Monte-Carlo Event Generator for forward hadron productions

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- Introduction
- Hybrid formula (DHJ) for forward hadron production
- Event generator version of DHJ formula
- Transverse momentum spectra at RHIC and LHC
- Summary

J.L.Albacete, W-T. Deng, A. Dumitru,
H. Fujii, K. Itakura

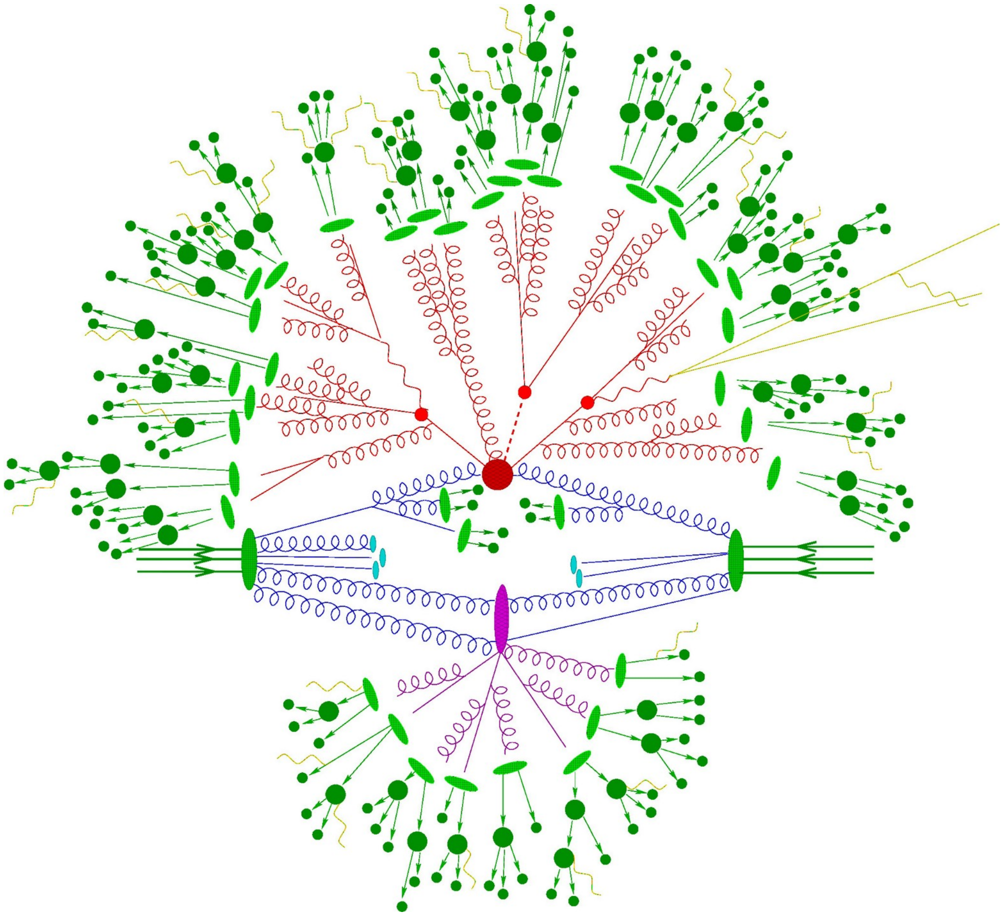
2022/7/15 18th High energy QCD,RIKEN

General purpose Event generators

- Pythia8, Herwig++, Sherpa

- pQCD hard scattering
- Multiple scattering
- Initial state radiation
- Final state radiation
- Soft physics
- Hadronization

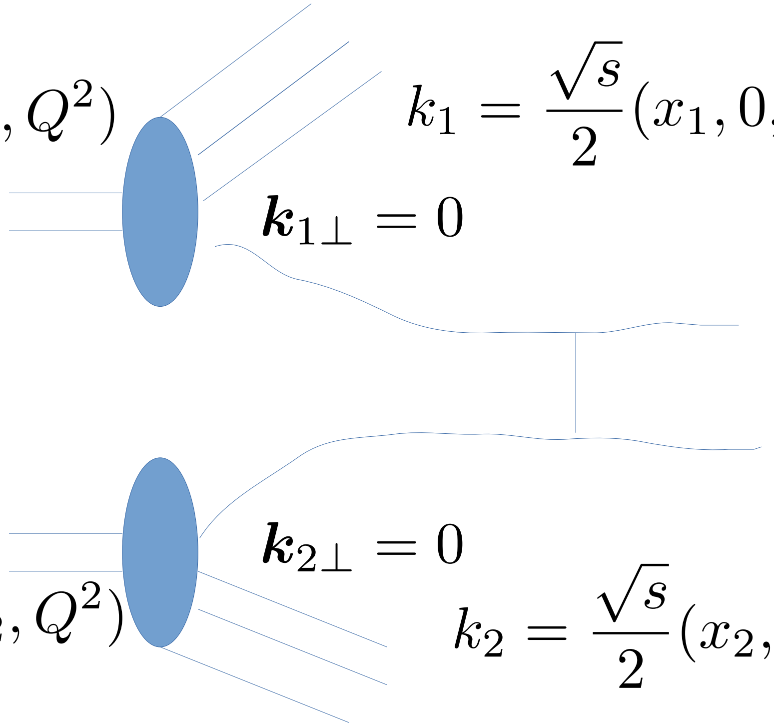
Collinear factorization



Collinear-factorization

Traditional collinear factorization: two partons with no transverse momenta scatter.

$$d\sigma = x_1 f(x_1, Q^2) x_2 f(x_2, Q^2) d\hat{\sigma}$$



$$f(x_1, Q^2)$$

$$k_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1)$$

$$\boldsymbol{k}_{1\perp} = 0$$

$$p_3 = (p_T \cosh y_3, \boldsymbol{p}_\perp, p_T \sinh y_3)$$

$$p_4 = (p_T \cosh y_4, -\boldsymbol{p}_\perp, p_T \sinh y_4)$$

$$\boldsymbol{k}_{2\perp} = 0$$

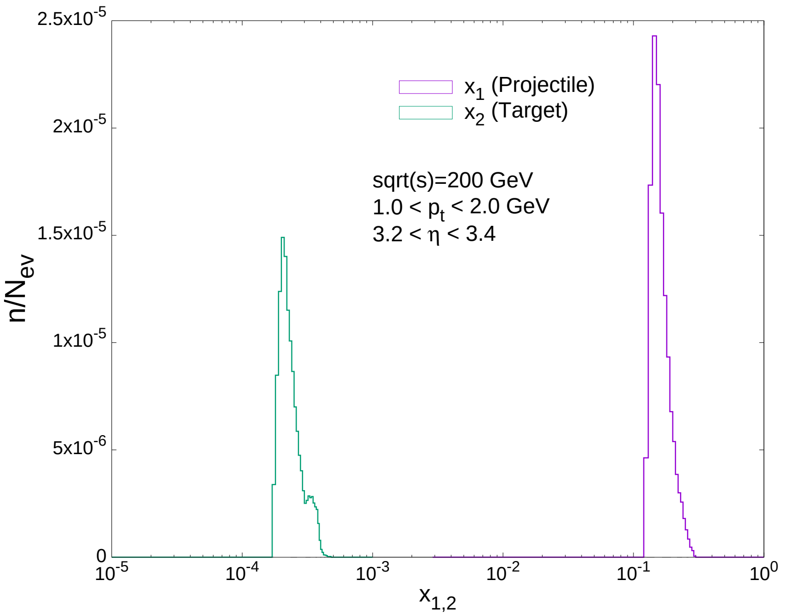
$$f(x_2, Q^2)$$

$$k_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

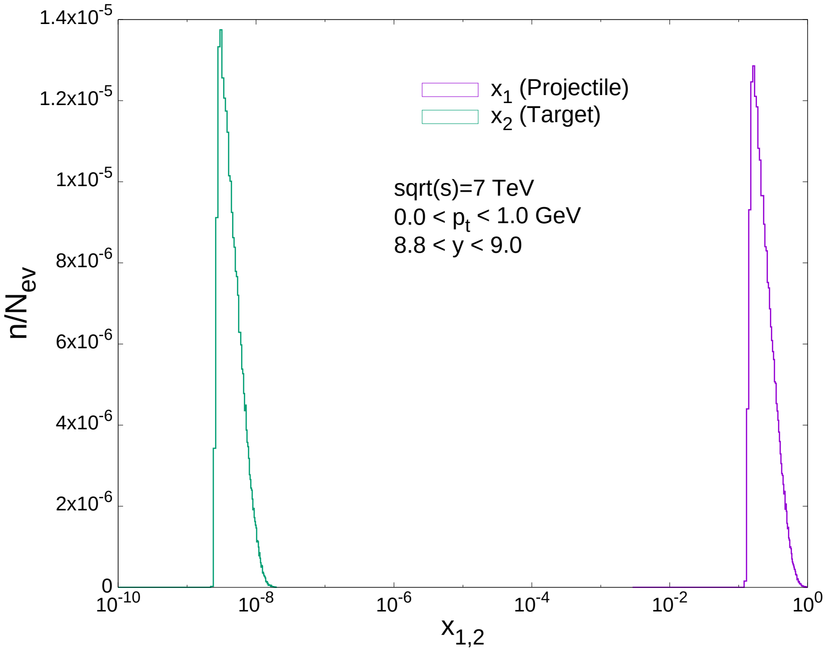
x values of projectile and target at forward scattering

$$x_p = \frac{p_T}{\sqrt{s}}(e^{y_3} + e^{y_4}), \quad x_t = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

$$x_p = \frac{p_T}{\sqrt{s}}e^{y}, \quad x_t = \frac{p_T}{\sqrt{s}}e^{-y}$$



$$x_p \approx 0.2 \quad x_t \approx 10^{-3}$$



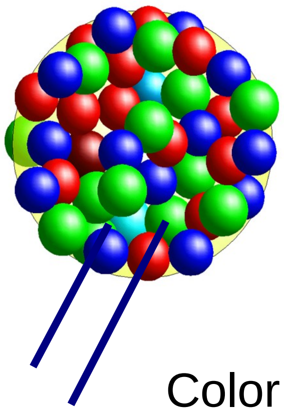
$$x_p \approx 0.1 \quad x_t \approx 10^{-8}$$

Structure of the nucleus at high energies

E.Levin anL.V.Gribovd M.G.Ryskin, '83
A. H. Mueller and J. Qiu, '86
J. P. Blaizot and A. H. Mueller,'87

Nonlinear effect

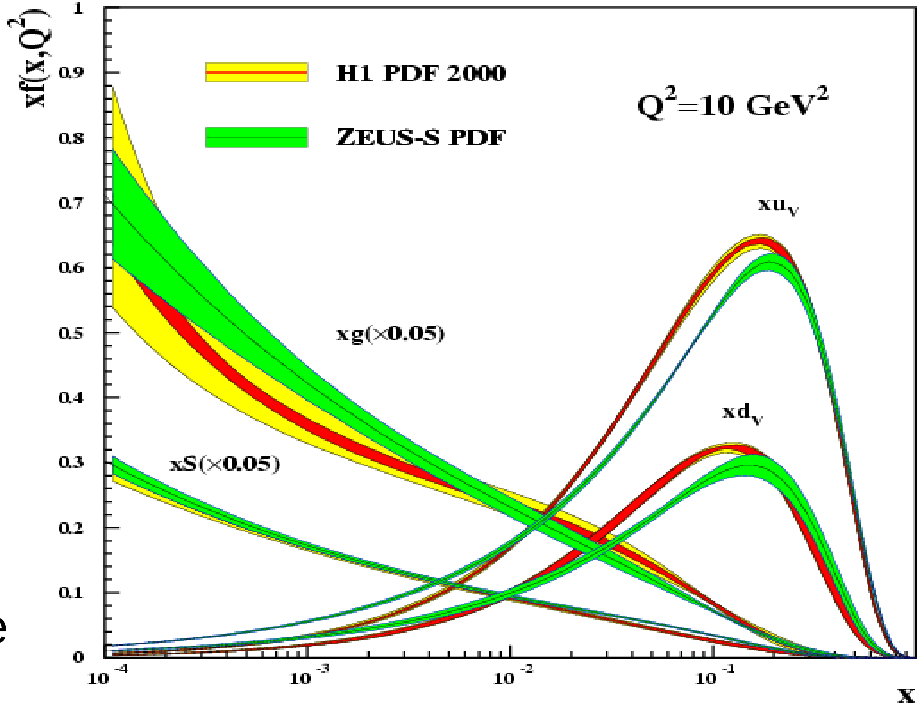
Gluon saturation



Color Glass Condensate

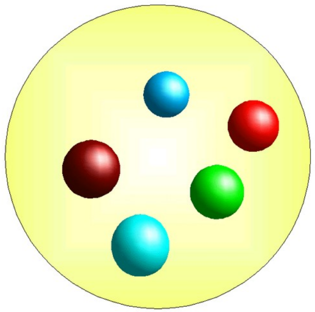
$$r \sim \frac{1}{Q_s}$$

Saturation scale



QCD Linear Evolution Equations, DGLAP and BFKL predict rapid rise for x ≪ 1.

Linear

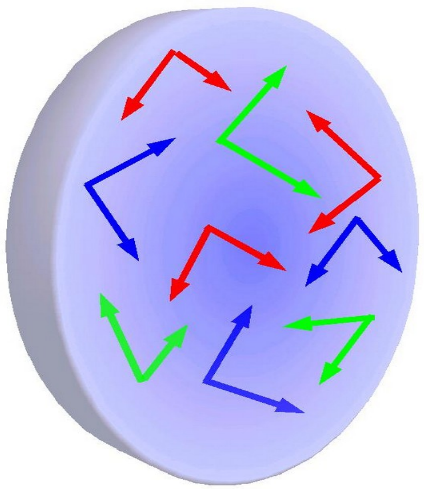


High x and low Q

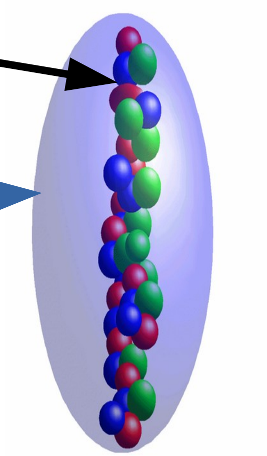
Gauge field in the MV model

The gluon distribution is large:

Suggest the use of the semi-classical methods



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

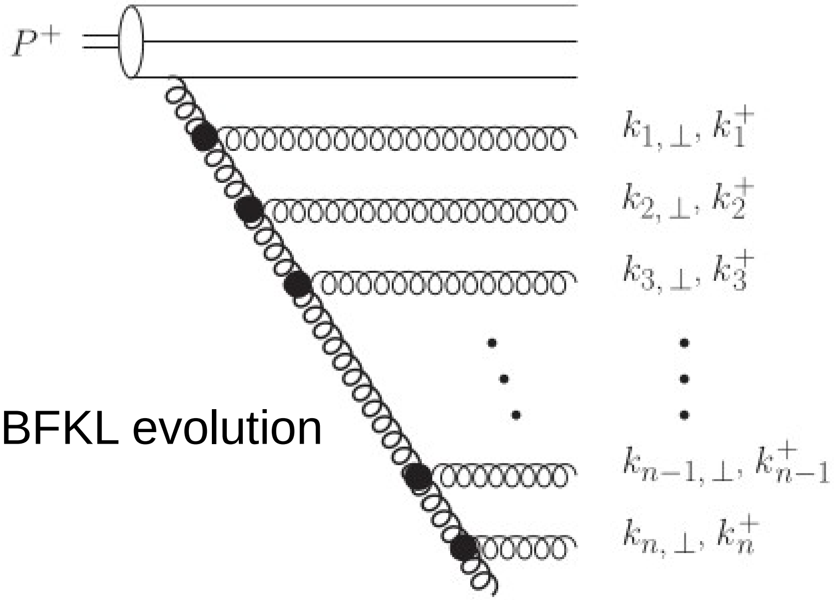


Color Glass Condensate

$$\boldsymbol{B}\cdot\boldsymbol{E}=0,\ \boldsymbol{B}_z=\boldsymbol{E}_z=0$$

Kt-factorization for small-x

Small-x: x-evolution of gluons produces many gluons with transverse momentum.



BFKL evolution

$$d\sigma = x_1 f(x_1, Q^2) x_2 f(x_2, Q^2) d\hat{\sigma}$$

$$xf(x, Q^2) = \int^{Q^2} \phi(x, k_\perp^2) dk_\perp^2$$

$\phi(x, k_\perp^2)$: unintegrated gluon distribution

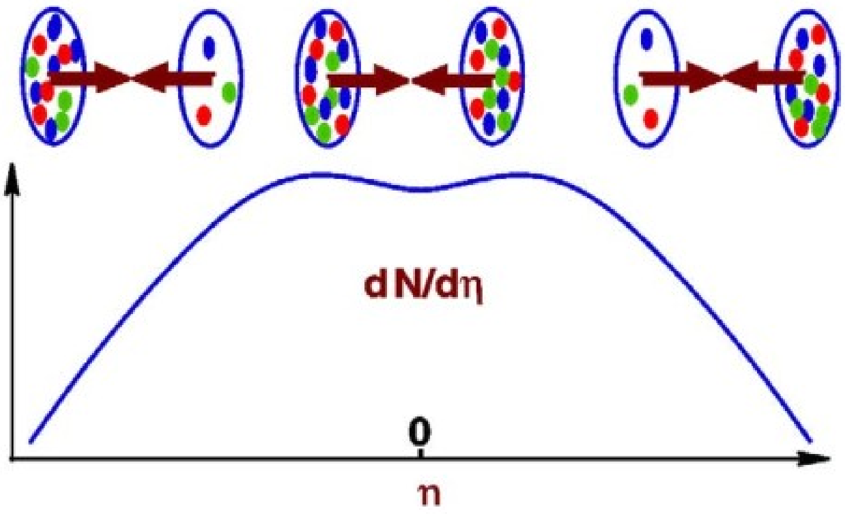
$$d\sigma = d\boldsymbol{k}_{1\perp}^2 d\boldsymbol{k}_{2\perp}^2 \phi(x_1, \boldsymbol{k}_{1\perp}) \phi(x_2, \boldsymbol{k}_{2\perp}) d\hat{\sigma}$$

Hybrid formula for asymmetric situation

For the asymmetric stituation $x_1 \gg x_2$ in the forward hadron production,

$$d\sigma = d\boldsymbol{k}_{2\perp}^2 x_1 f(x_1, Q^2) \phi(x_2, \boldsymbol{k}_{2\perp}) d\hat{\sigma}$$

Large x   Small x

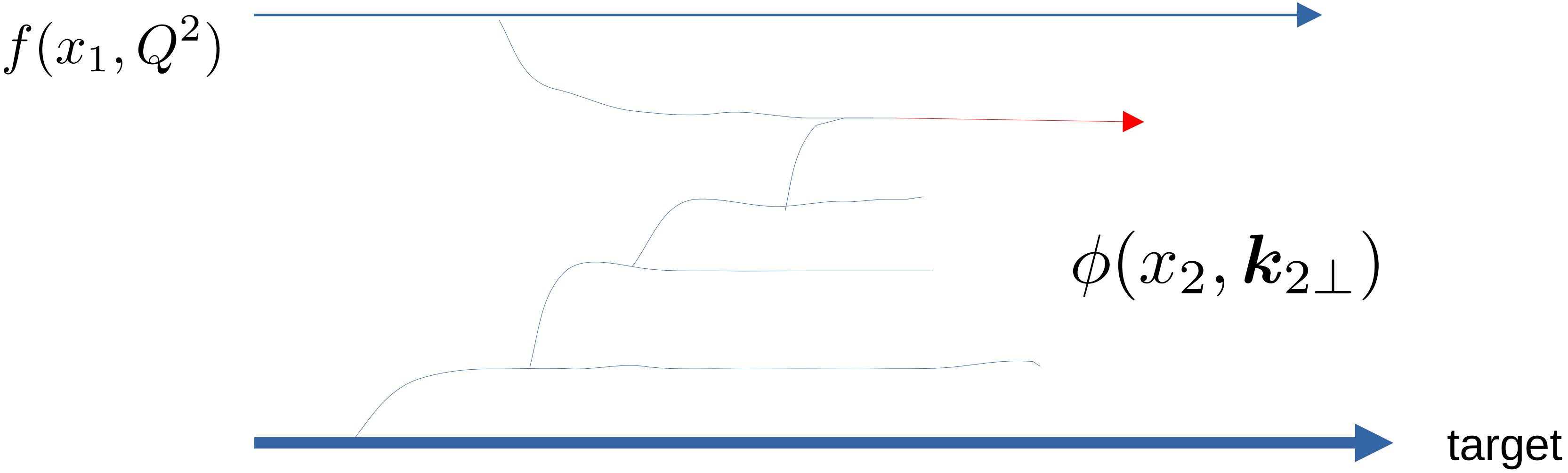


D. Kharzeev et al. / Nuclear Physics A 747 (2005) 609–629

Hybrid formula (DHJ)

A. Dumitru, A. Hayashigaki, J.Jalilian-Marian, NPA765(2006)464,NPA770(2006)57

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

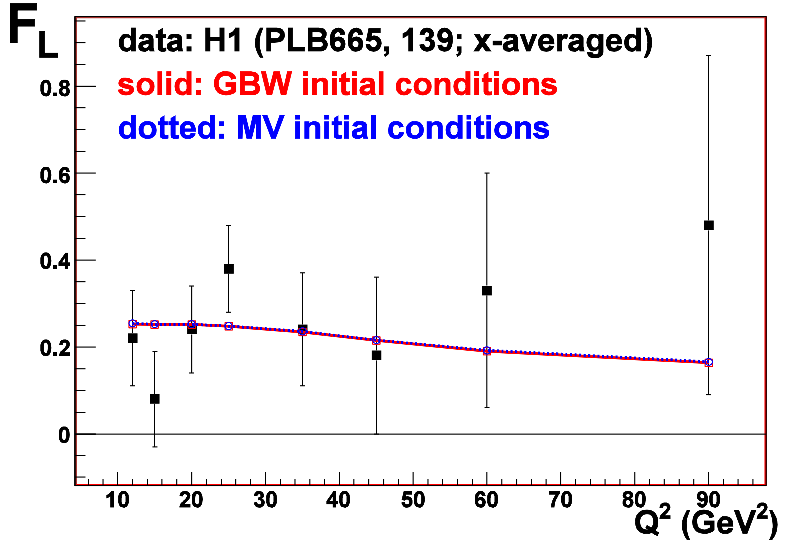


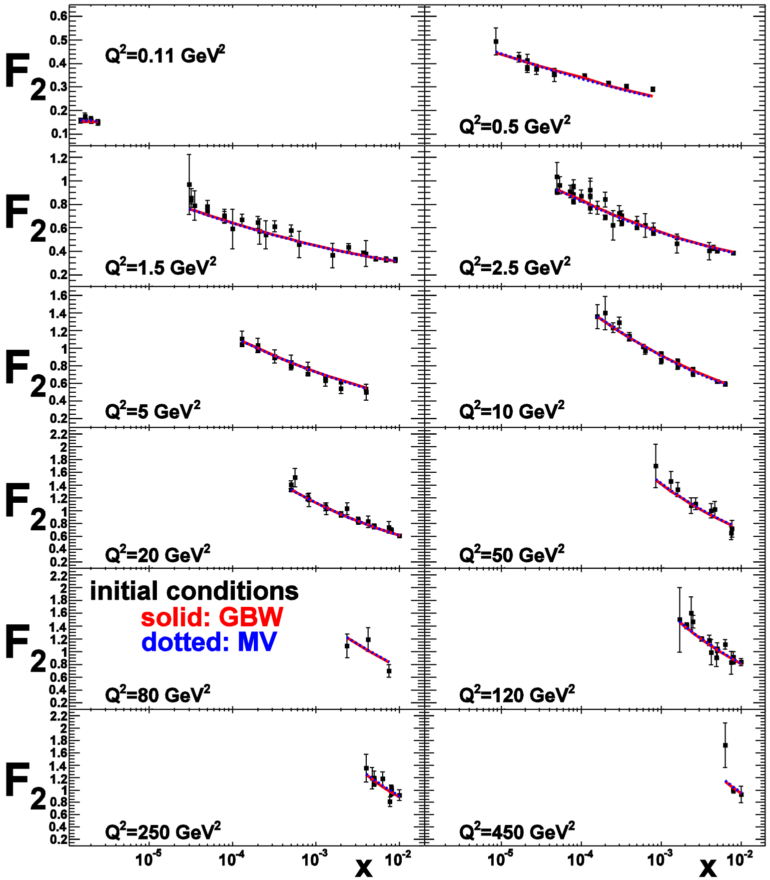
running coupling Balitsky-Kovchegov (rcBK) evolution for dipole amplitude N

HERA F2 data global fit from rcBK equation

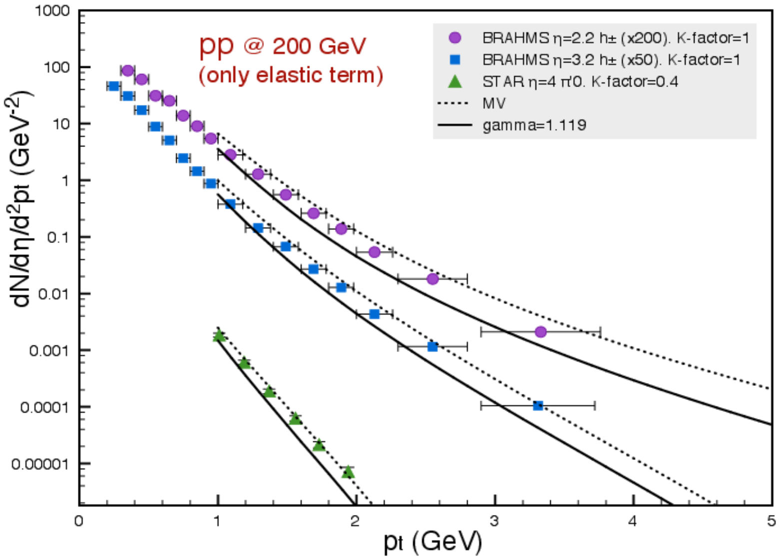
$$\frac{\partial \mathcal{N}(r,x)}{\partial y} = \int d^2 r_1 \; K(r,r_1,r_2)\left[\mathcal{N}(r_1,y)+\mathcal{N}(r_2,y)-\mathcal{N}(r,y)-\mathcal{N}(r_1,y)\mathcal{N}(r_2,y)\right]$$

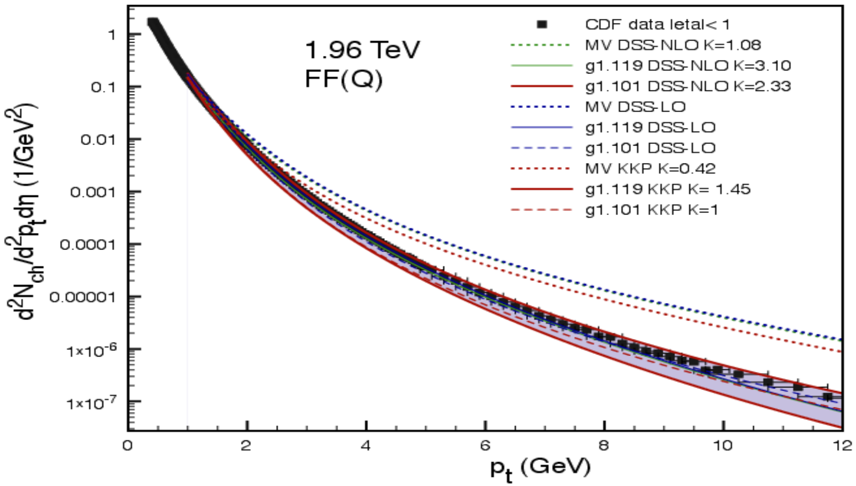
Albacete, Armesto, Mihano, Salgado 2009

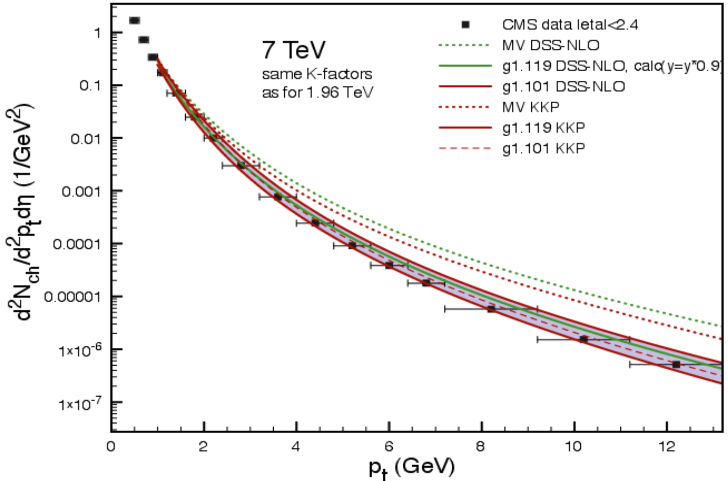




Comparison to RHIC/LHC data for pp collisions







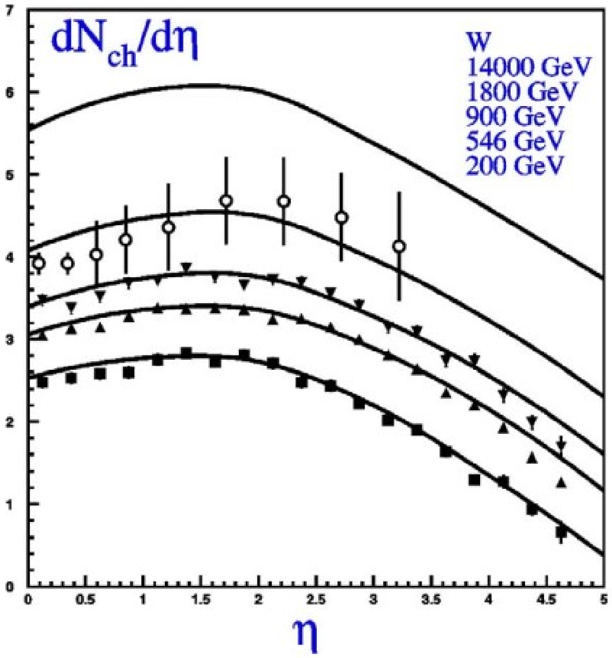
Strong constraint to
the initial condition at LHC

γ>1 → evolution slow down

J.L.Albacete, A. Dumitru, H. Fujii, Y.N. NPA897(3013)1

How do you treat low pt region?

Perturbative approach is limited for large pt region, however, most particles are produced with low pt (pt < 1 GeV).



Local Parton hadron duality (entropy conservation): assumption that multiplicity of parton is the same as that of hadrons.

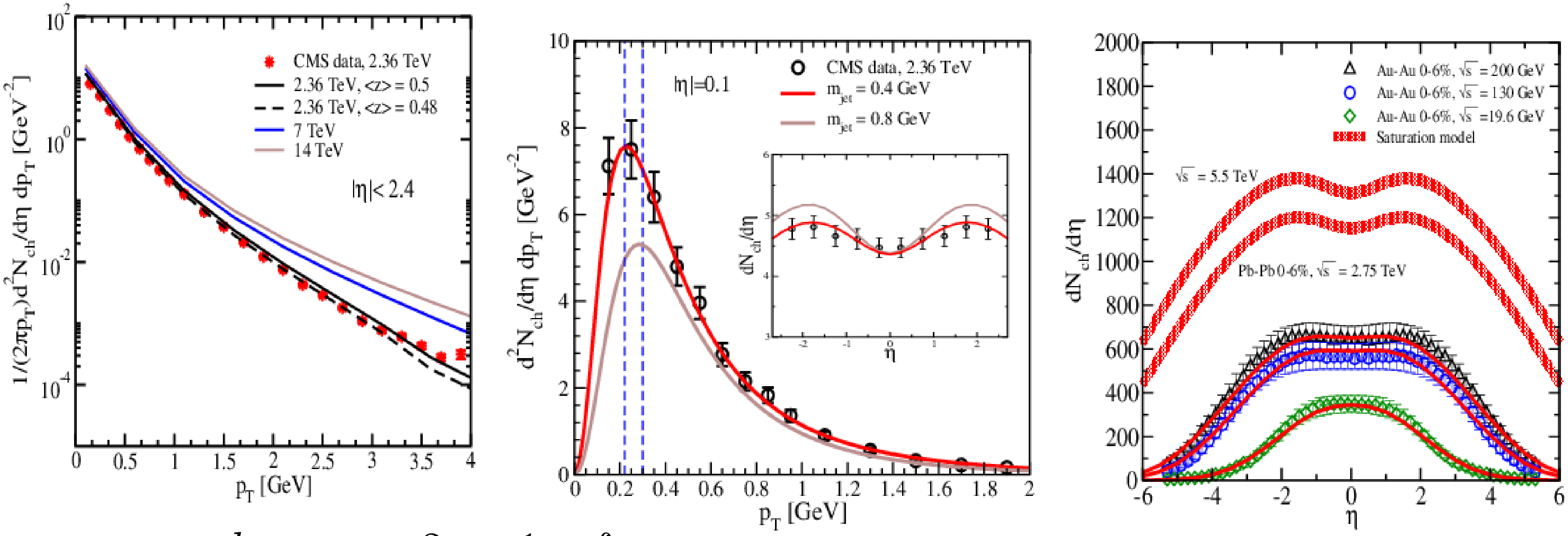
KLN/CGC gluon distribution are compared with the charged hadrons in pp collisions.

D. Kharzeev et al. Nucl. Phys. A747 (2005) 609–629

Local parton-hadron duality

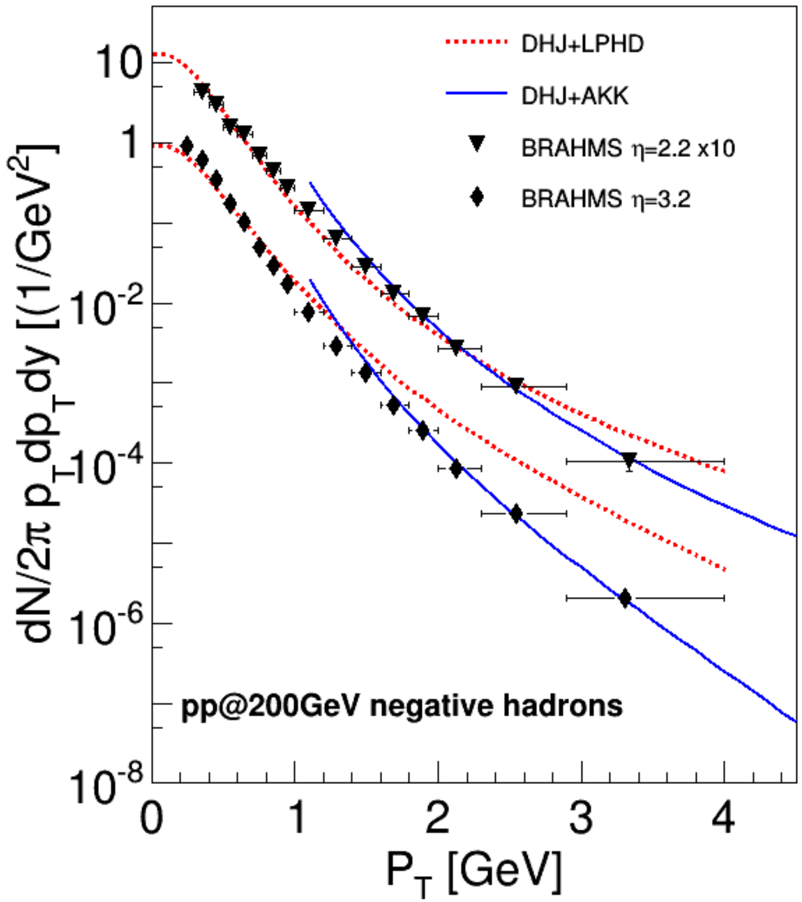
Kt-factorization + LPHD

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



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

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..

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

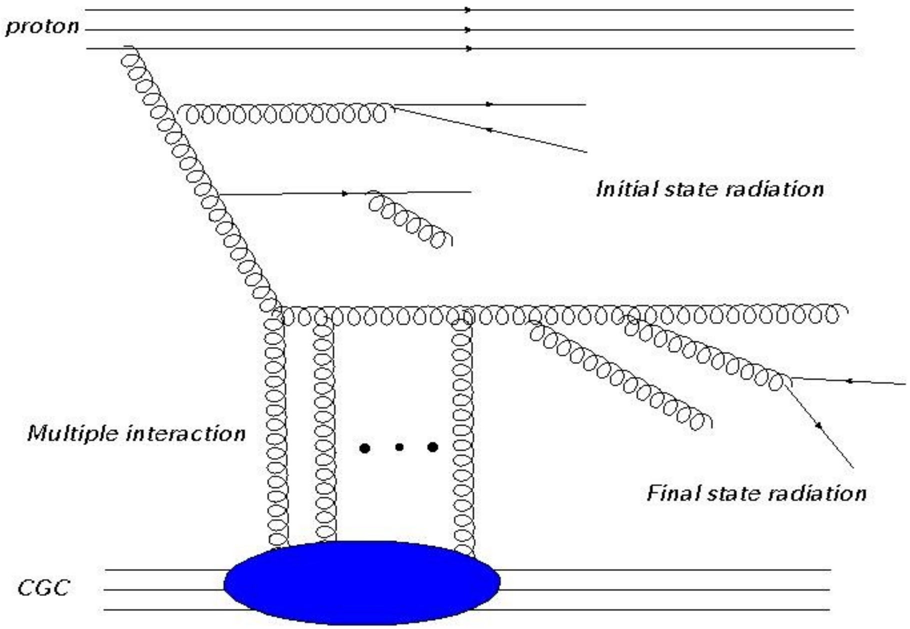
We would like to develop generator based on

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

for the description of forward hadron productions.

Monte-Carlo Event Generator for DHJ approach

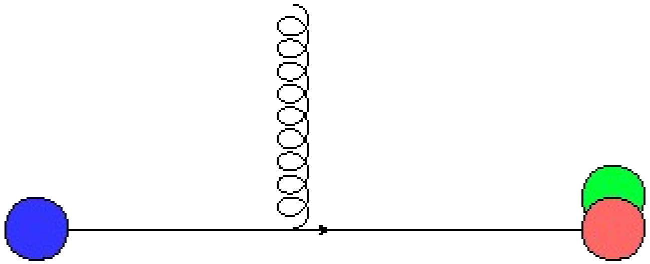
$gg \to g,\ gq \to q$ with initial and final state radiations



Gluons and quarks are generated according to the DHJ formula.

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

Hadrons are produced by the Lund string fragmentation model

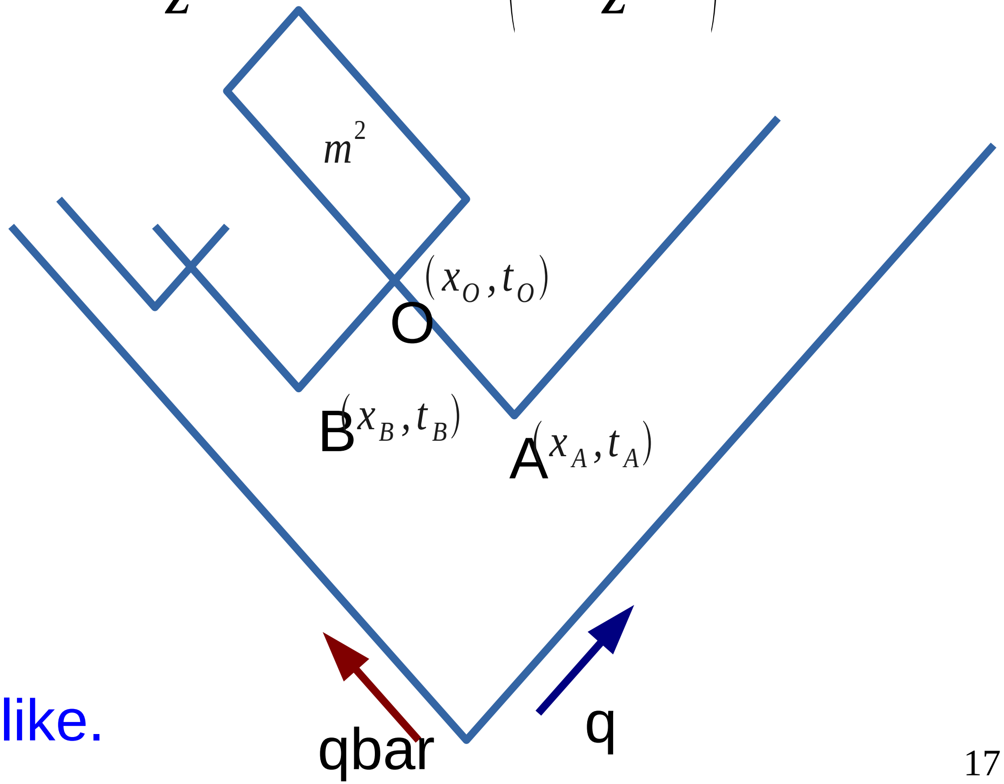


String breaking

$$E_A = \kappa(x_A - x_0), \quad E_B = \kappa(x_0 - x_B)$$
$$p_A = \kappa(t_A - t_0), \quad p_B = \kappa(t_0 - t_B)$$

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

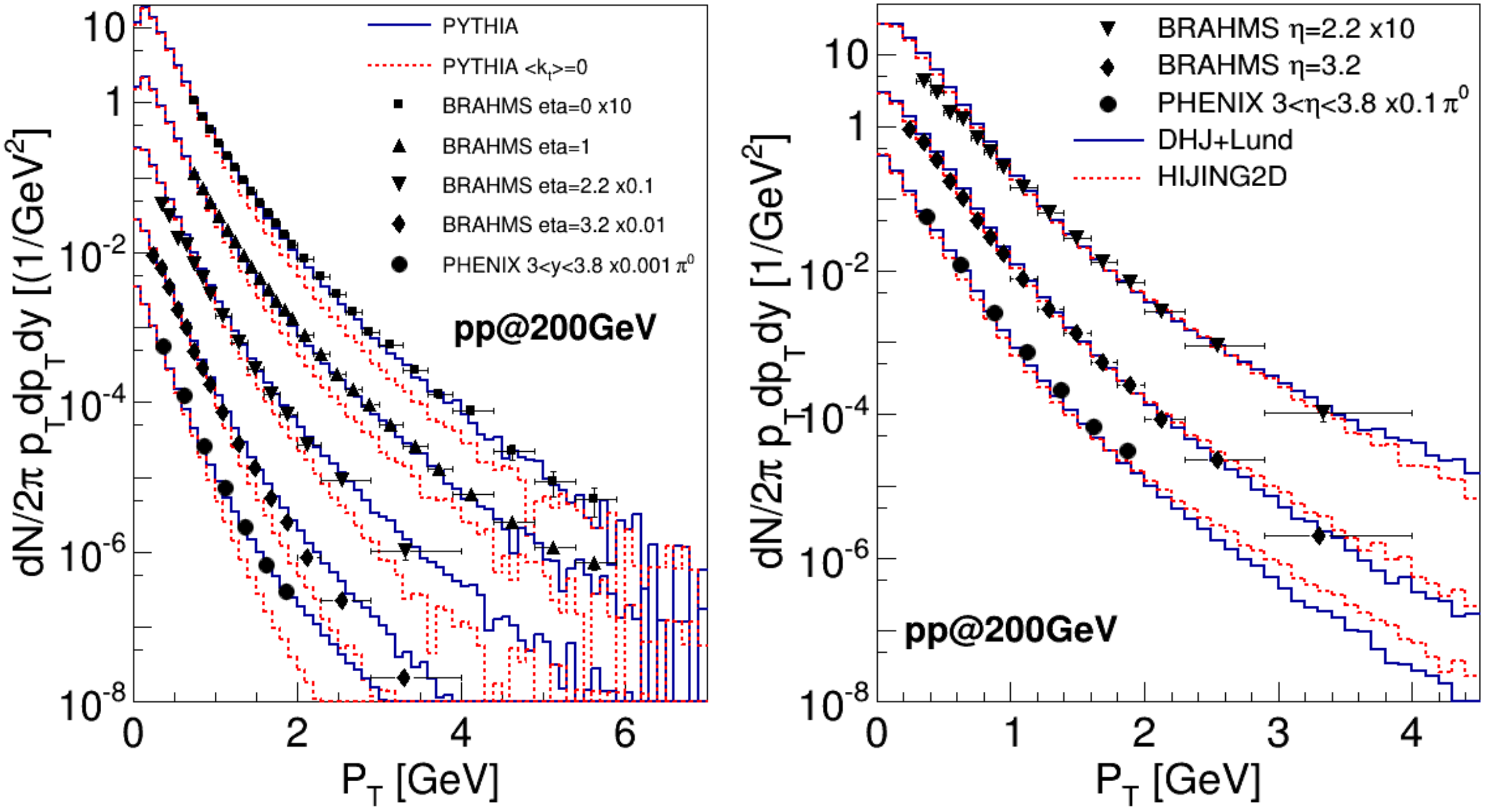
$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$



Vertex A and B are space-like.

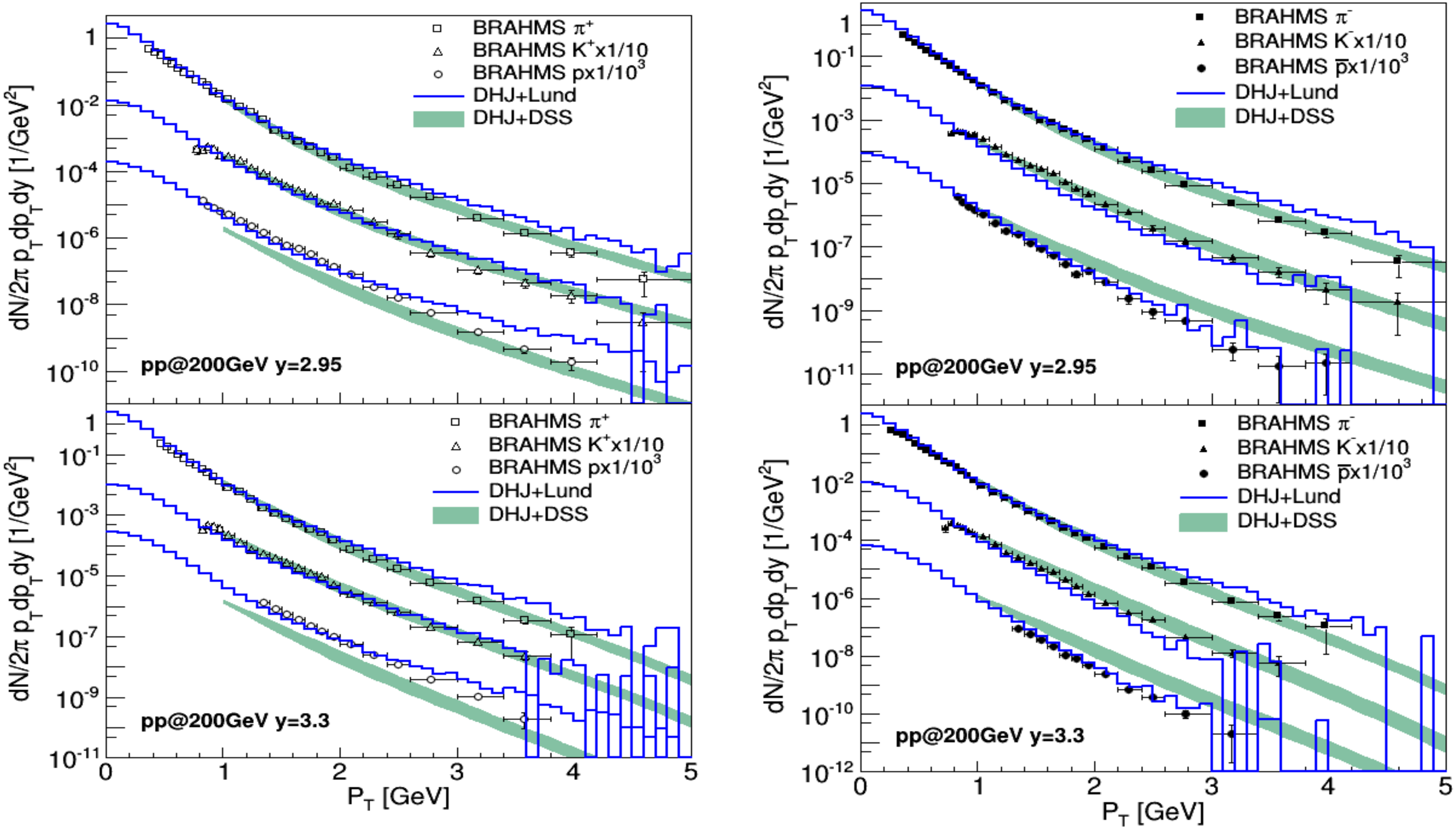
W-T. Deng, et.al PRD91 (2015) 014006

P + P@200GeV negative hadrons

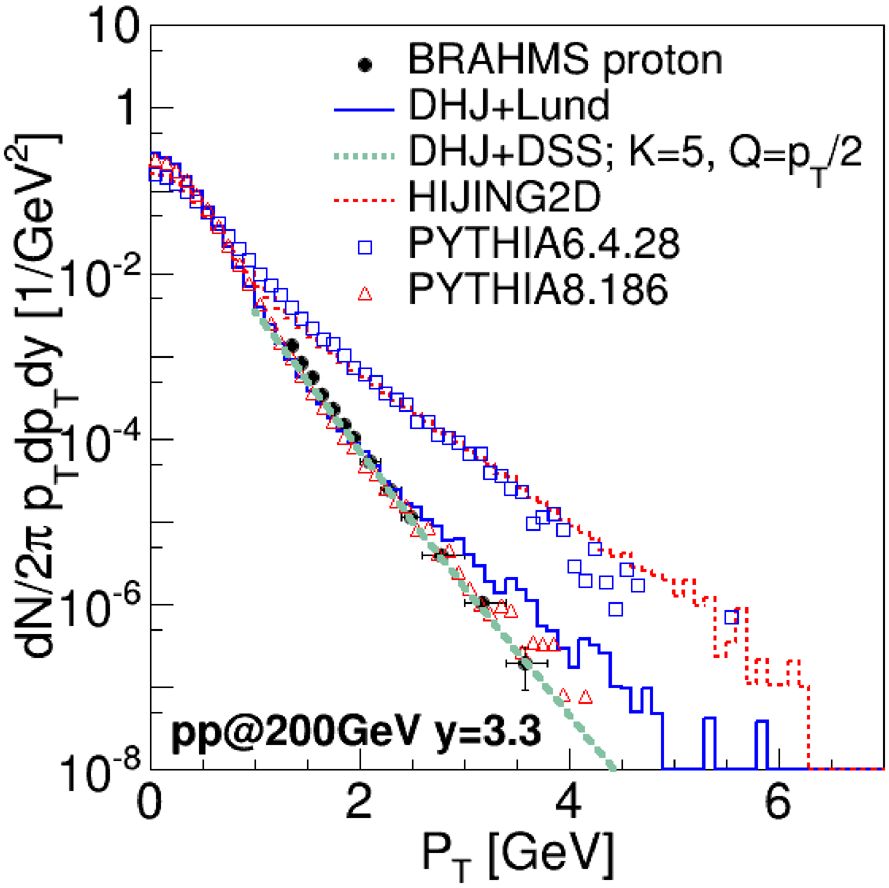


Pythia and HIJING need primordial kt=2GeV to fit the data.

Identified hadrons@200GeV



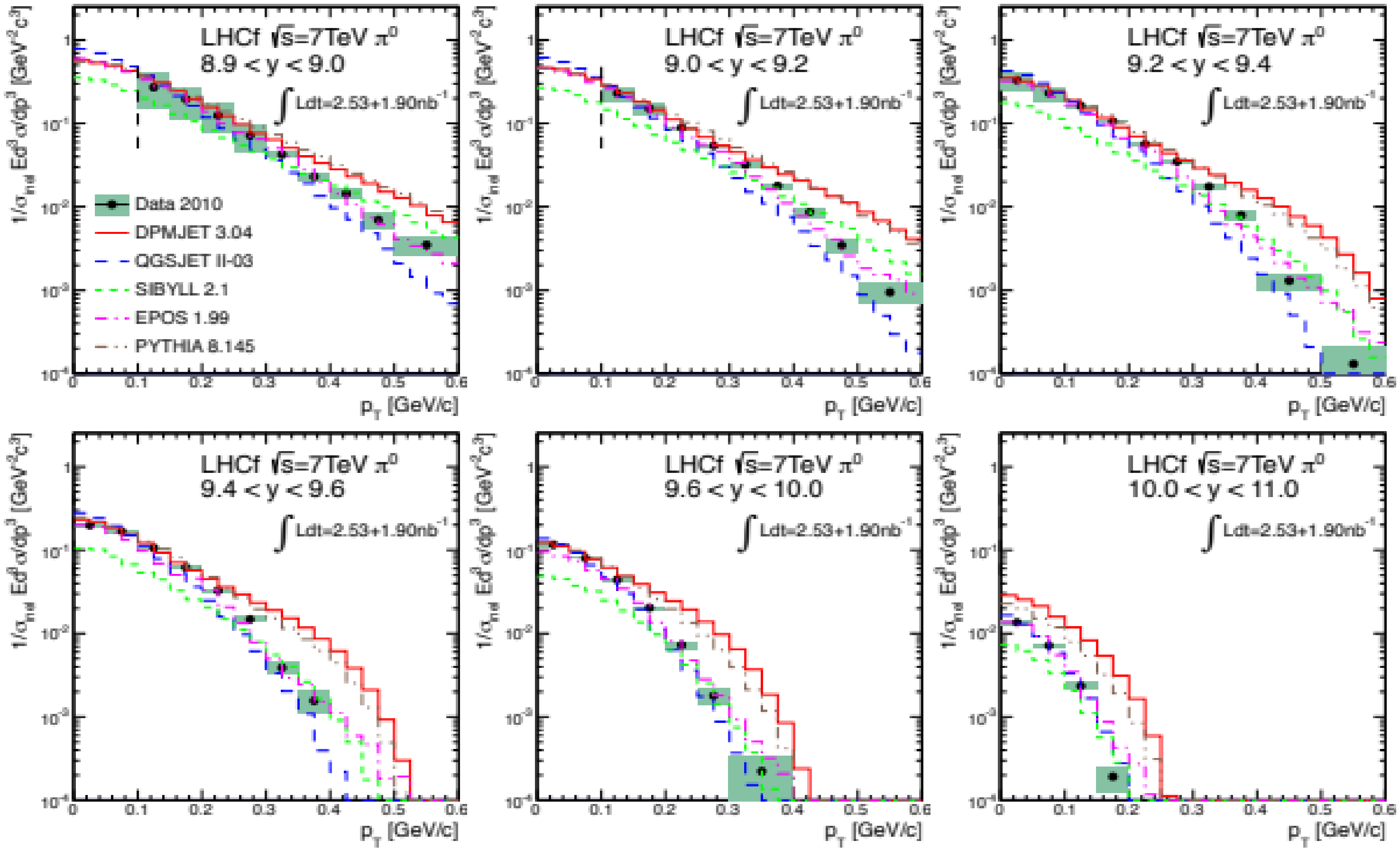
Proton distribution at y=3.3



Pythia8 improves the description of baryon spectra.

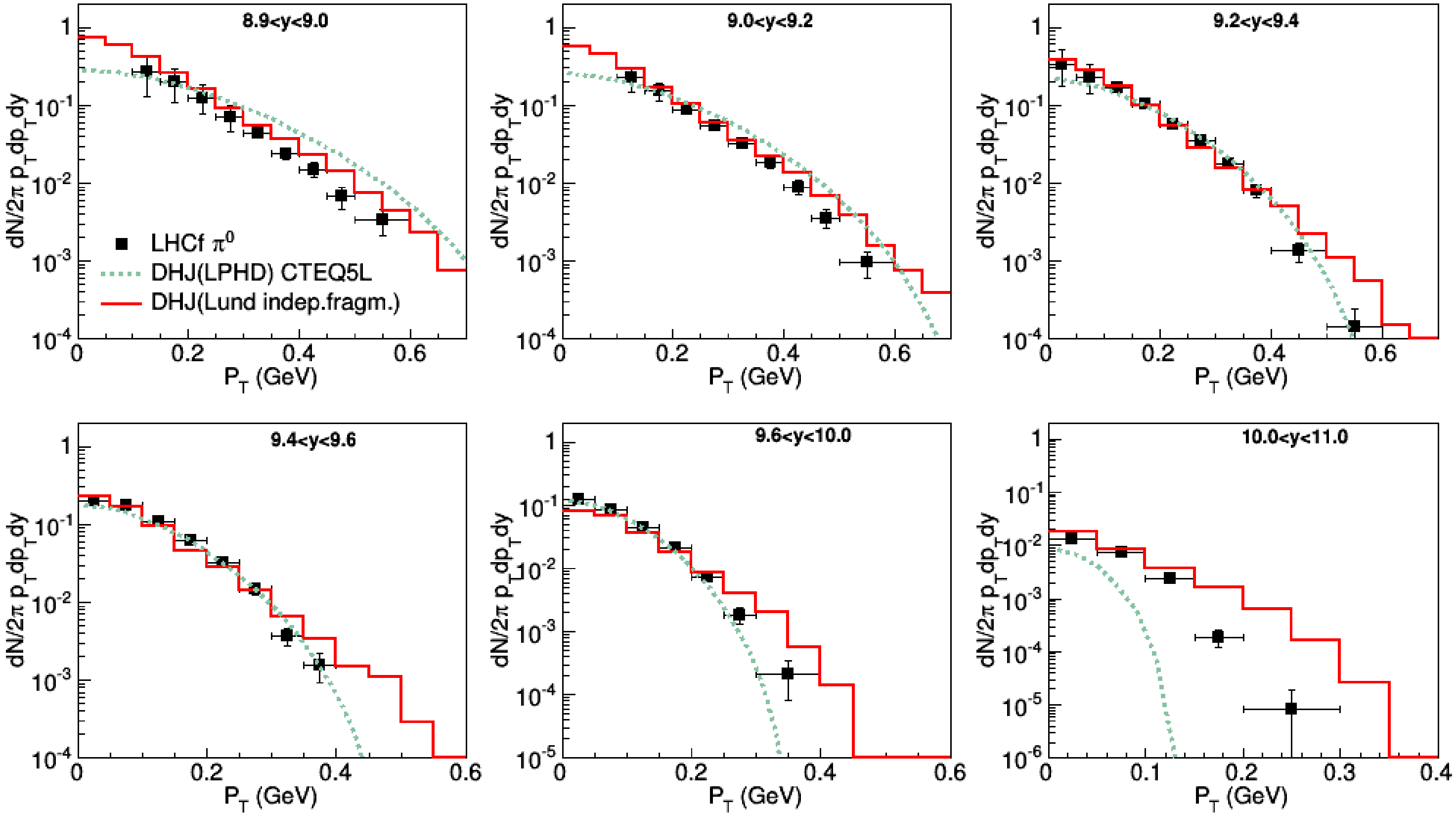
Forward neutral pion from LHCf

$x \approx 1 \times 10^{-7}$ O. Adriani et al. (LHCf Collaboration), Phys. Rev. D86,092001 (2012).



Gluon contribution? LHCf pp@7TeV

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

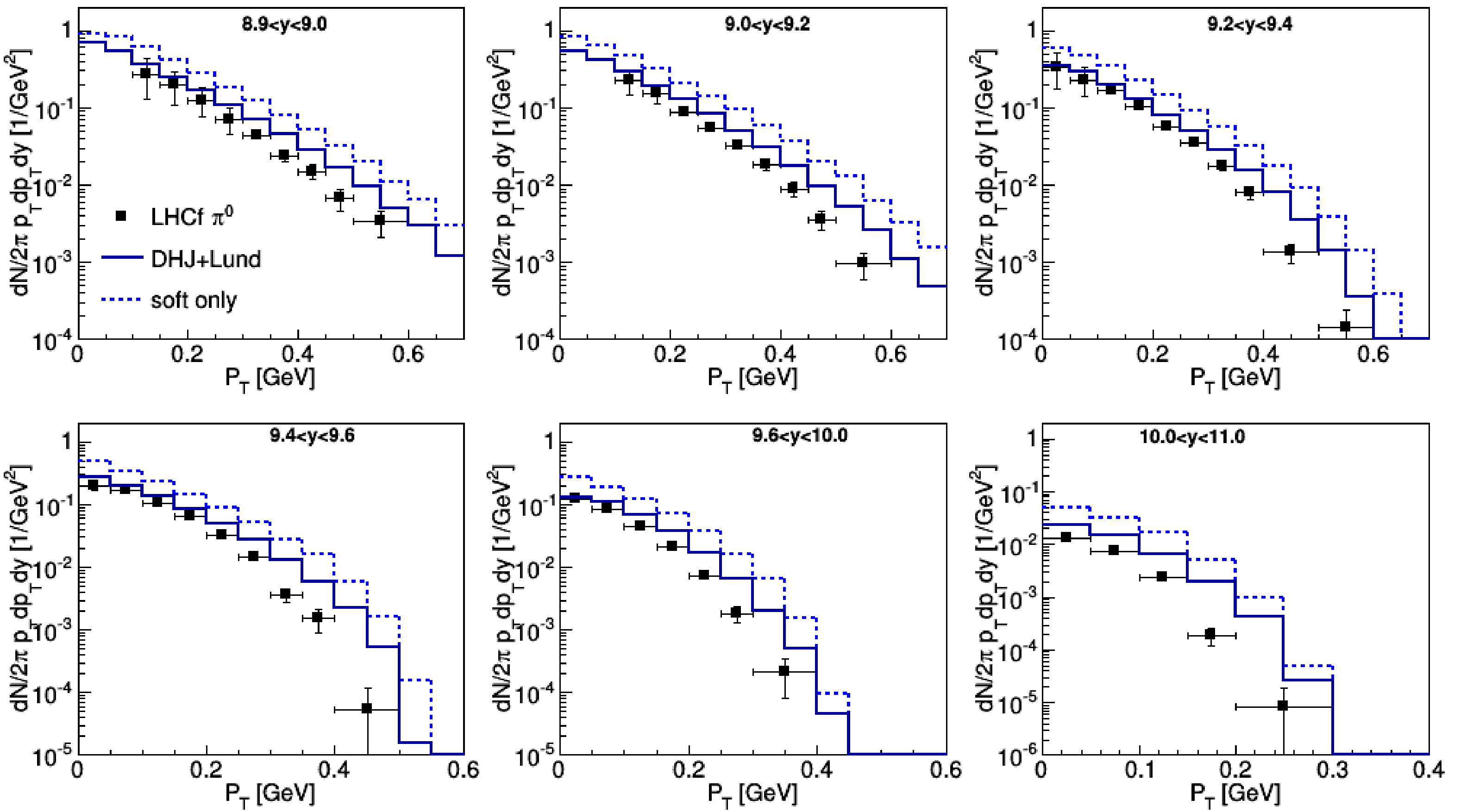


LPHD K=22

Indep K=2.5

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

W-T. Deng, et.al PRD91 (2015) 014006



summary

- Monte-Carlo Event Generator version of DHJ model has been 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
  - NLO
  - Initial state radiation due to x-evolution

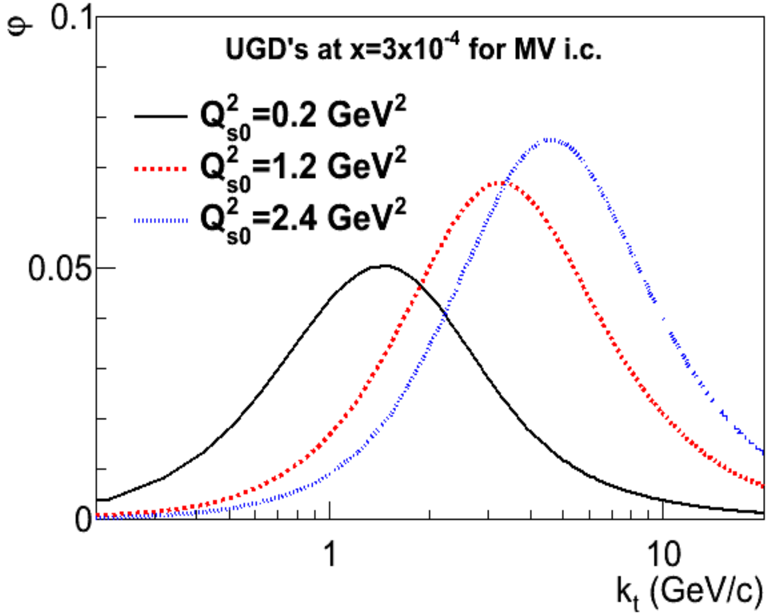
Unintegrated gluon distribution

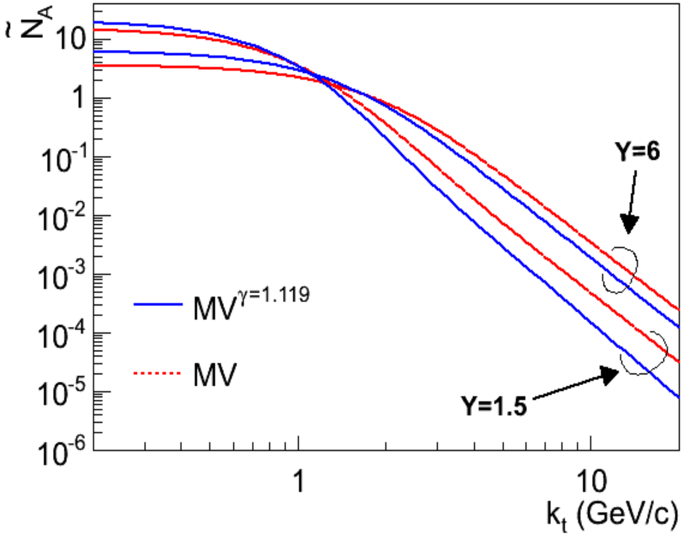
$$\mathcal{N}(r, Y=0) = 1 - \exp\left[-\frac{(r^2\, Q_{s0}^2)^\gamma}{4}\, \ln\left(\frac{1}{\Lambda\, r} + e\right)\right] \qquad \gamma = 1.119$$

$$Q_{s0}^2 = 0.168\, \mathrm{GeV}^2$$

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

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





Rapidity evolution

running coupling Balitsky-Kovchegov (rcBK) evolution

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

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

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

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

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

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))

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

1+1D Motion of relativistic string

$$H=\sqrt{p_1^2+m_1^2}+\sqrt{p_2^2+m_2^2}+\kappa|x_1-x_2|$$

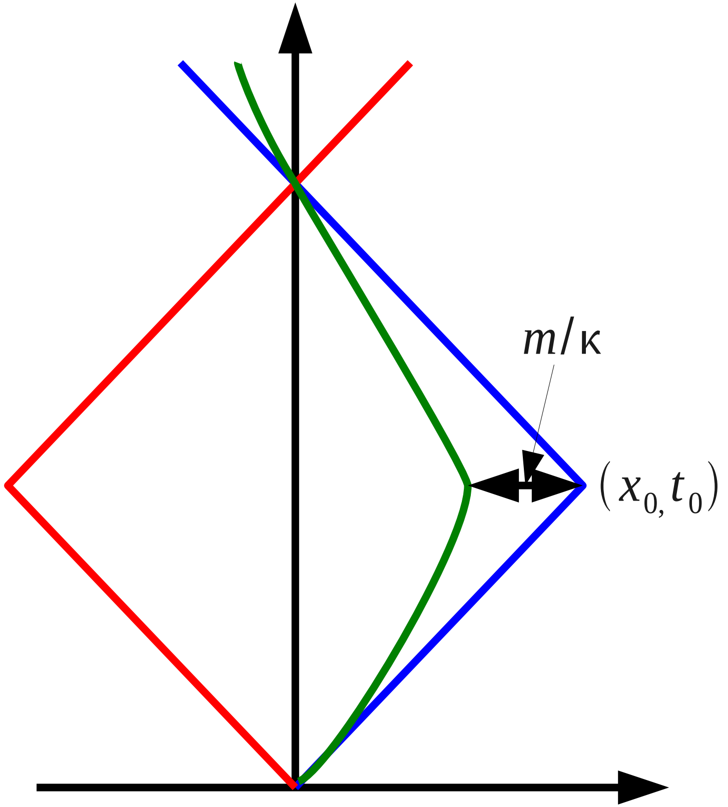
$$\frac{dx_i}{dt}=\frac{\partial H}{\partial p_i}=\frac{p_i}{E_i}, \qquad \frac{dp_i}{dt}=-\frac{\partial H}{\partial x_i}=\pm\kappa$$

Motion due to linear potential (Lorentz invariant)

$$p(t)=\kappa(t_0-t),\quad E(t)=\kappa(x_0-x)$$

$$m^2=E^2-p^2=\kappa^2[(x_0-x)^2-(t_0-t)^2]$$

Hyperbolic curve in space-time coordinate



yo-yo motion