Λ-Λ Correlation in Relativistic Heavy Ion Collisions

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Ref.) Phys. Rev. C91, 024916 (2015)

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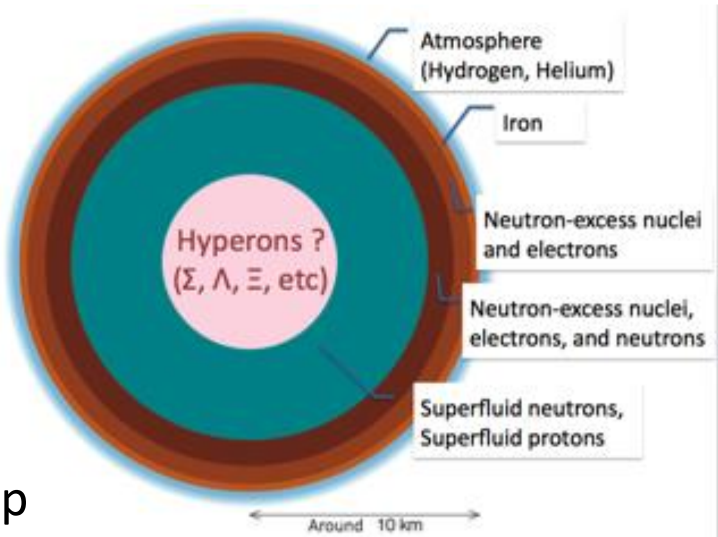
Role of ΛΛ Interaction

Possible Emergence of Hyperons in NS core



from KEK.jp

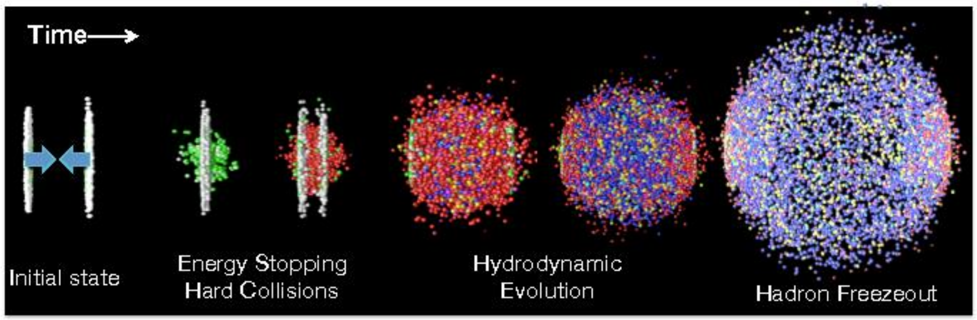
To understand EoS,

Information on **Hyperon-Hyperon** Interaction is indispensable

H-dibaryon (uuddss)?

- Λ-Λ bound state due to strong attraction?
- Resonance?

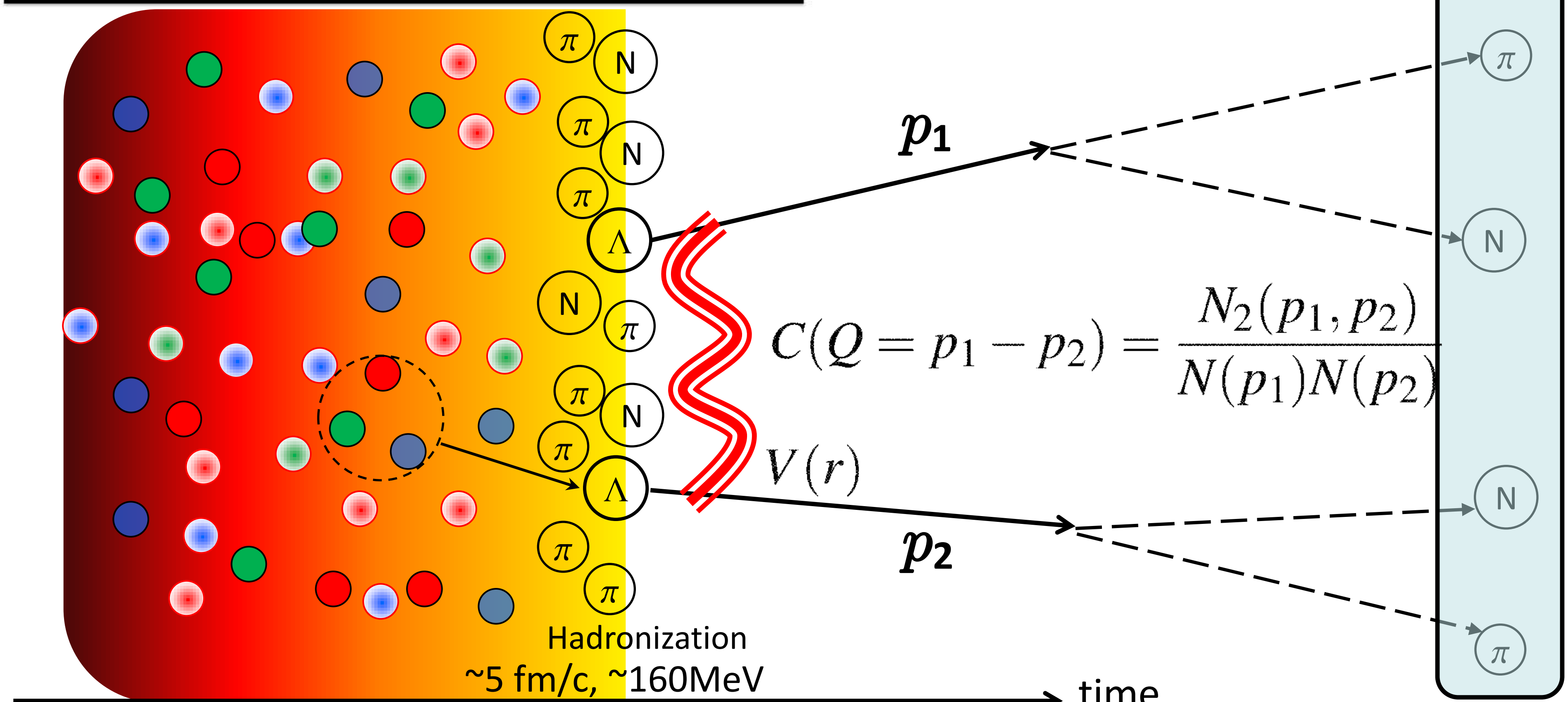
RHIC Can Tell Us about ΛΛ interaction



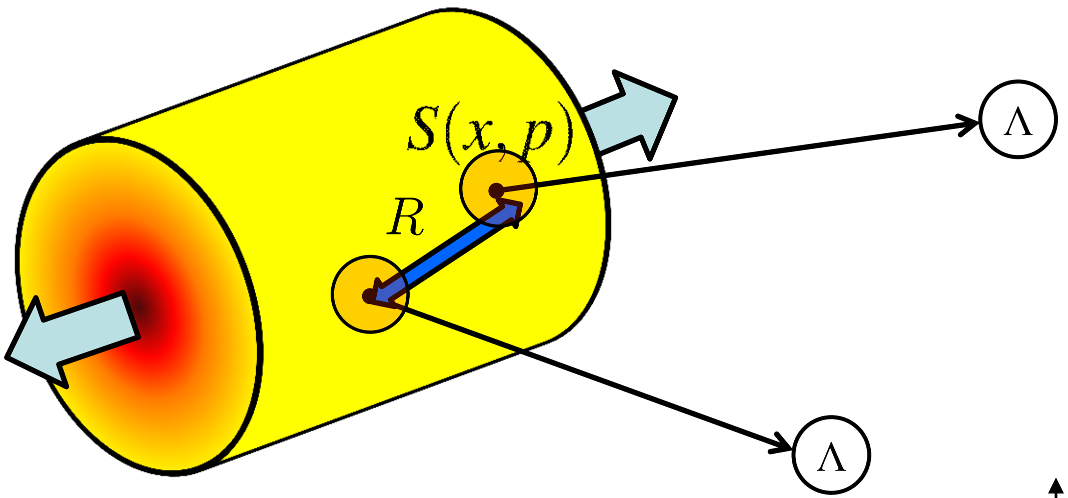
Au+Au 200AGeV

$$\frac{dN_\Lambda}{dy} \simeq 0.6 - 13 \quad \times 10^8 \text{ events}$$

(60-80%) (0-5%)



ΛΛ Correlation in HIC



Independent (Chaotic) emission
(←Thermal Source)

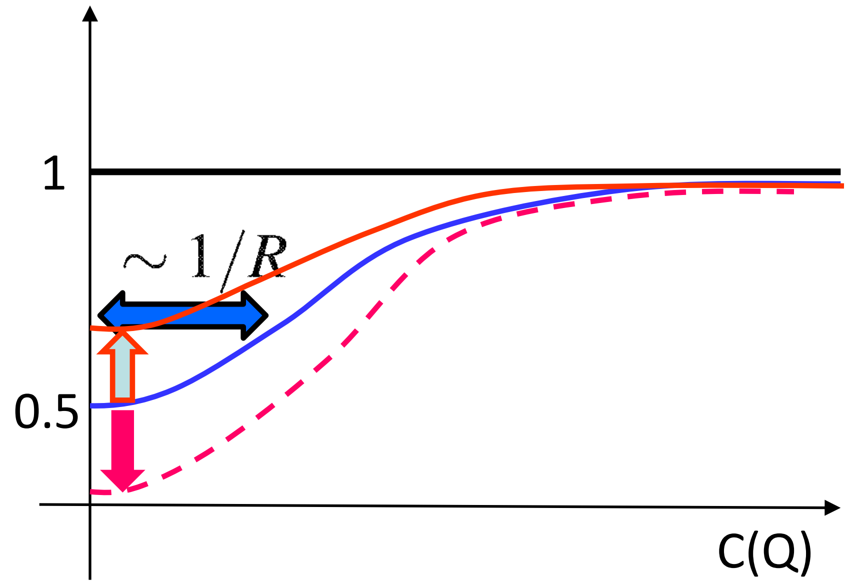
Identical particle correlation from quantum statistics (HBT effect)

C(Q) : effective source size

ΛΛ Interaction : No Coulomb!

Affects C(Q) when effective range r_{eff} is comparable with R

Different results for repulsive and attractive interaction



Approach : Thermal Source + $V_{\Lambda\Lambda}$

Formula (Gong et al., '91)

$$C_2(Q,K) = \frac{\int d^4x_1 d^4x_2 S(x_1,K) S(x_2,K) |\Psi_{12}(Q, x_1 - x_2 - (t_2 - t_1)K/m)|^2}{\int d^4x_1 d^4x_2 S(x_1,k_1) S(x_1,k_2)}$$

Emission source function

= direct emission + decay daughters

= (direct + short-lived resonances)

+ Long-lived resonances

EM + Weak

Thermal source model
(Mimic hydro)

ΛΛ relative wave function

Modification of S-wave by interaction

Various potentials
(via 2 or 3 range Gaussian Fit)

Meson exchange models (Nijmegen model D, F, Soft Core89/97, ESC08)

Phenomenological (Ehime)
Quark model (fss2)

Fit to $_{\Lambda\Lambda}{}^{6}$He(Nagara) Filikhin-Gal (FG)
Hiyama et al. (HKMYY)

ΛΛ Wave Function

$$|\Psi|^2 = \frac{1}{4}|\Psi_s|^2 + \frac{3}{4}|\Psi_t|^2$$

→ Spin: symmetric
Spatially anti-symmetric
No S-wave

$$\Psi_t = \frac{1}{\sqrt{2}} e^{2iK\cdot X}\left(e^{iQ\cdot r} - e^{-iQ\cdot r}\right)$$

↓ Spin: anti-symmetric
Spatially symmetric
Modification in S-wave

$$\Psi_s = \sqrt{2} e^{iK\cdot X}\left[\cos(Q\cdot r/2) + \chi_Q(r) - j_0(Qr/2)\right]$$

⇧

$$\left[-\frac{1}{m_\Lambda}\frac{d^2}{dr^2} + V(r)\right][r\chi_Q(r)] = \frac{Q^2}{4m_\Lambda}[r\chi_Q(r)]$$

Schrödinger Eq.

Potential, Wave func., / Correlation

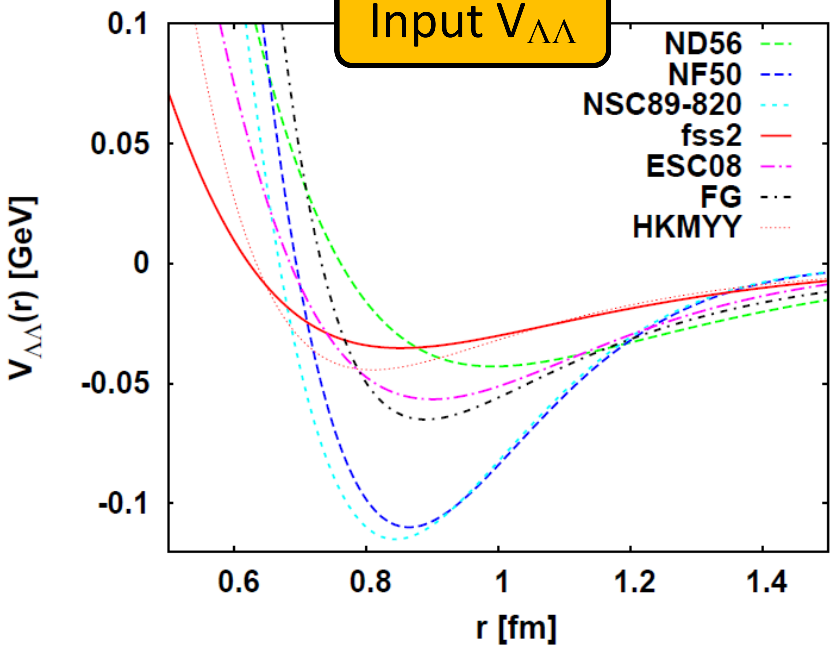
Correlation Function for the Static Source

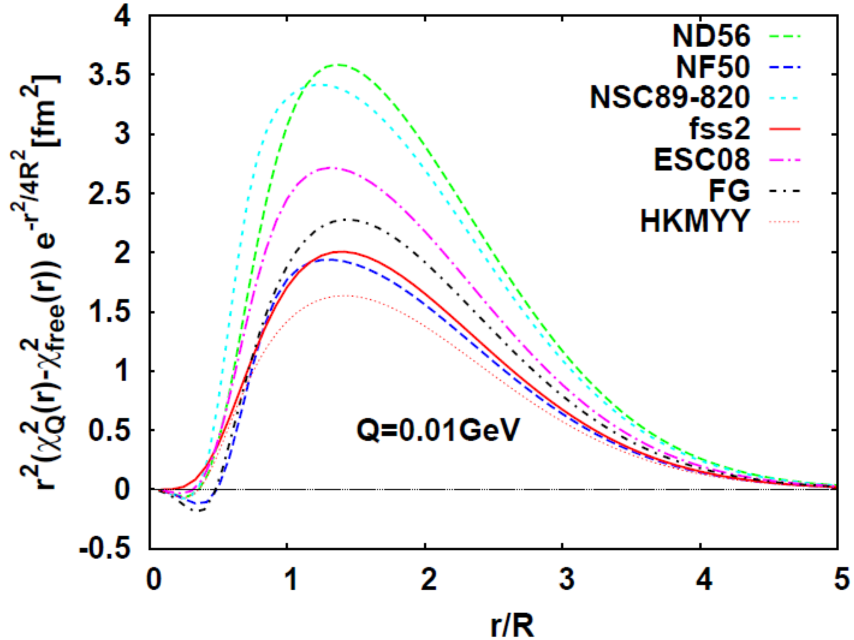
$$C_{\rm stat}(Q) = 1 - \frac{1}{2}e^{-Q^2R^2} + \frac{1}{4\sqrt{\pi}R^3}\int_0^\infty dr\, r^2 e^{-\frac{r^2}{4R^2}} \left[[\chi_Q(r)]^2 - [j_0(Qr/2)]^2\right]$$

HBT (size R)

Interaction : deviation from free w.f.

Input $V_{\Lambda\Lambda}$





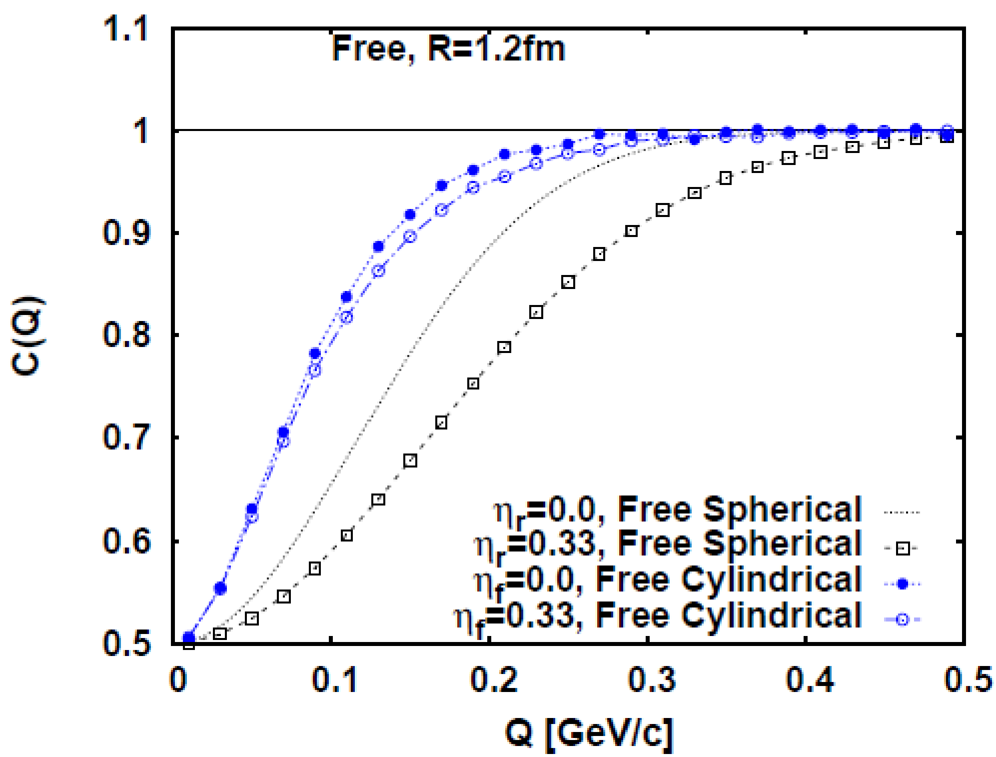
Expanding Source Model

S.Chapman et al., '95

$$S(x,k) \propto m_T \cosh(y - Y_L) n_F(u \cdot k/T) \exp\left[-\frac{(\tau-\tau_0)}{2(\Delta\tau)^2} - \frac{x^2+y^2}{2R^2}\right]$$

$$\sim \exp\left[-\frac{\gamma_T M_T}{T}\cosh(y-Y_L)\right] \exp\left[\frac{\gamma v_T k_T \cos\phi}{T}\right]$$

Give a finite longitudinal extent $R_L \sim \tau_0 \sqrt{\frac{T}{M_T}}$

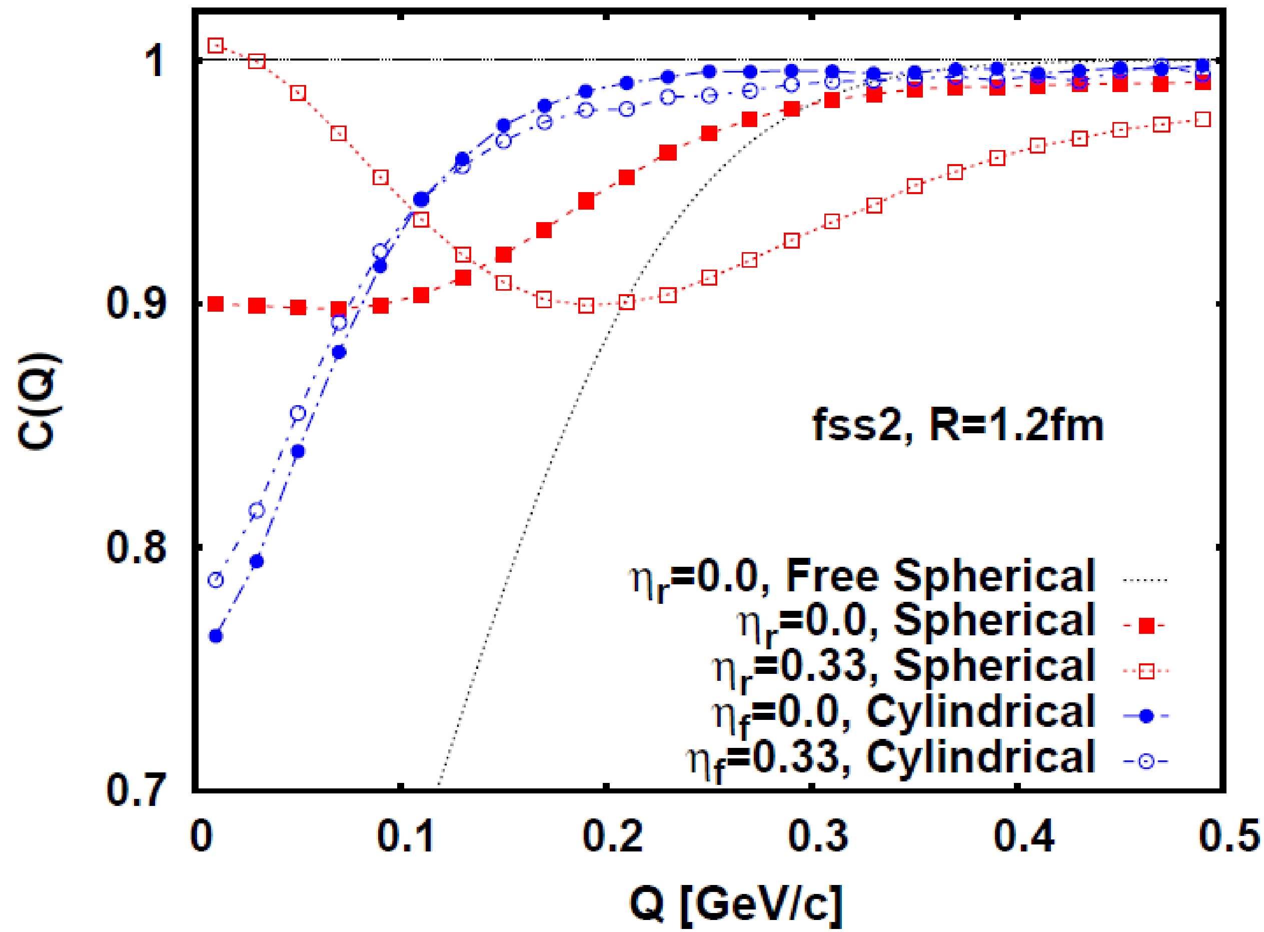


Width of C(Q) ($Q=|p_1-p_2|$) : effective 3d size

Large R_L : narrow width

Transverse flow: fit to p_t distribution of Λ (STAR '12)

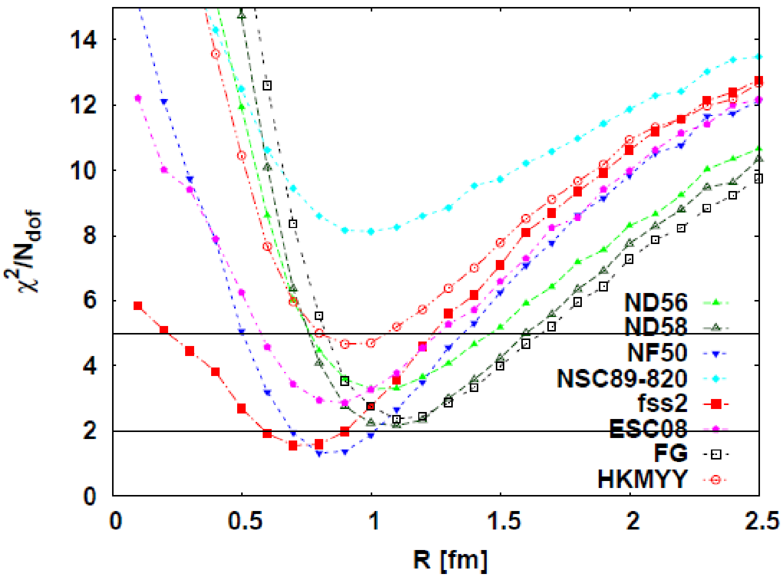
Results from Boost-invariant Source



Effect of η_f is rather small : longitudinal expansion dominates C(Q)

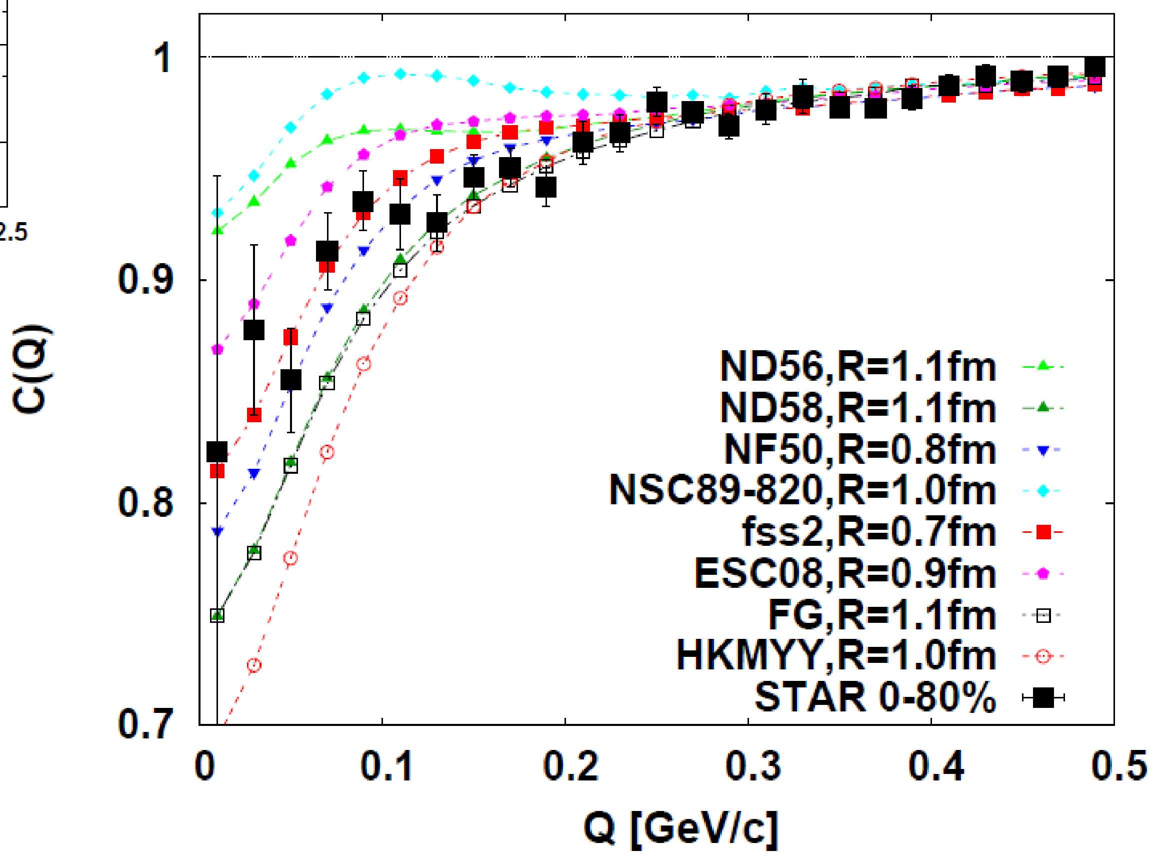
Behavior at small Q is different from the static source !

$V_{\Lambda\Lambda}$ from Expanding Source Model



Minimize χ^2 against R

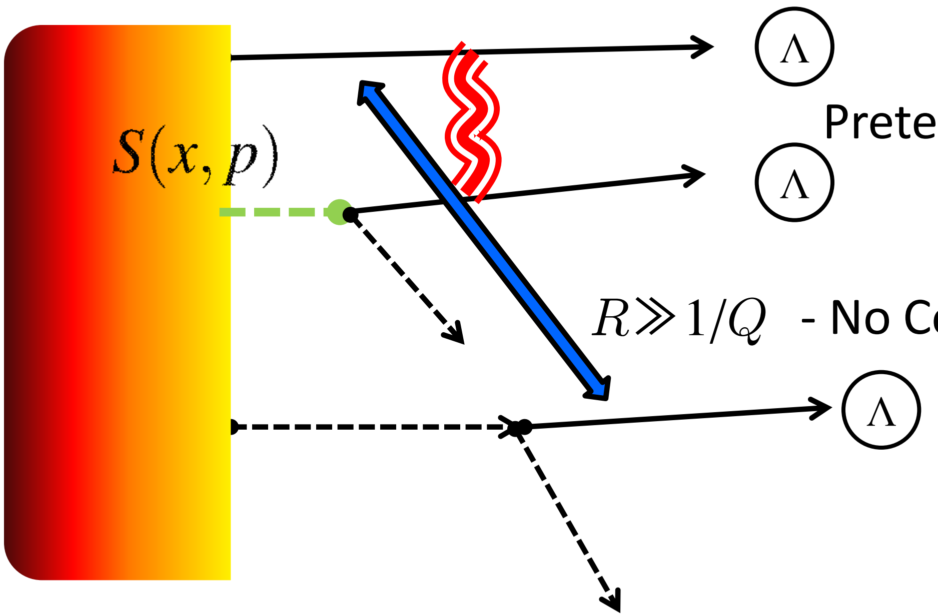
Low Q region sensitive to $V_{\Lambda\Lambda}$



Feed-Down Contribution

- **Short-Lived (Σ^*, N* etc) : large R, τ and $\delta\tau$**
- **$\Xi \rightarrow \Lambda + \pi$ partly subtracted**
- **$\Sigma^0 \rightarrow \Lambda + \gamma$**

$$C(Q) \to 1 + \left(\frac{\Lambda^{\rm dir}}{\Lambda^{\rm tot}}\right)^2 (C(Q) - 1)$$



$(0.67)^2$

consistent w/ thermal model

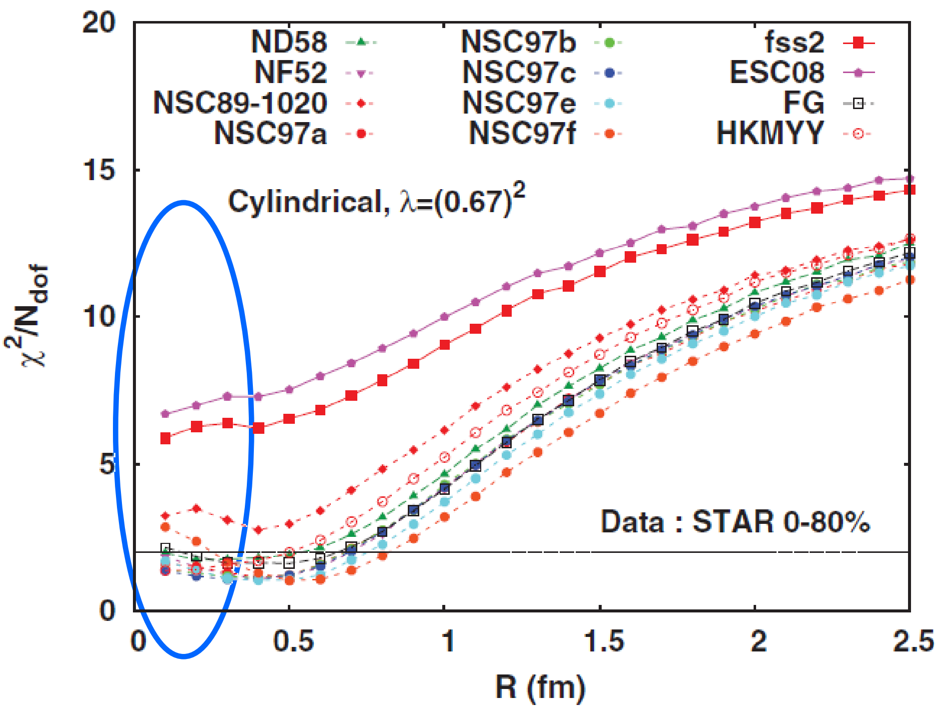
(0.52 if including Ξ)

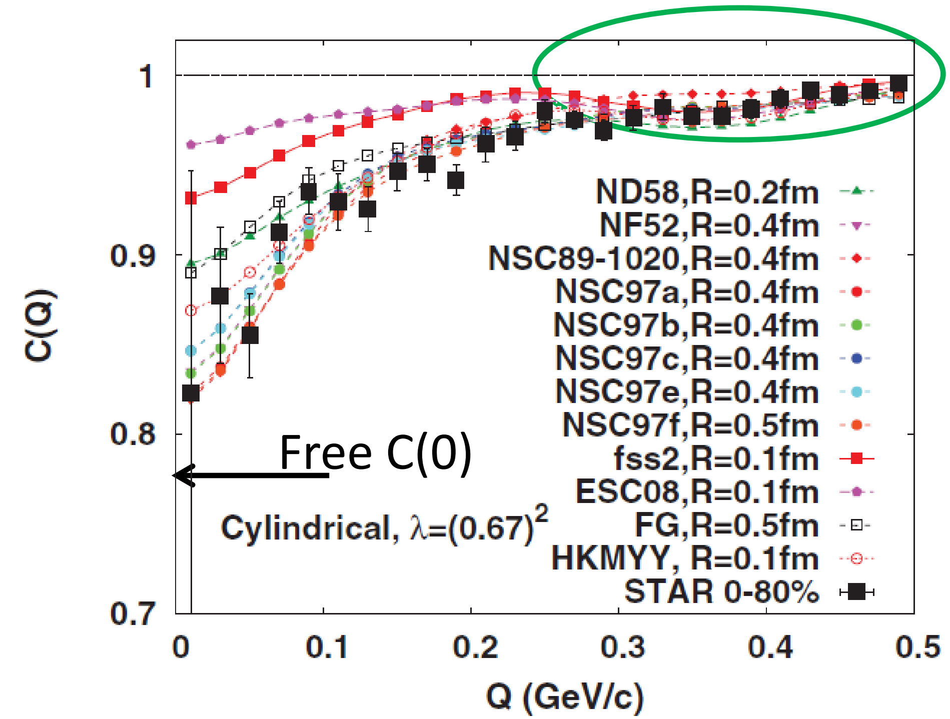
Using Σ^0/Λ =0.278 (p+Be data) and Ξ/Λ = 0.15 (RHIC), $\Lambda^{\rm dir}/\Lambda^{\rm tot}$ = 0.67

Long Tail in C(Q)

$$C(Q) \to 1 + (0.67)^2 (C(Q) - 1)$$

- **Sensitivity at low Q is reduced**





- **Unphysically small size is preferred;**

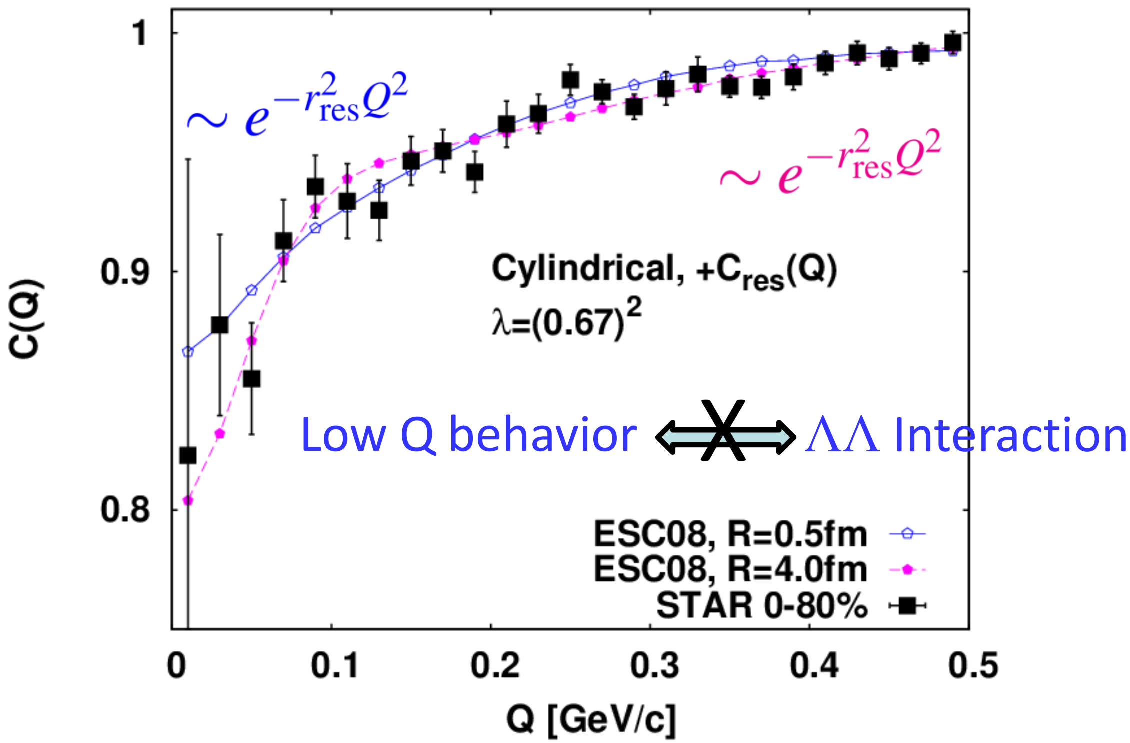
  due to the long tail in C(Q) which cannot be included in the present framework

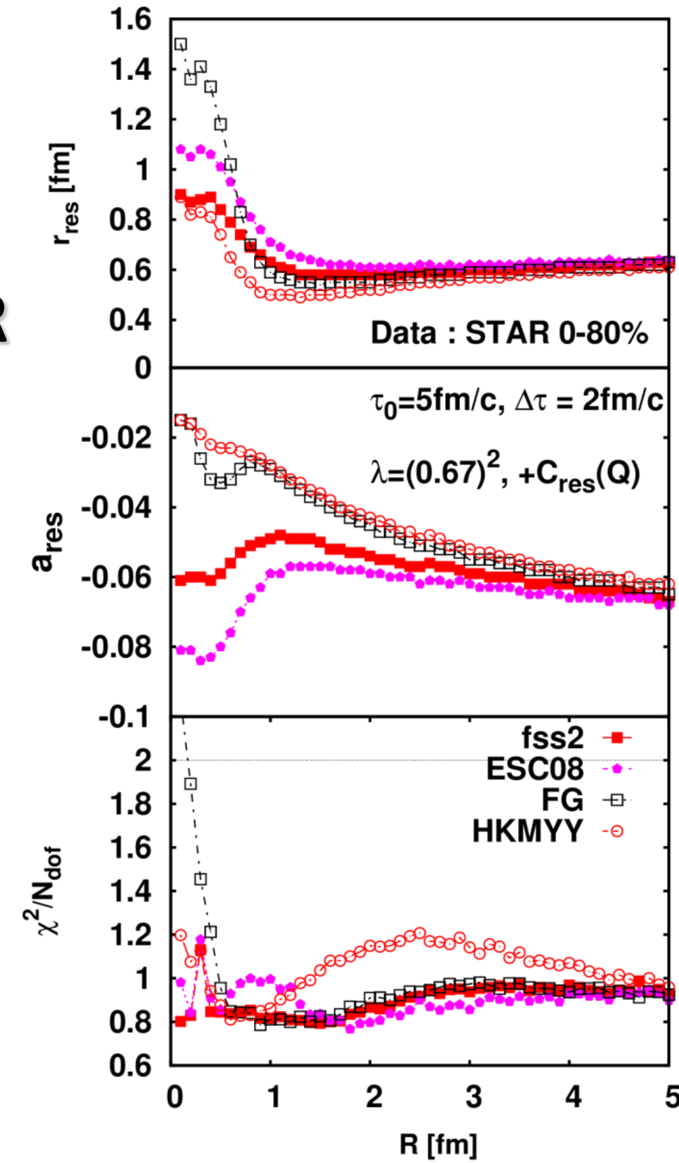
Long Tail : Residual Correlation?

- **Assume**

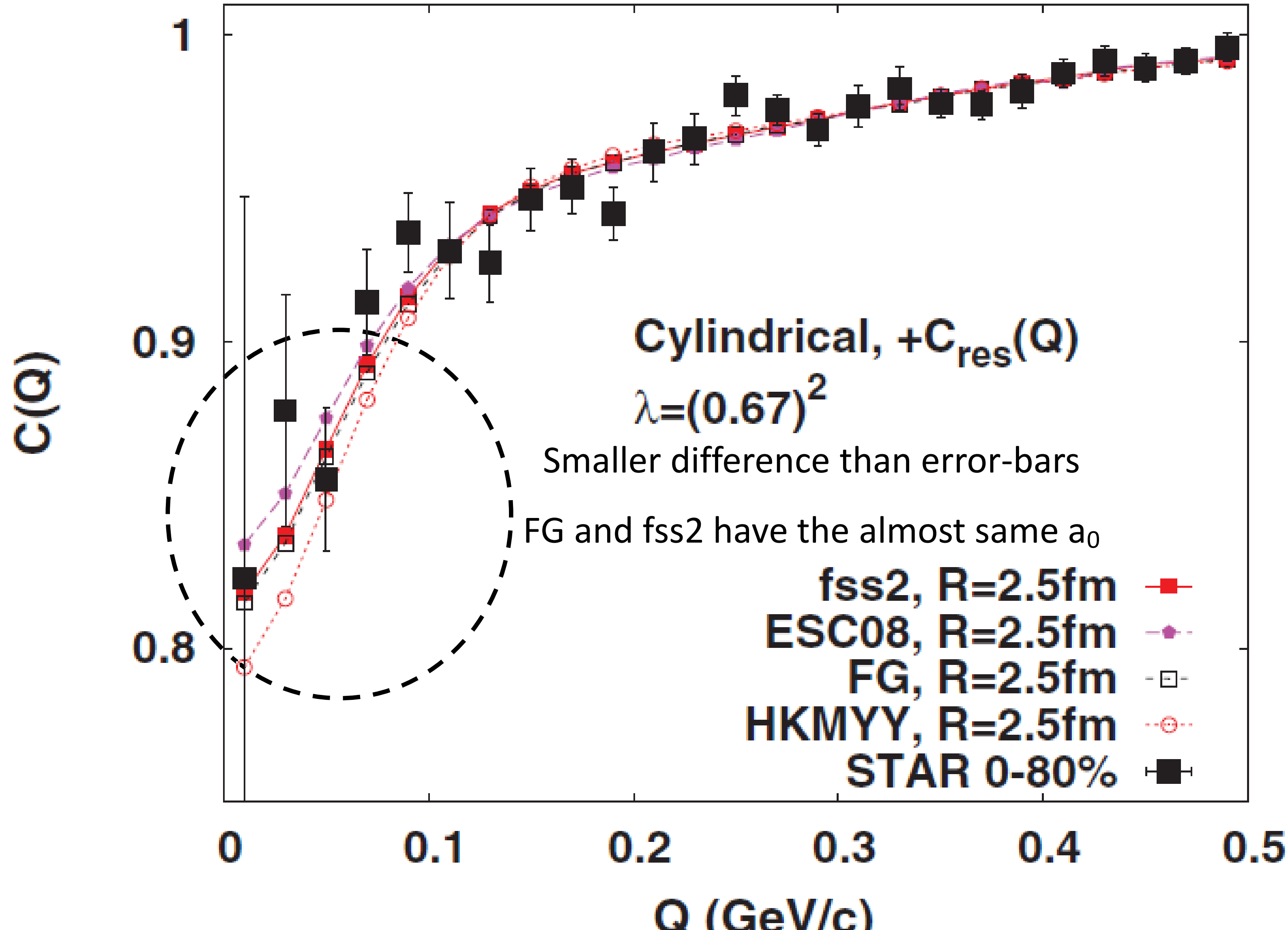
$$C(Q) \to C(Q) + a_{\rm res} e^{-r_{\rm res}^2 Q^2}$$

- **minimize χ^2 in (a_{res}, r_{res}) for each R**

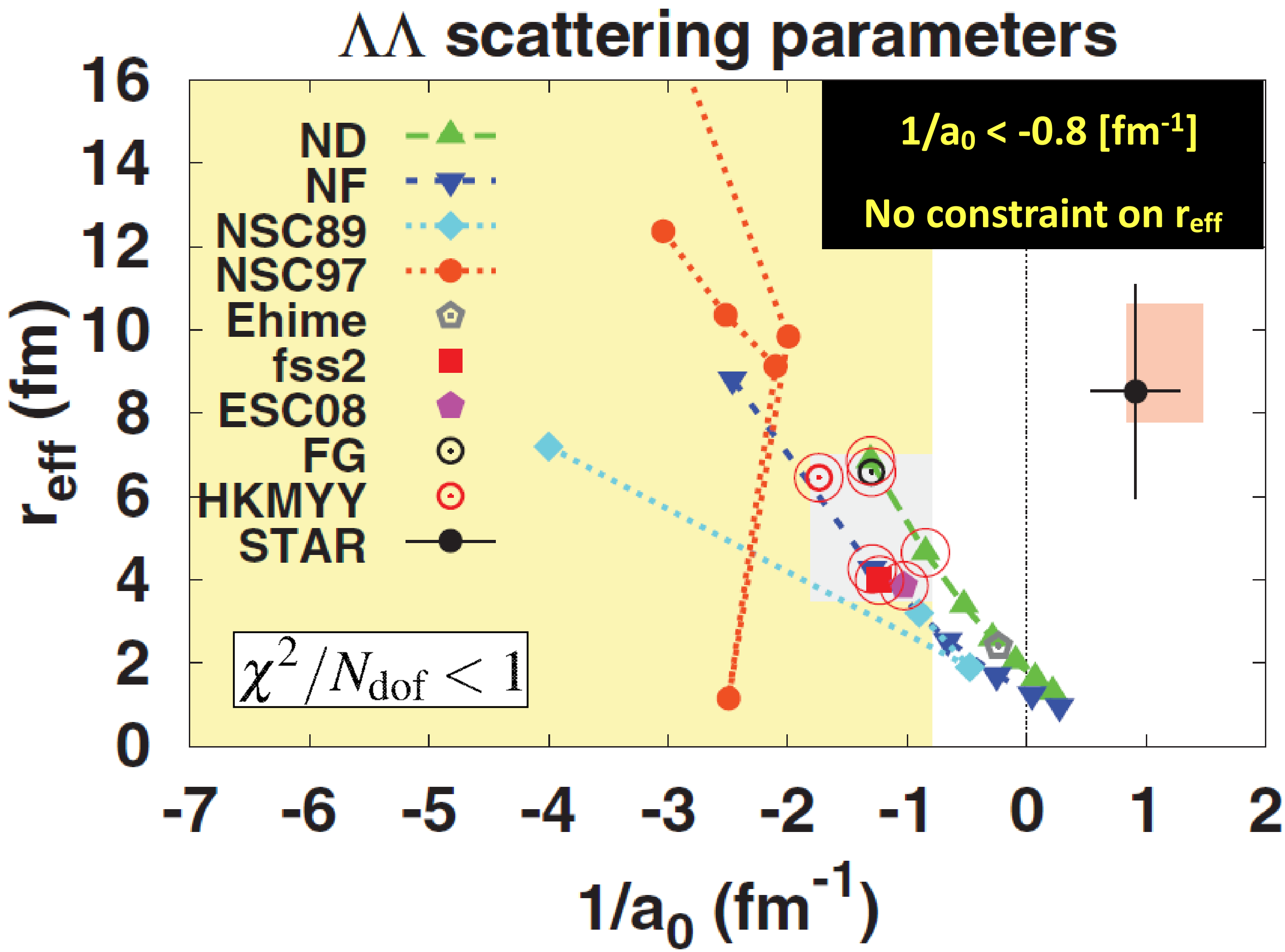




Sensitivity to Interaction Remains



Constraints on a_o and r_{eff}



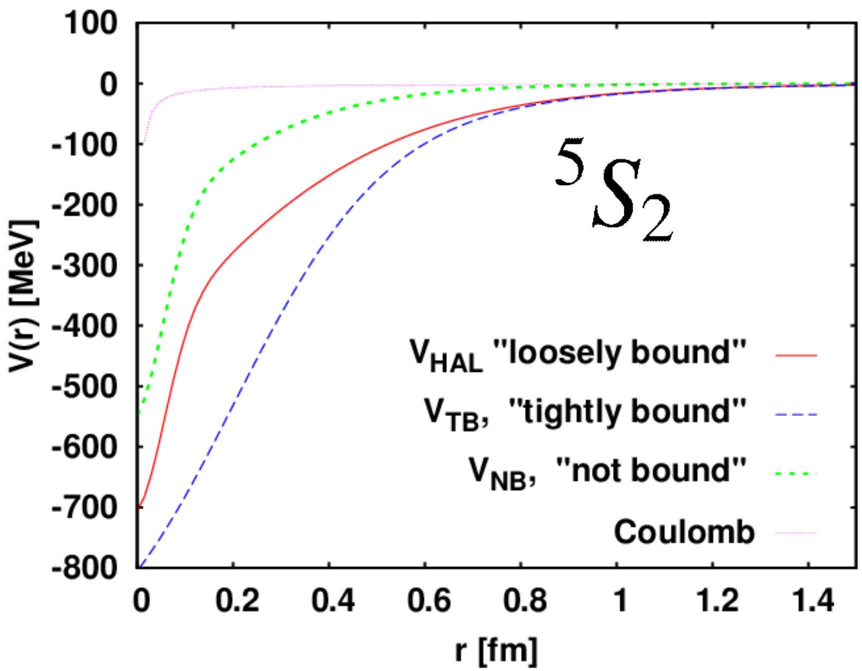
Summary and Outlook

- HIC have potential to determine $\Lambda\Lambda$ interaction
- Ideal measurements (i.e., decay contribution is subtracted) will give stronger constraints
  - Feed-down effect reduces resolving power
- Long-tail in STAR data needs to be subtracted and its origin needs to be understood
- Scattering length $1/a_0 < -0.8$ fm^{-1}
  - Weakly attracting - Implies no bound H-dibaryon
- Applicable to other systems
  - HIC as strange hadron factory!

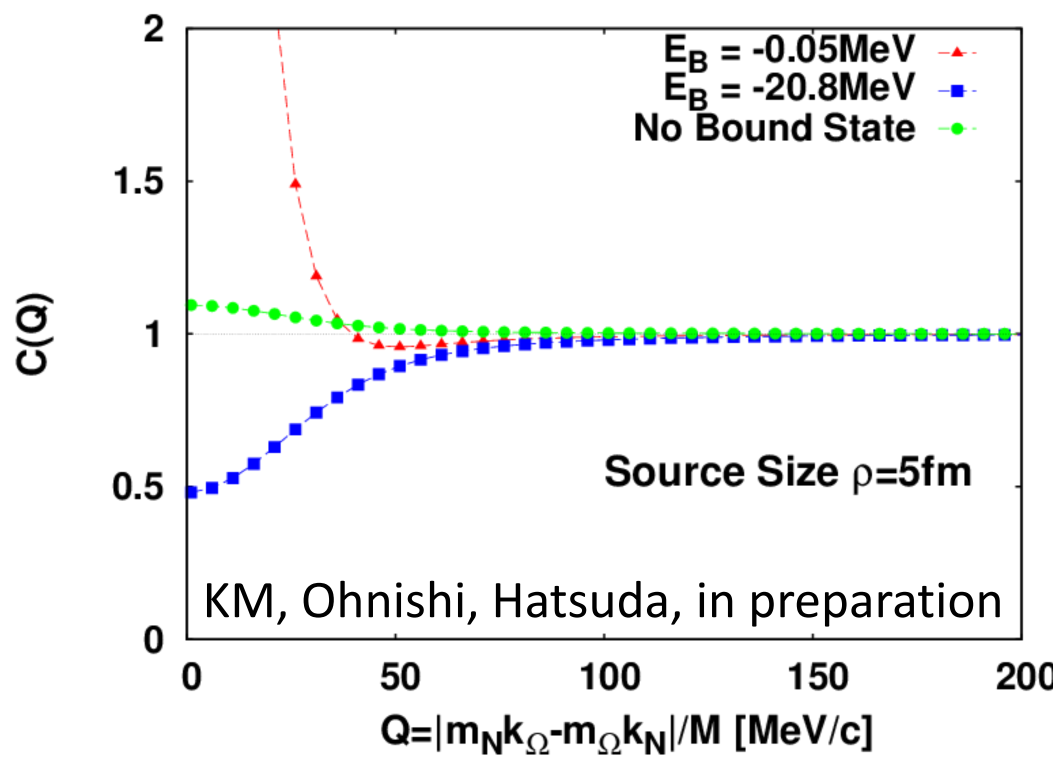
ΩN Correlation

No Pauli Blocking : bound state candidate

Potential from HAL QCD (Etminen et al., NPA'14)



$$|\Psi_{\Omega N}|^2 = \frac{3}{8}\underbrace{|\Psi(^3S_1)|^2}_{=1} + \frac{5}{8}|\Psi(^5S_2)|^2$$



KM, Ohnishi, Hatsuda, in preparation

Physical baryon masses

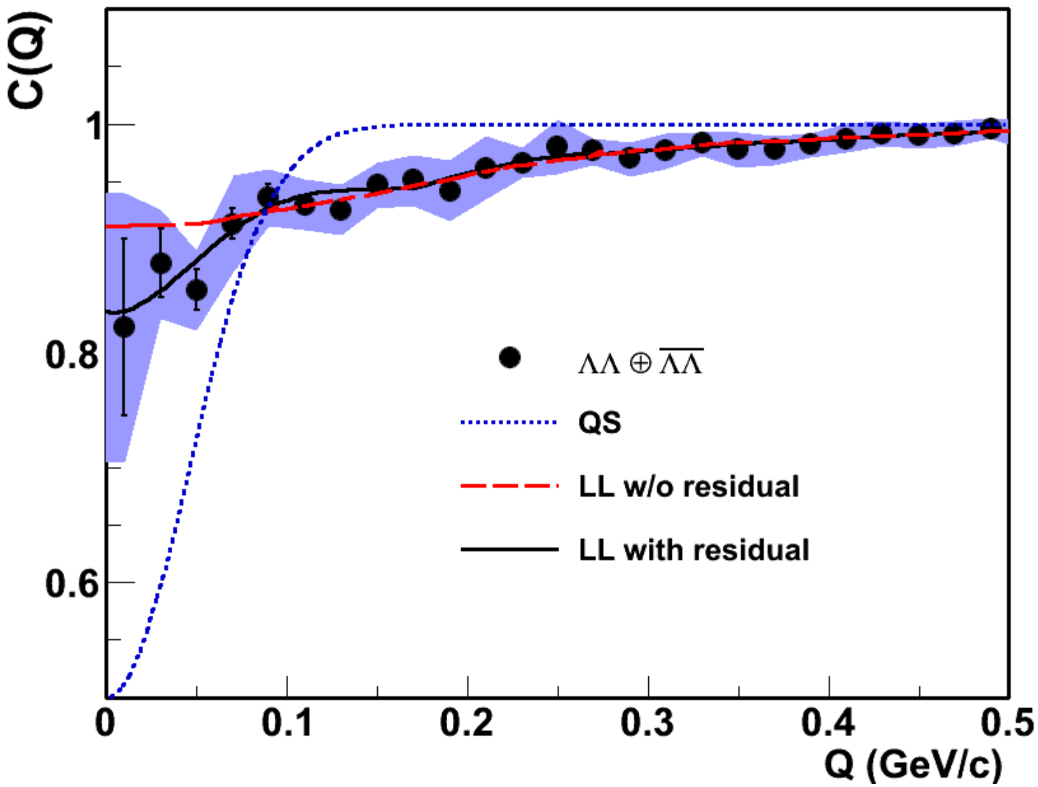
Keep a_0 and r_{eff}

Tune parameters

Backup

Analysis by STAR Coll.

arXiv:1408.4360



Fit w/ Lednicky-Lyuboshitz model

Data: long tail (→ Small source size)

Introduce "residual correlation" for a better fit to data

$$a_0 = -1.10 \pm 0.37^{+0.68}_{-0.08}\ \mathrm{fm}$$
$$r_{\mathrm{eff}} = 8.52 \pm 2.56^{+2.09}_{-0.74}\ \mathrm{fm}$$
$$\chi^2/N_{\mathrm{dof}} = 0.56$$

$$C_{\mathrm{fit}}(Q) = N\left[1 + \lambda\left\{-\frac{1}{2}e^{-r_0{}^2Q^2} + \chi(a_0, r_{\mathrm{eff}})\right\} + a_{\mathrm{res}}\exp(-r_{\mathrm{res}}^2 Q^2)\right]$$

HBT (size r_0) Interaction Residual correlation

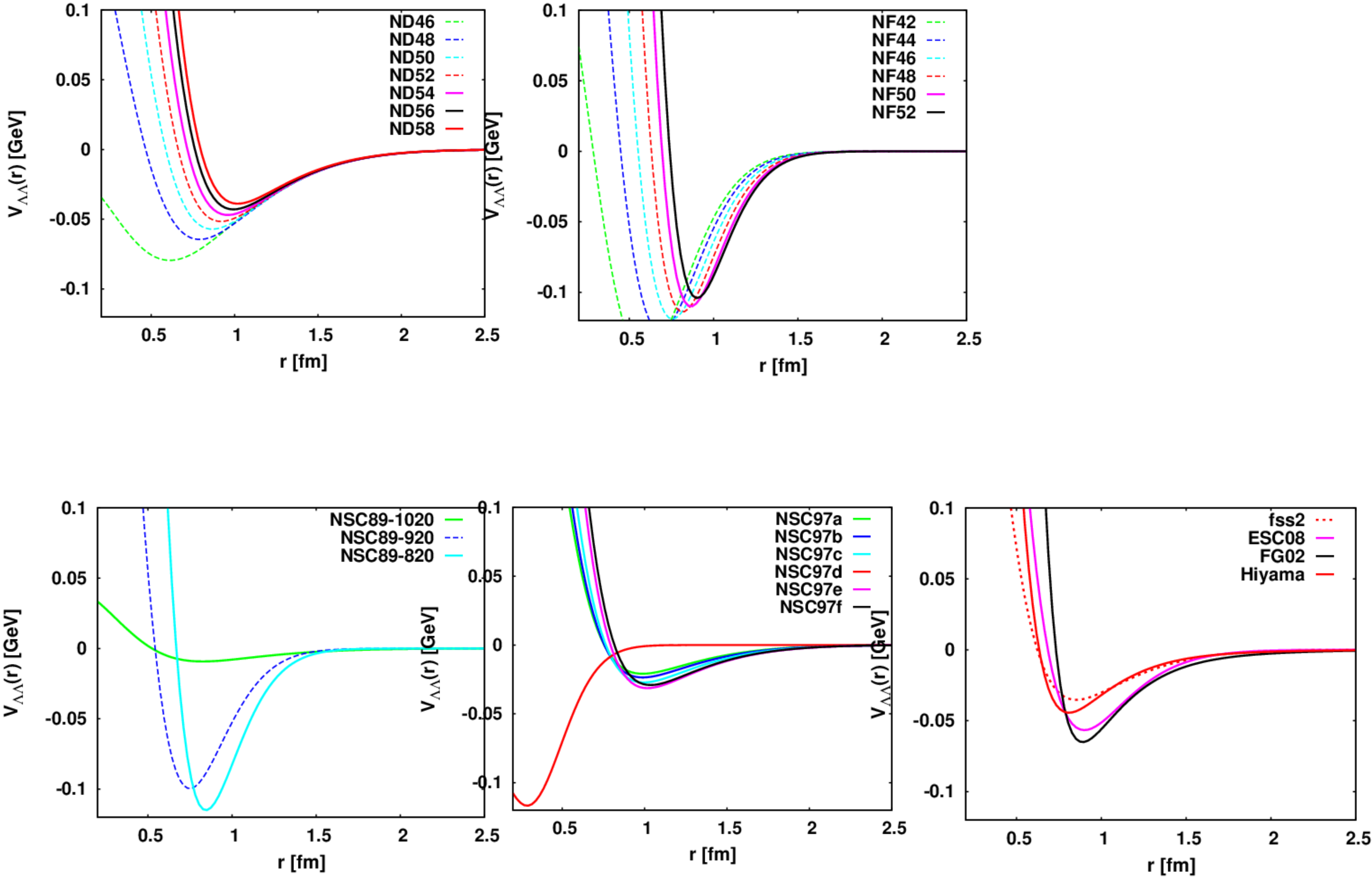
1.006 0.18 2.96 fm -0.044 0.43 fm

TABLE I: ΛΛ potentials. The scattering length (a_0) and effective range ($r_{\rm eff}$) are fitted using a two-range gaussian potential, $V_{\Lambda\Lambda}(r) = V_1 \exp(-r^2/\mu_1^2) + V_2 \exp(-r^2/\mu_2^2)$.

Model	a_0 (fm)	$r_{\rm eff}$ (fm)	μ_1 (fm)	V_1 (MeV)	μ_2 (fm)	V_2 (MeV)	Ref.
ND46	4.621	1.300	1.0	−144.89	0.45	127.87	[18] $r_c = 0.46$ fm
ND48	14.394	1.633	1.0	−150.83	0.45	355.09	[18] $r_c = 0.48$ fm
ND50	−10.629	2.042	1.0	−151.54	0.45	587.21	[18] $r_c = 0.50$ fm
ND52	−3.483	2.592	1.0	−150.29	0.45	840.55	[18] $r_c = 0.52$ fm
ND54	−1.893	3.389	1.0	−147.65	0.45	1114.72	[18] $r_c = 0.54$ fm
ND56	−1.179	4.656	1.0	−144.26	0.45	1413.75	[18] $r_c = 0.56$ fm
ND58	−0.764	6.863	1.0	−137.74	0.45	1666.78	[18] $r_c = 0.58$ fm
NF42	3.659	0.975	0.6	−878.97	0.45	1048.58	[19] $r_c = 0.42$ fm
NF44	23.956	1.258	0.6	−1066.98	0.45	1646.65	[19] $r_c = 0.44$ fm
NF46	−3.960	1.721	0.6	−1327.26	0.45	2561.56	[19] $r_c = 0.46$ fm
NF48	−1.511	2.549	0.6	−1647.40	0.45	3888.96	[19] $r_c = 0.48$ fm
NF50	−0.772	4.271	0.6	−2007.35	0.45	5678.97	[19] $r_c = 0.50$ fm
NF52	−0.406	8.828	0.6	−2276.73	0.45	7415.56	[19] $r_c = 0.52$ fm
NSC89-1020	−0.250	7.200	1.0	−22.89	0.45	67.45	[20] $m_{\rm cut} = 1020$ MeV
NSC89-920	−2.100	1.900	0.6	−1080.35	0.45	2039.54	[20] $m_{\rm cut} = 920$ MeV
NSC89-820	−1.110	3.200	0.6	−1904.41	0.45	4996.93	[20] $m_{\rm cut} = 820$ MeV
NSC97a	−0.329	12.370	1.0	−69.45	0.45	653.86	[21]
NSC97b	−0.397	10.360	1.0	−78.42	0.45	741.76	[21]
NSC97c	−0.476	9.130	1.0	−91.80	0.45	914.67	[21]
NSC97d	−0.401	1.150	0.4	−445.77	0.30	373.64	[21]
NSC97e	−0.501	9.840	1.0	−110.45	0.45	1309.55	[21]
NSC97f	−0.350	16.330	1.0	−106.53	0.45	1469.33	[21]
Ehime	−4.21	2.41	1.0	−146.6	0.45	720.9	[23]
fss2	−0.81	3.99	0.92	−103.9	0.41	658.2	[25]
ESC08	−0.97	3.86	0.80	−293.66	0.45	1429.27	[22]

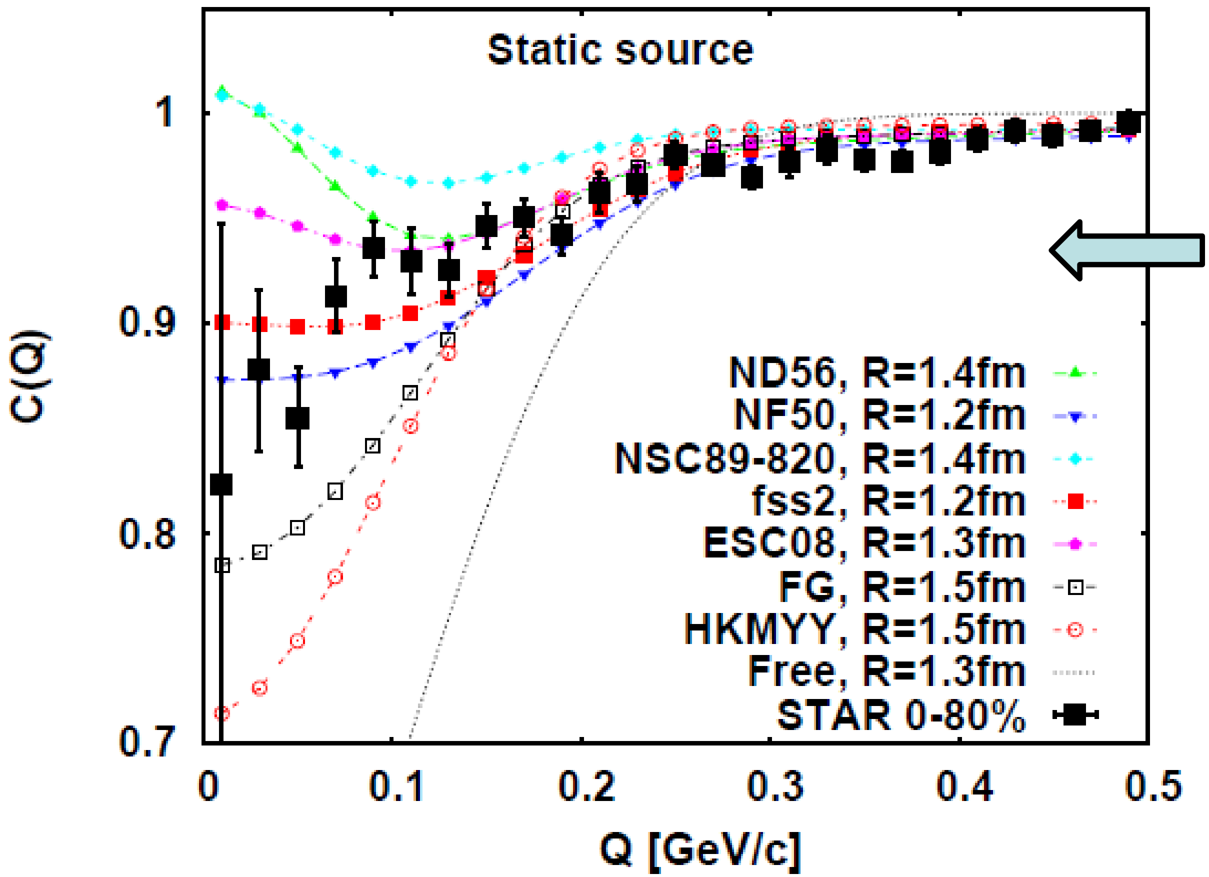
TABLE II: ΛΛ potentials from Nagara event. The scattering length (a_0) and effective range ($r_{\rm eff}$) are fitted using a three-range gaussian potential, $V_{\Lambda\Lambda}(r) = V_1 \exp(-r^2/\mu_1^2) + V_2 \exp(-r^2/\mu_2^2) + V_3 \exp(-r^2/\mu_3^2)$.

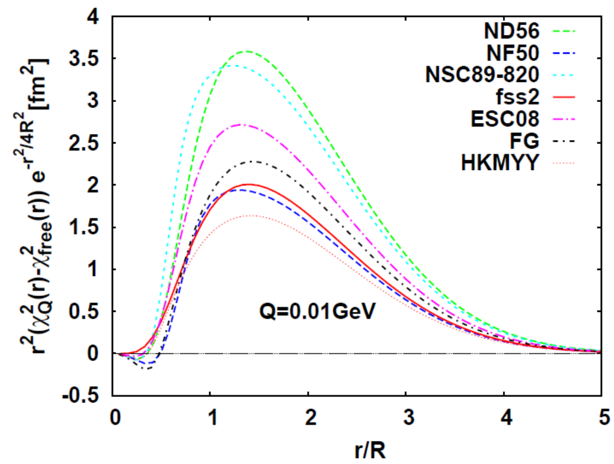
Model	a_0 (fm)	$r_{\rm eff}$ (fm)	μ_1 (fm)	V_1 (MeV)	μ_2 (fm)	V_2 (MeV)	μ_3 (fm)	V_3 (MeV)	Ref.
HKMYY	−0.575	6.45	1.342	−10.96	0.777	−141.75	0.35	2136.6	[3]
FG	−0.77	6.59	1.342	−21.49	0.777	−250.13	0.35	9324.0	[2]



ND46
ND48
ND50
ND52
ND54
ND56
ND58
NF42
NF44
NF46
NF48
NF50
NF52
NSC89-1020
NSC89-920
NSC89-820
NSC97a
NSC97b
NSC97c
NSC97d
NSC97e
NSC97f
fss2
ESC08
FG02
Hiyama
$V_{\Lambda\Lambda}(r)$ [GeV]
r [fm]

Results from the Static Source





Strong attraction is reflected onto C(Q)

Larger variation among potentials than data error-bars

Size : determined from min. χ^2

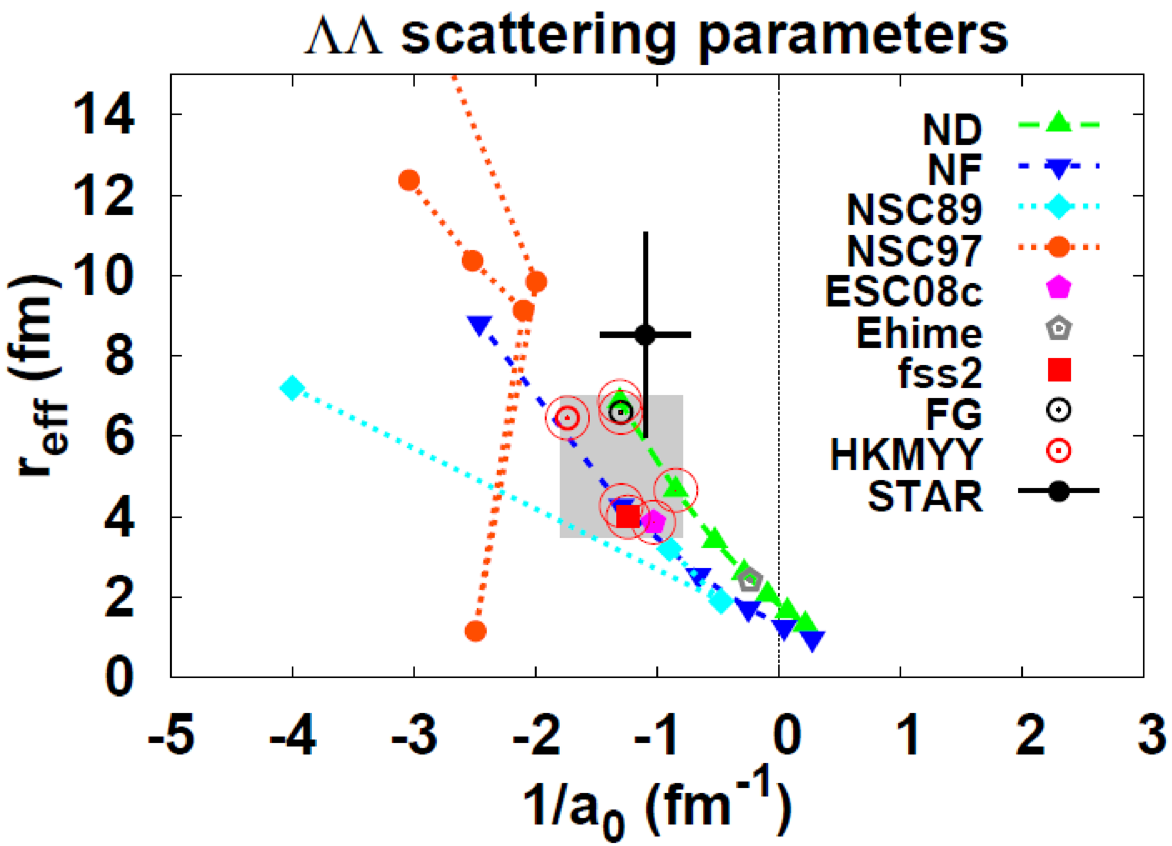
Collectivity Deforms Source Function

$$C_2(Q,K) = \frac{\int d^4x_1 d^4x_2 S(x_1,K) S(x_2,K) \left|\Psi_{12}(Q, x_1 - x_2 - (t_2 - t_1)K/m)\right|^2}{\int d^4x_1 d^4x_2 S(x_1,k_1) S(x_1,k_2)}$$

Influence on the best-fit potentials?

C(Q) is fairly sensitive to interaction

Scattering Length and Effective Range



$-1.8 < 1/a_0 < -0.8$ [fm^{-1}]

$3.5 < r_{eff} < 7$ [fm]

- Σ^0 feed-down affects this ?

Approach : Thermal Source + $V_{\Lambda\Lambda}$

Formula (Gong et al., '91)

$$C_2(Q,K) = \frac{\int d^4x_1 d^4x_2 S(x_1,K)S(x_2,K)|\Psi_{12}(Q,x_1-x_2-(t_2-t_1)K/m)|^2}{\int d^4x_1 d^4x_2 S(x_1,k_1)S(x_1,k_2)}$$

Emission source func. ⇧ Thermal source model (Mimic hydro)

- Static Spherically Symmetric
- Spherically Symmetric + Hubble Flow
- Cylindrically Symmetric + Boost-invariance + Transverse flow

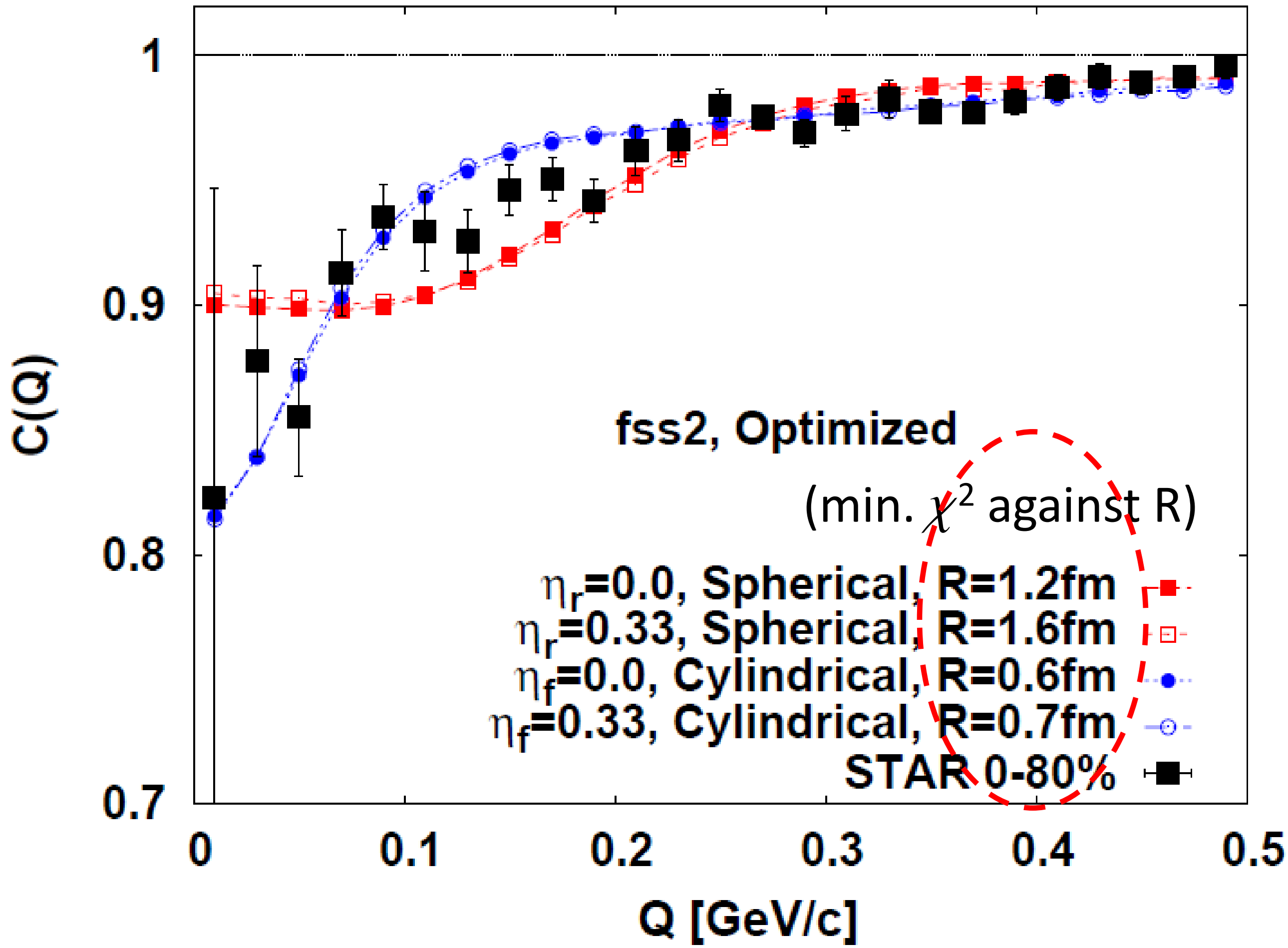
ΛΛ relative S-wave func. ⇧ Various potentials (via 2 or 3 range Gaussian Fit)

Meson exchange models (Nijmegen model D, F, Soft Core89/97, ESC08)

Phenomenological (Ehime)
Quark model (fss2)

Fit to $_{\Lambda\Lambda}{}^{6}$He(Nagara) Filikhin-Gal (FG)
Hiyama et al. (HKMYY)

Combined effects from flow and $V_{\Lambda\Lambda}$



Effect of η_f is absorbed into change of R_{opt}

Longitudinal expansion gives another type of "best fit"