Recent KTeV Results on Rare and LFV Decays

Arizona, UCLA, UCSD, Campinas, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, Sao Paolo, Virginia, Wisconsin

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Electroweak Moriond 2007

Outline

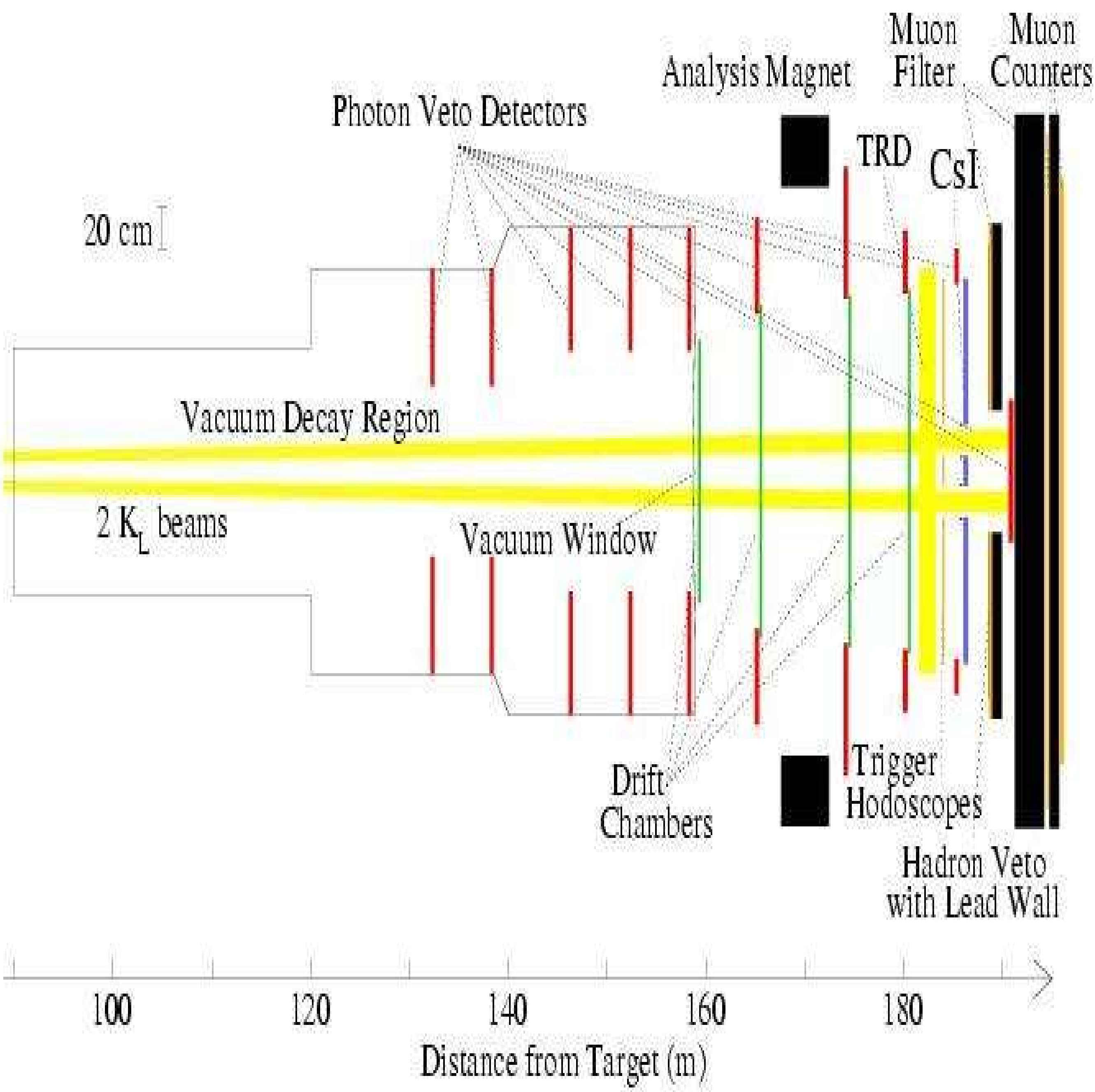
KTeV was constructed primarily to measure the direct CPV parameter ε'/ε.

Ran in 1997 and 1999 at Fermilab.

Rich number of other physics topics from KTeV due to excellent detector acceptance to many rare K decay modes.

For this talk, I present recent KTeV measurements of:

- BR($\pi^0 \to ee\gamma$) "Dalitz decay"
- BR($K_L \to \pi^0\gamma\gamma$) and BR($K_L \to \pi^0 ee\gamma$)
- LFV limits on $K_L \to \pi^0\pi^0\mu e$ and $\pi^0 \to \mu e$



Large acceptance for nearly all neutral kaon decays

Spectrometer:

$\sigma(P)/P=0.38\% + 0.16\%P$

CsI calorimeter:

$\sigma(E)/E=0.45\% + 2\%/\sqrt{E}$

Transition Radiation Detector for additional particle-ID

Ran in 1997 and 1999 at Fermilab, with an exposure of ~ 10^{12} K_L decays in the fiducial volume

A New Measurement of BR($\pi^0 \to ee\gamma$) "Dalitz decay"

An important engineering measurement for HEP.
Many measurements use BR($\pi^0 \to ee\gamma$) as a scale factor
(ie. an external systematic error).

Current Measurements of BR($\pi^0 \to ee\gamma$)/BR($\pi^0 \to \gamma\gamma$)

(1.17 $\pm$ 0.15)%	27 events	Budagov	1960	– JETP 11
(1.166 $\pm$ 0.047)%	3071 events	Samios	1961	– Phys. Rev. 121
(1.25 $\pm$ 0.04)%	~10^3 events	Schardt	1981	– Phys. Rev. D 23
(1.213 $\pm$ 0.030)%	PDG Average (2.5% relative uncertainty)			

Theory

1.185% R. Dalitz 1951 – Proc. Phys. Soc. A64

1.196% D. Joseph 1960 – Nuovo Cimento 16

1.196% K. Mikaelian & J. Smith 1972 – Phys. Rev. D 5

Analysis Technique

Signal Mode

$K_L \rightarrow \pi^0\pi^0\pi^0$

$\gamma\gamma \quad \gamma\gamma \quad ee\gamma$

7 clusters in CsI

2 tracks, well-separated in the drift chambers

Reconstruction

Fully reconstructed

Choose among 15 photon pairings by requiring the 3 pions to have decayed at the same z position

Decay must occur in 40 m vacuum region

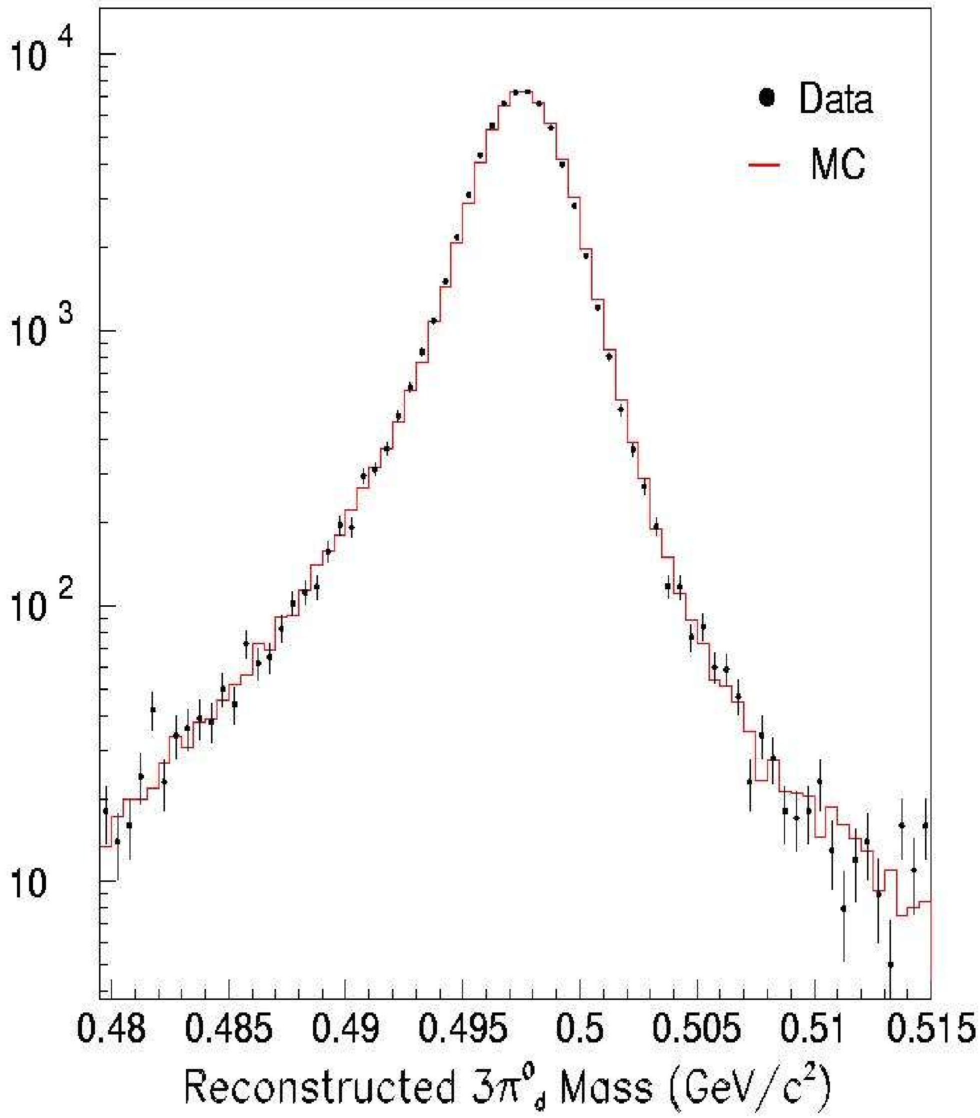
66,000 Dalitz Decays!

Normalization Mode

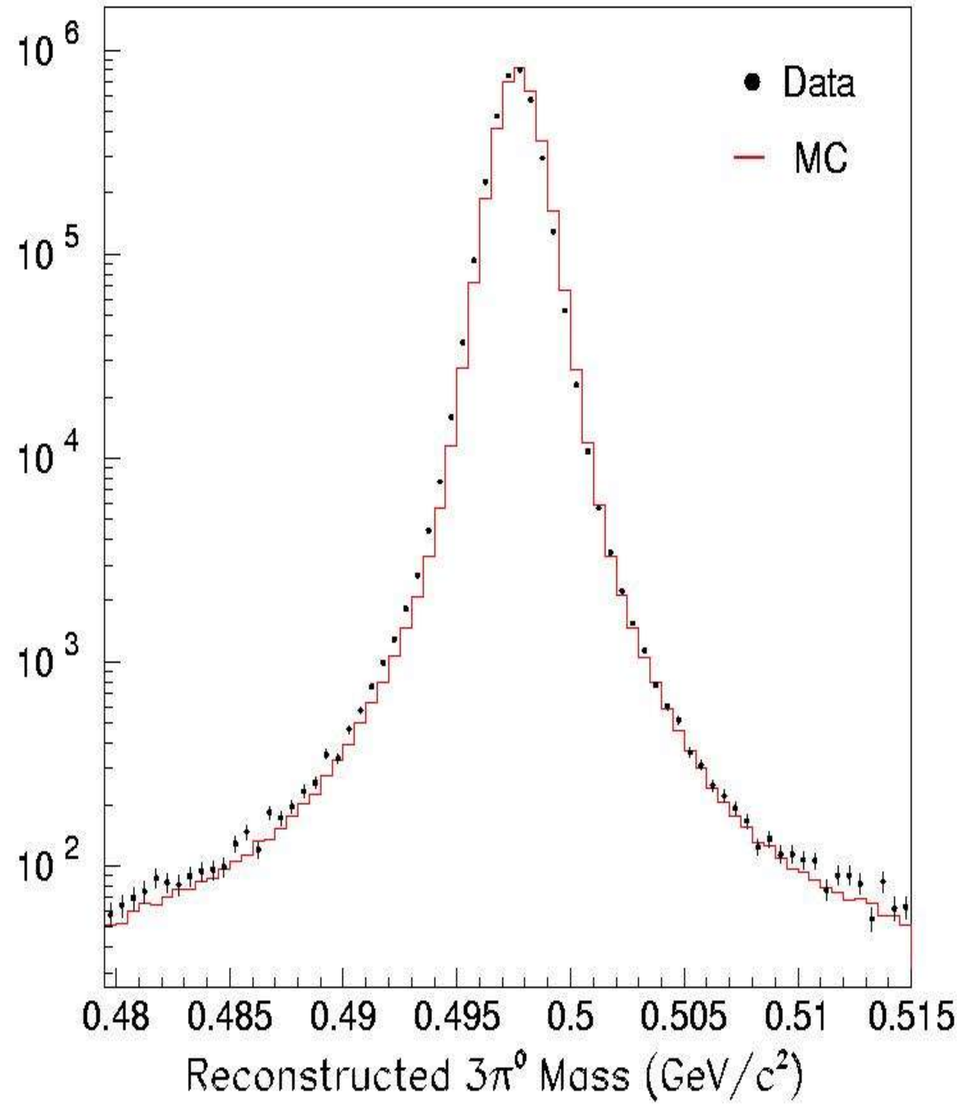
$K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma$

6 clusters in CsI

Dalitz Signal

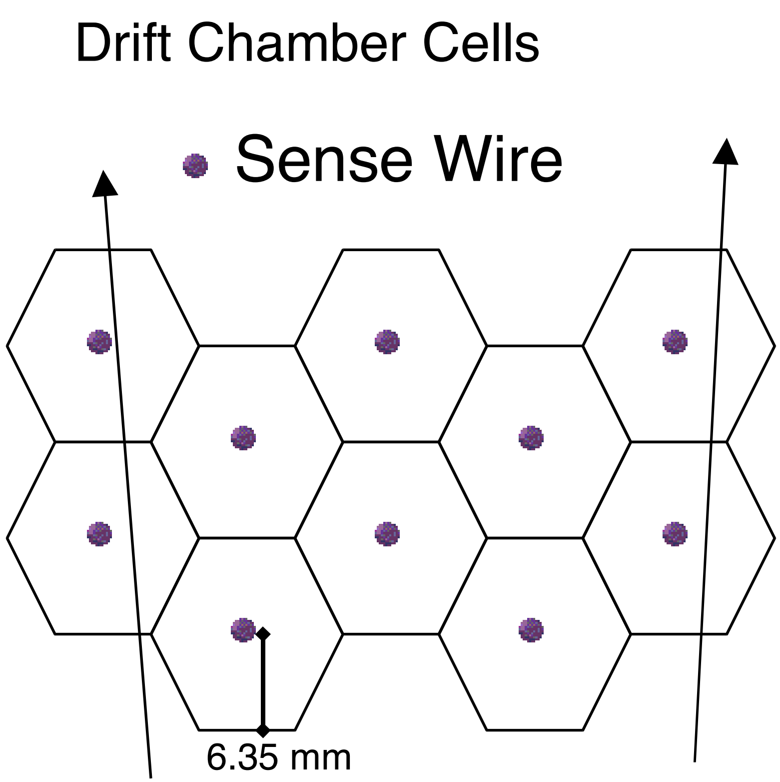


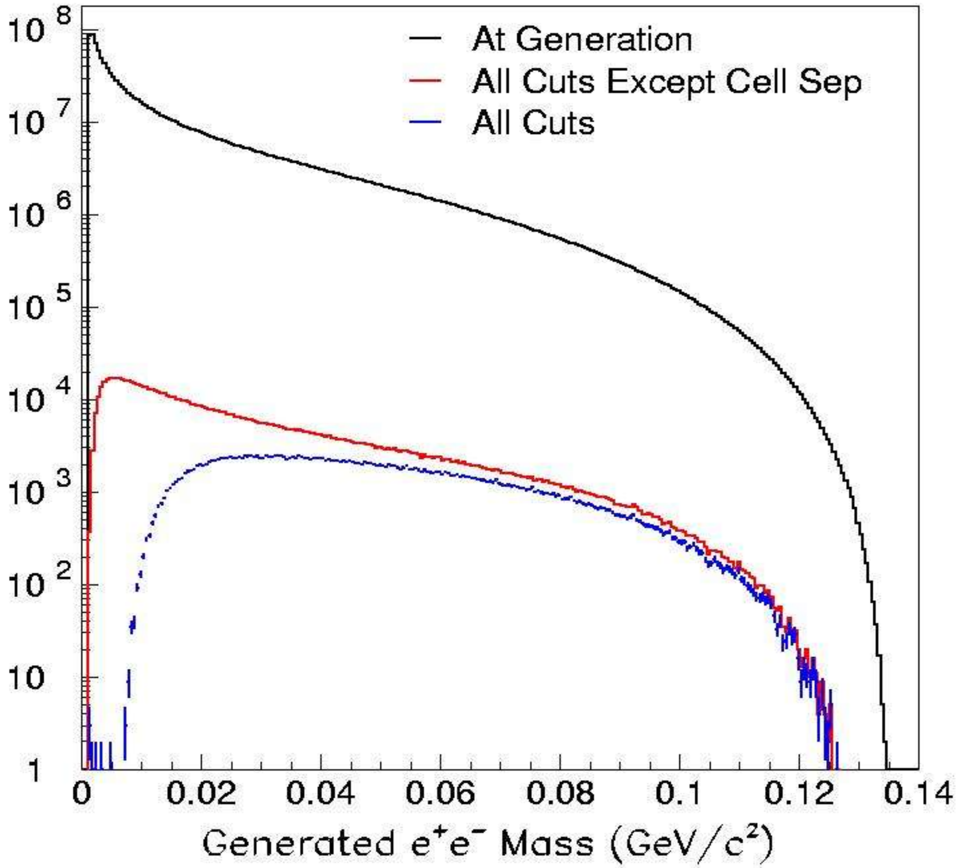
$3\pi^0$ Normalization Mode



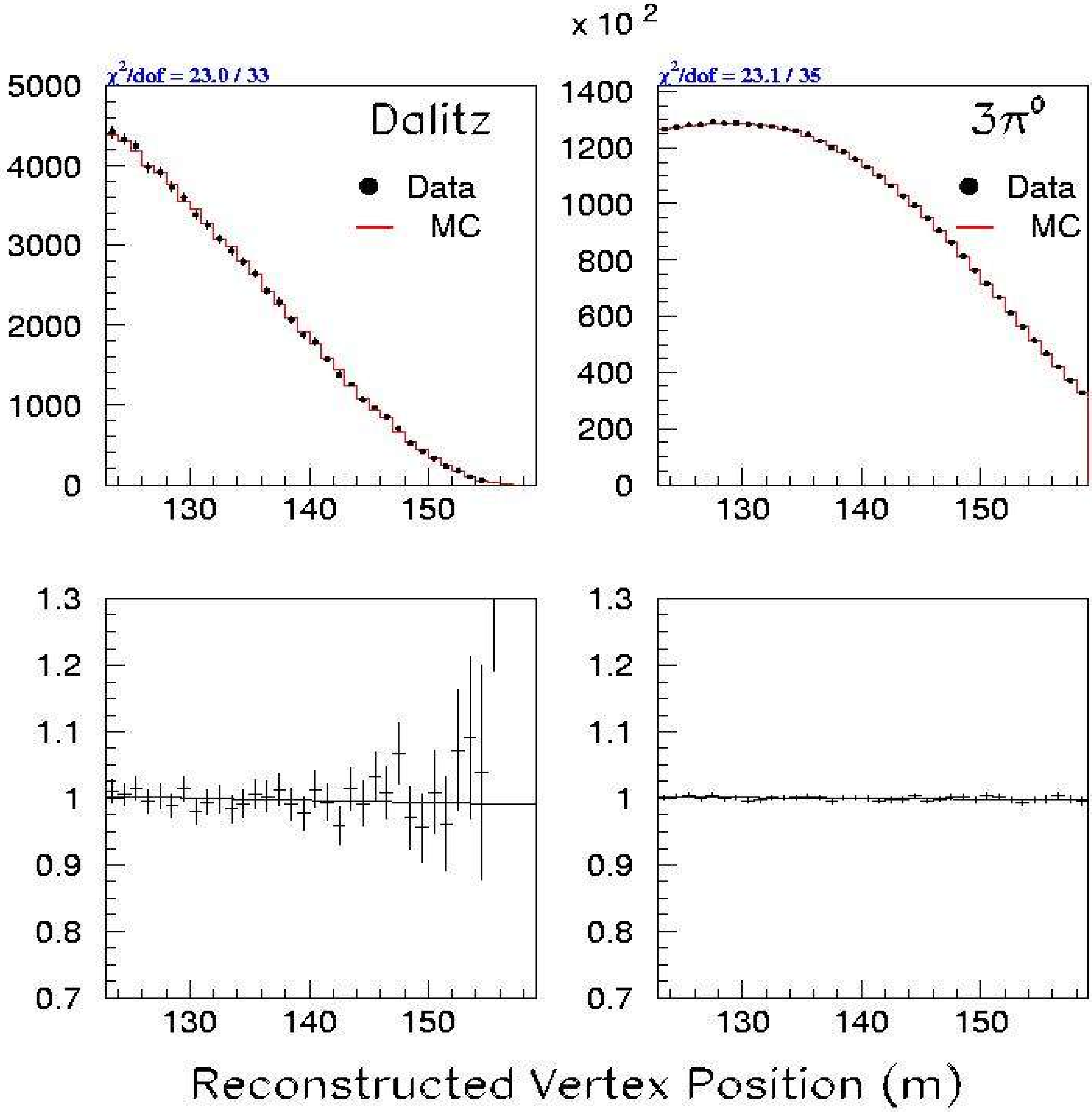
e^+e^- Track Separation Requirement to Ensure Good Acceptance Measurement

Track Cell Separation Requirement: >3 cells → Effective e^+e^- Mass Cutoff





Relative Acceptance



Good Match between Data and MC is essential

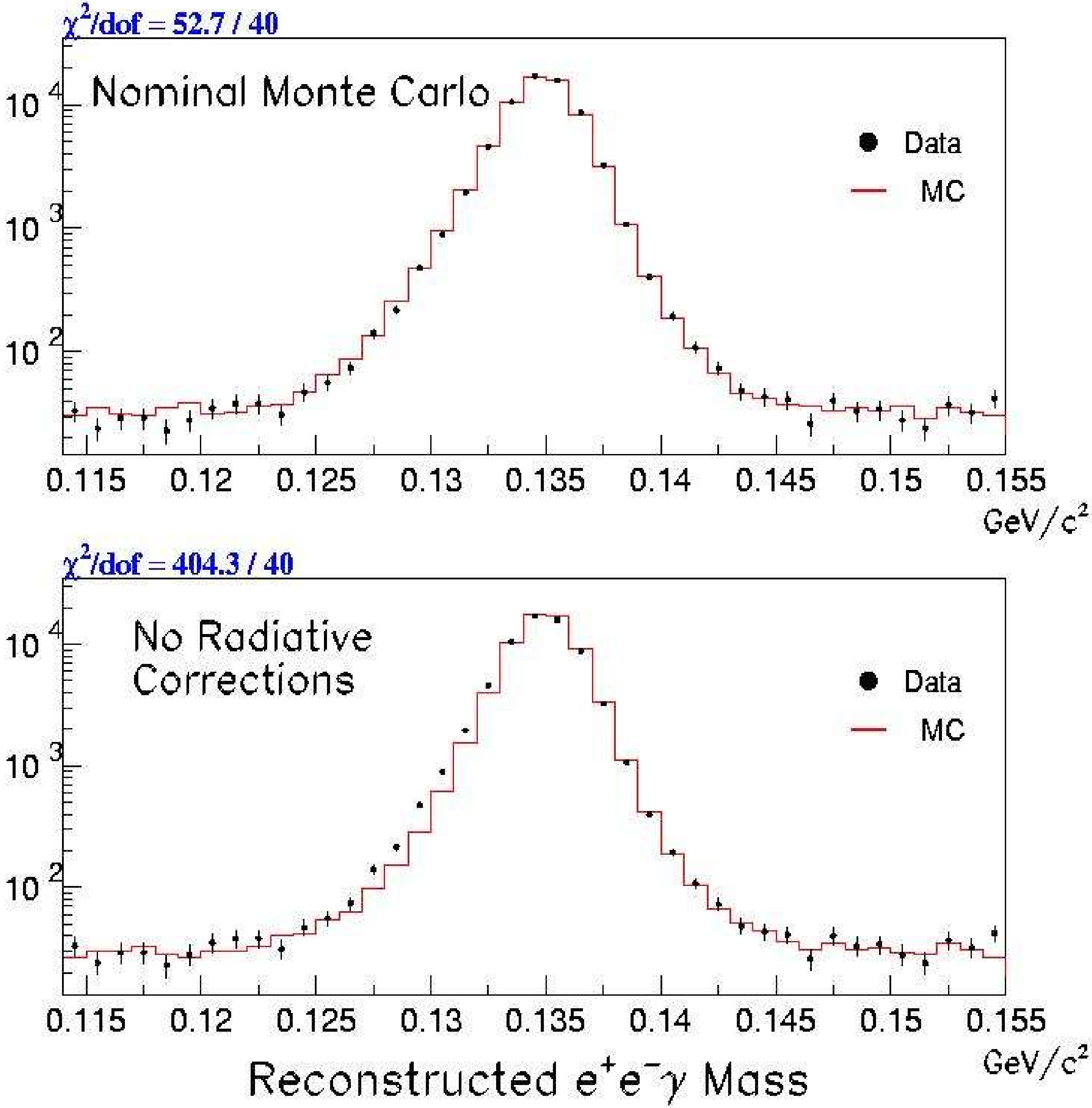
Shapes match to better than 1.5σ

Source of Systematic Error	Preliminary Uncertainty
Radiative Corrections	1.02%
Tracking Inefficiency	0.68%
Detector Material	0.37%
Accidentals	0.10%
Trigger Inefficiency	0.14%
Trigger 6 Prescale	<0.1%
Form Factor	0.07%
Photon Inefficiency	0.01%
Background	<0.1%
Cut Variations	<0.1%
Monte Carlo Statistics	0.19%
Total Systematic Error	1.32%

66,432 Dalitz events

0.39% relative statistical uncertainty

Radiative Corrections

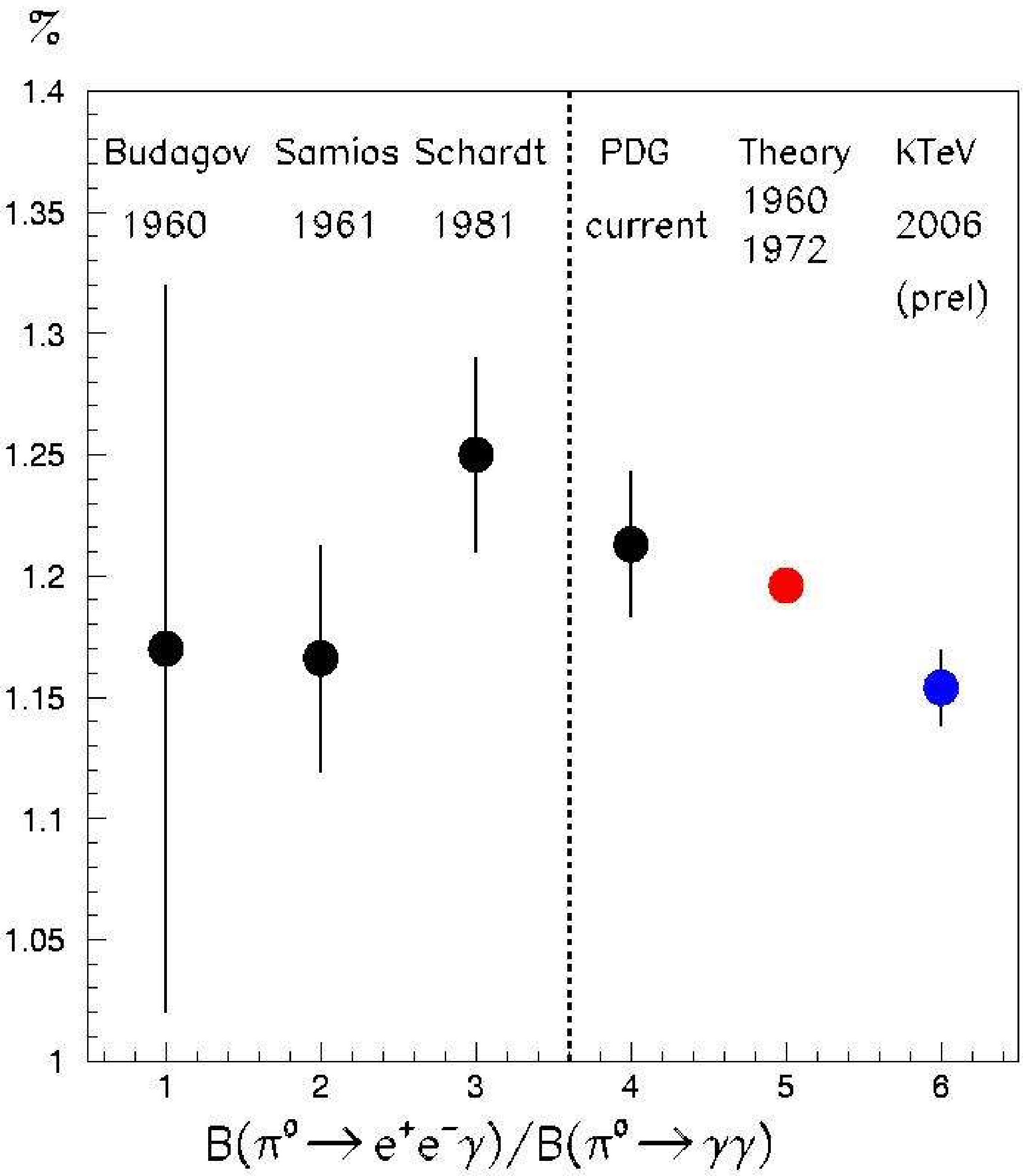


Radiative corrections lowers the acceptance by ~5%

Width of $e^+e^-\gamma$ mass distribution disagrees with data

Conservatively assign a systematic error of ~1% of the acceptance

New KTeV Measurement of BR($\pi^0 \to ee\gamma$)/BR($\pi^0 \to \gamma\gamma$)



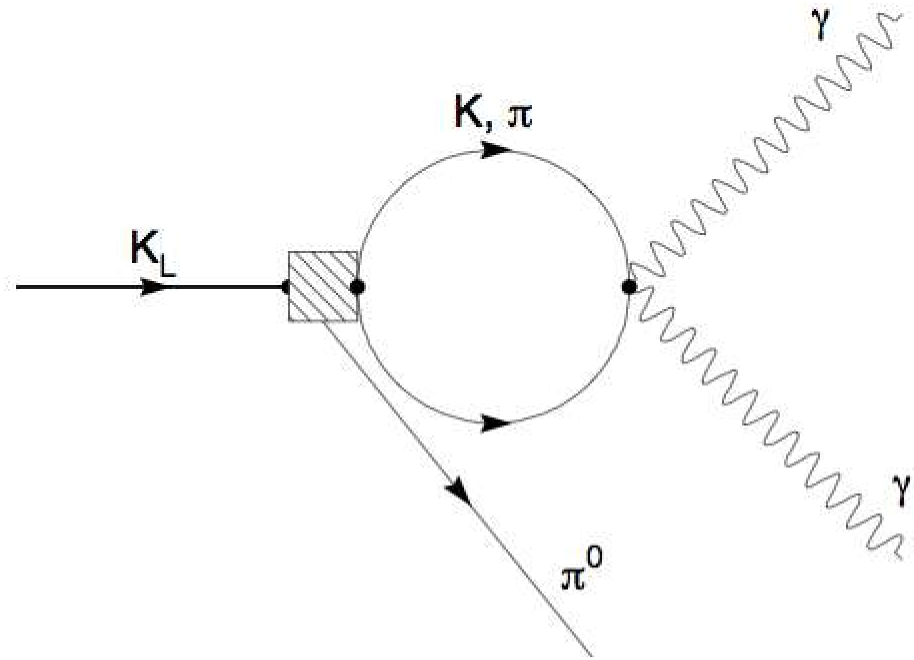
(1.1539 ± 0.0045 ± 0.0152) %

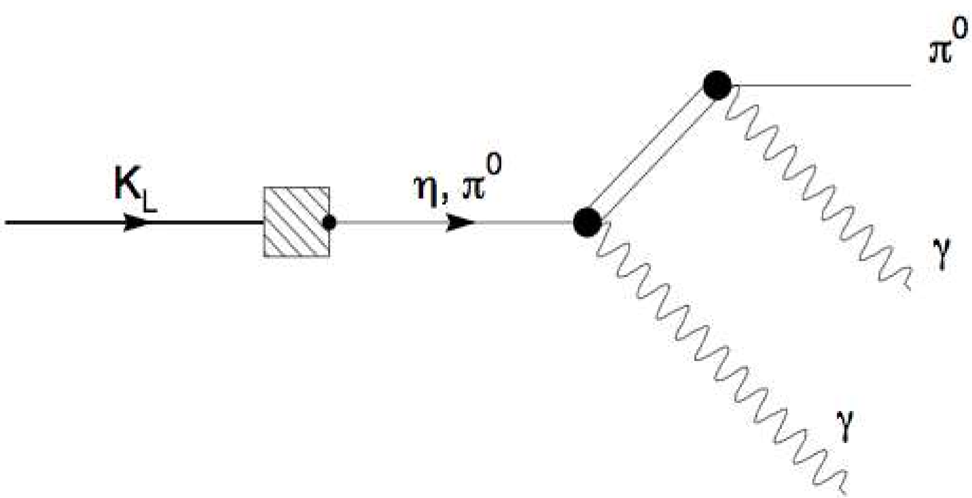
Consistent with previous measurements and with theory

Half the uncertainty of current PDG average

2.5 times better than best previous measurement

Physics of $K_L \rightarrow \pi^0\gamma\gamma$





Relevant for untangling the CP decomposition of $K_L \rightarrow \pi^0 ee$ (related to ImV_{TD})

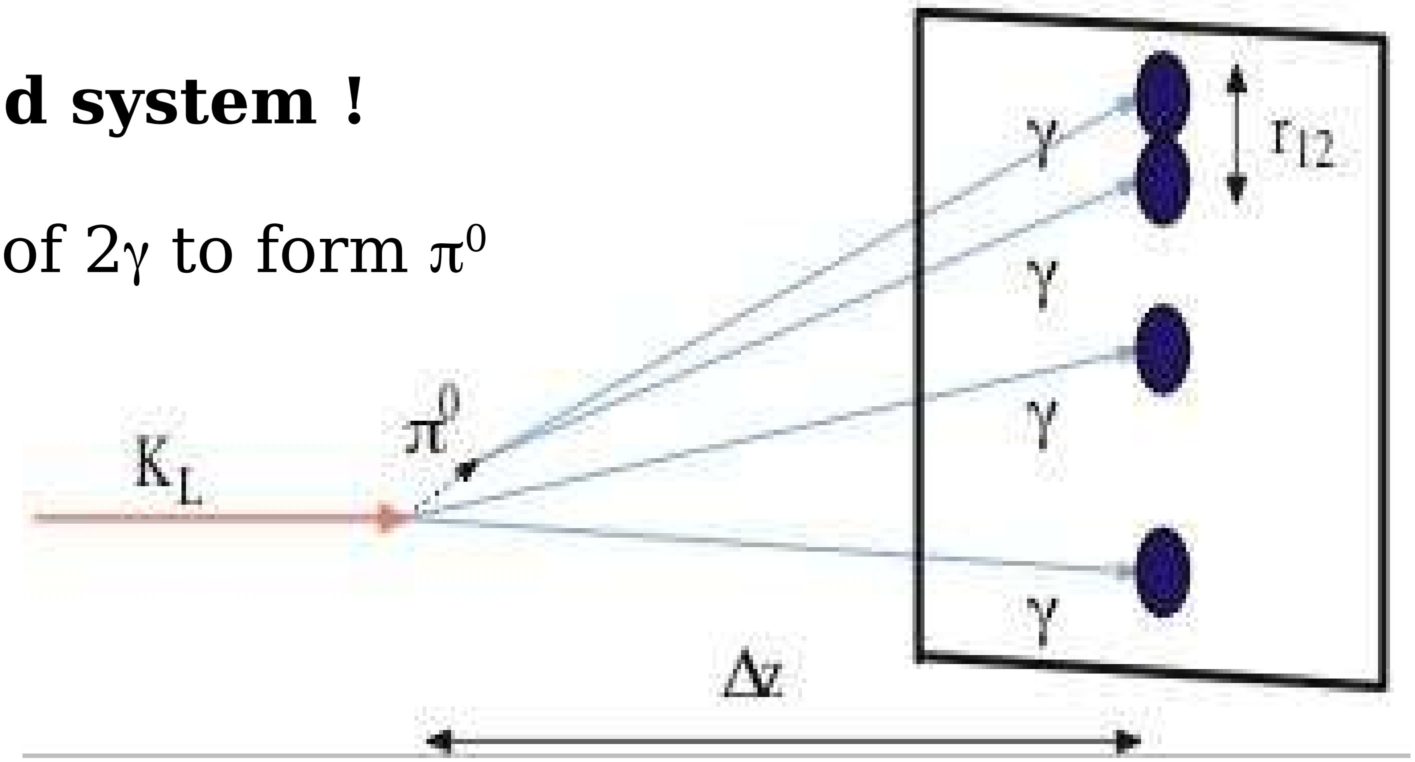
- $O(p^4)$ χPT predicts BR ~ 10^{-6} and small contribution to $K_L \rightarrow \pi^0 ee$. Prediction low by factor of 2-3.

- $O(p^6)$ χPT and the VMD parameter a_v can accommadate the measurements. Large contribution to $K_L \rightarrow \pi^0 ee$.

Signature is 4 EM showers in CsI

Underconstrained system !

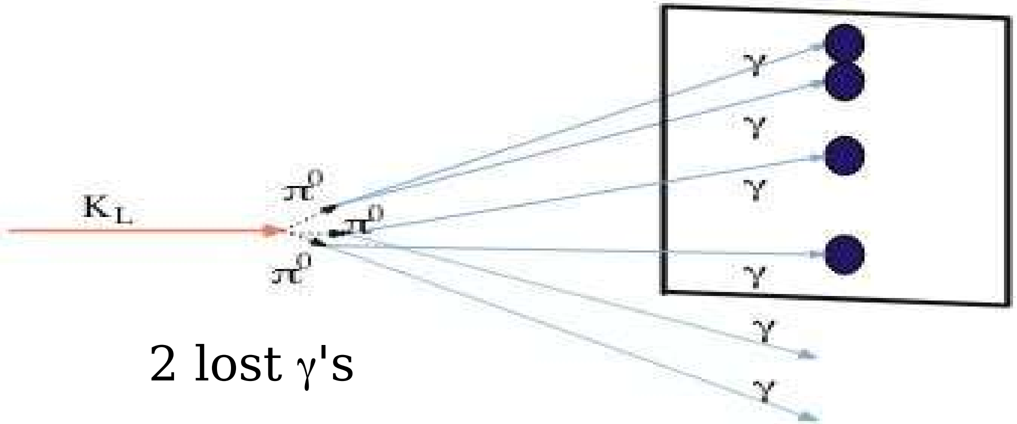
3 possible pairing of 2γ to form π^0



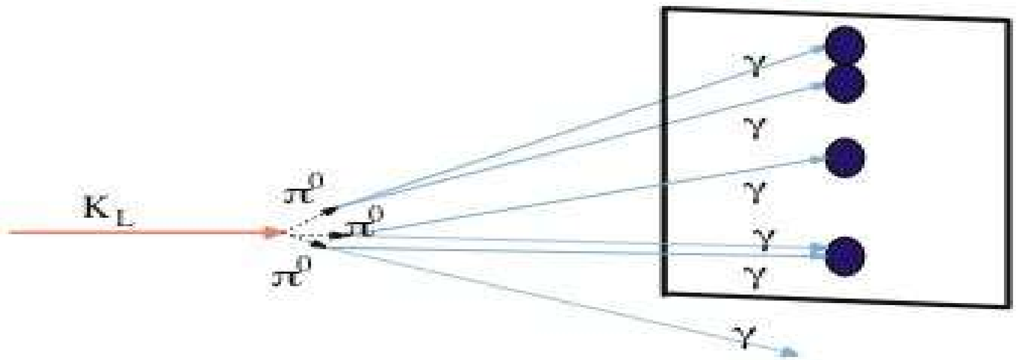
Use Kaon Mass constraint to create 3 possible hypothesis for the K_L decay vertex location.

Select hypothesis with best possible π^0 mass

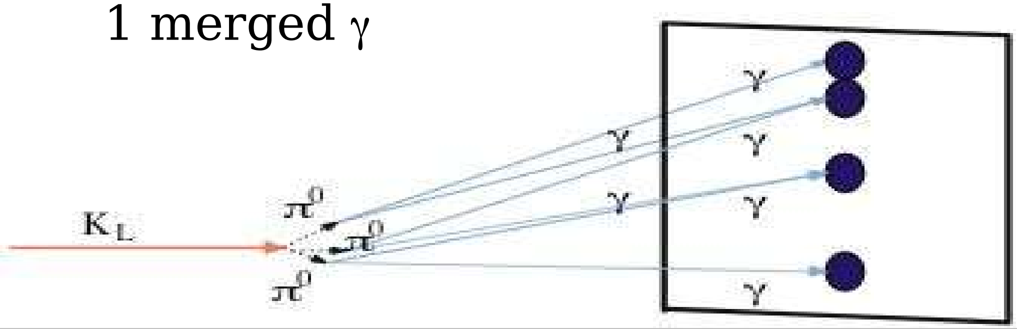
Serious Background from $K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma$



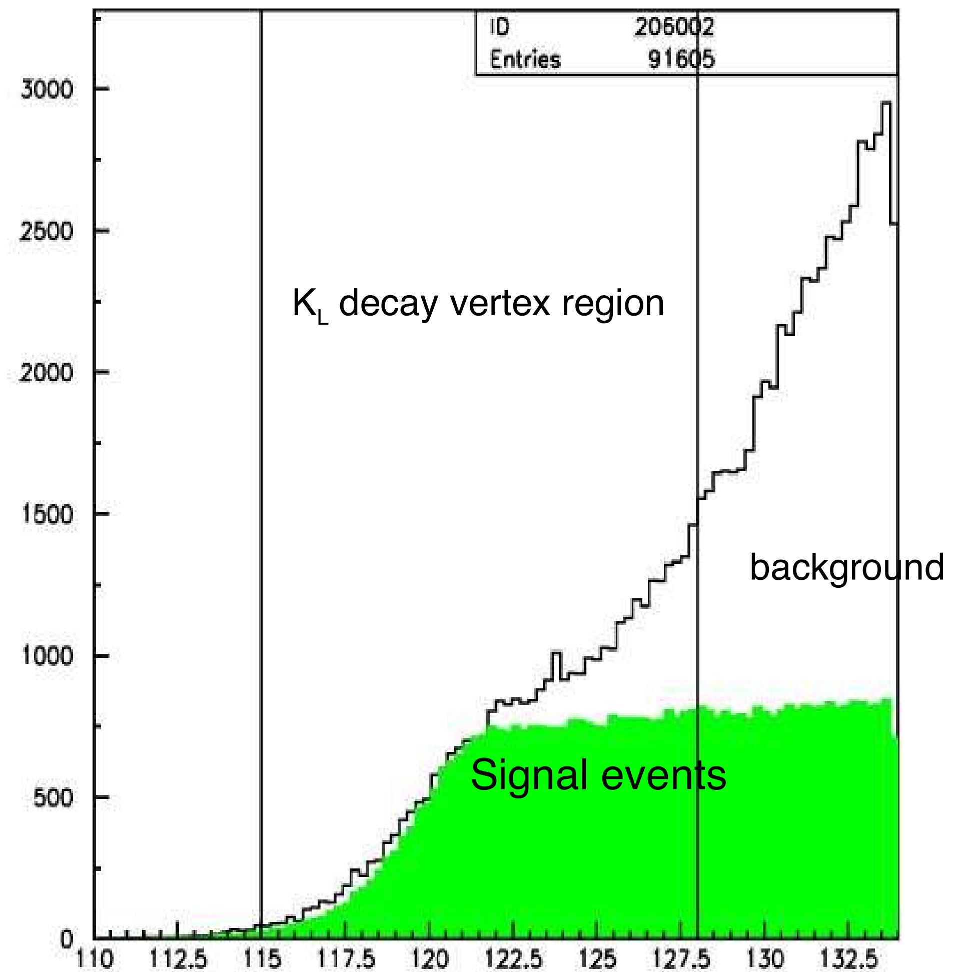
2 lost γ's



1 lost γ
1 merged γ

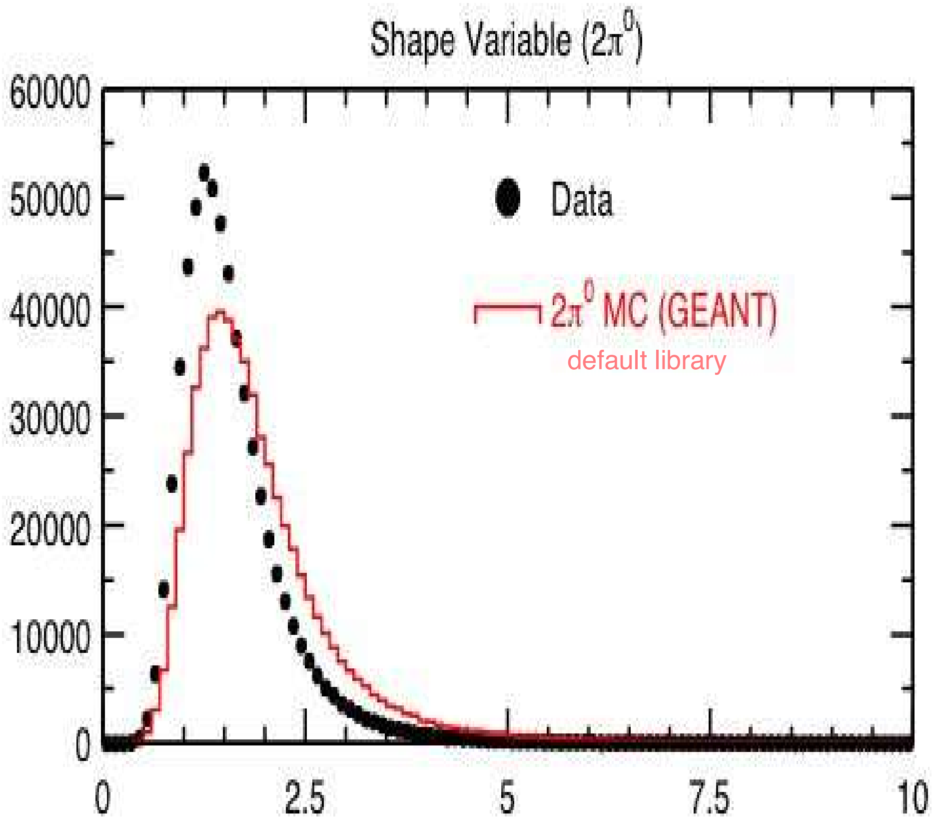


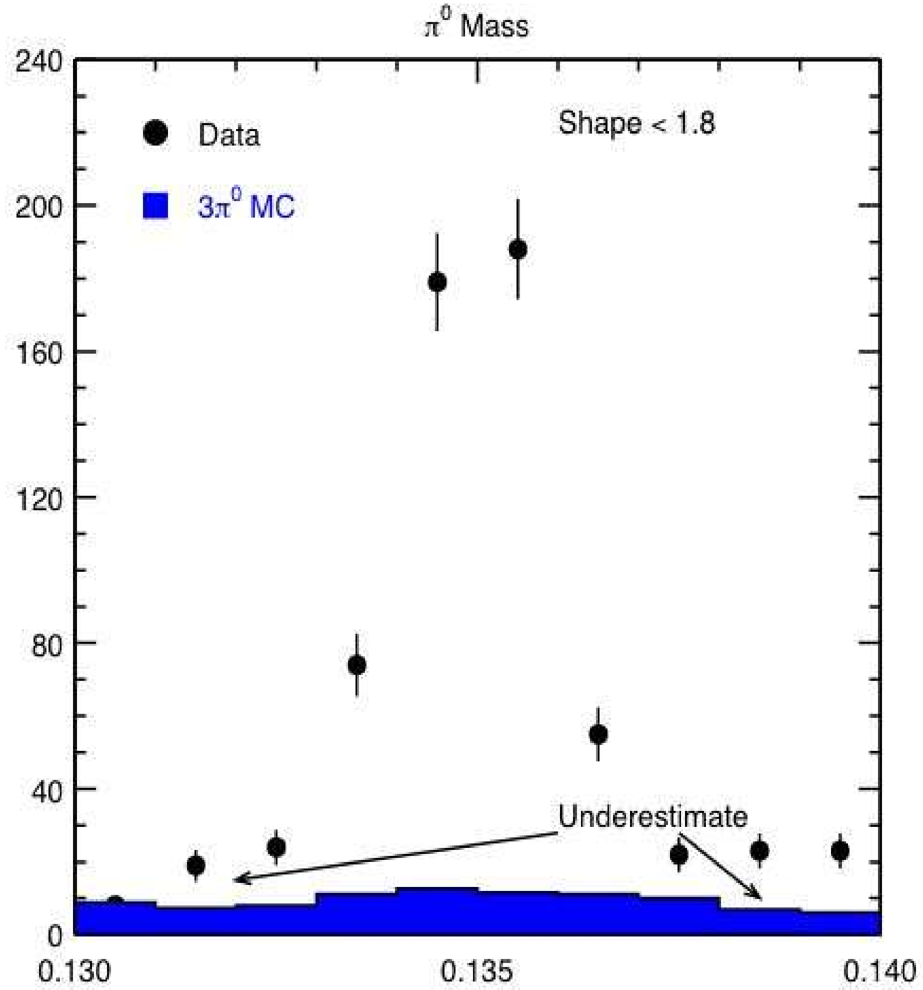
2 merged γ



Background tendencies:
- reconstructs downstream
- bad cluster shapes

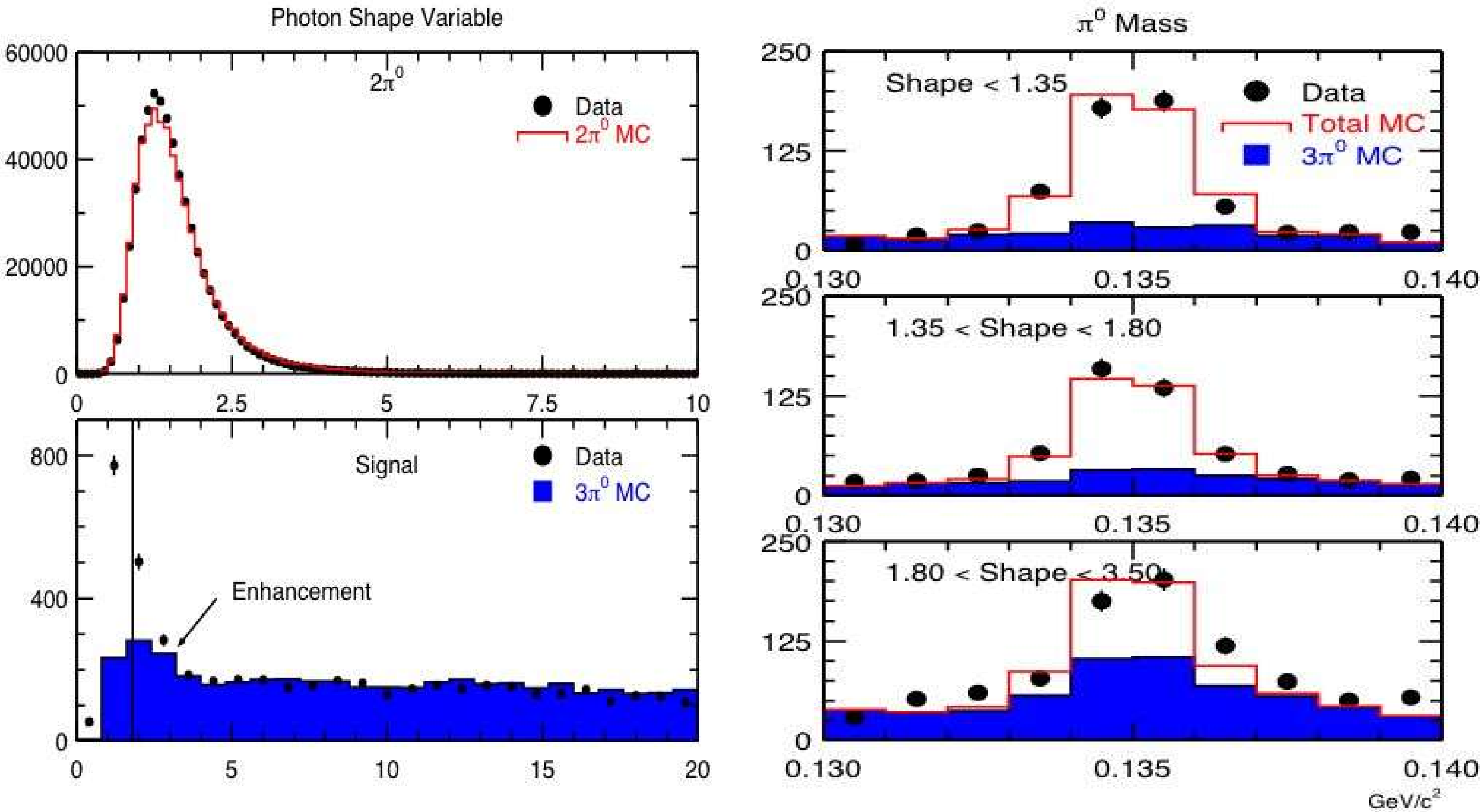
$K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma$ Background from Published Result





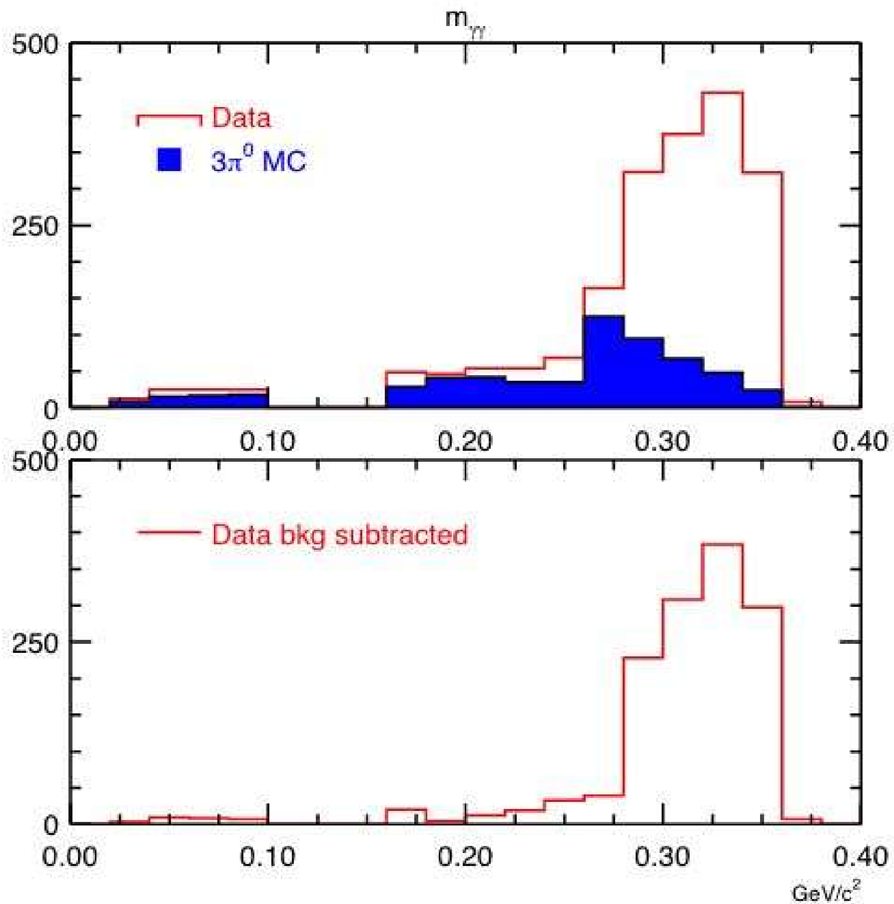
Due to DATA/MC mismatch in the cluster shape variable,
we underestimated the $K_L \rightarrow \pi^0\pi^0\pi^0$ background in this publication.

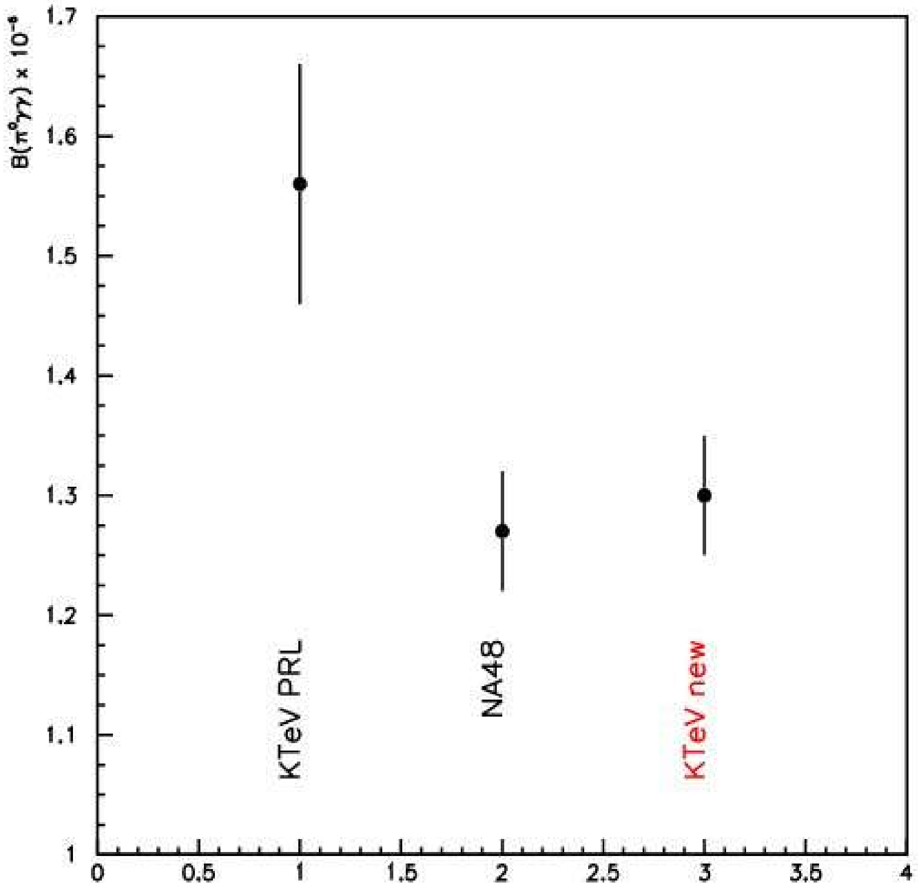
Improved Simulation of the Cluster Shape Variable



Better Data/MC agreement in the tails.
Result: Increased Background Level.

Updated Result on BR($K_L \to \pi^0\gamma\gamma$)





1982 events observed from full data set

BR($K_L \to \pi^0\gamma\gamma$) = (1.30 ± 0.03(stat) ± 0.04(sys))$\cdot 10^{-6}$

Normalized to BR($K_L \to \pi^0\pi^0$)

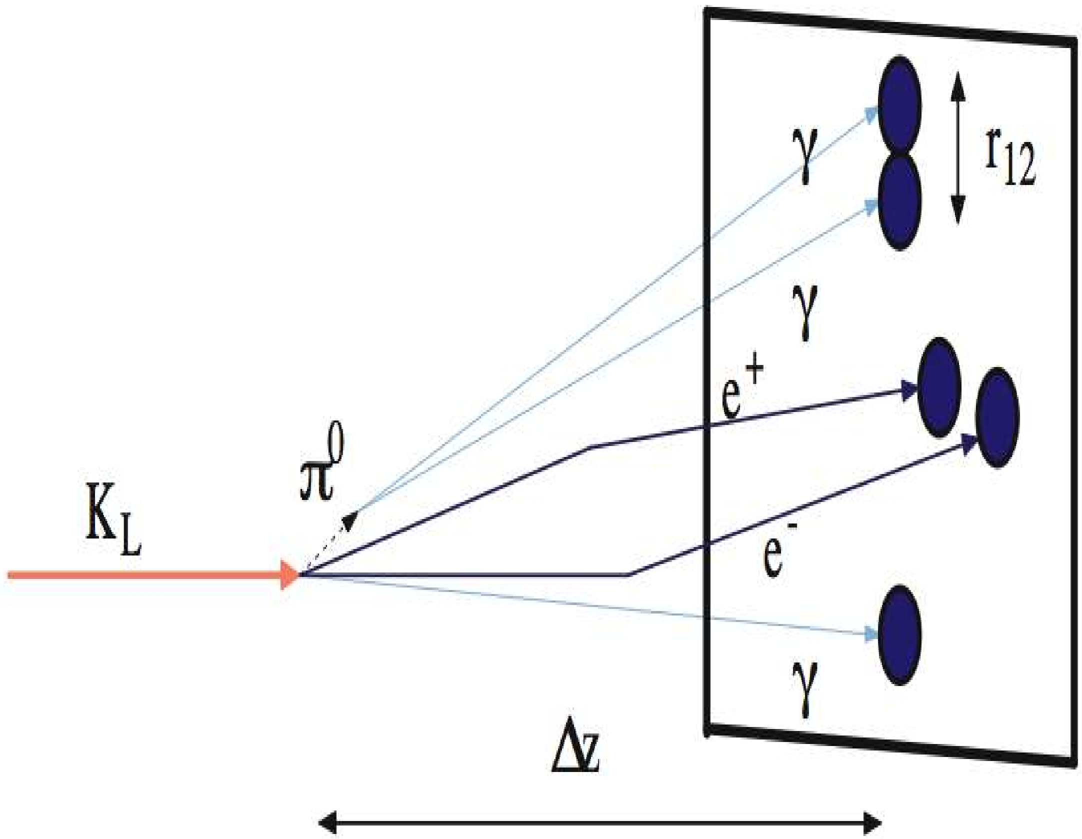
BR($K_L \rightarrow \pi^0\gamma\gamma$) Systematic Uncertainties

Source of Uncertainty	Uncertainty (%)	
a_V dependence	1.5	
$3\pi^0$ background	1.3	
MC statistics		1.0
Normalization		0.9
Photon Shape	1.1	
Tracking Chambers	0.9	
$2\pi^0$ branching ratio	0.9	
Photon vetoes	0.9	
Kaon Energy	0.7	
Decay Vertex	0.4	
Total	2.9	

Measurement of BR($K_L \to \pi^0 ee\gamma$)

Similar Physics to $K_L \to \pi^0\gamma\gamma$ but much easier event topology.

Can fully reconstruct event.



χPT Predictions

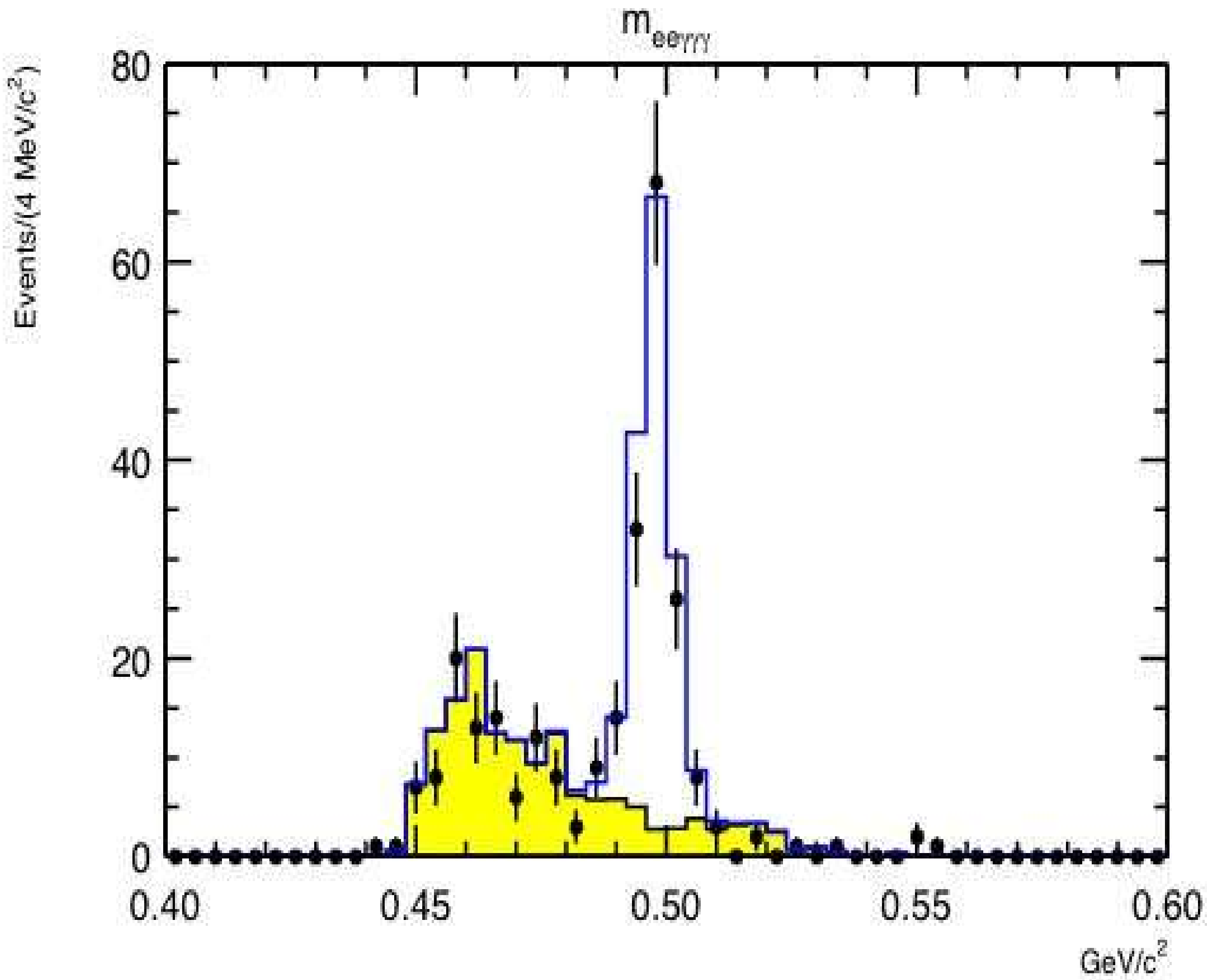
- $O(P^4)$: $1.0 \cdot 10^{-8}$
- $O(P^6)$: $2.4 \cdot 10^{-8}$ (PRD56, 1605)

KTeV published result [PRL87, 21801(2001)]

$(2.34 \pm 0.35 \pm 0.13) \cdot 10^{-8}$

Preliminary Result on BR($K_L \to \pi^0 ee\gamma$)

$$BR = (1.90 \pm 0.16 \pm 0.12) \cdot 10^{-8}$$



139 signal events

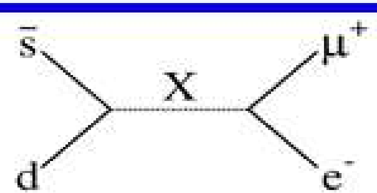
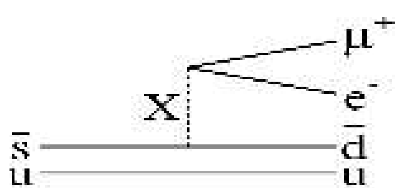
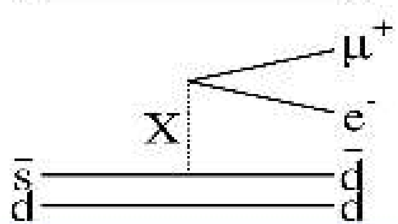
14.4 background events from
$K_L \to \pi^0 \pi^0_D$
$K_L \to \pi^0 \pi^0 \pi^0_D$

Lepton Flavor Violating Decays

LFV is permitted within SM by presence of neutrino mixing, but heavily suppressed. Therefore, LFV decays are sensitive to new physics.

LFV decays in the kaon sector is expected in many new scenarios.

Mass scale probed by LFV kaon decays through a hypothetical LFV vector boson X.

	Branching Fraction Limit	Mass Limit
	$B(K_L \to \mu e) < 4.7 \cdot 10^{-12}$ PRL **81**, 5734 (1998)	150 TeV/c^2
	$B(K^+ \to \pi^+ \mu^+ e^-) < 1.3 \cdot 10^{-11}$ PRD **72**, 012005 (2005)	31 TeV/c^2
	$B(K_L \to \pi^0 \mu e) < 3.4 \cdot 10^{-10}$ (KTeV Preliminary)	37 TeV/c^2

New KTeV Limits on Lepton Flavor Violating Decays

- KTeV has good sensitivity to a number of LFV decays

$K_L \rightarrow \pi^0 \mu e$

$K_L \rightarrow \pi^0 \pi^0 \mu e$

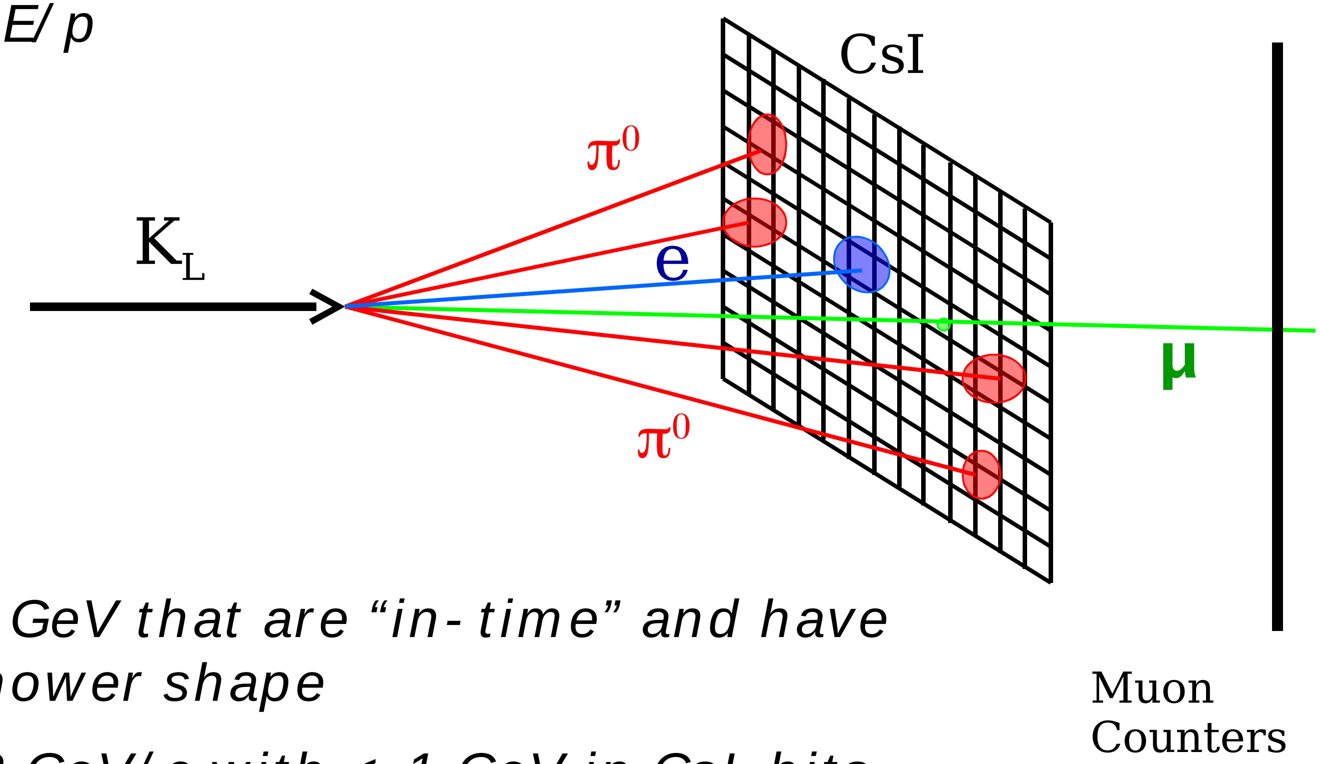
$\pi^0 \rightarrow \mu e$ (from $K_L \rightarrow 3\pi^0$)

} New Preliminary Results

- KTeV's large kaon flux and well understood beam and detector make this an ideal environment to search for rare decays.

$K_L \to \pi^0\pi^0\mu\, e$ decay signature is clean due to multiple constraints.

- *Vertex location is constrained by charged tracks and $2\pi^0$ mass constraint.*
- *Identify electrons using E/p*

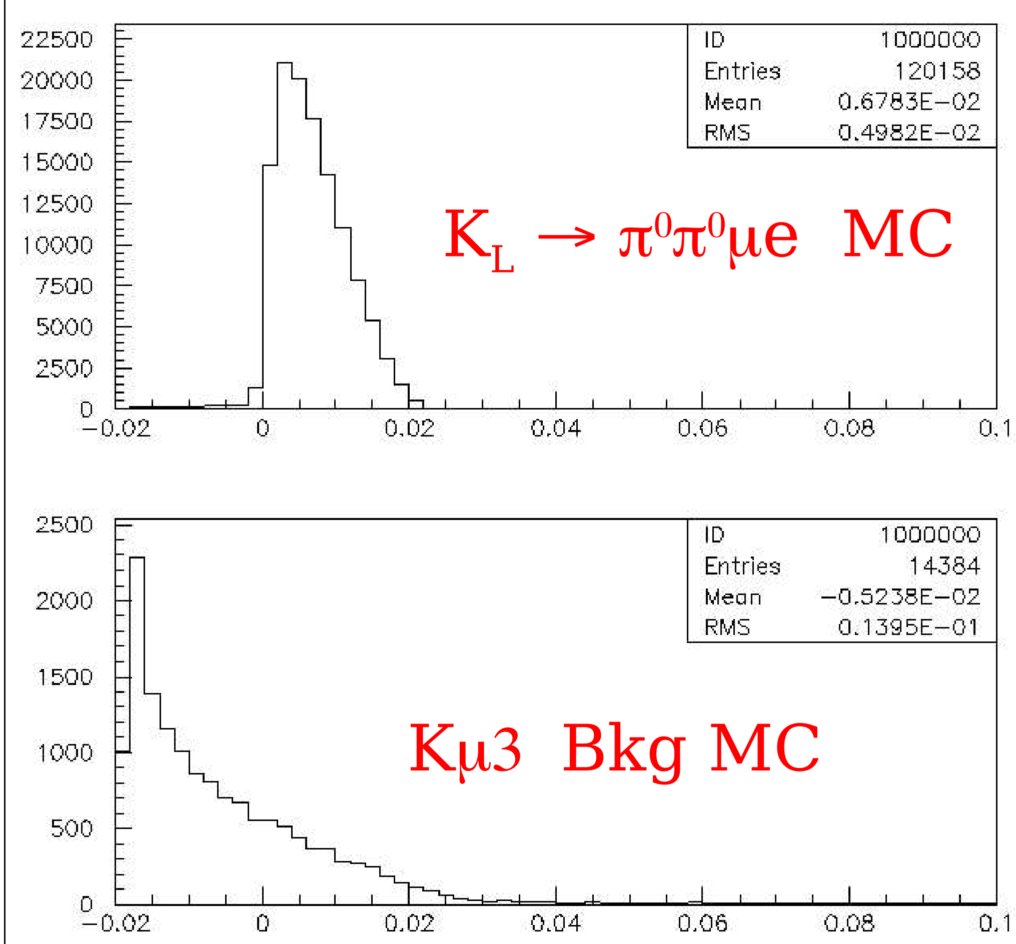


- *Identify CsI clusters > 2 GeV that are "in-time" and have good electromagnetic shower shape*
- *Identify muons by E_μ > 8 GeV/c with < 1 GeV in CsI, hits in μ counters, and Transition Radiation Hits.*
- *Kaon Mass and Transverse Momentum Constraint*

Backgrounds

- *$K_L \rightarrow \pi\mu\nu$ with 4 accidental photons*
- *$K_L \rightarrow \pi\nu e$ with 4 accidental photons and the π misidentified as a μ*
- *$K_L \rightarrow \pi^0 \pi^0 \pi^0_D$ with accidental μ*

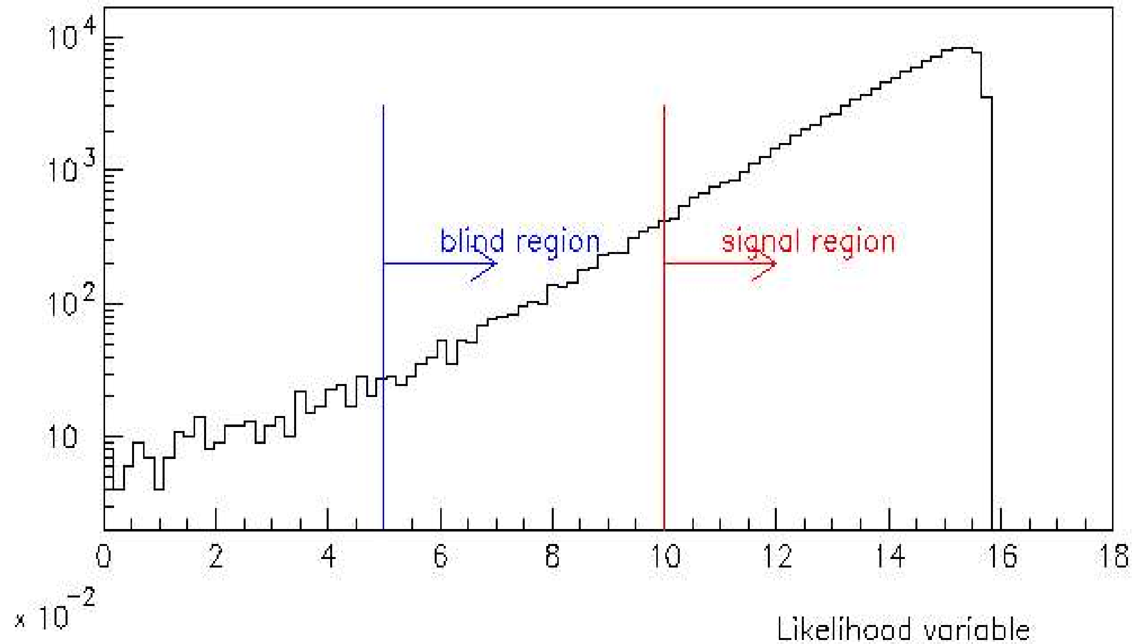
The square of the π^0 momentum in the K_L rest frame is a good discriminant against this background.

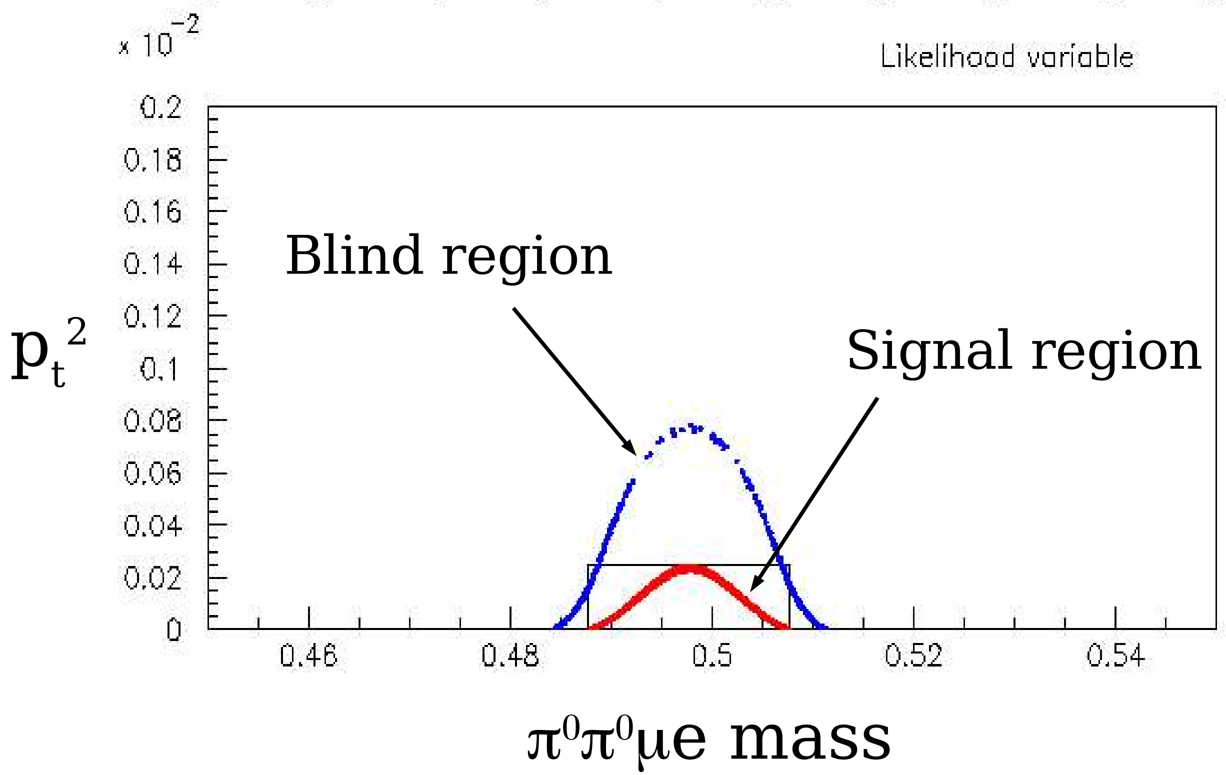


π^0 momentum squared in the K_L rest Frame

Likelihood Distribution for $K_L \rightarrow \pi^0\pi^0\mu e$

- Blind analysis
- Signal region defined by p_t^2 and kaon mass
- Final cuts made on the likelihood variable based on PDFs of the p_t^2 and kaon mass.
- Signal acceptance ~2% after all cuts.
- Cut at 10 preserves 95% of the signal events remaining after all cuts.





Background Estimate

- We don't trust the MC to estimate background to 1 part in 10^{10}. Use data.
- Relax kinematic, PID, and accidental cuts, and fit for background in the likelihood distribution.
- Determine suppression factors of each of the cuts.
- Final background estimate is suppressed by the cuts. However, technique works if the cuts are relatively independent.

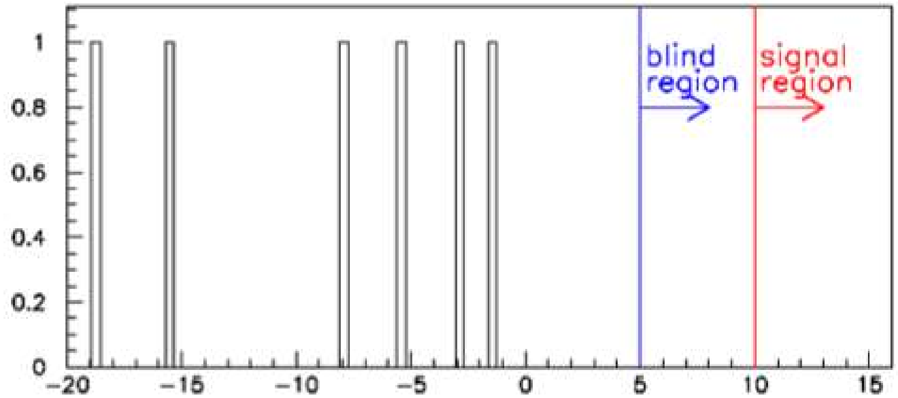
Cut set	**Suppression factor**
Kinematic	0.092 ± 0.016
Particle ID	0.273 ± 0.024
Accidental	0.261 ± 0.024
Kinematic * ID (actual)	0.012 ± 0.009
Kinematic * ID (estimated)	0.025 ± 0.005
Kinematic * Accidental (actual)	0.025 ± 0.009
Kinematic * Accidental (estimated)	0.024 ± 0.005
ID * Accidental (actual)	0.077 ± 0.015
ID * Accidental (estimated)	0.071 ± 0.009

Result for $K_L \to \pi^0\pi^0\mu e$

Expected background = 0.44 $\pm$ 0.12 events

Box opened

No events in signal or blind region



Likelihood Variable

PRELIMINARY result using Feldman-Cousins method

BR($K_L \to \pi^0\pi^0\mu e$) < 1.58×10^{-10} (90% CL)

$KL \to \pi^0\pi^0\pi^0_D$ used as Normalization Mode

$\pi^0 \to \mu e$ from $K_L \to 3\pi^0$

Identical to $K_L \to \pi^0\pi^0\mu e$ analysis. Just add cut on $M_{\mu e}$

Expected background = 0.03 ± 0.02 events

Box opened. No events in signal or blind region.

PRELIMINARY result using Feldman-Cousins method

BR($\pi^0 \to \mu e$) < *3.63 x 10^-10 (90% CL)*

Previous results

BR($\pi^0 \to \mu e$) <	*1.72 x 10^-8 (90% CL)*	*PL B320 407 (94)*
BR($\pi^0 \to \mu^+ e^-$) <	*3.8 x 10^-10 (90% CL)*	*PRL 85 2450 (00)*
BR($\pi^0 \to \mu^- e^+$) <	*3.4 x 10^-9 (90% CL)*	*PRL 85 2877 (00)*

Summary

Preliminary measurements of:

- $BR(\pi^0 \to ee\gamma)/BR(\pi^0 \to \gamma\gamma)$

$(1.1539 \pm 0.0045 \pm 0.0152)$ %

- $BR(K_L \to \pi^0\gamma\gamma)$ and $BR(K_L \to \pi^0 ee\gamma)$

$BR(K_L \to \pi^0\gamma\gamma) = (1.30 \pm 0.03(stat) \pm 0.04(sys)) \cdot 10^{-6}$

$BR(K_L \to \pi^0 ee\gamma) = (1.90 \pm 0.16 \pm 0.12) \cdot 10^{-8}$

- LFV limits on $K_L \to \pi^0\pi^0\mu e$ and $\pi^0 \to \mu e$

$BR(K_L \to \pi^0\pi^0\mu e) < 1.58 \times 10^{-10}$ (90% CL)

$BR(\pi^0 \to \mu e) < 3.63 \times 10^{-10}$ (90% CL)

Backup Slides

Analysis Cuts for $K_L \rightarrow \pi^0\pi^0\mu e$

- Z vertex between 96 and 155 m. X & Y vertex inside CsI beam holes.
- Difference between charged and neutral vertices less than 2.5 m.
- Square of π^0 momentum in K rest frame between 0 and 0.025 $(GeV/c)^2$
- π^0 masses between 0.132 and 0.138 GeV/c^2

- E/p for electron between 0.95 and 1.05
- TRD signal for μ track is not consistent with electron ($prob_\mu > 0.015$)
- Fusion $\chi^2 < 10$ for electron and neutral clusters (eliminates overlapping clusters)
- μ momentum > 8 GeV. μ energy < 1 GeV in CsI.

- **Exactly 5 in-time clusters above 2 GeV in CsI.**
- **< 0.3 GeV in photon veto counters.**
- **< 15 GeV in beam veto counter.**
- **< 3 extra in-time drift chamber hit pairs.**

Kinematic cuts Particle ID Cuts **Accidental cuts**