高密度物質と中性子星の物理
Physics of Neutron Star Matter

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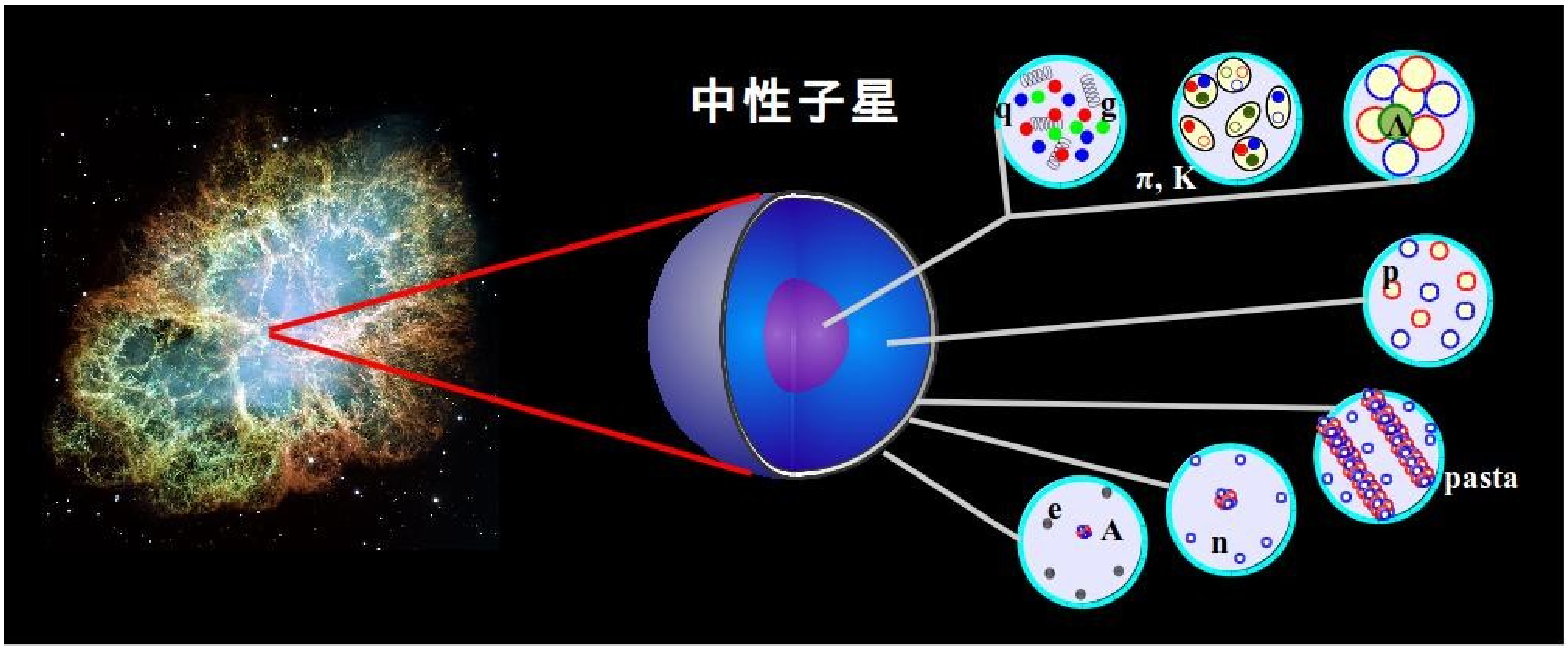
1. 中性子星の基本的性質
2. 状態方程式を記述する理論模型
3. 対称エネルギーと非対称核物質の状態方程式
4. ハイパー核物理と高密度核物質の状態方程式

- 中性子星におけるエキゾチック自由度
  → YYN3 体力 : 重イオン衝突とハイパー核から中性子星へ

九州大学集中講義 7/8-10

Neutron Star Matter

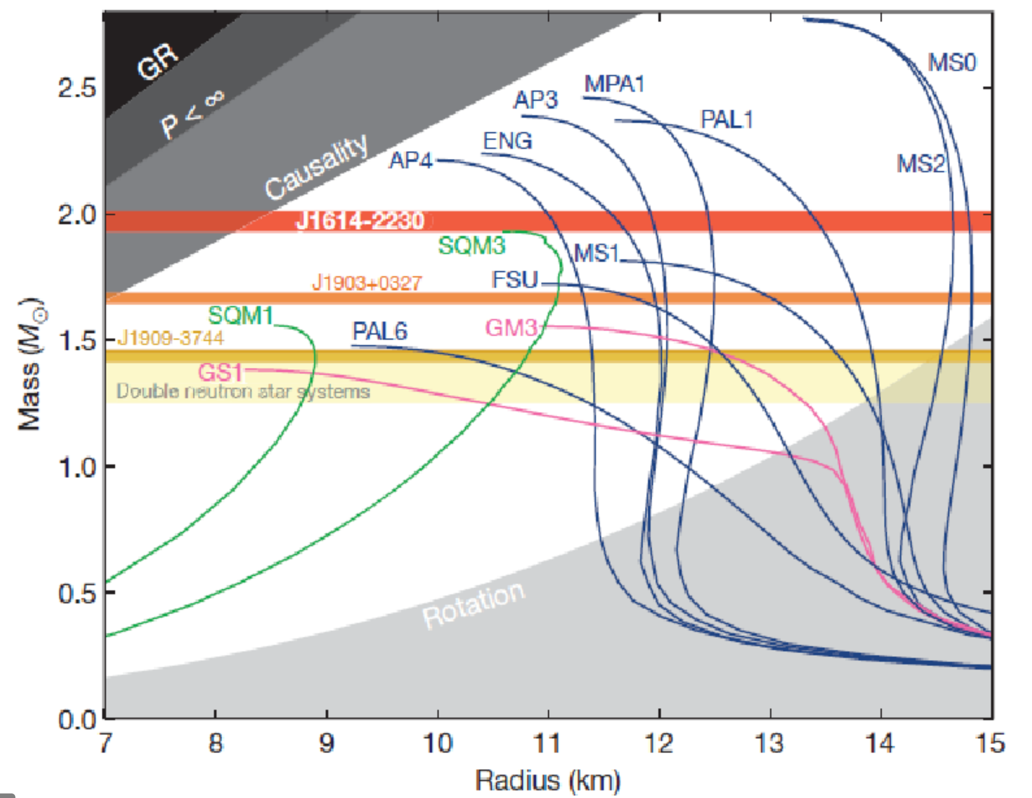
- **Cold, dense, charge neutral**
- **Constituents**
  - **n, p, e, μ, Y, π, K, q, di-quark, ...**



Can we determine int. btw constituents ?

Massive Neutron Stars

- M_{NS}=1.97±0.04 Msun measured using Shapiro delay (GR effect).
- EOSs w/ strange hadrons are "ruled out",
  while Lab. exp. suggest their existence in NS.



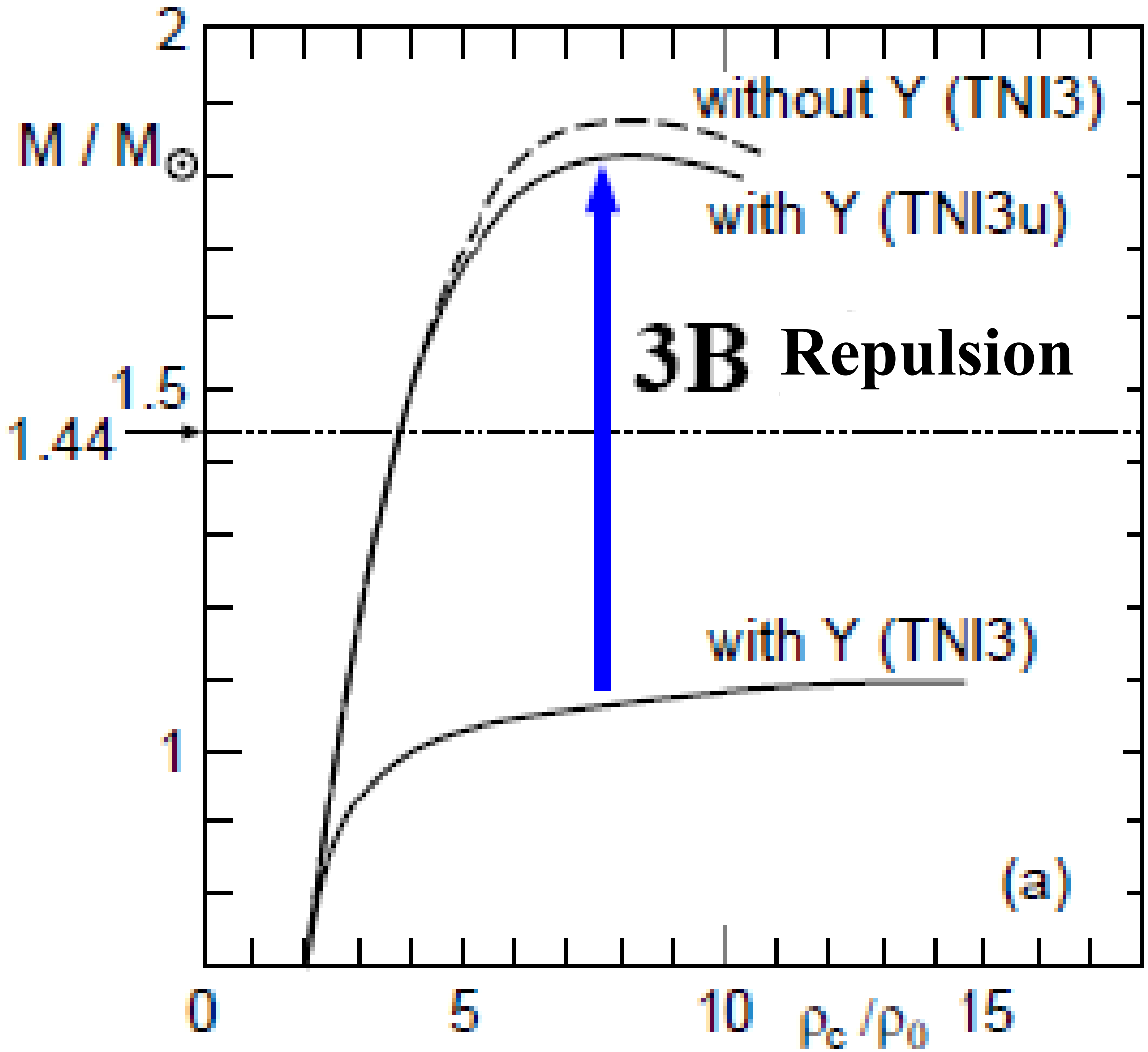
Massive Neutron Star Puzzle

Demorest et al., Nature 467 (2010) 1081.

NS matter EOS with hyperons

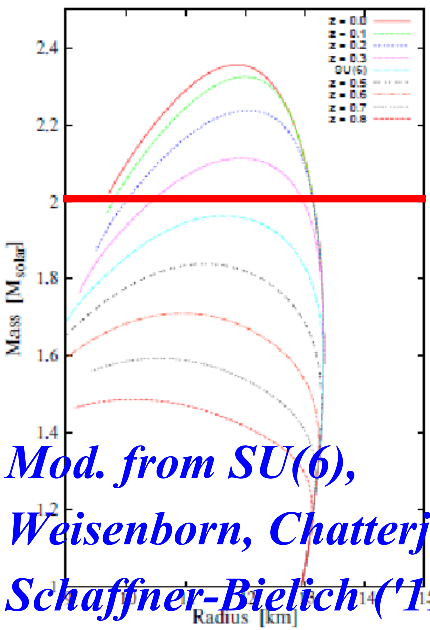
- **"Ruled-out" hyperonic EOS = Naive RMF**
  Glendenning, Moszkowski ('91)
  - **SU(6) coupling (~ quark counting)** $g_{\sigma\Lambda} = 2/3\ g_{\sigma N}$
  - **No** $s\bar{s}$ **mesons**
- **Proposed prescription after 2 Msun NS**
  - **Modify coupling constant from SU(6) value**
    Weisenborn et al., ('11); Tsubakihara, AO, Harada ('13)
  - **Introducing three-body repulsion**
    Bednarek, et al.('11); Miyatsu, Yamamuro, Nakazato ('13)
  - **Crossover transition to quark matter**
    Masuda, Hatsuda, Takatsuka ('12)

Three Baryon Repulsion

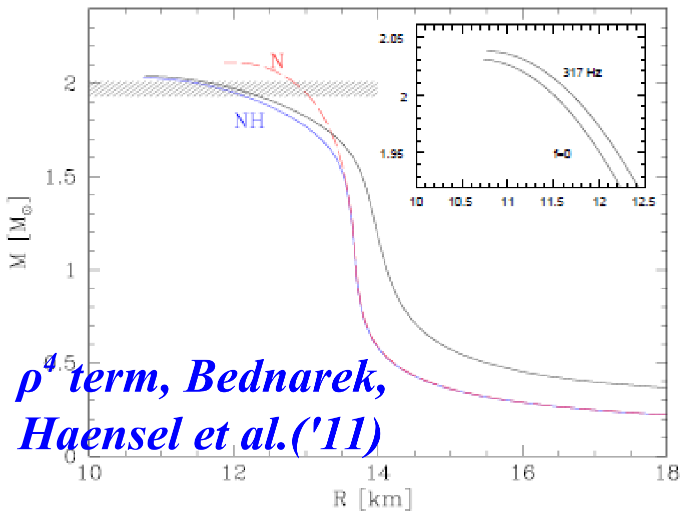


Nishizaki, Takatsuka, Yamamoto ('02)

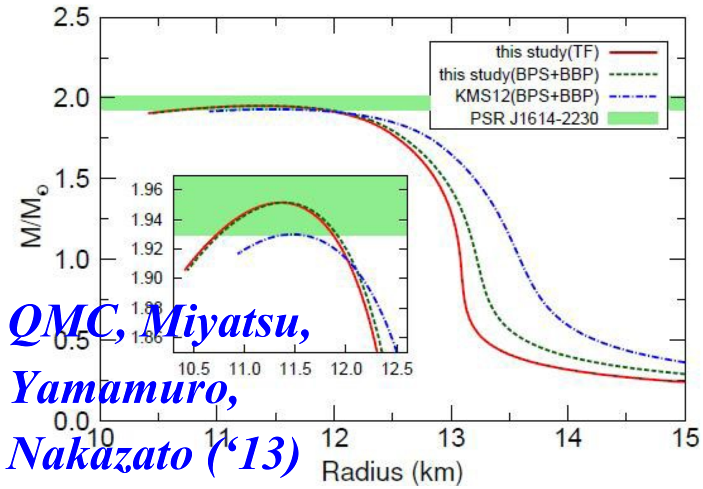
NS matter EOS with hyperons



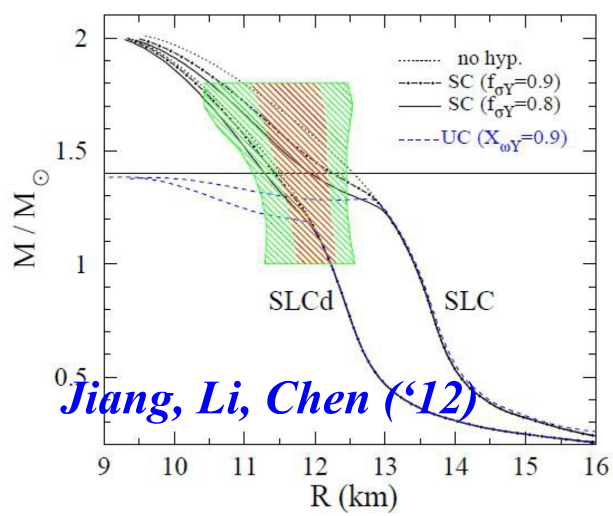
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



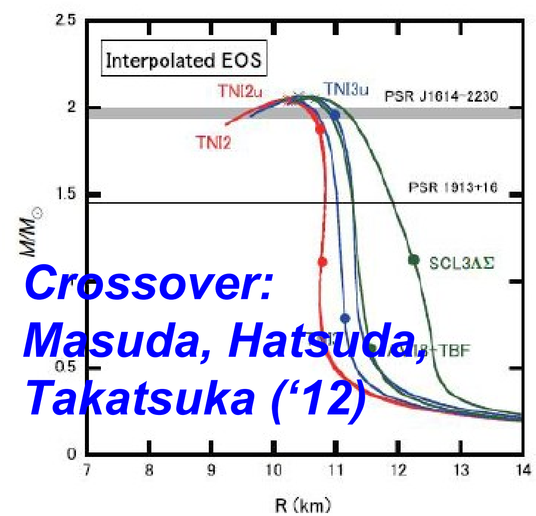
ρ^4 term, Bednarek, Haensel et al.('11)



QMC, Miyatsu, Yamamuro, Nakazato ('13)

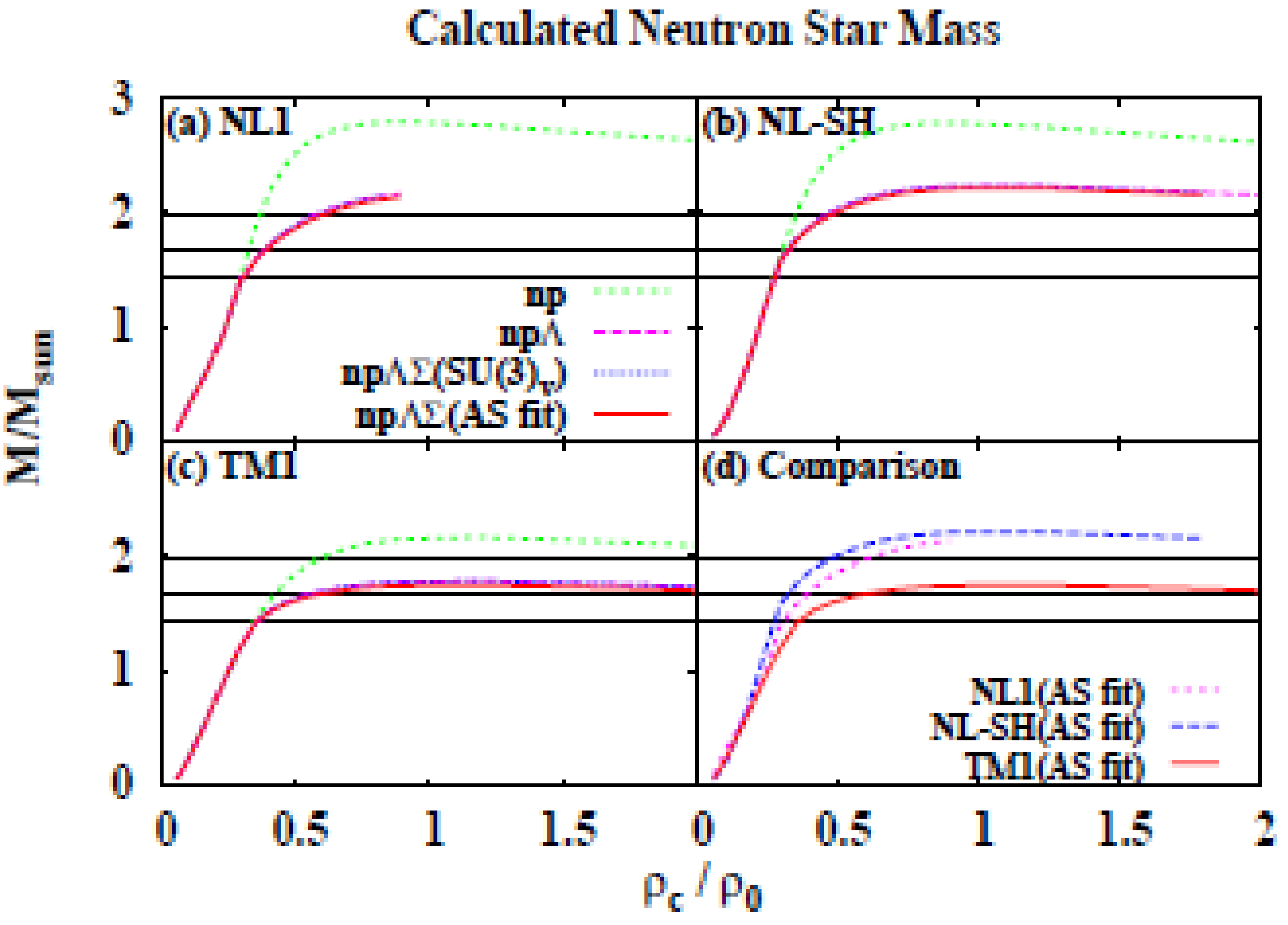


Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

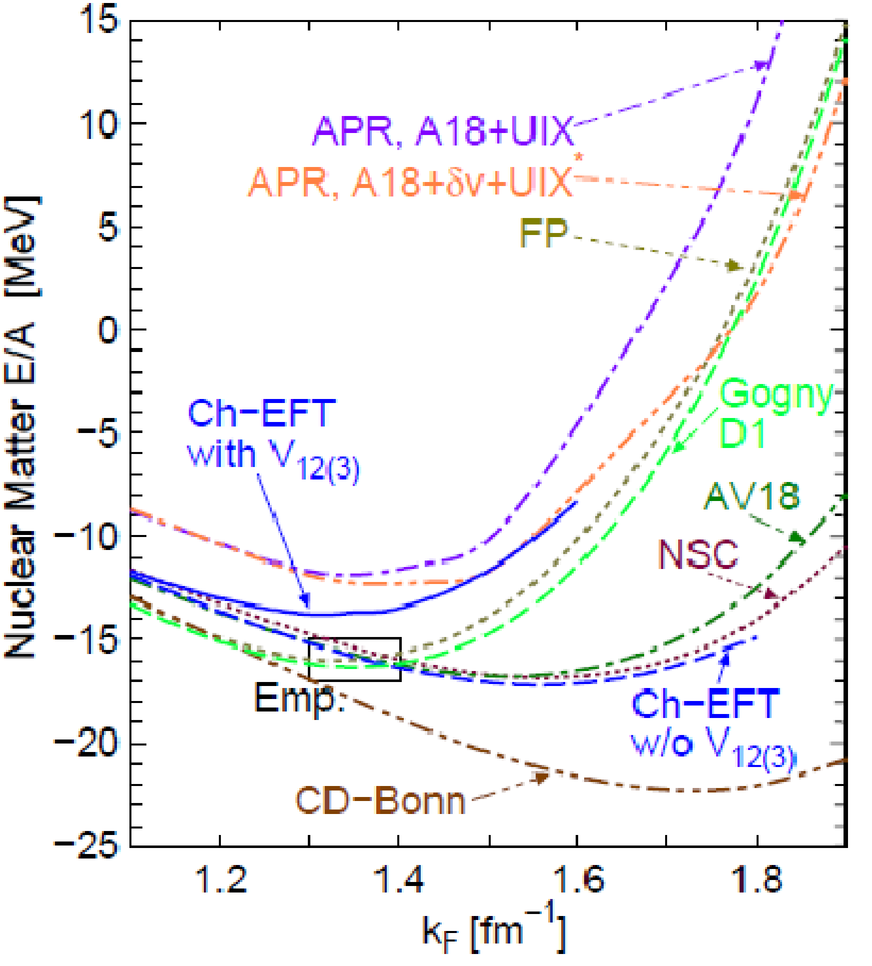
NS matter EOS with hyperons



Non-linear term dep. +Atomic shift fit:
Tsubakihara, AO, Harada, arXiv:14020979

Ch-EFT EOS

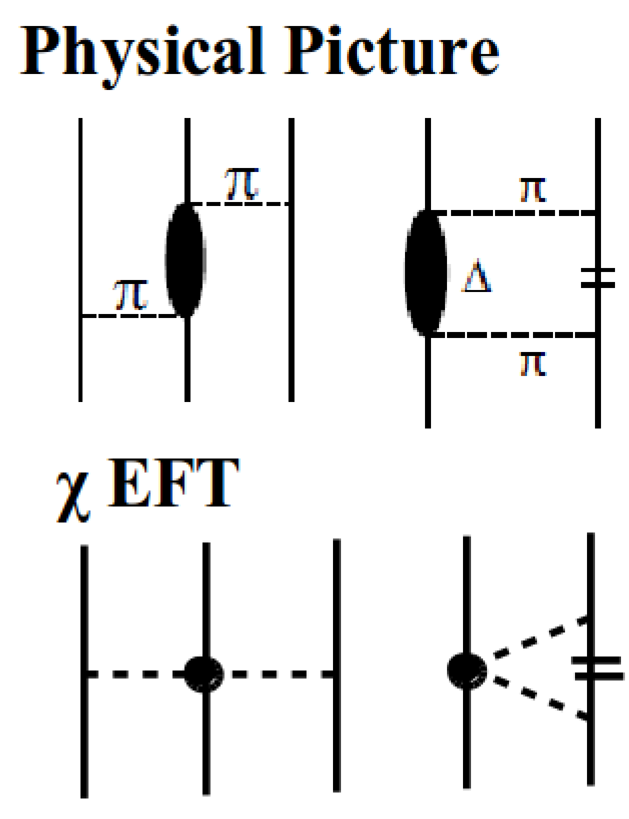
- **Phen. models need inputs from**
  Experimental Data and/or Microscopic (Ab initio) Calc.
- **Recent Ch-EFT EOS is promising !**
  NN (N3LO)+3NF(N2LO)
  Kohno ('13)



M. Kohno, PRC 88 ('13) 064005

"Universal" mechanism of "Three-body" repulsion

- **"Universal" 3-body repulsion is necessary to support NS. Nishizaki, Takatsuka, Yamamoto ('02)**
- **Mechanism of "Universal" Three-Baryon Repulsion.**
  - **"σ"-exchange ~ two pion exch. w/ res.**
  - **Large attraction from two pion exchange is suppressed by the Pauli blocking in the intermediate stage. Kohno ('13)**

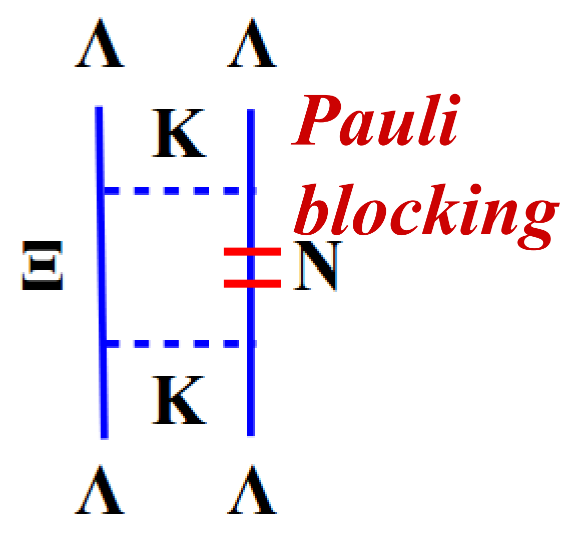


"Universal" TBR
- ***Coupling to Res. (hidden DOF)***
- ***Reduced "σ" exch. pot. ?***

How about YNN or YYN ?

$\Lambda\Lambda$ interaction in vacuum and in nuclear medium

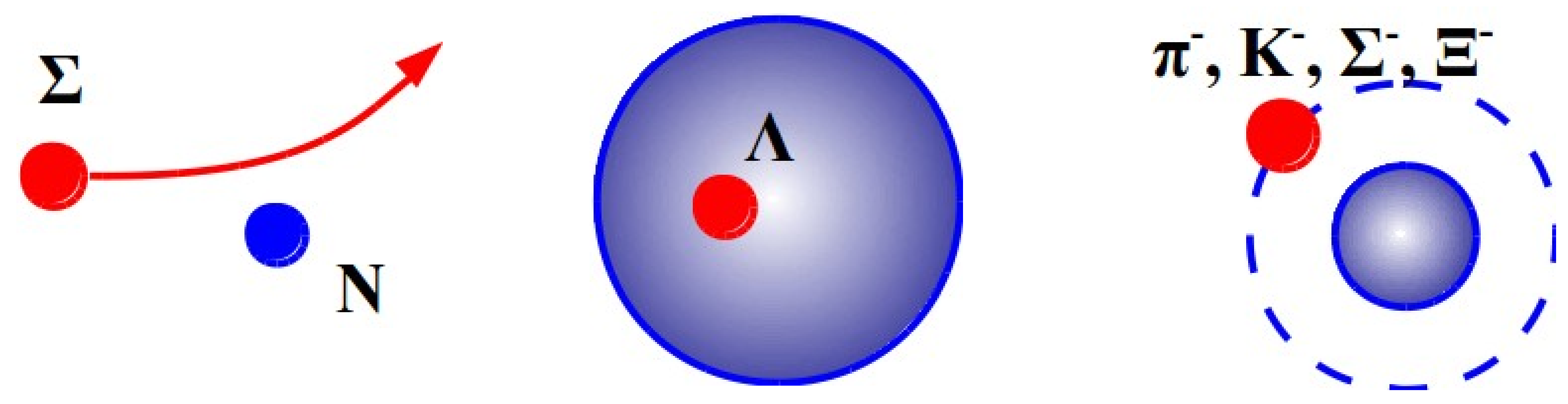
- **Vacuum ΛΛ interaction may be theoretically accessible Lattice QCD calc. HAL QCD ('11) & NPLQCD ('11)**
- **In-medium ΛΛ interaction may be experimentally accessible**
  - **Bond energy of $^{6}_{\Lambda\Lambda}He$**
    $\Delta B_{\Lambda\Lambda}$=1.0 MeV → 0.6 MeV
  - **a_0(Nagara fit) = - 0.575 fm ($\Delta B_{\Lambda\Lambda}$=1.0 MeV)**
    Hiyama et al. ('02)
- **Difference of vacuum & in-medium ΛΛ int. would inform us ΛΛN int. effects.**
  - **ΛΛ-ΞN couples in vacuum**
  - **Coupling is suppressed in $^{6}_{\Lambda\Lambda}He$**



Is there Any way to access vacuum ΛΛ int. experimentally ?

Interactions btw short-lived hadrons

- Scattering, Nuclear bound state, Atomic shift



NS matter grant

- Exotic hadron spectroscopy
- Correlations from heavy-ion collisions
  - STAR data of ΛΛ correlation

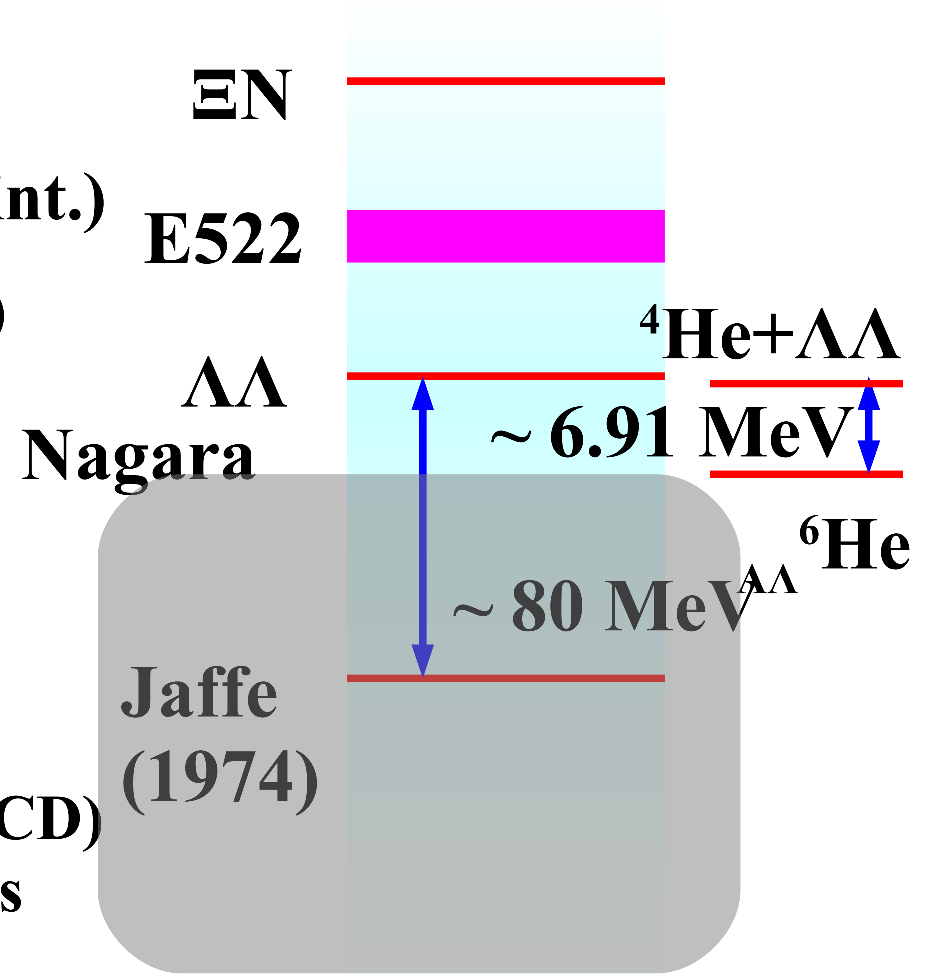
This Lecture

Contents

- Introduction
  - Massive NS and NS matter EOS
  - Strangeness in NS matter
  - "Universal" Three-Baryon Repulsion
- Constraint on ΛΛ interaction from HIC
  - ΛΛ correlation in heavy-ion collisions
  - Constraint on ΛΛ interaction from HIC data
- Discussion
  - Can we see the difference btw vacuum and in-medium ΛΛ interaction ?
  - Do we see H in ΛΛ correlation ?
- Summary

Where is the S=-2 dibaryon (uuddss) "H" ?

- Jaffe's prediction (1977)
  → 80 MeV below ΛΛ
  (strong attraction from color mag. int.)
- Double hypernuclei $_{\Lambda\Lambda}{}^{6}$He (Nagara)
  → No deeply bound "H"
- Resonance or Bound "H" ?
  - KEK-E522 (Yoon et al., ('07))
    → "bump" at $E_{\Lambda\Lambda} \sim 15$ MeV
  - Lattice QCD (HAL QCD & NPLQCD)
    → bound H at large ud quark mass
- How about HIC ?
  - RHIC & LHC = Hadron Factory including Exotics
  - "H" would be formed as frequently as stat. model predicts.
    Cho,Furumoto,Hyodo,Jido, Ko, Lee,Nielsen,AO,Sekihara,Yasui,Yazaki (ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302



Nagara event

- $_{\Lambda\Lambda}{}^{6}$He hypernuclei

  Takahashi et al., PRL87('01)212502

  (KEK-E373 experiment)

Lambpha

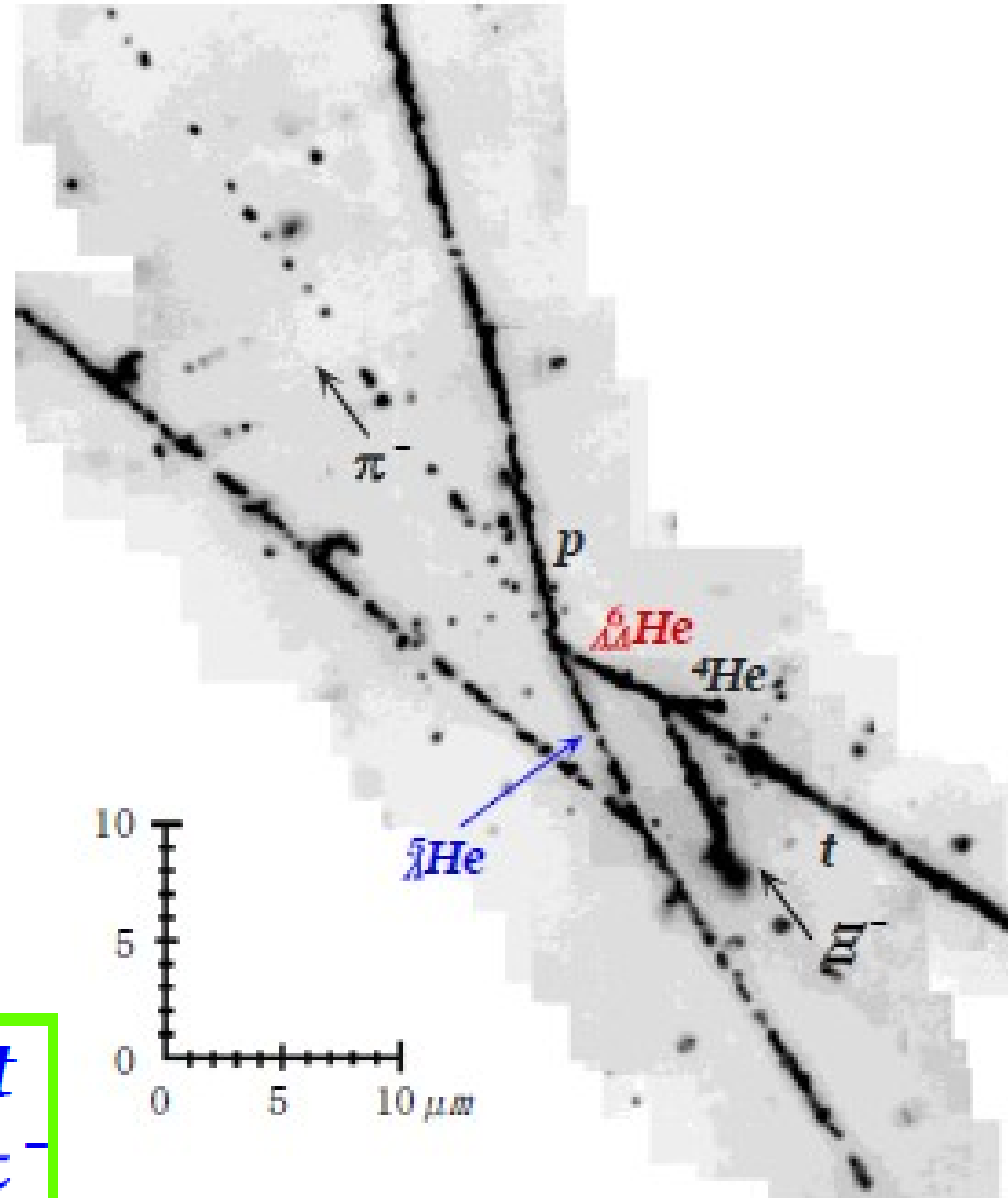
$$m({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 5951.82 \pm 0.54\,\mathrm{MeV}$$

$$B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}\,\mathrm{MeV}$$

(assumed $B_{\Xi^-} = 0.13$ MeV)

→ $B_{\Lambda\Lambda}$ = 6.91 MeV (PDG modified(updated) Ξ^- mass)

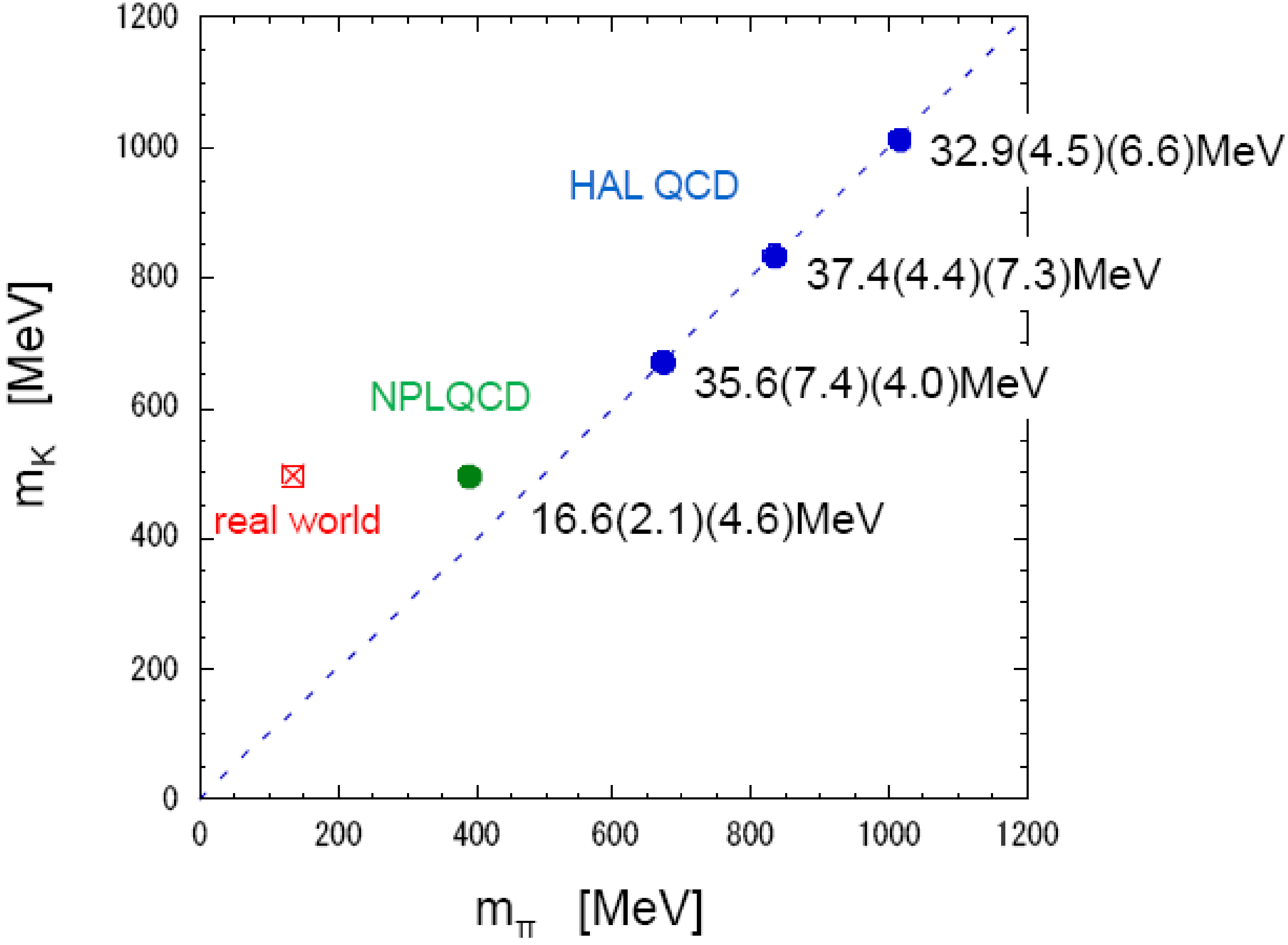


$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$${}^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

Lattice QCD predicts bound "H"

- **"H" bounds with heavy π (M_π > 400 MeV)**



NPLQCD Collab., PRL 106 (2011) 162001; HAL QCD Collab.,PRL 106 (2011) 162002

Hadron-Hadron correlation in HIC

- **Hanbury-Brown and Twiss Effects for free bosons**

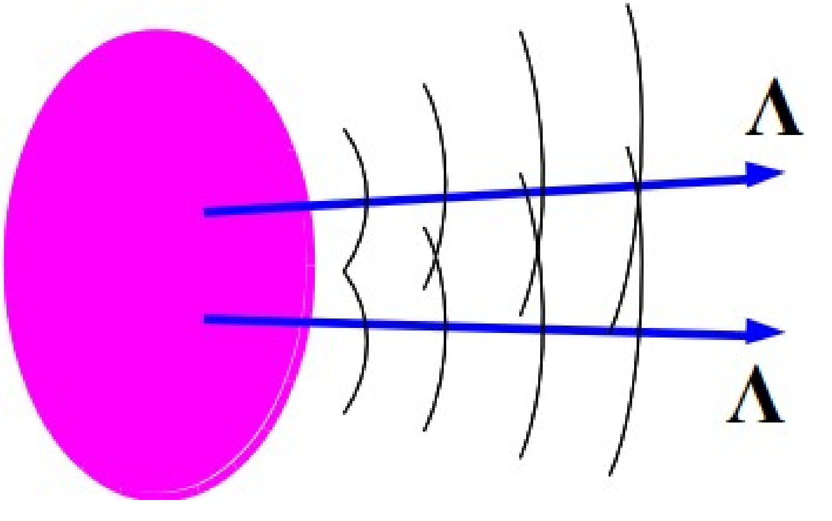
$$C(q) = \int d\boldsymbol{x} \underbrace{\frac{\exp(-\boldsymbol{x}^2/4R^2)}{(4\pi R^2)^{-3/2}}}_{\text{Source}} \underbrace{|\sqrt{2}\cos \boldsymbol{q}\cdot\boldsymbol{x}|^2}_{|\Psi|^2} = 1 + \exp(-4q^2 R^2)$$

- **Correlation func. ~ ∫ Source x |Ψ|²**
  → If source is known, corr. fn. tells us w.f. or interaction.
  Bauer, Gelbke, Pratt ('92); Lednicky ('09).

- **ΛΛ correlation is measured in (K-,K+) reaction**
  C.J.Yoon et al. (KEK-E522)('07); J.K.Ahn et al. (KEK-E224)

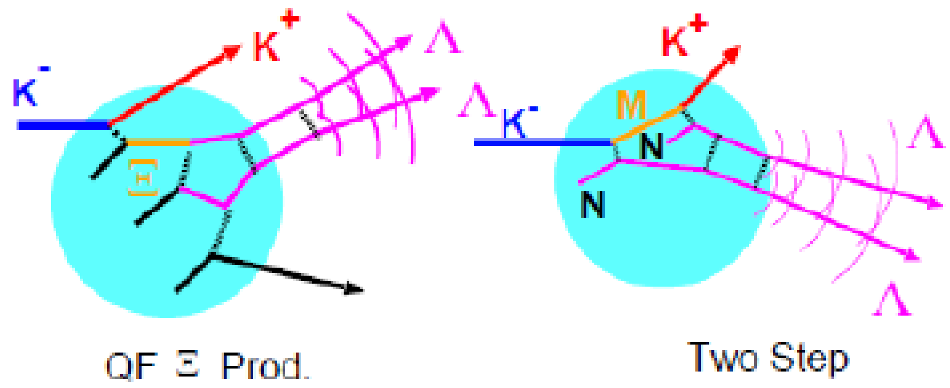
- **STAR measured ΛΛ correlation at RHIC**
  N. Shah et al.('12)

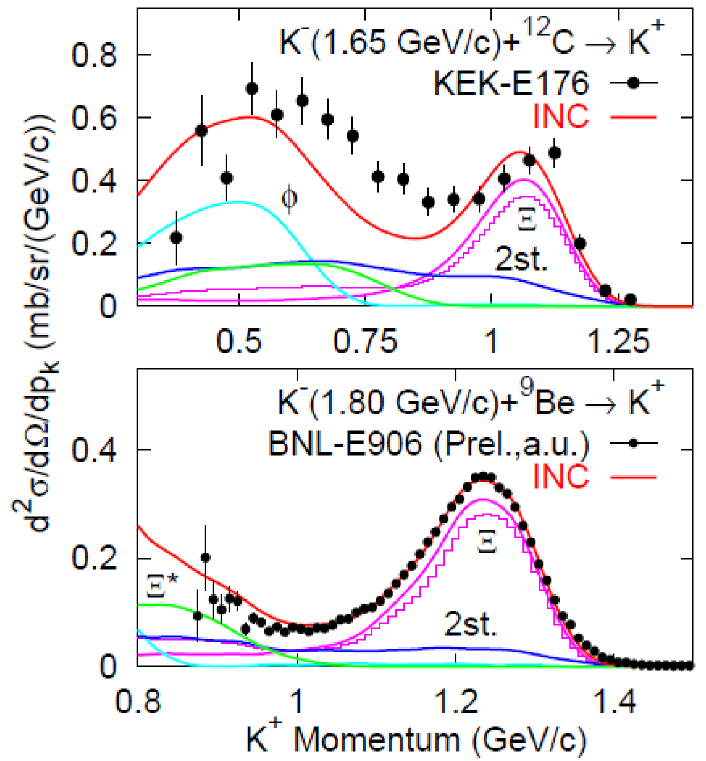
Let's try to constrain ΛΛ interaction !

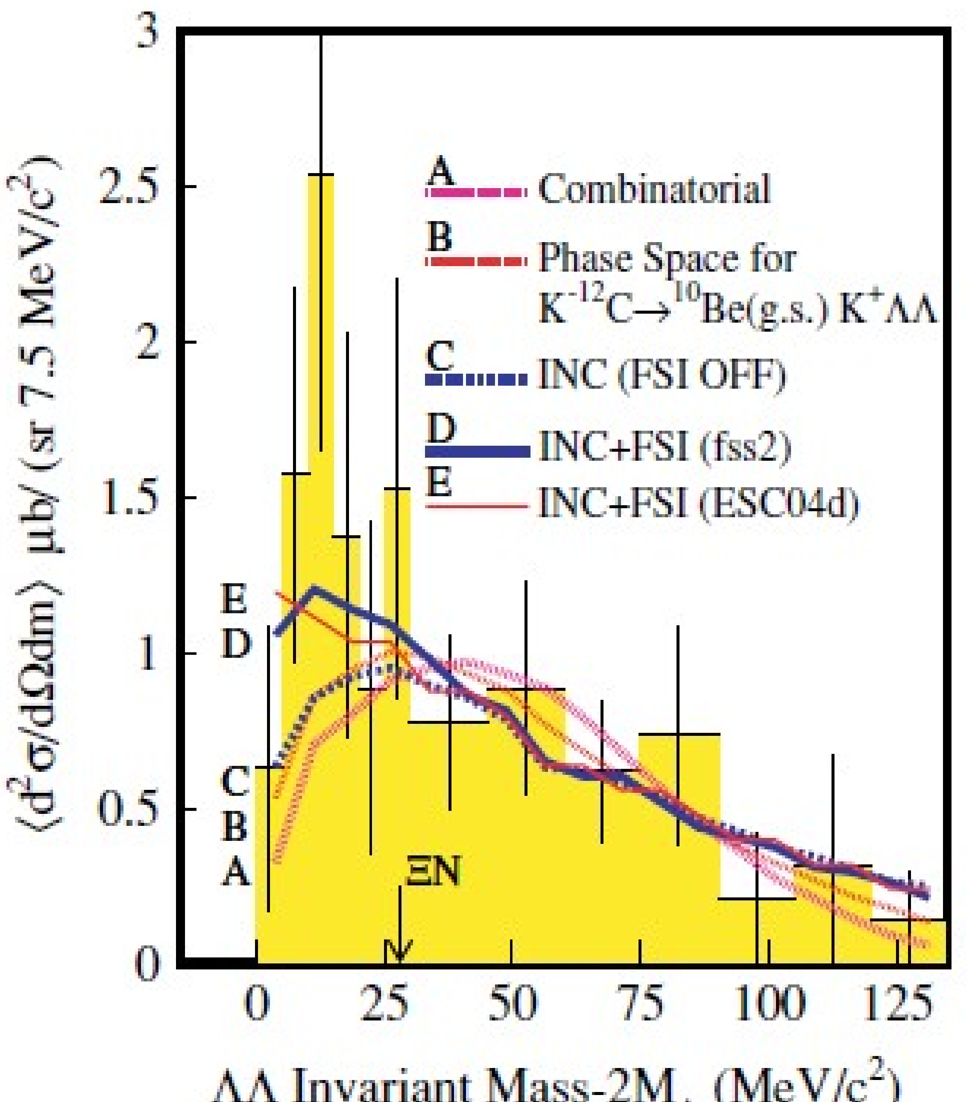


$\Lambda\Lambda$ correlation from $(K^-,K^+\Lambda\Lambda)$ reaction

- **Enhancement at ~ 2 M(Λ)+ 10 MeV,**

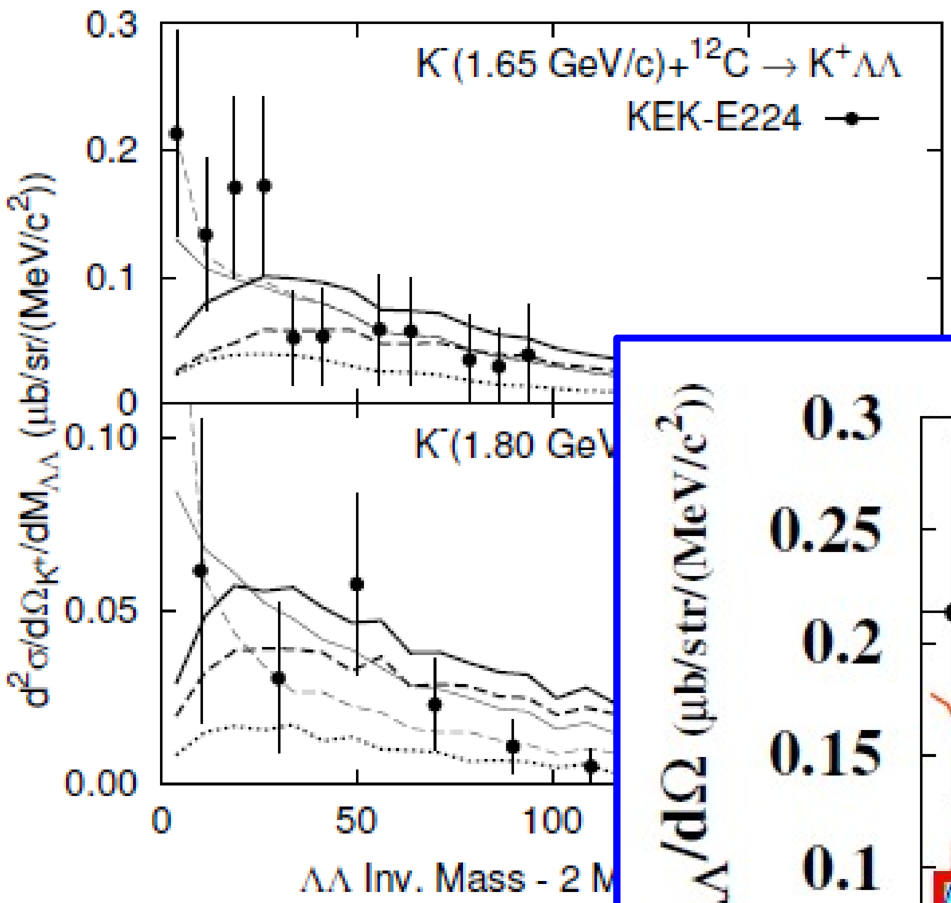






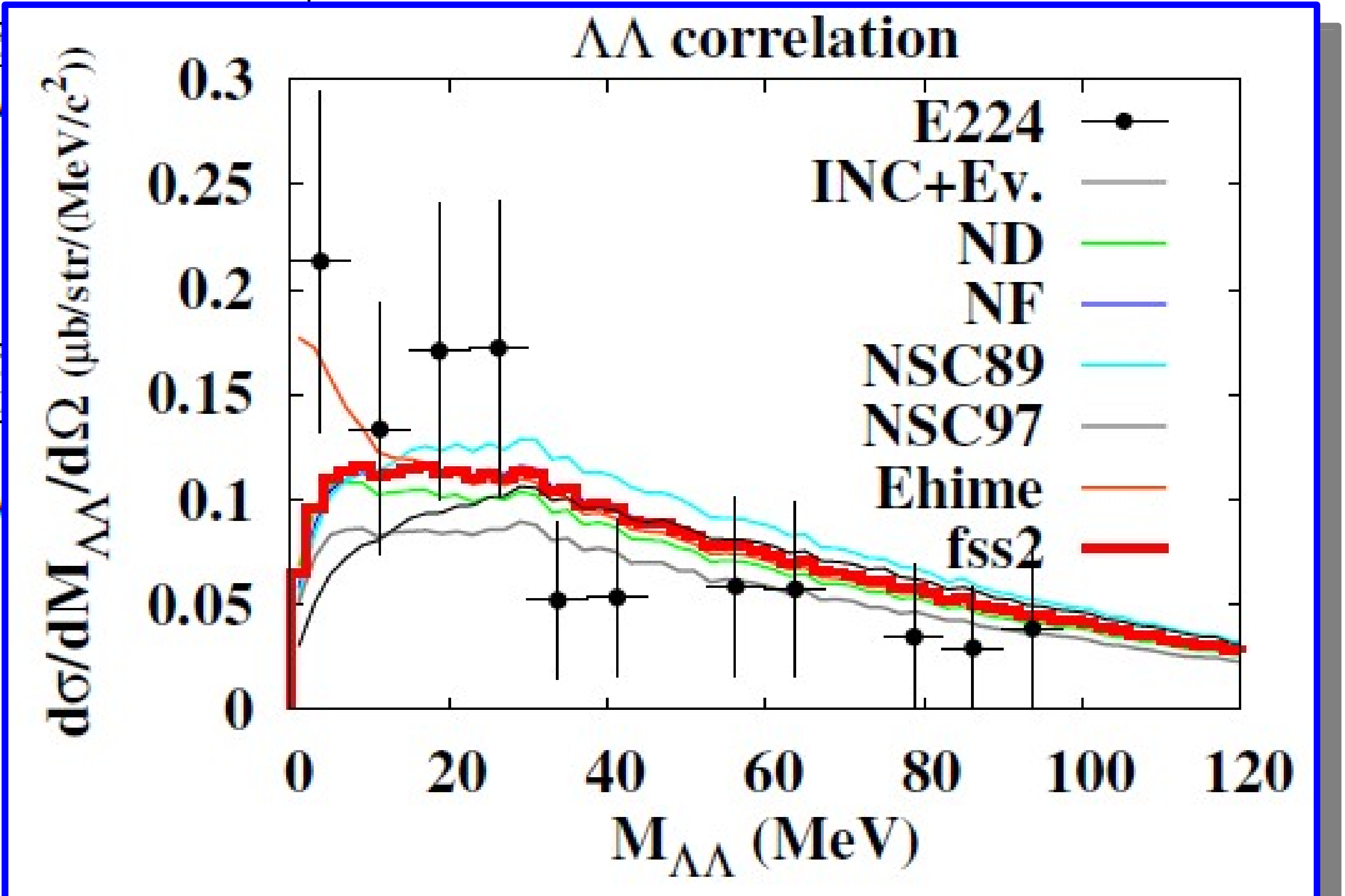
C.J.Yoon, …, (KEK-E522),AO, PRC75 (2007) 022201(R)
J. K. Ahn et al. (KEK-E224).

ΛΛ Invariant Mass Spectrum



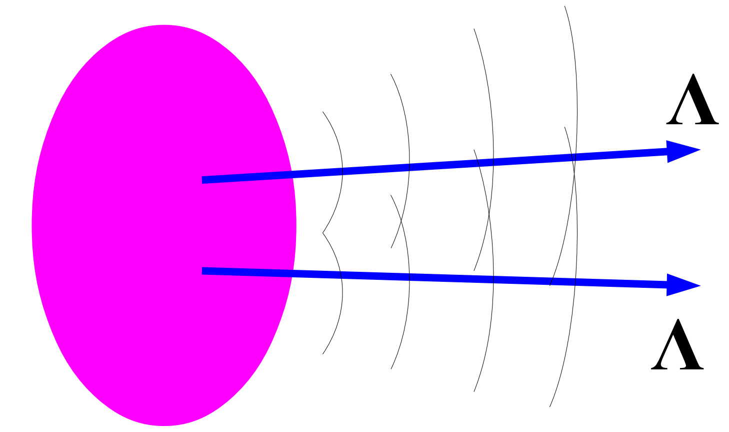
$\Lambda\Lambda$ int. constrained in HIC are consistent with ΛΛ inv. mass spectrum in (K^-,$K^+\Lambda\Lambda$)

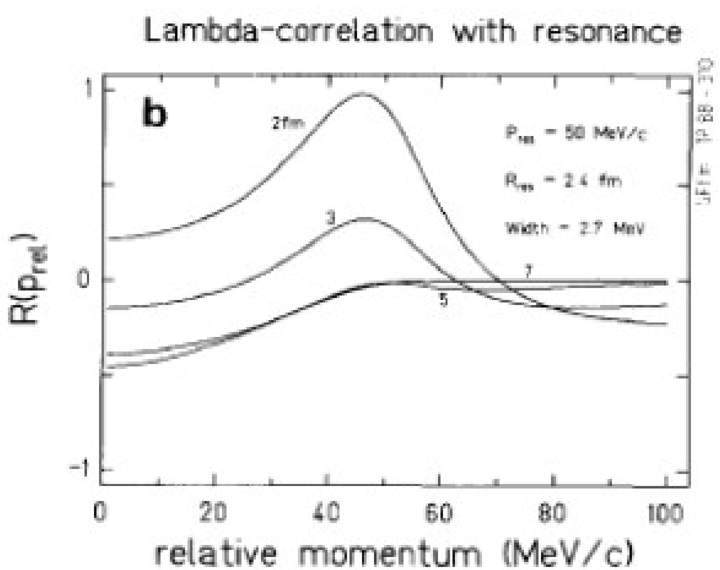
AO, Hirata, Nara, Shinmura, Akaishi, NPA684(2001), 595c



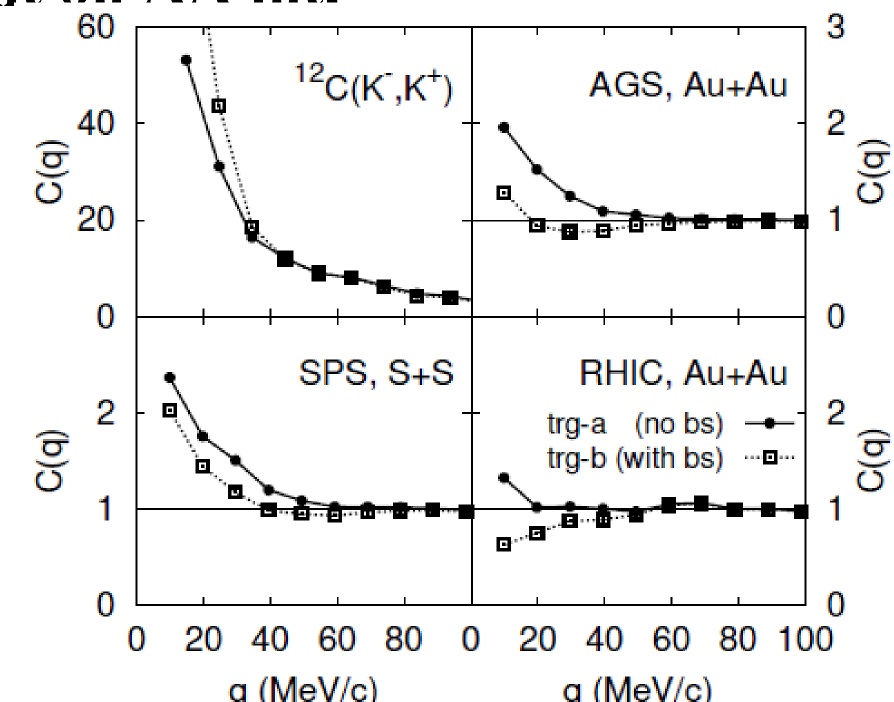
ΛΛ correlation in HIC

- **Merit of HIC to measure ΛΛ correlation**
  - **Source is “Simple and Clean” !**
    T, μ, flow, size, … are well-analyzed.
  - **Nearly Stat. prod.**
    → Many exotics will be produced.
    Cho et al.(ExHIC Collab.) ('11)
  - **Discovery of “H” and/or Constraint on ΛΛ int.**



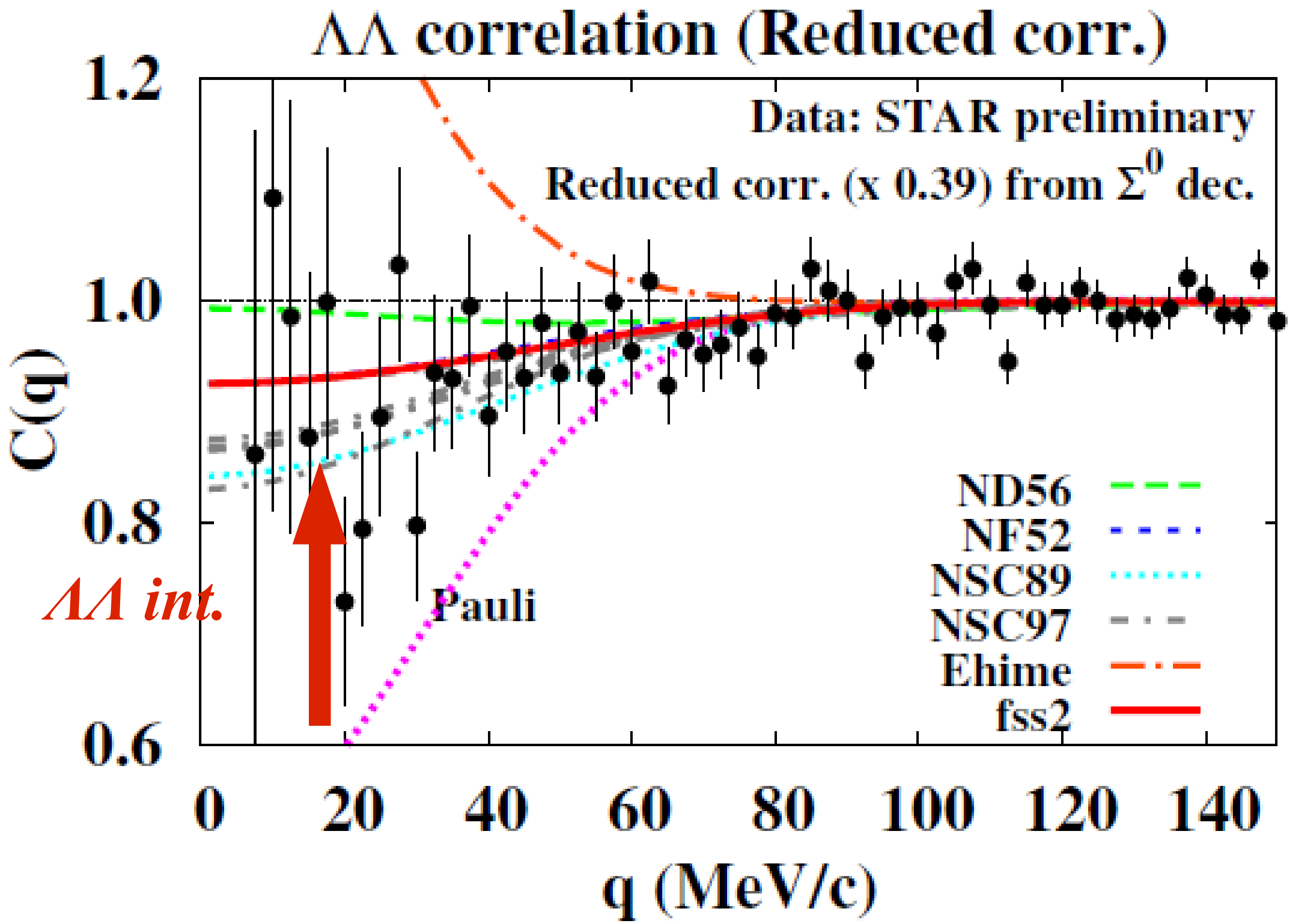


C. Greiner, B. Muller, PLB219('89)199.



AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c

ΛΛ correlation at RHIC



Data (STAR prelim.): N. Shah et al.('12), Cal.: AO for ExHIC ('13)

$\Lambda\Lambda$ interaction models

- **Boson exchange potentials**
  - **Nijmegen potentials: various versions** *Rijken et al., ('77-'10)*
    Hard core: Nijmegen model D & F (ND, NF)
    Soft core: Nijmegen soft core '89 & '97 (NSC89, NSC97)
    Extended soft core: ESC08
  - **Ehime potential: would be too attractive.** *Ueda et al., ('98)*
    Ehime fits old double Λ hypernucl. data, $\Delta B_{\Lambda\Lambda}$ =4 MeV
- **Quark cluster model**
  - **fss2** *Fujiwara, Kohno, Nakamoto, Suzuki ('01)*
    Short range repulsion from quark Pauli blocking & OGE
    Core is softer due to non-locality
- **Modified Nijmegen potentials fitting Nagara data.**
  Filikhin, Gal ('02), Hiyama et al.('02)
  - **Potential Fitting Nagara data $\Delta B_{\Lambda\Lambda}$ =1.0 MeV**

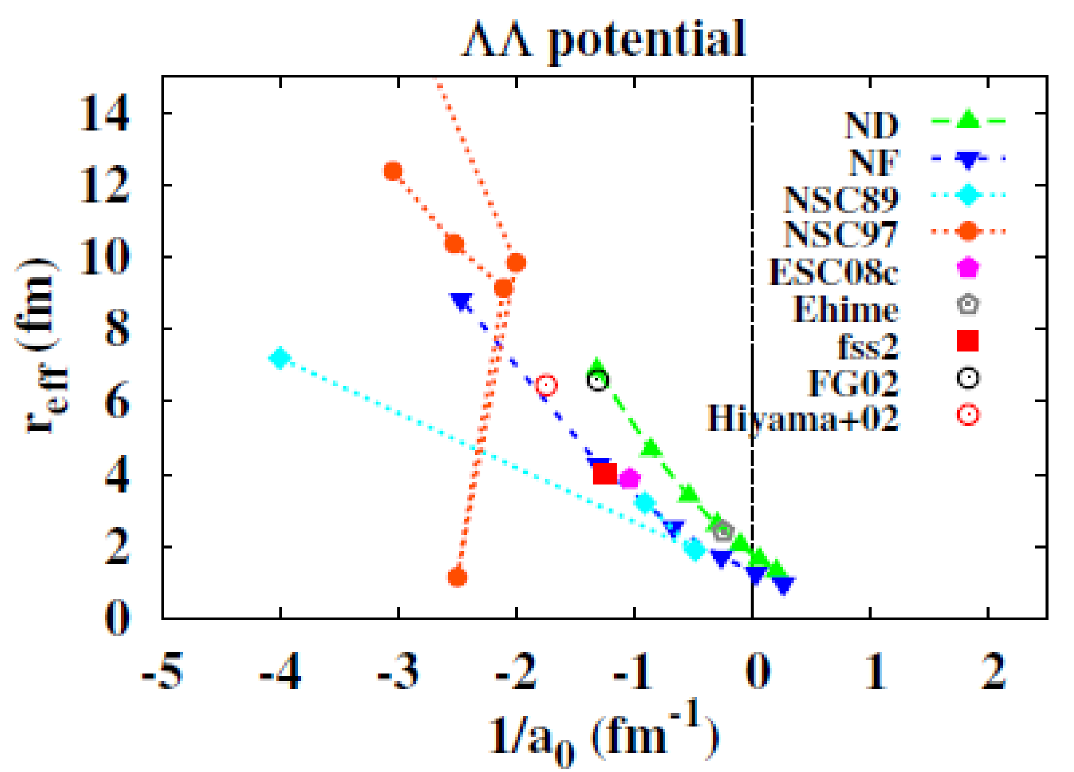
ΛΛ interaction models

- **Low energy scattering parameters, (a_0, r_{eff})**

$$k \cot \delta = -\frac{1}{a_0} + \frac{1}{2} r_{\mathrm{eff}} k^2 + O(k^4)$$

  - **$a_0 > 0$ (bound region), $a_0 < 0$ (no bound region)**

- **Potential parameters**
  - **Hard core radius (ND, NF), cutoff mass (NSC89), spin dependence (NSC97a-f).**



$\Lambda\Lambda$ correlation function

- **Two particle correlation function** *Koonin ('77)*

$$C_2(Q,K) = \frac{W_2(k_1,k_2)}{W_1(k_1)W_1(k_2)} = \frac{\int d^4x_1 d^4x_2 S(x_1,K)S(x_2,K)|\Psi_{12}(Q,\boldsymbol{x_1}-\boldsymbol{x_2}-(t_2-t_1)\boldsymbol{K}/m)|^2}{\int d^4x_1 d^4x_2 S(x_1,k_1)S(x_1,k_2)}$$

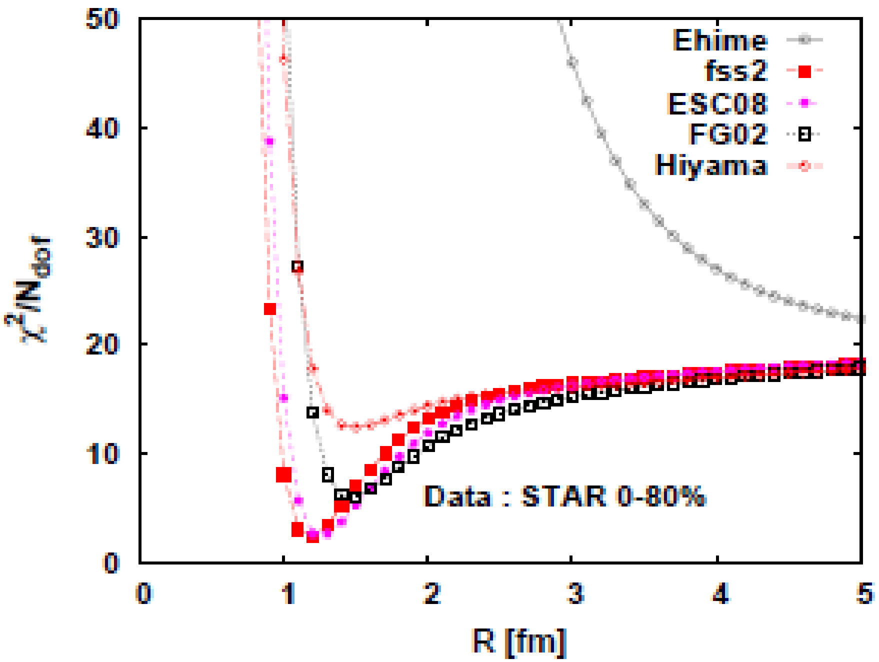
  - **W_1(k), W_2(k_1,k_2): 1 & 2 partcl. dist., S(x, k): phase spc. dist. Q=(k_1-k_2), K=(k_1+k_2)/2**
  - **Wave fn. Ψ (assumption: only the s-wave partial wave is modified.)**

$$\Psi_s = \sqrt{2}\left[\cos \boldsymbol{Q}\cdot\boldsymbol{r}/2 + \chi_Q(r) - j_0(Qr/2)\right]$$
$$\Psi_t = \sqrt{2}\, i \sin \boldsymbol{Q}\cdot\boldsymbol{r}/2$$
$$|\Psi_{12}|^2 = 1 - \frac{1}{2}\cos \boldsymbol{Q}\cdot\boldsymbol{r} + \cos(\boldsymbol{Q}\cdot\boldsymbol{r}/2)\Delta\chi_Q(r) + [\Delta\chi_Q(r)]^2$$
$$\Delta\chi_Q(r) = \chi_Q(r) - j_0(Qr/2)$$

Static Spherical Source

- **Correlation fn. with static, spherical gaussian source**

$$C_{\Lambda\Lambda}(Q) \simeq 1 - \frac{1}{2}\exp(-Q^2R^2) + \frac{1}{2}\int dr\, S_{12}(r)\left(|\chi_Q(r)|^2 - |j_0(Qr/2)|^2\right)$$



Morita, Furumoto, AO (to be submitted)

Geometry & Flow Effects

- **Boost invariant source with flow effects**
  S. Chapman, P. Scotto, U. Heinz, Heavy Ion Phys. 1, 1 (1995).

$$S(x,k) = \frac{m_T \cosh(y - Y_L)}{(2\pi)^3\sqrt{2\pi(\Delta\tau)^2}} n_f(u\cdot k, T)\ \exp\left[-\frac{(\tau-\tau_0)}{2(\Delta\tau)^2} - \frac{x^2+y^2}{2R^2}\right]$$

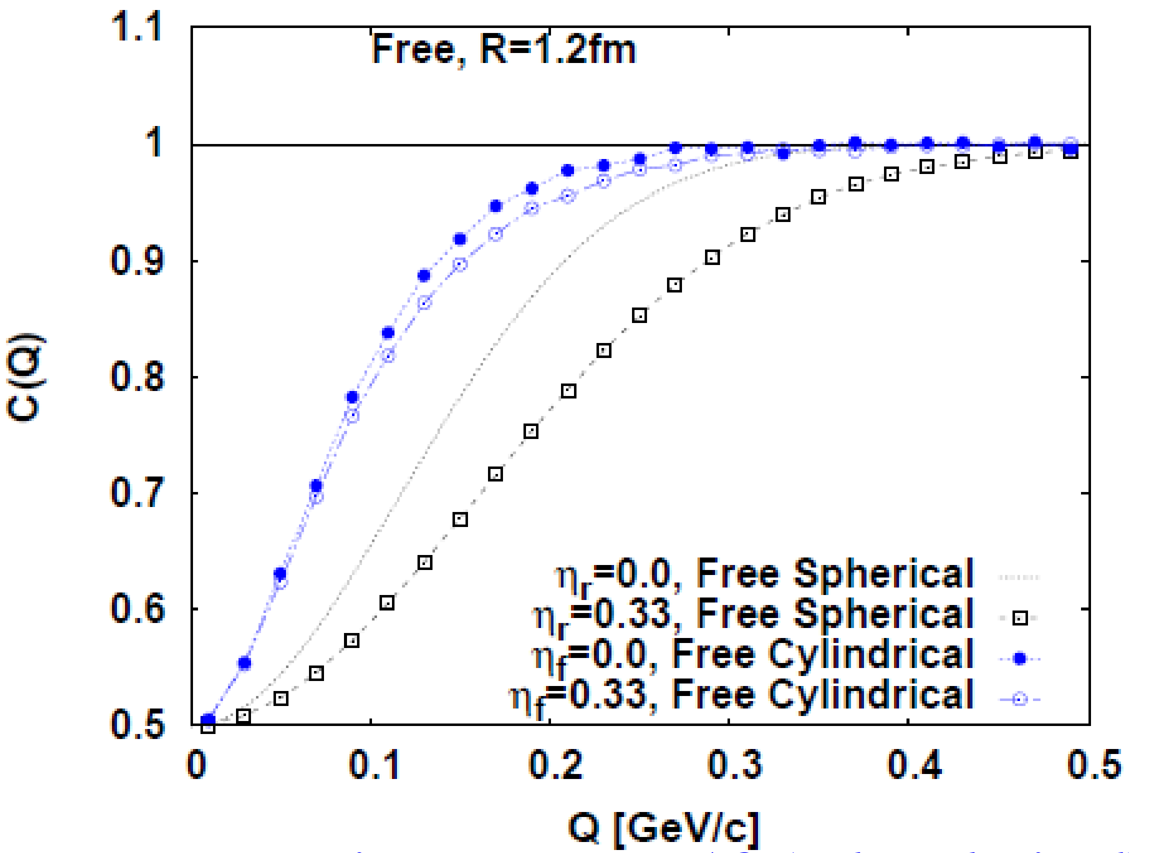
- **Fluid velocity**

$$u^t = \cosh Y_T \cosh Y_L$$
$$u^z = \cosh Y_T \sinh Y_L$$
$$u^x = \sinh Y_T \cos\phi$$
$$u^y = \sinh Y_T \sin\phi.$$

$$Y_L = \eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

$$Y_T = \eta_f \frac{r_T}{R}$$

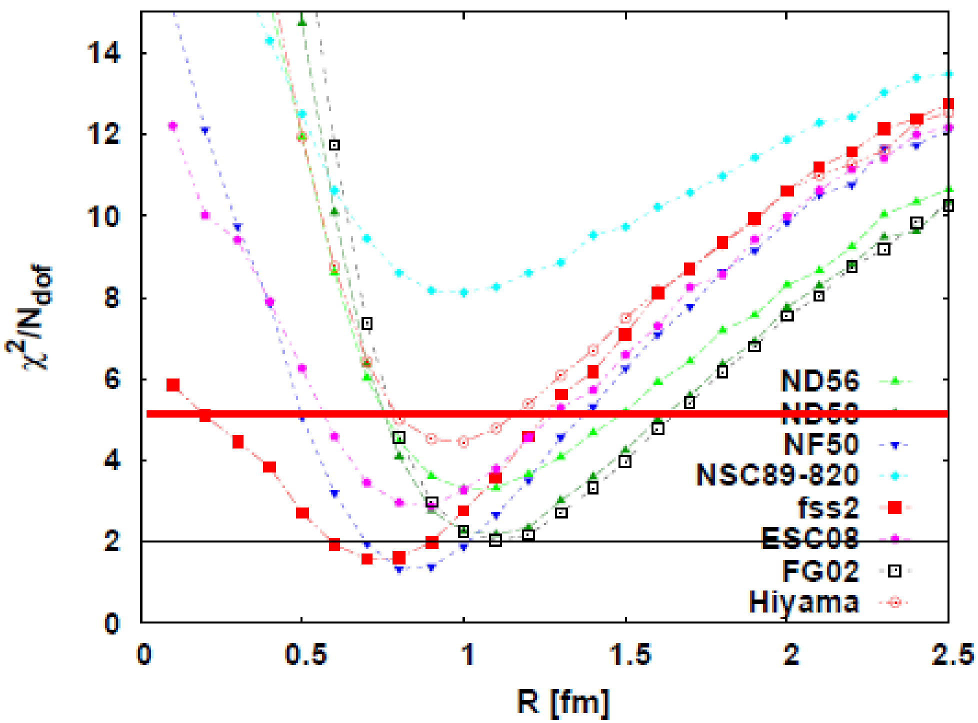
Transverse flow η_f = 0.33
(from m_T spectrum)



Morita, Furumoto, AO (to be submitted)

$\Lambda\Lambda$ correlation with flow effects

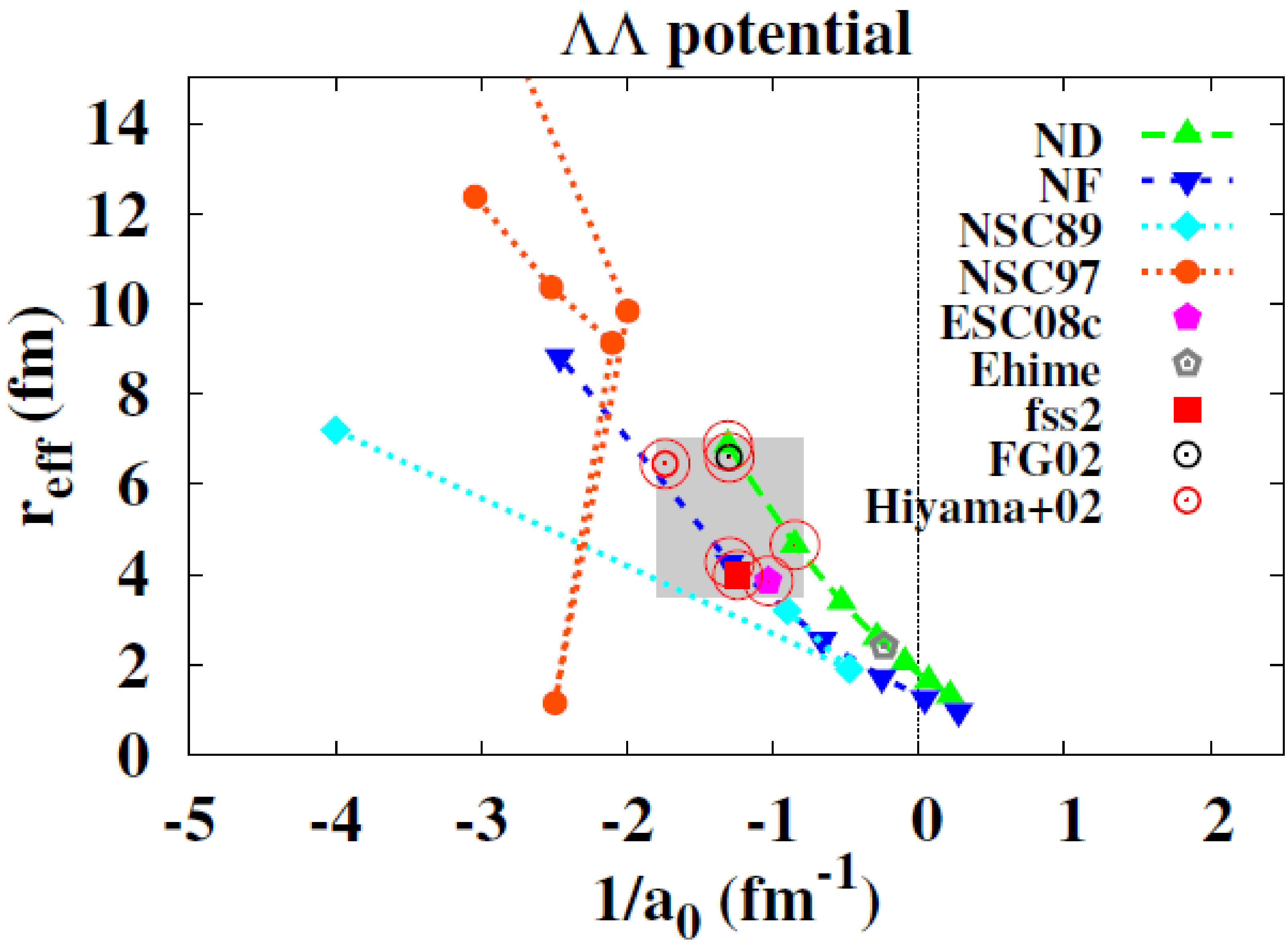
- **Results with flow effects**
  - **Optimal transverse source size R ~ (0.8-1.1) fm**
  - **HBT source size is interpreted as the "homogeneity length", but it is still too small compared with the proton source size, R_p ~ (2-4) fm.**



Cylindrical

Morita, Furumoto, AO (to be submitted)

Preferred ΛΛ interactions



Preferred ΛΛ interaction parameters
$-1.8\ fm^{-1} < 1/a_0 < -0.8\ fm^{-1}$, $3.5\ fm < r_{eff} < 7\ fm$

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  - Do we see H in ΛΛ correlation ?
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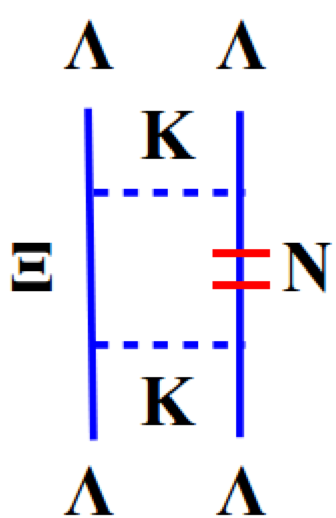
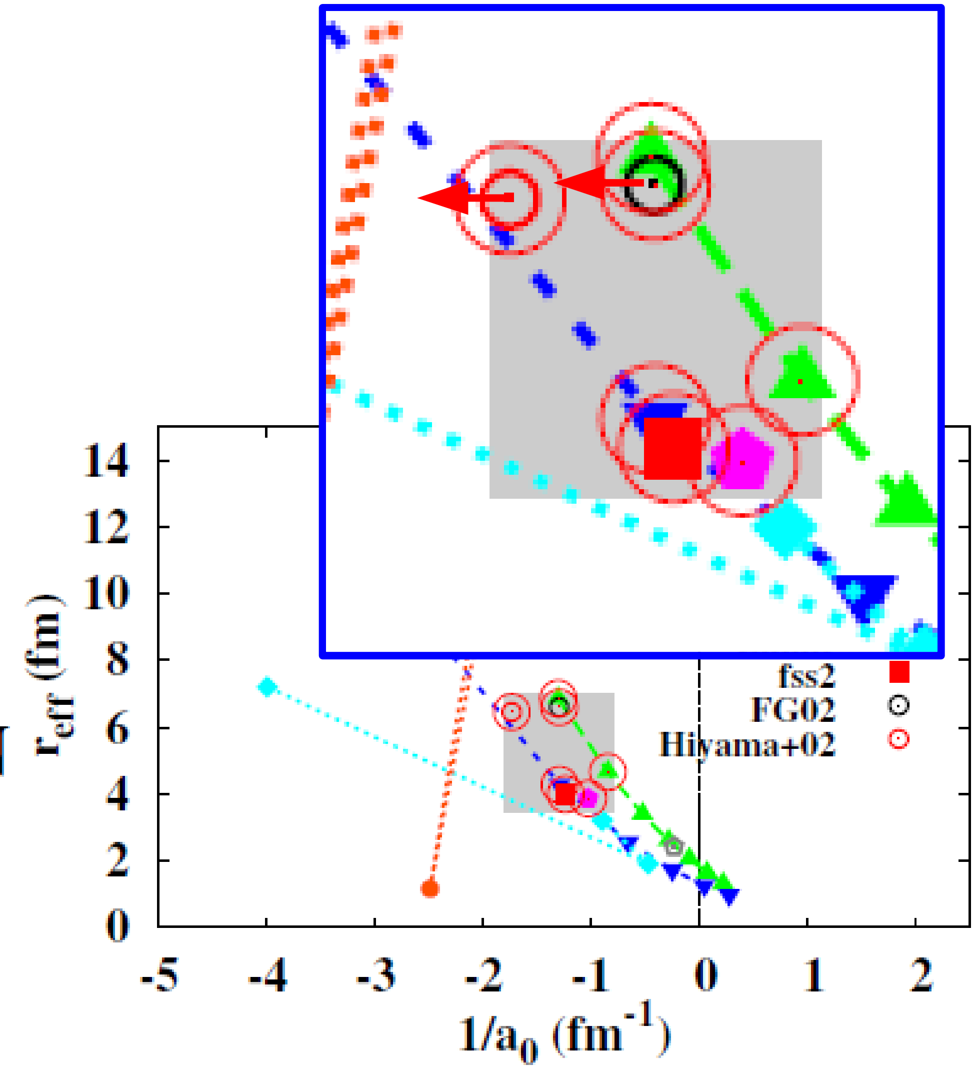
Comparison with In-medium interaction.

- ΛΛ interactions from Nagara event ($\Delta B_{\Lambda\Lambda}$ =1.0 MeV)
  - Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02)
    (a_0 , r_{eff}) = (-0.575 fm, 6.45 fm)
  - Filikhin, Gal ('02)
    (a_0 , r_{eff}) = (-0.77 fm, 6.59 fm)
- Ξ^- mass is updated by PDG
  - Bond energy is updated
    $\Delta B_{\Lambda\Lambda}$ =0.67 MeV
    → a_0 will be reduced
    by 10-20 %
    a_0 ~ -(0.5-0.65) fm





Do we see H as a resonance ?

- **Deeply bound H is ruled out by double Λ hypernuclear mass.**
  $M_H > 2\, M_\Lambda - 6.91$ MeV
- **Existence of H as a resonance is not ruled out.**
  → Let's try to find it !
- **Procedure**
  - **Assume the bump comes from H, and give (E_H, Γ_H).**
  - **Compare the bump height with statistical model yield.**
  - **If H exists at low E (E=(1-2) MeV), we can find the signal by reducing the error by a factor of two.**

Morita, Furumoto, AO (to be submitted)

Other source of correlation ?

- **ΛΛ correlation would be modified by**
  - **Feed down effects from Ξ and Σ^0 decay,**
    $\Xi^- \to \pi^- \Lambda$ (detectable)
    $\Sigma^0 \to \gamma \Lambda$ (will be detectable at LHC (Kwon et al.))
    Σ^0 effects can be taken are of by multiplying 0.41 to (C-1), and preferred V(ΛΛ) are similar to the present result.
  - **If feed down Λ is included, the correlation is affected by the parent pair interaction.**
    E.g. pp correlation is significantly affected by V(pΛ).
    ($\Lambda \to \pi^-$ p and no Coulomb suppression in pΛ channel.)

    Since there is no Coulomb suppression in ΛΛ pair, parent pair interaction effects may be less serious than in pp correlation.
- **Further investigation is necessary to pin down ΛΛ interaction more precisely.**

Summary of Lecture(?) 5

- **We need additional repulsion to solve massive neutron star puzzle related to strangeness hadrons.**
  - **Need exp. data and ab initio calc.
    J-PARC exp. / Lattice BB and BBB int. / Ch-EFT**
- **We have constrained ΛΛ low energy scattering parameters using ΛΛ correlation data from STAR collaboration.**
  - **Optimal source size & flow parameter are fixed by using correlation and pT spectrum.**
  - **Preferred scattering parameters are found to be in the range,**
    $-1.8\ \mathrm{fm}^{-1} < 1/a_0 < -0.8\ \mathrm{fm}^{-1}$, $3.5\ \mathrm{fm} < r_{eff} < 7\ \mathrm{fm}$
  - **Other mechanisms may need to be taken care of.**
- **Information on ΛΛN may be accessible via correlation in HIC**
  - **In-medium ΛΛ interaction seems to be weaker than vacuum interaction.**

Report 問題

- 中性子、陽子、電子のみからなる中性子星物質を考える。電子の質量を無視すると、核子あたりのエネルギーは、Lecture 1 で示したように

$$E_{\mathrm{NSM}}(\rho)=E_{\mathrm{SNM}}(\rho)+S(\rho)\delta^2+\frac{\Delta M}{2}\delta+\frac{3}{8}\hbar k_F(1-\delta)^{4/3}$$

  と与えられる。ここで $\Delta M=M_n-M_p$、k_F は同じ密度での対称核物質のフェルミ波数である。非対称度 δ は、核子あたりのエネルギーが最小になるように選ばれる。
  - 上の表式を導け。
  - 核子あたりのエネルギーが最小となる非対称度 δ を求めよ。
    (３次方程式を解くこととなる。$S(\rho)$, k_F, ΔM は与えられているとしてよい。)
- 今回の講義において、中性子物質の物理の課題の中で各自が興味を持った項目をあげ、その理由を述べよ。

単位認定について

- 次の条件で単位を出します。
  - 6コマの講義中、4コマ以上出席。
  - 6コマの講義中、1コマ以上出席し、レポートを提出。
- レポート問題は Lec.2 後にお知らせしたものです。
  1つ目の問題を次の問題に置き換えてもよい。
  - SU(3) 不変な相互作用

$$\mathcal{L}_{\rm BV} = \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\left(\bar{B}B\right) + g_D\,{\rm tr}\left(\bar{B}\left\{M_v, B\right\}\right) + g_F\,{\rm tr}\left(\bar{B}\left[M_v, B\right]\right)\}$$
$$= \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\left(\bar{B}B\right) + g_1\,{\rm tr}\left(\bar{B}M_vB\right) + g_2\,{\rm tr}\left(\bar{B}BM_v\right)\}$$

において、バリオン・メソンの結合定数を g_D, g_F, g_s を用いて表せ。

Thank you

ΛΛ interaction and correlation

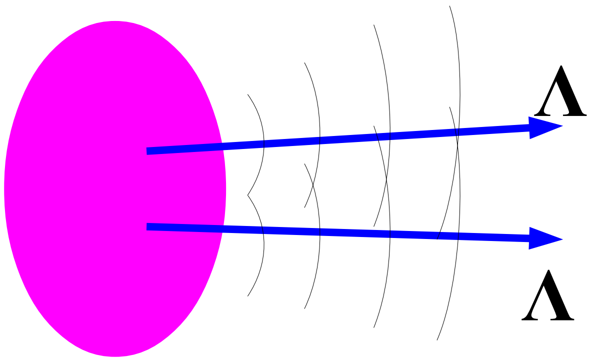
- ΛΛ int.
  - Nijmegen models
    Rijken et al.
  - quark model (fss2)
    Fujiwara et al. (‘01)
  - Nagara fit
    Filikhin, Gal (‘02);
    Hiyama et al.(‘02)
- Source models
  - sph. static source
  - cylindrical source w/ flow

K. Morita, AO, T. Furumoto (in prep.)

ΛΛ correlation in HIC and ΛΛ interaction

- **Two particle correlation from chaotic source**

  c.f. Bauer, Gelbke, Pratt,
  Annu. Rev. Nucl. Part. Sci. 42('92)77.

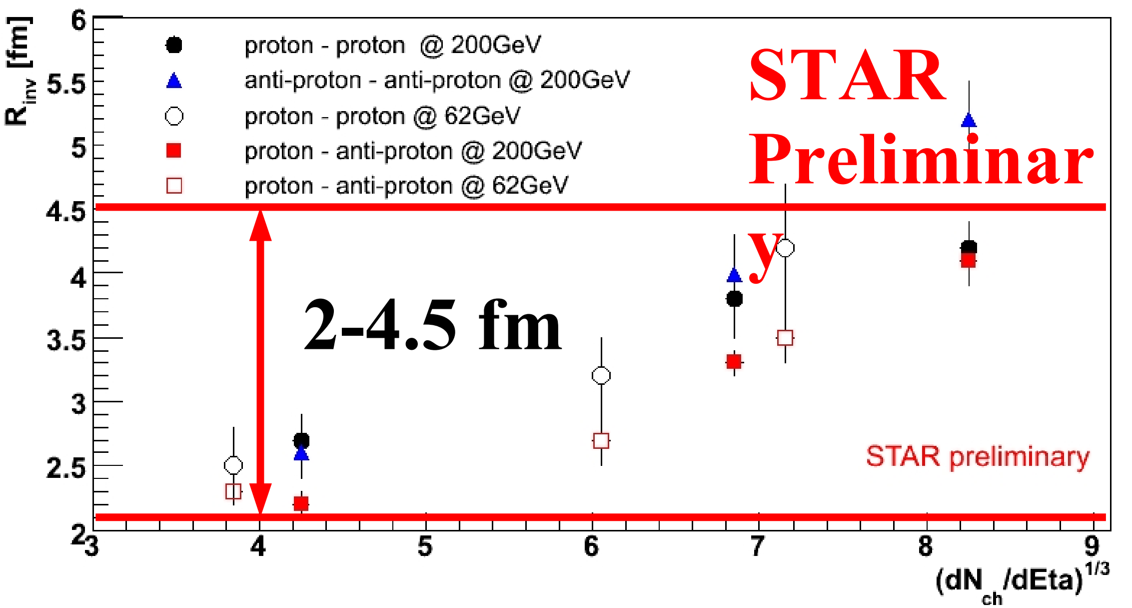


$$C_{\Lambda\Lambda}(q) = \frac{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q) |\psi^{(-)}(x_{12}, q)|^2}{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q)}$$

$$\simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int dr\, S_{12}(r)\left(|\chi_0(r)|^2 - |j_0(qr)|^2\right)$$

(χ_0 : s-wave wave func., $S_{12}(x) = (2R\sqrt{\pi})^{-3} \exp(-r^2/4R^2)$)

- **Baryon Source size**
  R = (2-4.5) fm
  - **Smaller than π, K source.**



$\Lambda\Lambda$ interaction

- **Type of ΛΛ interactoin**
  - **Meson exchange models: Nijmegen model D, F, Soft Core (89, 97)**
    Nagels, Rijken, de Swart ('77, '79), Maessen, Rijken, de Swart ('89), Rijken, Stoks, Yamamoto ('99)
  - **Quark cluster model interaction: fss2**
    Fujiwara, Fujita, Kohno, Nakamoto, Suzuki ('00)
  - **Phenomenological model: Ehime**
- **Two (or three) range gaussian fit results are used in the analysis.**