Experimental study of in-medium spectral change of vector mesons and its polarization dependence at J-PARC.

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J-PARC Hadron Section.

ExHIC-p workshop on polarization phenomena in nuclear collisions

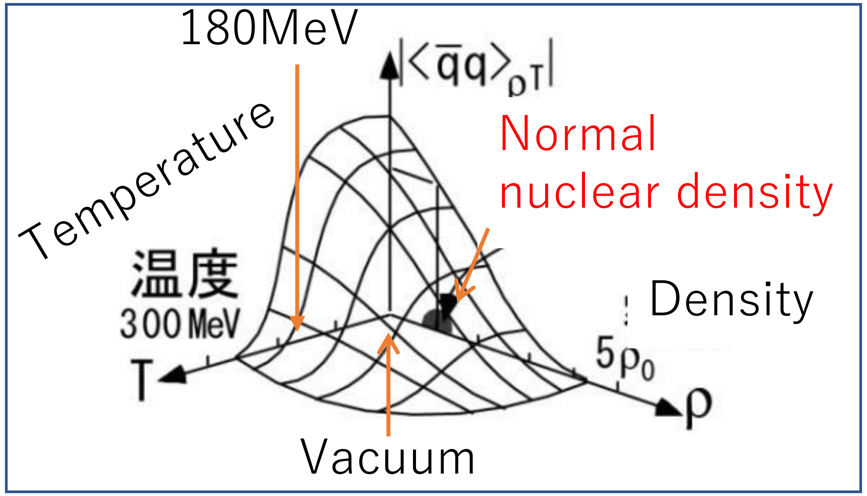
(Mar 16, 2024. Academia Sinica)

CONTENTS

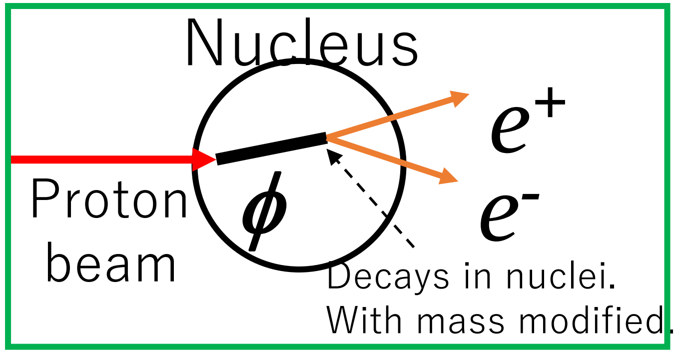
- J-PARC E16 experiment (p+A → ϕ → e^+e^-)
  - Physics motivation (measure in-medium spectral change of VM)
  - Experimental setup
  - Staging strategy
  - Expected results.
- Measurement of polarization dependence of spectral change.
  - Motivation and principle of spin dependent measurement
  - Expected spectra
  - How to extract spin dependence
  - J-PARC E88 : ϕ → K^+K^-
- 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.



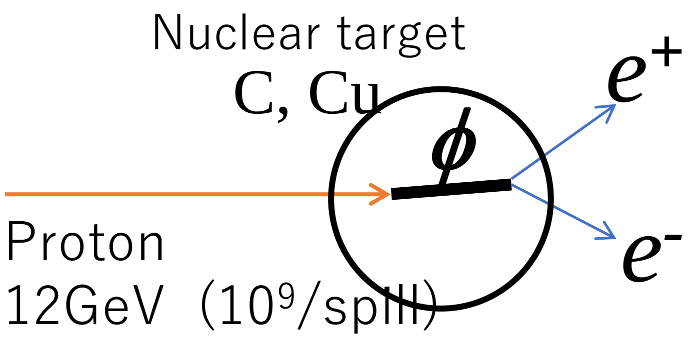
NJL model
M. Lutz et al.
Nucl.Phys. A542,52(1992)

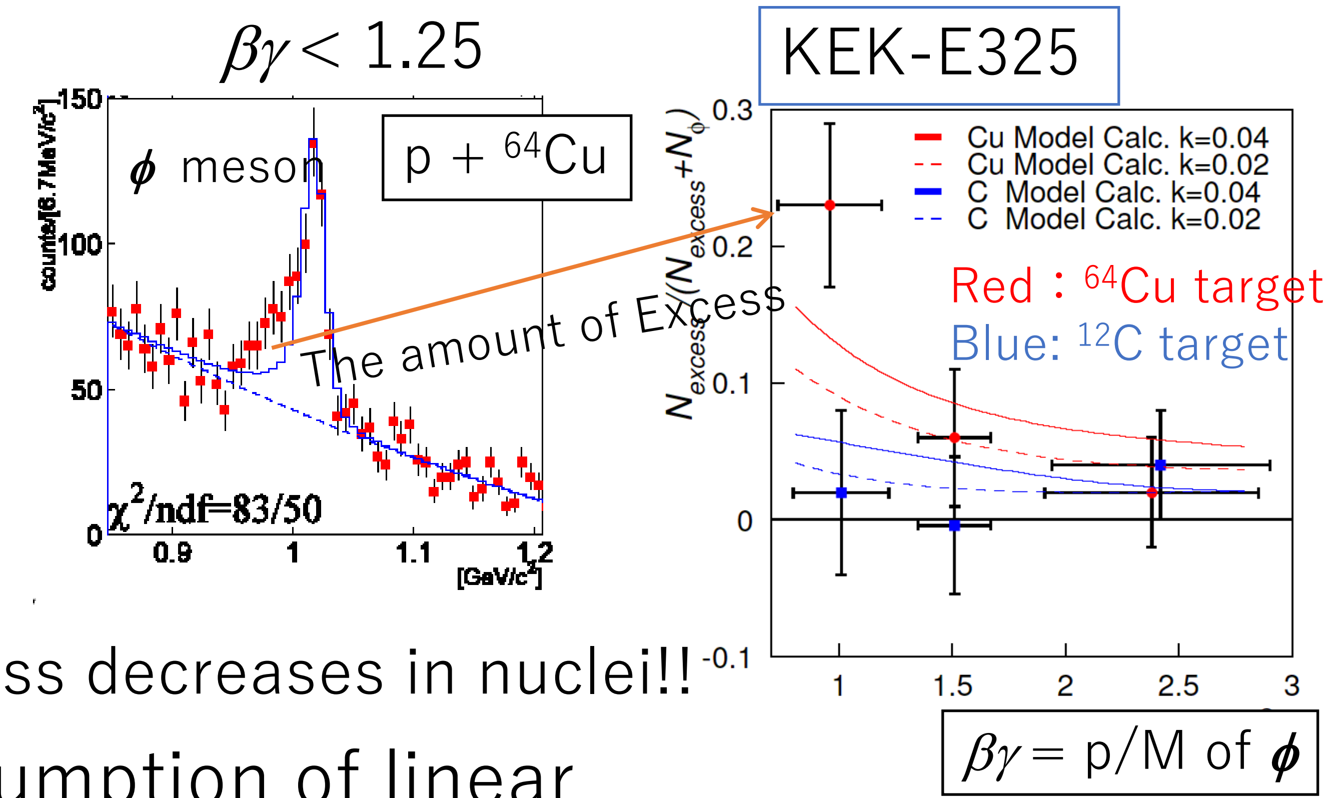


J-PARC E16

KEK-E325 results of ϕ meson

- The world's first results of ϕ modification.





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

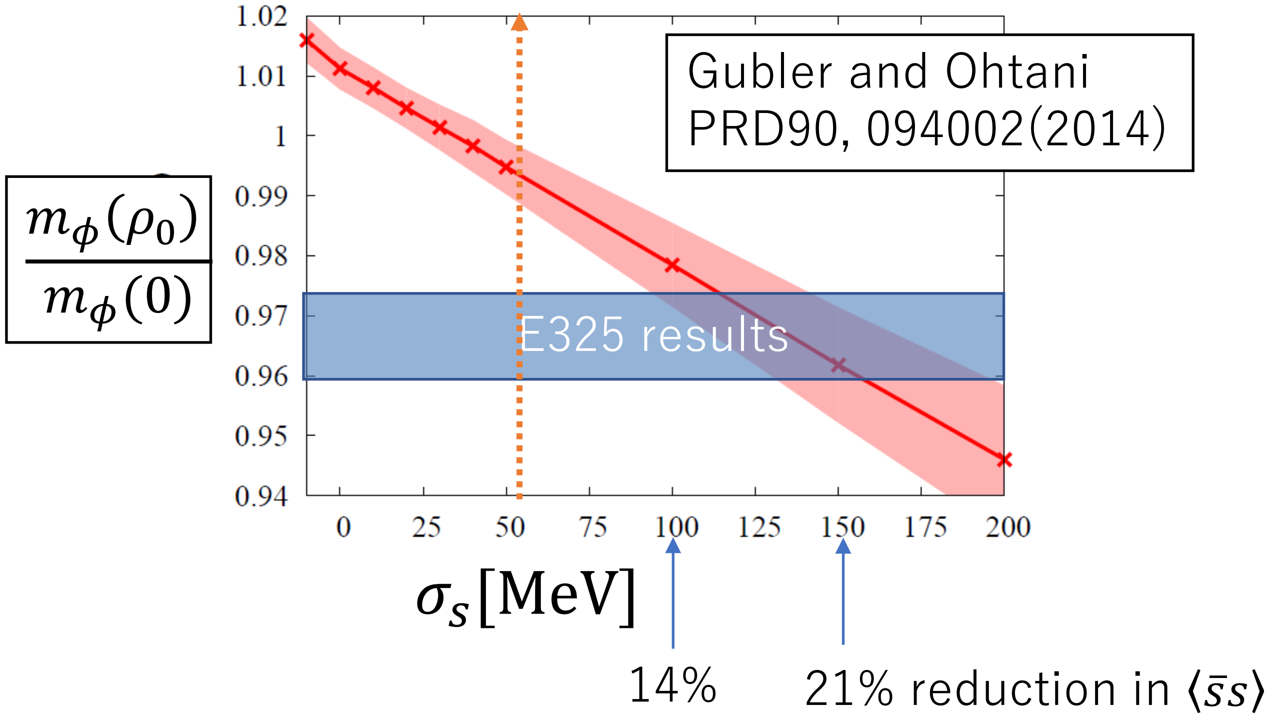
Assumption
In analysis

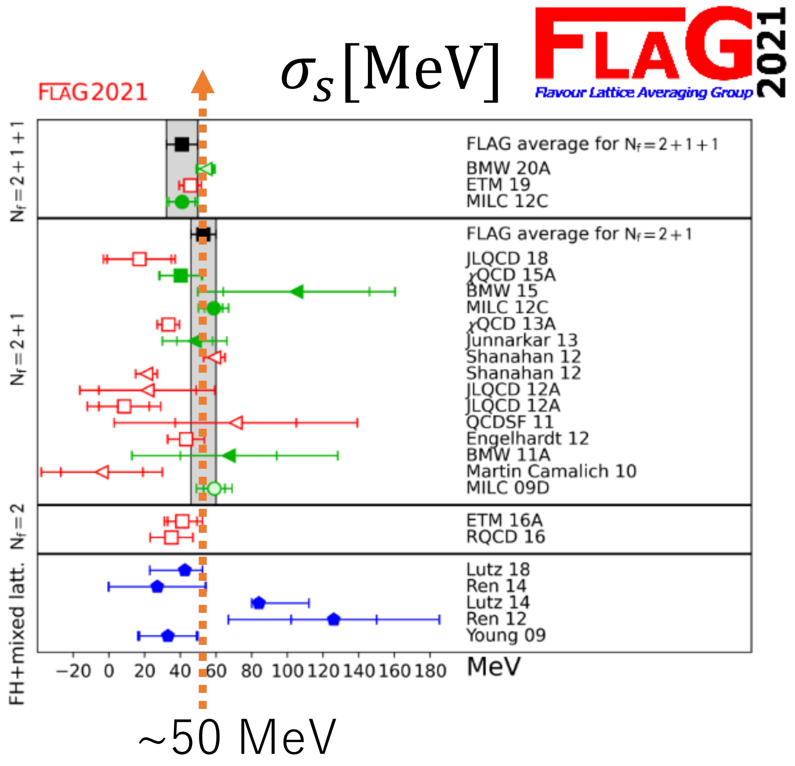
$$\frac{m(\rho)}{m(0)} = 1 - k_1\left(\frac{\rho}{\rho_0}\right)$$

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

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.





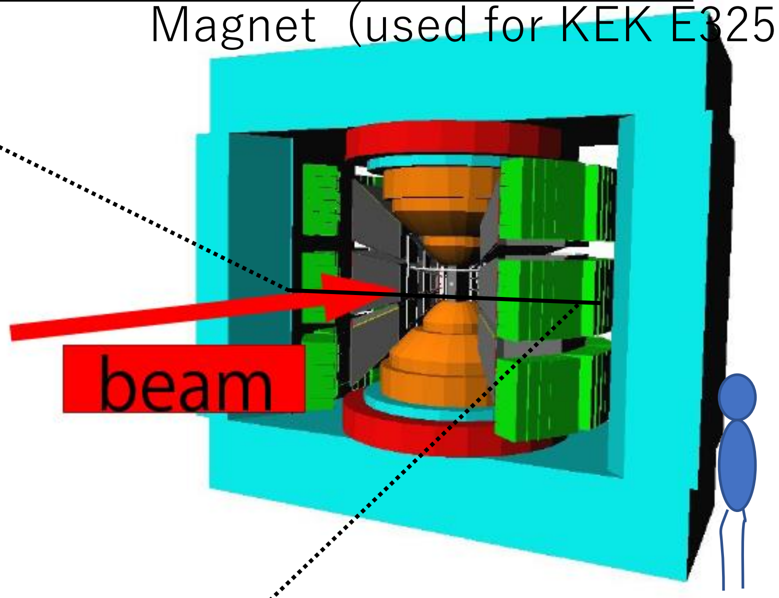
If one takes σ_s from Lattice and QCD sum rule,
Mass reduction should be much smaller. (dM<~1%)

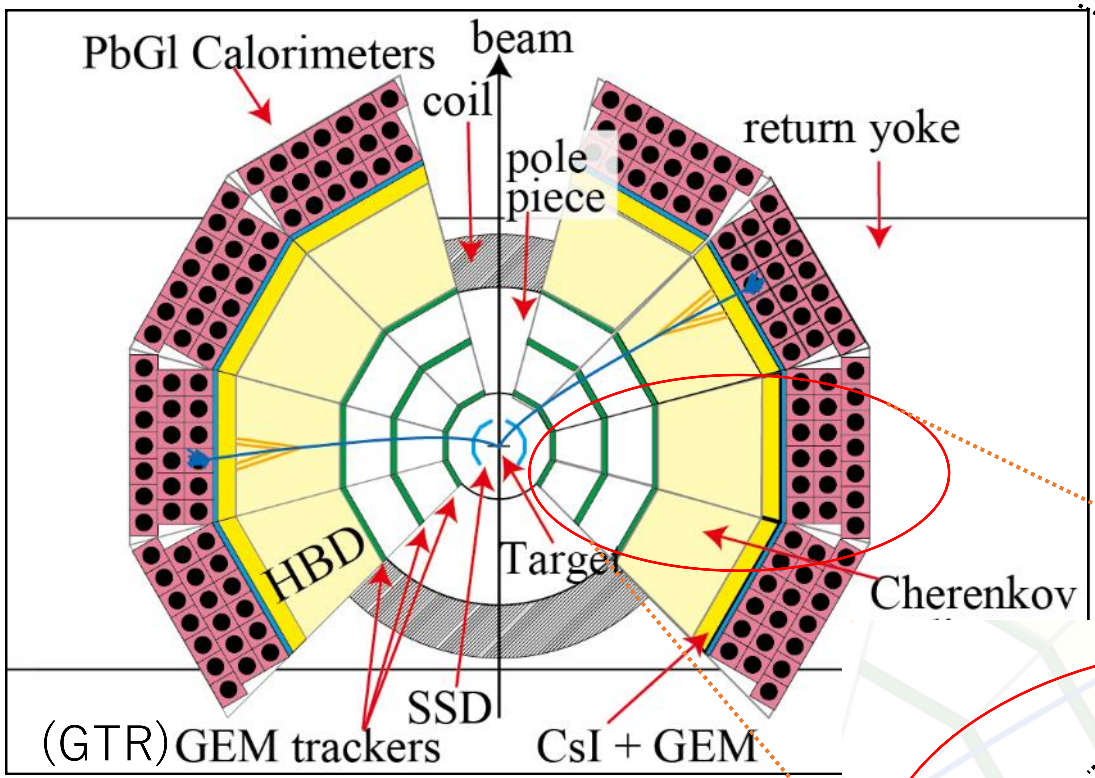
$$\langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \langle N|\bar{s}s|N \rangle \rho$$

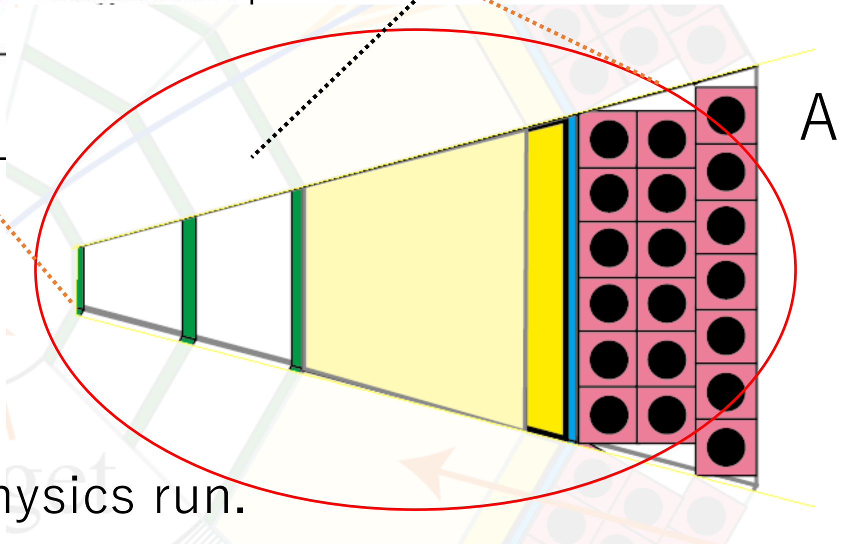
$$\sigma_s = m_s \langle N|\bar{s}s|N \rangle \quad \left(= m_s \frac{\partial M_N}{\partial m_s}\right)$$

The J-PARC E16 spectrometer

Magnet（used for KEK E325)







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

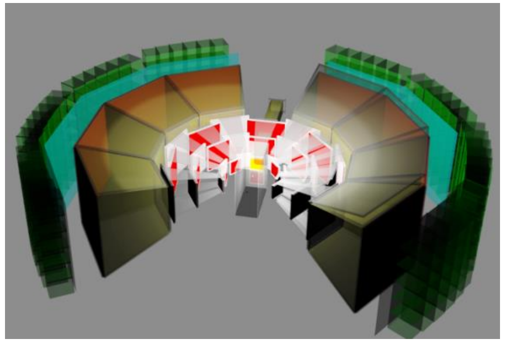
Staging approach

- **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 -- 222 hours.**
  - **8(SSD) + 10 (GTR) + 8 (HBD) + 8 (LG)**
  - Beam / Detector comm. + yield.
  - Upgraded Accelerator / DAQ. / Detectors.

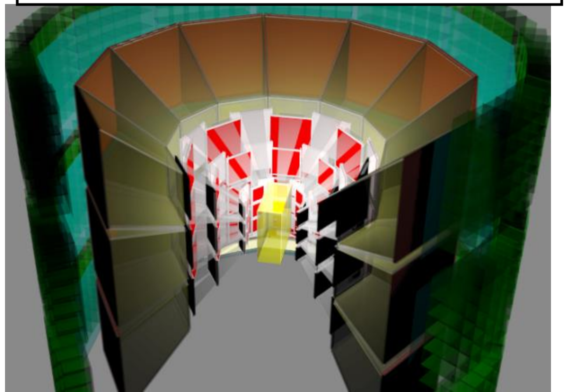
PAC approved

- **RUN 1 2024(?)** -- 1280hrs (~53days)
  - **10 (SSD) + 10 (GTR) + 8 (HBD) + 8(LG)**
  - Physics data taking. ϕ: 15k for Cu.
- **RUN 2** -- 2560 hrs (~107 days)
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - + Pb/CH2 target
  - Needs additional budget.

RUN 1 (8 modules)

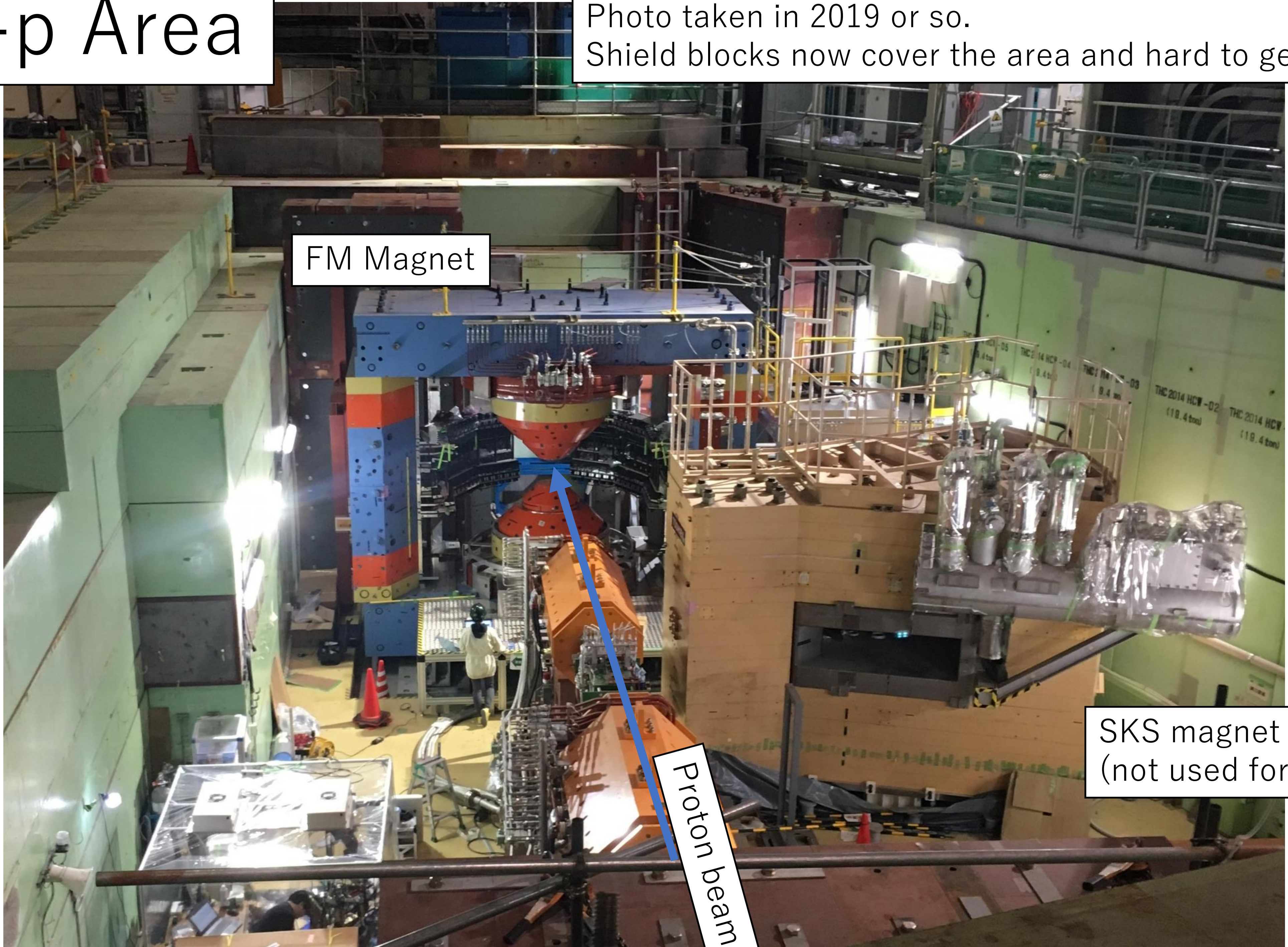


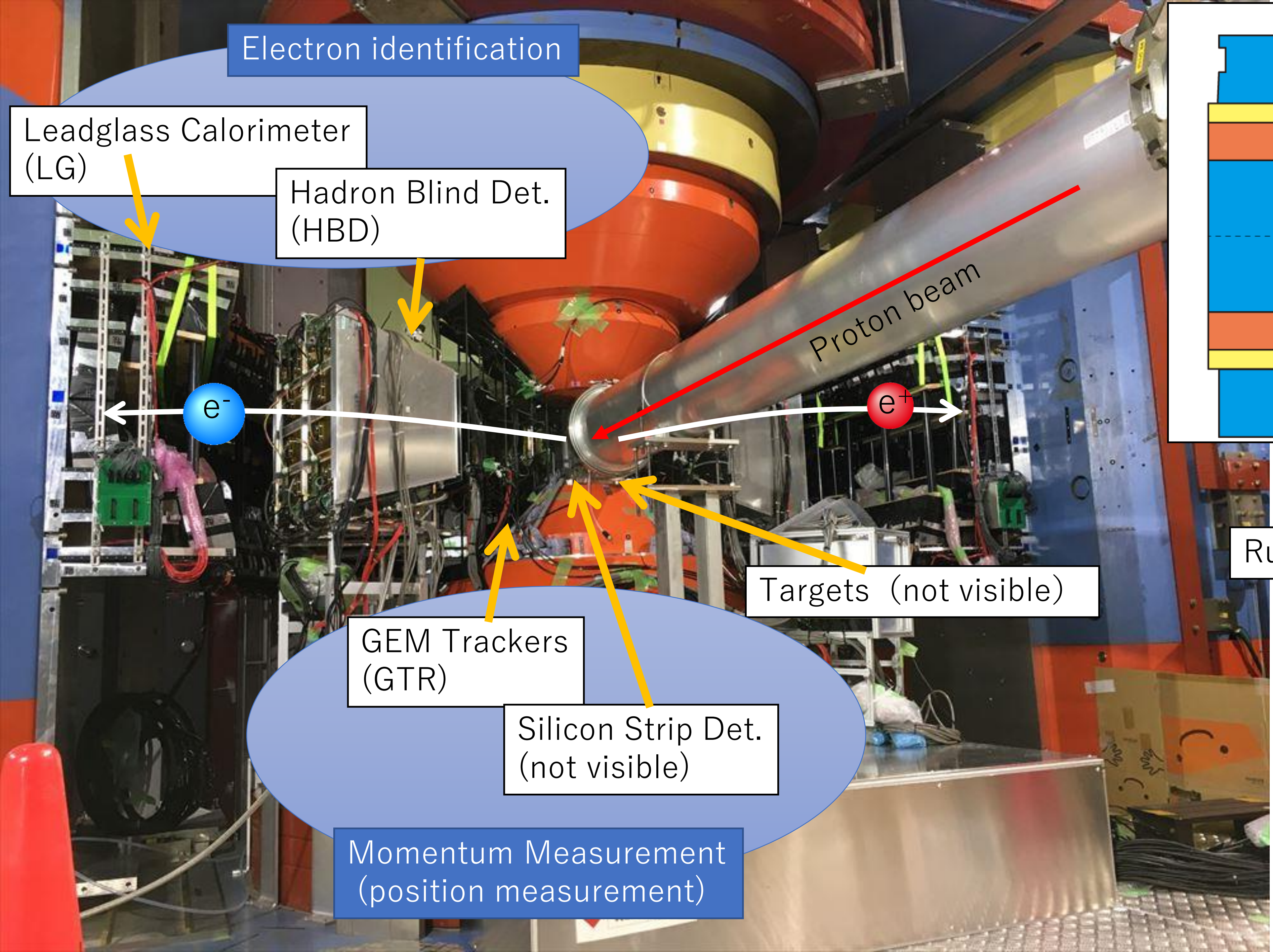
RUN 2 (26 modules)

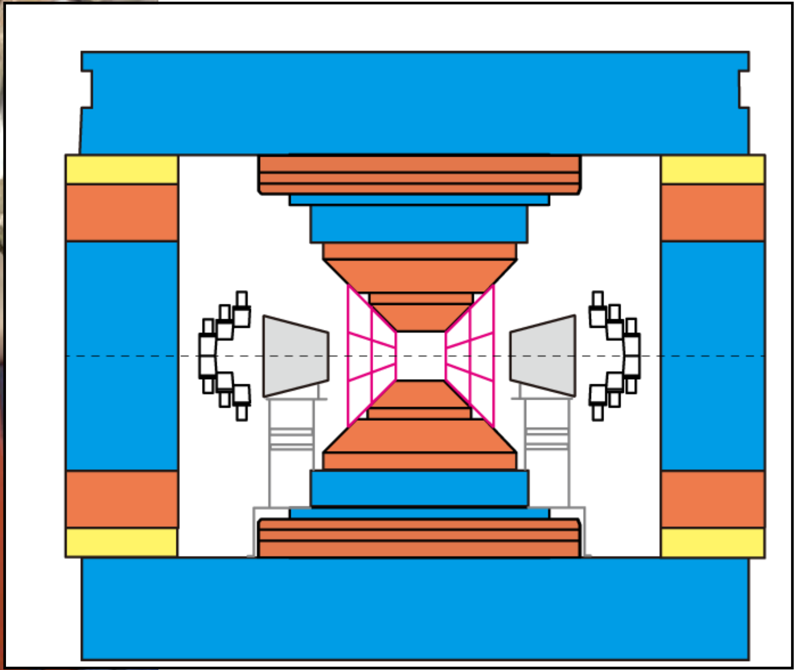


High-p Area

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







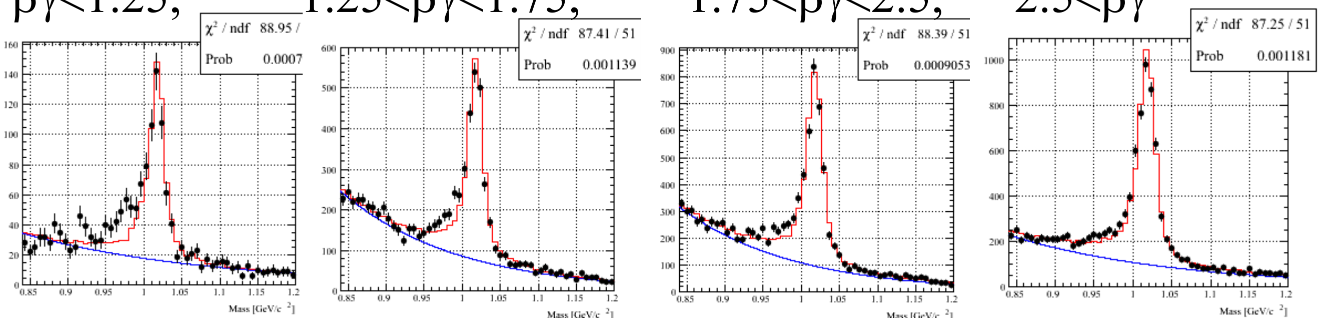
Run0b/c configuration(2021)

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

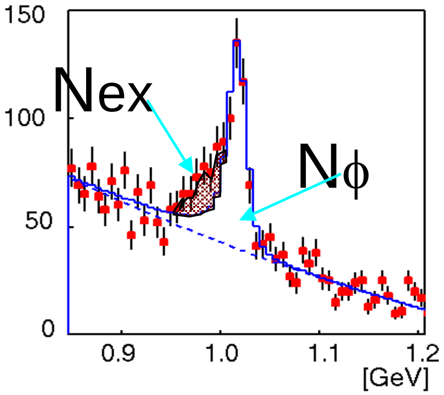
RUN1, Cu (INPUT:E325-BW) Excess ratio vs $\beta\gamma$

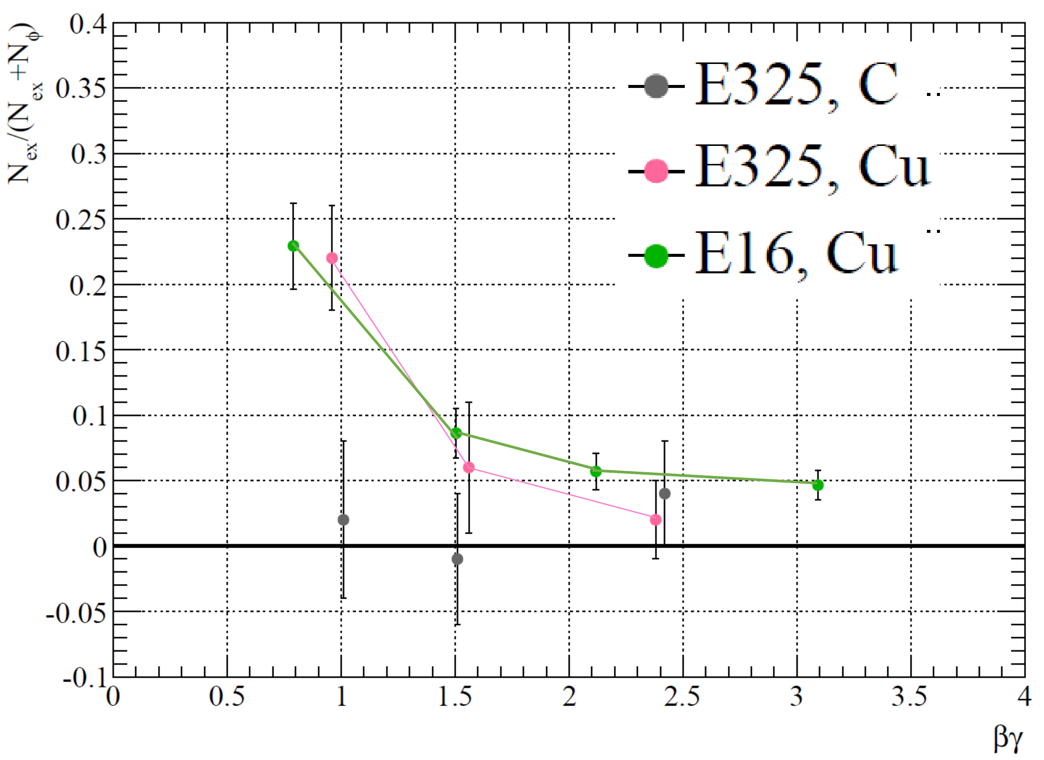
βγ<1.25, 1.25<βγ<1.75, 1.75<βγ<2.5, 2.5<βγ



(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.

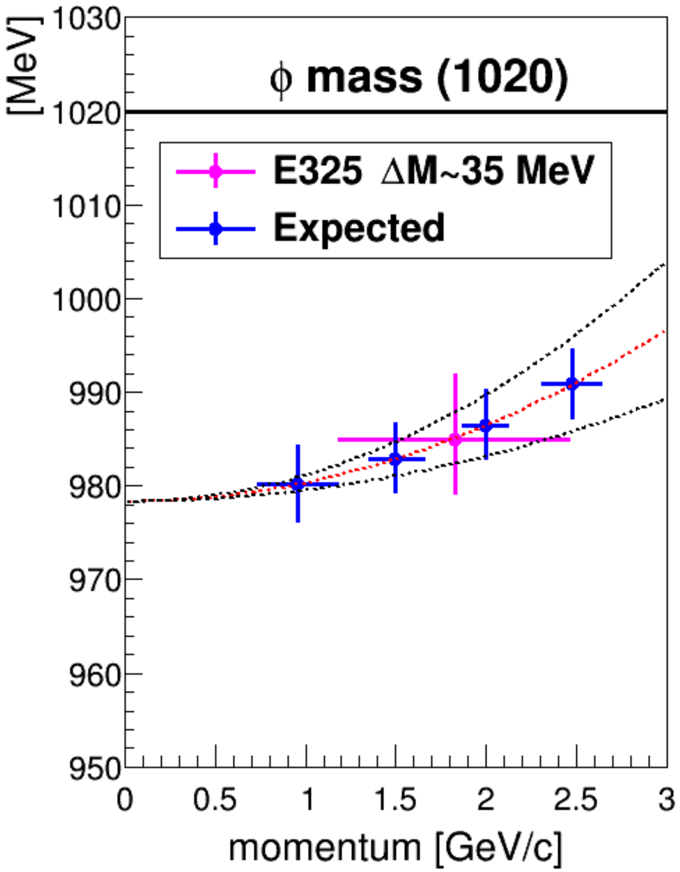
Momentum dependence (Dispersion relation)

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.

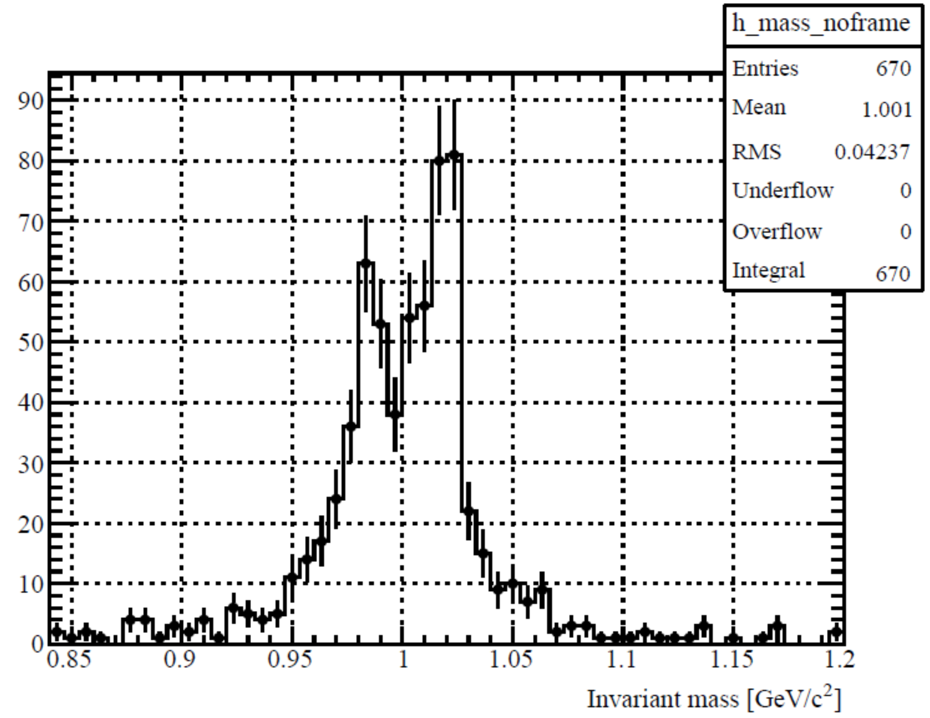


S.H. Lee PRC57, 927(1998)

Expected in RUN2

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

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



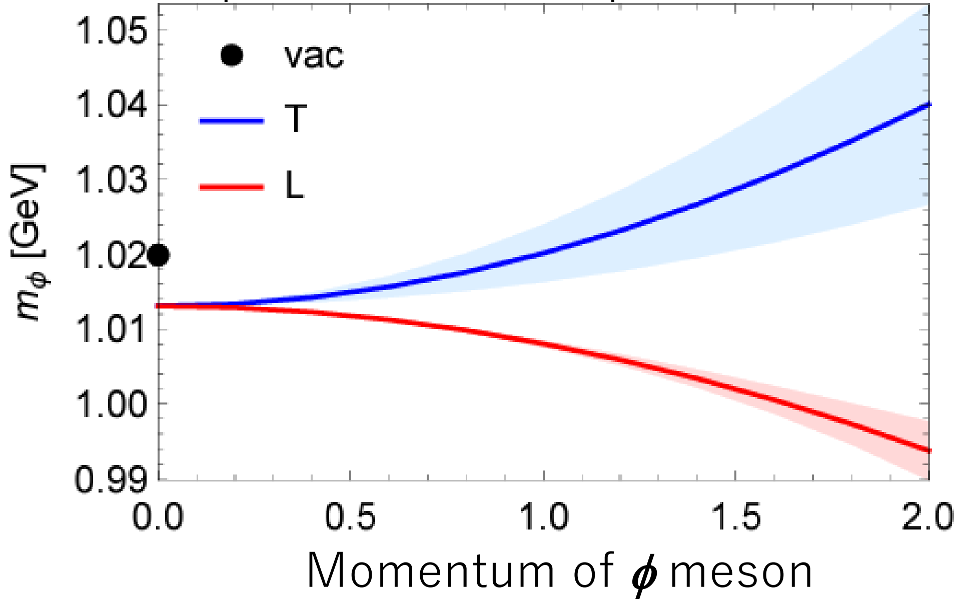
Measurement of polarization dependence

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.

- Decay angle ϕ → e+e / K+K-
- Expected spectrum
  - Based on E325-type model calc.
- How can we experimentally separate
  - Finding orthogonal functions.
- Do the methods work?

Dispersion relation up to 3 GeV/c

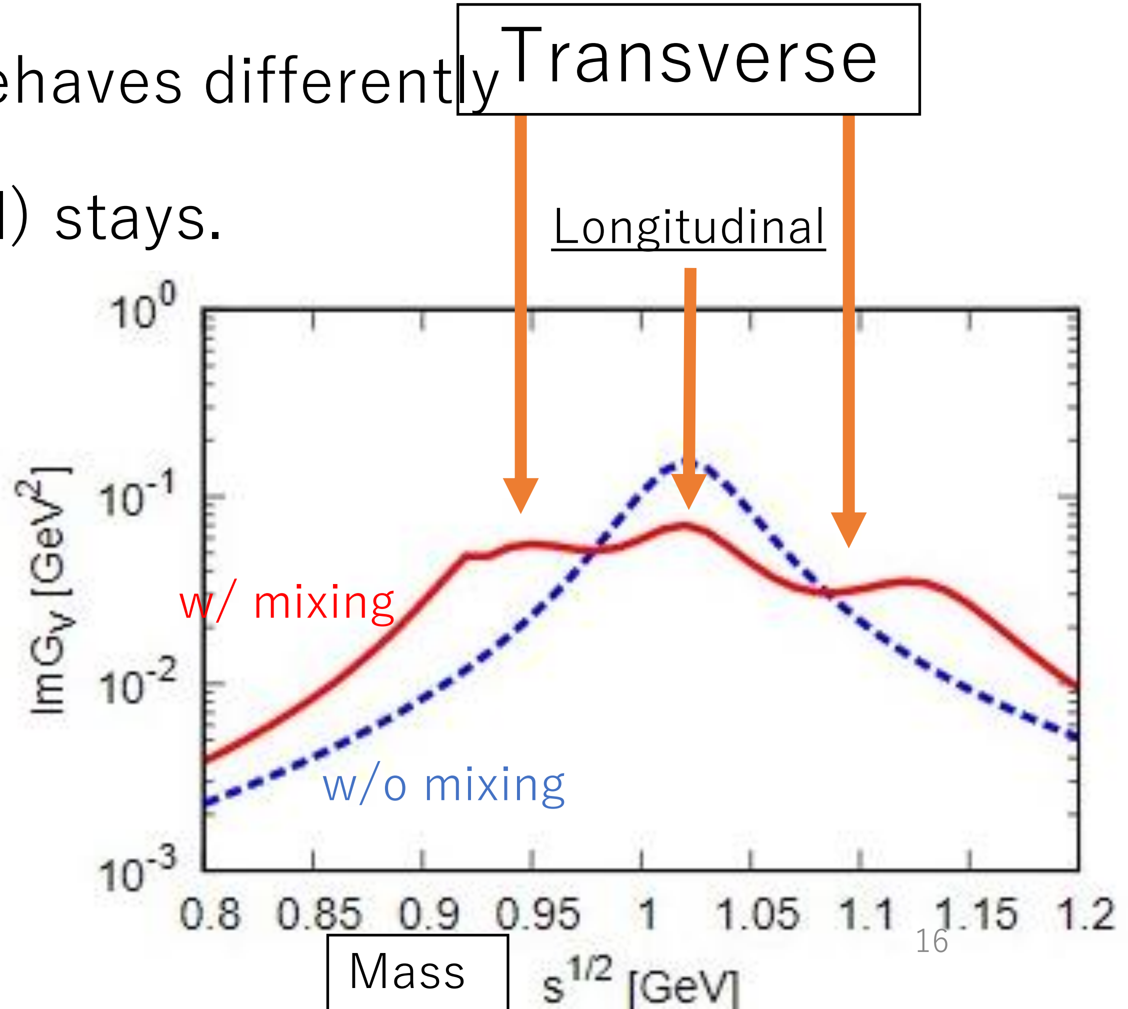


Anomaly-induced chiral mixing of ϕ and $f_1(1420)$

- Genuine signal of chiral symmetry restoration:
  Degeneracy of chiral partner! by theorists.
- Phys. Rev. D106, 5 (2022) C. Sasaki
  - Chiral mixing effect in dense matter behaves differently when chiral symmetry is restored.
  - T(Transverse) affected. L(Longitudinal) stays.
- Motivation for T/L separation

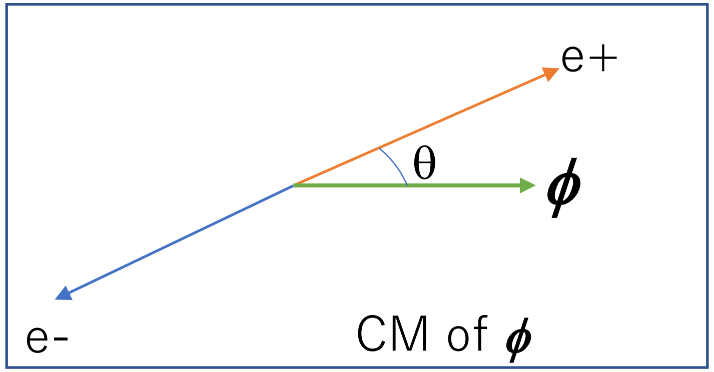
$p = 1.0 \mathrm{GeV}/c$

$T = 50$ MeV
$\rho = 2.5\rho_0$

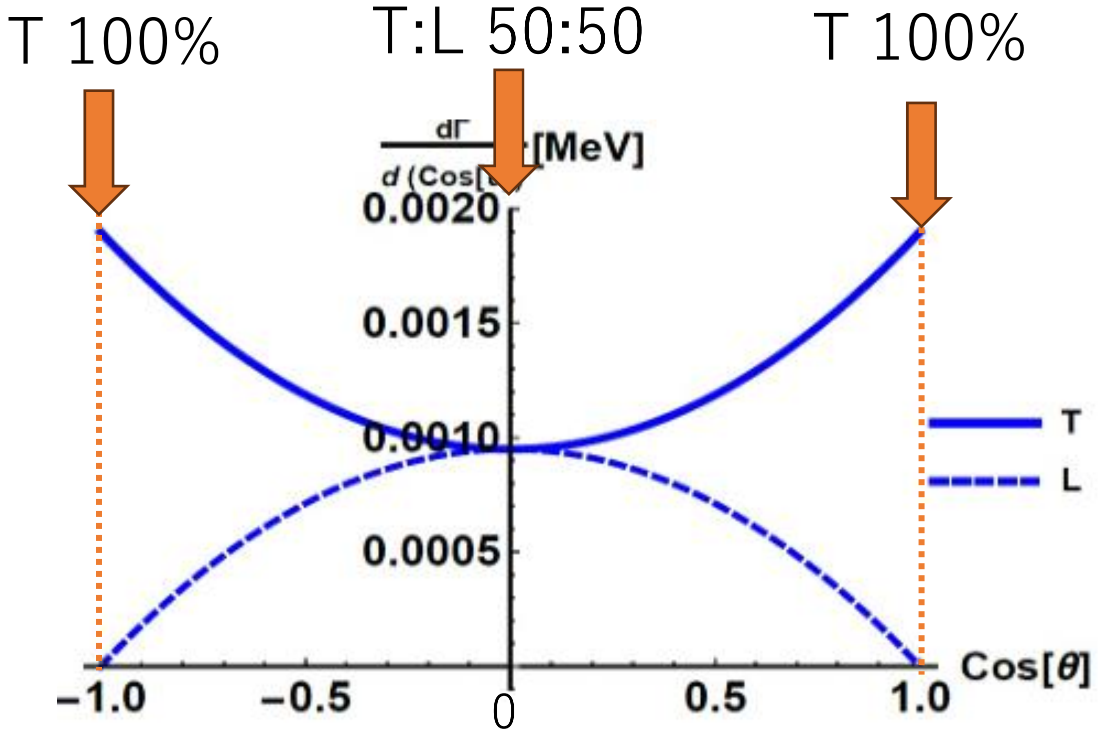


Polarization ←→ Angular dist. in helicity rest frame

Helicity rest frame (of ϕ meson)



- Phys. Rev. D 107, 074033(2023)
  I.W. Park, H. Sako, K.A., P.Gubler, S.H.Lee
- ϕ →ee
  - Spin 1 is taken by the spin of ee.
    - $\cos\theta = \pm 1$: T 100%
    - $\cos\theta = 0$: L 50%, T 50%
  - Small FSI
  - Limited acceptance at $\cos\theta = \pm 1$

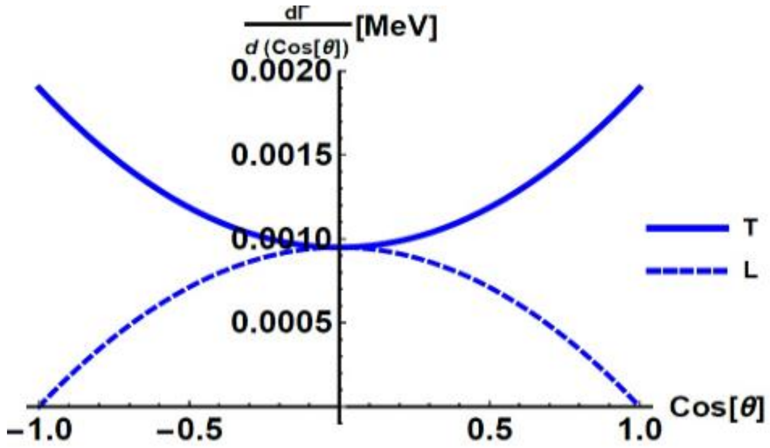


ϕ →e+e-

$\phi \to e^+e^-$ vs $\phi \to K^+K^-$

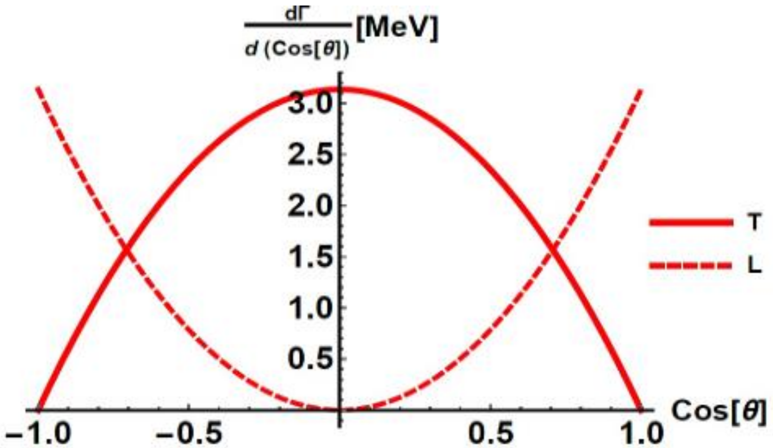
$\phi \to e^+e^-$

- Spin 1 is taken by ee pol.
  - 😇 $\cos\theta = \pm 1$: T 100%
  - ☹ $\cos\theta = 0$: L 50%, T 50%
- 😇 Small FSI
- ☹ Small BR (2.98×10^{-4})
  - 15k for 53 days (E16 Run1)



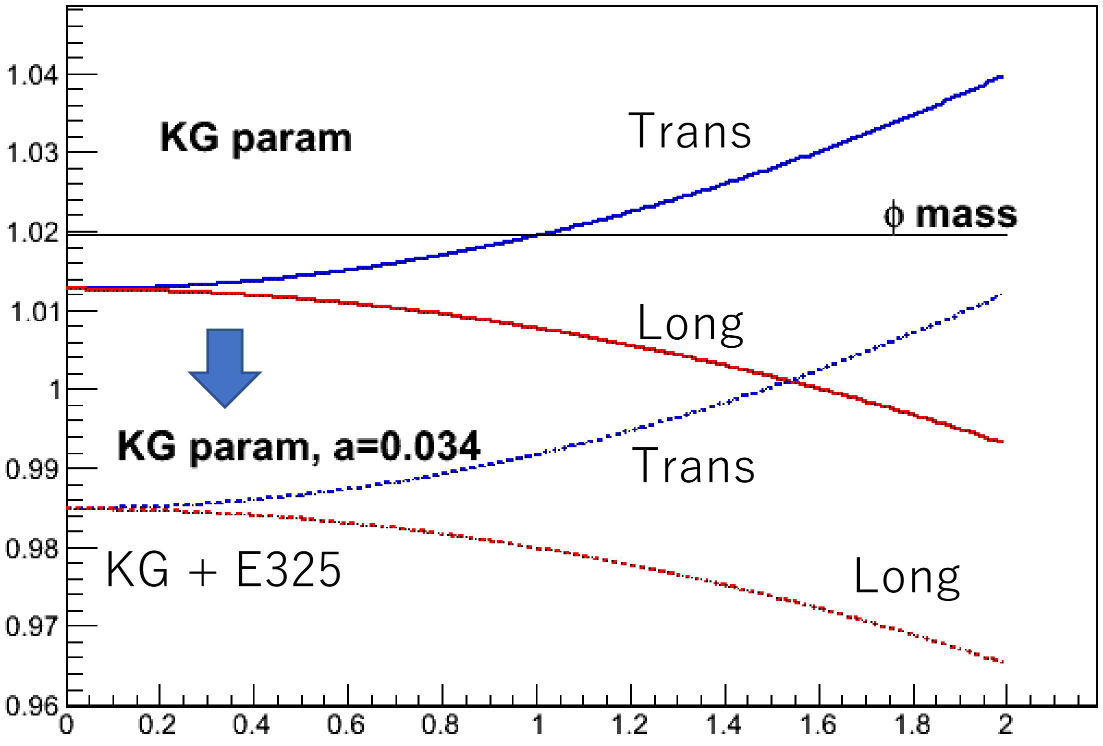
$\phi \to K^+K^-$

- Spin 1 is taken by KK OAM
  - 😇 $\cos\theta = \pm 1$: L 100%
  - 😇 $\cos\theta = 0$: T 100%
- ☹ Suffer from FSI
  - Treated by transport model
- 😇 Large BR (49.1%)
  - 260k for 30 days (E88)



Play with Kim-Gubler model to get expected mass spectra

- PLB 805, 10 (2020)
  - T: Transverse / L: Longitudinal
  - T : L = 2:1
- I replaced the shift with the E325 value.

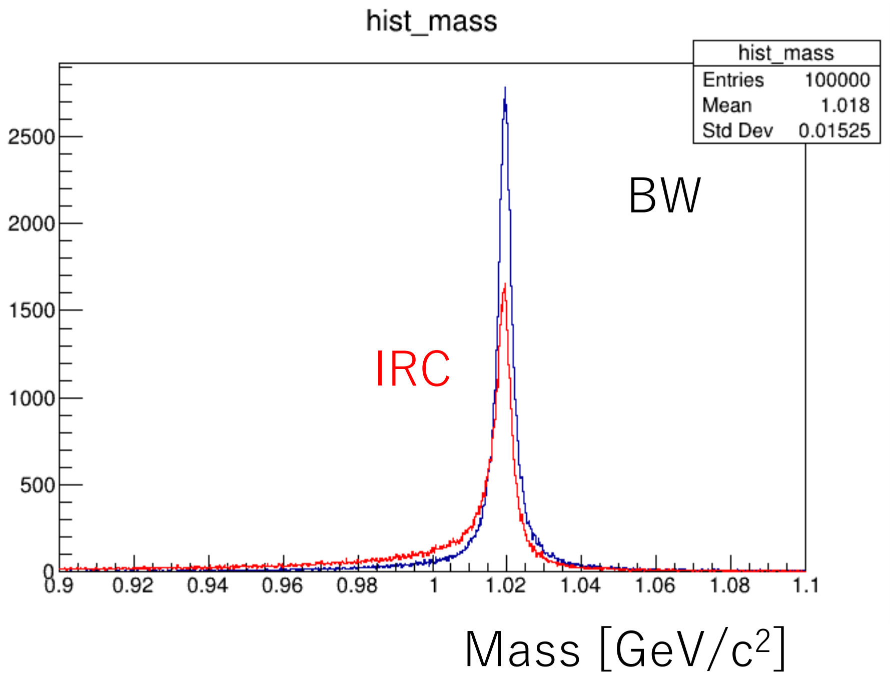


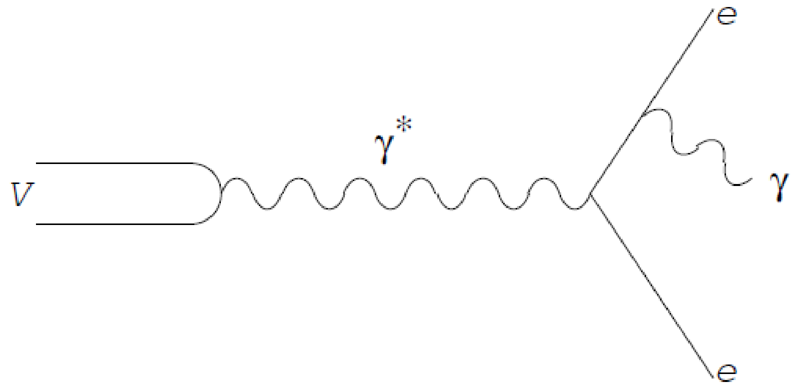
$$\frac{m_\phi^{\mathrm{L/T}}(\rho_N, \vec{q})}{m_\phi^{\mathrm{vac}}} = 1 + \left(a + b^{\mathrm{L/T}}|\vec{q}|^2\right)\frac{\rho_N}{\rho_0}.$$

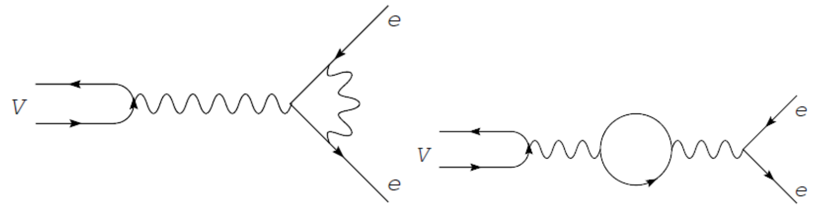
- KG param
  - b(T) = 0.067 pm 0.0034
  - b(L) = -0.0048 pm 0.0008/GeV
  - a = -0.0067
- KG + E325 param
  - a=0.034
  - b : same as KG param.

Monte Carlo simulation input

- Momentum distribution is taken from JAM.
- Mass: Breit-Wigner distribution.
- Internal Radiative Correction (IRC)
  - Calculated by PHOTOS
  - IRC makes a tail on the lower side.

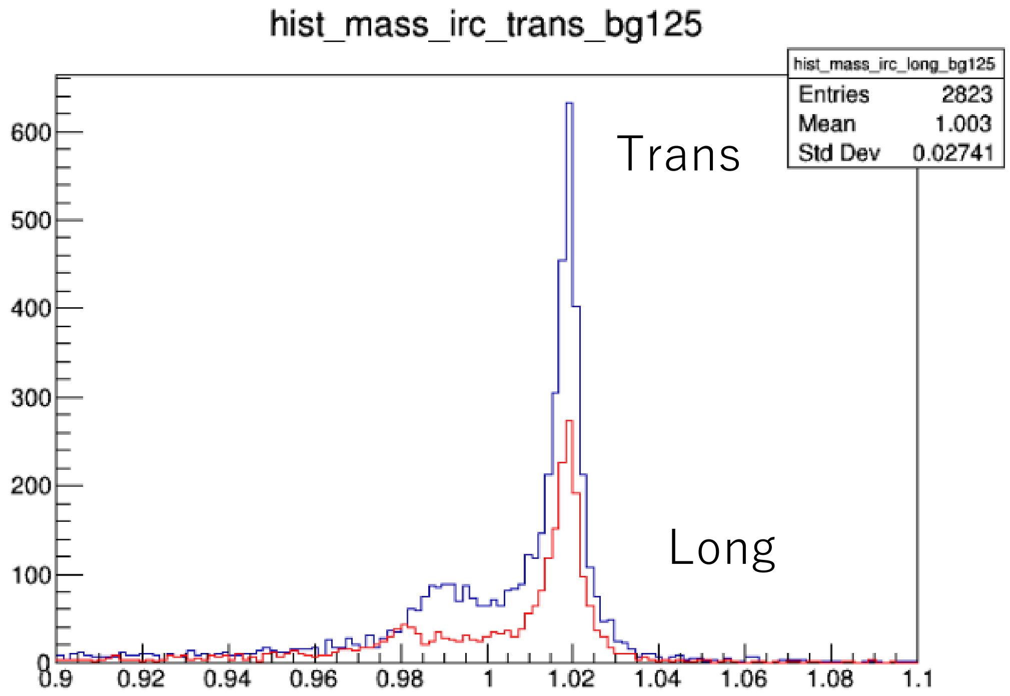


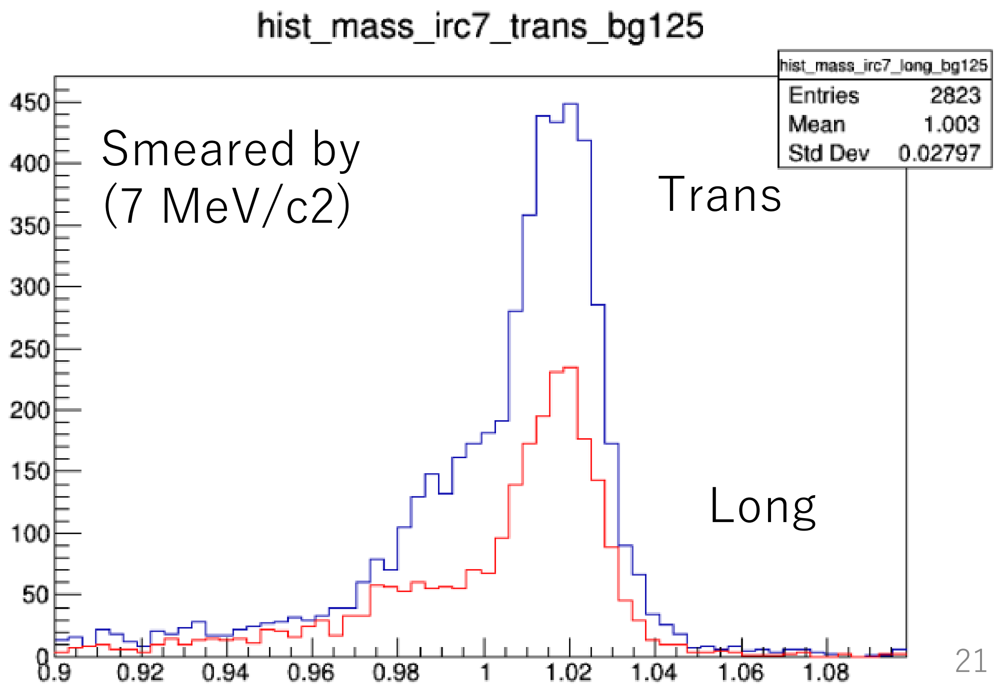




E325-type calculation using KG param.

- 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

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

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.

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

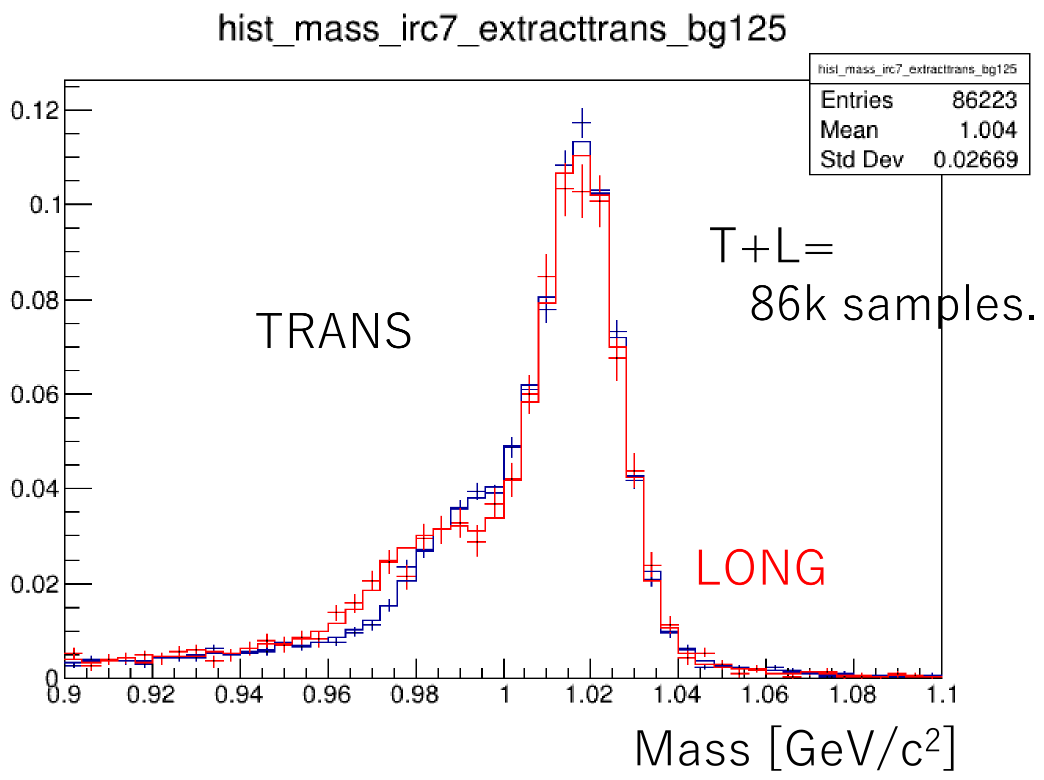
$$\begin{aligned} f_T &= 1 + x^2 \\ f_L &= 1 - x^2 \\ h_T &= 5x^2 - 1 \\ h_L &= 2 - 5x^2 \end{aligned}$$

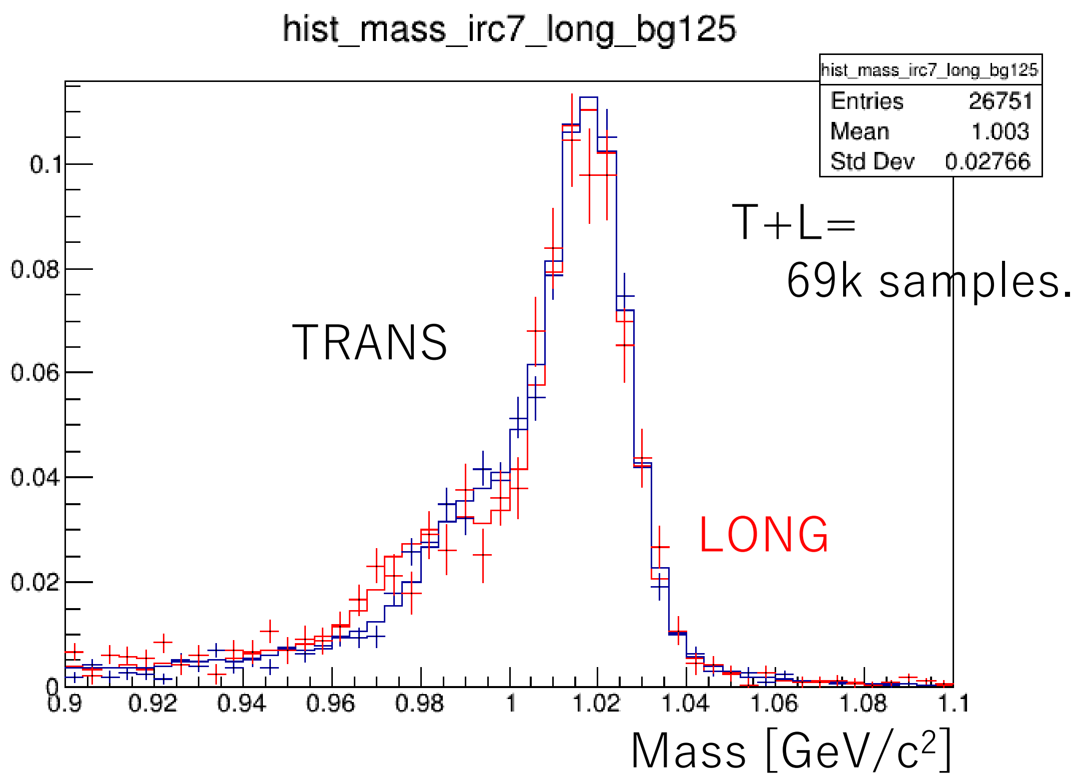
$$x = \cos\theta = [-0.8,0.8]$$

$$\begin{aligned} f_T &= 1 + x^2 \\ f_L &= 1 - x^2 \\ h_L &= 3.1897 - 13.108x^2 \\ h_T &= 13.1077x^2 - 2.18963 \end{aligned}$$

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

- $\cos\theta = [-1,1]$
- $\cos\theta = [-0.8,0.8]$



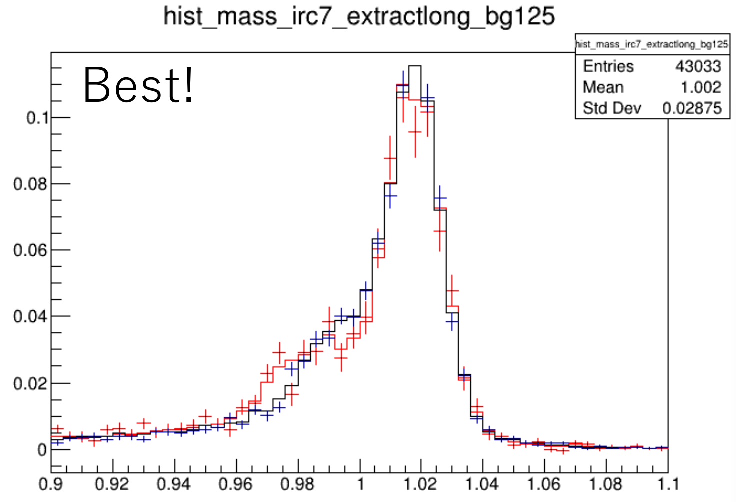


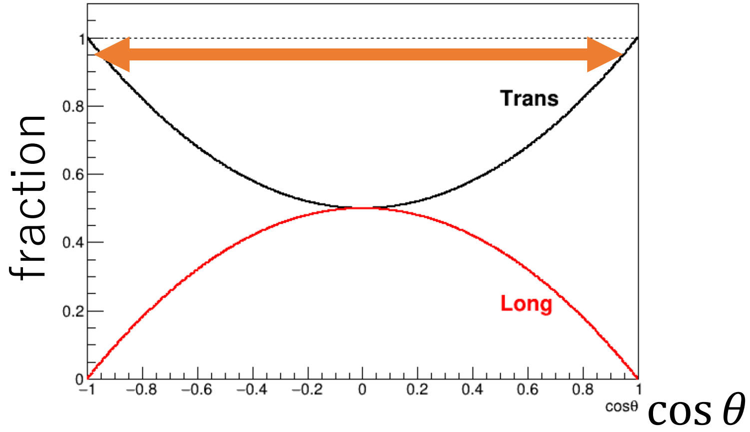
LINE : According to polarization information which God only knows

\+ : Extracted using the orthogonal functions $h_T(x), h_L(x)$

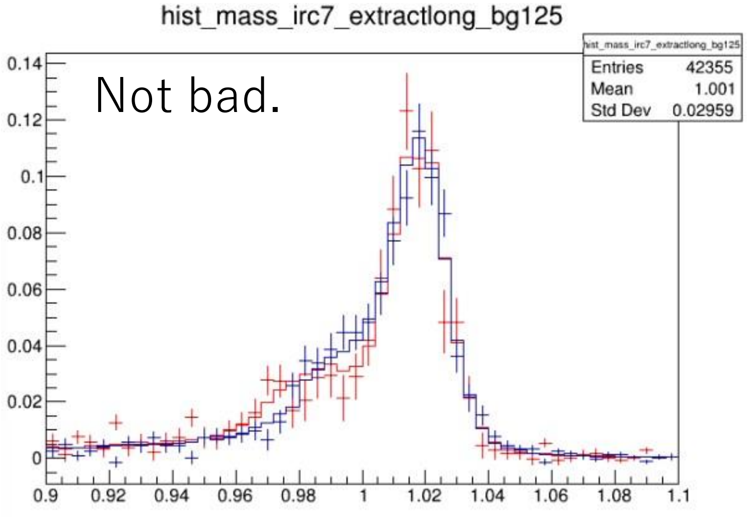
Same statistics but different angular acceptance in the rest frame of $\boldsymbol{\phi}$.

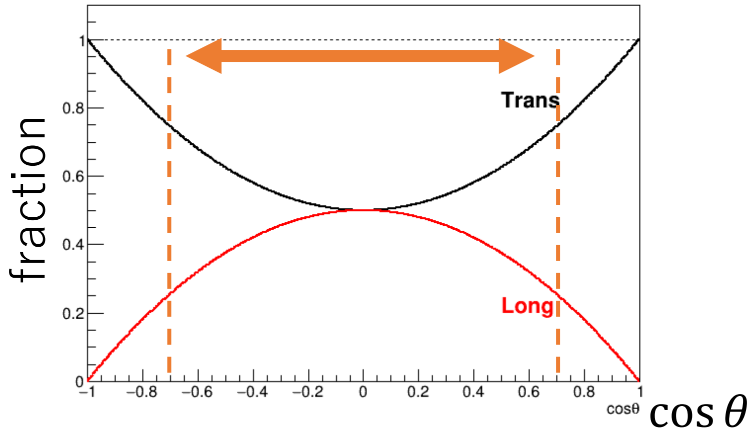
- $\cos\theta = [-1,1]$



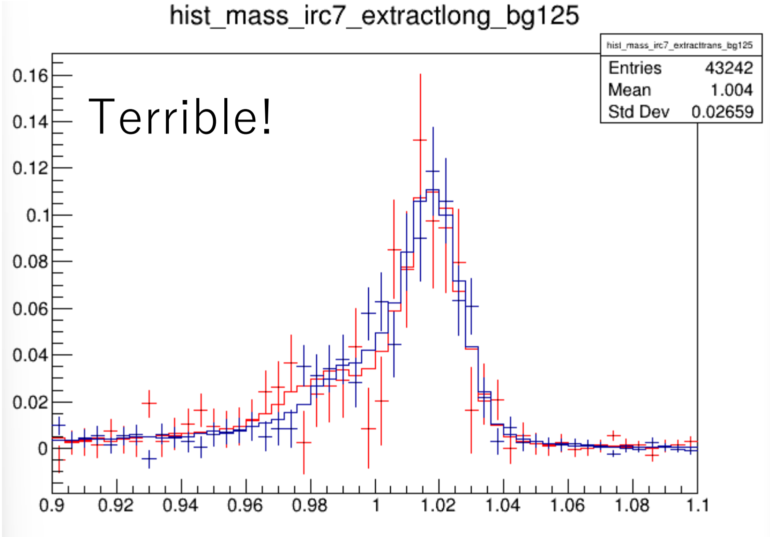


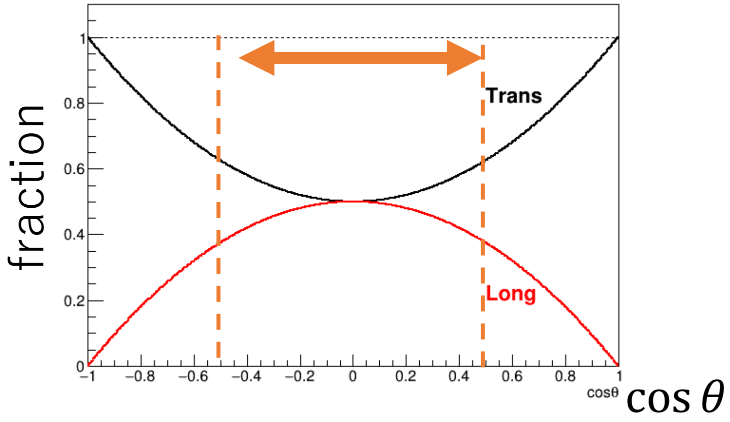
- $\cos\theta = [-0.7,0.7]$





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



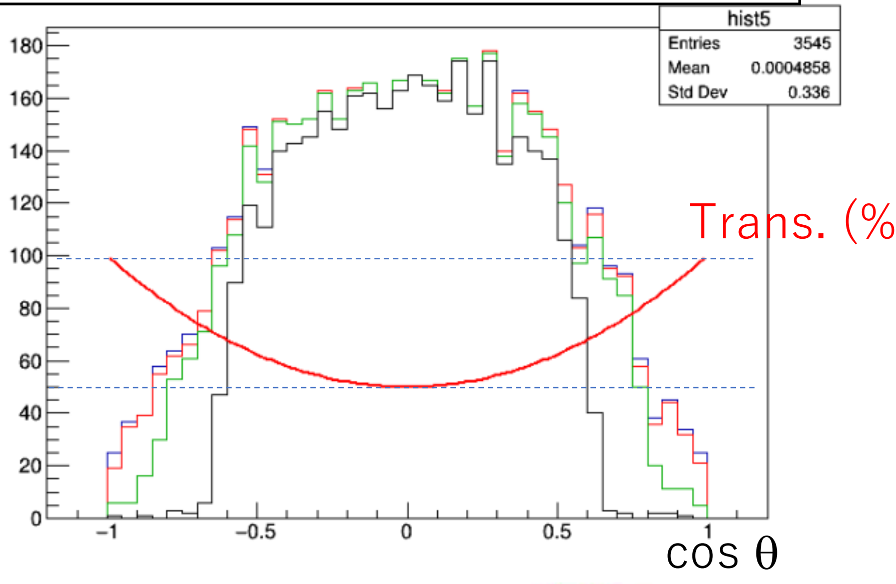


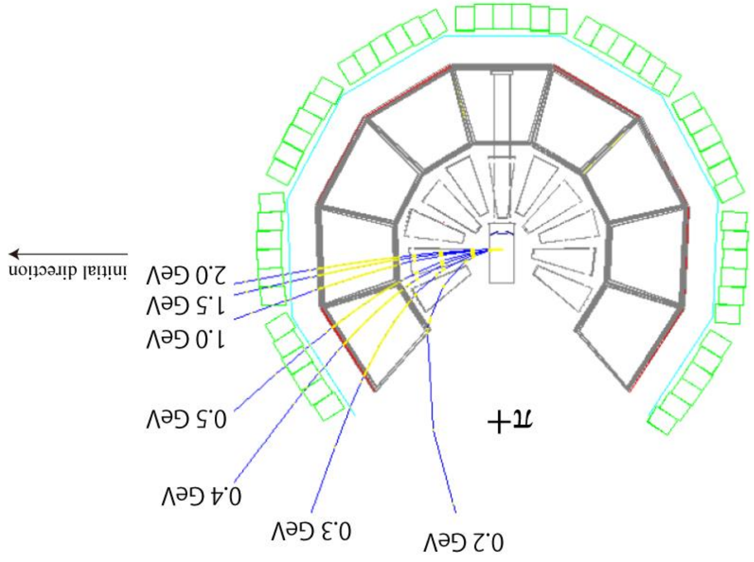
Angular acceptance in the rest frame of ϕ.

- GEANT4 as an acceptance filter.
  - Notes on the plot
    - # of entry is arbitrary.
    - Transverse pol fraction is overlayed.
  - Results
    - Smaller acceptance for $\cos\theta = \pm 1$
    - 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.

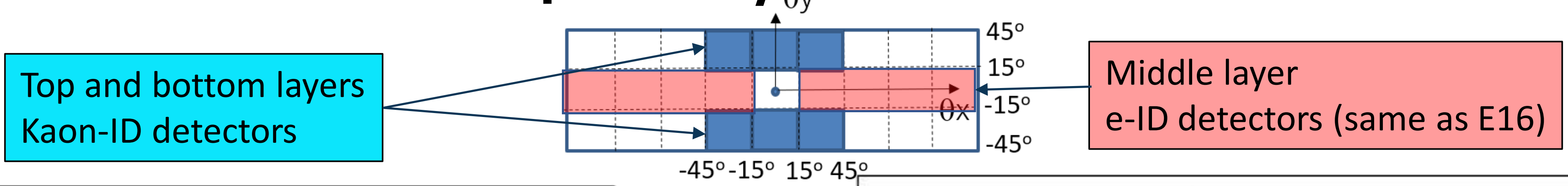
In the acceptance & phi mom<1.25 & e+- momentum cut

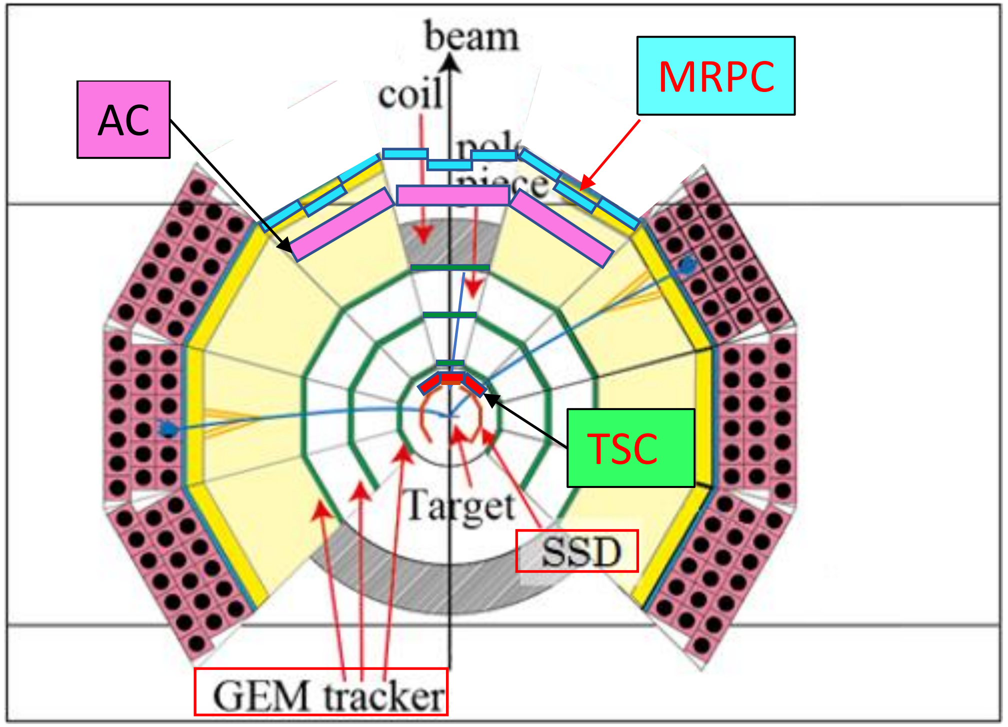
none
>0.2
>0.3
>0.4

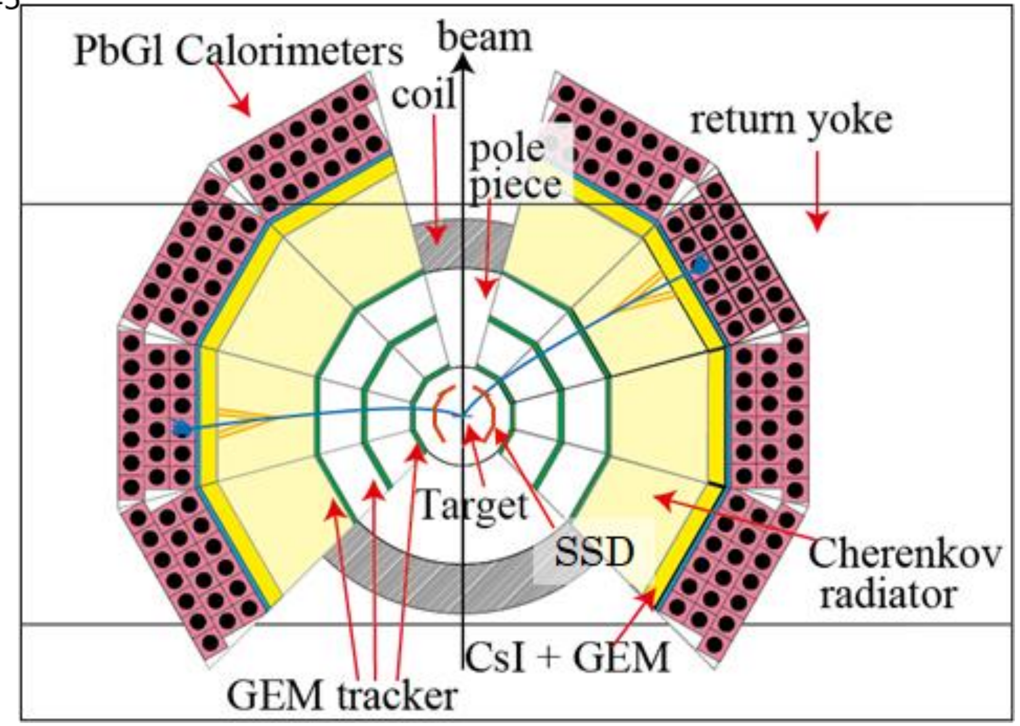




J-PARC E88 : pA→ϕ→K$^+$K$^-$

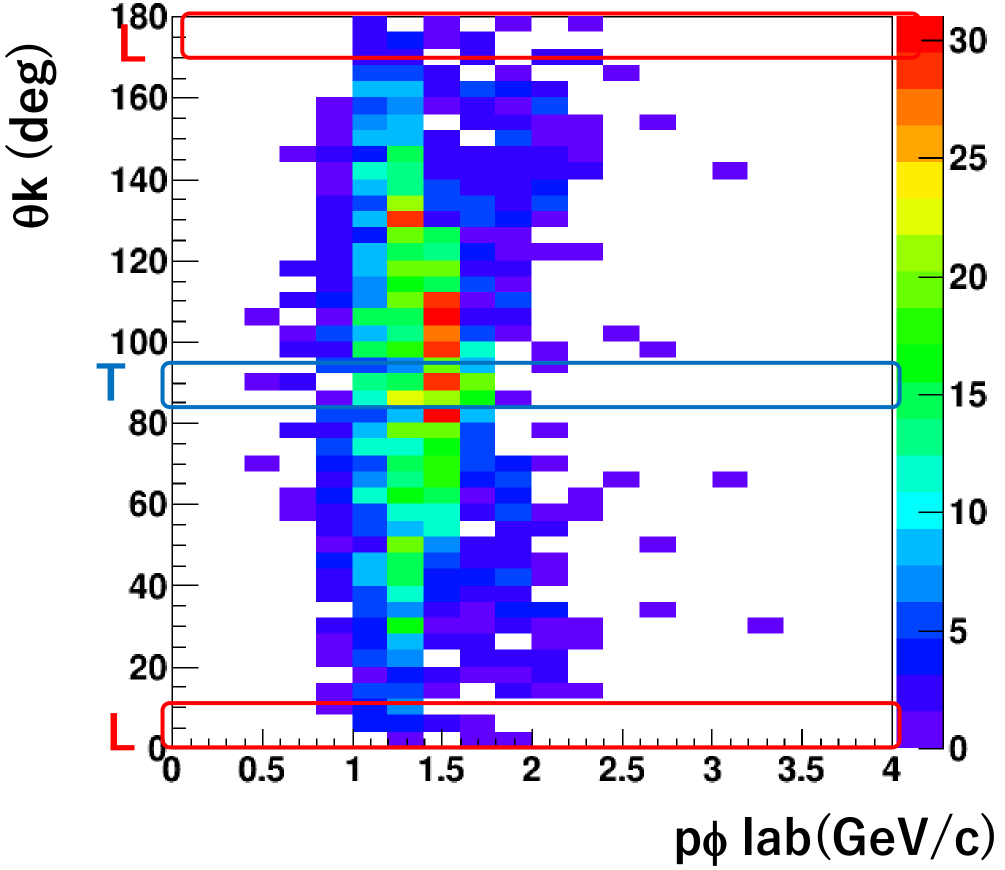


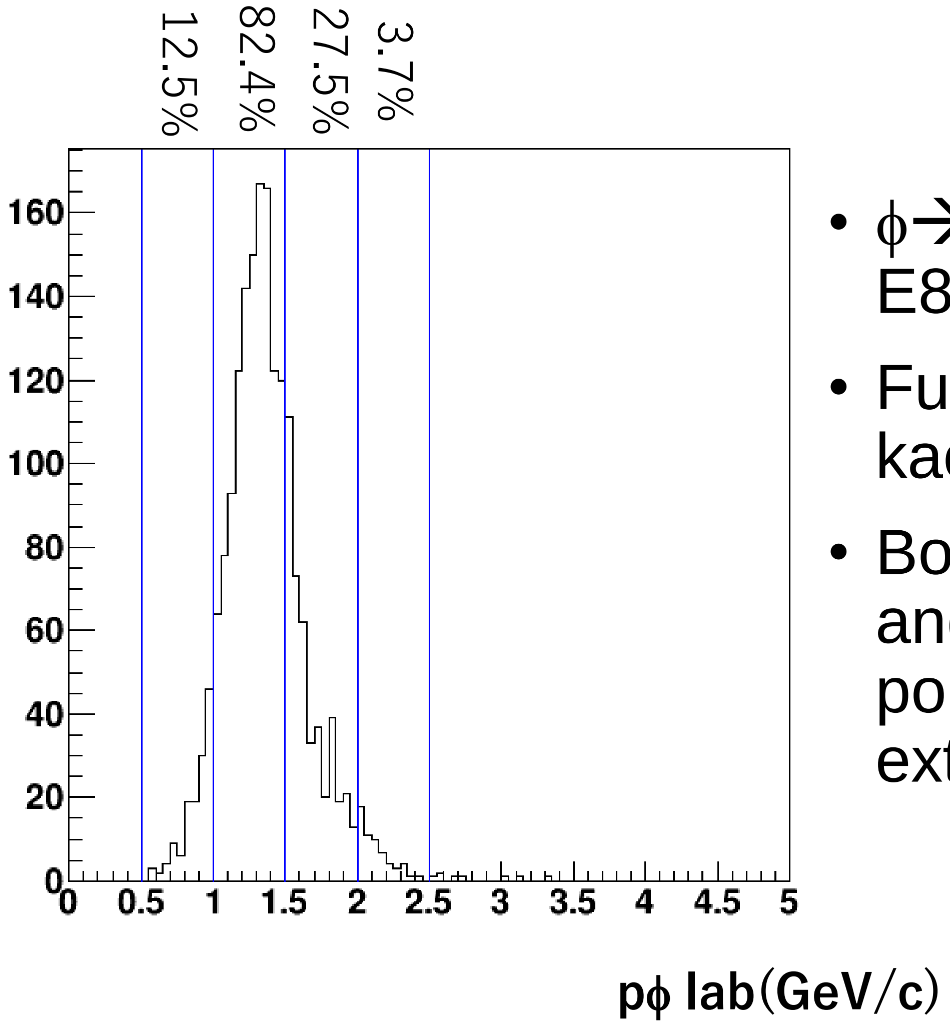




- 6 forward modules (detector unit) in top and bottom layers
- MRPC (Multi-gap Resistive Plate Chamber) and TSC(Track start counter) for Time-of-Flight measurement
- AC (Aerogel Cherenkov Counter) for pion rejection
- SSDs (Silicon Strip Detectors) and GTRs (GEM Trackers) for tracking

Distinguishing ϕ polarization at E88





- ϕ→K+K- within E88 acceptance
- Full acceptance in kaon decay angle
- Both transverse and longitudinal polarized ϕ can be extracted

Orthogonal functions for K+K-

- We can also find orthogonal functions for KK
- Thanks to the high statistics and lucky distribution, we may simply select sweet spots (near cos=1 or 0) to see the spectrum.
    - KK
    - ee

KK:

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

$$\begin{aligned} f_T(x) &= (1-x^2) \\ f_L(x) &= x^2 \\ h_T(x) &= \frac{1}{2}[3-5x^2] \\ h_L(x) &= \frac{1}{2}[5x^2-1] \end{aligned}$$

ee:

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

$$\begin{aligned} f_T &= 1+x^2 \\ f_L &= 1-x^2 \\ h_T &= 5x^2-1 \\ h_L &= 2-5x^2 \end{aligned}$$

Polarization-dependent mass measurement

- Model independent T/L separation is pursued here for ee.
  - Note: Model comparison is possible w/o separating T/L experimentally.
- Need further consideration
  - Angular dependence of acceptance/efficiency.
  - Background effects
  - Increase statistics / acceptance if necessary
    - Widen acceptance for low momentum particles.
    - Covering wider acceptance, closer to the targets.
- KK performs better in terms of polarization dependence measurement although FSI need to be taken care of.

Summary

- J-PARC E16 will measure ee in pA collisions at 30GeV to study the origin of hadron mass through the spectral change of vector mesons in the nuclear medium.
- We gradually increased our acceptance and reached an intermediate goal (RUN1), which is 1/3 of the design configuration(RUN2).
- We are preparing for Run0e planned in 2024.
  - Get PAC approval for RUN1 (1st physics runs).
- The possibility of measuring polarization-dependent mass modification.
  - Extraction method.
  - Its results. (further realistic consideration needed.)
  - E88 (KK) performs better in terms of pol measurement. Commentary each other.

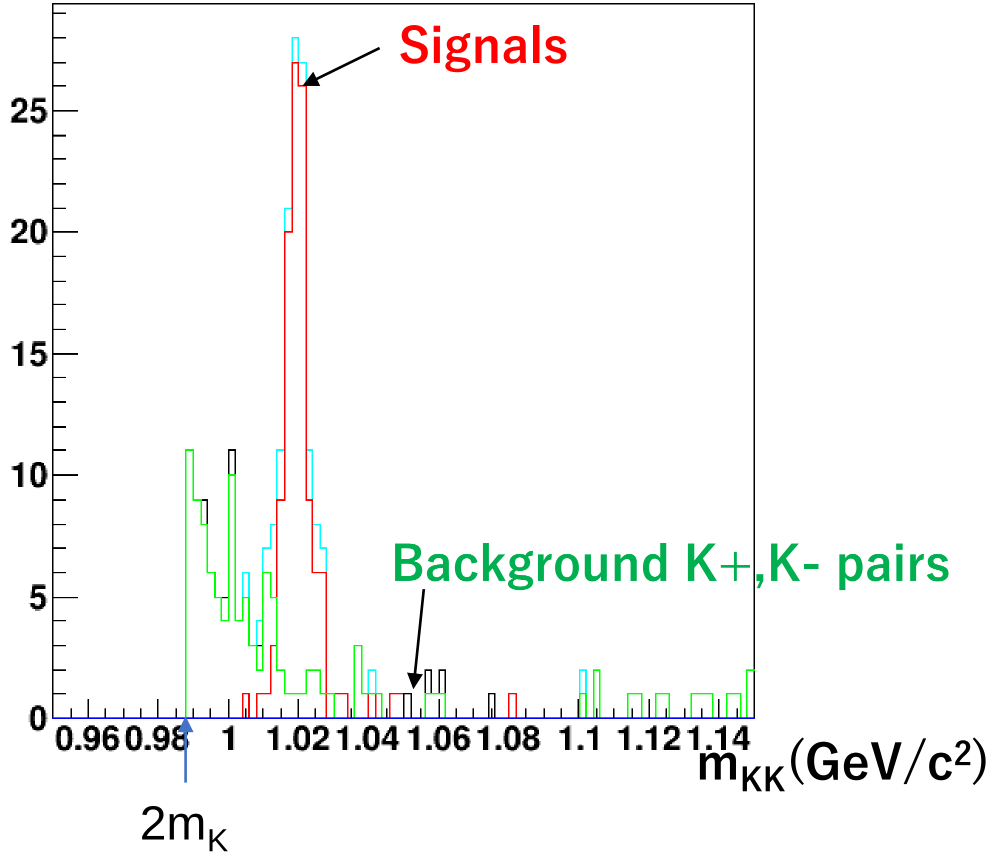
Expected S/B

p+Cu, JAM event generator + GEANT4

- S/B ~ 7.1 (integral in 1.013-1.028 GeV/c^2)

  ~ 27 (at the ϕ peak)

w/KK trigger, w/ PID cuts



Simple method (maybe easier to subt. BG)

- Divide sample into two : Say, A ={x; |x|>0.5}, B={x; |x|<0.5}
  - (Subtract BG at this point.)

$$
\begin{aligned}
G_A(m) &= \int_A G(m,x) \\
&= \int_A g_T(m) f_T(x) + g_L(m) f_L(x) dx \\
&= g_T(m) \int_A f_T(x) dx + g_L(m) \int_A f_L(x) dx \\
&\equiv C \cdot g_T(m) + D \cdot g_L(m)
\end{aligned}
$$

$$
\begin{aligned}
G_B(m) &= \int_B G(m,x) \\
&= \int_B g_T(m) f_T(x) + g_L(m) f_L(x) dx \\
&\equiv E \cdot g_T(m) + F \cdot g_L(m)
\end{aligned}
$$

角度サンプルA＝　C x　Trans + D x Long

角度サンプルB＝　E x Trans + F x Long

- Then solve them. (連立一次方程式)

$$
\begin{aligned}
g_T(m) &= \frac{F \cdot G_A(m) - D \cdot G_B(m)}{CF - DE} \\
g_L(m) &= \frac{E \cdot G_A(m) - C \cdot G_B(m)}{DE - FC}
\end{aligned}
$$

Expected statistics

Beam time: 30 days with 30 GeV proton beam at 10^9 / spill

- C (0.1% int.) + Cu (0.1% int.) + new Pb (0.1% int.) target

ϕ→K+K- signals				E325	
	C	Cu	Pb	C	Cu
Total ϕ	159k	262k	662k	419	833
ϕ ($\beta\gamma<1.25$)	72k	113k	314k		
ϕ ($1.25<\beta\gamma<1.75$)	84k	146k	340k		

ϕ→K+K- rate			
	C	Cu	Pb
ϕ signal rate (/spill)	2.95	5.41	12.8
Trigger rate (/spill)	78	161	365

F. Sakuma, et al,
PRL 98, 152302 (2007)

Information from p-ϕ interaction
Attractive interaction → mass reduction

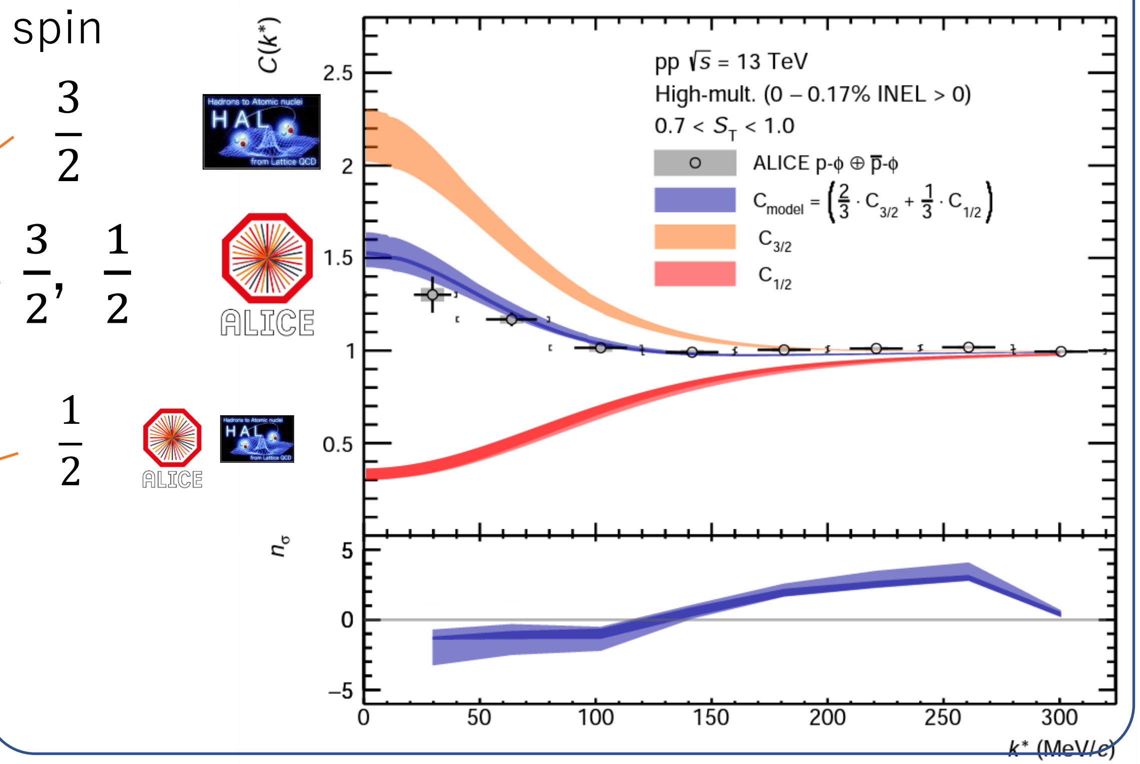
p-ϕ interaction info in terms of
scattering length and
effective range.

- Mass reduction
  - HAL : 5.3% ± 0.4%
  - ALICE : 5.8% ± 1.8%
  - ALICE-HAL: 1.3~9.0%

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

arXiv: 2212.12690

Two-particle correlation



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

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

HAL QCD method, arXiv:2205.10544 (2022)

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

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

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

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