重イオン衝突を用いたハドロン物理
(Hadron Physics using Heavy-Ion Collisions)

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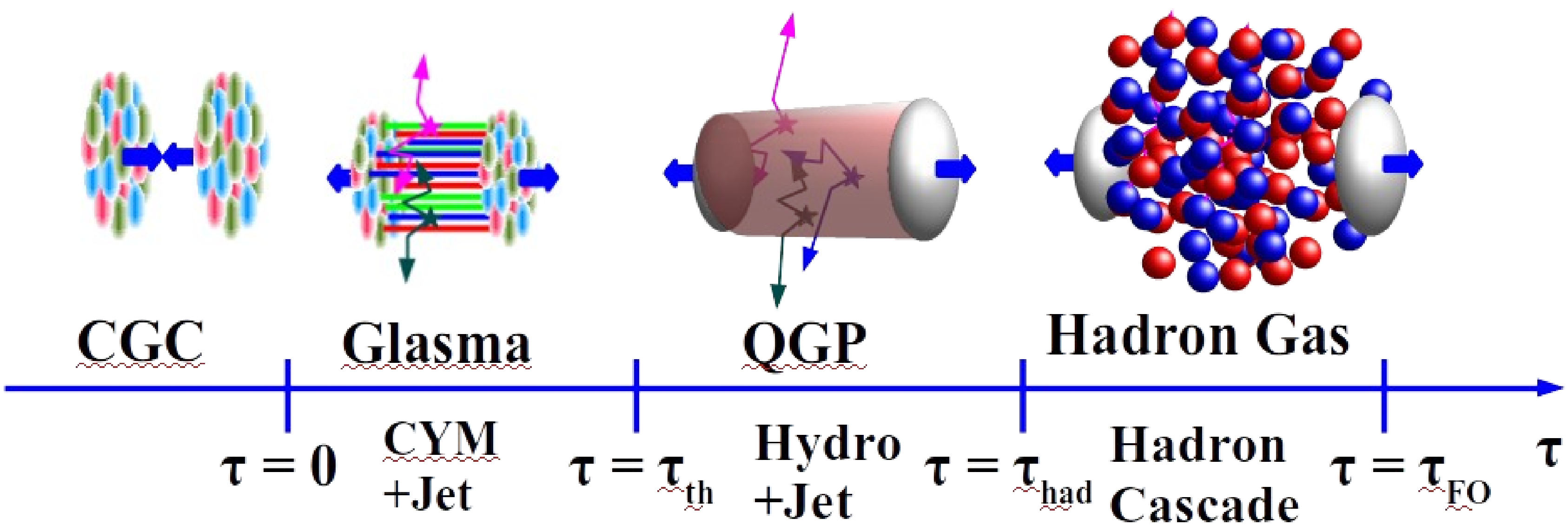
J-PARC-HI の物理を語る夕べ #8
(A J-PARC-HI Evening #8)
Nov. 30, 2021, Online

- Introduction
- Exotic hadrons from heavy-ion collisions
- Femtoscopic study of hadron-hadron interaction
- Dense baryonic matter EOS from collective flow in HIC & Onset energy of QGP
- Summary

High-Energy Heavy-Ion Collisions

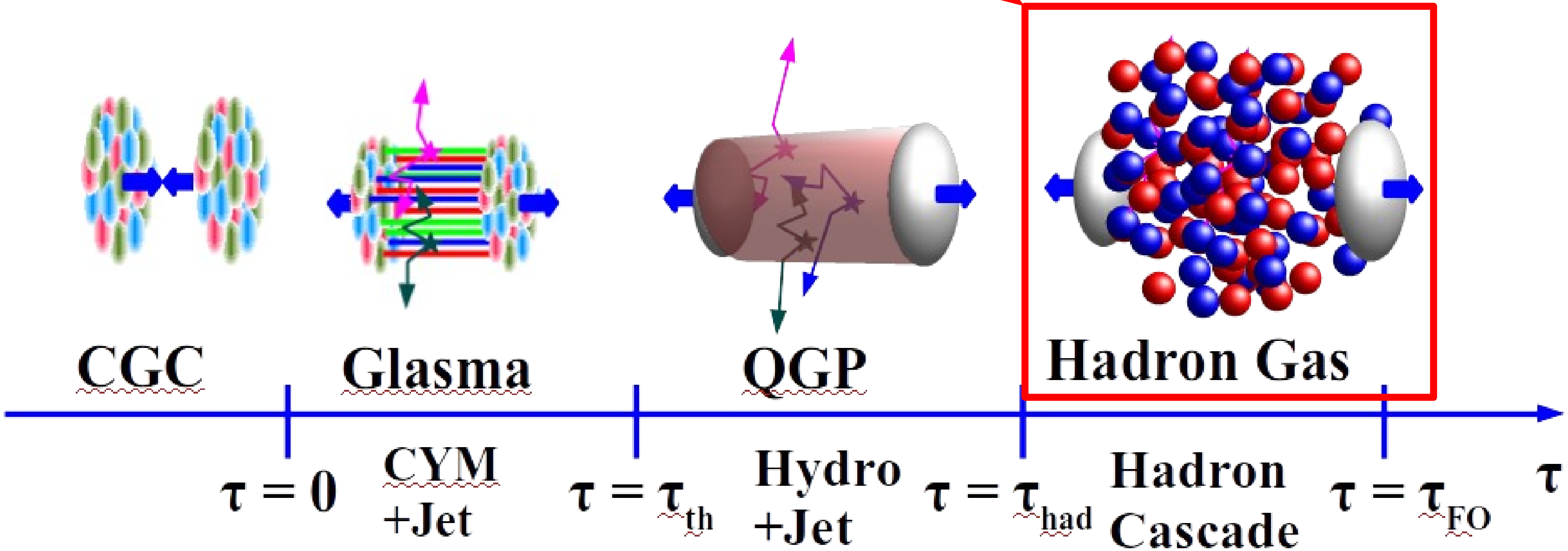
- Naïve Goal of HEHIC physics: History of Universe/Matter (Shigaki)
  - CGC/Glasma → QGP : Quantum simulation of inflation
  - QGP → Hadrons : last phase transition of vacuum in the Universe
  - Properties of QGP : Evolution of the Universe before 10^{-6} sec.
- HIC as a playground / tool
  - Viscos Hydro, Thermalization, Hydrodynamization, Hadronization, ...
    → Development of dynamical models
  - High T, Large μ, Large B & ω, Chirality imbalance, ...
    → Physics of extreme conditions and/or strong field
  - Hadron physics



Hadron Physics using High-Energy HIC

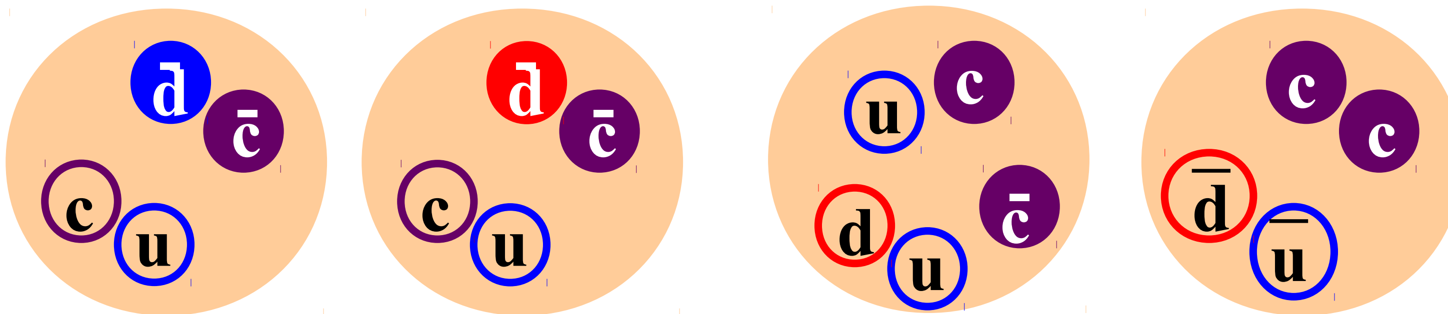
- **High-Energy Heavy-Ion Collisions**
  - **Too complex → Statistical → Simple and Clean !**
  - **High *T* & Large volume → Abundant hadrons**
  - **Nearly 4π detector / Vertex detector**

Let's study Hadron Physics
by using High-Energy Nuclear Collisions
as Hadron Factories.



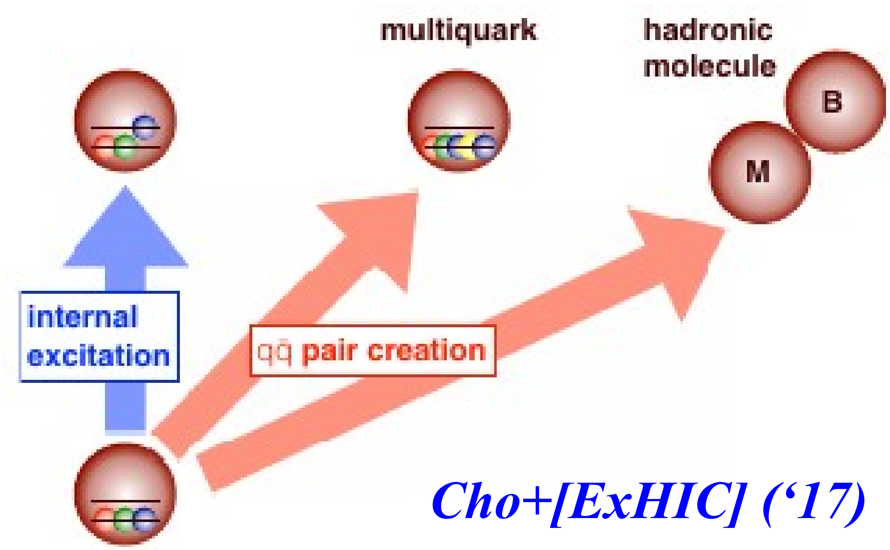
Exotic Hadrons

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



X(3872) Z(4430) Pc T_{cc}

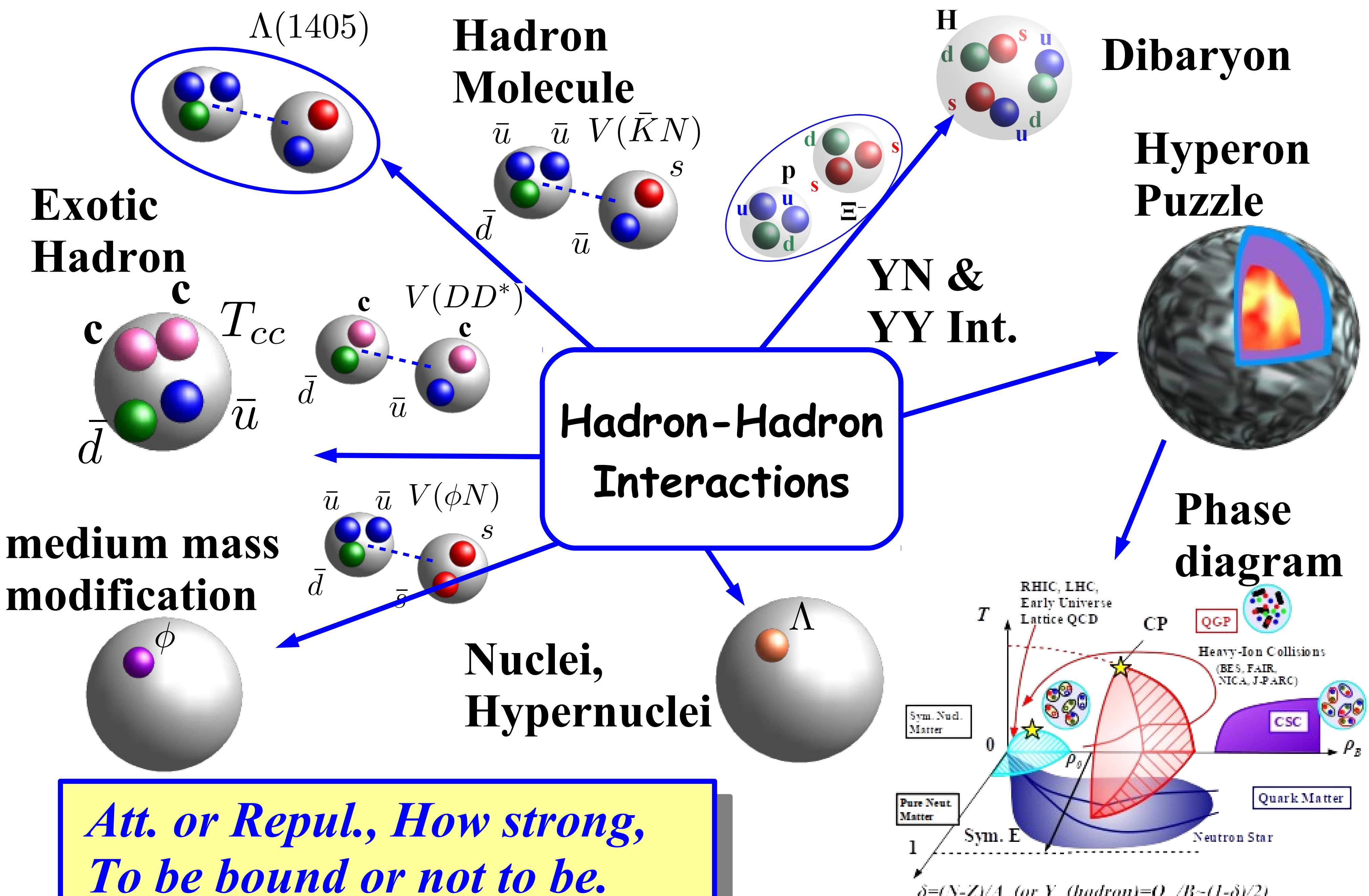
- Various pictures
  - Compact multiquark state (with di-quark component)
  - Hadronic molecule
  - (Triangle) Singularity
  - $Q\bar{Q}$ couples with $Q\bar{Q}\,q\bar{q}$
  - …



Cho+[ExHIC] ('17)

What is the structure of exotic hadrons ?
Can we access h-h interactions with heavy quarks ?

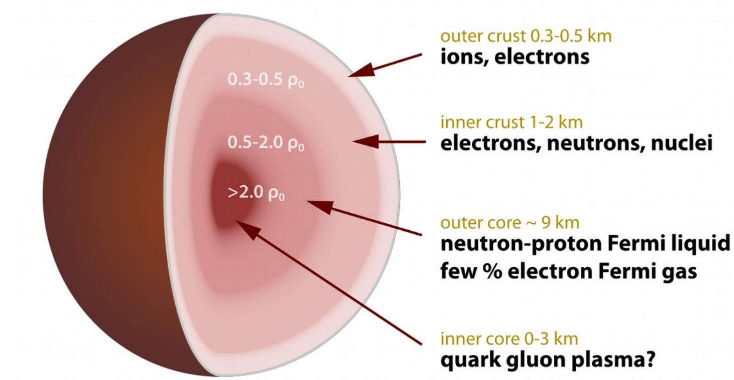
Hadron-Hadron Interactions



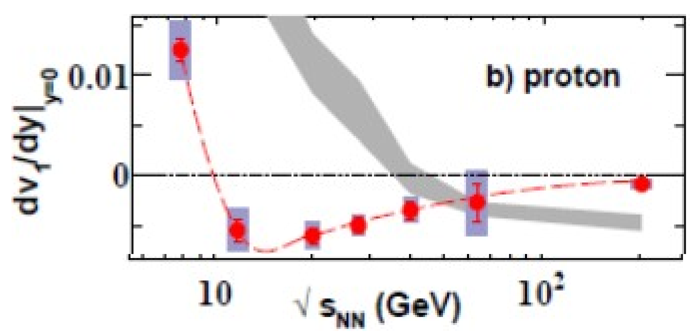
Att. or Repul., How strong,
To be bound or not to be.

Dense Hadronic Matter EOS

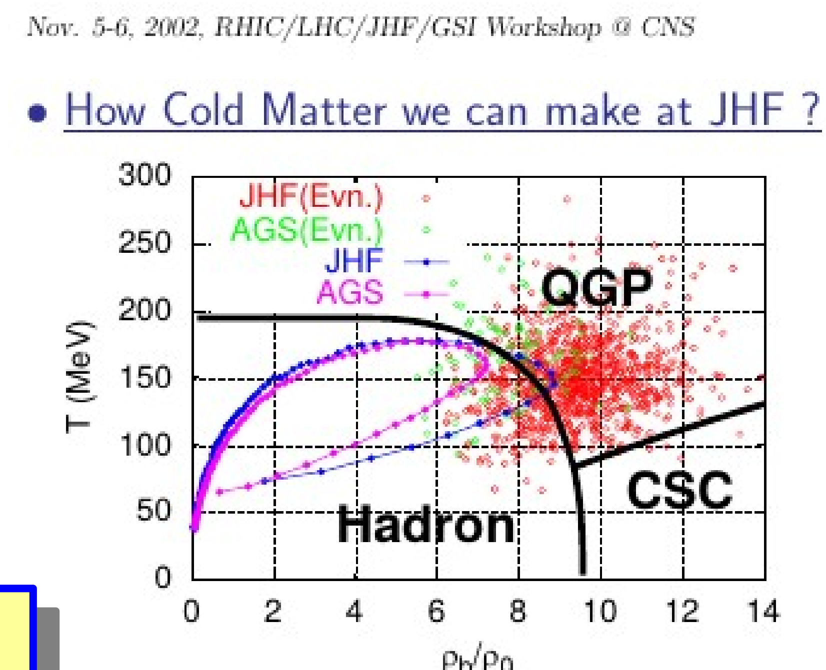
- Important from (at least) two aspects.
  - Compact star matter EOS (e.g. hyperon puzzle)
  - Finite density QCD phase transition
- One of the unsolved puzzles = Non-monotonic energy dep. of proton v_1 slope
  - Softest point of EOS (=signal of phase transition)?
  - Other explanation ?



Wikipedia



STAR, PRL112('14)162301



Dense QCD phase transition ?
Flow → EOS ? Hyperon potential ?

Outline of this talk

- Contents
  - Introduction (5 min.)
  - Exotic hadrons from heavy-ion collisions (10 min.)
  - Femtoscopic study of hadron-hadron interaction (15 min.)
  - Dense matter EOS from heavy-ion collisions (10 min.)
    & Onset energy of QGP
  - Summary (5 min.)

- 重イオン衝突を用いて展開された / できるハドロン物理について、紹介・議論します。

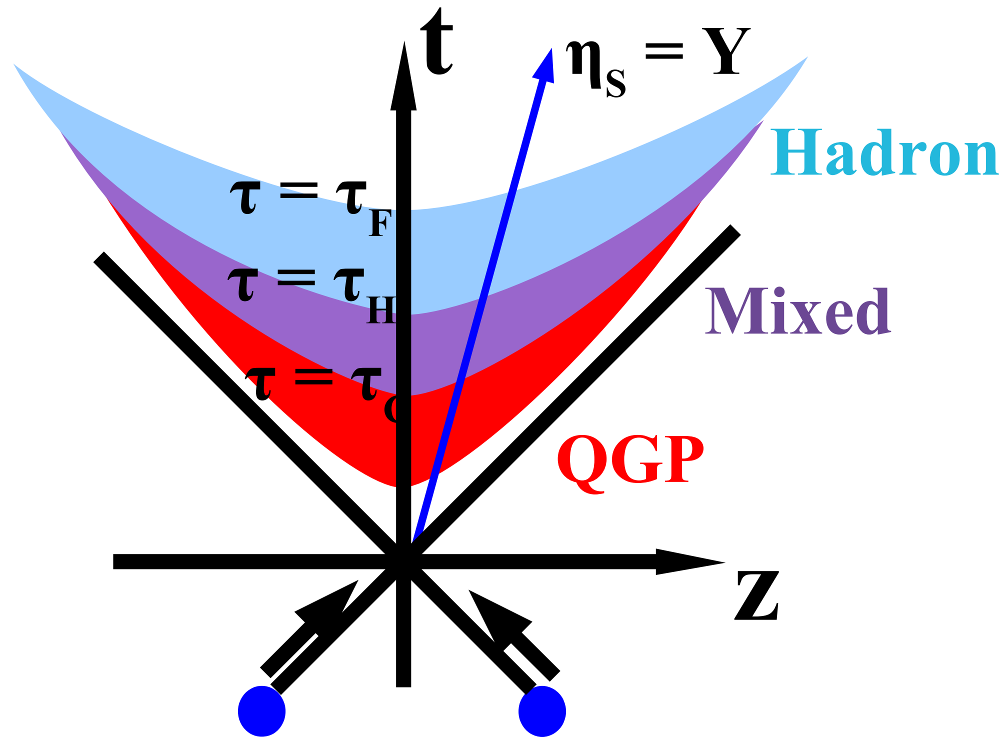
- 極めて個人的な視点からの talk であること、ご容赦ください。

Exotic Hadrons from High-Energy Nuclear Collisions

Schematic picture of HIC

- **HIC picture based on the (approximate) 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**

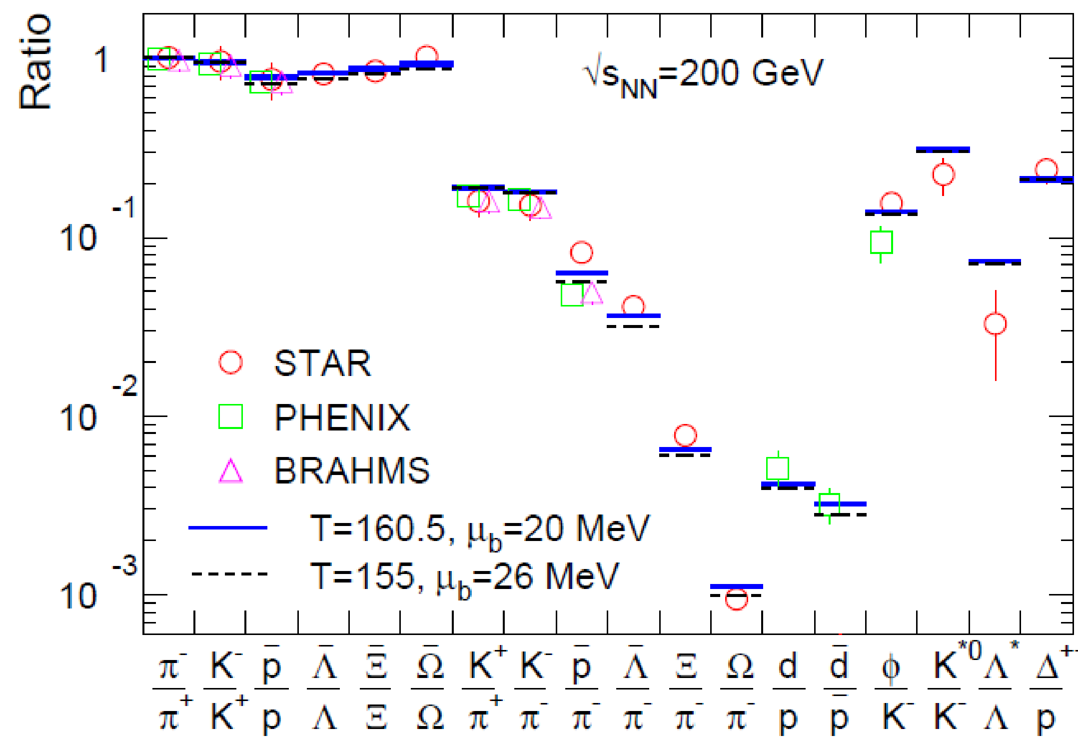
$$N_h^{\rm stat} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_h^{-1} e^{E_h/T_H} \pm 1}$$

(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.

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



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)

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

- **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)

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

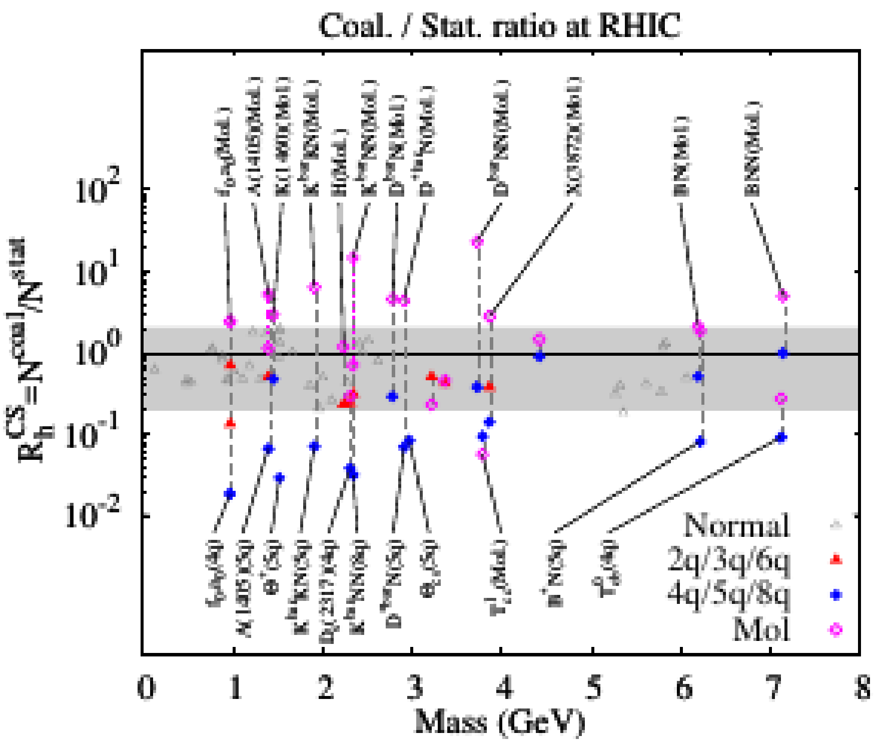
σ = Gaussian width, μ=reduced mass, N = constituent yield

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

Coalescence / Statistical Ratio

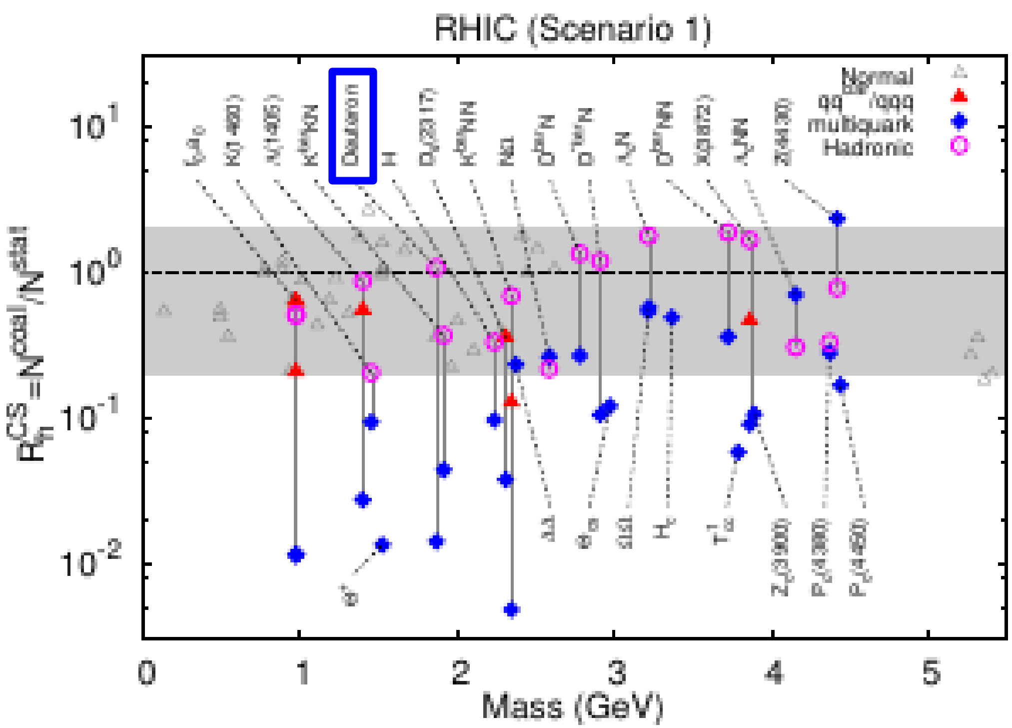
- **If the coalescence is the underlying hadronization mechanism, hadron yields will deviate from statistical model estimate depending on the number of constituents, spin, and size.**

ExHIC (2011)



Coalescence deuteron yield is larger than stat. model. ($R^{CS}_d \sim 1$ in data.)

ExHIC (2017)



Freeze-out T is carefully chosen to give $R^{CS}_d \sim 1$.

Which hadrons are enhanced in coalescence ?

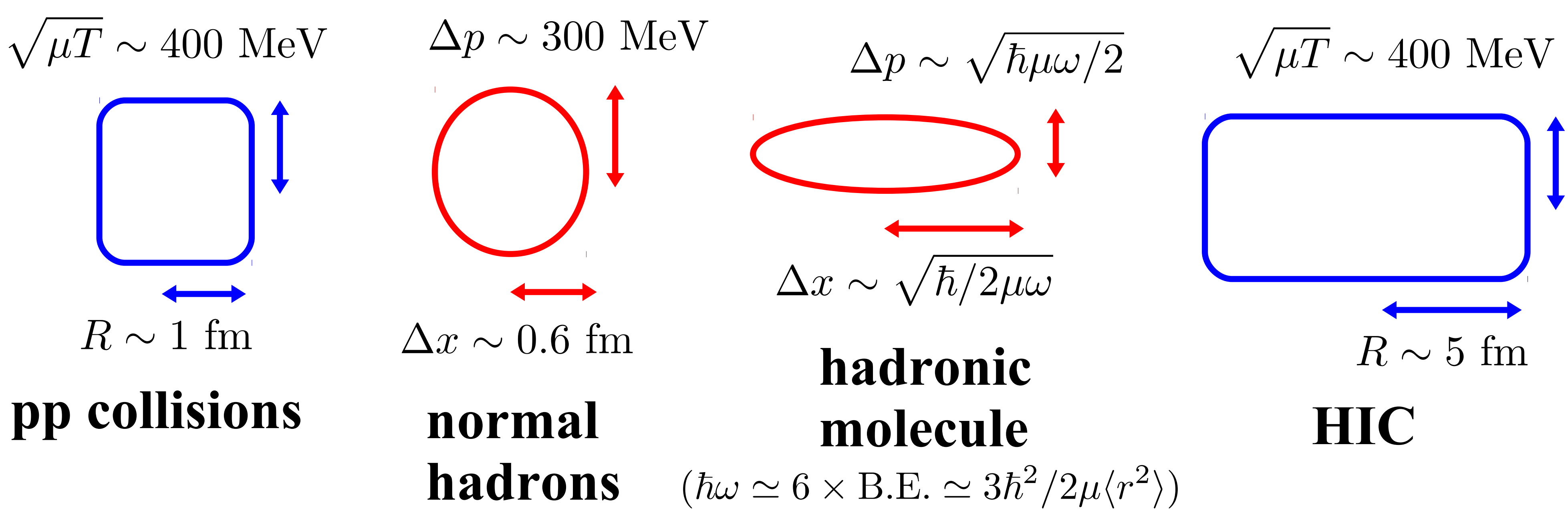
- **Simple estimate: 2-body, Gaussian w.f. + Thermal dist. of constiuents**
  → Yield is large when f_w shape is similar to f_{th} in phase space.

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

Intrinsic **Constituents (thermal)**

$$\boxed{f_W(x,p) = \left(\frac{\hbar}{\Delta x \Delta p}\right)^D \exp\left(-\frac{x^2}{2(\Delta x)^2} - \frac{p^2}{2(\Delta p)^2}\right)}$$

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



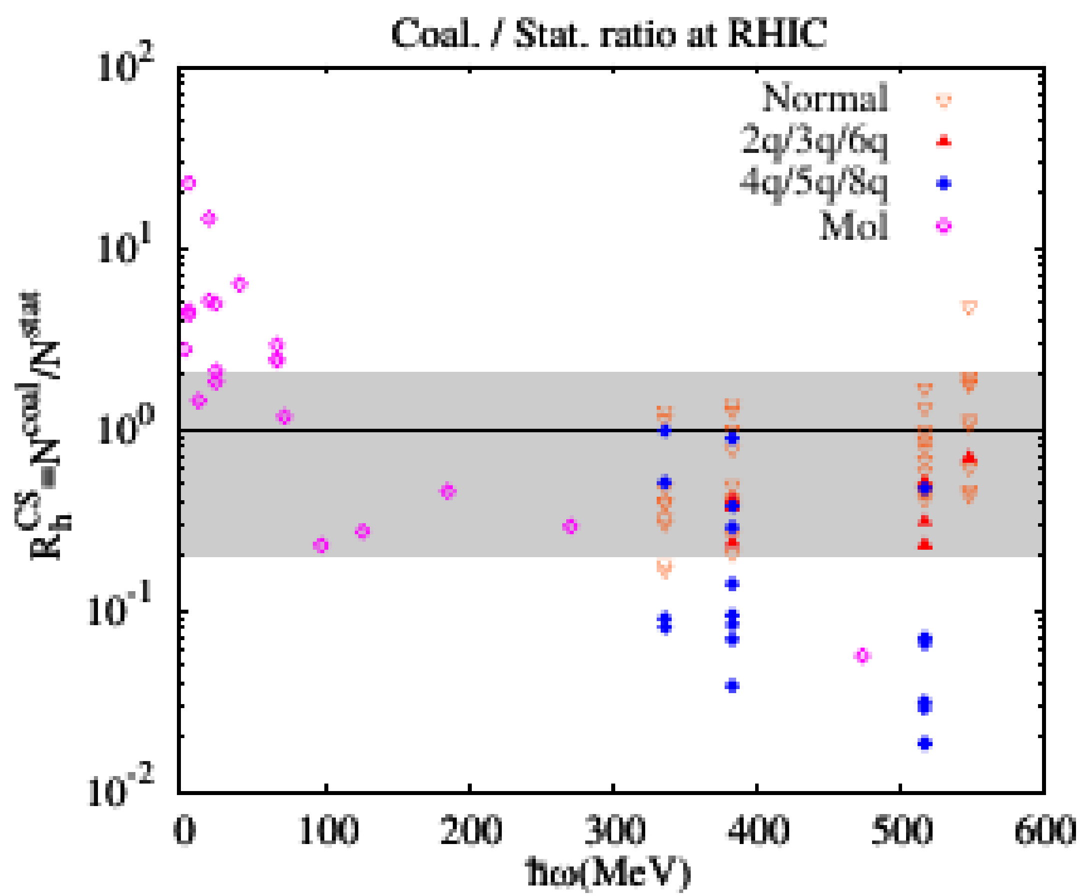
Which hadrons are enhanced in coalescence ?

- "Optimal" size of hadrons
  - The shapes of f_w and f_{th} are similar in phase space.

$$(\Delta p/\Delta x)^2 = \mu T/2R^2 \to \hbar\omega = \sqrt{\hbar^2 T/2\mu R^2}$$

  - hadrons with heavy-quarks (μ ~ 1 GeV),
    T ~ Tc ~ 160 MeV,
    HIC (R ~ 5 fm)
    → ħω = 11 MeV
    (B.E. ~ 2 MeV)

Loosely bound hadronic molecules are favored in HIC, with coalescence !



AO+('13) [Hyp2012 proc.]

Conclusion by ExHIC(2017) collaboration

Provided that coalescence is the underlying hadron production mechanism,
loosely bound hadronic molecules will be produced as frequently as normal hadrons,
while compact multiquark states
would be suppressed (by coal. penalty factor)
in heavy-ion collisions.

A New Insight from CMS: Exotic/Normal Ratio

- **ExHIC index = Coalescence / Statistical Ratio**

$$R_h^{\mathrm{CS}} = \frac{\text{Yields in Coalescence}}{\text{Yields in Statistical model}}$$

- **CMS index = Exotic / Normal Ratio**

Sirunyan+ [CMS], arXiv:2102.13048

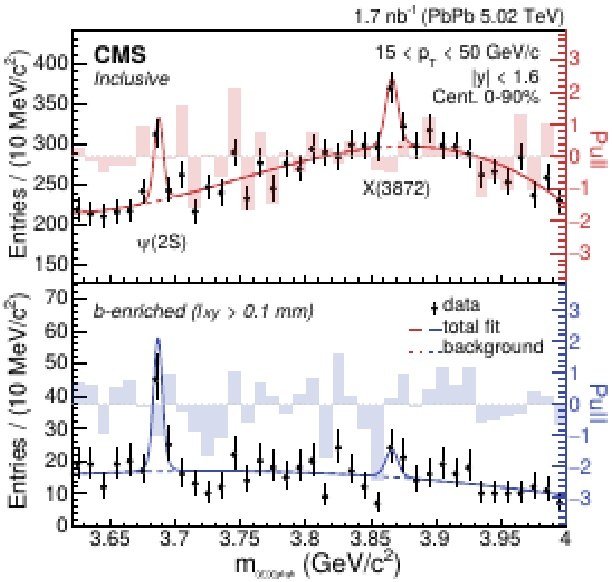
$$\rho_{\mathrm{exo/nor}} = \frac{N(\text{Exotic hadron candidate})}{N(\text{Normal hadron})}$$

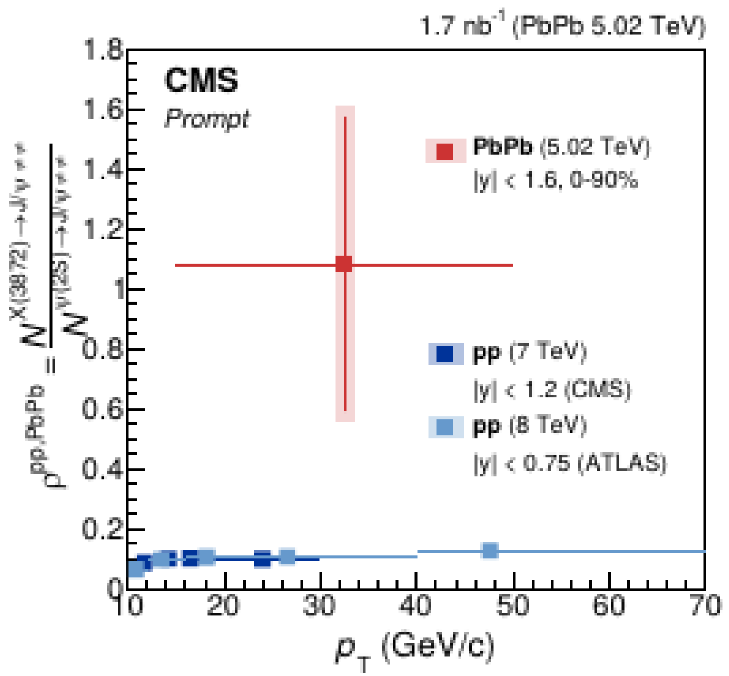
- **X(3872) / ψ(2S) ratio in pp and PbPb collisions.**

$$\rho_{X/\psi}(\mathrm{PbPb}) = 1.08 \pm 0.49(\mathrm{stat.}) \pm 0.52(\mathrm{syst.})$$

$$\rho_{X/\psi}(pp) \simeq 0.1$$

ExHIC prediction is found to be (qualitatively) true !





Toward Qunatitative Understanding...

- **With the mass difference from M(ψ(2S)=3686 MeV), R^{CS}_{X} from data would be larger than ExHIC prediction (R~2). [ExHIC(2011) precition: R ~ 2.8]**

$$R^{\rm CS}_{X(3872)}(\rm HIC) = 1.08 \times \exp((3872/3686)/T) \simeq 3.1$$

→ Earlier hadronic coalescence with heavy quarks ?

- **AMPT prediction** ***Zhang+(PRL 126, 012301 (2021))***

$$R^{\rm molecule}_{AA} \gg R^{\rm tetraquark}_{AA} \quad (R_{AA} = N_h(AA)/N_h(pp))$$

- **TAMU transport model** ***Wu+ (EPJA 57, 122 (2021))***

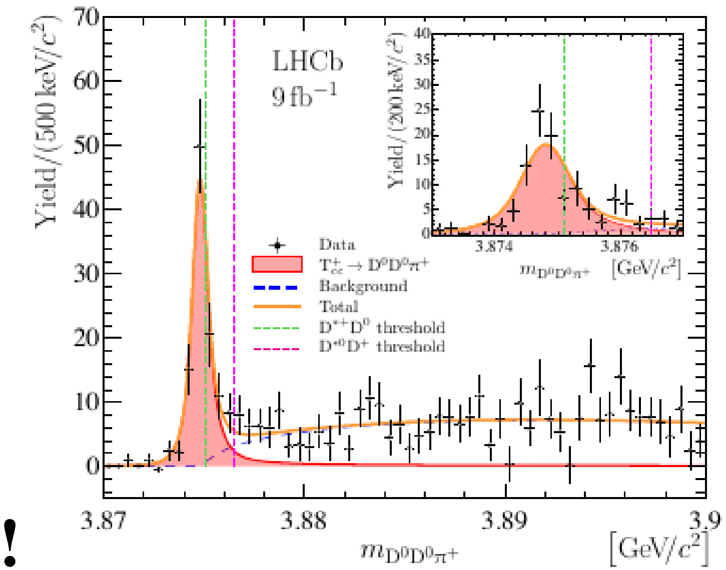
$$R^{\rm molecule}_{AA} \sim R^{\rm tetraquark}_{AA}/2$$

- **Suppression of ψ(2S) ($R^{\psi(2S)}_{AA}$ ~ 0.14) caused the apparent enhancement ?**

Theorists have to work harder on production of exotic hadrons with heavy quarks toward a few 10 % level of accuarcy !

Another interesting peak: Tcc

- Tcc $(cc\bar{u}\bar{d})$ observed in $D^0 D^0 \pi^+$ spectrum
  LHCb collaboration, arXiv 2109.01038 [hep-ex], 2109.01056 [hep-ex]
  - Very close to DD* thresholds
    (~ 300 keV below $D^{*+}D^0$)
  - Tcc = DD* molecule ?

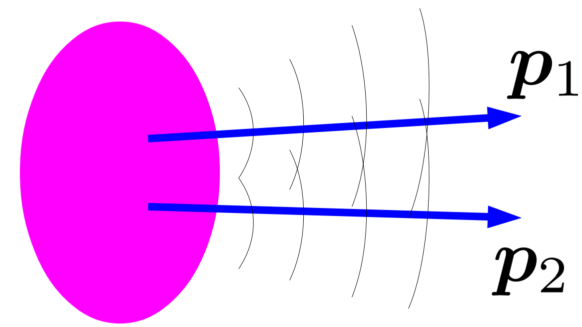


- If the followings are confirmed,
  the peak is likely to be a hadron molecule !
  - Mass is around threshold → Peak in invariant mass spectrum
  - Wave function is widely spread → Size dependence of yield
  - Attractive interactions among constituent hadrons → Femtoscopy
- X(3872) & Tcc
  - X(3872) → O, O, ?
  - Tcc → O, ?, ?
  - Λ(1405) → O, ?, O
    [Λ(1405) → πΣ is not measurable at LHC/RHIC]

Hadron-Hadron Interaction from High-Energy Nuclear Collisions

- **Basic theoretical framework in femtoscopic study of hadron-hadron interactions**
- **Recent & future femtoscopic studies of hadron-hadron interactions**

Femtoscopic study of hadron-hadron interaction



- **Correlation function (CF)**
  - **One can access various hadron-hadron interactions using CFs (femtoscopy).**
  - **CF=convolution of source fn. and |w.f.|²**
    (Koonin-Pratt formula) *Koonin('77), Pratt('86), Lednicky+('82)*

$$C(\boldsymbol{p}_1,\boldsymbol{p}_2)=\frac{N_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1)N_2(\boldsymbol{p}_2)}\simeq\int d\boldsymbol{r}\,\underbrace{S(\boldsymbol{r})}_{\text{source fn.}}\underbrace{|\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2}_{\text{relative w.f.}}$$ **(q=rel. mom.)**

- **Source size from quantum stat. + CF (HBT-GGLP effect)**

  Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)

- **Hadron-hadron interaction from source size + CF**
  - **CF of non-identical pair from static spherical source**
    Lednicky, Lyuboshits ('82); Morita, Furumoto, AO ('15)

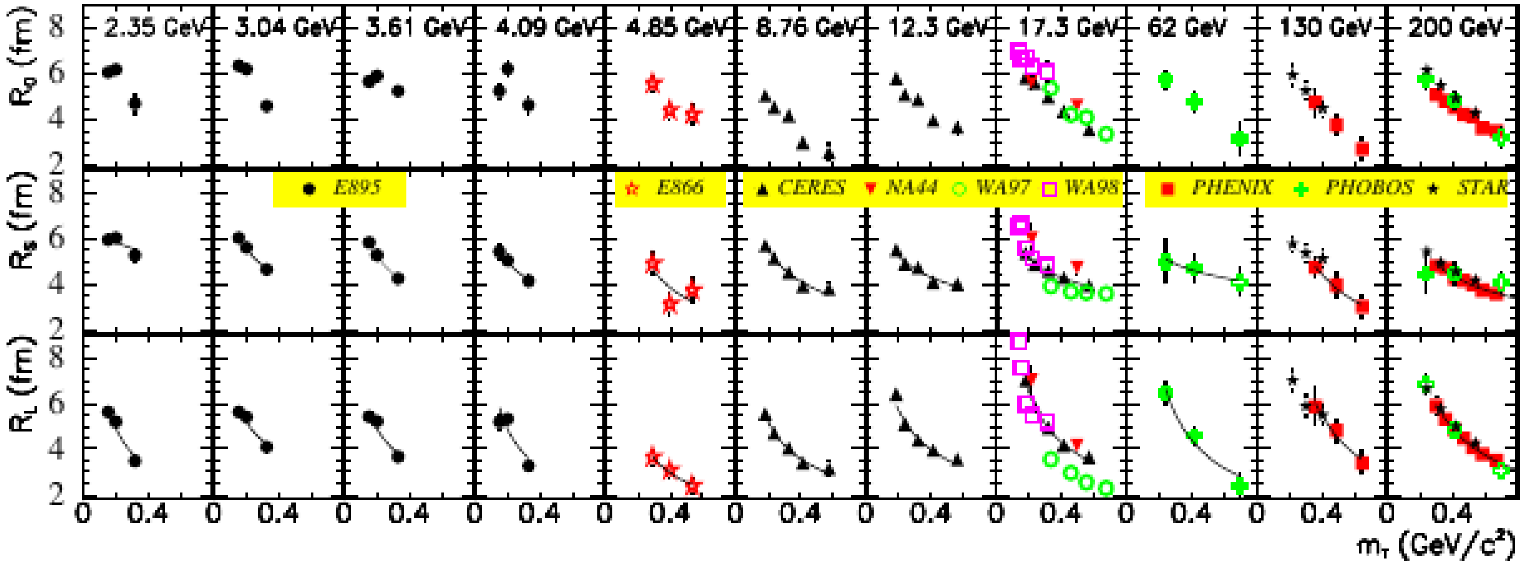
$$C(\boldsymbol{q})=1+\int d\boldsymbol{r}\,S(r)\left\{|\varphi_0(r)|^2-|j_0(qr)|^2\right\}\qquad(\varphi_0=\text{s-wave w.f.})$$

CF shows how much $|\varphi|^2$ is enhanced → V_{hh} effects !

State-of-the-art Femtoscopy of radii

- **Systematic measurement of 3D HBT radii (side, out, long)**

M. A. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402.



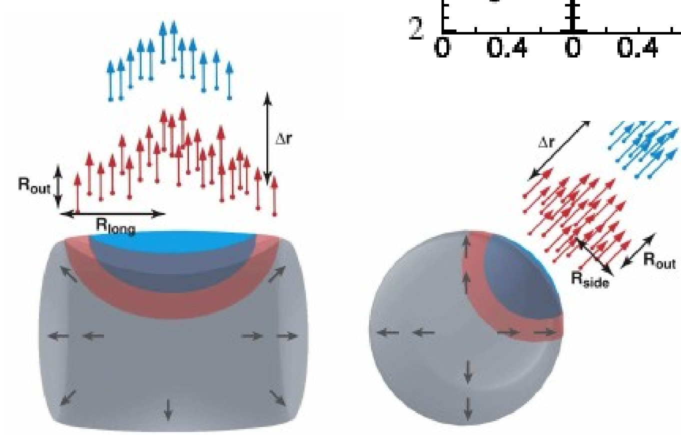
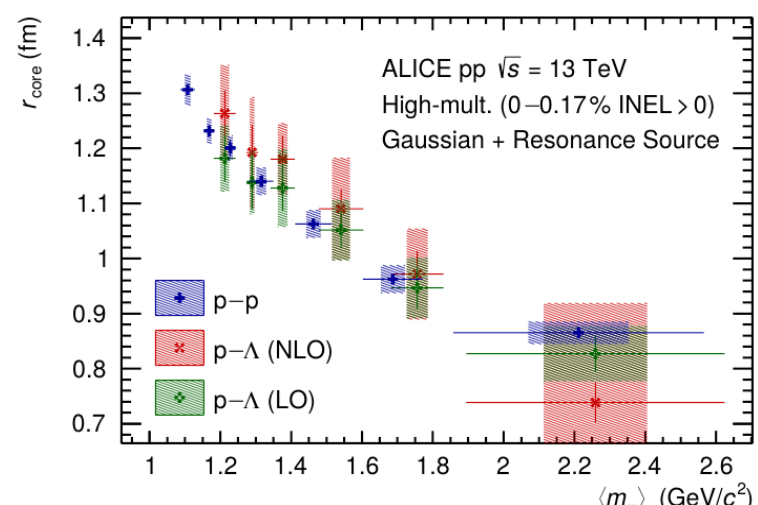


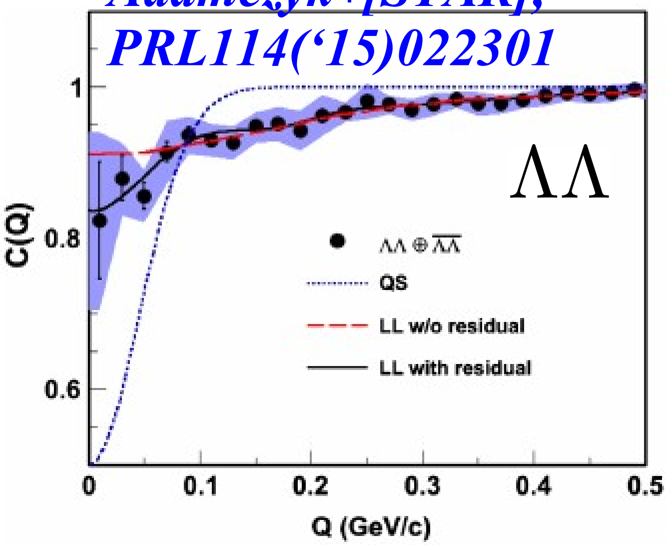
Figure 3: because particles with heavier masses have smaller thermal velocities, their source volumes are more strongly confined by collective flow. For longitudinal flow (*left panel*) this results in smaller values of $R_{\rm long}$ for particles with higher $m_T = \sqrt{m^2 + p_T^2}$. For radial flow (*right panel*) this confines heavier particles toward the surface, which results in both a reduced volume and an offset Δr in the outward direction.

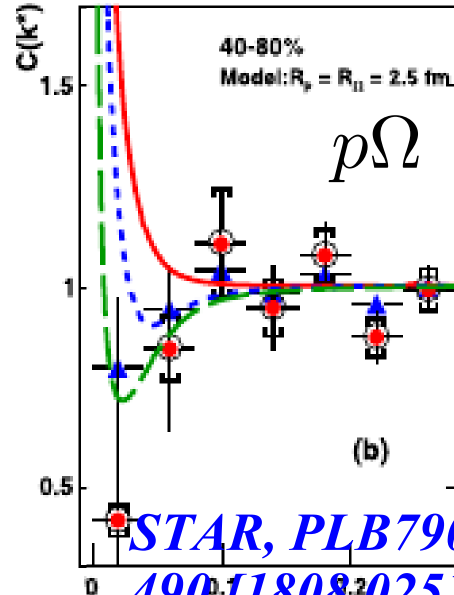


S. Acharya+[ALICE], PLB811('20)135849

Measured Flavored Hadron CFs (examples)

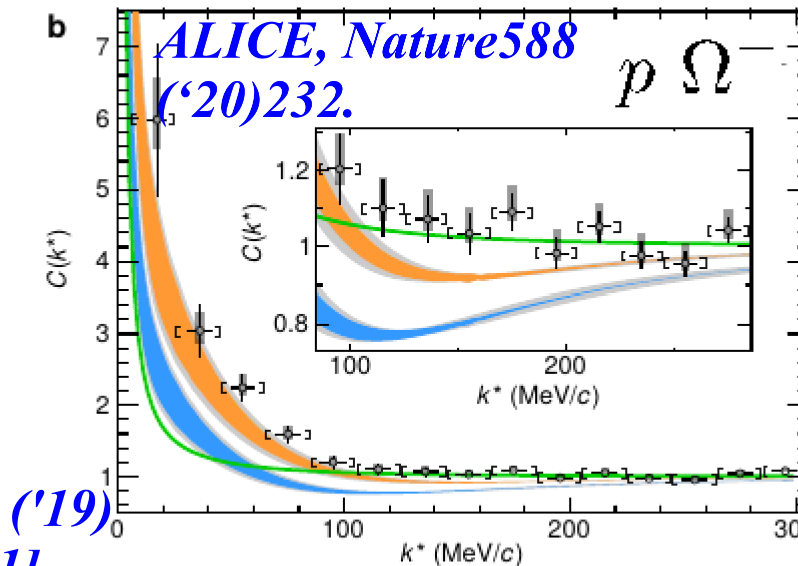
Adamczyk+[STAR], PRL114('15)022301

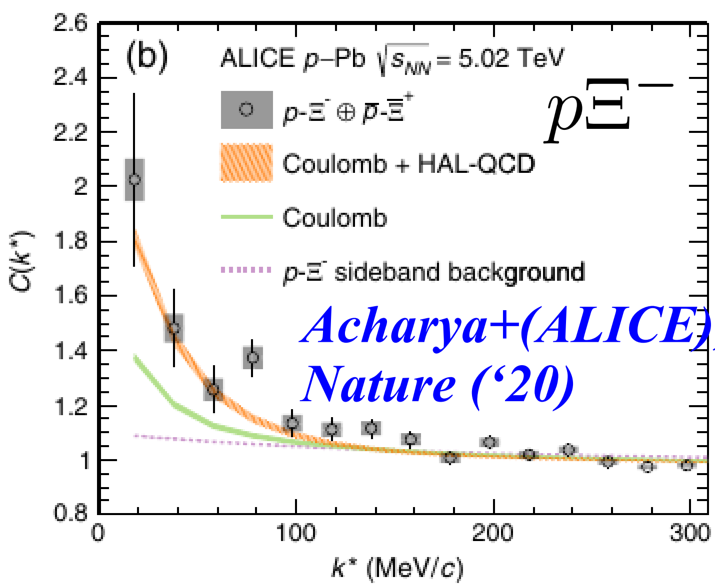




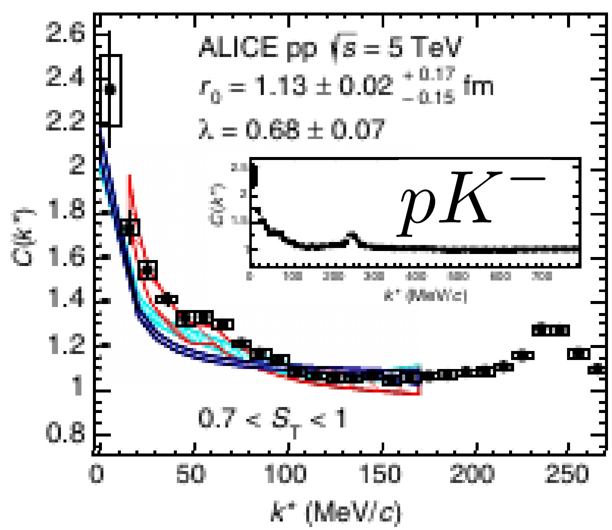
STAR, PLB790 ('19) 490 [1808.02511].

ALICE, Nature588 ('20)232.

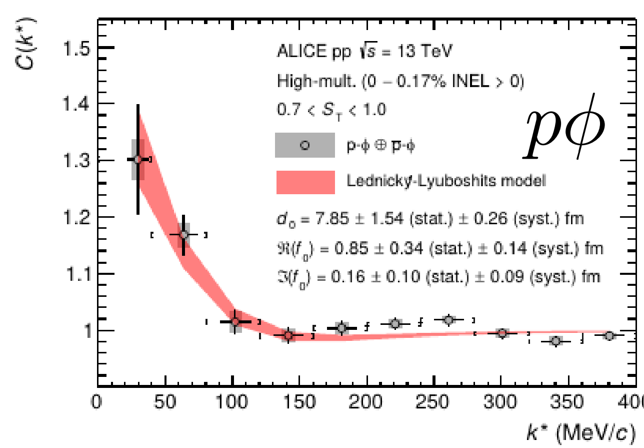




Acharya+(ALICE), Nature ('20)



S. Acharya+[ALICE], PRL124('20)092301



ALICE, 2105.05578

Lednicky-Lyuboshits (LL) model

- **Lednicky-Lyuboshits analytic model (Asymp. w.f.+eff. range corr.+Gaussian source)**

  Lednicky, Lyuboshits ('82)

  - **CF = a known function of f(q), R, r_{eff}, and q.**

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

$$\boxed{\begin{aligned} C_{\rm LL}(q) =& 1 + \int d\boldsymbol{r} S_{12}(r)\left(|\psi_{\rm asy}(r)|^2 - |j_0(qr)|^2\right) \\ =& 1 + \frac{|f(q)|^2}{2R^2}F_3\left(\frac{r_{\rm eff}}{R}\right) + \frac{2{\rm Re}f(q)}{\sqrt{\pi}R}F_1(2x) - \frac{{\rm Im}f(q)}{R}F_2(2x) \end{aligned}}$$

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

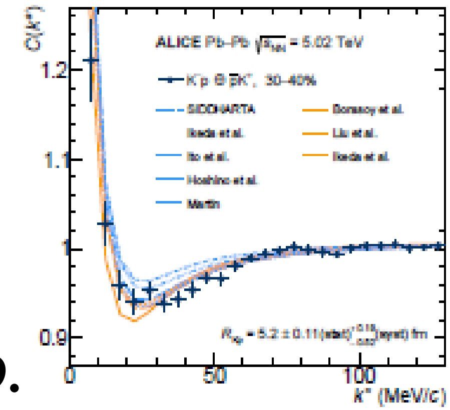
  - **Scattering amplitude at low energies**

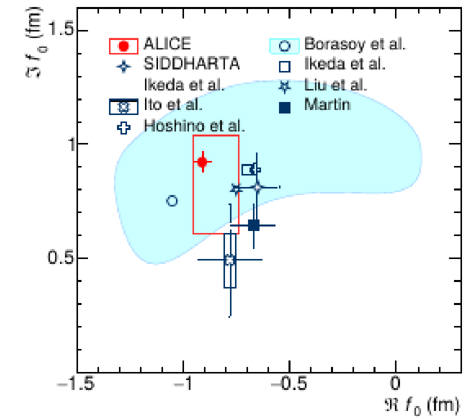
$$q\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}q^2 + \mathcal{O}(q^4) \to f(q) = (q\cot\delta - iq)^{-1}$$

From scattering length (a_0) and effective range (r_{eff}), one can calculate the correlation function !

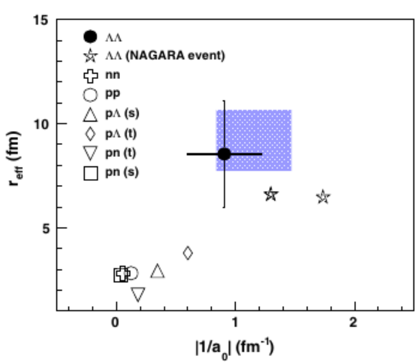
Scattering length from CFs

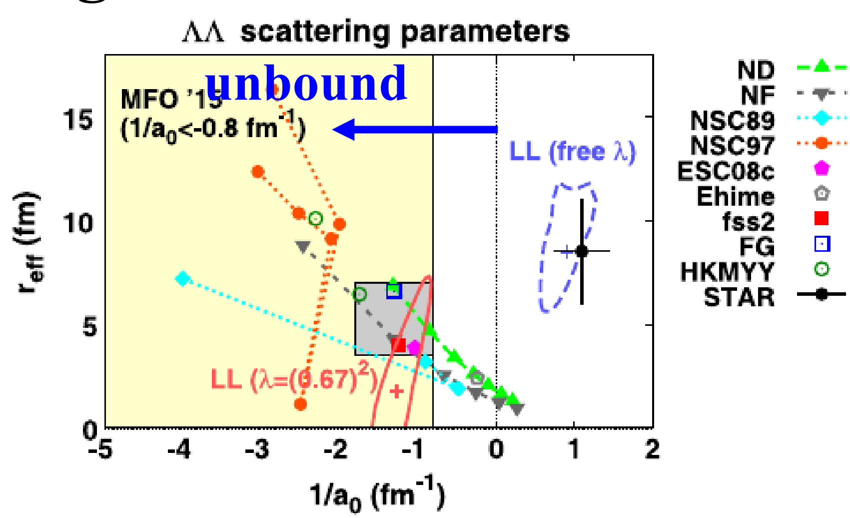
- $K^- p$
  - LL (w/ Coulomb) gives a_0
  - Comparable with kaonic atom data (SIDDHARTA).
  - See also Siejka+[STAR],NPA982('19)359.
- $\Lambda\Lambda$
  - Quantum statistics + LL
    $\to$ (a_0,r_{eff}) region

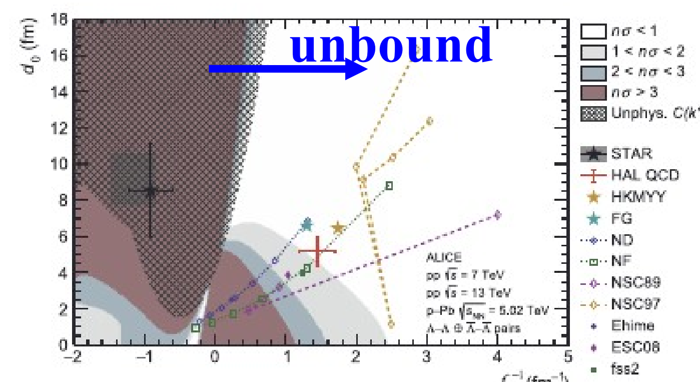




Acharya+[ALICE], PLB822('21),136708 [2105.05683] ($\delta \sim a_0 q$)







L. Adamczyk+ [STAR], PRL114 ('15)022301

K.Morita, T.Furumoto, AO, PRC91 ('15) 024916; AO, Morita, Miyahara, Hyodo, NPA954('16)294 ($\delta \sim -a_0 q$)

S. Acharya [ALICE], PLB797 ('19) 134822 ($\delta \sim a_0 q$).

Femtoscopic diagnosis of bound state existence

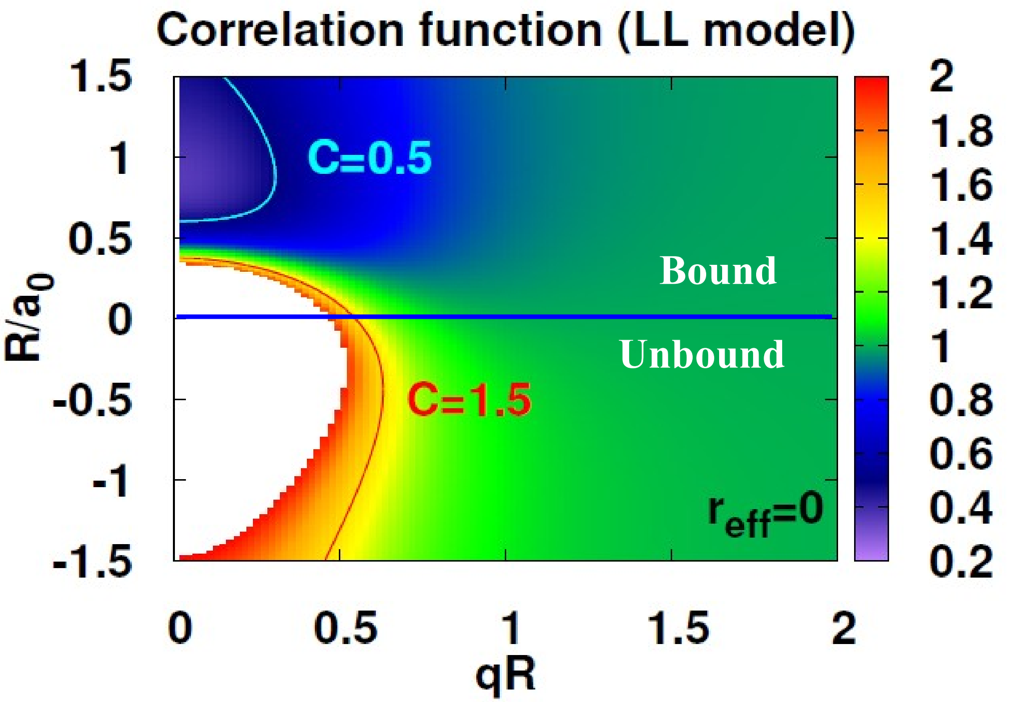
- **Lednicky-Lyuboshits model with zero effective range $\rightarrow$ CF = C(qR, R/a$_0$)**

$$r_{\rm eff} = 0 \rightarrow q\cot\delta = -1/a_0 \rightarrow f(q) = (q\cot\delta - iq)^{-1} = -\frac{R}{R/a_0 + iqR}$$

$$\boxed{C(x,y) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}F_1(2x) - xF_2(2x)\right] \quad (x = qR, y = R/a_0)}$$

$$= \frac{1}{2}\left(\frac{1}{y} - \frac{2}{\sqrt{\pi}}\right)^2 + 1 - \frac{2}{\pi} \quad (F_1 \to 1, F_2 \to 0 \text{ at } x \to 0)$$

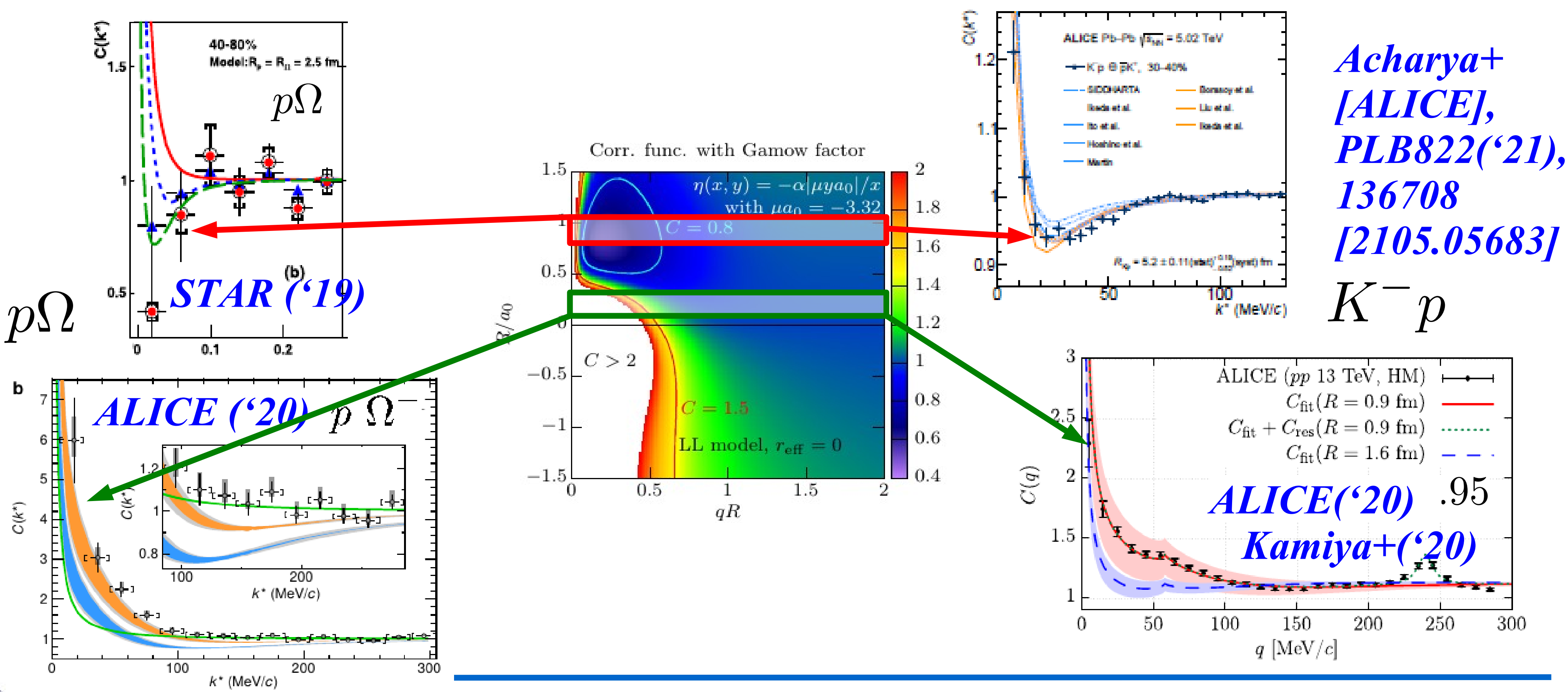
  - **With a bound state, CF is suppressed at low q.**
  - **Scattering w.f. needs to have a node to be orthogonal to b.s.**



E.g. AO, Morita, Miyahara, Hyodo ('16)

Hadronic molecules suggested by CFs

- $p\Omega$ and K^-p
  - **Bound states are expected.**
    Goldman+('87); Oka ('88); Etminan+[HAL QCD] ('14); Iritani+[HAL QCD]('19); Dalitz, Tuan ('59); Akaishi, Yamazamki ('02); Jido+('03); Hyodo, Jido ('12)
  - **Dip is expected at R ~ $|a_0|$** *Morita+('16,'20); Kamiya+('20); Haidenbauer('18)*
  - **Data support the existence of a BS.**



Coupled-Channel Correlation Function

- **Schrodinger Equation (s-wave, measured channel=1)**

$$\begin{pmatrix} -\frac{\nabla_1^2}{2\mu_1} + V_{11} & V_{12} & \cdots \\ V_{12} & -\frac{\nabla_2^2}{2\mu_2} + V_{22} + \Delta_2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \psi_1^{(-)} \\ \psi_2^{(-)} \\ \vdots \end{pmatrix} = E \begin{pmatrix} \psi_1^{(-)} \\ \psi_2^{(-)} \\ \vdots \end{pmatrix}$$

$$\psi_j^{(-)}(r) \to [\delta_{j1}\, e^{iq_j r} + A_j(q) e^{-iq_j r}]/2iq_j r \text{ (No Coulomb case)}$$

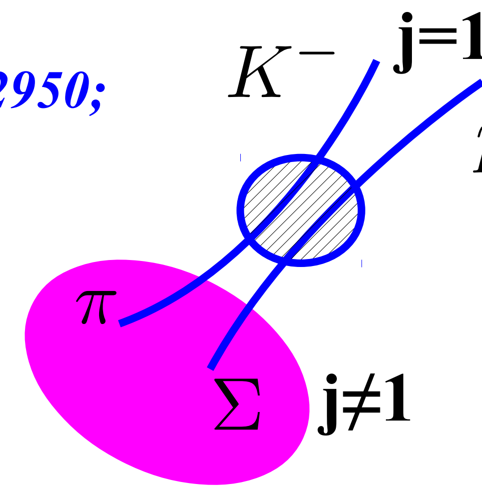
μ_j = reduced mass
V_{ij} = strong + Coulomb
Δ_j = threshold difference

- **KPLLL formula**

Lednicky, Lyuboshits, Lyuboshits, Phys. Atom. Nucl. 61 (1998), 2950;
J. Haudenbauer, NPA981('19) 1 [1808.05049];
Y. Kamiya, T.Hyodo, K.Morita, AO, W.Weise, PRL('20).

$$C(q) = 1 + \int dr S_1(r) \left[|\psi_1^{(-)}(r;q)|^2 - |j_0(qr)|^2 \right]$$

$$+ \int dr \sum_{j \neq 1} \omega_j S_j(r) |\psi_j^{(-)}(r;q)|^2$$

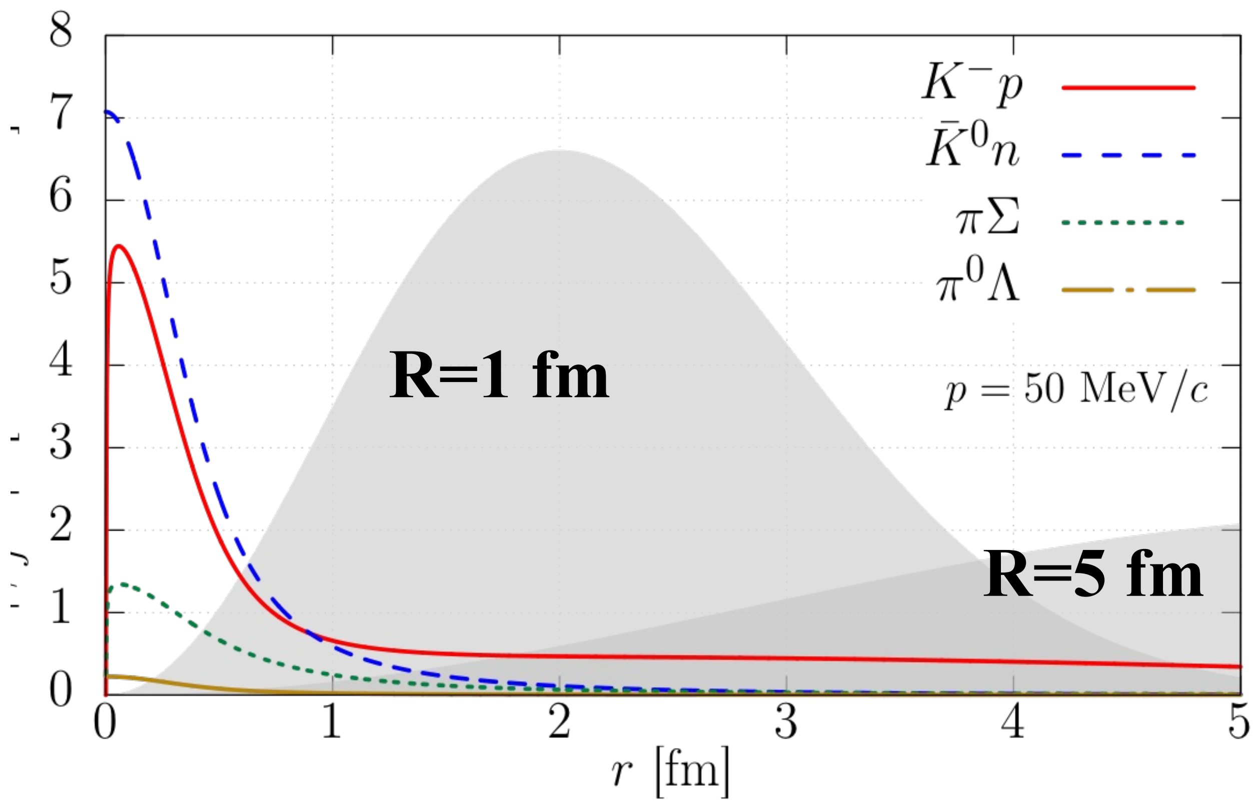


$$\underbrace{\omega_j}_{\text{Source weight}} \underbrace{S_j(\boldsymbol{r})}_{\text{Normalized Source fn.}} |\psi_j^{(-)}(r;q)|^2$$

- **Wave functions of other channels also contribute to correlation functions.**
- **Source weights ω_j ($j \neq 1$) appear additional parameters.**

Discriminating Coupled-Channel Effects

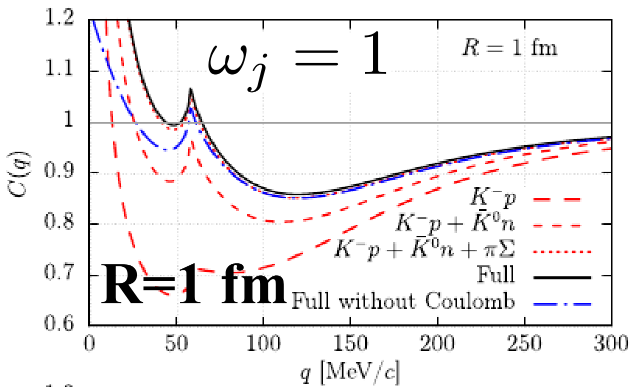
- **Source size dependence again !**
  - **Unmeasured coupled-channel wave functions disappear soon.**
    → CFs with large source is dominated
    by the measured channel wave function !
  - **Scattering parameters from CFs with large source**
    Coupled-channel effects from CFs with small source.

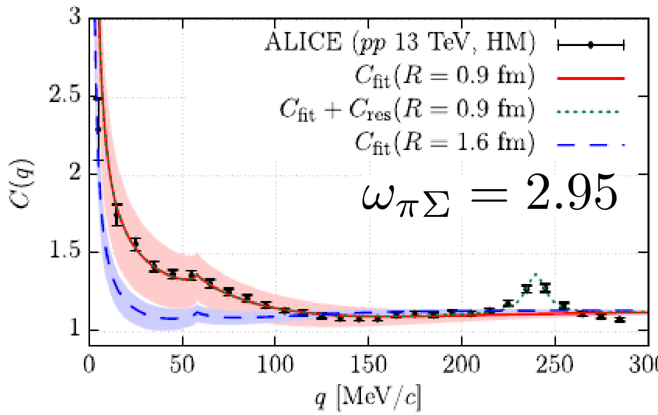


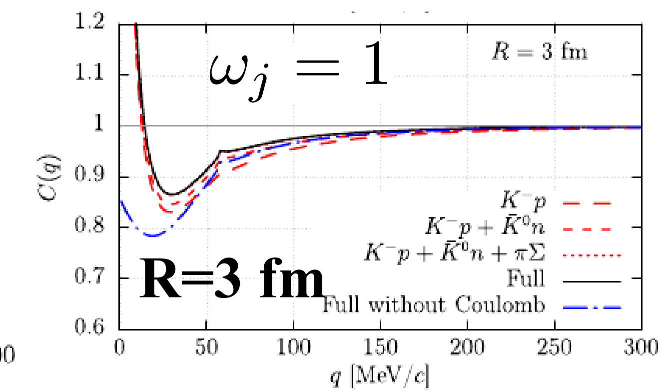
w.f. Kamiya+,arXiv:1911.01041v1

Source Size Dependence of C(K⁻p)

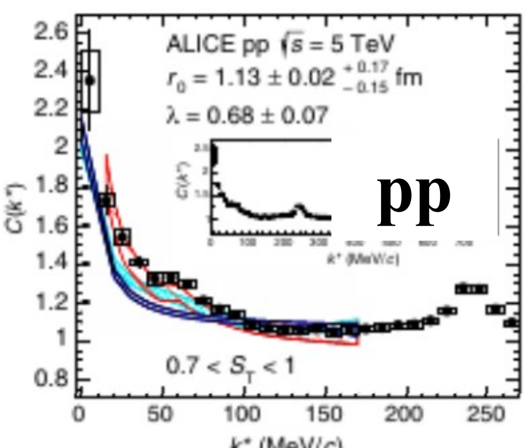
- **Coupled-channel effects are suppressed when R is large, and “pure” K⁻p wave function may be observed in HIC.**



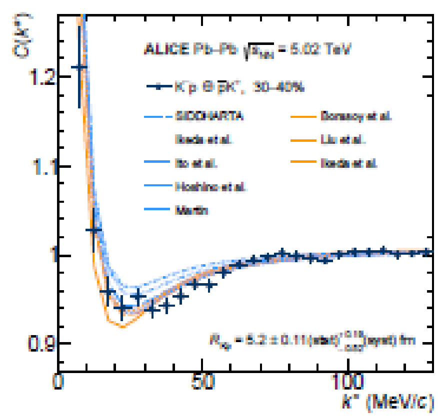




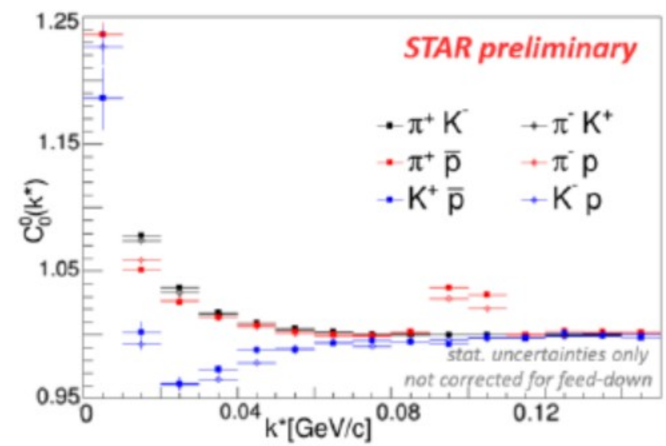
Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124(‘20)132501.



S. Acharya+[ALICE], PRL124(‘20)092301



S. Acharya+[ALICE], PLB822(‘21)136708

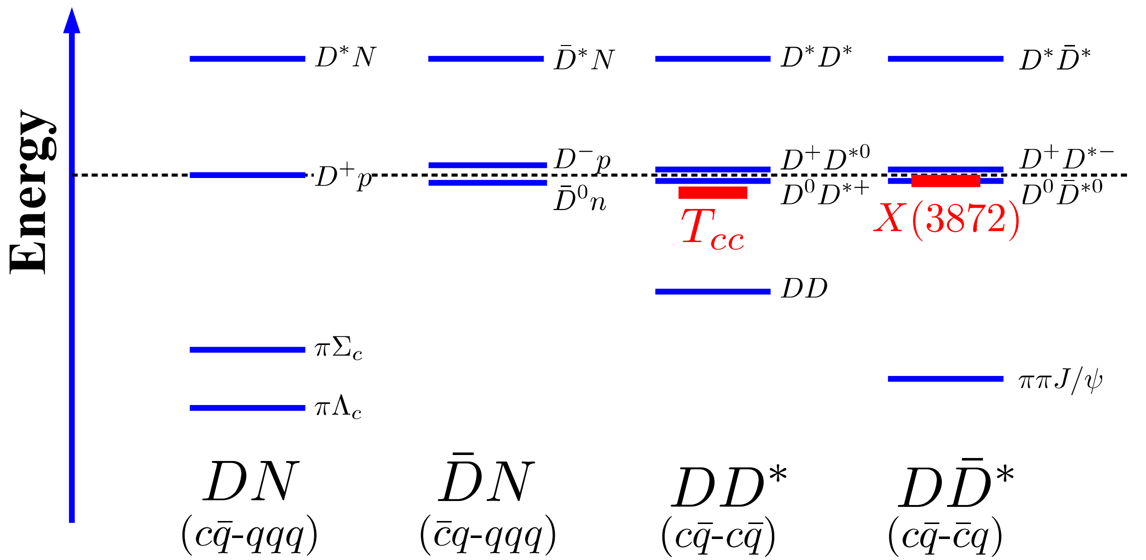


Siejka+[STAR, preliminary], NPA982 (‘19)359.

Let me show some of the correlation functions which have been by now or will be measured in the (near?) future.

Charmed Hadron Interactions

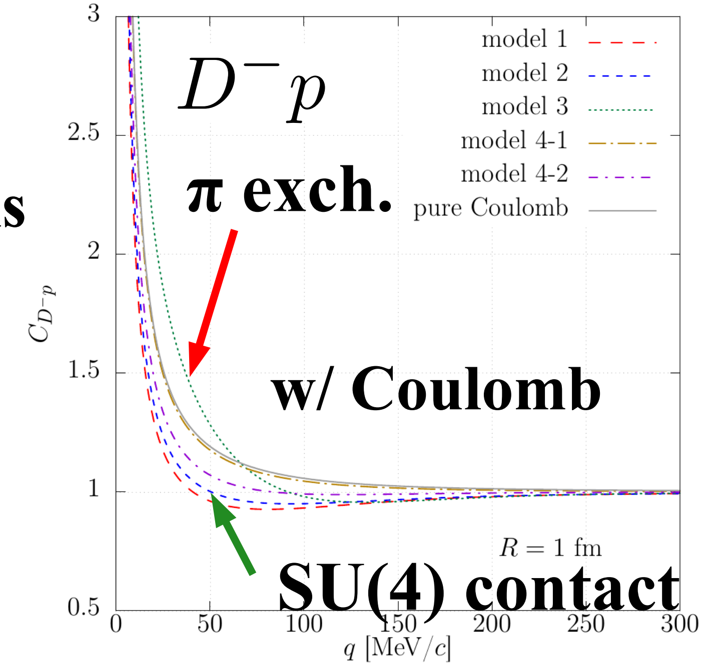
- **Charmed hadron interactions are extremely important in exotic hadron physics.**
- **Example:** $D^{(*)}N, \bar{D}^{(*)}N, D^{(*)}\bar{D}^{(*)}, D^{(*)}D^{(*)}$ $(D^{(*)} = c\bar{q}, \bar{D}^{(*)} = \bar{c}q)$
  - **Peaks around threshold for mesons. How about baryons ?**

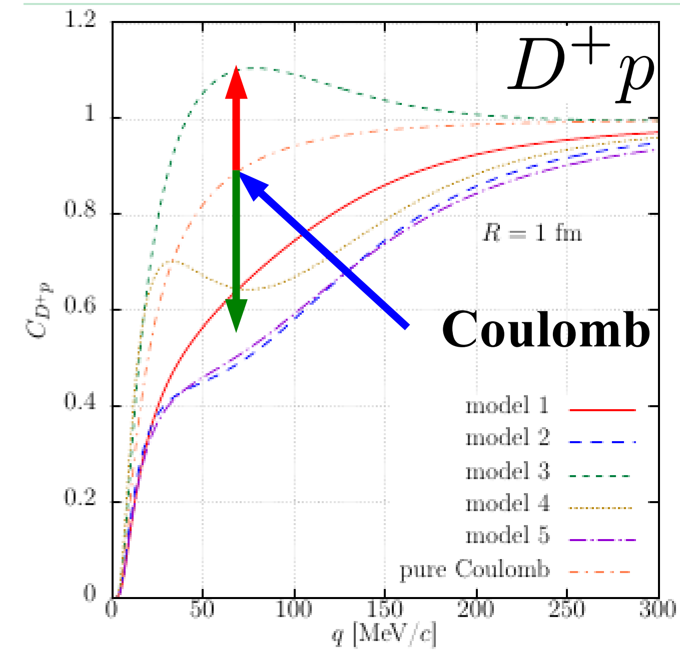


- **First try: One-range Gaussian potential** $V(r) = V_0 \exp(-m_\rho^2 r^2)$
  - **V_0 from model scattering lengths** $(DN, \bar{D}N)$
  - **V_0 from binding energy** $(DD^*, D\bar{D}^*)$

D^-p and D^+p correlation functions

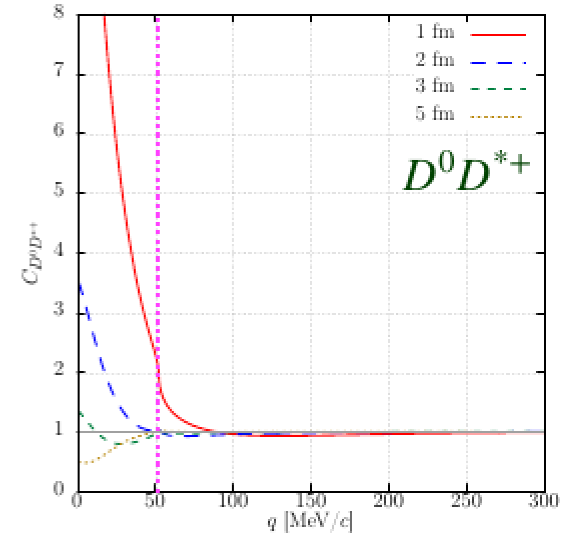
- D^-p correlation function ($\bar{c}duud$, exotic)
  Kamiya, Hyodo, AO (in prep.)
  - Coupled with $\bar{D}^0n$, No lower decay channels
  - Theoretical models
    1:Hofmann+('05), 2:Haidenbauer+('07), 3:Yamaguchi+('11), 4:Fontoura+('13)
    Mostly repulsive from vector meson exchange
    Model 3 with a bound state from pion exch.
- D^+p correlation functions
  - With decay channels $(c\bar{d}uud)$
  - Theoretical models
    1:Hofmann+('05), 2:Mizutani+('06), 3:Garcia-Recio+('09), 4:Haidenbauer+('11), 5: Raha+('18)
  - Model 3 predicts enh. from pure Coulomb
- To be judged by data
- Models are summarized in
  Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, PPNP96('17)88.



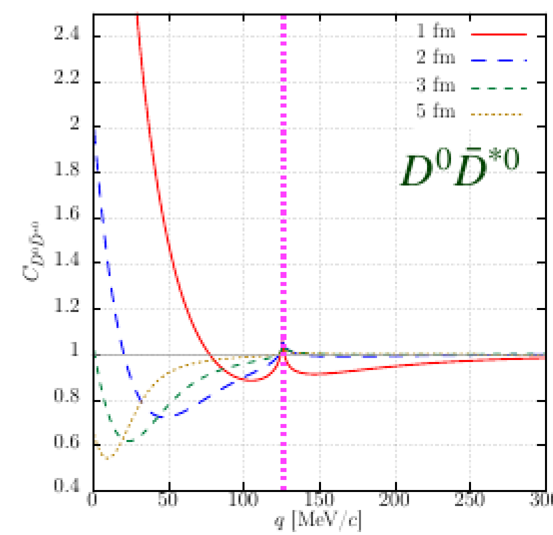


DD^* and $D\bar{D}^*$ correlation functions

- $D^0 D^{*+}$ correlation functions (T_{cc} channel)
  - **Bound state feature**
    - **Enhanced C(q) at small q with small source**
    - **Suppressed C(q) at small q with large source**
  - **What happens when Tcc's main component is a compact tetraquark state ?**
    4q source fn. → DD* process dominates ?
    (Weaker source size dependence ?)

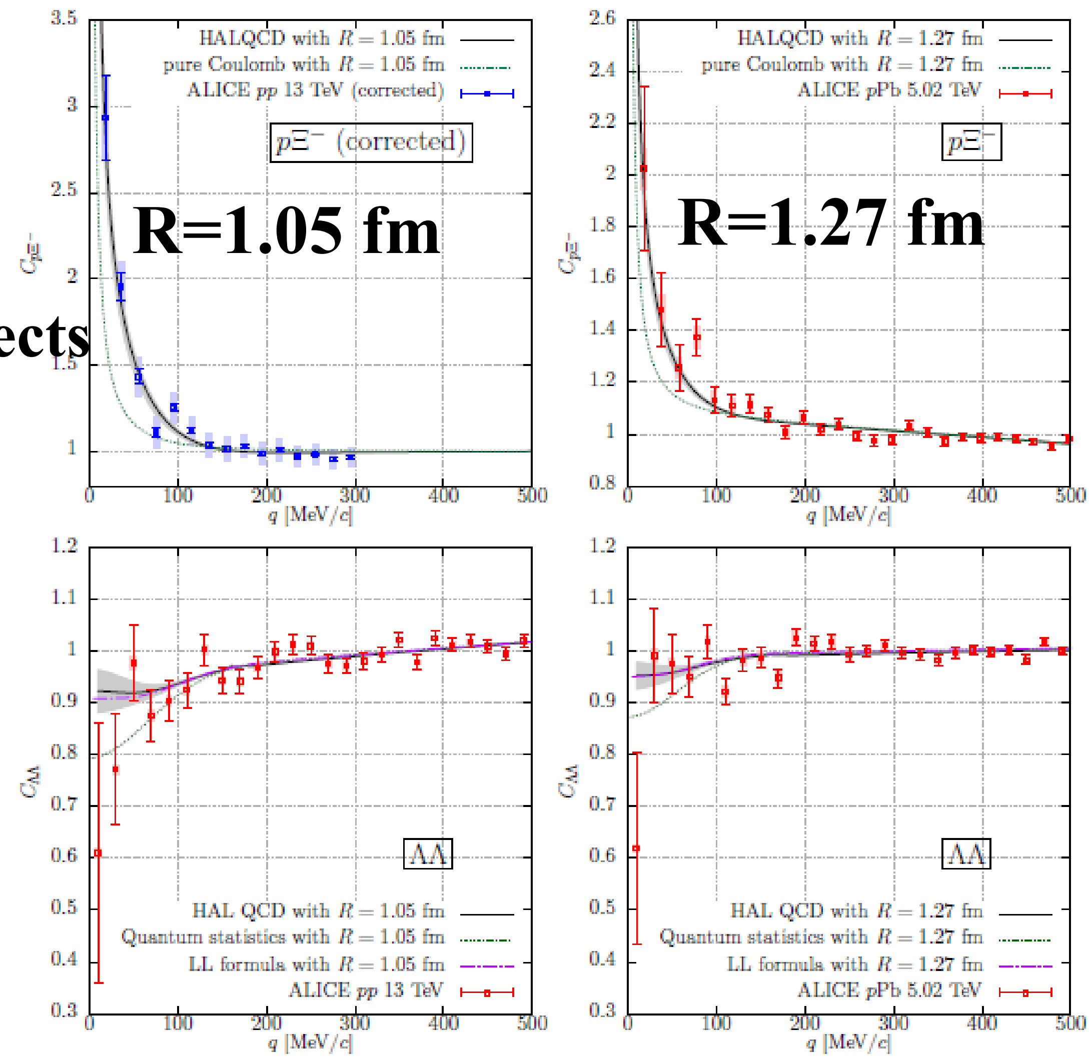


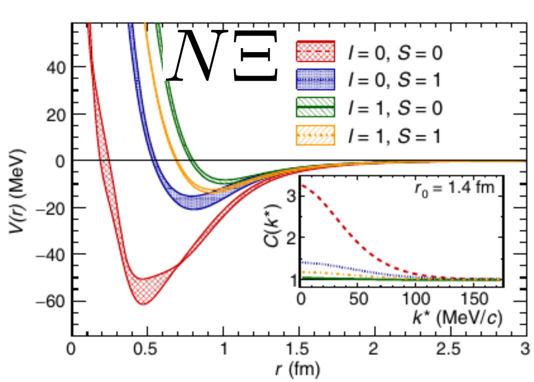
- $D^0 \bar{D}^{*0}$ correlation functions ($X(3872)$ channel)
  - **Bound state feature**
    - **Enh. (Suppr.) of C(q) with small (large) source**
  - **Stronger size dependence than DD*.**
    (Due to larger scattering length ?)
  - **Sizable D$^+$D^{*-} cusp**



Ξ^-p & $\Lambda\Lambda$ correlation functions (pp and pA)

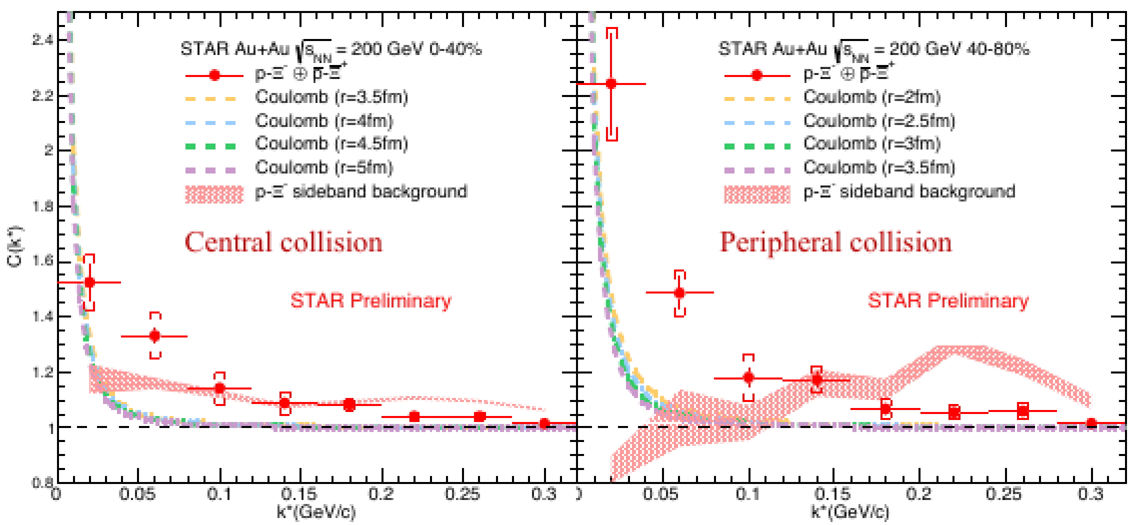
- **Correlation function data from pp and pA collisions**
  S. Acharya et al. [ALICE], PLB 797('19)134822 ($\Lambda\Lambda$); PRL123('19)112002 (Ξ^-p from pA); Nature 588('20)232 (Ξ^-p from pp).
  - CF(Ξ^-p) is enhanced at low q. → Att. pot.
  - CF($\Lambda\Lambda$) is slightly enhanced from quantum stat. result. → Weakly attractive pot.
  - CFs with coupled-channel effects using lattice QCD potential explains the data well.
    K. Sasaki [HAL QCD]('20); Y.Kamiya+, arXiv:2108.09644.



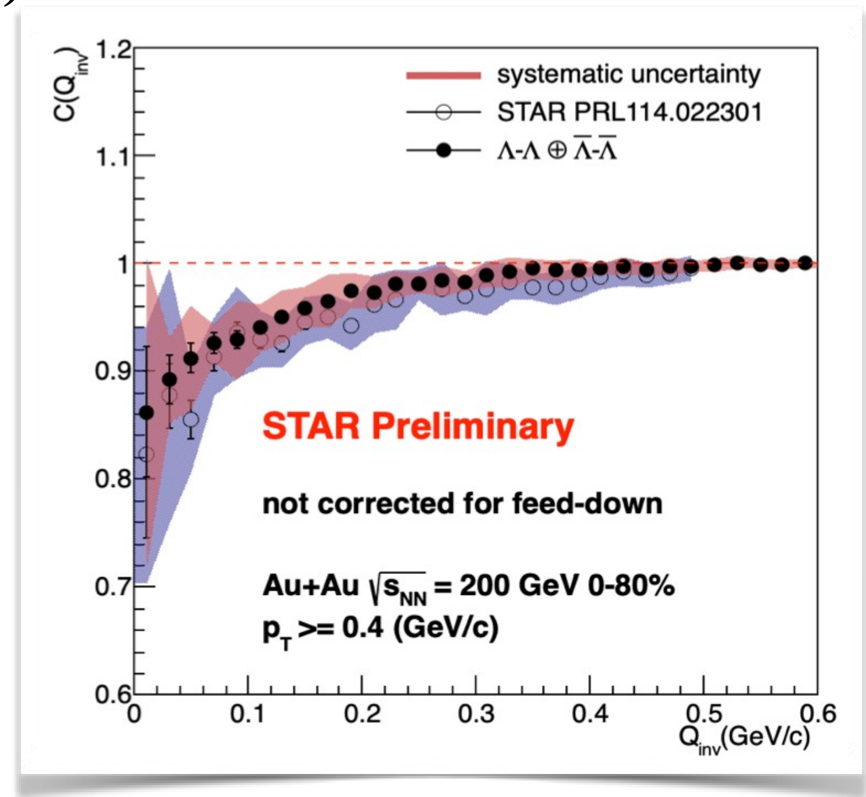


$\Xi^- p$ & $\Lambda\Lambda$ correlation functions (AA)

- **Correlation function data from AA collisions**
  [c.f. Shah, Mon., Isshiki, Tue.]
  K. Mi+(STAR, preliminary), Au+Au 200 AGeV, APS2021.
  Moe Isshiki+ (STAR, preliminary), Strangeness physics workshop, 2021.
  - **We do not see a dip in C(Ξ^- p) from Au+Au.**
    → There will be no bound state of Ξ^- p.
  - **Much higher statistics data of C($\Lambda\Lambda$) from Au+Au are obtained.**
    → LL formula fit will be possible.



K. Mi+(STAR, preliminary),
Au+Au 200 AGeV, APS2021.
(No Dip at larger R)

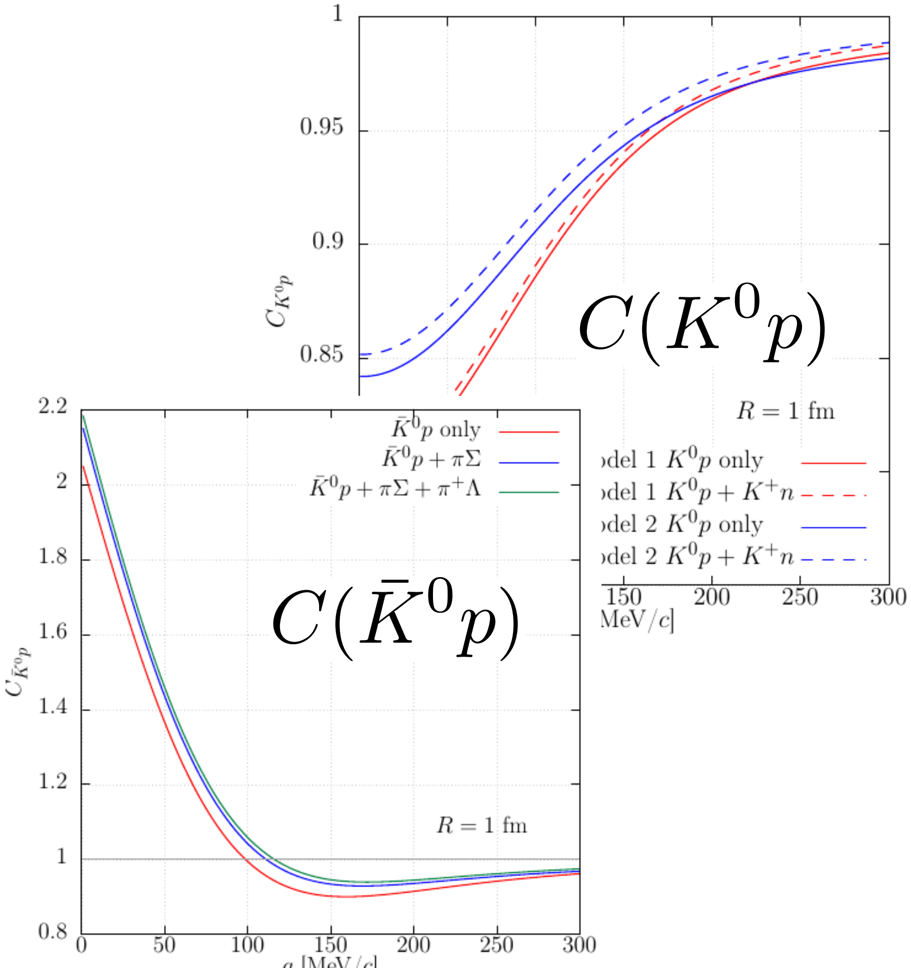


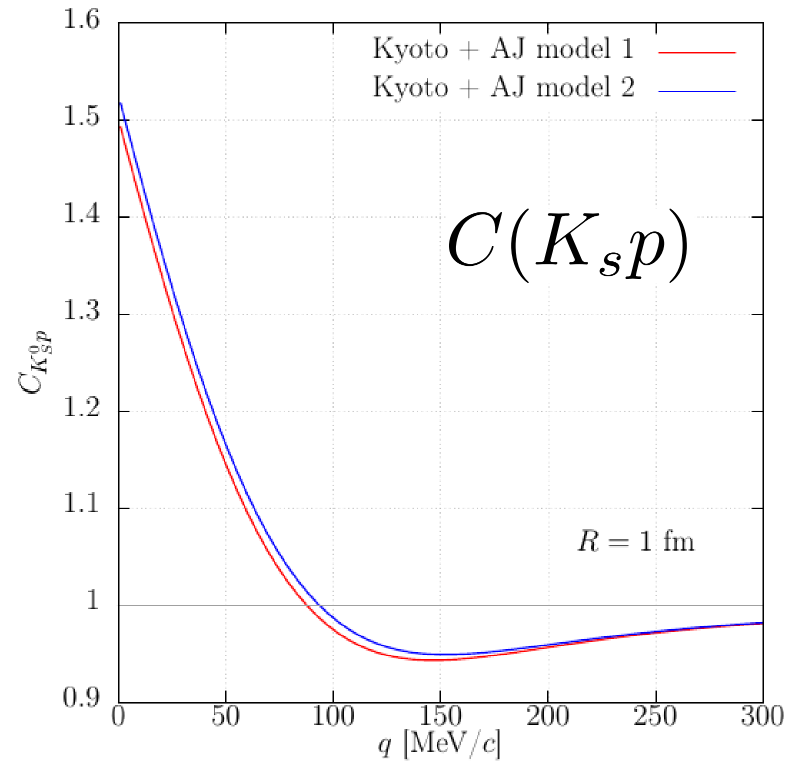
Moe Isshiki+ (STAR, preliminary).

Ks p correlation function

- **Ks wave function** ***Kamiya+(in prep.)***

$$|K_s\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right] \to C(K_s p) = \frac{1}{2}\left[C(K^0 p) + C(\bar{K}^0 p)\right]$$





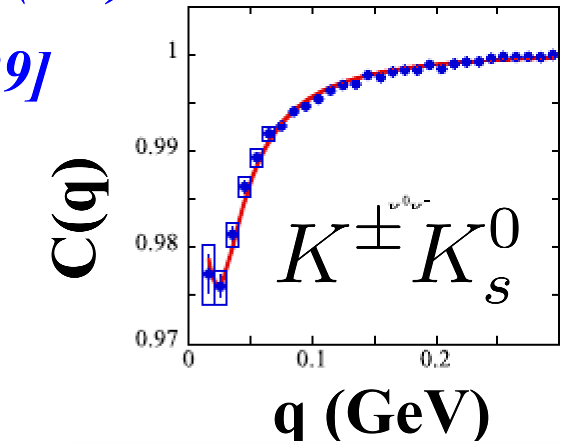
$K^-p, K^+p, K_sp,$ and K^-n or $K^+\bar{n}$ (missing)
to obtain KN and $\bar{K}N$ interactions with $I = 0, 1$

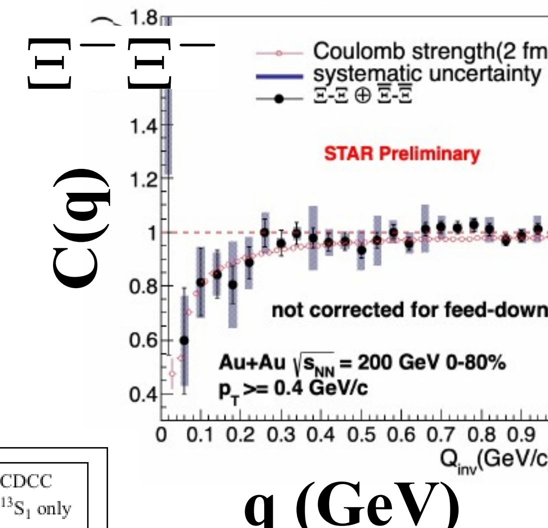
$V(\bar{K}N)$:Chiral SU(3) (Kyoto-Münich) model
(Miyahara, Hyodo, Weise ('18))

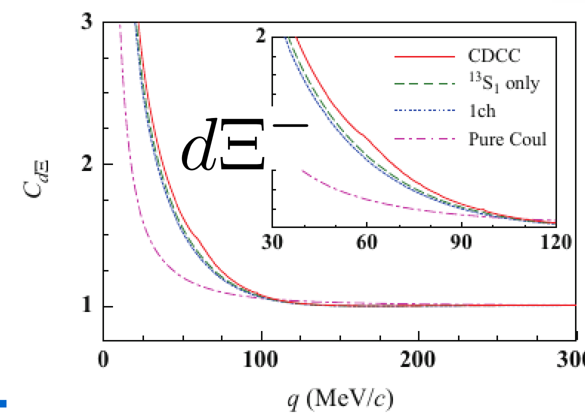
$V(KN)$:Chiral SU(3) based model
(Aoki, Jido ('19))

Other Correlation Functions

- $\bar{p}\bar{p}, p\bar{\Lambda}$ *E.g. A. Kisiel [ALICE], Acta Phys.Polon.Supp. 6 ('13)519*
- $K^{\pm}K^0_s$ *S.Acharya+ [ALICE], PLB774 ('17)64 [1705.04929]*
  - Slightly suppressed at low q
    Tetraquark component of a_0 meson
- $p\bar{\Lambda}, \Lambda\bar{\Lambda}$ [2105.05190][ALICE],
  $p\Sigma^0$ ['20 [1910.14407]] [ALICE]
- $\Xi^-\ \Xi^-$ [STAR] (e.g. ATHIC talk by Isshiki)
- deuteron-hadron CF
  S. Mrówczyński and P. Słoń,
  Acta Phys.Polon.B51('20)1739;
  F. Etminan, M. M. Firoozabadi,
  [1908.11484];
  J. Haidenbauer, PRC102('20)034001;
  K.Ogata, T.Fukui, Y.Kamiya, AO,
  PRC103('21)065205 .







Ogata+('21)

We are sorry for using a Gaussian Source !

- **Calculating HBT radius in dynamical models is not easy (HBT puzzle).**
  - *M.A.Lisa, S.Pratt, R.Soltz, U.Wiedemann, Ann.Rev.Nucl.Part.Sci.55('05)357 [nucl-ex/0505014];*

choices then tends to exceed the number of experimental constraints. In fact, all the model results that we review in the current subsection remain unsatisfactory with this respect: They either deviate significantly from femtoscopic data, or they reproduce these data at the price of missing other important experimental information. In particular, there is so far no dynamically consistent model that reproduces quantitatively both the systematic trends discussed in Section 4 and the corresponding single inclusive spectra. In this situation, the scope of this subsection is

  - *S. Pratt, PRL102('09)232301 [0811.3363].*

Two particle correlation data from the BNL Relativistic Heavy Ion Collider have provided detailed femtoscopic information describing pion emission. In contrast with the success of hydrodynamics in reproducing other classes of observables, these data had avoided description with hydrodynamic-based approaches. This failure has inspired the term "HBT puzzle," where HBT refers to femtoscopic studies which were originally based on Hanbury Brown–Twiss interferometry. Here, the puzzle is shown to originate not from a single shortcoming of hydrodynamic models, but the combination of several effects: mainly prethermalized acceleration, using a stiffer equation of state, and adding viscosity.

How about afterburner effects ?

Scope of Femtoscopic study of HHI

	n	p	K⁻	K⁺	π⁻	π⁺	Λ	Σ	Ξ⁻	Ω⁻	D⁻	D⁺	Ks	+α
n														
p		O	O	O	△	△	O	O	O	O	O	O	O	
K⁻		O	O	O	O	O							O	
K⁺		O	O	O	O	O							O	
π⁻		△	O	O	O	O								
π⁺		△	O	O	O	O								
Λ		O					O							
Σ		O												
Ξ⁻		O												
Ω⁻		O												
D⁻		O												
D⁺		O												
Ks		O	O	O										
+α														

pK⁻
Chiral CC pot. (examined)
Bound state (favored)

pΞ⁻
Lattice QCD CC pot. (examined)
Bound state (disfavored)

pΩ
Lattice QCD pot. J=2 (examined)
Bound state (favored)

ΛΛ
Scattering pars. (a_0, r_{eff}) (constrained)
Bound state (disfavored)

pD±
Chamed hadron-nucleon interaction (work in prog.)

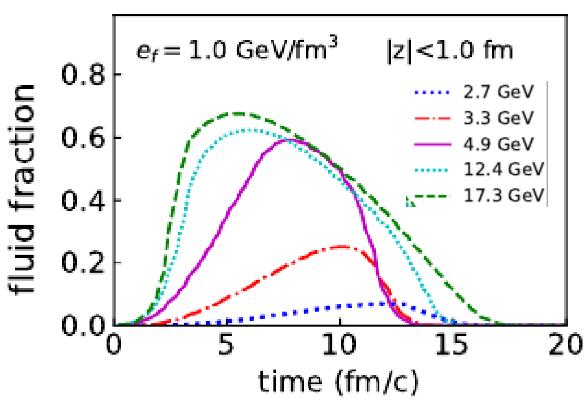
$K^{\pm}K^0_s$
Tetraquark component in a_0 meson

100 マス計算 (by 慈道) が急速に進んでいる。

Dense Baryonic Matter EOS from Collective Flow in HIC & Onset energy of QGP

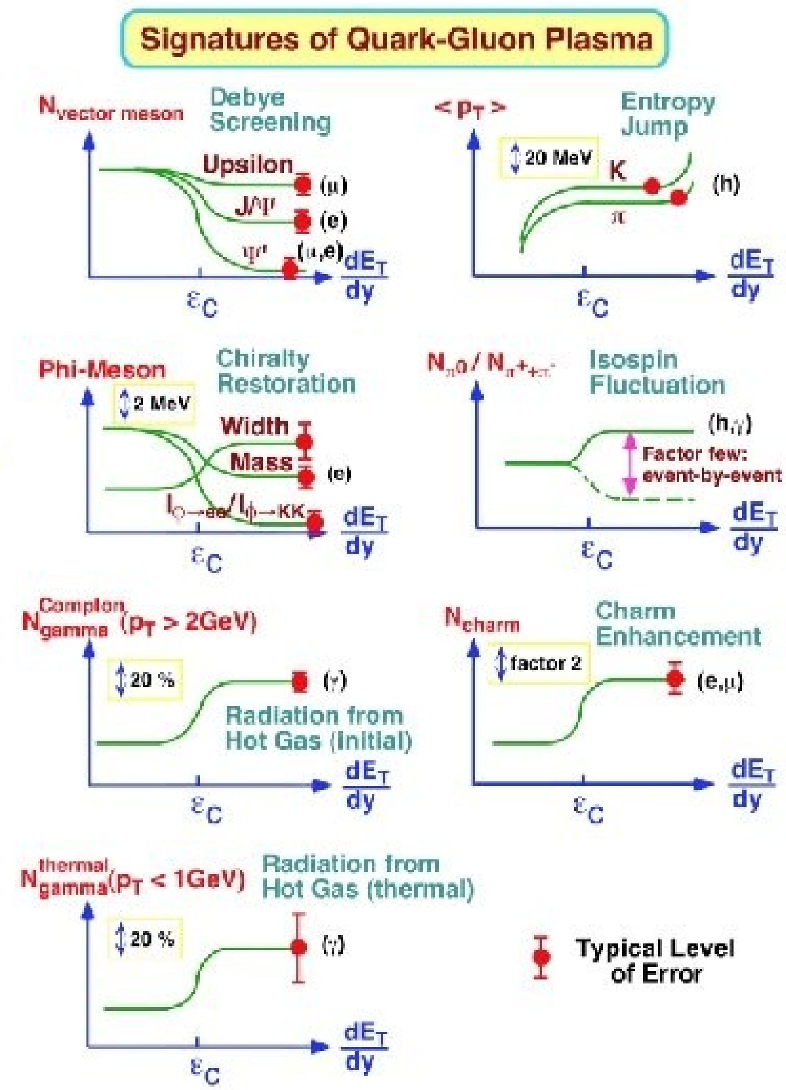
Onset Beam Energy of (bulk) QGP formation

- Nagamiya Plot
  - Simultaneous change of many signals
  - Finite volume smears sharp signal of 1st ord. p.t. even if it exists.
    → Gradual increase of QGP fraction ?



Hadronic fluid or QGP ?

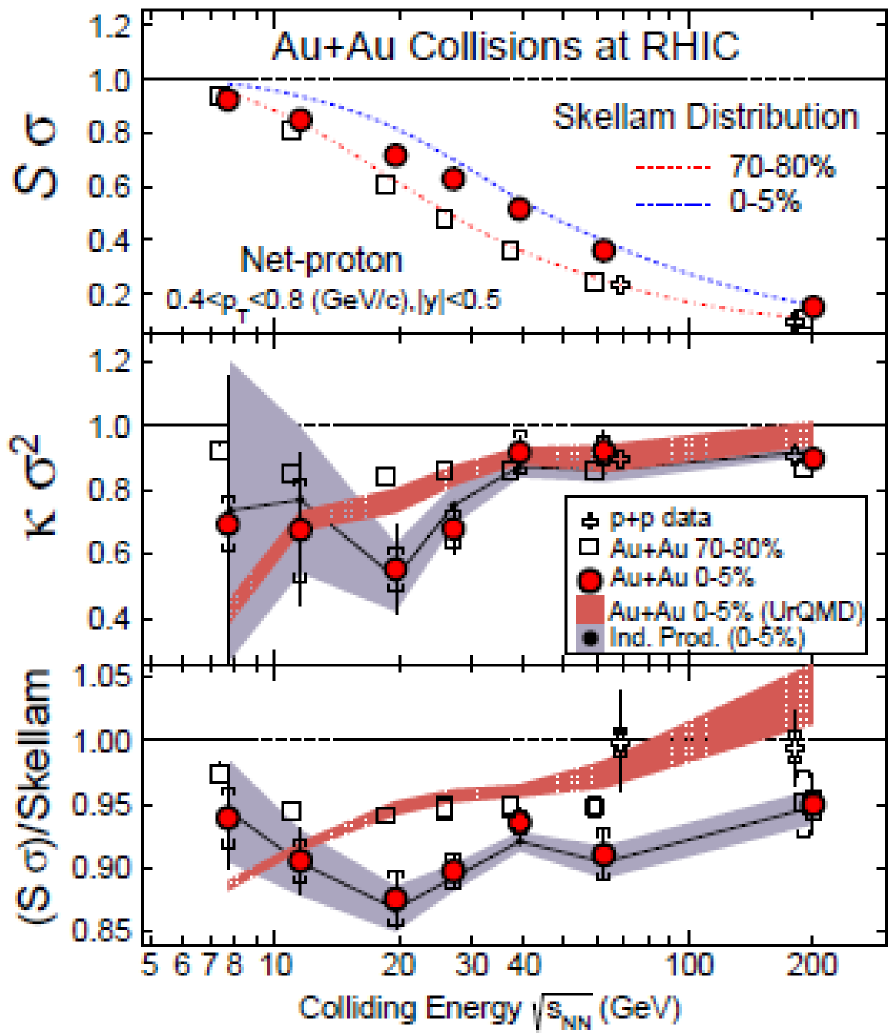
Y.Akamatsu, M.Asakawa, T.Hirano, M.Kitazawa, K.Morita, K.Murase, Y.Nara, C.Nonaka, AO, PRC98('18)024909.



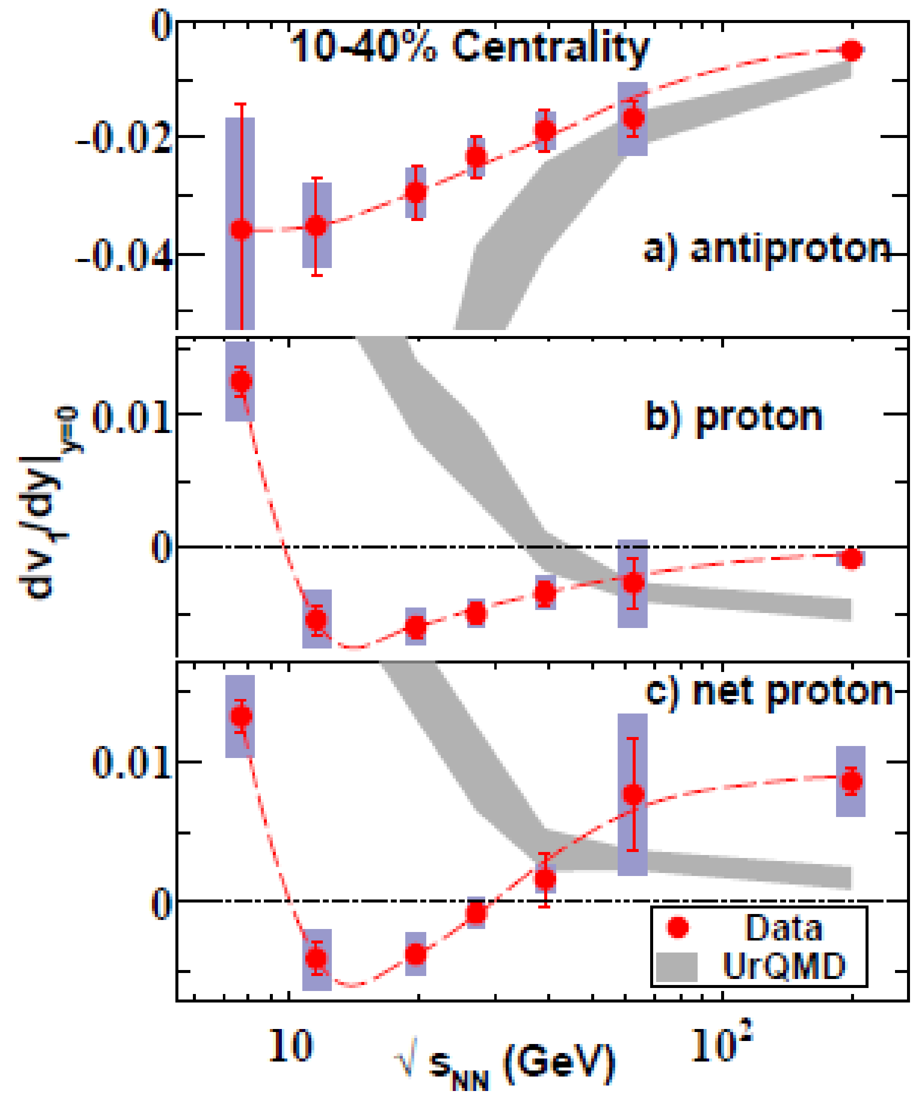
Taken from S. Nagamiya's Talk @ RIKEN, 2013/08/02

- Non-monotonic dep. on beam E.
  - Net-Proton Number Cumulants
    STAR Collab. PRL 112('14)032302; PRC104 ('21) 024902.
  - Directed Flow
    STAR Collab., PRL 112('14)162301.

Net-Proton Number Cumulants & Directed Flow



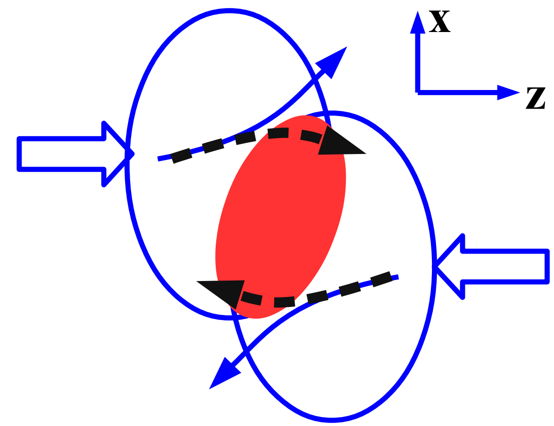
STAR, PRL 112('14)032302



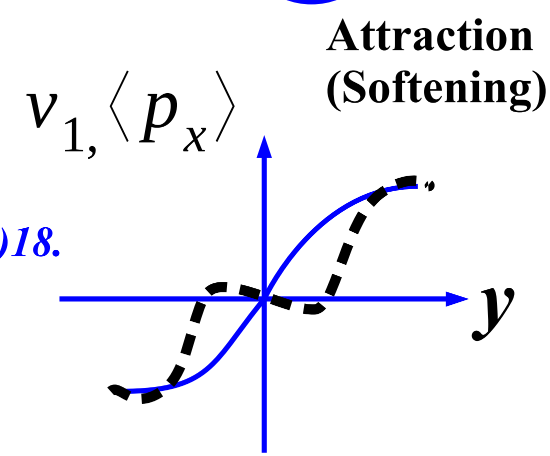
STAR, PRL 112('14)162301.

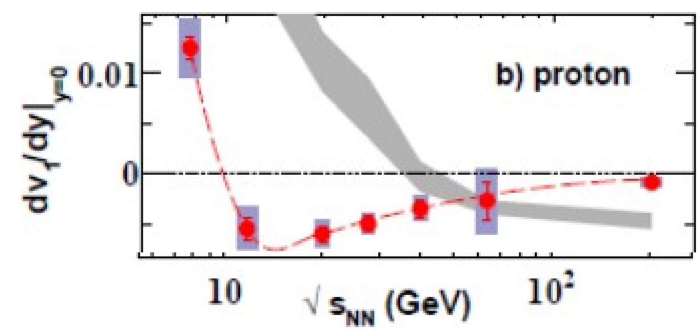
Non-Monotonic Beam E. dep. of v_1 slope

- **Directed flow (v_1 or $<p_x>$) is created in the overlapping stage of two nuclei**
  → Sensitive to the EOS of dense matter.



- **BES (Beam Energy Scan) result**
  → Non-monotonic beam E. dep. of v_1 slope
  - **EOS softening ?**
    Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 (‘16)034906;
    Y.Nara, H.Niemi, J.Steinheimer, H.Stoecker, PLB769 (‘17) 543;
    Y.Nara, H.Niemi, AO, J.Steinheimer, X.F.Luo, H.Stoecker, EPJA54 (‘18)18.
  - **None of fluid and hybrid models explain the beam energy dependence with a single EOS**

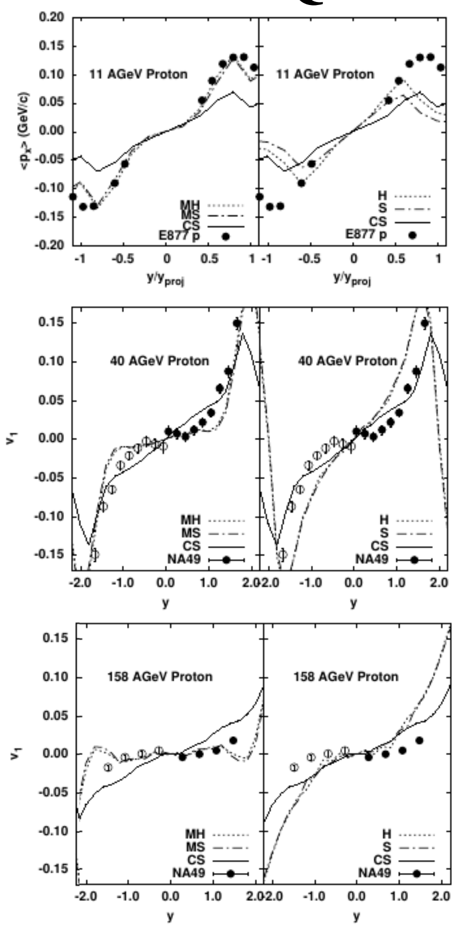




STAR, PRL112(’14)162301

Past tries

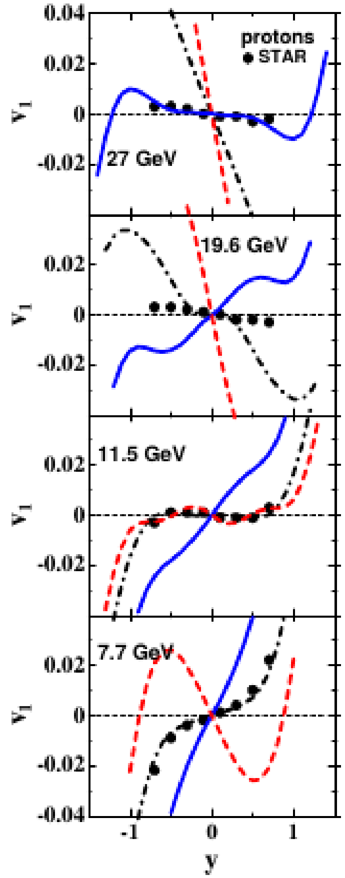
JAM-RQMD



p-dep. p-indep.

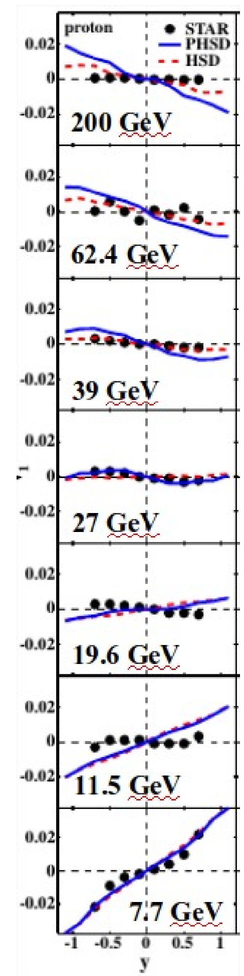
M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72('05)064908 (There was a mistake...)

3FD



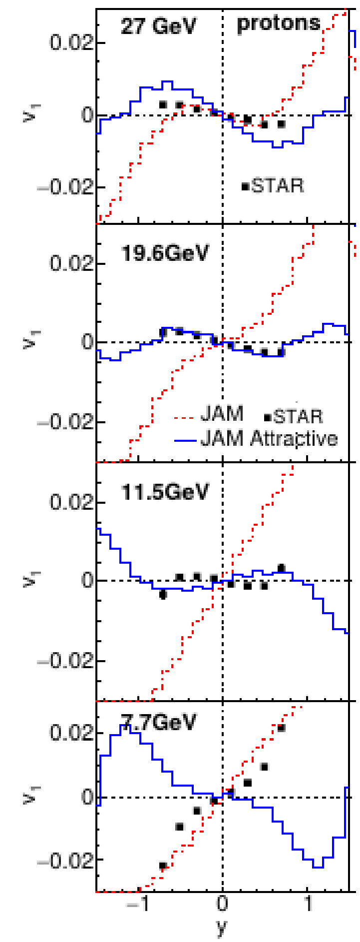
Y.B.Ivanov, A.A.Soldatov, PRC91('15) 024915

HSD/PHSD



V.P.Konchakovski, W.Cassing, Y.B.Ivanov, V. D. Toneev, PRC90('14)014903

JAM+Att.



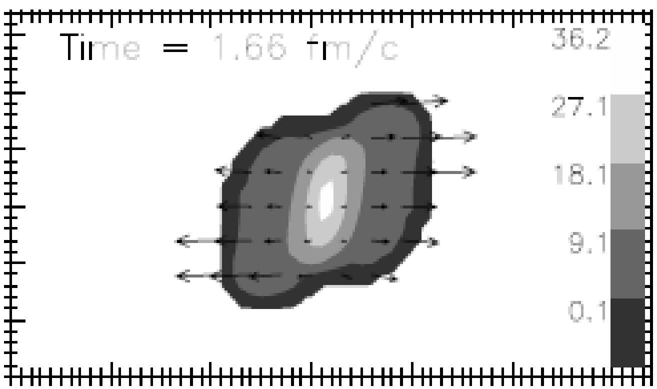
Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 ('16)034906

What happens ?

- Positive & Negative Flow の起源
  - 圧縮時の斥力 → positive flow ($dv_1/dy > 0$)
  - 膨張時の tilted matter → negative flow ($dv_1/dy < 0$)
- バランスエネルギー ($\sqrt{s_{NN}} \sim 10$ GeV) では EOS の軟化 or 初期・後期の釣り合いが起きているだろう。

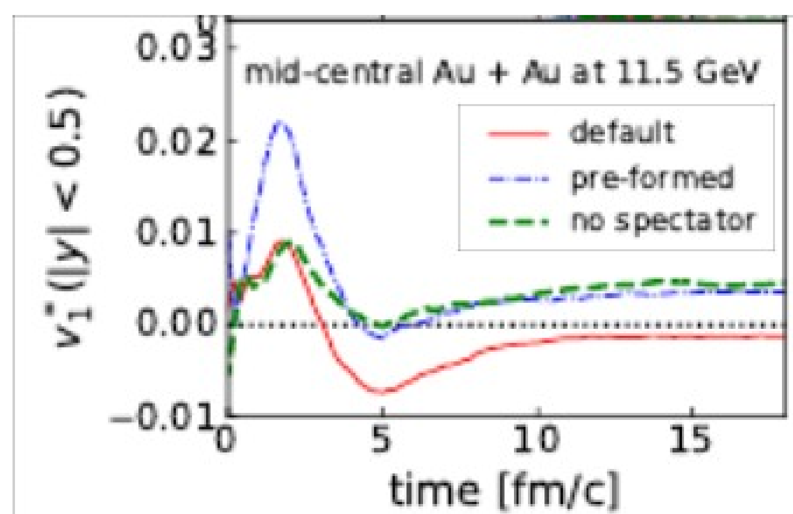
Nara+('16,'17,'18); Y. Nara, AO, arXIv:2109.07594

$$v_1^* = \int_{-0.5}^{0.5} dy v_1(y) \mathrm{sign}(y)$$



18 GeV, 3-fluid

Toneev et al. ('03)



Y. Nara, AO, arXiv:2109.07594

Relativistic QMD/Simplified (RQMD/S)

- **RQMD is developed based on constraint Hamiltonian dynamics**
  H. Sorge, H. Stoecker, W. Greiner, Ann. Phys. 192 (1989), 266.
  - **8N dof → 2N constraints → 6N (phase space)**
  - **Constraints = on-mass-shell constraints + time fixation**
- **RQMD/S uses simplified time-fixation**
  Tomoyuki Maruyama, et al. Prog. Theor. Phys. 96(1996),263.
  - **Single particle energy (on-mass-shell constraint) and EOM**

$$p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2m_i V_i} \to \frac{d\boldsymbol{r}_i}{dt} = \frac{\boldsymbol{p}_i}{p_i^0} + \sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{p}_i}\,,\quad \frac{d\boldsymbol{p}_i}{dt} = -\sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{r}_i}\,,$$

  - **Potential V_i is Lorentz scalar and becomes weaker at high E.**
- **Stronger potential effect is necessary → Vector-type potential**
  Y.Nara, T.Maruyama, H.Stoecker, PRC102('20)024913; Y.Nara,AO,arXiv:2109.07594

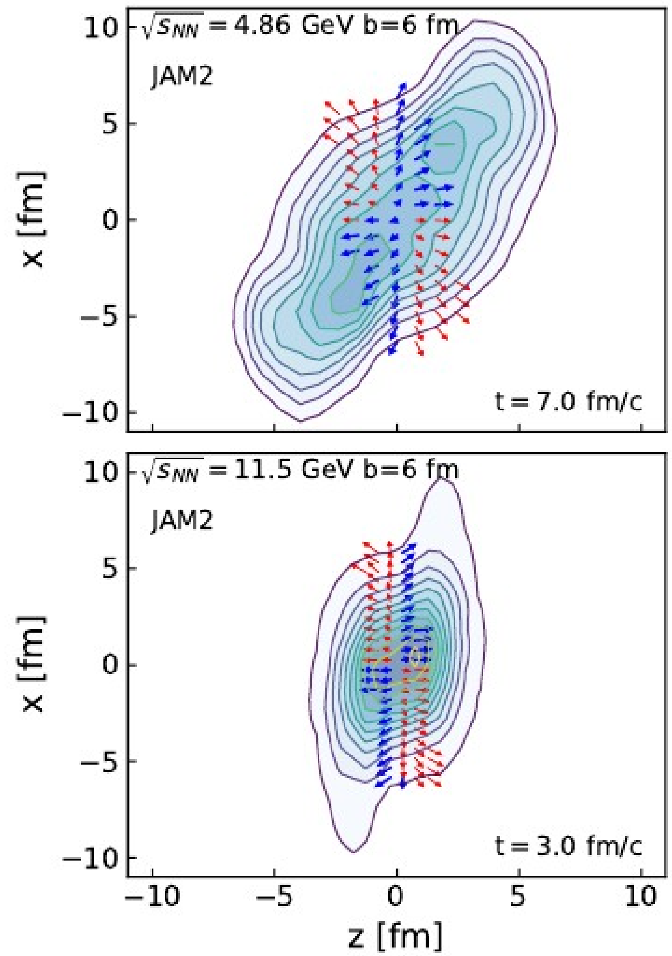
$$p_i^0 = \sqrt{\boldsymbol{p}_i^{*2} + m_i^2} + V_i^0 \to \frac{d\boldsymbol{r}_i}{dt} = \frac{\boldsymbol{p}_i^*}{p_i^{*0}} + \sum_j v_j^{*\mu}\frac{\partial V_{j\mu}}{\partial \boldsymbol{p}_i}\,,\quad \frac{d\boldsymbol{p}_i}{dt} = -\sum_j v_j^{*\mu}\frac{\partial V_{j\mu}}{\partial \boldsymbol{r}_i}$$

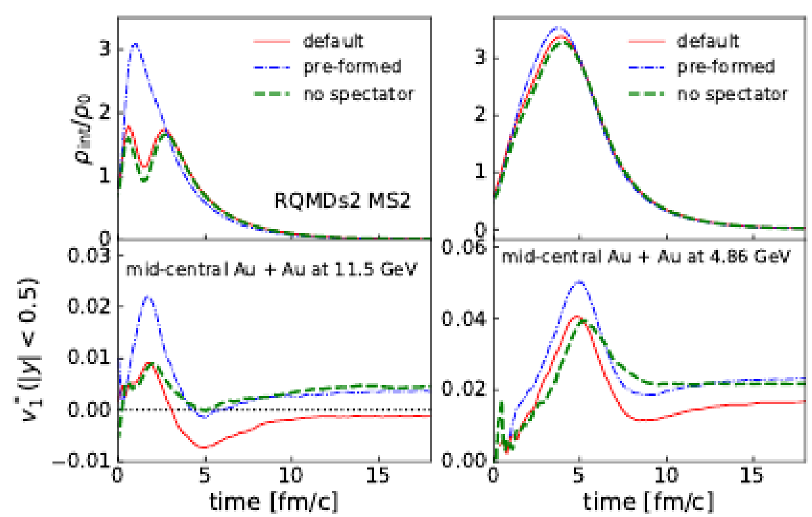
$$(p_j^{*\mu} = p_j^\mu - V_j^\mu\,,\ v_j^{*\mu} = p_j^{*\mu}/p_j^{*0})$$

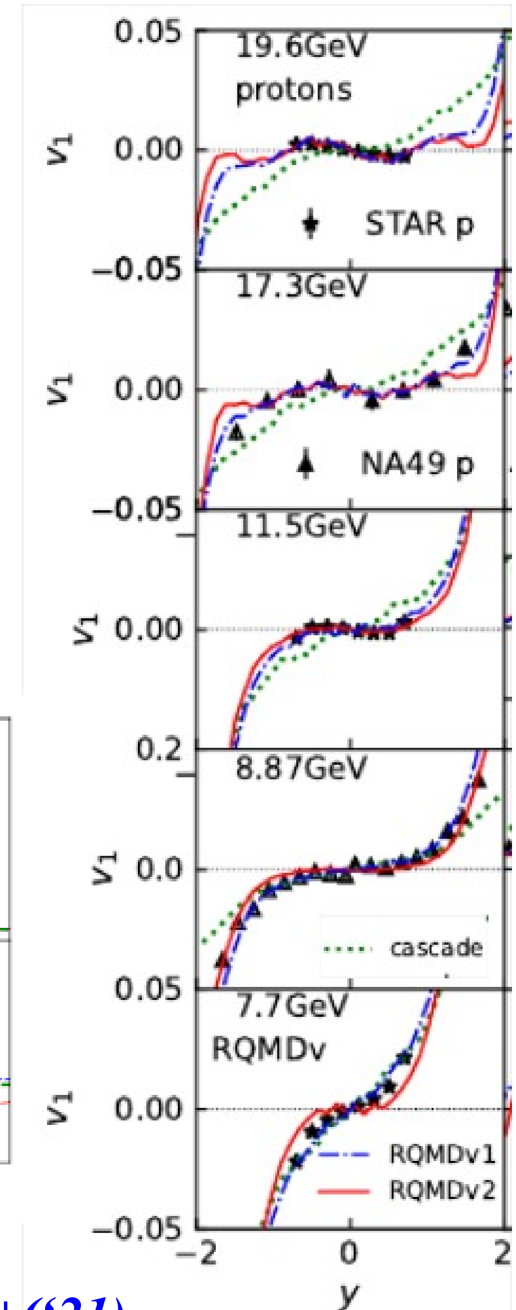
  - **Potential effect remains at high energy.**

JAM2 + RQMDv

- **Beam energy dependence of dv_1/dy can be explained in JAM2+RQMDv.**
- **The negative flow in the expansion stage becomes dominant at higher beam energies.**





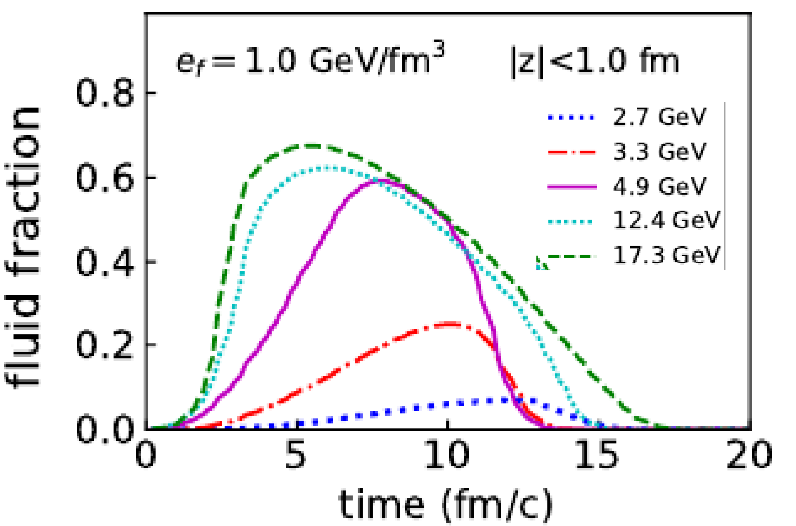


Nara+('21)

Onset energy, revisited

- $\sqrt{s_{NN}}$=10 GeV 付近での EOS の軟化は必ずしも必要でない。
- ただし流体・粒子統合模型は、$\sqrt{s_{NN}}$=5-20 GeV で 50% 以上流体成分が作られることを予言。
- 流体成分 (エネルギー密度 > 1 GeV/fm^3) の一部は QGP になっていると考えるのが自然。
- QGP が主要成分である場合のシグナルは？
- 流体模型を使う模型計算において確認するには、(おそらく) 動的な初期条件 (dynamical initialization) と流体・粒子の同時発展 (integrated model) を用いた定量的研究が必要。

Kanakubo+(E.g. ATHIC); Akamatsu+.



Y.Akamatsu, M.Asakawa, T.Hirano, M.Kitazawa, K.Morita, K.Murase, Y.Nara, C.Nonaka, AO, PRC98('18)024909.

Summary

- 重イオン衝突はハドロン物理学にも有用である。
  - エキゾチックハドロンの物理は現在大きな盛り上がりを見せており、高エネルギー原子核衝突 (pp, pA, AA) の貢献も大きい。
  - ハドロン相関からハドロン間相互作用を制限する研究は近年急速に進展。
  - AA 衝突のフロー、特に dv_1/dy の入射エネルギー依存性は、高密度バリオン物質 EOS 研究におけるパズルとなっている。
- 衝突領域のサイズ依存性は、ハドロン構造・ハドロン間相互作用の理解に重要な情報を与える。
  - 収量はコンパクトな多クォーク状態とハドロン分子状態が区別するヒント。
  - 相関関数のサイズ依存性は束縛状態の有無を推定するヒント。
- ハドロン物理学の進展は重イオン物理にも有用
  - エキゾチックハドロン生成量はハドロン化の機構を反映。
  - ハドロン間相互作用の解明によりソース関数サイズの精密化が可能。
  - 高密度物質状態方程式は重イオン物理の目標の一つ。

J-PARC-HI への期待

- J-PARC-HI の特徴
  - 入射エネルギーは限られる ($\sqrt{s_{NN}}$ <5 GeV or $\sqrt{s_{NN}}$ < 6.3 GeV (50 GeV p))
    (charm は生成量が小さいが、ハイペロンは多く作られる)
  - 統計は十分 (FAIR と比べても桁違い)
- ストレンジネス・高密度・高統計での勝負に期待。
  - Σ バリオンは TPC では観測困難。
    一方 J-PARC E40 実験では $\Sigma^{+,-}$ を同定してビームとして利用もしている。
    → Σ に崩壊するハドロン分光・ Σ を含む相関関数
  - Λ- 原子核相関関数 → Λ- 原子核ポテンシャル
    deuteron は LHC-ALICE の目標の範囲内だが、 A>3 は統計が足りないはず。 (例えば FSI による Λ-α 散乱が見られる可能性)
  - Λ, Σ, Ξ の集団フローから高密度でのハイペロンポテンシャルへ
    → ハイペロンパズル
  - $\sqrt{s_{NN}}$ ~ 5 GeV でも部分的に小さな QGP は作られているかも。
    よいシグナルがあれば ...

Thank you for your attention !