微視的輸送模型:***JAM***

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高エネルギー重イオン衝突におけるハドロンカスケード模型

モデルの説明: インプット (ハドロン散乱レベルでの素過程)

Resonance production,string, hard scattering

応用例

まとめ

セミナー J-PARC Tokai , Aug. 7 2013

開発動機

Microscopic transport models for nuclear collisions at intermediate energies

1988 BUU (PR160, Bertsch,Gupta)
1990 BUU (PR188, Giessen)
1991 QMD (PR202, Aichelin)
1993 RBUU (RPP56,Giessen)

JAPAN (Kyoto Horiuch group)
1990 VUU (A.Ohnishi)
1990 QMD (T. Maruyama)
1992 AMD (A.Ono)
1995 QMD (Niita)

Monte-Carlo event generator for high energy hadronic collisions

PYTHIA (Lund model)
HERWIG
VENUS

FRITIOF
QGSM
RQMD, UrQMD

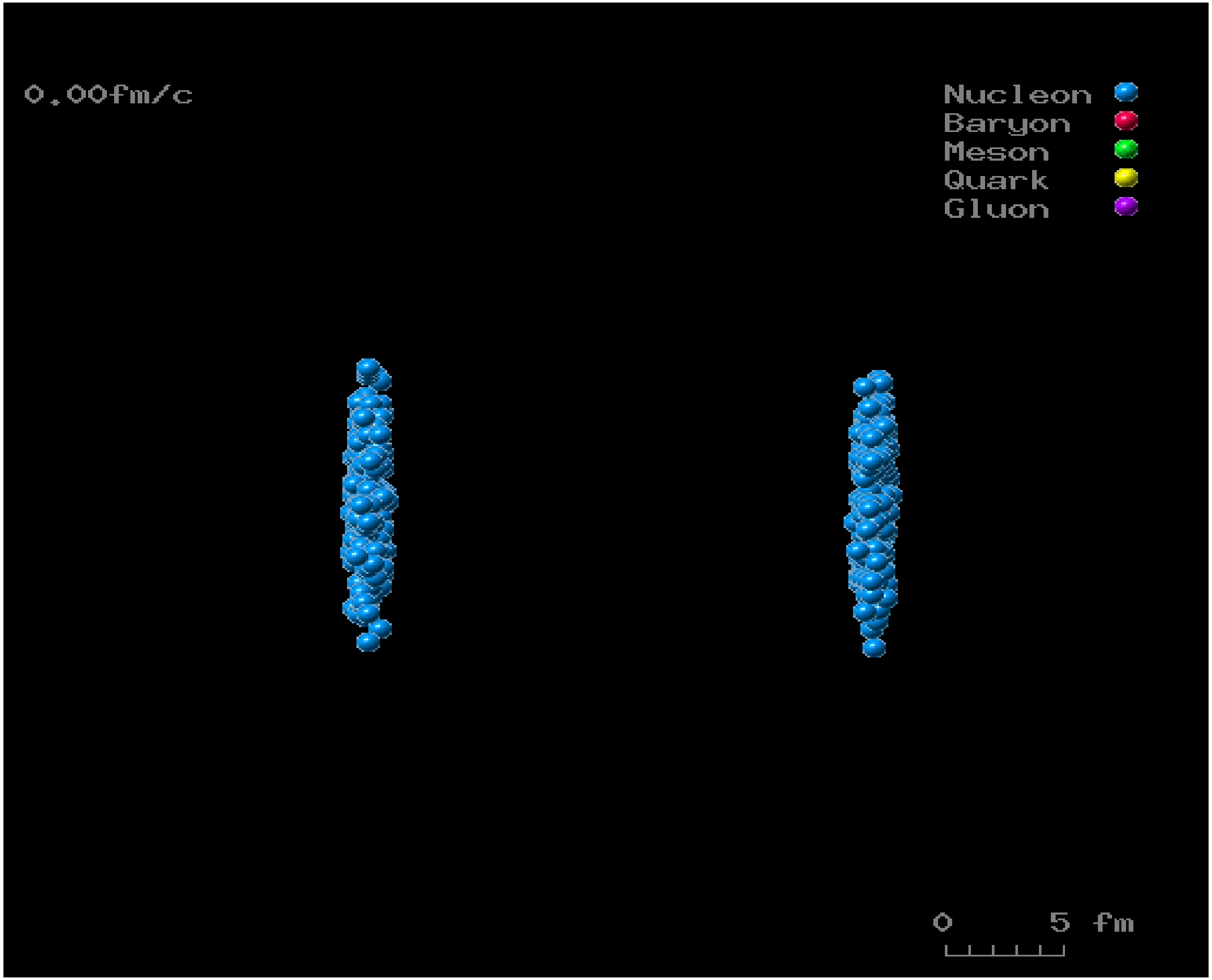
HIJING

1996-2000 JAMを開発 (主に原研のポスドク時代)

High energy heavy ion collision

Pb+Pb collision at E=200 AGeV

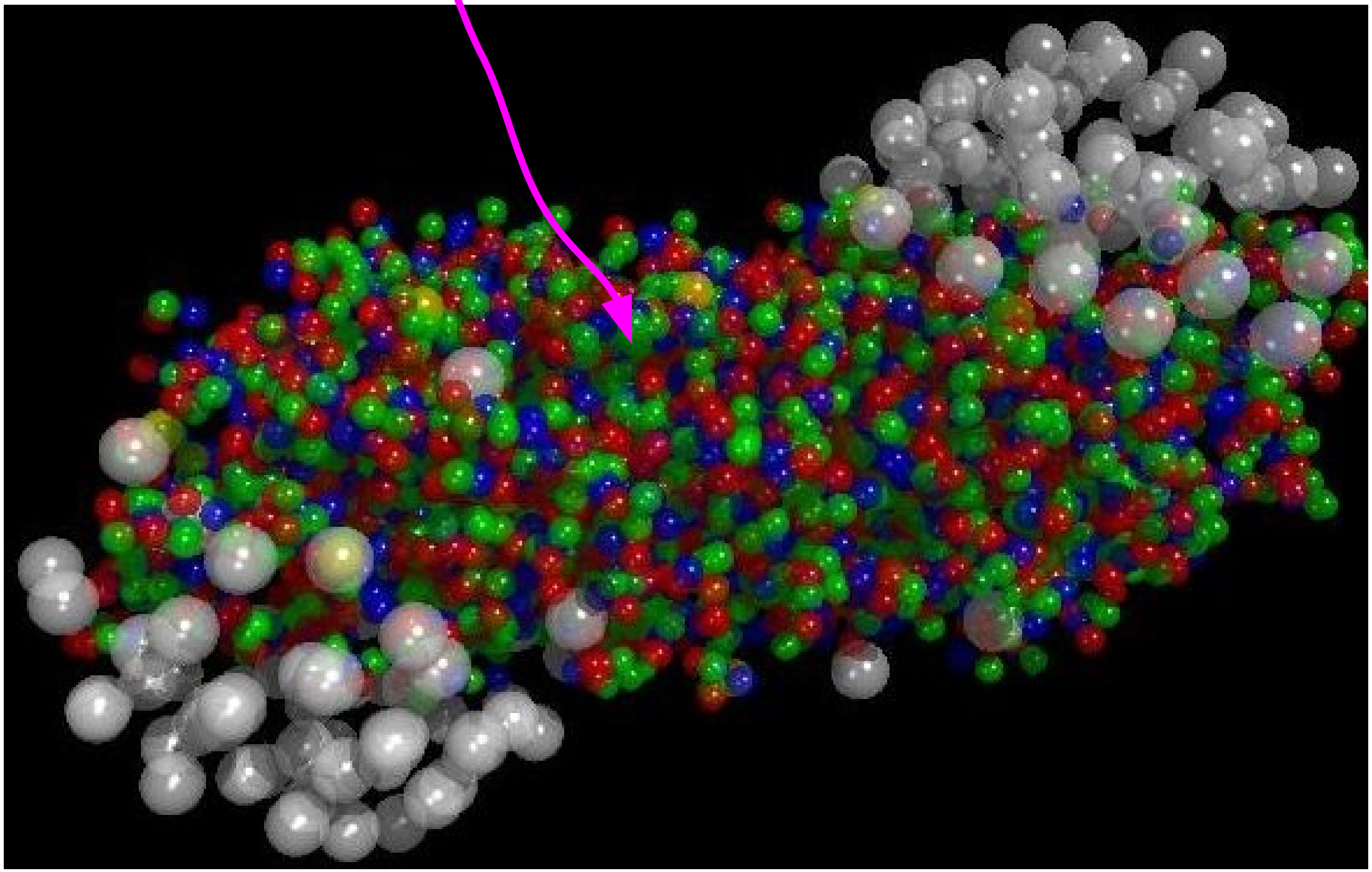
Animation from Hdronic Cascade model JAM



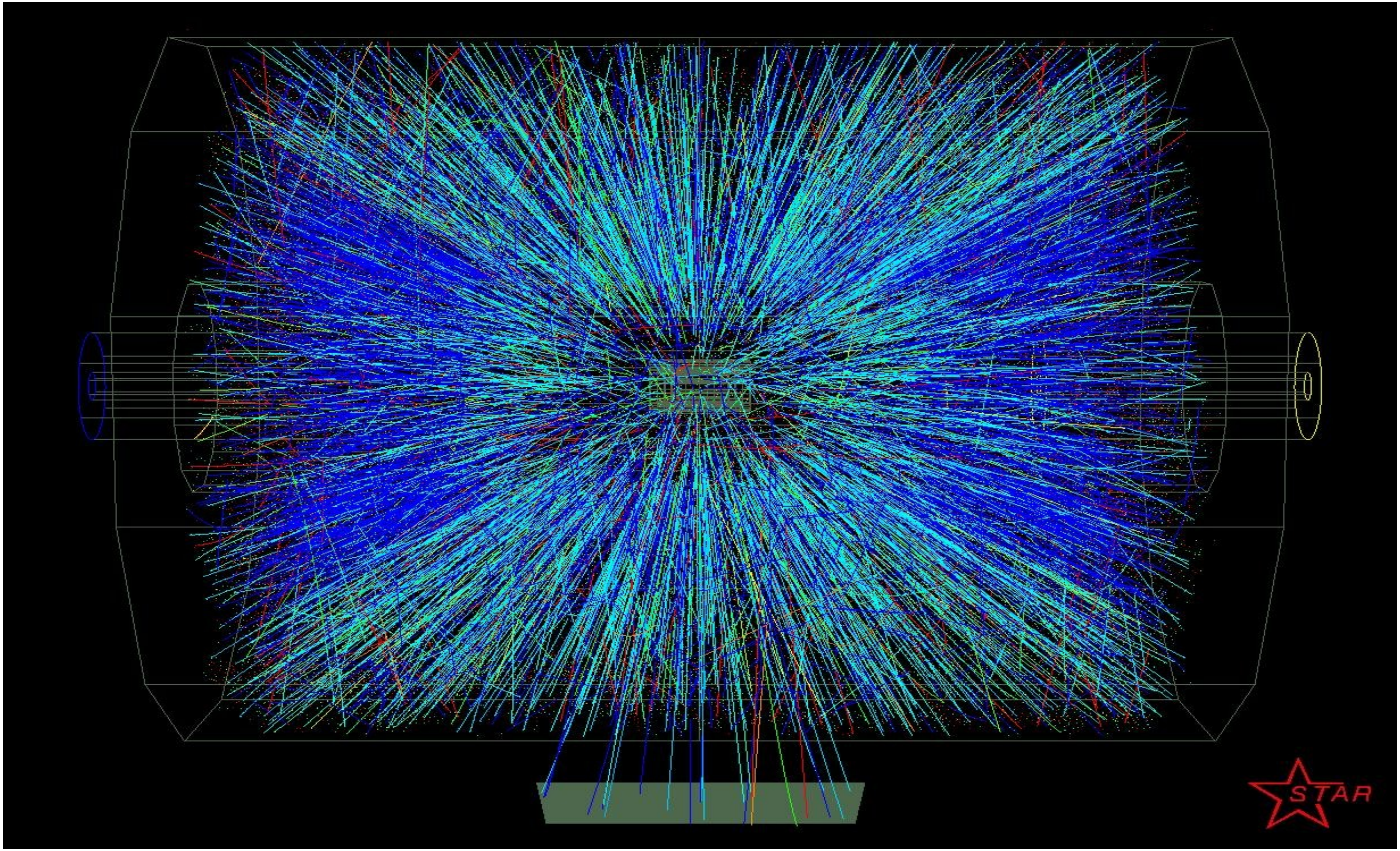
After the collision, matter looks like this.

UrQMD simulation

Hot and dense matter created!



Gold beam-beam collision event at RHIC experiment



Hadronic transport models

OSCAR (Open Standard Codes and Routines)

http://karman.physics.purdue.edu/OSCAR/index.php/Main_Page

RQMD
UrQMD Frankfurt group: http://th.physik.uni-frankfurt.de/~urqmd/

GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck project
http://gibuu.physik.uni-giessen.de/GiBUU/

JAM http://quark.phy.bnl.gov/~ynara/jam/
http://www.aiu.ac.jp/~ynara/jam

Y.Nara, N.Otuka, A.Ohnishi, K.Niita and S.Chiba, Phys. Rev. C61, 024901 (2000)
T. Hirano and Y. Nara PTEP 2012 (2012)01A203

Applications of hadronic cascade model

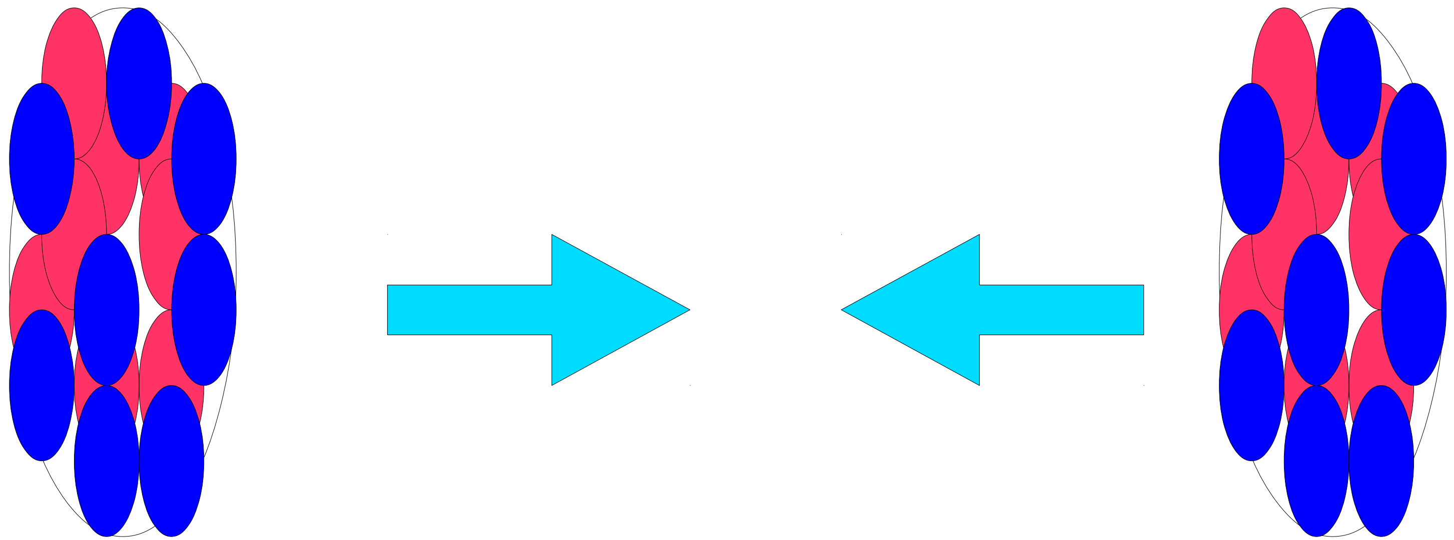
hadron-nucleus collisions (proton, pion, kaon,....)
Nucleus-nucleus collisions
Gamma-nucleus collisions

Hydrodynamics + hadron cascade
Parton cascade + hadron cascade
GIANT4
Air shower model of cosmic ray

Hadron cascade の簡単な説明

Initial state (before collision): Nucleons are sampled according to Woods-Saxon distribution, momentum of each nucleon is sampled by Fermi momentum,

boost two nucleus according to the corresponding incident energy.

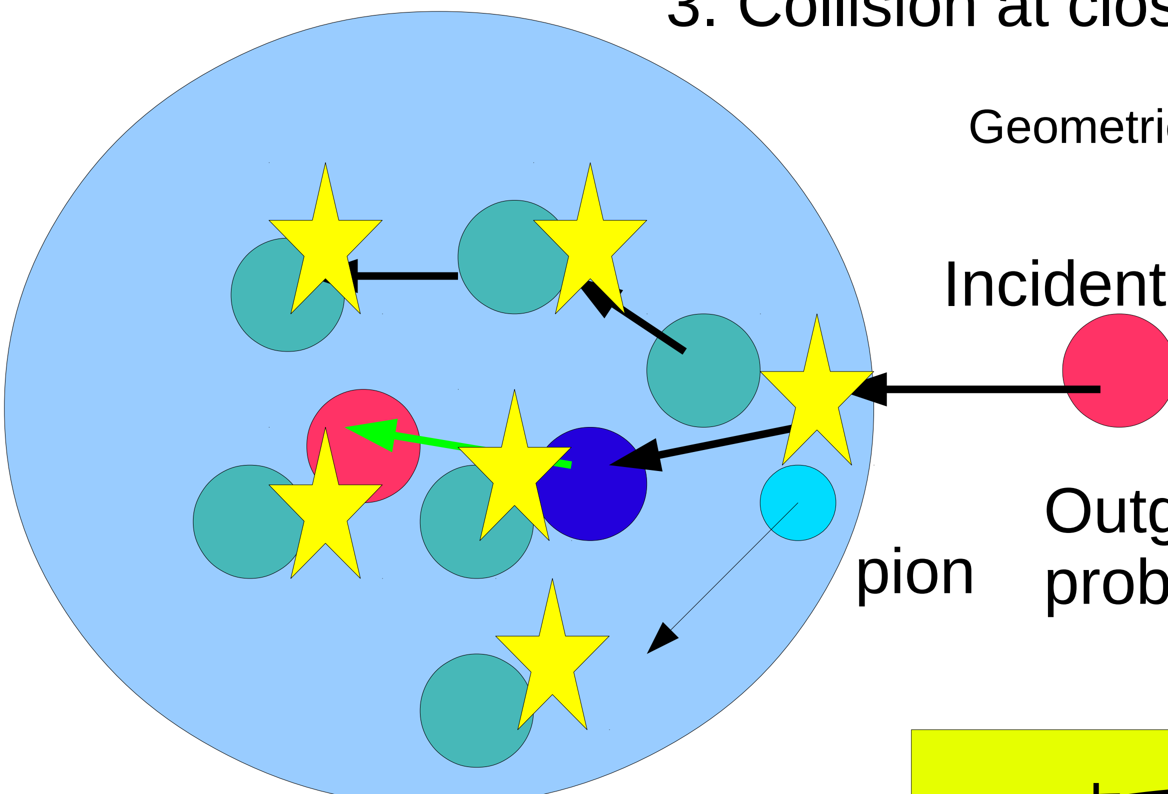


ハドロン-ハドロン散乱の インコヒーレントな重ね合わせ

2. Straight line trajectories until particles interact

3. Collision at closest approach $d < \sqrt{\sigma_{tot}/\pi}$

Geometrical interpretation of cross section



Outgoing channel selection:
prob. of elastic = $\frac{\sigma_{el}}{\sigma_{tot}}$

すてべの可能な素過程
粒子発生の時空発展

Closest distance approach

$$b \leq \sqrt{\frac{\sigma(\sqrt{s})}{\pi}}$$

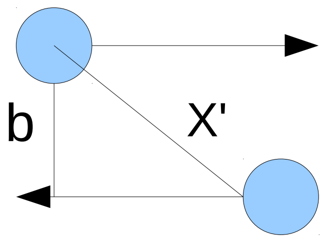
Closest distance between two colliding particles is defined by

$$b^2 = -x^2 + \frac{(P \cdot x)^2}{P^2} + \frac{(q \cdot x)^2}{q^2}$$

$$x = x_1 - x_2 = (t_1 - t_2, \vec{x}_1 - \vec{x}_2), \quad p = p_1 - p_2 = (E_1 - E_2, \vec{p}_1 - \vec{p}_2),$$

$$P = p_1 + p_2 = (E_1 + E_2, \vec{p}_1 + \vec{p}_2), \quad q = p - \frac{P \cdot p}{P^2} P$$

$$\vec{x}'^2 = -x^2 + \frac{(P \cdot x)^2}{P^2} \qquad -\frac{(\vec{x}' \cdot \vec{p}')^2}{\vec{p}'^2} = \frac{(q \cdot x)^2}{q^2}$$



$$b^2 = \vec{x}'^2 - \frac{(\vec{x}' \cdot \vec{p}')^2}{\vec{p}'^2}$$

$$(x_1' - x_2') \cdot (p_1' - p_2') = 0$$

Collision time

$$x_1' = x_1 + \frac{P \cdot (x_c - x_1)}{P \cdot p_1} p_1, \quad x_2' = x_2 + \frac{P \cdot (x_c - x_2)}{P \cdot p_2} p_2$$

Using the condition $(x_1' - x_2') \cdot (p_1 - p_2) = 0$, one can get the collision times:

$$\frac{P \cdot (x_c - x_1)}{P \cdot p_1} = \frac{(P \cdot x)(p_2 \cdot p) - (p \cdot x)(P \cdot p_2)}{(p \cdot p_1)(P \cdot p_2) - (p \cdot p_2)(P \cdot p_1)},$$

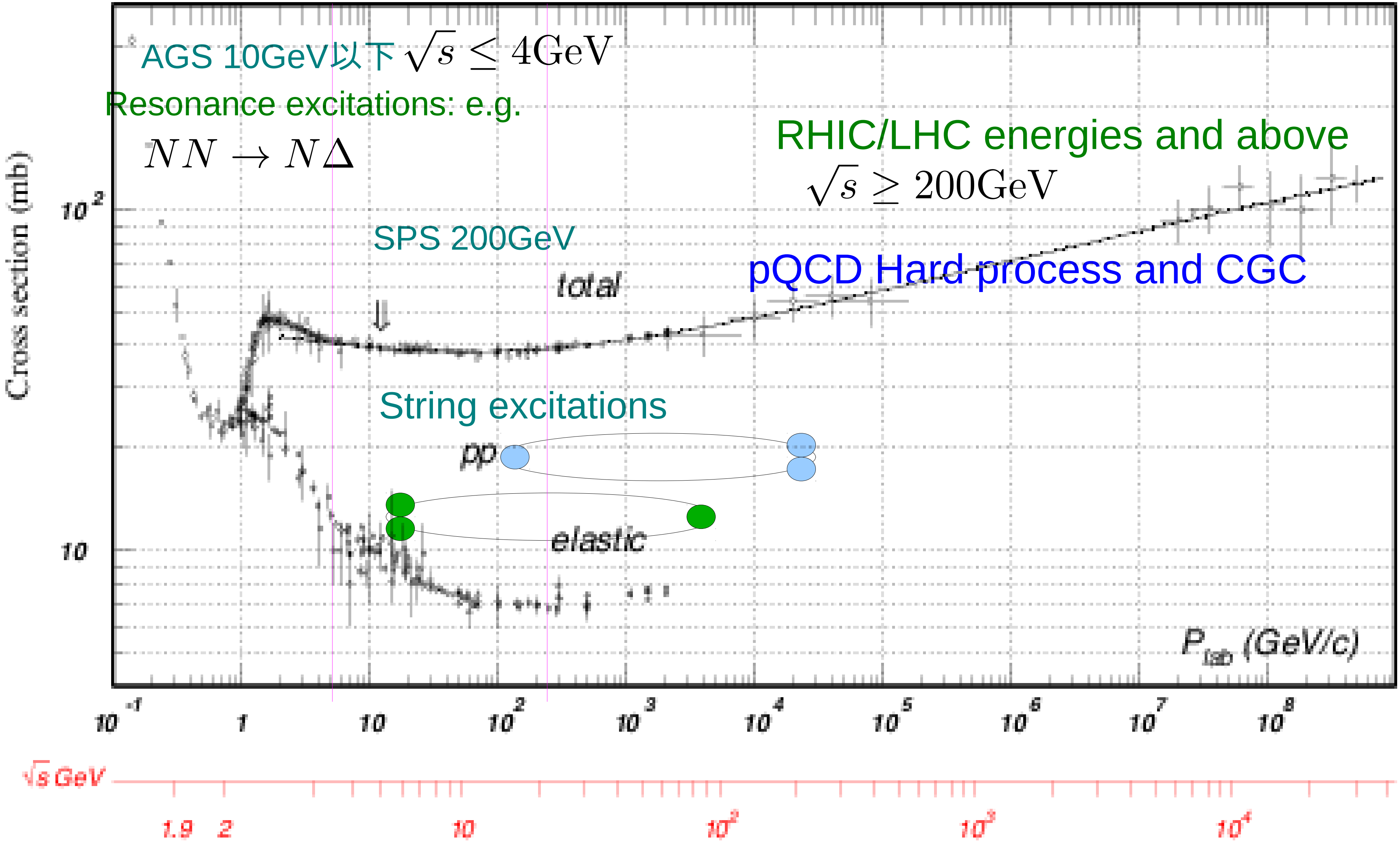
$$\frac{P \cdot (x_c - x_2)}{P \cdot p_2} = \frac{(P \cdot x)(p_1 \cdot p) - (p \cdot x)(P \cdot p_1)}{(p \cdot p_1)(P \cdot p_2) - (p \cdot p_2)(P \cdot p_1)}.$$

$$t_{c1} = t_1 + \frac{p_2^2 (x \cdot p_1) - (p_1 \cdot p_2)(x \cdot p_2)}{(p_1 p_2)^2 - p_1^2 p_2^2} E_1,$$

$$t_{c2} = t_2 - \frac{p_1^2 (x \cdot p_2) - (p_1 \cdot p_2)(x \cdot p_1)}{(p_1 p_2)^2 - p_1^2 p_2^2} E_2.$$

The two collision times are in general different in the lab. Frame.

Physics of elementary processes



Hadronic Cross sections in JAM

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{ch}(s) + \sigma_{ann}(s)$$
$$+ \sigma_{t-R}(s) + \sigma_{s-R}(s) \quad : \text{Resonance}$$
$$+ \sigma_{t-S}(s) + \sigma_{s-S}(s) \quad : \text{String}$$

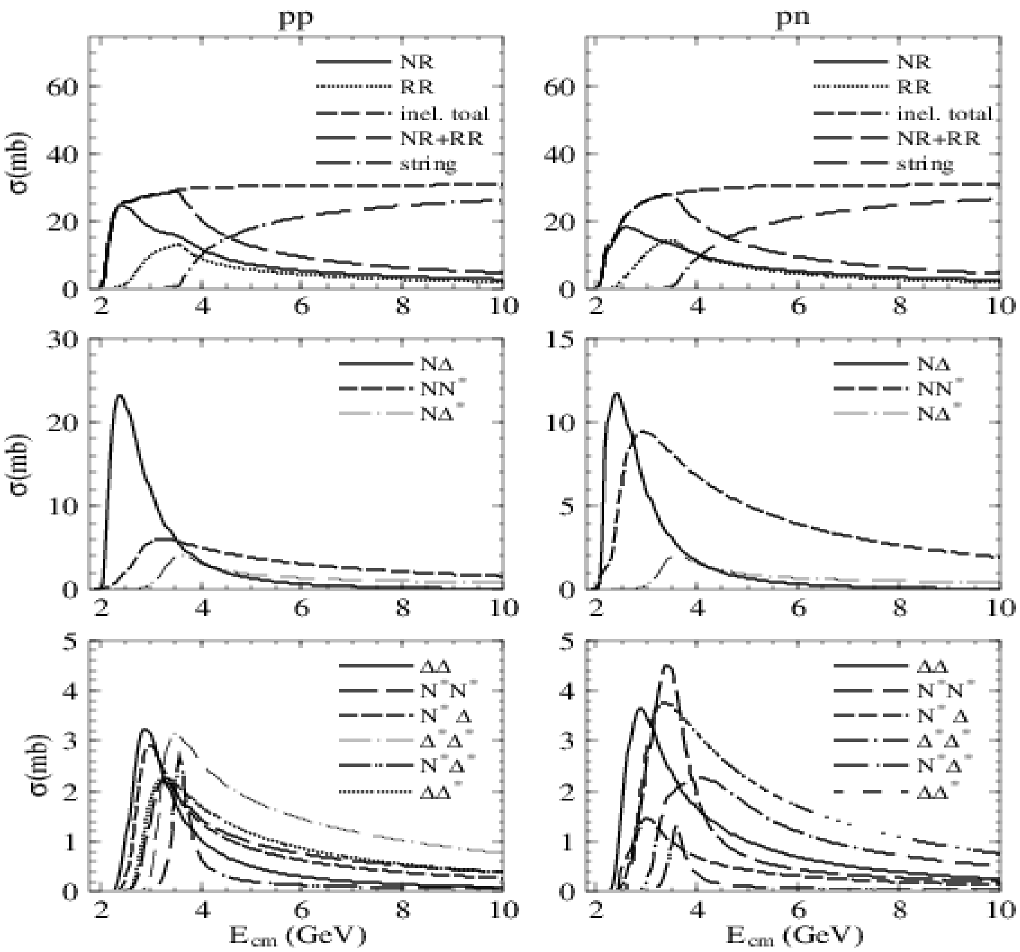
Resonance production (absorption)

$$\sigma_{t-R}(s) : NN \leftrightarrow N\Delta, \quad NN \leftrightarrow N^*\Delta^*, \cdots$$
$$\sigma_{s-R}(s) : \pi N \leftrightarrow \Delta, \quad \bar{K}N \leftrightarrow Y^*, \cdots$$

String formation

$$\sigma_{t-S}(s) : hh \to \text{String} + \text{String}, \quad hh \to \text{string} + h$$
$$\sigma_{s-S}(s) : \pi N \to \text{String}$$

Parametrization of the Resonance productions in pp

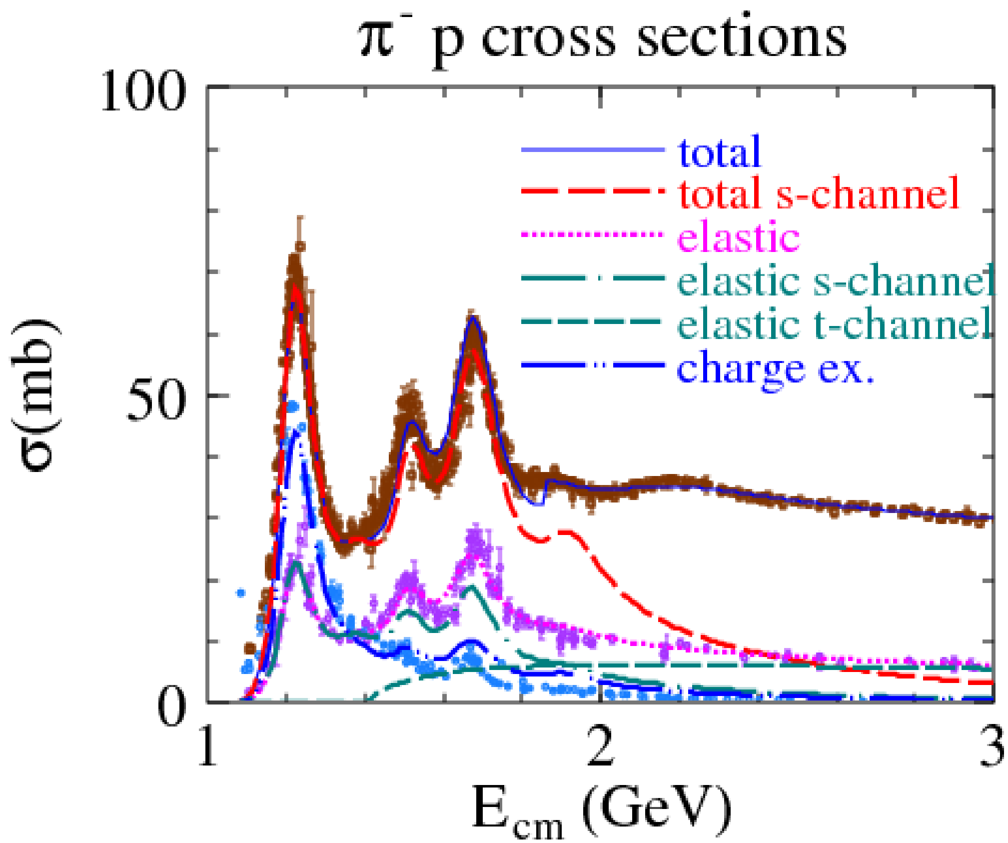


$$\sigma(\sqrt{s}) = \frac{\mathrm{a}(\sqrt{s}/\sqrt{s}_{th} - 1)^{\mathrm{b}}\mathrm{d}}{(\sqrt{s}/\mathrm{c} - 1)^2 + \mathrm{d}^2}$$

$NN \to \pi d$ process is treated as Δ production.

$$\sigma_1(NN \to N\Delta(1232)) = \frac{0.0052840\sqrt{/2.0139999 - 1}}{(-2.11477)^2 + 0.0171405^2} + \frac{28.0401(/2.124 - 1)^{0.480085}}{((/2.06672) - 1)^2 + 0.576422^2}$$

Modeling low energy π-p cross sections



S-channel inelastic:
pi-p -> resonance (or string)

T-channel inelastic:
pi-p -> resonance + resonance

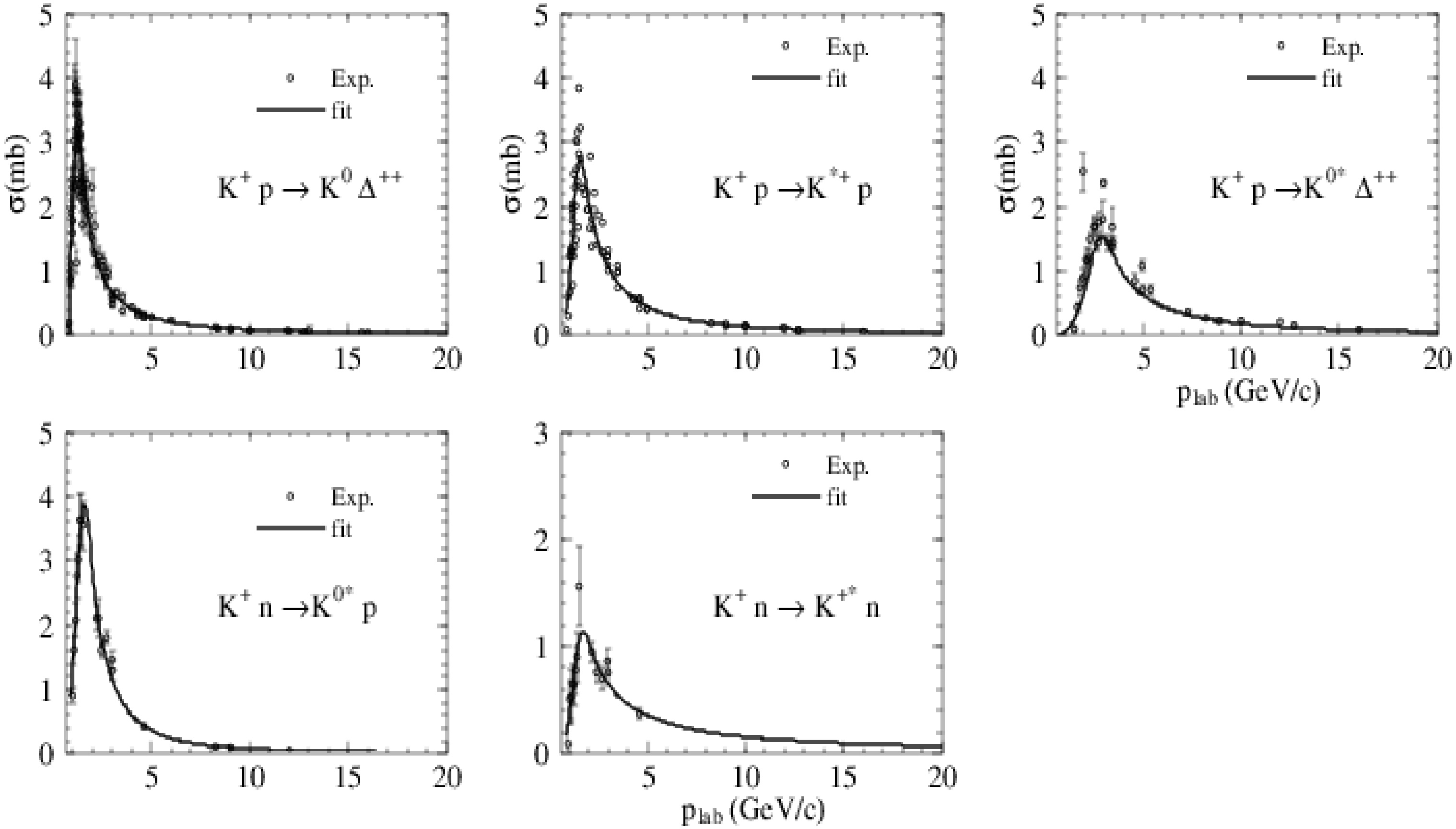
Elastic

Charge exchange: $\pi^- p \to \pi^0 n$

$$\sigma(MB \to R) = \frac{\pi(\hbar c)^2}{p_{\rm cm}^2} \sum_R |C(MB,R)|^2 \times \frac{(2S_R+1)}{(2S_M+1)(2S_B+1)} \frac{\Gamma_R(MB)\Gamma_R(\mathrm{tot})}{(\sqrt{s}-m_R)^2+\Gamma_R(\mathrm{tot})^2/4}$$

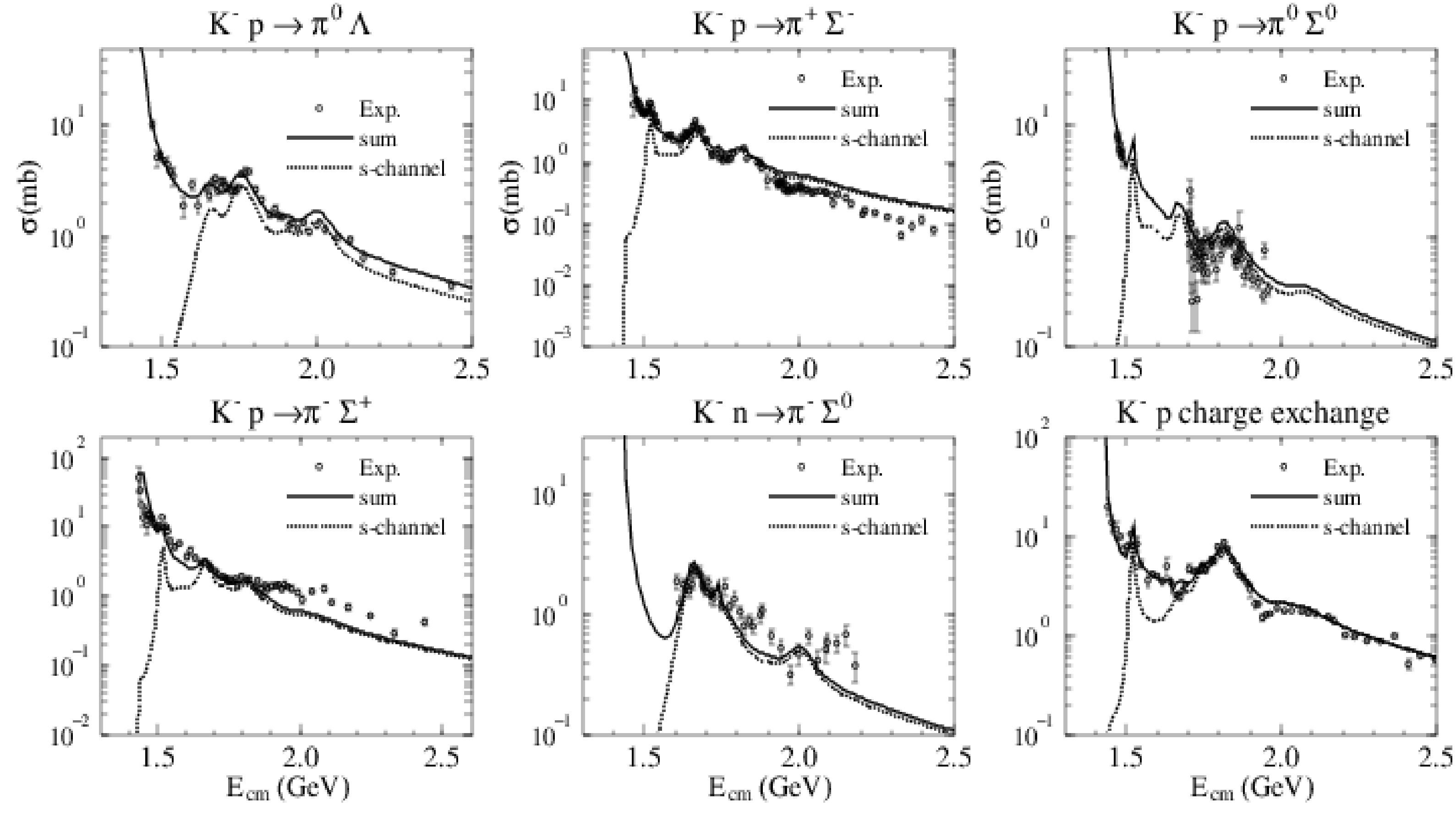
R=N(1440)−N(1990),Δ(1232) -Δ(1950), Γ_R : momentum dependent width

Kaon + proton inelastic



$$\sigma_{tot}^{\bar{K}N} = \sigma_{t-R} + \sigma_{el} + \sigma_{ch} + \sigma_{t-S}$$

Anti-kaon + proton inelastic



$$\sigma_{tot}^{\bar{K}N} = \sigma_{BW} + \sigma_{el} + \sigma_{ch} + \sigma_{\pi Y} + \sigma_{s-S} + \sigma_{t-S}$$

Other elementary processes

Resonance absorption process: detailed balance formula

$$\frac{d\sigma_{34\to12}}{d\Omega} = \frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\frac{p_{12}^2}{p_{34}}\frac{d\sigma_{12\to34}}{d\Omega}\frac{1}{\int\int p_{34}A(m_3)A(m_4)d(m_3^2)d(m_4^2)}$$

Cross section from the Additive quark model

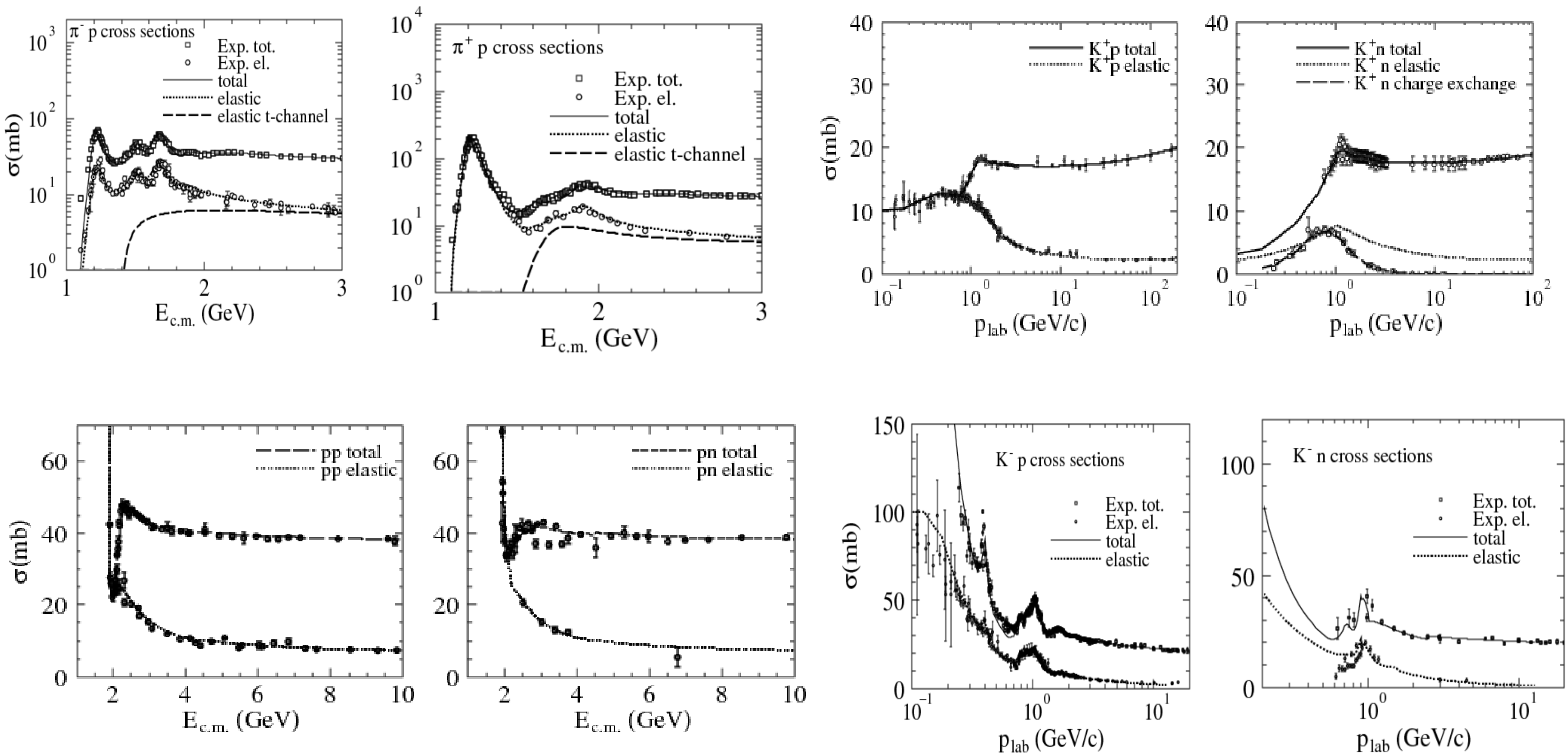
$$\sigma_{\rm tot} = \sigma_{NN}\frac{n_1}{3}\frac{n_2}{3}\left(1-0.4\frac{n_{s1}}{n_1}\right)\left(1-0.4\frac{n_{s2}}{n_2}\right)$$

n_i is the number of constituent quarks in a hadron

n_{si} is the number of strange quarks in a hadron

$\sigma_{K-p} \approx 21$ mb and $\sigma_{\Lambda p} \approx 35$ mb

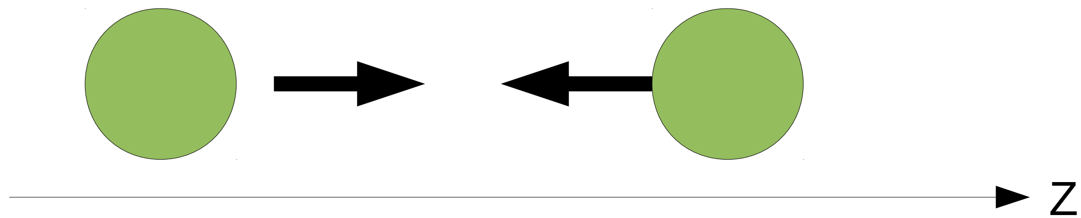
JAM: total cross sections



$\Lambda(1405)$ - $\Lambda(2110)$, $\Sigma(1385)$ - $\Sigma(2030)$ and $\Xi(1535)$ - $\Xi(2030)$

String excitation and decay above resonance region

$p_1 = (p_1^+, p_1^-, 0_\perp)$ $\quad p_2 = (p_2^+, p_2^-, 0_\perp)$ $\quad p^\pm = E \pm p_z$



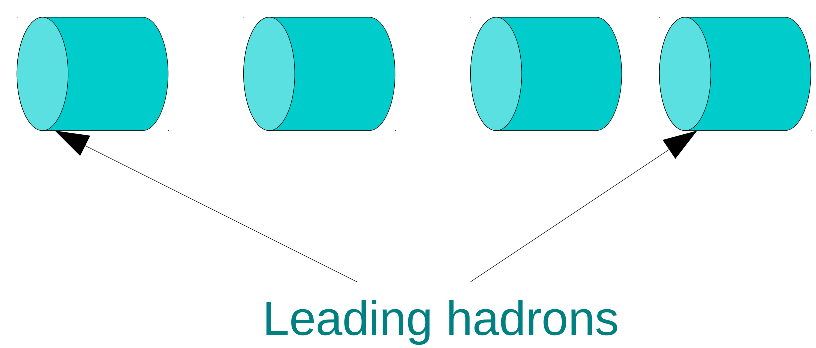
String excitation of hadrons

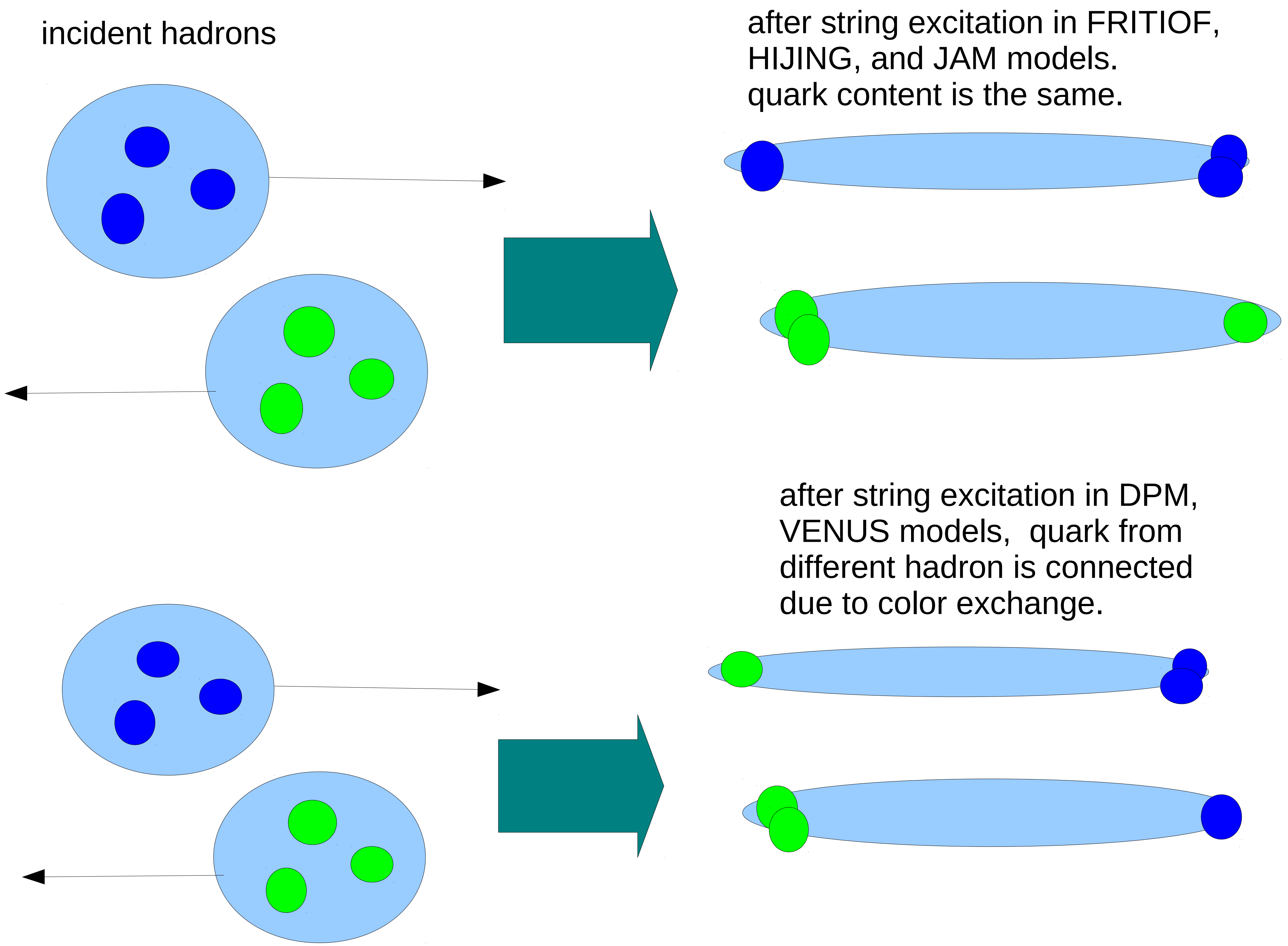
light-cone momentum exchange $q = (q^+, q^-, \mathbf{q}_\perp)$

$p_1' = (p_1^+ - q^+, p_1^- + q^-, p_\perp)$

$p_2' = (p_2^- + q^+, p_2^- - q^-, -p_\perp)$

String decay into hadrons





incident hadrons
after string excitation in FRITIOF, HIJING, and JAM models. quark content is the same.
after string excitation in DPM, VENUS models, quark from different hadron is connected due to color exchange.

String excitation

$$p_1 = (p_1^+, p_1^-, 0_\perp)$$

$$p_2 = (p_2^+, p_2^-, 0_\perp)$$

$$q = (q^+, q^-, \mathbf{q}_\perp)$$

$$p_1' = (p_1^+ - q^+, p_1^- + q^-, p_\perp)$$

$$p_2' = (p_2^- + q^+, p_2^- - q^-, -p_\perp)$$

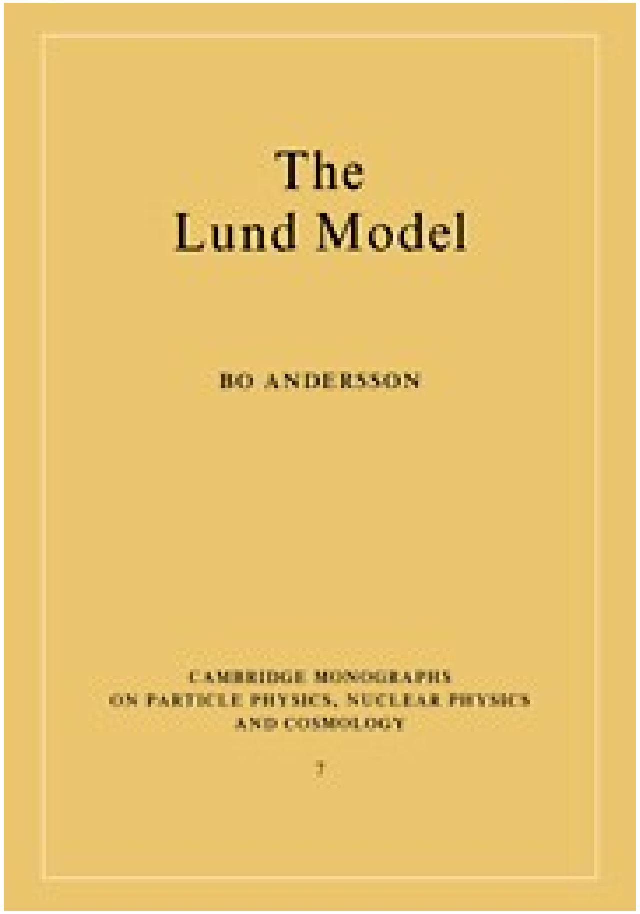
$$\text{light-cone momenutm fraction: } x^+ \equiv \frac{q^+ + p_2^+}{\sqrt{x}},\ \mathrm{x}^- \equiv \frac{q^- + p_1^-}{\sqrt{x}}$$

$$p_1' = ((1 - x^+)\sqrt{x}, x^-\sqrt{x}, p_\perp), \quad p_2' = (x^+\sqrt{x}, (1 - x^-)\sqrt{x}, -p_\perp)$$

DPM (dual parton model) type momentum transfer:

$$P(x^\pm) = \frac{(1 - x^\pm)^{1.5}}{(x^{\pm 2} + c^2/s)^{1/4}}$$

The Lund Model



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

``Parton Fragmentation And String Dynamics,''

Phys. Rept. 97, 31 (1983).

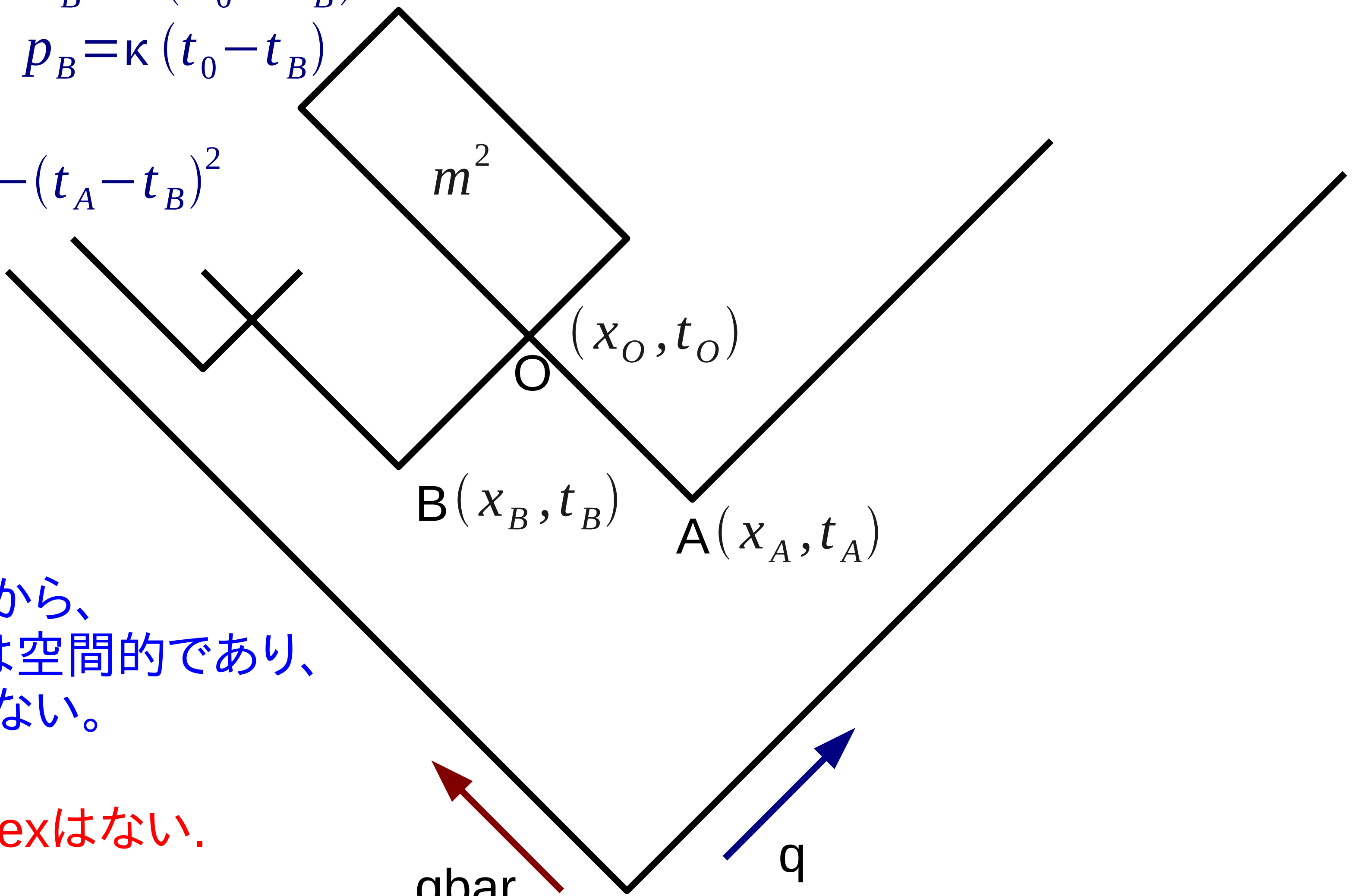
PYTHIA6.4 Physics and Manual 489pages
JHEP 0605:026 (2006)

String breaking

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

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

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



質量は実数であるから、
Vertex AとBの間は空間的であり、
なんの因果関係もない。

特別なvertexはない.

String decay by the Lund string model

破砕過程がquarkとantiquakのどちらから行っても同じである (left-right symmetry)
と要請すれば、破砕関数の形は一意に決まる。

Lund symmetric fragmentation function

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

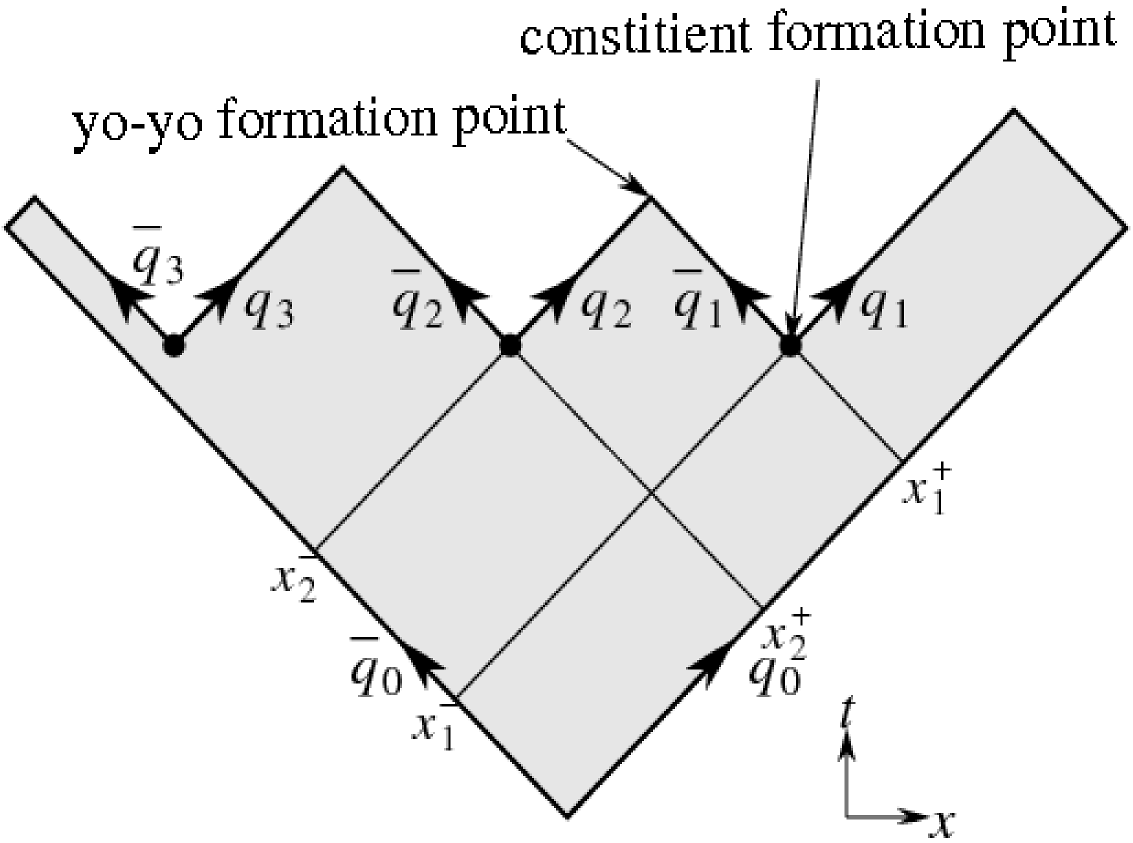
m and $p_\perp$ denote the mass and transverse momentum of the produced hadron, respectively.

$$u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} = 1 : 1 : 0.3 : 10^{-11}$$

$$\frac{\rho}{\rho+\pi} \approx 0.5, \quad \frac{K^*}{K^*+K} \approx 0.6 \quad \frac{D^*}{D^*+D} \approx 0.75$$

Different from statistics $S_3 : S_1 = 3 : 1$

Hadron formation point from string decay

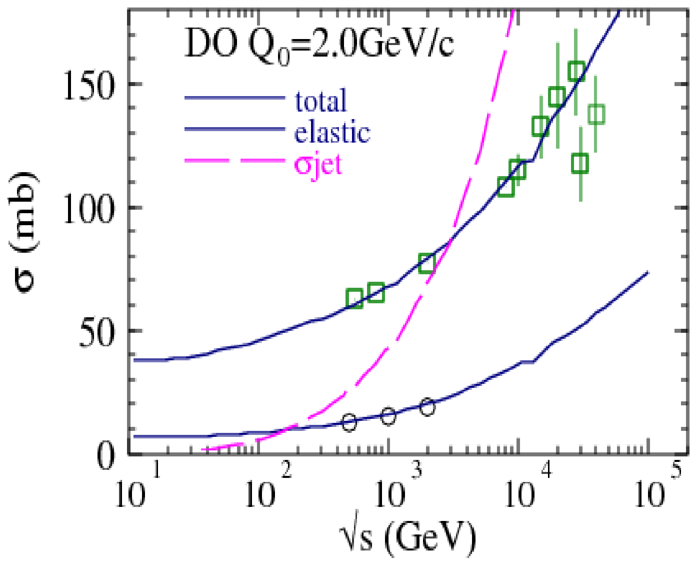


Spacetime picture
of q-qbar string motion

Eikonal Formulation for pQCD (HIJING)

$$\sigma_{t-S}(s) = 2\pi \int_0^\infty db^2 \left[1 - \exp(\chi(b,s))\right],$$

$$\chi(b,s) = \frac{1}{2}\left(\sigma_{jet}(s) + \sigma_{soft}(s)\right) A(b,s)$$



$$\sigma_{jet} = \int_{p_0^2}^{s/4} dp_T^2 dy_1 dy_2 \frac{1}{2} K \sum_{a,b} x_1 x_2 f_a(x_1, P_T^2) f_b(x_2, P_T^2) \frac{d\sigma^{ab}(\hat{s},\hat{t},\hat{u})}{d\hat{t}}$$

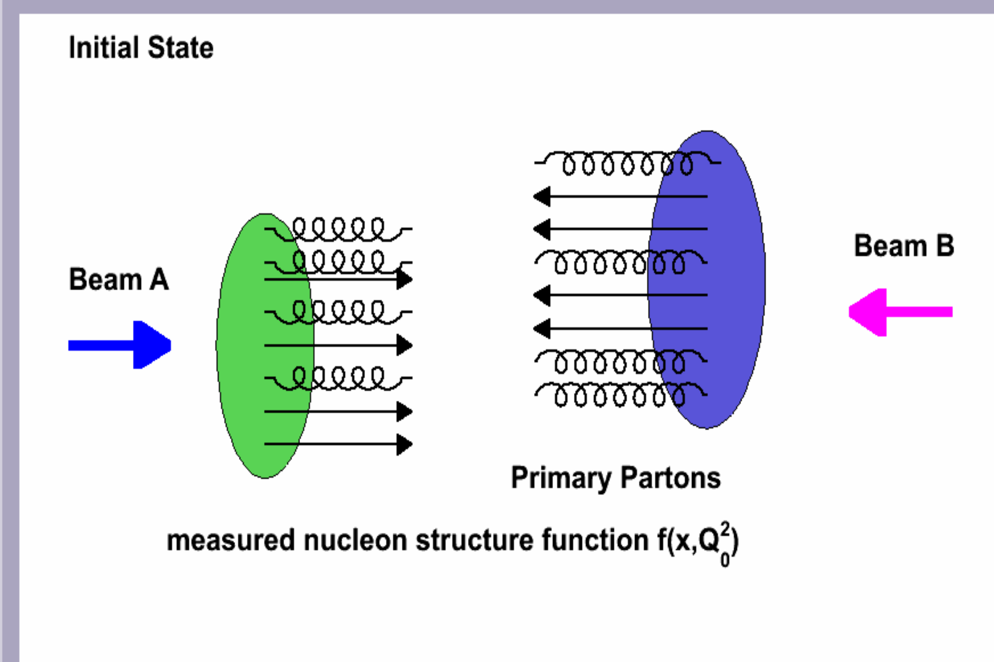
T. Sjostrand and M. van Zijl, Phys. Rev. D36 (1987)2019

Pythia hadronic collisions

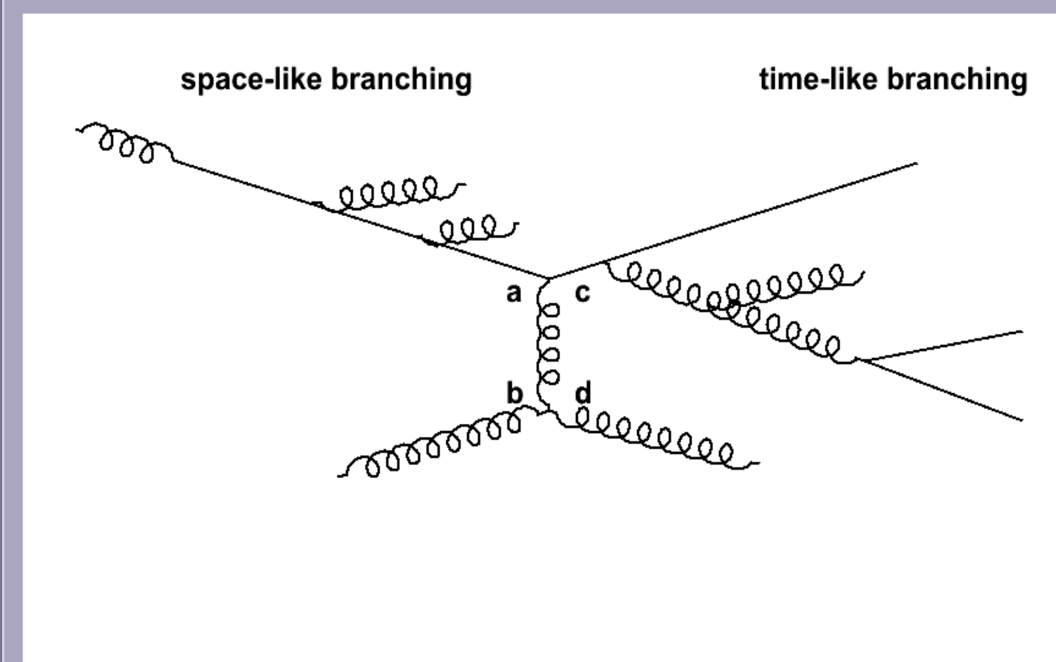
Hard scattering (pQCD) + soft interaction (longitudinal excitation) + hadronization via string fragmentation.

$$\sigma = K \int dx_1 dx_2 dt\, f_1(x_{1,} Q^2)\, \sigma_{QCD}\, f_2(x_{2,} Q^2)$$

Initital Condition



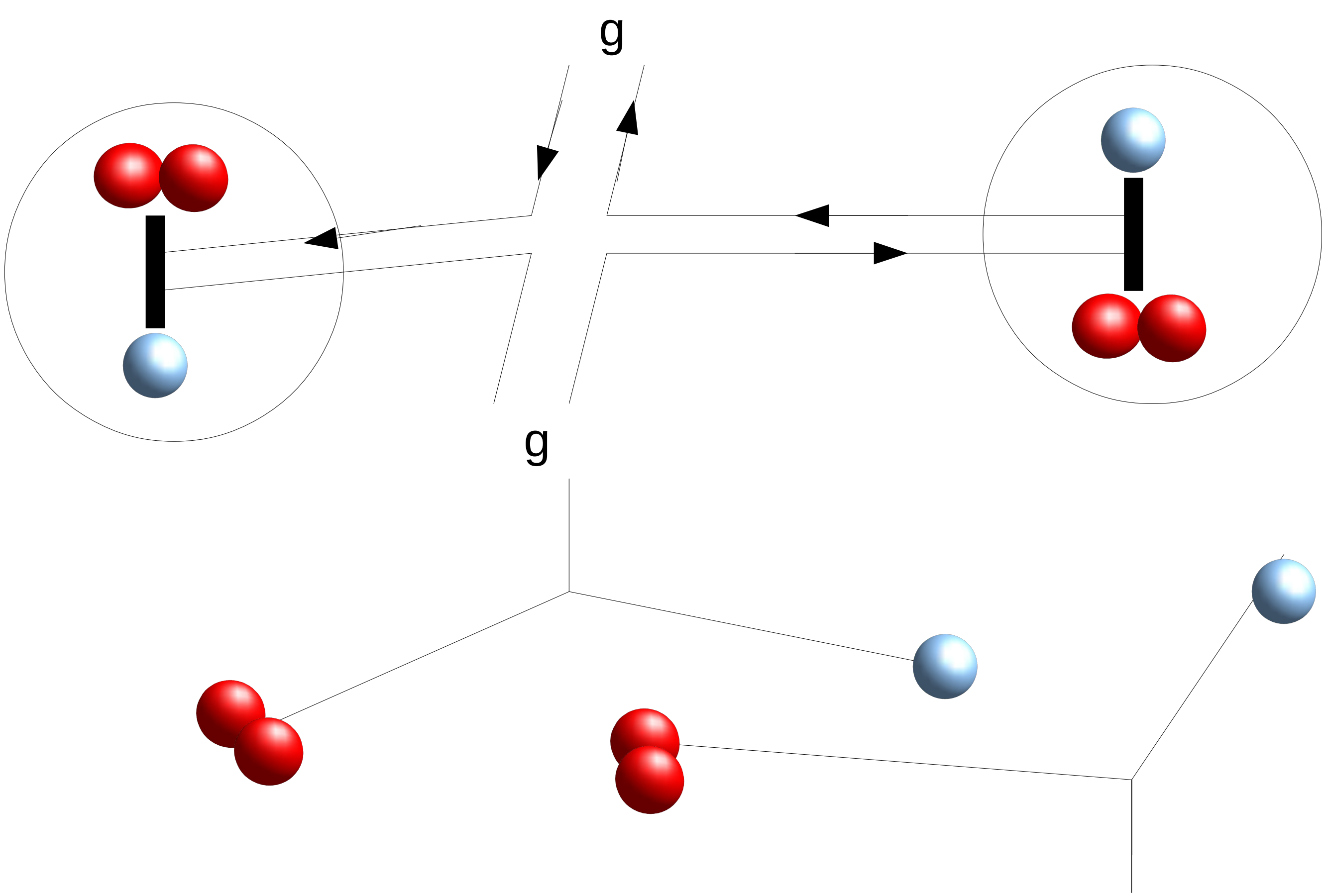
Parton Cascade Development



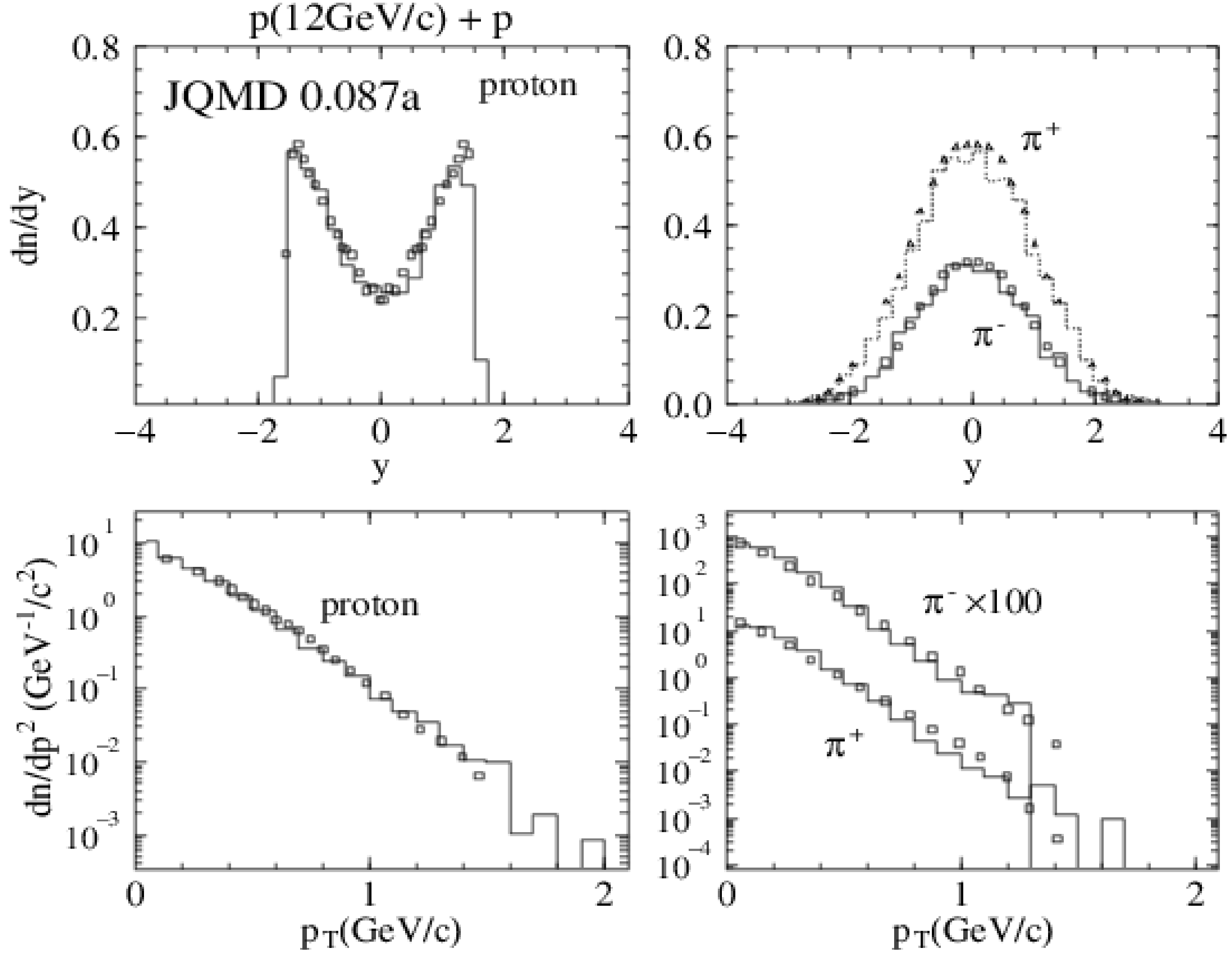
String-drawing issues

Color flow についてはMatrix element の干渉項は無視 (1/N_c^2)

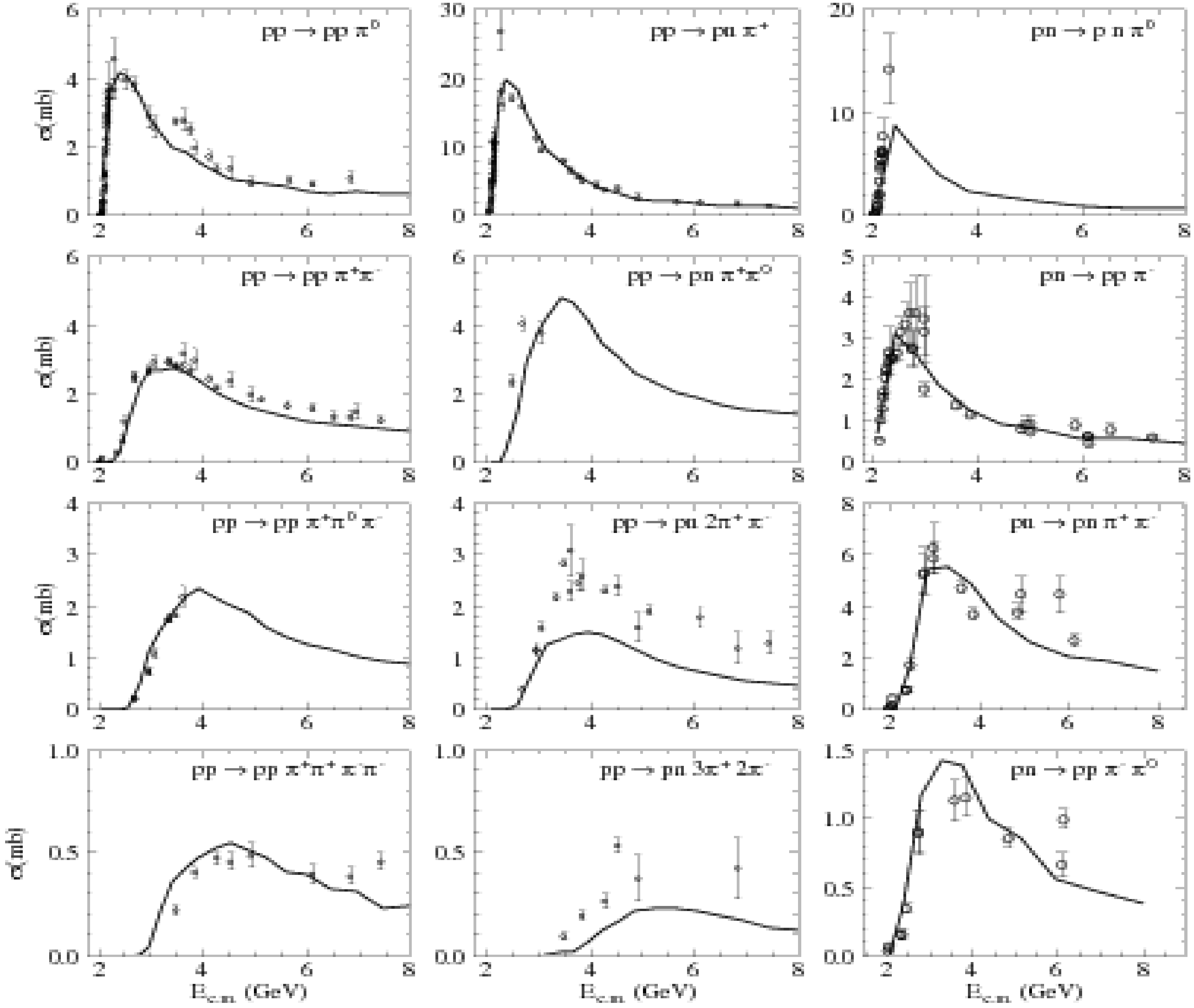
$g\,g \to g\,g$ Process in proton-proton collision



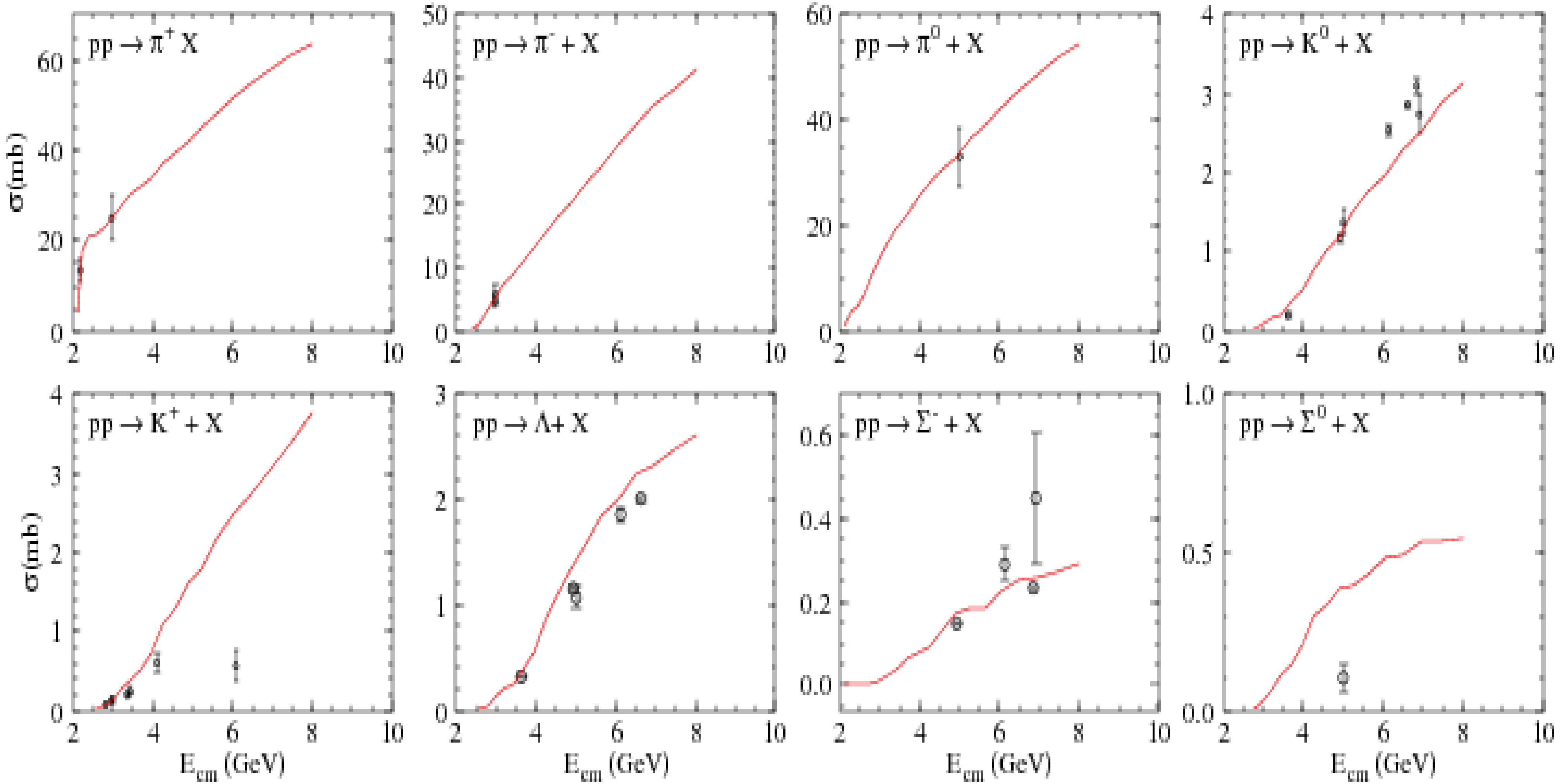
Proton-proton collisions at 12 GeV/c

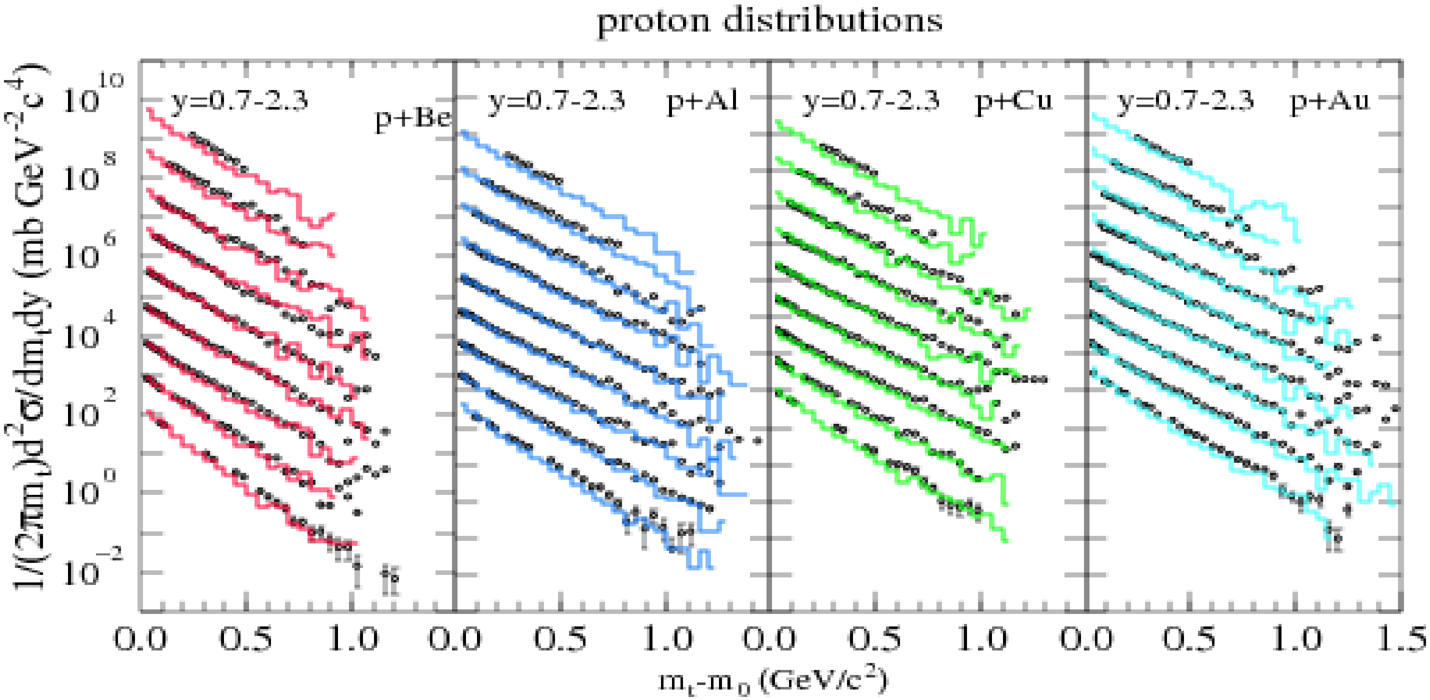


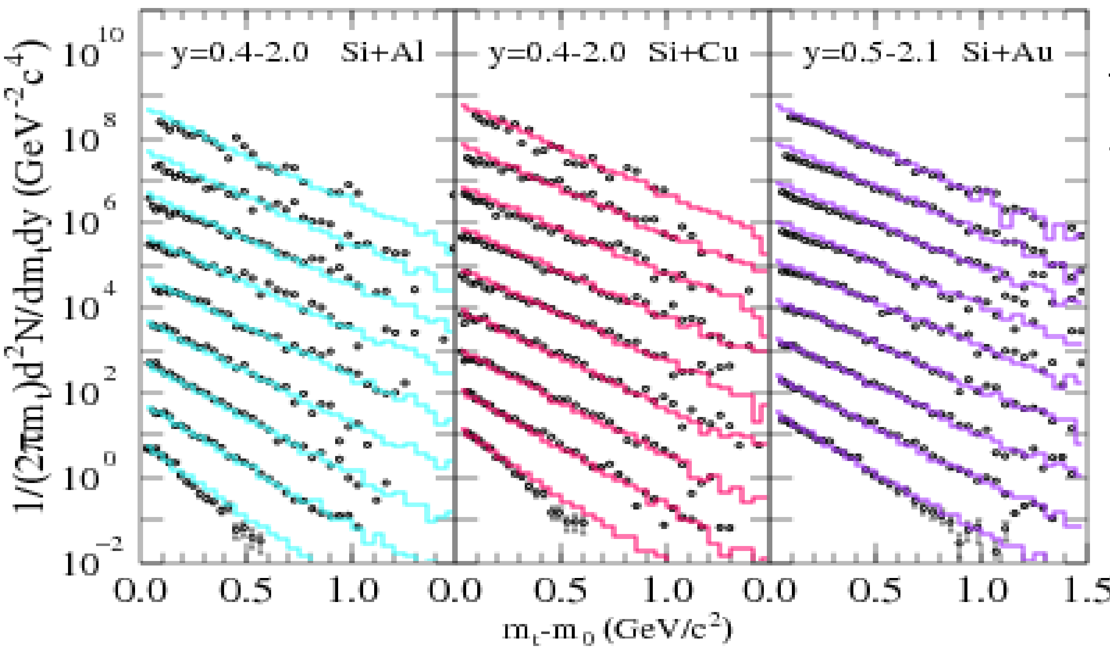
Pion production cross sections in JAM



Excitation function of p+p -> x in JAM



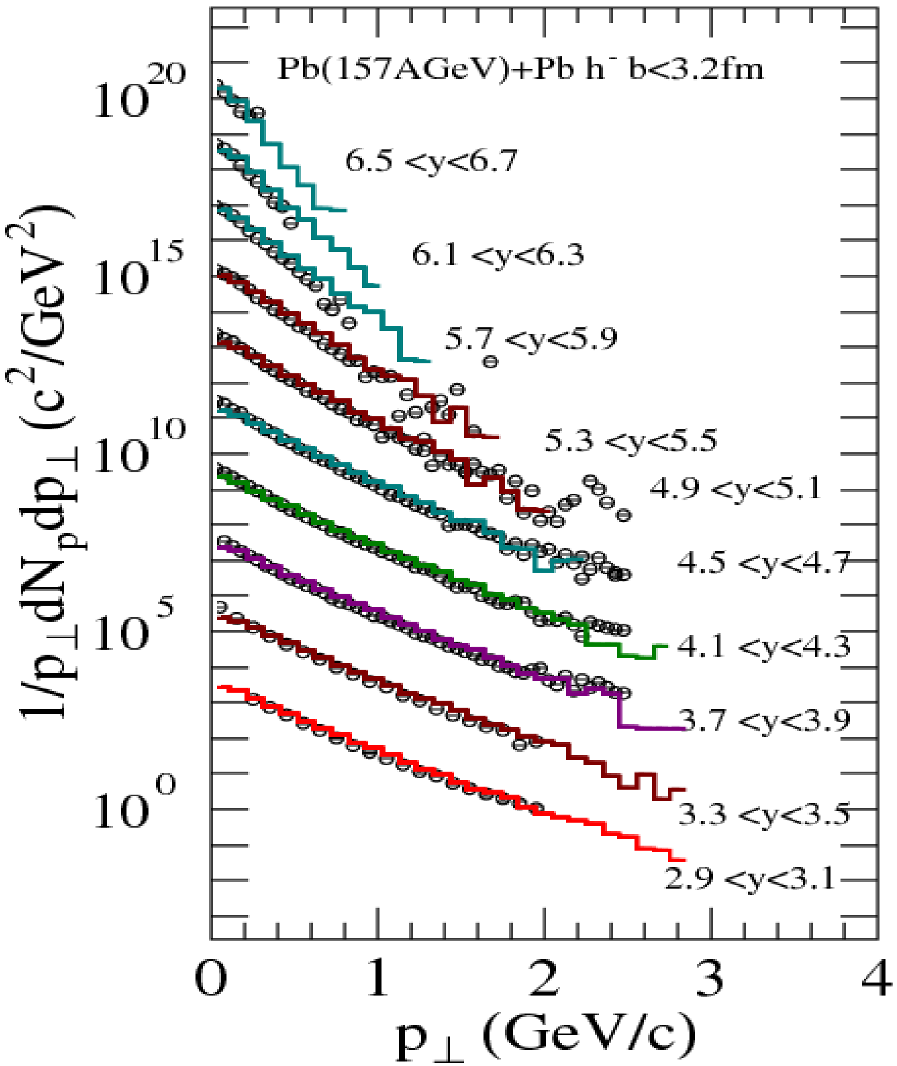


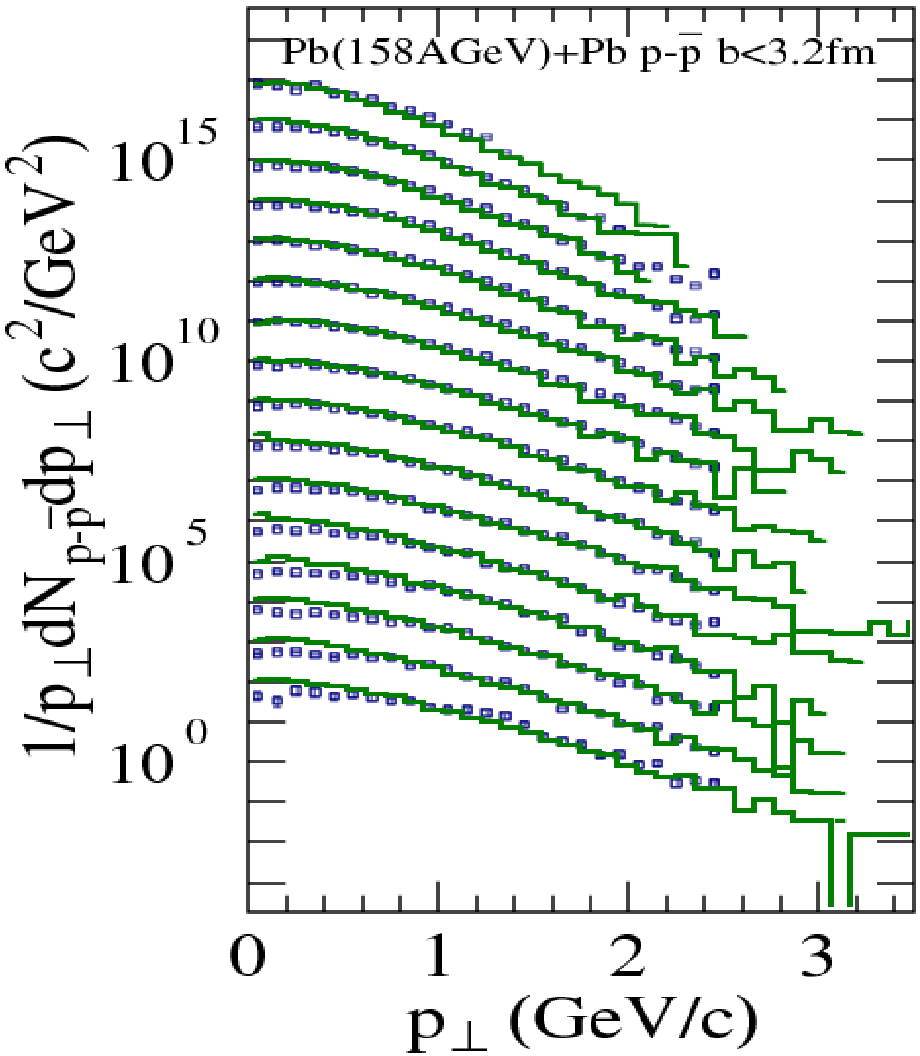


Proton distribution at AGS energy

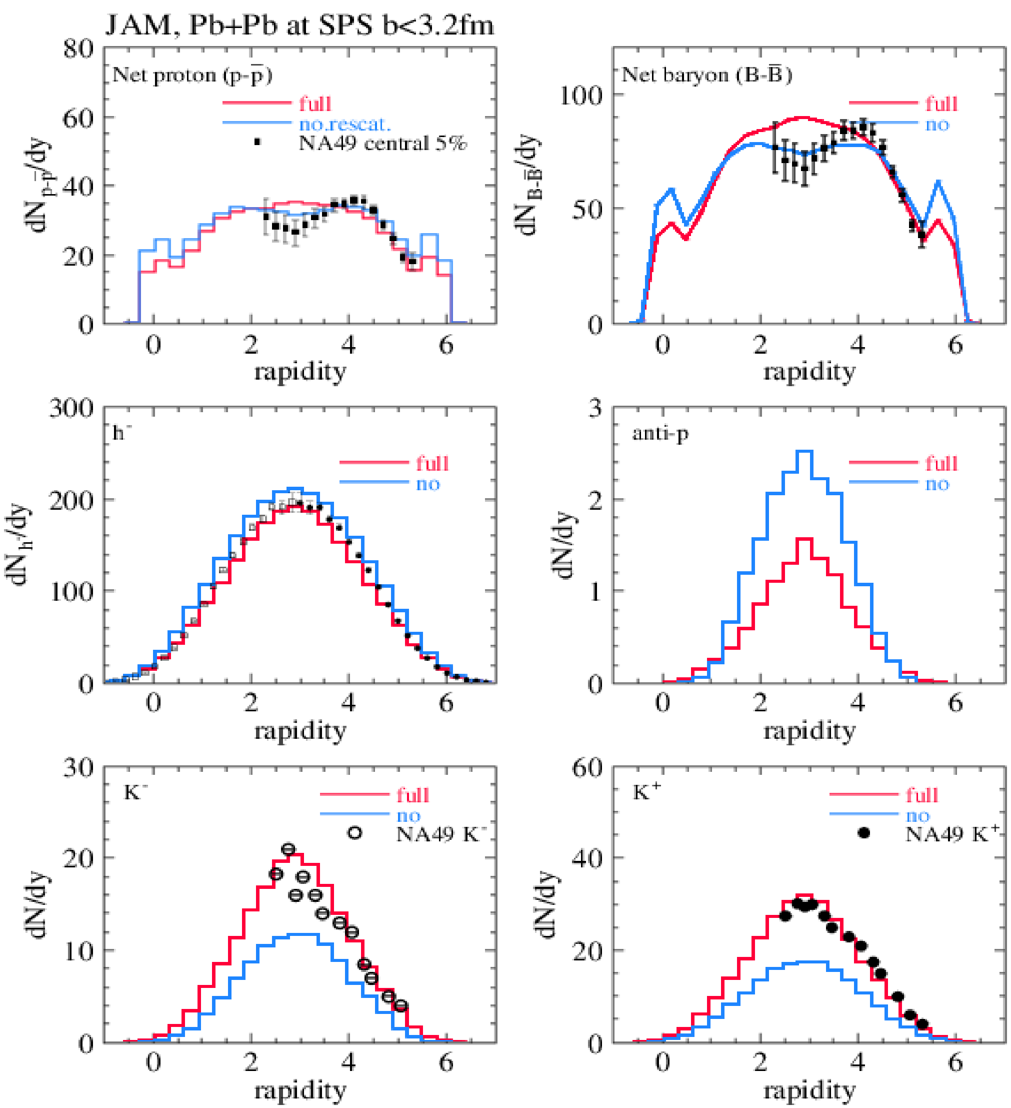
pion distribution
at AGS energy
(E=14GeV)

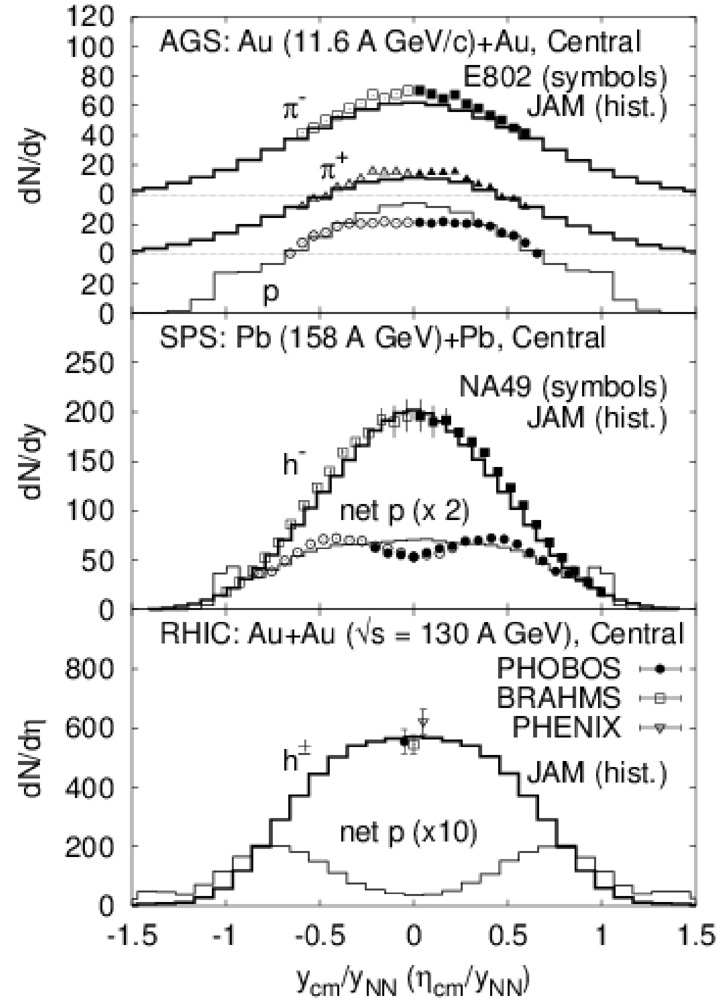
Transverse momentum distribution at SPS energy (160AGeV)





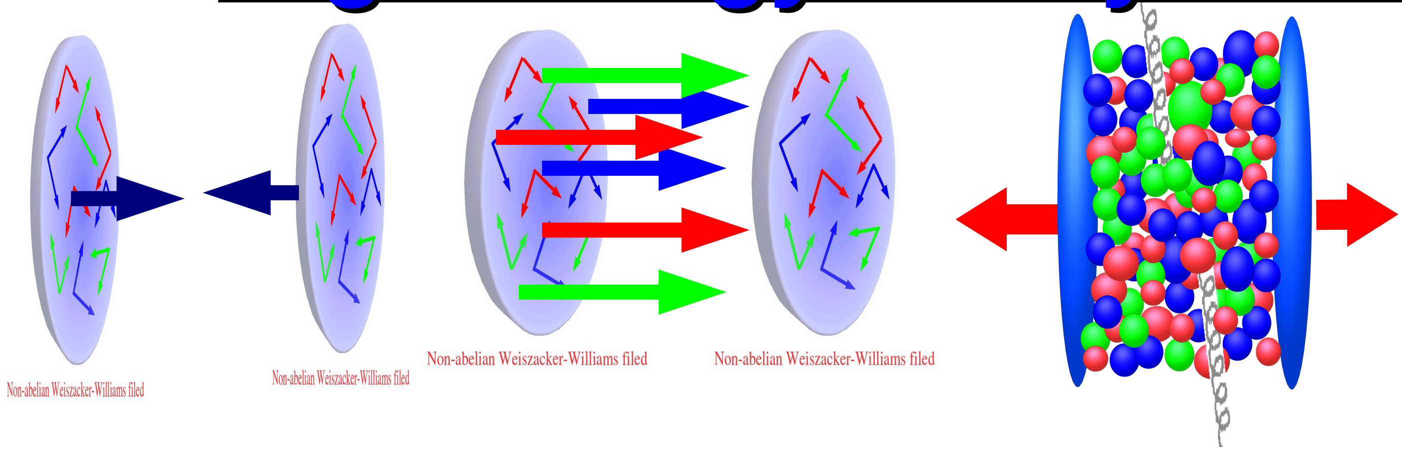
Rapidity distributions



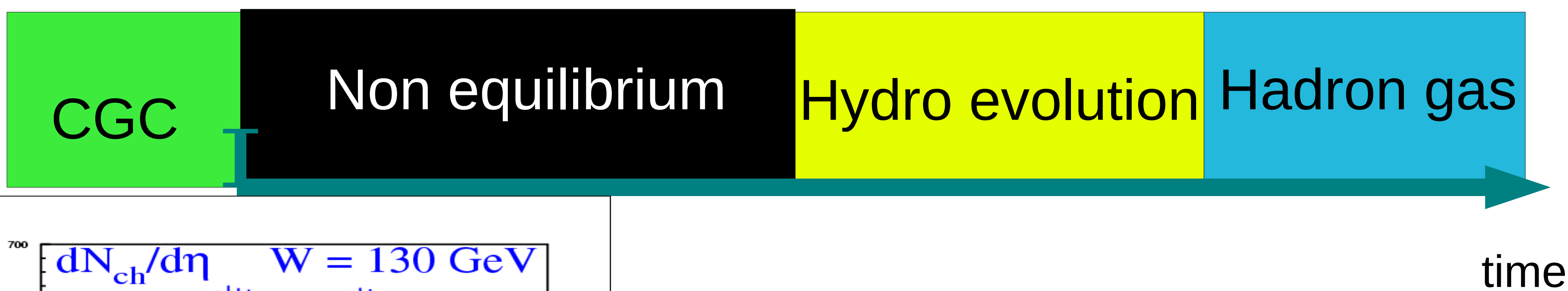


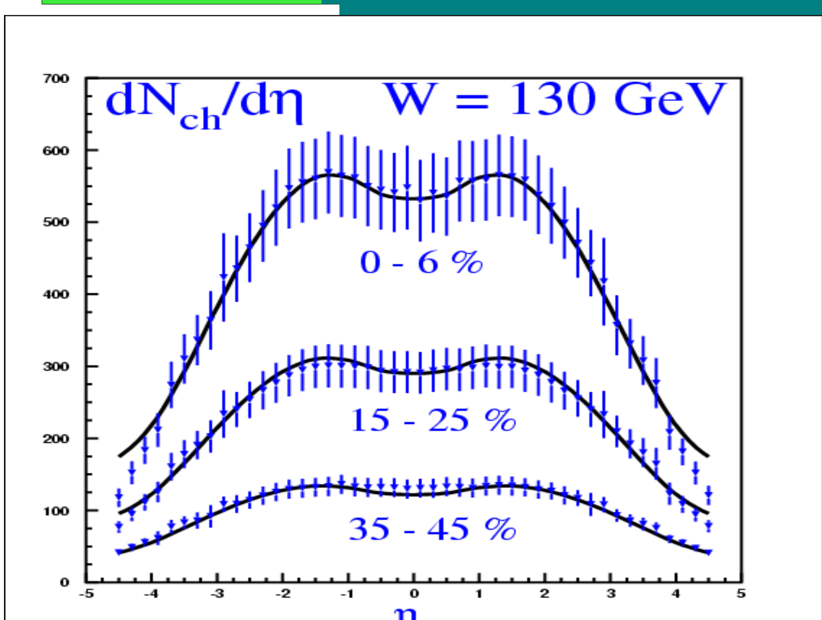
Nucl-th/0102051

High energy heavy ion collisions

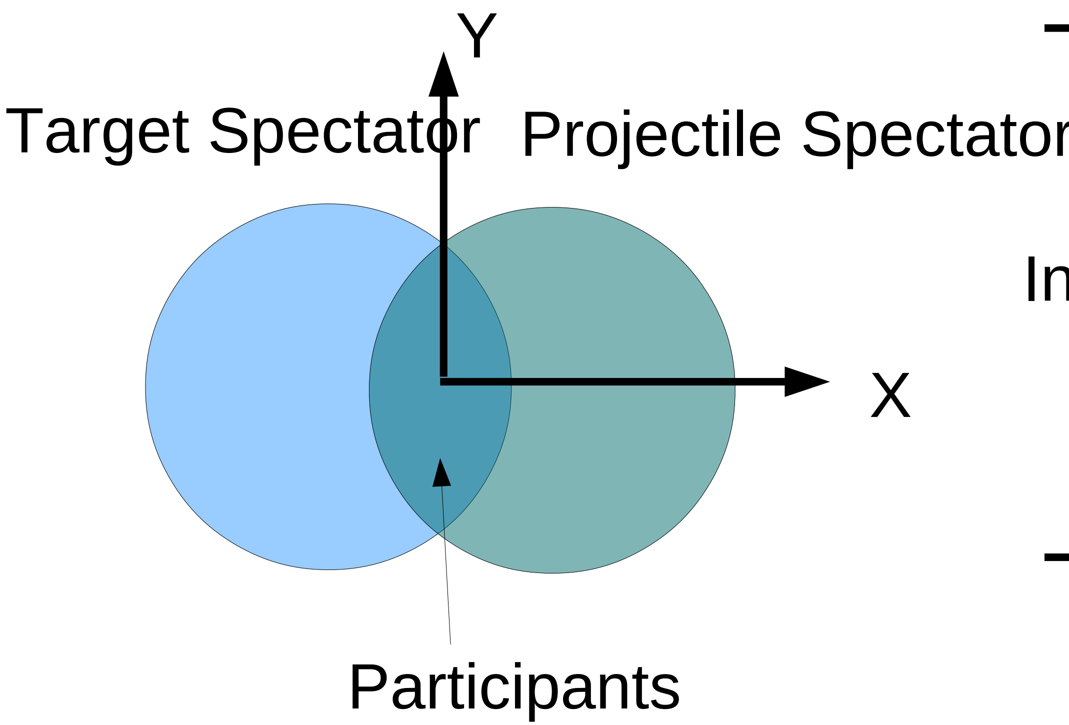


$\tau = 0$ $\quad \tau \approx 1/Q_s$ $\quad \tau \approx 1 \sim 2\, fm/c$

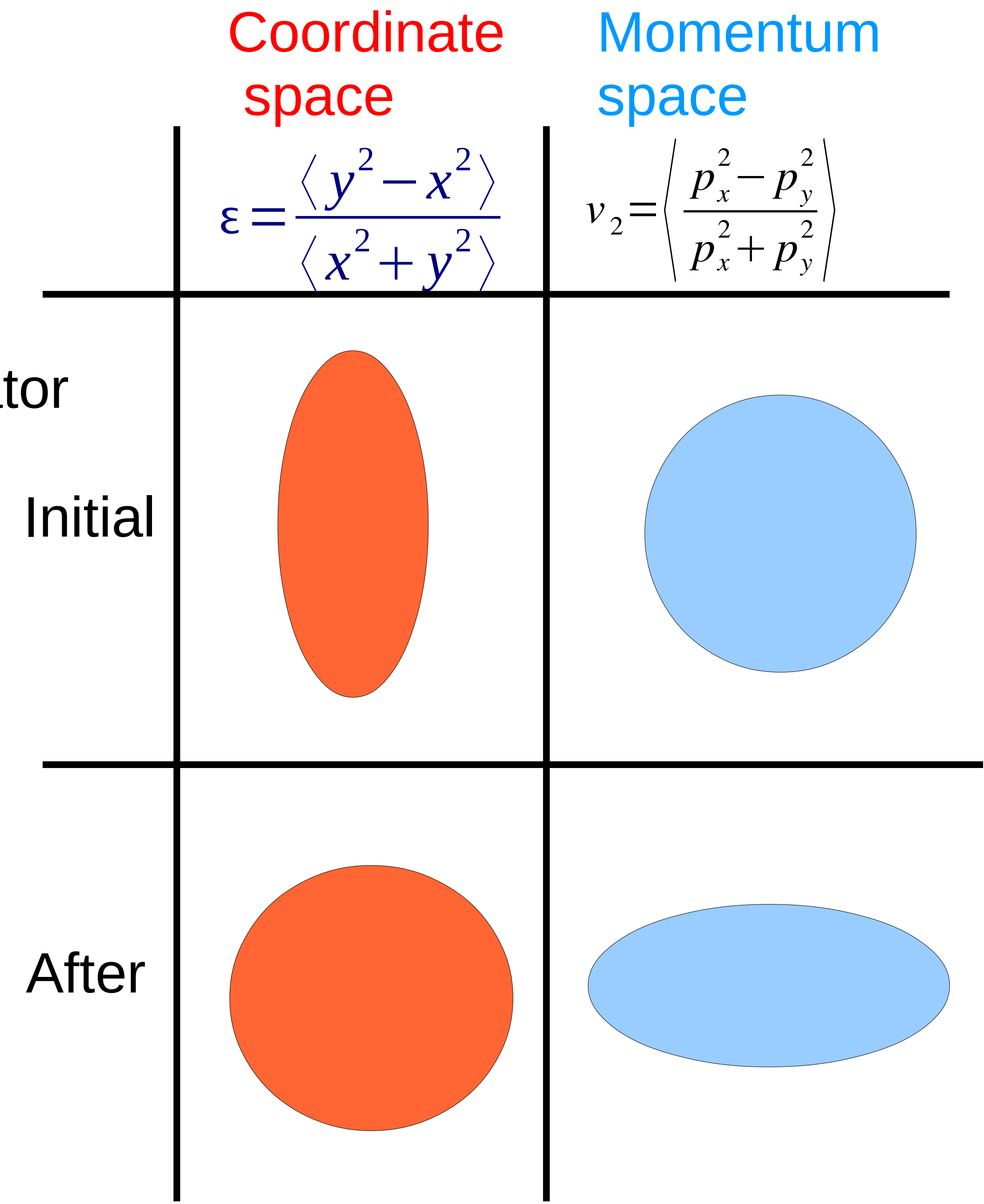




Collective behavior
Elliptic flow



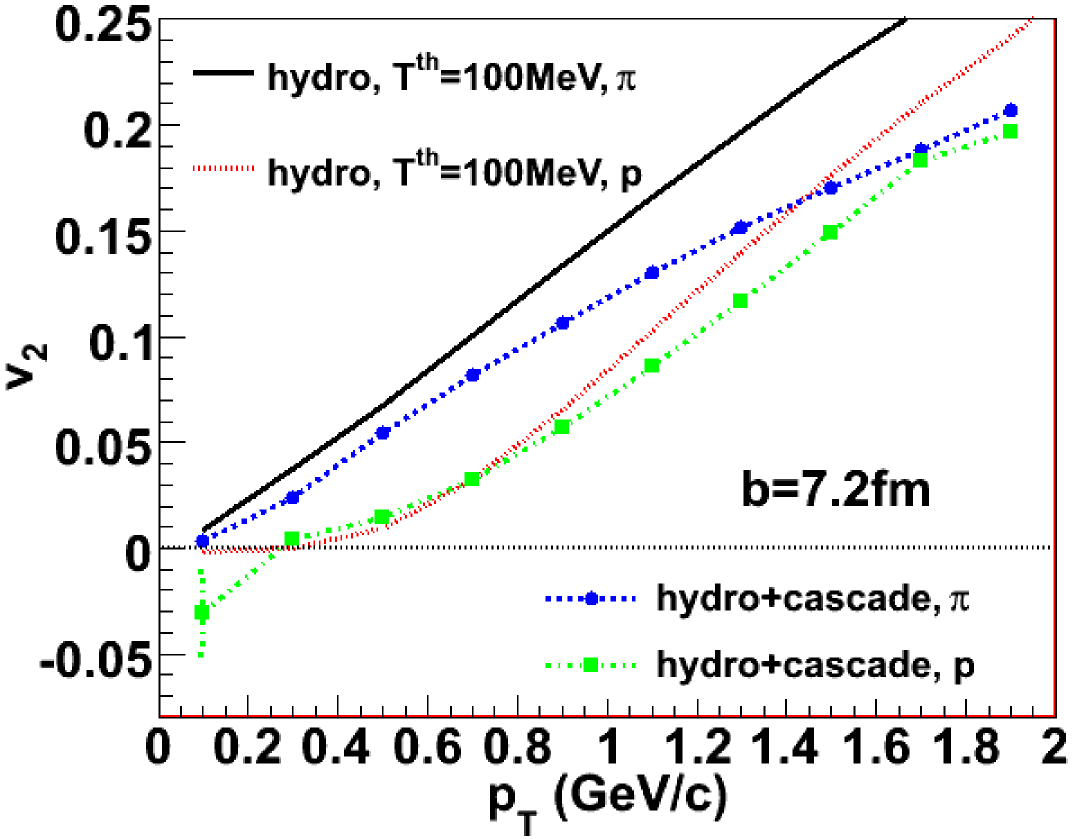
$$v_2 \equiv \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

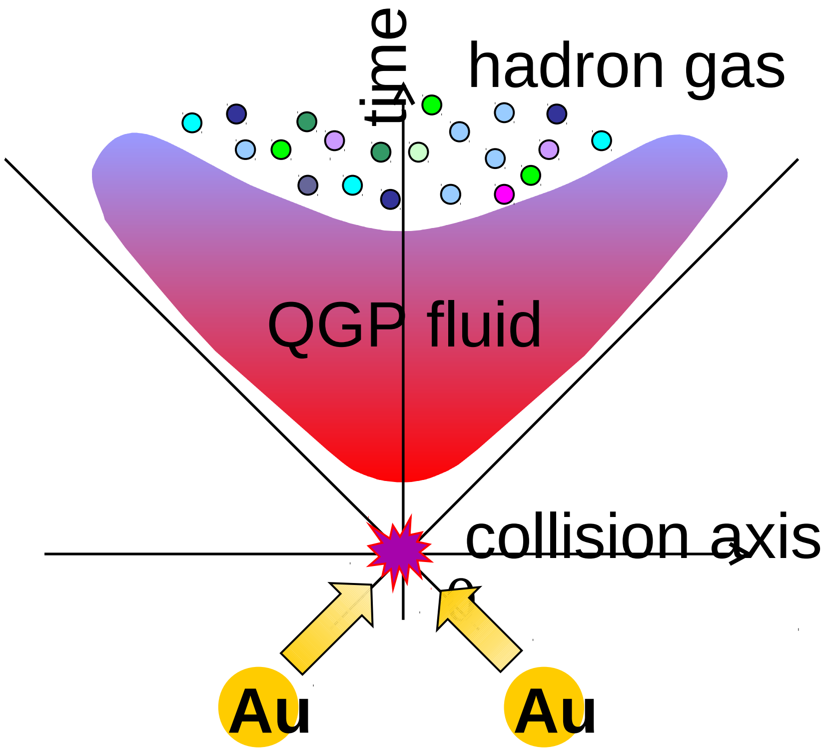


Idea : Interaction ⇨ convert space anisotropy to momentum anisotropy

Hadronic dissipative effect on the elliptic flow

Phys.Rev. C77 (2008) 044909



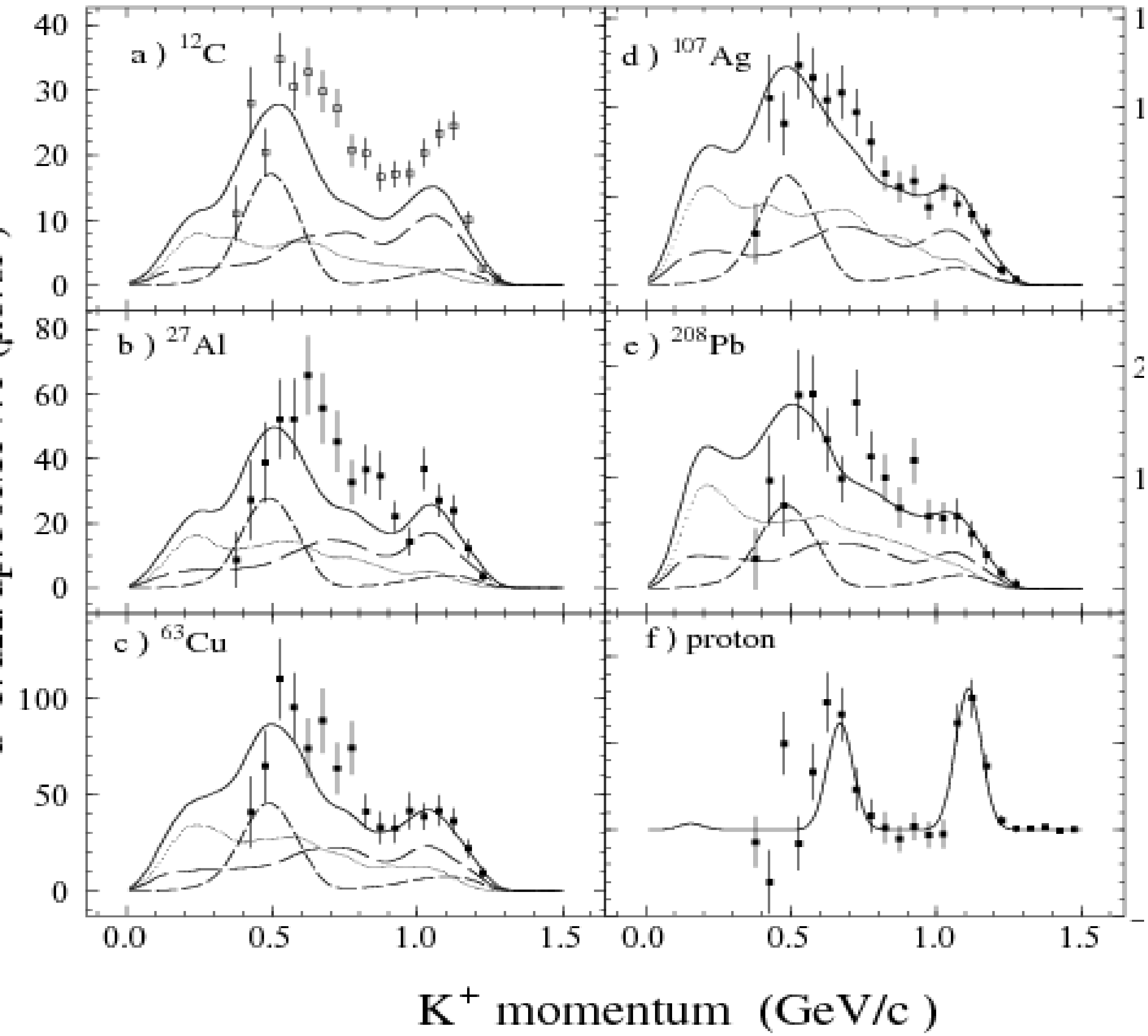


(1D) Bass, Dumitru (2D) Teaney, Lauret, Shuryak, (3D) Nonaka et al., Hirano et al.

Possible improvements in JAM

- More systematic implementation of elementary processes
  - Low energy particle productions
  - Direct pion/kaon production
  - Latest PDF
  - CGC?
- C++ version
  - いろいろupdateしたいがFortranのままだと無理
  - 現在はバグフィックスのみ。
- Explicit treatment of spacetime evolution of partons

$(K^-,K^\pm)$ reactions
This is not JAM results.



$\bar{K}N \to K\Xi, K\Xi^*(1530)$

$\bar{K}N \to (\phi, a_0, f_0)\Lambda$

$(\phi, a_0, f_0) \to K^+K^-$

$\bar{K}N \to (\pi, \rho, \eta, \omega, \eta')(Y, Y^*)$

$(\pi, \rho, \eta, \omega, \eta')N \to$

$(K, K^*)(Y, Y^*), \phi N$

Y.Nara, A.Ohnishi, T.Harada and A.Engel, Nucl. Phys. A614, 433 (1997)

まとめ

ハドロニックカスケードモデルは、重イオン衝突や、ハドロン-原子核反応
の古典的時空発展をミクロに記述するものである。

現時点ですべての 素過程 を満足できる形で導入したモデル
はない。

現在最高エネルギーで原子核を衝突できるRHIC energy まで、
粒子の multiplicity などのバルクな観測量はよく再現できるが、
集団効果,例えば楕円形フローなどは再現できない。