高エネルギー原子核衝突を用いたハドロン物理

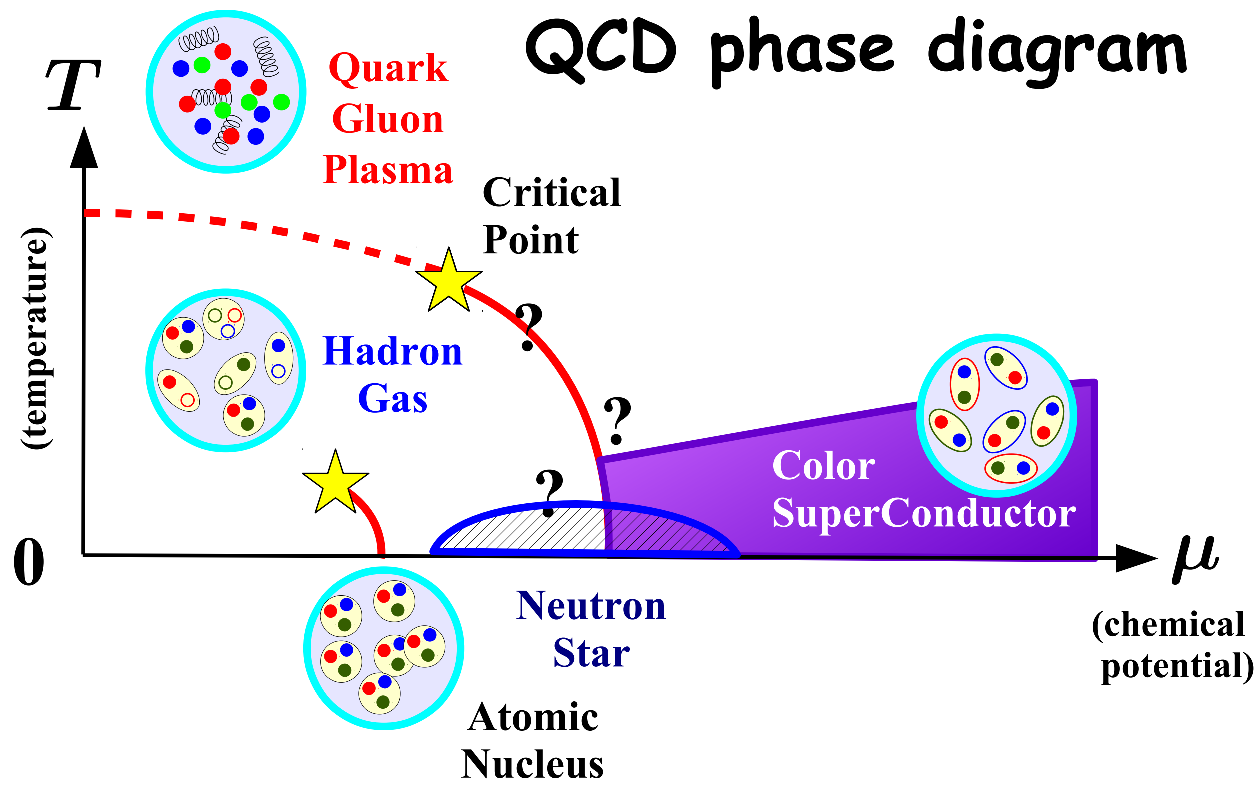
大西　明 (基研)

- Introduction
- 高エネルギー原子核衝突を用いたハドロン間相互作用の研
  - Femtoscopic study of charm hadron interactions –
- 高エネルギー重イオン衝突を用いた高密度 QCD 相転移の研究
  - Does non-monotonic behavior of proton directed flow imply the onset of QGP formation ?
- Summary

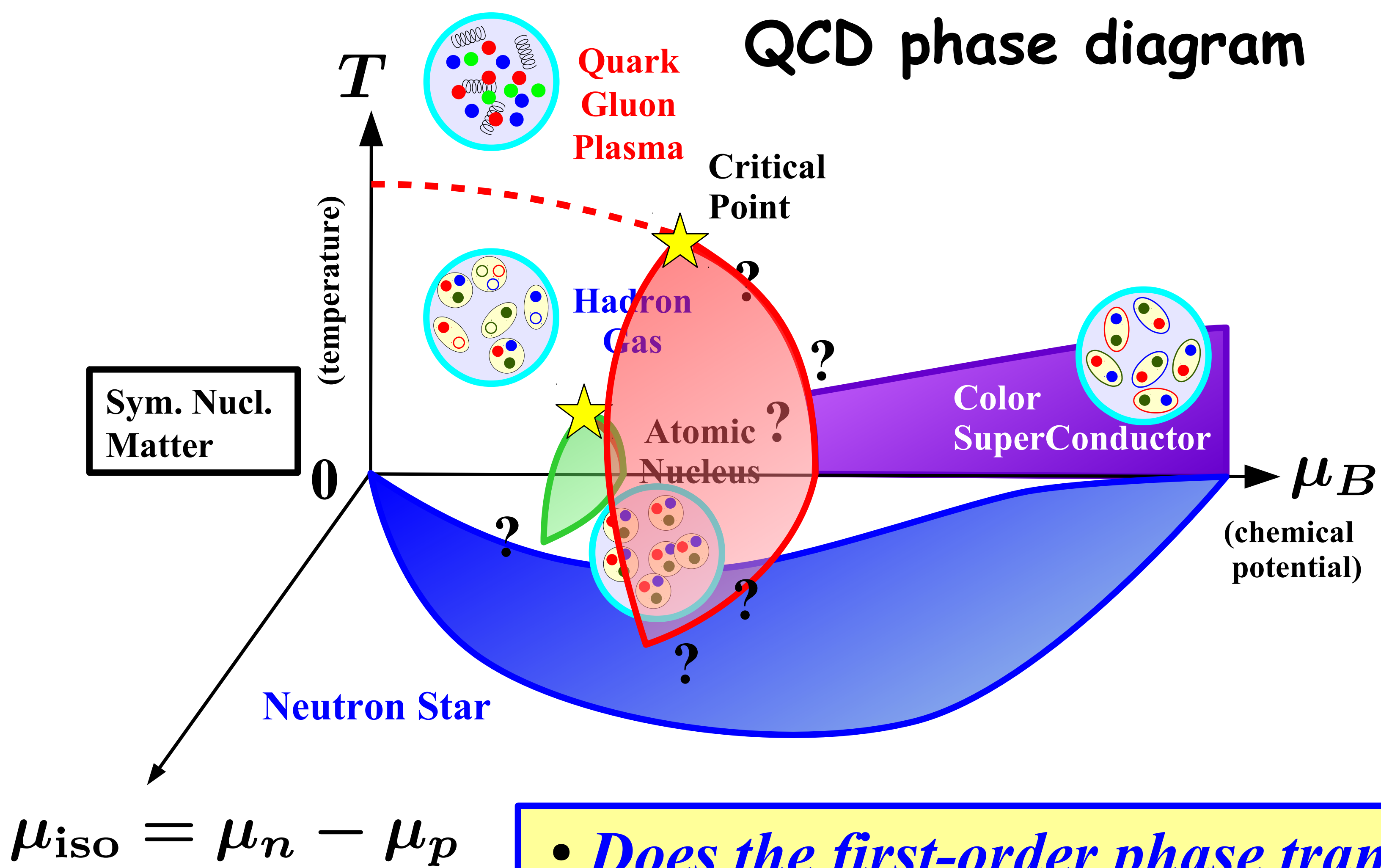
自己紹介 A. Ohnishi

- **履歴書：** 1964 年神戸生まれ ,1992 年京都大学博士 (理学)
  1992 年 RCNP(学振), 1993-2008 北大 , 2008 年 ~ 基研
- **研究課題：核物質の相図と状態方程式の解明を目指す**
  (クォーク・ハドロン物理の物質的側面)
  - 重イオン衝突
    非平衡グルーオン動力学 (松田、国広、高橋)
    5 次元時空でのレプリカ発展による量子場時間発展 (同上 +α?)
    重イオン衝突での物質の回転にともなう奇妙な現象 (ExHIC-P)
    フローによる状態方程式の軟化の探索 (奈良、 Stöcker, Steinheimer, ...)
  - QCD 相図と中性子星物質状態方程式
    重イオン衝突を用いたハイペロンパズル解決法の検証（神野、村瀬、奈良）
    経路最適化法を用いた符号問題の研究（森、柏、滑川）
    重イオン衝突を用いた対称エネルギーの制限（池野、小野、奈良）
    対称エネルギーから中性子星物質状態方程式へ (Kolomeitsev, Lattimer, Tews)
  - ストレンジネス ＆ ハドロン物理
    ハドロン相関によるハドロン間相互作用の探求
    (神谷、兵藤、森田、初田 (HAL QCD) 、 Weise 、福井、緒方、 ALICE)
    静止 Ξ^- 吸収からのダブルハイパー核生成 (北大 collab)

QCD phase diagram



QCD phase diagram



- *Does the first-order phase transition exist at finite baryon density ?*
- *Do hyperons mix in neutron star core ?*

高密度物質の性質 (状態方程式・相転移) を知るには どうすればよい？

Bottom-up approach:
ハドロン間相互作用を明らかにして、多体理論で予測する。

Top-down approach:
QCD に基づいて計算する。

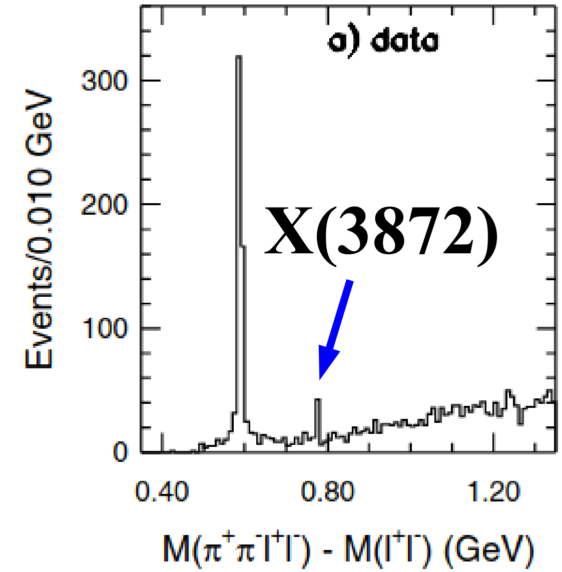
これらをつなぐ (外挿・内挿) 試みが行われているが、
(第一原理計算で正確に求められないなら) その結果は実験で検証すべきだろう。

→ 相関関数用いたハドロン間相互作用、
フロー を通じた有限密度 QCD 相転移探索

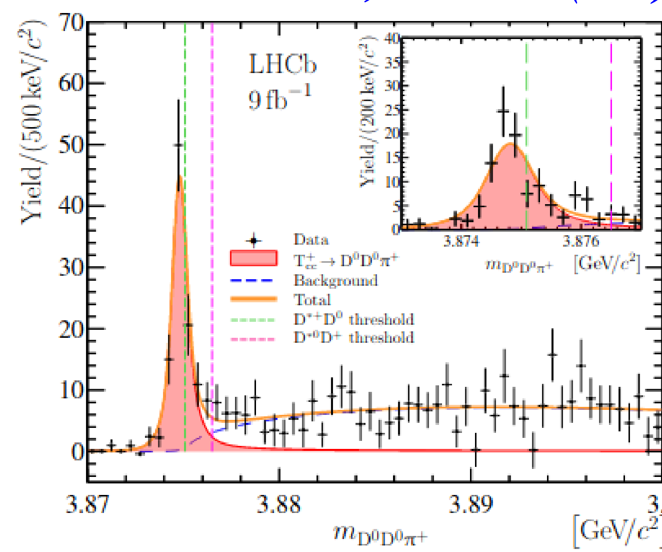
Femtoscopic study of charm hadron interactions

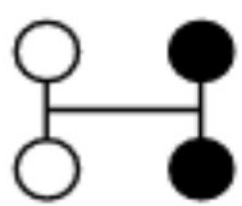
Exotic Hadrons including $c\bar{c}$ / cc / $\bar{c}\bar{c}$

- **Main play ground of exotic hadron physics**
  - **X(3872)** ***Belle ('03)*** $c\bar{c}q\bar{q}$
  - **Many X,Y,Z states**
    Belle, CDF, BaBar, LHCb, CMS, BESIII, ...
  - **Charmed pentaquark Pc** ***LHCb ('15, '19)***
  - **Doubly charmed tetraquark state Tcc**
    LHCb ('21) $cc\bar{q}\bar{q}$
- **Structure of exotic hadrons**
  - **Compact multiquark states**
    → "good" [ud] diquark gains energy
  - **Hadronic molecules**
    → Many exotic states around thresholds
  - **Their mixture...**

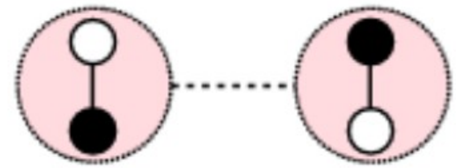


S.K.Choi+[Belle], PRL91, 262001 ('03)





Tetraquarks



Hadronic Molecules

R. Aaji+ [LHCb], 2109.01038, 2109.01056

"Good" diquark

- **A color-(anti)triplet & spin-singlet diquark pair gains energy**
  - **One-gluon exchange potential**

$$V_{ij}^{\rm OGE} = \frac{\alpha_s}{4} \underbrace{(\lambda^{(i)} \cdot \lambda^{(j)})}_{\rm color} \left[\frac{1}{r_{ij}} - \frac{\pi}{2}\delta(\boldsymbol{r}_{ij}) \left(\frac{1}{M_i^2} + \frac{1}{M_j^2} + \underbrace{\frac{4\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3M_iM_j}}_{\rm spin} \right) + \cdots \right],$$

  - **Attractive for color (anti-)triplet, spin-singlet (then flavor antisymmetric) pairs**

$$(\sum_{i=1}^{n} \lambda^{(i)})^2 = n(\lambda^{(1)})^2 + n(n-1)(\lambda^{(1)} \cdot \lambda^{(2)}) = 0$$

$$\to (\lambda^{(i)} \cdot \lambda^{(j)}) = -\frac{2(N_c^2-1)}{N_c(n-1)} = -16/3, -16/6, -16/9 \text{ (for } q\bar{q}, qqq, qq\bar{q}\bar{q})$$

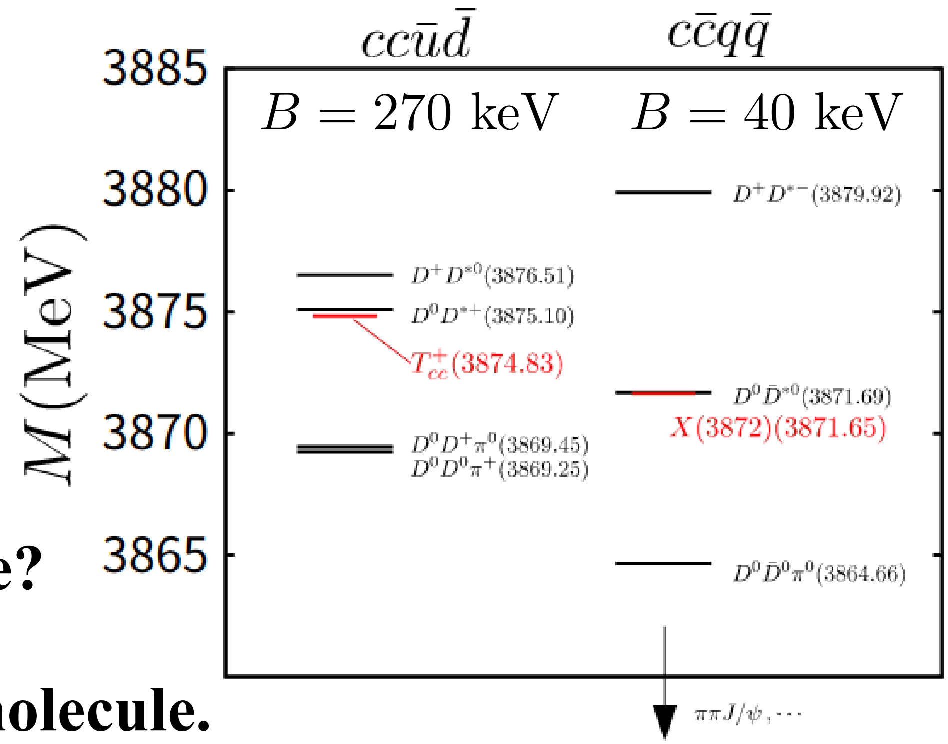
$$\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j = 2S(S+1) - 3 = -3, 1 (\text{for spin singlet and triplet})$$

- **spin 0 の [ud] (=ud-du) クォーク対は大きな引力を得る (good diquark) → Tcc は compact tetraquark 配位が主要項だろう**

Compact Tetraquarks or Hadronic Molecules

- **Tcc = Compact Tetraquark ?**
  Good $[\bar{u}\bar{d}]$ diquark gains energy
  S. Zouzou+('86), ZPC30,457.

- **X(3872)**
  - **$c\bar{c}$ component ? production cross section** *Bignamini+ (0906.0882)*
  - **Large yield in Pb+Pb → Molecule?**
    Sirunyan+ [CMS] (2102.13048)
    c.f. Δr/Δp is similar in HIC and molecule.
    ExHIC ('11,'11,'17)

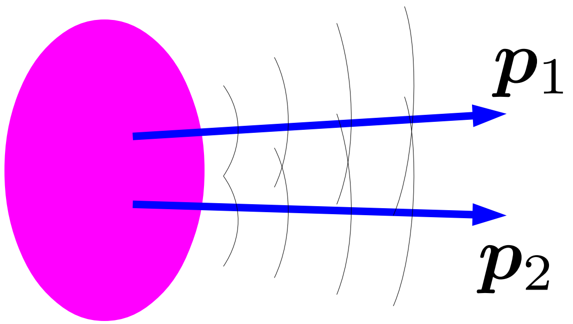


- **Hadronic Molecule Conditions**
  - **Appears around the threshold → OK**
  - **Have large size $R \simeq 1/\sqrt{2\mu B}$ → Yield**
  - **Described by the *hh* interaction**

How can we access hh int. with charm ?
→ Femtoscopy

Femtoscopic study of hadron-hadron interaction

- How can we study interactions between short-lived particles ? → Femtoscopy !
- Correlation function (CF)
  - Koonin-Pratt formula



Koonin('77), Pratt+('86), Lednicky+('82)

source fn. relative w.f.

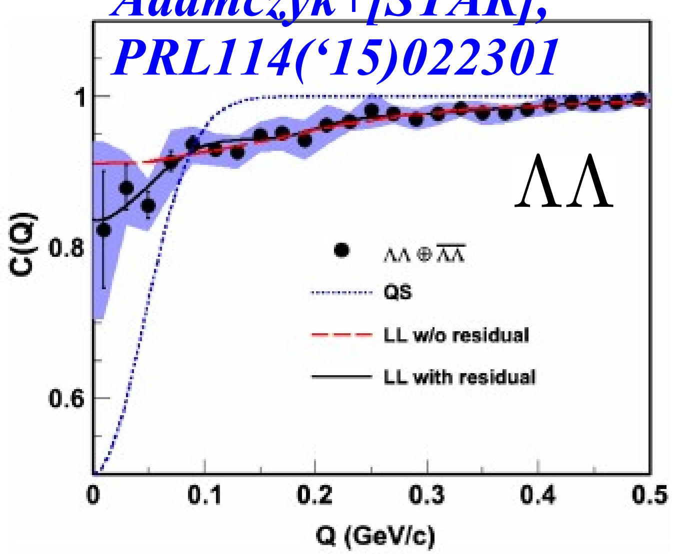
$$C(\boldsymbol{p}_1,\boldsymbol{p}_2)=\frac{N_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1)N_2(\boldsymbol{p}_2)}\simeq\int d\boldsymbol{r}\,\underline{S_{12}(\boldsymbol{r})}\,\underline{|\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2}$$

- Source size from quantum stat. + CF (Femtoscopy)
  Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)
- Hadron-hadron interaction from source size + CF
  - CF of non-identical pair from Gaussian source
    R. Lednicky, V. L. Lyuboshits ('82); K. Morita, T. Furumoto, AO ('15)

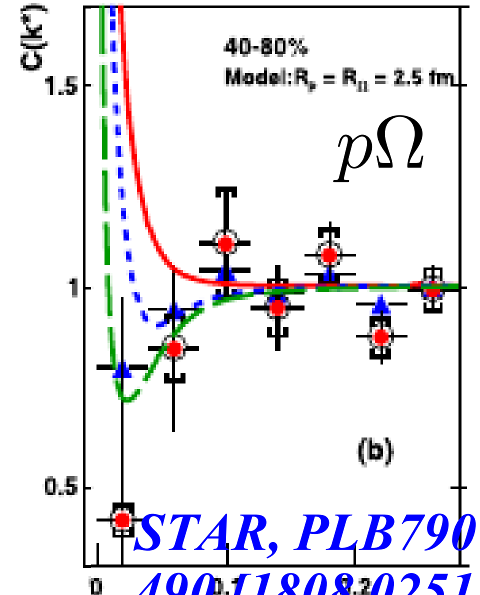
$$C(\boldsymbol{q})=1+\int d\boldsymbol{r}S(r)\left\{|\varphi_0(r)|^2-|j_0(qr)|^2\right\}\quad(\varphi_0=\text{s-wave w.f.})$$

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

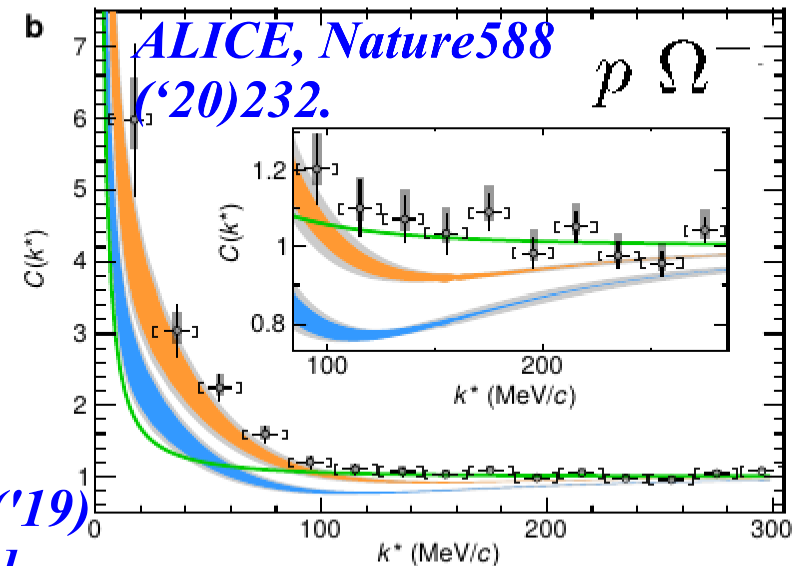
Measured Correlation Functions (examples)



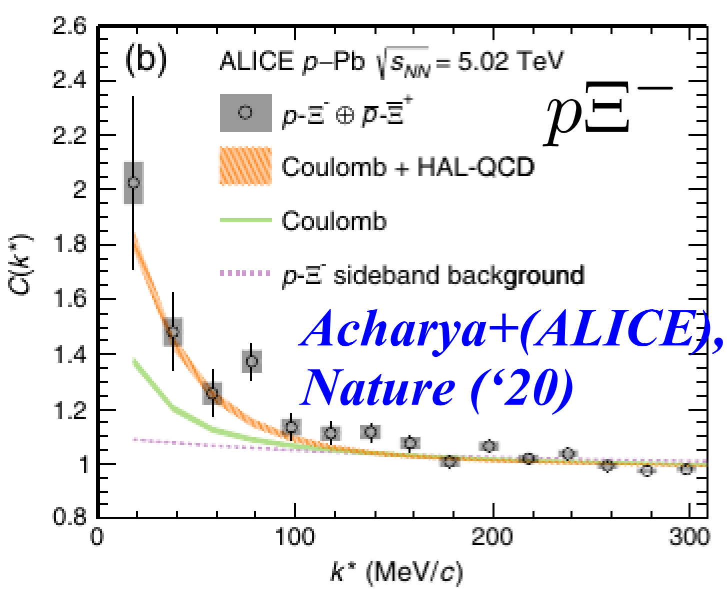
Adamczyk+[STAR], PRL114('15)022301



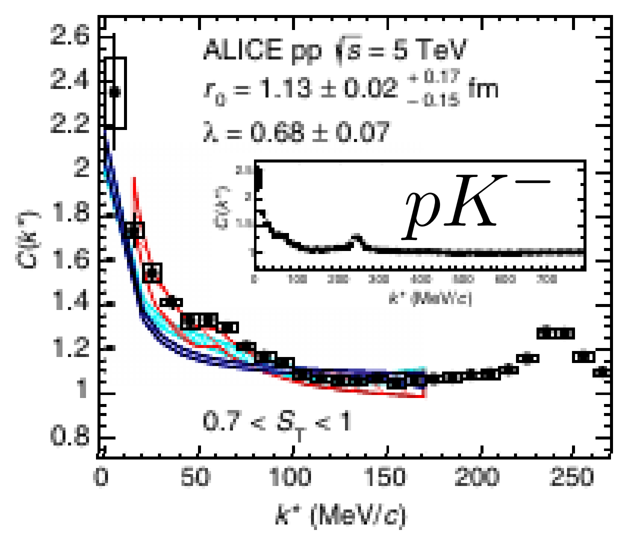
STAR, PLB790 ('19) 490 [1808.02511].



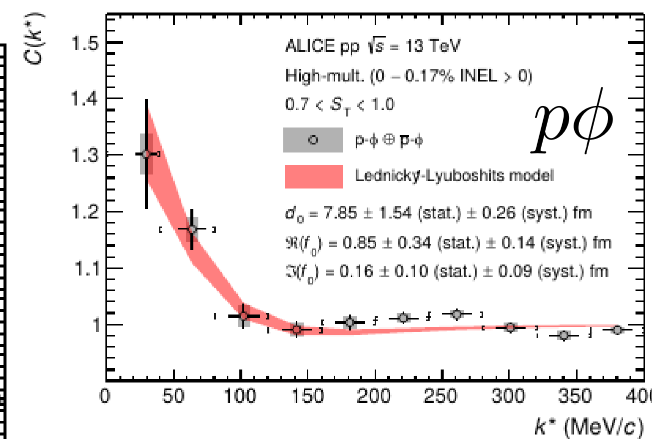
ALICE, Nature588 ('20)232.



Acharya+(ALICE), Nature ('20)



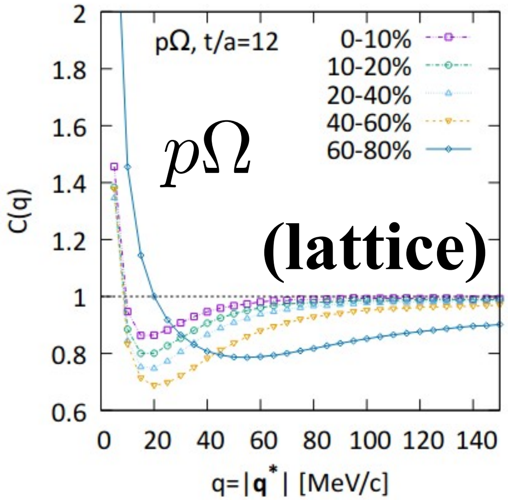
S. Acharya+[ALICE], PRL124('20)092301



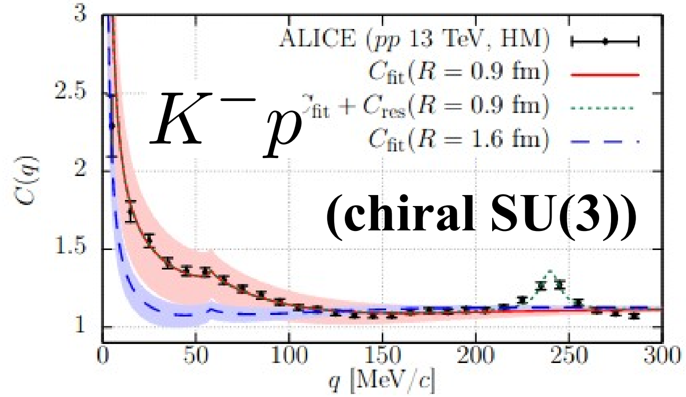
ALICE, 2105.05578

c.f. talk by V. Mantovani Sarti, F. Grosa, N. Agrawal

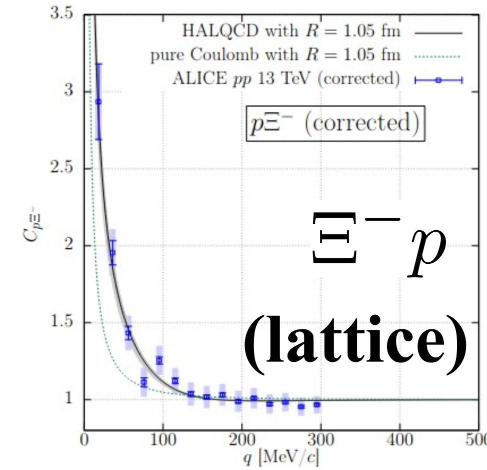
Theoretical femtoscopic study of hh int. (examples)



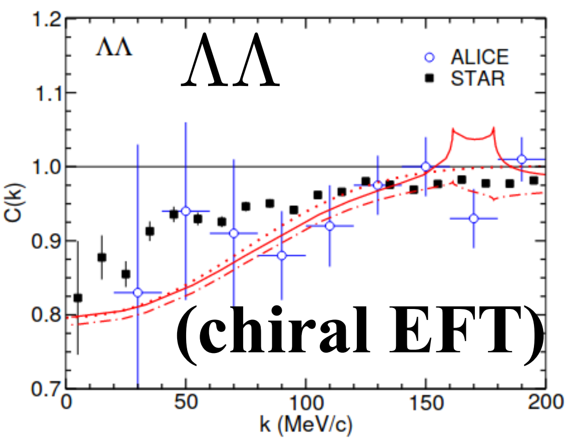
Morita, Gongyo et al., (1908.05414),
Morita, AO, Etminan, Hatsuda (1605.06765)



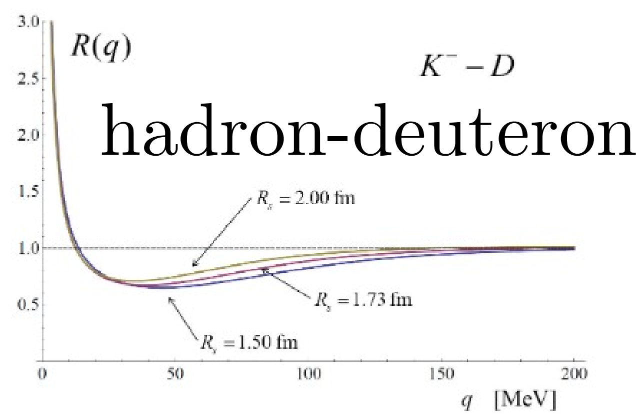
Kamiya+(1911.01041)



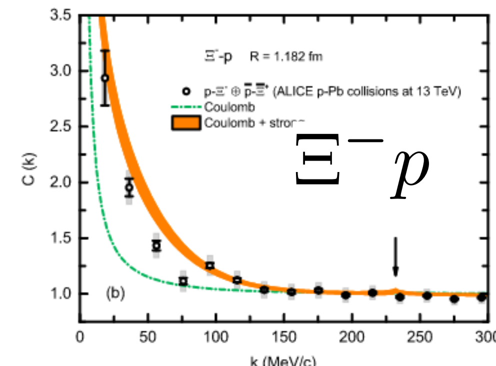
Y.Kamiya, K.Sasaki, et al., (2108.09644)



Haidenbauer(1808.05049), Morita+(1408.6682)



Mrówczyński, Słón (1904.08320, K⁻d), Haidenbauer (2005.05012, Λd), Etminan, Firoozabadi (1908.11484, Ωd), K.Ogata+ (Ξ⁻ d,2103.00100)



(covariant χEFT, S=-2)

Z.-W. Liu, K.-W. Li, L.-S. Geng (2201.04997)

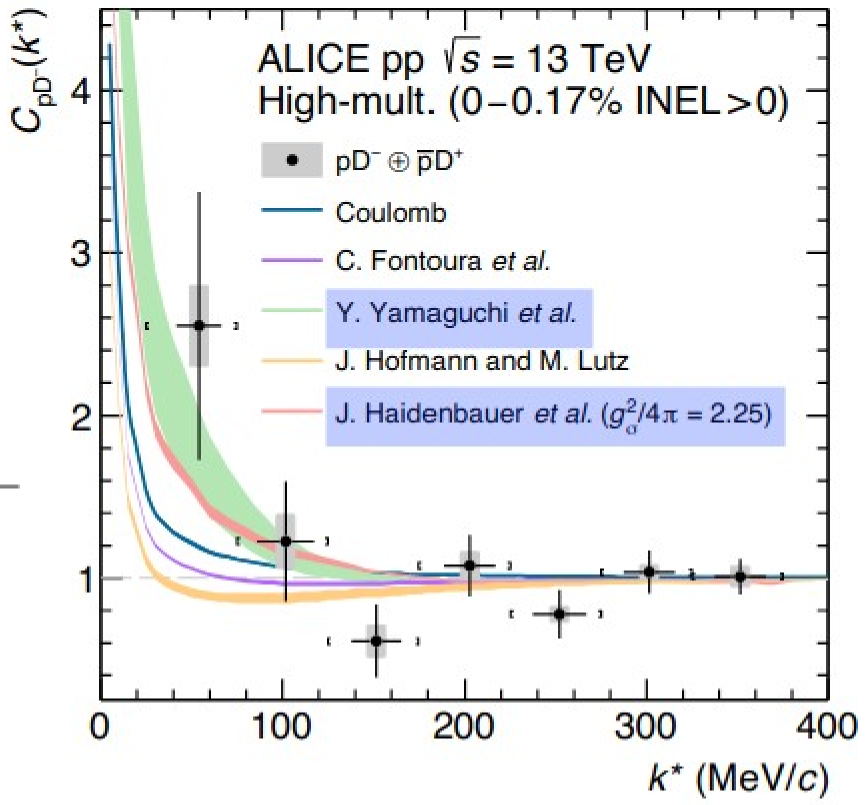
Femtoscopic study of charmed hadron int.(1)

- **"First study of the two-body scattering involving charm hadrons"**

  Acharya+[ALICE] (2201.05352)

  - **D^- p corr. func. is measured.**
  - **Enhanced CF from Coulomb.**
  - **One range gaussian potential with strength fitted to the I=0 scattering length of the model → attractive potentials are favored**

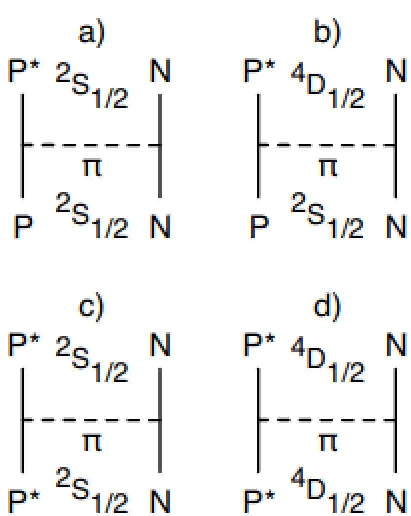
Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
Coulomb			(1.1–1.5)
Haidenbauer et al. [21]			
– $g_\sigma^2/4\pi = 1$	0.14	−0.28	(1.2–1.5)
– $g_\sigma^2/4\pi = 2.25$	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [22]	−0.16	−0.26	(1.3–1.6)
Yamaguchi et al. [24]	−4.38	−0.07	(0.6–1.1)
Fontoura et al. [23]	0.16	−0.25	(1.1–1.5)



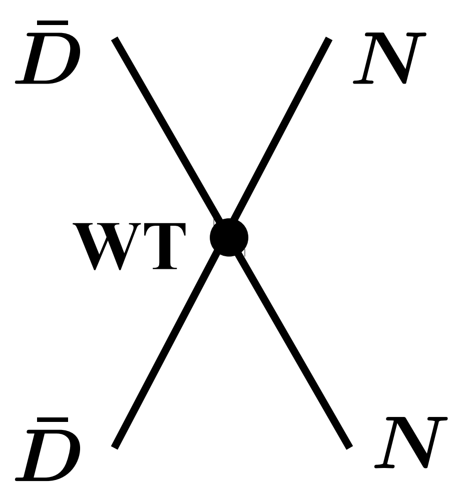
[21] Haidenbauer+(0704.3668) (weakly / mildly attractive (I=0))
[22] Hofmann, Lutz (hep-ph/0507071) (repulsive (I=0))
[23] Fontoura+(1208.4058) (weakly attractive (I=0))
[24] Yamaguchi, Ohkoda, Yasui, Hosaka (1105.0734) (att., w/ bound state (I=0))

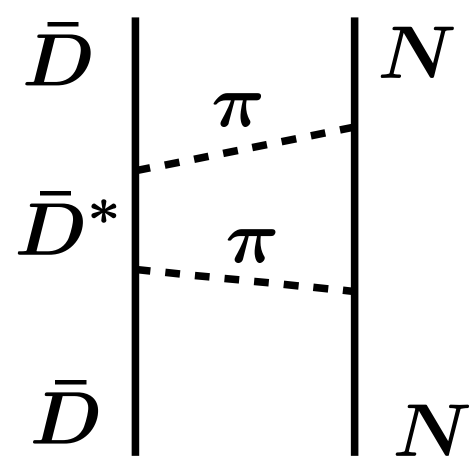
Pion Exchange in D⁻ p

- Chiral Effective Field Theory (EFT) の主要項 (leading order terms) は vector 相互作用 (Weinberg-Tomozawa) であり、係数・強度がチャネルにより決まっている。
  exotic channel ではほぼ斥力。$D^- p = (\bar{c}d)(uud)$
  T. Hyodo, D. Jido, A. Hosaka (PRL('06), hep-ph/0609014)
- クォーク質量が重いとき、 pseudoscalar meson (0⁻) と vector meson (1⁻) の間の質量が近くなる。→ pion exchange が影響を持つ。
  S. Yasui, K. Sudoh (0906.1452)



Yasui, Sudoh ('09)





To be bound or not to be bound

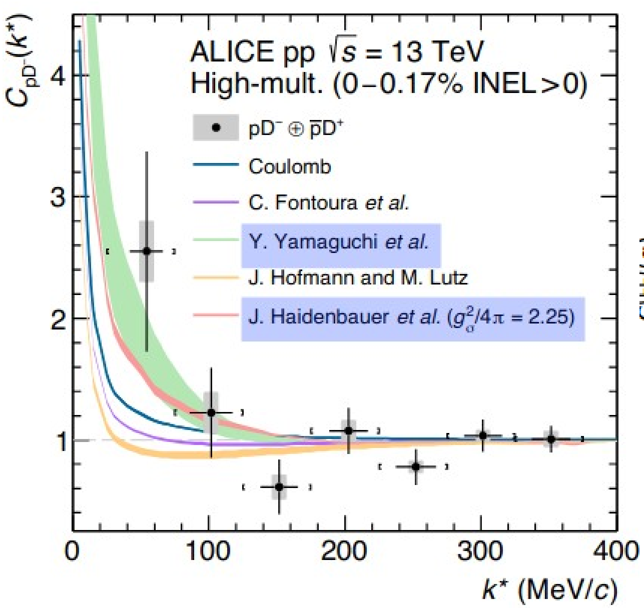
- **When there is a bound state, CF shows interesting dependence on the source size and relative momentum.**
- **D^- p corr. func. shows the behavior with a bound state, and the best fit parameter set (R, a_0) is in the bound region. (If bound, it is the first weakly decaying pentaquark state.)**

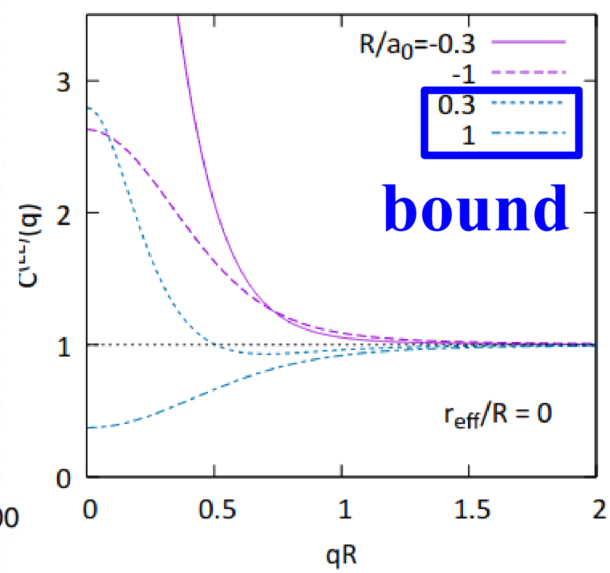
$$k\,\cot\delta = -\frac{1}{a_0} + \frac{1}{2} r_{\rm eff} k^2 + \mathcal{O}(k^3)$$

(Nuclear and atomic phys. convention.)

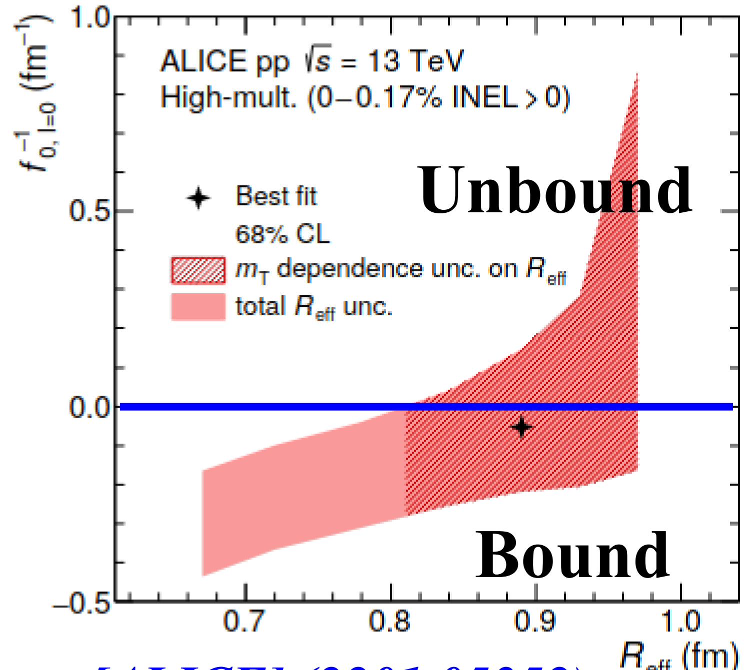
$$k\,\cot\delta = +\frac{1}{f_0} + \frac{1}{2} r_{\rm eff} k^2 + \mathcal{O}(k^3)$$

(High-E. phys. convention.)





Morita+(1908.05414)



[ALICE] (2201.05352)

Femtoscopic diagnosis of bound state existence

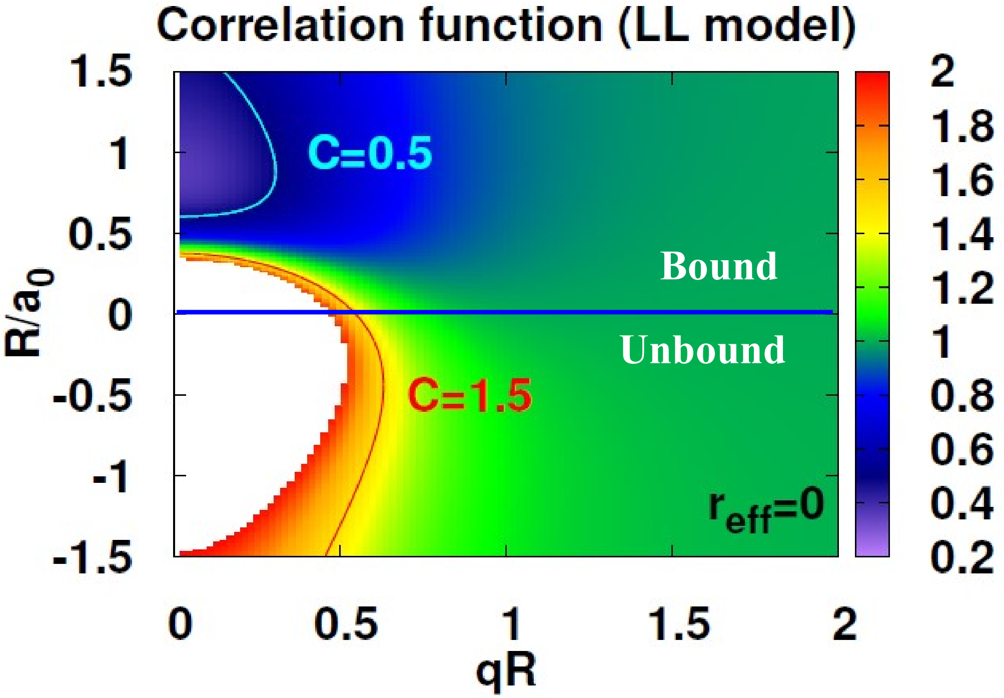
- **Lednicky-Lyuboshits model with zero effective range**
  → CF = C(qR, R/a_0)

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

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

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

- **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)

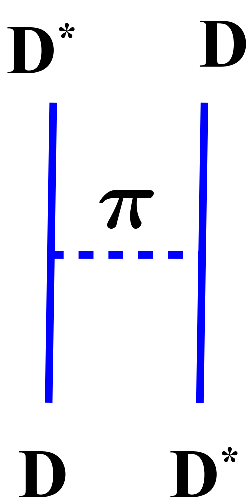
Femtoscopic study of charmed hadron int. (2)

- DD^* and $D\bar{D}^*$ **correlation functions.** *Kamiya, Hyodo, AO, in prep.*
  - **Related with Tcc and X(3872)**
  - DD^* and $D\bar{D}^*$ **interactions**

$$V = \frac{1}{2}\begin{pmatrix} V_{I=0}+V_{I=1} & V_{I=0}-V_{I=1} \\ V_{I=0}-V_{I=1} & V_{I=0}+V_{I=1} \end{pmatrix}$$

  - **I=0: One range gaussian, strength fitted to the mass**
  - **I=1: ignored**
  - **Range = one pion exchange** *Yasui, Sudoh (0906.1452)*
  - **Strength is fitted to the pole mass.**

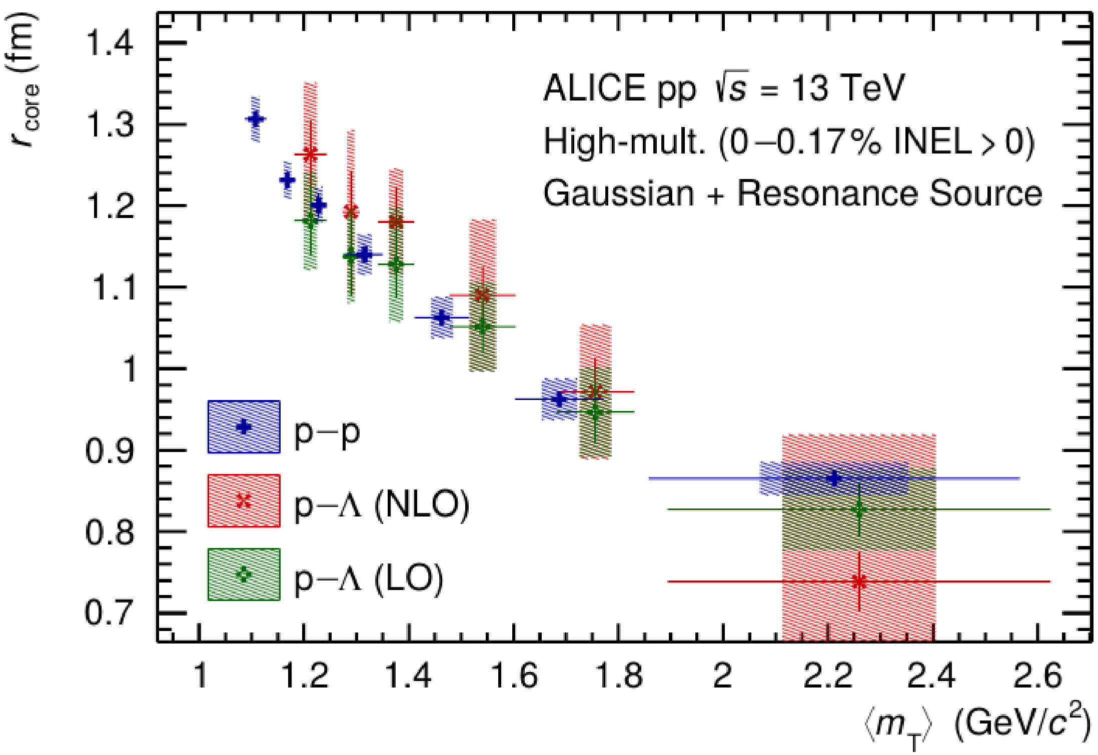
$$\{D^0\bar{D}^{*0}\} = (D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2}\ (C=+1)$$
$$\{D^+D^{*-}\} = (D^+D^{*-} + D^- D^{*+})/\sqrt{2}\ (C=+1)$$



DD^*	V_0 [MeV]	$a_0^{D^0 D^{*+}}$ [fm]	$a_0^{D^+ D^{*0}}$ [fm]
	$-36.569 - i1.243$	$-7.16 + i1.85$	$-1.75 + i1.82$
$\{D\bar{D}^*\}$	V_0 [MeV]	$a_0^{\{D^0 \bar{D}^{*0}\}}$ [fm]	$a_0^{\{D^+ D^{*-}\}}$ [fm]
	$-43.265 - i6.091$	$-4.23 + i3.95$	$-0.41 + i1.47$

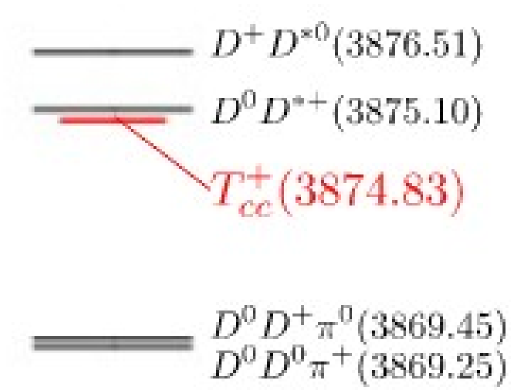
We are sorry, but we use a Gaussian Source !

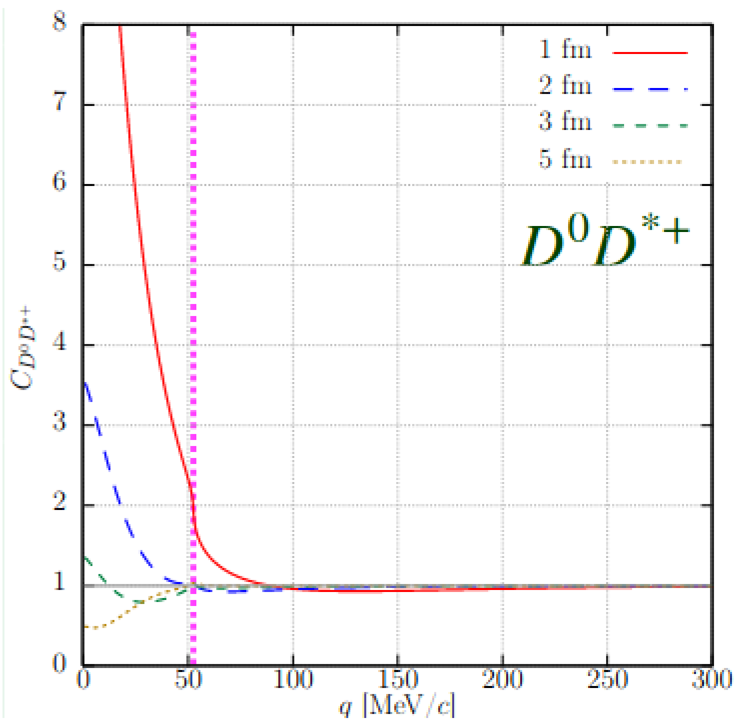
- **Calculating HBT radius in dynamical models is not easy**
  M.A.Lisa, S.Pratt, R.Soltz, U.Wiedemann, Ann.Rev.Nucl.Part.Sci.55('05)357 [nucl-ex/0505014]; S. Pratt, PRL102('09)232301 [0811.3363].
- **and a Gaussian source seems to work at the current precision of hh interaction studies.**
  S. Acharya+[ALICE], PLB811('20)135849.
  - **primary (universal ?)+ decay of short-lived resonances ~ eff. Gaussian**
  - **Flow and source geometry effects are seen in CF, but the uncertainty of hh int. is the largest.**

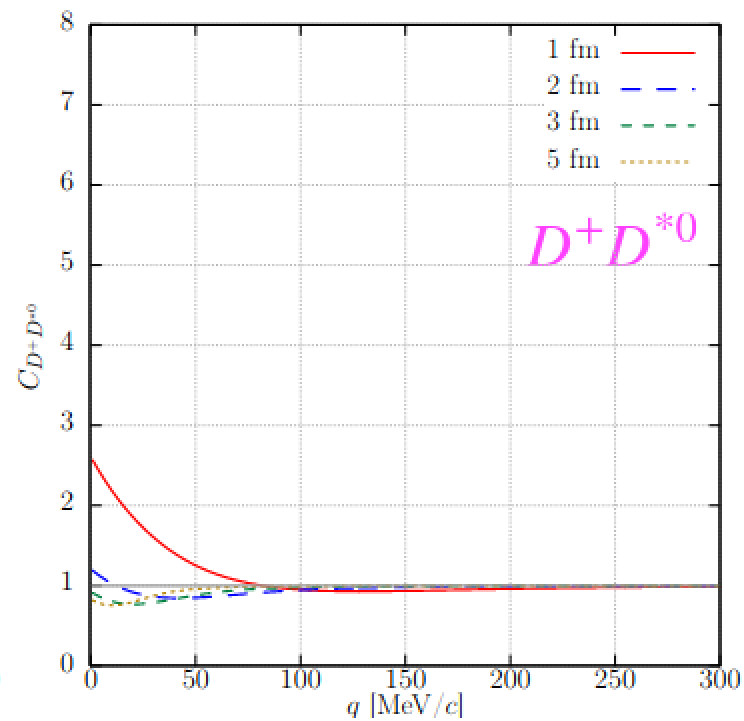


$D^0 D^{*+}$ and $D^+ D^{*0}$ Correlation Functions

- **For small source (R= 1 fm)**
  C(q) > 8 for the lower channel (D^0D^{*+}) (Very strong)
  C(q) ~ 2.5 for upper channel (D^+D^{*0}) (strong)
- **For large source (R=5 fm), CF show a dip**
- **Strong enhancement for small source, dip for large source**
  → Characteristic dependence with a bound state (Tcc)
- **Cusp is not significant**

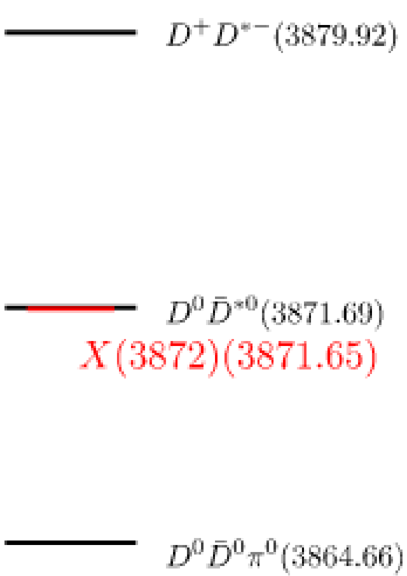


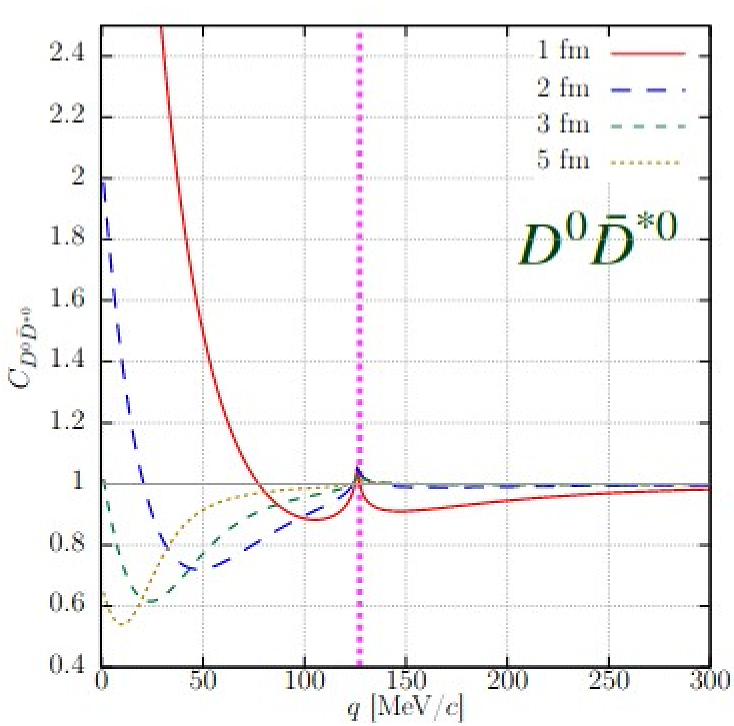


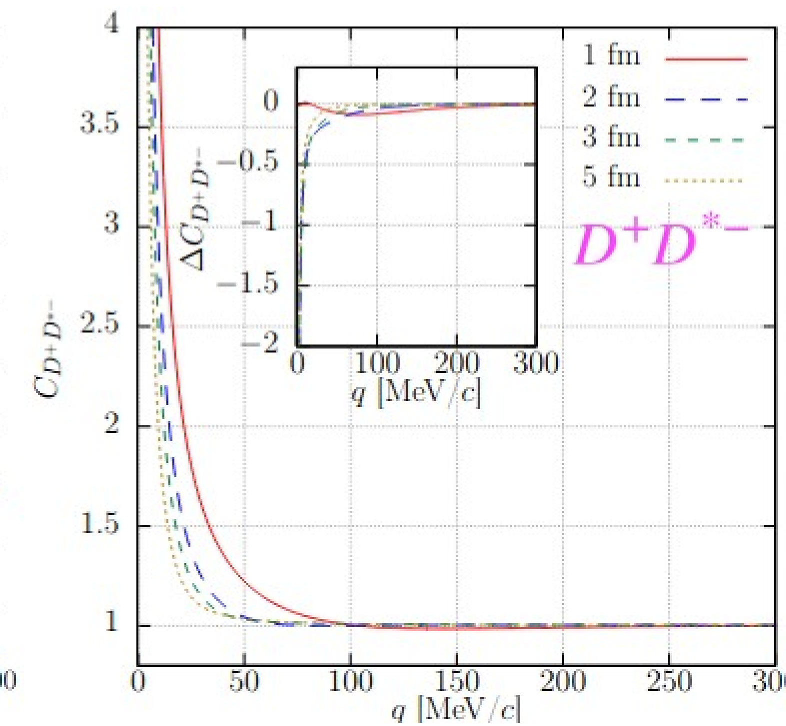


$D^0\bar{D}^{*0}$ and D^+D^{*-} Correlation Functions

- $C(D^0\bar{D}^{*0})$: Strong enh. for small source, dip for large source
  $\rightarrow$ Characteristic dependence with a bound state (X(3872))
- $C(D^+D^{*-})$: Coulomb dominant
- Cusp may be observed for small size







Tcc and X(3872) structure

- **Hadronic molecule structure is assumed**
  → Eigenmomentum $k \simeq -i/a_0\,,\ a_0 \simeq R = 1/\sqrt{2\mu B}$
- **What happens when multiquark state mixes ?**
  → Deviation from weak binding relation
  Weinberg, Phys. Rev. 137, B672 (1965), Hyodo, Jido, Hosaka (1108.5524), Kunigawa, Hyodo (2112.00249)

$$a_0 = R\left[\frac{2X}{1+X}\right] + \mathcal{O}(R_{\rm typ})$$

$$\left[R_{\rm typ} = \max(m_\pi^{-1}, r_{\rm eff}), R = 1/\sqrt{2\mu B}\right]$$

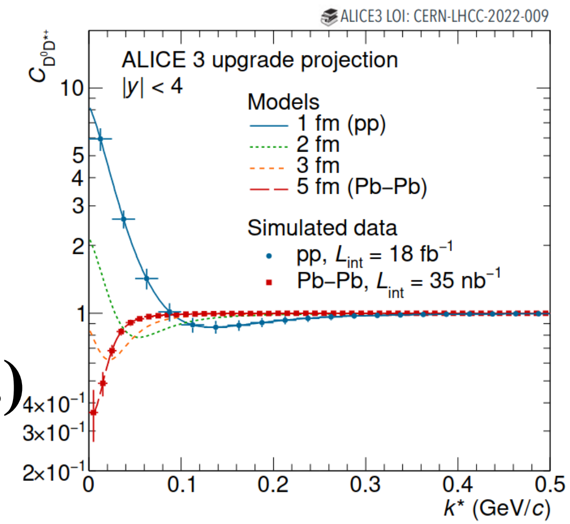
  - **Smaller scattering length in DD* may signal the *genuine* tetraquark nature of Tcc.**

$$f = \frac{1}{k\cot\delta - ik} \simeq \frac{1}{1/a_0 - ik}$$

(High-energy phys. convention)

Short Summary

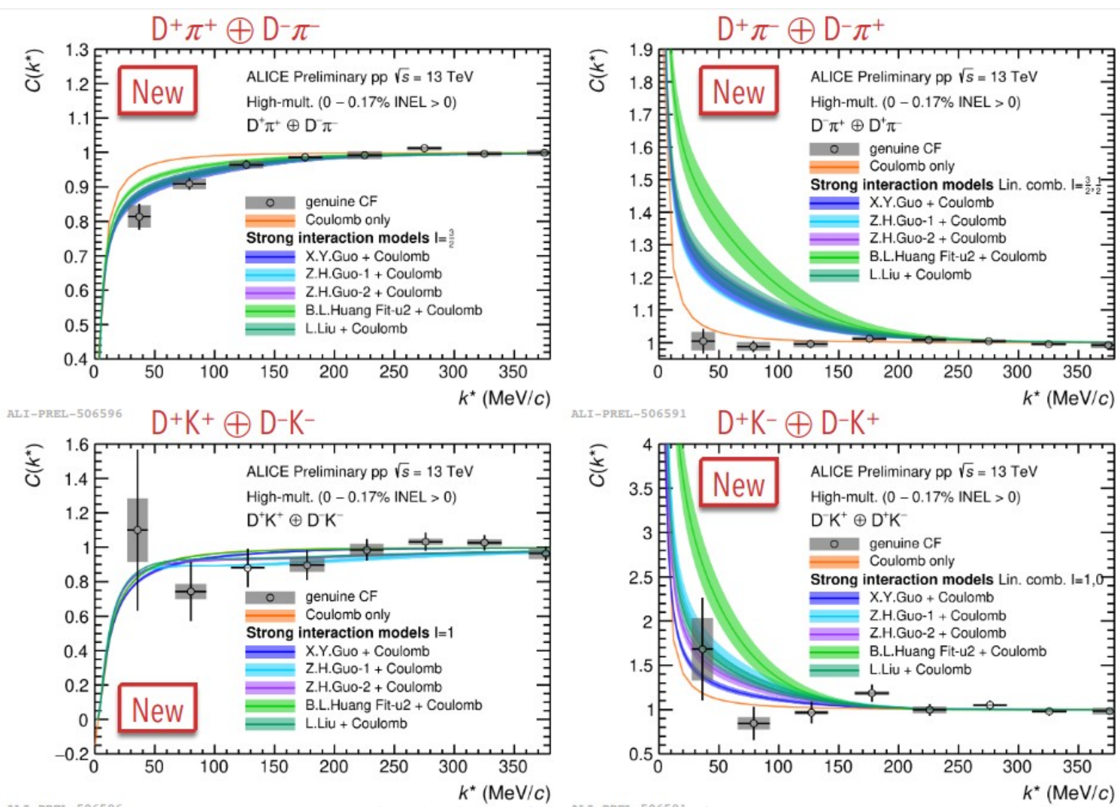
- Two-particle correlation functions are useful to deduce
  - Scattering length
  - Existence of a bound state
  - and hopefully the compositeness
- Charm hadron interactions are within the reach.
  - D^-p correlation function has been measured, and the data favor attractive interaction. *ALICE (2201.05352)*
  - DD^* and $D\bar{D}^*$ correlation functions are predicted to reflect the existence of bound states (Tcc and X(3872)) by using simple potentials fitting to the mass and width. *Y. Kamiya, T. Hyodo, AO (2203.13814)*
  - Precise measurement of the correlation function will constrain the scattering length, which may tell us the structure of exotic hadrons. (Letter of Intent is submitted to measure DD^* and $D\bar{D}^*$ correlation functions in ALICE3.)



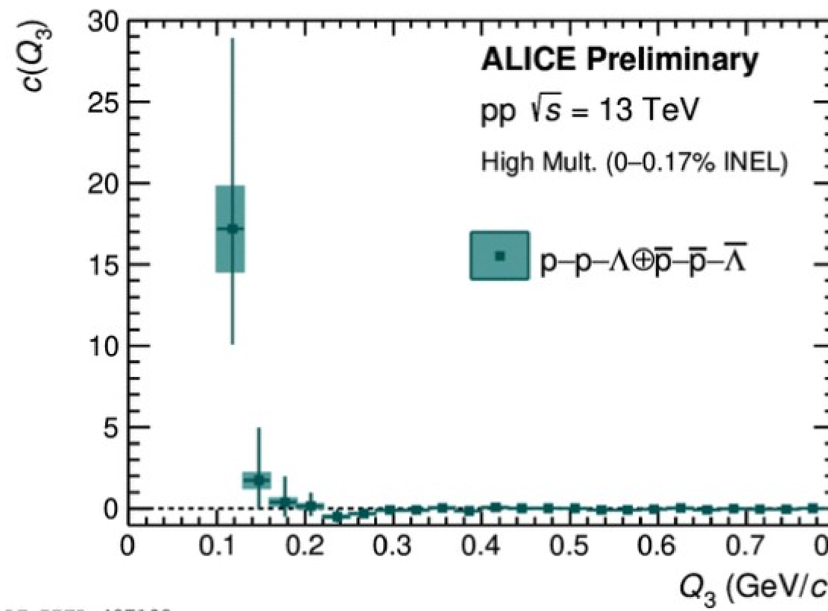
H. S. Scheid @ QM2022

ALICE からの宿題

- カイラル模型で合わない相関関数は何を意味するのか？
  - C(D+π−) が模型計算より斥力的 → puzzle
  - C(D^+K^-) が模型計算より引力的 → σ 交換？(higher-order in chiEFT)
- 3 体相関関数から 3 体力は引き出せるか？
  - Born では (多分) 足りない。 3 体波動関数を解く必要あり。



Fabrizio Grosa@QM2022

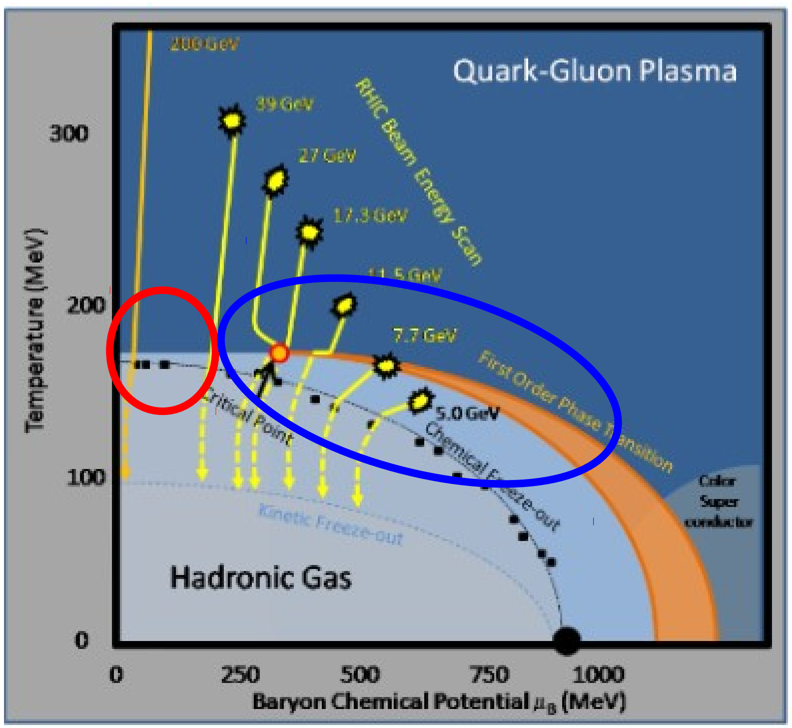


Raffaele Del Grande @QM2022

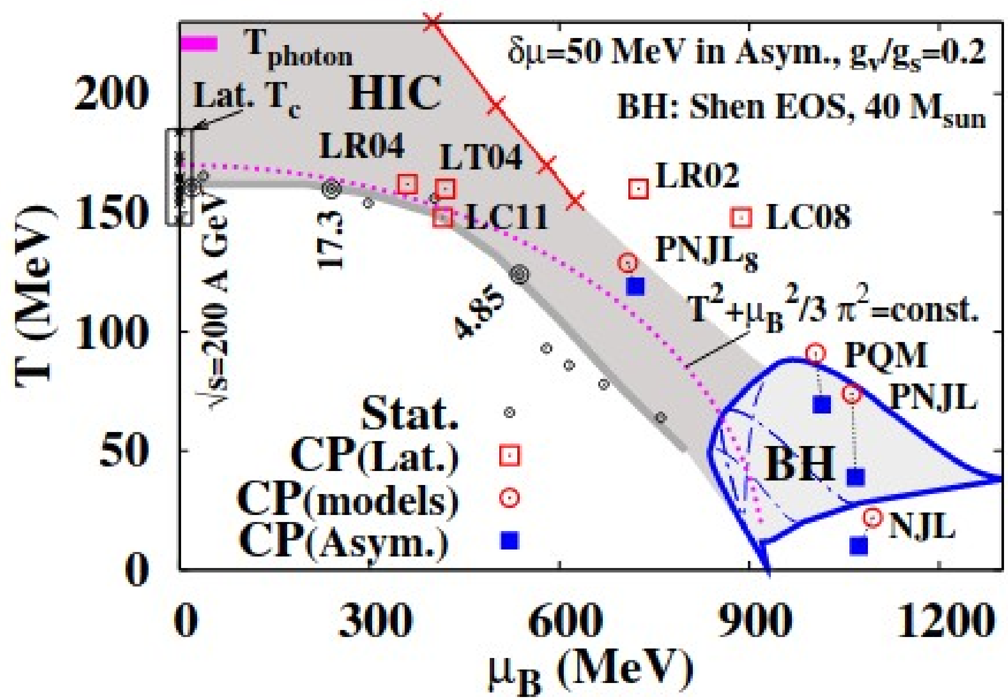
Dense Baryonic Matter EOS from Collective Flow in HIC & Onset energy of QGP

Main Goals of Heavy-Ion Physics

- **Study of QGP and its properties (EOS, viscosity, constituents, …)**
- **Study of QCD phase diagram (phase boundary and critical point)**
- **Study of physics of matter under extreme conditions (dense hadronic matter, matter with strong vorticity and magnetic field)**



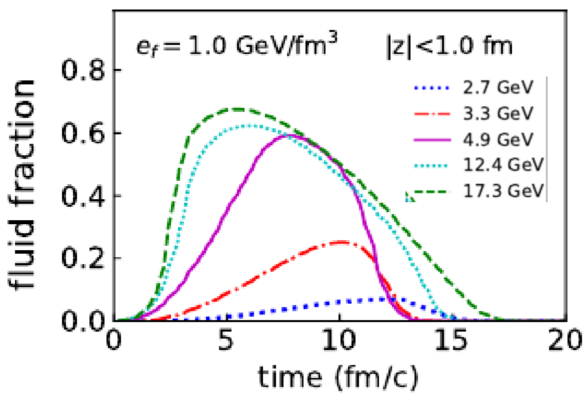
STAR (1007.2613)



AO (1112.3210)

Onset Beam Energy of (bulk) QGP formation

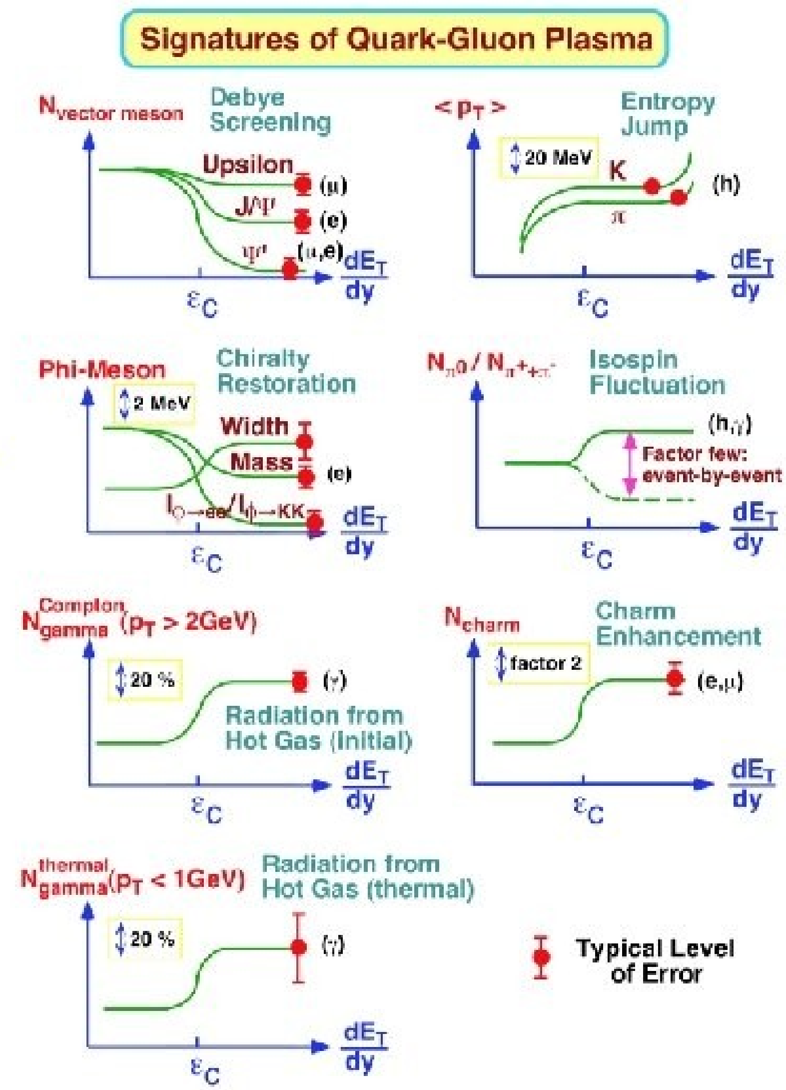
- **Nagamiya Plot**
  - **Simultaneous change of many signals**
  - **Finite volume smears sharp signal of 1st ord. p.t. even if it exists.**
    → Gradual increase of QGP fraction ?



Hadronic fluid or QGP ?

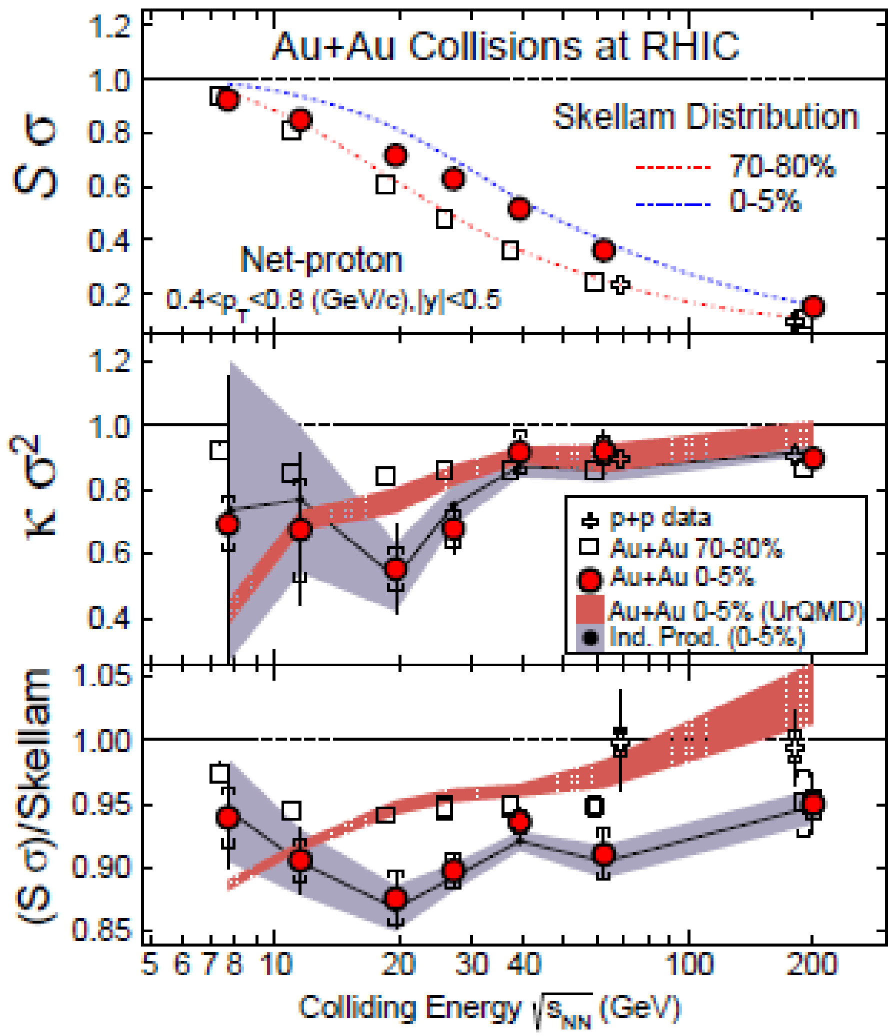
Y.Akamatsu, M.Asakawa, T.Hirano, M.Kitazawa, K.Morita, K.Murase, Y.Nara, C.Nonaka, AO, PRC98('18)024909.

- **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.

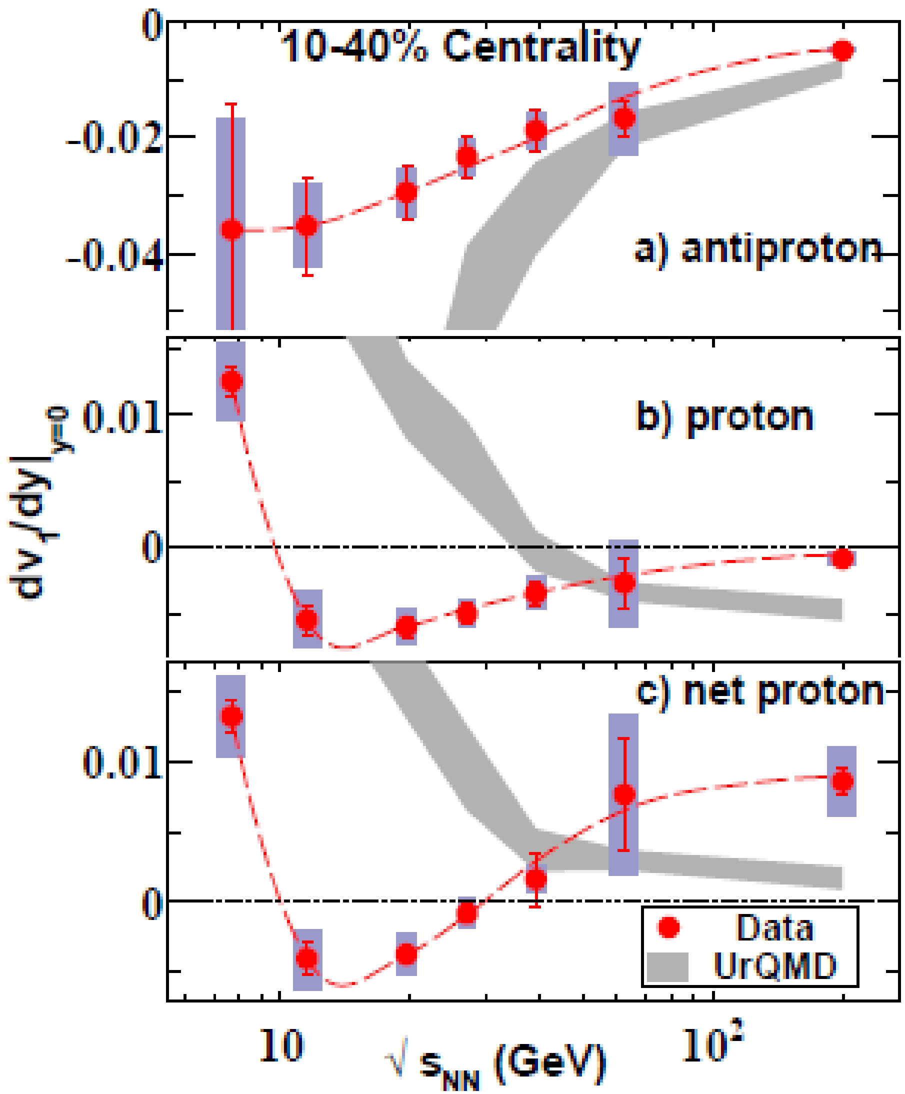


Taken from S. Nagamiya's Talk @ RIKEN, 2013/08/02

Net-Proton Number Cumulants & Directed Flow



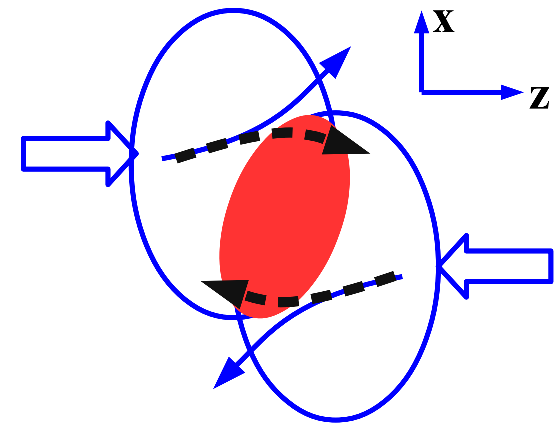
STAR, PRL 112('14)032302

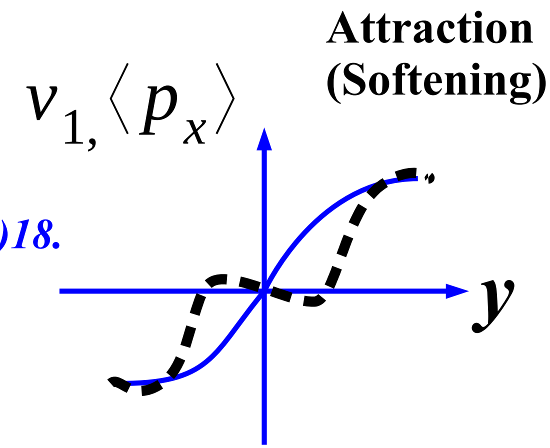


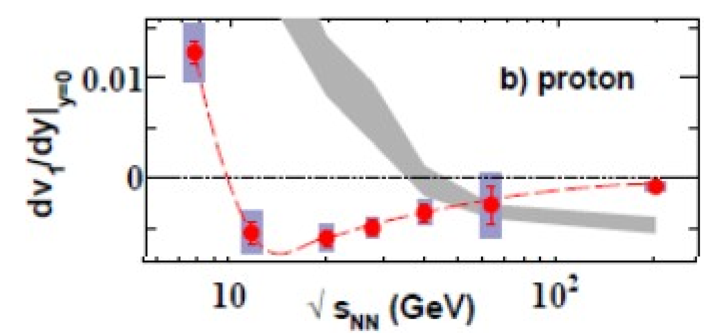
STAR, PRL 112('14)162301.

Non-Monotonic Beam E. dep. of v_1 slope

- **Directed flow (v_1 or $\langle p_x \rangle$) 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**



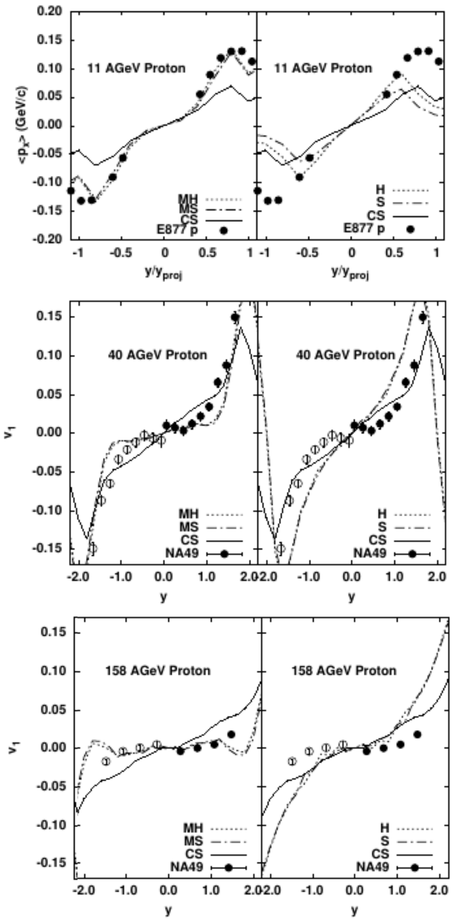




STAR, PRL112('14)162301

Past tries

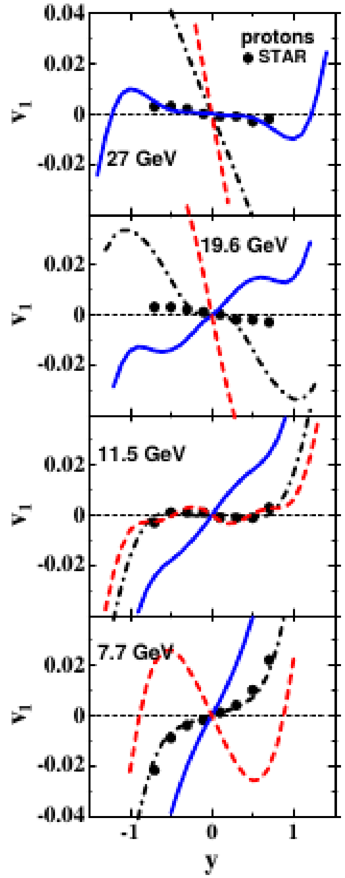
JAM-RQMD



p-dep. p-indep.

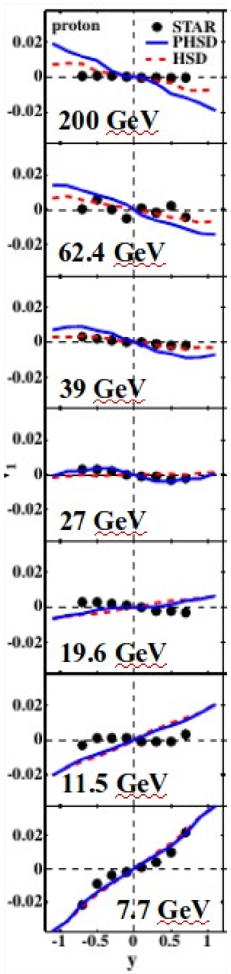
M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72('05)064908 (There was a mistake...)

3FD



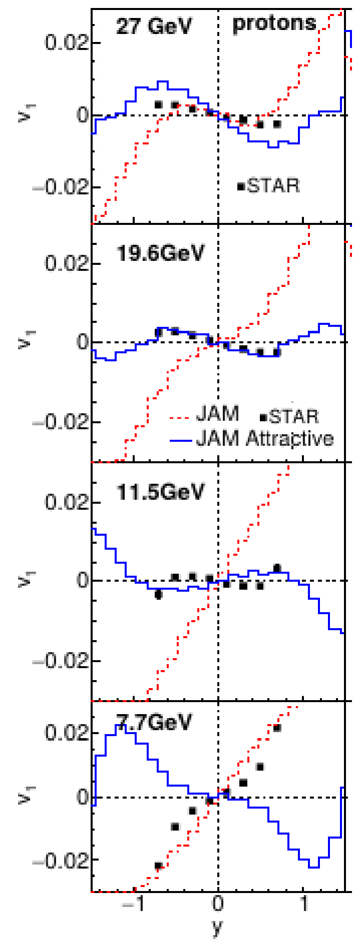
Y.B.Ivanov, A.A.Soldatov, PRC91('15) 024915

HSD/PHSD



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

JAM+Att.



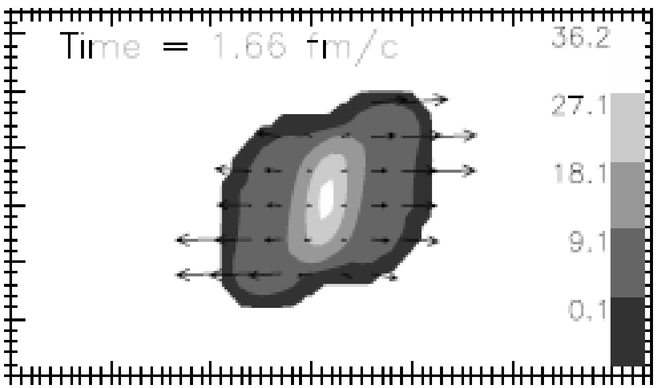
Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 ('16)034906

What happens ?

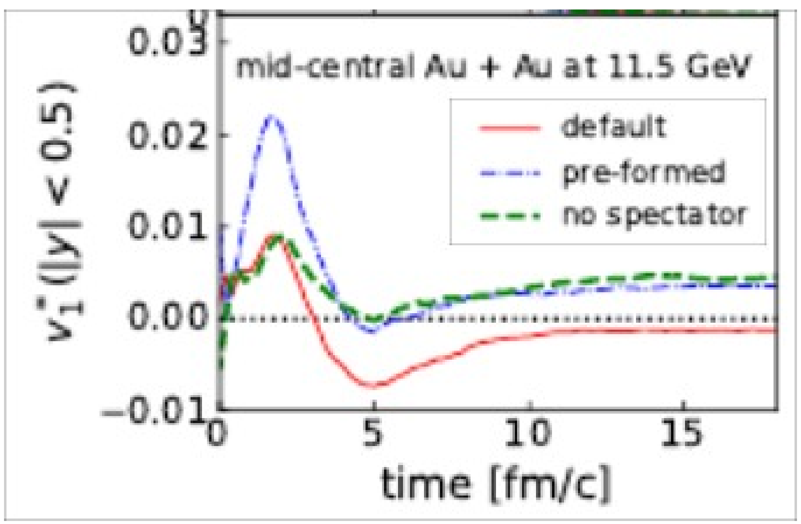
- Positive & Negative Flow の起源
  - 圧縮時の斥力 → positive flow ($dv_1/dy > 0$)
  - 膨張時の tilted matter → negative flow ($dv_1/dy < 0$)
- バランスエネルギー ($\sqrt{s_{NN}} \sim 10$ GeV) では
  EOS の軟化 or 初期・後期の釣り合いが起きているだろう。

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

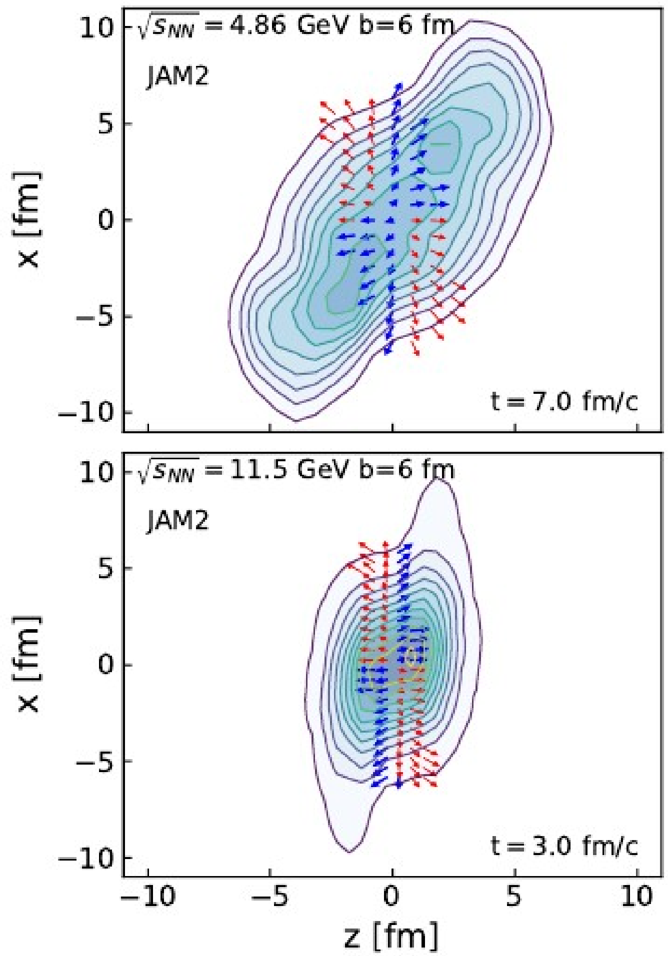
$$p_i^0 = \sqrt{\boldsymbol{p}_i^{*2} + m_i^2} + V_i^0 \to \frac{d\boldsymbol{r}_i}{dt} = \frac{\boldsymbol{p}_i^*}{p_i^{*0}} + \sum_j v_j^{*\mu}\frac{\partial V_{j\mu}}{\partial \boldsymbol{p}_i}\,,\quad \frac{d\boldsymbol{p}_i}{dt} = -\sum_j v_j^{*\mu}\frac{\partial V_{j\mu}}{\partial \boldsymbol{r}_i}$$

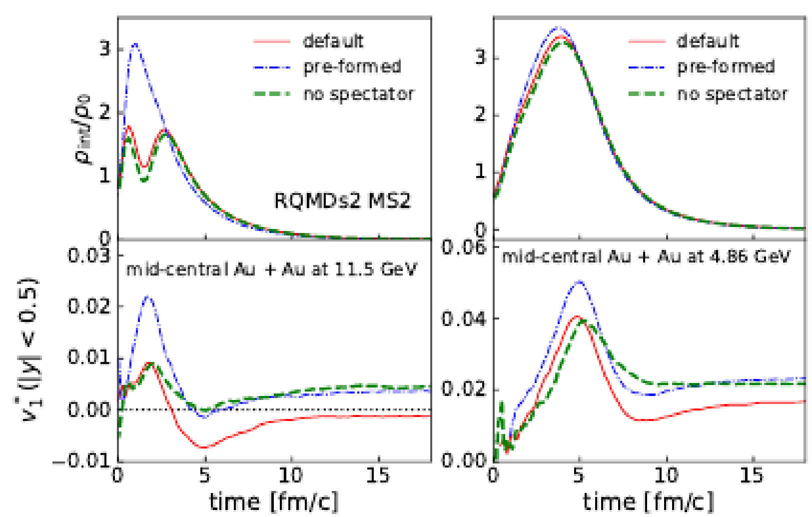
$$(p_j^{*\mu} = p_j^\mu - V_j^\mu\,,\ v_j^{*\mu} = p_j^{*\mu}/p_j^{*0})$$

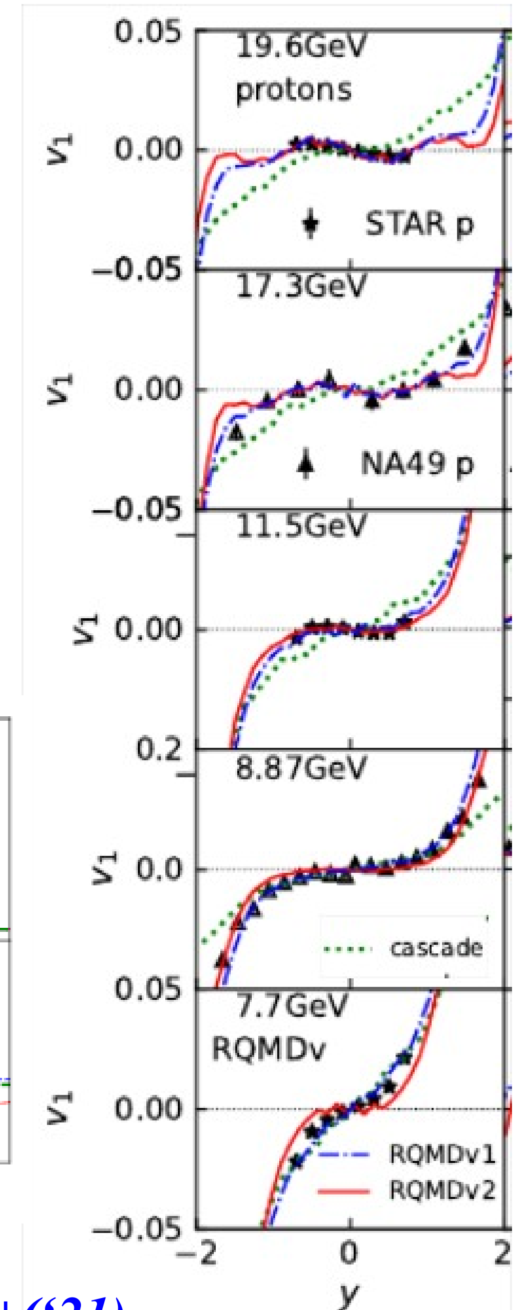
  - **Potential effect remains at high energy.**

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.**



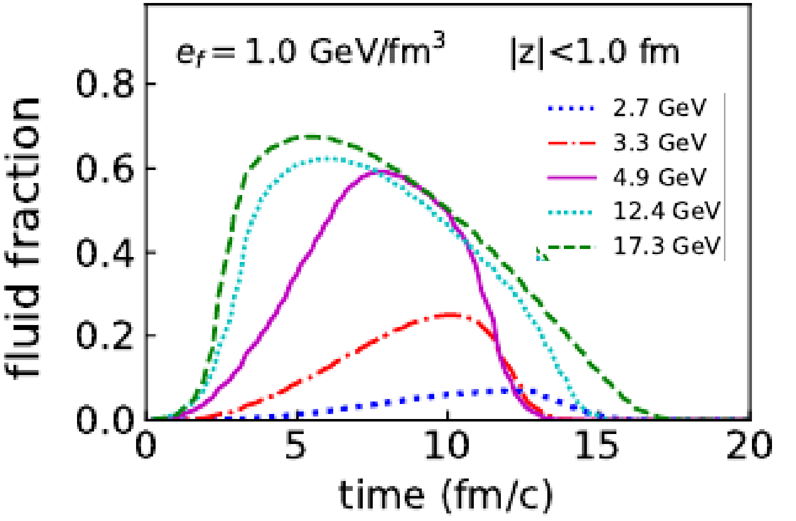




Nara+('21)

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。



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

Short Summary

- 有限密度 QCD 相転移の研究には、
  入射エネルギーの「非単調関数」が重要かも知れない。
  - 陽子数のゆらぎ (キュムラント) 、 Directed flow 。
- 陽子 directed flow slope の非単調性の起源は？
  - 高バリオン密度での状態方程式のソフト化
    → 前後のエネルギーでの振る舞いが説明出来ていない。
  - 高バリオン密度での強い斥力
    → 圧縮時・膨張時の正負の contributions の釣り合いが非単調性を生み出す
    Nara, AO, PRC105 (‘22), 014911 (2109.07594)
  - ハドロン生成量との一貫した理解は得られていない。
- Directed flow slope が強い斥力によるなら、他のハドロンでは？
  - 高密度での Λ の強い斥力ポテンシャルは、
    中性子星のハイペロンパズルを解く有力な候補。
    → Λ のフローは？ (神野くんの修論)

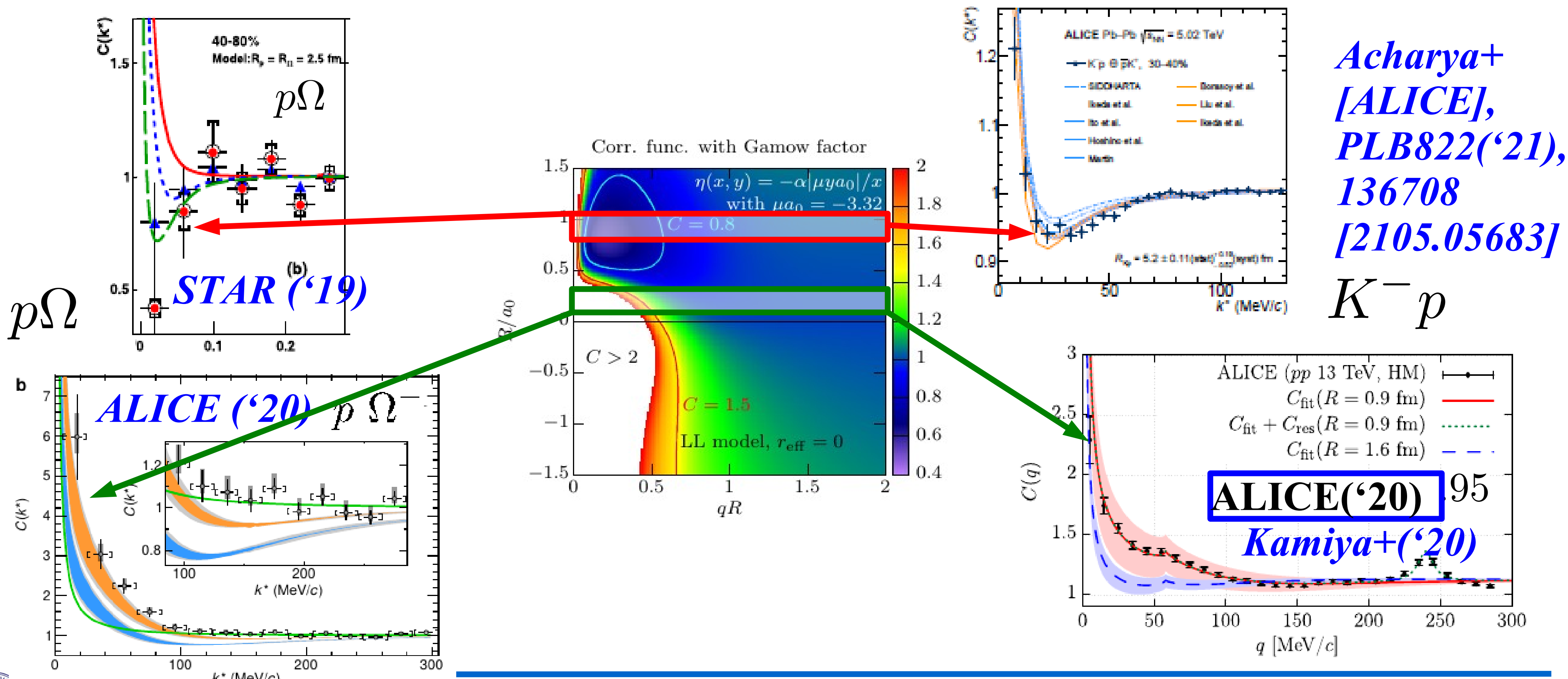
Summary

- 高エネルギー原子核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。
  - 重イオン衝突でのフローは高密度での状態方程式を探るヒントを与える。
- 相関関数を用いたハドロン間相互作用の研究
  - チャームクォークを含む相互作用も実験で探索可能になった。
  - 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を区別するヒント。
- Proton dv_1/dy puzzle
  - 入射エネルギーについての非単調性は一次相転移なしでも記述可能。
  - 実際の機構は未確定。
  - ハイペロンパズルの理解につながるか？

Thank you for your attention !

Hadronic molecules suggested by CFs

- **pΩ 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)**

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

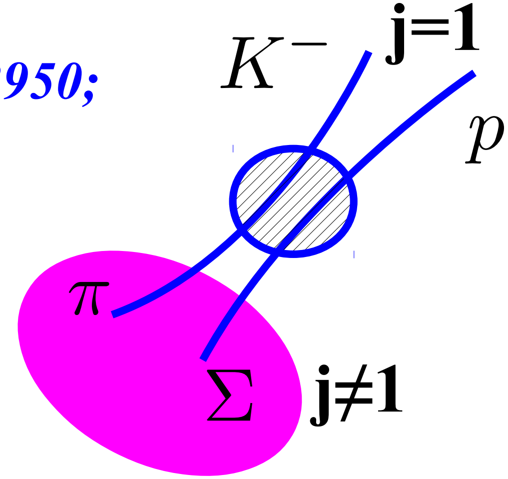
$$\psi_j^{(-)}(r) \to [\delta_{j1}\, e^{iq_j r} + A_j(q) e^{-iq_j r}]/2iq_j r \ \text{(No Coulomb case)}$$

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).

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



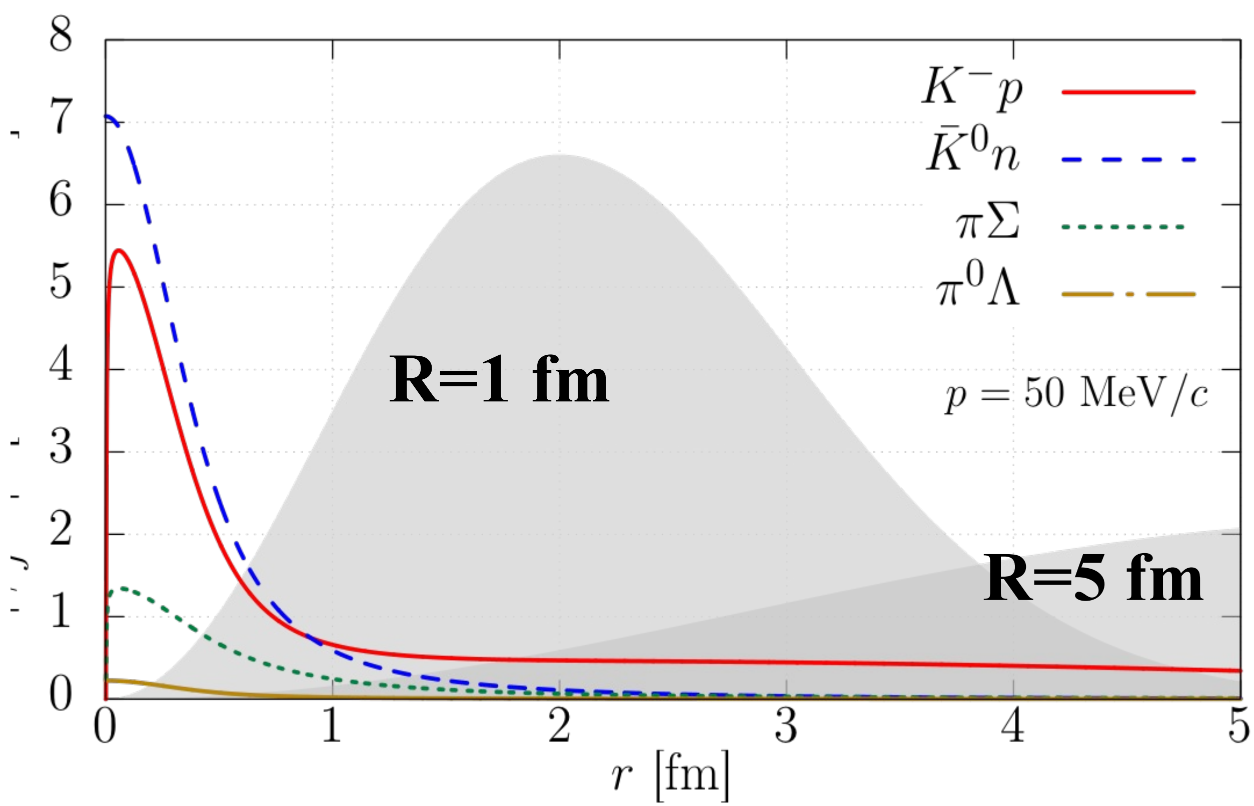
$$\omega_j S_j(r) |\psi_j^{(-)}(r;q)|^2$$

Source weight — Normalized Source fn.

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

Discriminating Coupled-Channel Effects

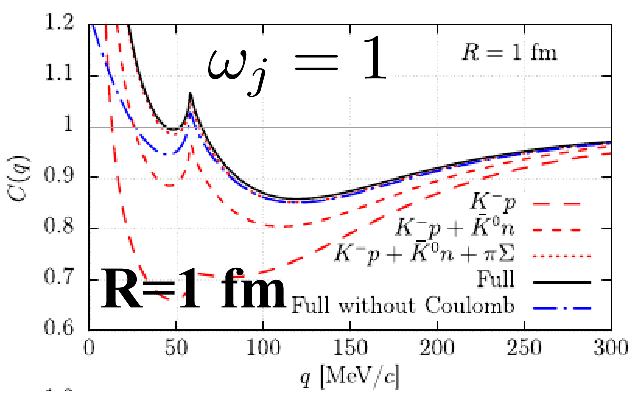
- **Source size dependence again !**
  - **Unmeasured coupled-channel wave functions disappear soon.**
    → CFs with large source is dominated
    by the measured channel wave function !
  - **Scattering parameters from CFs with large source**
    Coupled-channel effects from CFs with small source.

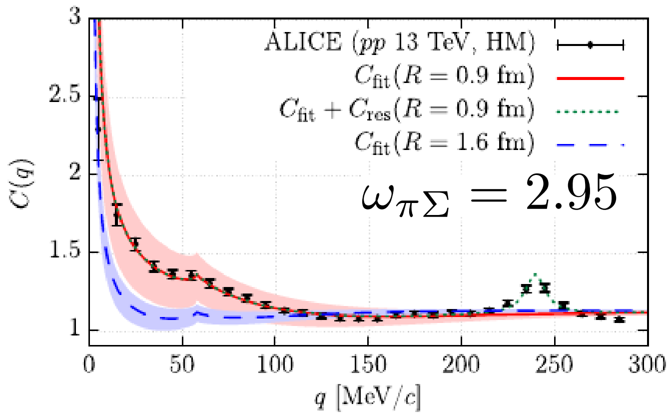


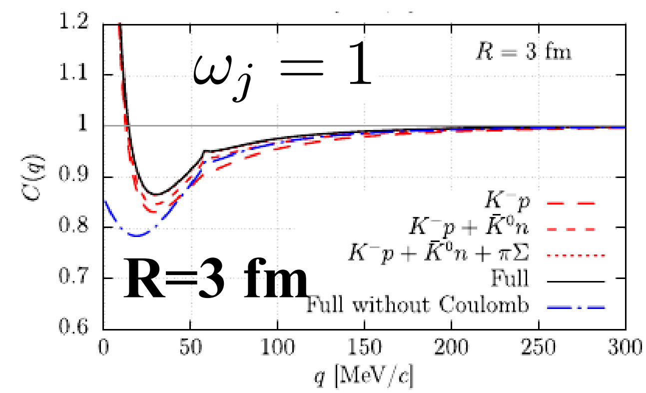
w.f. Kamiya+,arXiv:1911.01041v1

Source Size Dependence of C(K⁻p)

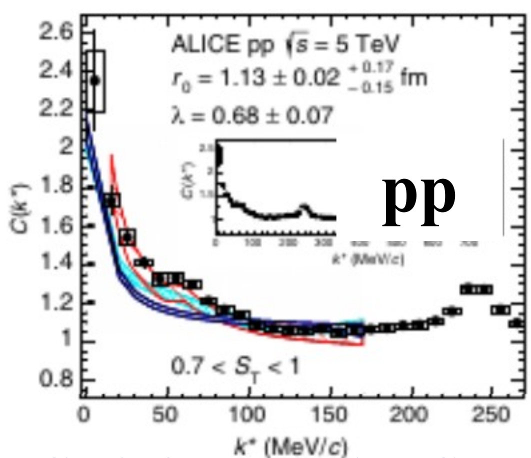
- **Coupled-channel effects are suppressed when R is large, and "pure" K⁻p wave function may be observed in HIC.**



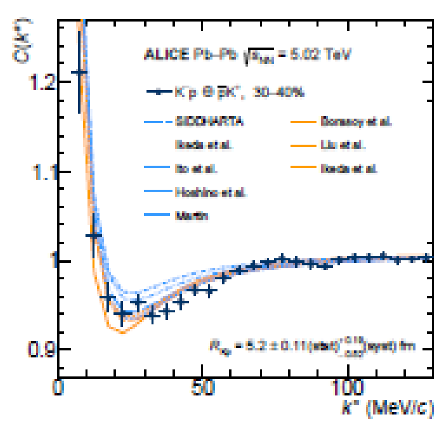




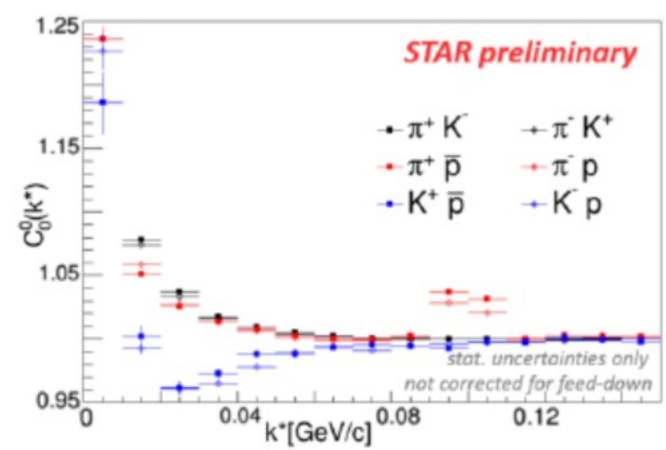
Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501.



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



S. Acharya+[ALICE], PLB822('21)136708



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

RHIC Heavy-ion Program

Main goals:

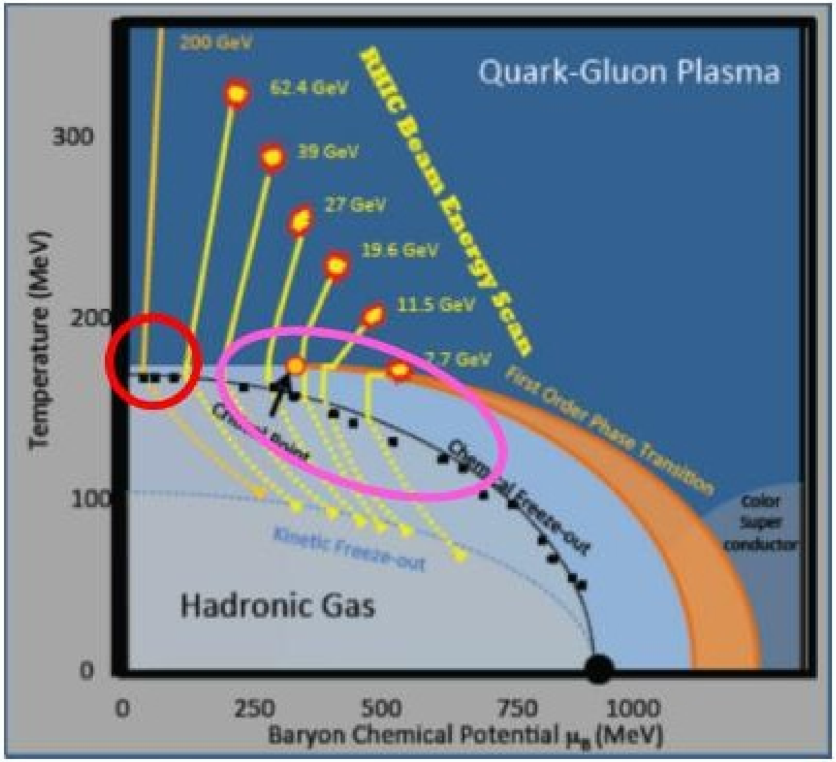
1. Study QGP and its properties:
   - Detailed studies for temperature, viscosity, and energy density

2. Study QCD phase diagram:
   - Search for the signals of possible phase boundary
   - 1st order phase transition
   - Search for the possible QCD Critical Point

   ⇨ **Beam Energy Scan**

STAR: Nucl. Phys. A 757, 102 (2005)

QCD Phase Diagram:



http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493: arXiv:1007.2613