Hadron-Hadron Interactions from Two-Particle Correlation in Heavy-Ion Collisions

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talk based on works in collaboration with

K. Morita, T. Furumoto, K. Miyahara, T. Hyodo, F. Etiminan, T. Hatsuda

MIN16 - Meson in Nucleus 2016 -, Jul.31-Aug.2, 2016, YITP, Kyoto

- *K. Morita, T. Furumoto, AO, PRC91('15)024916.* *$\Lambda\Lambda$*
- *AO, K. Morita, K. Miyahara, T. Hyodo, NPA954(2016), 294 [arXiv:1603.05761]* *$\Lambda\Lambda$, $K^{-}p$*
- *K. Morita, AO, T. Hatsuda, JPSJ-Conf. Proc., in press (Hyp2015 proc.)*
  K. Morita, AO, F. Etminan, T. Hatsuda, arXiv:1605.06765 [hep-ph] *$\Omega^{-}p$*

Contents

- Introduction
- Correlation Function Formula
  - Koonin-Pratt (KP) formula
  - Lednicky-Lyuboshits (LL) model
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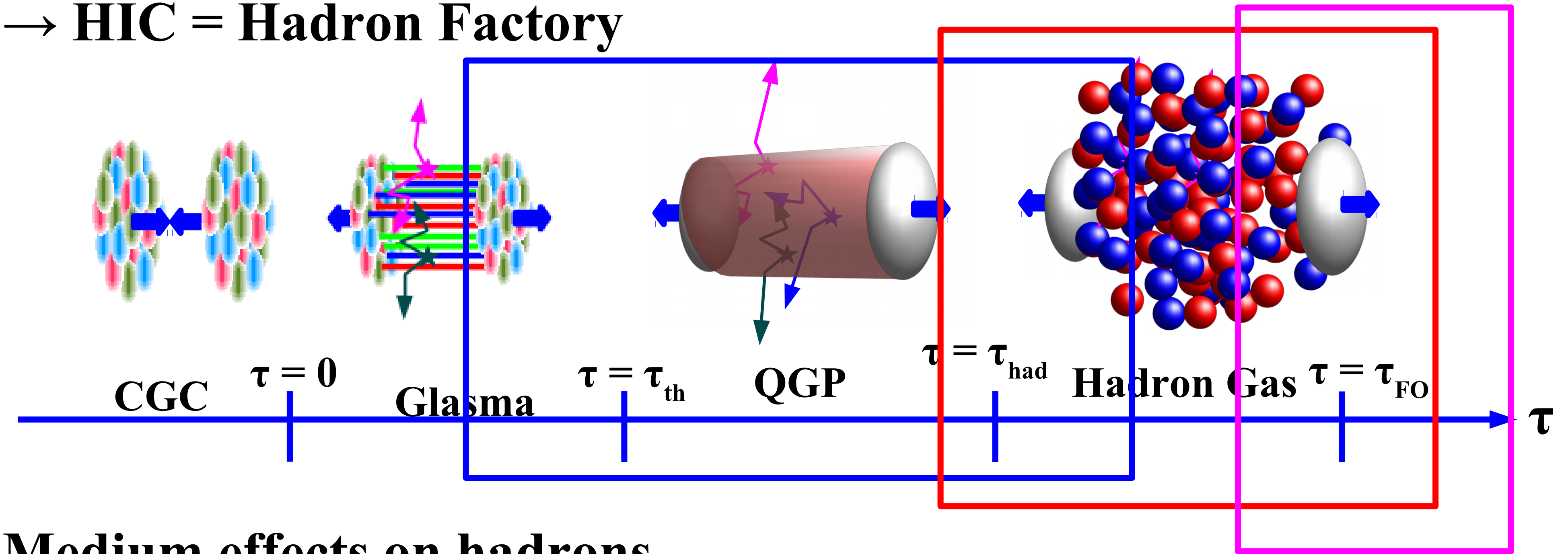
  - $\Lambda\Lambda$ correlation and $\Lambda\Lambda$ interaction
  - $K^{-}p$ correlation and correlation in couple channels
  - $\Omega^{-}p$ correlation and Coulomb potential effects
- Summary

Hadron Physics via Heavy-Ion Collisions

Heavy-Ion Collision as a Hadron Factory

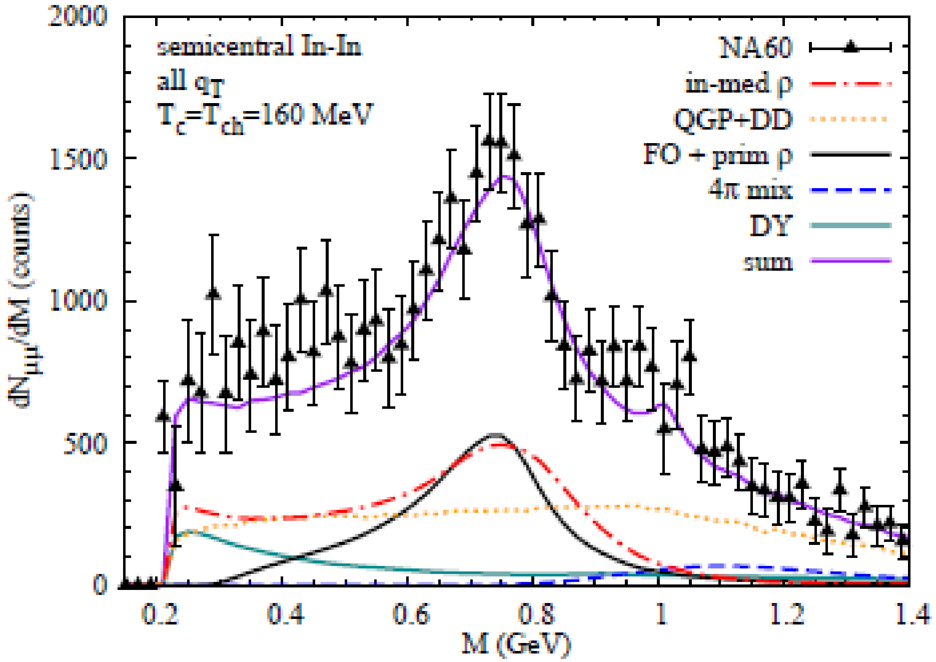
- Many hadrons are produced simultaneously in high-energy HIC
  → HIC = Hadron Factory



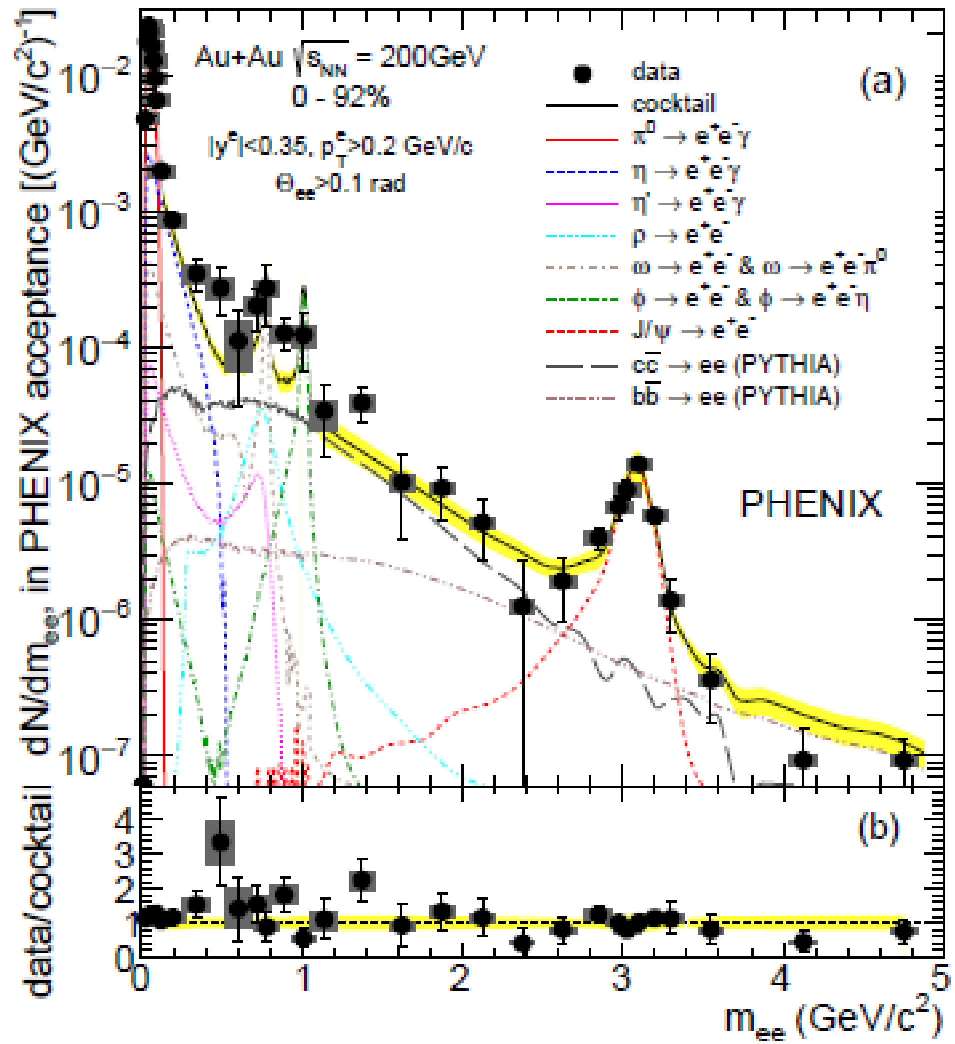
- Medium effects on hadrons
- Formation mechanism of hadrons
- Interaction between hadrons

Thermal Modification of Hadron Spectral Function

- **Low mass dilepton**
  - **Enhanced dilepton invariant mass spectrum may be explained with broadening of ρ meson and other mechanisms.**



NA60 Collab. (R. Arnaldi et al.), PRL96('06)162302.
H. van Hees, R. Rapp, NPA806('08)339

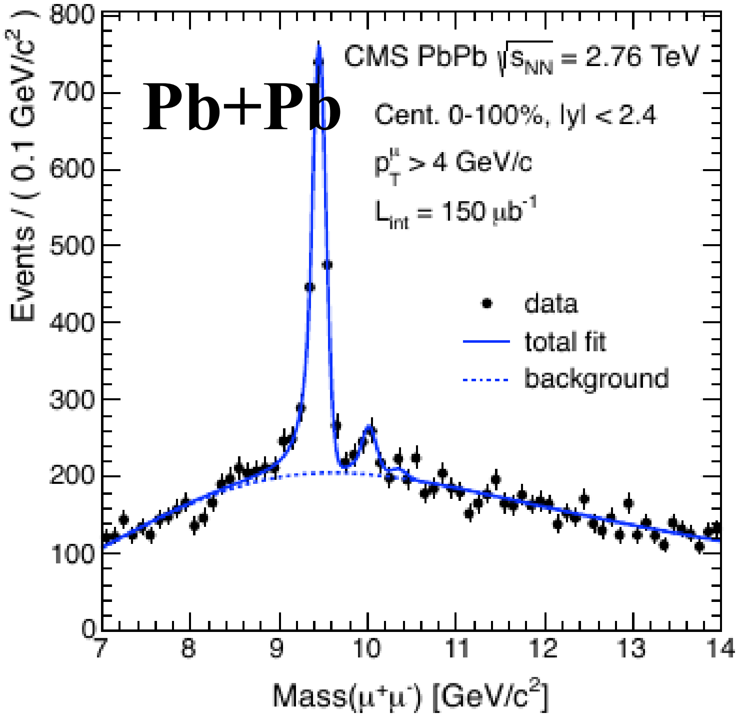


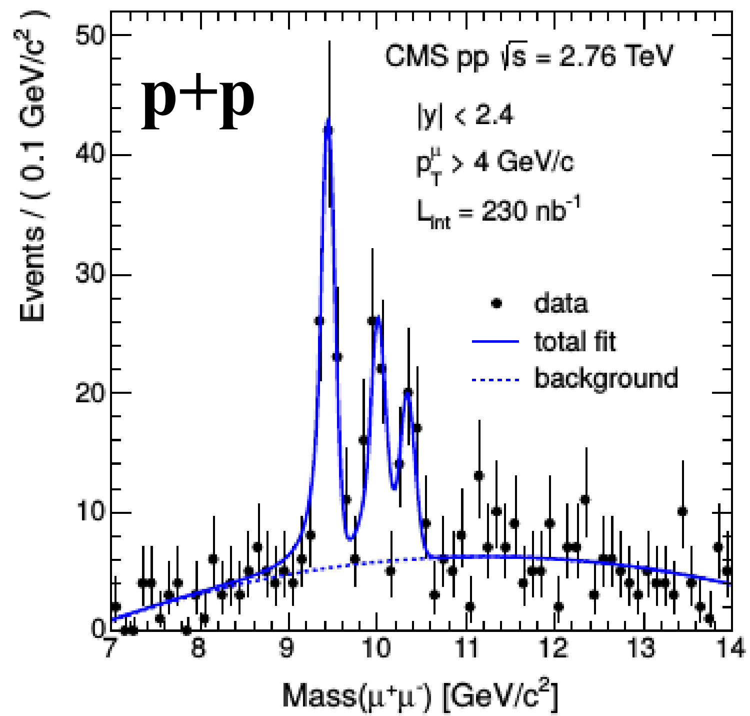
PHENIX Collab. (A. Adare et al.), PRC93('16)014904

STAR Collab. (L. Adamczyk et al.), PRL113 ('14)022301

Thermal Modification of Hadron Spectral Function

- **Excited Upsilon (2S, 3S) are suppressed in Pb+Pb**
  CMS Collab. (S. Chatrchyan et al.), PRL107('11)052302; PRL 109 ('12) 222301
  → Excited quarkonium may melt before g.s. does by hot-medium effects



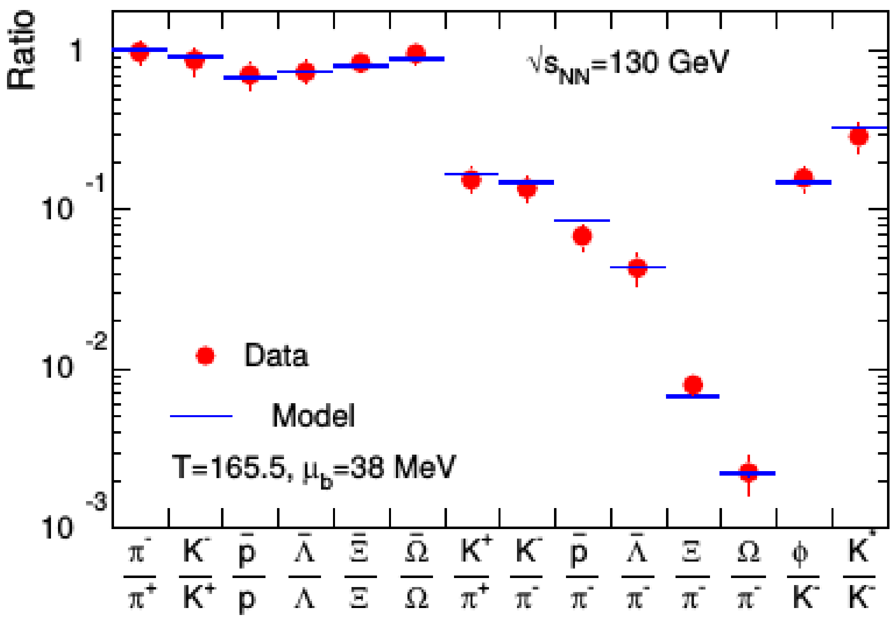


- **η' mass reduction ?** **T.Csorgo, R.Vertesi, J.Sziklai, PRL105('10)182301**

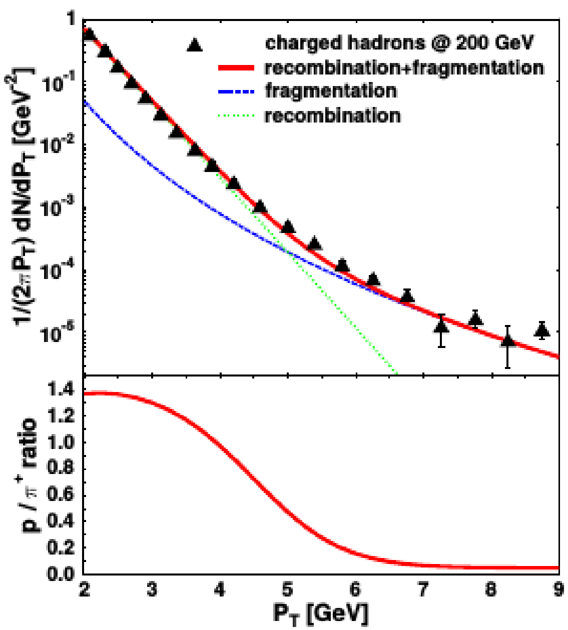
Modification by T, complementary to pA reactions.

Hadron Formation Mechanism

- **Statistical Model**
  A. Andronic, P. Braun-Munzinger, J. Stachel, NPA772('06)167; J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton, PRC 73 ('06), 034905
  Hadron yields are well explained by the statistical model.



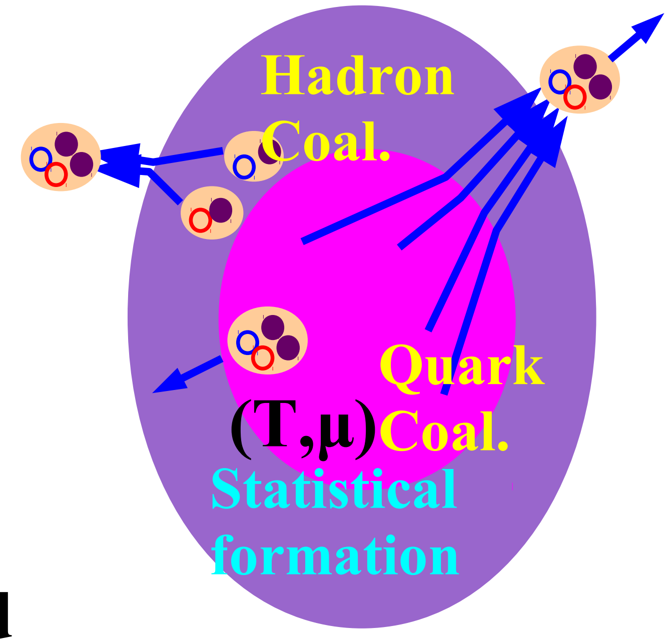
- **Coalescence of quarks**
  R.J.Fries, B. Muller, C. Nonaka, S.A.Bass, PRL90('03)202303;
  V. Greco, C.M.Ko, P. Levai, PRL90('03)202302;
  R.C.Hwa, C.B.Yang, PRC67('03)034902
  pT spectra and v2 are explained by coalescence of quarks.



- **Coalescence of hadrons**
  H.Sato, K. Yazaki, PLB98('81)153
  Deuteron spectrum is explained by the coalescence of pn.

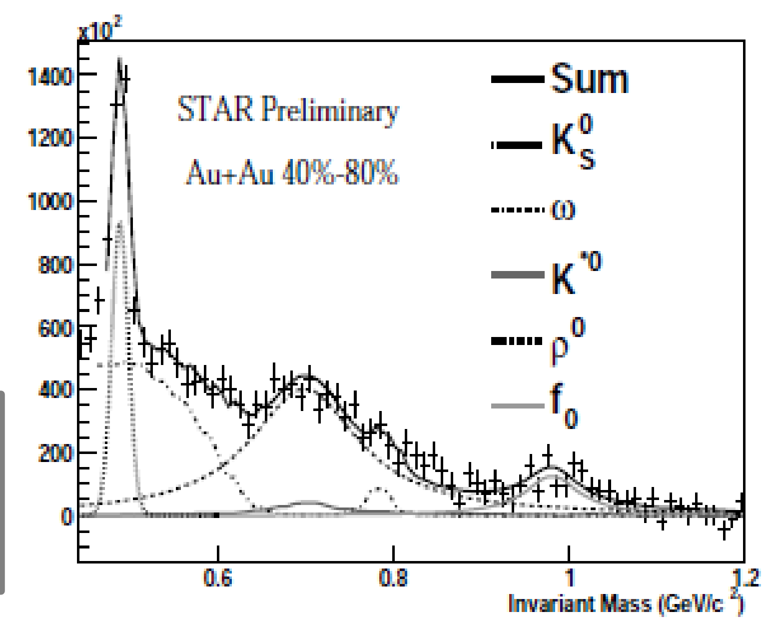
Exotic Hadron Production in HIC

- **How do exotic hadrons are produced ?**
  Statistical ?
  Quark Coalescence ?
  Hadron Coalescence ?



- **Statistical model overestimates Λ(1520, 3/2-) yield.**
  L=2 effects: Kanada-En'yo, Muller ('06)

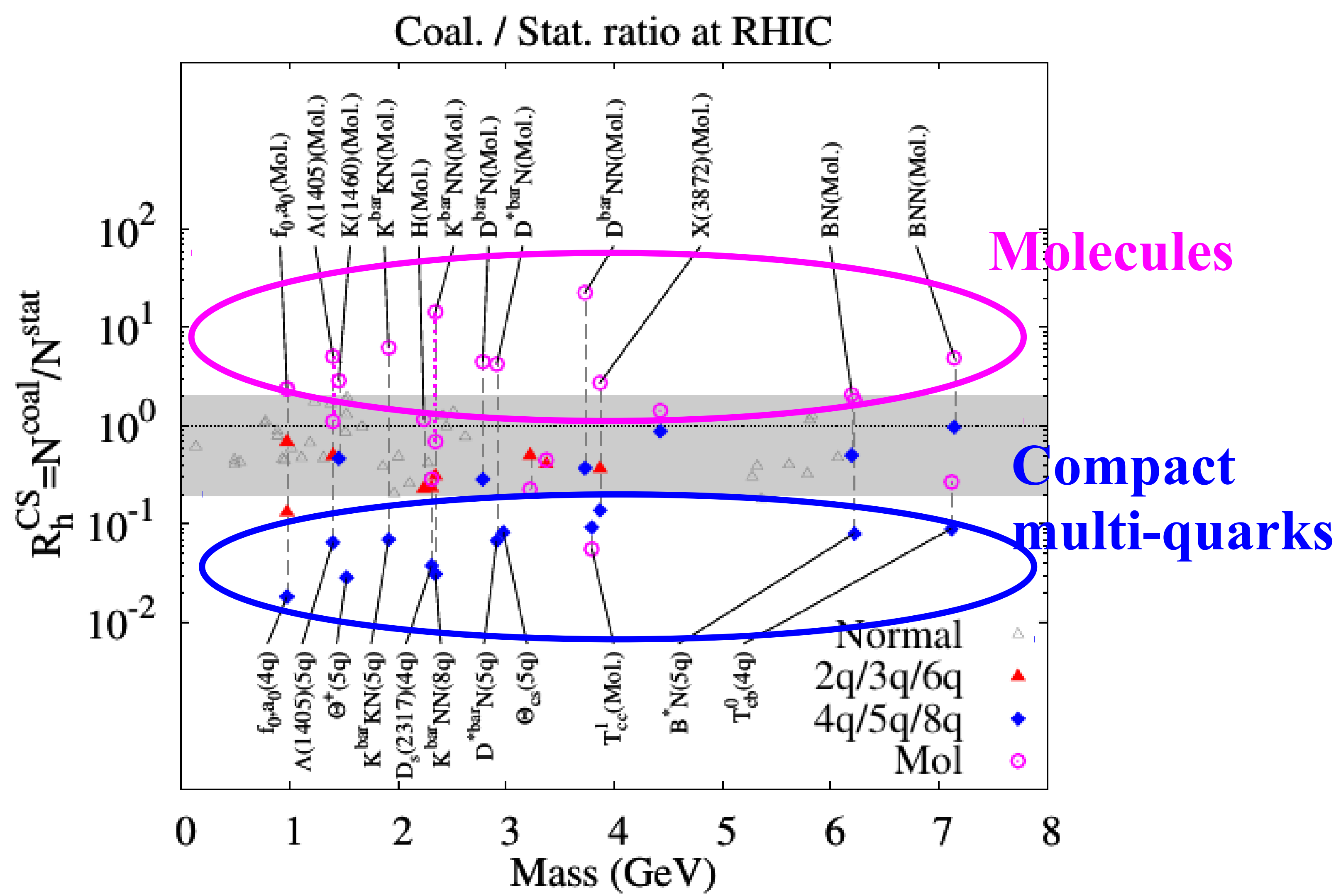
- **Statistical model underestimates f_0(980) yield**
  P. Fachini [STAR Collab.], NPA715('03)462.
  STAR: N(f_0(980)) ~ 8.4, Stat: 5.6,
  Coal: 2q:0.76-3.8, 4q:0.1, Mol: 13
  S. Cho et al. [ExHIC Collab.],PRL106 ('11)212001.



Production yield in HIC may tell us the nature of exotic hadrons !

Exotic Hadron Production in HIC

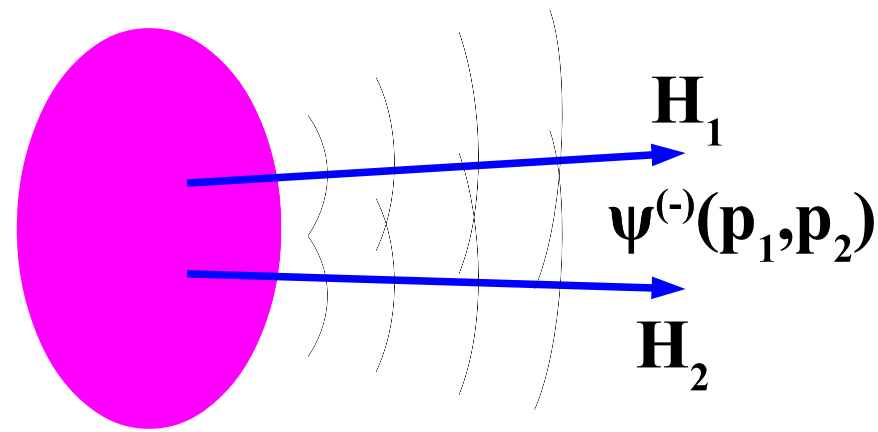
S. Cho et al. [ExHIC Collab.],PRL106 ('11)212001; PRC84('11)064910.



Hadronic molecules will be made more abundantly in HIC than stat. model predictions.

Hadron-Hadron Correlation in HIC

- **Hadron-Hadron Correlation Func. (Koonin-Pratt (KP) formula)**



$$C(p_1,p_2)=\frac{P(p_1,p_2)}{P(p_1)P(p_2)}$$

Density matrix

$$=\frac{\left\langle\psi^{(-)}(p_1,p_2)\mid\rho\mid\psi^{(-)}(p_1,p_2)\right\rangle}{\langle\psi(p_1)\mid\rho\mid\psi(p_1)\rangle\,\langle\psi(p_2)\mid\rho\mid\psi(p_2)\rangle}$$

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

int. → relative w.f.

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

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

(Spherical source, Identical Fermion)

> ***Corr. Fn. has been utilized to obtain the source size, but it contains information on hadron-hadron interaction.***

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; R. Lednicky, V. L. Lyuboshits, Sov. J. Nucl. Phys. 35 (1982) 770.

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

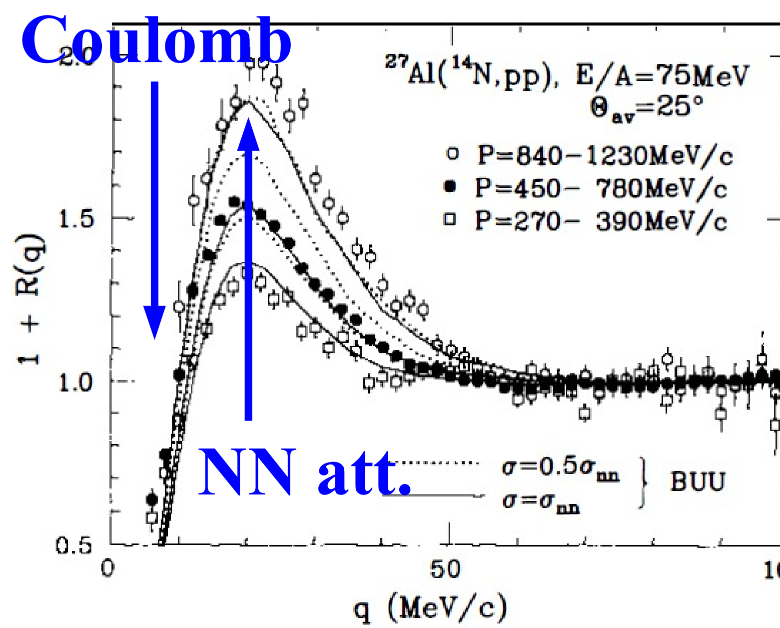
int. → relative w.f.

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

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 ?

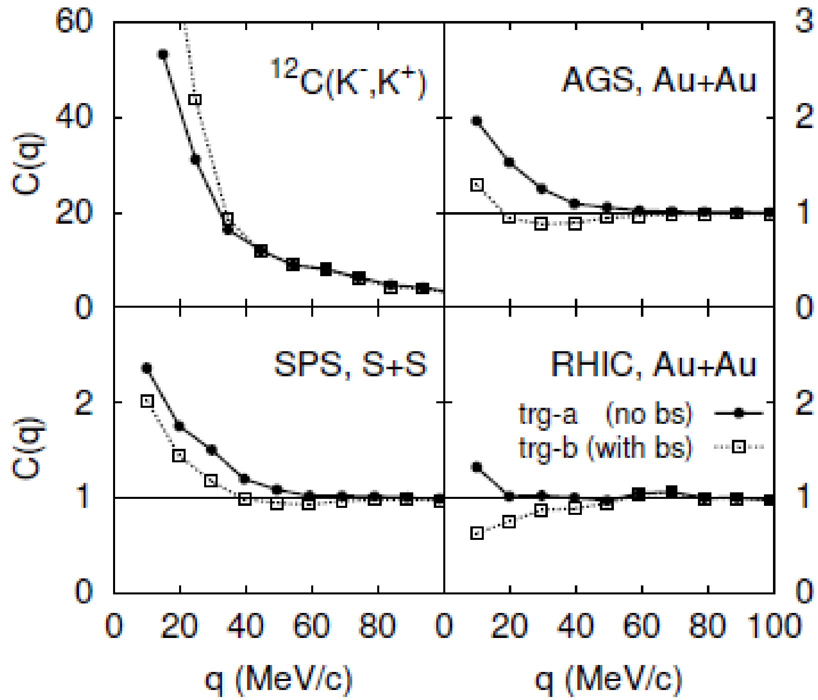
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left|\psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$

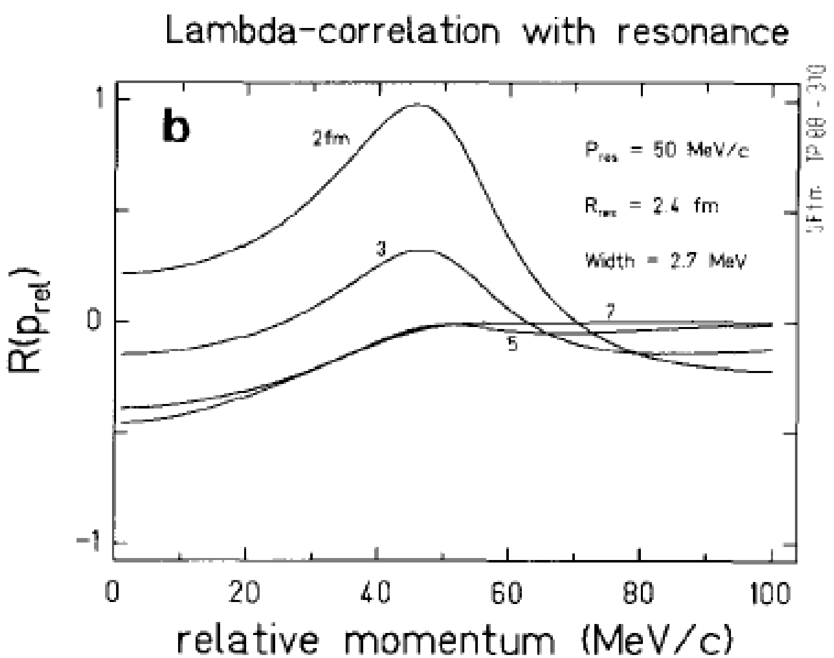
Let us try to constrain hh interaction from hh correlation !

Examples: ΛΛ, K^-p and Ω^-p

Correlation → Interaction

- **If we know correlation and source, it should be possible to get knowledge of hadron interactions !**
- **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)

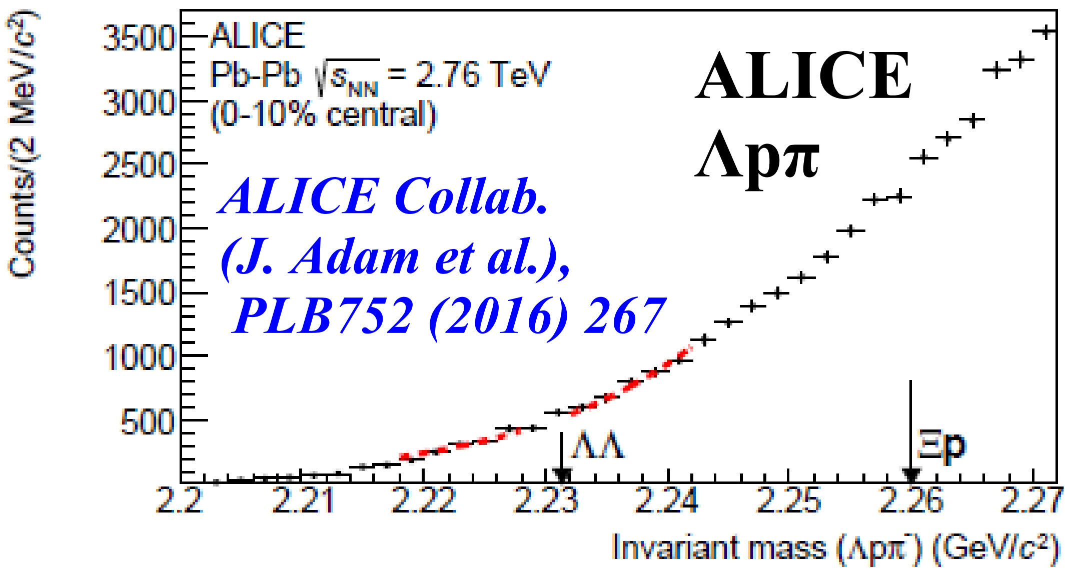




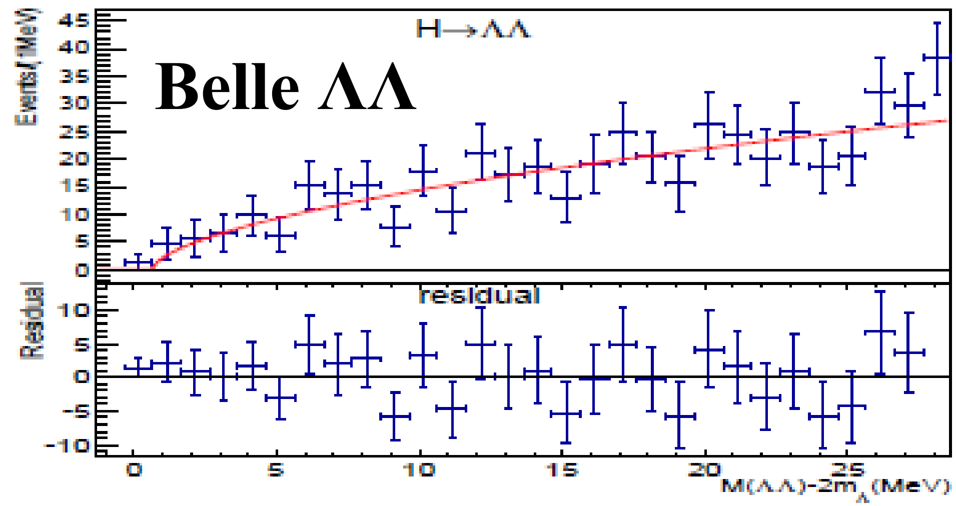
AO, Y. Hirata, Y. Nara, S. Shinmura, Y. Akaishi Nucl. Phys. A 670 (2000), 297c

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

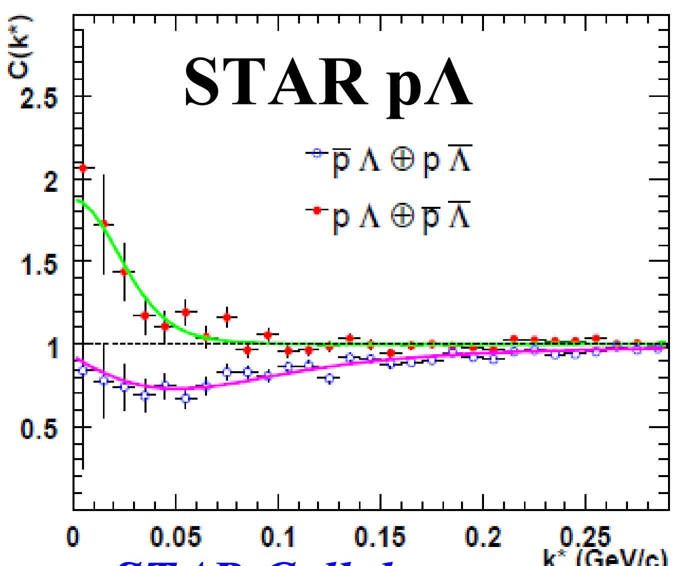
ΛΛ invariant mass / BB correlation function



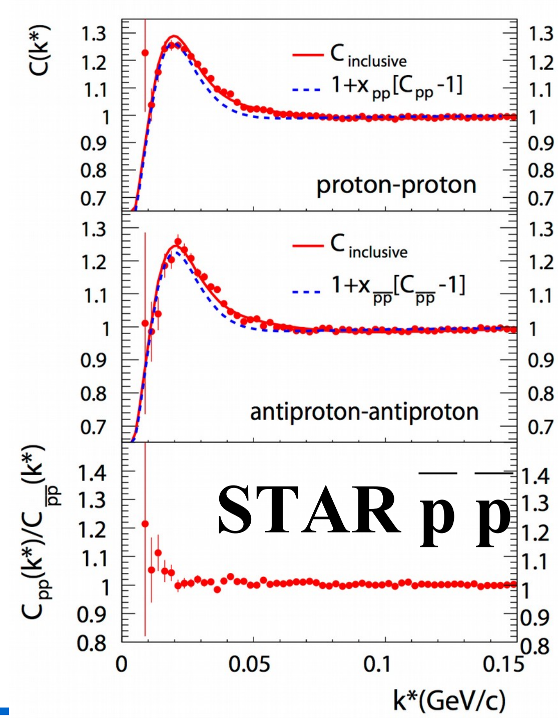
ALICE Collab. (J. Adam et al.), PLB752 (2016) 267



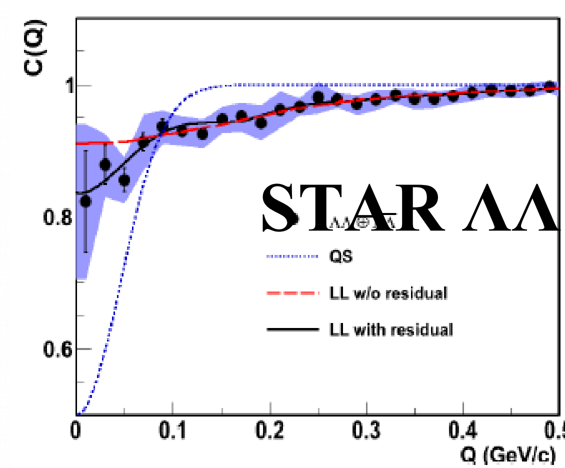
Belle Collaboration (Kim, B.H. et al.), PRL110('13)222002.



STAR Collab. (J. Adams et al.), PRC74('06)064906.



STAR Collab. (J. Adams et al.) Nature 527('15)345



n),
01.

Interaction dependence of two particle intensity correlation

Correlation function formula (for identical Fermions)

- **Koonin-Pratt formula (Spherical Gaussian Source)**

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

$$\simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int d^3r\, \underbrace{S_{12}(\mathbf{r})}_{\text{Source}} \left[\underbrace{|\chi_0(r)|^2}_{\text{w.f.}} - \underbrace{|j_0(qr)|^2}_{\text{free}}\right]$$

Fermion

$$= C_{\mathrm{HBT}}(q) + \frac{1}{2}\Delta C(q)$$

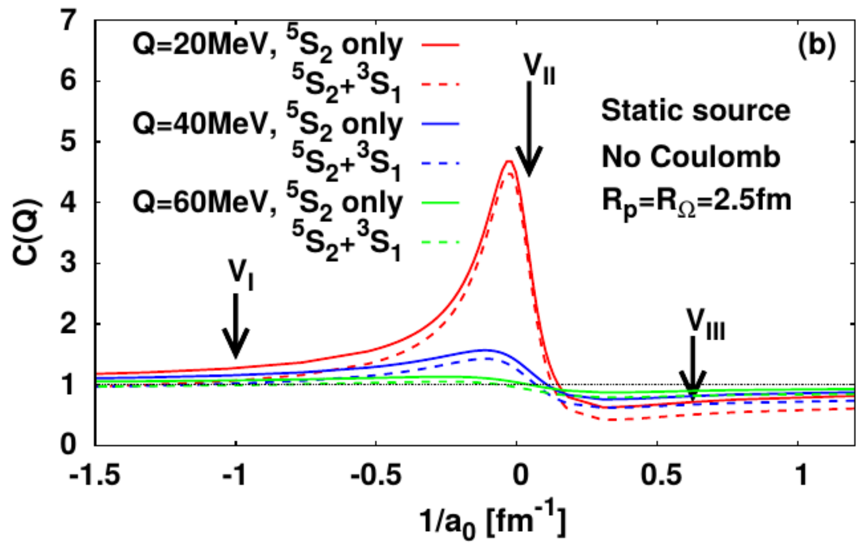
- **Lednicky-Lyuboshits analytic model**
  - **Asymp. w.f. + Eff. range corr. + $\psi^{(-)} = [\psi^{(+)}]^*$**

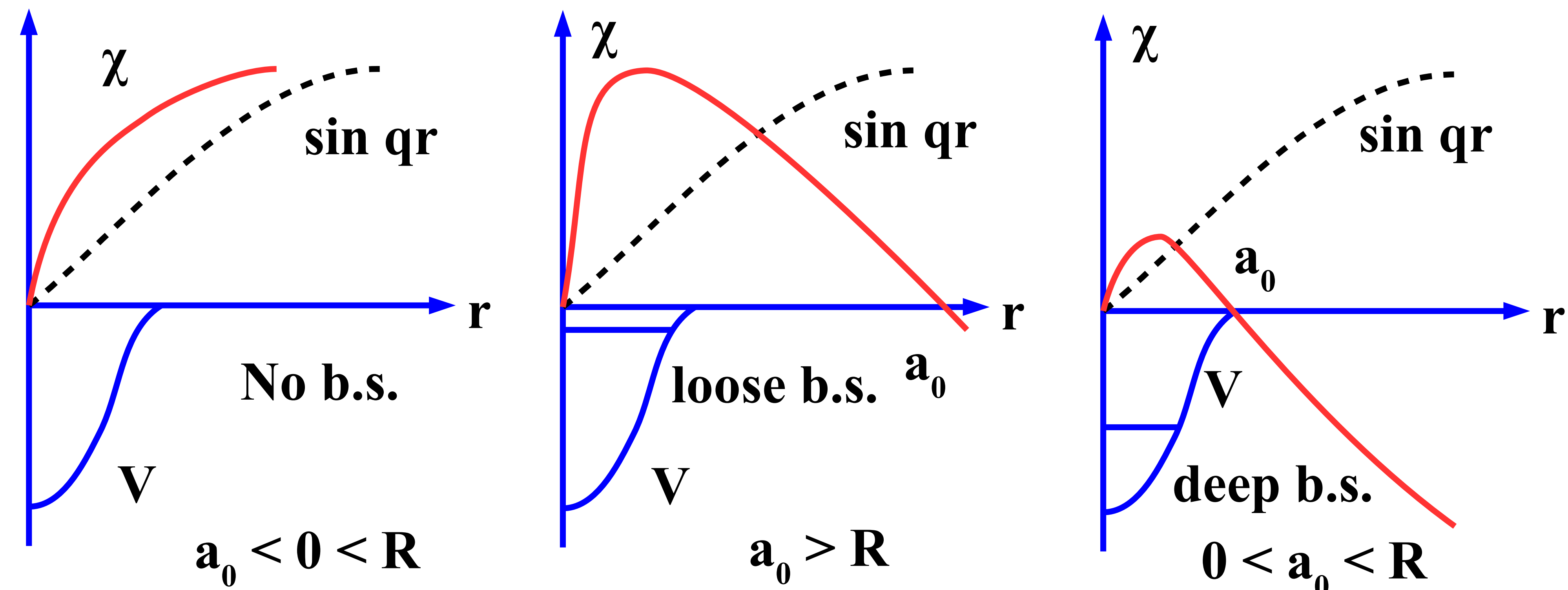
$$\psi_{\mathrm{asy}}(r) = \frac{e^{-i\delta}}{qr}\sin(qr+\delta) = \mathcal{S}^{-1}\left[\frac{\sin qr}{qr} + f(q)\frac{e^{iqr}}{r}\right]$$

$$\Delta C_{\mathrm{LL}}(q) = \frac{|f(q)|^2}{2R^2} F_3\left(\frac{r_{\mathrm{eff}}}{R}\right) + \frac{2\mathrm{Re} f(q)}{\sqrt{\pi}R} F_1(x) - \frac{\mathrm{Im} f(q)}{R} F_2(x)$$

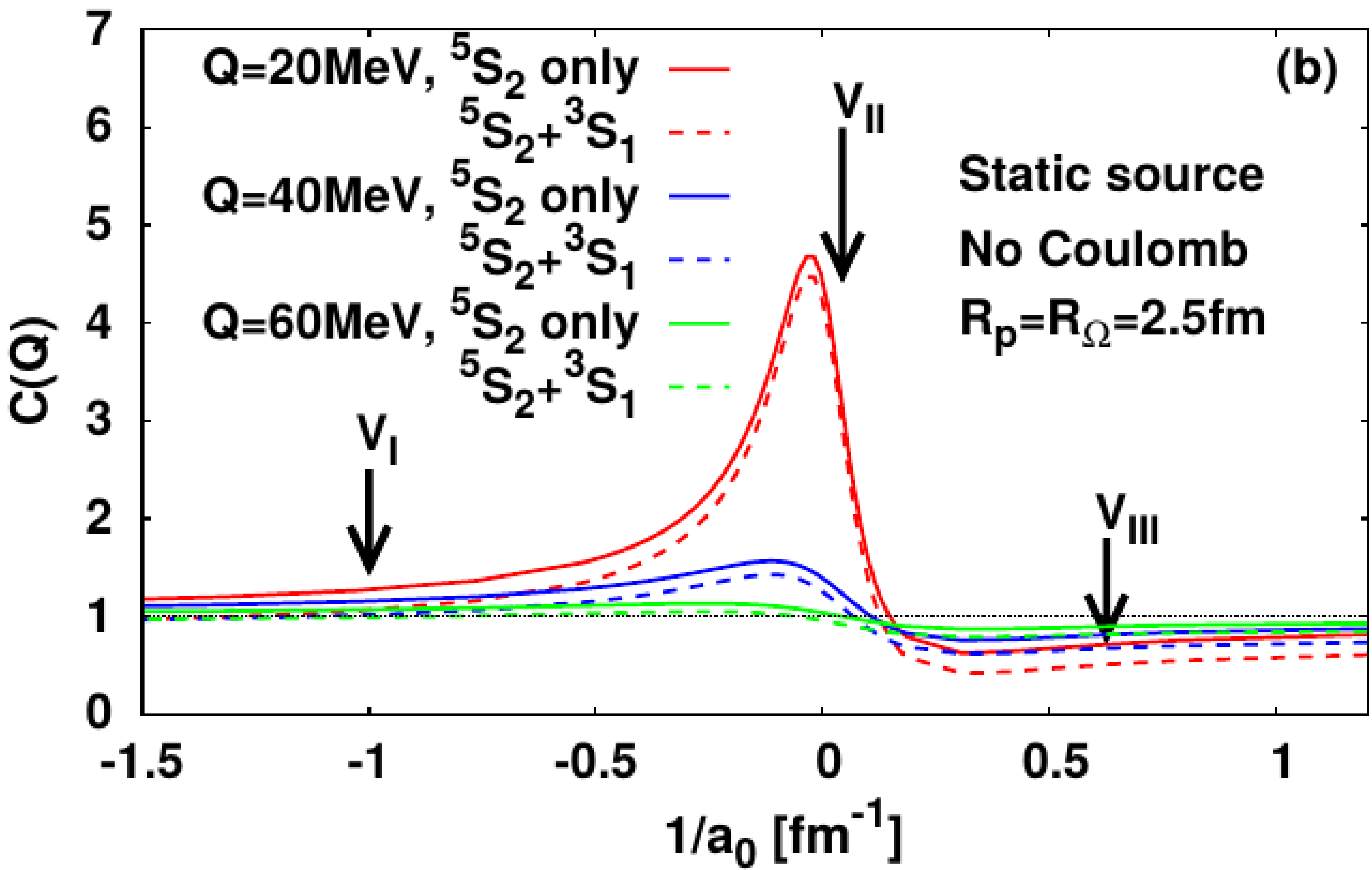
$$(x = 2qR,\, R = \text{Gaussian size},\, F_1, F_2, F_3 : \text{Known function})$$

Interaction Dependence of Correlation Function



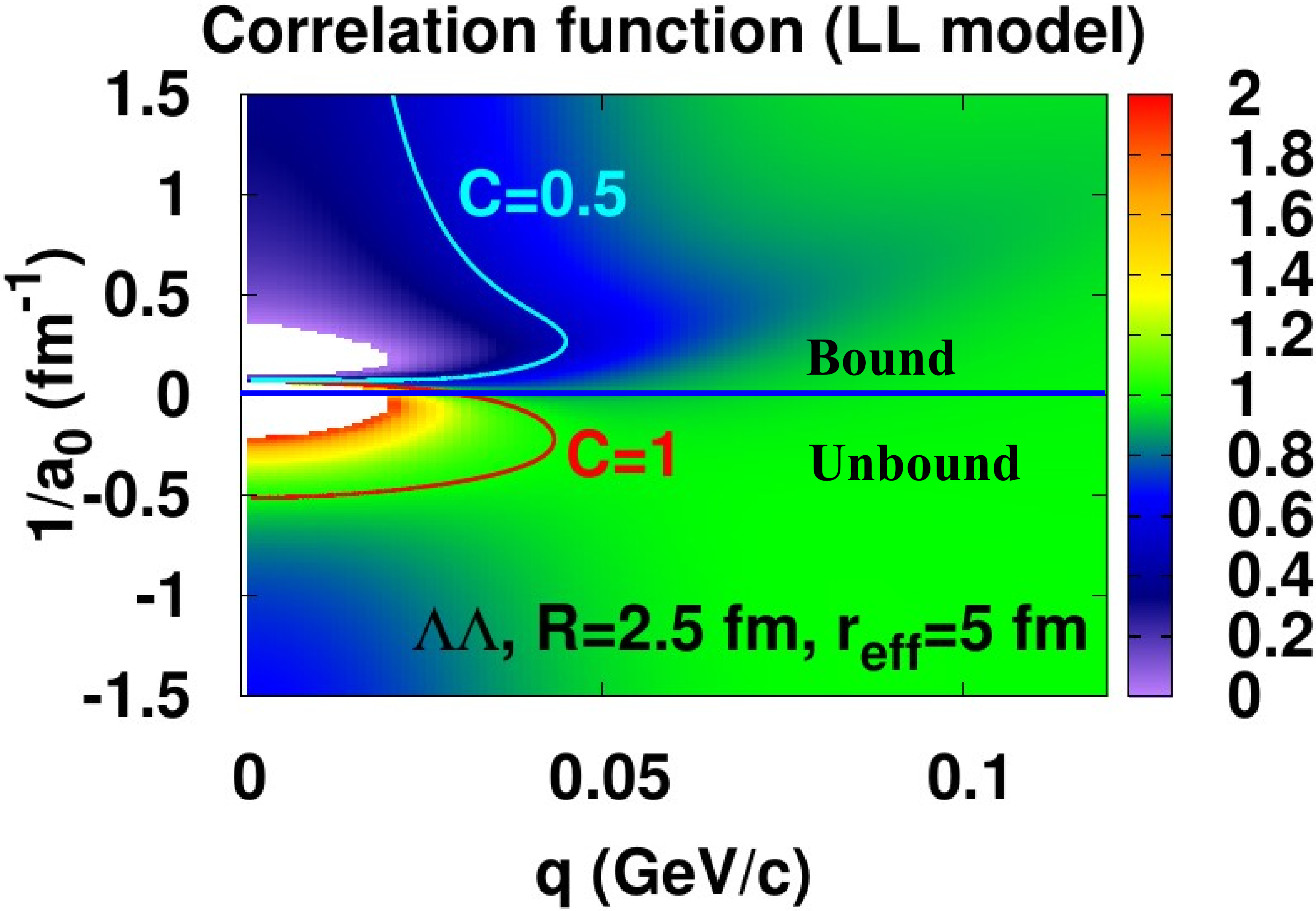


Interaction Dependence of Correlation Function



K. Morita, AO, F. Etminan, T. Hatsuda, arXiv:1605.06765 [hep-ph]

Interaction Dependence of Correlation Function



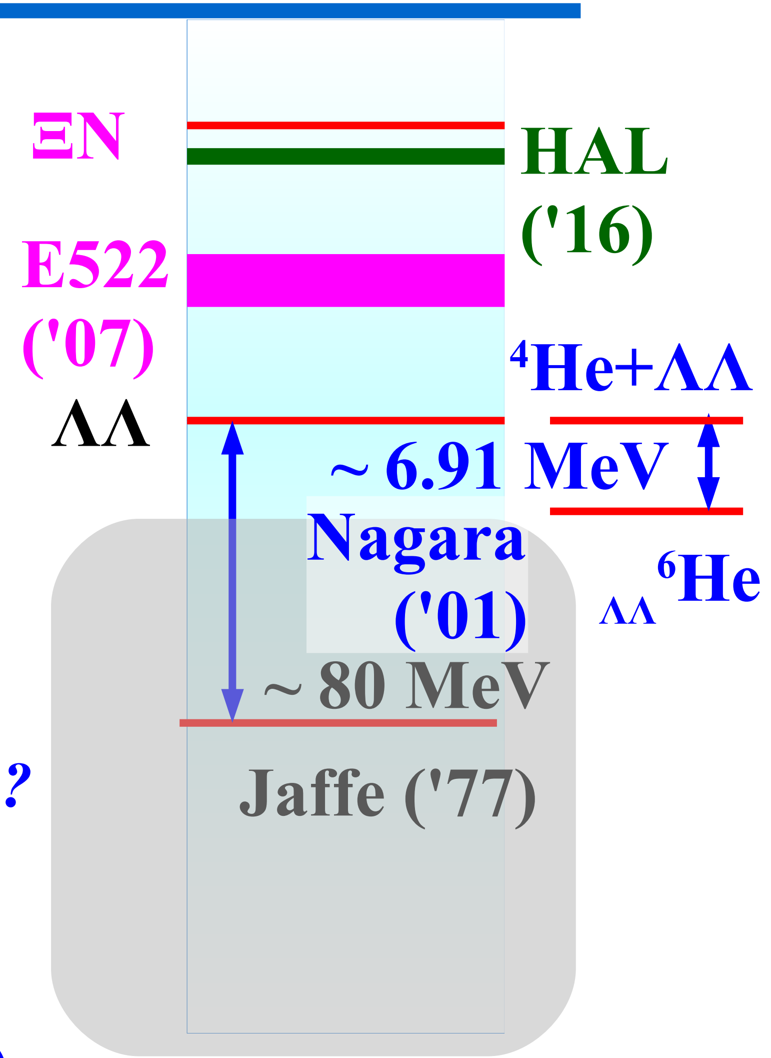
$$q \cot \delta = -1/a_0 + r_{eff}\, q^2/2 + O(q^4)$$

AO, K. Morita, K. Miyahara, T. Hyodo, NPA954 ('16), 294.

ΛΛ correlation and ΛΛ interaction

Relevance of ΛΛ interaction to physics

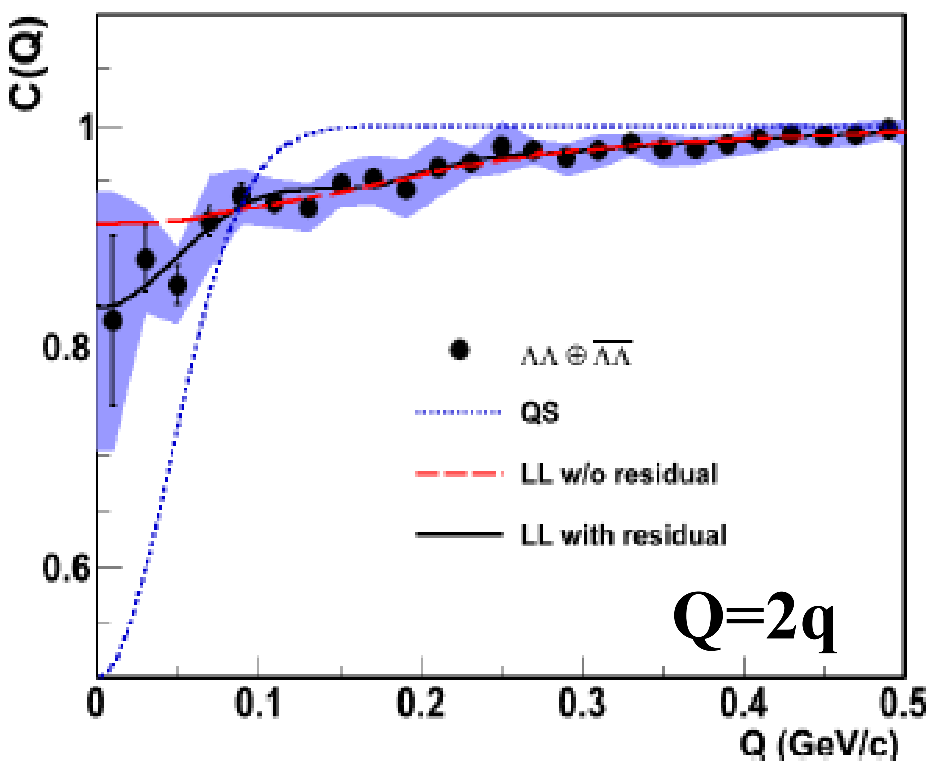
- **H-particle: 6-quark state (uuddss)**
  - **Prediction:** *R.L.Jaffe, PRL38(1977)195*
  - **Ruled-out by double Λ hypernucleus**
    Takahashi et al.,PRL87('01) 212502
  - **Resonance or Bound "H" ?**
    Yoon et al.(KEK-E522) ('07)
  - **Lattice QCD**
    HAL QCD & NPLQCD ('11)
    HAL QCD ('16): H as a loosely bound ΞN ?

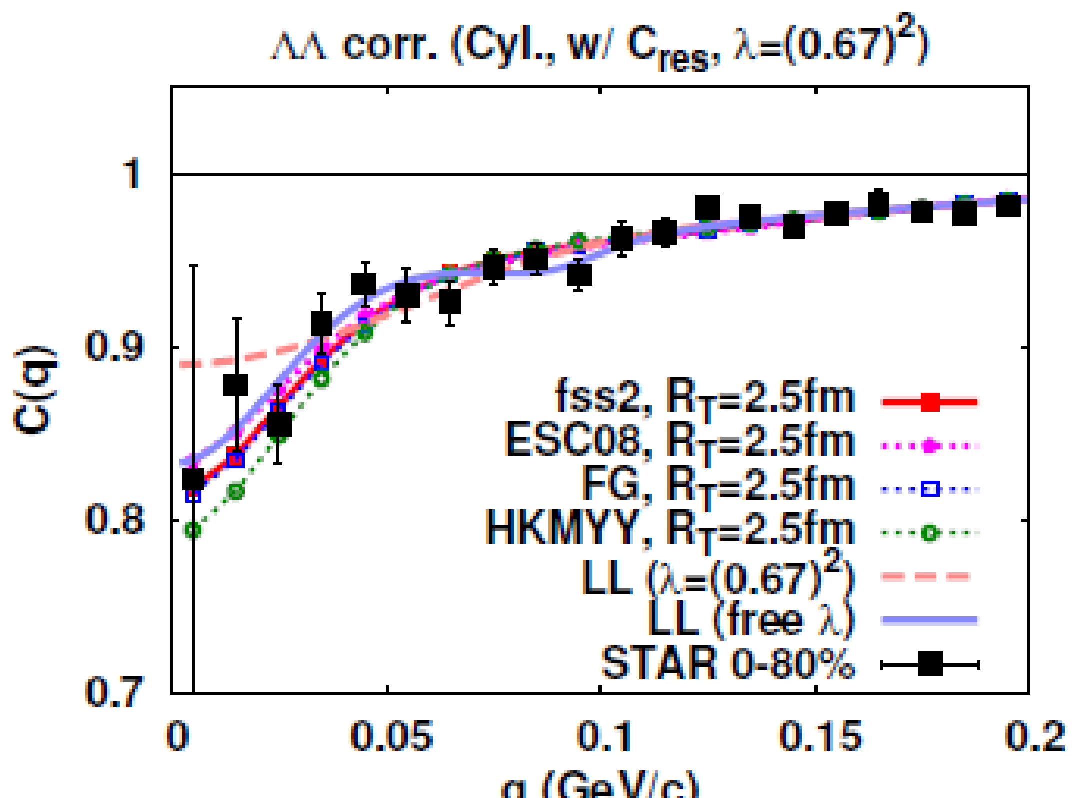


- **Neutron Star Matter EOS**
  - **Hyperon Puzzle**
    Demorest et al. ('10), Antoniadis et al. ('13)
  - **Cooling Puzzle (ΛΛ superfluidity)**
    T. Takatsuka, R. Tamagaki, PTP 112('04)37
- **QGP signal, BB interaction model, ….**

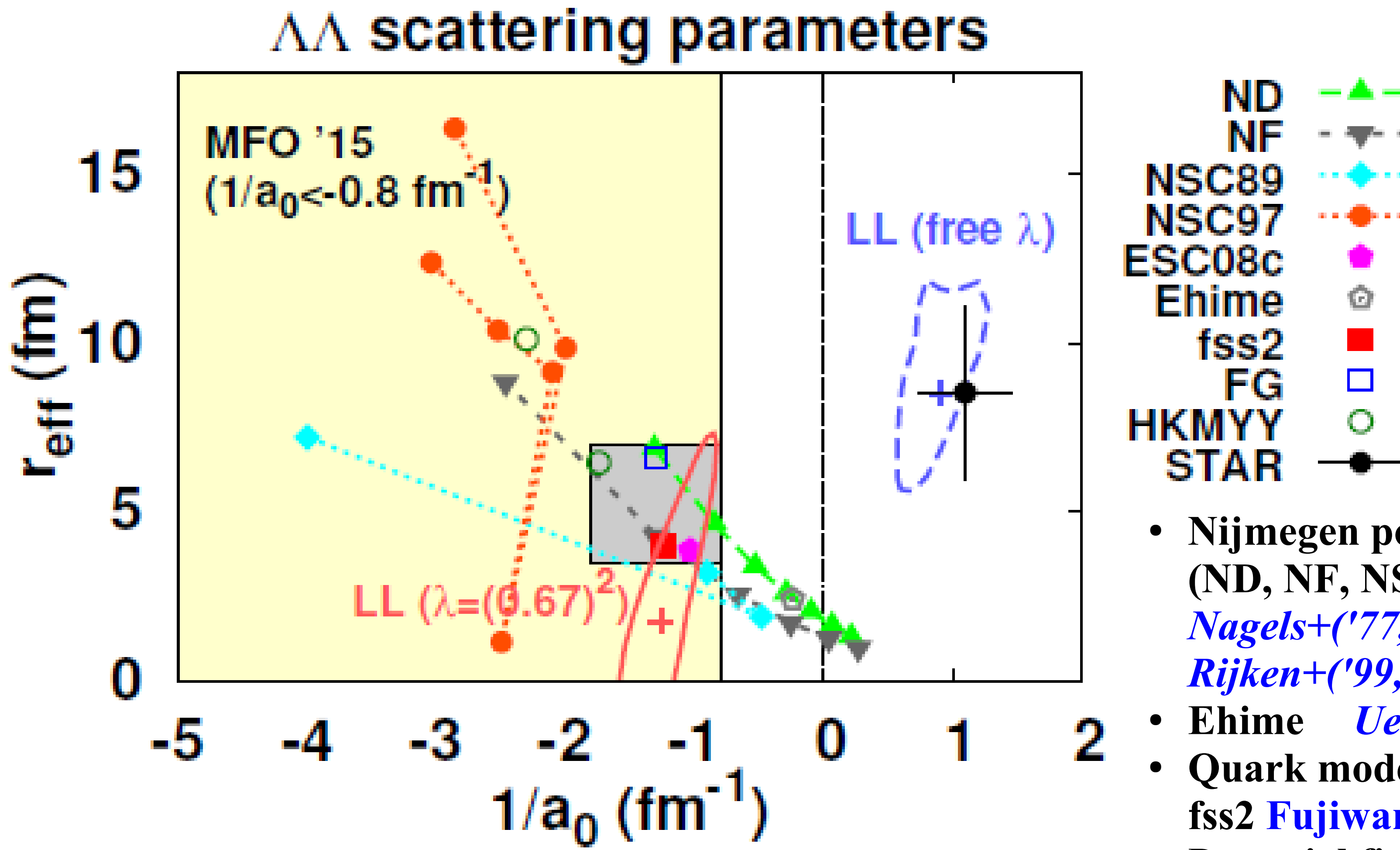
ΛΛ correlation at RHIC

- **STAR collaboration at RHIC measured ΛΛ correlation !**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  - **RHIC, Au+Au ($\sqrt{s_{NN}}$=200 GeV), Weak decay vertex analysis.**
- **Theoretical Analysis well explains the data**
  K.Morita et al., T.Furumoto, AO, PRC91('15)024916; AO, K.Morita, K.Miyahara, T.Hyodo, NPA954 ('16), 294.





$\Lambda\Lambda$ interaction from $\Lambda\Lambda$ correlation



- 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)
- Potential fitted to Nagara *Filikhin, Gal ('02) (FG), Hiyama et al. ('02, '10)(HKMYY)*

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

Positive a_0 (STAR) $\longleftrightarrow$ Negative a_0 (MFO'15)

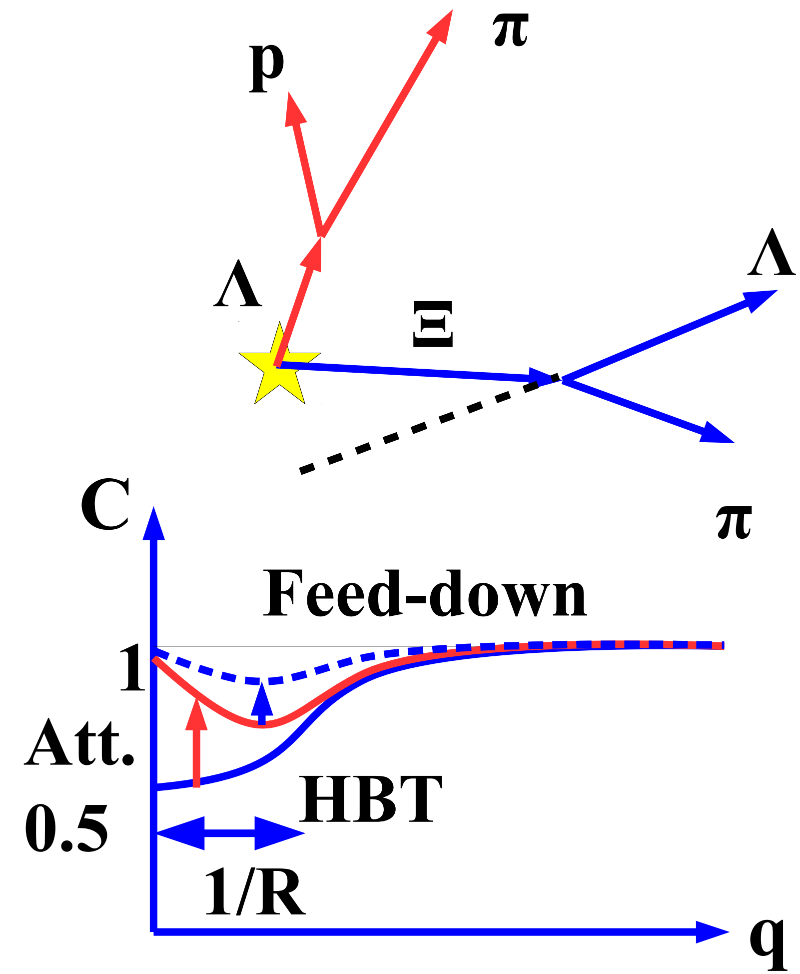
Feed-Down Effects & Residual Source

- **Correlation Fn. w/ Feed-down & Residual source effects.**

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

- **Purity of ΛΛ pair λ**
  - **Not easy to reject Σ^0 decay in exp't.**
    → λ ~ $(1-\Sigma^0/\Lambda)^2$
  - **Morita, Furumoto, AO ('15)**
    → λ=$(0.67)^2$ =0.45
    Σ^0/Λ=0.278 (p+Be, 28.5 GeV/c)
    Sullivan et al. ('87)
    Ξ/Λ = 15 % (RHIC)
  - **STAR ('15)**
    → λ = Free parameter ~ 0.18

C(q~0)~ 0.8 suggests
attraction with large λ (λ> 0.35)
repulsion with small λ (λ < 0.35)

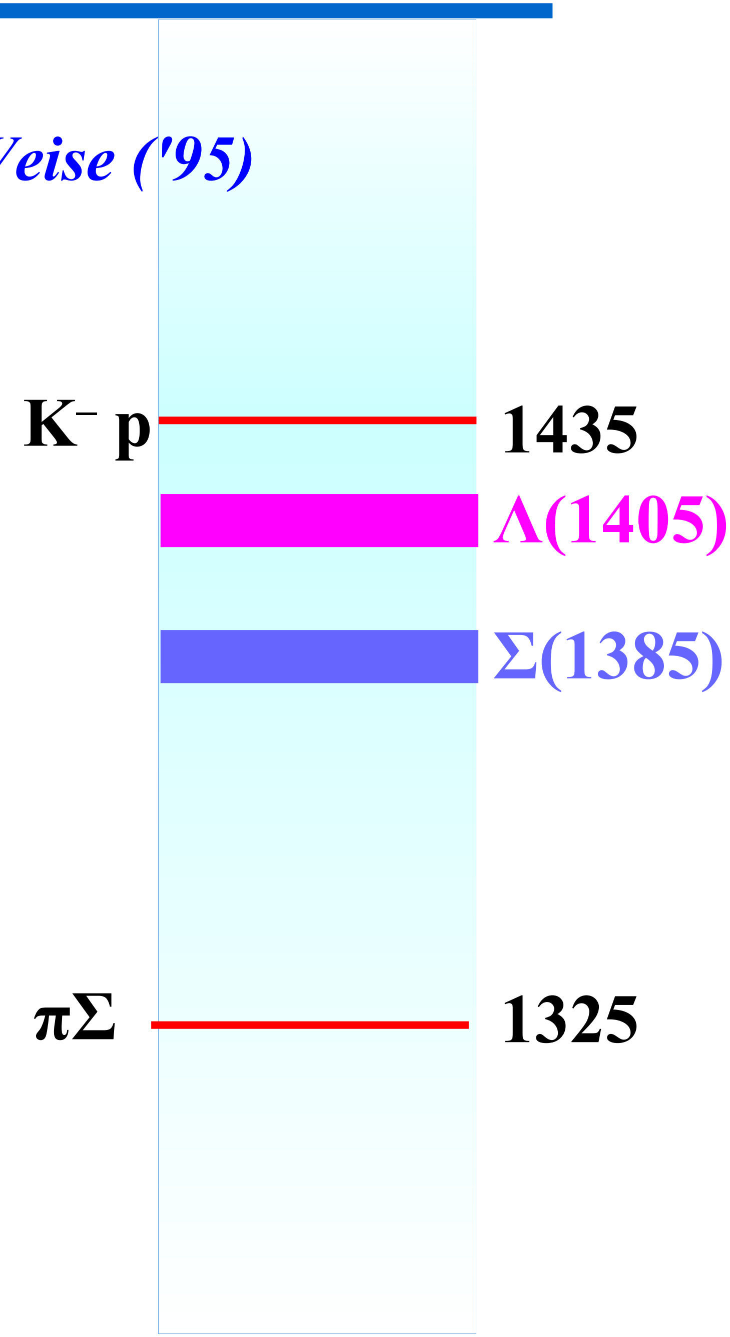


AO, Morita, Mihayara, Hyodo ('16)

$K^{-}p$ correlation

K^- p interaction

- **$\Lambda(1405)$ $\bar{K}N$ quasi-bound state**
  Dalitz, Tuan ('60), Koch ('94), Kaiser, Siegel, Weise ('95)
  - **Positive scattering length in K^- atoms**
    M.Iwasaki et al. PRL78('97)3067;
    M.Bazzi et al. [SIDDHARTA Collab.],
    PLB704('11)113.
- **Kaonic nuclei ?**
  Nogami ('63); Akaishi, Yamazaki ('02)
  → Needs precise info. on $\bar{K}N$ int.
  - **Scattering amplitude and Potential fitting scattering and SIDDARTA data in chiral approach**
    Ikeda, Hyodo, Weise ('11,'12),
    Miyahara, Hyodo ('16)
- **How about K^- p correlation ?**



K^- p scattering and K^- p correlation

- **K^- p scattering: Plane wave + Outgoing spherical wave**

$$\Psi^{(+)}(K^- p) \to \exp(i kz)\chi(K^- p) + \frac{\exp(ikr)}{r}\left[f(K^- p \to K^- p)\chi(K^- p) + f(K^- p \to \bar{K}^0 n)\chi(\bar{K}^0 n)\right]$$

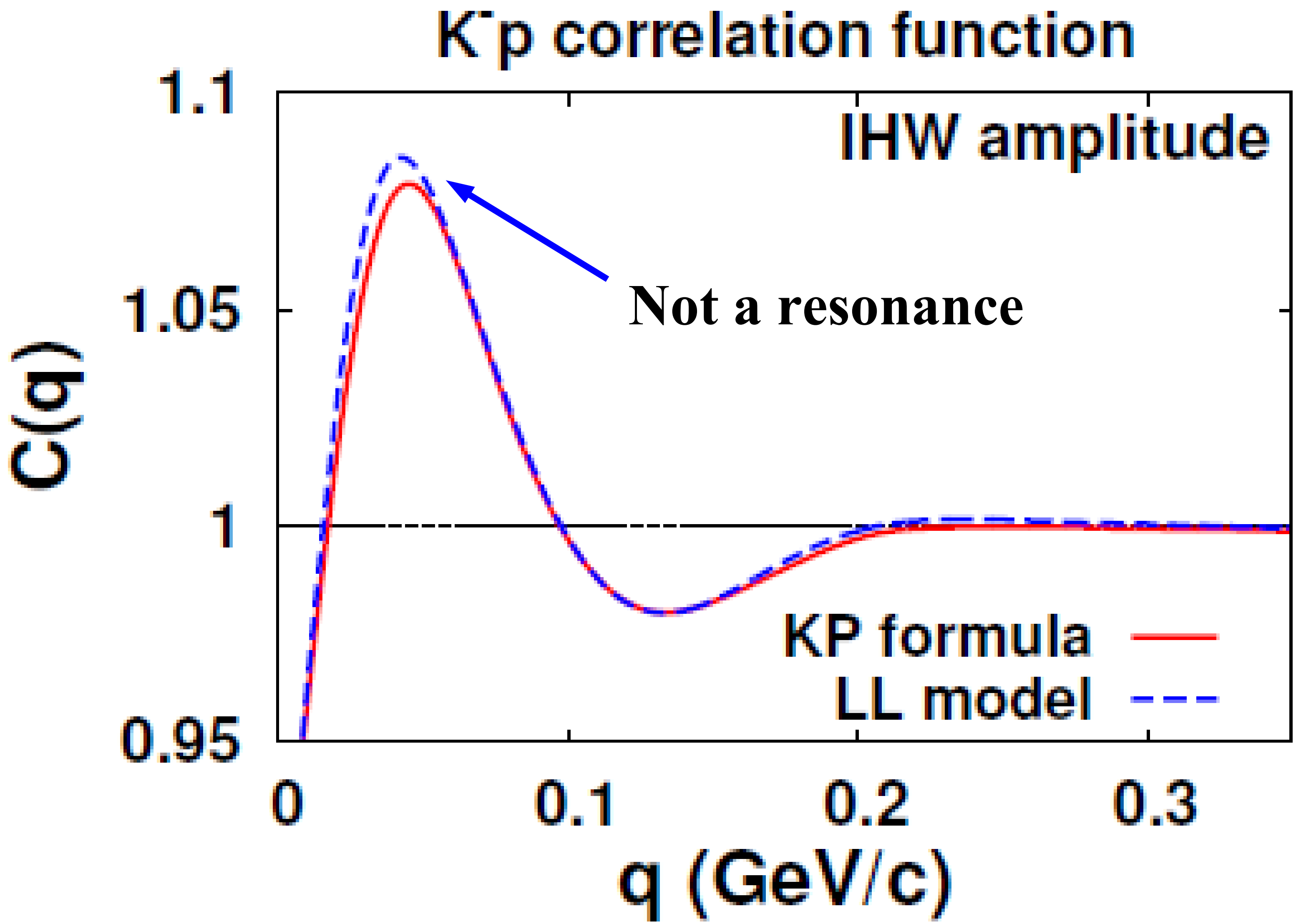
- **K^- p correlation: Plane wave + Incoming spherical wave**

$$\Psi^{(-)}(K^- p) \to \exp(i kz)\chi(K^- p) + \frac{\exp(-ikr)}{r}\left[\tilde{f}(K^- p \to K^- p)\chi(K^- p) + \tilde{f}(K^- p \to \bar{K}^0 n)\chi(\bar{K}^0 n)\right]$$

$$\tilde{f}(K^- p \to K^- p) = \frac{\tilde{S}-1}{2iq} \neq f(K^- p \to K^- p) \quad , \quad \tilde{S} = \left[\frac{S_{I=0}^{-1} + S_{I=1}^{-1}}{2}\right]^{-1}$$

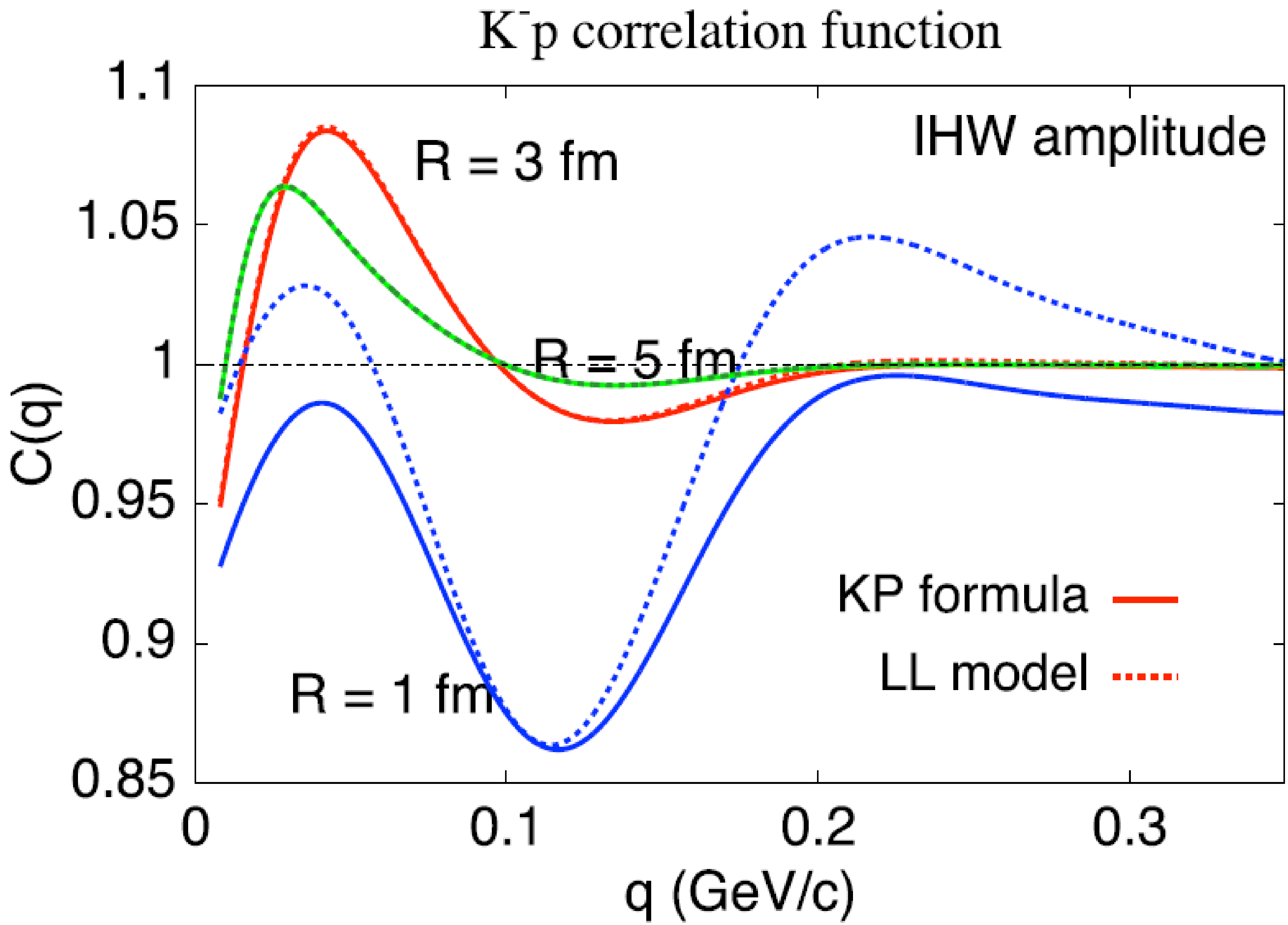
K^- p correlation probes different combination of I=0, 1 from K^- p scattering

$K^{-}p$ correlation



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

$K^{-}p$ correlation

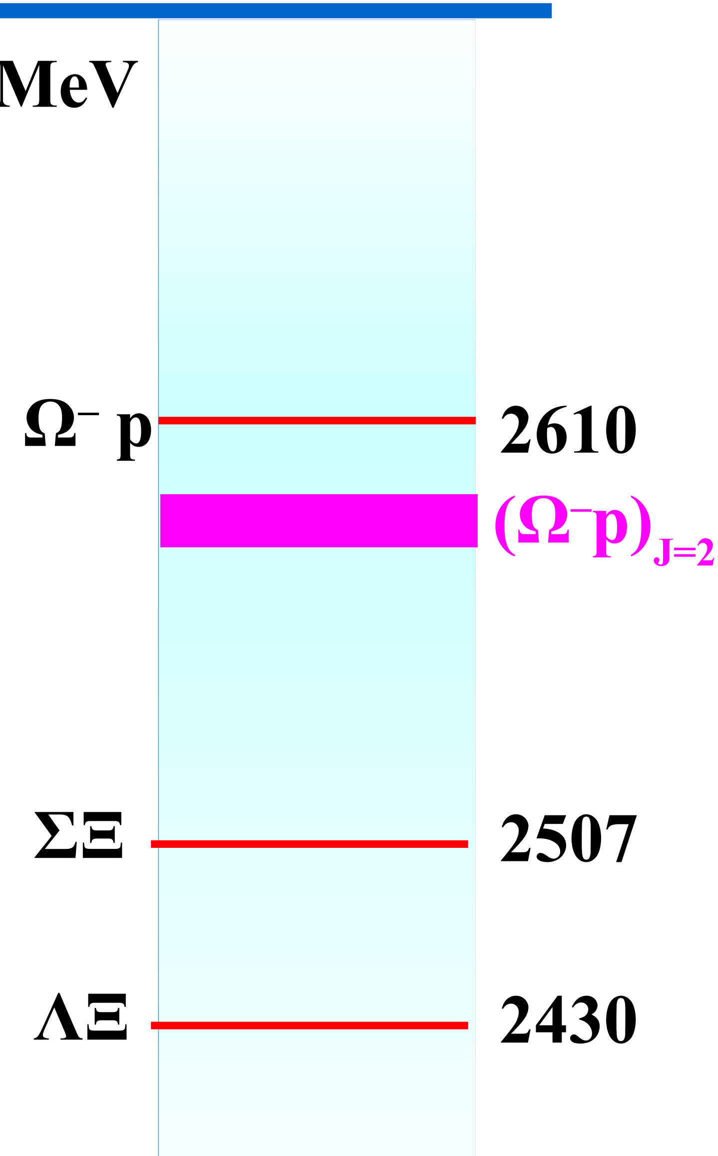


K. Miyahara

$\Omega^{-}p$ correlation

Ω^- p interaction

- Ω^- : quark content=sss, Jπ=3/2+, M=1672 MeV
- Ω^- p bound state as a S= –3 dibaryon ?
  F.Etminan et al. (HAL QCD Collab.), NPA928('14)89.
  - No quark Pauli blocking in ΩN and H=uuddss channels.
    Oka ('88), Gal ('16)
  - J=2 state ($^5S_2$) couples to Octet-Octet baryon pair only with L ≥ 2
    → Small width is expected.
    Etminan et al. (HAL QCD)('14)
  - Correlation is measurable at RHIC !
    Neha Shah (STAR), private commun.

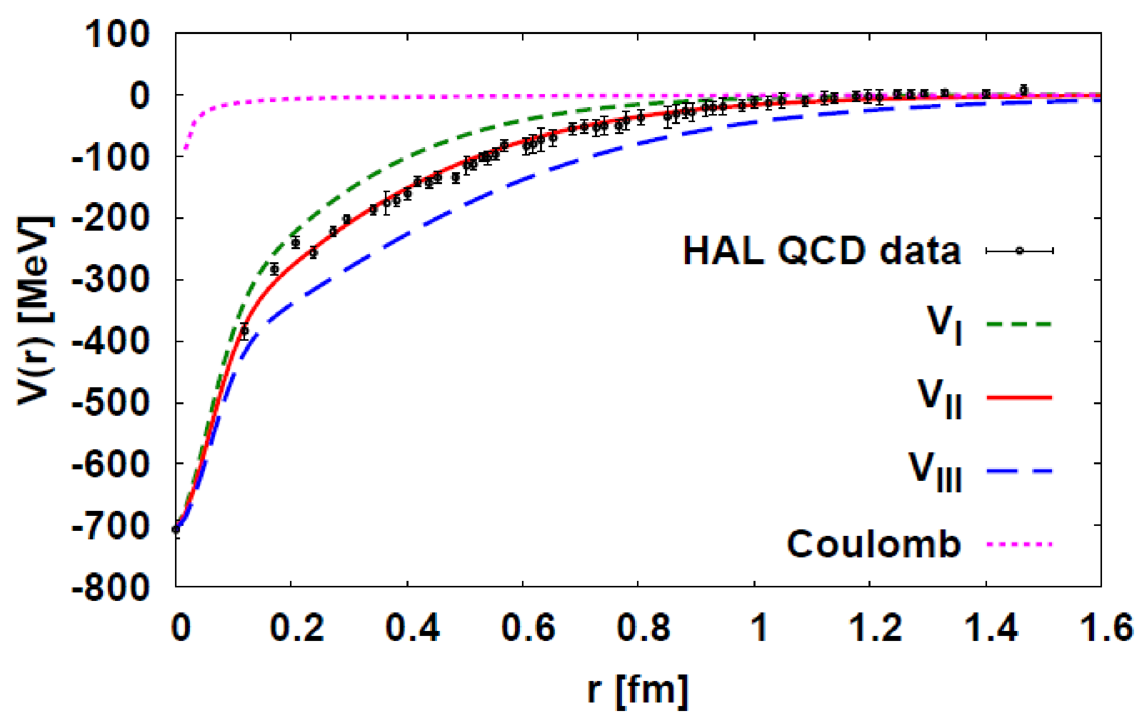


Let us try to discover the first(?) dibaryon (after deuteron) !
(First dibaryon with S<0 !)

Ω⁻ p potential from lattice QCD

- **Lattice QCD predicts Ω⁻ p bound state at large quark mass, mπ=875 MeV (B.E.~ 19 MeV)**
  F.Etminan et al. (HAL QCD Collab.), NPA928('14)89.
- **Extrapolation to physical quark mass**
  - **VI → Weaker potential (no b.s.)**
  - **VII → Same potential (shallow b.s.)**
  - **VIII → Stronger potential (deep b.s.)**

Spin-2 $N\Omega$ Potentials		$V_{\rm I}$	$V_{\rm II}$	$V_{\rm III}$
	$E_{\rm B}$ [MeV]	–	0.05	24.8
without Coulomb	a_0 [fm]	−1.0	23.1	1.60
	$r_{\rm eff}$ [fm]	1.15	0.95	0.65
	$E_{\rm B}$ [MeV]	–	6.3	26.9
with Coulomb	a_0 [fm]	−1.12	5.79	1.29
	$r_{\rm eff}$ [fm]	1.16	0.96	0.65

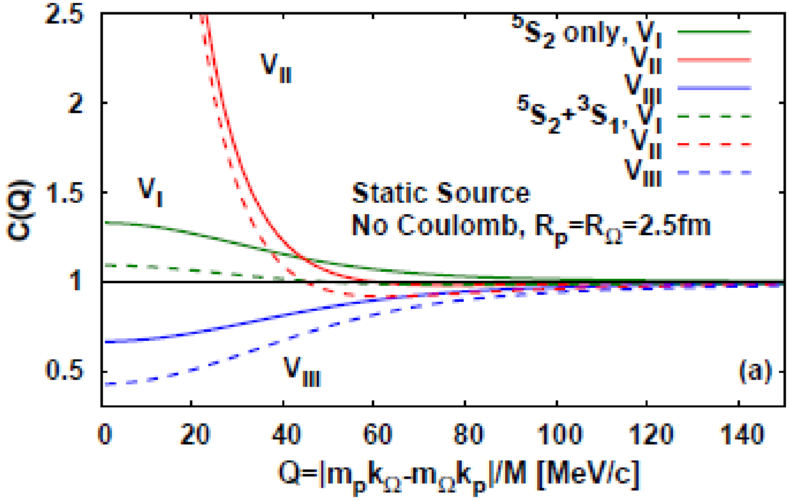


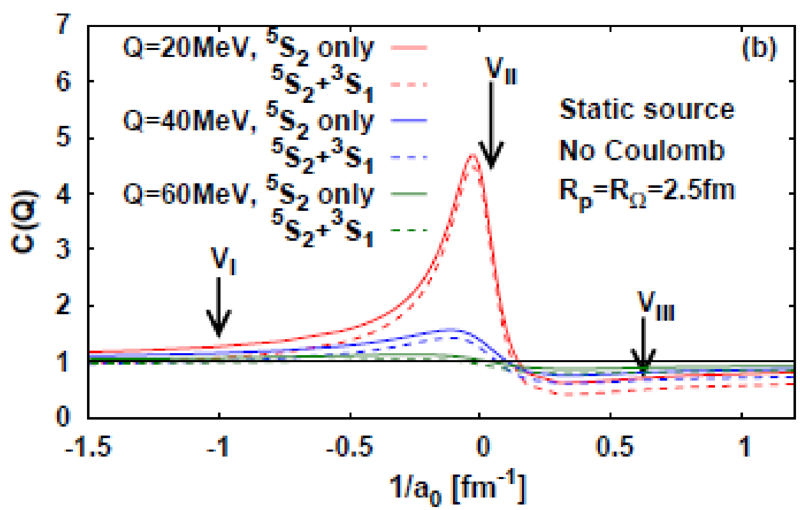
$^3S_1$ contribution

- $\Omega(J=3/2)$ and p $(J=1/2)$ can take spin quintet ($^5S_2$) and triplet ($^3S_1$) states for L=0.
  - $^5S_2$ (J=2) couples with octet-octet (e.g. $\Lambda\Xi$) via L=2.
  - $^3S_1$ (J=1) couples with octet-octet (e.g. $\Lambda\Xi$) via L=0.
    → strong absorption is expected at short distances.
- Our assumption: Strong absorption at r < 2 fm.
  - Strong absorption limit = Hard core boundary condition.
  - Intermediate absorption gives similar results.

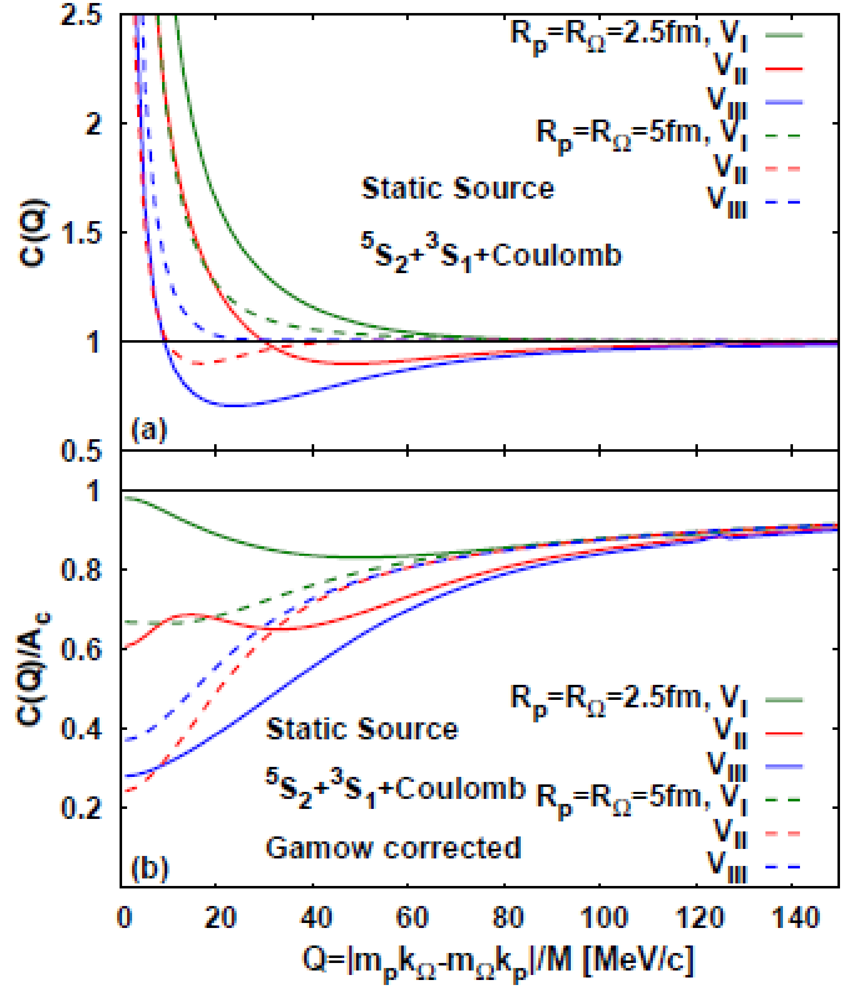
Ω^- p correlation

w/o Coulomb



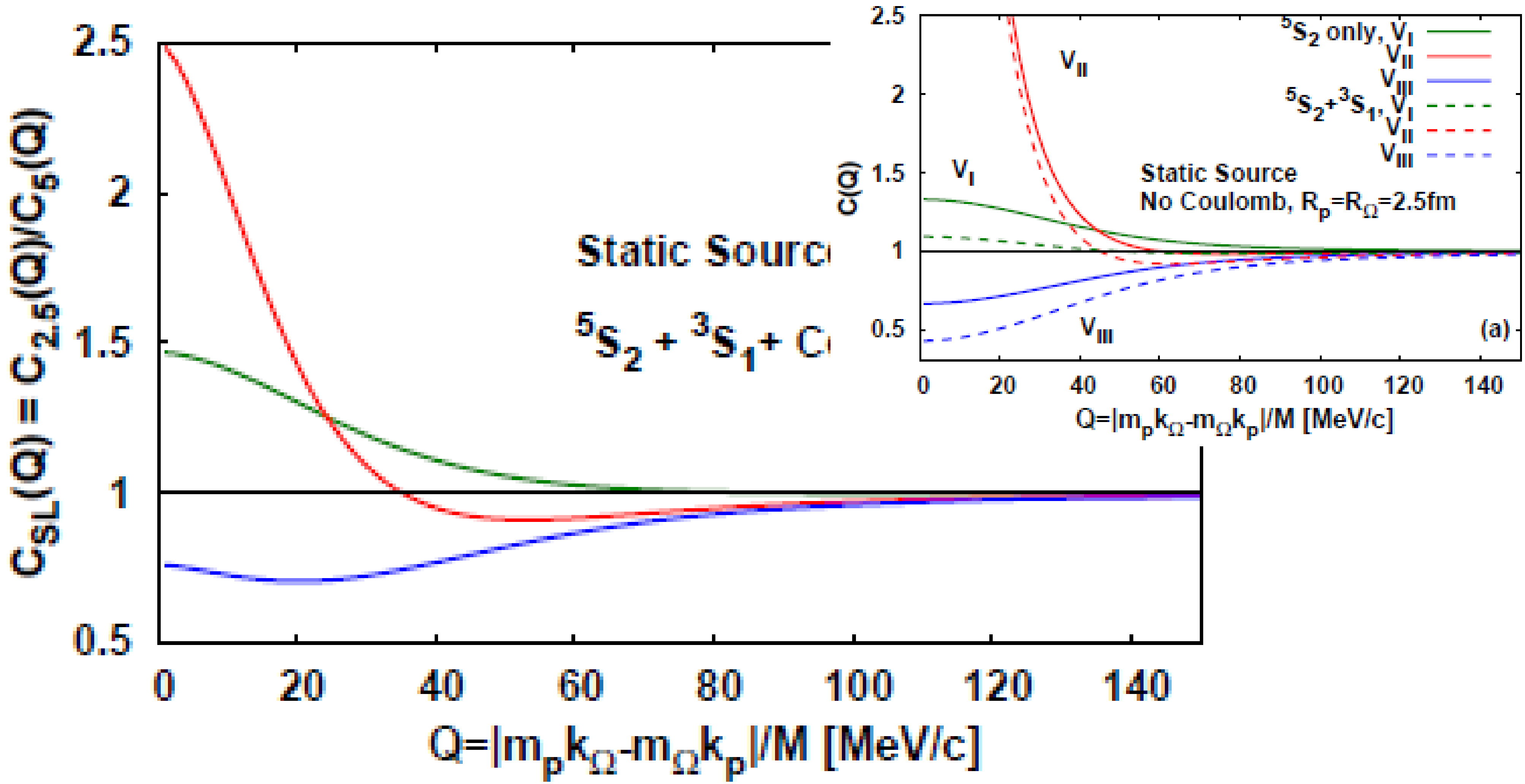


w/ Coulomb



Coulomb potential washes out the features of VI, VII, VIII, and Gamow correction is not enough.

Ω^- p correlation: Small / Large Ratio



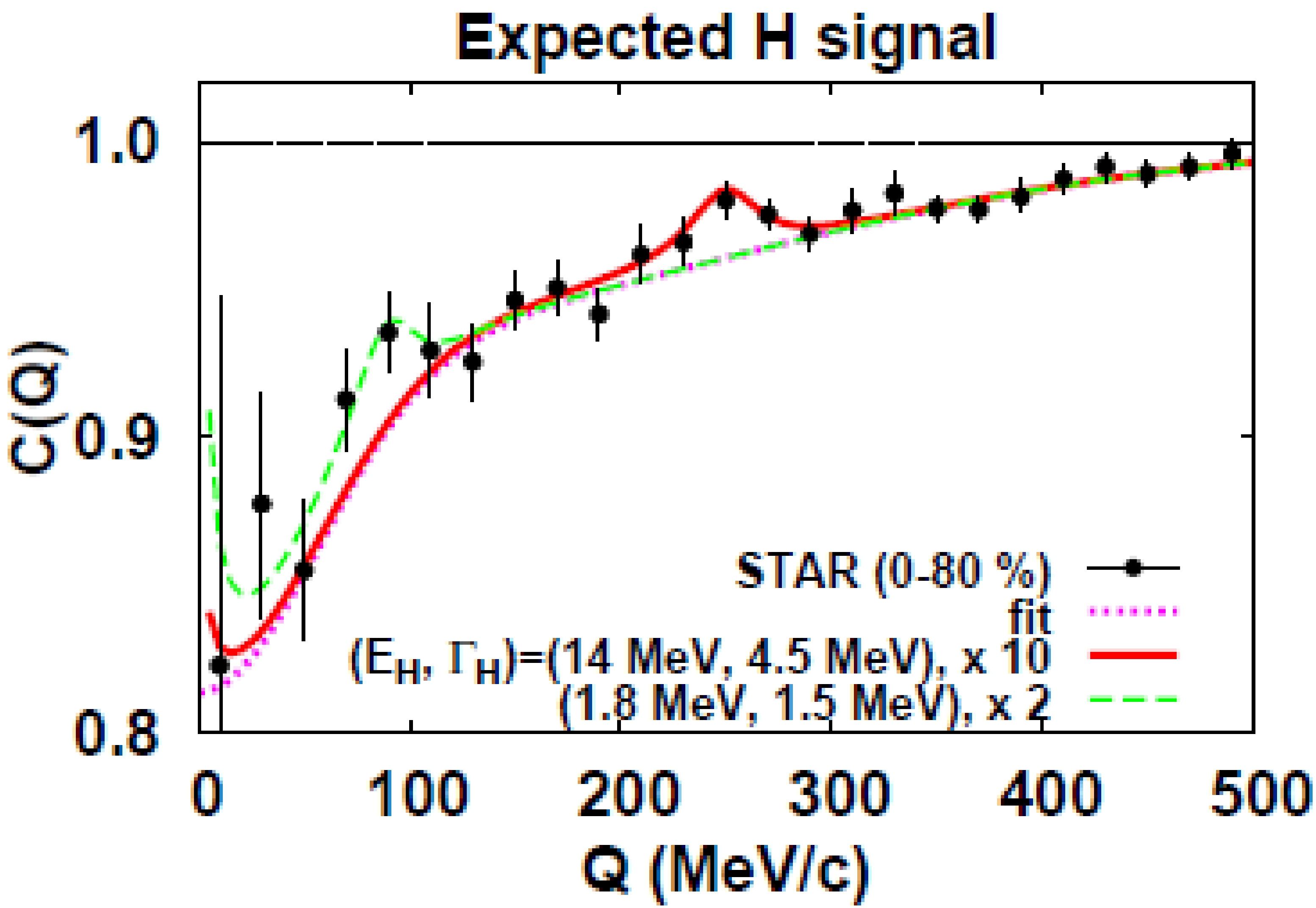
By taking small (R=2.5 fm) / large (R=5 fm) ratio, we approximately see the corr. fn. w/o Coulomb !

Summary

- **Heavy-ion collisions are hadron factories, and can be utilized to proceed hadron physics as well.**
- **Hadron-Hadron correlation contains information on interactions.**
  - **Correlations in various pairs have been measured:** **$\pi\pi$, KK, pp, nn, $\bar{p}\,\bar{p}$, $\Lambda\Lambda$, Λp, (K^- p, Ω^- p,) …**
  - **When the pair purity is large enough, corr. fn. has sensitivity to hh interaction.**
- **Some of hh correlations have been discussed.**
  - **$\Lambda\Lambda$ correlation data is consistent with Λ Λ interaction with $1/a_0 < -0.8\ \mathrm{fm}^{-1}$, provided that pair purity is large enough, $\lambda > 0.35$.**
  - **K^- p correlation is found to probe other combination of scattering amplitudes of I=0 and I=1.**
  - **Ω^- p correlation may tell us the existence of a S=-3 dibaryon.**
- **Many (?) other type of pairs are waiting for us.**

Thank you !

Detecting H Resonance



When the resonance energy is much above the threshold, detecting a resonance is not easy because of huge background.