Parton Cascade Simulation – Heavy Ion Collisions

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- **Congratulation to Prof. Shim**
- **I remember Prof. Shim is a senior professor who does not ask for to be a senior.**
- **Wish to come to talk & work together**

I. Introduction

- UrHIC at RHIC and LHC

stage 1 stage 2 stage 3 stage 4 stage 5

It is dream to understand these processes!

2. Quick Description of each process

- Possible dominant physics of each process

Stage 1: Parton distributions of nucleus

- Parton distribution of nucleon(p):
  - CTEQ: only proton
  - GRV : only proton
    - Neutron: u ↔ d of proton
  - EKS(include nucleon shadow effects)

  - Wood-Saxon or constant density for spacial distribution

  - Lorentz Boost and Contraction

- CGC: KNV(Krasnitz, Nara, Venugopalan) model

- For example, traditional model,

$$f_{i/A}(x, Q^2) = f_{i/N}(x, Q^2) R_A(x, Q^2),$$

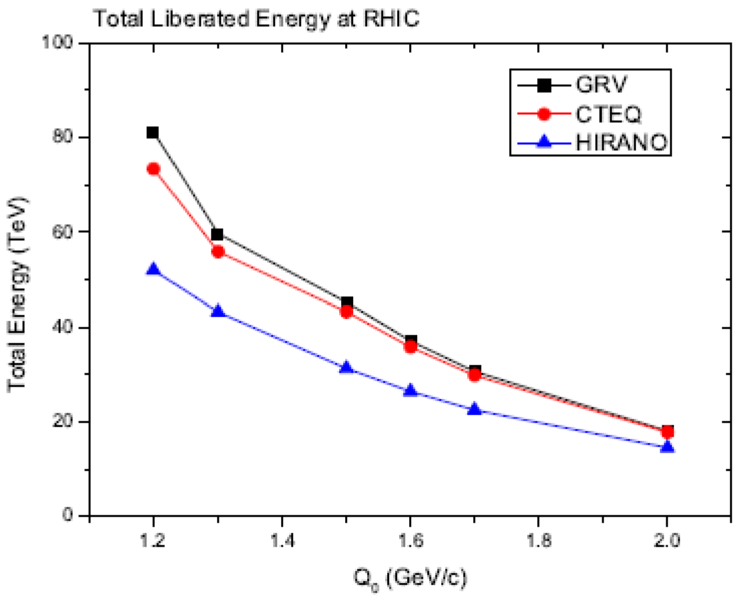
- or KNV model,

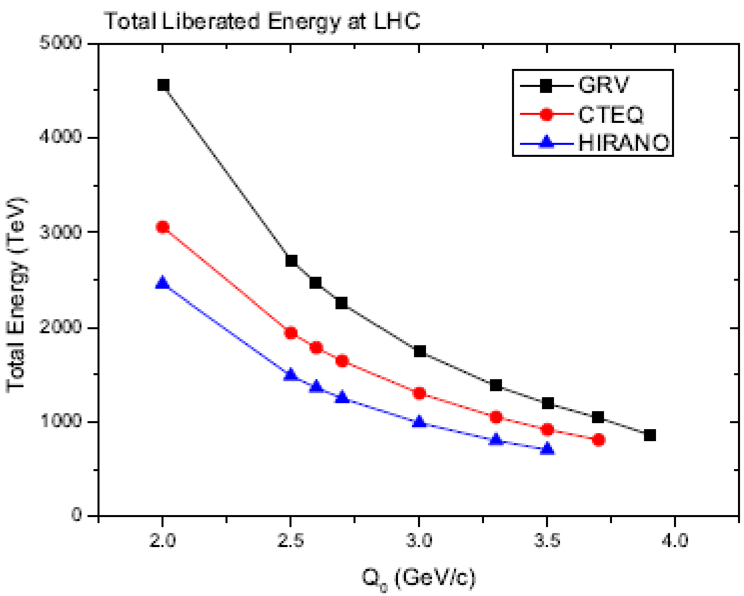
$$xG(x, Q^2) = A \log\left(\frac{Q^2 + \Lambda^2}{\Lambda_0^2}\right) x^{-\lambda} (1 - x)^n$$

$A = 0.3$, $\Lambda = \Lambda_0 = 0.2$, $n = 4$ and $\lambda = 0.2$.

Stage 2: Primary Collisions

$$\frac{dN^{jet}}{dp_T dy} = KT(b)\int dy_4 \frac{2\pi p_T}{\hat{s}} \sum_{ij,kl} x_1 f_{i/A}(x_1, p_T^2) x_2 f_{j/B}(x_2, p_T^2) \frac{1}{2} \frac{d\sigma^{ij\to kl}(\hat{s},\hat{t},\hat{u})}{d\hat{t}},$$





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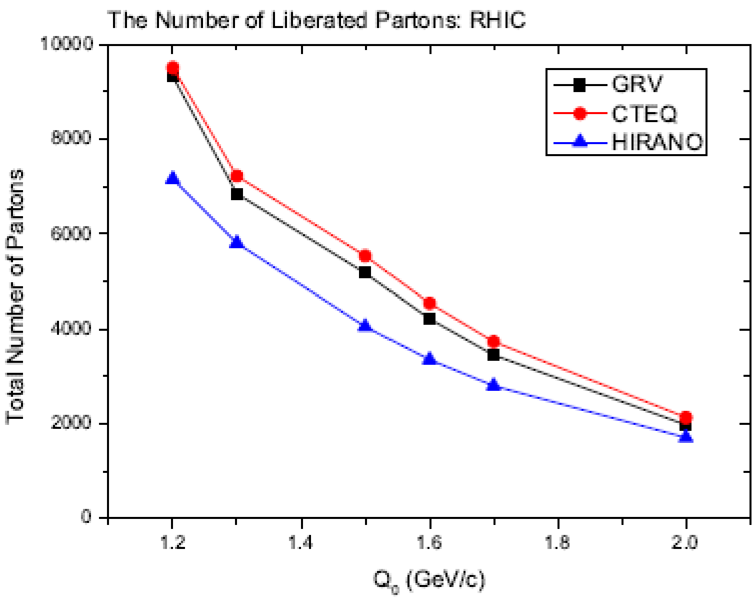

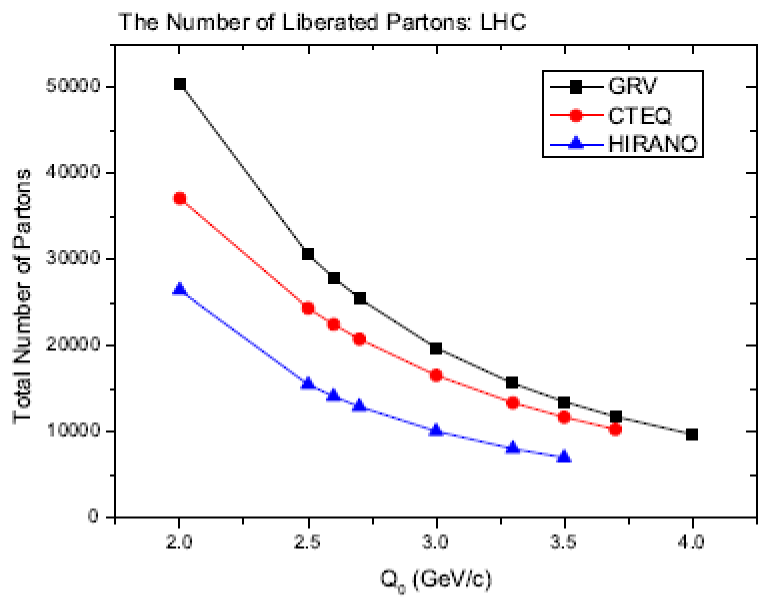

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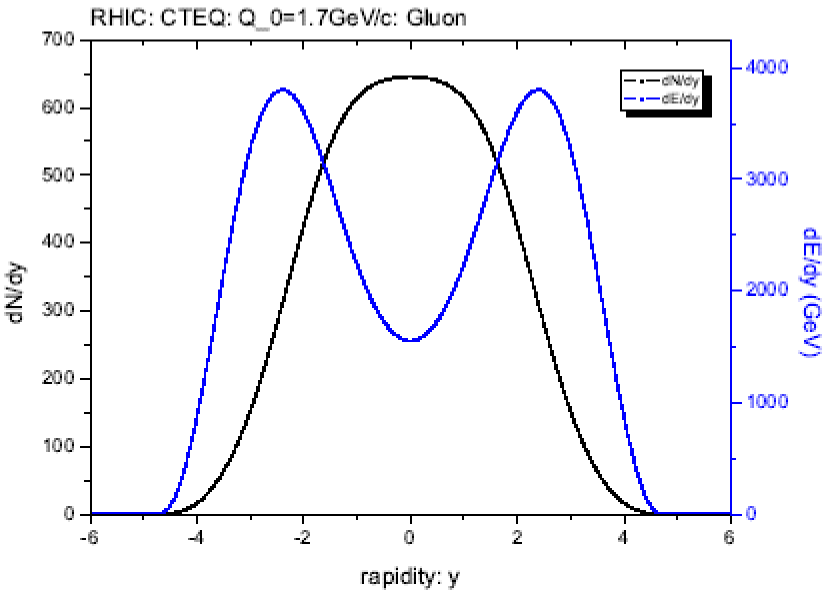

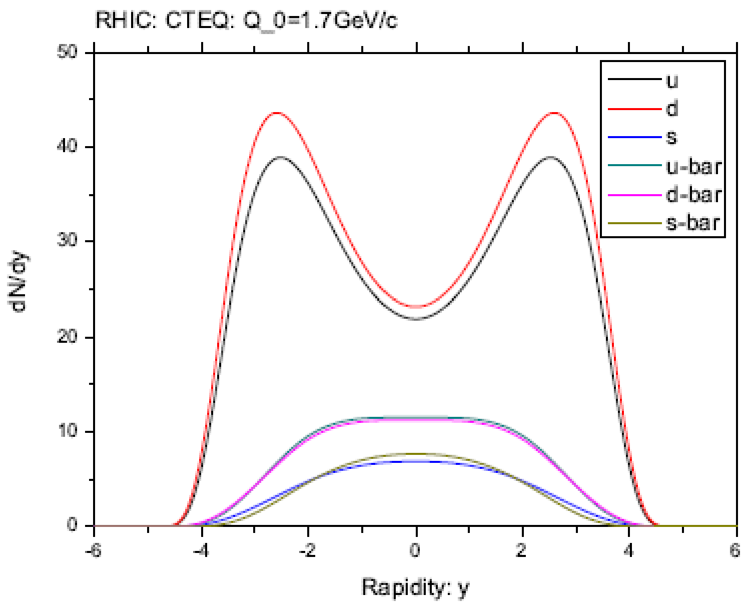

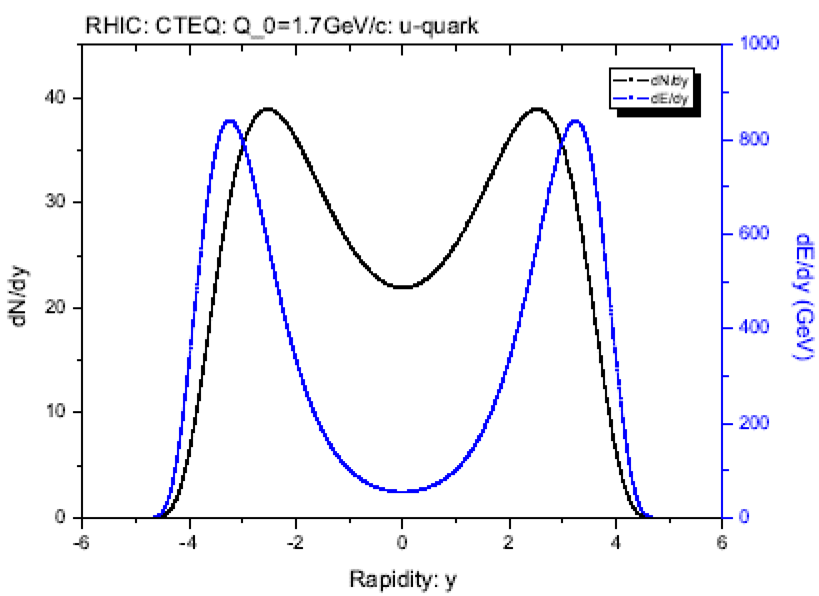

	RHIC: $Q_0 = 1.7$ GeV		LHC: $Q_0 = 3.5$ GeV	
parton	N	$\bar{E}$	N	$\bar{E}$
g	3062	7.01	10380	66.8
u	230	13.9	356	235.7
d	255	14.5	384	253.3
s	33	7.9	122	79.9
$\bar{u}$	62	8.1	170	90.2
$\bar{d}$	61	8.2	168	92.0

TABLE I: Initial distribution data: using CTEQ distribution function.

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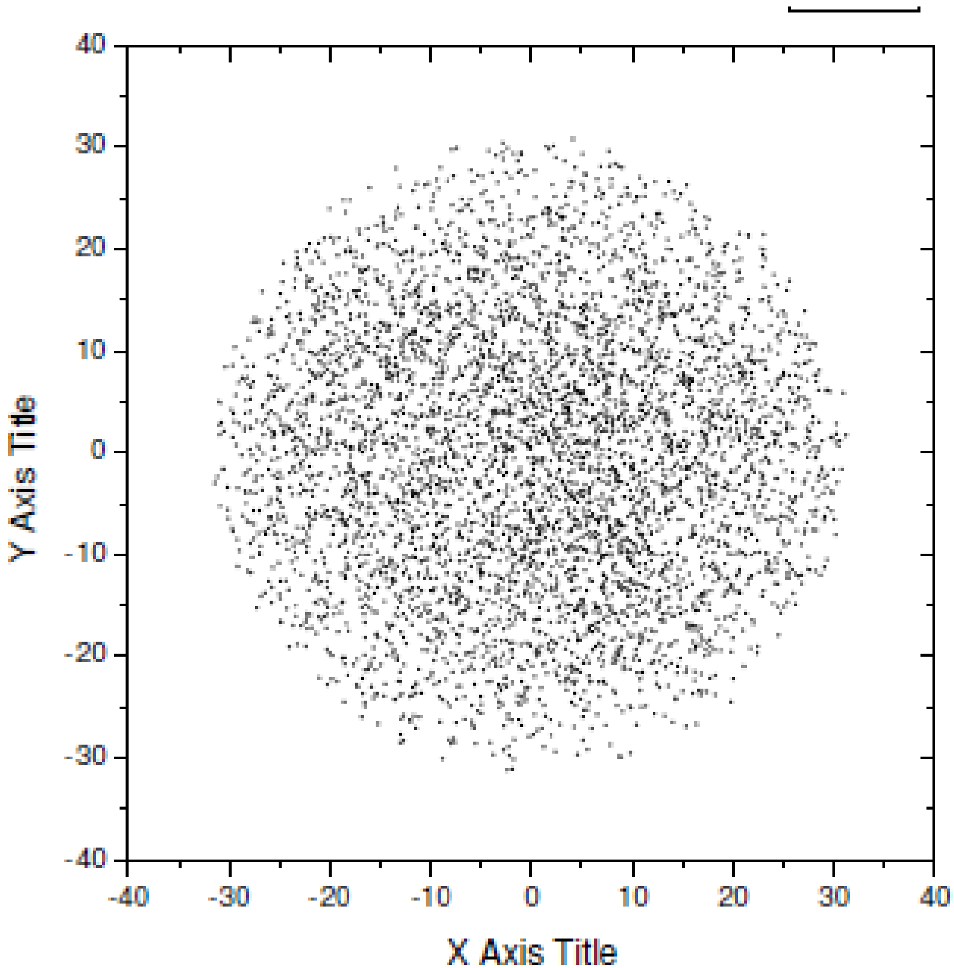


Stage 3: Secondary Collisions & QGP

- Picture 1: Assume ON-SHELL particles

$$\frac{d\sigma^{gg\to gg}}{dt} = \frac{9\pi\alpha_s^2}{2s^2}(3 - \frac{tu}{s^2} - \frac{su}{t^2} - \frac{st}{u^2})$$

$$\frac{d\sigma^{gg\to q_a\bar{q}_b}}{dt} = \frac{\pi\alpha_s^2}{6s^2}\delta_{ab}(\frac{u}{t} + \frac{t}{u} - \frac{9}{4}\frac{t^2+u^2}{s^2})$$

$$\frac{d\sigma^{gq\to gq}}{dt} = \frac{4\pi\alpha_s^2}{9s^2}(-\frac{u}{s} - \frac{s}{u} + \frac{9}{4}\frac{s^2+u^2}{t^2})$$

$$\begin{aligned}\frac{d\sigma^{q_a q_b\to q_a q_b}}{dt} &= \frac{4\pi\alpha_s^2}{9s^2}[\frac{s^2+u^2}{t^2} \\ &\quad +\delta_{ab}(\frac{t^2+s^2}{u^2} - \frac{2}{3}\frac{s^2}{ut})]\end{aligned}$$

$$\begin{aligned}\frac{d\sigma^{q_a\bar{q}_b\to q_c\bar{q}_d}}{dt} &= \frac{4\pi\alpha_s^2}{9s^2}[\delta_{ac}\delta_{bd}\frac{s^2+u^2}{t^2} \\ &\quad +\delta_{ab}\delta_{cd}\frac{t^2+u^2}{s^2} - \delta_{abcd}\frac{2}{3}\frac{u^2}{st}]\end{aligned}$$

$$\frac{d\sigma^{q_a\bar{q}_b\to gg}}{dt} = \frac{32\pi\alpha_s^2}{27s^2}\delta_{ab}[\frac{u}{t} + \frac{t}{u} - \frac{9}{4}\frac{t^2+u^2}{s^2}]$$

$$\begin{aligned}\frac{d\sigma^{g\bar{q}\to g\bar{q}}}{dt} &= \frac{d\sigma^{gq\to gq}}{dt}, \\ \frac{d\sigma^{\bar{q}\bar{q}\to\bar{q}\bar{q}}}{dt} &= \frac{d\sigma^{qq\to qq}}{dt}.\end{aligned}$$

- Gluon radiation included (based on pQCD):

$$\frac{d\sigma^{gg\rightarrow ggg}}{dq_\perp^2\,dy\,dk_\perp^2} = \frac{9C_A\alpha_s^3}{2}\frac{q_\perp^2}{(q_\perp^2+\mu_D^2)^2}\cdot \frac{\Theta(k_\perp\lambda_f-\cosh y)\Theta(\sqrt{s}-k_\perp\cosh y)}{k_\perp^2\sqrt{(k_\perp^2+q_\perp^2+\mu_D^2)^2-4k_\perp^2 q_\perp^2}}$$

- Picture 2: Bremsstrahlung
  - Primary partons have high virtuality
  - The branching reduce the virtuality until the limited mass via pQCD
  - Cons: elliptic flow cannot explained

Real world: Off-shell partons will make collisions as well as branchings

- Once thermalized, we can follow the evolution using:
  - Hydrodynamic Expansion:
    - 3+1 D Hydro developed by Jeon and Schenke
    - Nonaka et al
  - Boltzmann-like expansion:
    - Many groups working on: ZPC, VNI, …

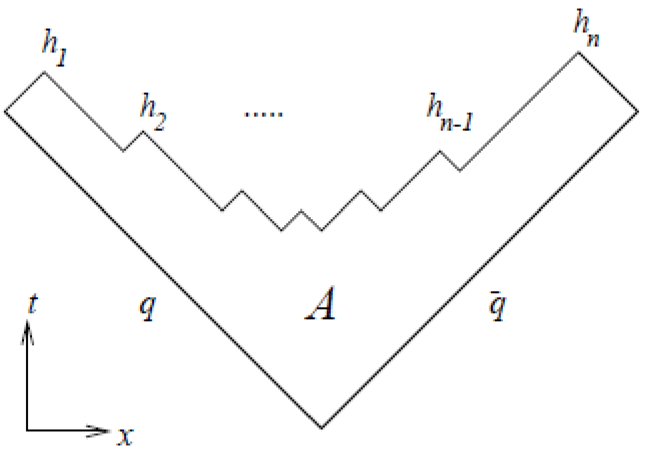
Stage 4: Hadronization:

- Model 1: Independent Fragmentation Model (Field-Feynman Model)
  - Consider e+ e- → γ* → hX
  - γ* → q q-bar
    - q → q' + M(q q'-bar), where M is a meson
    - q-bar →q-bar' + M(q' q-bar)
  - g→q q_bar and one of them has all the energy and monentum
  - further hadron production
  - Pros: explains reasonably the experiments
  - Cons: energy & momentum non-conservation; need color & flavor neutralization; Distinguishable with collinear jets

- Model 2: String Model (PYTHIA,..)
  - LUND model
  - UCLA model

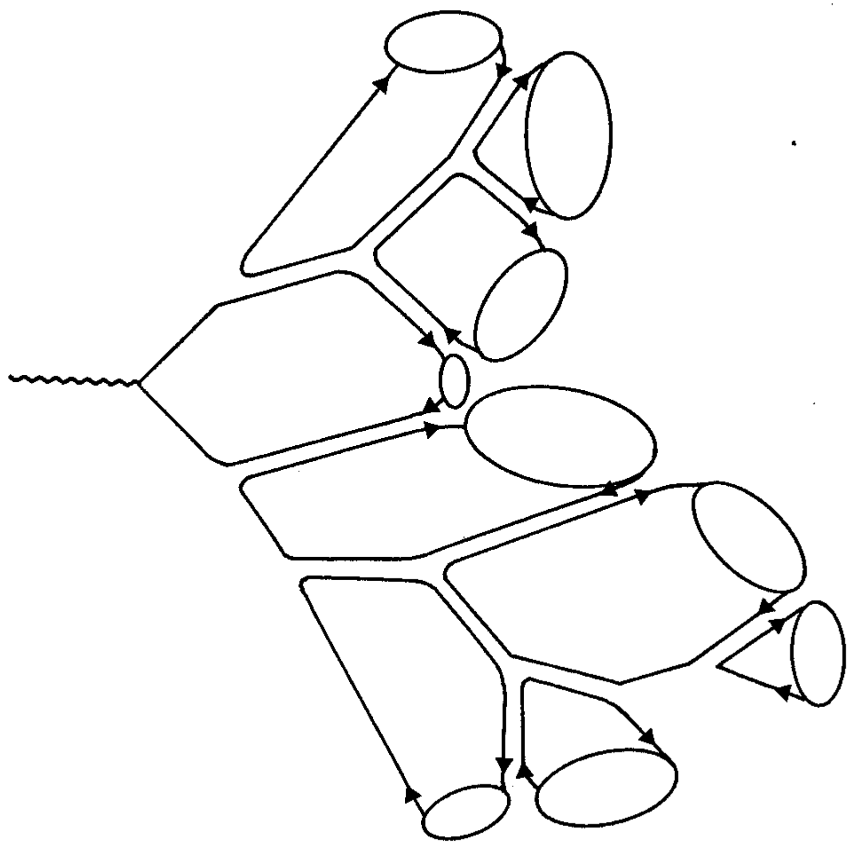
  - String breaks up into hadron-sized piece through spontaneous q q-bar pair production
  - If there is a gluon, = kink on the string to produce angular distribution
  - Pros: more consistent and covariant picture
  - Cons: for multi-parton system, there is ambiguity to connect string among them and kinks

One example of string model:

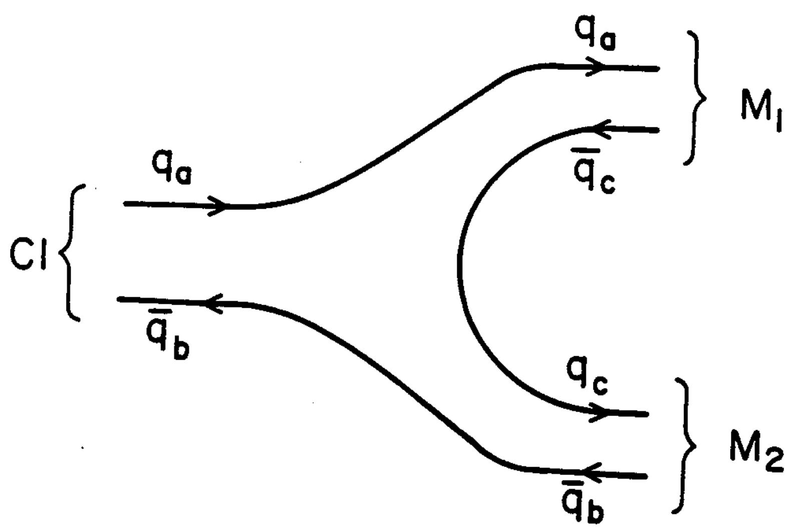


- Model 3: Cluster Model(HERWIG, …)
  - Field-Wolfram, Weber-Marchesini, Gottschalk
  - Initial partons will Bremsstrahlung or branching until some perturbative cutoff Q_0(~ 1 GeV)
  - All the gluon will split into q q_bar by force
  - Non-perturbative set in, and combine neighboring quarks and antiquarks to produce colorless preconfinement clusters
  - Each cluster decay into hadrons (usually 2)

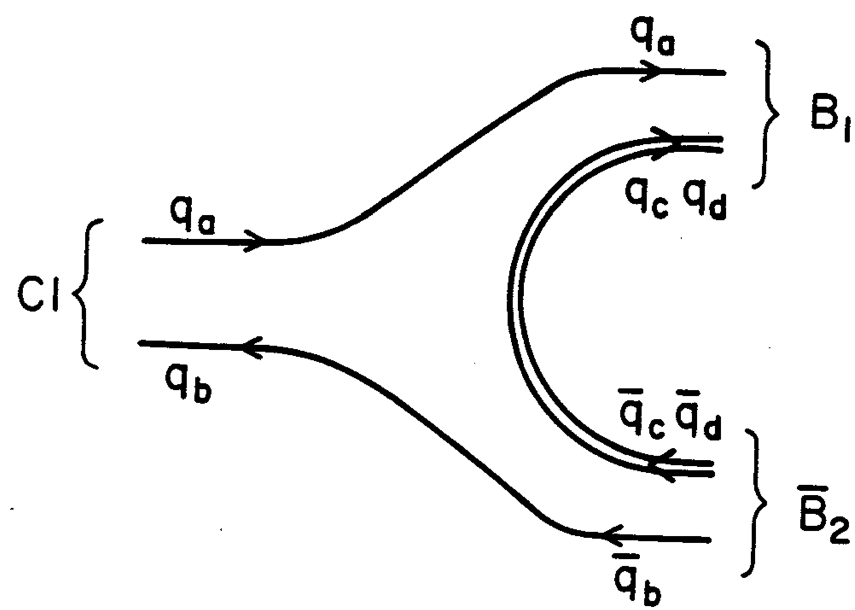
One example of Cluster model:



MESON PRODUCTION



BARYON PRODUCTION



- Possible Model: in our study
  - Partons will make collision and radiation ($gg \rightarrow ggg$)
  - At the end of pQCD, gluons will split into q q-bar by force
  - Colorless clusters (q q-bar, qqq) will be formed; if the mass (energy) is too large, it can make further cluster decay ($Cl1 \rightarrow Cl2 + Cl3$)
  - Each cluster will decay into two hadrons just like excited resonance of same quark constituents

Stage 5: Hadron Expansion

- UrQMD is good
- But the free flow may be enough

3. Final Comments

- Need systematic studies with all the possible parameters and models
- Compare the experiments to fix parameters and models
- Hopely understand the non-perturbative phenomena
- And study the exotic quantum state (QGP)