有限温度・有限密度下における低質量レプトン対測定のこれまでとこれから

小沢恭一郎（KEK）

主に、カイラル対称性関連の話
有限密度の話が多め

WHICH IS IMPORTANT?
CRITICAL POINT OR CHIRAL RESTORATION?

Critical Point: Asakawa and Yazaki

Nuclear Physics **A504** (1989) 668–684
North-Holland, Amsterdam

CHIRAL RESTORATION AT FINITE DENSITY AND TEMPERATURE

Masayuki ASAKAWA and Koichi YAZAKI

Department of Physics, Faculty of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

Received 2 May 1988
(Revised 24 April 1989)

Abstract: We investigate the chiral symmetry breaking, its restoration and related quantities at finite density and temperature in the Nambu–Jona-Lasinio model. It is shown in the mean field approximation that a first-order transition exists at zero and low temperatures and that this transition can be identified as the chiral restoration.

Case of zero temperature and finite chemical potential

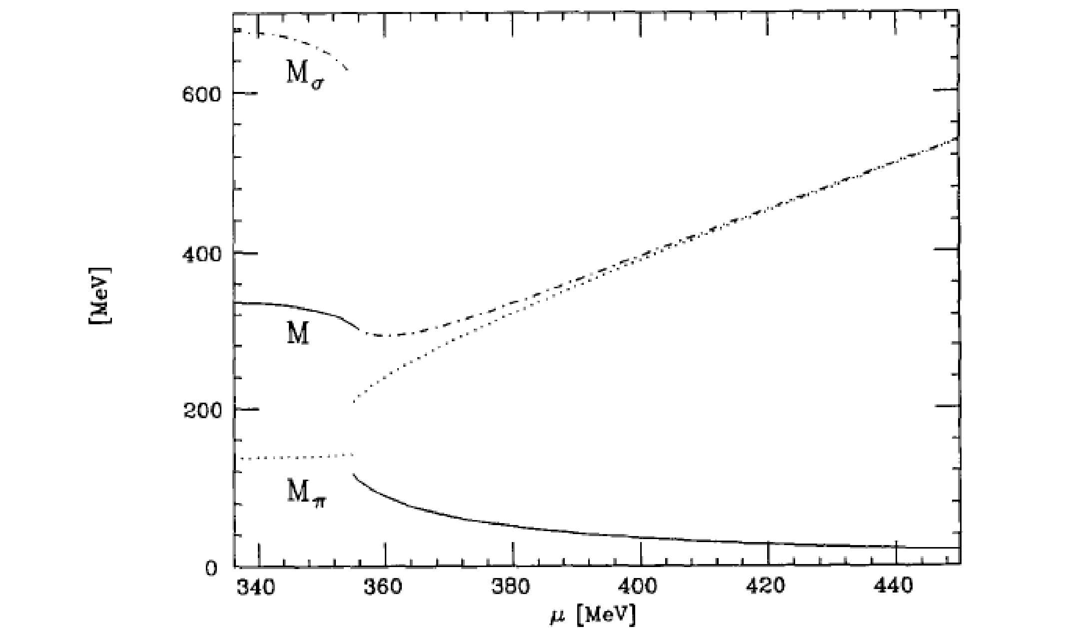


Fig. 4. The pion mass, the sigma mass and the effective quark mass at $T=0$ for the case (I).

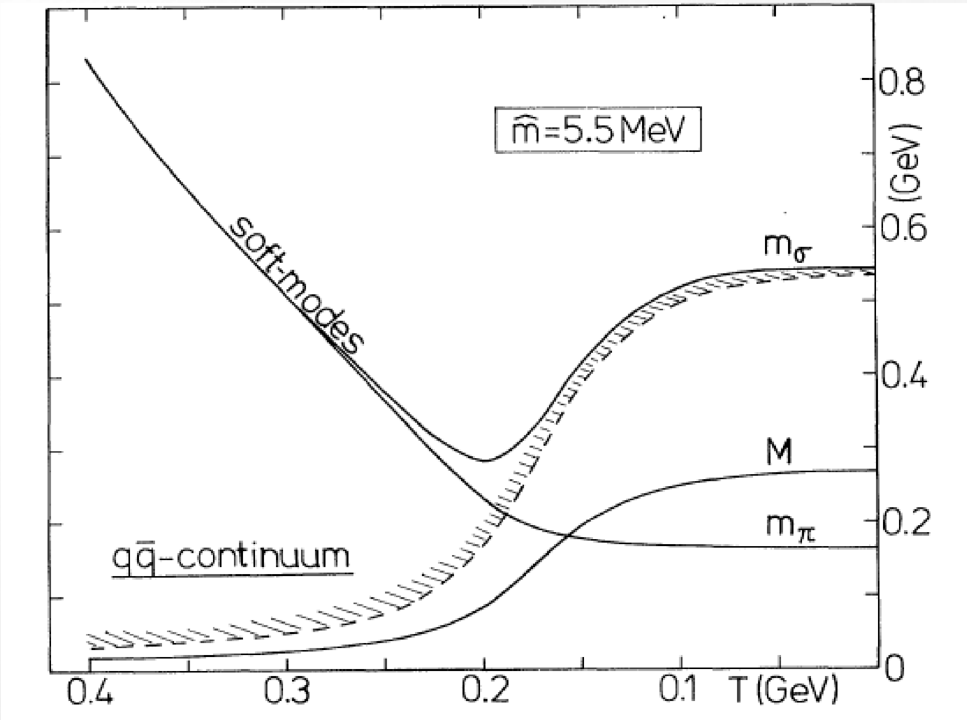
Case(I): T. Hatsuda and T. Kunihiro, PTP Sup. 91(1987) 284

It is shown in the mean field approximation that a first-order transition exists at zero and low temperatures and that this transition can be identified as the chiral restoration.

SIGNALS OF CHIRAL RESTORATION

T. Hatsuda and T. Kunihiro, PRL55(1985)158

- CHANGE OF VACUUM STRUCTURE
  - CHANGE OF $\bar{q}q$ CONDENSATION
  - $\rightarrow$ CHANGE OF σ MESON PROPERTIES
    - SOFTENING OF THE σ AND A DEGENERACY OF THE σ AND π
- DEGENERACY OF CHIRAL PARTNER
  - VECTOR – AXIAL VECTOR
  - WEINBERG TYPE SUM RULE
    - $\int_0^\infty d\omega^2 \omega^2 \left(\rho_V(\omega) - \rho_A(\omega)\right) = -\frac{4}{3}\pi\alpha_s \langle O_{4q} \rangle$
      - $\rho_V(\omega),\ \rho_A(\omega)$: SPECTRAL FUNCTION
    - PRL 18 (1967) 507



SIGNALS OF CHIRAL RESTORATION

- CHANGE OF $\bar{q}q$ CONDENSATION
  - GELL MANN-OAKES-RENNER RELATION
    - $f_\pi^2 m_{\pi^\pm}^2 \simeq -\widehat{m}\langle \bar{u}u + \bar{d}d \rangle$
    - $\widehat{m} = (m_u + m_u)/2$
      - PHYS. REV. 175 (1968) 2194
- BROWN RHO SCALING
  - $m_\sigma^*/m_\sigma \approx m_\rho^*/m_\rho \approx m_\omega^*/m_\omega \approx f_\pi^*/f_\pi$
    - PRL 66 (1991) 2720

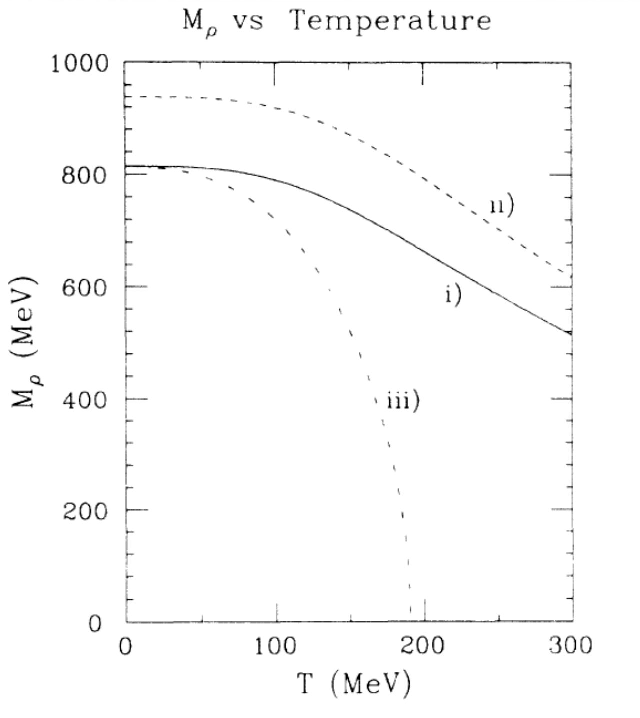
- QCD SUM RULE
  - RELATION BTW SPECTRAL SUM (MOMENT) AND VACUUM CONDENSATES
  - <u>VECTOR MESON </u>IN VACUUM
    - BOREL SUM RULE
      - $\frac{1}{\pi M^2}\int d\omega \mathrm{Im}\prod(\omega)\, e^{-\omega/M^2} = -C_1 + C_2\frac{m_q\langle\bar{q}q\rangle}{M^4} + C_3\frac{\langle G^2\rangle}{M^4}\cdots$
    - M. A. SHIFMAN *ET AL.*, NUCL. PHYS. B147 (1979) 385

VECTOR MESON AS A SIGNAL

- QCD SUM RULE IS APPLIED TO VECTOR MESONS IN A MEDIUM
  - A. I. BOCHKAREV AND M.E. SHAPOSHNIKOV, NP B268 (1986) 220
  - R. J. FURNSTAHL, T. HATSUDA, S.H. LEE, PRD 42 (1990) 1744
  - T. HATSUDA AND S.H. LEE, PRC 46 (1992) R34
- ASSUME THE SPECTRAL FUNCTION
  - $\rho_{pole} + \theta(\omega^2 - S_0)\rho_{cont} + \delta(\omega^2)\rho_\pi$

PRD 42 (1990) 1744

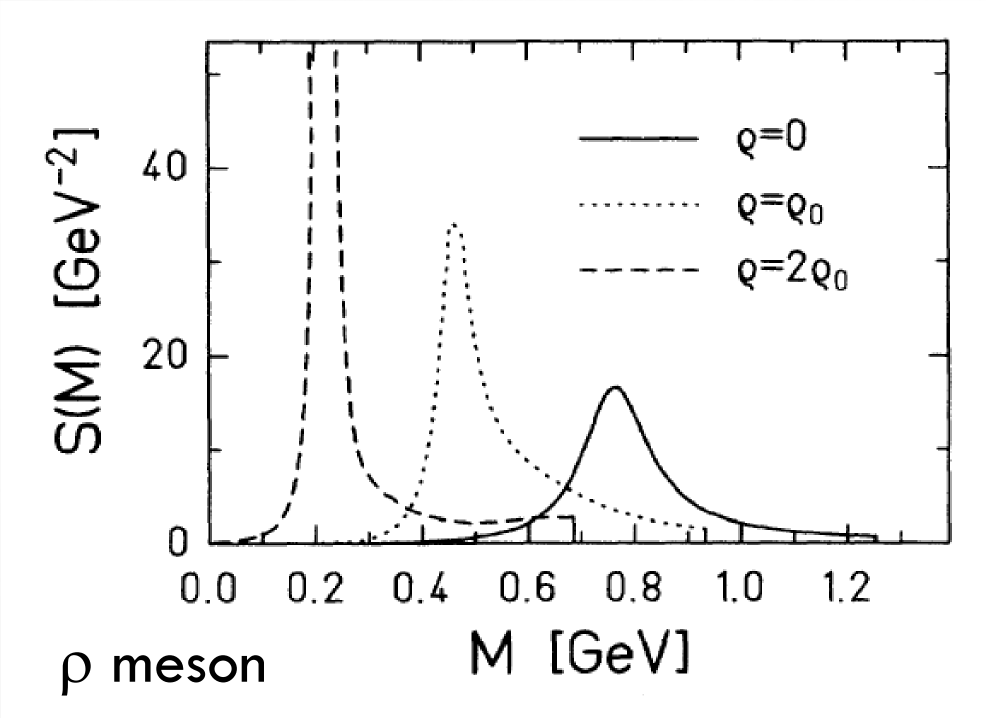
ρ meson case



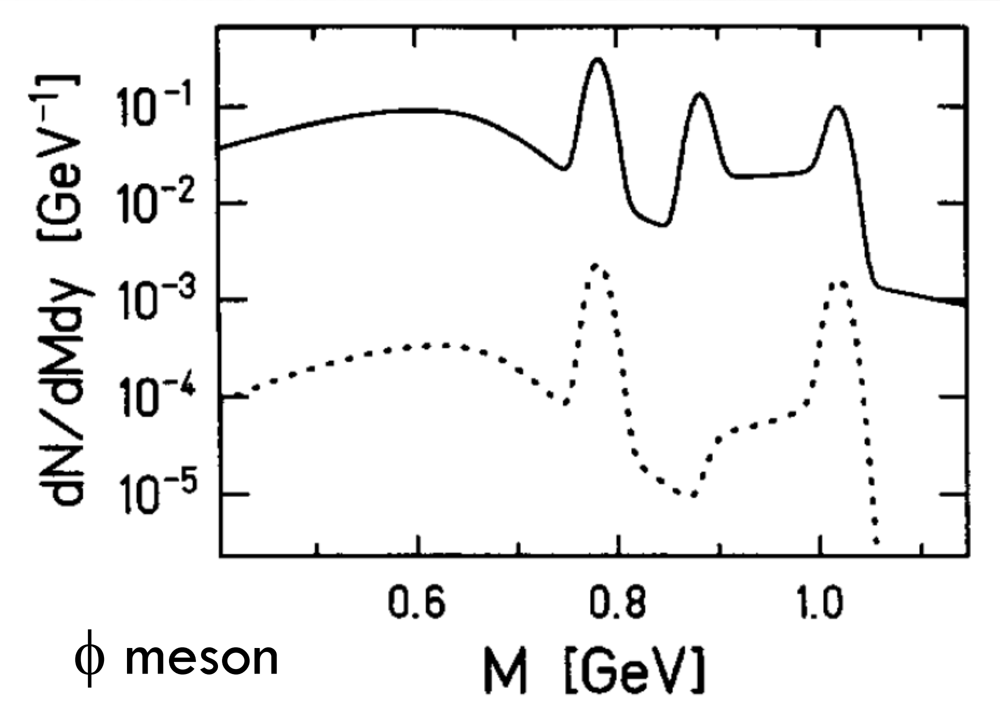
(i), (ii), (iii): different assumption for expansion coefficient

FURTHER PREDICTIONS

M. Asakawa and C. M. Ko, PRC 48 (1993) R526



M. Asakawa and C. M. Ko, PLB 322 (1994) 33



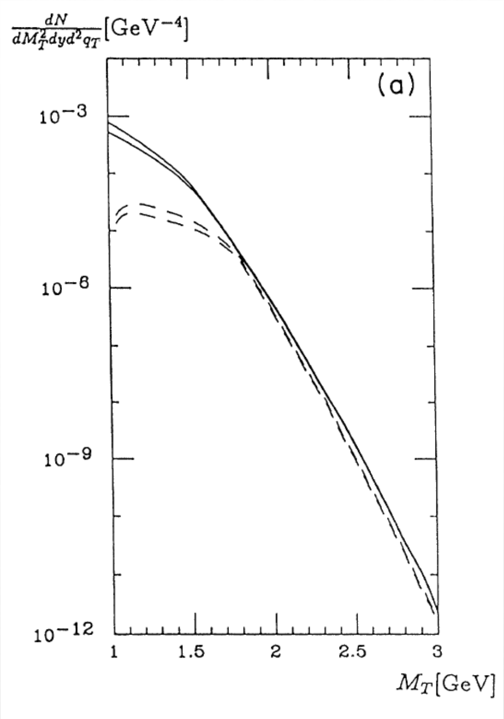
Resonance shape: $$S(s) = -\frac{2\Sigma_I(s)}{[s - m_\rho^2 - \Sigma_R(s)]^2 + [\Sigma_I(s)]^2}$$

MEASUREMENTS

- VECTOR MESON VIA LEPTON PAIR SPECTRUM
  - LEPTONS ARE TRANSPARENT PROBES FOR STRONGLY INTERACTED MATTER
- ISSUE: MANY LEPTON PAIRS PRODUCED BY DECAYS OF VIRTUAL PHOTONS
  - DI-LEPTON RATE

$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\,\mathrm{Im}\,\Pi^{\mu}_{\mathrm{em}\mu}(M,q;T,\mu_B)f_B(q_0,T)$$

  - WE NEED TO DISCUSS BOTH RADIATIONS AND RESONANCE DECAYS
- CONFUSION: QCD SUM RULE DOESN'T TELL US DETAILS OF THE SPECTRUM



M. Asakawa, T. Matsui, PRD 43 (1991) 2817

Dilepton production from a nonequilibrium quark-gluon plasma in ultrarelativistic nucleus-nucleus collisions

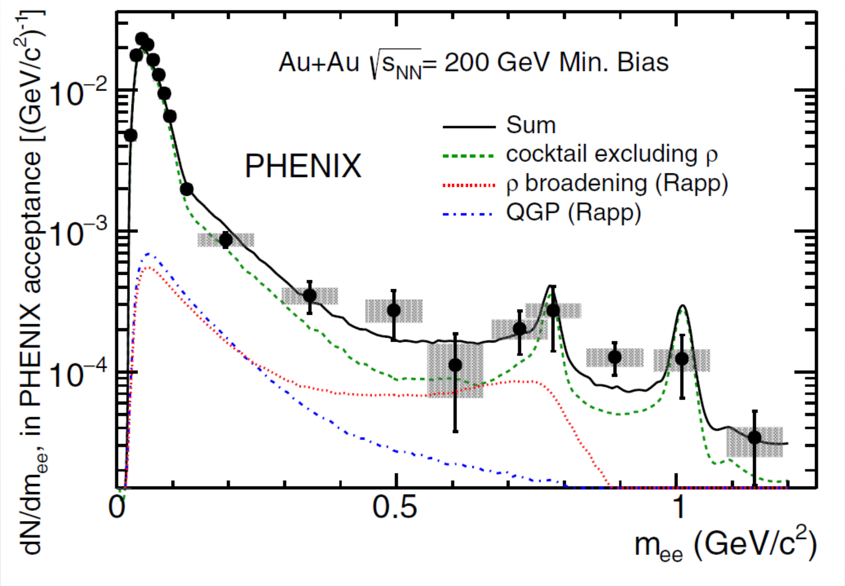
M. Asakawa
*Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Department of Physics, Faculty of Science, University of Tokyo, Tokyo 113, Japan**

T. Matsui
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 8 November 1990)

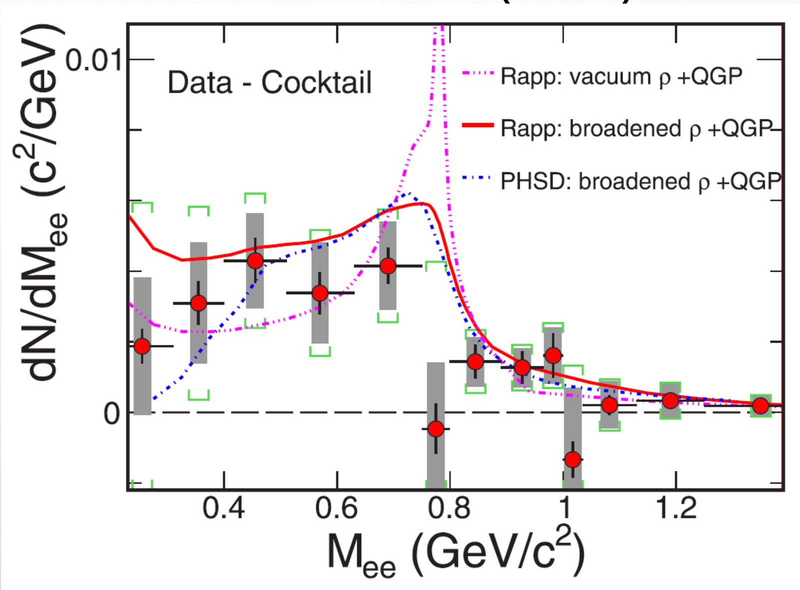
EXPERIMENT RESULTS I

PRC93(2015) 014904



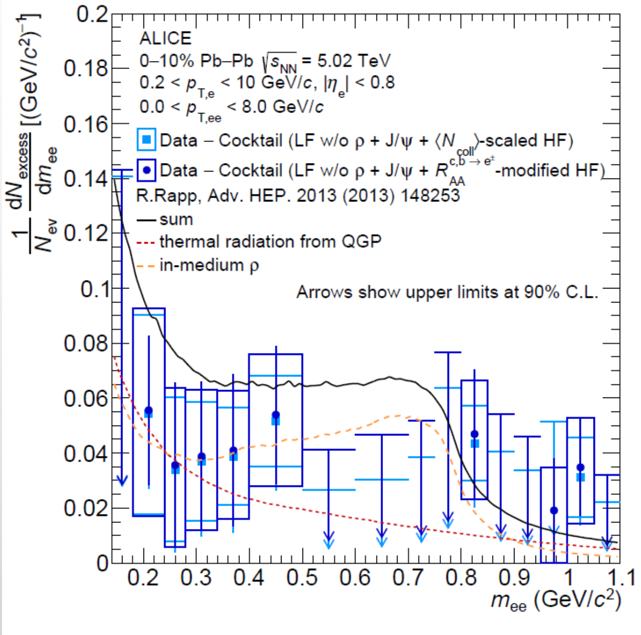
PHENIX

PRC92(2015) 024912



STAR

arXiv:2308.16704



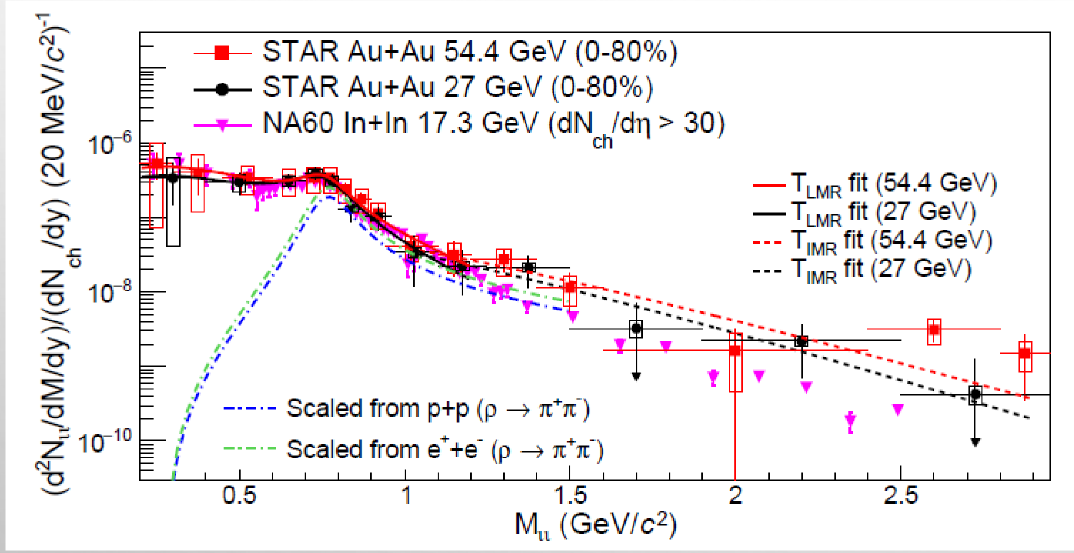
ALICE

Perform comparison between measurements and model calculation

Information of condensates is not yet extracted from the spectra

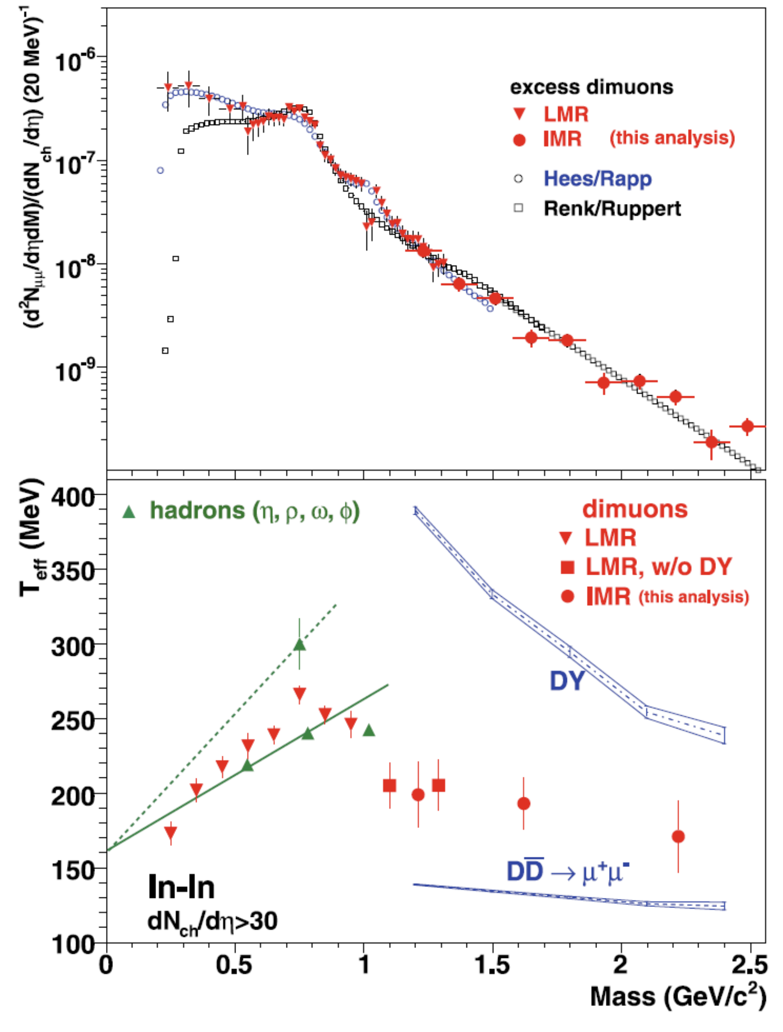
EXPERIMENT RESULTS II

arXiv:2402.01998



STAR

Eur. Phys. J. C 59 (2009), 607



NA60

Temperature is evaluated from the data: $f^{BW} \cdot e^{-M/k_B T}$

カイラル対称性の回復は見えたか?

- 測定した分布を理解しているのか？
  - 実験的には、仮想光子輻射を含む、込みこみの測定
  - 仮定に基づいたモデル計算との比較
    - 計算の仮定の正当性や仮定の違いによる影響の定量的な検証が（素人には）難しい
  - そもそもNON-PHYSICSなBACKGROUNDが多すぎて、RHIC/LHCは統計が足りない
    - ALICE3に期待
  - RADIATIONとVECTOR MESONを区別できる何らかの測定量があると良いのか
    - 偏極とか
  - 媒質からの電子対生成のSPECTRUMとして理解したほうが良いのか
    - 時代が浅川さんに追いついたか
    - MT SCALING, PRL. 70 (1993) 398
- クォーク凝縮に関わる量を引き出せるか？
  - 測定は、時間方向にも積分されている
    - 生成された系の時間的・空間的発展の詳細な理解が必須
    - 適切な計算がされているのか？
      - BY 浅川さん
  - 寿命的に考えて、大きな効果を期待できるのは、ρ MESON
    - 幅の広さは、SPECTRUMの理解を難しくしている印象
    - 高統計があれば、ω, ϕ も可能か
- <u>QCD SUM RULEの適用限界をふまえた議論が必要</u>

QCD SUM RULEでの近似

M. Asakawa and C. M. Ko, NP A572 (1994) 732

ϕ mesonに対する計算

6次までの展開

$$\frac{m_\phi^2}{M^2} = \left[a\left(b - \frac{s_0 c}{M^2}\right) - \frac{8\pi^2 m_s}{M^4}\langle\bar{s}s\rangle_\rho - \frac{\alpha_s \pi}{3M^4}\langle G_{\mu\nu}G^{\mu\nu}\rangle_\rho + \frac{896\alpha_s\pi^3}{81M^6}\langle\bar{s}s\rangle_\rho^2 - \frac{4\pi^2}{M^4}A_{1,N}^s m_N\rho + \frac{20\pi^2}{3M^6}A_{3,N}^s m_N^3\rho\right] \times \left[ab - \frac{6m_s^2}{M^2} + \frac{8\pi^2 m_s}{M^4}\langle\bar{s}s\rangle_\rho + \frac{\alpha_s\pi}{3M^4}\langle G_{\mu\nu}G^{\mu\nu}\rangle_\rho - \frac{448\alpha_s\pi^3}{81M^6}\langle\bar{s}s\rangle_\rho^2 + \frac{4\pi^2}{M^4}A_{1,N}^s m_N\rho - \frac{10\pi^2}{3M^6}A_{3,N}^s m_N^3\rho\right]^{-1}$$

線形密度近似

$$\langle\bar{s}s\rangle_\rho \approx \langle\bar{s}s\rangle_0 + \langle\bar{s}s\rangle_N\rho,$$

$$\frac{\alpha_s}{\pi}\langle G_{\mu\nu}G^{\mu\nu}\rangle_\rho \approx \frac{\alpha_s}{\pi}\langle G_{\mu\nu}G^{\mu\nu}\rangle_0 - \tfrac{8}{9}m_N^0\rho,$$

平均場近似

$$\langle(\bar{s}\gamma_\mu\gamma_5\lambda^a s)(\bar{s}\gamma^\mu\gamma_5\lambda^a s)\rangle_\rho \approx \tfrac{16}{9}\langle\bar{s}s\rangle_\rho^2,$$

$$\langle(\bar{s}\gamma_\mu\lambda^a s)(\bar{s}\gamma^\mu\lambda^a s)\rangle_\rho \approx -\tfrac{16}{9}\langle\bar{s}s\rangle_\rho^2,$$

$$\langle(\bar{s}\gamma_\mu\lambda^a s)(\bar{u}\gamma^\mu\lambda^a u)\rangle_\rho \approx 0,$$

$$\langle(\bar{s}\gamma_\mu\lambda^a s)(\bar{d}\gamma^\mu\lambda^a d)\rangle_\rho \approx 0.$$

浅川さんのコメント

We have calculated $\langle\bar{s}s\rangle_\rho^2$ using Eq. (3.4) and have thus included the quadratic term in density. The phi meson mass is, however, not affected much if only the term linear in density is kept, because, due to the large mass of the strange quark, the $m_s\langle\bar{s}s\rangle_\rho$ term contributes to the phi meson mass more than the $\langle\bar{s}s\rangle_\rho^2$ term.

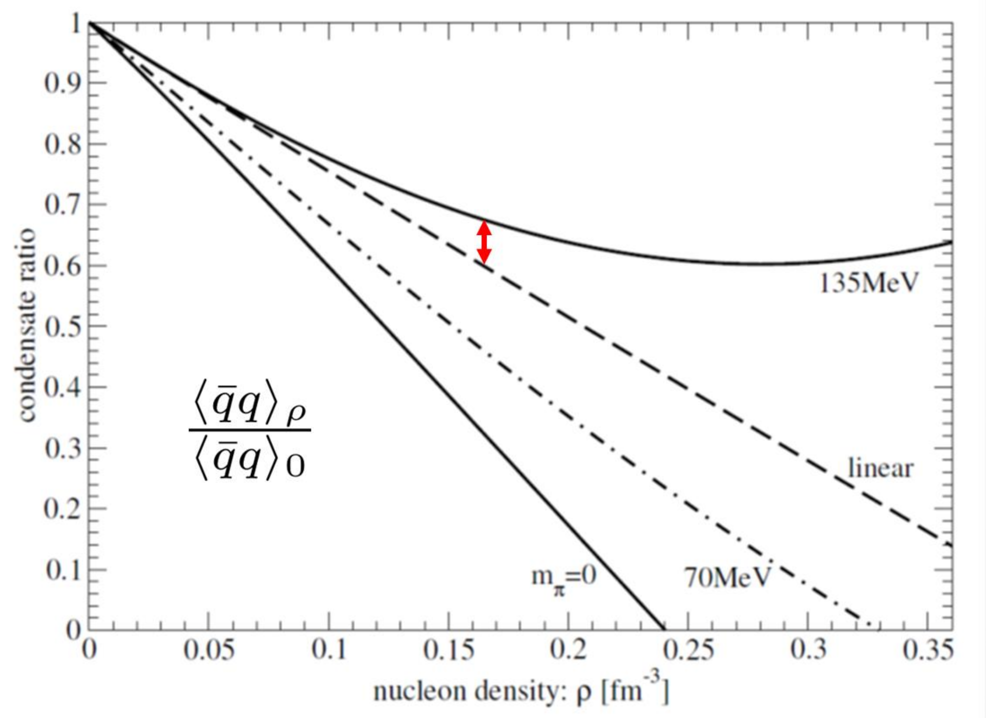
最近の検討

P. Gubler and K. Ohtani, Phys. Rev. D 90, 094002 (2014)

See also: S. Goda and D. Jido, Phys.Rev. C **88**, 065204 (2013).
N. Kaiser, P. de Homont and W. Weise, Phys.Rev. C **77**, 025204 (2008).

- 同様の議論が、主に原子核密度での測定に向けて、P. GUBLER氏らが展開
    - 同様の近似を適用
    - 原子核密度程度なら、線形密度近似は悪くない

$$G_{OPE}(M^2) = \frac{1}{4\pi^2}(1+\frac{\alpha_s}{\pi}) - \frac{1}{M^2}\frac{6m_s^2}{4\pi^2} + \frac{1}{M^4}(2m_s\langle\bar{s}s\rangle_{\rho_N} + \frac{1}{12}\langle\frac{\alpha_s}{\pi}G^2\rangle_{\rho_N}) - \frac{1}{M^6}\frac{112\pi}{81}\alpha_s\langle\bar{s}s\bar{s}s\rangle_{\rho_N} + \frac{1}{M^4}A_2^s M_N \rho - \frac{1}{M^6}\frac{5}{3}A_4^s M_N^3 \rho + \cdots$$



原子核密度では、どうか？

KEK-PS E325 実験

12 GeV proton induced.

p+A → ρ/ω/ϕ + X

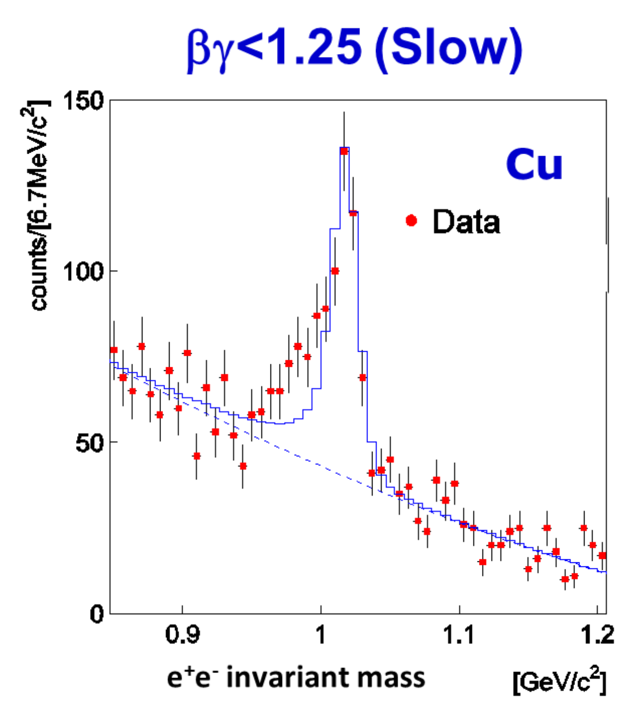
Electrons from meson decays are detected.

The exp. results show

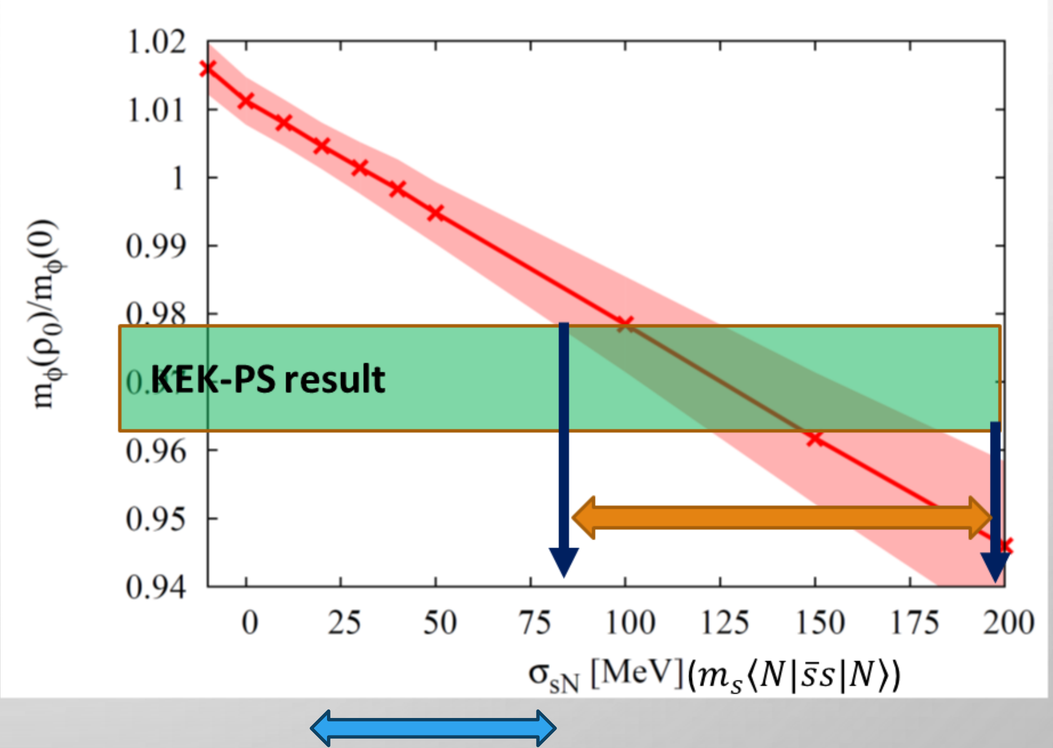
$\Delta m = 0.034 \pm 0.007$

$\Delta\Gamma = 2.6 \pm 1.5$

R. Muto et al., PRL 98(2007) 042581



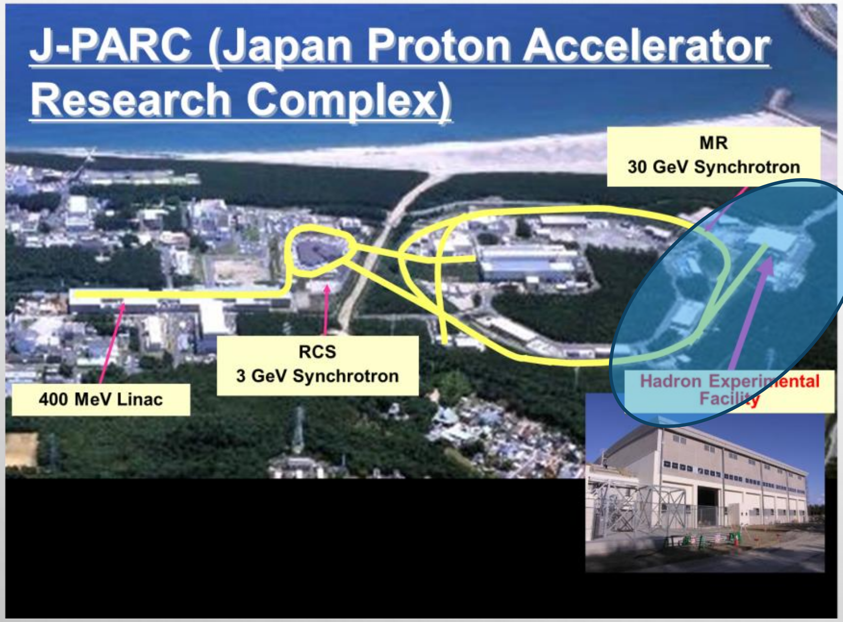
P. Gubler and K. Ohtani, Phys. Rev. D 90, 094002 (2014)

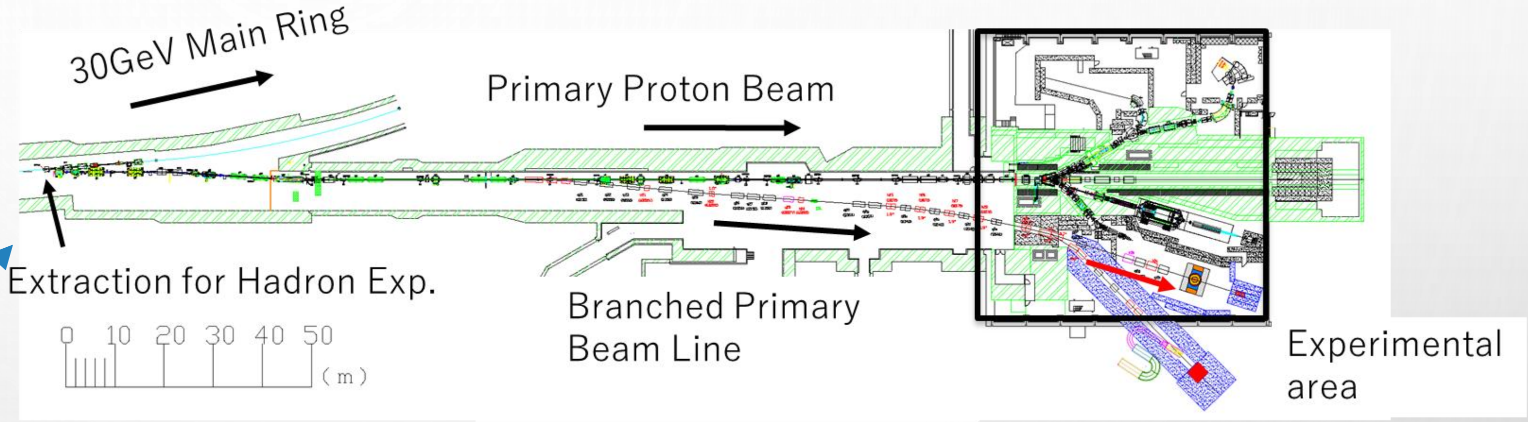


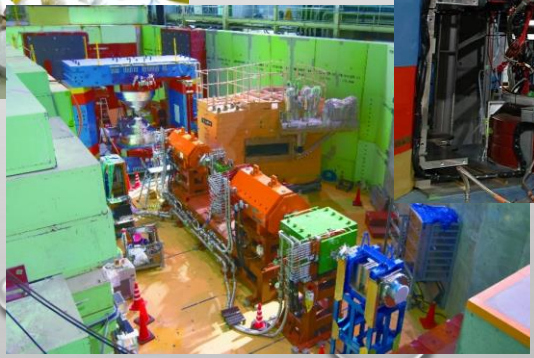
Lattice計算はこのあたり

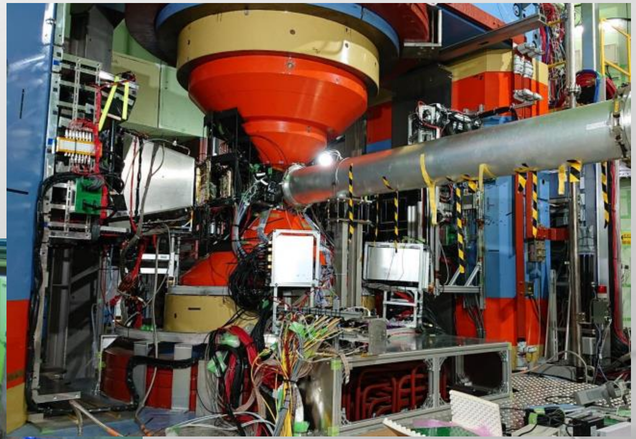
例えば、M. Gong et al. (χQCD Collaboration), arXiv:1304.1194 [hep-ph]

EXPERIMENT AT J-PARC



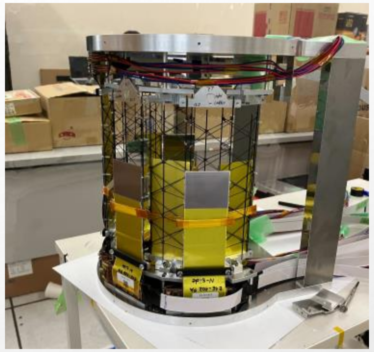


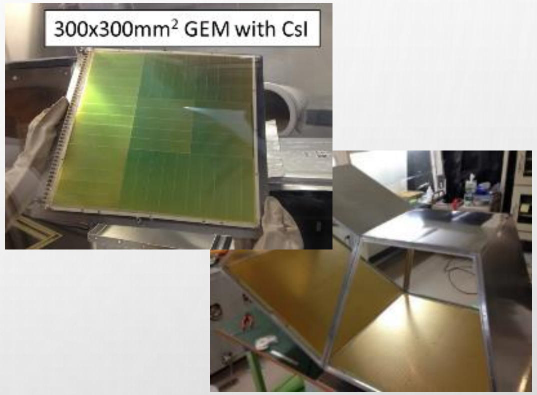


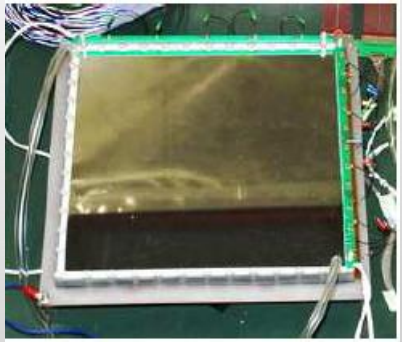


J-PARC E16 EXPERIMENT

- MEASUREMENTS OF E^+E^- PAIR INVARIANT MASS SPECTRA IN NUCLEUS
- 10 TIMES LARGER STATISTICS COMPARED TO THE KEK EXPERIMENT
  - 10^{10} PROTONS PER SPILL (10 TIMES HIGHER THAN KEK)
  - COUNTING RATE: 5 KHZ/MM^2 (MAXIMUM)
- TWO TIMES BETTER RESOLUTION THAN KEK
  - LARGER MAGNETIC FIELD
  - BETTER POSITION RESOLUTION (~100 μM)

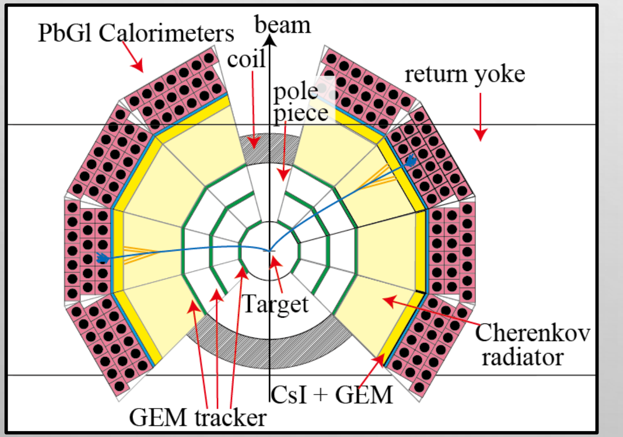


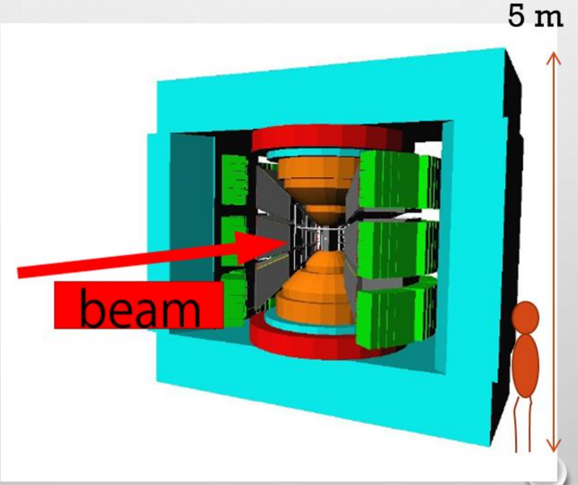




Trackers

Electron ID

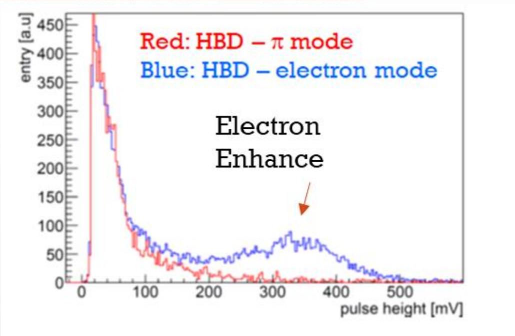


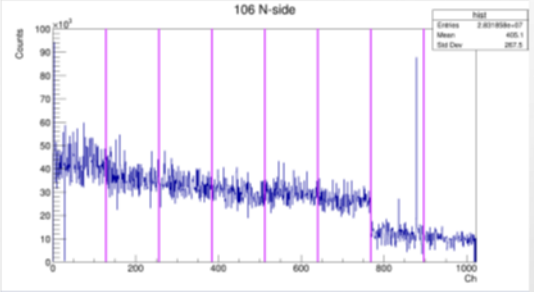


STATUS OF THE EXPERIMENT

- HISTORY
  - FIRST BEAM: MAY 24, 2020.
  - COMMISSIONING RUNS: JUNE 2020, JUNE 2021, JUNE 2023, AND JUNE 2024
  - ALL DETECTORS, TRIGGERS, AND DAQ WORKED WELL
  - DETECTOR PERFORMANCE IN COMMISSIONING DATA ARE BEING EVALUATED
- WE WILL HAVE THE PHYSICS DATA IN A YEAR

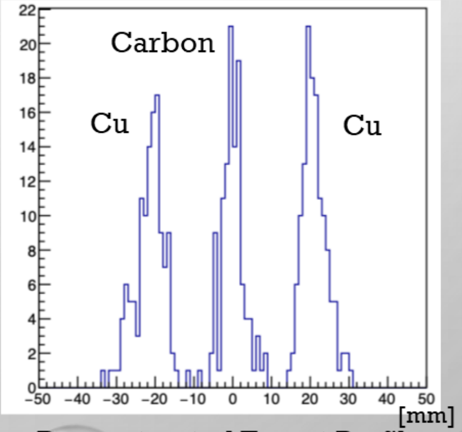
Pulse Hight @ Lead Glass





Obtained Profile
(新シリコン検出器)

Track reconstruction



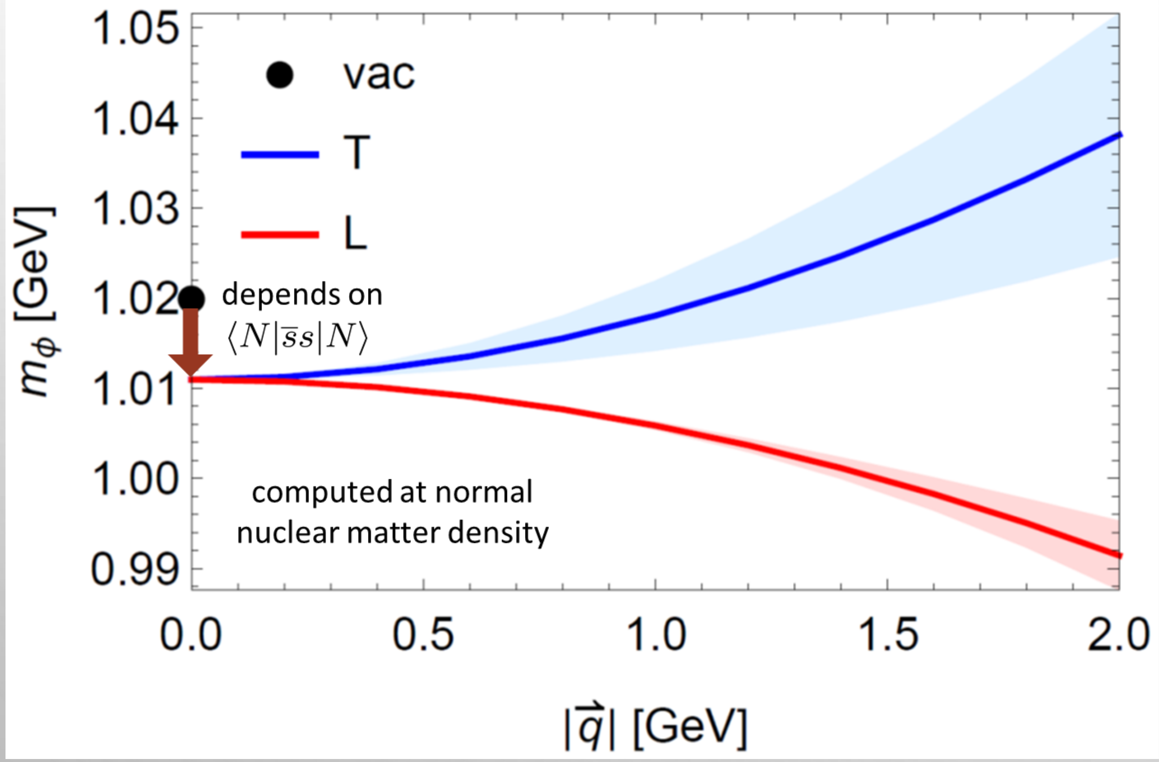
Reconstructed Target Profile

今後の展開

- 大統計による新たな測定量
  - 偏極
  - AXIAL VECTOR
  - DISORIENTED CHIRAL SYMMETRY RESTORATION
  - (ALICE3)
- FAIR/J-PARCでの重イオン衝突実験による高密度媒質の実現
  - 超低質量域
    - COLOR SUPERCONDUCTING

POLARIZATION OF ϕ MESON

H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).



caused by

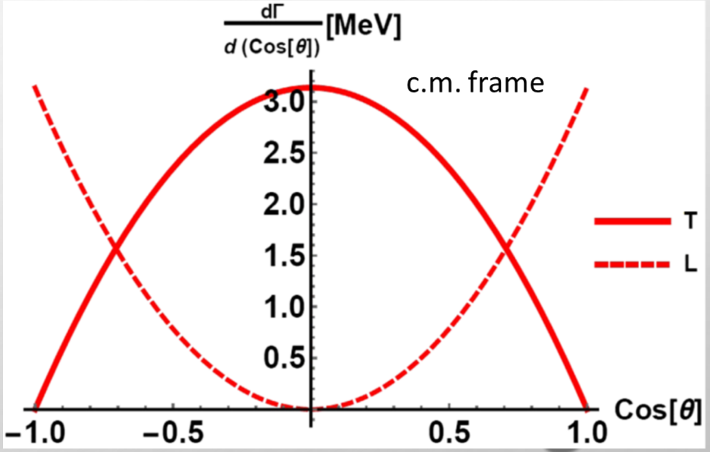
$$\langle N|\mathcal{ST}\bar{s}\gamma^\alpha iD^\beta s|N\rangle$$
$$+$$
$$\langle N|\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

caused by

$$\langle N|\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

KK decays are preferable

K^+K^- decay angular distribution



I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, PRD **107**, 074033 (2023).

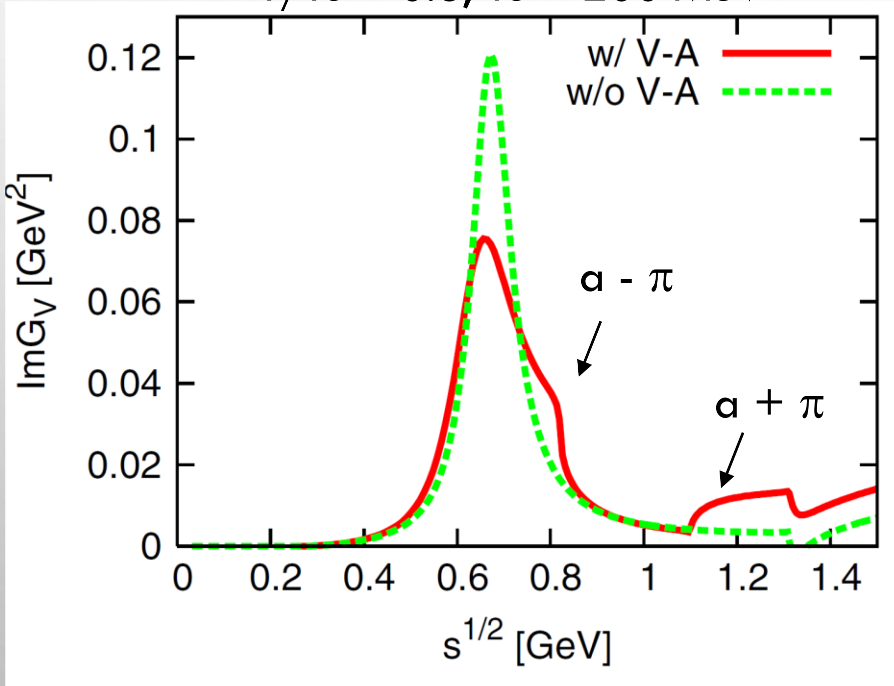
AXIAL VECTOR MESONへのアプローチ

Vector meson spectrum への干渉効果が見える可能性

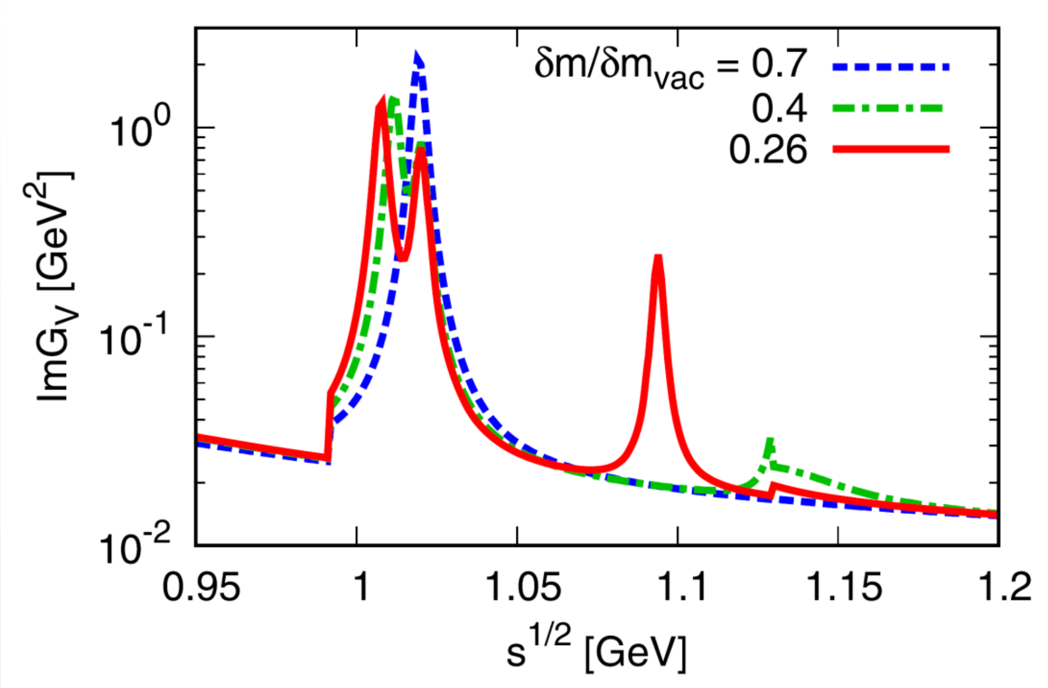
M.Harada, C.Sasaki and W.Weise, PRD 78 (2008) 114003

C. Sasaki, PLB 801 (2020) 135172

T/Tc = 0.8, Tc = 200 MeV



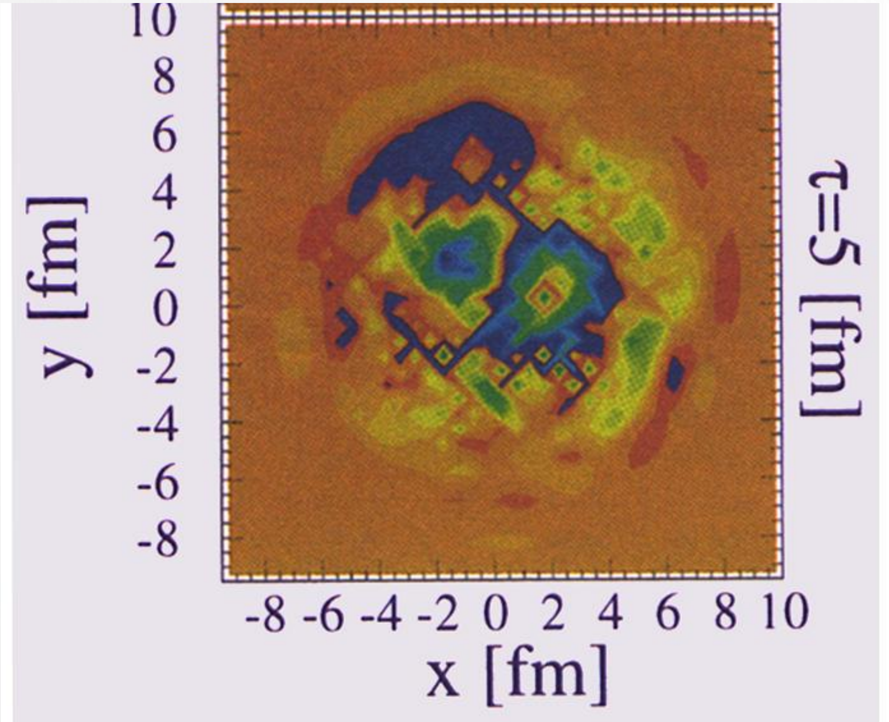
T = 50 MeV, mixing parameter c ≈ 34MeV



DISORIENTED CHIRAL CONDENSATE

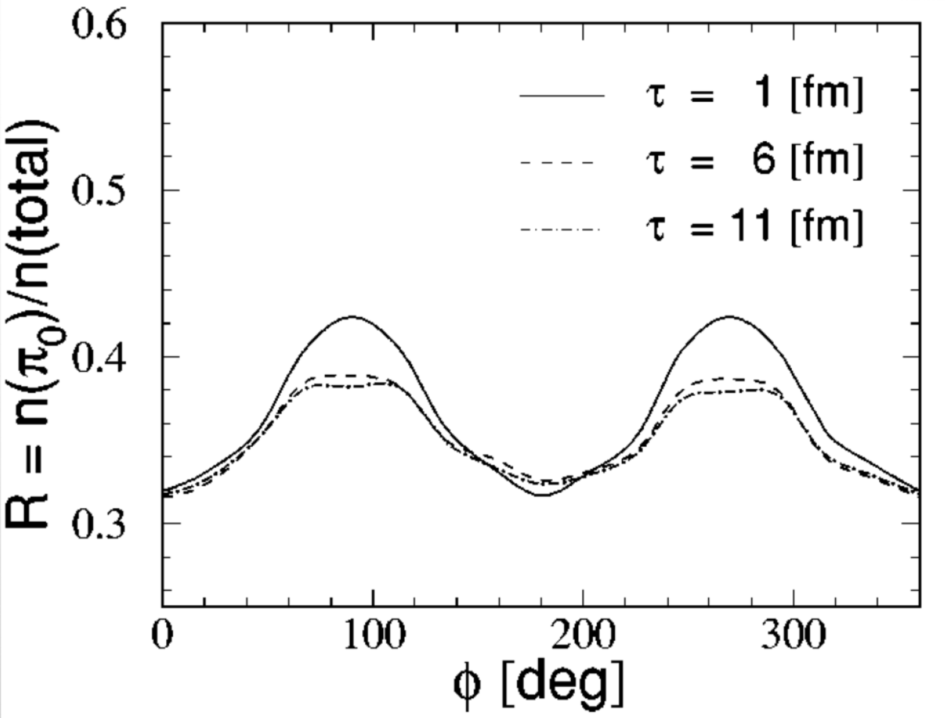
M. Asakawa, Z. Huang and X.N. Wang, PRL 74 (1995) 3126

Countour plot of π_2



M. Asakawa, H. Minakata and B. Muller, PRC 65 (2002) 057901

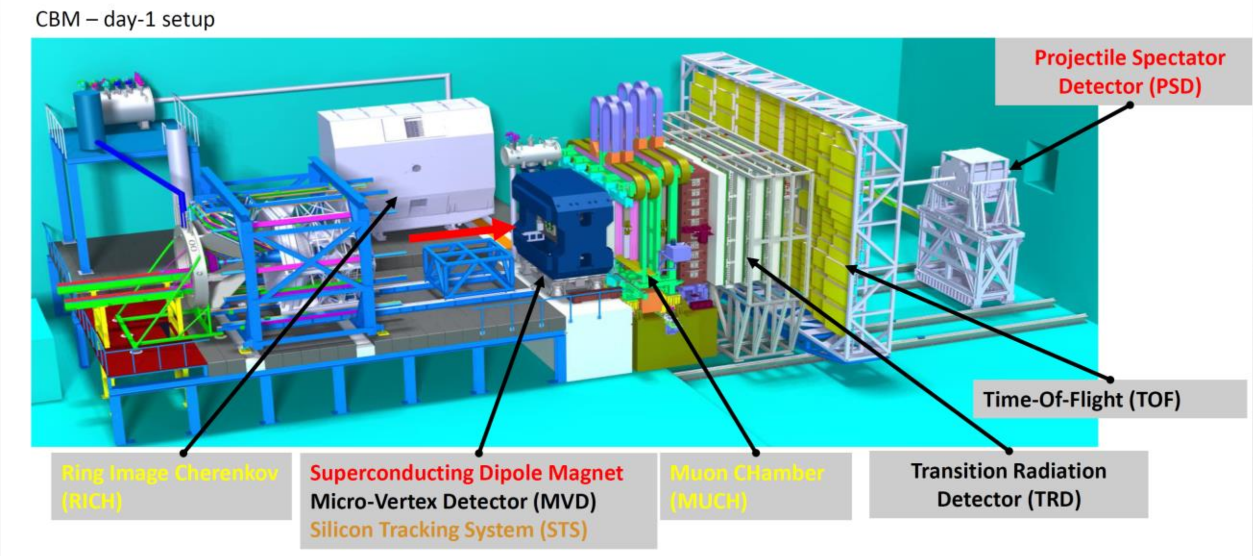
Azimuthal angle dependence of the ratio n_{π^0} / n_{π}



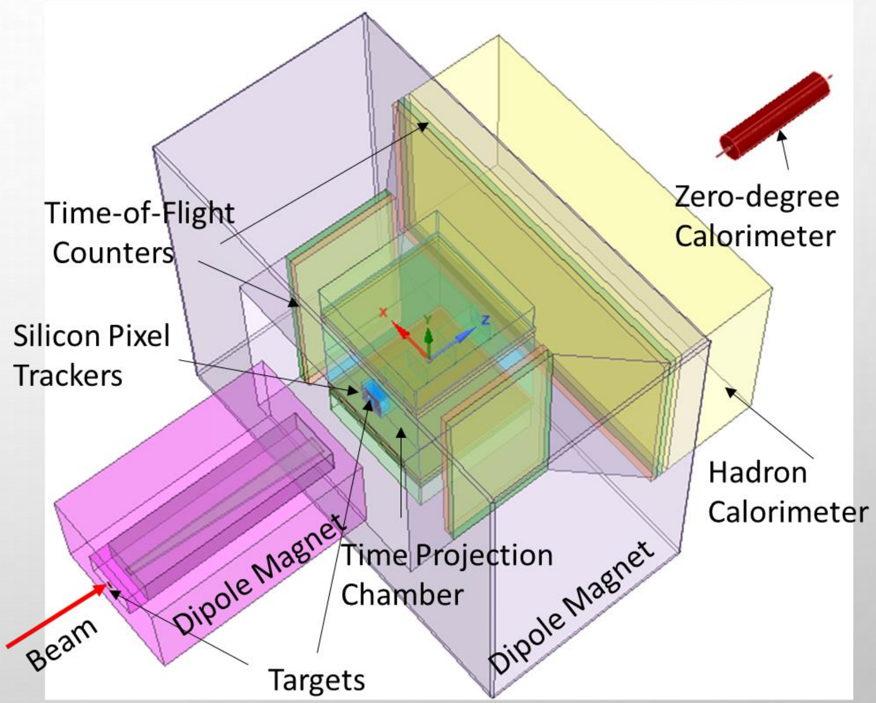
Candidate of Experimental Signature

高密度領域の探索

FAIR CBM実験



J-PARC Heavy Ion 実験



どちらも

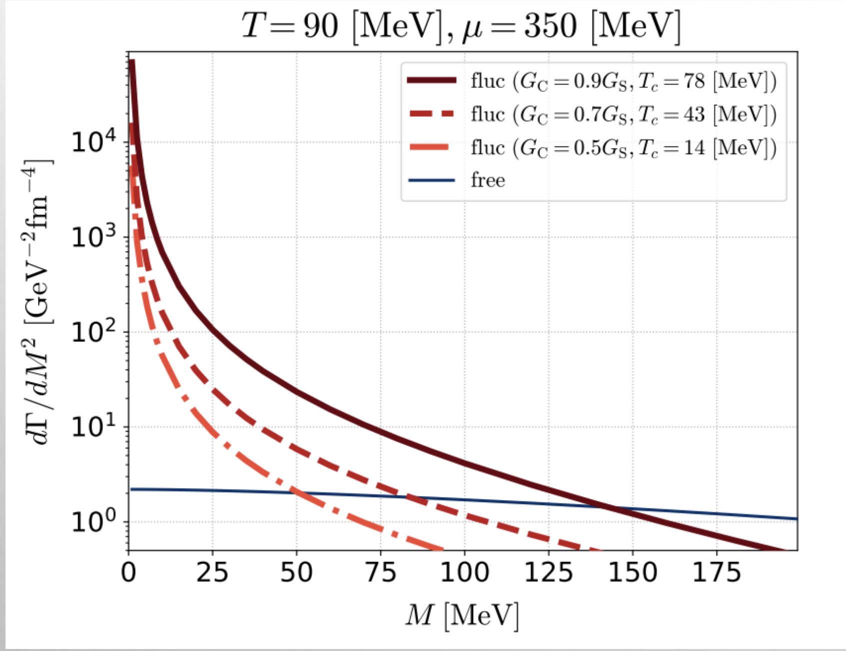
Beam Energy: $\sqrt{S_{NN}} \sim 2 - 5$ GeV

Maximum Beam Intensity: $10^{10} \sim 10^{11}$ Hz

超低運動量領域の測定

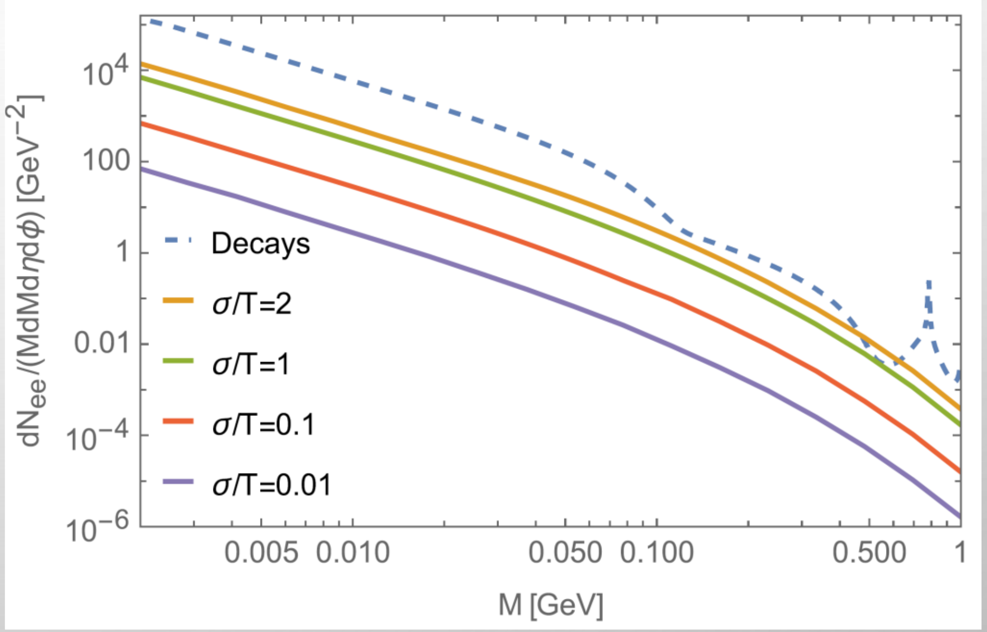
T. Nishimura, M. Kitazawa, T. Kunihiro,　PTEP 2022, 093D002

Di-electron pair emission in phase transition for super conductivity



S.Floerchinger, C.Gebhardt, K.Reygers,　PLB 837 (2023) 137647 093D002

Effects of electrical conductivity on the spectrum



実験的には、難しい
J-PARC Heavy Ion 実験では、積極的に検討中

SUMMARY

- QCD相図を理解するためにカイラル対称性は大事
  - 実験的にその変化を捉えるのは難しいががんばっていきます。

浅川さん

還暦おめでとうございます。

DILEPTONの物理は、いろいろな意味で浅川さんと共にあったと思います。

コロンビアのPDの時に、PHENIX向けの計算をサポートしたという噂も聞いたことがあります。

今後とも、よろしくお願いします。