Hadron-Hadron Correlation and Interaction from Heavy-Ion Collisions (and Summary)

Akira Ohnishi [1]

in collaboration with

K. Morita [123], T. Furumoto[4], K. Miyahara [5], T. Hyodo [1], T. Hatsuda [6]

1.YITP, 2.Frankfurt, 3.Wroclaw, 4.Ichinoseki, 5. Kyoto U, 6. RIKEN

K. Morita, T. Furumoto, AO, PRC91('15)024916 [arXiv:1408.6682]
K. Morita, T. Furumoto, AO, EPJ Web Conf. 97 (2015), 00020.
AO, K. Morita, T. Furumoto, arXiv:1512.08444 (Hyp2015 proc.)
AO, K. Morita, K. Miyahara, T. Hyodo, arXiv:1603.05761
K. Morita, AO, T. Hatsuda, Hyp2015 proc./in prep.

Exotics from Heavy-Ion Collisions (2010)

S.H.Lee, C.M.Ko, A.Ohnishi, D.Jido, T.Hyodo, S.Yasui, M. Nielsen, S.Cho, (K.Yazaki, T.Sekihara, T.Furumoto), **ExHIC collab.**

A.Martinez Torres,
A.Hosaka, S.Kumano, C.Nonaka,
P.Gubler, M.Oka, A.Titov, H.Suganuma,

H.Z.Huang (STAR),
In-Kwon Yoo (ALICE),
Y. Kwon (Belle),
Y.Miake (PHENIX), M.Shimomura (PHENIX), M.Niiyama (SPring8),
K.Imai, C. Yoon, H.Fujioka.

- ΛΛ corr. (2015)
- D, B, Λ_c, ...
- K*, Ξ*, d*, N*, Pc …
- H
- Λ*
- Λp corr. (HADES)

Contents

- Introduction:
  Two particle intensity correlation
  – from star size to hh interaction –
- Correlation Function Formula
  - Koonin-Pratt formula
  - Lednicky-Lyuboshits model
- ΛΛ correlation and ΛΛ interaction
- K^-p correlation
- Summary

Two particle intensity correlation – from star size to hh interaction –

How can we measure the radius of a star ?

- **Two photon intensity correlation**
  Hanbury Brown & Twiss, Nature 10 (1956), 1047.
  - **Simultaneous two photon observation probability is enhanced from independent emission cases**
    → angular diameter of Sirius=0.0063”

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN
Jodrell Bank Experimental Station, University of Manchester
AND
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock

NATURE November 10, 1956 VOL. 178

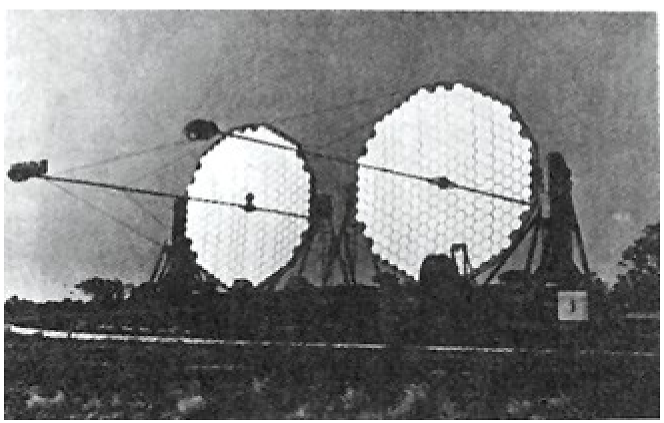


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

HBP telescope (from Goldhaber, ('91))

$$C = \langle I_1 I_2 \rangle / \langle I_1 \rangle \langle I_2 \rangle$$

$$\frac{C(d)-1}{C(0)-1}$$

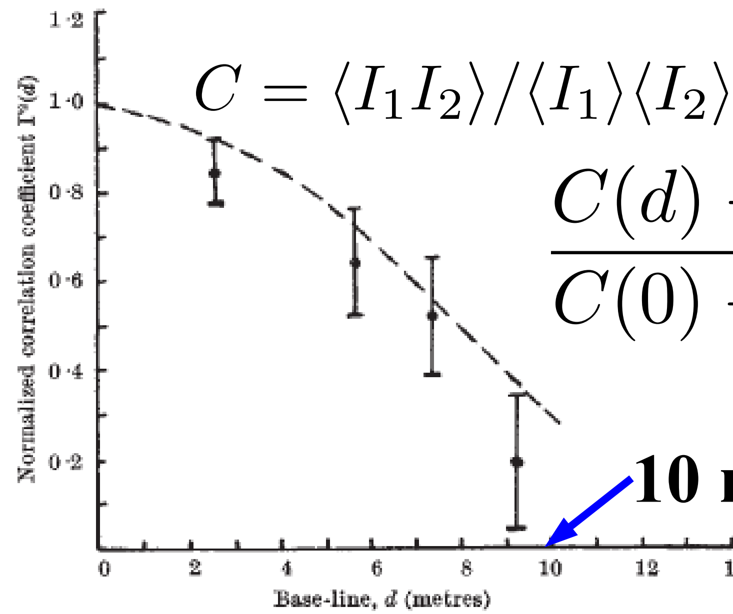


Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

HBT ('56)

Two particle intensity correlation

- **Wave function symmetrization from quantum statistics**

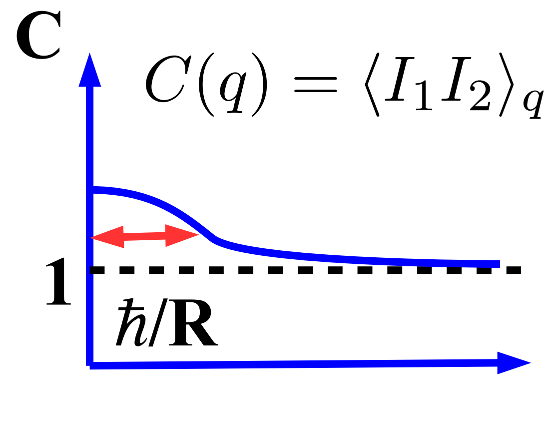
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left| \frac{1}{\sqrt{2}} (e^{i\mathbf{q}\cdot\mathbf{r}} + e^{-i\mathbf{q}\cdot\mathbf{r}}) \right|^2 \simeq 1 + \exp(-4q^2R^2)$$

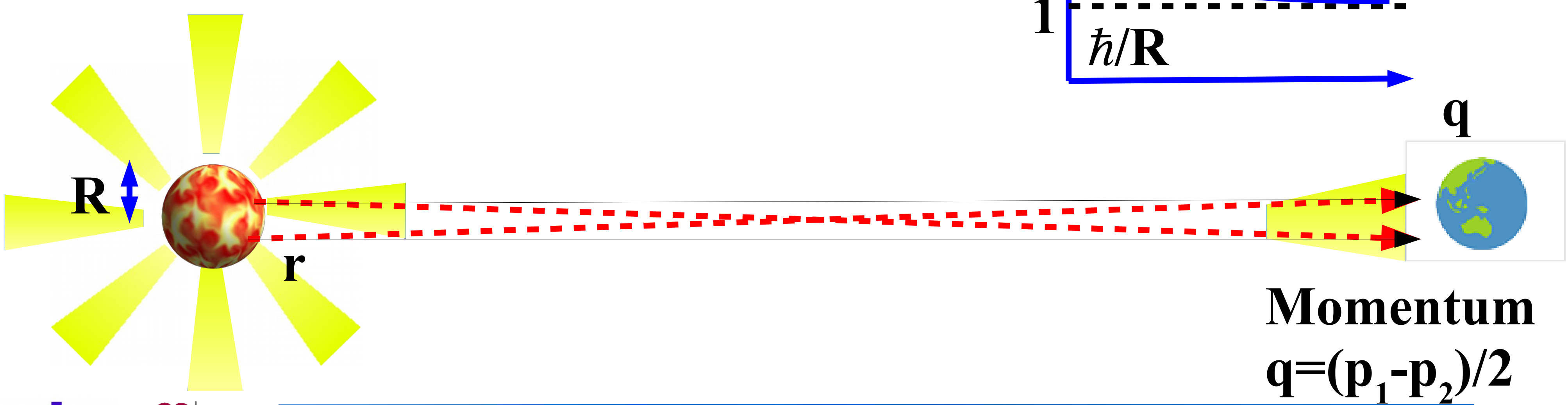
Source fn.
(r=relative coordinate)

(symmetrized w.f.)^2

Static spherical source case

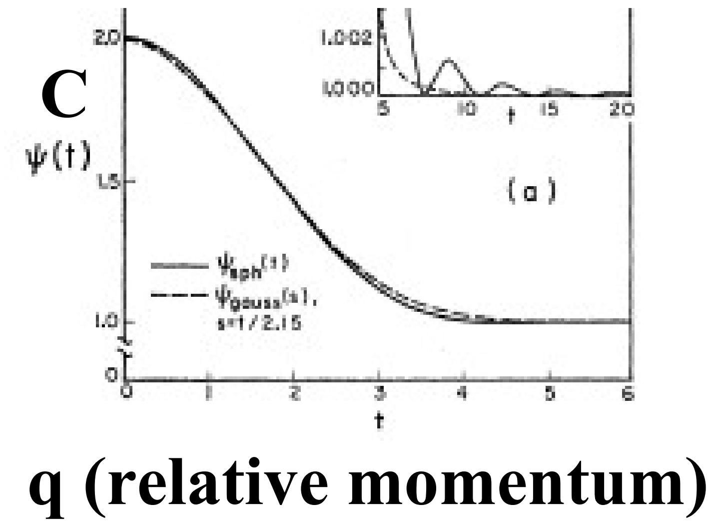
→ **Small relative momenta are favored due to symmetrization of the relative wave function.**





How can we measure source size in nuclear reactions ?

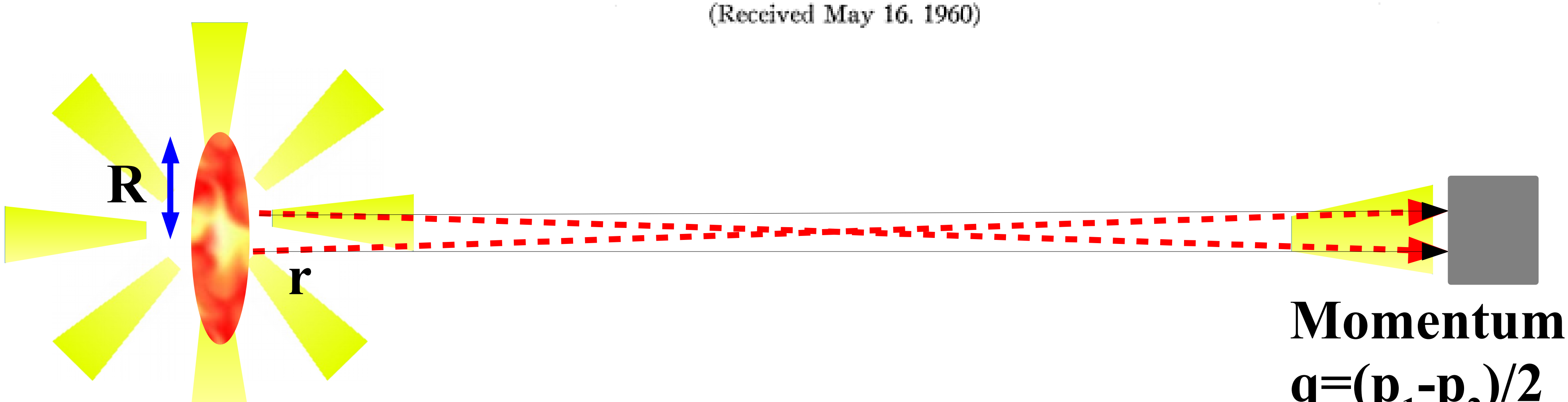
- **Two pion interferometry**
  G. Goldhaber, S. Goldhaber, W. Lee, A. Pais, Phys. Rev. 120 (1960), 300
  - **Two pion emission probability is enhanced at small relative momenta**
    → Pion source size ~ 0.75 ℏ / μc



PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

GERSON GOLDHABER, SULAMITH GOLDHABER, WONYONG LEE, AND ABRAHAM PAIS†
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16. 1960)



How does interaction modifies correlation ?

- **Interaction modifies the relative wave function, and modifies correlation.**
  S. E. Koonin, PLB 70 ('77) 43; S. Pratt, T. Csorgo and J. Zimanyi, PRC42 ('90) 2646; W. Bauer, C.-K. Gelbke, S. Pratt, Annu. Rev. Nucl. Part. Sci. 42 (1992)77.

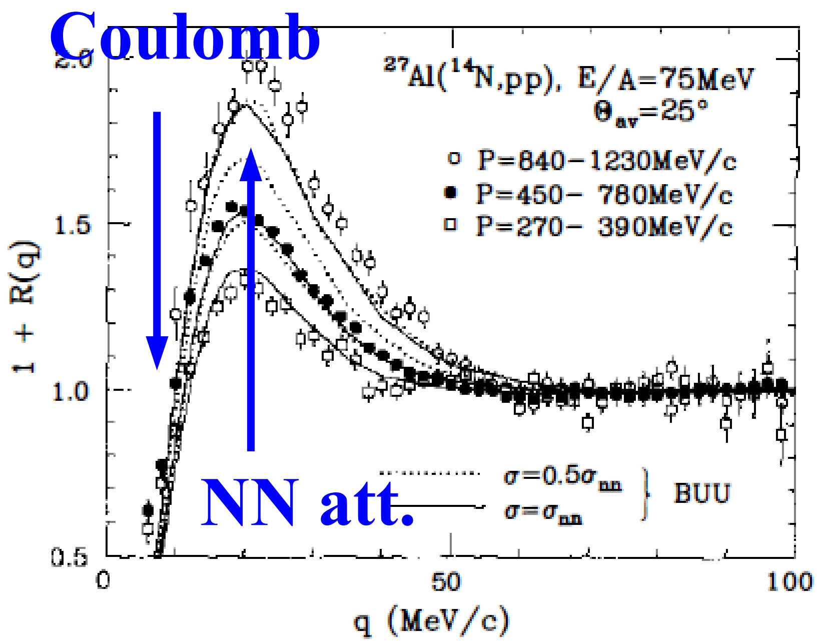
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left|\psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$ **int. → relative w.f.**

$$\simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int d^3r S_{12}(\mathbf{r}) \left[|\chi_0(r)|^2 - |j_0(qr)|^2\right]$$

Fermion **Source** **w.f.** **free**

(Koonin-Pratt formula)

- **pp correlation from heavy-ion collisions is well understood by the (vacuum) NN interaction and the source function from a transport model.**

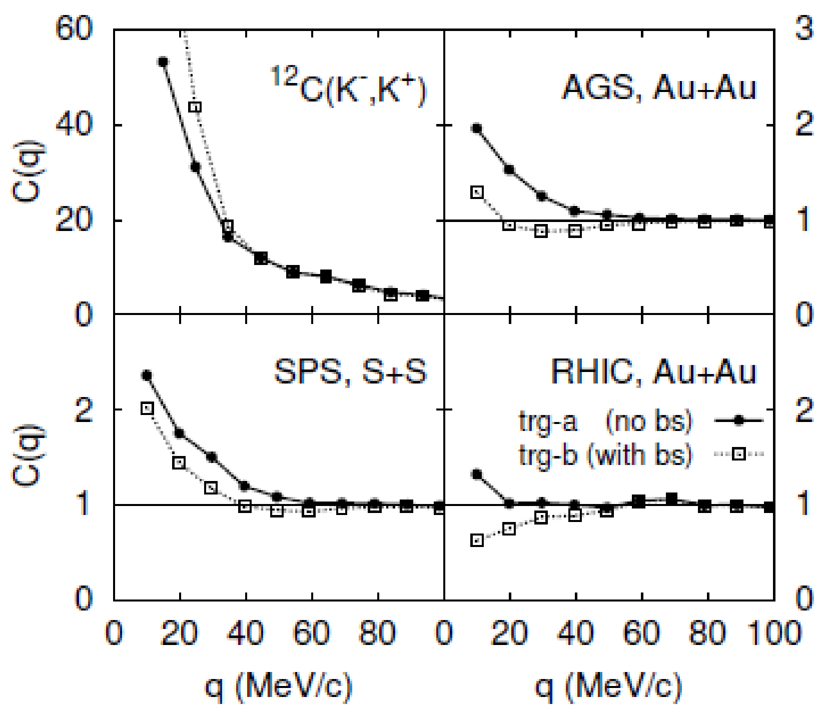


Idea of Reversal: Can we determine hh interaction from hh correlation ?

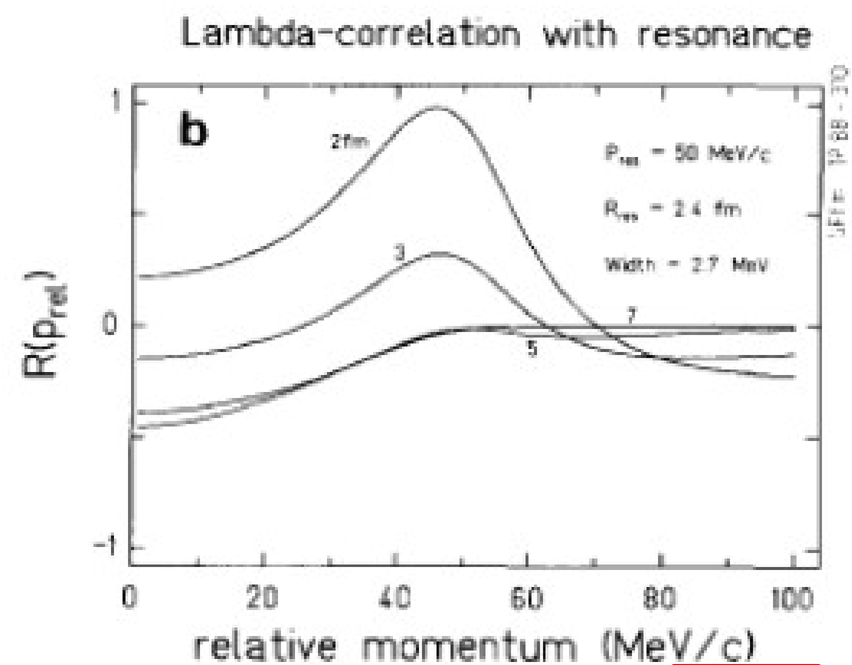
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left|\psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$

Correlation → Interaction

- **If we know correlation and source,**
  it should be possible to get knowledge of hadron intearctions !
- **How about ΛΛ interaction ?**
  - **Λ particle is too short-lived to perform scattering experiments.**
    Mass=1115.6 MeV, τ= 2.6 x 10^{-10} s, cτ = 7.89 cm
    quark content = uds (p=uud, n=udd)



AO, Y. Hirata, Y. Nara, S. Shinmura, Y. Akaishi
Nucl. Phys. A 670 (2000), 297c



C. Greiner, B. Muller, PLB219 (1989) 199.

Let us try to constrain hh interaction from hh correlation !

Example: ΛΛ (c.f. Shah), Ω^- p (c.f. Morita), and K^-p

Interaction dependence of two particle intensity correlation

Lednicky-Lyuboshits formula (1)

- **Koonin-Pratt formula**

$$C_{\mathbf{P}}(\mathbf{q}) = \int d^3r\, S_{\mathbf{P}}(\mathbf{r}) \left|\Psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$

- **ΛΛ wave fn. with outgoing boundary condition**

$$\Psi_{\Lambda\Lambda}^{(-)} = \sqrt{2}\chi_s \left[\cos(\mathbf{q}\cdot\mathbf{r}) + \psi_{\Lambda\Lambda}(r) - j_0(qr)\right] + \sqrt{2}i\chi_t \sin(\mathbf{q}\cdot\mathbf{r})$$

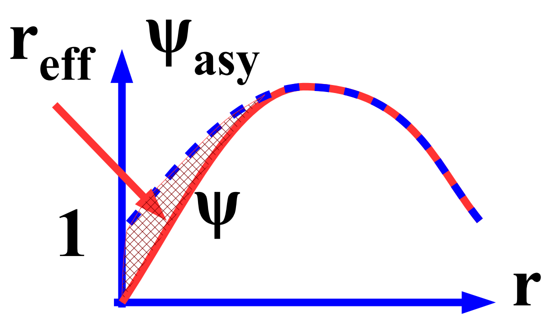
$$\psi_{\Lambda\Lambda}(r) \to \psi_{\mathrm{asy}}(r) = \frac{e^{-i\delta}}{qr}\sin(qr+\delta) = \mathcal{S}^{-1}\left[\frac{\sin qr}{qr} + f(q)\frac{e^{iqr}}{r}\right]$$

- **Spherical (& static) source**

$$\mathrm{S}_{12}(r) = \frac{4\pi r^2}{(2\sqrt{\pi}R)^{3/2}} e^{-4r^2q^2}$$

- **Effective range**

$$\lim_{q\to 0}\frac{1}{|f(q)|^2}\int_0^\infty r^2 dr\left[|\psi|^2 - |\psi_{\mathrm{asy}}|^2\right] = -\frac{1}{2}r_{\mathrm{eff}}$$



Lednicky-Lyuboshits formula (2)

- **Spherical source + Asymptotic w.f. + Effective range correction → Correlation function**

$$C^{\rm LL}(q) \simeq 1 - \frac{1}{2}e^{-4q^2R^2} + \frac{1}{2}\Delta C_{\rm asy} + \frac{1}{2}\Delta C_{\rm eff}$$

$$\Delta C_{\rm asy} = \int_0^\infty dr\, S_{12}(r)\left[|\psi_{\rm asy}(r)|^2 - |j_0(qr)|^2\right]$$

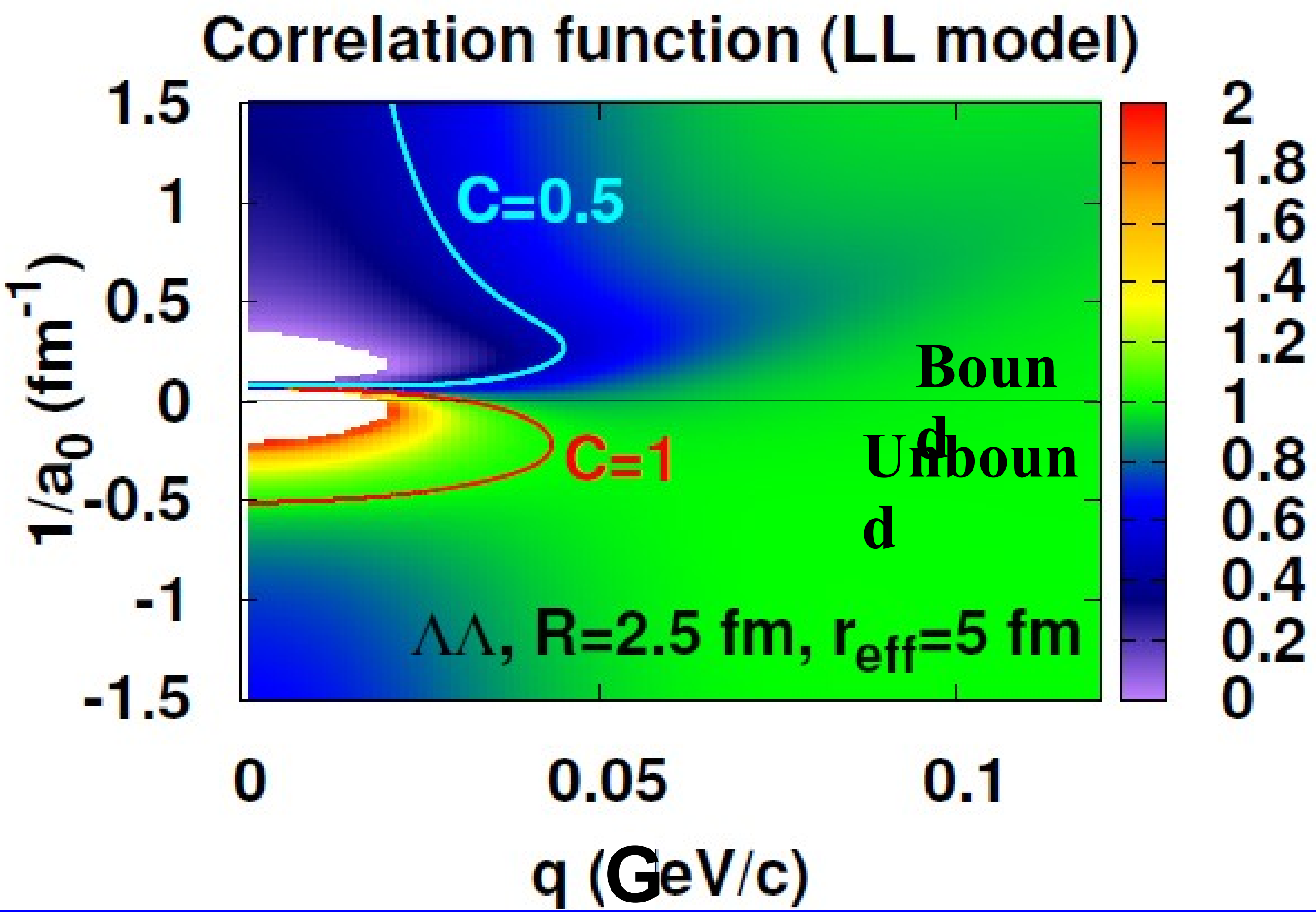
$$\Delta C_{\rm eff} = \int_0^\infty dr\, S_{12}(r)\left[|\psi|^2 - |\psi_{\rm asy}|^2\right] \simeq \frac{|f(q)|^2}{4\sqrt{\pi}R^3}\, r_{\rm eff}$$

$$\Delta C^{\rm LL}(q) = \frac{1}{|\mathcal{S}|^2}\left[\frac{|f(q)|^2}{2R^2}F_3\left(\frac{r_{\rm eff}}{R}\right) + \frac{2{\rm Re}f(q)}{\sqrt{\pi}R}F_1(x) - \frac{{\rm Im}f(q)}{R}F_2(x)\right] + \frac{1-|\mathcal{S}|^2}{|\mathcal{S}|^2}\frac{F_2(x)}{x}$$

(F_1, F_2, F_3: Known function)

R. Lednicky, V. L. Lyuboshits, Sov.J.Nucl.Phys.35 ('82) 770 [Yad.Fiz.35('82)1316]
AO, K.Morita, K.Miyahara, T.Hyodo, arXiv:1603.05761

Interaction Dependence of Correlation Function



Non-monotonic behavior
$1/a_0>0$ (large) → $C<1$, $1/a_0>0$ (small) or $1/a_0<0$ → $C<1$

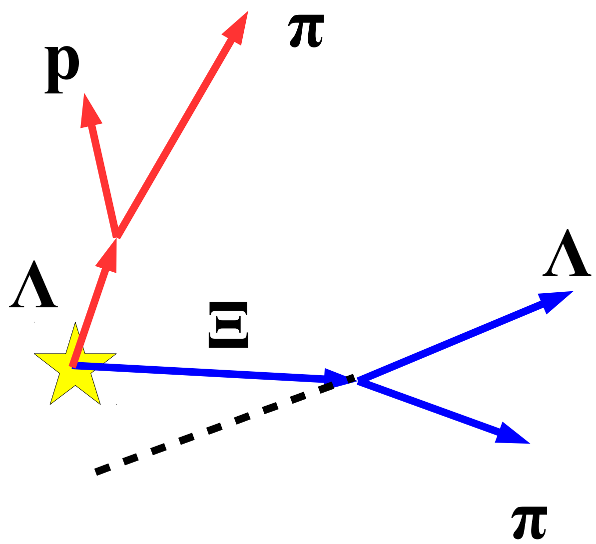
$q \cot\delta = -1/a_0 + r_{eff}\, q^2/2 + O(q^4)$

Feed-Down Effects & Residual Source

- **Feed down effects**

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

λ = Purity of ΛΛ pair

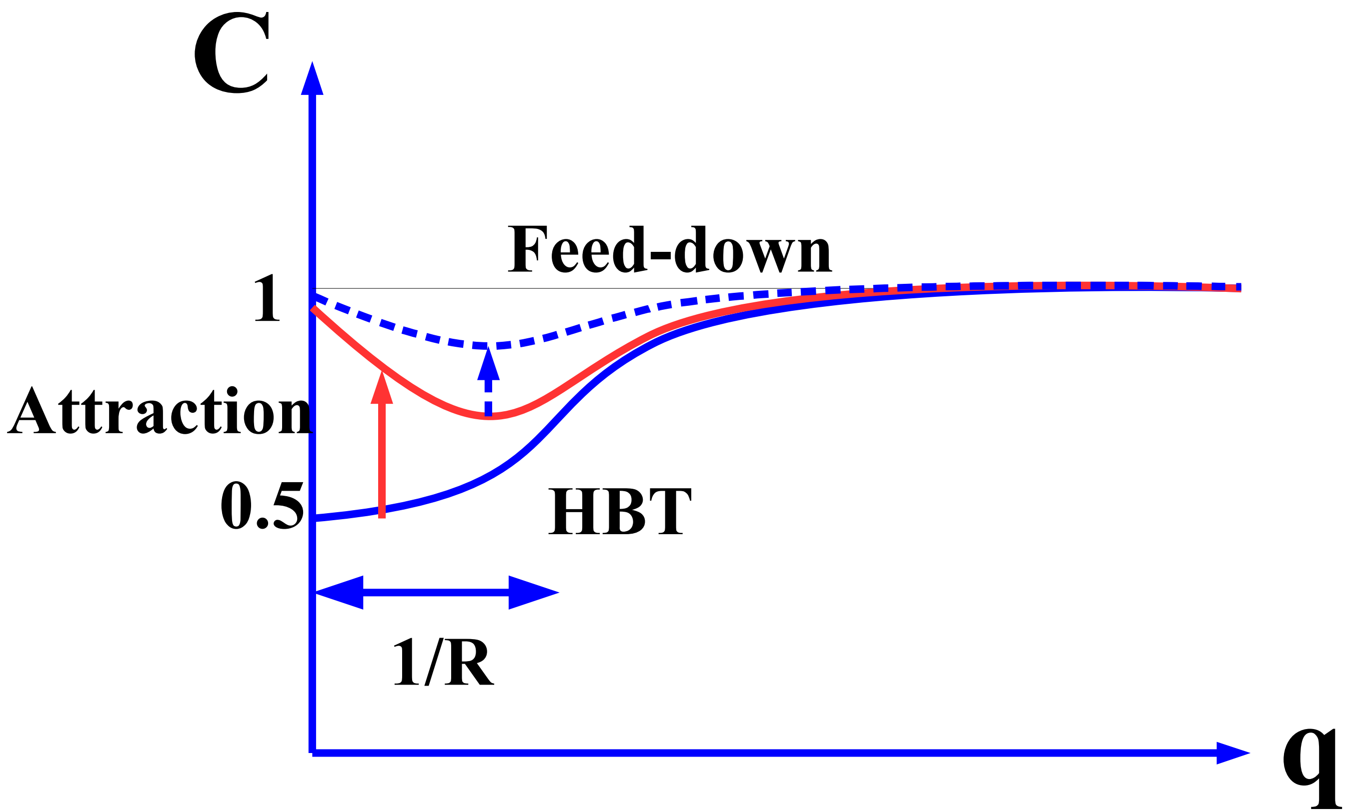


  - **Short-lived Y* → mod. of source fn.**
  - **Ξ → Λπ can be excluded (cτ=8.71 cm)**
  - **$\Sigma^0 \to \Lambda\gamma$ is difficult to reject**
  - **Data based purity $\lambda=(0.67)^2$**
    Σ^0/Λ=0.278 (p+Be, 28.5 GeV/c) ***Sullivan et al. ('87)***
    Ξ/Λ = 15 % (RHIC)

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

$$C_{\rm corr}(q) = 1 + \lambda(C_{\rm bare}(q) - 1) + a_{\rm res}\exp(-4r_{\rm res}^2 q^2)$$

Feed-Down Effects & Residual Source

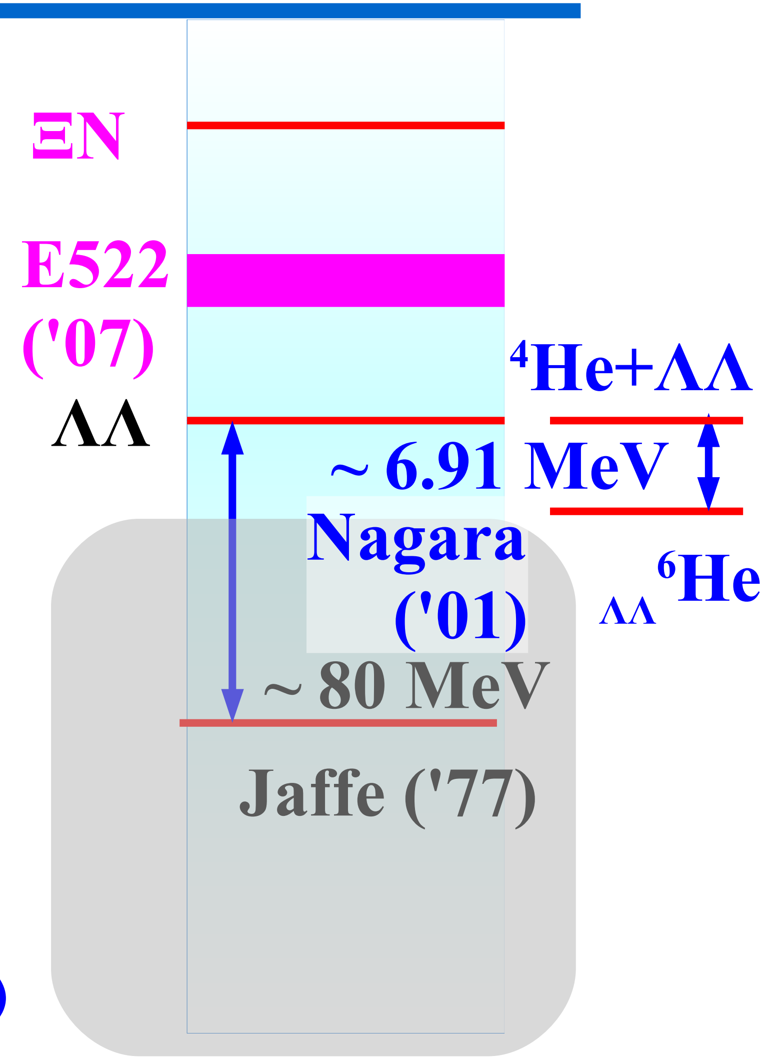


Correlation (C-1) becomes small when feed-down effect is strong (λ << 1)

ΛΛ correlation and ΛΛ interaction

Relevance of ΛΛ interaction to physics

- **H-particle: 6-quark state (uuddss)**
  - **Prediction:** ***R.L.Jaffe, PRL38(1977)195***
  - **Ruled-out by double Λ hypernucleus**
    Takahashi et al.,PRL87('01) 212502
  - **Resonance or Bound "H" ?**
    Yoon et al.(KEK-E522) ('07)
  - **Lattice QCD**
    HAL QCD & NPLQCD ('11)
- **Neutron Star Matter EOS**
  - **Hyperon Puzzle**
    Demorest et al. ('10), Antoniadis et al. ('13)
  - **Cooling Puzzle (ΛΛ superfluidity)**
    T. Takatsuka, R. Tamagaki, PTP 112('04)37
- **QGP signal, BB interaction model, ….**



Λ Λ interaction models

- **Boson exchange potential**

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

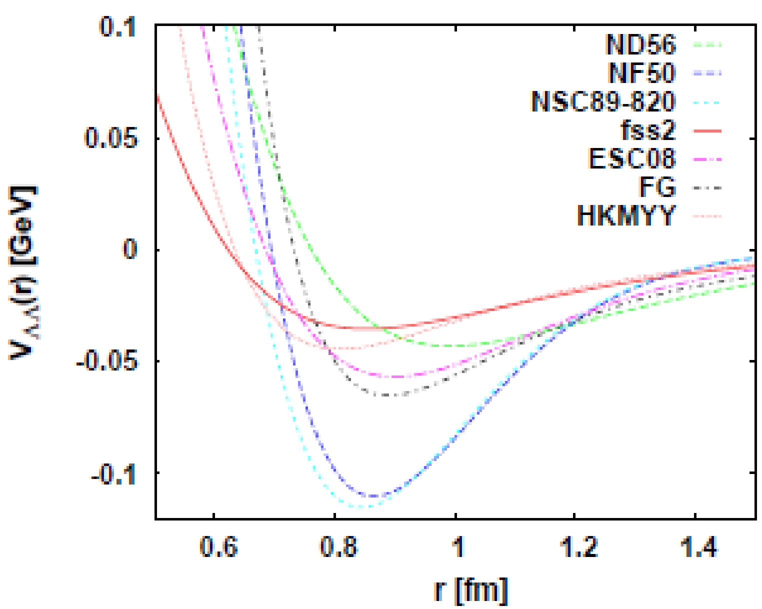
  Nagels+('77, '79), Maessen+('89), Rijken+('99,'10)

  Ehime ***Ueda et al. ('98)***

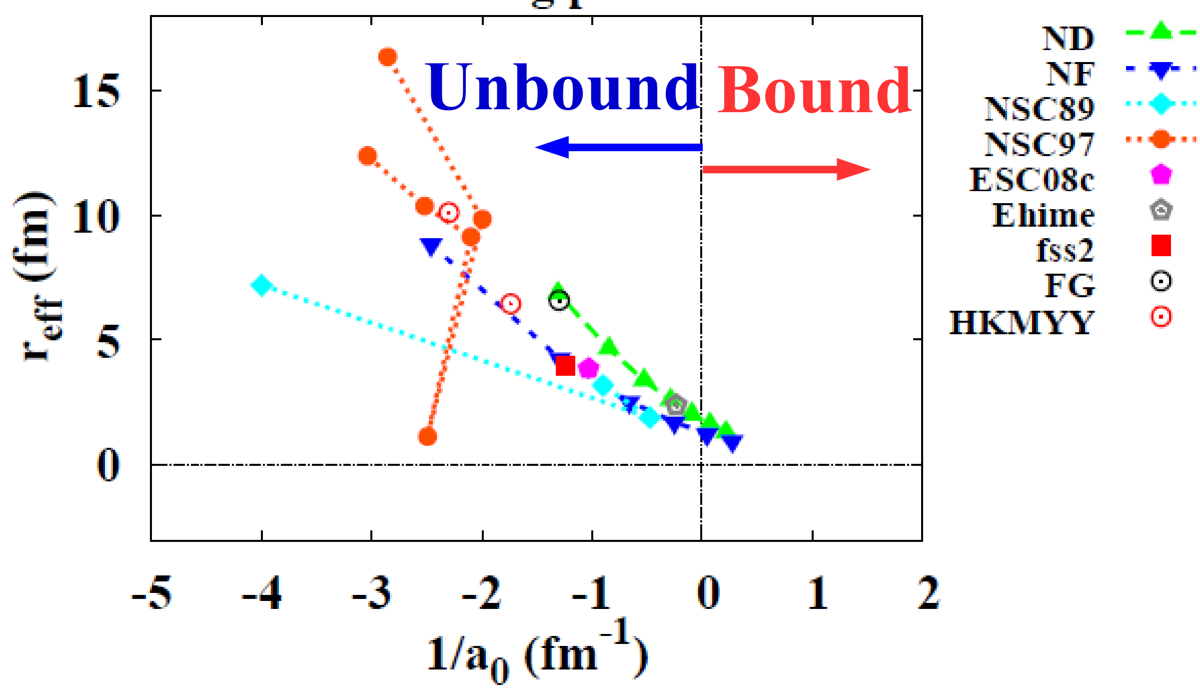
- **Quark model interaction: fss2 Fujiwara et al.('07)**

- **Tuned potential to Nagara**

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

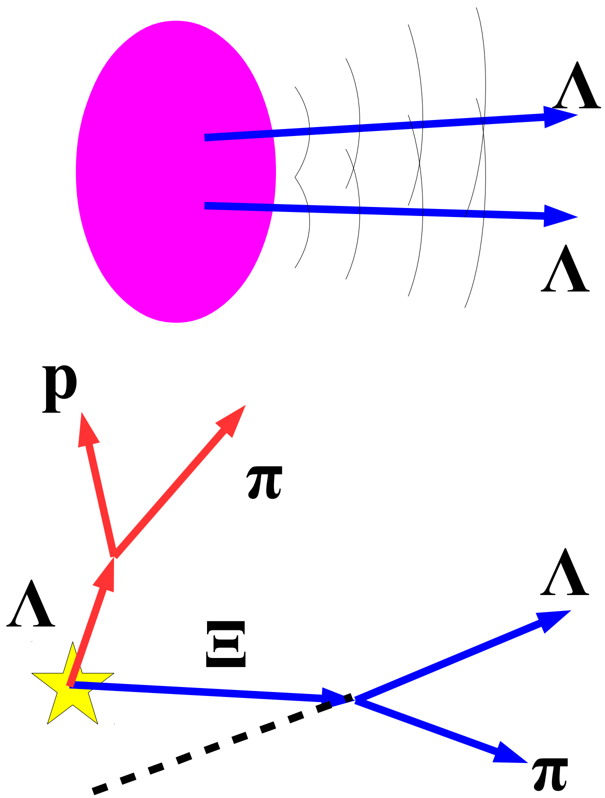


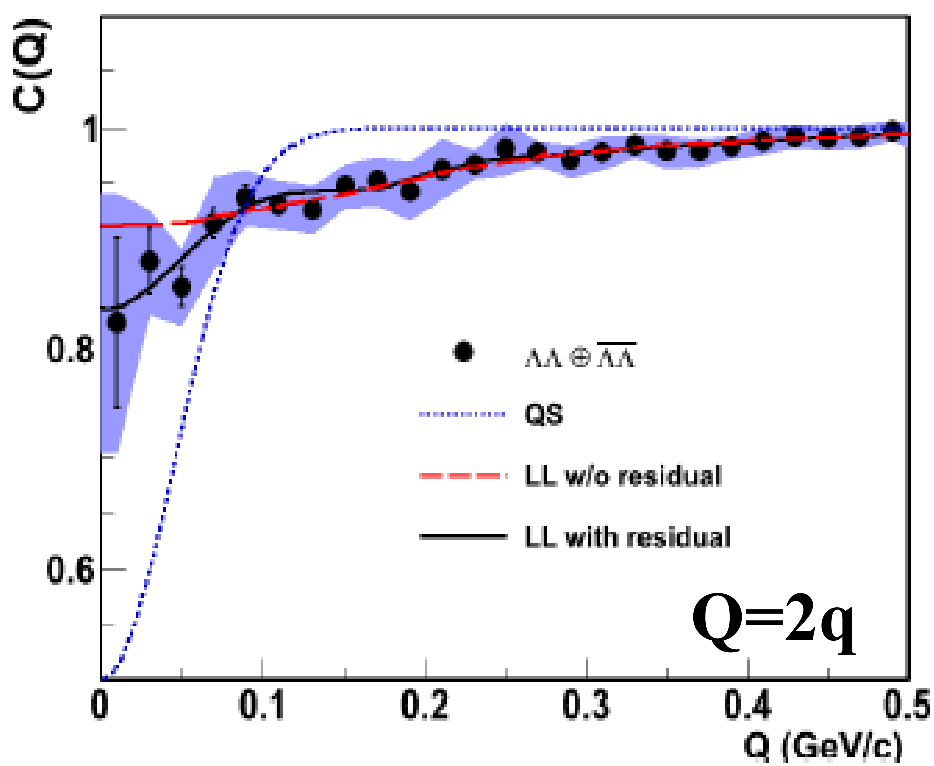
ΛΛ scattering parameters



Measurement at RHIC

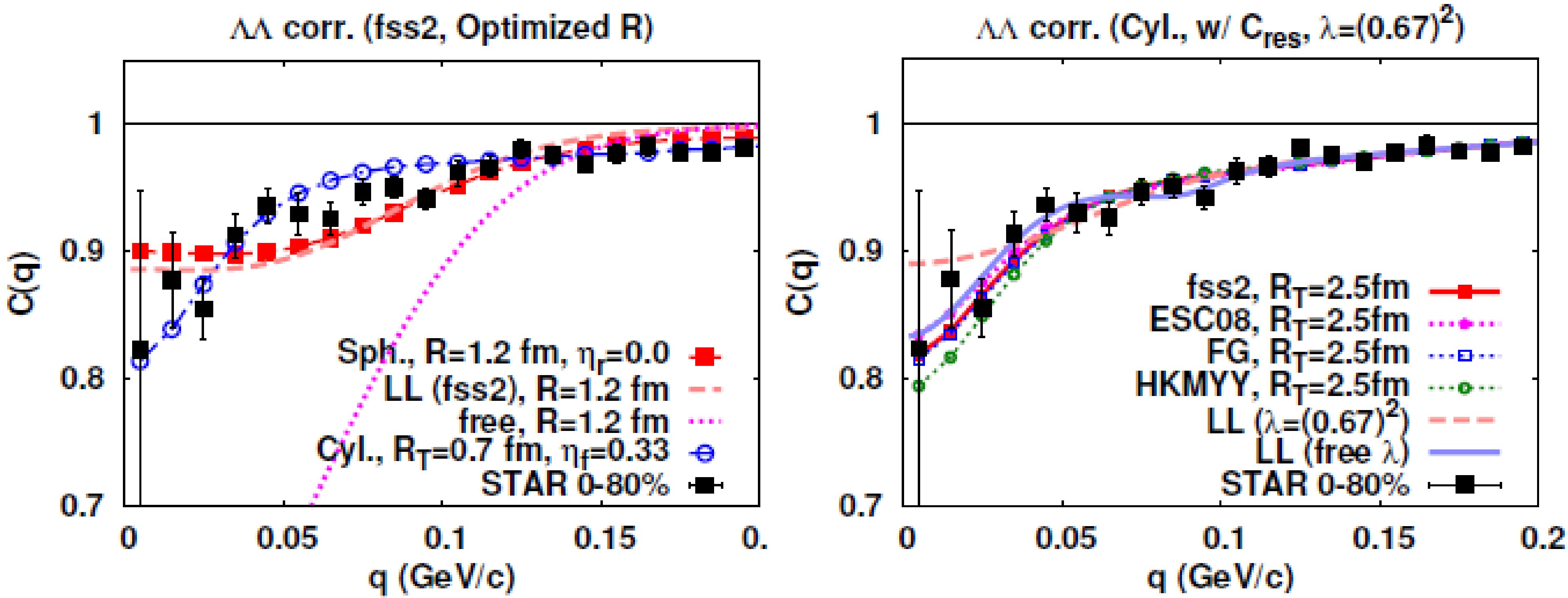
- **STAR collaboration at RHIC measured ΛΛ correlation !**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  - **RHIC (Relativistic Heavy-Ion Collider @ Brookhaven Nat. Lab.) Au+Au (100 GeV+100 GeV per nucleon pair)**
  - **Track analysis enhances S/N ratio.**
- **Enhanced correlation from free Fermion correlation**





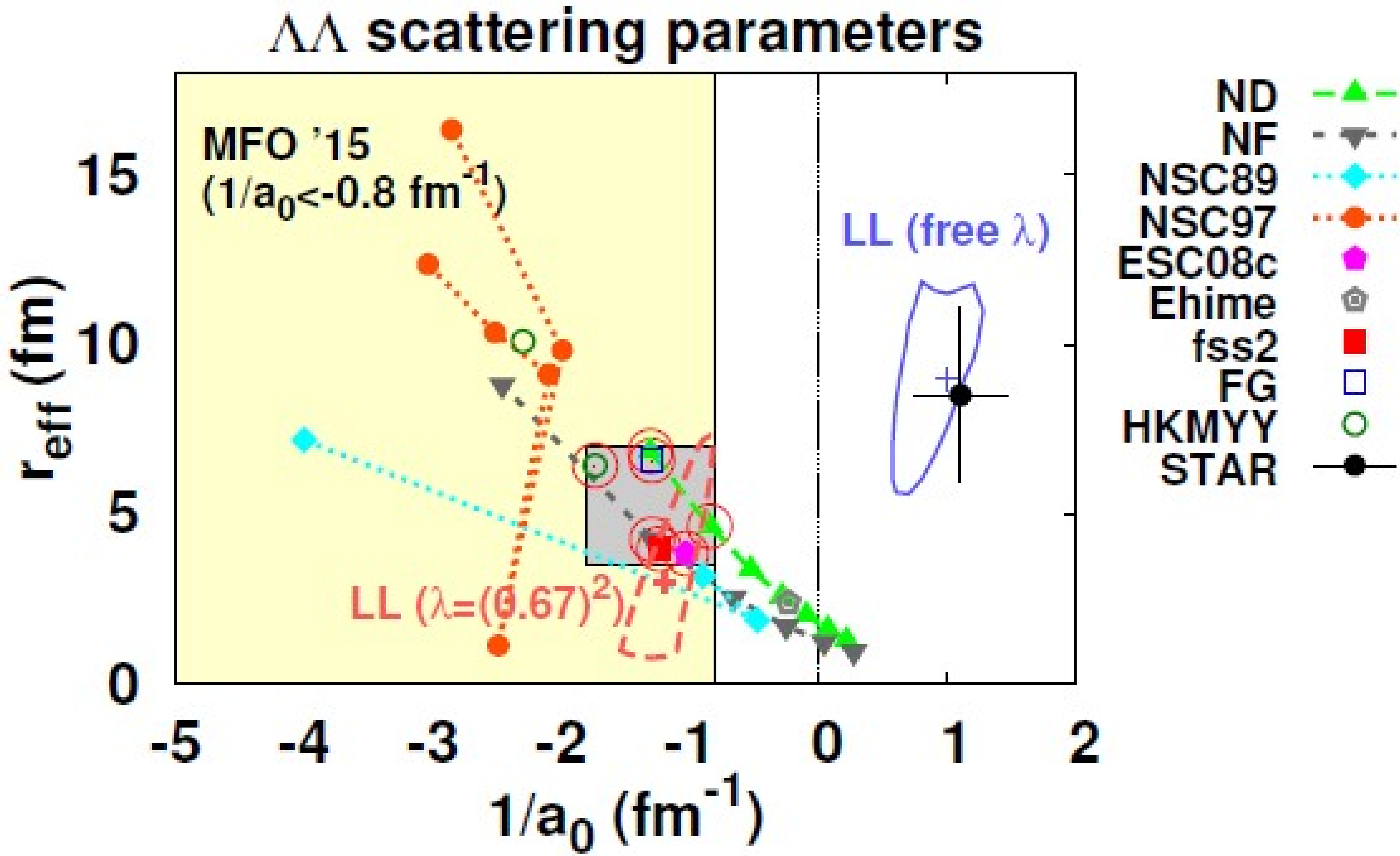
Another Theoretical Analysis

- Spherical source: low q suppression is not well explained.
- Flow effects: improved fit (χ^2/DOF ~ 1.5)
- Feed-down + residual source: χ^2/DOF ~ 1, smaller int. sensitivity.



K.Morita, T.Furumoto, AO, PRC91('15)024916 [arXiv:1408.6682]
AO, K.Morita, K.Miyahara, T.Hyodo, arXiv:1603.05761
Data: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

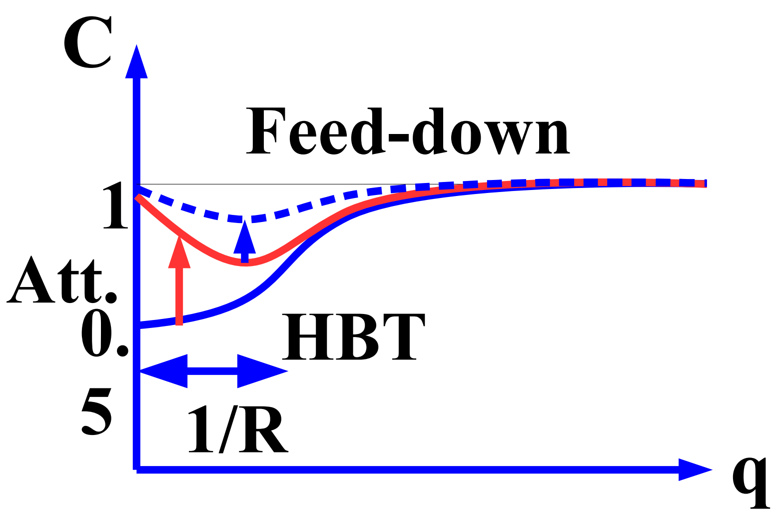
ΛΛ interaction from ΛΛ correlation

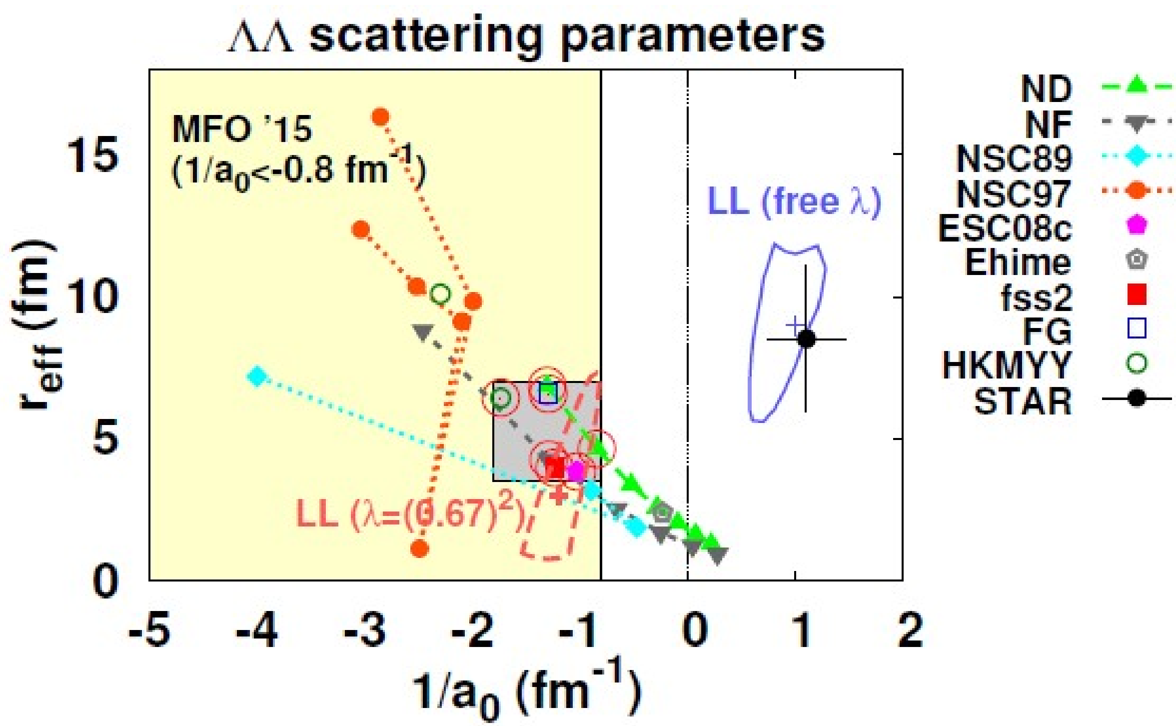


Positive a_0 (STAR) ←→ Negative a_0 (MFO'15)

Scattering length: Positive or Negative ?

- **Analysis by STAR: λ is regarded as a free parameter**
  - **optimal λ ~ 0.18, ΛΛ int. need to suppress C**
- **MFO'15: λ is evaluated on the basis of measured Σ^0/Λ ratio**
  - **$\lambda = (0.67)^2$, ΛΛ int. need to enhance C**





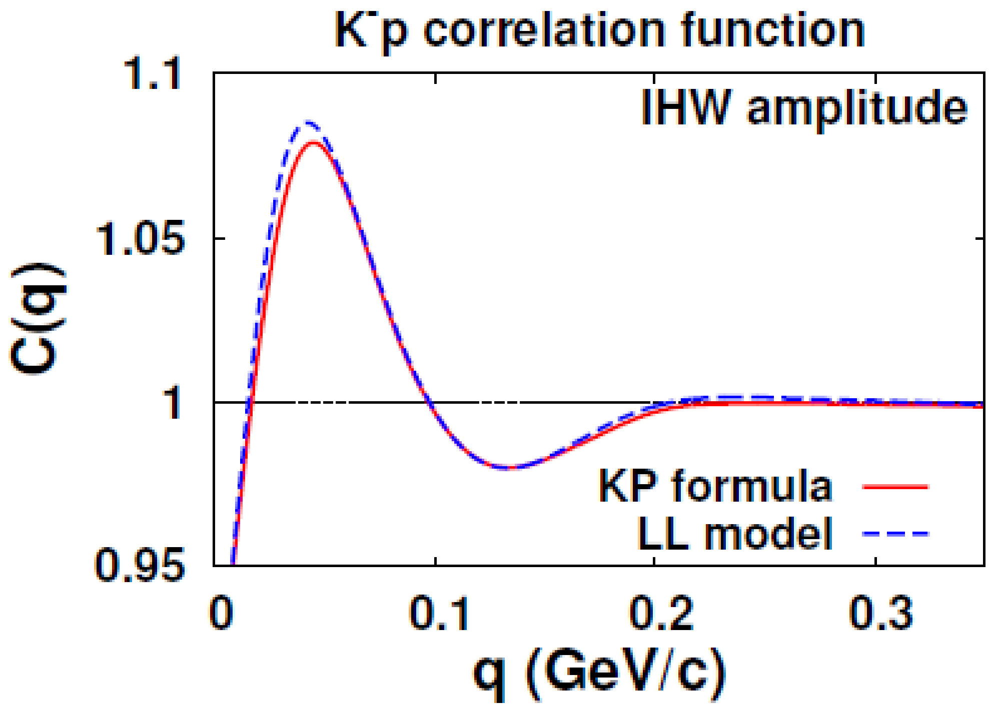
$K^{-}p$ correlation

$K^{-}p$ correlation

- **Coupled channel of I=0 and I=1**

$$\psi_{K^-p}(r) \to \frac{1}{2iqr}\left[e^{iqr} - \tilde{S}^{-1}_{K^-p} e^{-iqr}\right], \quad \tilde{S}_{K^-p} = 2\left(S_0^{-1} + S_1^{-1}\right)^{-1}, \quad S_I = e^{2i\delta_I}.$$

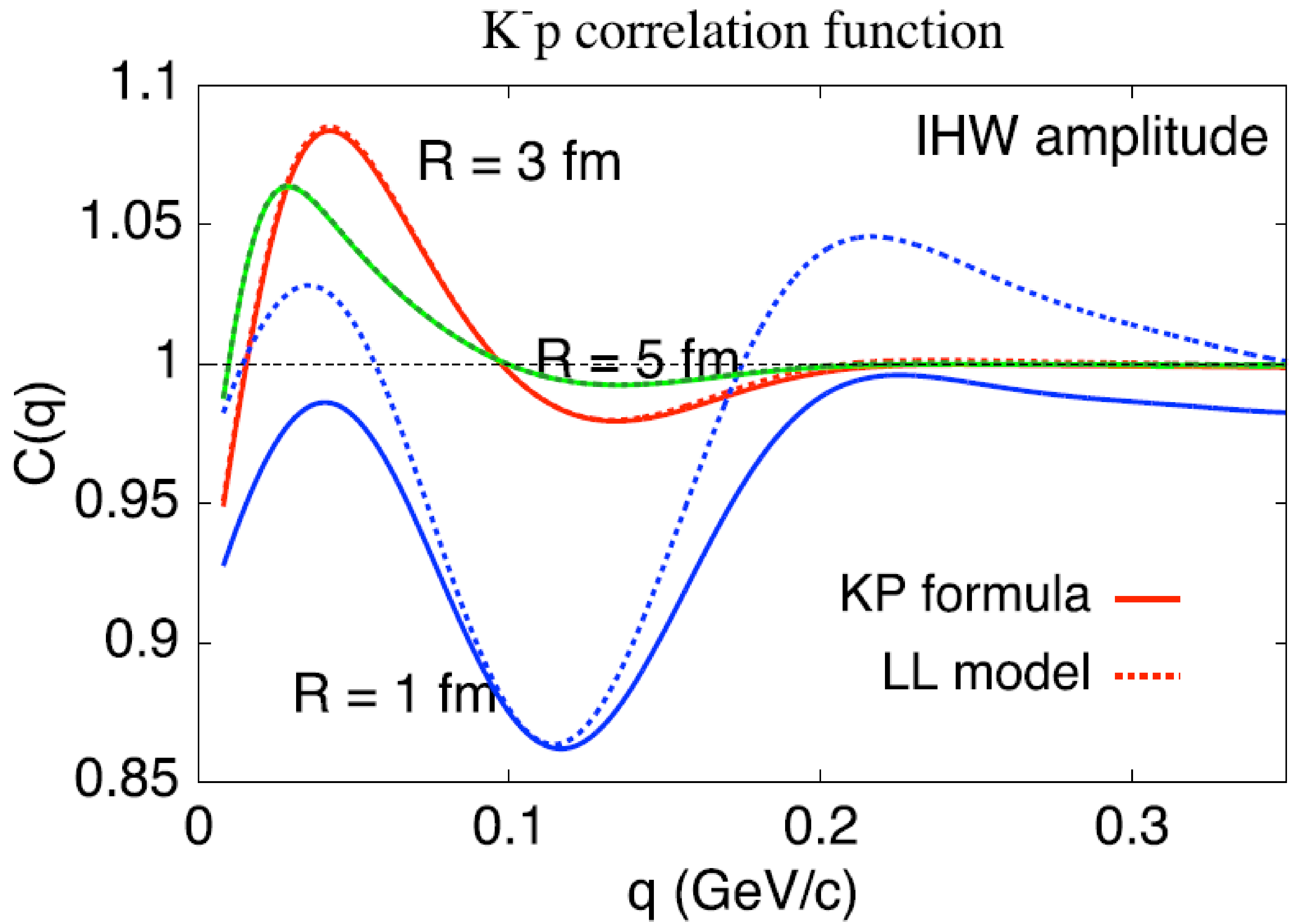
  - **Outgoing boundary condition in K^{-}p channel (charge base) requires combination of amplitudes different from K^{-}p elastic scattering.**



Potential: K. Miyahara, T. Hyodo, PRC93 ('16) 015201.
Amplitude: Y. Ikeda, T. Hyodo, W. Weise, PLB 706 ('11) 63; NPA 881 ('12) 98.
Fitting SIDDHARTA data: M. Bazzi et al. [SIDDHARTA Collab.], PLB 704 ('11) 113.

AO, K.Morita, K.Miyahara, T.Hyodo, arXiv:1603.05761

$K^{-}p$ correlation



K. Miyahara

Summary

- **Hadron-Hadron correlation contains information on interaction as well as the resonance pole information.**
  - **pp, nn (scatt. length), ΛΛ (Shah), Λp (Fabietti), K^- p, ...**
  - **Pair purity λ is an important parameter, which determines the correlation strength at $q \to 0$.**
- **ΛΛ correlation data is consistent with Λ Λ interaction with $1/a_0 < -0.8\ \mathrm{fm}^{-1}$.**
  - **Provided that all weak decays are rejected, we have $\lambda = (1-\Sigma^0/\Lambda)^2$.**
  - **Remaining problem: High-momentum tail (Λ Λ, Λp, BB, …) → Coupling to other channel (Kisiel), Correlation in the parent channel (Shah), Color flux tube (AO in Hyp2015), p-wave ?**
- **K^- p correlation from heavy-ion collisions is determined by a combination of I=0, 1 amplitudes different from elastic scattering.**

ExHIC 2010 → ExHIC 2016

Exotics from Heavy-Ion Collisions (2010)

S.H.Lee, C.M.Ko, A.Ohnishi, D.Jido, T.Hyodo, S.Yasui, M. Nielsen, S.Cho, (K.Yazaki, T.Sekihara, T.Furumoto), ExHIC collab.
A.Martinez Torres,
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H.Z.Huang (STAR),
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Y. Kwon (Belle),
Y.Miake (PHENIX), M.Shimomura (PHENIX), M.Niiyama (SPring8),
K.Imai, C. Yoon, H.Fujioka.

Several meetings
Yonsei, Kyoto

Exotic hadrons from HIgh energy Collisions (2016)

K. Morita, Y. Maezawa,
K. Miyahara, Y. Kamiya,
X. Liu, S. Maeda,
T. Hirano,

J. Chen, N. Shah (STAR),
Y. Watanabe, L. Fabbietti,
J. Song (ALICE)
Y. Kato (Belle & Belle II)

We should not forget our secretary, Chiyo Nagae !


Thank you, and see you again !

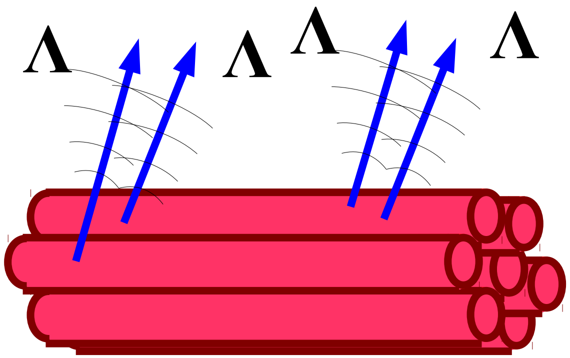
Thank you !

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**