Chiral mixing in E16

2024/09/09

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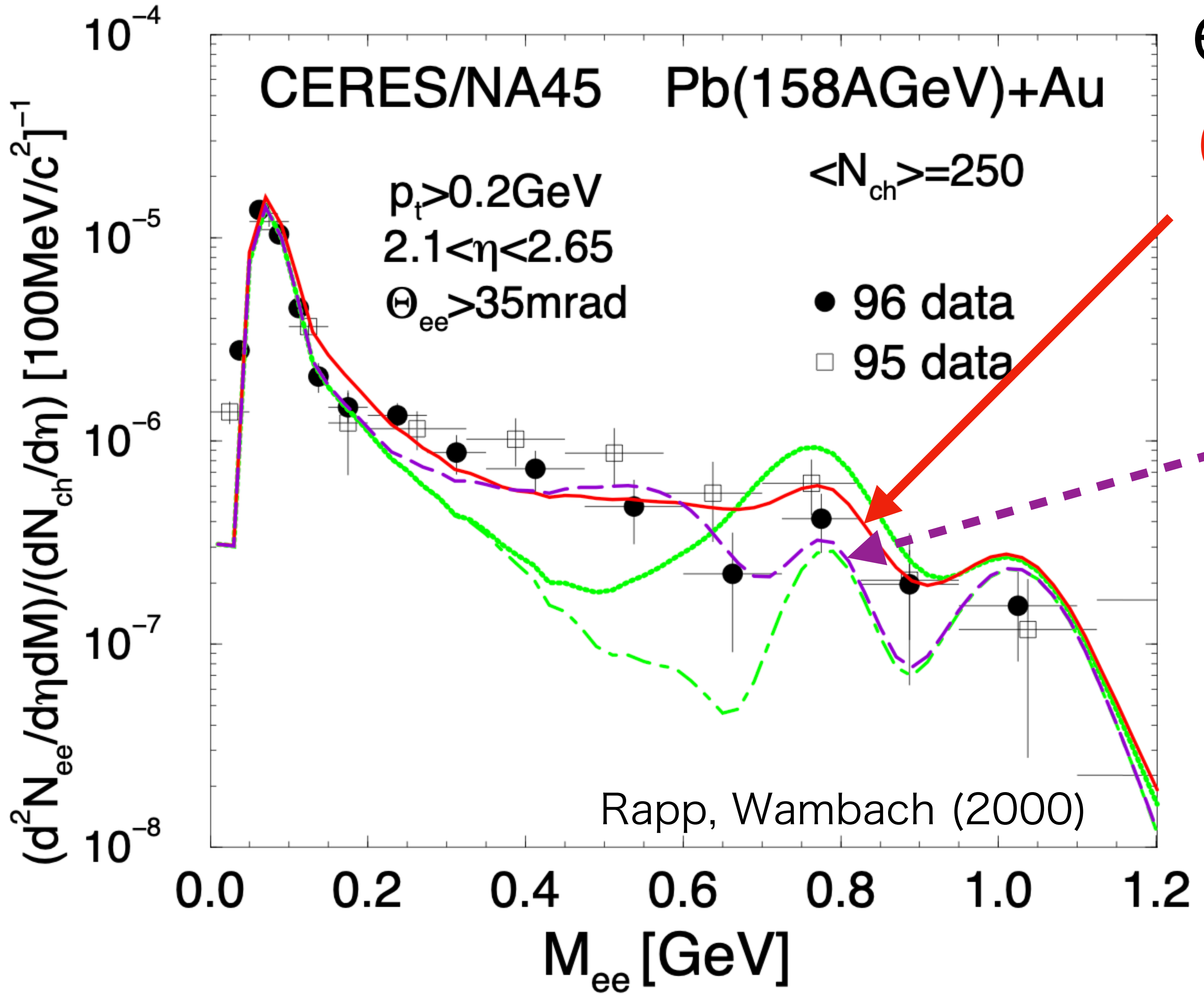
Introduction

How do we understand dilepton's mass dist?



ex) ρ meson @NA45

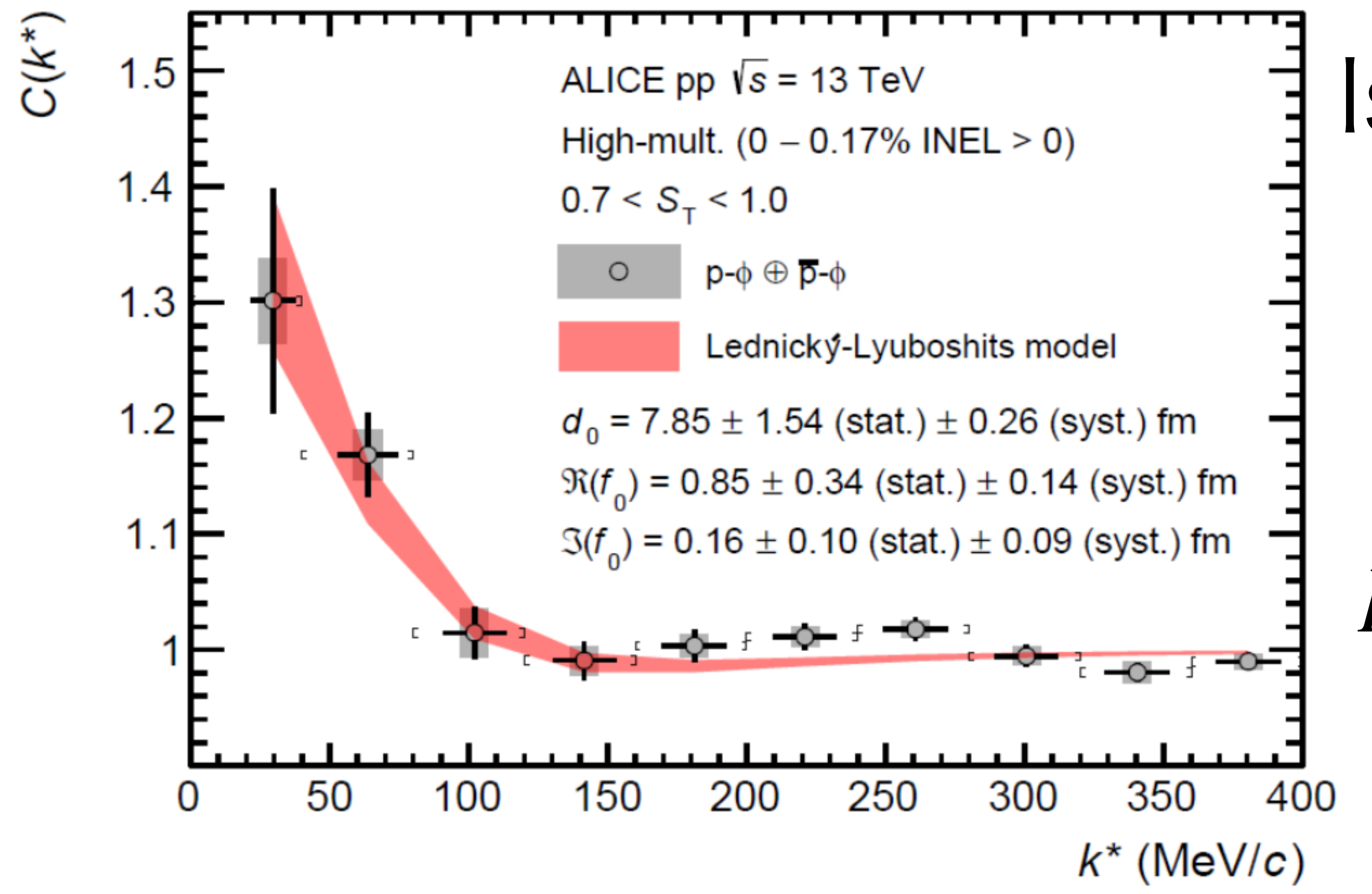
Collision broadening

(Hadron's many-body interaction)

dropping ρ

(BR scaling)

Collision broadening can also explain mass dist even without CSR.



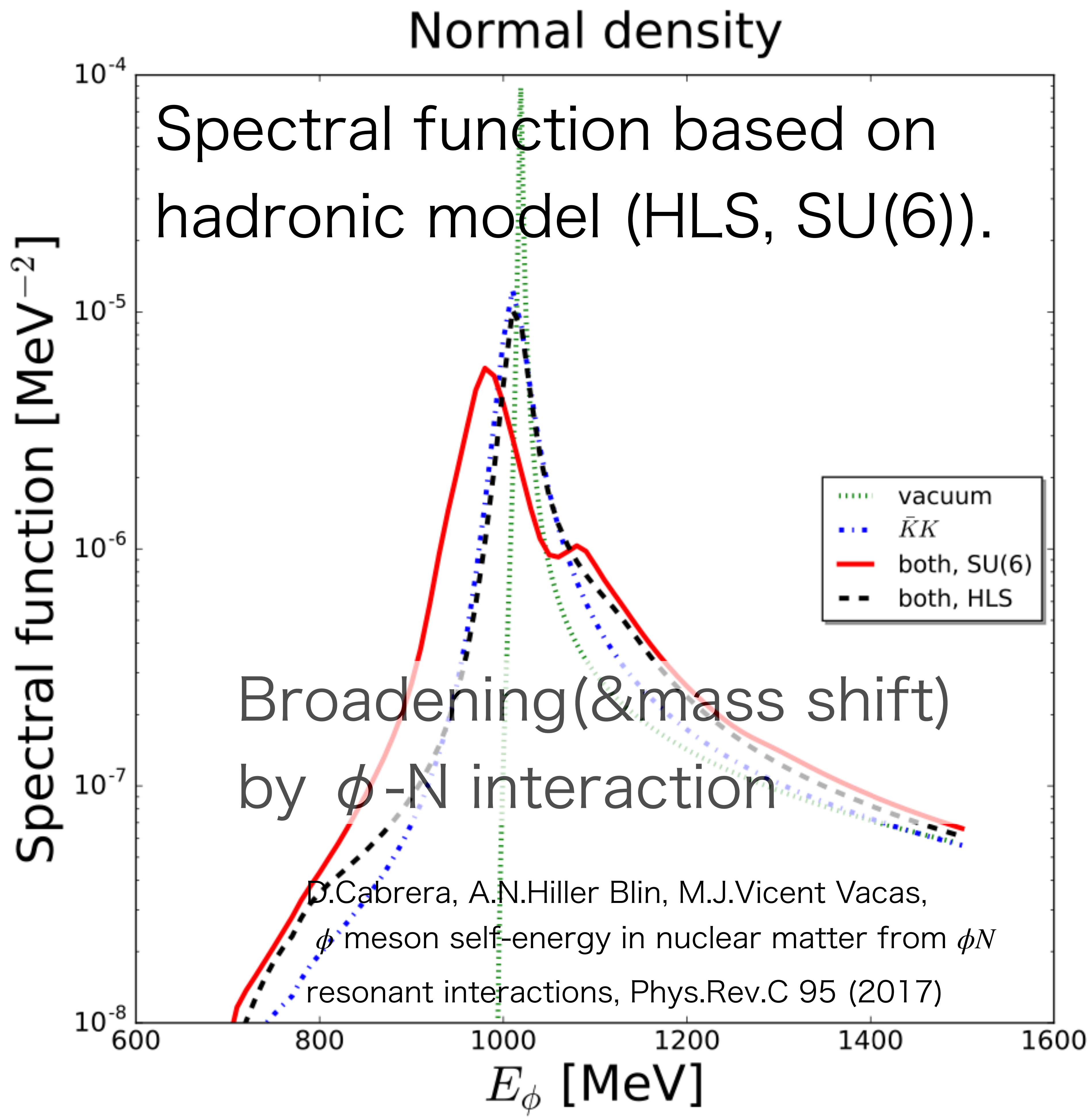
Is strange sector clear?

$p-\phi$ correlation function

@ALICE pp collision

$p-\phi$ interaction is attractive.

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



Spectral function based on hadronic model (HLS, SU(6)).

Broadening(&mass shift) by ϕ-N interaction

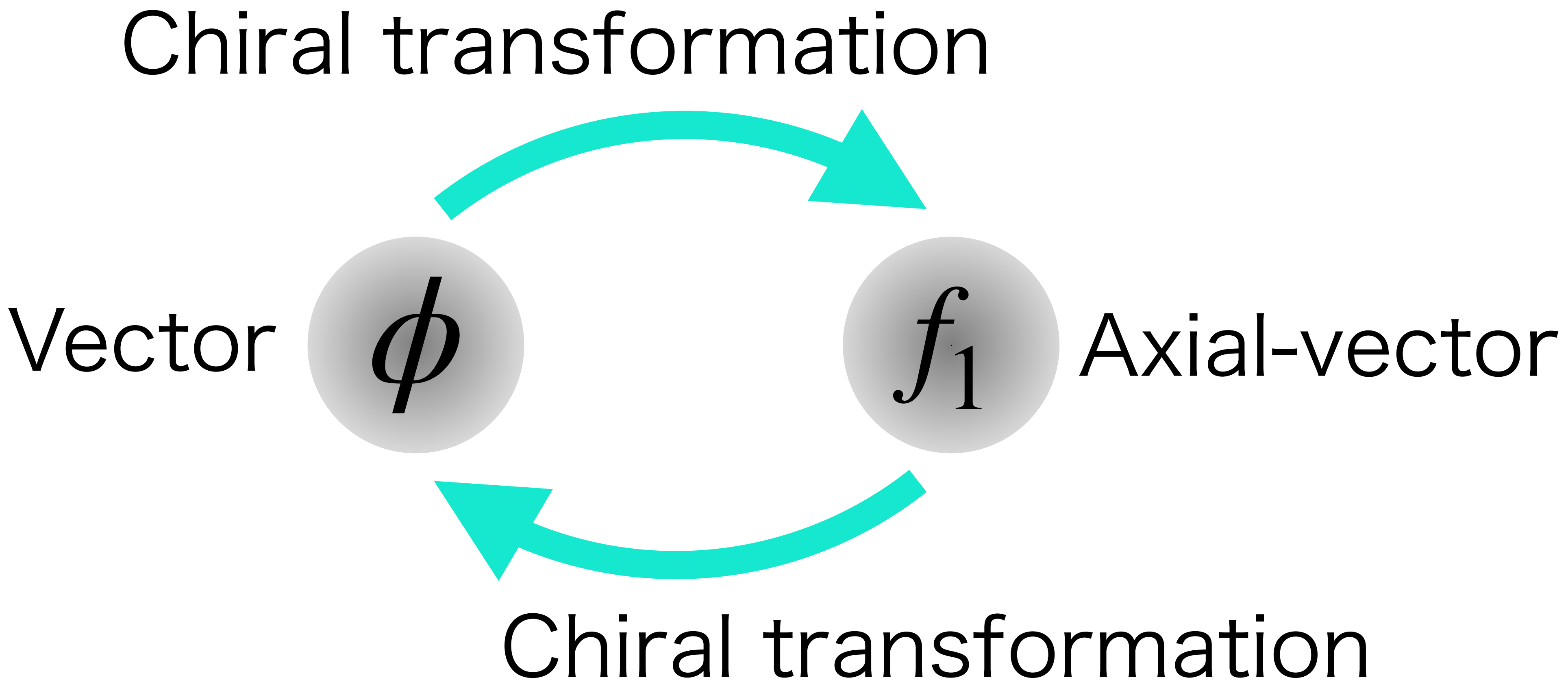
D.Cabrera, A.N.Hiller Blin, M.J.Vicent Vacas, ϕ meson self-energy in nuclear matter from ϕN resonant interactions, Phys.Rev.C 95 (2017)

The explanation depends on which ϕ-N model is used.

My strategy

How can we verify CSR more directly?

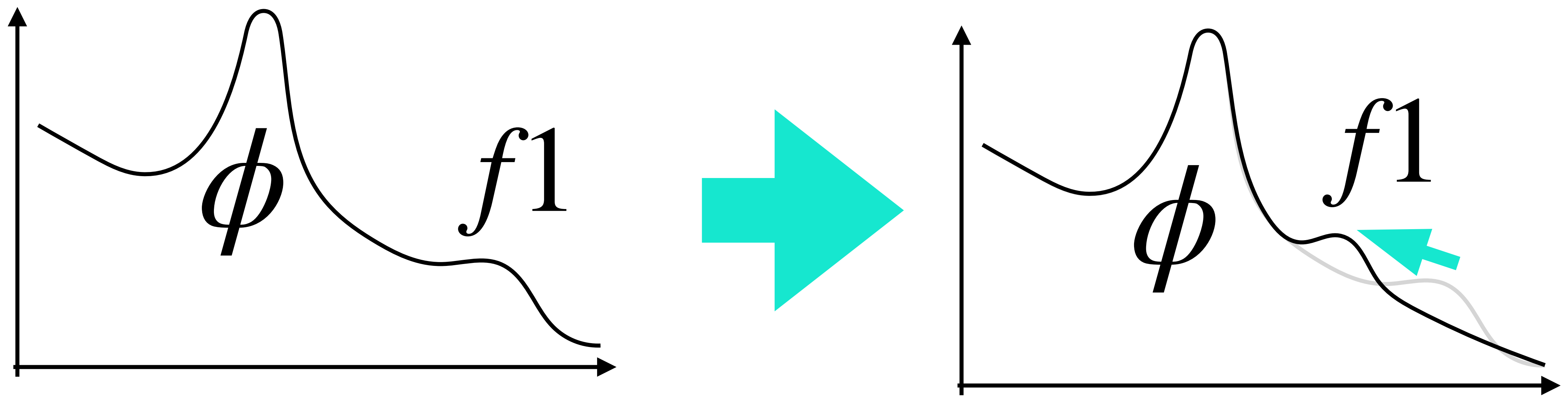
Degeneration of chiral partner



Symmetrical: Same mass after χ trans.
Not symmetrical: Different mass after χ trans.

ϕ meson's chiral partner: $f_1(1420)$

Signal of this measurement



In vacuum In dense matter

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

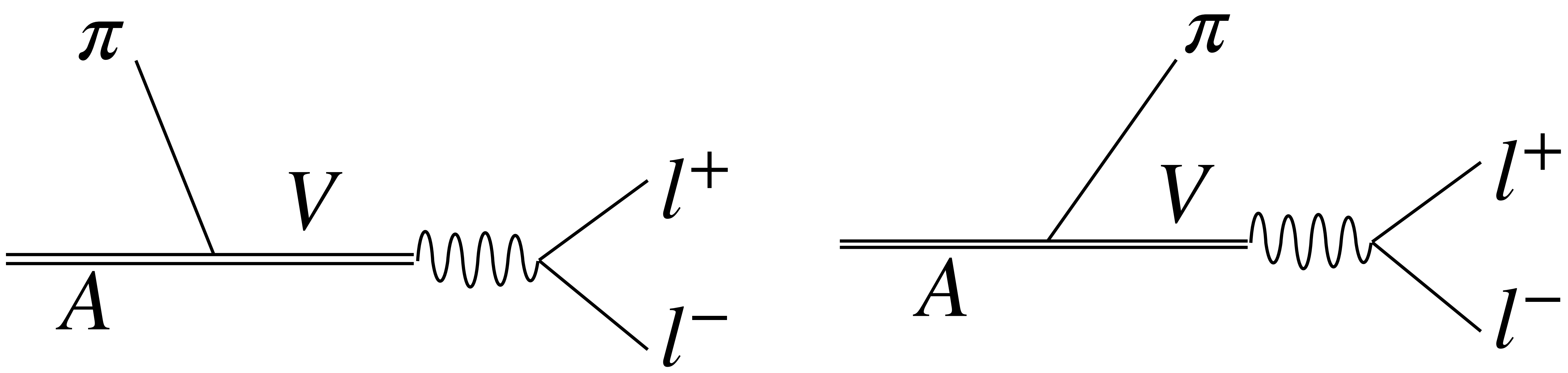
Btw, Axial-vector can't decay into di-lepton directly… We need "Chiral(V-A) mixing".

Chiral mixing in Hot matter

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

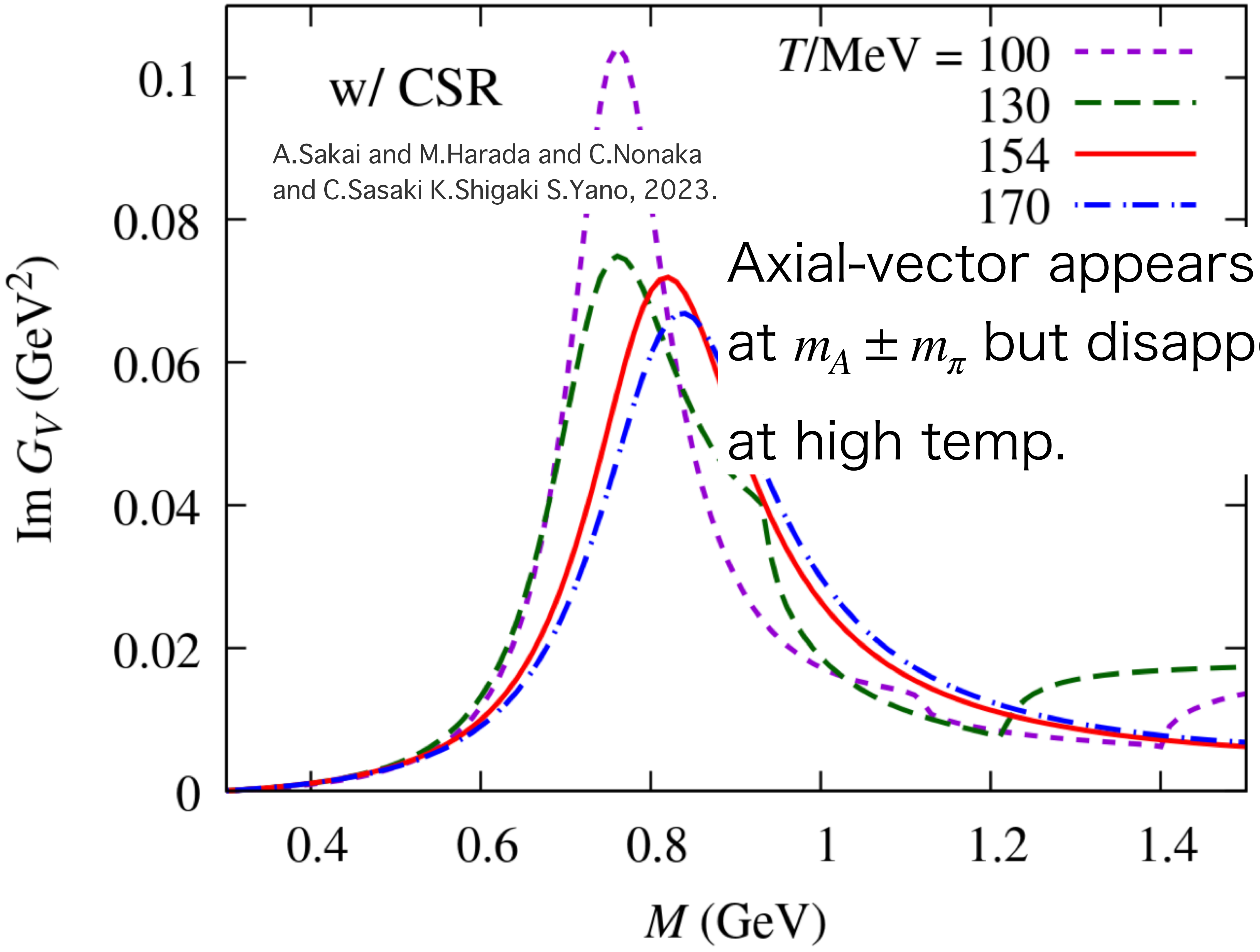
Chiral partner's degeneration has been tried
to observe but no one has succeeded.

Coupling const. of chiral mixing in hot matter



$$g_{a_1\rho\pi} \propto \langle \bar{q}q \rangle \to 0$$

Chiral mixing will be suppressed at Tc.



Axial-vector appears
at $m_A \pm m_\pi$ but disappear
at high temp.

Chiral mixing in Dense matter

Chiral mixing in dense matter

Finite baryon density makes
ω's time-part not C inv.

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

$$\mathcal{L}_\omega \sim \bar{N}\gamma^\mu \omega_\mu N \quad \rightarrow \mu_B N^\dagger N$$

The lowest term with chiral/parity symmetry, without C-inv

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

→tree level chiral mixing
Holographic QCD(Chern-Simons term)
WZW action(same form in leading order)

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

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:

$$p_0^2 \sim m_{V,A}^2 + \left(1 \pm \frac{4c^2}{m_A^2 - m_V^2}\right)\vec{p}^2$$

Chiral mixing is enhanced with high momentum, degeneration of VA

Chiral mixing strength c

this parameter has model dependence

Holographic QCD: $c = 1.0\frac{\rho}{\rho_0}[\mathrm{GeV}]$

WZW action: $c = 0.1\frac{\rho}{\rho_0}[\mathrm{GeV}]$

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

Spectral Function

Chiral mixing term in dense matter

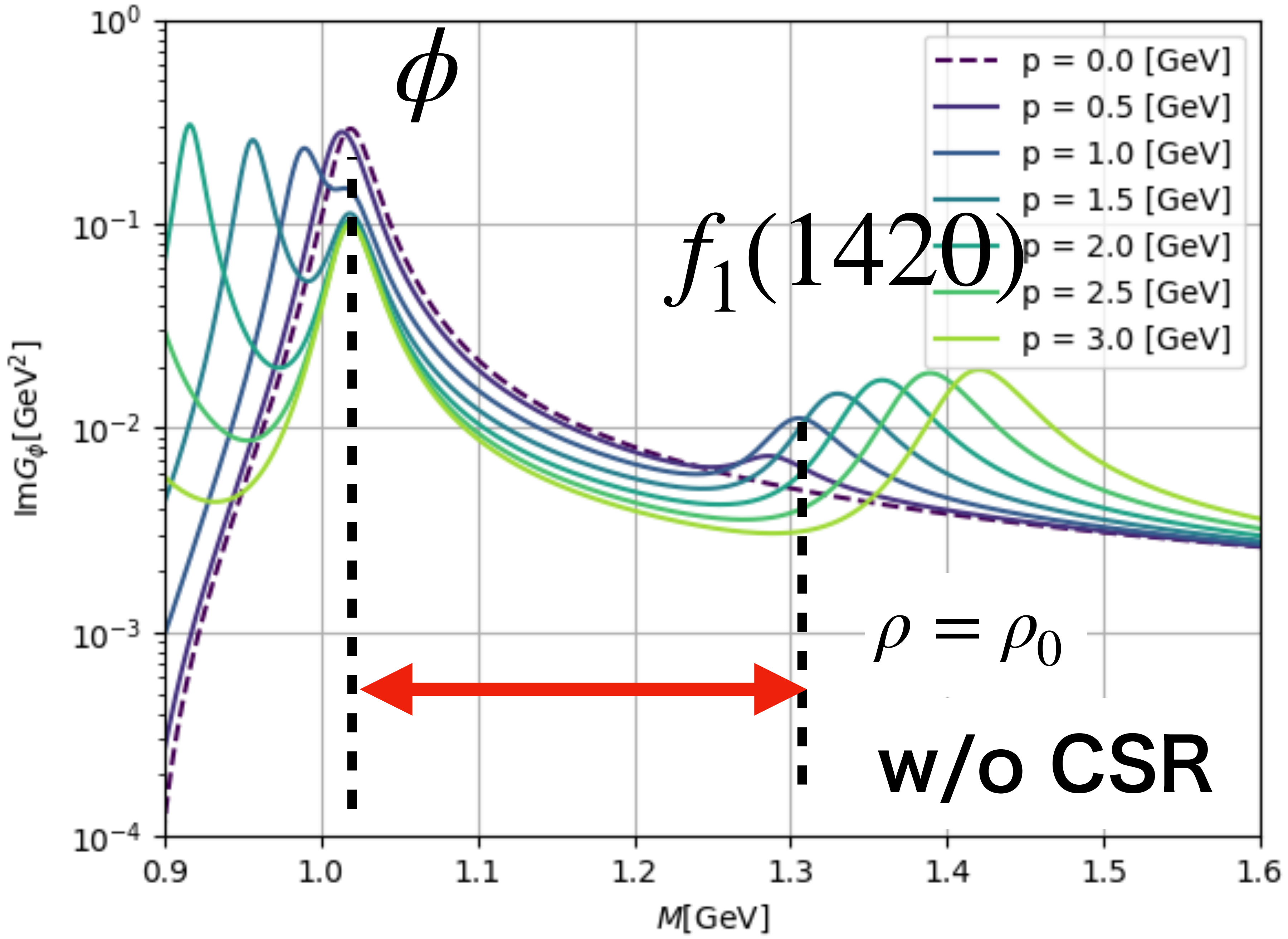
$$L = 2c\epsilon^{0\mu\nu\lambda}\mathrm{tr}\left[\partial_\mu V_\nu \cdot A_\lambda + \partial_\mu A_\nu \cdot V_\lambda\right]$$

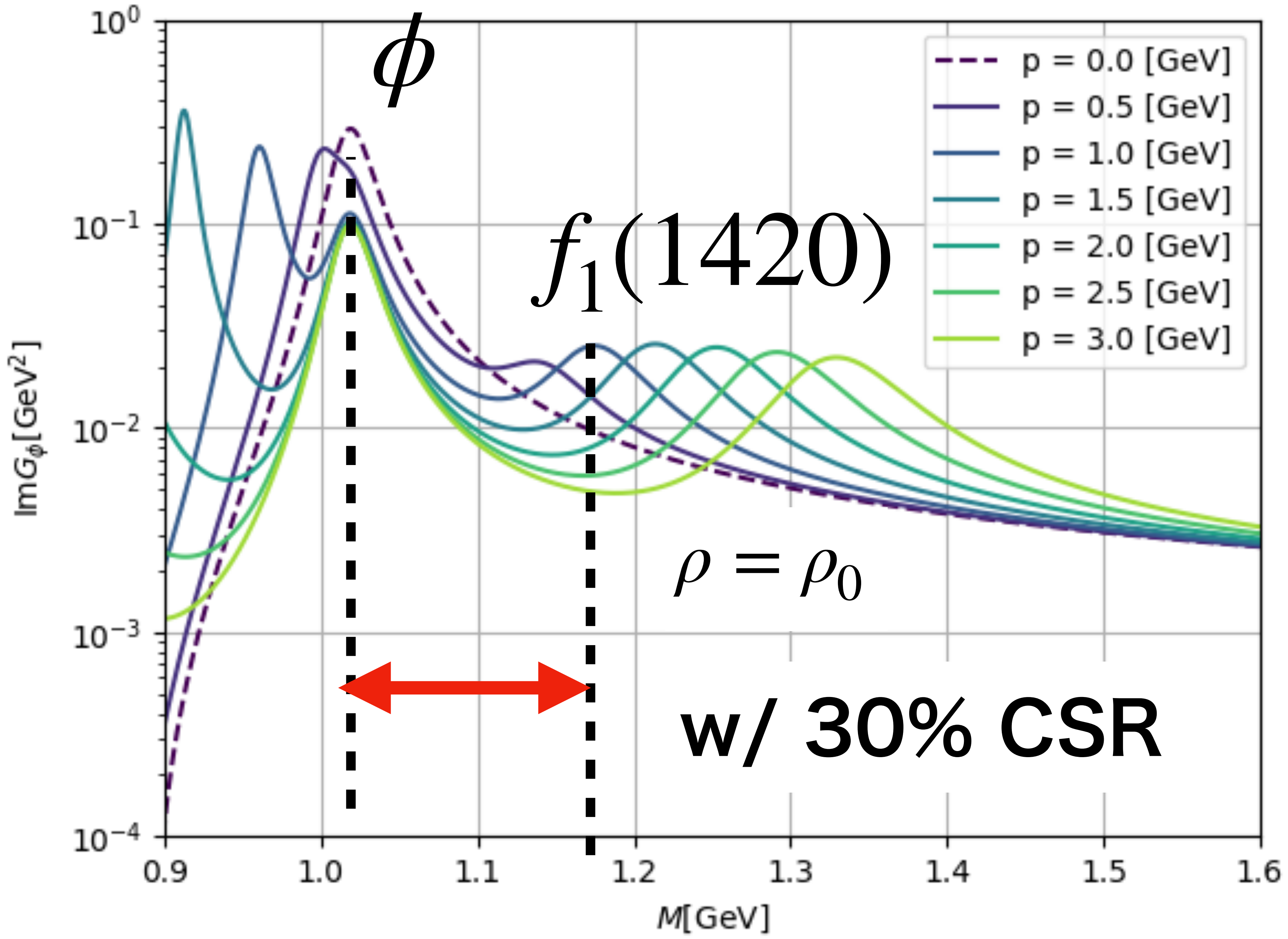
change dispersion relation

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($\mathrm{Im}G_V$) can be calculated like this





Spectral function is changed to have 3 structures:

- longitudinal vector
- transverse

Can we observe this degeneration experimentally?

advantage of J-PARC E16

Mixing strength:

Holographic QCD:

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

WZW action:

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

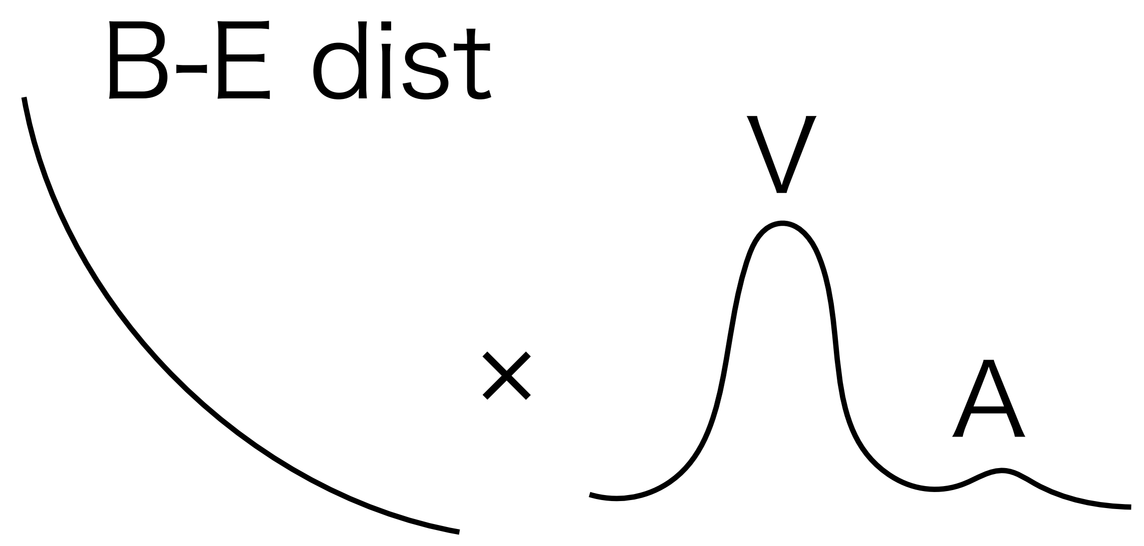
More high density: HADES, etc

→ also have finite temperature

(T~50MeV $< m_\pi$ =no chiral mixing by finite temperature)

Spectral function in finite temperature:

$$\frac{dN}{d^4p}(p_0,\vec{p};T,\mu_B) = \frac{\alpha^2}{\pi^3 s}\frac{\mathrm{Im}G_V(p_0,\vec{p};T,\mu_B)}{e^{p_0/T}-1}$$



Axial vector will be very small

(Boltzmann suppress)

p+A(E16) is (almost) zero temperature→no Boltzmann suppress

Other advantages:

high statistics / specialized to measure di-electron / Fixed target(no time evolution of density)…etc

Estimation of ee inv. mass dist.

Invariant mass distribution

Invariant mass distribution can be calculated like this using spectral function

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

Spectral Fx Kinematic dist Background Detector responce

Invariant mass distribution

Invariant mass distribution can be defined like this using spectral function

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

Spectral function of ϕ

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

Current-Current correlation function:

$$G^{\mu\nu}_{V,A}(p_0,\vec{p}) = P^{\mu\nu}_L G^L_{V,A}(p_0,\vec{p}) + P^{\mu\nu}_T G^T_{V,A}(p_0,\vec{p})$$

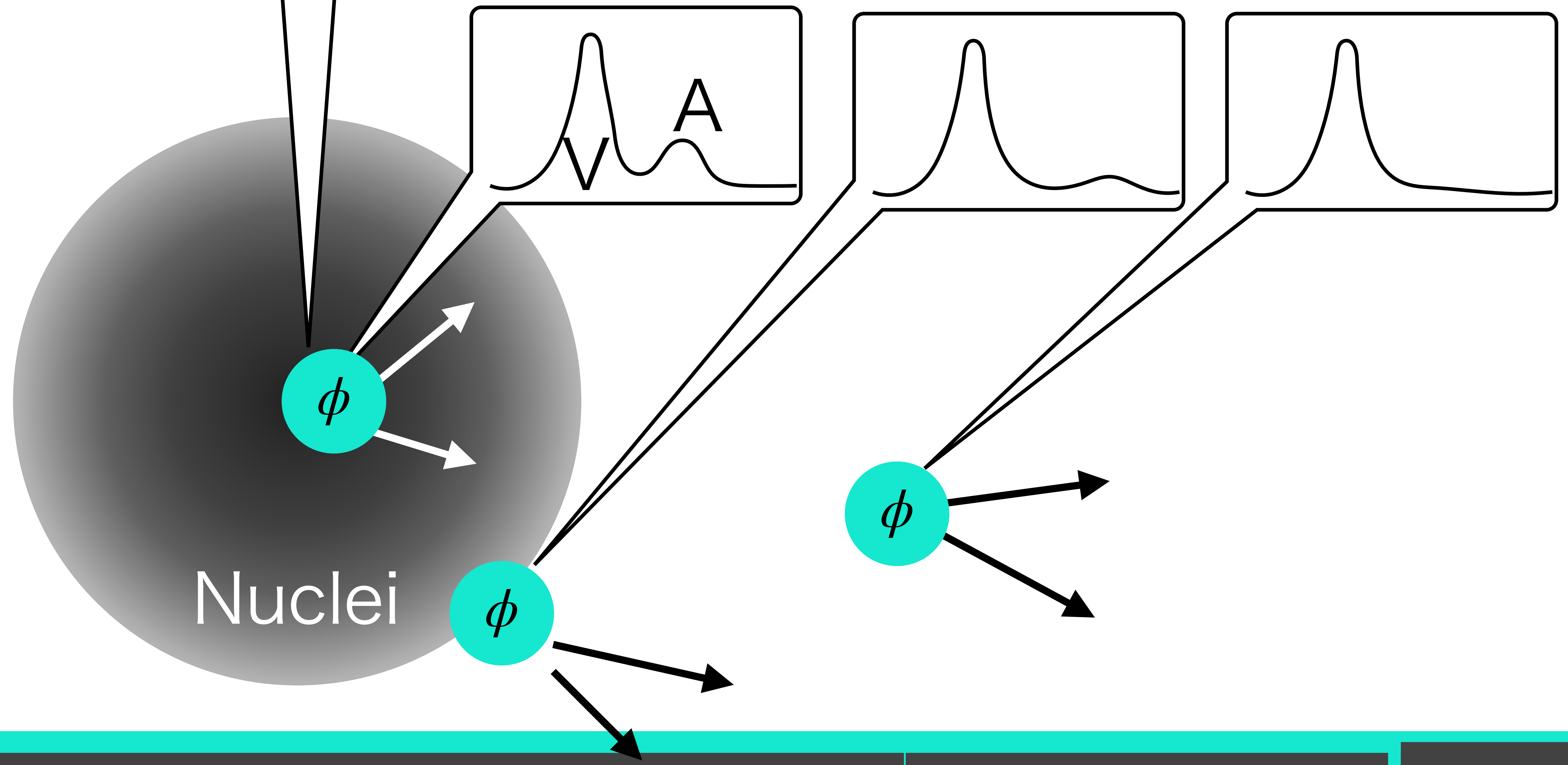
$$G^L_V = \left(\frac{g_V}{m_V}\right)^2 \frac{-s}{D^L_V} \qquad G^T_V = \left(\frac{g_V}{m_V}\right)^2 \frac{-sD^T_A + 4c^2\vec{p}^2}{D^T_V D^T_A - 4c^2\vec{p}^2}$$

$$D^{L,T-1}_{V,A} = \frac{1}{s - m^2_{V,A} - \Sigma^{L,T}_{V,A}}$$

Inside nuclei:

- CSR effect on $\phi - f_1(1420)$
- ϕ-N interaction

as a function of density



CSR Effect on f1(1420)'s spectral function

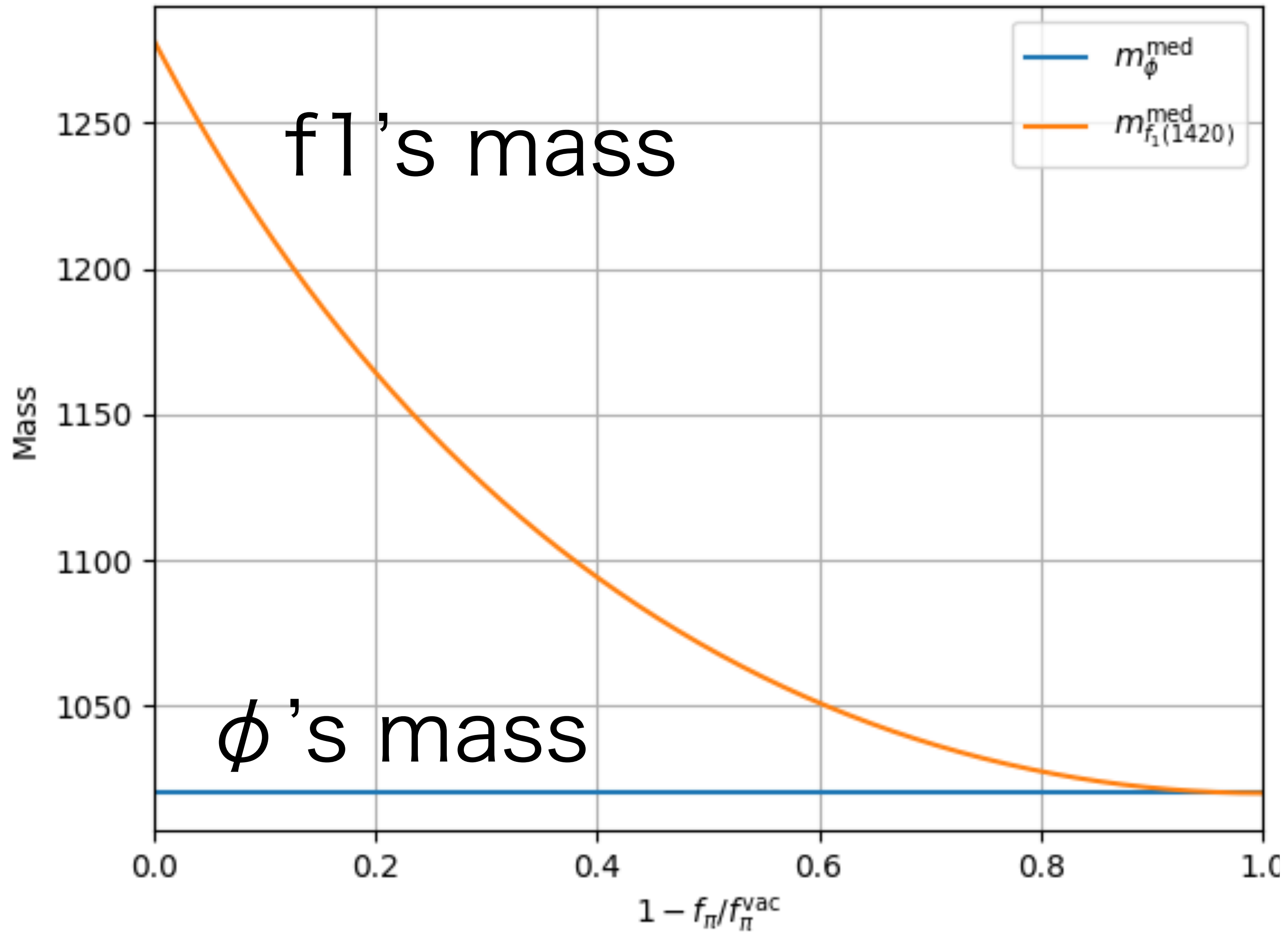
I used following relationship obtained from GHLS(generalized hidden local symmetry).

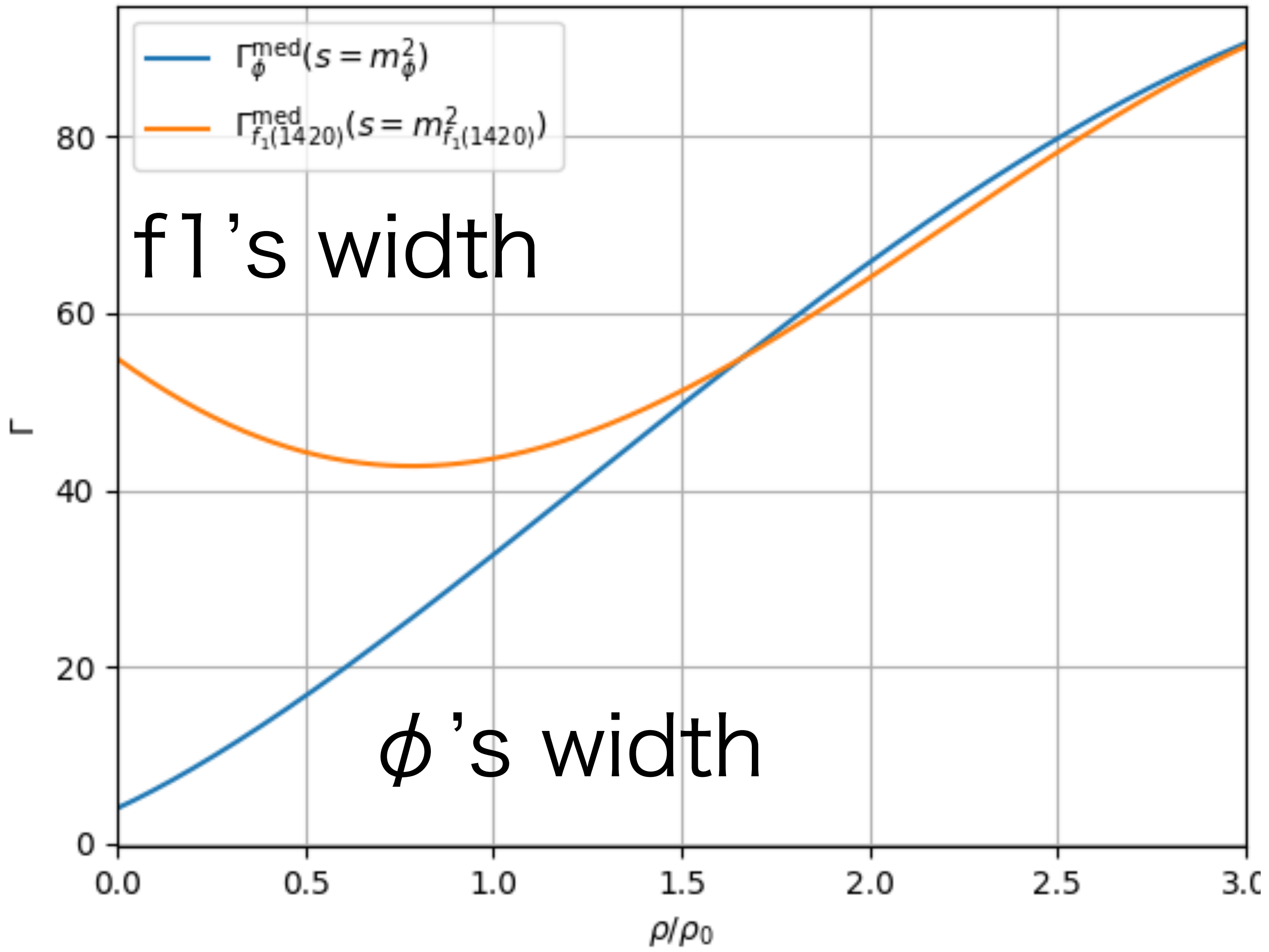
$$m_A^2 - m_V^2 = g^2 \frac{m_A^2}{m_V^2} f_\pi^2 \quad \rightarrow \quad m_A = \frac{m_V^2}{\sqrt{m_V^2 - g^2 f_\pi^2}}$$

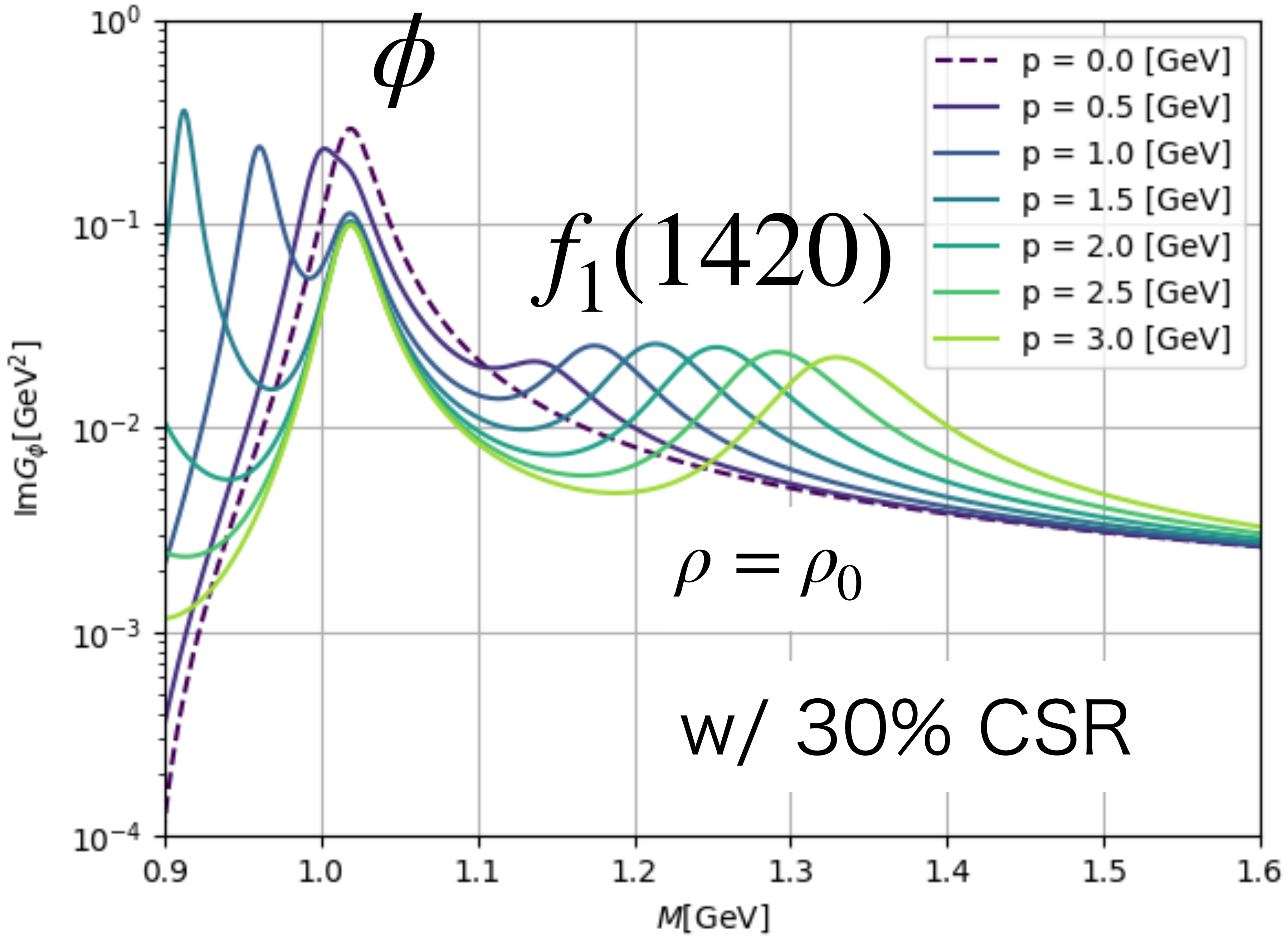
For width, I assumed like this

$$\Gamma_{f_1(1420)}(s) \sim \Gamma^{\mathrm{vac}}_{f_1(1420)} \left(\frac{f_\pi^{\mathrm{med}}}{f_\pi^{\mathrm{vac}}} \right)^2 + \Gamma_\phi^{\mathrm{med}}(s, f_\pi^{\mathrm{med}}) \left(1 - \left(\frac{f_\pi^{\mathrm{med}}}{f_\pi^{\mathrm{vac}}} \right)^2 \right)$$

(In this study, I didn't consider ϕ's mass shift and broadening by CSR)

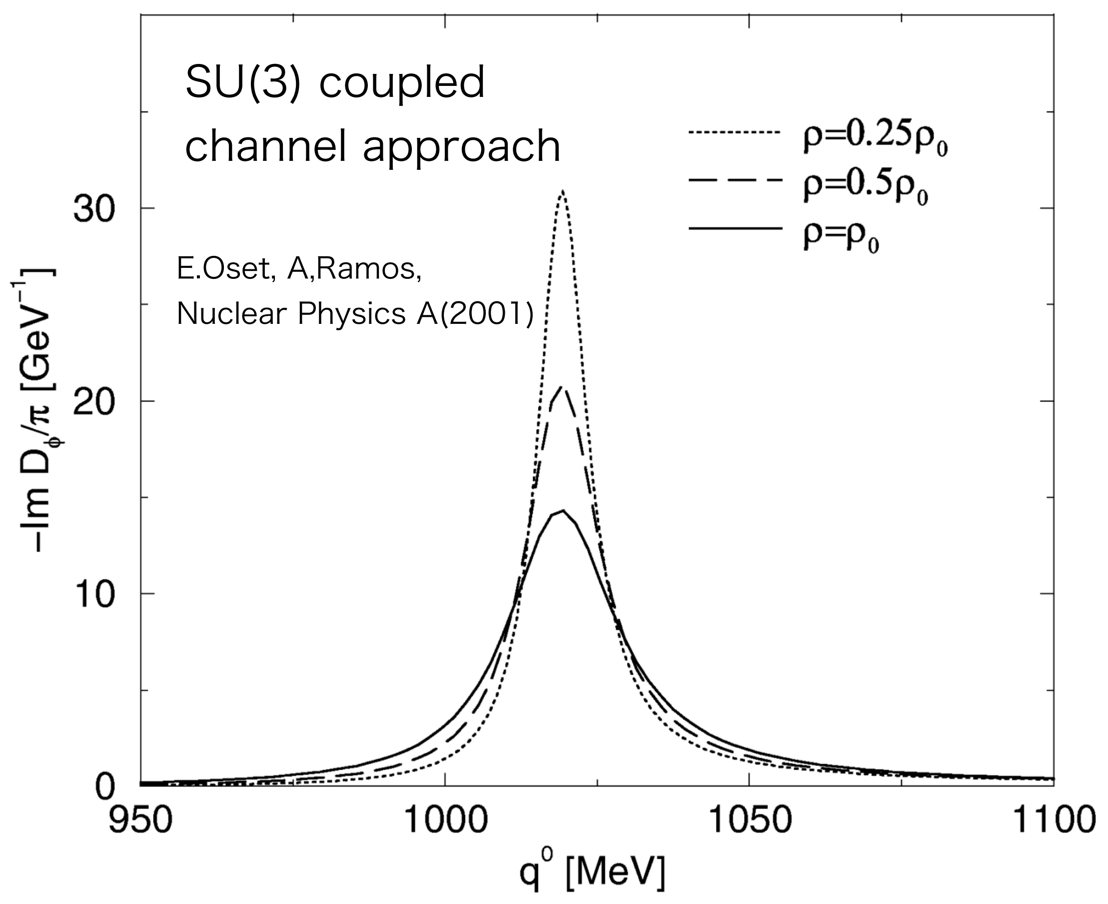


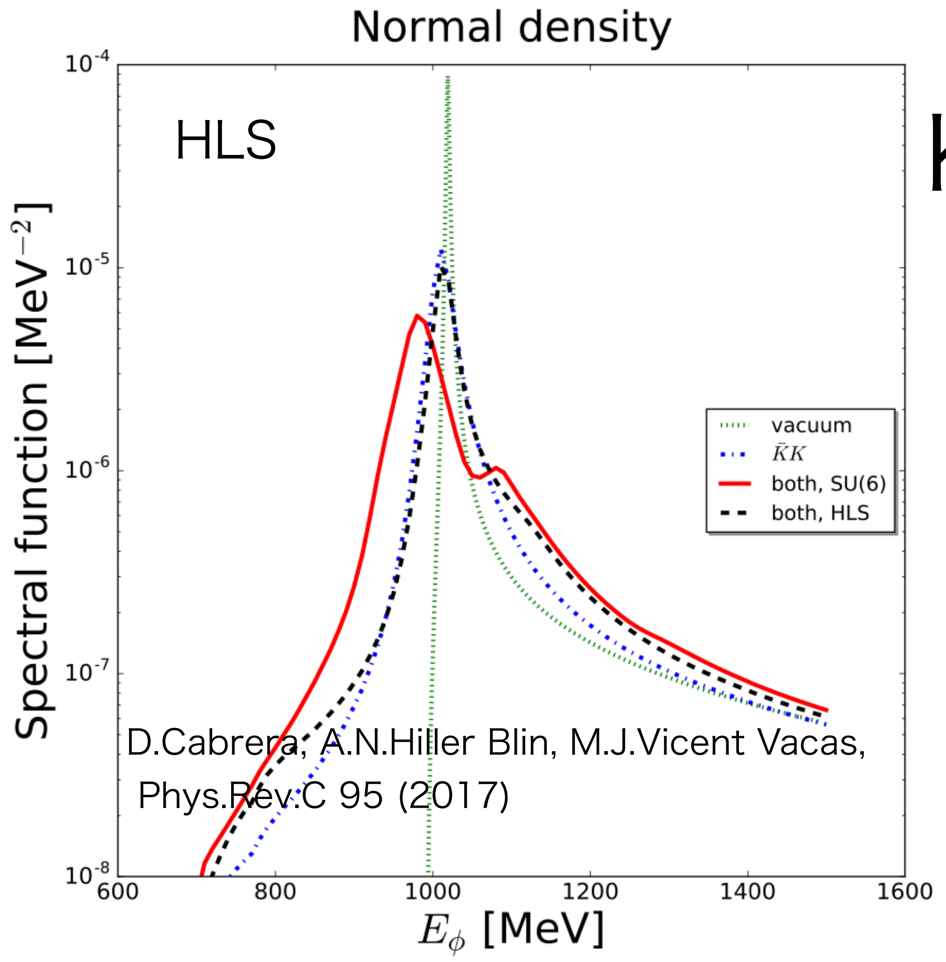




φ-N interaction

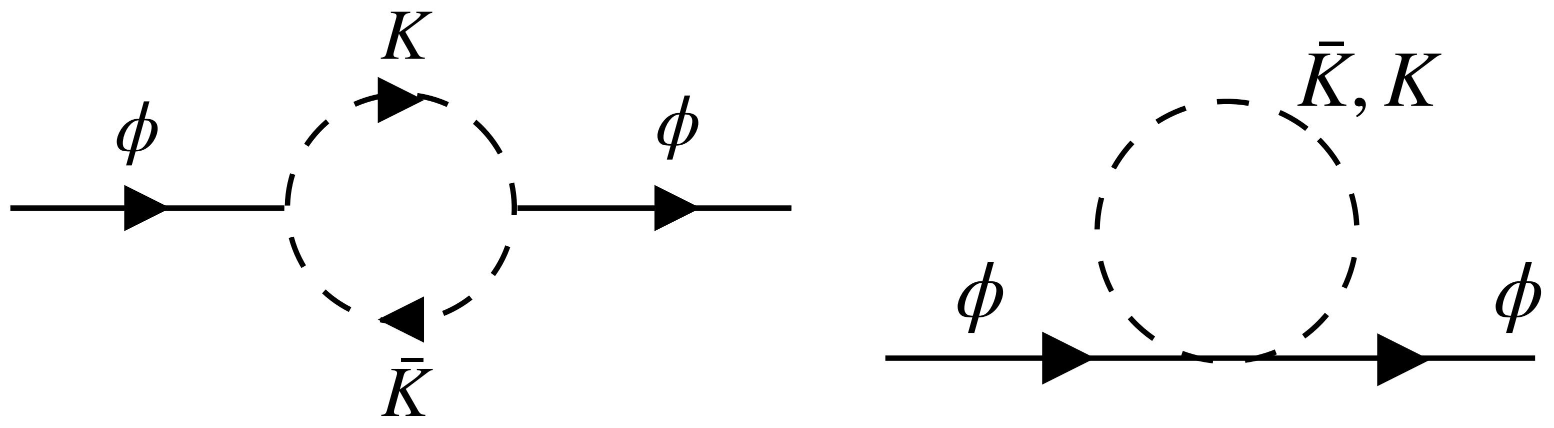
ϕ's modification by ϕ-N interaction





mass shift is zero or small, but broadened.

The simplest cause of modification in medium is interaction between N and $K\bar{K}$ loop(ϕ's self E)



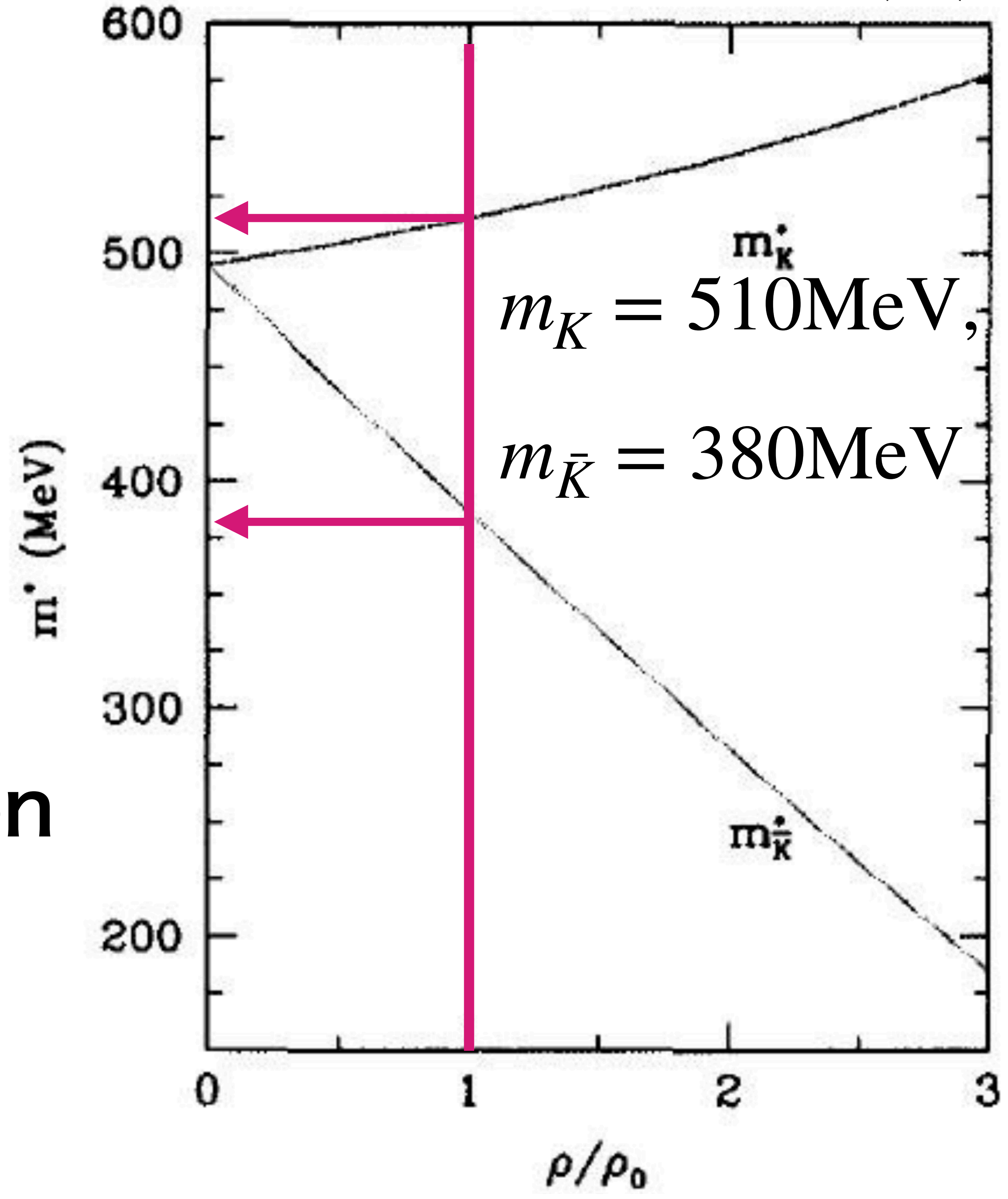
To estimate ϕ's width, I used mean-field approximation.

K's mass in dense matter Kaplan, Nelson (86)

$$m_K^* = \left[m_K^2 - a_K\rho_S + (b_K\rho_B)^2\right]^{1/2} + b_K\rho_B$$

$$m_{\bar{K}}^* = \left[m_{\bar{K}}^2 - a_{\bar{K}}\rho_S + (b_K\rho_B)^2\right]^{1/2} - b_K\rho_B$$

Li, Lee, Brown (97)



ϕ's width

broadened by ϕ-N interaction

W.S.Chung, C.M.Ko, G.Q.Li (1998)

$$\Gamma_\phi(s) = \frac{g_{\phi K\bar{K}}^2}{3\pi}\frac{k(s)^3}{s}$$

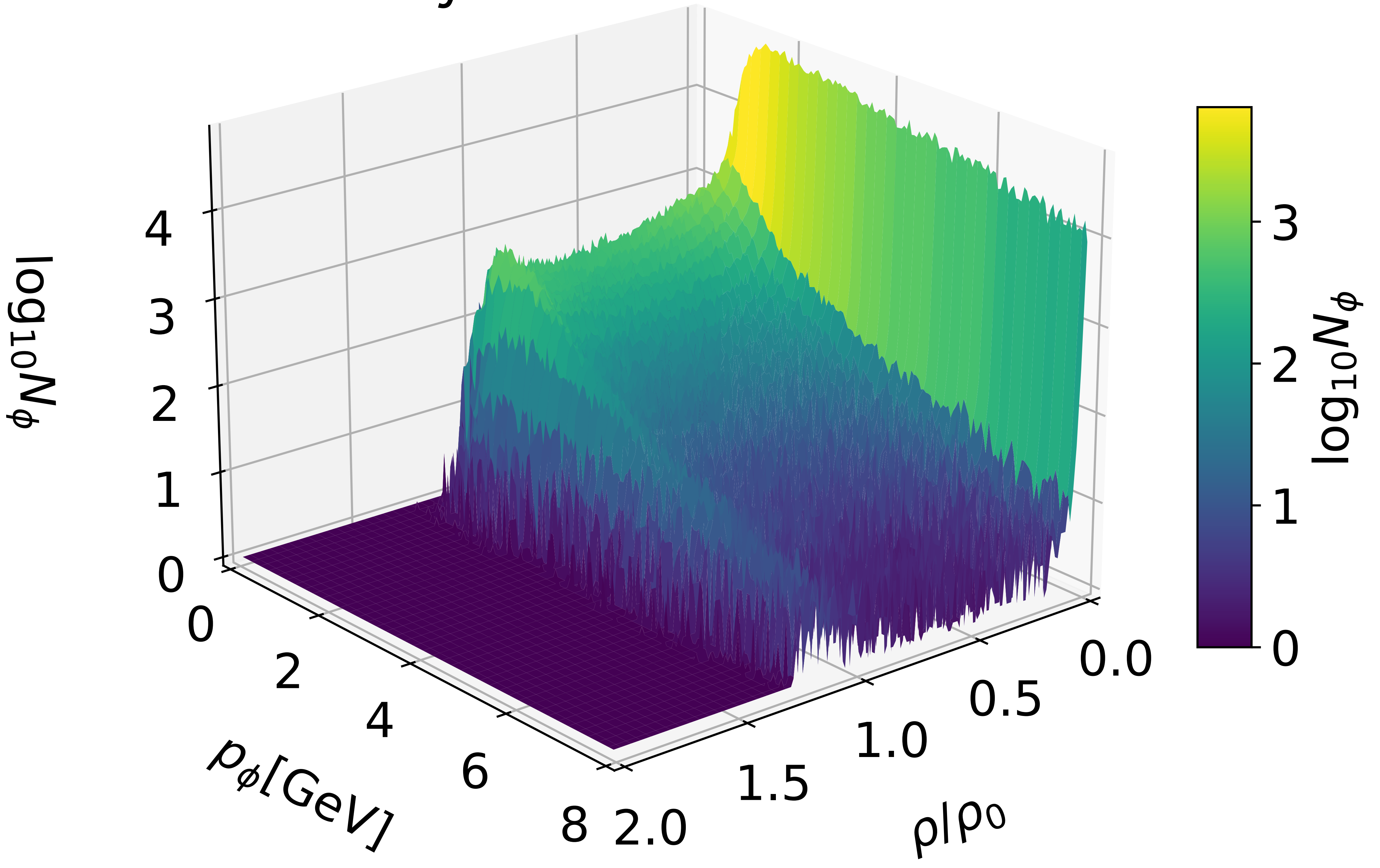
$$k(s) = \frac{1}{2\sqrt{s}}\left[(s-(m_K^*+m_{\bar{K}}^*)^2)(s-(m_K^*-m_{\bar{K}}^*)^2)\right]^{1/2}$$

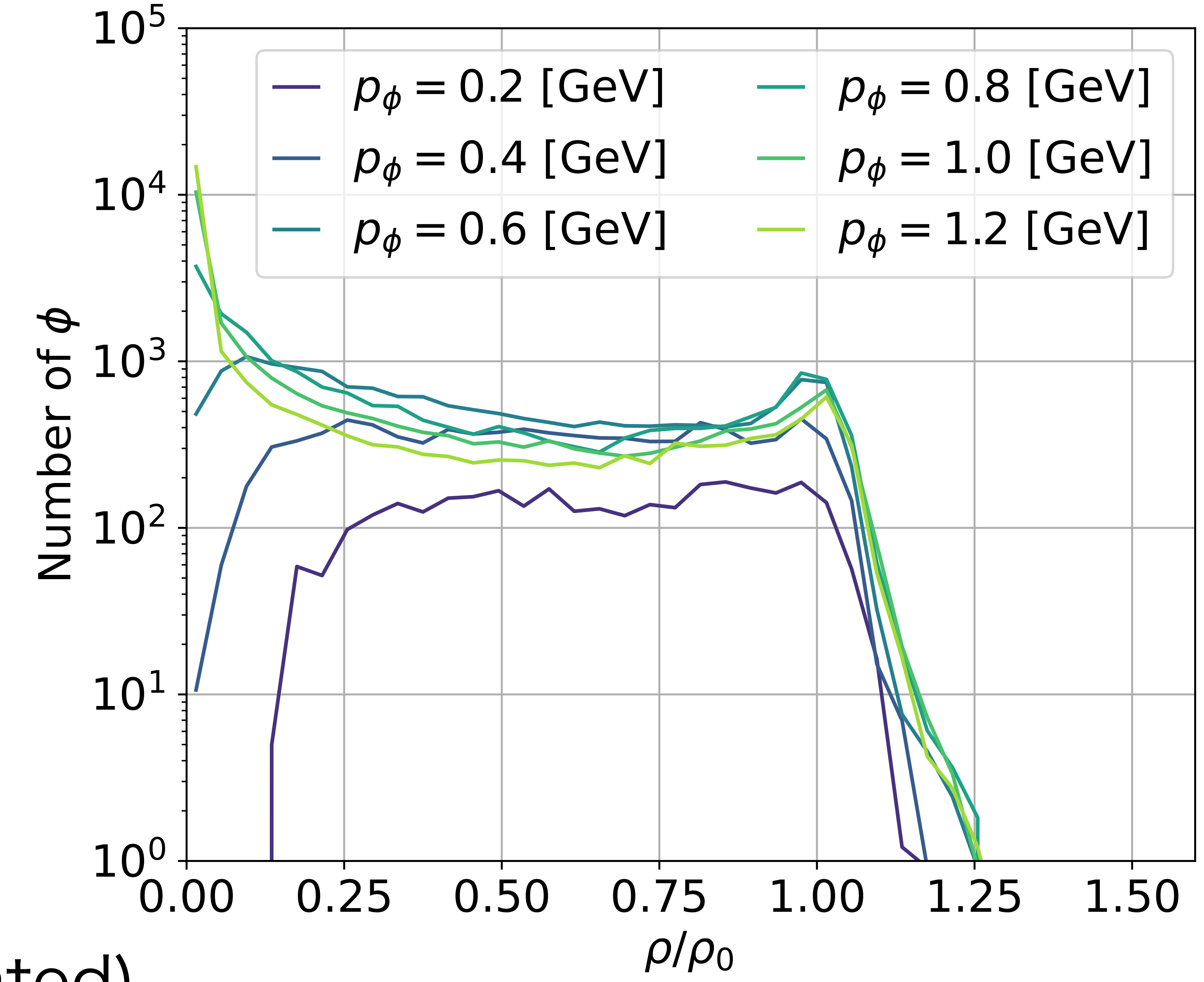
modification of phase space

Invariant mass distribution

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

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



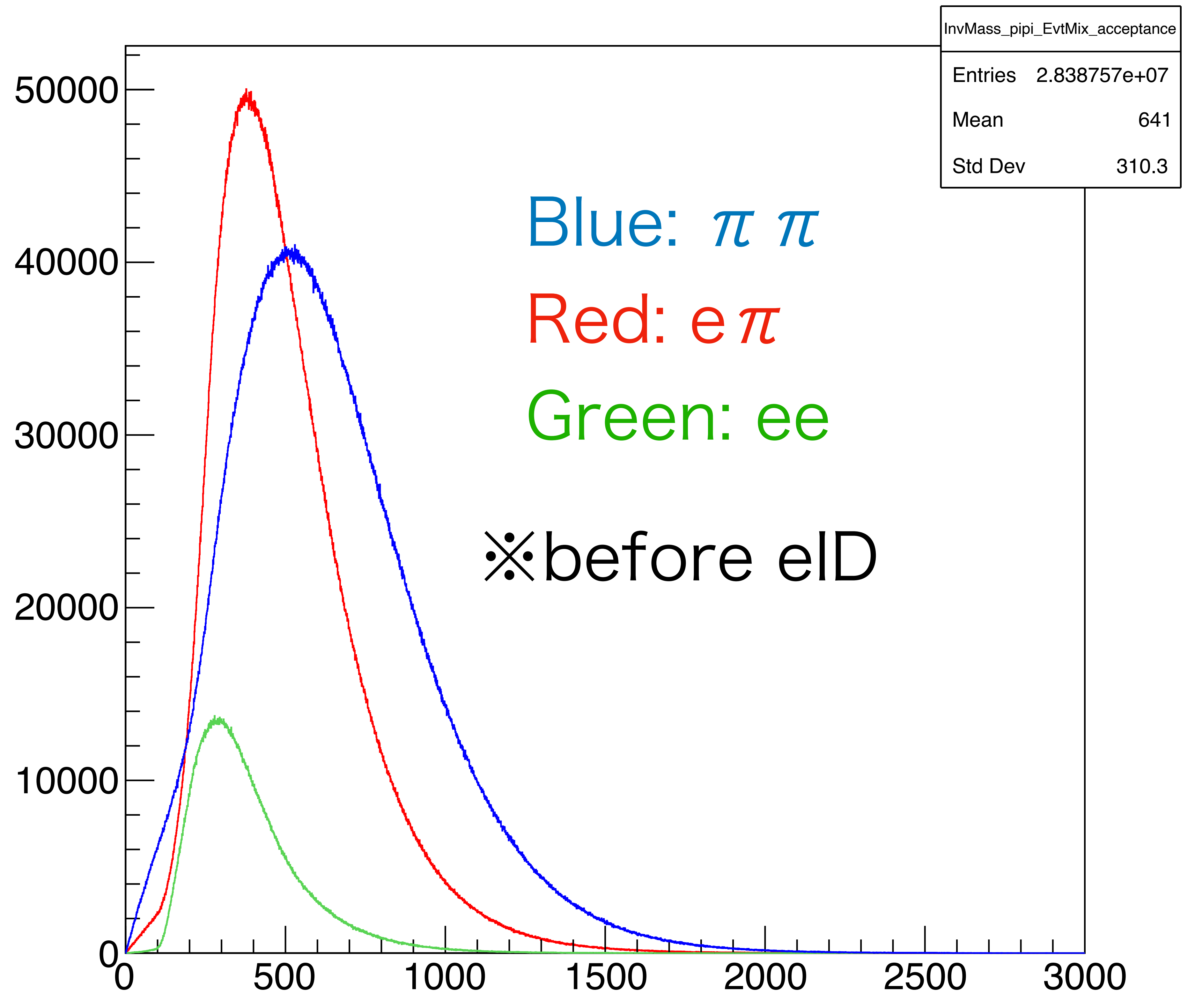


(Both are t-integrated)

Invariant mass distribution

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

Background: Simulated by JAM→Geant4
Main component of background :
π^0Dalitz, $\pi^{\pm}$, γ conversion, and combinatorial.



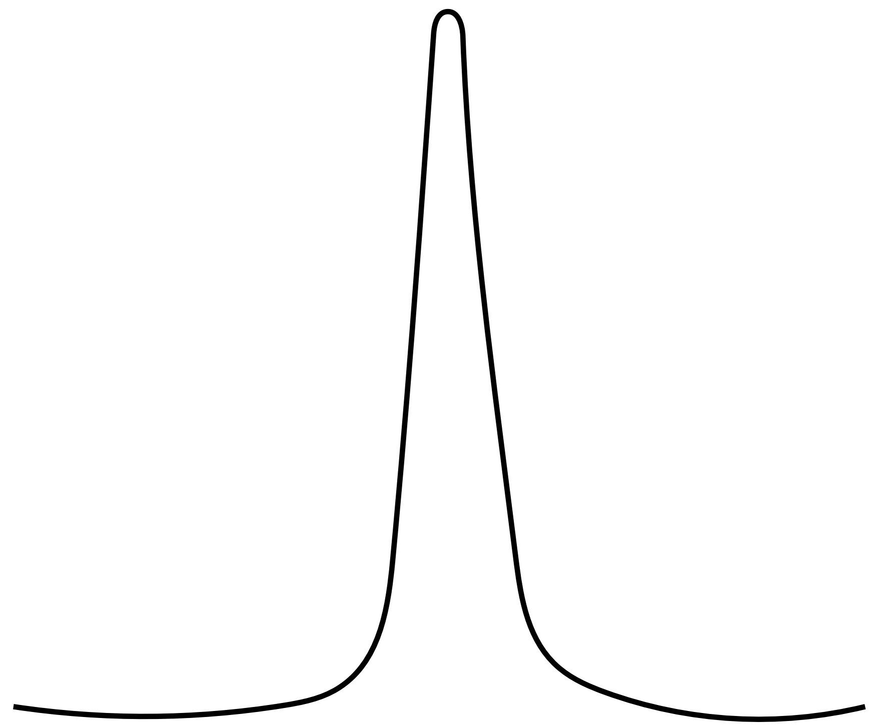
Spectral function and background is adjusted
to expected yield considering
- cross section
- acceptance
- length of beam time
- various efficiency(beam live, DAQ, Analysis, eID, π rejection,⋯)

Invariant mass distribution

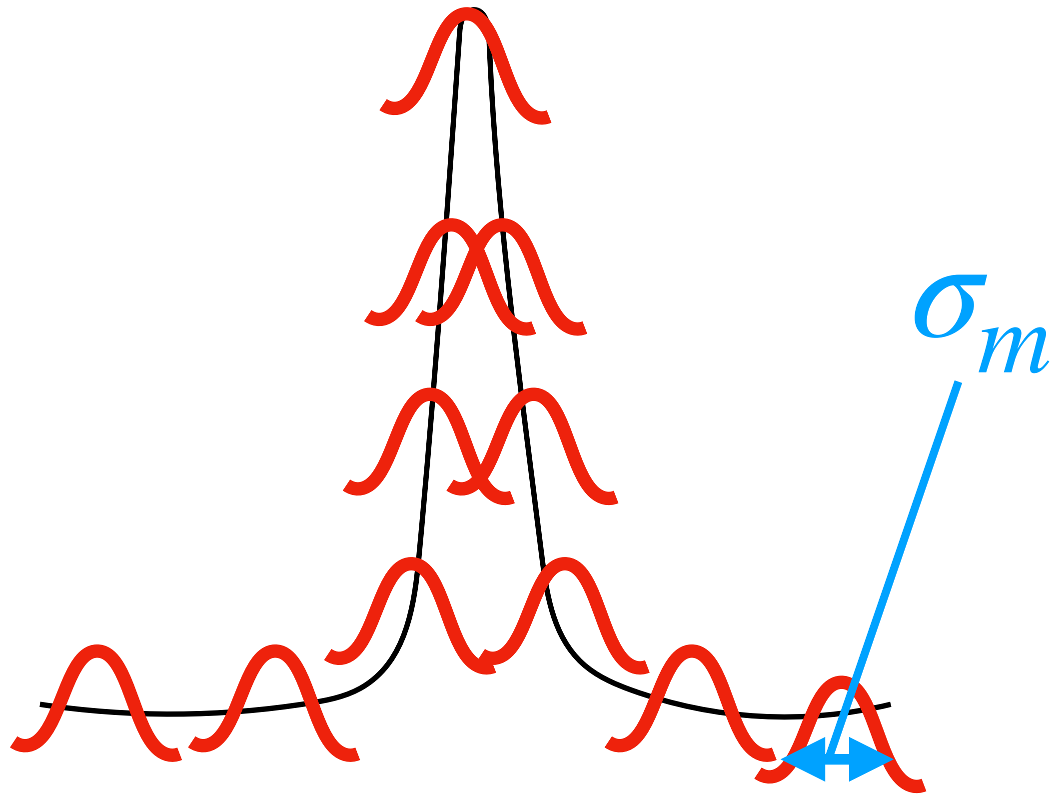
$$\text{InvMassDist} = \int \left[\int \text{Im}G_V(s,p,\rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt + \int \text{Bkg}(s,p)dp \right] g(m-s) ds$$

convolute with Gaussian

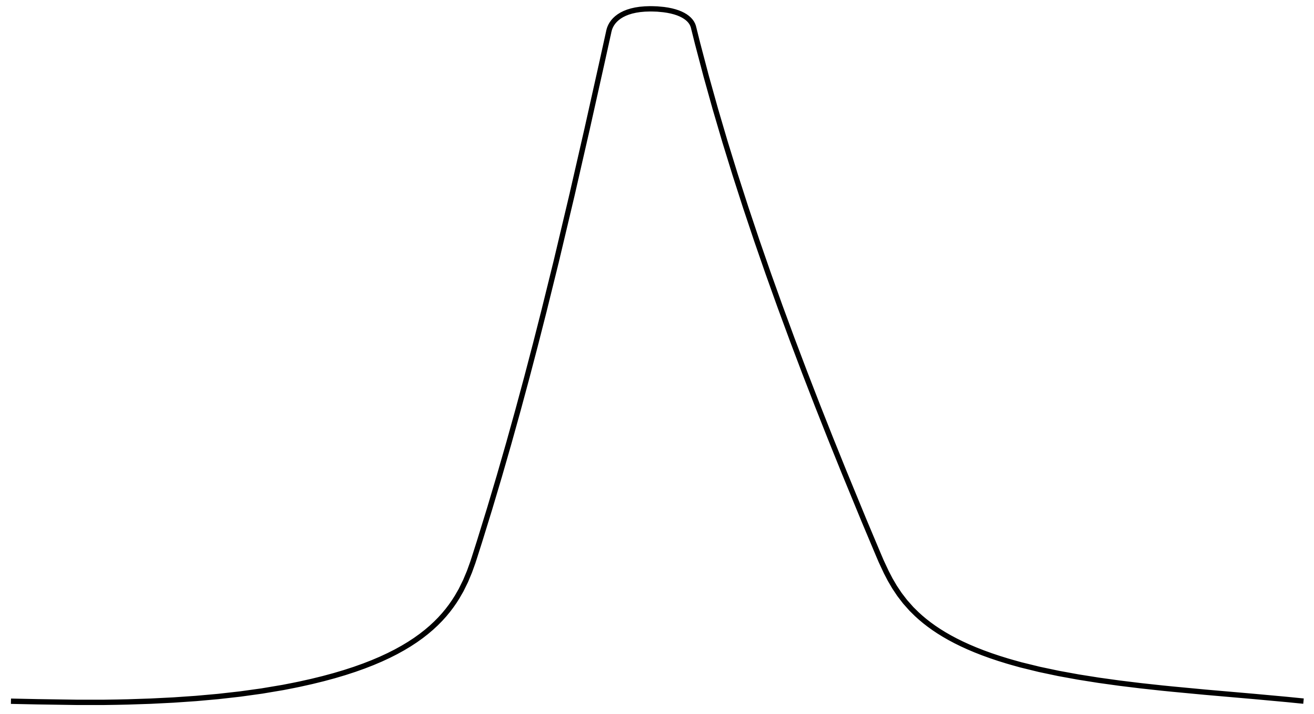
Detector response(mass resolution) effect



Ideal inv mass dist



Each point will have width of mass resolution.

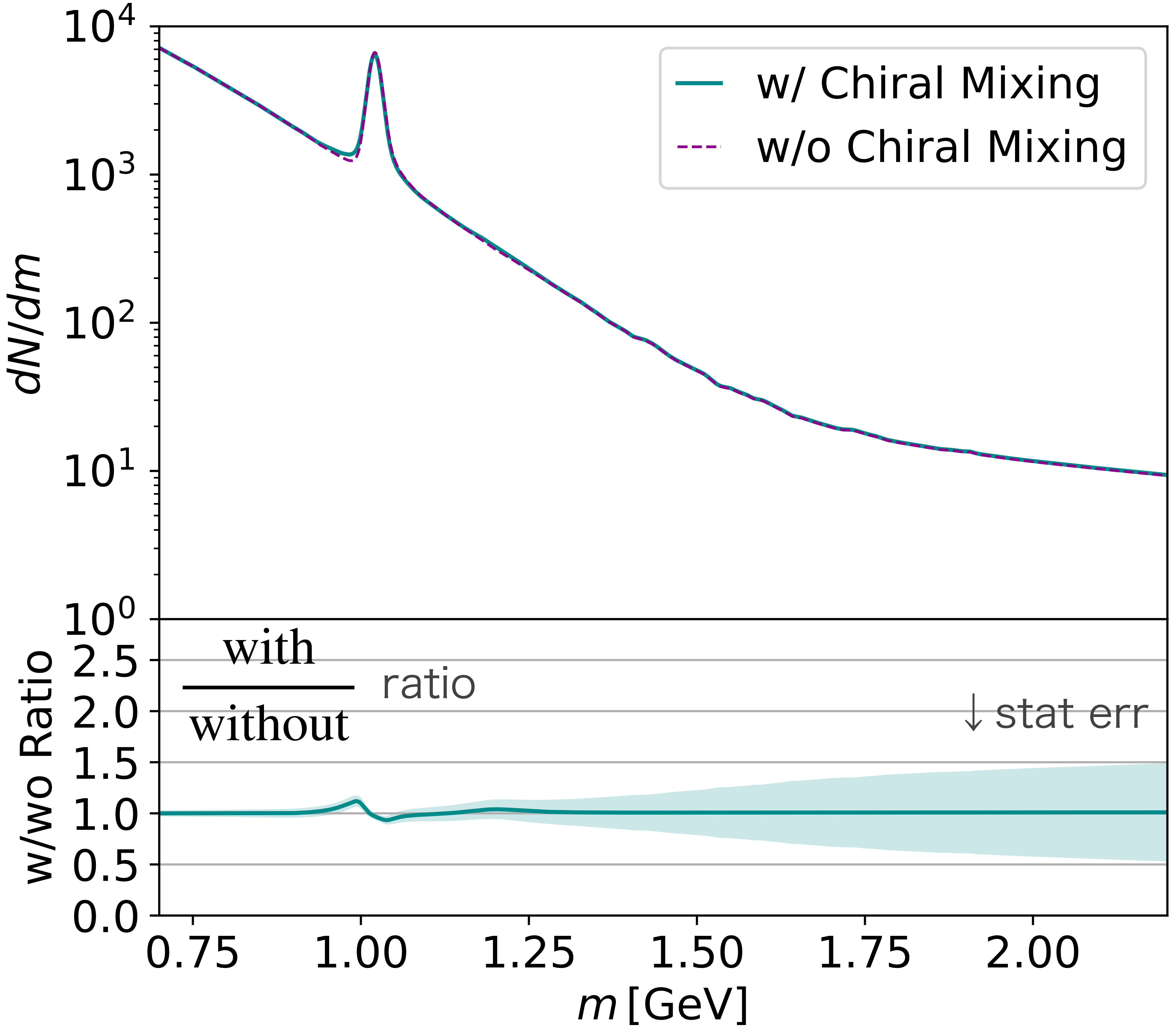


After integrate those red gaussian, inv mass dist with detector response can be obtained

Results

Result with Cu target, c=0.1ρ/ρ0

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Mixing strength has uncertainty

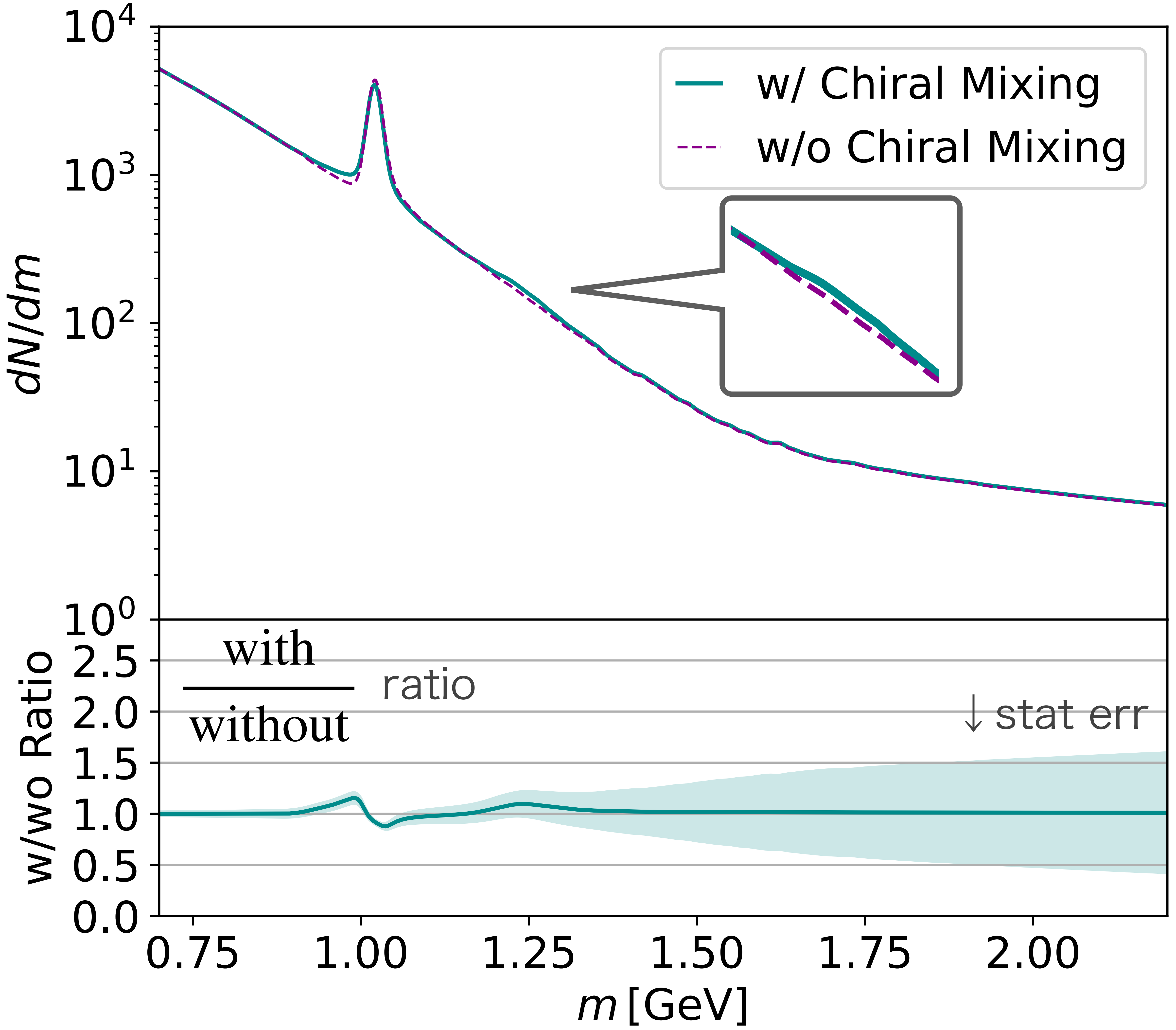
$$c = \boxed{0.1}\frac{\rho}{\rho_0}$$

0.1: consistent with WZW action

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

Result with Cu target, c=0.2ρ/ρ0

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Mixing strength has uncertainty

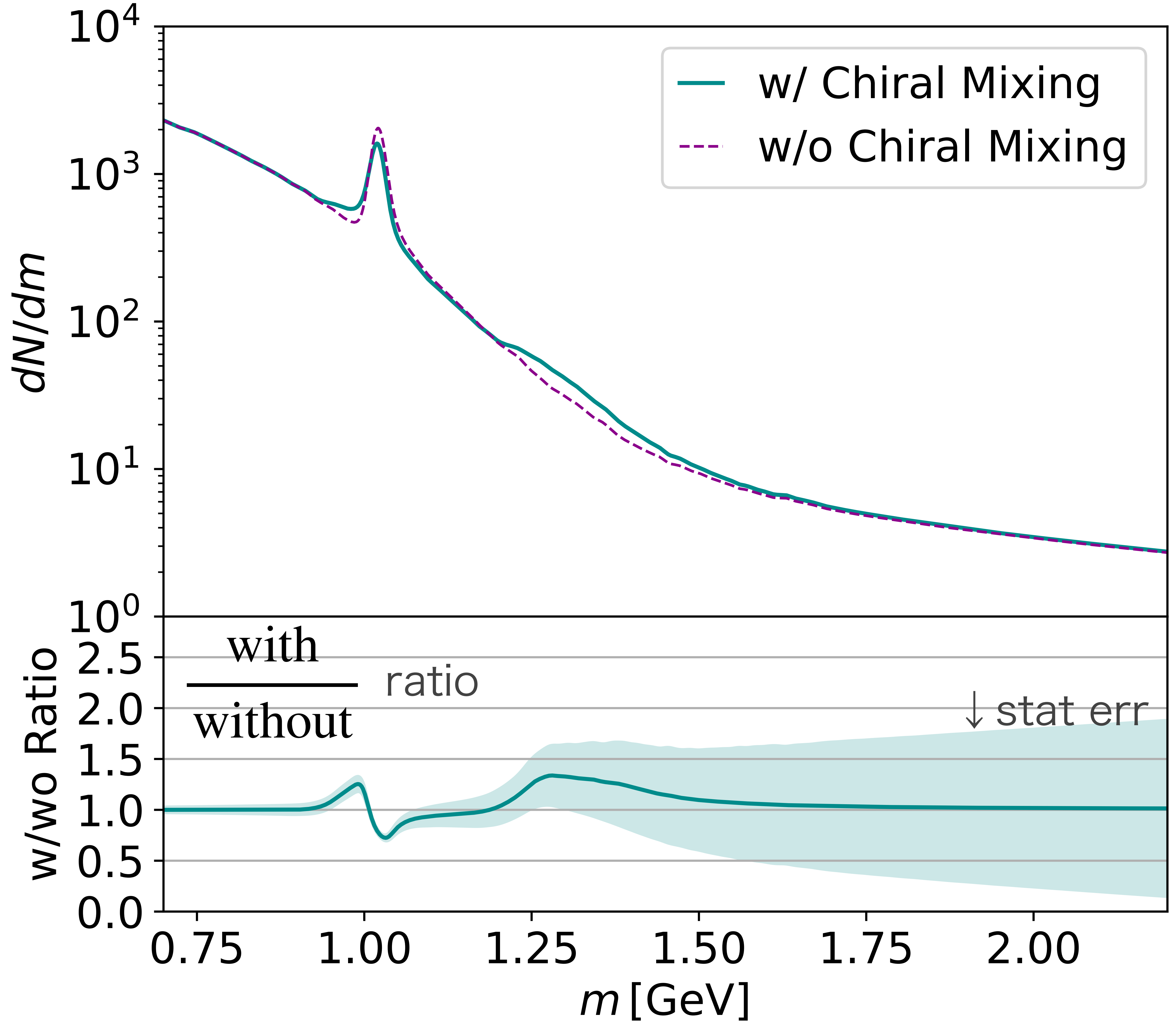
$$c = \boxed{0.2}\frac{\rho}{\rho_0}$$

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=0.5ρ/ρ0

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Mixing strength has uncertainty

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

0.1: WZW action's expectation

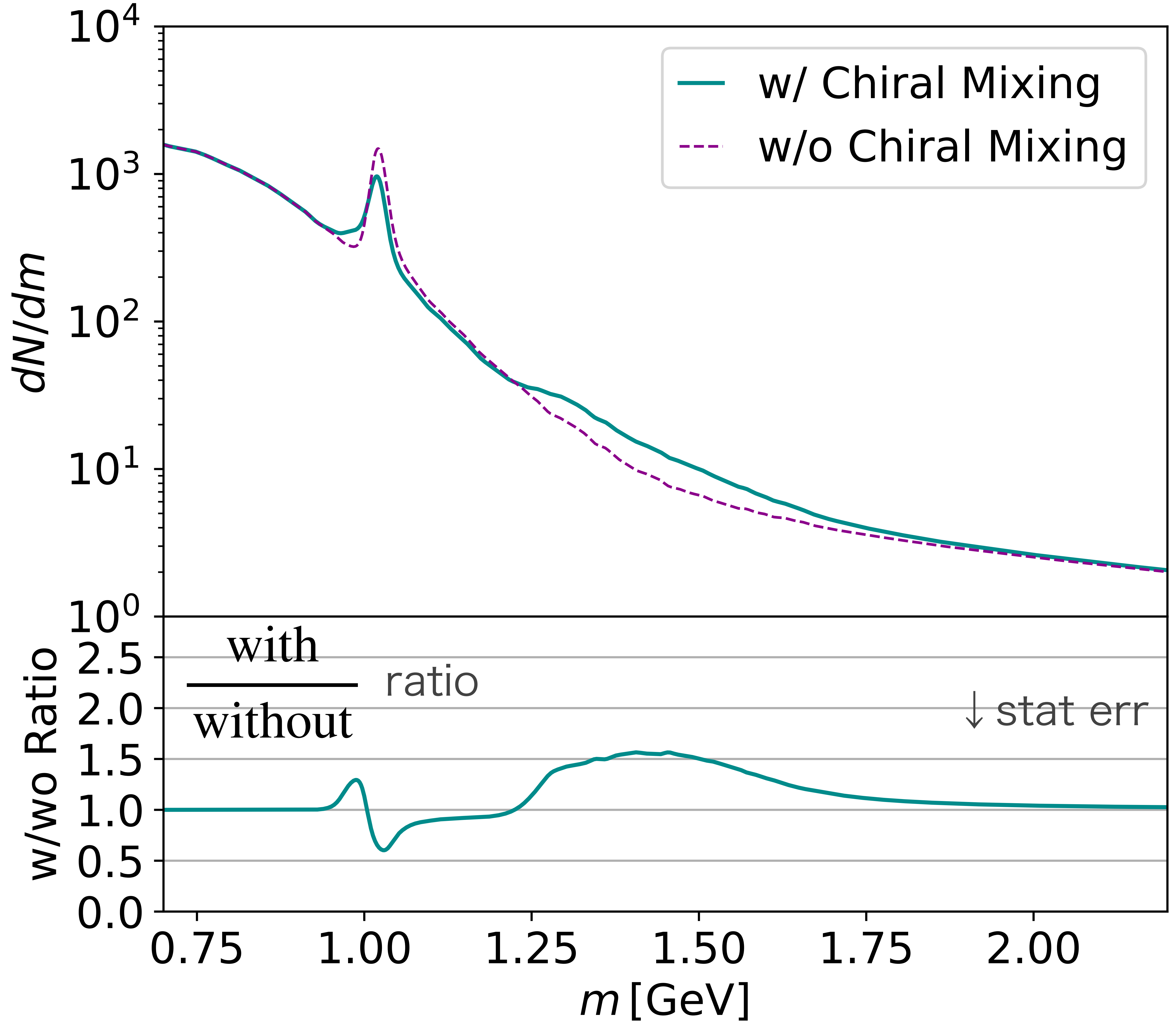
1.0: holographic QCD's expectation

$f_1(1420)$'s structure become obvious.

but still ~1 σ

Result with Cu target, c=1.0ρ/ρ0

Cu target, E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Mixing strength has uncertainty

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

0.1: WZW action's expectation

1.0: holographic QCD's expectation

$f_1(1420)$'s structure become broad

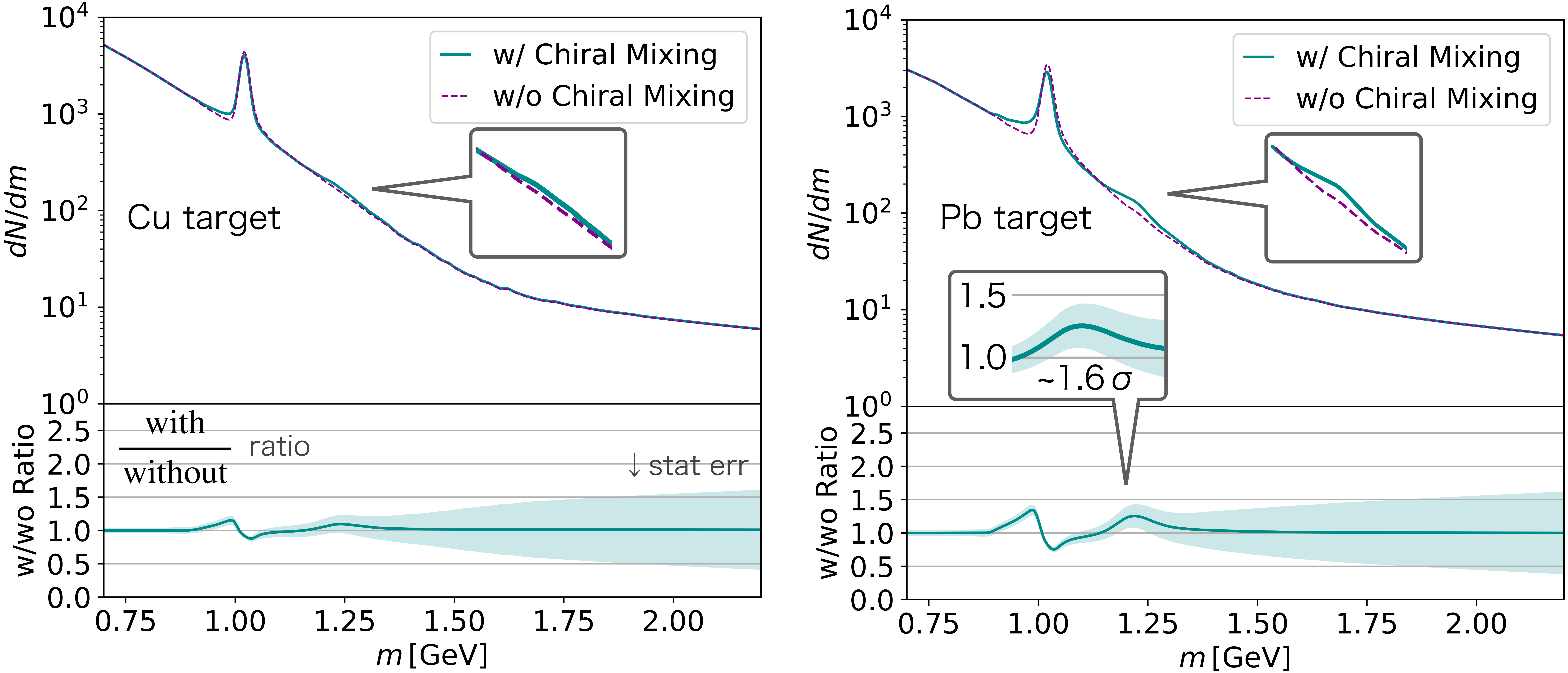
due to dispersion relation.

Difficult to discuss mass degeneracy.

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

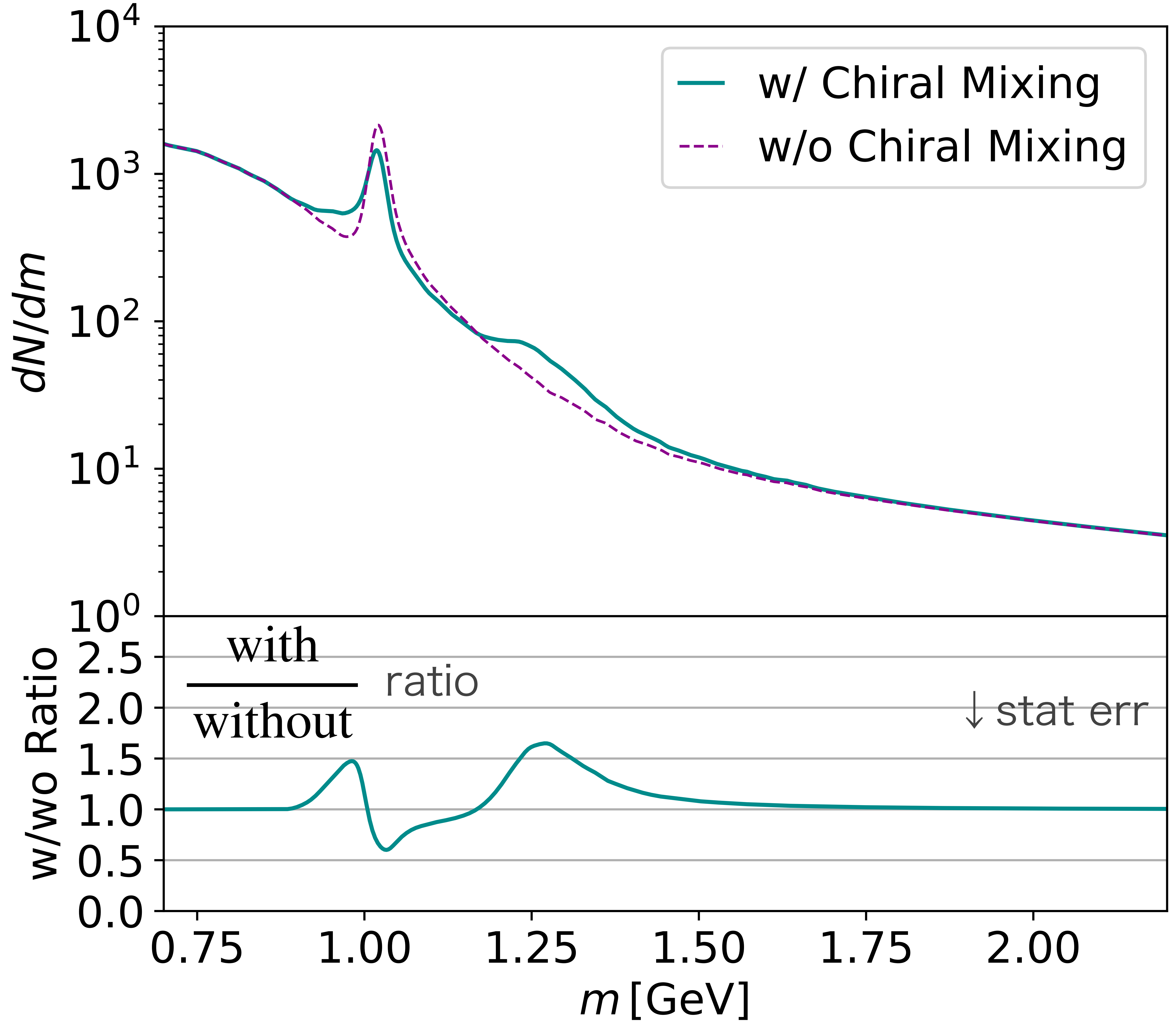
Result with Pb target, c=0.2ρ/ρ0

E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Result with Pb target, c=0.4ρ/ρ0

Pb target, E16 Run2 statistics, 30%CSR, no dropping/broadening ϕ by CSR



Mixing strength has uncertainty

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

0.1: WZW action's expectation

1.0: holographic QCD's expectation

If the mixing strength is such value,

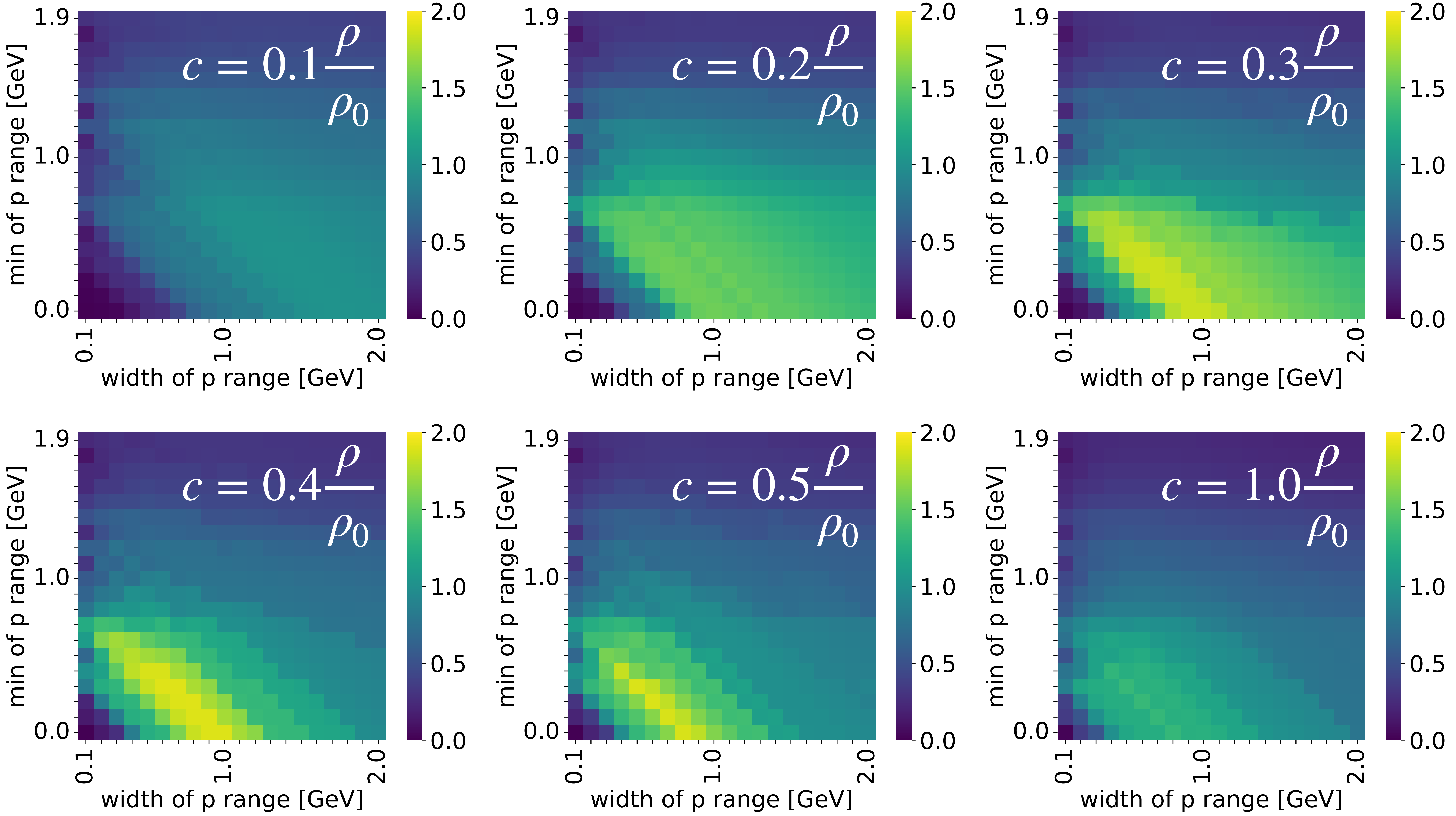
$f_1(1420)$ is visible with ~2σ and

the structure of it is narrow

to discuss mass degeneracy.

momentum region dependence

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

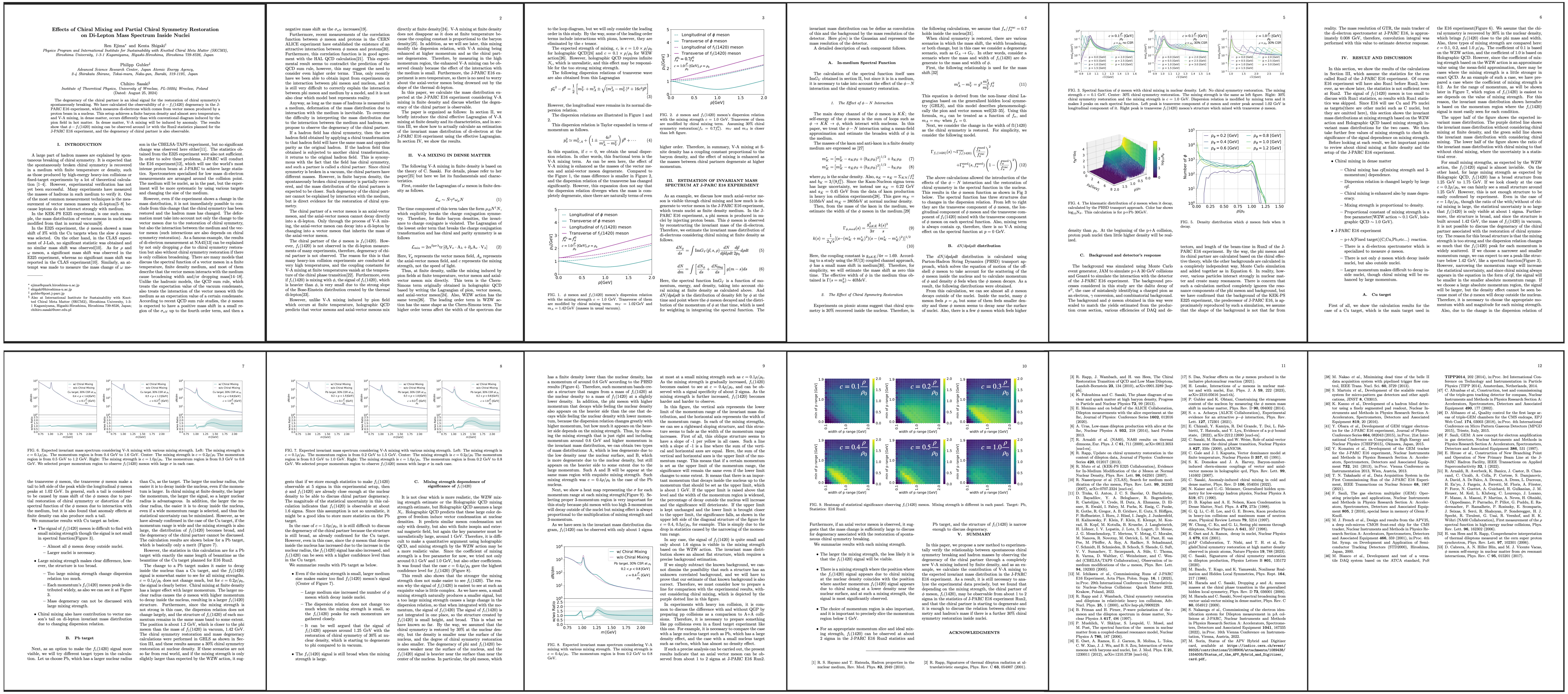
is required

paper in progress

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

R. Ejima, P. Gubler, C. Sasaki, K. Shigaki

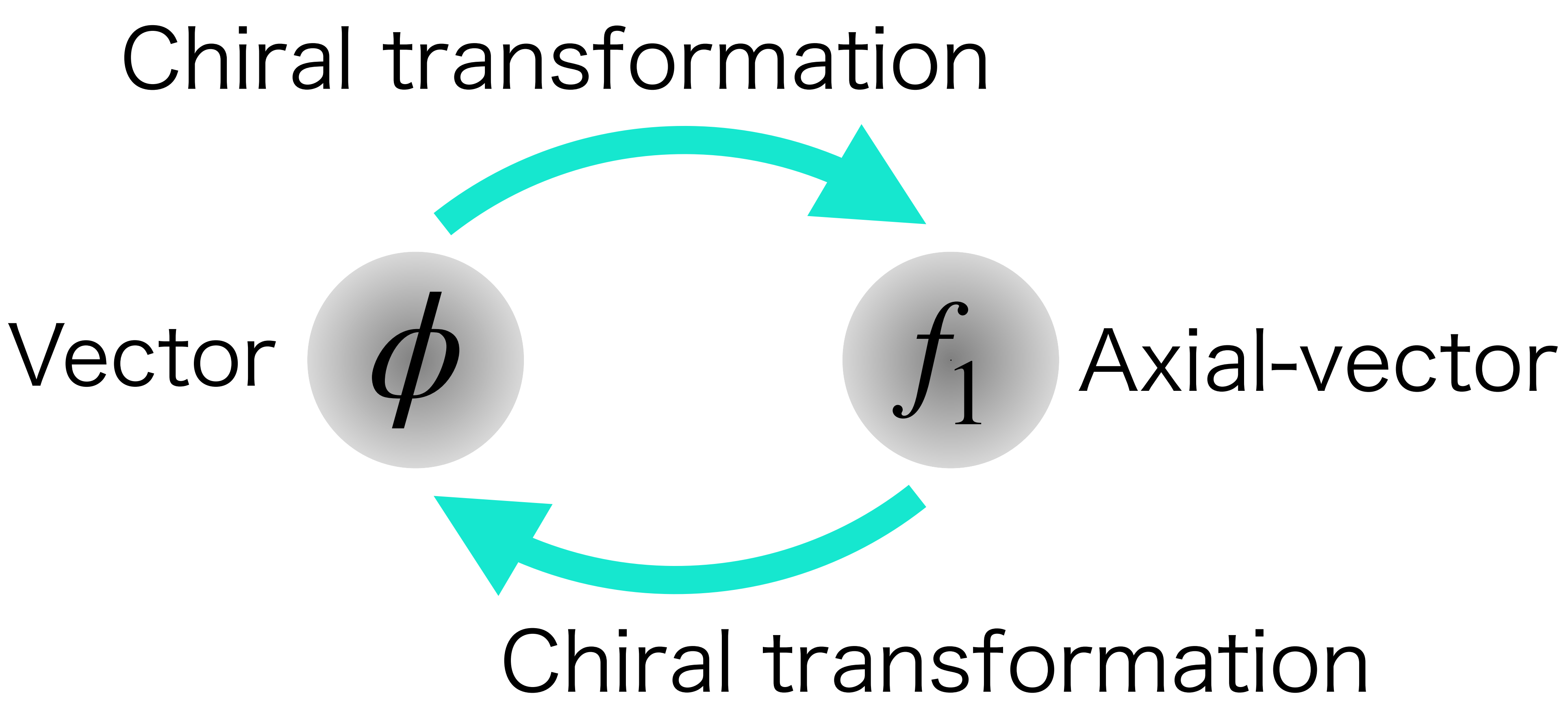
To be submitted to PRC


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

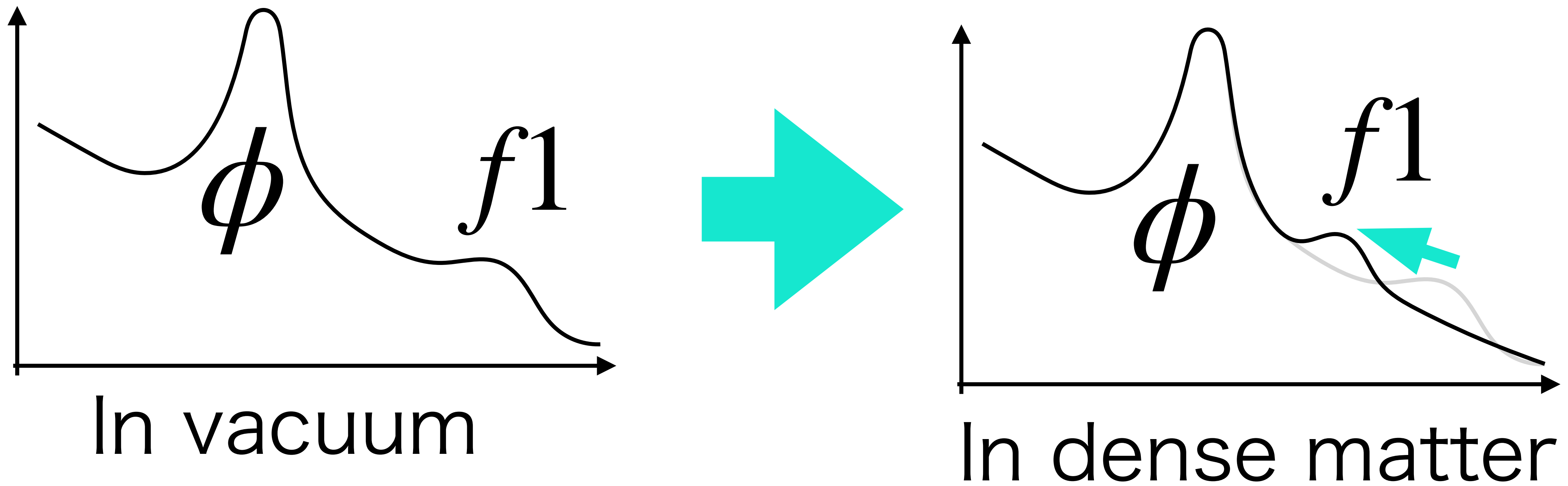
Ren Ejima and Kenta Shigaki

Summary

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



Chiral partner should have
exactly the same mass in chiral limit



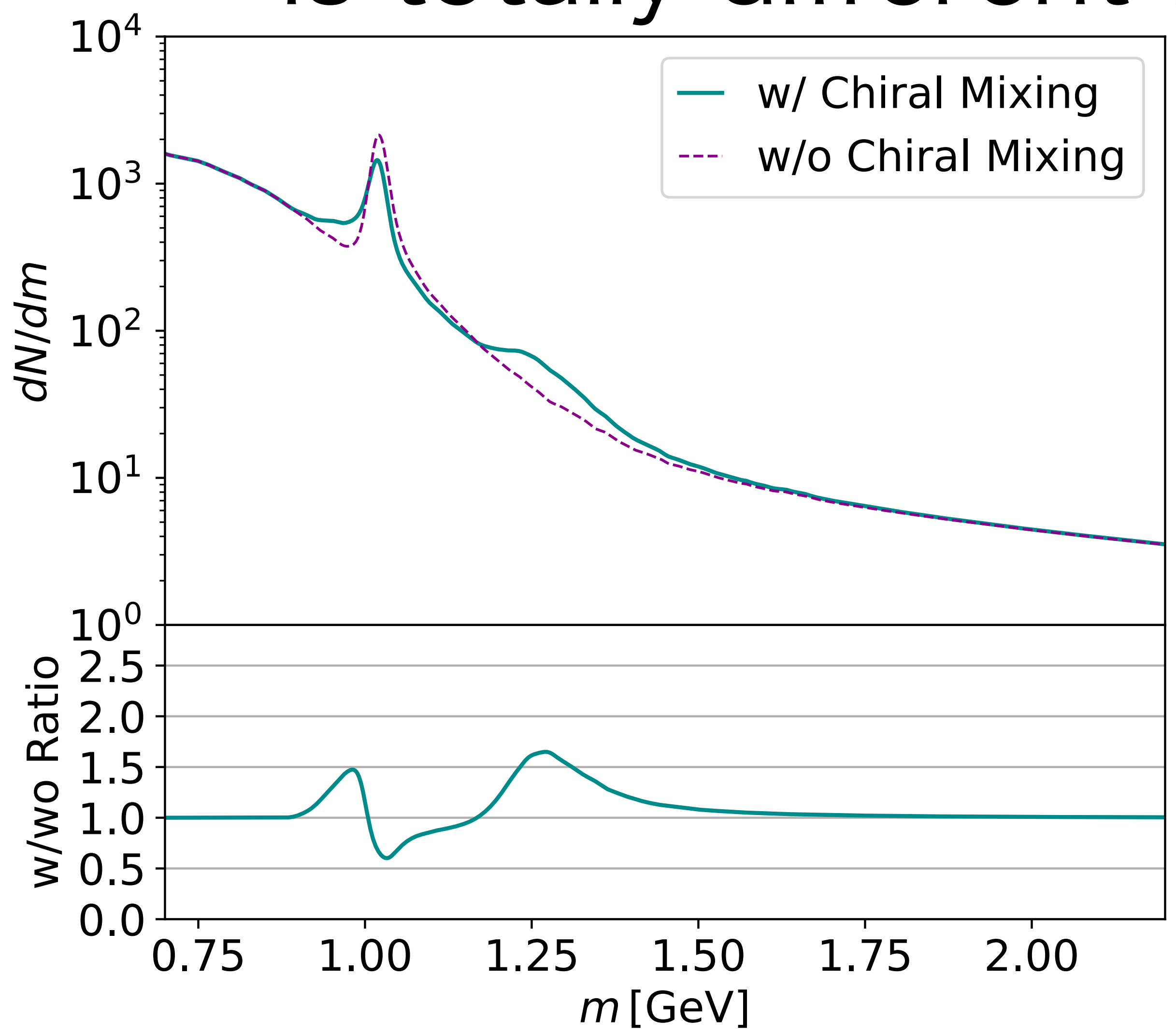
Mass dist. is degenerated in dense matter.

This is equivalent to partial CSR.

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 ϕ in J-PARC E16 experiment.

visible with 2σ…?

Back up

Low energy theorem

$$G_V^{\mu\nu}(T) = (1-\epsilon)G_V^{\mu\nu}(0) + \epsilon G_A^{\mu\nu}(0)$$

$$G_A^{\mu\nu}(T) = (1-\epsilon)G_A^{\mu\nu}(0) + \epsilon G_V^{\mu\nu}(0)$$

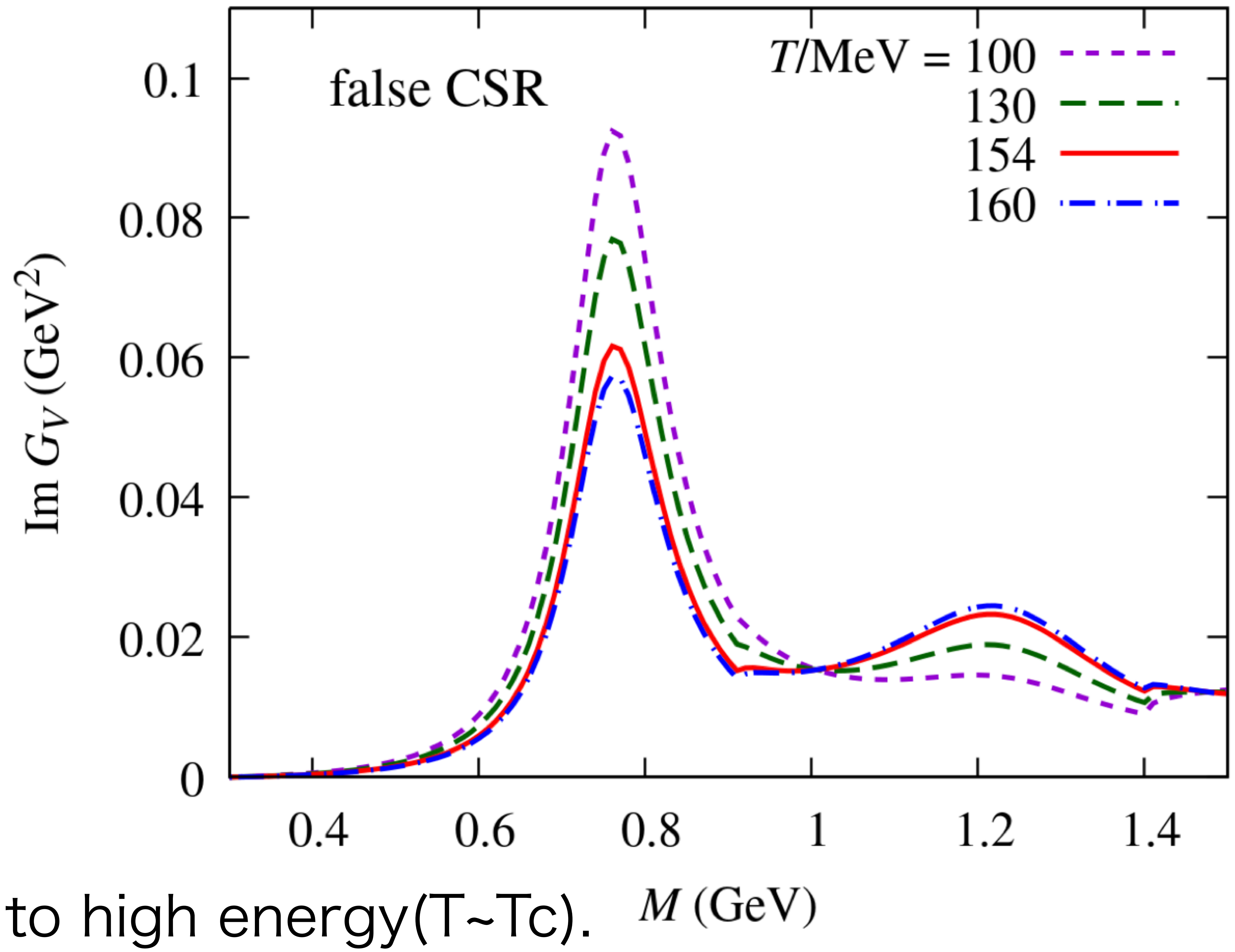
$$\epsilon = \frac{T^2}{6f_\pi^2}$$

[Dey, Eletsky and Ioffe(90)]

[finite ρ: Krippa(98)]

$\epsilon = 1/2 \rightarrow G_V = G_A$: Is this the signal of CSR?

$\varepsilon = 1/2 \Rightarrow$ T=160MeV



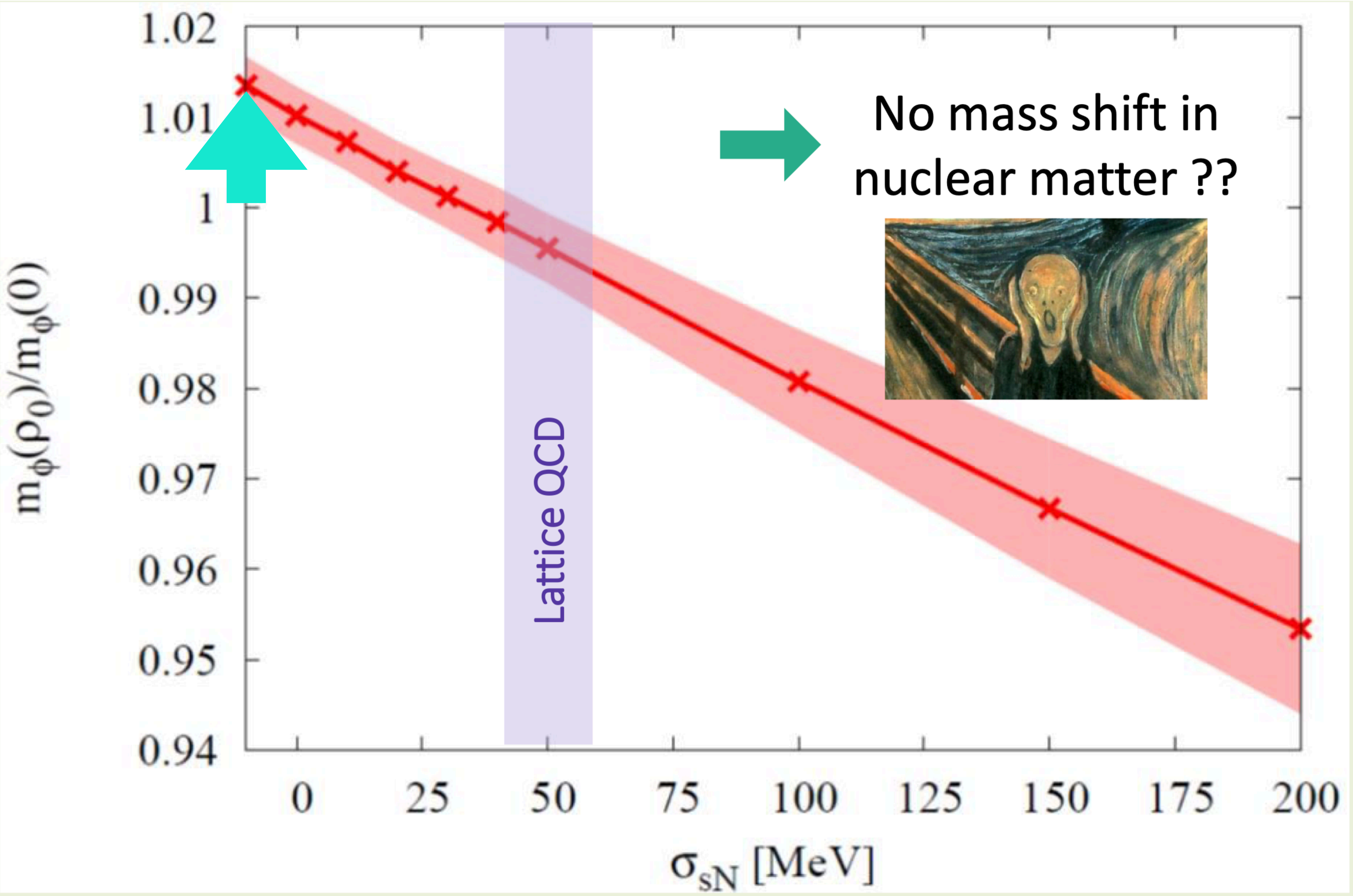
Actually this is only able to apply to low energy, not to high energy(T~Tc).

There is no mass degeneration.

Chiral mixing will be maximized at Tc?

→When we consider the diagram of chiral mixing in hot matter, chiral mixing should be disappeared.

φ-N interaction in QCD sum rule

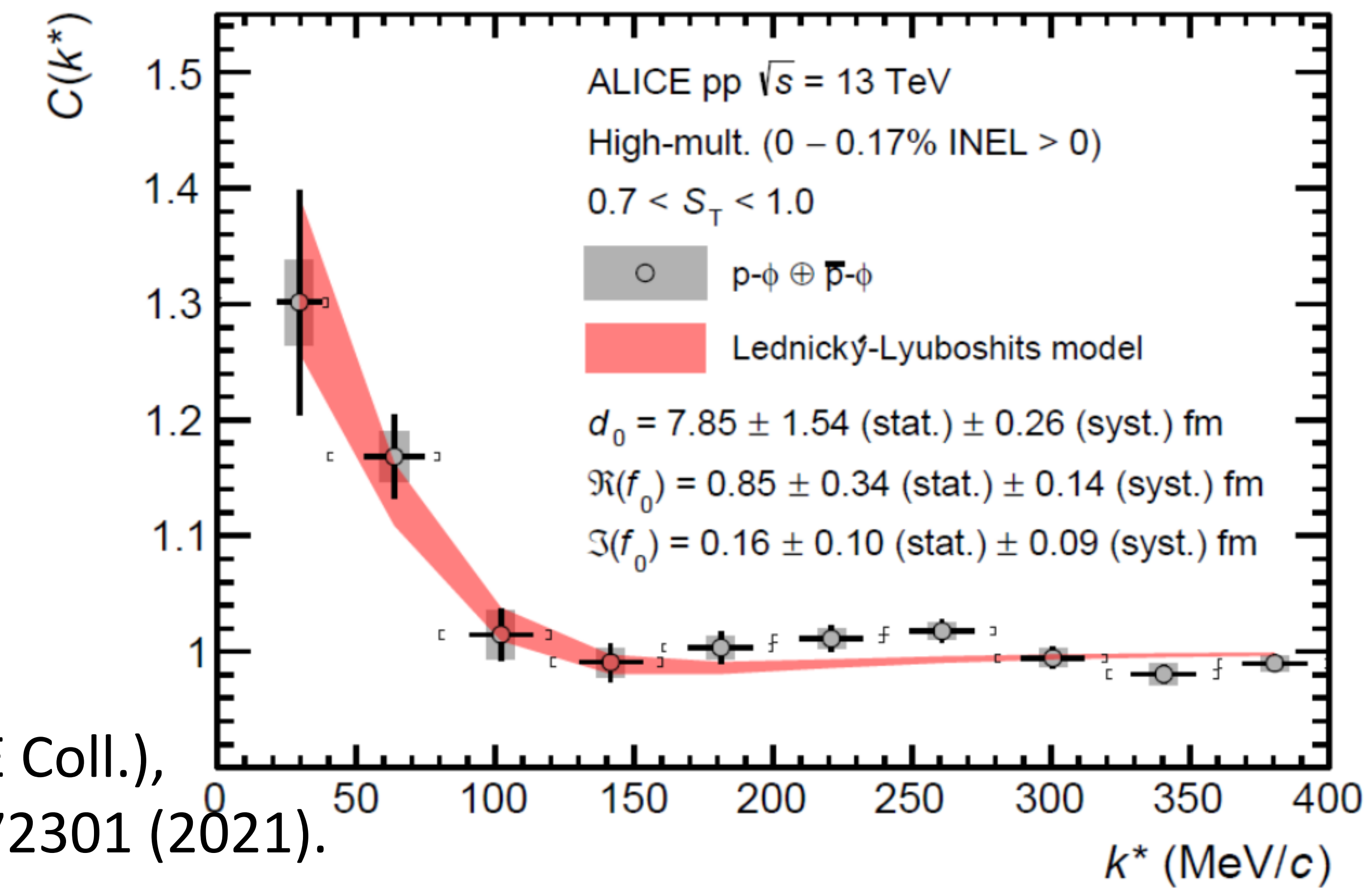


From Philipp-san's slide.

$$|\langle \bar{s}s \rangle| = |\langle \bar{s}s \rangle|_0 - \frac{\sigma_{sN}}{m_s}\rho \qquad \sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$

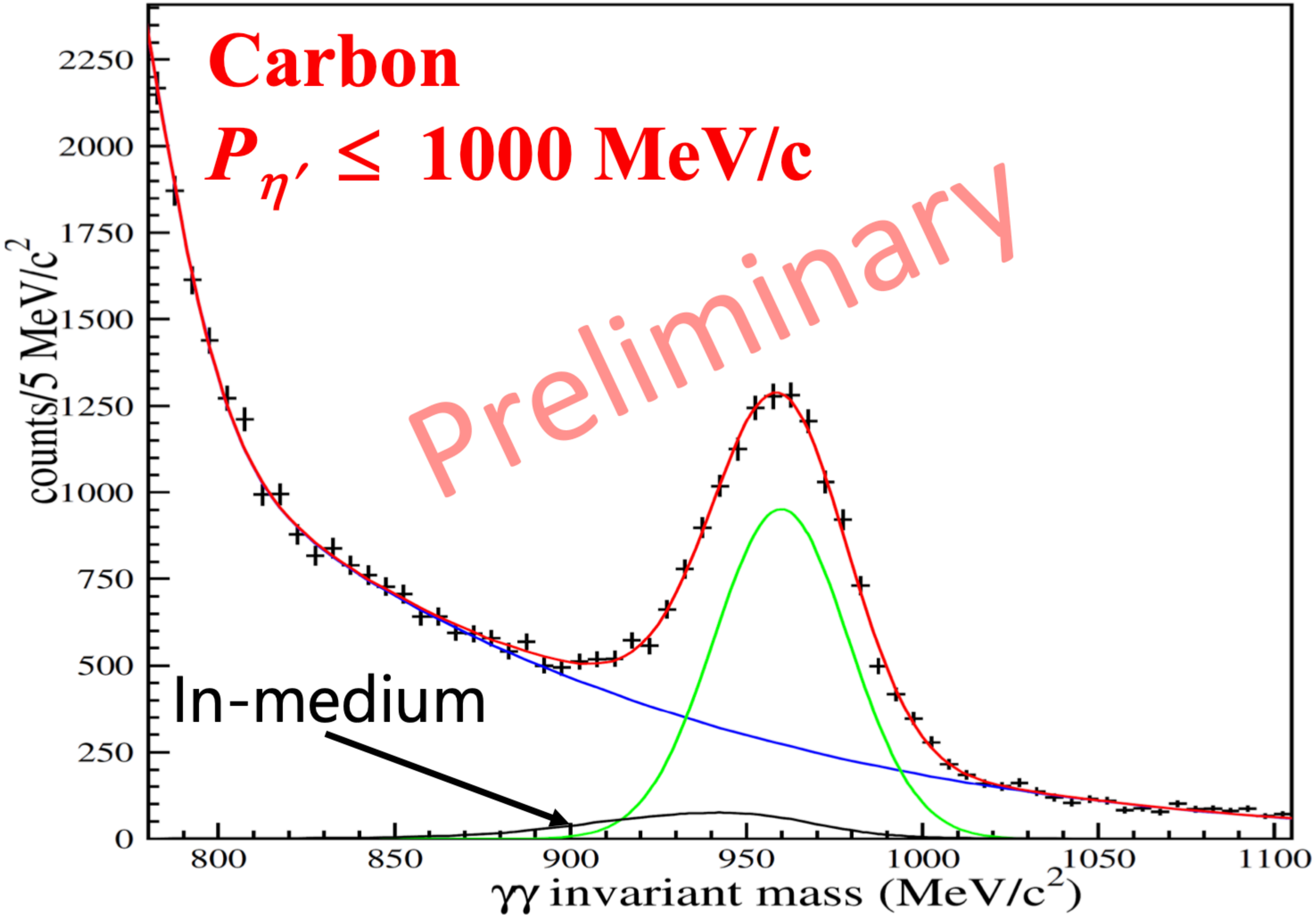
In QCD sum rule, ϕ-N interaction w/o CSR effect is expressed in terms of gluon condensation.

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

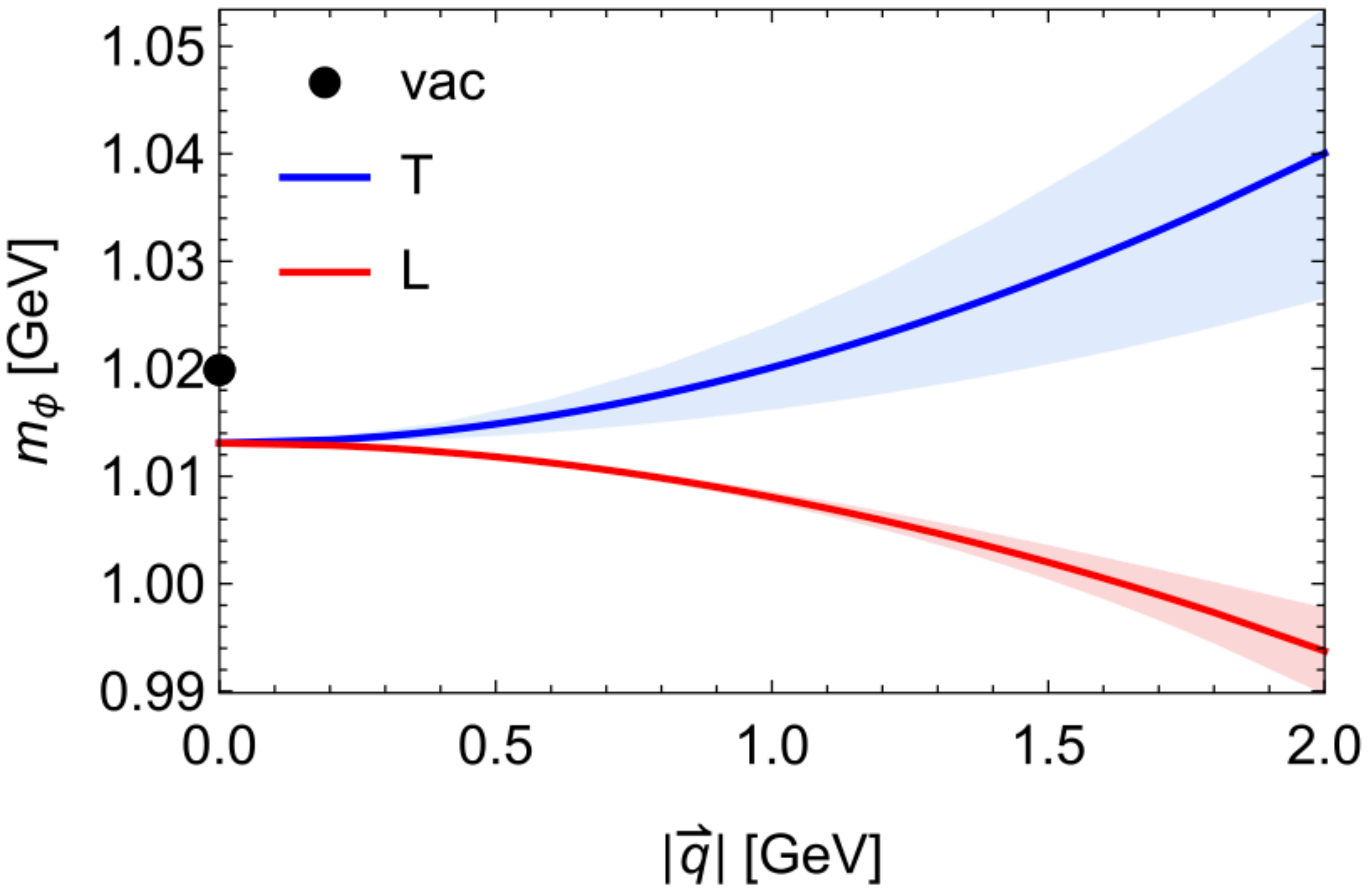


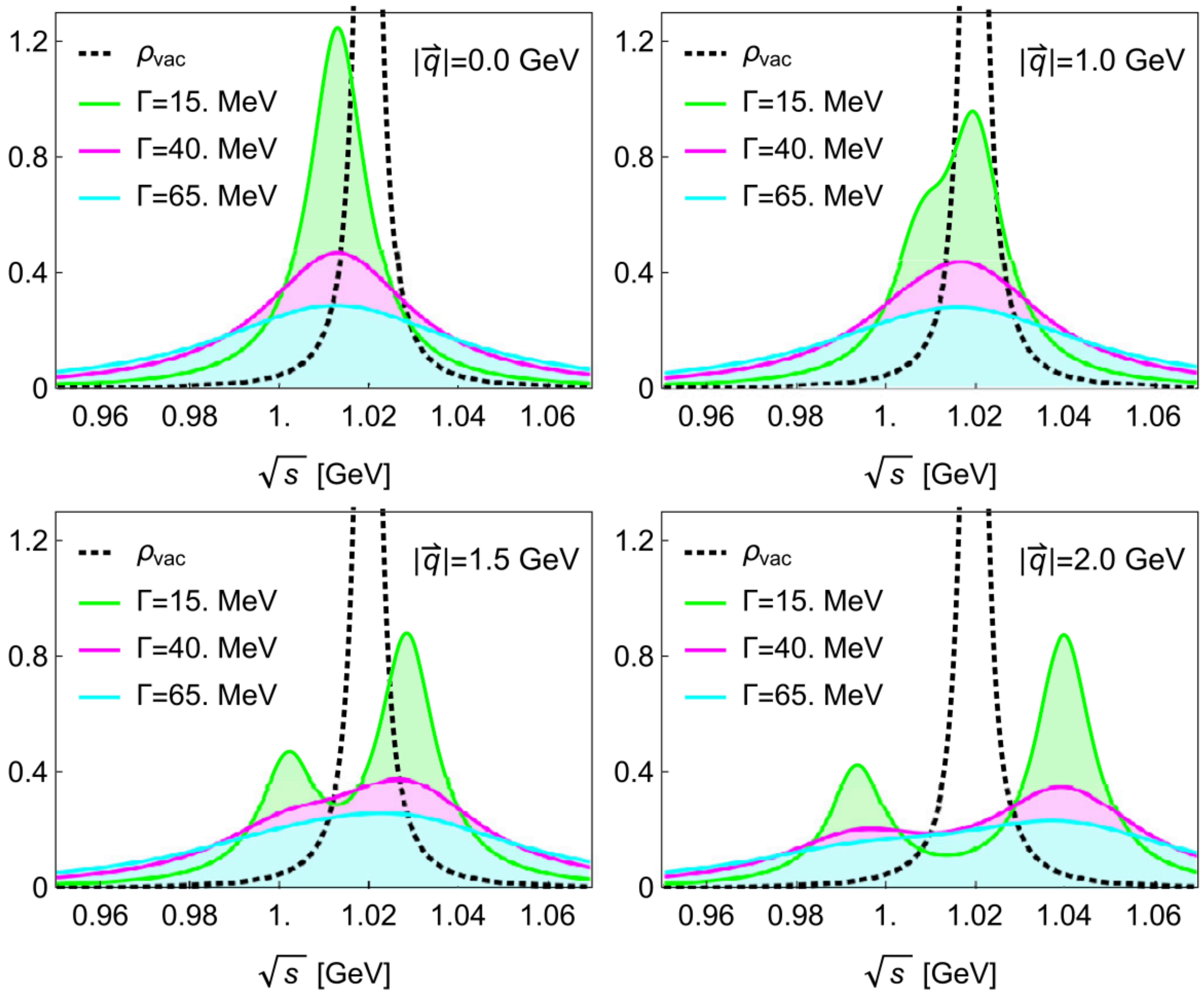
S. Acharya et al. (ALICE Coll.), Phys. Rev. Lett. **127**, 172301 (2021).

LEPS2's result

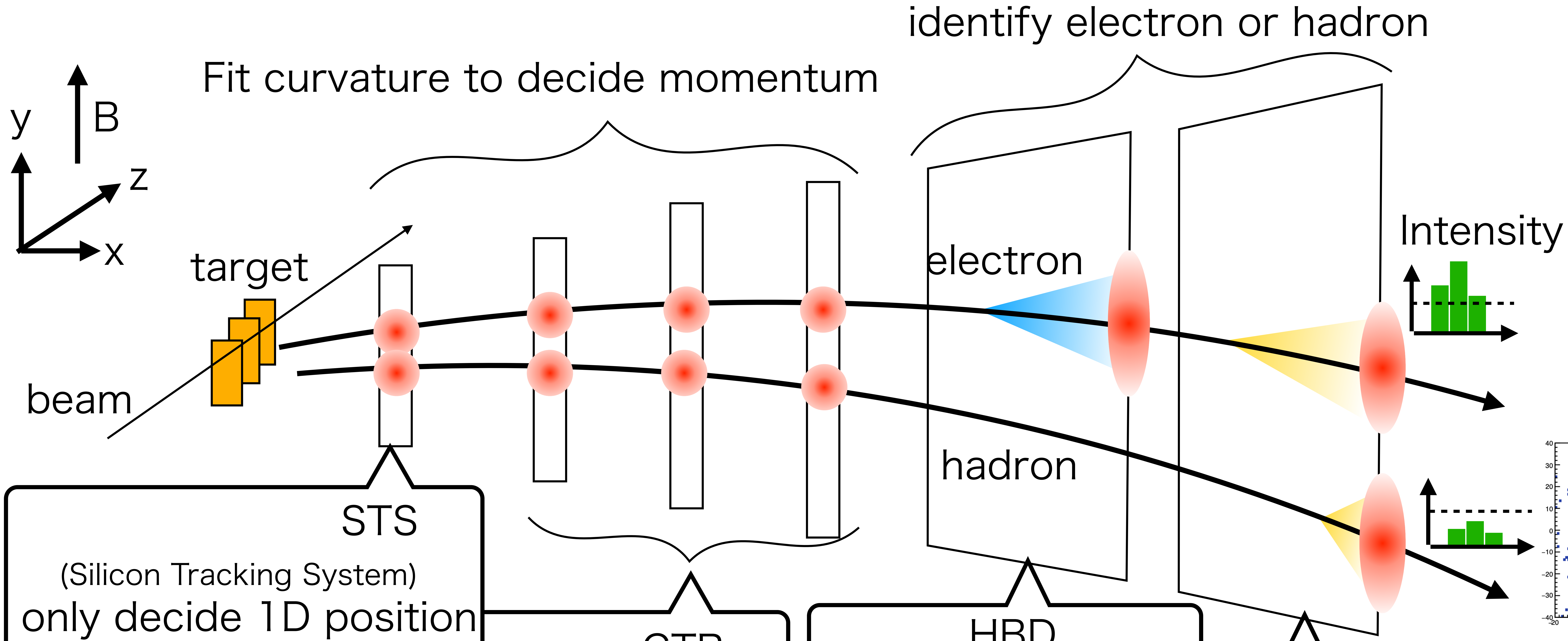


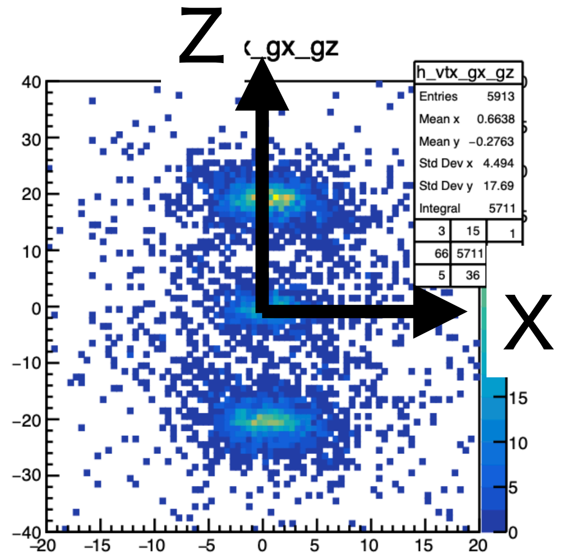
breaking of lorenz invariant

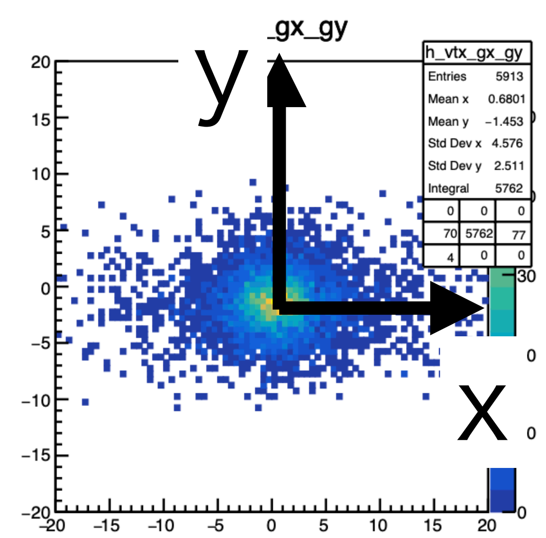




J-PARC E16 Detector







STS
(Silicon Tracking System)
only decide 1D position
from CBM experiment

GTR
(GEM Tracker)
measure 2D position
on each plane

HBD
(Hadron Blind Detector)
only e can
emit cherenkov
hadron can't emit

LG
(Lead-Glass calorimetor)
Intensity of EM shower
is different between e and hadron