Lambda-Lambda interaction from two-particle intensity correlation in relativistic heavy-ion collisions

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in collaobration with

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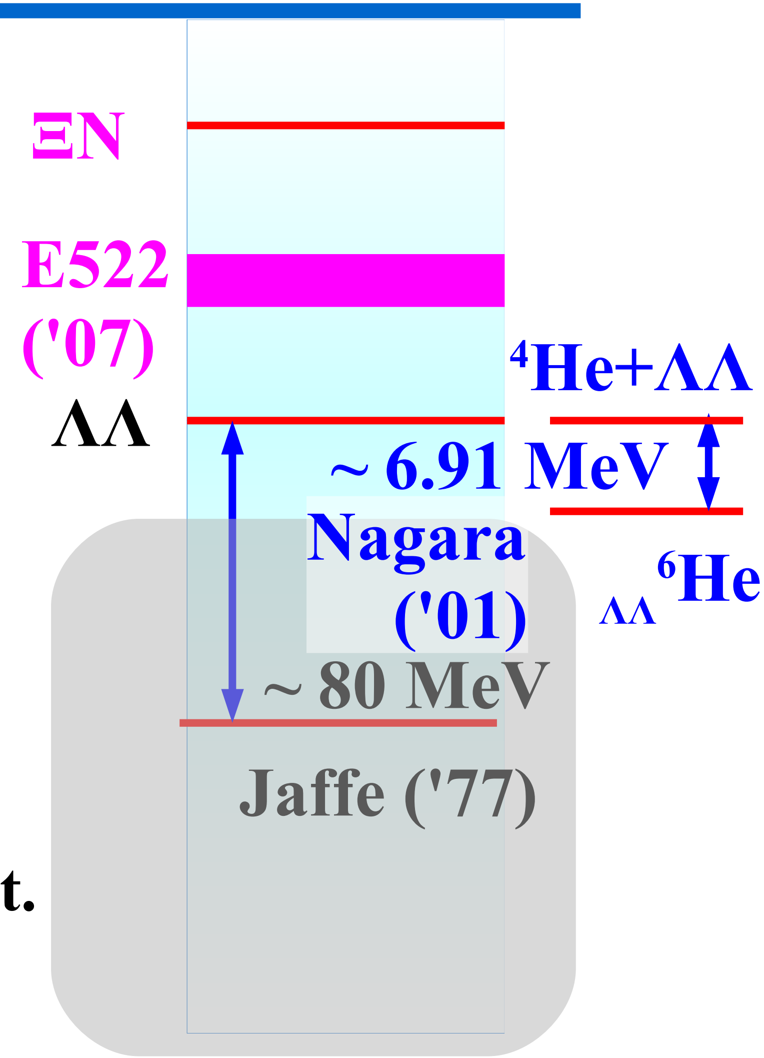
based on K. Morita, T. Furumoto, AO, Phys. Rev. C91 (2015), 024916 [arXiv:1408.6682]

$\Lambda\Lambda$ interaction & Exotic Hadron (H particle)

- **Deeply bound H ?** *Jaffe ('77)*
  - **Strong Attraction from Color Mag. Int.**
    → 80 MeV below ΛΛ
- **No observation for a long time.**
- **Why there is no bound state ?**
  - **Repulsive Instanton Ind. Int.**
    Oka, Takeuchi ('91)
- **Nagara event $_{\Lambda\Lambda}{}^{6}$He** *Takahashi et al. ('01)*
  - **No deeply bound "H", Weakly Att. ΛΛ int.**
- **Resonance or Bound "H" ?**
  - **2 σ "bump" at $E_{\Lambda\Lambda}$ ~ 15 MeV**
    Yoon et al.(KEK-E522) ('07)
  - **Bound H at large *ud* quark masses**
    HAL QCD & NPLQCD ('11), Haidenbauer, Meissner ('11)



Λ Λ interaction models

- **Boson exchange potential**

  Nijmegen potentials (ND, NF, NSC89, NSC97, ESC08)

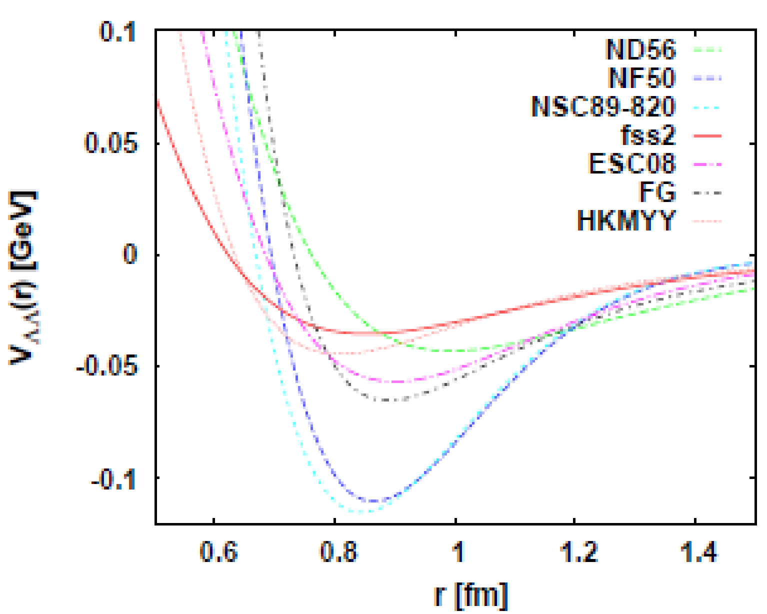
  Nagels+('77, '79), Maessen+('89), Rijken+('99,'10)

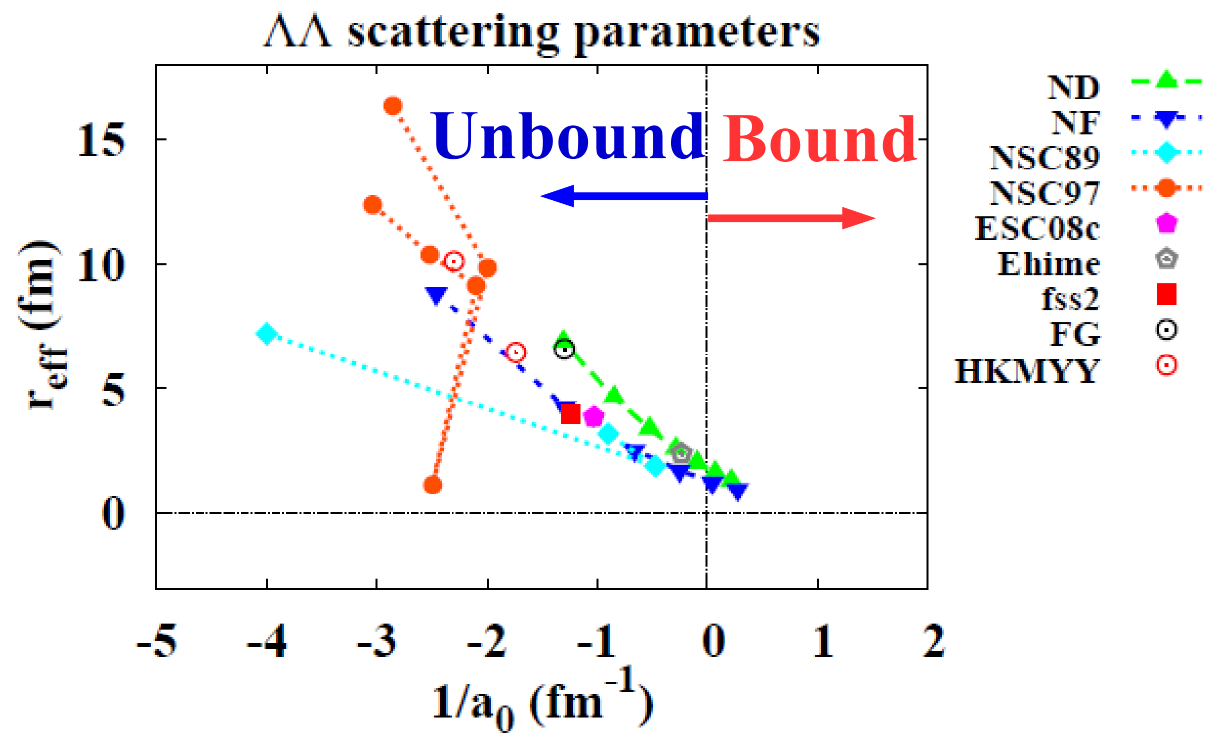
  Ehime *Ueda et al. ('98)*

- **Quark model interaction: fss2** **Fujiwara et al.('07)**

- **Tuned potential to Nagara**

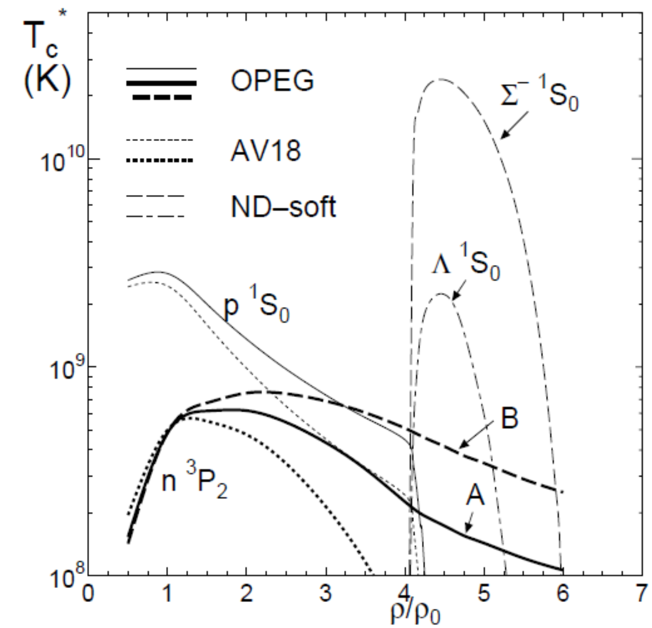
  Filikhin, Gal ('02) (FG), Hiyama et al. ('02, '10)(HKMYY)





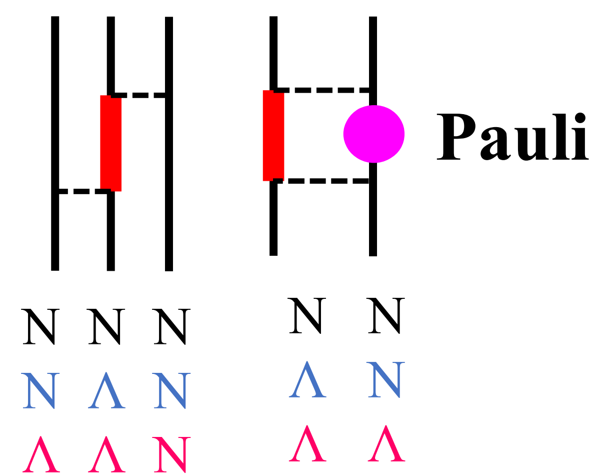
Λ Λ interaction and Neutron Star

- **Hyperon superfluidity puzzle**
  - **"Exotic" components are necessary to explain fast cooling of some of NSs.**
  - **"Exotic" superfluidity is necessary to forbid too fast cooling.**
  - **Nagara-fit ΛΛ interaction is too weak for Λ superfluidity.**



T. Takatsuka, R. Tamagaki, PTP 112('04)37

- **Massive Neutron Star Puzzle**
  - **Hyperons should appear in dense matter.**
  - **EOSs w/ Y are too soft to support 2 $M_\odot$ NS**
  - **Three-body repulsion involving Y may help to stiffen EOS at high density.**
    NS session (Gandolfi, Bombaci, Yamamoto, Takatsuka, Togashi, Lonardoni, Muto, Miyatsu, Nakamoto)Kohno ('13) / Myint, Shinmura, Akaishi ('03) / Machleidt.



Impact of ΛΛ interaction

- **ΛΛ interaction is relevant to the existence of H dibaryon.**
  - **One of the long-standing problem in hadron physics.**
- **ΛΛ interaction is important to understand BB interaction models.**
  - **No pion exchange → middle and core range int. are visible.**
  - **No quark pauli blocking in the flavor singlet (H) channel.**
- **ΛΛ and ΛΛN interaction is important to neutron stars.**
  - **Hypern superfluidity is preferred to explain NS cooling.**
  - **3-body force including Y is necessary to support 2 $M_\odot$ NS.**
    $V_{\Lambda\Lambda}$ in vacuum & medium → $V_{\Lambda\Lambda N}$

Other observables than double hypernuclei ?
→ ΛΛ intensity correlation from heavy-ion collisions
Recent data by STAR Collab.
Talk by N. Shah (Adamczyk et al., PRL 114 ('15) 022301.)

Contents

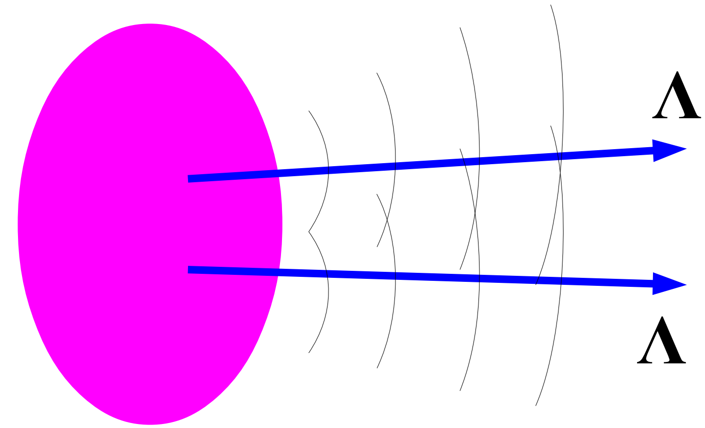
- Introduction
- Λ Λ correlation and interaction from heavy-ion collisions
K. Morita, T. Furumoto, AO, PRC
  - Comparison of correlation function obtained with various ΛΛ model interactions with STAR data.
  - Expansion effects, Feeddown effects, and Residual source effects
  - Favored ΛΛ interaction
- ΛΛ scattering length: Negative or Positive ?
  - STAR analysis: $a_0 > 0$, MFO analysis: $a_0 < 0$
  - Re-analysis based on Lednicky-Lyuboshits '81 model
- Summary

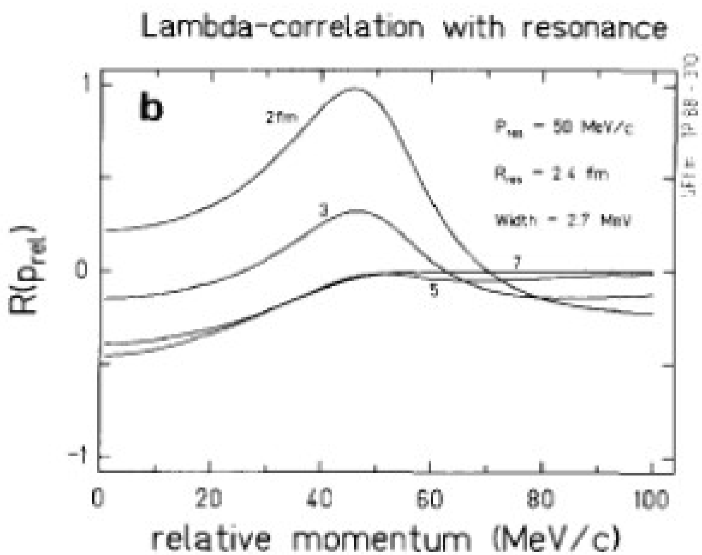
ΛΛ correlation and interaction from heavy-ion collisions

K. Morita, T. Furumoto, AO,
Phys. Rev. C91 (2015), 024916 [arXiv:1408.6682]

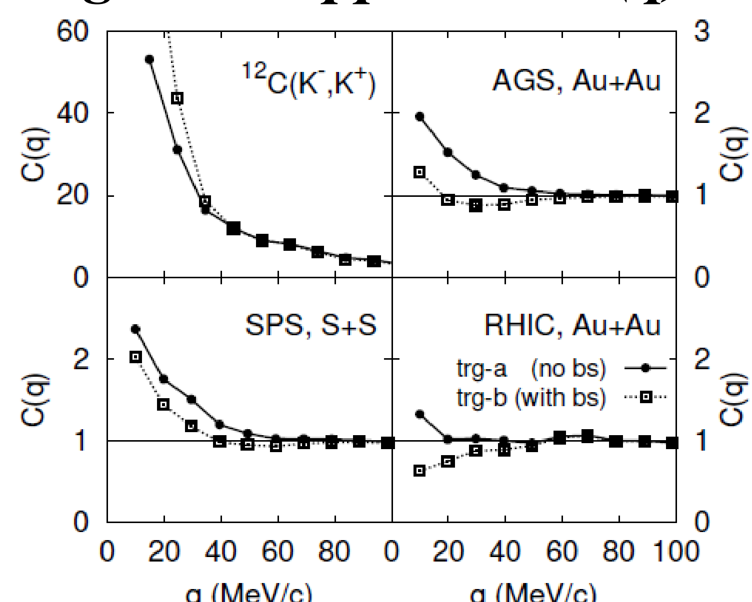
$\Lambda\Lambda$ correlation in HIC

- **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.
    Schaffner-Bielich, Mattiello, Sorge ('00), Cho et al.(ExHIC Collab.) ('11)
  - **Discovery of "H" and/or Constraint on ΛΛ int.**
    Bound state exhaust the low q strength → suppressed C(q).





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



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

$\Lambda\Lambda$ correlation in HIC and $\Lambda\Lambda$ interaction

- **Two particle correlation from chaotic source** *Bauer, Gelbke, Pratt ('92)*

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

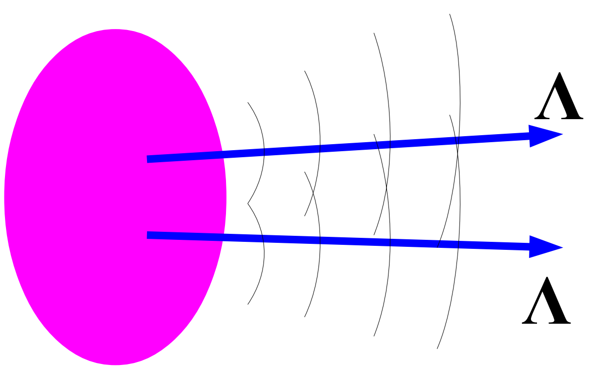
- **Static spherical source, s-wave only** **s-wave w.f. enh.**

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

HBT

$q=(p_1-p_2)/2$, χ_0: s-wave wf, $S_{12}(x)=r^2 \exp(-r^2/4R^2)/2R^3\sqrt{\pi}$

- **HBT term: Suppression due to anti-symmetryzation for Fermions**
  0 x 3/4 (triplet) + 2 x 1/4 (singlet) = 1/2
  Hanbury Brown, Twiss ('56),
  Goldhaber, Goldhaber, Lee, Pais ('60)
- **Enhancement of wf by $\Lambda\Lambda$ attraction**

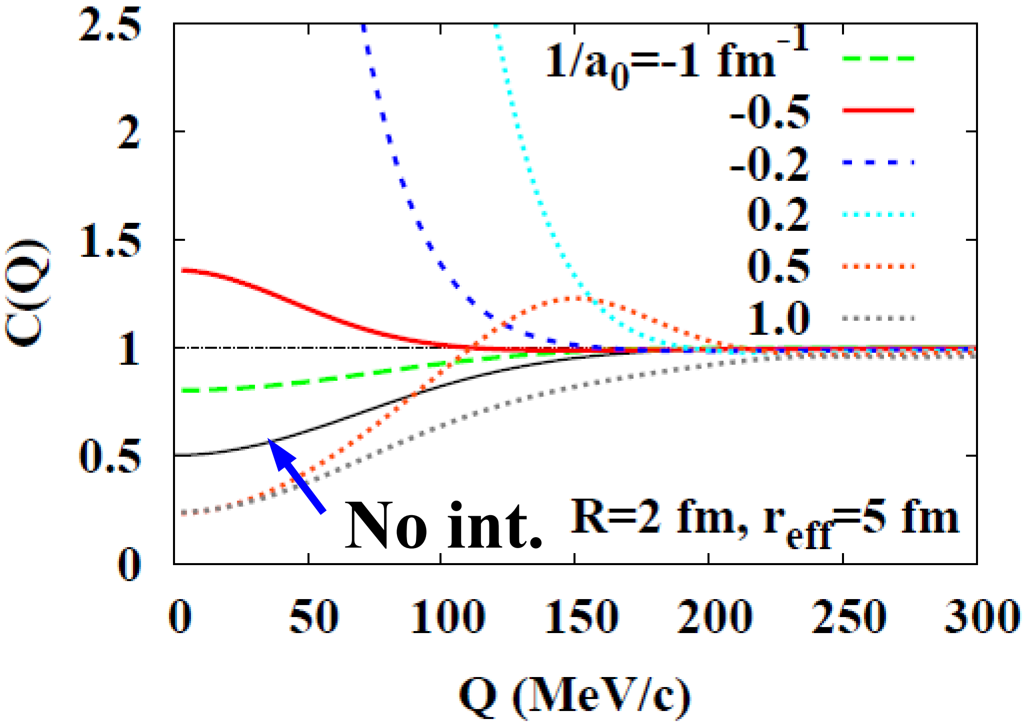


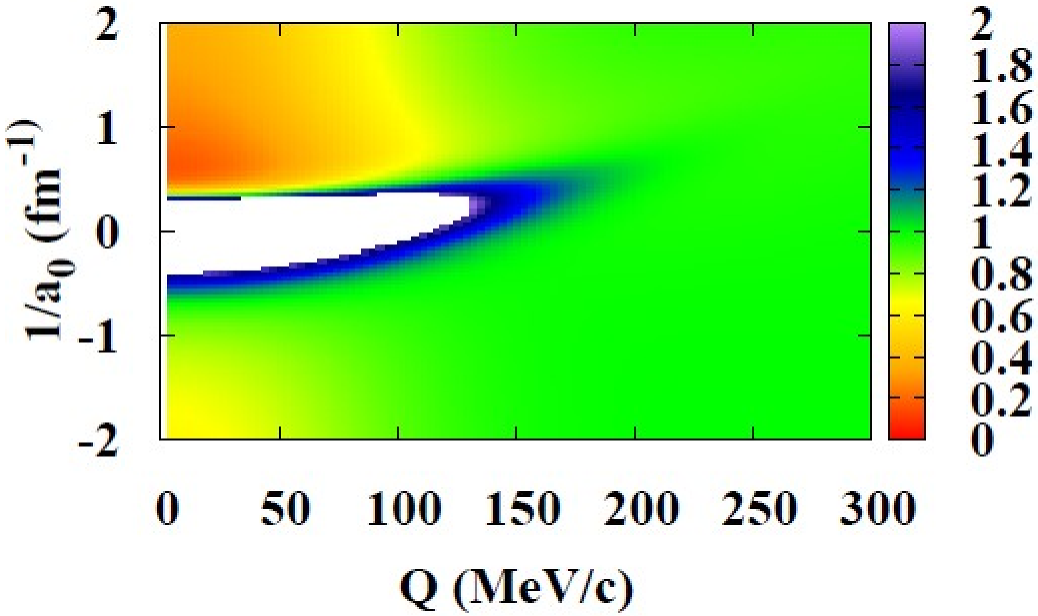
Correlation function and scattering length

- **Low E scatt. is mainly determined by the scattering length (a_0)**

  $$q \cot\delta = -1/a_0 + r_{eff}\, q^2/2 + O(q^4)$$ **Nuclear phys. convention**

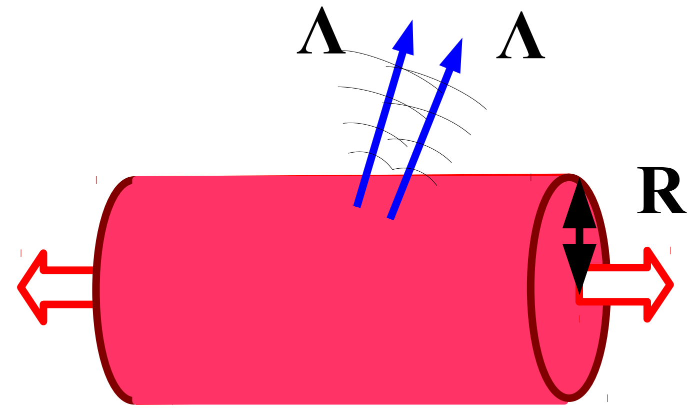
  - **Negative a_0 : enhanced correlation**
  - **Positive a_0 : suppressed correlation**
    - **w/ bound state → scatt. wf has a node**
    - **w/o bound state → repulsion suppress wf**



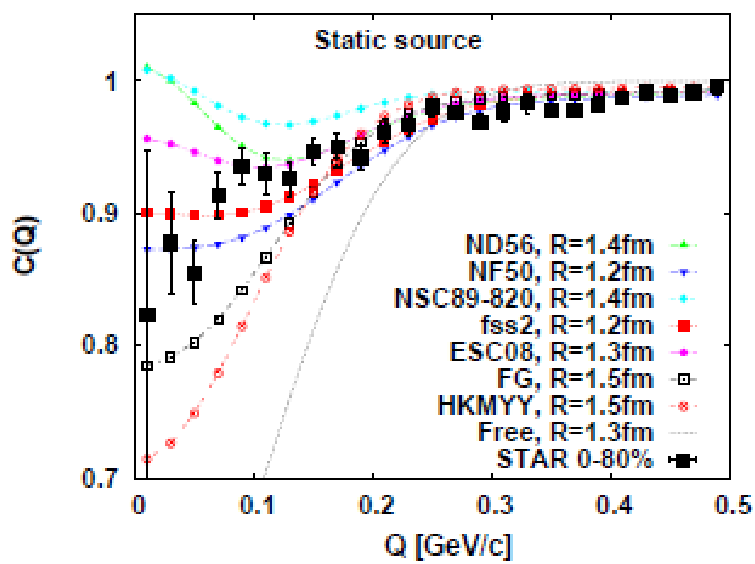


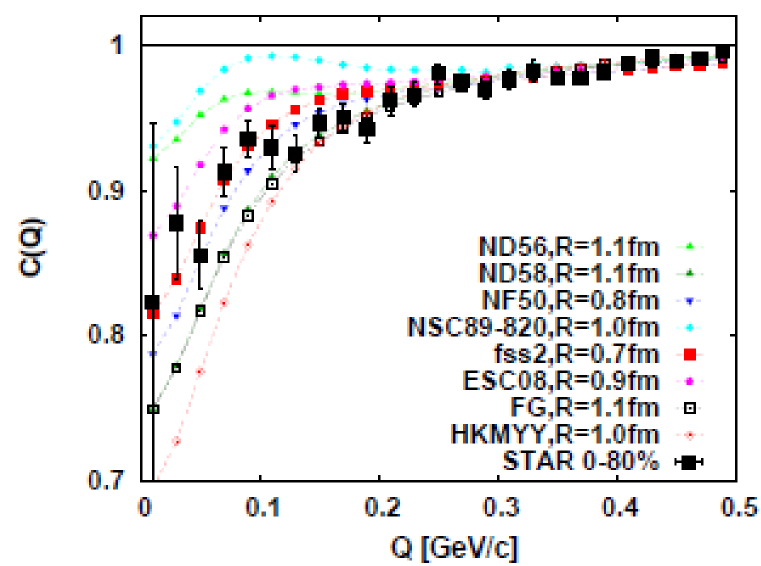
Source models

- **Static & Spherical source**
  - **Source size R = (1-1.5) fm, χ^2/DOF ~ 2**
- **Cylindrical source**
  - **Bjorken expansion in long. direction**
  - **Transverse flow from pT spectrum**
  - **Source size R = (0.7-1.1) fm, χ2/DOF ~ 1.5**



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





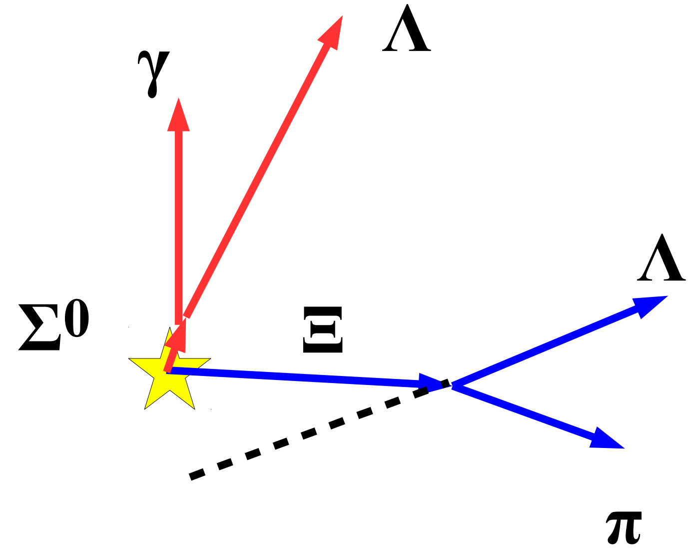
Additional Source

- **Feed down effects**

$$C_{\rm corr}(Q) = 1 + \lambda(C_{\rm bare}(Q) - 1)$$

λ = Purity of ΛΛ pair

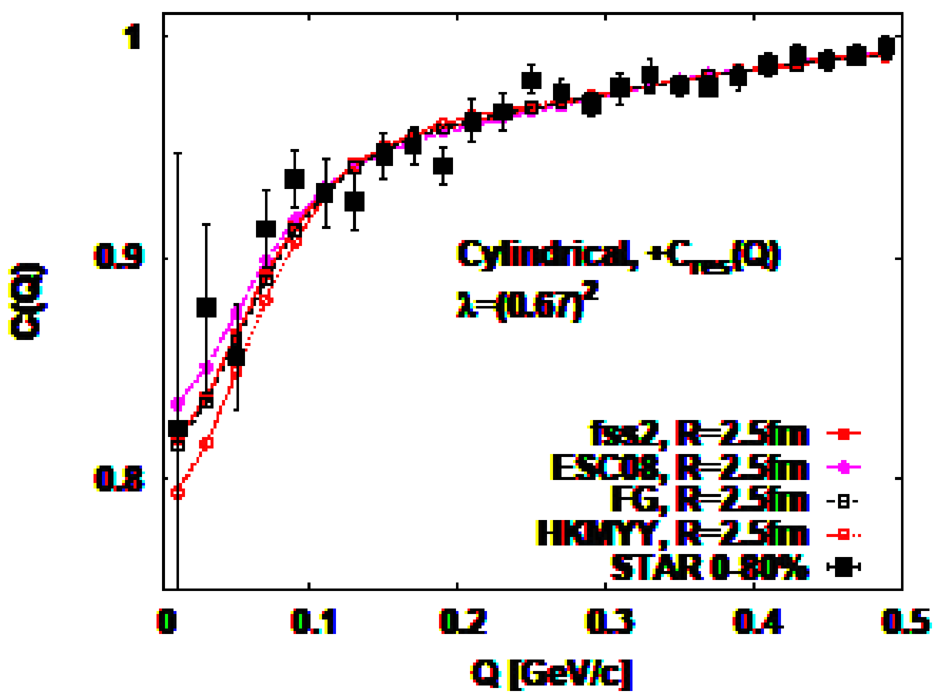
  - **Short-lived Y* → mod. of source fn.**
  - **Ξ → Λπ can be excluded (cτ=8.71 cm)**
  - **Σ^0 → Λγ is difficult to reject**
  - **Data based purity $\lambda=(0.67)^2$**
    Σ^0/Λ=0.278 (p+Be, 28.5 GeV/c) ***Sullivan et al. ('87)***
    Ξ/Λ = 15 % (RHIC)

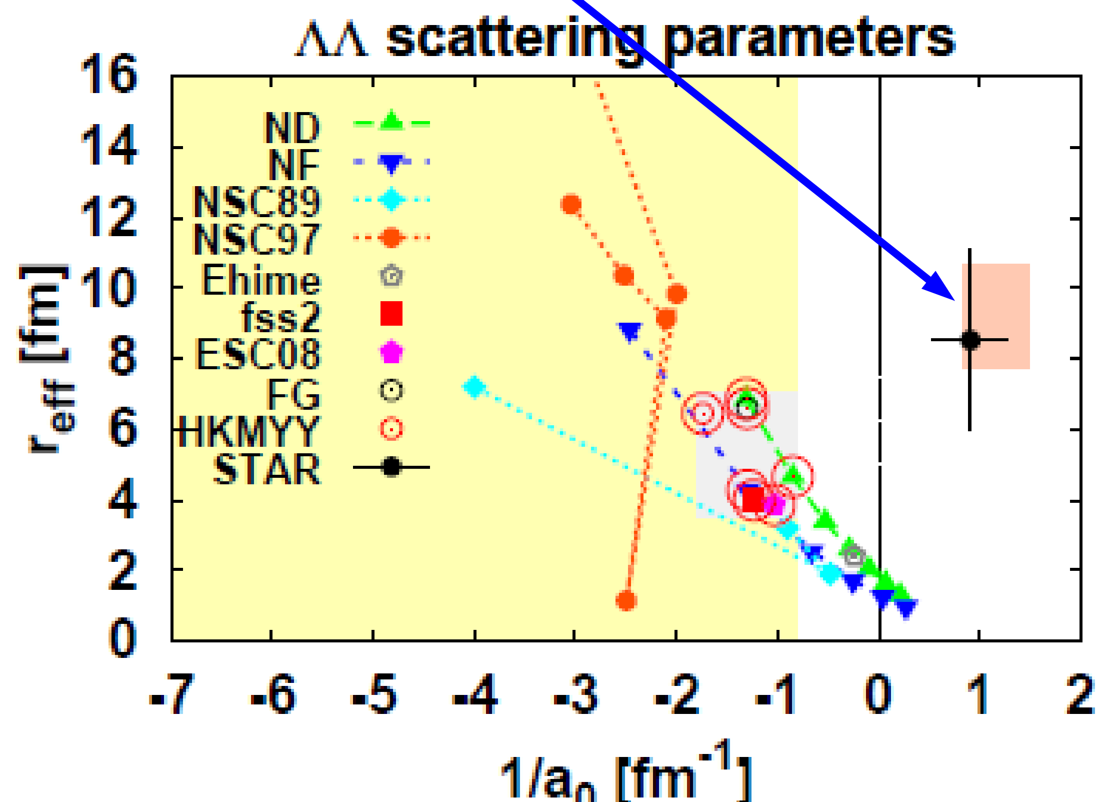


- **"Residual" source**
  - **High-momentum tail → R_{res} ~ 0.5 fm (STAR collab.)**

$\Lambda\Lambda$ interaction from $\Lambda\Lambda$ correlation at RHIC

- HBT + ΛΛ int. + Expansion + Feed down + "Residual" source
  - $1/a_0 < -0.8\ \mathrm{fm}^{-1}$
  - Source size dependence is small, $\chi^2/\mathrm{DOF} \sim 1$
- Question: STAR analysis $a_0 = 1.10 \pm 0.37$ fm > 0





K.Morita, T.Furumoto, AO, PRC91('15)024916 [arXiv:1408.6682]
Data: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

$\Lambda\Lambda$ scattering length
Positive or Negative ?

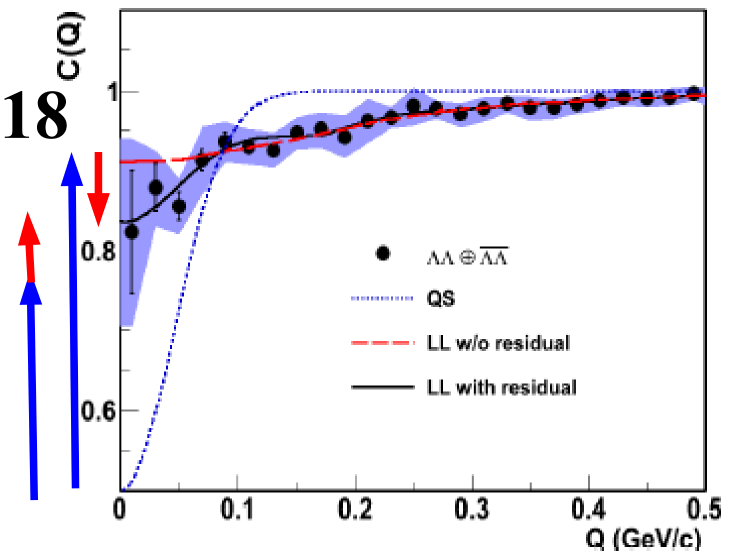
STAR collab. analysis

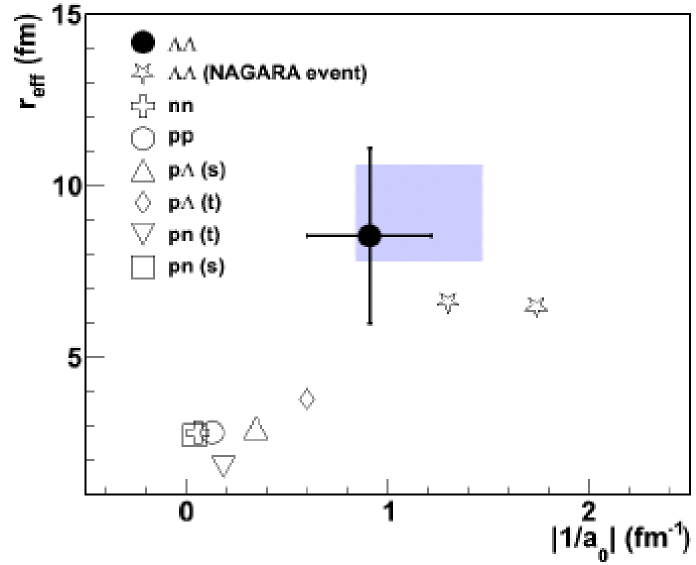
- **Lednicky-Lyuboshits (LL '81) model**
  R. Lednicky, V. L. Lyuboshits, Sov.J.Nucl.Phys.35('82)770; Yad.Fiz.35 ('81) 1316.
  - **Analytic model including a_0 and r_{eff}.**
- **Intercept (pair purity) parameter is treated as a free parameter.**
- **STAR Collab. analysis implies positive scatt. length.**

$$a_0 = 1.10 \text{ fm} \;, \quad r_{\text{eff}} = 8.52 \text{ fm} \;, \quad \lambda = 0.18$$

$\lambda = 0.18$

$\lambda = (0.67)^2$





Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

Which is correct ? Positive a_0 or Negative a_0 ?

- **Lednicky-Lyuboshits (LL '81) model**
  R. Lednicky, V. L. Lyuboshits, Sov.J.Nucl.Phys.35('82)770; Yad.Fiz.35 ('81) 1316.
  - **Analytic model including FSI effects**

$$C(Q) = N\left[1+\lambda\left(-\exp(-R^2Q^2)/2 + C_{\mathrm{int}}(Q) - 1\right) + a_{\mathrm{res}}\exp(-R_{\mathrm{res}}^2Q^2)\right]$$

$$C_{\mathrm{int}}(Q) = 1 + \frac{|f(k)|^2}{4R^2}\left(1 - \frac{r_{\mathrm{eff}}}{2\sqrt{\pi}R}\right) + \frac{\mathrm{Re}f(k)}{\sqrt{\pi}R}F_1(QR) - \frac{\mathrm{Im}f(k)}{2R}F_2(QR)$$

$$f(k) = \left(-1/a_0 + r_{\mathrm{eff}}k^2/2 - ik\right)^{-1} \quad (k = Q/2)$$ **scattering amp.**

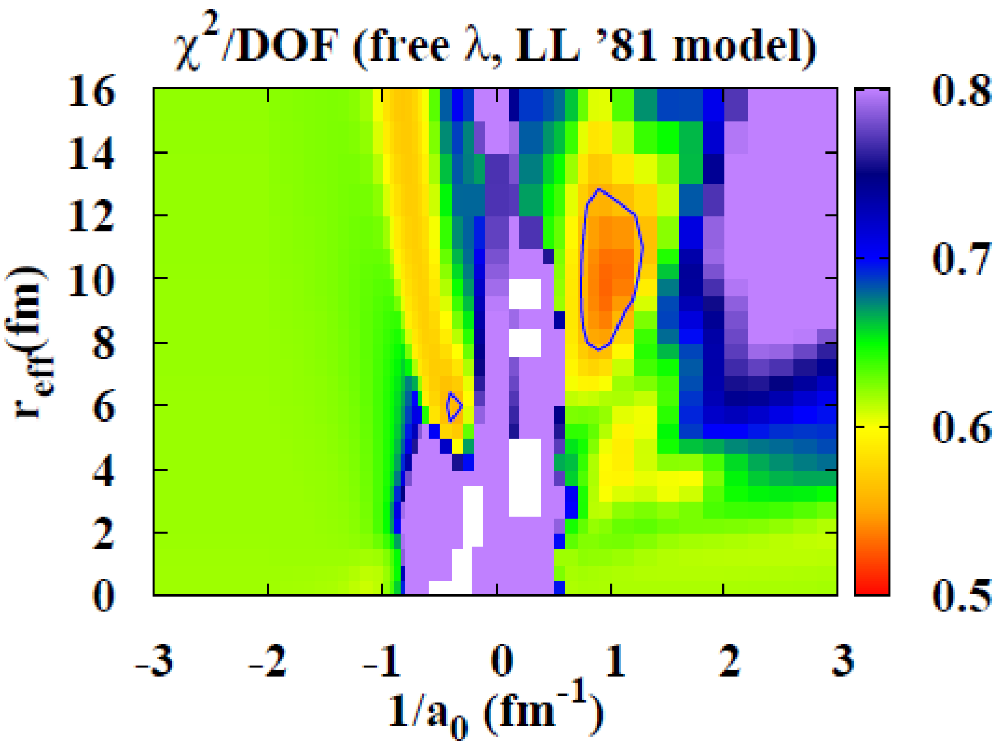
$$F_1(z) = \int 0^z e^{x^2-z^2}/z\ , \quad F_2(z) = (1-e^{-z^2})/z$$

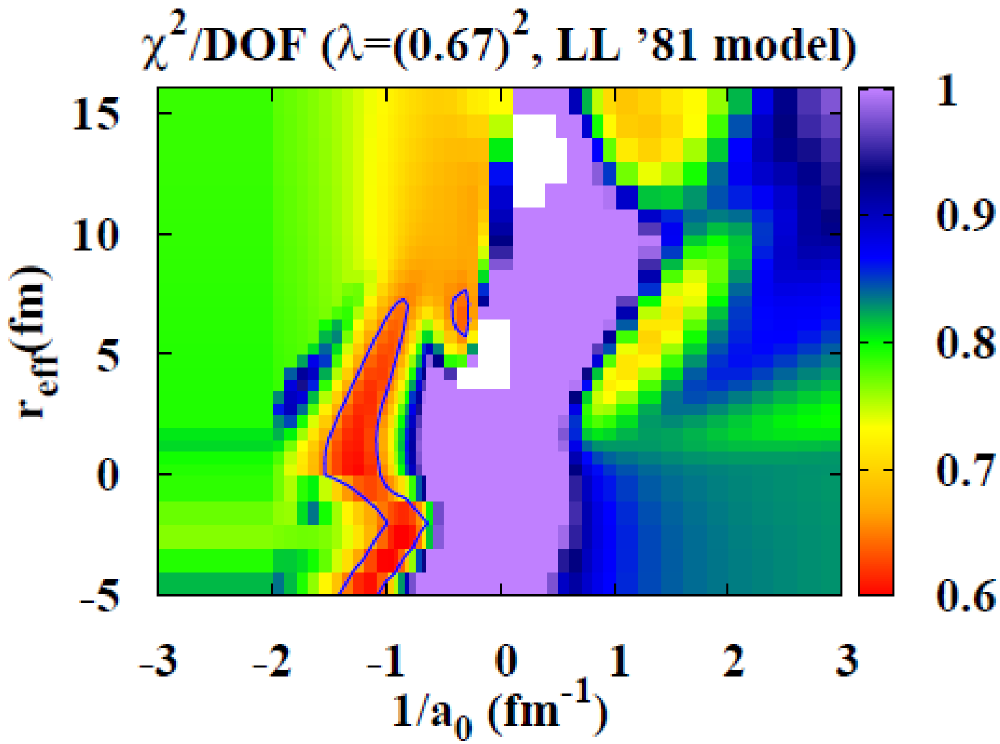
$$k\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\mathrm{eff}}k^2 + \mathcal{O}(k^4)$$ **phase shift**

Let us examine LL '81 model results with fixed λ !

a_0 (ΛΛ): Positive or Negative ?

- **Key parameter = intercept parameter λ**
  - **λ = free parameter ~ 0.18 → positive a_0 at χ^2 min.**
    (χ^2/DOF ~ 0.56)
  - **Measured Σ^0 / Λ ratio**
    $\lambda = (\Lambda / (\Lambda + \Sigma^0))^2 \sim (0.67)^2$ → negative a_0 at χ^2 min.
    (χ^2/DOF ~ 0.65)

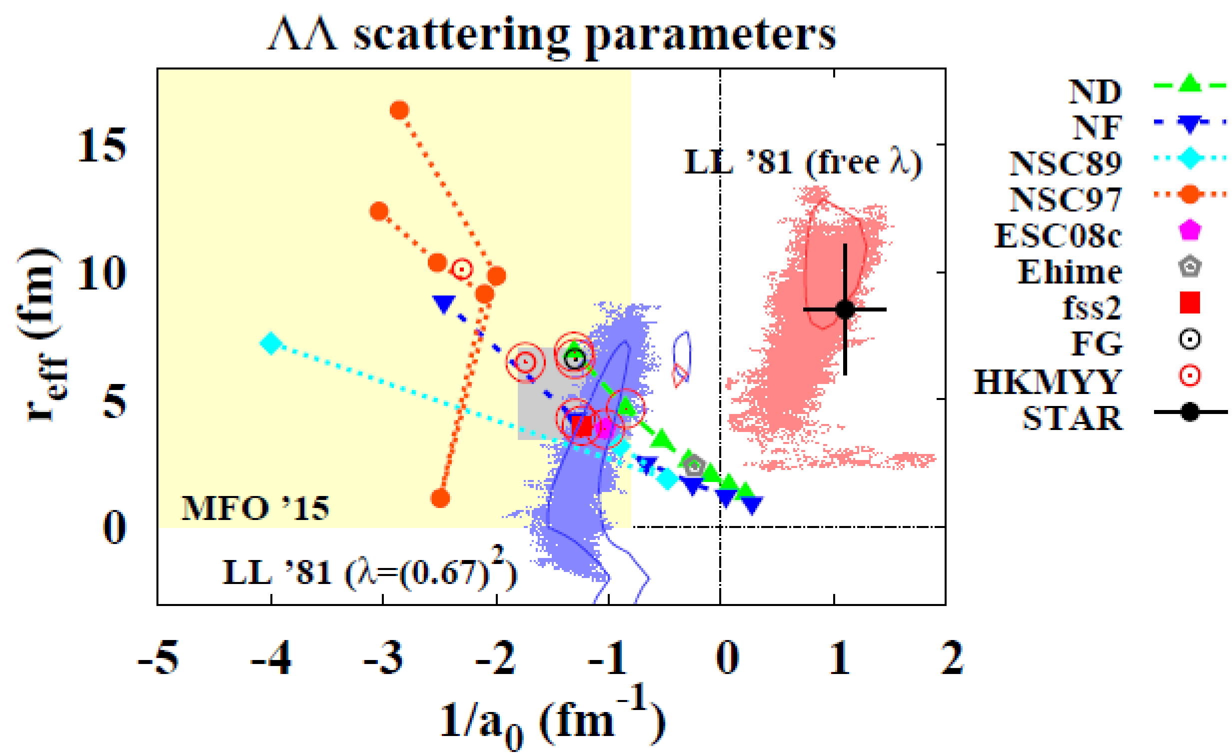




a_0 ($\Lambda\Lambda$): Positive or Negative ?

- χ^2 analysis
  - Gradient method (gnuplot) & Markov Chain MC (MCMC) in LL '81 model
  - Free λ result ~ STAR ('15) analysis : $a_0 > 0$
  - Fixed λ result ~ Our analysis : $a_0 < 0$

Difference btw STAR collab. analysis and our analysis comes from λ

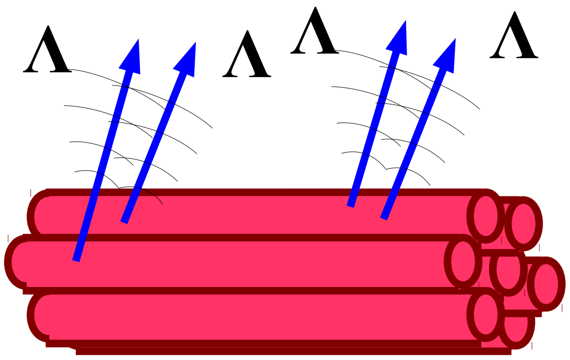


What is the origin of the long tail ?

- **Do we have a physical origin ?**
- **Two source model + LL '81 model**

$$S_{12}(\mathbf{x}) = \frac{w}{(2R_1\sqrt{\pi})^3}\exp\left(-\frac{x^2}{4R_1^2}\right) + \frac{1-w}{(2R_2\sqrt{\pi})^3}\exp\left(-\frac{x^2}{4R_2^2}\right)$$

  - **Fix Λ Λ interaction, and obtain R_1 and R_2.**
    R_1 = (0.65-1.30) fm
    R_2 = (0.33-0.54) fm
    for fss2, ESC08, FG, HKMYY interactions.
    χ^2/DOF = (0.6-0.65)



- **Λ might be produced from small tubes.**
  - **FSI with hot medium (~ π gas) is small for Λ**

Summary

- **ΛΛ intensity correlation in high-energy heavy-ion collisions has sensitivity to ΛΛ interaction.**
- **Our analysis of the STAR data implies that the favored ΛΛ interaction has negative scattering length ($1/a_0 < -0.8$ fm^{-1}, $\delta > 0$), which is consistent with the Nagara event analysis.**
  - **Anti-symm. + ΛΛ interaction + Expansion + Feeddown + Residual**
- **Difference between the STAR collab. analysis and ours lies in the assumption on the pair purity (chaoticity, intercept) parameter.**
  - **$\Sigma^0/\Lambda \sim 0.67$: p+Be, consistent with stat. model (T~170 MeV)**
- **Further studies are necessary to pin-down ΛΛ interaction.**
  - **Higher precision data are expected, Σ^0 detection is desired, Comparison with A(K^-, K^+)ΛΛ reaction *C.J.Yoon et al.('07)/J-PARC***
- **We can access other hh interactions using correlations.**
  - **ΩN interaction from ΩN correlation *K. Morita's talk***

Thank you !