Direct Emission in $K_L \to \pi^+\pi^-\gamma$

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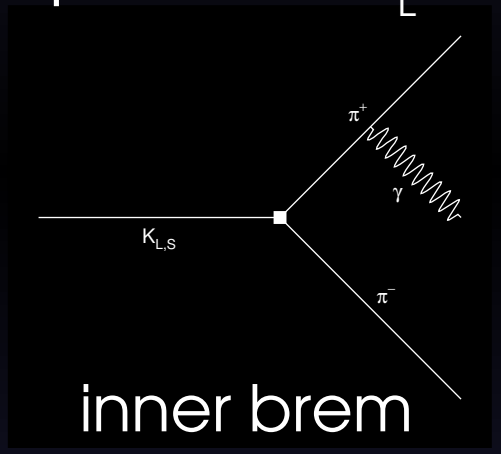
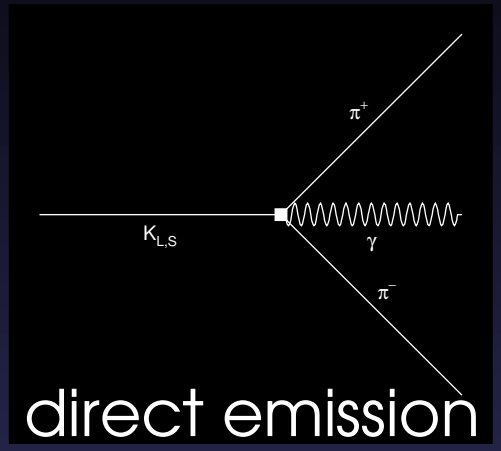
The decay $K_L \rightarrow \pi^+\pi^-\gamma$

- This decay is composed of two different processes:
  - inner bremsstrahlung from one of the pions in $K_L \rightarrow \pi^+\pi^-$
    - violates CP
  - direct emission from decay vertex
    - dominated by M1 term
      - conserves CP
    - E1 term may be present as well
      - violates CP
  - similar to $K_L \rightarrow \pi^+\pi^-e^+e^-$



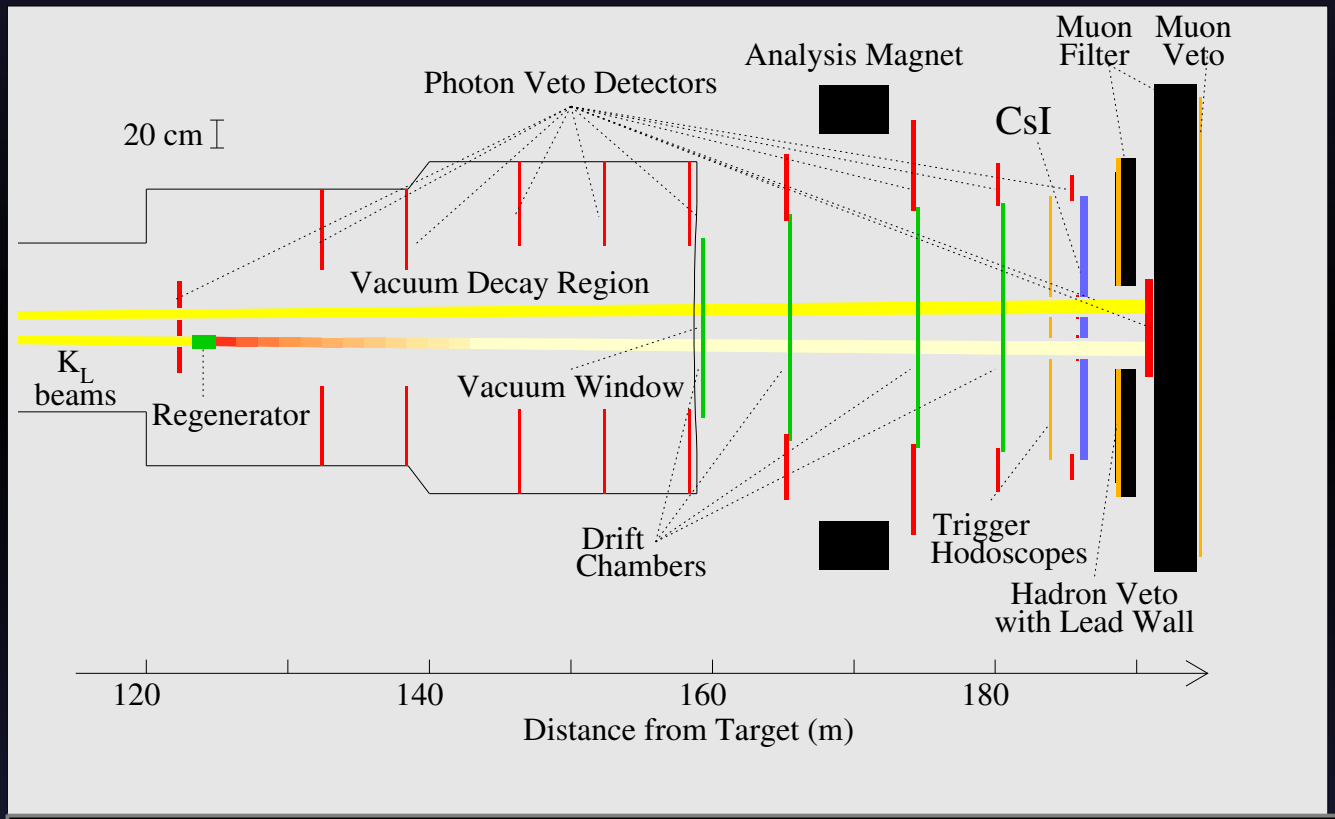


The KTeV Collaboration

- Universidade Estadual de Campinas
- Universidade de Sao Paulo
- U. Chicago
- U. Colorado
- Osaka University
- U. Wisconsin
- U. Arizona
- UC San Diego
- Elmhurst College
- Fermilab
- UCLA
- Rutgers
- Rice
- U. Va.

The KTeV/E832 Detector

Pure K_L "vacuum" beam used in this analysis



Two Beams

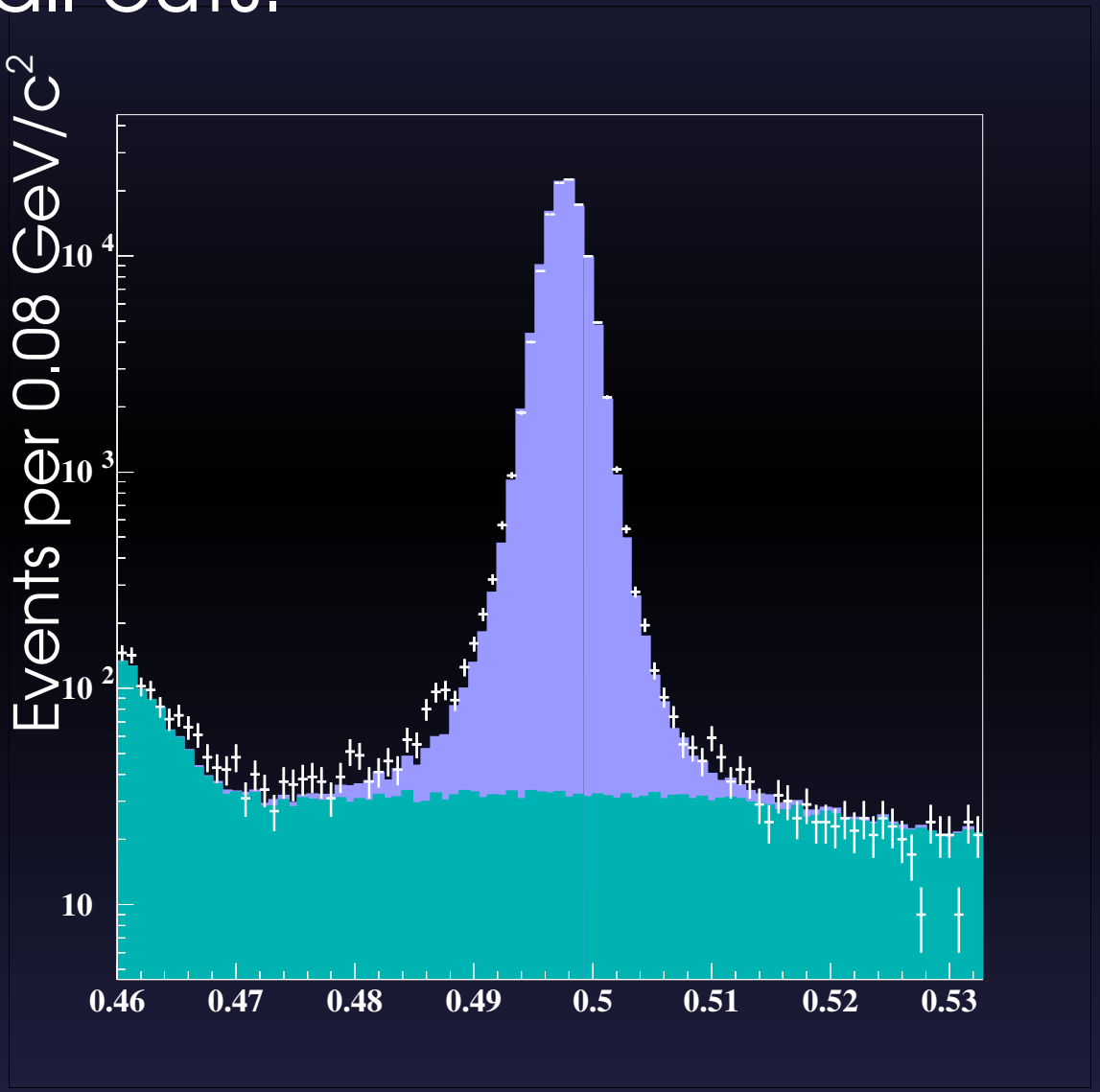
Coherent K_L and K_S "regenerator" beam

Used for measurement of $Re(\epsilon'/\epsilon)$ in $K \to \pi\pi$

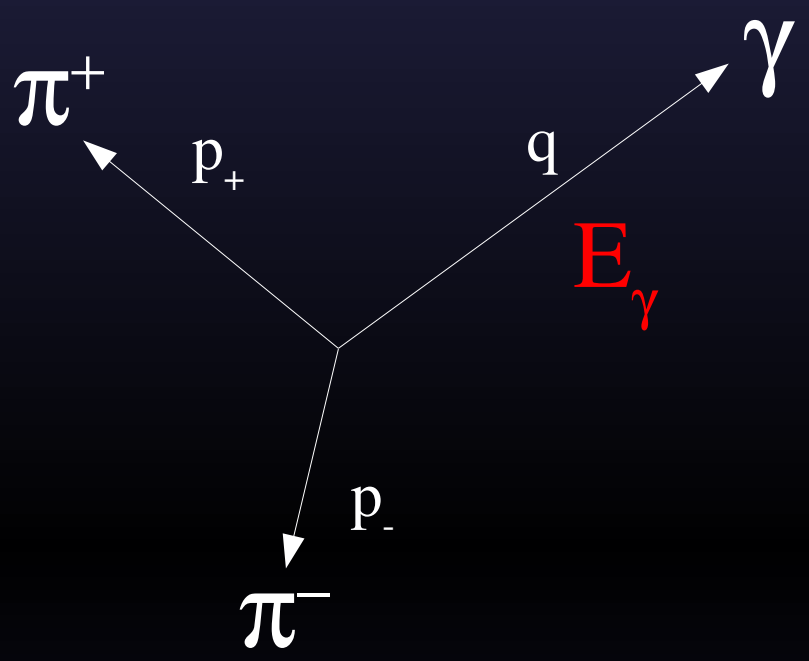
Can look for direct CP violation in $K_{L,S} \to \pi^+\pi^-\gamma$ - analysis forthcoming

Mass Plot

- 111.4K events after all cuts.
  - Background is 0.6%.
  - mostly semileptonic with an accidental photon
  - some $K_L \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$ with a γ missed

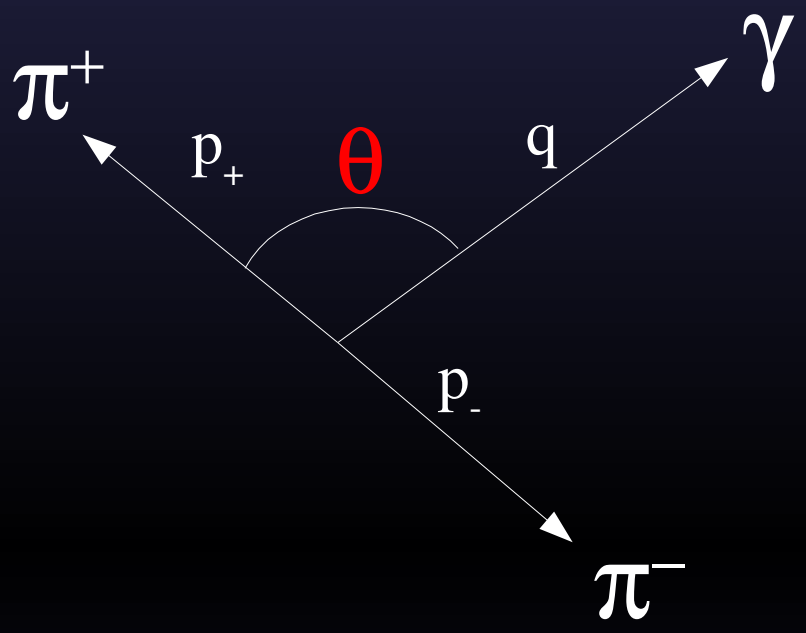


Kinematic Variables



Kaon Rest Frame

$$\vec{p}_+ + \vec{p}_- + \vec{q} = 0$$



ππ Rest Frame

$$\vec{p}_+ + \vec{p}_- = 0$$

Decay Rate For $K_L \rightarrow \pi^+\pi^-\gamma$

- The decay rate is composed of amplitudes for IB, M1 DE and if present, E1 DE
  - IB and E1 DE interfere
  - M1 does not

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

  - Model taken from Sehgal and Wanninger, Physical Review D46,1035, 1992

Model of decay

- Three different decay amplitudes contribute to $K_L \to \pi^+\pi^-\gamma$

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

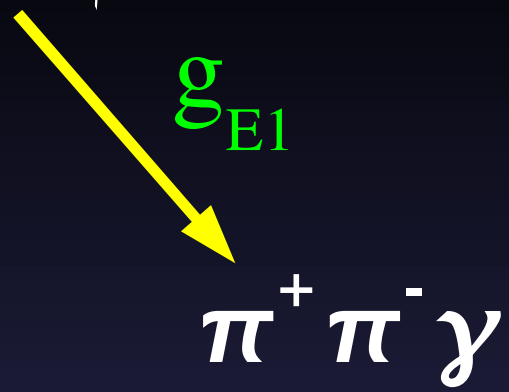
$$M_{DE}(K_L) = i\,\tilde{g}_{M1} \left| \frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K} + 1 \right| e^{i\delta_1}$$

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

E1 violates CP

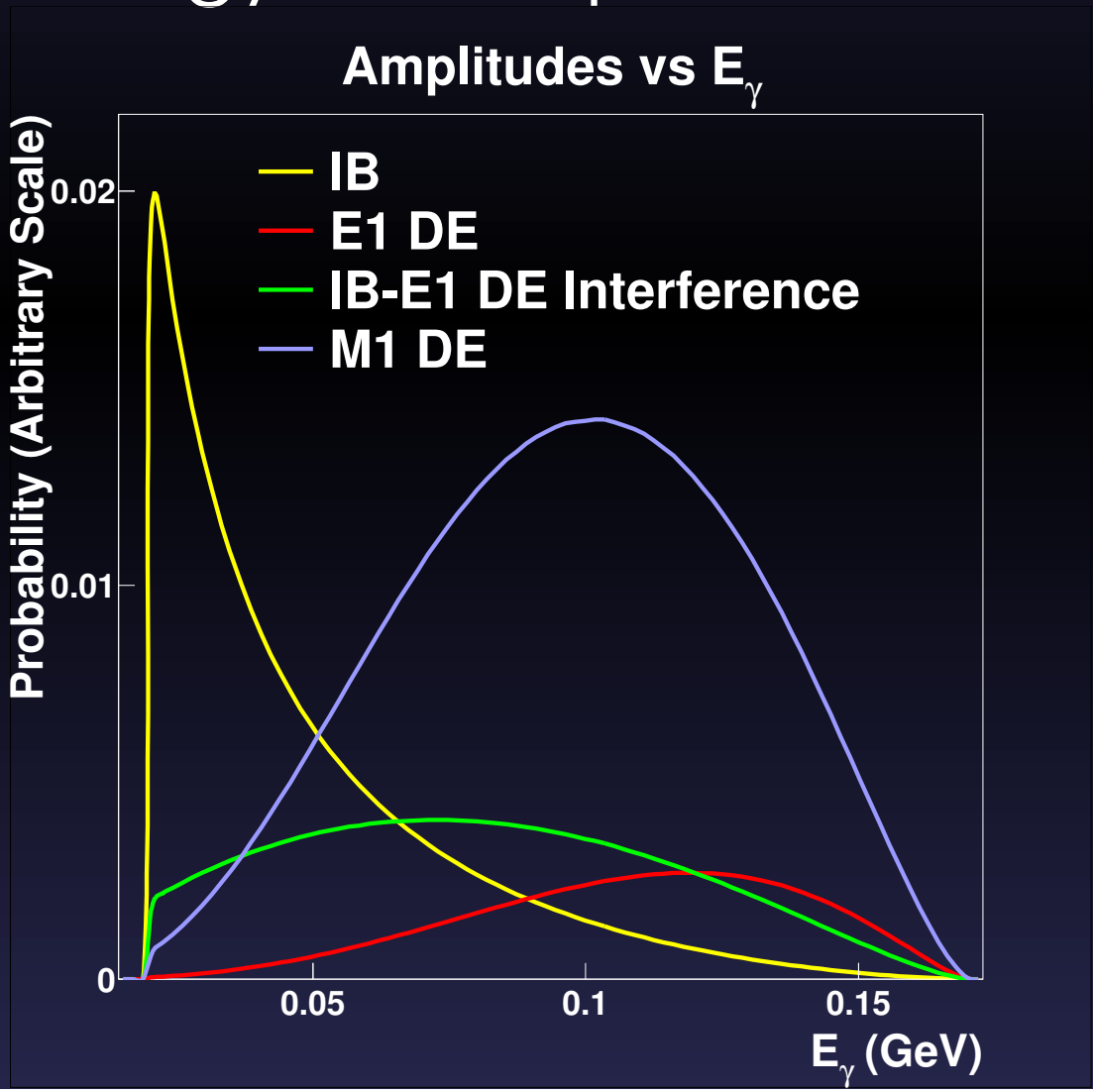
- g_{E1} describes the amplitude for the process $K_1 \rightarrow \pi^+\pi^-\gamma$ via an E1 photon
- This is mixing type (indirect) CP violation

$$|K_L\rangle \propto |K_2\rangle + \epsilon |K_1\rangle$$



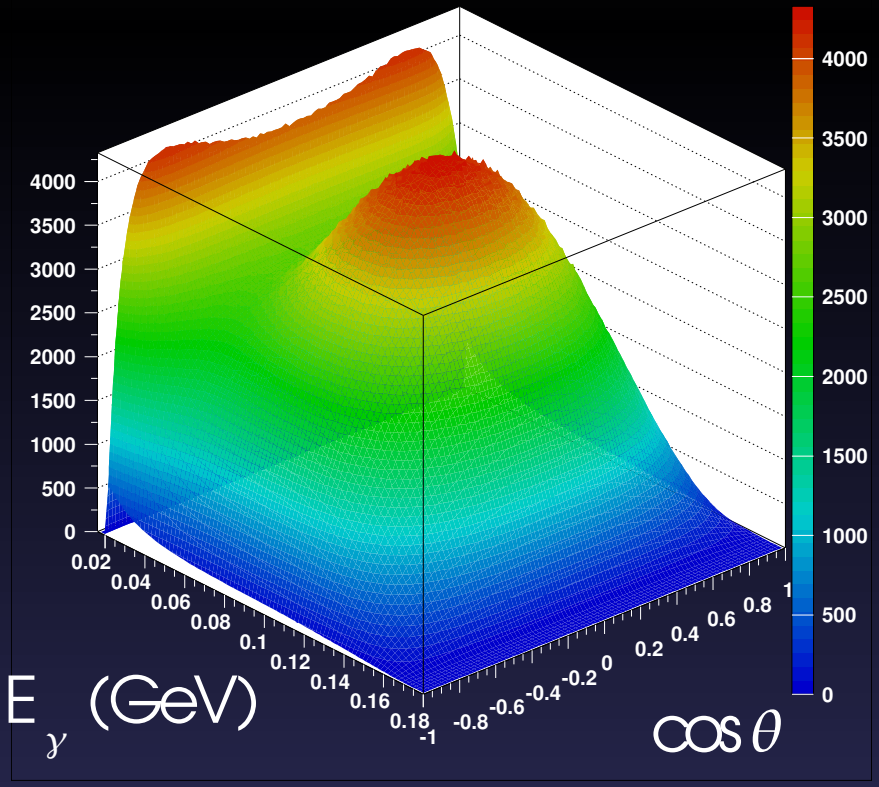
Energy Spectrum

- E_γ spectrum dominated by low energy IB photons and high energy M1 DE photons
- Normalization between components is arbitrary



Likelihood Fit

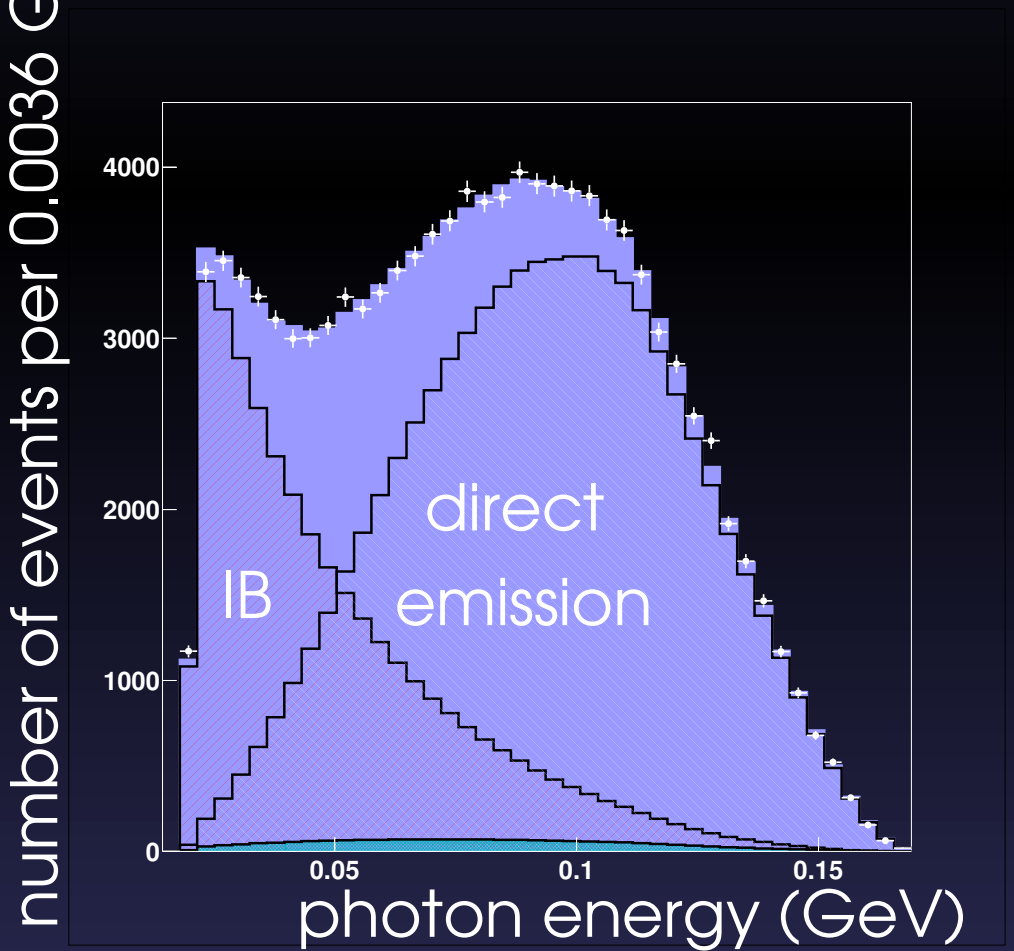
- Used method of maximum likelihood to estimate parameters g_{M1}, a_1/a_2, g_{E1}
- Use model described earlier and KTeV/ε' Monte Carlo to estimate acceptance



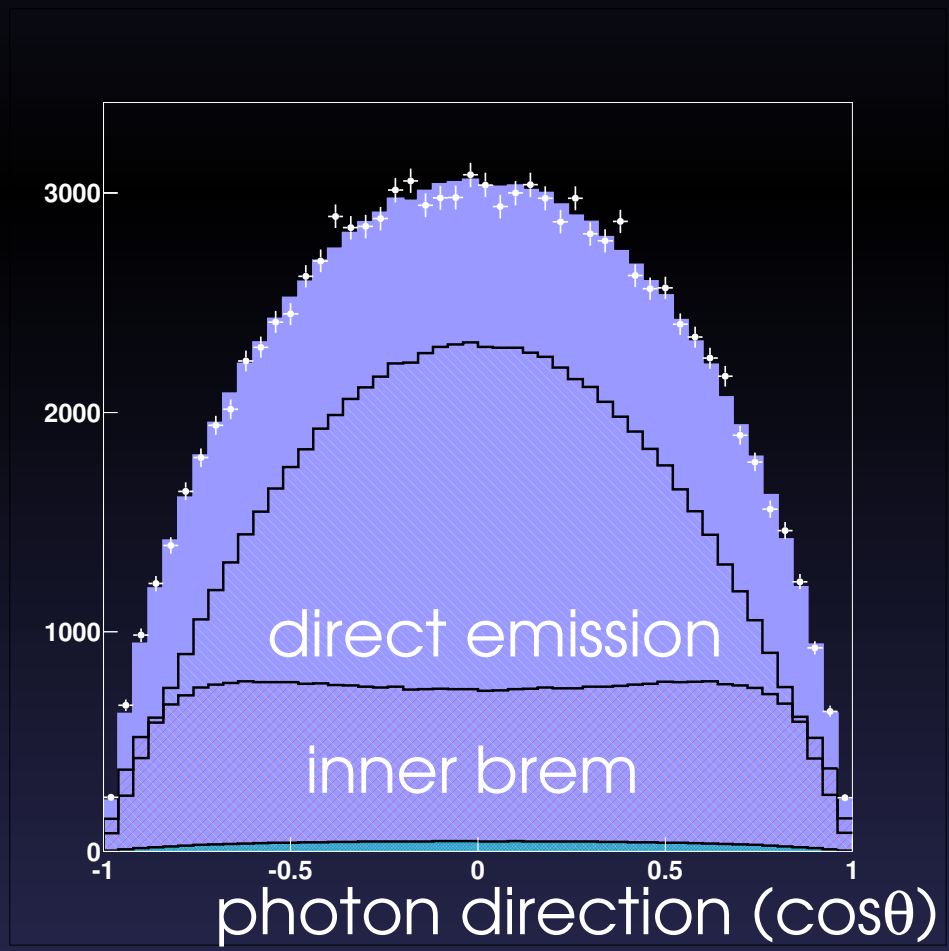
Best Fit

- The likelihood fit results in good agreement between data and Monte Carlo

$\chi^2_{DOF} = 85.8/85$



$\chi^2_{DOF} = 118.0/99$

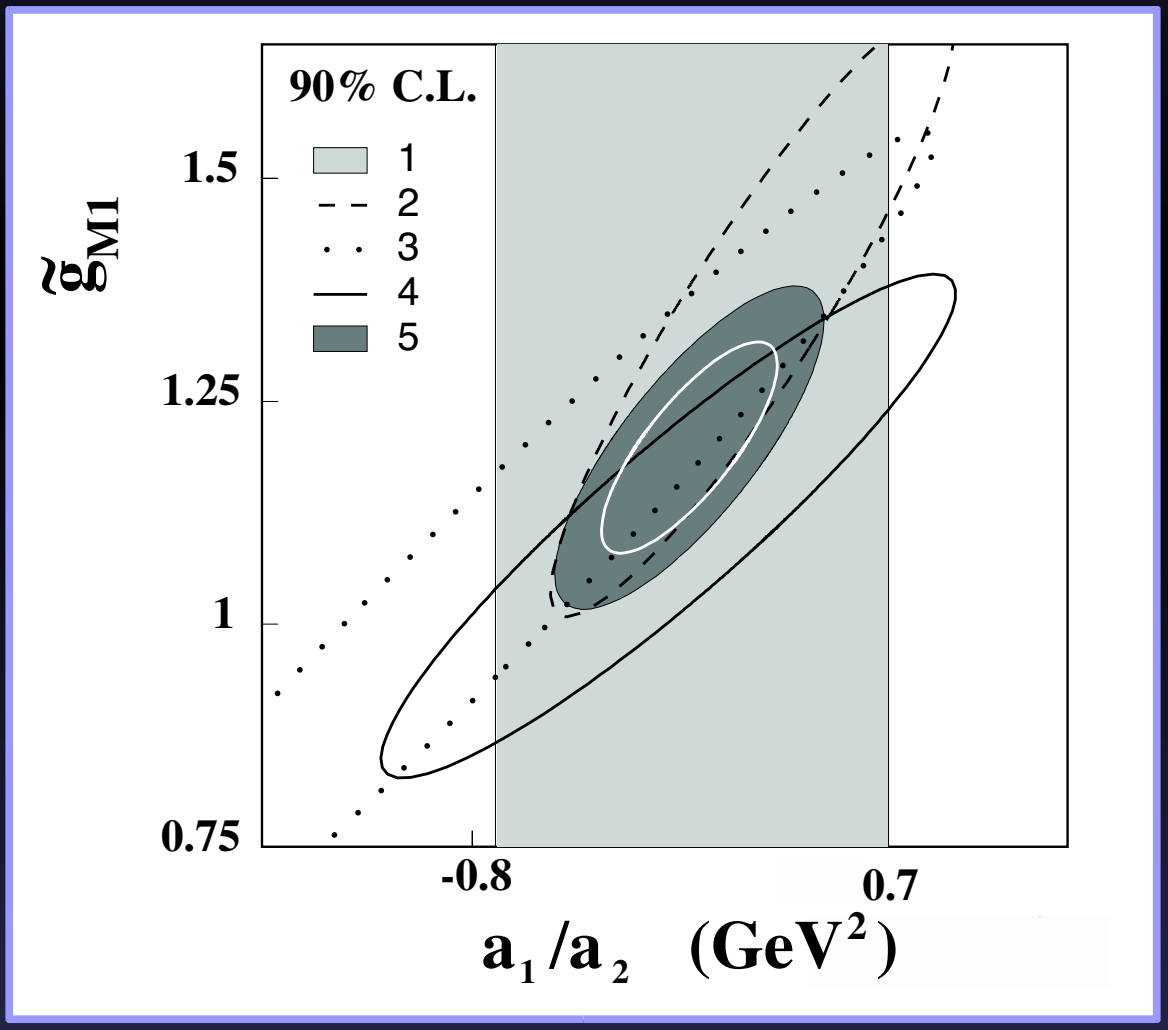


Dominant Systematic Errors

- largest systematic errors for g_{m1} were:
  - drift chamber geometry
  - second order radiative effects
  - background
  - physics cuts
- largest systematic errors for a_1/a_2 and g_{e1} were second order radiative effects

Results For 1997 Data

- Parameters for CP conserving M1 direct emission



- Legend:
  - 1) 96 KTeV $K_L \to \pi^+\pi^-\gamma$
  - 2) 97 KTeV $K_L \to \pi^+\pi^-e^+e^-$
  - 3) NA48 $K_L \to \pi^+\pi^-e^+e^-$
  - 4) 97+99 KTeV $K_L \to \pi^+\pi^-e^+e^-$
  - 5) This result:
    - $g_{M1} = 1.198$
    - $a_1/a_2 = -0.738$

Results For 1997 Data

- Determined upper limit for CP violating direct emission:
  - $g_{E1} < 0.21$ (90% Confidence)
  - Sensitivity : 0.078(stat) , 0.117(syst)
- Using fit parameters, can calculate:
  - DE/(DE+IB) = 0.689 ± 0.021 ($E_\gamma > 20$MeV)
- Paper describing this analysis has been submitted to PRL.
- Preprint is hep-ex/0604035

Extra Slides

Results For 1997 Data

- Measured parameters for CP conserving Direct Emission:
- $g_{M1} = 1.198 \pm 0.035(\text{stat}) \pm 0.086(\text{syst})$
- $a_1/a_2 = -0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst})$
- Results for g_{M1} and a_1/a_2 are most precise to date.

Other Results: g_{M1}

- NA48: from $K_L \to \pi^+\pi^- e^+ e^-$
  - : $0.99\ ^{+0.28}_{-0.27(\text{stat})} \pm 0.07$ (syst)
- KTeV: from $K_L \to \pi^+\pi^- e^+ e^-$ (1997 data only)
  - : $1.35\ ^{+0.20}_{-0.17(\text{stat})} \pm 0.04$(syst)
- KTeV: from $K_L \to \pi^+\pi^- e^+ e^-$ (1997+1999)
  - 1.11 ± 0.12 (stat) ± 0.08(syst)

Other Results : a_1/a_2

- NA48: From $K_L \to \pi^+\pi^-e^+e^-$
  - $-0.82\ ^{+0.07}_{-0.13\ \mathrm{stat}} \pm 0.02$ (syst)
- KTeV From $K_L \to \pi^+\pi^-\gamma$ (1996 Data only)
  - -0.737 ± 0.026(stat) ± 0.022(syst)
- KTeV from $K_L \to \pi^+\pi^-e^+e^-$ (1997 data only)
  - -0.720 ± 0.028(stat) ± 0.009(syst)
- KTeV from $K_L \to \pi^+\pi^-e^+e^-$ (1997 +1999)
  - -0.744 ± 0.027(stat) ± 0.032(syst)

Other Results : g_{E1}

- KTeV from $K_L \to \pi^+\pi^-e^+e^-$ (1997 +1999)
  - $g_{E1} < 0.03$ (90% Confidence)

Other Results: DE/(DE+IB)

- Old KTeV result from $K_L \to \pi^+\pi^-\gamma$
  - : 0.683 ± 0.011 using 1996 data
- FNAL E731 from $K_L \to \pi^+\pi^-\gamma$
  - : 0.685 ± 0.041

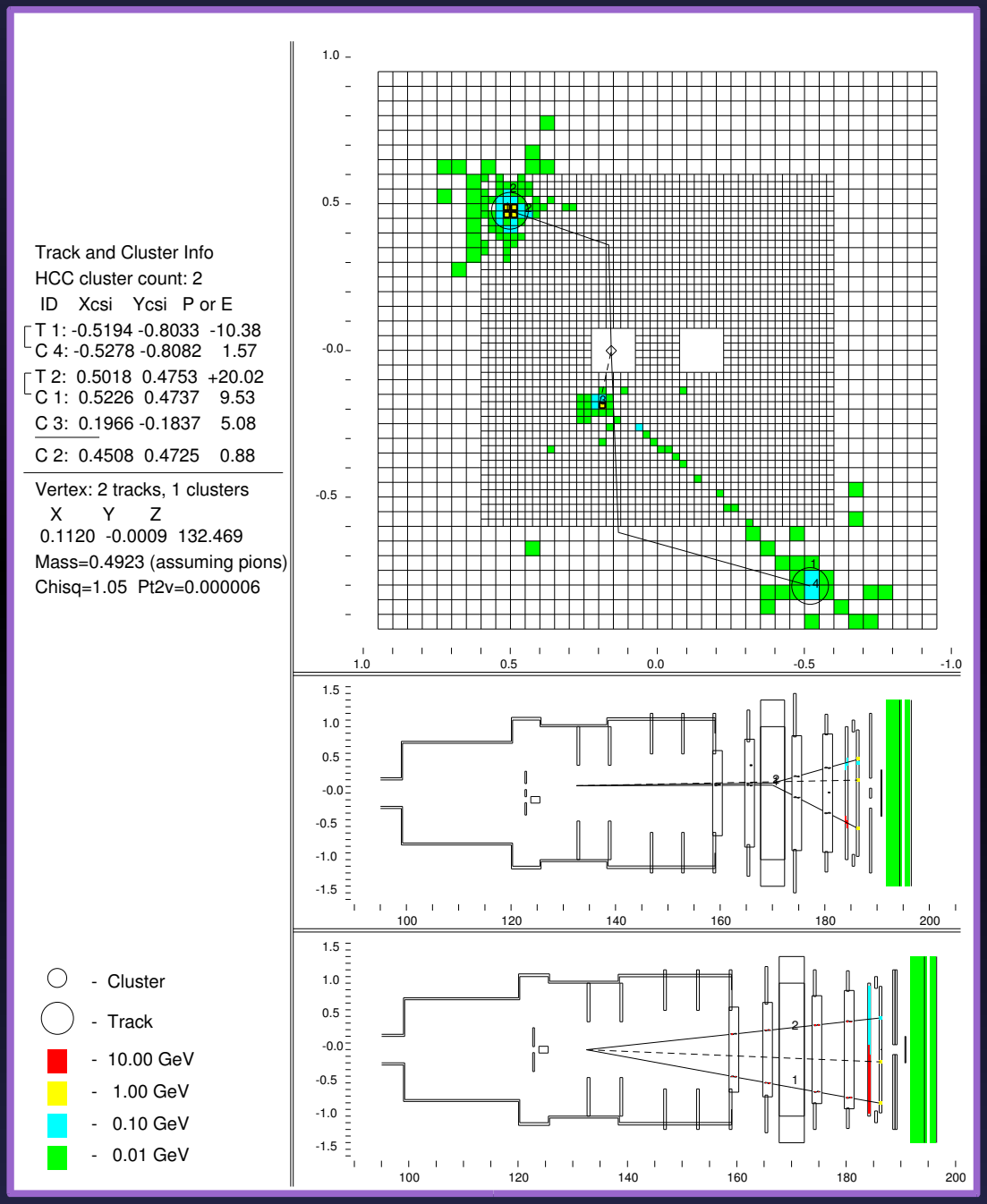
References

- "A Measurement of The K0 Charge Radius And A CP Violating Asymmetry Together With A Search for CP Violating E1 Direct Emission in the Rare Decay K(L) -->Pi+pi-e+e-", E.Abouzaid et al., Physical Review Letters, in press, hep-ex/0508010
- "Simultaneous Measurement of K_S and K_L Decay into $\pi\pi\gamma$", E.J. Ramberg, et.al. Physical Review Letters 70, 2525 April 1993

References

- "Investigation of K(L,S) -> pi+pi-e+e- Decays" A. Lai et al., Eur. Phys.J.C30:33, 2003
- "Study Of the KL -> pi+pi-gamma Direct Emission Vertex" ,A. Alavi-Harati et al. Phys ical Review Letters,86,761 (2001), hep-ex/008045
- "New Measurement of Ke4+ decay and the s-wave Scattering Length a00" S. Pislak, et al. Physical Review Letters 87, 221801 (2001)

Event Display of a $\pi^+\pi^-\gamma$ Decay



Analysis 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	$P_T^2 < 2.4 \times 10^{-4}\ GeV^2/c^2$
Kaon Momentum	25.0 GeV/c $< P_{\pi\pi\gamma} <$ 160.0 GeV/c
Photon Energy in Lab Frame	$E_\gamma > 1.5$GeV
Photon Energy in Kaon Rest Frame, From Calorimeter	20MeV $< E_\gamma <$ 175.0 MeV
Photon Energy in Kaon Rest Frame, From Kinematics	20MeV $< E_\gamma <$ 170.1 MeV
$\pi\pi$ Invariant Mass, Implied From Above Cut	$0.2799\ GeV/c^2 < M_{\pi\pi} < 0.4772\ GeV/c^2$
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. Regenerator	$-0.10\ GeV^2/c^2 < P^2_{\pi^0} < -0.0055\ GeV^2/c^2$
pp0kin w.r.t. Target (Crunch Cut)	$P^2_{\pi^0} < -0.002\ GeV^2/c^2$
L3 pp0kin	passes
Z vertex	120.0 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
Track x Separation at CsI	$\Delta x > 3.0$ cm
Number of Tracks	NTRK = 2
Beam Selection	GTREG*VTXX $<$ 0

Systematic Errors

Source	$\lvert\tilde{g}_{M1}\rvert$	a_1/a_2	$\lvert g_{E1}\rvert$
Differing initial MC parameters	0.0093	0.0021	0.013
Kaon Beam Momentum Uncertainty	0.0031	0.0004	0.005
Background uncertainty	0.0355	0.0067	0.045
Pion bremsstrahlung	0.0326	0.0140	0.097
Non-Orthogonality of chambers	0.0402	0.0013	0.009
Physics cut variations	0.0463	0.0056	-
Fitting resolution	0.014	0.0056	0.024
E_γ,cosθ resolution	0.023	0.0042	0.038
η_{+-} uncertainty	0.0171	0.0014	-
δ_0 phase uncertainty	0.0111	0.0021	-
δ_1 phase uncertainty	0.0053	-	-
Total Systematic Error	0.086	0.018	0.117