Update on $K_{L,S} \rightarrow \pi^+\pi^-\gamma$

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Status of fitter

- The fitter for the analysis has been written
  - Using an unbinned likelihood fit with a decent sized sample. This means it is SLOW.
    - Calculate likelihood in parallel
  - Uses Minuit to maximize likelihood
    - Minuit can also estimate the stat error for the fit
  - e-hat, g_{E1}, g_{M1} and a_1/a_2 are current fit parameters
  - Now in debugging and testing stage.......

Likelihood function

- This is the likelihood function:

$$\log L\left(\vec{\alpha}\right)=\log L^{97}_{vac}\left(\vec{\alpha}\right)+\log L^{97}_{reg}\left(\vec{\alpha}\right)+\log L^{99}_{vac}\left(\vec{\alpha}\right)+\log L^{99}_{reg}\left(\vec{\alpha}\right)$$

decay rate (see next slide)

where

$$\log L^{year}_{beam}\left(\vec{\alpha}\right)=\sum_{i=1}^{N_{Data}}\log D(\vec{x}_i;\vec{\alpha})-N_{Data}\log\sum_{i=1}^{N_{MC}}\frac{D\left(\vec{x}_i;\vec{\alpha}\right)}{D\left(\vec{x}_i;\vec{\alpha}_0\right)}$$

fit parameters

(E_γ, $\cos\theta$, z, p_K)

generation parameters

- Note that it is split up by year and beam
- A single fit could use all data at once.

Decay Rate

- In the likelihood function, D =

$$\frac{dN}{d\tau\, dE_\gamma\, d\cos(\theta)} = N_K \left[\left|\rho^2\right| \left[\frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \right] e^{-\frac{\tau}{\tau_s}} + \left[\frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos\theta} \right] e^{-\frac{\tau}{\tau_L}} \right.$$

where

$$\left. + 2\, Re\left[\rho \frac{d\gamma^*_{LS}}{dE_\gamma\, d\cos(\theta)} e^{i\Delta m_K \tau} \right] e^{-\left(\frac{1}{\tau_L}+\frac{1}{\tau_S}\right)\frac{\tau}{2}} \right]$$

$$\frac{d\gamma_{LS}}{dE_\gamma\, d\cos(\theta)} \propto \left[E_{IB}(K_L) + E_{DE}(K_L)\right] * \left[E^*_{IB}(K_S) + E^*_{DE}(K_S)\right] + M(K_L)\, M^*(K_S)$$

$$\frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_L) + E_{DE}(K_L)\right|^2 + \left|M(K_L)\right|^2$$

$$\frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_S) + E_{DE}(K_S)\right|^2$$

Decay Amplitudes

$$E_{IB}(K_S) = \left(4\frac{M_K^2}{E_\gamma^2}\right)\frac{e^{i\delta_0}}{1-\beta^2\cos^2(\theta)}$$

CP Conserving

$$E_{IB}(K_L) = \left(4\frac{M_K^2}{E_\gamma^2}\right)\frac{\overbrace{\eta_{+-}}^{\epsilon+\epsilon'}\, e^{i\delta_0}}{1-\beta^2\cos^2(\theta)}$$

CP Violating

$$M(K_S) = i\,\epsilon\, g_{M1}\left(\frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K}+1\right)e^{i\delta_1}$$

CP Violating

$$M(K_L) = i\, g_{M1}\left(\frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K}+1\right)e^{i\delta_1}$$

CP Conserving

$$E_{DE}(K_S) = \frac{g_{E1}}{\epsilon}e^{i(\delta_1+\phi_\epsilon)}$$

CP Conserving

$$E_{DE}(K_L) = \underbrace{g_{E1}\,e^{i(\delta_1+\phi_\epsilon)}}_{\text{Indirect CP Violating Term}} + \underbrace{i\,16\,\hat{\epsilon}\,e^{i\delta_1}}_{\text{Direct CP Violating Term}}$$

CP Violating

Tests for fitter

- Can generate “fake data” with known parameters.
  - If best fit is not equal to the generation parameters, within statistical error, there's a problem with the fitter.
  - Fitter currently cannot reproduce generated parameters.
    - There's a confirmed problem with K_S / K_L normalization in fitter – the K_S part of the wave function is larger than it should be.

Current Bug

- The time dependence in the decay rate needs an accurate description of the average K_S/K_L amplitudes in the decay region.
- Looking at the beginning of the decay region (z ~ 125.5m) in the vacuum beam, The ratio between the K_S and K_L amplitudes is an order of magnitude larger in the fitter, compared to the same ratio for the MC.

Bug in kaon production or propagation?

- I Use the KTEVMC functions k0dp and kbdp to weight the relative contributions of K0 and K0-BAR to the initial kaon state.
  - Combined, these will produce the average K_S/K_L amplitude.
- Then I use kev832, also from KTEVMC, to propagate the kaon up to the decay region.
- The amplitude problem exists in the decay region, so I don't know if the bug is in the production or propagation of the kaon.
- Working on this now......

To Do

- Continue to debug until the fitter can accurately converge on generated parameters when running on "fake" data
- Fit a number of "fake" data samples and calculate standard deviation of fit parameters, then check against Minuit's errors.

More To Do

- Using more "fake" data, fit and extract stat errors for:
  - vacuum beam data only
  - regenerator beam data only
  - vacuum beam data and regenerator beam data combined.
  - use whichever option better constrains e-hat.

Even more to do

- See if it is necessary to fit for all parameters, since we're only interested in e-hat now.
  - Fixing M1 parameters might help, but I should worry about correlations.
  - Same holds for g_{E1}
- Finally compare statistical sensitivity to e-hat to the older method's sensitivity to ε'_{+-g}
  - Remember, the two parameters are related

Extra Slides

- Define:

$$\widetilde{\eta_{+-\gamma}} = \eta_{+-} + \left[\hat{\epsilon} + \underbrace{\frac{i}{16}\frac{\epsilon'}{\epsilon} g_{E1}\, e^{i\phi_{\epsilon}}}_{\text{Upper Limit} \sim \epsilon'} \right] e^{i\left(\delta_1 - \delta_0 + \frac{\pi}{2}\right)} \left| 2\frac{E_\gamma}{M_K} \right|^2 \left(1 - \beta^2 \cos^2(\theta)\right)$$

$$\widetilde{\eta_{+-\gamma}} = \eta_{+-} + \widetilde{\epsilon'_{+-\gamma}}$$

- We can also define

$$\eta_{+-\gamma} = \eta_{+-} + \epsilon'_{+-\gamma}$$

$$\epsilon'_{+-\gamma} = \frac{1}{\Gamma_{K_S \to \pi^+ \pi^- \gamma}} \int d[PS]\, \tilde{\epsilon}'_{+-\gamma} \left| E_{IB}(K_S) + E_{DE}(K_S) \right|^2$$

which is the connection between the “new” and “old” direct CP violation parameters for this mode. Given one, the other can be computed.

Cuts

Cut Variable	**Keep Event If...**
Kaon Mass	0.48967 $GeV/c^2 < M_{\pi^+\pi^-\gamma} <$ 0.50567 GeV/c^2
P_T^2 w.r.t Target and Regenerator	$P_T^2 < 2.5 \times 10^{-4}\ GeV^2/c^2$
Kaon Momentum	40.0 GeV/c $< P_{\pi^+\pi^-\gamma} <$ 160.0 GeV/c
Photon Energy in Lab Frame	$E^*_\gamma >$ 1.5GeV
Photon Energy in Kaon Rest Frame, From Calorimeter	5.0MeV $< E^*_\gamma <$ 175.0 MeV
Photon Energy in Kaon Rest Frame, From Kinematics	5.0MeV $< E^*_\gamma <$ 175.0 MeV
$\pi\pi$ Invariant Mass, Implied From Above Cut	0.2799 $GeV/c^2 < M_{\pi\pi} <$ 0.492 GeV/c^2
Shape χ^2 For Photon Cluster	$\chi^2 < 48$
Outer Fiducial Cut For Photon Cluster	ISEEDRING < 18.1 cm
Inner Fiducial Cut For Photon Cluster	ISMLRING2 > 4.5 cm
Photon/Track Separation at CsI	d > 30 cm
Number of Photon Candidates That Pass ALL Cuts	$N_{CLUS} = 1$ ONLY
pp0kin w.r.t. Target and Regenerator	-0.10 $GeV^2/c^2 < P^2_{\pi^0} <$ -0.0055 GeV^2/c^2
L3 pp0kin	passes
Z vertex	125.5 m < VTXZ < 158.0 m
E/p	E/p < 0.85
Track Momentum	TRKP > 8.0 GeV
Vertex χ^2	VTXCHI < 50.0
Magnet Offset χ^2	TRKOCHI < 50.0
M_Λ	$M_\Lambda <$ 1.112 GeV/c^2 OR $M_\Lambda >$ 1.119 GeV/c^2
Track x separation at CsI	$\Delta x >$ 3.0 cm
Number of Tracks	NTRK = 2
Beam Selection — vertex	GTREG*VTXX < 0
Beam Selection — trajectory	kaon trajectory can be traced back to regenerator
RECON832	Returns with no errors
MSK_VT0832	= 0
MSK_L1VER832	= 0
FID832	Event Passes Cuts