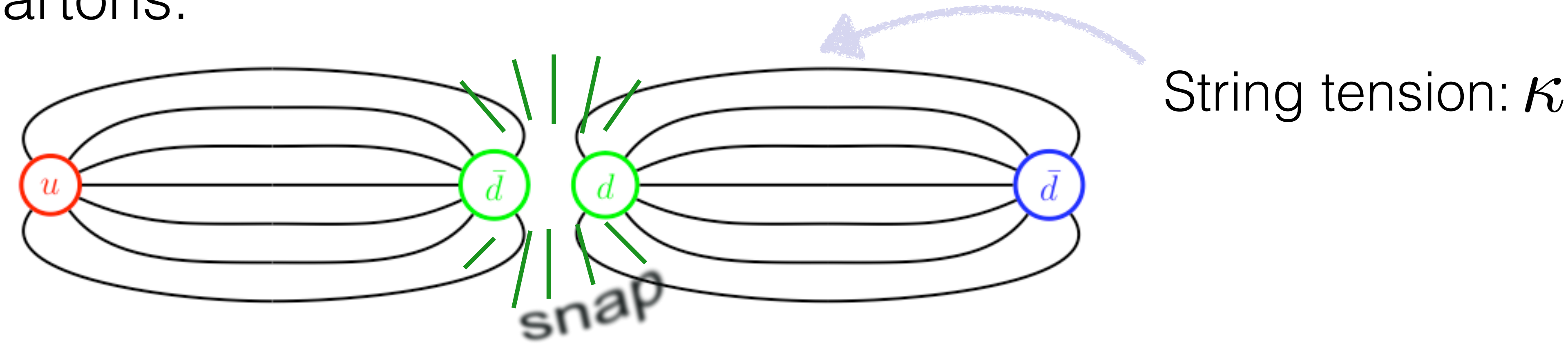

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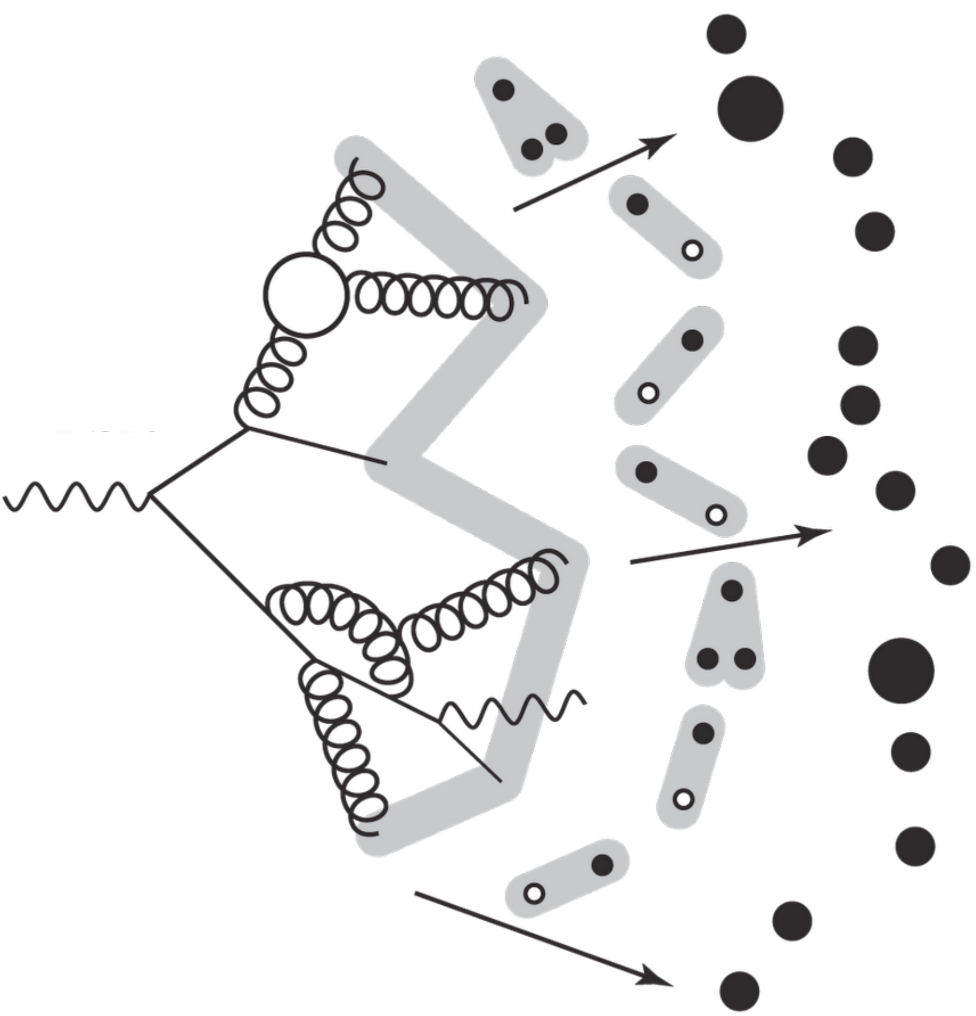


$$\text{Prob}(m_q^2, p_{\perp q}^2) \;\propto\; \exp\left(\frac{-\pi m_q^2}{\kappa}\right) \exp\left(\frac{-\pi p_{\perp q}^2}{\kappa}\right)$$

- Lund fragmentation function:

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

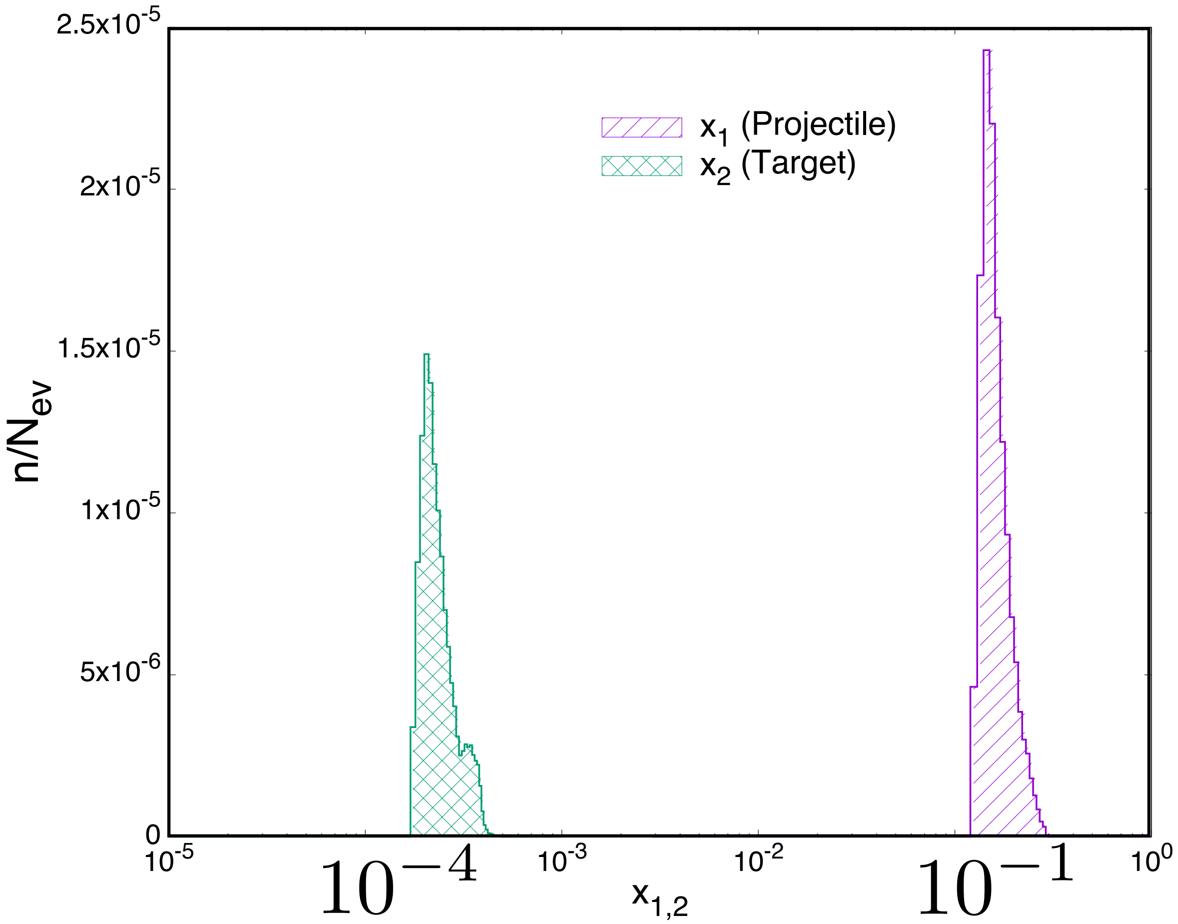
As implemented in: **PYTHIA 8**

3. Results

RHIC: d-Au @ 200 GeV

- Forward spectra observed at RHIC allows for a description in terms of CGC:

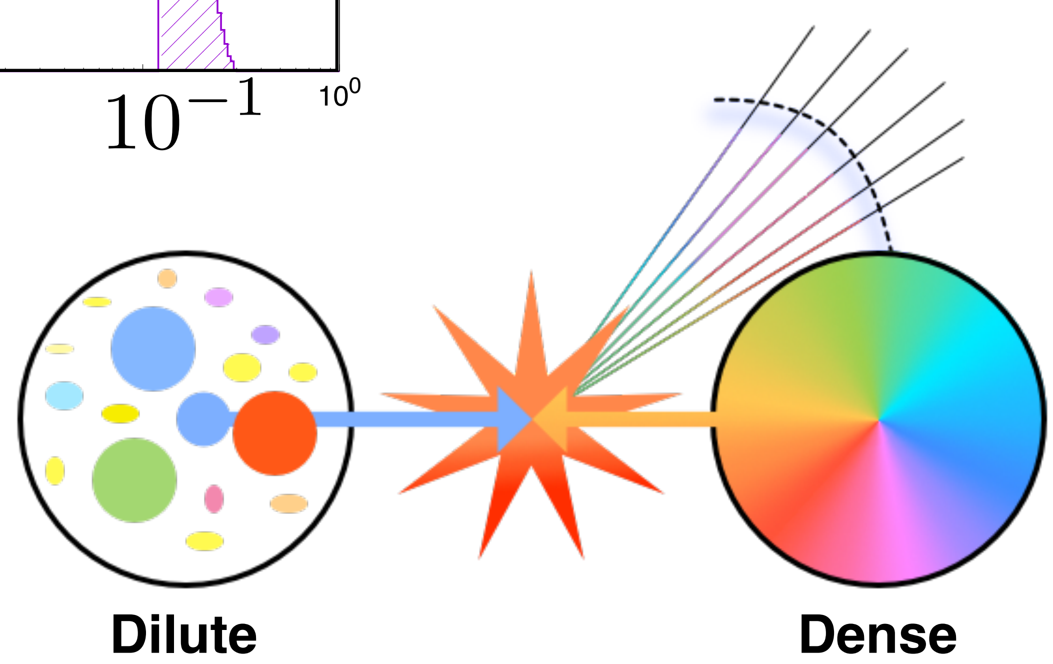
RHIC:



10^{-4} 10^{-1}

$$\sqrt{s} = 200 \text{ GeV}$$
$$1 < p_t < 2 \text{ GeV}$$
$$3.2 < y < 3.4$$

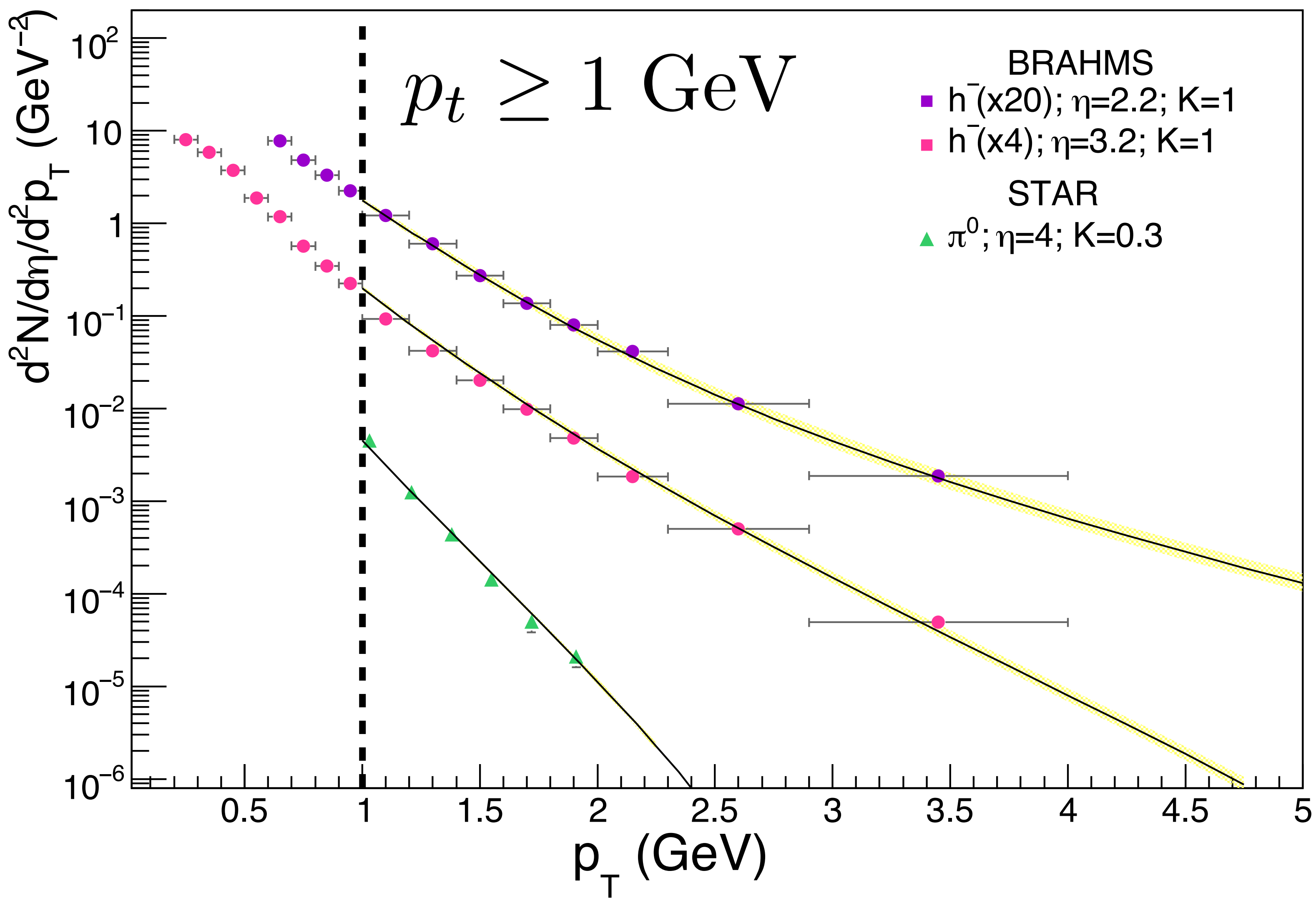
$$x_p \sim 10^{-1}$$
$$x_t \sim 10^{-4}$$



Forward particle production in the Color Glass Condensate

- Previous approaches:

$$\frac{d\sigma^{hadrons}}{d^2k_\perp dy} = \frac{d\sigma^{partons}_{\rm DHJ}}{d^2k_\perp dy} \otimes D_{h/p}$$



Albacete, Javier L. et al. Phys.Lett. B687 (2010) 174-179 arXiv:1001.1378 [hep-ph]

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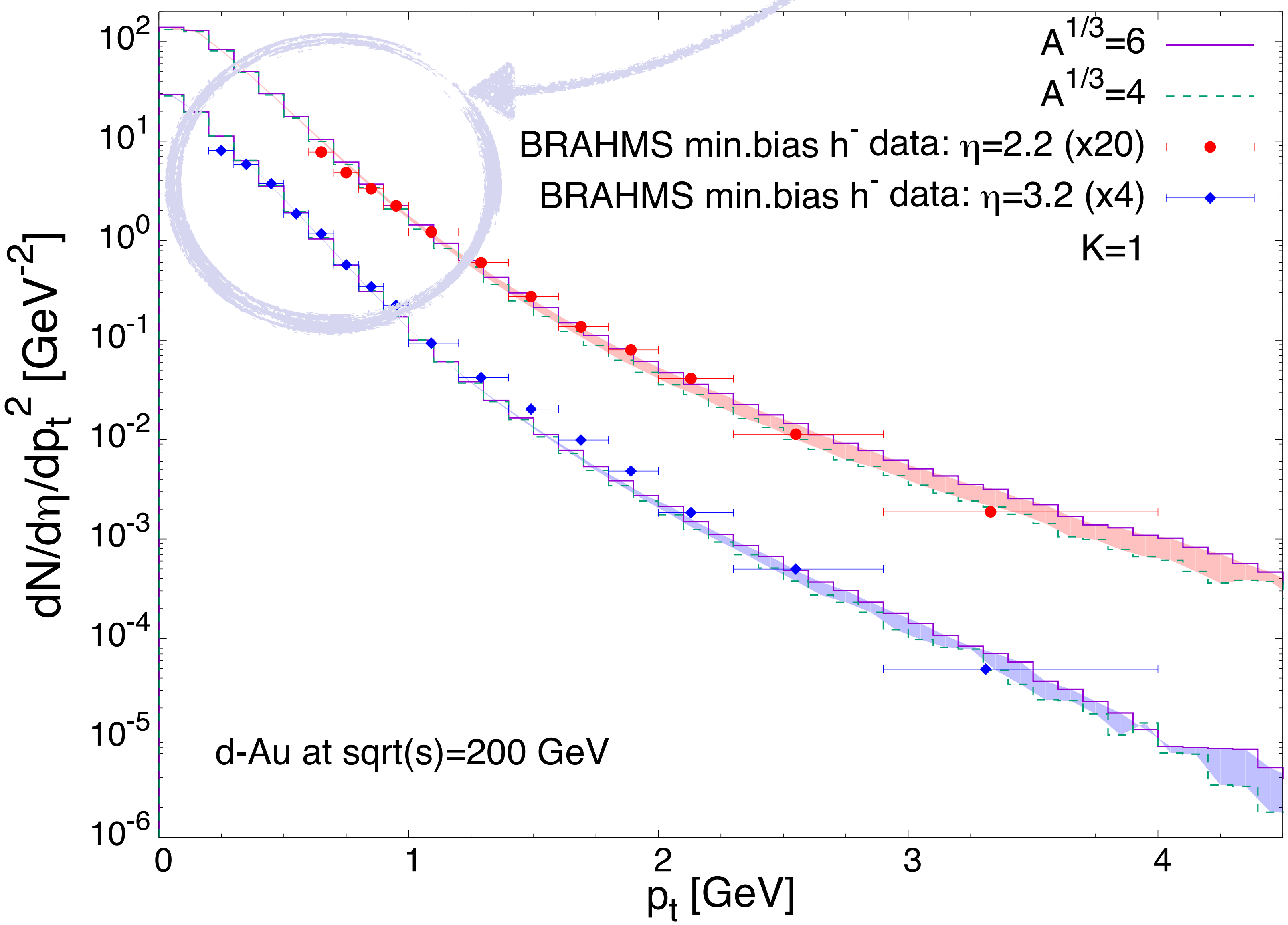
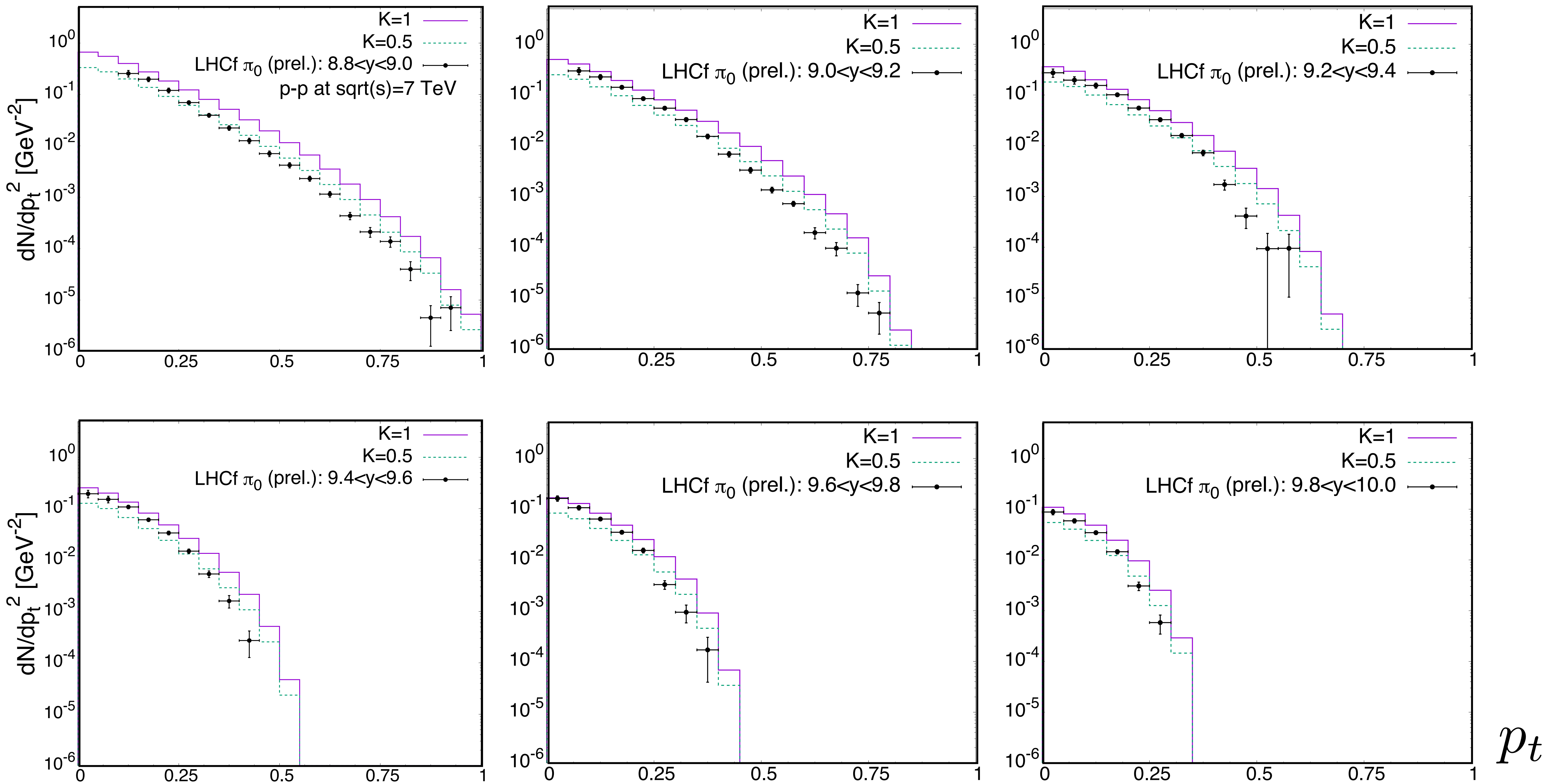
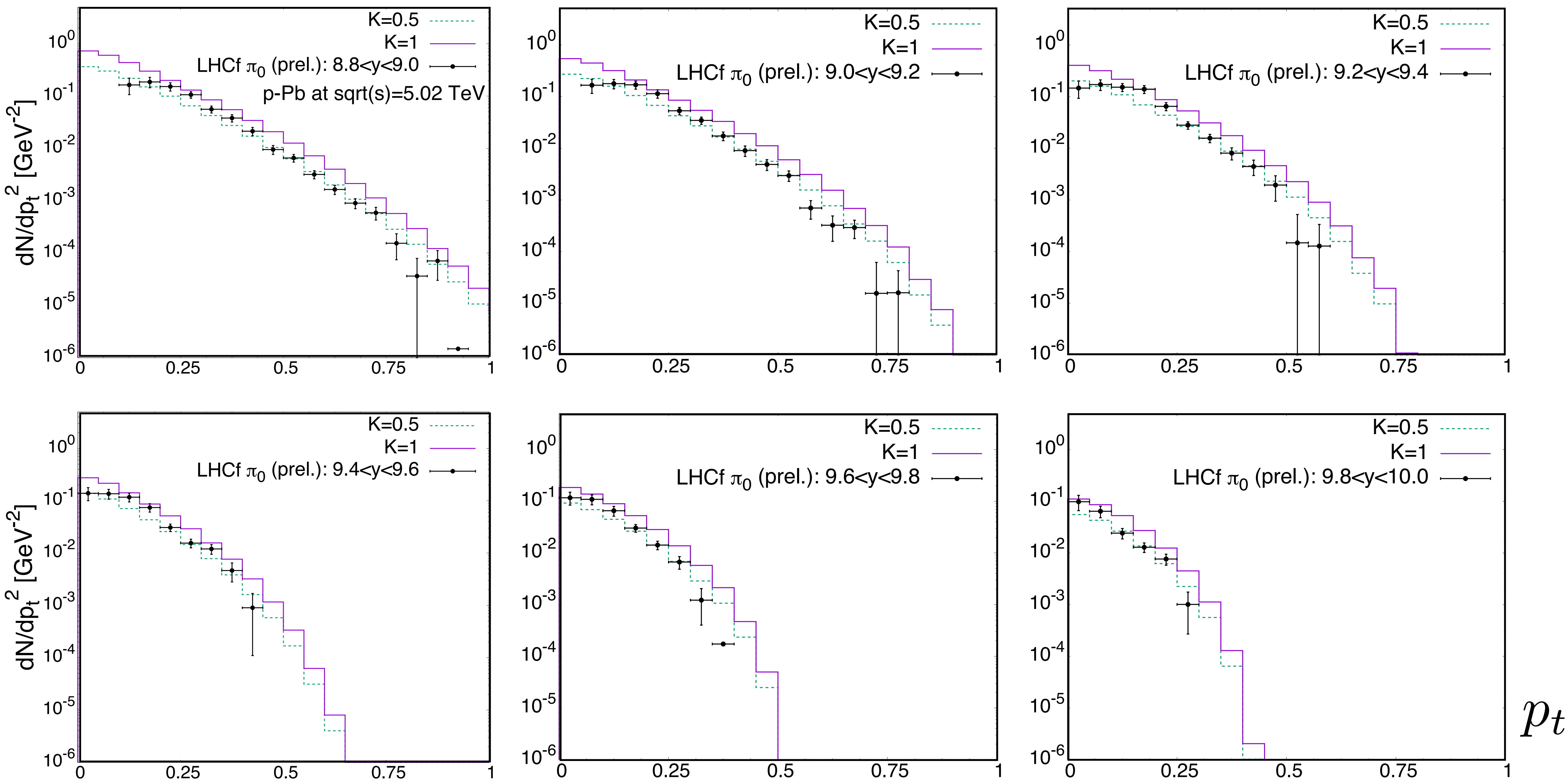


As implemented in: **PYTHIA 8**

LHCf: p-p @ 7 TeV

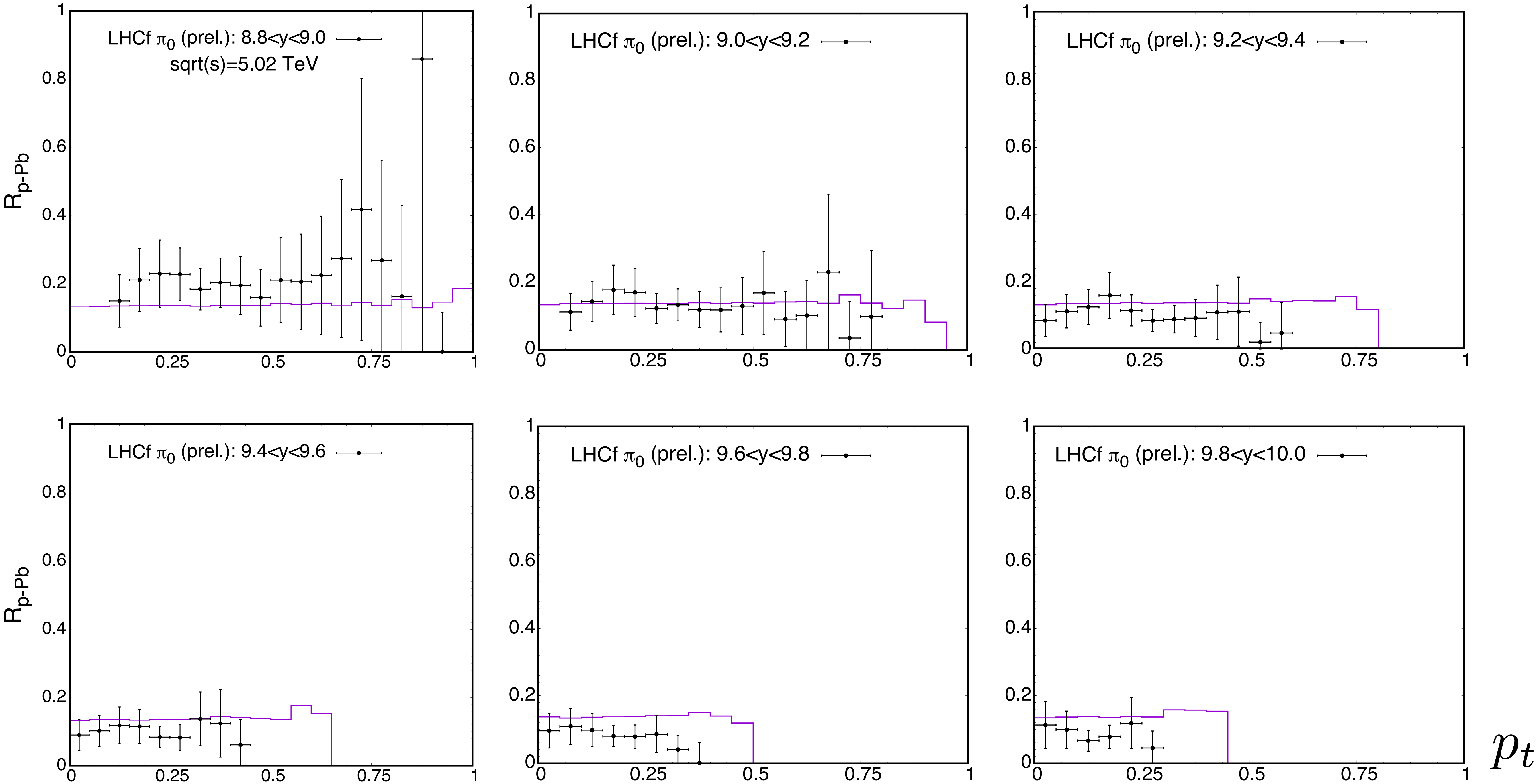


- Increment of evolution rapidity with respect to RHIC: $\Delta Y \sim \ln\left(\frac{x_0}{x}\right) \sim 14$
- Only difference with respect to RHIC set: **dynamical evolution of uGD's according to rcBK equation**.



- Similar situation that in the proton-proton case.
- Plenty of room for improvement in the proton-nucleus implementation.
- Low momentum region well described.

LHCf: nuclear modification factor $R_{\text{p-Pb}}$ @ 5.02 TeV



$$R^{\pi^0}_{\text{p-Pb}} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{dN^{\text{pPb}\to\pi^0 X}/dyd^2p_t}{dN^{\text{pp}\to\pi^0 X}/dyd^2p_t}$$

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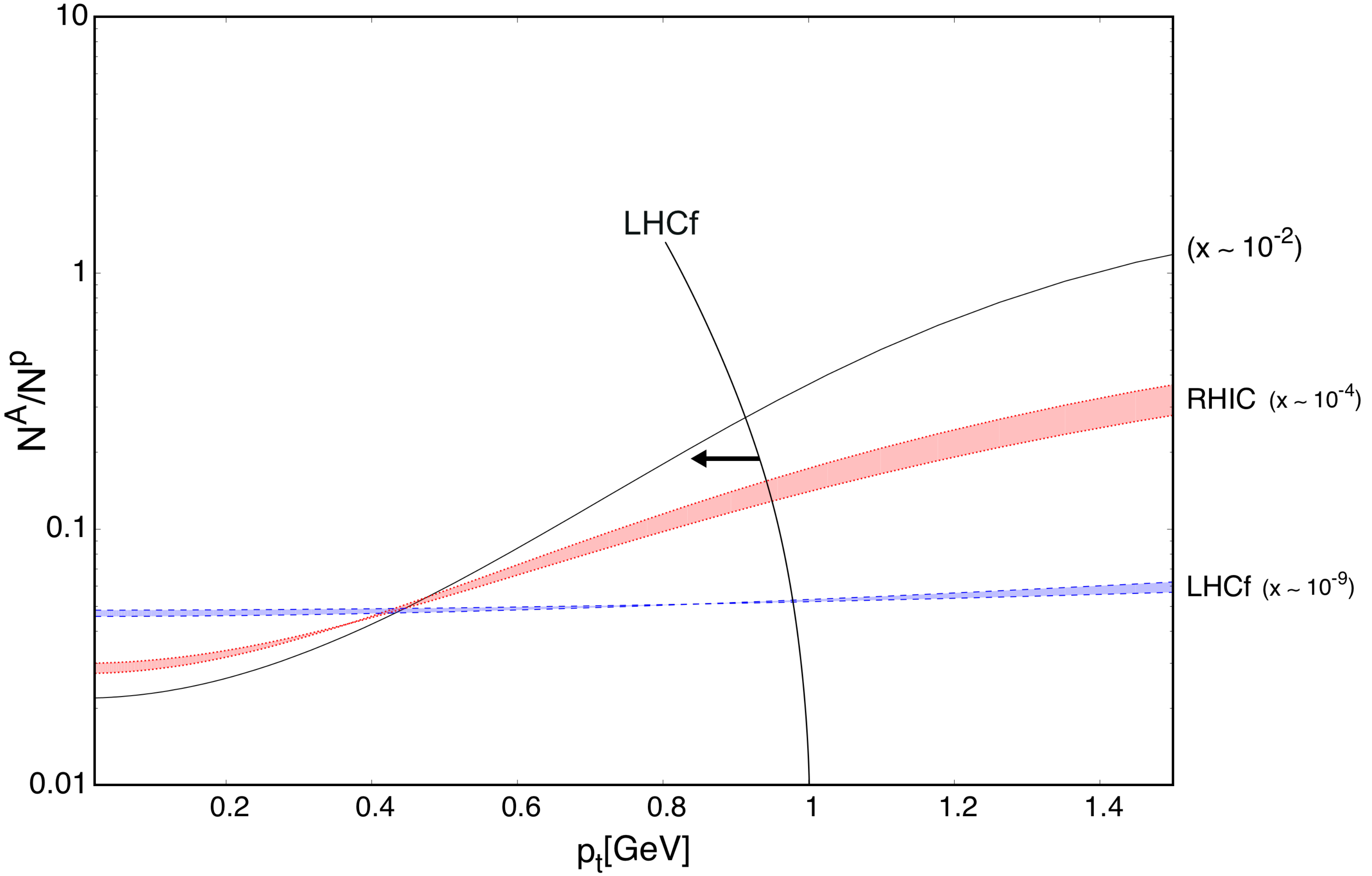
- This behavior can be understood as a direct consequence of the behavior of the ratios of the uGD's:



4. Conclusions, future prospects

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- There is still a **lot of room for improvement!** (NLO corrections, proper Monte-carlo implementation of proton-nucleus, etc.)