A CGC Monte-Carlo Event Generator For forward hadron productions

Yasushi Nara (Akita International Univ.)

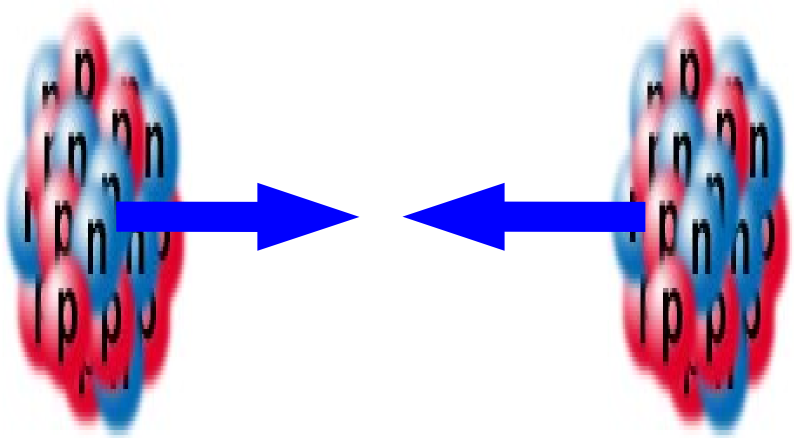
ArXiv:hep-ph1410.2018

- Introduction
- Monte-Caro kt-factorization approach
- Event generator version of DHJ formula
- Transverse momentum spectra at RHIC and LHC
- Summary

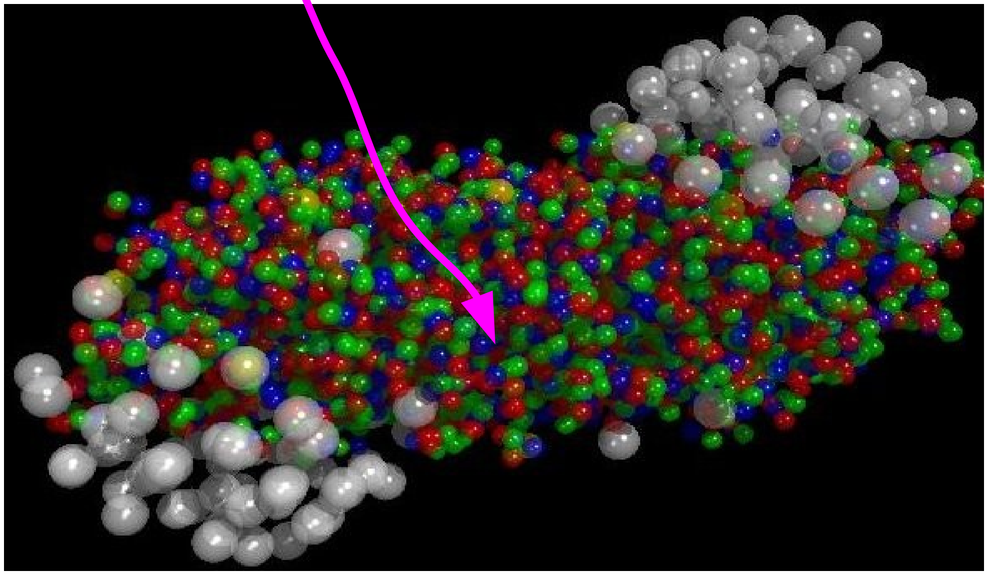
KMI Mini-Workshop 2014 Nagoya, Oct 23th 2014

RHIC and LHC

The 3.8 km circumference



Creation of Hot and dense matter.



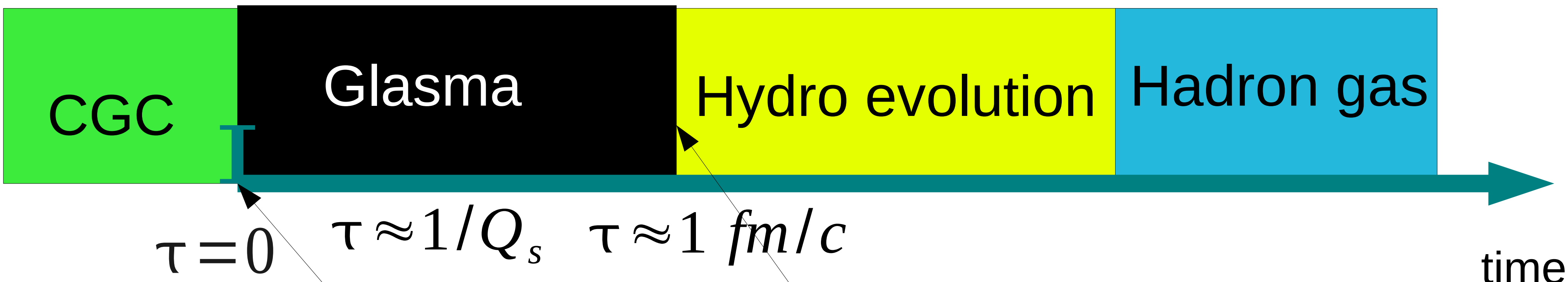
RHIC: Au+Au at C.M. Energy of 200GeV per nucleon.

LHC: Pb+Pb at C.M. Energy of 2.76TeV per nucleon.

High energy heavy ion collisions

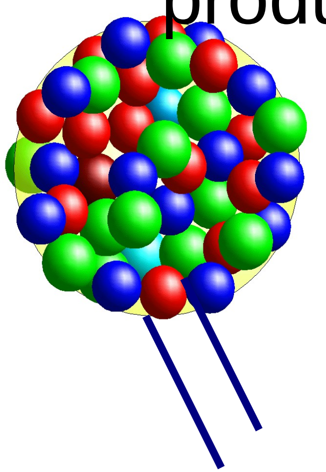
Initial state interactions

Final state interactions



Initial condition for hydro

Gluon production



$$r \sim \frac{1}{Q_s}$$

p+A collision is important:

Initial condition for non-equilibrium evolution

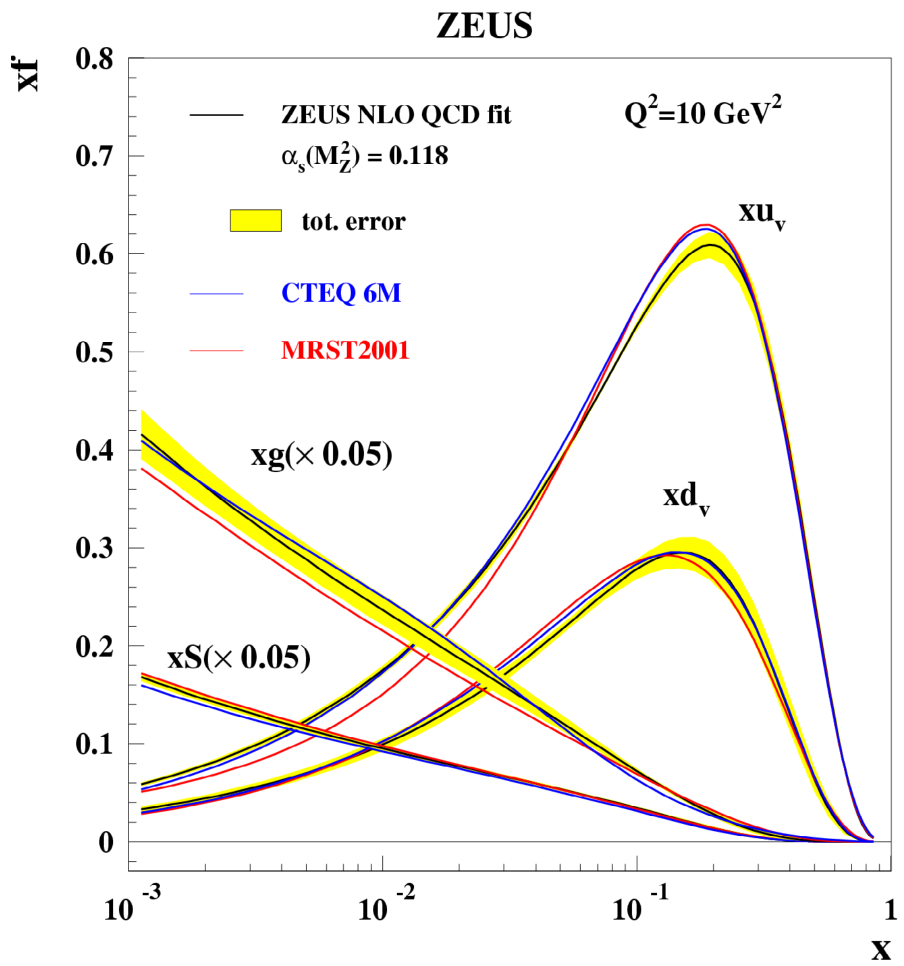
Testing QCD at small Bjorken x

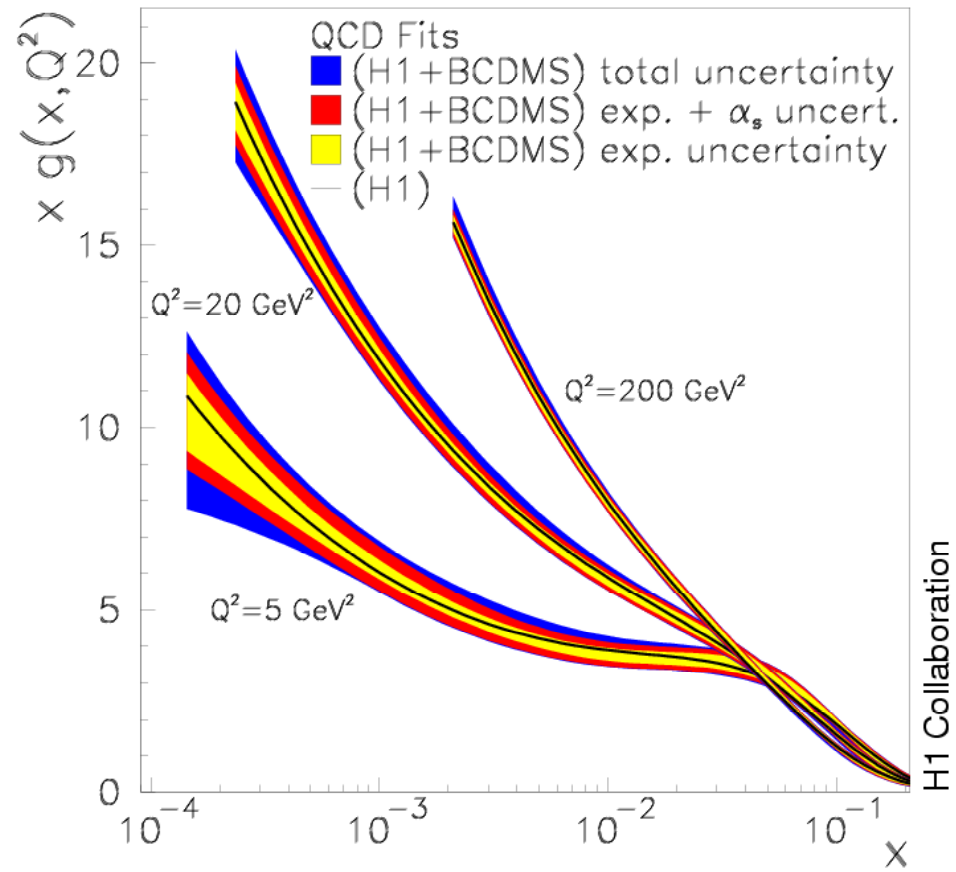
Hydrodynamics and inputs

- Initial condition:
  - thermalization time
  - energy density
  - (flow profile)
- Equation of state:
  - lattice QCD
- freezeout:
  - Hadron cascade after burner
  - (hadronic dissipative effects)
- Dissipative effects

Purpose: test uncertainties of the initial conditions.

Gluon density





Gluon density dominates F_2 for *x* < 0.01

Gauge field in the MV model

The gluon distribution is large:

Suggest the use of the semi-classical methods

$$D_\nu F^{\nu\mu} = J^\mu$$

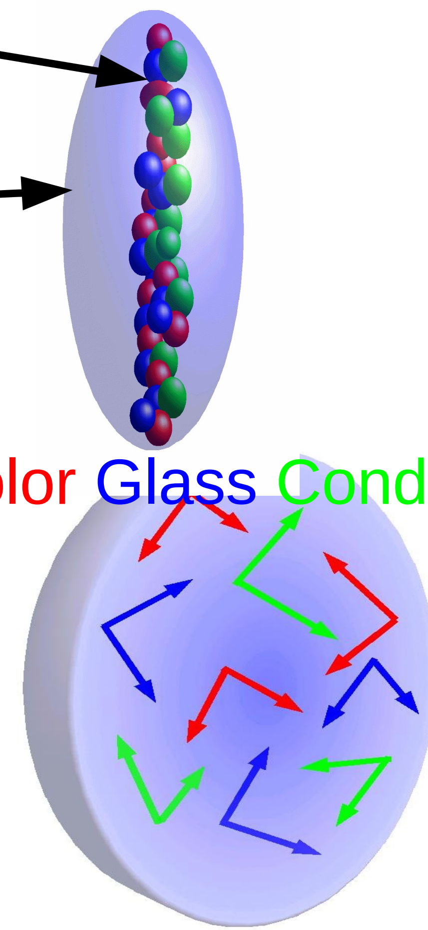
In the light-cone gauge: $A^+ = 0$,
a solution can be

$$A^- = 0, \quad A^i = \frac{i}{g} U \partial^i U^\dagger,$$

$$U = P \exp\left[ig \int \Lambda \, dz^- \right], \quad -\Delta_\perp \Lambda = \rho$$

$$\Lambda = A^+$$

in covariant gauge



Non-abelian Weiszacker-Williams filed

transverse component:
gauge transformation of vacuum : $F^{ij} = 0$

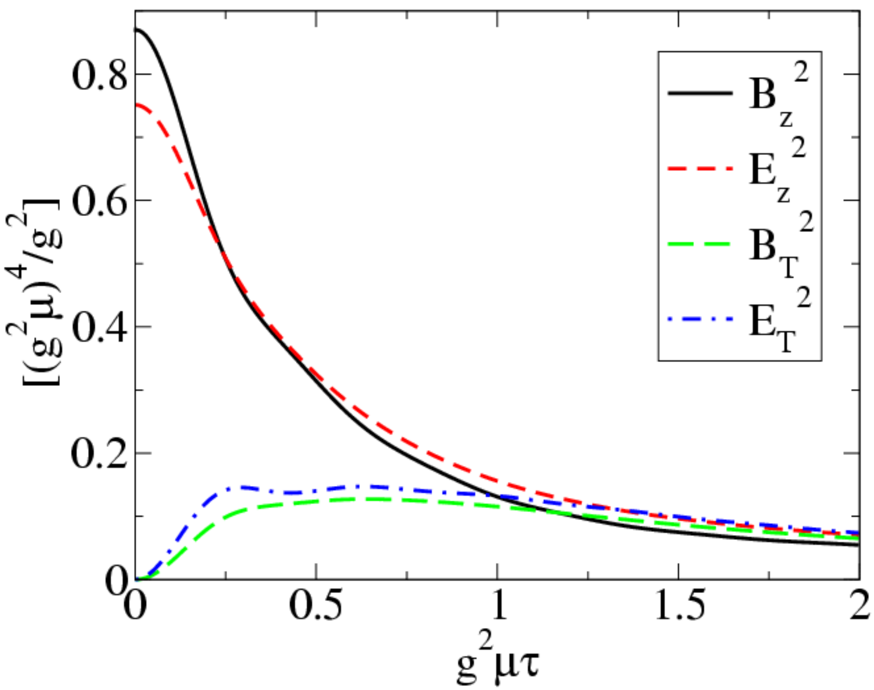
The only non-zero component of the field strength: $F^{+i} \neq 0$

$$\boldsymbol{B} \cdot \boldsymbol{E} = 0, \; B_z = E_z = 0$$

$\tau < 1/Q_s$: Yang-Mills field dynamics

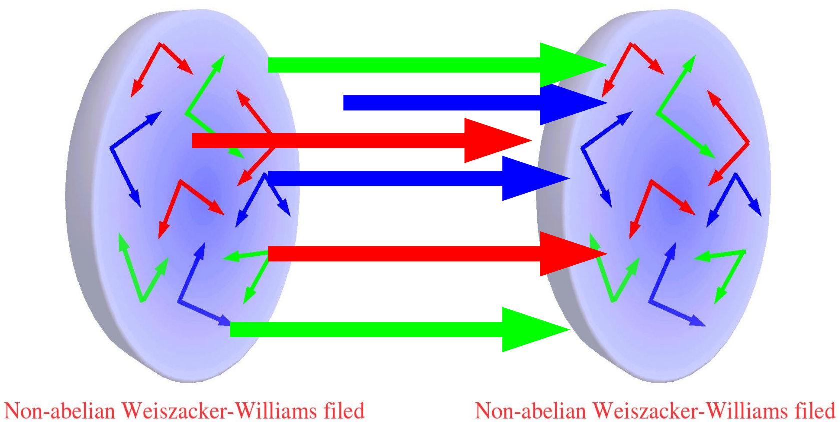
Real time evolution of the Classical Yang-Mills

T.Lappi, L. McLerran, N.P.A772



Similar to Lund string model picture: but produce both color electric and magnetic fields.

Production of longitudinal color EM fields.



Instabilities of Yang-Mills field :

P.Romatschke, R.Venugopalan,K.Fukushima, Gelis, McLerran, A.Iwazaki

Gluon production based on CGC

- x-evolution + Solving classical Yang-Mills equation

  CYM + IP-sat model, Schenke, Tribedy, Venugopalan

  CYM+JIMWLK evolution, Lappi, Phys.Lett.B703(2011)325

- rcBK evolution + kt-factorization formula

$$\frac{dN_g}{d^2 x_t \, dy} = \frac{4\pi N_c}{N_c^2 - 1} \int \frac{d^2 p_t}{p_t^2} \int d^2 k_t \, \alpha_s \, \varphi(x_{1,} k_t^2) \, \varphi(x_{2,} (p_t - k_t)^2)$$

Albacete, Armesto,Mihano, Salgado 2009 for HERA fit

Forward particle production: Dumitru Hayashigaki Jalilian-Marian (DHJ)

$$\frac{dN}{dy_h d^2 p_\perp} = \frac{K}{(2\pi)^2} \sum_{i=q,g} \int_{x_F}^{1} x_1 f_{i/p}(x_1, p_\perp^2) N_i(x_2, p_\perp/z) D_{h/i(z,p_\perp)}$$

Rapidity evolution

running coupling Balitsky-Kovchegov (rcBK) evolution

$$\frac{\partial \mathcal{N}(r,x)}{\partial y} = \int d^2 r_1 \; K(r, r_1, r_2) \left[\mathcal{N}(r_1, y) + \mathcal{N}(r_2, y) - \mathcal{N}(r, y) - \mathcal{N}(r_1, y)\, \mathcal{N}(r_2, y)\right]$$

$$y = \ln(x_0/x)$$

$$Q_s^2 \sim x^{-\lambda_{LO}}, \text{ with } \lambda_{LO} \simeq 4.88\, N_c\, \alpha_s/\pi$$

$$\text{HERA fit yields } \lambda \sim 0.2 - 0.3$$

$$K^{\rm LO}(\mathbf{r}, \mathbf{r_1}, \mathbf{r_2}) = \frac{N_c\, \alpha_s}{2\pi^2} \frac{r^2}{r_1^2\, r_2^2}$$

LO-BK shows too fast evolution to fit HERA data.

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

Running of the coupling reduces the evolution speed down to values compatible with data (JLA PRL 99 262301 (07))

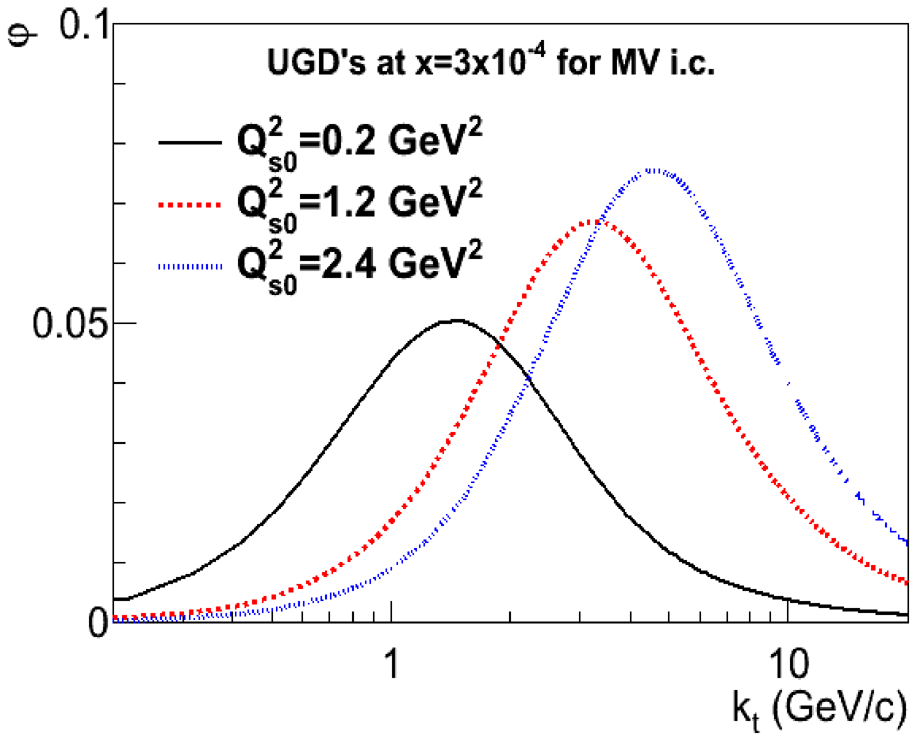
$$\mathcal{N}(r, x{=}x_0) = 1 - \exp\left[-\frac{\left(r^2\, Q_{s\,0}^2\right)^{\gamma}}{4} \ln\left(\frac{1}{r\,\Lambda} + e\right)\right]$$

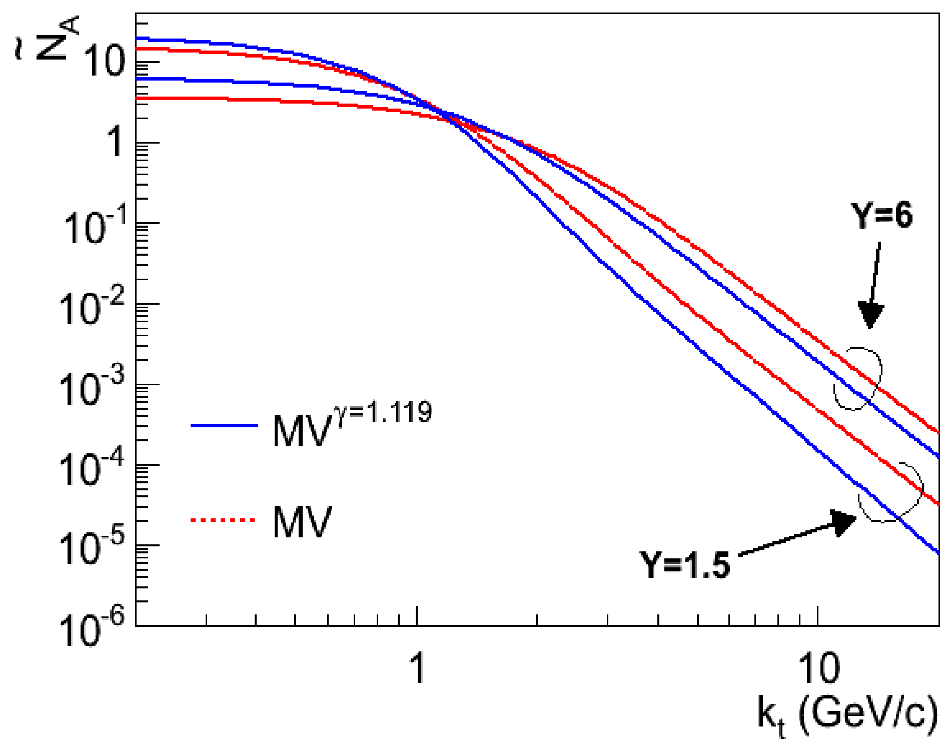
Unintegrated gluon distribution

$$\mathcal{N}(r, Y=0) = 1 - \exp\left[-\frac{(r^2\, Q_{s0}^2)^\gamma}{4}\, \ln\left(\frac{1}{\Lambda\, r} + e\right)\right] \quad \begin{array}{c}\gamma = 1.119 \\ Q_{s0}^2 = 0.168\,\mathrm{GeV}^2\end{array}$$

$$\varphi(k, x, b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3} \int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla^2_{\mathbf{r}}\, \mathcal{N}_G(r, Y = \ln(x_0/x), b)$$

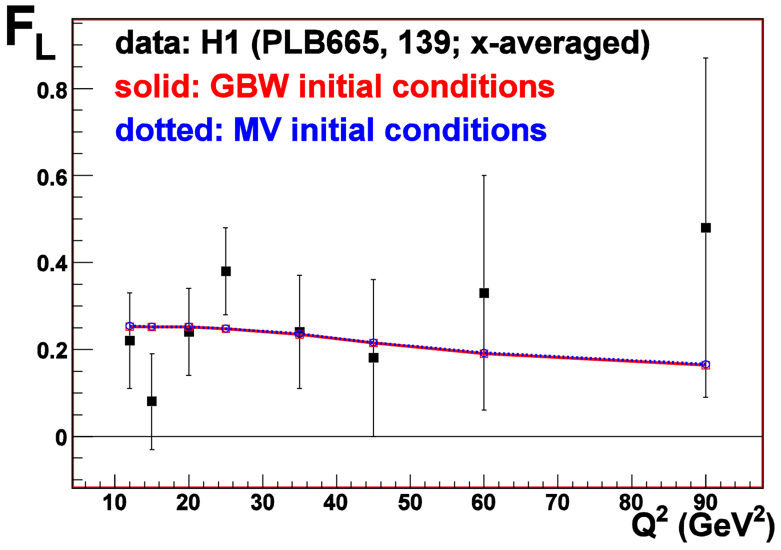
MV i.c.: $\gamma = 1,\; Q_{s0}^2 = 0.2\mathrm{GeV}^2$

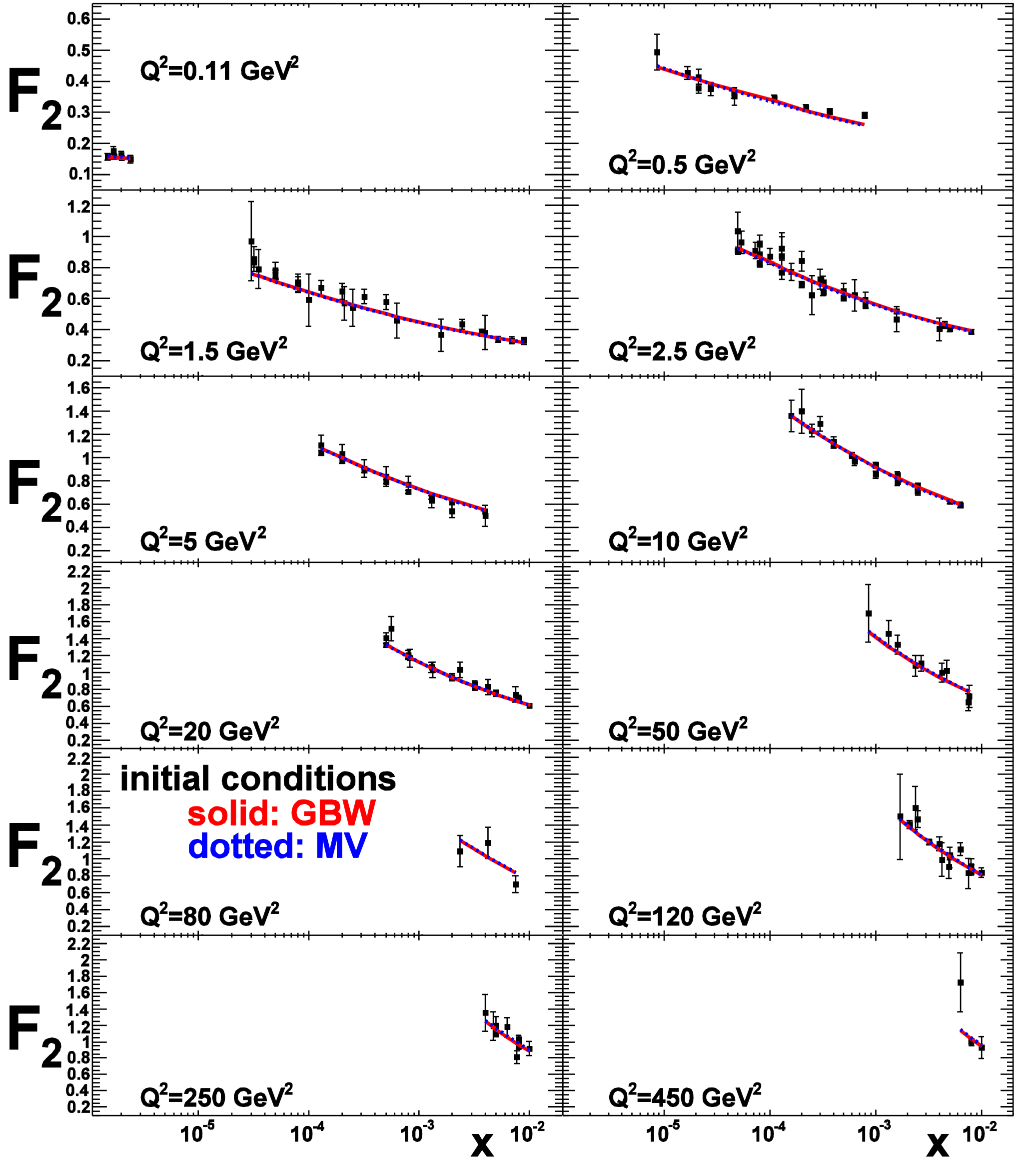




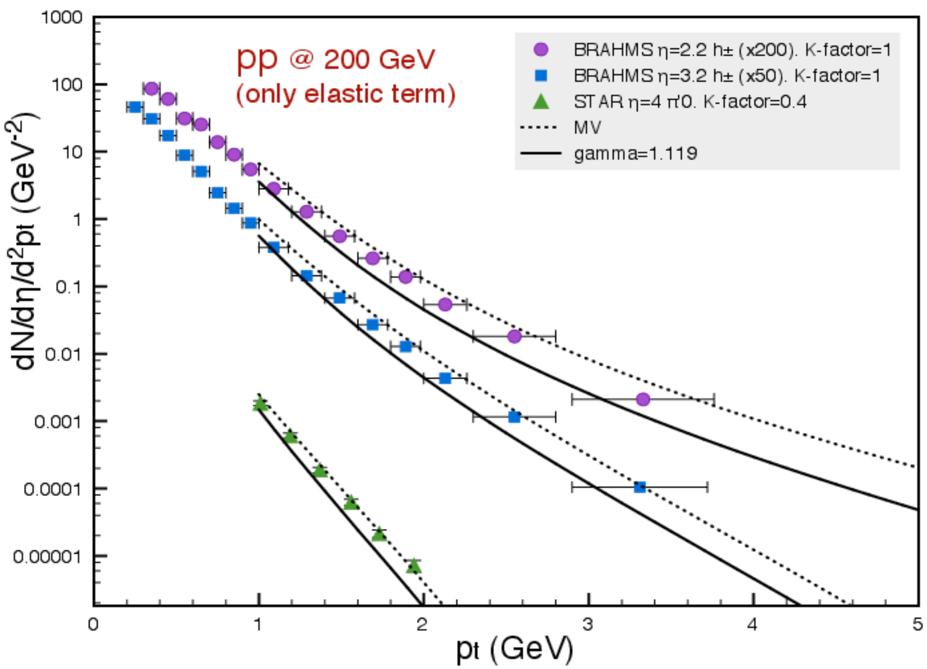
HERA F2 data global fit from rcBK equation

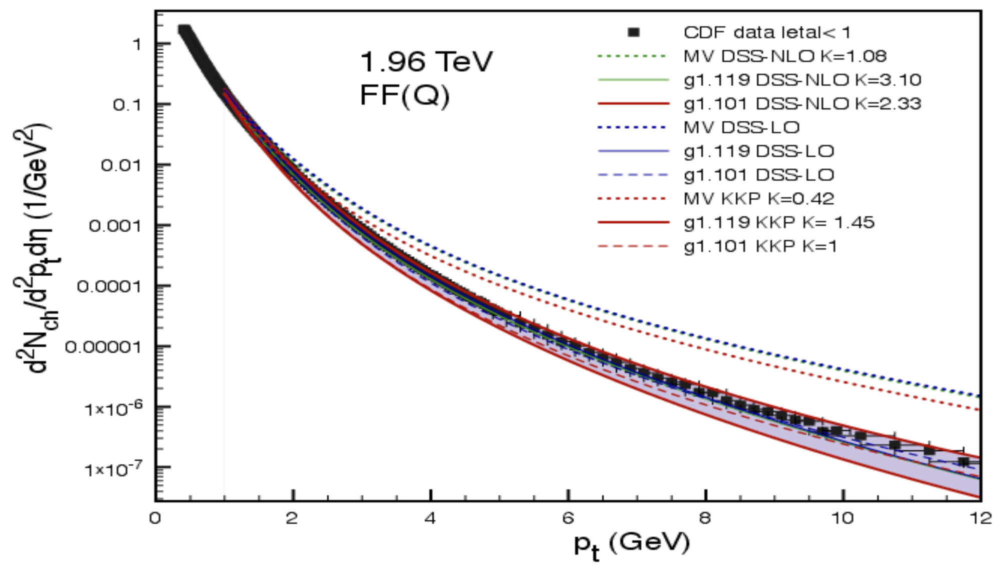
Albacete, Armesto, Mihano, Salgado 2009

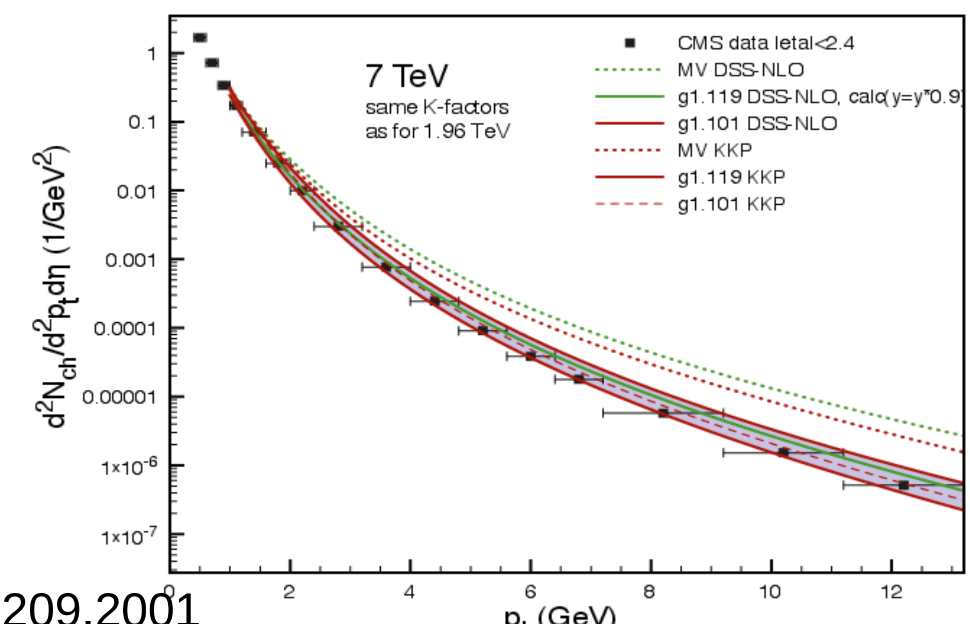




Comparison to RHIC/LHC data for pp collisions







Strong constraint to
the initial condition at LHC

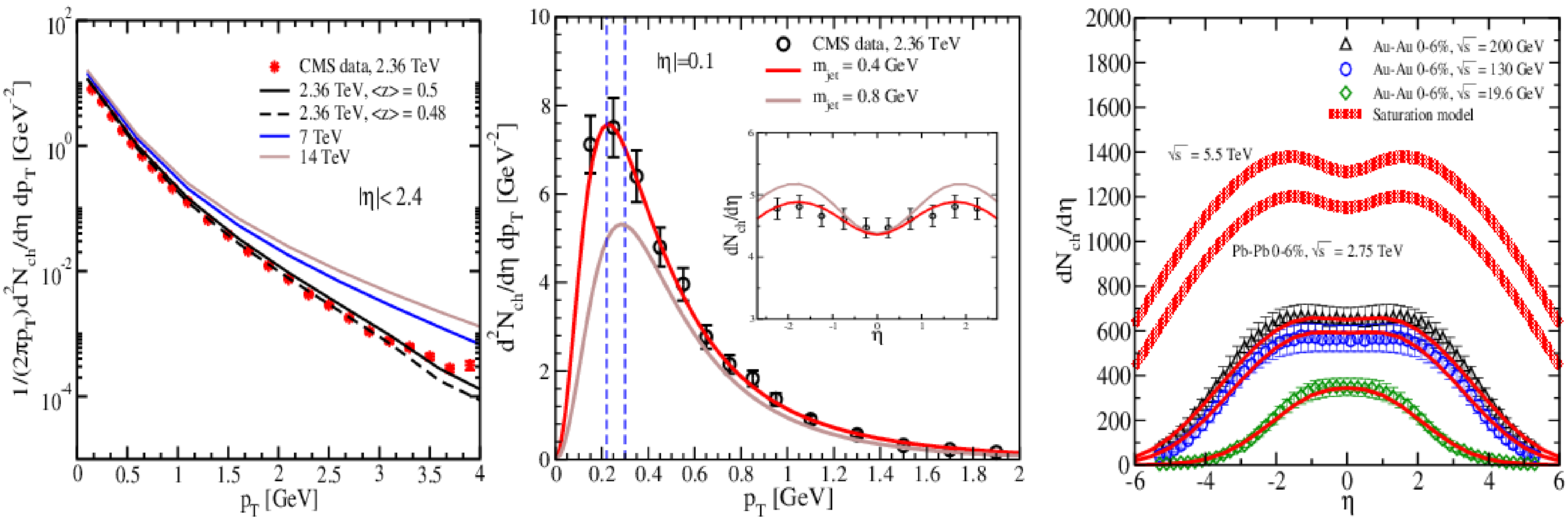
γ>1 → evolution slow down

J.L.Albacete, A. Dumitru, H. Fujii, Y.N. Hep-ph1209.2001

Local parton-hadron duality

Kt-factorization + LPHD

E.Levin and A. H.Rezaeian, Phys. Rev. D82,(2010)014022, Phys.Rev. D82 (2010) 054003



$$\frac{d\sigma}{dy\, d^2 p_T} = \frac{2\alpha_s}{C_F}\frac{1}{p_T^2}\int d^2\vec{k}_T\, \phi(x_1;\vec{k}_T)\, \phi(x_2;\vec{p}_T-\vec{k}_T)\,,$$

$$p_{\mathrm{jet},T} = \frac{p_T}{<z>}, \quad <z> = 0.5 \qquad p_T \to \sqrt{p_T^2 + m_{\mathrm{jet}}^2}$$

Development of the model

- KLN model (2001): analytic expression for dN/dy
- KLN + hydrodynamics (2004)
- fKLN (2006)
- MC-KLN (2007)
- MC-kt/rcBK and MC-DHJ/rcBK (2012)
- MC-Event Generator version of DHJ (2014)

Monte-Carlo implementation

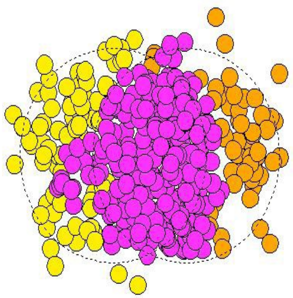
- Sample A and B nucleons according to the Woods-Saxon distribution.
- Collision: NN collision probability $P(b) = 1 - \exp[-kT_{pp}(b)]$

$$T_{pp}(b) = \int d^2 s T_p(s) T_p(s-b) \qquad (x_i - x_j)^2 + (y_i - y_j)^2 \le \frac{\sigma_{NN}}{\pi}$$

k is fixed by the relation $\sigma_{in} = \int d^2 b \, (1 - \exp[-kT_{pp}(b)])$

- Local density of nucleons at each grid is obtained by
-

$$T_p(r) = \frac{1}{2\pi B} \exp[-r^2/(2B)]$$



which is used to simulate coherent scattering

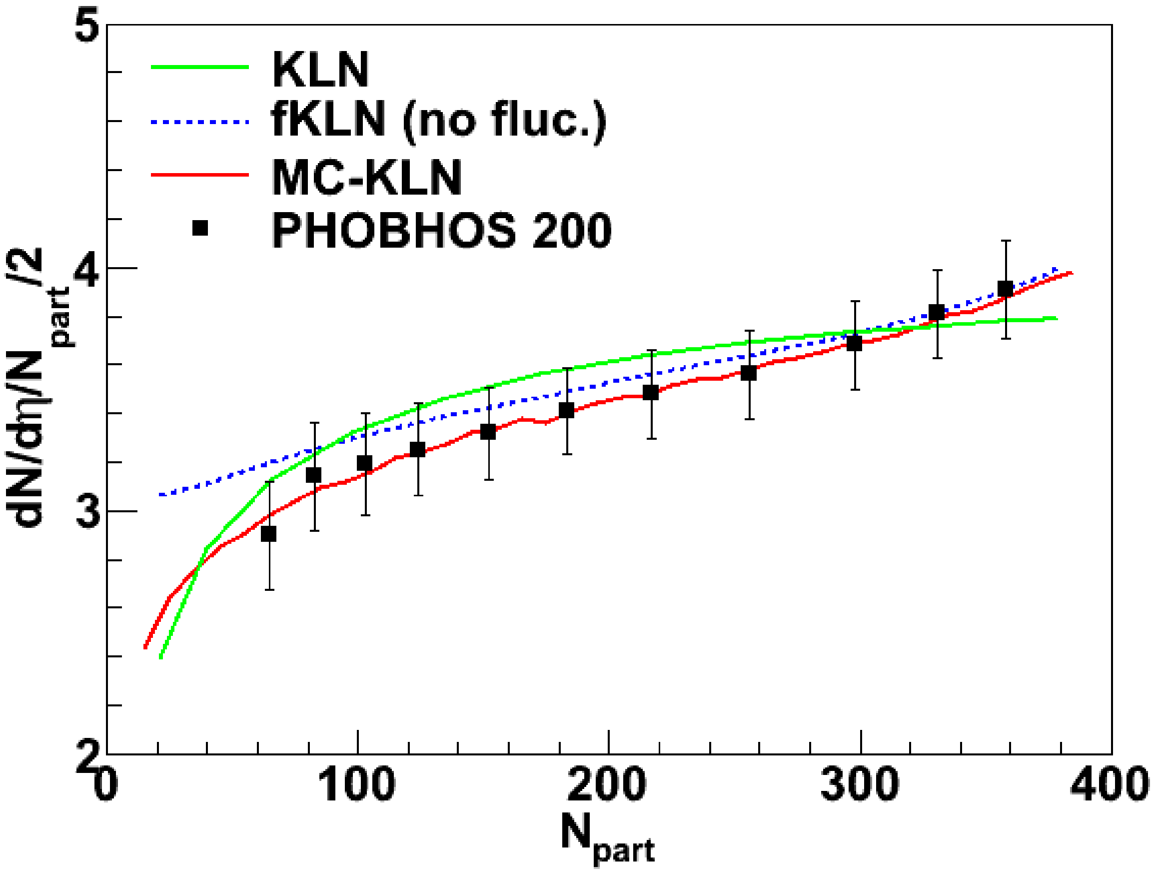
- For each generated configuration, we apply the k_t-factorization formula at each transverse grid. $\frac{dN_g}{d^2 x_t dy} = \frac{4\pi N_c}{N_c^2 - 1} \int \frac{d^2 p_t}{p_t^2} \int d^2 k_t \alpha_s \varphi(x_1, k_t^2) \varphi(x_2, (p_t - k_t)^2)$

$$\varphi(k, x, b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3} \int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla^2_{\mathbf{r}} \mathcal{N}_G(r, Y = \ln(x_0/x), b)$$

implemented by A.Dumitru by using the solution of rcBK from J. L. Albacete.

http://physics.baruch.cuny.edu/node/people/adumitru/res_cgc

Centrality dependence at y=0



$$\frac{1}{N_{\rm part}}\frac{dN}{dy} = c \ln\left(\frac{Q_s^2}{\Lambda_{\rm QCD}^2}\right)$$

The effect of fluctuation is seen in the peripheral collisions (Npart < 200).

Initial transverse geometry for hydro initial conditions

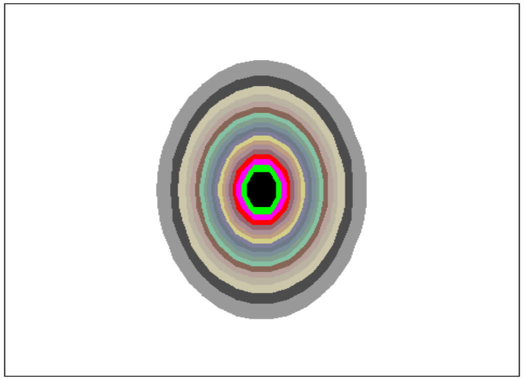
Glauber model

$$\frac{dN}{d^2\boldsymbol{x}_\perp dy} \sim N_{part,1}(\boldsymbol{x}_\perp) + N_{part,2}(\boldsymbol{x}_\perp)$$

CGC

$$\frac{dN}{d^2\boldsymbol{x}_\perp dy} \sim \min\{N_{part,1}(\boldsymbol{x}_\perp), N_{part,2}(\boldsymbol{x}_\perp)\}$$

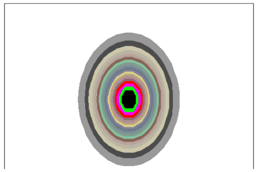
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

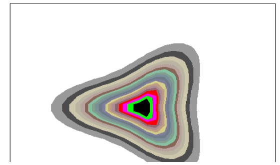


$$\varepsilon_{CGC} > \varepsilon_{Glauber}$$

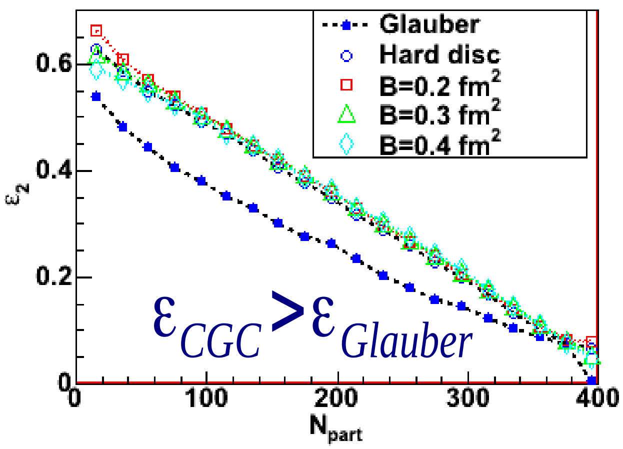
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

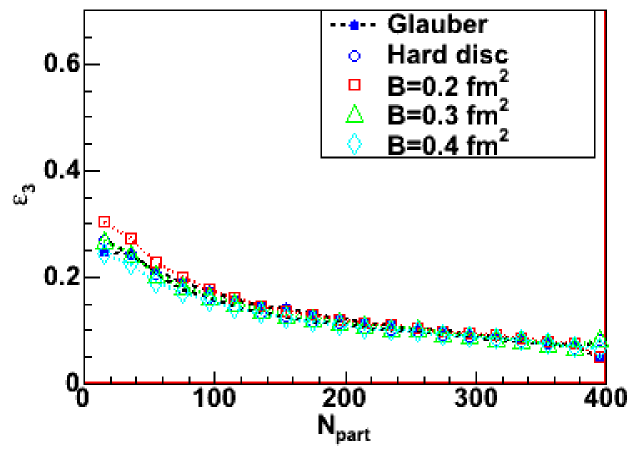
Large v2 in CGC

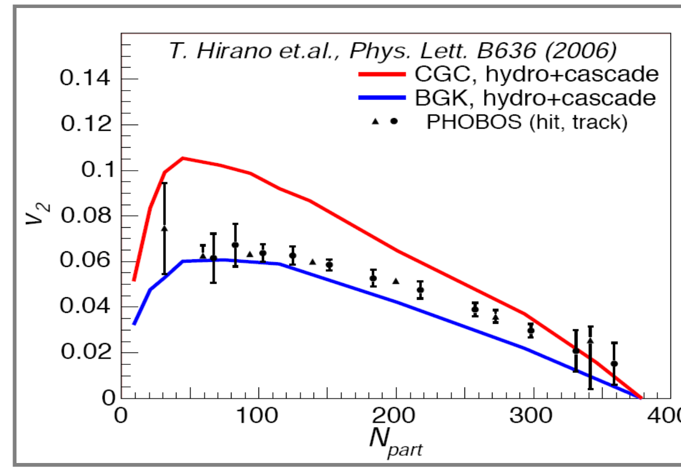


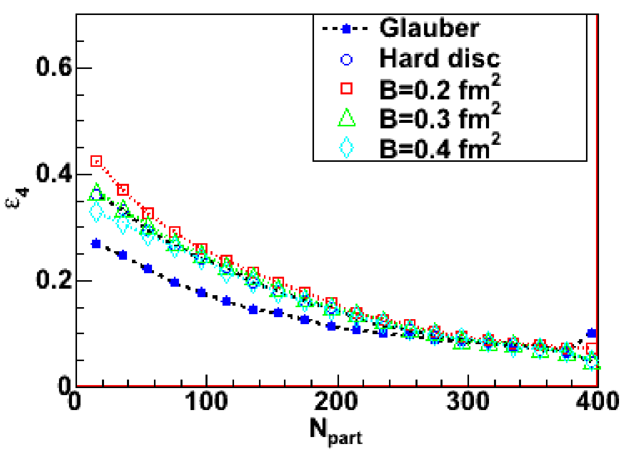


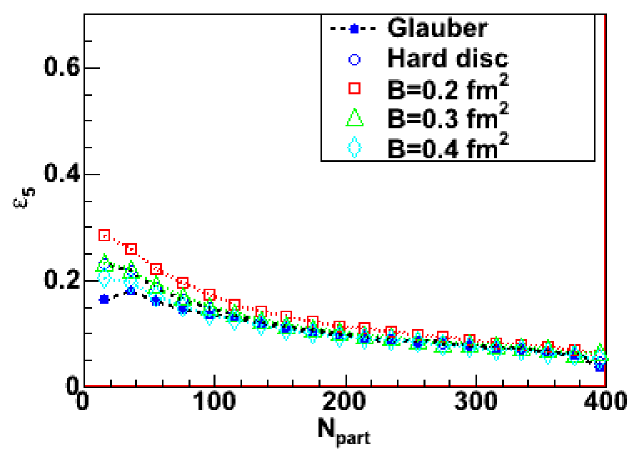
$$\epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi)\rangle^2 + \langle r^2 \sin(n\phi)\rangle^2}}{\langle r^2 \rangle}$$



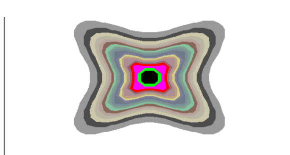


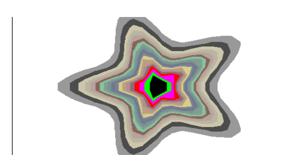






$$v_2 \equiv \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$





Monte-Carlo event generator for CGC

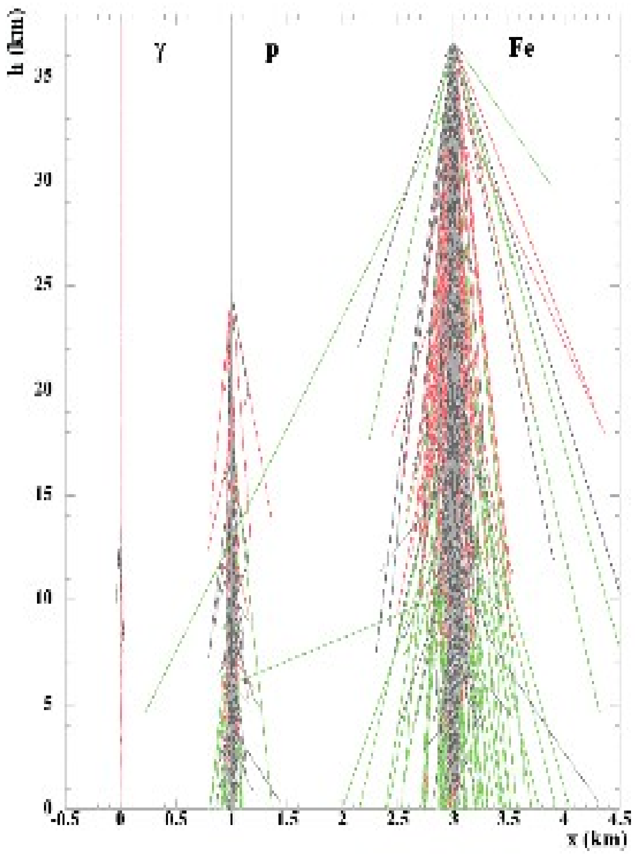
First attempt: BBL (Black-Body limit) Monte-Carlo Model
based on kt-factorization and SIBYLL
by
H.J. Drescher, A. Dumitru, M. Strikman, Phys.Rev.Lett. 94 (2005) 2

We would like to develop generator based on

DHJ (Dumitru-Hayashigaki-Jalilian-Marian) formula with rcBK unintegrated gluon dist.

for the description of forward hadron productions.

High energy cosmic rays and extensive air showers



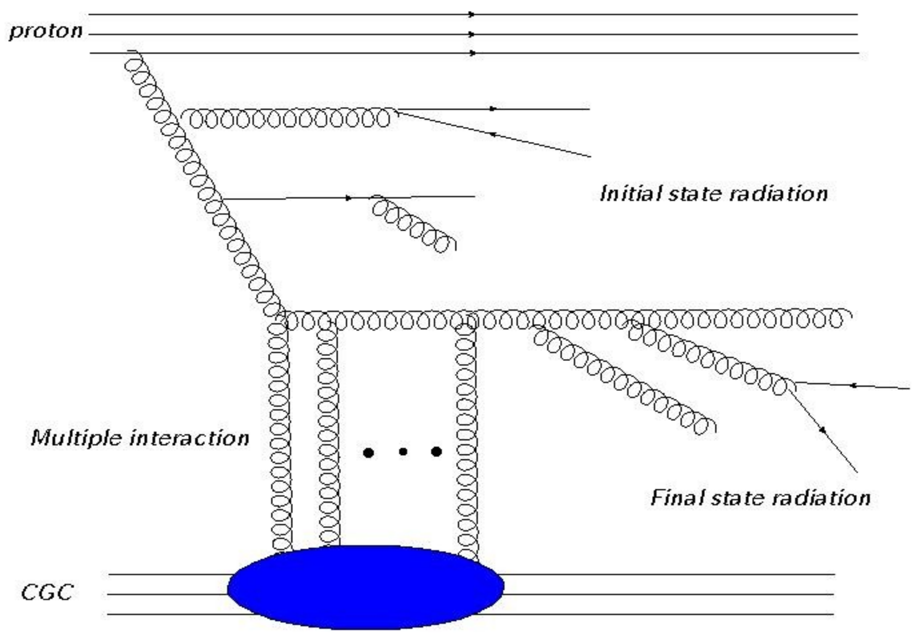
Air showers are initiated by extremely energetic primary cosmic ray hadrons

$$E > 10^{13}\mathrm{eV} \text{ or } > 10\mathrm{TeV}$$

Largest systematic uncertainty in the analysis of air shower is caused by the uncertainly of hadronic interaction of cosmic ray in atmosphere.

Monte-Carlo Event Generator for DHJ approach

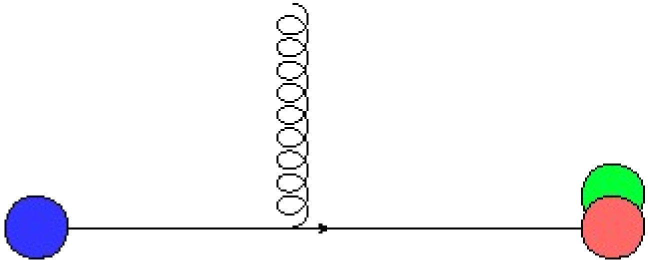
$gg \to g,\ gq \to q$ with initial and final state radiations



Gluons and quarks are generated according to the DHJ formula.

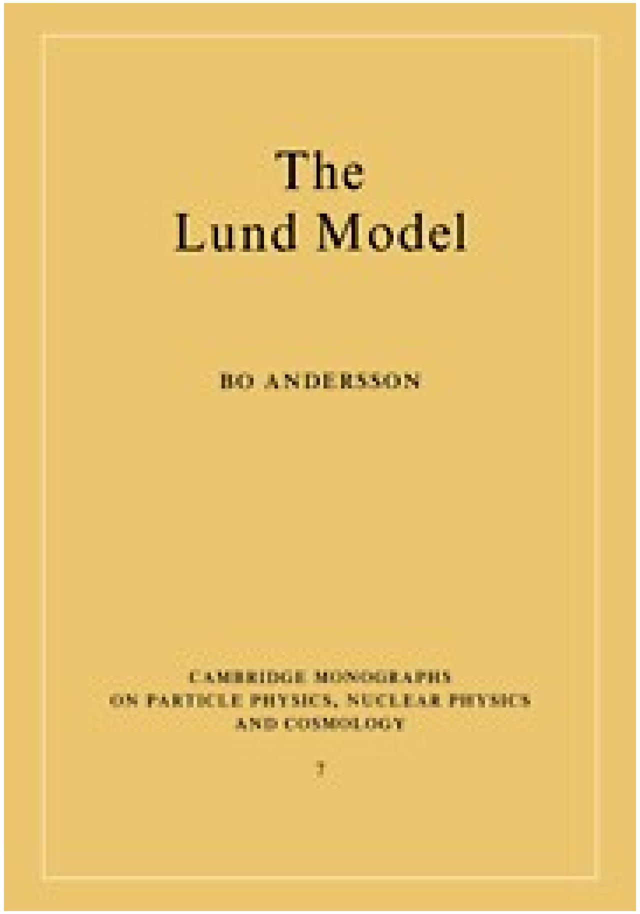
$$\frac{dN}{dy d^2 p_\perp} = \frac{K}{(2\pi)^2} f_{i/p}(x_1, p_\perp^2) N_i(x_2, p_\perp^2)$$

Hadrons are produced by the Lund string fragmentation model



Lund model

http://home.thep.lu.se/~torbjorn/Pythia.html



B. Andersson, G. Gustafson, G. Ingelman and T. Sjostrand,

``Parton Fragmentation And String Dynamics,''

Phys. Rept. 97, 31 (1983).

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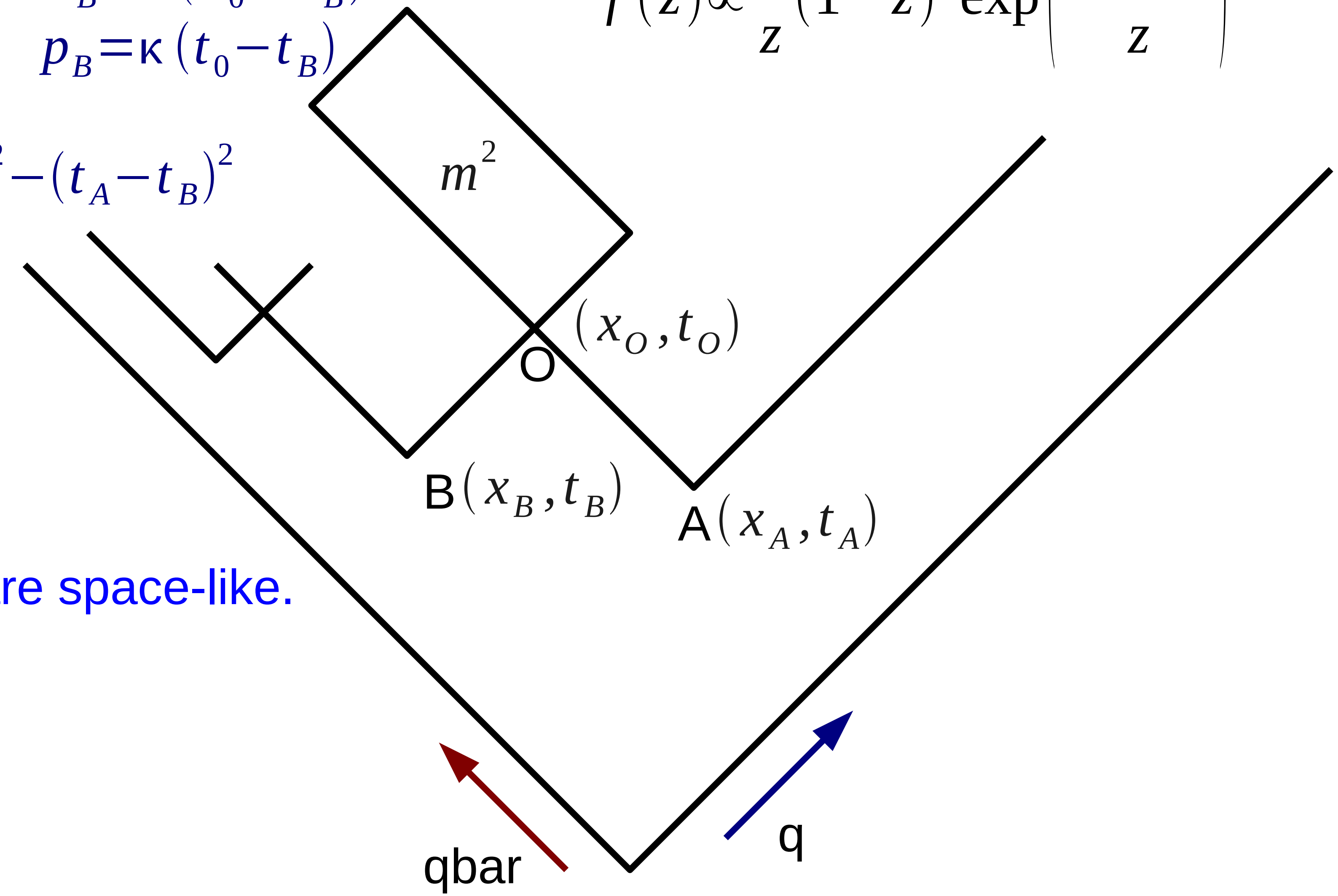
String breaking

$$E_A = \kappa(x_A - x_0), \quad E_B = \kappa(x_0 - x_B)$$

$$p_A = \kappa(t_A - t_0), \quad p_B = \kappa(t_0 - t_B)$$

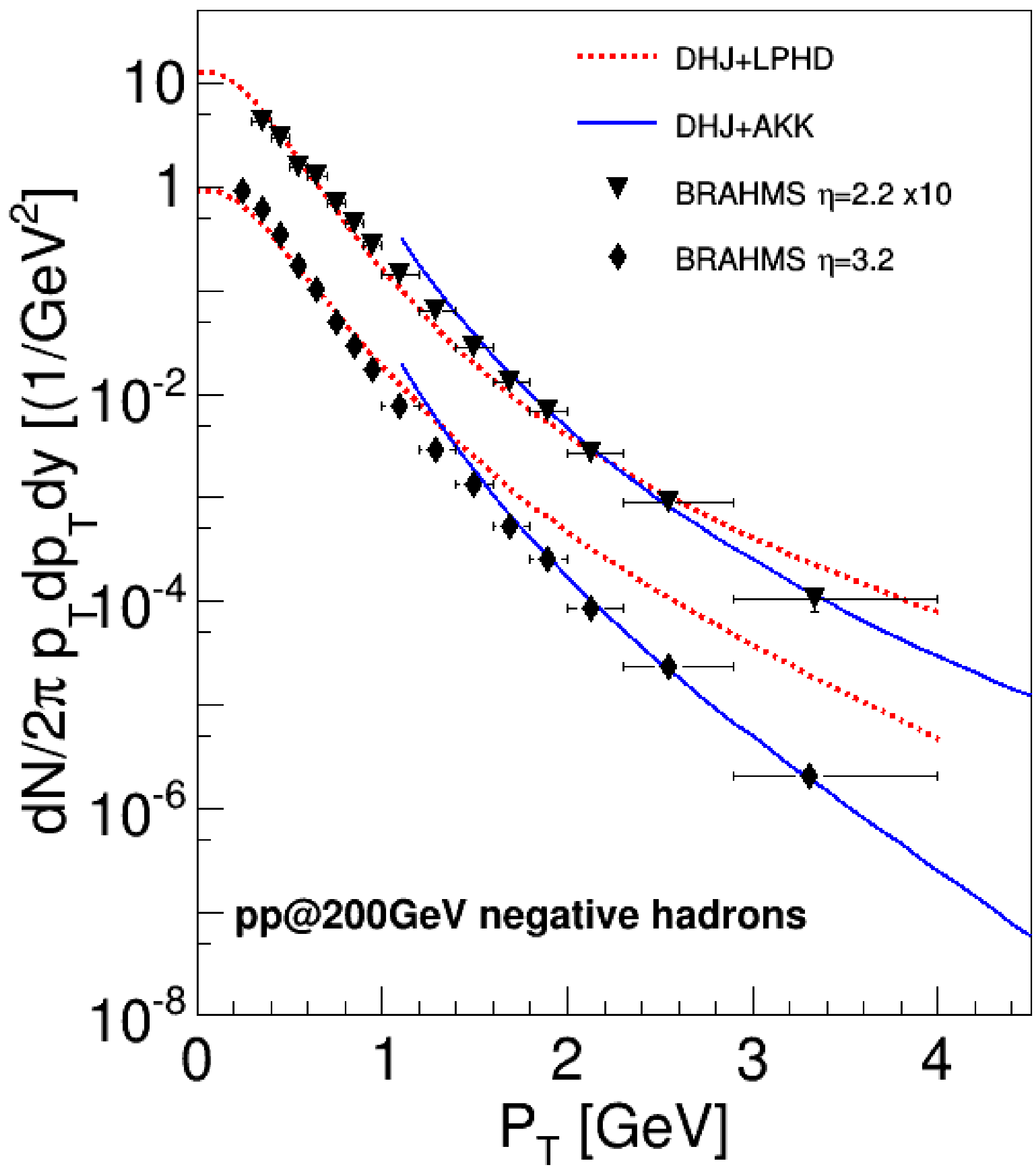
$$\frac{m^2}{\kappa^2} = (x_A - x_B)^2 - (t_A - t_B)^2$$

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-b m_\perp^2}{z}\right)$$



Vertex A and B are space-like.

LPHD and FF in DHJ

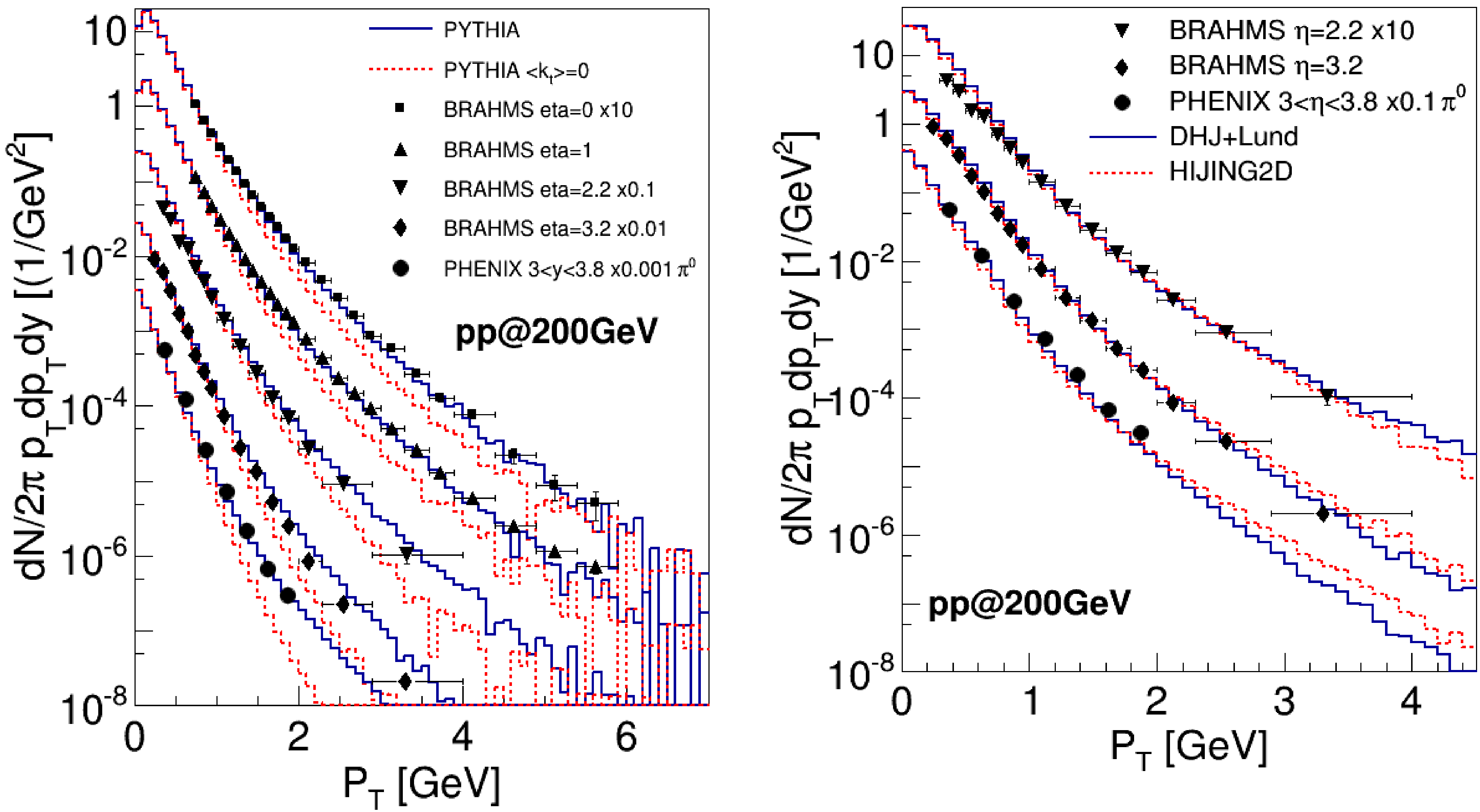


Within kt-factrizaton approach, High pt hadrons are well described by the Fragmentation function,

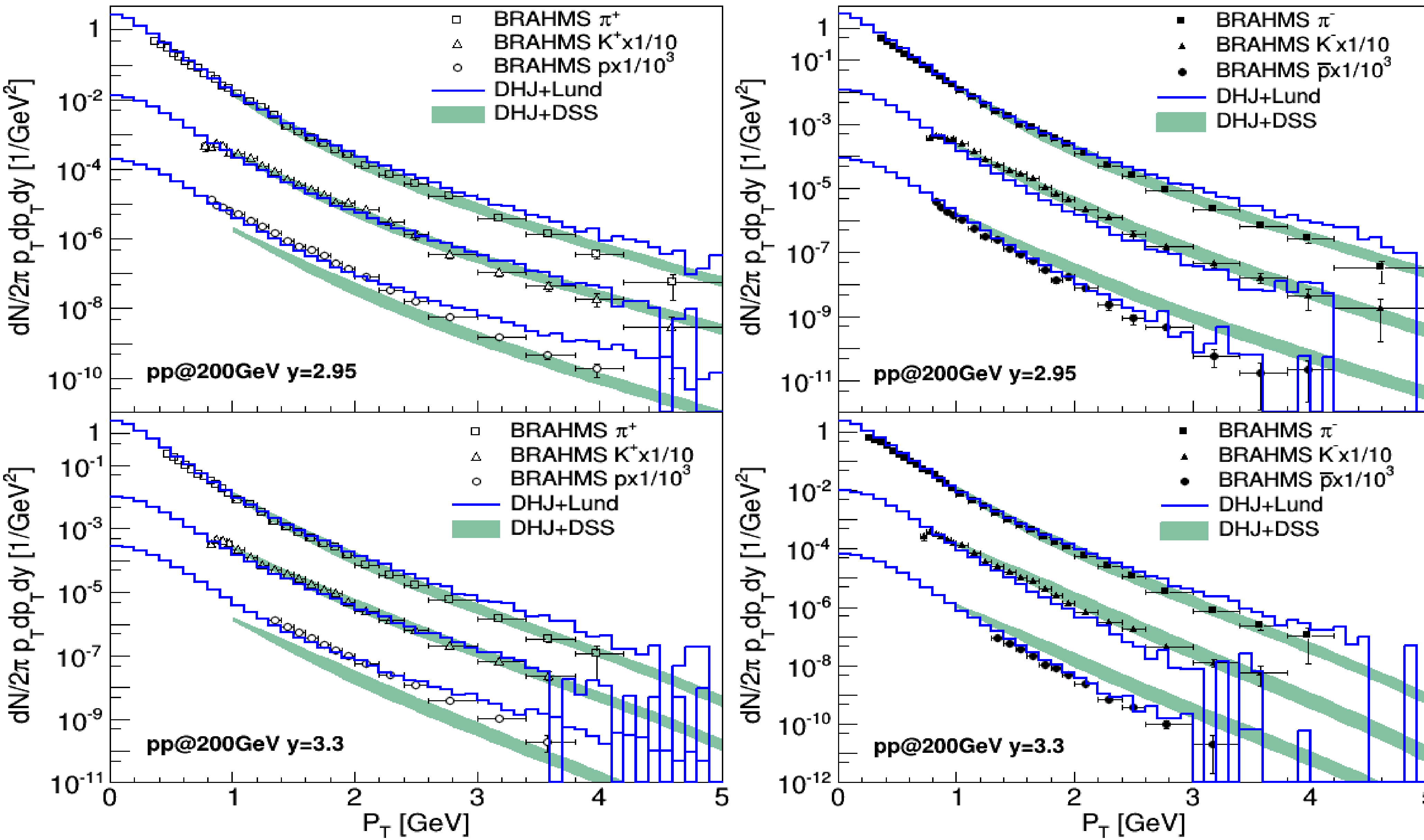
Low pt hadrons including multiplicity are well described by the parton-padron duality.

More realistic model:
event generator version is needed for the unified description..

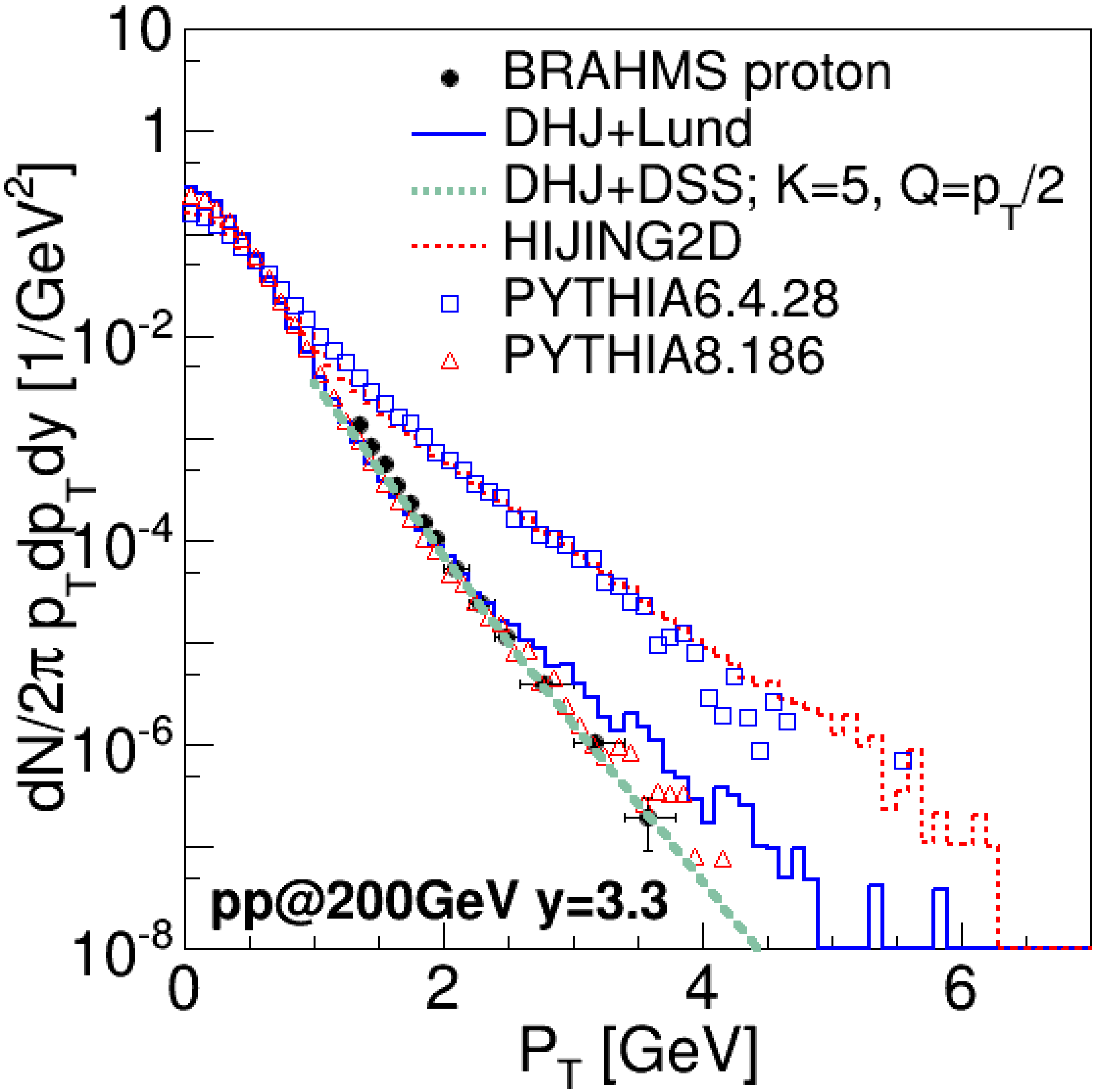
P + P@200GeV negative hadrons



Identified hadrons@200GeV

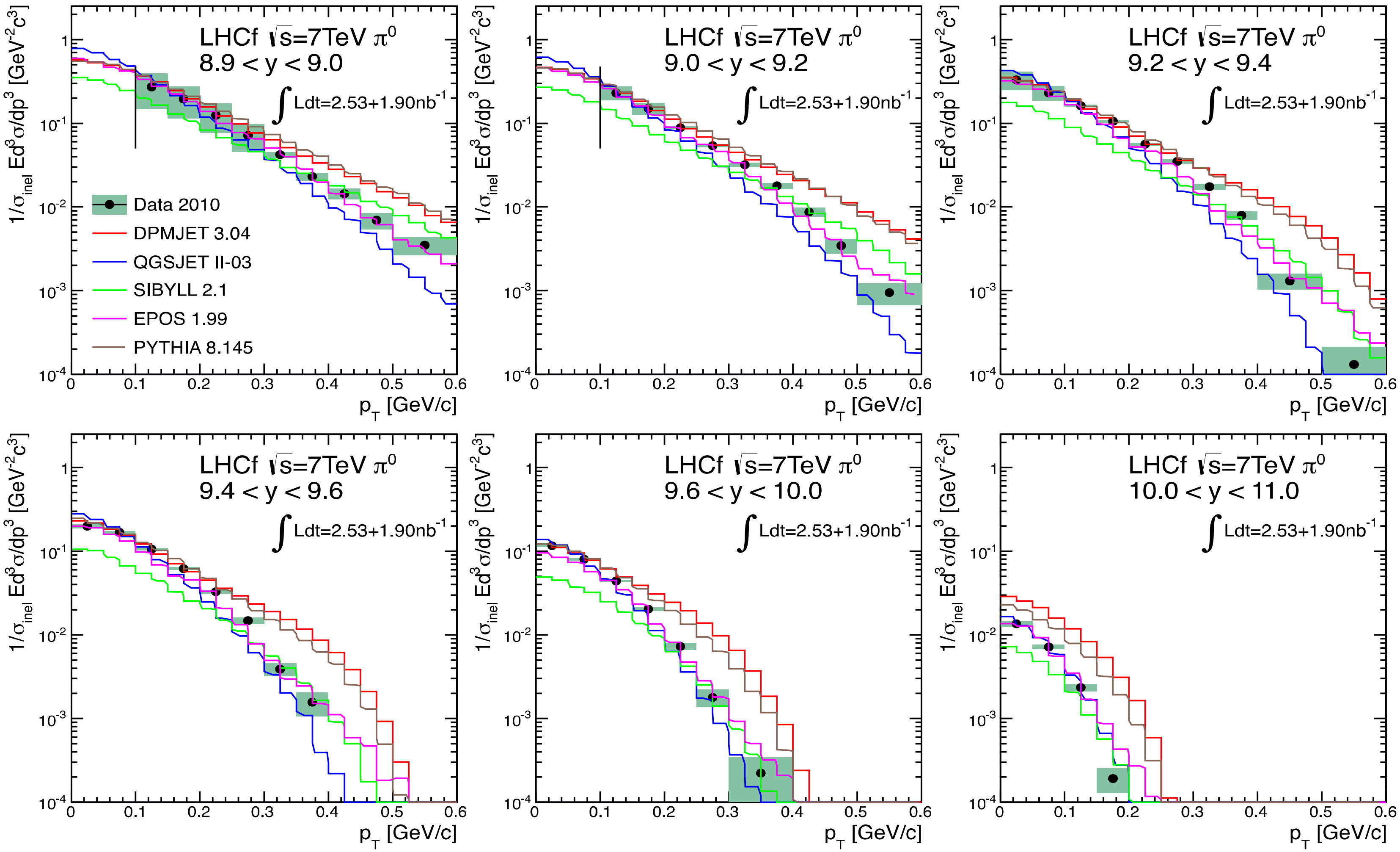


Proton distribution at y=3.3



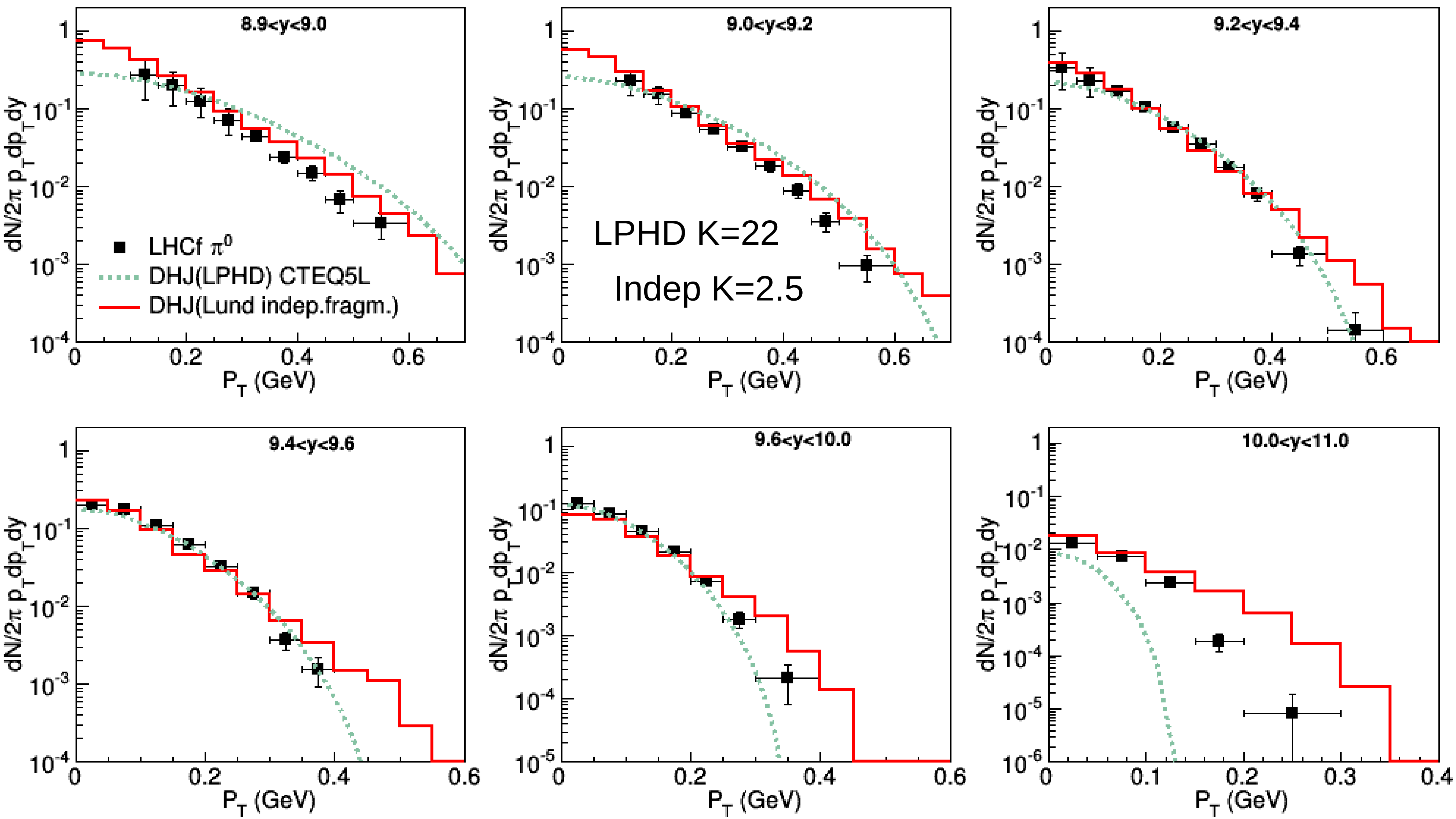
Forward neutral pion from LHCf

$$x \approx 1 \times 10^{-7}$$

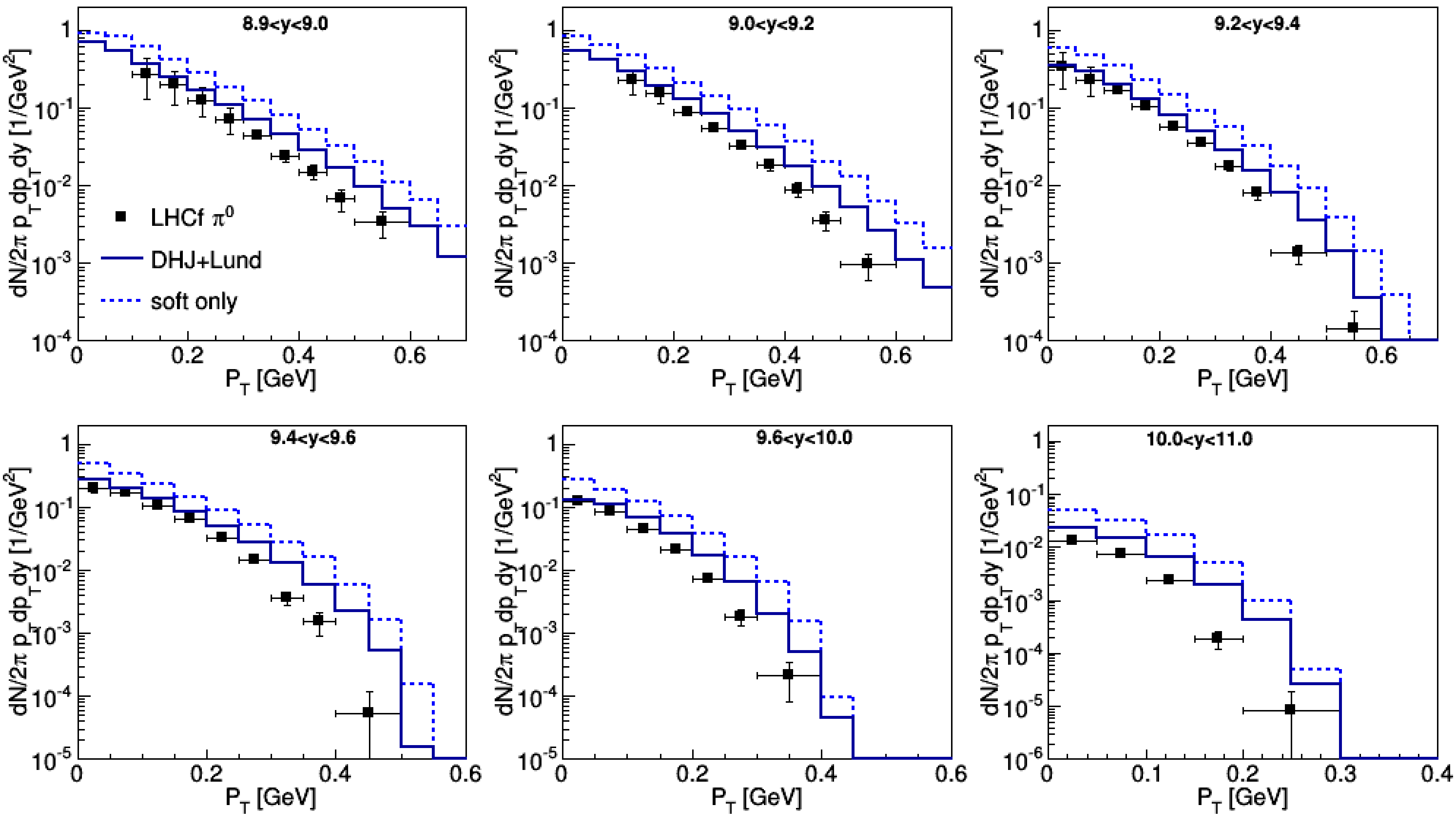


Gluon contribution? LHCf pp@7TeV

$< z >= (1 + z_{\min})/2 \qquad x \approx 1 \times 10^{-7}$



DHJ+Lund v.s. soft string fragm.py8



summary

- Monte-Carlo Event Generator version of DHJ model has been newly developed.
  DHJ + Lund string fragmentation model
- We use unintegrated gluon function from rcBK equation which is fitted by HERA data at x<0.01.
- Particle distribution for pp collisions are well fitted by the model from low to high momentum region.

  - Extension to pA and AA
  - Initial state radiation due to x-evolution