1999/07/14-16, 集中講義 @ TITech

原子核反応のシミュレーション
— ストレンジネス核反応から重イオン反応まで

北大理　大西　明

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現在の"核反応"研究の課題

⋆ 新しい原子核を作る/大きさを測る/励起状態を調べる
中性子過剰核、超重核、ハイパー核、ダブル・ハイパー核、...

⋆ 核構造を調べる
原子核の電磁気的応答、スピン応答、アイソスピン応答、超変形、高速回転、バリア以下の核融合、...

⋆ 反応機構を調べる
核分裂、多重破砕、...

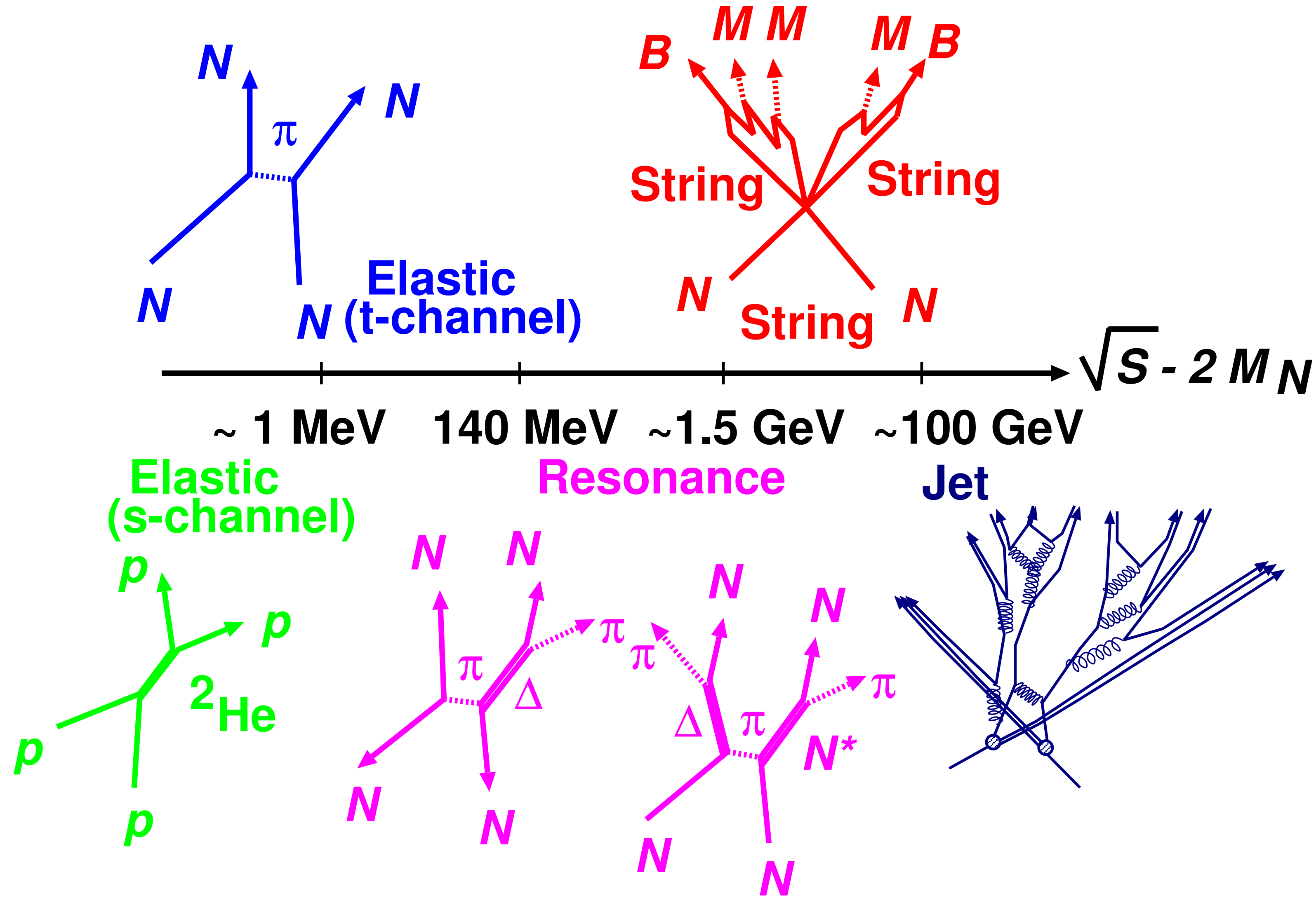
⋆ 宇宙を調べる
天体核反応、核物質の状態方程式、...

⋆ ハドロンを調べる
ハドロン内部構造、核内でのハドロンの性質の変化、ハドロン間相互作用、...

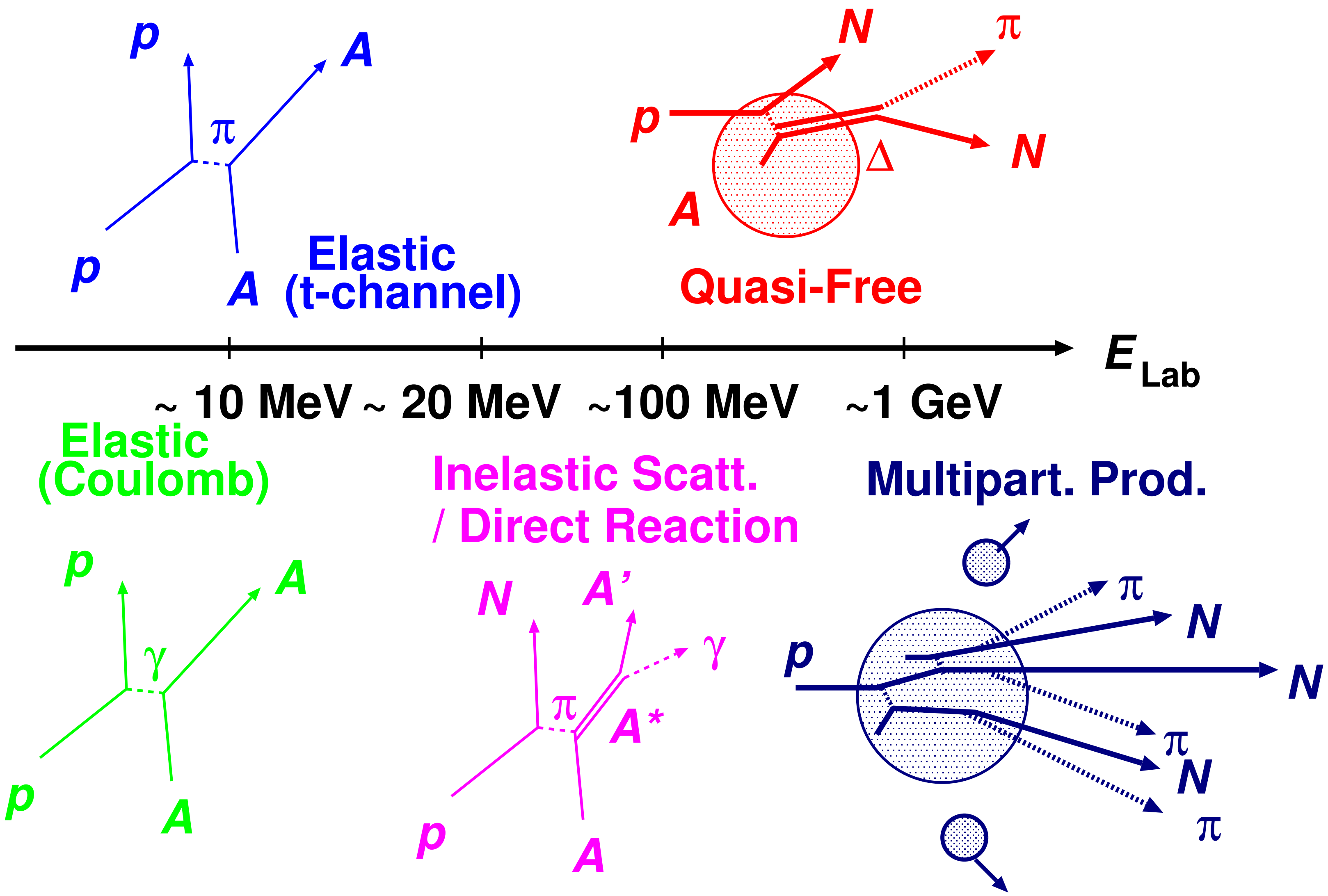
⋆ 核物質を調べる
核物質の状態方程式、粒子生成、多重破砕、...

⋆ ハドロン物質を調べる
状態方程式、粒子生成、核内ハドロン、クォーク・グルーオン・プラズマ、パートンの動力学、...

Energy Dependence of NN Reaction Mechanism



Energy Dependence of pA Reaction Mechanism



原子核反応の理論 (I)

Direct Reaction → Cascade

- Formal Theory

— e.g, Lipmann-Schwinger 方程式

$$\begin{aligned} \Psi^{(+)} &= \Phi + G\,V\,\Psi^{(+)} \\ T &= V + V\,G\,T \\ d\sigma &= \frac{1}{v_i}\frac{2\pi}{\hbar}\,|T|^2\,d\rho \end{aligned}$$

- Impulse 近似

$$T_{fi}^{\mathrm{DWIA}} = \langle \chi_f^{(-)}\,\Phi_f | \sum_i t_{0i} | \chi_i^{(+)}\,\Phi_i \rangle$$

t_{0i} : 入射粒子と核内の i 番目の核子の t-matrix
χ : 相対運動の歪曲波
Φ : 内部運動の波動関数

- Eikonal 近似 (歪曲波の評価)

$$\begin{aligned} \chi^{Eikonal}(x,y,z) &= \exp\left(ik_i z - \frac{i}{\hbar v_i}\int_{-\infty}^{z} U(x,y,z')\,dz' \right) \\ &\simeq \exp\left(ik_i z - \frac{1}{2}\int_{-\infty}^{z} \sigma\,\rho(x,y,z')\,dz' \right) \end{aligned}$$

- **歪曲効果の Factorization (有効核子数近似)**

$$|T^{DW}|^2 \simeq \frac{A_{eff}}{A}|T^{PW}|^2$$
$$A_{eff} = \int d^3r\, \rho(\vec{r}) \exp(-\sigma \int dz'\, \rho(\vec{r}))$$

- **励起状態 $\simeq$ 一粒子励起**

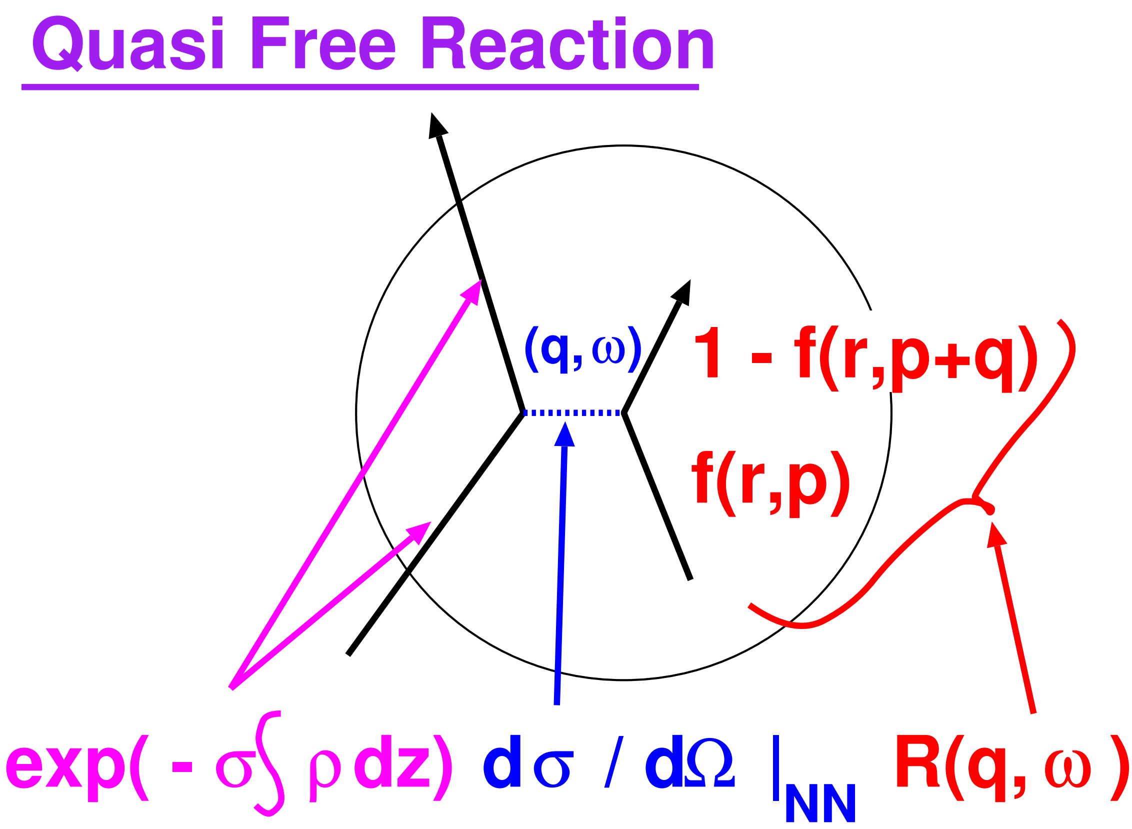
$$\begin{aligned}
&\sum_{n\neq 0} |T_{k'n,k0}|^2\, \delta(\omega + E_0 - E_n) \\
\rightarrow\ & \sum_j^{Unocc} \sum_i^{Occ} |T_{k'j,ki}|^2\, \delta(\omega + \epsilon_i - \epsilon_j) \\
=\ & \sum_j^{Unocc} \sum_i^{Occ} |\langle \vec{k}'\phi_j | t | \vec{k}\phi_i \rangle|^2\, \delta(\omega + \epsilon_i - \epsilon_j) \\
\simeq\ & |t(\vec{q}, E)|^2 \int \frac{d\vec{r}\, d\vec{p}}{(2\pi\hbar)^3}\ f(\vec{r},\vec{p})\ (1 - f(\vec{r},\vec{p}+\vec{q})) \\
& \qquad \times \delta(\omega + h(\vec{r},\vec{p}) - h(\vec{r},\vec{p}+\vec{q}))
\end{aligned}$$

$$\sum_i^{Occ} \phi_i(\vec{r})\, \phi_i^*(\vec{r}') = \int \frac{d\vec{p}}{(2\pi\hbar)^3}\ f\left(\frac{\vec{r}+\vec{r}'}{2}, \vec{p}\right)\ \exp\left(i\vec{p}\cdot(\vec{r}-\vec{r}')\right)$$

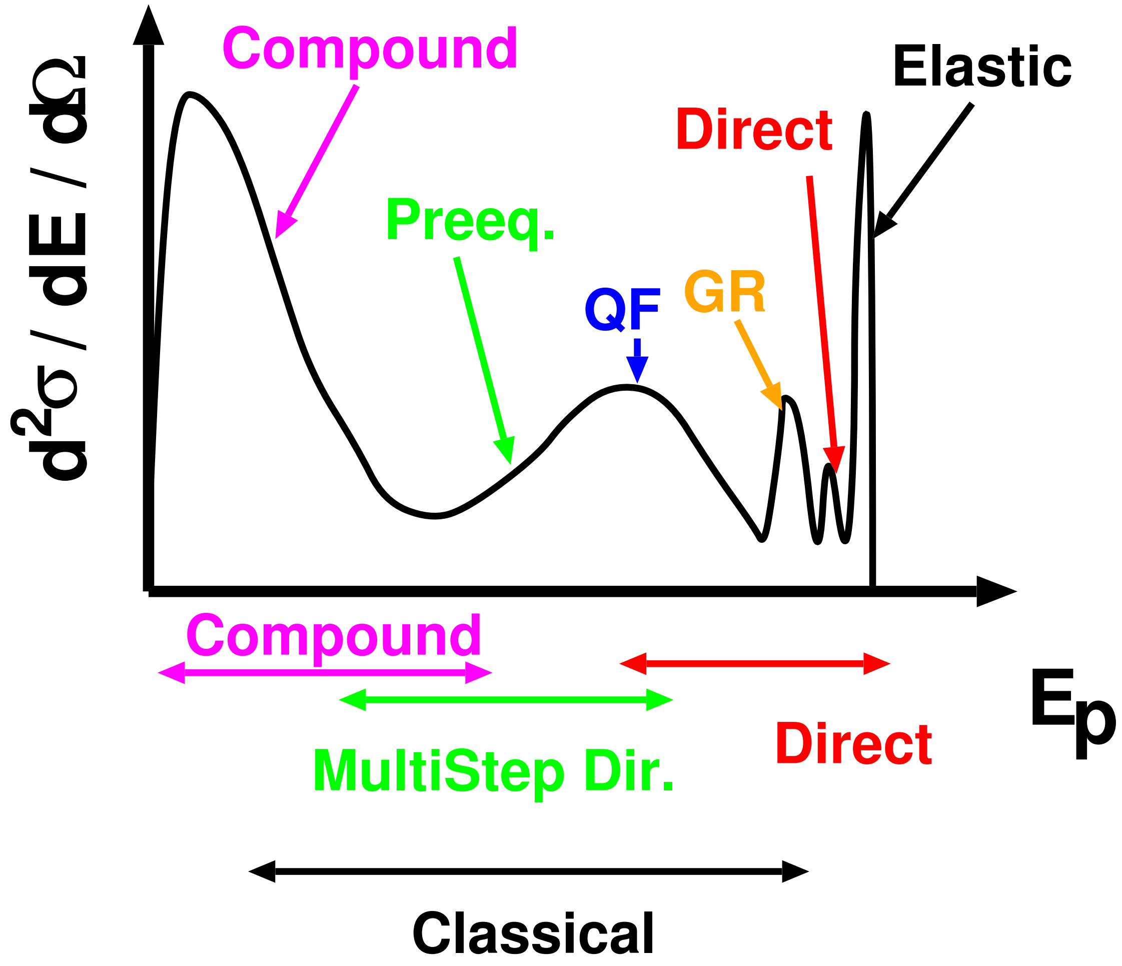
- **連続状態への二重微分断面積**

$$\begin{aligned}
\frac{d^2\sigma}{d\omega d\Omega} &\simeq A_{eff}\ \left.\frac{d\sigma}{d\Omega}\right|_{NN}\ R(\vec{q},\omega) \\
R(\vec{q},\omega) &= -\frac{1}{\pi A}\, \mathrm{Im}\, \langle \Phi_0 |\ \delta\hat{O}^\dagger(\vec{q})\ G(\omega)\ \delta\hat{O}(\vec{q})\ |\Phi_0\rangle \\
&\simeq \frac{1}{A}\int \frac{d\vec{r}\, d\vec{p}}{(2\pi\hbar)^3}\ f(\vec{r},\vec{p})\ (1 - f(\vec{r},\vec{p}+\vec{q})) \\
&\qquad \times \delta(\omega + h(\vec{r},\vec{p}) - h(\vec{r},\vec{p}+\vec{q})) \\
\hat{O}(\vec{q}) &= \sum_i \exp(i\vec{q}\cdot\vec{r}_i)\, \hat{O}_{S,T,Y,..}
\end{aligned}$$

$\rightarrow$ 確率的・古典的な 2 体衝突 (**Cascade** 模型)

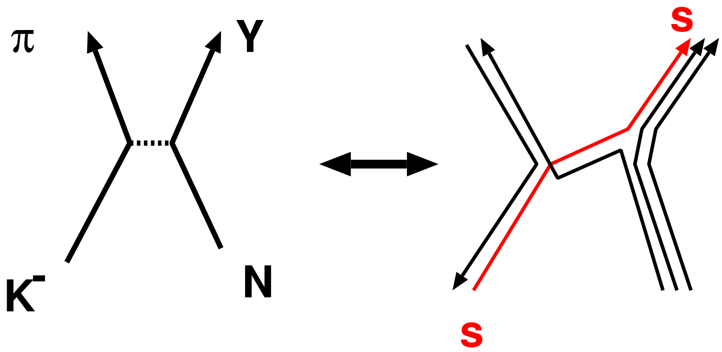


Quasi Free Reaction
(q, ω)
1 - f(r,p+q)
f(r,p)
exp(- σ∫ ρ dz) dσ / dΩ |NN R(q, ω)

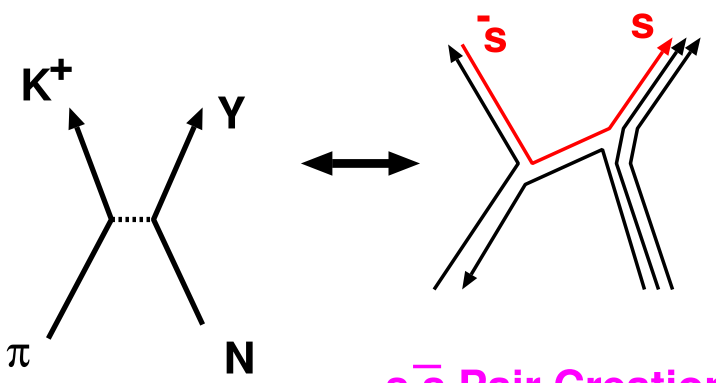


d²σ / dE / dΩ
Compound
Elastic
Direct
Preeq.
QF
GR
Compound
Direct
MultiStep Dir.
Ep
Classical

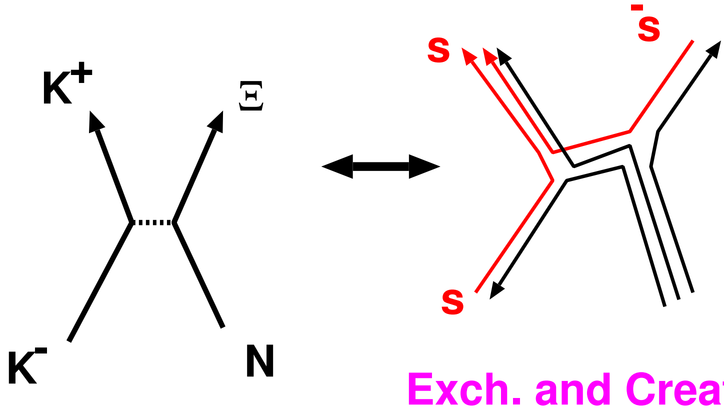
Strangeness Nuclear Reaction



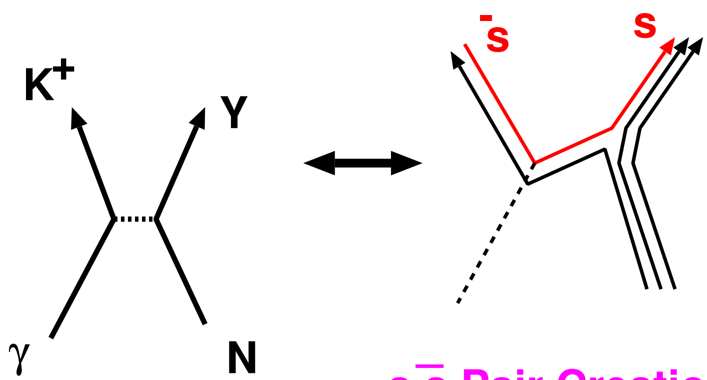
Strangeness Exch.



$s\bar{s}$ Pair Creation



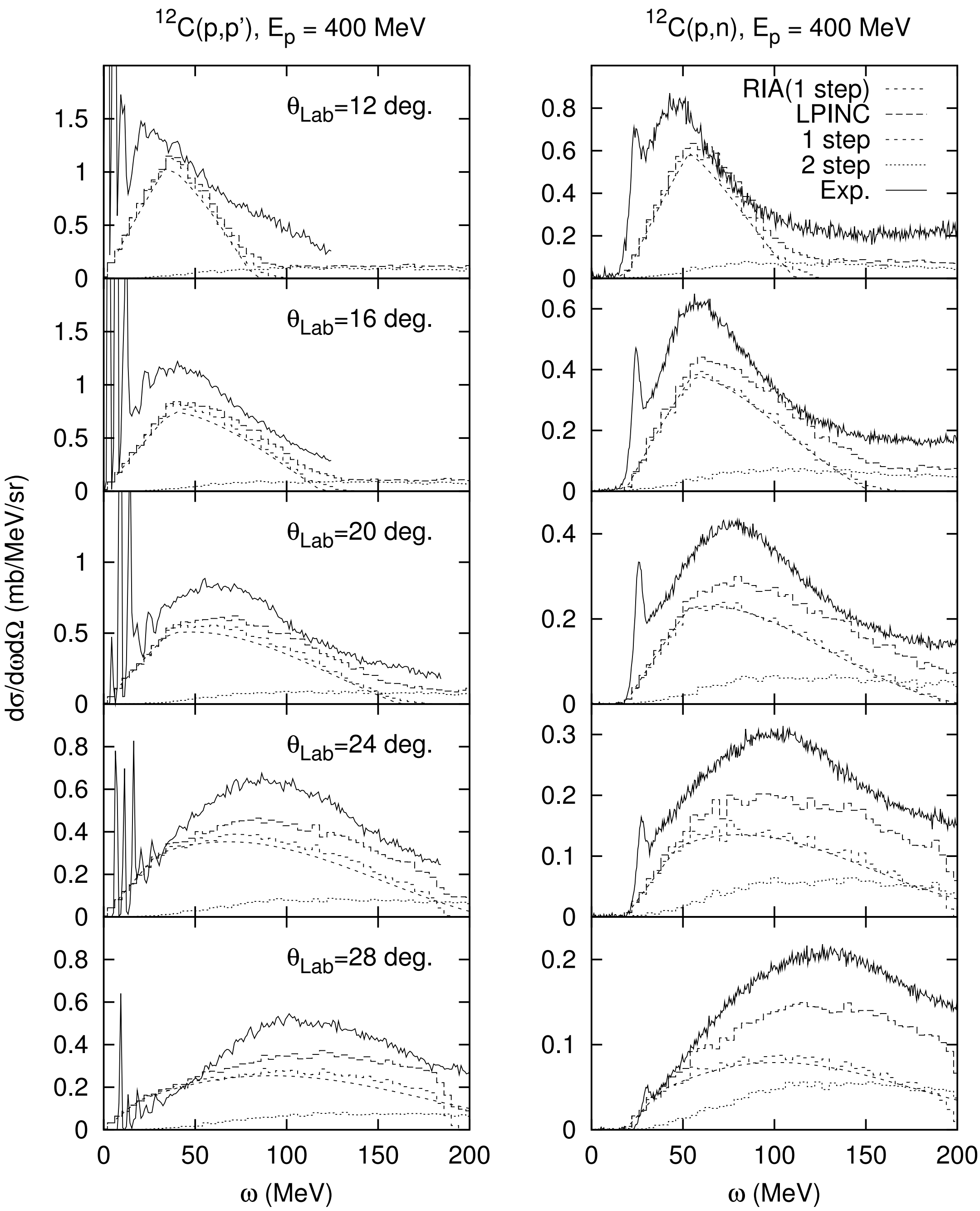
Exch. and Creation



$s\bar{s}$ Pair Creation

準弾性散乱 (衝突)

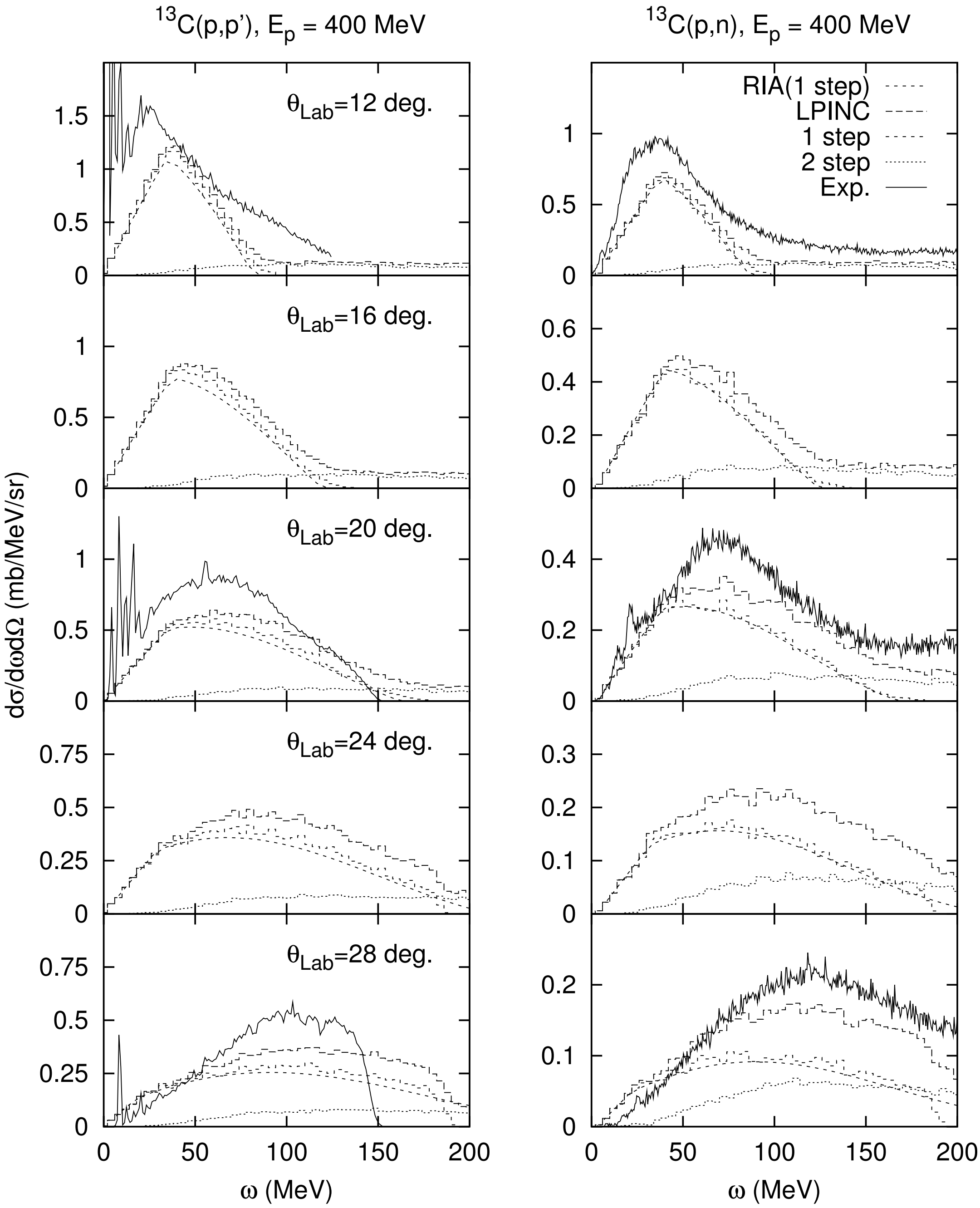
最も簡単な (?) 連続状態への一段階直接反応



Data: Otsu et al.(RCNP exp.),

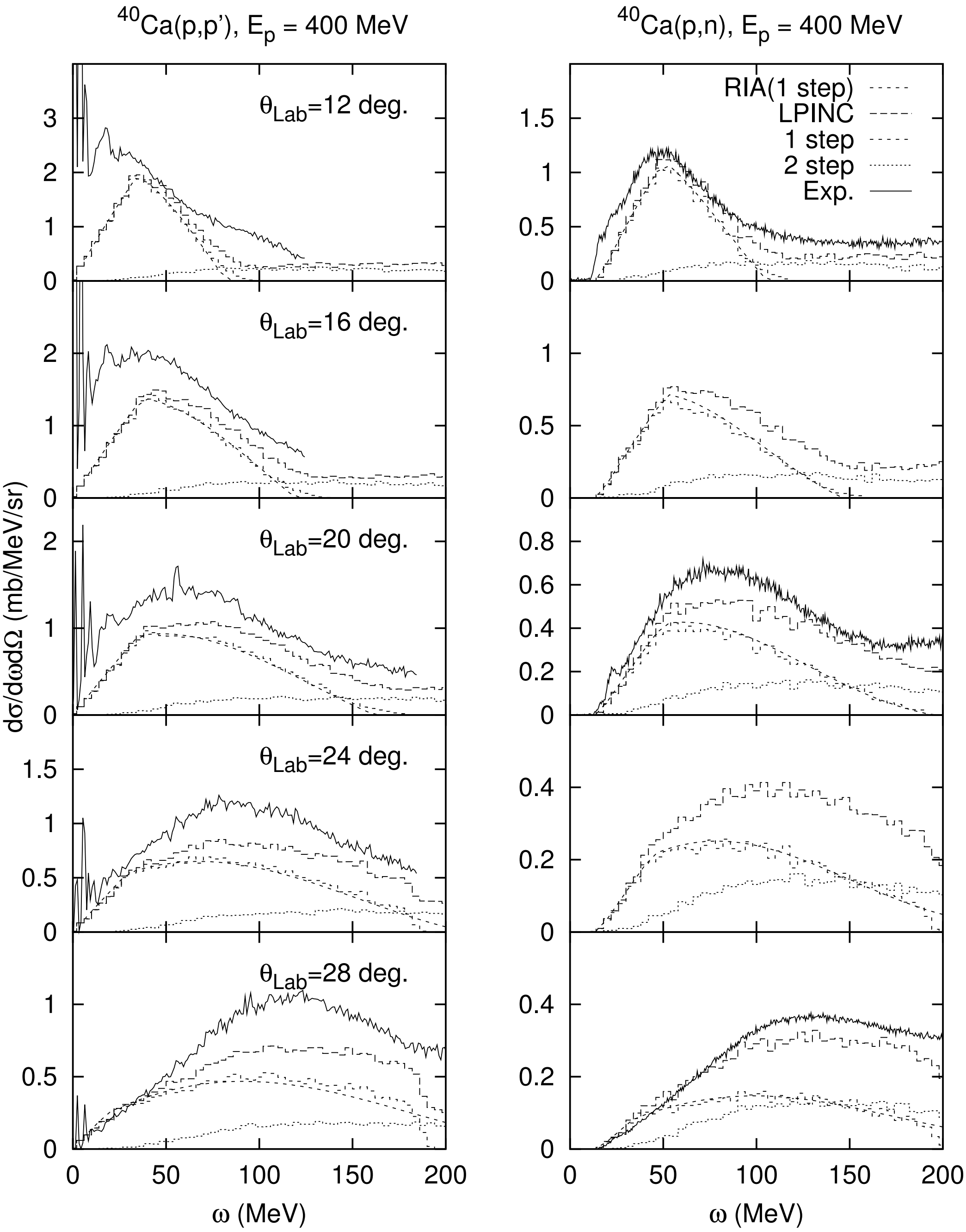
Calc.: Uchida, Master thesis, 1997, unpublished.

Fermi Gas $(\vec{r}, \vec{p})$ momentum dist. + No Real Pot.
+ Q-Value (^{12}C $\leftrightarrow$ ^{12}N)



Data: Otsu et al.(RCNP exp.),

Calc.: Uchida, Master thesis, 1997, unpublished.



Data: Otsu et al.(RCNP exp.),

Calc.: Uchida, Master thesis, 1997, unpublished.

原子核反応の理論 (II); TDHF → BUU

- **Mean Field Theory**

  — e.g, Time-Dependent Hartree-Fock 理論

$$i\hbar\frac{\partial\phi_i}{\partial t} = \hat{h}\phi_i$$

$$\rho(\vec{r},\vec{r}') \equiv \sum_i^{Occ} \phi_i(\vec{r})\,\phi_i^*(\vec{r}')$$

$$i\hbar\frac{\partial\rho}{\partial t} = \left[\hat{h},\rho\right]$$

- **Wigner 変換と Wigner-Kirkwood 展開**

(c.f. Ring-Schuck)

$$O_W(\vec{r},\vec{p}) = \int d\vec{s}\ \exp(-i\vec{p}\cdot\vec{s})\langle\vec{r}+\vec{s}/2\,|\,\hat{O}\,|\,\vec{r}-\vec{s}/2\rangle$$

$$(AB)_W = A_W(\vec{r},\vec{p})\,\exp(i\hbar\Lambda/2)\,B_W(\vec{r},\vec{p})$$

$$\Lambda \equiv \overleftarrow{\nabla}_r\,\overrightarrow{\nabla}_p - \overleftarrow{\nabla}_p\,\overrightarrow{\nabla}_r$$

$$[A,B]_W = 2i\,A_W(\vec{r},\vec{p})\,\sin(\hbar\Lambda/2)\,B_W(\vec{r},\vec{p})$$

$$= i\hbar\,\{A_W(\vec{r},\vec{p}),B_W(\vec{r},\vec{p})\}_{P.B.} + \mathcal{O}(\hbar^3)$$

- **Vlasov 方程式**

$$f(\vec{r},\vec{p}) = \rho_W; \quad \text{(Wigner 関数} \simeq \text{位相空間分布関数)}$$

$$\frac{\partial f}{\partial t} = \{h,f\}_{P.B.} + \mathcal{O}(\hbar^2)$$

$$\partial f/\partial t + \vec{v}\cdot\vec{\nabla}_r f - \vec{\nabla}_r U\ \cdot\vec{\nabla}_p f = 0 \quad \text{(Vlasov 方程式)}$$

• Test Particle Method

C.Y.Wong, PRC25('82),1460

$$f(\vec{r},\vec{p}) = \frac{1}{N_0}\sum_{i=1}^{AN_0} \delta(\vec{r}-\vec{r}_i)\,\delta(\vec{p}-\vec{p}_i)$$

$$\frac{d\vec{r}_i}{dt} = \frac{\vec{p}_i}{m}\,, \quad \frac{d\vec{p}_i}{dt} = -\vec{\nabla}_r U(\vec{r})|_{\vec{r}_i}$$

(位相空間分布を点粒子の集合として表し、それぞれの点粒子の軌道を古典的に追えばよい。)

• Boltzmann-Uehling-Uhlenbeck 方程式

Bertsch and Das Gupta, PRep 160('88), 190

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla}_r f - \vec{\nabla}_r U \cdot \vec{\nabla}_p f = I_{Coll}[f]$$

$$I_{Coll}[f] = -\frac{1}{2}\int \frac{d^3p_2 d\Omega}{(2\pi\hbar)^3}\, v_{12}\, \frac{d\sigma}{d\Omega}$$
$$\times [f_1 f_2 (1-f_3)(1-f_4) - f_3 f_4 (1-f_1)(1-f_2)]$$

BUU 方程式に入っている要素

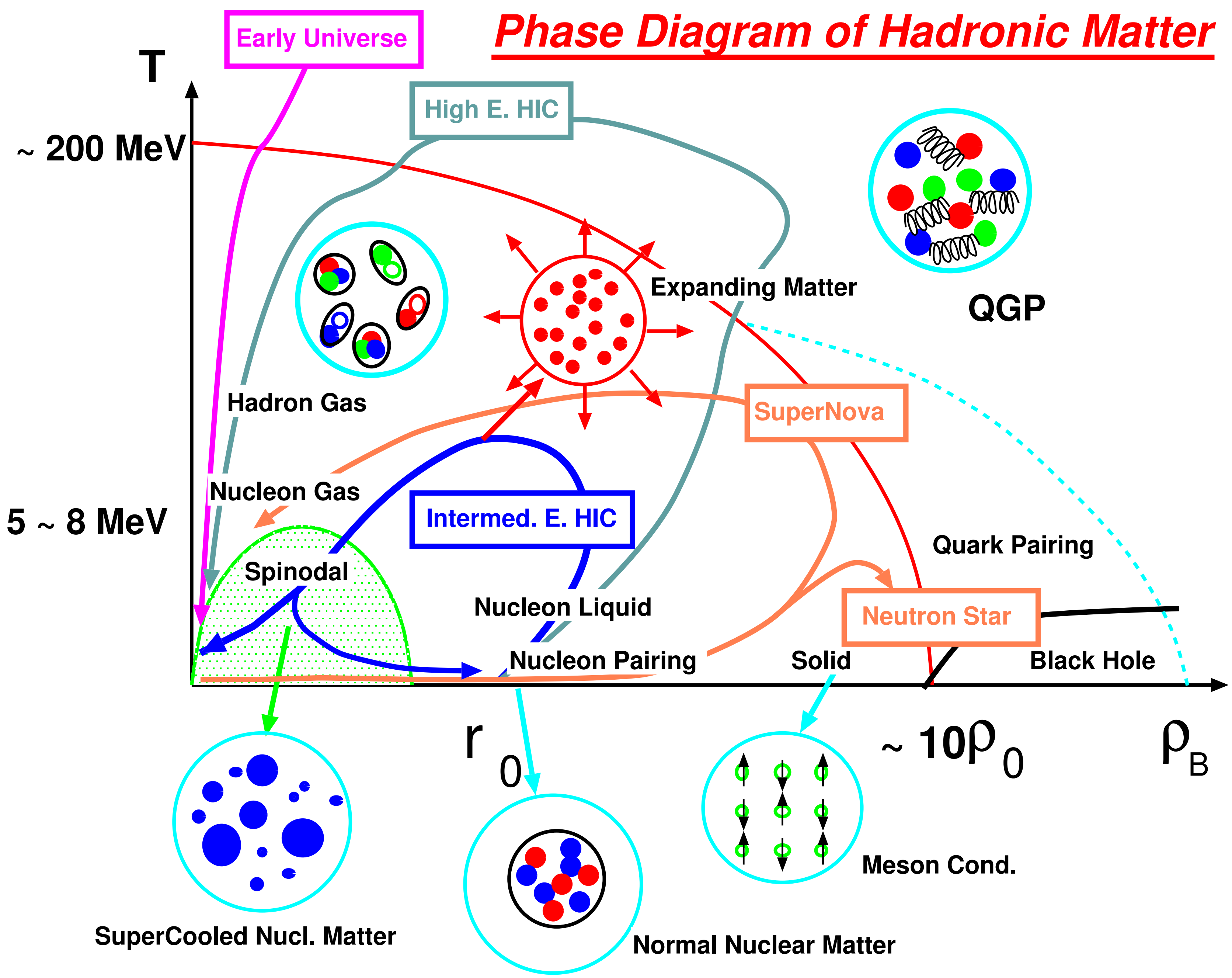
⋆ 平均場による時間発展

⋆ 2 核子衝突項

⋆ 2 核子衝突におけるパウリ排他律

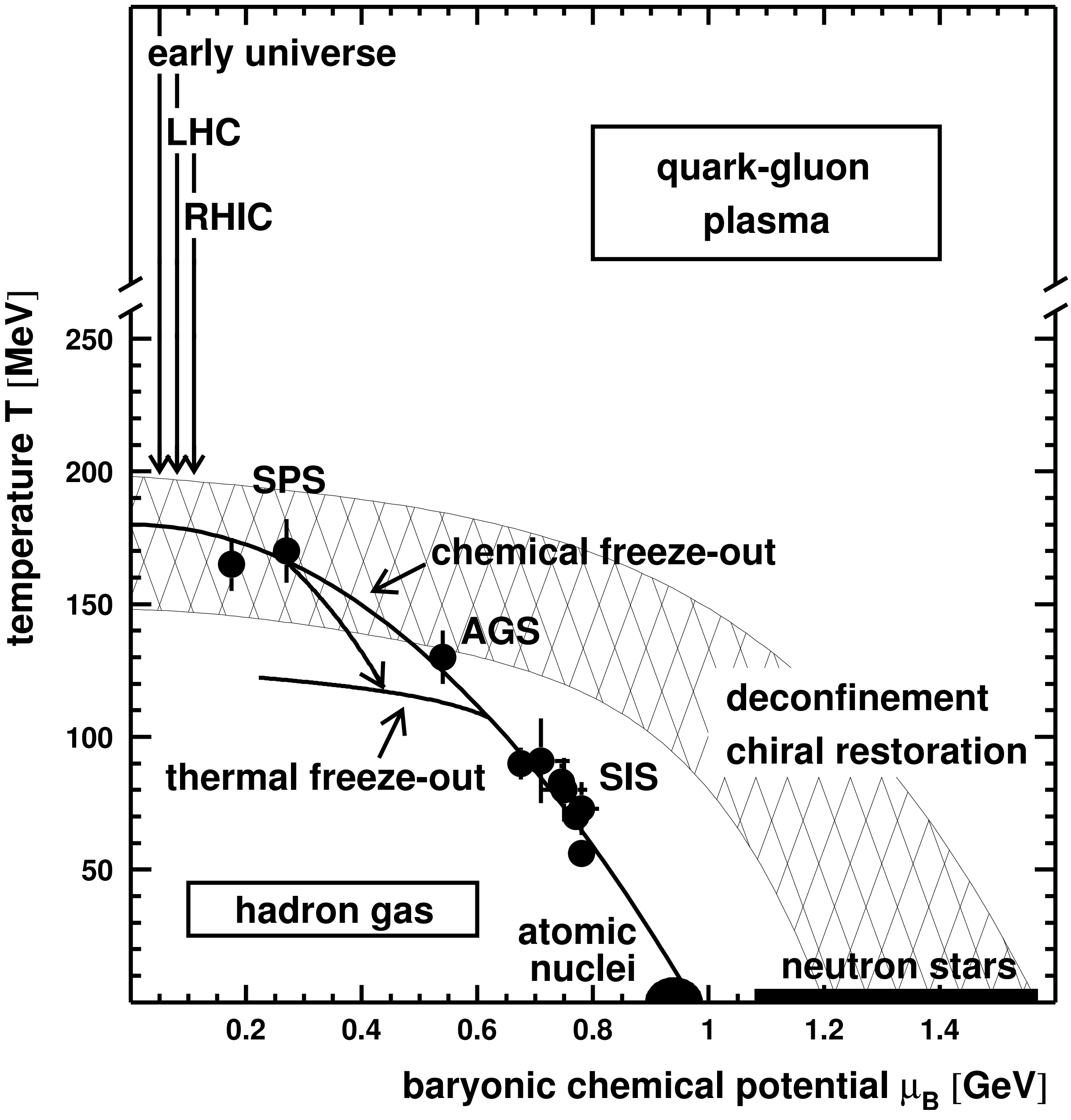
$\rightarrow$ 一粒子分布の平均的時間発展 (粒子スペクトル、フロー、...)

$\not\rightarrow$ フラグメントの生成、**Event** ごとの揺らぎ、...


Phase Diagram of Hadronic Matter
Early Universe
High E. HIC
T
~ 200 MeV
5 ~ 8 MeV
Hadron Gas
Expanding Matter
QGP
SuperNova
Nucleon Gas
Intermed. E. HIC
Spinodal
Nucleon Liquid
Nucleon Pairing
Quark Pairing
Neutron Star
Solid
Black Hole
r 0
~ 10ρ 0
ρ B
SuperCooled Nucl. Matter
Normal Nuclear Matter
Meson Cond.

高エネルギー重イオンにおけるフリーズ・アウト

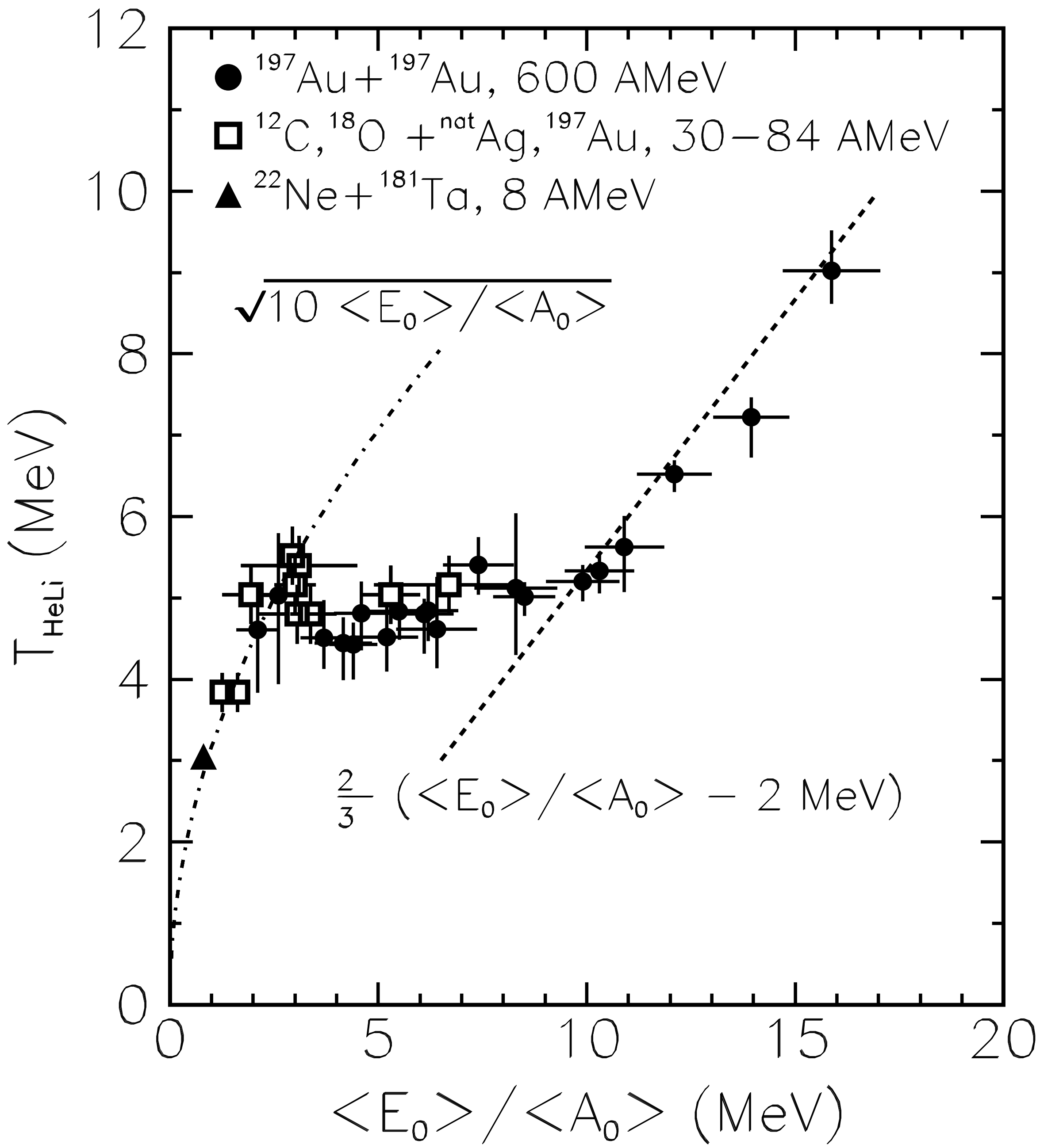
J. Stachel, Proc. of INPC98



$$T_{\text{Thermal}} < T_{\text{Chemical}}$$

原子核のカロリー曲線と液相・気相相転移

J.Pochadzalla et al.(ALADIN Collab.@GSI), PRL75('95),1040.



Low-T	$\leftrightarrow$	**High-T**
液体	$\leftrightarrow$	気体
$E^*/A = aT^2$	$\leftrightarrow$	$E^*/A = 1.5T + c$
量子統計的相	$\leftrightarrow$	古典統計的相

原子核反応の理論 (III); 分子動力学

• Anti-symmetrized Molecular Dynamics (AMD)

波動関数

$$
\begin{aligned}
|\Psi(Z)\rangle &= \mathcal{A}\prod_i |\psi_i\rangle \\
\psi_i &= \phi(\vec{r};\vec{z}_i)\,\chi_i(\sigma\tau) \\
\phi(\vec{r};\vec{z}) &= (\frac{2\nu}{\pi})^{3/4}\exp\left(-\nu(\vec{r}-\frac{\vec{z}}{\sqrt{\nu}})^2+\frac{1}{2}\vec{z}^2\right) \\
&\propto \exp\left(-\nu(\vec{r}-\vec{d})^2+i\,\vec{k}\cdot(\vec{r}-\vec{d})/\hbar\right) \\
\vec{z}_i &= \sqrt{\nu_i}\,\vec{d}_i+\frac{i}{2\hbar\sqrt{\nu_i}}\vec{k}_i
\end{aligned}
$$

時間依存変分原理 $\longrightarrow$ 運動方程式

$$
\mathcal{L}=\frac{\langle\Psi|i\hbar\partial/\partial t-\hat{H}|\Psi\rangle}{\langle\Psi|\Psi\rangle}
$$

$$
\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{\vec{\bar{z}}}_i}-\frac{\partial\mathcal{L}}{\partial\vec{\bar{z}}_i}=0\ \longrightarrow\ i\hbar C_{i\alpha,j\beta}\dot{z}_{j\beta}=\frac{\partial\mathcal{H}}{\partial\bar{z}_{i\alpha}}\quad(\alpha,\beta=x,y,z)
$$

$$
\begin{aligned}
C_{i\alpha,j\beta} &= \frac{\partial^2}{\partial\bar{z}_{i\alpha}\partial z_{j\beta}}\log\det B \\
B_{ij} &= \langle\psi_i|\psi_j\rangle=\exp(\vec{\bar{Z}}_i\cdot\vec{Z}_j)\,\delta_{ij}^{\sigma\tau}
\end{aligned}
$$

反対称化を無視すると $(B_{ij}=\delta_{ij}\exp(\vec{\bar{Z}}_i\cdot\vec{Z}_i))$、

$$
\frac{d\vec{d}_i}{dt}=\frac{\partial\mathcal{H}}{\partial\vec{k}_i}\,,\qquad \frac{d\vec{k}_i}{dt}=-\frac{\partial\mathcal{H}}{\partial\vec{d}_i}
$$

→ **Quantum Molecular Dynamics (QMD)**

• AMD における衝突項

$\vec{z}_i = (\vec{d}_i, \vec{k}_i)$: パラメータ → $\vec{w}_i = (\vec{r}_i, \vec{p}_i)$: (近似的) 正準変数

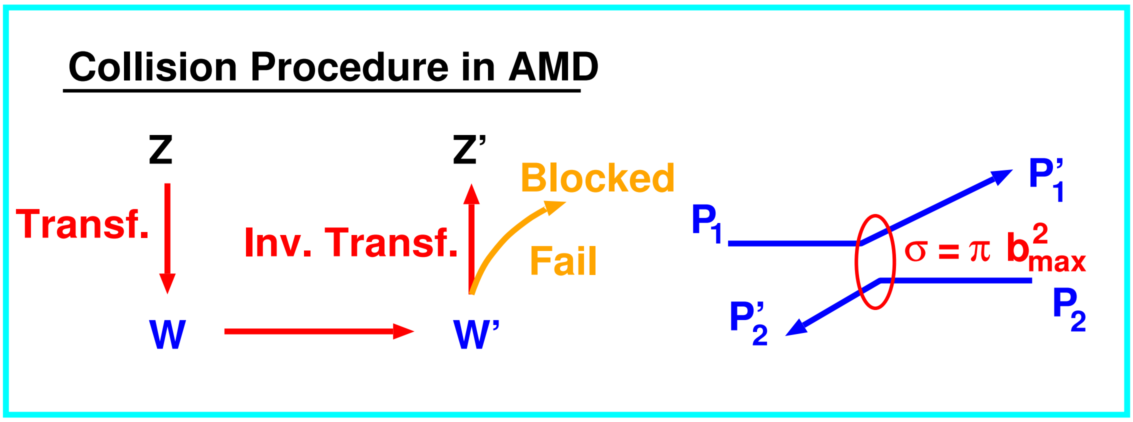
$$\vec{w}_i = \sqrt{Q}_{ij}\,\vec{z}_j \;, \qquad Q_{ij} \equiv B_{ij}\,B_{ji}^{-1}$$

Example;

$$\langle \hat{a}^\dagger \hat{a} \rangle = \sum_{ij} B_{ji}^{-1}\,B_{ij}\,\vec{z}_j^{\,*} \cdot \vec{z}_i = \sum_i \vec{w}_i^{\,*} \cdot \vec{w}_i = \sum_i \nu\,\vec{r}_i \cdot \vec{r}_i + \frac{1}{4\hbar^2\nu}\,\vec{p}_i \cdot \vec{p}_i$$

$$\langle \hat{\vec{L}} \rangle = \sum_{ij} B_{ji}^{-1}\,B_{ij}\,\frac{1}{i}\vec{z}_j^{\,*} \times \vec{z}_i = \sum_i \frac{1}{i}\vec{w}_i^{\,*} \times \vec{w}_i = \sum_i \vec{r}_i \times \vec{p}_i$$

→ $\vec{w}$ を用いて、古典的な粒子描像に基づいて確率的な 2 体衝突を取り入れる。



AMD に入っている要素

⋆ 反対称化された波動関数の時間発展

⋆ 2 核子衝突項 **with Pauli blocking**

⋆ **Event** ごとの揺らぎ、フラグメント生成

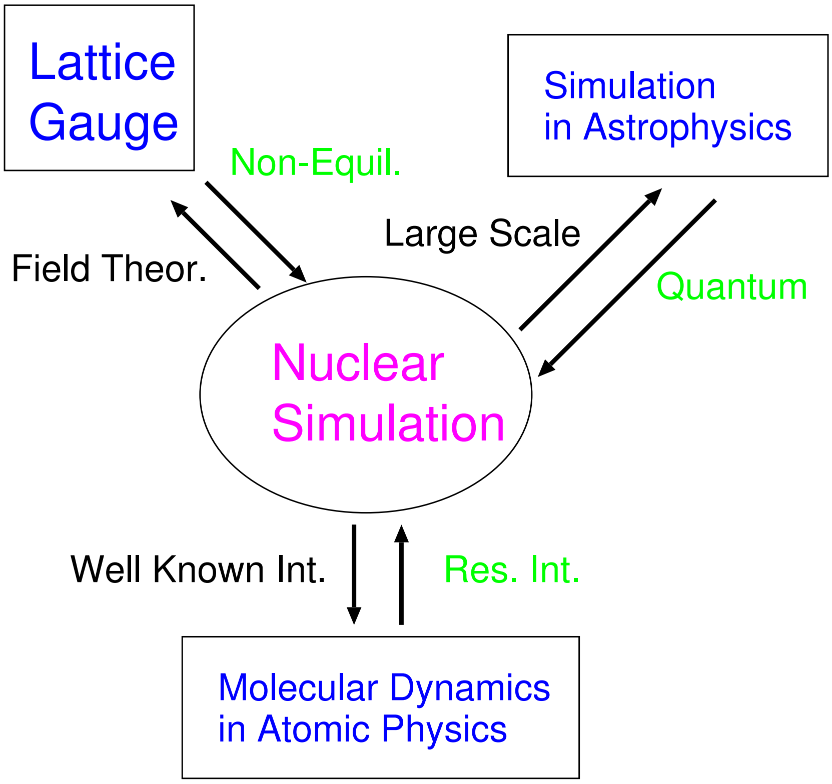
問題点

⋆ 波束の運動 ＝ エネルギー固有状態でない、J^π 射影されていない

⋆ フラグメント終状態: 量子化されていない

⋆ 2 核子衝突項の導入: **derivation** されていない (古典的描像)

原子核反応のシミュレーション



分子動力学＝(半)古典的粒子シミュレーション

＝ (パラメータ化された) 積波動関数 (↔ 粒子描像)

$$|\Psi_Z\rangle = (\mathcal{A}) \prod_i |\phi(\mathbf{r}_i; \vec{Z}_j)\rangle \quad (\vec{Z}_j\text{; パラメータ} \approx \text{位相空間})$$

＋ 時間依存変分原理から得られる運動方程式 (↔ 平均場)

$$\mathcal{L} = \frac{\langle\Psi_Z|i\hbar\partial/\partial t - \hat{H}|\Psi_Z\rangle}{\langle\Psi_Z|\Psi_Z\rangle}$$

$$\rightarrow \quad \dot{R}_i = \frac{\partial\mathcal{H}}{\partial P_i}, \qquad \dot{P}_i = -\frac{\partial\mathcal{H}}{\partial R_i} \qquad \left(\mathcal{H} = \frac{\langle\Psi_Z|\hat{H}|\Psi_Z\rangle}{\langle\Psi_Z|\Psi_Z\rangle}\right)$$

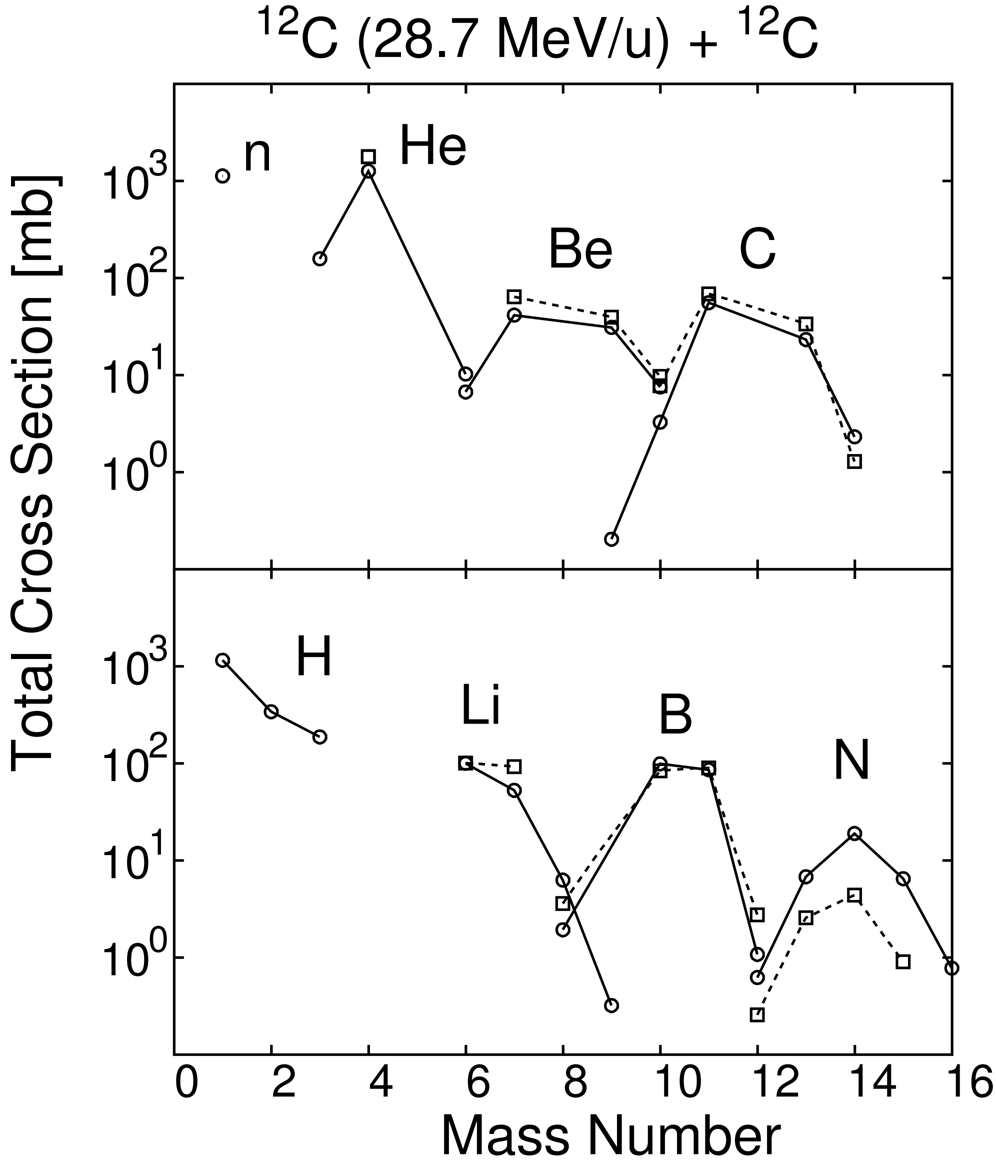
$$(R = R(\vec{Z}), P = P(\vec{Z}) \text{ は正準変数})$$

＋ 残留相互作用 (↔ 粒子衝突, 粒子生成, 粒子崩壊, 揺らぎ ...)

反対称化分子動力学 (AMD) の 重イオン反応への適用例

Ono, et al., PRC47('93),2652; PRL68('92)2898.

- $^{12}C+^{12}C$ 反応でのフラグメント生成断面積



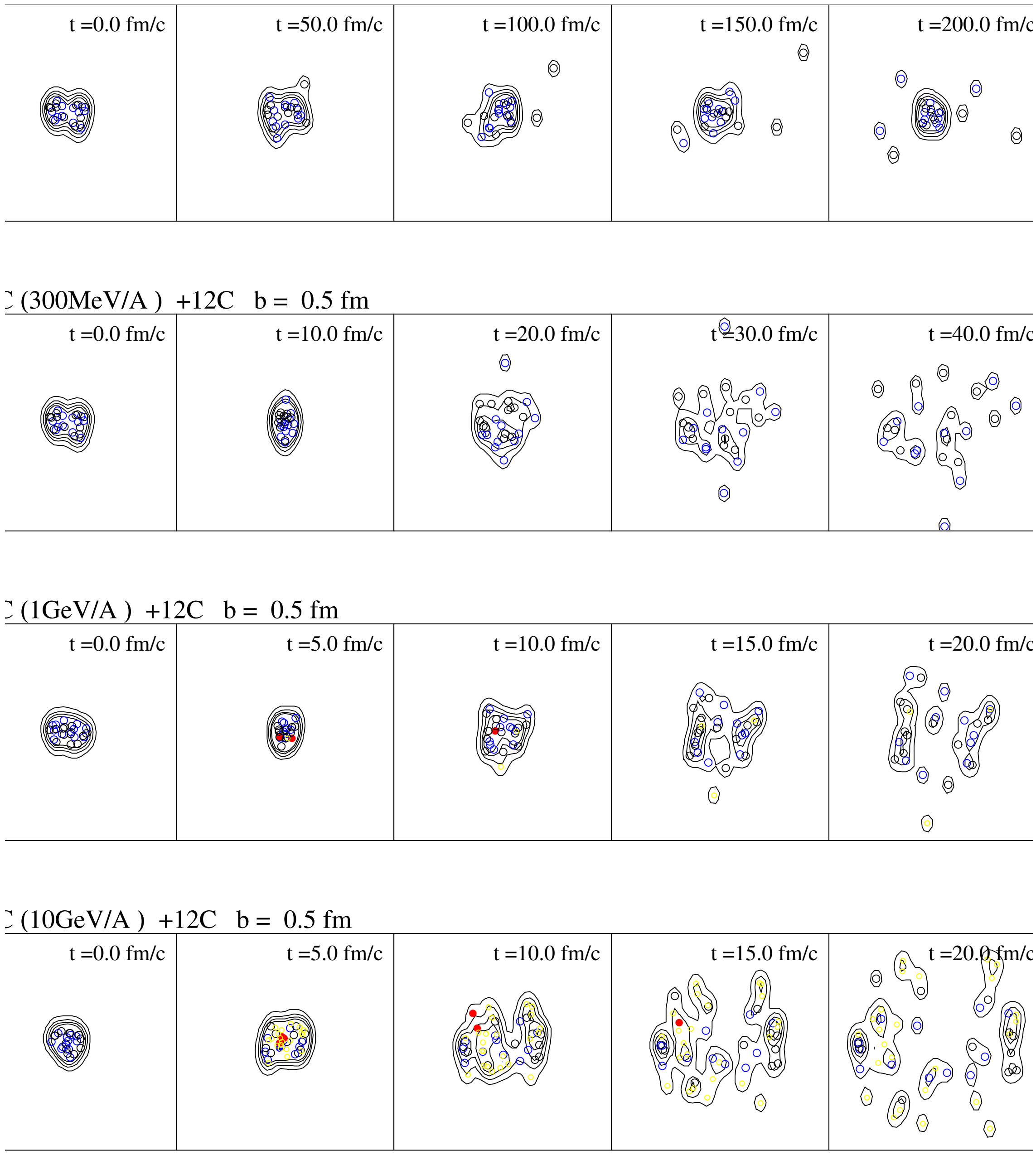
Calc.; Solid lines, Exp.: Dashed lines

アイソトープ分布まで含めて実験を非常によく再現

原子核反応のエネルギー依存性

— 大きな残留相互作用と揺らぎ (破砕、粒子生成、. . .)

Y.Nara, Ph. D., March 1996.



SNP99, Feb. 19-22, 1999, Seoul, Korea

Λ-Λ interferometry in (K^-, K^+) and AA reactions

A. Ohnishi[A], Y. Hirata[A], Y. Nara[B],
S. Shinmura[C], Y. Akaishi[D]
Hokkaido U.[A], JAERI[B], Gifu U.[C], KEK-IPNS[D]

1. **$\Lambda\Lambda$ Interaction: How can we get it ?**
2. **$\Lambda\Lambda$ Inv. Mass Spec. $\rightarrow$ $\Lambda\Lambda$ Int.**
   - ⋆ **IntraNuclear Cascade model + Correlation**
   - ⋆ **Comparison with Nijmegen Models**
3. **Do Two Lambdas Bound ?**
   - ⋆ **Double-well Structure**
   - ⋆ **$\Lambda\Lambda$ Correlation at AGS, SPS, and RHIC**
4. **Summary**

Refs. of Ours

(K^-, K^+)	Nara, Ohnishi, Harada, Engel, NPA614 (97), 433
AA	Nara, NPA638 ('98), 555c; nucl-th/9802016
	Nara et al., to be submitted.
Corr. to nn Int.	Slaus, Akaishi, Tanaka, PRep. 173, ('89), 257.
$\Lambda\Lambda$ Int.	Ohnishi, Hirata, Nara, Shinmura, Akaishi, in preparation
	Hirata, Ohnishi, Ohtsuka, Nara, in preparation

$\Lambda\Lambda$ Interaction: How can we get it ?

⋆ **IMPORTANT**

Baryon-Baryon Int. with SU$_f$(3),
Double Hypernuclei, H particle, Neutron Star, ...

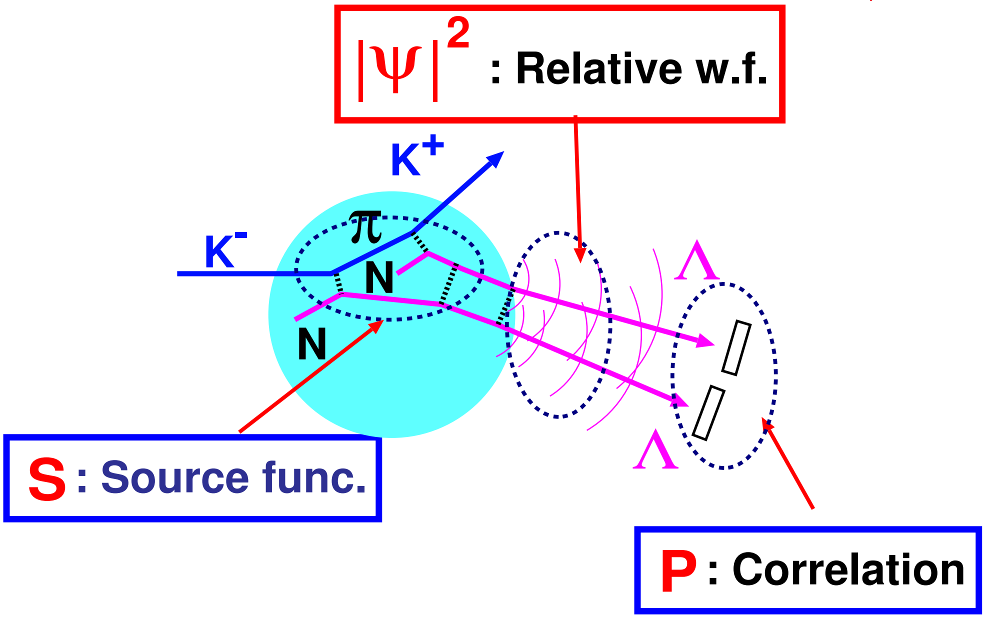
⋆ **but DIFFICULT to measure**

- **Double Hypernuclei → 3 events/35 years, Only $^1S_0$**
- **Scattering Exp. → Compact Collider**

- **Enh. of Λ-Λ Inv. Mass Spec. at Low E.**

Ahn et al. (KEK E224 coll.), KEK Preprint 98-24, 1998; PRL, in press

- **Two-Particle Momentum Correlation**
= Source Func. + Relative w.f.



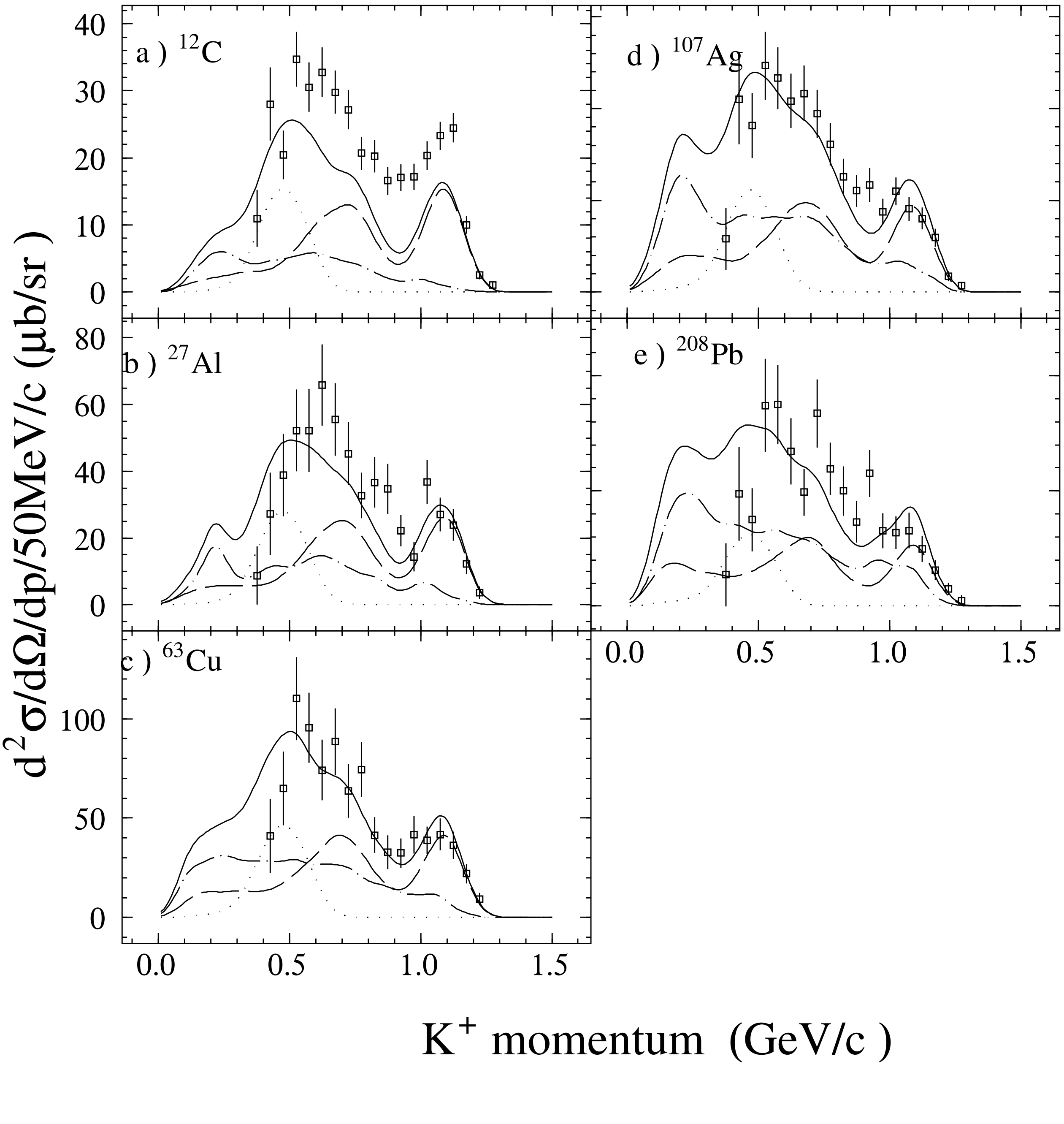
$$P(p_1, p_2) = \int dx_1 dx_2 S(p_1, x_1, p_2, x_2) |\psi^{(-)}(k, r_{12})|^2$$

$$\vec{r}_{12} = \vec{r}_1 - \vec{r}_2 + \vec{P}(t_2 - t_1)/2m\ , \quad \vec{P} = \vec{p}_1 + \vec{p}_2\ , \quad \vec{k} = \frac{1}{2}(\vec{p}_1 - \vec{p}_2)\ ,$$

W. G. Gong et al., PRC 43 ('91), 781.
Slaus, Akaishi, Tanaka, PRep. 173, ('89), 257.

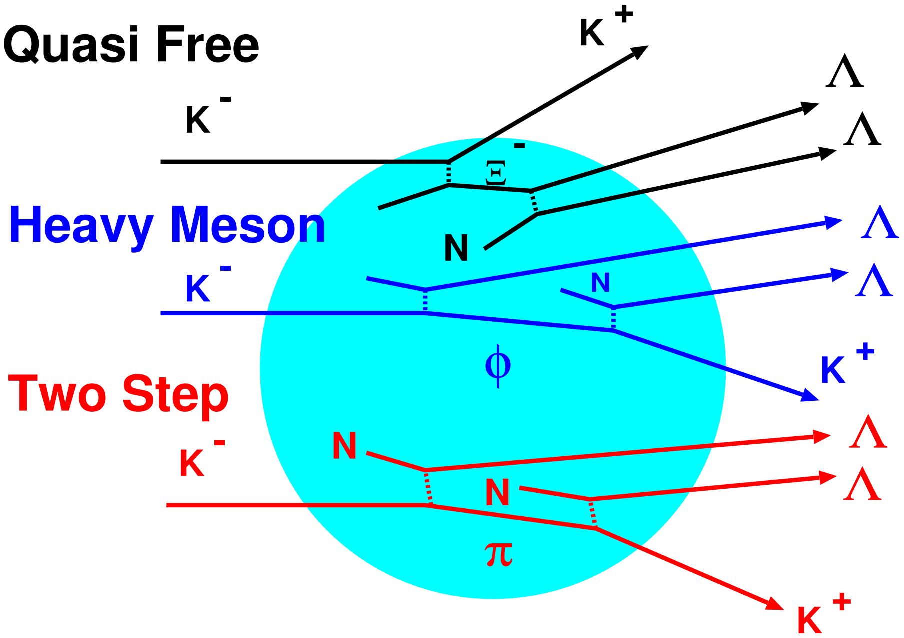
Is there any reliable source function ?

→ **INC: Nara,Ohnishi,Harada, Engel, NPA614 (97), 433.**



Source Func. = IntraNuclear Cascade

Nara,Ohnishi,Harada, Engel, NPA614 (97), 433.



- **K^+ Production Mech.**

Quasi Free	$K^-N \to K^+\Xi^{(*)}$
Heavy-Meson (Gobbi-Dover-Gal)	$K^-N \to MY, M \to K^-K^+$ $MN \to K^+\Lambda$ $(M = \phi, f_0, a_0)$
Two-Step	$K^-N \to MY^{(*)}, MN \to K^+Y^{(*)}$ $(M = \pi, \eta, \rho, \omega, \eta')$

- **Baryon-Baryon Collision**

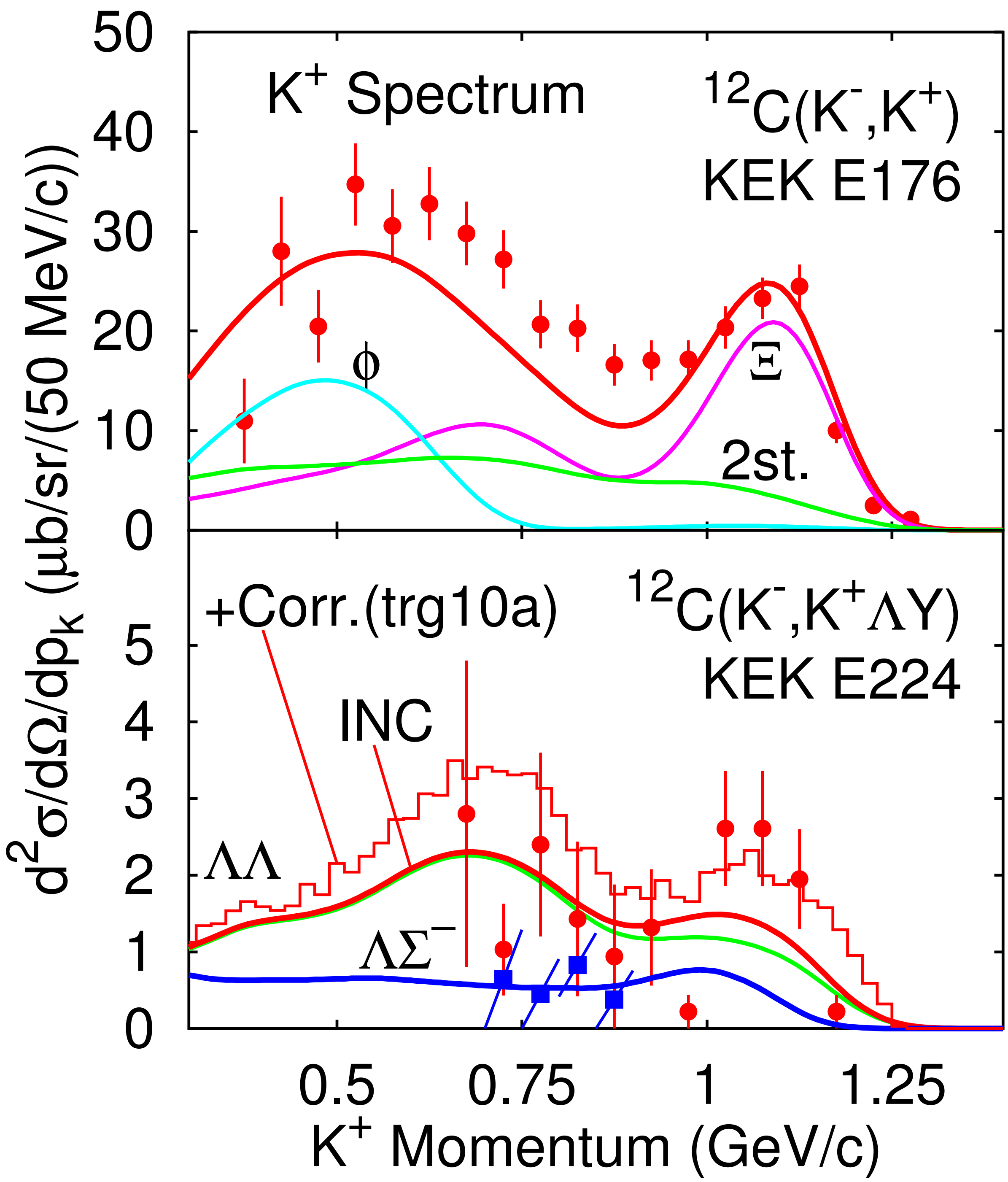
⋆ $NN \to NN$, $NY \to NY'$ (ND)

⋆ $\Xi N \to \Lambda\Lambda$ (ND, r_c=0.5 fm)

- **Mean Field Effects**

⋆ $U_\Lambda = -30$ MeV, $U_\Sigma = -10$ MeV
$U_\Xi = -16$ MeV (Fukuda et al. PRC58 (98) 1306)

K^+ Spectrum in ^{12}C(K^-, K^+)

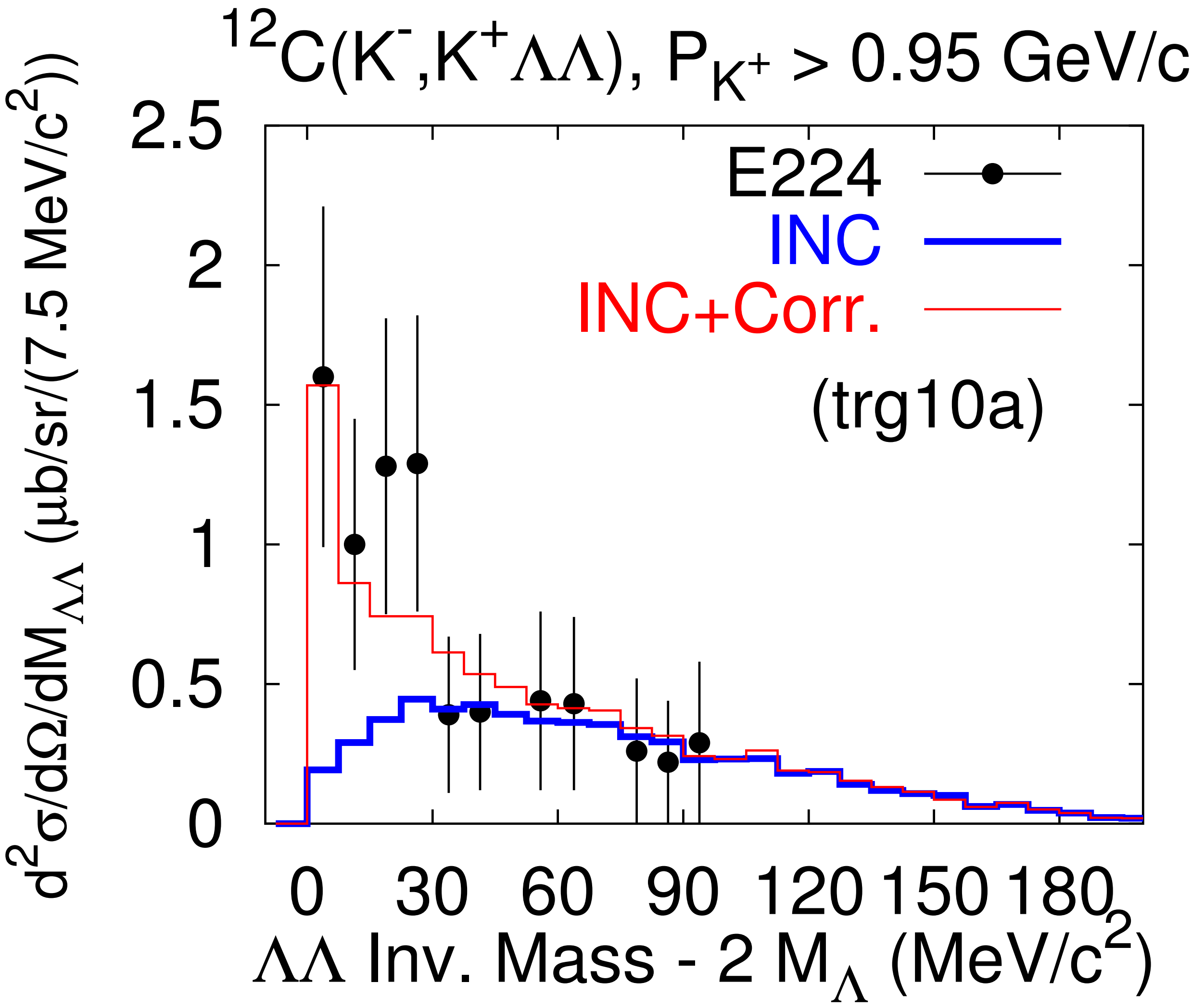


- **INC** results of $(K^-, K^+\Lambda\Lambda)$

  ⋆ **Underestimate of around 3 μb** ($P(K^+) > 0.95$ **GeV/c**)

  ⋆ **Two-Step Processes are dominant even in QF region.**

Λ-Λ Inv. Mass Spectrum



- **INC results**

  ⋆ **Underestimate** ($\sim 3\mu$b) **at Low** $M_{\Lambda\Lambda}$

  ⋆ **Reproduces at** $E_{\Lambda\Lambda} > 50$ **MeV** $\cdots$ **Source Size** $\leq$ **3 fm**

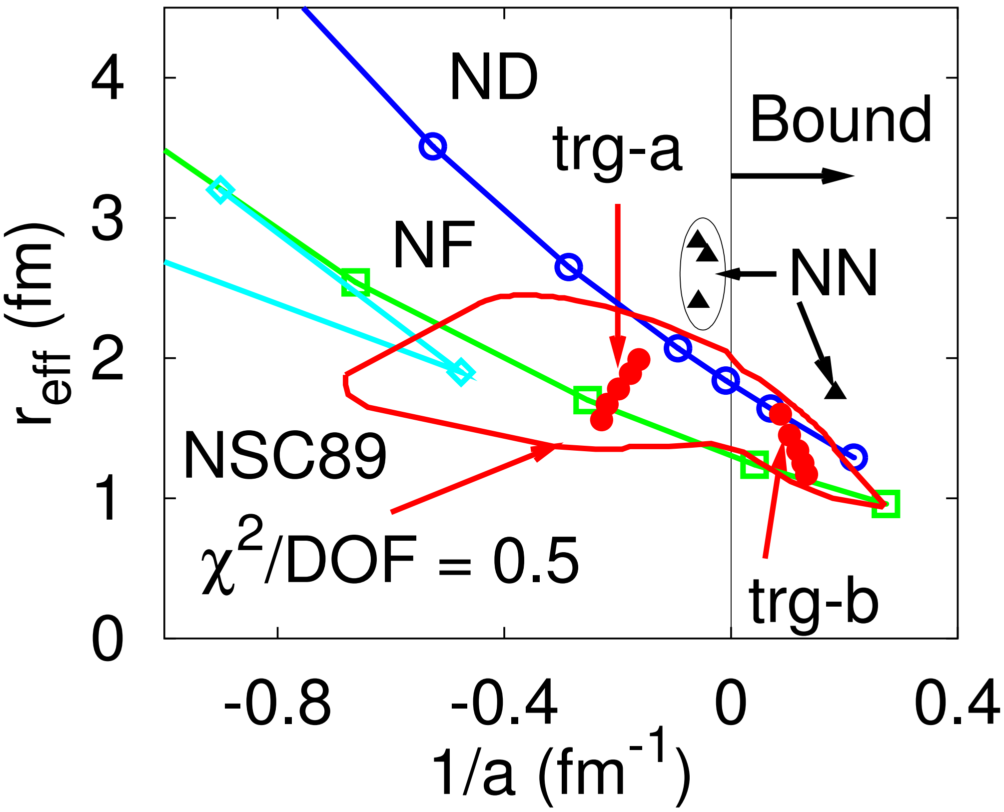
- **INC+Corr. results**

  ⋆ **Attr. ΛΛ Int.** $\rightarrow$ **Fast Growth of W.F.**
  $\rightarrow$ **Enh. of Inv. Mass Spec.**

Extracted Λ-Λ Interaction

• χ^2-Fit within Two-Range Gauss Interaction

	μ_l	μ_s	v_l	v_s	a	$r_{\rm eff}$	$\tilde{\chi}^2$	B.E.
		(fm)		(MeV)		(fm)		(MeV)
trg06a	0.6	0.45	-900	1440	-4.4	1.6	0.34	U.B.
trg08a	0.8	0.45	-230	470	-5.0	1.8	0.36	U.B.
trg10a	1.0	0.45	-105	200	-6.2	2.0	0.39	U.B.
trg06b	0.6	0.45	-950	1310	7.5	1.2	0.37	0.72
trg08b	0.8	0.45	-270	410	8.5	1.3	0.40	0.56
trg10b	1.0	0.45	-135	210	11.5	1.6	0.43	0.29



Comparison with Nijmegen Models

⋆ **ND with** $r_c = 0.5 \sim 0.52$ **fm** ↔ **trg10a**

⋆ **NF with** $r_c = 0.46$ **fm** ↔ **trg06a**

⋆ **NSC98 with** $M_{cut} = 920$ **MeV**

Does Λ-Λ System Bound ?

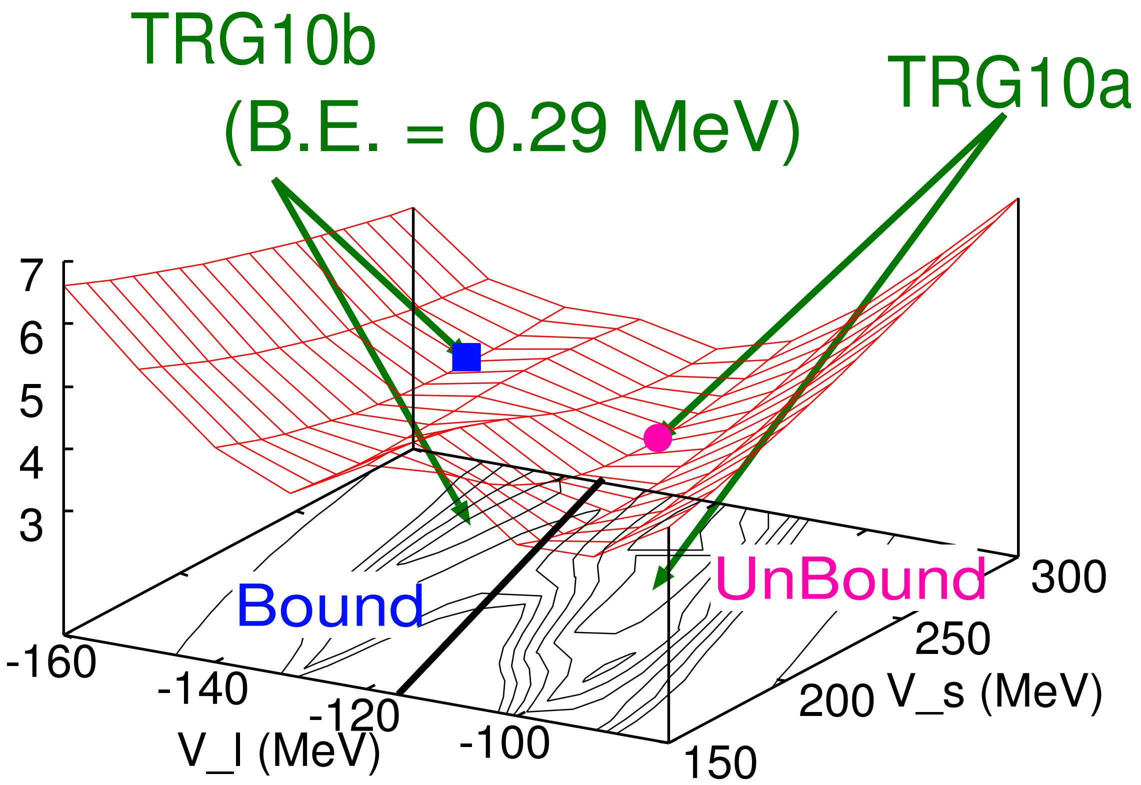
- **Corr. Formula + Long Wave Approx.**
  → Enhancement Factor

$$
\begin{aligned}
P(\vec{p}_1,\vec{p}_2) &= 2\ F(k)\ P_c(\vec{p}_1,\vec{p}_2)\ ,\\
P_c(\vec{p}_1,\vec{p}_2) &= \int d^4x_1\, d^4x_2\, S(\vec{p}_1,x_1,\vec{p}_2,x_2)\ ,
\end{aligned}
$$

$$
F(k) = \left|\frac{\sin(kb+\delta_0)}{\sin kb}\right|^2 \xrightarrow{k\to 0} \left(1-\frac{a}{b}\right)^2 - ck^2
$$

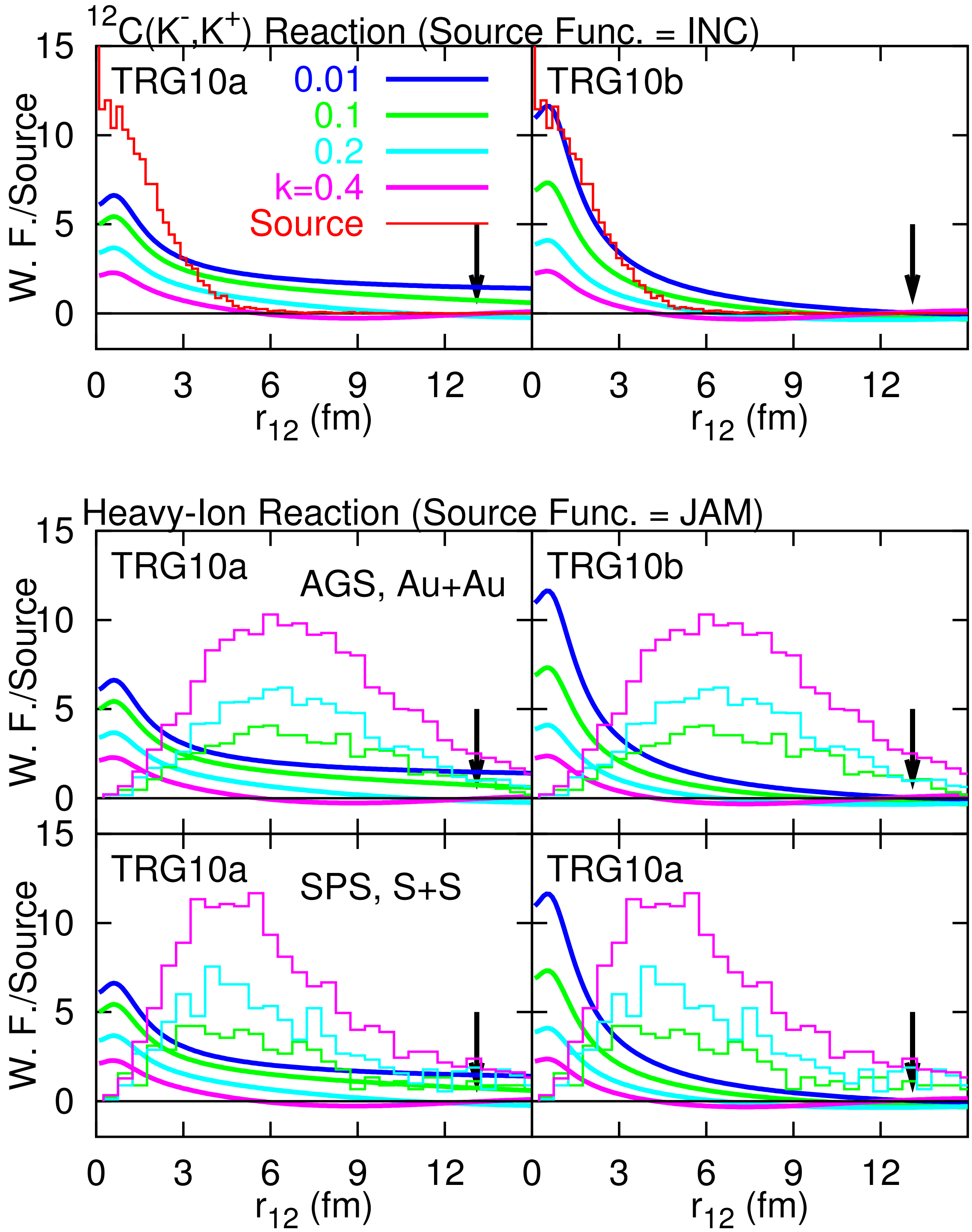
a: **scattering length,** b: **intrinsic range**

→ **Double-well structure:** $a \simeq b(1 \pm \sqrt{F(0)})$



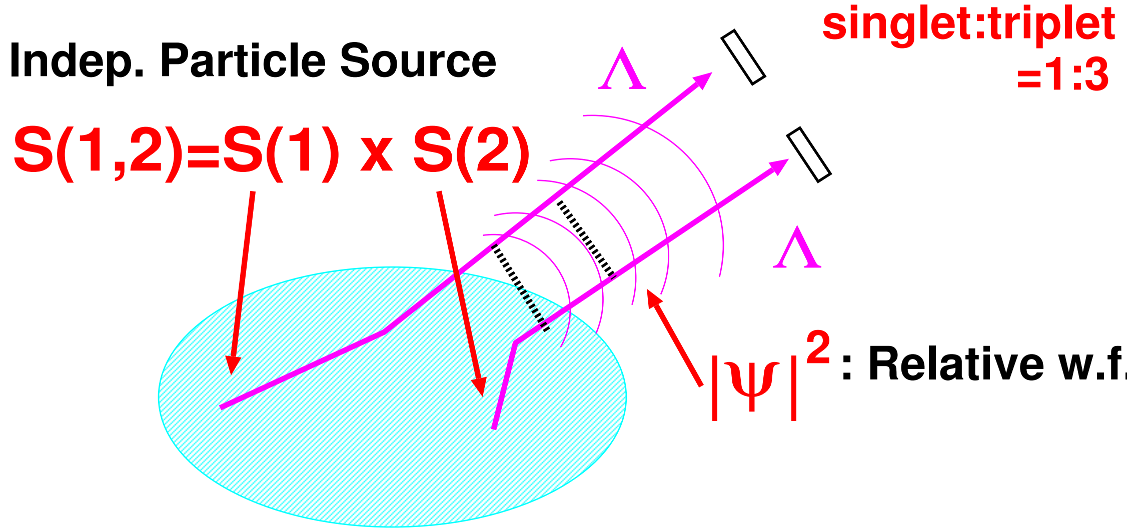
• **How to Distinguish Them ?**

→ **Use Reactions with Different Source Size, covering the region around Scattering Length.**



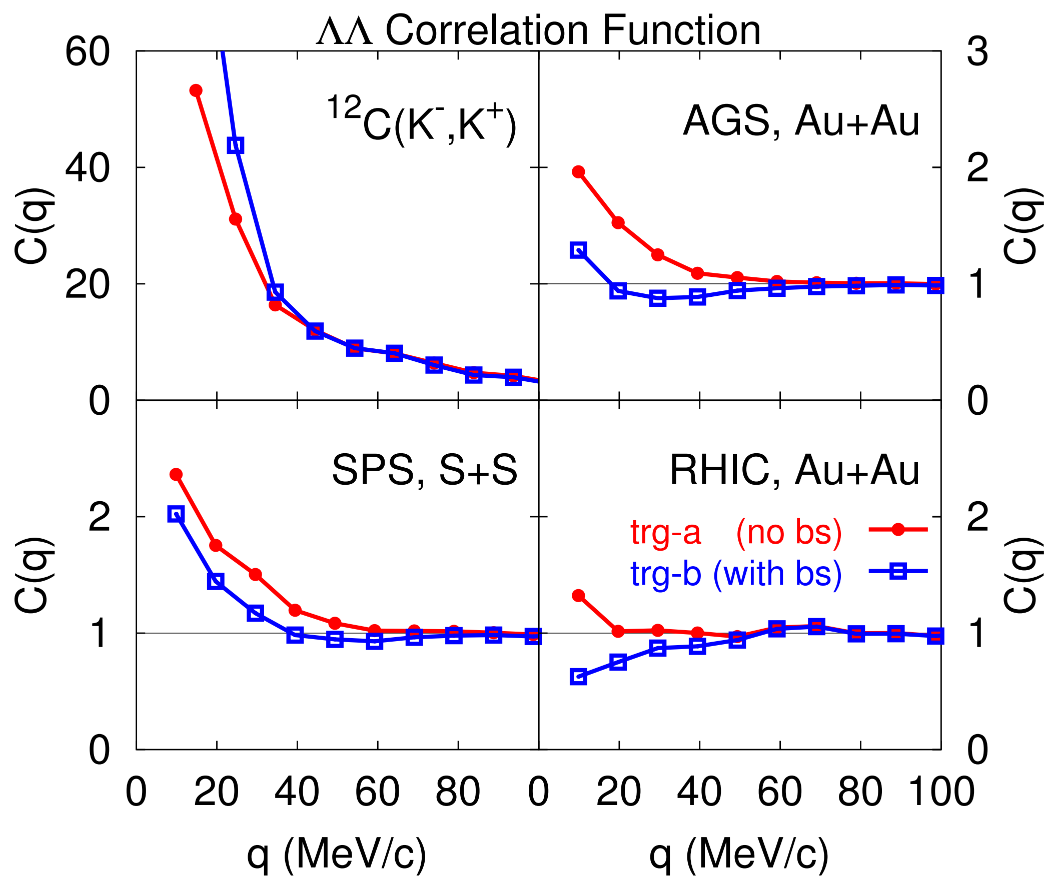
JAM: Y.Nara, NPA638 ('98), 555c; nucl-th/9802016
Y.Nara et al., to be submitted.

Particle Correlation in HIC



$$C(q) = \frac{\int dP\, dx_1 dx_2\, S(p_1,x_1,p_2,x_2)\,|\psi^{(-)}(k,r_{12})|^2}{\int dP\, dx_1 dx_2\, S(p_1,x_1,p_2,x_2)}$$

$p_1 = P/2 + q \qquad p_2 = P/2 - q$



Summary

1. **Source Func. (INC) + Λ-Λ Corr. (Inv. Mass Spec.)**
   → Λ-Λ Interaction
   (We can use HBT INVERSELY)

2. **Extracted Λ-Λ Int. at χ^2 Local Min.**

   ⋆ **Best Fit Parameters: No Bound State.**
   → $a \simeq -5$ **fm,** $r_{\text{eff}} \simeq 1.8$ **fm**

   ⋆ **Double well structure**
   → **We cannot exclude** $a > 0$ **(bound)**

   ⋆ χ^2**/DOF** $\simeq$ **0.4: Large Error Bar of Data**

3. **Λ-Λ Interferometry in (K^-, K^+) and AA Reaction**

	Source	Corr.
(K^-, K^+)	Small, Dyn. Corr.	Large
AA	Large, Indep.	Small

   ⋆ (K^-, K^+) **Reaction**
   - **One-Dim. Prod. Mech. + Small Source Size**
   → **Large Enh.**

   ⋆ **Relativistic Heavy-Ion Collision**
   - **Indep. Prod. Mech. + Large Source Size**
   → **Corr. Func. is Available through Exp.**
   → **Covers Scat. Length Region of Small B.E.**

• Remaining Problems

1. **Resonance of $\Lambda\Lambda$-ΞN Coupling or ^{3}P$_2(\Lambda\Lambda)$**
   c.f. Oka-Yazaki '84, Shinmura et al.
2. **Assumption in this work**
   (a) **Spin Singlet dominance**
   (b) **Only the $L = 0$ partial waves are distorted.**
   $\cdots$ **Odd partial waves $\leftarrow$ Spin dist. in ^{12}C**
3. **Other Hyperon-Hyperon Interaction**
   $\cdots$ $\Lambda\Sigma^-$, $\Sigma^+\Sigma^-$ **(BNL-E906)**
4. **Mean Field Effects in AA Collision**
   $\cdots$ **Flow at AGS and SPS energies (P.K. Sahu et al.)**
5. **Small Yield of Low Energy $\Lambda\Lambda$ in AA**
6. **Evaporation from Hypernuclei in (K^-, K^+) Reaction.**
7. **.....**

Branching ratio change in K^- absorption at rest and the nature of the $\Lambda(1405)$

A. Ohnishi (Hokkaido U.)
Y. Nara (JAERI)
V. Koch (LBNL)

1. **$\bar{K}N$ interaction $\leftrightarrow$ $\Lambda(1405)$ puzzle**
   - ⋆ **Repulsive**
     ⋯ **Experimental data**
     (Scattering & Kaonic Hydrogen)
   - ⋆ **Attractive**
     ⋯ **K^-A optical potential**

   ⋯ **Boundstate picture of $\Lambda(1405)$ may solve it.**

2. **Mass shift of $\Lambda(1405)$ in Medium**
   - ⋆ **Boundstate Picture of $\Lambda(1405)$**
   - ⋆ **Mass shift of $\Lambda(1405)$ from Pauli blocking**
   - ⋆ **$I = 0$ ($\Lambda(1405)$ channel) and $I = 1$ interference**
     $\rightarrow$ **Branching Ratio Change**

3. **Comparison of Two Scenarios of $\Lambda(1405)$**
   - ⋆ **Stopped K^- Reaction**
   - ⋆ **(K^-, π^-) and (K^-, π^+) Spectrum**

4. **Summary**

∗ **Phys. Rev. C, in press; Eprint nucl-th/9706084**

$\bar{K}N$ Interaction: Attractive or Repulsive ?

- **Repulsive (Exp. in $\bar{K}N$)**

  ⋆ **Low Energy Scattering** $\rightarrow a_{K^-p} \simeq -0.15$ **fm**
  (Martin, NP B179 ('81), 33)

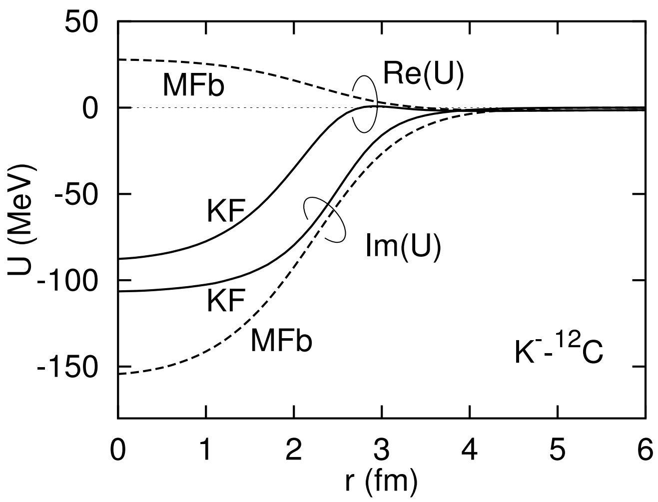
  ⋆ **$1s$ Energy Shift of Kaonic Hydrogen** $\rightarrow -323$ **eV**
  (Iwasaki et al., PRL 78 ('97), 3067)

- **Attractive (Theory, $\bar{K}A$)**

  ⋆ **Kaonic Atom (not hydrogen)**

$$U_N(K^-A) = \alpha\rho + \beta\rho^2 \neq -\frac{2\pi\hbar^2}{\mu_{KN}} a_{K^-N}\ \rho$$

(Friedman et al., PL B308 ('93), 6)



⋯ **How can we solve this problem ?**
→ Boundstate Picture of Λ(1405) May Help it.

$\Lambda(1405)$ Puzzle

- $\Lambda(1405)$ **Resonance**

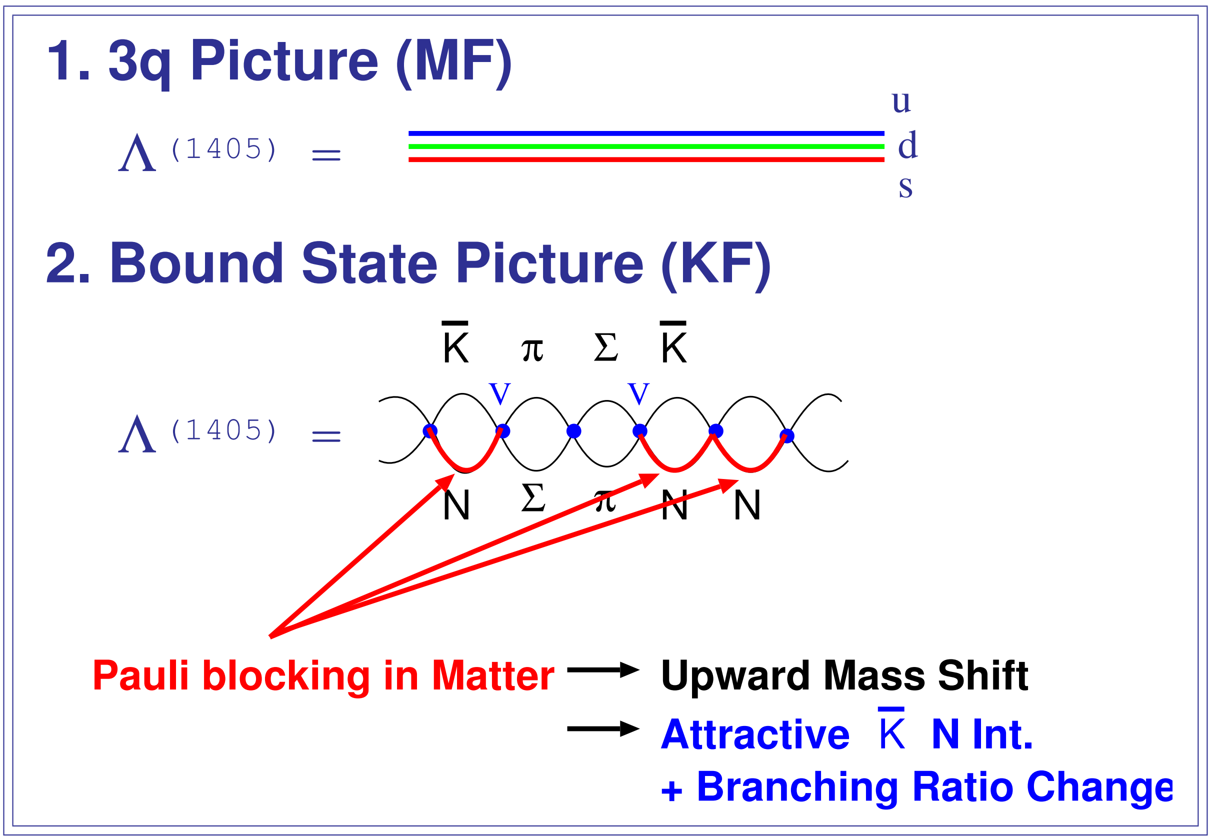
  $\star$ $I = 0, J^\pi = 1/2^-$ **(S-wave)**

  $\star$ **Just below $\bar{K}N$ threshold (1432 MeV)**
  $\rightarrow$ **Repulsive contribution to Scattering Length**

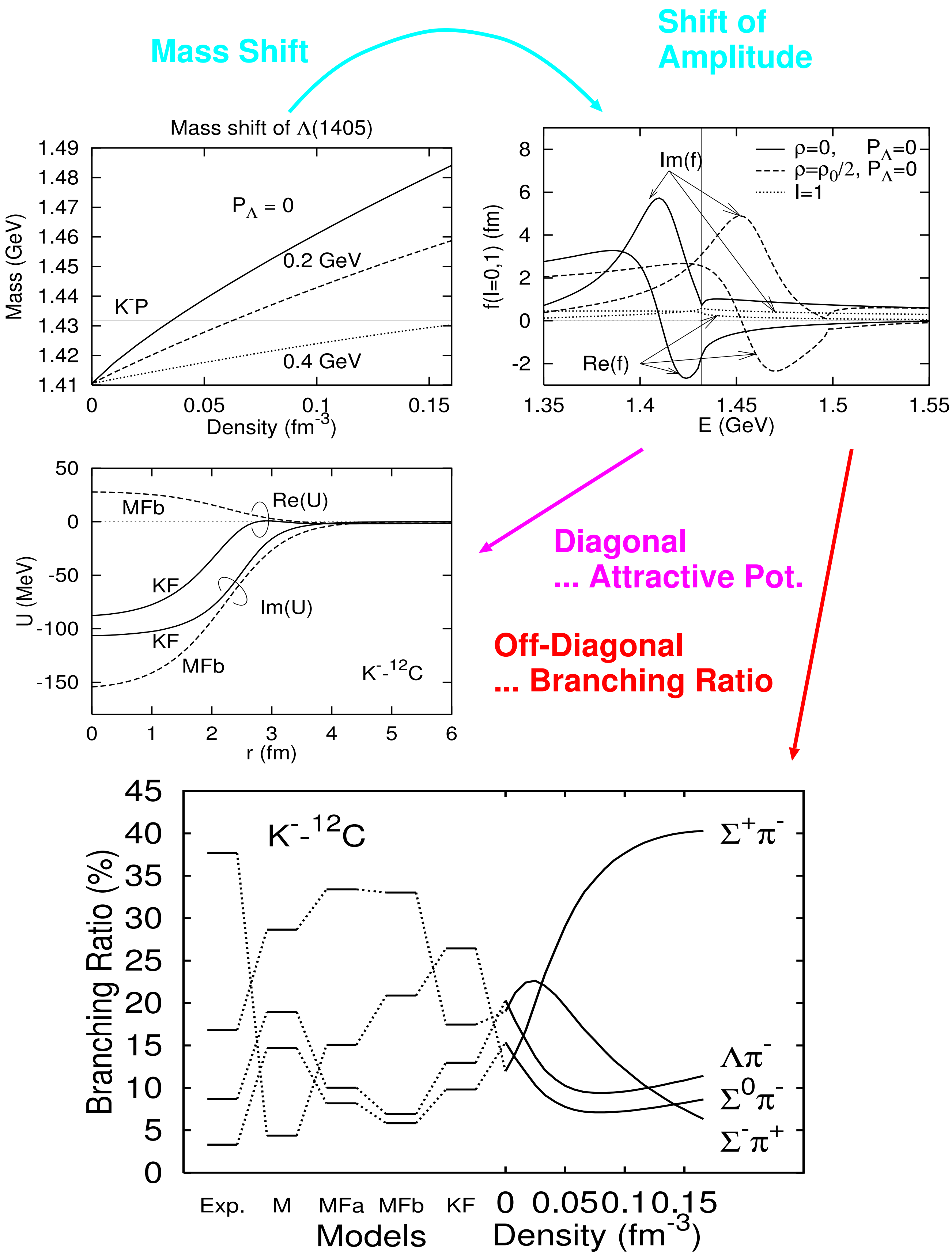
- **Two Pictures of $\Lambda(1405)$**

1. $\Lambda(1405) \simeq 3q$

2. $|\Lambda(1405)> = |\bar{K}N> + |\Sigma\pi> =$ **Boundstate of $\bar{K}N$** (Dalitz et al., PR 153 ('67),617, Siegel and Weise, PR C38 ('88),2221) $\leftrightarrow$ **Difficulty in "pure" quark model for $\Lambda(1405)$**
(c.f. Hamaie,Arima,Masutani, NP A591 ('95), 675)



Branching Ratio Change in Medium



Two Scenarios of $\Lambda(1405)$

1. **Model MF:** $\Lambda(1405) \simeq 3q$
   - $\star$ **Martin's Amp. w. Fermi ave.+B.E. Corr.**
   - $\star$ **No Medium Effects on** $\Lambda(1405)$
   - $\star$ **Br. Rat. in ^{12}C(Stopped K^-,π):** $\Sigma^-\pi^+ > \Sigma^+\pi^-$
2. **Model KF:** $\Lambda(1405) \simeq$ **Bound State of** $\bar{K}N$
   - $\star$ **Koch's Amp. with Pauli blocking in** $\Lambda(1405)$
     (Koch, PL B337 ('94), 7, Waas et al., PL B365 ('94), 12
     Staronski et al., J.Phys.G13('87),1361, Masutani, NPA483('88),565)
   - $\star$ **Density Dependent** $\Lambda(1405)$ **Mass**
   - $\star$ **Br. Rat. in ^{12}C(Stopped K^-,π):** $\Sigma^-\pi^+ < \Sigma^+\pi^-$

Stopped K^- Reaction

(Exp: Tamura et al., PR C40('89),R479, Kubota et al. NP A602('96),327
Theor: Nara et al., PL B346('95), 217; INS 23,
Staronski et al., J.Phys.G13('87),1361, Masutani, NPA483('88),565)

- **Advantages**

1. $I = 0$ **Branches are dominant** $\cdots$ $\Lambda(1405)$ **Tail**
2. **A lot of Exp. Data**
   $(K^-,\pi^\pm)$ **on various nuclear targets**
3. **Spectrum is sensitive to B.R.**
4. **Slow** $\Lambda(1405)$ **is produced.**

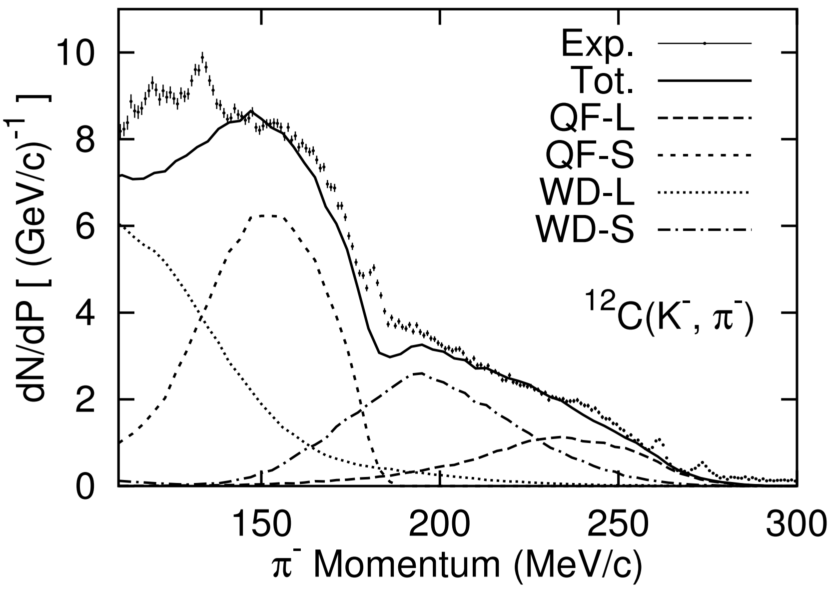
- **Disadvantages**

1. **Reaction processes are complex.**
   Σ **conversion to** Λ, π **rescattering**
   $\rightarrow$ **Monte Carlo Simulation**

- (K^-, π^-) **Spectrum**

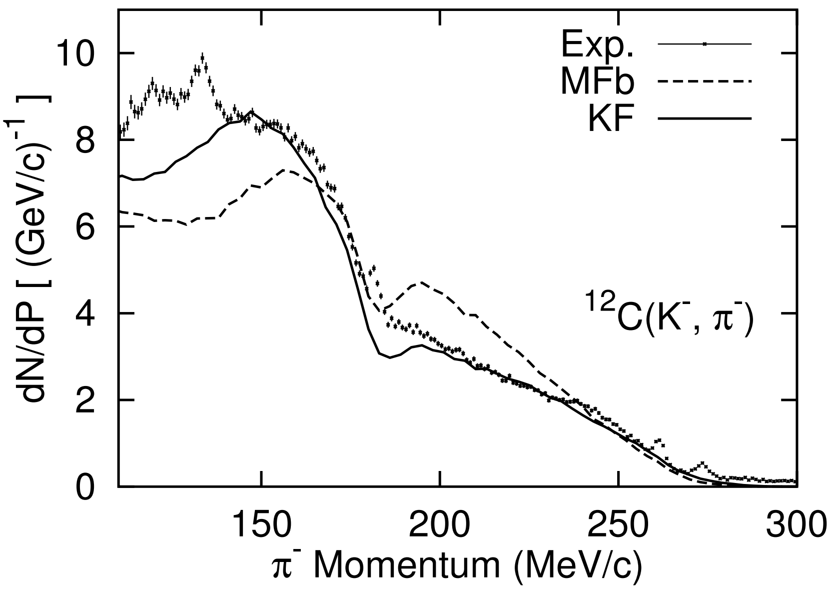
(Exp: Tamura et al., PR C40('89),R479)

⋆ **Components of (K^-, π^-) Spectrum**



⋆ **Comparison of Two Scenarios**

··· **Model KF is slightly better.**



• (K^-, π^+) **Spectrum**

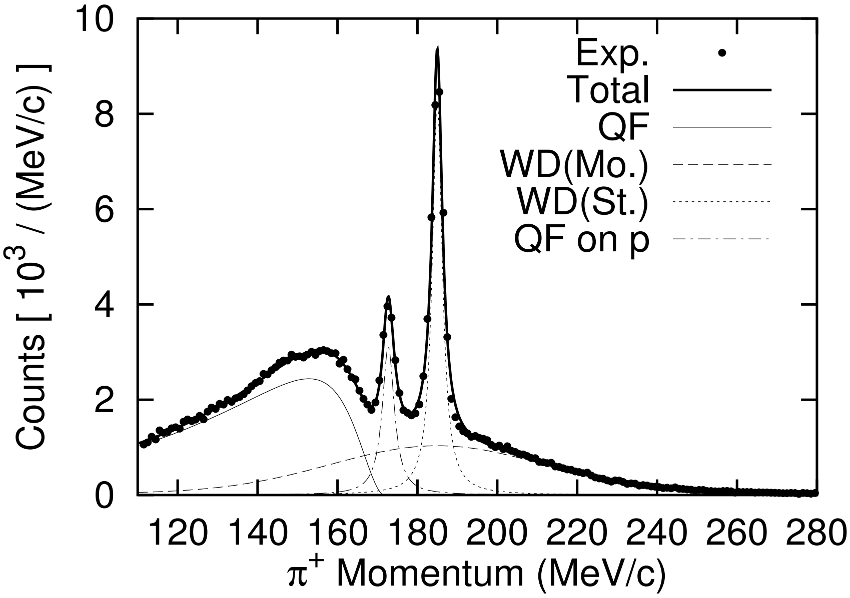
(Exp: Kubota et al. NP A602('96),327)

π^+ **comes from**

QF $(K^- p \to \Sigma^- \pi^+)$

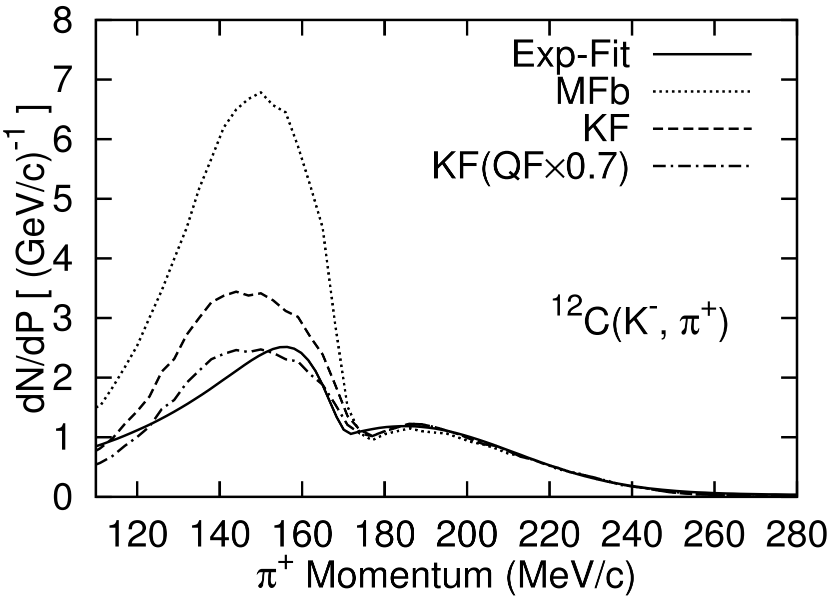
or **WD** $(K^- p \to \Sigma^+ \pi^-, \Sigma^+ \to \pi^+ n)$

⋆ **Components of** (K^-, π^-) **Spectrum**



⋆ **Comparison of Two Scenarios**

⋯ **Model KF is much better.**



Summary and Future Work

- **Summary**

1. **$\Lambda(1405)$ mass shift induces**
   LARGE Branching Ratio Change
   at finite ρ ($\Sigma^+\pi^- \leftrightarrow \Sigma^-\pi^+$).

2. Stopped K^- Reaction
   - ⋆ (K^-, π^-);
     Various QF ($K^-N \to Y\pi^-$)
     \+ Various WD ($K^-N \to Y\pi, Y \to \pi^-N$)
   - ⋆ (K^-, π^+); Clean Reaction
     QF ($K^-p \to \Sigma^-\pi^+$)
     \+ WD ($K^-p \to \Sigma^+\pi^-, \Sigma^+ \to \pi^+n$)

3. Boundstate picture gives better description,
   especially of (K^-, π^+) spectrum.

- **Future Work**

1. **Remaining differences from data**
   - ⋆ **Final state interaction ?**
     $\cdots$ Σ conversion, π absorption ?
   - ⋆ **More mass shift ?**
   - ⋆ **B. E. corr., or $\Lambda(1405)$ potential ?**

2. **Direct measurement of mass shift**
   $K^-A \to \pi\Lambda(1405)$ **(Magic momentum)**

July 14-16, 1999 @ TITech

重イオン反応でのフラグメント生成における量子揺らぎの効果

北海道大学　大西　明

1. Introduction

- ⋆ 核物質の相
- ⋆ 核物質の液相・気相相転移と多重破砕
- ⋆ 分子動力学の成功例と失敗例

2. 波束の統計力学

- ⋆ 波束基底による分配関数の評価
- ⋆ 原子核のカロリー曲線
- ⋆ 原子核の熱破砕

3. 重イオン反応への応用

- ⋆ 量子揺らぎを含む分子動力学
- ⋆ 重イオン反応での多重破砕の記述

4. フラグメントは"過冷却核子気体"中で作られるか？

- ⋆ フラグメント生成時の温度と密度

5. まとめと今後の展望

共同研究者: 平田 (北大)、**J.Randrup(LBL)**

分子動力学の問題点

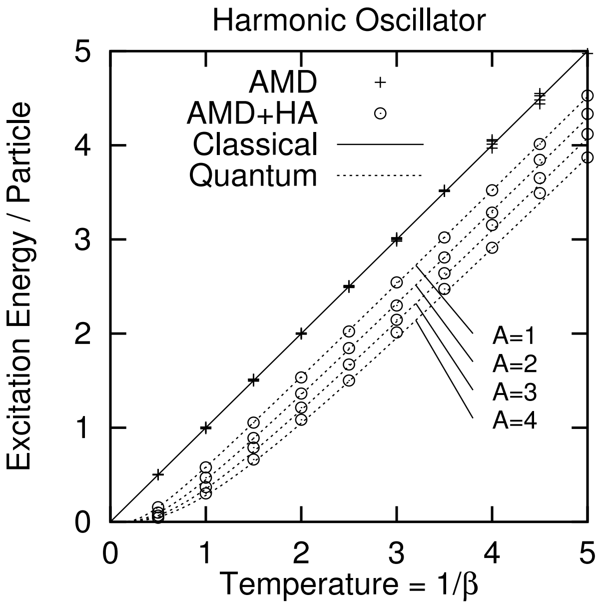
• 分子動力学の統計的性質

⋆ 運動方程式から期待される分配関数

$$\mathcal{Z} = \int d\Gamma \exp(-\beta\mathcal{H})$$

→ 低温でも $E^* \propto 1/\beta \equiv T$ ⋯ 古典的？

⋆ 基底状態 $\mathcal{H} = E_{g.s.}$ が担う分配関数 ≈ 0
(パラメータ空間では１点)



(A.O. and J.Randrup, NPA 565('93),474.)

• 解決方法

1. β の再解釈と波動関数自体の分析
Schnack-Feldmeier, NPA 601('96), 181, Ono-Horiuchi, PRC53 ('96), 2341.
パラメータ空間では古典統計となるが、波動関数で見れば量子統計性がみえる。しかし、フラグメント生成にはこの量子統計性は効果無し。

2. 量子揺らぎを含む分子動力学
Ohnishi-Randrup, 1993-; Ono-Horiuchi, PRC53 ('96)845, PRC53("96), 2958.)

波束基底の統計力学から
量子揺らぎを含む分子動力学へ

問題: 波束 $|\Psi_Z\rangle$ はハミルトニアンの固有状態ではない。
　　= エネルギーに揺らぎがある

- **平衡状態**: 分配関数を求めればよい

$$
\begin{aligned}
\mathcal{Z}_\beta &\equiv \mathrm{Tr}\left(\exp(-\beta\hat{H})\right) = \int d\Gamma_Z \mathcal{W}_\beta(\vec{Z}) \\
\mathcal{W}_\beta(\vec{Z}) &= \langle\Psi_Z|\exp(-\beta\hat{H})|\Psi_Z\rangle = \exp(-\mathcal{F}(\vec{Z})) \\
&\neq \exp(-\beta\mathcal{H})
\end{aligned}
$$

- **非平衡状態**: 平衡状態に近付いて行く方程式を作る

⋆ $\mathcal{W}_\beta(\vec{Z})$ を平衡分布とするフォッカー・プランク方程式

$$
\frac{D\phi(\vec{Z};t)}{Dt} = \frac{\partial}{\partial\mathbf{q}} \cdot \left(\mathbf{M}\cdot\frac{\partial\mathcal{F}}{\partial\mathbf{q}} + \mathbf{M}\cdot\frac{\partial}{\partial\mathbf{q}}\right)\phi\ ,
$$

$$
\{\mathbf{q}\} = \{\mathbf{r},\mathbf{p}\}, \qquad \mathbf{M} = \mathbf{g}\cdot\mathbf{g} : \text{Mobility Tensor}
$$

⋆ 同値なランジュバン方程式 (量子ランジュバン方程式)

$$
\begin{aligned}
\frac{d\mathbf{p}}{dt} &= -\frac{\partial\mathcal{H}}{\partial\mathbf{r}} - \mathbf{M}^p\cdot\frac{\partial\mathcal{F}}{\partial\mathbf{p}} + \mathbf{g}^p\cdot\zeta^p\ , \\
\frac{d\mathbf{r}}{dt} &= \frac{\partial\mathcal{H}}{\partial\mathbf{p}} - \mathbf{M}^r\cdot\frac{\partial\mathcal{F}}{\partial\mathbf{r}} + \mathbf{g}^r\cdot\zeta^r\ ,
\end{aligned}
$$

正準方程式　　Drift　　Diffusion

→ 時間についての常微分方程式 = (数値的に) 解ける！

ボルツマン演算子による波束の歪曲

- **演算子の統計平均**

$$\prec \hat{O} \succ_\beta \equiv \frac{1}{\mathcal{Z}_\beta} \mathrm{Tr}\left(\hat{O}\exp(-\beta\hat{H})\right) = \frac{1}{\mathcal{Z}_\beta}\int d\Gamma\, \mathcal{W}_\beta(\vec{Z})\ \mathcal{O}_\beta(\vec{Z})$$

$$\mathcal{O}_\beta(\vec{Z}) \equiv \frac{\langle \Psi_Z(\beta/2)|\hat{O}|\Psi_Z(\beta/2)\rangle}{\mathcal{W}_\beta(\vec{Z})} \neq \langle \hat{O} \rangle$$

$$|\Psi_Z(\beta/2)\rangle = \exp(-\beta\hat{H}/2)|\Psi_Z\rangle$$

⋆ ”冷やされた”状態 $|\Psi_Z(\beta/2)\rangle$ による
演算子期待値の **Weighted average**

⋆ $\mathcal{H}_\beta < \mathcal{H}$:

→ 量子統計的には波束はそれ自身の期待値より
低いエネルギーを運ぶ

- **分子動力学におけるボルツマン演算子による歪曲:**

虚時間推進 ＝ 冷却方程式を $\tau = \beta\hbar/2$ まで解く

$$\frac{d\mathbf{p}}{d\tau} = -\frac{2\Delta p^2}{\hbar}\frac{\partial\mathcal{H}}{\partial\mathbf{p}}\ , \qquad \frac{d\mathbf{r}}{d\tau} = \frac{2\Delta r^2}{\hbar}\frac{\partial\mathcal{H}}{\partial\mathbf{p}}\ .$$

いかにして統計重率 $\langle\Psi_Z|\exp(-\beta\hat{H})|\Psi_Z\rangle$ を求めるか？

- **通常の高温展開**

$$\mathcal{F}(\vec{Z}) \equiv -\log\{\langle\Psi_Z|\exp(-\beta\hat{H})|\Psi_Z\rangle\} \approx \beta\mathcal{H} - \beta^2\sigma^2/2$$

$$\sigma^2 \equiv \langle\hat{H}^2\rangle - \langle\hat{H}\rangle^2$$

$\cdots T = 1/\beta < \sigma^2/\mathcal{H}$ で破綻 ($\beta \to \infty$ で発散)

- **調和近似**

$$\frac{d\mathcal{F}(\vec{Z})}{d\beta} = \mathcal{H}_\beta \;, \qquad \frac{d\mathcal{H}_\beta}{d\beta} = -\sigma_\beta^2 < 0 \quad (\textbf{Exact})$$

$\star$ $\mathcal{H}_\beta$ は β の減少関数

$\star$ 波束に少しでも基底状態が混じっていれば

$$\mathcal{H}_\beta \to E_{g.s.}(\beta \to \infty)$$

$$\begin{aligned}\mathcal{H}_\beta &\approx (\mathcal{H} - E_{g.s.})\;\exp(-\beta D) + E_{g.s.}\\ D &\equiv \sigma^2/(\mathcal{H} - E_{g.s.})\end{aligned}$$

- **分子動力学による波束のエネルギー揺らぎの表現**

$$\begin{aligned}\sigma^2(\vec{Z}) &= \frac{\partial\mathcal{H}}{\partial\vec{Z}}\cdot\mathbf{C}\cdot\frac{\partial\mathcal{H}}{\partial\vec{Z}^*}\\ &= \Delta p^2\frac{\partial\mathcal{H}}{\partial\mathbf{p}}\cdot\frac{\partial\mathcal{H}}{\partial\mathbf{p}} + \Delta r^2\frac{\partial\mathcal{H}}{\partial\mathbf{r}}\cdot\frac{\partial\mathcal{H}}{\partial\mathbf{r}}\\ \mathbf{C} &= \frac{\partial^2}{\partial\vec{Z}^*\partial\vec{Z}}\log\left(\langle\Psi_Z|\Psi_Z\rangle\right)\end{aligned}$$

Soluble Example

• One Particle in a Harmonic Oscillator

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{m\omega^2 \hat{r}^2}{2}$$

$$\mathcal{H} = \hbar\omega \bar{Z} Z = \frac{p^2}{2m} + \frac{m\omega^2 r^2}{2} \qquad \left(Z = \sqrt{\nu} r + \frac{i\,p}{2\hbar\sqrt{\nu}} \right)$$

$$D(\vec{Z}) \equiv \langle \vec{Z} | \hat{H}^2 - \mathcal{H}^2 | \vec{Z} \rangle / \mathcal{H} = \hbar\omega$$

$$\mathcal{W}_\beta(\vec{Z}) \equiv \langle \vec{Z} | \exp(-\beta \hat{H}) | \vec{Z} \rangle = \exp(-\alpha\beta\mathcal{H}) \qquad \left(\alpha = \frac{1 - e^{-\beta\hbar\omega}}{\beta\hbar\omega} < 1 \right)$$

$$\prec \hat{H} \succ_\beta^U \equiv \frac{1}{\mathcal{Z}_\beta} \int d\Gamma\, \mathcal{W}_\beta(\vec{Z})\ \mathcal{H}(\vec{Z}) = \frac{T}{\alpha} > T$$

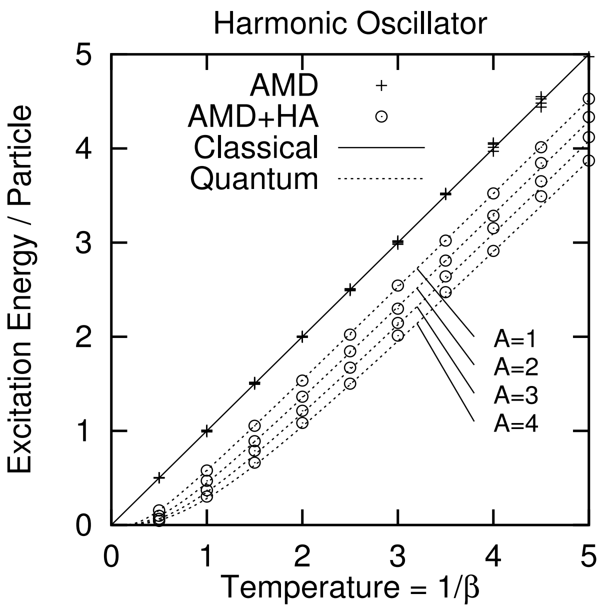
$\cdots$ **w.o Distortion = Wrong !**

$$\prec \hat{H} \succ_\beta = \frac{1}{\mathcal{Z}_\beta} \int d\Gamma\, \mathcal{W}_\beta(\vec{Z})\ \mathcal{H}_\beta(\vec{Z}) = \frac{\hbar\omega}{e^{\beta\hbar\omega} - 1} \qquad \cdots \textbf{Exact}$$

$\cdots$ **Larger Fluctuations + Intrinsic Distortion = Exact**

• Fermions in a Harmonic Oscillator

(A.O. and J.Randrup, NPA 565('93),474.)



Even with AntiSymm.,

$E^* = T = 1/\beta$

without σ_E^2 **Effects**

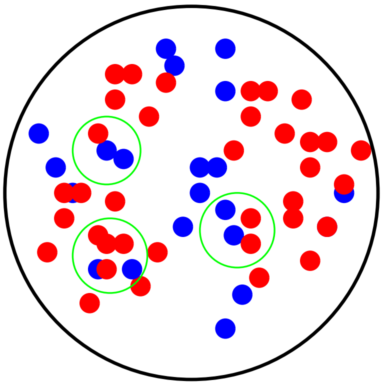
$\Downarrow$

Improved by H.A.

incl. A**-dep.**

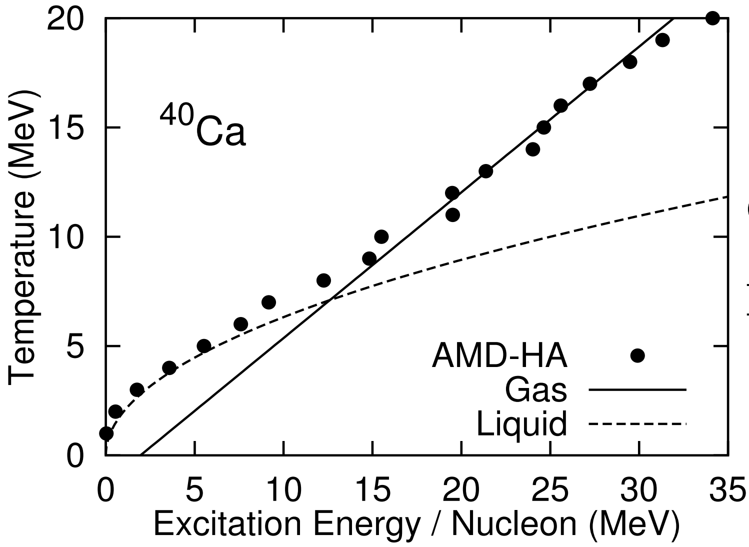
Statistical Properties of Nuclei

(A.O. and J.Randrup, PRL 75('95),596;AOP 253('97),279;
A.O. et al., Proc. NN97, NPA, in press.)



- ⋆ **Equilibrium in a Sphere** $R = r_0 A^{1/3}$ ($r_0 = 2.0$ **fm**)
- ⋆ **AMD w.f. and** $\mathcal{H}$ **(Volkov)**
- ⋆ **Harmonic Approx.**
- ⋆ **Metropolis Sampling**

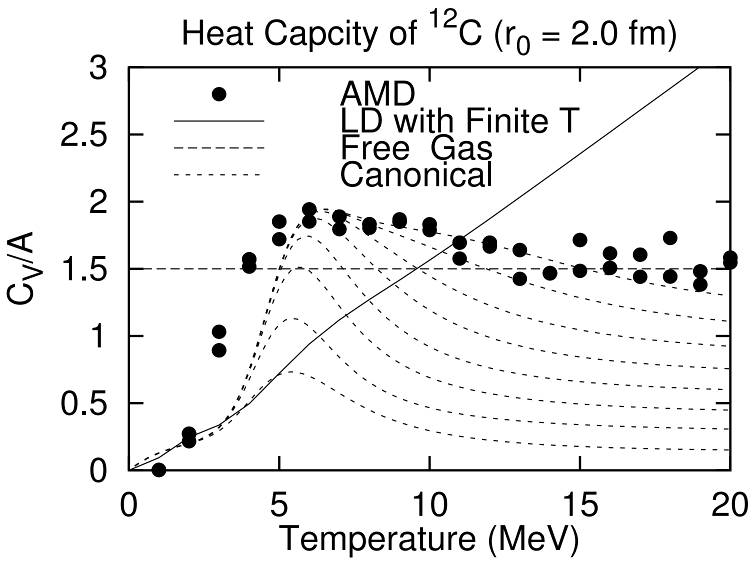
• Caloric Curve



G: $T = \frac{2}{3}(E/A - 2)$ **MeV**

L: $T = 2\sqrt{E/A}$ **MeV**

• Heat Capacity



Multifragmentation ?
Canonical
→ upto 9-body

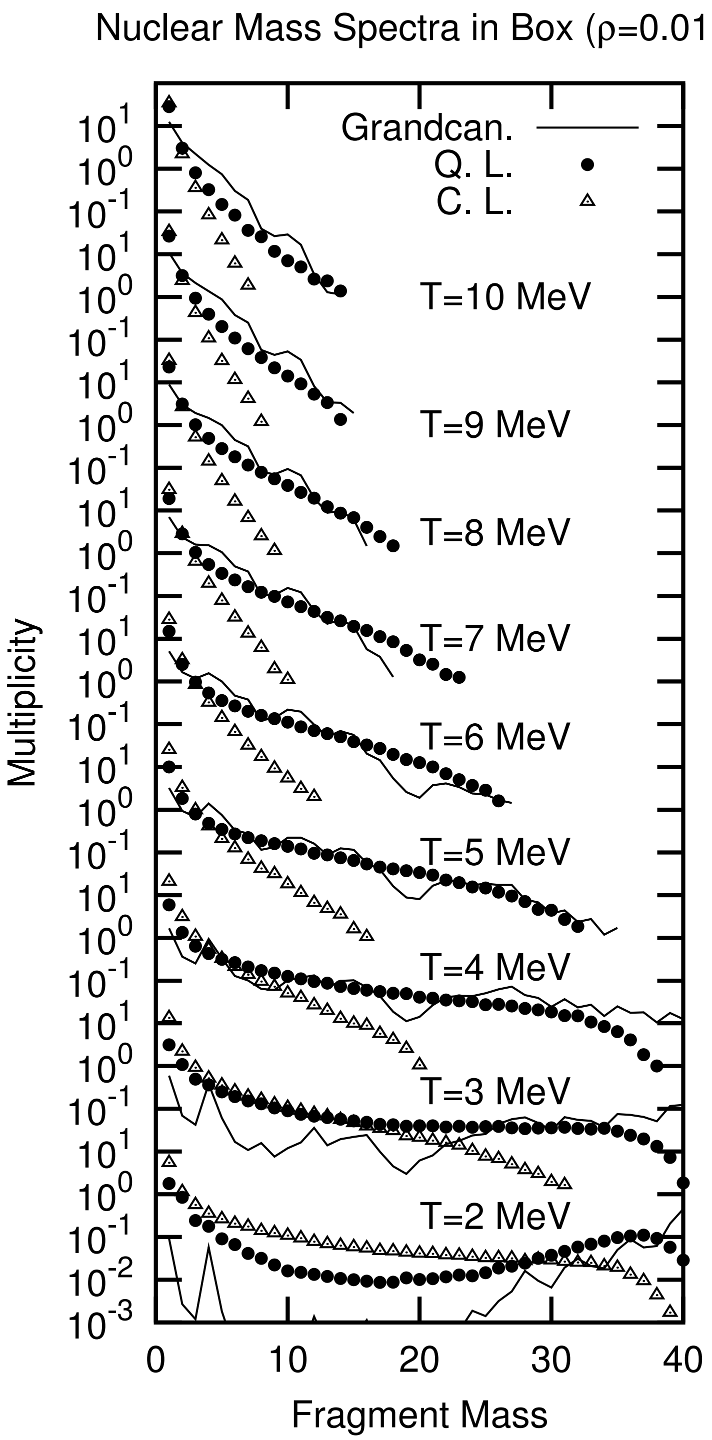
Thermal Fragmentation of Nuclei

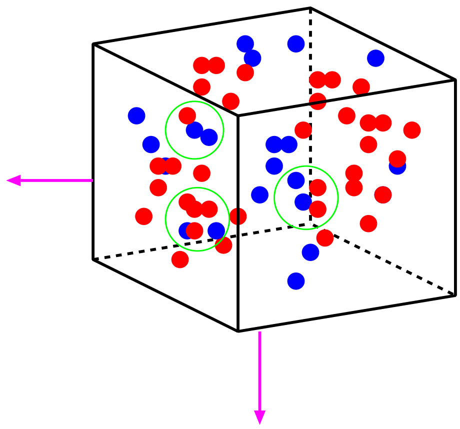
(A.O. and J. Randrup, PL B394('97), 260)

⋆ **Equilibrium in a Box with Periodic B.C.**

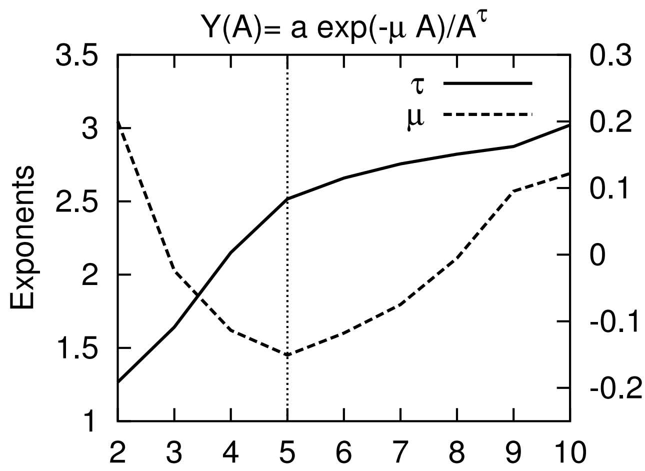
⋆ **Time-Average by using QMD (Gogny) +Q.L.**

- **Mass Dist. at Fixed T**





- **Critical Properties**



Quantal Langevin Equation at Given E

- **Equilibrium Distribution $\cdots$ Q. Microcan.**

$$\phi_{\rm eq}(\vec{Z}) \equiv \exp(-\mathcal{F}(\vec{Z})) = \langle \vec{Z}|\delta(E-\hat{H})|\vec{Z}\rangle \neq \delta(E-\mathcal{H})$$

- **Fokker-Planck Equation:** $\phi_{\rm eq}$ = **Static Solution**

$$\frac{D\phi(\vec{Z};t)}{Dt} = \frac{\partial}{\partial \mathbf{q}} \cdot \left(\mathbf{M} \cdot \frac{\partial \mathcal{F}}{\partial \mathbf{q}} + \mathbf{M} \cdot \frac{\partial}{\partial \mathbf{q}} \right) \phi \ , \qquad \{\mathbf{q}\} = \{\mathbf{r},\mathbf{p}\}$$

$$\mathbf{M} = \mathbf{g}\cdot\mathbf{g}: \quad \text{Mobility Tensor}$$

- **Equivalent Langevin Equation at Fixed E**

$$\dot{\mathbf{p}} = \mathbf{f} - \beta_{\mathcal{H}}\mathbf{M}^p\cdot(\mathbf{v}-\mathbf{u}) + \mathbf{g}^p\cdot\boldsymbol{\zeta}^p \ ,$$

$$\dot{\mathbf{r}} = \mathbf{v} + \beta_{\mathcal{H}}\mathbf{M}^r\cdot\mathbf{f} + \mathbf{g}^r\cdot\boldsymbol{\zeta}^r \ ,$$

Drift **Diffusion**

$\star$ **Effective Inverse Temperature:**

$$\beta_{\mathcal{H}} \equiv \frac{\partial \mathcal{F}}{\partial \mathcal{H}} \approx \frac{\mathcal{H}-E}{\sigma_E^2} \qquad (\text{Harm. Approx. to } \langle \vec{Z}|\delta(E-\hat{H})|\vec{Z}\rangle)$$

$\cdots$ **Drift Term Acts as a Energy Recovering Force**

$\star$ $\mathbf{u}$ **: Local Collective Velocity $\approx$ Classical**

$\star$ $\prec \zeta_i(t)\zeta_j(t') \succ = 2\delta(t-t')$ **: White Noise**

- **Intrinsic Distortion of Wave Packets** $\cdots\sqrt{\delta(E-\hat{H})}|\vec{Z}\rangle$

Canonical-type Distortion is used.

$$\frac{d\mathbf{p}}{d\tau} = -\frac{2\Delta p^2}{\hbar}(\mathbf{v}-\mathbf{u}) \ , \qquad \frac{d\mathbf{r}}{d\tau} = \frac{2\Delta r^2}{\hbar}\mathbf{f}$$

until $\mathcal{H}=E$ before making an observation

Soluble Example

• Distinguishable Particles in a Harmonic Oscillator

(A.O. and J.Randrup, AOP 253('97),279.)

⋆ **Number of States = Phase Volume**

$$\Omega(E) = \frac{(E+N-1)!}{E!\ (N-1)!} = \frac{\Gamma(E+N)}{\Gamma(E+1)\Gamma(N)}$$

$$\frac{1}{T} \equiv \frac{\partial}{\partial E}\log(\Omega(E))$$

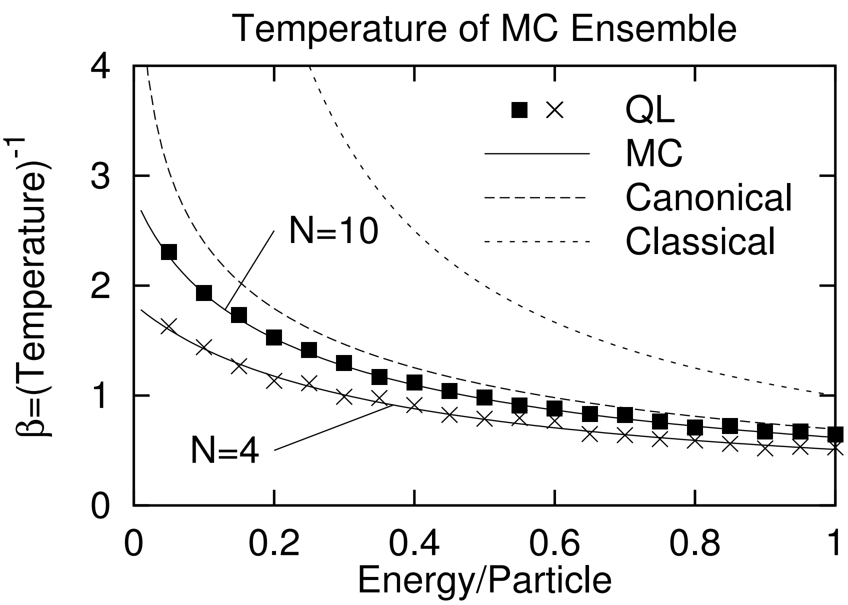
⋆ **Harm. Approx. to** $\langle\vec{Z}|\delta(E-\hat{H})|\vec{Z}\rangle$

$$\rho_E(\vec{Z}) \equiv \langle\vec{Z}|\delta(E-\hat{H})|\vec{Z}\rangle \approx e^{-\mathcal{H}}\frac{\mathcal{H}^E}{\Gamma(E+1)}$$

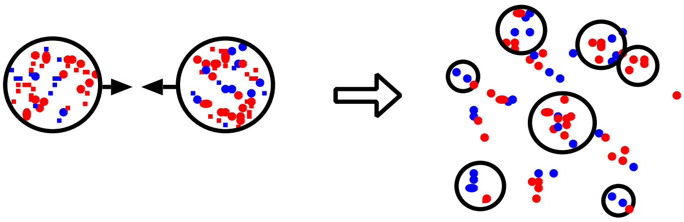
⋆ **Quantal Langevin Model**

$$\frac{1}{T} \equiv \frac{1}{\Omega(E)}\int d\Gamma \rho_E(\vec{Z})\ \beta_E(\vec{Z}) \approx \prec \beta_E(\vec{Z}) \succ_{TimeAverage}$$

$$\beta_E(\vec{Z}) \equiv \frac{\partial\log(\rho_E(\vec{Z}))}{\partial E} \qquad > \beta_{\mathcal{H}}$$

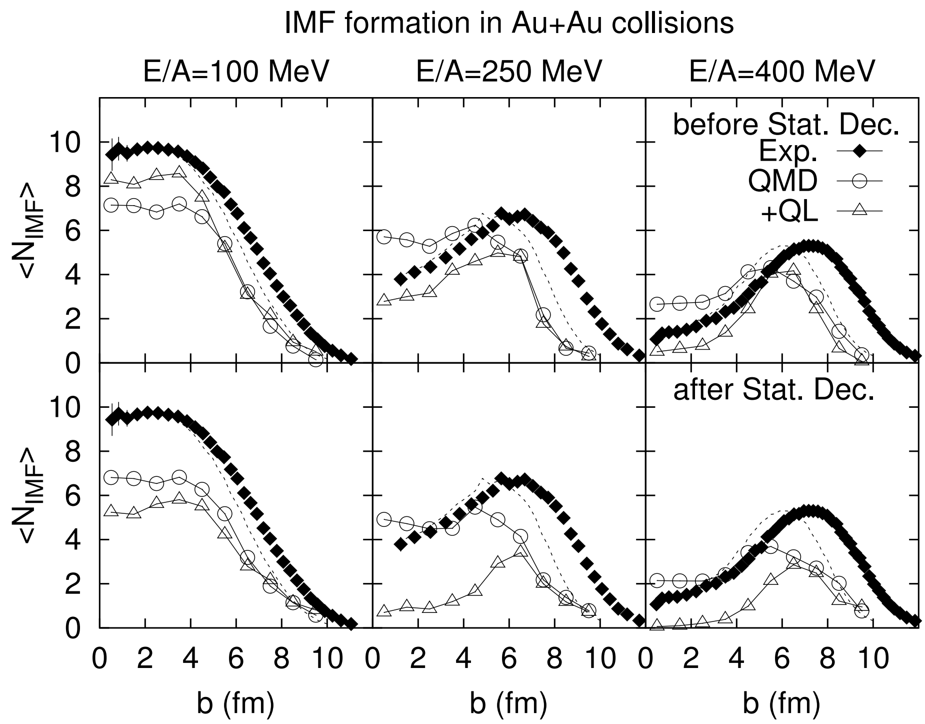


Multifragmentation from Au+Au (I)
– IMF Multiplicity



• MSU/ALADIN Data — E_{inc} and b-dependence

M.B.Tsang et al., PRL 71 ('93), 1502.
A.O. and J. Randrup, PL B394('97), 260.
T.Maruyama et al. PTP 98('97),87, Barz et al. PLB 359('96),261.



⋆ Exp.: b_{imp} sort = PM, $3 \leq Z_{imf} \leq 30$

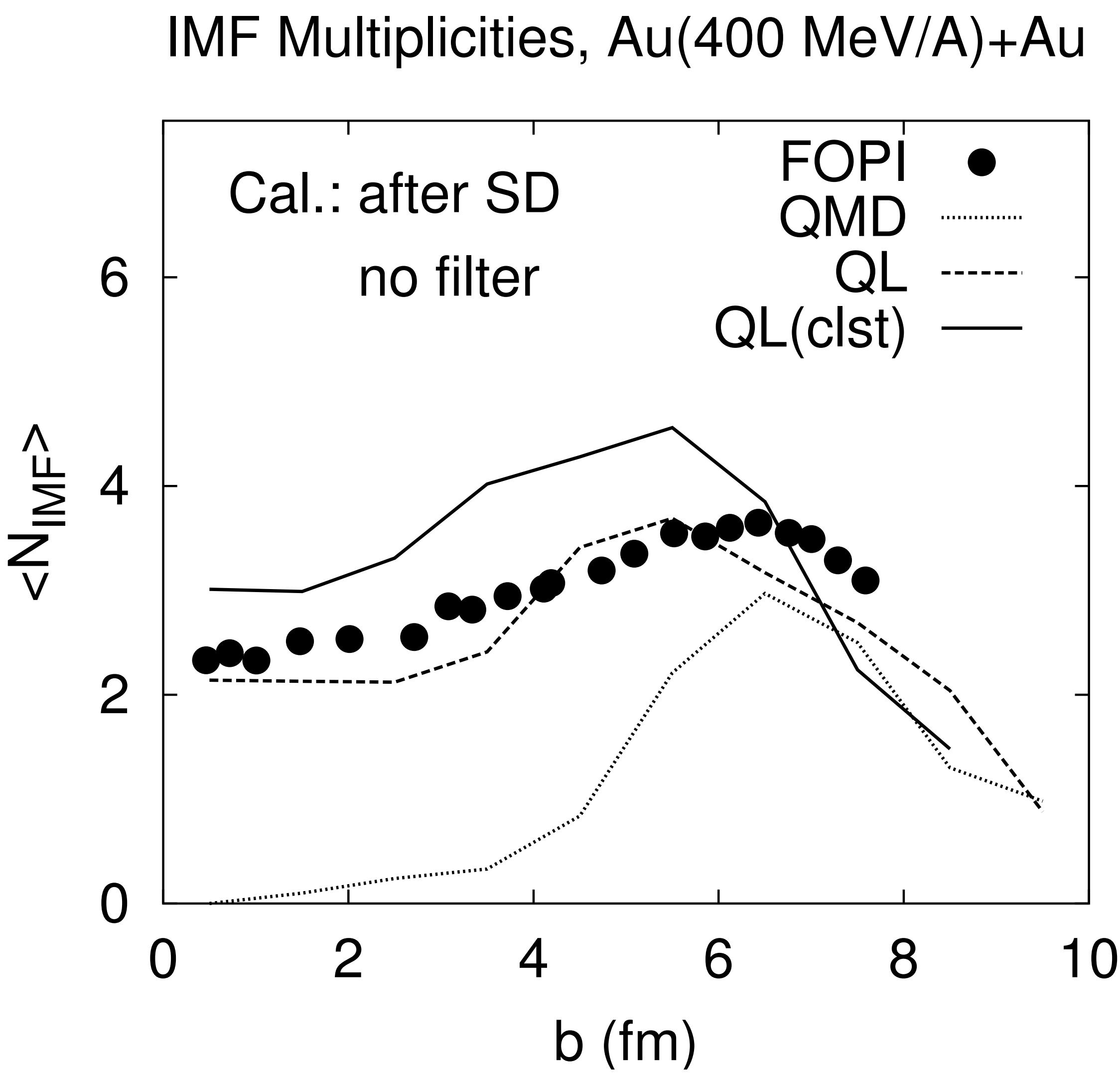
⋆ Calc.: QMD, Gogny+Pauli, No Det. Eff. is incl.

→ Dynamically Produced Fragments are cool enough to Survive Statistical Decay in QMD-QL !

Multifragmentation from Au+Au (II) – Comparison with New Data

- **FOPI Data b-dependence at E_{inc}=400 MeV/A**

W. Reisdorf et al., NP A612 ('97), 493



⋆ **Exp:** b_{imp} **sort = ERAT,** $3 \leq Z_{imf} \leq 15$

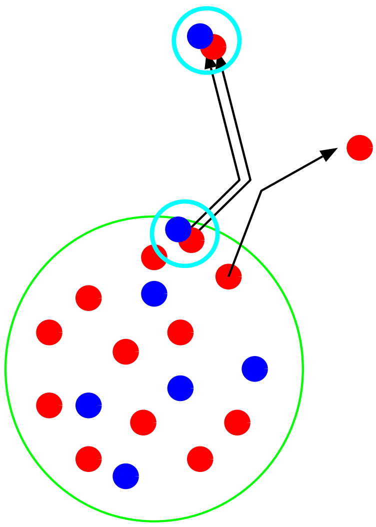
⋆ **Calc.: QMD, Gogny+Pauli, No Det. Eff. is incl.**

⋆ **QL(clst): with Cluster-Cluster coll.**

→ **Flatter** b **dependence with ERAT sort**

• Cluster-Cluster Scattering

Danielewicz and Bertsch, NP A533 ('91), 712: (d, t, h)
Ono et al., PRC 47 ('91), 2652: (Nα)
Y. Nara et al. PL B346 ('95), 217: ($K^-\alpha \to \pi {}^4_\Lambda$H)

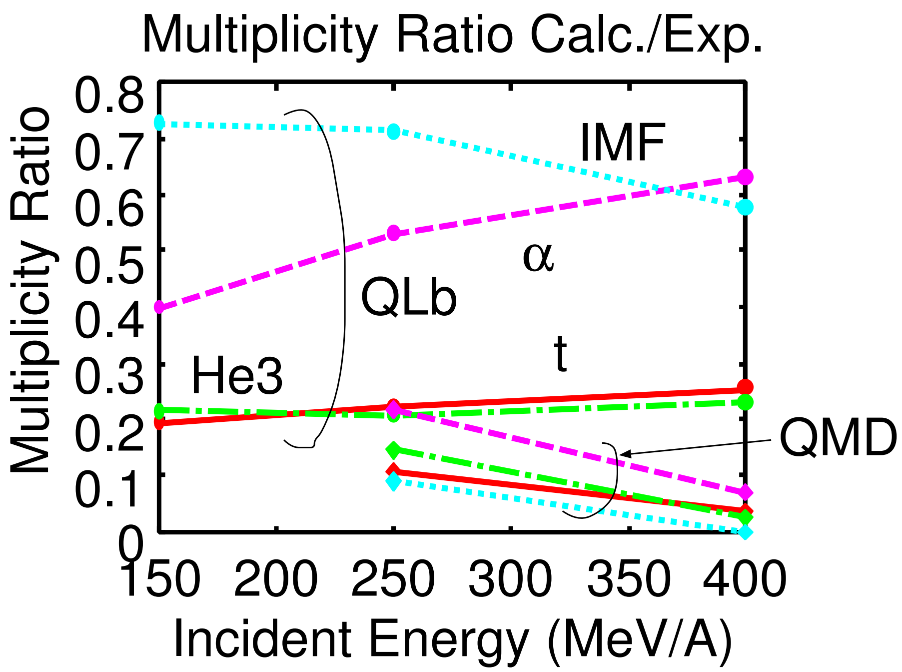


Cluster-Cluster (or N) Scattering

- **Black Disc Ang. Dist. &σ are assumed**
- **Seed of IMFs**
- **Only 0s clusters are considered**

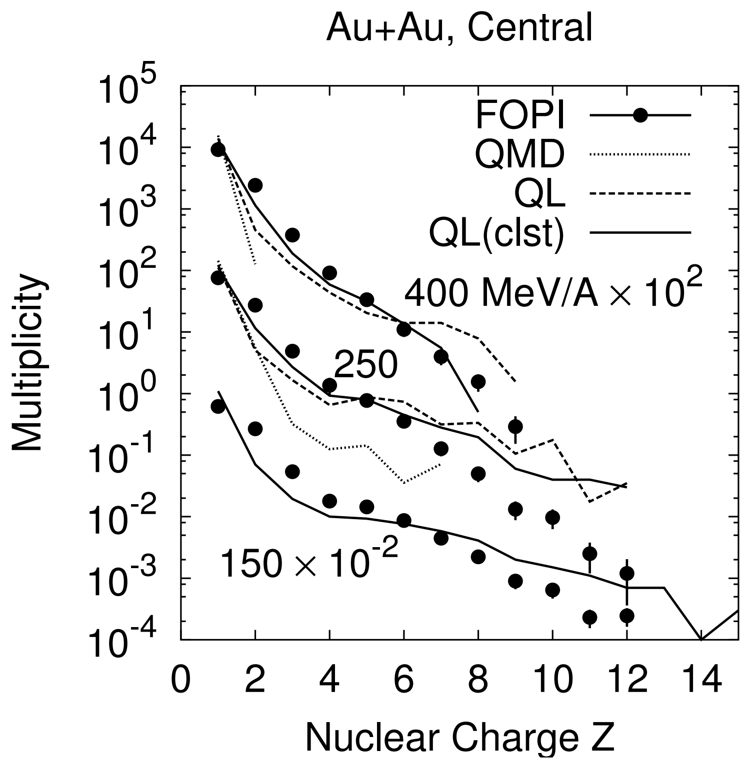
• Light Charged Particle Multiplicity

· · · **Large underestimate for A=3**

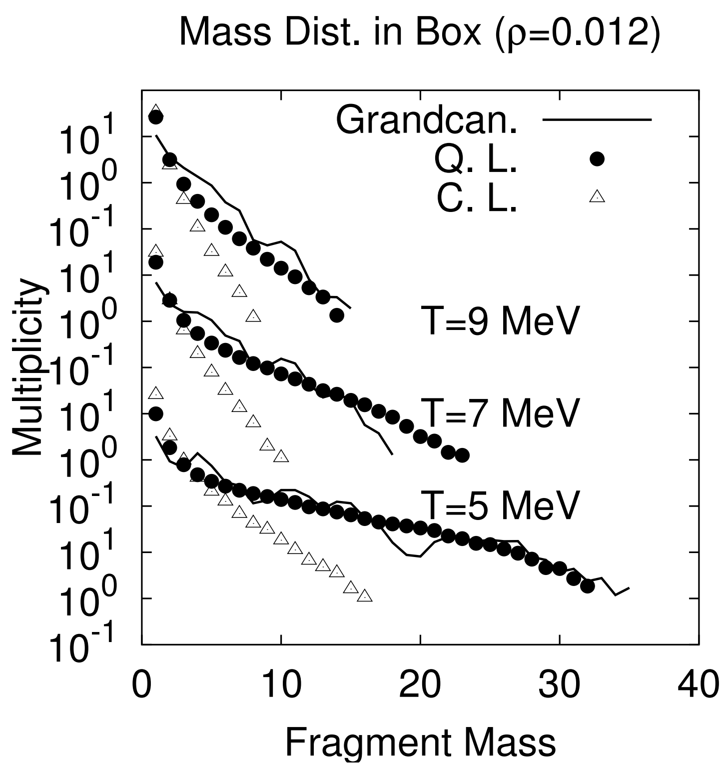


Charge and Mass Distribution

• Heavy-Ion Collision: Non-Equilibrium



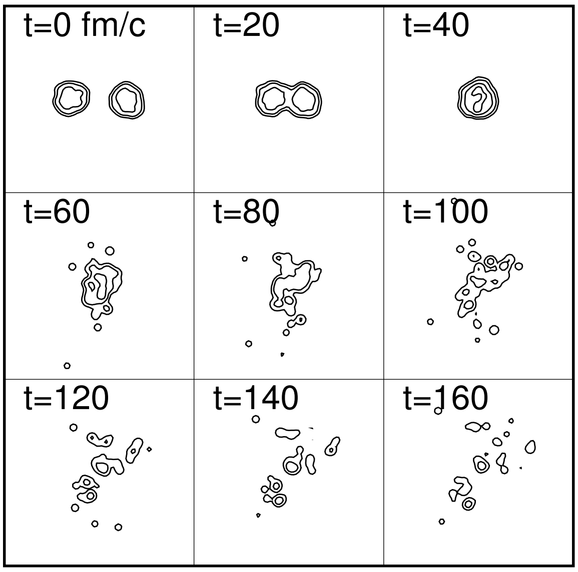
• Statistical Sampling: Equilibrium



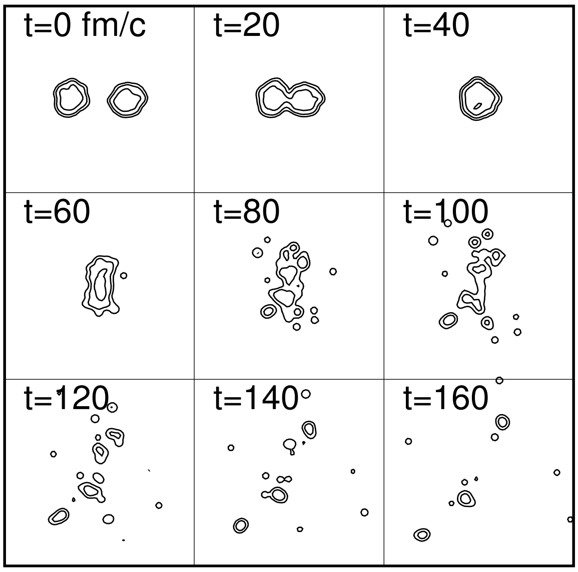
→ **Are fragments produced after equilibration ?**

Density Evolution in Au+Au Collision

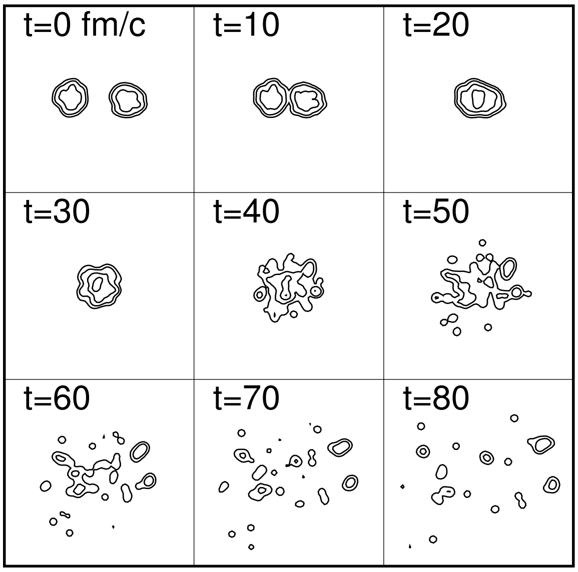
Au(150 MeV/A)+Au, QMD



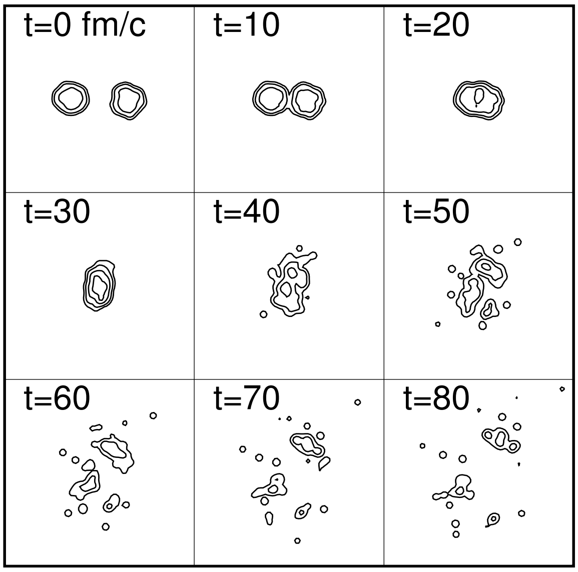
Au(150 MeV/A)+Au, QL



Au(400 MeV/A)+Au, QMD



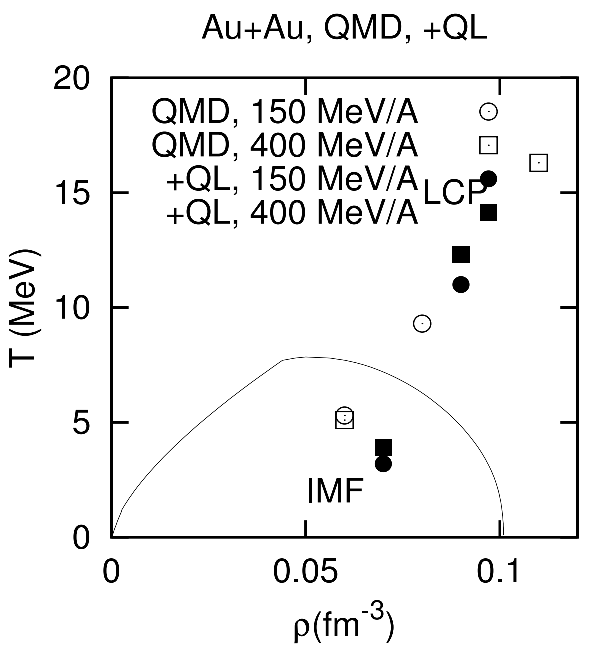
Au(400 MeV/A)+Au, QL



Density and Temperature

at IMF formation

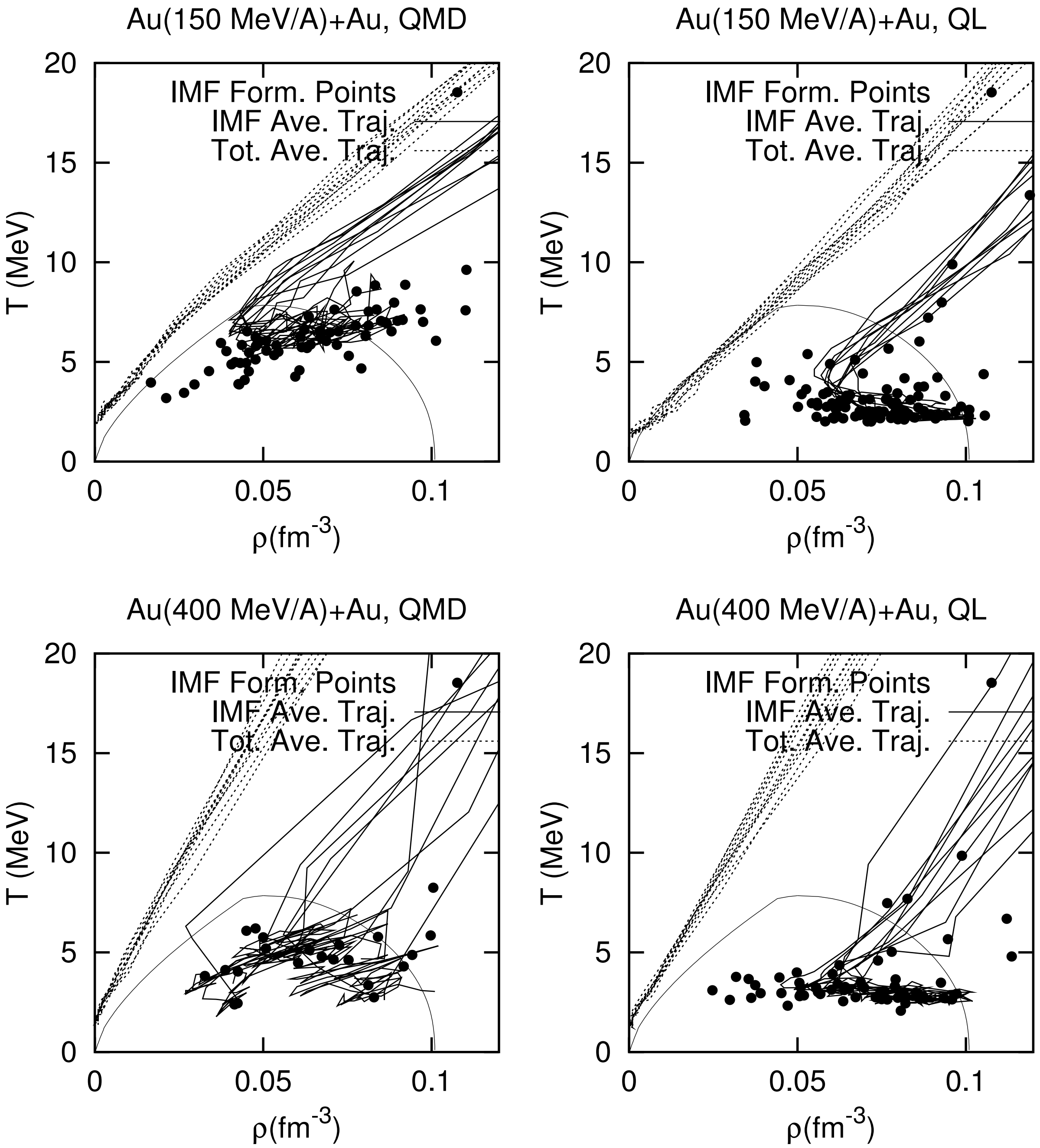
- **Average ρ-T at Fragment Formation**



E_{inc}			$\prec \rho \succ$ (fm^{-3})	$\prec T \succ$ (MeV)	$\prec T' \succ$ (MeV)
150 MeV/A	QMD	LCP	0.08	9.3	5.8
		IMF	0.06	5.3	1.9
	QL	LCP	0.09	11.0	7.4
		IMF	0.07	3.2	0.6
400 MeV/A	QMD	LCP	0.11	16.3	12.4
		IMF	0.06	5.1	1.7
	QL	LCP	0.09	12.3	8.7
		IMF	0.07	3.9	1.0

In Average, IMF's are seems to be made in the spinodal region...

ρ-T Evolution in Au+Au Collision
– Time-Dependence

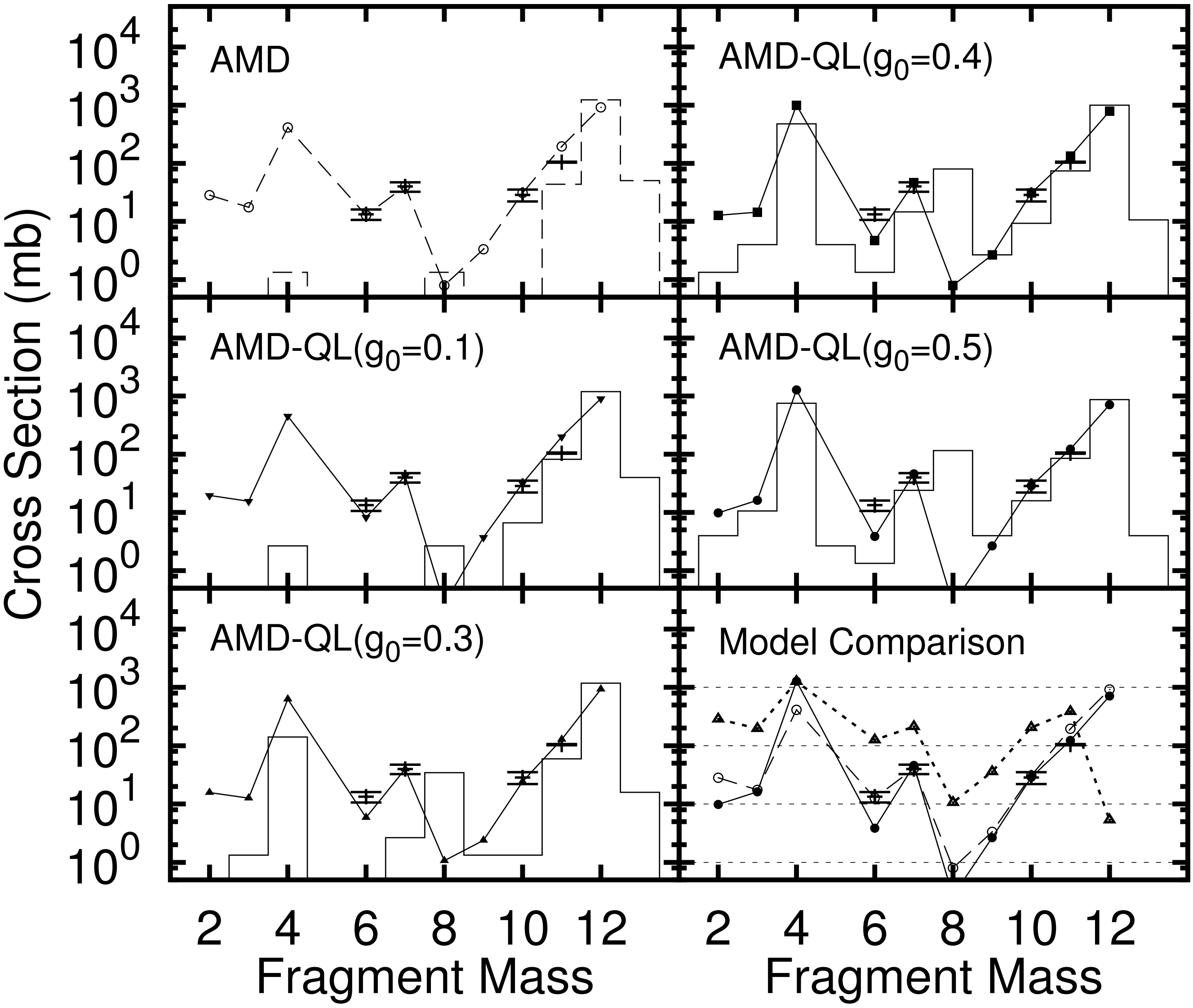


⋆ **IMF's are mainly formed**
during re-compression stage
in Unstable Region of Nuclear Matter
if Quantum Fluctuation is incorporated.

Light Ion Induced Reaction — AMD-QL

Hirata, Nara, Ohnishi, Harada, Randrup, submitted

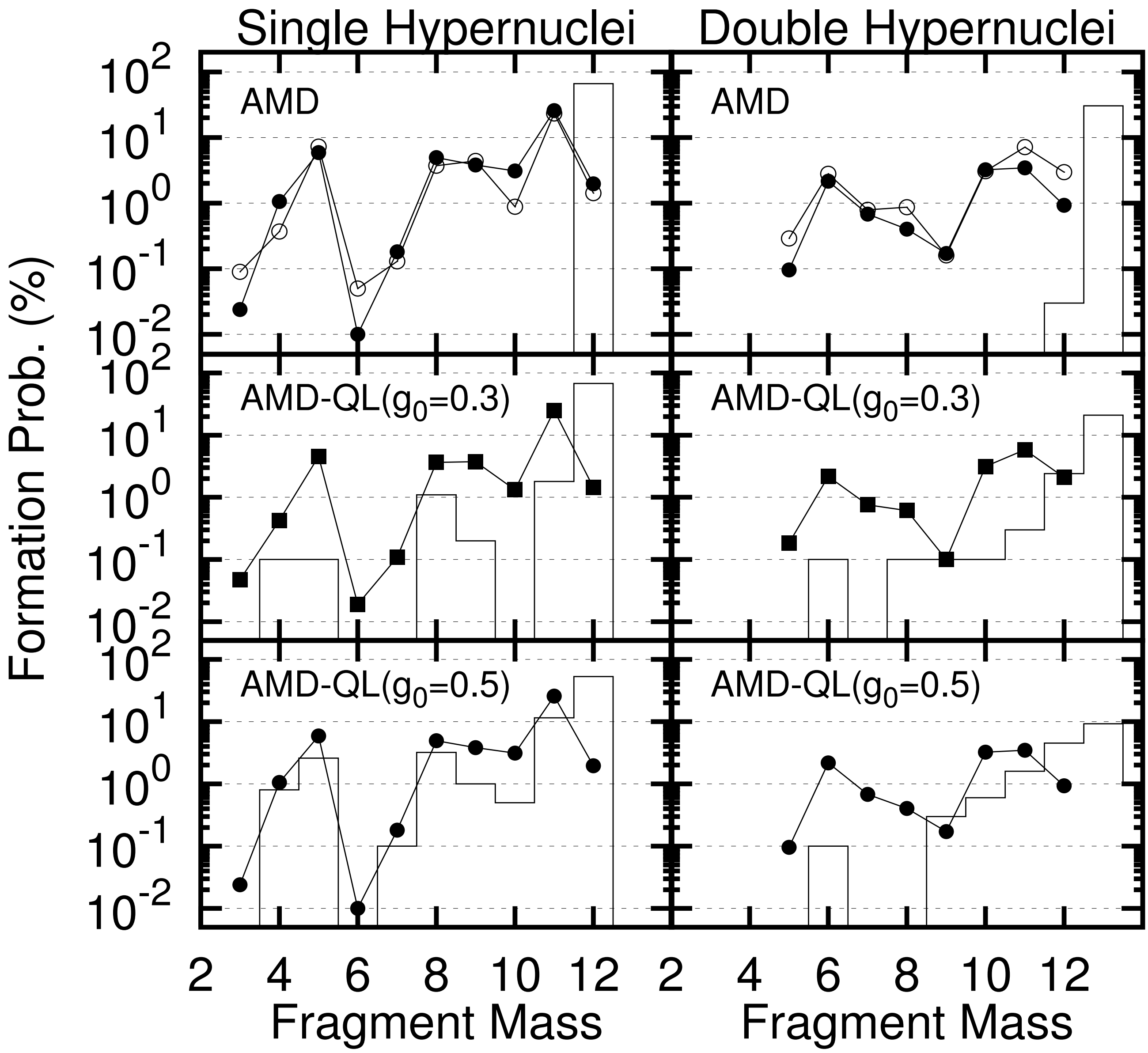
- **Proton Induced Reaction at 45 MeV**



⋆ **Sufficient Fluctuation Strength**

→ **Fragments are produced at low excitation DYNAMICALLY**

• Ξ^- Absorption at Rest



⋆ Fluctuation Effects can be found even in the Major Channels

SUMMARY & OUTLOOK

- **Quantal Langevin Model**
  - ⋆ Based on the energy fluctuations of wave packets, which are not energy eigen states.
  - ⋆ Dynamical Relaxation to Quantum Stat. Equil.
  - ⋆ Larger Fluctuations (Quantum & Statistical) +Intrinsic Distortion (Smaller Excitation Energy) → Enhancement of Stable Dynamical Fragments

- **Achievements**

  a. Caloric Curve (Liquid → Gas)

  b. Thermal Fragmentation (Critical behavior)

  c. Dynamical Fragmentation in Light-Ion Induced Reactions (Proton-Induced, Ξ^- Absorption)

  d. Dynamical Fragmentation in Heavy-Ion Collisions (Au+Au, 150 $\sim$ 400 MeV/A)

- **ρ-T at Fragment Formation**
  - ⋆ LCP $\cdots$ all the region of ρ-T
  - ⋆ IMF $\cdots$ mainly formed during the re-compression stage in Unstable Region of Nuclear Matter
    Exception: 400 MeV/A w.o. Quantum Fluctuation

- **Remaining Problems**
  - ⋆ Mobility Tensor M cannot be determined only from stat. requirements.
  - ⋆ Light Charged Particle (LCP) formation ($d, t, {}^3\mathrm{He}, \alpha$)
    Underesitmate by a factor of 4 $\sim$ 10 for $A = 3$
    → Coalescence ?

July 17, 1999 @ TITech Workshop

Heavy-Ion Collisions at AGS Energies — Particle Production Mechanism and Baryon Flow —

A. Ohnishi Hokkaido Univ.

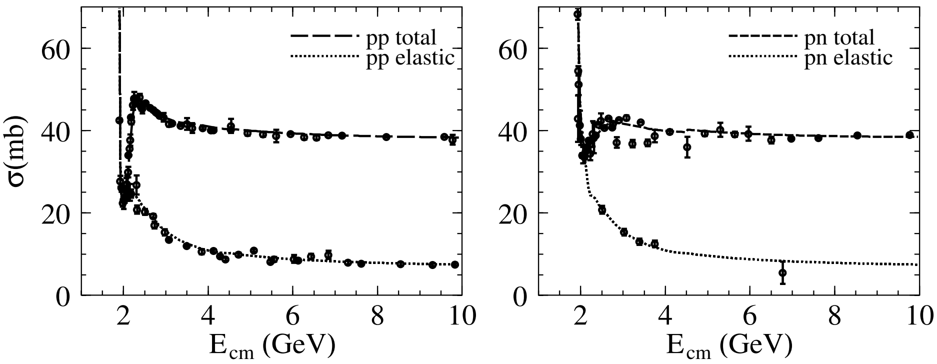
1. **$\Lambda\Lambda$ Interaction: How can we get it ?**
2. **$\Lambda\Lambda$ Inv. Mass Spec. $\rightarrow$ $\Lambda\Lambda$ Int.**
   - $\star$ **IntraNuclear Cascade model + Correlation**
   - $\star$ **Comparison with Nijmegen Models**
3. **Do Two Lambdas Bound ?**
   - $\star$ **Double-well Structure**
   - $\star$ **$\Lambda\Lambda$ Correlation at AGS, SPS, and RHIC**
4. **Summary**

Refs. of Ours

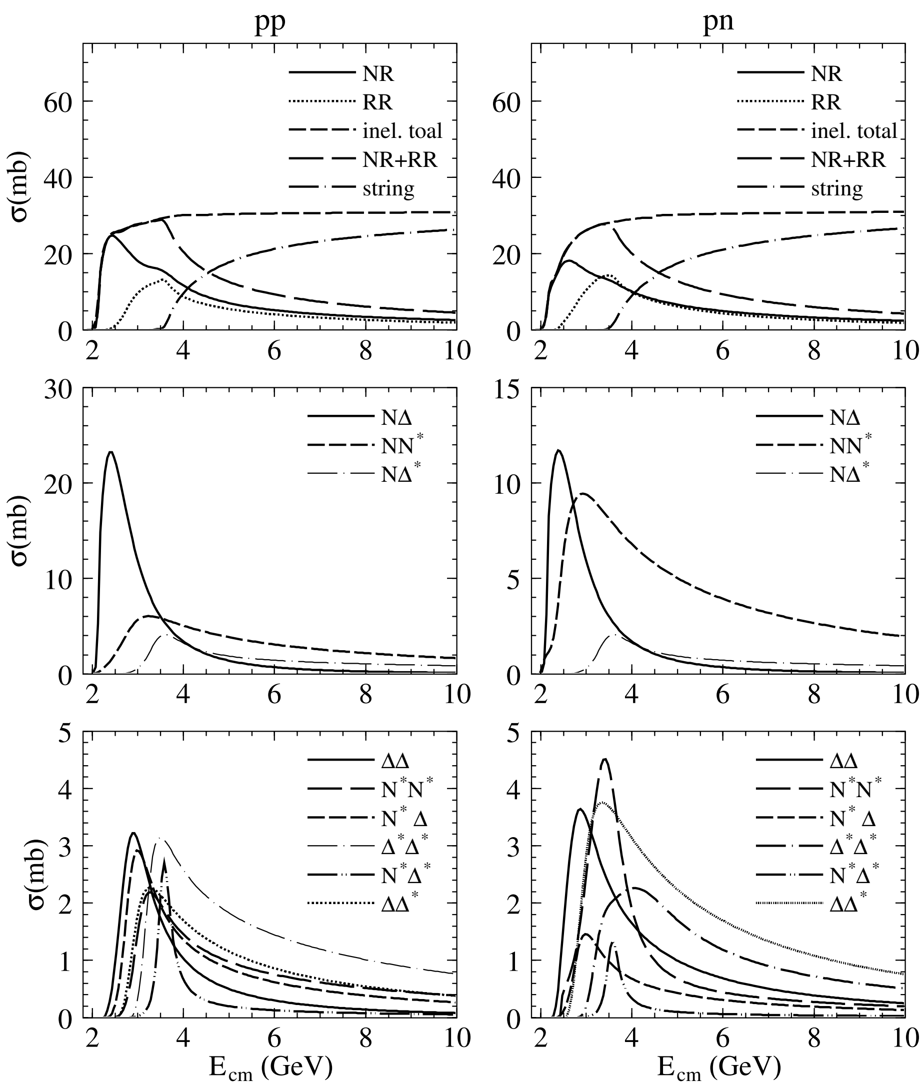
(K^-, K^+)	Nara, Ohnishi, Harada, Engel, NPA614 (97), 433
AA	Nara, NPA638 ('98), 555c; nucl-th/9802016
	Nara et al., to be submitted.
Corr. to nn Int.	Slaus, Akaishi, Tanaka, PRep. 173, ('89), 257.
$\Lambda\Lambda$ Int.	Ohnishi, Hirata, Nara, Shinmura, Akaishi, in preparation
	Hirata, Ohnishi, Ohtsuka, Nara, in preparation

Elementary Cross Sections

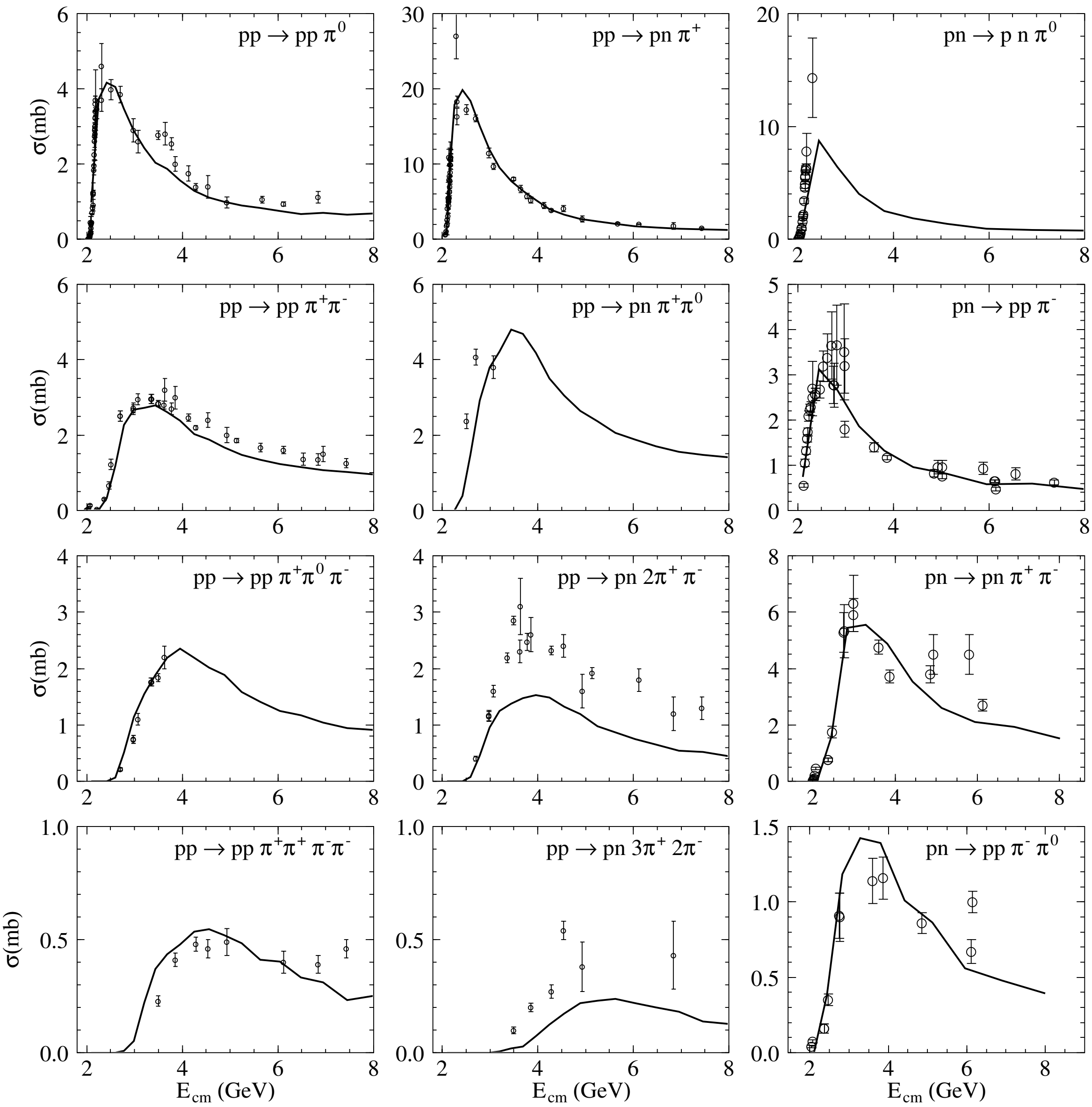
• NN Total Cross Section



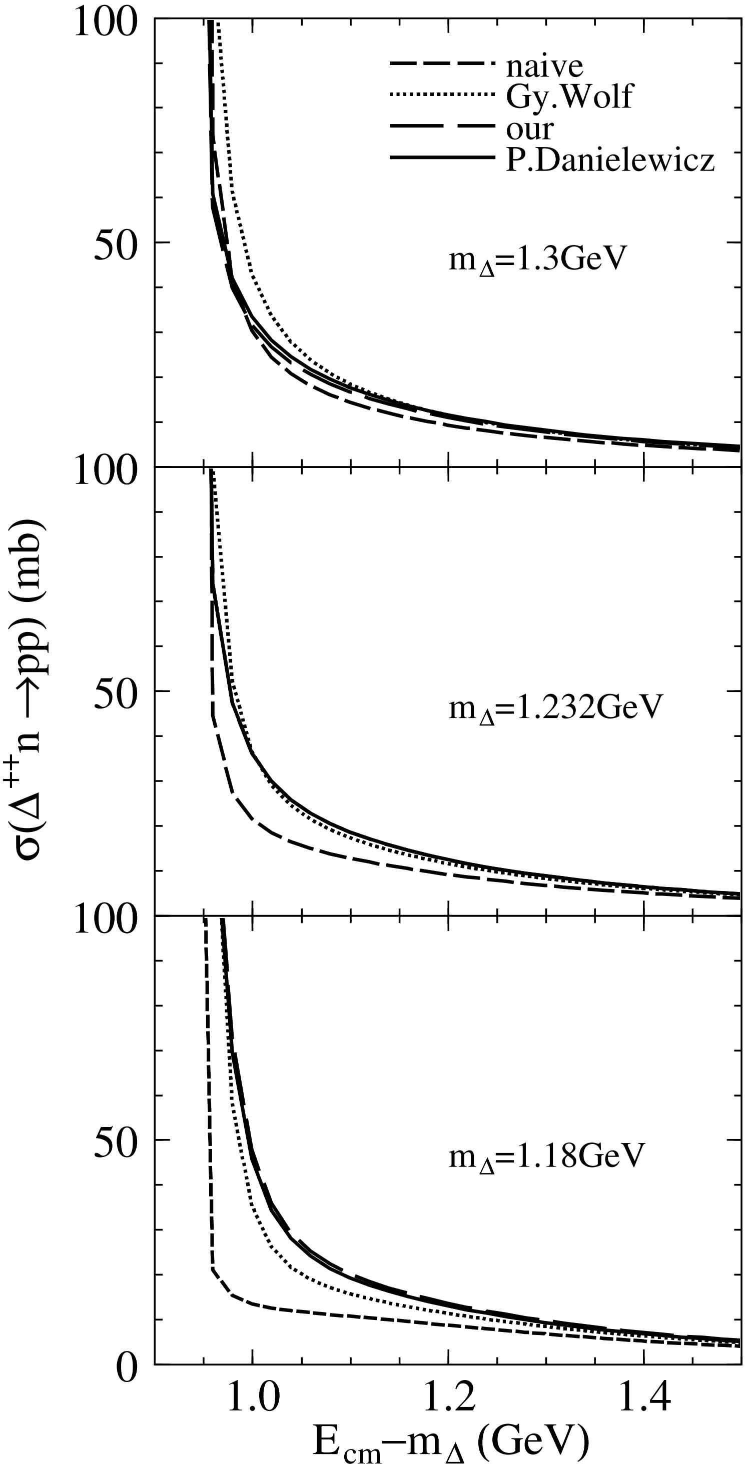
• Resonance/String Formation Cross Section



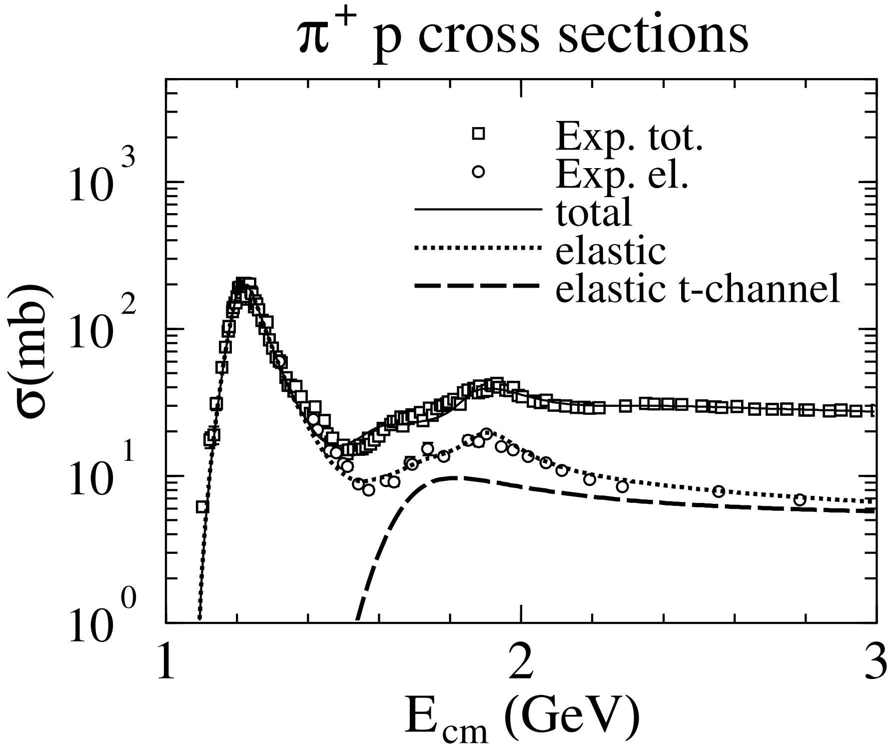
• Pion Production Exclusive Cross Sections

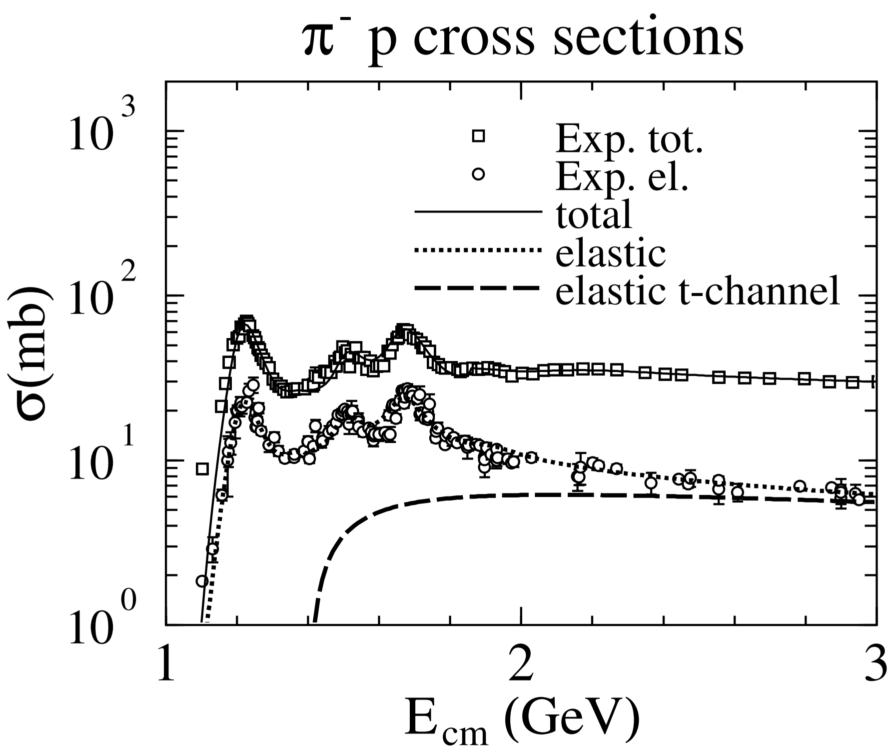


• Generalized Detailed Balance

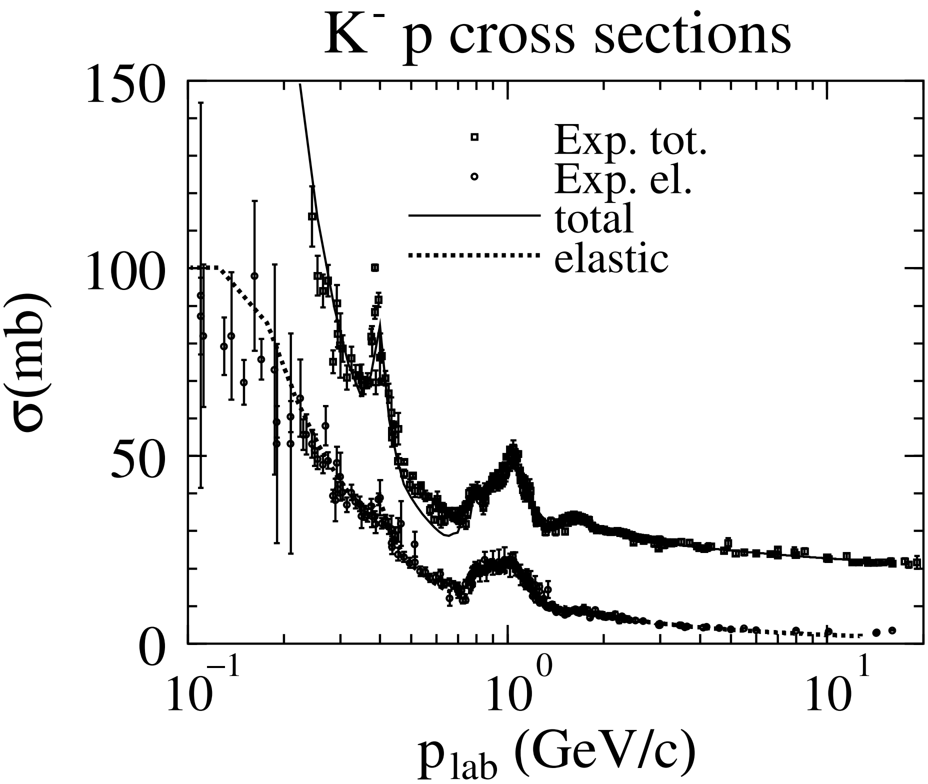


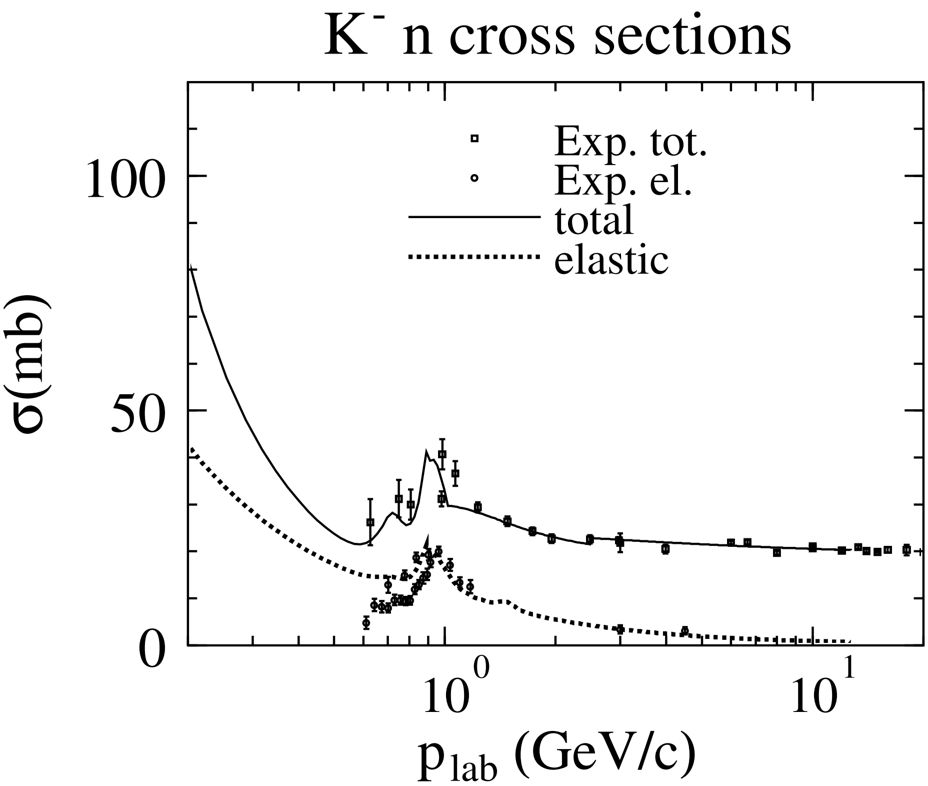
• Pion-Nucleon Cross Sections



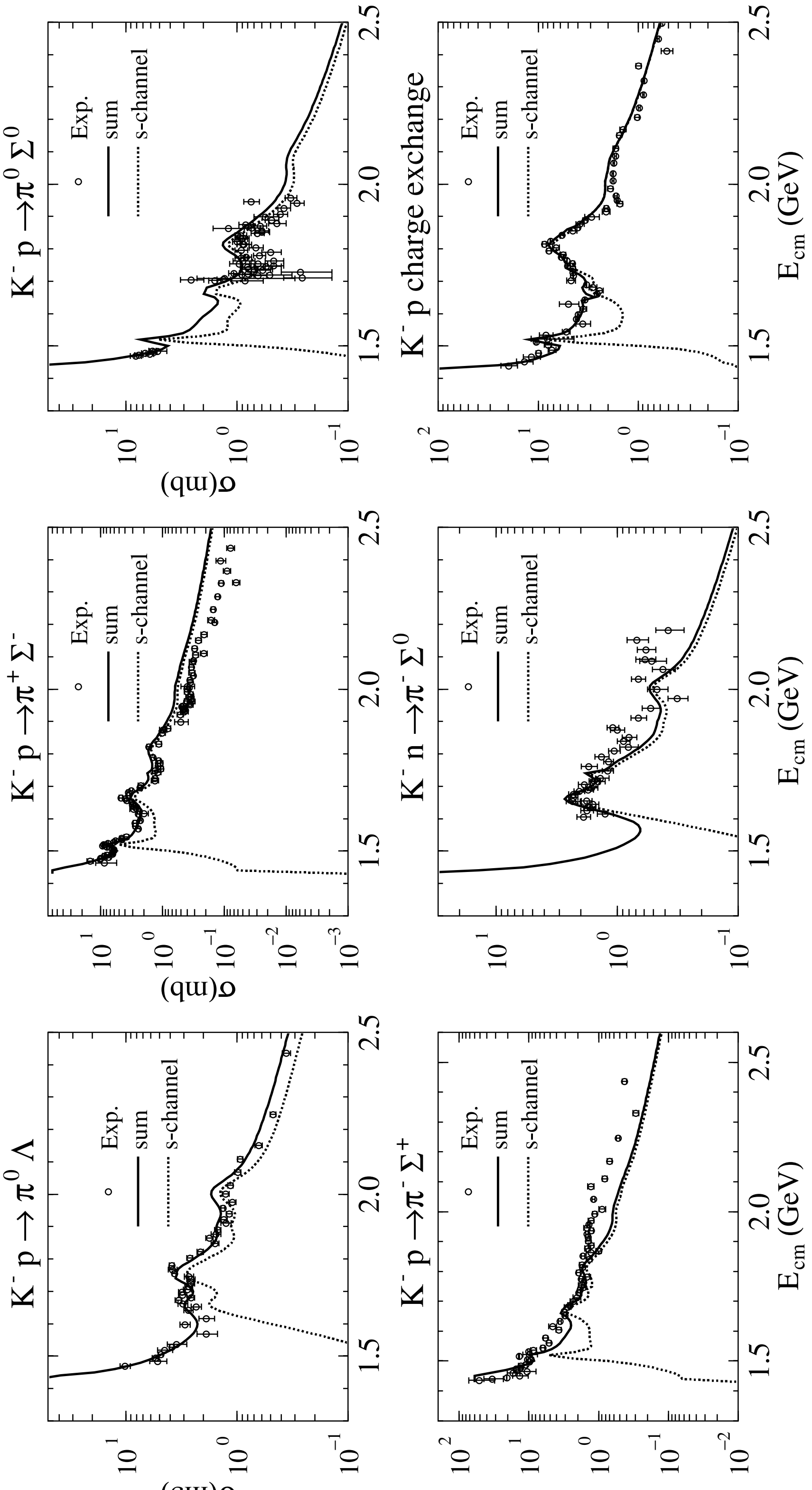


• $\bar{K}N$ Cross Sections

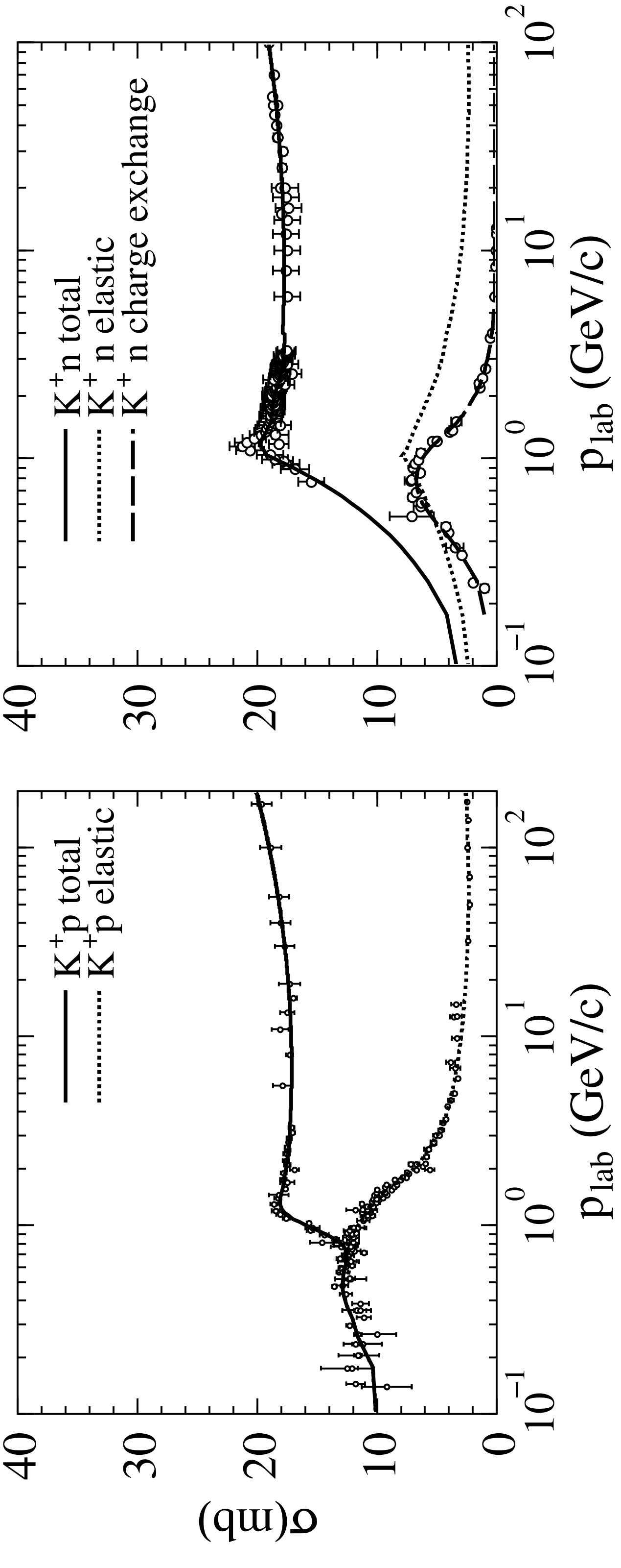




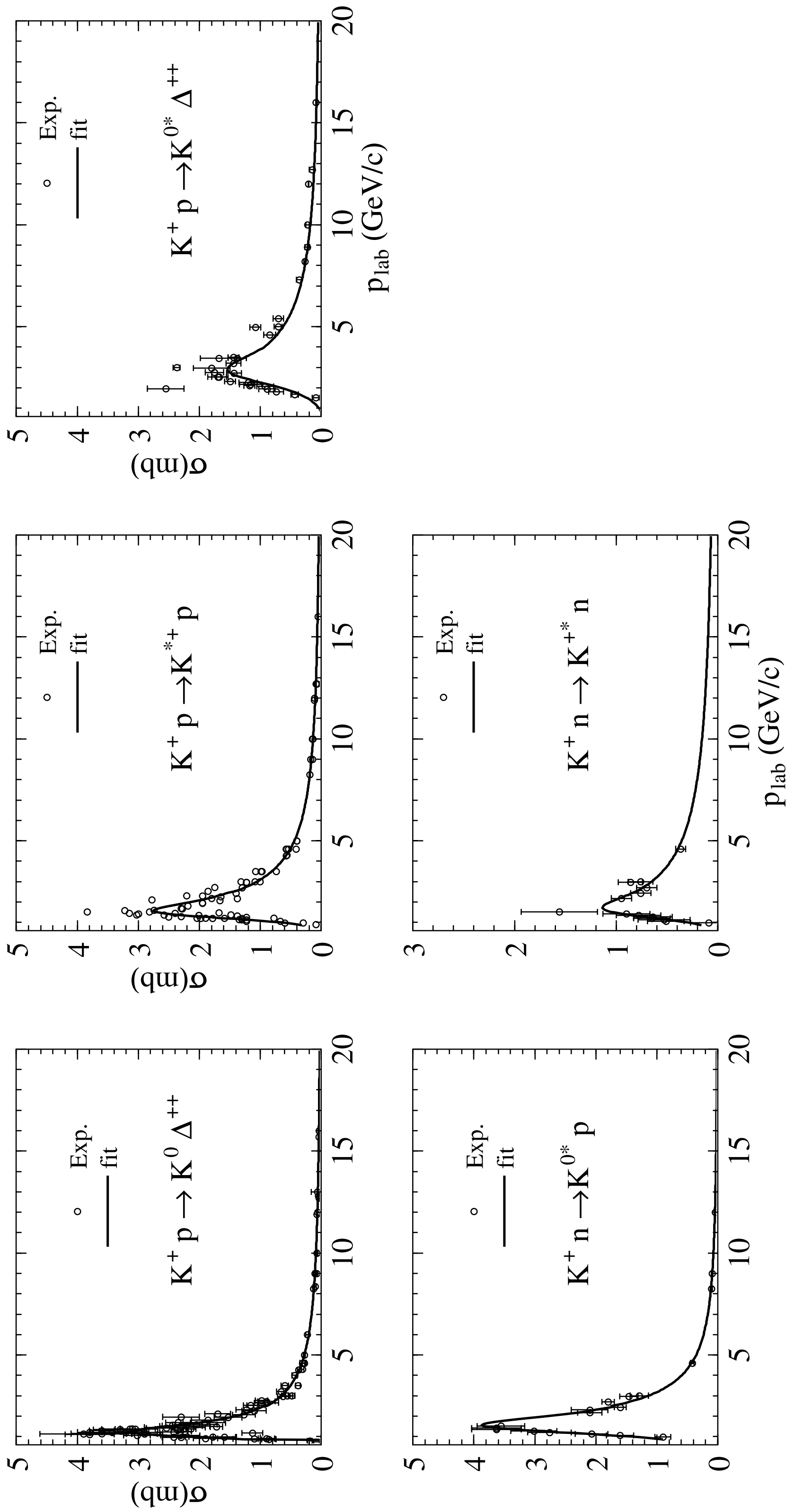
• $\bar{K}N$ Cross Sections (Hyperon Prod.)



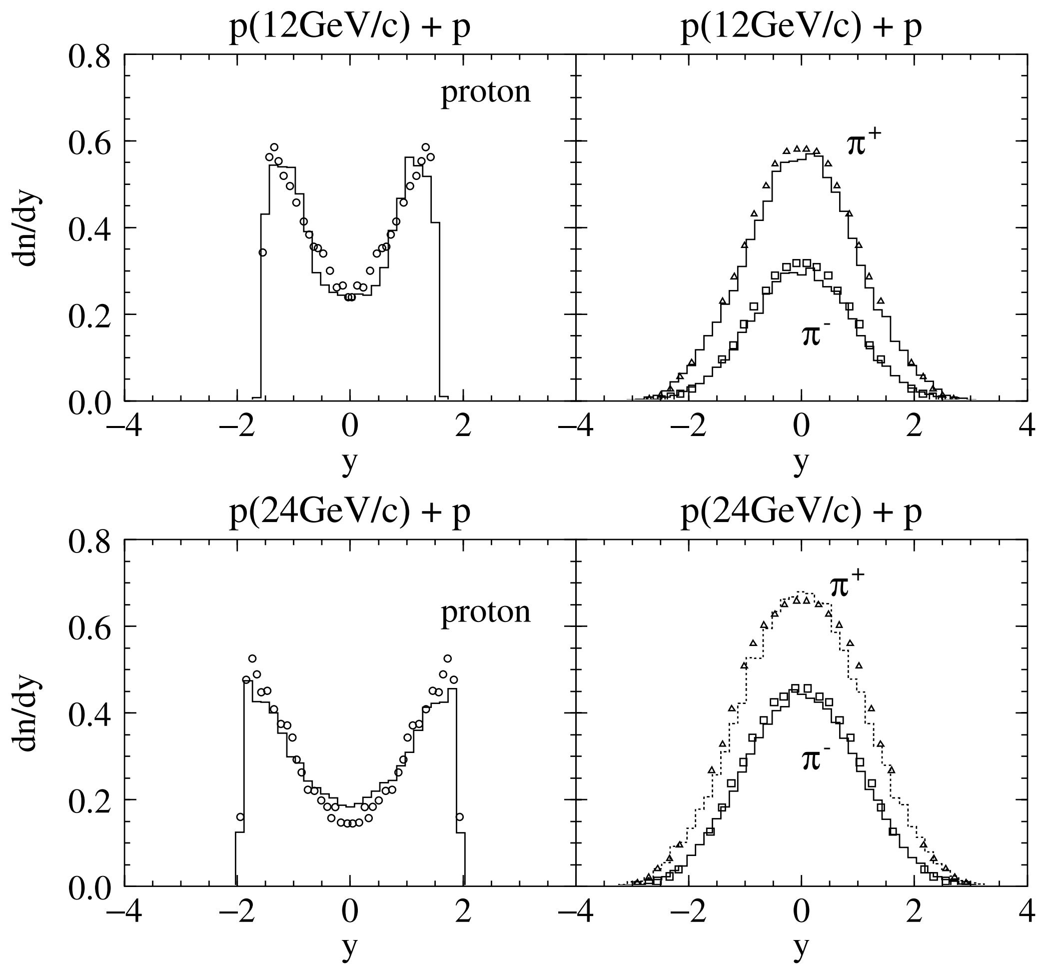
• KN Cross Sections

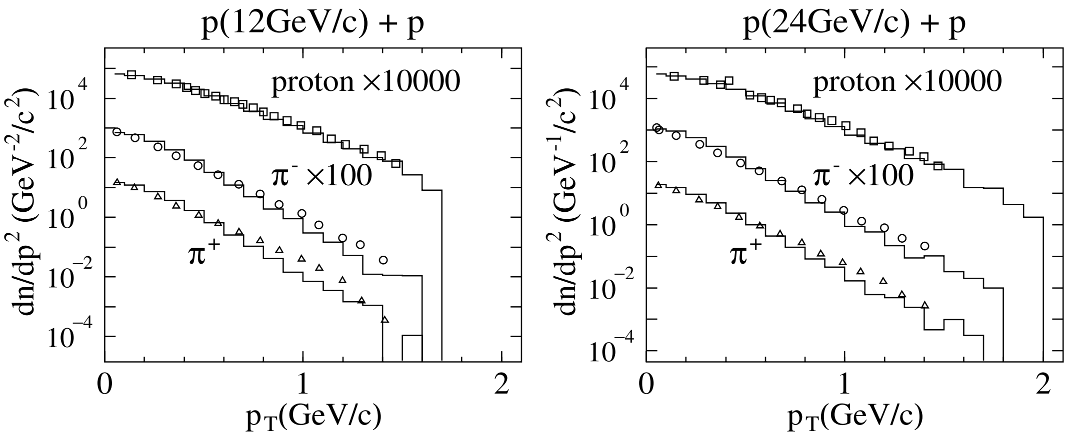


• KN Cross Sections (Res. Exc.)



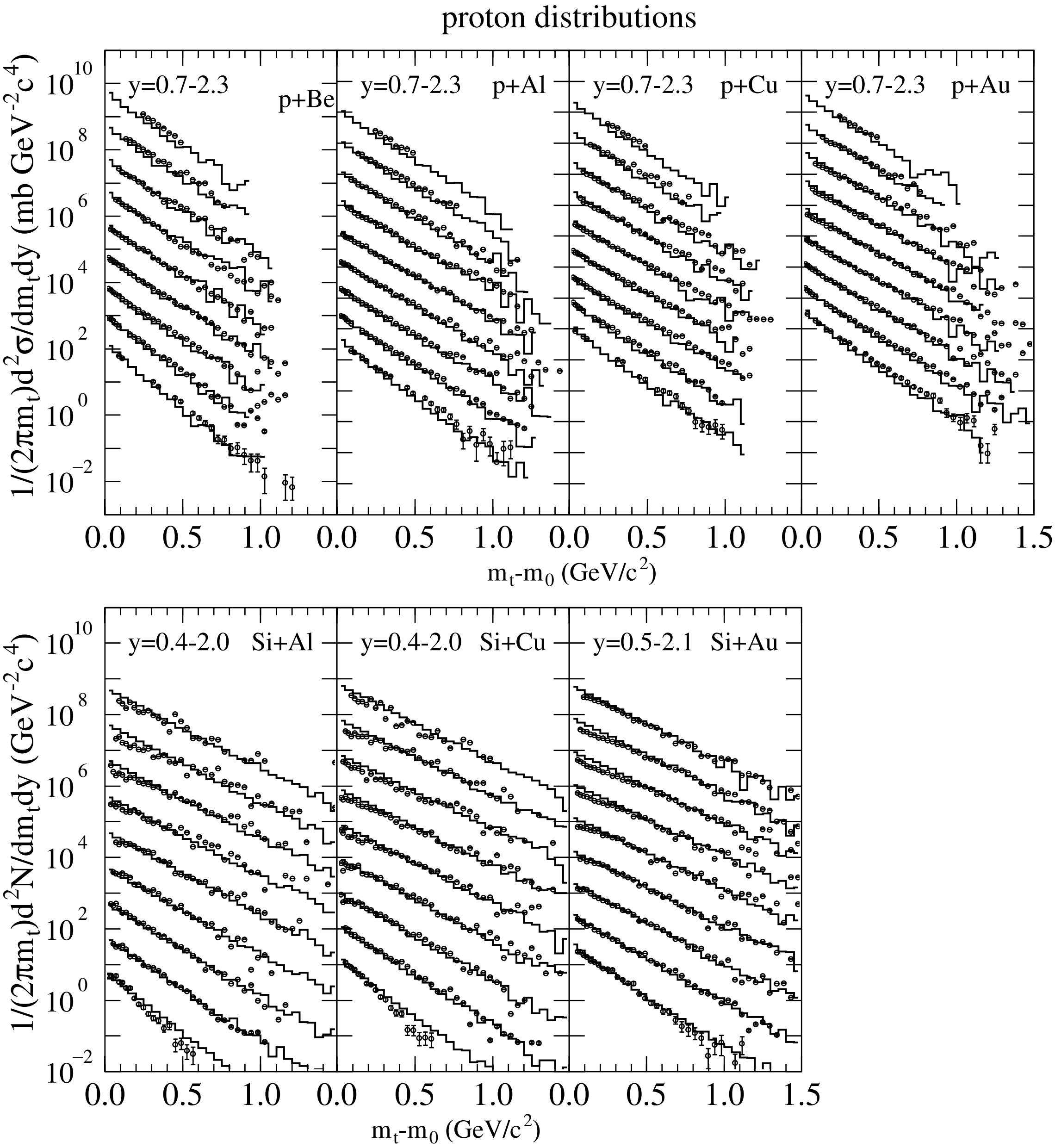
• Rapidity and M_T Dist. in pp Collisions



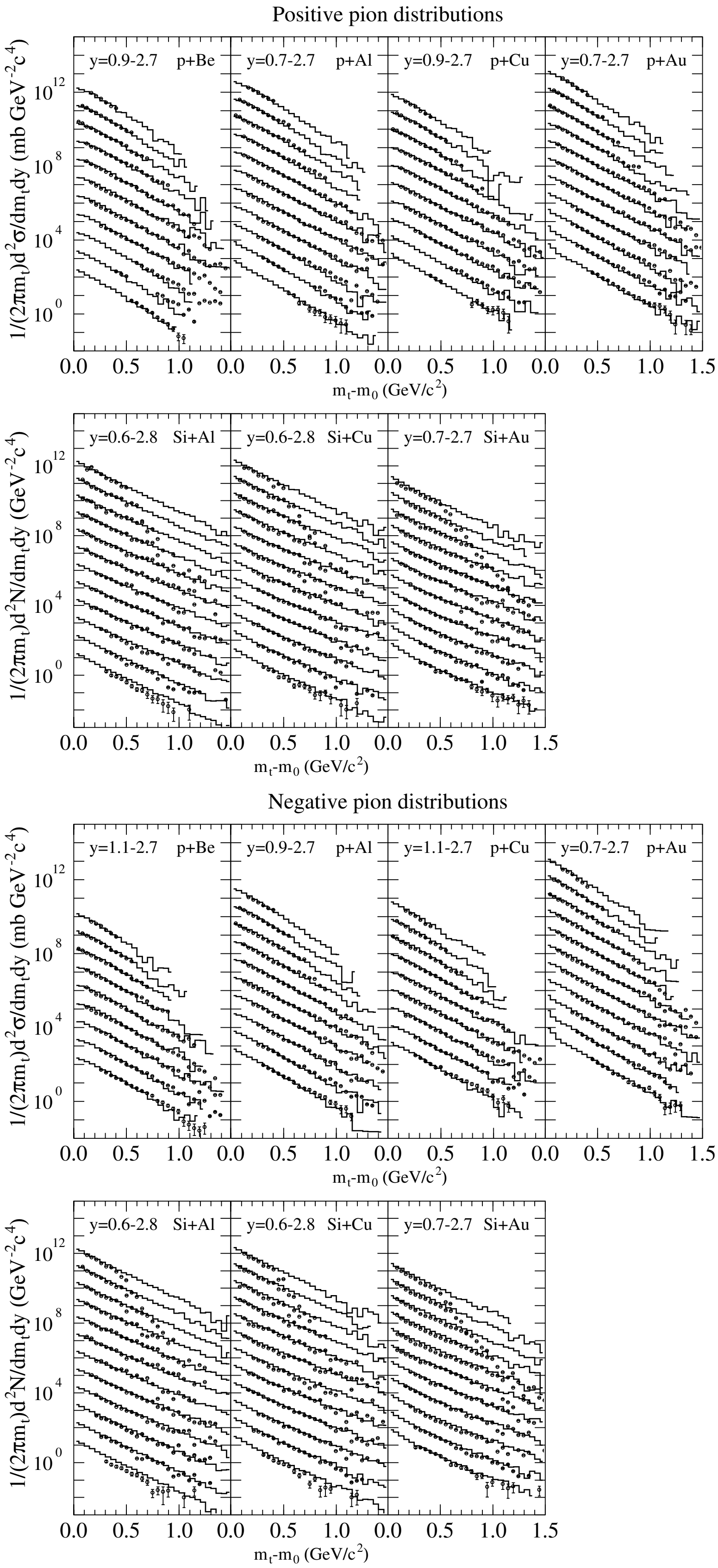


$pA \sim$ Si+Au Collisions

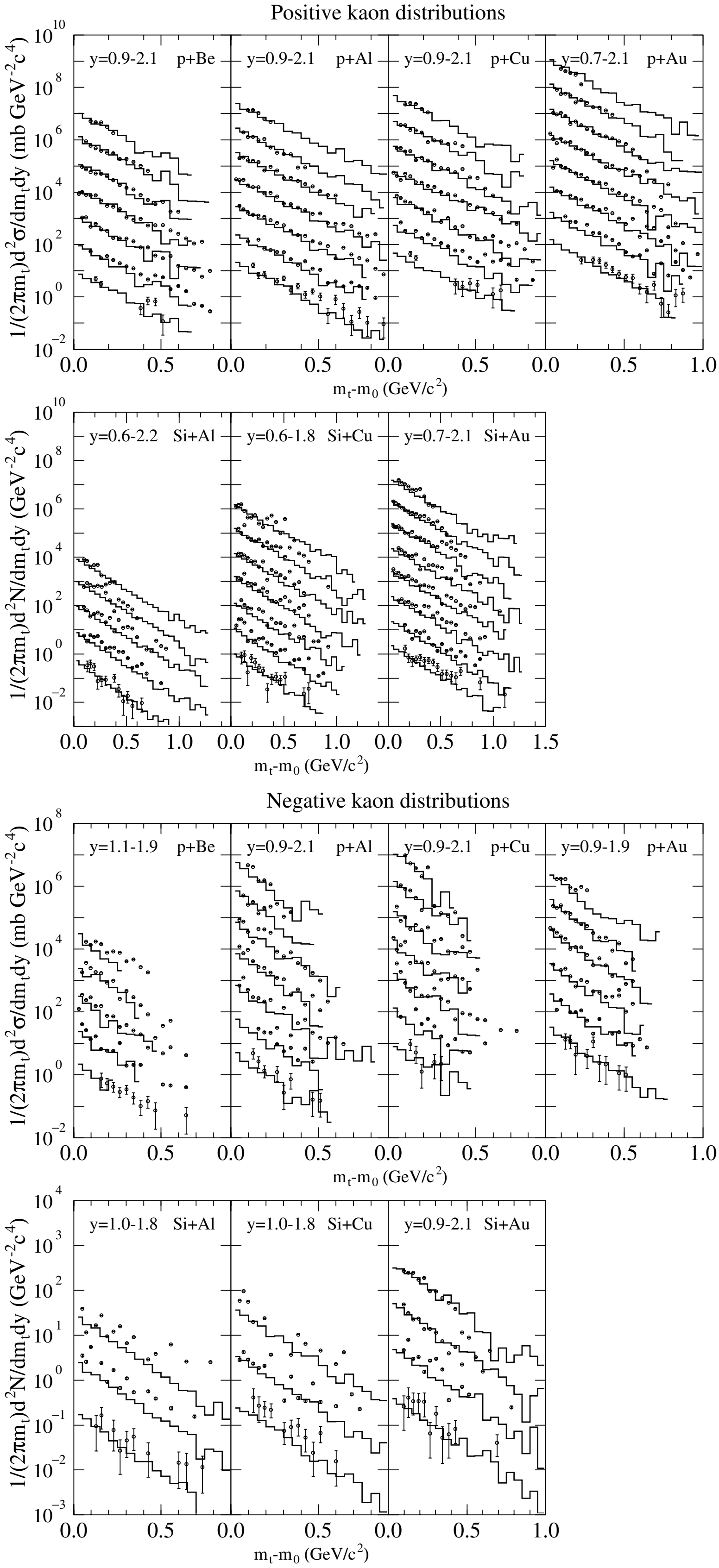
- **Proton M_T Spectrum**



• M_T Spectrum of Pions

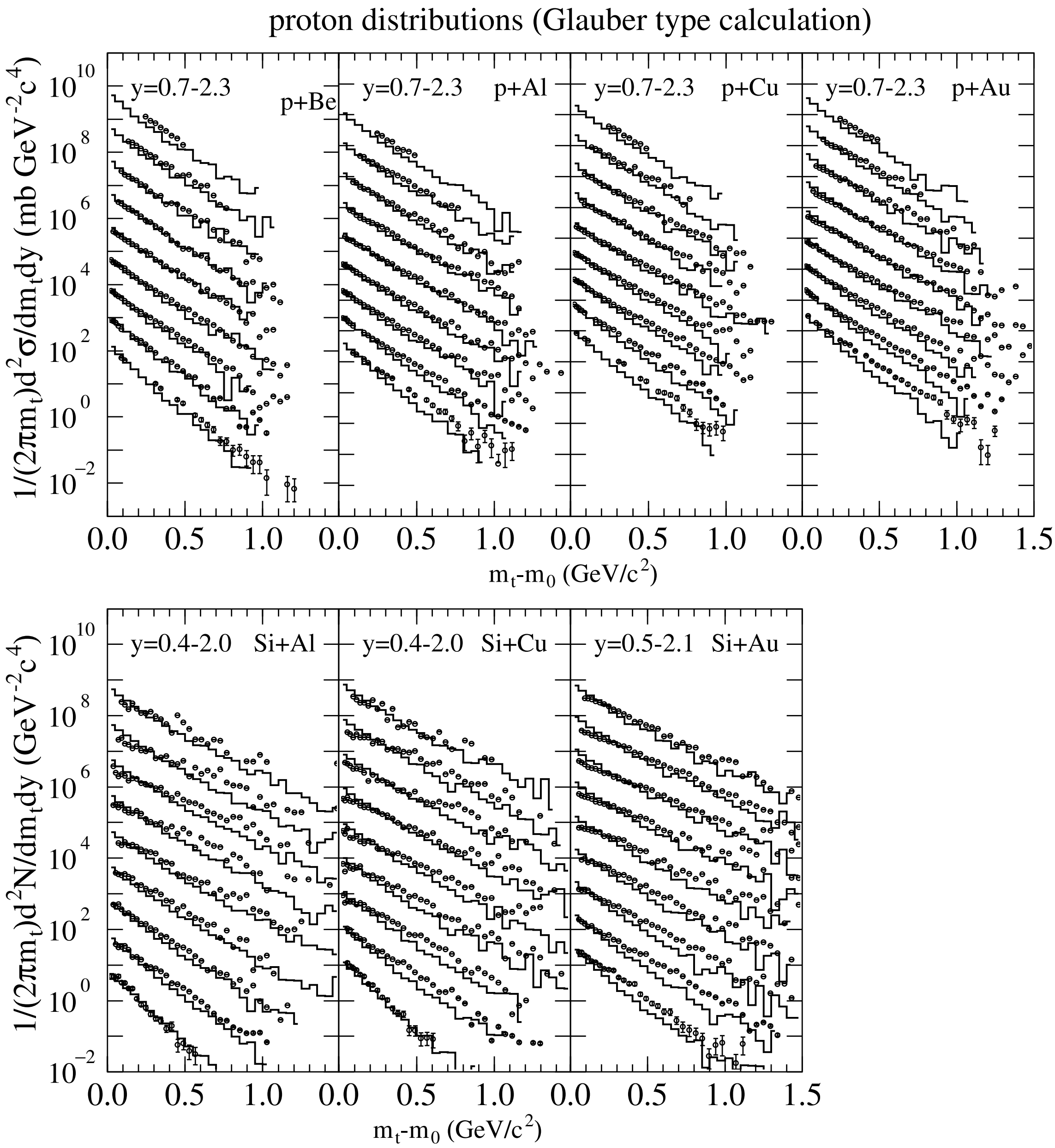


• M_T Spectrum of Kaons

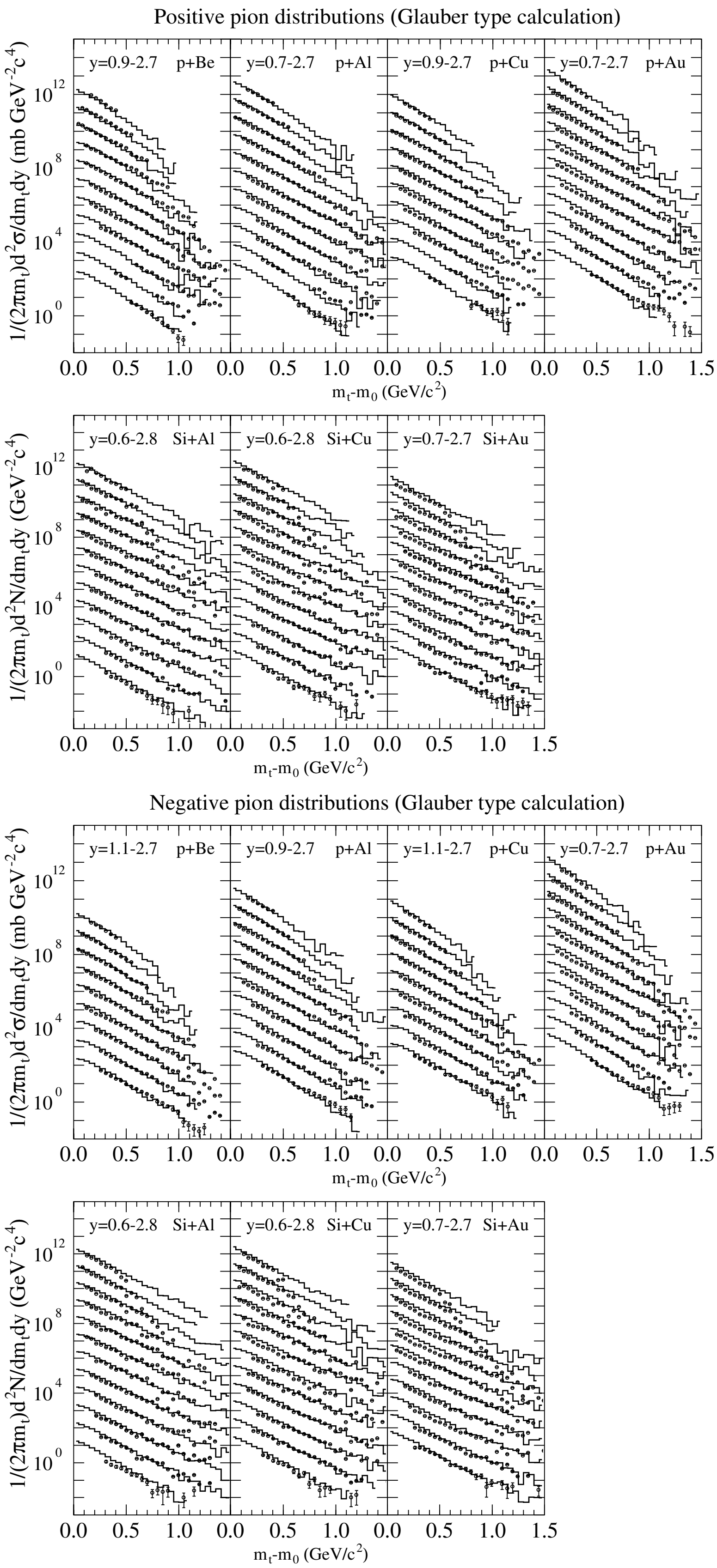


Glauber-type Calc. (No Rescatt.)

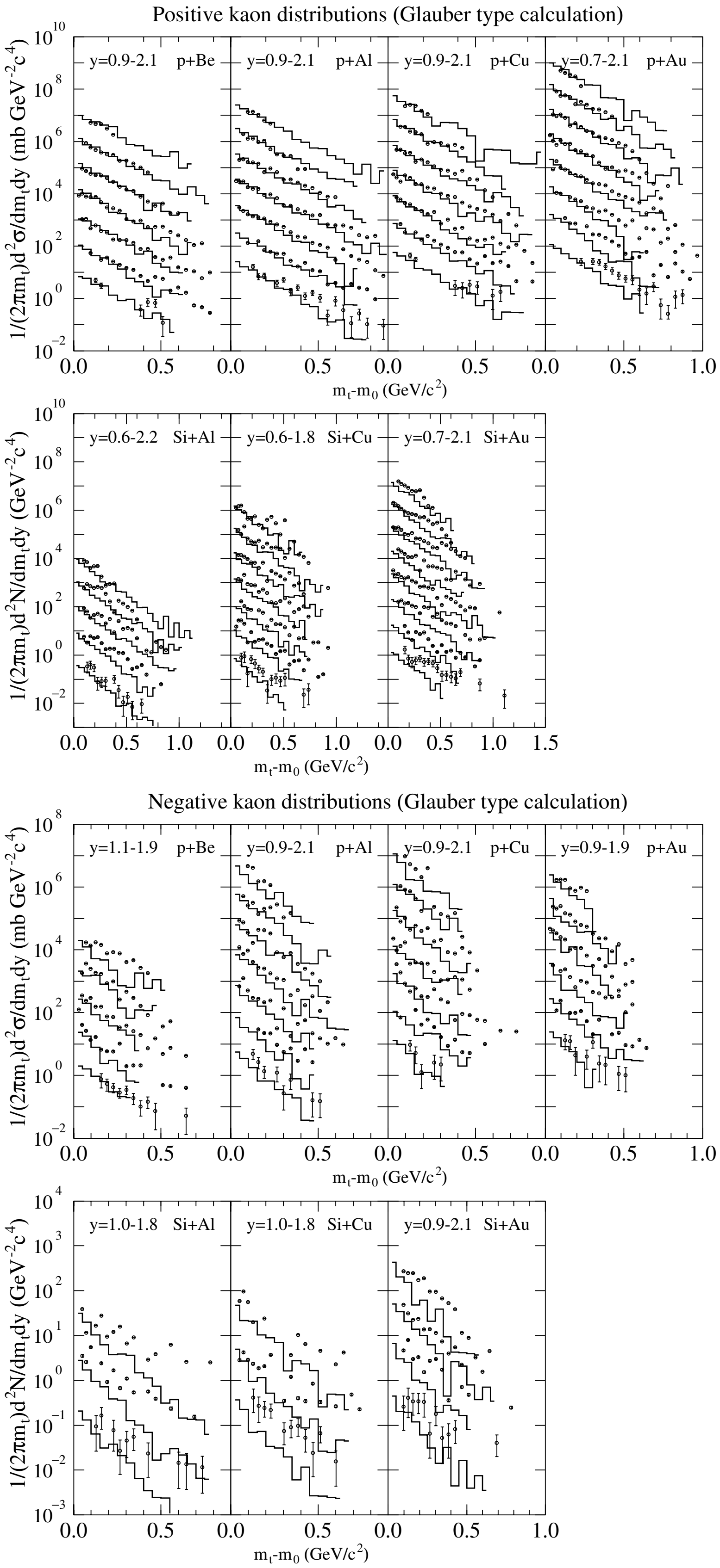
- **Proton M_T Spectrum**



• M_T Spectrum of Pions

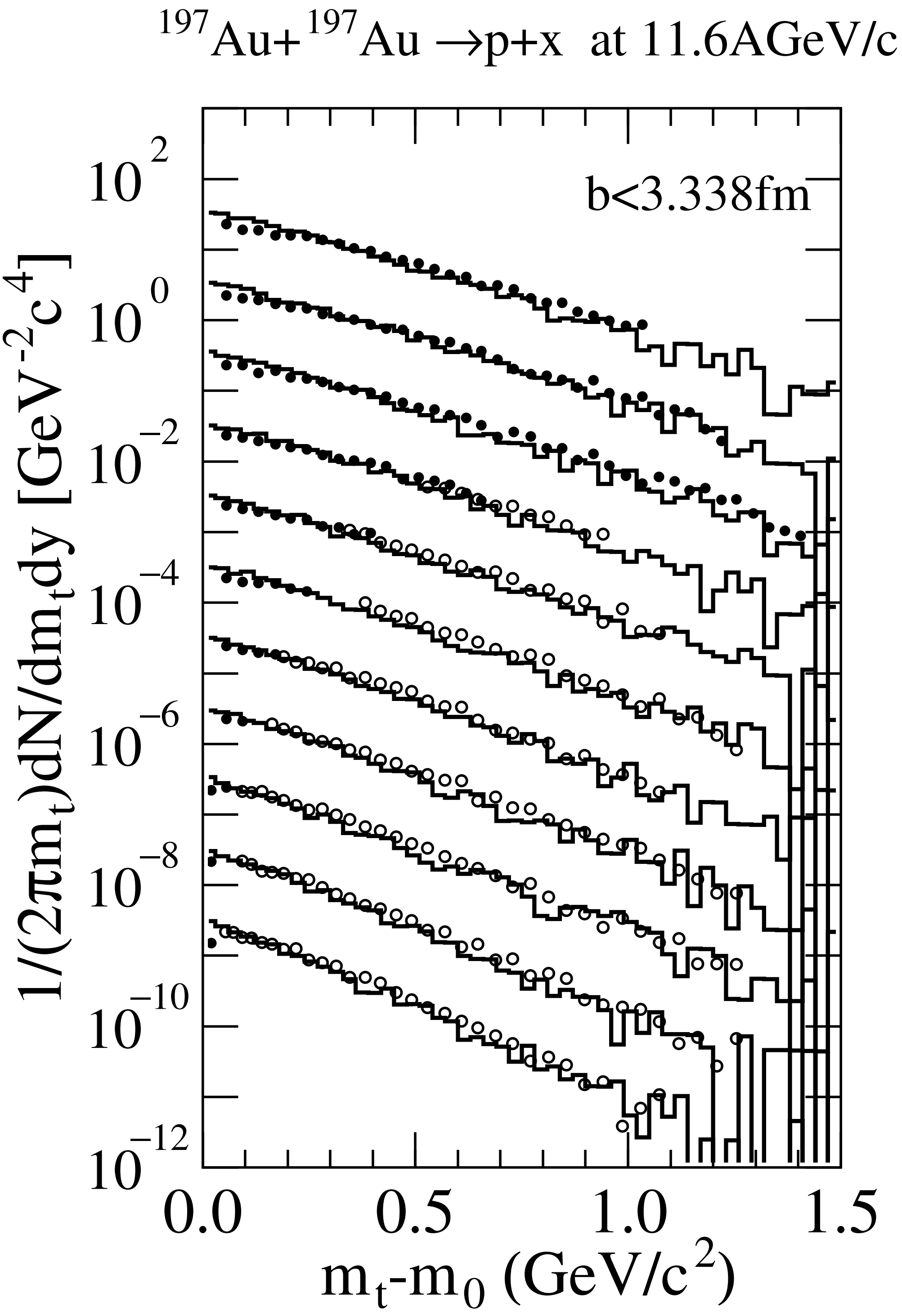


• M_T Spectrum of Kaons

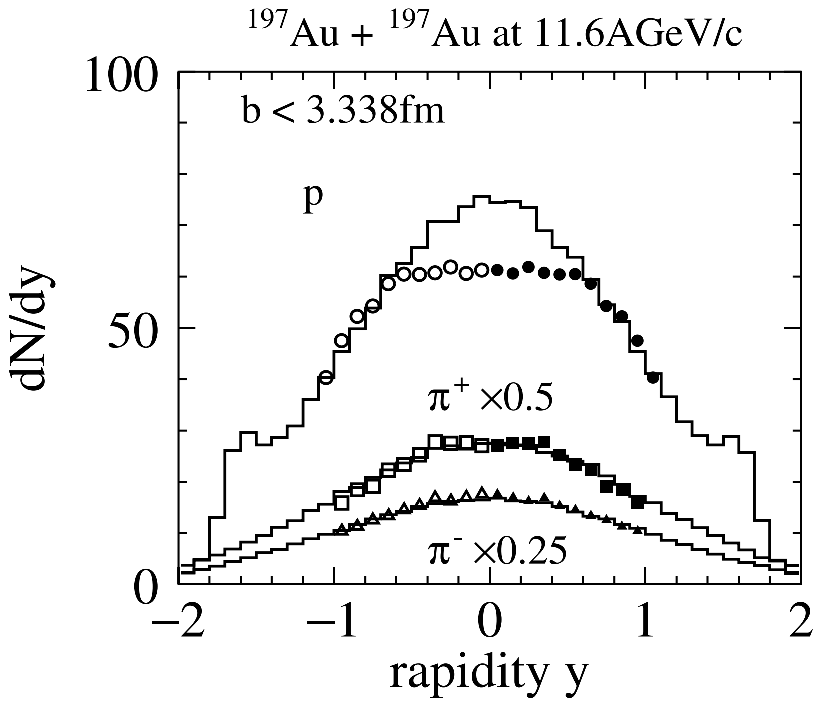


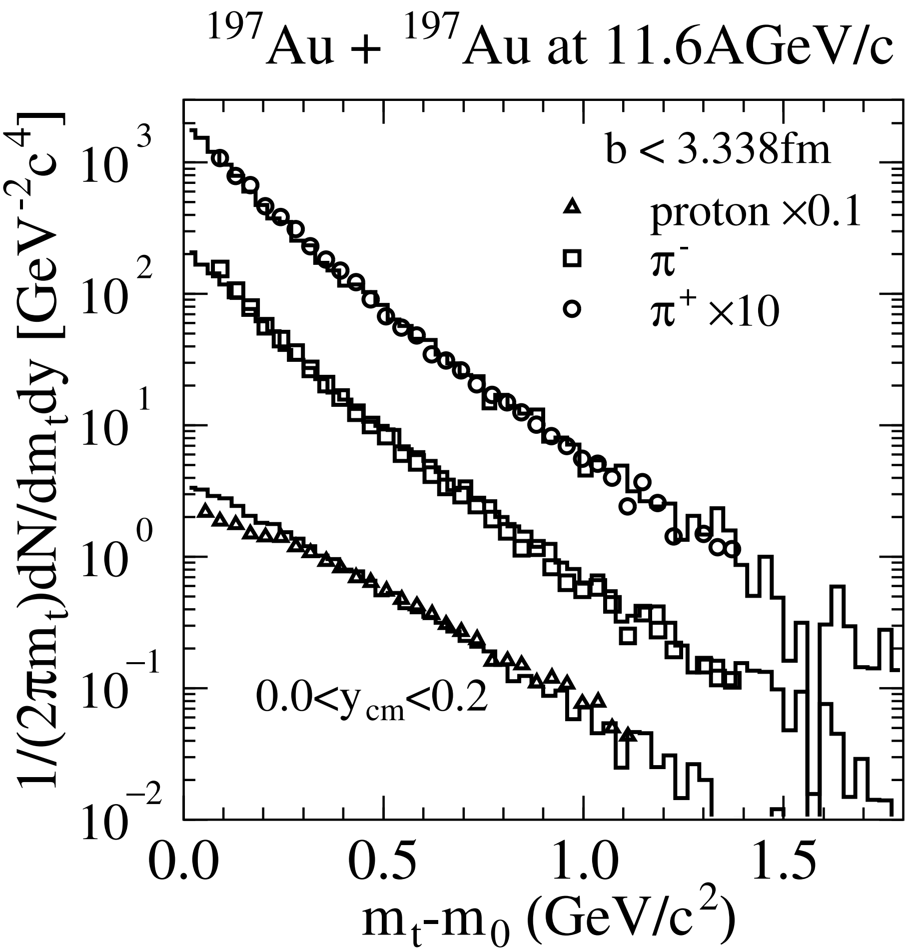
Au + Au Collisions at AGS Energy

- **Proton M_T Spectra**

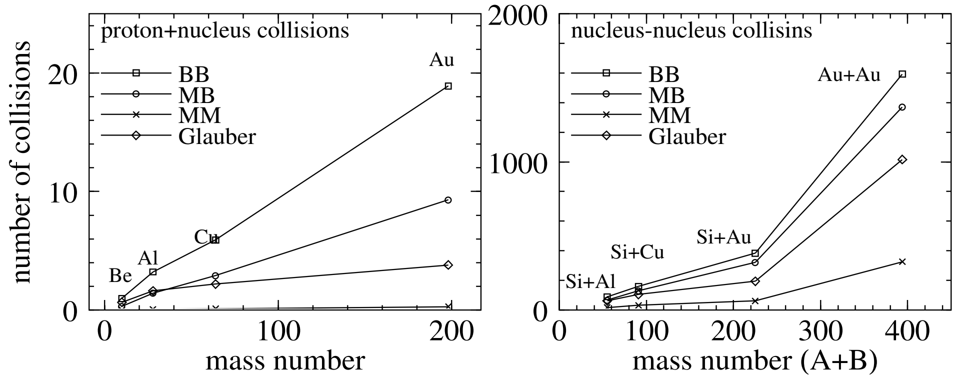


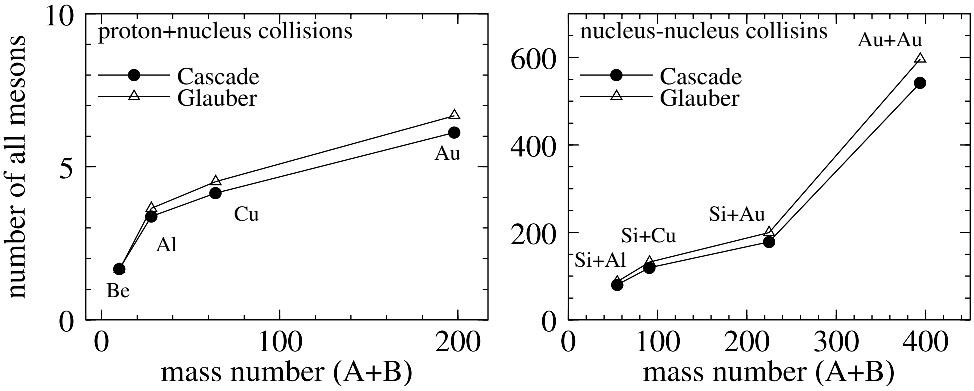
• Rapidity and M_T Spectra

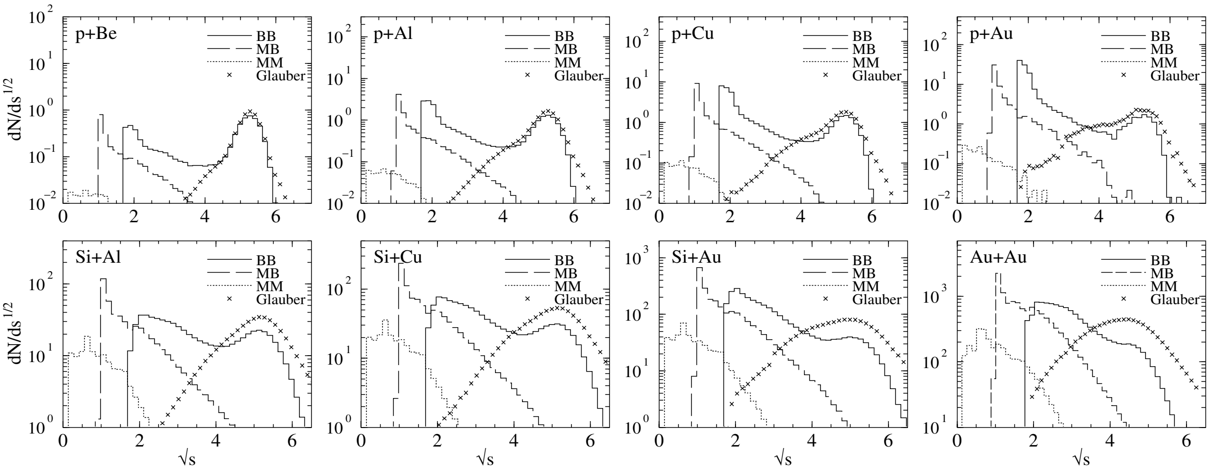




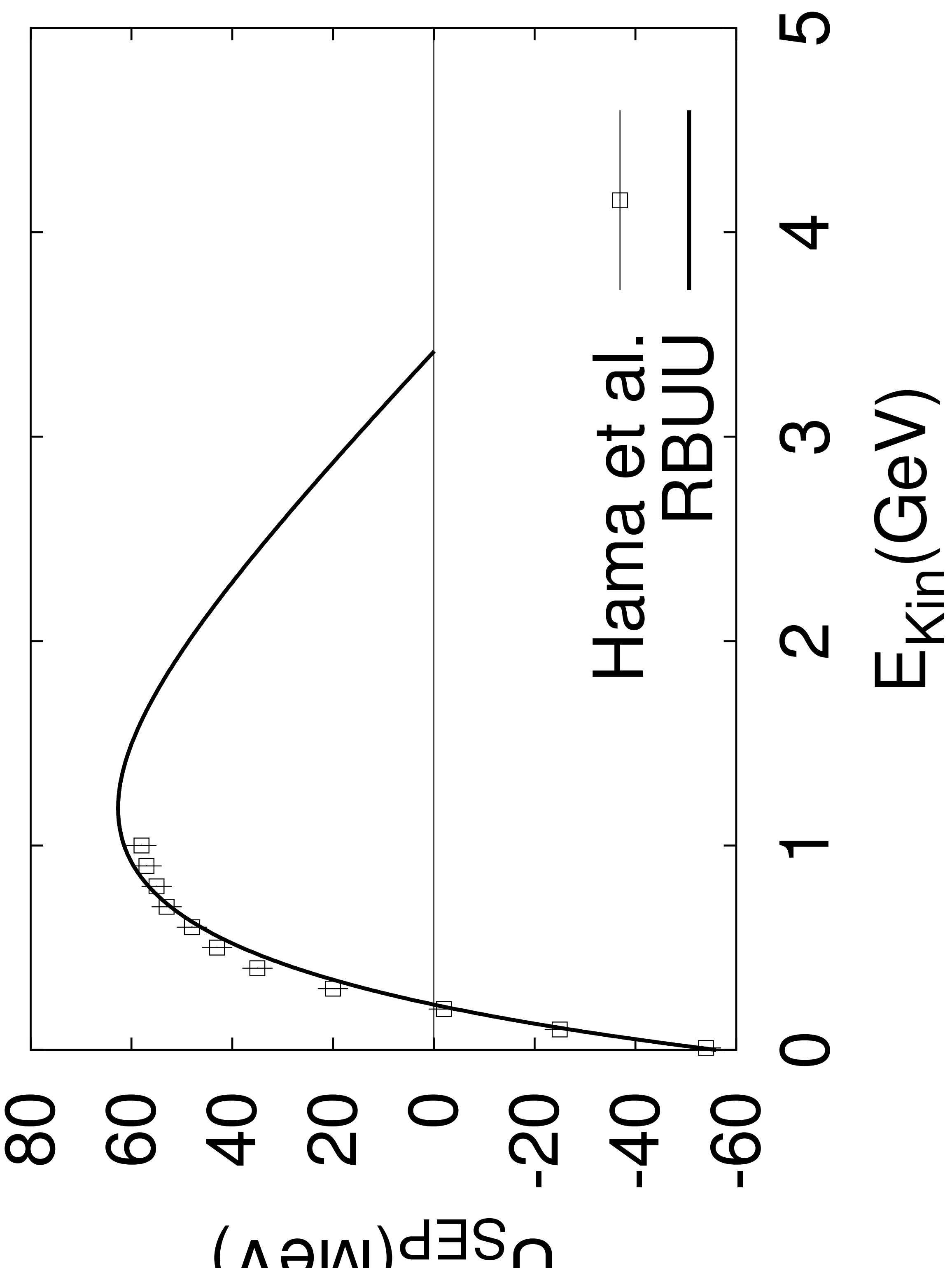
• Rescattering Effects



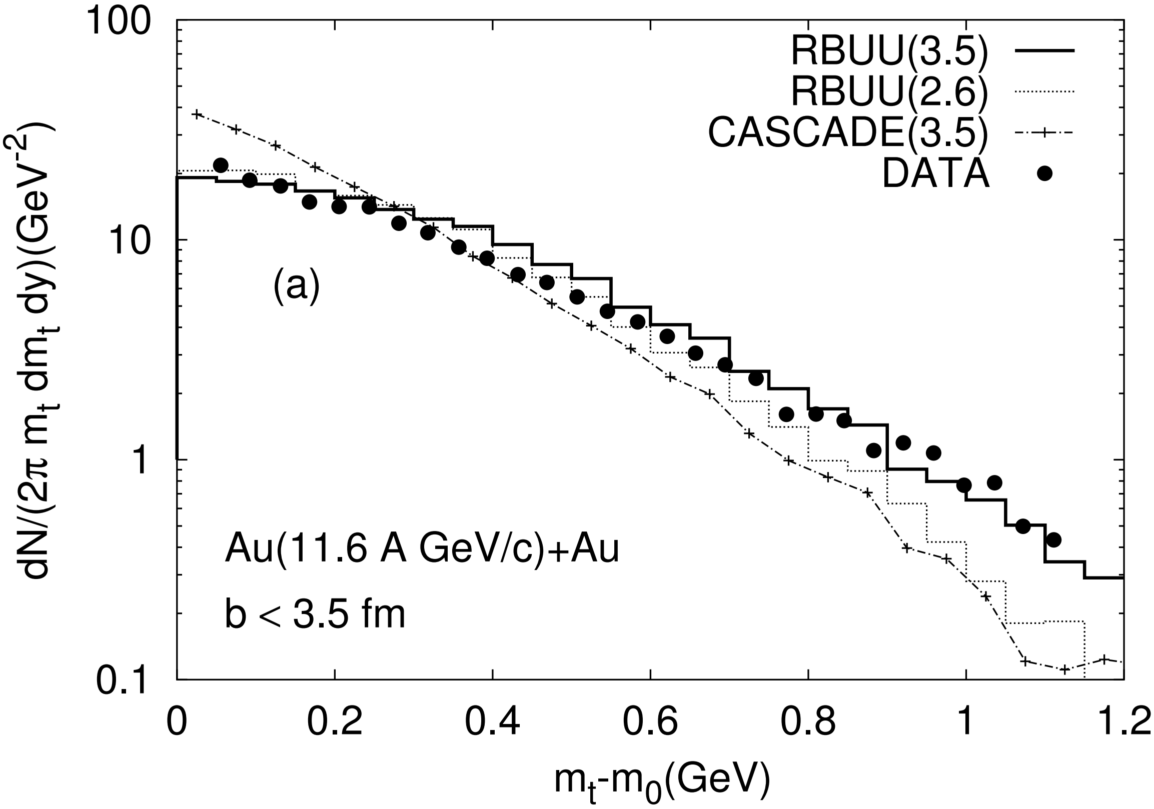


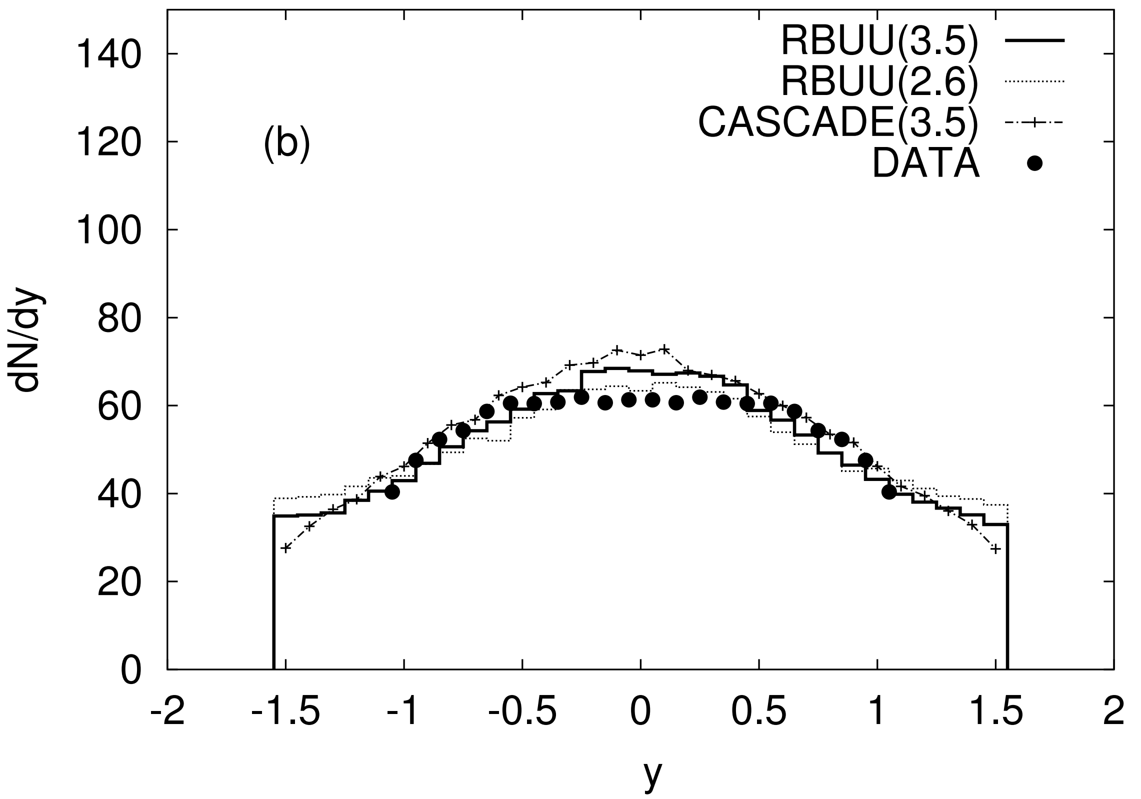


E-dep. of Nucleon Optical Potential

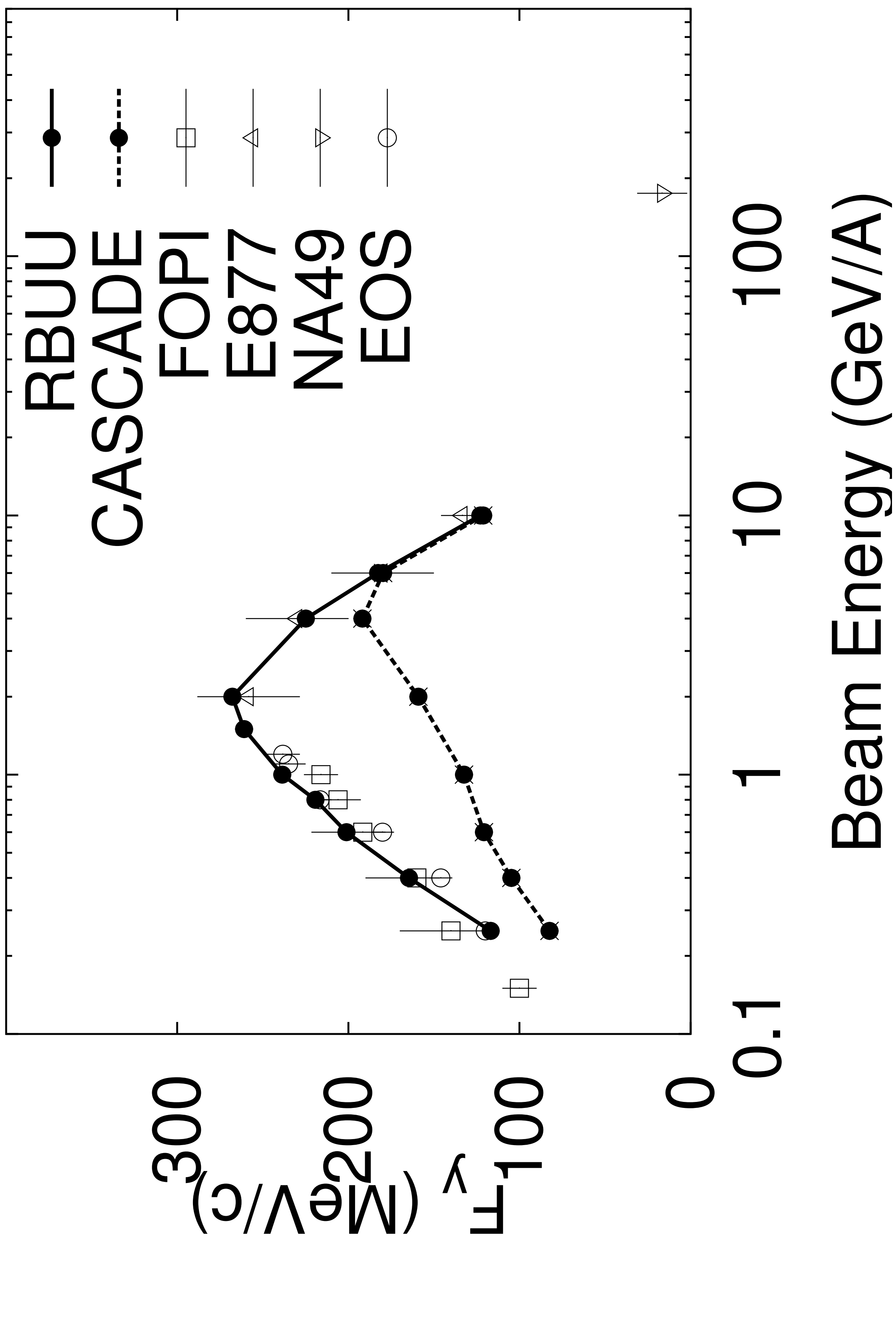


Proton Distribution in Au+Au Collision

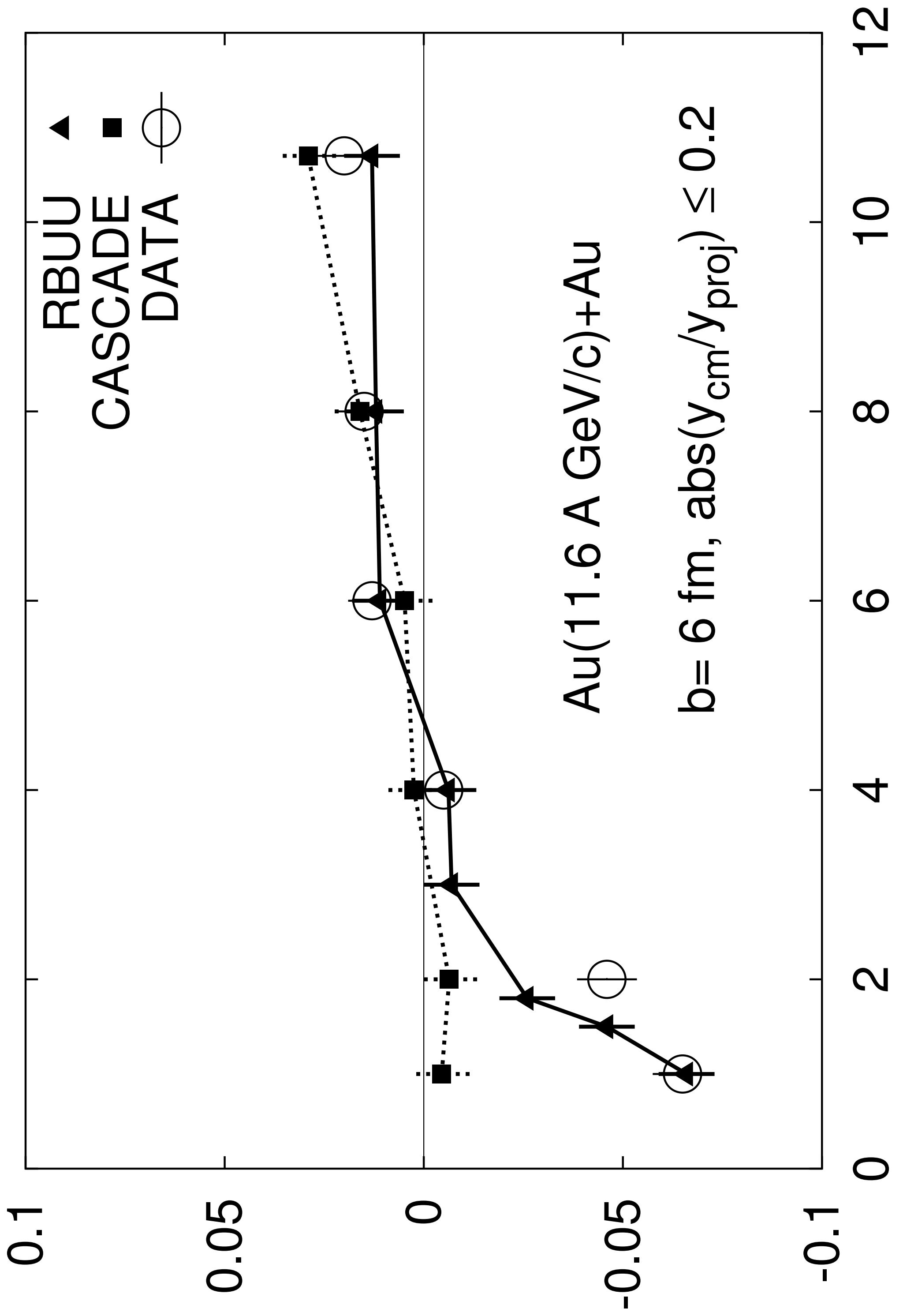




Proton Sideward Flow



Proton Elliptic Flow



静止 Ξ^- 反応におけるハイパー核の生成

平田 雄一, 奈良 寧, 大西 明, 原田 融, **J. Randrup**

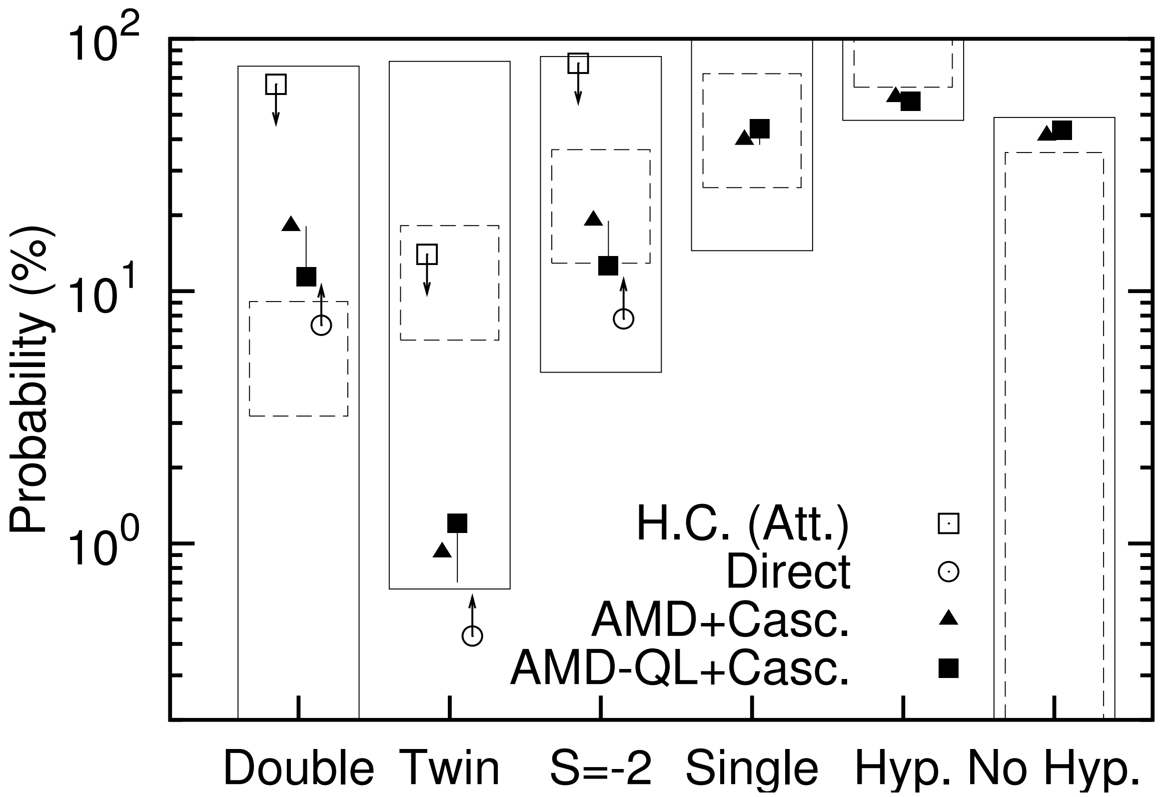
静止 Ξ^- 反応からのハイパー核生成
— 実験と理論の現状

- **E176 実験での統計** Nakazawa et al., Proc. of INS 23rd.

	Hyperfragment	(A)	(B)	(C)
$S=-2$	**Double**	1	} +1 (Double, Twin)	} +8 (Double, Twin, Single)
	Twin	2		
$S=-1$	**Single**	8		

Hyp.Frag.	L. L. (%)	U. L. (%)	Rough Est. (%)
Double	– } 4.8 } 47.6	77.9	3 – 9
Twin	0.66	81.5	6 – 18
Single	14.5	–	26 – 73
No Hyp. F.	–	48.8	–

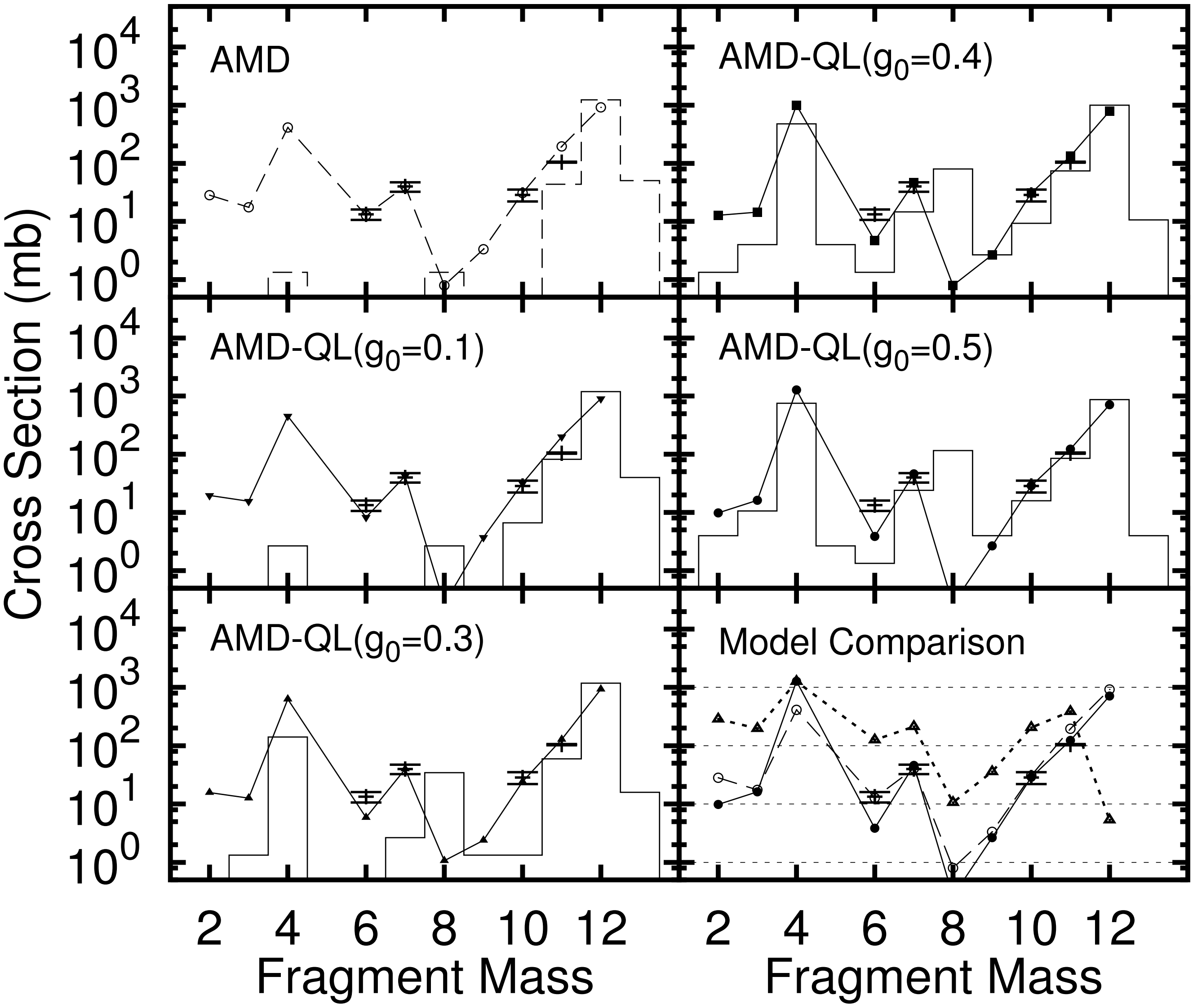
- **現在までの理論計算との比較**



Light Ion Induced Reaction — AMD-QL

Hirata, Nara, Ohnishi, Harada, Randrup, PTP, in press

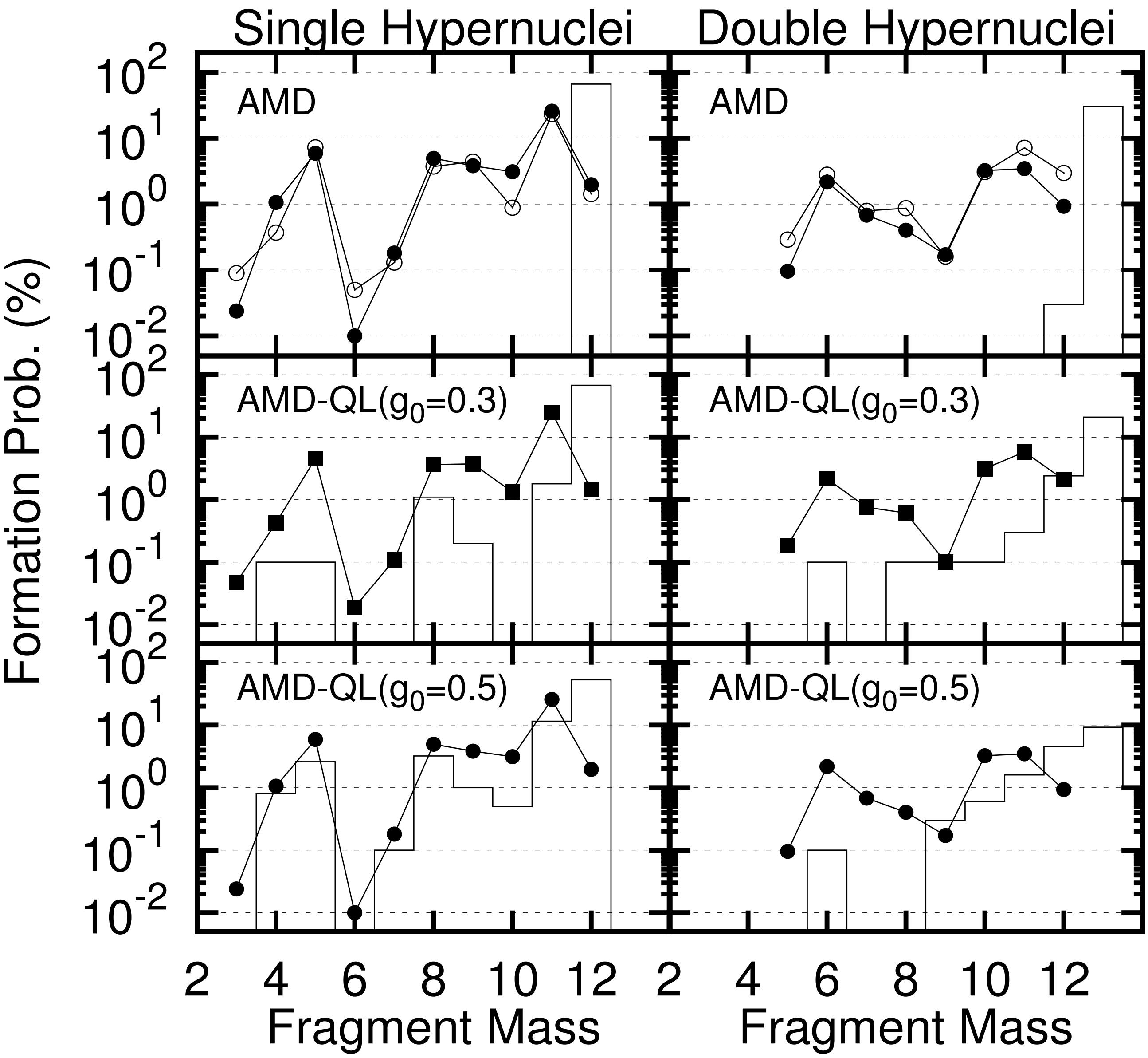
• Proton Induced Reaction at 45 MeV



⋆ **Sufficient Fluctuation Strength**

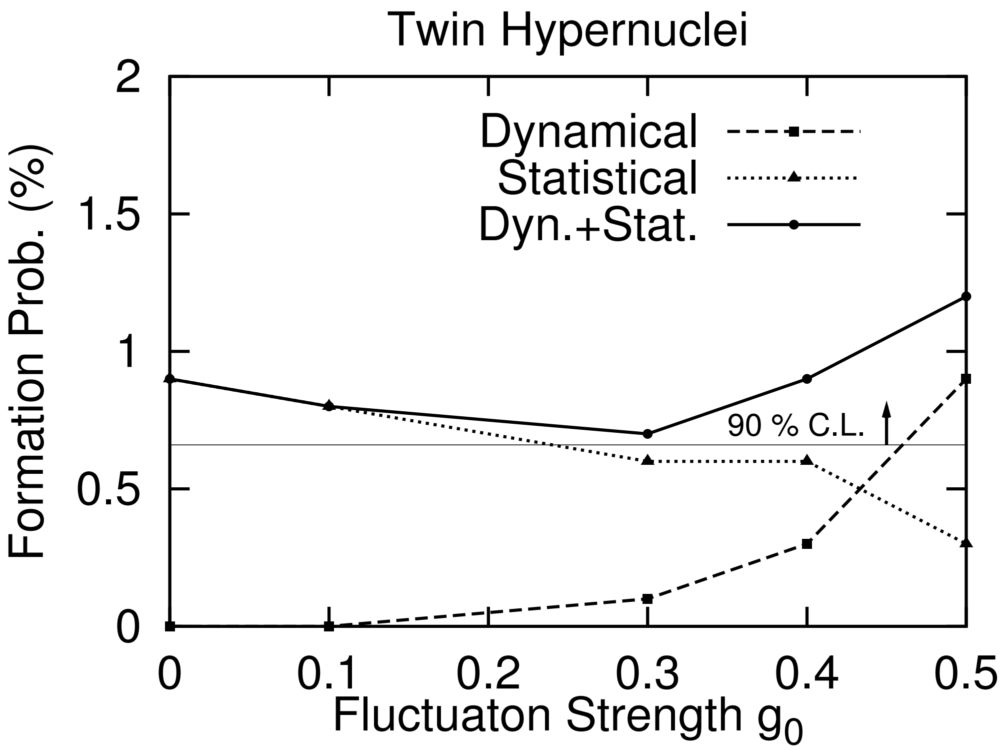
→ **Fragments are produced at low excitation DYNAMICALLY**

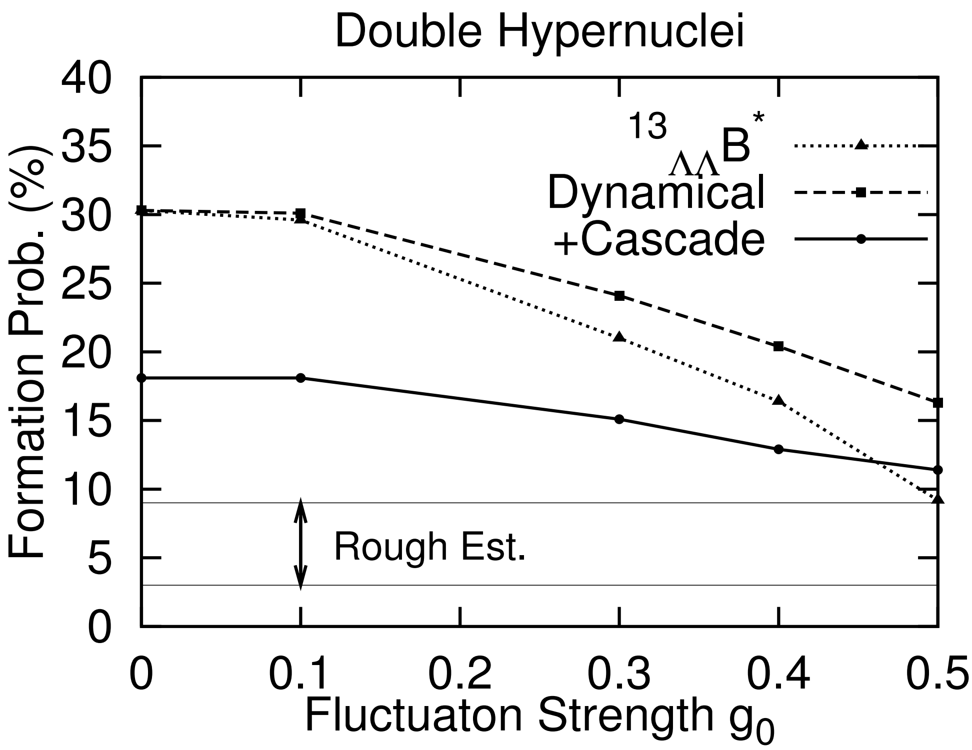
• Ξ^- Absorption at Rest



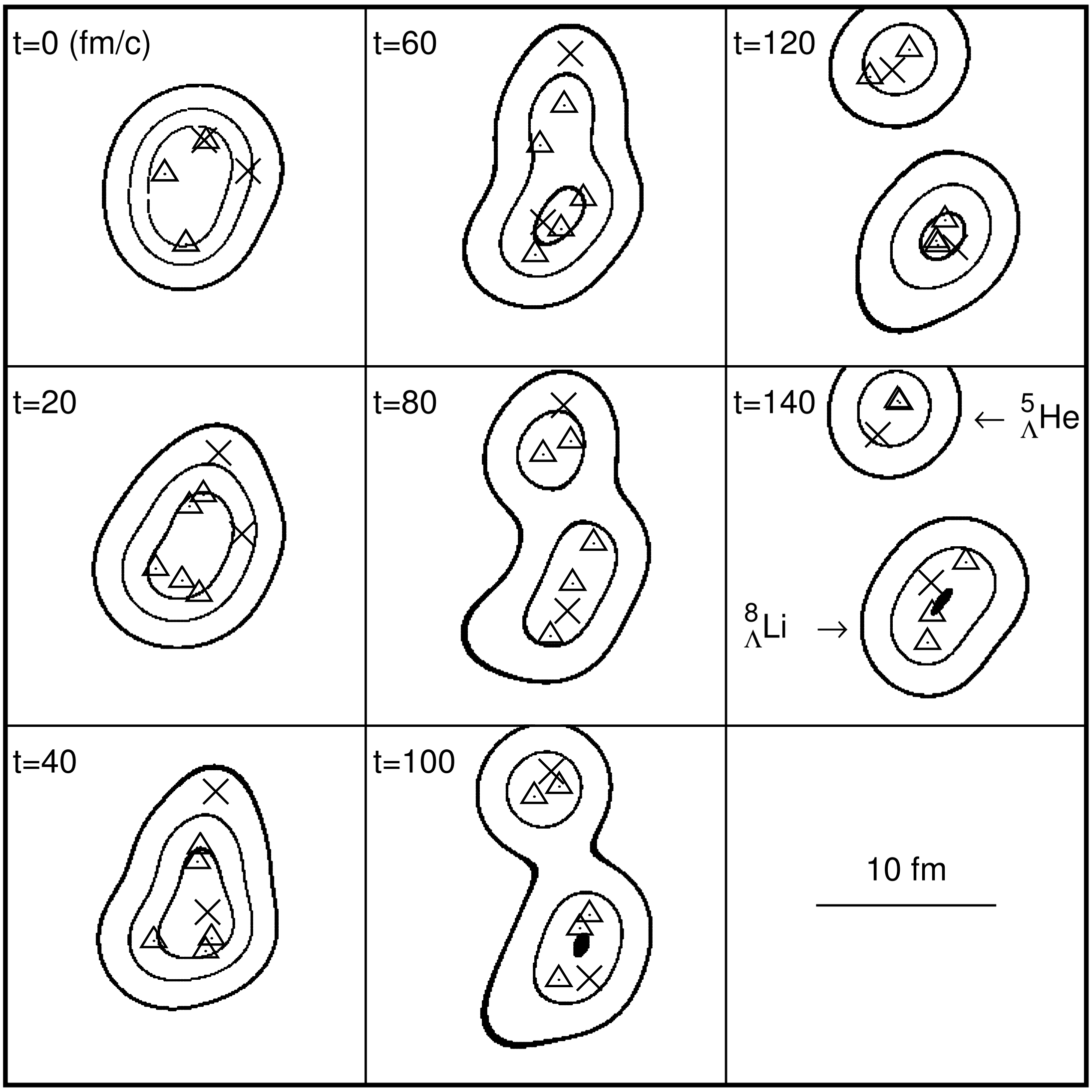
⋆ **Fluctuation Effects can be found even in the Major Channels**

ダブル、ツイン・ハイパー核の揺らぎ強度依存性





ツイン・ハイパー核生成での時間スケール



フラグメント生成の時間; **60** $\sim$ **80 fm**/c
直接反応と統計崩壊の中間程度

Λ 粒子の一粒子エネルギー