Measurement of polarization dependence

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E16 workshop @ Taiwan
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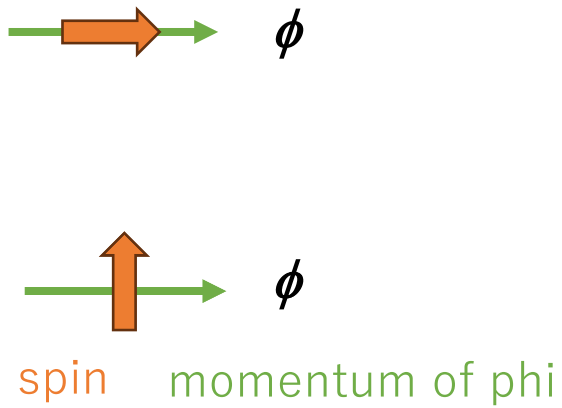
Pol dependence of mass distribution

- PLB805 (2020) 135412, Kim-Gubler
  - calculated the momentum dependence of phi mass (dispersion relation)
  - Also polarization dependence of mass.
  - Experimental investigation important.

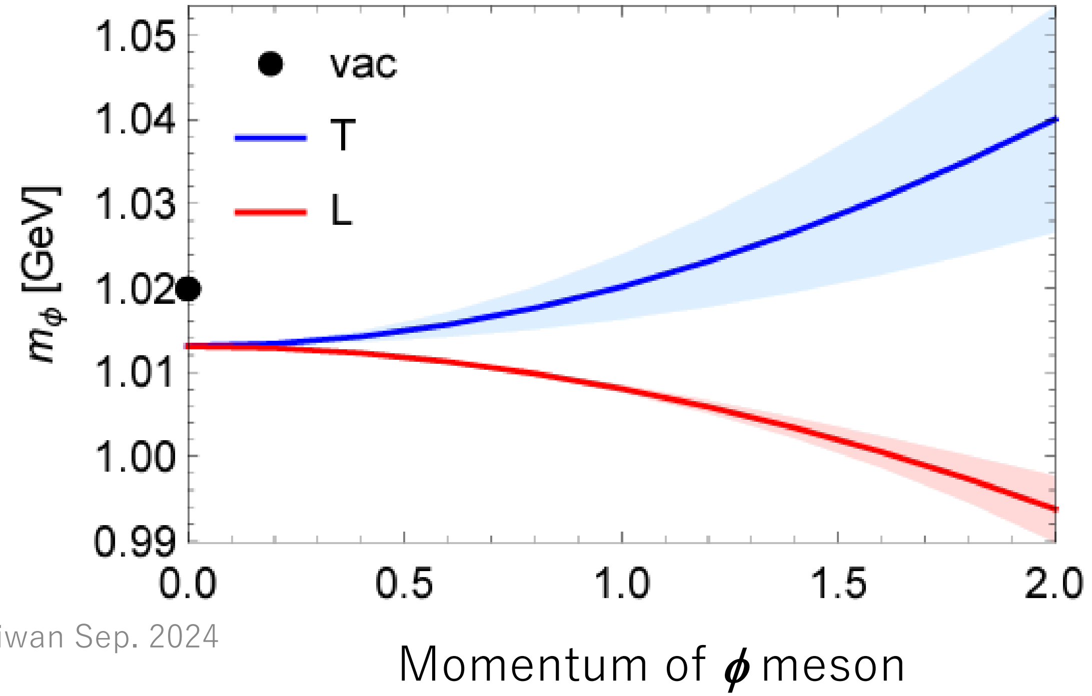
Definition for spin-1 particle

Transverse

Longitudinal



Dispersion relation up to 3 GeV/c

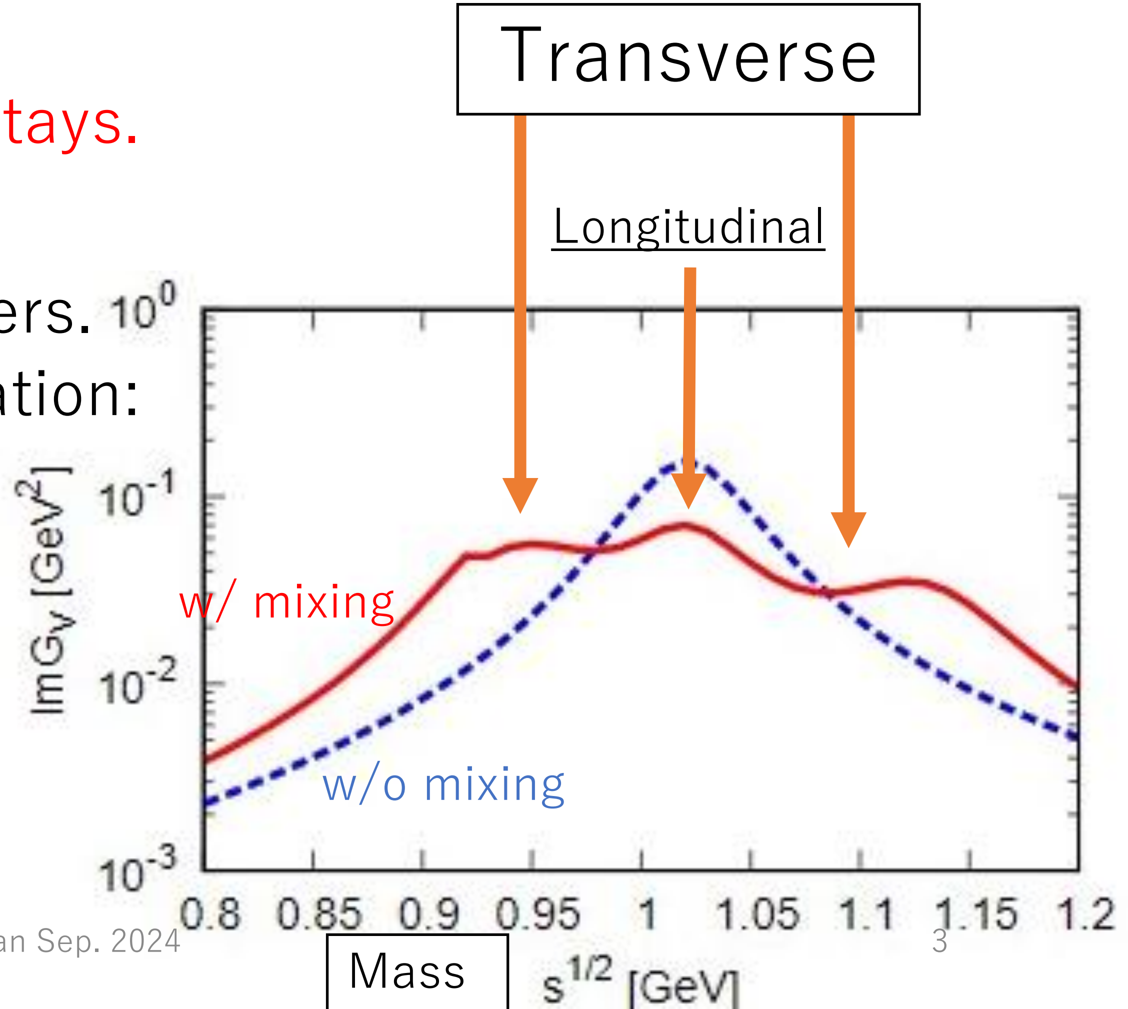


Anomaly-induced chiral mixing of ϕ and $f_1(1420)$

- 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!

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

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



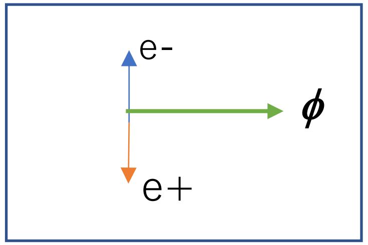
We have learned from Ejima-san that the unpol measurement itself is difficult…

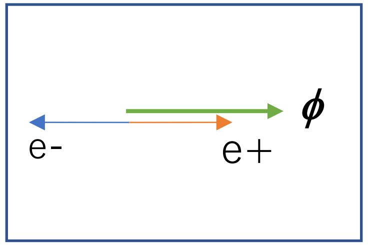
CONTENTS

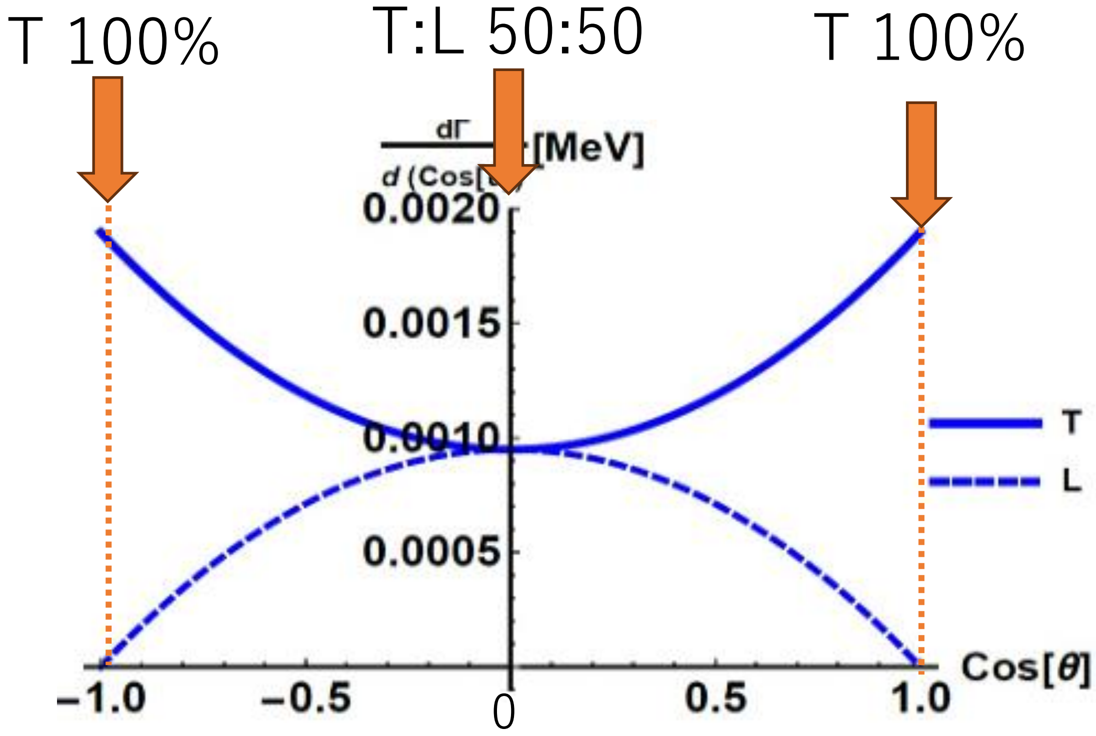
- Decay angle $\phi \rightarrow e^+e^-$ / K+K- to access polarization
- Expected spectrum
  - Based on E325-type model calc.
- How can we experimentally separate?
  - Finding orthogonal functions.
- Do the methods work?
- How to improve?

Polarization ←→ Angular dist. in helicity rest frame

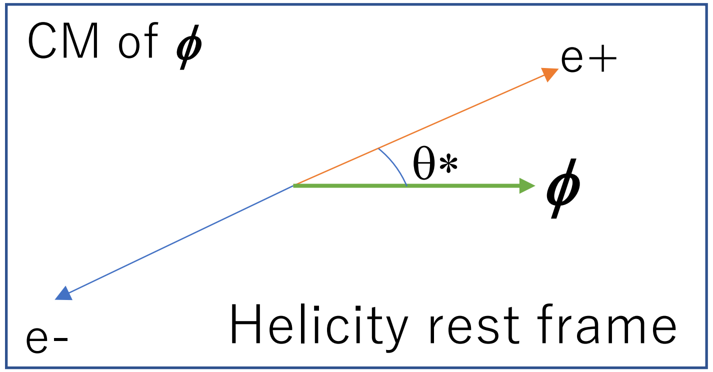
- Phys.Rev. D 107,7 (2023)
  I.W. Park, H. Sako, K.A., P.Gubler, S.H.Lee
- ϕ →ee
  - Spin 1 is taken by the spin of ee.
    - $\cos\theta = \pm 1$: T 100%
    - $\cos\theta = 0$: L 50%, T 50%
  - Small FSI
  - Limited acceptance at $\cos\theta^* = \pm 1$







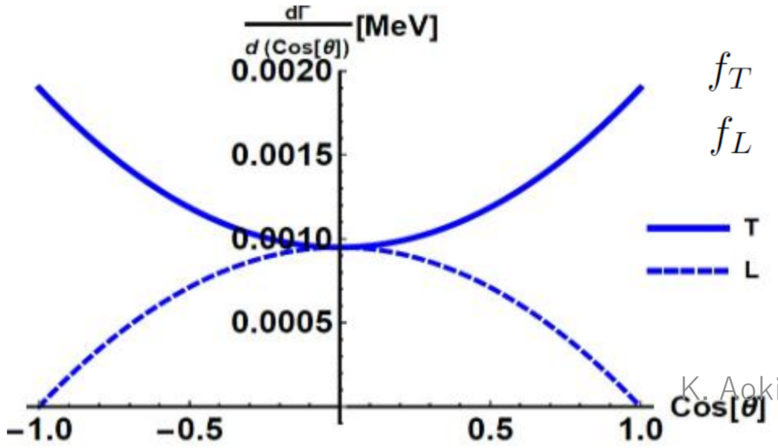
$x = \cos\theta^*$



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

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

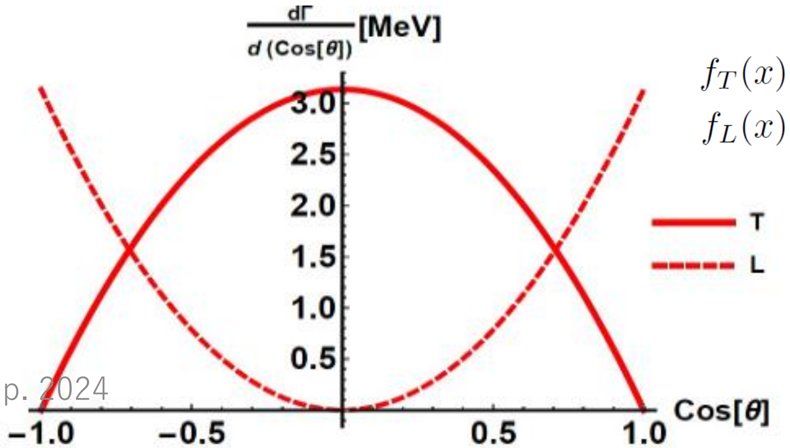
- Spin 1 is taken by ee pol.
  - $\cos\theta = \pm 1$: T 100%
  - $\cos\theta = 0$: L 50%, T 50%
- Small FSI
- Small BR (2.98 x 10^{-4})
  - 15k for 53 days (E16 Run1)



$$f_T = 1 + x^2$$
$$f_L = 1 - x^2$$

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

- 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)

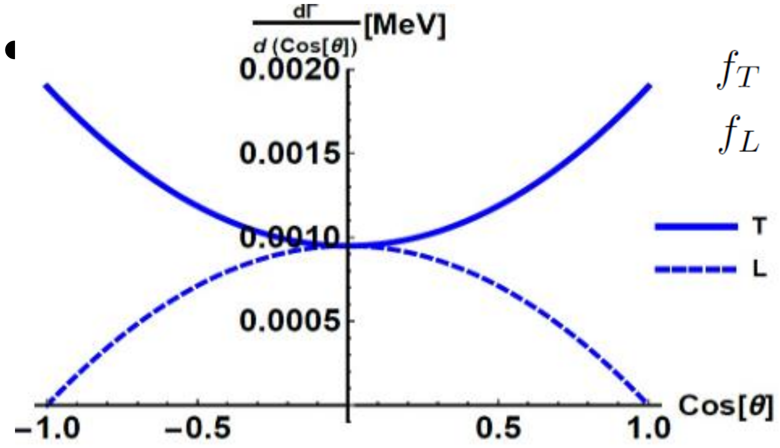


$$f_T(x) = (1 - x^2)$$
$$f_L(x) = x^2$$

Spin dependence.

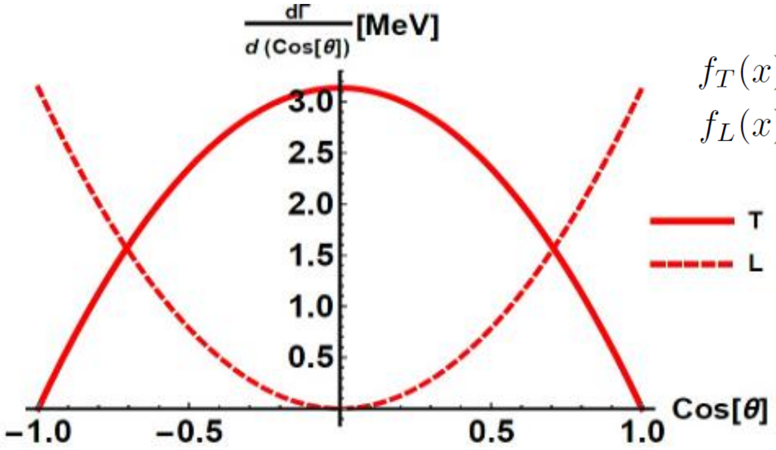
Spin of phi |1,1> |1,0> |1,-1>

Spin of ee |1,1> |1,-1>



$$f_T = 1 + x^2$$
$$f_L = 1 - x^2$$

OAM of KK



$$f_T(x) = (1 - x^2)$$
$$f_L(x) = x^2$$

X=cos(θ)

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

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

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

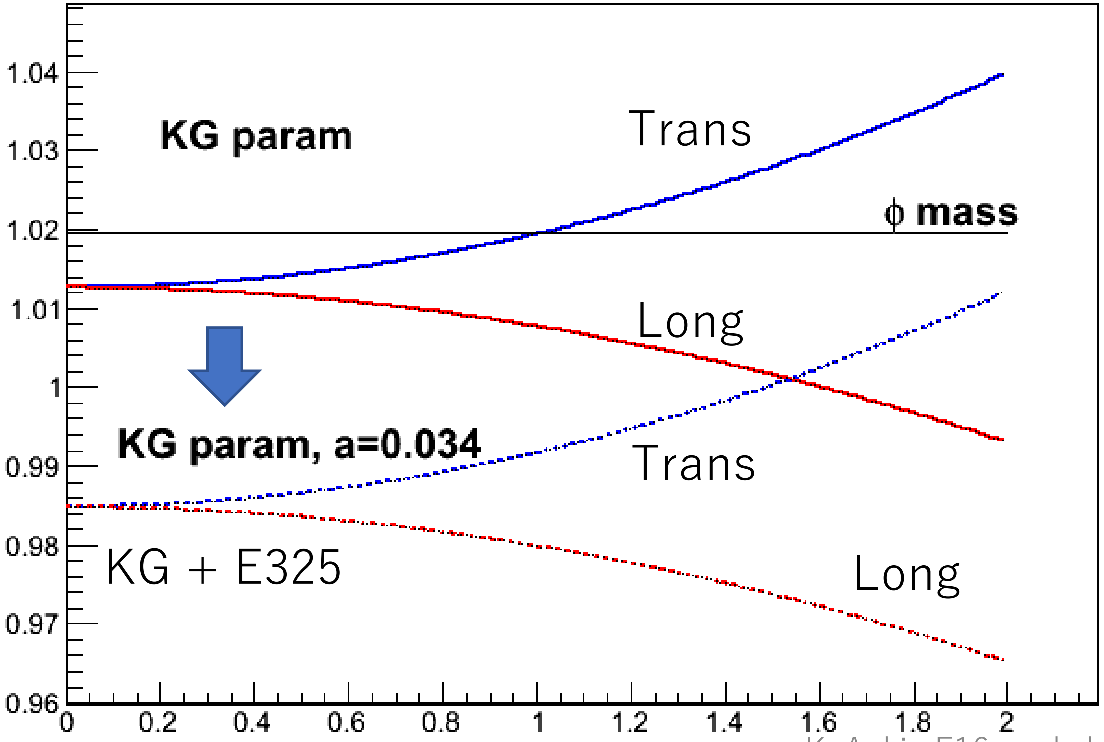
L $Y^0_1 = \sqrt{\frac{3}{4\pi}} \cos\theta$

T $Y^1_1 = -\sqrt{\frac{3}{8\pi}} \sin\theta\, e^{i\phi}$

2×

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.

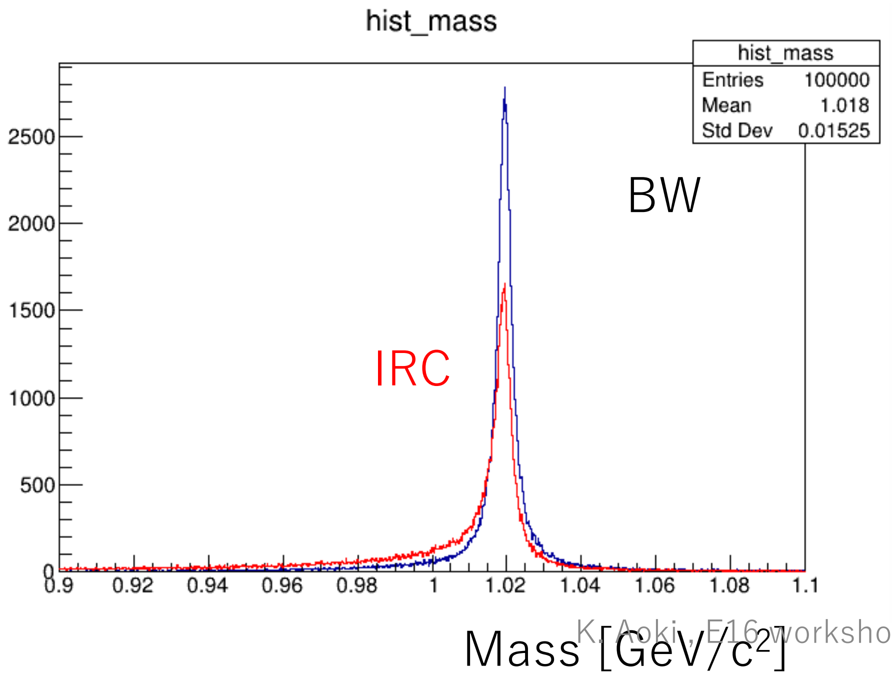


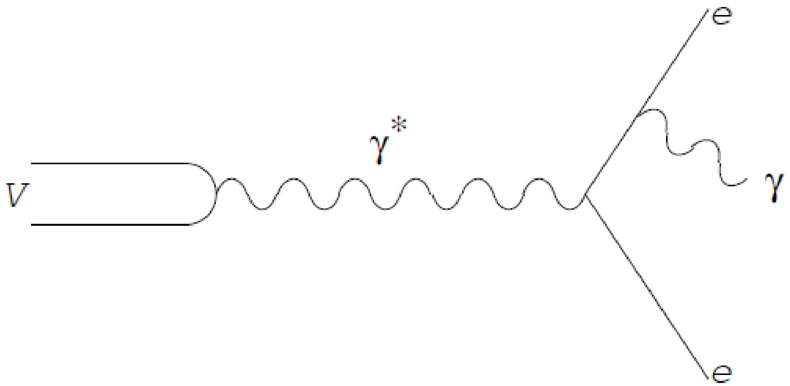
$$\frac{m_\phi^{\mathrm{L/T}}(\rho_N,\vec{q})}{m_\phi^{\mathrm{vac}}} = 1 + \left(a + b^{\mathrm{L/T}}|\vec{q}|^2\right)\frac{\rho_N}{\rho_0}.$$

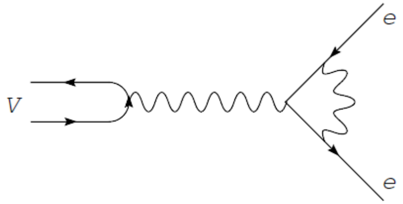
- KG param
  - b(T) = 0.067 pm 0.0034
  - b(L) = -0.0048 pm 0.0008/GeV
  - a = -0.0067
- KG + E325 param
  - a=0.034
  - b : same as KG param.

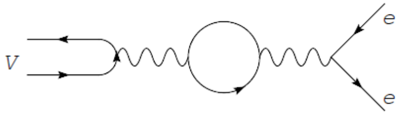
Monte Carlo simulation input

- 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.



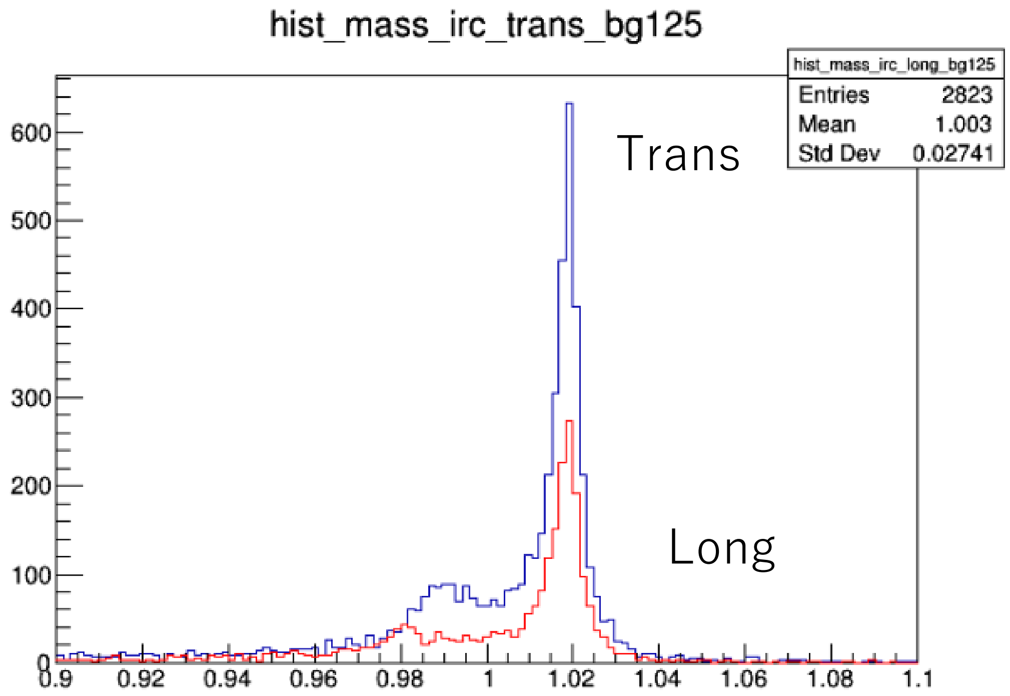


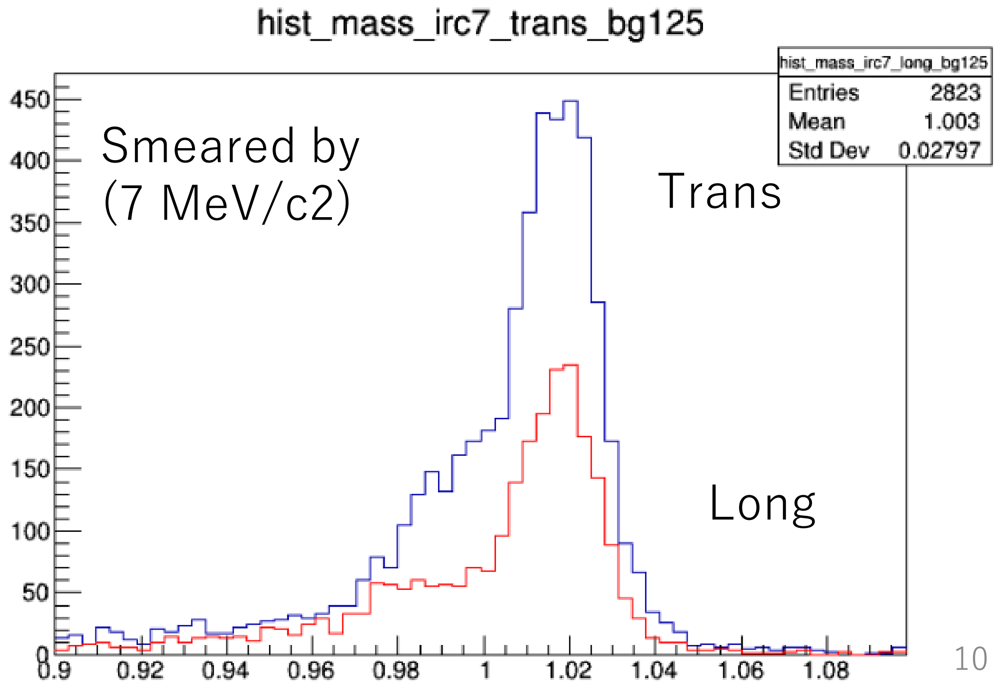




E325-type calculation using KG param.

- 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: $G(m,x)$; Want to know: $g_T(m)$, $g_L(m)$; Known: $f_T(x)$, $f_L(x)$)

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

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

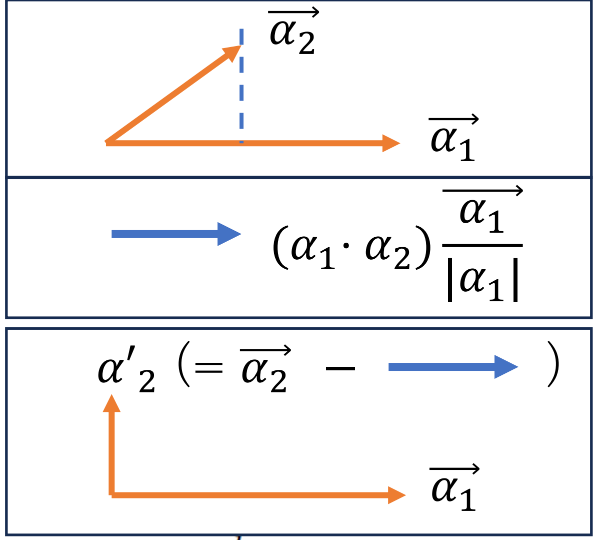
- If we can find a function $h_T(x)$ that is orthogonal to $f_L(x)$
  - $h_T(x)$: eliminates L and what's left is T.

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

(Measured: $G(m,x)$; Want to know: $g_T(m)$, $g_L(m)$; Known: $f_T(x)$, $f_L(x)$; the term $g_L(m) f_L(x)$ is crossed out)

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

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.

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

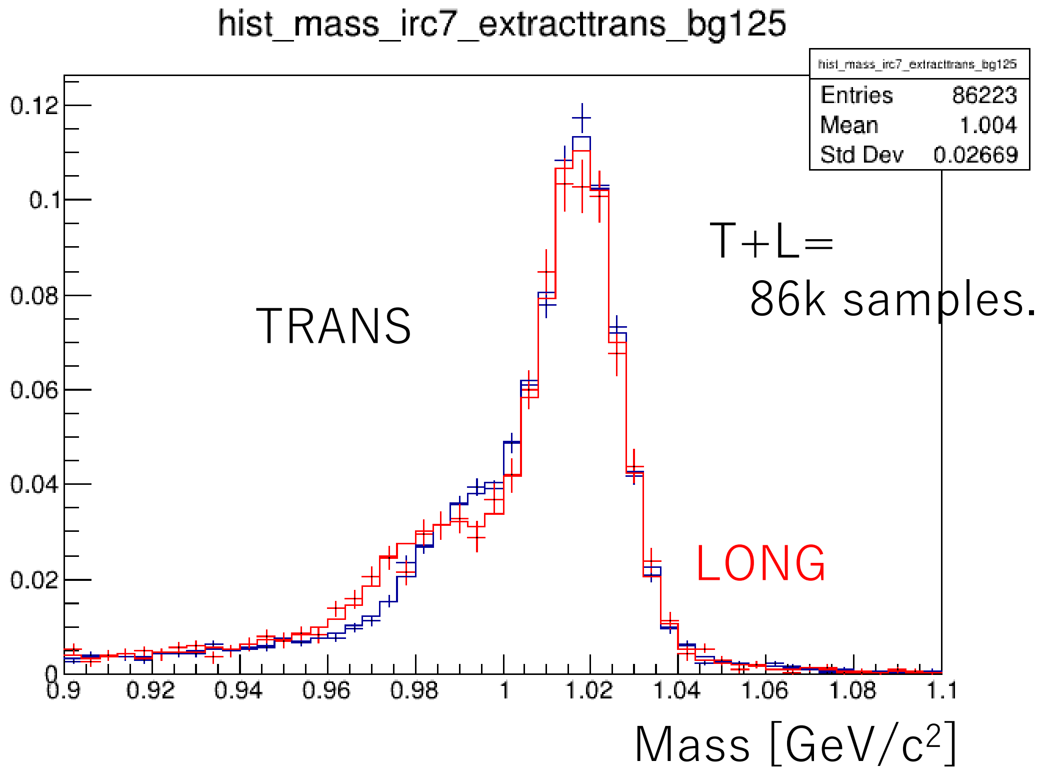
$$f_T = 1 + x^2$$
$$f_L = 1 - x^2$$
$$h_T = 5x^2 - 1$$
$$h_L = 2 - 5x^2$$

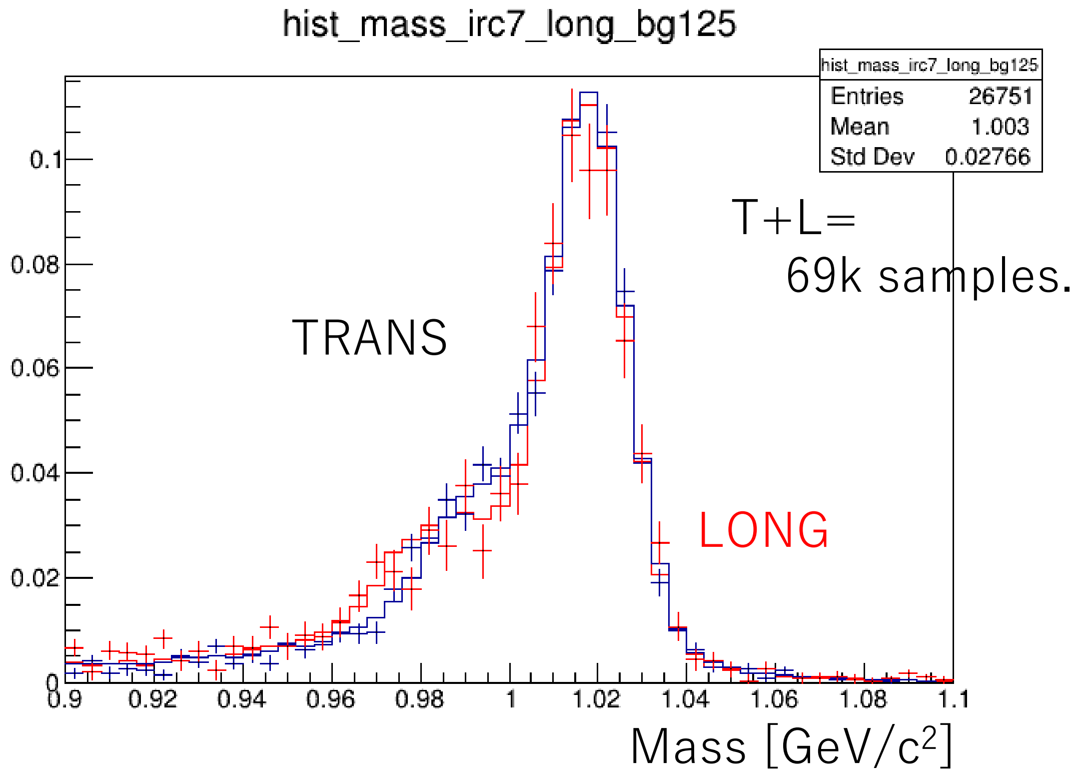
$x = \cos\theta = [-0.8,0.8]$

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

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

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

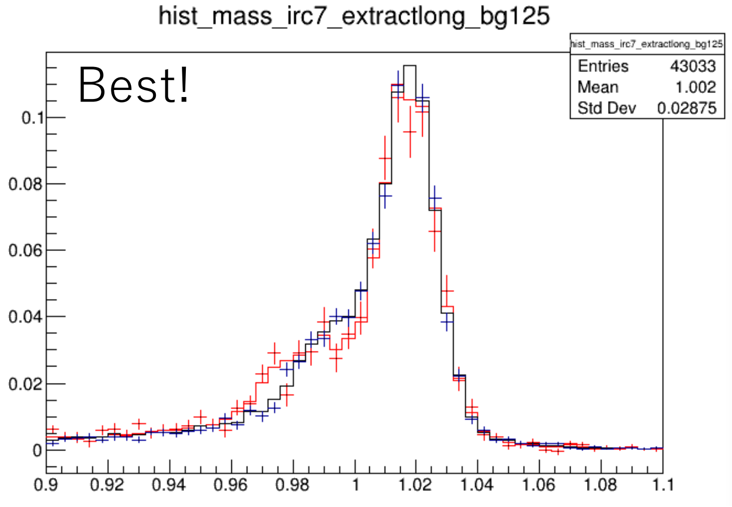


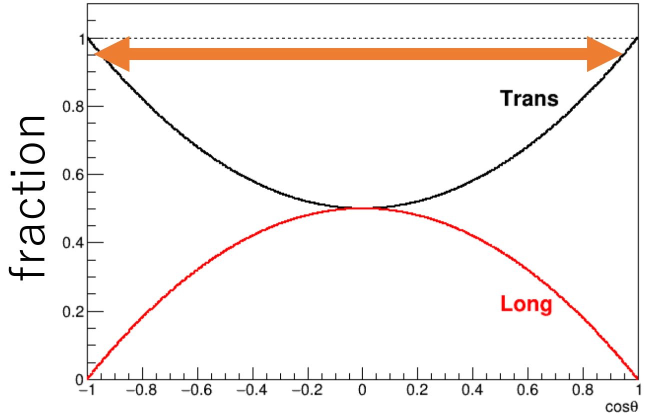


LINE : According to polarization information which God only knows
\+ : Extracted using the orthogonal functions $h_T(x), h_L(x)$

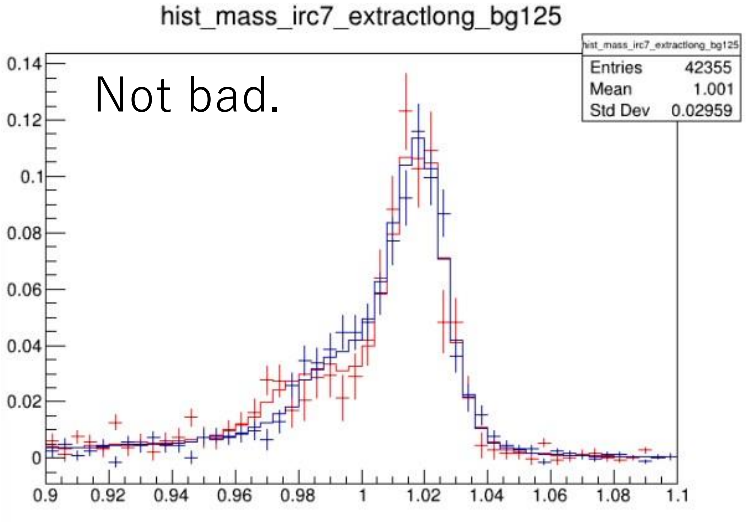
Same statistics but different angular acceptance in the rest frame of $\boldsymbol{\phi}$.

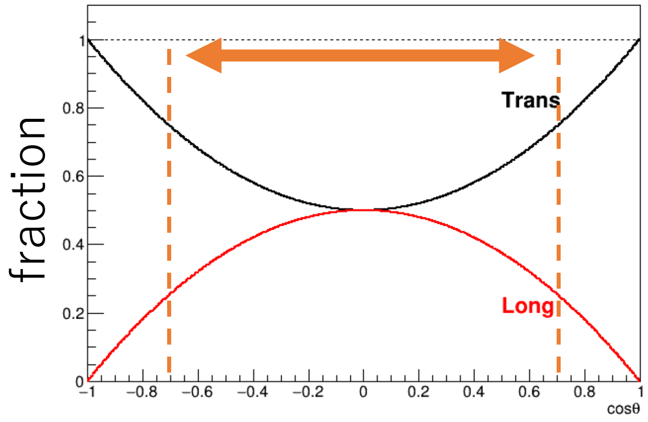
- $\cos\theta = [-1,1]$



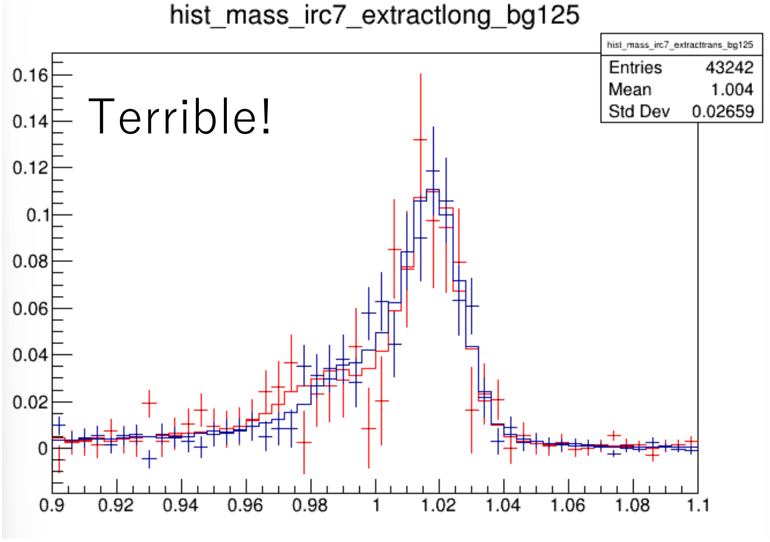


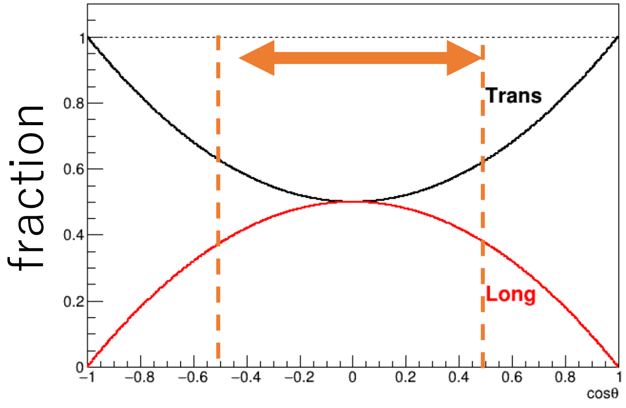
- $\cos\theta = [-0.7,0.7]$





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

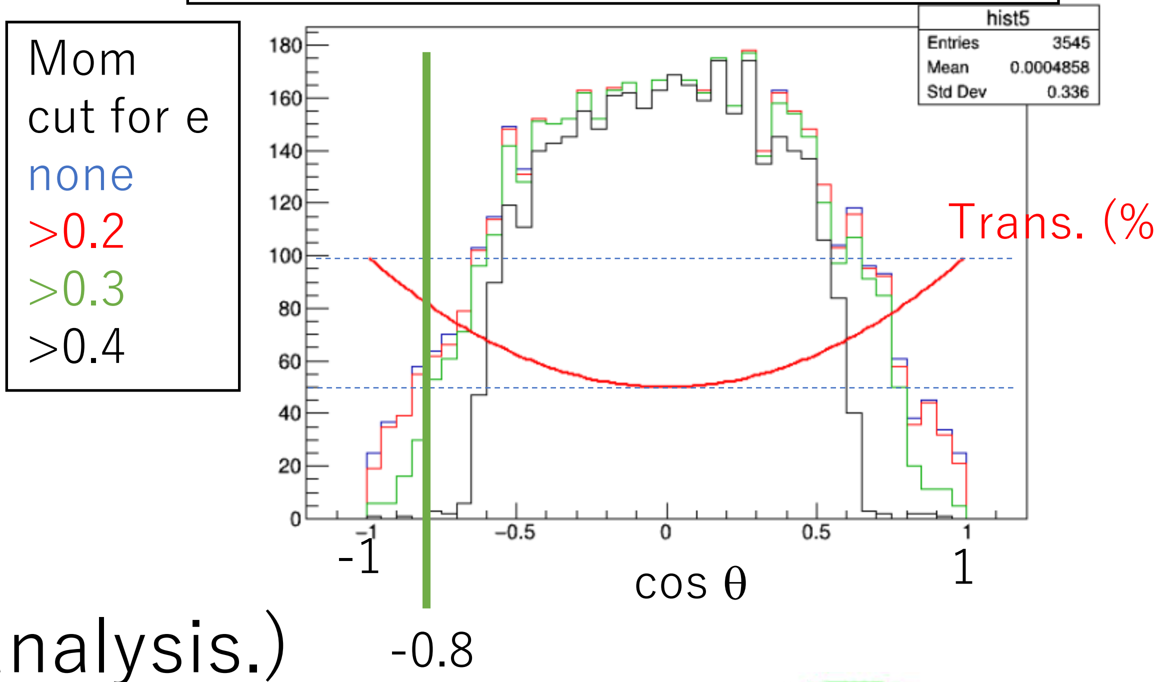


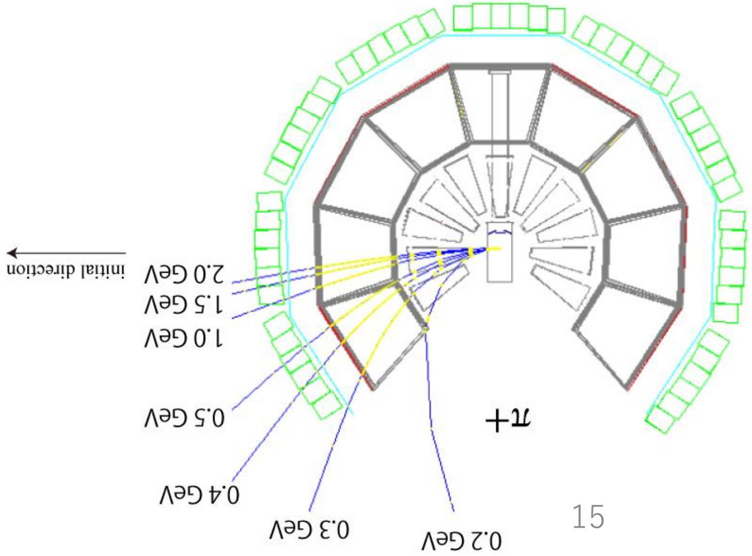


Angular acceptance of ϕ. E16 case.

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

- GEANT4 as an acceptance filter.
- Results
  - LG trig eff has to be multiplied
    - ~90% 0.4GeV, ~75% 0.3GeV
  - Reality is between Green and black.
  - Smaller acceptance for $\cos\theta = \pm 1$
- (Needs acceptance correction for analysis.)
- $|\cos\theta| < 0.7 \sim 0.8$ maybe used w/ acceptance correction but rather marginal.



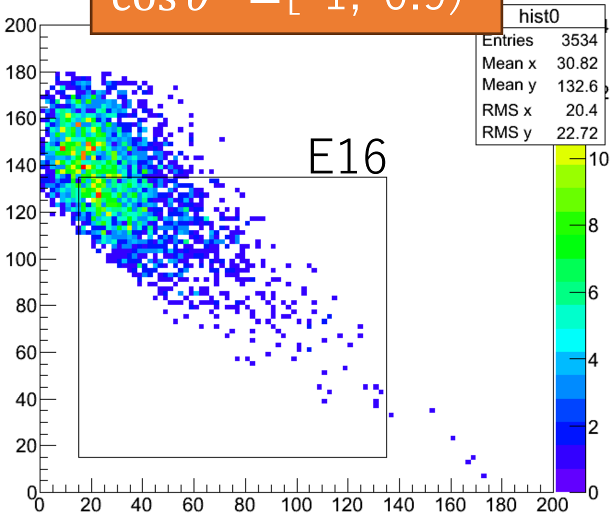


- How can we increase the sensitivity to $|\cos\theta| \to 1$

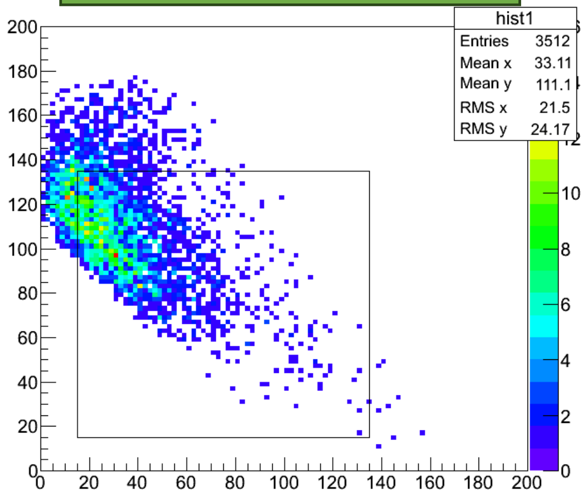
$e^+ e^-$ angle at lab. ϕ meson $\beta\gamma$<1.25 JAM+IRC w/o GEANT4.

(T~100%) ⟷

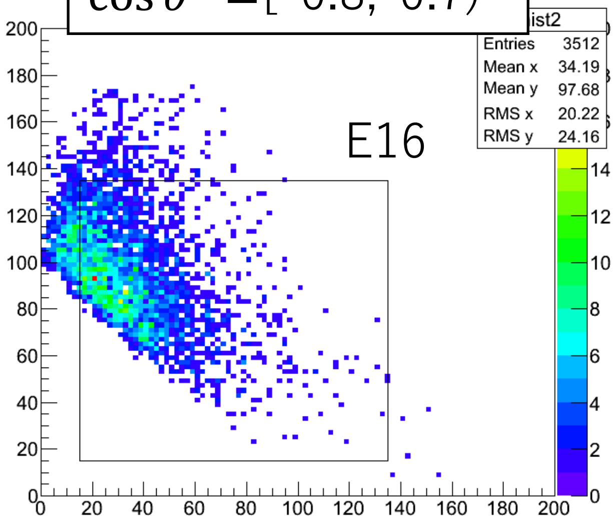
$\cos\theta^* = [-1,-0.9)$



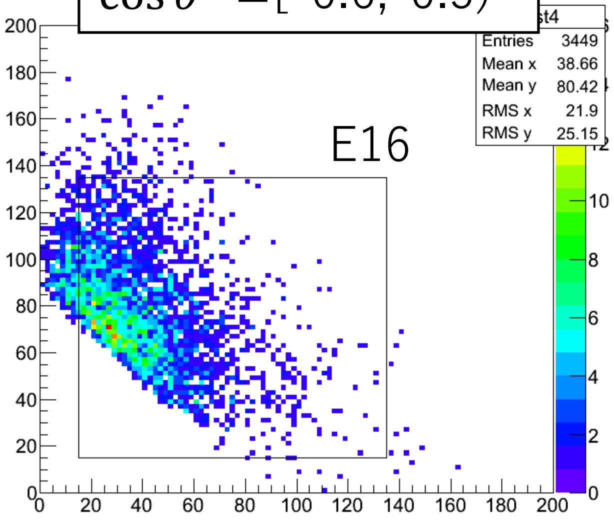
$\cos\theta^* = [-0.9,-0.8)$

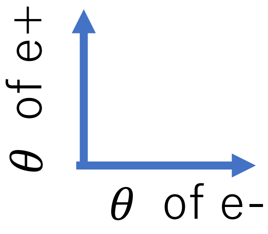


$\cos\theta^* = [-0.8,-0.7)$

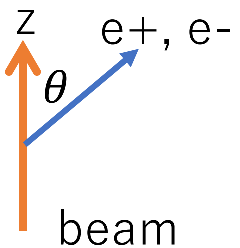


$\cos\theta^* = [-0.6,-0.5)$





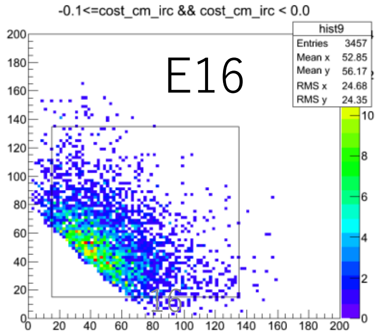
Plot's axis



Definition of θ

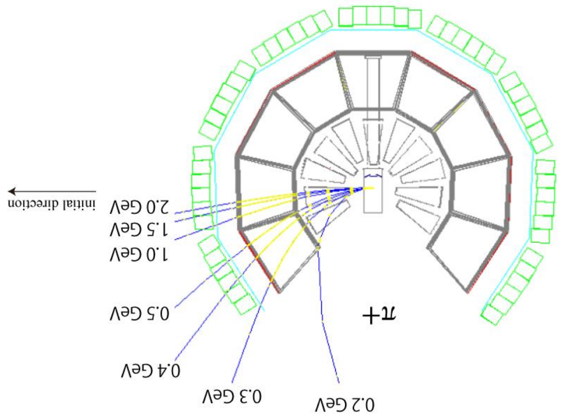
T:L = ~50%:50%

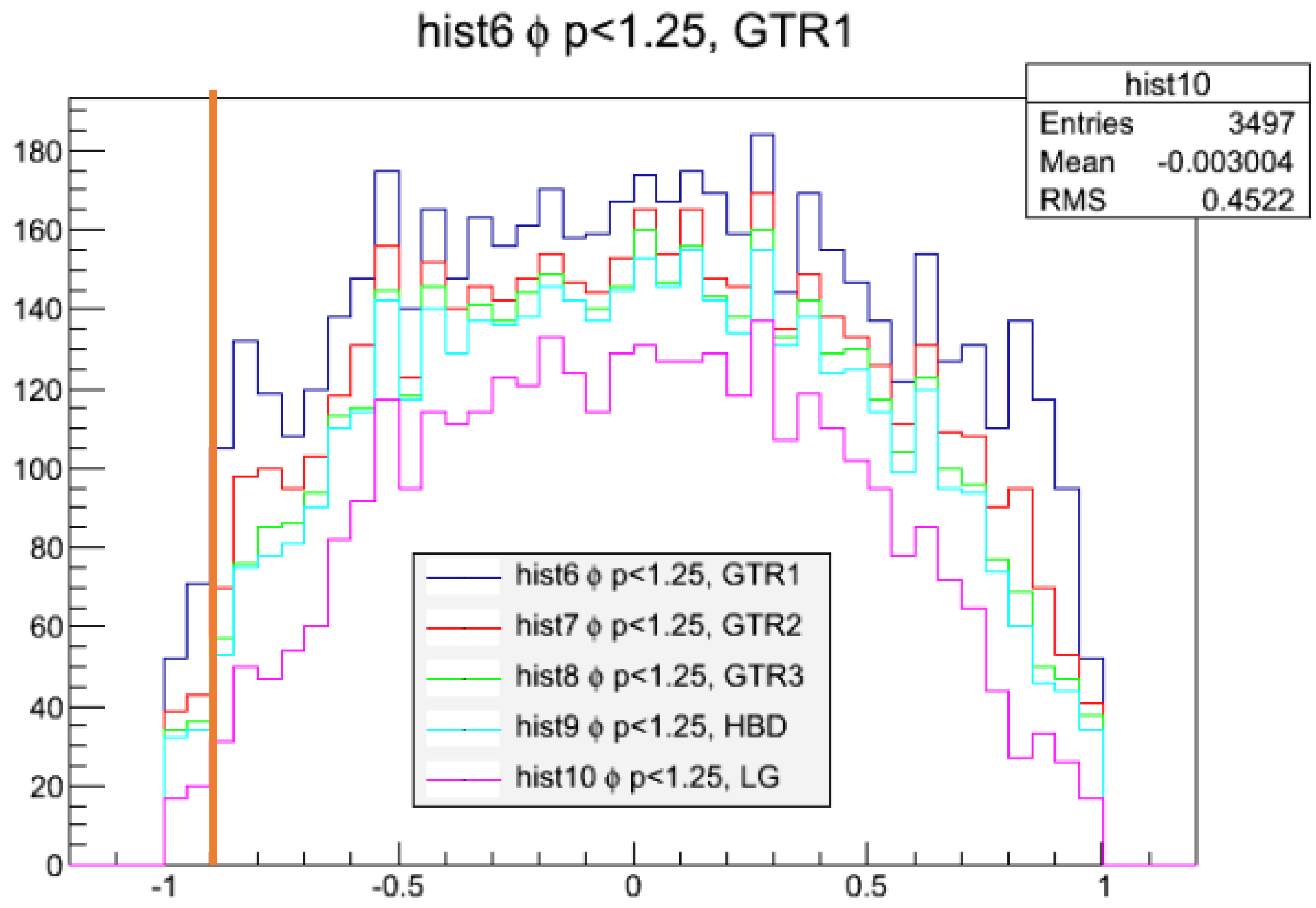
$\cos\theta^* = [-0.1,0)$



- The box is the E16 "ANGULAR" coverage.
- $\cos\theta^* = [-1,-0.9)$: (Most wanted) : Coverage missed majority.
- $\cos\theta^* = [-0.9,-0.8)$: Angular coverage wise OK?

E16 spectrometer case but release requirements.





- If we restrict ourselves to
  - GTR1(R~200mm)
  - GTR2(R~400mm)
  - GTR3(R~600mm)
  - HBD(R~1200mm)
  - LG（R~1500mm) ← E16.
- Making it compact
  - TOF for low momentum e. triggerless DAQ.
  - Add backward modules.
- Making it wider
  - TPC-type configuration

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:

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

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

Summary

- Good motivation for polarization dependent mass meas.
  - It can be studied by exploiting decay angular distribution.
- KK vs ee
  - KK:
    - Good: Lot of statistics. Lucky angular distribution.
    - Bad: FSI. Treated by PHSD.
  - ee:
    - Good: Free from FSI.
    - Bad: small statistics, unlucky angular distribution.
- Orthogonal function can be used to extract polarization dependence.
- Backward daughter has lower momentum, open angle at lab wide.
  - Compact or wide angular coverage is highly desired.
- E16 spectrometer
  - |Theta| < 0.7 or 0.8 marginal.
- Beyond E16 spectrometer
  - Make it compact and/or wider acceptance.