Jul. 31-Aug. 2, CJjNPS IV @ IMP, Lanzhou

Hadronic Degrees of Freedom in High Energy Heavy-Ion Collisions

A. Ohnishi Hokkaido U.

1. Physics of HIC @ SIS-AGS-JHF Energies
   - ⋆ *Is it in Yukawa phase or Hagedorn phase ?*
2. Particle Spectra in HIC and Hadronic DOF
   - ⋆ *Hadronic Transport Models:*
     HANDEL, JAM and RBUU
   - ⋆ *How M_t spectrum is related to Hadronic DOF*
3. Collective Flows and Nuclear EOS
   - ⋆ *Nuclear Mean Field: ρ and E dep.*
   - ⋆ *How is the EOS soften in Hadronic Scenario ?*
4. Thermal Properties of Hadronic Cascade Models
   - ⋆ *Cascade in a Box: What do they tell ?*
5. Summary

Collaborators:
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T. Maruyama, T. Maruyama (JAERI), Y. Nara (BNL),
W. Cassing, U. Mosel (Giessen)

Refs.
- Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba
  Phys. Rev. C **61** (2000), 024901. (JAM)
- P. K. Sahu, W. Cassing, U. Mosel and A. Ohnishi
  Nucl. Phys. **A672** (2000), 376. (RBUU, Flow)
- N. Otuka et al., in preparation.

⋆ What we are AIMING at in High-Energy Heavy-Ion Collisions

- **Hot and Dense Matter Properties**
  - ⋆ Phase Diagram: Q-H, L-G
  - ⋆ Equation of State (EOS): Soft/Stiff/Mom. Dep.

General EOS f(E/V,N/V,T,P,...) = 0

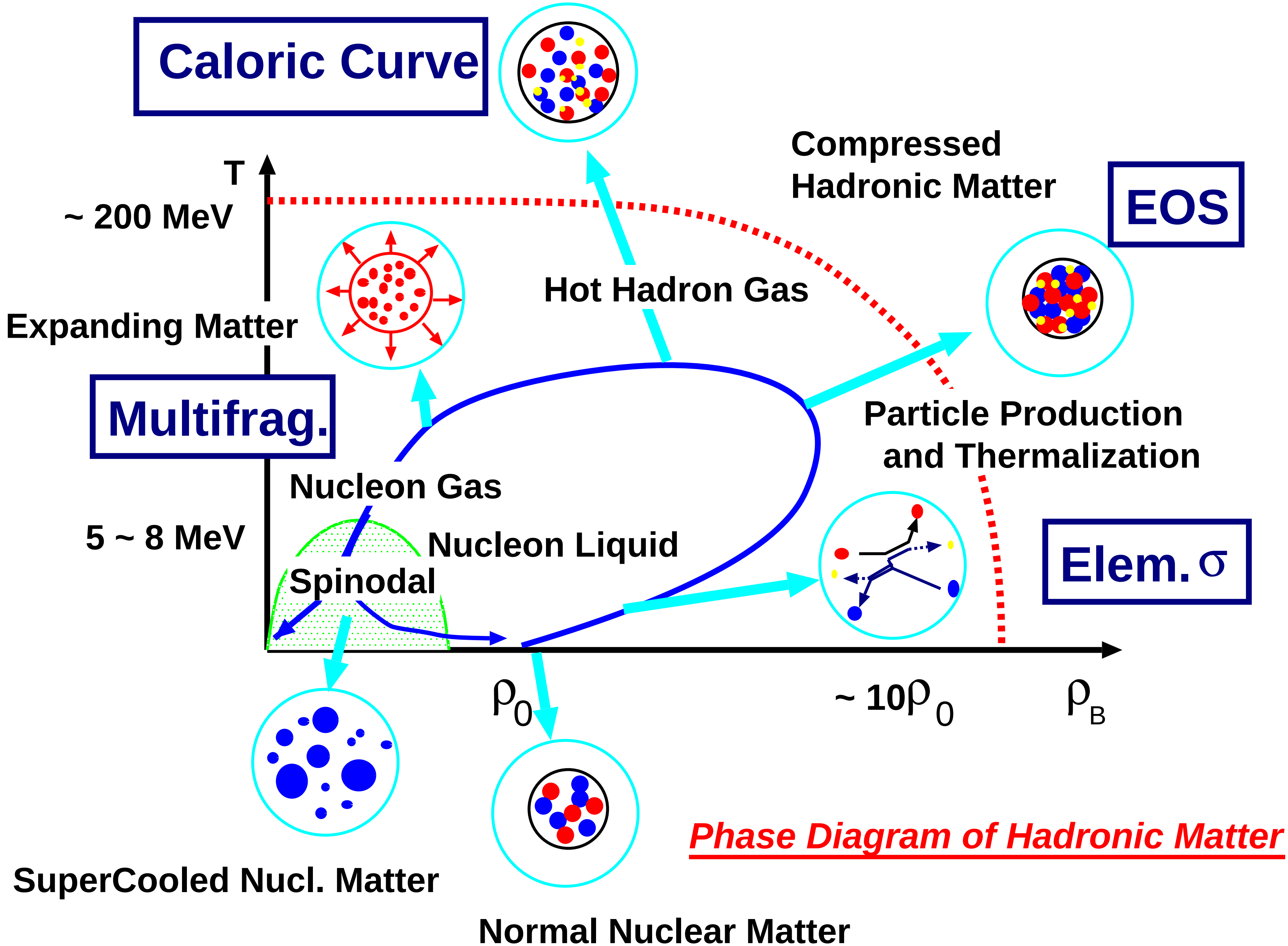
$\rightarrow \begin{cases} \text{EOS (narrow):} & E/A = f(\rho_B) \text{ at fixed } T \\ \text{Caloric Curve:} & T = f(E/V) \text{ at fixed } \rho_B \text{ or } P \end{cases}$

⇕ Make a Link between Stat. & Dyn.

- **Model Inputs**
  - ⋆ Particle DOF $(N, \pi, \Delta, N^*, K, ...q, g)$ ↔ Elementary σ
  - ⋆ Nuclear Mean Field, Medium Effects

⇕ Explain the Data

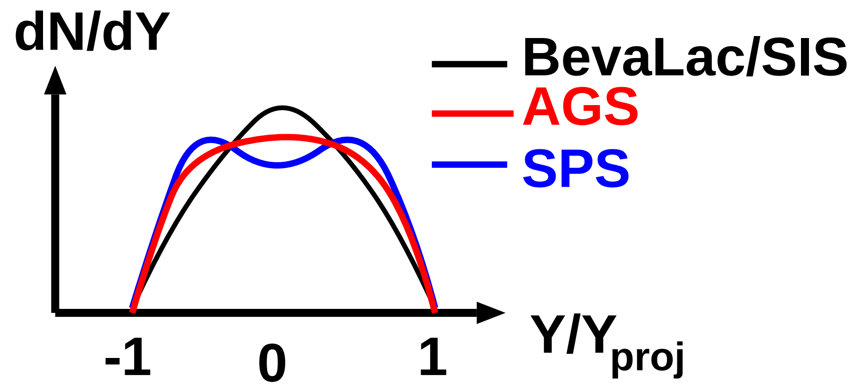
- **HIC Observables**
  - ⋆ Particle Spectra $\cdots dN/dY, dN/dM_t$
  - ⋆ Collective Flows
  - ⋆ Particle Correlations


Caloric Curve
Compressed
Hadronic Matter
EOS
T
~ 200 MeV
Hot Hadron Gas
Expanding Matter
Multifrag.
Particle Production
and Thermalization
Nucleon Gas
5 ~ 8 MeV
Nucleon Liquid
Elem. σ
Spinodal
ρ0
~ 10ρ 0
ρB
Phase Diagram of Hadronic Matter
SuperCooled Nucl. Matter
Normal Nuclear Matter

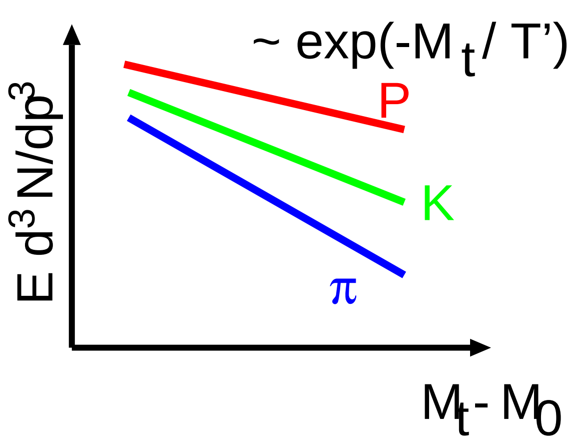
⋆ Experimental Status

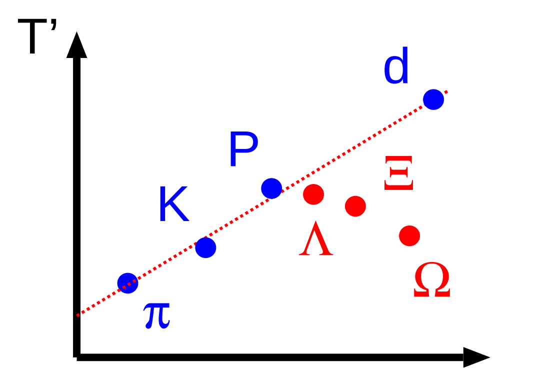
Bevalac	SIS	AGS	JHF	SPS	RHIC	LHC
(LBL)	(GSI)	(BNL)	(KEK-JAERI)	(CERN)	(BNL)	(CERN)
0.8 AGeV	1∼ 2	10	25	200	100+100	3+3 ATeV

⋆ Rapidity Dist.
(= Stopping Power)



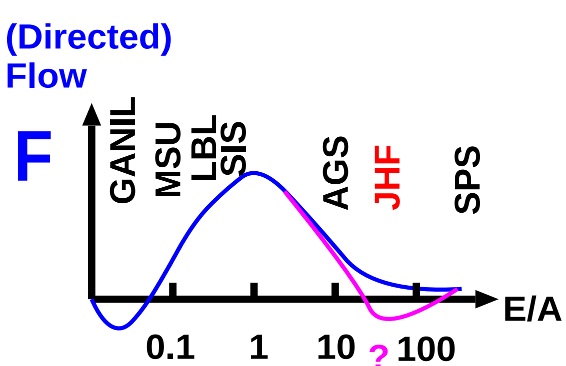
⋆ M_T Spectrum ··· $T_0(SPS) > T_0(AGS)$, $\beta(SPS) < \beta(AGS)$

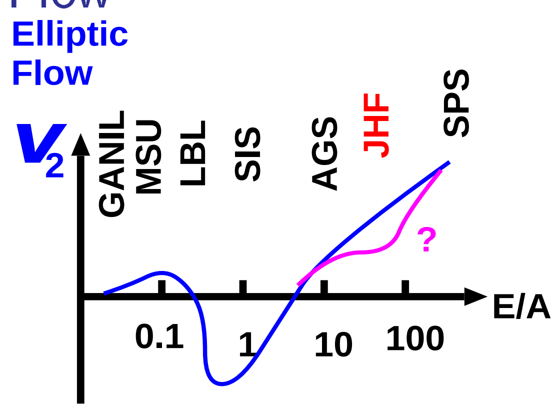




$T' \sim T_0 + M_0\beta^2/2$

⋆ Collective Transeverse Flow





⋆ Chemical/Thermal Freeze-Out: Strangeness Enh. !

⋆ J/ψ Suppression, Dileption Enh., $\pi\pi$, KK corr.,...

⋆ Physics of HIC @ SIS-AGS-JHF Energies

× QGP Search

◯ Hot & Dense Hadronic/String Matter

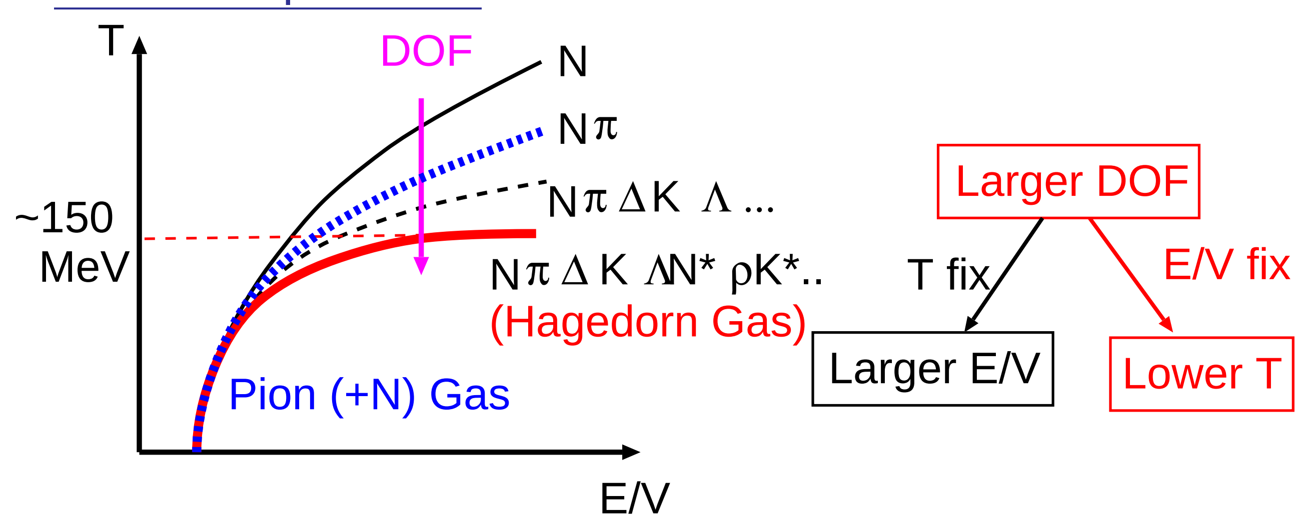
Hadronic Particle Degrees of Freedom (DOF)

→ Is the Hot and Dense Matter in

Yukawa phase (pion gas)

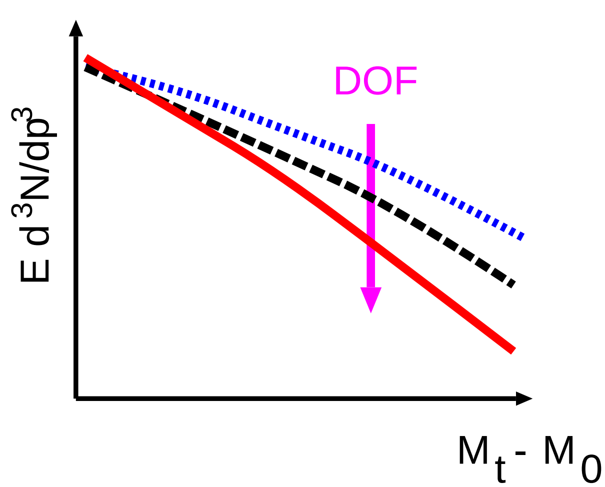
or *Hagedon phase* (resonance gas)

• DOF at Equilibrium



⇒ **How much DOF are Necessary/Enough to describe HIC ?**

DOF @ HIC
→ M_t Spectrum ⇒

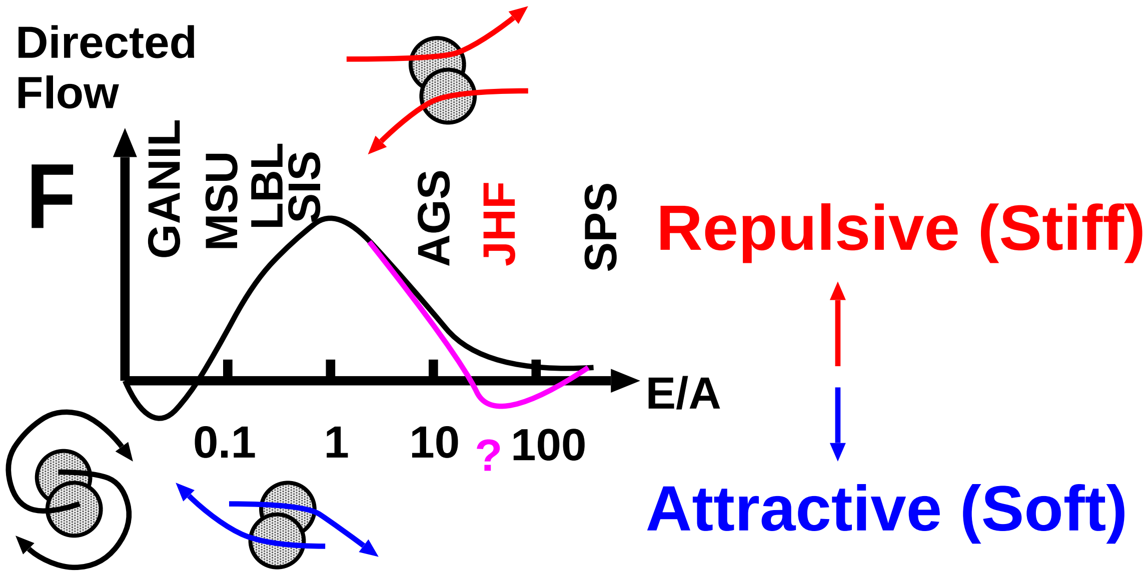


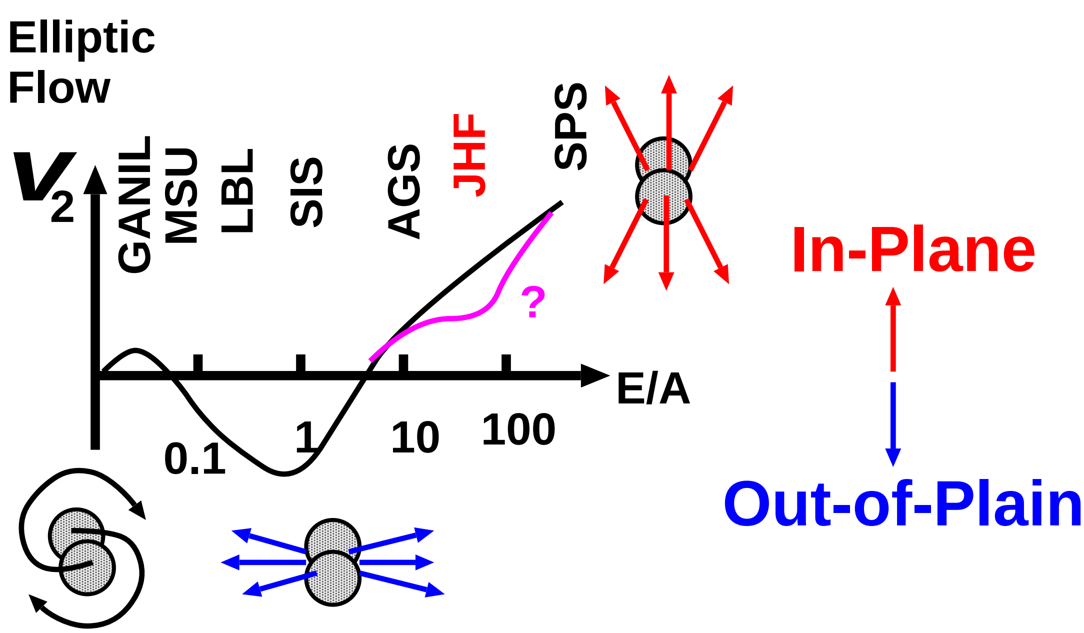
Equation of State (EOS): How Stiff is the Matter ?

Particle DOF + Nuclear Int. (Mean Field)

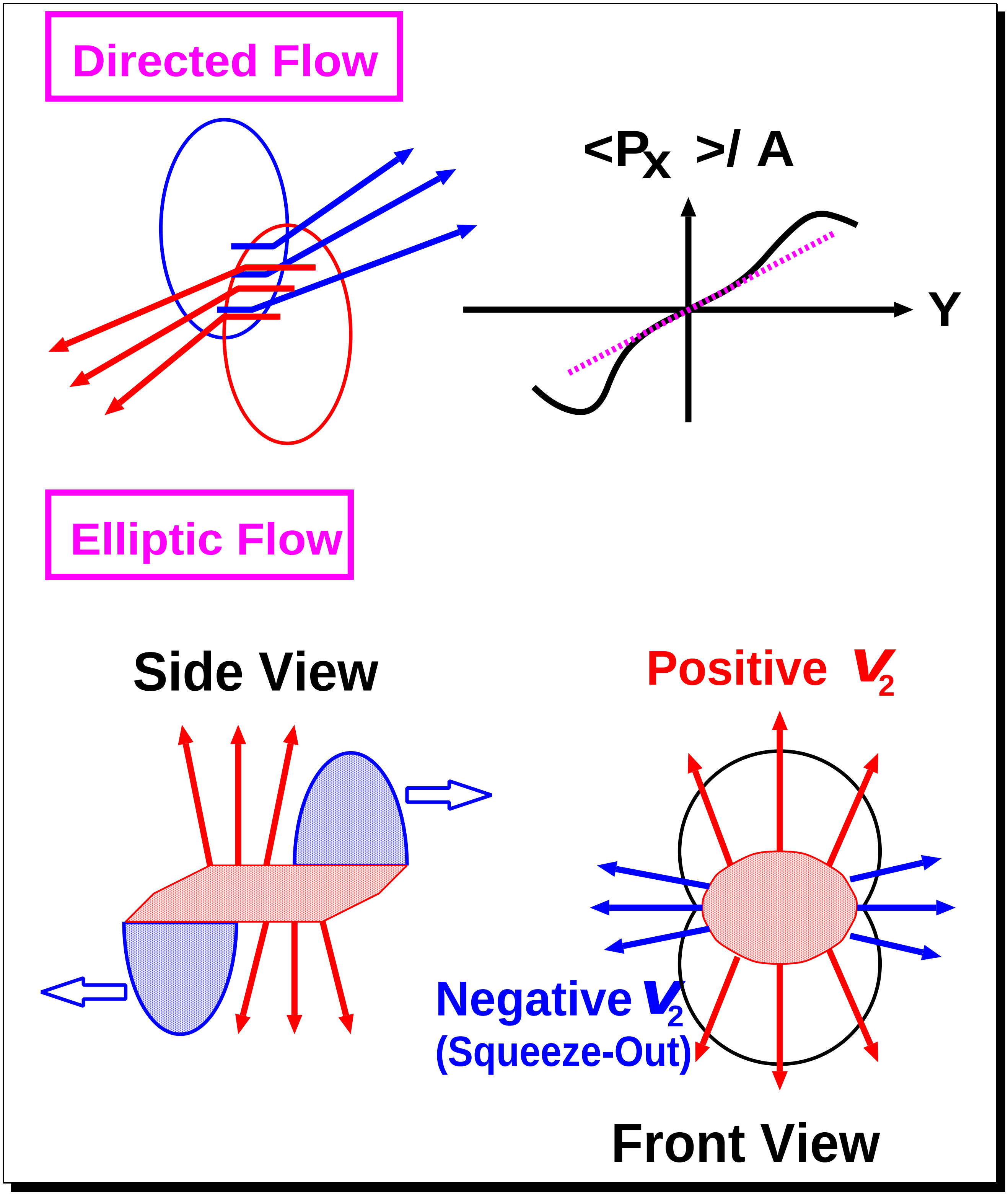
$\rightarrow$ Consistent Understanding of

$U_N(E)$, dN/dY, dN/dM_t and Flows ?





☞ How is the EOS soften above AGS energies ?


Directed Flow
<P$_X$ >/ A
Y
Elliptic Flow
Side View
Positive v_2
Negative v_2
(Squeeze-Out)
Front View

⋆ How can we Extract Hadronic Matter Properties ?

— From a "Hadron-String" View Point

1. Hadronic Cascade: Particle DOF

Starting from

- ⋆ Well-known σ(Cross Sections)
  (Exp. Data + Well-Established Concept)
- ⋆ and Well-Established Particle DOF
  (Resonances + Strings),

2. Nuclear Mean Field: EOS

and Incorporate

- ⋆ Well-known Mean Field, including Mom. Dep.
  (U_N is known, upto $E_{inc} = 1$ GeV).

Comparison with HIC Data

Then make Systematic Studies

- ⋆ Energy/System Size/Impact Par. Dependence

on Various Observables.

3. Matter Properties

Finally,

- ⋆ Put Particles in a box and Run the Code.
  Then we get Matter Properties.

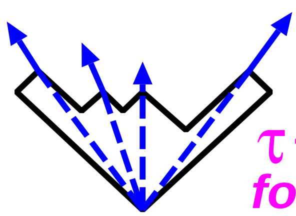
⋆ Hadronic Cascade Models

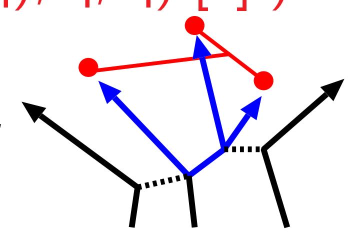
JAM (Jet Aa Microscopic transport model)

Y. Nara et al., PRC61('00), 024901.

⋆ DOF: h(B, B*, M, M* (m $\le$ 2 GeV)) + s(Strings)
+ Partons (at higher energies)

⋆ σ: Hadronic ($hh \leftrightarrow hh$, $hh \leftrightarrow h$)
+ Soft ($hh \leftrightarrow s$, $hh \to hs$, $hh \to ss$, $s \to hhh$... [1]
$ch \leftrightarrow ch$, $ch \to cs$ (c= (qq), q, q̄) [2])





+ Hard (Jet Production, at higher energies)

⋆ No Mean Field (in progress), No Medium Modification

[1] "DPM + Lund" (∼ HIJING) + Phase Space
[2] Consituent Rescattering (∼ RQMD), c= (qq), q, q̄

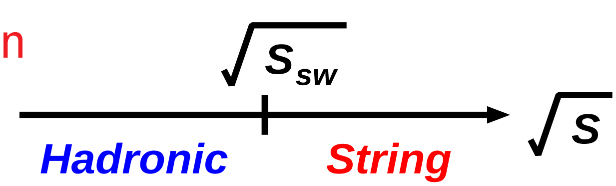
RBUU (Relativistic Boltzmann-Uehling-Uhlenbeck model)

P. K. Sahu et al., NPA672('00)376.

⋆ DOF: h(B, B*, M, M* (m $\le$ 2 GeV)) + s(Strings)

⋆ σ: Hadronic (BB $\leftrightarrow$ BB*, NN $\leftrightarrow$ $\Delta\Delta$, MB $\leftrightarrow$ B*, ...)
+ String Form. and Frag. (HSD by Cassing)

⋆ Energy Domain Separation



⋆ Relativistic Mean Field ($\sigma\omega$ + U(σ) + Form Factor)

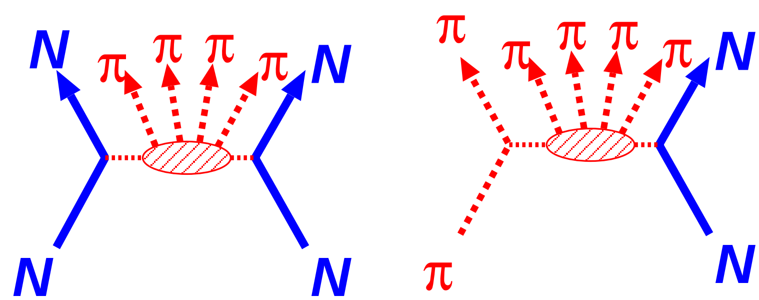
⋆ Medium Modifications

HANDEL (HAdronic Nucleus-nucleus cascade moDEL)

N. Otuka et al., in preparation.

⋆ DOF: g.s. Hadrons and Low-lying Res.
(N, Δ, N*(1440), N*(1535), Λ, Σ, Ξ,
π, K, η, ρ, ω, K*)

⋆ σ: Purely Hadronic (Binary + Multi)
BB $\leftrightarrow$ BR, BB $\leftrightarrow$ RR, NN $\rightarrow$ NKΛ
NN $\rightarrow$ NN$\pi\pi\pi\pi$...
MB $\leftrightarrow$ R, MB $\leftrightarrow$ MB,
πN $\rightarrow$ N$\pi\pi\pi\pi$...



- Relation to Other Models

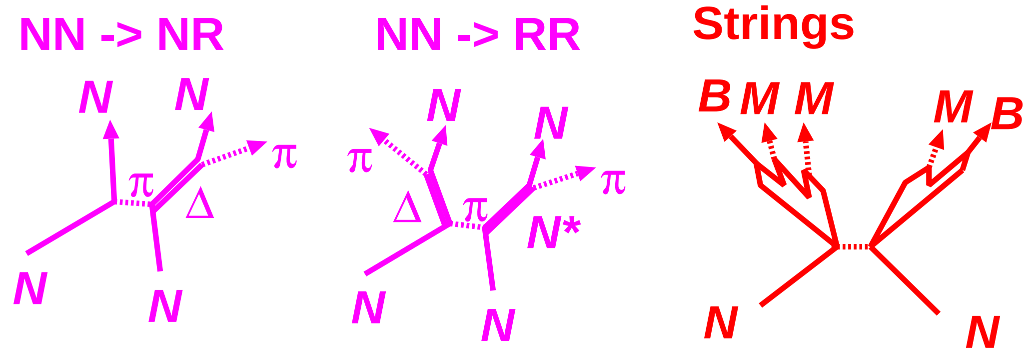
⋆ JAM: $\simeq$ RQMD (H. Sorge, PRC52('95),3291)
for Soft Processes. (except ss fusion)
$\simeq$ Phase Space Ver. of HIJING
(X.-N. Wang et al., PRep280('97)287)
for Hard Processes.

⋆ RBUU: = HSD (Ehehalt & Cassing, NPA602('96)449)
in Cross Sections except $\sqrt{s}$sw.
$\simeq$ RBUU (P.K.Sahu et al., NPA640('98)493)
in Mean Field.

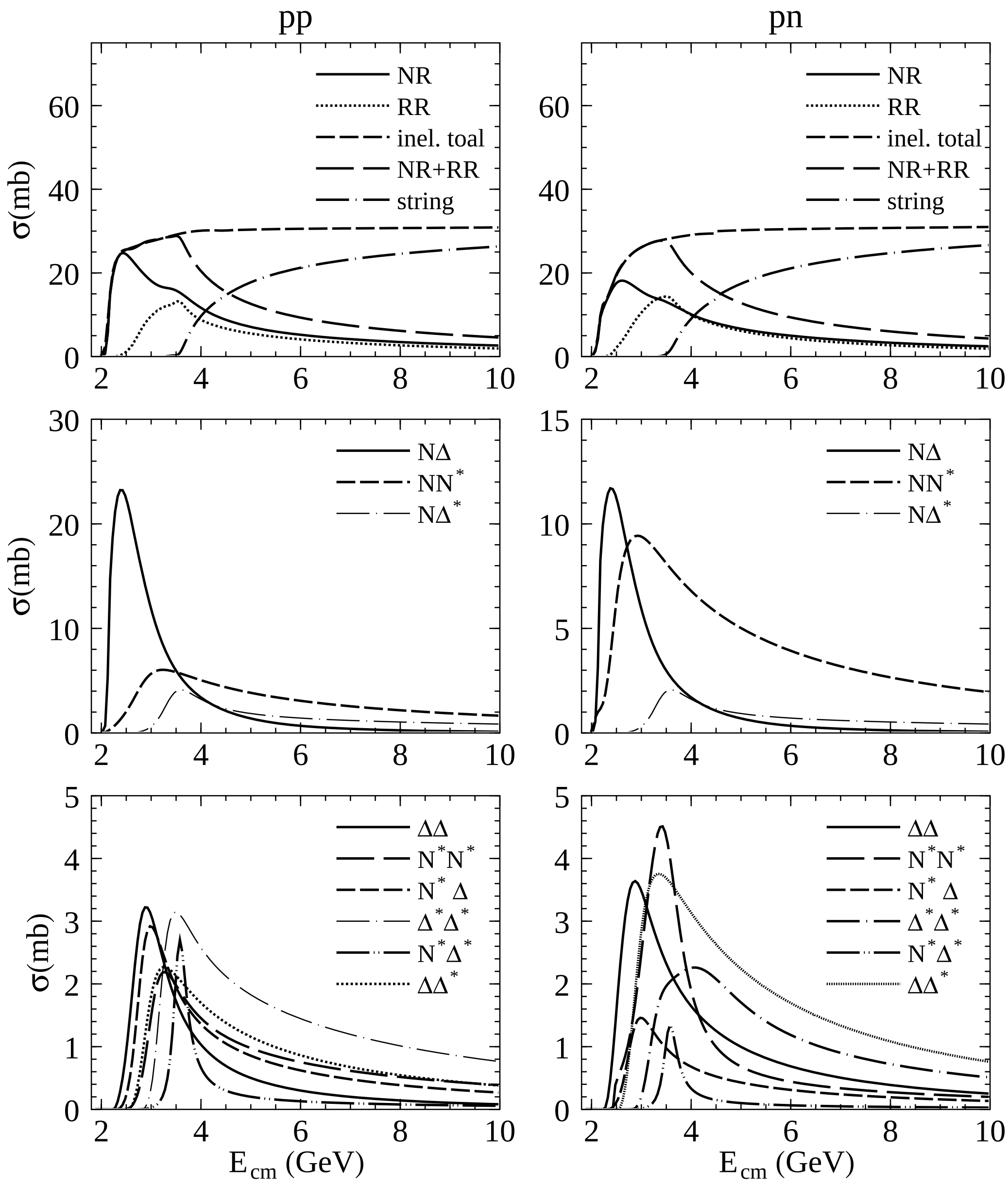
⋆ HANDEL: $\simeq$ ARC (Y.Pang et al. PRL68('92)2743)
& ART (B.A.Li & C.M.Ko, PRC52('95)2037)

⋆ Elementary σ@ SIS-AGS-JHF Energies

BB: Single- and Double-Resonance Formation $\to$ Strings

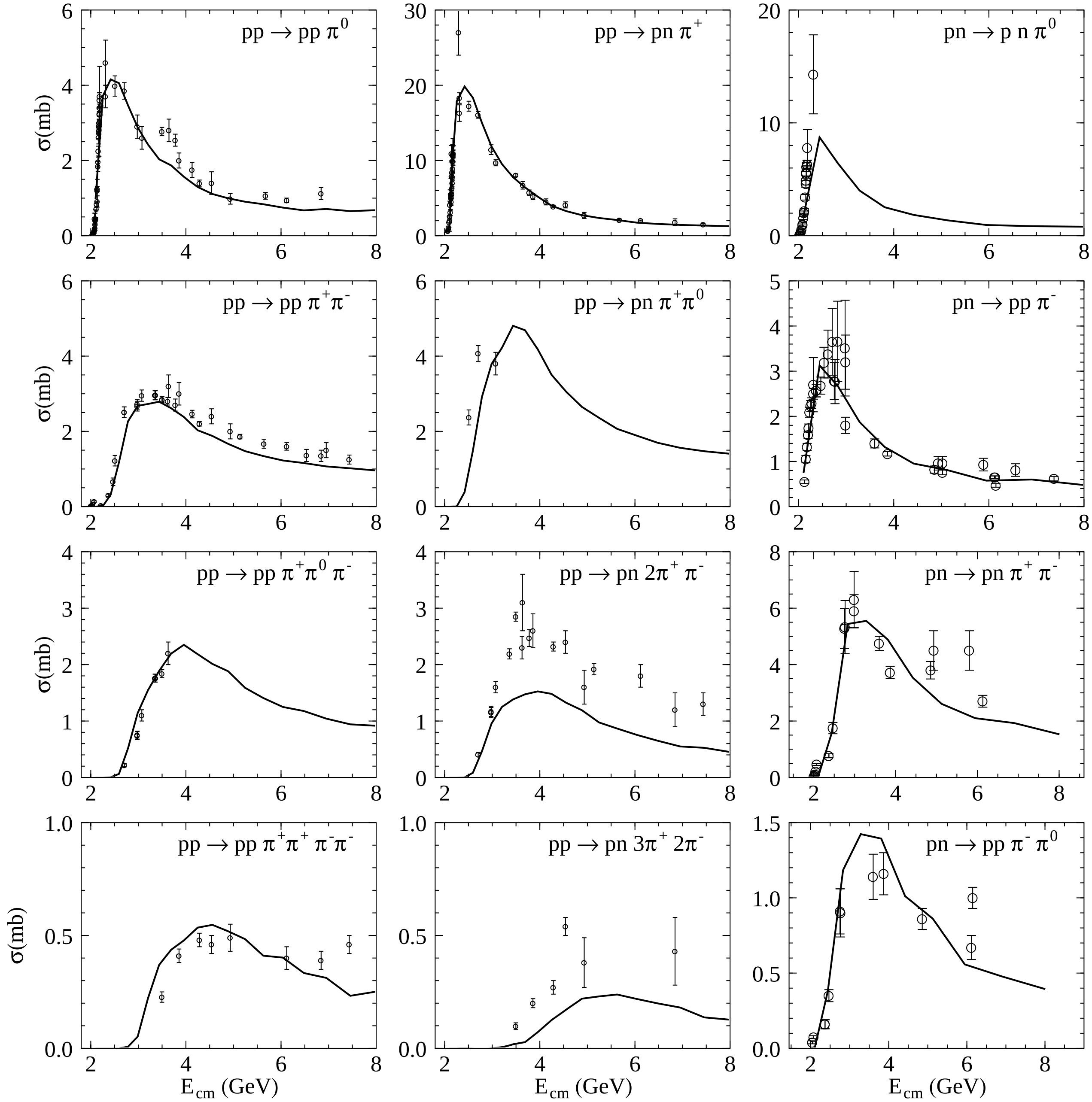


- Example: σ(NN $\to$ NR, RR, Strings) in JAM

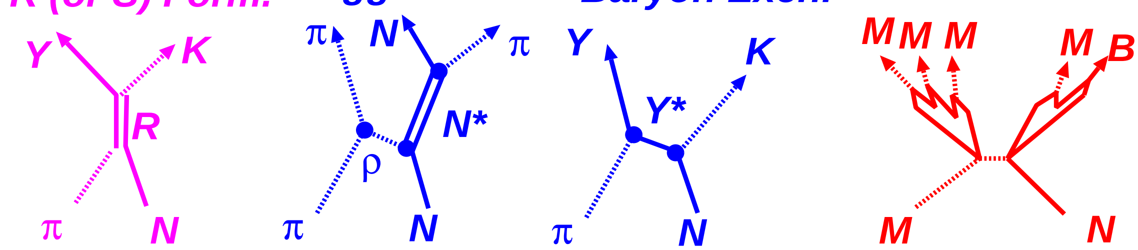


- <u>NN Exclusive σ</u>

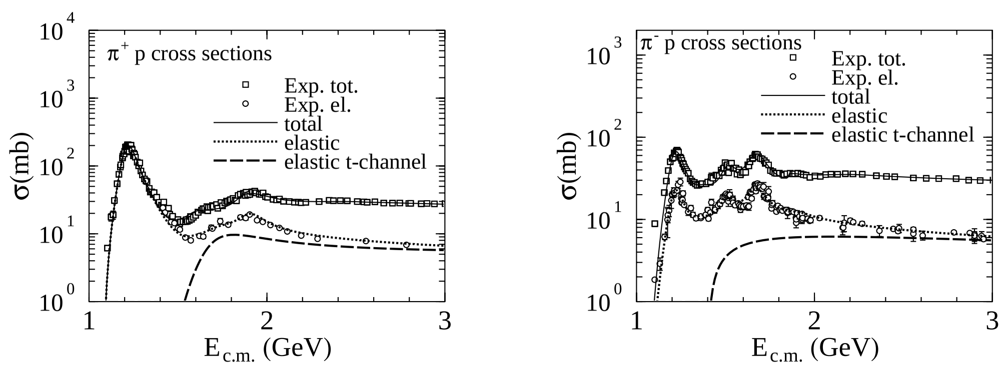
$\cdots$ Data exist upto 4 $\sim$ 5 π Prod.



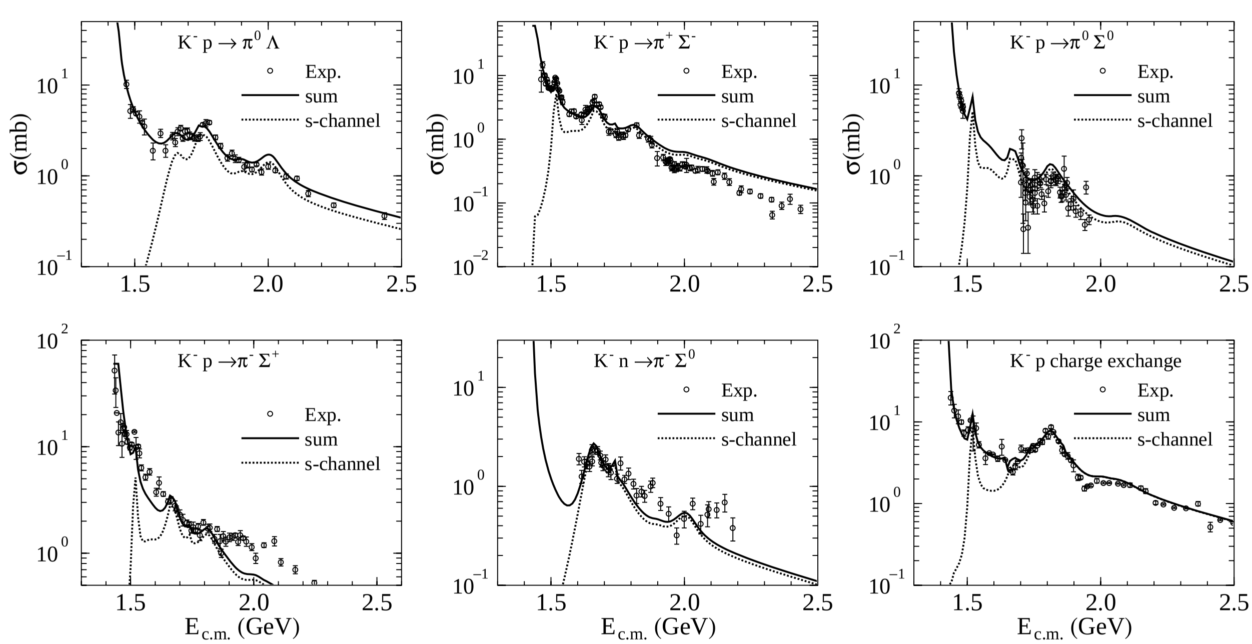
MB: s-channel → t- and u-channel, → Strings



- Example: $\sigma(\pi N)$ in JAM

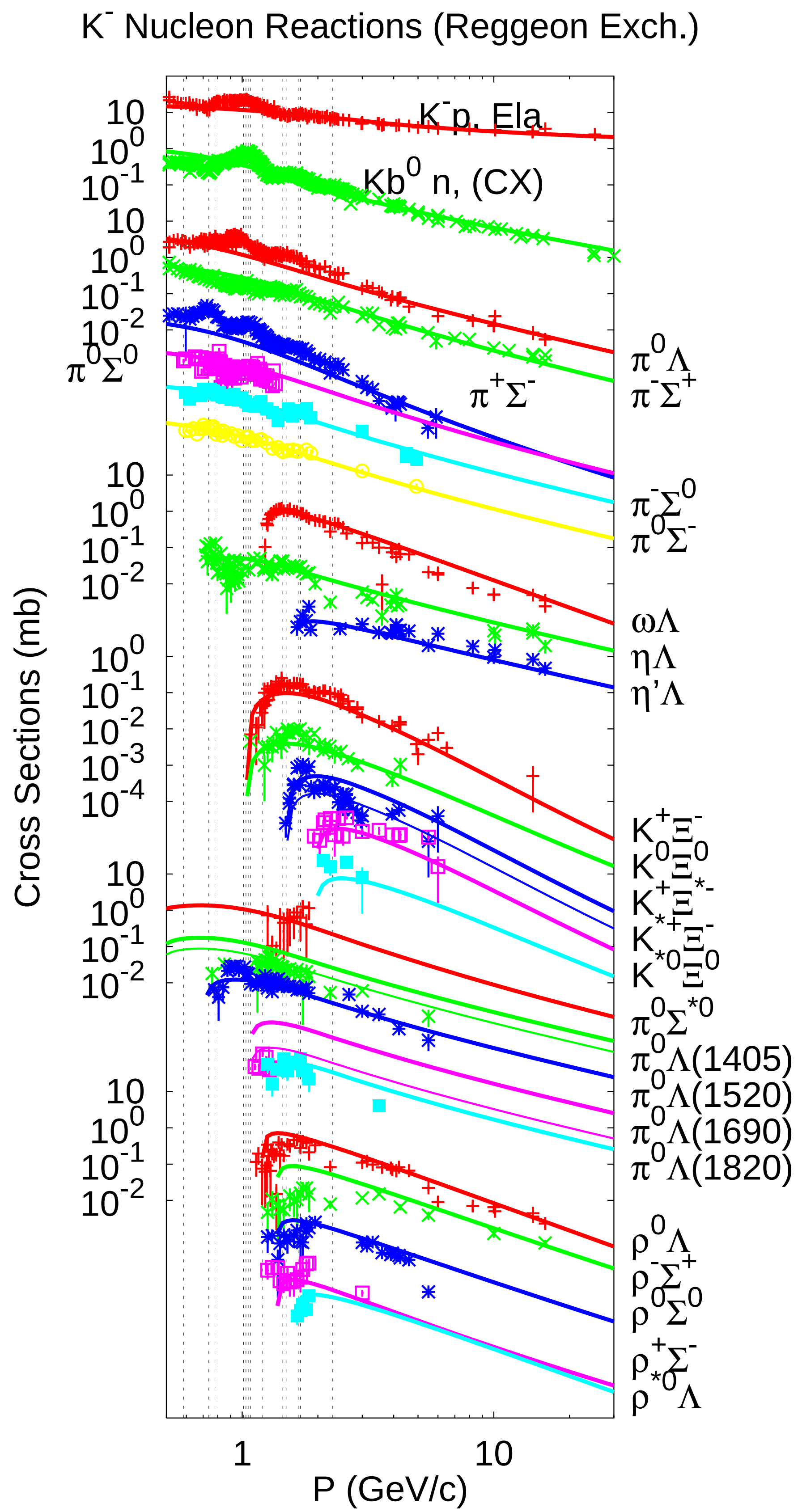


- Example: $\sigma(KN \to \pi Y)$ in JAM

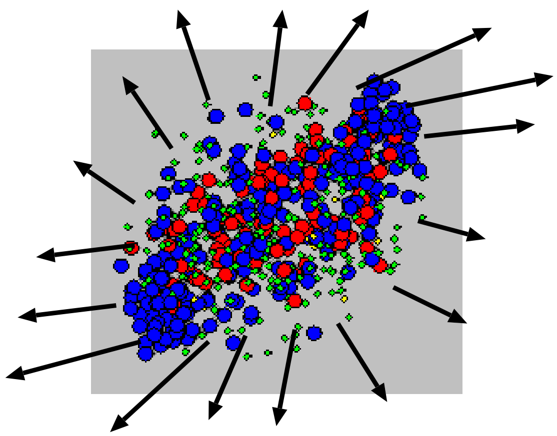


Note: t- and u-channel Reggeon Exch. are not completely incoroprated.

Reggeon Exchange Cross Sections



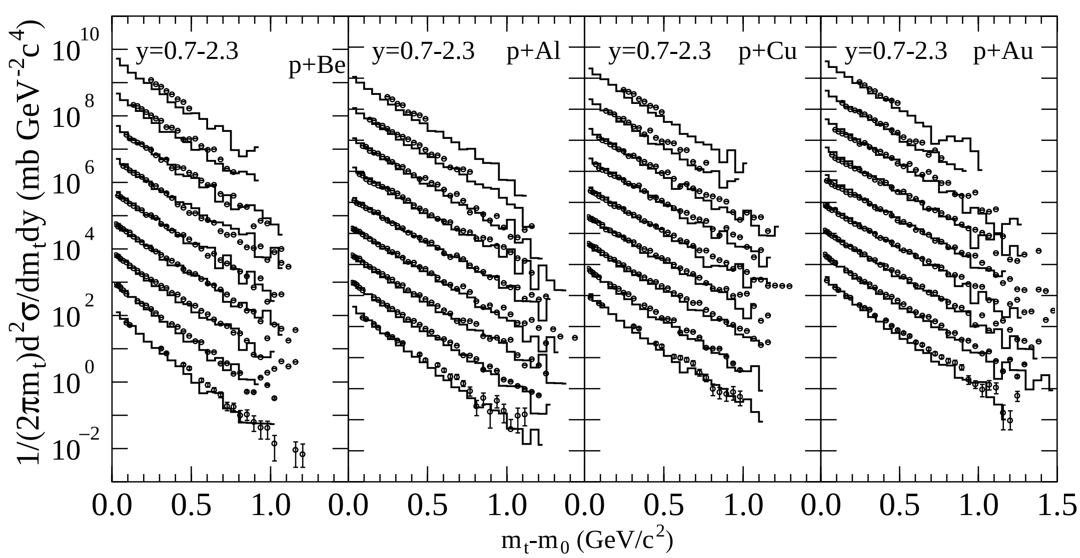
⋆ M_t Spectrum in HIC



$$M_t = \sqrt{M_0^2 + P_t^2}$$

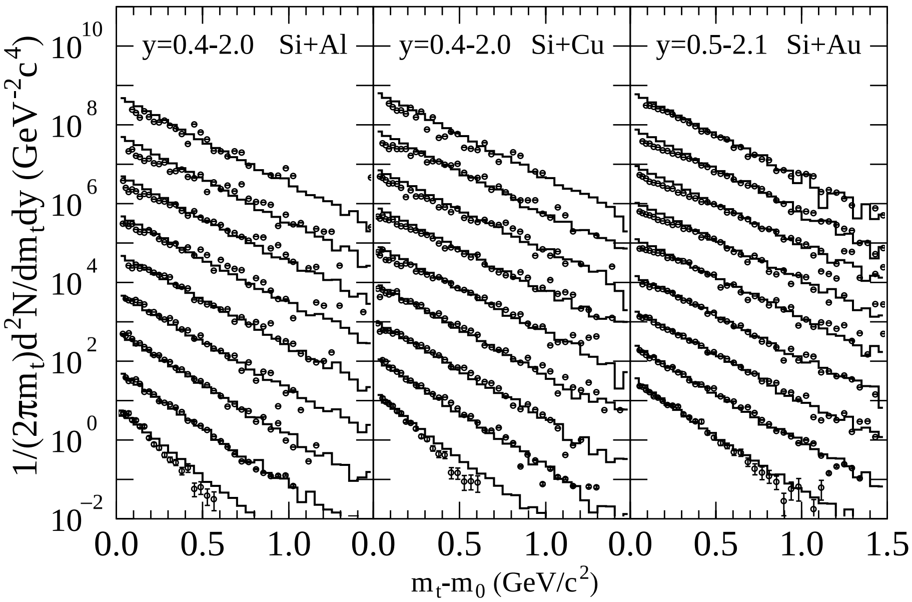
Measure of
Created Pressure

Proton Spectrum in pA Collisions (JAM)

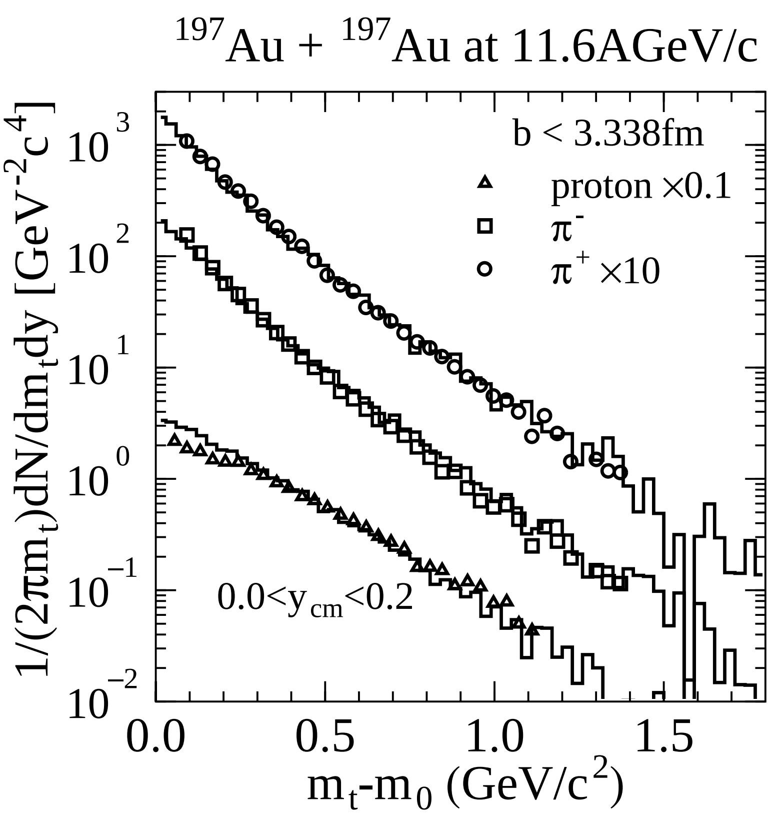


☞ What happens in HIC ?

Proton Spectrum in Light Heavy-Ion Collisions (JAM)

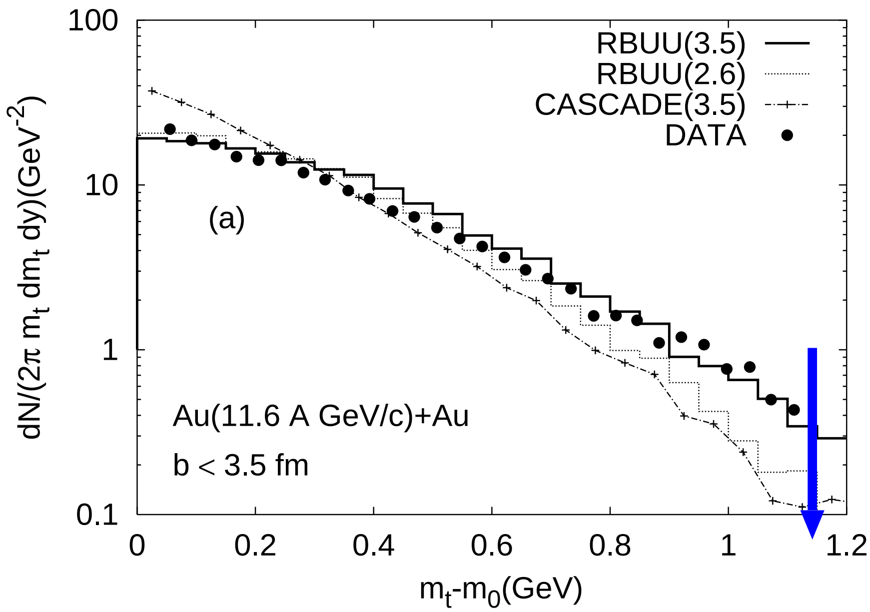


Proton and Pion Spectrum in Au+Au Collisions (JAM)



☞ What is the Role of DOF ?

Proton Spectrum in Au+Au Collisions (RBUU)



$\sqrt{s_{sw}}$ = 3.5 GeV

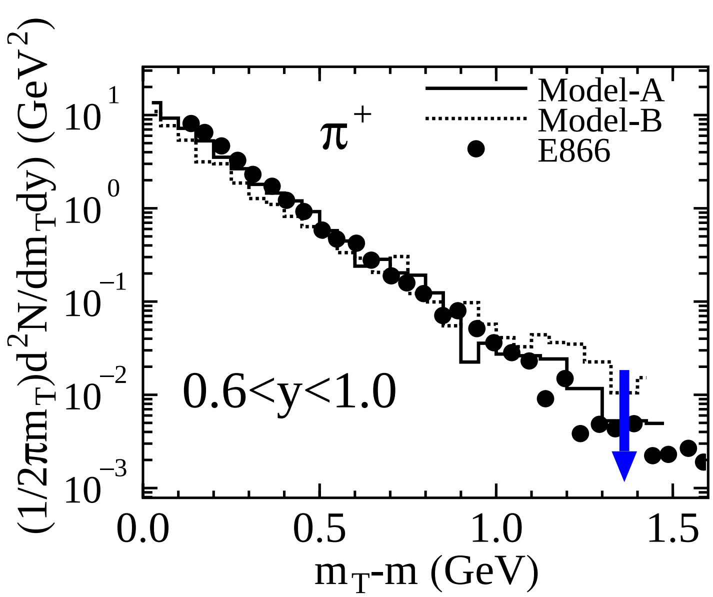
String =Continuum

Larger DOF

$\sqrt{s_{sw}}$ = 2.6 GeV

How about Smaller DOF Model ?

(Y.Nara et al. PTP Suppl.129('97)33)



Model-B

Larger DOF

Model-A

Model-A: Previous JAM
Model-B: Old HANDEL (No Multi., No Reggeon Exch.)

☞ M_t Spec. Softening Comes from Larger DOF
··· Approximate Hagedorn Gas seems to be Realized.

⋆ Collective Flows and Nuclear EOS

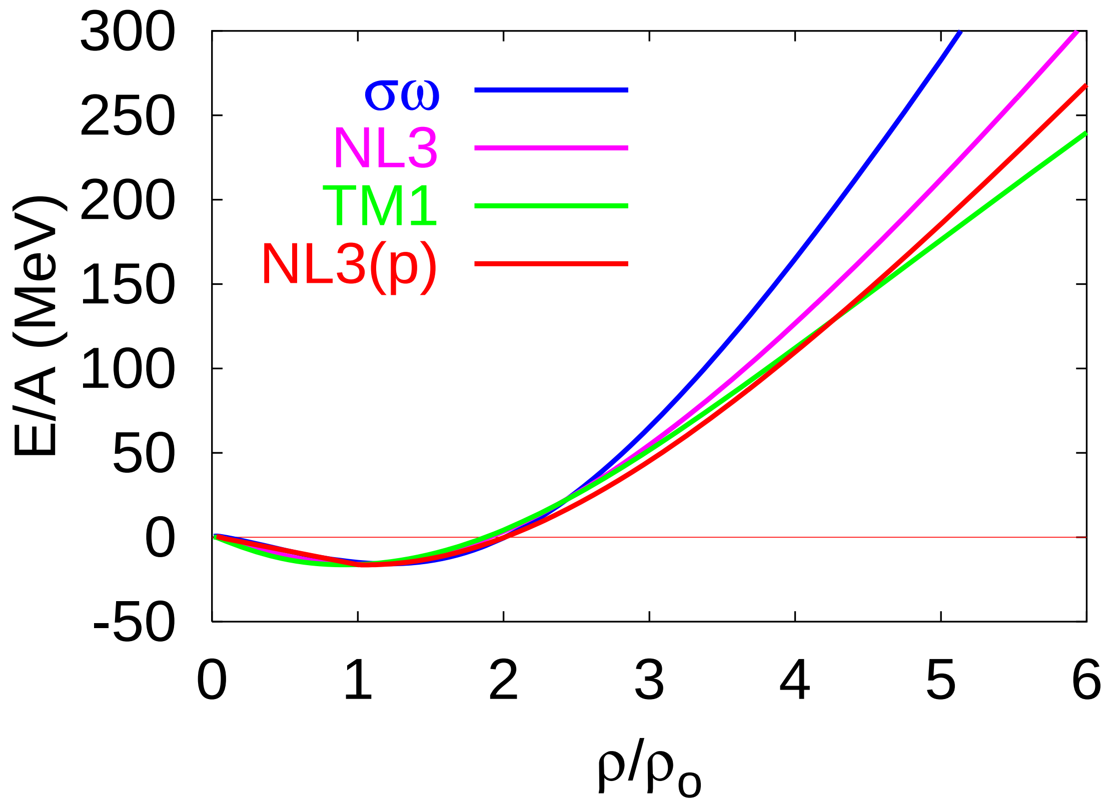
Nuclear Mean Field

In HIC, both of

Density and Energy

dependences of U are important.

- Density Dependence: EOS (Narrow Sense)



$\sigma\omega$ model: Too Stiff (K $>$ 500 MeV)

Non-Linear σ terms: Softer (K $\simeq$ (280-330) MeV)

☞ How about E_{inc} Dependence ?

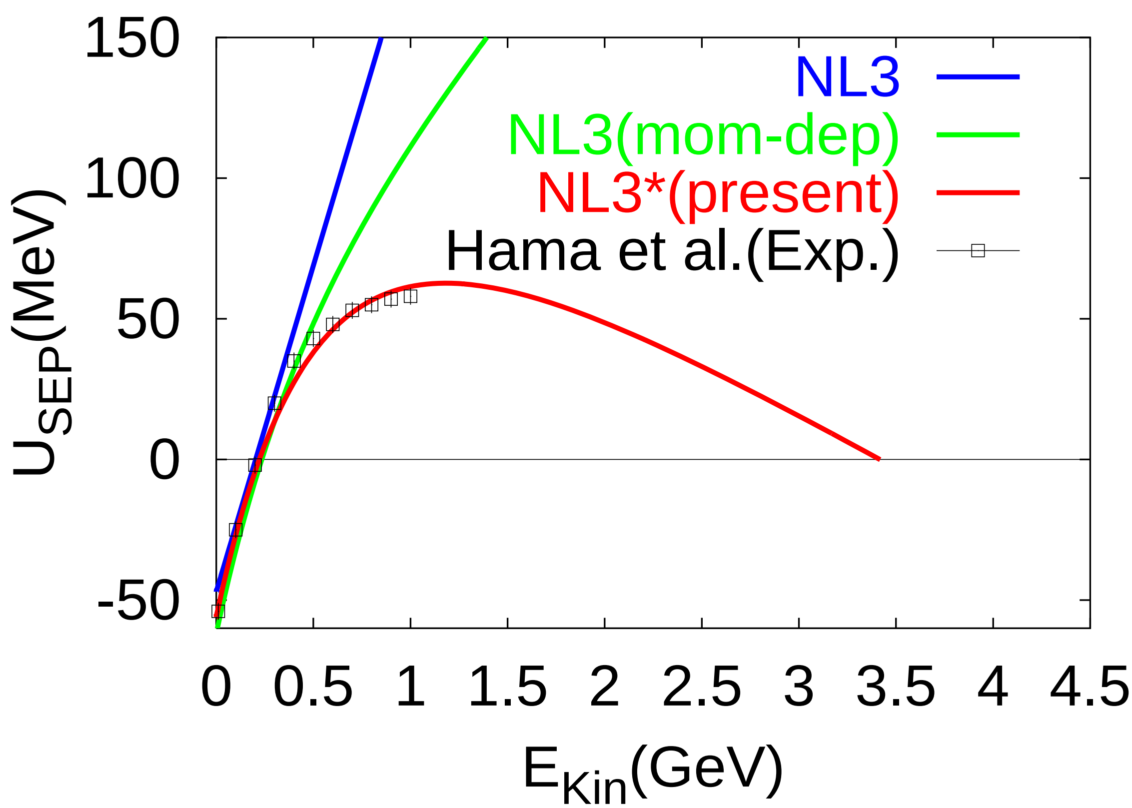
- Energy Dependence: Form Factor of MB Coupling

Schrödinger Equivalent Potential

$$U_{sep}(E_{kin}) = U_S + U_0 + \frac{1}{2M}(U_S^2 - U_0^2) + \frac{U_0}{M}E_{kin}$$

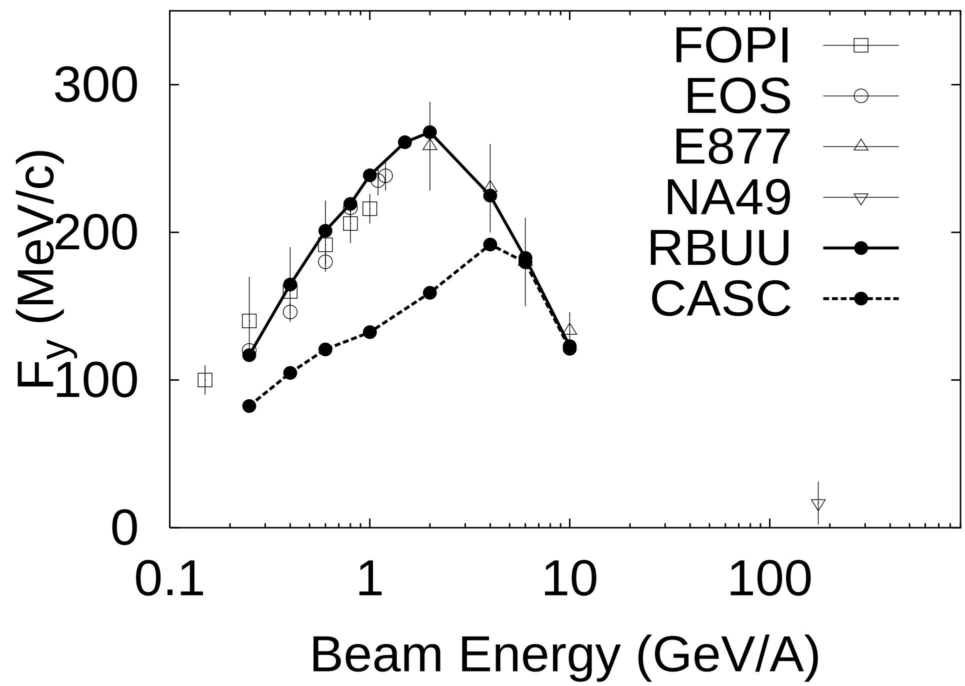
Form Factor: Reduce MB Coupling at High Momentum

$$f_S(\mathbf{p}) = \frac{\Lambda_S^2 - \alpha \mathbf{p}^2}{\Lambda_S^2 + \mathbf{p}^2} \quad \text{and} \quad f_V(p) = \frac{\Lambda_V^2 - \beta \mathbf{p}^2}{\Lambda_V^2 + \mathbf{p}^2} \ ,$$

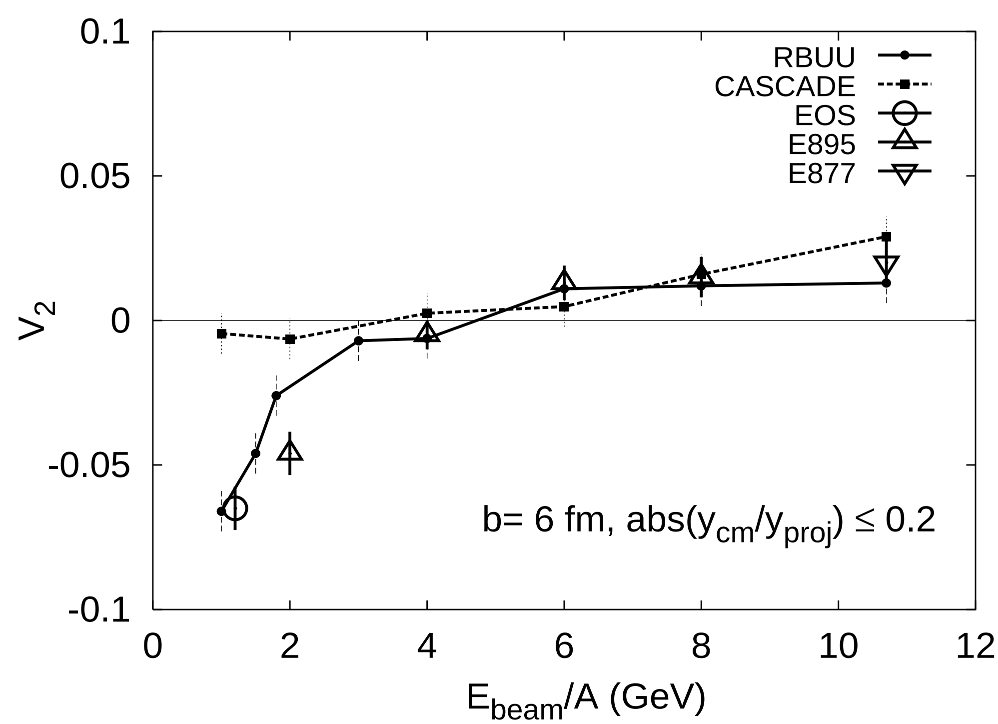


Effects on Flow Observables ?

Directed (Sidewards) Flow (RBUU)



Elliptic Flow (RBUU)



Softening seen in Flow Observables:
$\cdots$ Non-Linear σ Pot. + MB Form Fact. + Large DOF

⋆ Thermal Properties of Hadronic Cascade

Model with Small DOF may give Too Stiff Spectra

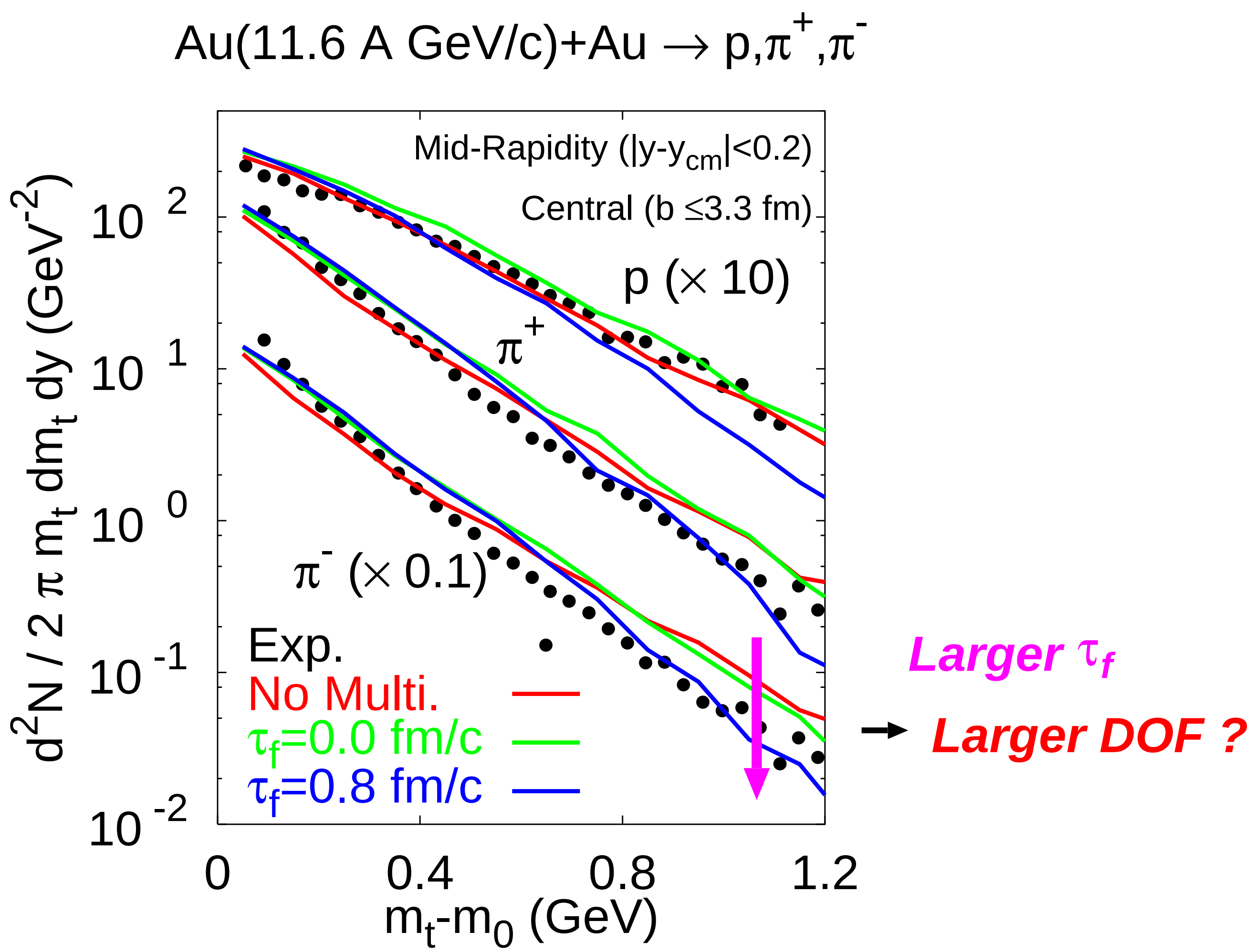
… Why do ARC and ART Explain Data ?

The Answer lies in

Multiparticle Prod. and *Formation Time*

ARC: Y.Pang et al. PRL68('92)2743,
ART: B.A.Li & C.M.Ko, PRC52('95)2037; PRC57('98)2065.

M_t Spectra with Multi. Prod. (HANDEL)

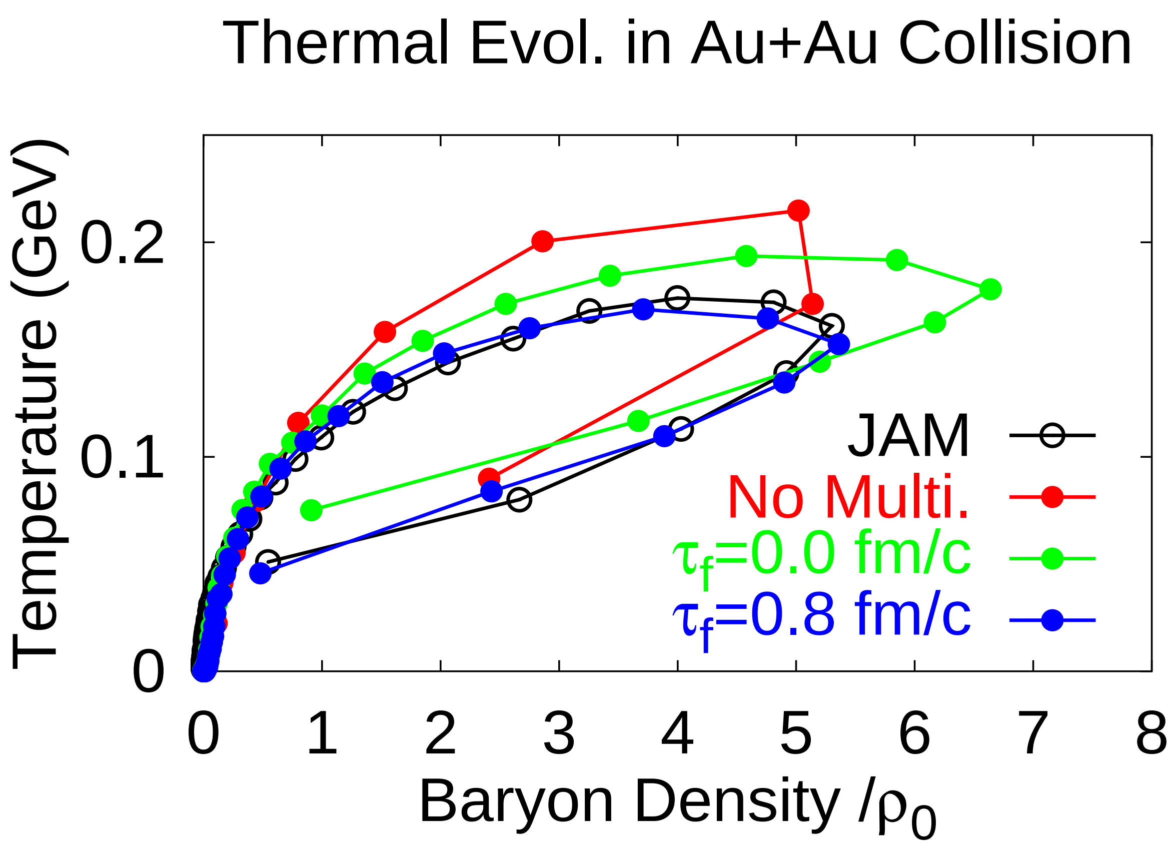


Thermal Evolution of Matter (JAM and HANDEL)

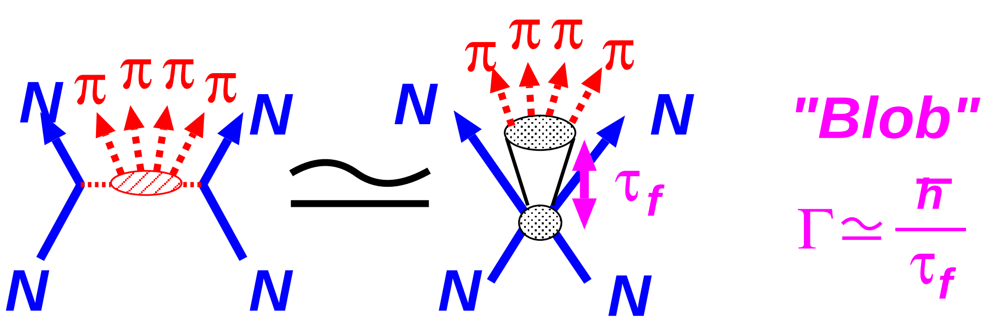
Temperature during HIC

$$T \simeq P/\rho \quad \text{(Ideal Gas EOS)}$$

$\rho =$ Total Hadron Number Density



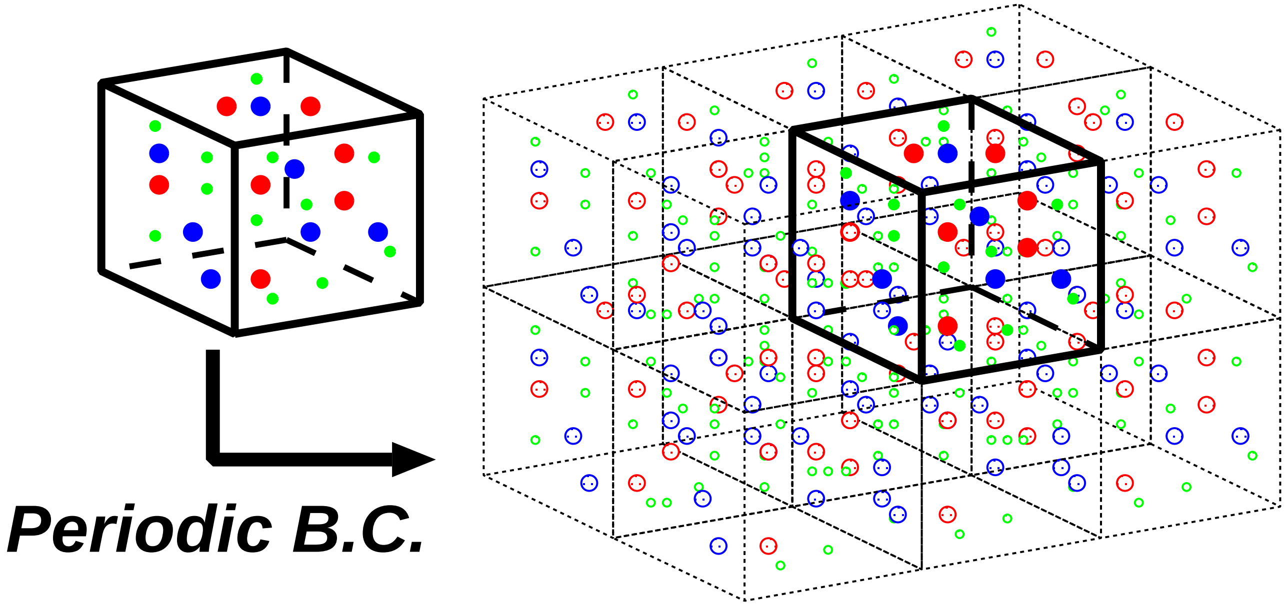
Why Multi Pion Production Reduces P (and thus T)?
→ "Blob" may play a role of Massive (Continuum) DOF.



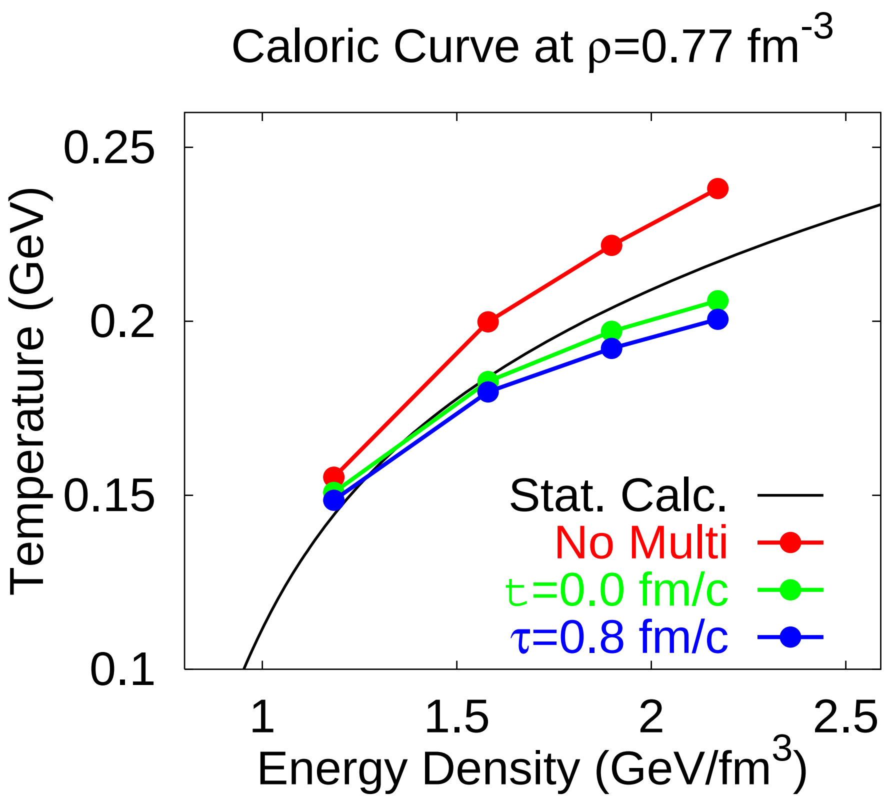
☞ Is it true at Equilibrium ?

⋆ Put Particles in a Box

··· Simulation of Hadronic Matter



Caloric Curve of Hot and Dense Matter (HANDEL)



☞ Yes, It IS True.

⋆ Summary and Conclusion

⋆ Heavy-Ion Collisions at AGS energies have been studied from a view point of Softening caused by

the Increase of Eff. DOF

and

ρ and Momentum Dep. Mean Field.

⋆ To explain particle M_t spectra at AGS energies, it is nececcary to invoke DOF other than N and π either through

Explicit Treatment of Heavy-Res. and Strings

or

Implicit Inclusion through Multi. Prod. with τ_f.

It strongly suggests that

Appr. Hagedon Gas is Realized

in this energy region.

- ⋆ M_t spectra in various pA, AA reactions are well described consistently in JAM (devel. by Y. Nara).
- ⋆ Both of Dir. Flow and Ellip. Flow at SIS-AGS energies have been explained simultaneously for the First Time after fitting $U_N(p)$ (through Λ) and M_t spectra (through $\sqrt{s_{SW}}$) in RBUU (maintained by P.K.Sahu).
- ⋆ In small DOF model, Multi. Prod. with finite τ_f generates Effective Large Mass DOF, and compensates the explicit small DOF. This point is shown through M_t spectra in HIC and Matter Simulation in HANDEL (developed by N.Otuka).
- ⋆ Unification of these models and Applying it to higher JHF-SPS energies are in progress.