

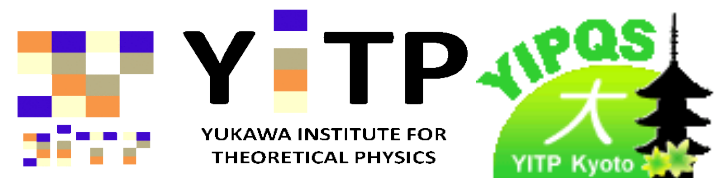
Lambda-Lambda correlation in (K^- , K^+) reactions and in HIC

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YITP, Kyoto Univ.

- Introduction: Where is “H” ?
- $\Lambda\Lambda$ correlation in heavy-ion collisions
- $\Lambda\Lambda$ correlation in (K^- , K^+) reaction
- Summary

*Hyperon-Hyperon Interactions and
Searches for Exotic Di-Hyperons in Nuclear Collisions
Feb.29-Mar.2, 2012, BNL*

AO, Furumoto, in prep.



Where is the $S=-2$ dibaryon ($uuddss$) “H” ?

- Jaffe's prediction (1977)
 - 80 MeV below $\Lambda\Lambda$
 - (strong attraction from color mag. int.)

- Double hypernuclei ${}_{\Lambda\Lambda}{}^6\text{He}$ (Nagara)
 - No deeply bound “H”

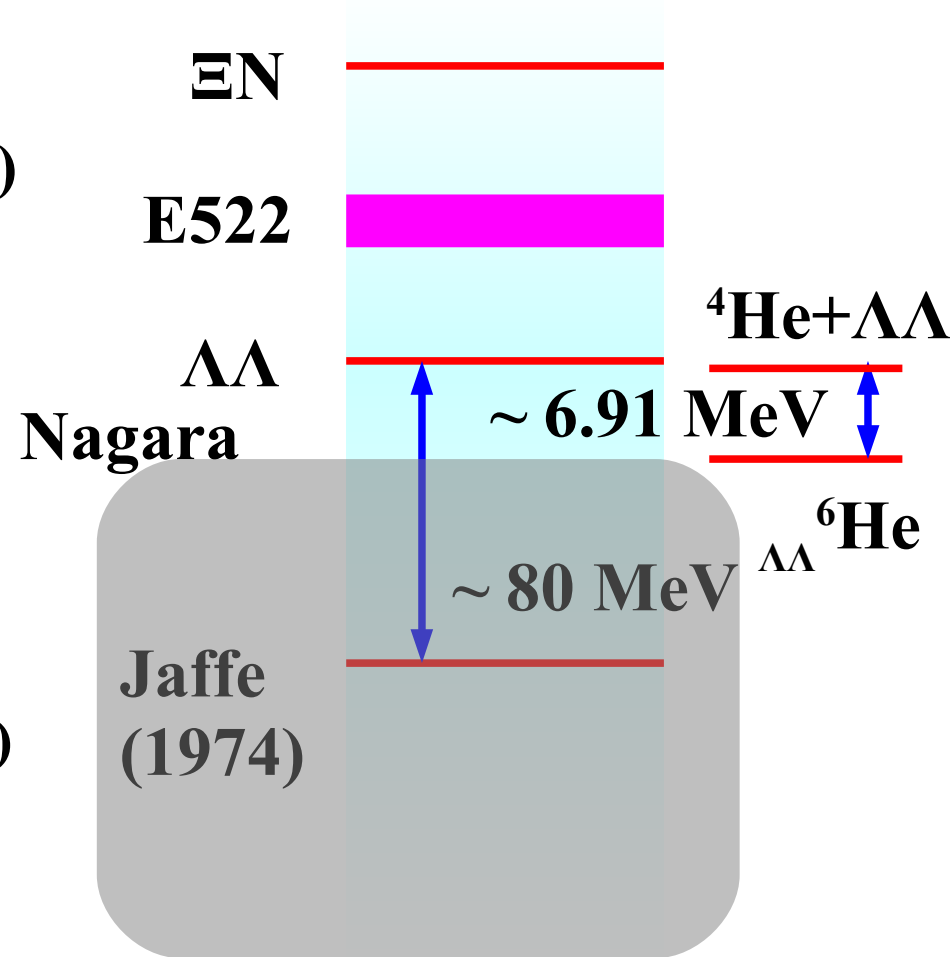
- Resonance or Bound “H” ?

- 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

■ ${}_{\Lambda\Lambda}{}^6\text{He}$ hypernuclei

Takahashi et al., PRL87('01)212502

(KEK-E373 experiment)

Lambpha

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

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

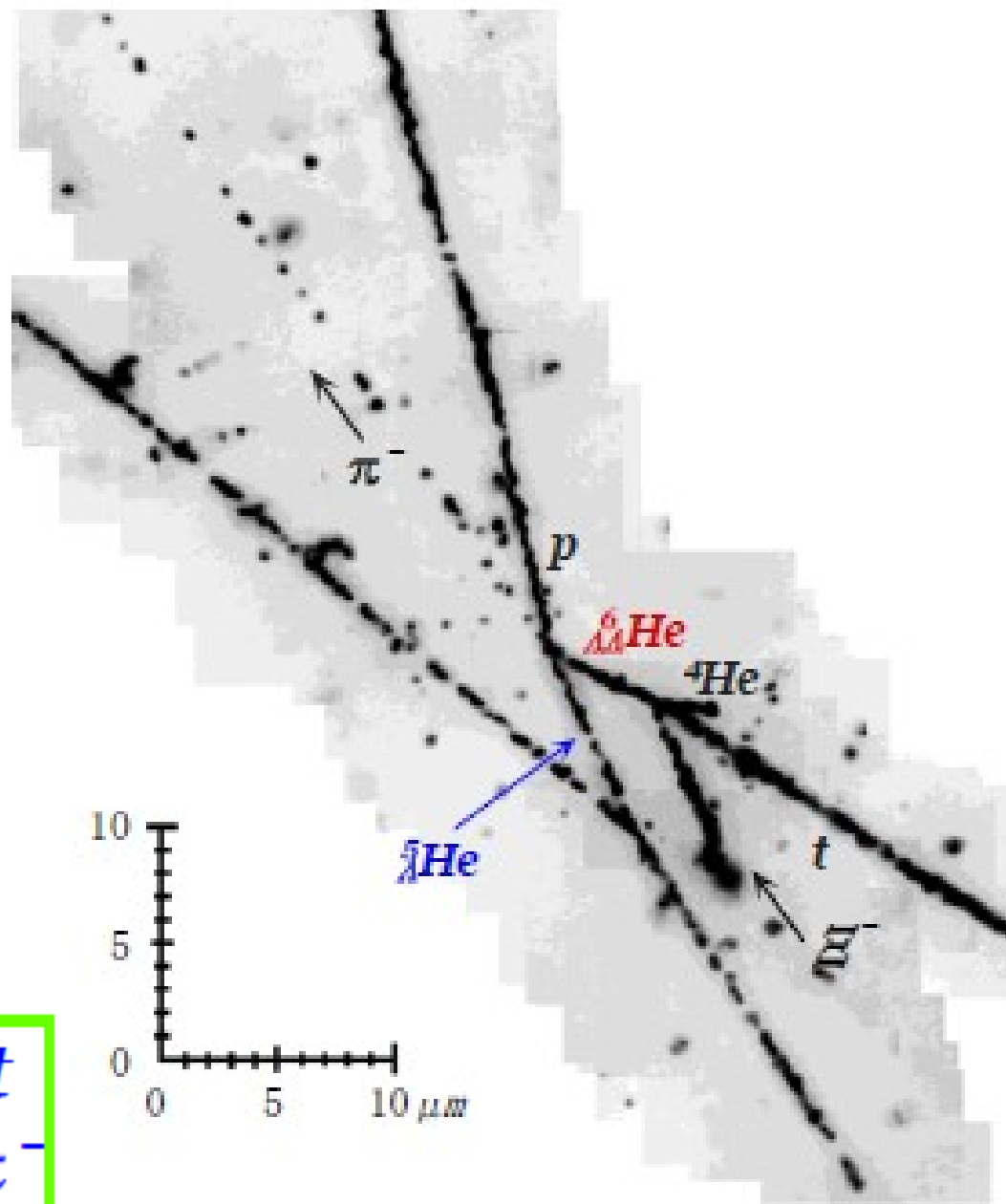
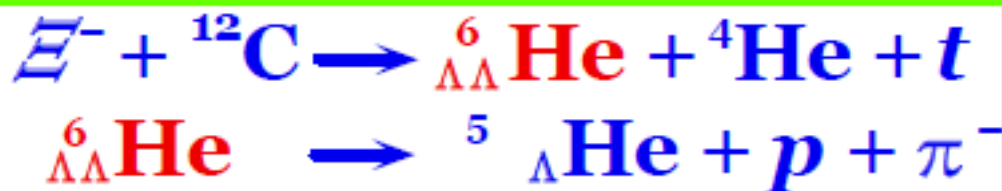
$$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20_{-0.11}^{+0.18} \text{ MeV}$$

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

$$\rightarrow B_{\Lambda\Lambda} = 6.91 \text{ MeV}$$

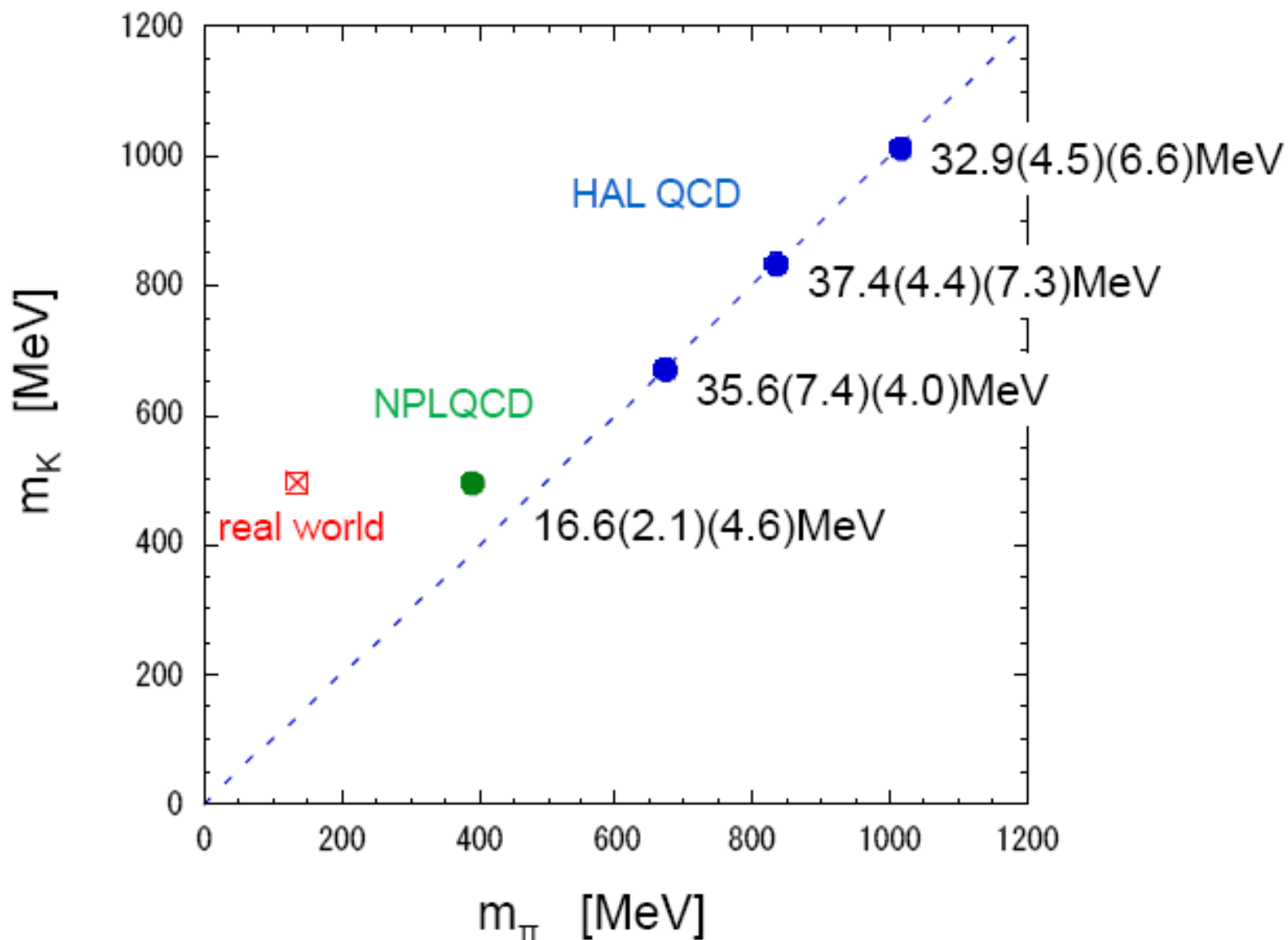
(PDG modified(updated)

Ξ^- mass)



Lattice QCD predicts bound “H”

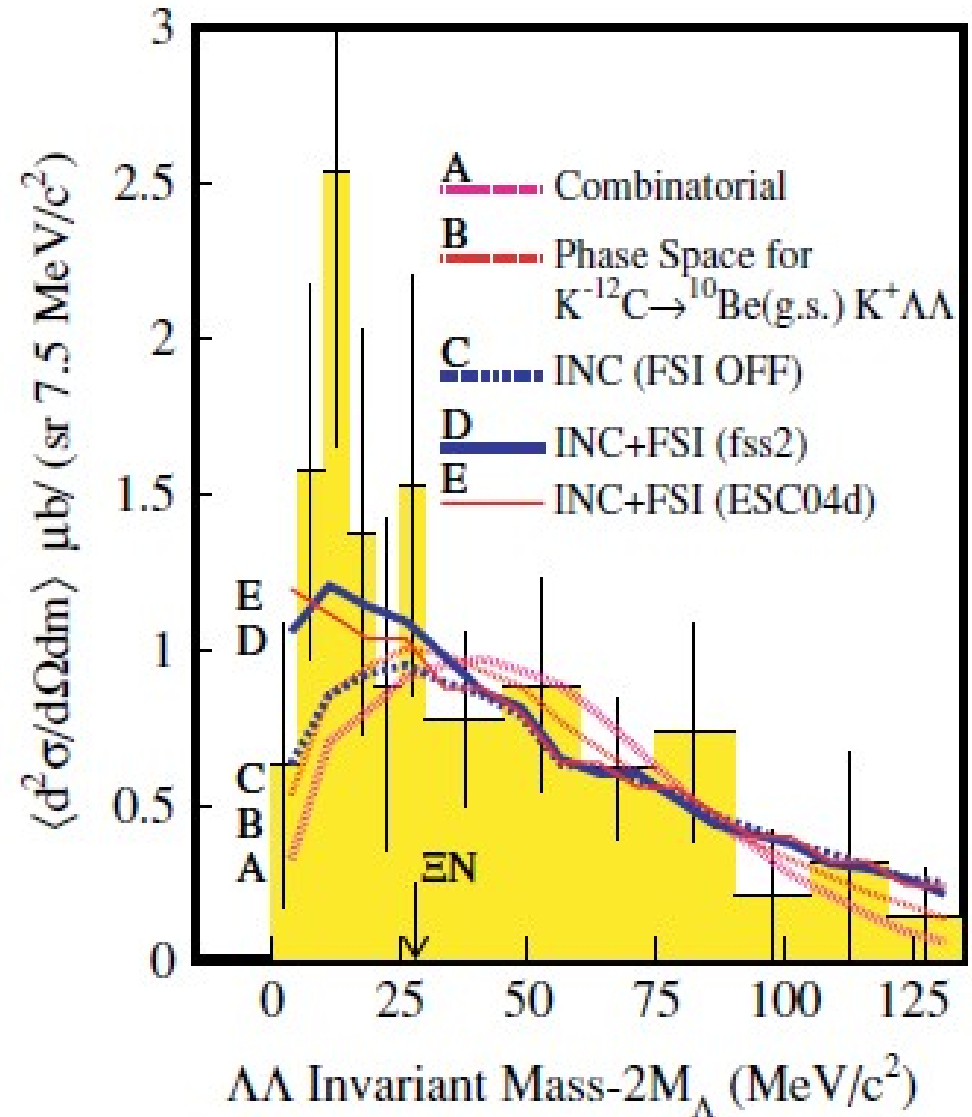
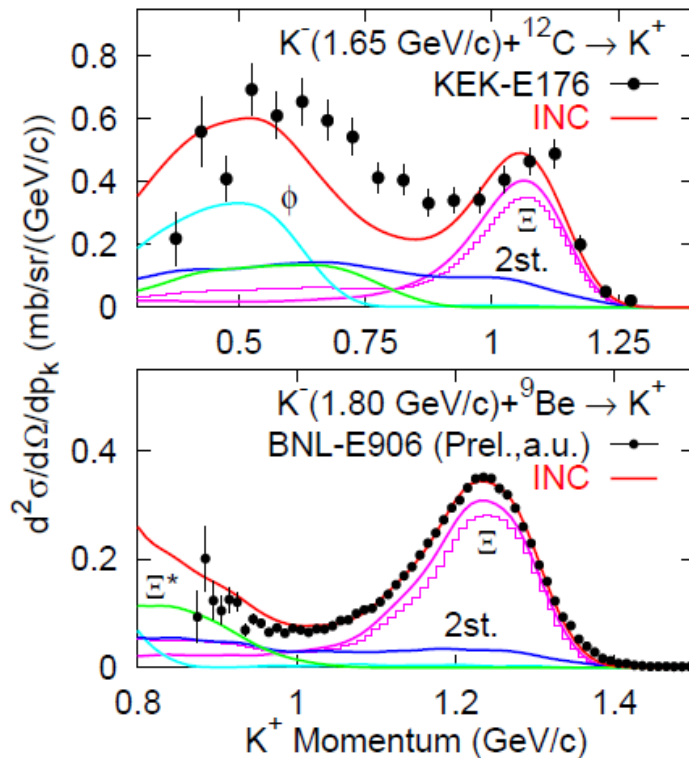
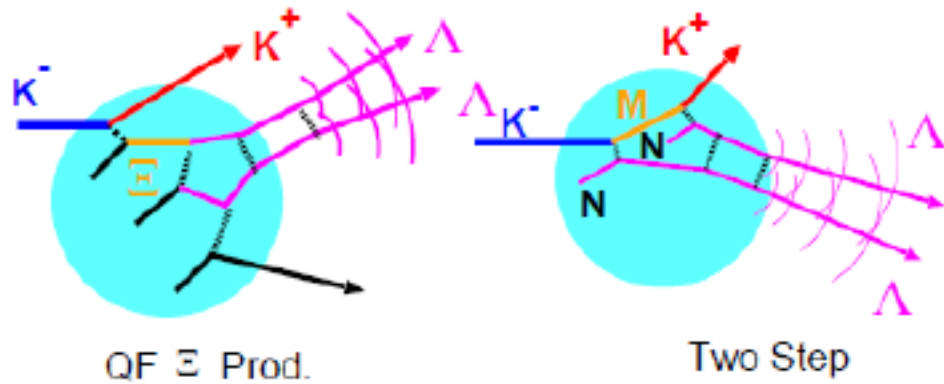
- “H” bounds with heavy π ($M_\pi > 400$ MeV)



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

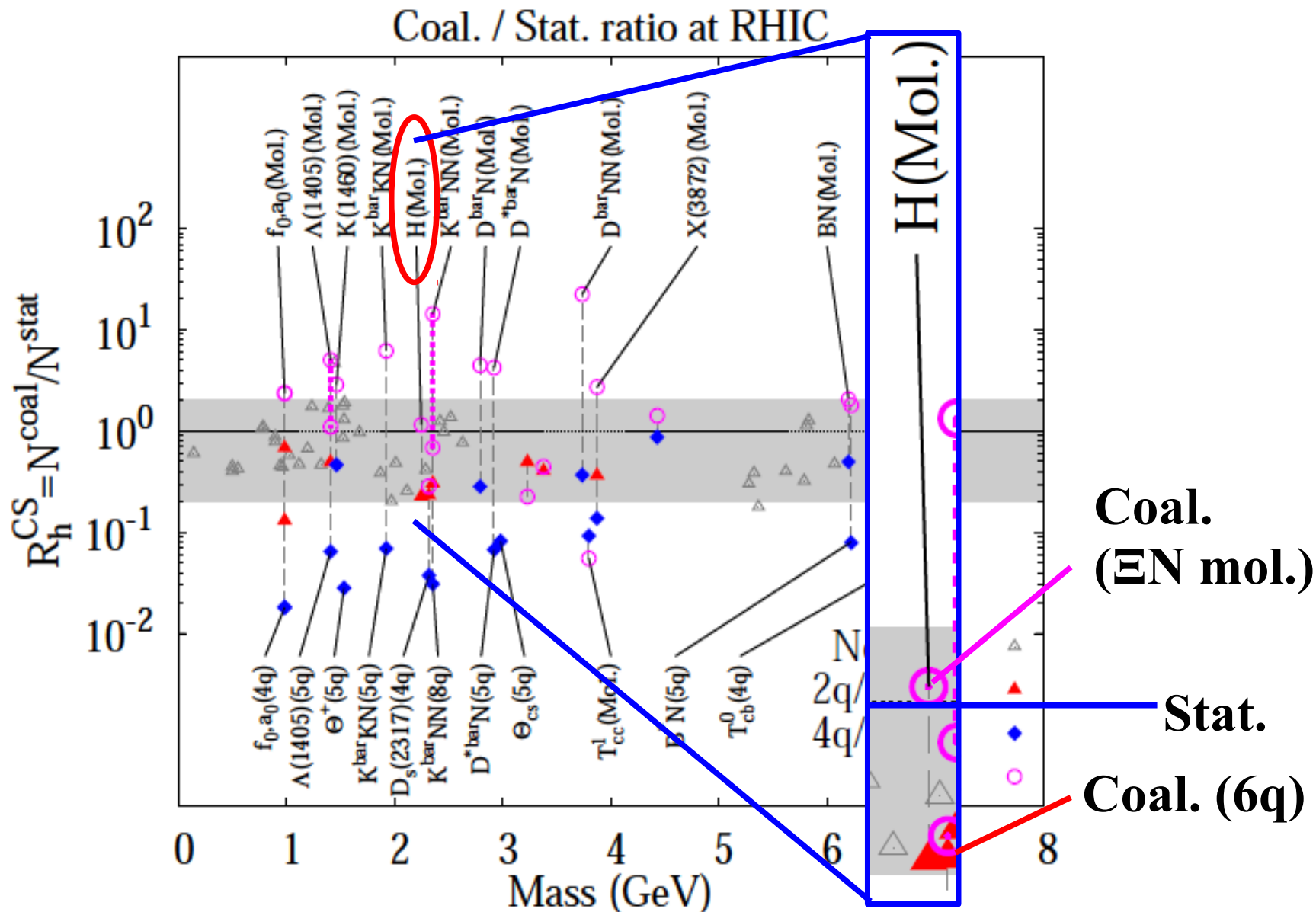
$\Lambda\Lambda$ correlation from $(K^-, K^+ \Lambda\Lambda)$ reaction

- Enhancement at $\sim 2 M(\Lambda) + 10$ MeV, $CL=2\sigma$



C.J. Yoon, ..., (KEK-E522), AO, PRC75 (2007) 022201(R)

Exotics from Heavy-Ion Collisions



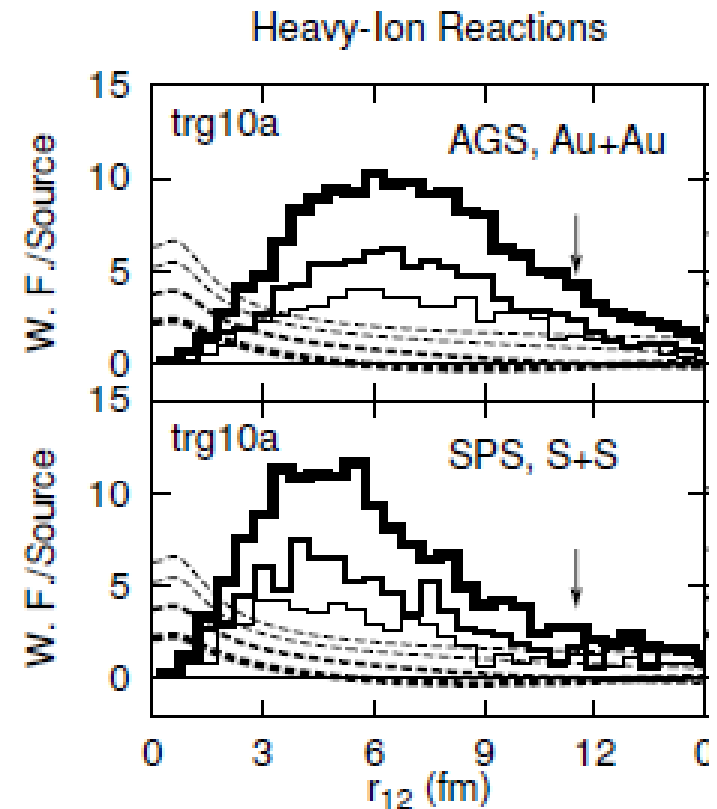
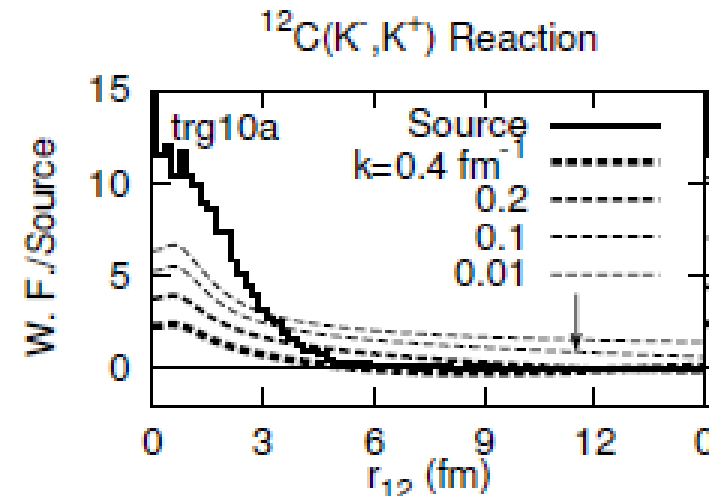
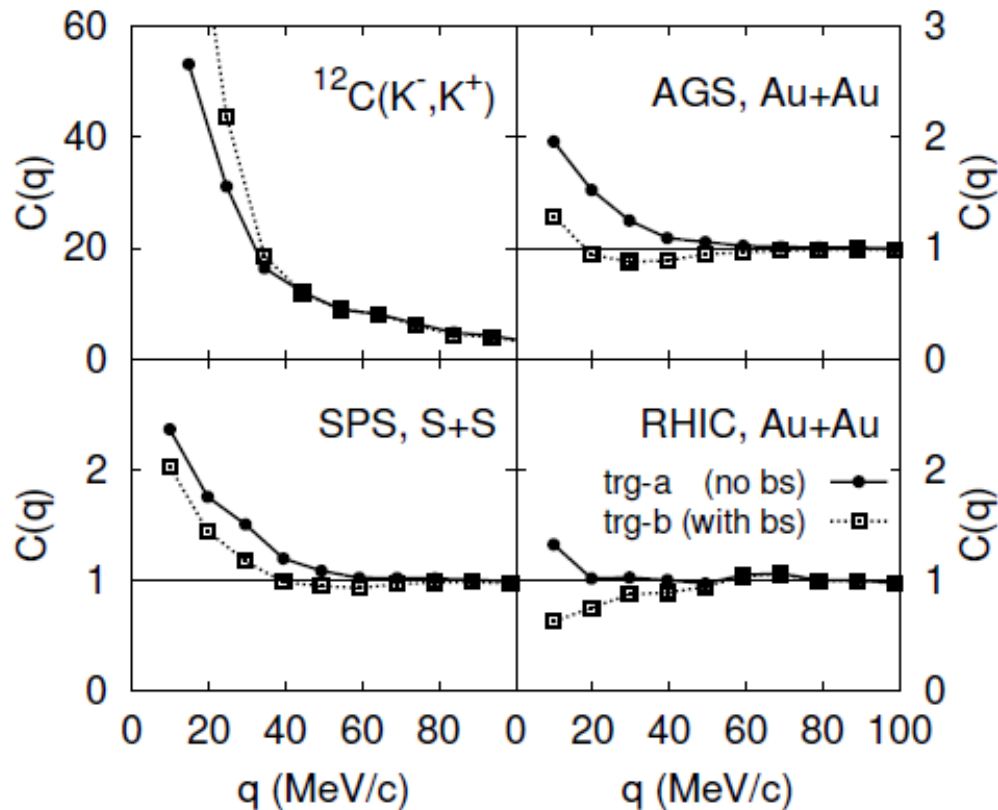
Cho, Furumoto, Hyodo, Jido, Ko, Lee, Nielsen, AO, Sekihara, Yasui, Yazaki
(ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302

Previous Work (before RHIC & Nagara)

■ Hadronic transport (JAM)

+ Two Range Gaussian $V_{\Lambda\Lambda}$

● w/ bound state \rightarrow w.f. node suppresses $C(q)$



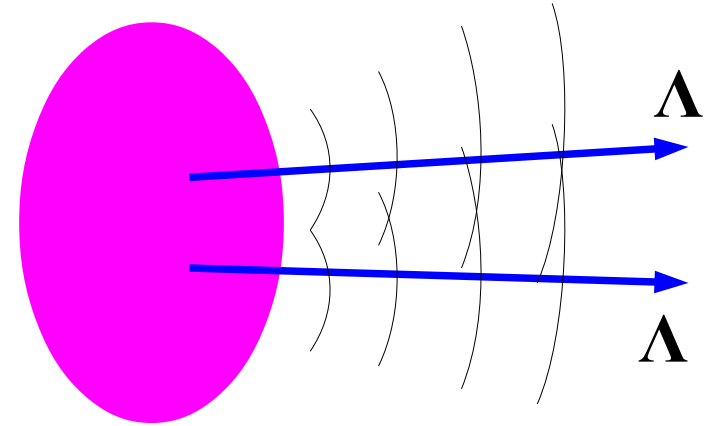
AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c
[arXiv:nucl-th/9903021]; SNP2000 proc. p175.

JAM: Nara, Otuka, AO, Niita, Chiba, PRC61 ('00), 024901.

$\Lambda\Lambda$ correlation in HIC

■ Merit of HIC to measure $\Lambda\Lambda$ correlation

- Source is “simple and clean” !
T, μ , flow, size, ... are well-analyzed.
- Source size is big and probes w.f. tail.
- Discovery of “H” and/or Constraint on $\Lambda\Lambda$ int.



■ Gaussian Source + s-wave int.

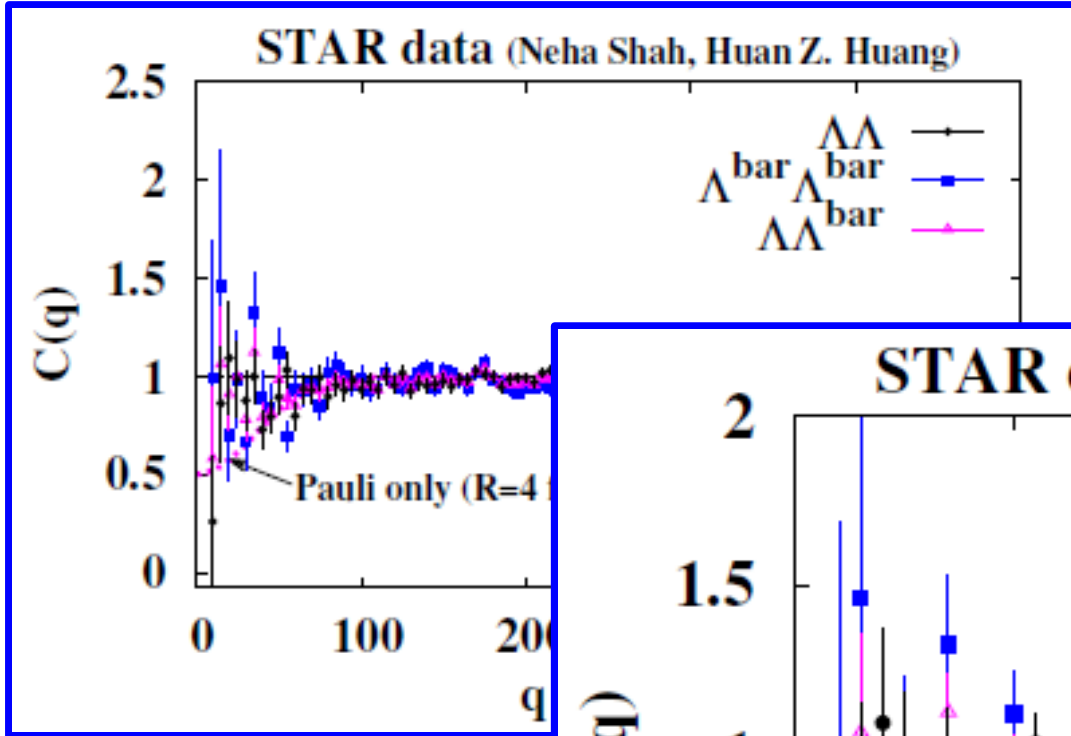
c.f. P. Danielewicz; Bauer, Gelbke, Pratt, Annu. Rev. Nucl. Part. Sci. 42('92)77.

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

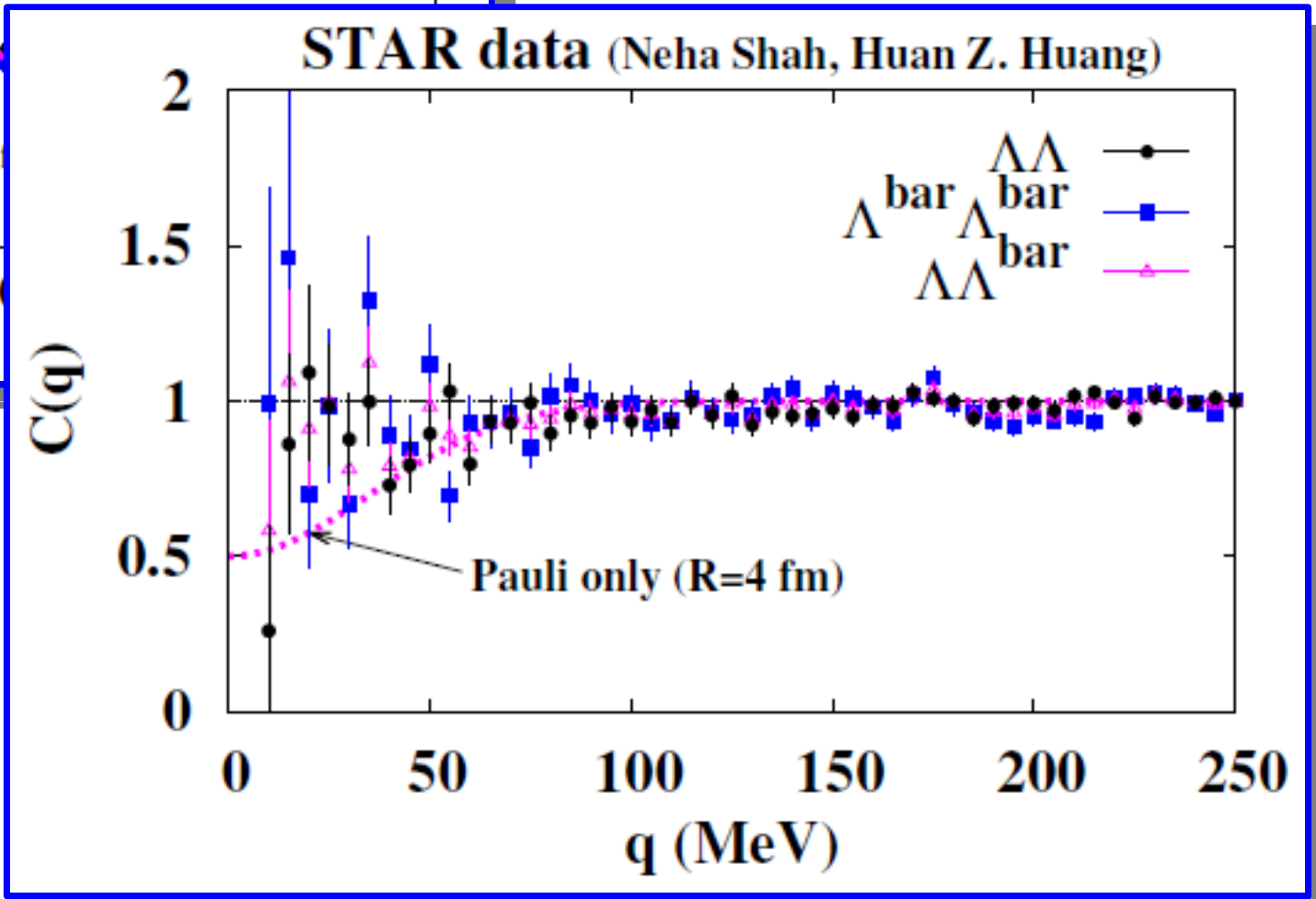
$$\simeq 1 - \frac{1}{2} \exp(-q^2 R^2) + \frac{1}{2} \int dr S_{12}(r) (|\chi_0(r)|^2 - |j_0(qr)|^2)$$

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

STAR data



Clear Enh. from Free corr. (Pauli) is seen !



$\Lambda\Lambda$ corr. in (K^-, K^+) and $\Lambda\Lambda$ reactions

Question:

*Can we constrain $\Lambda\Lambda$ interaction
from correlation data at RHIC ?*

*Is the constraint consistent
with $\Lambda\Lambda$ corr. in (K^-, K^+) reaction ?*

Does H exist as a bound state or a resonance ?

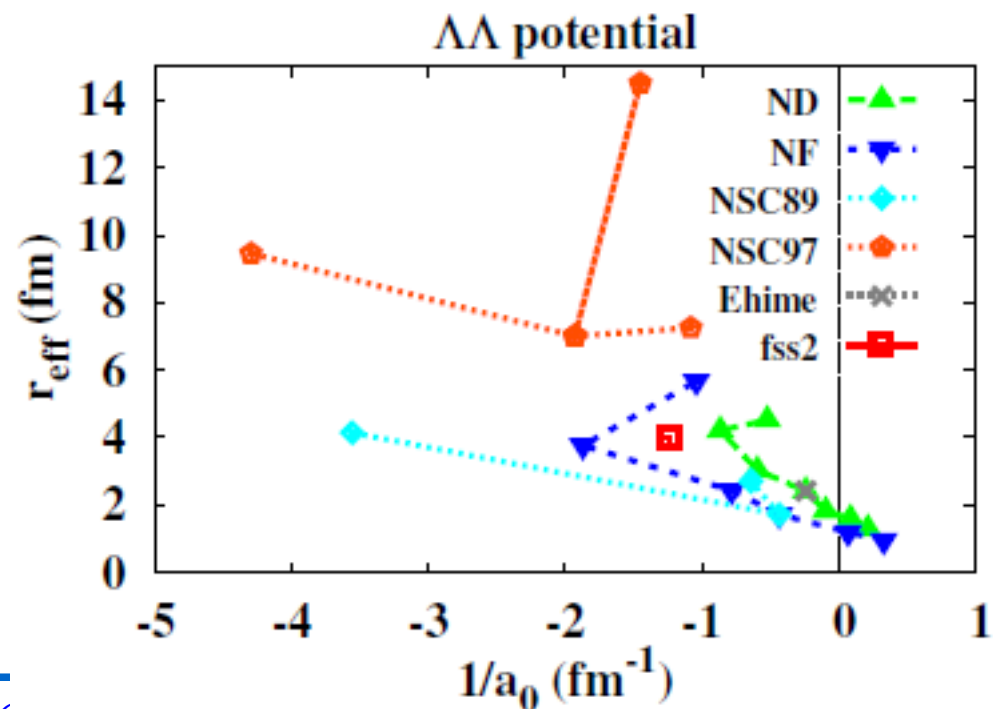
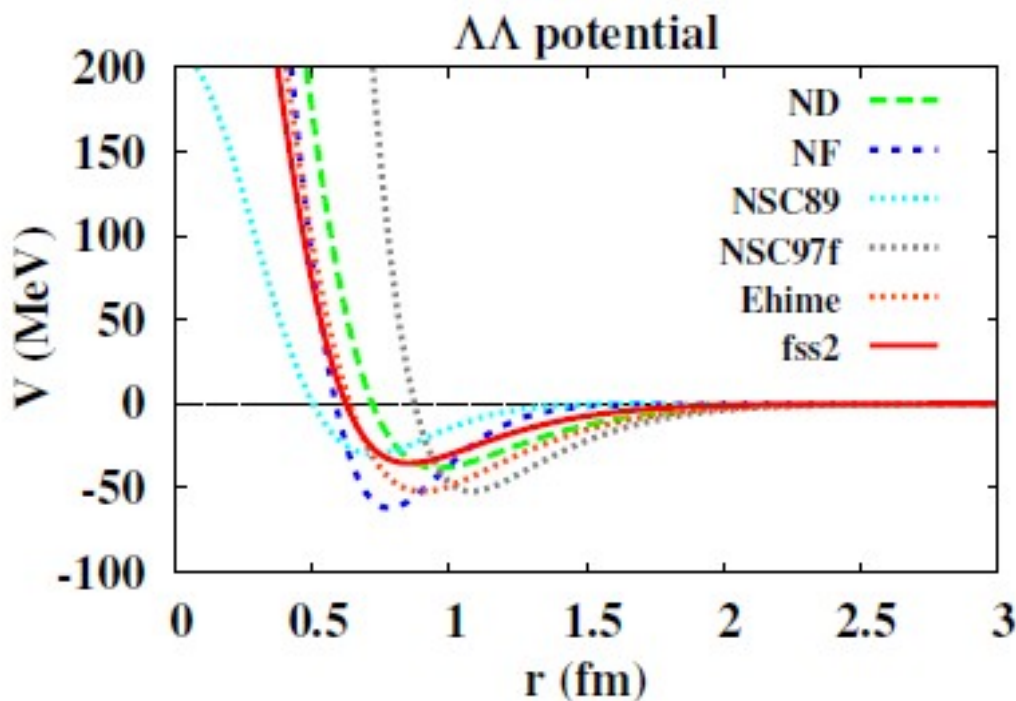
- **Source:** Gaussian (HIC), Cascade model results (K^-, K^+)
- **Interaction:** ND, NF, NSC89, NSC97, Ehime, fss2
(two or three range gaussian fit)
- **Other channel:** $\Lambda\Lambda$ - ΞN couple channels, Σ^0 decay feed effects

$\Lambda\Lambda$ interaction

■ Type of $\Lambda\Lambda$ interaction

- 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

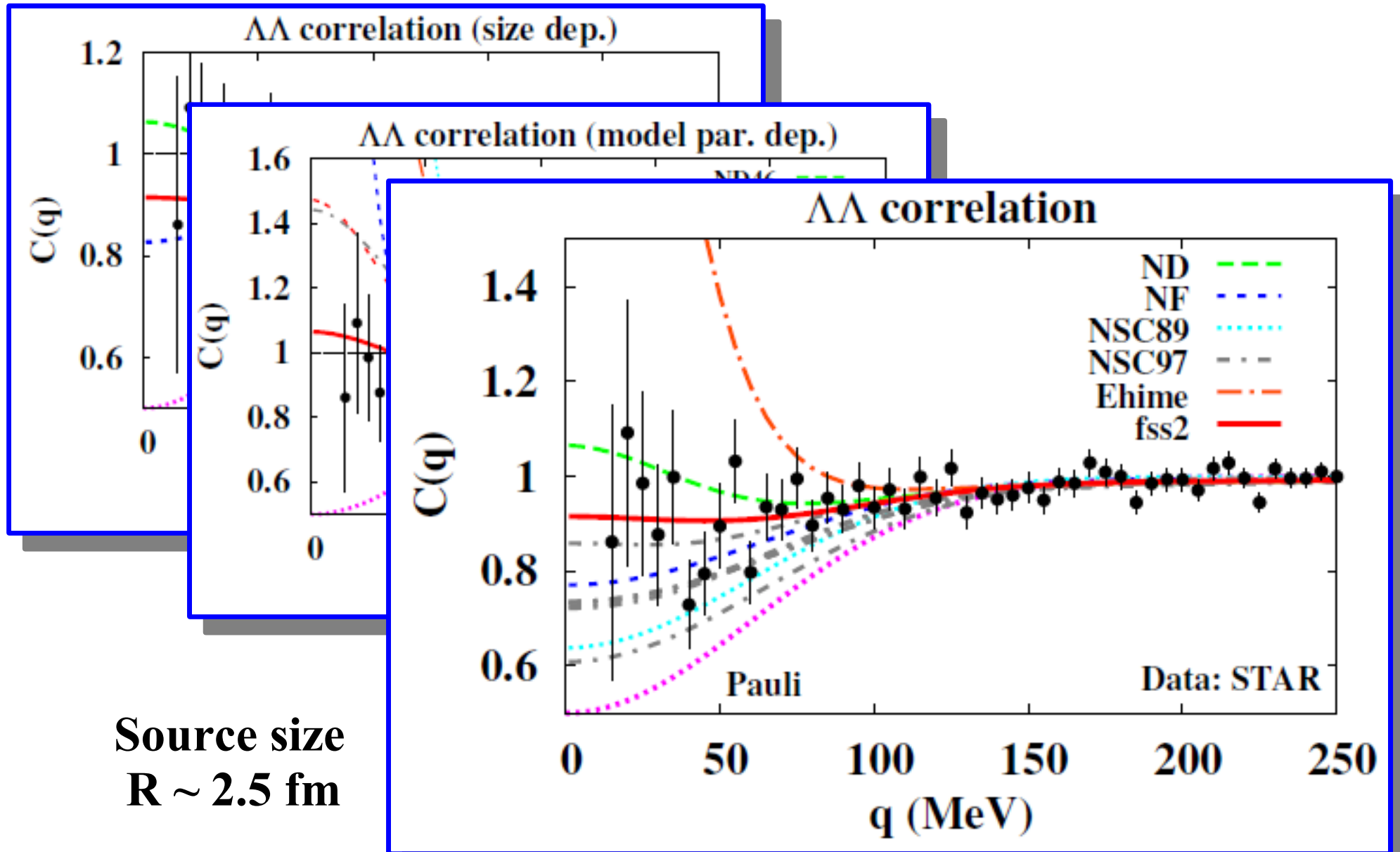
■ Two (or three) range gaussian fit results are used in the analysis.



*Lambda-Lambda Interaction
and
Lambda-Lambda Correlation at RHIC*

How can we constrain $\Lambda\Lambda$ interaction from HIC data ?

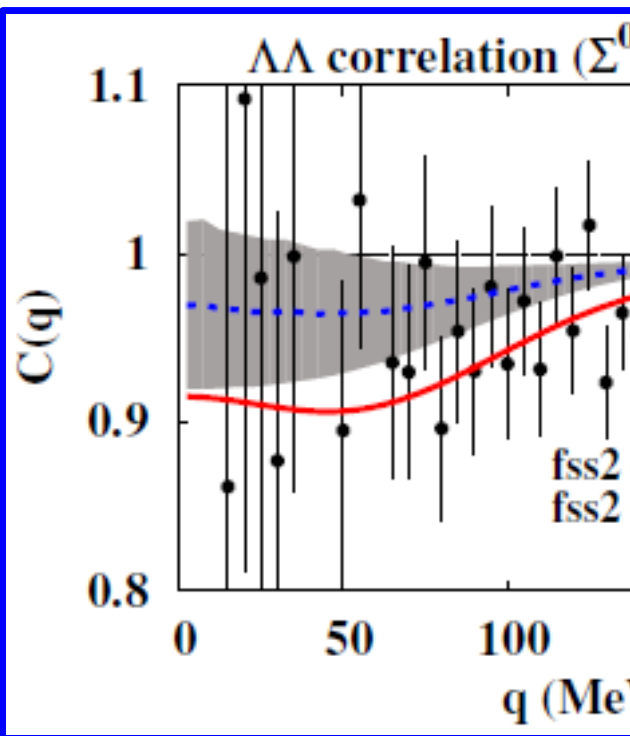
- $C(q)$ at large $q \rightarrow R$, $C(q)$ at small $q \rightarrow$ model par. dep.



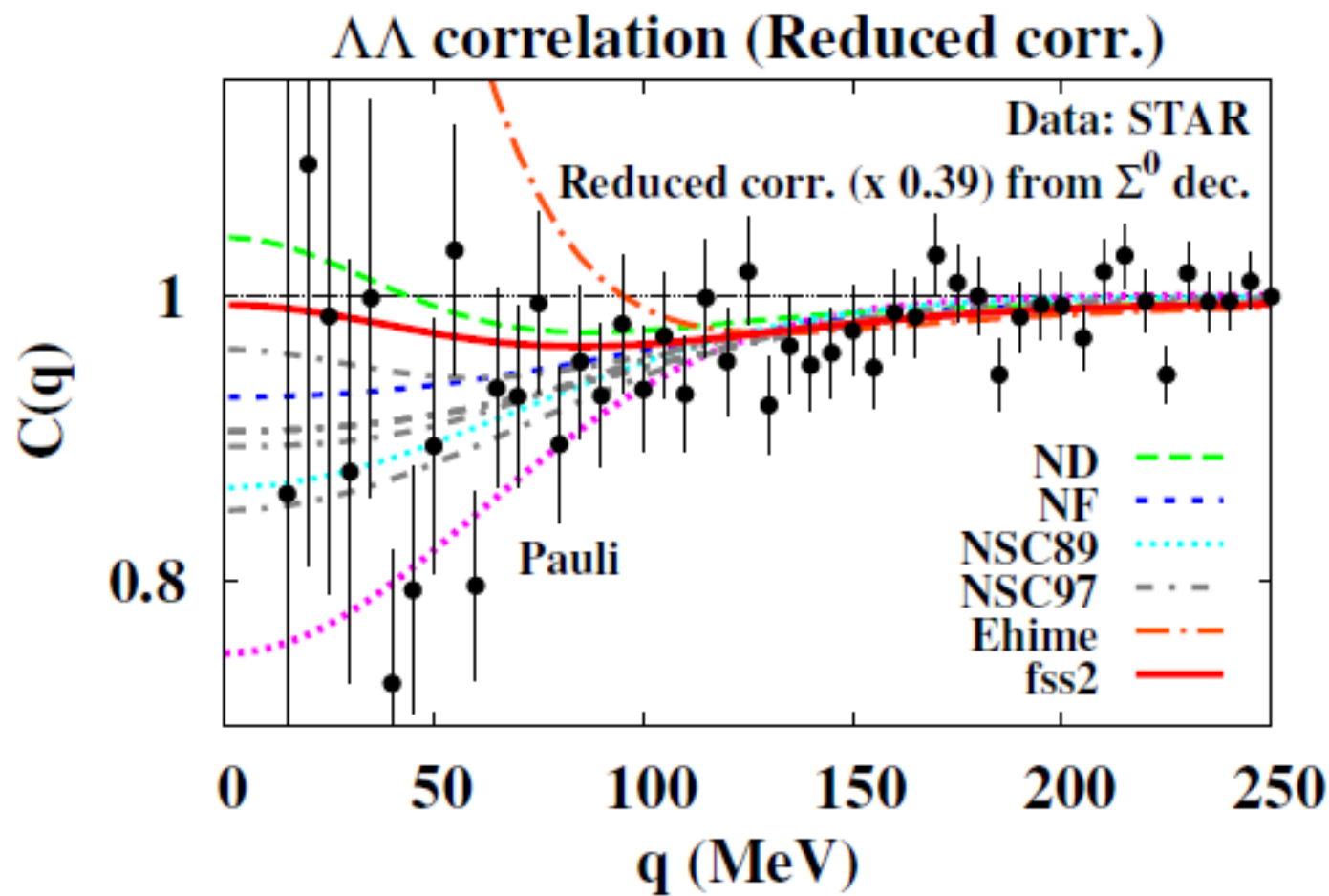
Source size
 $R \sim 2.5$ fm

Effects of Other Channels

- Feed from other particles would modify $\Lambda\Lambda$ corr.
(E.g. $\Lambda \rightarrow p \pi^-$ in pp corr., $\Sigma^0 \rightarrow \Lambda + \gamma$ in $\Lambda\Lambda$ corr.)
 - $Y(\Sigma^0) \sim 0.6 Y(\Lambda)$ (Stat. model) $\rightarrow 0.39 \times (C(q)-1)$
 - 10 % corr. in $\Lambda\Sigma, \Sigma\Sigma$ channel \rightarrow 5 % in $C(q)$

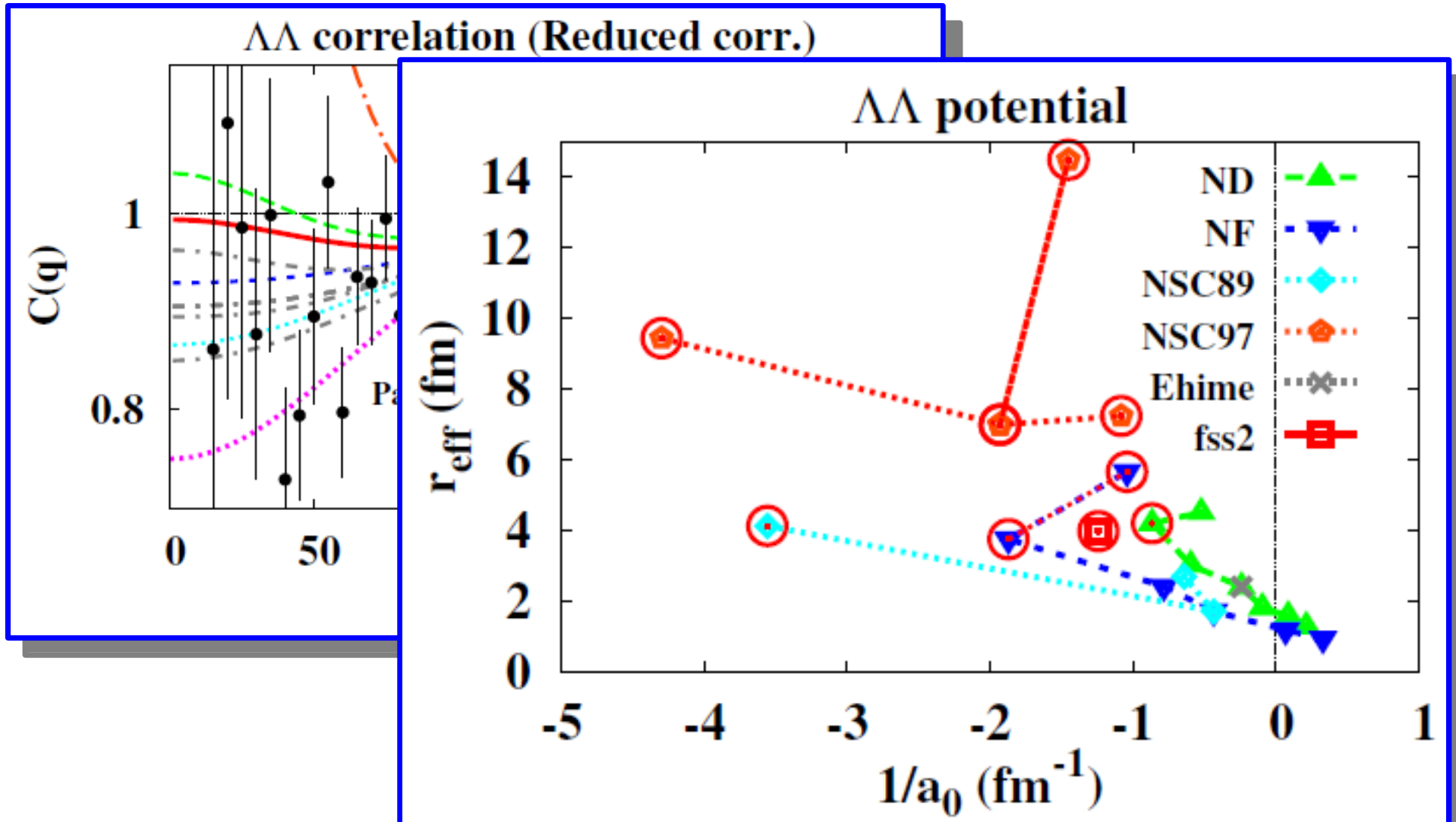


Source size
 $R \sim 2$ fm



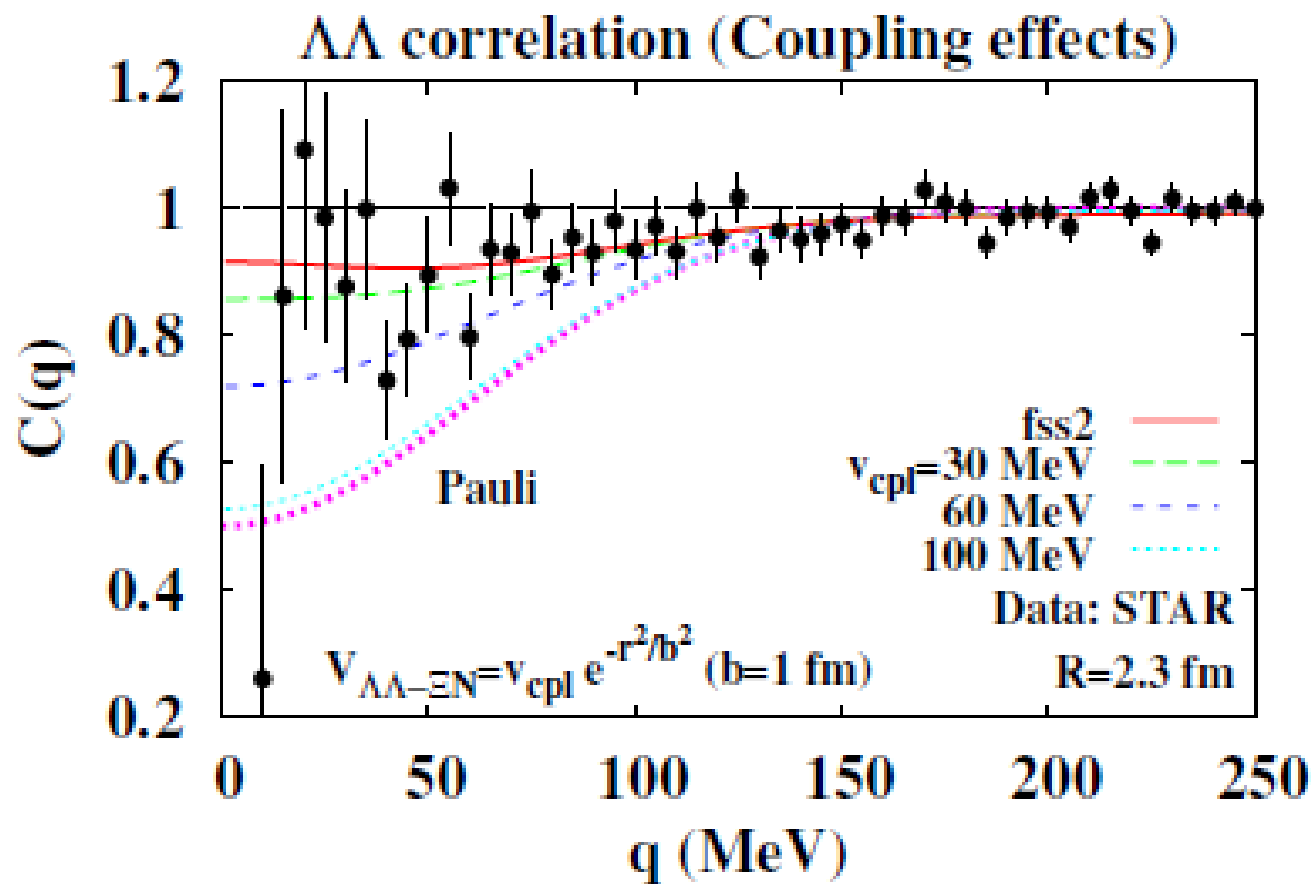
Preferred $\Lambda\Lambda$ Interaction

- STAR data choose some of the $\Lambda\Lambda$ interaction
→ $1/a_0 < -1 \text{ fm}^{-1}$, $r_{\text{eff}} > 3 \text{ fm}$ seems to be preferred.



Coupling Effects

- Coupled channels effects with ΞN channel is considered.
 - Coupling with ΞN channel suppresses $C(q)$ at low q . (\sim Imag. pot.)
 - Unreasonably large coupling would meaningfully modify $C(q)$.

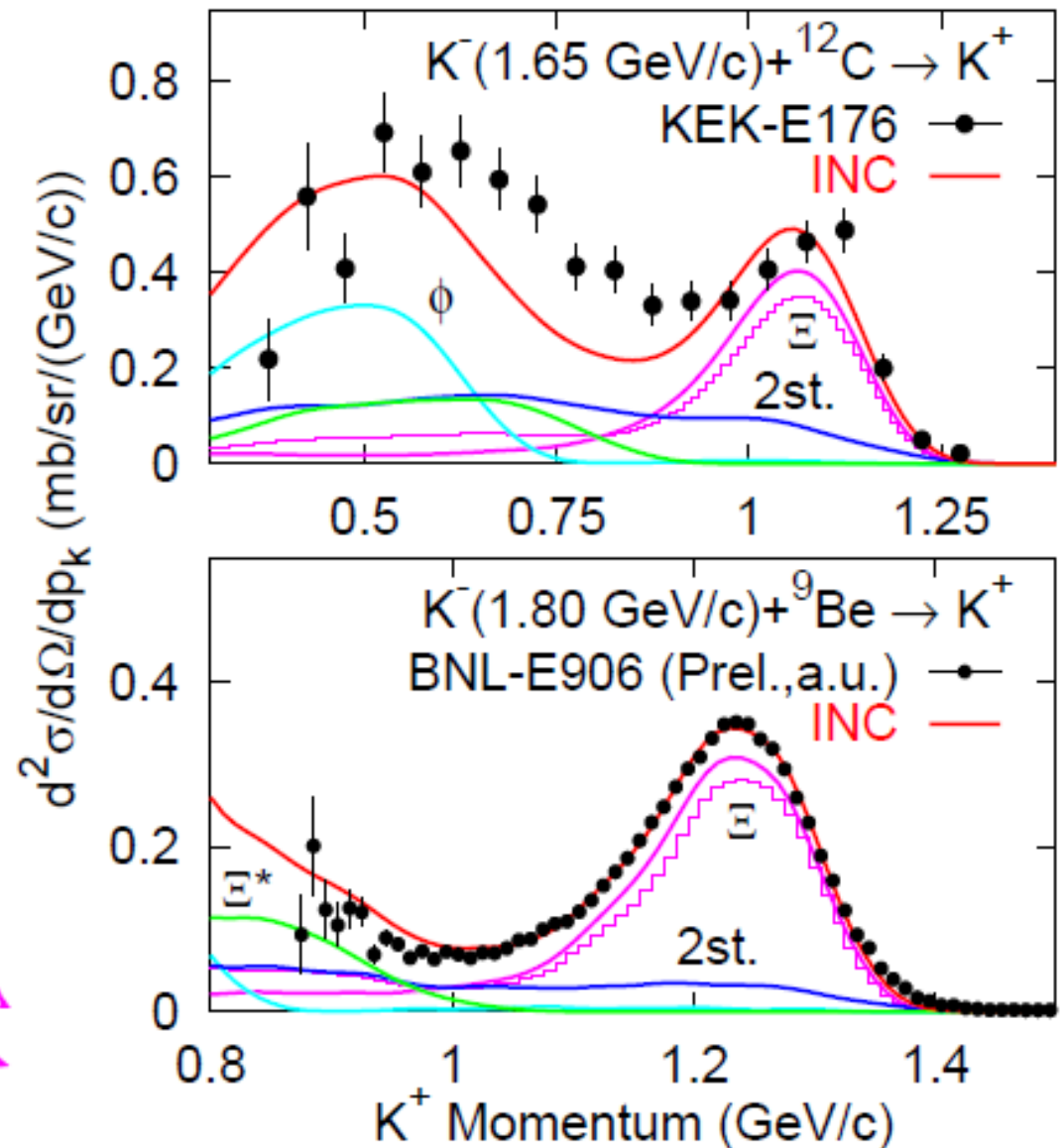
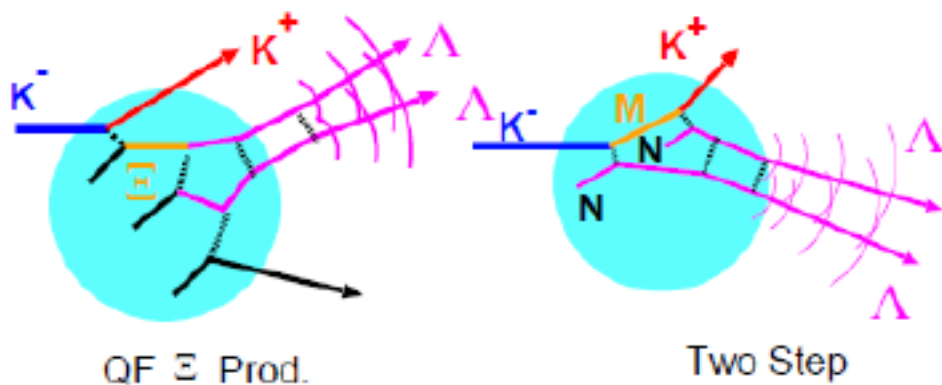


$\Lambda\Lambda$ Correlation in (K^-, K^+) Reaction

$\Lambda\Lambda$ Correlation in (K, K^+) Reaction (1)

■ K^+ production mechanism

- QF Ξ production
- Heavy meson production and Decay
Gobbi, Dover, Gal, PRC50 (1994) 1594.
- Two step processes
Nara, AO, Harada, Engel, NPA614 (1997) 433

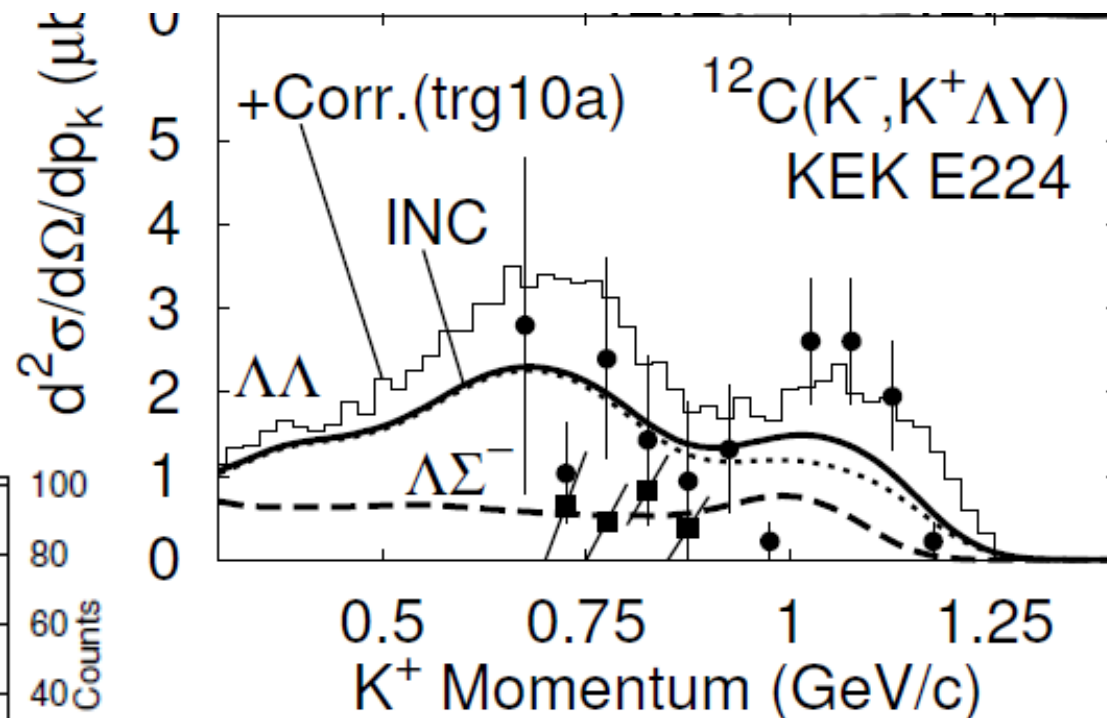
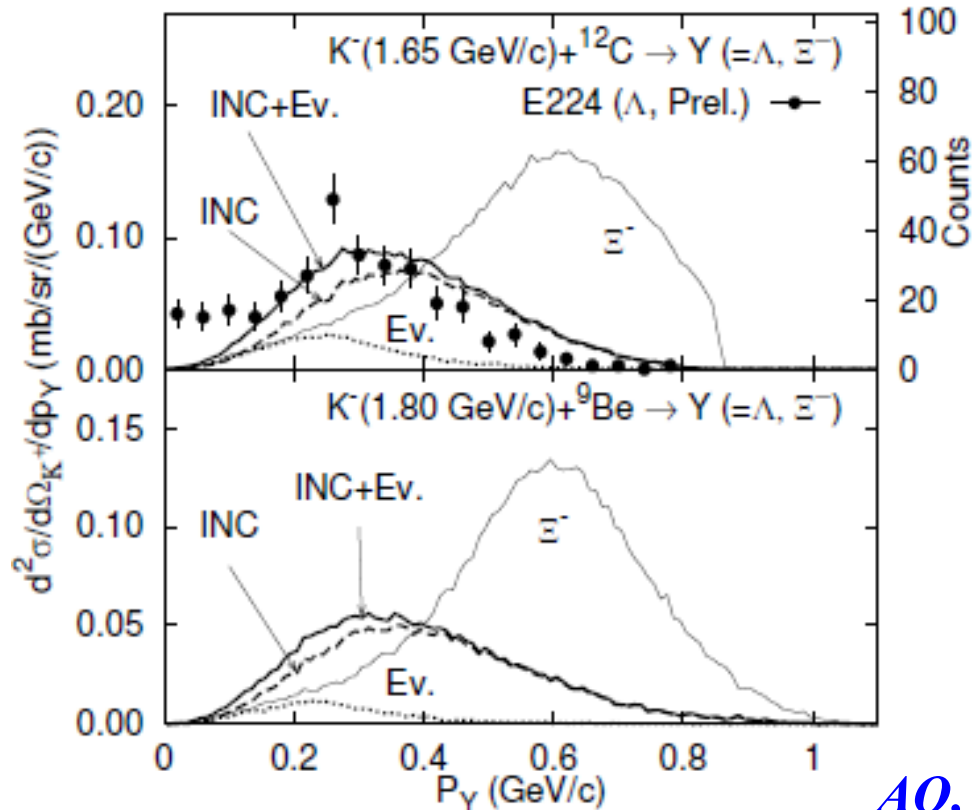


AO, Hirata, Nara, Shinmura, Akaishi, Few-Body Syst. Suppl. 12 (2000), 367

$\Lambda\Lambda$ Correlation in (K, K^+) Reaction (2)

■ Λ production mechanism

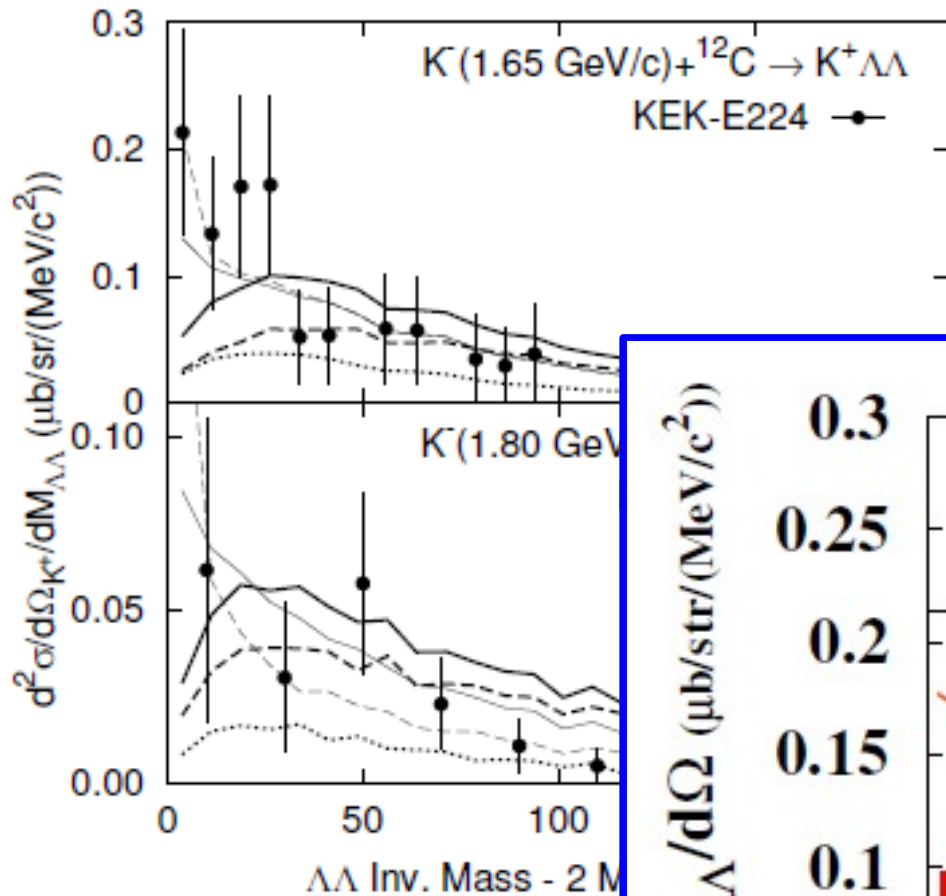
- Cascade processes
- Evaporation from hyper compound nuclei



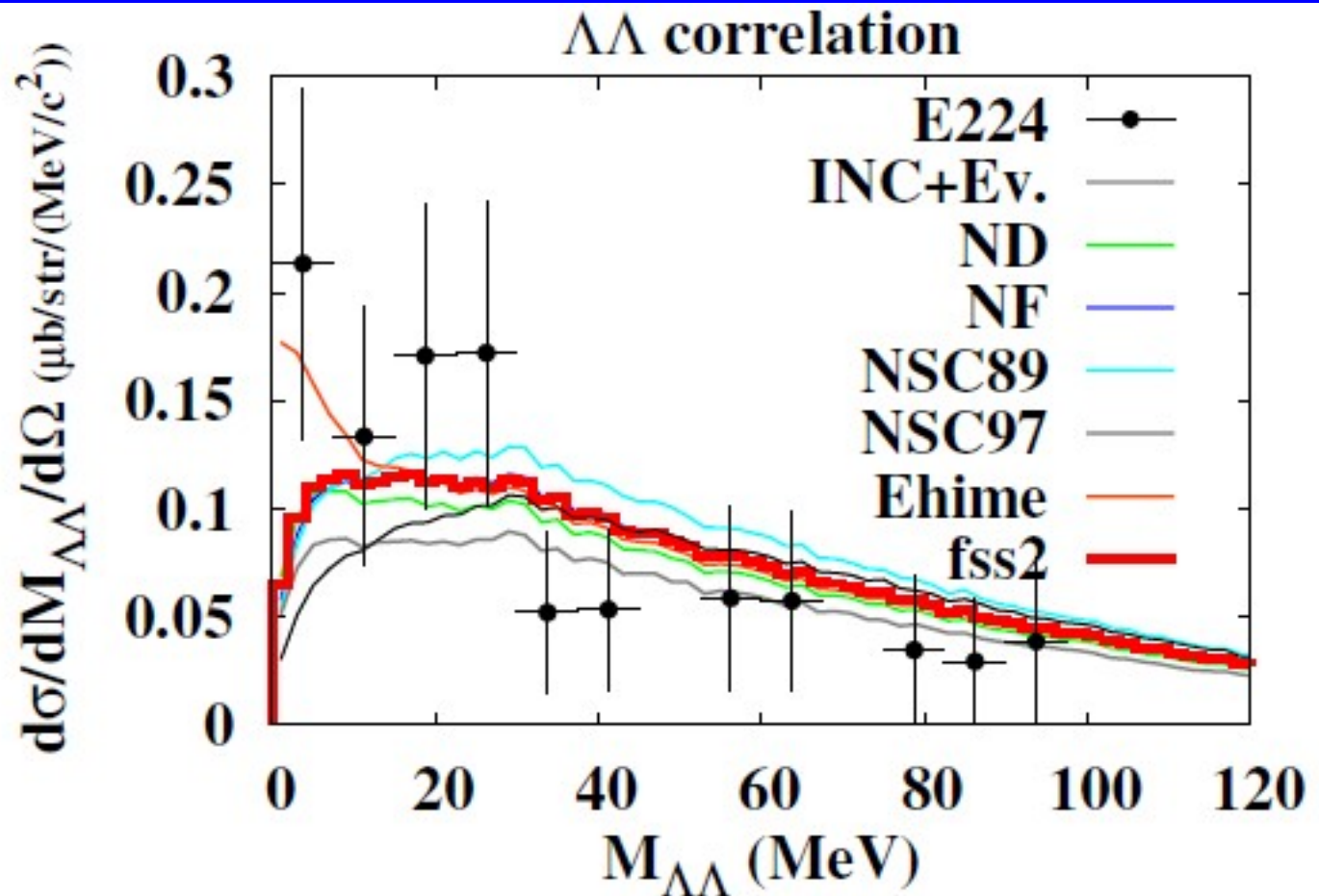
AO, Hirata, Nara, Shinmura, Akaishi, NPA670(2000), 297c

AO, Hirata, Nara, Shinmura, Akaishi, NPA691(2001), 242c

$\Lambda\Lambda$ Invariant Mass Spectrum



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



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

Summary

- We studied $\Lambda\Lambda$ correlation in heavy-ion collisions and $(K^-, K^+\Lambda\Lambda)$ reactions.
- Recent STAR (preliminary) data clearly show enhanced $\Lambda\Lambda$ correlation compared to the free fermion correlation.
 - Preferred $\Lambda\Lambda$ interactions have $1/a_0 < -1 \text{ fm}^{-1}$, $r_{\text{eff}} > 3 \text{ fm}$.
 - Σ^0 decay effects are well simulated by multiplying 0.39 to (C-1), if there is no strong correlation in $\Lambda\Sigma$ channel.
 - Coupled channel effects with ΞN is expected to be minor.
- Preferred $\Lambda\Lambda$ interactions in HIC are also consistent (not inconsistent) with $\Lambda\Lambda$ invariant mass spectrum in ^{12}C $(K^-, K^+\Lambda\Lambda)$ reaction.
 - Both Cascade and Evaporation have to be considered.
 - Enhancement at 10-20 MeV cannot be explained by FSI.
- Higher statistics data in HIC (RHIC, LHC) and ^{63}Cu $(K^-, K^+\Lambda\Lambda)$ (J-PARC proposal) are desired to pin down $\Lambda\Lambda$ interaction.

Thank you !

Fate of the prediction

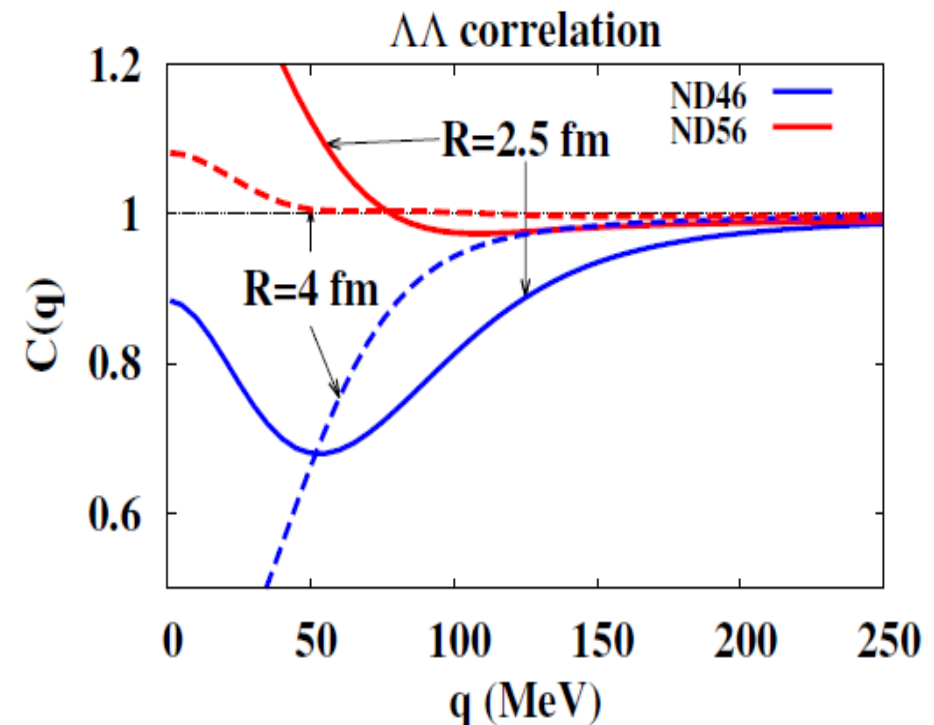
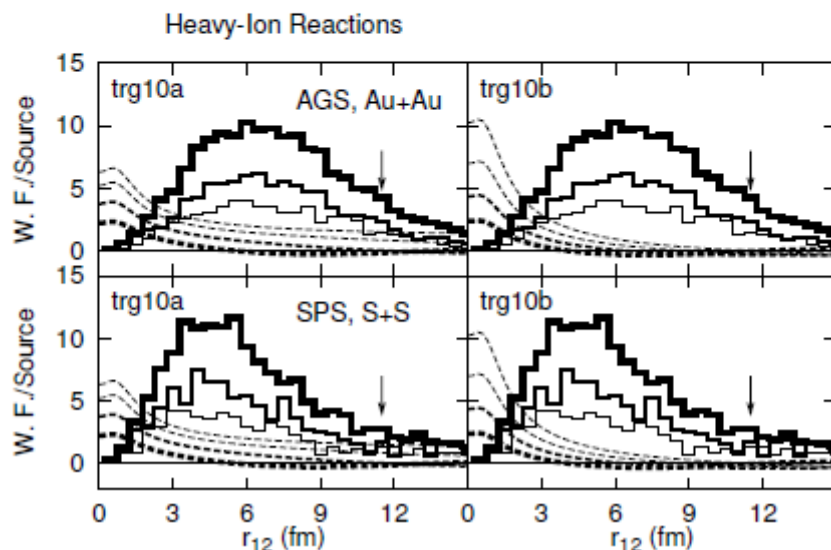
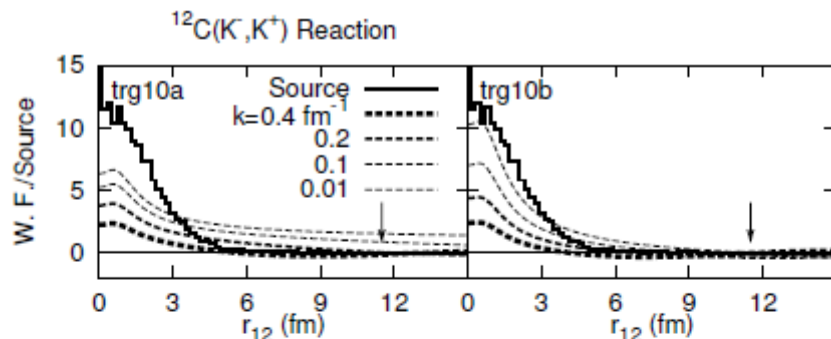
Conjecture in 2000

Suppressed $\Lambda\Lambda$ correlation may suggest the existence of a bound H

- Bound H \rightarrow Node in scattering $\Lambda\Lambda$ wf \rightarrow suppressed correlation

AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c
[arXiv:nucl-th/9903021]; SNP2000 proc. p175.

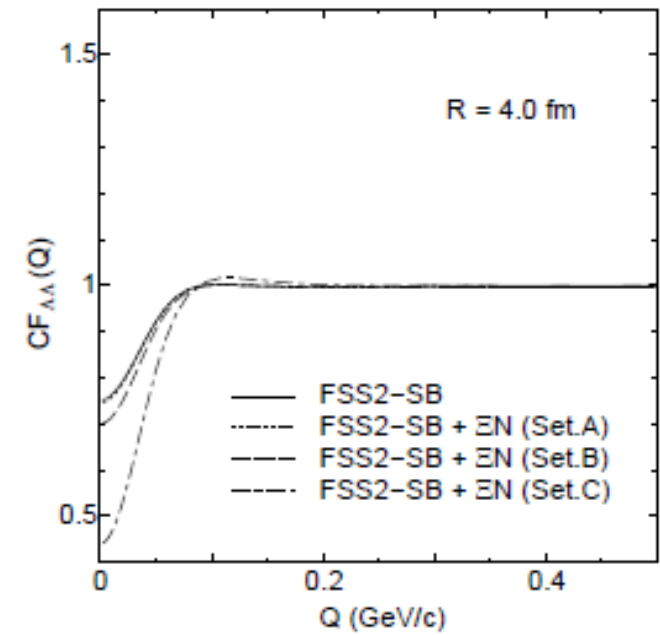
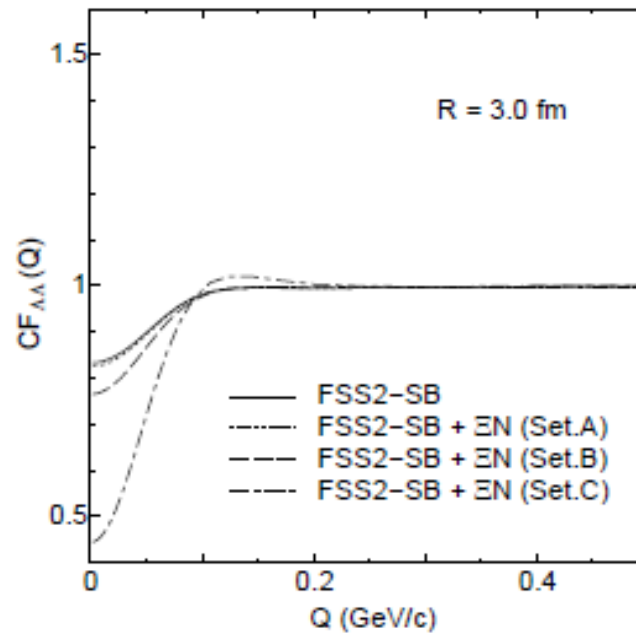
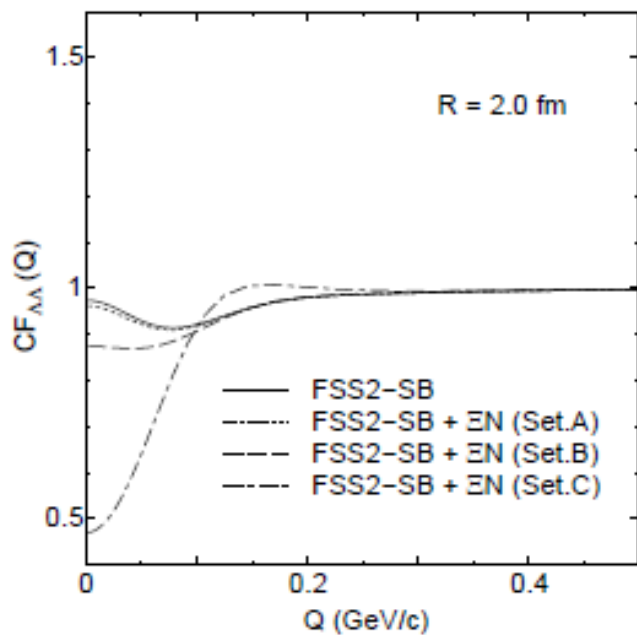
- When the source (homogeneity) size is small, we find a dip with/without bound state.



Source size dependence

- Larger size → Smaller Q region
- No dip structure for larger size.
(Anti-symmetrization effects > Interaction effects)
→ Sensitive only to the scattering length.

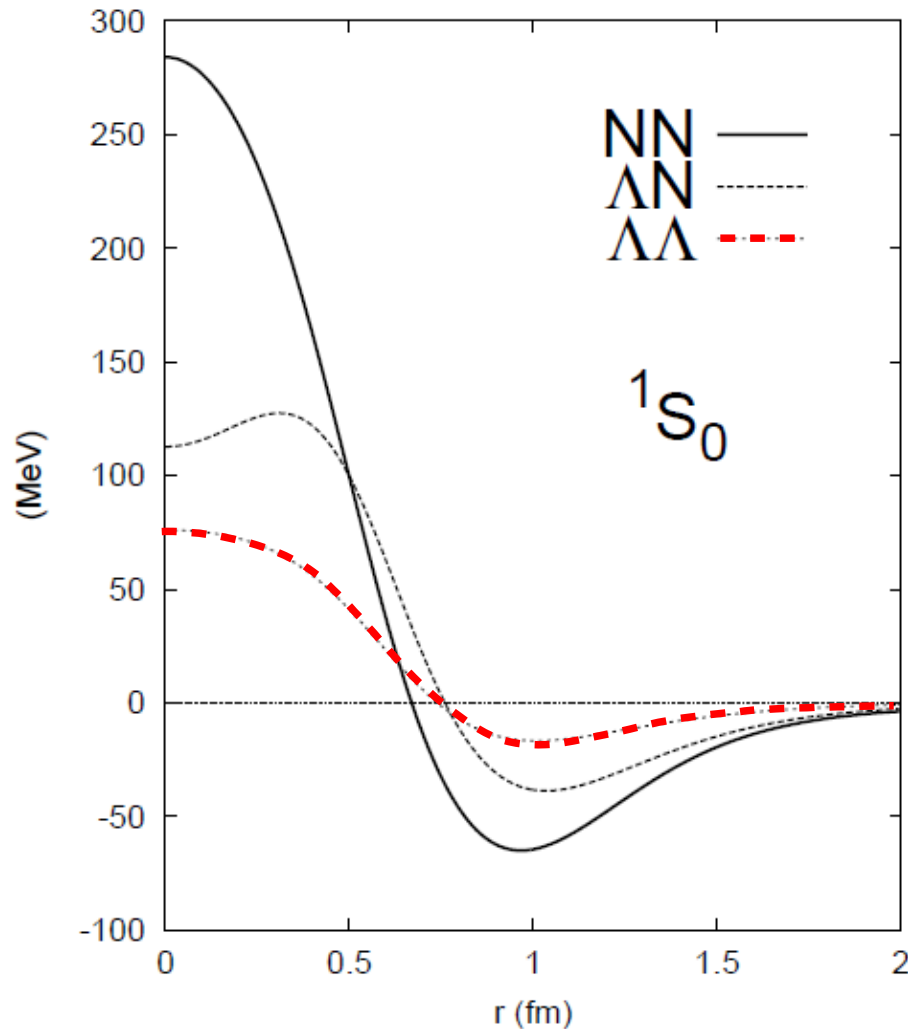
$$C(Q \rightarrow 0) \simeq \frac{1}{2} - \frac{2}{\sqrt{\pi}} \frac{a_0}{R} + \left(\frac{a_0}{R} \right)^2 \quad (\text{if "Interaction Range"} \ll R)$$



AO, Furumoto, in prep.

$\Lambda\Lambda$ potential

fss2 Phase shift equivalent potential



■ fss2

● $a_0 = -0.82$ fm, $r_{\text{eff}} = 4.1$ fm

■ Nagara fit

*E. Hiyama, M. Kamimura, T. Motoba,
T. Yamada, Y. Yamamoto,
PRC66('02)024007.*

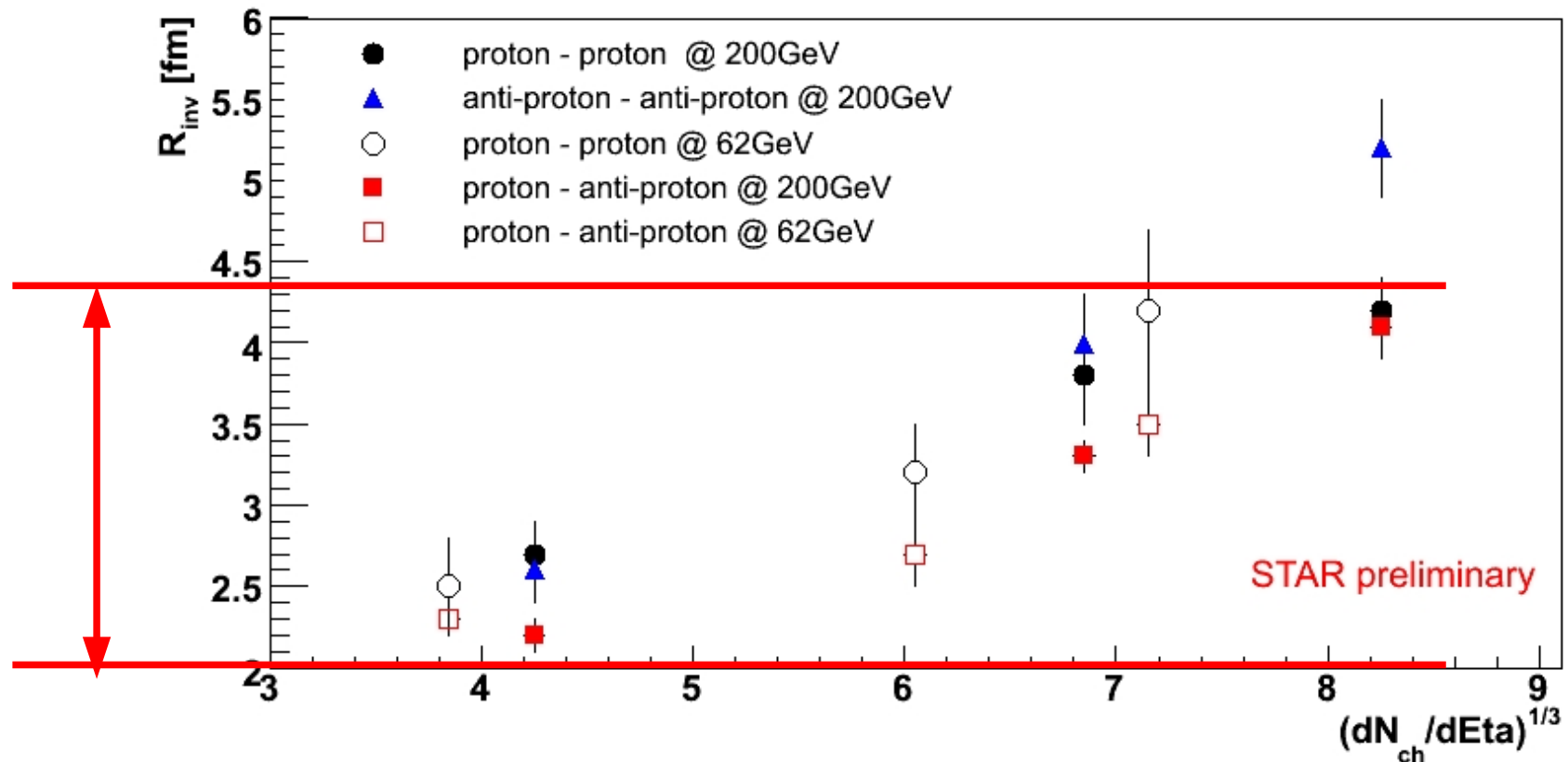
● $a_0 = -0.575$ fm, $r_{\text{eff}} = 6.45$ fm

*Y. Fujiwara, Y. Suzuki, C. Nakamoto,
Prog.Part.Nucl.Phys. 58 (2007) 439-520*

Toward $\Lambda\Lambda$ correlation at RHIC: Source Size

■ Source size : $R = (2-4.5)$ fm

- Smaller than last collision point dist. results in hadron cascade (JAM)
→ Interaction in the early stage at RHIC
- Smaller than π , K homogeneity length
→ Further smaller for Λ ?



A. Kisiel (H. P. Zbroszczyk) (STAR)

Toward $\Lambda\Lambda$ correlation at RHIC: $\Lambda\Lambda$ interaction

■ $\Lambda\Lambda$ interaction

After Nagara, “plausible” $\Lambda\Lambda$ interaction becomes weaker.

Bond energy $\Delta B_{\Lambda\Lambda} = 0.7$ MeV (old guess = (3-6) MeV)

- fss2 (quark model interaction): No bound state

Y. Fujiwara, M. Kohno, C. Nakamoto, Y. Suzuki, PRC64('01)054001

Bond energy $\Delta B_{\Lambda\Lambda} = (1.2-1.9)$ MeV (depending on ΛN int.)

- Nijmegen model D (boson exch., $R_c = 0.46$ fm): with bound state

M.M. Nagels, T.A. Rijken, J.J. de Swart, PRD15('77)2547

B.E.(H) ~ 1.6 MeV

■ Resonance “H” btw $\Lambda\Lambda$ - ΞN threshold

→ Couple channel calc. is required

- One range gaussian coupling potential is assumed.

- ΞN potential (diagonal) effects on $C(q)$ is almost negligible.

