# Chiral mixing in E16

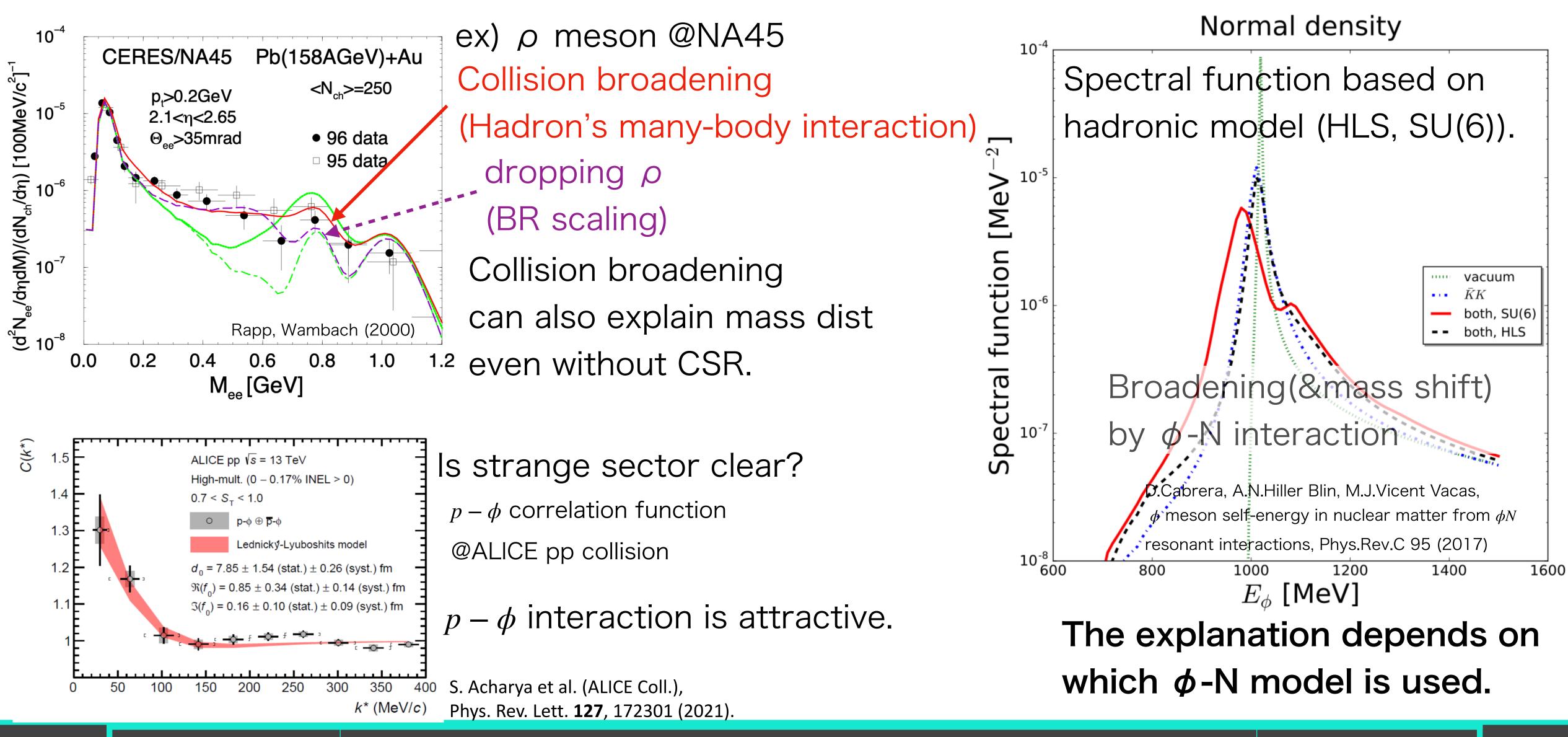


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# Introduction

### How do we understand dilepton's mass dist?



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### How can we verify CSR more directly?

### **Degeneration of chiral partner**

Chiral transformation

Axial-vector

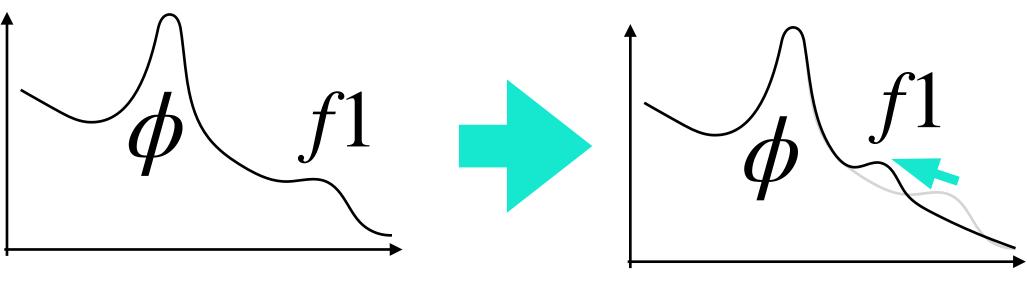
Chiral transformation

Symmetrical: Same mass after  $\chi$  trans. Not symmetrical: Different mass after  $\chi$  trans.

 $\phi$  meson's chiral partner:  $f_1(1420)$ 

Vector

### Signal of this measurement



In vacuum

In dense matter

Mass dist. is degenerated in dense matter. This is equivalent to partial CSR.

Btw, Axial-vector can't decay into di-lepton directly... We need "Chiral(V-A) mixing".

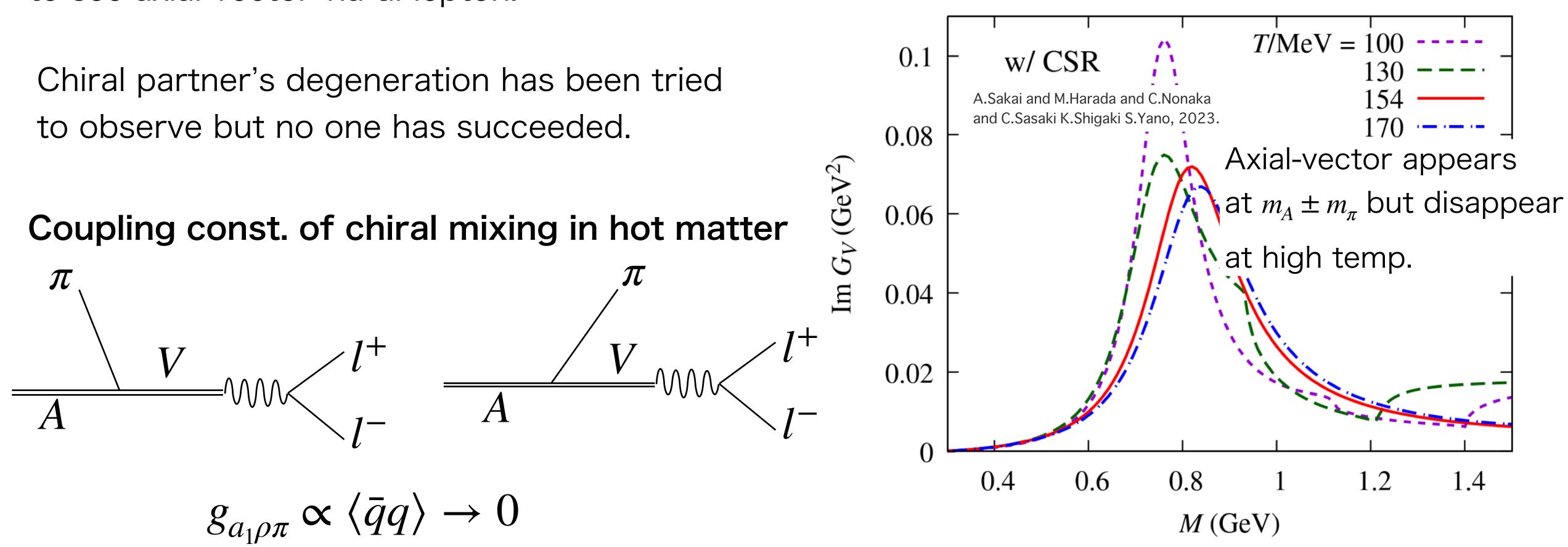
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# Chiral mixing in Hot matter

Chiral mixing is necessary to see axial-vector via di-lepton.



Chiral mixing will be suppressed at Tc.

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# Chiral mixing in Dense matter

### Chiral mixing in dense matter

Finite baryon density makes  $\omega$ 's time-part not C inv.

$$\langle \omega_0 \rangle = g_{\omega NN} \cdot n_B / m_{\omega}^2$$

$$\mathscr{L}_{\omega} \sim \bar{N} \gamma^{\mu} \omega_{\mu} N \quad \rightarrow \mu_{B} N^{\dagger} N$$

This term change dispersion relation of transverse Vector and Axial-vector.

$$s = p_0^2 - \vec{p}^2 = \frac{1}{2} \left[ m_V^2 + m_A^2 \pm \sqrt{(m_A^2 - m_V^2)^2 + 16c^2 \vec{p}^2} \right]$$

Tyler expansion at small p:  $p_0^2 \sim m_{V,A}^2 + \left(1 \pm \frac{4c^2}{m_A^2 - m_V^2}\right) \bar{p}^2$ 

Chiral mixing is enhanced with high momentum, degeneration of VA

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The lowest term with chiral/parity symmetry, without C-inv  $L = 2c\epsilon^{0\mu\nu\lambda} \mathrm{tr} \left[ \partial_{\mu}V_{\nu} \cdot A_{\lambda} + \partial_{\mu}A_{\nu} \cdot V_{\lambda} \right]$ 

 $\rightarrow$ tree level chiral mixing Holographic QCD(Chern-Simons term)

WZW action(same form in leading order)

C. Sasaki, Phys. Rev. D 106 054034 (2022)

Chiral mixing strength c

this parameter has model dependence

Holographic QCD: WZW action:

$$c = 1.0 \frac{\rho}{\rho_0} [\text{GeV}]$$

 $c = 0.1 \frac{\rho}{\rho_0} [\text{GeV}]$ 

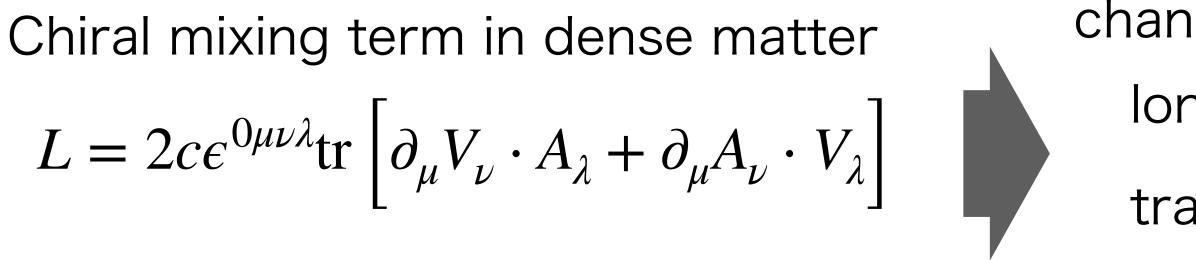
Coupling constant is proportional to density. There is no suppression.

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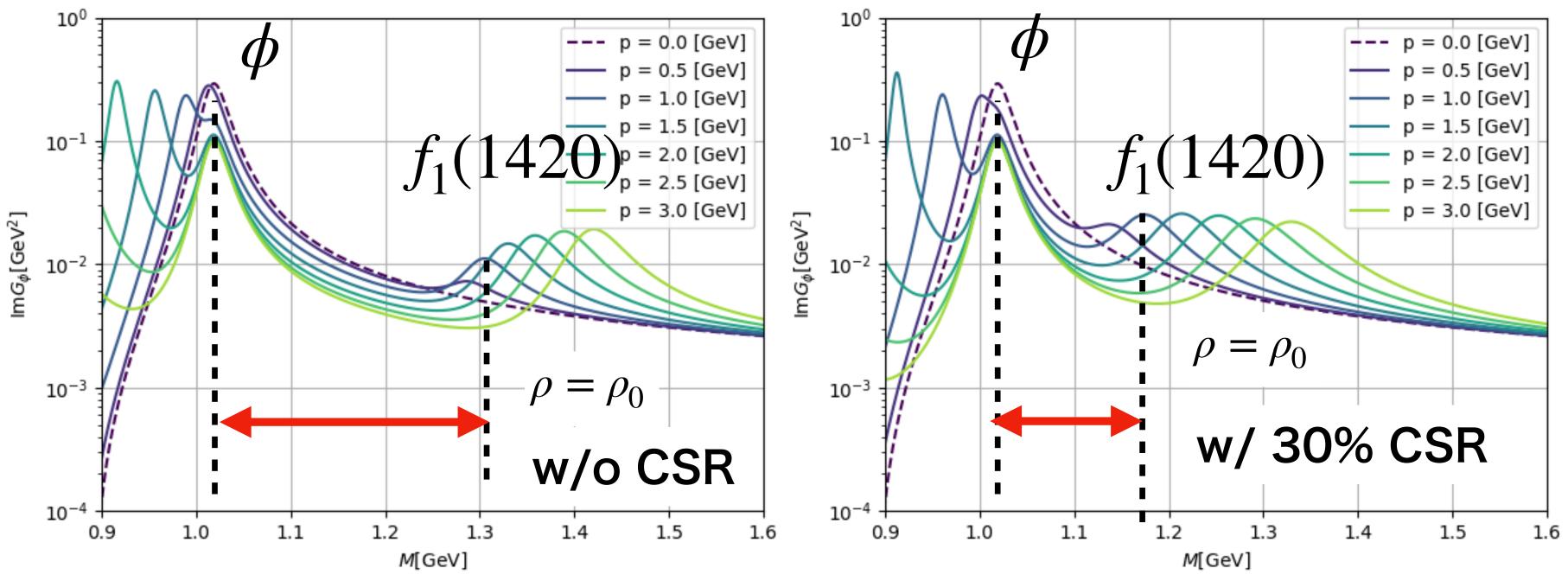




# Spectral Function



Spectral function ( $ImG_V$ ) can be calculated like this



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change dispersion relation longitudinal  $s = p_0^2 - \vec{p}^2 = m_{V,A}^2$ transverse  $s = p_0^2 - \vec{p}^2 = \frac{1}{2} \left[ m_V^2 + m_A^2 \pm \sqrt{(m_A^2 - m_V^2)^2 + 16c^2 \vec{p}^2} \right]$ 

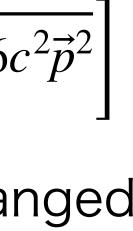
Spectral function is changed to have 3 structures:

- longitudinal vector
- transverse

Can we observe this degeneration experimentally?

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# advantage of J-PARC E16

Mixing strength:

Holographic QCD:

$$c = 1.0 \frac{\rho}{\rho_0} [\text{GeV}]$$

WZW action:

$$c = 0.1 \frac{\rho}{\rho_0} [\text{GeV}]$$

More high density: HADES, etc.

 $\rightarrow$  also have finite temperature (T~50MeV <  $m_{\pi}$  =no chiral mixing by finite temperature)

p+A(E16) is (almost) zero temperature $\rightarrow$ no Boltzmann suppress

Other advantages: high statistics / specialized to measure di-electron / Fixed target(no time evolution of density)...etc



Spectral function in finite temperature:

 $\frac{dN}{d^4p}(p_0, \vec{p}; T, \mu_B) = \frac{\alpha^2}{\pi^3 s} \frac{\text{Im}G_V(p_0, \vec{p}; T, \mu_B)}{e^{p_0/T} - 1}$ B-E dist Axial vector will be very small (Boltzmann suppress)

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# Estimation of ee inv. mass dist.

Invariant mass distribution can be calculated like this using spectral function

InvMassDist = 
$$\int \left[ \int \frac{dN}{d\vec{p} d\rho dt} \frac{d\vec{p}}{dp} d\rho dt + \frac{d\vec{p}}{dp} d\rho dt \right] d\rho dt$$



+ 
$$\int Bkg(s,p)dp \left[ g(m-s)ds \right]$$

Spectral Fx Kinematic dist Background Detector response



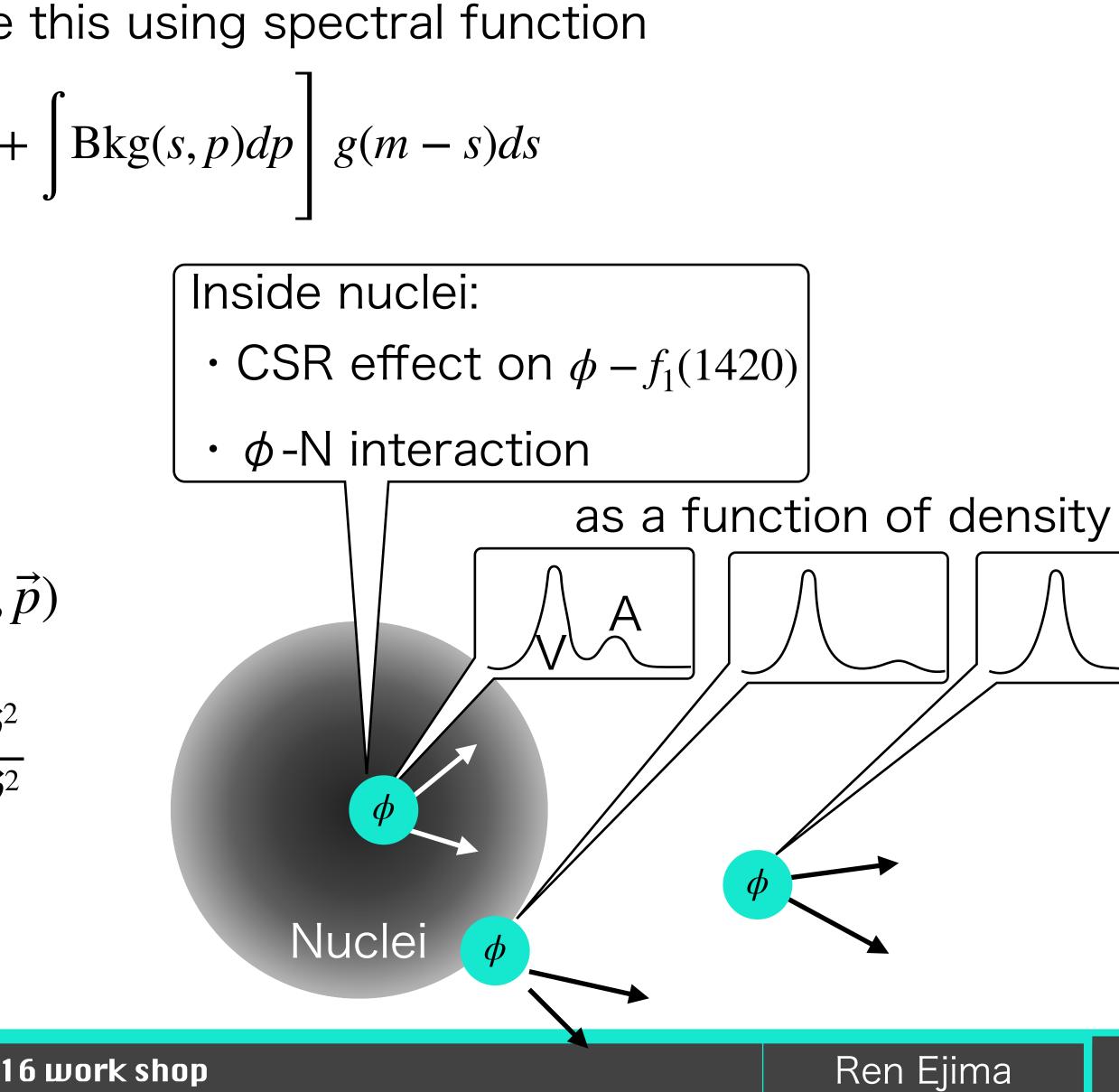




Invariant mass distribution can be defined like this using spectral function

InvMassDist =  $\int \left| \int \boxed{\text{Im}G_V(s,p,\rho)} \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt + \int \text{Bkg}(s,p)dp \right| g(m-s)ds$ Spectral function of  $\phi$  $L = 2c\epsilon^{0\mu\nu\lambda} \mathrm{tr} \left[ \partial_{\mu}V_{\nu} \cdot A_{\lambda} + \partial_{\mu}A_{\nu} \cdot V_{\lambda} \right]$ Current-Current correlation function:  $G_{V,A}^{\mu\nu}(p_0, \vec{p}) = P_L^{\mu\nu}G_{V,A}^L(p_0, \vec{p}) + P_T^{\mu\nu}G_{V,A}^T(p_0, \vec{p})$  $G_{V}^{L} = \left(\frac{g_{V}}{m_{V}}\right)^{2} \frac{-s}{D_{V}^{L}} \qquad G_{V}^{T} = \left(\frac{g_{V}}{m_{V}}\right)^{2} \frac{-sD_{A}^{T} + 4c^{2}\vec{p}^{2}}{D_{V}^{T}D_{A}^{T} - 4c^{2}\vec{p}^{2}}$  $r L T^{-1}$ 

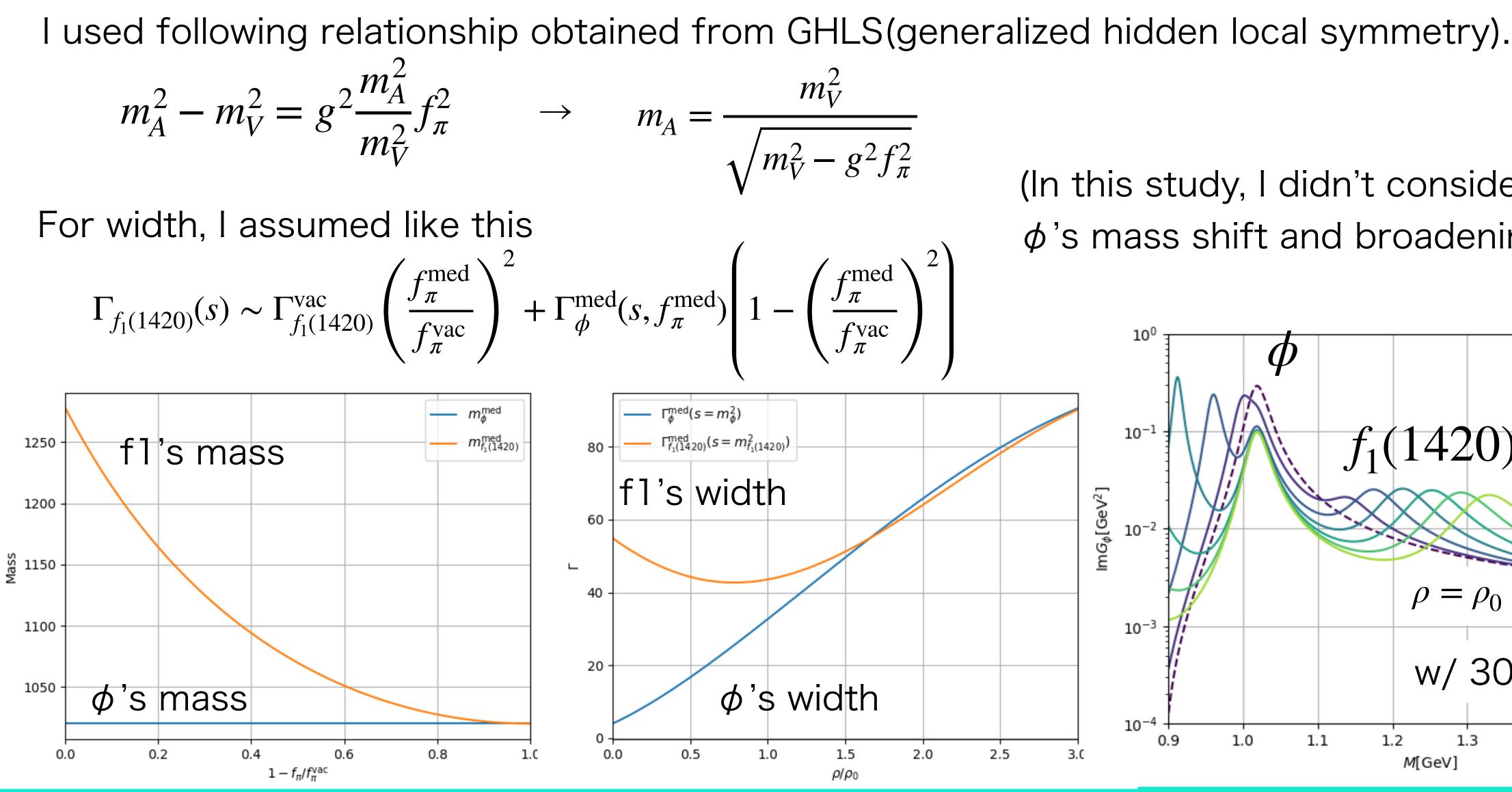
$$P_{V,A}^{L,T} = \frac{1}{s - m_{V,A}^2 - \Sigma_{V,A}^{L,T}}$$



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### CSR Effect on f1(1420)'s spectral function

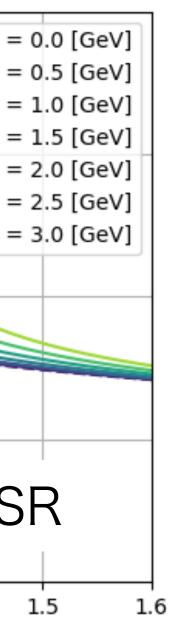


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### (In this study, I didn't consider $\phi$ 's mass shift and broadening by CSR) p = 0.0 [GeV] p = 3.0 [GeV] lm*G*¢[GeV²] $\rho = \rho_0$ 10<sup>-3</sup> w/ 30% CSR 10-4 -1.1 0.9 1.0 1.2 1.3 1.4 1.5 1.5 2.0 2.5 3.0 M[GeV] $\rho/\rho_0$

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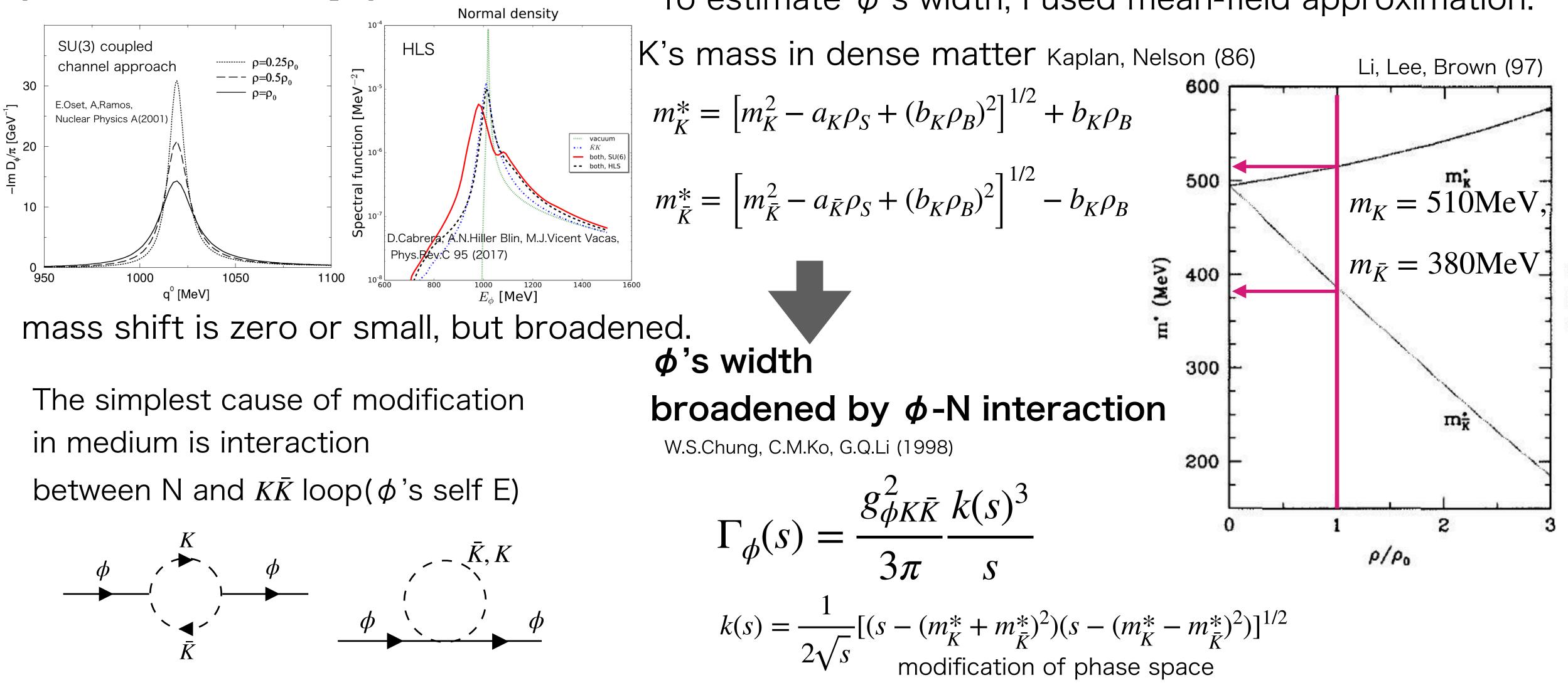


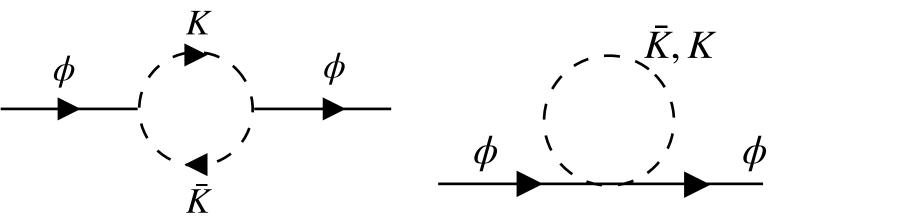




# *p-N interaction*

### $\phi$ 's modification by $\phi$ -N interaction





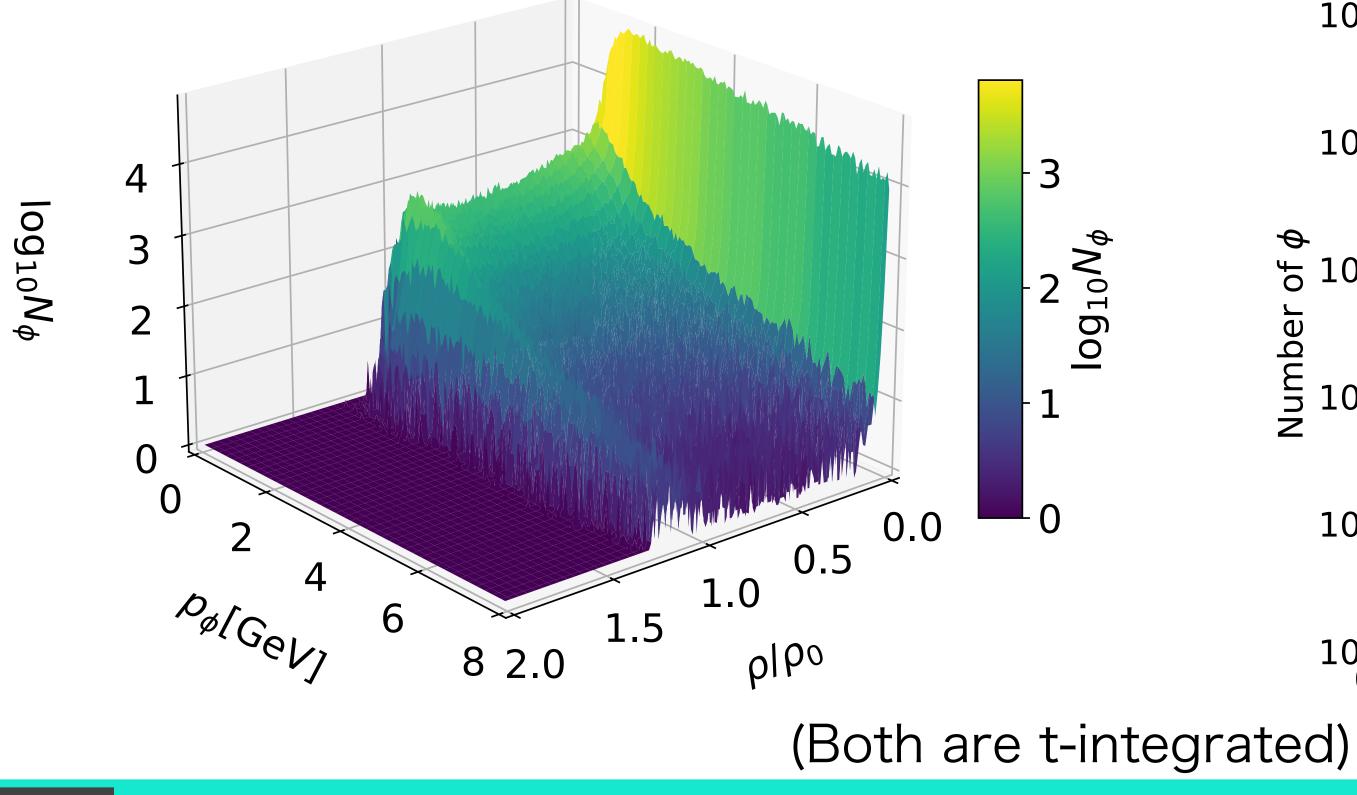
To estimate  $\phi$ 's width, I used mean-field approximation.

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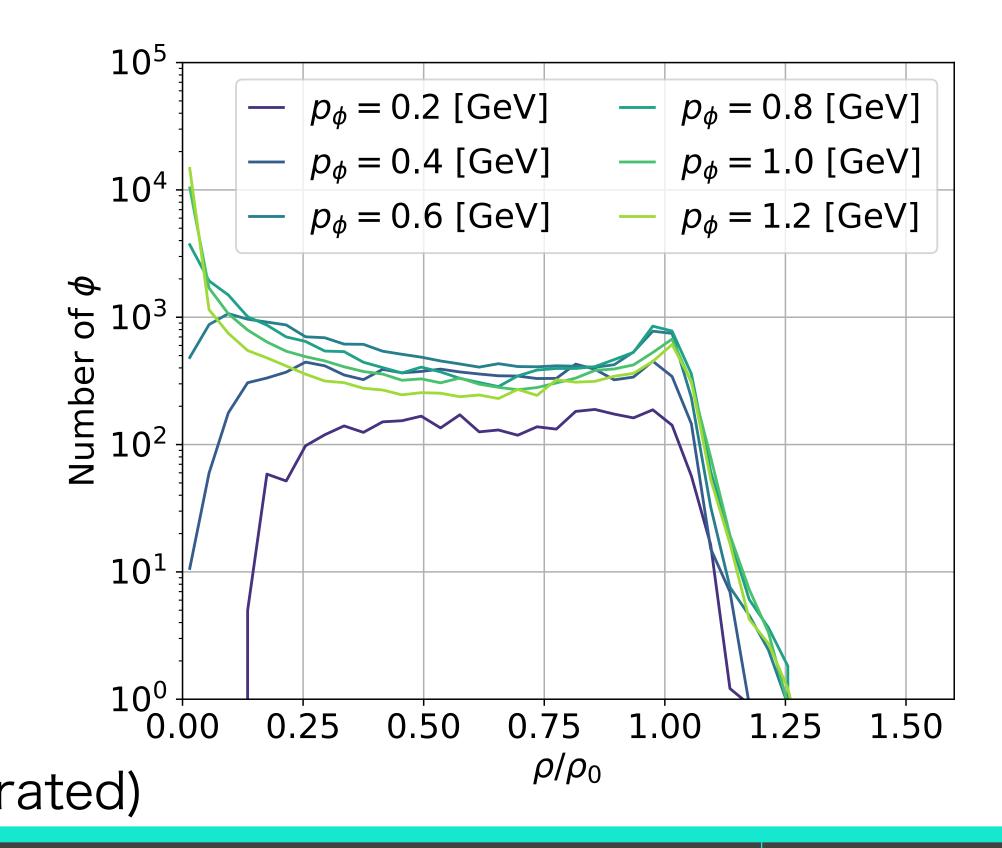


InvMassDist = 
$$\int \left[ \int \text{Im}G_V(s, p, \rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt + \int \text{Bkg}(s, p)dp \right] g(m-s)ds$$

Distribution of momentum and density which  $\phi$  meson feels when they decay is calculated by PHSD.



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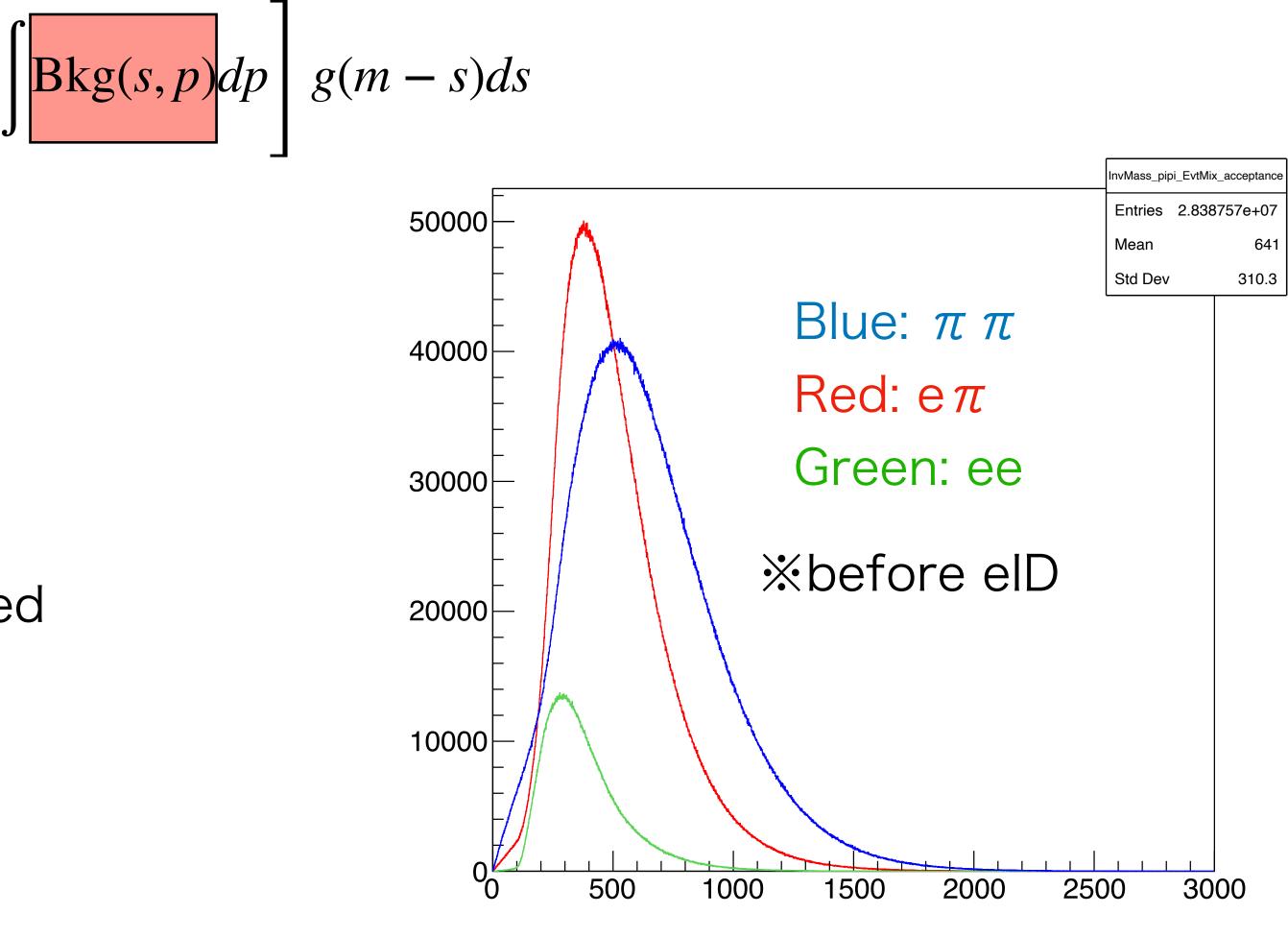
InvMassDist = 
$$\int \left[ \int \text{Im}G_V(s, p, \rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt + \int d\vec{p} d\rho dt \right]$$

Background: Simulated by JAM→Geant4 Main component of background :

 $\pi^0$ Dalitz,  $\pi^{\pm}$ ,  $\gamma$  conversion, and combinatorial.

Spectral function and background is adjusted to expected yield considering

- cross section
- acceptance
- length of beam time
- various efficiency (beam live, DAQ, Analysis, eID,  $\pi$  rejection,…)

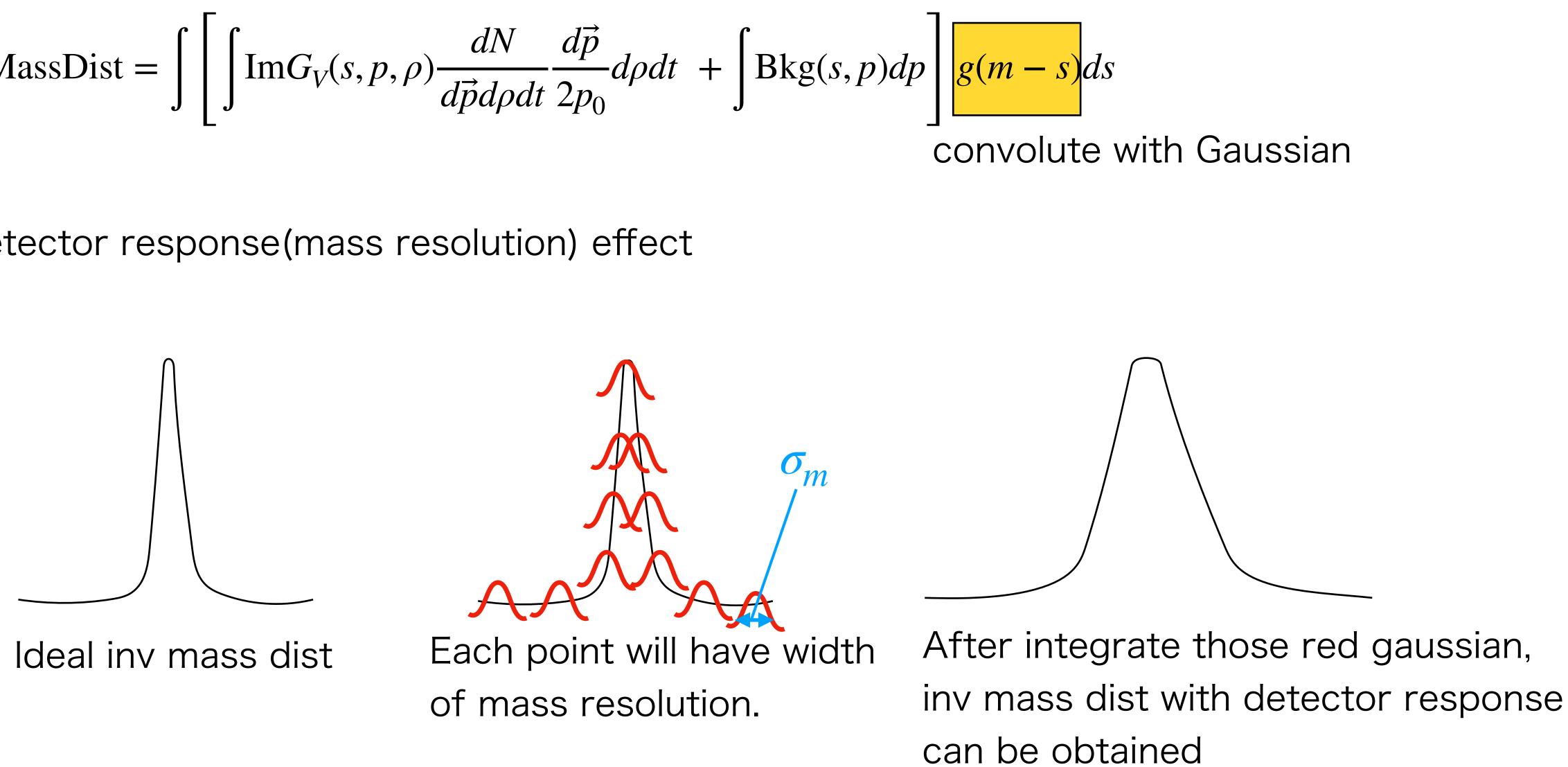






InvMassDist = 
$$\int \left[ \int \text{Im}G_V(s, p, \rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt + \right]$$

Detector response (mass resolution) effect





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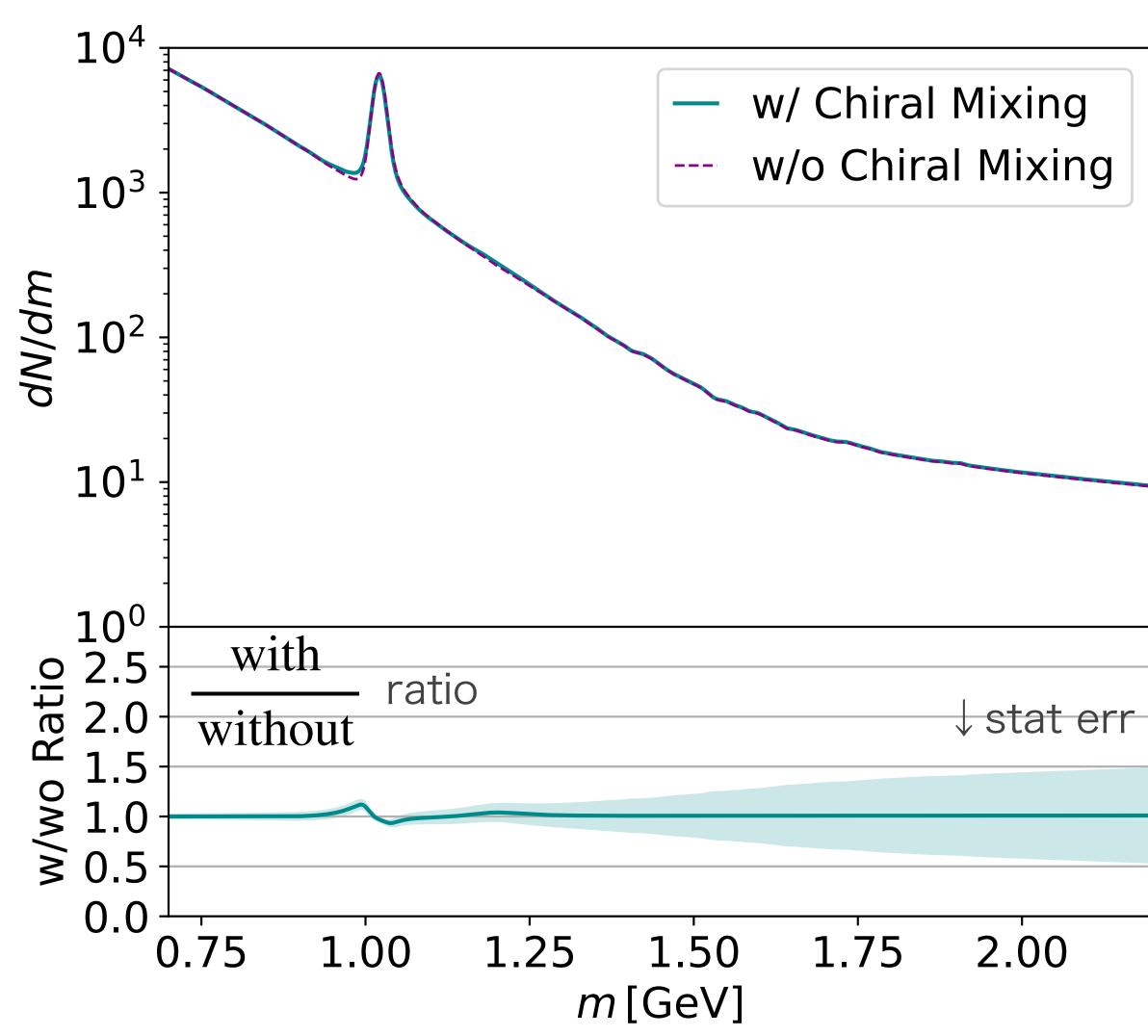




# Results

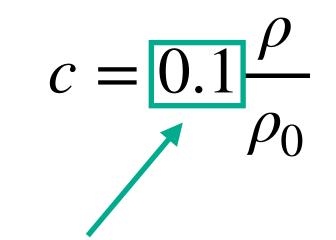
# Result with Cu target, $c=0.1\rho/\rho_0$

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR





Mixing strength has uncertainty



0.1: consistent with WZW action

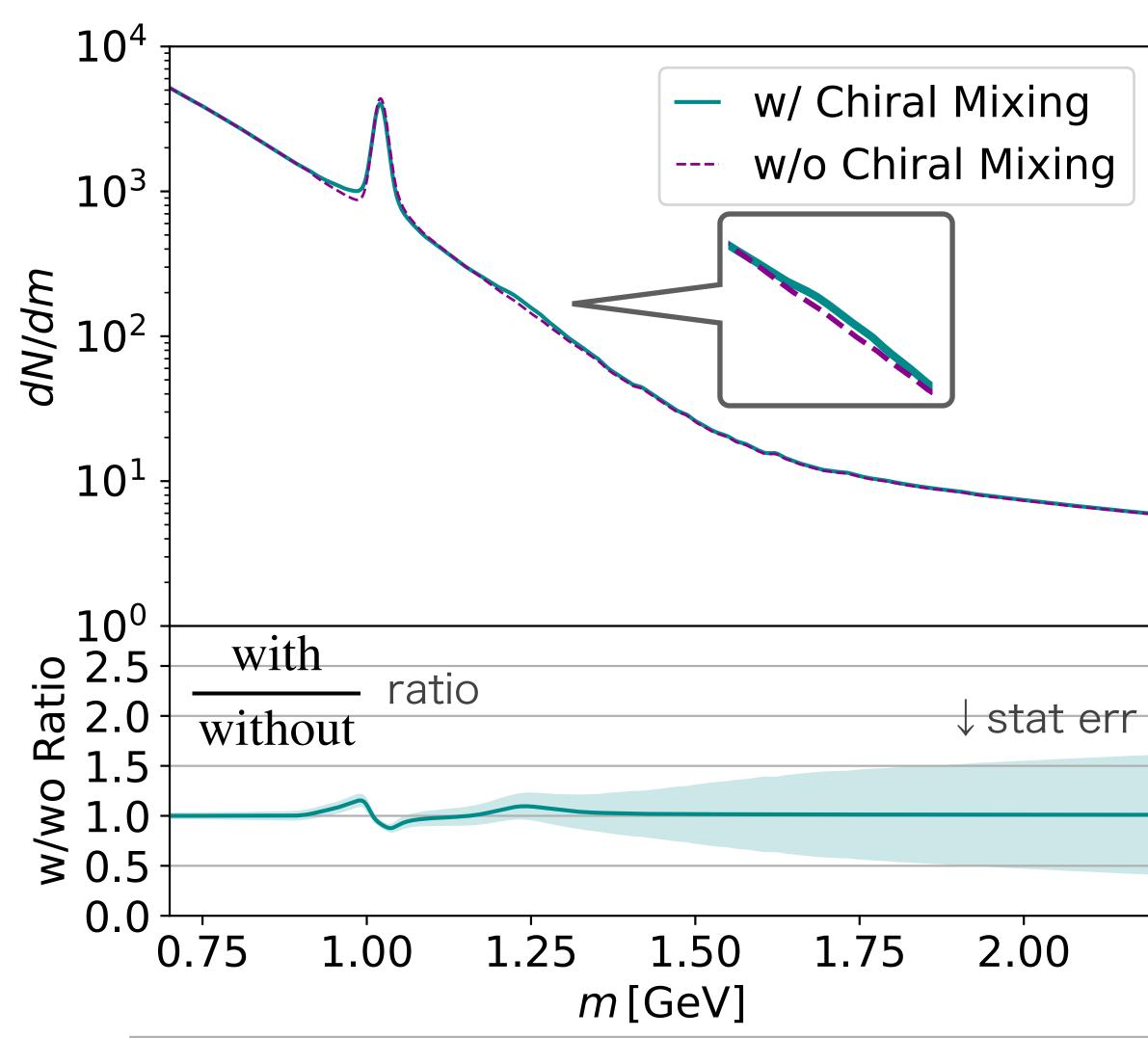
 $f_1(1420)$ 's structure is too small





# Result with Cu target, $c=0.2\rho/\rho_0$

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR



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Mixing strength has uncertainty

$$c = 0.2 \frac{\rho}{\rho_0}$$

0.1: consistent with WZW action but mean field-approx is used in this calc. There is possibility that the value is larger.

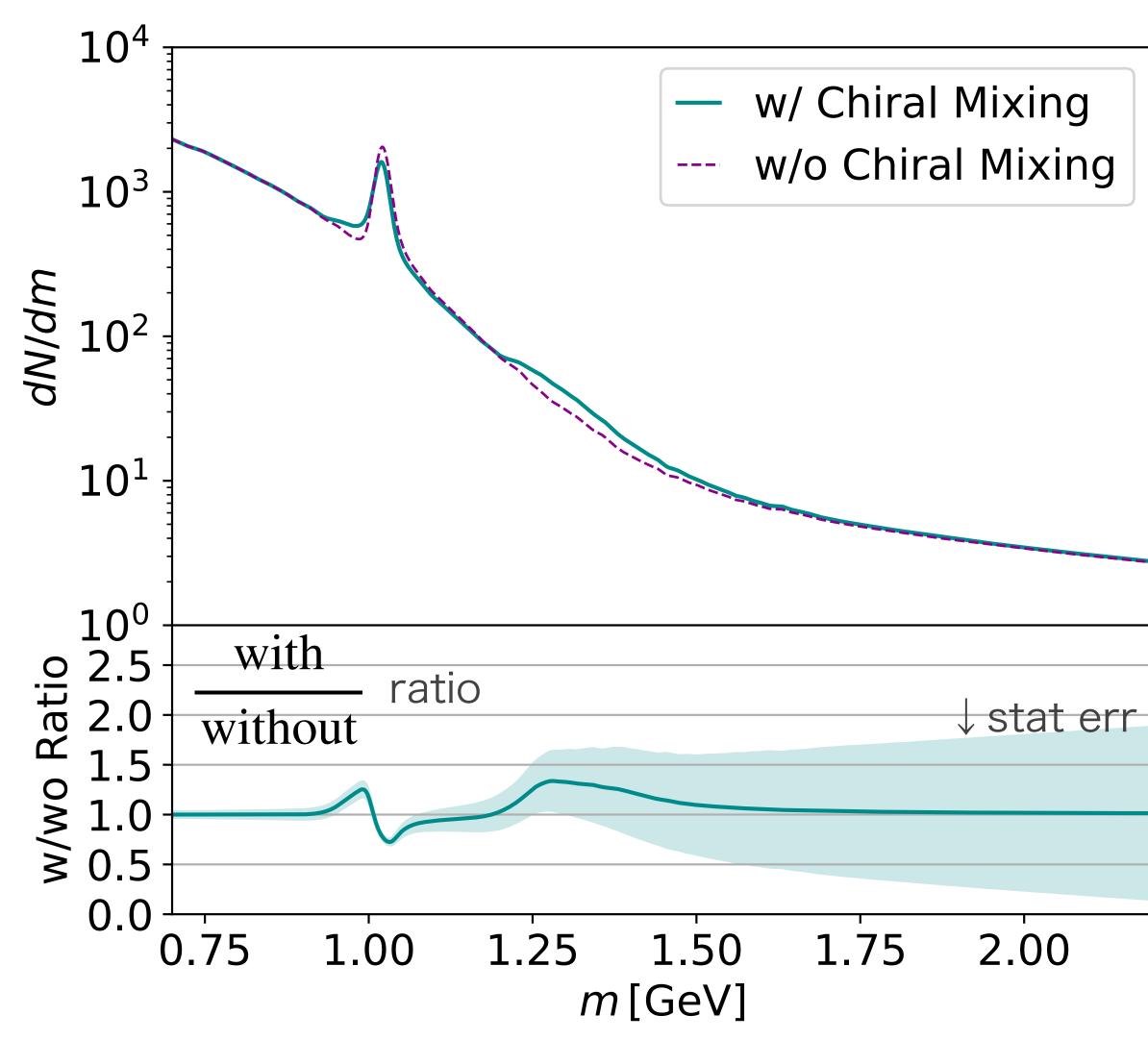
 $f_1(1420)$ 's structure is still too small.





# Result with Cu target, c=0.5p/po

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR





Mixing strength has uncertainty

$$c = 0.5 \frac{\rho}{\rho_0}$$

0.1: WZW action's expectation 1.0: holographic QCD's expectation

 $f_1(1420)$ 's structure become obvious. but still ~1  $\sigma$ 

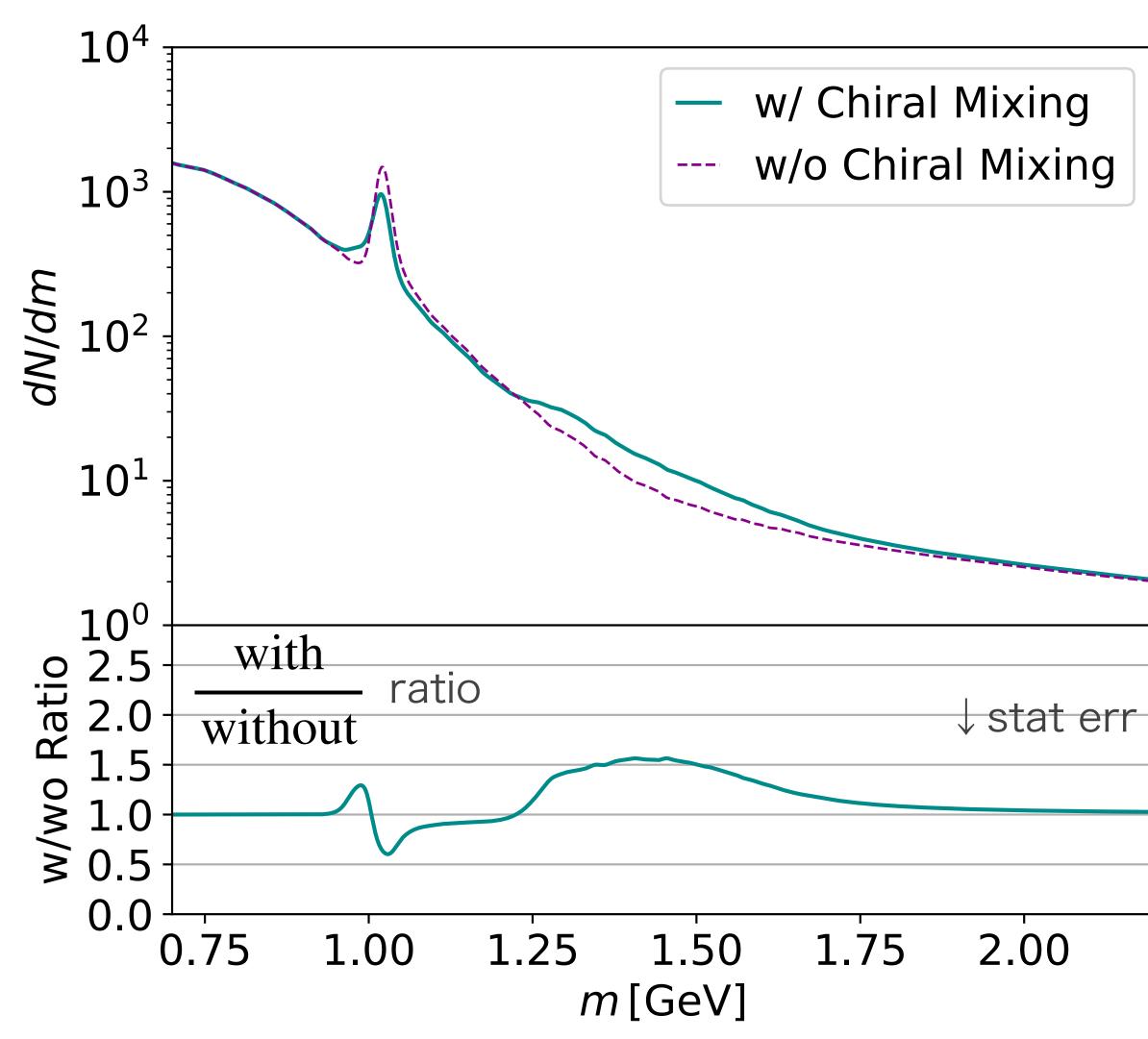






# Result with Cu target, c=1.0p/po

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR





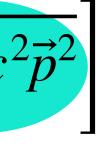
Mixing strength has uncertainty

$$c = 1.0 \frac{\rho}{\rho_0}$$

0.1: WZW action's expectation 1.0: holographic QCD's expectation

 $f_1(1420)$ 's structure become broad due to dispersion relation. Difficult to discuss mass degeneracy.

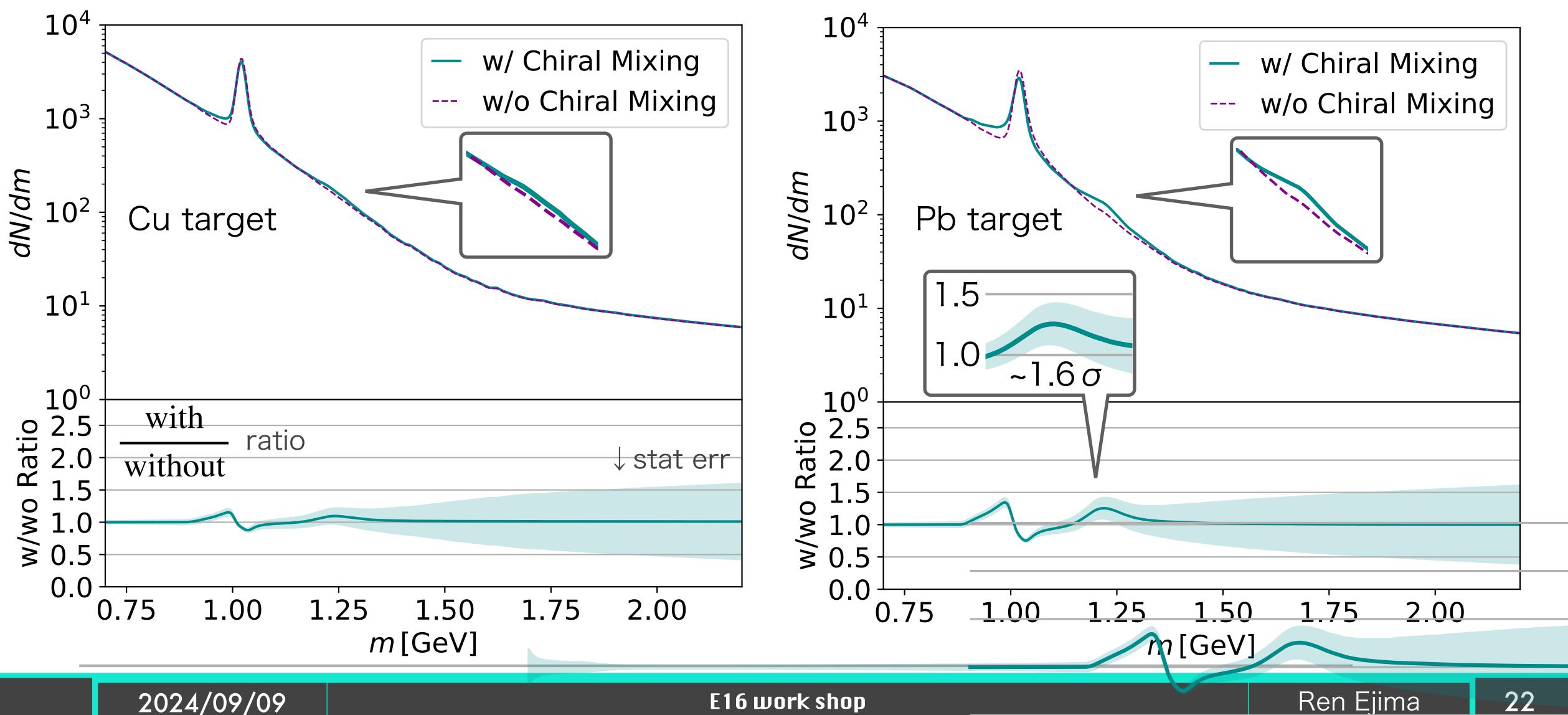
$$s = p_0^2 - \vec{p}^2 = \frac{1}{2} \left[ m_V^2 + m_A^2 \pm \sqrt{(m_A^2 - m_V^2)^2 + 16\alpha} \right]$$





# Result with Pb target, c=0.2p/po

E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR



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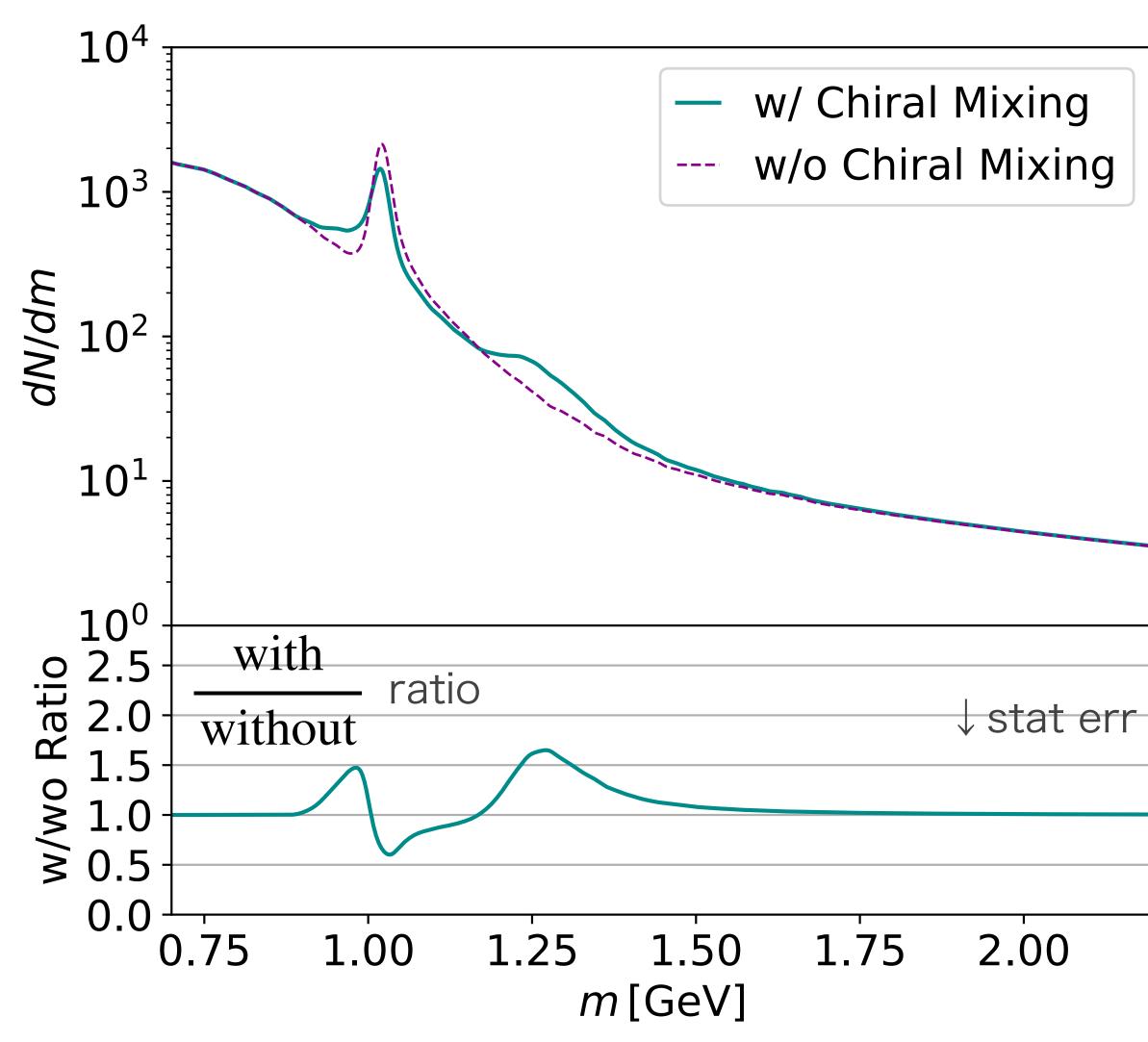


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# Result with Pb target, c=0.4p/po

Pb target, E16 Run2 statistics, 30%CSR, no dropping/broadening  $\phi$  by CSR





Mixing strength has uncertainty

$$c = 0.4 \frac{\rho}{\rho_0}$$

0.1: WZW action's expectation 1.0: holographic QCD's expectation

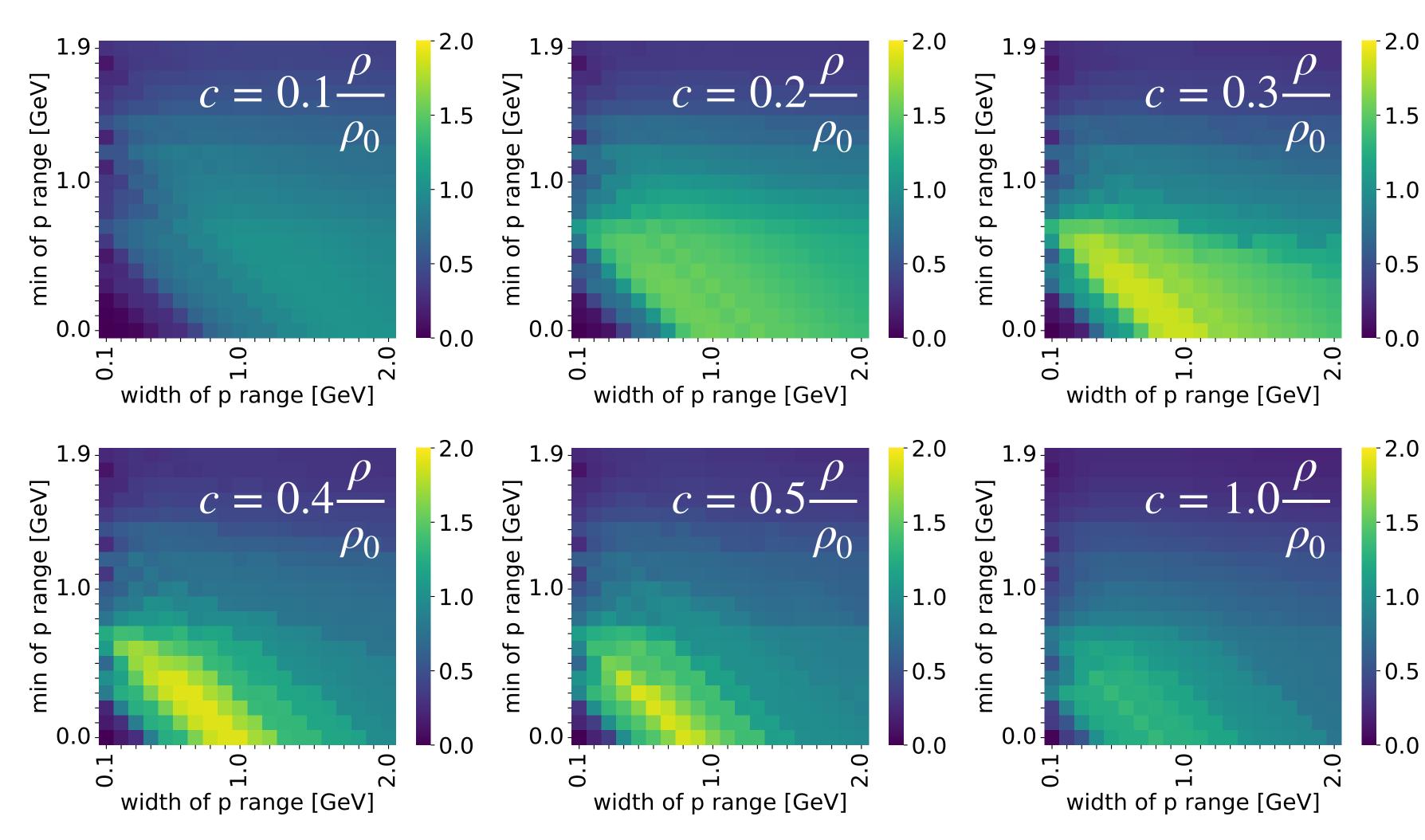
If the mixing strength is such value,  $f_1(1420)$  is visible with ~2 $\sigma$  and the structure of it is narrow to discuss mass degeneracy.







# momentum region dependence



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Heat map of significance of f1. Y-axis: min of momentum range, X-axis: width of momentum range

- decay inside nuclei
- →low momentum
- mixing effect:  $c\vec{p}$ 
  - →high momentum

Precisely selection of momentum is required

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# paper in progress

### Title: (temporary) Toward a Direct Measurement of Partial Restoration of Chiral Symmetry at J-PARC via Density-induced Chiral Mixing

### Effects of Chiral Mixing and Partial Chiral Symmetry Restoration on Di-Lepton Mass Spectrum Inside Nuclei

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Philipp Gubler<sup>‡</sup> Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan

Chihiro Sasaki<sup>§</sup> Institute of Theoretical Physics, University of Wroclaw, PL-50204 Wroclaw, Poland (Dated: August 25, 2024)

The degeneracy of the chiral partner is an ideal signal for the restoration of chiral symmetry's spontaneously breaking. We have calculated the observability of  $\theta - f_1(1420)$  degeneracy in the J-PARC E16 experiment, which measures di-electrons which comes from vector meson produced by a proton beam in a nucleus. This setup achieves a finite baryon density and almost zero temperature, both beam in a nucleus - inflored parameters a limit our join using that allows zero drawn induced by d V-A mixing, in dense matter, occurs differently than with conventional diagram induced by an field in hot matter. In dense matter, V-A mixing will be induced by anomaly. The r w that  $\phi - f_1(1420)$  mixing can be observed around 1 $\sigma$  with the Run2 statistics planned fc

A large part of hadron masses are explained by spon-eous breaking of chiral symmetry. It is expected that spontaneously broken chiral symmetry is recovered taneous oreasing of chiral symmetry. It is expected unta the spontaneously broken chiral symmetry is recovered in a medium with finite temperature or density, such as these produced by bick approximation colliging or its. Spectrometers specialized for low mass di-electr in a medium with finite temperature or density, such as those produced by high-energy heavy-ion collisions or fixed-target experiments by a lot of theoretical calculation [1–4]. However, experiments have measured the masses of hadrons in such medium to verify it. One of the most common measurement techniques is the measurement of vector meson masses via di-lepton[5–8] because leptons do not interact strongly with medium. In the KEK-PS E325 experiment, is one such example, the mass distribution of vector mesons in much avenum[9]. In the E325 experiment, the  $\phi$  meson showed a mass hift of 3% with the Cu targets when the slow  $\phi$  meson

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son in the CBELSA-TAPS experiment, change was observed here either[11]. ' tained from the E325 experiment were a n order to solve these problems, J-PARC will condu-

In the E325 experiment, the  $\phi$  meson showed a mass selected. On the other hand, in the CLAS experi-ment of J-Lab, no significant statistic was obtained a three distances are also depends on chiral symmetry restoration). As a famous example, the results are a significant mass shift was observed [10]. As for  $\rho$  and  $\omega$  meson, a significant mass shift was observed in the CLAS experiment, whereas no significant mass shift was reported in the CLAS experiment [10]. Similarly, an at-tempt was made to measure the mass change of  $\omega$  me-describe that the vector meson interacts with the medium.

cause broadening with and/or dropping mass[14-18]. Unlike the hadronic models, the QCD sum rule, which treats the expectation value of the vacuum condensate, also treats the interaction of the vector meson with the nability with Knot-ima University, 1-3-ma 739-8526, Japan; is expected to have a positive mass shift in a small r

- w/ Chiral Mixing - w/o Chiral Mixing Cu target, 30% CSR at  $\rho_0$  0.3 [GeV] $<math>c = 1.0 \frac{\rho}{\rho_0}$  [GeV]

regative mass shift as the a, w increases [19].
Furthermore, recent measurements of the correlation function between \u03c6 messon and protons [30].
Furthermore, this correlation function is in good agreement with the HAL QCD calculation[21]. This septiment arises the correlation function is in good agreement with the HAL QCD calculation[21]. This septiment arises to contradict the prediction of the interaction between \u03c6 messon and motions is most of the set of the interaction between \u03c6 messon and medican by a model, and it is still server defined to the interaction between phi messon and nucleon, and is still server difficult to correlative set presents resit.
Anyway, as long as the mass of hadrons is measured, and it is still server degeneracy of the final partner have final partner by interaction between the medium is invertable. To overcall, and third partners have observe the degeneracy of the chiral partner by the interaction between the medium and hadrons, fir the hadron field thas chiral symmetry, then the interfunction field viblance of the interaction structure the seame and options for the final partner by a subjected to another chiral transformation subject another chiral transformation symmetry is subject to acother direction structure the field has chiral symmetry is subjected to acother chiral symmetry.
Hore have a partner is called a chiral partner. Since divide the seame distribution due to the field the field has chiral symmetry.
Hore have a partner is called a chiral partner is an optimation of the vibration field. This is symmetry is broken in a vacuum, the chiral partner is an optimation of the vibration field shares of the field has chiral symmetry.
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the chiral partner of a vector meson is an axial-vector meson, and the axial-vector meson cannot decay directly in the vector meson cannot decay directly in meson, and the axial-vector meson cannot decay directly into a di-lepton. Only through the process of V-A mix-ing, the axial-vector meson can decay into a di-lepton by changing into a vector meson that inherits the mass of the axial-vector meson.

changing into a vector meson that inherits the mass of the axial-vector meson. The chiral partner of the  $\phi$  meson is  $f_1(1420)$ . However,  $f_1(1420)$  is not observed in the di-lepton measurements of many experiments, therefore, degeneracy of the target partner is not observed. The reason for this is that may heavy-ion collision experiments are conducted at very high temperatures, and the coupling constants for V-A mixing at finite temperatures vanish at the temperature of the chiral phase transition[22]. Furthermore, even the temperature of the basel by write flaught, but the signal of  $f_1(1420)$ , which is heavier than  $\phi$ , is very small due to the strong slope of the Bose-Einstein distribution created by the thermal di-lepton[23]. However, unlike V-A mixing induced by pion field which occurs at finite temperature, begraphic QCD predicts that vector mesons and axial-vector mesons mix directly. Also, WZW action has the same shape as the Chern-Simons term. The higher order terms affect the width of the spectrum due

• Even if the mixing strength is small, larger medium size makes easier too find  $f_1(1420)$  meson's signal

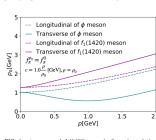
rmation and has chiral and parity symmetry is as follows

to the loop diagram, but we will only consider the leading order in this study. By the way, some of the leading order terms include interactions with pions, however, they are eliminated by the  $\epsilon$  tensor. The expected strength of mixing, c, is  $c=1.0\times\rho/\rho_0$  for M2ZW action[26]. However, holographic QCD requires infinite action[26]. However, holographic QCD requires infinite action[26]. However, holographic QCD requires infinite  $N_c$ , which is unrealistic, and this effect may be responsible for the too strong mixing strength. The following discovering relations of tensors of ten

The following dispersion relations of transverse wave re also obtained from this Lagrangian  $\vec{p_0}^2 - \vec{p}^2 = \frac{1}{2} \left[ m_V^2 + m_A^2 \pm \sqrt{(m_A^2 - m_V^2)^2 + 16c^2 \vec{p}^2} \right]$ 

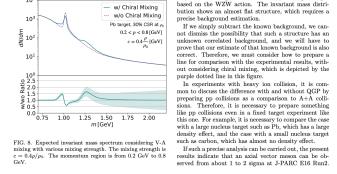
reston relation. The dispersion relations are illustrated in Figure 1 and This dispersion relation is Taylor expanded in terms of nomentum as follows.  $(A^2)$   $(A^2)$  (

### (4) higher order. Therefore, in summary, V-A mixing at finite density has a coupling constant proportional to the baryon density, and the effect of mixing is enhanced as the masses of the vector meson and axial-vector meson degenerate. Compared to the Figure 1, the mass difference is smaller in Figure 2, and the dispersion relation of the transverse has changed significantly. However, this expansion determines the standard definition of the transverse has changed in the dispersion relation of the tr ficantly. However, this expansion does not say the lispersion relation diverges when the mass is con ly degenerate, since there are naturally terms of eve



with the mixing strength c = 1.0 GeV. Transverse of them are modified by chiral mixing term.  $m_V = 1.02$  GeV and  $m_A = 1.42$  GeV (masses in usual vacuum).

has a finite density lower than the nuclear density, has a momentum of around 0.6 GeV according to the PHSD results (Figure 4). Therefore, such momentum bands cre-ate a structure that ranges from a mass of  $f_1(1420)$  at slightly lower density. In addition, the phi meson with higher momentum the decays while fooling the muclear density and bar of  $f_1(1420)$  the structure that ranges from a mass of



the transverse  $\phi$  meson, the transverse  $\phi$  meson make a than Cu, as the target. The larger the nuclear radius, the tail to left side of the peak while the longitudinal  $\phi$  meson the target. The larger the nuclear radius, the peaks at 1.02 GeV. In general, such at all is considered time is larger. In chiral mixing at finite density, the larger to be caused by mass shift of the  $\phi$  meson due to partial restoration of chiral symmetry or distortion of the ite density can also produce such a tail. We summarize results with Cu target as below.

FIG. 6. Expected invariant mass spectrum considering V-A mixing with various mixing strength. Left: The mixing strength is  $c = 0.1 \rho/\rho_0$ . The momentum region is from 0.4 GeV to 1.6 GeV. Center: The mixing strength is  $c = 0.2 \rho/\rho_0$  The momentum region is from 0.5 GeV to 1.2 GeV. Right: The mixing strength is  $c = 1.0 \rho/\rho_0$ . The momentum region is from 0.3 GeV to 0.8 GeV. We selected proper momentum region to observe  $f_1(1420)$  meson with large  $\sigma$  in each case.

 The signal of f<sub>1</sub>(1420) meson is difficult to find with small mixing strength though the signal is not small in spectral function(Figure 3). lmost all  $\phi$  meson decay outside nuclei.

 Larger nuclei is necessary. • Large mixing strength makes clear difference, how-

- Too large mixing strength change dispersion

aa restoration or chirat symmetry or distortion or the pectral function of the  $\phi$  meson due to interaction with he medium, but it is also found that anomaly effects at have already continued in the case of the Cu target, if the momentum range is wide and the mixing strength is also large, the distribution of  $f_1(1420)$  becomes broad, and the degeneracy of the chiral partner cannot be discussed. The calculation results are shown below for a Pb target, which is basically only a merit (Figure 7). However, the statistics in this calculation are for a Pb target with exactly the same length of beamtime as the beamtime of the Cu target planned for E16 Run2.

The change to a Pb target makes it easier to deca inside the nucleus than a Cu target, and the  $f_1(1420$ simultice and the second target to see for all mining strength relation too much. - Each momentum's  $f_1(1420)$  meson peak i gis tributed widely, as also we can see it at Figure 3. - Mass degeneracy can not be discussed with large mixing strength. • Chiral mixing as have contribution to vector me-son's tail on di-lepton invariant mass distribution due to changing dispersion relation. B. Pb target Next, as an option to make the  $f_1(1420)$  signal more visible, we will try different target types in the calcula-tion. Let us choose Pb, which has a larger nuclear radius

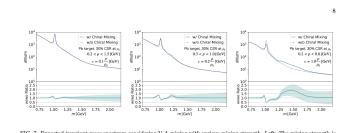


FIG. 1. Expected invariant mass spectrum to according to the form of the spectrum of the spec

### gests that if we store enough statistics to make $f_1(1420)$ observable at 5 sigma in this experimental setup, then $\phi$ and $f_1(1420)$ are already close enough at the nuclear density to be able to discuss chiral partner degeneracy. The magnitude of the statistical uncertainty in this cal-culation indicates that $f_1(1420)$ is observable at about C. Mixing strength dependence of significance of $f_1(1420)$

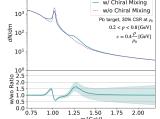
φ and  $f_1(1420)$  are already close enough at the nuclear density to be able to discuss chiral partner degeneracy. The magnitude of the statistical uncertainty in this cal-culation indicates that  $f_1(1420)$  is observable at about 1.6 sigma. Since this assumption is not so unrealistic, it might be a good idea to store more statistics on the Y-R. Holographic QCD reducts that these large color de-gress of freedom induce vector condensation and exter-is still broad, as already confirmed for the Cu target. rget. In the case of  $c = 1.0\rho/\rho_0$ , it is still difficult to discuss he degeneracy of the chiral partner because the structure is still broad, as already confirmed for the Cu target. However, even in this case, since the  $\phi$  meson that decays inside the nucleus has increased due to the increase in the nuclear radius, the  $f_1(1420)$  signal has also increased, and increase in the seven with a higher confidence level than increase in the seven with the seven with the seven with the seven with the seven wither the seven wither the seven wither the seven with the se Star radius, the  $f_1(x,y)$  represents the higher confidence level than the Cu target. We summarize results with Pb target as below. Twas found that the case  $c = 0.4 \rho/\rho_0$  gave the highest confidence level for  $f_1(1420)$  (Figure 8).

son why the signal of  $f_1(1420)$  is easiest to see at such an

(Center of Figure 7).
- Large medium size increased the number of phenometry is a sense of the sense of

the nuclear density to a mass of  $f_1(1420)$  at a slightly lower density. In addition, the pair measus with higher momentum that decays while feeling the nuclear density also appears on the heavier side than the one that de-cays while feeling the nuclear density with lower momen-tum, because the dispersion relation changes greatly with higher momentum. That is just right and including momentum around 0.6 GeV and higher momentum into iterating strength that is just right and including momentum around 0.6 GeV and higher momentum into iterating strength that is just right and including momentum. Such A and B will be appear at the same mass region with exquisite mixing strength, but still appears on the heavier side to some extent due to the low degenerate due to the nuclear sufface, and B, which is more degenerate due to the nuclear sufface, and B, which is more degenerate due to the nuclear sufface, and B, which is gream on the neavier side to some extent. It is the upper limit of the momentum trange, this start due horizontal axces is the upper limit of the some mass region with exquisite mixing strength. Such is set and horizontal axces is the upper limit is stand and horizontal axces is the upper limit is stand and horizontal axces is the upper limit is stagnificance will remain the same ever is a due horizontal axces is the upper limit, which is sout 1 GeV. If the upper limit is raised above that level and the width of the momentum range, the significance fulls, as shown in the parentage of decay outside the nucleus will increase and the significance sufficience fulls, as shown in the parentage and the lower limit, which is tept unchanged and the lower limit, basing informace fulls, as shown in the or to apper limit, the significance fulls, as shown in the or the state store scenaple. This is simply due to the drop in statistics caused by the narrowing of the momentur trange.

tum range. In any case, the signal of  $f_1(1420)$  is quite small and only about 1.6 sigma is visible in the mixing strength based on the WZW action. The invariant mass distri-bution shows an almost flat structure, which requires a precise background estimation.



precise background estimation. If we simply subtract the known background, we can not dismiss the possibility that such a structure has a  $c = 0.4 \frac{\rho}{\rho_0}$  [GeV] unknown correlated background, and we will have to prove that our estimate of that known background is also correct. Therefore, we must consider how to prepare a line for comparison with the experimental results, with-out considering chiral mixing, which is depicted by the purple dotted line in this figure.

### 2024/09/09

### R. Ejima, P. Gubler, C. Sasaki, K. Shigaki To be submitted to PRC

Longitudinal of  $\phi$  meson Transverse of  $\phi$  meson Longitudinal of  $f_1(1420)$  meson - Transverse of  $f_1(1420)$  meson  $b = 0.7 f_{\pi}^{0}$ 

=  $1.0 \frac{\rho}{\rho_0}$  [GeV],  $\rho = \rho_0$ 

0.0

0.5 1.0 1.5 2.0 p[GeV]

As an example, we discuss how much axial-vector me-son is visible through chiral mixing and how much is de-generate to vector meson in the J-PARC E16 experiment, which treats nuclei as finite density medium. In the J-PARC E16 experiment, a phi meson is produced in nu-clei by injecting proton beam. This  $\phi$  meson is observed by reconstructing the invariant mass of the di-electron. Therefore, we estimate the invariant mass distribution of di-electrons considering chiral mixing at finite density as trons considering chiral mixing at finite density as  $\frac{dN_{\phi}}{ds} = \int \mathrm{Im}G_V(\vec{p}, s, \rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt \qquad (5)$ 

 $\frac{dN}{dm} = \int \left[ \frac{dN_{\phi}}{ds} + \frac{dN_{\text{Bkg}}}{ds} \right] g(m-s)ds \quad (6)$ Here, the spectral function  $ImG_V$  is a function of mo-Here, the spectral mitcher may is a function of mergy and density, taking into account chi-ral mixing at finite density as calculated above. And  $dN/dpd\rho dt$  is the distribution of density felt by  $\phi$  at th-time and point where the  $\phi$  meson decaved and the distribution of the momentum of  $\phi$  at that time, which is used for weighting in integrating the spectral function. The



/ obtained in section II, but since it is in a medium, accessary to take into account the effect of the  $\phi - N$ action and the chiral symmetry restoration.

 $k(s) = \frac{1}{2\sqrt{s}} [(s - (m_K^* + m_{\bar{K}}^*)^2)(s - (m_K^* - m_{\bar{K}}^*)^2)]^{1/2}$ 

2. The Effect of Chiral Symmetry Restoration

ained is  $\Gamma(s = m_{\phi}^2) \sim 40 \text{MeV}$ 

(10)

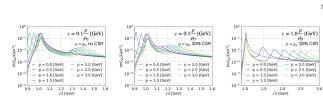
 $m_A^2 - m_V^2 = g^2 \frac{m_A^2}{m_V^2} f_{\pi}^2$  (11) 1. The Effect of  $\phi - N$  Interaction The main decay channel of the  $\phi$  meson is  $K\bar{K}$ ; the self-energy of the  $\phi$  meson is the sum of loops such as  $\phi \to K\bar{K} \to \phi$ , which interact with nucleons. In this paper, we treat the  $\phi - N$  interaction using a mean-field upproximation and estimate the broaden width of  $\phi$  in The masses of the kaon and anti-kaon in a finite density viluum are expressed as [27]

 $\Gamma_{f_1(1420)}(s) \sim \Gamma_{f_1(1420)}^{\text{vac}} \left(\frac{f_{\pi}^{\text{med}}}{f_{\pi}^{\text{vac}}}\right)^s$  $m_K^* = [m_K^2 - a_K \rho_S + (b_K \rho_B)^2]^{1/2} + b_K \rho_B$  (7)

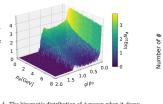
 $+\Gamma_{\phi}^{\text{med}}(s, f_{\pi}^{\text{med}})\left(1 - \left(\frac{f_{\pi}^{\text{med}}}{f_{\pi}^{\text{vac}}}\right)^{2}\right)$  (12)  $m_{\bar{K}}^* = [m_{\bar{K}}^2 - a_{\bar{K}}\rho_S + (b_K\rho_B)^2]^{1/2} - b_K\rho_B$  (8)

where  $\rho_s$  is the scalar density. Also,  $a_k = a_k = \sum_{K N} f_{\pi^*}^2$ and  $b_K = 3/(8f_{\pi^*}^2)$ . Since the Kaon-Nucleon signa term has large uncertainty, we instead use  $a_K = 0.22$  GeV and  $a_K^2 = 0.45$  GeV from the data of kaon production in heavy ion collision experiments[38]. This gave  $m_K =$ 500MeV and  $m_K^2 = 3300$  W4 a tornal nuclear density. Then, from the mass of the kaon in the medium.[29]  $\Gamma_{\phi,med}(s) = \frac{g_{\sigma,K}^2}{3\pi} \frac{\kappa(s)^3}{s}$  (9)  $k(s) = \frac{1}{-c} [(s - (m_K^* + m_K^*)^2)]s(s - (m_K^* - m_K^*)^2)]^{1/2}$ 

Here, the coupling constant is  $g_{\phi K K}/4\pi = 1.69$ . Accord, ing to a study using the SU(3) coupled channel approach,  $\phi$  has a small mass shift in medium[30]. Therefore, for simplicity, we will estimate the mass shift as zero this time. The effective width of  $\phi$  in the medium thus ob- $\phi$  meson inside the nucleus and to calculate momentum a atom-manual string Dynamics (PHSD) transport approach, which solves the equation of motion of the off-shell  $\phi$  meson to take account for the scattering of the  $\phi$  meson inside the nucleus and to calculate momentum of  $\phi$  and density  $\phi$  feels when the  $\phi$  meson decays. As a result, the following distributions were obtained. From this calculation, we can see almost all  $\phi$  mesor decays outside of the nuclei. Inside the nuclei, many of meson feels  $\rho = \rho_0$  but some of them feels smaller den experiments on pionic atoms suggest that chiral sym 



G. 3. Spectral function of  $\phi$  meson with chiral mixing in nuclear density. Left: No chiral symmetry restoration. The mixin sength c = 0.1 GeV. Center: 30% chiral symmetry restoration. The mixing strength is the same as left figure. Right: 30% rial symmetry restoration and the mixing strength is c = 1.0 GeV. Dispersion relation is modified by mixing term and i alsee 3 peaks on each spectral function. Left peak is transverse component of  $\phi$  meson and center peak around 1.02 GeV i guidualia component of it. Right peak is transverse ( $f_1(420)$  meson's structure which mixed with transverse  $\phi$  meson.



The background was simulated p+A 30 GeV collisions and Geant4 to simulate the interaction with the detector of the J-PARC E16 experiment. The background processes considered in this study are the daitz decay of  $\pi^0$ , the case of mistakenly identifying a charged pion an electron,  $\gamma$  conversion, and combinatorial background. The background and  $\phi$  meson obtained in this way were

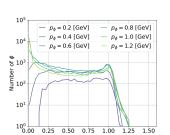


FIG. 5. Density distribution which  $\phi$  meson feels when it decay.

tectors, and length of the beam-time in Run2 of the J-PARC E16 experiment. By the way, the phi meson and its chiral partner are calculated based on the chiral effec-tive theory, while the other backgrounds are calculated in pletely independent way, Monte Carlo simulation tion cross section, various efficiencies of DAQ and de-

f the statistic statis

• Chiral mixing in dense matter

Chiral mixing has cp(mixing strength and 3-

- Dispersion relation is changed largely by large Chiral mixing is enhanced also by mass degen-

Mixing strength is proportional to density.

- Proportional constant of mixing strength is a free parameter (WZW action  $\sim 0.1~{\rm GeV},$  holographic QCD  $\sim 1.0~{\rm GeV}).$ 

### • J-PARC E16 experiment p+A(Fixed target)(C.Cu.Pb.etc...) reaction.

There is a di-electron spectrometer which is specialized to measure  $\phi$  meson.

- There is not only  $\phi$  meson which decay inside Information range, we can expect to see a peak-new studie ture below 1.42 GeV, like a spectral function (Figure 3). However, narrowing the momentum range will increase the statistical uncertainty, and since chiral mixing always appears in the equation in the form of  $\sigma_1$ , the signal will be smaller in the smaller absolute momentum range. nuclei, but also outside nuclei. Larger momentum makes difficult to decay in-side nuclei, though chiral mixing will be en-

### anced by large momentum A. Cu target

First of all, we show the calculation results for the target, which is the main target used in

[38] M. Nakao et al., Minimizing dead time of the belle II

TIPP2014, 202 (2014), in:Proc. 3rd Internat

For small mixing strengths, as expected by the WZW action, the  $f_1(1420)$  signal is almost invisible. On the other hand, for large mixing strength as expected by Holograpic QCD,  $f_1(1420)$  has a broad structure from 1.25 GeV to 1.75 GeV. If we look closely at the case  $c = 0.2a/\rho_0$ , we can faintly see a small structure around 1.25 GeV. However, this is not enough structure to be availy comfound the structure to be

easily confirmed by experiment. Even in the case  $c = 1.0\rho/\rho_0$ , though the ratio of the with/without of d ral mixing is large, the statistical uncertainty is so lar that  $f_1(1420)$  is only visible at about 1 sigma. Further

more, the structure is broad, and since the structure is built around 1.42 GeV, the mass of  $f_1(1420)$  in vacuum it is not possible to discuss the degeneracy of the chiral partner associated with the restoration of chiral symme-

ry. The reason for this broad structure is that the mixin

we choose a large absolute momentum region, the sign will be larger, but the density effect cannot be seen l

Also, due to the change in the dispersion relation of

Ference on Technology and Instrumentation in Particle Physics (TIPP 2014), Amsterdam, Netherlands, 2014. C. Altunbas et al., Construction, test and commissioning of the triple-gem tracking detector for compass, Nuclean Instruments and Methods in Physics Research Section A Instruments and Methods in Physics Research Section A Accelerators, Spectrometers, Detectors and Associated Equipment 490, 177 (2002). 48] D. Abbaneo et al., Quality control for the first large ar-eas of triple-GEM chambers for the CMS endcaps, EPJ Web Conf. 174, 03003 (2018), in:Proc. 4th Internationa Conference on Micro Pattern Gaseous Detectors (MPGI 2015), Trieste, Italy, 2015. 19] F. Sauli, GEM: A new concept for electron amplification

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urthermore, if an axial vector meson is observed, it sug-ests that the mass change is sufficiently large to discuss or degeneracy associated with the restoration of sponta-eous chiral symmetry breaking. We summarize results with each mixing strength. The larger the mixing strength, the less likely it is that the  $f_1(1420)$  signal will be visible.

- There is a mixing strength where the position where the  $f_1(1420)$  signal appears due to chiral mixing at the nuclear density coincides with the position
- For an appropriate momentum slice and ideal mix-ing strength, f<sub>1</sub>(1420) can be observed at about 2 sigma in the J-PARC E16 Run2 statistics and
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- Pb target, and the structure of  $f_1(1420)$  is narrow enough to discuss degeneracy. V. SUMMARY
- In this paper, we propose a new method to e
- symmetry breaking and hadron masses by observing the degeneracy of the chiral partner through a completely new V-A mixing induced by finite density and as an where another momentum  $f_1(120)$  signal appears due to chiral mixing at a lower density near the nuclear surface, and at such a mixing strength, the signal is most significantly observed. The choice of momentum region is also important, and it is important to precisely slice the momentum region below 1 GeV.
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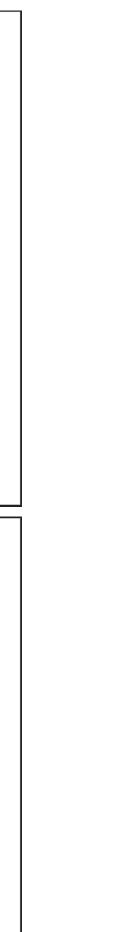
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Ren Ejima

### E16 work shop

calculated ustribution of  $\phi$  meson when it decay, calculated by the PHSD transport approach. Color bar shows  $\log_{10}N_{\phi}$ . This calculation is for p+Pb 30GeV. density than  $\rho_0$ . At the beginning of the p+A collision, proton push nuclei then little higher density will be real-C. Background and detector's response The background was simulated using Monte Carlo





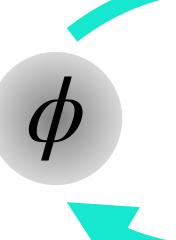
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# Summary

### To verify the relationship between chiral symmetry and hadron's mass,



Vector

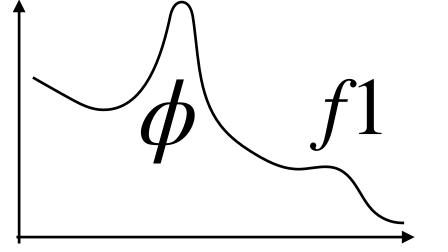


Axial-vector

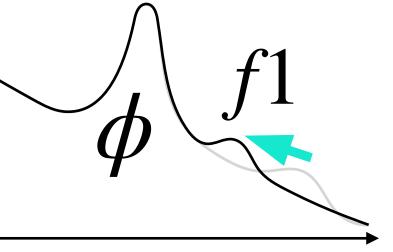
Chiral transformation

Chiral partner should have

exactly the same mass in chiral limit







In vacuum

In dense matter

Mass dist. is degenerated in dense matter.

This is equivalent to partial CSR.

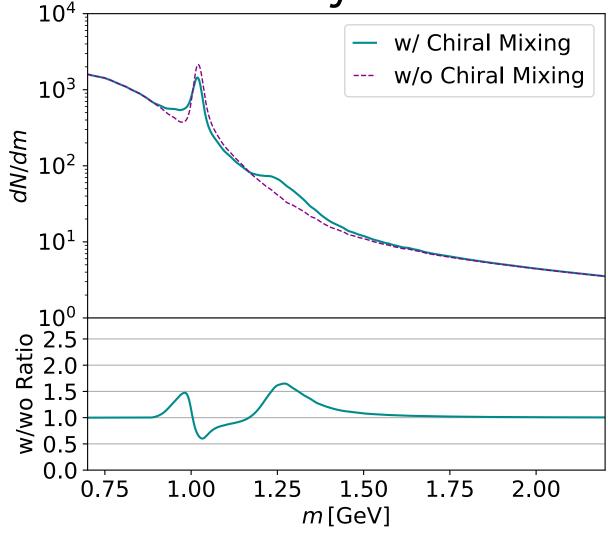
2024/09/09

Di-lepton is clear probe in quark matter but axial-vector can't decay into di-lepton directly. We have to use Chiral Mixing:

$$L = 2c\epsilon^{0\mu\nu\lambda} \mathrm{tr} \left[ \partial_{\mu}V_{\nu} \cdot A_{\lambda} + \partial_{\mu}A_{\nu} \cdot V_{\lambda} \right]$$

Chiral mixing in dense matter

is totally different from one in hot matter

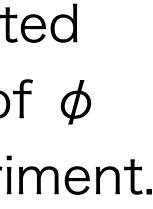


We calculated expected invariant mass dist. of  $\phi$ in J-PARC E16 experiment.

visible with  $2\sigma \cdots$ ?











# Low energy theorem

$$G_{V}^{\mu\nu}(T) = (1 - \epsilon)G_{V}^{\mu\nu}(0) + \epsilon G_{A}^{\mu\nu}(0)$$
$$G_{A}^{\mu\nu}(T) = (1 - \epsilon)G_{A}^{\mu\nu}(0) + \epsilon G_{V}^{\mu\nu}(0)$$

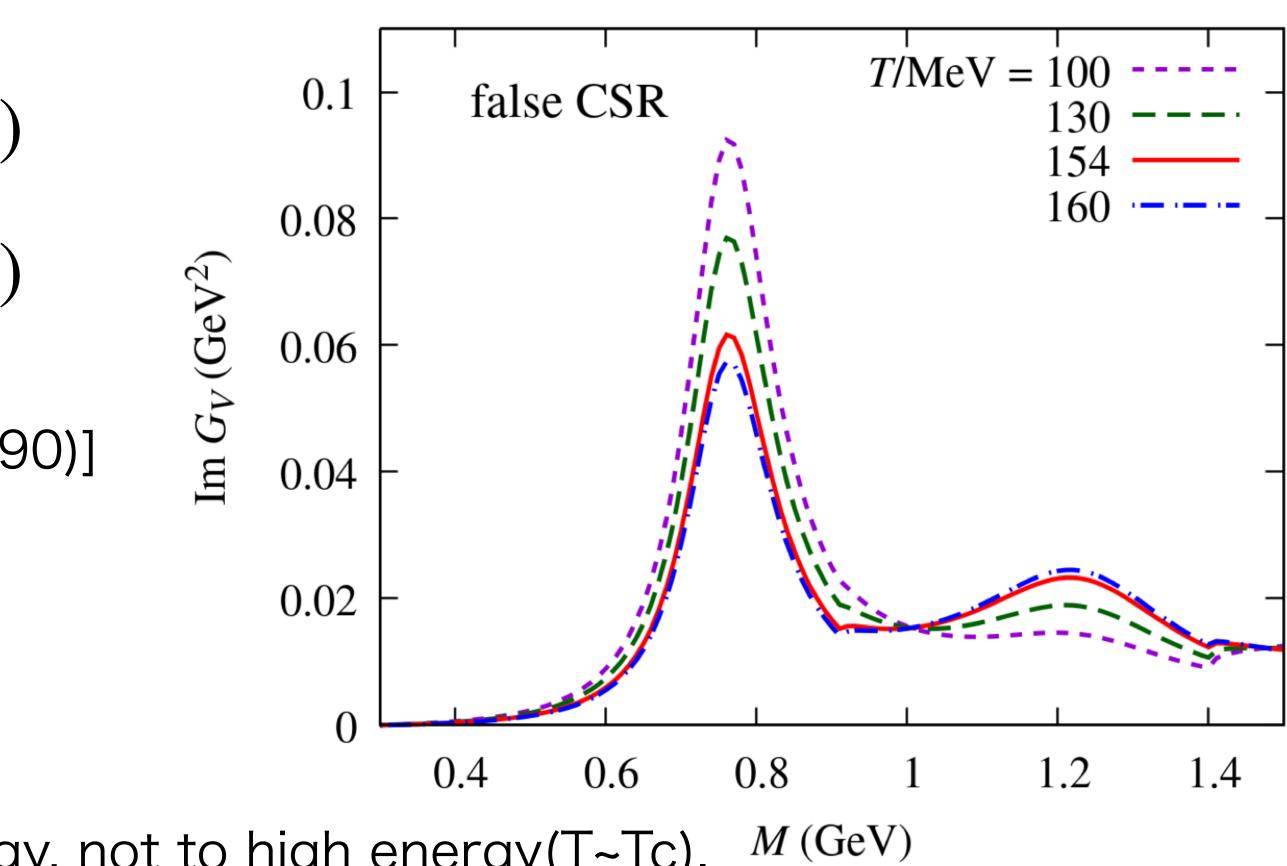
 $T^2$ [Dey, Eletsky and loffe(90)]  $\epsilon =$  $\overline{6f_{\pi}^2}$ [finite  $\rho$ : Krippa(98)]

 $\epsilon = 1/2 \rightarrow G_V = G_A$ : Is this the signal of CSR?  $\varepsilon = 1/2 \Rightarrow T = 160 \text{MeV}$ 

Actually this is only able to apply to low energy, not to high energy(T~Tc). There is no mass degeneration.

Chiral mixing will be maximized at Tc?  $\rightarrow$ When we consider the diagram of chiral mixing in hot matter, chiral mixing should be disappeared.

### 2024/09/09

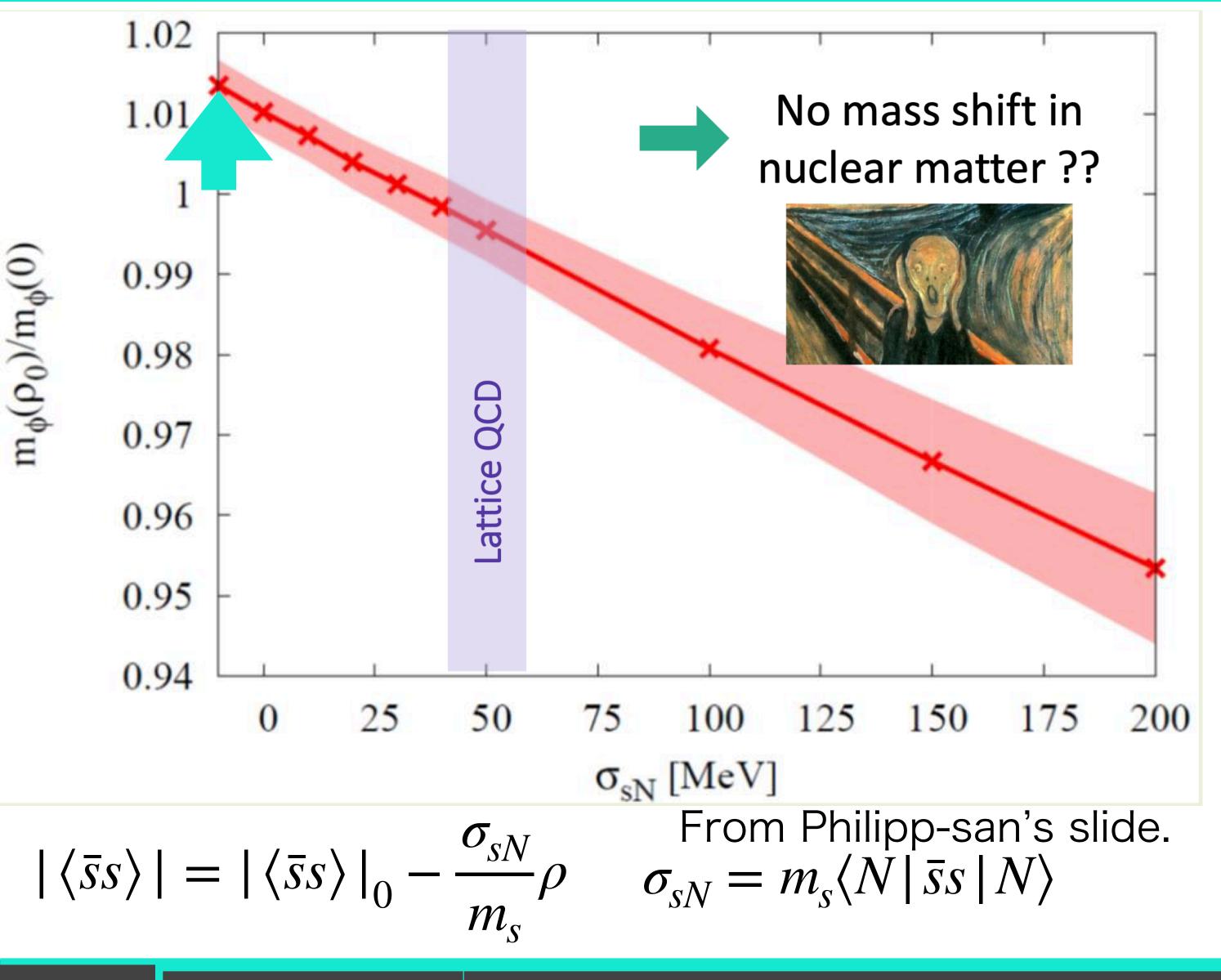


E16 work shop





# **p-N** interaction in QCD sum rule



2024/09/09

In QCD sum rule,  $\phi$ -N interaction w/o CSR effect is expressed in terms of gluon condensation.

When  $\sigma_{sN} = 0$  (=no CSR), QCD sum rule says positive mass shift. This is inconsistent with ALICE's measurement and many hadronic model. C(k\*) ALICE pp √s = 13 TeV

50

100

150

S. Acharya et al. (ALICE Coll.), Phys. Rev. Lett. **127**, 172301 (2021).

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250

300

200

High-mult. (0 - 0.17% INEL > 0)

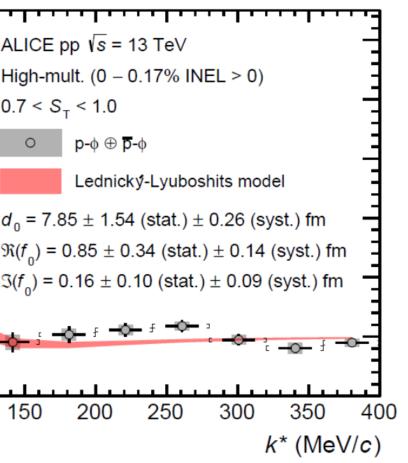
ednický-Lyuboshits model.

b-q ⊕ p-q

 $0.7 < S_{\tau} < 1.0$ 

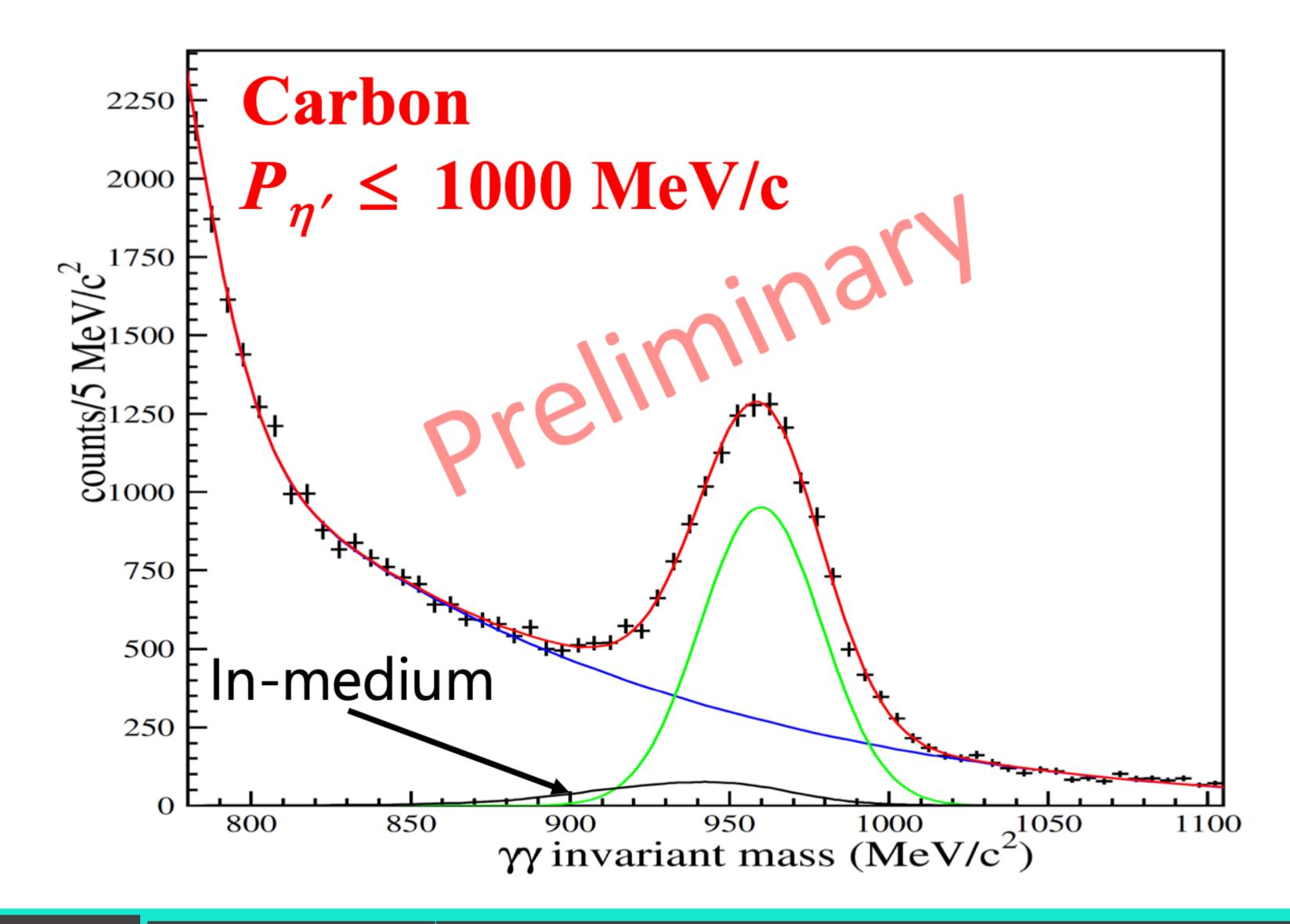








## LEPS2's result

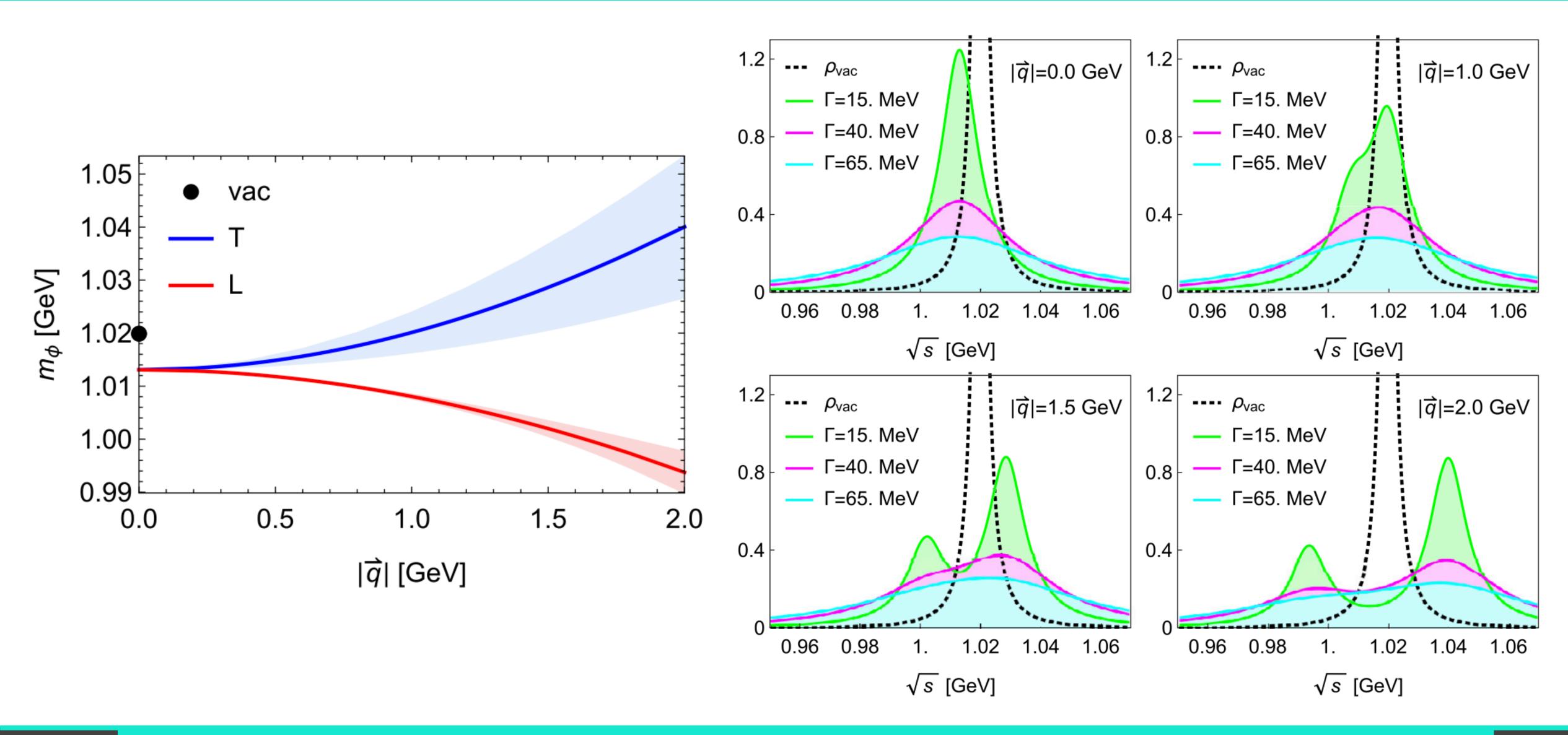




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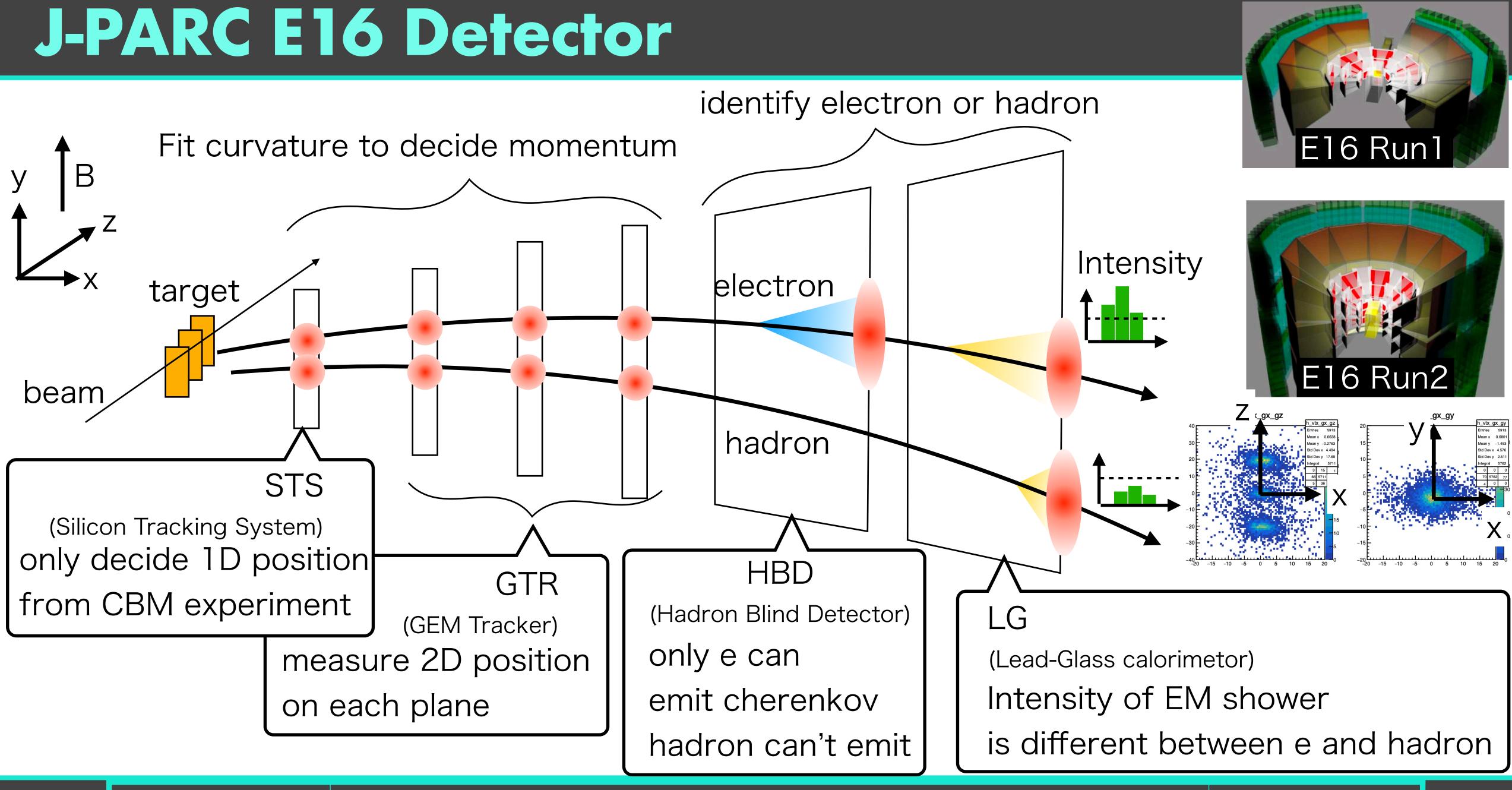


# breaking of lorenz invariant



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