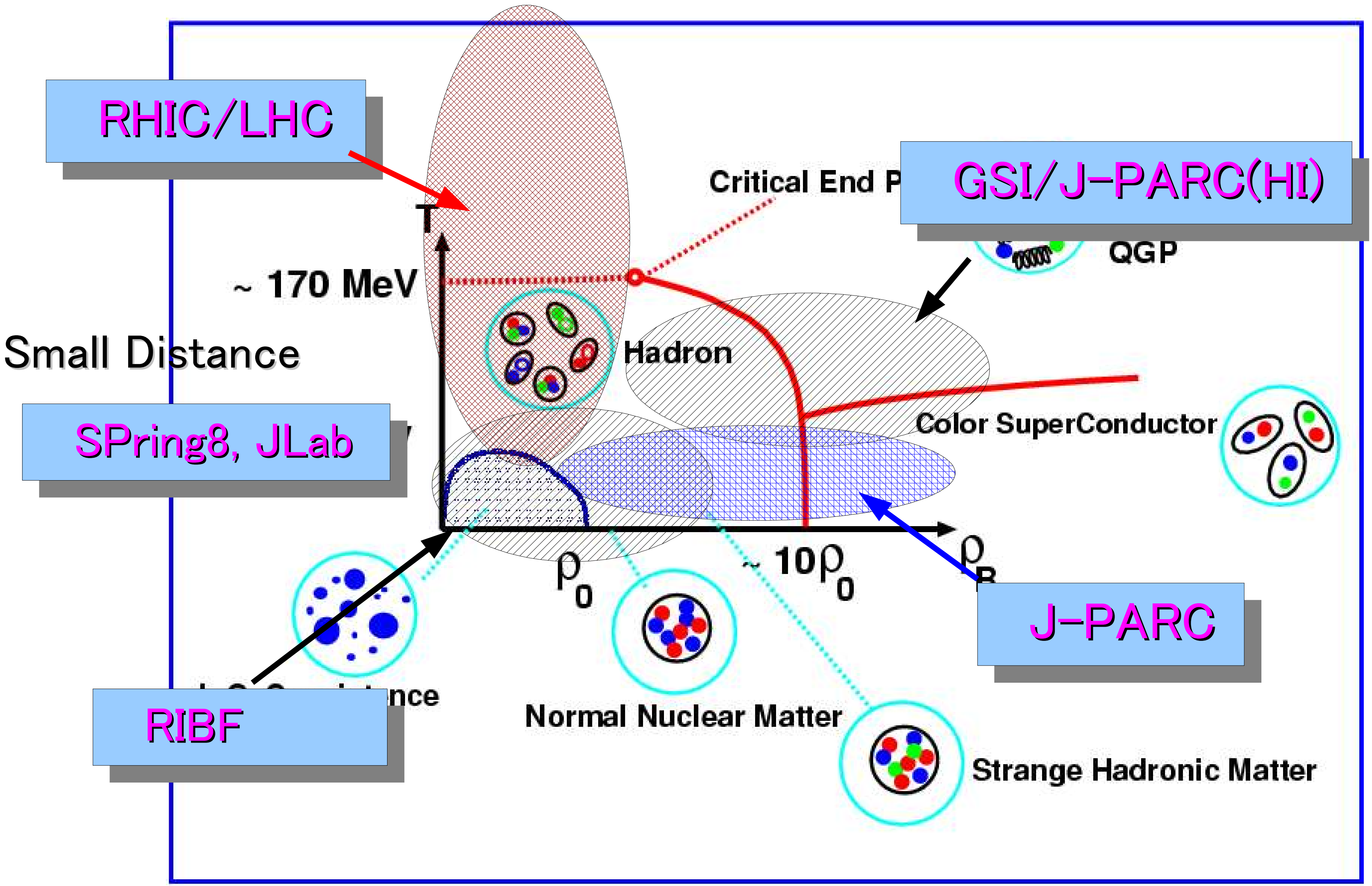
Hyperon Potential in Nuclear Matter and Its Effects on Supernova Explosion

Akira Ohnishi (Hokkaido Univ.)

- Introduction
- Continuum State Spectroscopy of Hyperons in Nuclei
  (H. Maekawa and AO)
- Hyperon Effects on Supernova Explosion
  (C. Ishizuka, AO, K. Sumiyoshi, S. Yamada)
- Summary

Introduction

Hadronic Matter Phase Diagram



What is Expected in Dense Matter ?

⋆ *Hyperons in Neutron Star*

Nucleon Superfluid $({}^1S_0, {}^3P_2)$

Pion Condensation

Strangeness

Hyperon Matter

Tsuruta-Cameron (66), Langer-Rosen (70), Pand-haripande (71), Itoh(75), Glendenning, Weber-Weigel, Sugahara-Toki, Schaffner-Mishustin, Balberg-Gal, Baldo et al., Vidana et al., Nishizaki-Yamamoto-Takatsuka, Kohno-Fujiwara et al., ...

Kaon Condensation

Kaplan-Nelson(88), Forkel-Rho et al.(SUNY), Davidson-Miller, Claymans et al., Politzer-Wise, Miller et al., Muto-Tatsumi, Brown-Thorsson-Lee-Rho-Min, Fujii et al., Yabu et al, Maruyama et al., Ellis-Knorren-Prakashi (with Y), Li-Ning, Li-Brown, Tiwari-Prasad-Singh, Glendenning-Schaffner, ...

Quark-Gluon Plasma

We cannot understand Highly Dense Hadronic Matter
without the Knowledges of Strangeness Nuclear Physics

Why Are Hyperons Important in Dense Matter ?

Constituents:

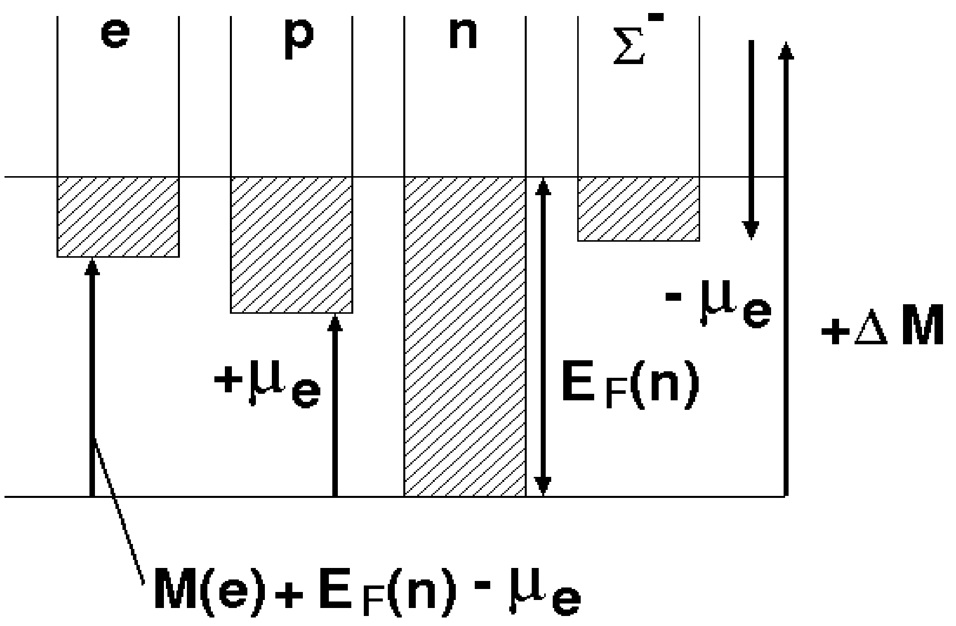
$$p, n, e^{\pm}, \mu^{\pm}, \Lambda, \Sigma^{\pm,0}, \ldots$$

Chemical Equilibrium:

× Strangeness (Weak)

× Lepton (ν **Emission)**

$$\mu_i = B_i \mu_B + Q_i \mu_Q$$

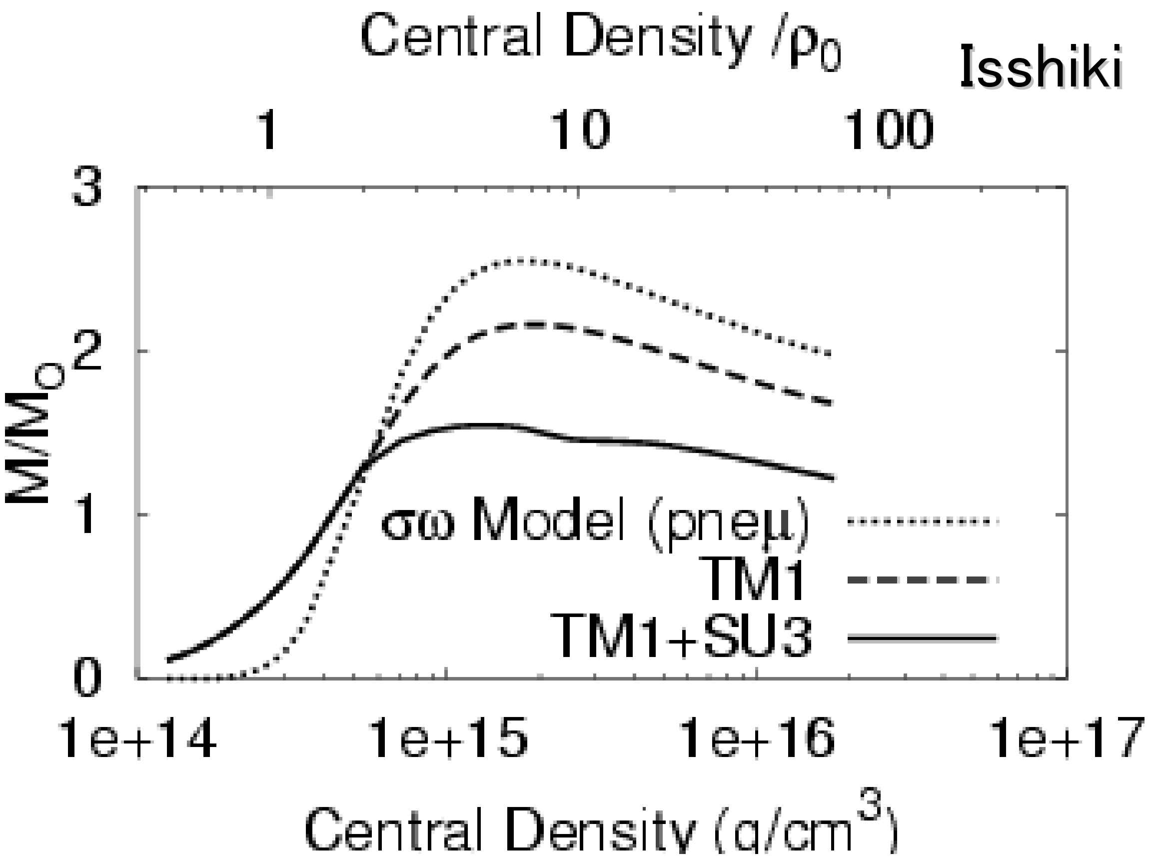


Negatively Chaged or Neutral Baryons are Favored

$$E_F^*(n) + U(n) + \mu_e = M^*(\Sigma^-) + U(\Sigma^-)$$ Σ **appears**

$$E_F^*(n) + U(n) = M^*(\Lambda) + U(\Lambda)$$ Λ **appears**

Example: Neutron Star Max. Mass

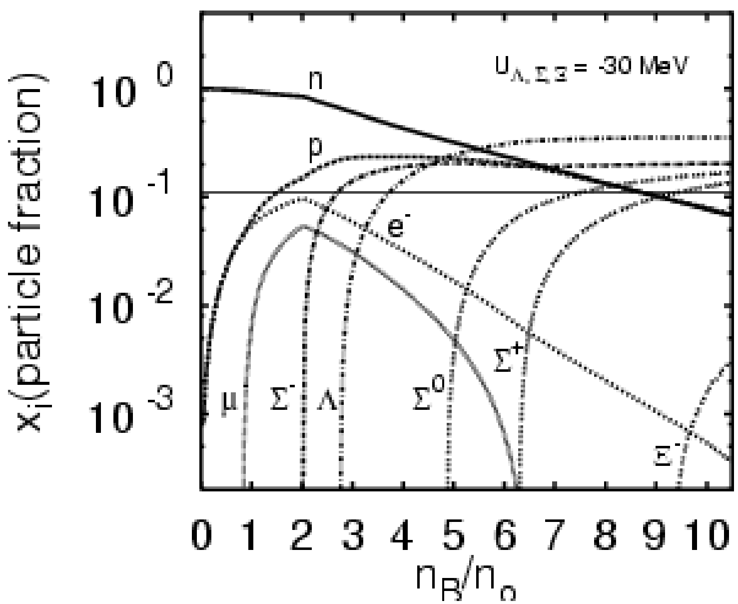


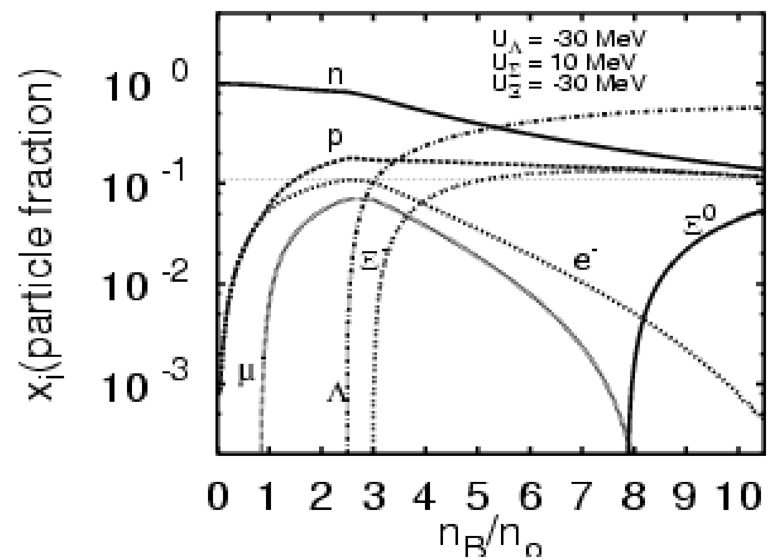
Serot−Walecka ($\sigma\omega$); Sugahara−Toki (TM1);
Glendenning; Schaffner−Mishustin (TM1+SU3); ...

Maximum Mass Reduction ~ 0.5−1.0 M_{sun}

Σ Potential Effects in Neutron Star

(RMF: Sahu, Ohnishi Nucl. Phys. A691 (2001), 439.)





Attractive Potential for Σ

→ Σ **appears at around** $\rho \approx 2\rho_0$

Repulsive Potential for Σ

→ Σ **does not appear**

Max. Mass and Compositions are SENSITIVE to Interaction !!

E.g. Nishizaki-Takatsuka-Yamamoto, PTP 108 (02) 703.

G-matrix Approach

Nishizaki-Takatsuka-Yamamoto,
PTP 108 (2002),703.
G-matrix for NN and YN, YY
+ Three Baryon Int.(phen.)

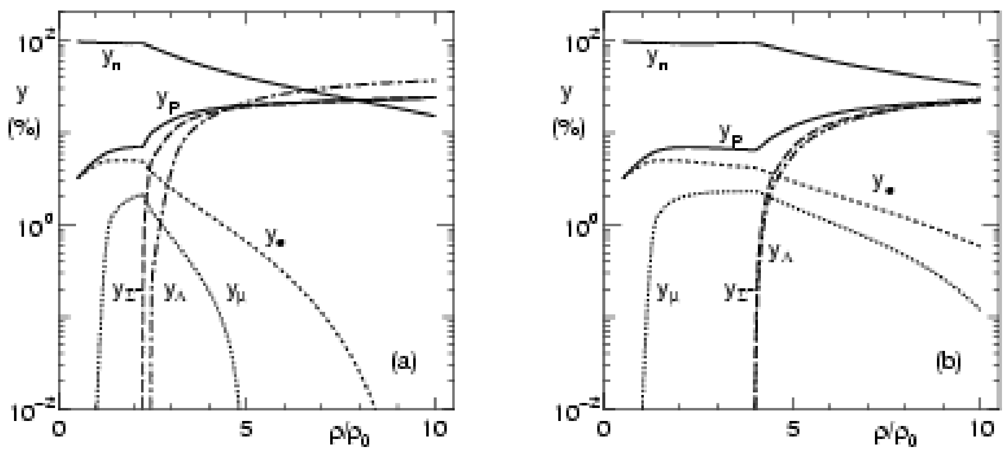


Fig. 4. The fractions of constituent particles as functions of the baryon density. (a) TNI3 only for the NN part (TNI3), (b) TNR3 for the YN and YY parts and for the NN part (TNI3u).

Hyperon Composition

Max. Mass

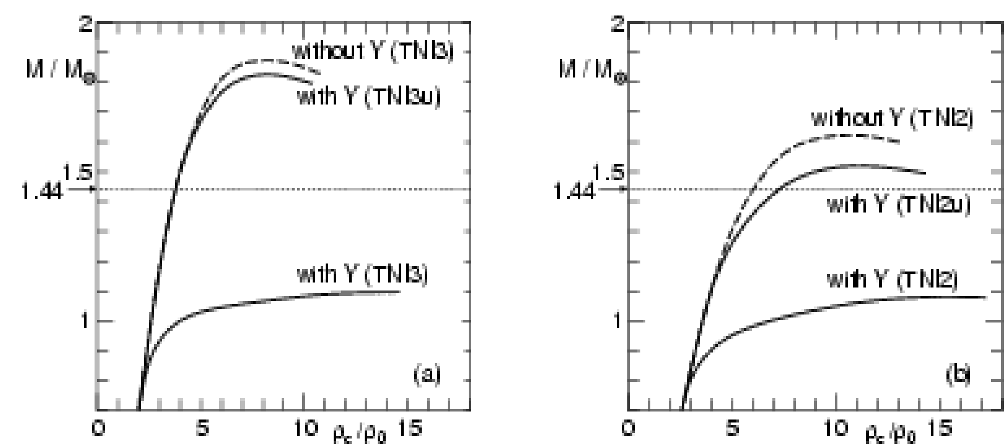


Fig. 9. The mass of a neutron star in units of the solar mass $M_\odot$ as functions of the central baryon density ρ_c with use of (a) TNI3 and (b) TNI2. The notation here is the same as in Fig. 8.

What Should Be Discussed ?

- ***How much do we know Hyperon Potential in (Dense) Nuclear Matter ?***
  - ➔ ***Λ: Bound State Spectroscopy***
  - ➔ ***Σ and Ξ: Continuum Spectroscopy***
- ***Hyperons will Definitely Affect Neutron Stars***
  - ➔ ***How do Hyperons Affect Supernova Explosion ?***

Continuum State Spectroscopy of Hyperons in Nuclei

Hyperon Potentials: How much do we know ?

- **Hyperon Potentials at around $\rho \approx \rho_0$**
  - ***U(Λ) ≈ -30 MeV: Bound State Spectroscopy***
  - ***Σ and Ξ hyperons: # of Bound state is small !***
    (or Resolution is too bad to Specify B.S.)

    ➔ ***Continuum State Spectroscopy***
- **Hyperon Potentials at High Densities**
  - ***Hyperon Collective Flow at AGS (2-10 A GeV)***

    ➔ ***Less Repulsive than Nucleons in Nucleon Dominant Matter***
  - ***K+ Enhancement at Lower SPS energy***

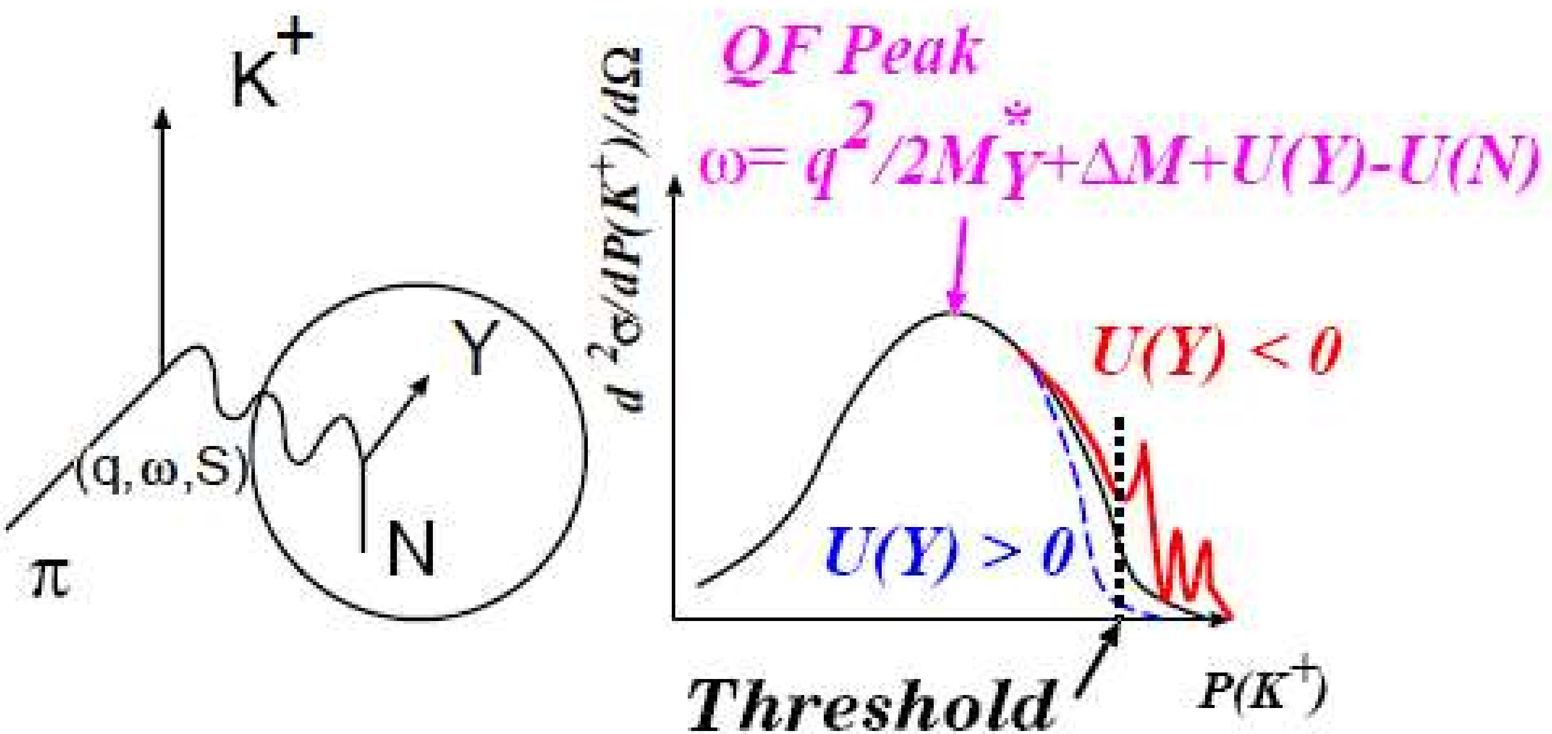
    ➔ ***Less Repulsive Hyperon Potential may help***
  - ***Theoretical Prediction: Strong Model Deps.***

Continuum Spectroscopy of Hyperons

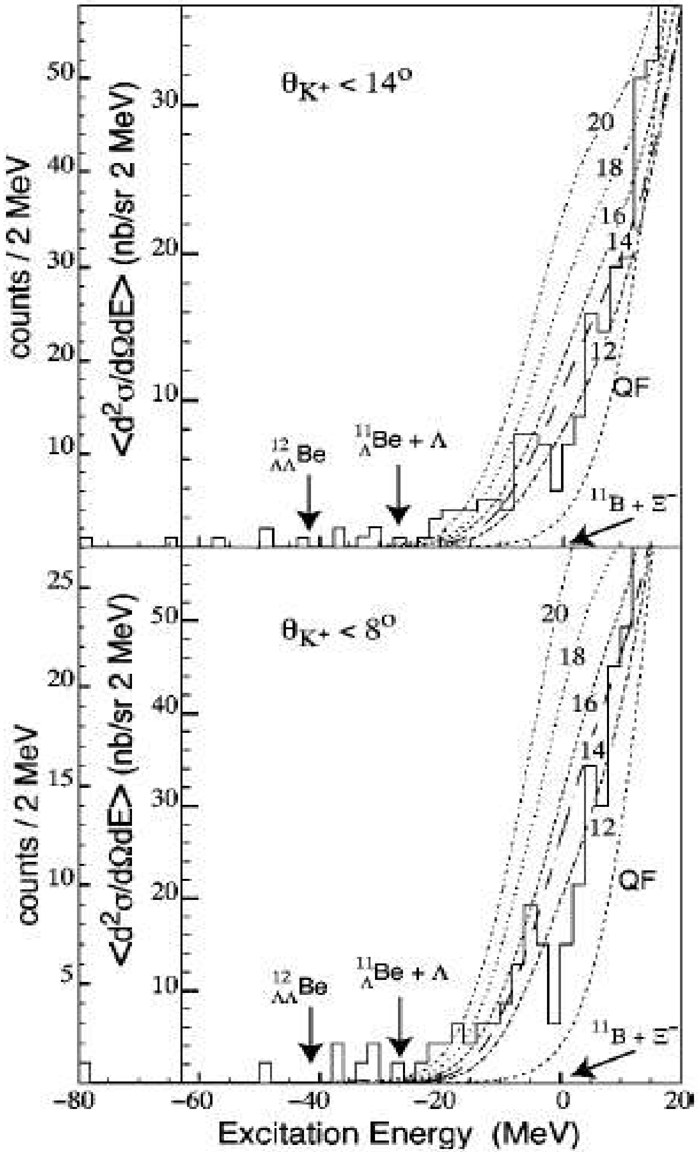
$^{A}Z(\pi^{+}, K^{+})$: Λ Production inside Nuclei

$^{A}Z(\pi^{-}, K^{+})$: Σ^{-} Production

$^{A}Z(K^{-}, K^{+})$: Ξ^{-} Production



Ξ – Nucleus potential: Bound State Region



$^{12}C(K^-,K^+)^{11}B^*\Xi^-$ Spectrum

BNL−E885 Experiment
(P. Khaustov et al., PRC61(00),054603)
Bound state region spectroscopy
→ U(Ξ) ≈ −(12−14) MeV

Results in Other Experiments
(KEK−E224, BNL−E906)
are also consistent with

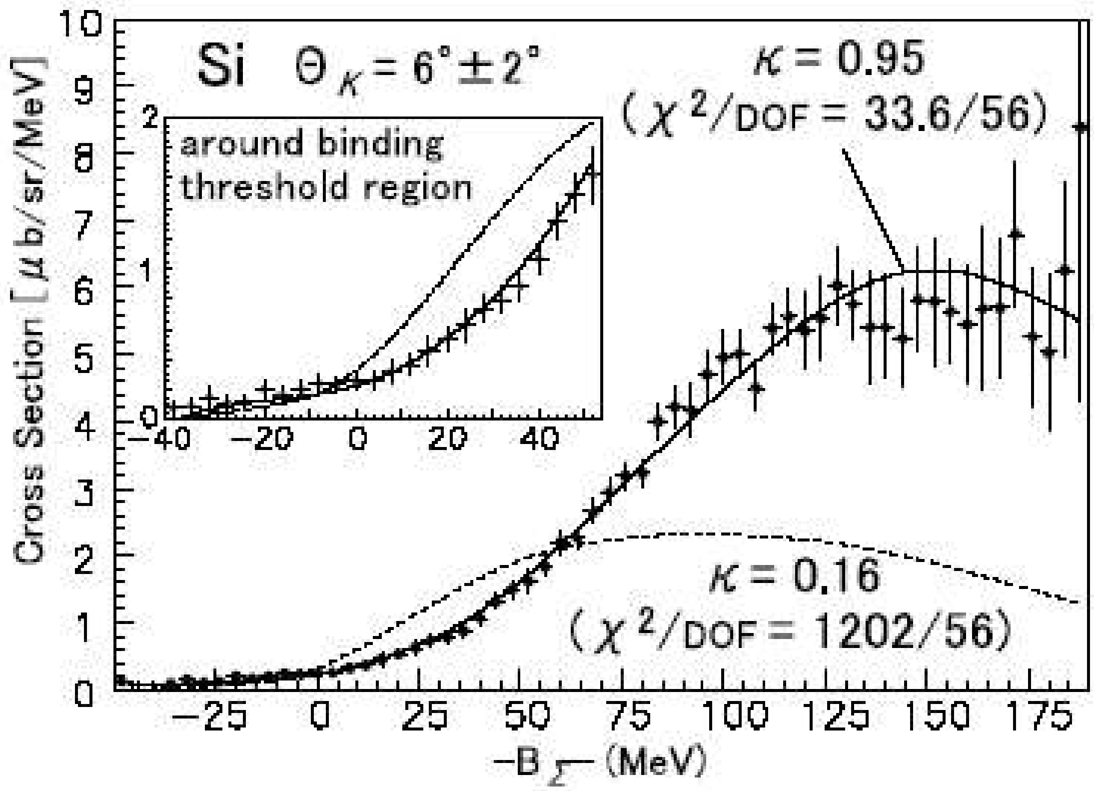
U(Ξ) ≈ −(12−16) MeV

U(B) in Nuclear Matter
∝ Number of ud Quarks ?

Σ Potential: Quasi Free (π^-,K^+) Spectrum

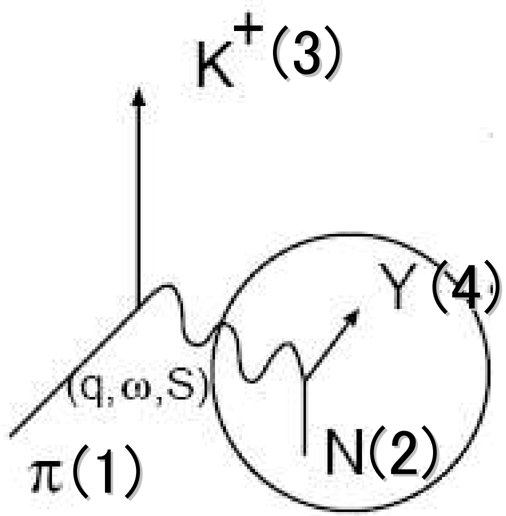
$^{28}Si(\pi^-, K^+)^{27}Al^{(*)}\Sigma^-$ Spectrum at 1.2 GeV/c

KEK-E428 Experiment: H.Noumi et al Phys.Rev.Lett 89(2002) 072301



DWIA + WS pot.
→ U(Σ) ≈+150 MeV
(Strongly Repulsive)

Distorted Wave Impulse Approximation (DWIA)



Green Function Method

$$\frac{d^2\sigma}{dE\,d\Omega}=\frac{p_3 E_3}{(2\pi\hbar^2)^2 v_1}\ S(E)\ |t_{elem}|^2$$

(Morimatsu and Yazaki)

$$\simeq\beta\left(\frac{d\sigma^{Elem}}{d\Omega}\right)_{Lab} S(E)\ |t_{elem}|^2$$

Kinematical Factor

(Tadokoro and Akaishi)

$$S(E)=-\frac{1}{\pi}Im\int d^3r\,d^3r'\,f^*_{\alpha'}(r')G_{\alpha'\alpha}(E;r',r)f_\alpha(r)$$

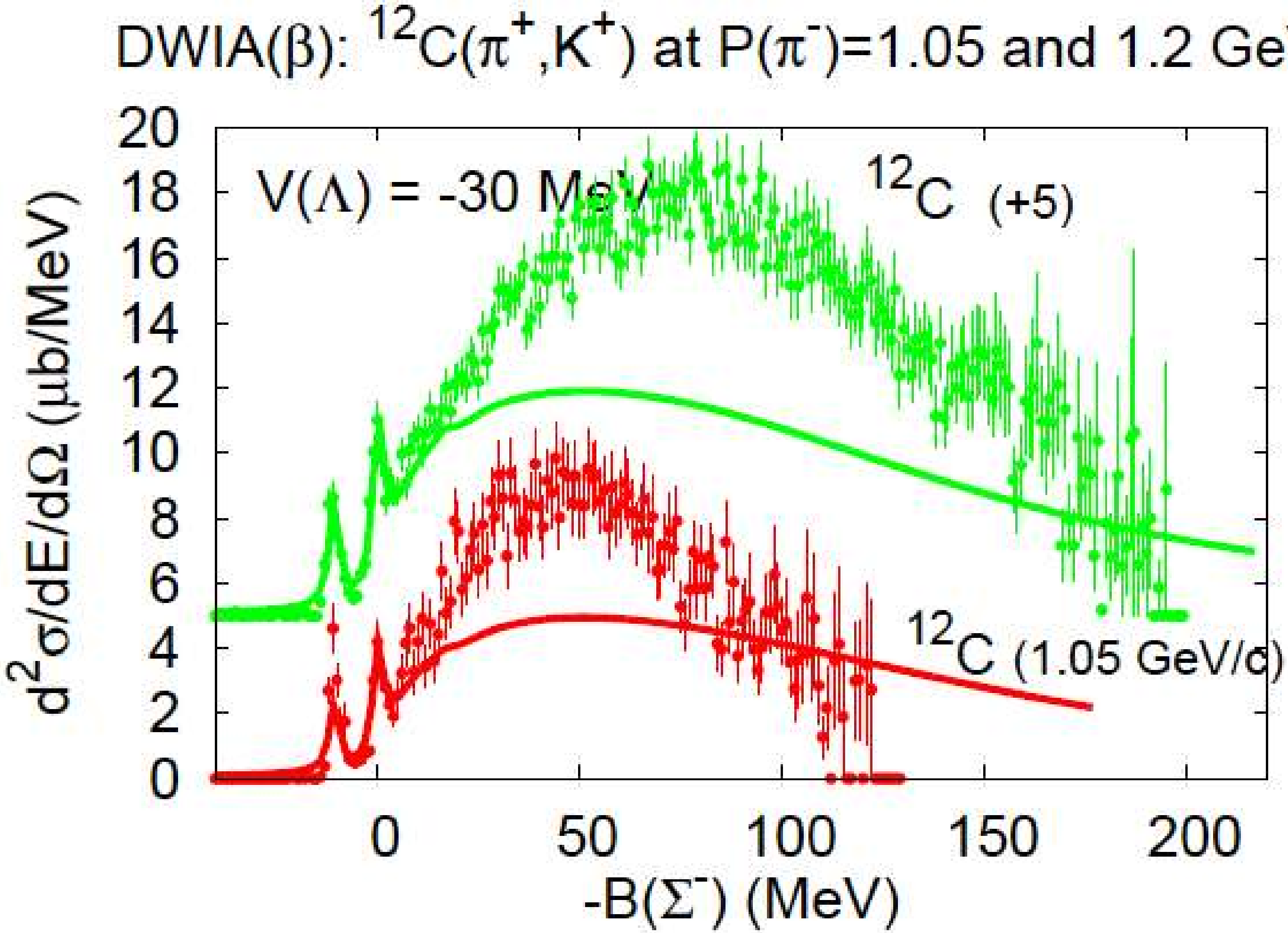
$$f_\alpha(r)=(\chi^{(-)}(r))^*\chi^+(r)\langle\alpha|\psi_N|i\rangle$$

Y–A Potential

$$G_{\alpha'\alpha}(E;r',r)=\frac{1}{E-H_{\alpha'\alpha}-K_Y-U_{YA}+i\epsilon}$$

Problems in "beta" Factorization

Good at Bound State Energies,
but not Good Enough in the Whole QF Spectrum



Improved Treatment: Optimal Momentum Appr.

Harada's talk (July 31), submitted, H. Maekawa's talk (July 31)
Saha et al.(KEK-E428 Collab.), nucl-ex/04

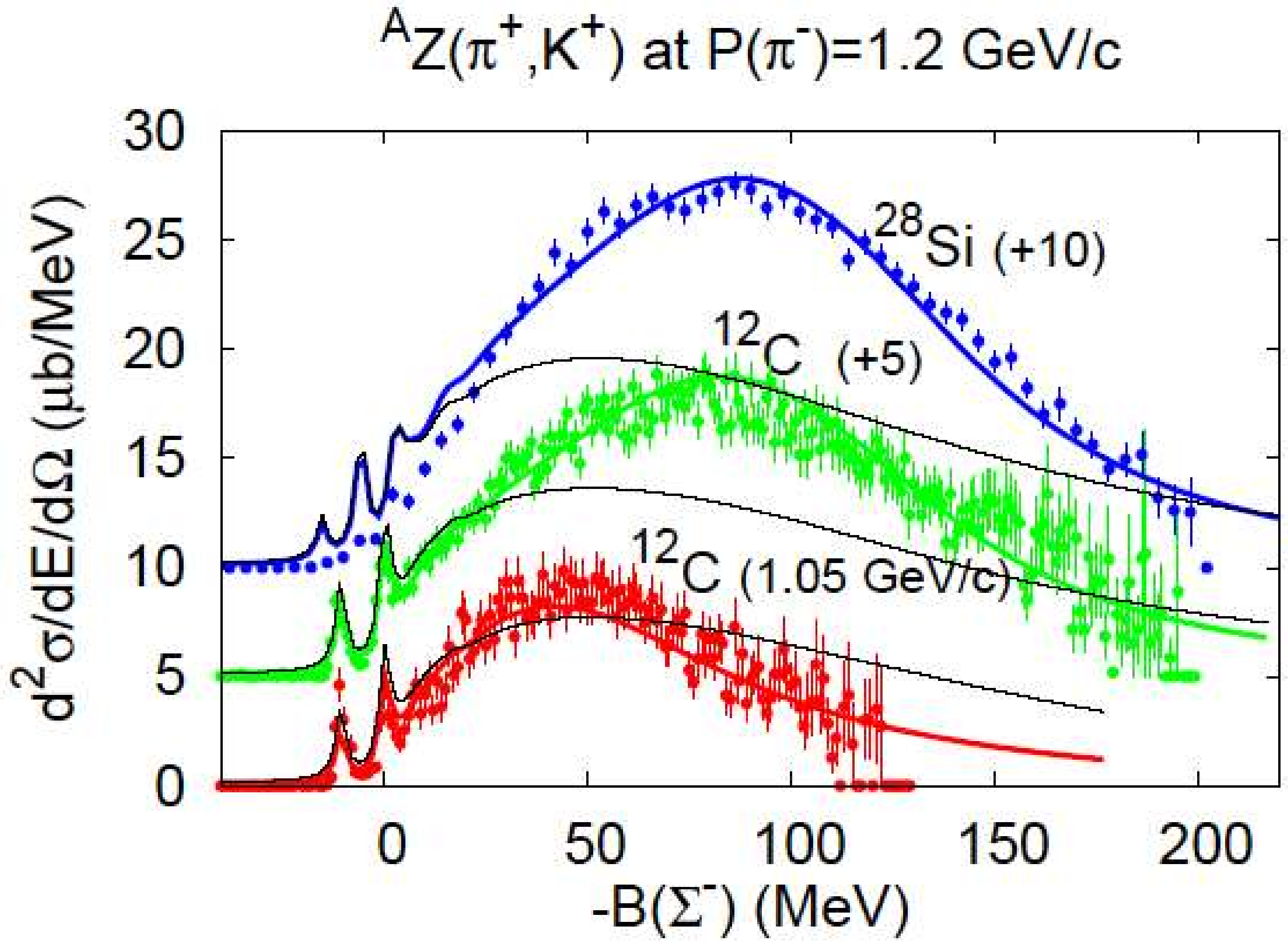
$$\frac{d^2\sigma}{dE\,d\Omega}=\frac{p_3 E_3}{v_1}\;S(E)\;\left\langle \frac{1}{E_1^L E_2^L E_3^L E_4^L}\frac{s\,p_i}{p_f}\left(\frac{d\sigma}{d\Omega}\right)_{CM}^{Elem}(s,t)\right\rangle_{Opt.}$$

- ✔ For each p3, get Optimal momentum p2 which satisfy the energy-momentum conservation with on-shell or appropriate off-shell condition.
- ✔ Obtain CM cross section and t-matrix squrared
- ✔ Transform t-matrix from CM to Lab. Frame
- ✔ Optionally, Average over the Fermi Sphere

Harada: Average of t-matrix amplitude with optimal momentum
Saha et al.: Average of Lab. cross section with optimal momentum keeping the kinematical factor
Ours: $|t|^2$ average or at an appropriate optimal momentum

(π^+, K^+) Reaction

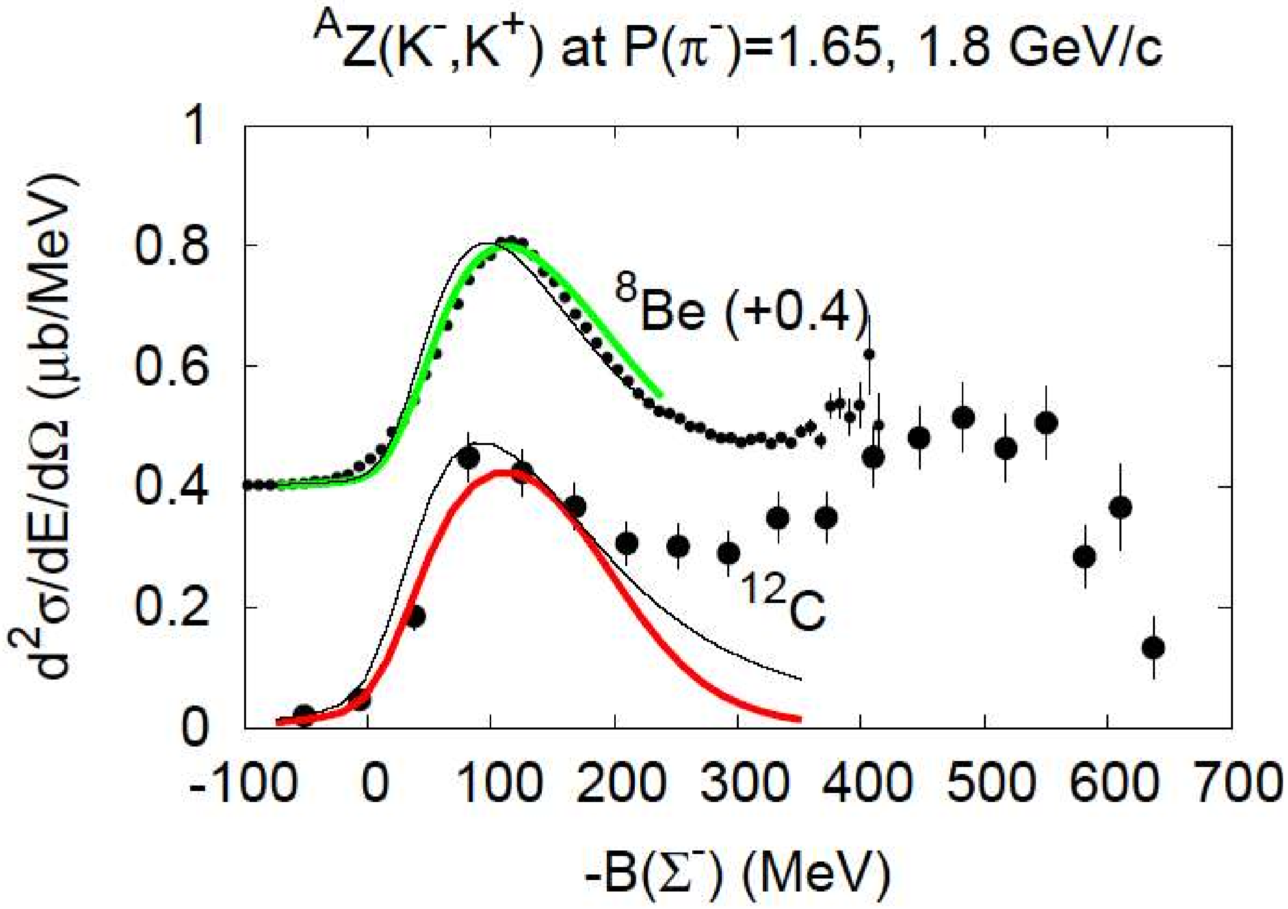
$U(\Lambda) \simeq (28-30)$ *MeV*

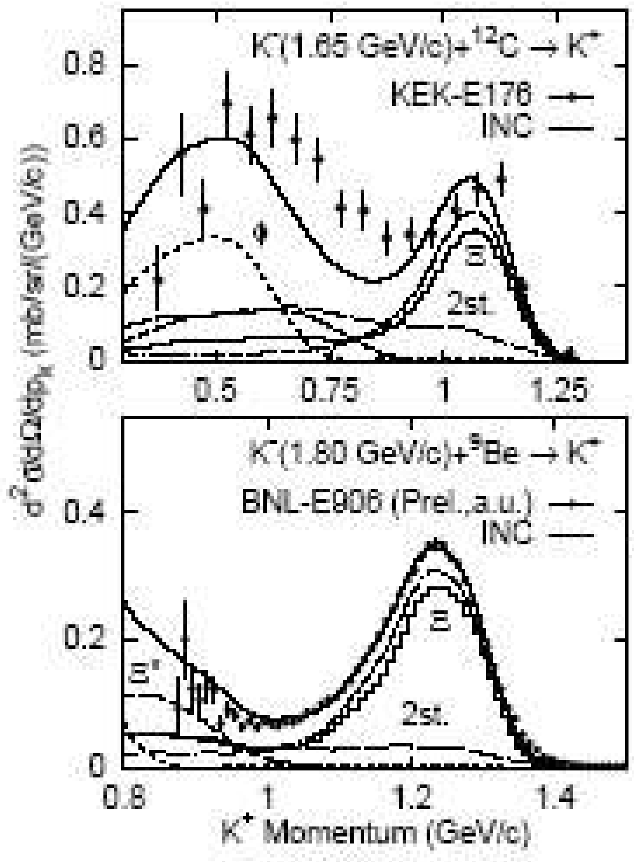


(K^-,K^+) Reaction

$U(\Xi) \simeq -14$ MeV

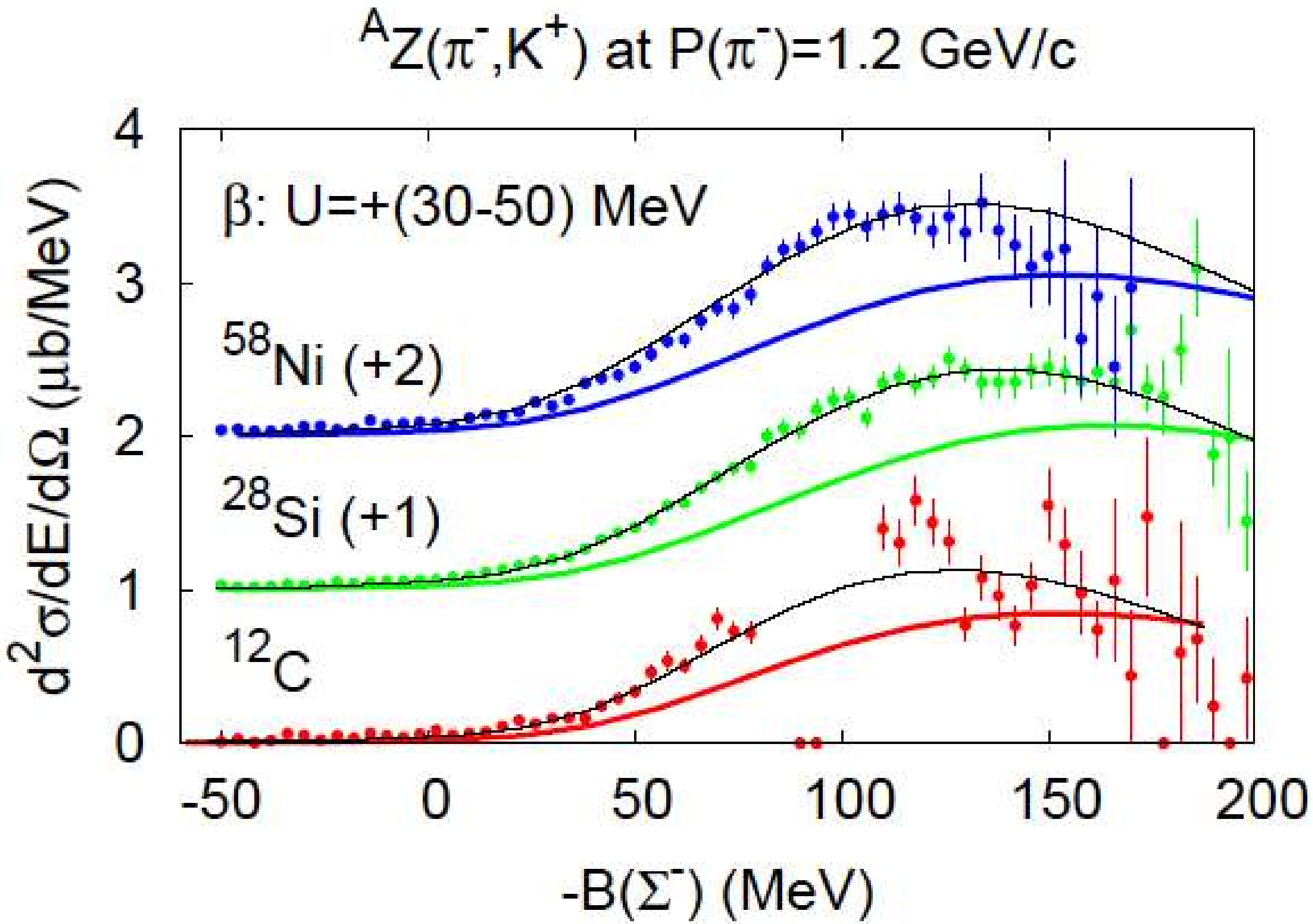
Cascade Results
(AO,Hirata,Nara,Shinmura,Akaishi)





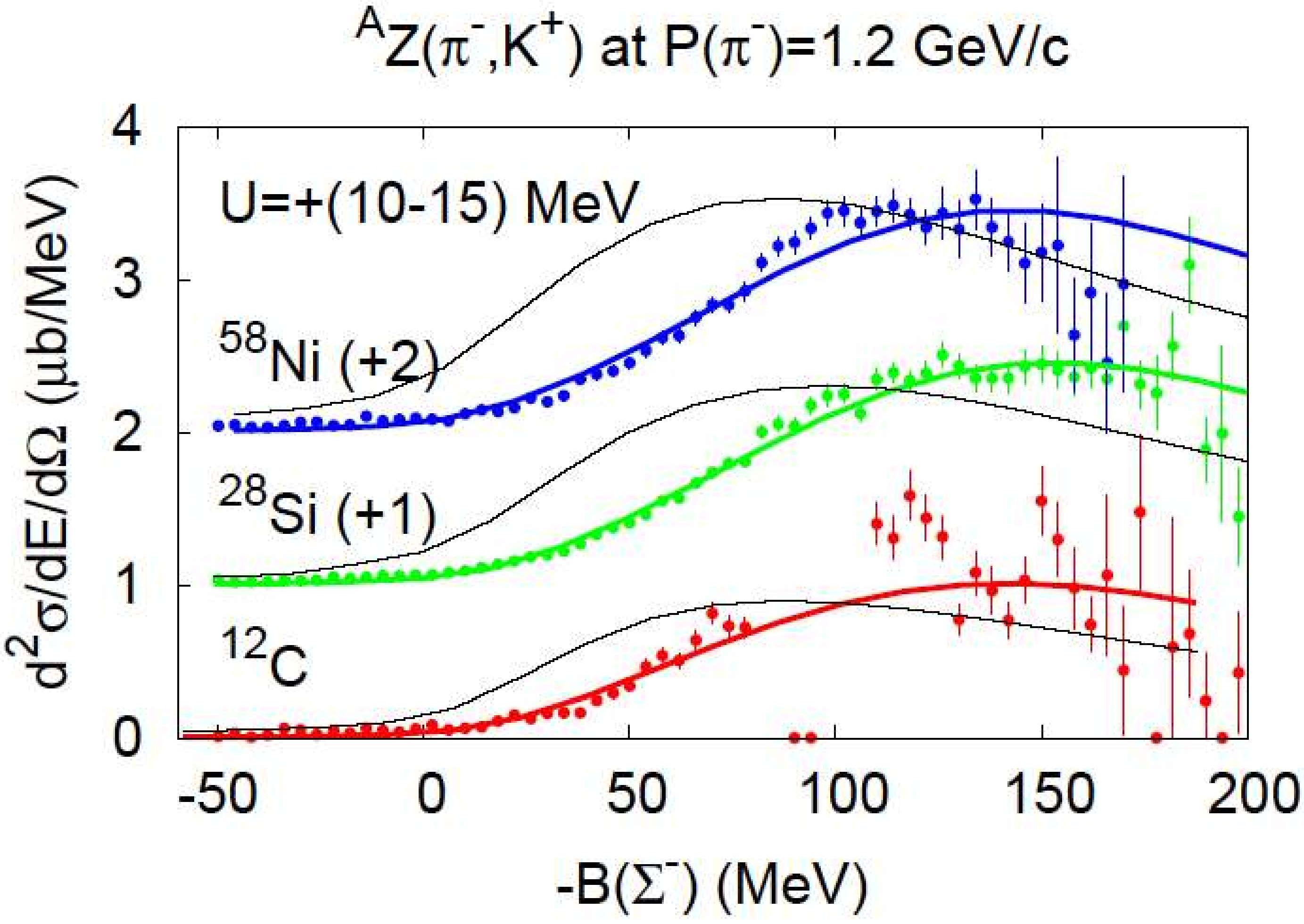
(π^-, K^+) Reaction (I): Beta fit

Average of Cross Sections: Strongly Repulsive Pot. is Favored...



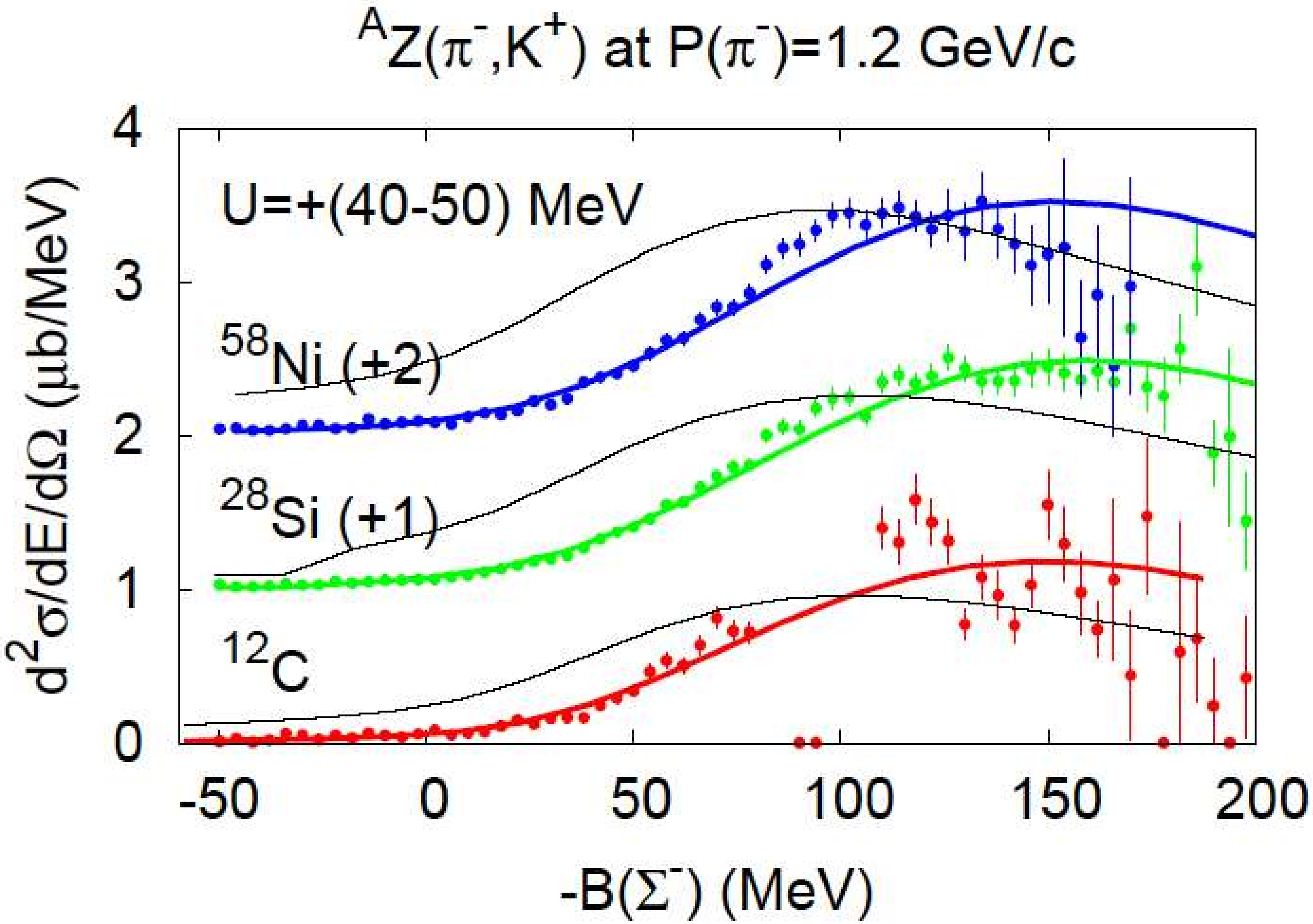
(π^-,K$^+$) Reaction (II): Weaker Repulsive

Averaged $|t|^2$: Repulsive but weaker potential (R_0=1.27 fm)



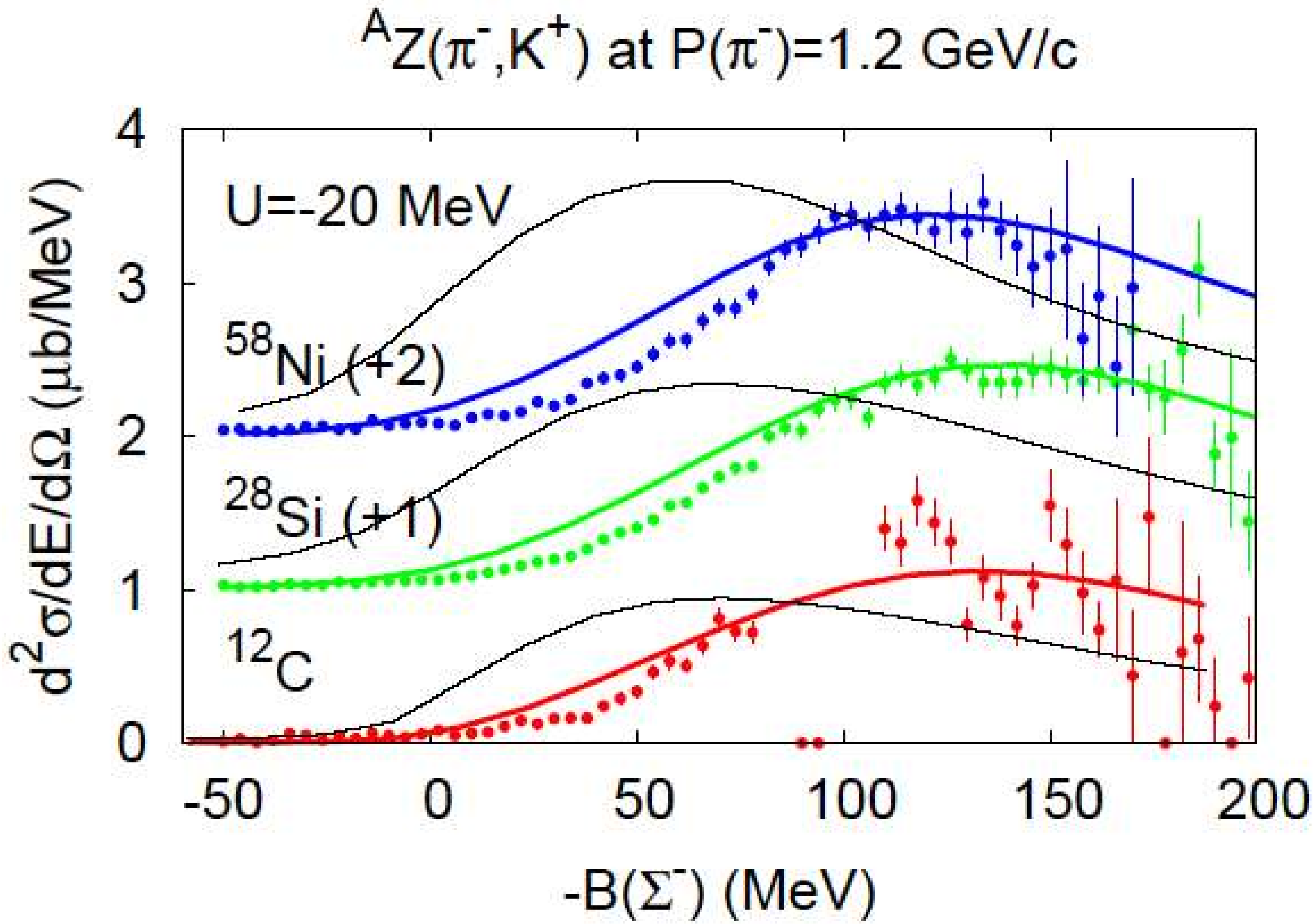
(π^-,K^+) Reaction (III): Sensitive to Radius

More Repulsive Potential is required for Smaller R. (R_0 = 1.09 fm)



(π^-,K^+) Reaction (IV): Attractive

QF Peak can be explained even with Attractive potential.



Hyperon Effects in Supernova Explosion

Possible Role of Hyperons in Supernova

- *Hyperons would exist in Neutron Star Core*
  - ➔ *Should appear during the cooling stage*
- *Density and Temperature are High in the Collapse and Bounce Stage*
  - ➔ *May appear even in the Early (Bounce) Stage*
- *Hyperons Soften EOS*
  - ➔ *May Increase the Explosion Energy*

Let's Check it Out !

Supernova Explosion Model

EOS table based on RMF and Thomas-Fermi approx.

- Well reproducing nuclear experimental data
  [Ref.] H. Shen et al., PTP 100 (1998), 1013.
- Containing full baryon octet
  [Ref.] J. Schaffner and I. Mishustin, PRC 53 (1996), 1416.

YN interactions

- U_Σ=−30MeV → U_Σ=+30~+90MeV
- U_Ξ=−30MeV → U_Ξ=−15MeV

[Ref.] H. Noumi et al., RPL 89 (2002), 072301

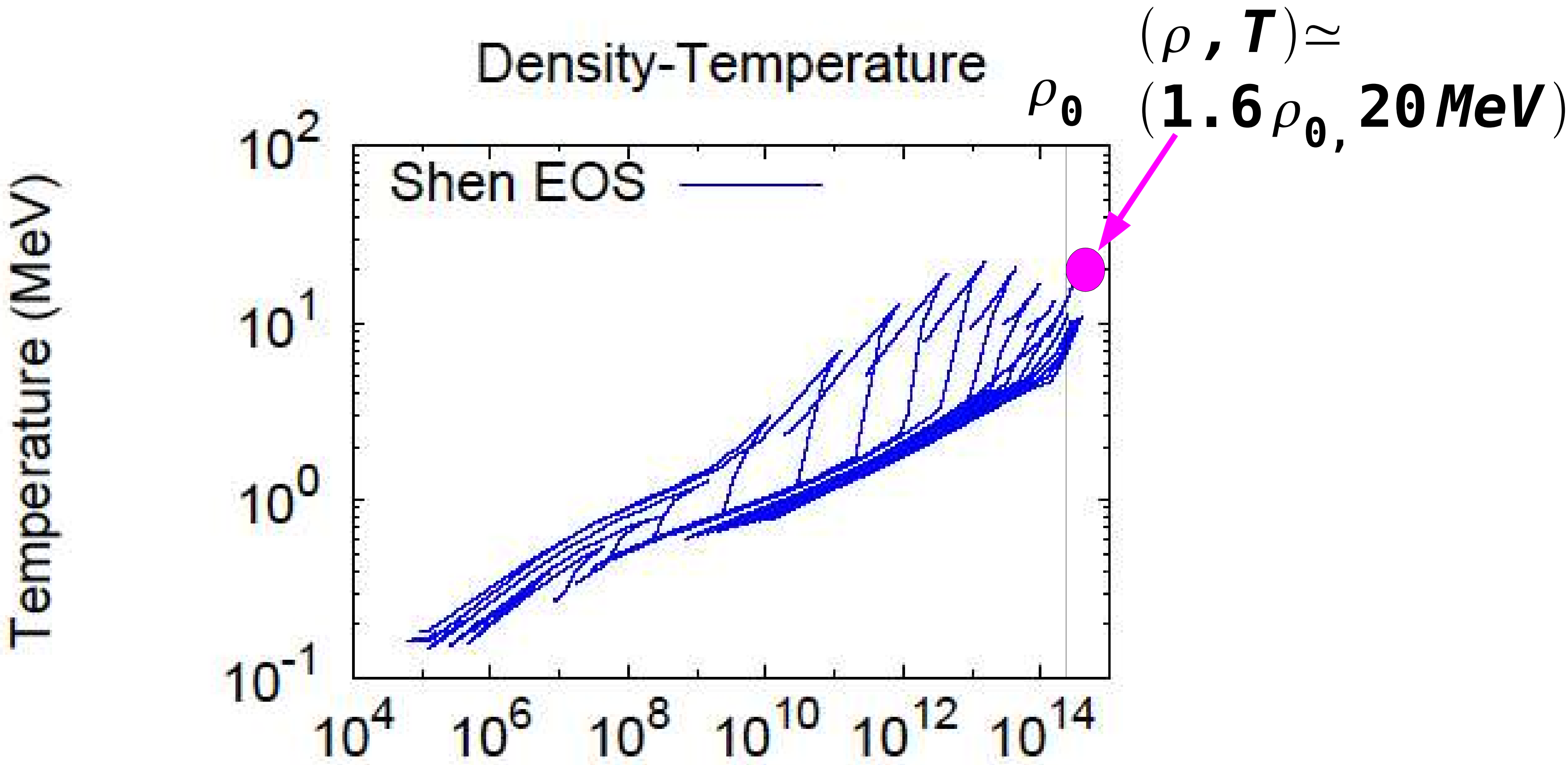
Leptons

- muons, muon neutrinos
- thermal electron neutrinos

Hydrodynamical calculation

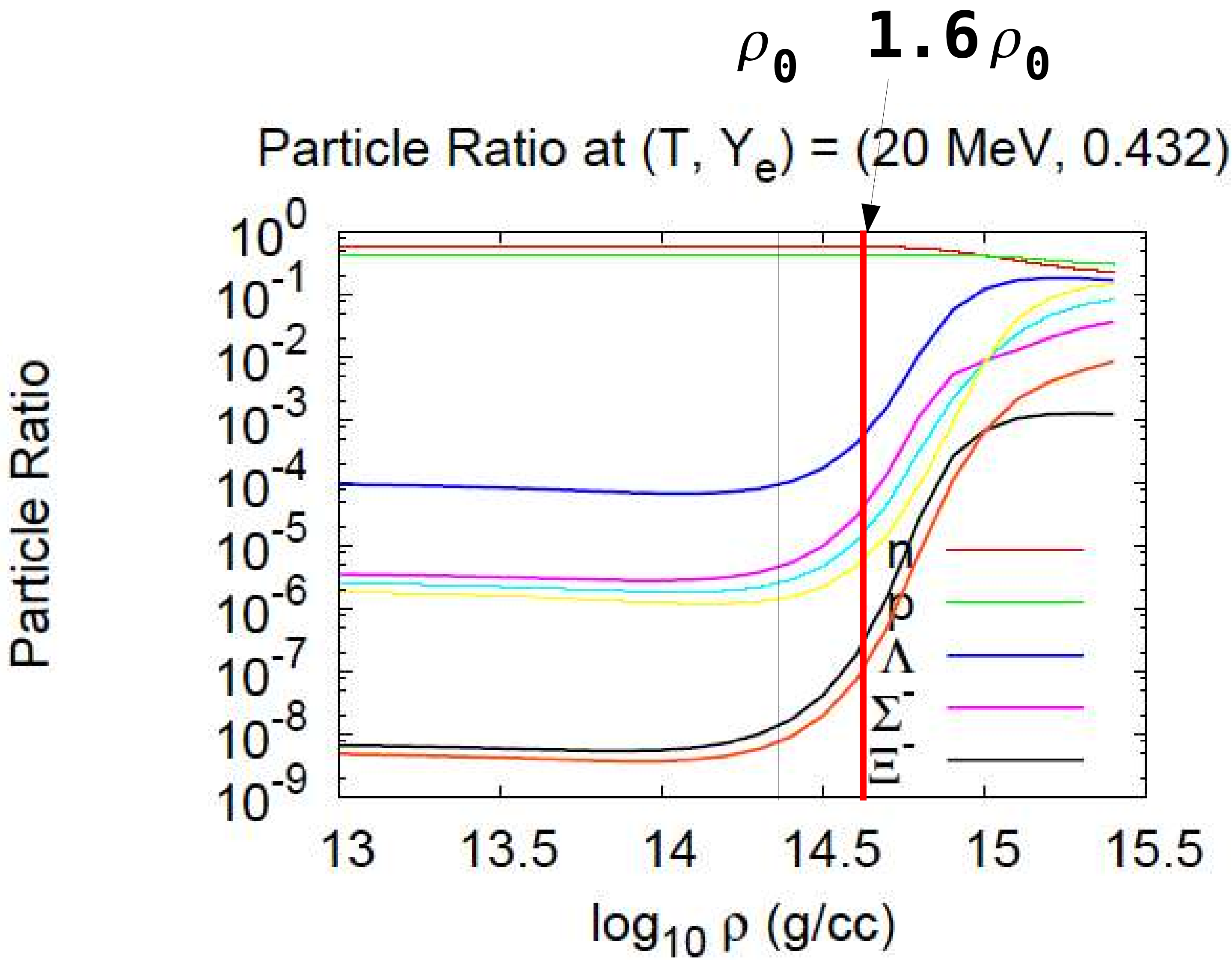
- 1dim. Spherical hydro. calc.
- adiabatic expansion (without neutrino transport)
- Initial model = WW95
  [Ref.] K. Sumiyoshi et al., NPA 730 (2004), 227

Density and Temperature in SN Expl.



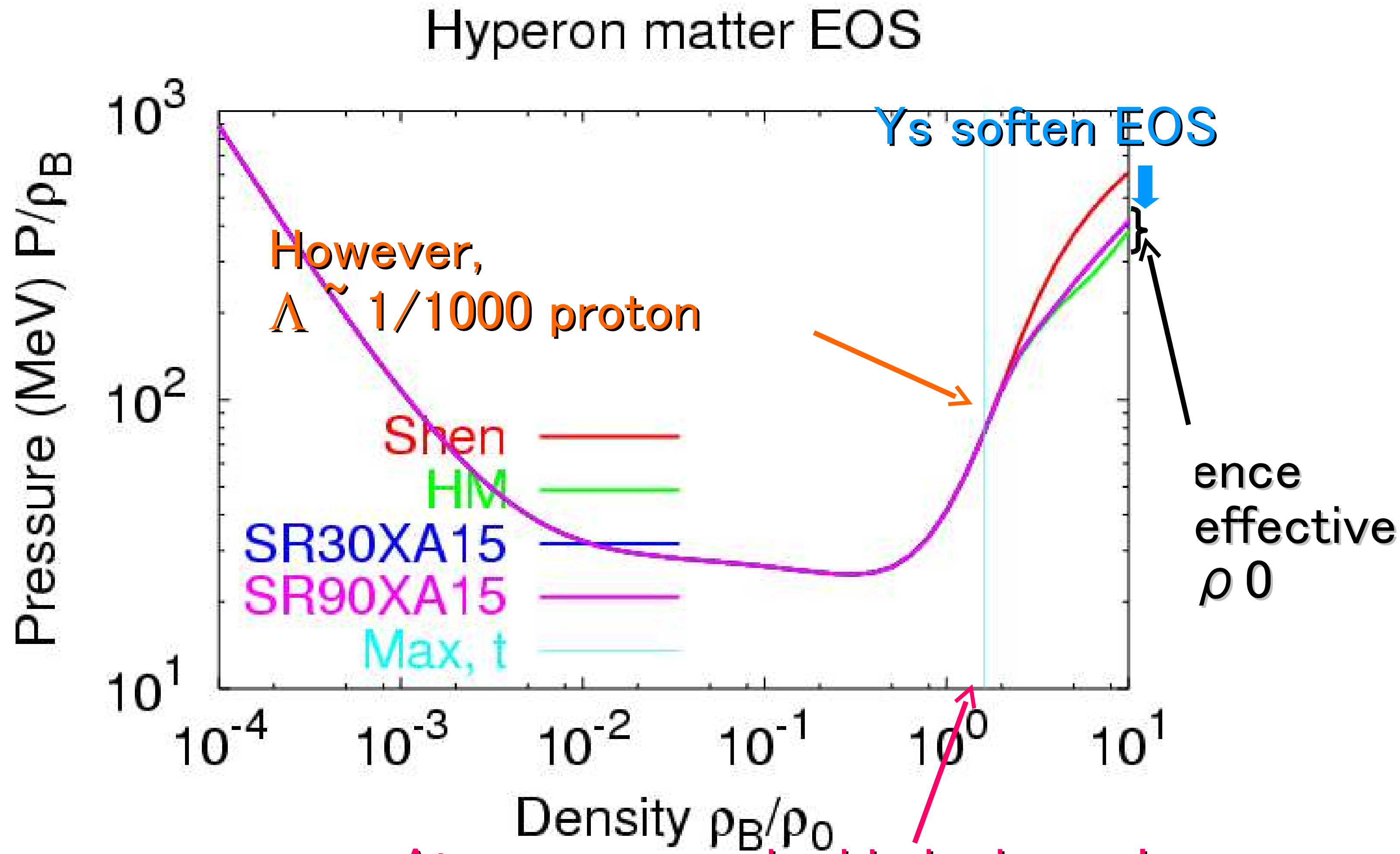
Density: Smaller than the Critical Density of Σ^-, but Finite Temperature may help.

Particle Fractions at around the bounce



Fraction = $10^{-4} - 10^{-3}$ (small), but Chemical Pot. change is not small.

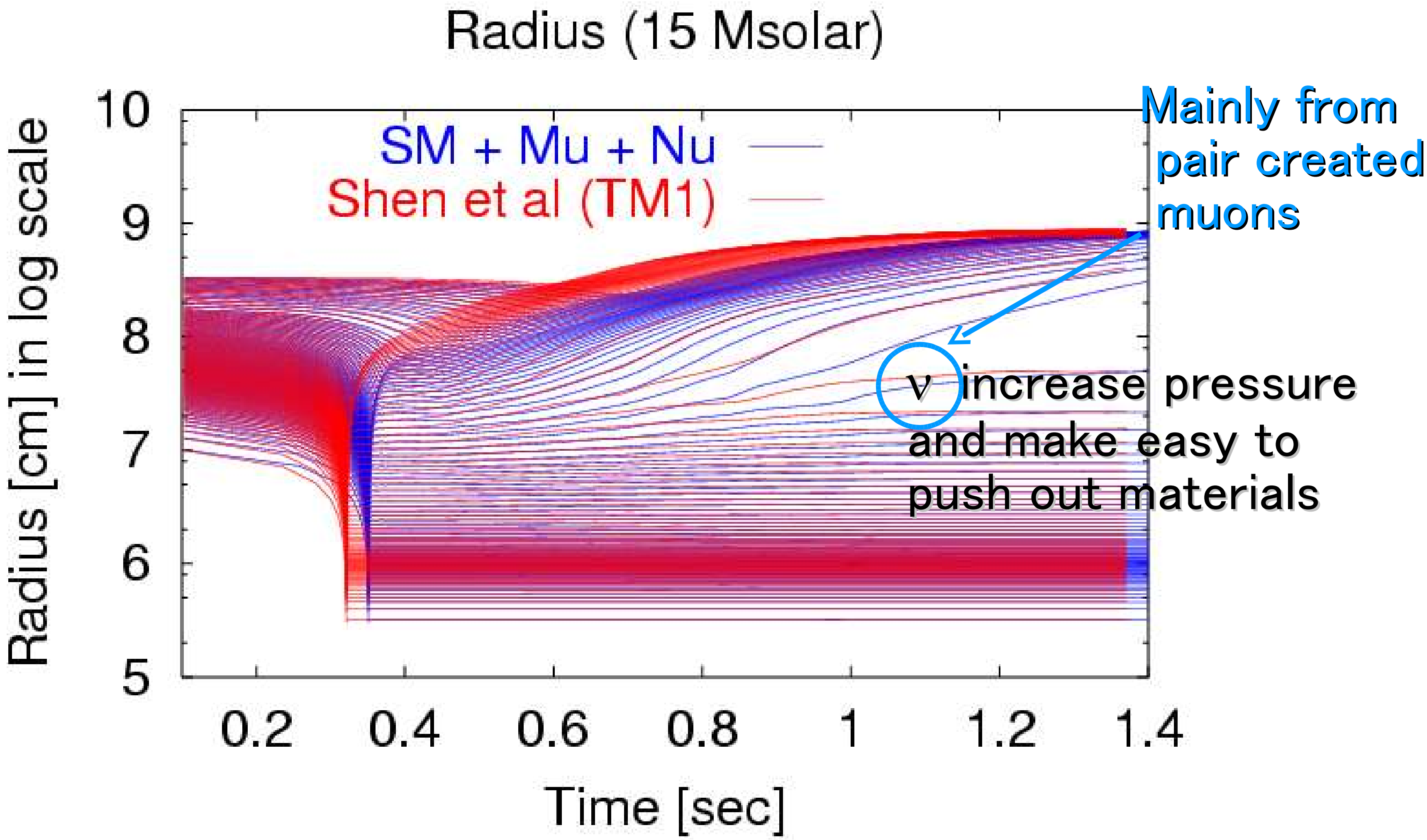
Hyperon effects on EOS



At max. ρ_B reached in hydro. calc., differences in EOS are quite small.

Y effect to E_{exp} cannot be seen in this model.

Example: Y+Muon+ν_μ+ ν_e^{th} (Hydro. Result)



Hyperons in Supernova Explosion

- **Environment in Supernova Explosion**
  - **Smaller Density than Neutron Star (X)**
  - **Finite Temperature around 10-30 MeV (O)**
  - **Larger Electron Fraction (Ye) (X)**

➔ **Totally, Hyperon Effects amount to be small**

- **Difference from the Previous Results**
  - **Last Autumn: 4 % Increase of Explosion E.**
    - **Connecting EOS table at a fixed density**
  - **This time: Almost No Change**
    - **Smooth continuation**

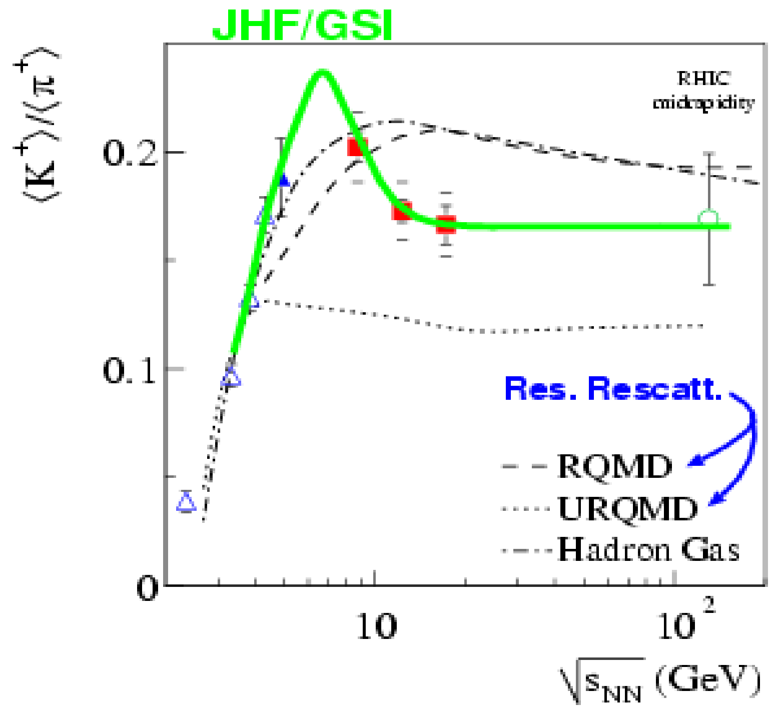
Summary

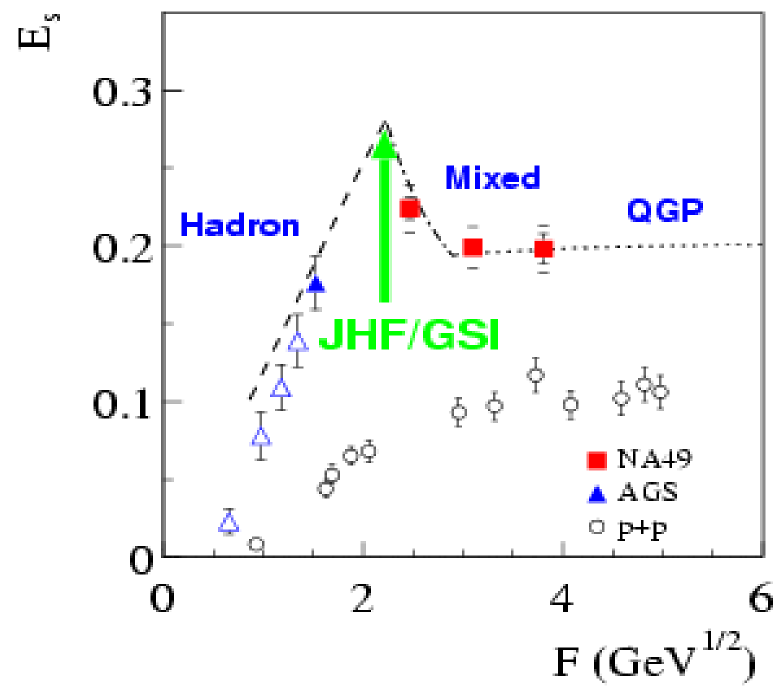
- *Hyperon Potentials in Nuclei are studied through Continuum State Spectroscopy*
  - *Λ: Consistent Understanding of B.S., Continuum, Energy Deps. is achieved.*
  - *Ξ: Continuum Spectra seems to be consistent with (12-16) MeV depth*
  - *Σ: Strongly Depends on the treatment. To be investigated more carefully.*
- *Hyperon Effects in Supernova Explosion*
  - *Prompt Explosion: Almost No Effects are Seen.*
  - *Cooling of Neutron Star at Birth, and Delayed Explosion with ν Transport: To be studied more.*

Strangeness Enhancement: Rescattering, Potential, or Phase Transition ?

Strangeness is Enhanced Sharply at Einc = 10 ~ 40 GeV/A !

NA49 (nucl-ex/0205002)

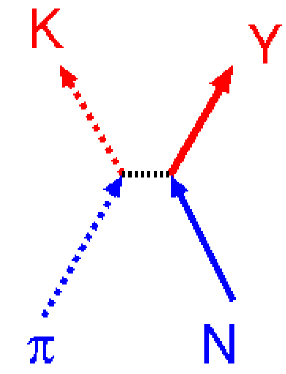


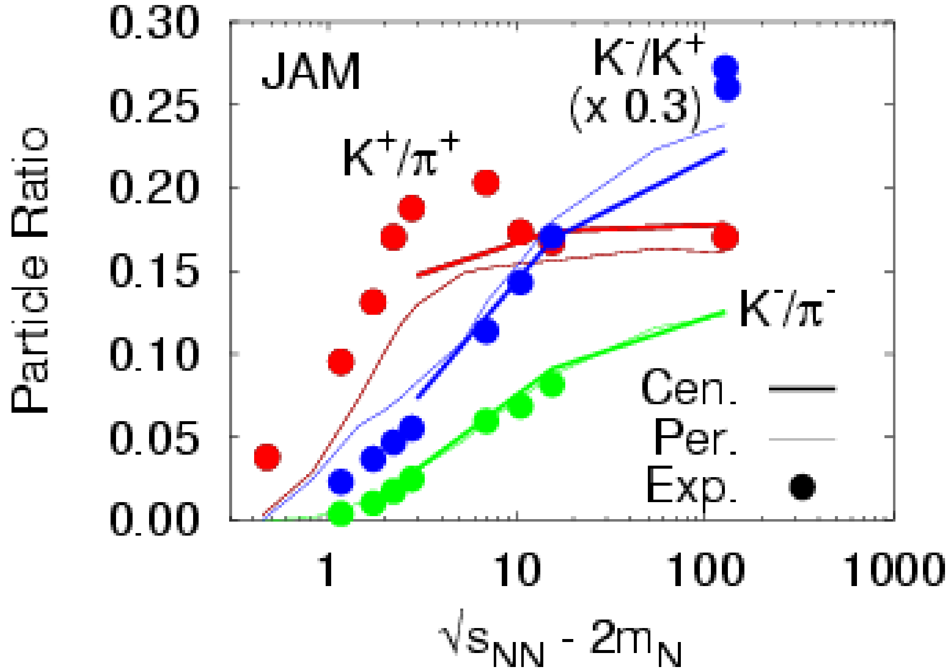


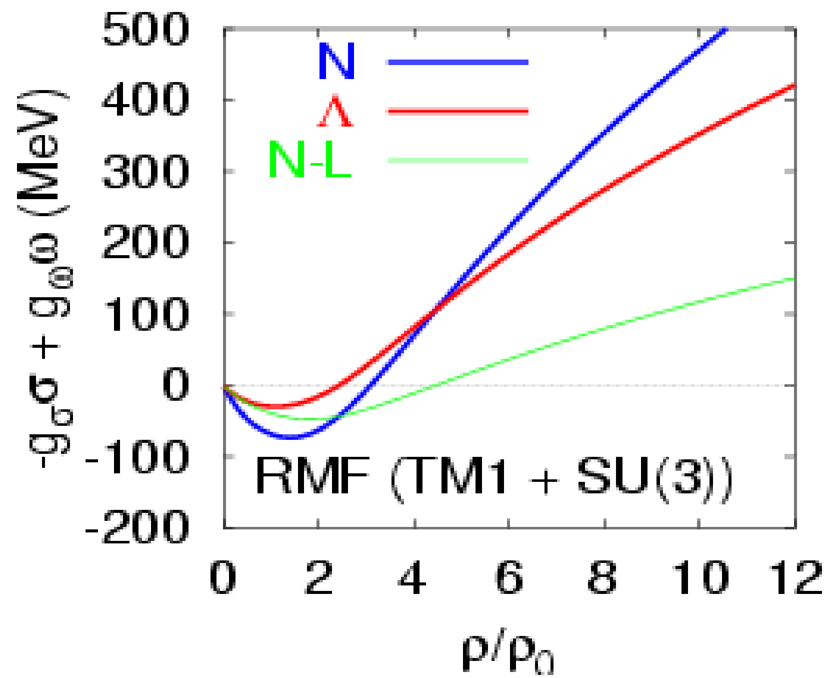
JHF Energy: ~ Maximum K/π ratio

Does Hyperon Potential Help It ?

- Rescattering of Resonances/Strings (RQMD)
- Baryon Rich QGP Formation
- High Baryon Density Effect (Associated Prod. of Y







At $\rho > 4\rho_0$, Hyperon Feels More Attractive Potential than N

Hyperons in Dense Matter

✭ *Hyperons in Neutron Star*

Tsuruta-Cameron (66), Langer-Rosen (70), Pand-haripande (71), Itoh(75), Glendenning, Weber-Weigel, Sugahara-Toki, Schaffner-Mishustin, Balberg-Gal, Baldo et al., Vidana et al., Nishizaki-Yamamoto-Takatsuka, Kohno-Fujiwara et al., ...

✭ *Hyperons during Supernova Explosion*

- Supernova explode in pure 1D hydro,
  but with ν transport shock stalls.
- 3 %increase of ν flux revive shock wave (Janka et al.)

Hyperons may play crutial roles in dense matter,
such as in neutron stars and supernova explosion.

Hyperon Potentials: How Much Do We Know ?

Hyperon Potentials at around ρ_0

$U(\Lambda) \sim -30$ MeV

$U(\Xi) \sim -(14-16)$ MeV (KEK-E224, BNL-E885, BNL-E906)

$U(\Sigma) \sim (-30 \sim +150)$ **MeV** (KEK-E438)

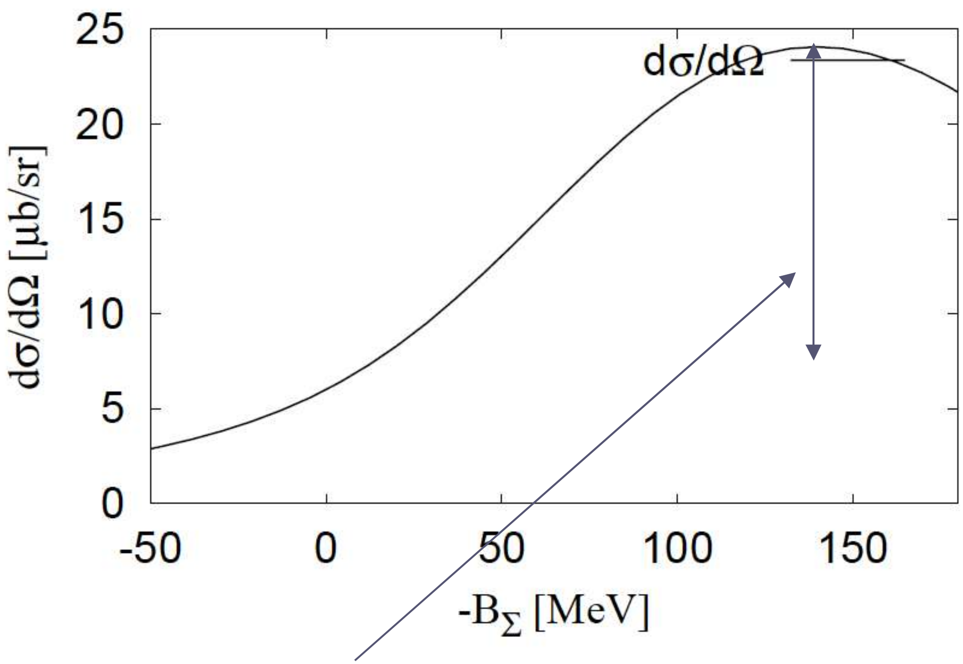
Hyperon Potentials at high densities

Exp't Info. : Hyperon flow, K^+/π^+ enhancement, ...
Theor. Prediction: Strongly depends on the model

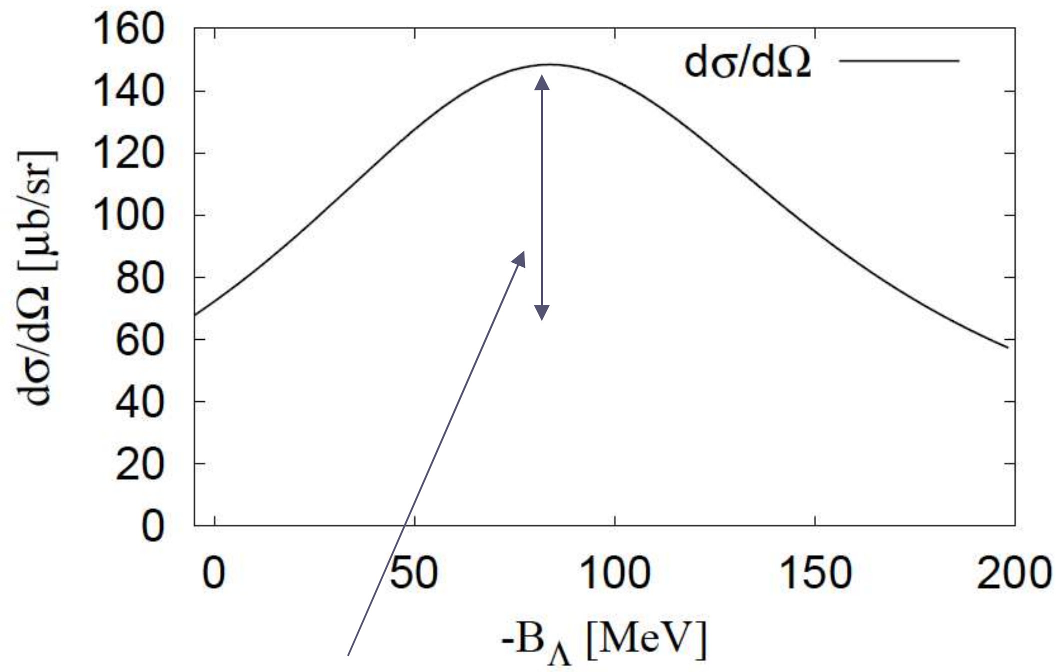
Elementary cross section on (π ,K$^+$) reaction

$$\pi^- + p \rightarrow K^+ + \Sigma^-$$

$$\pi^+ + n \rightarrow K^+ + \Lambda$$



Factor:4



Factor:2