Hadron-Hadron Correlation and Interaction from High-Energy Collisions

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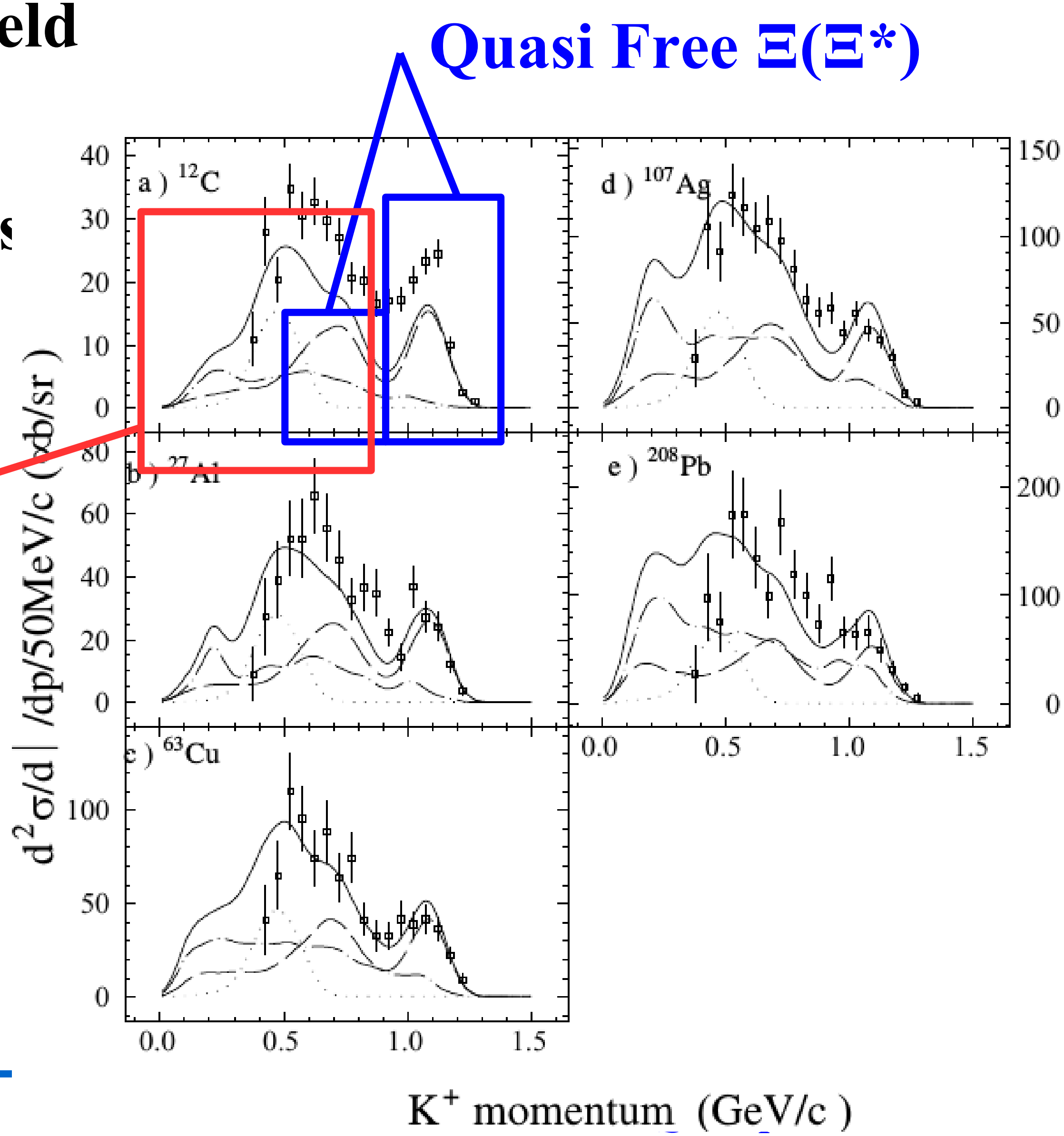
Hadron Interactions and Polarization from Lattice QCD, Quark Model, and Heavy-Ion Collisions, Mar. 25- Apr. 5, 2019, Kyoto, Japan

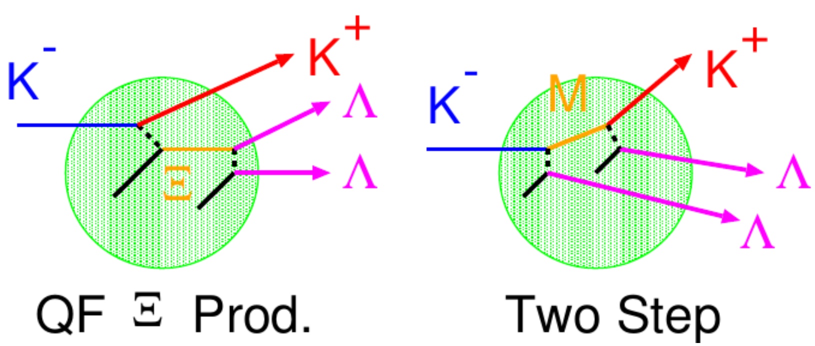
K. Morita, T. Furumoto, AO, PRC91('15)024916 (ΛΛ)
AO, K. Morita, K. Miyahara, T. Hyodo, NPA954 ('16)294 (ΛΛ, K–p).
K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16), 031901(R) (ΩN).
S. Cho et al.(ExHIC Collab.), Prog.Part.Nucl.Phys.95('17)279 (ΛΛ, K–p).
T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17), 856 (Ξ–p).
K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep. (NΩ, ΩΩ)

Pre-History

(K⁻, K⁺) reaction

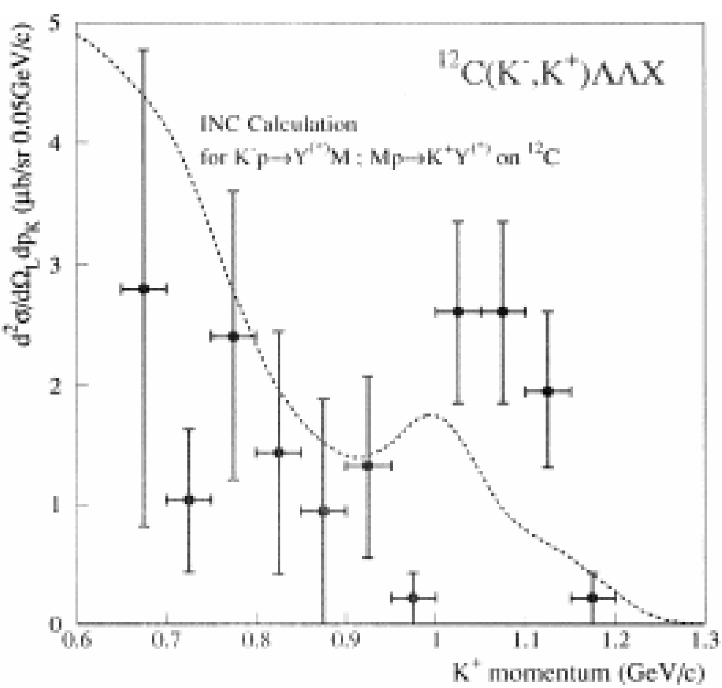
- **(K⁻, K⁺) reaction = doorway to produce S=-2 systems**
  - **K⁻ p → K⁺ Ξ⁻ → Ξ nuclei, stopped Ξ to ΛΛ nuclei, …**
- **What is the origin of large yield at smaller K+ momentum ?**
  T. Iijima et al., NPA546('92) 588.
  → Various two step processes
  Y. Nara, AO, T. Harada, A. Engel, NPA614('97)433

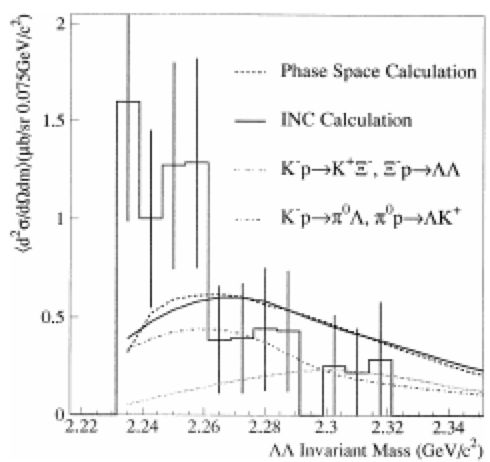


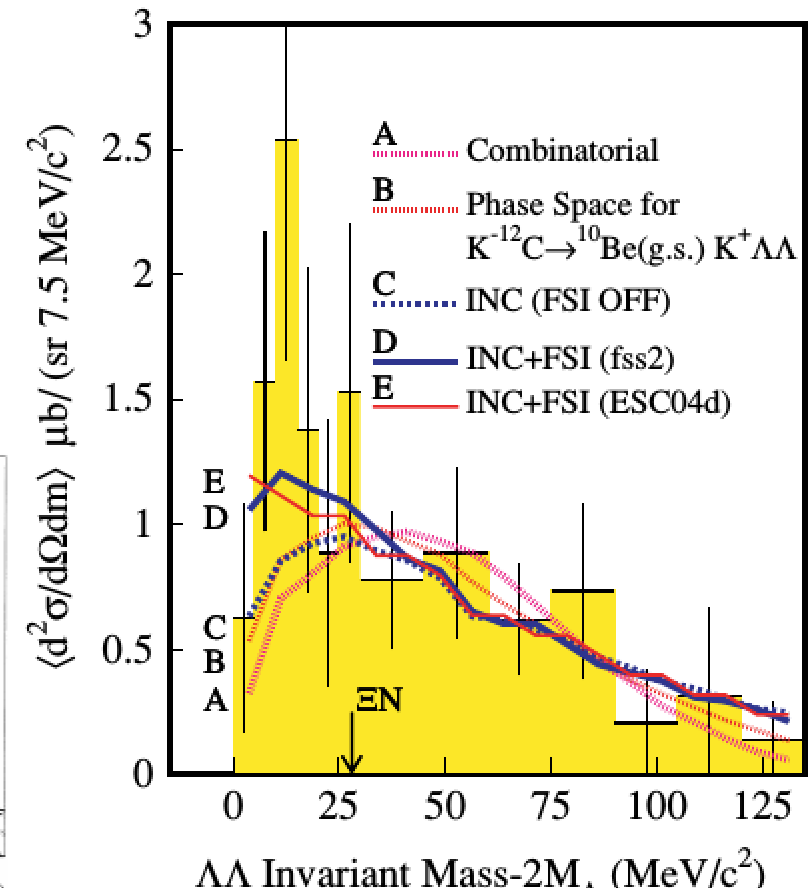


Two Λ production in (K^-, K^+) reactions

- **Experimentalists really measured two Λ emission !**
  J.K.Ahn et al. (KEK-PS E224 Collab.), PLB444('98)267.
  C. J. Yoon et al. (KEK-PS E522 Collab. +AO), PRC75('07)022201
- **Invariant mass spectrum of ΛΛ is enhanced from our cascade calculation.**
  → FSI enhancement ? or H particle ?





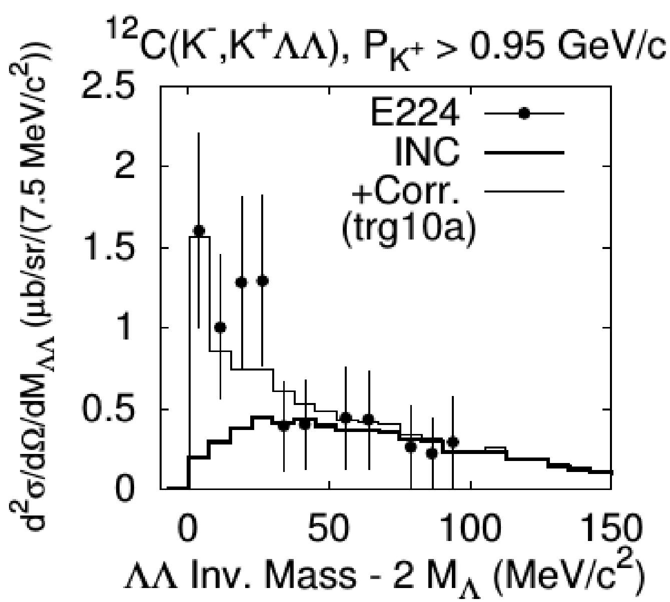


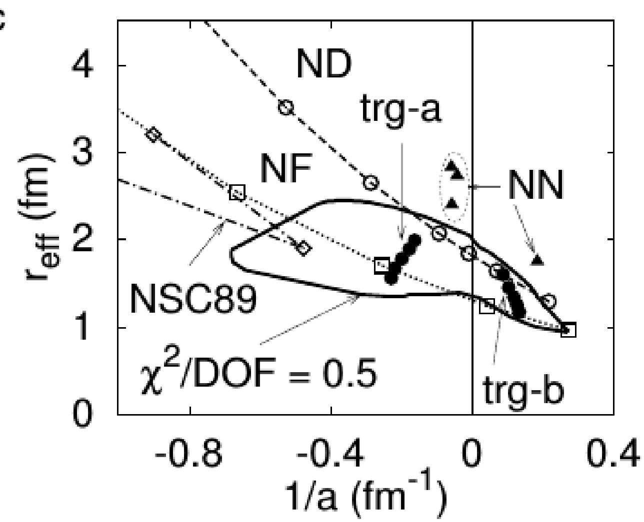
Ahn et al. (E224)('98)

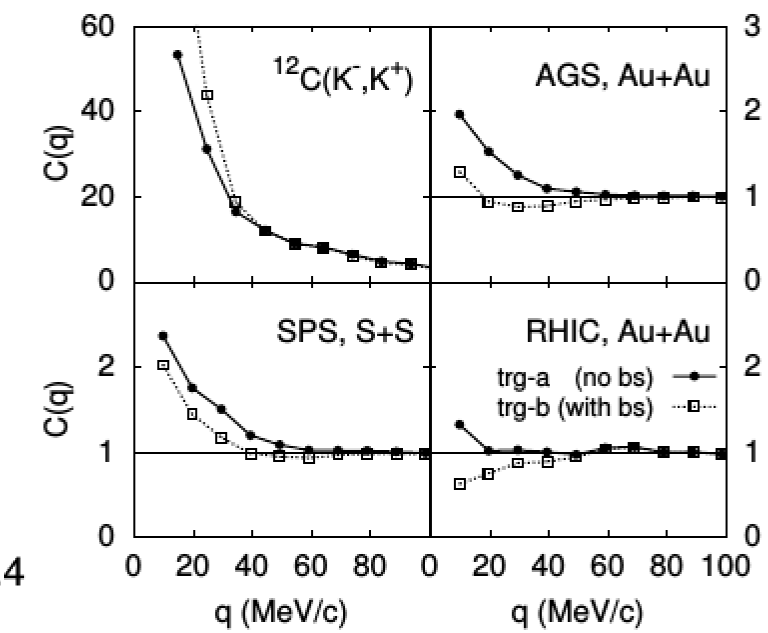
Yoon et al. (E522)('07)

From correlation to interaction

- **Enhancement of ΛΛ may show ΛΛ interaction effects !**
  AO, Y. Hirata, Y. Nara, S. Shinmura, Y. Akaishi,
  NPA670('00)297c; NPA684('01)595; NPA691('01)242c
  - **Enh. is roughly explained by ΛΛ final state int.**
  - **It should be clearer to measure in heavy-ion collisions.**
    Enh. w/o bound state, Suppression w/ bound state.
    → I asked Prof. Huan Z. Hunag (STAR) in ExHIC 2010 meeting
    and they measured it !







AO, Hirata, Nara, Shinmura, Akaishi ('00)

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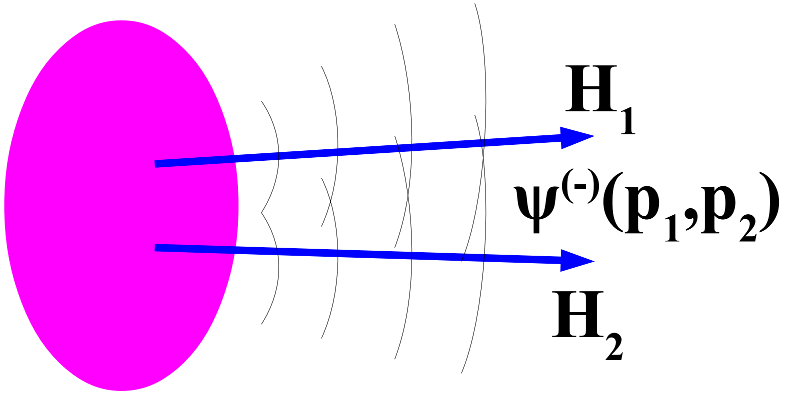
- **Summary**

Two Particle correlation and Correlation Function

Hadron-Hadron Correlation in HIC

- **Hadron-Hadron Correlation Func. (Koonin-Pratt (KP) formula)**
  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 ('92)77; R. Lednicky, V. L. Lyuboshits, Sov. J. Nucl. Phys. 35 ('82) 770.



$$C(\boldsymbol{q}) = \frac{E_1 E_2 dN_{12}/d\boldsymbol{p}_1 d\boldsymbol{p}_2}{(E_1 dN_1/d\boldsymbol{p}_1)(E_2 dN_2/d\boldsymbol{p}_2)} \simeq \int d\boldsymbol{r}\, \underline{S_{12}(\boldsymbol{r})}\, \underline{\left|\psi_{12}^{(-)}(\boldsymbol{r},\boldsymbol{q})\right|^2}$$

Source fn. **int. → relative w.f.**

q: rel. mom. (referred to also as k*)

- **Static sph. Gaussian source, Int. for s-wave, Identical fermions**

$$C(q) \simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int d^3r\, \underline{S_{12}(r)} \left[\underline{|\psi_0(r)|^2} - \underline{|j_0(qr)|^2}\right]$$

Fermion (Quant. Stat.) **Source** **s-wave w.f.** **free**

Lednicky-Lyuboshits (LL) model

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

$$\psi_0(r) \to \psi_{\rm asy}(r) = \frac{e^{-i\delta}}{qr}\sin(qr+\delta) = \mathcal{S}^{-1}\left[\frac{\sin qr}{qr} + f(q)\frac{e^{iqr}}{r}\right]$$

$$\Delta C_{\rm LL}(q) = \int d\boldsymbol{r} S_{12}(r)\left(|\psi_{\rm asy}(r)|^2 - |j_0(qr)|^2\right)$$
$$= \frac{|f(q)|^2}{2R^2}F_3\left(\frac{r_{\rm eff}}{R}\right) + \frac{2{\rm Re}f(q)}{\sqrt{\pi}R}F_1(x) - \frac{{\rm Im}f(q)}{R}F_2(x)$$

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

- **Phase shifts**

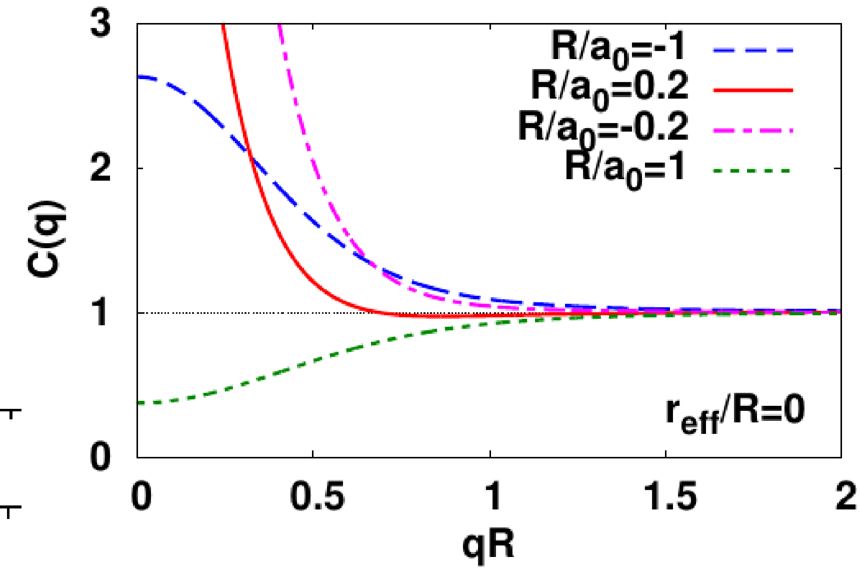
$$q\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}q^2 + \mathcal{O}(q^4) \to \delta \simeq -a_0 q + {\rm O}(q^3)$$

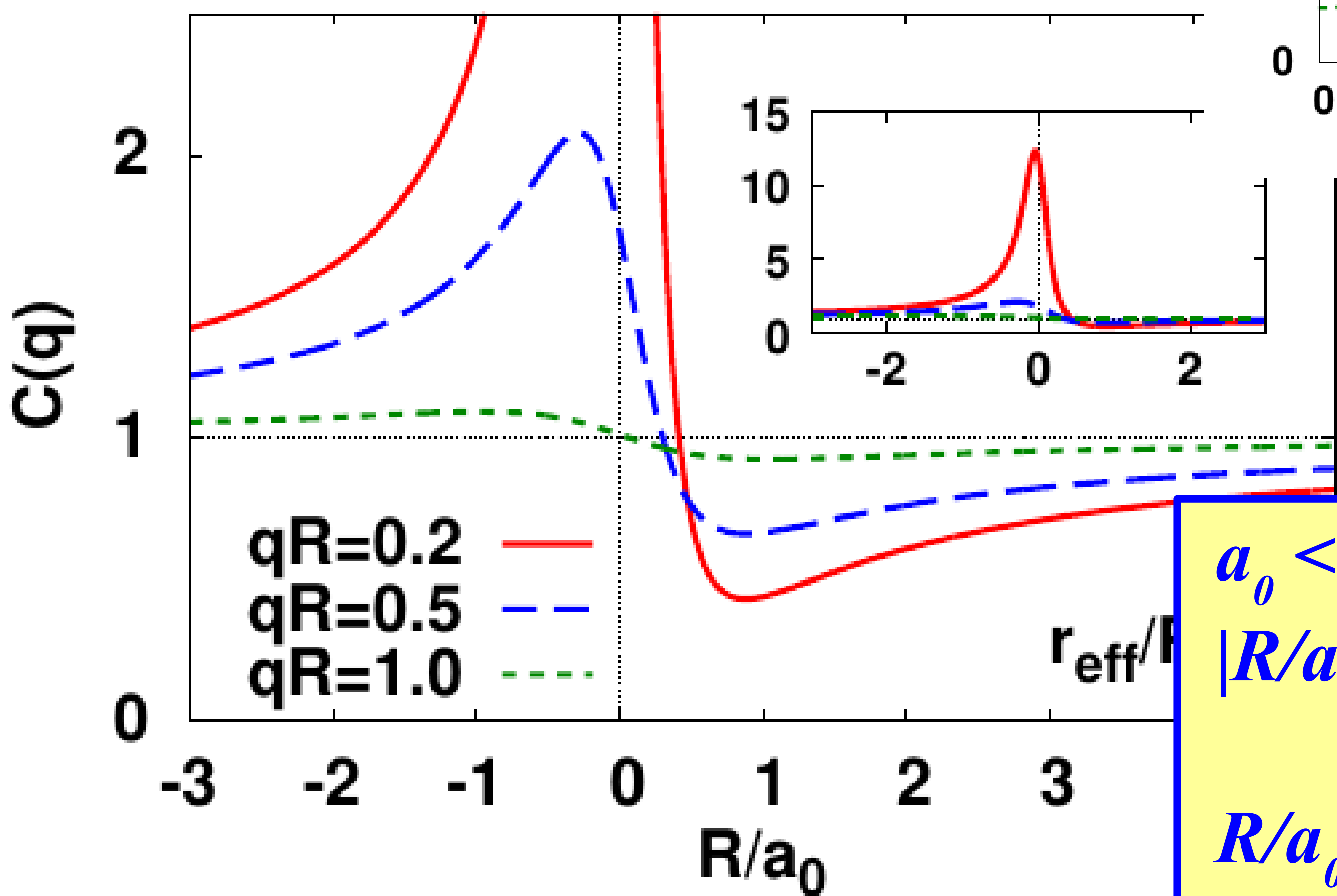
$$\sin(qr+\delta) \simeq \sin(q(r-a_0)+\cdots)$$

Node at r ~ a_0 for small q

Interaction Dependence of Correlation Function

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



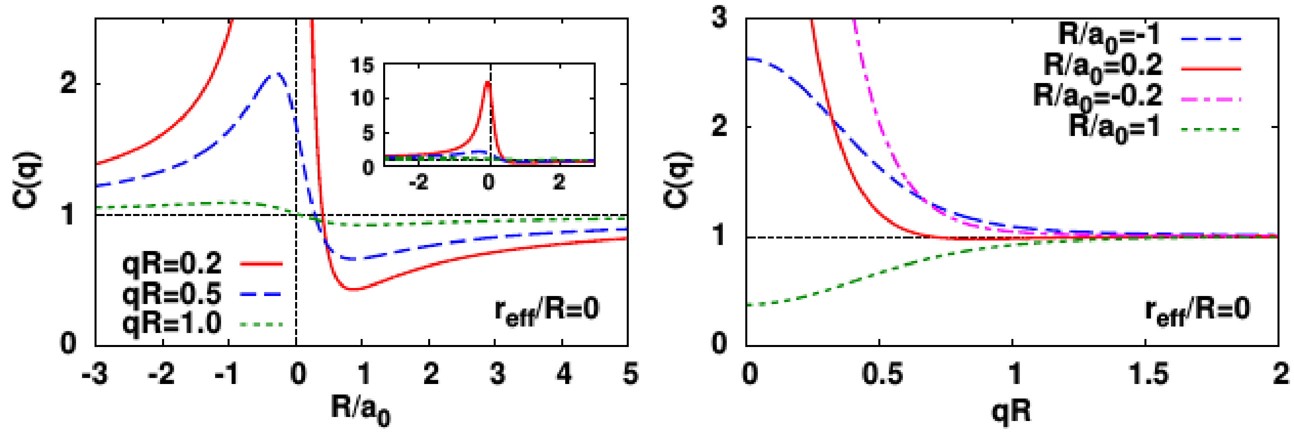


$a_0 < 0 \rightarrow$ Enhancement

$|R/a_0| \ll 1 \rightarrow$ Strong enh. at small q

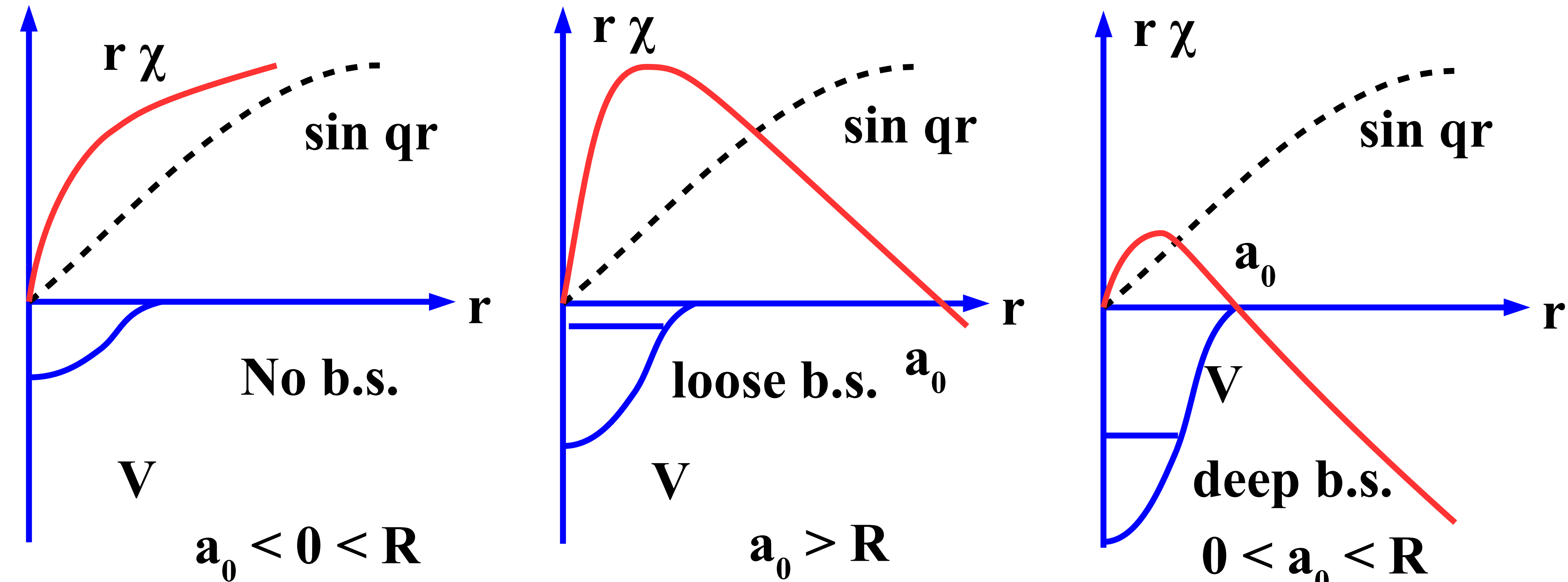
$R/a_0 > 1 \rightarrow$ Suppression

Interaction Dependence of Correlation Function

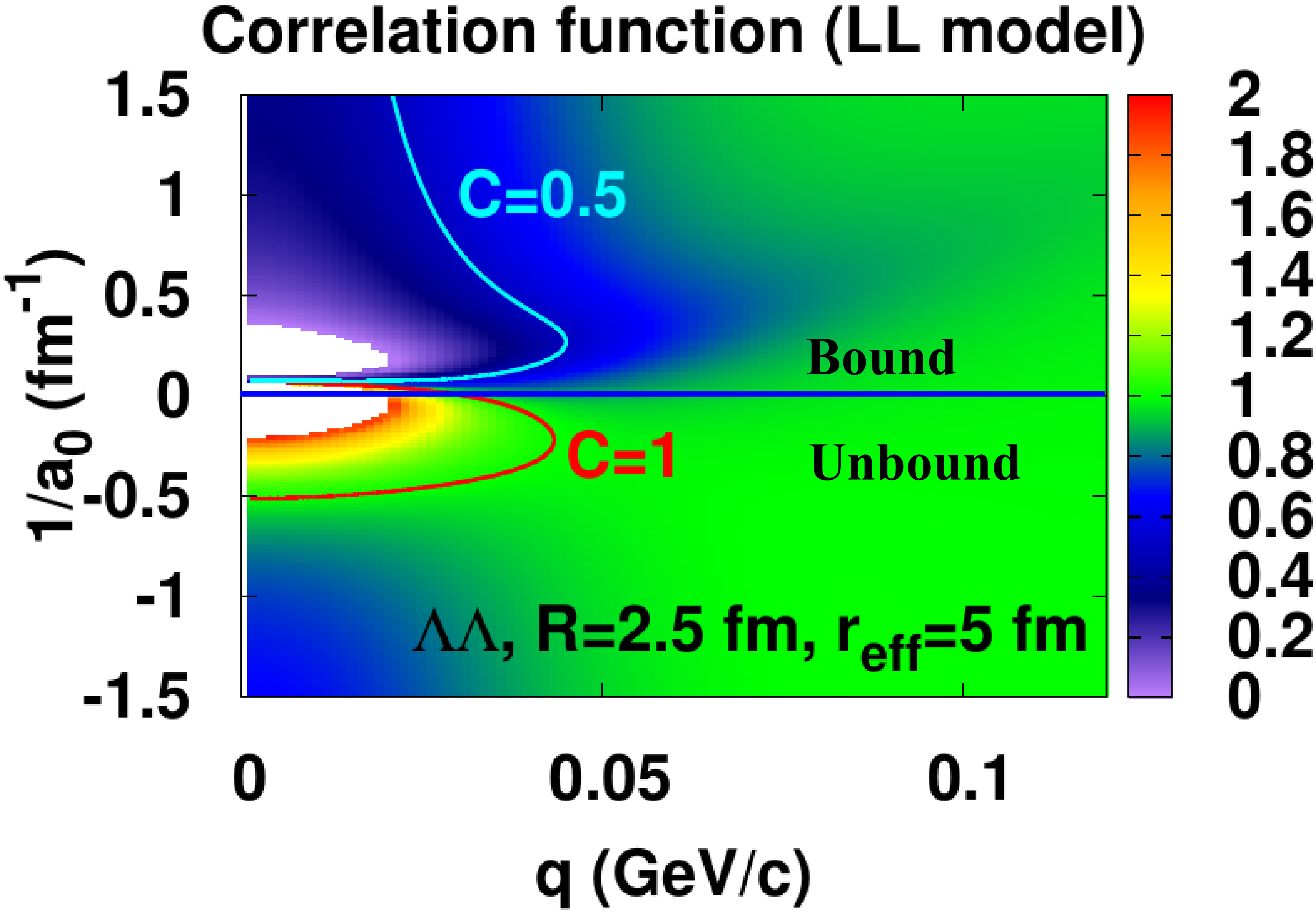


$$q \cot \delta = -1/a_0 + r_{\rm eff}\, q^2/2 + O(q^4)$$

w.f. node suppresses CF



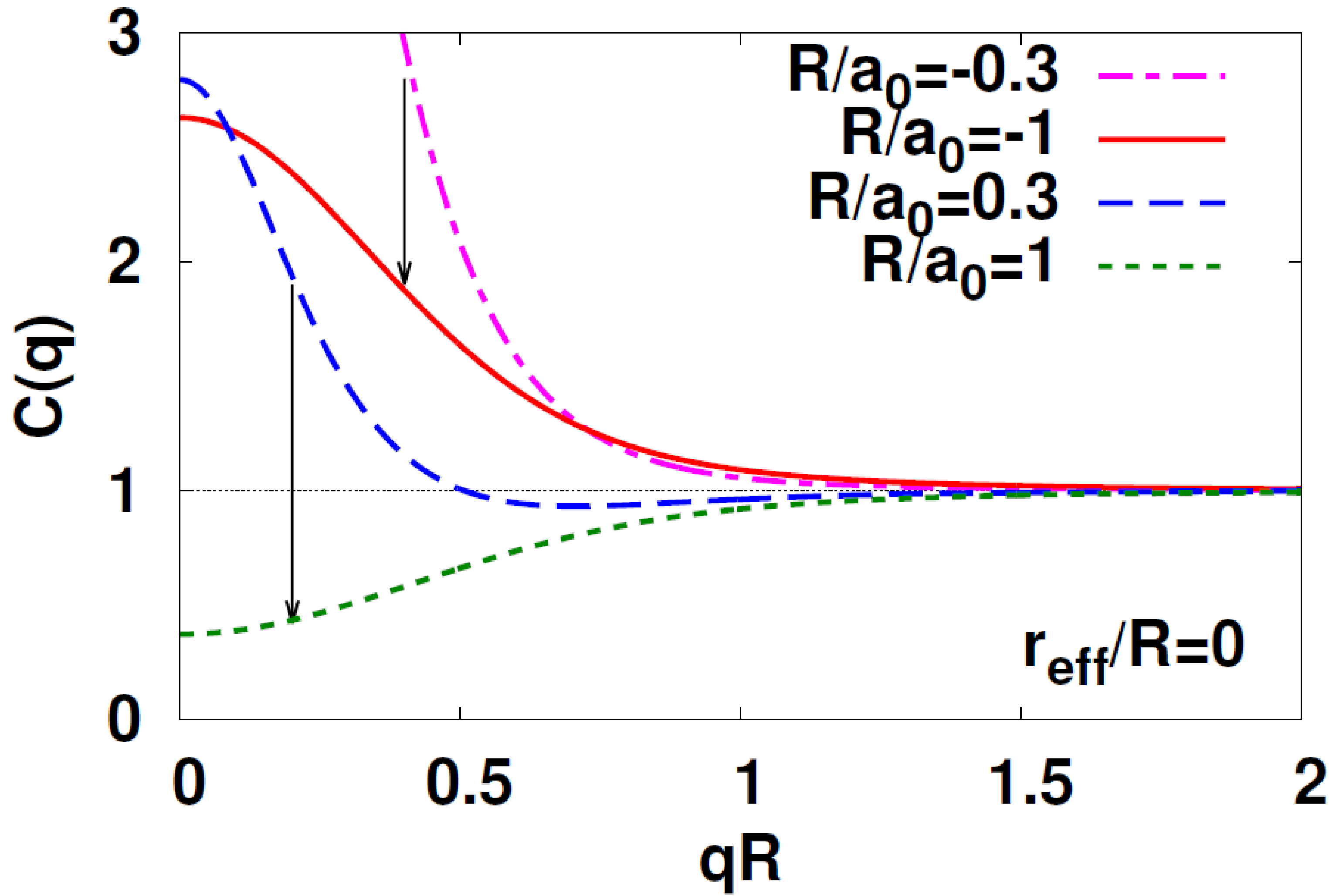
Interaction Dependence of Correlation Function



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

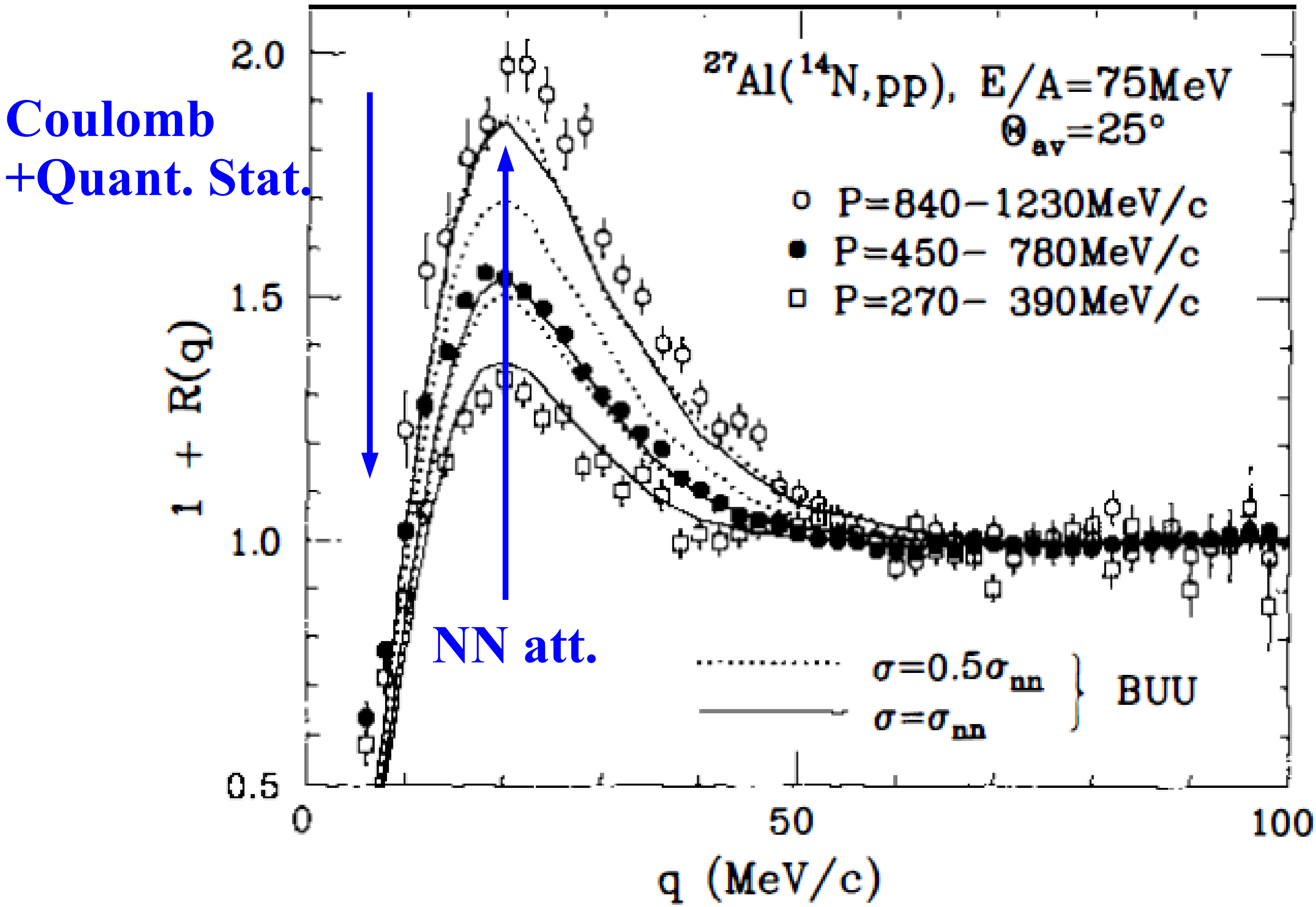
AO, K. Morita, K. Miyahara, T. Hyodo, NPA954 ('16), 294.

How can we distinguish positive and negative a_0 ?



Size dependence will help to tell the sign of a0.
Positive a0 → CF decreases and becomes negative for large R
Negative a0 → CF decreases but stay above unity.

How does interaction modifies correlation ?



Bauer et al. ('92)

Standard Usage
Known Int. + Corr. Fn. → Source Size

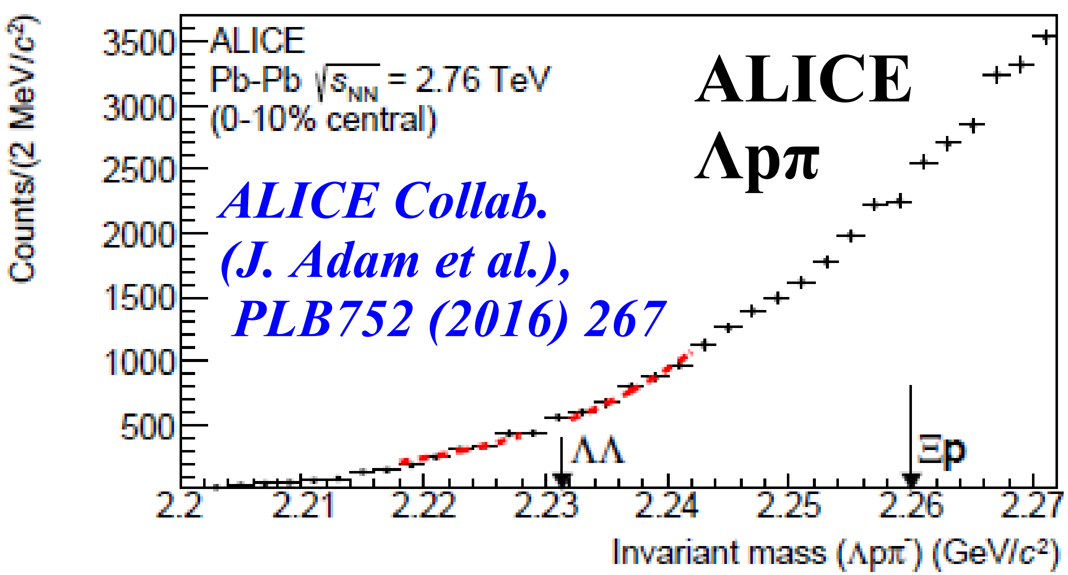
$$C(\mathbf{q}) = \int d^3r\, S_{12}(\mathbf{q},\mathbf{r}) \left|\psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$

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

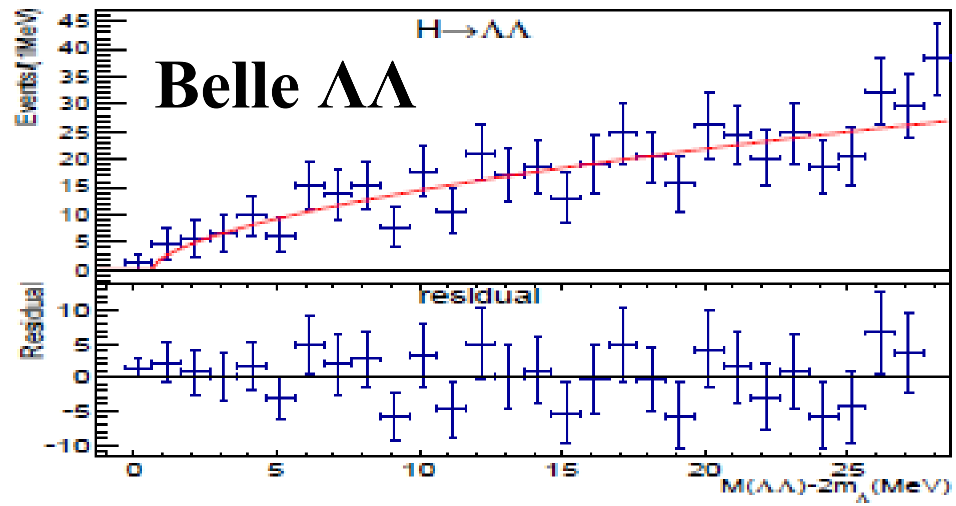
Let us try ! Examples: ΛΛ, Ω^- p, and K^-p

Previous works (ΛΛ):C. Greiner, B. Muller, PLB219('89)199.; AO, Y. Hirata, Y. Nara, S. Shinmura, Y. Akaishi , NPA 670 ('00), 297c

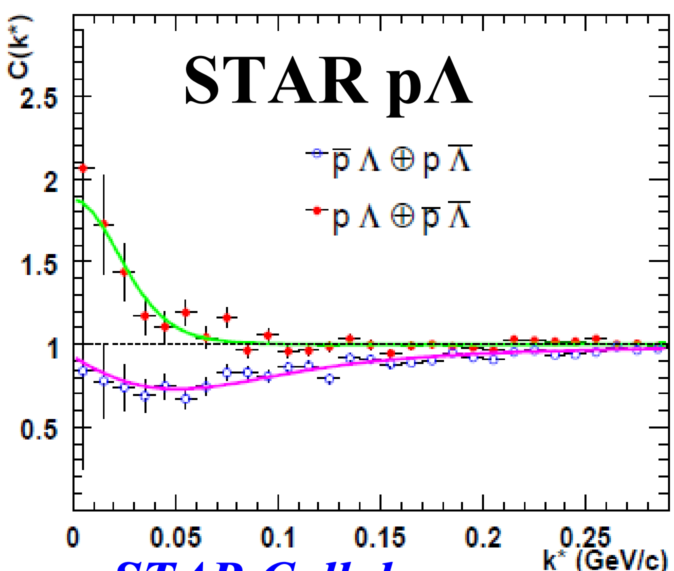
ΛΛ invariant mass / BB correlation function (as of 2016)



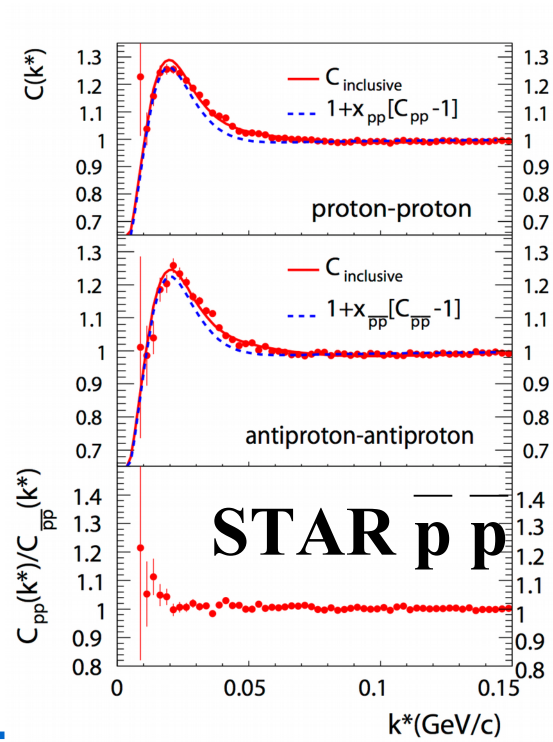
ALICE Collab. (J. Adam et al.), PLB752 (2016) 267



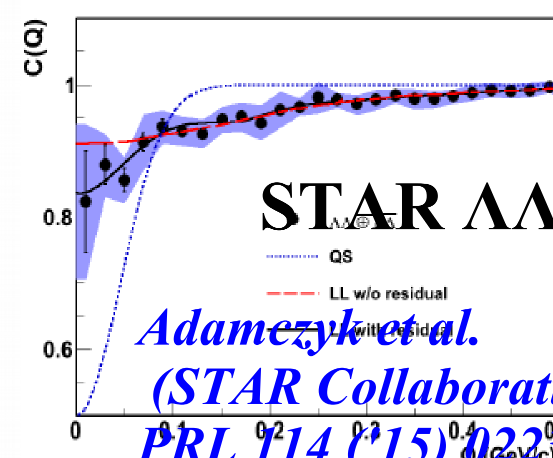
Belle Collaboration (Kim, B.H. et al.), PRL110('13)222002.



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



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

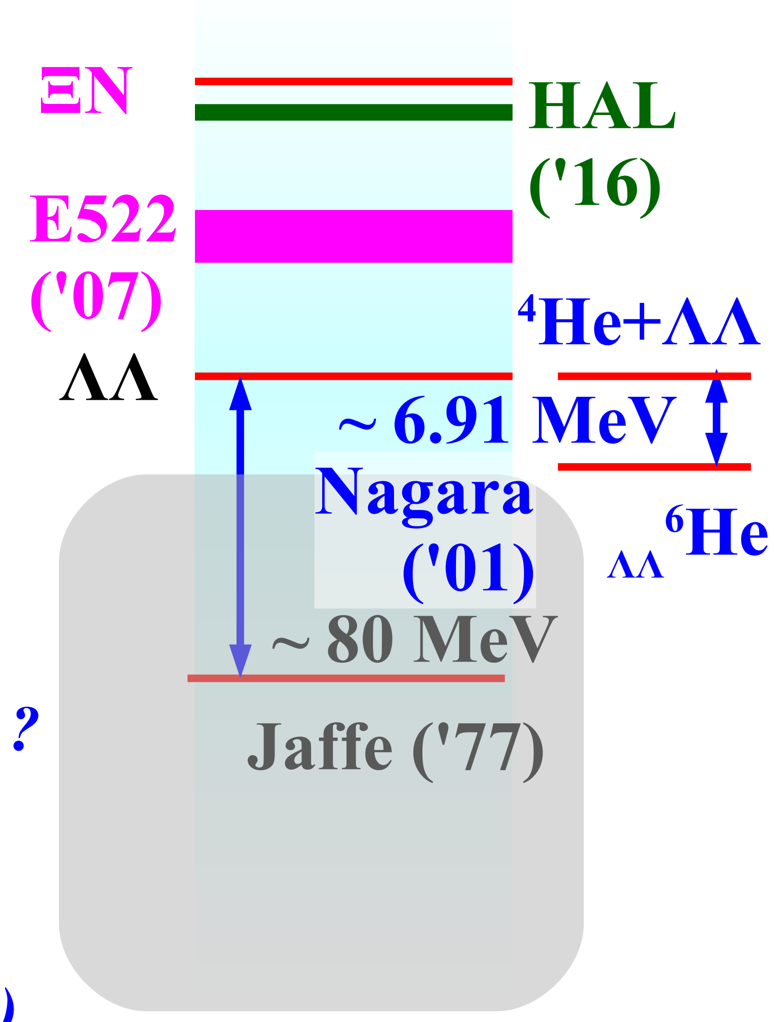


Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

ΛΛ correlation and ΛΛ interaction

Relevance of ΛΛ interaction to physics

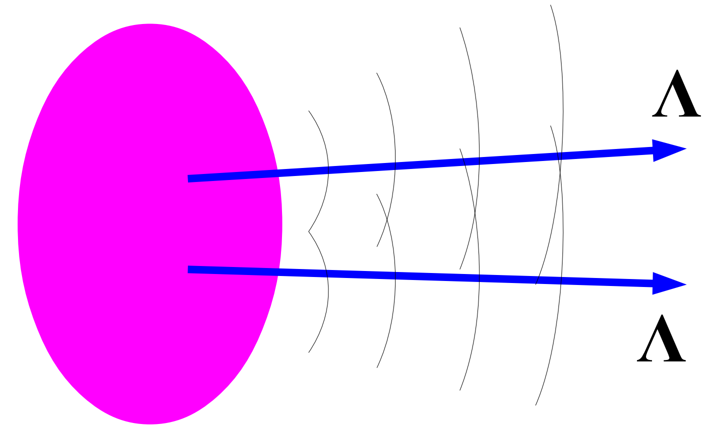
- **H-particle: 6-quark state (uuddss)**
  - **Prediction:** *R.L.Jaffe, PRL38(1977)195*
  - **Ruled-out by double Λ hypernucleus**
    Takahashi et al.,PRL87('01) 212502
  - **Resonance or Bound "H" ?**
    Yoon et al.(KEK-E522)+AO ('07)
  - **Lattice QCD**
    HAL QCD & NPLQCD ('11)
    HAL QCD ('16):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

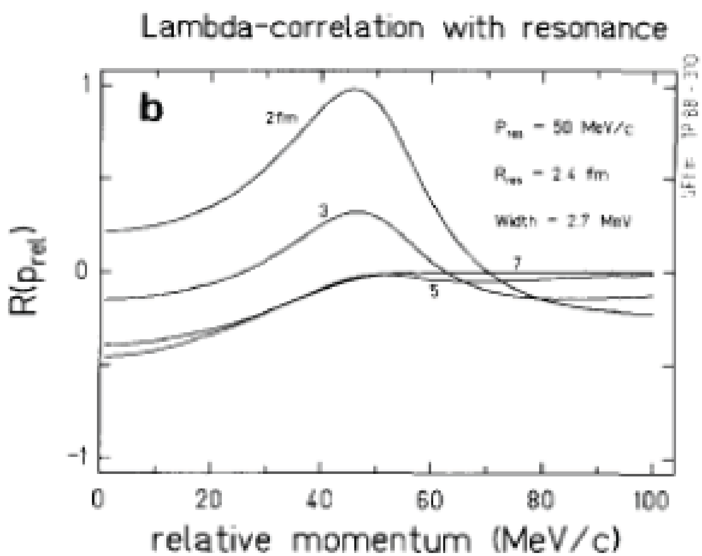


- **Neutron Star Matter EOS**
  - **Hyperon Puzzle**
    Demorest et al. ('10), Antoniadis et al. ('13)
  - **Cooling Puzzle (ΛΛ superfluidity)**
    T. Takatsuka, R. Tamagaki, PTP 112('04)37

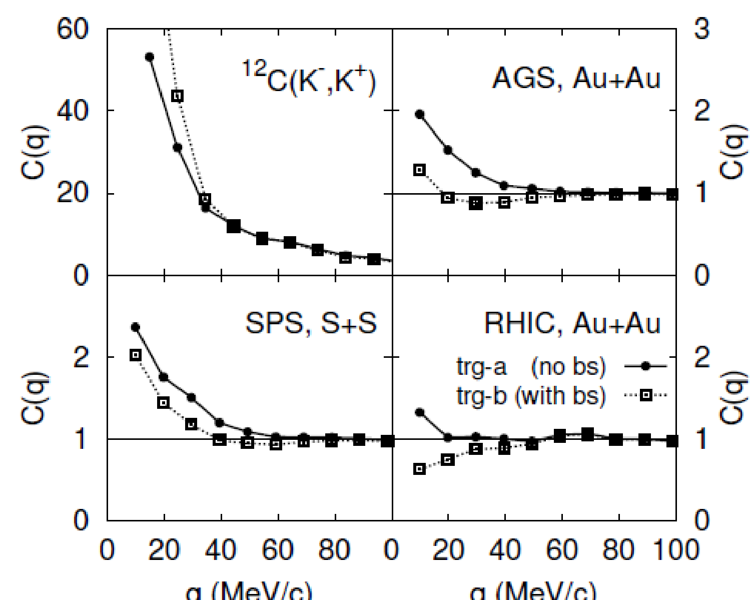
ΛΛ correlation in HIC

- **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).





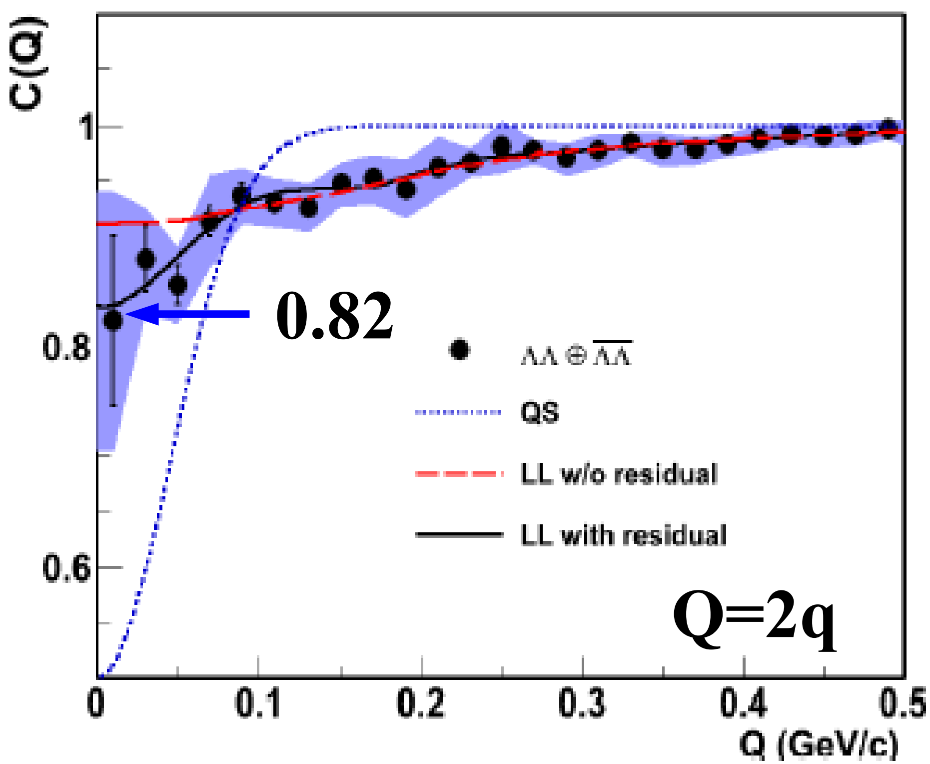
C. Greiner, B. Muller, PLB219('89)199.

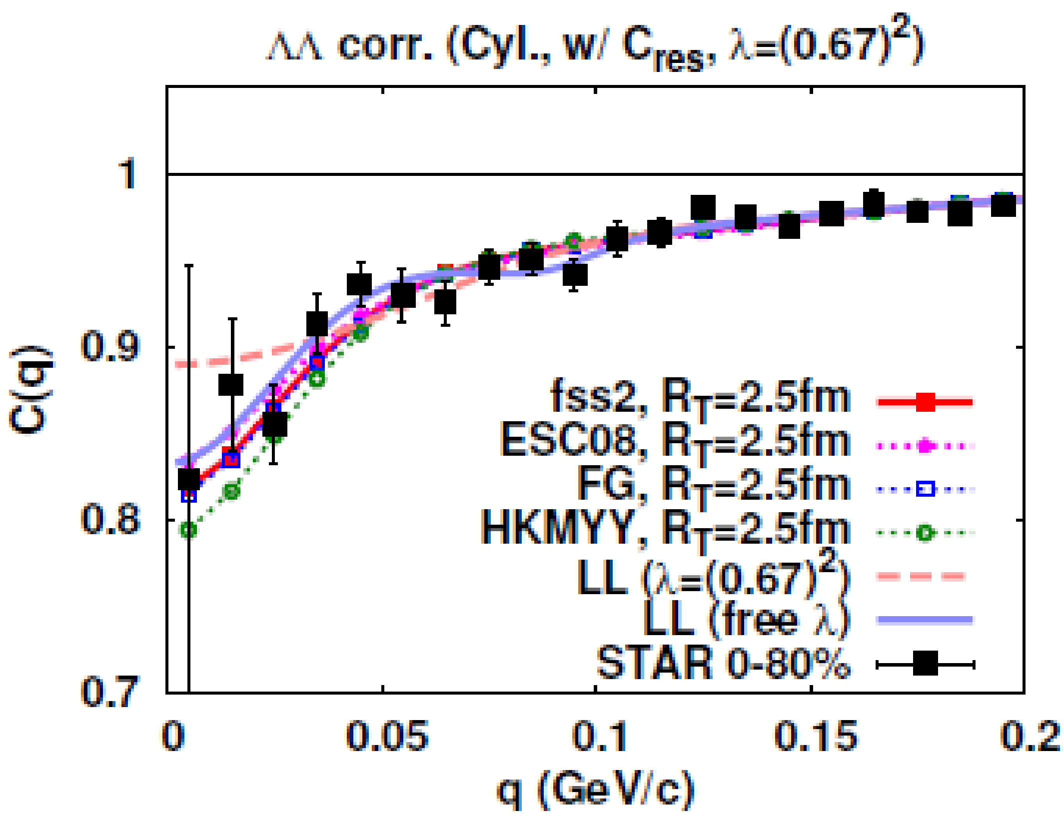


AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c

$\Lambda\Lambda$ correlation at RHIC

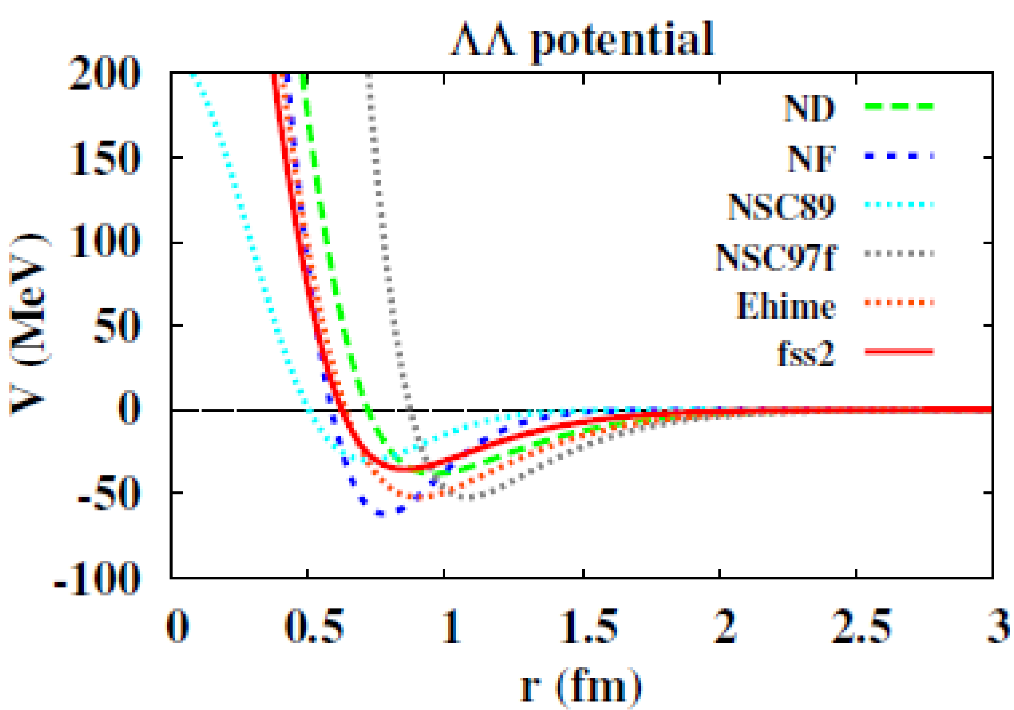
- **STAR collaboration at RHIC measured ΛΛ correlation !**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  - **RHIC, Au+Au ($\sqrt{s_{NN}}$=200 GeV), Weak decay vertex analysis.**
- **Theoretical Analysis well explains the data**
  K.Morita et al., T.Furumoto, AO, PRC91('15)024916;
 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

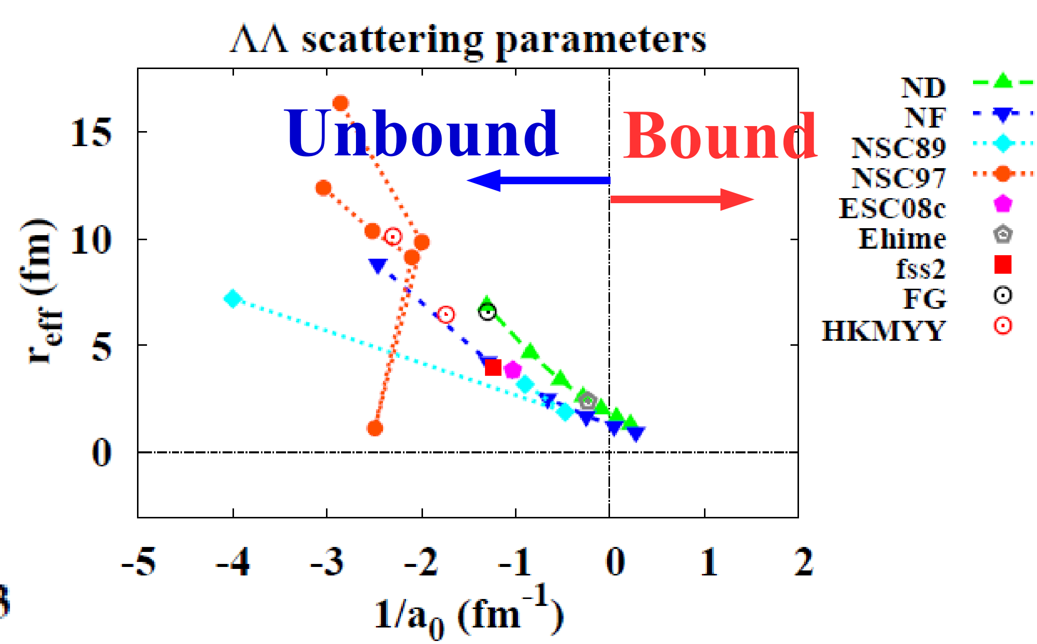




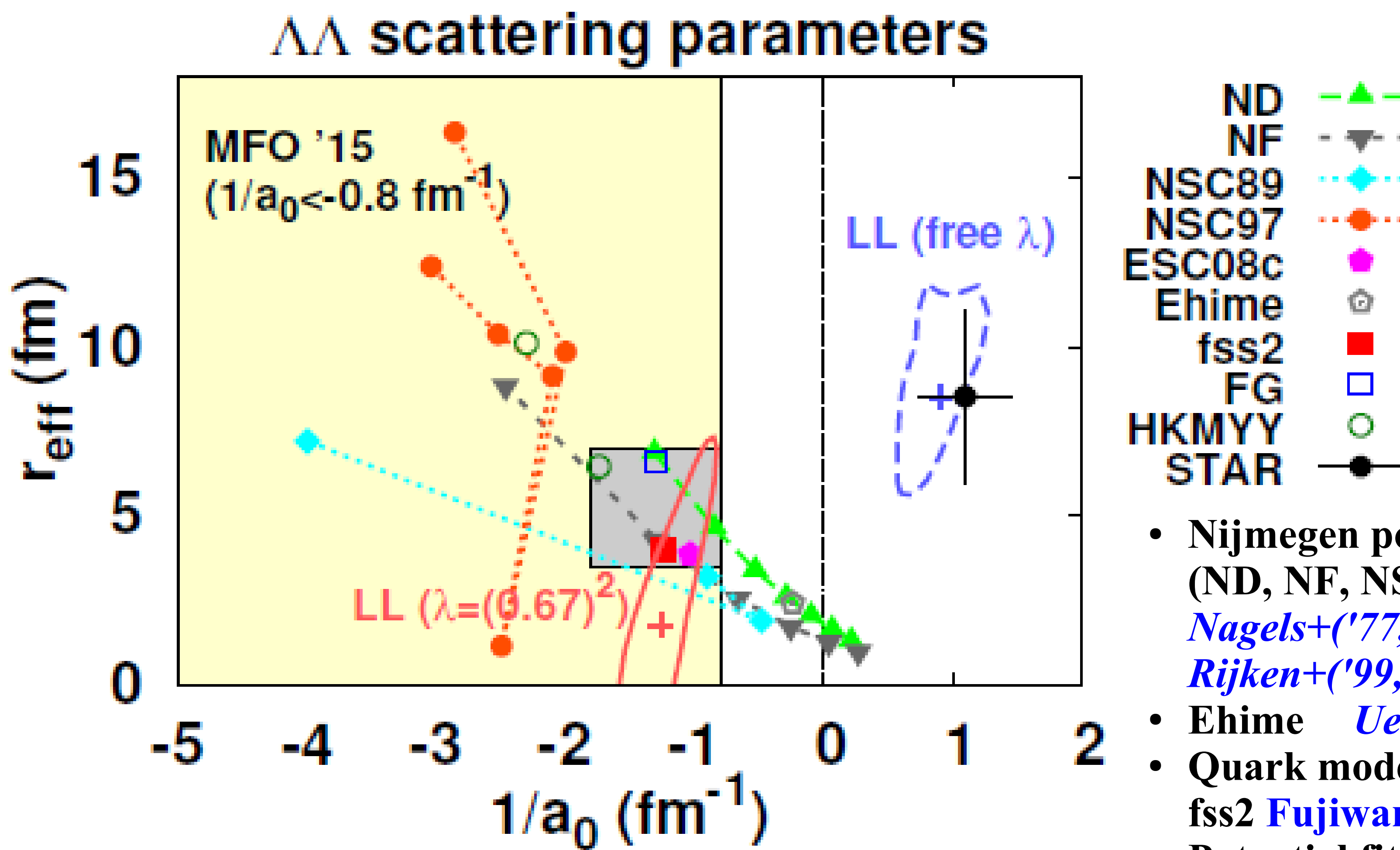
ΛΛ interaction

- **Propsed ΛΛ interactions**
  - **Meson Ex. models: Nijmegen model D, F, Soft Core (89, 97), ESC08**
    Nagels, Rijken, de Swart ('77, '79), Maessen, Rijken, de Swart ('89), Rijken, Stoks, Yamamoto ('99); Rijken, Nagels, Yamamoto ('10).
  - **Quark cluster model interaction: fss2**
    Fujiwara, Fujita, Kohno, Nakamoto, Suzuki ('00)
  - **Phenomenological model: Ehime** **T. Ueda et al. ('99).**
- **Two (or three) range gaussian fit results are used in the analysis.**





ΛΛ interaction from ΛΛ 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) ←→ Negative a_0 (MFO'15)
Difference comes from the pair purity

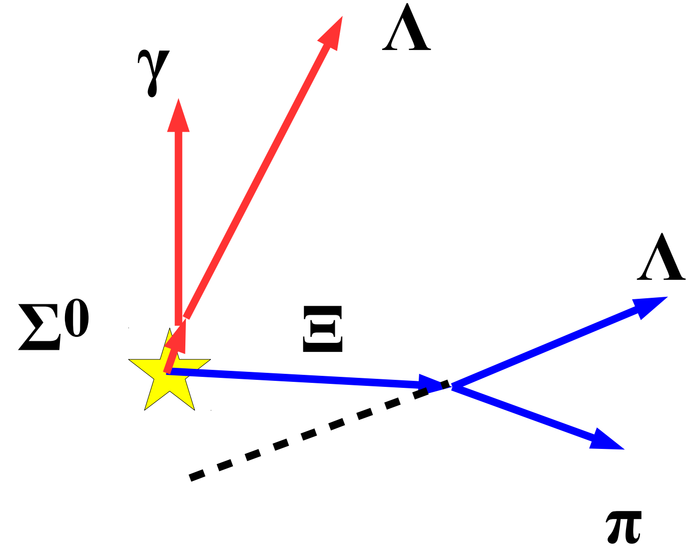
Additional Source

- **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)**
  - **$\Sigma^0 \to \Lambda\gamma$ 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)

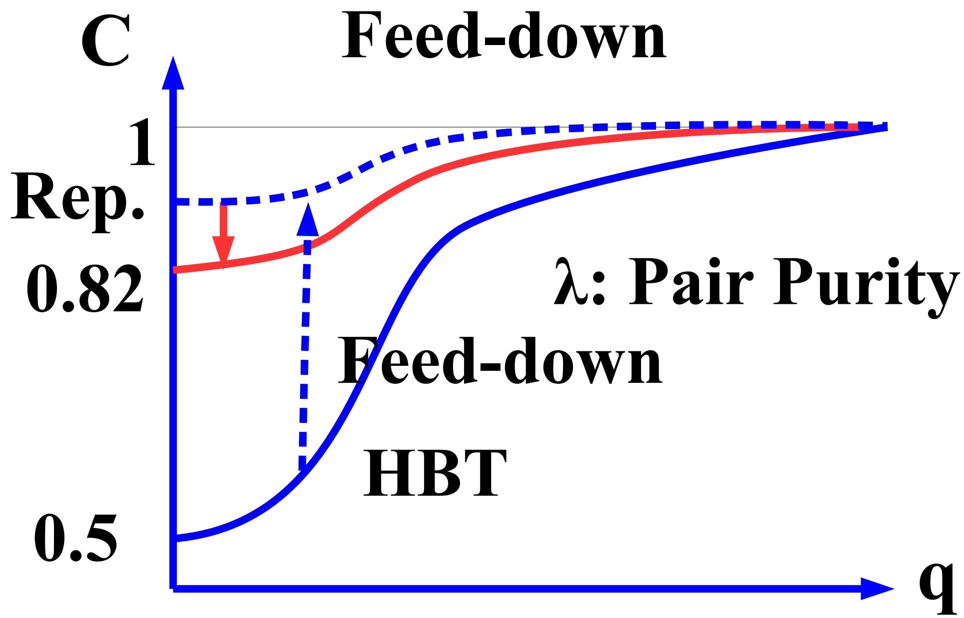


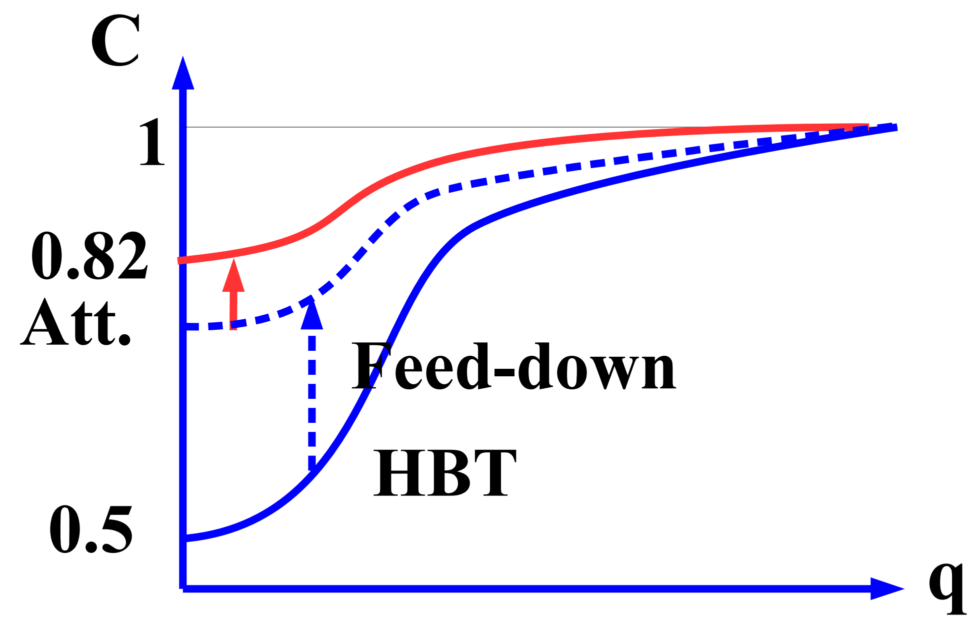
- **"Residual" source**
  - **High-momentum tail → $R_{\rm res}$ ~ 0.5 fm (STAR collab.)**

Feed-Down Effects & Residual Source

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

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





STAR:
λ ~ 0.18 (free para.)

Morita et al. (MFO15):
λ ~ 0.45

Pair purity (λ) should be determined experimentally !
Puzzle: Residual source

Σ^0/Λ=0.278 (p+Be, 28.5 GeV/c)
Sullivan et al. ('87)
Ξ/Λ = 15 % (RHIC)

AO, Morita, Mihayara, Hyodo ('16)

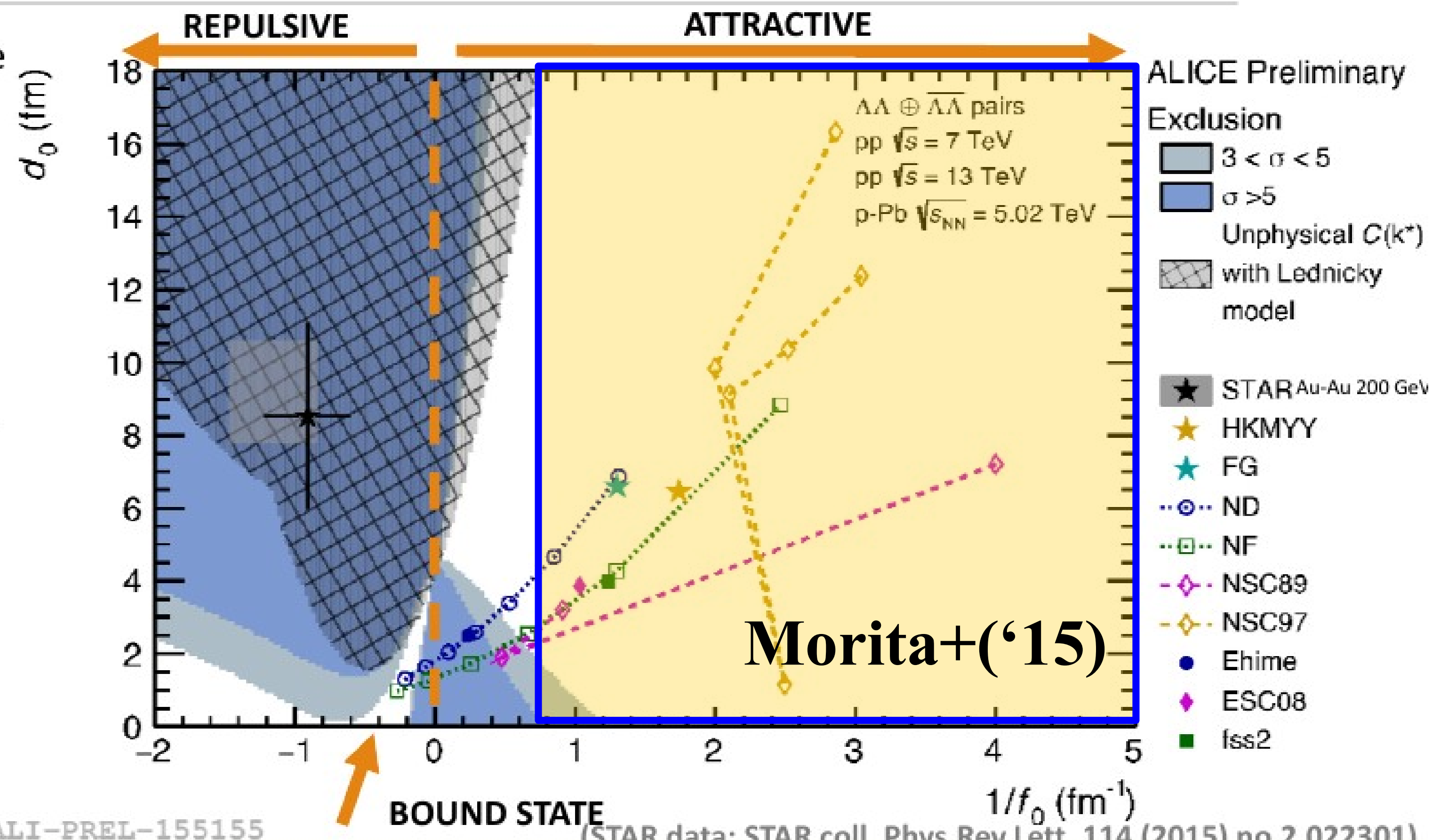
New Data from LHC-ALICE

V. Mantovani-Sarti (ALICE Collab.), MESONS 2018

Λ–Λ Correlations: Combined Exclusion Plot

ALICE

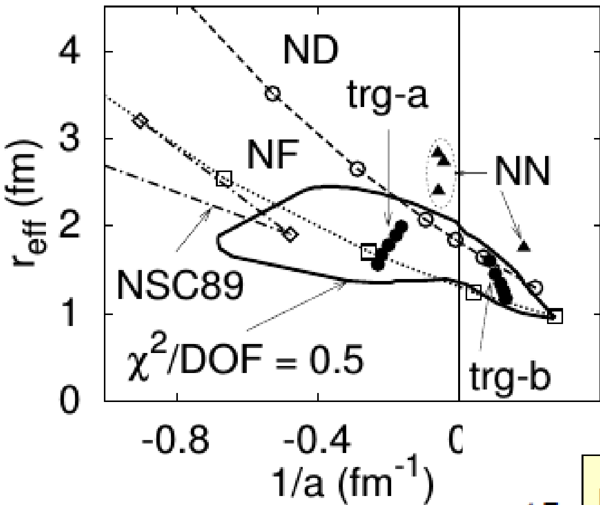
- Combination of all available datasets: **pp 7 TeV, pp 13 TeV, p-Pb 5.02 TeV**
- Test of the **agreement between data and the prediction by the Lednicky model by nσ**
- Small source size, large d_0 and negative f_0 limit the prediction power of Lednicky



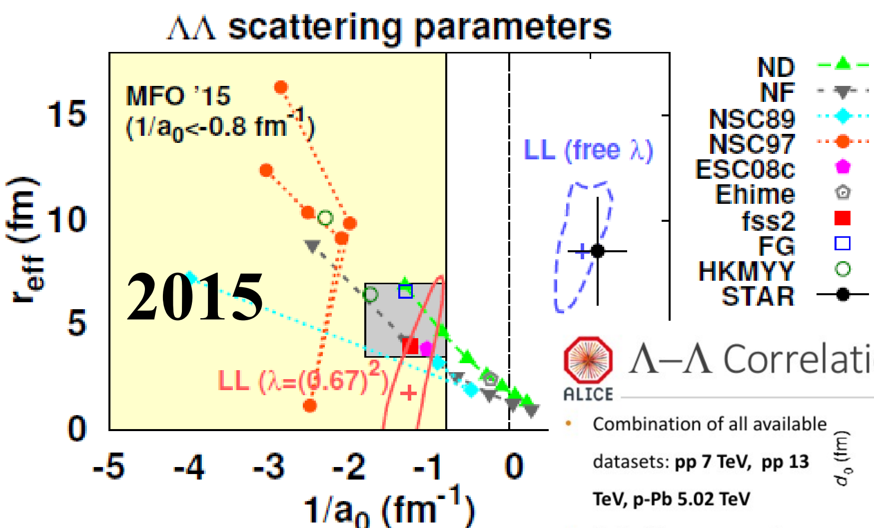
(STAR data: STAR coll. Phys.Rev.Lett. 114 (2015) no.2,022301)

Valentina Mantovani Sarti (TUM Physics Department – E62) 9

Time dependence of ΛΛ interaction

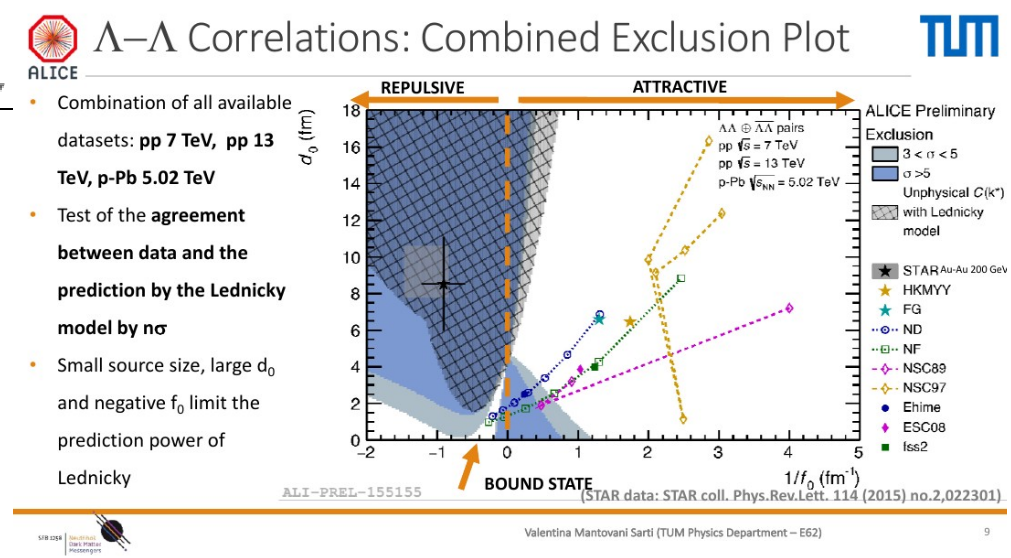


2000



2015

2018

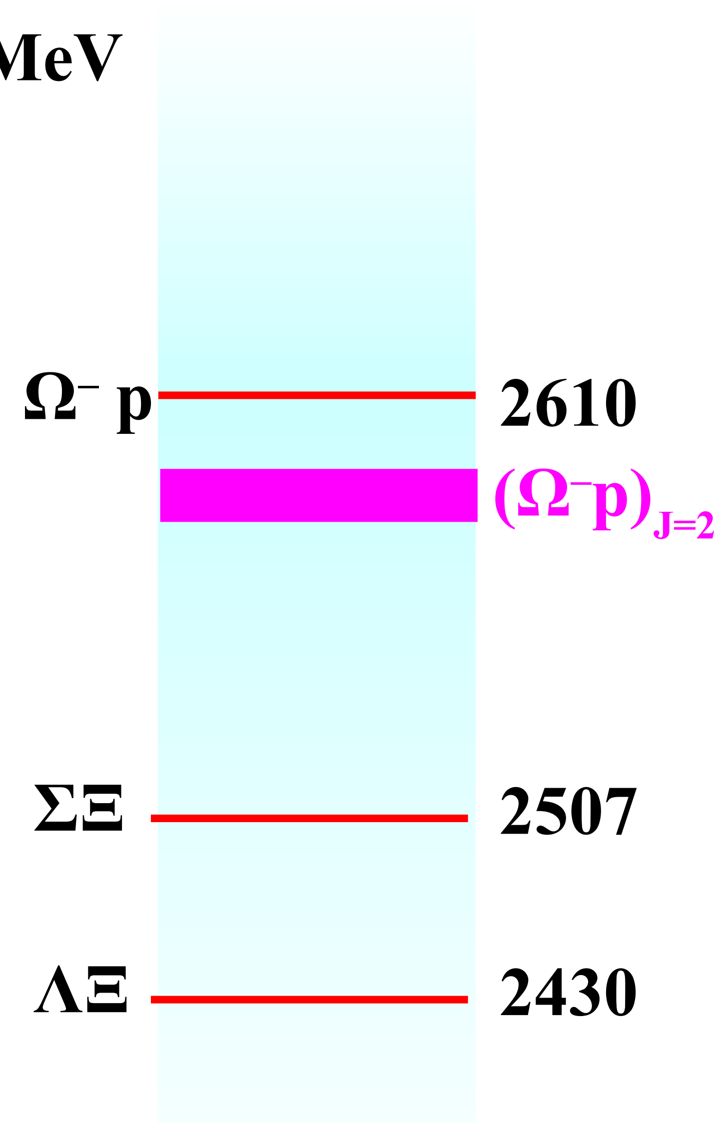


Nagara (2001)

$\Omega^{-}p$ correlation

Ω^- p interaction

- Ω^- : quark content=sss, J^π=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, H=uuddss, and d*=ΔΔ 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.

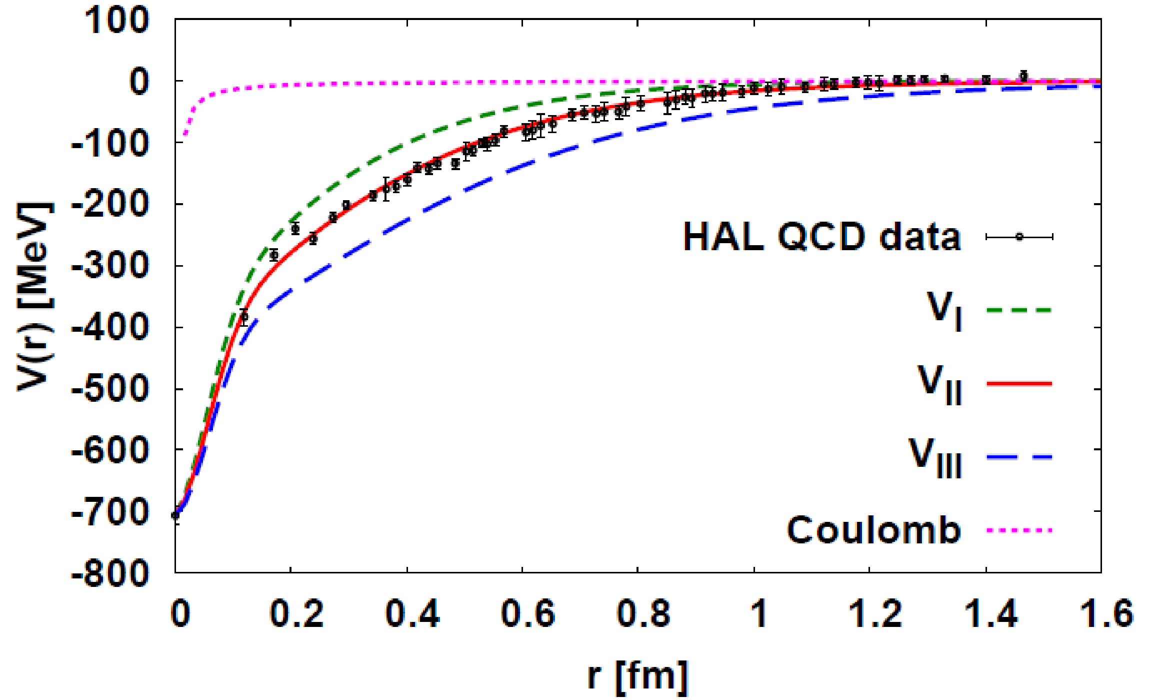


Let us try to discover the first(?) dibaryon (after deuteron) !
(First dibaryon with S<0 !)

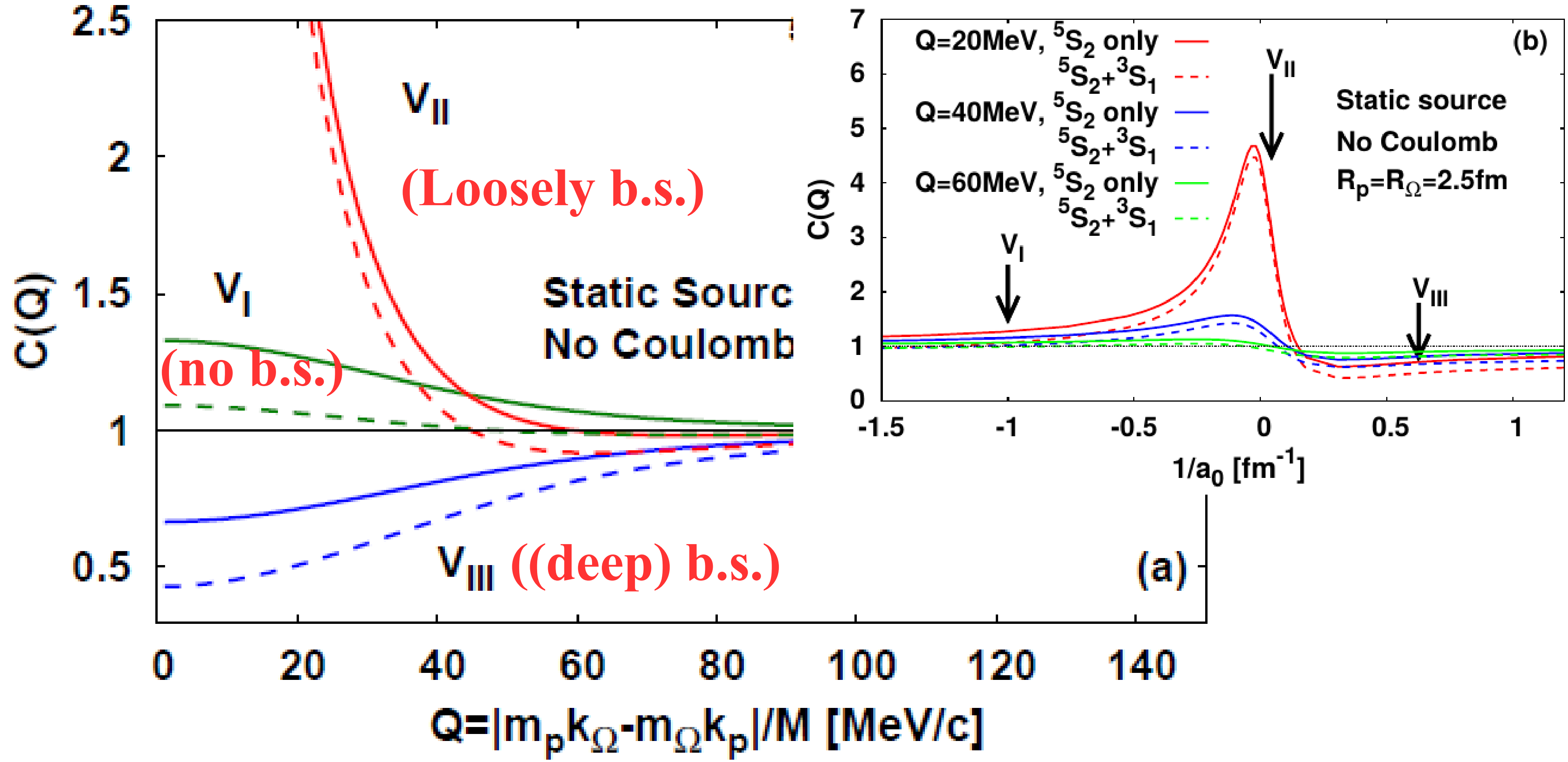
Ω^- p potential from lattice QCD

- **Lattice QCD predicts Ω^- p bound state at large quark mass, m_π=875 MeV (B.E.~ 19 MeV) in $^5S_2$ channel.**
  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_I	V_{II}	V_{III}
without Coulomb	E_B [MeV]	–	0.05	24.8
	a_0 [fm]	−1.0	23.1	1.60
	r_{eff} [fm]	1.15	0.95	0.65
with Coulomb	E_B [MeV]	–	6.3	26.9
	a_0 [fm]	−1.12	5.79	1.29
	r_{eff} [fm]	1.16	0.96	0.65



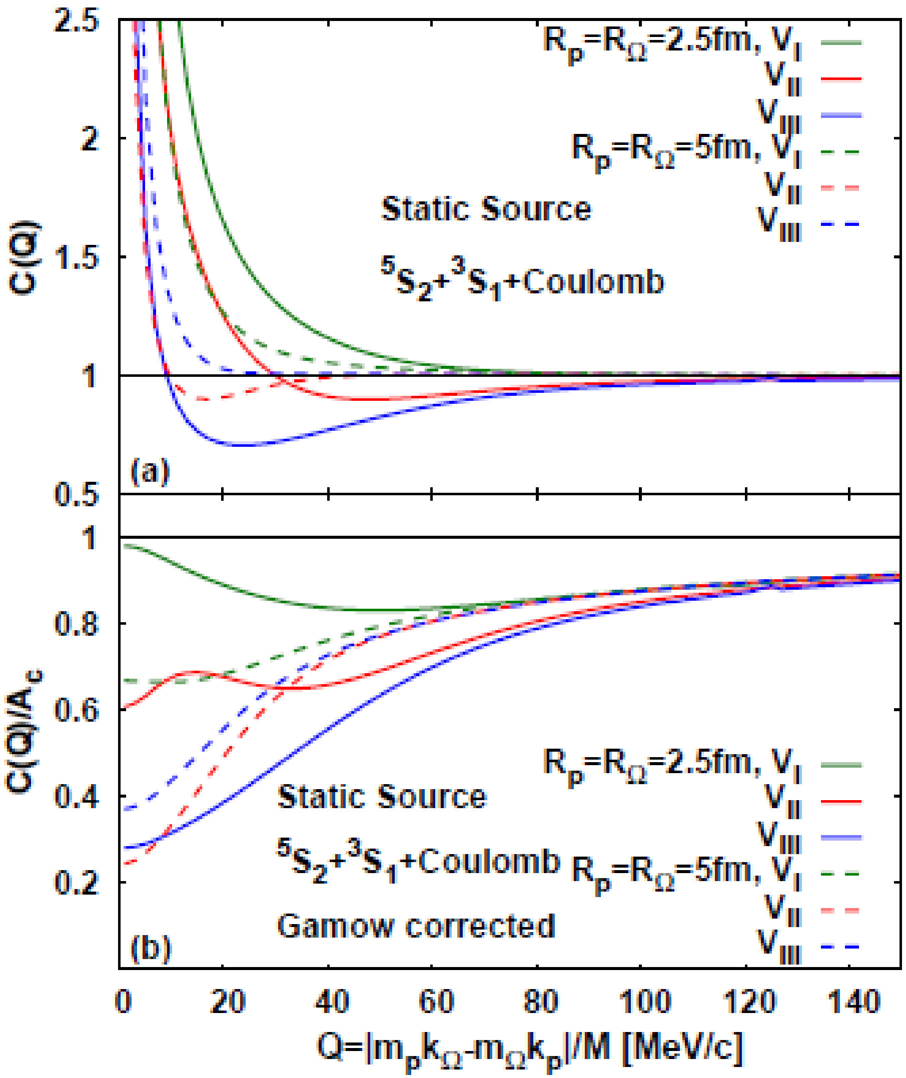
$\Omega^{-}p$ correlation



(w/o Coulomb, Strong absorption at r< 2 fm in $^3S_1$ (decay to 8-8 in S-wave))

K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R) [arXiv:1605.06765 [hep-ph]]

Ω^- p correlation w/ Coulomb

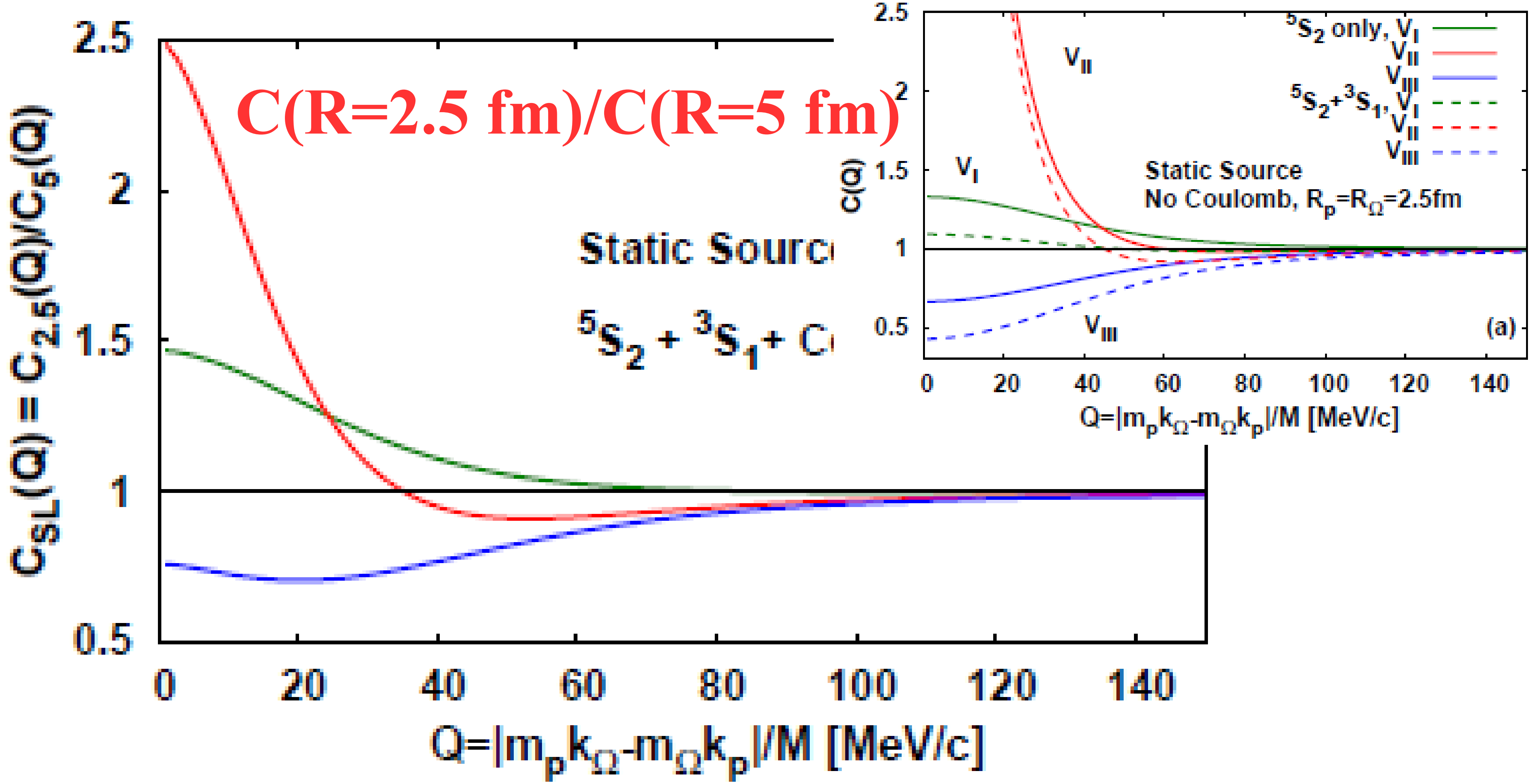


With Coulomb

Coulomb + Gamow corr.

Coulomb potential washes out the features of V_I, V_{II}, V_{III}, and Gamow correction is not enough.

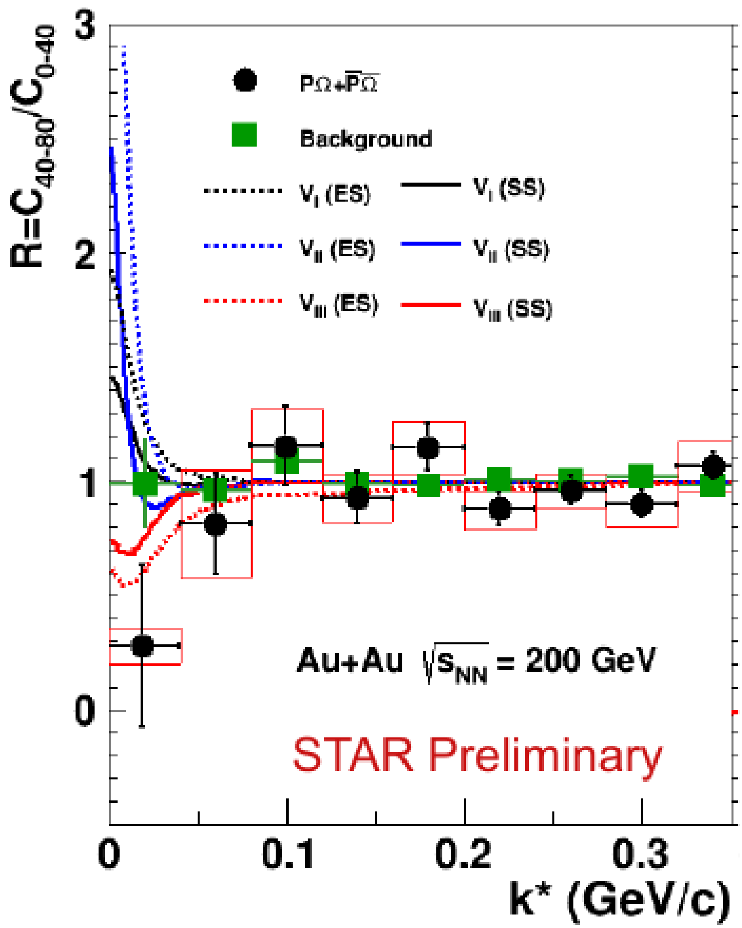
Ω⁻ p correlation: Small / Large Ratio

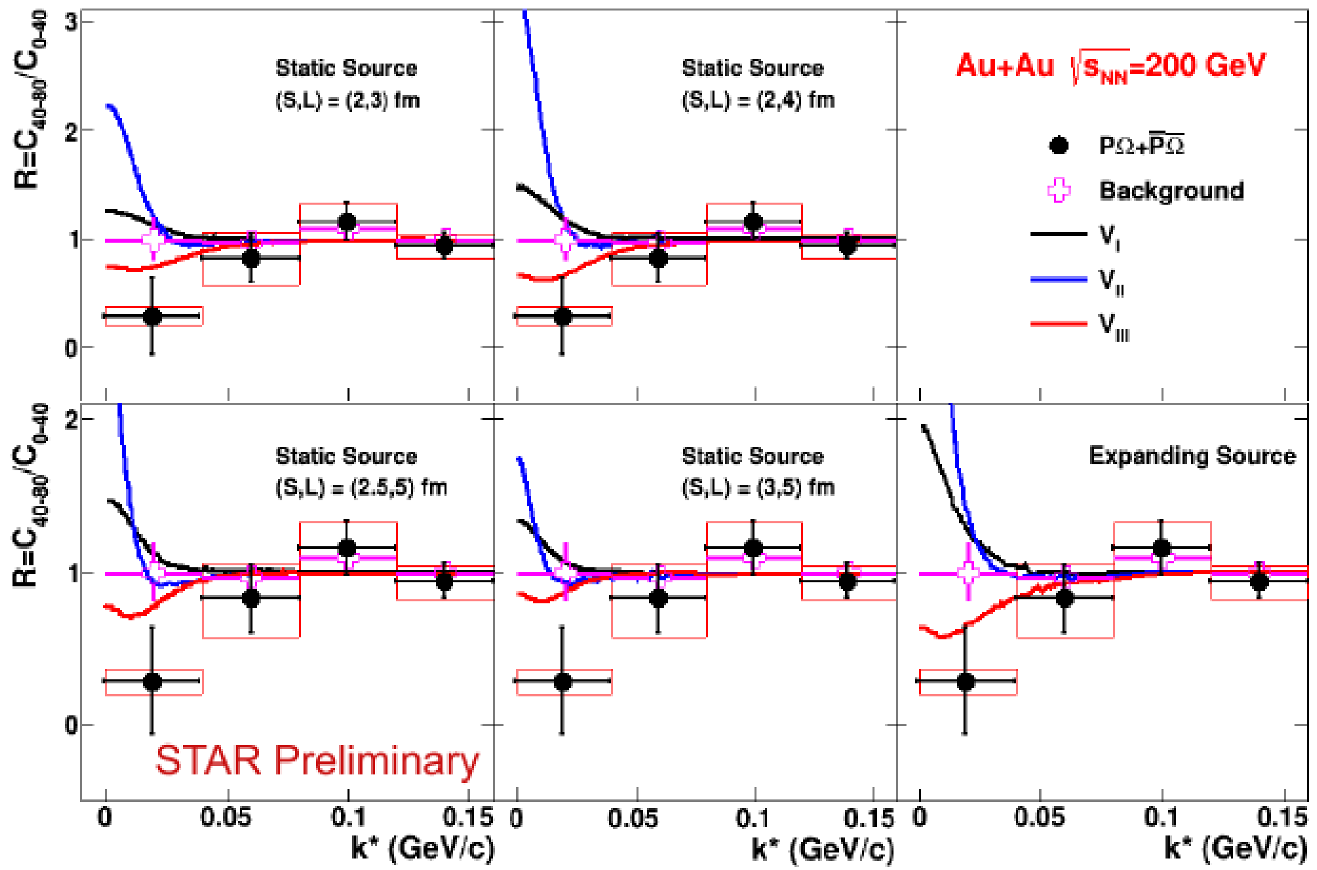


By taking small (R=2.5 fm) / large (R=5 fm) ratio, we approximately see the corr. fn. w/o Coulomb !

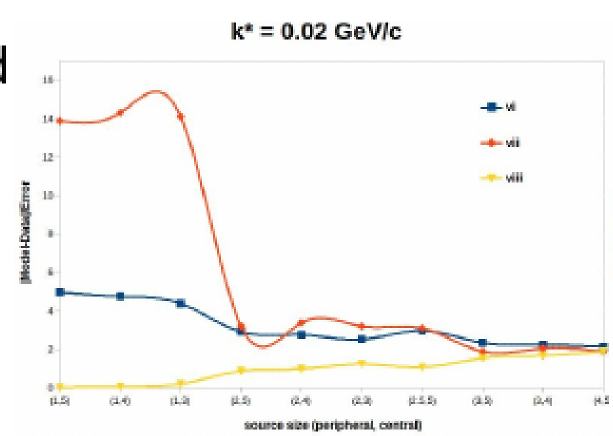
J. Chen (STAR Collab.), NFQCD 2018

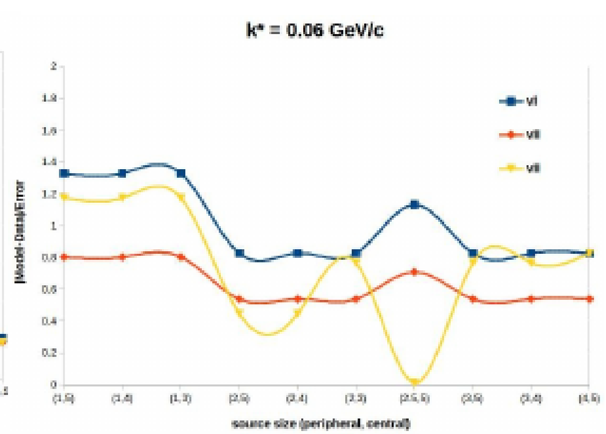
STAR Source Size Analysis on pΩ Correlation Function





☑ The source parameters are derived from other PID and centrality dependence measurements at RHIC





https://drupal.star.bnl.gov/STAR/files/Zbroszczyk_Hanna.pdf

Results with ppdated HAL QCD potential

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

- **Updated HAL QCD NΩ potential**
  T. Iritani et al. (HAL QCD Collab.), 1810.03416
  Almost physical point m_π = 146 MeV
  → K. Sasaki's talk

t/a	a_0 [fm]	$r_{\rm eff}$ [fm]	E_B [MeV]
11	3.45	1.33	2.15
12	3.38	1.31	2.27
13	3.49	1.31	2.08
14	3.40	1.33	2.24

- **Cylindrical source with radial transverse flow**
  → pT spectra of protons and Ωs
- **Small-Large ratio to suppress the Coulomb effects**
  & Absorptive potential in J=1 channel
  K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R) [arXiv:1605.06765 [hep-ph]]

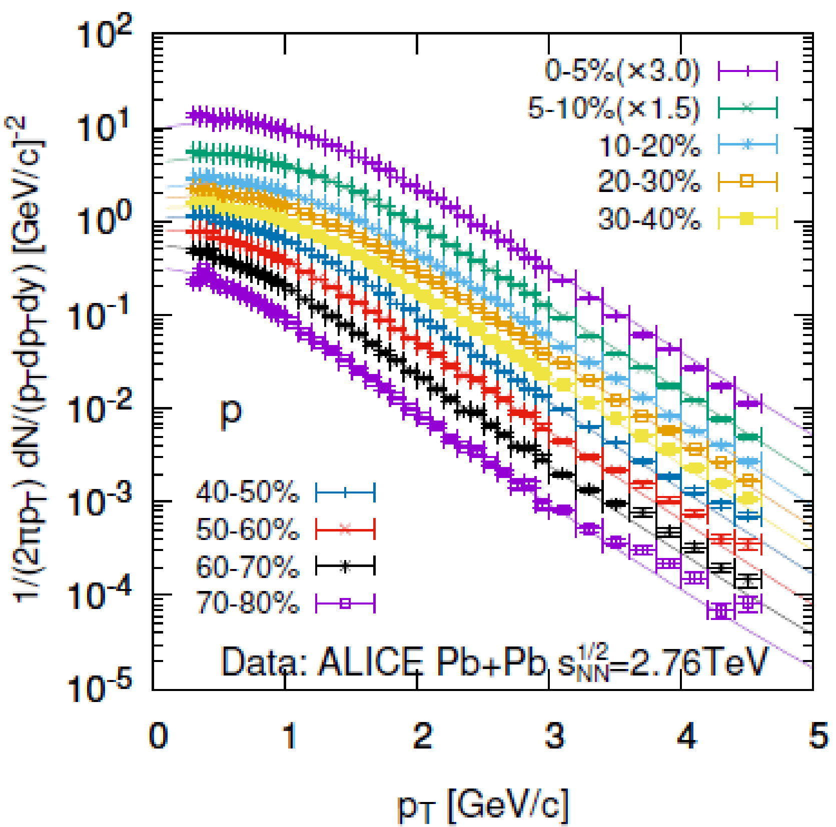
Source function

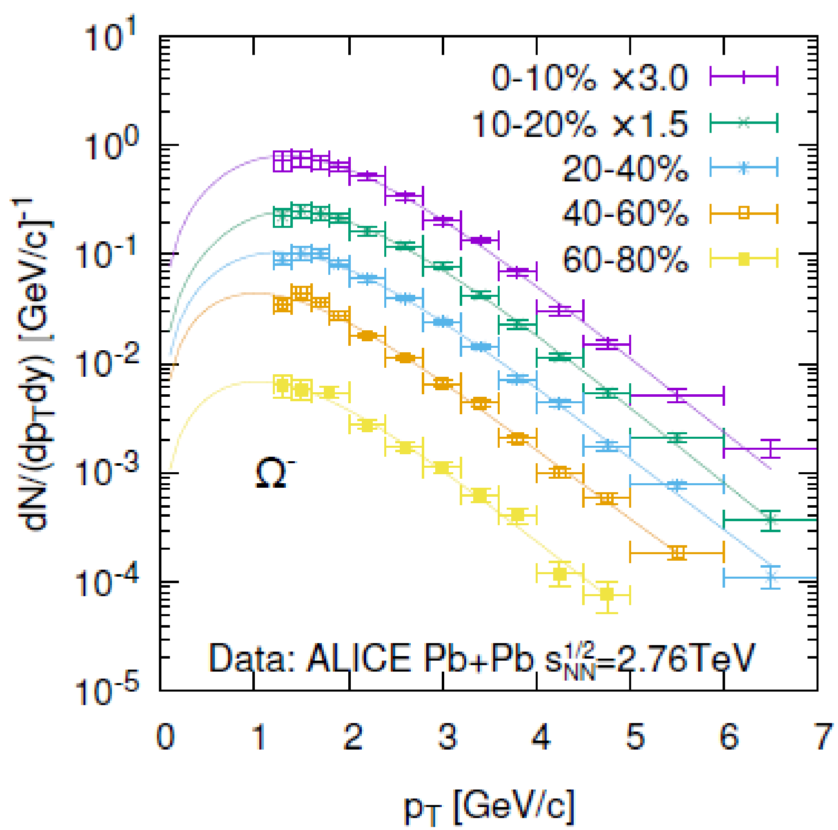
- **Blast wave model fit**

Flow velocity

$$d^4 x S_i(x,p) = \tau_0 d\eta_s d^2 r_T \frac{d}{(2\pi)^3} \underline{n_f(u \cdot p, T)} \exp\left(-\frac{r_T^2}{2R_T^2}\right)$$

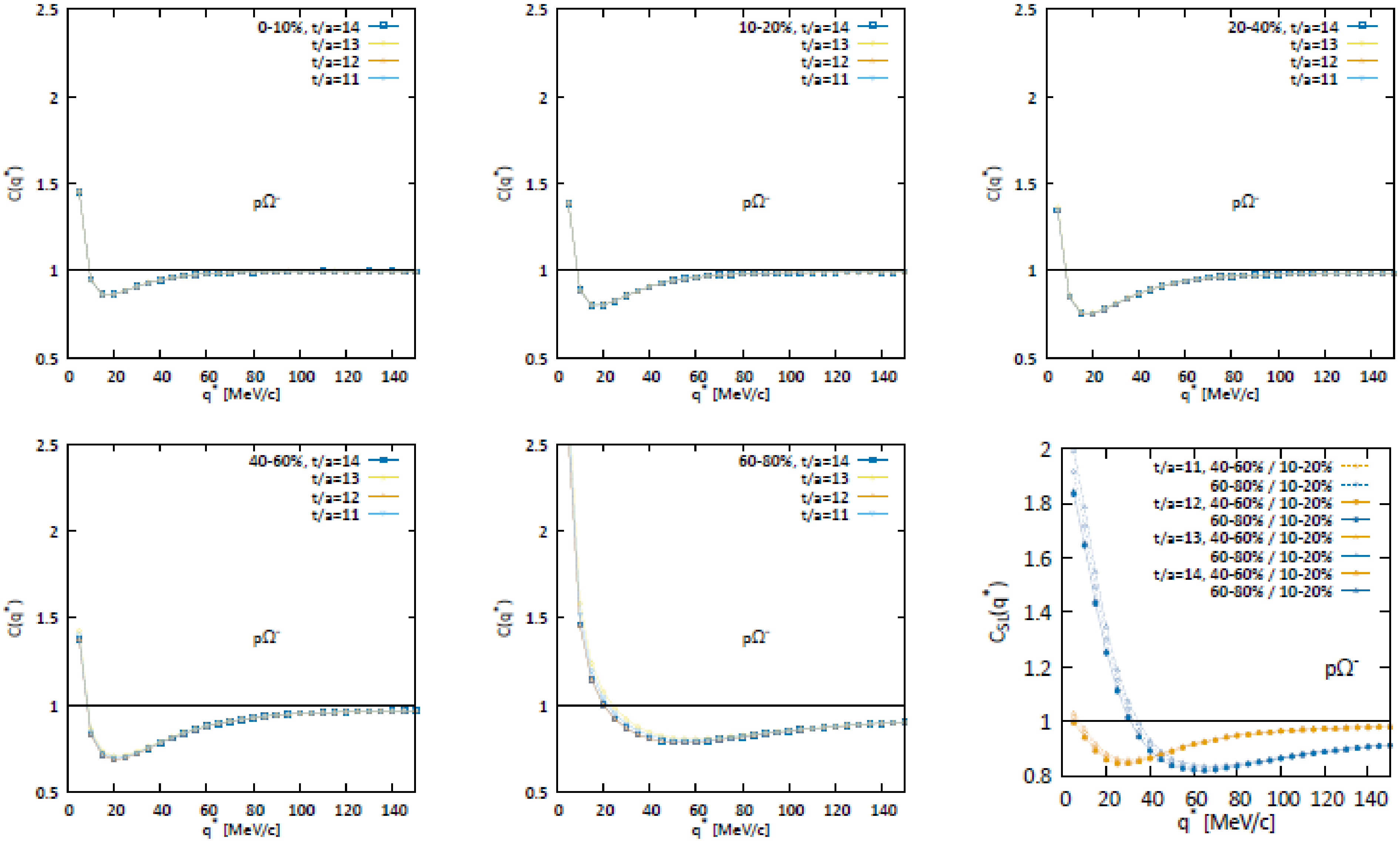
Fermi dist.





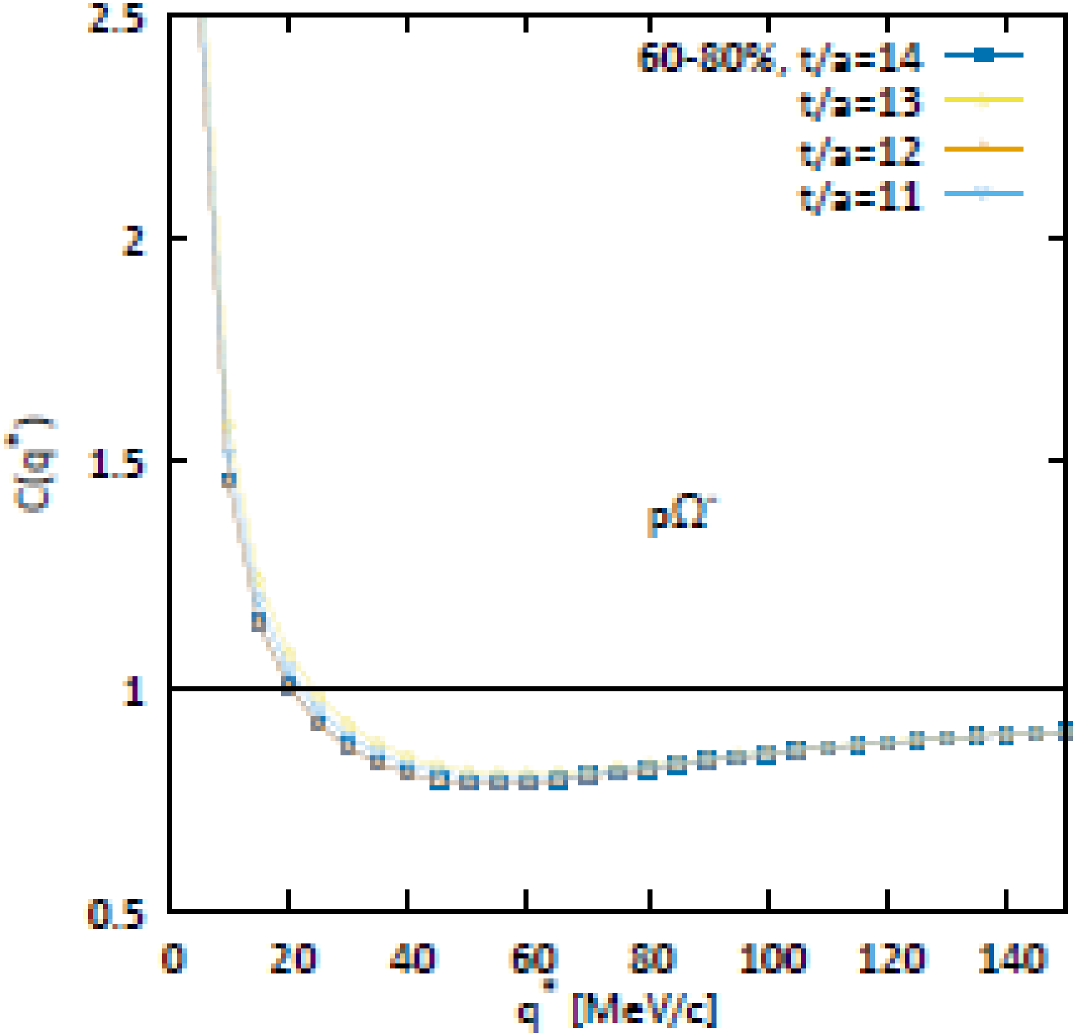
K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

Correlation function from heavy-ion collisions



K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

Correlation function from heavy-ion collisions



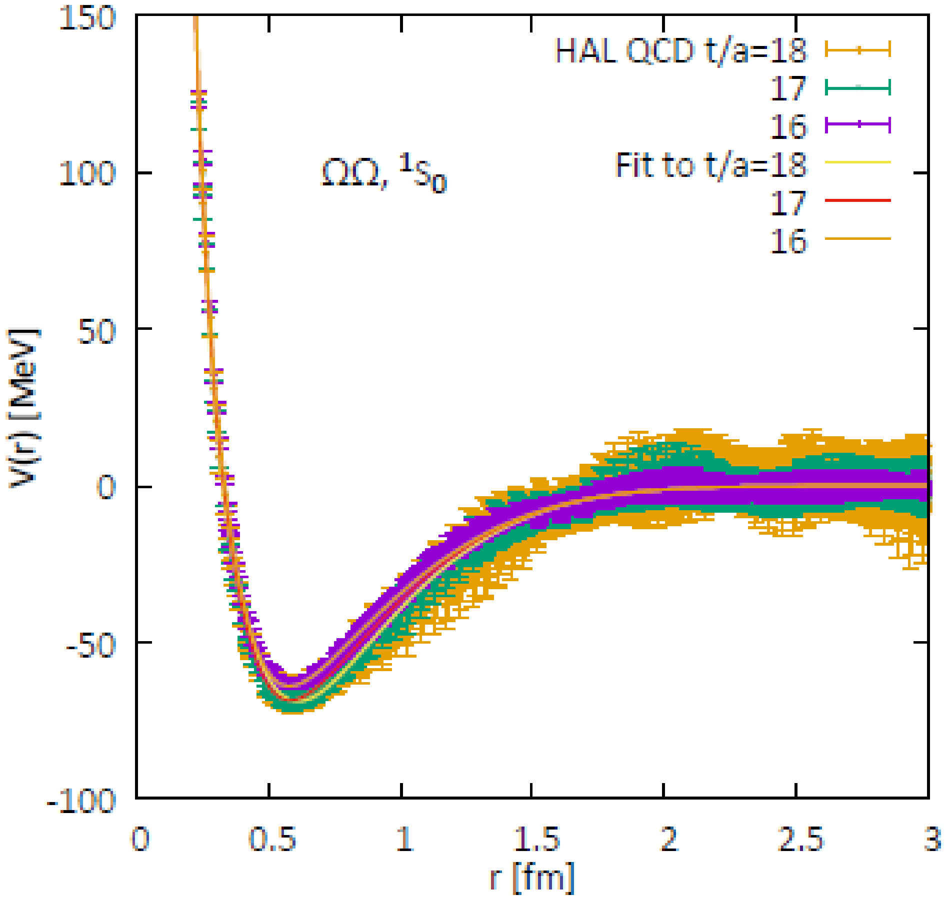
Peripheral collisions
(R ~ (2-3) fm)
→ Strong enhancement at small q,
+ Suppressed CF at finite q

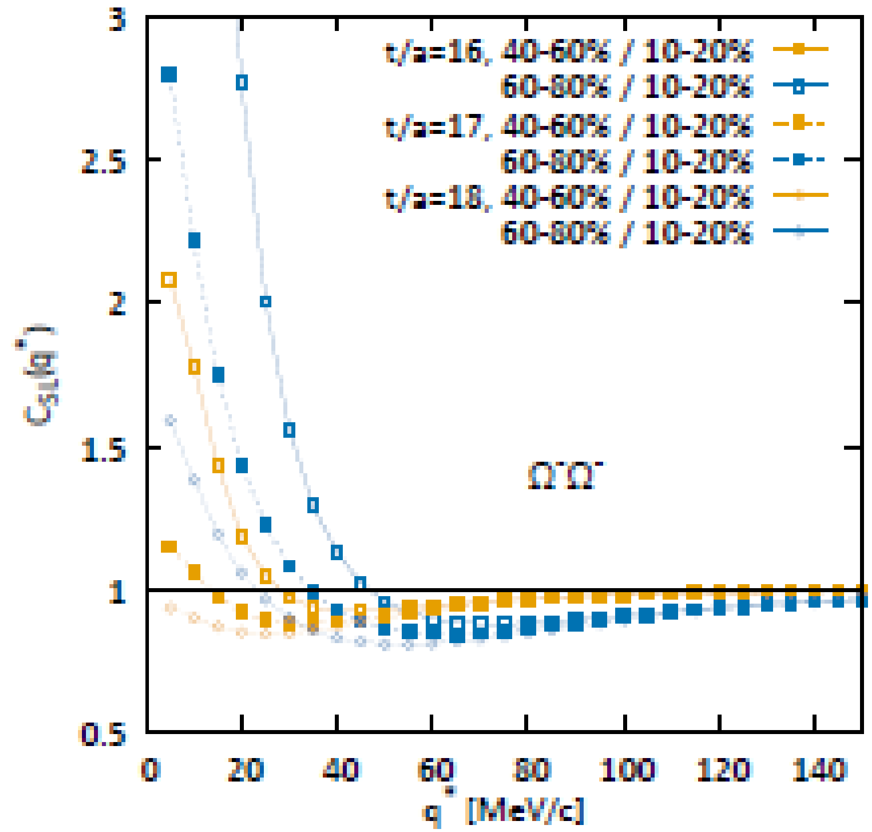
Centrality	τ_0 [fm/c]	R_T^Ω [fm]	R_T^p	α^Ω	β^Ω	α^p	β^p
0 – 10%	10.0	8.0	6.8	0.584	0.628	0.759	0.421
10 – 20%	9.085	6.75	6.23	0.618	0.579	0.750	0.425
20 – 40%	7.5	5.88	5.2	0.546	0.692	0.707	0.466
40 – 60%	5.5	4.38	3.92	0.444	0.858	0.604	0.6
60 – 80%	3.62	2.12	2.66	0.456	0.812	0.456	0.82

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

ΩΩ correlation

ΩΩ potential: S. Gongyo et al. (HAL QCD Collab), Phys. Rev. Lett. 120, 212001 (2017), 1709.00654.



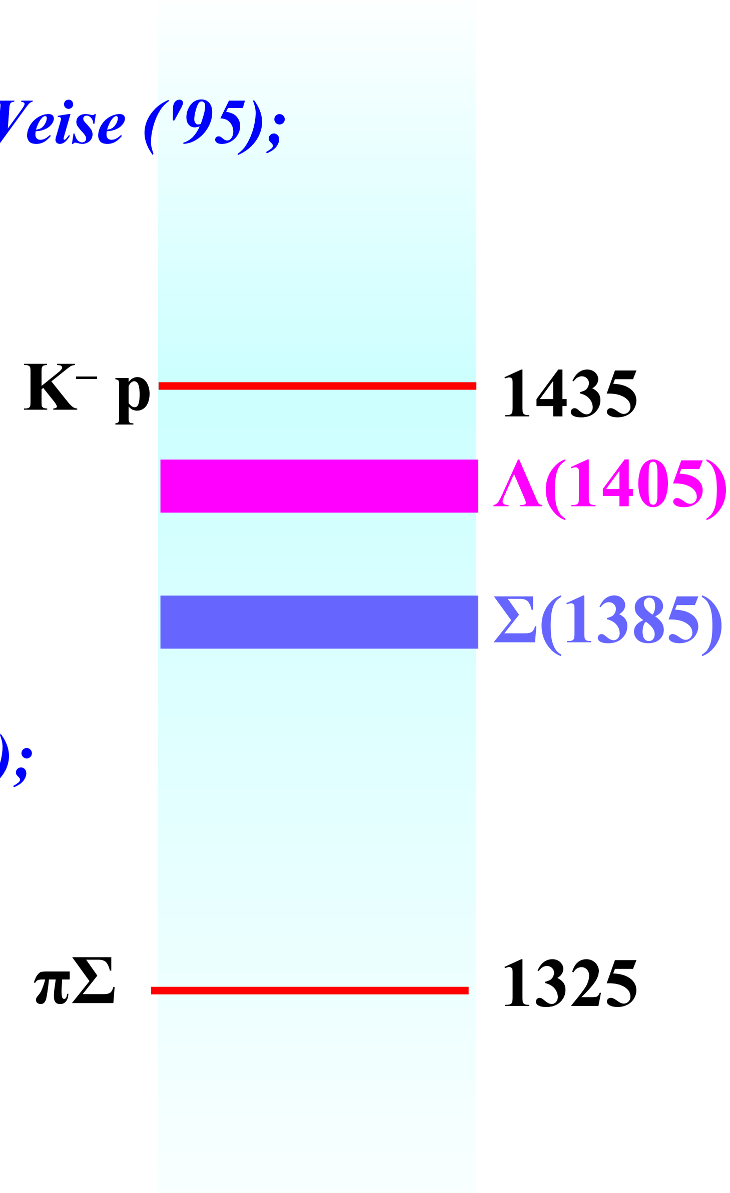


K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

$K^{-}p$ correlation

K^- p interaction

- Λ(1405) $\bar{K}N$ quasi-bound state
  Dalitz, Tuan ('60); Koch ('94); Kaiser, Siegel, Weise ('95); AO, Nara, Koch ('97)
  - 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); Shevchenko, Gal, Mares ('07); Ikeda, Sato ('07); Dote, Hyodo, Weise ('09)
  → 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**

$$\Psi^{(+)}_{K^-p}(\boldsymbol{r}) \to \exp(i\boldsymbol{q}\cdot\boldsymbol{r})\chi(K^-p) + \frac{e^{iqr}}{r}\left[f_{K^-p\to K^-p}\chi(K^-p) + f_{K^-p\to\bar{K}^0 n}\chi(\bar{K}^0 n)\right]$$

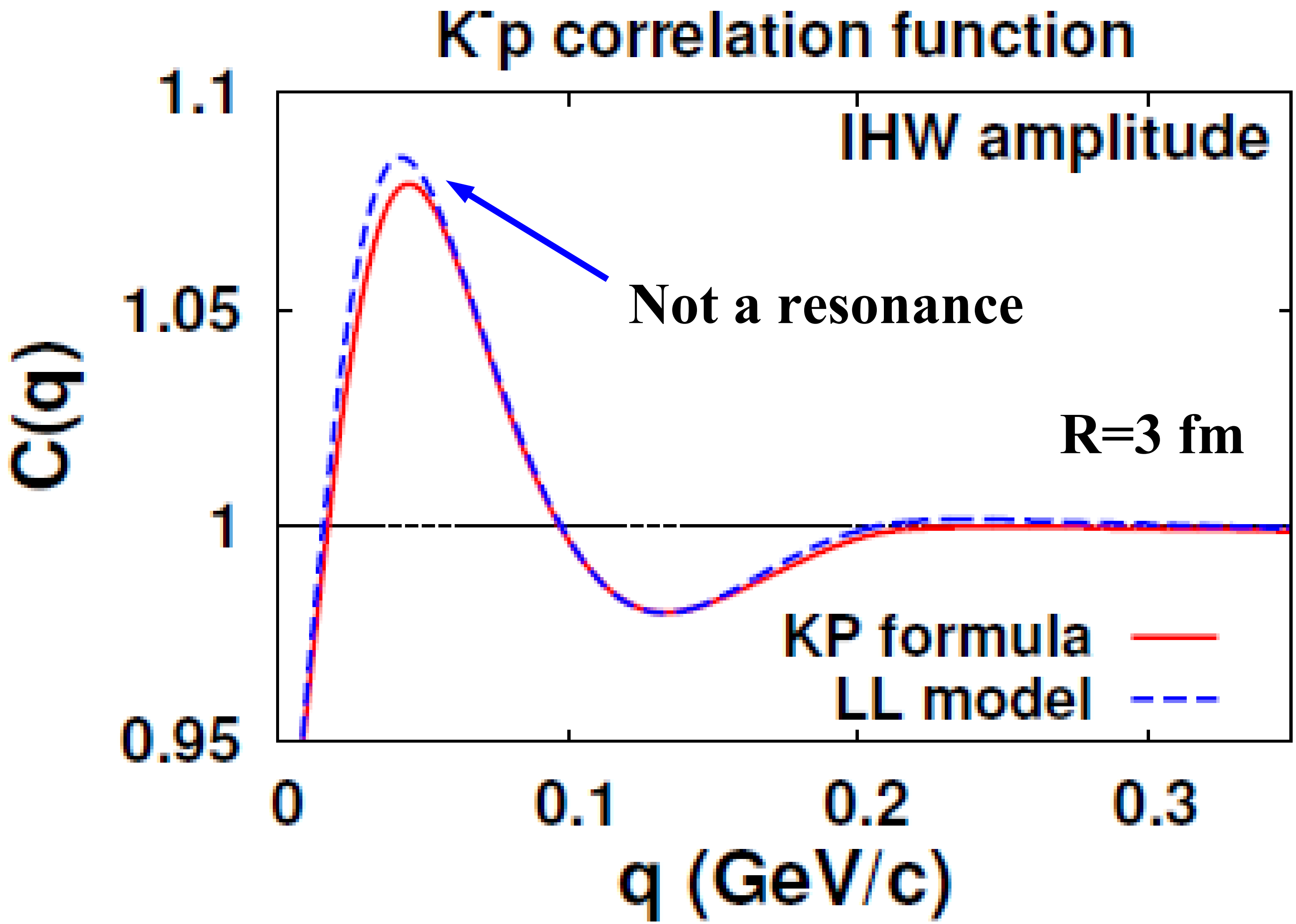
- **K^- p correlation: Plane wave + Incoming spherical wave**

$$\Psi^{(-)}_{K^-p}(\boldsymbol{r}) \to \exp(i\boldsymbol{q}\cdot\boldsymbol{r})\chi(K^-p) + \frac{e^{-iqr}}{r}\left[\tilde{f}_{K^-p\to K^-p}\chi(K^-p) + \tilde{f}_{K^-p\to\bar{K}^0 n}\chi(\bar{K}^0 n)\right]$$

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

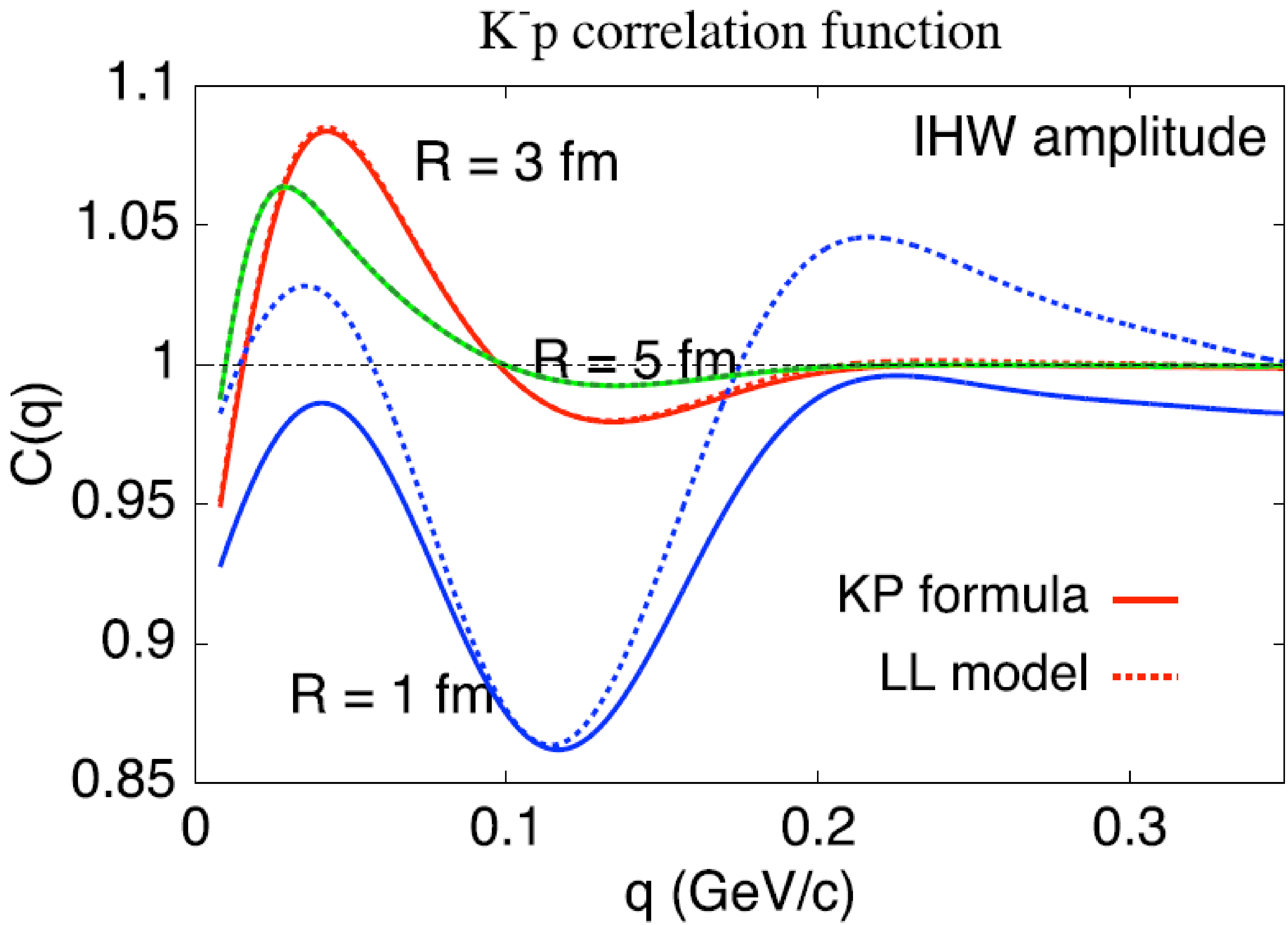
$\Psi^{(-)} \neq (\Psi^{(+)})^* \to K^-$ p correlation probes different combination of I=0, 1 from K^- p scattering

K⁻p correlation



Calc: AO, K. Morita, K. Miyahara, T. Hyodo, NPA954 ('16)294 (ΛΛ, K–p).
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



$\psi^{(-)}$: Another source of fake peak ?

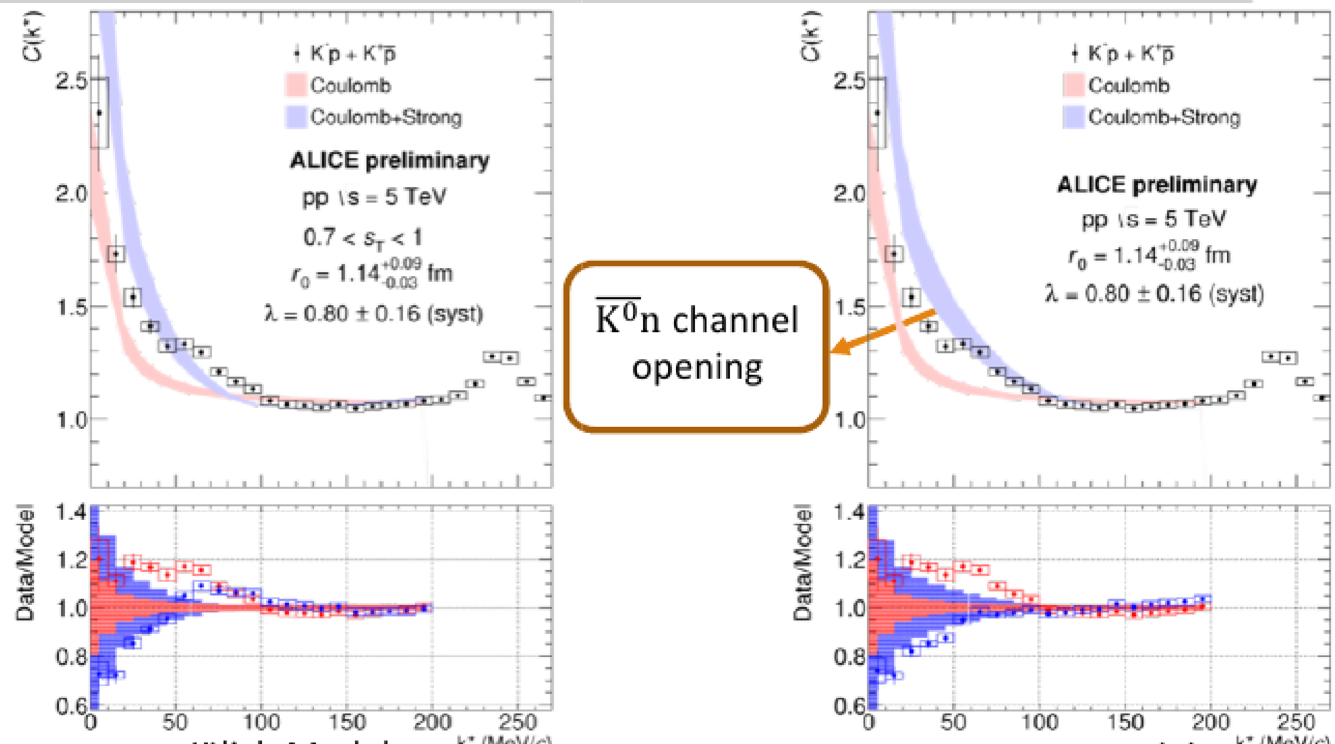
K. Miyahara

New Data from LHC-ALICE

V. Mantovani-Sarti (ALICE Collab.), MESONS 2018

K⁻- p Correlation-pp 5 TeV, 7 TeV, 13 TeV

- Analysis on datasets:
  - **pp 5 TeV, 7 TeV, 13 TeV**
- **Short range $\overline{K}N$ interaction:**
  - Λ(1405), kaonic atoms and kaonic clusters
- Kaonic atoms and scattering data



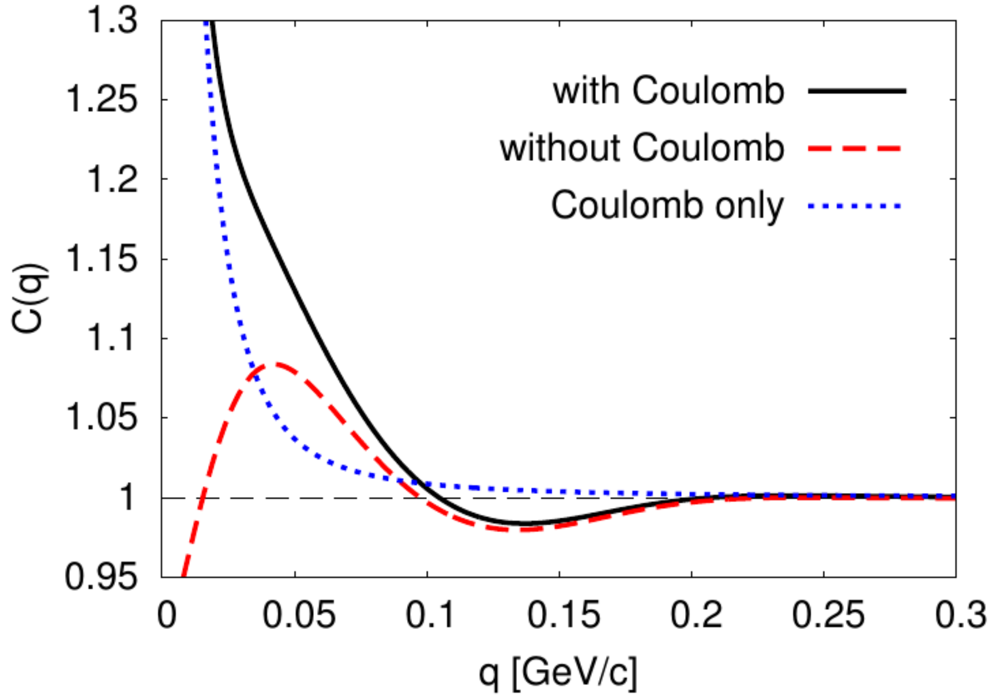
Jülich Model (Haidenbauer et al., Phys.Rev. C66 (2002) 055214)

Kyoto Model (Hyodo et al., Phys.Rev. C95 (2017) no.6,065202)

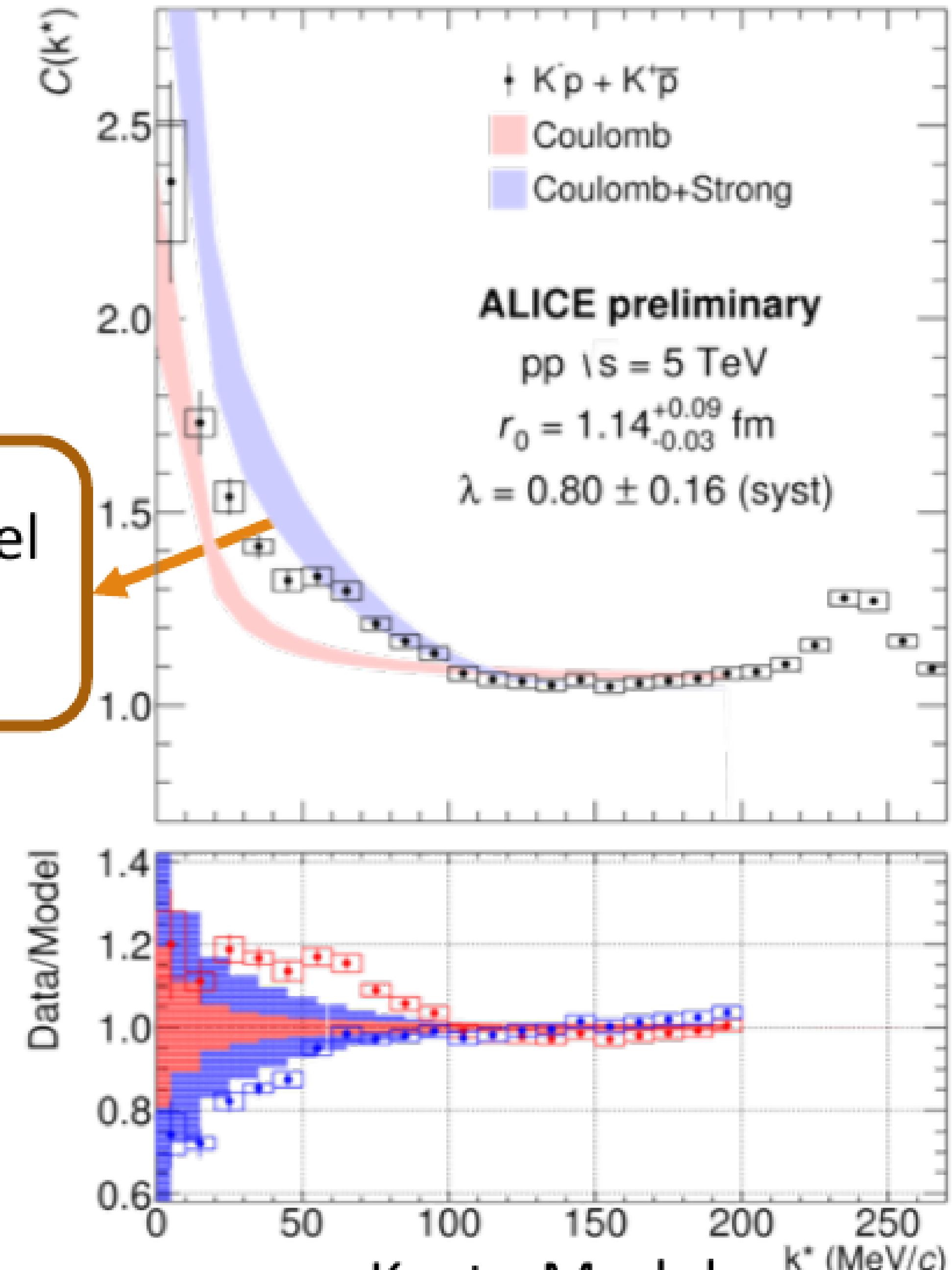
Analysis performed by R.Lea (INFN-TS)

New Data from LHC-ALICE

- Data shows shoulder at q ~ 50 MeV
  - Threshold effect ?
  - Interference of I=0 and I=1 amplitudes ? (Cho et al. ('17))



Cho et al. (ExHIC Collab.) ('17)



Kyoto Model

Coupled Channels Effects Revisited

- **J. Haidenbauer (arXiv:1808.05049)**
  - **Coupled channels effects strongly modifies the correlation funciton of K- p and Ξ- p.**
  - **Threshold difference needs to be taken care of.**
  - **Source of other channels need to be added.**
  - **No Coulomb, No Flow, Gaussian source with a fixed size, ...**
- **Two channel closure approximation is used in our previous works, and source function of other channels were missed (forgotten to add).**
  Cho et al. ('17), AO et al. ('16)

$$\widetilde{S} = (S_{2\times 2})^{-1} \neq (S^\dagger)_{2\times 2}$$

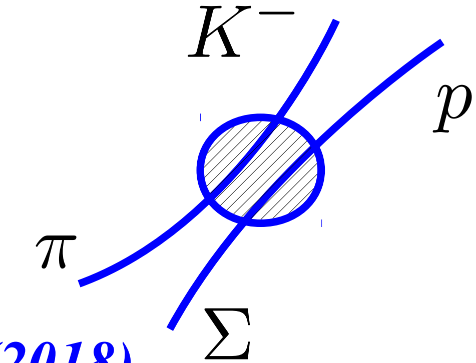
→ We need to revisit K- p correlation ...

Correlation Function with Coupled Channels

- **Contribution of the source in other channels**

$$C_\alpha(\boldsymbol{q}) = \sum_\beta \int d\boldsymbol{r}\, \underline{S_\beta(\boldsymbol{r})} \left|\psi^{(-)}_{\beta\alpha}(\boldsymbol{r},\boldsymbol{q})\right|^2$$

Source fn.



- **Asymptotic wave function**

  K. Miyahara, T. Hyodo, W. Weise, Phys. Rev. C 98, 025201 (2018), arXiv:1804.08269.

$$|\Psi^{(\pm)}_\alpha\rangle = \sum_\beta \psi^{(\pm)}_{\beta\alpha} |\beta\rangle$$

No outgoing w.f. for β !=α

$$\psi^{(+)}_{\beta\alpha}(r) \to \frac{-1}{2ik_\alpha}\left[\delta_{\beta\alpha}\frac{e^{-ik_\beta r}}{r} - \sqrt{\frac{v_\alpha}{v_\beta}} S_{\beta\alpha}\frac{e^{ik_\beta r}}{r}\right] \quad (v_\alpha = k_\alpha/\mu_\alpha)$$

- **Asymptotically outgoing wave function**

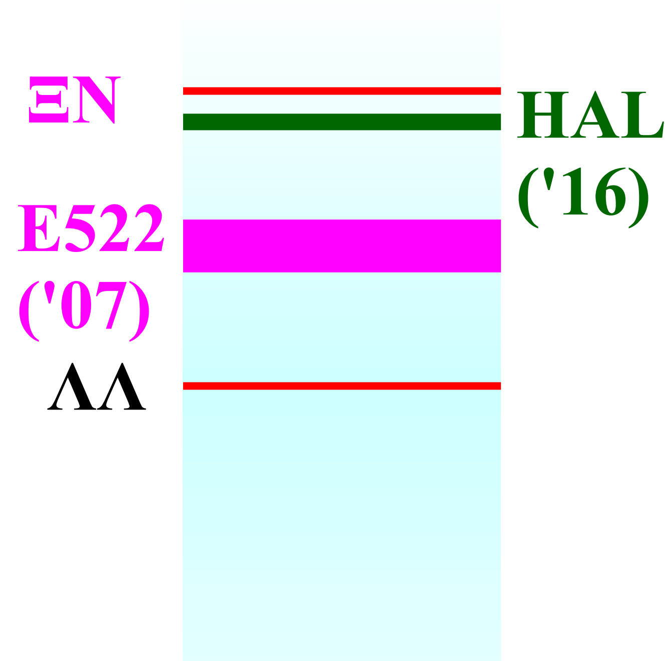
$$\psi^{(-)}_{\beta\alpha}(r) = \frac{1}{k_\alpha}\sum_\gamma \psi^{(+)}_{\beta\gamma}(r) S^\dagger_{\gamma\alpha} k_\gamma \sqrt{\frac{v_\alpha}{v_\gamma}} \to \frac{1}{2ik_\alpha}\left[\delta_{\beta\alpha}\frac{e^{ik_\beta r}}{r} - \sqrt{\frac{v_\alpha}{v_\beta}} S^\dagger_{\beta\alpha}\frac{e^{-ik_\beta r}}{r}\right]$$

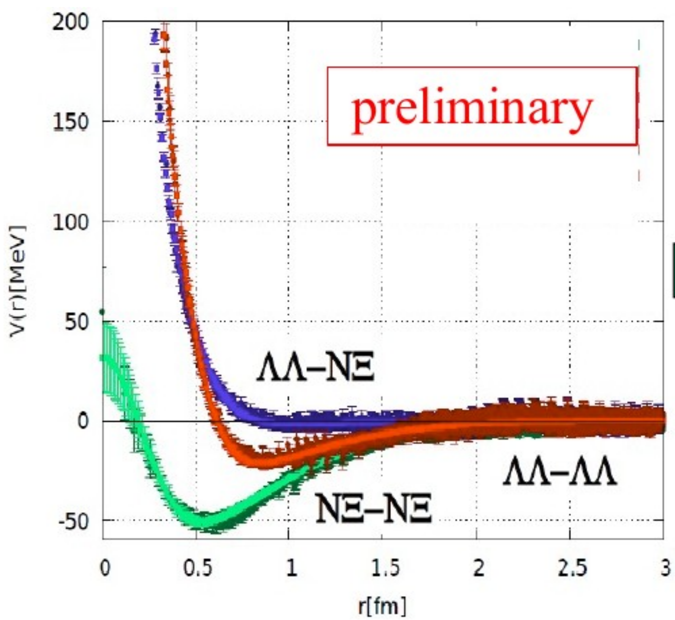
- **Difference of $\widetilde{S}$ and $S^\dagger$ may lead to different results….**

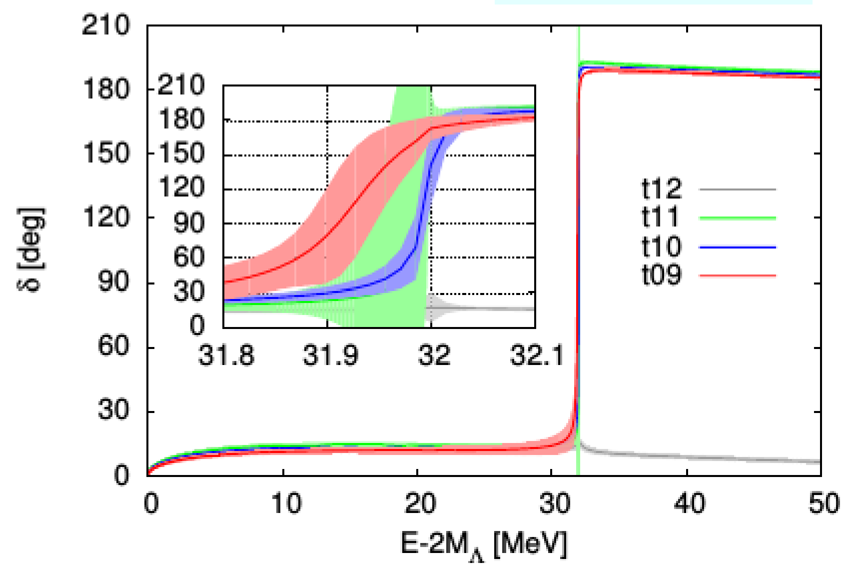
$\Xi^- p$ correlation

Relevance of ΞN interaction to physics

- **H-particle: 6-quark state (uuddss) may be realized as a loosely bound state of ΞN (I=0)**
  K. Sasaki et al. (HAL QCD, '16,'17)
- **Repulsive ΞN interaction (I=1) may help to support 2 $M_\odot$ Neutron Star**
  Weissborn et al., NPA881 ('12) 62.







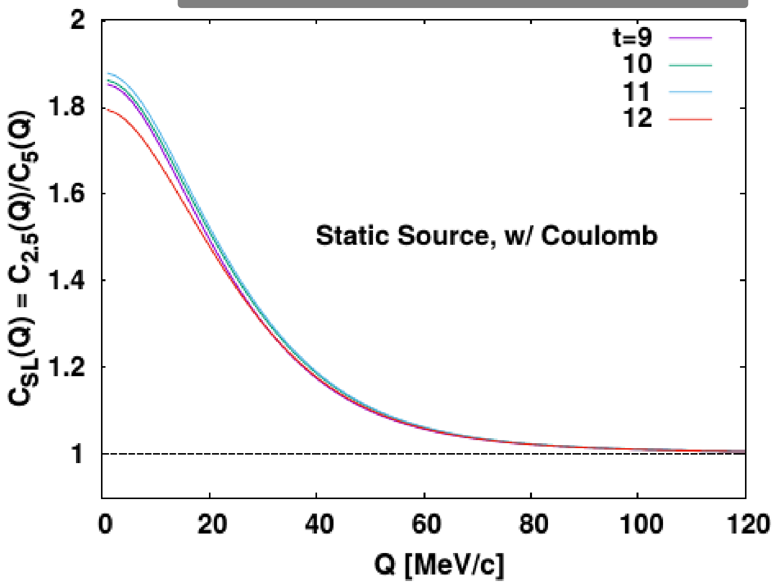
K. Sasaki et al. (HAL QCD Collab.), EPJ Web Conf. 175 ('18) 05010.

Ξ⁻ p correlation

- **Prediction of the correlation function by using ΞN potential (HAL QCD Collab.) + Coulomb potential**

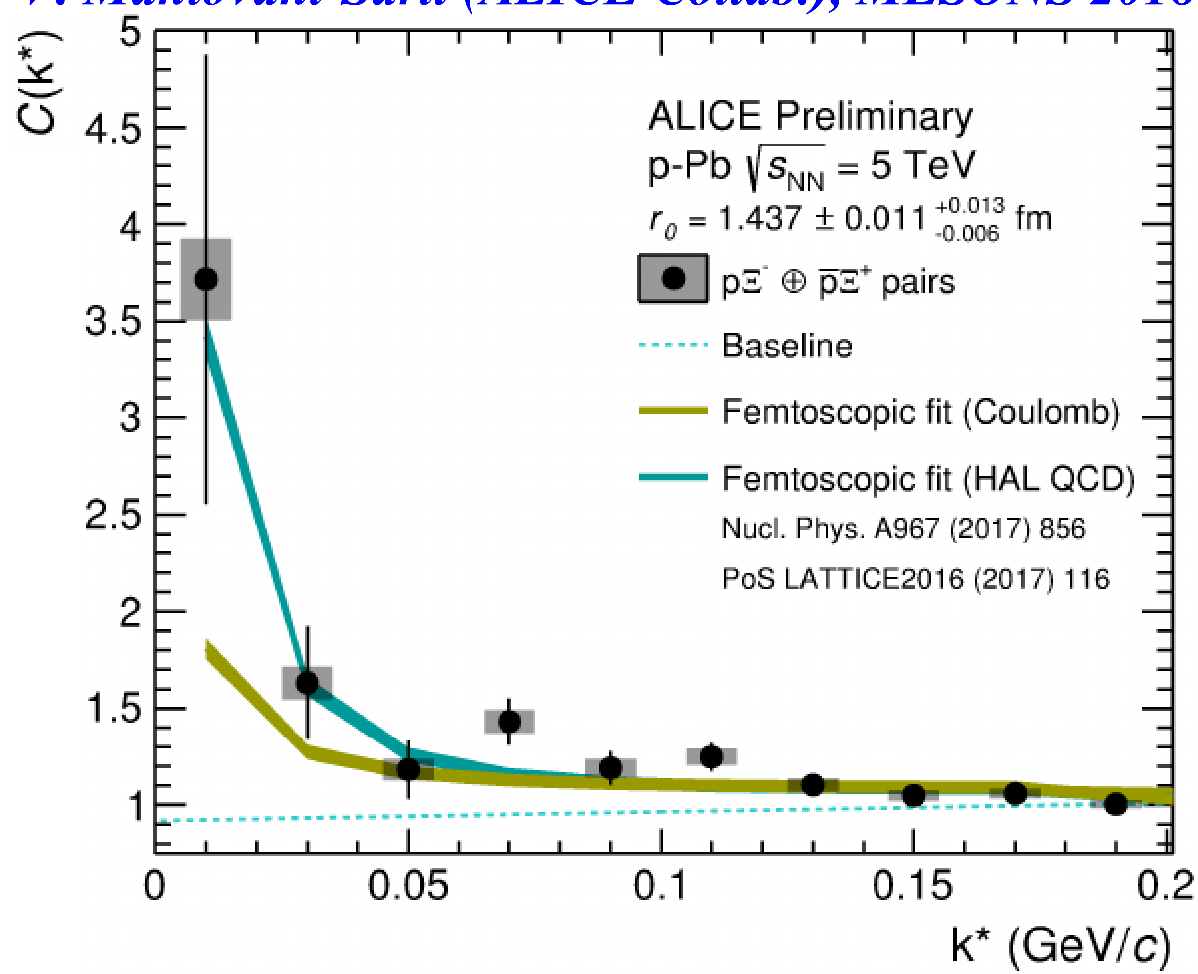
$$|\psi|^2_{\rm spin\ av.} = \frac{1}{2}\sum_{I=0,1}\left[\frac{1}{4}|\psi_I^{J=0}|^2 + \frac{3}{4}|\psi_I^{J=1}|^2\right]$$

HAL prediction is examined !



T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17), 856.

V. Mantovani-Sarti (ALICE Collab.), MESONS 2018



Summary

- **High energy collisions (incl. heavy-ion collisions) are hadron factories, and can be utilized to perform 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, Ξ^-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 constrain (a_0, r_{eff}) region of $\Lambda\Lambda$ interaction.**
  - **Ω^- p correlation suggests the existence of a S=-3 dibaryon.**
  - **K^- p correlation shows "shoulder" structure.**
  - **Ξ^- p correlation has examined the prediction by HAL QCD Collab.**
- **Many other type of pairs are waiting for us.**

Challenge, Lessons, and Reflections

- **Challenge**
  - **"Static Gaussian source + single channel problem" can be now done by experimentalists.**
    D. L. Mihaylov et al. EPJC78('18), 394.
  - **Coupled channels problem needs to be investigated further, including the effects of threshold difference.**
  - **Source fn. needs to be studied more.**
    Combination with transport models
    Gaussian source for pp and e^+e^- collisions ?
- **Lessons**
  - **Let's draw some graph on observables which Experimentalists have not shown ! It can be a prediction !**
  - **It can take 20 years before your prediction is examined.**
- **Reflections: We need to write "original" papers rather than proceedings.**

Thank you
for participating HIPLQH !

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

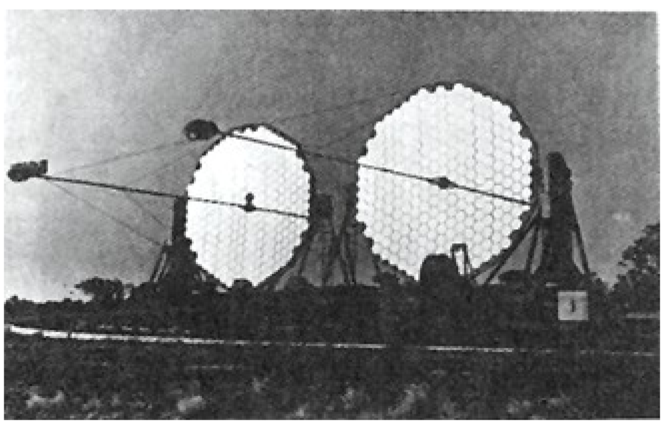
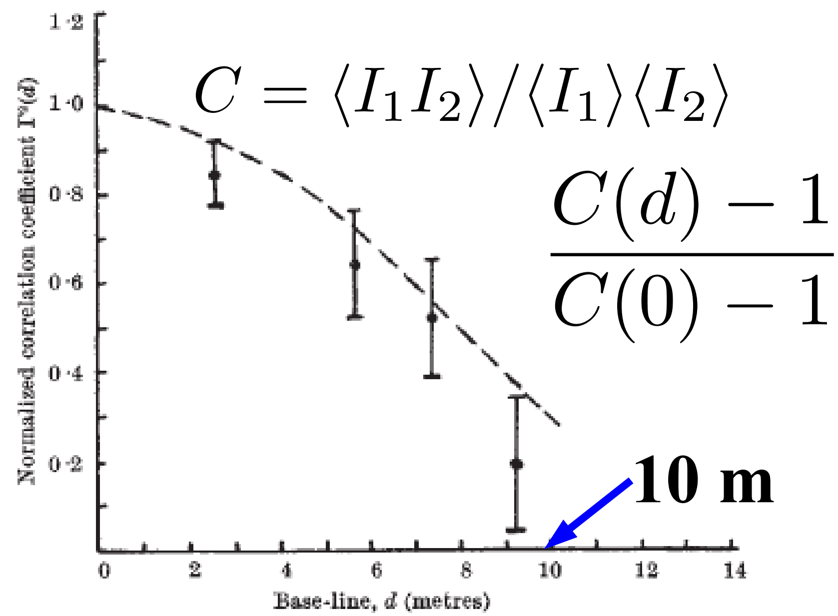


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

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 Γ²(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**

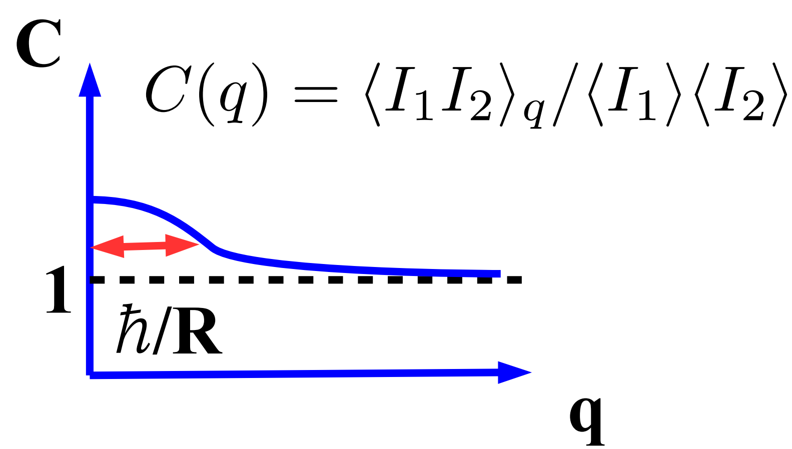
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left| \frac{1}{\sqrt{2}} (e^{i\mathbf{q}\cdot\mathbf{r}} + e^{-i\mathbf{q}\cdot\mathbf{r}}) \right|^2 \simeq 1 + \exp(-4q^2R^2)$$

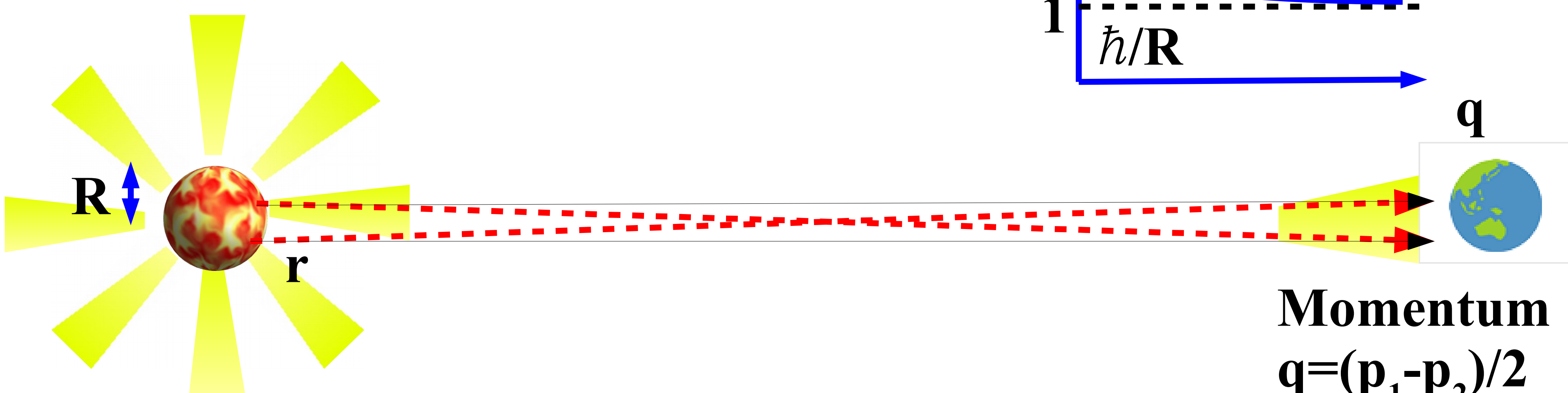
Source fn. (r=relative coordinate)

(symmetrized w.f.)^2

Static spherical source case

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

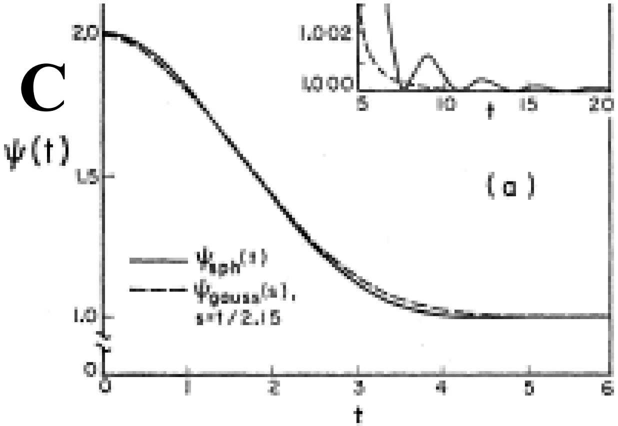




How can we measure source size in nuclear reactions ?

- **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

C



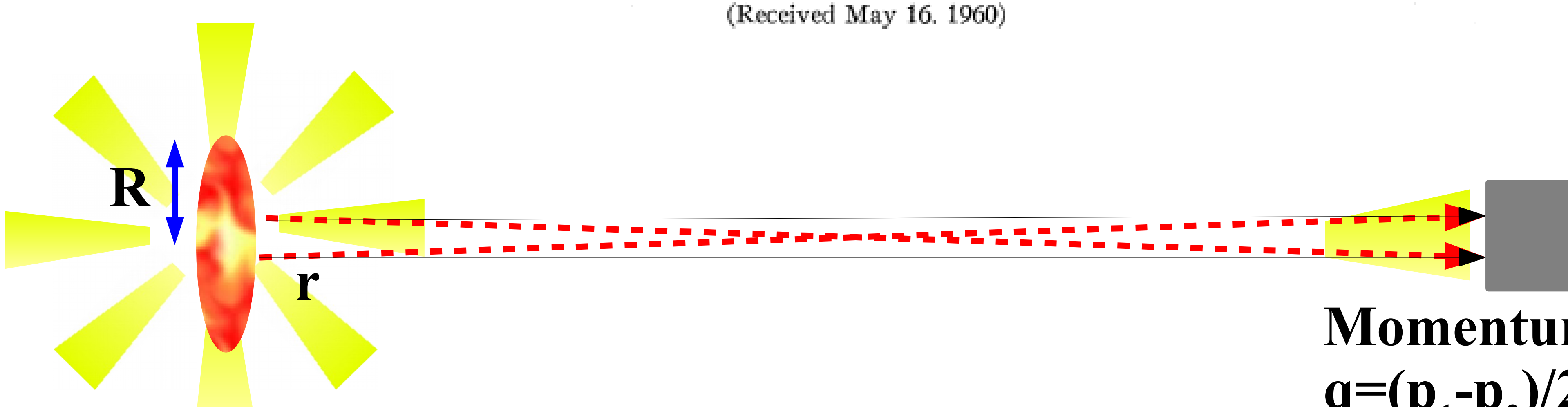
q (relative momentum)

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)



Momentum
$q=(p_1-p_2)/2$