Experimental study of the hadron mass via vector meson production in pA collisions at J-PARC

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KEK / J-PARC

Workshop on recent developments from QCD to nuclear matter

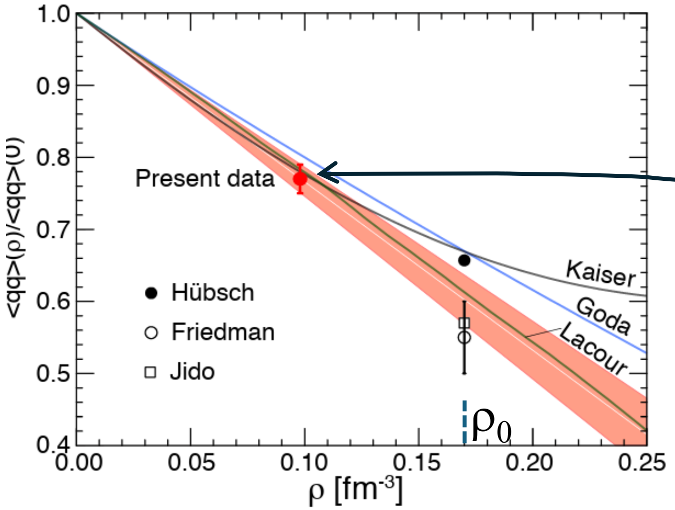
2025.12.17

Physics motivation

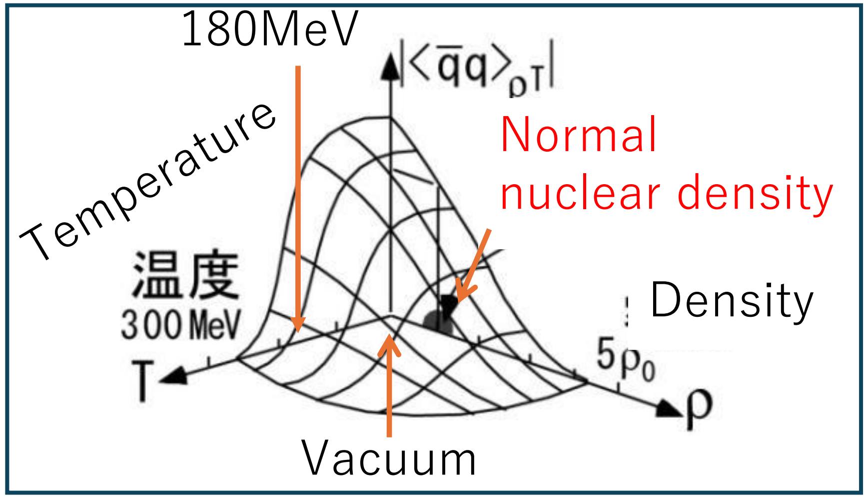
♪ Hadrons ♪
Elementary Excitation of QCD

- The origin of Hadron mass.
- The study of QCD vacuum
  - **Spontaneous breaking of the chiral symmetry.**
    - An order parameter: $\langle \bar{q}q \rangle \neq 0$
    - $\langle \bar{q}q \rangle$ 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***? →Want to use ϕ as probe, who is $s\bar{s}$

$$\frac{\langle \bar{q}q \rangle(\rho)}{\langle \bar{q}q \rangle(0)}$$



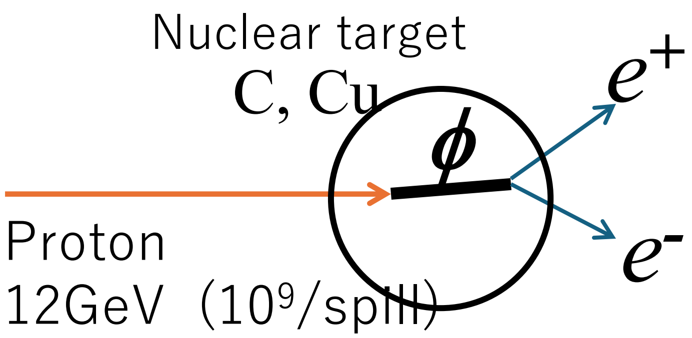
Deeply bound pionic atom
Nature Phys. 19, 788 (2023)

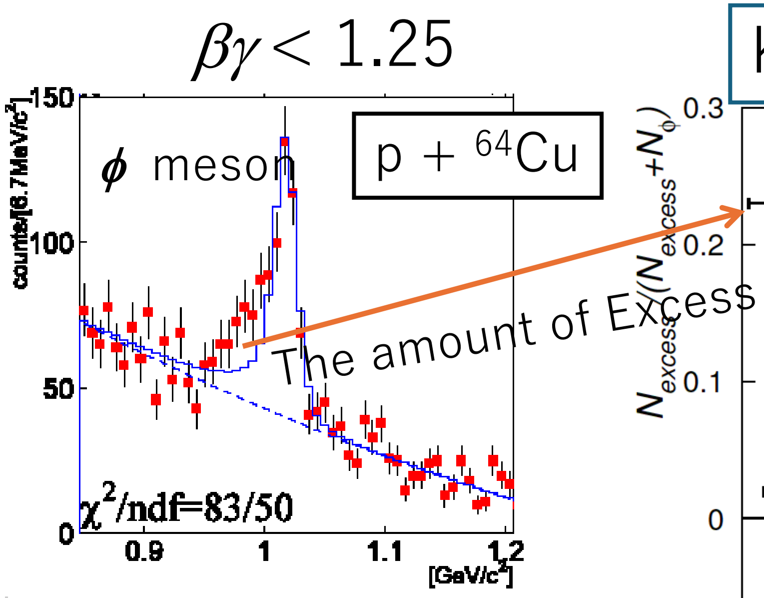


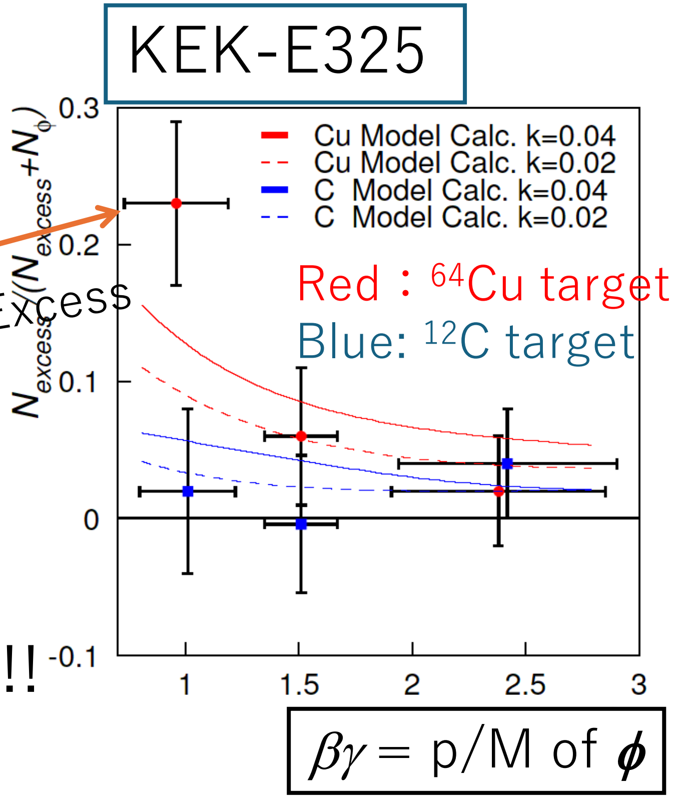
NJL model : M. Lutz et al.
Nucl. Phys. A542,52(1992)

KEK-E325 results of ϕ meson

- The world's first results of ϕ modification.







- **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: $\times 3.6^{+1.8}_{-1.2}$

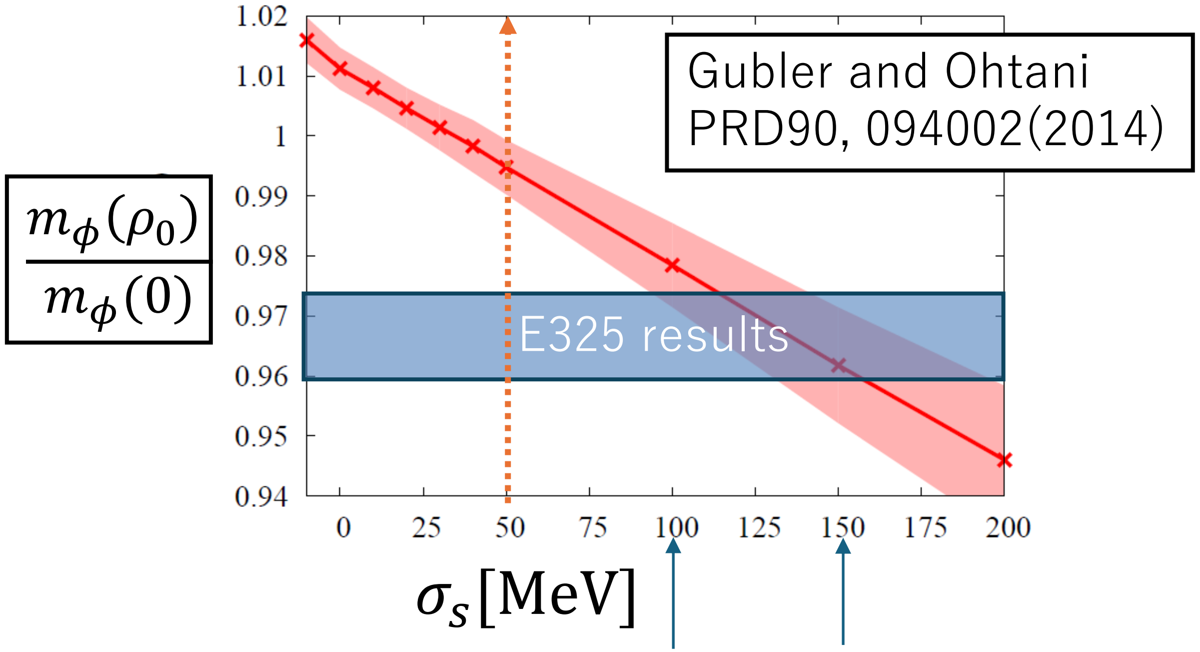
Assumption
In analysis

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

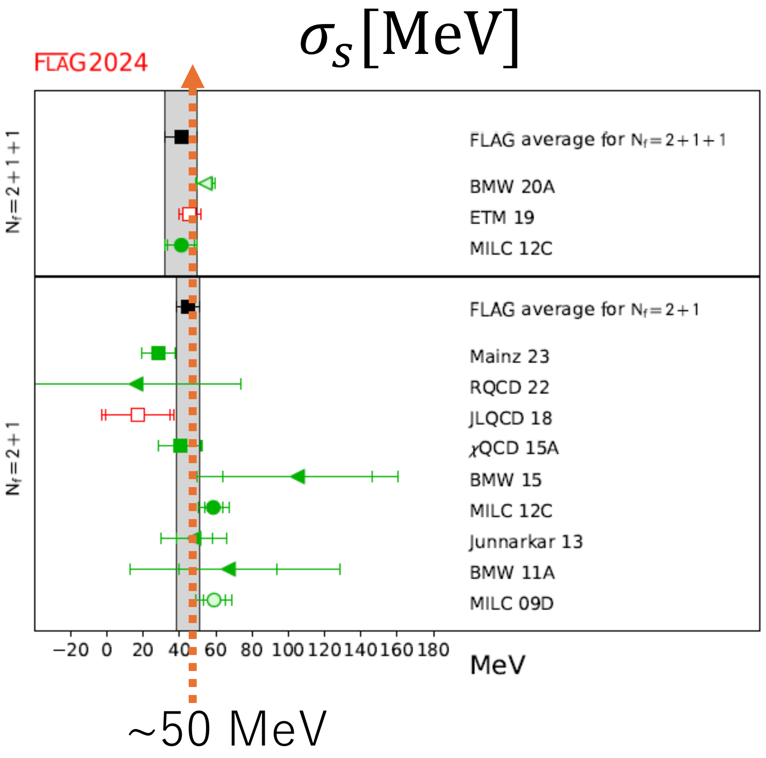
$$\frac{\Gamma(\rho)}{\Gamma(0)} = 1 + k_2\left(\frac{\rho}{\rho_0}\right)$$

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.



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



$$\langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \frac{\sigma_s}{m_s}\rho$$

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

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

p-ϕ attractive interaction
→ effective potential for ϕ in nuclei
→ mass reduction

- Mass reduction
  - HAL : 5.3% ± 0.4%
  - ALICE : 5.8% ± 1.8%
  - ALICE-HAL: 1.3~9.0%
  - CLAS γ+p : 0.5%

  - E325 : 3.4% $^{+0.6}_{-0.7}$

nucl-ex/0306011(2003) and E. Chizzali, R. Del Grande, L. Fabbietti

f_0, d_0 → First order optical potential

$$V(r) \sim \frac{1}{2m_\phi} 4\pi\rho(r) \frac{b}{1+\frac{b}{d_0}}, \quad b = f_0\left(1+\frac{m_\phi}{m_{proton}}\right)$$

arXiv: 2212.12690:

$$E_B \simeq \frac{1}{2\mu d_0^2}\left(1-\sqrt{1+2\frac{d_0}{f_0}}\right)^2, \quad E_B \simeq 13.6\text{-}92.0 \text{ MeV},$$

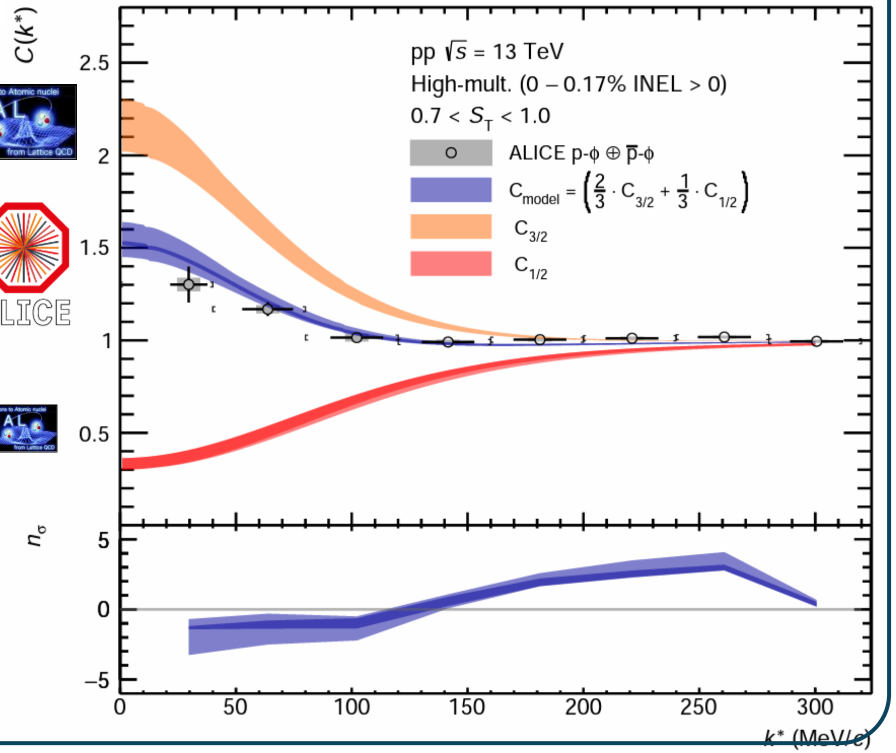
arXiv: 2212.12690 femtoscopy

spin

$\frac{3}{2}$

$\frac{3}{2}, \frac{1}{2}$

$\frac{1}{2}$



HAL QCD method, arXiv:2205.10544 (2022)

$a_0^{(3/2)} = -1.43(23)$ fm

$r_0^{(3/2)} = 2.36(10)$ fm

γ+p
PhysRevC.101.045201
|a|=0.063 ± 0.010 fm

ALICE: Phys. Rev. Lett. 127, 172301(2021)

$d_0 = 7.85 \pm 1.54$ (stat.) ± 0.26 (syst.) fm

$\Re(f_0) = 0.85 \pm 0.34$ (stat.) ± 0.14 (syst.) fm

$\Im(f_0) = 0.16 \pm 0.10$ (stat.) ± 0.09 (syst.) fm

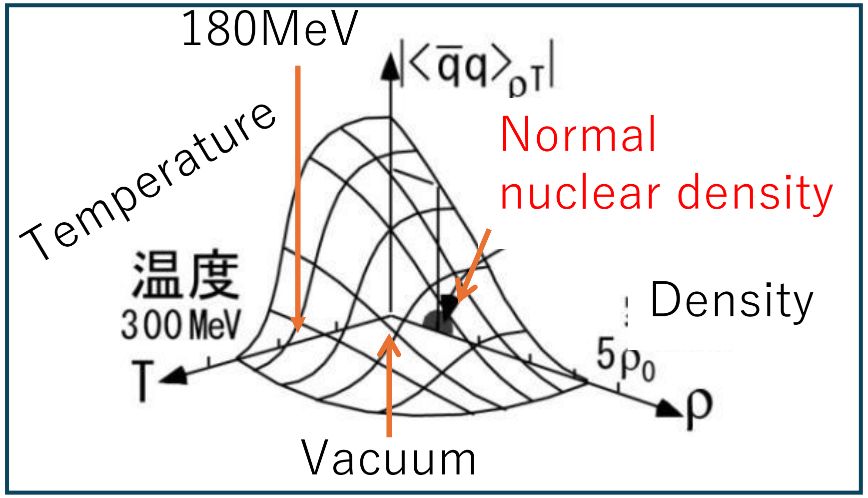
ALICE-HAL: arXiv: 2212.12690

$$\text{Re } f_0^{(1/2)} = -1.47^{+0.44}_{-0.37}(\text{stat.})^{+0.14}_{-0.17}(\text{syst.}) \text{ fm},$$

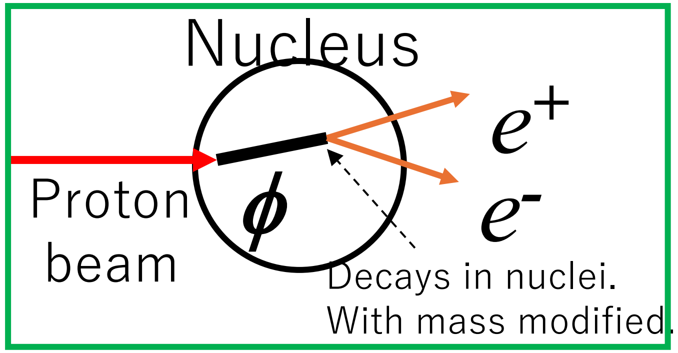
$$\text{Re } d_0^{(1/2)} = +0.37^{+0.07}_{-0.08}(\text{stat.})^{+0.03}_{-0.03}(\text{syst.}) \text{ fm},$$

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.

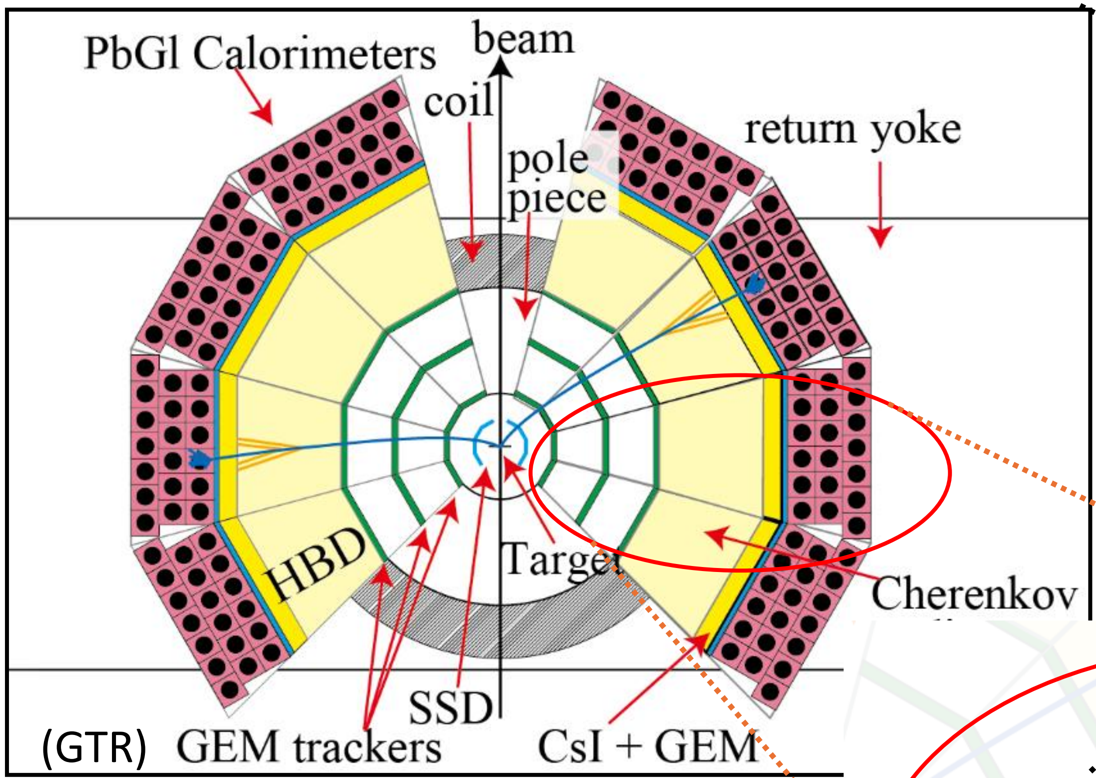


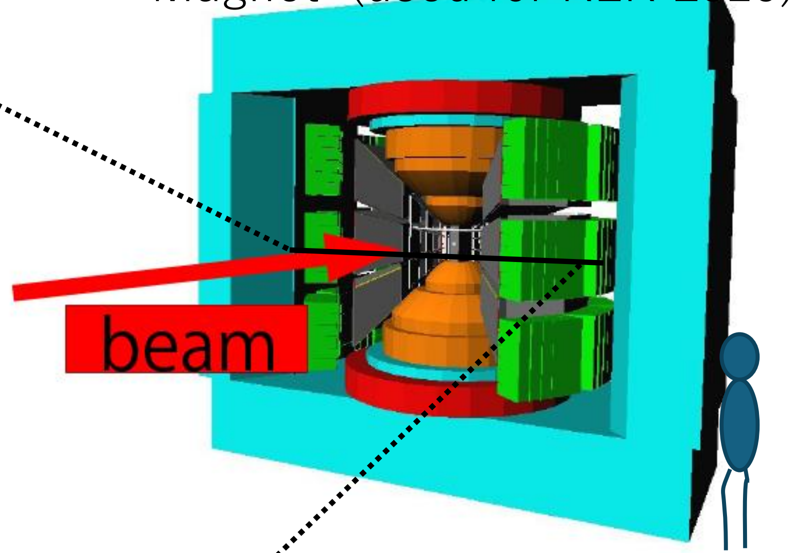
NJL model
M. Lutz et al.
Nucl. Phys. A542,52(1992)

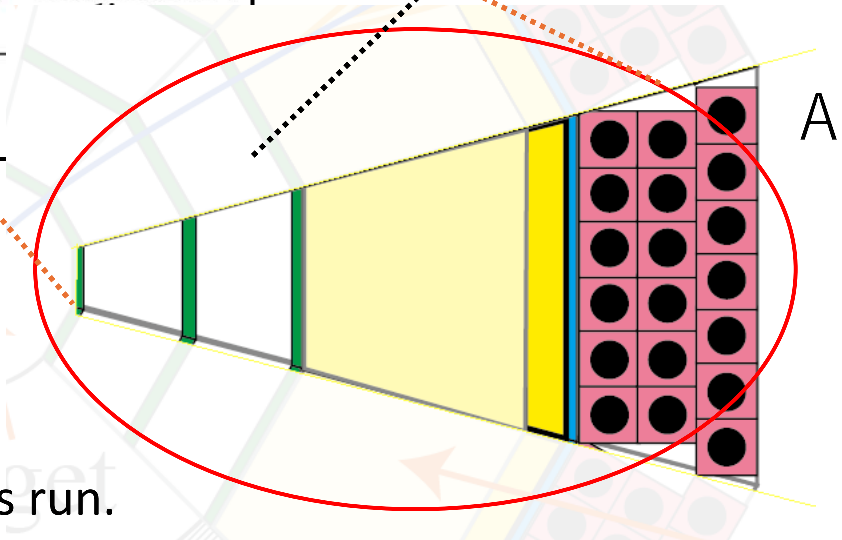


J-PARC E16

The J-PARC E16 spectrometer



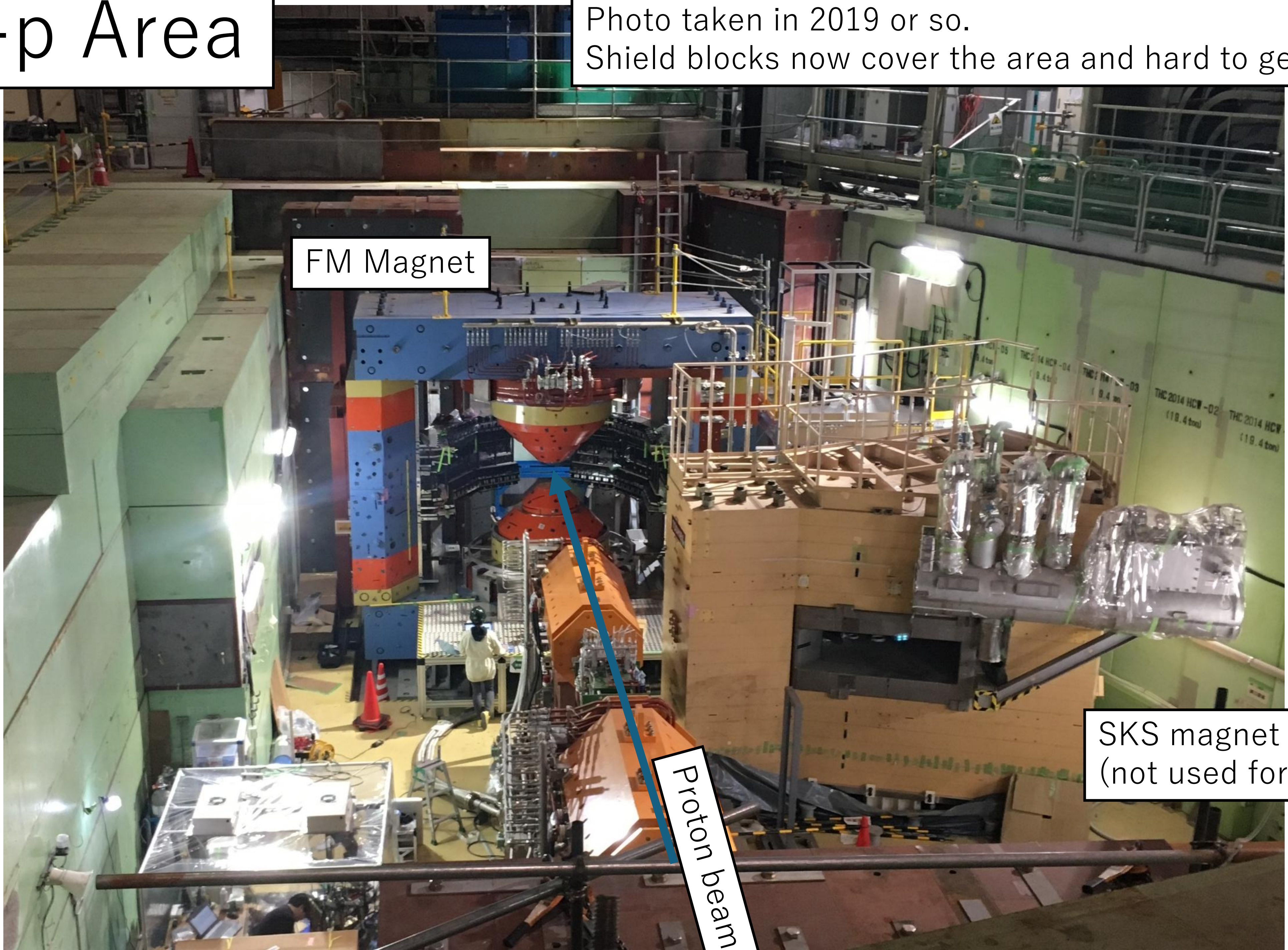


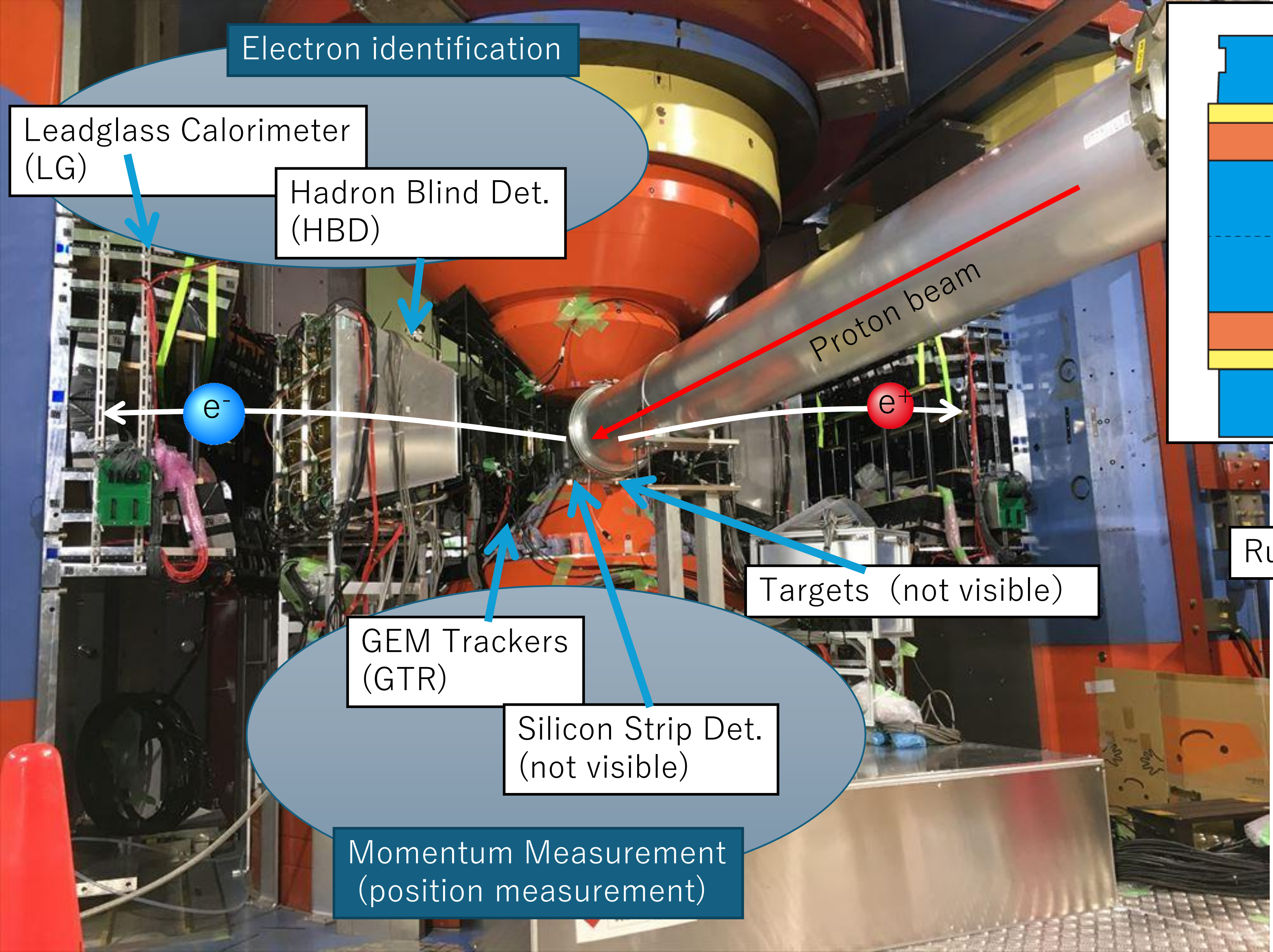


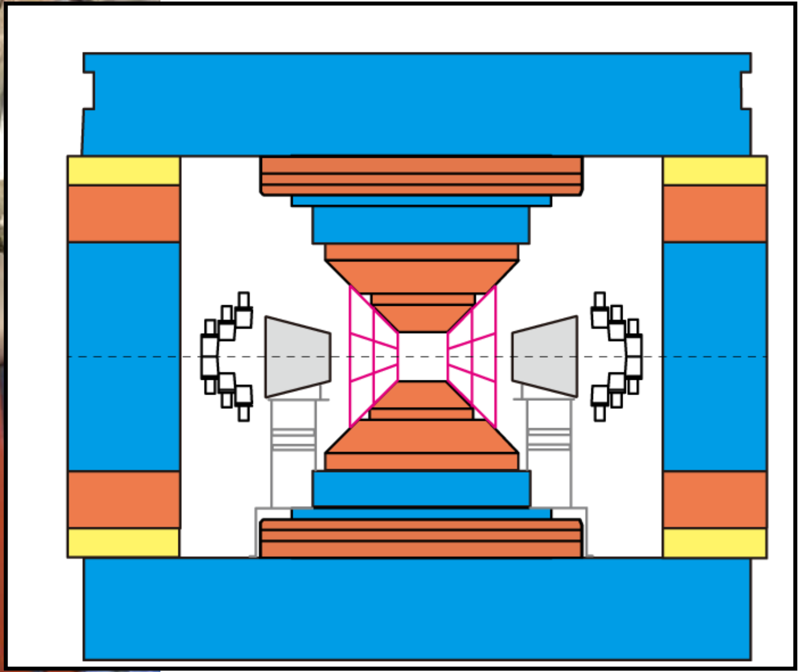
STS : Tracking (SSD)
GTR : Tracking (GEM Tracker)
HBD : eID (Cherenkov)
LG : eID (Calorimeter)
26 modules in total. 8 for the 1st physics run.

High-p Area

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







Run0b/c configuration(2021)

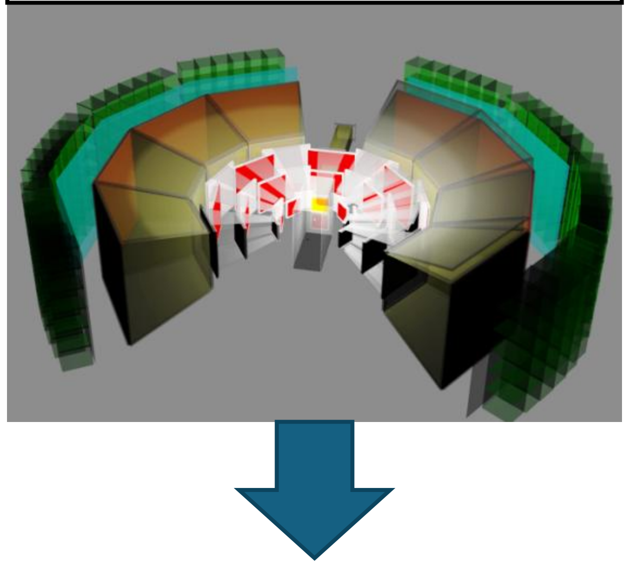
J-PARC E16 Collaboration

- 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

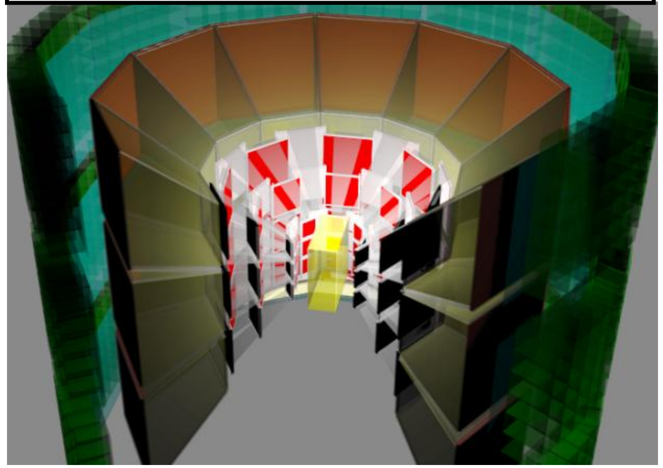
Staging approach

- **RUN 0a/b/c/d/e - 2020,2021,2023,2024**
  - **10 (SSD) + 8 (GTR) + 8 (HBD) + 8 (LG)**
  - C+Cu targets
  - Beamline and detector commissioning
  - Gradually increased acceptance and reached interm. Goal. Detector and DAQ upgrade.
- **RUN 1 2025- (started!)**
  - **10 (SSD) + 8 (GTR) + 8 (HBD) + 8(LG)**
  - C+Cu targets
  - Physics data taking. ϕ : 15k for Cu.
  - Run1a: Nov 2025 (160h), Run1b: Apr. 2026...
- **RUN2**
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - + Pb/CH2 target
    - New target chamber being developed.
  - Real SSD chamber design underway (Kakenhi)
  - Needs additional budget for construction of detectors.

RUN 1 (8 modules)

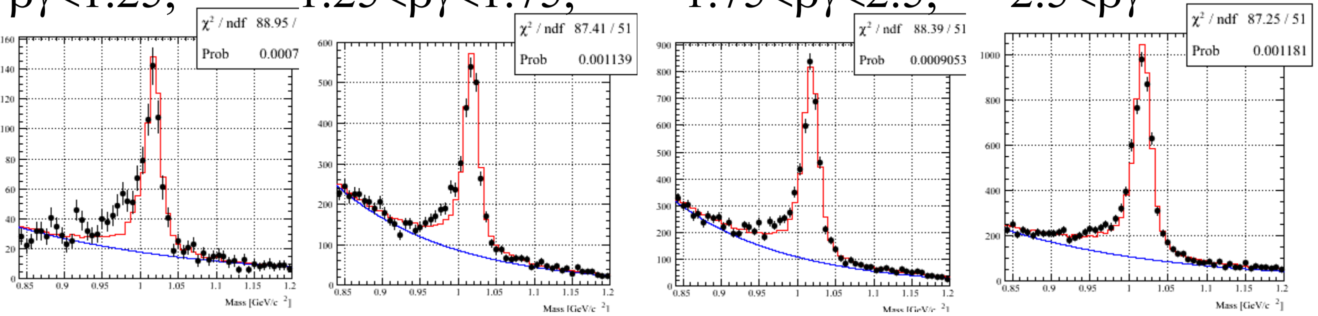


RUN 2 (26 modules)



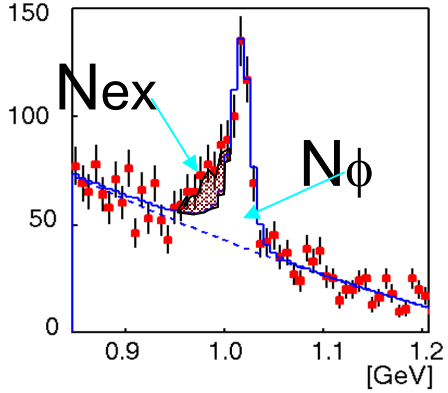
RUN1, Cu (INPUT:E325-BW) Excess ratio vs $\beta\gamma$

βγ<1.25, 1.25<βγ<1.75, 1.75<βγ<2.5, 2.5<βγ

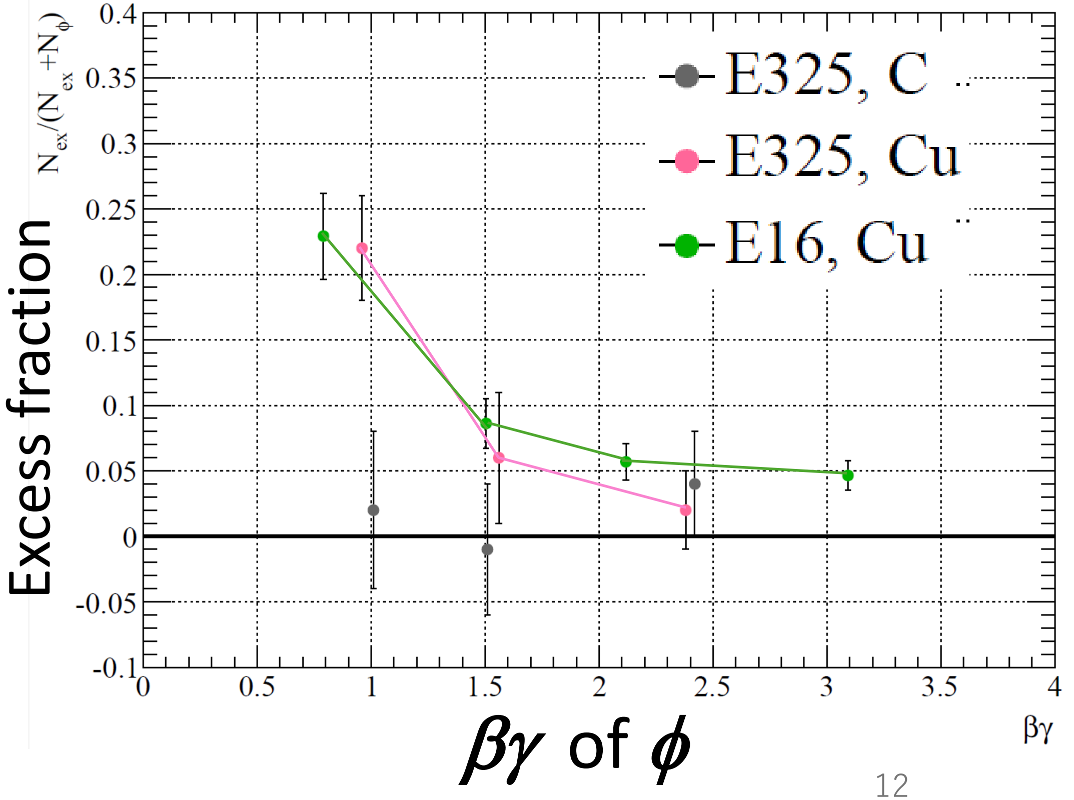


(Fit fails when vacuum shapes are used.)

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



- ~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.



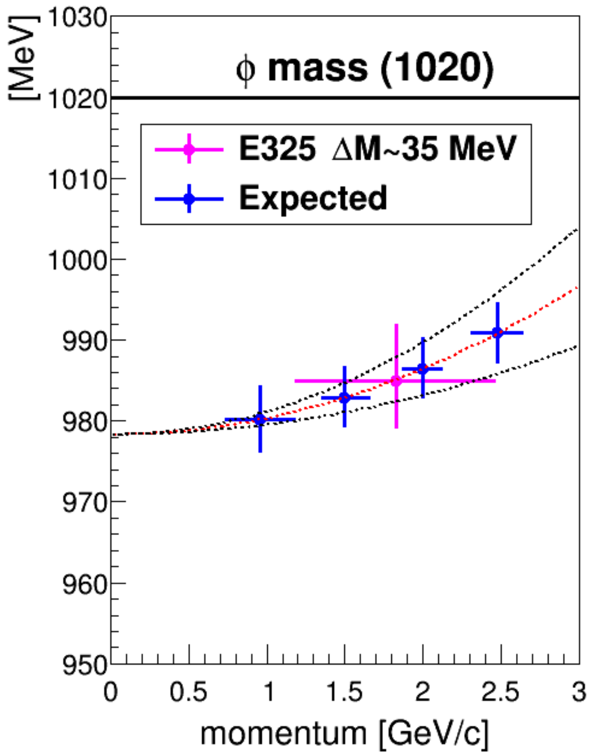
- Larger excess in lower $\beta\gamma$ bin.
- The tendency becomes clearer and more significant compared to E325.

Momentum dependence (Dispersion relation)

- Momentum dependence of mass can be obtained for the first time.
- Expectation of RUN1 x 1.7 is shown.

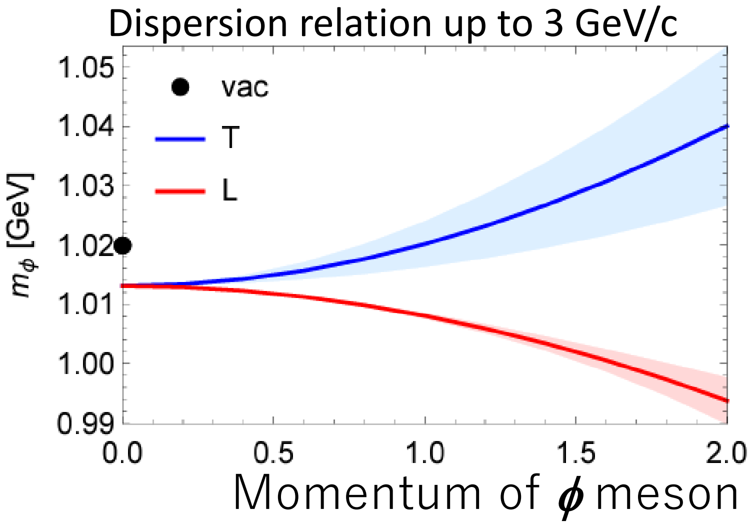
- Dispersion relation itself is an important property of pseudo particles.
- We can extrapolate mass into 0 momentum

- Calculation predicts polarization dependence. Can be accessed using angular distribution.



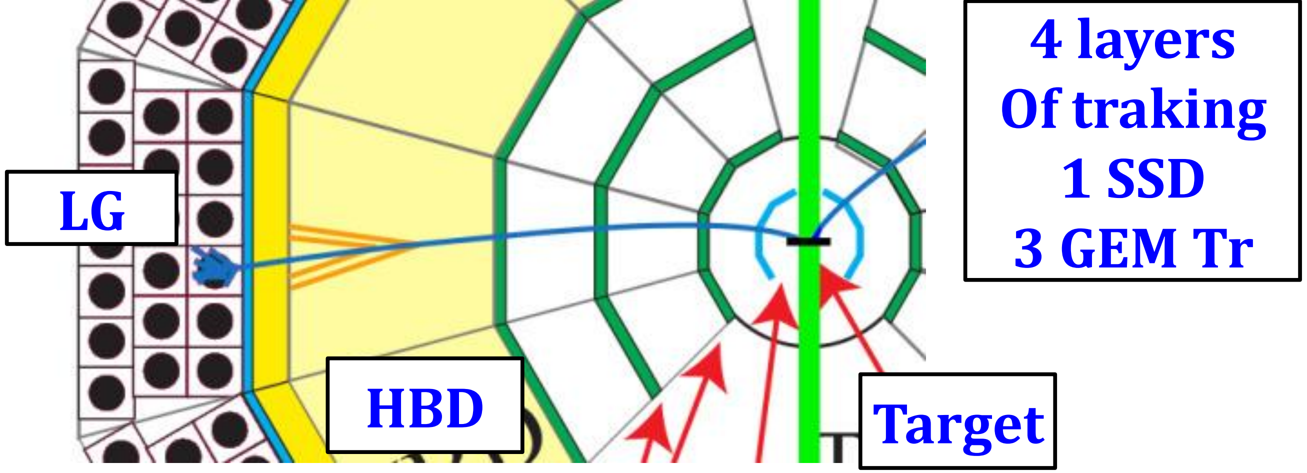
S.H. Lee PRC57, 927(1998)
Curve valid up to 1GeV, extrapolated.
Adjusted to match with E325 results.
E16 expectation overlayed with transversely polarized case.

H. Kim P. Gubler extends the validity of momentum range.

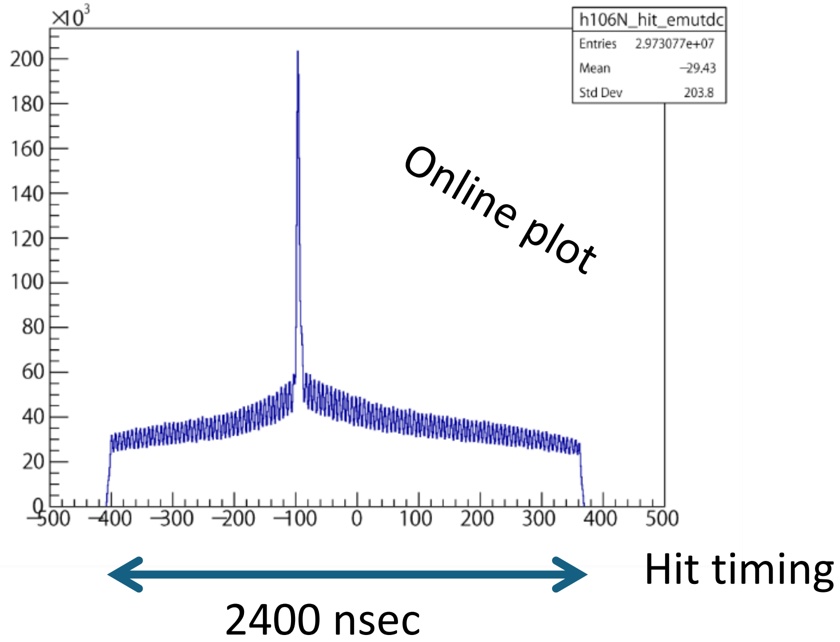


H.J. Kim, P. Gubler, PLB805, 135412 (2020)

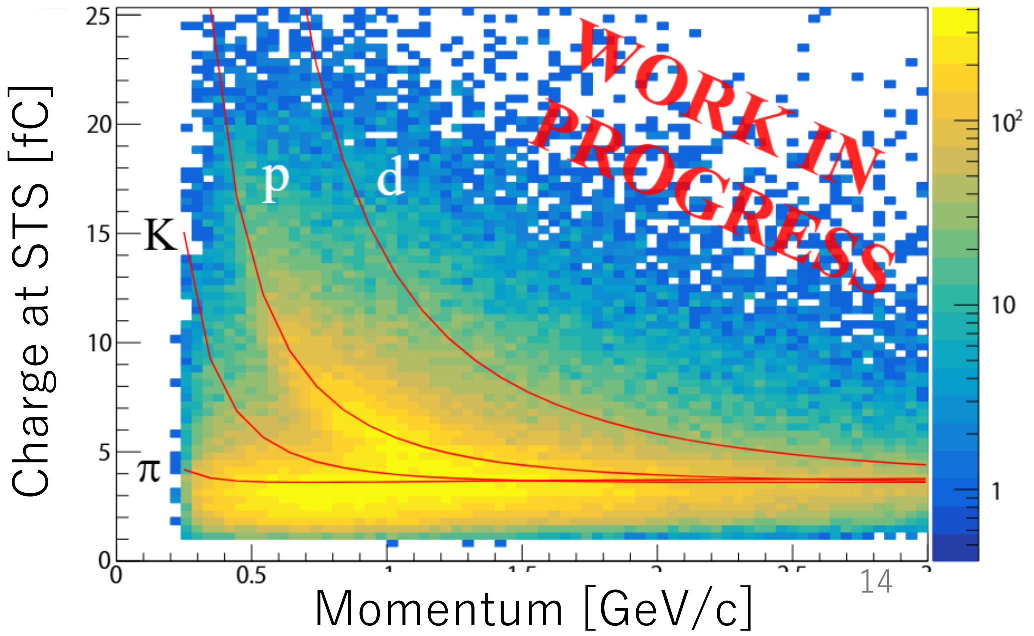
J-PARC E16 from commissioning run.



- Innermost tracking device, STS (Silicon Tracking System), was developed in collaboration with GSI-CBM. Installed in later stage.
- Originally developed as streaming-DAQ, adopted to be able to online-select hits in coincidence with E16 trigger.

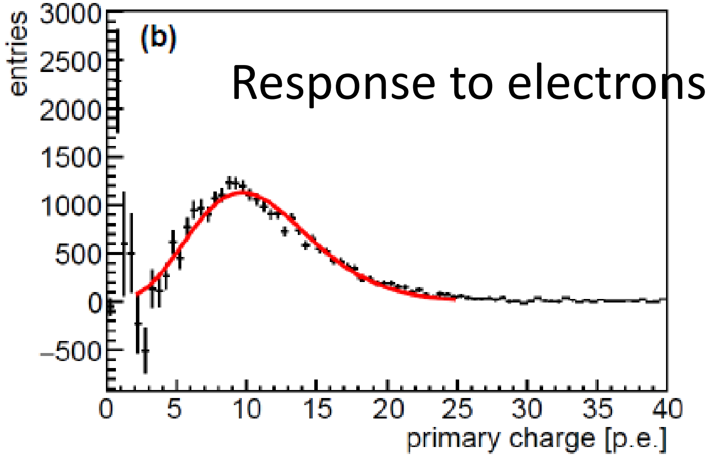


- Tracking: 1-layer of Silicon detector and 3-layers of GEM tracker.
- Clear proton locus. Demonstrating successful operation.

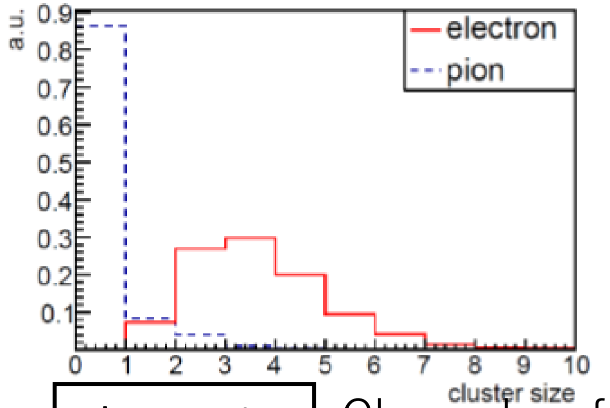


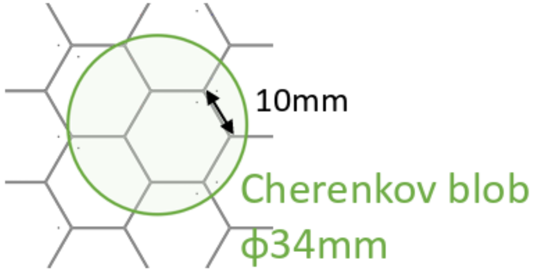
J-PARC E16
from commissioning run.

Hadron Blind Detector (Cherenkov detector)



NIM A 1082, 170956 (2026)



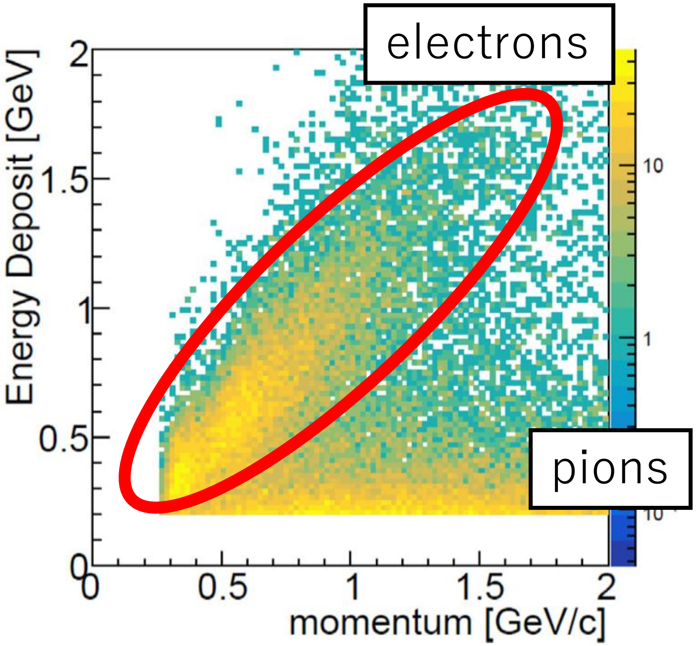


Cluster size

Cherenkov from e spreads
While residual signal from pion does not

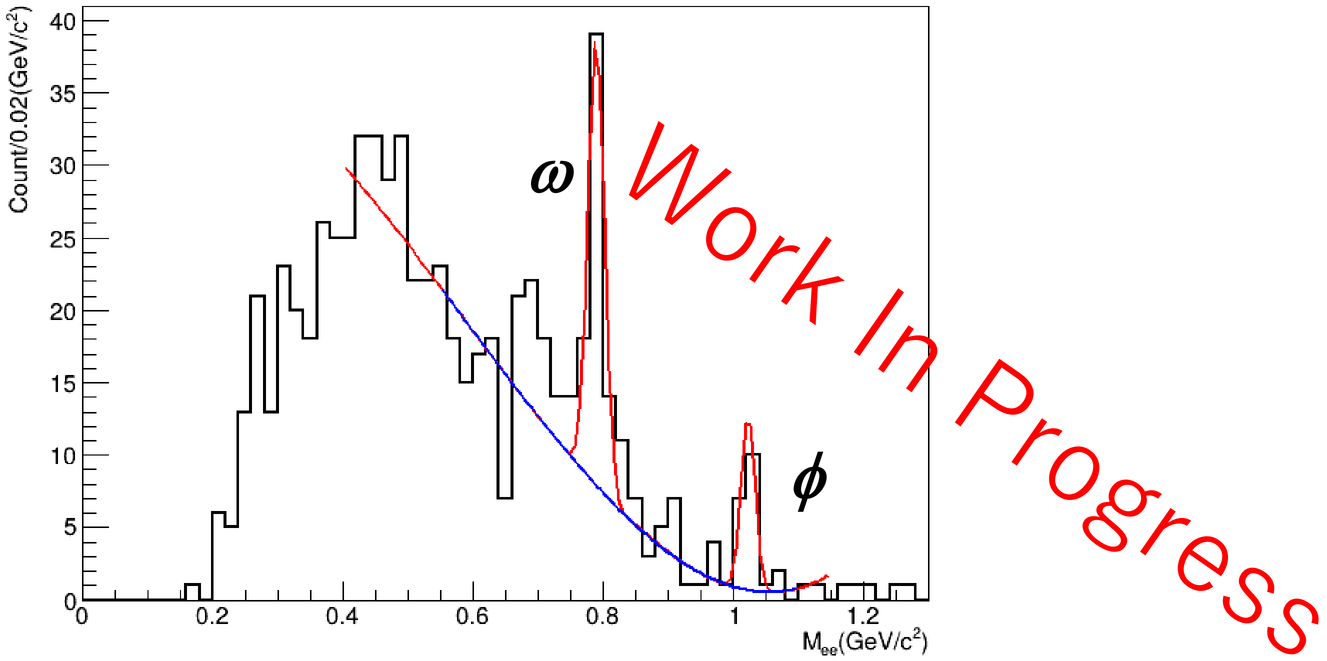
LG (Leadglass Calorimeter)

- Hadron Blind Detector (Cherenkov detector) was used to enhance electrons in making the plot below.
- Clear Momentum vs Energy (deposit on LG calorimeter) correlation of electron seen.



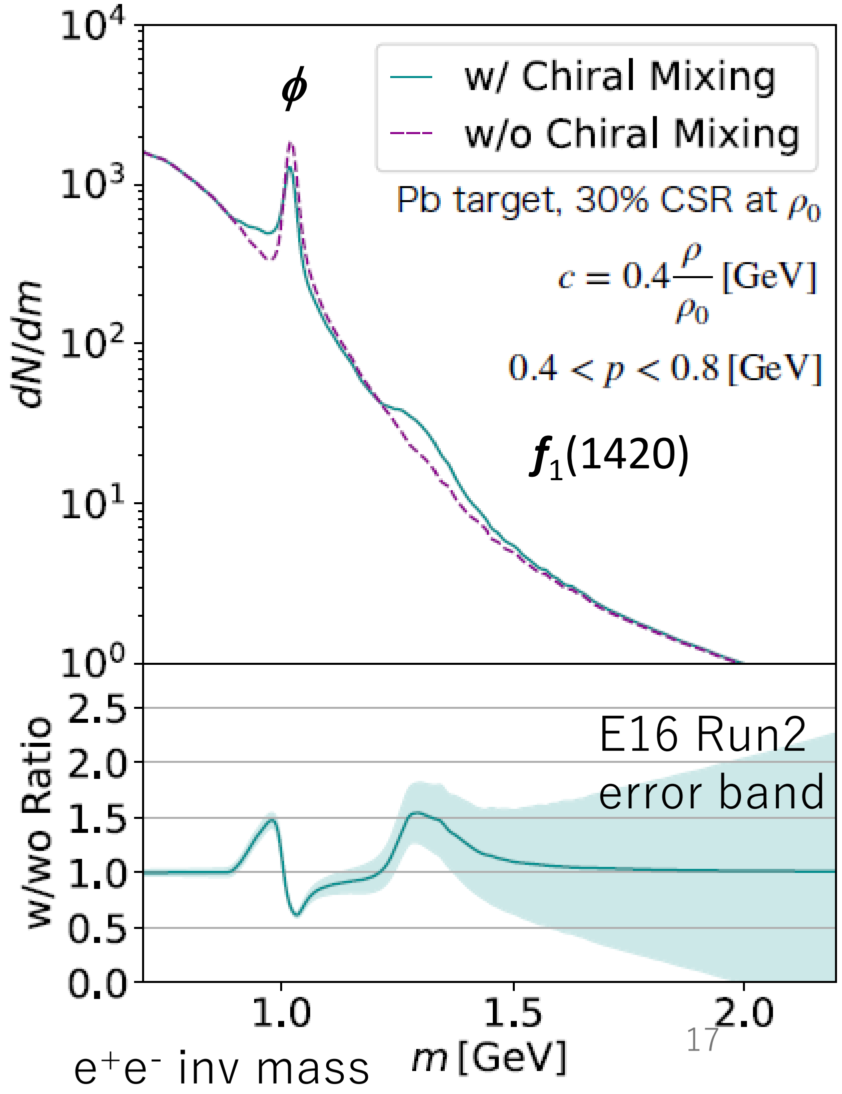
Invariant mass spectrum of e+e-

- 1st physics paper to be submitted very soon.
  - Discussing on mass number dependence of production cross section.
- We continue data taking…



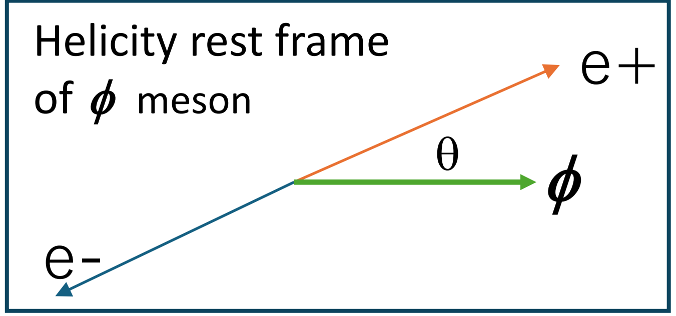
Anomaly-induced chiral mixing of ϕ and $f_1(1420)$

- Chiral partner
  - Genuine signal of chiral symmetry restoration: Degeneracy of chiral partner!
  - ϕ and $f_1(1420)$ are parity partner.
    - (Part of their components are chiral partners.)
- Phys. Rev. D106, 5 (2022) C. Sasaki
  - Chiral mixing effect in dense matter can be seen in e^+e^- channel.
  - T(Transverse) affected. L(Longitudinal) stays.
- Phys. Rev. C111, 055201 (2025) R. Ejima et al.
  - PHSD transport calculation → realistic estimate of E16 Run2 sensitivity
    - Sensitivity depends on
      - Unknown strength of mixing
      - Degrees of chiral symmetry restoration



Polarization ←→ angular dist.

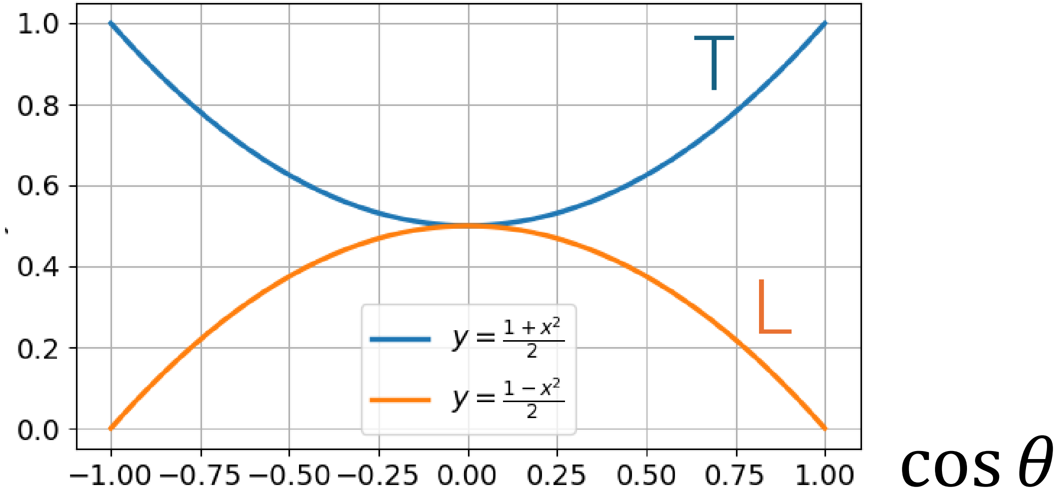
I.W. Park, H. Sako, K. A., P. Gubler, and S.H. Lee PRD 107, 074033 (2023)



Pol of ϕ : $|1,1\rangle$, $|1,-1\rangle$, $|1,0\rangle$

Transverse Longitudinal

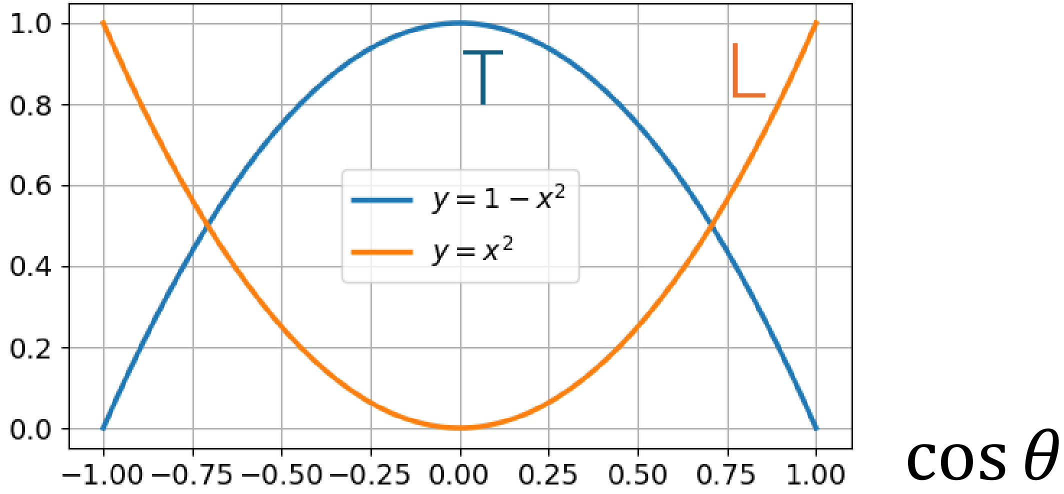
$\phi \rightarrow e^+e^-$, pol carried by spin of e^+e^- pair $|1,1\rangle$, $|1,-1\rangle$



T $d^1_{1,1} = \frac{1+\cos\theta}{2}$ $d^1_{1,-1} = \frac{1-\cos\theta}{2}$

L $d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$

$\phi \rightarrow K^+K^-$, pol carried by OAM of KK



T $Y_1^1 = -\sqrt{3/8\pi}\sin\theta$ $Y_1^{-1} = \sqrt{3/8\pi}\sin\theta$

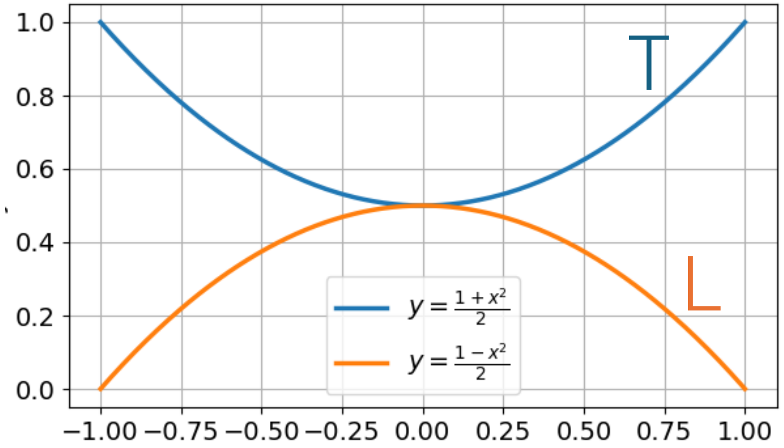
L $Y_1^0 = \sqrt{3/4\pi}\cos\theta$

Polarization ←→ Angular dist.

$\phi \rightarrow e^+e^-$

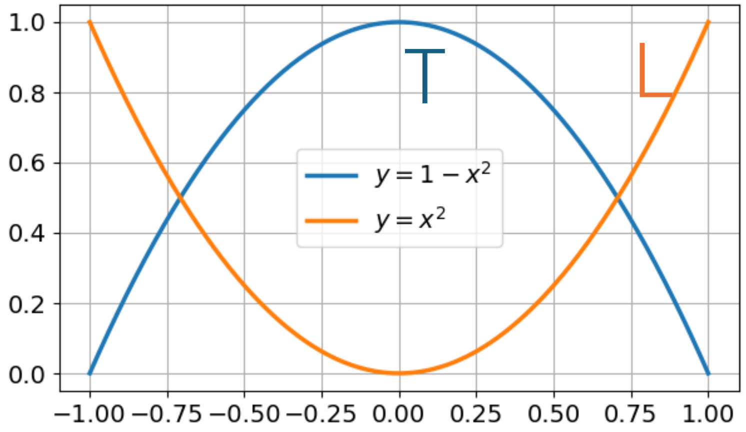
- Small FSI ← This is why E16 is good.
- Spin 1 is carried by ee pol.
  - $\cos\theta = \pm 1$: T 100%
  - $\cos\theta = 0$: L 50%, T 50%
- Small acceptance for $\cos\theta = \pm 1$
- Small BR (2.98×10^{-4})
  - 15k (E16 Run1)

Experimental separation challenging.
Refer K. Aoki et al, JSPC 3, 100019 (2025)

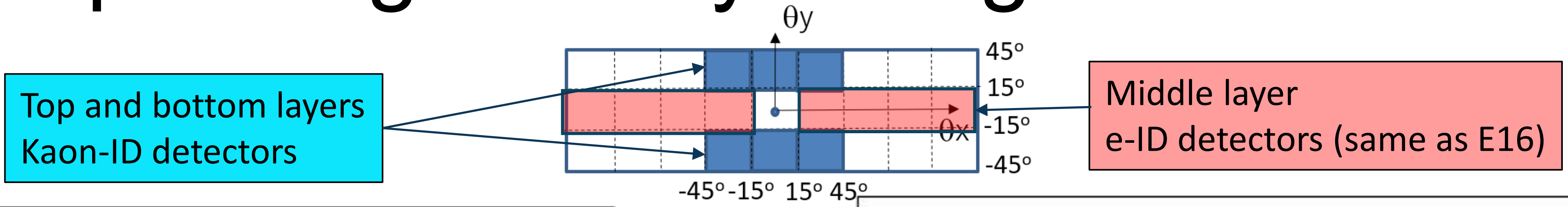


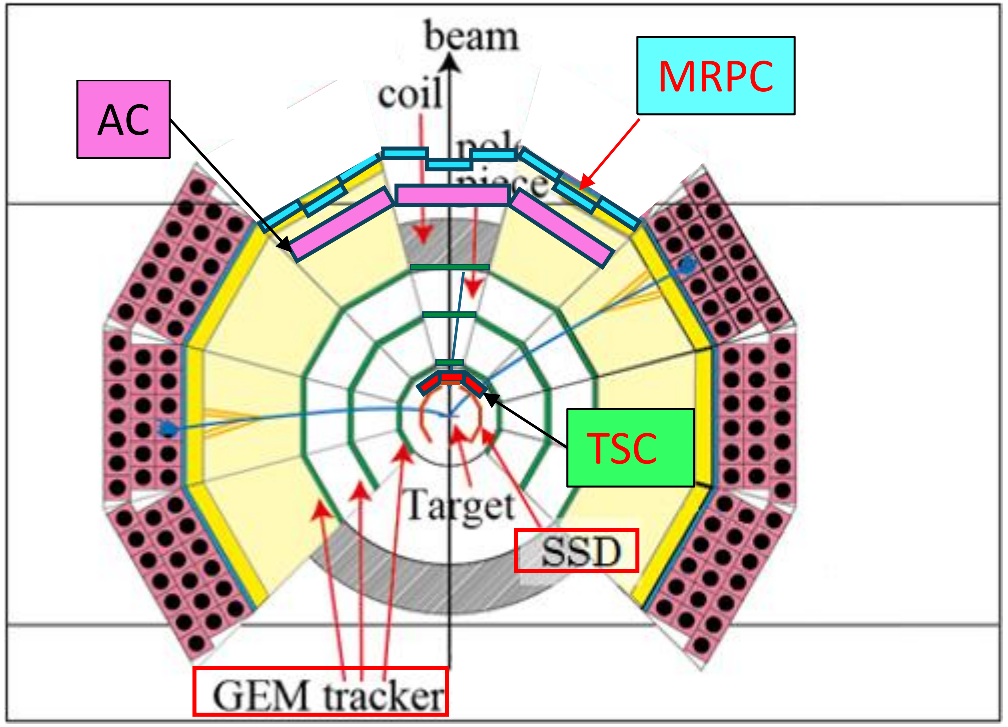
$\phi \rightarrow K^+K^-$

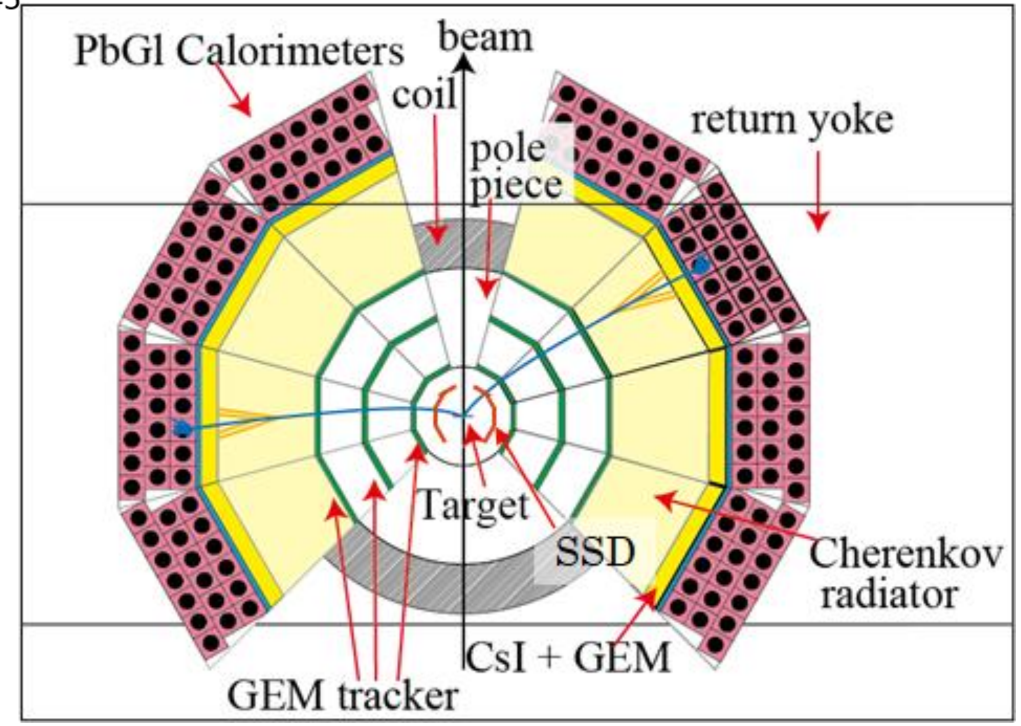
- Suffer from FSI
- Spin 1 is carried by KK OAM
  - $\cos\theta = \pm 1$: L 100%
  - $\cos\theta = 0$: T 100%
- Uniform $\cos\theta$ acceptance
- Large BR (49.1%)
  - 260k (E88)



Proposed geometry configuration of E88



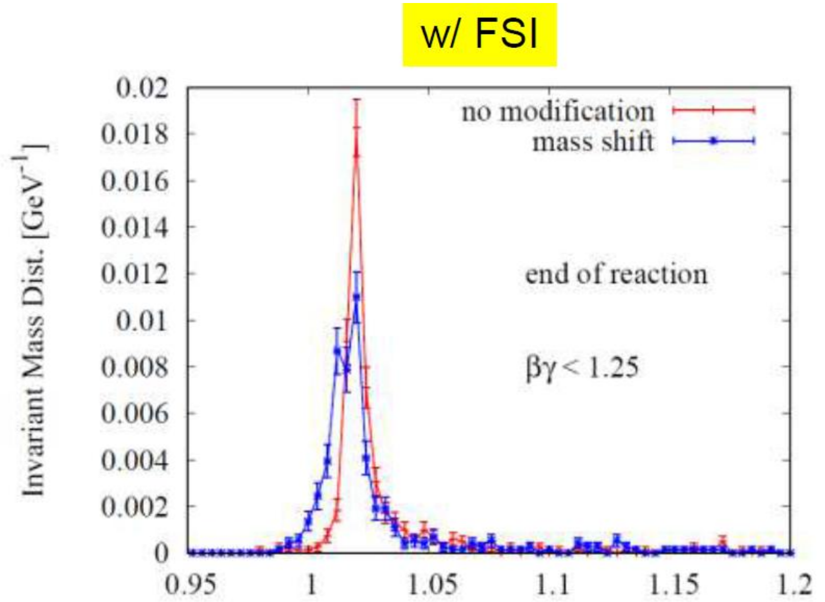


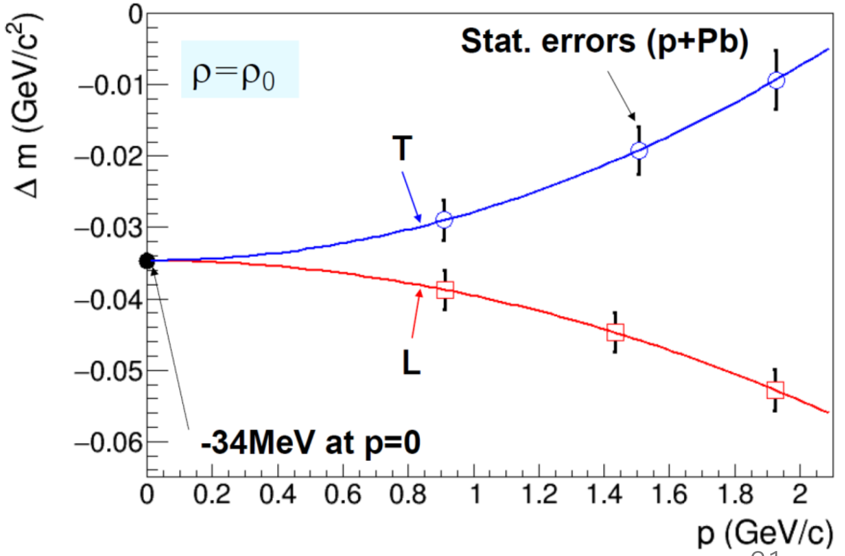


- 6 forward modules (detector unit) in top and bottom layers
- MRPC (Multi-gap Resistive Plate Chamber) and TSC(Track start counter) for Time-of-Flight measurement
- AC (Aerogel Cherenkov Counter) for pion rejection
- SSDs (Silicon Strip Detectors) and GTRs (GEM Trackers) for tracking

J-PARC E88 (ϕ→KK)

- Measure ϕ→KK (E88) by adding Kaon identification detectors outside of E16 Run1 acceptance.
- PHSD calculation (P. Gubler, E. Bratkovskaya et al.) suggests signals survive the FSI.
- Polarization dependent measurement possible.

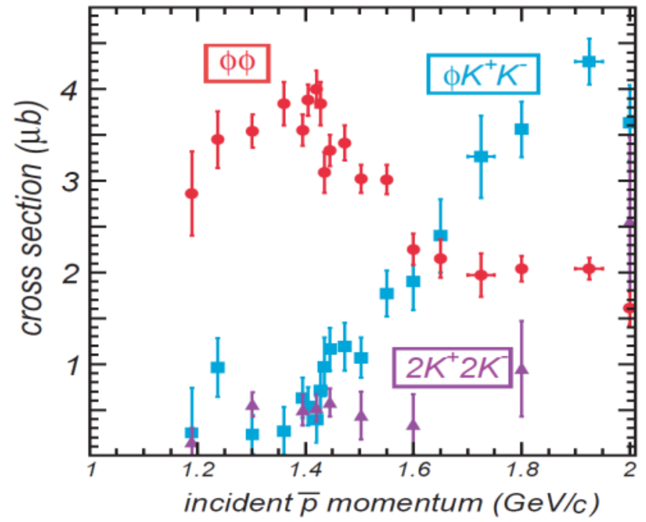




Bound state identification by missing mass

- J-PARC E29 (K1.1) searches for bound state
  - $\bar{p}$ + C/Cu/CH_2 → [ϕ+(A−1)] ϕ
    - $\bar{p}$+p → $\phi\phi$ cross-section is large near threshold.
  - $\bar{p}$ -- 1.1 GeV/c, 1 x 10^6 /spill

JETSET at LEAR



Strangeness > 3

$\bar{p}$ + A → ϕ (in nucleus) + ϕ (forward)

ϕ (in nucleus) → K^+ Λ, Λ → p π^-

ϕ (forward) → K^+K^-

Missing mass is calculated

- J-PARC E104 (K1.8BR)
  - Study of $\bar{p}$ + p → $\phi\phi$ reaction near threshold using HypTPC
  - 10 days and scan beam mom 0.87-1.17 GeV/c.

Summary

- J-PARC E16 experiment will measure e+e- in pA collisions at 30GeV to study the origin of hadron mass through the spectral change of vector mesons in the nuclear medium.
- Our 1st physics paper is to be submitted soon based on a commissioning run (Run0e).
- We are taking physics data (Run1) and continue to do so for a few years.
- J-PARC E88 measures the KK channel.
- Dispersion relation / polarization dependence.
- Bound state of phi meson.