Exotic hadrons and hadron-hadron interactions in heavy ion collisions

Akira Ohnishi [1] for ExHIC Collaboration

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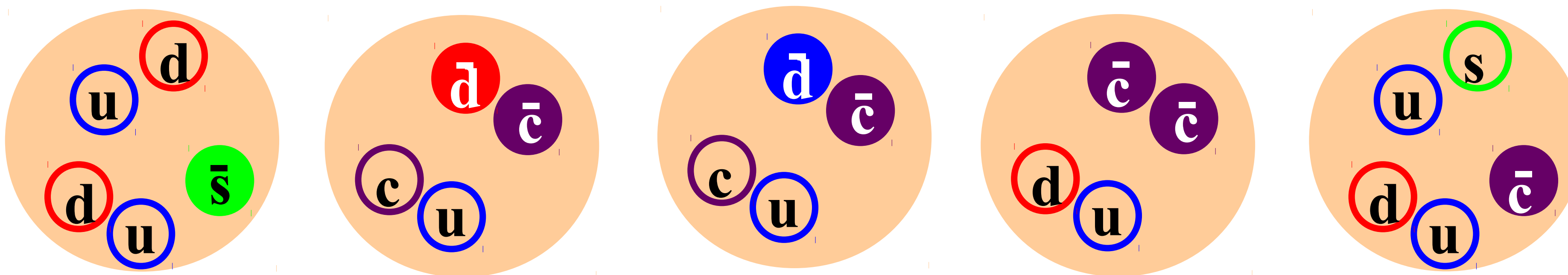
- **Introduction**
- **Exotic Hadron Yields in Heavy Ion Collisions**
- **Exotic Interaction from heavy ion collisions**
  – H particle and ΛΛ interaction –
- **Summary**

Hyp2012: XI Int. Conf. on Hypernuclei and Strange Particle Physics, Oct. 1-5, 2012, Barcelona, Spain.

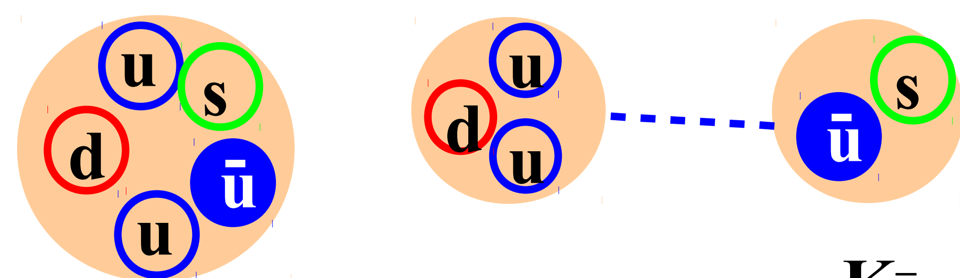
Exotic Hadrons

- Exotic hadrons
  → Θ^+, Z, X, Y, …. Discovered/Proposed at LEPS, Belle, BaBar,…



Θ^+ Z(4430)   X(3872) T_{cc} Θ^+_{cs}

- Various pictures
  - Di-quark component
  - Hadronic molecule
  - $Q\bar{Q}$ couples with $Q\bar{Q}\, q\bar{q}$

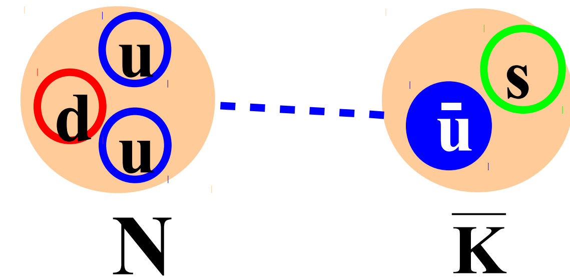


uudsū   p K^-

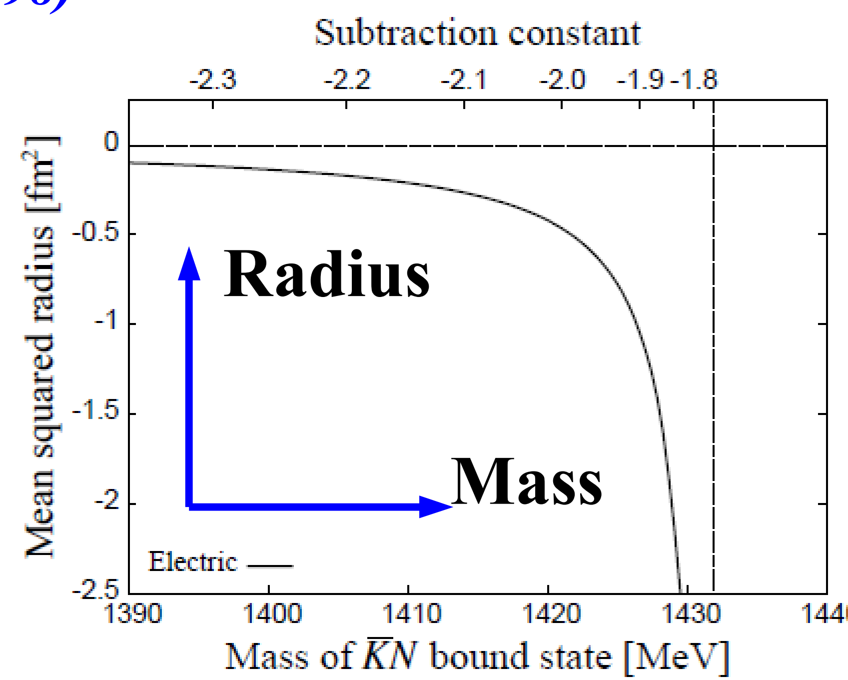
Λ (1405)

Example 1: Λ(1405)

- **Λ(1405) as a bound state of $\bar{K}$N**
  Dalitz, Wong ('67); Siegel, Weise ('88)
  How can we confirm it ?



- **Binding Energy**
  → Deep (~ 30 MeV) or Shallow (~ 10 MeV) binding
  Akaishi, Yamazaki ('02); Jido, Oller, Oset, Ramos, Meissner ('03); Hyodo, Weise ('08); Shevchenko, Gal, Mares ('07); Ikeda, Sato ('07), …
- **Medium effects → Upward mass shift or No change**
  Koch ('94); Waas, Kaiser, Weise ('96); Lutz ('98)
- **In-medium Branching Ratio Change**
  → Indirect (?)
  Vander Velde-Wilquet et al. ('77); AO, Nara, Koch ('98)
- **Form factor → Not measured yet**
  Sekihara, Hyodo, Jido ('08, '11) → **(Fig.)**

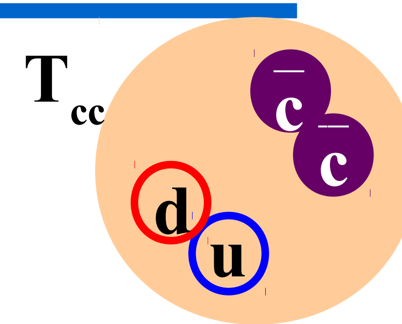


Key quantity = Size !

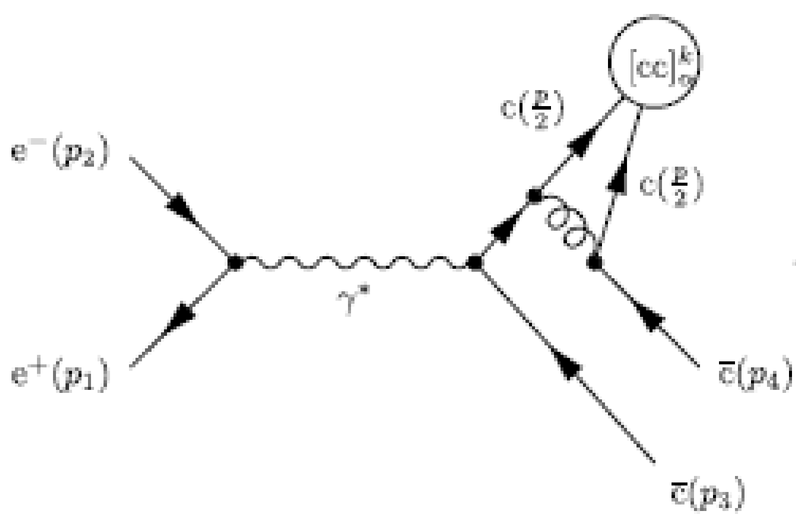
Example 2: Tcc (doubly charmed tetra-quark)

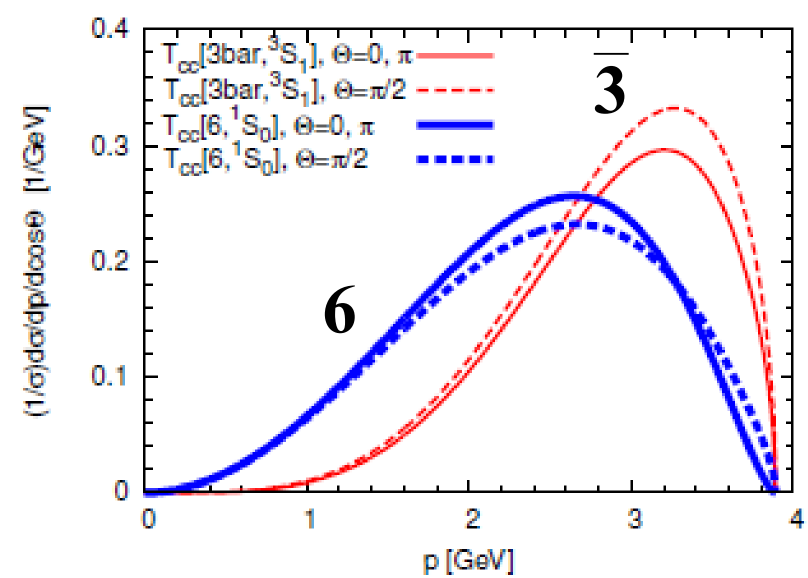
- $T_{cc} = qq\bar{c}\,\bar{c}$ (q=u or d)

  Zouzou et al. ('86); Selem, Wilczek ('06); Vijande, Valcarce, Tsushima ('06); Lee, Yasui, Liu, Ko ('08); Lee, Yasui ('09); Manohar, Wise ('93); Schaffner-Bielich, Visher ('98). Oka (Wed)



  - **ud diquark is favored by the color-magnetic int. (below $\overline{DD}^*$ threshold)**
    Confining force → Tcc should be compact !
  - **T^1_{cc} ($J^P=1^+$) → strong decay into $\overline{DD}$ is forbidden**
  - **Production in e^-e^+ annihilation**

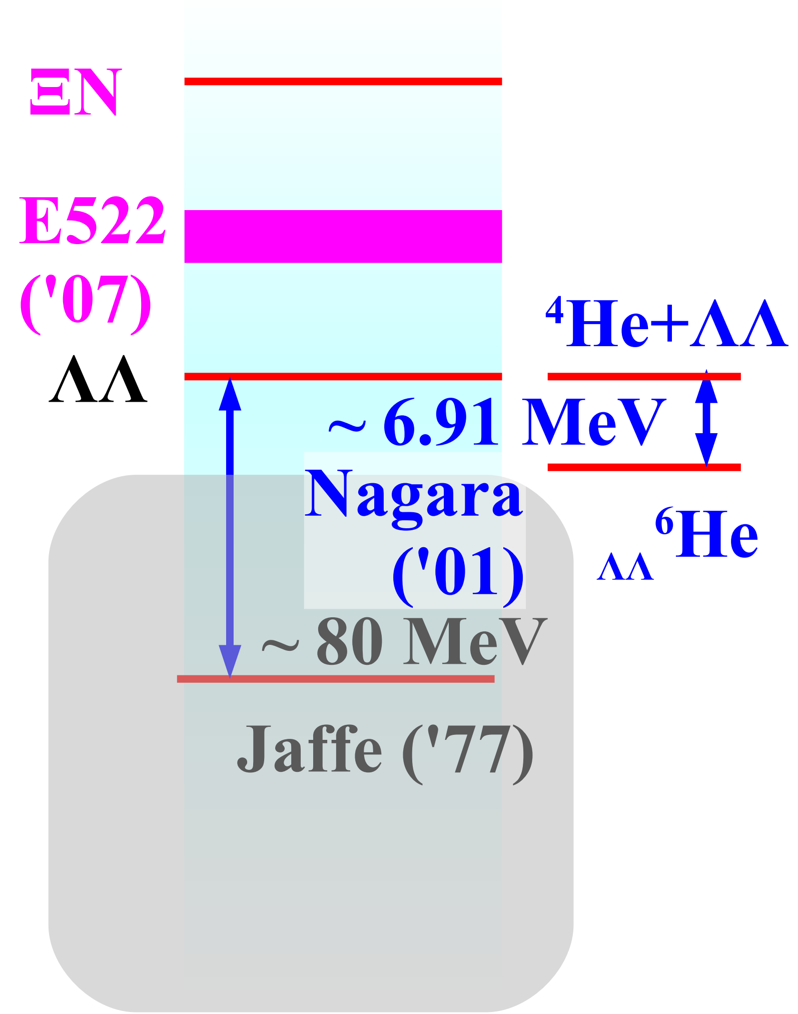




Hyodo, Liu, Oka, Sudoh, Yasui, arXiv:1209.6207

Example 3: H particle

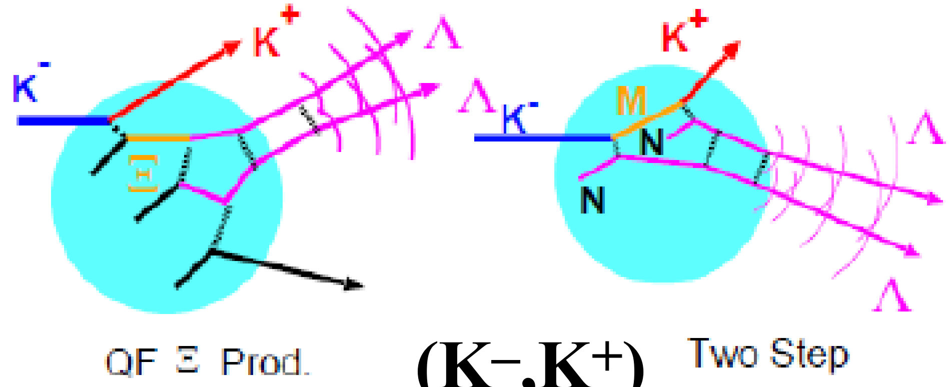
- Deeply bound H ? *Jaffe ('77)*
  - Strong Attraction from Color Mag. Int. → 80 MeV below ΛΛ
- No observation for a long time. Why there is no bound state ?
  - Color Mag. + Repulsive Instanton Ind. Int. *Oka, Takeuchi ('91)*
- Nagara event $_{\Lambda\Lambda}{}^{6}$He *Takahashi et al. ('01)*
  - No deeply bound "H", Weakly Att. ΛΛ int.
- Resonance or Bound "H" ?
  - 2 σ "bump" at $E_{\Lambda\Lambda}$ ~ 15 MeV *Yoon et al.(KEK-E522) ('07)*
  - bound H at large *ud* quark masses *HAL QCD & NPLQCD ('11), Haidenbauer, Meissner ('11)*



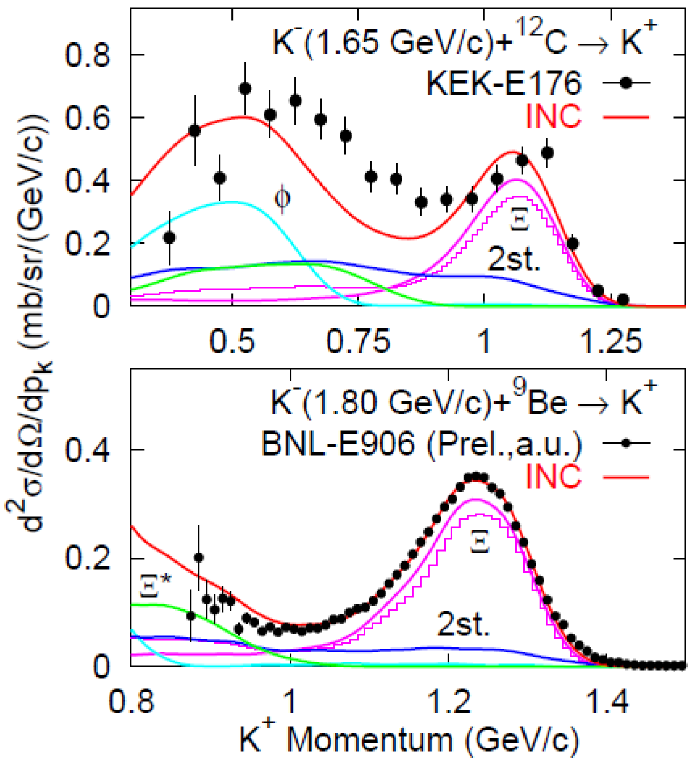
Shah,
Fernandez Carames (Mon)
Beane, Hatsuda,
Haidenbauer (Tue)
Ahn (Poster)

ΛΛ correlation from (K^-,K^+ΛΛ) reaction

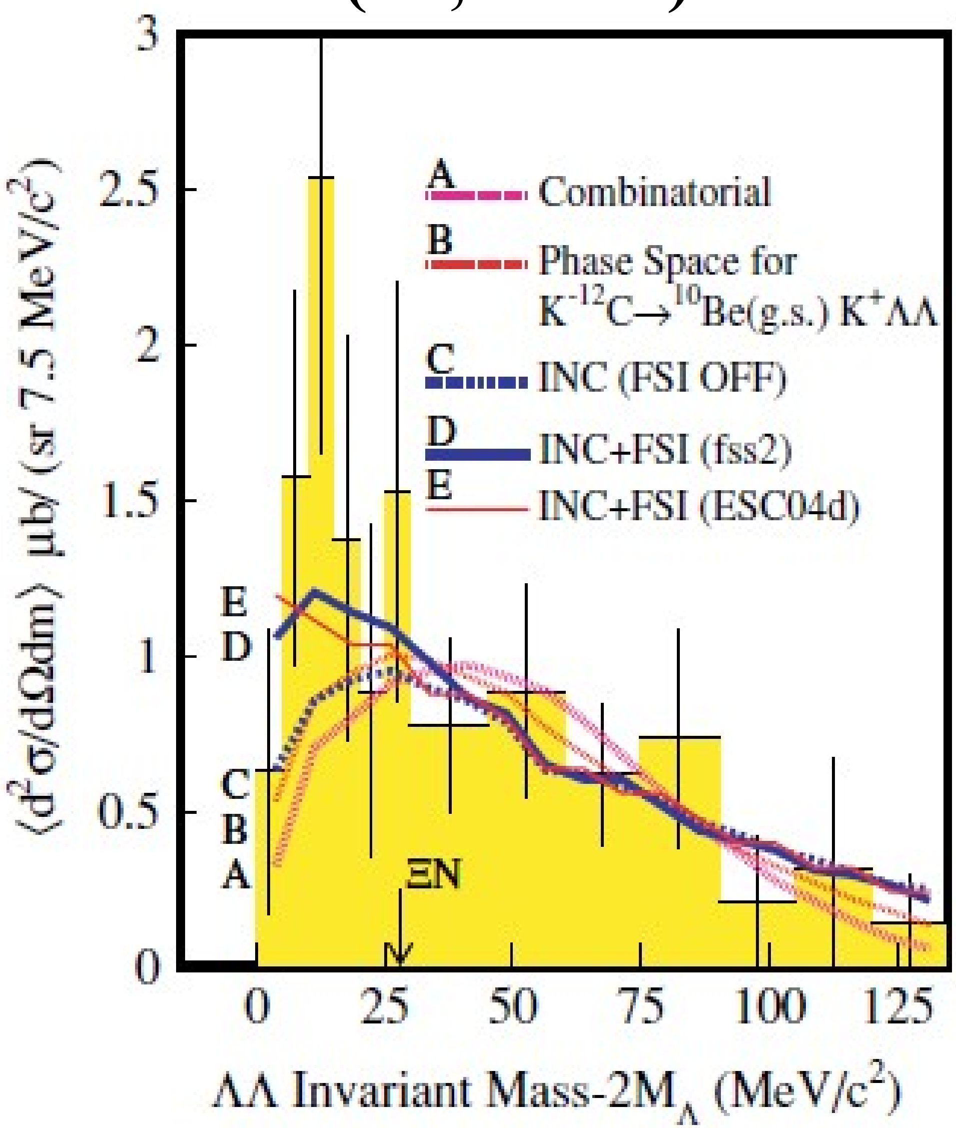
- **Enhancement at ~ 2 M(Λ)+ 10 MeV, CL=2σ**



(K^-,K^+)



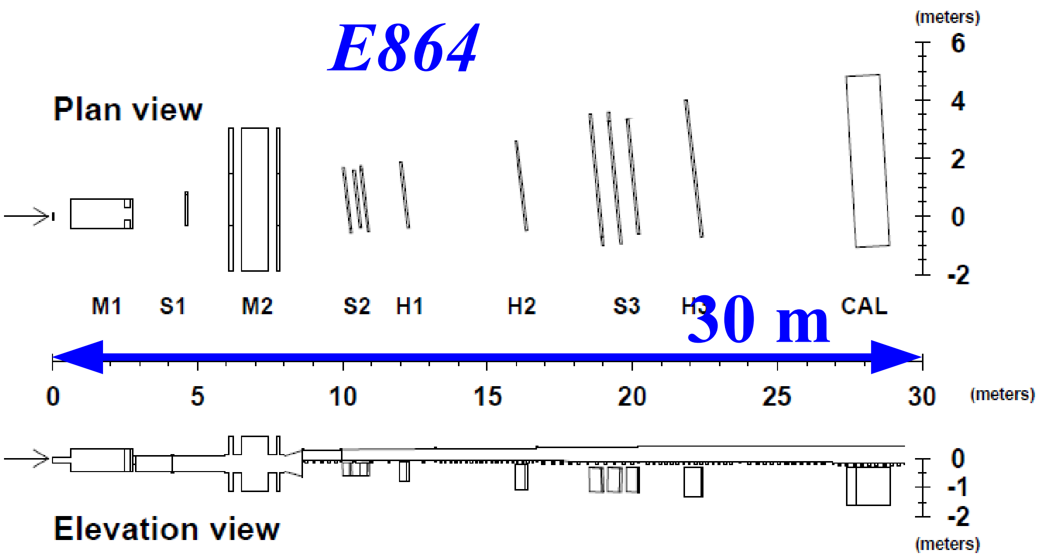
(K^-,K^+Λ Λ)

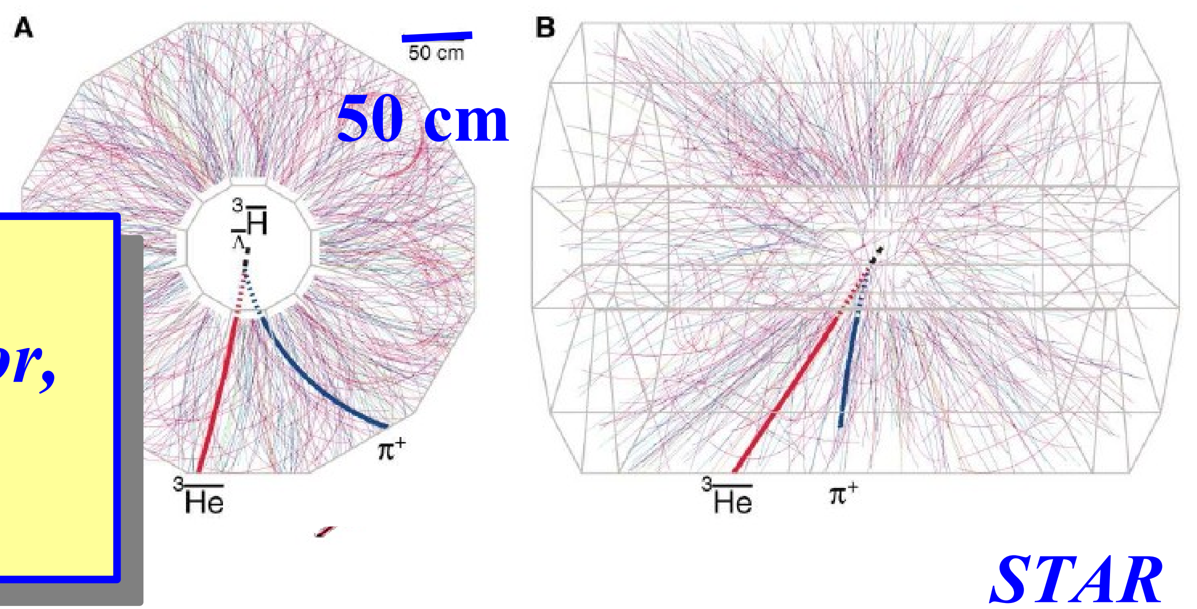


C.J.Yoon, …, (KEK-E522),AO, PRC75 (2007) 022201(R)
J. K. Ahn et al. (KEK-E224).

Exotics from Heavy Ion Collisions

- **Exotic search from HIC (~ 90's)**
  E864, E896, NA52, ..
  - **Fixed target**
    → Exotics in forward decector (5-30 meters away !)
    Only very long lived exotics can be found.
- **Exotic search at RHIC / LHC**
  - **Collider & 4π detector**
    → Anti-hypertriton





BNL-AGS (CERN-SPS) is not only the beam injector, but also a spirit injector of RHIC (LHC).

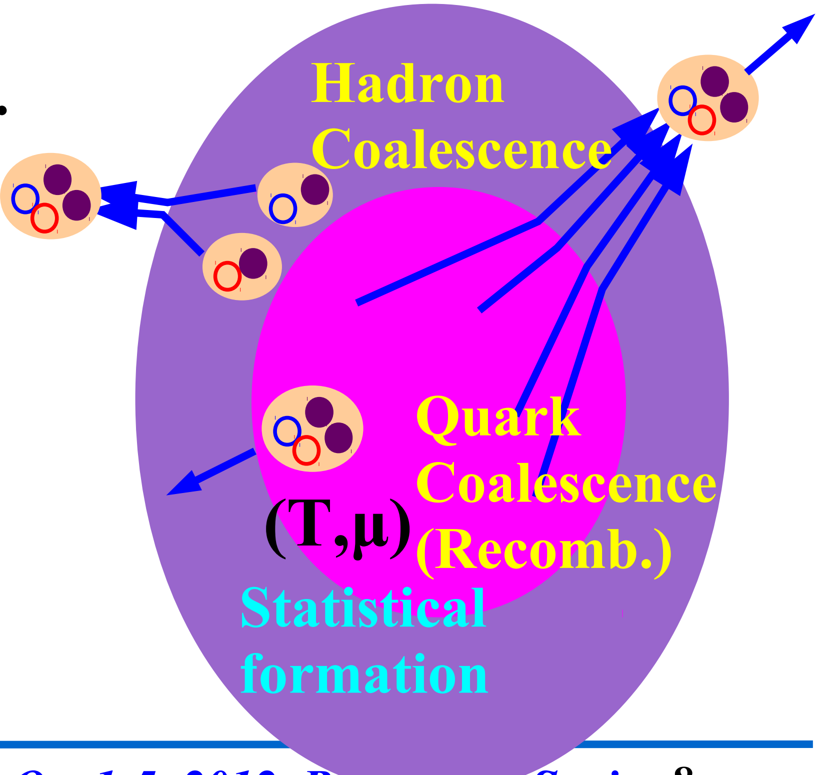
Don't forget Dubna, GSI.

Exotics from Heavy Ion Collisions

- **High-Energy Heavy-Ion Collisions**
  - **Too complex → Statistical → Simple and Clean !**
  - **High *T* & Large volume → Abundant hadrons**
  - **RHIC & LHC → Nearly 4π detector / Vertex detector**

→ Let's regard RHC & LHC as Exotic Hadron Factories

- **What can we learn ? Existence, Mass, Width, Size, Interaction, ..**
  - **Formation mechanism of hadrons**
    = Statistical , Coalescence, Fragmentation.
    → Yields are sensitive to hadron size in Coal.
    Chen, Greco, Ko, Lee, Liu, ('04)
  - **Correlation func. ~ ∫ Source x $|w.f.|^2$**
    → Once we know source, Corr. Func. is sensitive to w.f. and pairwise interaction.
    Bauer, Gelbke, Pratt ('92); Lednicky ('09).

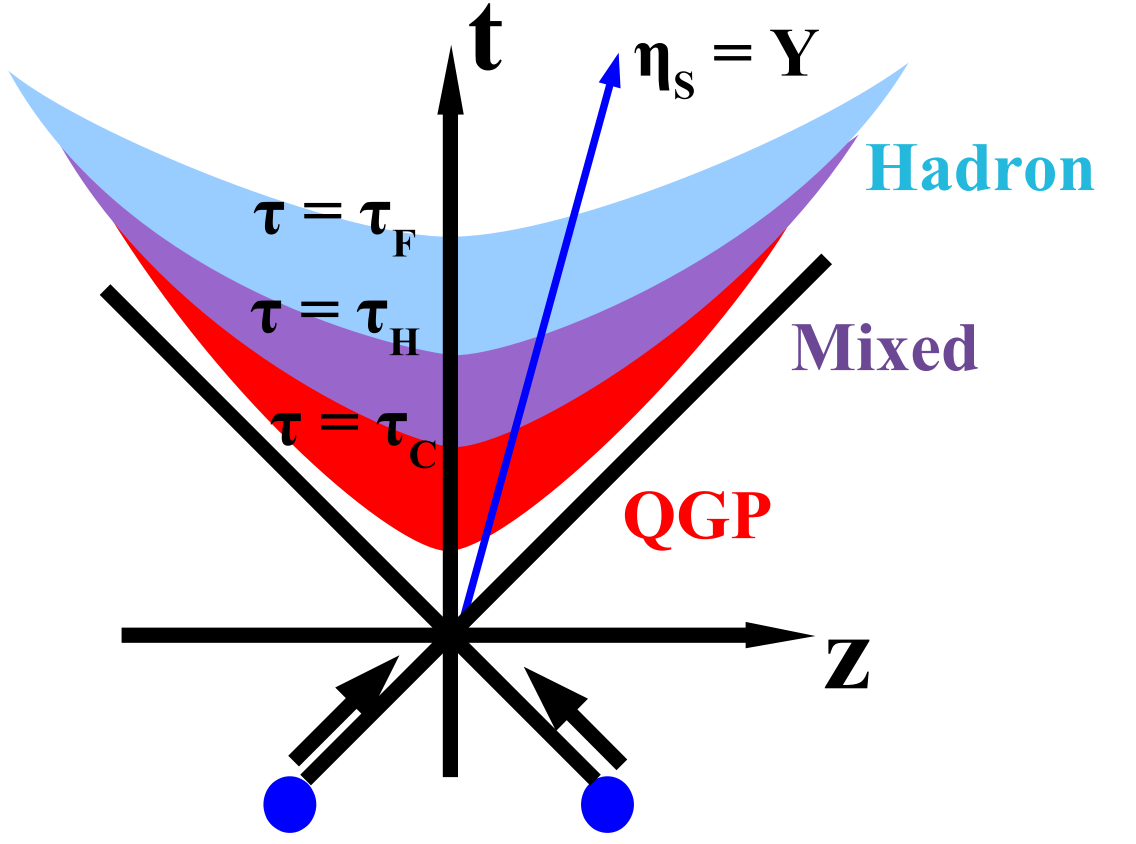


Exotic Hadron Yields in Heavy Ion Collisions

Schematic picture of HIC

- HIC picture based on the first order phase transition
  - $\tau = \tau_C$, $T=T_C$, $V=V_C$ → QGP start to hadronize (quark coal.)
  - $\tau = \tau_H$, $T=T_H=T_C$, $V=V_H$ → Hadronization is over (stat. model)
  - $\tau = \tau_F$, $T=T_F$, $V=V_F$ → Hadronic Freeze-out (hadron coal.)

	RHIC	LHC
$N_u = N_d$	245	662
$N_s = N_{\bar{s}}$	150	405
$N_c = N_{\bar{c}}$	3	20
$N_b = N_{\bar{b}}$	0.02	0.8
V_C	1000 fm^3	2700 fm^3
$T_C = T_H$	175 MeV	175 MeV
V_H	1908 fm^3	5152 fm^3
μ_B	20 MeV	20 MeV
μ_s	10 MeV	10 MeV
V_F	11322 fm^3	30569 fm^3
T_F	125 MeV	125 MeV



L.W.Chen, V.Greco, C.M.Ko, S.H.Lee, W.Liu, PLB 601('04)34.

Statistical Model

- **Statistical model**

$$N_h^{\rm stat} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_h^{-1} e^{E_h/T_H} \pm 1}$$

(N_h = dN_h/dy (y=rapidity), V_H=Chem. freeze-out vol.)

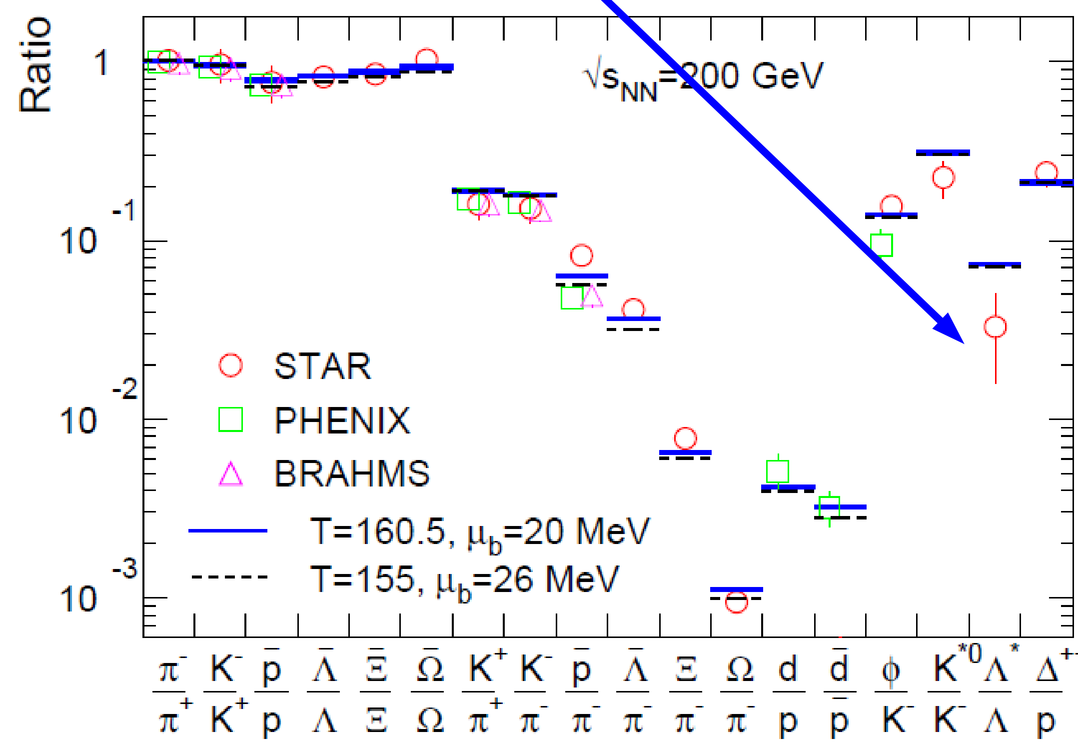
→ Successful to predict the hadron yield ratio at RHIC

- **Fugacity factor γ**
  - **u,d,s: chem. equil.**
  - **c,b: enhanced by initial hard processes**

Fugacities of c and b quarks are set to reproduce expected c and b quark numbers.

$$\gamma_h = \gamma_c^{n_c+n_{\bar{c}}} \gamma_b^{n_b+n_{\bar{b}}} e^{(\mu_B B + \mu_s S)/T_H}$$

L effects: Kanada-En'yo, Muller ('06)



A. Andronic, P. Braun-Munzinger, J. Stachel, NPA772('06)167.

Coalescence model

- **Yield = Overlap of const. dist. & Hadron intrinsic Wigner func. (Sudden approximation)**
  Sato, Yazaki (1984), Hwa, Yang (2003), Greco, Ko, Levai (2003), Fries, Muller, Nonaka, Bass (2003), Chen, Ko, Lee (2003)

$$N_h^{\mathrm{coal}} = g_h \int \underbrace{\left[\prod_{i=1}^{n} \frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{\mathrm{d}^3 \mathrm{p}_i}{E_i} f(x_i, p_i)\right]}_{\text{Dist. of constituents}} \times \underbrace{f^W(x_1, \cdots, x_n : p_1, \cdots, p_n)}_{\text{Intrinsic Wigner func.}}$$

Dist. of constituents **Intrinsic Wigner func.**

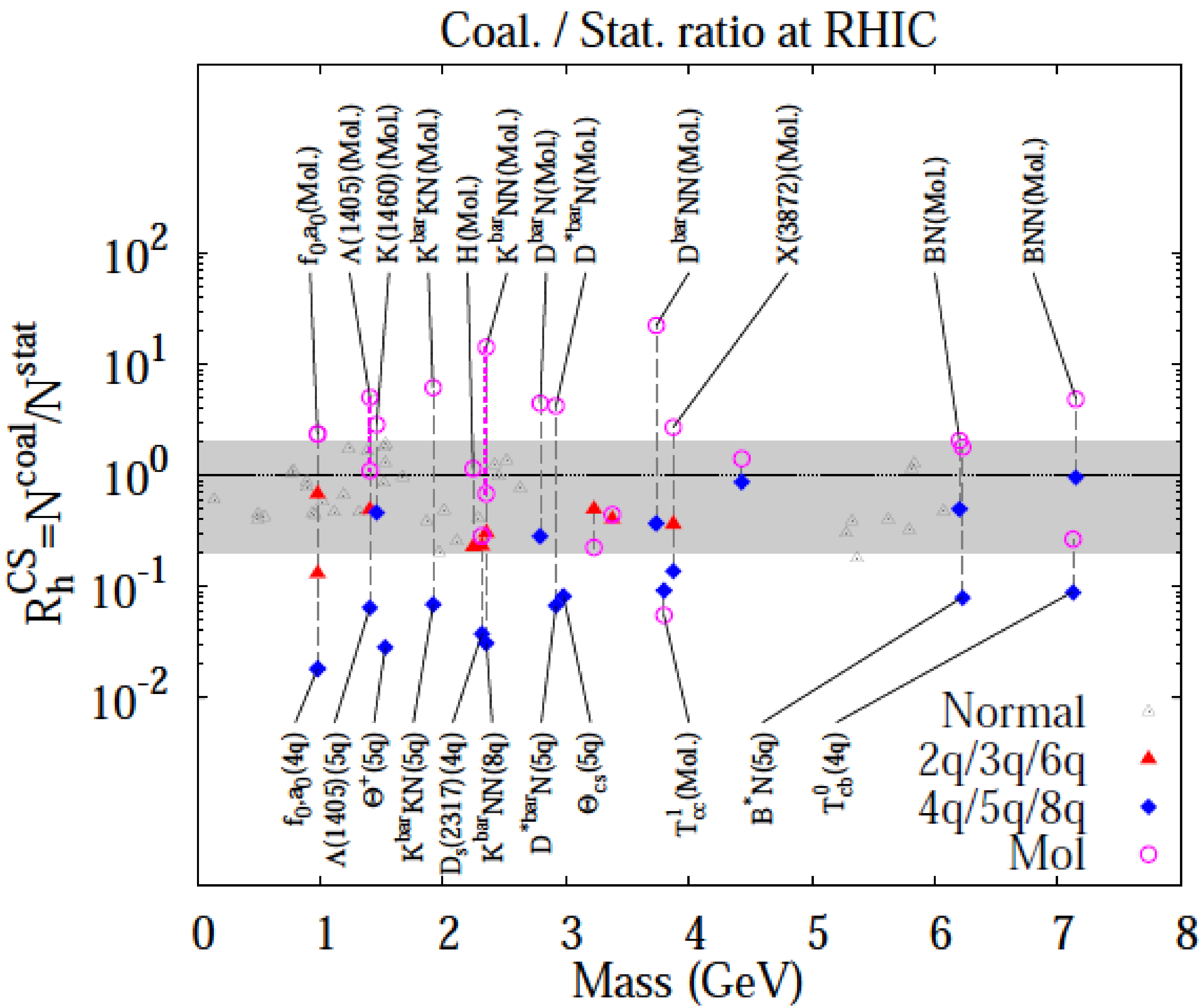
- **Yield in HIC**
  - **Quark & hadron dist. = Transverse Boltzmann + Bjorken**
    Chen, Ko, Liu, Nielsen (2007)
  - **Hadron intr. Wigner func. = s-wave and p-wave HO w.f.**
    Kanada-En'yo, Muller (2006)

$$N_h^{\mathrm{coal}} \simeq g_h \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \left[\frac{4\mu_i T\sigma_i^2}{3(1+2\mu_i T\sigma_i^2)}\right]^{l_i}$$

σ = Gaussian width, μ=reduced mass, N = constituent yield

  - **Available structure information → σ (or ħω)**

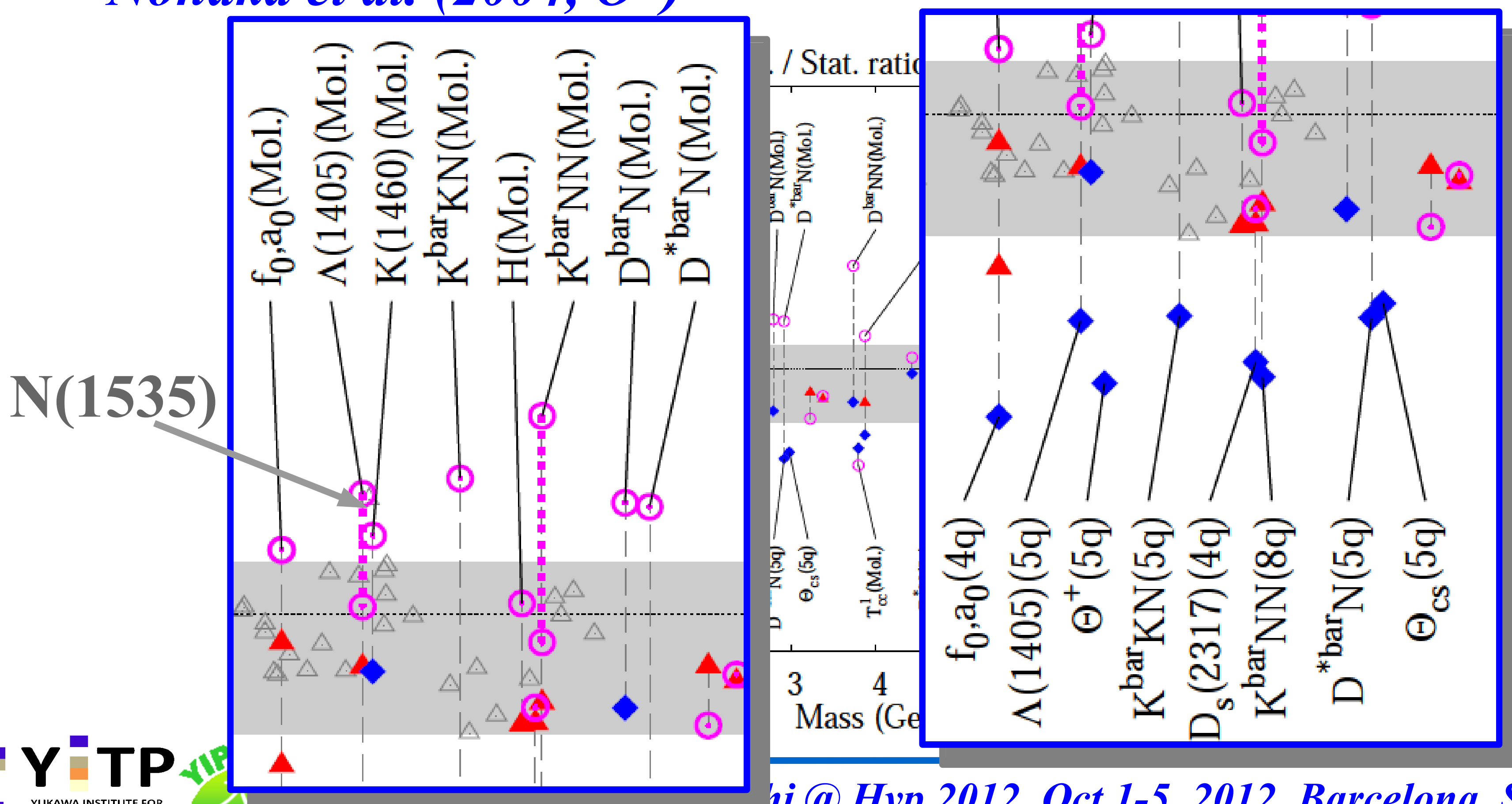
Coalescence / Statistical Ratio



S. Cho et al. (ExHIC Collab.), PRL106('11)212001; PRC 84 ('11) 064910

Coalescence / Statistical Ratio

- **Normal hadrons: Rcs = (0.2-2)** ***Normal band***
- **Extended hadronic molecule: Large yield is expected, Rcs > 2.**
  Λ(1405)=$\bar{K}$N, $\bar{K}$NN, $\bar{K}$KN, $\bar{D}$NN, … (ħω=(6-50) MeV)
- **Compact Multiquark states will be suppressed in HICs, Rcs < 0.2**
  f_0/a_0($qq\bar{q}\bar{q}$), Θ^+($uudd\bar{s}$), H(uuddss), Θ_{cs}($uuds\bar{c}$), …
  Nonaka et al. (2004, Θ^+)



Enhancement of Hadronic Molecules: Why ?

- **Simple estimate: 2-body, Gaussian w.f. + Thermal dist. of constiuents**

$$N_h \propto \int \frac{d^D x\, d^D p}{(2\pi\hbar)^D} \underline{f_W(x,p)}\, \underline{f_{\rm th}(x,p)} = \left[\left(\frac{4}{\hbar^2}\right) \left((\Delta p)^2 + \mu T\right) \left((\Delta x)^2 + 2R^2\right) \right]^{-D/2}$$

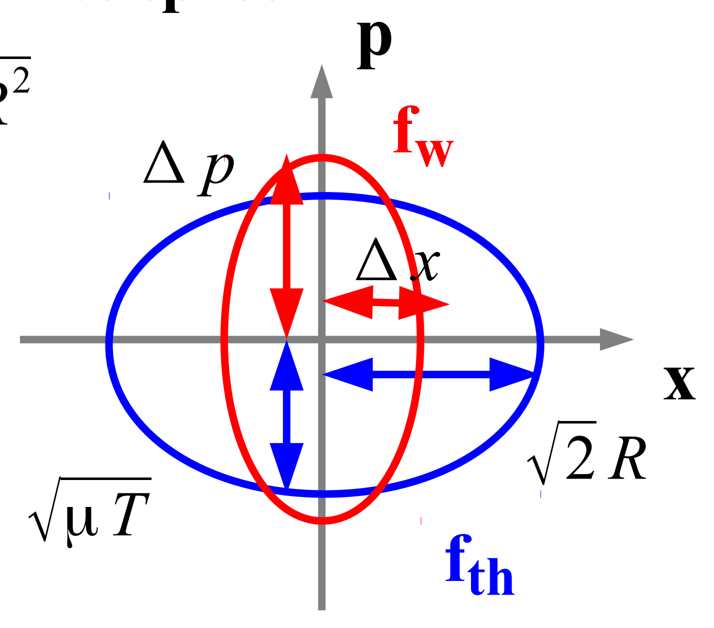
Intrinsic **Constituents (thermal)**

$$f_W(x,p) = \left(\frac{\hbar}{\Delta x \Delta p}\right)^D \exp\left(-\frac{x^2}{2(\Delta x)^2} - \frac{p^2}{2(\Delta p)^2}\right), \quad f_{\rm th}(x,p) = \left(\frac{\hbar^2}{2\mu T R^2}\right)^{D/2} \exp\left(-\frac{x^2}{4R^2} - \frac{p^2}{2\mu T}\right)$$

- **N_h is large when f_w shape is similar to f_{th} in phase space.**

$$\Delta x : \Delta p = \sqrt{2} R : \sqrt{\mu T} \;\rightarrow\; \hbar\omega = \sqrt{\hbar^2 T / 2\mu R^2}$$

- **Example: T=170 MeV, μ=500 MeV (red. mass), R = 5 fm (source size) → optimal hω ~ 16 MeV (<< 300-500 MeV)**



Large source size & Moderate T prefer extended hadrons

Why are Multi-quark Configs. Suppressed ?

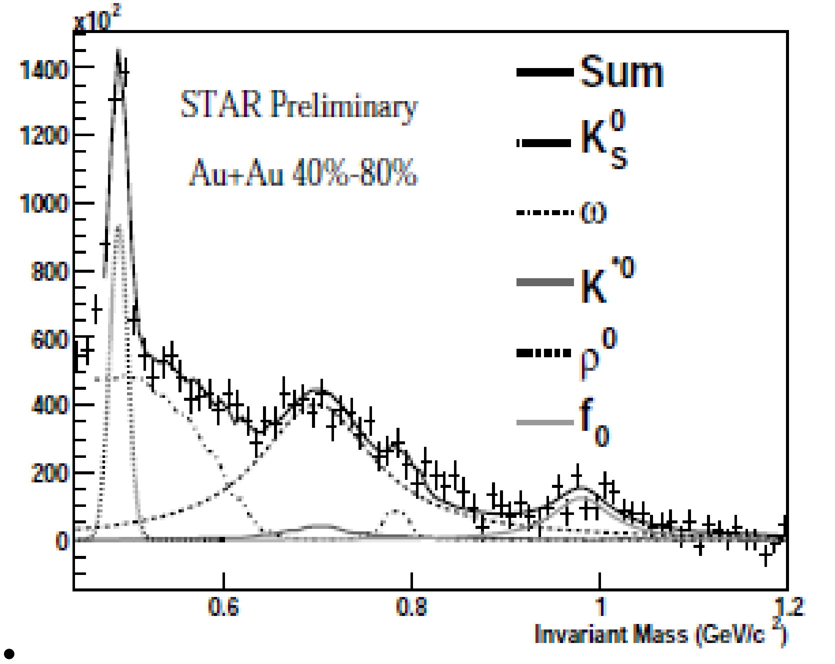
- **Hadron yield is sensitive to the structure in coal.**
  - **Additional q penalty factor**

s-wave $\frac{1}{g_i}\frac{N_i}{V}\frac{(4\pi\sigma_i^2)^{3/2}}{(1+2\mu_i T\sigma_i^2)}$ **~ 0.36**

p-wave $\frac{1}{g_i}\frac{N_i}{V}\frac{2}{3}\frac{(4\pi\sigma_i^2)^{3/2}2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)^2}$ **~ 0.09**

Nonaka et al. (2004, Θ⁺)
Kanada-En'yo, B. Muller (2006, Λ(1520))
Large V disfavors multi-quarks !

- **STAR data (2003): N(f_0(980)) ~ 8.4**
  [f_0(980)/ ρ^0 ~ 0.2, stat. N(ρ^0) ~ 42]
  Stat: 5.6, 2q:0.76-3.8, 4q:0.1, Mol: 13
  → Tetra-quark picture
  underestimate the measured yield of f_0 .

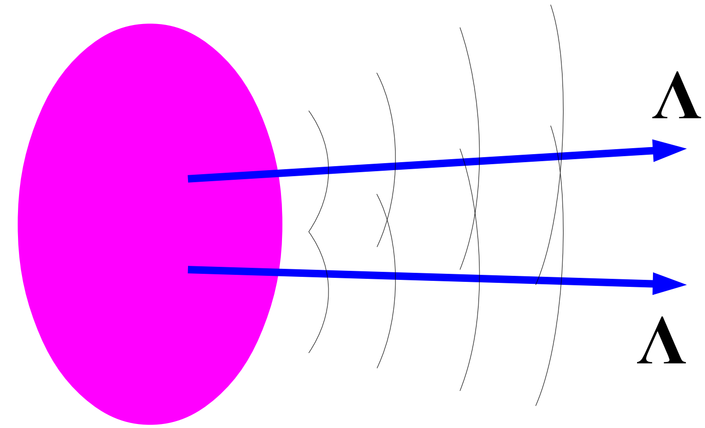


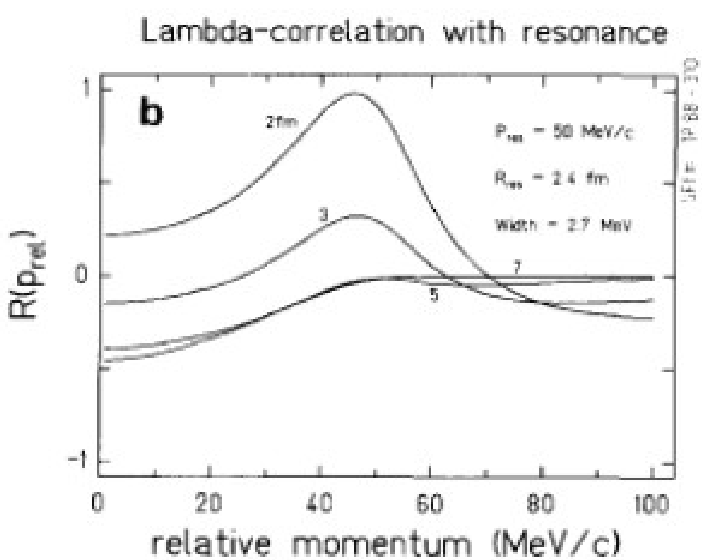
P. Fachini [STAR Collaboration], Nucl. Phys. A 715,462 (2003).

Exotic Interactions from Heavy Ion Collisions --- H particle and $\Lambda\Lambda$ interaction ---

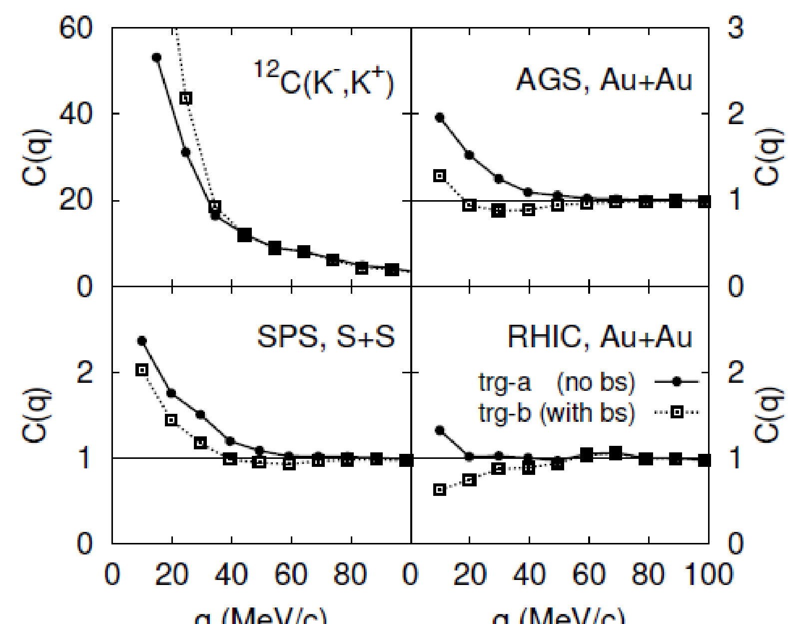
ΛΛ correlation in HIC

- **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).





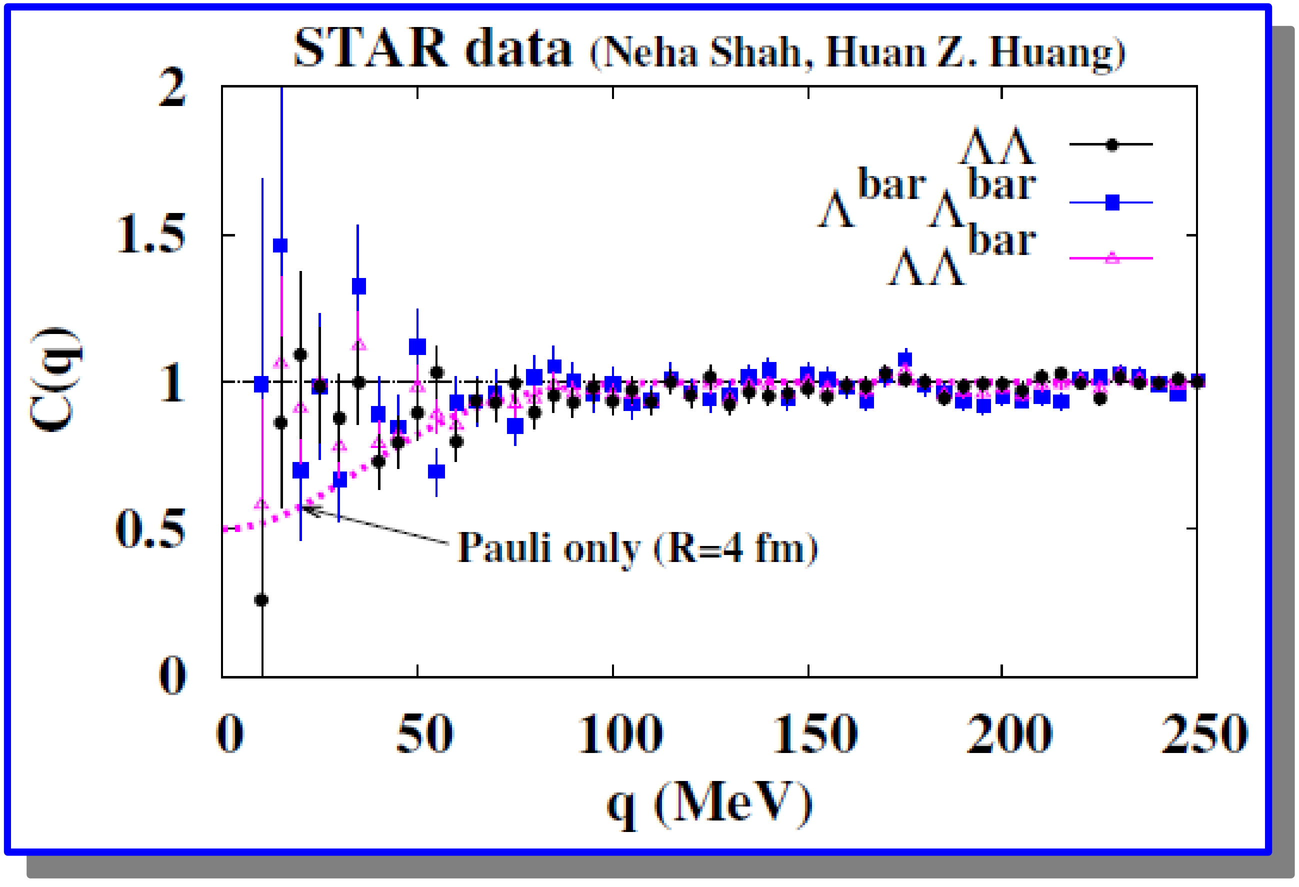
C. Greiner, B. Muller, PLB219('89)199.



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

ΛΛ correlation in HIC

- **Real Data at RHIC are measured, and Enhancement from Fermi correlation is clearly seen !**

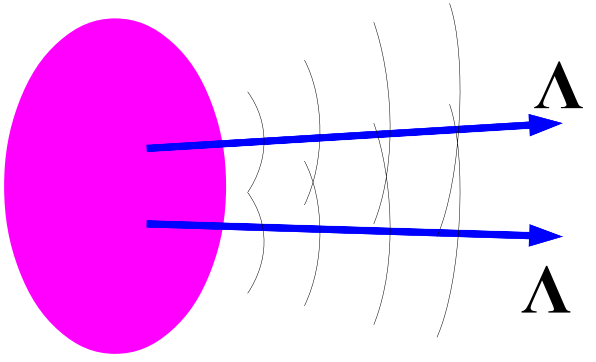


Shah (Mon.); Neha Shah et al. (STAR Collab.), Acta Phys. Pol. Suppl. 5 ('12) 593 [arXiv:1112.0590].

Can we constrain ΛΛ interaction from RHIC data ?
Does H exist as a bound state or a resonance ?

ΛΛ correlation in HIC and ΛΛ interaction

- **Two particle correlation from chaotic source**



c.f. Bauer, Gelbke, Pratt,
Annu. Rev. Nucl. Part. Sci. 42('92)77.

$$C_{\Lambda\Lambda}(q) = \frac{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q) |\psi^{(-)}(x_{12}, q)|^2}{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q)}$$

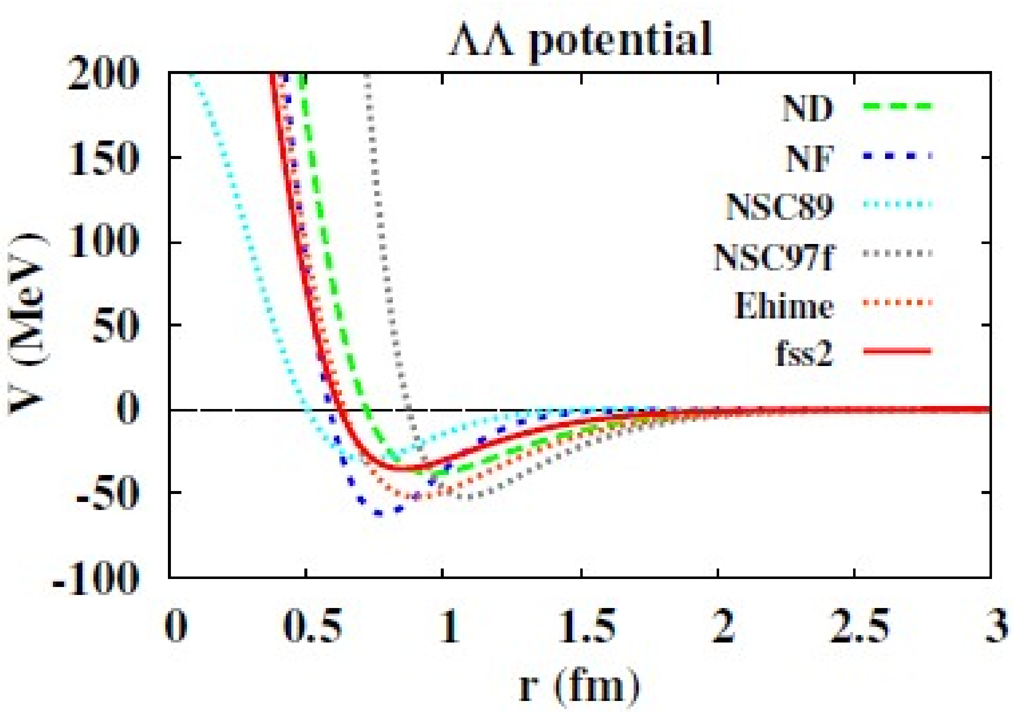
$$\simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int dr\, S_{12}(r)\left(|\chi_0(r)|^2 - |j_0(qr)|^2\right)$$

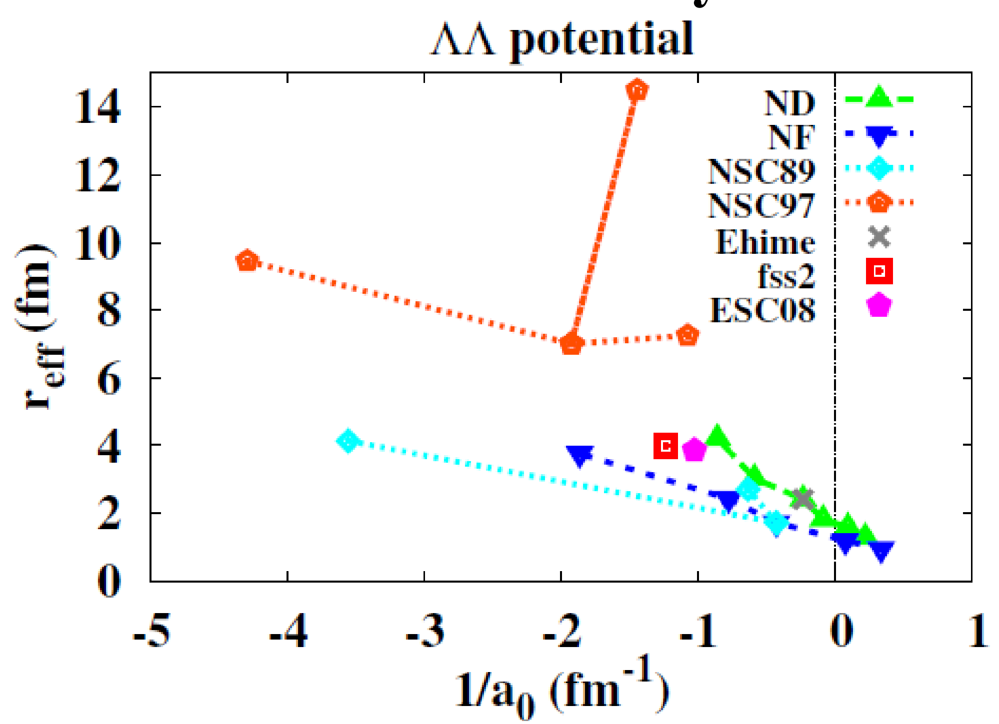
(χ_0 : s-wave wave func., $S_{12}(x)=(2R\sqrt{\pi})^{-3}\exp(-r^2/4R^2)$)

- **Baryon Source size: R = (2-4.5) fm (STAR preliminary)**
  → Smaller than π, K source.
- **Other Effects (than Λ Λ interaction) to be considered**
  - **Feed down effects from Σ^0 decay ($\Sigma^0 \to \Lambda\gamma$)**
  - **Coupled channel effects ΞN ↔ ΛΛ**
  - **Flow effects**

ΛΛ interaction

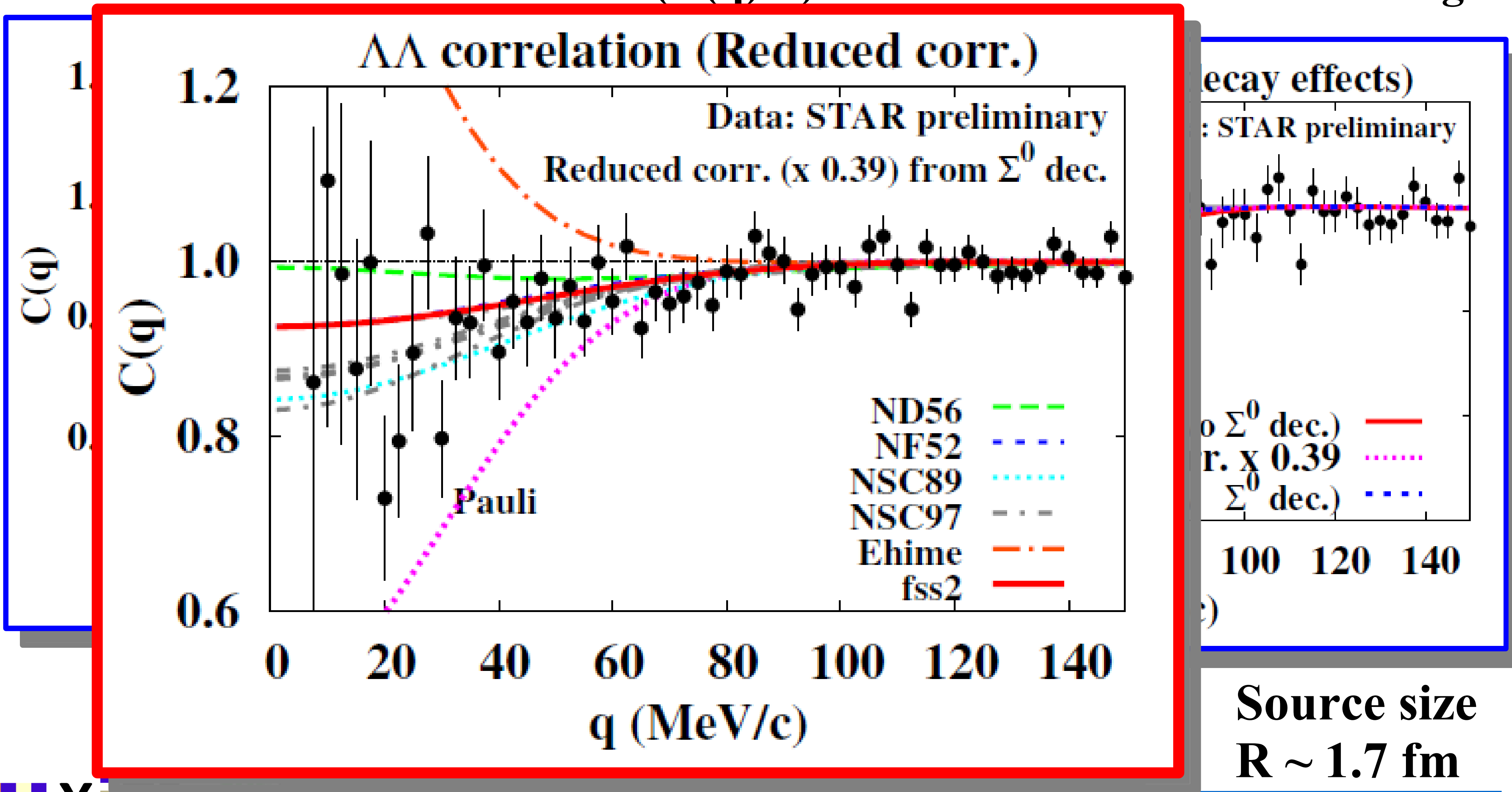
- **Type of ΛΛ interactoin**
  - **Meson exchange models: Nijmegen model D, F, Soft Core (89, 97), ESC08**
    Nagels, Rijken, de Swart ('77, '79), Maessen, Rijken, de Swart ('89), Rijken, Stoks, Yamamoto ('99); Rijken, Nagels, Yamamoto ('10).
  - **Quark cluster model interaction: fss2**
    Fujiwara, 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.**





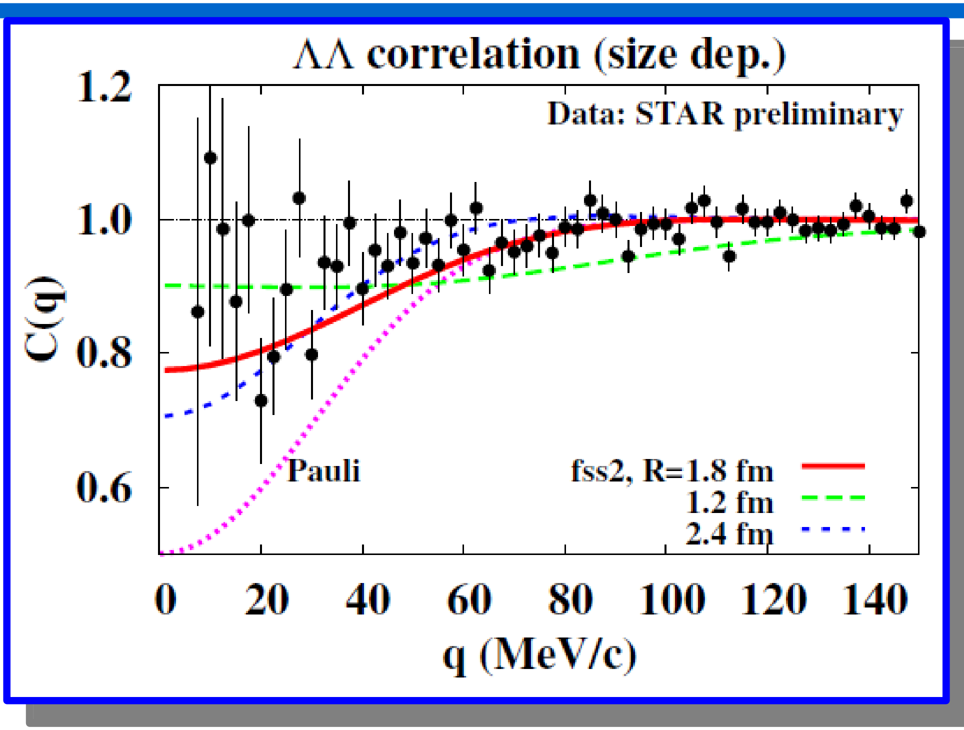
ΛΛ interaction from HIC data

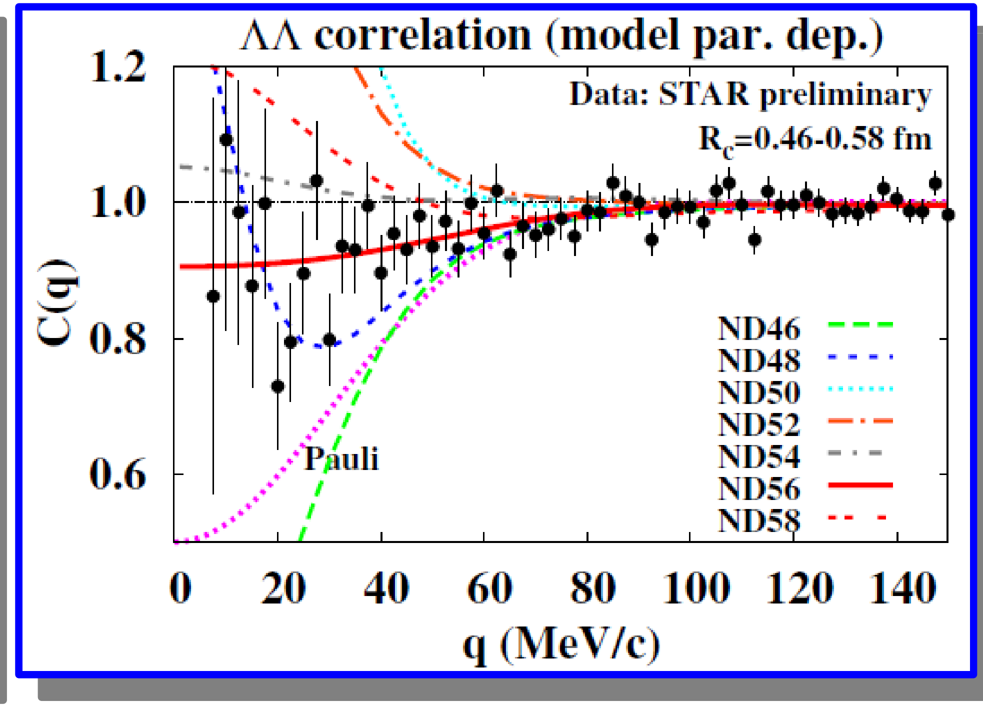
- Source size is determined by C(q) at large q → R *(c.f. J. Pochodzalla)*
- Intrinsic parameters (e.g. hard core radius) from C(q) at small q
- Feed down from Σ^0 → 0.39 x (C(q)-1) if ΛΣ and ΣΣ corr. is not strong.

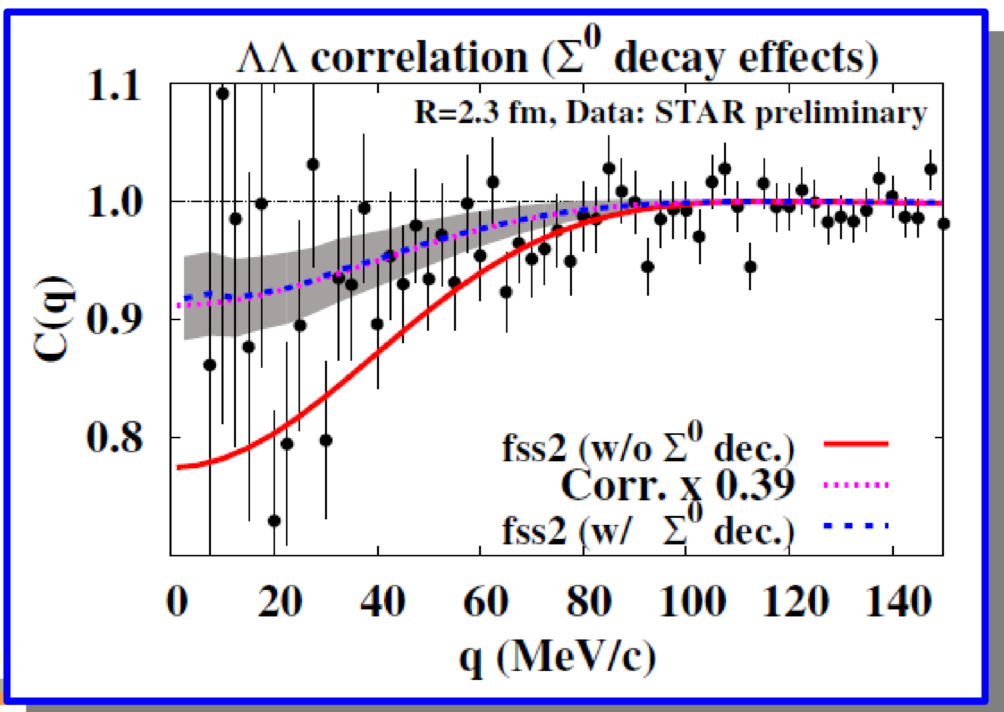


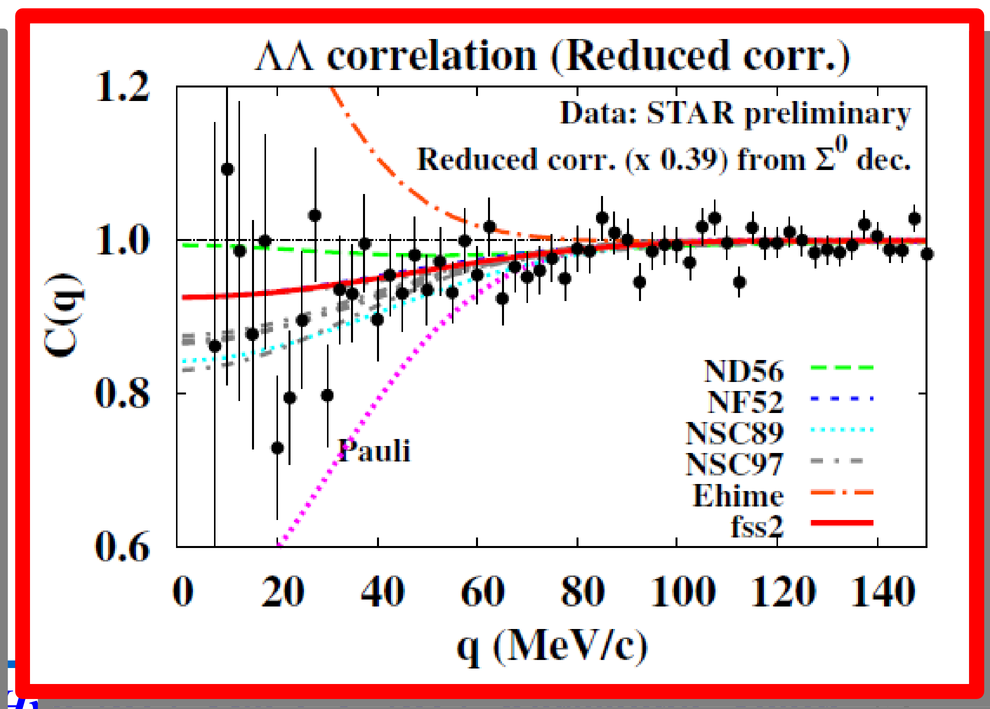
Source size
R ~ 1.7 fm

ΛΛ interaction from HIC data



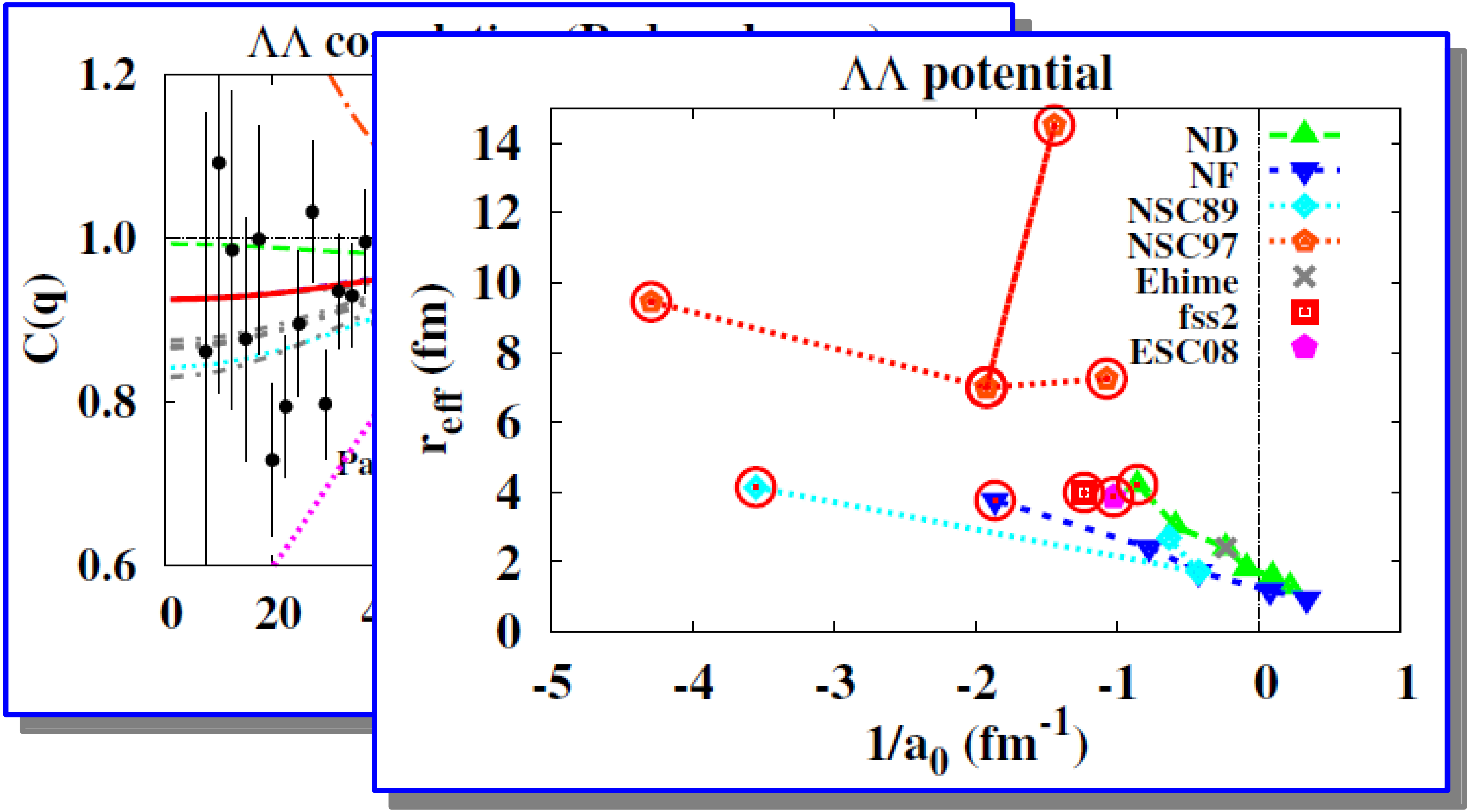






Preferred ΛΛ Interaction

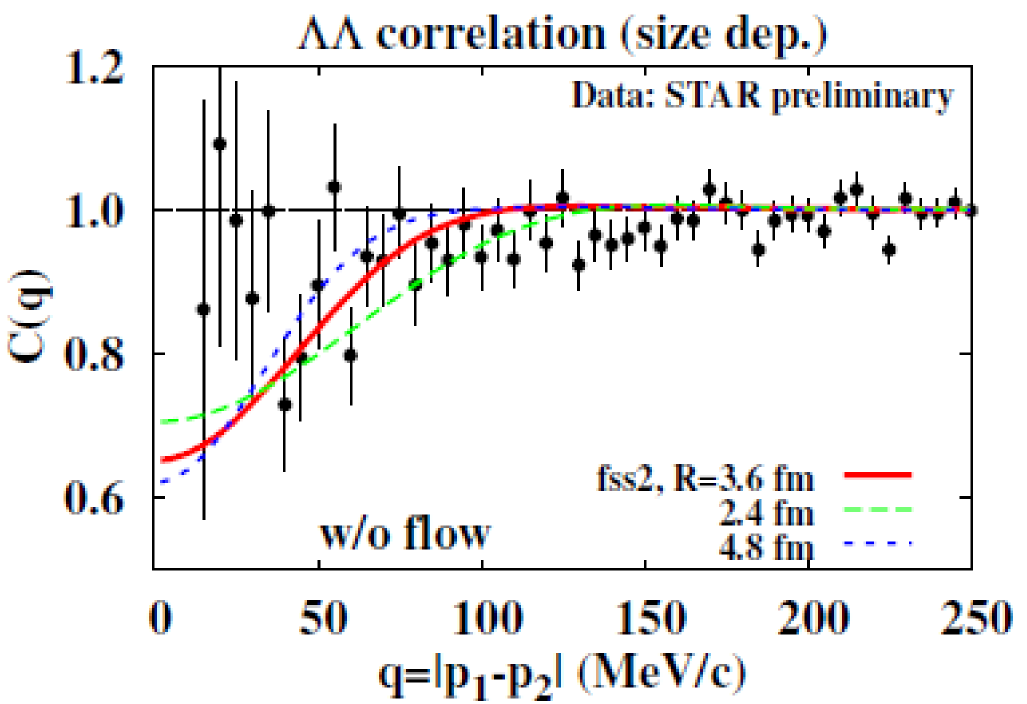
- **STAR data choose some of the ΛΛ interaction**
  → $1/a_0 < -0.8\ \mathrm{fm}^{-1}$ ($-1.2\ \mathrm{fm} < a_0 < 0$), $r_{eff} > 3$ fm seems to be preferred.

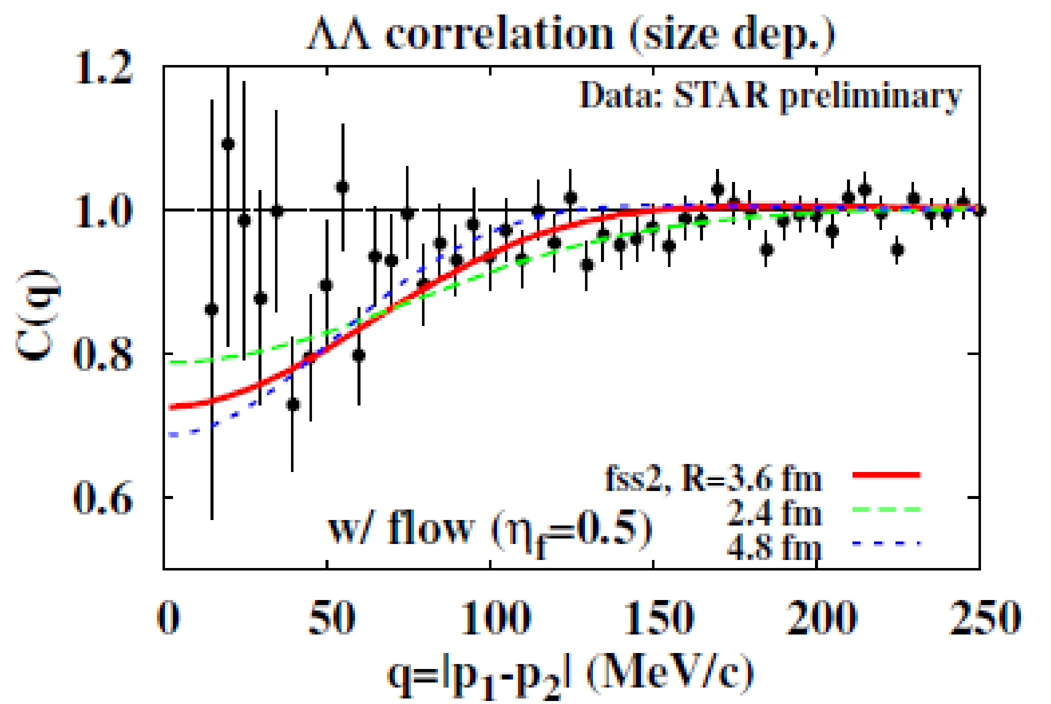


AO, T.Furumoto, K. Morita, in prep.

Flow Effects

- Too small source size ~ 1.7 fm with Σ^0 feed down effects ?
- Flow effects make the “apparent” size smaller.
  - Relative momentum is enhanced by the flow.
    → Actual size ~ 3 fm (consistent with proton source size)



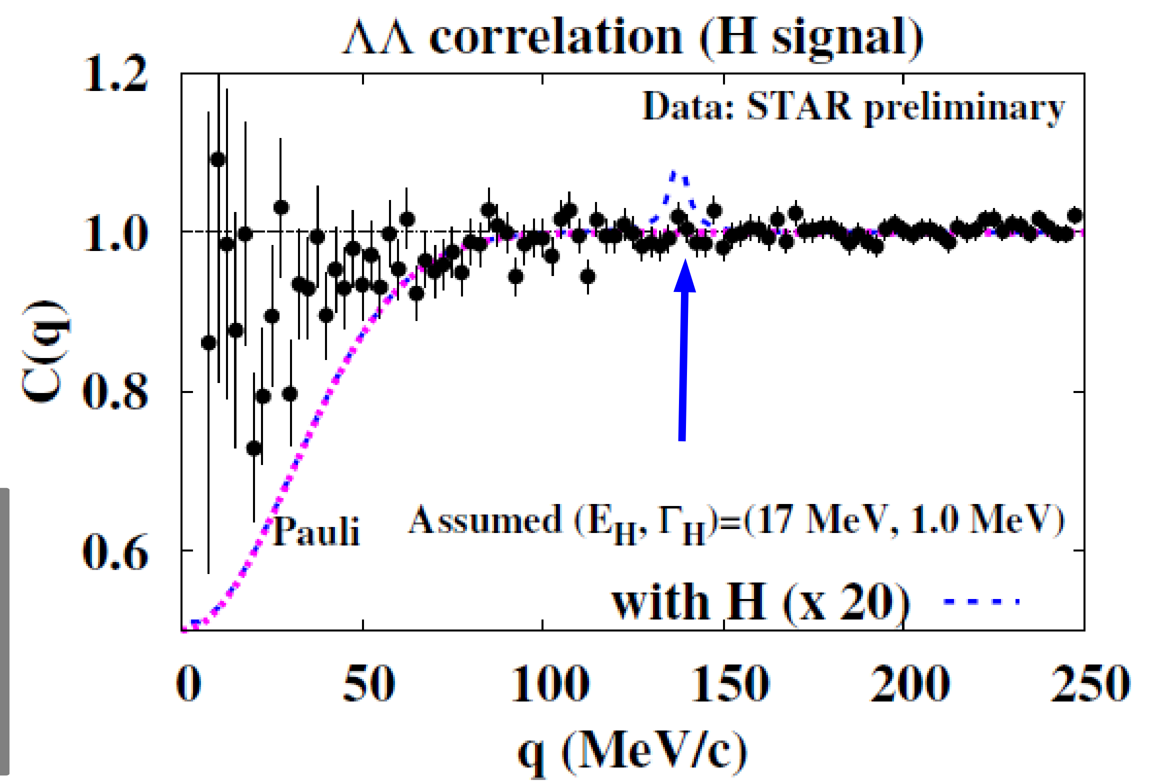


Transverse rapidity, $Y_T = \eta_f \, r_T / R$

Morita

H particle: Excluded ?

- **Expected H yield**
  - **N_H(=dN/dy (H))~ 1.3 x 10^{-2} (Stat.), 1.6 x 10^{-2} (ΞN b.s.), 3 x 10^{-3} (6q)**
  - **c.f. RQMD+Coal. 10^{-3}~10^{-2}** *Schaffner-Bielich, Mattiello, Sorge ('00)*
- **Signal / Background**
  - **Bound state: No signal is seen in $\Lambda p \pi^-$ channel** *Shah (STAR)(Mon.)*
  - **Resonance: N_Λ~ 30**
    → S/N = 10^{-2} / (30 x 30) ~ 10^{-5}



If H is not a potential res and is produced at large q, we need more statistics.

Summary

- **Various exotic hadrons will be formed in heavy ion collisions, and it is the right time to search them.**
  - **Extended hadron molecule production is enhanced in HICs.**
  - **Compact multiquark states may be suppressed in HICs.**
  - **Systematic study of exotics from e^+e^- reaction may be promising.**
- **ΛΛ correlation observed at RHIC is useful to distinguish proposed ΛΛ potentials.**

  N.Shah et al. (STAR Collab.), Acta Phys. Pol. Suppl. 5 ('12) 593.
  - **Preferred ΛΛ interactions have $1/a_0 < -0.8\ \mathrm{fm}^{-1}$, $r_{eff} > 3$ fm. Weakly attractive. Consistent with Nagara event (a_0=-(0.7-1.3) fm)**

    E. Hiyama et al. PRC66('02)024007; A.M.Gasparyan et al. PRC85('12)015204.
  - **Source size is R ~ 3 fm, if we take account the flow effects. Consistent with proton source size (2.5-4) fm *(STAR preliminary)*.**
  - **Existence of resonance "H" requires higher statistics.**
  - **Other YY (and hh) correlations would be measurable in HIC.**

Thank you for your attention !

ExHIC Collaboration

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S. Cho et al. (ExHIC Collab.), PRL106('11)212001.

S. Cho et al. (ExHIC Collab.), PRC 84 ('11) 064910.

AO, T.Furumoto, K. Morita, in prep.