Transport simulations of vector mesons in pA reactions

Philipp Gubler (JAEA)

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, in preparation.
R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, in preparation.

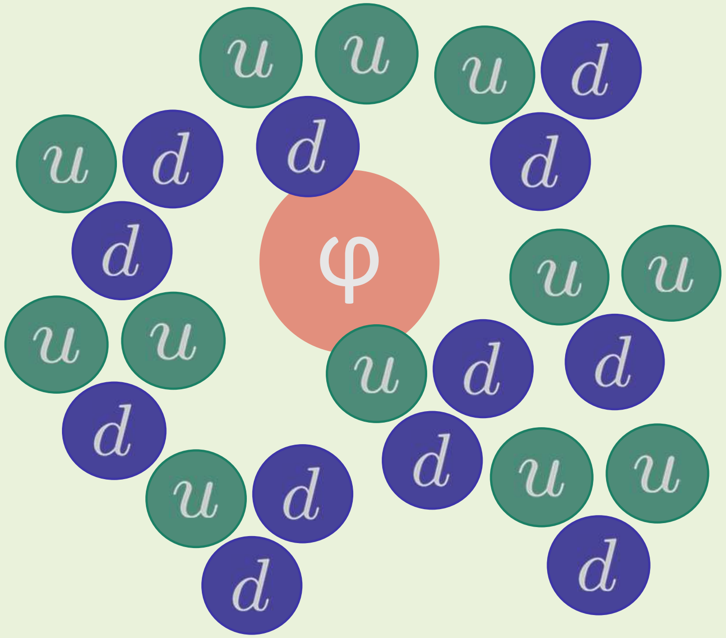
Talk at the International Workshop on Quark Structure of Hadrons 2024,
Wako-shi, Saitama, Japan
August 9, 2024

Work done in collaboration with:

M. Ichikawa (JAEA)
T. Song (GSI)
E. Bratkovskaya (Goethe U. Frankfurt)
R. Ejima (Hiroshima U.)
C. Sasaki (U. of Wroclav/Hiroshima U.)
K. Shigaki (Hiroshima U.)

Topics of this talk

$|\langle\overline{u}u\rangle_\rho|$ ↘
$|\langle\overline{d}d\rangle_\rho|$ ↘
$|\langle\overline{s}s\rangle_\rho|$ ↘



→ m_ϕ ↘ ?

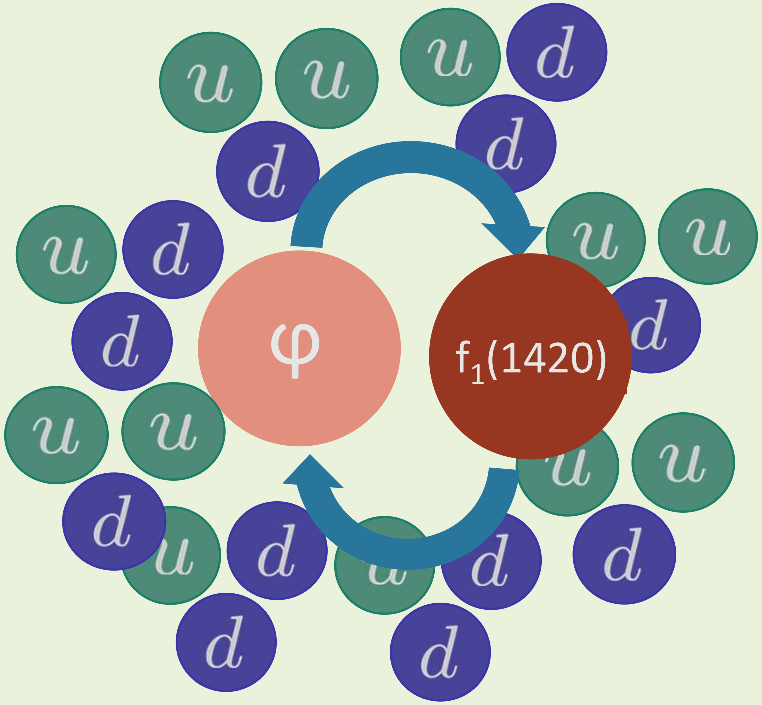
→ Γ_ϕ ↗ ?

Relation to the φN scattering length?

$a_{\phi N}$

Topics of this talk

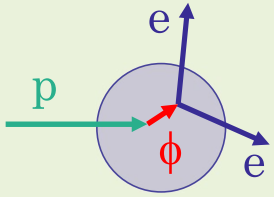
Broken C
(charge conjugation) symmetry



New peak in dilepton spectrum??

Previous experimental results

KEK
E325



12 GeV
pA-reaction

Pole mass: $$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0}$$

k_1: 0.034 ± 0.007

Pole width: $$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

k_2: 2.6 ± 1.5

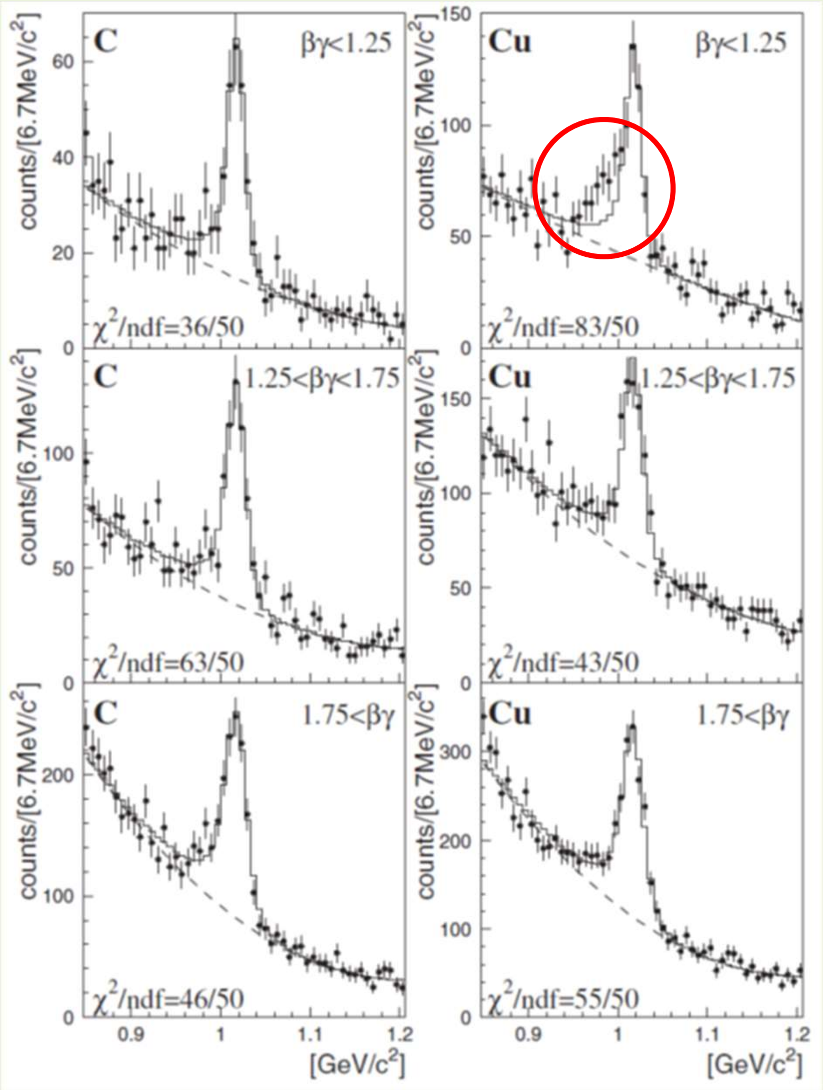
Measurement is being repeated with
~100x increased statistics at the
J-PARC E16 experiment!

slow φs

intermediate
φs

fast φs

$$\beta\gamma = \frac{|\vec{p}|}{m_\phi}$$

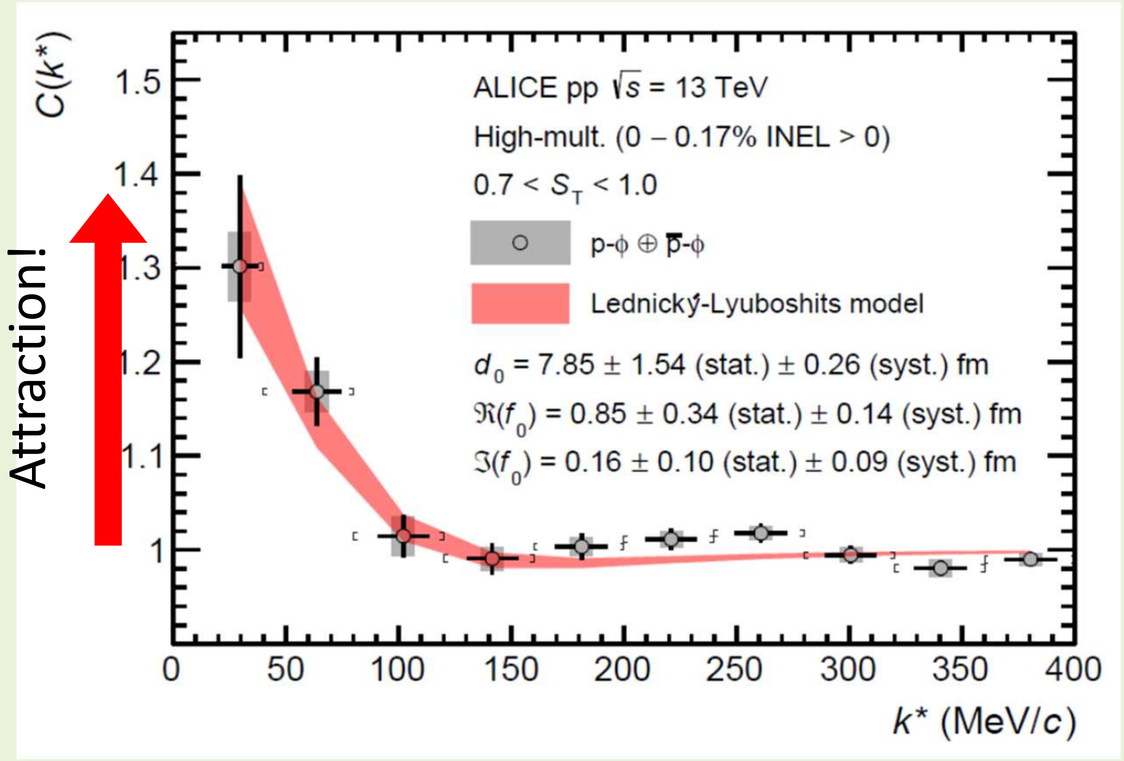


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

More recent results

ALICE: pp

Measurement of φN correlation



Attraction!

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

Qualitatively agrees with:

★ Y. Lyu et al. (Lattice QCD, HAL QCD Collaboration), Phys. Rev. D **106**, 074507 (2022).

$$a_0^{3/2} = 1.43(23)_{\text{stat.}}\left(^{+36}_{-06}\right)_{\text{syst.}}\ \text{fm}$$

Disagrees with:

★ Photoproduction measurement at CLAS

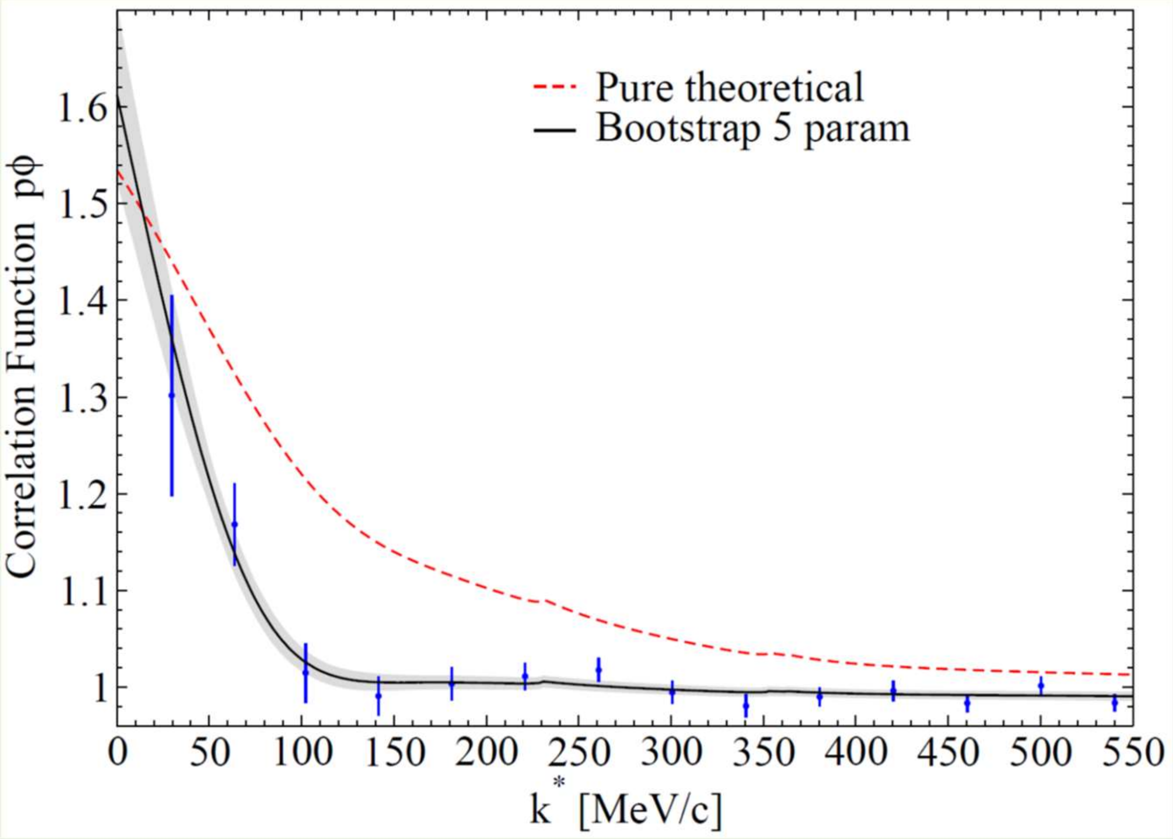
I.I. Strakovsky et al.,
Phys. Rev. C **101**, 045201 (2020).

$$|a_0| = 0.063 \pm 0.010\,\text{fm}$$

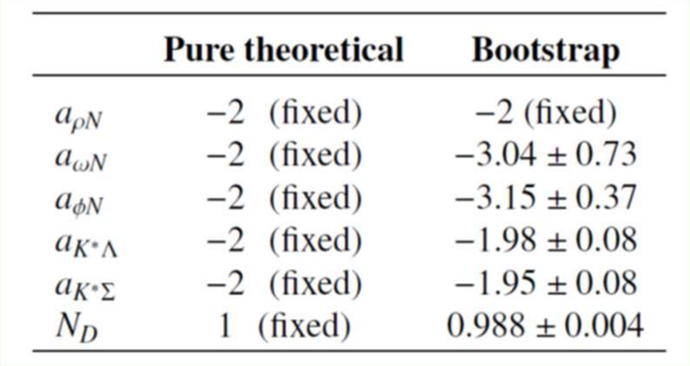
More recent results

New analysis of the ALICE data

A. Feijoo, M. Korwieser and L. Fabbietti, arXiv:2407.01128 [hep-ph].



Coupled channel approach, with subtraction constants as fittable parameters:



	Pure theoretical	Bootstrap
$a_{\rho N}$	−2 (fixed)	−2 (fixed)
$a_{\omega N}$	−2 (fixed)	-3.04 ± 0.73
$a_{\phi N}$	−2 (fixed)	-3.15 ± 0.37
$a_{K^*\Lambda}$	−2 (fixed)	-1.98 ± 0.08
$a_{K^*\Sigma}$	−2 (fixed)	-1.95 ± 0.08
N_D	1 (fixed)	0.988 ± 0.004

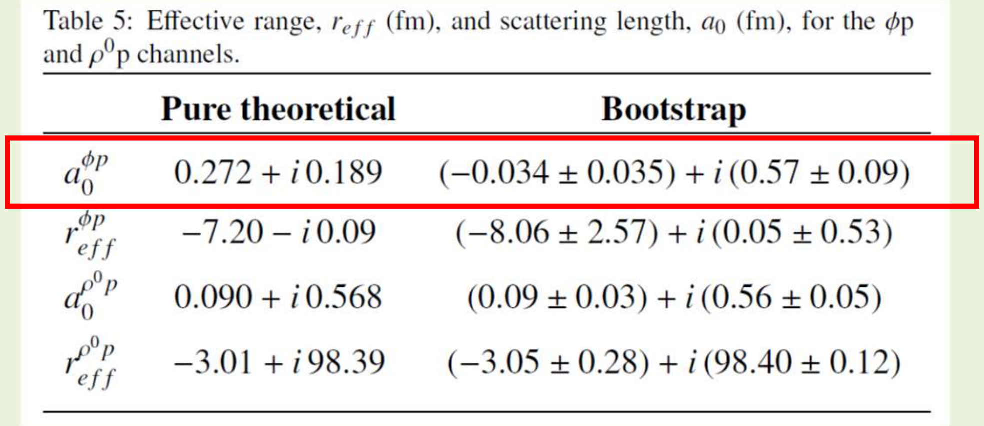


Table 5: Effective range, r_{eff} (fm), and scattering length, a_0 (fm), for the ϕp and ρ^0p channels.

	Pure theoretical	Bootstrap
$a_0^{\phi p}$	$0.272 + i\,0.189$	$(-0.034 \pm 0.035) + i\,(0.57 \pm 0.09)$
$r_{eff}^{\phi p}$	$-7.20 - i\,0.09$	$(-8.06 \pm 2.57) + i\,(0.05 \pm 0.53)$
$a_0^{\rho^0 p}$	$0.090 + i\,0.568$	$(0.09 \pm 0.03) + i\,(0.56 \pm 0.05)$
$r_{eff}^{\rho^0 p}$	$-3.01 + i\,98.39$	$(-3.05 \pm 0.28) + i\,(98.40 \pm 0.12)$

Simple relation between φN scattering length and φ meson mass shift in nuclear matter

$$\left.\begin{aligned} V_\phi(\rho) &= -\frac{2\pi}{m_\phi}\rho\left(1+\frac{m_\phi}{m_N}\right)a_0 \\ &\simeq -85\frac{\rho}{\rho_0}\left(\frac{a_0}{\mathrm{fm}}\right)\mathrm{MeV} \end{aligned}\right\}$$

Valid within the linear density approximation

Larger than 100 MeV IF HAL QCD result is true for all spin configurations!

However, Pauli corrections beyond linear density seem to be important…

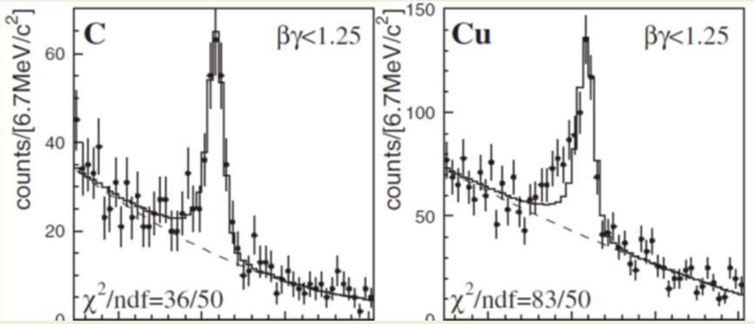
$$V_\phi(\rho) = -\underbrace{C_{\mathrm{Pauli}}(\rho)}_{\simeq\, 0.5 \text{ at } \rho_0}\frac{2\pi}{m_\phi}\rho\left(1+\frac{m_\phi}{m_N}\right)a_0$$

Comparison of theory and experiment

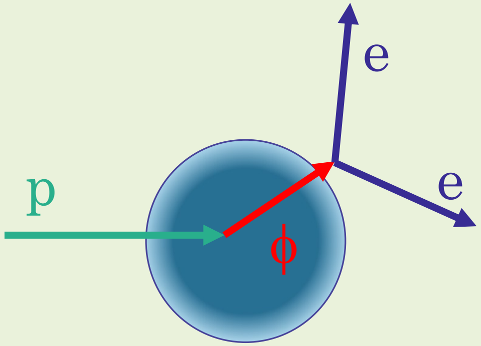
Information useful for theory

- Spectral function as a function of density
- Mass at normal nuclear matter density
- Decay width at normal nuclear matter density

Experimental data



Realistic simulation of pA reaction is needed!



Our tool: transport simulation
PHSD (Parton Hadron String Dynamics)

E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).
W. Cassing and E.L. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

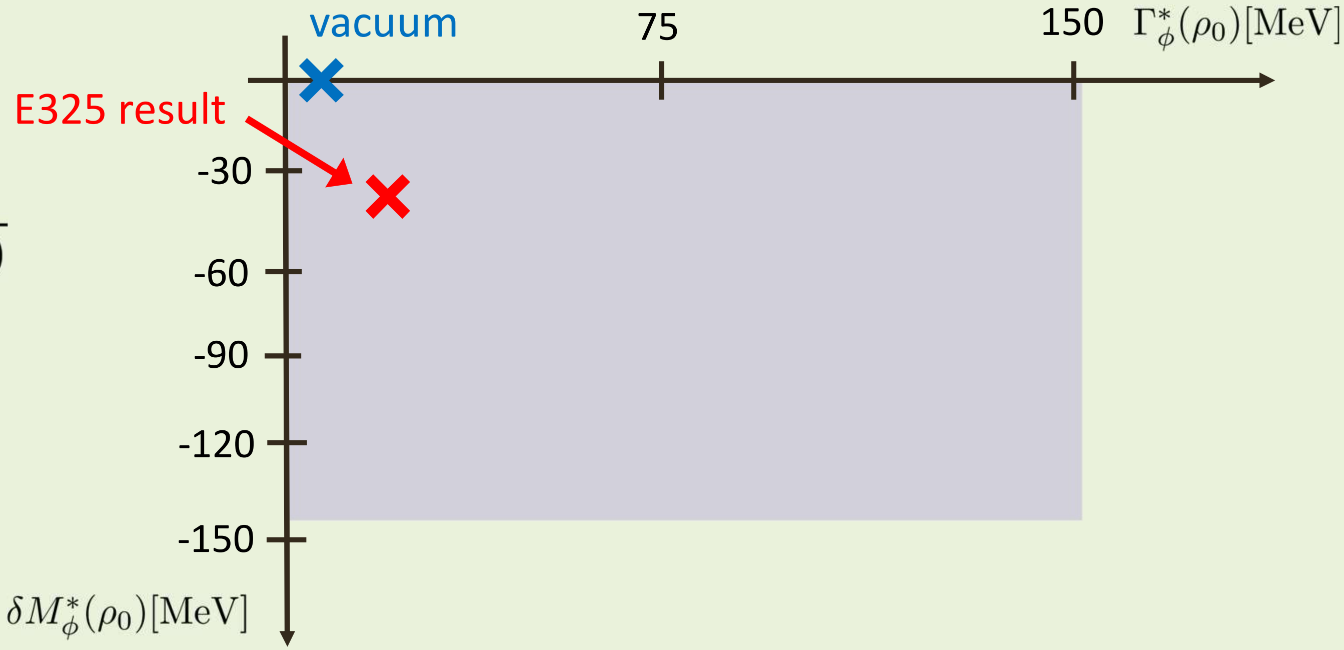
Off-shell dynamics of vector mesons and kaons
(dynamical modification of the mesonic spectral function during the simulated reaction)

Used spectral function:
Relativistic Breit-Wigner with density dependent mass and width

$$C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)}$$

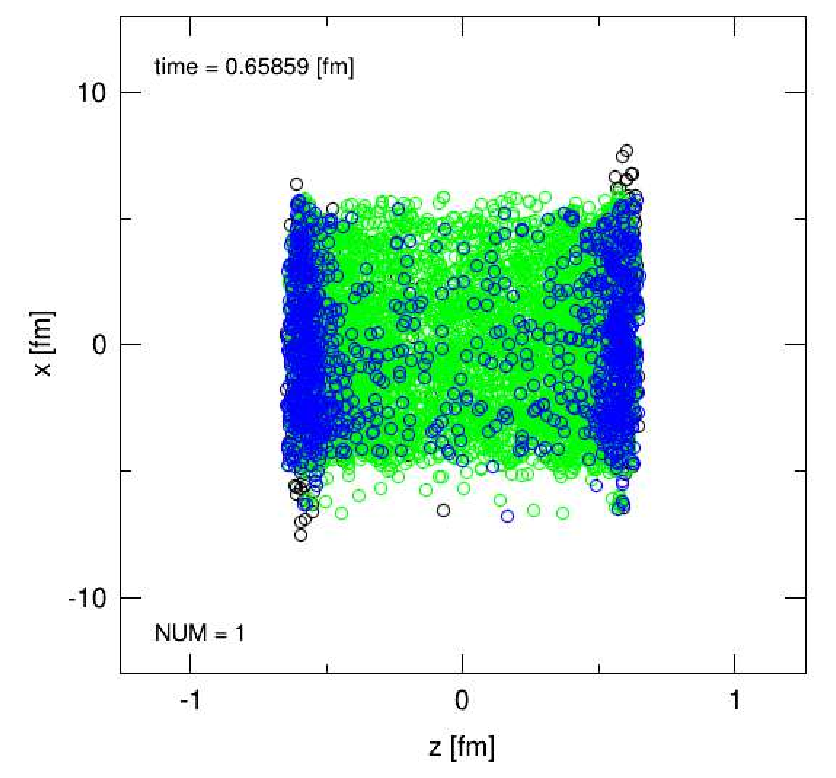
with
$$\begin{cases} M^*_\phi(\rho) = M^{\rm vac}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\rm vac}_\phi + \alpha^\phi_{\rm coll}\frac{\rho}{\rho_0} \end{cases}$$

Simulated scenarios:



Example of a transport calculation

Au+Au collision at $s^{1/2}$ = 200 GeV, b = 2 fm



nucleons

quarks

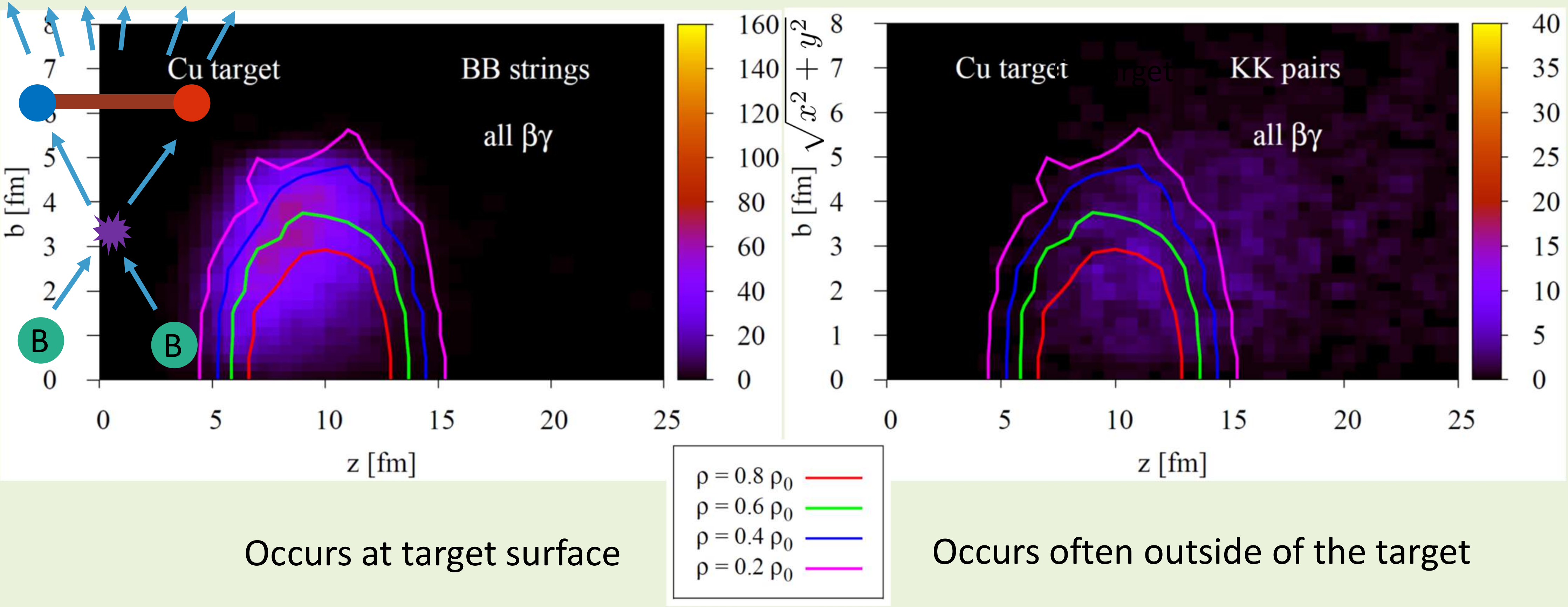
gluons

will not be included in the simulations shown in this talk

How are φ mesons produced?

Production through initial high-energy collisions (via strings)

Production through secondary low-energy hadron collisions



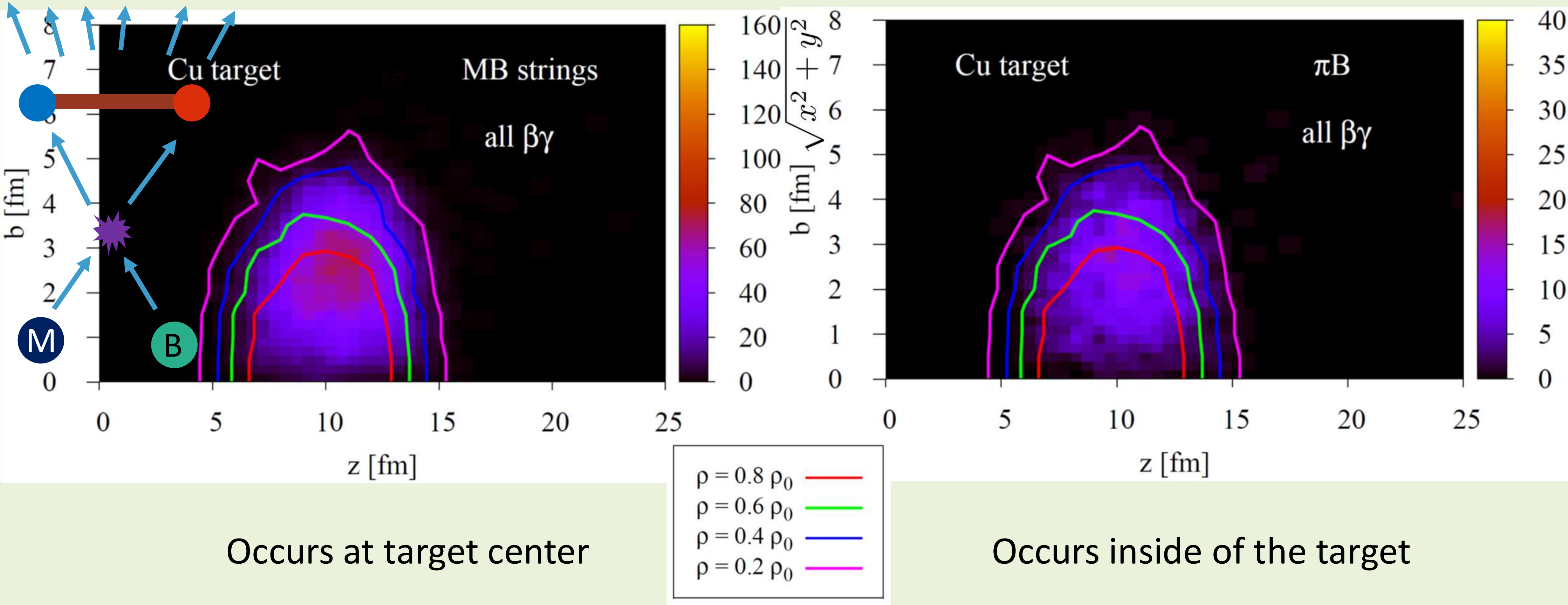
Occurs at target surface

Occurs often outside of the target

How are φ mesons produced?

Production through initial high-energy collisions (via strings)

Production through secondary low-energy hadron collisions

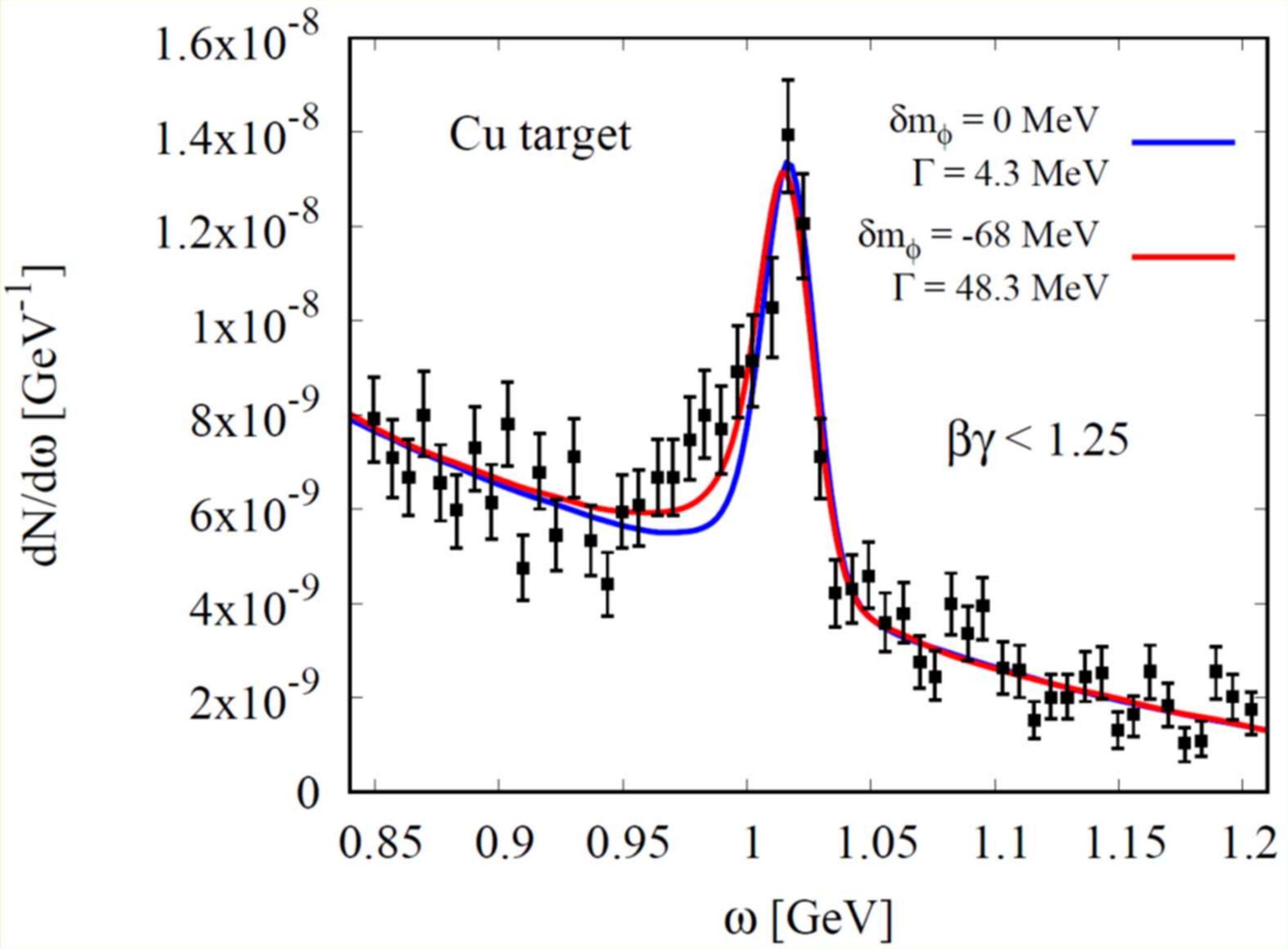


Occurs at target center

Occurs inside of the target

Fits to experimental Copper target data (KEK, E325)

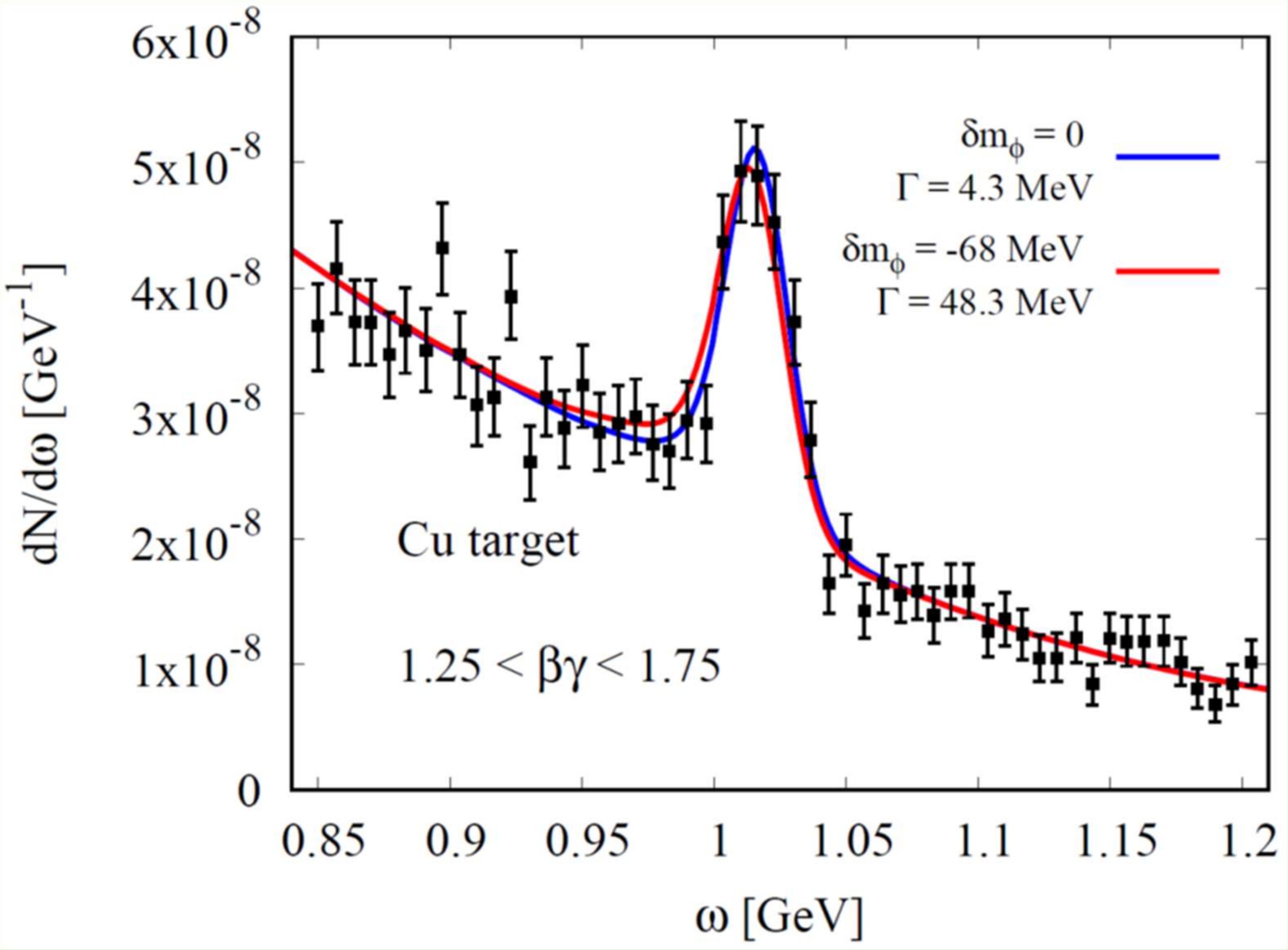
Preliminary



slow φs

Fits to experimental Copper target data (KEK, E325)

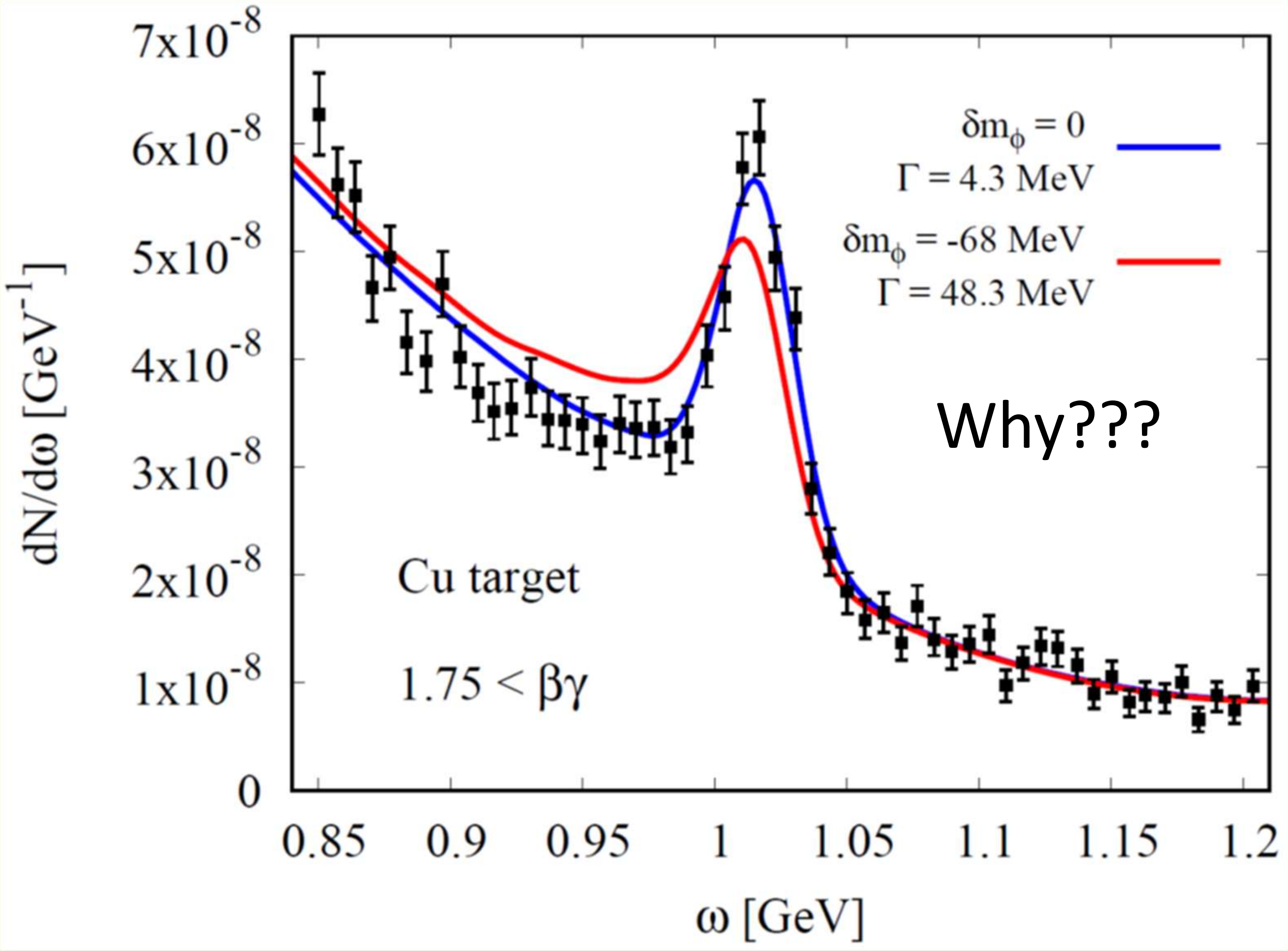
Preliminary



intermediate φs

Fits to experimental Copper target data (KEK, E325)

Preliminary

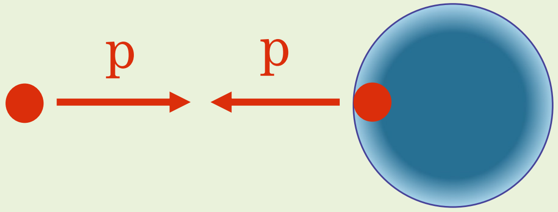


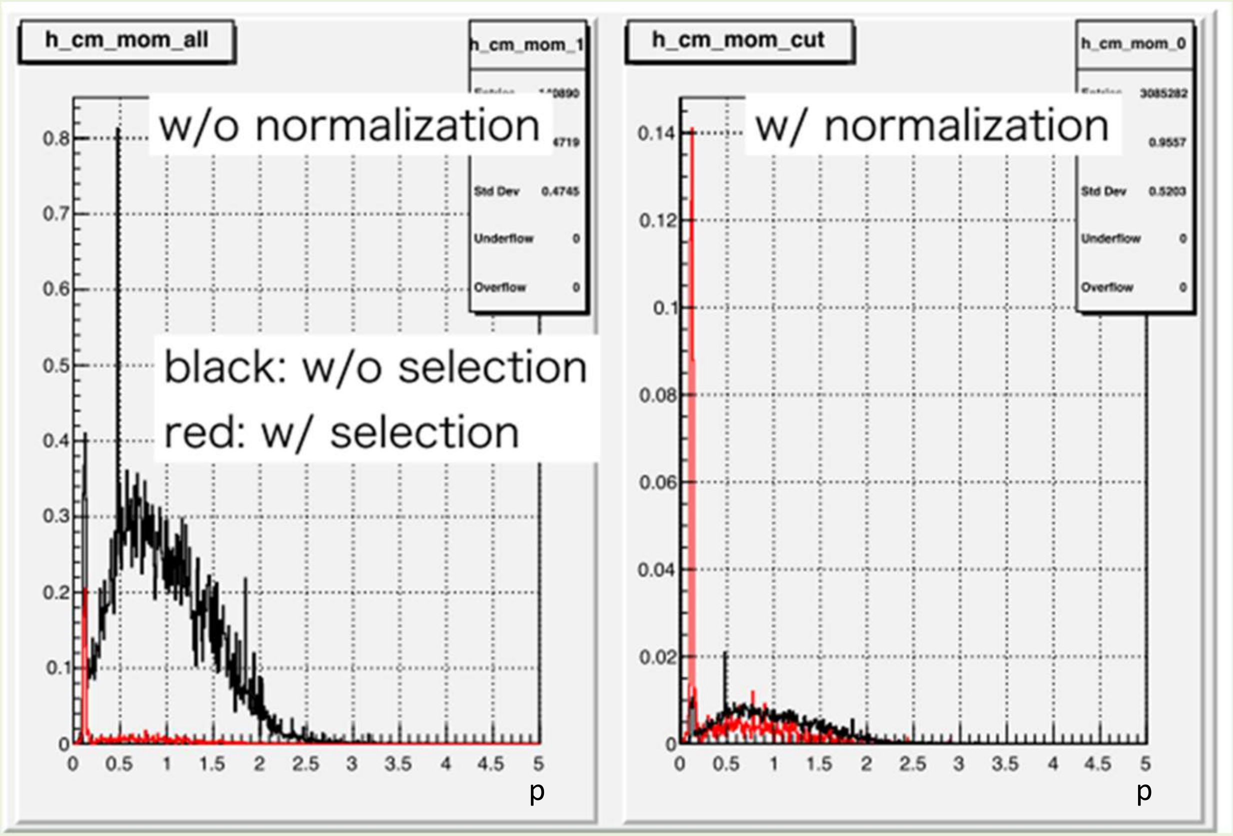
Why???

fast φs

The culprit are φs with very small momentum

Consider the frame in which the calculation is performed:
center of mass frame of the projectile and one target nucleon

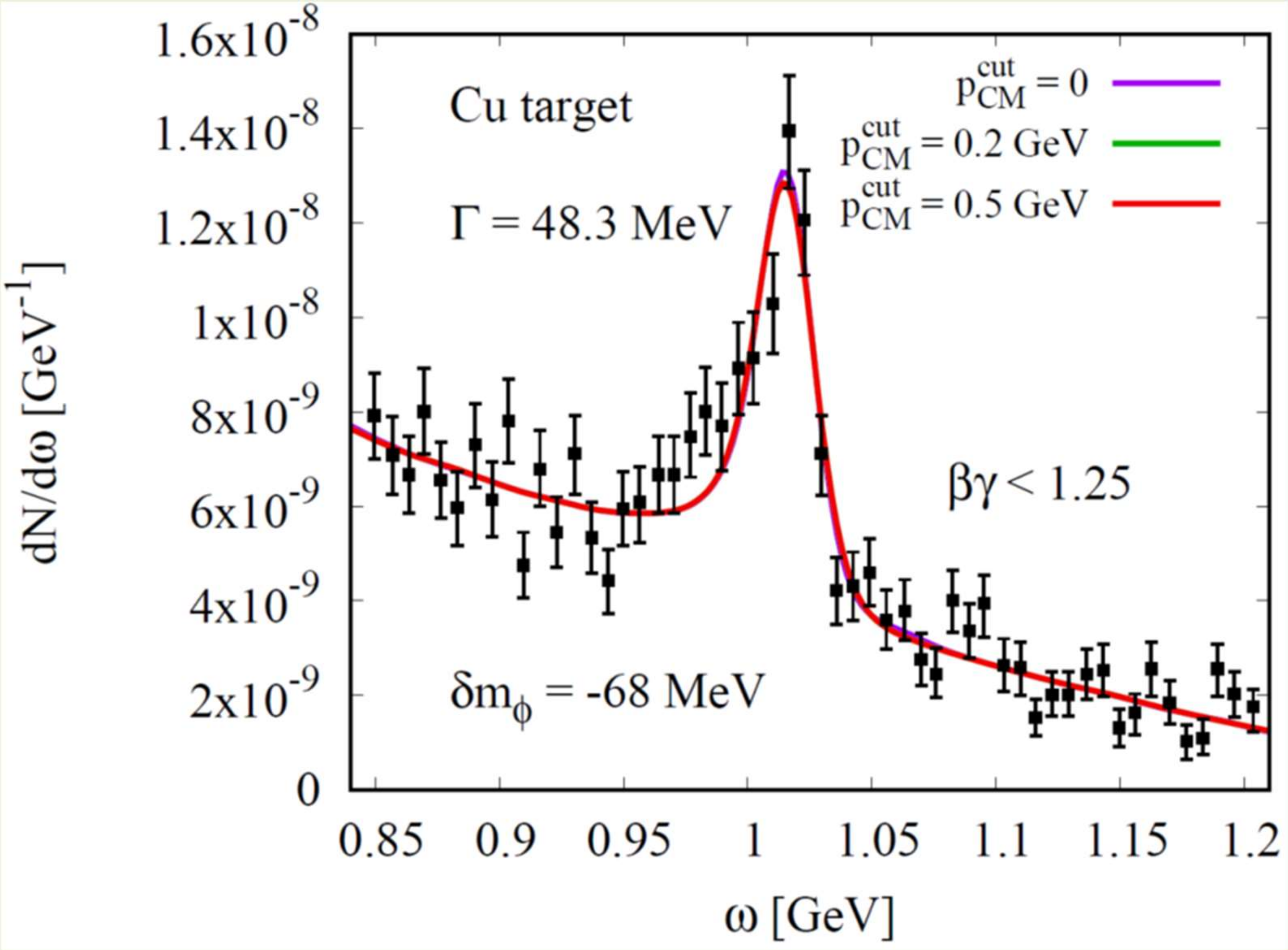




Problematic φs have low momentum in the calculational frame

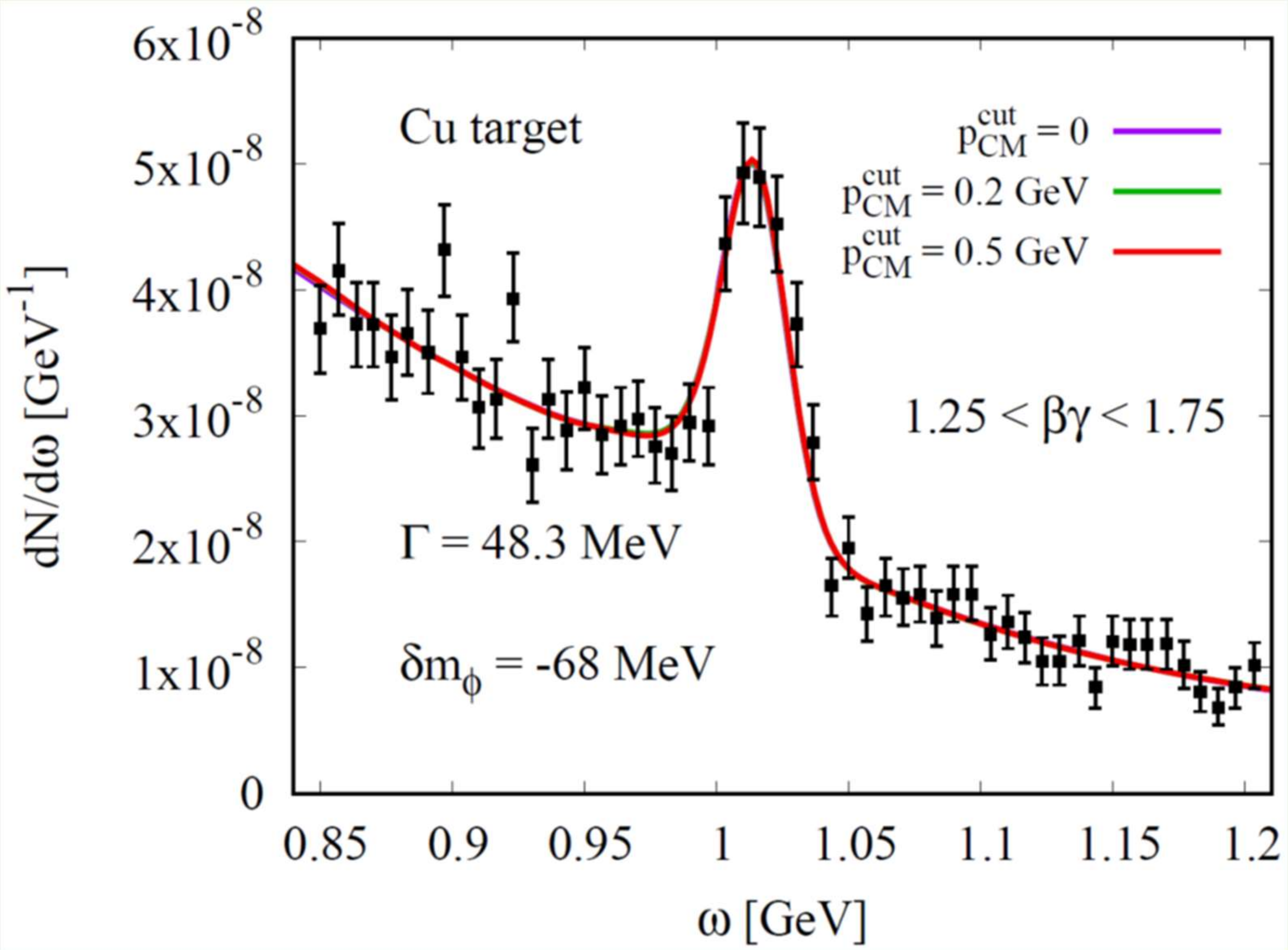
Found by the efforts of **Masaya Ichikawa**!

Fits to experimental Copper target data (including cut)



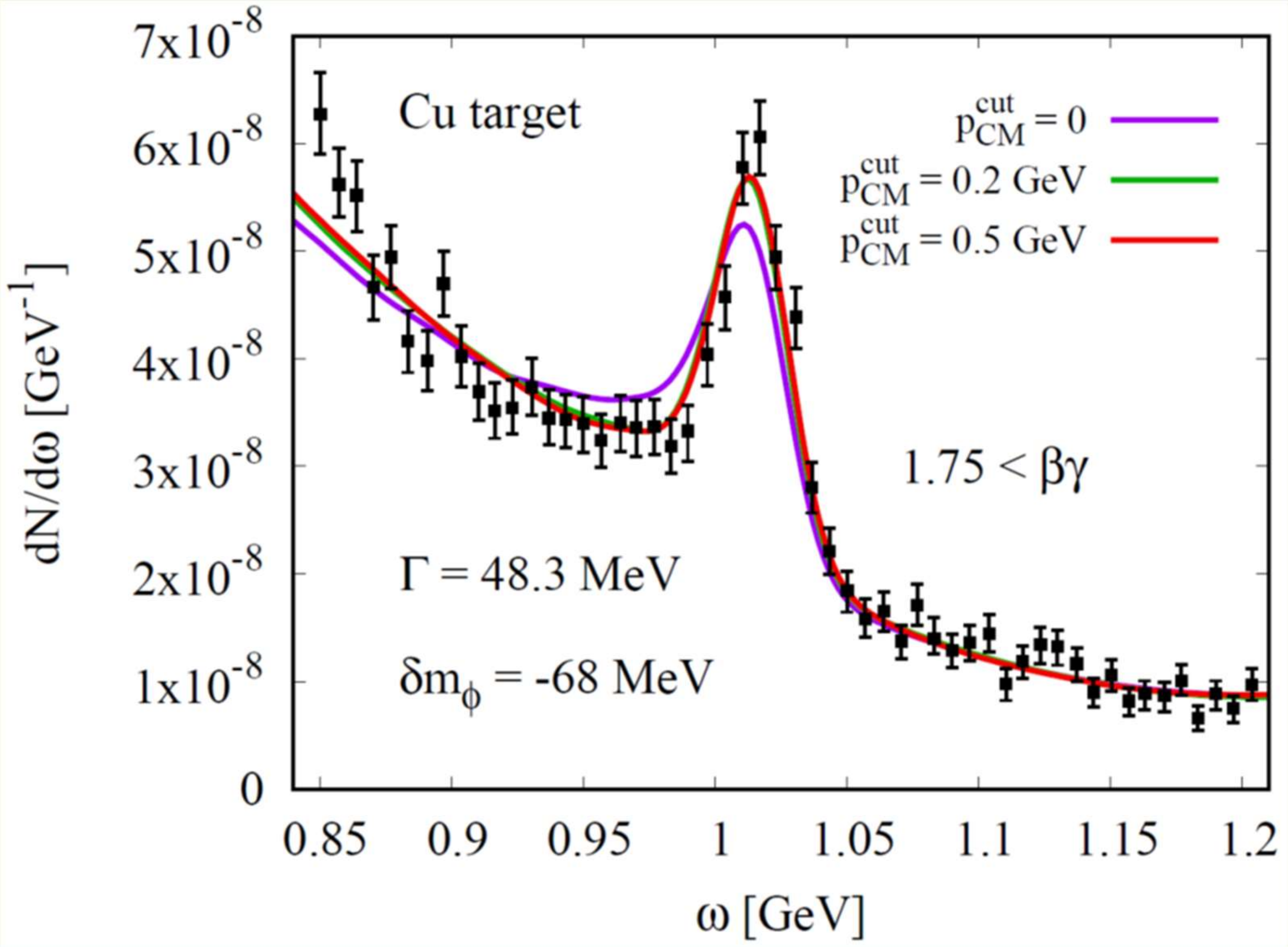
slow φs

Fits to experimental Copper target data (including cut)



intermediate φs

Fits to experimental Copper target data (including cut)

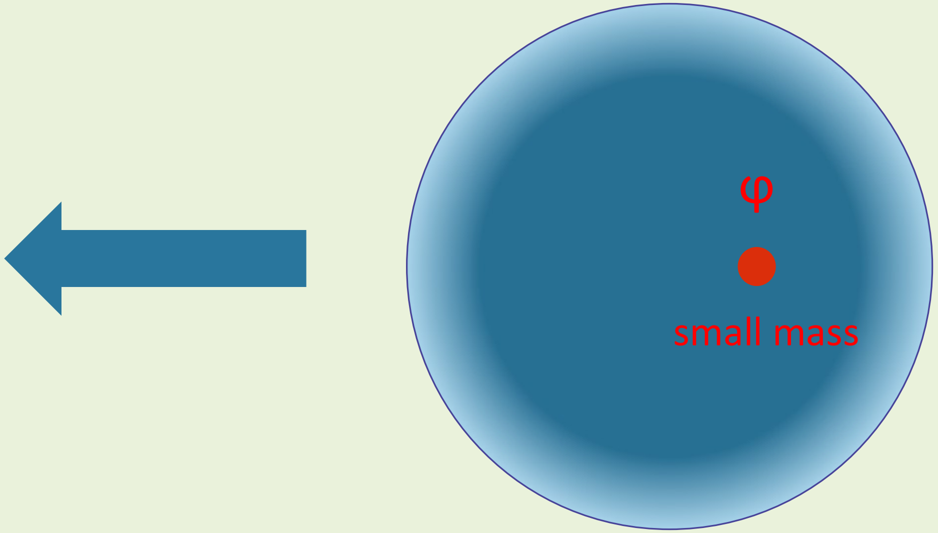


fast φs

Why did this problem happen?

Problem:

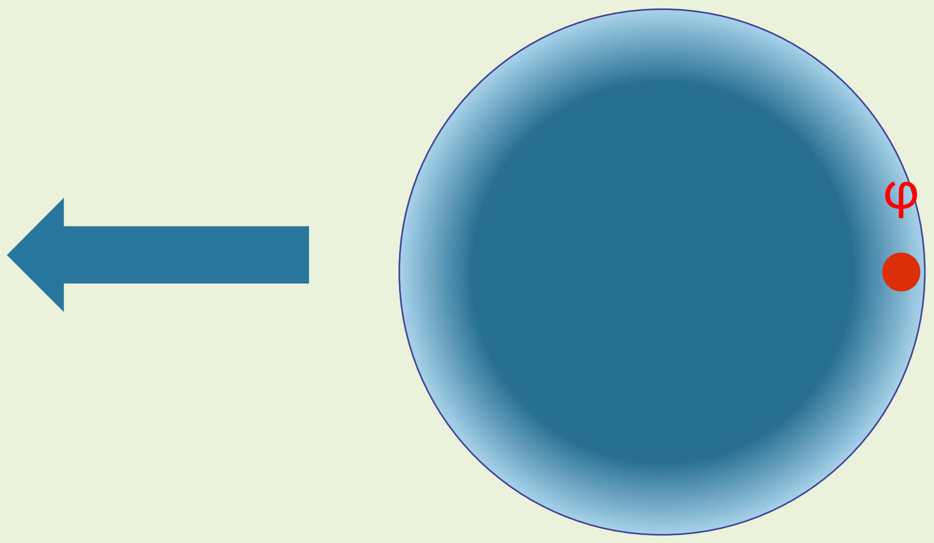
Conservation of energy ↔ Mass increase for particles almost at rest



Why did this problem happen?

Problem:

Conservation of energy ⟷ Mass increase for particles almost at rest

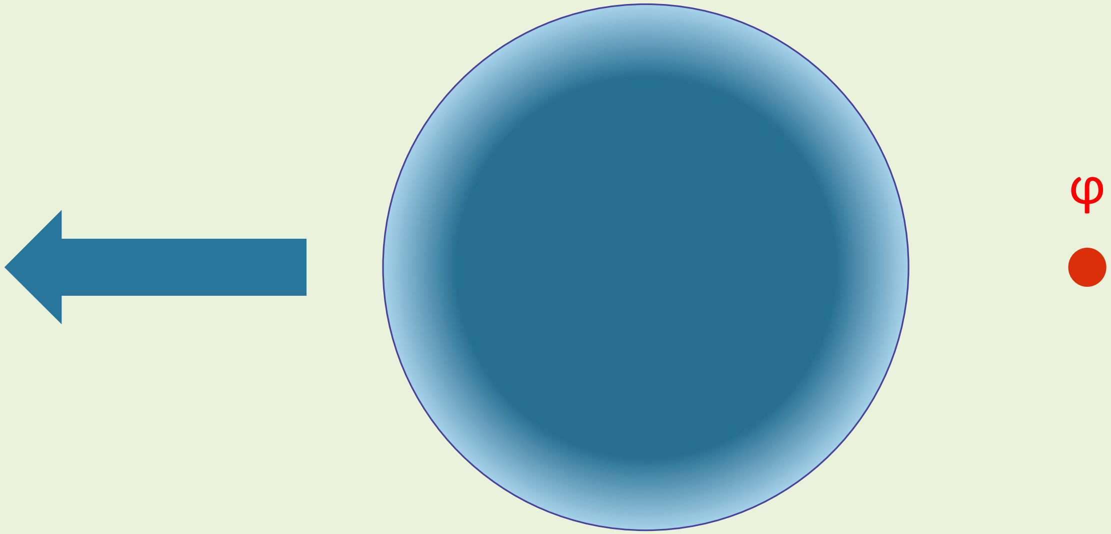


Mass should increase back to its vacuum value, but it cannot because of lack of energy

Why did this problem happen?

Problem:

Conservation of energy ↔ Mass increase for particles almost at rest



Mass values remains at reduced (unphysical) value

What remains to do

★ Accurately taking into account experimental effects → Ongoing effort by Ichikawa-san

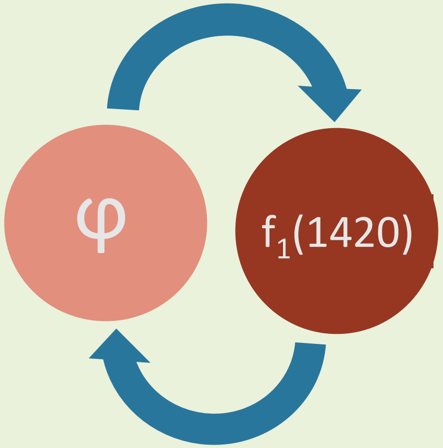
★ Find the the modification scenario best reproducing the experimental data → Ongoing!

Another possible effect: chiral mixing

Simple idea:
Charge conjugation (C) symmetry is broken in nuclear matter

→ Non-trivial mixing between different modes can occur

Here we consider the Vector – Axial-vector mixing in the strange quark sector



R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, in preparation.

Simple hadronic model including C-symmetry breaking

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

Can be understood from an anomalous ω-φ-f1 coupling with a coherent ω-field: $\langle\omega_0\rangle \sim \rho$

→ tree-level V-A mixing!

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

However, the coupling c is model dependent:

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

from holographic QCD

S. K. Domokos and J. A. Harvey,
Phys. Rev. Lett. **99**, 141602 (2007).

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

from gauged WZW action

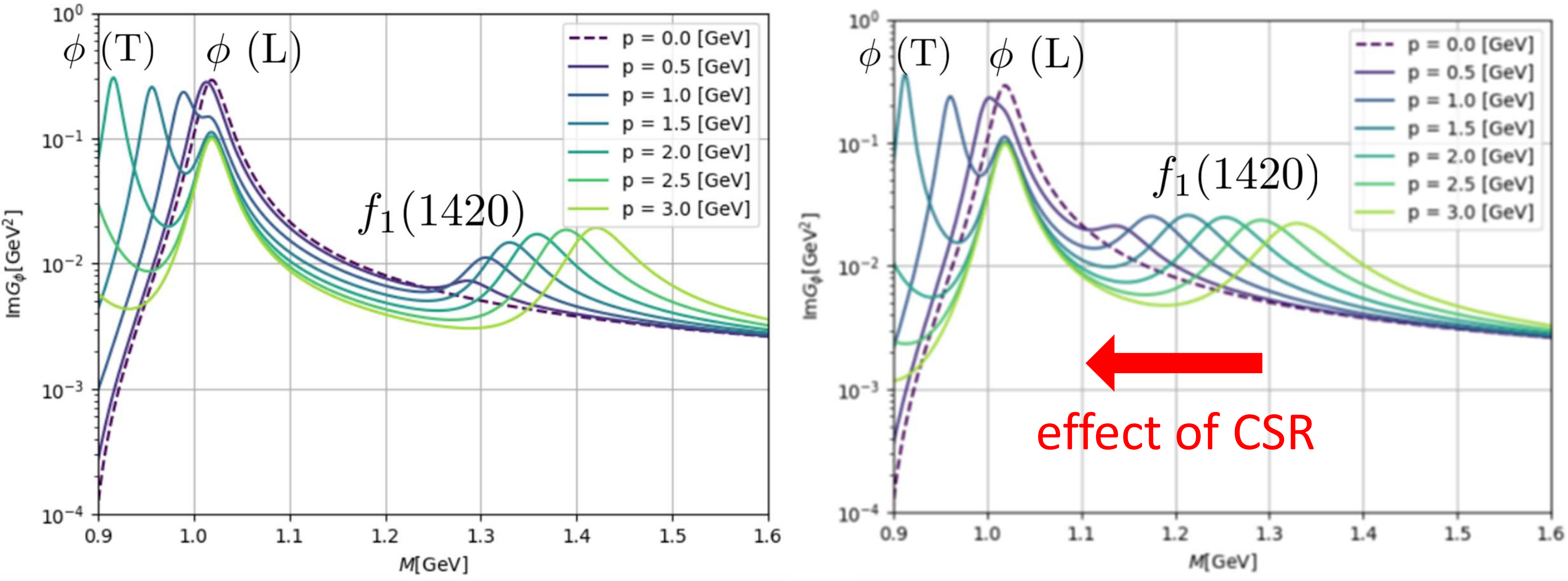
M. Harada and C. Sasaki,
Phys. Rev. C **80**, 054912 (2009).

Resulting spectral functions (at $\rho = \rho_0$)

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

without CSR

with CSR



effect of CSR

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

Experimentally measurable invariant mass distribution

Computed using a state-of-the art transport simulation (PHSD)

Convoluted by Gaussian to take into account experimental resolution

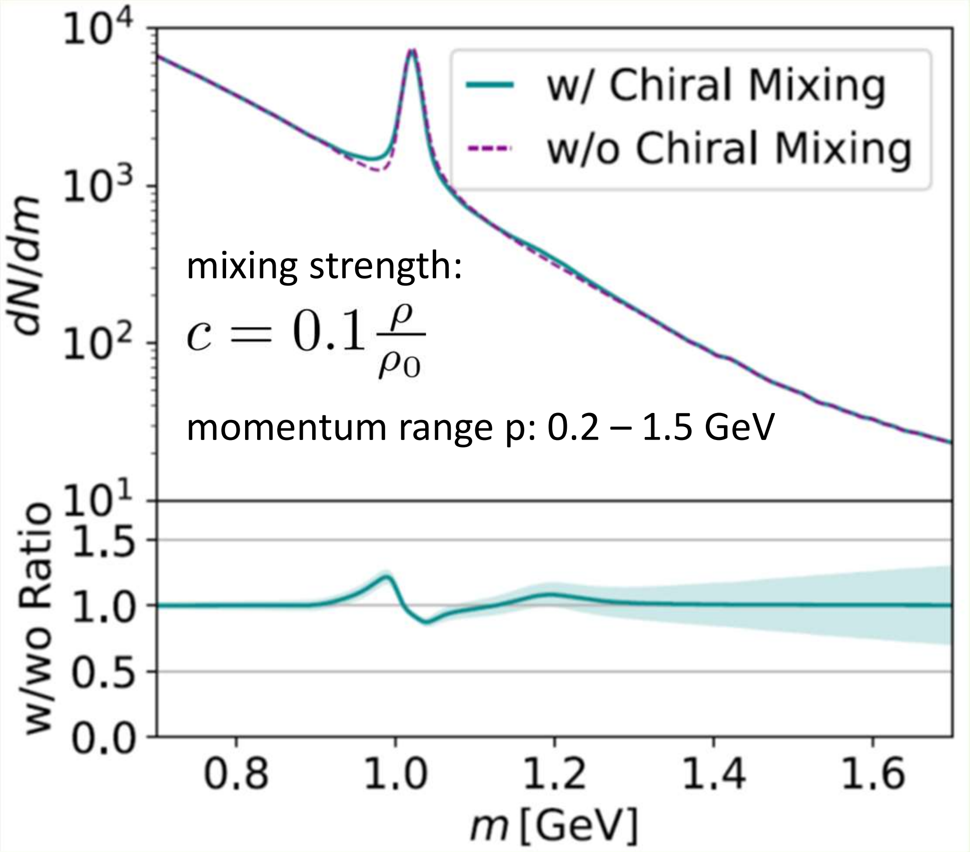
$$I(M) = \int \left[\int \boxed{\mathrm{Im}G_V(s,\vec{p},\rho)} \boxed{\frac{dN}{d\vec{p}d\rho dt}} \frac{d\vec{p}}{2p_0} d\rho dt + \int \boxed{\mathrm{Bkg}(s,\vec{p})} d\vec{p} \right] \boxed{g(M-s)} ds$$

Taken from the Sasaki-model (previous slide)

Background, obtained simulation of experimental conditions:
JAM → Geant4

Invariant mass distributions for different mixing strengths

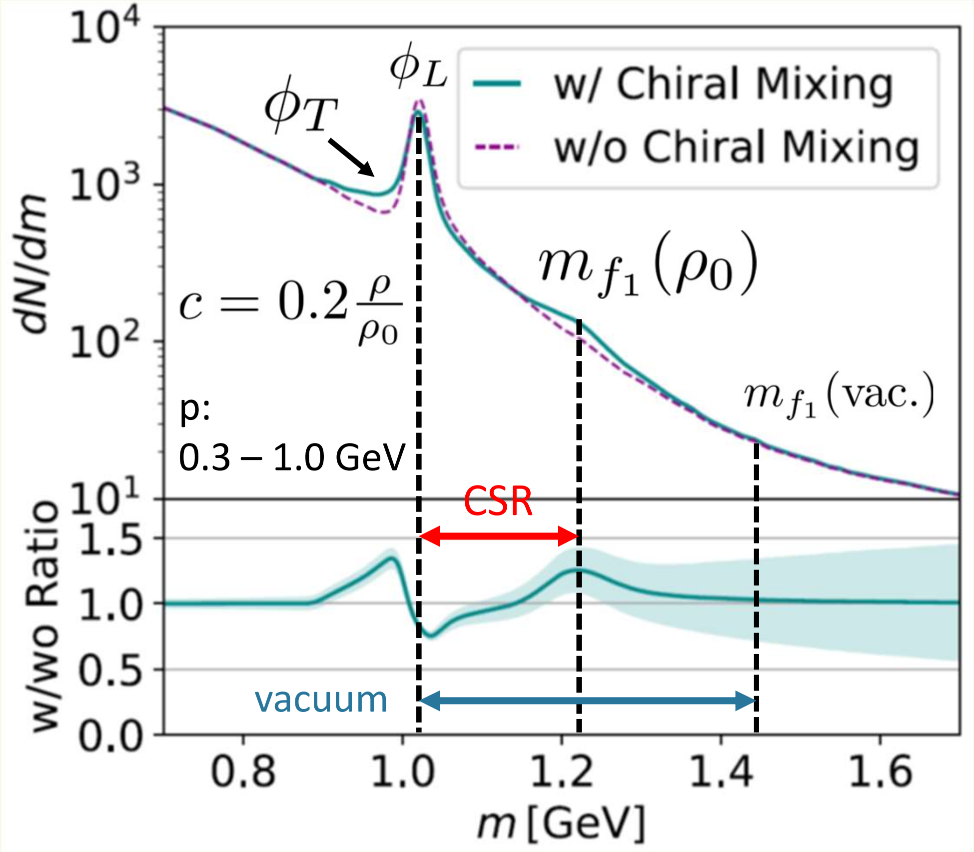
30 GeV pA collisions, Pb target, E16 Run2 statistics



mixing strength:

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

momentum range p: 0.2 – 1.5 GeV



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

p:
0.3 – 1.0 GeV

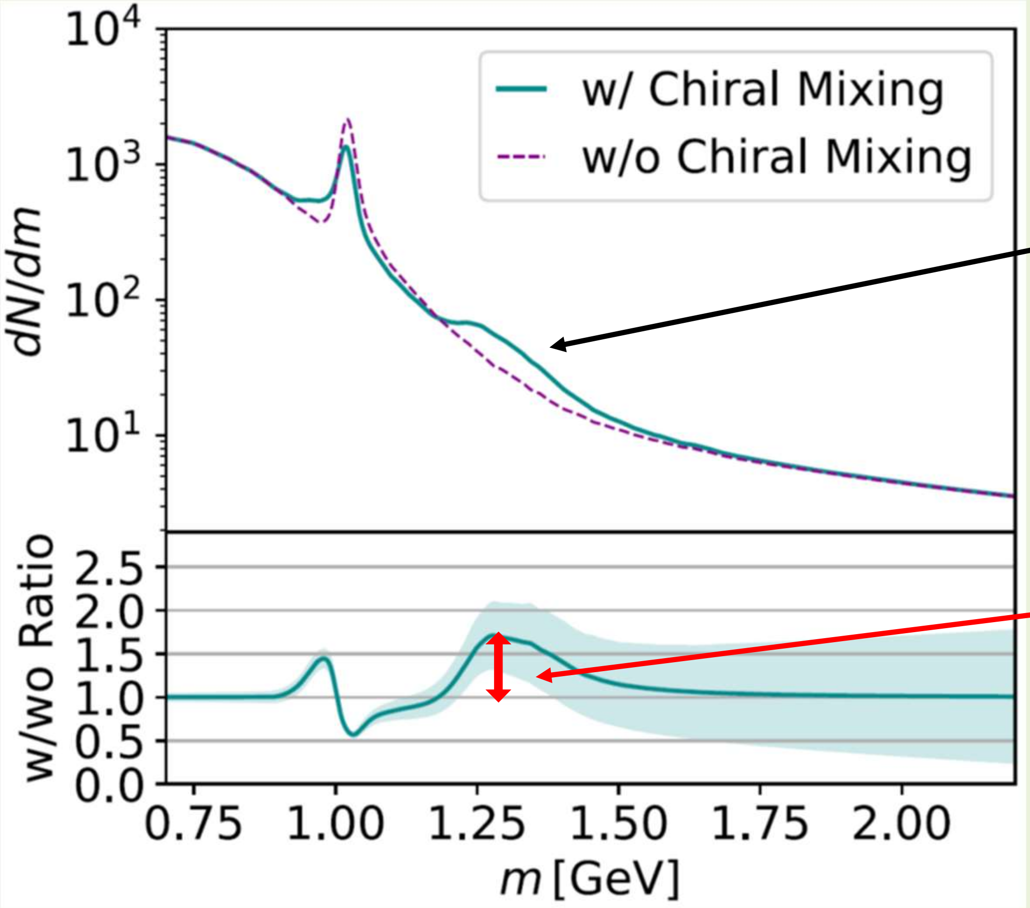
R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, in preparation.

Invariant mass distributions for different mixing strengths

30 GeV pA collisions, Pb target, E16 Run2 statistics

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

momentum range p:
0.2 – 0.8 GeV



Signal is spread for large mixing, because of large momentum dependence of the peak position

$\sim 1.9\,\sigma$!!

R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, in preparation.

Summary and conclusions

★ A lot of new experimental information about the φN and φ-nucleus interactions is becoming available (LHC, J-PARC, HADES) → **Needs better theoretical understanding!**

★ We have resolved the issue of large mass shift effects for φ with large momentum in the lab frame

→ Unphysical behavior of φ mesons with low momentum in the calculational frame used in our simulation

★ Chiral V-A mixing can happen in nuclear matter

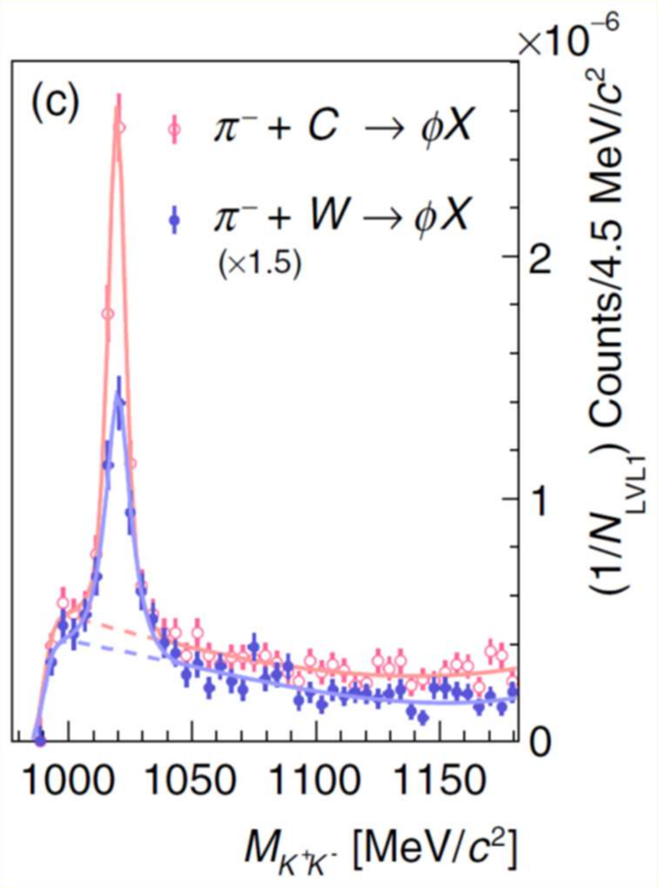
→ Measurable for strong enough mixing strength??

Backup slides

More recent results

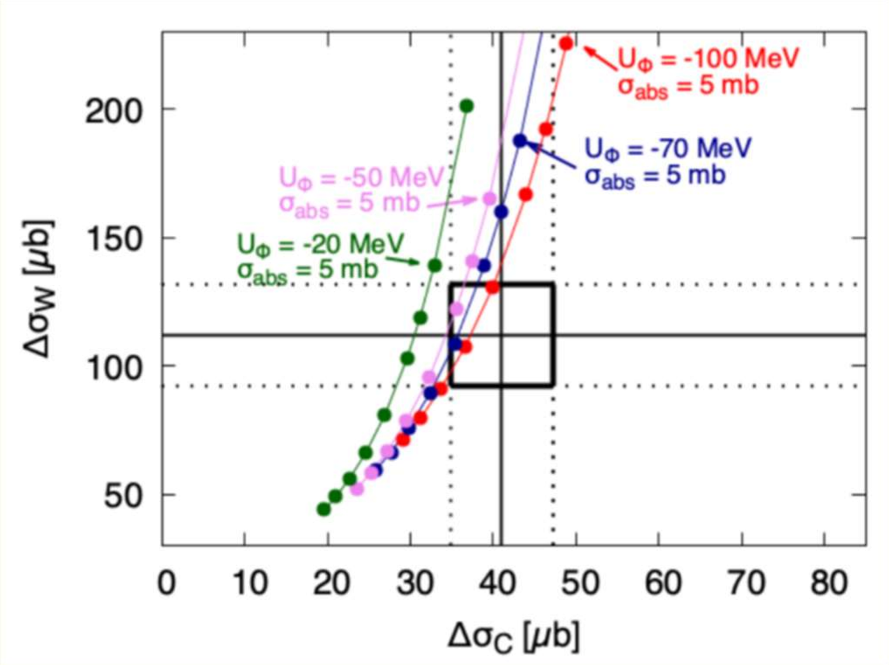
HADES: 1.7 GeV π^-A-reaction

K^+K^- - invariant mass spectrum



J. Adamczewski-Musch et al. (HADES Coll.),
Phys. Rev. Lett. **123**, 022002 (2019).

Theoretical analysis of the of the total φ meson production cross section:



E. Ya. Paryev, Nucl. Phys. A **1032**, 122624 (2023).

→ **Attractive φ-nucleus potential: -(50 - 100) MeV**

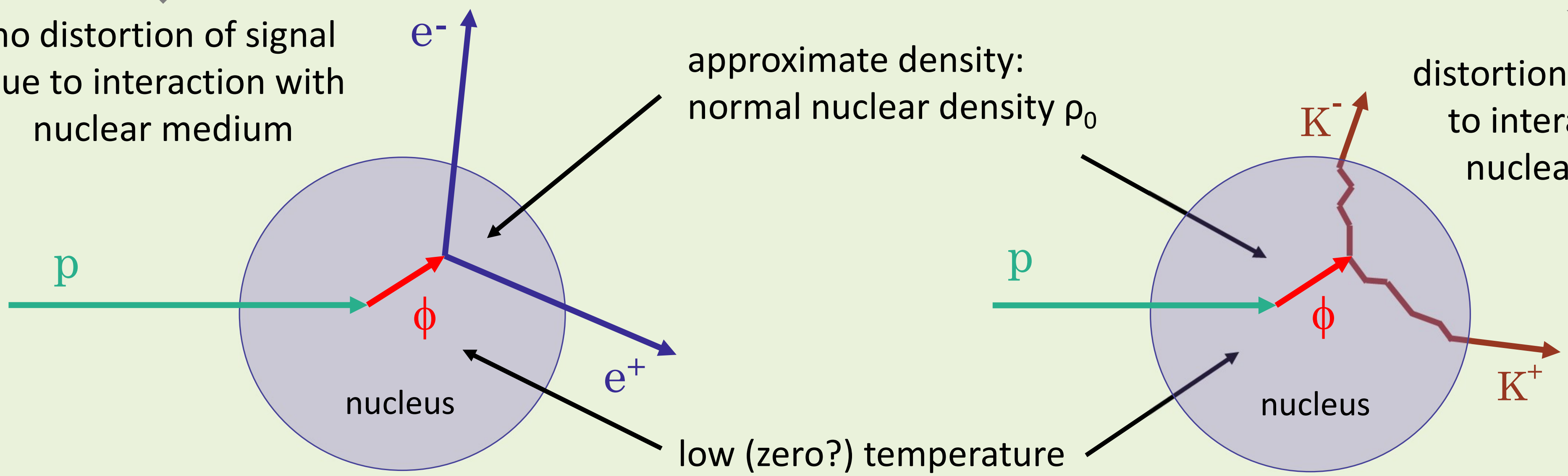
→ **Relatively small imaginary part: 20 – 25 MeV**

The φ meson in pA collisions

Experiments to be discussed in this talk

no strong interaction

no distortion of signal due to interaction with nuclear medium



approximate density:
normal nuclear density ρ_0

strong interaction

distortion of signal due to interaction with nuclear medium

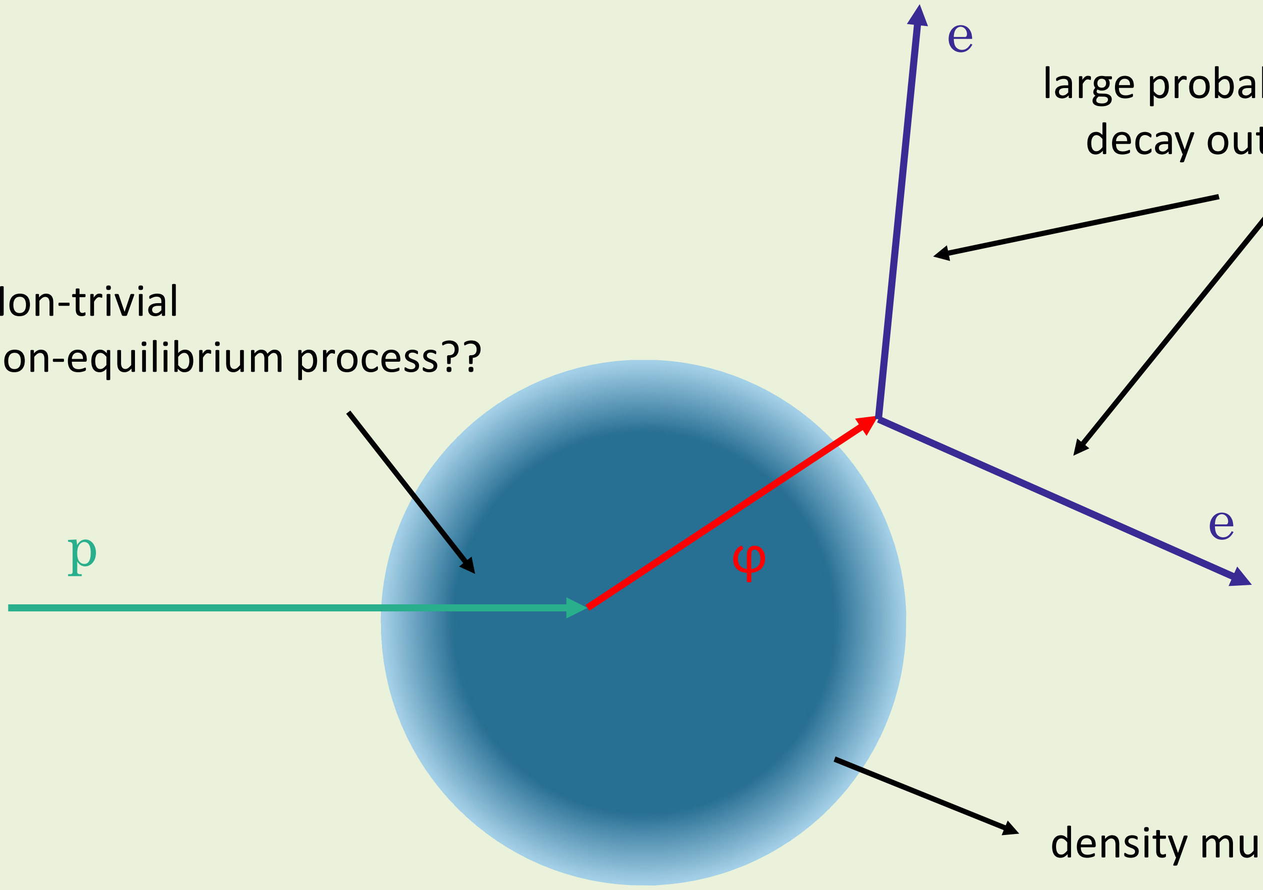
low (zero?) temperature

E325 (KEK)
E16 (J-PARC)

pion beam (HADES)
E88 (J-PARC)

In reality, things are more complicated…

Proton induced generation of vector mesons in nuclei



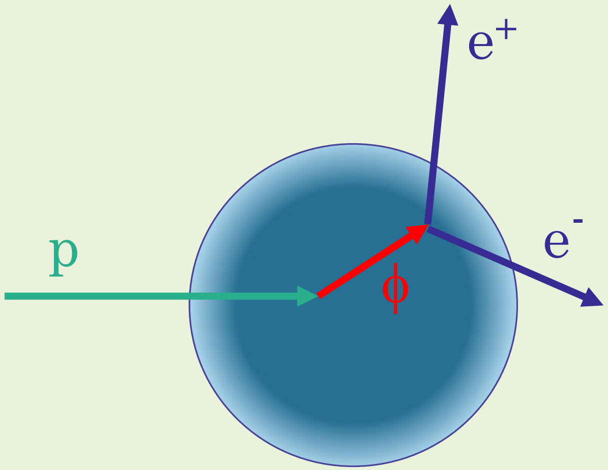
large probability of vector meson decay outside of the nucleus

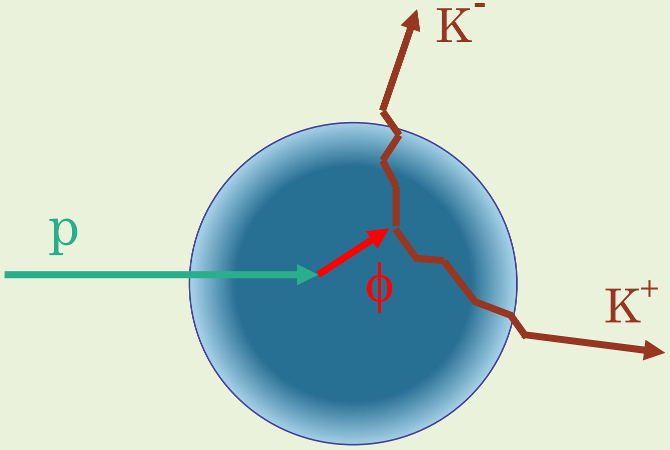
Non-trivial
non-equilibrium process??

density much below ρ_0

Further tasks for theory

Have a good understanding of the production mechanisms of the φ mesons in nuclei from pA reactions.





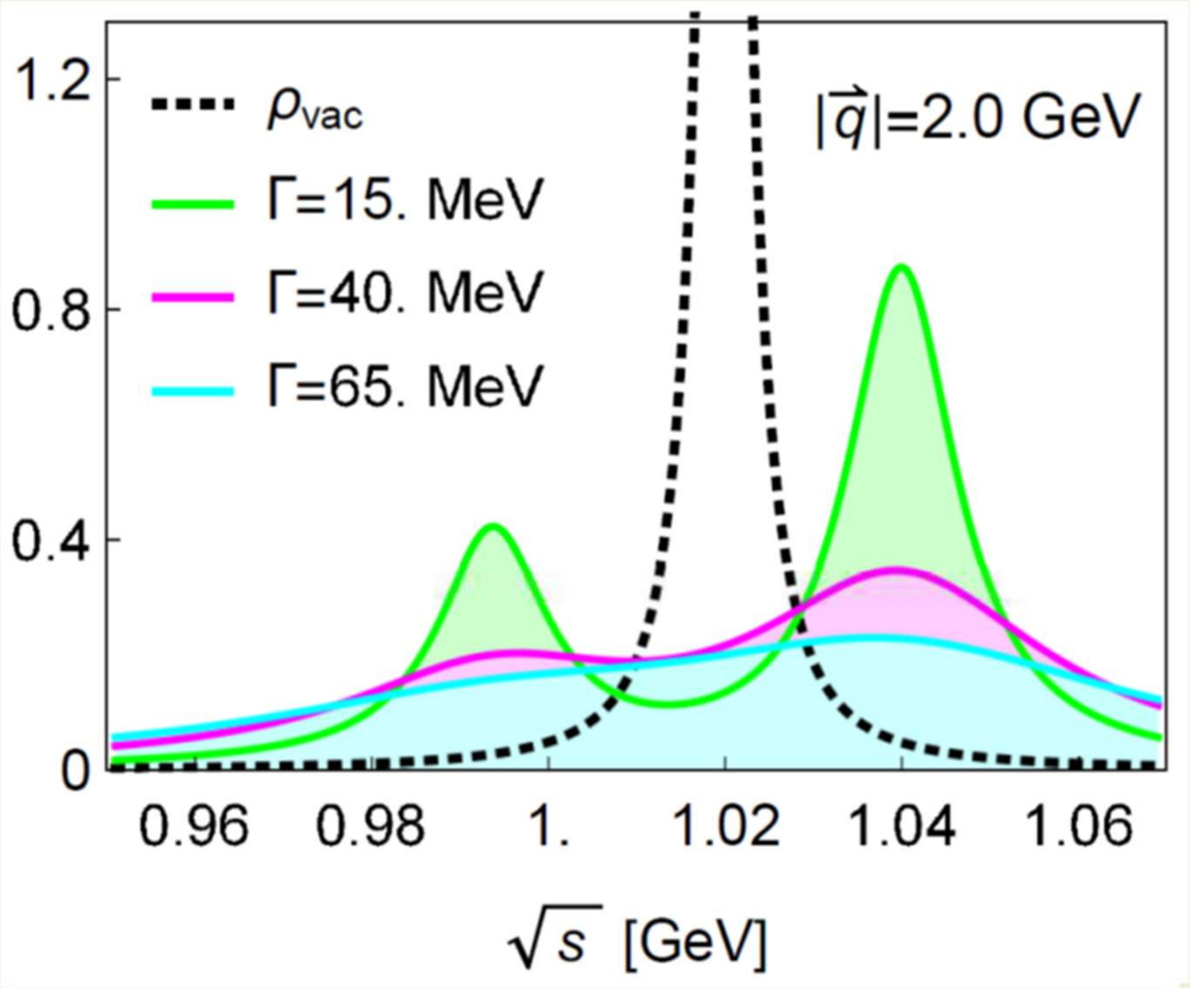
- ★ Where (and at what densities) is the φ meson produced and where does it decay?
- ★ How do the final state interactions of the decay particles influence the decay spectrum (especially for K^+K^-)?

➡ Realistic transport simulations using a transport approach (calculations using the PHSD code are ongoing)

➡ See talk by L. Oliva

The angle-averaged di-lepton spectrum

A double peak?



Computed at normal nuclear matter density

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

First application of our formalism

Thermal model with single freeze-out to describe soft hadron production for Au + Au collisions at top RHIC energies:

$$f_V(q, X) = e^{-q^\mu \beta_\mu(x) - \xi(x)}$$

(Jüttner distribution)

$$\beta^\mu = \frac{u^\mu}{T}, \qquad \xi = \frac{\mu}{T}$$

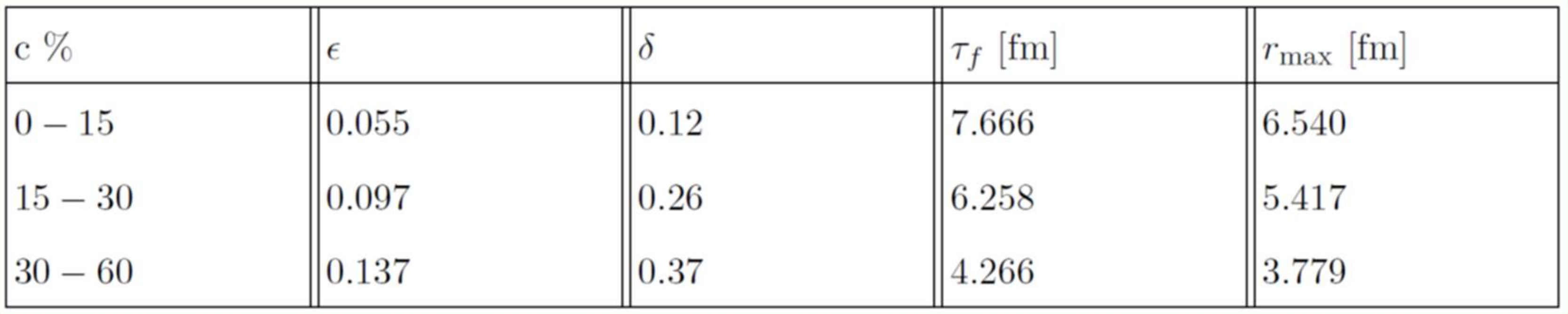
elliptical asymmetry:

$$\begin{cases} x = r_{\max}\sqrt{1-\epsilon}\cos\phi, \\ y = r_{\max}\sqrt{1-\epsilon}\sin\phi \end{cases}$$

elliptical flow: $u^\mu = \frac{1}{N}(t, x\sqrt{1+\delta}, y\sqrt{1-\delta}, z)$

PHOENIX data at

$\sqrt{s_{NN}} = 130$ GeV



c %	ϵ	δ	τ_f [fm]	$r_{\max}$ [fm]
$0-15$	0.055	0.12	7.666	6.540
$15-30$	0.097	0.26	6.258	5.417
$30-60$	0.137	0.37	4.266	3.779

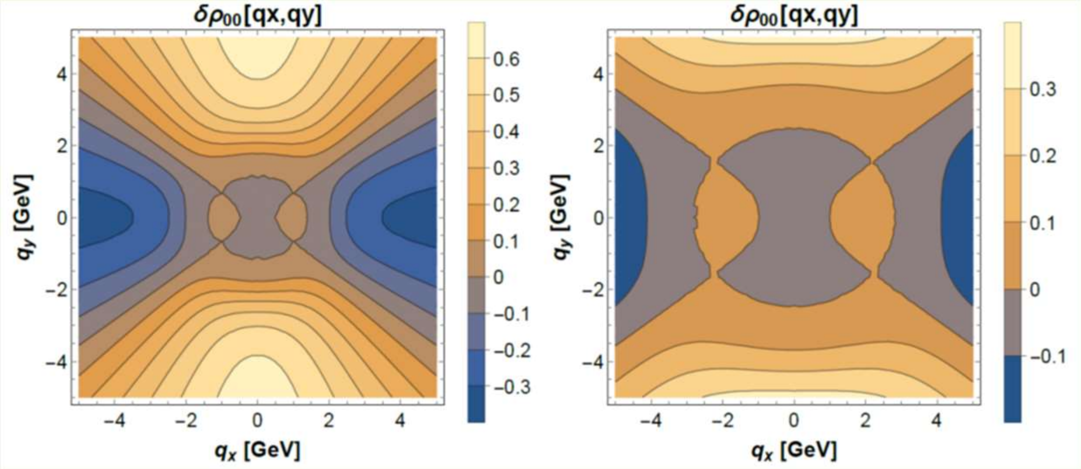
A. Kumar, D.-L. Yang and P. Gubler, 2312.16900 [nucl-th], to be published in PRD.

First application of our formalism

K^{*0} ϕ

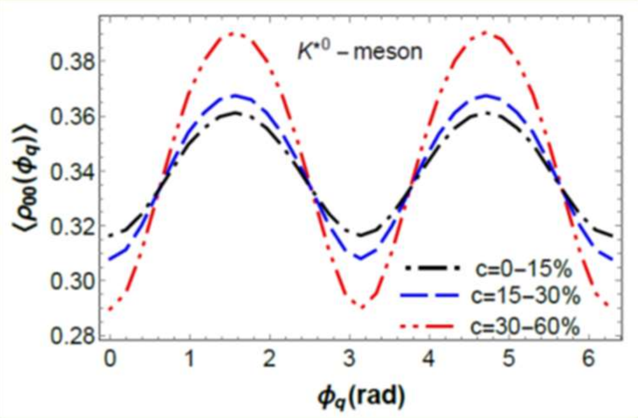
$\rho_{00} - \frac{1}{3}$

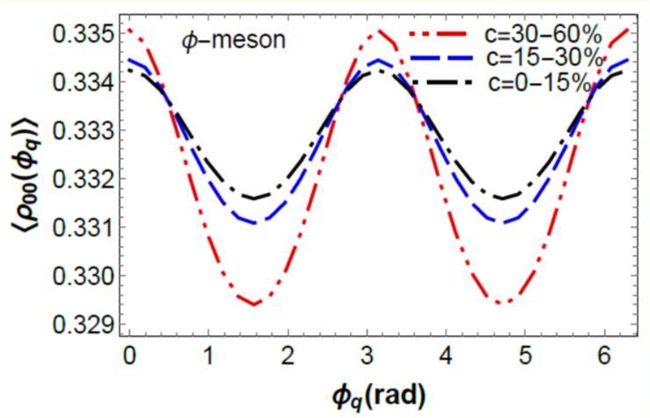
$c = 30 - 60\%$



ρ_{00}

Azimuthal angle dependence





A. Kumar, D.-L. Yang and P. Gubler, 2312.16900 [nucl-th], to be published in PRD.

φ meson at rest in nuclear matter

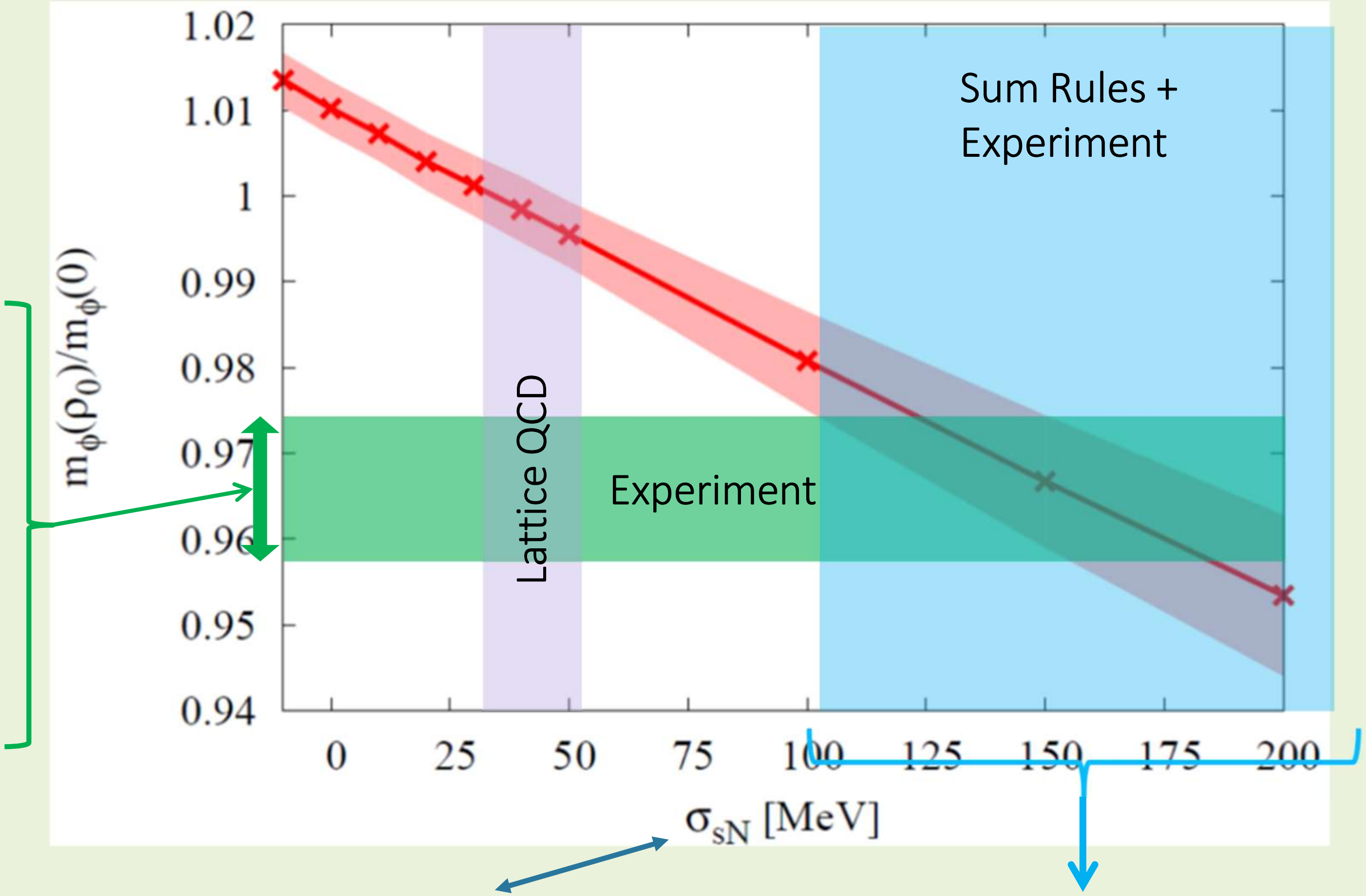
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

Not consistent?

R. Muto et al.
(KEK, E325 Collaboration),
Phys. Rev. Lett. **98**,
042501 (2007).

Measurement will be
repeated at the
J-PARC E16 experiment
(with 100 times
increased statistics!)

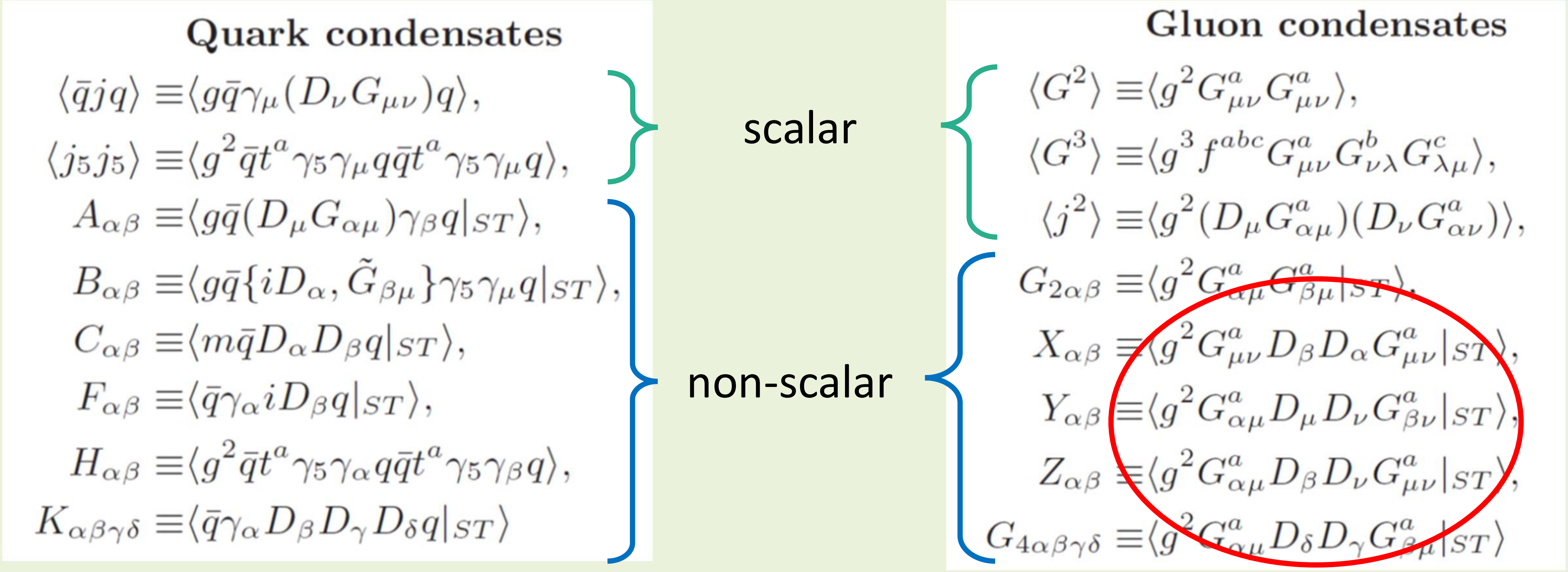
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$



$$\sigma_{sN} = m_s\langle N|\bar{s}s|N\rangle$$

$$\sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

Condensates that appear in the vector channel



Quark condensates

$$\langle \bar{q} j q \rangle \equiv \langle g\bar{q}\gamma_\mu (D_\nu G_{\mu\nu}) q \rangle,$$

$$\langle j_5 j_5 \rangle \equiv \langle g^2 \bar{q} t^a \gamma_5 \gamma_\mu q \bar{q} t^a \gamma_5 \gamma_\mu q \rangle,$$

$$A_{\alpha\beta} \equiv \langle g\bar{q}(D_\mu G_{\alpha\mu})\gamma_\beta q | ST \rangle,$$

$$B_{\alpha\beta} \equiv \langle g\bar{q}\{iD_\alpha, \tilde{G}_{\beta\mu}\}\gamma_5\gamma_\mu q | ST \rangle,$$

$$C_{\alpha\beta} \equiv \langle m\bar{q} D_\alpha D_\beta q | ST \rangle,$$

$$F_{\alpha\beta} \equiv \langle \bar{q}\gamma_\alpha i D_\beta q | ST \rangle,$$

$$H_{\alpha\beta} \equiv \langle g^2 \bar{q} t^a \gamma_5 \gamma_\alpha q \bar{q} t^a \gamma_5 \gamma_\beta q \rangle,$$

$$K_{\alpha\beta\gamma\delta} \equiv \langle \bar{q}\gamma_\alpha D_\beta D_\gamma D_\delta q | ST \rangle$$

scalar

non-scalar

Gluon condensates

$$\langle G^2 \rangle \equiv \langle g^2 G^a_{\mu\nu} G^a_{\mu\nu} \rangle,$$

$$\langle G^3 \rangle \equiv \langle g^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\lambda} G^c_{\lambda\mu} \rangle,$$

$$\langle j^2 \rangle \equiv \langle g^2 (D_\mu G^a_{\alpha\mu})(D_\nu G^a_{\alpha\nu}) \rangle,$$

$$G_{2\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} G^a_{\beta\mu} | ST \rangle,$$

$$X_{\alpha\beta} \equiv \langle g^2 G^a_{\mu\nu} D_\beta D_\alpha G^a_{\mu\nu} | ST \rangle,$$

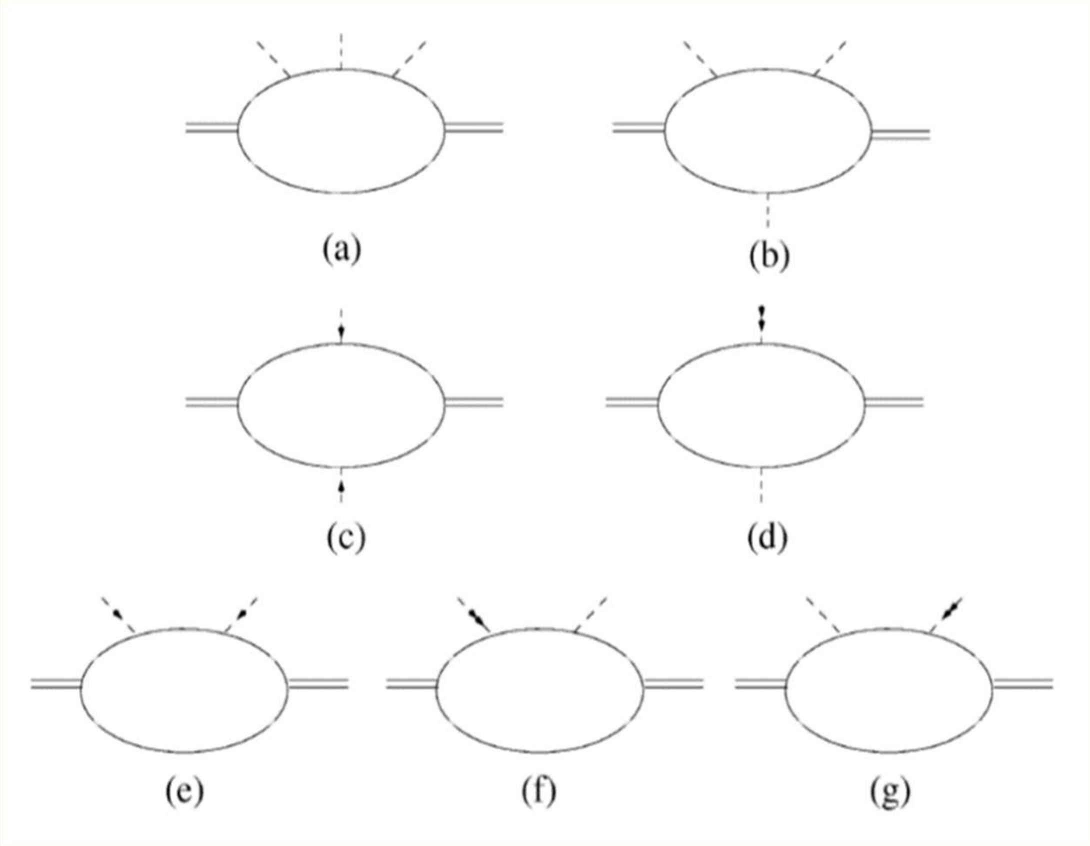
$$Y_{\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} D_\mu D_\nu G^a_{\beta\nu} | ST \rangle,$$

$$Z_{\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} D_\beta D_\nu G^a_{\mu\nu} | ST \rangle,$$

$$G_{4\alpha\beta\gamma\delta} \equiv \langle g^2 G^a_{\alpha\mu} D_\delta D_\gamma G^a_{\beta\mu} | ST \rangle$$

Wilson coefficients were not yet available until recently

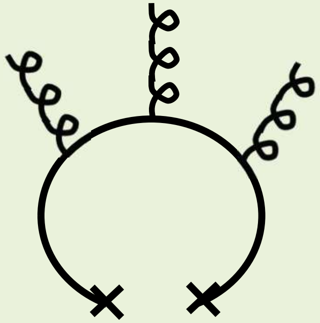
OPE calculation



Mass singularities in chiral limit!

$$\frac{1}{m^2},\ \log\left(\frac{\mu^2}{m^2}\right),\ \ldots$$

Subtract corresponding quark condensate contribution

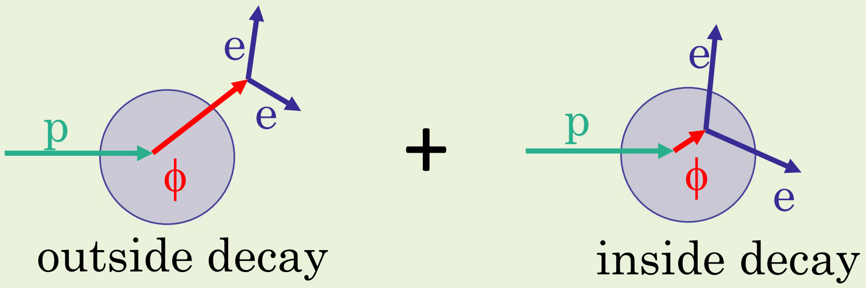


$$\langle \bar{q}\,\Gamma(D,G)q \rangle$$

S. Kim and S.H. Lee, Nucl. Phys. **679**, 517 (2001).

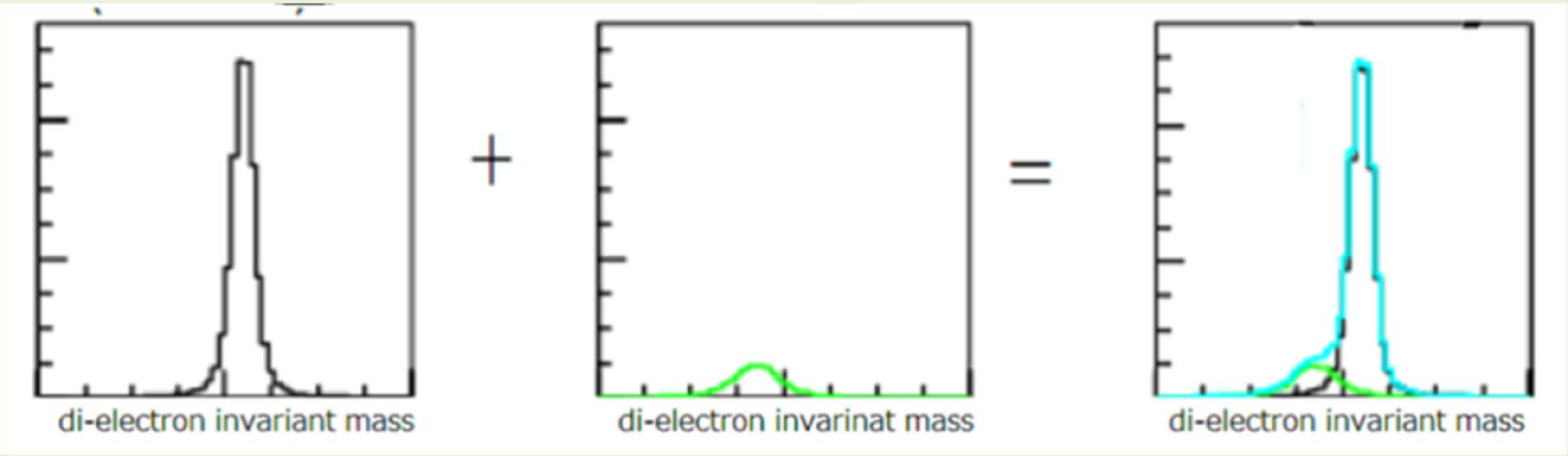
H.J. Kim, P. Gubler and S.H. Lee, Phys. Lett. B **772**, 194 (2017).

Experimental di-lepton spectrum



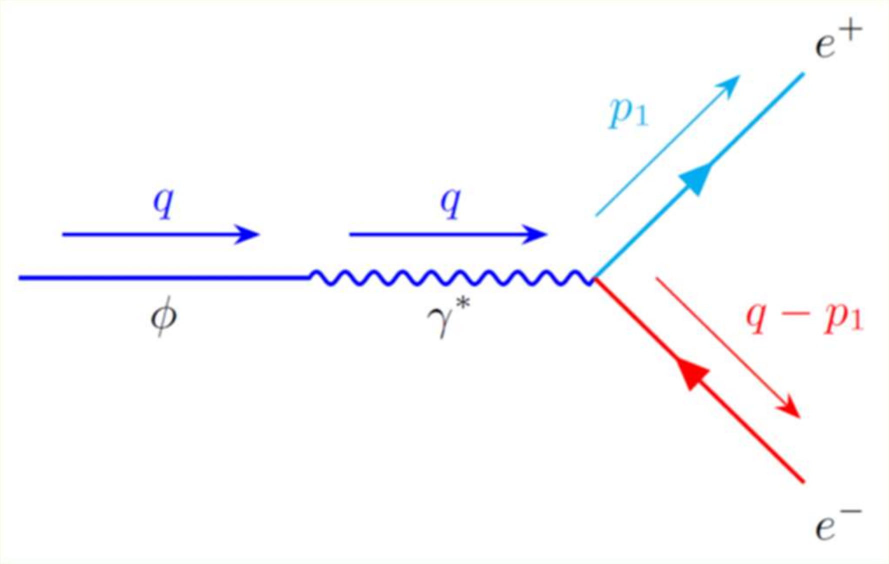
=

Experimentally observed spectrum

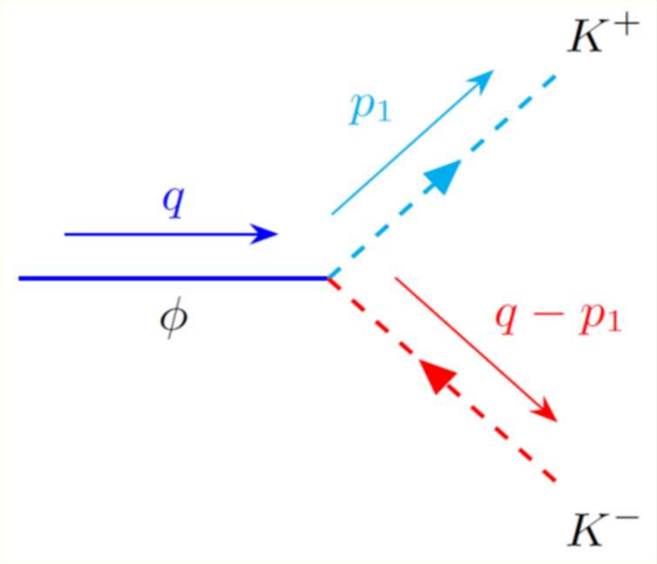


Can the two polarizations be disentangled?

➡ Look at the angular distributions of various decay channels



To be measured soon at
the J-PARC E16 experiment

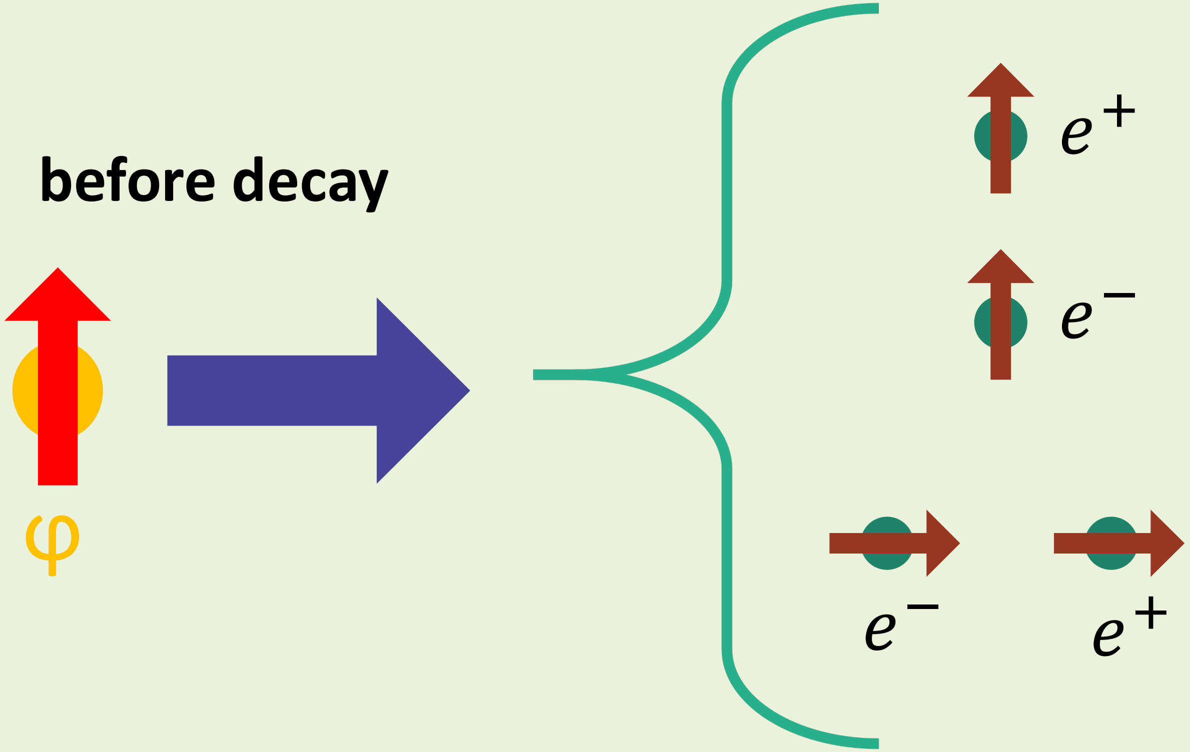


New E88 experiment
at J-PARC (in a few years)

A simple example of dilepton decay of a longitudinally polarized φ

before decay

after decay



decay perpendicular to
the φ meson momentum:
allowed

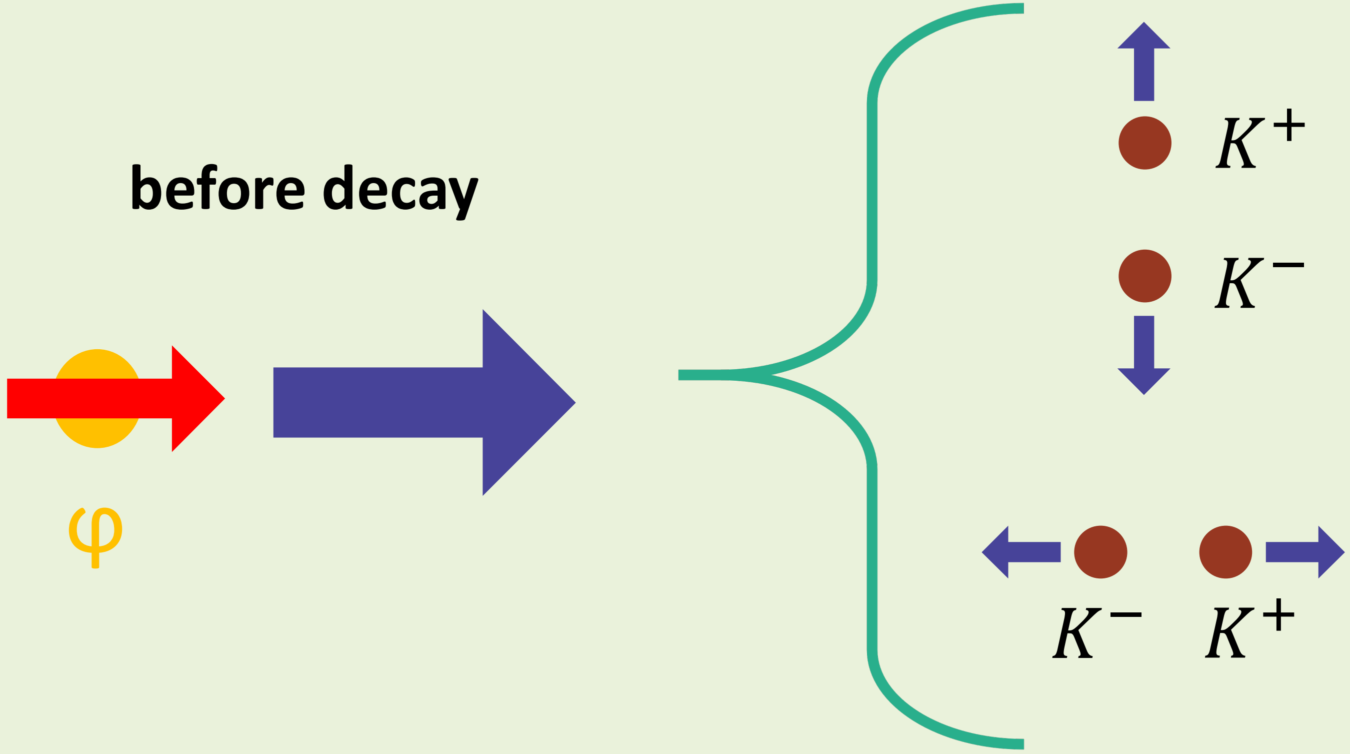
decay parallel to the
φ meson momentum:
not allowed

measurement in this direction
can be used to observe purely
transverse mode

A simple example of K^+K^- decay of a transversely polarized φ

before decay

$$|Y_1^1(\theta,\phi)|^2 \sim \sin^2\theta$$



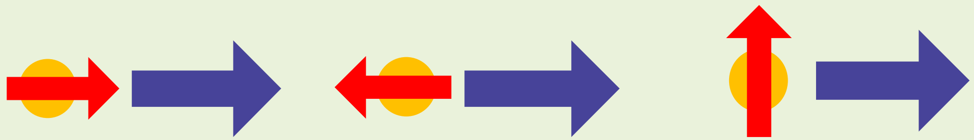
after decay

decay perpendicular to
the φ meson momentum:
allowed

decay parallel to the
φ meson momentum:
not allowed

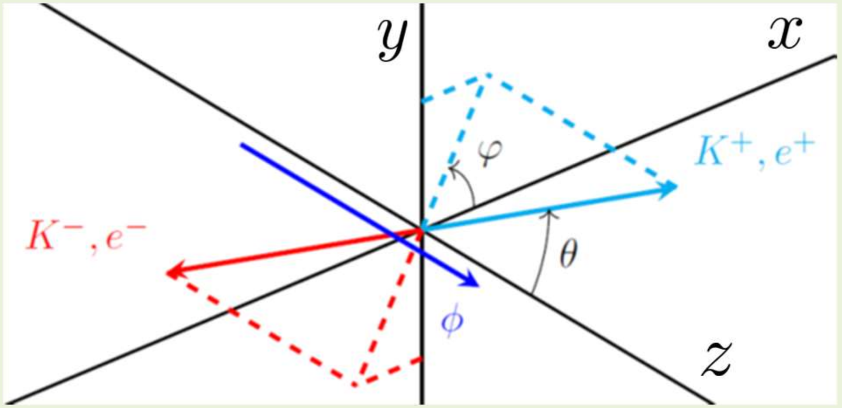
measurement in this direction
can be used to observe purely
longitudinal mode

Full angular distribution of dilepton decay



Initial polarization: $|V\rangle = \underbrace{a_{+1}|+1\rangle + a_{-1}|-1\rangle}_{\text{Transverse polarization}} + a_0|0\rangle$

Longitudinal polarization



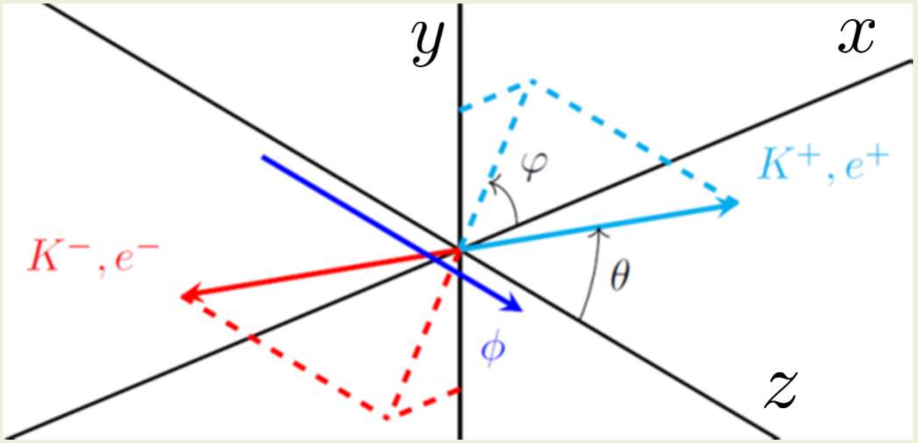
θ: polar angle

ϕ: azimuthal angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[(|a_{+1}|^2 + |a_{-1}|^2)(1+\cos^2\theta) + 2|a_0|^2(1-\cos^2\theta)$$
$$+2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$

other ϕ-dependent terms

Full angular distribution of dilepton decay



θ: polar angle
ϕ: azimuthal angle

With

$$|a_{+1}|^2 + |a_{-1}|^2 + |a_0|^2 = 1, \;\; |a_0|^2 = \rho_{00}$$

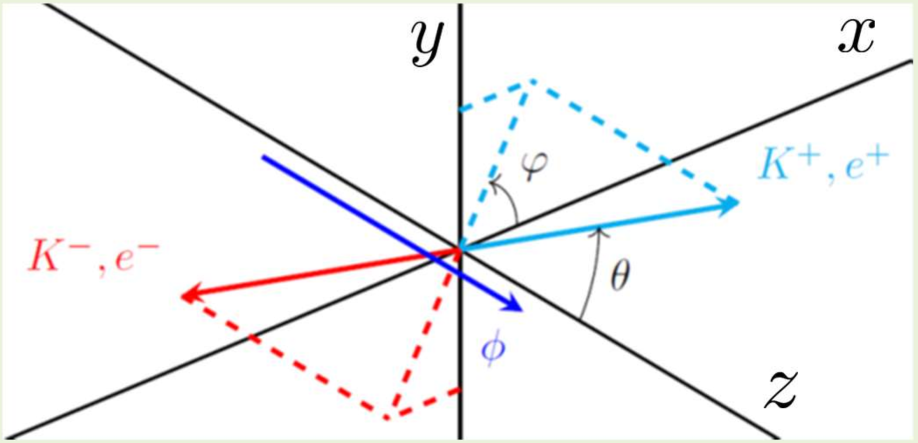
00-component of spin-density matrix

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\left[1 + \cos^2\theta + \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

$\rho_{00} = \frac{1}{3}$ Unpolarized case: vanishing θ-dependence

ϕ-dependent terms

Full angular distribution of K$^+$K$^-$ decay



θ: polar angle
ϕ: azimuthal angle

Longitudinal mode

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[\overbrace{\left(|a_{+1}|^2 + |a_{-1}|^2\right)}^{\text{Transverse modes}}\sin^2\theta + 2|a_0|^2\cos^2\theta$$

$$-2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$

$$= \frac{3}{16\pi}\left[1 - \cos^2\theta - \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

ϕ-dependent terms