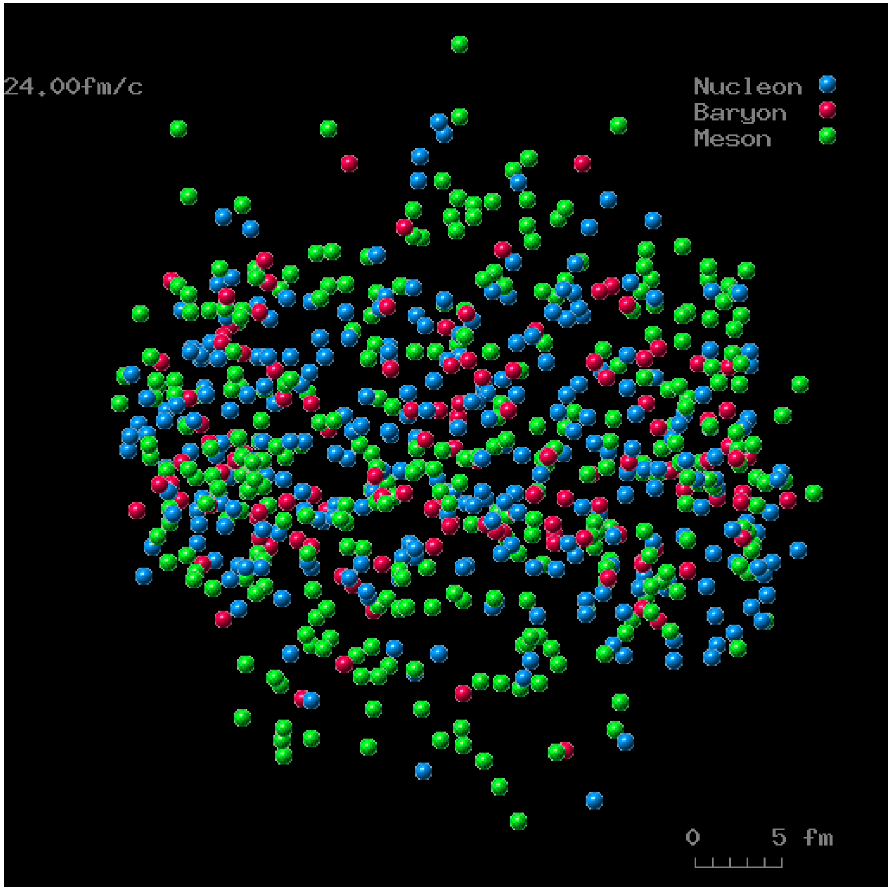
Hadronic Transport: JAM

Akira Ohnishi (Yukawa Inst., Kyoto U.)

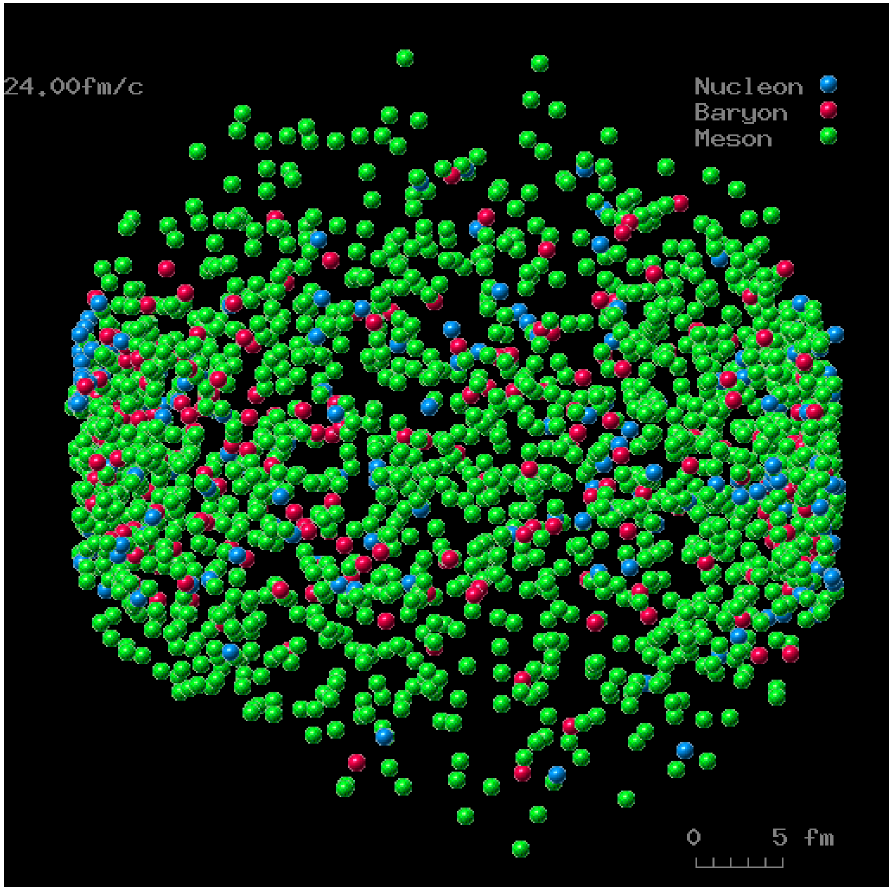
- **Introduction**
- **JAM (Jet AA Microscopic transport model)**
  - **Implemented degrees of freedom and cross sections**
  - **Applications (1): AGS, SPS, RHIC energies**
  - **Applications (2): Hydro+Cascade**
  - **Effects of DOF and mean field in particle spectrum**
- **Summary**

How do heavy-ion collisions look like ?

Au+Au, 10.6 A GeV



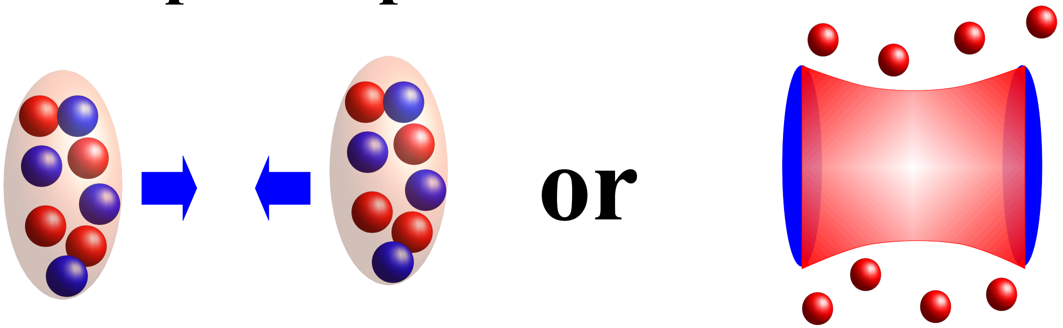
Pb+Pb, 158 A GeV



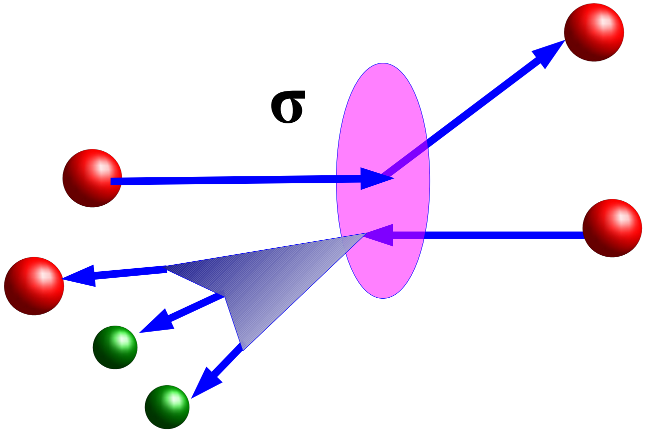
JAMming on the Web **http://www.jcprg.org/jow/**

Hadronic Cascade

- **Initial condition = phase space dist. of hadrons**

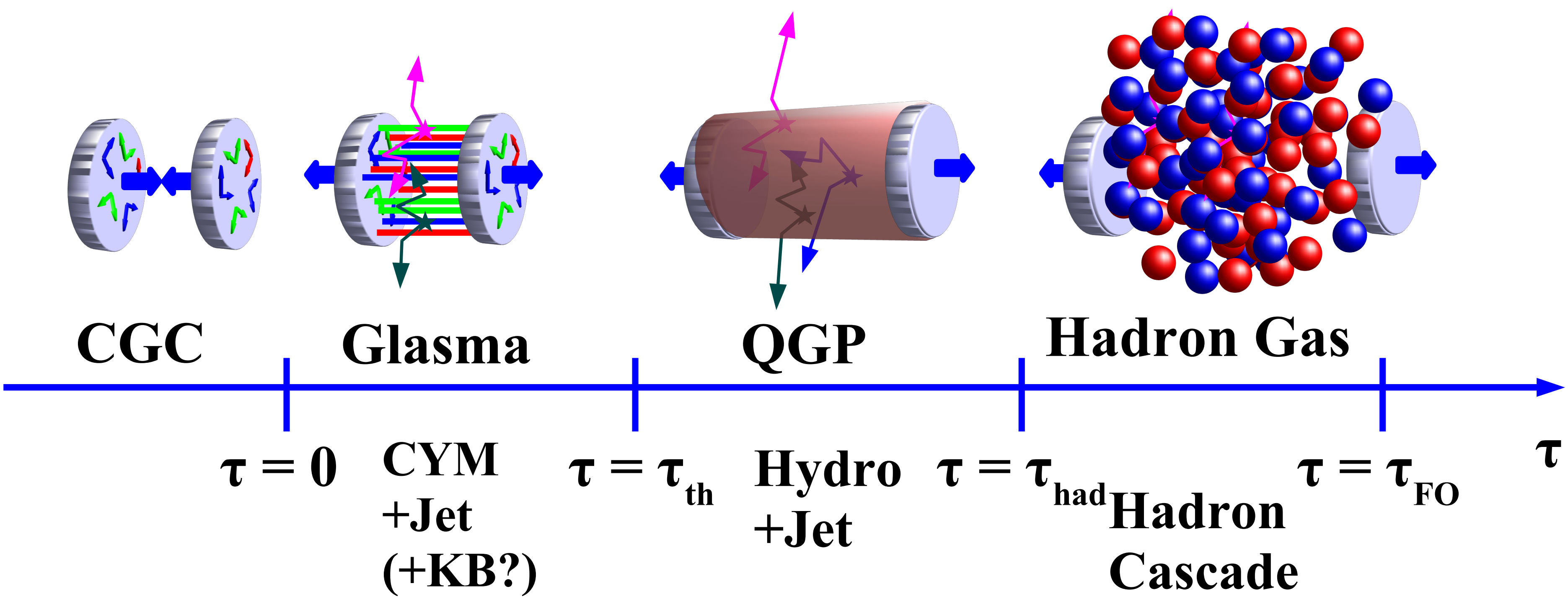


- **Straight path (or curved path with mean field) evolution between two hadron collisions**
- **Two-body collision at the closest distance according to σ.**



- **Particle production, evolution, next collisions, ...**
- **Measure observables in the final state**

Why Hadronic Transport Models ?



Hadron Transport is necessary even at very high energy, since the hadron appears in the final state.

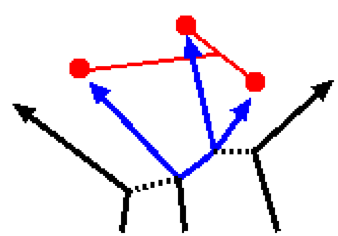
Hadronic Transport Models in OSCAR

- **OSCAR: Open Standard Codes and Routines**
- **UrQMD (http://urqmd.org)**
  → S. Bass's talk
- **GiBUU (http://gibuu.physik.uni-giessen.de/GiBUU/)**
  Giessen Boltzmann-Uehling-Uhlenbeck project
- **JAM (http://quark.phy.bnl.gov/~ynara/jam/)**
  (Jet AA Microscopic transport model)
  - **Y.Nara, N.Otuka, A.Ohnishi, K.Niita and S.Chiba,**
    ``Study of relativistic nuclear collisions at AGS energies from p + Be to Au + Au with hadronic cascade model,''
    Phys. Rev. C61, 024901 (2000) [arXiv:nucl-th/9904059].
  - **M. Isse, A. Ohnishi, N. Otuka, P. K. Sahu, Y. Nara,**
    “Mean-Field Effects on Collective Flows in High-Energy Heavy-Ion Collisions at 2-158 A GeV energies”,
    Phys. Rev. C 72 (2005), 064908 (15 pages) [arXiv:nucl-th/05020.58].
- **and more.**

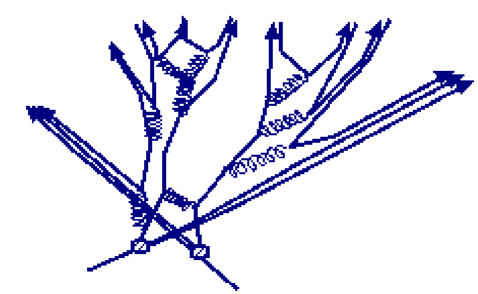
JAM (Jet AA Microscopic transport model)

Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.

- **Hadron-String Cascade with Jet production**
  - **Hadron Res. up to m < 2 GeV**
  - **String & Jet production and decay (← PYTHIA)**
    T. Sjostrand et al., Comput. Phys. Commun. 135 (2001), 238.
  - **String-Hadron collisions are simulated by *hh* collisions in the formation time (~ RQMD)** *H. Sorge,PRC52 ('95)3291.*
    Secondary partonic interactions are NOT included.
  - **Mean field effects (Optional)**
    Isse et al., PRC('05)

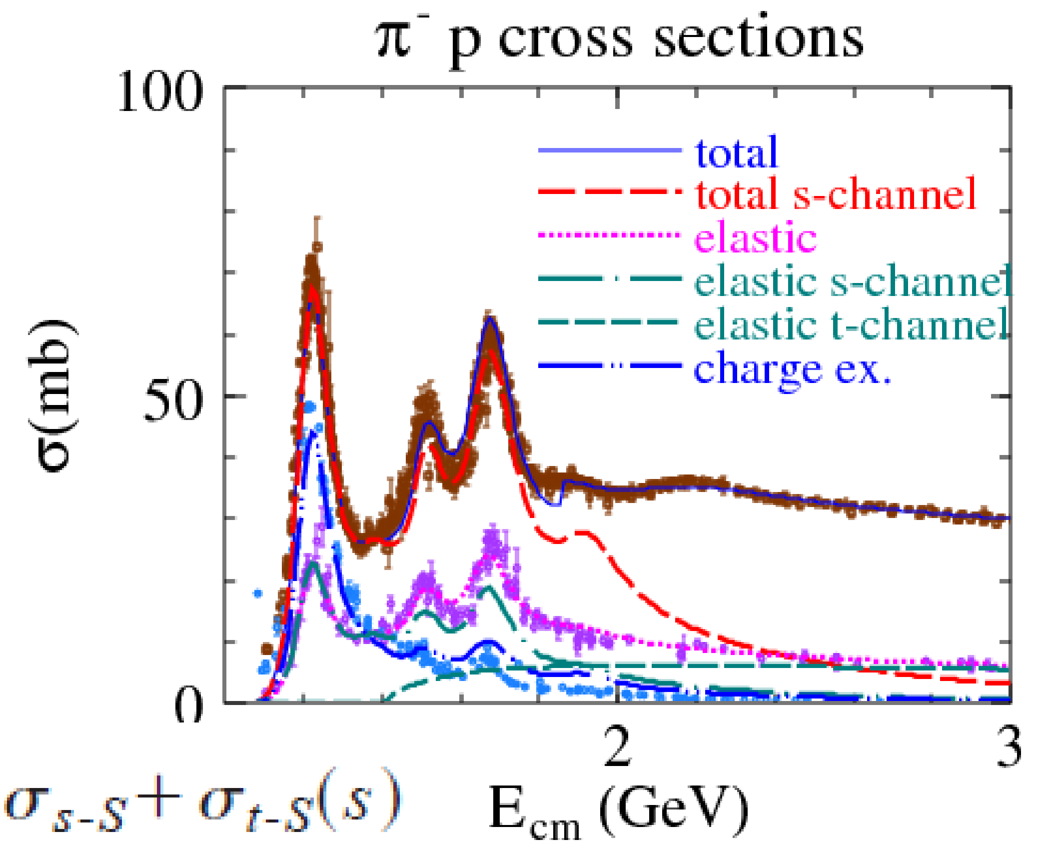


Resonance
+ String
+ Jet

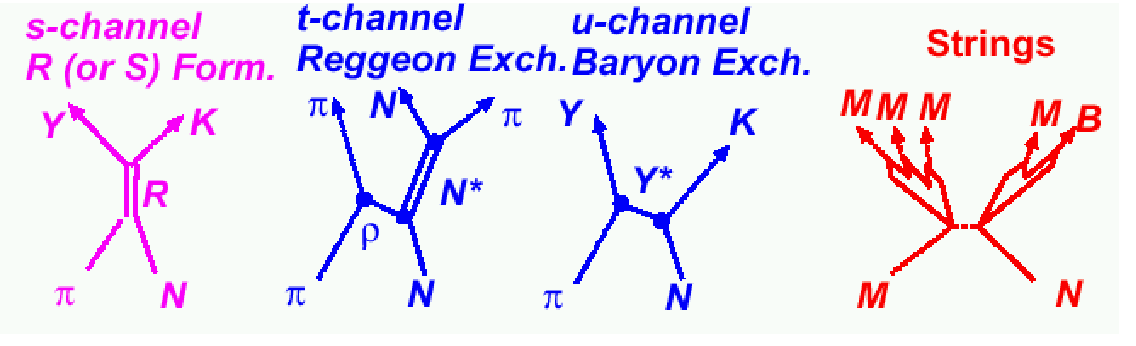


Modeling of low energy MB cross sections

- **Low E cross sections**
  ~ s-channel Breit-Winger Res. formation
  πN → resonance (or string)
  → πN, ππN, ...
- **t-channel:**
  πN → res.(or string)
  + res. (or string)

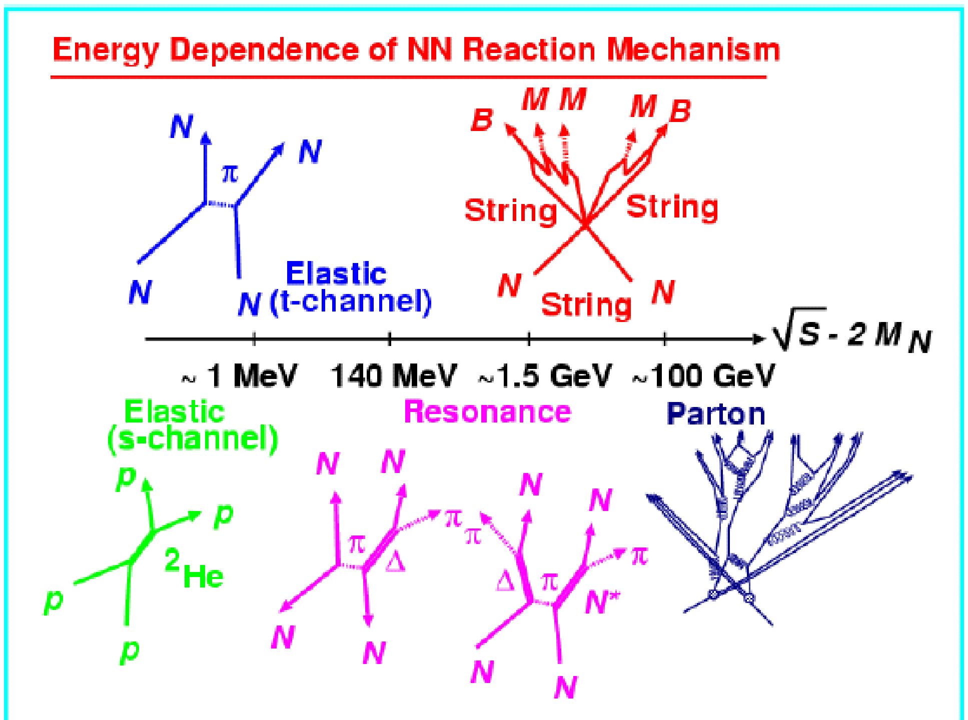


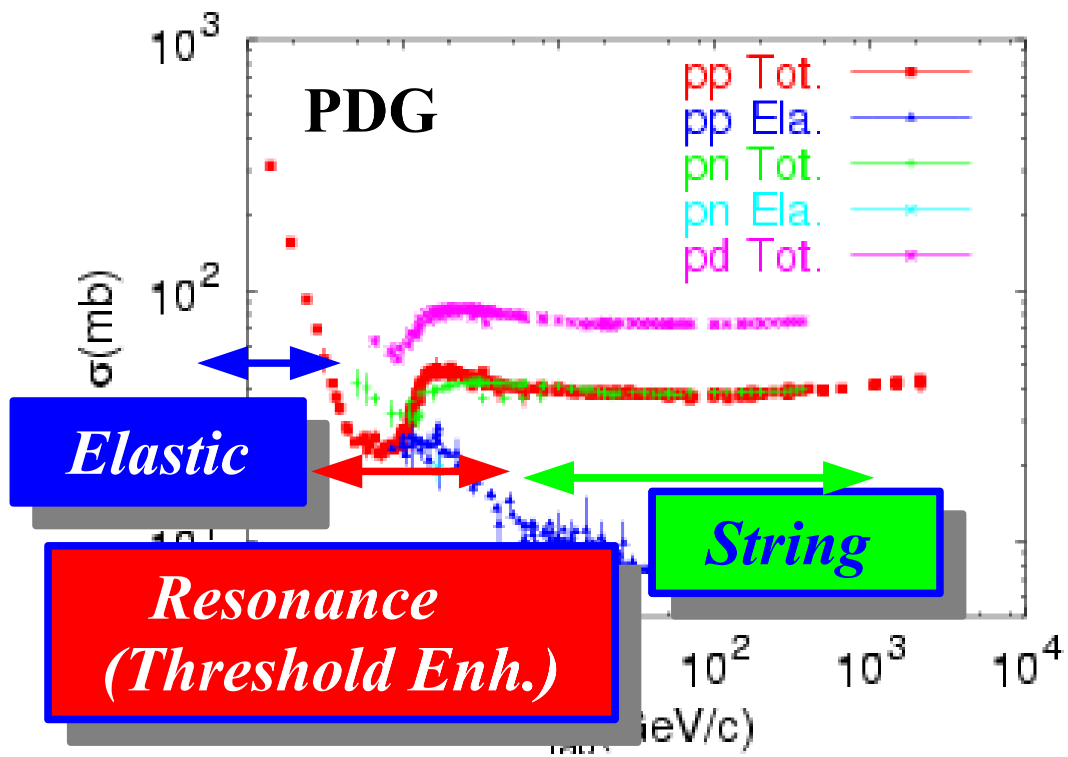
$$\sigma_{tot}(s)^{\pi N} = \sigma_{BW}(s) + \sigma_{el}(s) + \sigma_{s\text{-}S} + \sigma_{t\text{-}S}(s)$$



Modeling of low energy BB cross sections

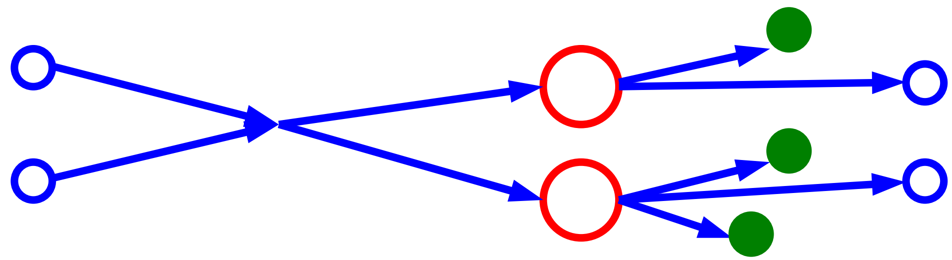
- **Total & Elastic (NN): Table fit**
- **Resonance formation**
  NN → NR, RR (R= Δ, N*) ←1 π, 2π prod. σ fit
- **Strong & Jet prod**
  Inclusive spectra (PYTHIA)

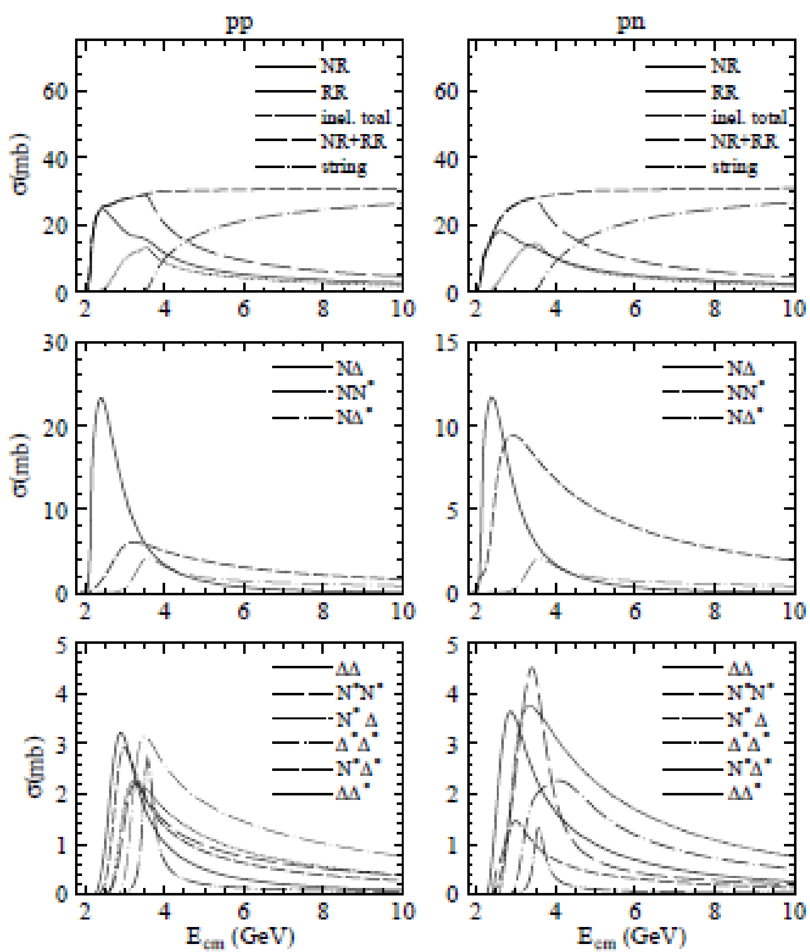


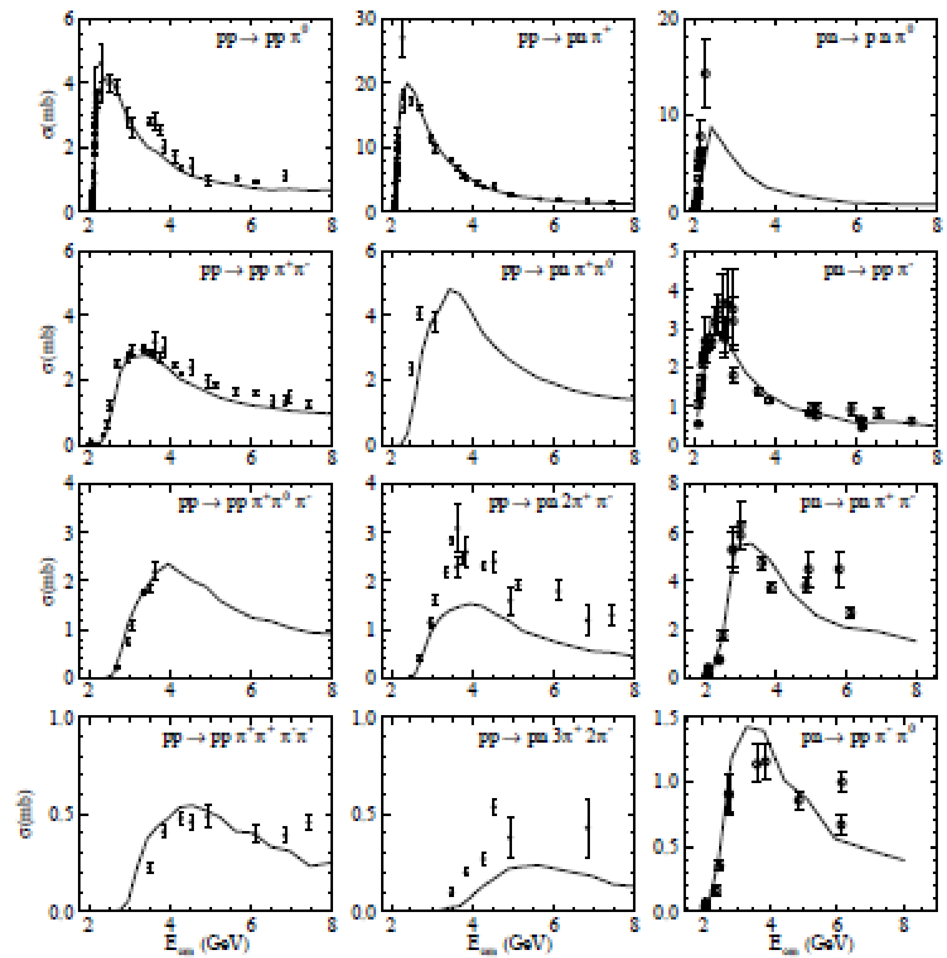


Modeling of low energy BB cross sections

- **NN → NR, RR, N+string, ...→ NN+π, NN+ππ, NN+πππ,**







High Energy Cross Sections

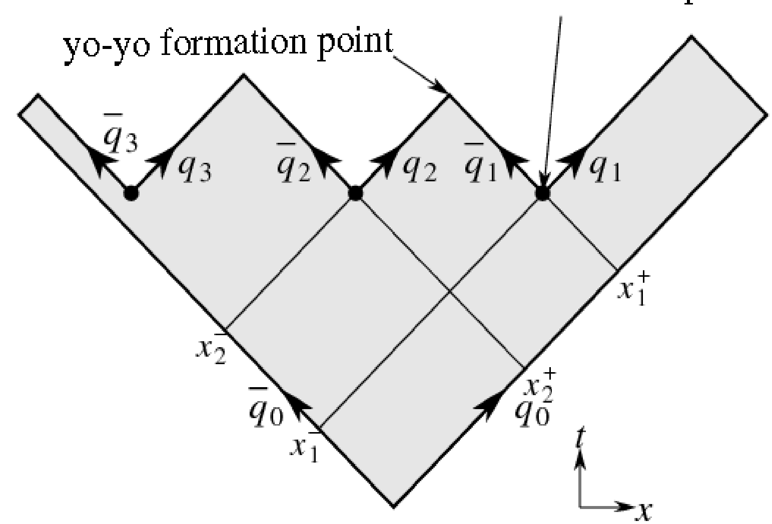
- **Eikonal formulation of pQCD**
  HIJING: X. N. Wang, Phys. Rep. 280('97)287
  PYTHIA6:T. Sjostrand et al., CPC 135('01),238

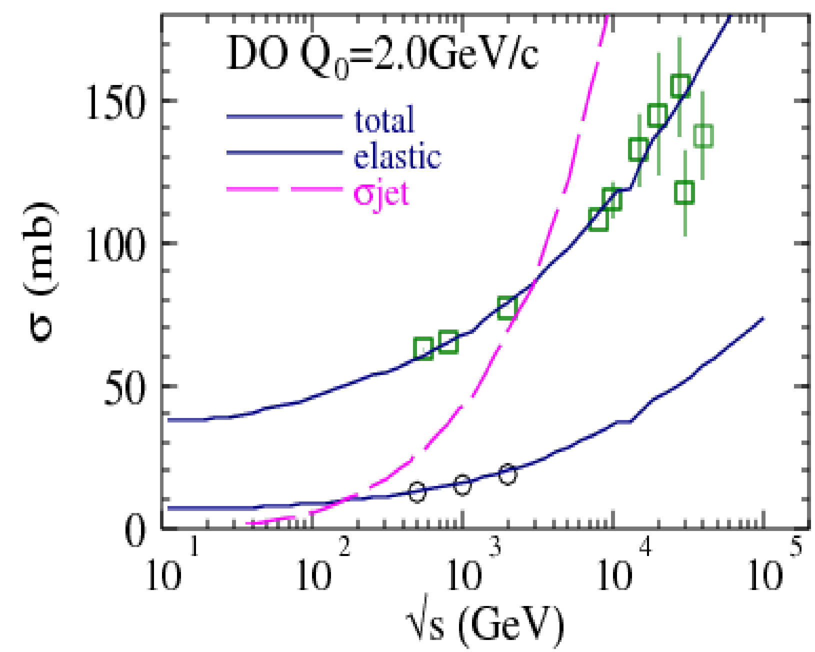
$$\sigma_{t-S} = 2\pi \int_0^\infty db^2 [1 - \exp \chi(b,s)]$$

$$\chi(b,s) = \frac{1}{2}[\sigma_{\rm jet}(s) + \sigma_{\rm soft}(s)] A(b,s)$$

$$\sigma_{\rm jet} = \int_{p_0^2}^{s/4} dp_T^2 dy_1 dy_2 \frac{1}{2} K \sum_{a,b} x_1 x_2$$

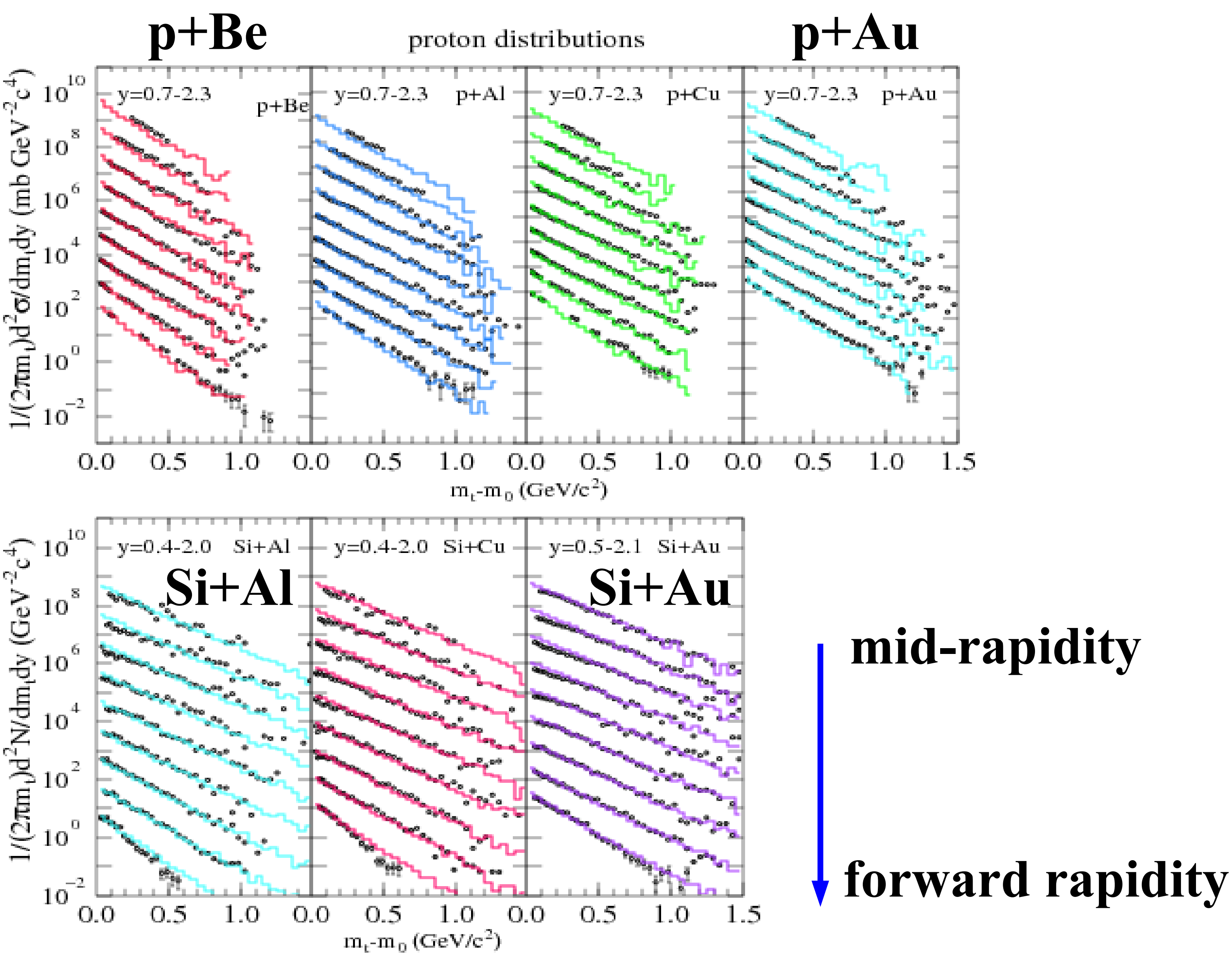
$$\times f_a(x_1, p_T^2) f_b(x_2, p_T^2) \frac{d\sigma^{ab}(\hat{s},\hat{t},\hat{u})}{d\hat{t}}$$





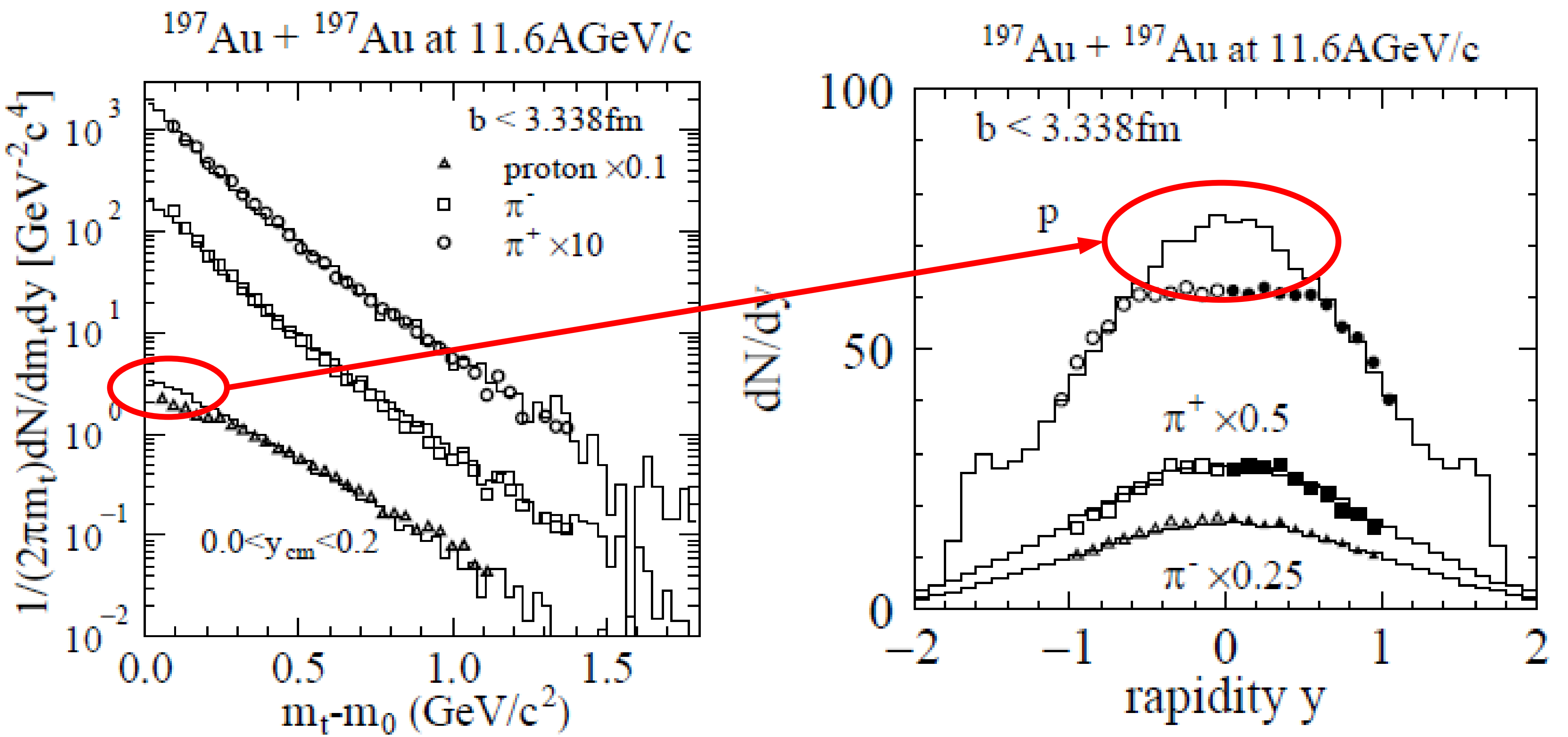
- **Soft part → Lund string formation (Light cone mom. transf.: HIJING)**
- **Jet part → pQCD x K factor**
- **Yo-yo formation point: UrQMD**

Proton p_T spectra at AGS



Y.Nara, N.Otuka, A.Ohnishi, K.Niita and S.Chiba, PRC61, 024901 (2000).

Hadron spectra in Au+Au at AGS

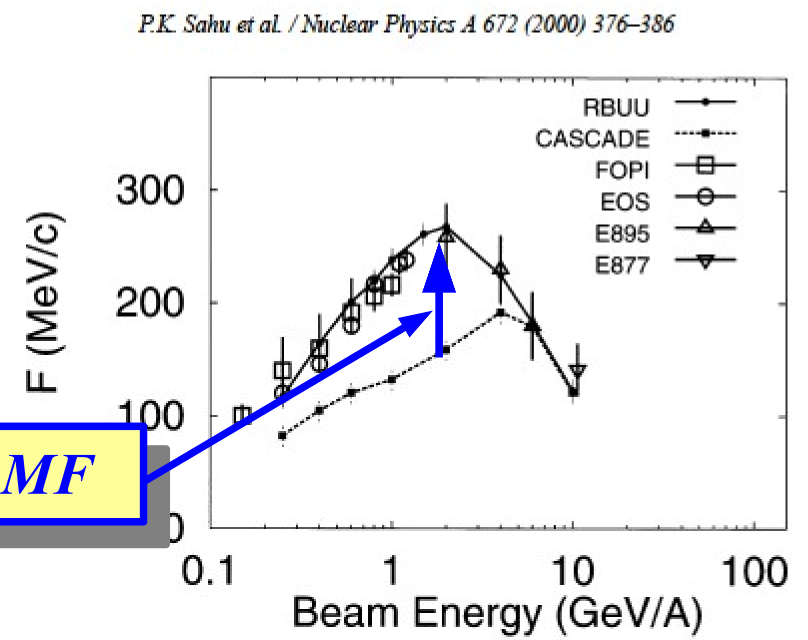


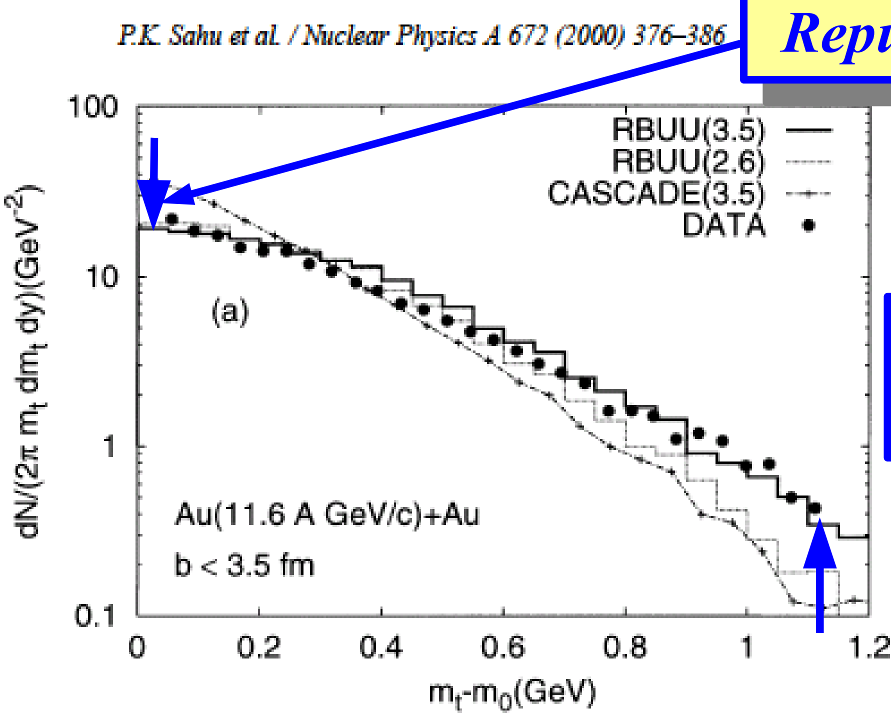
Hadron pT spectra at AGS are good, except for low pT protons (→ Mean Field Effects).

Mean Field and Particle DOF Effects @ AGS

- **Mean Field Effects at AGS**
  → Visible but small for p_T spectrum
  Essential for Flow
- **Particle DOF Effects**
  → Seen at high p_T

Sahu, Cassing, Mosel, Ohnishi, 2000





Repulsive MF

Switching √s = 3.5 GeV (JAM fit)

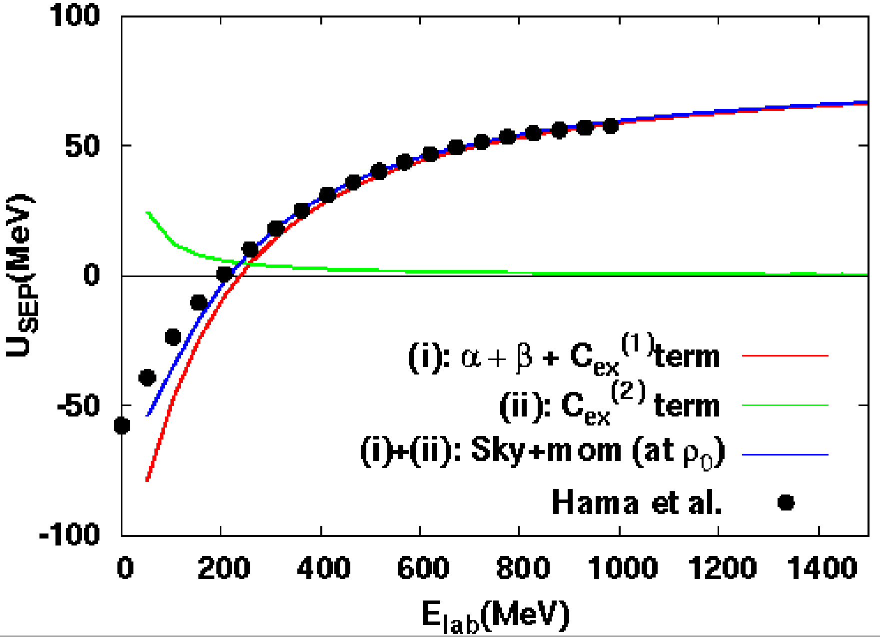
Switching √s = 2.6 GeV (HSD default)

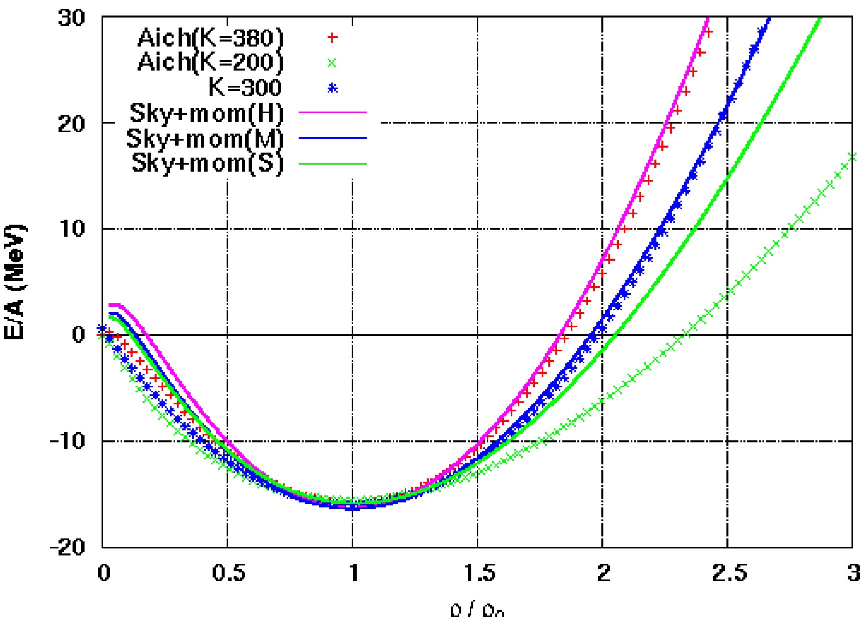
Phenomenological Mean Field

- **Skyrme type ρ-Dep. + Lorentzian p-Dep. Potential**

$$V=\sum_i V_i=\int d^3r\left[\frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{\beta}{\gamma+1}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}\right]$$

$$+\sum_k\int d^3r\,d^3p\,d^3p'\,\frac{C_{ex}^{(k)}}{2\rho_0}\,\frac{f(r,p)f(r,p')}{1+(p-p')^2/\mu_k^2}$$



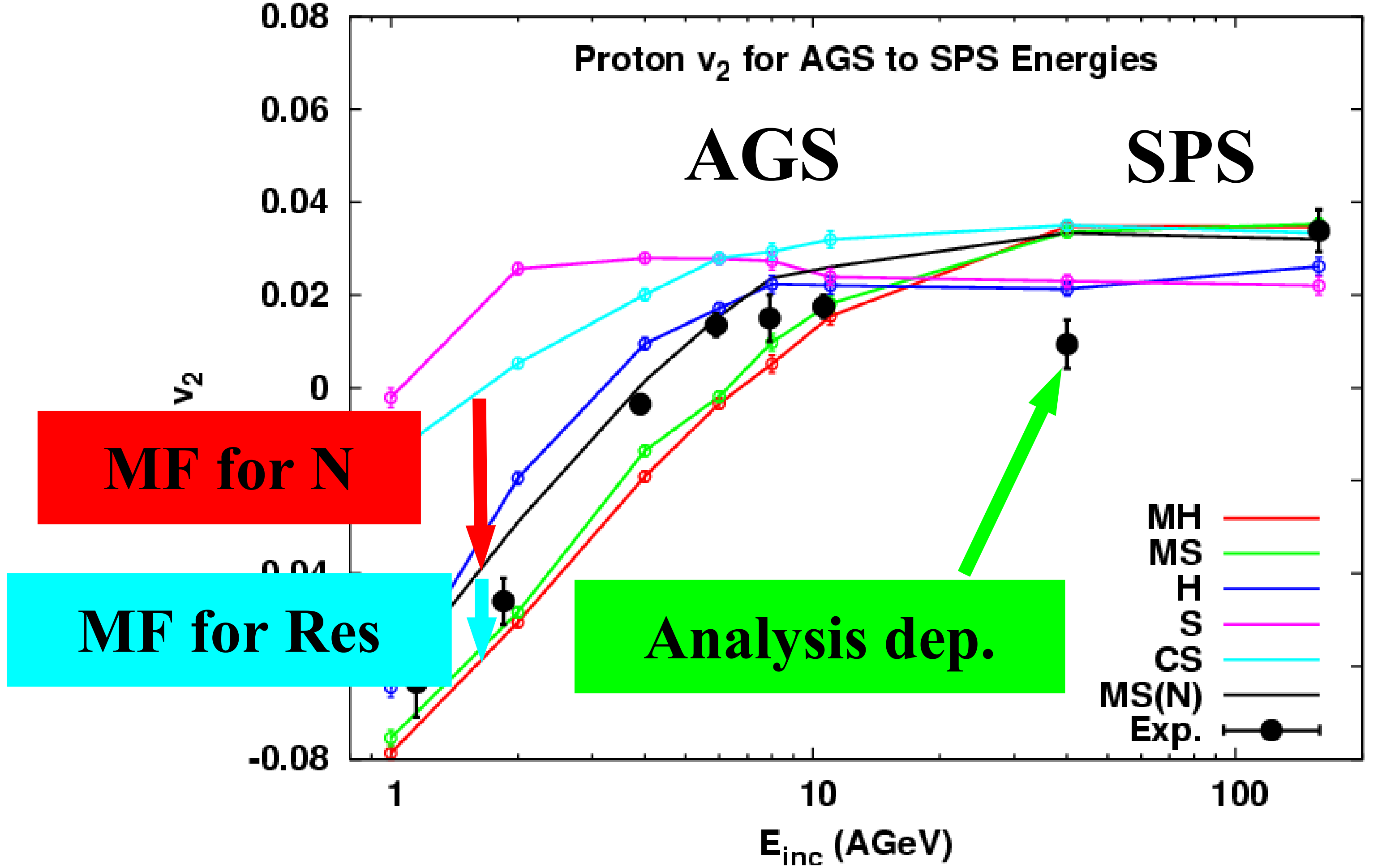


Simplified RQMD treatment of p- and ρ-dep. mean field in JAM

Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908

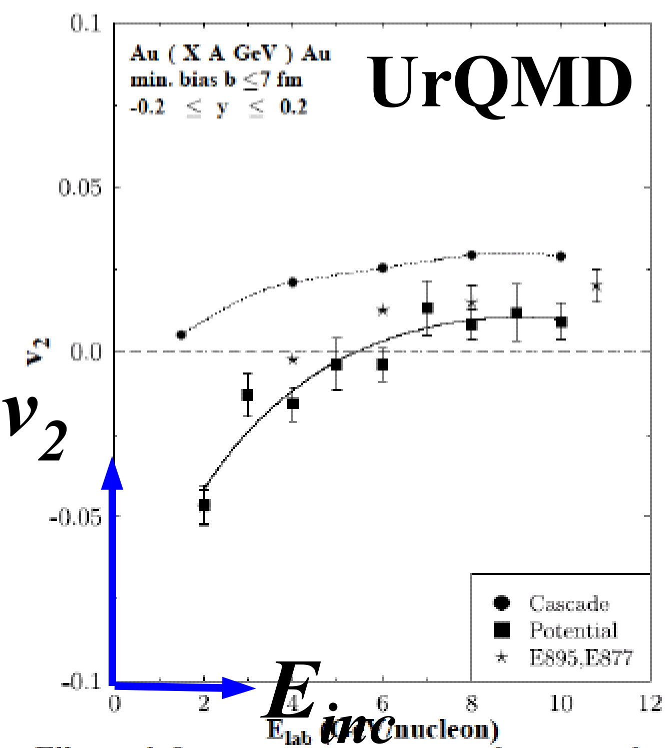
Elliptic Flow from AGS to SPS

- **JAM-MF with p dep. MF explains proton v2 at 1-158 A GeV**
  - **v2 is not very sensitive to K (incompressibility)**
  - **Data lies between MS(B) and MS(N)**

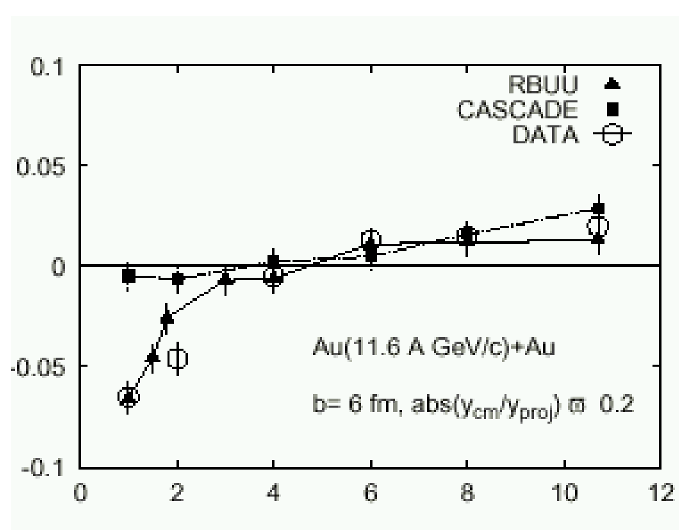


Elliptic Flow at AGS

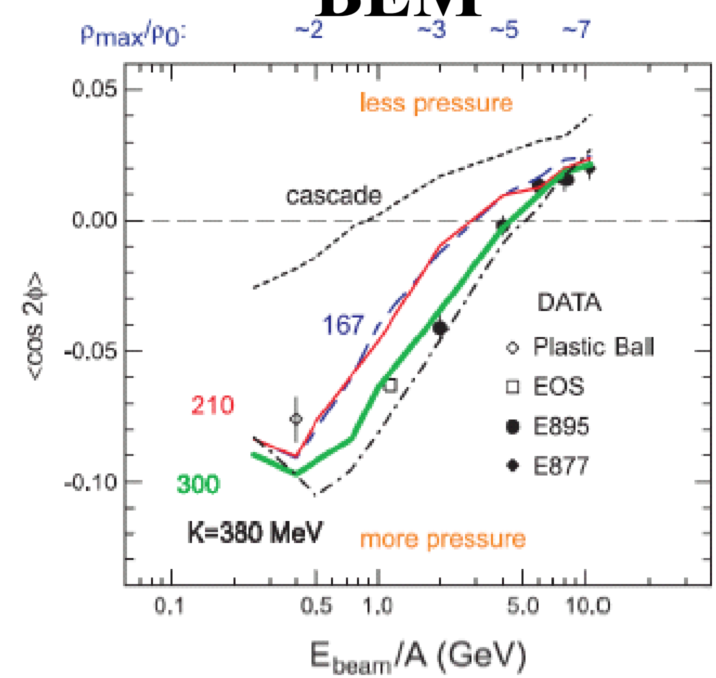
- **Other transport models also show the change from strong squeezing at low E (2-4 A GeV) to the particiant dynamics at higher E**
  - **UrQMD: Hard EOS (S.Soff et al., nucl-th/9903061)**
  - **RBUU : K ~ 300 MeV (Sahu,Cassing,Mosel,AO, 2000)**
  - **BEM: K = 167 → 300 MeV (Danielewicz,Lynch,Lacey,2002)**



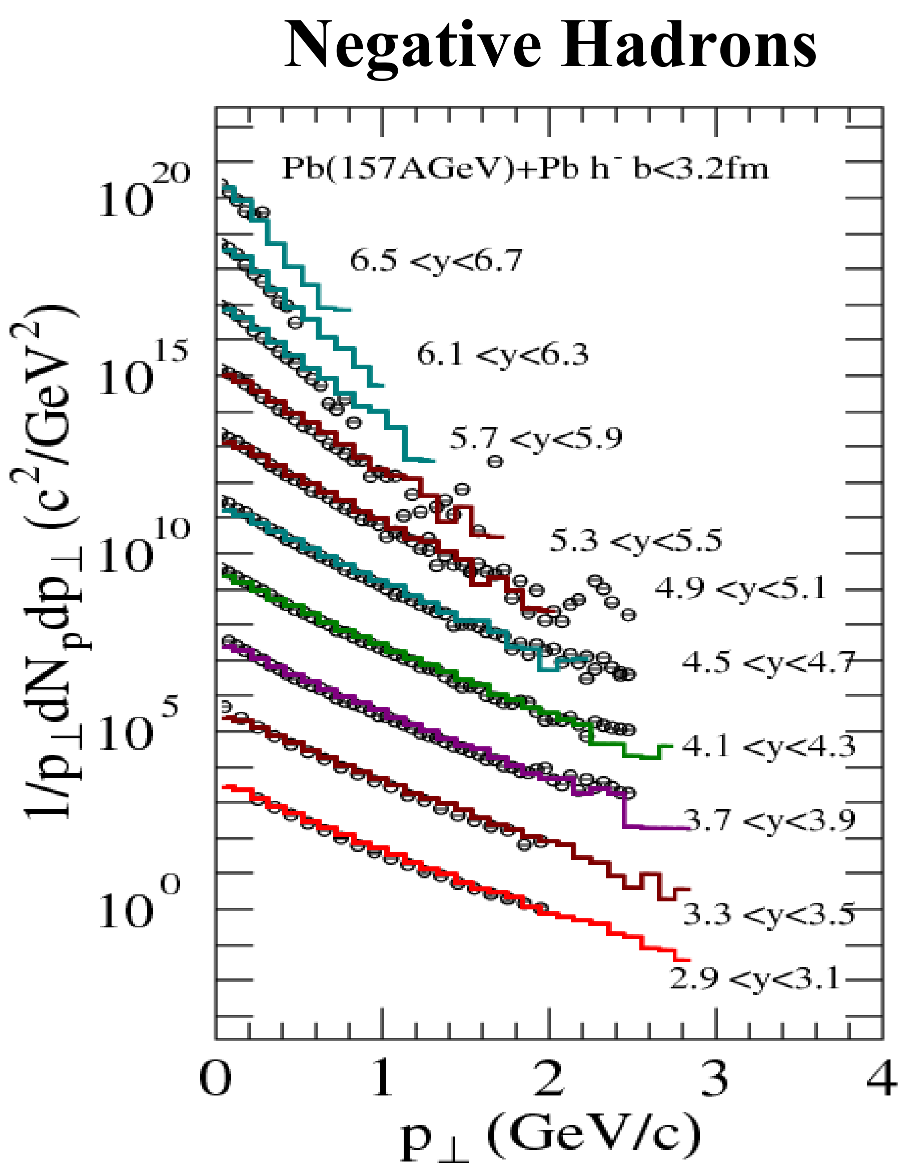
RBUU

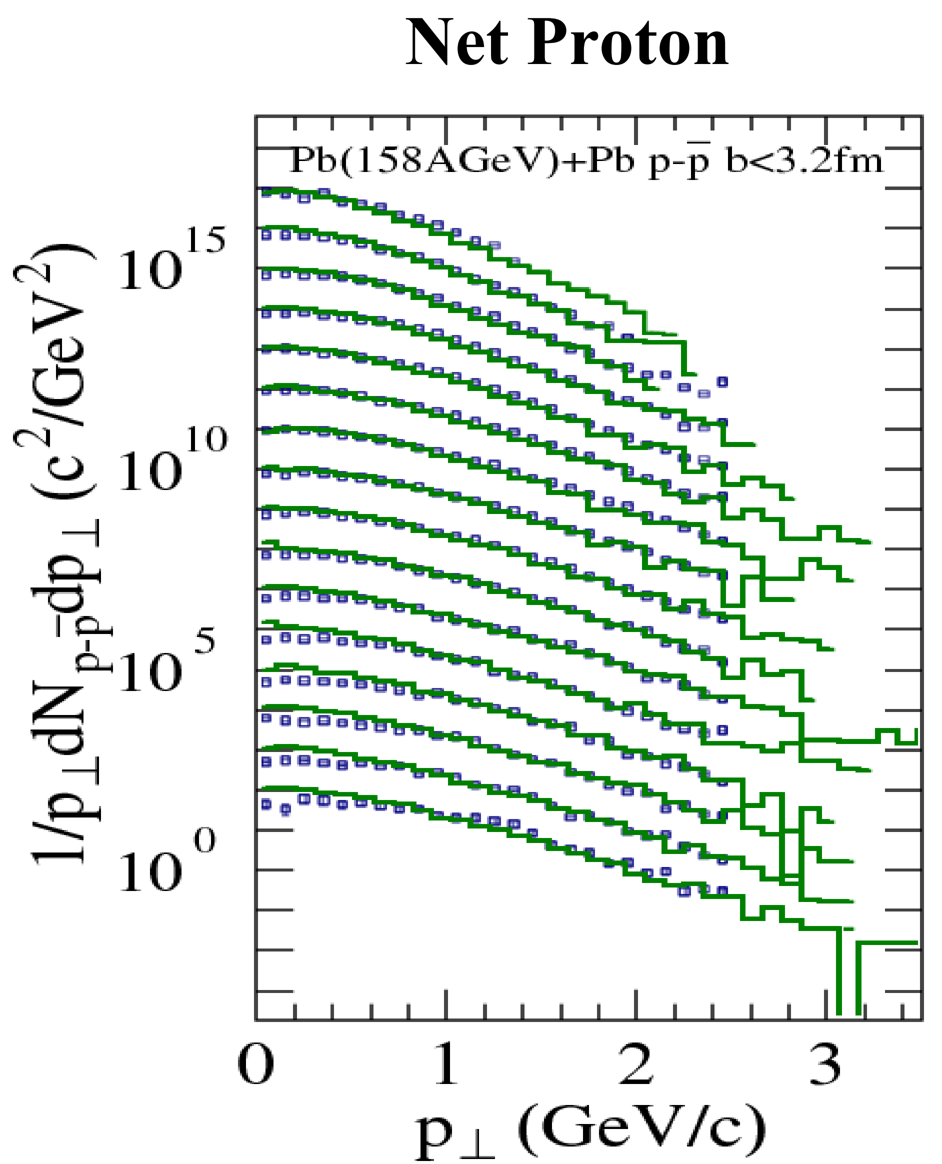


BEM



Hadron Spectra in Pb+Pb at SPS (158 A GeV)

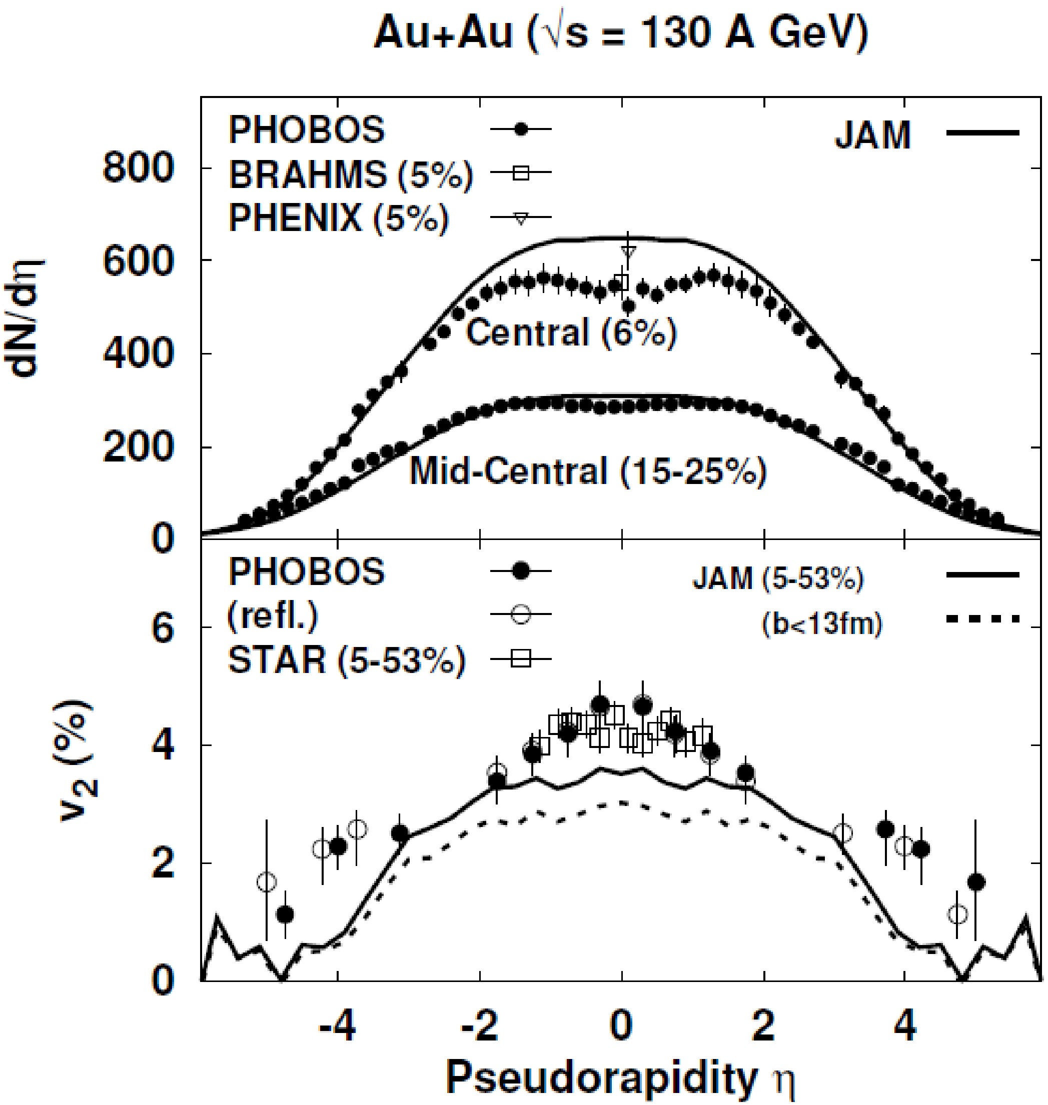


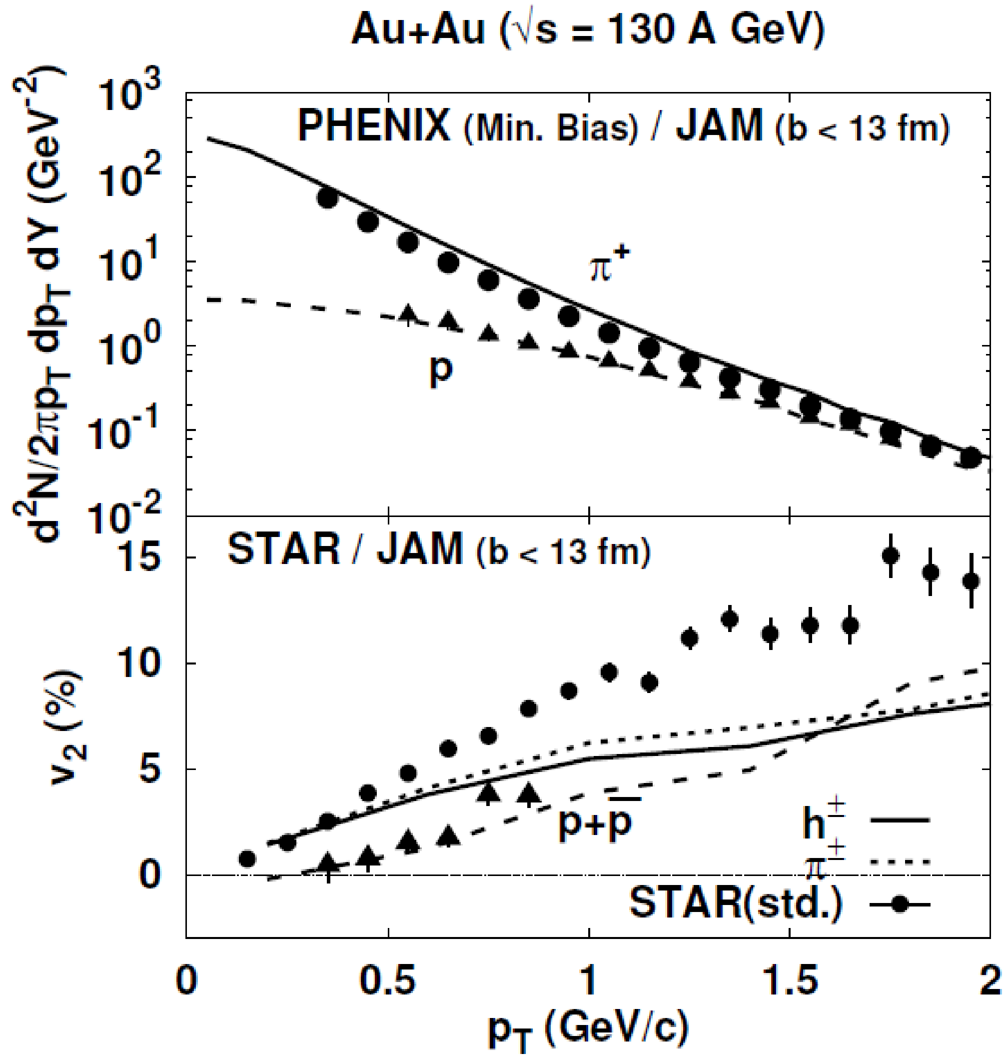


Hadron pT spectra at SPS are well explained in JAM.

JAM at RHIC

P.K.Sahu, A. Ohnishi, M. Isse, N. Otuka, S.C.Phatak, Pramana 67(2006),257.





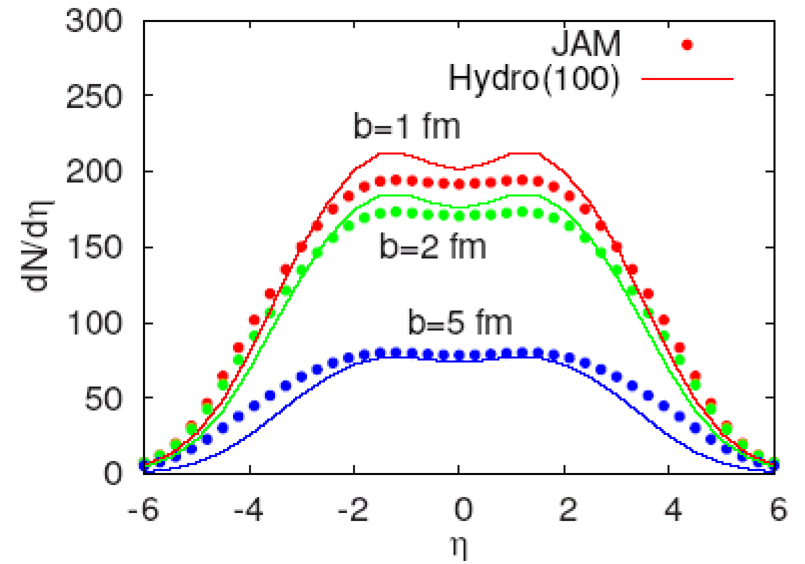
JAM underestimates v_2 at $p_T > 0.5$ GeV.

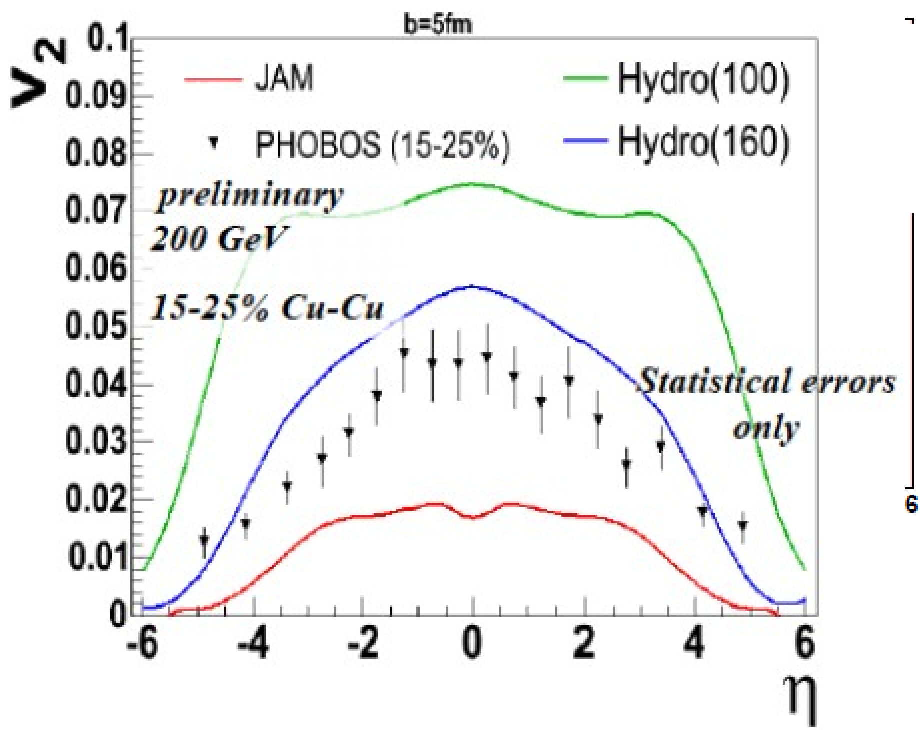
Hydro vs. Cascade in Cu+Cu

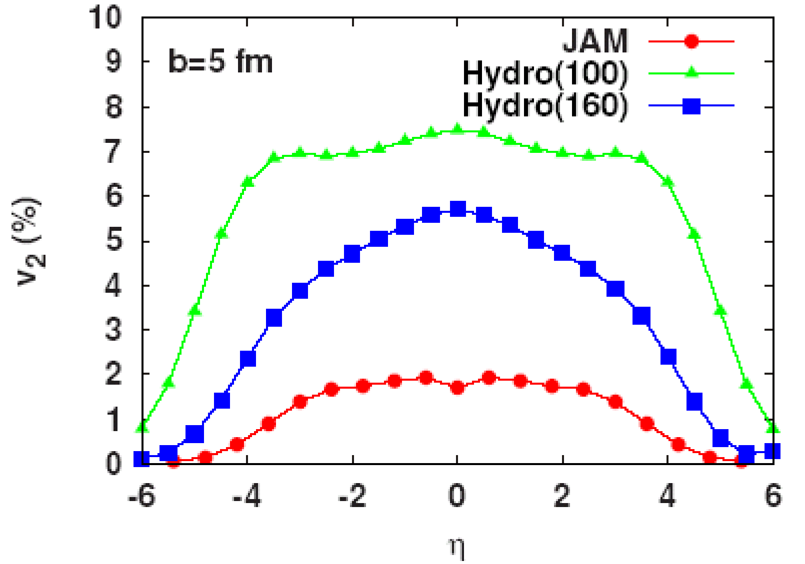
- **Comparison of Hydro and JAM for Cu+Cu collisionsat RHIC energy**

  Hirano, Isse, Nara, AO, Yoshino, 2005

  - **Hydro and Cascade predict similar dN/dη, but different v_2.**
  - **PHOBOS data prefers Hydro(160).**

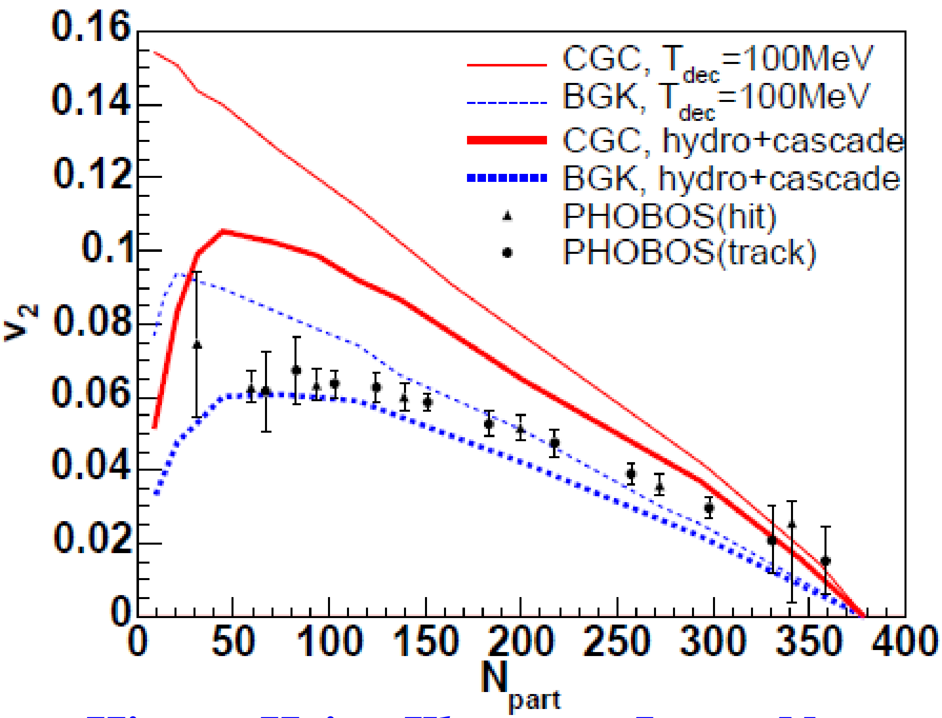






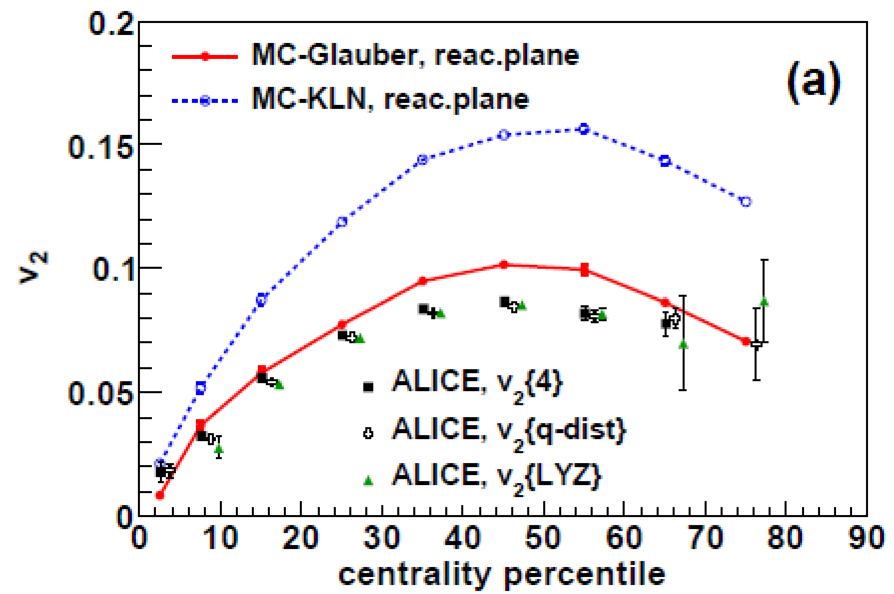
Hydro + Cascade at RHIC

- **JAM as a hadronic cascade afterburner of hydrodynamics → Hydro+Cascade Hybrid model**
  T.Hirano, U.Heinz,D.Kharzeev,R.Lacey,Y.Nara,PLB636,('06)299.
  - **Finite mfp → larger viscosity → smaller v2**
  - **With fluc. in mind, Hybrid model w/ BGK initial cond. would be good enough.**



Hirano,Heinz,Kharzeev, Lacey,Nara, PLB636 ('06)299.

LHC

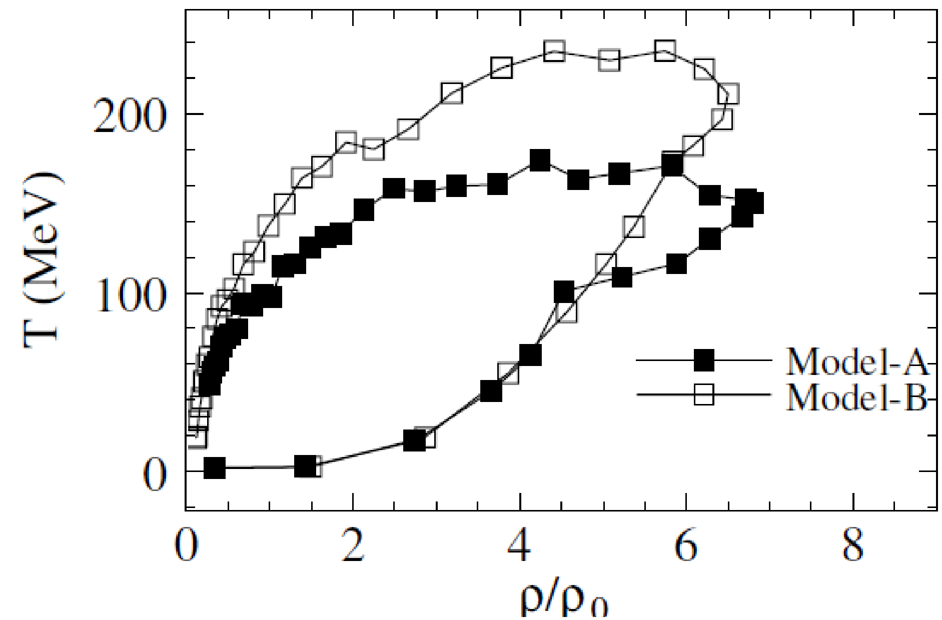


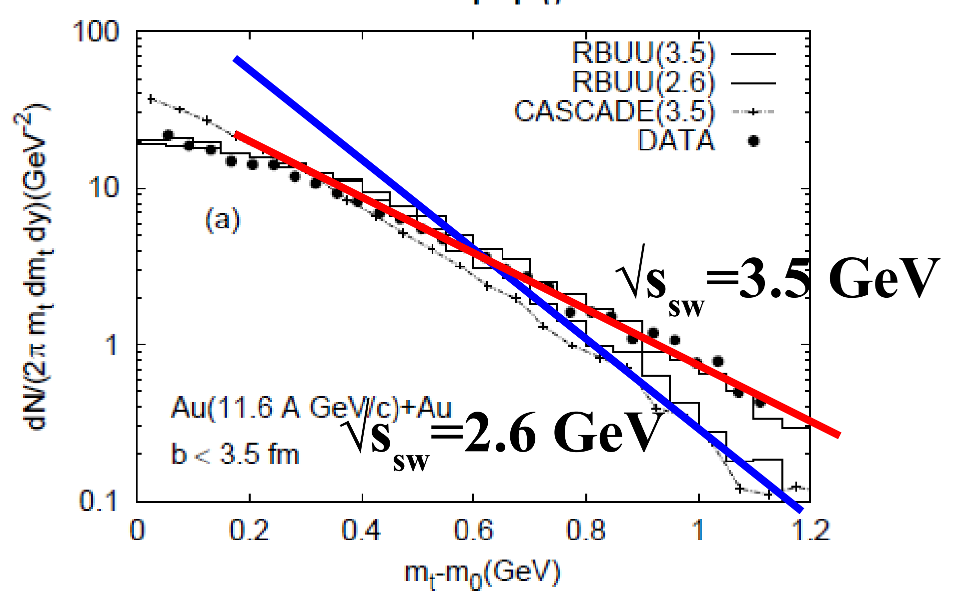
Hirano,Huovinen,Nara, arXiv:1012.3955

DOF Effects

- Can we obtain the hadronic level density from HIC ?
- Basic Idea: Microcanonical
  - Large DOF → Smaller T
  - Small DOF → Larger T
- Comparison of Large/Small DOF models
  - Model-A(JAM): Res.&Strings
    Model-B: N, Δ, N(1440), N(1535)
    → Larger DOF suppresses T
  - Hadron/String switching $\sqrt{s}$ dep.
    (smaller $\sqrt{s}_{sw}$ → larger DOF)

Y. Nara, N. Otuka, A. Ohnishi, T. Maruyama
Prog. Theor. Phys. Suppl. 129 ('97), 33.



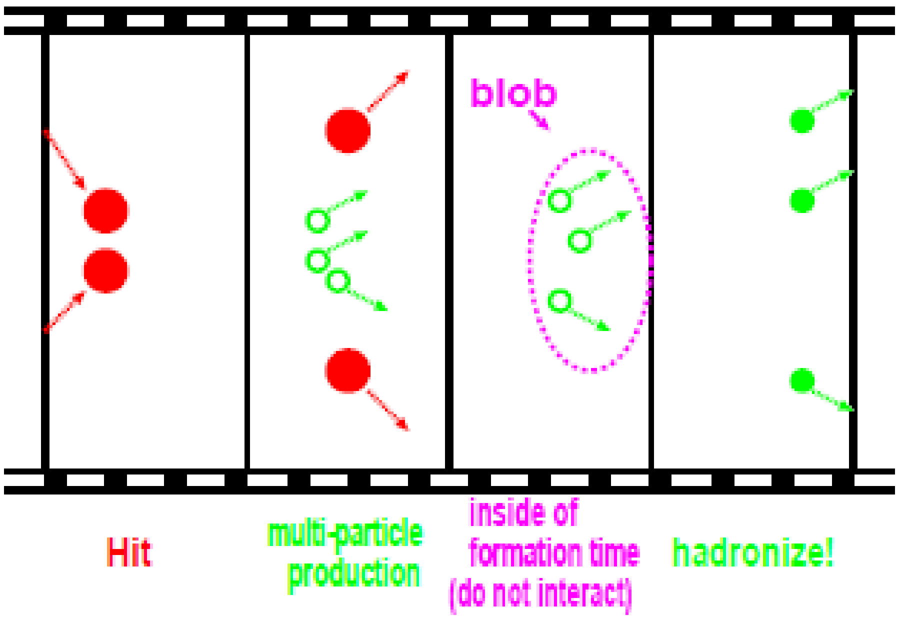


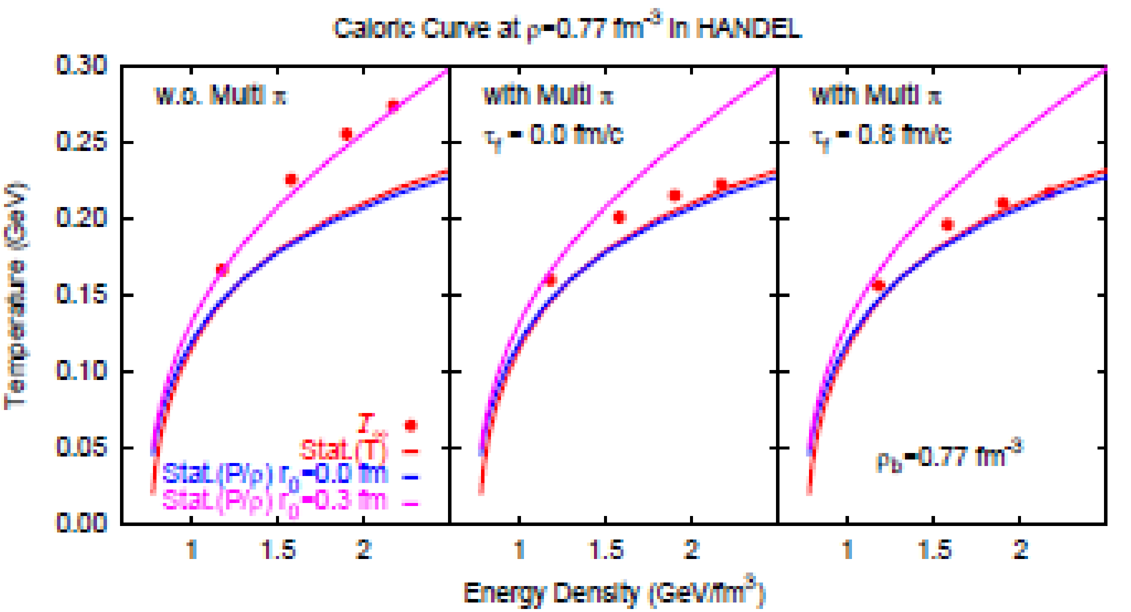
P. K. Sahu, W. Cassing, U. Mosel, A. Ohnishi
NPA672('00)376.

DOF effects (cont.)

- Objection !
  - Repulsive MF has also the effects to stiffen p_T spectrum.
  - We need direct multi π production in small DOF models, whose inverse processes are not included.
    → If we take "blob" into account, small DOF caloric curve is close to that in larger DOF models.

Left panel: small DOF HRG with finite excluded volume (c.f. J.Noronha-Hostler, C. Greiner, I. Shovkovy, 2010)

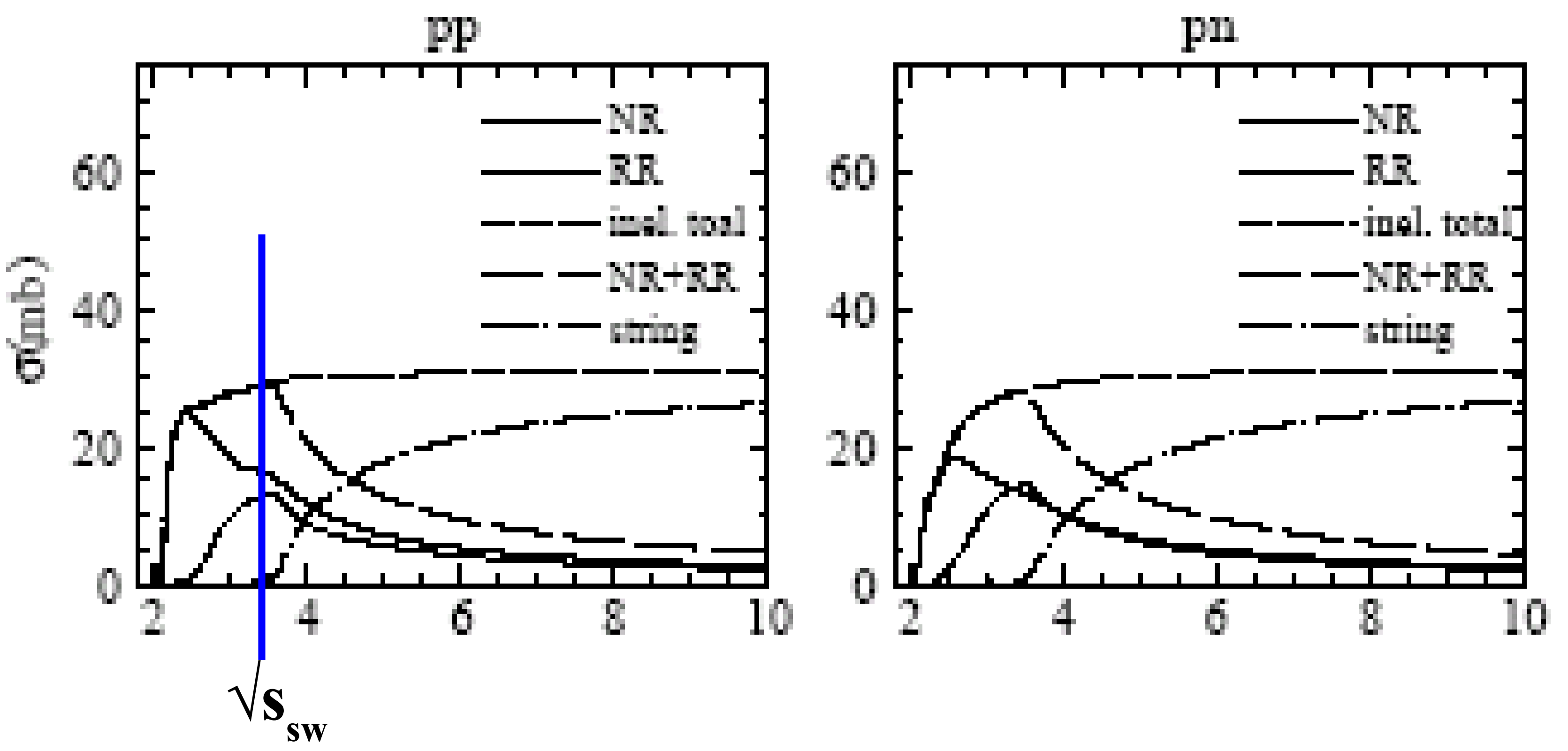




N. Otuka, Thesis, 2000

Where do strings dominate in NN collisions ?

- **JAM parametrization: √s ~ 3.5 GeV**
  → Vacuum hadron level density appearing in *hh* collision
  is not inconsistent with AA collisions up to SPS energies.
  It also shows Hagedorn gas like behavior in the caloric curve.



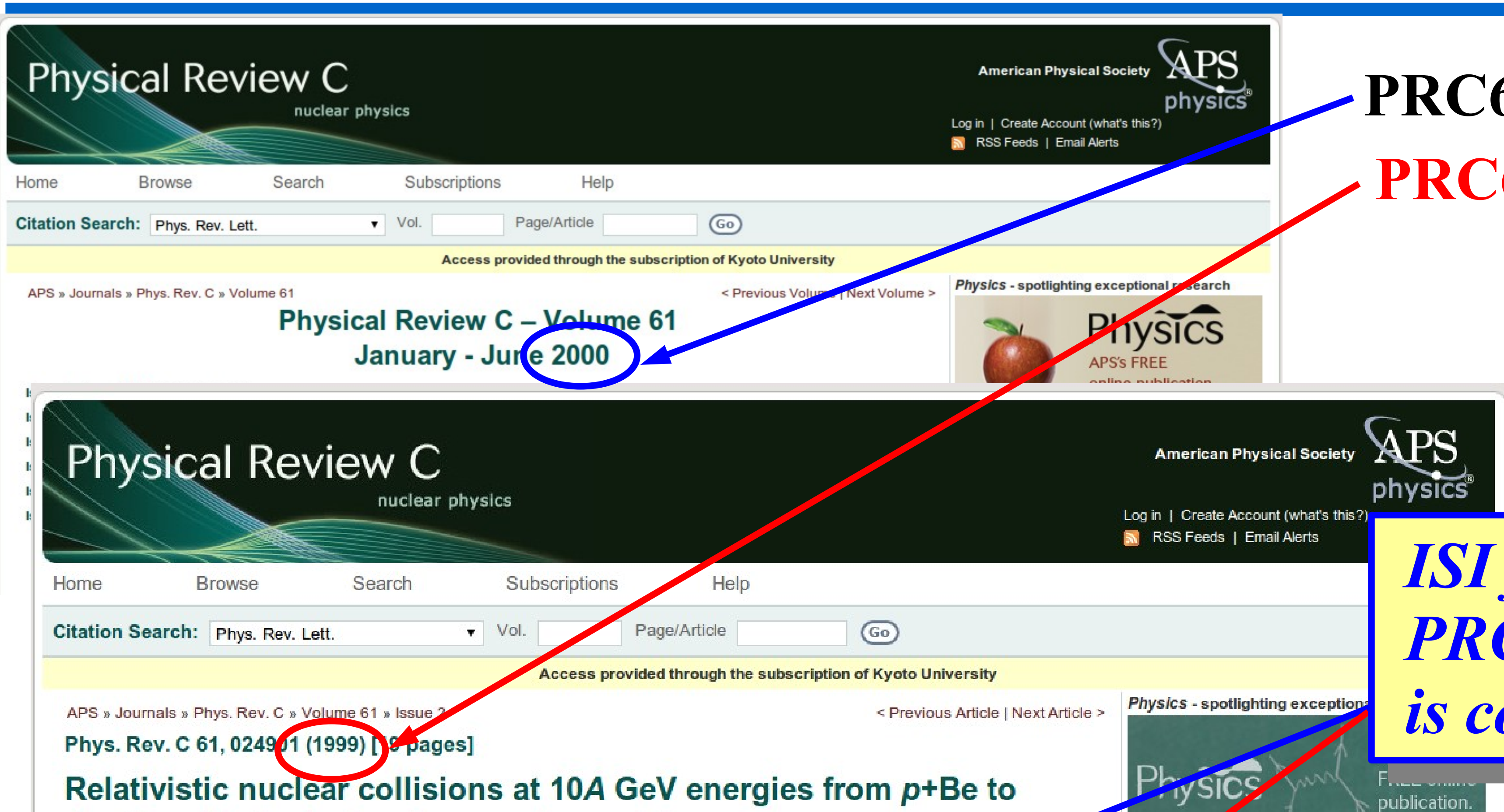
Summary

- Hadronic transport is important in heavy-ion collisoins even at very high energies. We need models which describes lower energy (AGS, SPS) HIC data.
- JAM offers a reasonable model description.
  - p_T spectra in pA and AA, Flow from 1-158 A GeV (with MF) at AGS and SPS energies.
  - Bulk observables (dN/dη and pT spectrum) at low p_T (p_T <2 GeV) at RHIC are also reasonably well described, but v_2 cannot be explained (Early time parton-parton interaction is important).
  - Hydro+Cascade(JAM) is successful at RHIC.
- Resonance DOF (level density) really affect the particle spectrum, but they would be easily masked by the multi π production processes and MF. We need careful treatment including σ fit with N* and study of flows with N*.

Published year of JAM's first paper

PRC61(2000)

PRC61(1999)?



...Nara Y	PHYS REV C	2002	66		ARTN 041901	42	レコードを表示
...Nara Y	PHYS REV C	2002	65		ARTN 024901	17	レコードを表示
NARA Y	PHYS REV C	2001	61		UNSP 024901	2	
NARA Y	PHYS REV C	2000	61		ARTN 024901	50	レコードを表示
NARA Y	PHYS REV C	2000	61		UNSP 02901	1	
NARA Y	PHYS REV C	2000	61		UNSP 010001	1	
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NARA Y	PHYS REV C	1999	61		UNSP 024601	1	
...Nara Y	PHYS REV C	1997	56	2767		12	レコードを表示

ISI judge PRC61(2000) is correct

Thank you !

Hydro vs. Cascade in Cu+Cu

- **Comparison of Hydro and JAM for Cu+Cu collisionsat RHIC energy**
  Hirano, Isse, Nara, AO, Yoshino, 2005
  - **Hydro and Cascade predict similar dN/dη, but different v_2.**
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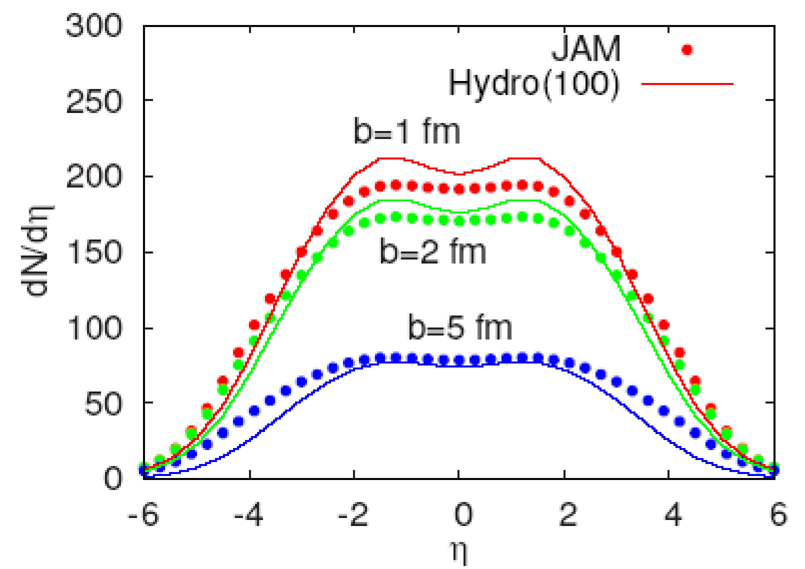
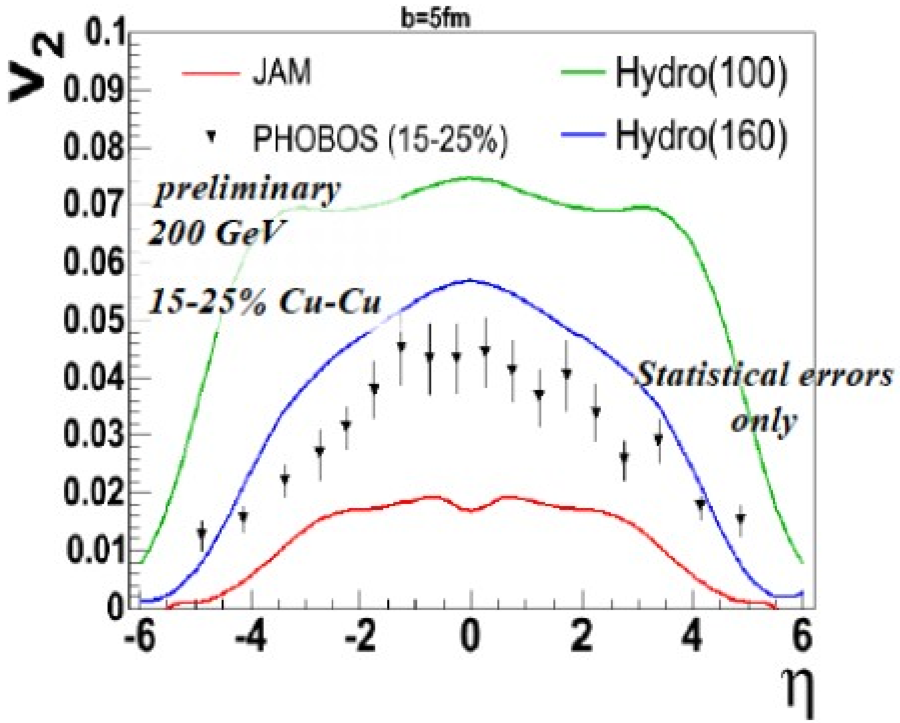
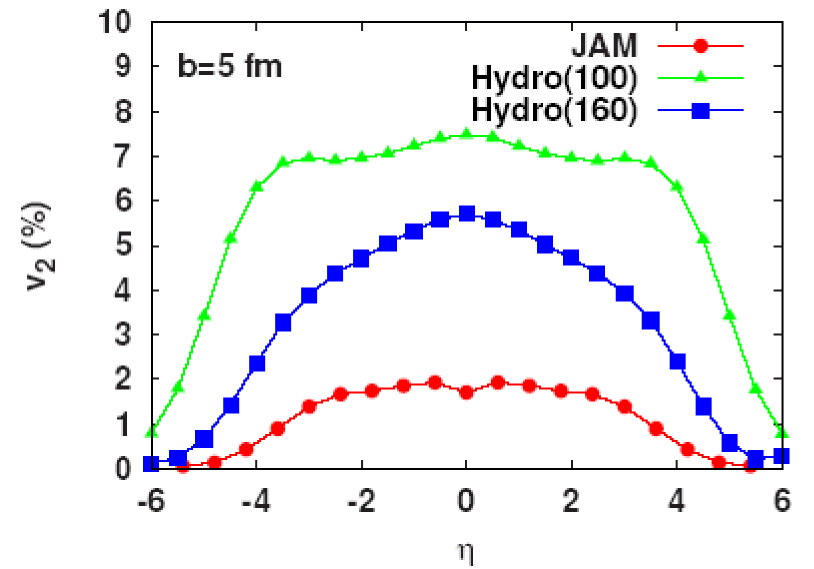






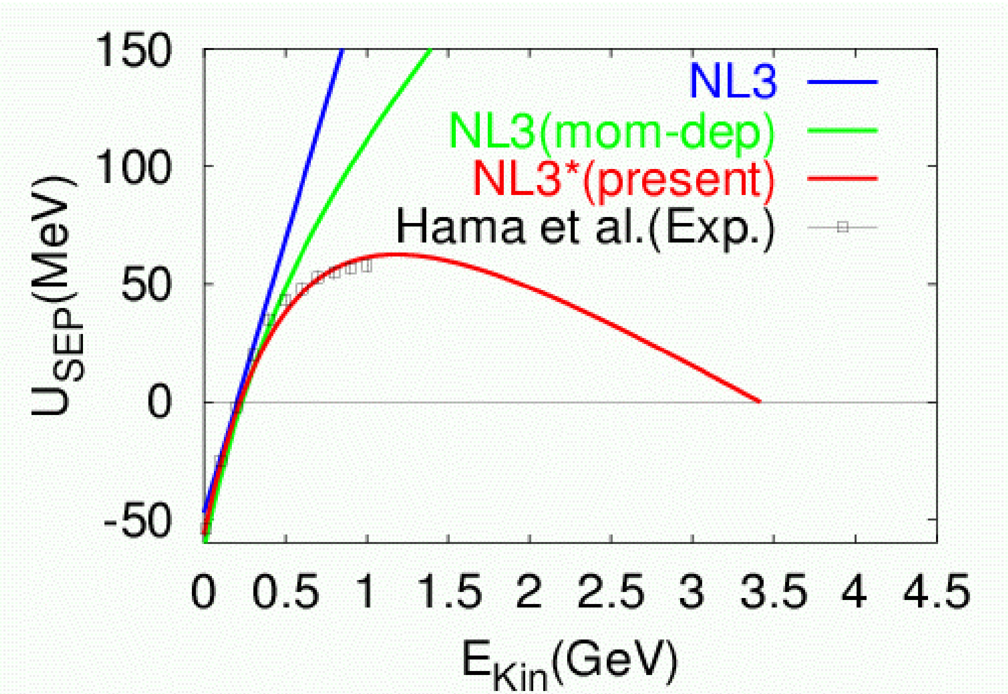
Relativistic Mean Field with cut-off

- **Dirac Equation** $\left(i\gamma\partial-\gamma^0 U_v-M-U_s\right)\psi=0\ ,\quad U_v=g_\omega\omega\ ,\quad U_s=-g_\sigma\sigma$
- **Schroedinger Equivalent Potential**

$$\begin{pmatrix} E-U_v-M-U_s & -i\sigma\cdot\nabla \\ i\sigma\cdot\nabla & -E+U_v-M-U_s \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix}=0$$

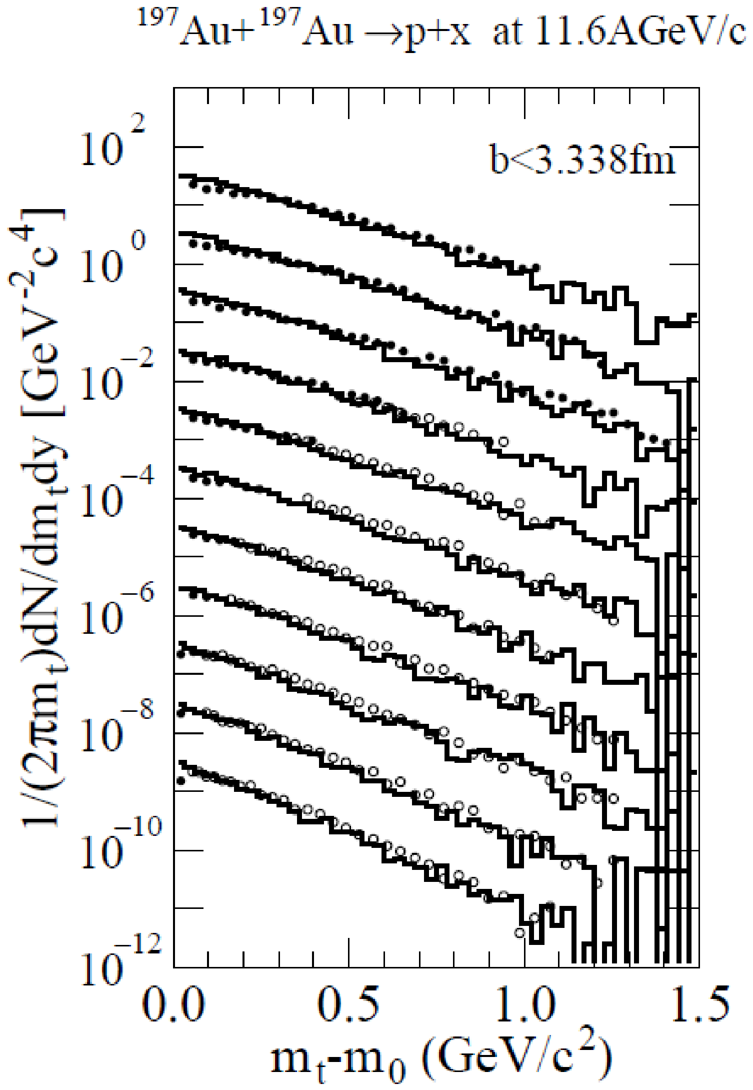
$$U_{sep}\sim U_s+\frac{E}{m}U_V=-g_\sigma\sigma+\frac{E}{m}g_\omega\omega$$

$$=-\frac{g_\sigma^2}{m_\sigma^2}\rho_s+\frac{E}{m}\frac{g_\omega^2}{m_\omega^2}\rho_B$$



Saturation: -Scalar+Baryon Density
Linear Energy Dependence: Good at Low Energies,
Bad at High Energies (We need cut off !)

(Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)

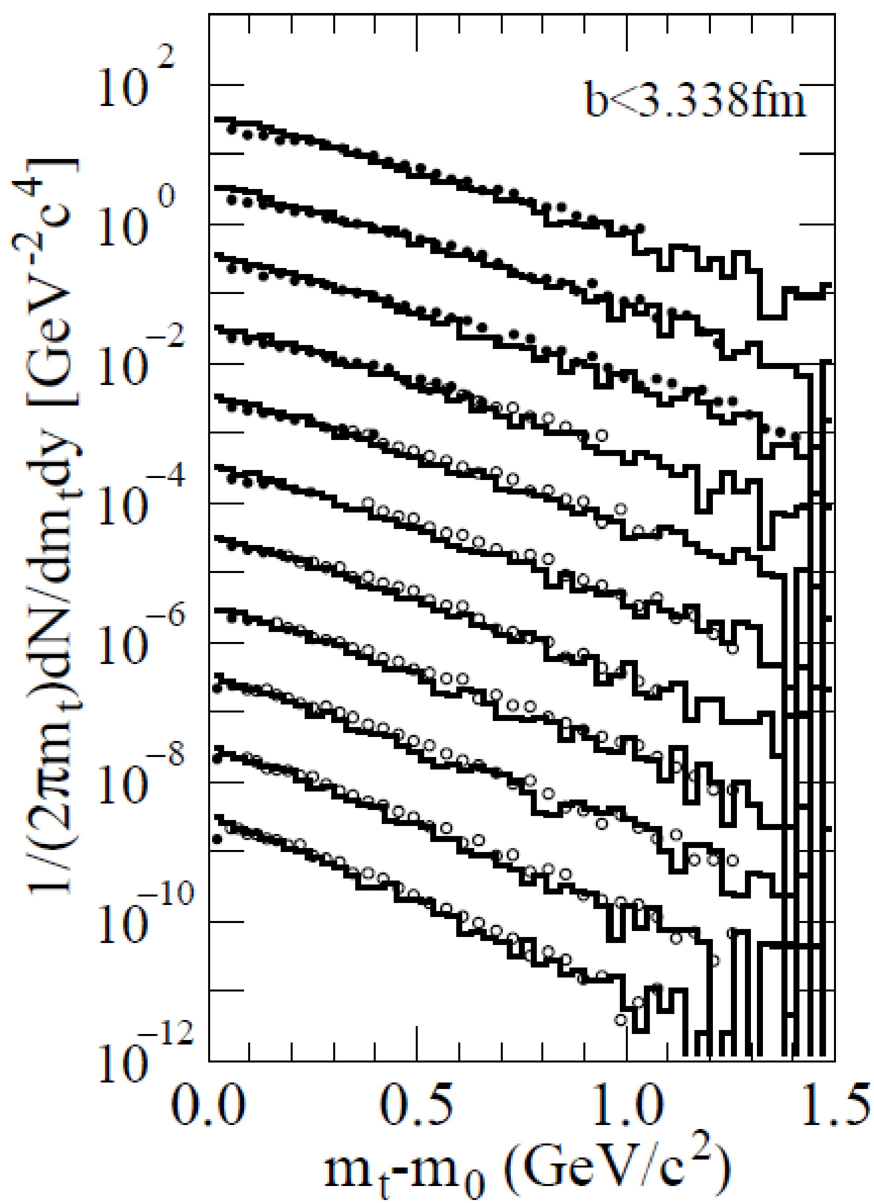


^{197}Au+^{197}Au →p+x at 11.6AGeV/c
b<3.338fm
1/(2πm$_t$)dN/dm$_t$dy [GeV^{-2}c^4]
m$_t$-m$_0$ (GeV/c^2)

AGS Energy

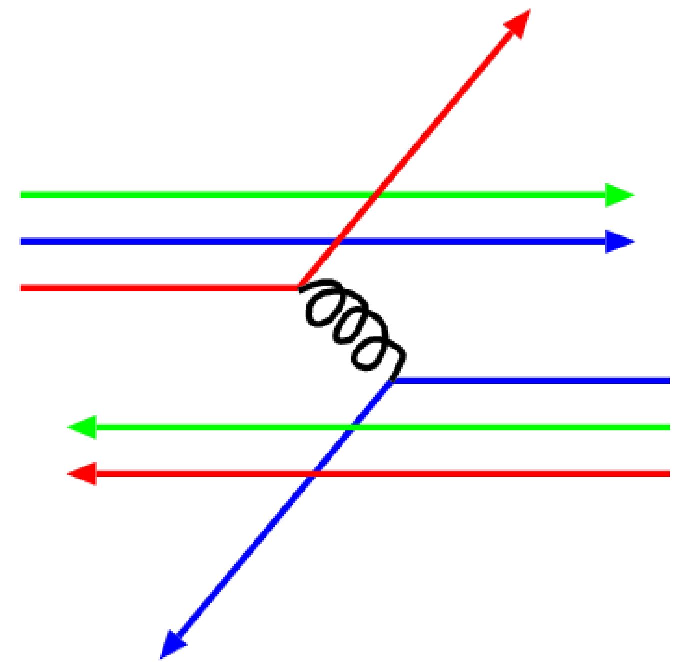
- **Jet AA Multiple scattering model**
  Nara, Otuka, AO, Niita, Chiba, 2000
  - Resonance, String, Parton(Jet) 生成を取り入れた輸送模型
  - hh, pA, AA 衝突を一つの枠組みで記述可能
  - Referee から「他の輸送模型も、これだけ完全にチェックして欲しいものだ」とお褒めの言葉。
  - 比較的多くの citation ！
- 技術（仁井田、奈良）＋激励（ Stoecker ）
  - フローなどもすぐに調べるべきだったなあ。

Nara et al., 2000

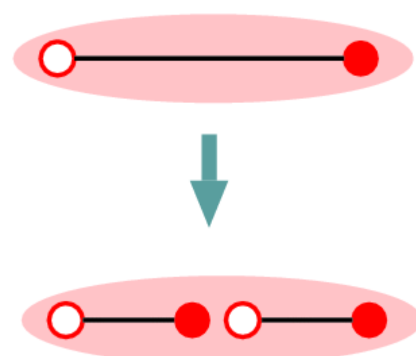


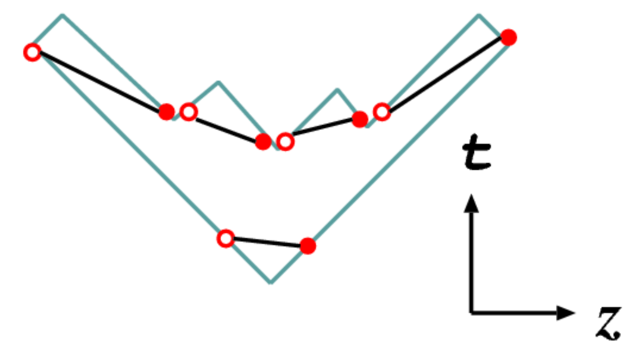
Jet Production

- **Elastic Scattering of Partons (mainly) with One Gluon Exch.**
- **Color Exch. between Hadrons**
  → Complex color flux starting from leading partons
  → many hadron production
  → Jet production



- ***PYTHIA***
  - **Event Generator of High Energy Reactions**
    → Jet production +String decay
    for QCD processes



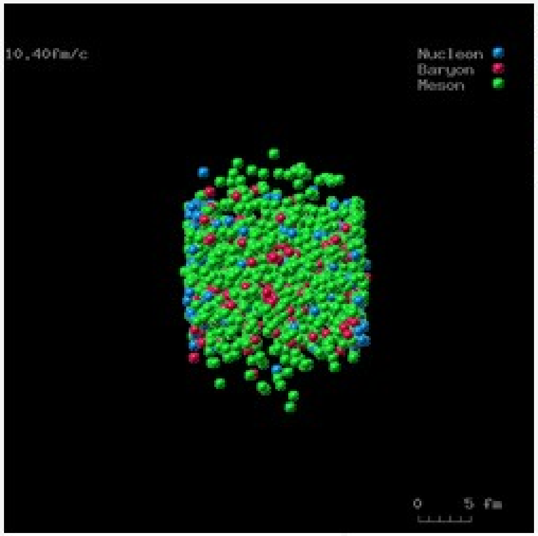


(T. Sjostrand et al., Comput. Phys. Commun. 135 (2001), 238.)

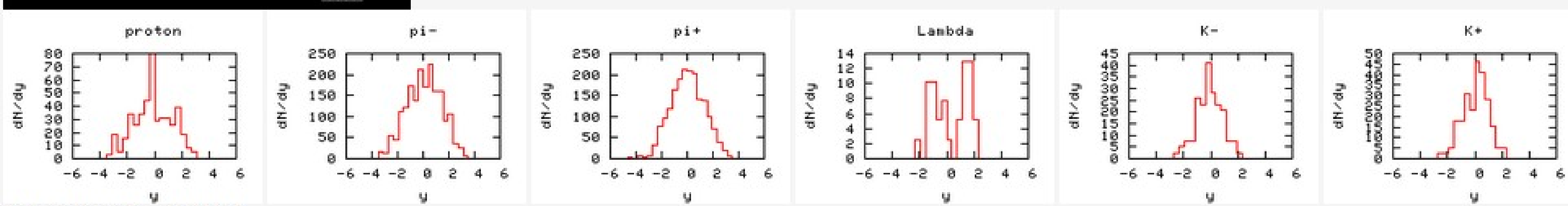
How do heavy-ion collisions look like ?

Japan Charged-Particle Nuclear Reaction Data Group (JCPRG)

JAMing on the Web (JoW) - Result -



Total Simulation Number :	1
Total Simulation Time :	12fm/c
Impact Parameter :	1fm<b<1fm
Calculation frame :	nn
Incident energy :	158GeV
Reaction :	$^{208}Pb+^{208}Pb$



Do you want to save this page?

Yes No submit

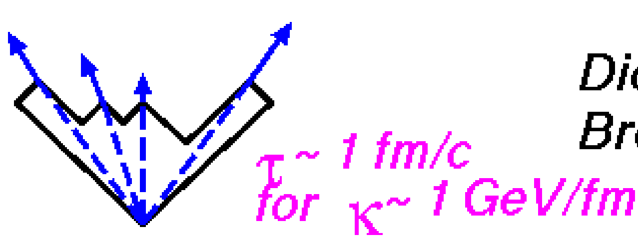
JAMming on the Web

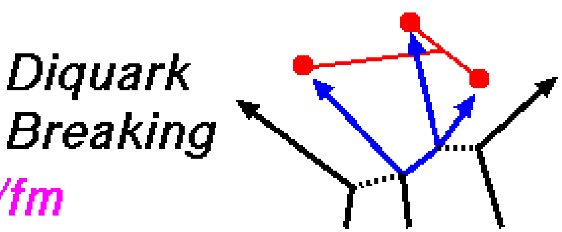
http://www.jcprg.org/jow/

JAM (Jet AA Microscopic transport model)

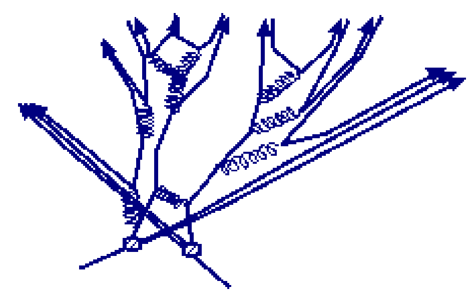
Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.

- **Hadron-String Cascade including Jet production**
- **DOF: Hadron Res. (m < 2 GeV (3.5 GeV) for M (B)) + String**
- **Cross sections** $\sigma_{\rm tot}(s)=\sigma_{\rm el}+\sigma_{\rm ch}+\underbrace{\sigma_{t-R}+\sigma_{s-R}}_{\text{Resonances}}+\underbrace{\sigma_{t-S}+\sigma_{s-S}}_{\text{Strings}}$
  - **Resonance production: NN → NΔ (t-R), πN → Δ (s-R), etc**
  - **String & Jet production (PYTHIA)**
    NN → String+String (t-S)
    πN → String (s-S), etc.
  - **String-Hadron collisions are simulated by *hh* collisio**
    Sorge,PRC52 ('95)3291.
    T. Sjostrand et al., Comput. Phys.
  - **Mean field effects (Optional)**
    Isse et al., PRC('05)
  - **Secondary partonic int.:**



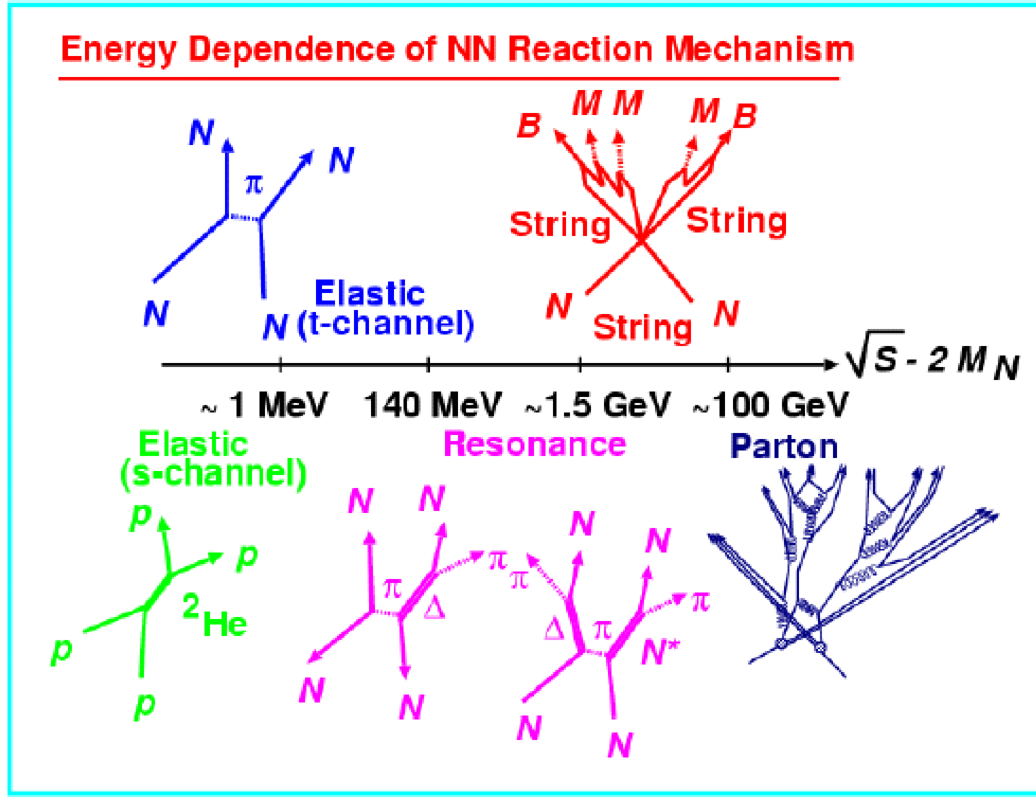


Resonance
+ String
+ Jet

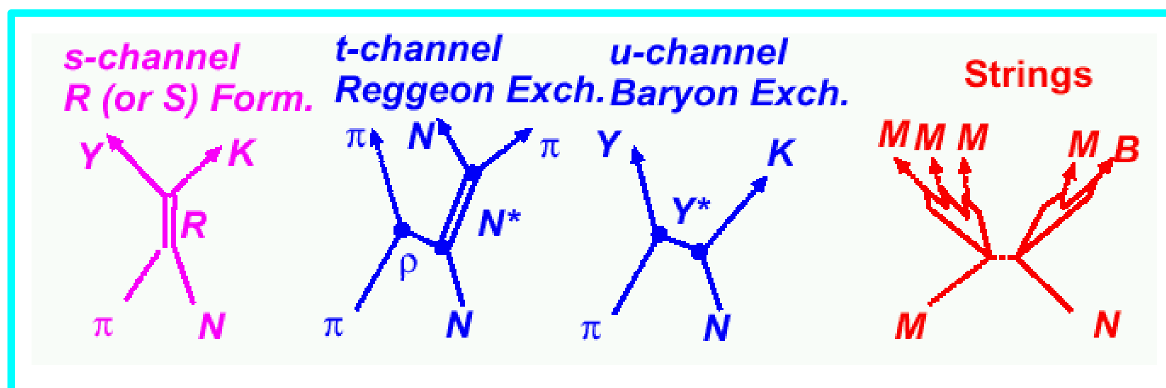


Baryon-Baryon and Meson-Baryon Collisions

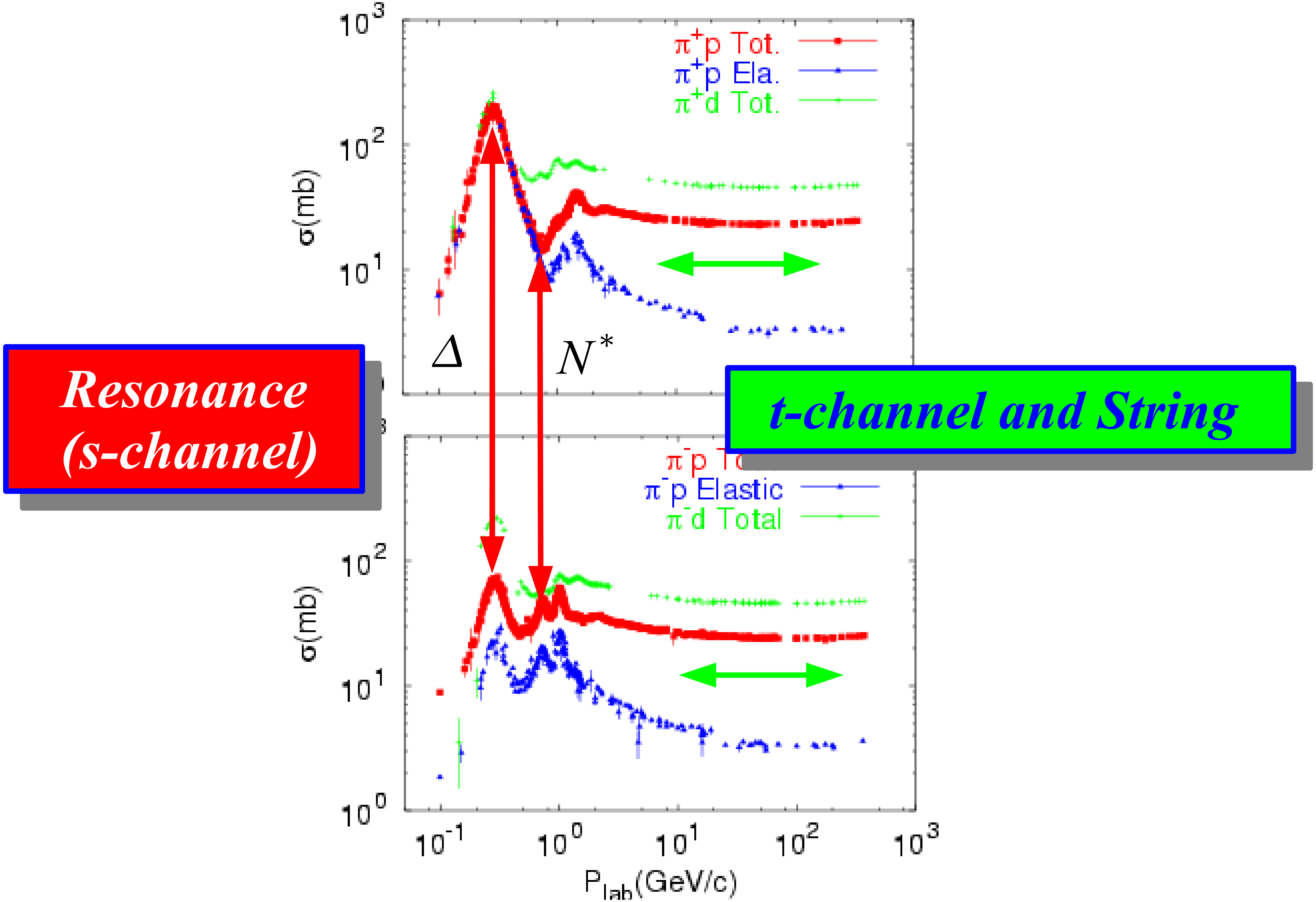
- **NN collision mechanism**
  Elastic
  → Resonance
  → String
  → Jet



- **Meson-Nucleon Collision**
  → s-channel Resonance
  → t-(u-) channel Res.
  → String formation



Meson-Baryon Cross Section



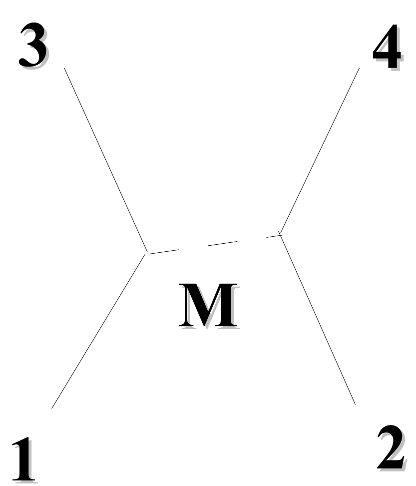
Reggeon Exchange

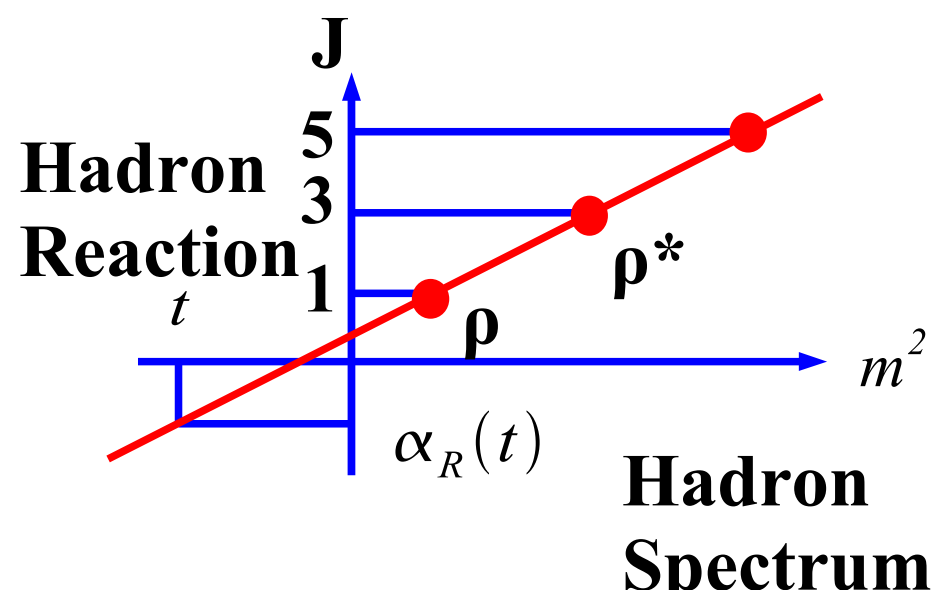
(Barger and Cline (Benjamin, 1969), H. Sorge, PRC (1995), RQMD2.1)

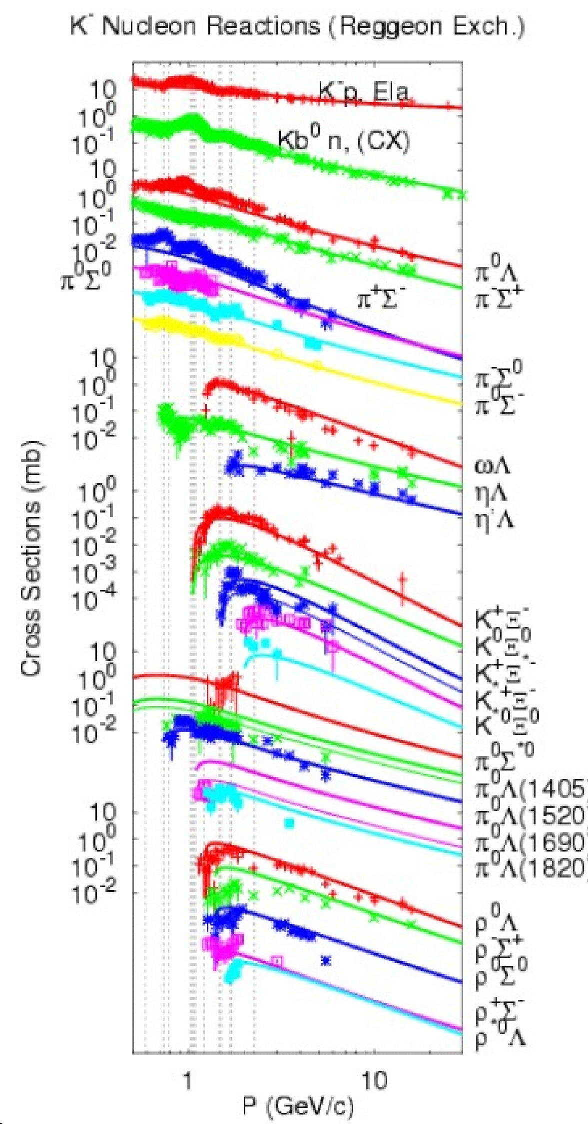
- **Regge Trajectory** $J=\alpha_R(t)\sim\alpha_R(0)+\alpha'_R(0)\,t$
- **2 to 2 Cross Section**

$$\frac{d\sigma}{d\Omega}=\frac{p_f}{64\pi s\,p_i}|M(s,t)|^2$$

$$M(s,t)\sim\sum_R\frac{(p_i p_f)^J}{t-M_R}\sim F(t)\exp\left[\alpha_R(t)\log(s/s_0)\right]$$







Hadronic Cross sections in JAM

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

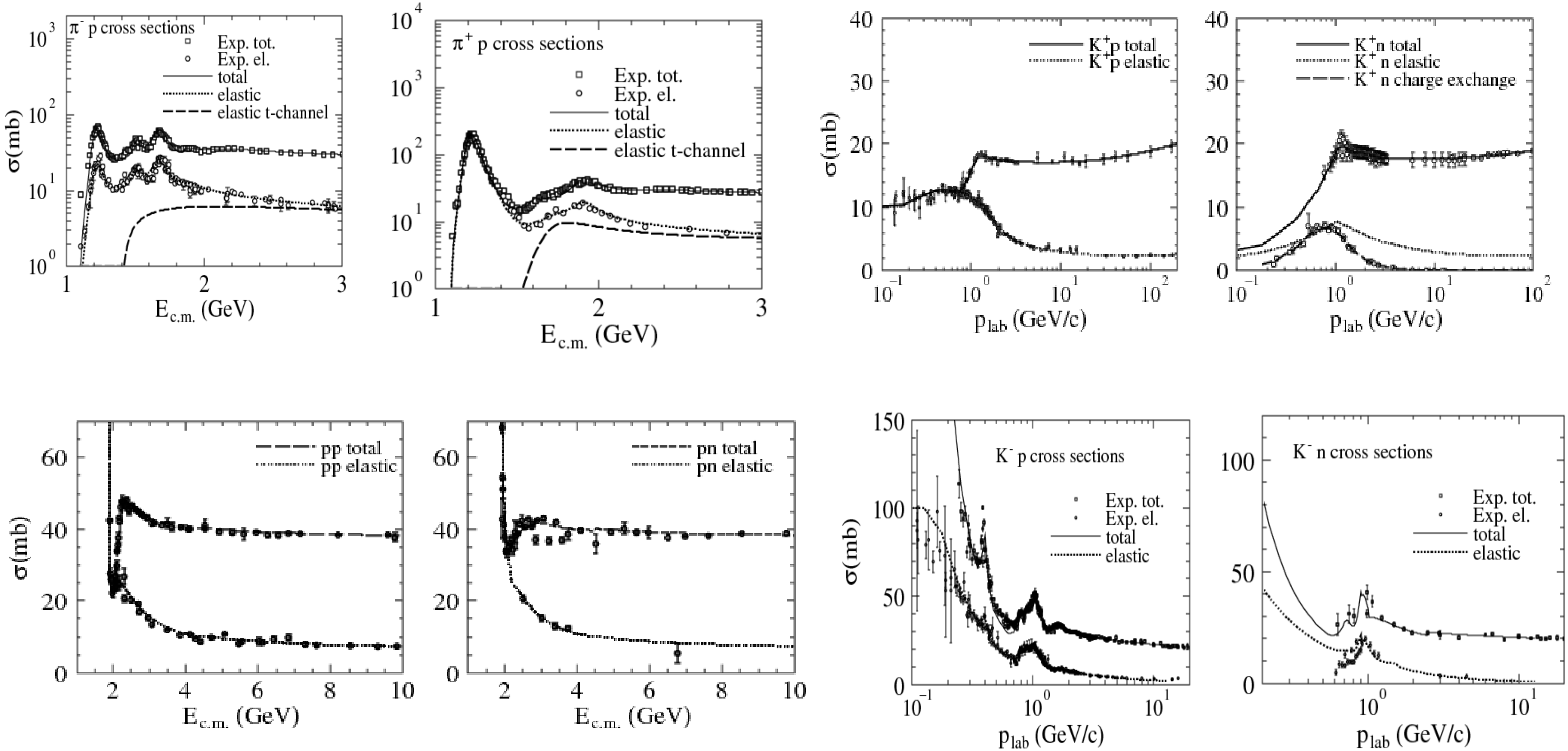
Resonance production (absorption)

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

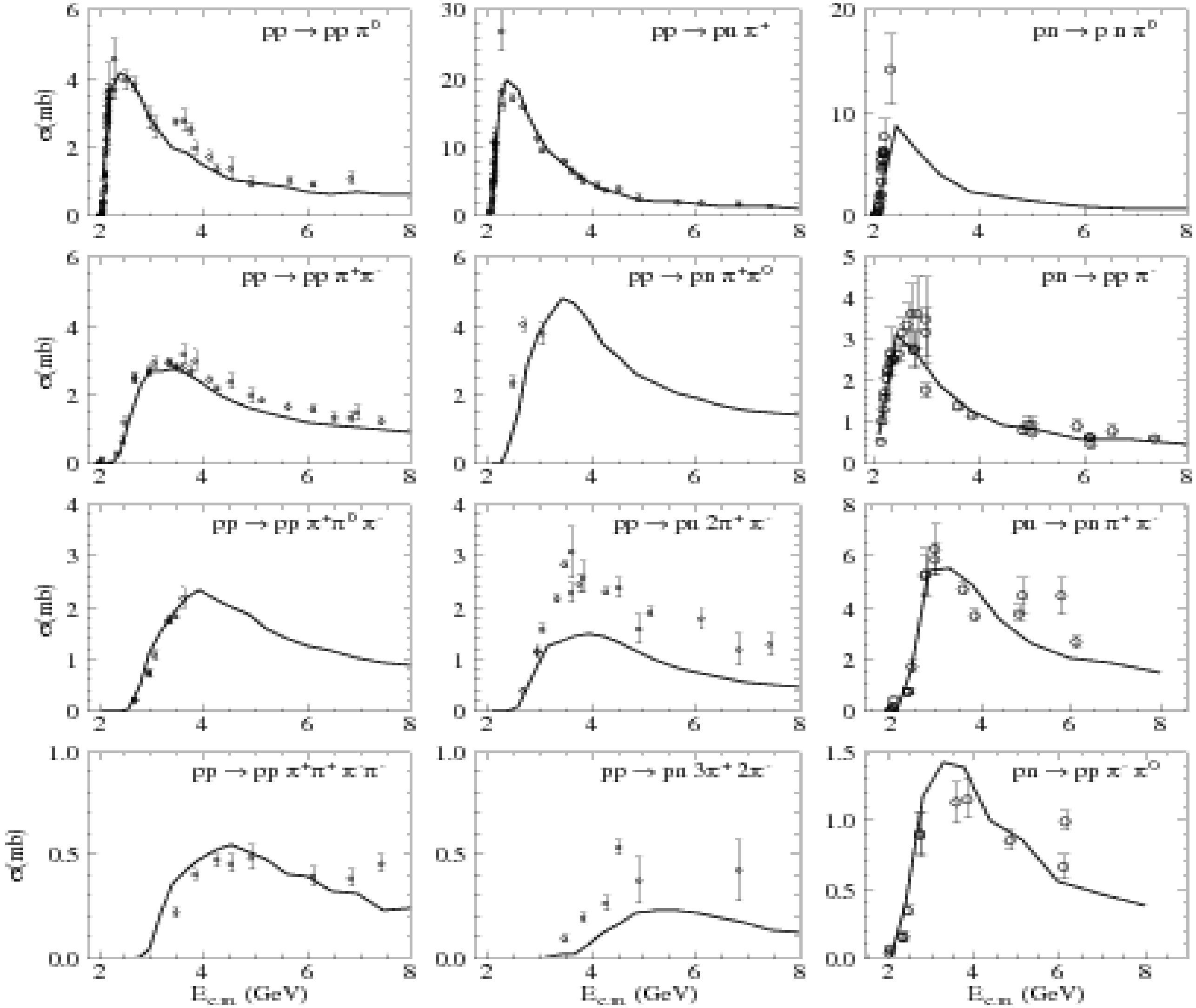
String formation

$$\sigma_{t-S}(s) : NN \rightarrow \text{String} + \text{String},$$
$$\sigma_{s-S}(s) : \pi N \rightarrow \text{String}$$

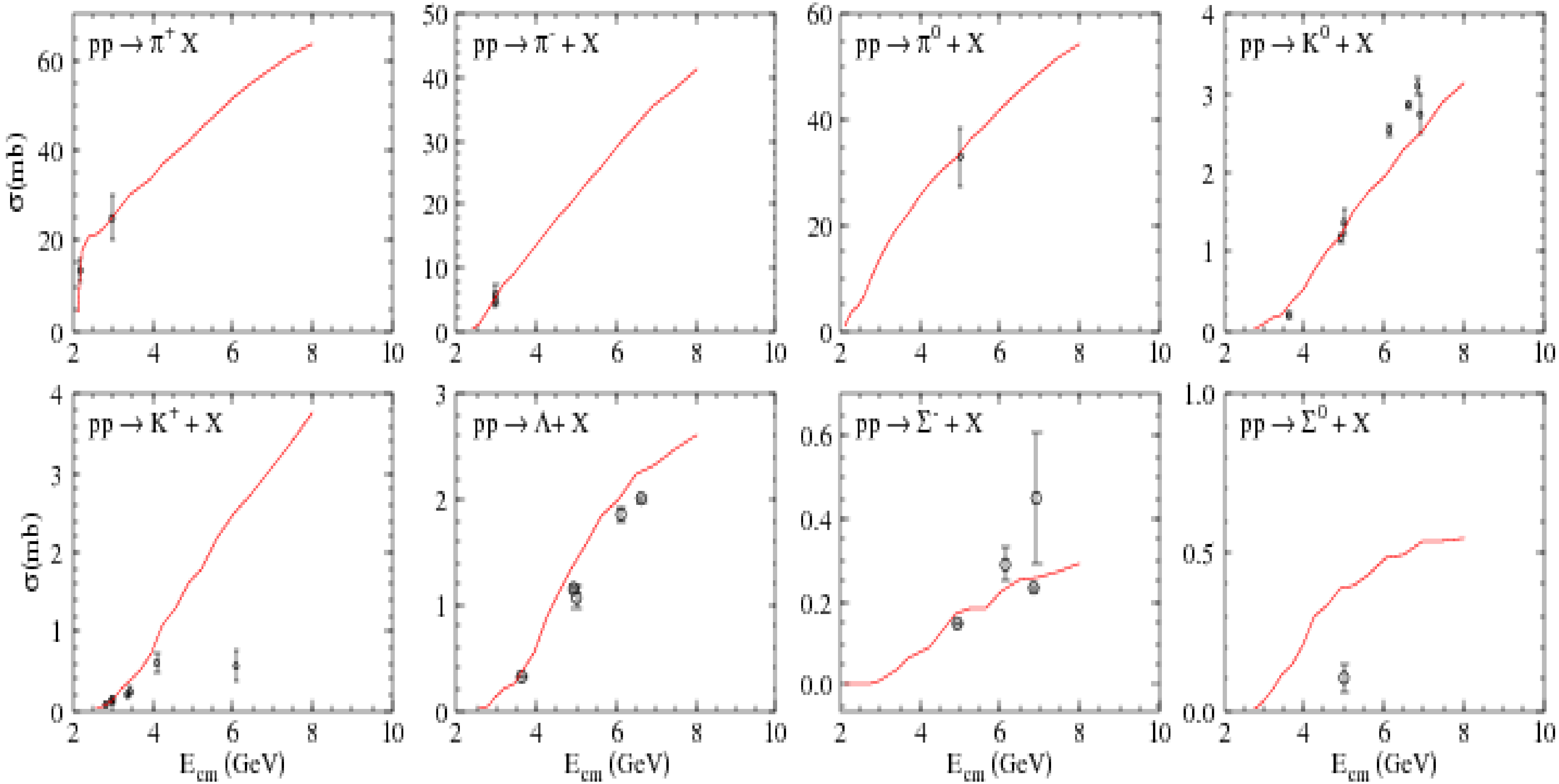
JAM: total cross sections



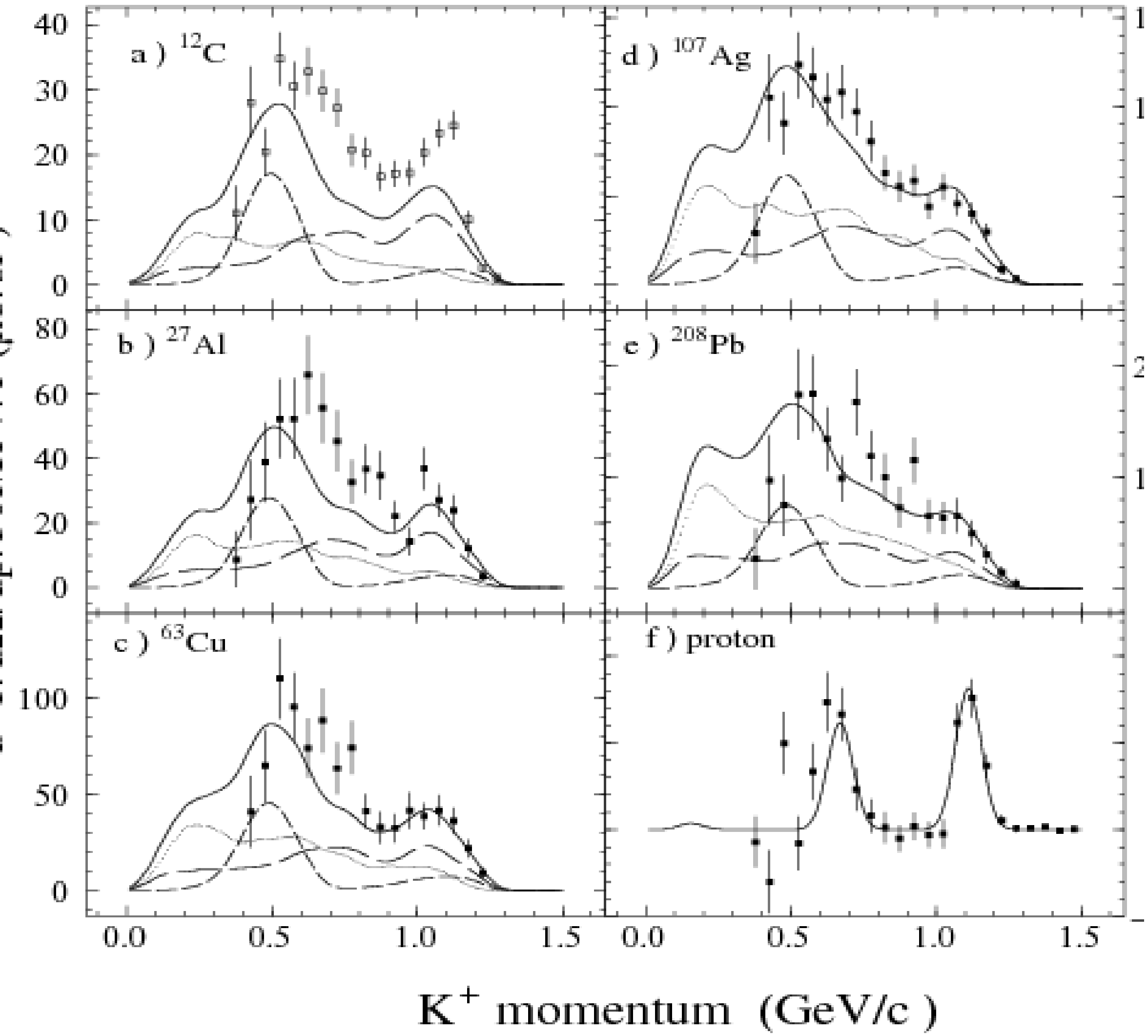
Pion production cross sections in JAM



Excitation function of p+p -> x in JAM



(K⁻,K±) reactions



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

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

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

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

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

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