Kaons, K_L K_S $K^{\pm}$

CP Violation : η

$\left(\frac{\epsilon'}{\epsilon}\right)_{2\pi}$

$K_L \to \pi^0 \nu\bar{\nu}$ $(\pi^0 e^+ e^-, \pi^0 \mu^+ \mu^-)$

$K_L \to \pi^+ \pi^- e^+ e^-$

ρ :

$K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \mu^+ \mu^- \gamma$

[π^0-factory]

$\not{L}$:

$K_L \to \pi^0 \mu^{\pm} e^{\mp}$

$K^+ \to \pi^+ \mu^+ e^-$

$K_L \to \mu^{\pm} e^{\mp}$

"EM" decays of neutral kaons:

$K_L \to \gamma^* \gamma$ and $K_L \to \gamma^* \gamma^*$

$K_L \to e^+ e^- \gamma$

$K_L \to \mu^+ \mu^- \gamma$

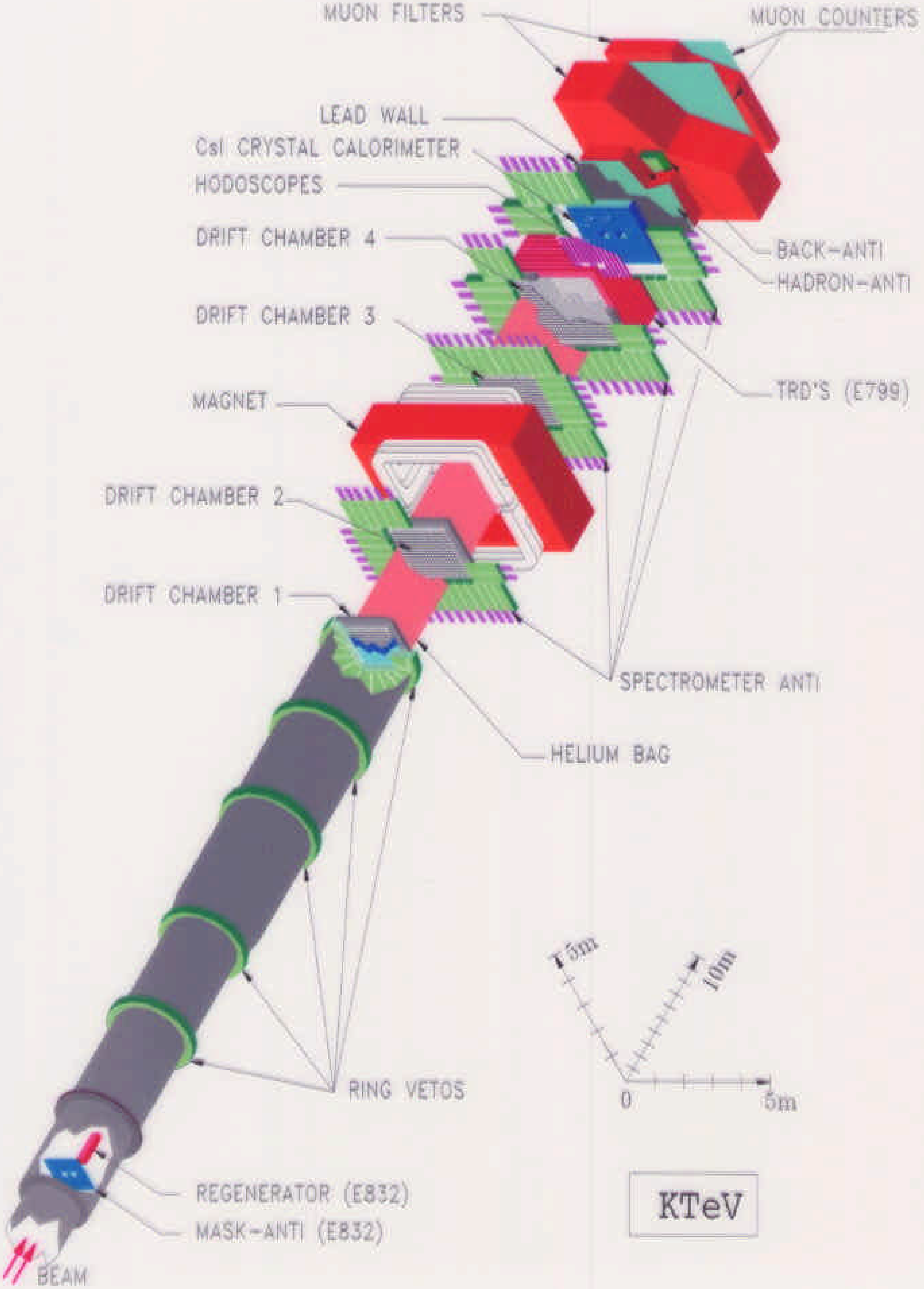
$K_L \to e^+ e^- e^+ e^-$

$K_L \to \mu^+ \mu^- e^+ e^-$

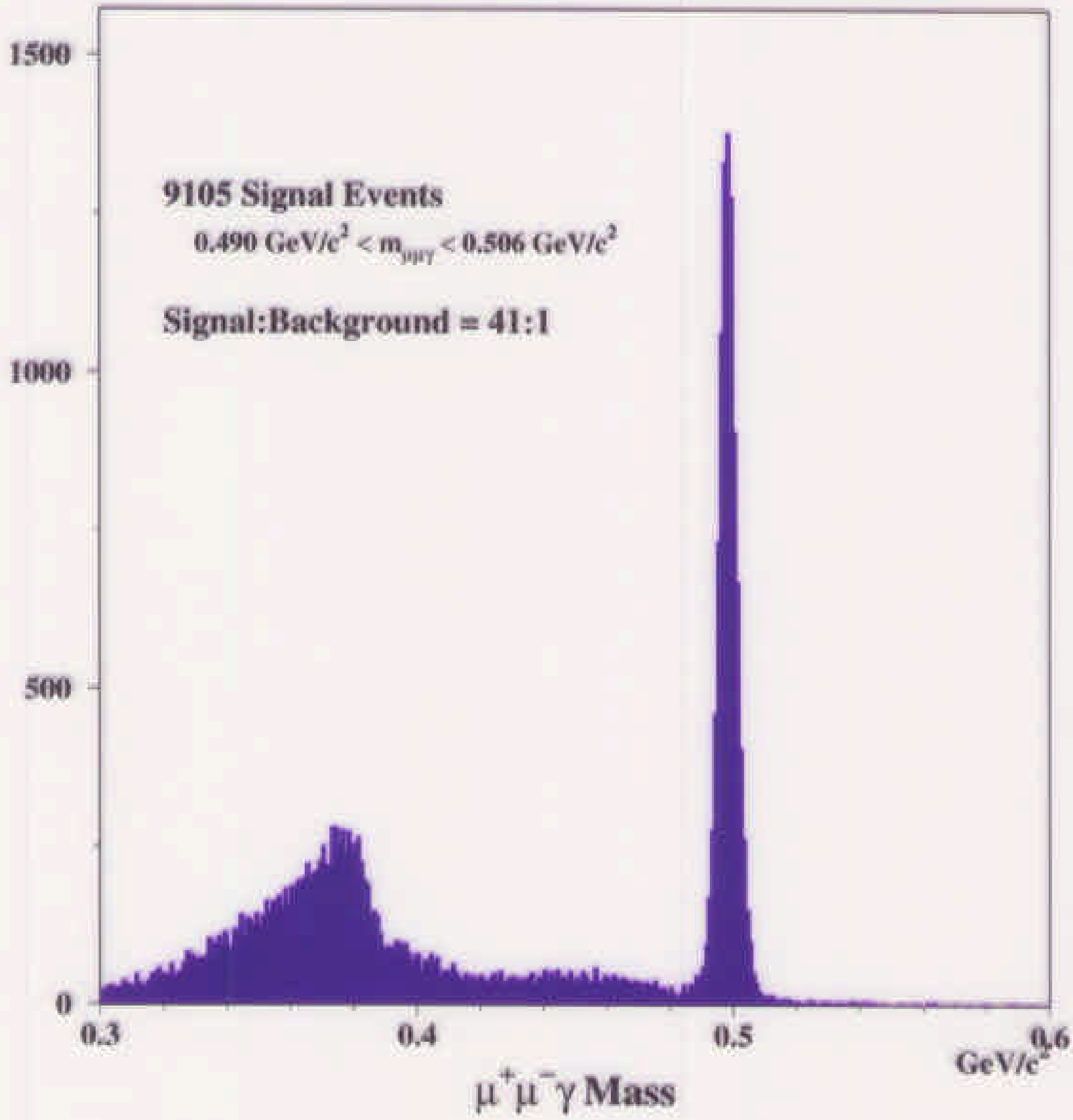
$K_L \to \mu^+ \mu^+ \mu^- \mu^-$

KTeV Collaboration

- Arizona
- UCLA
- UCSD
- CHICAGO
- Colorado
- Elmhurst
- FNAL
- Osaka
- Rice
- Rutgers
- Virginia
- Wisconsin
- Campinas
- Sao Paulo


MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
BACK-ANTI
HADRON-ANTI
DRIFT CHAMBER 3
TRD'S (E799)
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
5m
10m
0
5m
RING VETOS
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
KTeV

$K_L \to \mu^+ \mu^- \gamma$ Branching Ratio Measurement



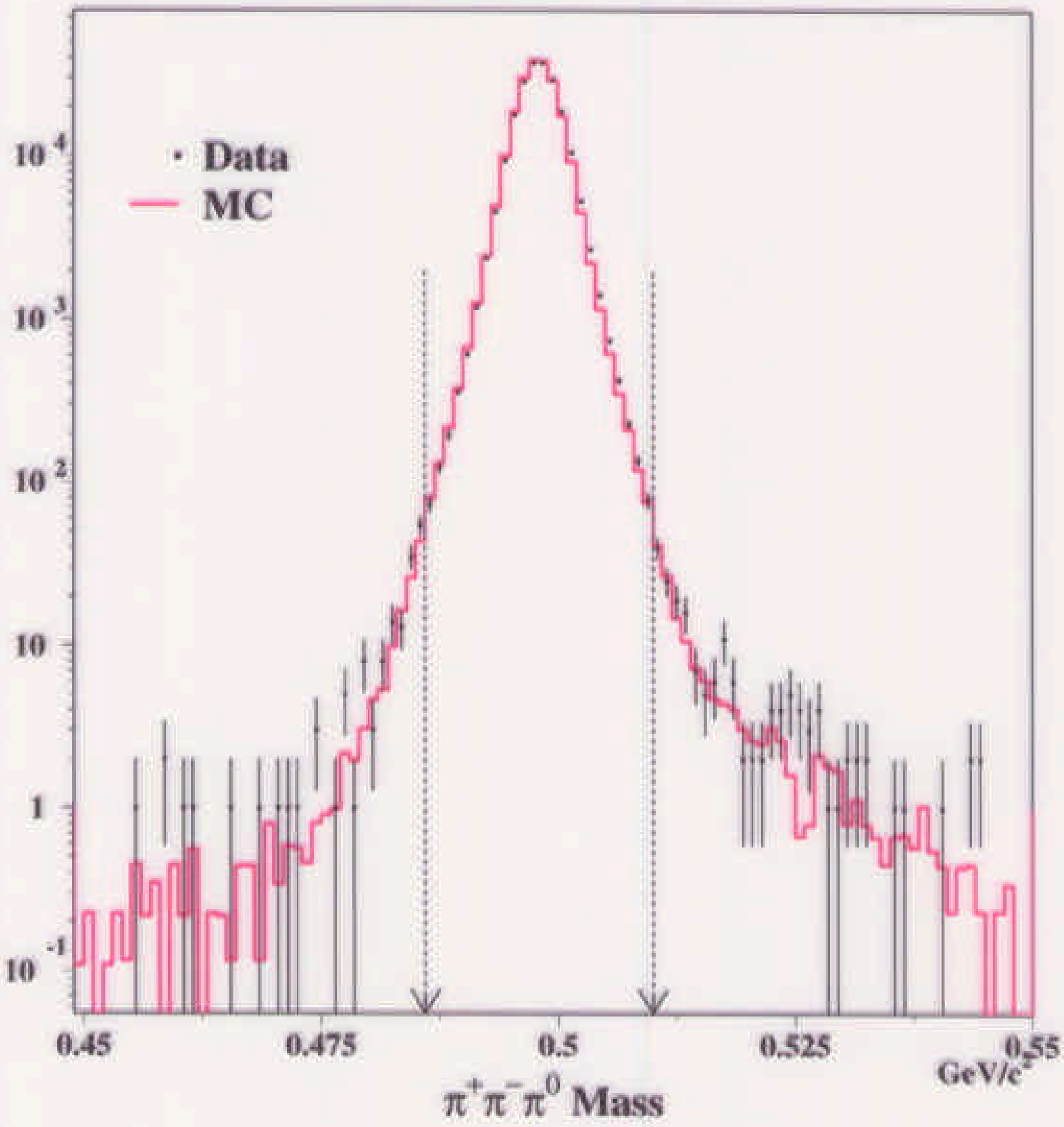
$$BR(K_L \to \mu^+ \mu^- \gamma) = (3.70 \pm 0.04_{stat} \pm 0.07_{sys}) \times 10^{-7}$$

$BR_{winter} = 3.69 \times 10^{-7}$

$BR_{summer} = 3.71 \times 10^{-7}$

$\pi^+\pi^-\pi^0$ Normalization Sample

Background-free normalization sample of 210,660 $K_L \to \pi^+\pi^-\pi^0$ events



Backgrounds to $K_L \to \mu^+\mu^-\gamma$

All backgrounds involve charged pions, and require the pions to decay or punch-through the filter steel. All MC backgrounds samples except $K_{\mu 3}$'s are scaled to the measured flux.

- $K_L \to \pi^+\pi^-\pi^0$
  - Generally very low mass due to lost photon, but has large BR
- $K_L \to \pi^+\pi^-\gamma$
  - Includes Direct Emission and Inner Brem
  - Near in mass, but low BR
- $K_L \to \pi^+\pi^-$
  - Includes External Brem, and accidental photons

Backgrounds to $K_L \to \mu^+\mu^-\gamma$

- $K_L \to \pi^\pm \mu^\mp \nu$
  - Requires an accidental photon $\to$ acceptance harder to understand
  - MC is normalized to sidebands in the data
  - Largest background
- $K_L \to \pi^\pm \mu^\mp \nu\gamma$
  - Recently measured by NA48
  - MC uses K_{e3} matrix element, with m_μ and $K_{\mu 3}$ form factor parameters
  - MC is normalized to sidebands in the data
- $K_L \to \pi^0 \pi^\pm \mu^\mp \nu$
  - No existing measurement of this mode
  - BR estimated from $K_L \to \pi^0 \pi^\pm e^\mp \nu$ and similar K^+ modes
  - Negligible

$\mu^+\mu^-\gamma$ Background Components

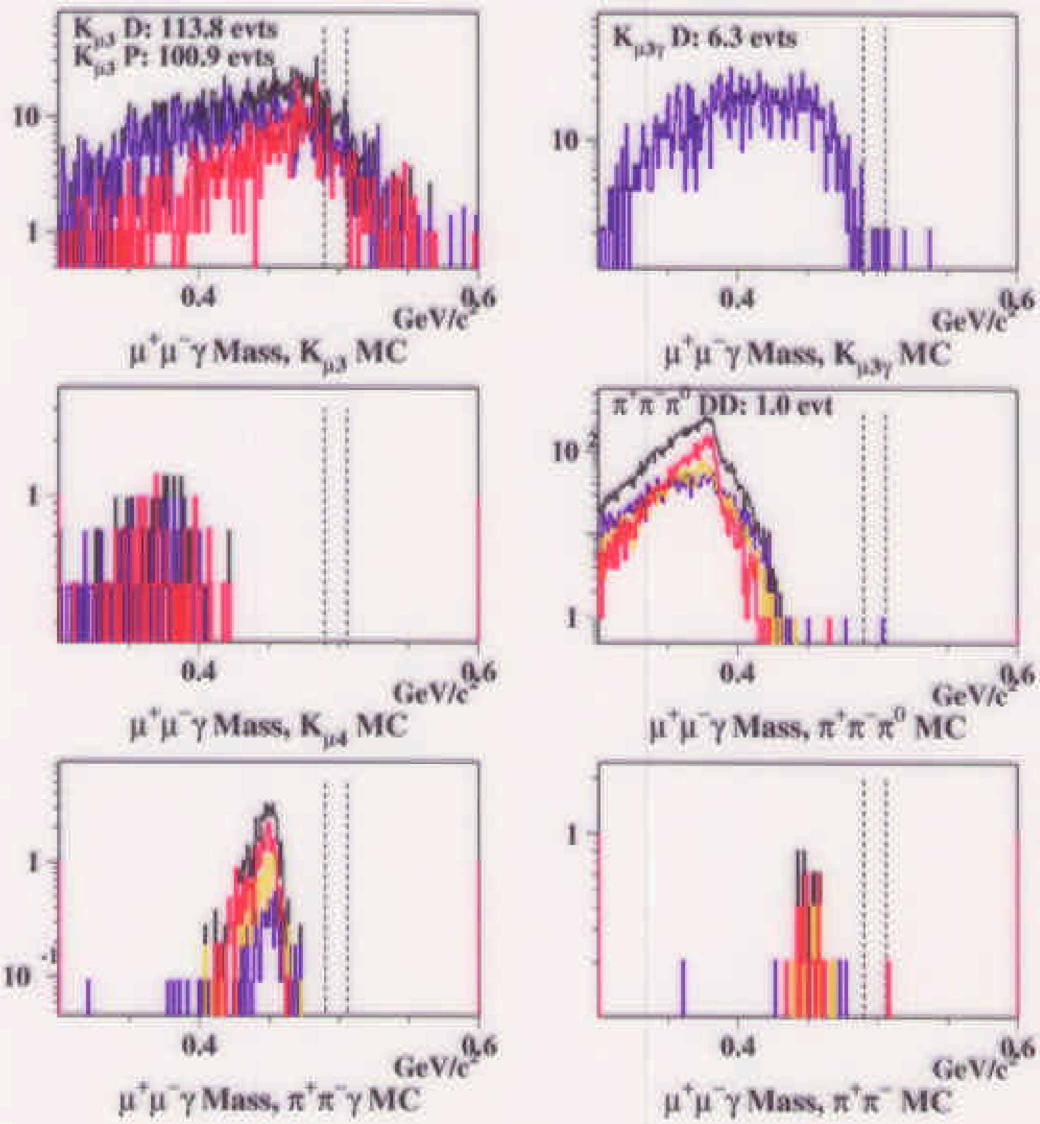
All components are normalized to the KTeV data set

Blue: π decay

Red: π punch-through

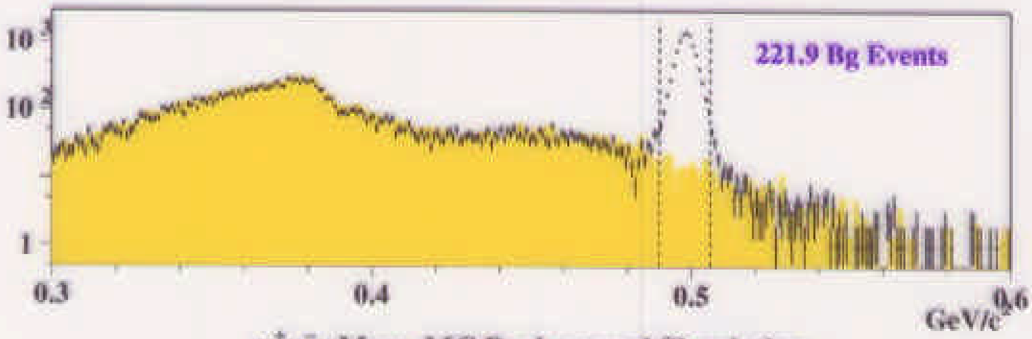
Yellow: one π decay, one π punch-through

Black: total

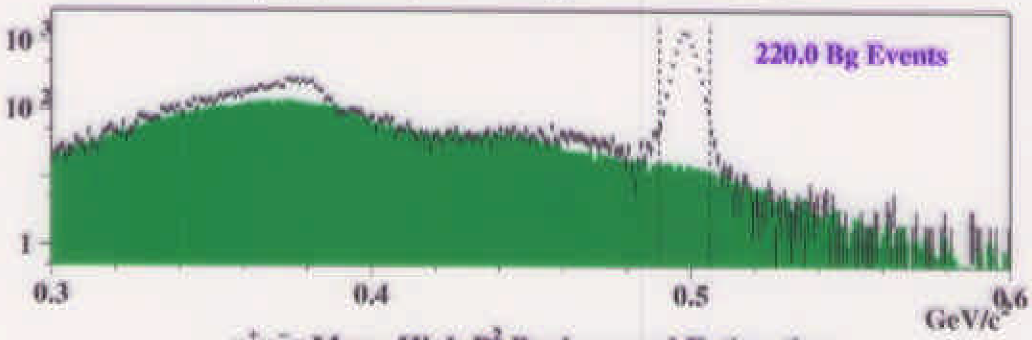


Estimation of Background to $K_L \rightarrow \mu^+\mu^-\gamma$

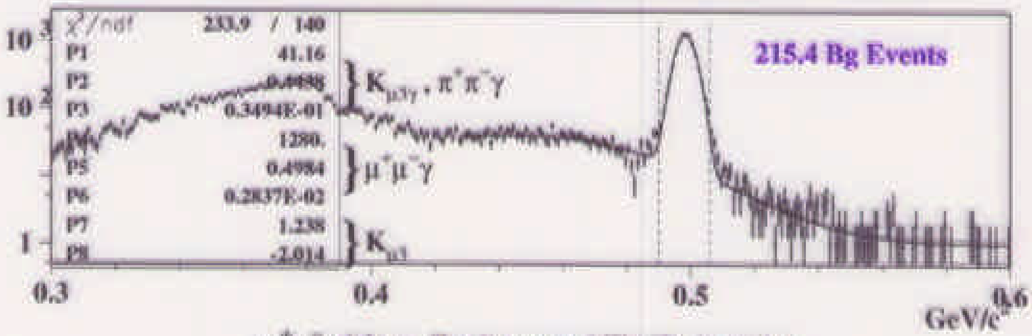
- MC is normalized to data
- $0.0004(GeV/c)^2 < P_t^2 < 0.001(GeV/c)^2$ data is scaled to signal region
- Data is fit to two gaussians and an exponential



μ⁺μ⁻γ Mass, MC Background Simulation



μ⁺μ⁻γ Mass, High P_t^2 Background Estimation



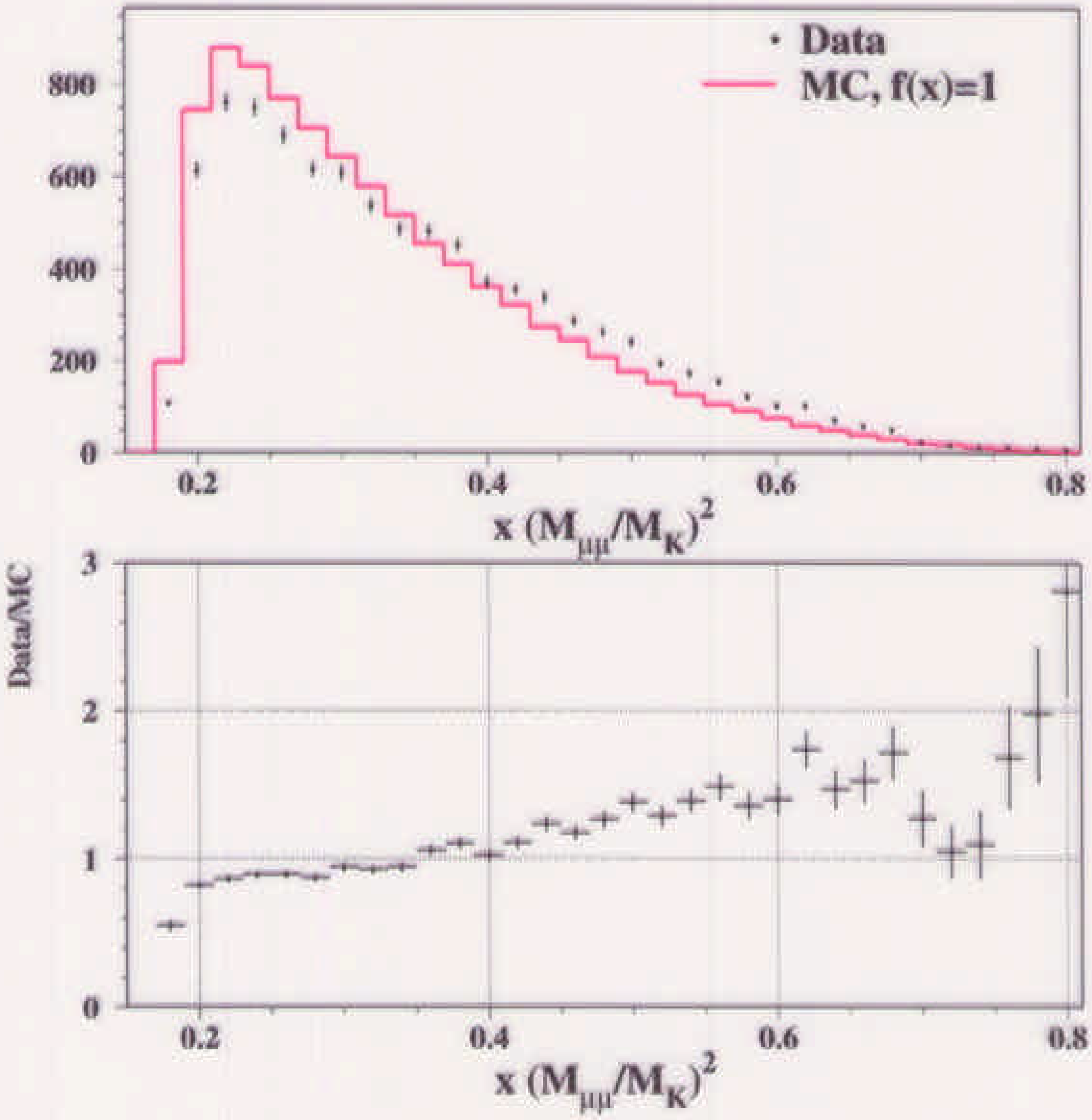
μ⁺μ⁻γ Mass, Background Fit Estimation

$K_L \to \mu^+\mu^-\gamma$ Systematic Errors

Source of Error	BR Error
MU3 Crack Simulation	0.5%
μ Filter Thickness	0.4%
DC Simulation (MAPS,Illum,Z)	0.5%
γ Energy Uncertainty	0.1%
P_t^2 Cut	0.6%
Track Momentum Cut	0.2%
Background Uncertainty	0.2%
MC Statistics	0.2%
MC form factor	0.4%
Total from internal syst. err.	1.1%
$BR(K_L \to \pi^+\pi^-\pi^0)$	1.6%
Total Systematic Error	1.9%

Dimuon Mass Distribution

- The Data/MC ratio is the measured value of the form factor, $| f(x) |^2$
- Completely model-independent



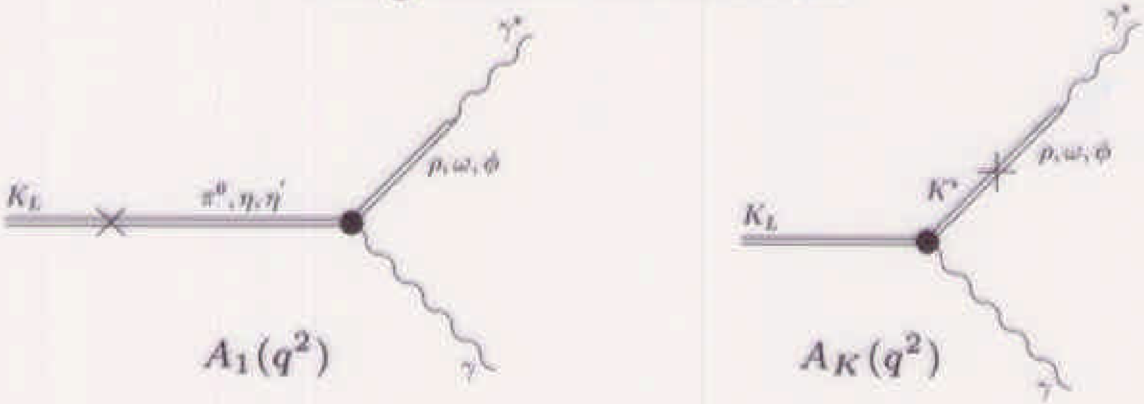
$K_L \to l^+ l^- \gamma$

$$K_L \to \gamma^* \gamma \to l^+ l^- \gamma$$

$$\frac{1}{\Gamma_{\gamma\gamma}} \frac{d\Gamma(K_L \to l^+ l^- \gamma)}{d(q^2)} = \frac{2\alpha_{EM}}{3\pi} \frac{|f(q^2)|^2}{q^2} \left(1 - \frac{q^2}{m_K^2}\right)^3 \left(1 + \frac{2m_l^2}{q^2}\right) \times \left(1 - \frac{4m_l^2}{q^2}\right)^{\frac{1}{2}}$$

Bergström, Massó, Singer

2 long distance contributions



$$f(q^2) \propto A_1(q^2) + \alpha_{K^*} A_K(q^2)$$

Measurement of α_{K^*}

Branching Ratio

Integrating the differential decay rate with the BMS form factor

$$f(x) = \frac{1}{1-0.418x} + \frac{2.3\alpha_{K^*}}{1-0.311x}\left(\frac{4}{3} - \frac{1}{1-0.418x} - \frac{1}{9(1-0.405x)} - \frac{2}{9(1-0.238x)}\right)$$

yields the expression

$$\frac{BR(K_L \to \mu^+\mu^-\gamma)}{BR(K_L \to \gamma\gamma)} = (14.33\alpha_{K^*}^2 - 51.91\alpha_{K^*} + 55.52) \times 10^{-5}$$

With our measurement of $BR(K_L \to \mu^+\mu^-\gamma)$ and the PDG value for $BR(K_L \to \gamma\gamma)$, α_{K^*} is calculated to be

$$\alpha_{K^*}^{BR} = -0.130^{+0.038}_{-0.037}.$$

Dimuon Mass Shape

An additional systematic error must be added to the shape anaylsis result of $\alpha_{K^*} = -0.193 \pm 0.035$. α_{K^*} varies slightly with the cut on track momentum. Fluctuations are all more negative and the largest is -0.034. With this systematic error included,

$$\alpha_{K^*}^{Shape} = -0.193^{+0.035}_{-0.049}.$$

Combined

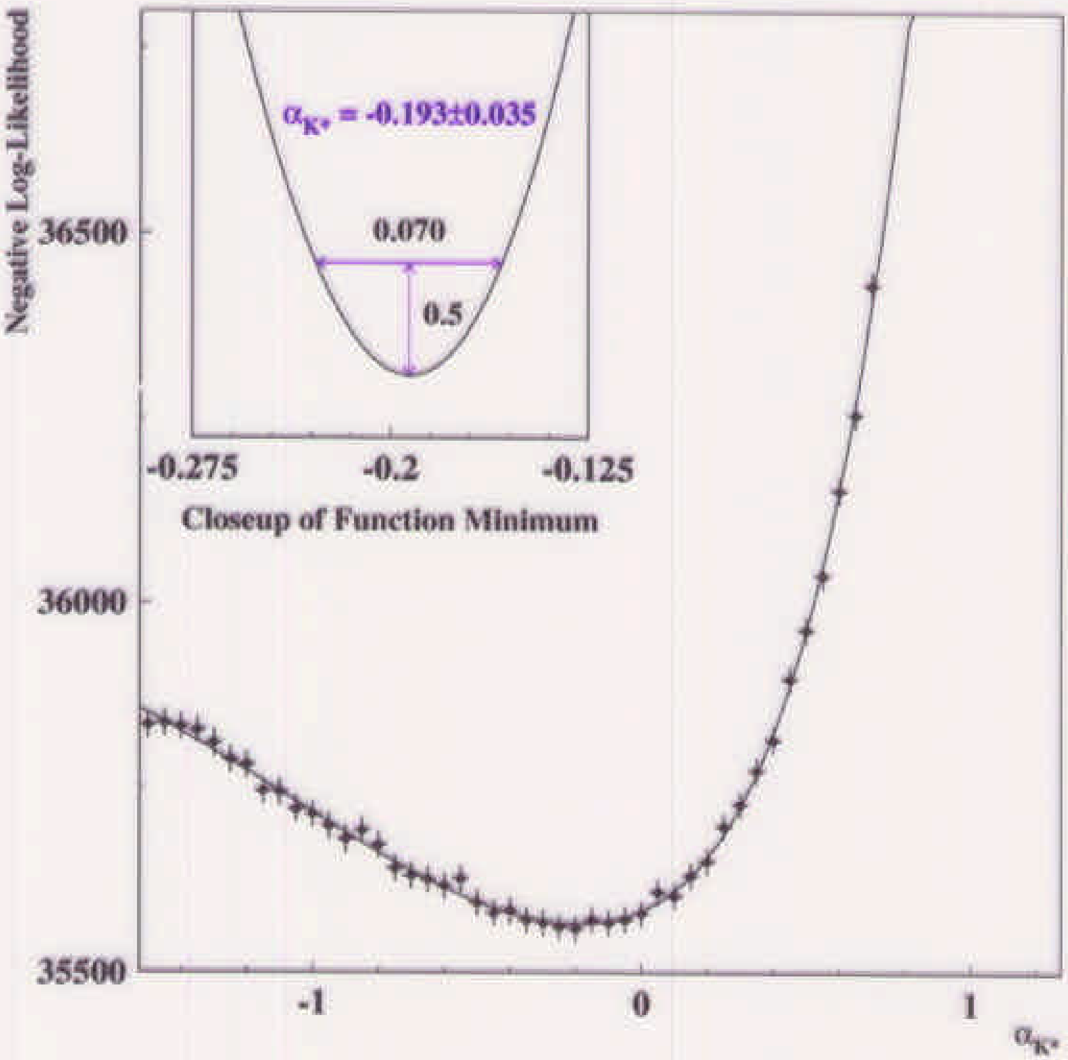
Combining these two measurements we find

$$\alpha_{K^*} = -0.163^{+0.026}_{-0.027}$$

Measurement of α_{K^*}

α_{K^*} is determined by calculating the NLL of the data being consistent with MC distributions generated at various values of α_{K^*}.

10000 MC 'Data' sets are generated with the measured α_{K^*}. The NLL method is used to measure α_{K^*} for each of these sets, and the width of that distribution is a check on the error.



$K_L \to l^+ l^- \gamma$

D'Ambrosio, Isidori, Portolés

$K_L \to \gamma^* \gamma^*$ form factor:

$$f(q_1^2, q_2^2) = 1 + \alpha \left(\frac{q_1^2}{q_1^2 - m_\rho^2} + \frac{q_2^2}{q_2^2 - m_\rho^2} \right) + \beta \frac{q_1^2 q_2^2}{\left(q_1^2 - m_\rho^2\right)\left(q_2^2 - m_\rho^2\right)}$$

- Most general parameterization compatible with a Chiral Perturbation Theory expansion
- Includes characteristic long distance pole behavior
- No specific diagrams of long distance processes are assumed
- Reduces to $K_L \to \gamma^* \gamma$ form factor by setting $q_2^2 = 0$

Dispersive long distance contribution is given by

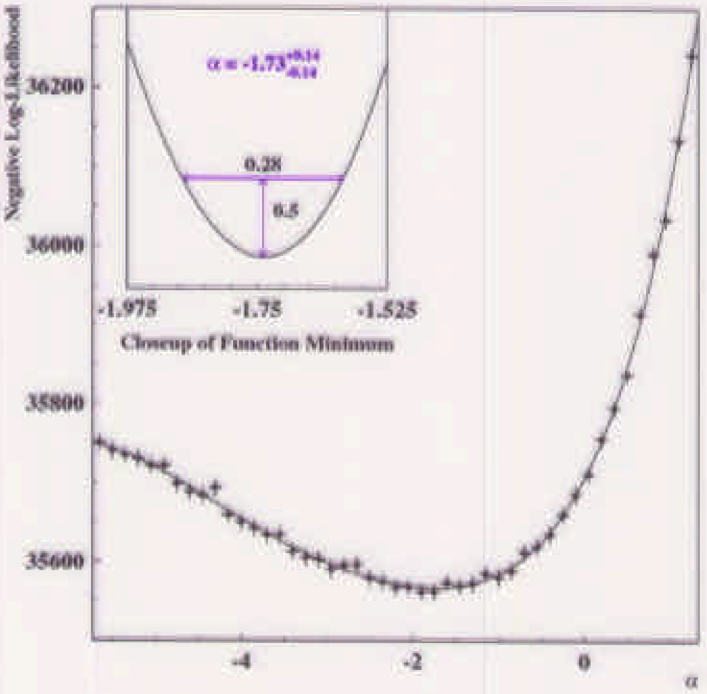
$$|\mathrm{Re}A_{LD}| = \left[\frac{2\alpha_{EM} \beta_\mu BR(K_L \to \gamma\gamma)}{\pi^2 m_K^2} \right]^{1/2} \times \left| 5.25 + 3.47\alpha + 3(1 + 2\alpha + \beta) \ln \frac{\Lambda}{m_\beta} \right|$$

where Λ is an ultraviolet cutoff, and perturbative QCD limits the last term to

$$|(1 + 2\alpha + \beta)| \ln \frac{\Lambda}{m_\beta} < 0.4$$

α is directly accessible through $K_L \to l^+ l^- \gamma$.

Measurement of α



Dimuon Mass Shape

With the track momentum cut systematic error included,

$$\alpha^{Shape} = -1.73^{+0.14}_{-0.18}.$$

Branching Ratio

Integrating the differential decay rate with the DIP form factor

$$f(x) = 1 + \alpha\left(\frac{x}{x - 2.40}\right),$$

and using our measurement of $BR(K_L \to \mu^+\mu^-\gamma)$ and the PDG value for $BR(K_L \to \gamma\gamma)$, α is calculated to be

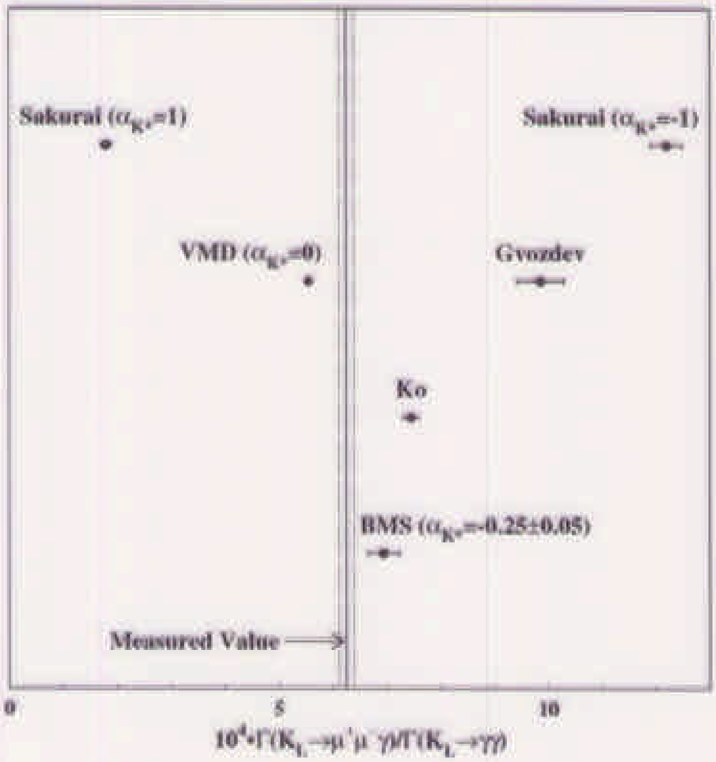
$$\alpha^{BR} = -1.42 \pm 0.12.$$

Combined

Combining these two measurements we find

$$\alpha = -1.55 \pm 0.09$$

Model Comparisons

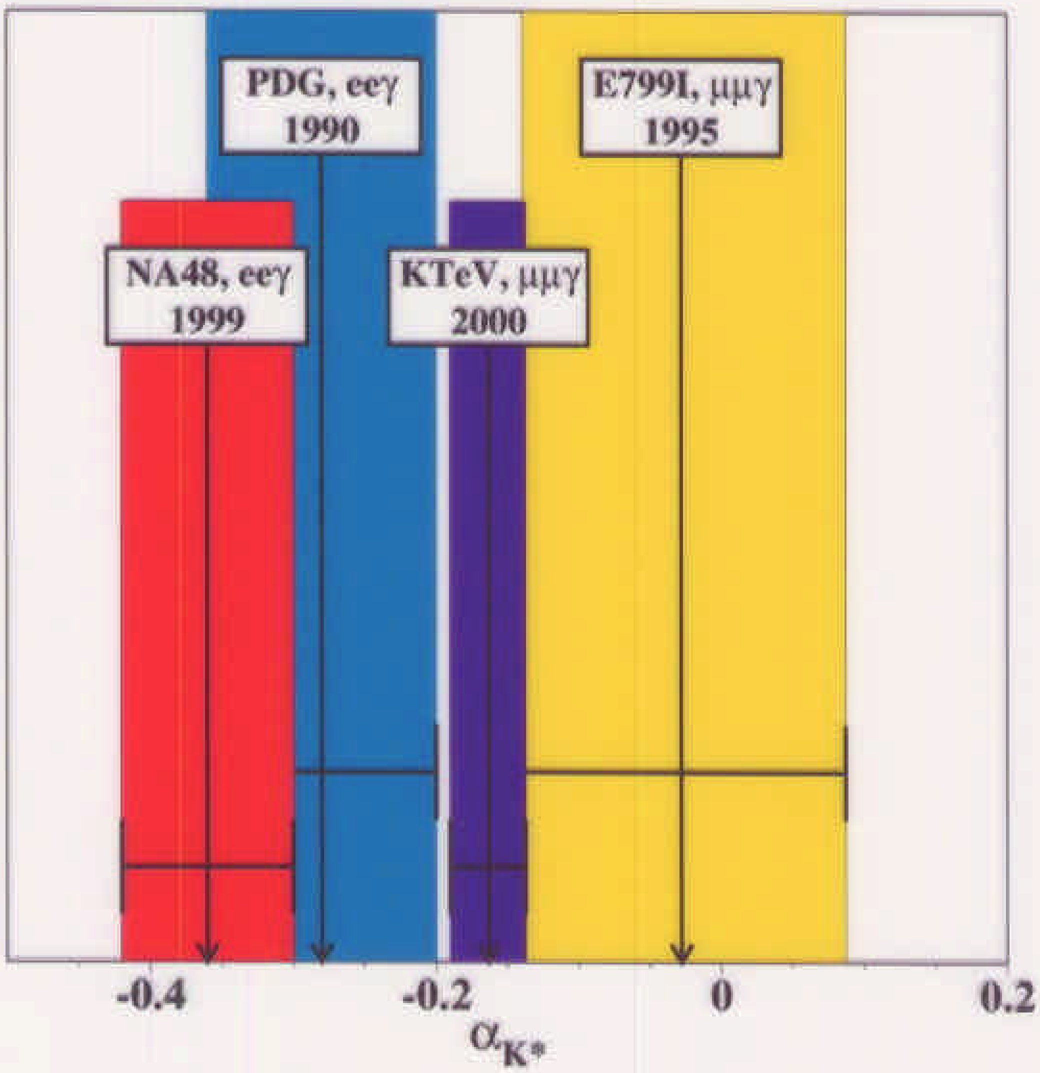


- DIP does not make a prediction for α
- No model predicts sign of α_{K^*} (negative value for BMS is unambiguously preferred based on proximity to measured value)
- Ko includes additional pole diagrams
- Gvozdev uses a quark model calculation

Self-consistency of BMS and DIP Models

Form Factor Model	Parameter Measurement Shape	BR	Significance of Difference
α_{K^*} (BMS)	$-0.193^{+0.035}_{-0.049}$	$-0.130^{+0.038}_{-0.037}$	1.2σ
α (DIP)	$-1.73^{+0.14}_{-0.18}$	-1.42 ± 0.12	1.6σ

Comparison with Previous Experiments



- Twice the precision of other experiments
- Difference between $K_L \to \mu^+\mu^-\gamma$ and $K_L \to e^+e^-\gamma$ established at the 3σ level

Limit on ρ :

$$B(K_L \to \mu^+\mu^-) = |Re\, A|^2 + |Im\, A|^2$$

dispersive → $Re\, A = A_{SD} + A_{LD}$

absorptive → "unitarity bound" $= (7.07 \pm 0.18) \times 10^{-9}$

$$|A_{SD}|^2 = 2\, Re(V_{td}^* V_{ts})$$
$$= [(0.852 \pm 0.273) \times 10^{-9}](1-\bar{\rho})^2$$

$$\Rightarrow \bar{\rho} = 1.2 - [(3.43 \pm 0.55) \times 10^{4}] \,\big|\, |Re\, A_{exp}| \pm |Re\, A_{LD}| \,\big|$$

↑ $B(K_L \to \mu\mu) = (7.18 \pm 0.17) \times 10^{-9}$

$|Re\, A_{LD}|$??

BMS :

$$(-5.1 - 11.0\alpha_{K^*})\times 10^{-5} < \mathrm{Re}\,A_{LD} < (-2.9 - 10.2\,\alpha_{K^*})\times 10^{-5}$$

$$\Rightarrow \rho > -1.0$$

DIP :

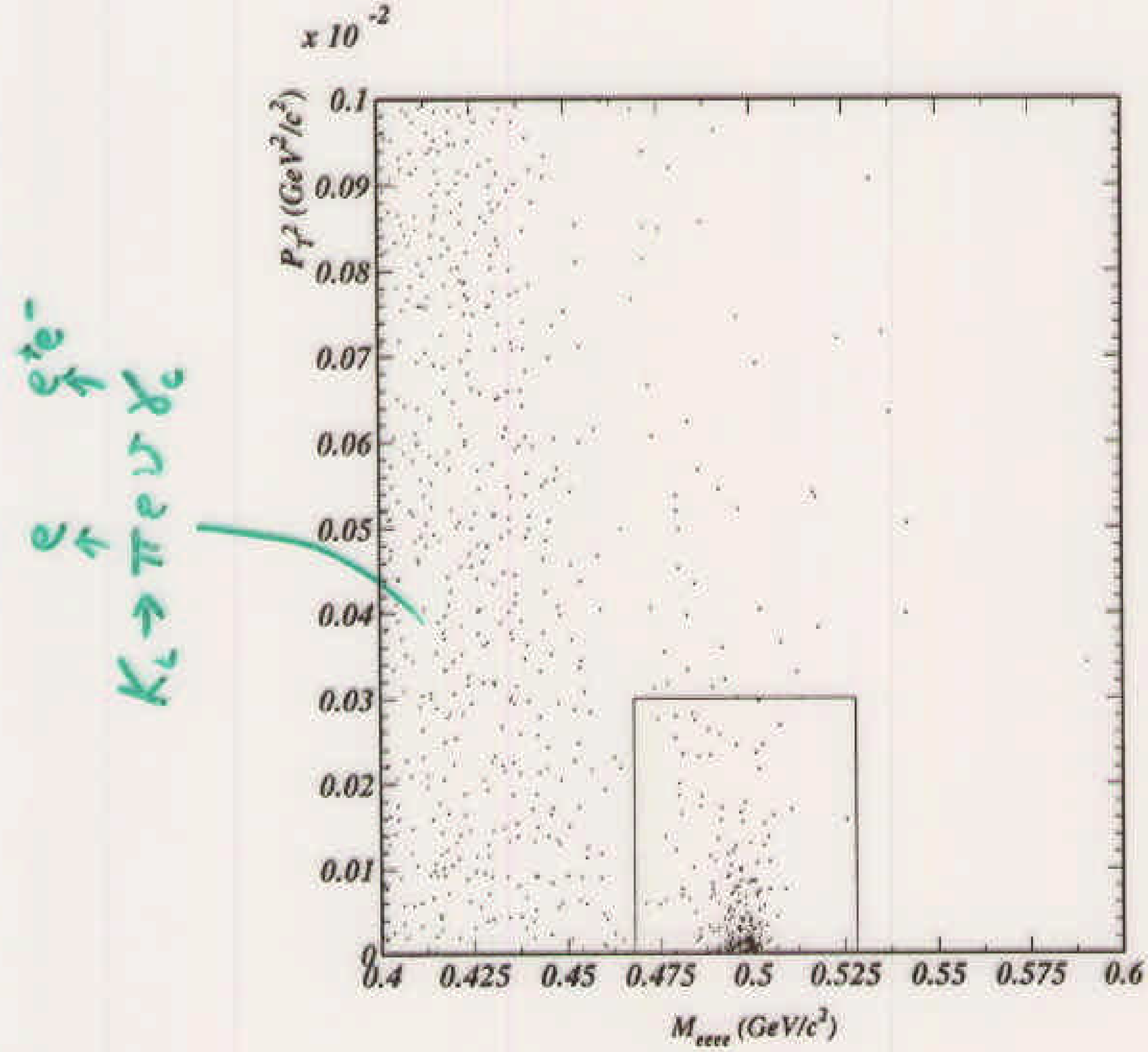
$$|\mathrm{Re}\,A_{LD}| = 1.61\times 10^{-5}\,\left|5.25 + 3.47\alpha + 3(1+2\alpha+\beta)\ln\frac{\Delta}{m_\rho}\right|$$

$$|(1+2\alpha+\beta)|\ln\frac{\Delta}{m_\rho} < 0.4$$

$$\Rightarrow \rho > -0.2$$

Note that this req' $\alpha \to \rho$, so need more validations on theories.

$K_L \to e^+e^-e^+e^-$



436 evts in the box

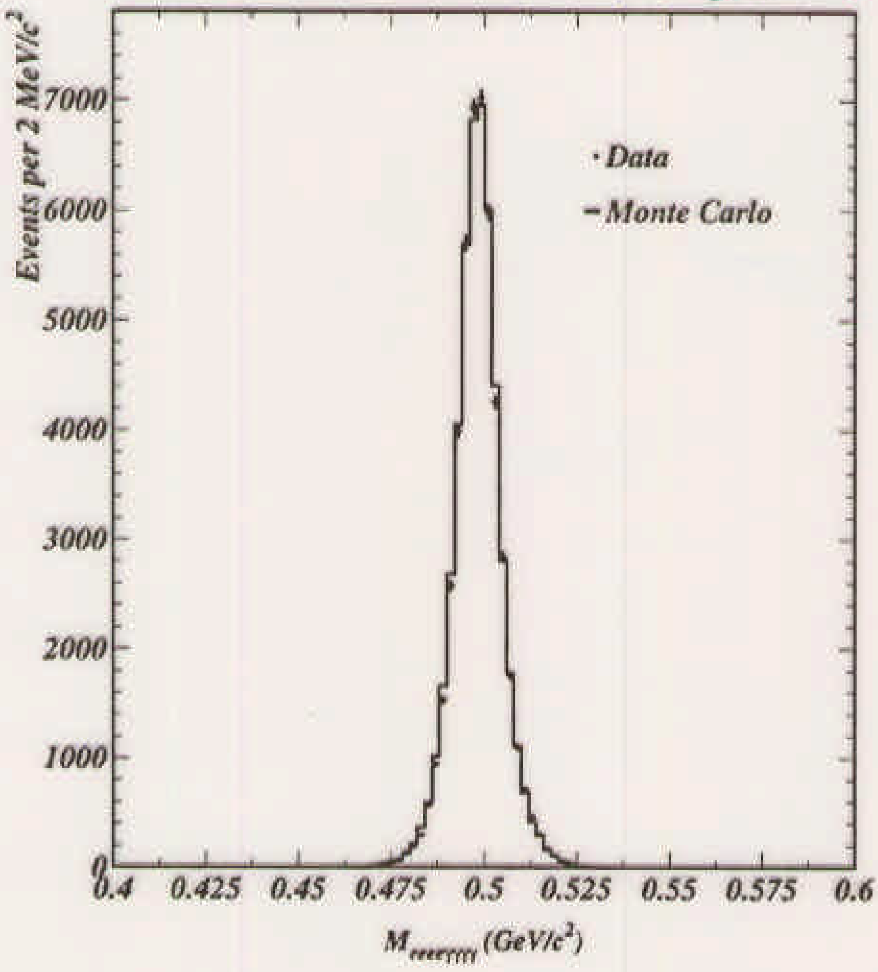
Bkgs: $K_L \to e^+e^-\gamma_c$ – track separation ~3 evts

$K_L \to \pi e \nu \gamma_c$ – " ~0.5 evts

$K_L \to \pi^0 \pi^0 \pi^0$

$\pi^0 \to e^+e^-\gamma$, $\pi^0 \to e^+e^-\gamma$

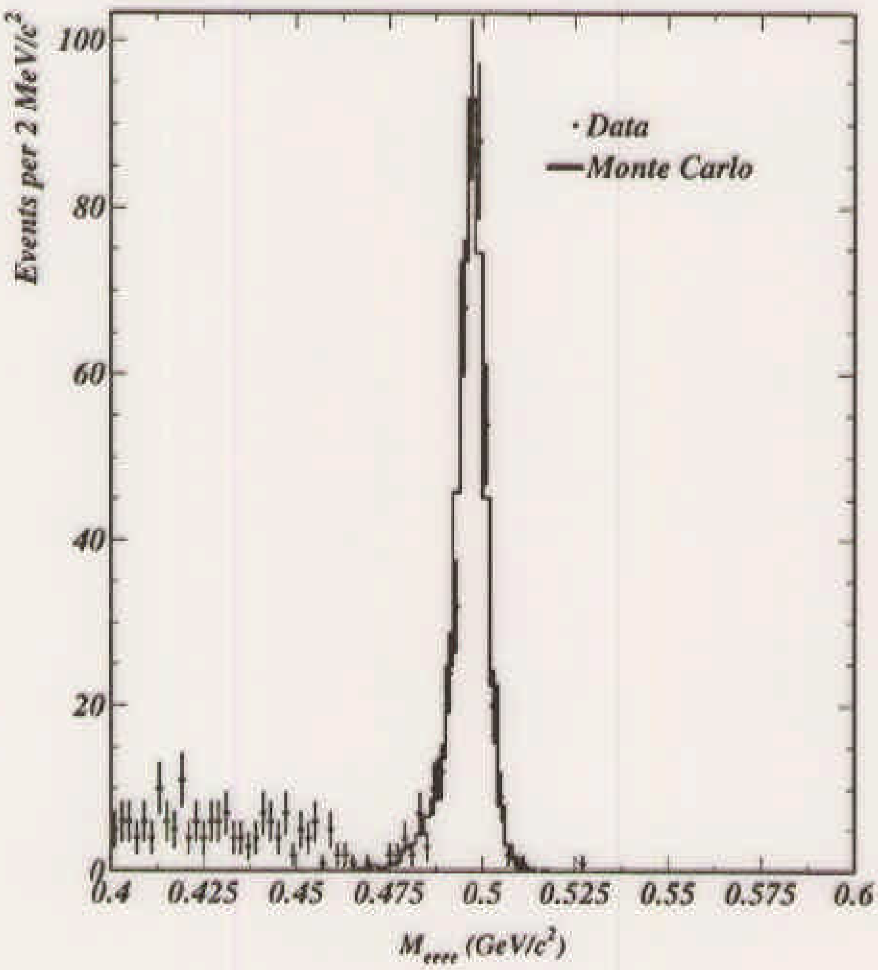
for normalization



$N_K\ (K_L \to \pi^0 \pi^0_D \pi^0_D) = (2.60 \pm 0.01 \pm 0.14) \times 10^{11}$

↑ from π^0_D br!

$K_L \to e^+e^-e^+e^-$



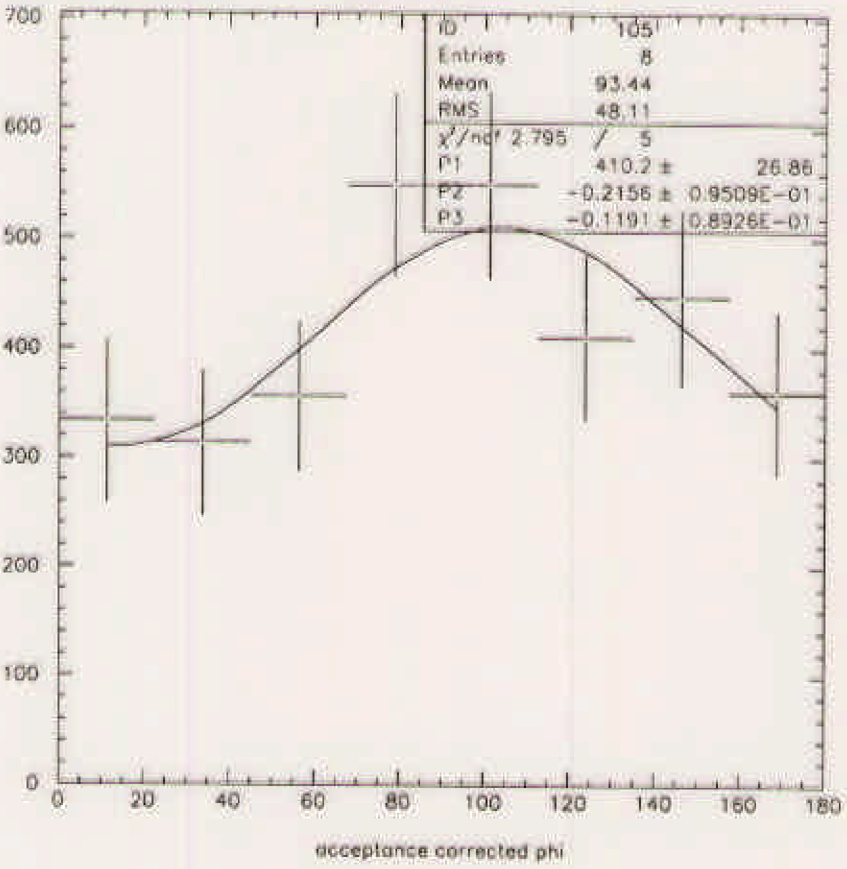
S : 436 evts with 3.5 evts bkgs, A = 4.46%

N : 47497 evts with 684 evts bkgs, A = 0.20%

$$BR(K_L \to e^+e^-e^+e^-) = (3.77 \pm 0.18 \pm 0.13 \pm 0.21) \times 10^{-8}$$

Stat — Syst — PDG

$K_L \to e^+e^-e^+e^-$



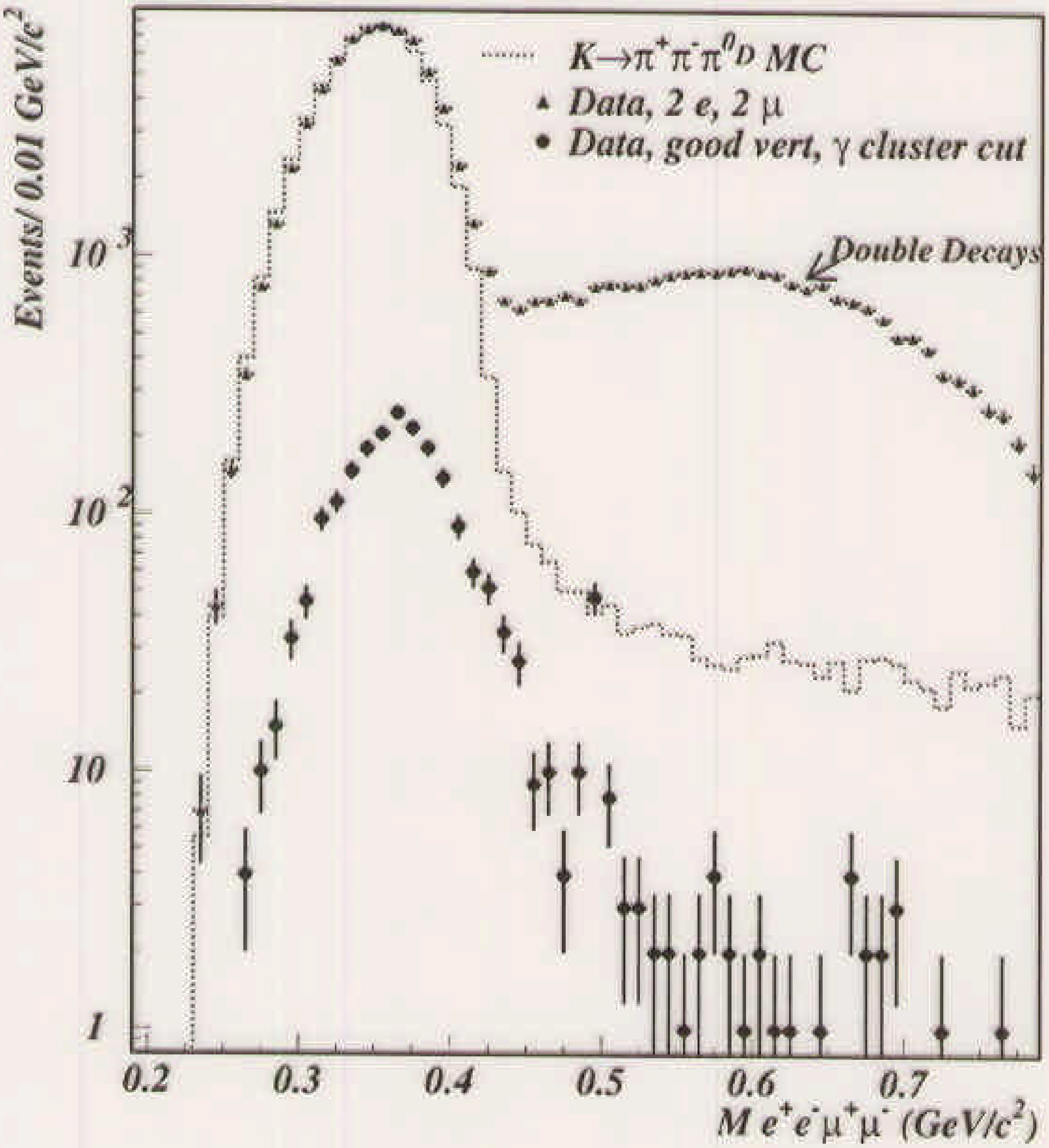
$$\frac{d\Gamma}{d\phi} \sim 1 + \beta\cos 2\phi + \gamma\sin 2\phi \; ; \qquad \beta = -0.212 \pm 0.091 \pm 0.02$$

$$\gamma = -0.119 \pm 0.085 \pm 0.02$$

$\uparrow$ (β) -0.2

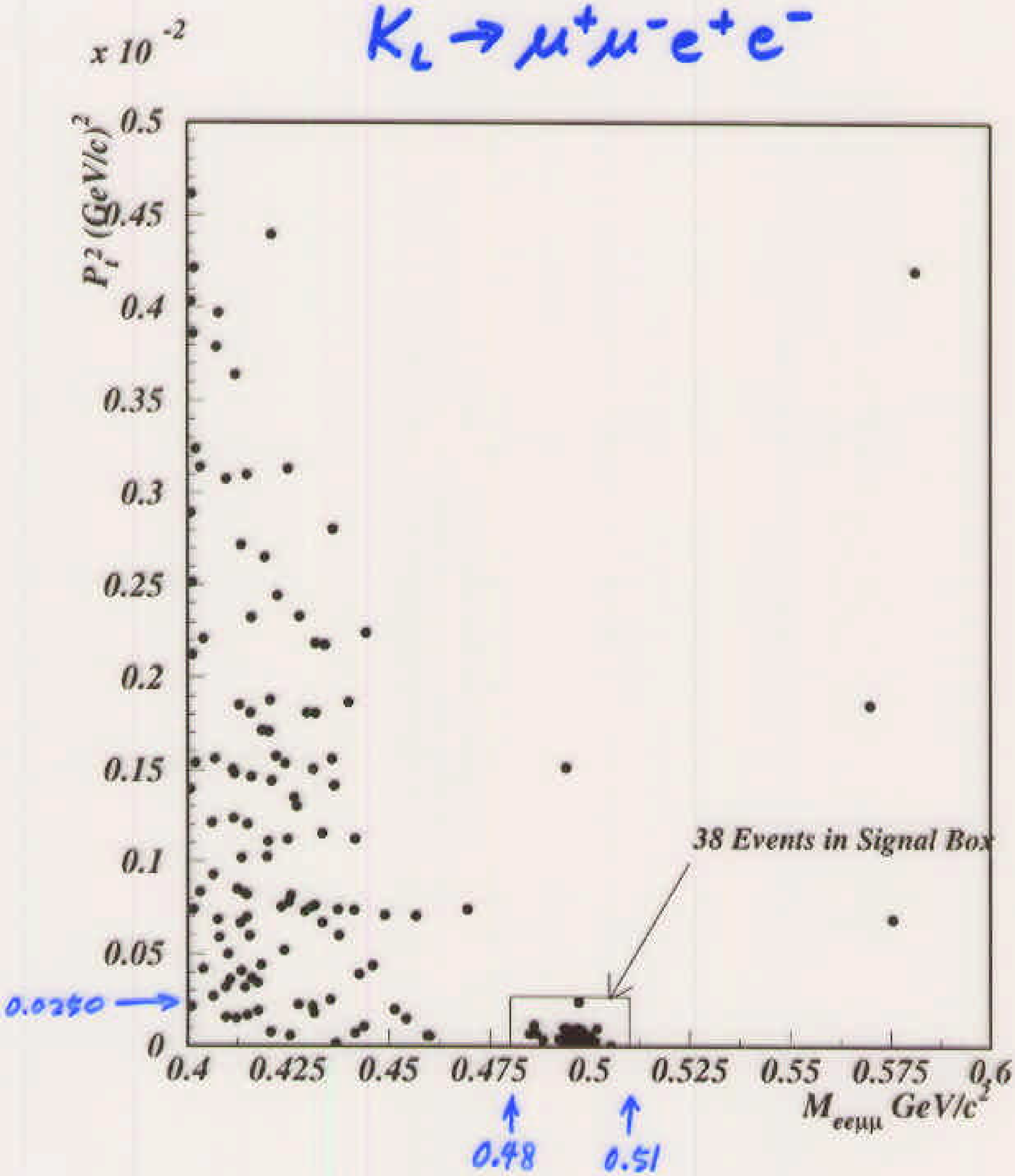
$$\alpha_{K^*}\,(\text{BMS}) = 0.03 \pm \underset{(\text{stat})}{0.17} \pm \underset{(\text{syst})}{0.18}$$

$K_L \to \mu^+\mu^-e^+e^-$



* Good vertex eliminates double decays
* Extra γ cluster eliminates $\pi^+\pi^-\pi^0_D$

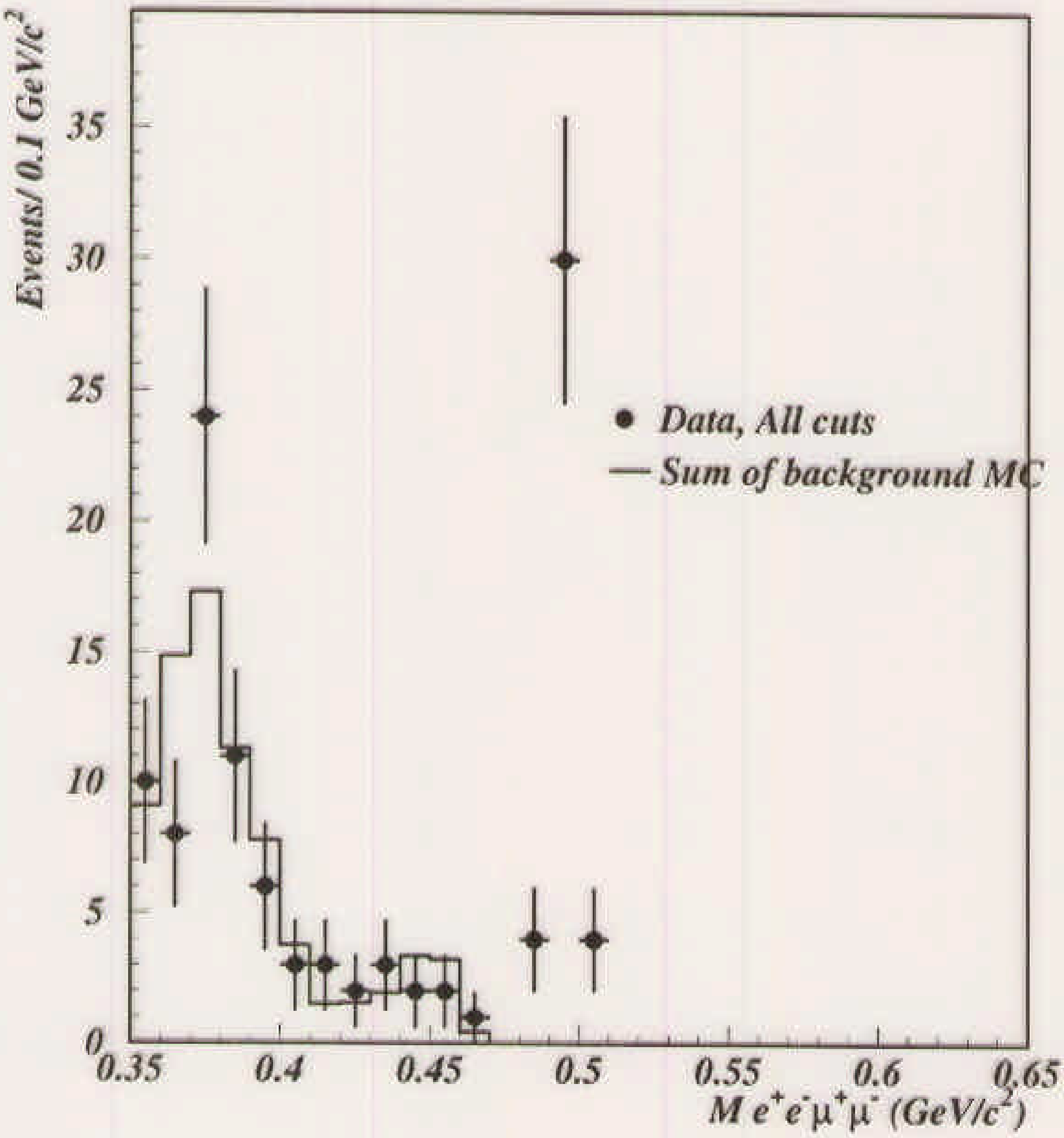
$K_L \to \mu^+\mu^- e^+ e^-$



Bkg [$\mu\mu\gamma_c$; $\pi^+\pi^-\pi^0_D$; $\pi^+\pi^- e^+ e^-$] ≃ 0.18 evts

Normalization $K_L \to \pi^+\pi^-\pi^0_D$ from minimum bias data

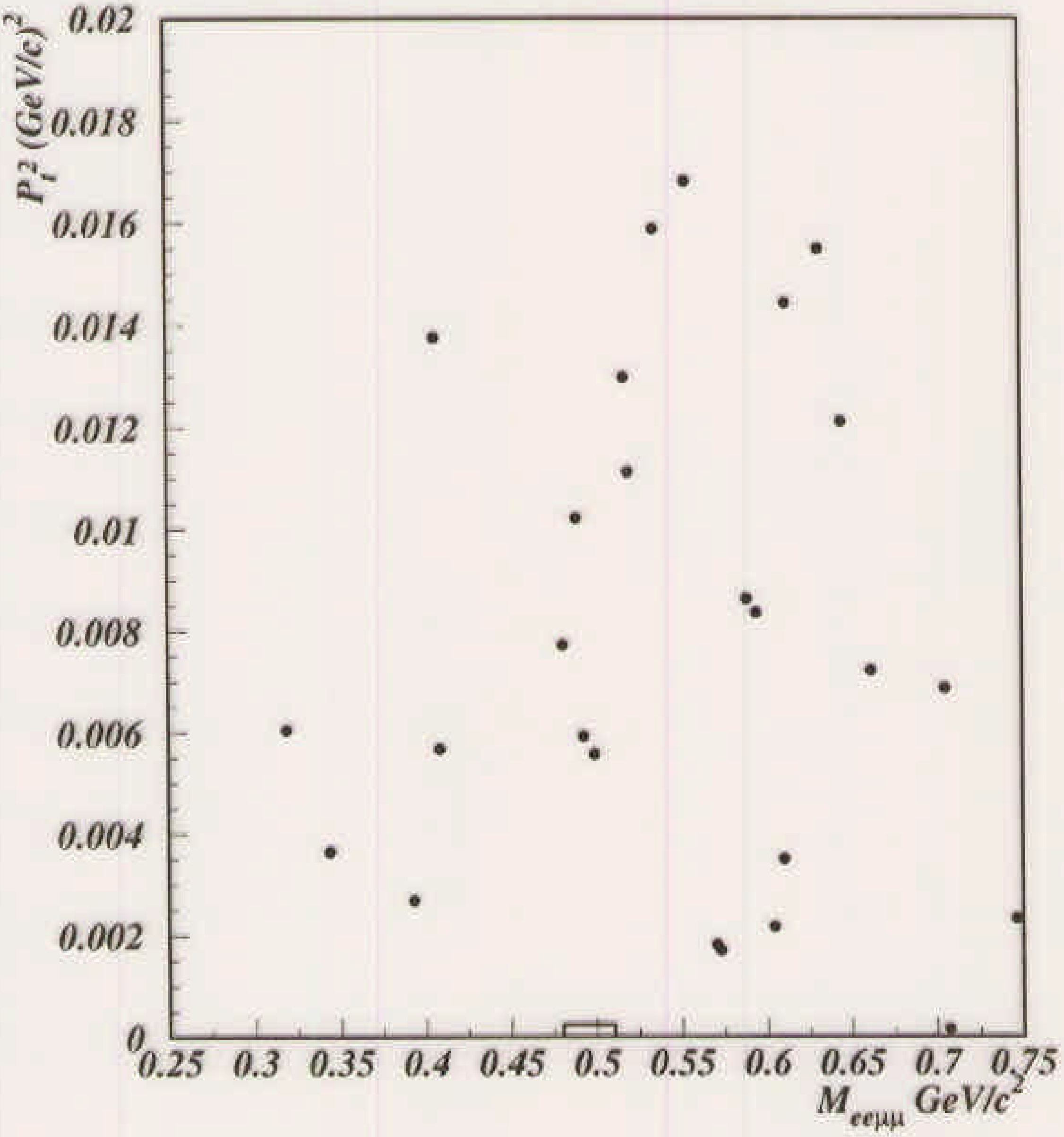
$K_L \to \mu^+\mu^- e^+e^-$



Acceptance$_{\mu^+\mu^-e^+e^-}$ ~ 5.6%

$BR(K_L \to \mu^+\mu^- e^+e^-) = (2.50 \pm 0.41 \pm 0.15) \times 10^{-9}$

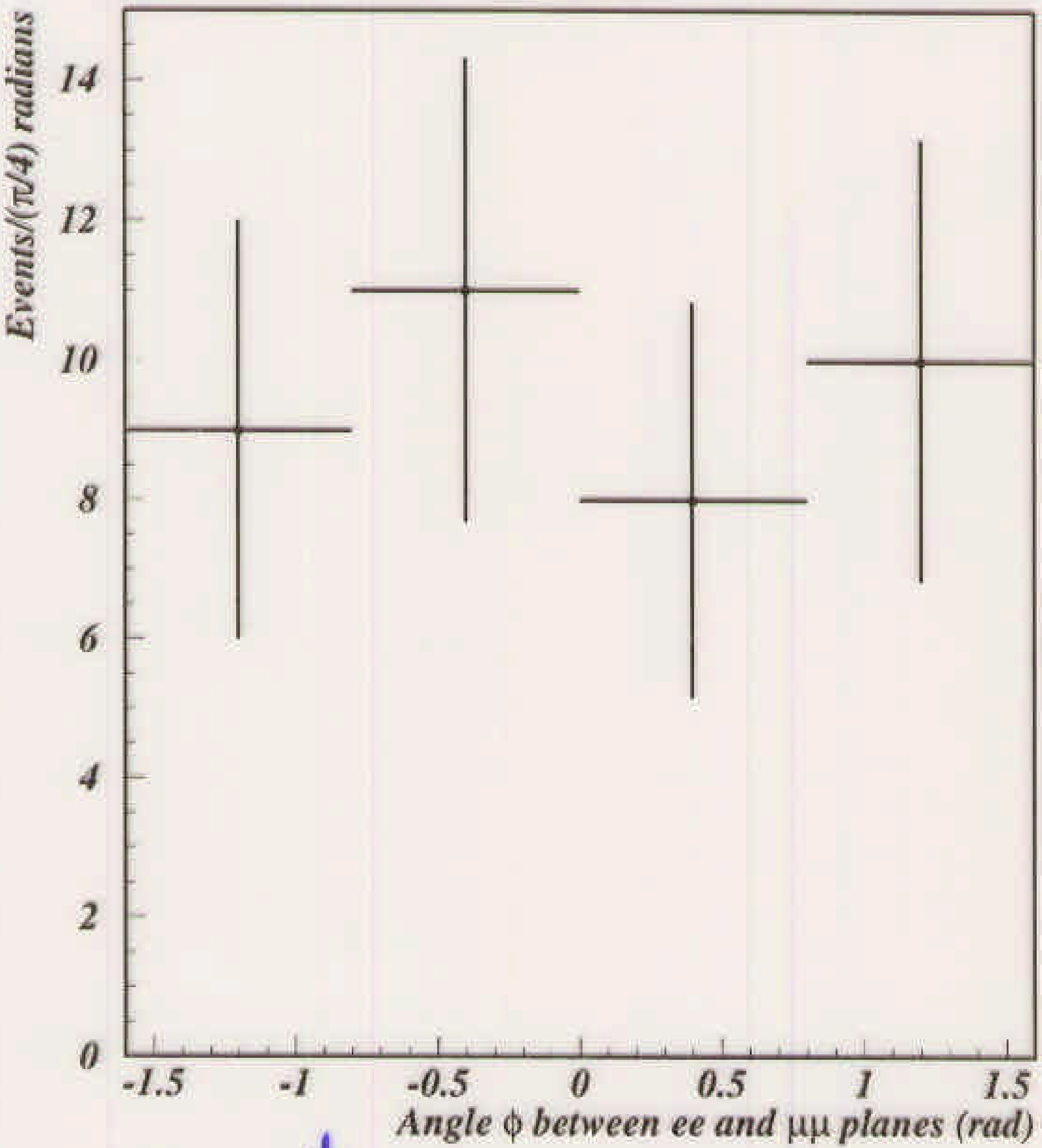
$K_L \to \mu^\pm \mu^\pm e^\mp e^\mp$

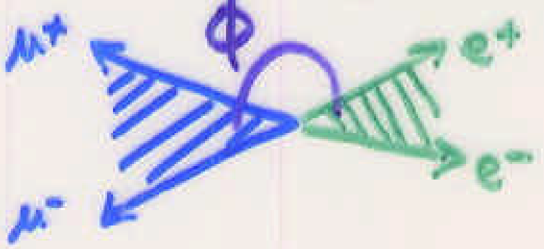


Acceptance = 6.65%

$BR(K_L \to e^\mp e^\mp \mu^\pm \mu^\pm) < 1.36 \times 10^{-10}$ (90% CL)

$K_L \to \mu^+\mu^-e^+e^-$





Small asymmetry in ϕ if CP violation.

Summary:

$BR(K_L \to \mu^+\mu^-\gamma) = (3.70 \pm 0.04 \pm 0.07) \times 10^{-7}$

$\alpha_{K^*} = -0.163^{+0.026}_{-0.027}$ (BMS)

$\alpha = -1.55 \pm 0.09$; $\rho > 0.2$ (DIP)

$BR(K_L \to e^+e^-e^+e^-) = (3.77 \pm 0.18 \pm 0.27) \times 10^{-8}$

$\beta = -0.21 \pm 0.10 \pm 0.02$

$\gamma = -0.12 \pm 0.09 \pm 0.02$

$\alpha_{K^*} = 0.03 \pm 0.17 \pm 0.18$

$BR(K_L \to \mu^+\mu^- e^+e^-) = (2.50 \pm 0.41 \pm 0.15) \times 10^{-9}$

$BR(K_L \to e^\mp e^\mp \mu^\pm \mu^\pm) < 1.36 \times 10^{-10}$ (90% CL)