Forward hadron production at collider energies and its possible application to cosmic ray physics

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Plan

- **Motivation**

  high-energy hadron-hadron collisions

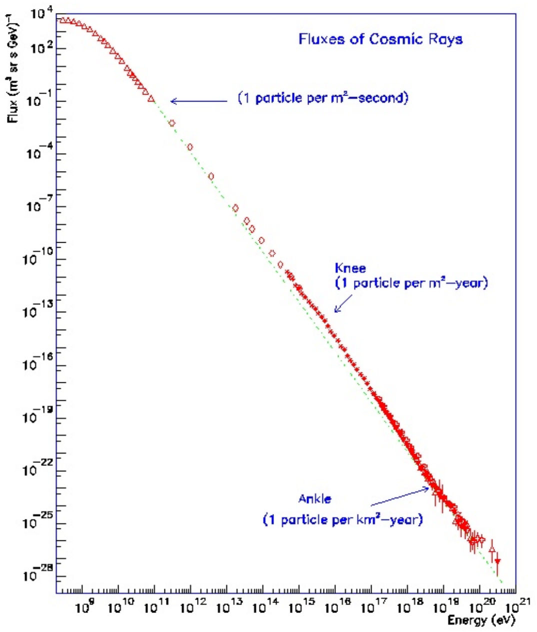
  vs first impact of cosmic ray air shower
- **Necessary ingredients for the calculation**
  1. Evolution eq.: rcBK - a new working paradigm
  2. ``Initial Cond.” : AAMQS - DIS global fit (see talk by J.G.Milhano)
  3. Formula: DHJ -forward hadron production
  4. MC treatment of nuclei
- **MC-DHJ/rcBK:** state-of-the-art calculation

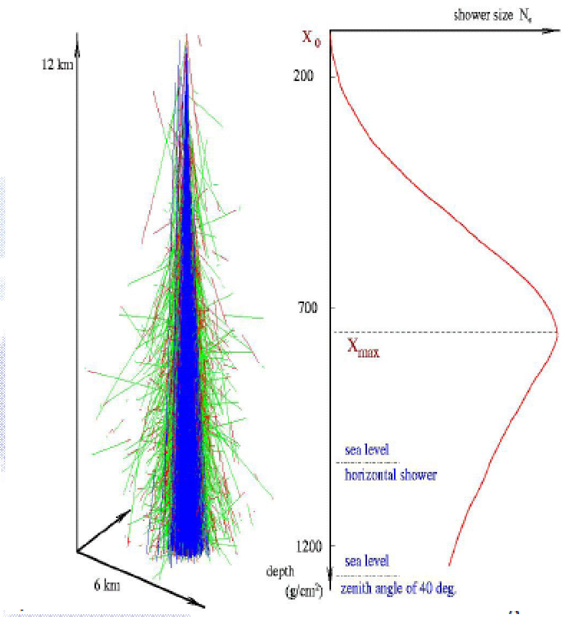
  work done with Fujii, Kitadono and Nara
- **Future prospect towards application to CRs**
- **Summary**

Motivation

- The first impact of cosmic ray air showers is an **<u>extremely high energy scattering</u>** of (probably) a proton off a nucleus in the air.

$$E_{\rm lab} = 10^{20}\,{\rm eV}, \quad \sqrt{s_{pp}} = 433\,{\rm TeV} \;\; >> \;\; \sqrt{s_{pp}} = 14\,{\rm TeV}\ ({\rm LHC})$$





- **<u>Hadronic interaction in the MC code</u>** is crucial for determination of composition and correct energy estimation of the primary cosmic rays. (see talk by T. Pierog)

- We, theorists (working on high-energy scatt.), must provide up-to-date information on **<u>forward hadronic cross section</u>** based on the modern picture of theory.

Aim of this talk

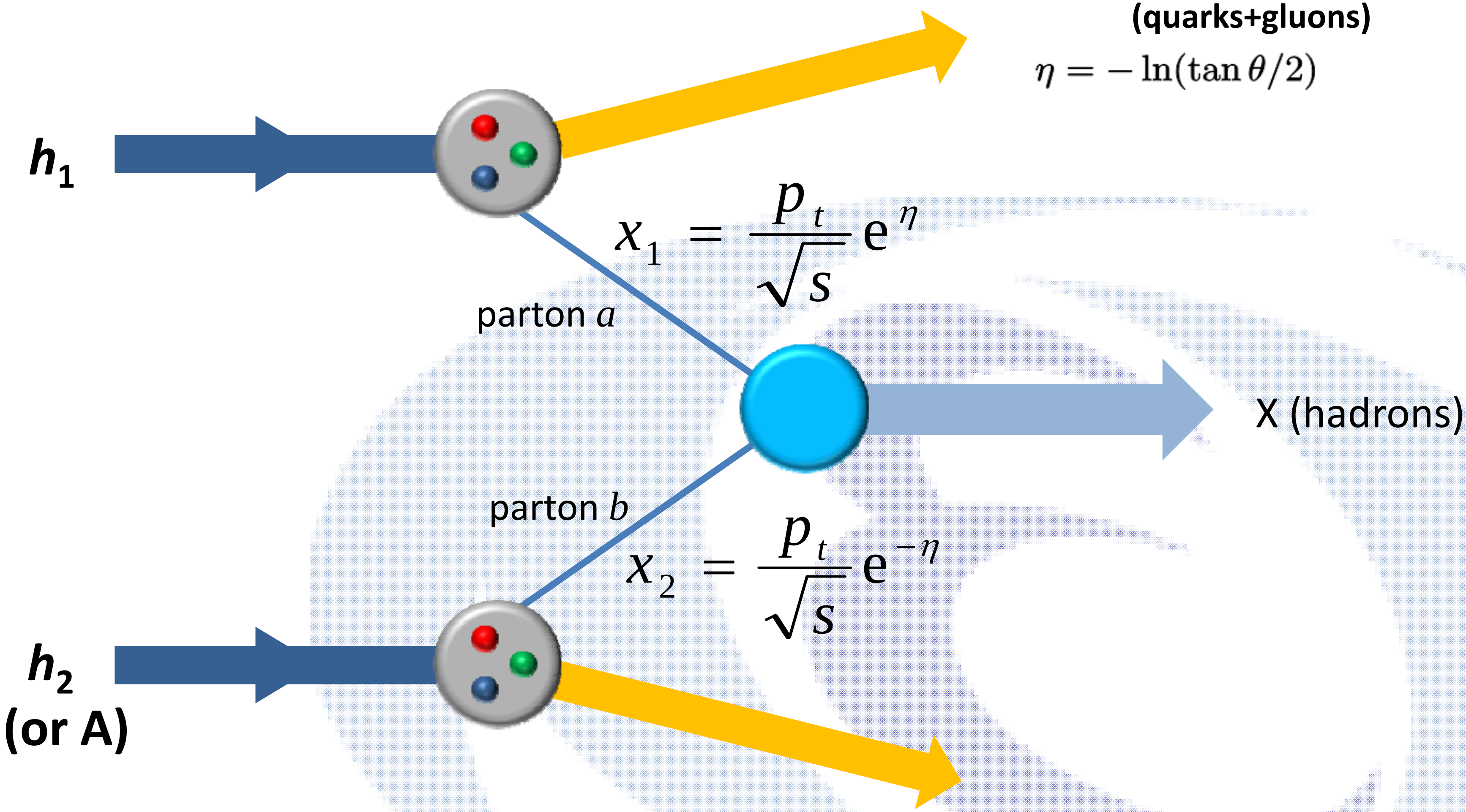
- To present (one of) the continuous efforts towards precise understanding of forward hadronic cross sections at high energies. (hadron production in hadron-hadron scattering)
- In particular, based on hard QCD picture. (could be irrelevant at very large rapidities, but not clear beyond which rapidity soft physics becomes dominant)

What is necessary?

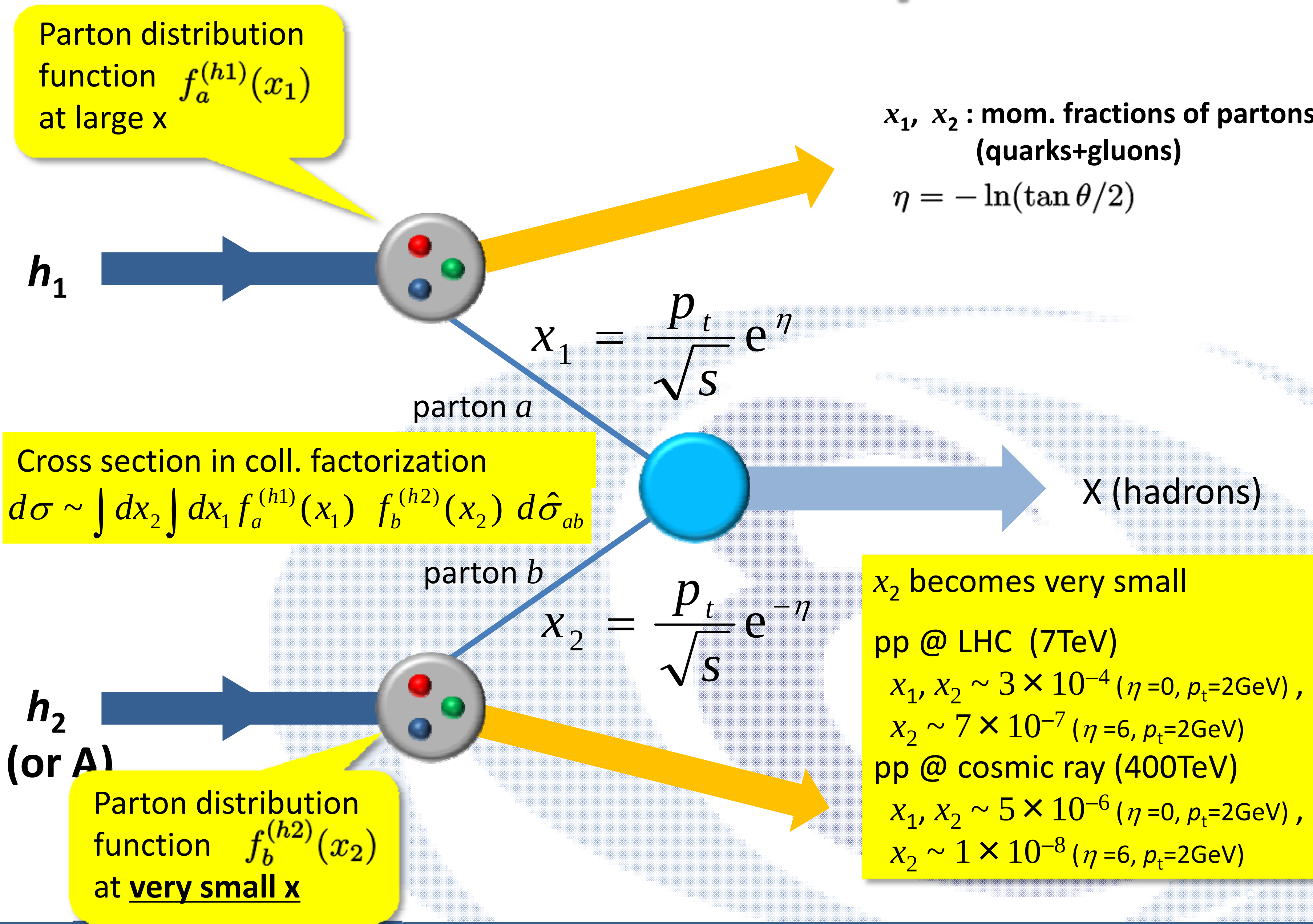
High-energy hadron-hadron scattering at forward rapidity $\eta >> 1$
hadron-nucleus

x_1, x_2 : mom. fractions of partons (quarks+gluons)

$$\eta = -\ln(\tan\theta/2)$$



What is necessary?

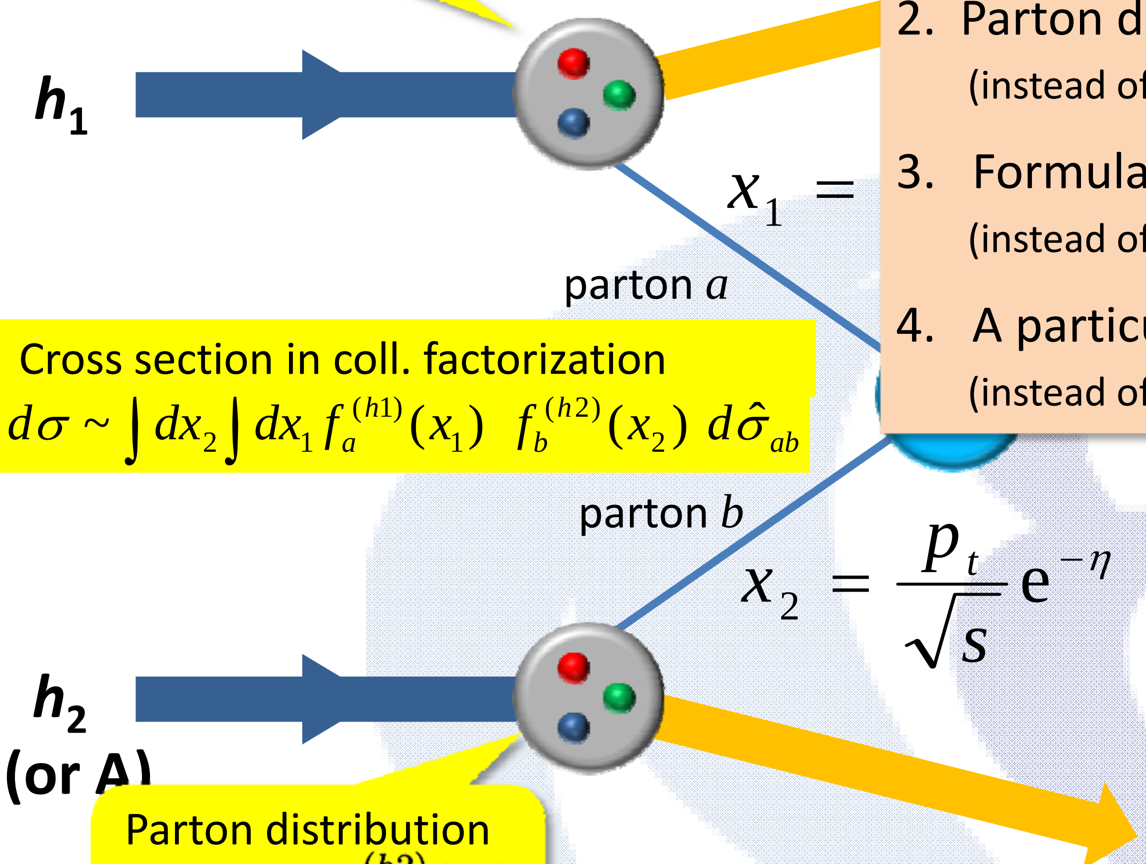


What is necessary?

Parton distribution function $f_a^{(h1)}(x_1)$ at large x

What we really need at forward rapidity is

1. Evolution equation to go to higher energy (smaller x, instead of DGLAP)
2. Parton distribution in the target (instead of ordinary pdf's)
3. Formula useful at forward rapidity (instead of the collinear fact. formula)
4. A particular method of treating nuclei (instead of a homogeneous nucleus)



Cross section in coll. factorization

$$d\sigma \sim \int dx_2 \int dx_1\, f_a^{(h1)}(x_1)\ \ f_b^{(h2)}(x_2)\ d\hat{\sigma}_{ab}$$

x_2 becomes very small

pp @ LHC (7TeV)

$x_1, x_2 \sim 3 \times 10^{-4}$ (η =0, p_t=2GeV) ,

$x_2 \sim 7 \times 10^{-7}$ (η =6, p_t=2GeV)

pp @ cosmic ray (400TeV)

$x_1, x_2 \sim 5 \times 10^{-6}$ (η =0, p_t=2GeV) ,

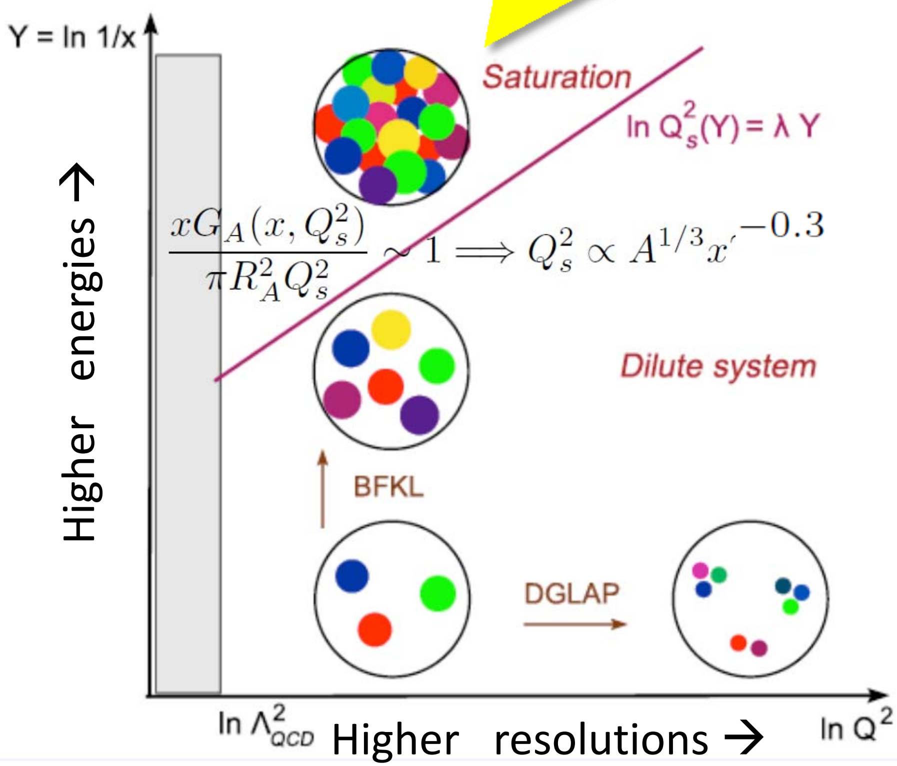
$x_2 \sim 1 \times 10^{-8}$ (η =6, p_t=2GeV)

Parton distribution function $f_b^{(h2)}(x_2)$ at **very small x**

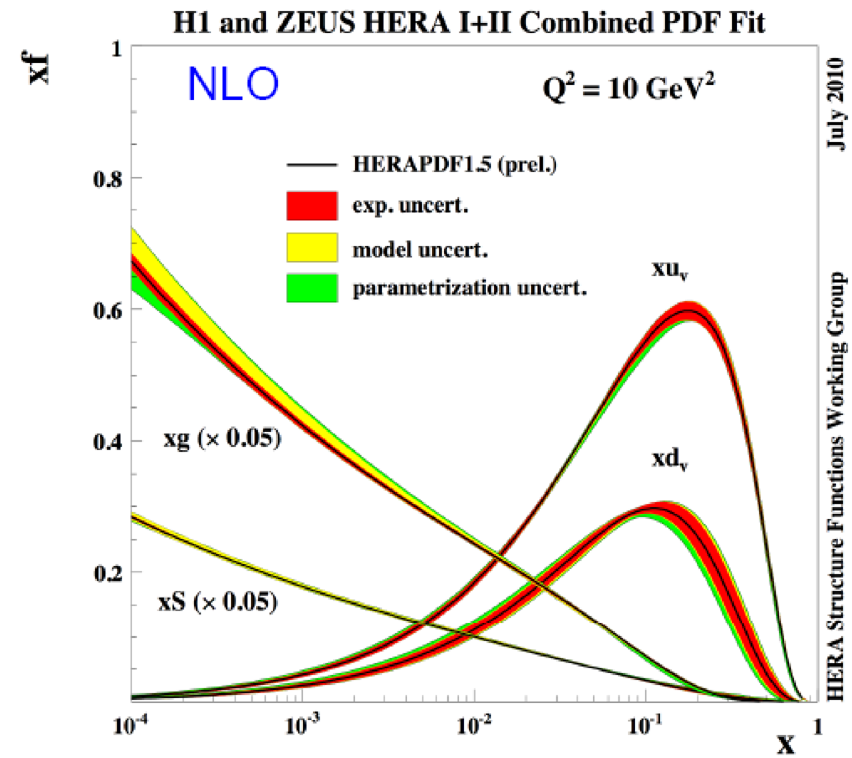
CGC appears at small x

See talks by Milhano and Blaizot

Color Glass Condensate:
High density gluonic states with saturation property



Internal structure of a proton



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$Q_s(x,A)$: saturation momentum boundary btw saturated and NON-saturated regimes

$Q_s \sim 1\text{GeV}$ at $x=10^{-4}$ for a proton

Going up higher energies: evolution eqs.

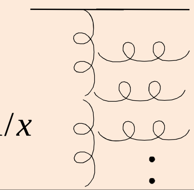
Evolution wrt x (or rapidity $y = \ln 1/x$) for unintegrated gluon distribution

- **BFKL** (LO : $(\alpha_s \ln 1/x)^n$, NLO: $\alpha_s (\alpha_s \ln 1/x)^n$)

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

Multiple gluon emissions

$N_g \sim e^{\omega \ln 1/x}$



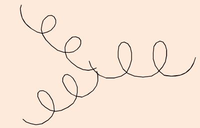
K : gluon splitting g→ gg

ϕ : unintegrated gluon distr.

Recombination of gluons

$N_g \leq 1$

Unitarity



- **BK** (includes the nonlinear effects)

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

Known up to full NLO accuracy. [Balitsky, Chirilli 2008]

But for practical purposes, we use BK with running coupling → "rcBK" [Balitsky, Gardi et al. , Kovchegov-Weigert]

$$K^{\rm run}(\mathbf{r}, \mathbf{r_1}, \mathbf{r_2}) = \underbrace{\frac{N_c\, \alpha_s(r^2)}{2\pi^2} \left[\frac{r^2}{r_1^2\, r_2^2}\right.}_{\rm LO} \left. + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

See talk by Milhano

Fit to HERA data: AAMQS_{2011}

- Initial Conditions : modified GBW/MV models

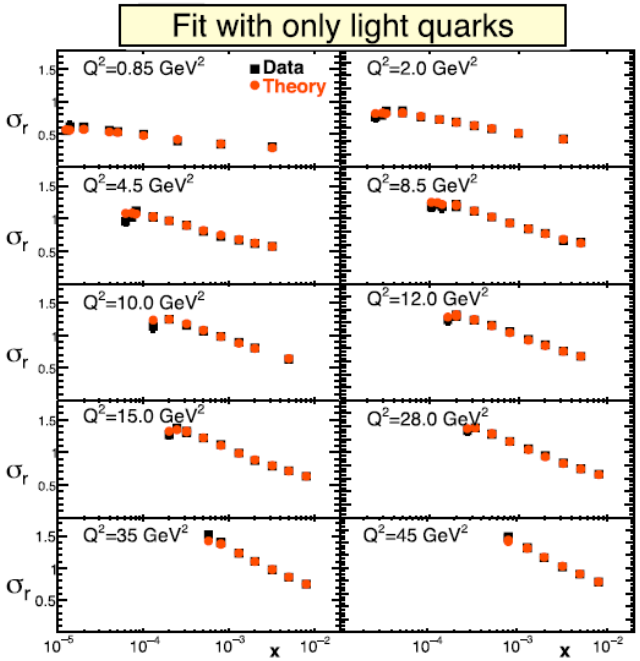
$x_0 = 0.00893$ or 0.008

$$\begin{cases} \mathcal{N}^{\rm GBW}(r, x=x_0) = 1 - \exp\left[-\dfrac{(r^2 Q_{s0}^2)^\gamma}{4}\right], & (\gamma\text{=1 : ordinary GBW}) \\ \mathcal{N}^{\rm MV}(r, x=x_0) = 1 - \exp\left[-\dfrac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\dfrac{1}{r\Lambda} + e\right)\right] & (\gamma\text{=1 : ordinary MV}) \end{cases}$$

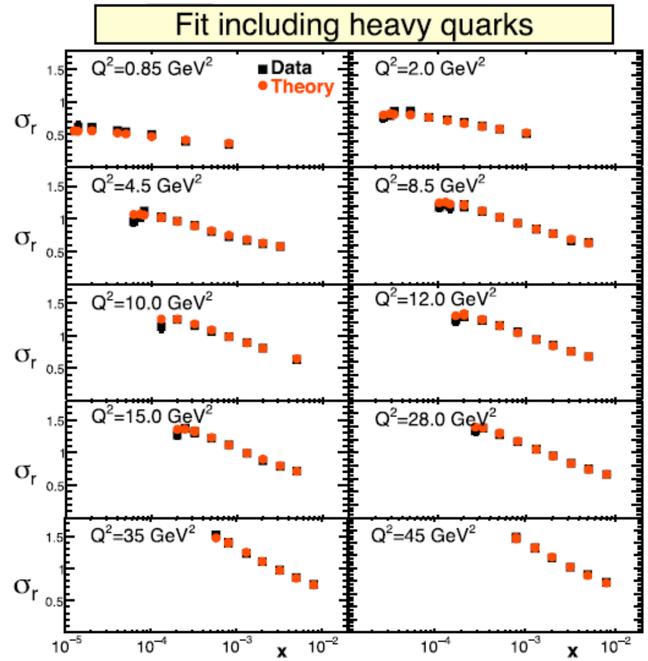
- IR regularization for 1-loop running coupling

$$\alpha_{s,n_f}(r^2) = \frac{4\pi}{\beta_{0,n_f} \ln\left(\frac{4C^2}{r^2 \Lambda_{n_f}^2}\right)}$$

freeze the coupling at $\alpha_s^{\rm fr} = 0.7$



$m_{\rm uds}$=140MeV



m_c=1.27GeV, m_b=4.2GeV

← Modified GBW

(Left) γ=0.971 Qs_0^2=0.241

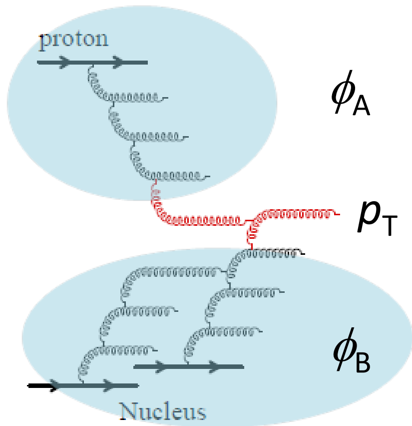
(Right) γ=0.959 Qs_0^2=0.240

There are two more parameters (C,σ_0)

Hadron collisions (pp/pA): two formulae

- k_t factorization

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

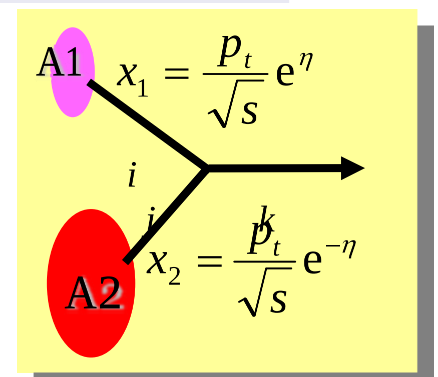


  - proved for pp, pA at LO
  - good when both A and B are saturated (mid rapidity at very high energy)
  - used in various calculations e.g. multiplicity distribution, etc

- DHJ formalism [Dumitru-Hayashigaki-Jalilian--Marian 2006]

$$\frac{dN}{dy_h\,d^2p_T} = \frac{K}{(2\pi)^2}\sum_{ijk}\int_{x_F}^{1}\frac{dz}{z^2}\,x_1 f_{i/p}(x_1,p_T^2)\,\tilde{N}_j\!\left(\frac{p_T}{z},x_2\right)D_{h/k}(z,p_T^2)$$

  - "Large-x / small-x" reactions: **valid at forward rapidity**
    x_1~1, x_2 <<1
  - $f_{i/p}$(x) : pdf for valence (large x) partons in the projectile
  - $D_{h/k}$(z) : frag. func. for outgoing hadron *h* from a parton *k*
  - *N* : un-integrated gluon distribution in the target



Hadron collisions (pp/pA): two formulae

- *k_t* **factorization**

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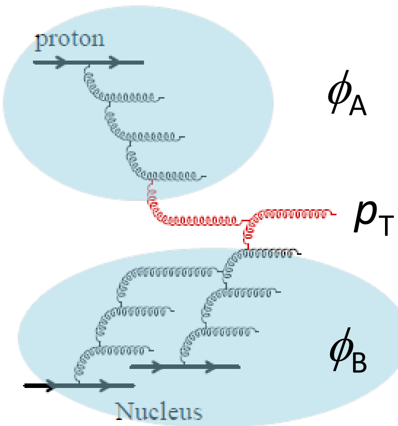

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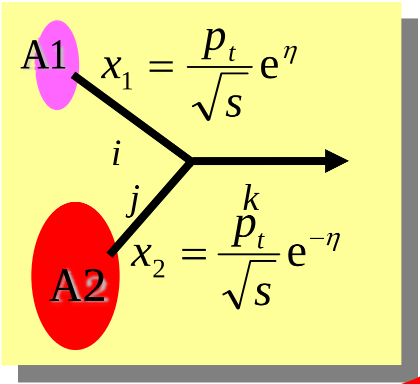
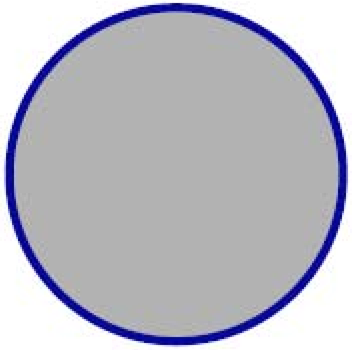


How to treat nuclei?

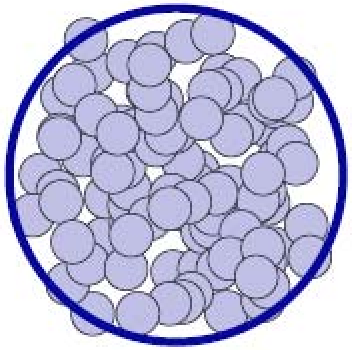
MC modeling for a nucleus:

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

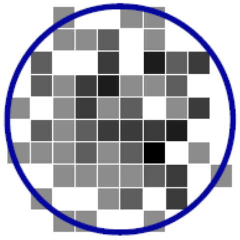


may use a simple parametrization by KLN,
or numerical solution to rcBK

- 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



Apply quantum evolution locally at different transverse bins $\Rightarrow$



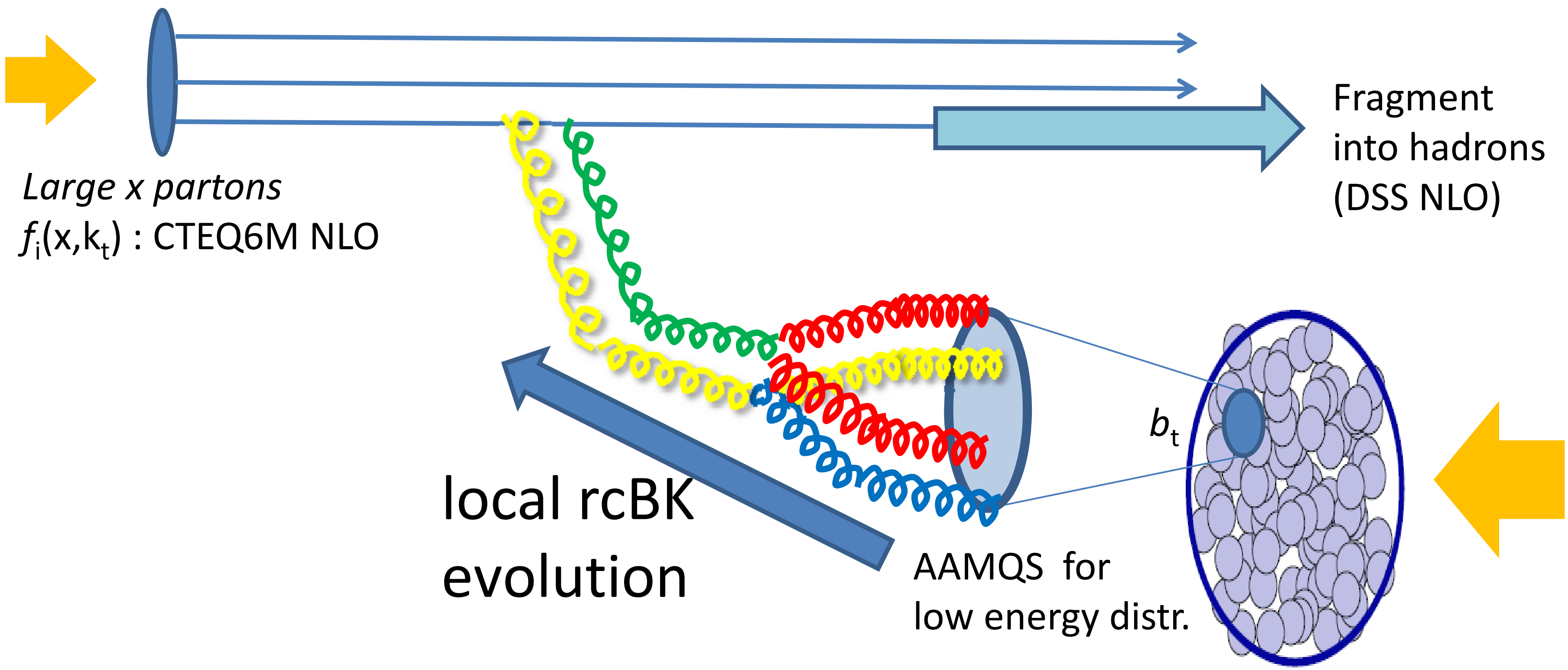
MC-DHJ/rcBK

[Fujii,KI,Kitadono,Nara, arXiv:1107.1333, more to come soon]

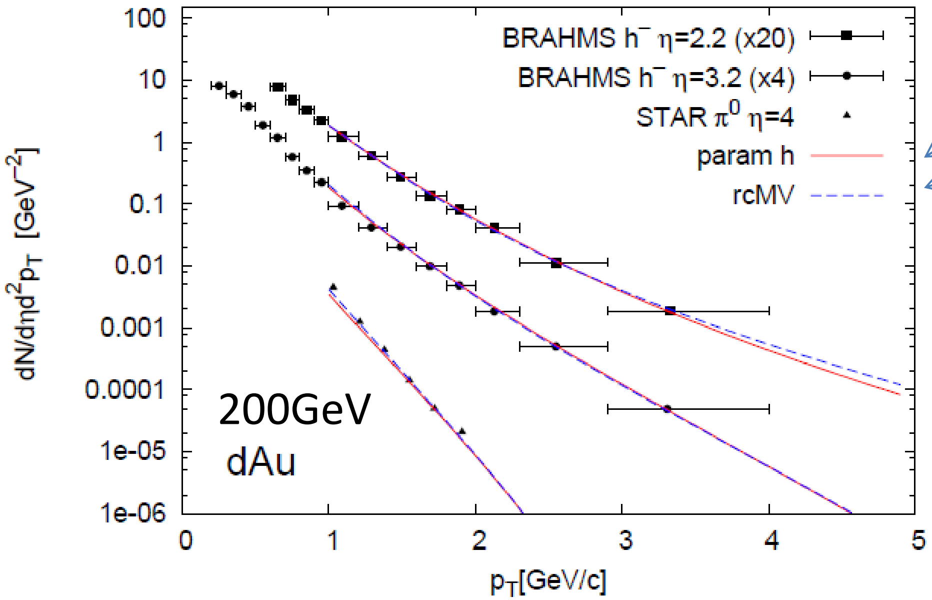
To reduce ambiguity

- construct a nucleus by randomly placing nucleons
- use AAMQS parameters for proton IC optimized for DIS at small-x
- quantum evolution is performed "locally" in b space with rcBK

(to avoid IR div. in b-dep BK)



MC-DHJ/rcBK : results



modified MV model $(\gamma = 1.118)$

"running coupling" version of MV model [Iancu-KI-Triantafylopoulos] : to be consistent with rcBK evolution

- reproduce the data nicely
- AAMQS set h and rcMV for $\mathcal{N}(r,y)$
- Q^2_{s0A} fixed by MC; no additional parameter

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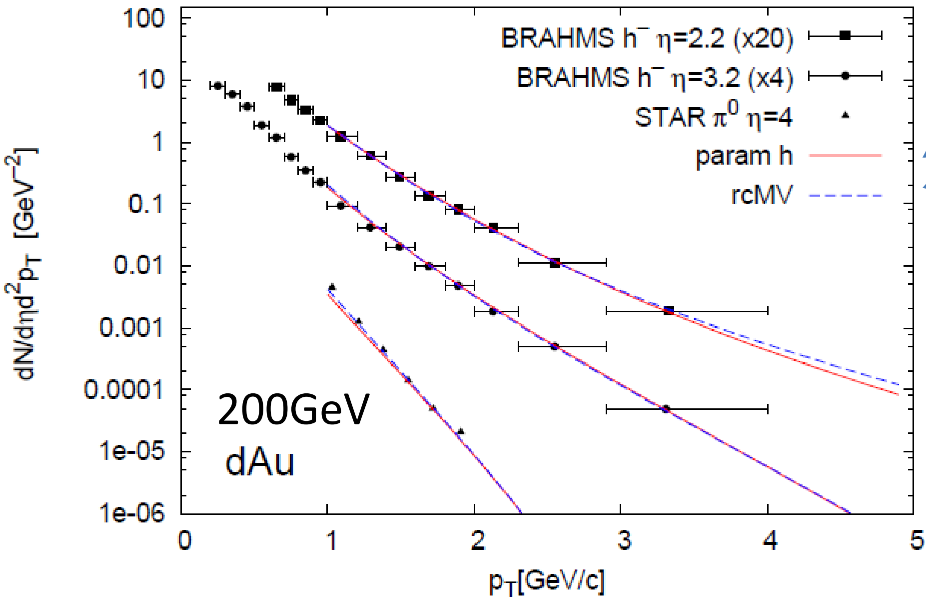

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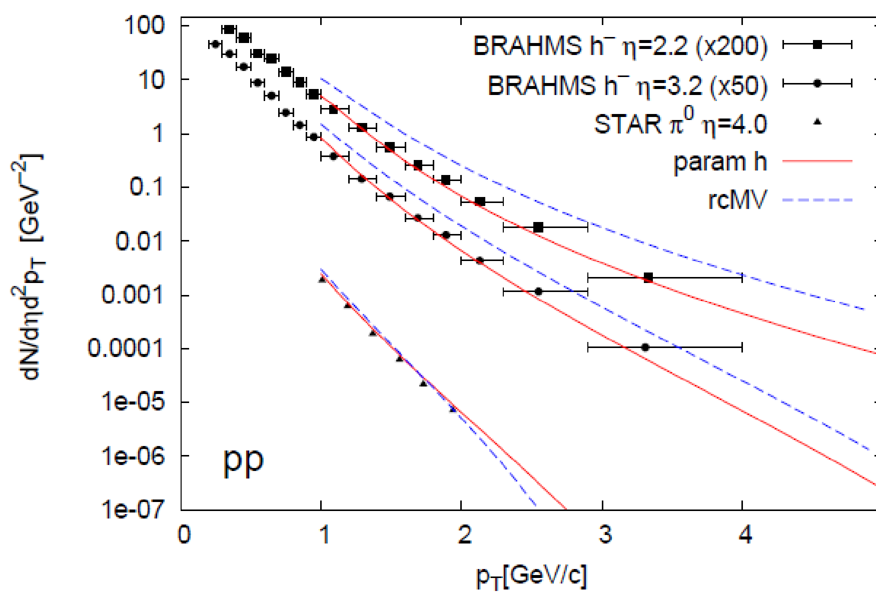
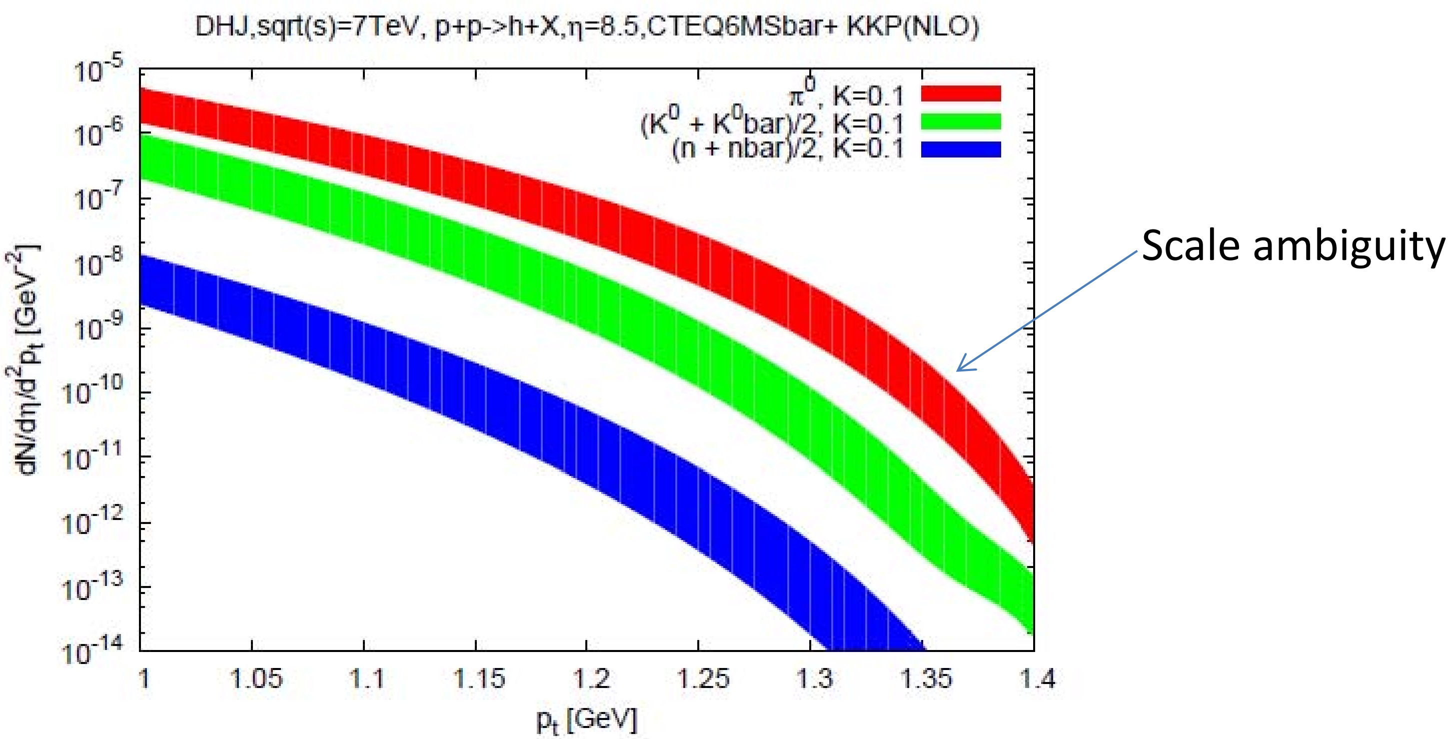
- Set *h* works well even in *pp*
- rcMV is not "tuned" (similar param as MV)
- However, both work quite well in dAu (IC dependence reduces at high rapidity)



Best results from theoretical point of view, but still needs better (global) description including pp data (tuning of rcMV is necessary)

MC-DHJ/rcBK extrapolated to LHC



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

Very forward region could be dominated by soft interaction, but still necessary to understand how much hard contribution exists.

Future prospect towards application to CRs

- Separation between soft and hard is not clear (model dependent)

- In several hadron interaction models (e.g. SIBYLL), IR cutoff for the hard contribution is energy dependent (very similar to Qs(s))

SIBYLL2.0
$$p_\perp^{cutoff} = p_\perp^0 + \Lambda \exp\left\{c\sqrt{\ln(s/\mathrm{GeV}^2)}\right\}$$
$$\text{with } p_\perp^0 = 1\,\mathrm{GeV}, \Lambda = 0.065\mathrm{GeV} \text{ and } c = 0.9$$

→ miss particle production in the semi-hard region!!

- CGC provides particle production in semi-hard region $\Lambda_{\mathrm{QCD}} < k_t < Q_s$ that expands with increasing energy

→ filling the gap btw soft and hard

- Calculations with CGC could help to "recover" the semi-hard contributions.

Summary

- Theoretical description of high-energy hadron scattering based on CGC is now (almost) established up to leading log accuracy with running coupling corrections. → rcBK paradigm

- In particular, phenomenological analysis with rcBK has been making a progress enough to be compared with experimental data. → HERA DIS at small-x, RHIC dAu at forward rapidity

- This approach can be, in principle, applied to higher energy collision, thus hopefully to the first impact of Cosmic Rays in the air.