RHICにおけるΛΛ相互作用

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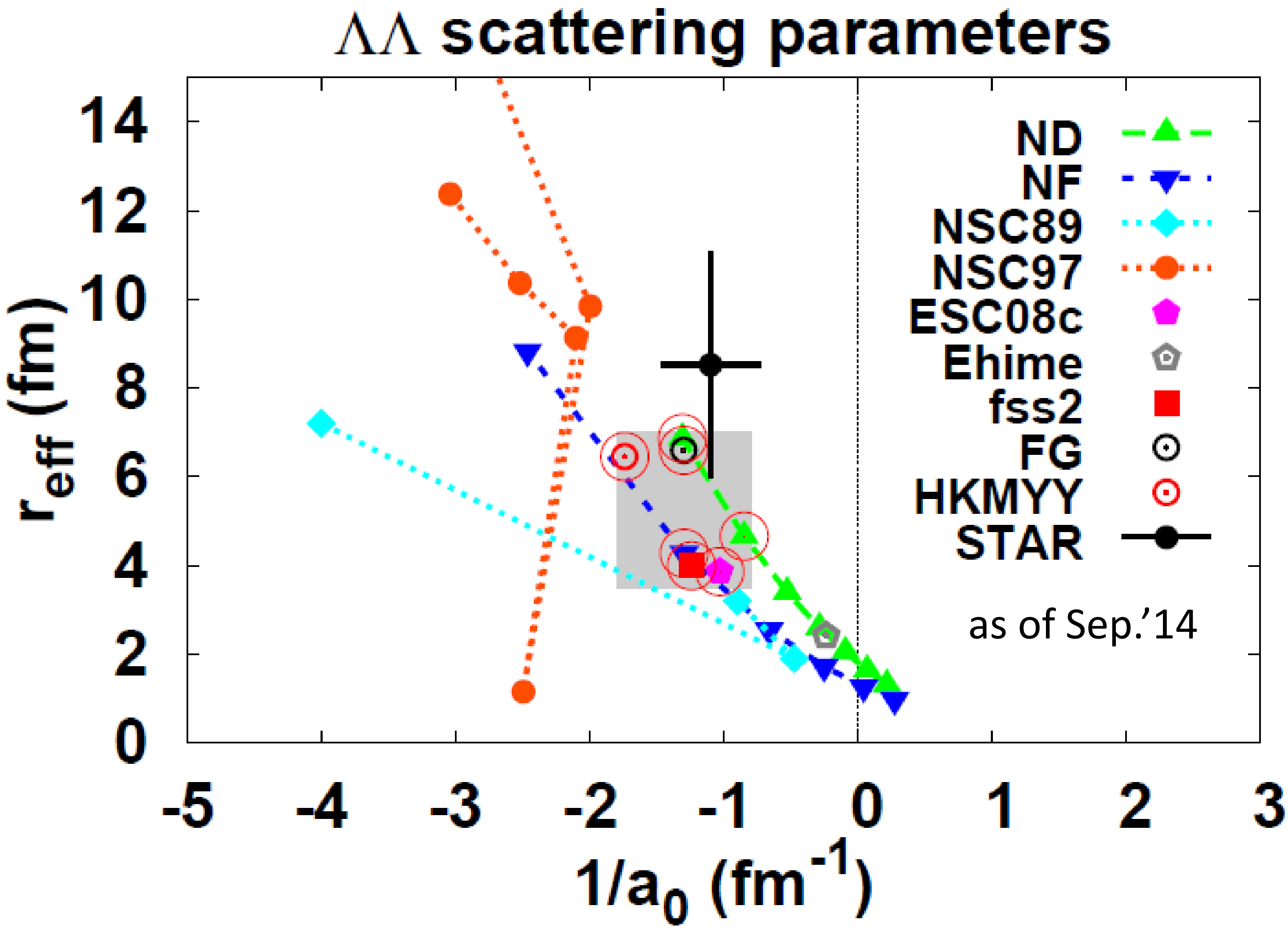
Ref.）Phys. Rev. C91, 024916 (2015)

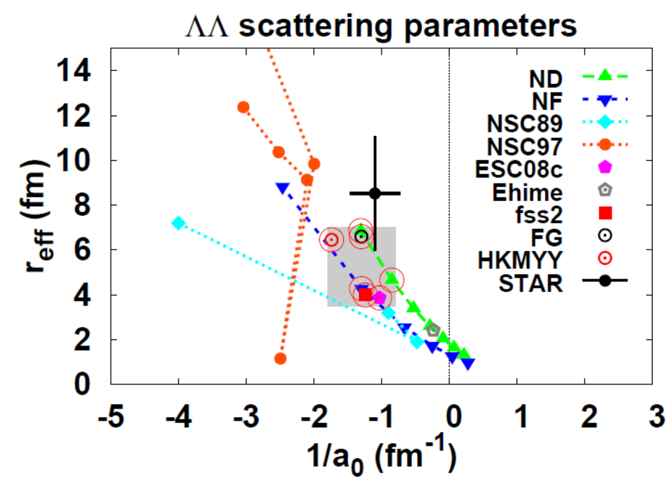
散乱長 a_o と有効レンジ r_{eff} への制限



Outline

重イオン衝突 (RHIC, LHC)→ ΛΛ相互作用

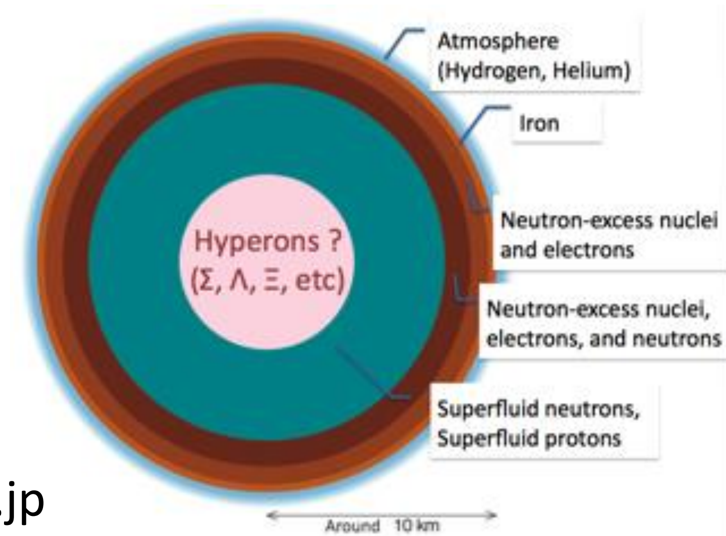
1. メカニズム
2. 重イオン衝突のダイナミクスの効果 (reminder)



3. Σ^0 -> $\Lambda\ \gamma$ の影響
4. 相関関数のロングテール
5. STARとの違い
6. まとめと展望

ΛΛ 相互作用の重要性

中性子星におけるハイペロン混合



from KEK.jp

状態方程式の軟化

観測との整合性？

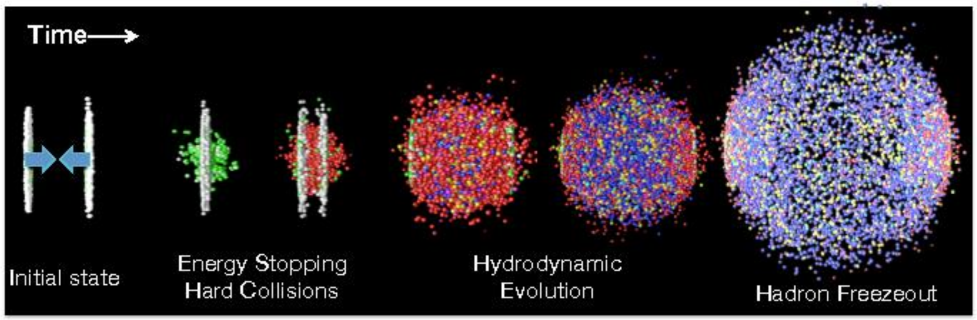
相互作用の影響は？

“H”-ダイバリオン

- Λ-Λ 束縛状態？(Lattice・重いπ)
- 共鳴状態があるかも？

森田健司 (京大基研)

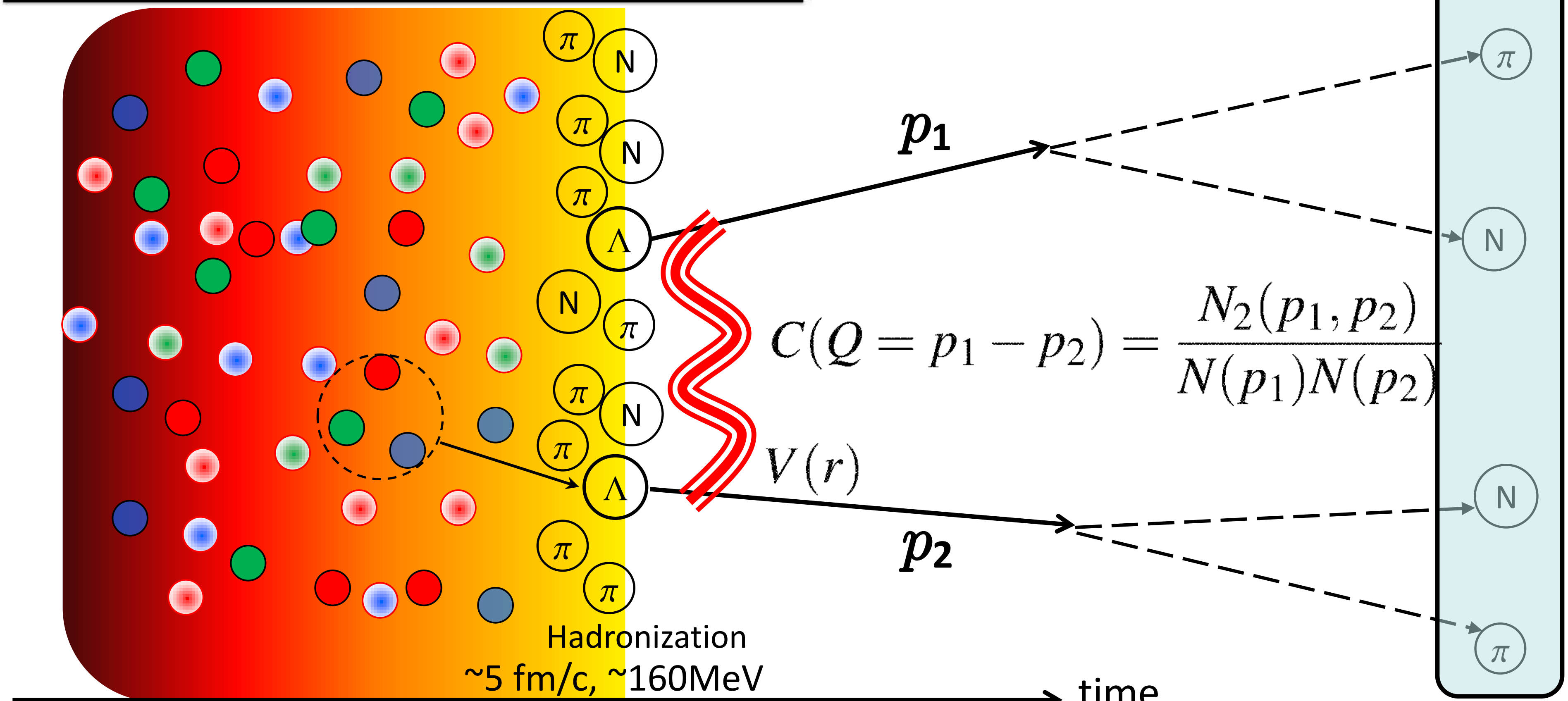
重イオン衝突での$\Lambda\Lambda$ 生成・相関



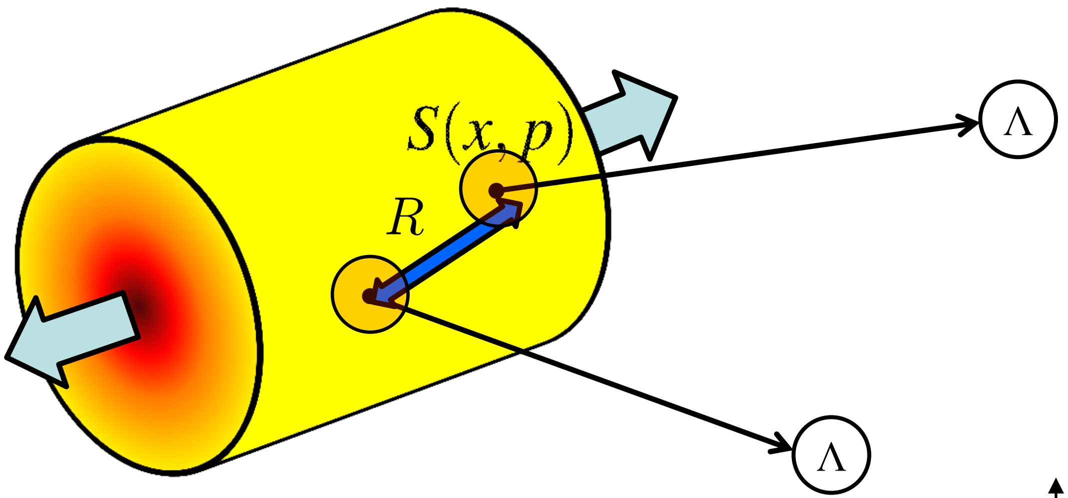
Au+Au 200AGeV

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

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



ΛΛ 相関関数



熱的粒子源：ランダム位相

同種粒子起因の相関（HBT)

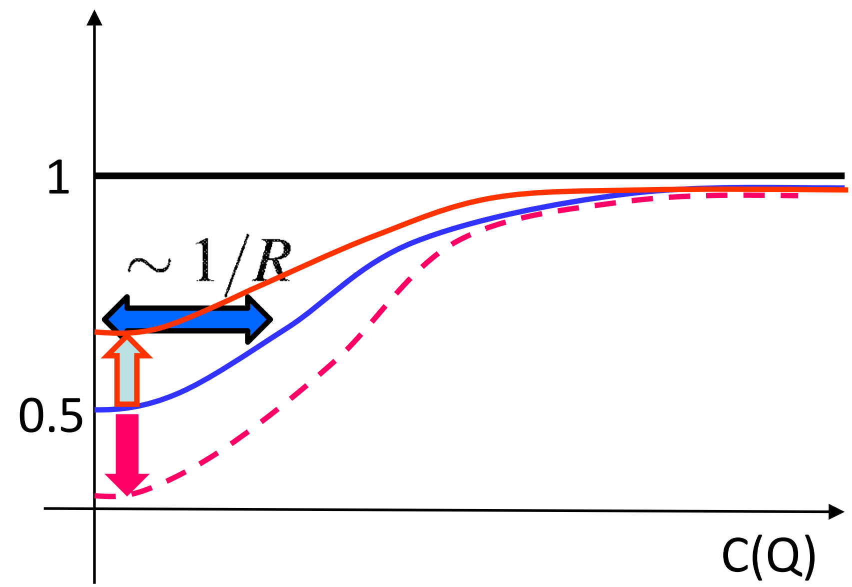
C(Q)：粒子源サイズ

ΛΛ 相互作用 : No Coulomb!

C(Q)への影響：effective range

r_{eff} ~R

repulsive / attractive interaction
での違い



手法：熱的粒子源モデル + $V_{\Lambda\Lambda}$

Formula (Gong et al., '91)

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

ソース関数（放出点分布）

⇧

熱的粒子源モデル

（理想：流体シミュレーション）

- ◆ 静的・球対称
- ◆ 球対称＋膨張
- ◆ 円筒対称＋縦ブースト不変性 ＋横膨張

$\Lambda\Lambda$ 相対波動関数 (S-wave)

⇧

ポテンシャル (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)

ポテンシャルと波動関数

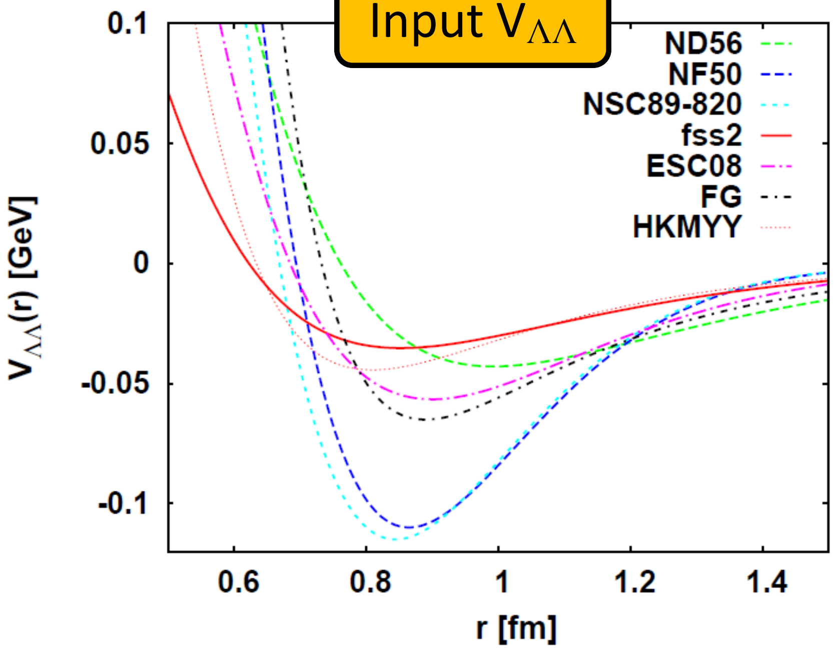
球対称静的ソース

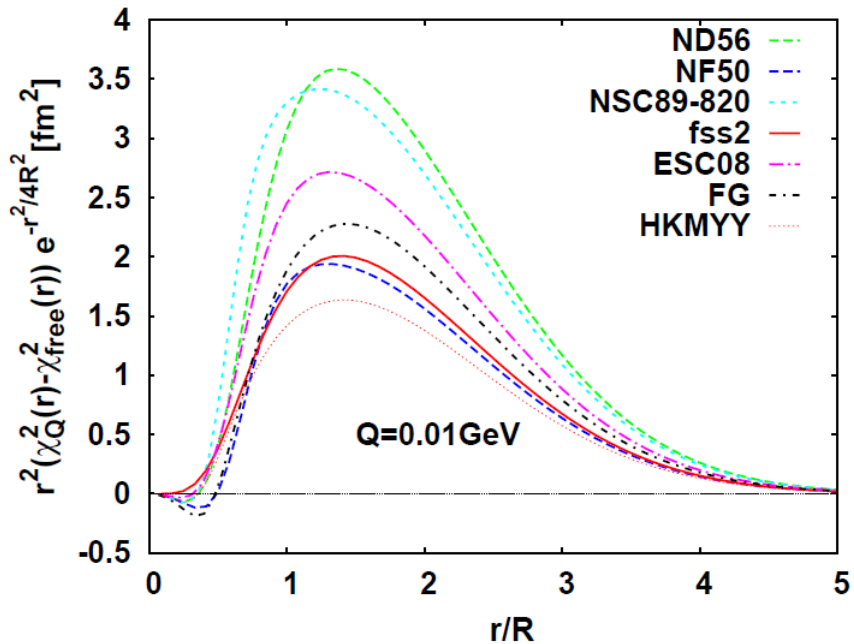
S-wave w.f.

$$C_{\mathrm{stat}}(Q) = 1 - \frac{1}{2}e^{-Q^2R^2} + \frac{1}{4\sqrt{\pi}R^3}\int_0^\infty dr\, r^2 e^{-\frac{r^2}{4R^2}} \underbrace{\left[[\chi_Q(r)]^2 - [j_0(Qr/2)]^2\right]}_{\text{Interaction : deviation from free w.f.}}$$

HBT (size R)

Input $V_{\Lambda\Lambda}$





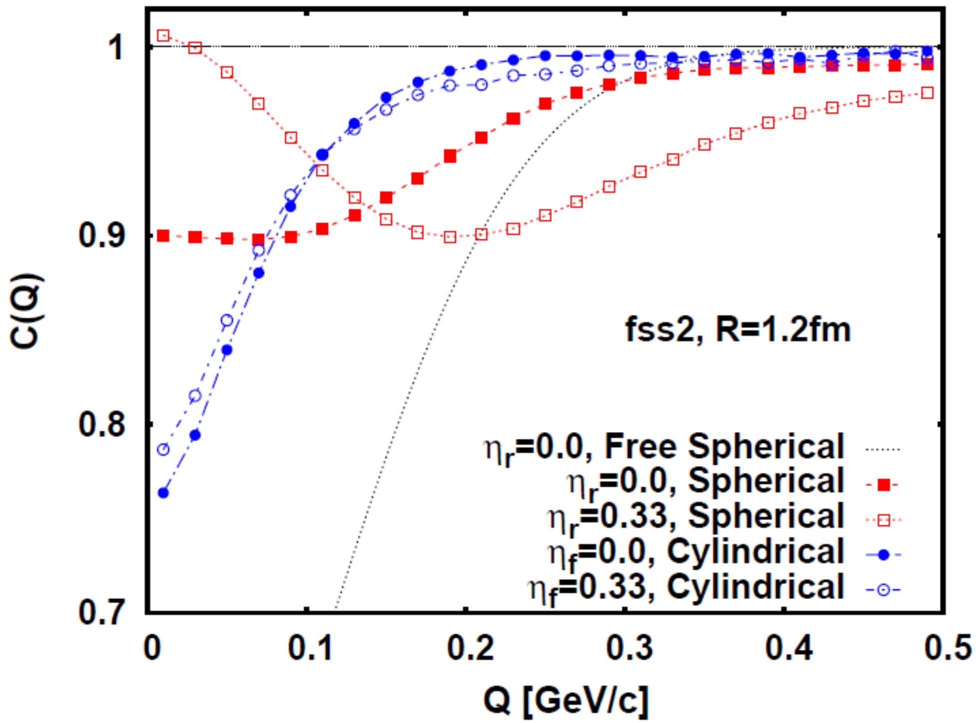
膨張粒子源モデル

S.Chapman et al., '95

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

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

ブースト不変でも縦に有限サイズ $R_L \sim \tau_0 \sqrt{\frac{T}{M_T}}$

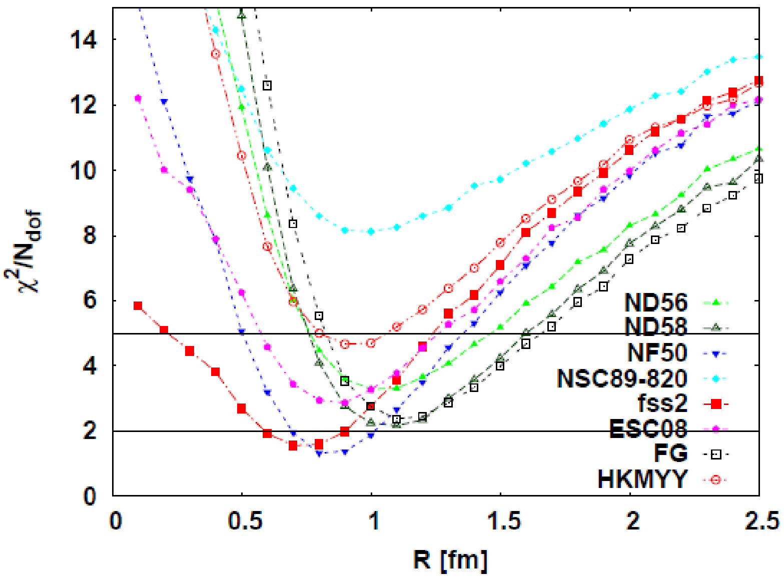


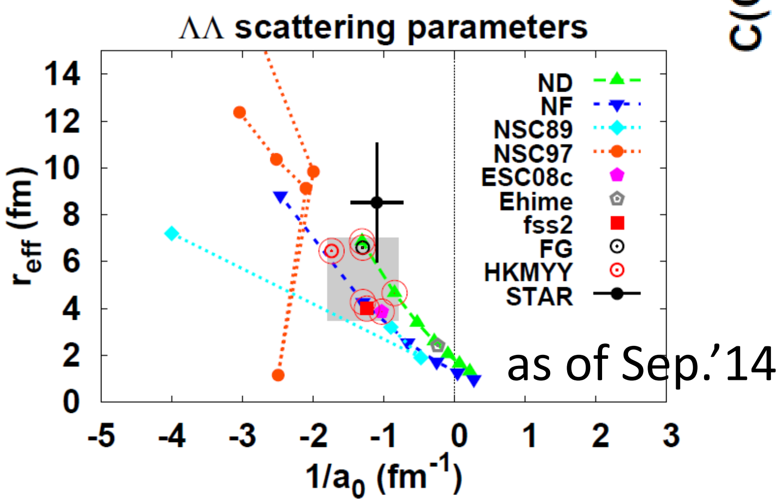
Width of C(Q) (Q=|p₁-p₂|) :
effective 3d size

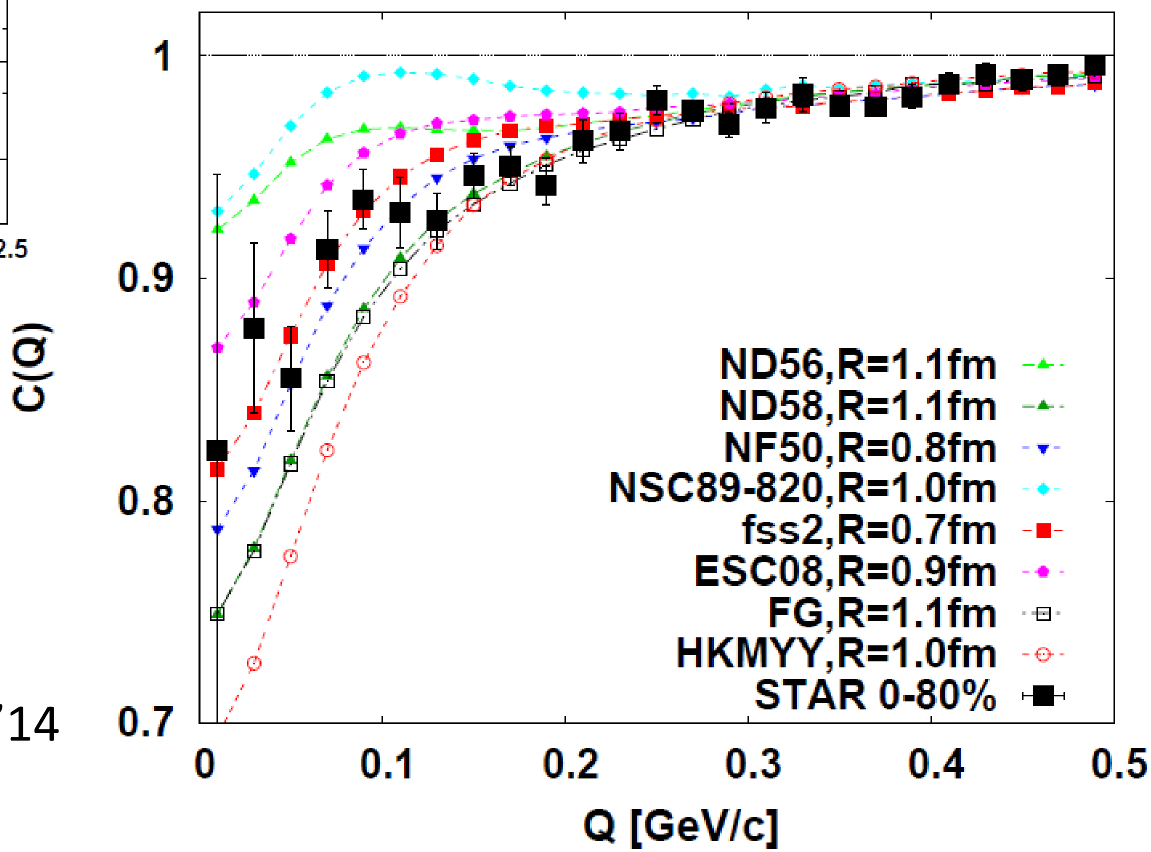
Large R_L : narrow width

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

$V_{\Lambda\Lambda}$ ：膨張粒子源モデルによるFit



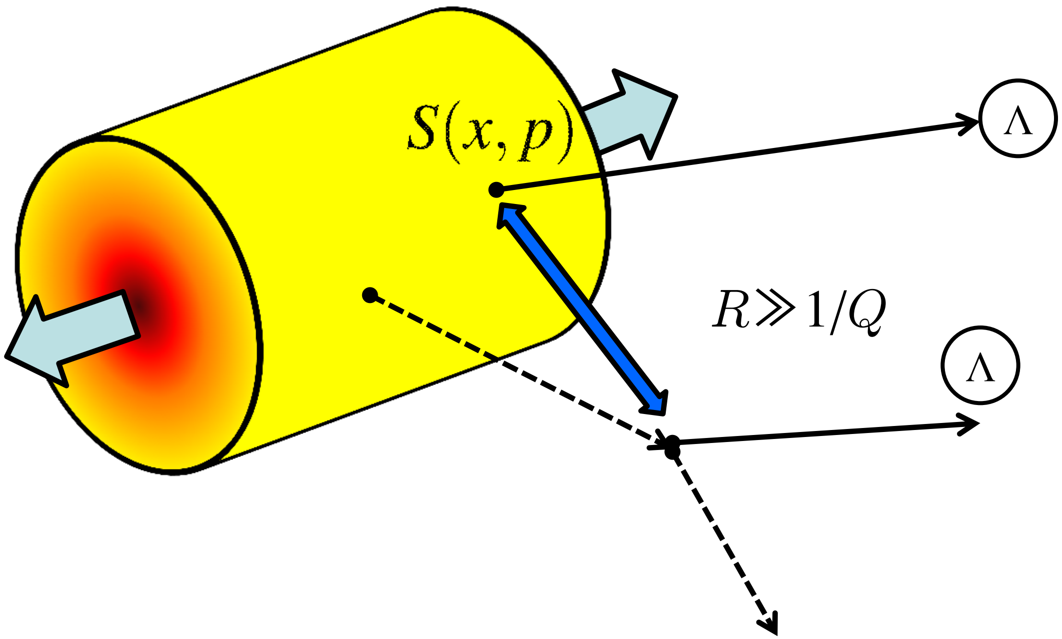




Feed-Down の寄与

- $\Xi \to \Lambda+\pi$: subtracted
  - DCA < 0.4cm from the primary vertex
- $\Sigma^0 \to \Lambda + \gamma$

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



$(0.67)^2$

熱的生成とconsistent

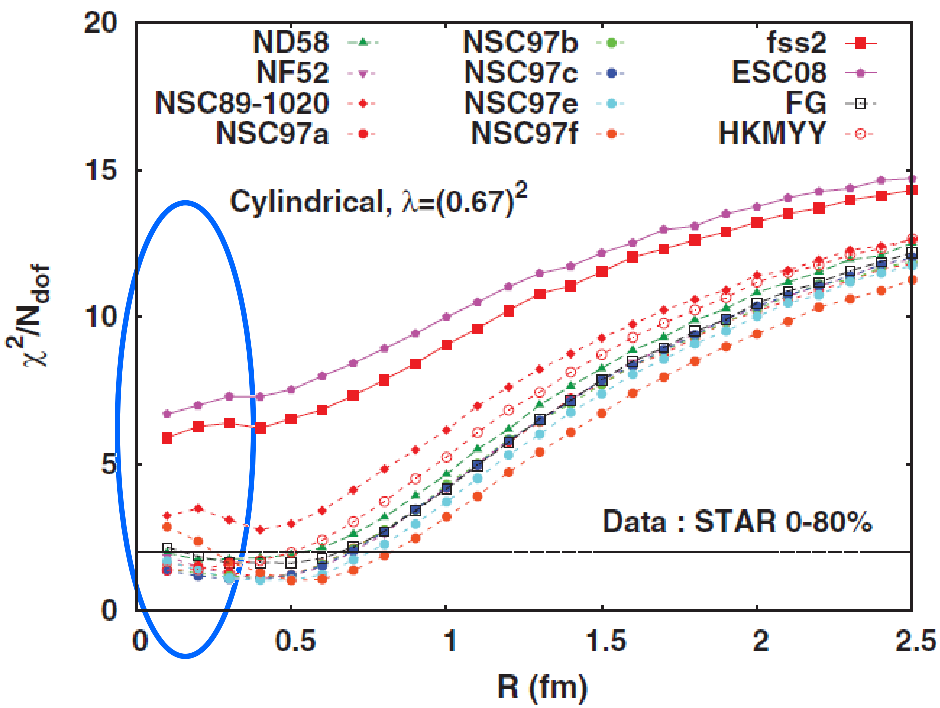
Σ^0/Λ =0.278 (p+Be data), Ξ/Λ = 0.85 (RHIC) → $\Lambda^{\rm dir}/\Lambda^{\rm tot}$ = 0.67

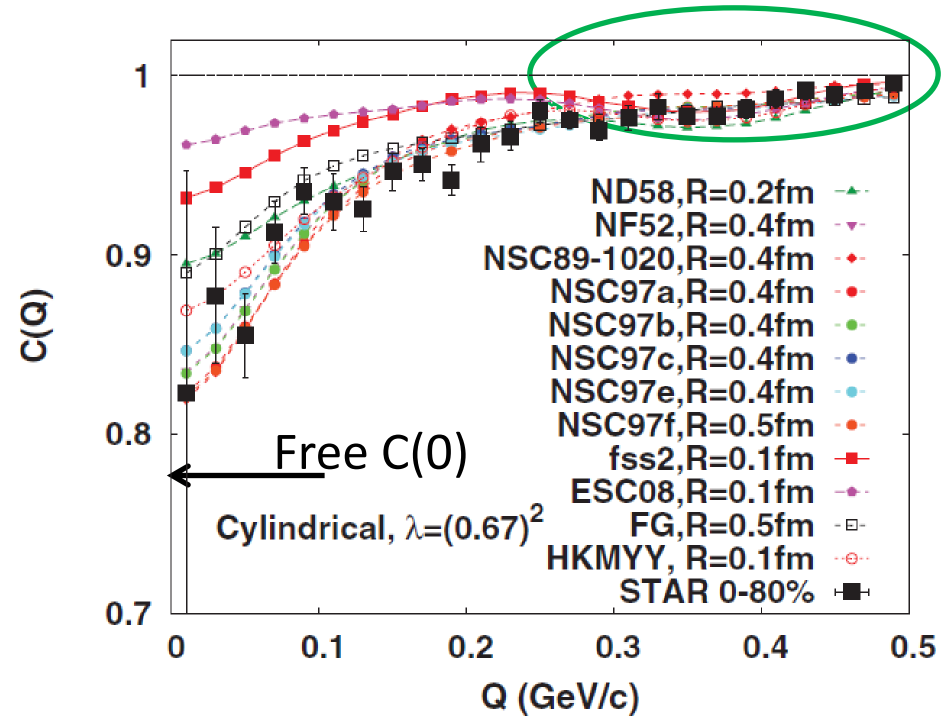
(0.52 if including Ξ)

Feed-Down の寄与

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

- Low Qでの相互作用依存性→弱くなる





- 非常に小さいサイズ？
  long tail を合わせるのに必要。。。

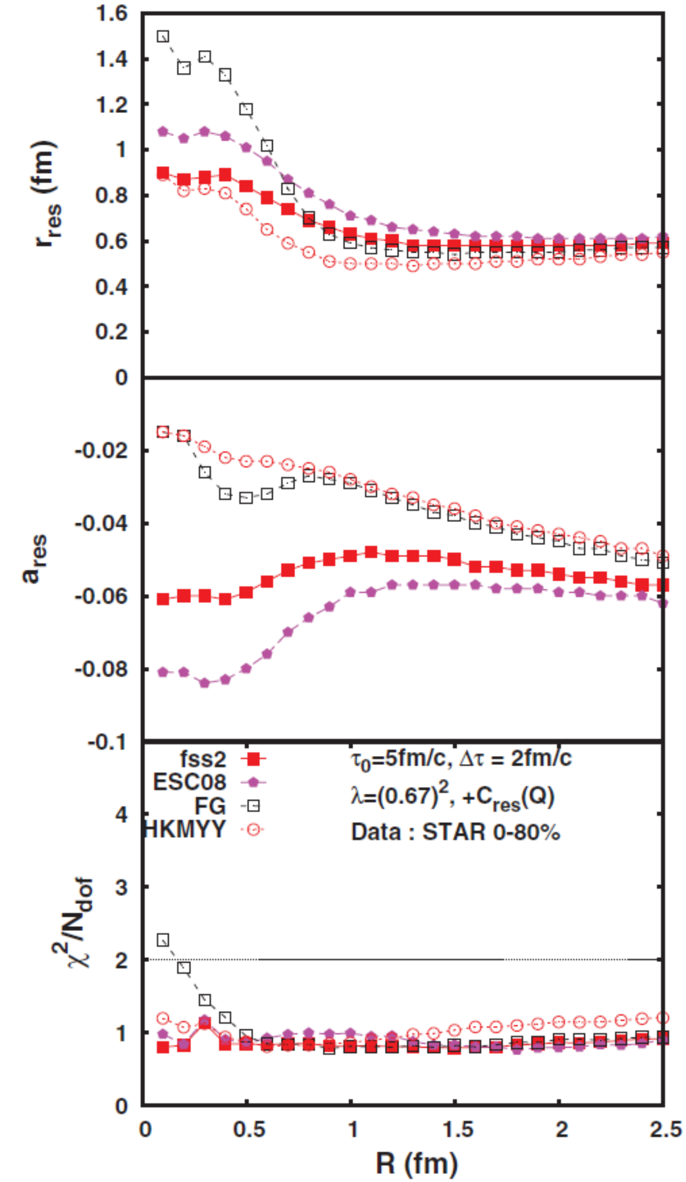
ロングテールを記述する相関？

別起源の相関

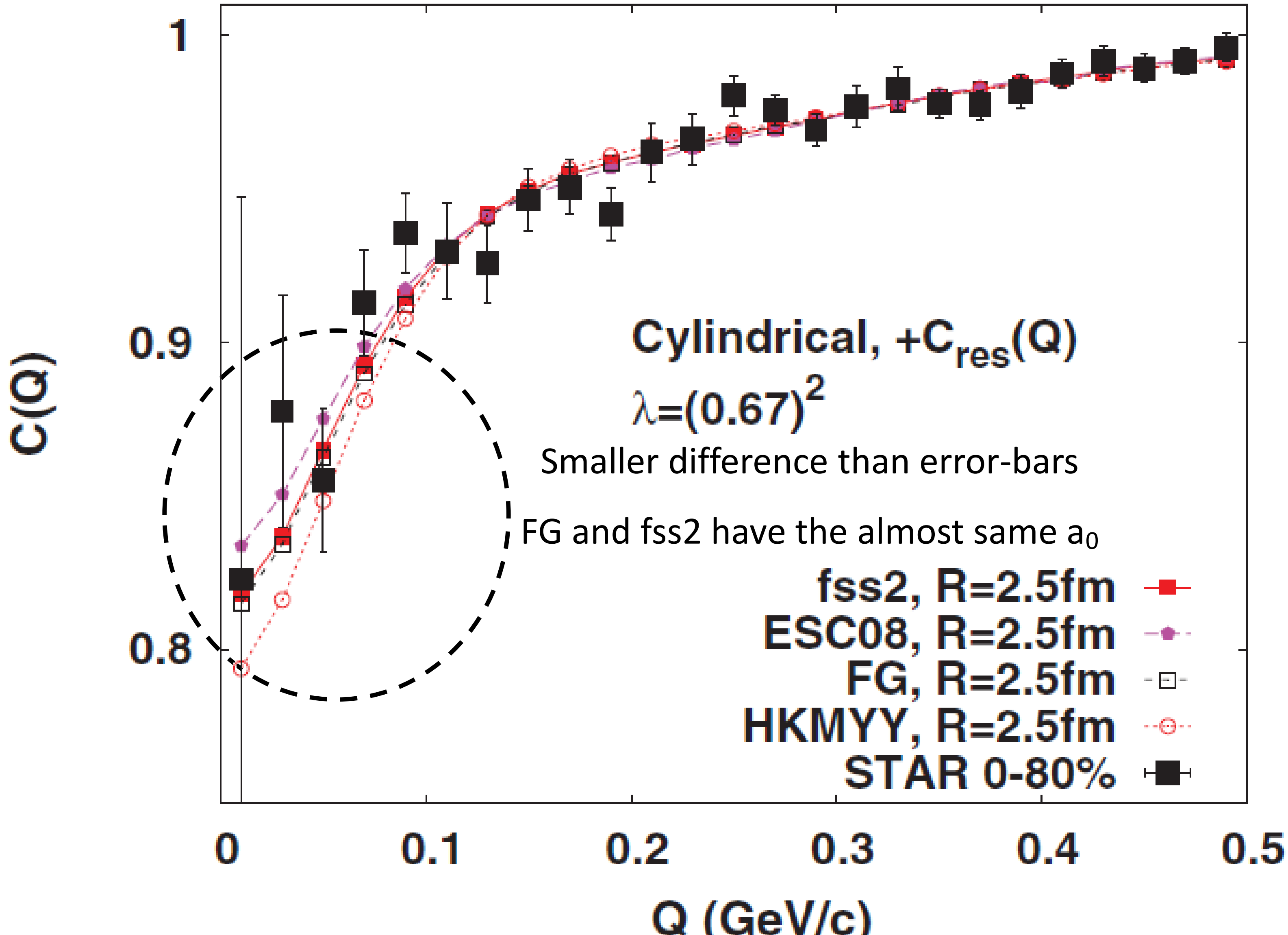
$$C(Q) \to C(Q) + a_{\rm res} e^{-r_{\rm res}^2 Q^2}$$

- それぞれのRについて
  $(a_{\rm res}, r_{\rm res})$ で$\min\chi^2$ 探索
- Rによらず $\chi^2/N_{\rm dof} \sim 1$
- Small R : Large $r_{\rm res}$ > R

Low Q behavior ⇎ $\Lambda\Lambda$ Interaction

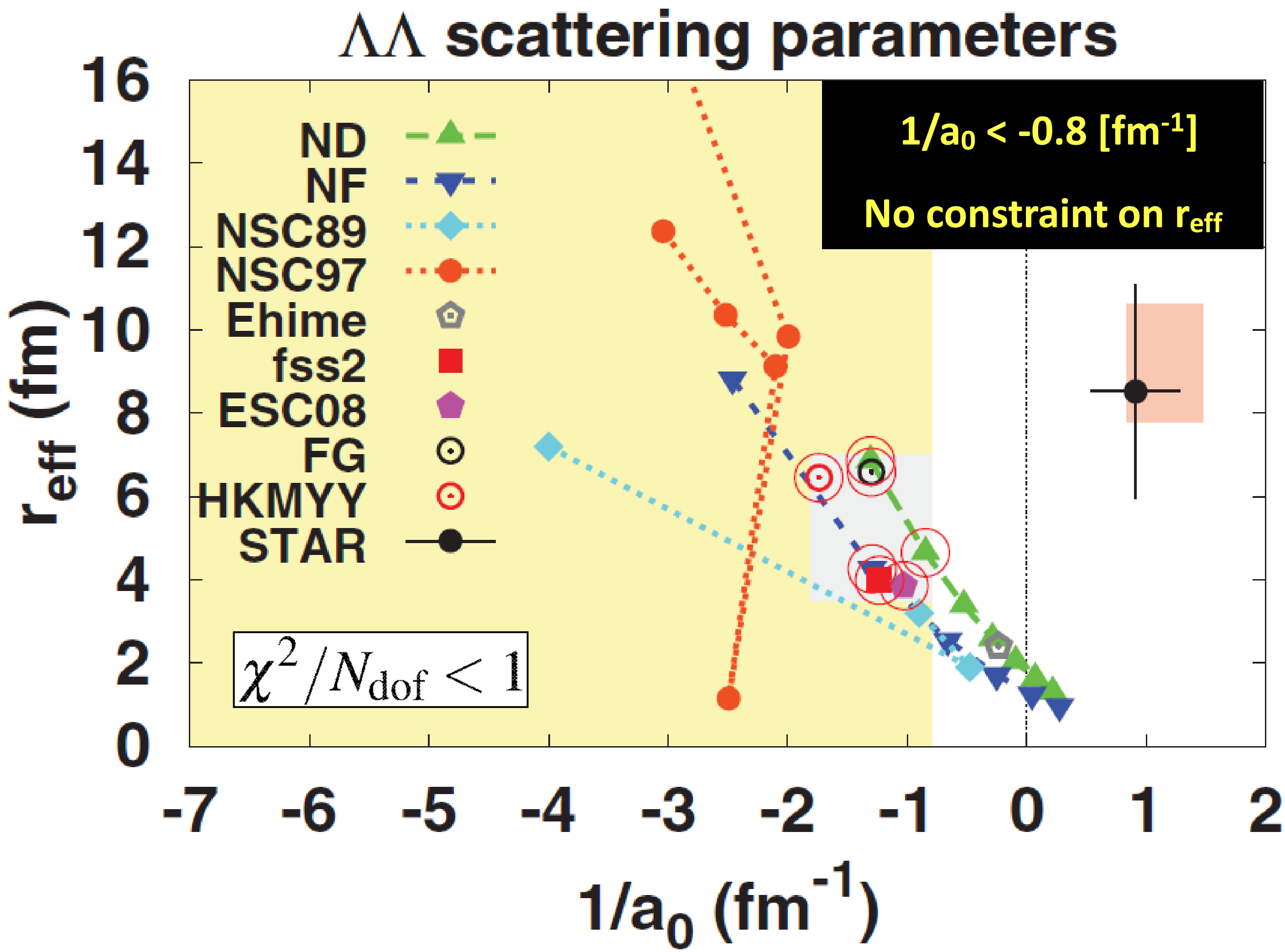


Fit結果例



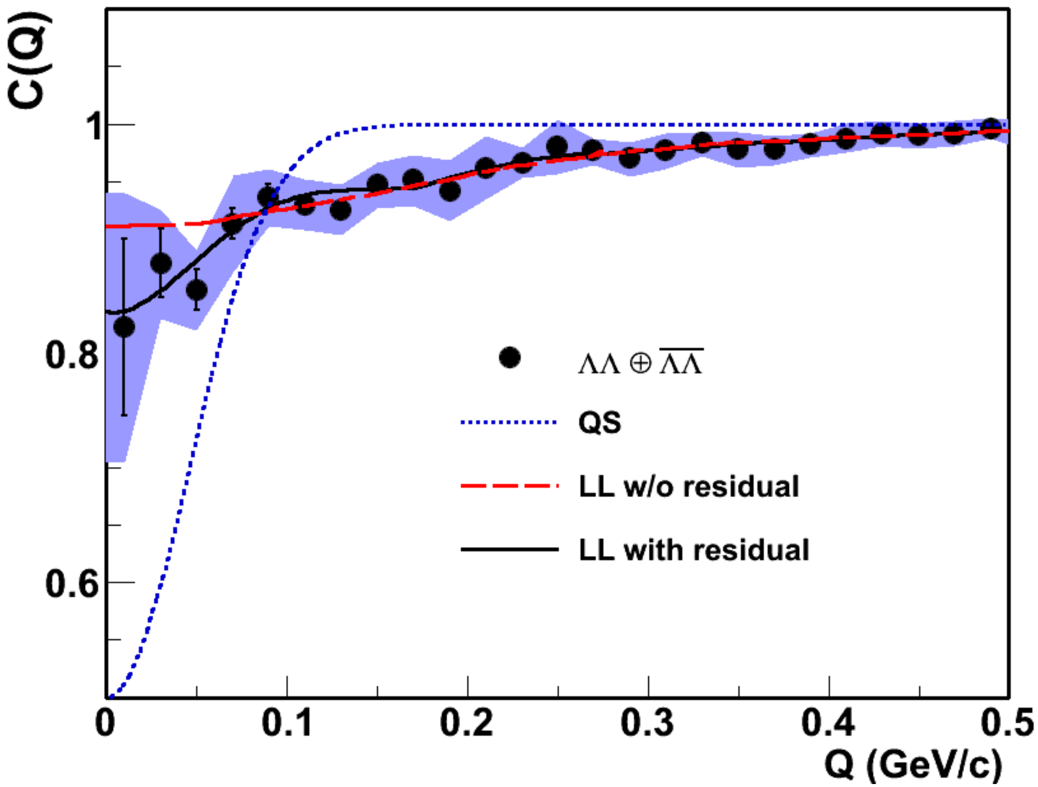
1
0.9
0.8
C(Q)
0
0.1
0.2
0.3
0.4
0.5
Q (GeV/c)
Cylindrical, +C_{res}(Q)
$\lambda=(0.67)^2$
Smaller difference than error-bars
FG and fss2 have the almost same a_0
fss2, R=2.5fm
ESC08, R=2.5fm
FG, R=2.5fm
HKMYY, R=2.5fm
STAR 0-80%

Constraints on a_0 and r_{eff}



STAR Coll.の解析

PRL114 '15



Interaction: Lednicky-Lyuboshitz model

Fit w/ 7 paramaters

$a_0 > 0$: 引力

$$a_0 = -1.10 \pm 0.37^{+0.68}_{-0.08}\ \mathrm{fm}$$

$$r_{\mathrm{eff}} = 8.52 \pm 2.56^{+2.09}_{-0.74}\ \mathrm{fm}$$

$$\chi^2/N_{\mathrm{dof}} = 0.56$$

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

HBT (size r_0) Interaction Residual correlation

1.006 0.18 2.96 fm -0.044 0.43 fm

まとめと展望

- 重イオン衝突(QGP生成)から $\Lambda\Lambda$ interaction
- 膨張の効果
- 崩壊から来る寄与の除去が重要
  - うまくできれば強い制限
  - できなければごく弱い制限
- $\Lambda\Lambda$散乱長： $1/a_0 < -0.8\ \mathrm{fm}^{-1}$

- 他のチャンネルにも応用可能
- 統計の問題：LHCに期待

(Λp は綺麗なデータがあり)

Backup

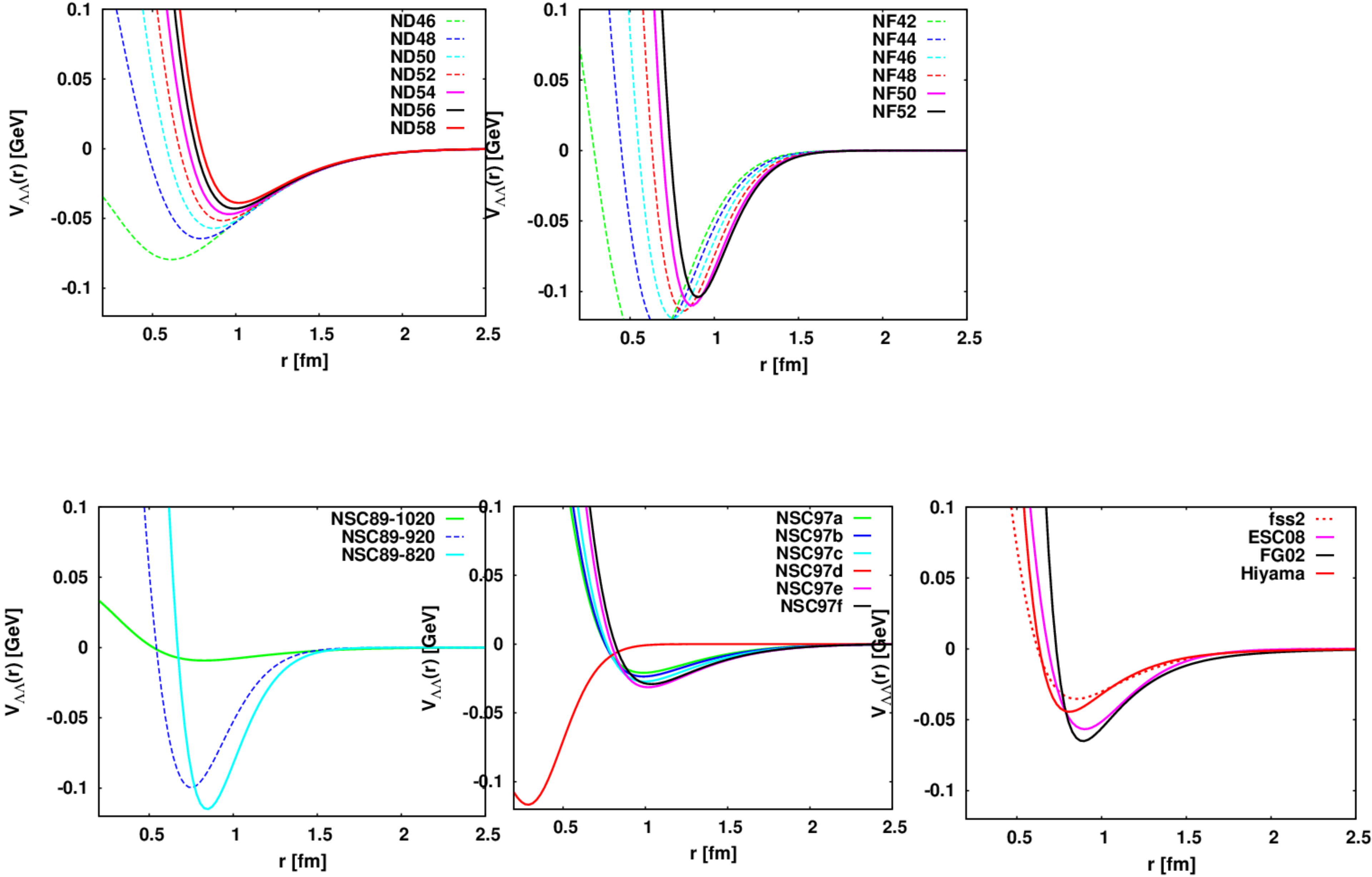
TABLE I: $\Lambda\Lambda$ potentials. The scattering length (a_0) and effective range ($r_{\rm eff}$) are fitted using a two-range gaussian potential, $V_{\Lambda\Lambda}(r) = V_1 \exp(-r^2/\mu_1^2) + V_2 \exp(-r^2/\mu_2^2)$.

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]

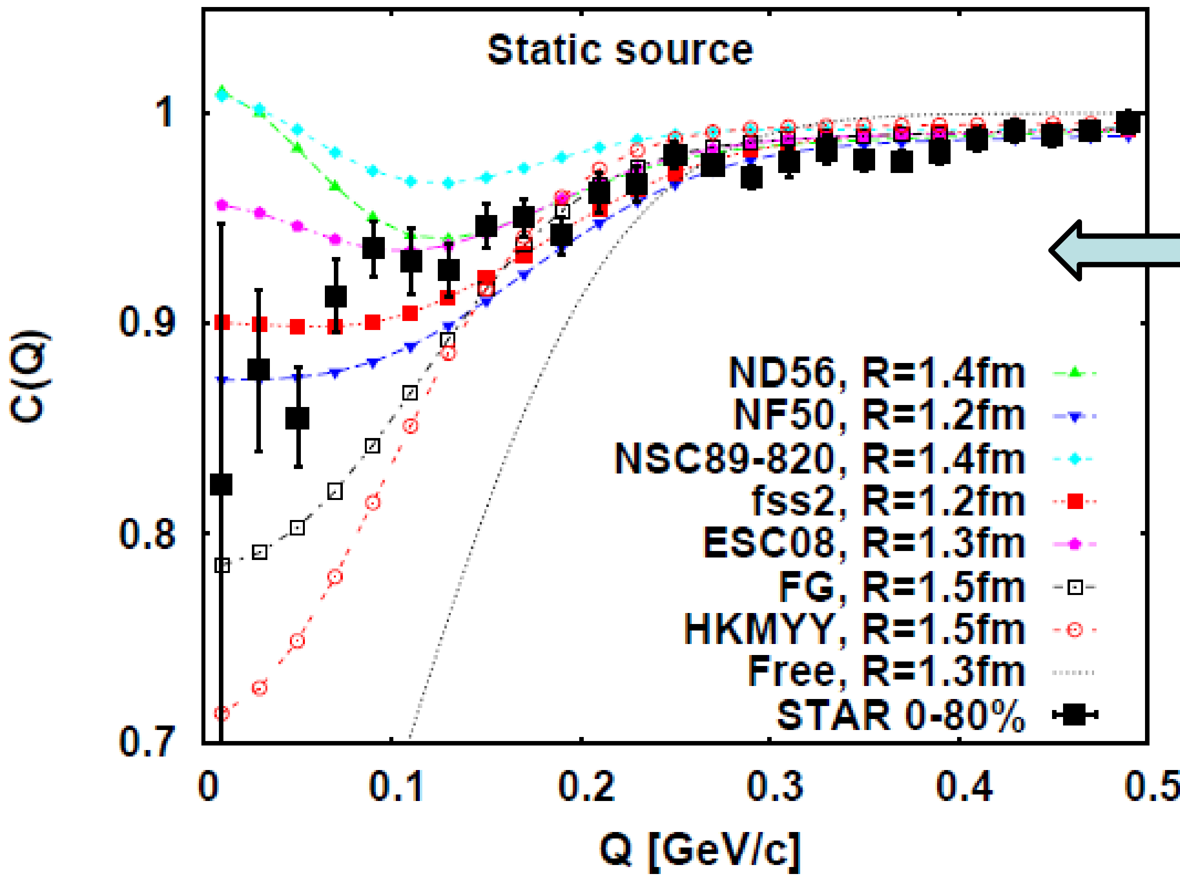
TABLE II: $\Lambda\Lambda$ potentials from Nagara event. The scattering length (a_0) and effective range ($r_{\rm eff}$) are fitted using a three-range gaussian potential, $V_{\Lambda\Lambda}(r) = V_1 \exp(-r^2/\mu_1^2) + V_2 \exp(-r^2/\mu_2^2) + V_3 \exp(-r^2/\mu_3^2)$.

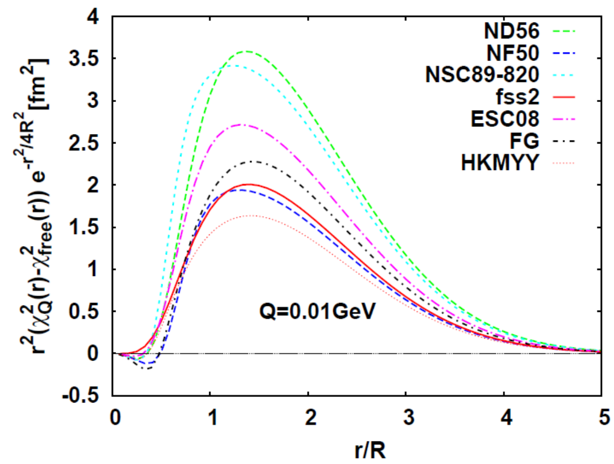
Model	a_0 (fm)	$r_{\rm eff}$ (fm)	μ_1 (fm)	V_1 (MeV)	μ_2 (fm)	V_2 (MeV)	μ_3 (fm)	V_3 (MeV)	Ref.
HKMYY	−0.575	6.45	1.342	−10.96	0.777	−141.75	0.35	2136.6	[3]
FG	−0.77	6.59	1.342	−21.49	0.777	−250.13	0.35	9324.0	[2]

$$
\begin{aligned}
N &= 1.006 \pm 0.001 \\
\lambda &= 0.18 \pm 0.05^{+0.12}_{-0.06} \\
a_0 &= -1.10 \pm 0.37^{+0.68}_{-0.08} \\
r_{\rm eff} &= 8.52 \pm 2.56^{+2.09}_{-0.74} \\
r_0 &= 2.96 \pm 0.38^{+0.96}_{-0.02} \\
a_{\rm res} &= -0.044 \pm 0.004^{+0.048}_{-0.009} \\
r_{\rm res} &= 0.43 \pm 0.04^{+0.43}_{-0.03} \\
\chi^2/N_{\rm dof} &= 0.56
\end{aligned}
$$


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

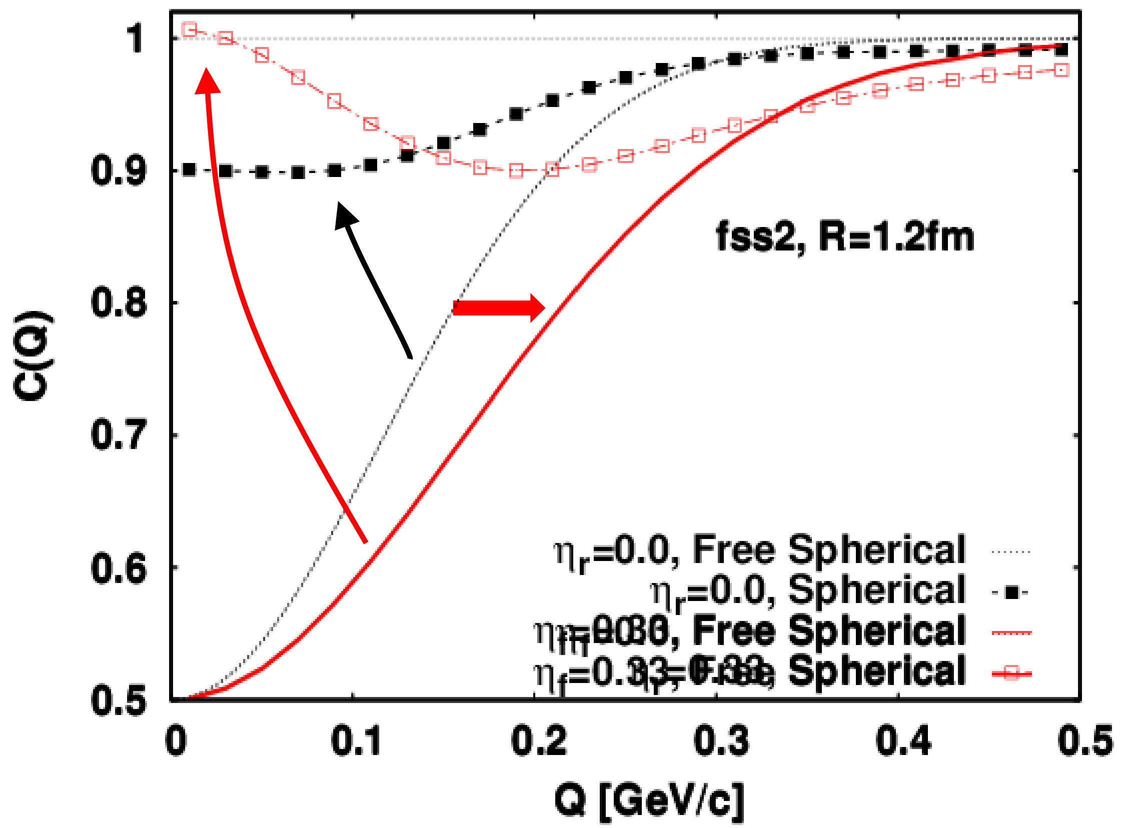
Collectivity Deforms Source Function

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

Influence on the best-fit potentials?

C(Q) is fairly sensitive
to interaction

Illustration : Spherical Source



Expansion makes the apparent source size smaller

Attraction in C(Q) becomes stronger