

Forward hadron production in pA collisions

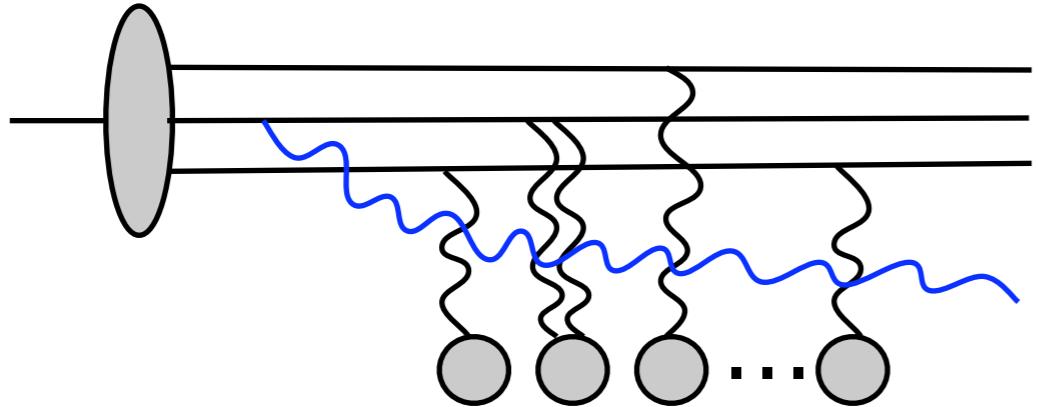
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Predictions for the LHC, May 29, 2007, CERN

Gluon production at small x



$$\frac{d\sigma^{pA}}{d^2kdy} = \frac{2\alpha_s}{C_F k^2} \int d^2q \phi_p(\underline{q}, Y - y) \phi_A(\underline{k} - \underline{q}, y)$$

Kovchegov, A. Mueller; Kovchegov, K.T.

$$\phi(x, \underline{k}^2) = \frac{C_F}{\alpha_s(2\pi)^3} \int d^2b d^2z e^{-i\underline{k}\cdot\underline{z}} \nabla_z^2 N_G(\underline{z}, \underline{b}, y)$$

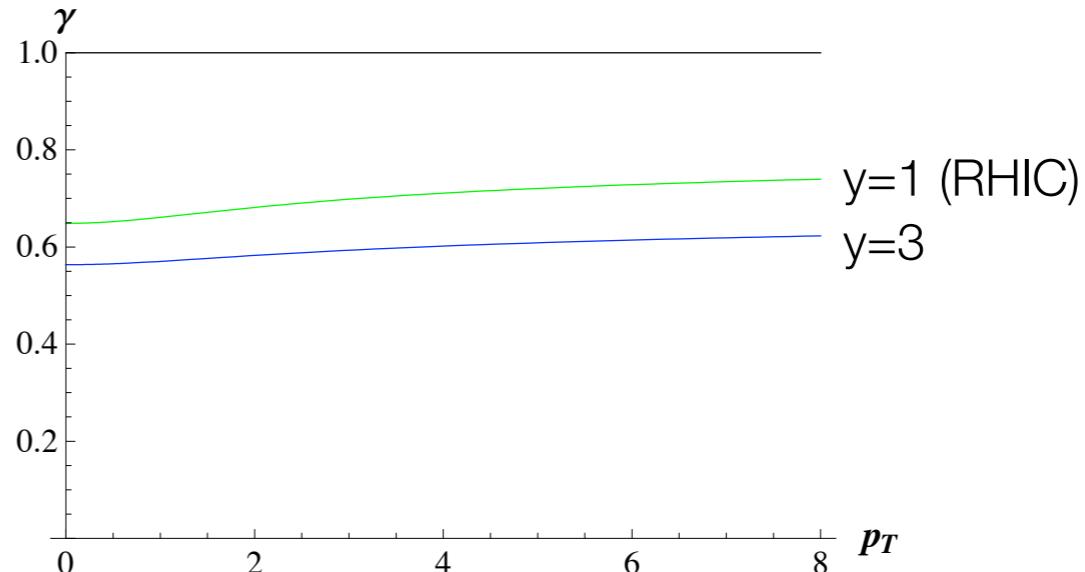
- The interaction is instantaneous:
 - ❖ Gluon production time k_+ / k_\perp^2
 - ❖ Interaction time $\sim R_A$
- Gluon production can be written in a k_T -factorized form even if the evolution is taken into account.
- ϕ is not Weizsäcker-Williams distribution; its factorization cannot be tracked in individual graphs in any known gauge.

KKT model (I)

- Gluon dipole scattering amplitude $N(\underline{r}, y) = 1 - \exp \left\{ -\frac{1}{4}(r^2 Q_s^2)^{\gamma(r,y)} \right\}$

- Anomalous dimension $\gamma(r, y) = \begin{cases} \frac{1}{2} \left(1 + \frac{\xi(r,y)}{|\xi(r,y)| + \sqrt{2|\xi(r,y)| + 14c\zeta(3)}} \right) & y > y_0, \\ 1 & y < y_0, \end{cases}$

with $\xi(r, y) = \frac{\ln [1/(r^2 Q_{s0}^2)]}{(\lambda/2)(y - y_0)}$



- This function satisfies limits:

* $\gamma \approx 1 - \sqrt{1/(2\xi)}$ double log approximation ($r \rightarrow 0$, y fixed)

* $\gamma \approx \frac{1}{2} + \frac{\xi}{c 14 \zeta(3)}$ leading log, BFKL saddle point ($y \rightarrow \infty$, r fixed)

KKT model (II)

- Gluon saturation momentum $Q_s^2(y) = \Lambda^2 A^{1/3} e^{\lambda y} = 0.13 \text{ GeV}^2 e^{\lambda y} N_{\text{coll}}$
with $\Lambda=600 \text{ MeV}$, $\lambda=0.3$ from DIS
- Quark dipole scattering amplitude $N_Q(\underline{r}, y) = 1 - \exp \left\{ -\frac{1}{4} (r^2 Q_s^2 / 2)^{\gamma(r,y)} \right\}$
 - Quark saturation momentum is $C_F Q_s^2 / N_c \approx Q_s^2 / 2$
- The cross section for inclusive gluon production
$$\frac{d\sigma_G}{d^2 k dy} = \frac{\alpha_s C_F}{\pi^2} \frac{S_A}{k^2} x_p^{-\lambda} (1 - x_p)^4 \int_0^\infty dz_T J_0(k_T z_T) \ln \frac{1}{z_T \mu} \partial_{z_T} [z_T \partial_{z_T} N_G(z_T, y)] \quad \text{Kovchegov, KT}$$
- For inclusive *valence* quark production $\frac{d\sigma_Q}{d^2 k} = \frac{S_A}{2\pi} \int_0^\infty dz_T z_T J_0(k_T z_T) [2 - N_Q(z_T, y)]$
Dumitru, Jalilian-Marian

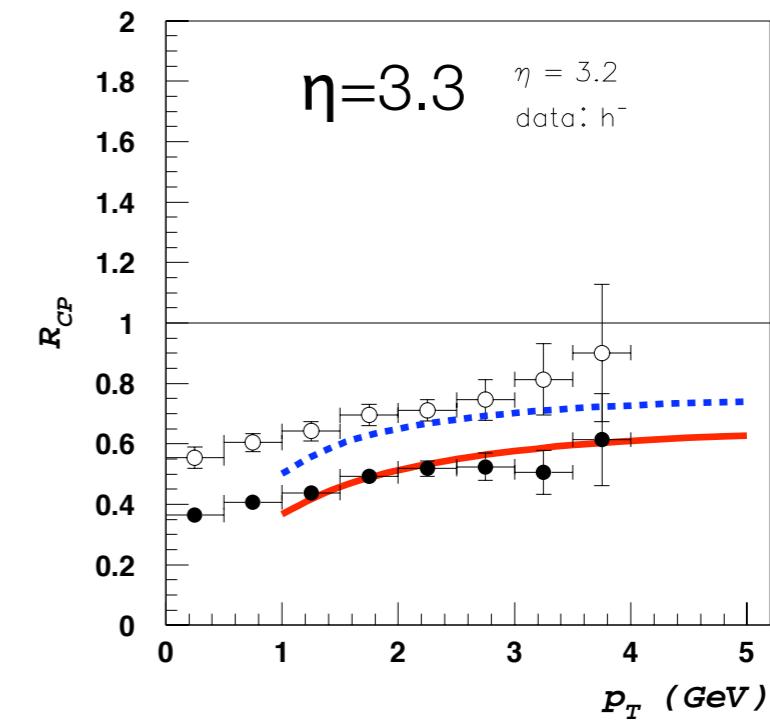
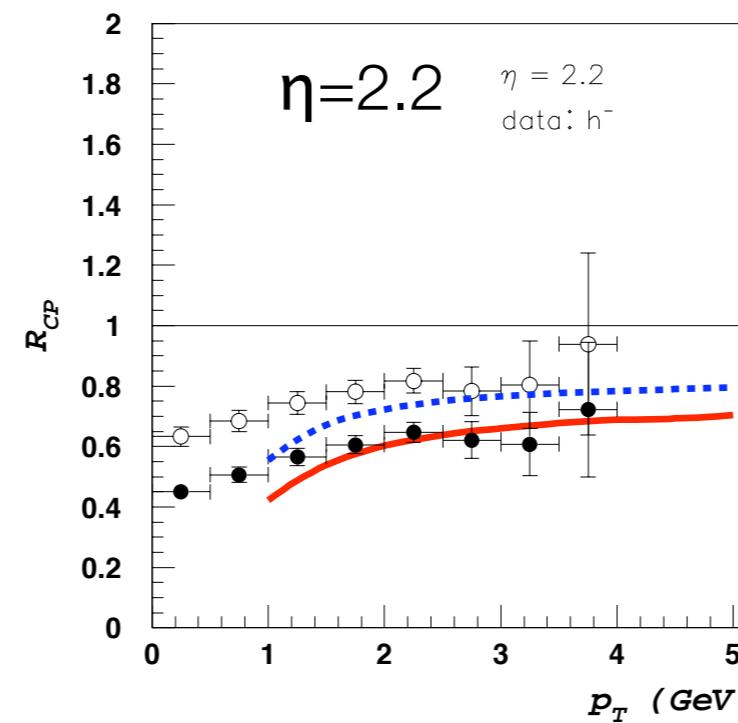
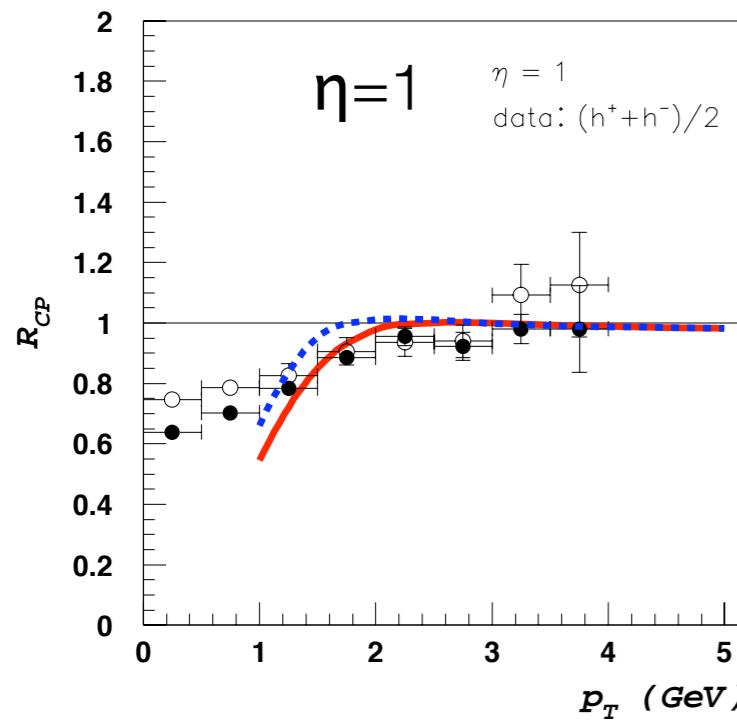
KKT model (III)

- Quark distribution is weighted with $xq_V(x) = 1.09 (1 - x_p)^3 x_p^{0.5}$

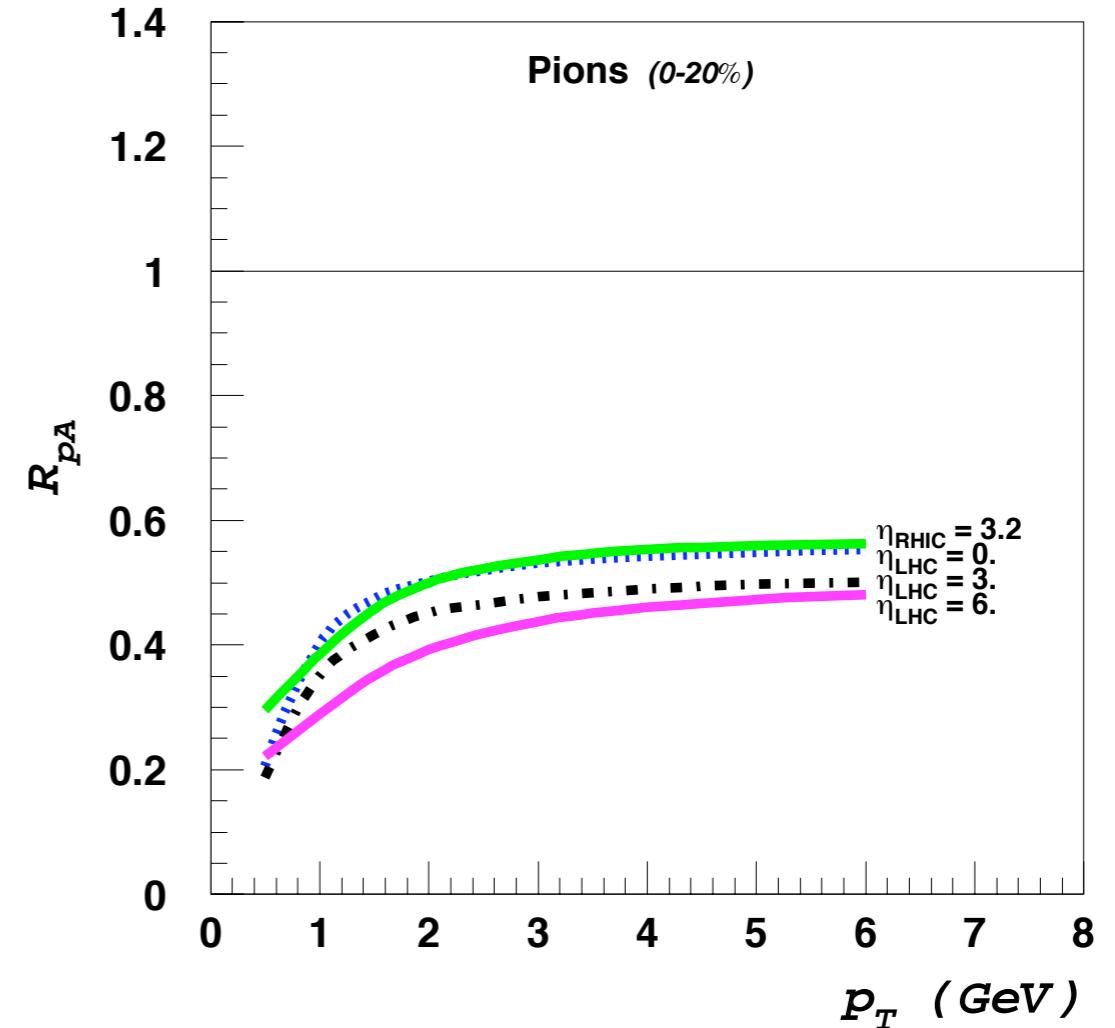
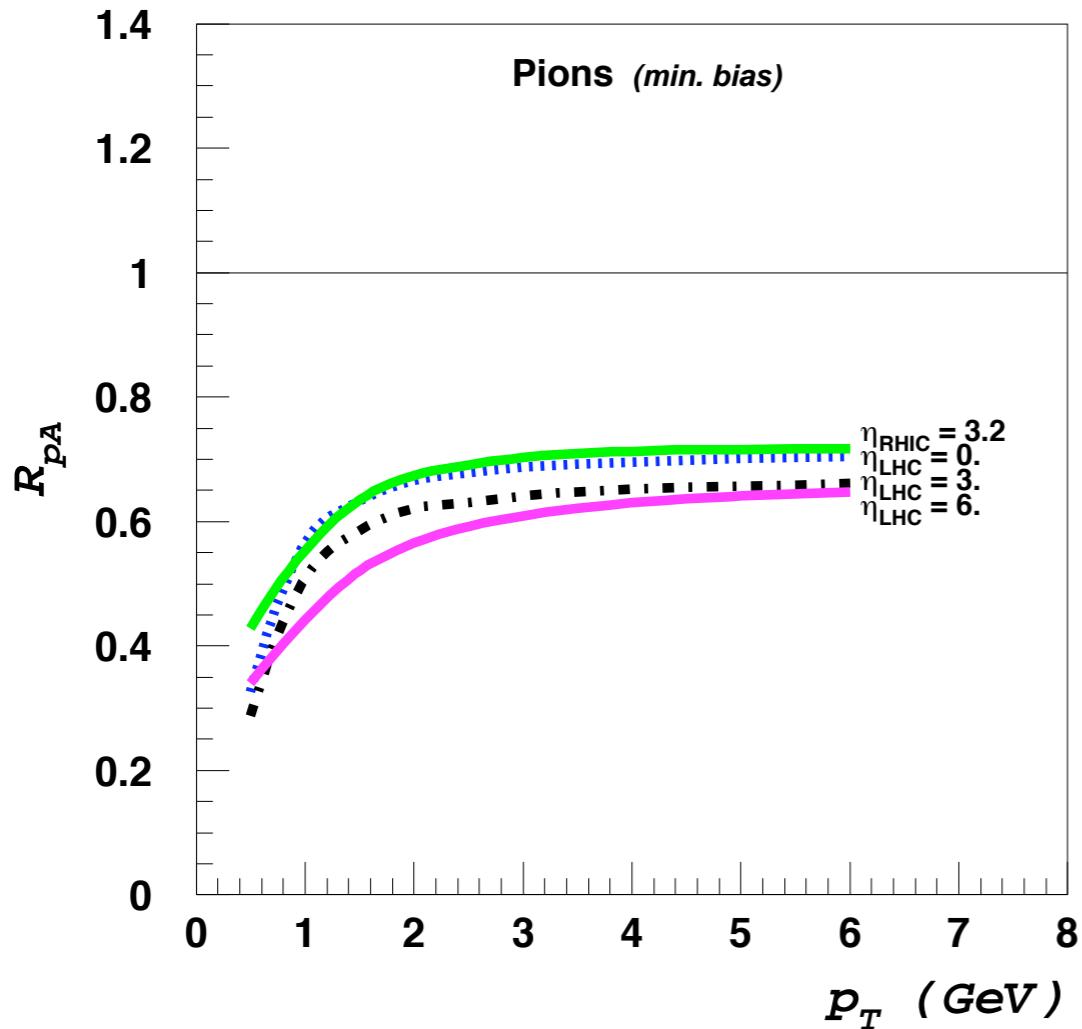
- Hadron cross section

$$\frac{d\sigma^h}{d^2k dy} = \int \frac{dz}{z^2} \frac{d\sigma_G}{d^2k dy}(k/z) D_G(z, k) F(k/z, y) + \int \frac{dz}{z^2} \frac{d\sigma_Q}{d^2k}(k/z) xq_V(y, k/z) D_Q(z, k_T) F(k/z, y).$$

★ This model works fine @ RHIC for hadron spectra, R_{dAu} , R_{CP}

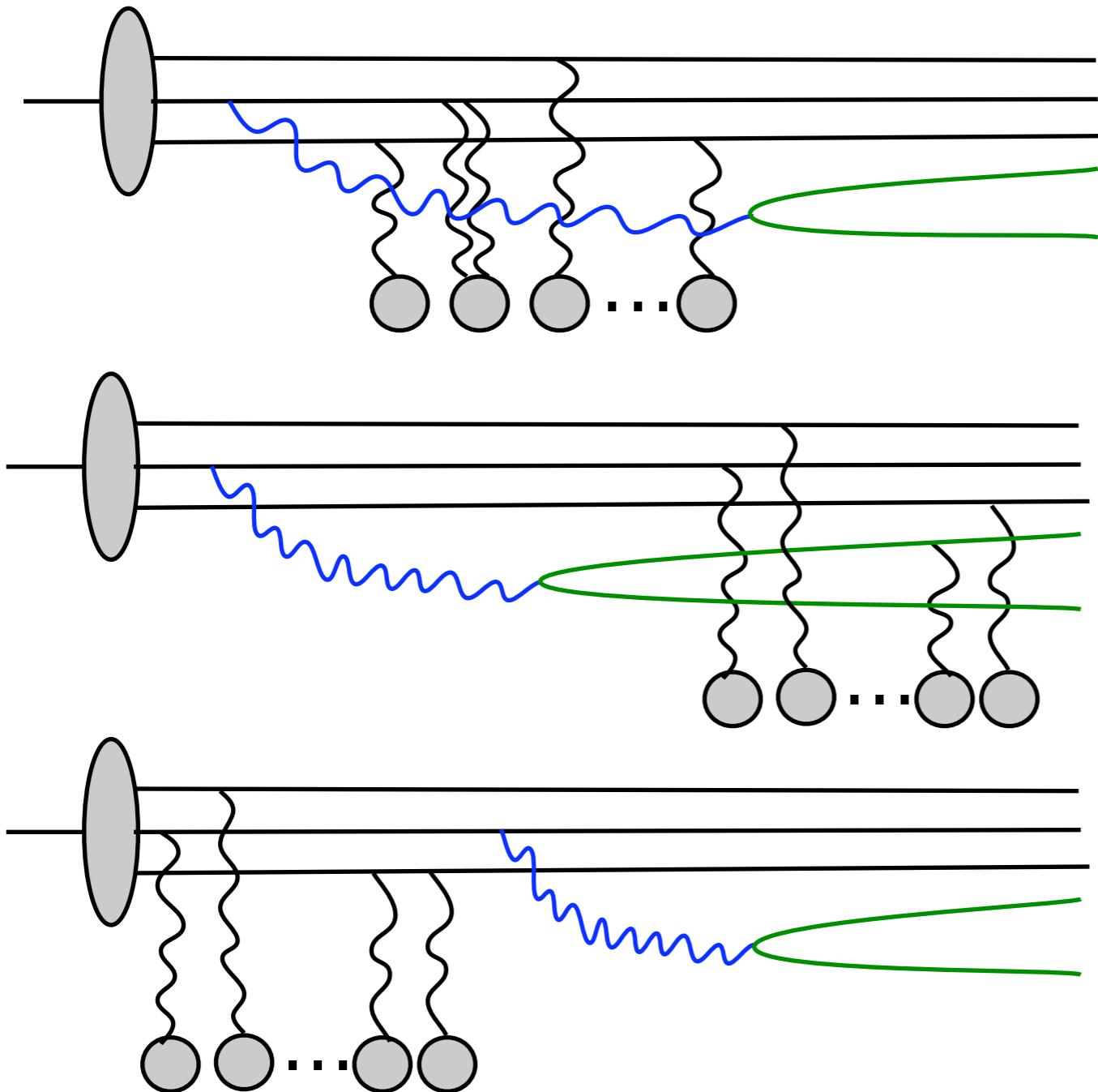


Pion NMF's



- The amount of suppression is $R_{pA} \simeq 1/A^{(1-\gamma)/3} \approx 1/N_{\text{coll}}^{1-\gamma}$
- Dependence on p_T and η is weak

Quark-antiquark production (I)



- Since the coherence length $\sim 1/x$, for high enough \sqrt{s} and/or y we can use the dipole model.
- Exact result: Kovchegov, KT (2006) - includes rescattering of the q , anti- q , gluon and valence quark and quantum evolution at all rapidity intervals.
- Factorization approximation:
$$q_\perp^2 \ll m^2$$
 KT, 2004

Kapeliovich,Tarasov(2002), Blaizot,Gelis,Venugopalan (2003-04), Kharzeev,KT(2003)

Quark-antiquark production (II)

- The lightcone “wave function”

$$\Phi_{11}(\underline{x}_1, \underline{x}_2; \underline{y}_1, \underline{y}_2; \alpha) = 4 C_F \left(\frac{\alpha_s}{\pi} \right)^2 \frac{m^2}{uv} \left\{ 2 \frac{\underline{x}_{12} \cdot \underline{y}_{12}}{x_{12} y_{12}} [(1 - \alpha^2) + \alpha^2] K_1(x_{12}m) K_1(y_{12}m) + K_0(x_{12}m) K_0(y_{12}m) \right\}$$

- The scattering amplitude

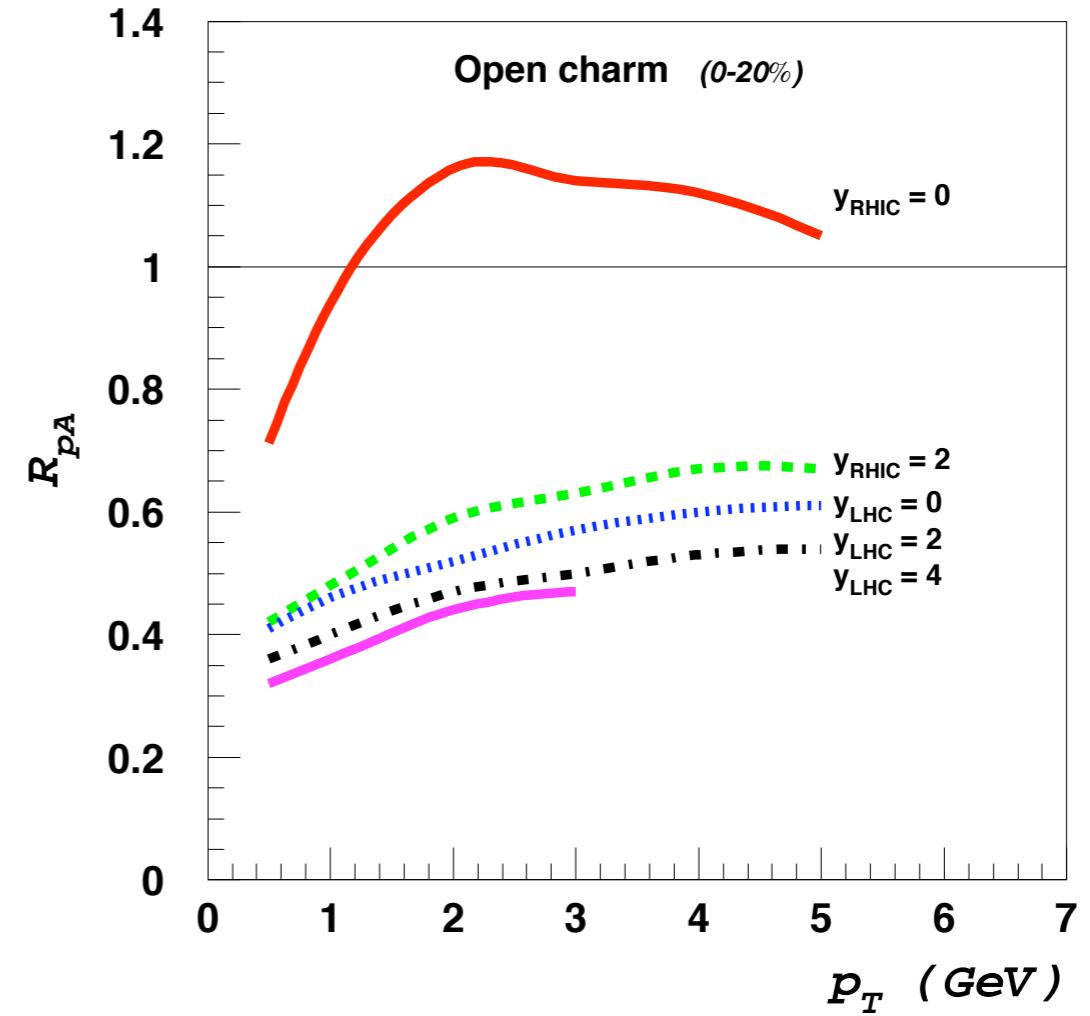
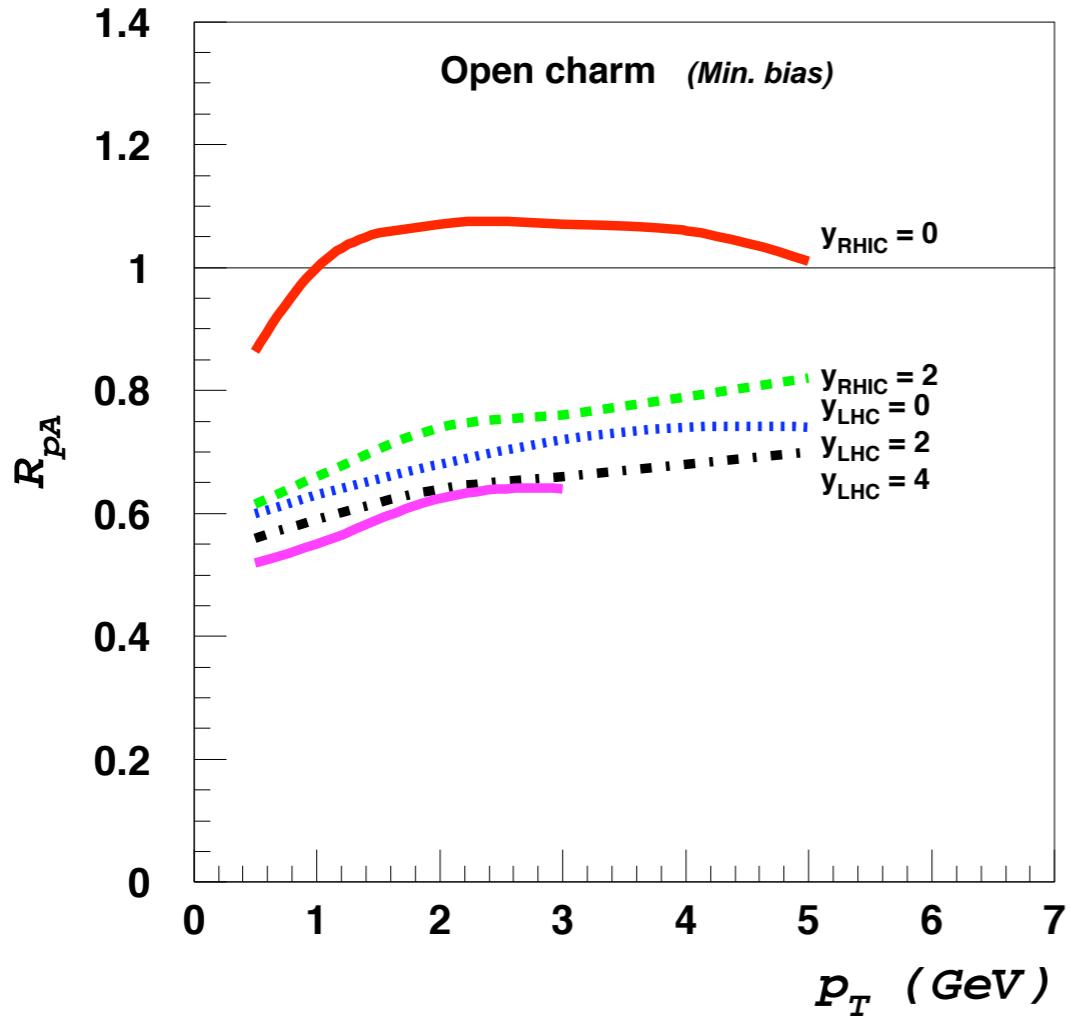
$$\begin{aligned} \Xi(\underline{x}_{12}, \underline{y}_{12}; \alpha) = & e^{-\frac{1}{4}(\underline{x}_{12} - \underline{y}_{12})^2(Q_s^2/2)} + e^{-\frac{1}{2}\alpha^2(\underline{x}_{12} - \underline{y}_{12})^2(Q_s^2/2)} \\ & - e^{-\frac{1}{4}(\underline{x}_{12} - \alpha \underline{y}_{12})^2(Q_s^2/2)} e^{-\frac{1}{4}\alpha^2 y^2(Q_s^2/2)} - e^{-\frac{1}{4}(\alpha \underline{x}_{12} - \underline{y}_{12})^2(Q_s^2/2)} e^{-\frac{1}{4}\alpha^2 x_{12}^2(Q_s^2/2)} \end{aligned}$$

- Quark cross section

$$\begin{aligned} \frac{d\sigma}{d^2k dy d^2b} = & \frac{C_F \alpha_s^2 m^2}{4\pi^5} \int_0^1 d\alpha \int d^2x_{12} d^2y_{12} e^{-i\underline{k} \cdot (\underline{x}_{12} - \underline{y}_{12})} \ln(1/\mu |\underline{x}_{12} - \underline{y}_{12}|) \\ & \times \left\{ 2 \frac{\underline{x}_{12} \cdot \underline{y}_{12}}{x_{12} y_{12}} [(1 - \alpha^2) + \alpha^2] K_1(x_{12}m) K_1(y_{12}m) + K_0(x_{12}m) K_0(y_{12}m) \right\} \Xi(\underline{x}_{12}, \underline{y}_{12}; \alpha) \end{aligned}$$

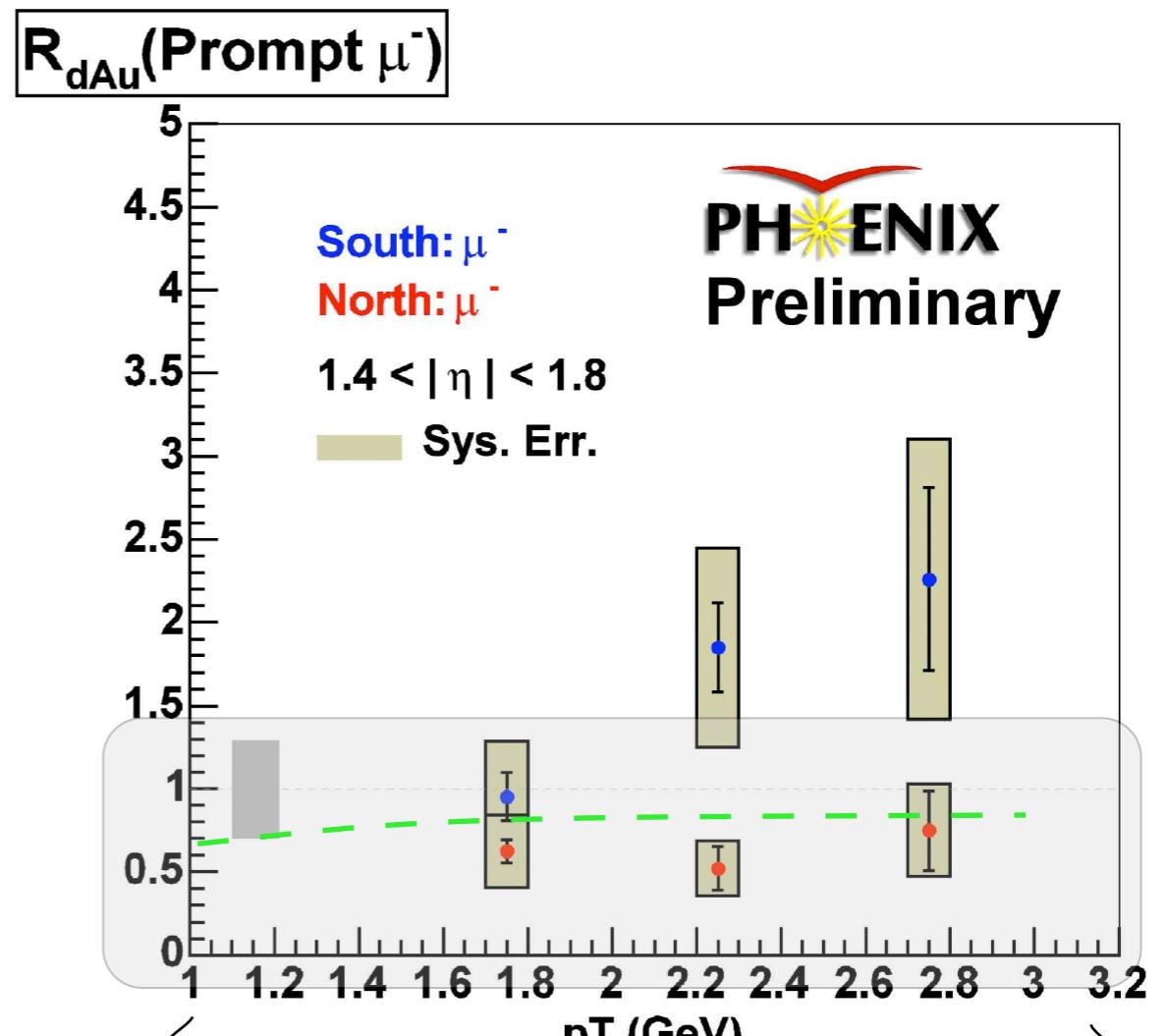
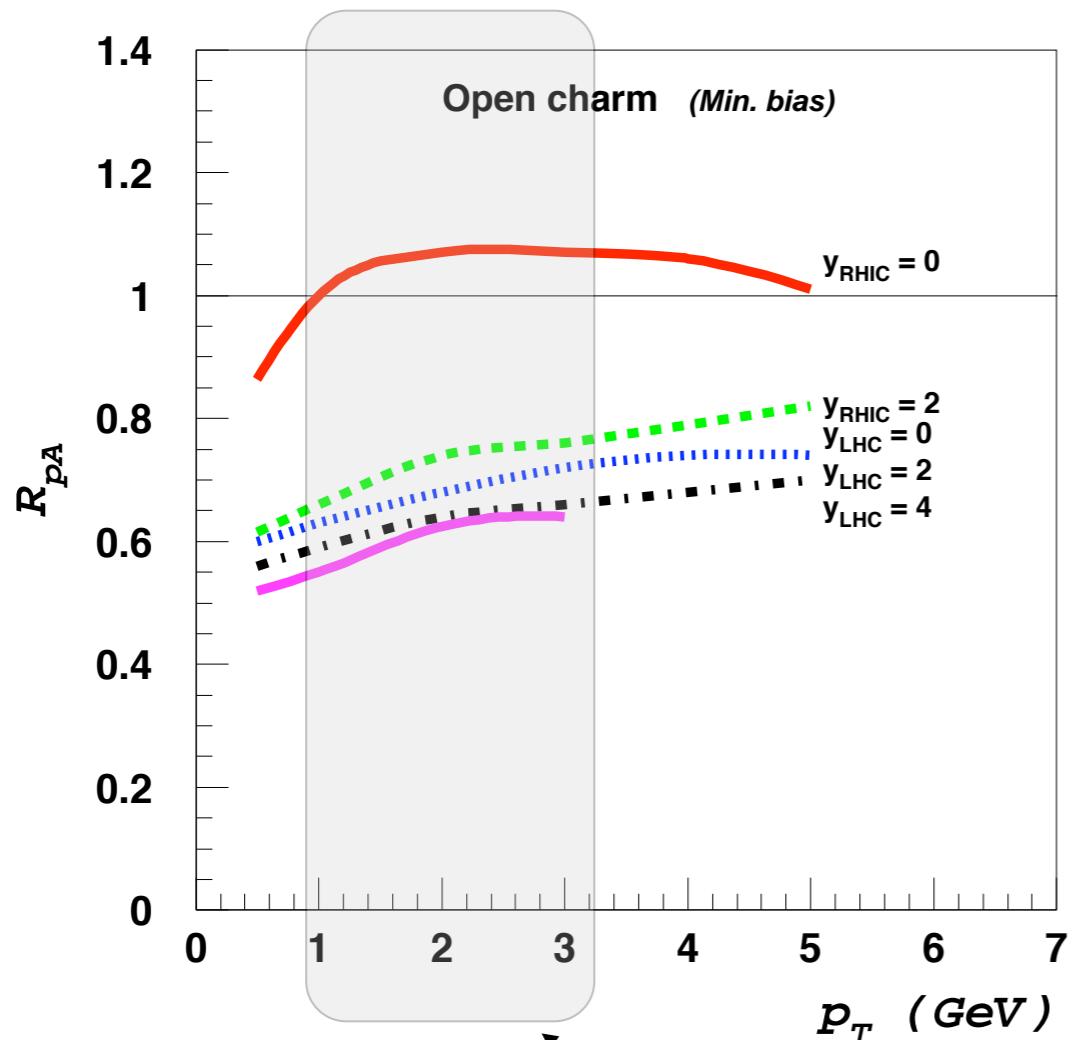
- Hadronization: $\frac{d\sigma_{\text{hadron}}}{d^2p dy} = \int_{z_{\min}}^1 \int d^2k \frac{d\sigma(\underline{k}, y)}{d^2k dy} \delta(\underline{p} - z\underline{k}) D(z) = \int_{z_{\min}}^1 \frac{dz}{z^2} \frac{d\sigma(p/z, y)}{d^2k dy} D(z)$

Open charm NMF's

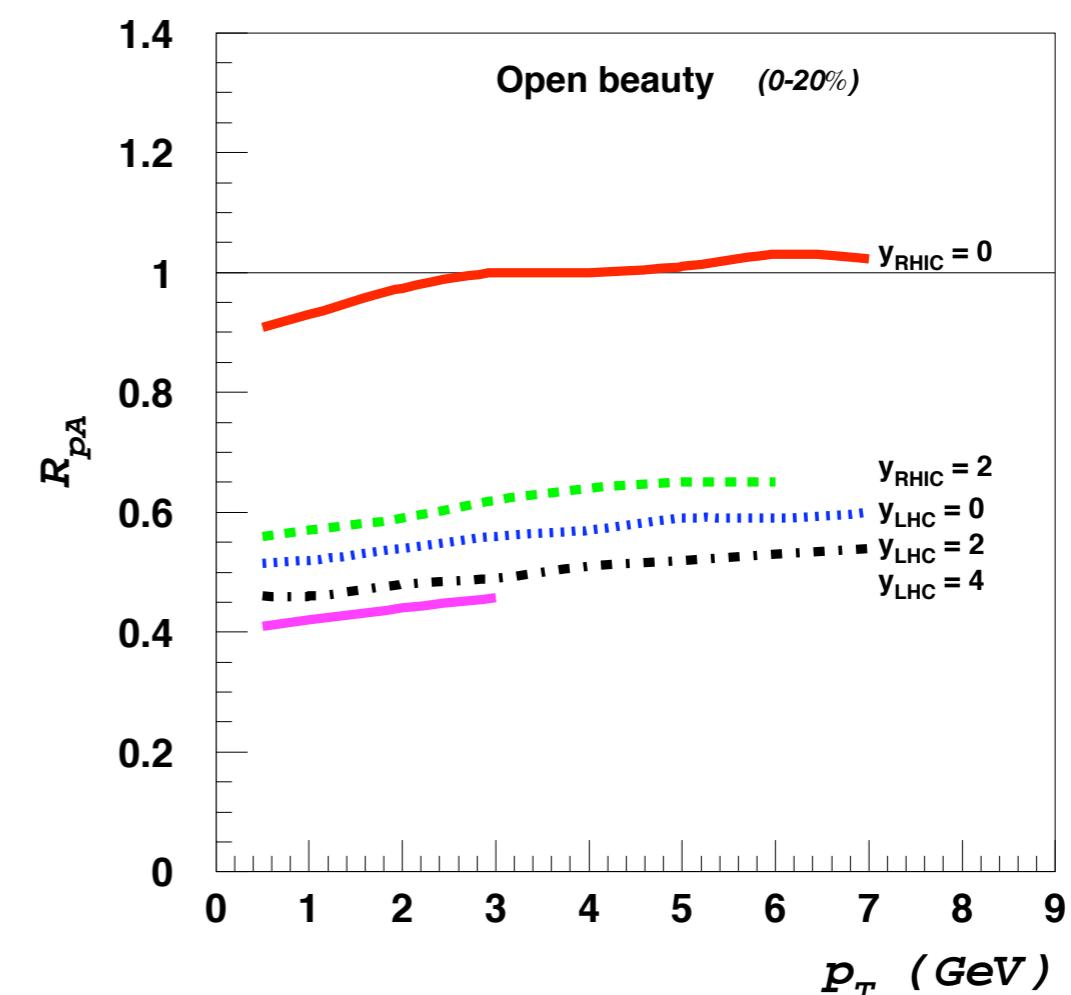
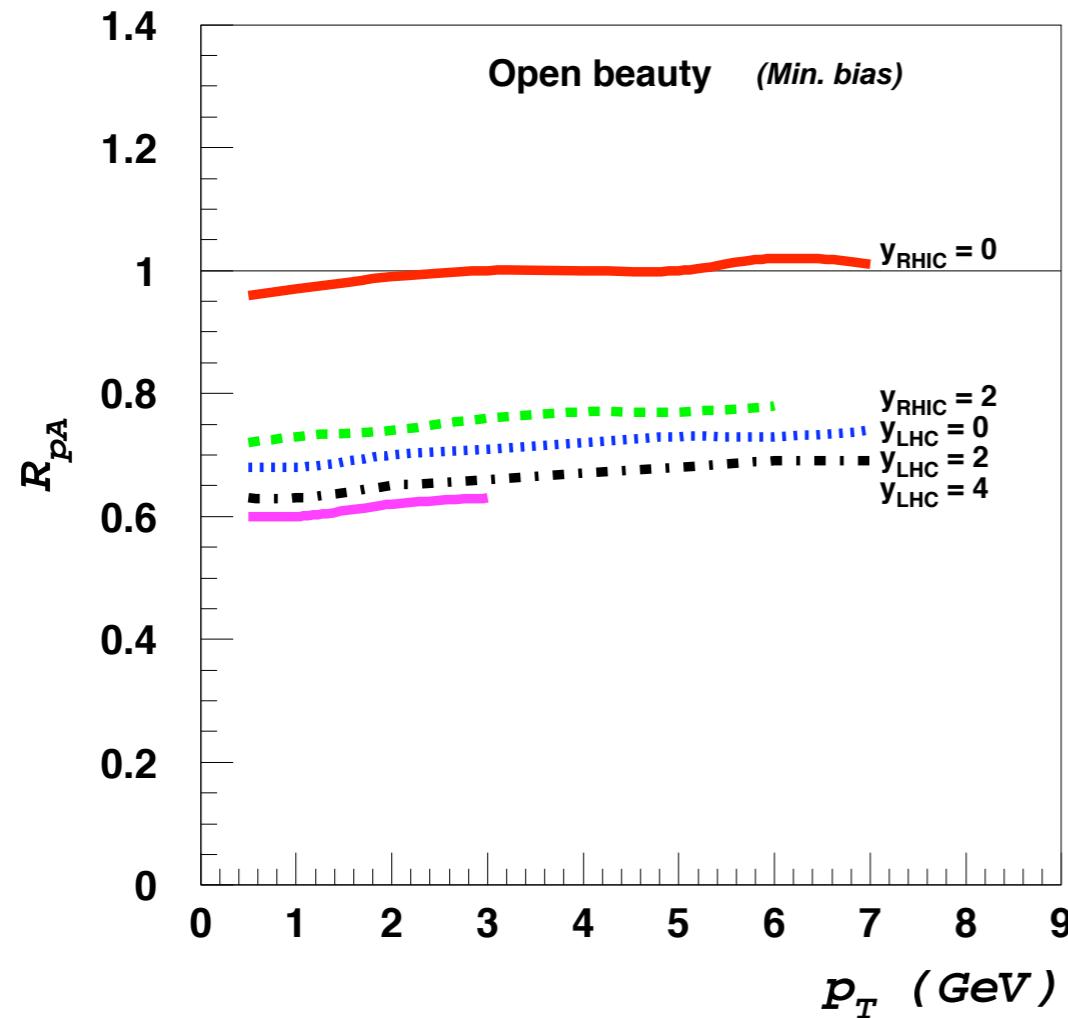


- NMF for charm shows the same suppression pattern as NMF for pions.

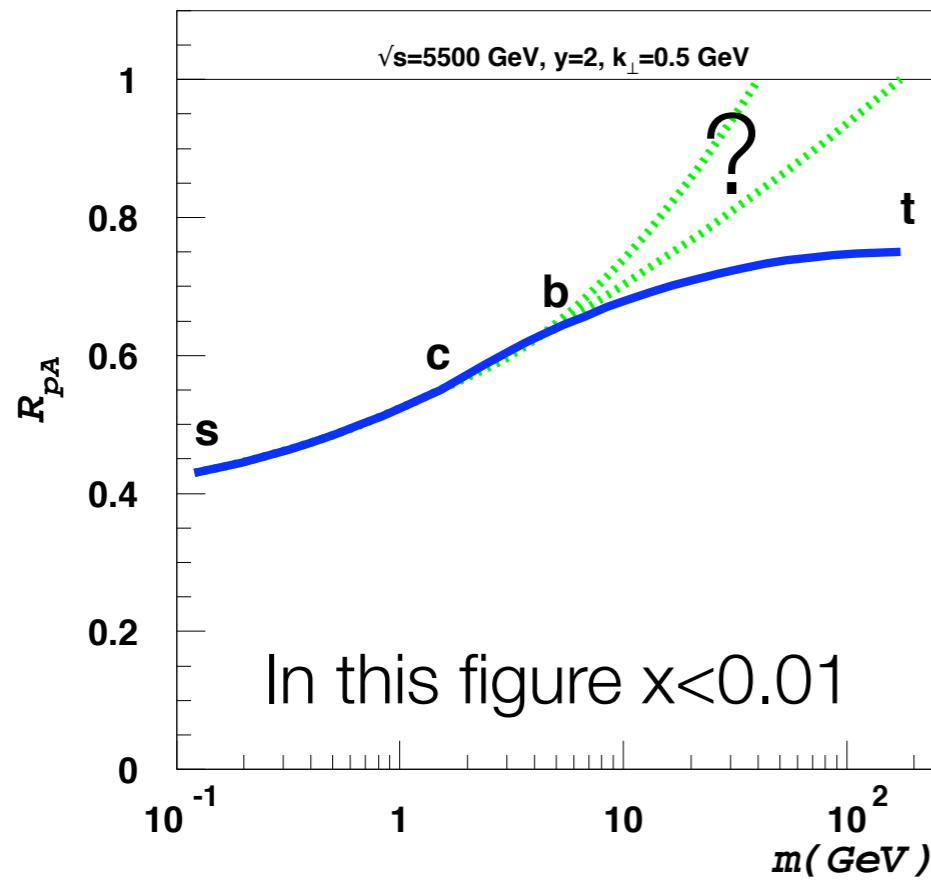
Open charm NMF's vs PHENIX data



Open beauty NMF's



When does the geometric scaling fails?



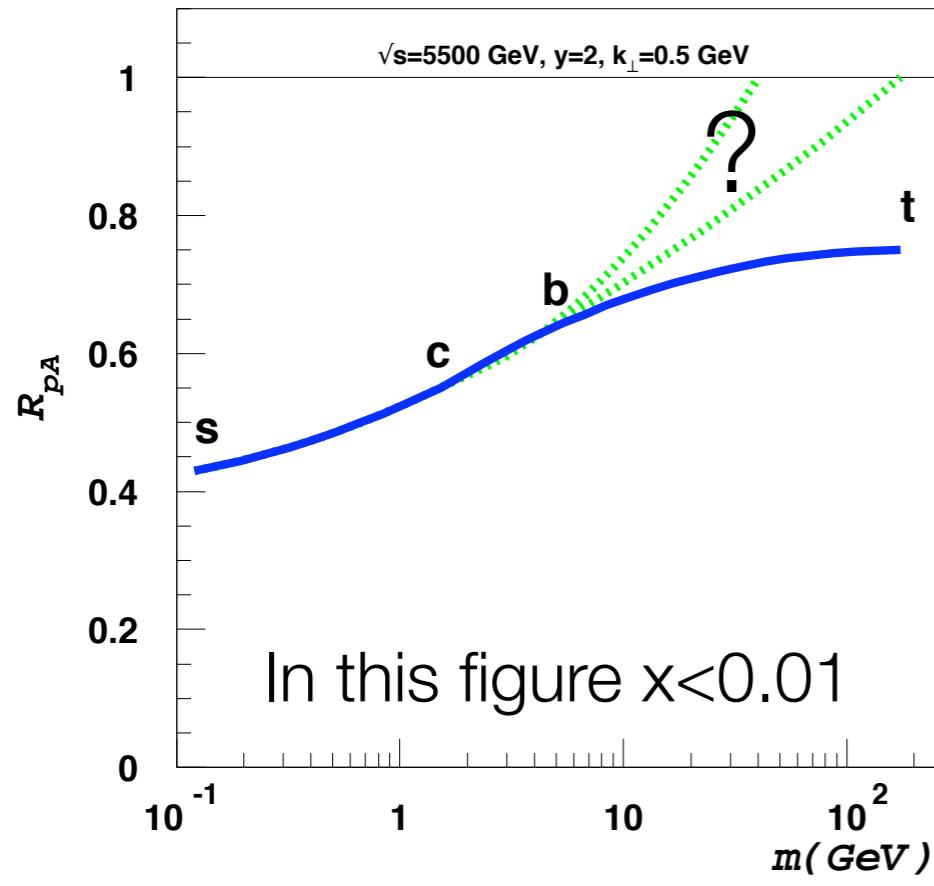
- Extended geometric scaling was observed in DIS for $x < 0.01$, $Q^2 < 450 \text{ GeV}^2$ (Stasto, Golec-Biernat, Kwiecinski, 2001)
- This is a property of the BK equation (Levin, KT, 2001)
- It is predicted to break down when DGLAP logs take over BFKL logs (Iancu, Itakura, McLerran, 2002)

$$\alpha_s \log(k_\perp/Q_s) \gtrsim \alpha_s y = \alpha_s \log(Q_s/\Lambda)$$

$$k_\perp \gtrsim \# Q_s^2/\Lambda$$

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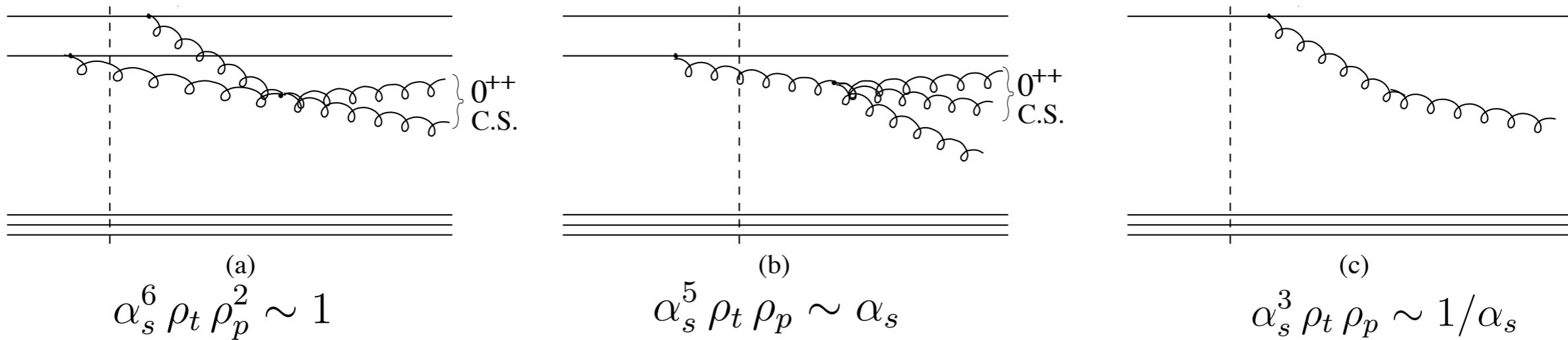
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? $= 5 \text{ GeV} @ y=2 \text{ (LHC)}$
 $= 2.7 \text{ GeV} @ y=0$

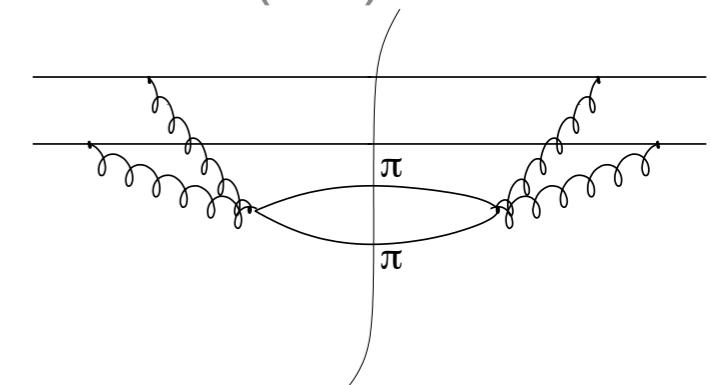
Factorization vs Recombination in AA ($T=0$)

Li and KT, 2007



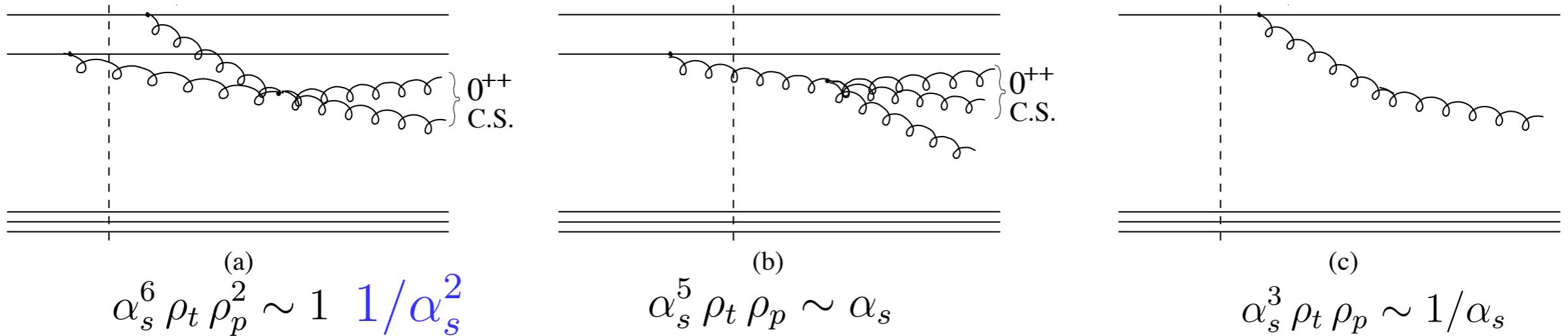
Recall, that $\alpha_s^2 \rho \sim \alpha_s^2 A^{1/3} \sim 1$

- $gg \rightarrow gg$ is proportional to $\text{Tr}(T_{\mu\nu})$ which acquires non-zero value due to the scale anomaly => Low Energy Theorems imply $\int dM \rho_{\text{Tr}(T_{..})}(M)/M = 8|\epsilon_v|$.
 - This sum rule allows to match the chiral Lagrangian at low M onto pQCD at high M .
 - At small invariant masses vertex $gg \rightarrow gg$ becomes $gg \rightarrow \pi\pi \sim O(\alpha_s^0)$.
 - On the other hand (a) is a sub-leading twist $(Q_s/k_T)^2$
 - Thus (a) dominates at $k_T < Q_s/\sqrt{\alpha_s} \sim 3 \text{ GeV}$ (RHIC)



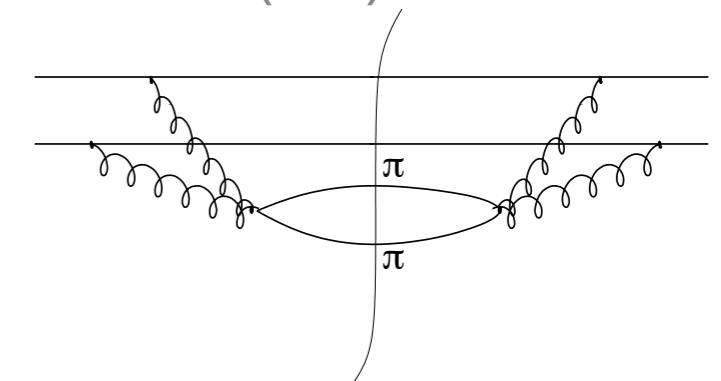
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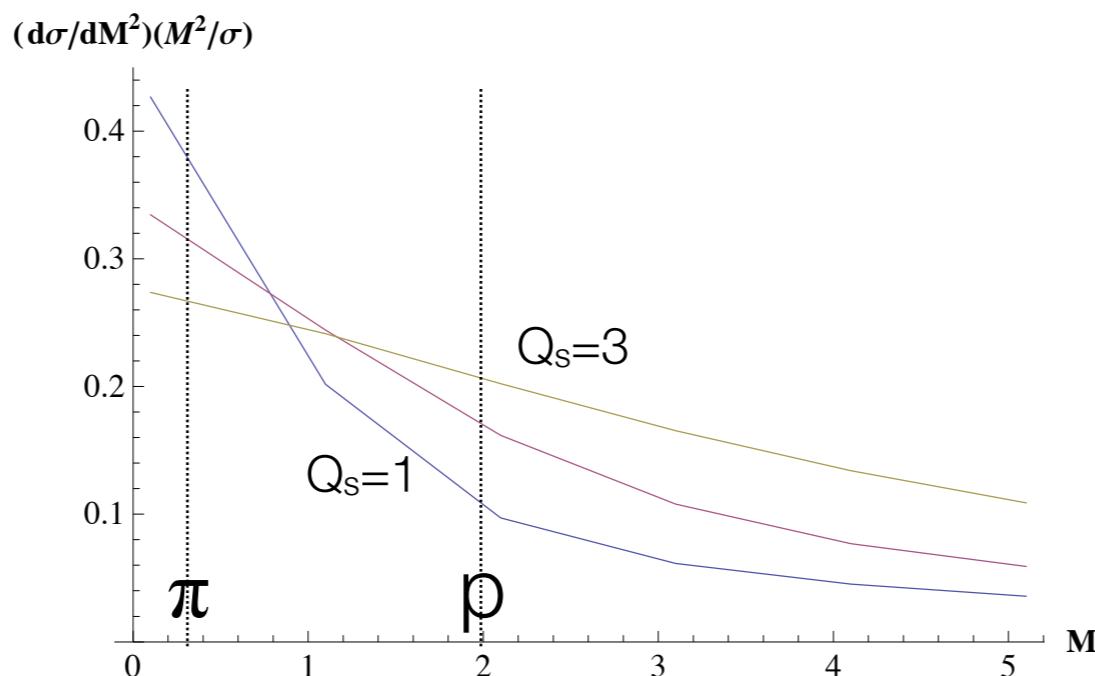
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“Baryons to Mesons” puzzle

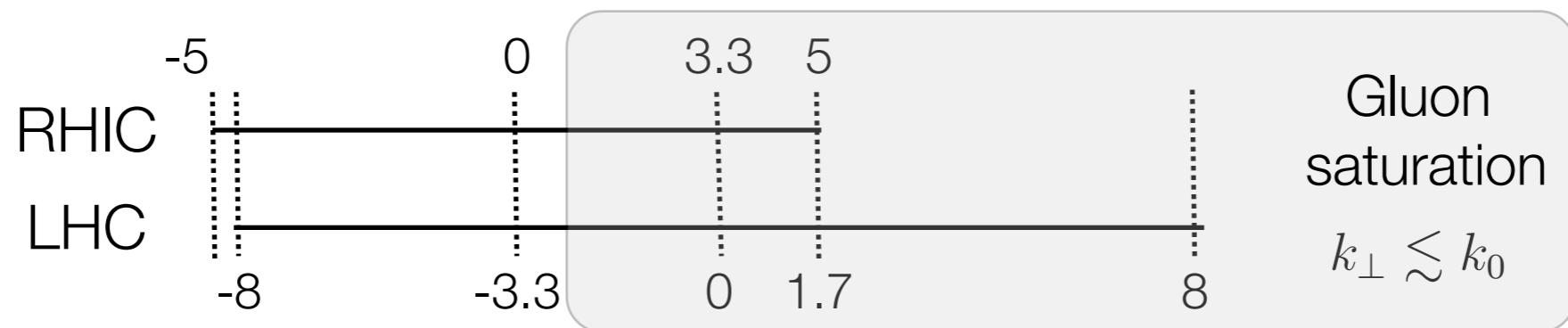
- Breakdown of factorization of fragmentation functions => strong dependence of fragmentation on energy and centrality.



- P to π ratio increases with energy and when $Q_s \gg m$ it tends to a constant.

Li, Kharzeev and KT, in preparation

Summary



- We examined inclusive production of π 's, D's and B's and found a strong Gluon Saturation effect.
- The amount of suppression of R_{pA} depends on centrality and is almost independent of y and p_T .
- Geometric scaling seems to hold for $\eta \geq 1$ at RHIC. It is not clear when it fails at LHC (if it does ☺).
- Non-factorable hadronization channels are important in AA collisions even at $T=0$.
- It is absolutely necessary for success of heavy ion program at LHC to have inclusive measurements in pA