Experimental investigation of vector mesons in medium through dielectron decay at J-PARC.

K. Aoki

IPNS, KEK

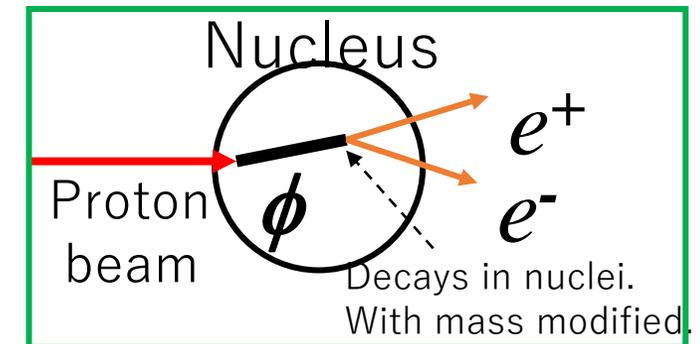J-PARC Hadron Section.

CONTENTS

- J-PARC E16 experiment (p+A $\rightarrow$ ϕ $\rightarrow$ e$^+$e$^-$)
  - Physics motivation (measure in-medium spectral change of VM)
  - Experimental setup
  - Staging strategy
  - Expected results.
  - Recent commissioning run (ended 24:00 June 3)
- Measurement of polarization dependence of spectral change.
  - Motivation and principle of spin dependent measurement
  - Expected spectra
  - How to extract spin dependence
- Summary

Physics

- The origin of Hadron mass.
- The study of QCD vacuum
  - **Spontaneous breaking of the chiral symmetry.**
    - An order parameter: $\langle \bar{q}q \rangle \neq 0$
    - Depends on temperature, and density
    - ***Partially restored even at normal nuclear density***.
    - Could result in a measurable change in mass.
    - $\langle \bar{q}q \rangle$ ~35% reduction at ρ_0 for ***u*** and ***d***. what about ***s***?
  - $\langle \bar{q}q \rangle$ ← QCD sum rule→ mass
- J-PARC E16 experiment:
  - Use **p + A → ρ/ω/φ → e+e-** , (**K⁺K⁻** E88)
  - Dielectron mass spectra are obtained.
    - mixture of decay inside and outside the nuclear target.
    - Sensitive to spectral change of vector mesons in the nuclear medium.
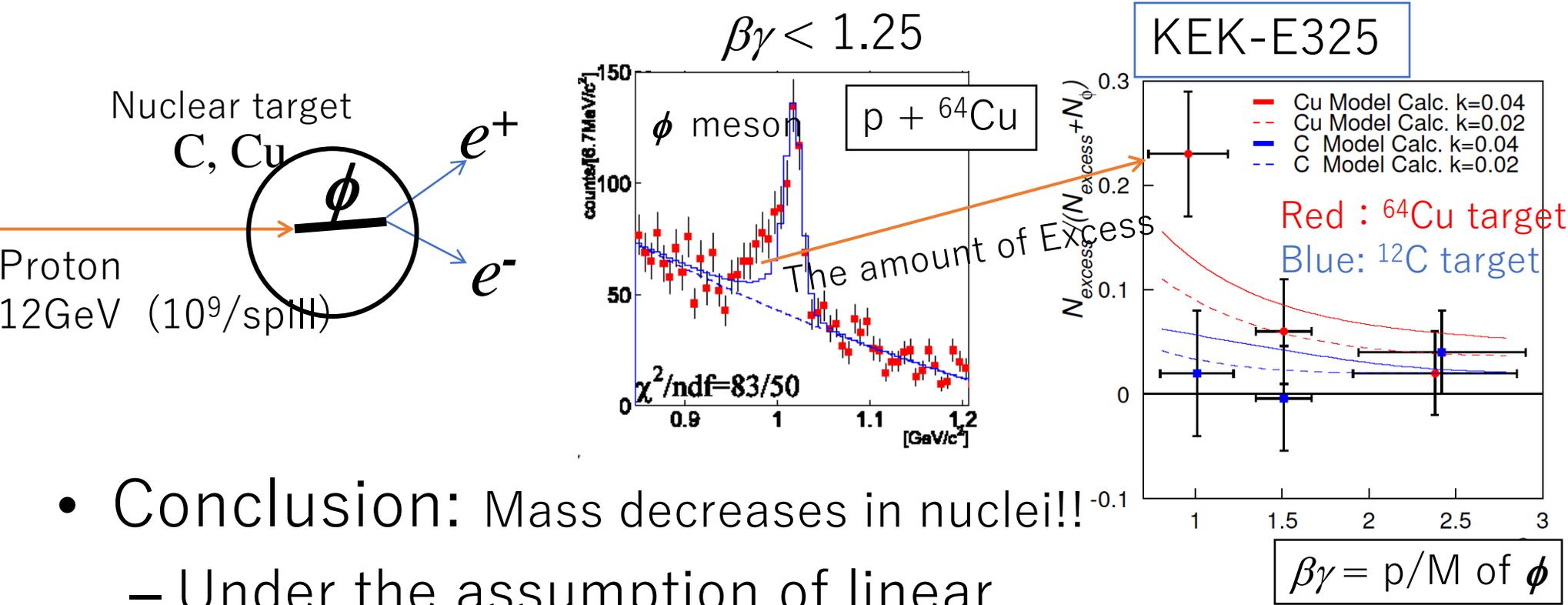 - Similar to KEK-E325, but collecting more data and doing more systematic study.
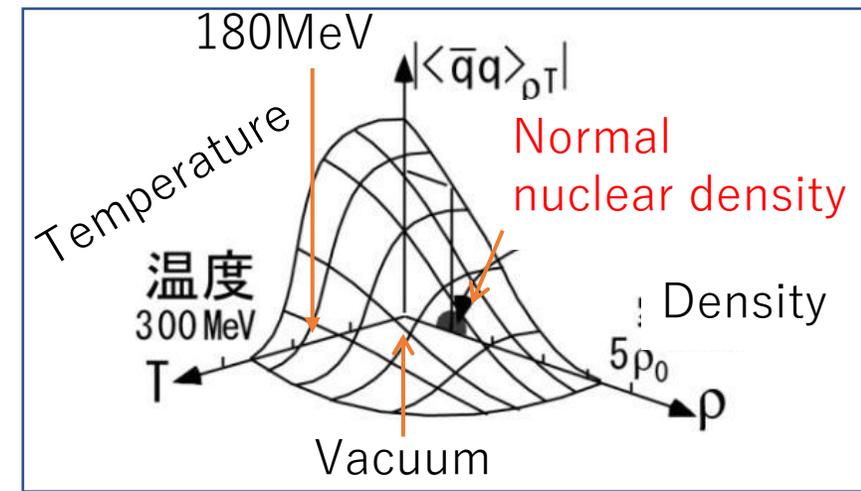
NJL model
M. Lutz et al.
Nucl. Phys. A542,52(1992)

J-PARC E16

KEK-E325 results of ϕ meson

- The world's first results of ϕ modification.

Nuclear target
C, Cu

Proton
12GeV (10^9/spill)

$\beta\gamma < 1.25$

ϕ meson

e^+

e^-

p + ^{64}Cu

χ^2/ndf=83/50

The amount of Excess

KEK-E325

- Cu Model Calc. k=0.04
- Cu Model Calc. k=0.02
- C Model Calc. k=0.04
- C Model Calc. k=0.02

Red : ^{64}Cu target
Blue: ^{12}C target

$N_{excess}/(N_{excess}+N_{\phi})$
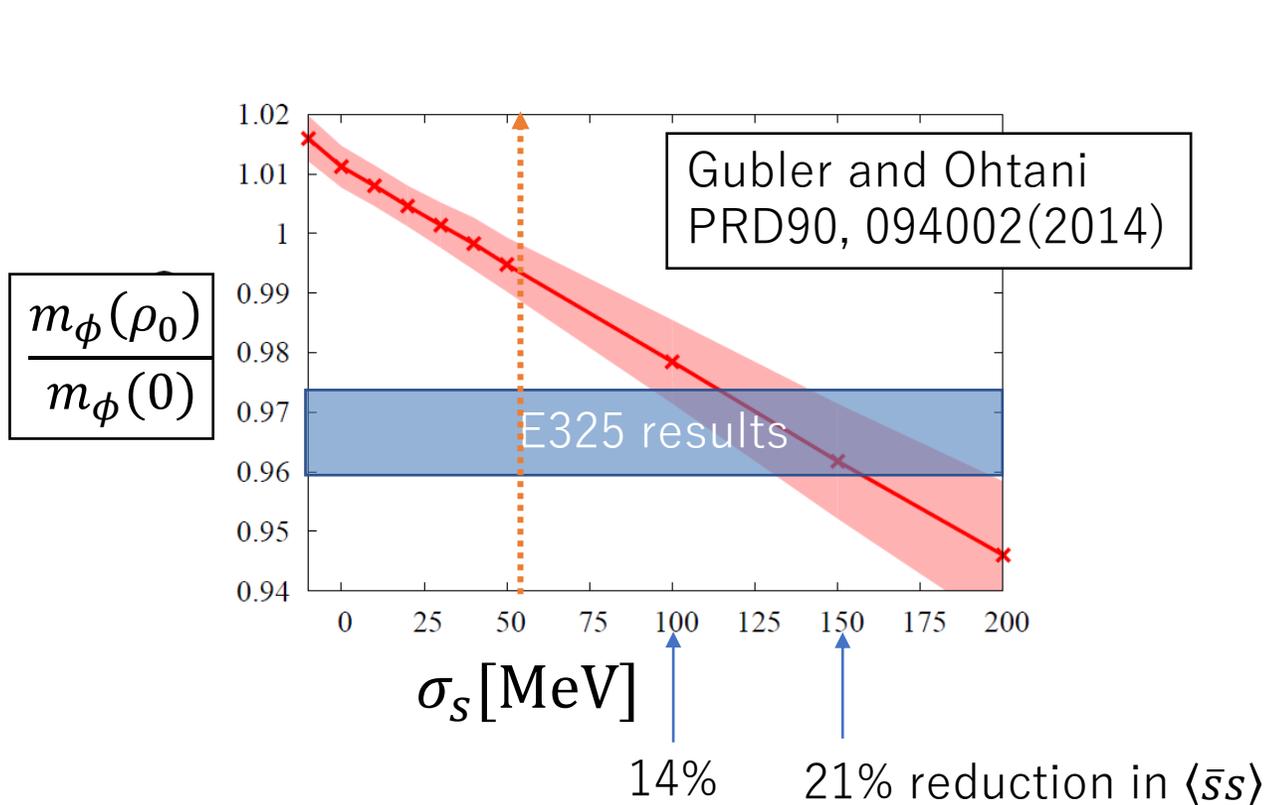
$\beta\gamma$ = p/M of ϕ

Assumption
In analysis

$$\frac{m(\rho)}{m(0)} = 1 - k_1\left(\frac{\rho}{\rho_0}\right)$$

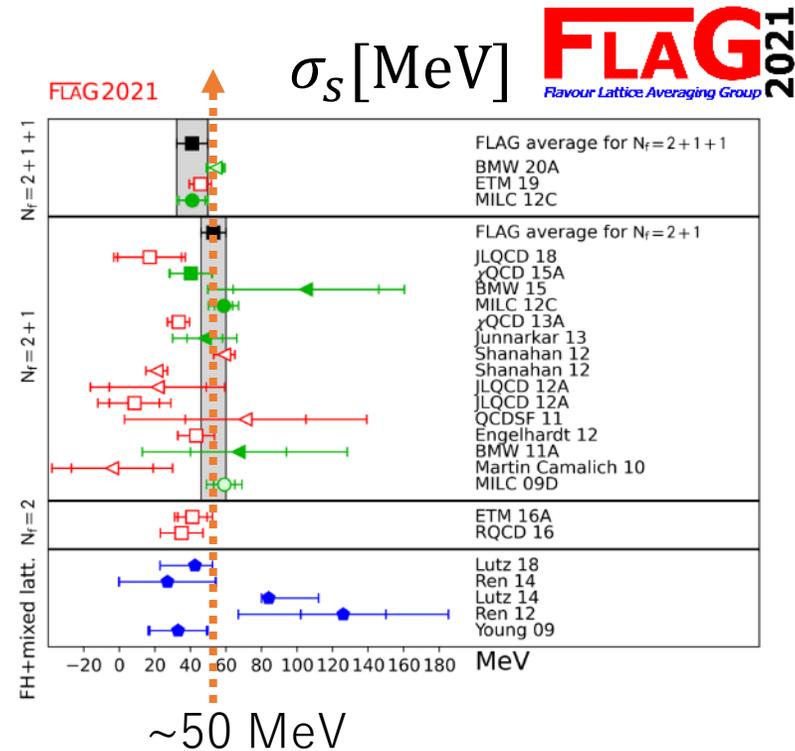$$\frac{\Gamma(\rho)}{\Gamma(0)} = 1 + k_2\left(\frac{\rho}{\rho_0}\right)$$

- **Conclusion:** Mass decreases in nuclei!!
  - Under the assumption of linear dependence of mass and width on density.
    - Mass: $- 3.4\,^{+0.6}_{-0.7}\%$ ↓ At normal nuclear density
    - Width: $\times 3.6^{+1.8}_{-1.2}$

QCD sum rule results

They provide mass of ϕ meson vs σ_s (strangeness sigma term)
The σ_s indicates how much $\langle \bar{s}s \rangle$ is reduced in nuclear matter.
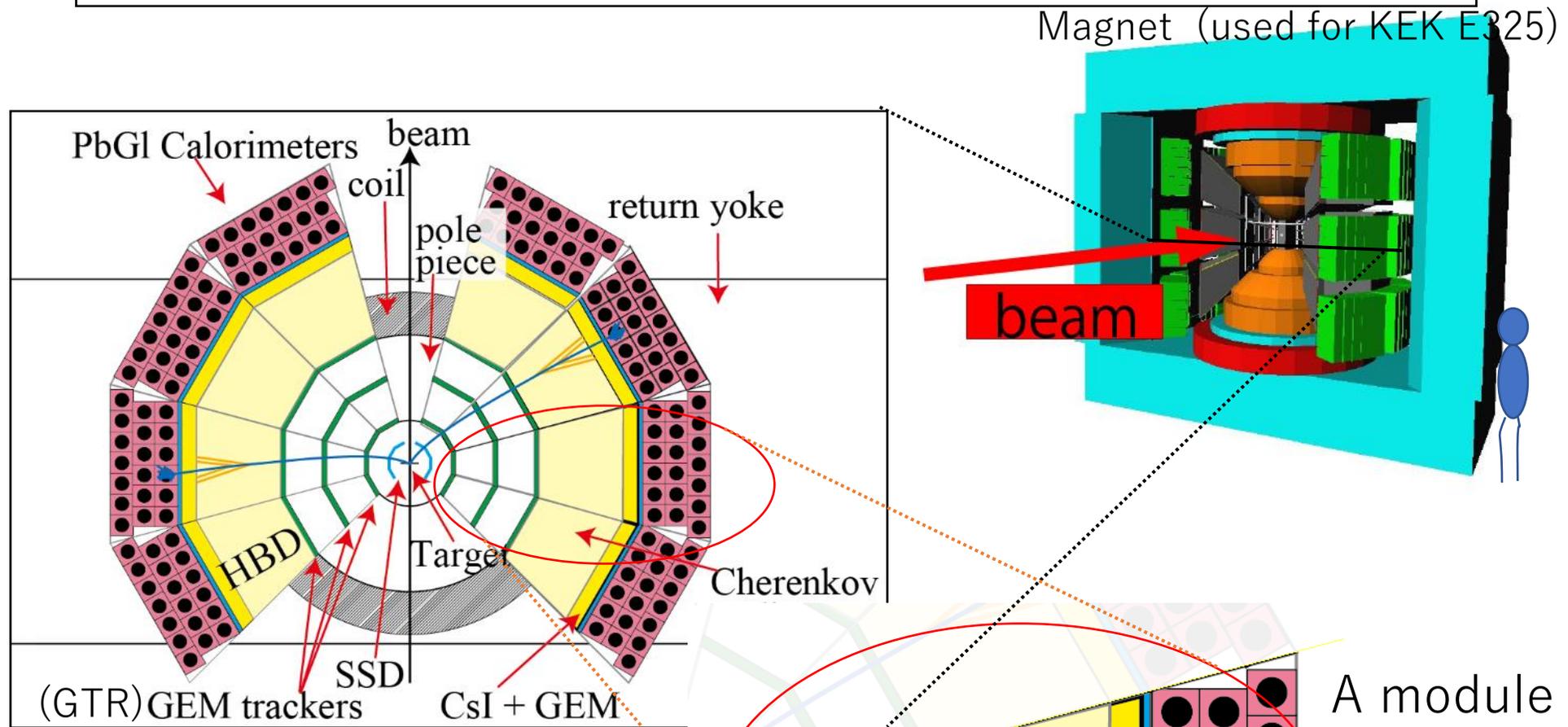

Gubler and Ohtani
PRD90, 094002(2014)

$\dfrac{m_\phi(\rho_0)}{m_\phi(0)}$

E325 results

σ_s[MeV]

14%   21% reduction in $\langle \bar{s}s \rangle$

If one takes σ_s from Lattice and QCD sum rule,
Mass reduction should be much smaller. (dM<~1%)

σ_s[MeV]

~50 MeV

$$\langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \langle N|\bar{s}s|N \rangle \rho$$

$$\sigma_s = m_s \langle N|\bar{s}s|N \rangle \quad (= m_s \frac{\partial M_N}{\partial m_s})$$

The J-PARC E16 spectrometer

Magnet (used for KEK E325)

beam

PbGl Calorimeters
beam
coil
return yoke
pole piece
HBD
Target
Cherenkov
SSD
(GTR) GEM trackers
CsI + GEM

A module

X 26

SSD : Tracking
GTR : Tracking
HBD : eID (Cherenkov)
LG   : eID (Calorimeter)
26 modules in total. 8 for the 1st physics run.

Staging approach

- **RUN 0a/b/c/d - 2020,2021,2023**– 413hrs.
  - **10 (SSD) + 8 (GTR) + 8 (HBD) + 8 (LG)** at last
    - Gradually increased acceptance and reached interm. Goal.
  - C+Cu targets
  - Beam / Detector commissioning
- **RUN 0e - 2024 (Apr.19-Jun.3) -- 206 hours.**
  - **8(SSD) + 10 (GTR) + 8 (HBD) + 8 (LG)**
  - Beam / Detector comm. + yield.
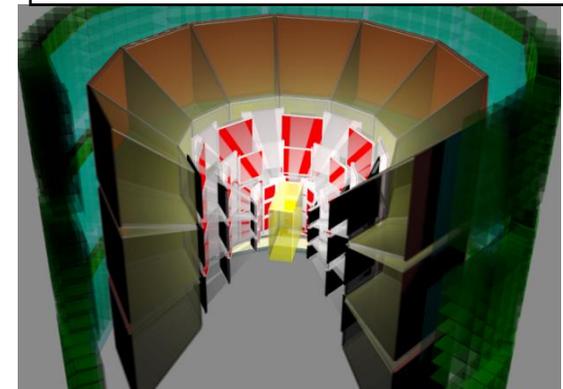 - Upgraded Accelerator / DAQ. / Detectors.
- **RUN 1 2025(?)** -- 1280hrs (~53days)
  - **10 (SSD) + 10 (GTR) + 8 (HBD) + 8(LG)**
  - Physics data taking. ϕ : 15k for Cu.
  - Needs PAC approval based on comm. Runs.
- **RUN 2**   -- 2560 hrs (~107 days)
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - + Pb/CH2 target
  - Needs additional budget.

PAC approved!

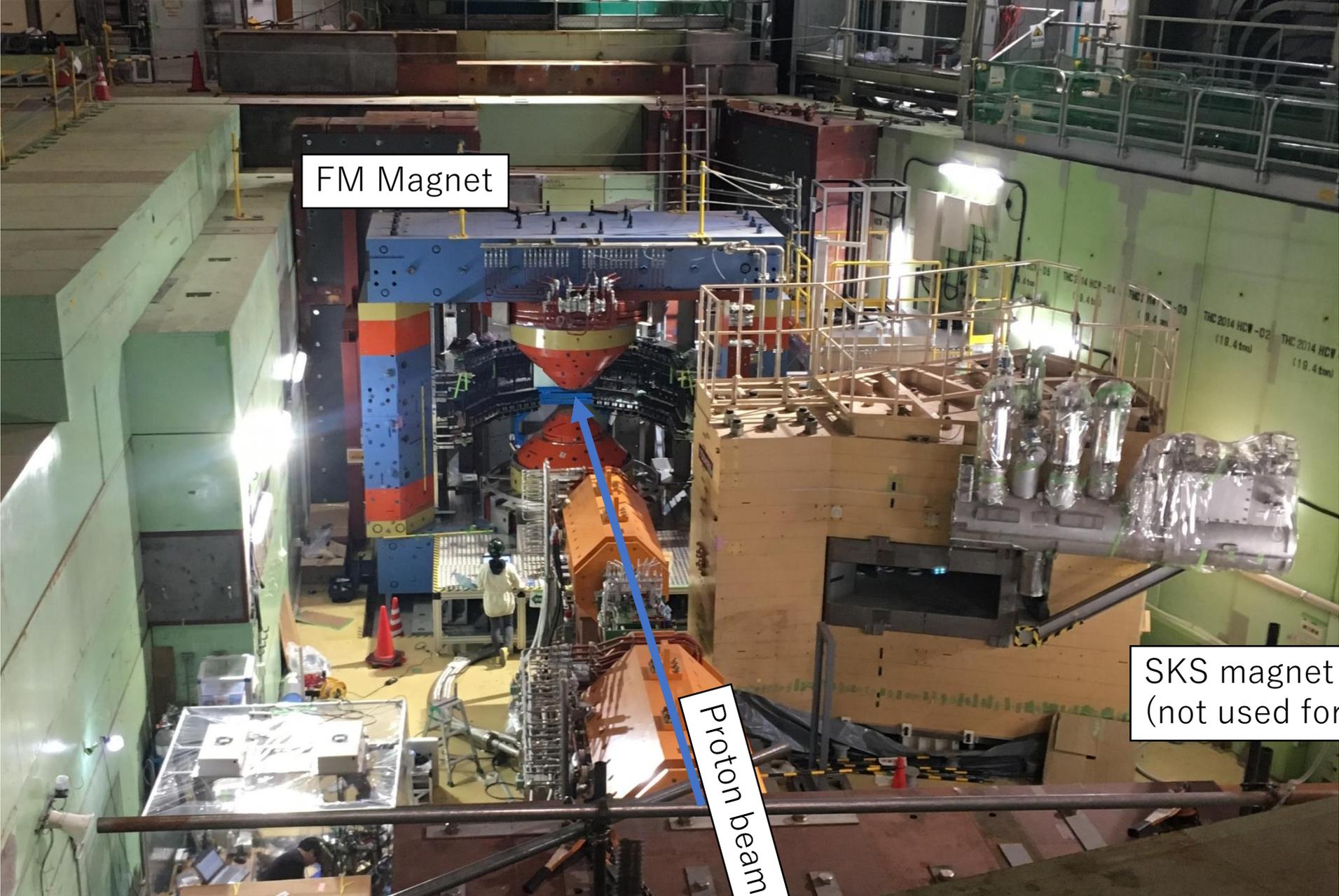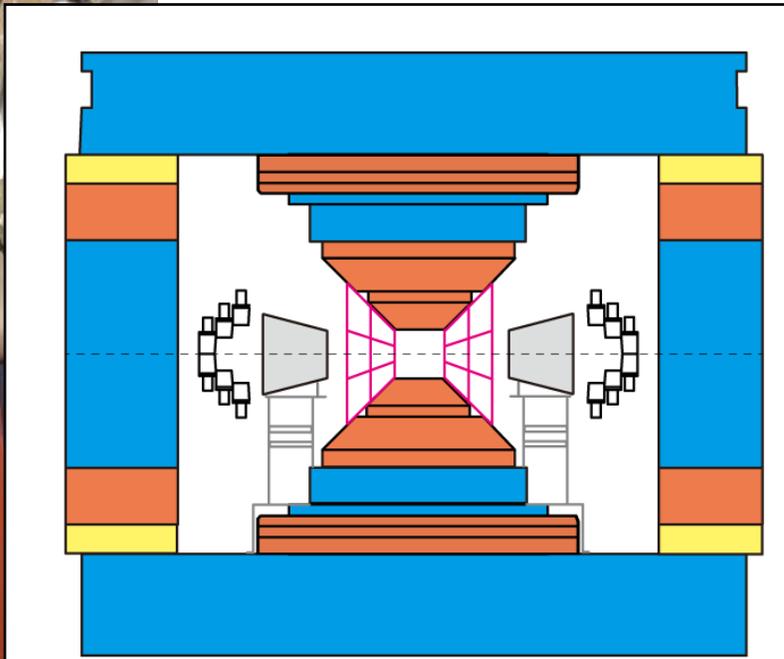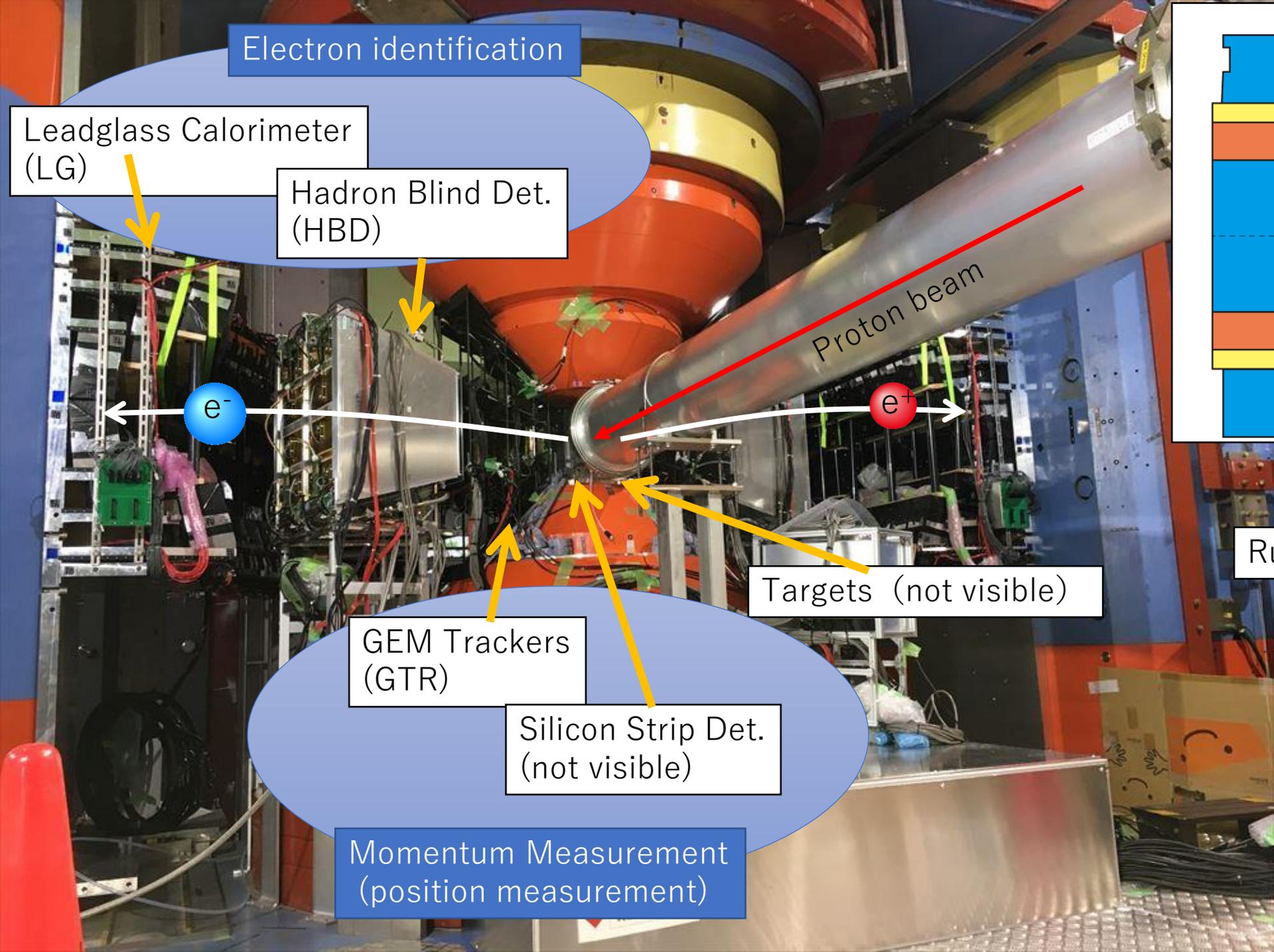Executed!

RUN 1 (8 modules)
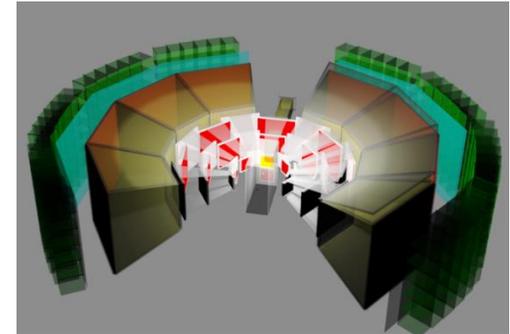
RUN 2 (26 modules)

High-p Area

Photo taken in 2019 or so.
Shield blocks now cover the area and hard to get this view.

FM Magnet

SKS magnet
(not used for E16)

Proton beam

Electron identification

Leadglass Calorimeter (LG)

Hadron Blind Det. (HBD)

Proton beam

e⁻

e⁺

Targets（not visible）

GEM Trackers (GTR)

Silicon Strip Det. (not visible)

Momentum Measurement (position measurement)

Run0b/c configuration(2021)

J-PARC E16 Collaboration

- RIKEN
  - S. Yokkaichi (spokesperson)
  - H. En'yo
  - F. Sakuma
- KEK
  - K. Aoki
  - R. Honda
  - K. Kanno
  - Y. Morino
  - R. Muto
  - W. Nakai
  - K. Ozawa
  - S. Sawada
  - M. Sekimoto
  - H. Sugimura

- Univ. of Tokyo
  - J. Kakunaga
  - H. Murakami
  - T.N. Murakami
- Kyoto Univ.
  - M. Ichikawa
  - S. Nagafusa
  - S. Nakasuga
  - M. Naruki
  - S. Ochiai
- RCNP
  - S. Ashikaga
  - H. Noumi
  - K. Shirotori
  - T.N. Takahashi
- NiAS
  - H. Hamagaki

- Hiroshima Univ.
  K. Shigaki
  R. Ejima
  R. Yamada
  Y.L. Yamaguchi
- JASRI
  - A. Kiyomichi
- Univ. Tsukuba
  - T. Chujo
  - S. Esumi
  - T. Nonaka
- JAEA
  - H. Sako
  - S. Sato
- BNL
  - T. Sakaguchi
- Tohoku Univ.
  - S. Kajikawa

- Academia Sinica
  - W.-C. Chang
  - C.-H Lin
  - C.-S. Lin
  - P.-H. Wang
- GSI
  - J. Heuser
  - A.R. Rodriguez
  - M. Teklishyn
- Goethe Univ.
  - D.R. Garces
  - A. Toia

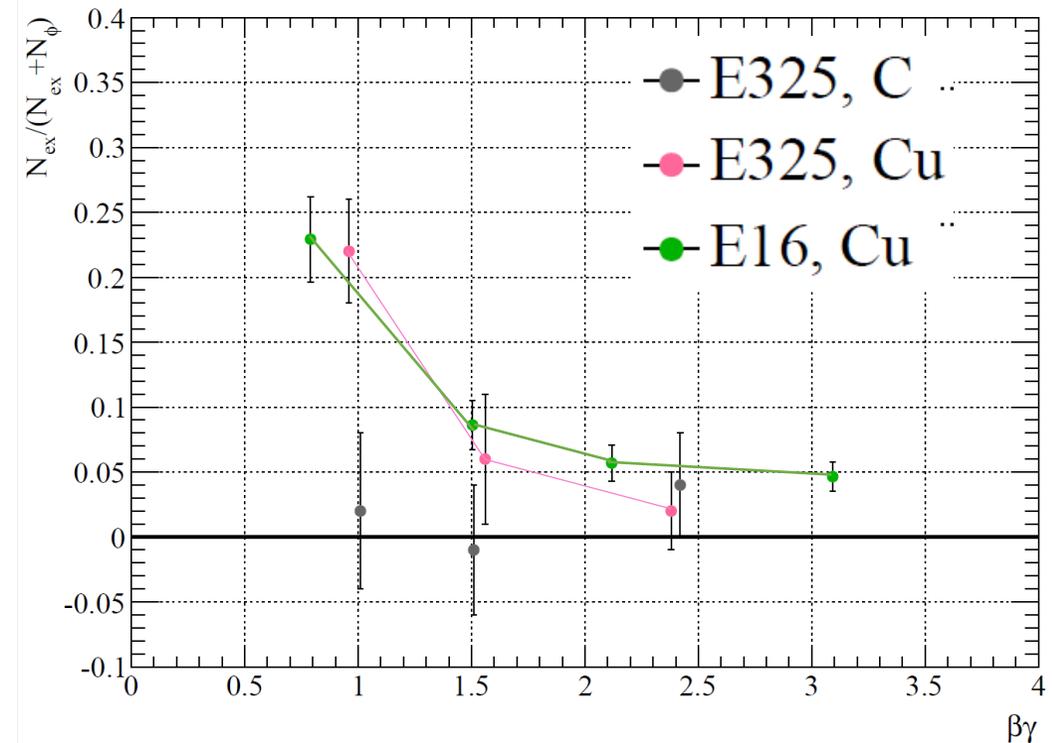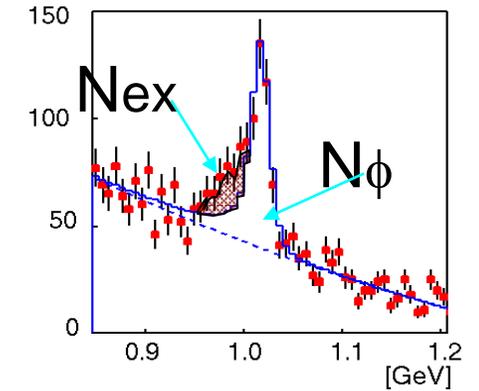# RUN1, Cu (INPUT:E325-BW)
Excess ratio vs $\beta\gamma$

βγ<1.25,   1.25<βγ<1.75,   1.75<βγ<2.5,   2.5<βγ
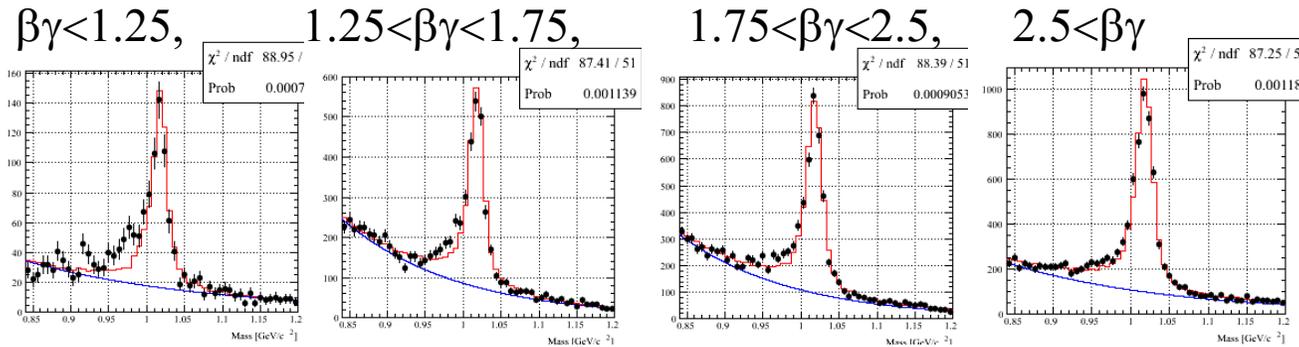
(Fit fails when vacuum shapes are used.)

$$\frac{N_{excess}}{N_{excess} + N_\phi}$$

- ~15k ϕ for Cu target expected in RUN1
- All $\beta\gamma$ bins for Cu are significant in E16
- (cf) E325 only fastest $\beta\gamma$ bin is significant.

- Larger excess in lower $\beta\gamma$ bin.
- The tendency becomes clearer and more significant compared to E325.

Momentum dependence (Dispersion relation)

H.Kim P. Gubler PLB805, 10 (2020)extends the validity of momentum range.
Show you on later slides.

- Momentum dependence of mass can be obtained for the first time.

- Expectation of RUN1 x 1.7 is shown.

- Dispersion relation itself is an important property of pseudo particles.

- We can extrapolate mass into 0 momentum, where most of the QCDSR calculation results apply.
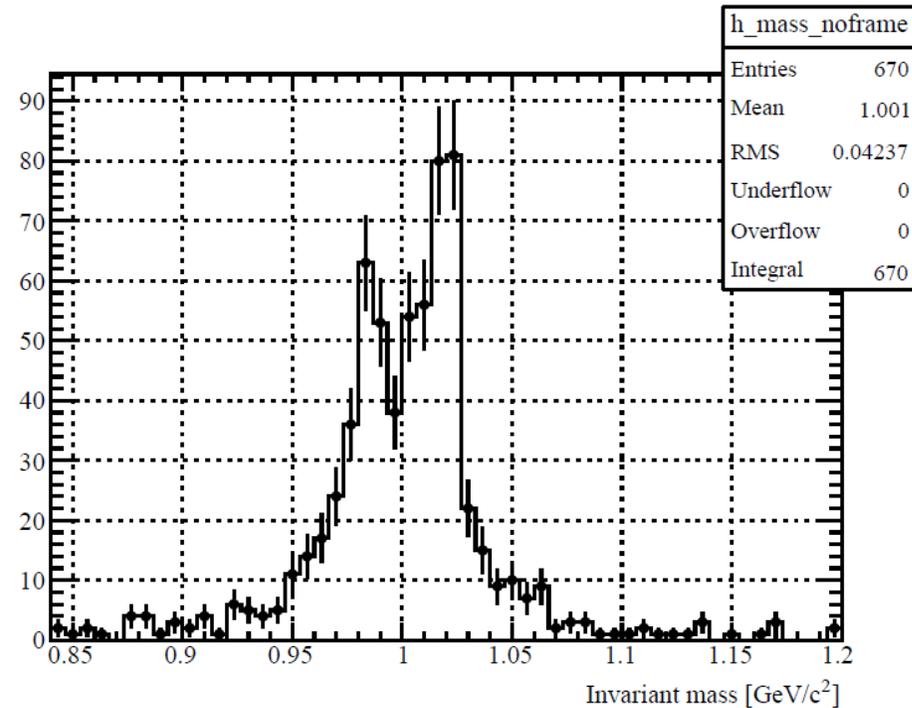
- More discussion on later slides.

φ mass (1020)
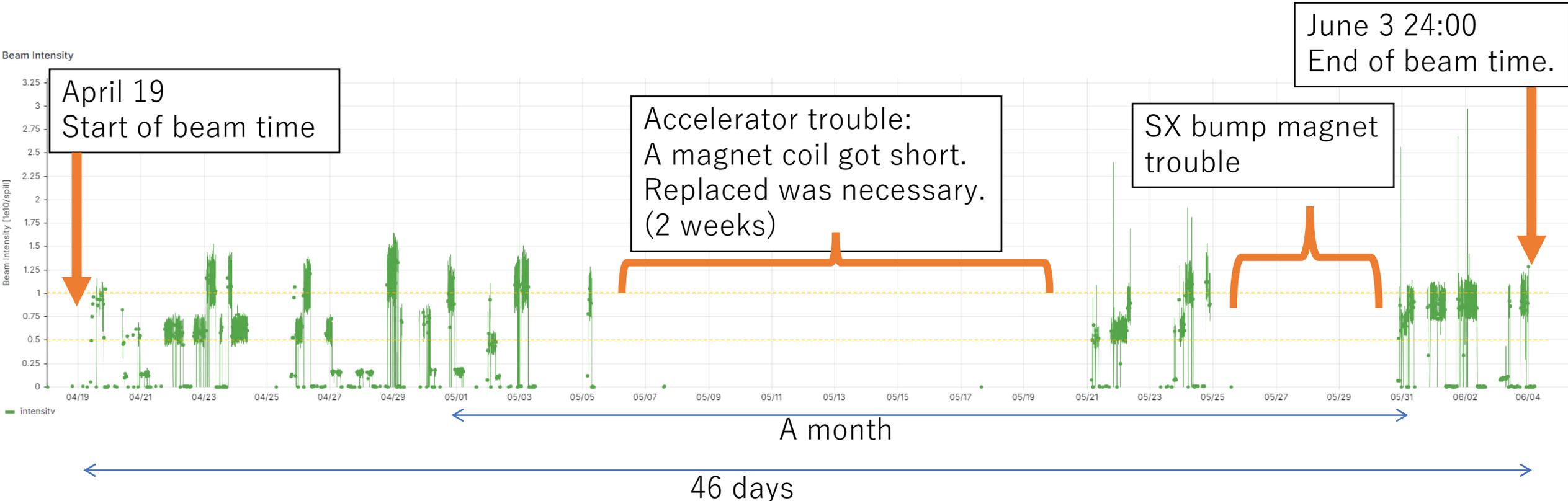E325 ΔM~35 MeV
Expected
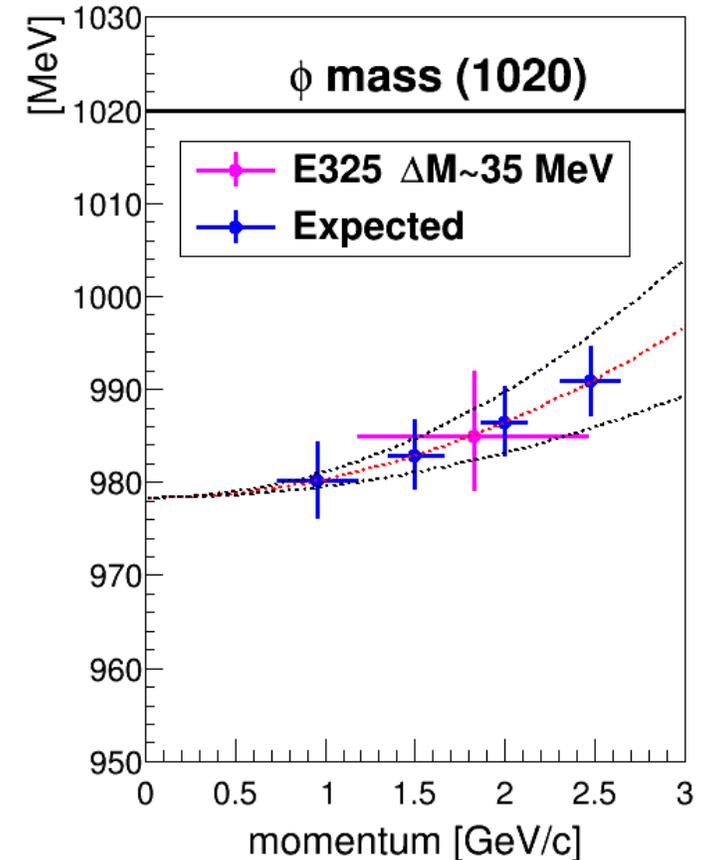
S.H. Lee PRC57, 927(1998)

Expected in RUN2

- RUN2 stat (320shifts)
- INPUT: E325-BW

- Pb target
- $\beta\gamma < 0.5$

h_mass_noframe	
Entries	670
Mean	1.001
RMS	0.04237
Underflow	0
Overflow	0
Integral	670

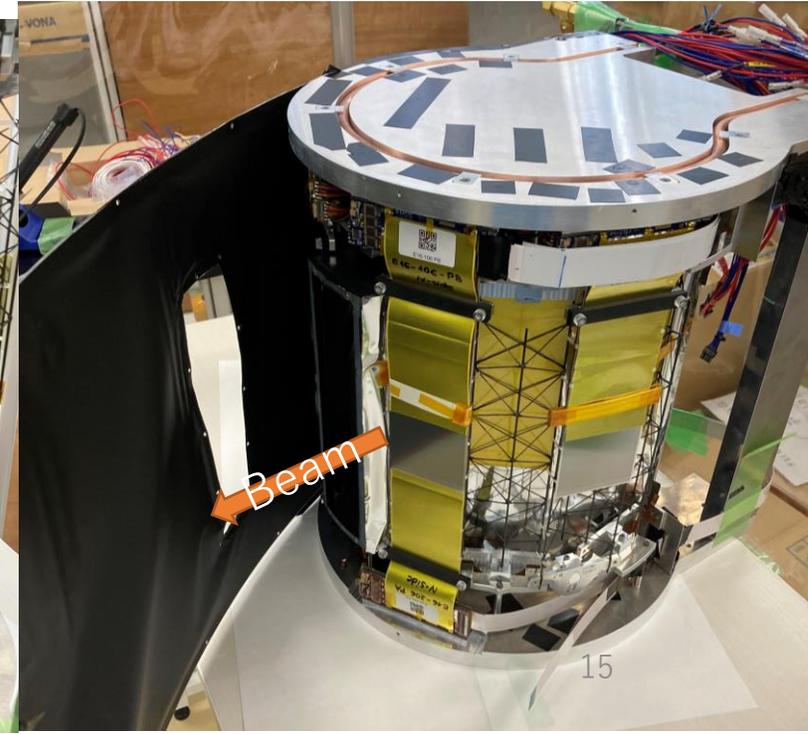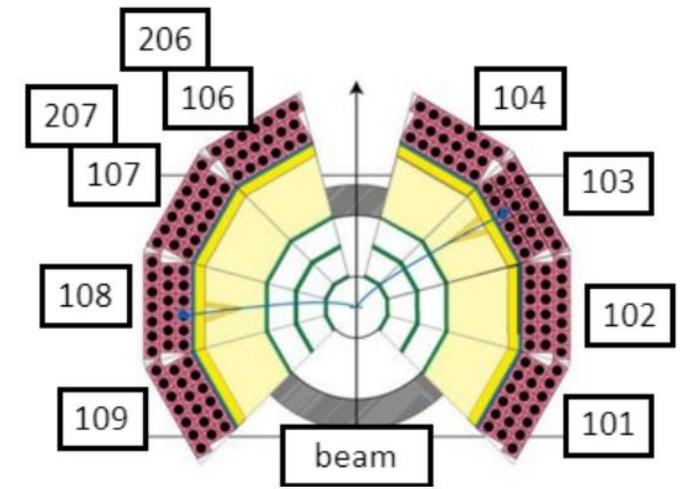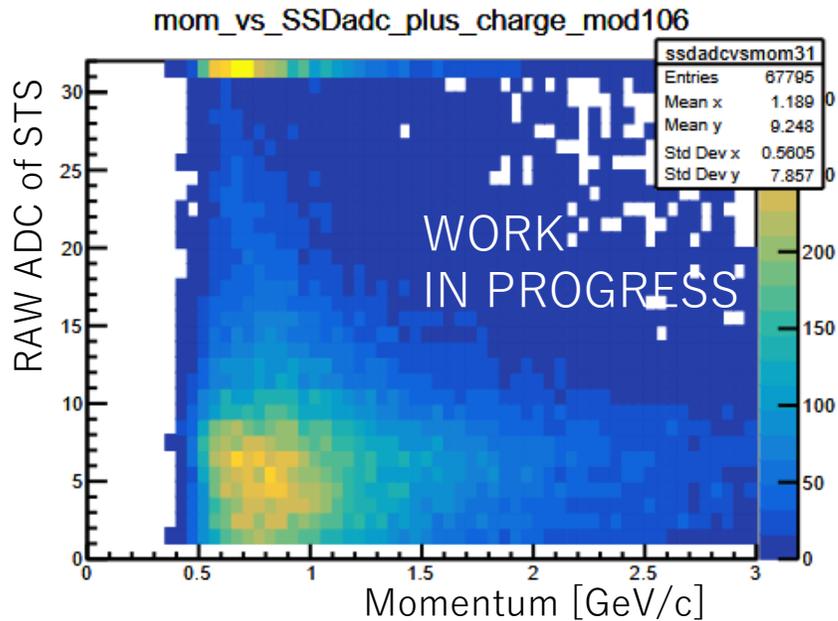Invariant mass [GeV/c^2]

Beam intensity history of Run0e

- Beam time: April 19 – June 3 (46 days⋯)
  - We had two major breaks (2 + 1 weeks) due to accelerator trouble and recovery process.
- Intensity of proton beam
  - Design : 1e10/spill   (spill = 2sec+2.4sec)
  - Three intensity settings.

- Beam from evening to morning.
  - That's why we have short breaks day by day.
- Accepted 206 h (+ 31h of beam tuning) beam
  - 60h of data taking incl. ramp up.
  - + detector setup / study / calibration.

Beam Intensity

April 19
Start of beam time

Accelerator trouble:
A magnet coil got short.
Replaced was necessary.
(2 weeks)

SX bump magnet trouble

June 3 24:00
End of beam time.

A month

46 days

Run0e

- DAQ live rate > 80% (was 15% @ run0c) thanks to DAQ upgrade
  - Live rate : Accepted / Triggered
- Calibration / analysis of data on-going.
- Maintenance work / preparation for 1st physics run on-going.
- Convince PAC that we are ready to proceed to the 1st physics run

- Silicon Tracking System (STS)
  - STS developed with GSI-CBM.
  - Successful operation during Run0e
  - Semi-online plot of Energy loss vs mom
    - proton locus

mom_vs_SSDadc_plus_charge_mod106

ssdadcvsmom31	
Entries	67795
Mean x	1.189
Mean y	9.248
Std Dev x	0.5605
Std Dev y	7.857

WORK IN PROGRESS

RAW ADC of STS

Momentum [GeV/c]

Beam

Upside-down

Beam

Measurement of polarization dependence

Pol dependence of mass distribution

- PLB805 (2020) 135412, Kim-Gubler
  - Prediction of the dispersion relation of phi meson based on the QCD sum rule.
  - Polarization dependence.
  - Interesting to see it experimentally.

- Polarization dep can be studied through decay angle φ ➔ e⁺e⁻ / K+K-
- Expected spectrum
  - Based on E325-type model calc.
- A method to experimentally separate
  - Finding orthogonal functions.

Dispersion relation up to 3 GeV/c

Momentum of φ meson
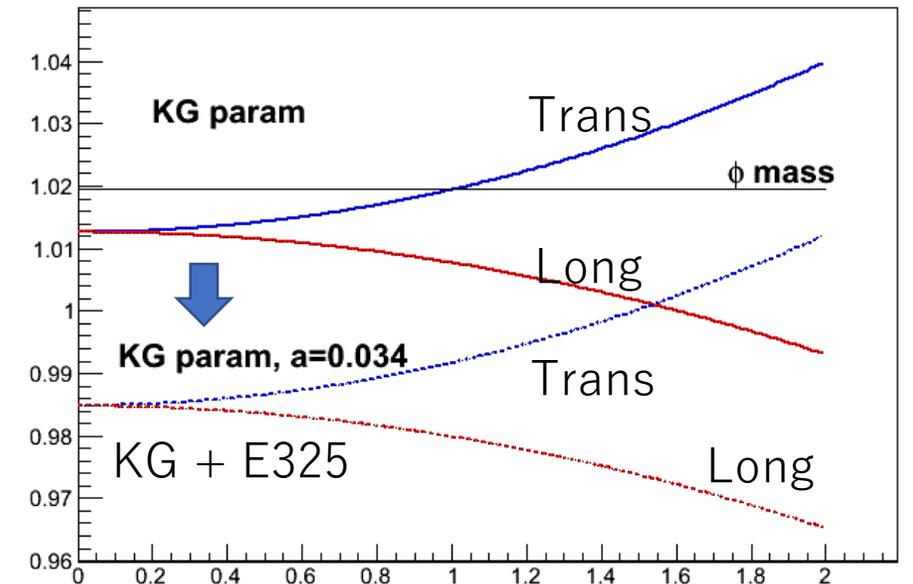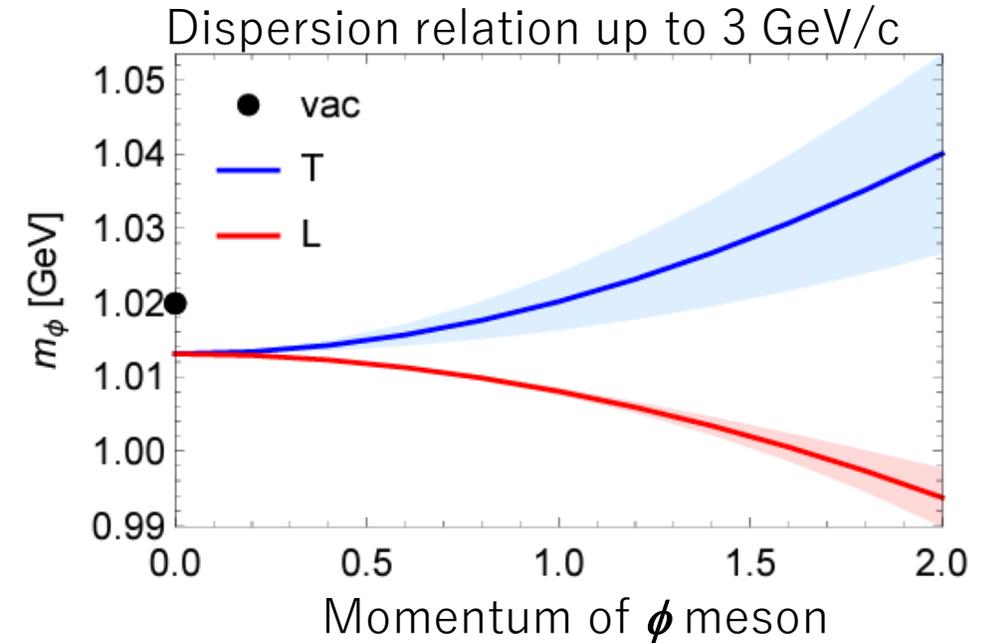
Anomaly-induced chiral mixing of ϕ and $f_1(1420)$

- Phys. Rev. D106, 5 (2022) C. Sasaki
  - Chiral mixing effect in dense matter can be seen in e+e- channel when chiral symmetry is restored. And it behaves differently for different pol.
  - T(Transverse) affected. L(Longitudinal) stays.
- ϕ and $f_1(1420)$ are parity partner.
  - Part of their components are chiral partners.
  - Genuine signal of chiral symmetry restoration: Degeneracy of chiral partner!
  - K* K1 case → tomorrow by InWoo.

p = 1.0GeV/c

T=50 MeV
$\rho = 2.5\rho_0$
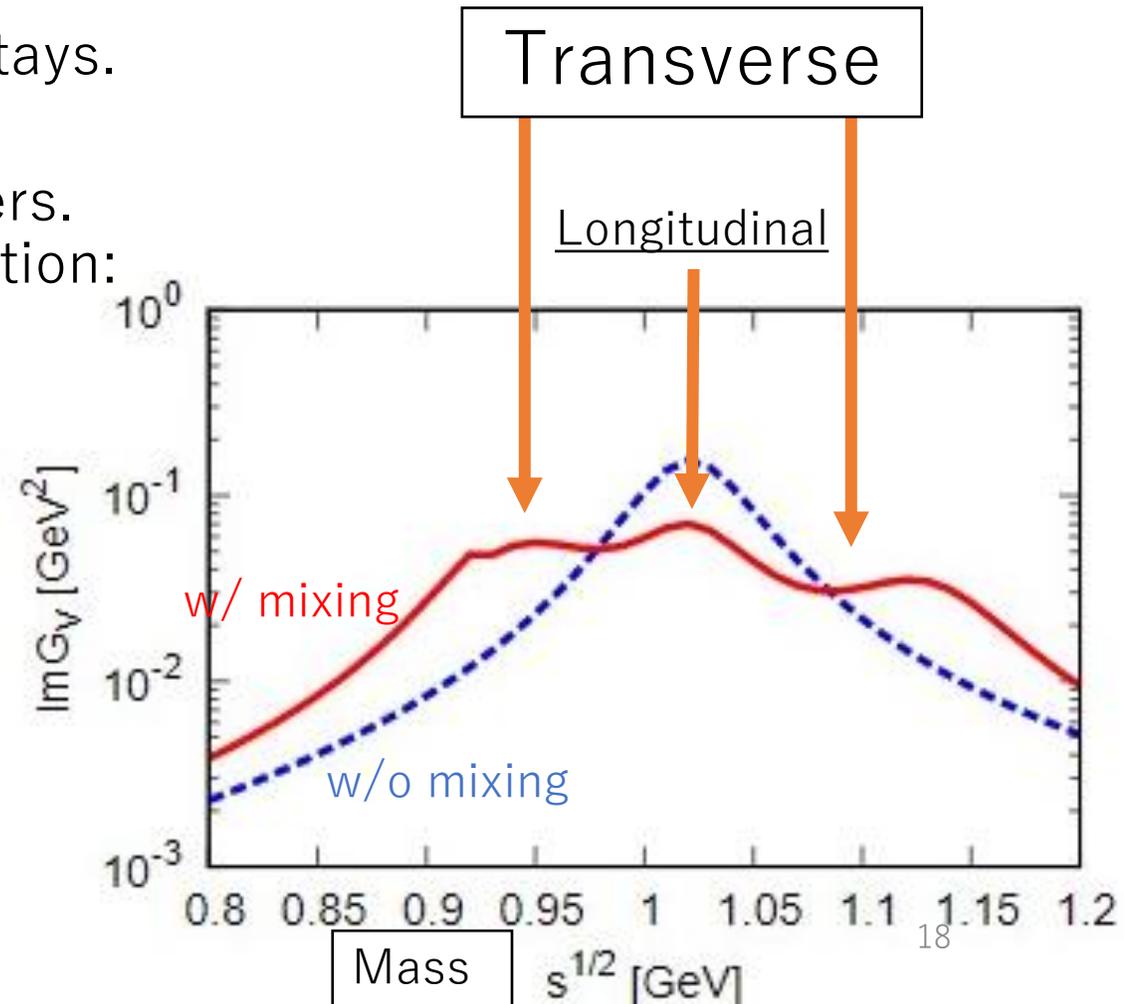
Polarization ⟷ Angular dist.

The rest frame of ϕ meson

e+

θ
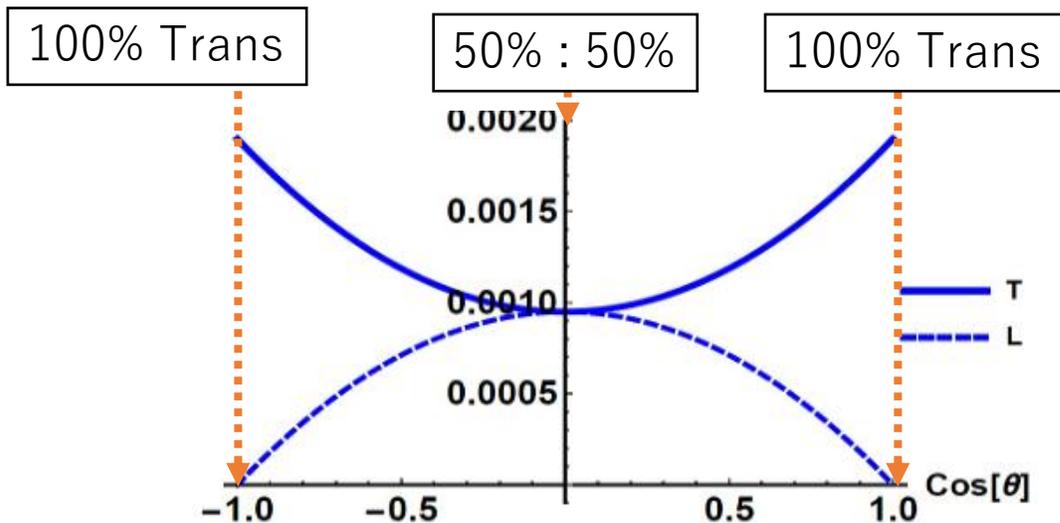
ϕ

e⁻
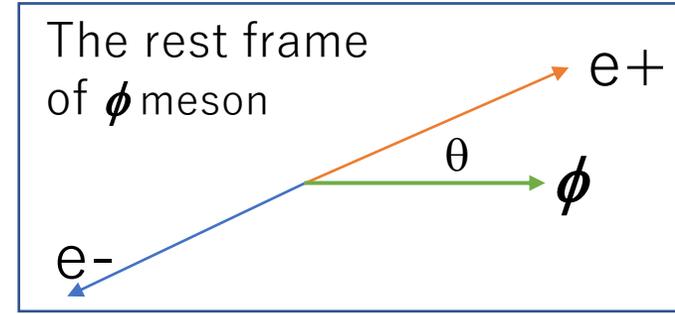
ϕ ➔ e⁺e⁻

- Spin 1 is taken by ee pol.
  - ☺ • $\cos\theta = \pm1$: T 100%
  - ☹ • $\cos\theta = 0$: L 50%, T 50%

- ☺ Small FSI

- Small BR (2.98 x 10⁻⁴)
  - ☹ • 15k for 53 days (E16 Run1)

ϕ ➔K⁺K⁻

- Spin 1 is taken by KK OAM
  - ☺ • $\cos\theta = \pm1$: L 100%
  - ☺ • $\cos\theta = 0$: T 100%

- ☹ • Suffer from FSI
 - • Treated by transport model (P. Gubler)

- Large BR (49.1%)
  - ☺ • 260k for 30 days (E88)

100% Trans   50% : 50%   100% Trans

100% Long   100% Trans   100% Long
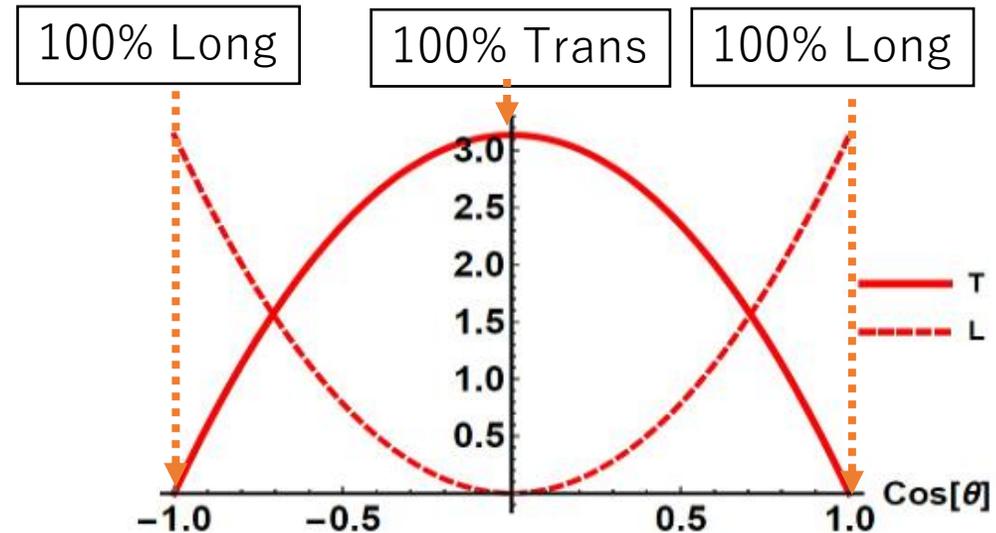
E325-type calculation using KG param.

- E325 model assumption
  - Density assumed to be WS potential shape.
  - ϕ production probability proportional to density.
    - According to mass-number dependence of σ ($\sigma_{pA} \sim A$)
  - # of entries is arbitrary.
    - (cf) Run1 exp: ~1.7k ($\beta\gamma$<1.25), Run2 exp: 12k for ($\beta\gamma$<1.25)
- Smearing (mimic experimental effect)
  - Mass by 7 MeV/c^2, cos(θ) by 0.01
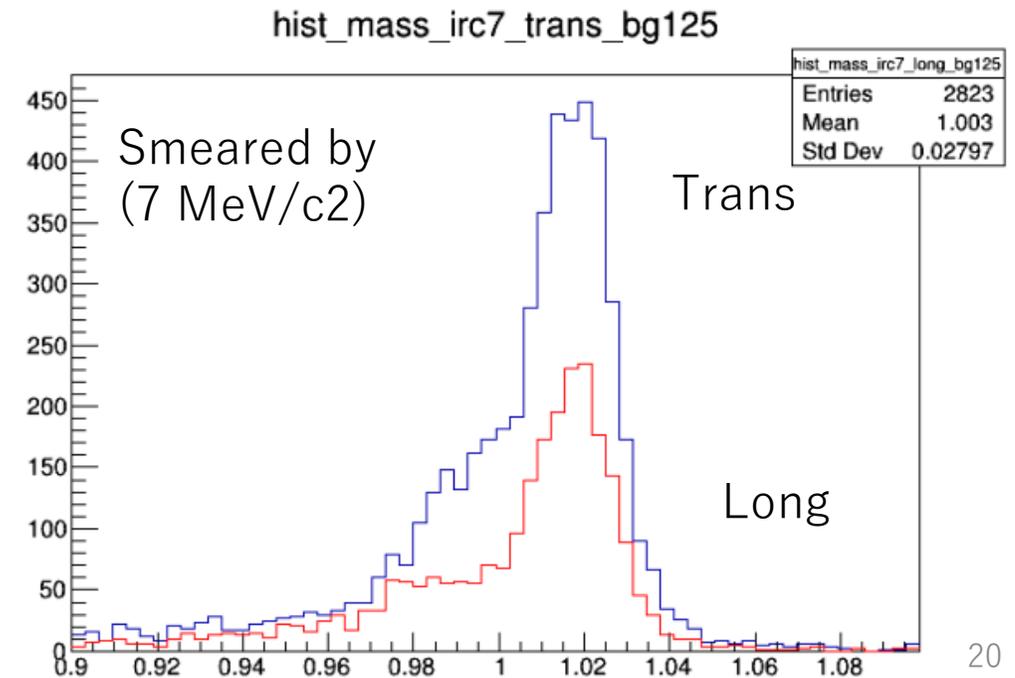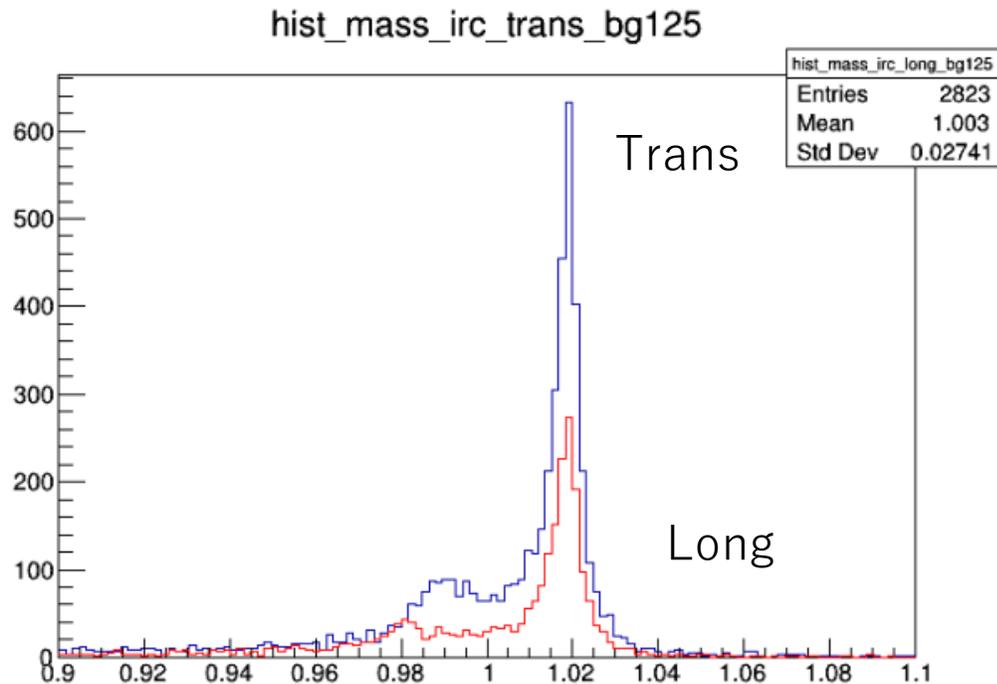
Basic idea: find orthogonal func. (to extract T. mass)

- $G(m, x)$: Measured mass (m) and angle ($x = \cos\theta$) distribution:

$$G(m, x) = g_T(m) f_T(x) + g_L(m) f_L(x)$$

Measured   Want to know   Known   Want to know   Known

- $g_{T,L}(m)$: Mass distribution for T and L.
- $f_{T,L}(x)$: Daughter particle's angular distribution for T and L.

$$f_T(x) \propto (1 + x^2)$$
$$f_L(x) \propto (1 - x^2).$$

- If we can find a function $h_T(x)$ that is orthogonal to $f_L(x)$
  - $h_T(x)$: eliminates L and what's left is T.

$$\int_a^b h_T(x)\, G(m, x) = h_T(x)\, g_T(m) f_T(x) + h_T(x)\, g_L(m) f_L(x)$$

Measured   Want to know   Known   Want to know   Known

$$\int_a^b G(m, x) h_T(x) dx = \int_a^b \left[g_T(m) f_T(x) h_T(x) + g_L(m) f_L(x) h_T(x) \right] dx$$
$$= g_T(m) \int_a^b f_T(x) h_T(x) dx$$
$$= g_T(m) \times \text{Const.}$$

21

Finding orthogonal functions

- The Gram-Schmidt's method:
  - Assume we have $\alpha_1(x), \alpha_2(x)$ and build two functions:

$$\alpha_1$$

$$\alpha_2 - \frac{\langle \alpha_1 \cdot \alpha_2 \rangle}{\langle \alpha_1 \cdot \alpha_1 \rangle} \alpha_1$$

Orthogonal to each other.

$$\langle \alpha_1 \cdot \alpha_2 \rangle = \int_a^b \alpha_1(x) \alpha_2(x) dx$$

  - $h_L(x)$: (orthogonal to f_T = eliminates T) extracts L.
  - $h_T(x)$: (orthogonal to f_L = eliminates L) extracts T.

$$x = \cos\theta = [-1,1]$$

$$f_T = 1 + x^2$$
$$f_L = 1 - x^2$$
$$h_T = 5x^2 - 1$$
$$h_L = 2 - 5x^2$$

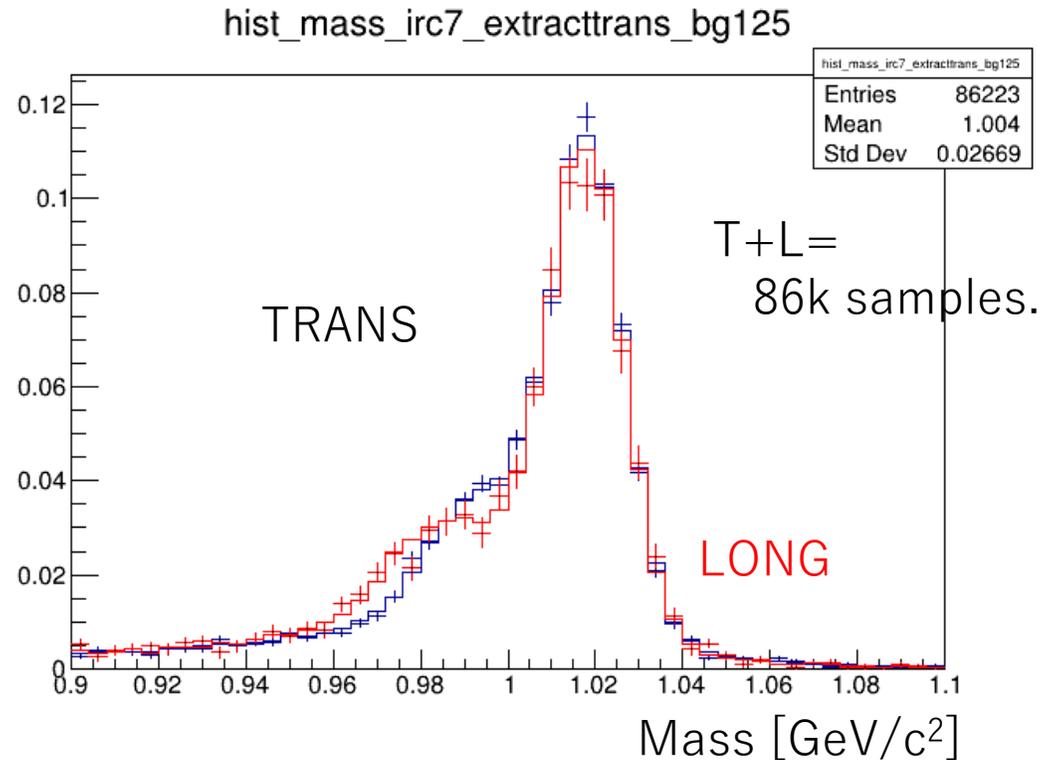$$x = \cos\theta = [-0.8, 0.8]$$

$$f_T = 1 + x^2$$
$$f_L = 1 - x^2$$
$$h_L = 3.1897 - 13.108x^2$$
$$h_T = 13.1077x^2 - 2.18963$$

The method applied. for $\beta\gamma<1.25$ sample.

- $\cos\theta = [-1,1]$
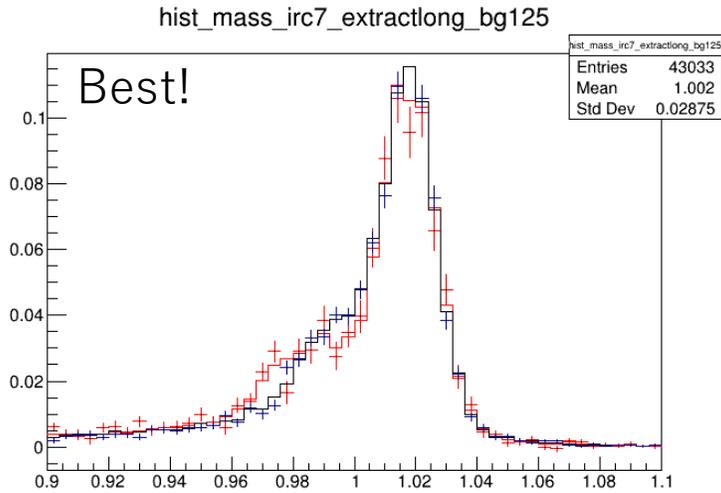
- $\cos\theta = [-0.8,0.8]$
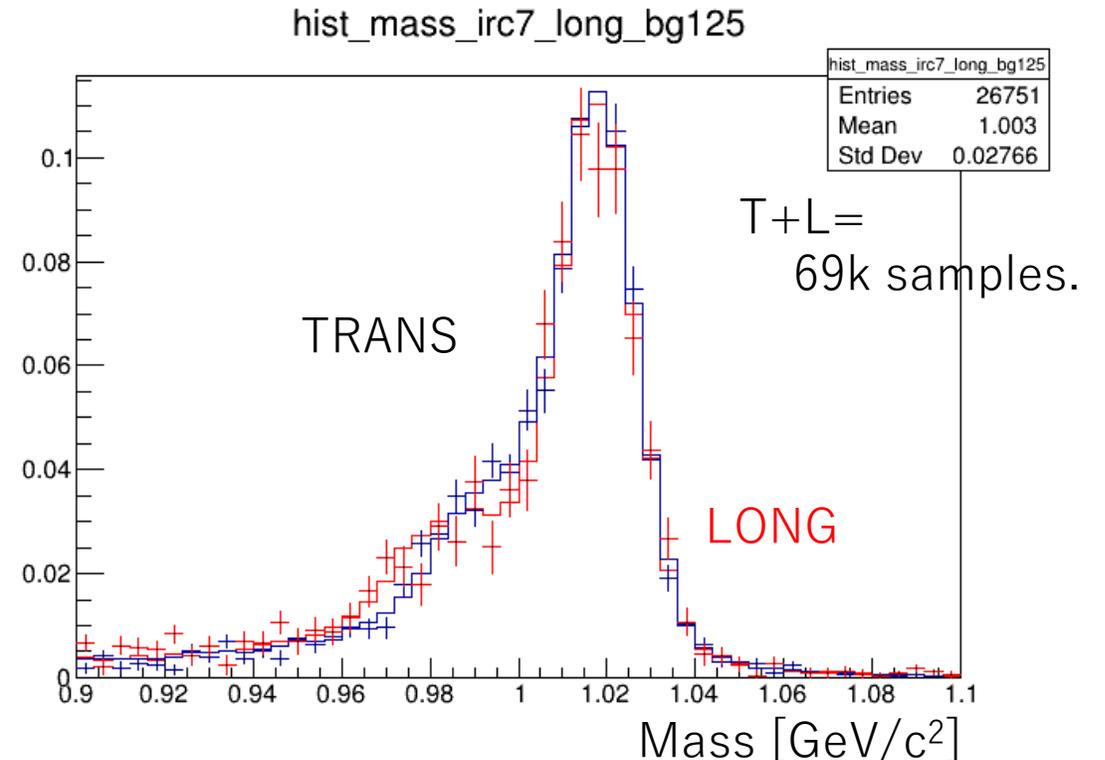
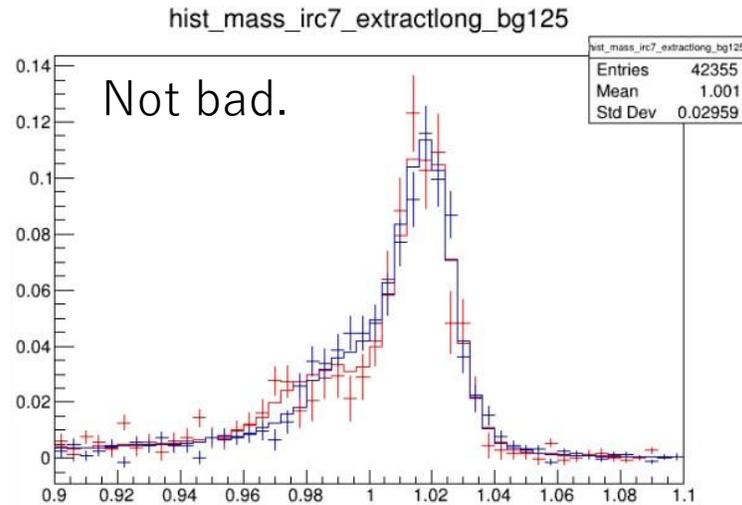LINE   : According to polarization information which God only knows
+   : Extracted using the orthogonal functions $h_T(x), h_L(x)$

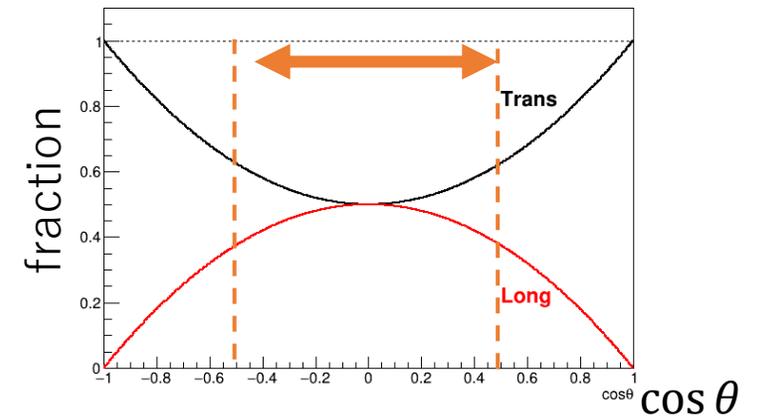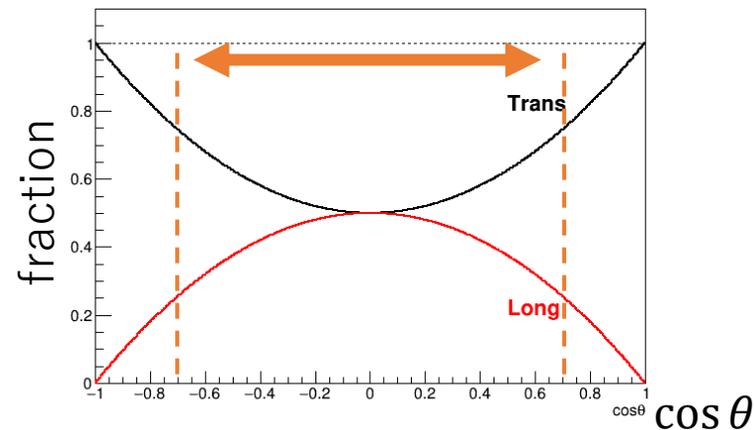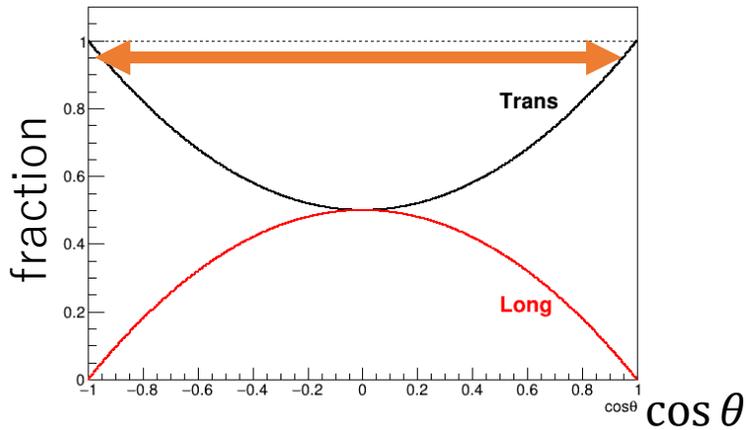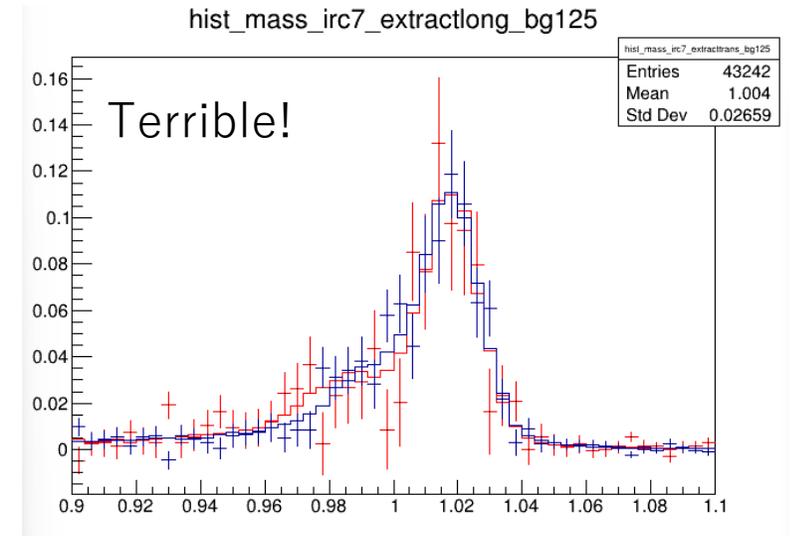# Same statistics but different angular acceptance in the rest frame of ϕ.

- $\cos\theta = [-1,1]$
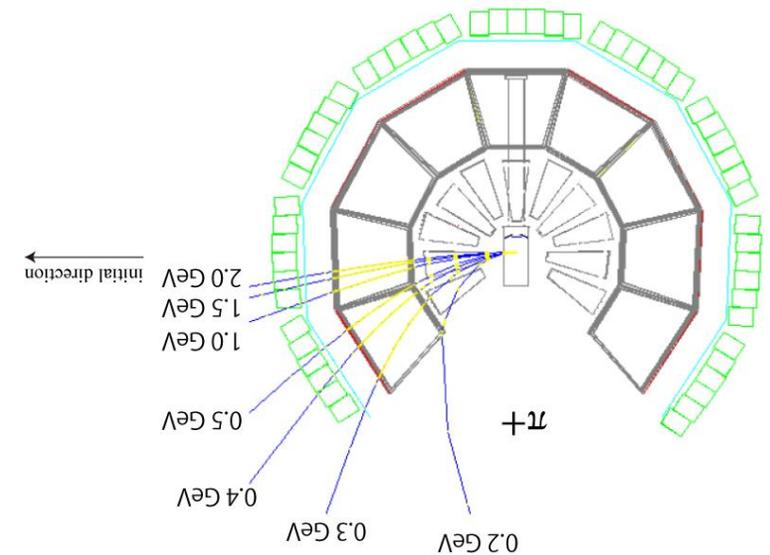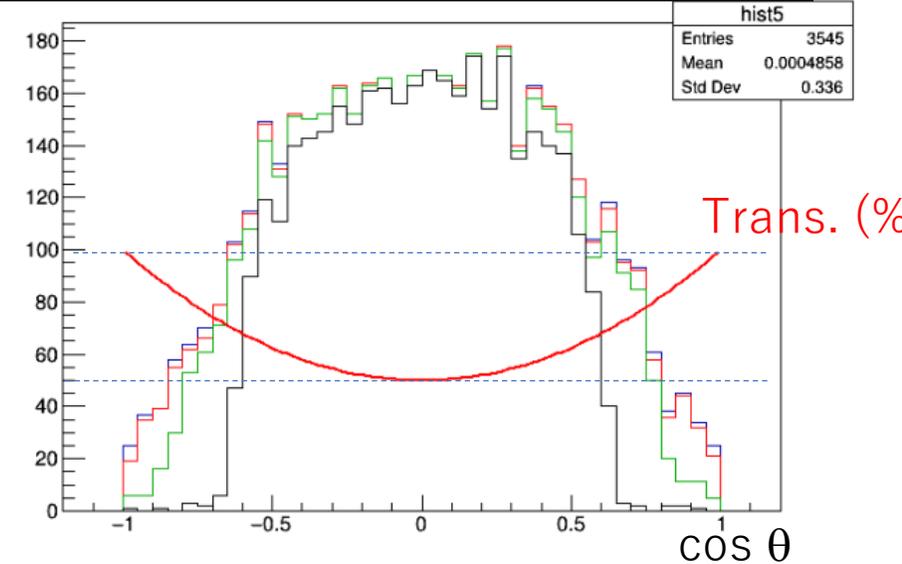- $\cos\theta = [-0.7,0.7]$
- $\cos\theta = [-0.5,0.5]$

Angular acceptance of ϕ. E16 case.

- GEANT4 as an acceptance filter.

- Results
  - Smaller acceptance for $\cos\theta = \pm1$
  - LG trig eff ~90% 0.4GeV, ~75% 0.3GeV
  - Reality is between Green and black.

- Needs acceptance correction for analysis.

- $\cos\theta = [-0.7, 0.7]$ maybe used w/ correction but rather marginal.

- More compact configuration to catch and PID low momentum particles is necessary.

In the acceptance & phi mom<1.25 & e+- momentum cut

none
>0.2
>0.3
>0.4

Trans. (%

hist5
Entries	3545
Mean	0.0004858
Std Dev	0.336

$\cos\theta$

initial direction
2.0 GeV
1.5 GeV
1.0 GeV
0.5 GeV
0.4 GeV
0.3 GeV
0.2 GeV
$\pi+$

Summary

- J-PARC E16 will measure e+e- spectra in pA collisions at 30GeV to investigate spectral change of vector mesons in medium.

- We gradually increased our acceptance and reached an intermediate goal (RUN1), which is 1/3 of the design configuration(RUN2).

- Commissioning run on April 19-June 3 ended successfully.

- Based on the outcome, we request PAC approval for Run1

- Possibility of measuring polarization dependence of phi meson in medium.
  - E88 (KK) performs better in terms of pol measurement in current setup.
  - Complimentary each other.