Particle multiplicities from CGC with local rcBK evolution

in high-energy hadronic collisions at RHIC/LHC

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Particle productions at collider energies

- dominated by small-x dof in hadrons
- BK evolution eqn for CGC sums $(\alpha_s \ln(1/x))^n$ and incorporates nonlinear effects
  $\Rightarrow$ saturation scale, $Q_s^2(x)$

- Successful phenomenology based on CGC picture in last decade
  - DIS at HERA (GBW, IIM, ...)
  - HIC at RHIC (KLN, ...)

- Recent highlight: **running coupling (rc) BK eqn**
  consistent with $Q_s^2(x) \sim 1/x^\lambda \sim 1/x^{0.3}$ Albacete

- Applications of rcBK:
  - Global analysis of DIS AAMQS, previous talk
  - Hadronic collisions, pp, pA and AA Albacete, Albacete-Marquet, Albacete-Dumitru

This work (in progress)

To develop MC-DHJ formalism with the rcBK,
aiming at forward physics in pA (AA) at RHIC and LHC, cosmic ray reactions

Framework I: rcBK eqn

rcBK eqn in Balitsky's prescription:

$$\frac{\partial \mathcal{N}(r,y)}{\partial y} = \int d^2\boldsymbol{r}_1\, K^{\rm run}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2)\, [\, \mathcal{N}(r_1,y) + \mathcal{N}(r_2,y) - \mathcal{N}(r,y) - \mathcal{N}(r_1,y)\mathcal{N}(r_2,y)\,]$$

- has the same structure as LO eqn with modified kernel:

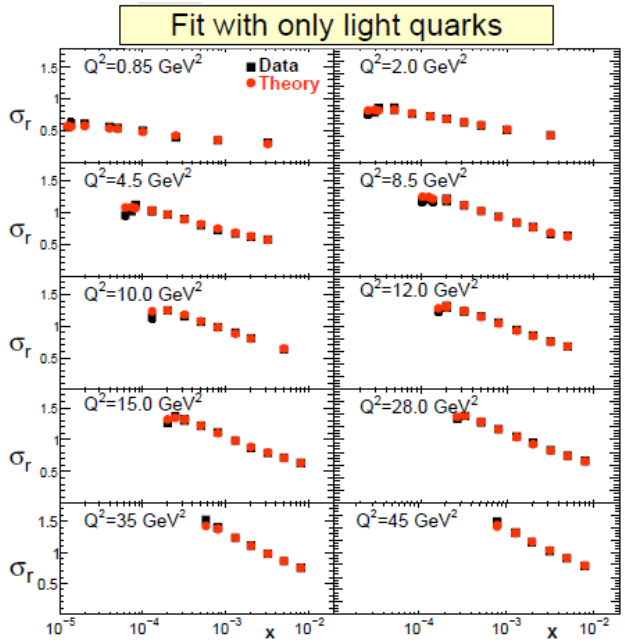
$$K^{\rm run}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2) = \frac{N_c \alpha_s(r)}{2\pi^2}\left[\frac{\boldsymbol{r}^2}{\boldsymbol{r}_1^2\boldsymbol{r}_2^2} + \frac{1}{\boldsymbol{r}_1^2}\left(\frac{\alpha_s(r_1)}{\alpha_s(r_2)} - 1\right) + \frac{1}{\boldsymbol{r}_2^2}\left(\frac{\alpha_s(r_2)}{\alpha_s(r_1)} - 1\right)\right],$$

where one-loop $\alpha_s(r) = 1/[b_0\, \ln(4C^2/r^2)\,]$ is cut off at $\alpha_{\rm cut} = 1.0$

- The initial condition at $x = x_0$ is assumed

$$\mathcal{N}(r,y_0) = 1 - \exp\left[-\frac{(r^2 Q_{s0}^2)^\gamma}{4}\ln\left(\frac{1}{\Lambda r} + e\right)\right]$$

AAMQS

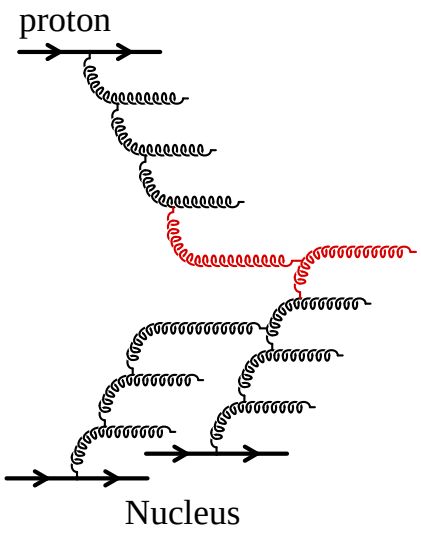


Framework II: hadronic collisions

k_t factorization form

$$\frac{d\sigma^{A+B\to g}}{dyd^2p_Td^2X} \sim K\,\frac{\alpha_s}{p_T^2}\,\phi(k_1,x_1,b)\otimes\phi(k_2,x_2,X-b)$$

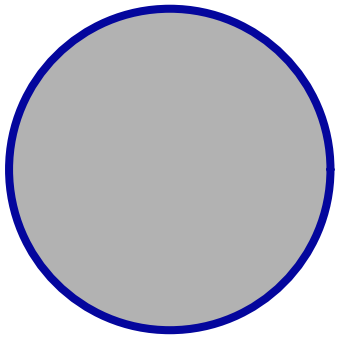
- is proved for pp, pA at LO, but is a working assumption for AA BGV
- $\phi(k,x) \propto k^2$ F.T. $\mathcal{N}_G(\boldsymbol{r},x)$ is the unintegrated gluon dist in the hadron.
- $\mathcal{N}_G = 2\mathcal{N} - \mathcal{N}^2$, with $\mathcal{N}$ constrained by DIS
- **$\mathcal{N}$ in a nucleus requires a modeling for a nucleus**



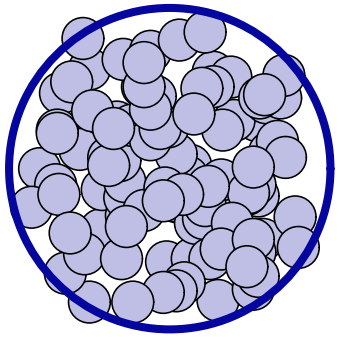
Framework II': hadronic collisions

MC modeling for a nucleus:

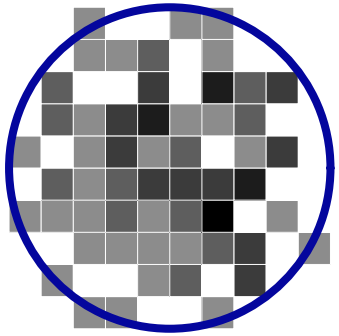
- The simplest will be a homogeneous disk
  no impact parameter dependence
  an additional parameter Q^2_{s0A} needed



- Random nucleons w/ Woods-Saxon dist.
  fluctuating density $\Rightarrow$ b-dependence
  $Q^2_{s0A} = Q^2_{s0p} \times N$ w/o additional parameter
  Drescher-Nara



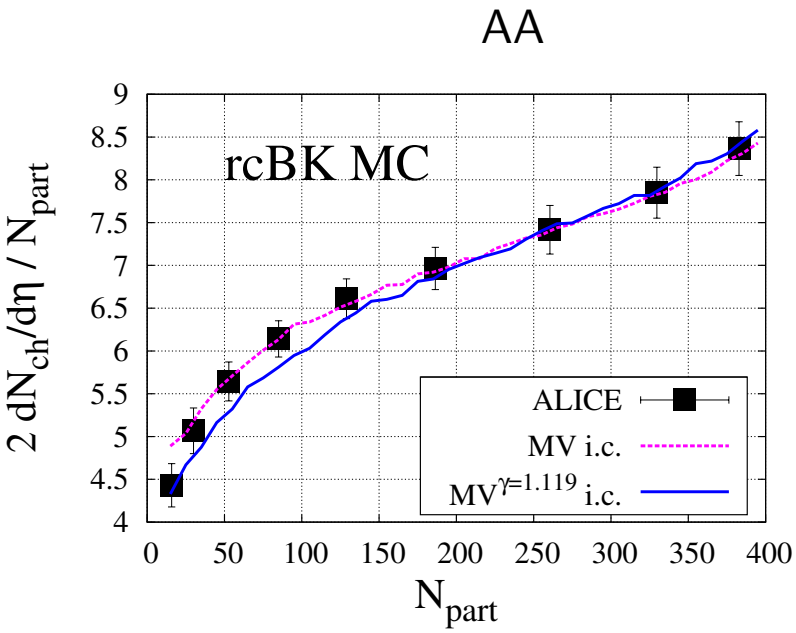
$\Rightarrow$

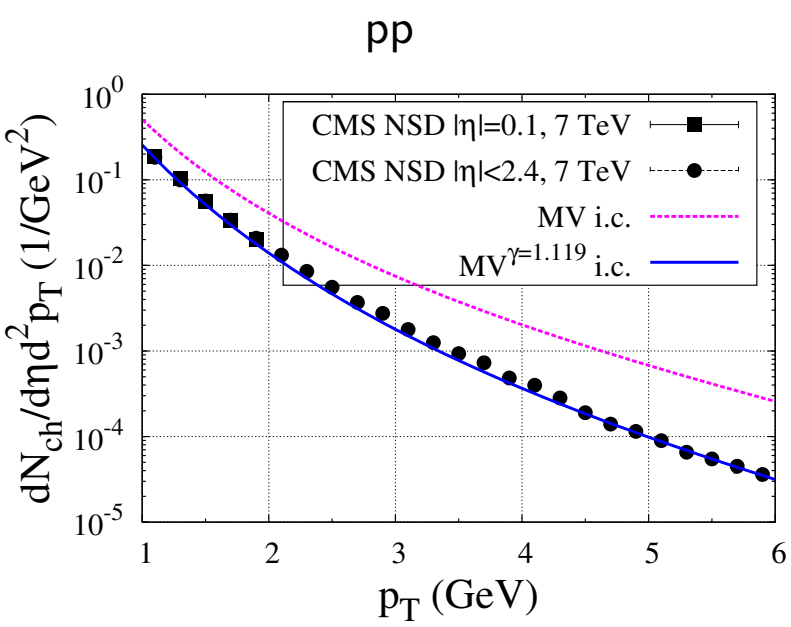


MC-KT model

Albacete-Dumitru

- **MC-KT/rcBK** $= k_T$ factorization formalism with ϕ obtained from rcBK evolution locally on transverse plane of a Monte-Carlo-generated nucleus
- applied at LHC





Framework III: forward particle production

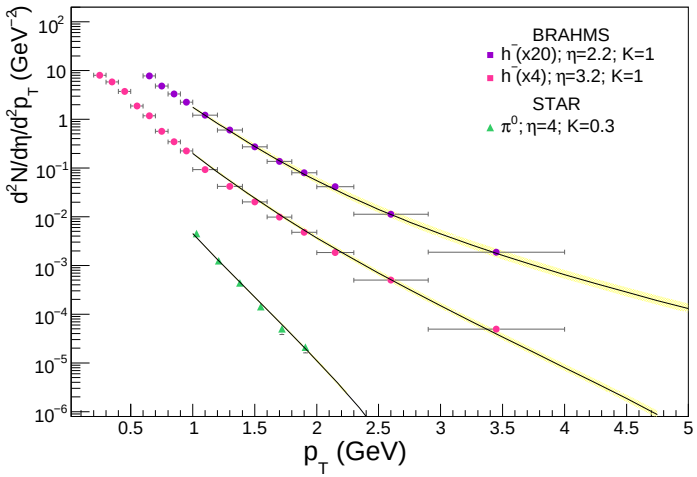
For pA or "Large-x – small-x" reactions: Dumitru-Hayashigaki-Jalilian-Marian (DHJ)

DHJ factorization form

$$\frac{dN}{dy_h d^2p_T} = \frac{K}{(2\pi)^2} \sum_i \int_{x_F}^1 \frac{dz}{z^2}\, x_1 f_{i/p}(x_1, p_T^2)\, \widetilde{\mathcal{N}}(\frac{p_T}{z}, x_2)\, D_{h/i}(z, p_T^2)\ ,$$

where the PDF $f_{i/p}$ describes the large-x, $\mathcal{N}$ the small-x, and the FF $D_{h/i}$ describes high-p_T fragmentation.

applied successfully to pA collisions, with rcBK solution for a homogeneous nucleus characterised by an effective scale Q_{sA}^2 Albacete-Marquet



Framework III': forward particle production

State-of-the-art models w/ rcBK

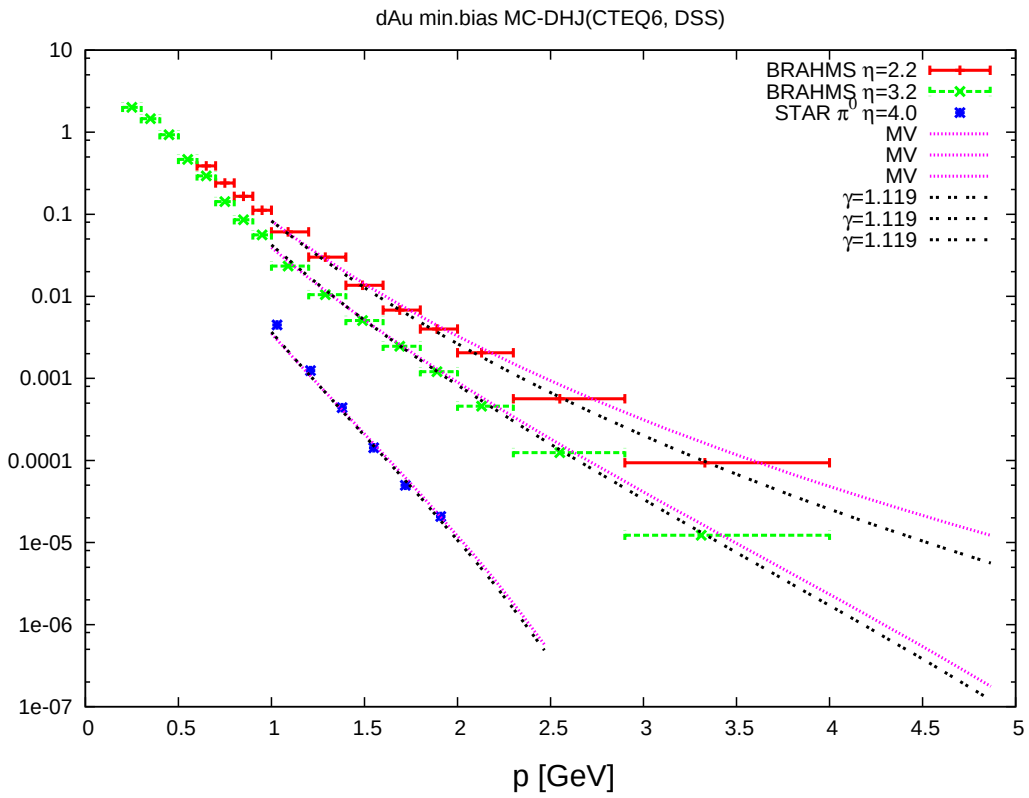
- **AAMQS:** ep @ HERA ... rcBK works and strongly constrains "MV" I.C.
- **AM** : pAu @ RHIC ... DHJ/rcBK nicely works
- **AD** : AA @ LHC ..... MC-KT/rcBK nicely works

Combining these aspects: HF-Itakura-Kitadono-Nara

MC-DHJ/rcBK model

- Initial configuration of the nucleus is prepared w/ Monte-Carlo
- rcBK performed locally on transverse plane w/ $Q_{sA}^2(x_0) = Q_{sp}^2(x_0) \times N$
  - no additional parameter
- Study various aspects of the forward physics in DHJ formalism
- Status report to this goal

The first result of MC-DHJ/rcBK



- this preliminary result (parameter sets: MV and h') fits data very well
- Q^2_{s0A} fixed by MC; no free parameter besides K
- MV gives slightly harder spectrum at $\eta = 2.2$, but no difference at $\eta = 3.2, 4.0$

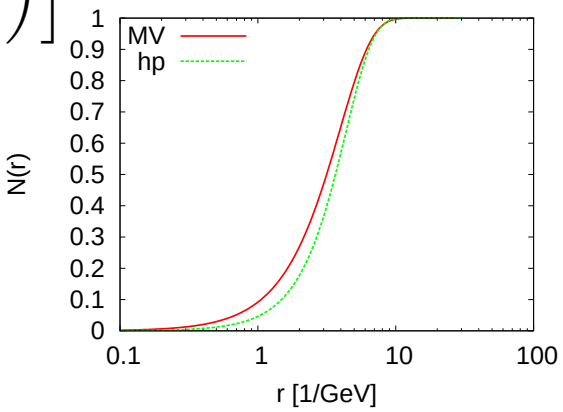
Initial condition for rcBK

- Adopted I.C. at $x_0 = 0.01$:

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

	γ	Q_{s0A}^2	C	Λ
MV	1.0	0.2	1.0	0.2
h'	1.119	0.168	1.715	0.241

N.B.: for a larger γ $\mathcal{N}(k)$ has negative values.

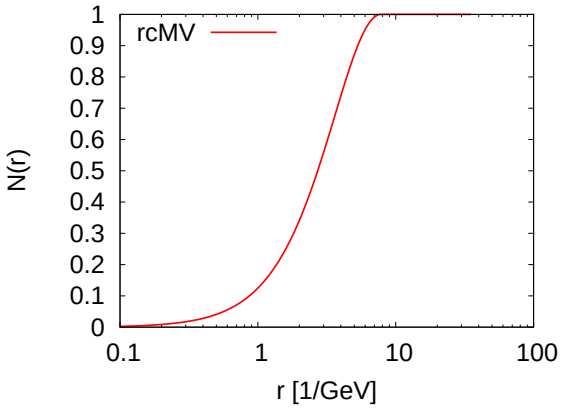


- Another possible I.C.: running coupling (rc) MV

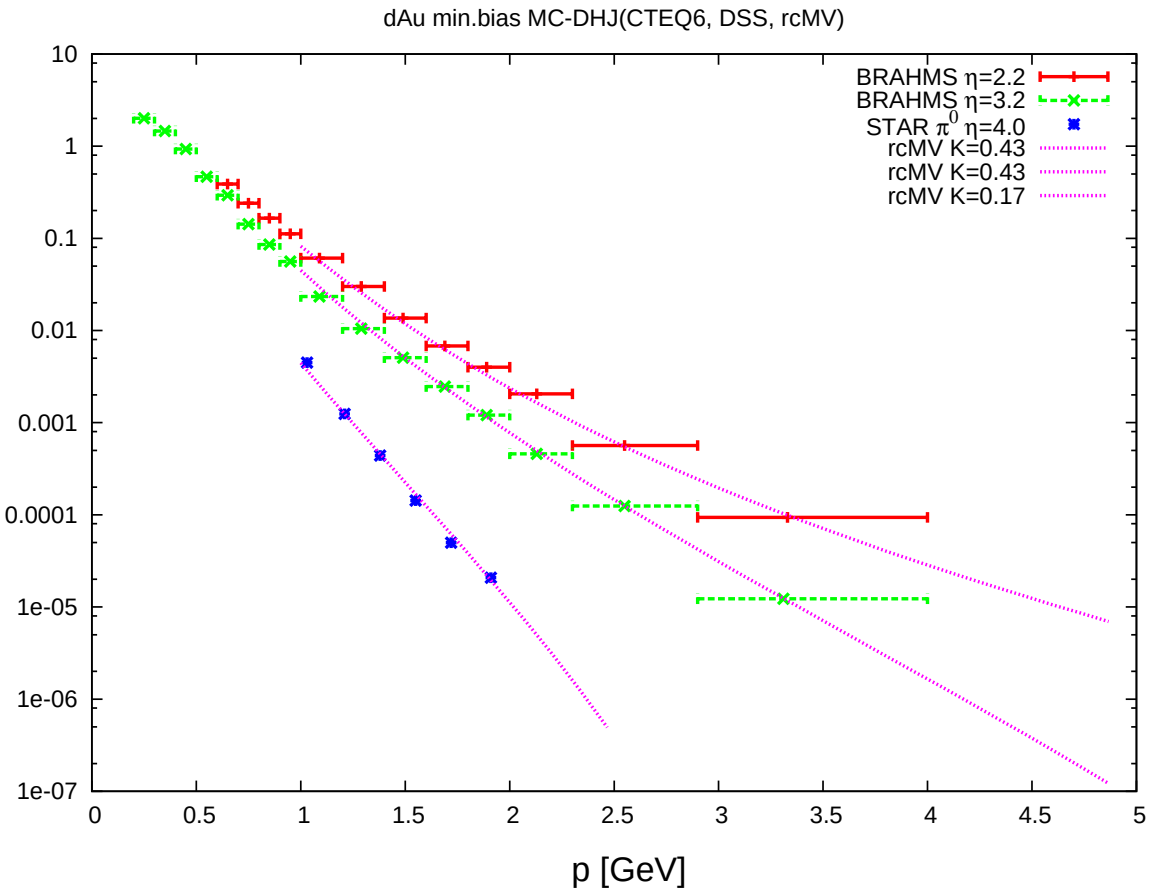
IIT

$$\mathcal{N}(r, x_0) = \frac{\alpha_s(\mu)}{\alpha_s(r)} \left(1 - \exp\left[-\frac{r^2 Q_A^2}{4}\right]\right)$$

N.B. Q_A^2 is not tuned, but fixed $Q_s^2 = Q_A^2 \ln(Q_s^2/\Lambda^2)$



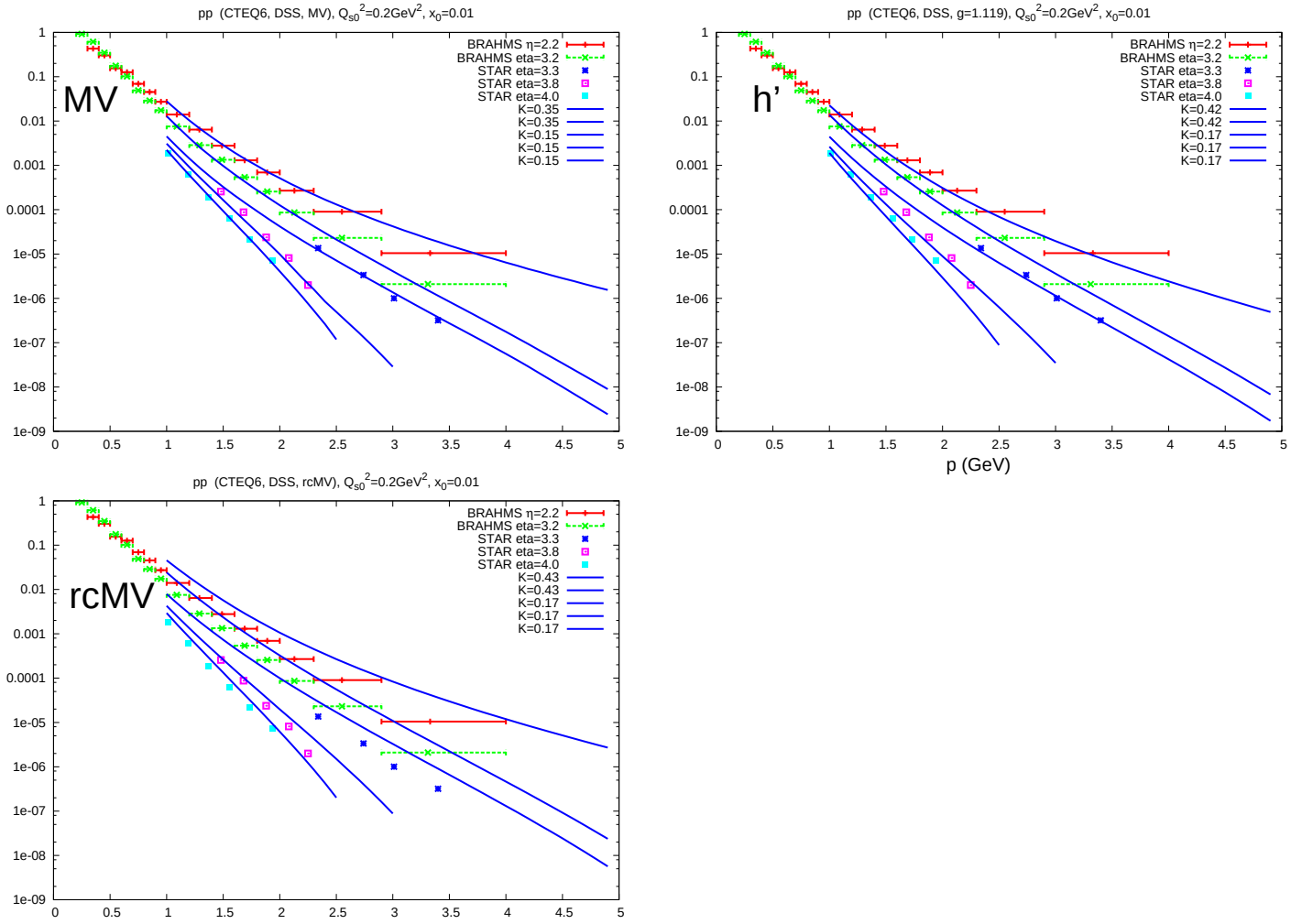
Attempt: rcMV to dAu at RHIC



- To my surprise, rcMV also does a good job (preliminary)

pp cross section at RHIC

- DHJ merginally describes pp @ RHIC at the same K as dA
- MV does a better job among three (preliminary)

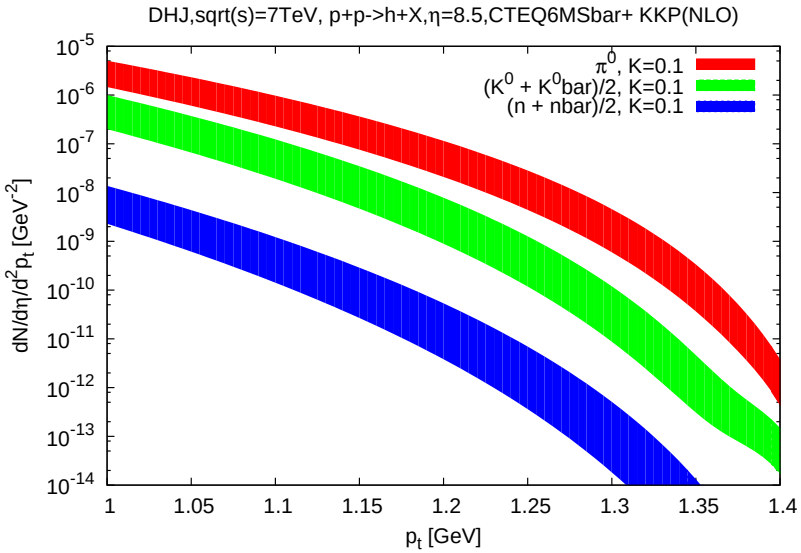


Summary

- **The rcBK eqn provides a useful tool for phenomenology**
  rcBK for DIS, MC-KT/rcBK for pp/AA, DHJ/rcBK for pA
- **Combining the above, we optimized our description for pA:**
  MC-DHJ/rc-BK
- **MC-DHJ/rcBK fits the forward data nicely**
- **New possibility for I.C. – rcMV – is proposed**

- Outlook:
  - More analyses on forward physics at RHIC to be done
  - Applications to forward physics at LHC and in cosmic ray
  - see an example -

Test calculation for forward physics at LHC



- Hadron productions (π^0, K^0 and n) at $\eta = 8.5$ at 7 TeV (LHCf) is being studied