Lambda-Lambda Correlation and Interaction from Heavy Ion Collisions

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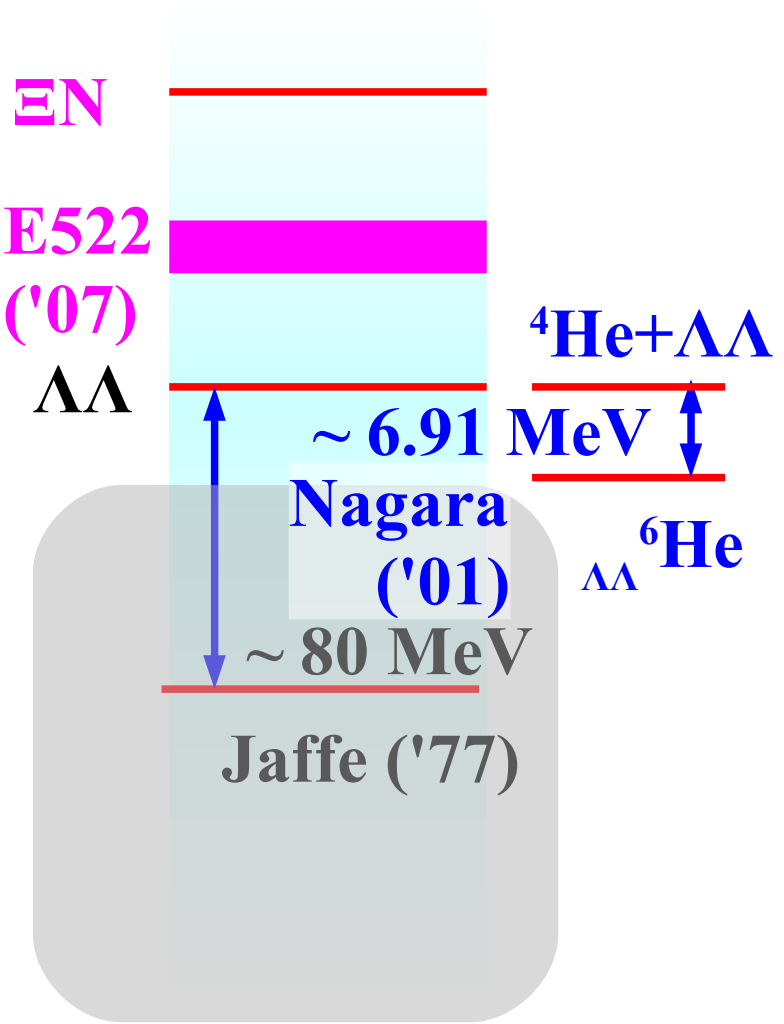
- **Introduction: Where is "H" ?**
- **ΛΛ correlation in heavy-ion collisions**
- **Summary**

SNP12 - International Workshop on Strangeness Nuclear Physics 2012
Aug.27-29, 2012, Osaka EC Univ., Neyanaga, Japan

AO, Furumoto, Morita, in prep.

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

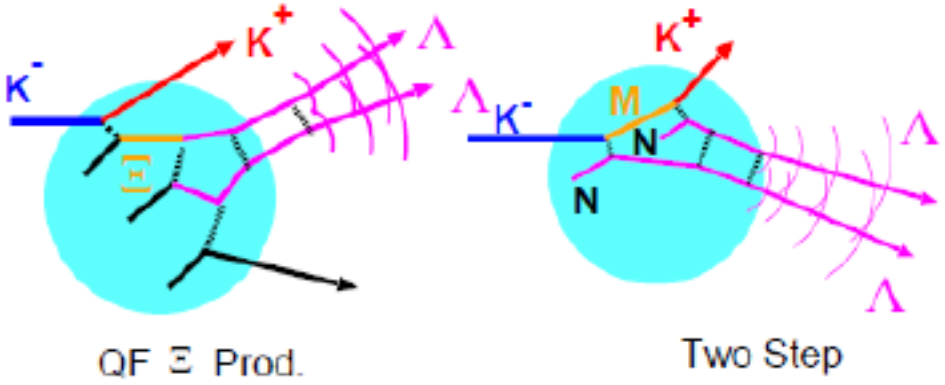
- **Deeply bound H ?** *Jaffe ('77)*
  - **Strong Attraction from Color Mag. Int.**
    → 80 MeV below ΛΛ
- **Nagara event $_{\Lambda\Lambda}{}^{6}$He** *Takahashi et al. ('01)*
  - **No deeply bound "H", Weakly Att. ΛΛ int.**
  - **Why ? Repulsive Instanton Induced Int.**
    Oka, Takeuchi ('91)
- **Resonance or Bound "H" ?**
  - **2 σ "bump" at $E_{\Lambda\Lambda}$ ~ 15 MeV**
    Imai &Ahn; Yoon et al.(KEK-E522) ('07)
  - **bound H at large *ud* quark masses**
    Inoue's talk; HAL QCD & NPLQCD ('11)

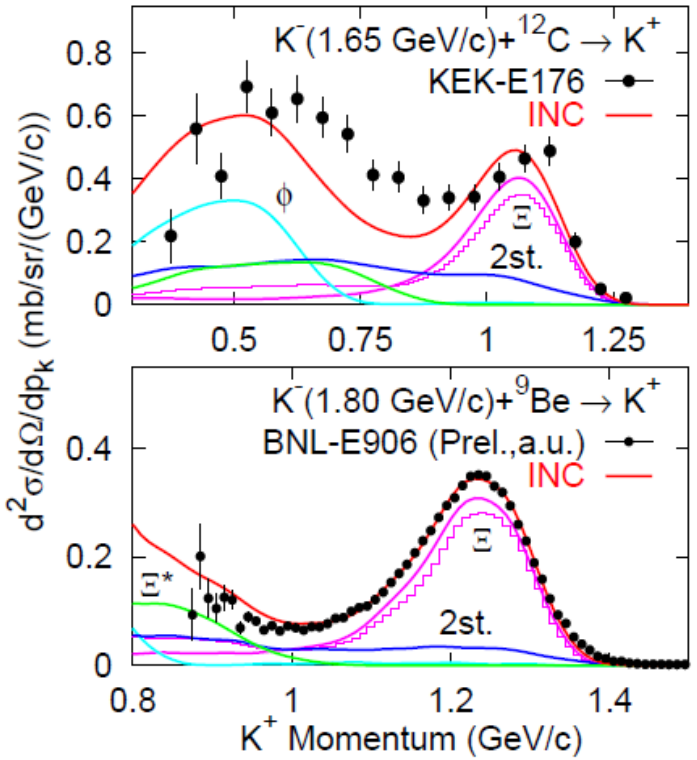


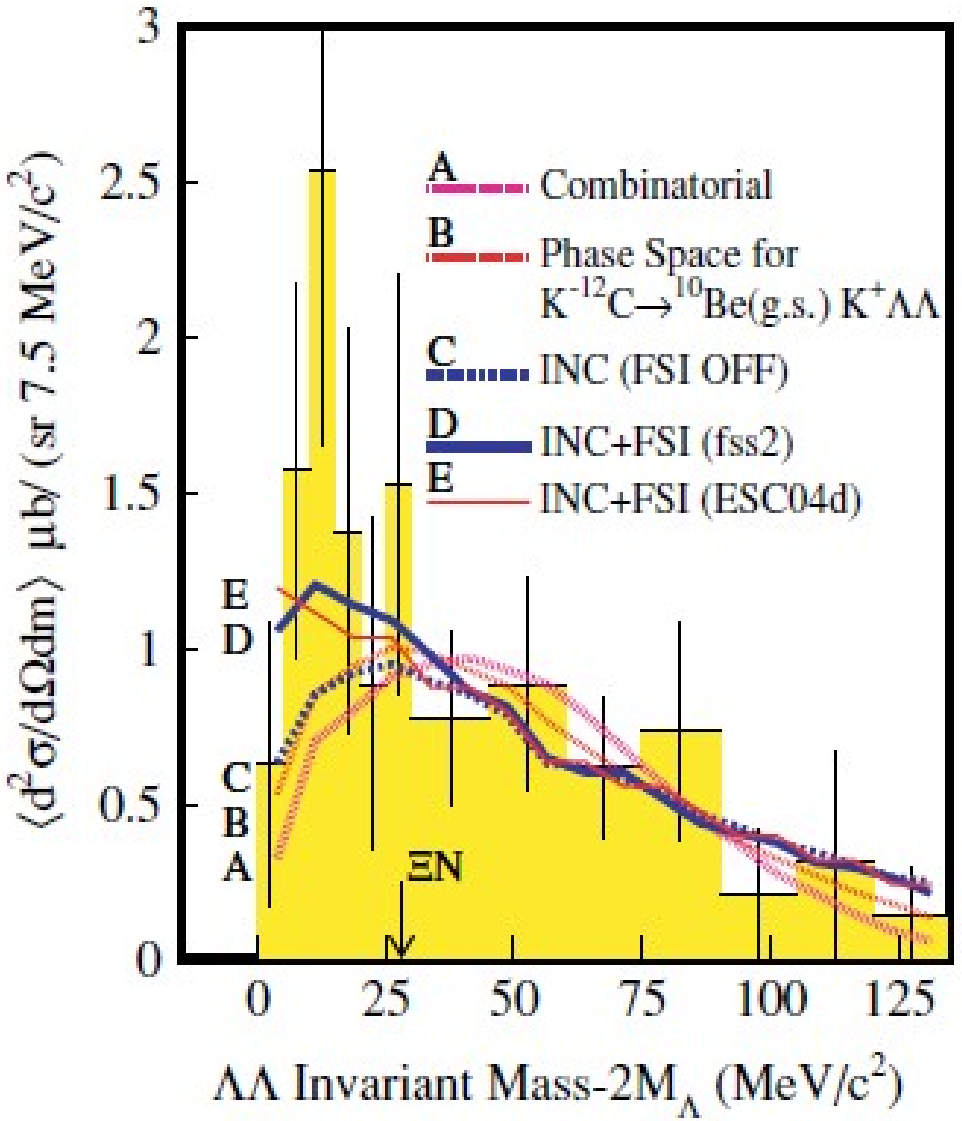
"H" and ΛΛ interaction = Long standing AND Current Subject.
→ Let's consider to measure them in Heavy Ion Collisions !

ΛΛ correlation from (K^-,K^+ΛΛ) reaction

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



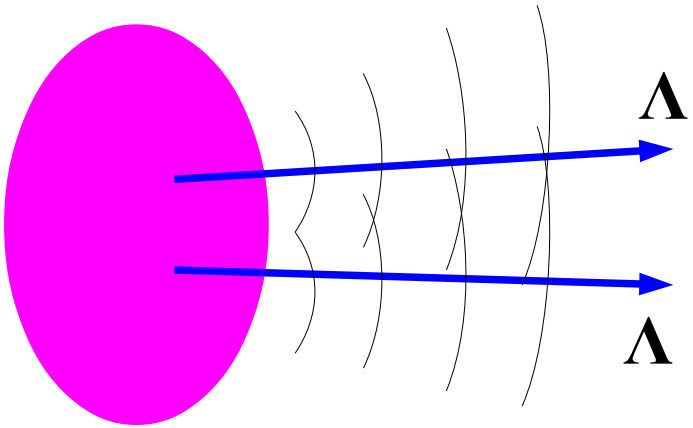


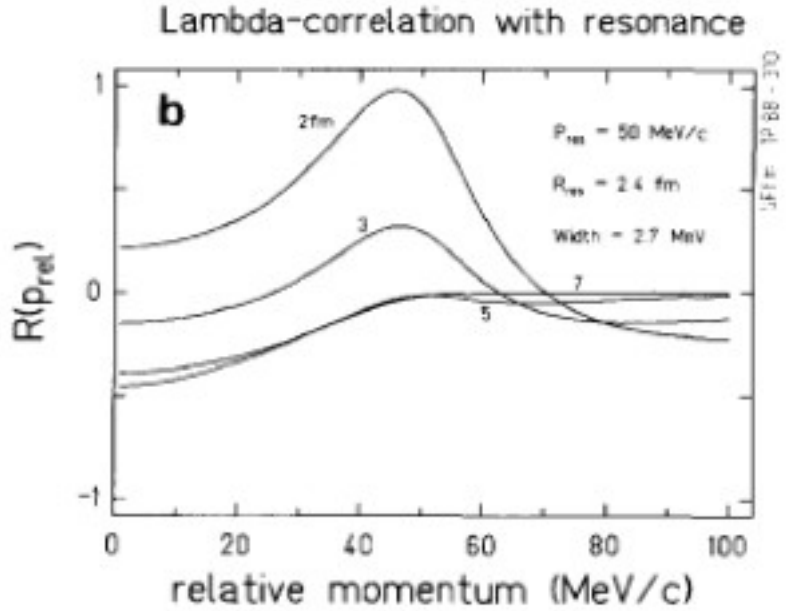


C.J.Yoon, …, (KEK-E522),AO, PRC75 (2007) 022201(R)
J. K. Ahn et al. (KEK-E224).

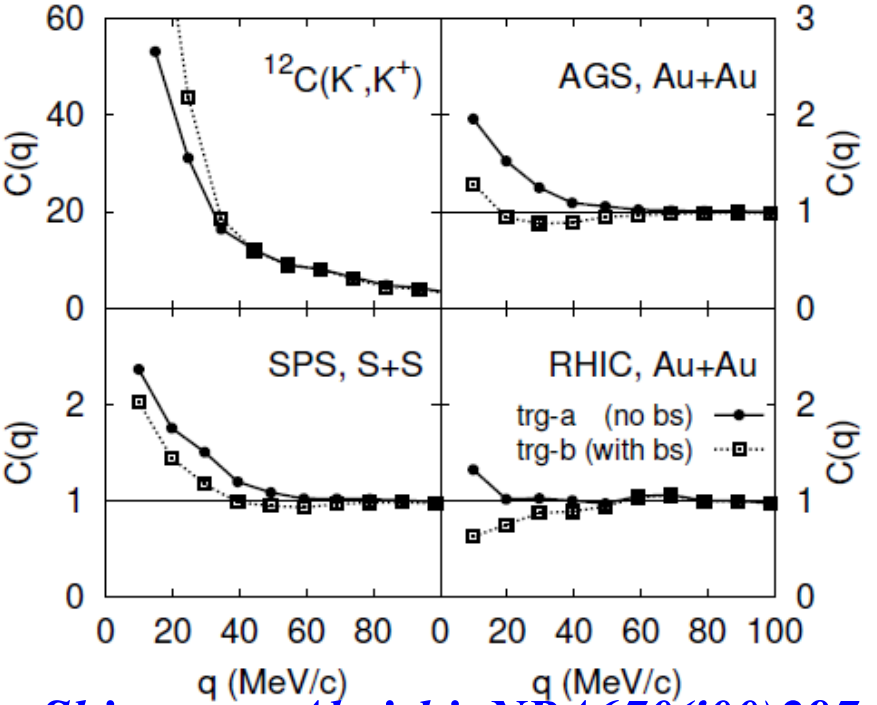
ΛΛ correlation in HIC

- **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.**





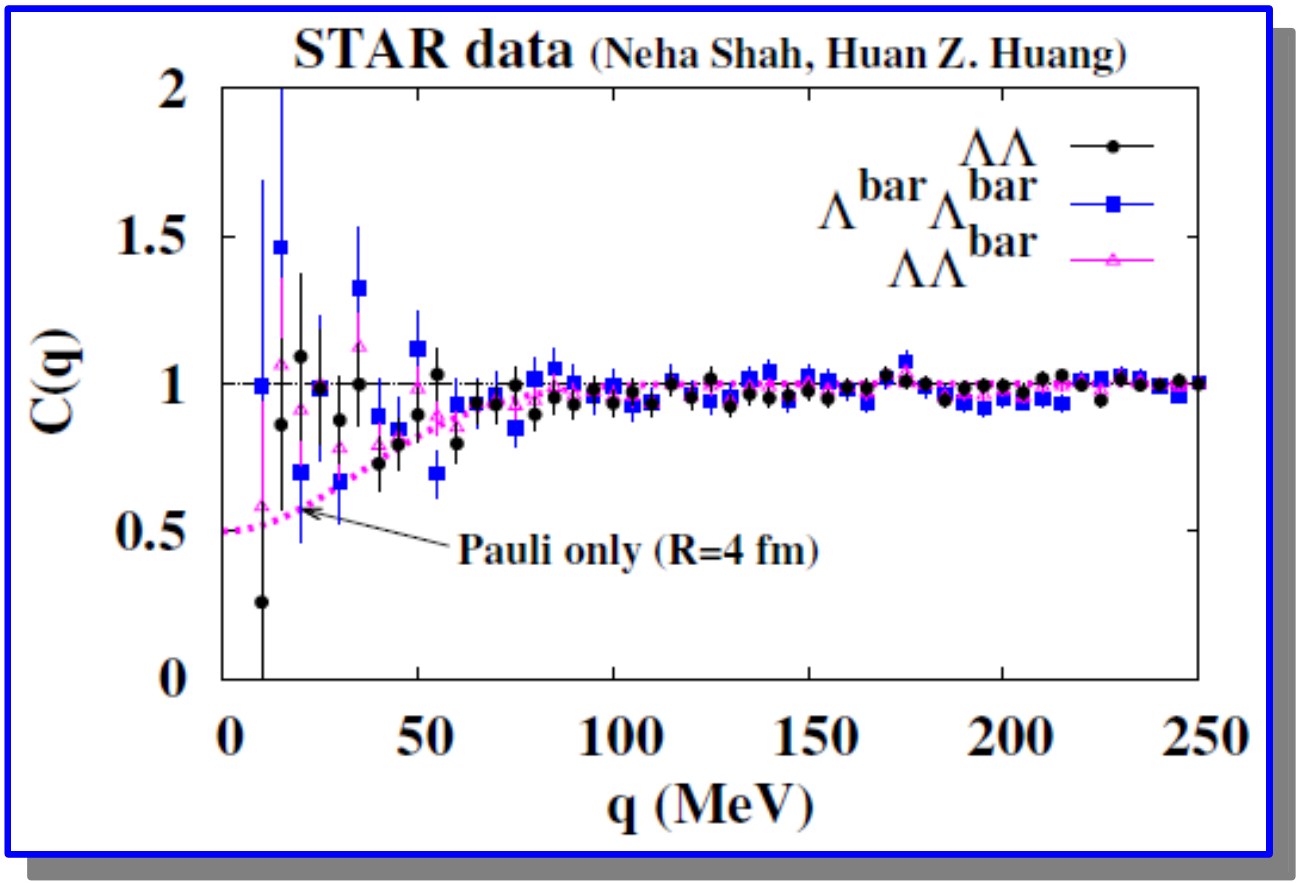
C. Greiner, B. Muller, PLB219('89)199.



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

ΛΛ correlation in HIC

- **Real Data at RHIC are measured,**
  and Enhancement from Fermi correlation is clearly seen !



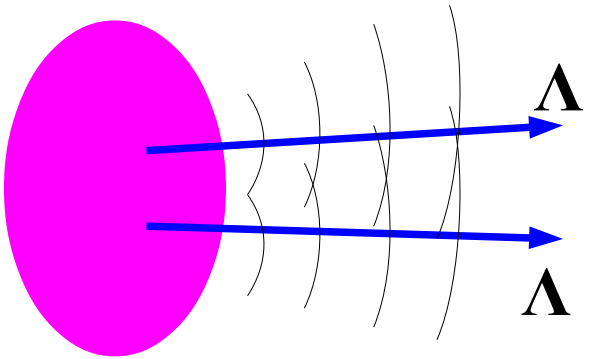
Neha Shah et al. (STAR Collab.), Acta Phys. Pol. Suppl. 5 ('12) 593 [arXiv:1112.0590].

Can we constrain ΛΛ interaction from RHIC data ?
Does H exist as a bound state or a resonance ?

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.

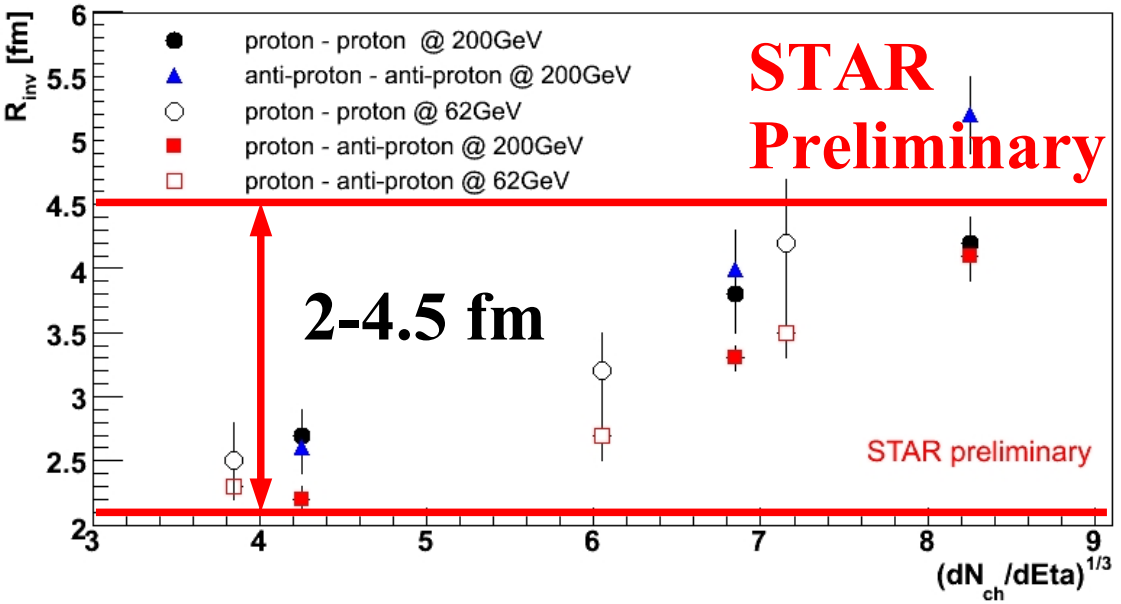


$$C_{\Lambda\Lambda}(q) = \frac{\int dx_1\, dx_2\, S(x_1, p+q)\, S(x_2, p-q)\, |\psi^{(-)}(x_{12}, q)|^2}{\int dx_1\, dx_2\, S(x_1, p+q)\, S(x_2, p-q)}$$

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

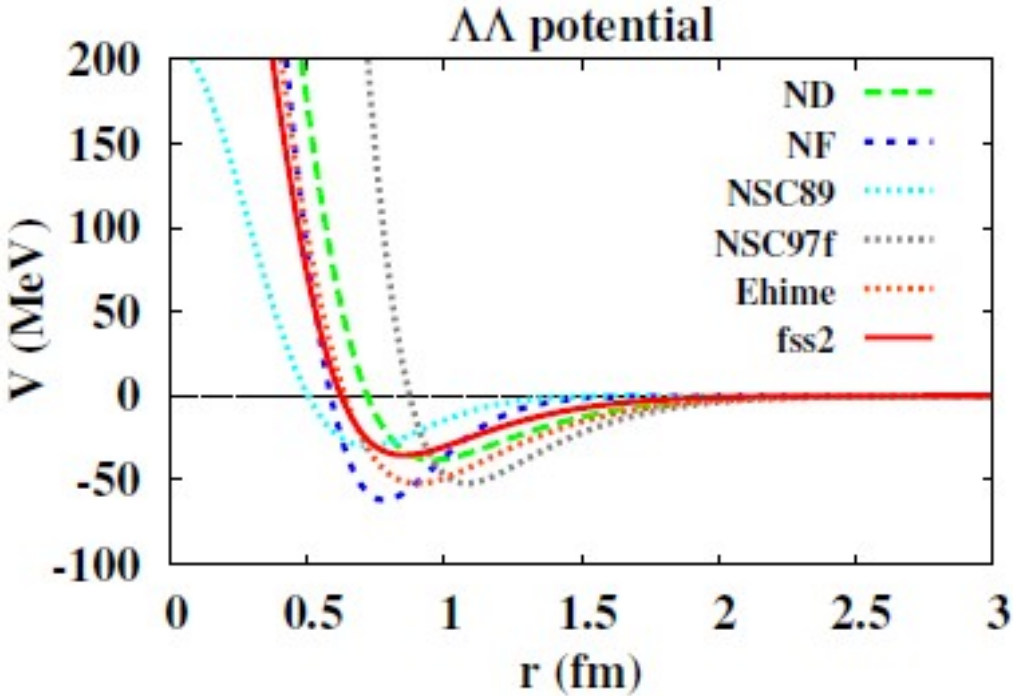
(χ_0 : s-wave wave func., $S_{12}(x)=(2R\sqrt{\pi})^{-3}\exp(-r^2/4R^2)$)

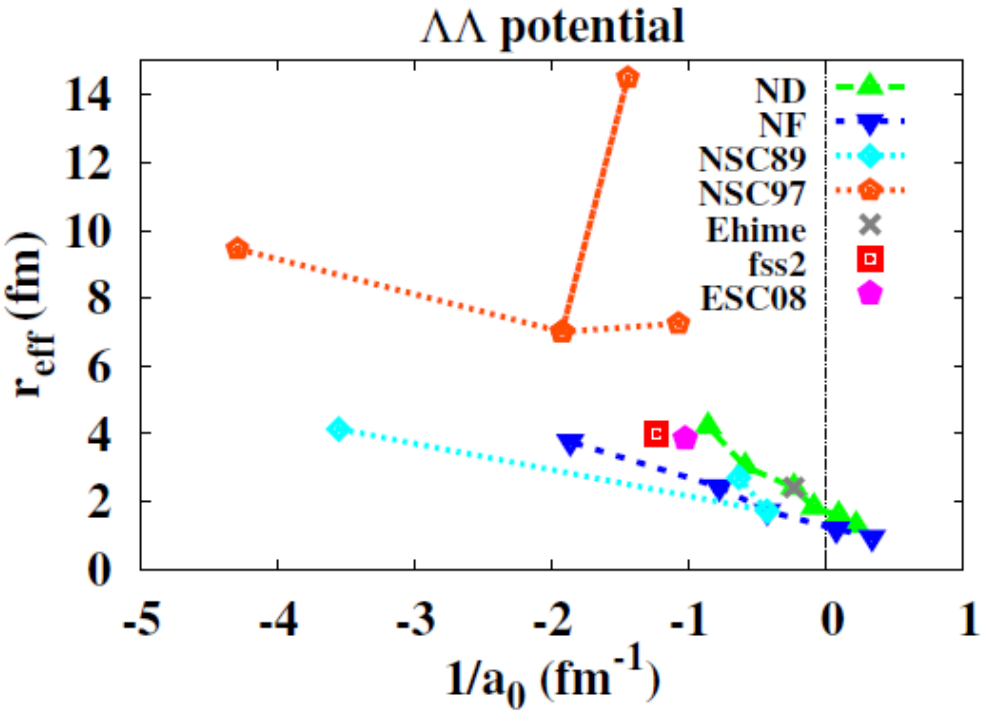
- **Baryon Source size**
  R = (2-4.5) fm
  - **Smaller than π, K source.**



ΛΛ interaction

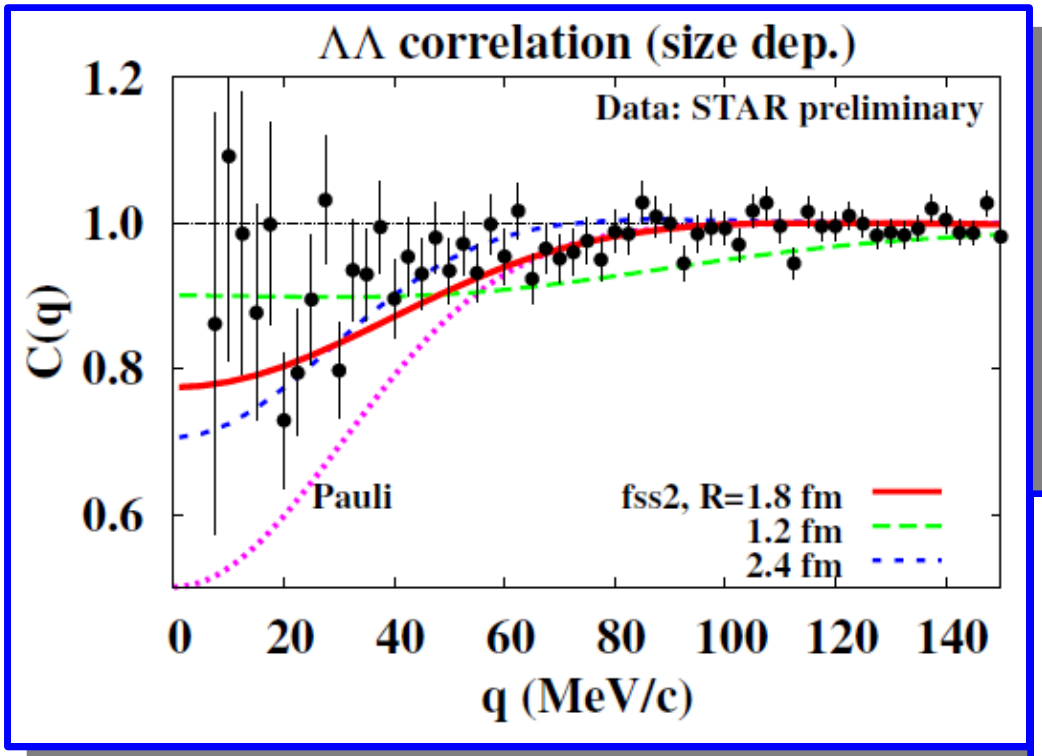
- **Type of ΛΛ interactoin**
  - **Meson exchange models: Nijmegen model D, F, Soft Core (89, 97)**
    Nagels, Rijken, de Swart ('77, '79), Maessen, Rijken, de Swart ('89), Rijken, Stoks, Yamamoto ('99)
  - **Quark cluster model interaction: fss2**
    Fujiwara, Fujita, Kohno, Nakamoto, Suzuki ('00)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

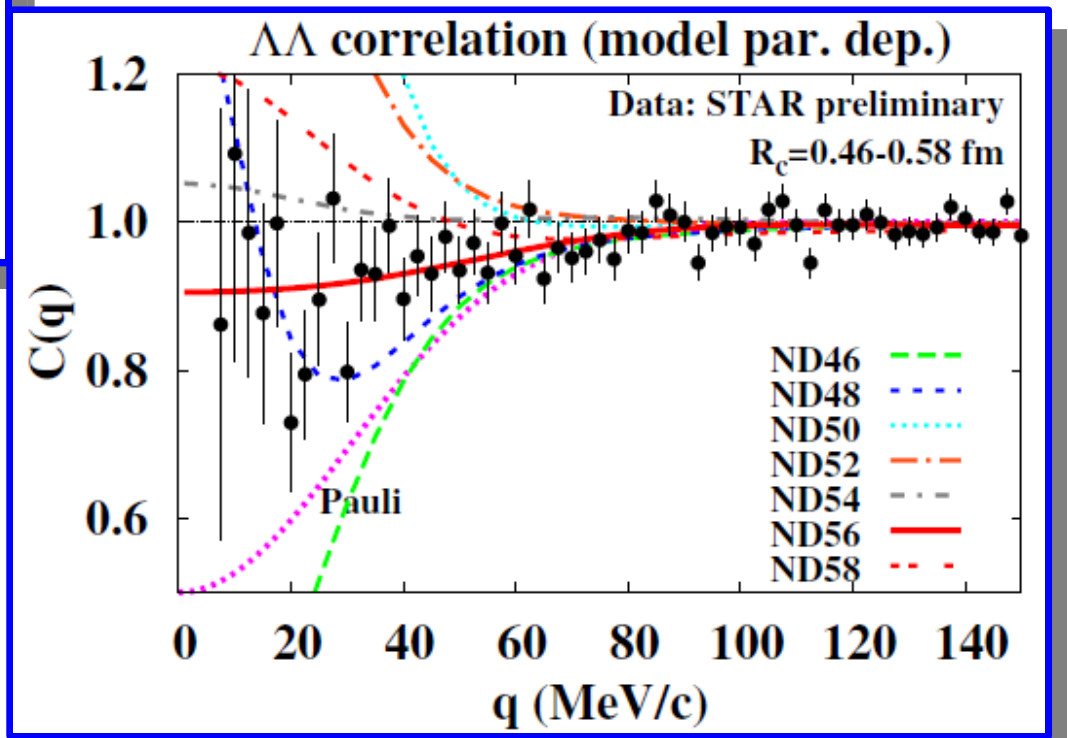




How can we constrain ΛΛ interaction from HIC data ?

- C(q) at large q → R, C(q) at small q → model par. dep.





Source size R ~ 2 fm

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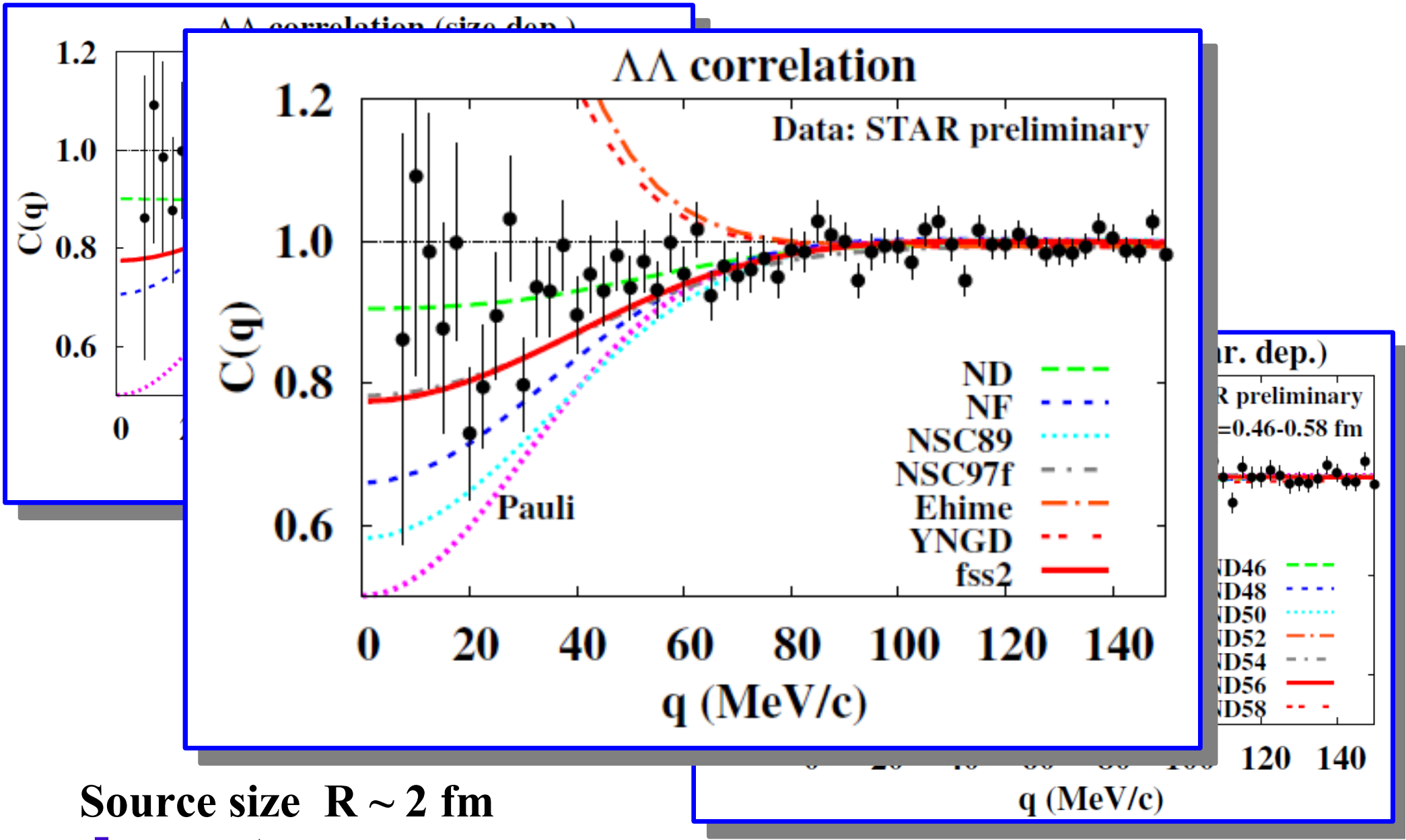
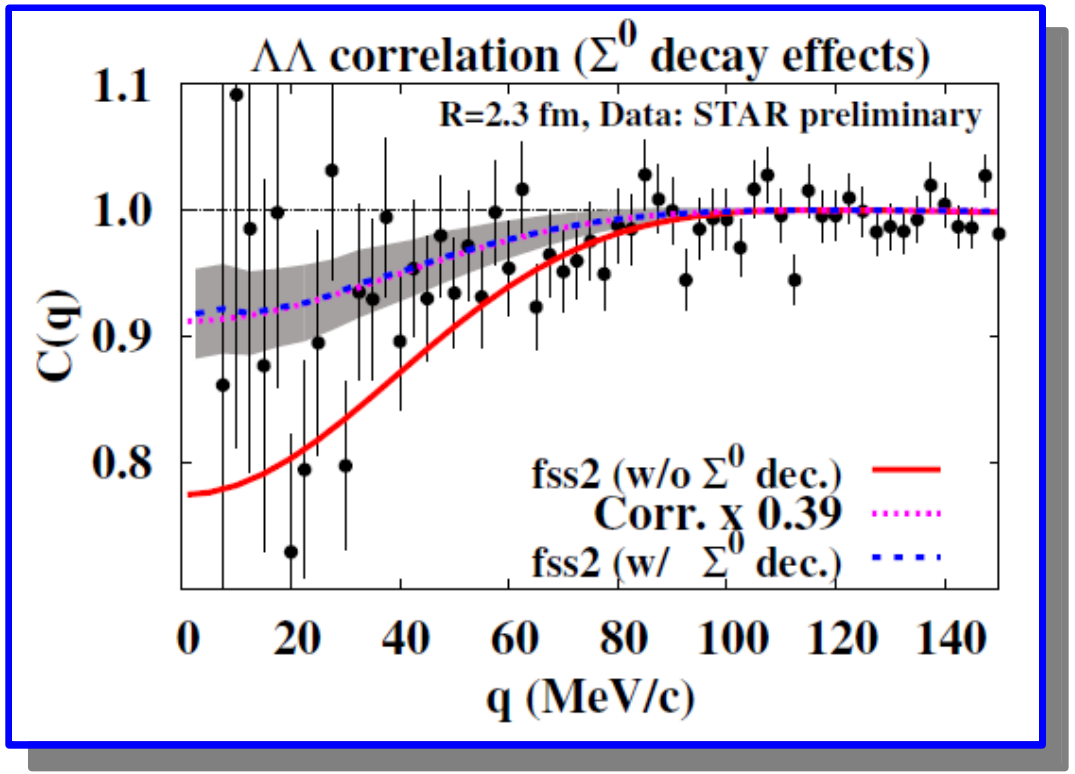


Source size R ~ 2 fm

Effects of Other Channels

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



Source size
R ~ 1.7 fm

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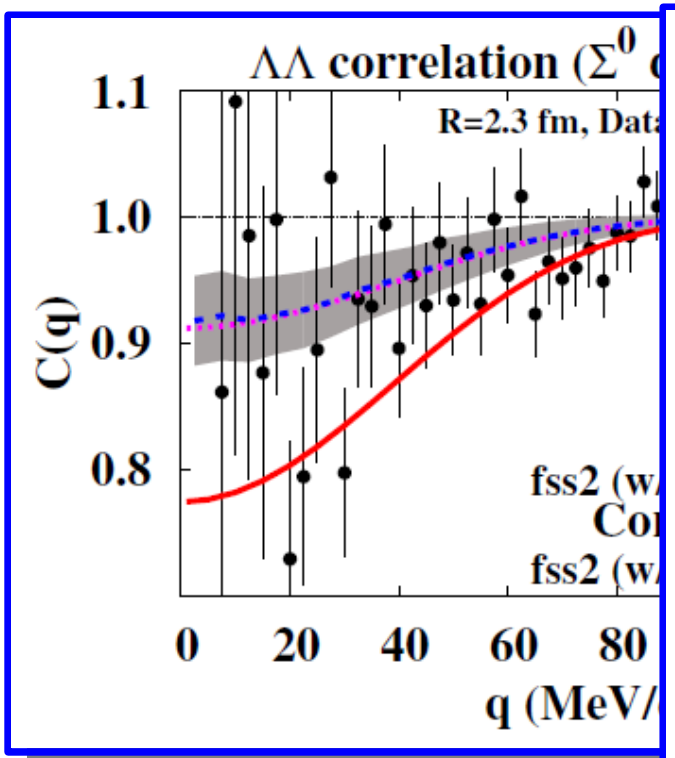

Source size
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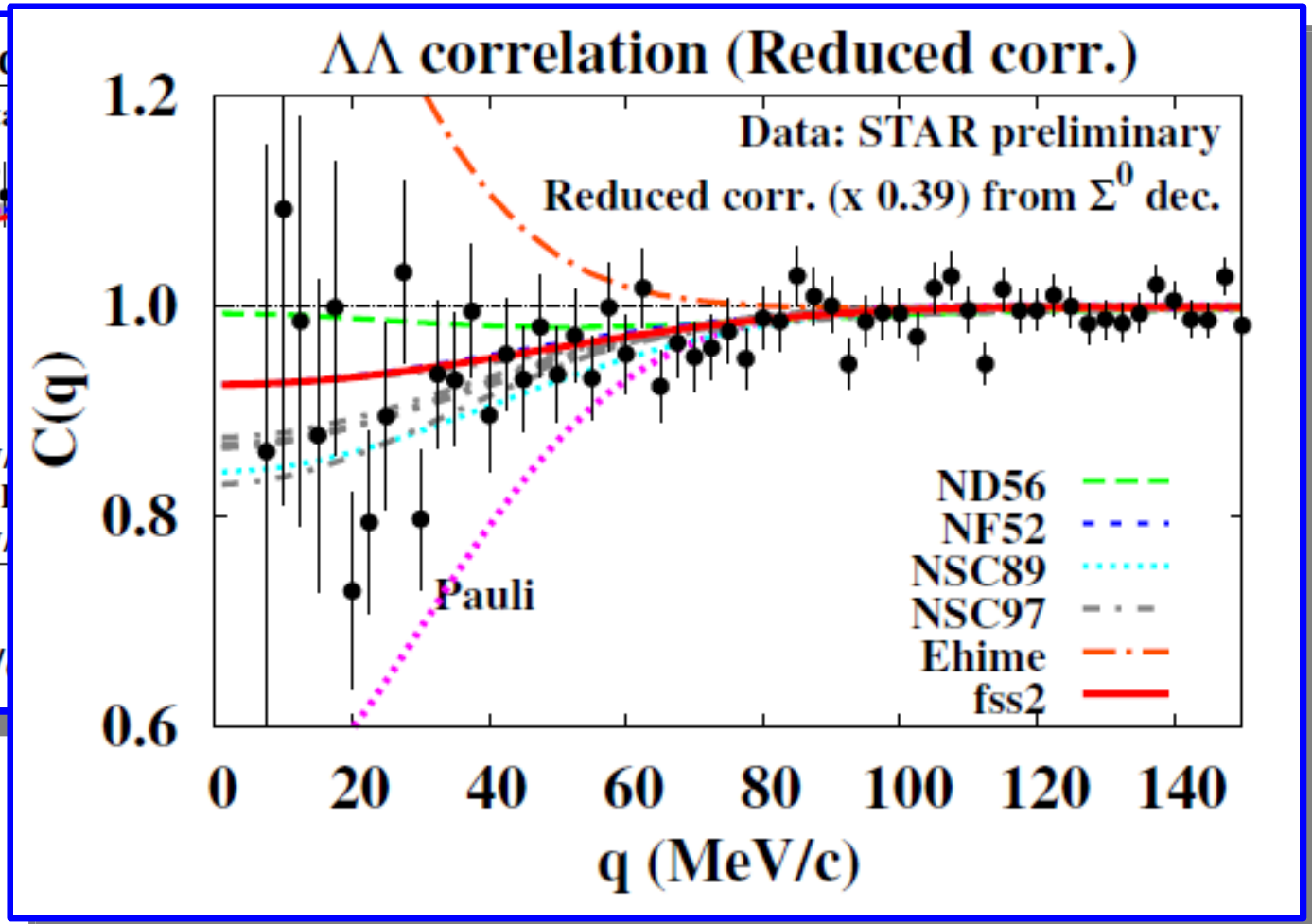
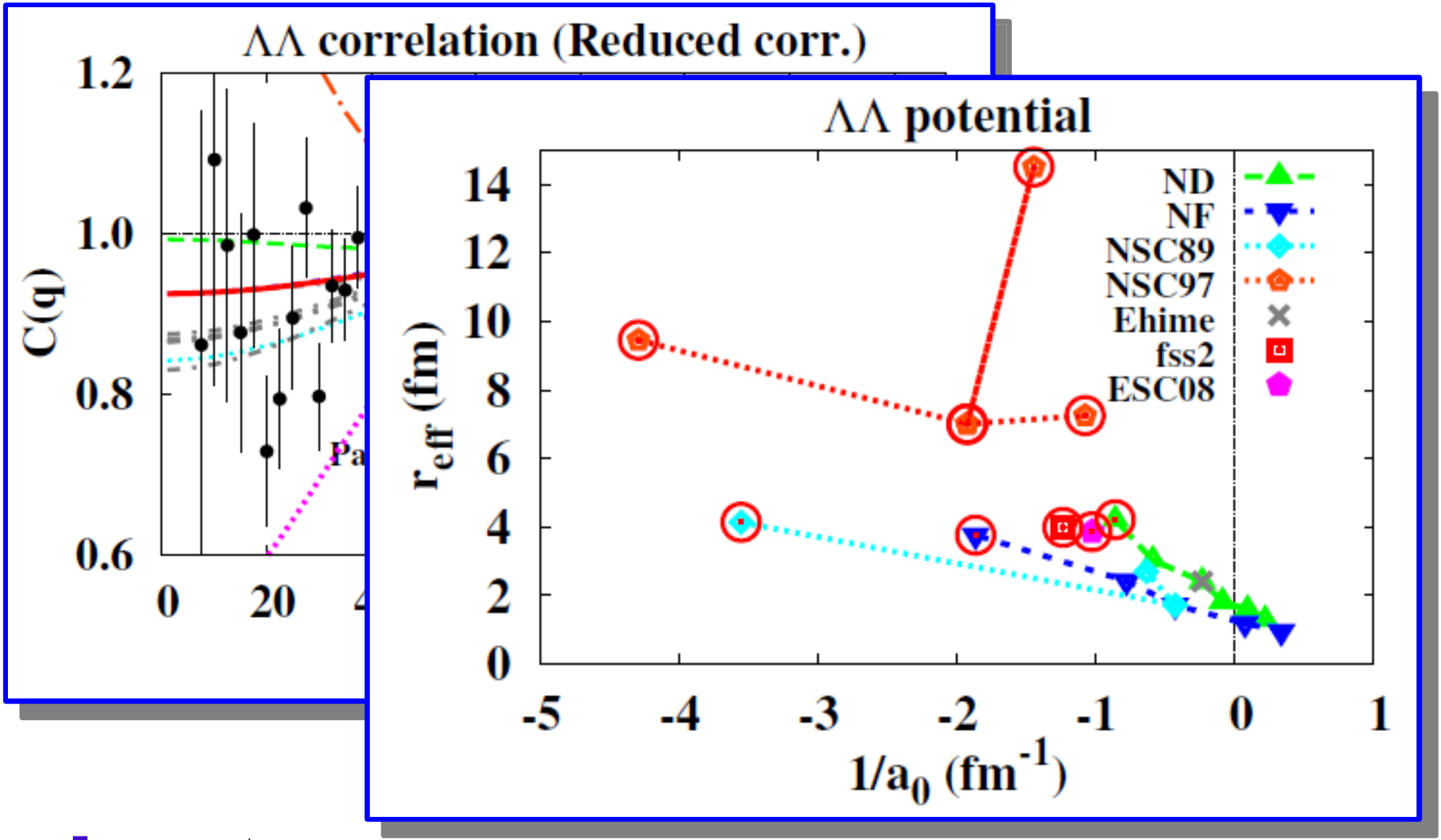


Preferred ΛΛ Interaction

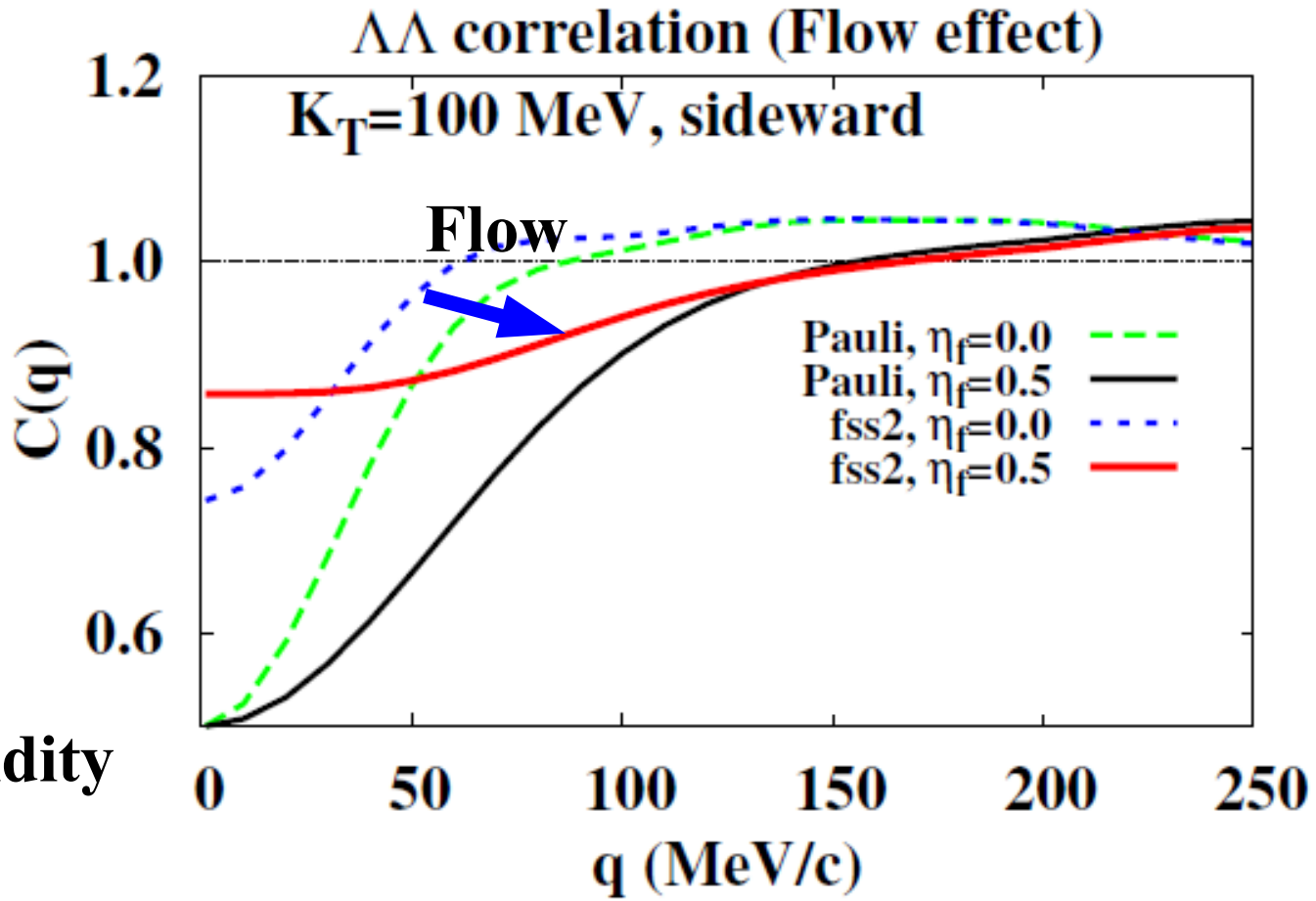
- **STAR data choose some of the ΛΛ interaction**
  → $1/a_0 < -0.8$ fm^{-1} (-1.2 fm $< a_0 < 0$), $r_{eff} > 3$ fm seems to be preferred.



Flow Effects

- **Too small source size ~ 1.7 fm with Σ^0 feed down effects ?**
- **Flow effects make the "apparent" size smaller.**
  - **Relative momentum is enhanced by the flow.**
    → Actual size ~ (3-4) fm (guess)

Morita



Transverse rapidity

$$Y_T = \eta_f \, r_T / R$$

Summary

- **We studied ΛΛ correlation in heavy-ion collisions at RHIC.**
  - **Recent STAR (preliminary) data clearly show enhanced ΛΛ correlation compared to the free fermion correlation** *N.Shah, H.Huan et al. (STAR Collab.), Acta Phys. Pol. Suppl. 5 ('12) 593 [arXiv:1112.0590].*
- **Preferred ΛΛ interactions have $1/a_0 < -0.8$ fm^{-1}, $r_{eff} > 3$ fm.**
  - **Weakly attractive. Consistent with Nagara event (a_0=-(0.7-1.3) fm)**
    E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, Y. Yamamoto, PRC66('02)024007; A. M. Gasparyan et al. PRC85('12)015204; A. Gal.
  - **Effects other than Λ Λ final state interaction.**
    - **Σ^0 decay effects are well simulated by multiplying 0.39 to (C-1), if there is no strong correlation in ΛΣ channel.**
    - **Coupled channel effects with ΞN should be considered with care.**
  - **Apparent source size (w/o flow effects) is estimated to be ~ 1.7 fm. With flow effects, real source size would be larger (~ (3-4) fm ?).**
- **Existence of resonance "H" requires higher statistics. Other YY (and hh) correlations would be measurable in HIC.**

Thank you !

Nagara event

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

  Takahashi et al., PRL87('01)212502

  (KEK-E373 experiment)

Lambpha

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

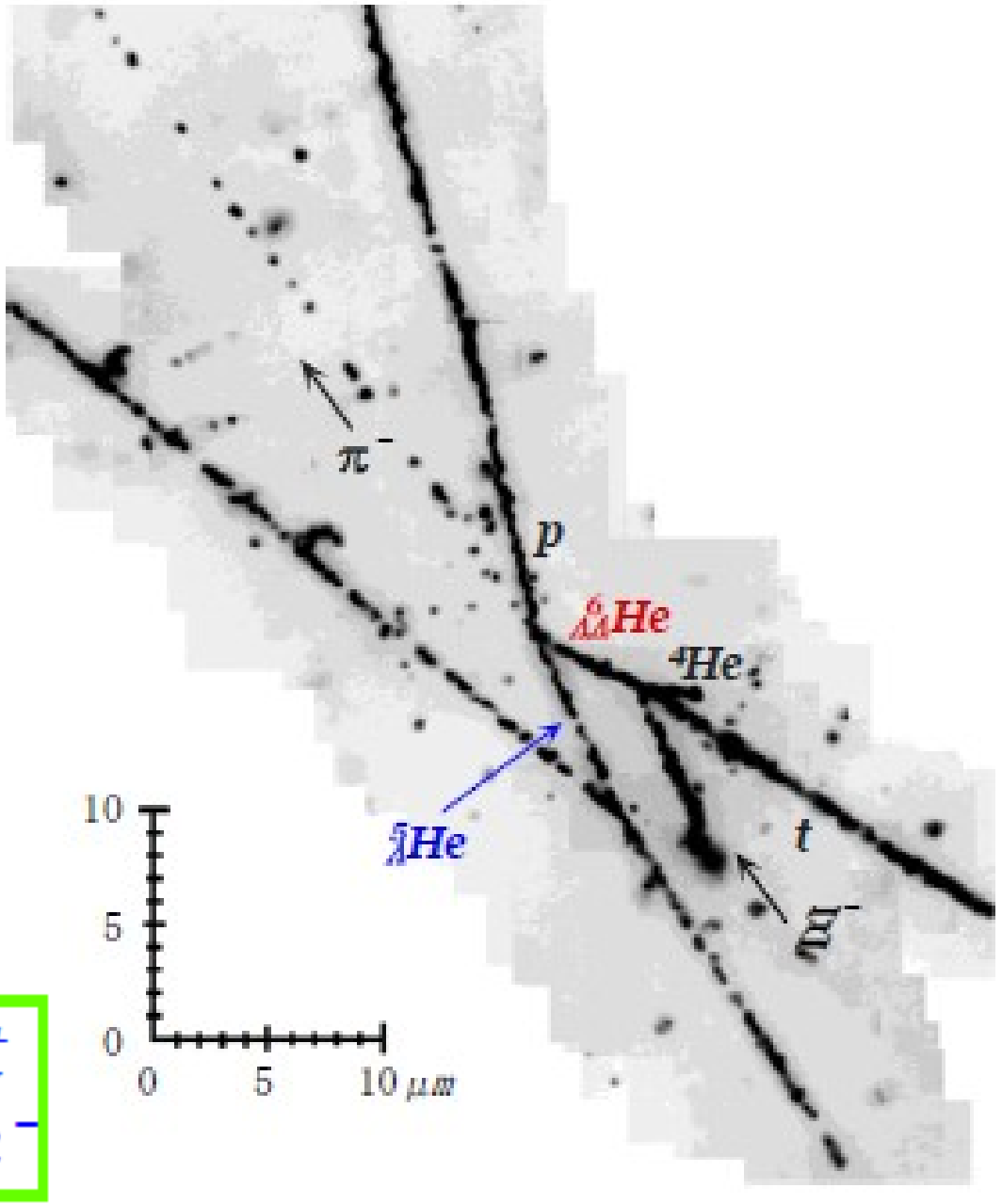
$$B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}\,\mathrm{MeV}$$

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

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

→ $B_{\Lambda\Lambda}$ = 6.91 MeV

(PDG modified(updated) Ξ^- mass)

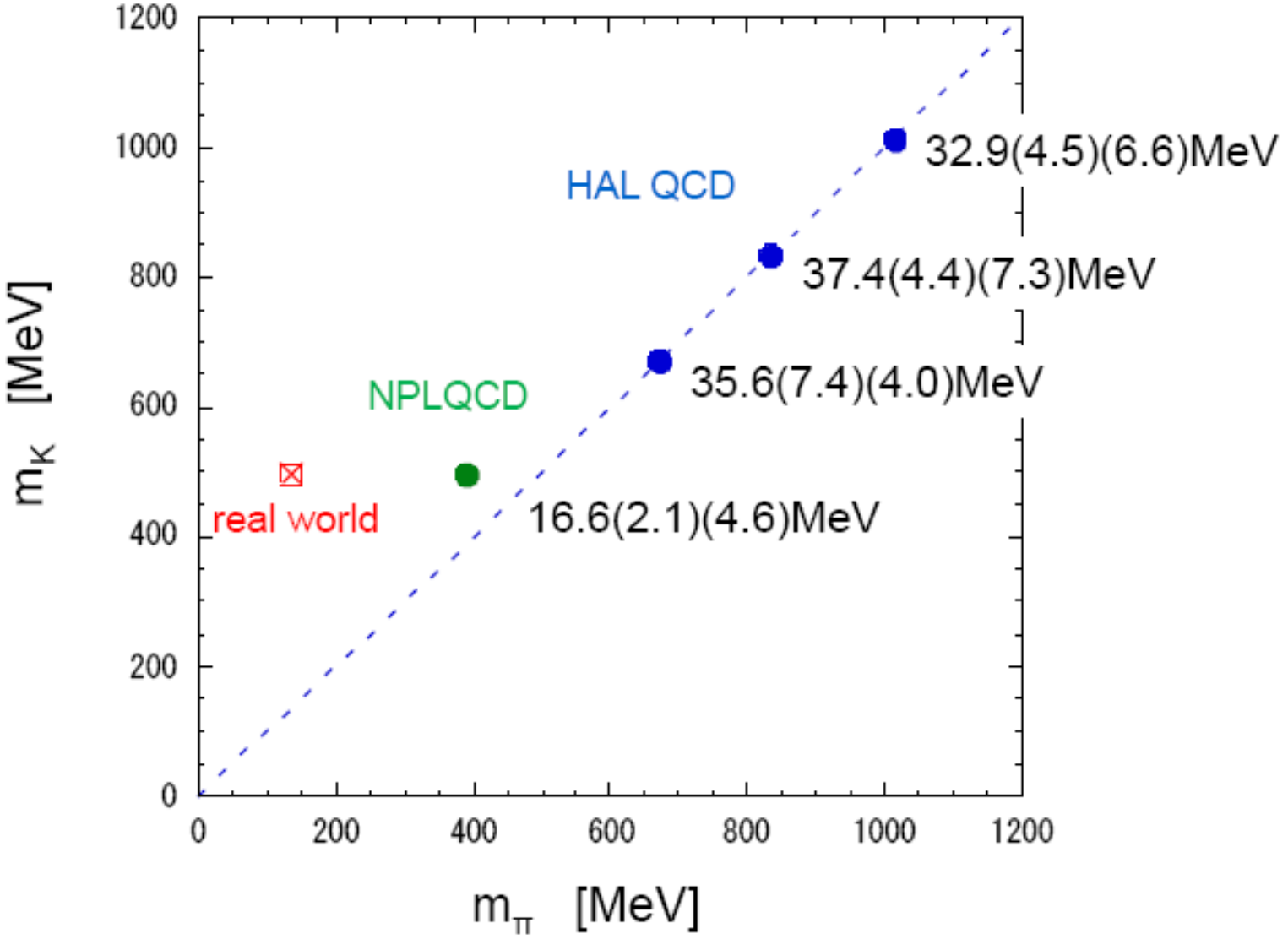


$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

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

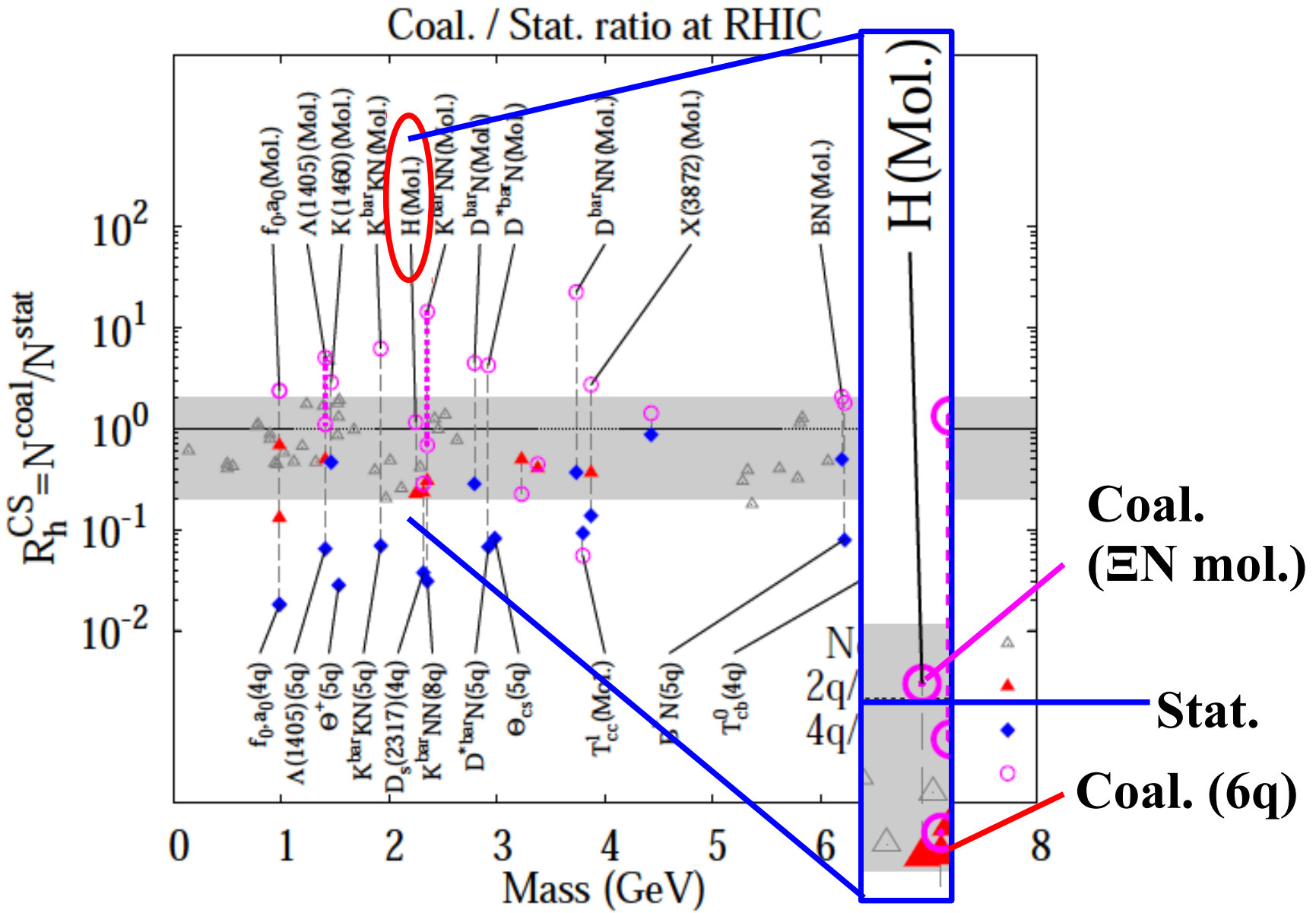
Lattice QCD predicts bound "H"

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



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

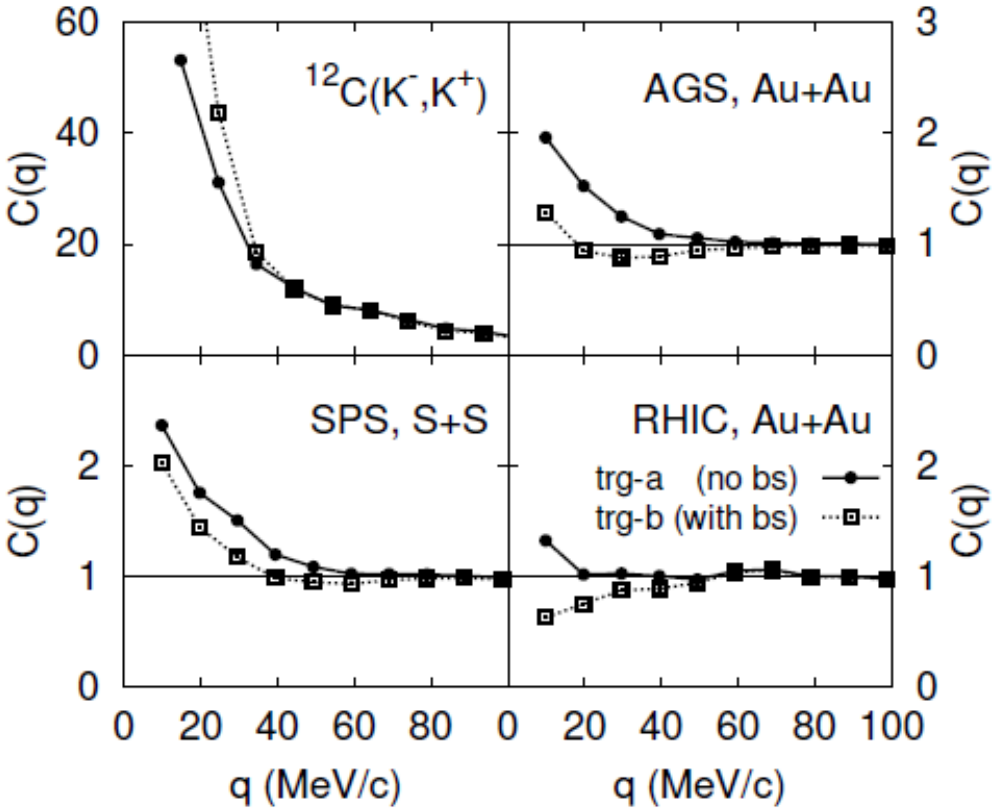
Exotics from Heavy-Ion Collisions

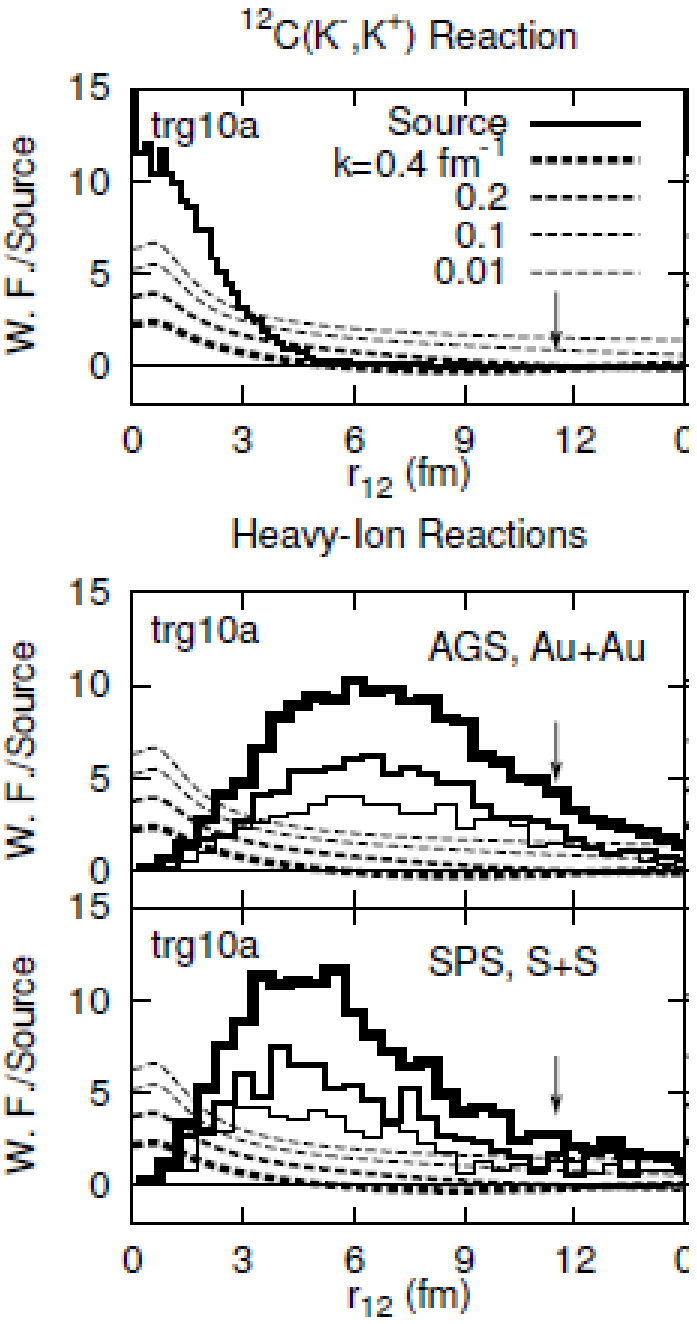


Cho,Furumoto,Hyodo,Jido, Ko, Lee,Nielsen,AO,Sekihara,Yasui,Yazaki (ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302

Previous Work (before RHIC & Nagara)

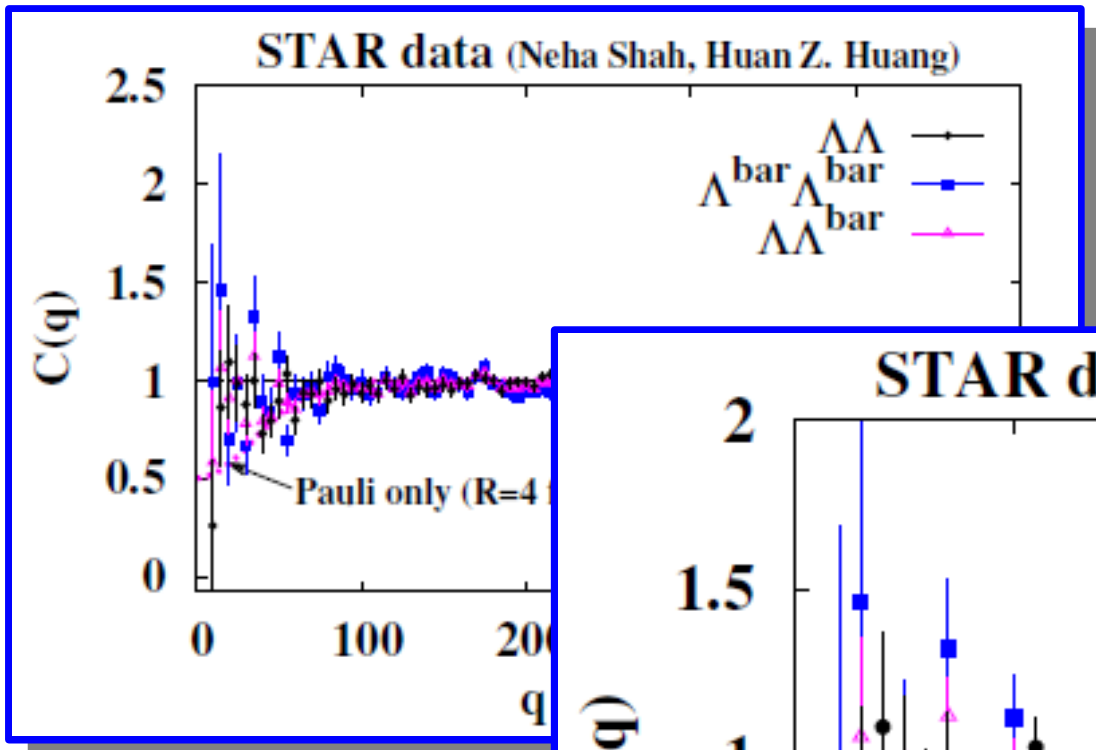
- **Hadronic transport (JAM) + Two Range Gaussian $V_{\Lambda\Lambda}$**
  - **w/ bound state → w.f. node suppresses C(q)**



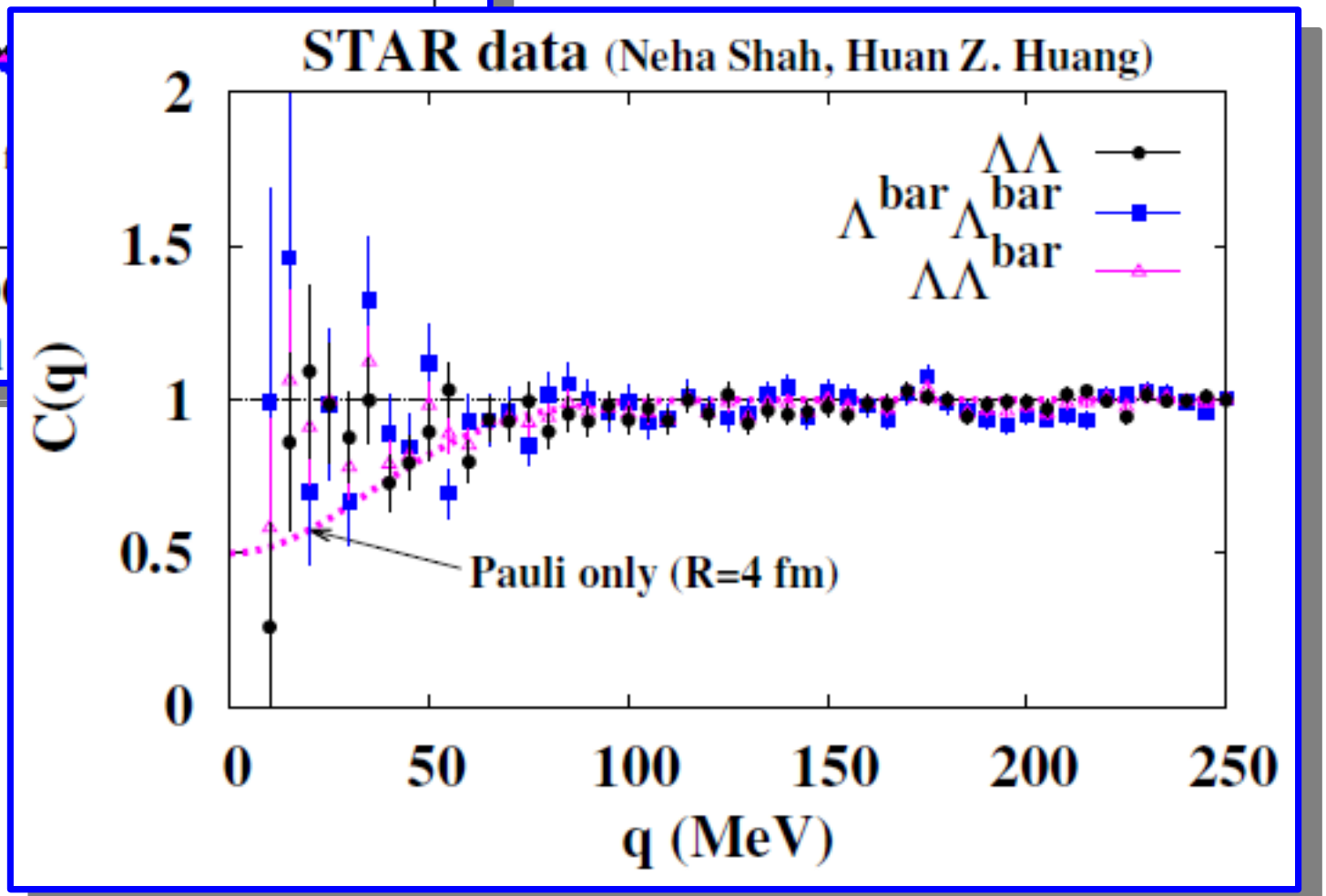


AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c [arXiv:nucl-th/9903021]; SNP2000 proc. p175.
JAM: Nara,Otuka, AO, Niita, Chiba, PRC61 ('00), 024901.

STAR data



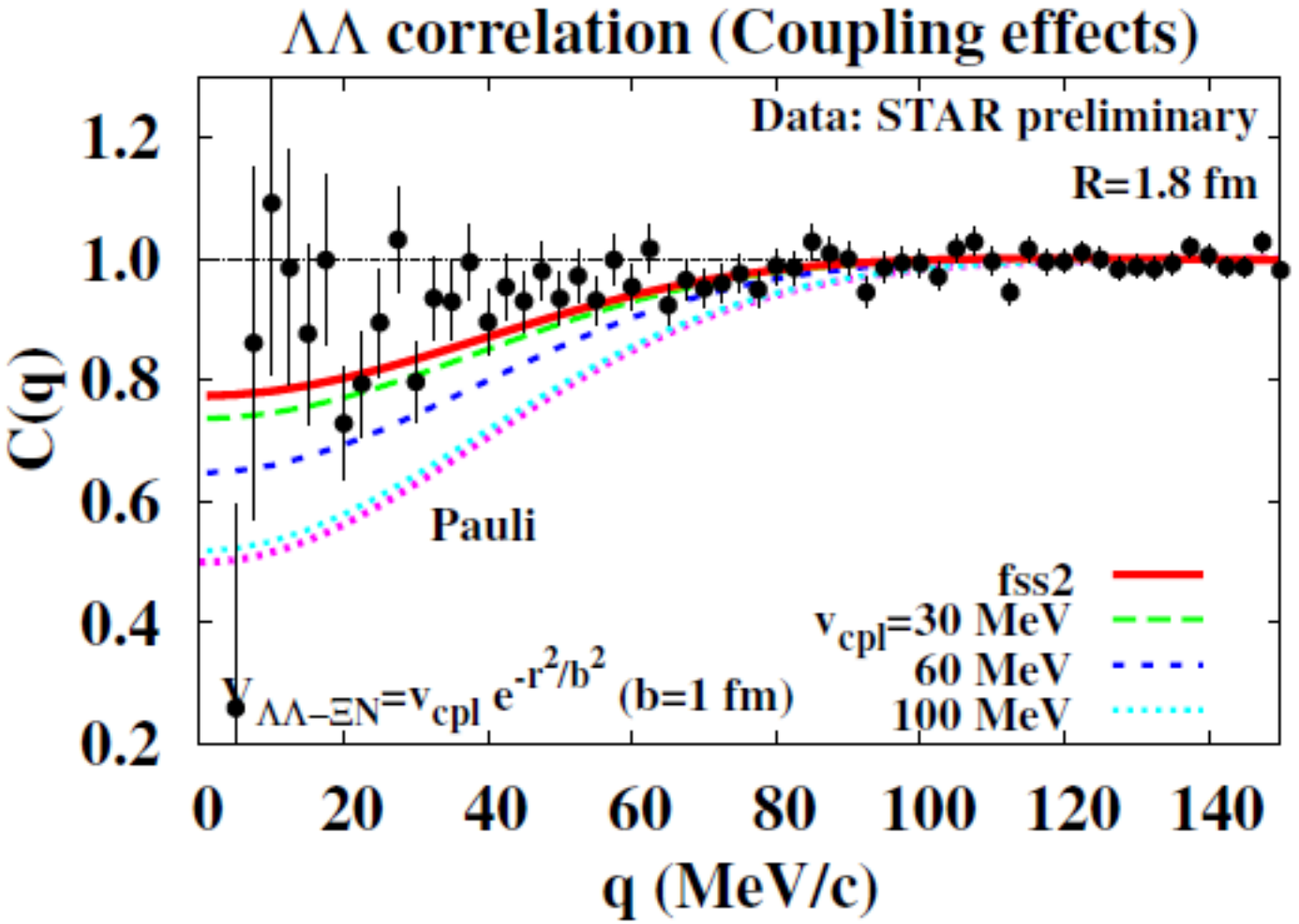
Clear Enh. from Free corr. (Pauli) is seen !



Lambda-Lambda Interaction and Lambda-Lambda Correlation at RHIC

Coupling Effects

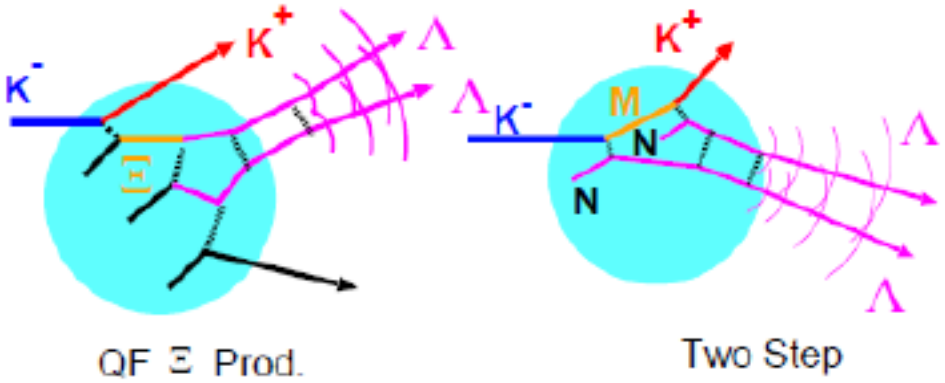
- Coupled channels effects with ΞN channel is considered.
  - Coupling with ΞN channel suppresses C(q) at low q. (~ Imag. pot.)
  - Unreasonably large coupling would meaningfully modify C(q).



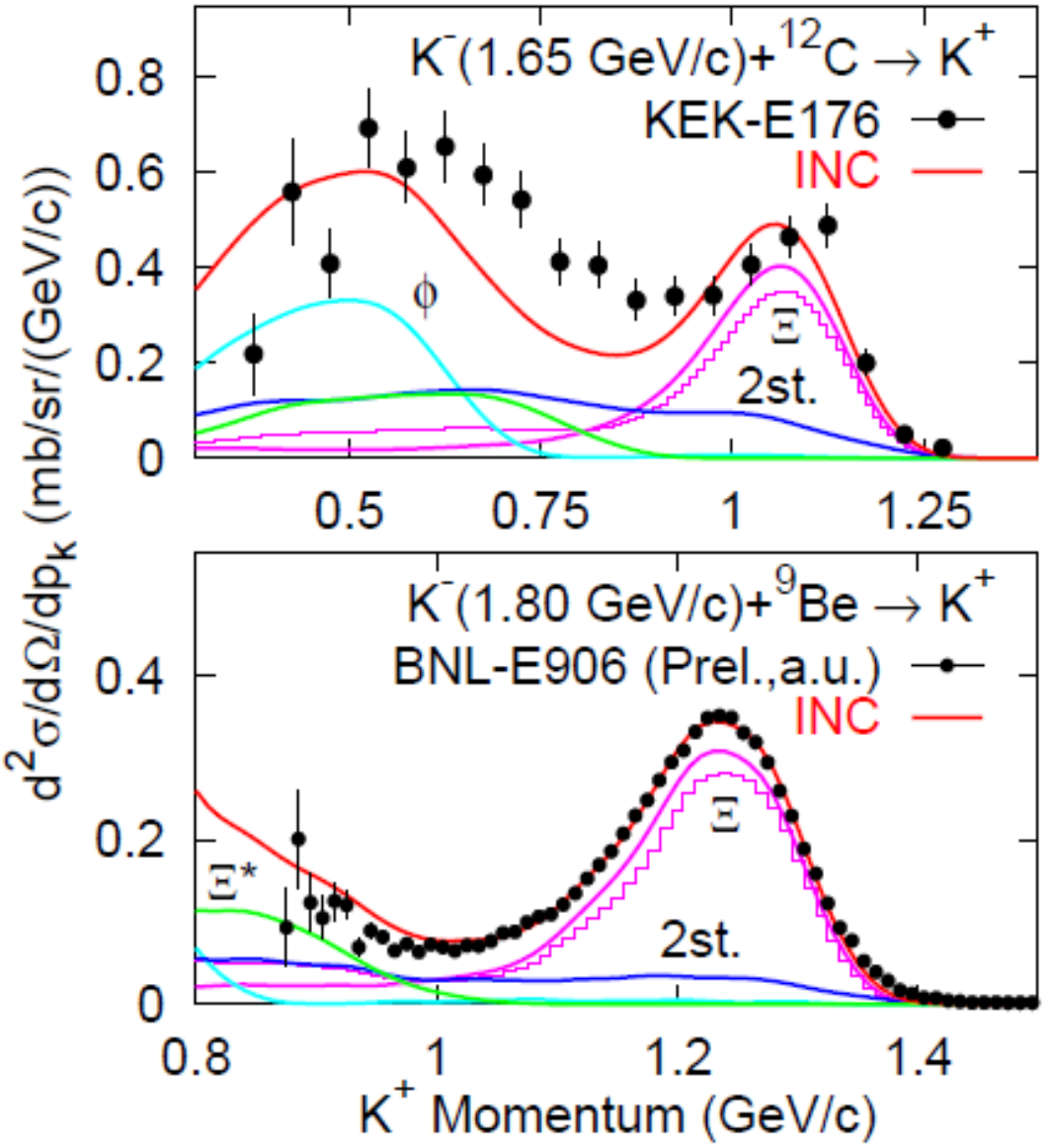
$\Lambda\Lambda$ Correlation in (K^-,K^+) Reaction

ΛΛ 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 procecces**
    Nara, AO, Harada, Engel, NPA614 (1997) 433



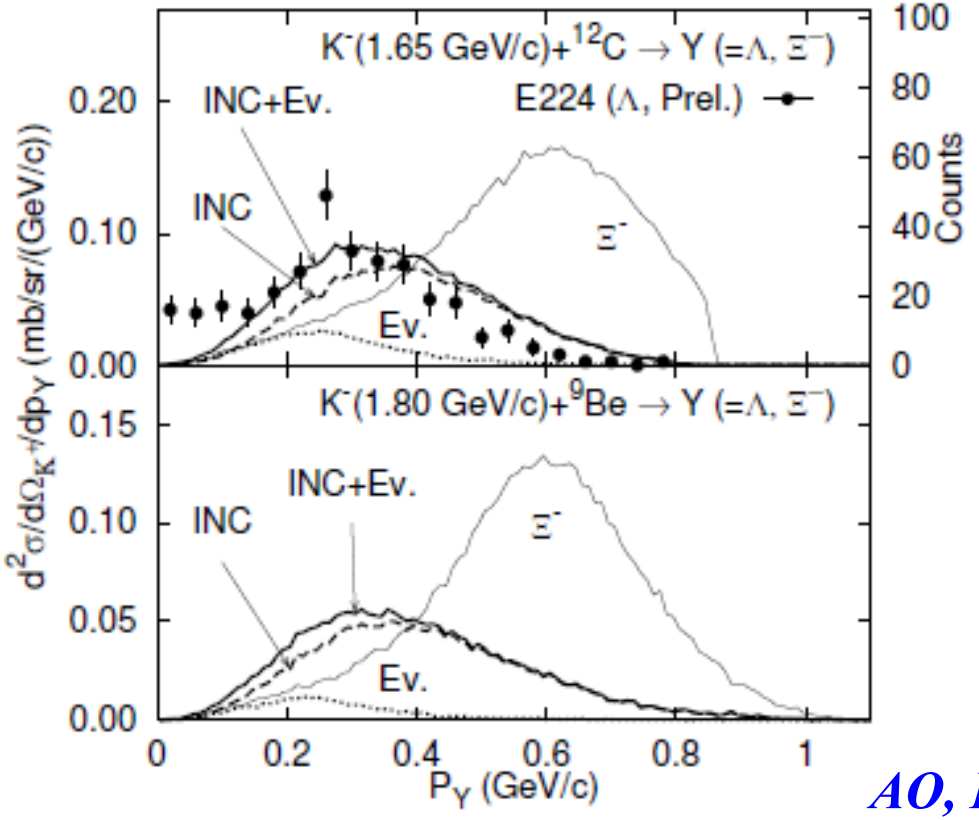
QF Ξ Prod. Two Step

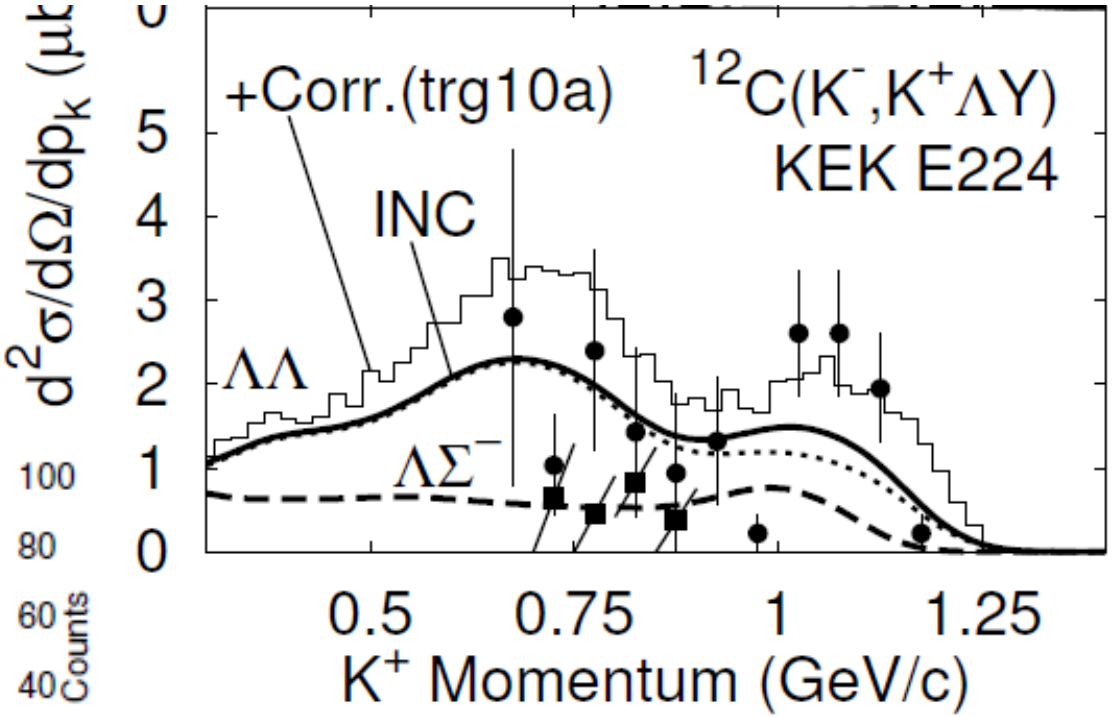


AO, Hirata, Nara, Shinmura, Akaishi, Few-Body Syst. Suppl. 12 (2000), 367

ΛΛ Correlation in (K^-,K^+) Reaction (2)

- **Λ production mechanism**
  - **Cascade procecces**
  - **Evaporation from hyper compound nuclei**



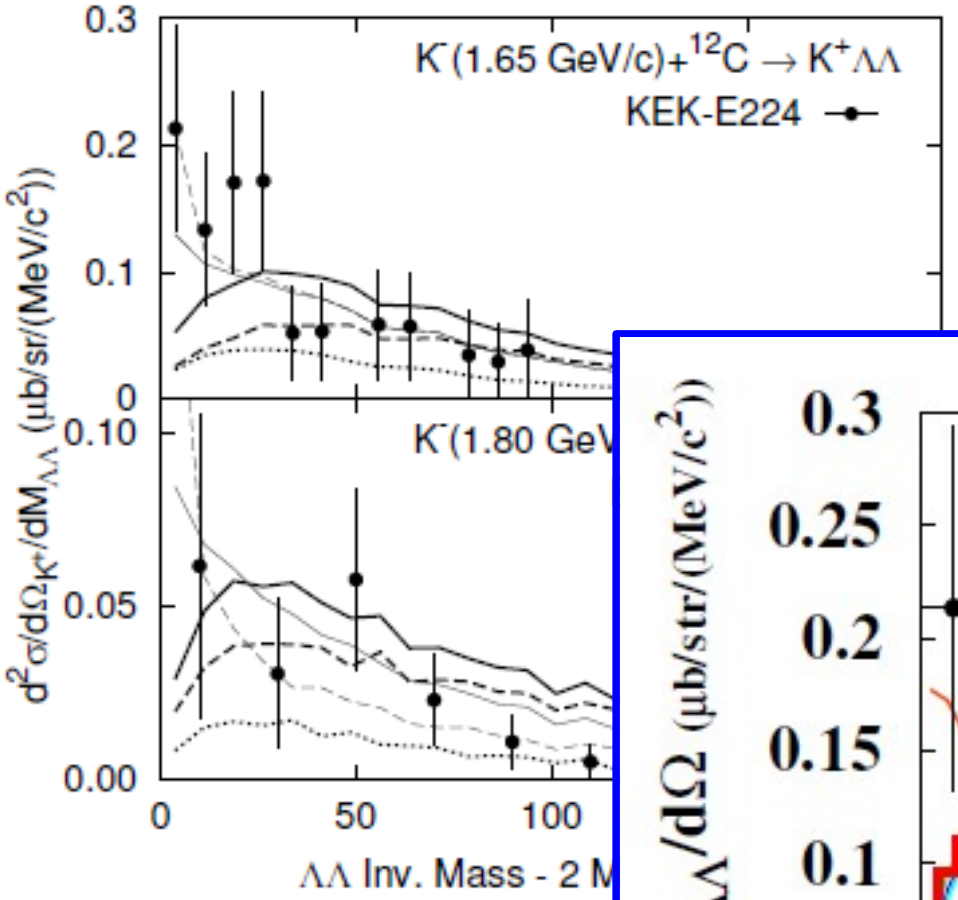


AO, Hirata, Nara, Shinmura, Akaishi, NPA670(2000), 297c

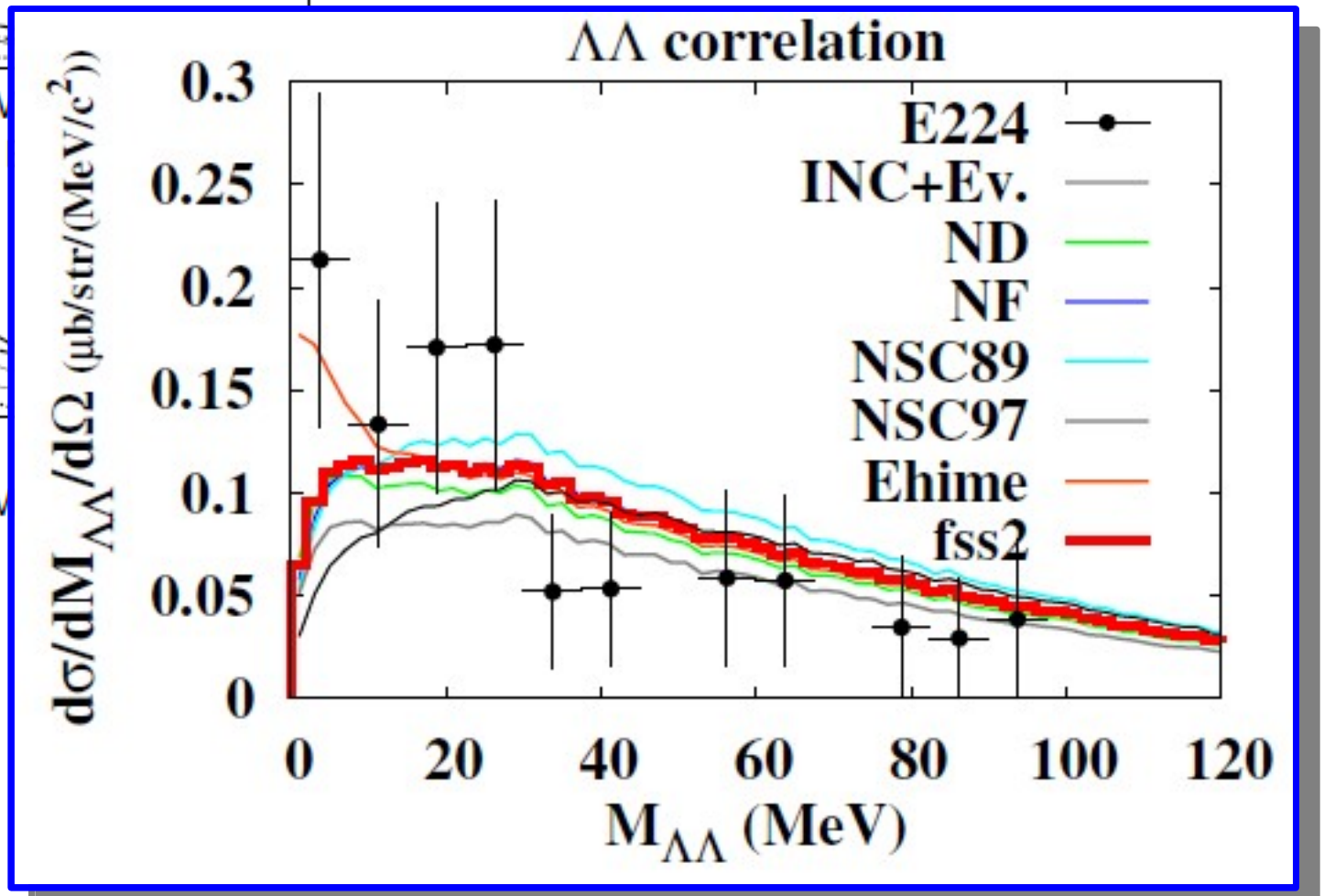
AO, Hirata, Nara, Shinmura, Akaishi, NPA691(2001), 242c

ΛΛ Invariant Mass Spectrum

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

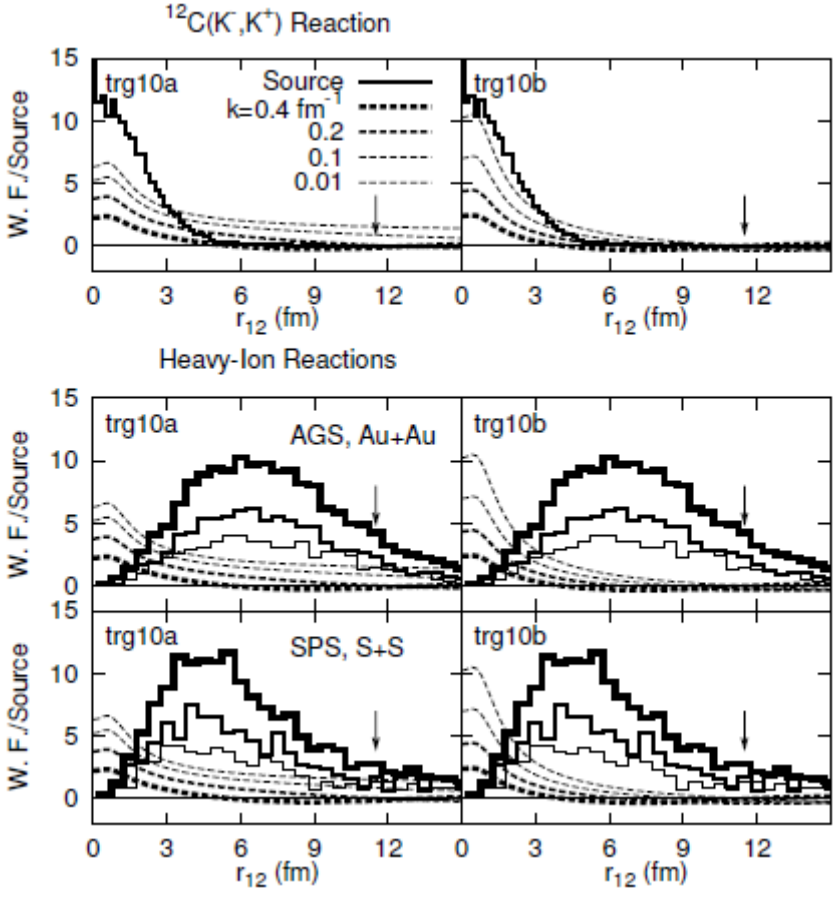


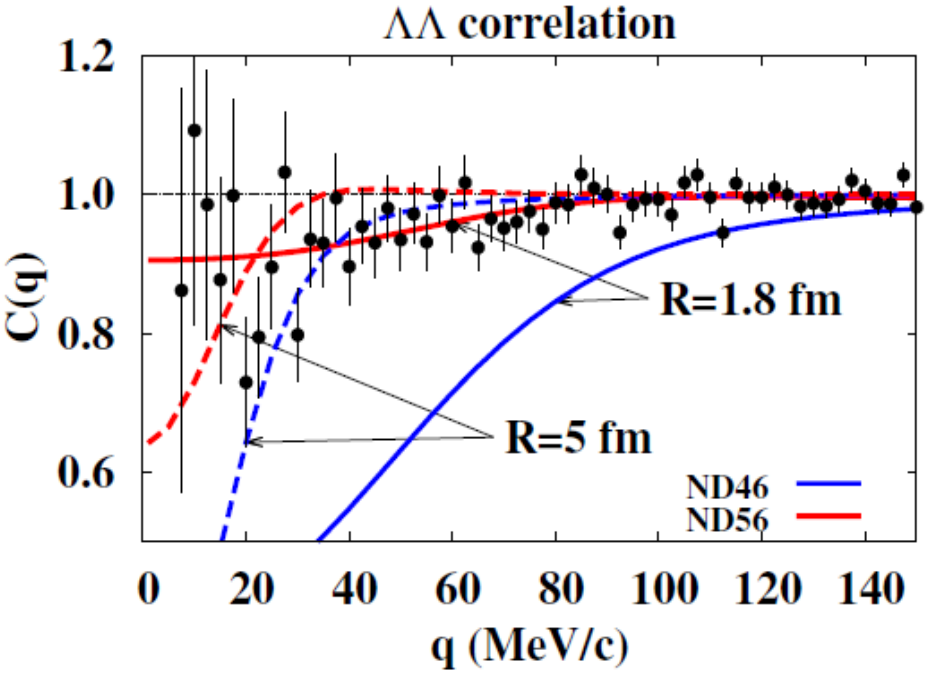
AO, Hirata, Nara, Shinmura, Akaishi, NPA684(2001), 595c



Fate of the prediction

- **Conjecture in 2000**
  Suppressed ΛΛ correlation may suggest the existence of a bound H
  - **Bound H → Node in scattering ΛΛ wf → 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.**

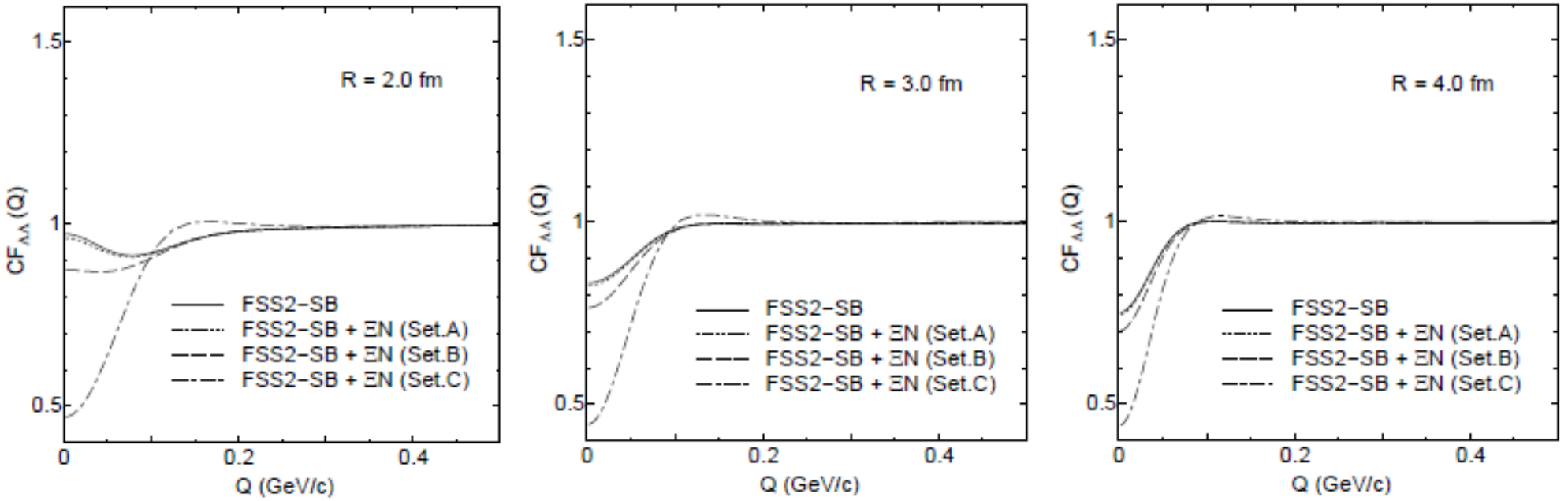




Source size dependence

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

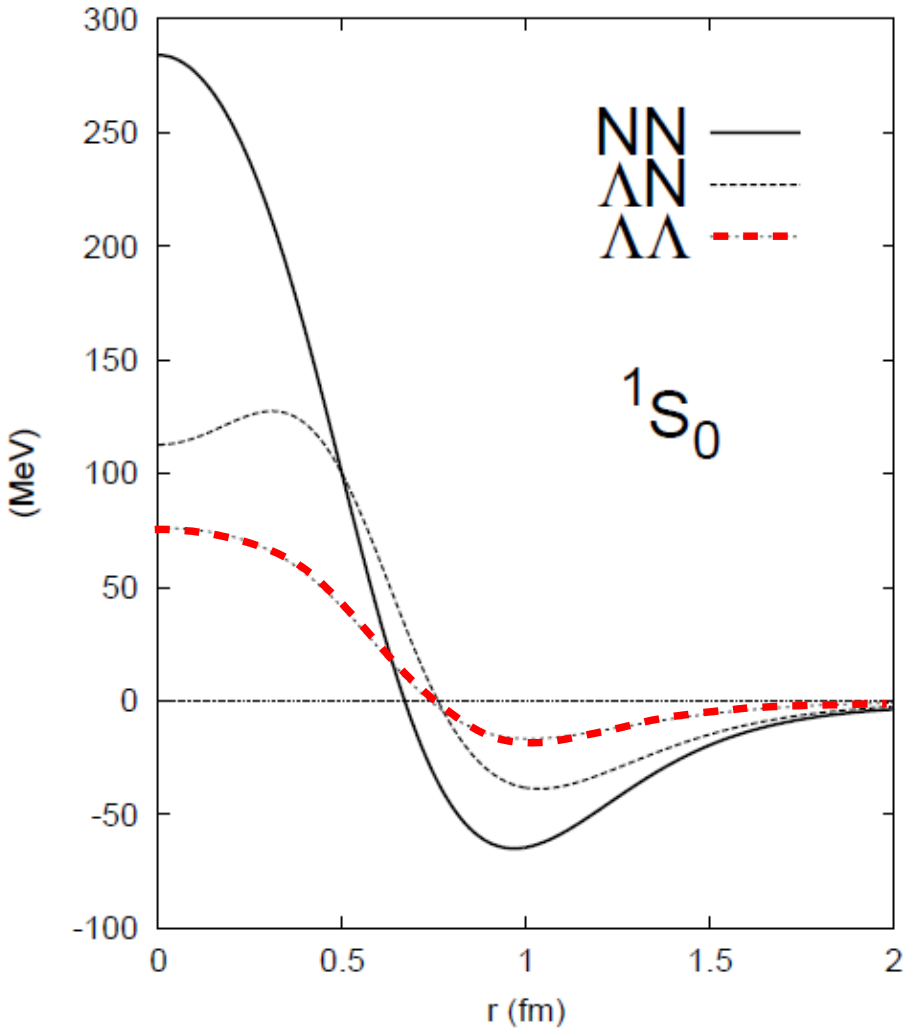
$$C(Q\to 0)\simeq \frac{1}{2}-\frac{2}{\sqrt{\pi}}\frac{a_0}{R}+\left(\frac{a_0}{R}\right)^2 \qquad \textit{(if "Interaction Range" << R)}$$



AO, Furumoto, in prep.

ΛΛ potential

fss2 Phase shift equivalent potential



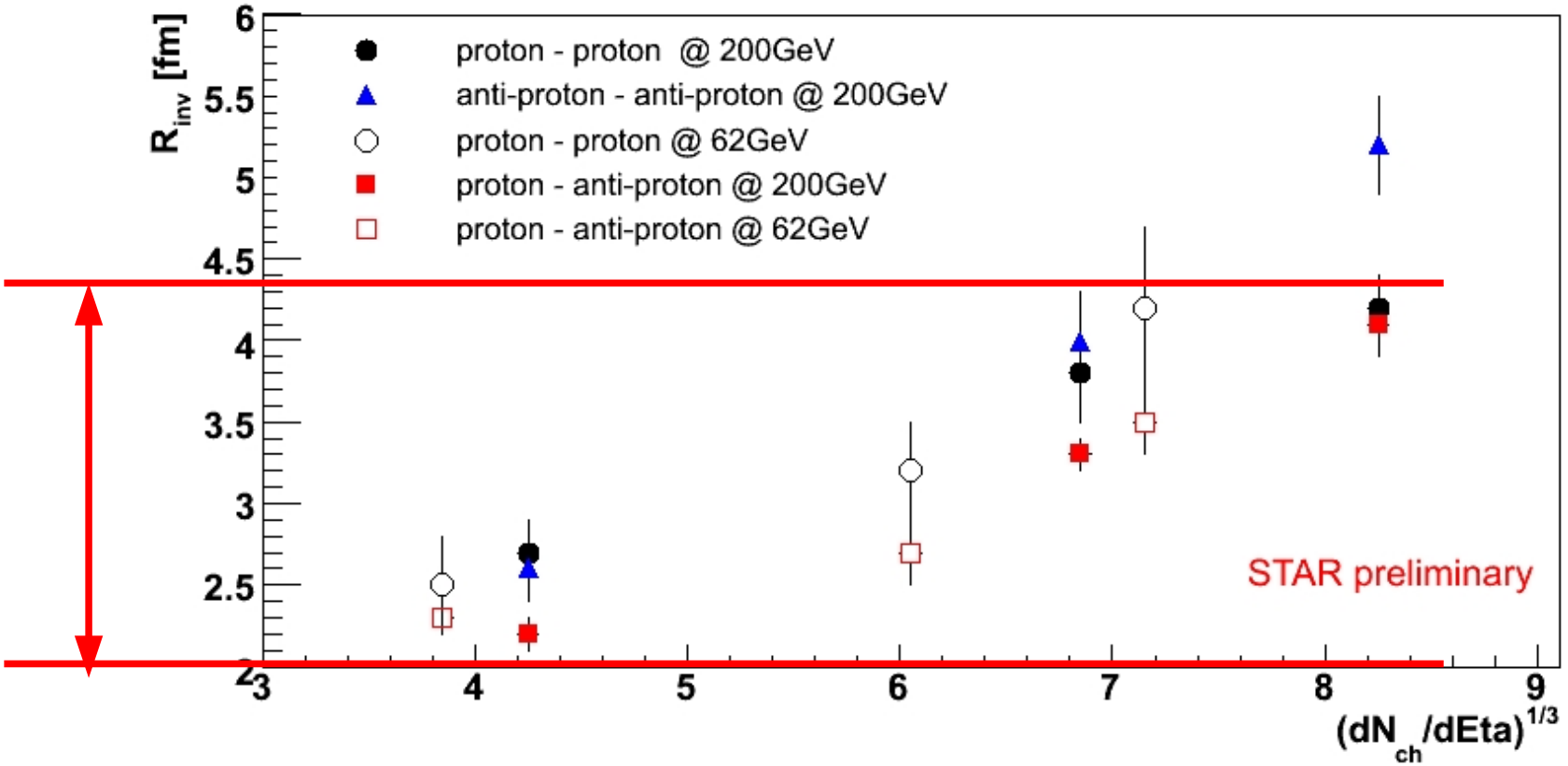
Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog.Part.Nucl.Phys. 58 (2007) 439-520

- **fss2**
  - **a_0 = - 0.82 fm, r_{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_{eff}= 6.45 fm**

Toward ΛΛ correlation at RHIC: Source Size

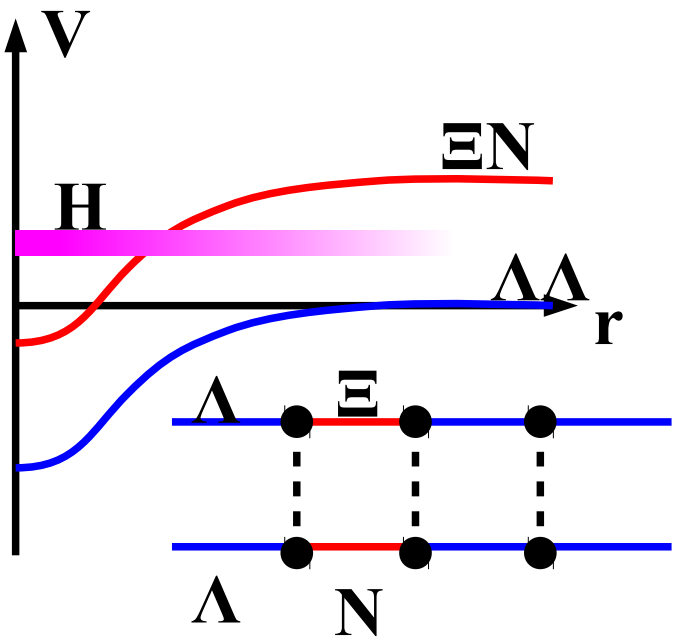
- **Source size : R = (2-4.5) fm**
  - **Smaller than last collision point dist. results in hadron cascade (JAM) → Interaction in the early stage at RHIC**
  - **Smaller than π, K homogeneity length → Further smaller for Λ ?**



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

Toward Λ Λ correlation at RHIC: ΛΛ interaction

- **ΛΛ interaction**
  After Nagara, "plausible" ΛΛ 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., Rc=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 ΛΛ- ΞN threshold**
  → Couple channel calc. is required
  - **One range gaussian coupling potential is assumed.**
  - **ΞN potential (diagonal) effects on C(q) is almost negligible.**



Memo

- **Lattice ΛΛ int. $a_0 \sim 3$ fm**
- **Stat. model: $N_\Lambda \sim 29.8$, $N_H \sim 0.013$ (dN/dY)**