π^0 AND K_L DECAY MEASUREMENTS FROM KTeV

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LXIII Rencontres de Moriond
La Thuile, 3 March 2008

π^0 AND K_L DECAY MEASUREMENTS FROM KTeV

- Collaboration, experiments, detector
- Decays of the neutral pion
  - Measurement of the π^0 Dalitz decay branching ratio
  - The decay $\pi^0 \rightarrow 4e$ and the parity of the π^0
  - $\pi^0 \rightarrow e^+e^-$
- Lepton Flavor Violation in K_L decays

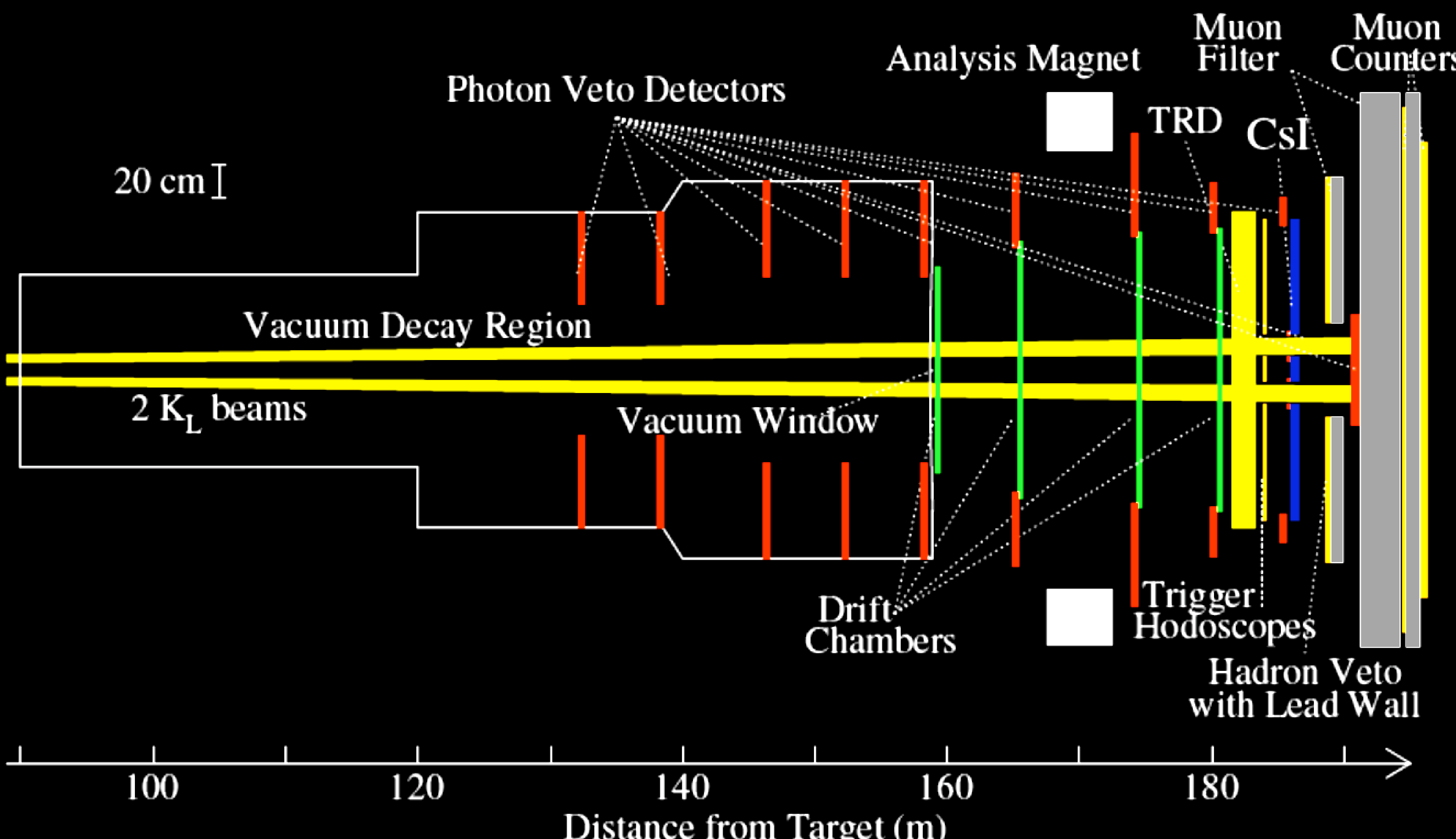
The KTeV Collaboration: Institutions

- University of Arizona
- University of California at Los Angeles
- Universidade Estadual de Campinas
- University of Chicago
- University of Colorado
- Elmhurst College
- Fermilab
- Osaka University
- Rice University
- Universidade de Sao Paulo
- University of Virginia
- University of Wisconsin

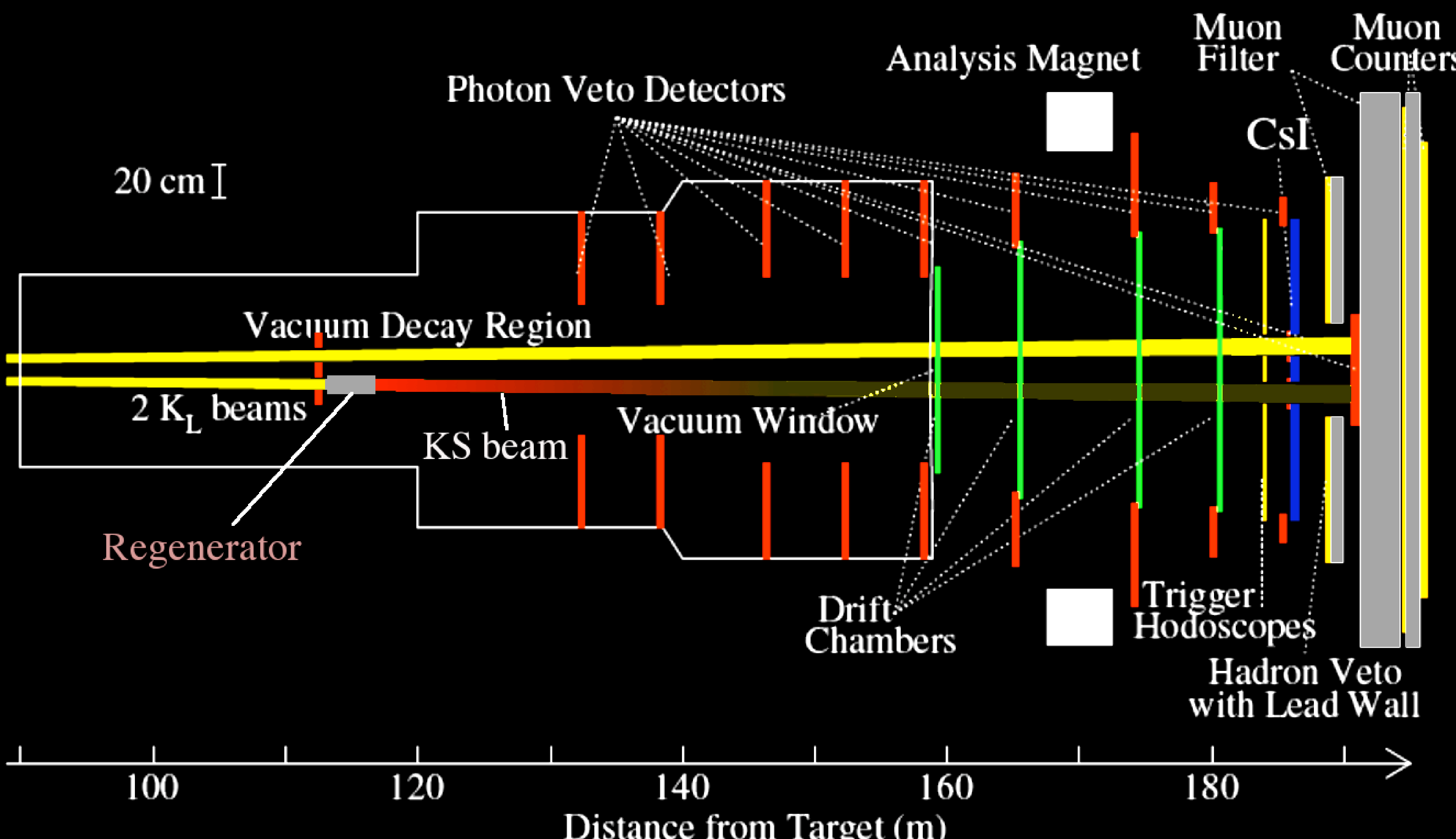
Two experiments:

- E799 (rare decays)
- E832 (ϵ')

The KTeV detector, E799 configuration: rare decays



The KTeV detector, E832 configuration: $\Re(\epsilon'/\epsilon)$



Decays of the neutral pion

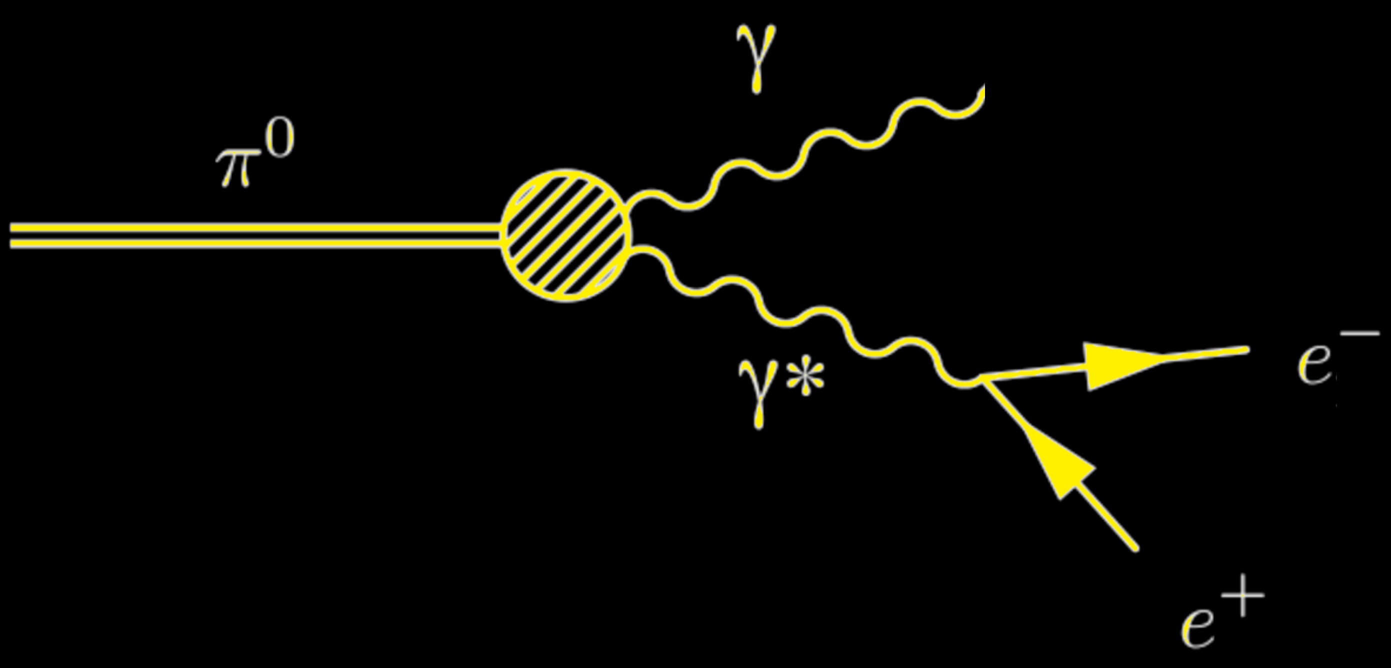
- A kaon beam is a source of plentiful tagged neutral pions
- Use decays such as $K_L \rightarrow \pi^0\pi^0\pi^0$ as π^0 source
- Fully reconstruct the kaon decay → non-π^0 backgrounds become negligible
- KTeV will have world's best measurements of all π^0 decays with electrons in final state (all known decays except γγ).

Decays of the neutral pion

- $\pi^0 \to \gamma\gamma$: 10^0
- $\pi^0 \to e^+e^-\gamma$: 10^{-2} ✓Preliminary result
- $\pi^0 \to e^+e^-e^+e^-$: 10^{-5} ✓Submitted paper
- $\pi^0 \to e^+e^-$: 10^{-8} ✓Published
- $\pi^0 \to \mu^\pm e^\mp$: LFV ✓Published
- $\pi^0 \to \nu\nu$: Forbidden except via neutrino mass

The Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$

- The Dalitz decay is the second most common π^0 decay mode
- Used to normalize other measurements of K_L and π^0 decays
- PDG 3% error on this branching ratio is limiting systematic error on many K_L and π^0 decay branching ratio measurements
- Not measured since early 1980s



- Difficult measurement because no normalization mode with charged tracks exists: tracking efficiency must be understood precisely.

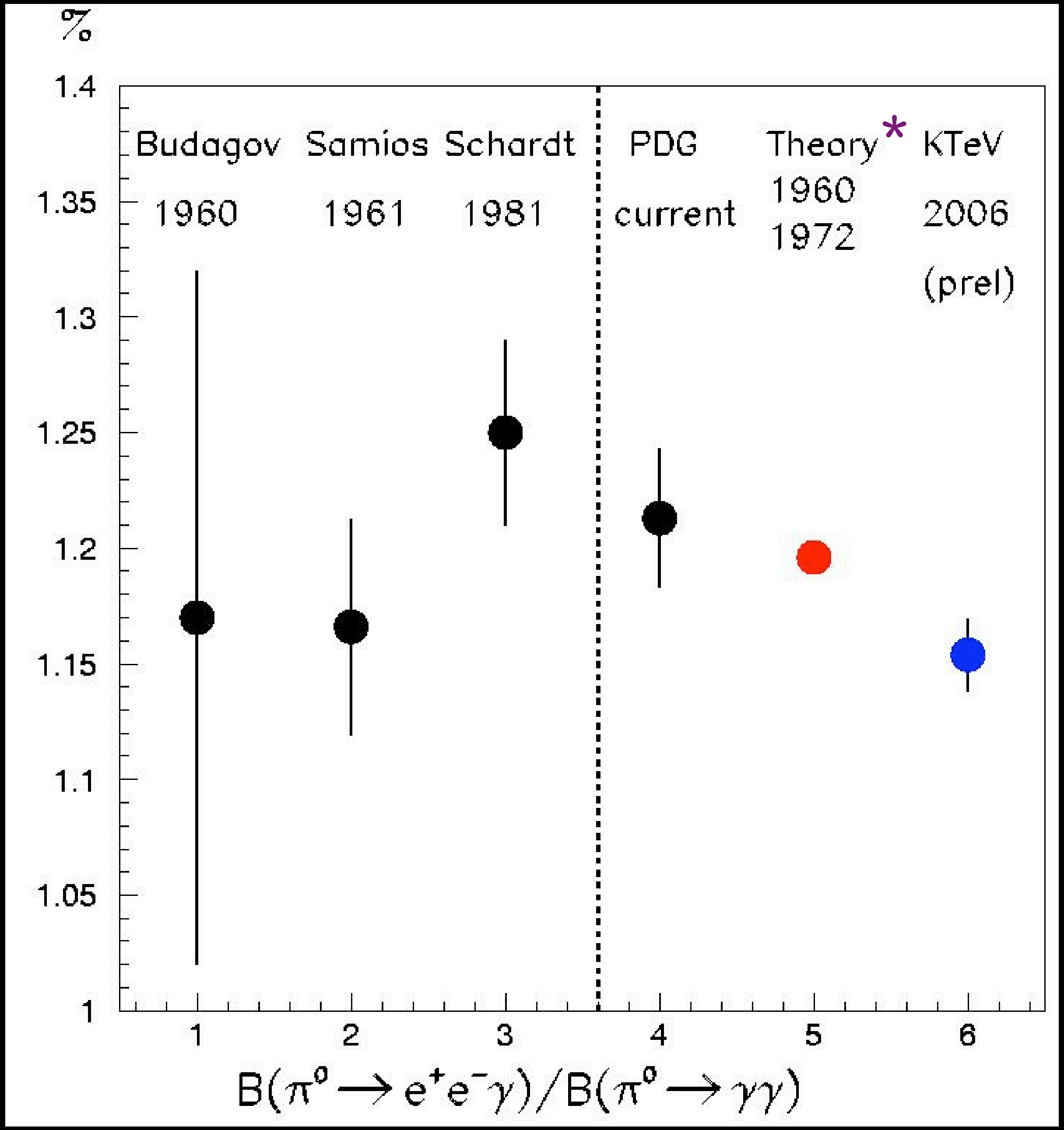
The Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$

- Existing measurements: $\frac{\Gamma(\pi^0 \rightarrow e^+e^-\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)}$
  - $(1.25 \pm 0.04)\%$ Schardt 1981
  - $(1.166 \pm 0.047)\%$ Samios 1961
  - $(1.17 \pm 0.15)\%$ Budagov 1960
  - Total of all measurements: ~4000 events
- Current PDG Average: $(1.213 \pm 0.030)\%$
- KTeV (E832): 66,000 events from $K_L \rightarrow \pi^0\pi^0\pi^0$ after cuts

The Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$

- Detailed analysis (can't do it justice in short talk) with charged-track mode normalized to all-neutral decay $K_L \rightarrow \pi^0\pi^0\pi^0$
- Tracking efficiency cross-checked with $K_L \rightarrow \pi^+\pi^-\pi^0$ decays
- Systematic error dominated by radiative corrections (1.02%) and tracking efficiency (0.68%)

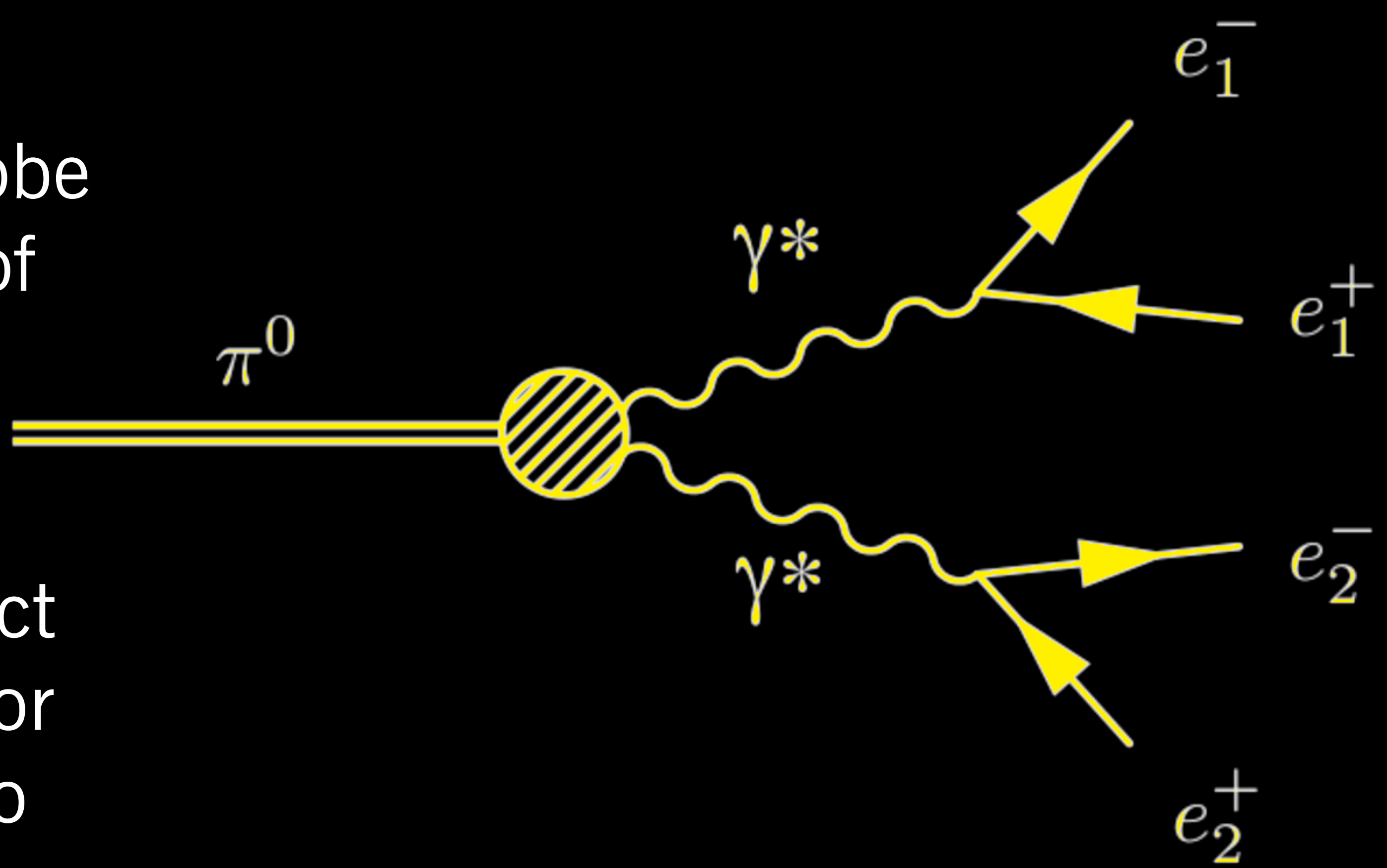
The Dalitz decay $\pi^0 \to e^+e^-\gamma$



- Preliminary result: $\Gamma(\pi^0 \to e^+e^-\gamma)/\Gamma(\pi^0 \to \gamma\gamma) = (1.1539 \pm 0.0045 \pm 0.0152) \times 10^{-2}$
- Half the uncertainty of current PDG average

The double Dalitz decay $\pi^0 \rightarrow e^+e^-e^+e^-$

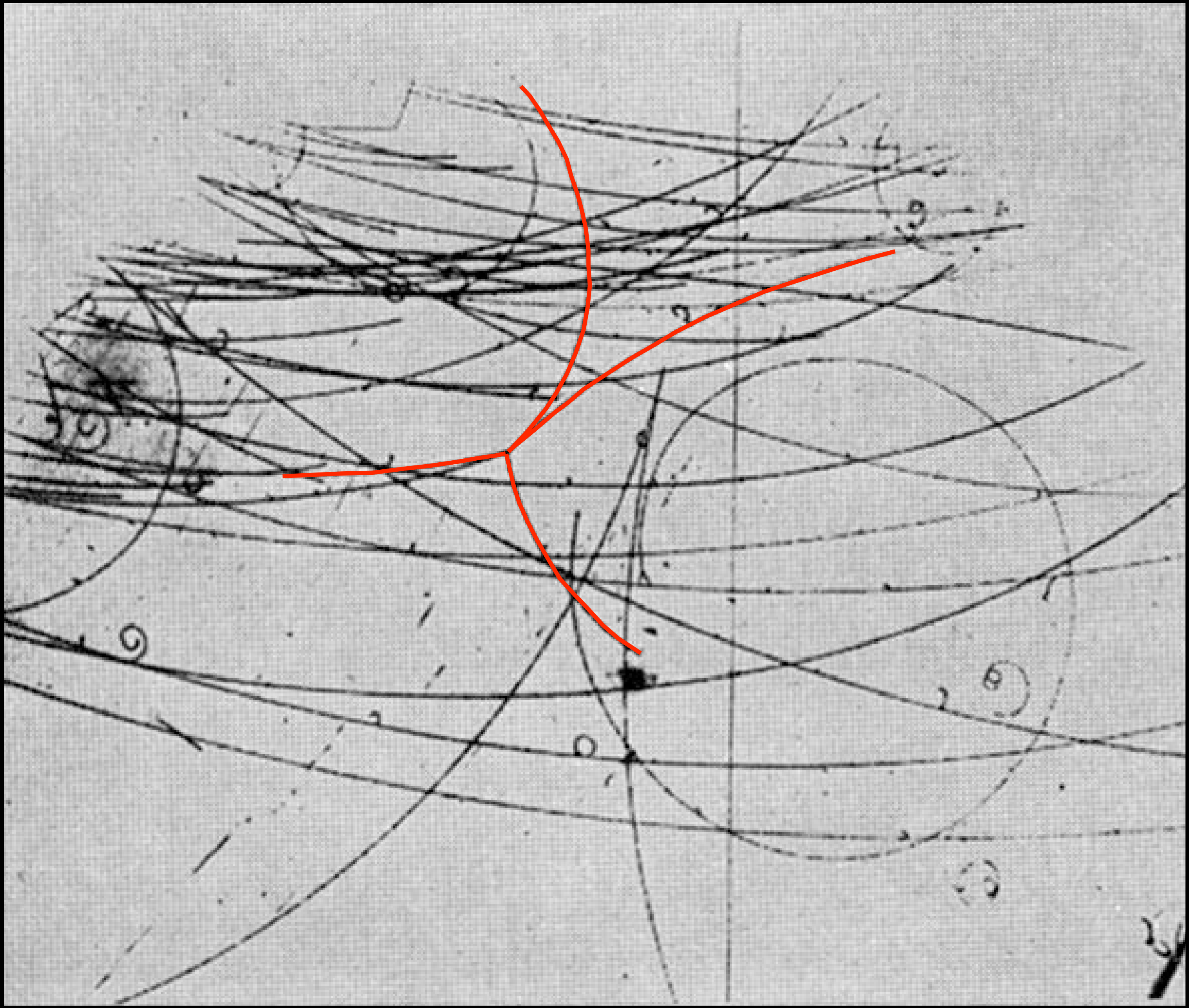
- Two internal conversions
- Only momentum-dependent probe of electromagnetic form factor of π^0 with two off-shell photons
- Orientation of the planes of the Dalitz pair provides unique direct probe of π^0 parity: can search for *P*, *CPT* violating contributions to decay.
- Direct contribution shown; second diagram exists with $e^+{}_1$ and $e^+{}_2$ exchanged.



- Long neglected decay: current measurement is one of the oldest in particle data book

NEVIS 1962

- Last measurement of this decay
- Hydrogen bubble chamber at Nevis cyclotron
- $\pi^- p \to \pi^0 n$ from stopped π^-
- Branching ratio based on 206 events: $(3.18 \pm 0.30) \times 10^{-5}$



Samios, Plano, Prodell, Schwartz, and Steinberger
Phys. Rev. **126** 1844 (1962)

NEVIS 1962

- Parity analysis based on 112 events
- Consistent with pseudoscalar
- Disfavors pure scalar by 3.3 to 3.6 sigma (depends on analysis)

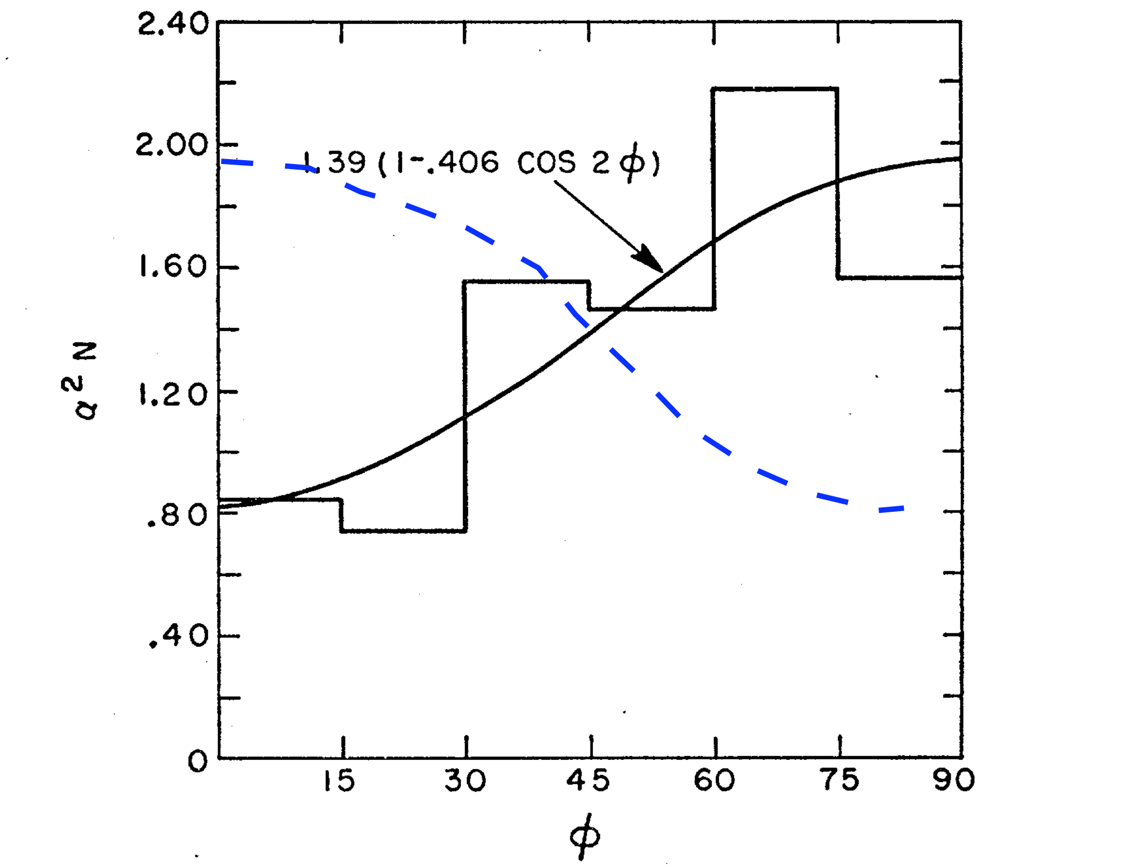
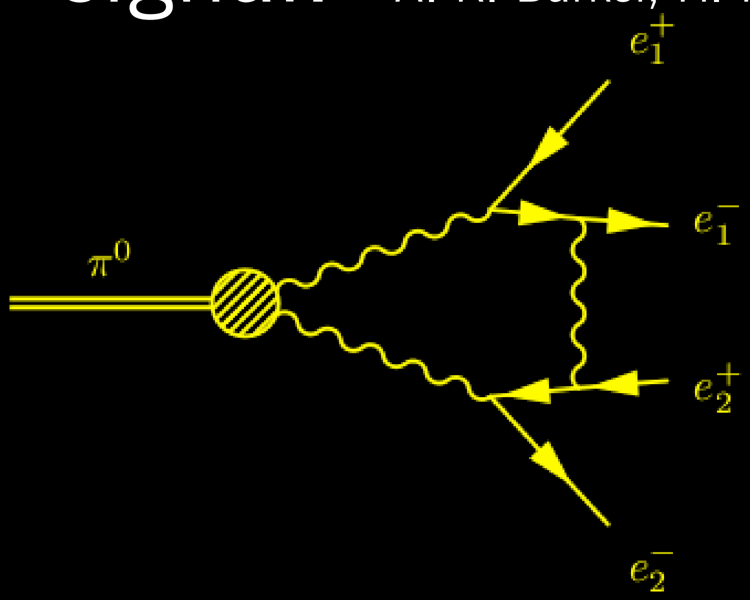


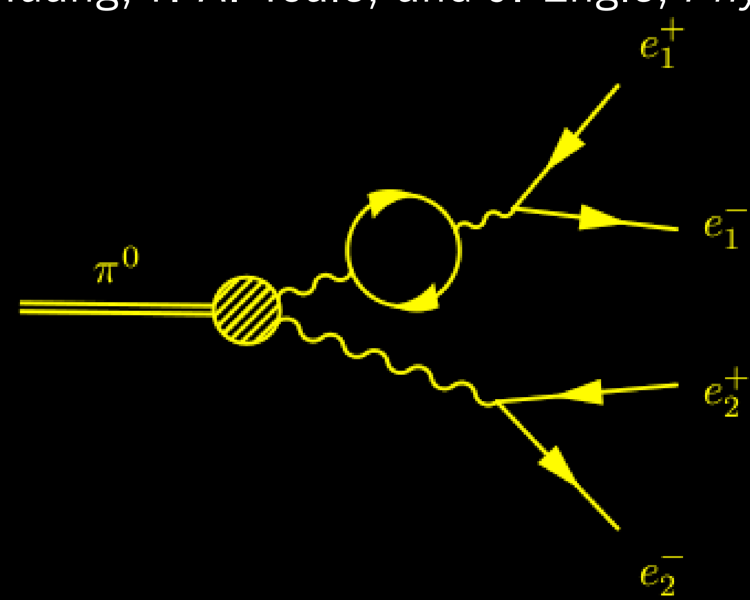
FIG. 9. Plot of the weighted frequency distribution of the angle between planes of polarization.

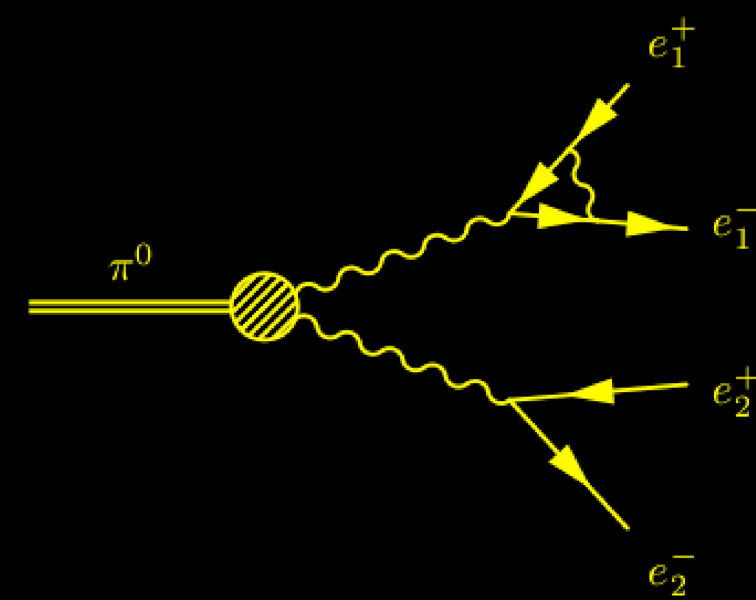
Samios, Plano, Prodell, Schwartz, and Steinberger
Phys. Rev. **126** 1844 (1962)

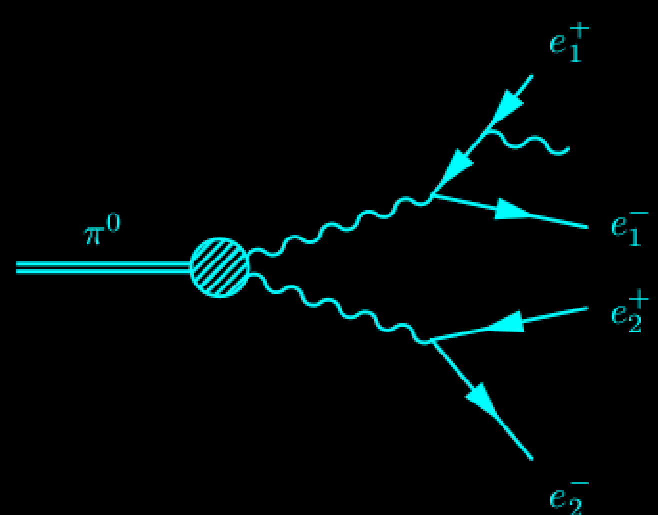
Radiative Corrections

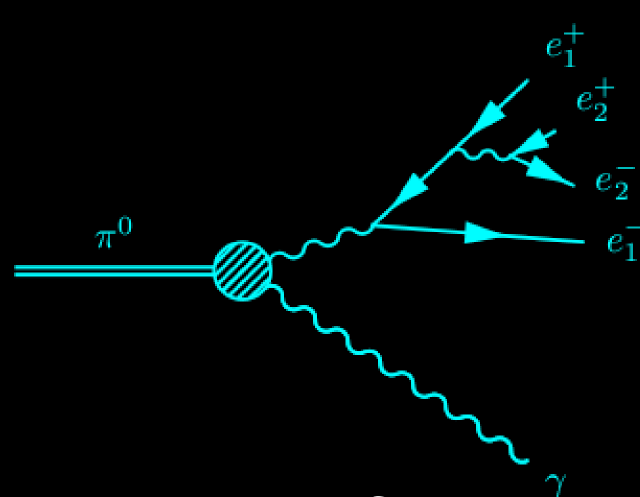
- MC uses analytic calculation of radiative corrections to signal: A. R. Barker, H. Huang, P. A. Toale, and J. Engle, *Phys. Rev.* **D67** 033008 (2003).







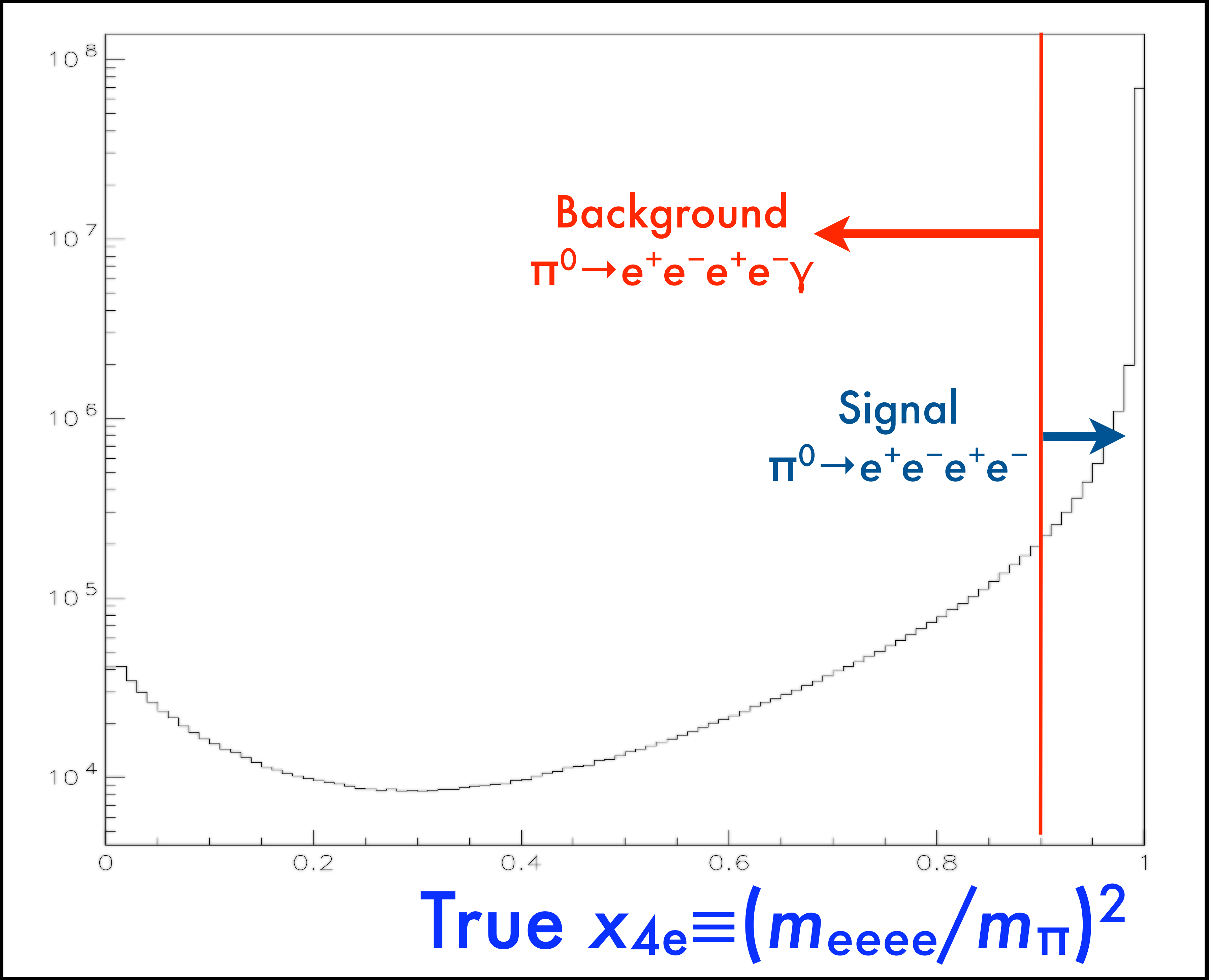




- Last two diagrams generate radiative final state

Definition of signal for radiative events:

- Define "signal" as $x_{4e}>0.9$ in MC generation
- $x_{4e}<0.9$ events are considered background
- By this definition, radiative background is 5.8% of inclusive rate
- Data events rejected if extra photon detected >2 GeV



Event selection: $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-e^+e^-$

- Require vertex with 4 tracks, two of each sign
- All tracks identified as electrons: $|E/p-1|<0.07$
- Also require exactly 4 photons (E>2 GeV) in calorimeter
- Total energy 40-210 GeV
- Total invariant mass 0.480-0.515 GeV/c^2
- Total p_T^2 relative to vertex-target line <800 MeV^2/c^4
- Tracks must be separated by >2mm at first drift chamber (removes external photon conversions)

Event identification

- These cuts yield a sample of >99.5% purity containing the following decay modes:

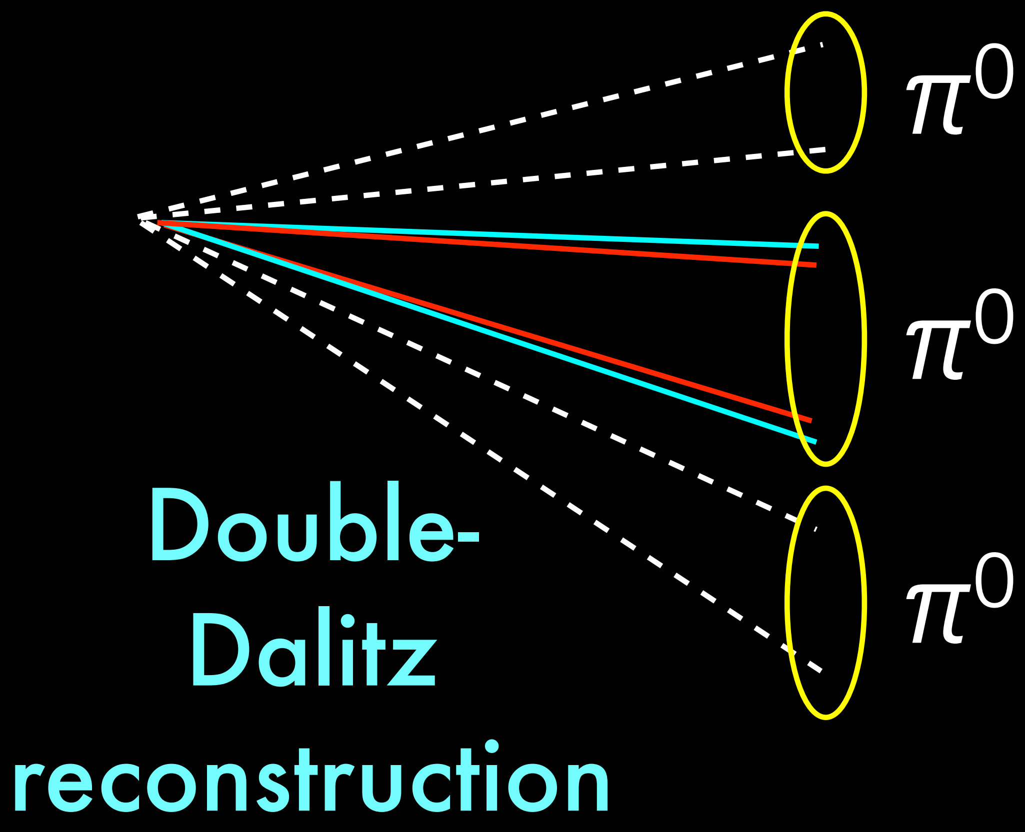
$$K_L \to \begin{cases} \pi^0 \to e^+e^-e^+e^- \\ \pi^0 \to \gamma\gamma \\ \pi^0 \to \gamma\gamma \end{cases} \qquad K_L \to \begin{cases} \pi^0 \to e^+e^-\gamma \\ \pi^0 \to e^+e^-\gamma \\ \pi^0 \to \gamma\gamma \end{cases}$$

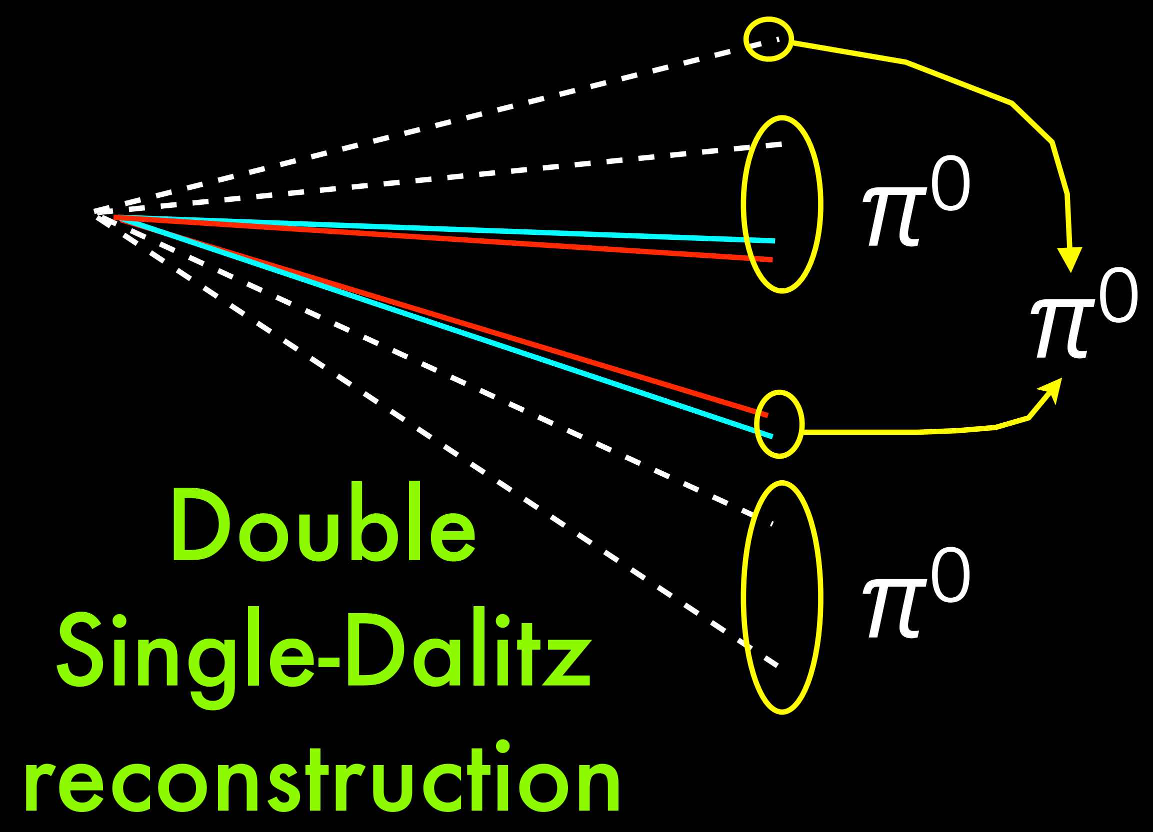
Double-Dalitz   Double Single-Dalitz

- We use the double single-Dalitz events to normalize the signal: same final state particles and nearly same average track/cluster momenta: detector systematics largely cancel in ratio.

Event identification

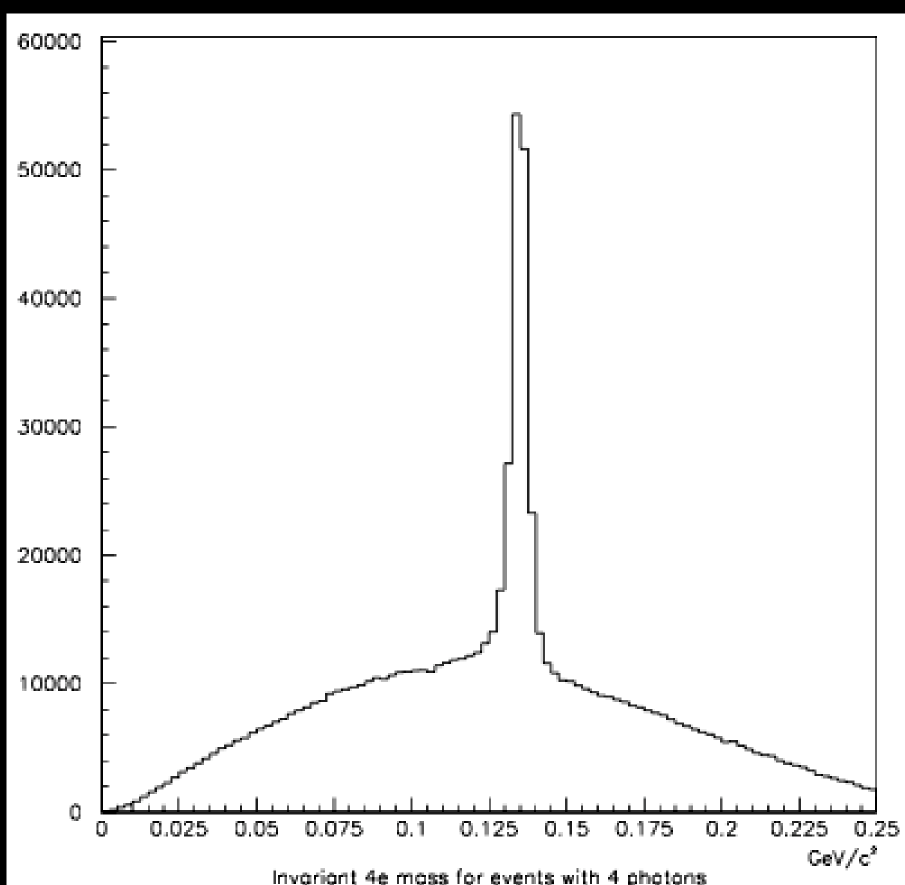
- Form χ^2 for the grouping of final-state particles to form three π^0 masses. use this to distinguish signal from normalization mode:

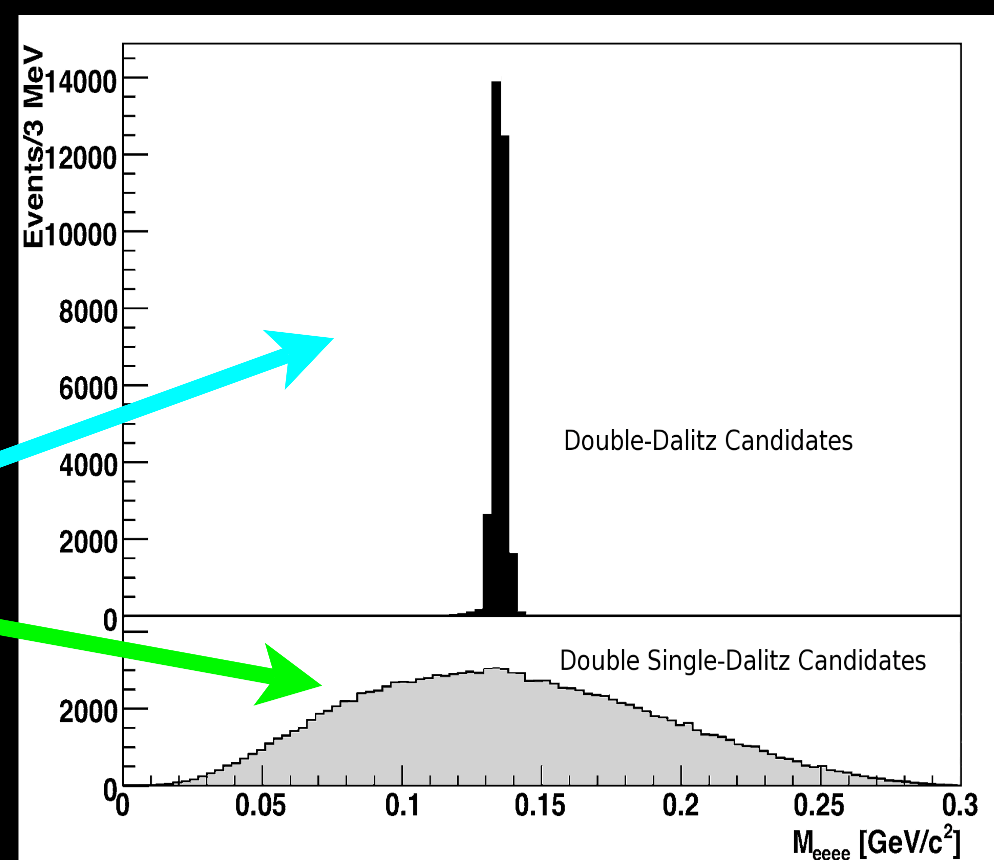




Event identification

- Selecting reconstruction with better χ^2 and requiring $\chi^2 < 12$ (with 3 dof), we correctly classify 99.5% of events:





30,511 events

141,251 events

Branching ratio measurement

- Numbers of events of each mode are found by:

$$N_{\mathrm{DD}} = 3 \cdot N_{3\pi^0} \cdot B_{\gamma\gamma}^2 \cdot B_{eeee} \cdot \epsilon_{\mathrm{DD}}$$
$$N_{\mathrm{2SD}} = 3 \cdot N_{3\pi^0} \cdot B_{\gamma\gamma} \cdot B_{ee\gamma}^2 \cdot \epsilon_{\mathrm{2SD}}$$

  - DD = double Dalitz
  - 2SD = double single-Dalitz
  - $N_{3\pi^\circ}$ = number of $K_L \rightarrow 3\pi^0$ decays
  - B = branching ratio
  - ϵ = geometric acceptance × cut efficiency (~0.25%)
- So double branching ratio is:

$$\frac{B_{eeee} \cdot B_{\gamma\gamma}}{B_{ee\gamma}^2} = \frac{N_{DD}}{N_{2SD}} \cdot \frac{\epsilon_{2SD}}{\epsilon_{DD}} = 0.2245 \pm 0.0014(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$$

Branching ratio measurement

- From double ratio:

$$\frac{B_{eeee} \cdot B_{\gamma\gamma}}{B^2_{ee\gamma}} = \frac{N_{DD}}{N_{2SD}} \cdot \frac{\epsilon_{2SD}}{\epsilon_{DD}} = 0.2245 \pm 0.0014(\text{stat}) \pm 0.0009(\text{syst})$$

- Use known values:

$$B_{\gamma\gamma} = 0.9880 \pm 0.0003; B_{ee\gamma} = (1.198 \pm 0.032) \times 10^{-2}$$

- Branching ratio result:
  - $x > 0.9$: $(3.26 \pm 0.18) \times 10^{-5}$
  - Inclusive of radiative decays: $(3.46 \pm 0.19) \times 10^{-5}$
  - Error is completely dominated by $B_{ee\gamma}$; will recalculate when KTeV $B_{ee\gamma}$ result is published
  - Agrees well with 1962 result of $(3.18 \pm 0.30) \times 10^{-5}$

Form factor and parity fit

- Coupling of π^0 to two virtual photons has the generic form:

$$C \propto f(x_1, x_2)[P \cos\zeta + S e^{i\delta} \sin\zeta]$$

where *P* is pseudoscalar and *S* is scalar coupling.

- Distribution of signal event candidates fit using an unbinned likelihood function of all phase space variables under both direct and exchange diagrams.

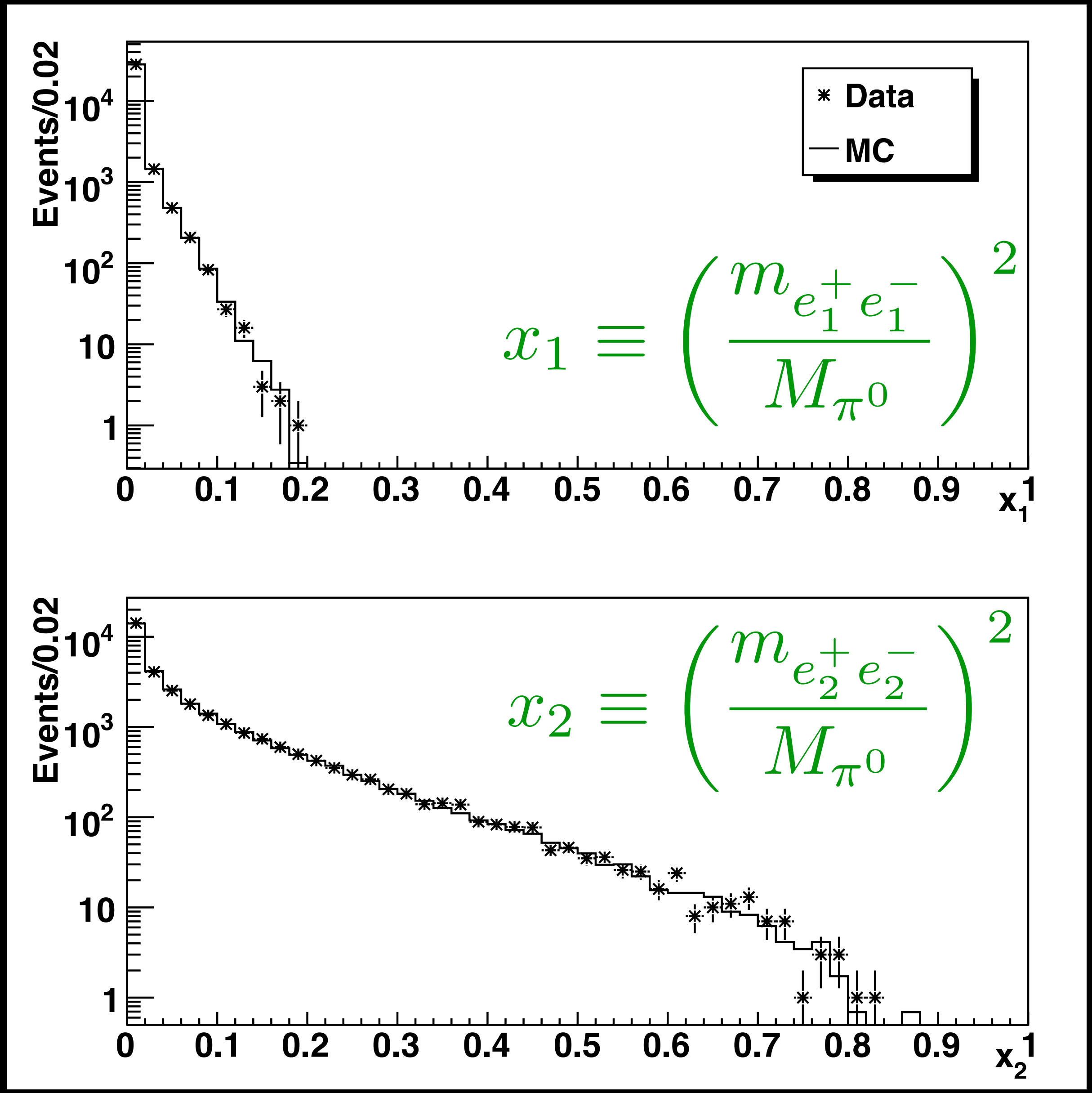
- Use a modified D'Ambrosio, Isidori, Portoles parametrization of the $\pi^0\gamma\gamma$ form factor, where $\mu \equiv (M_\pi/M_\rho)^2$ and x_1 and x_2 are the q^2 of each Dalitz pair:

$$f_{\mathrm{DIP}}(x_1, x_2; \alpha) = \frac{1 - \mu(1+\alpha)(x_1 + x_2)}{(1 - \mu x_1)(1 - \mu x_2)}$$

- Fit yields momentum-dependence parameter α and pseudoscalar-scalar mixing angle ζ and phase δ (if ζ nonzero).

Form factor fit

- The x distributions agree very nicely with MC
- Fit yields $\alpha = 1.3 \pm 1.0$ (stat) $\pm$ 0.9 (syst).
- Form factor sensitivity is limited in neutral pion decays, since the slope parameter is known to be small.

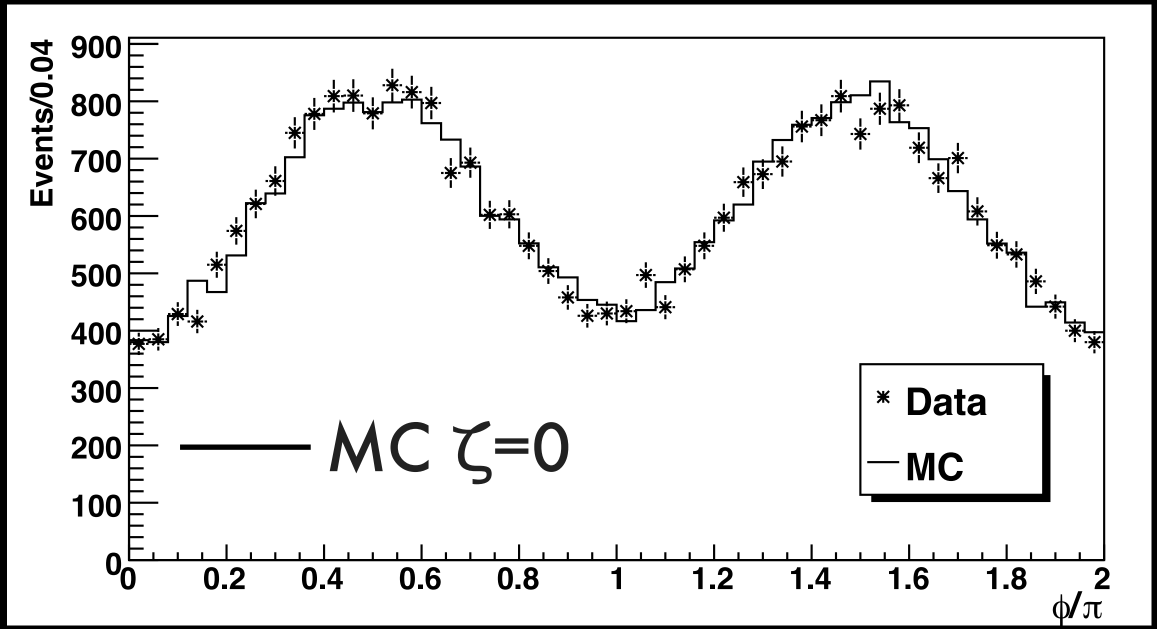


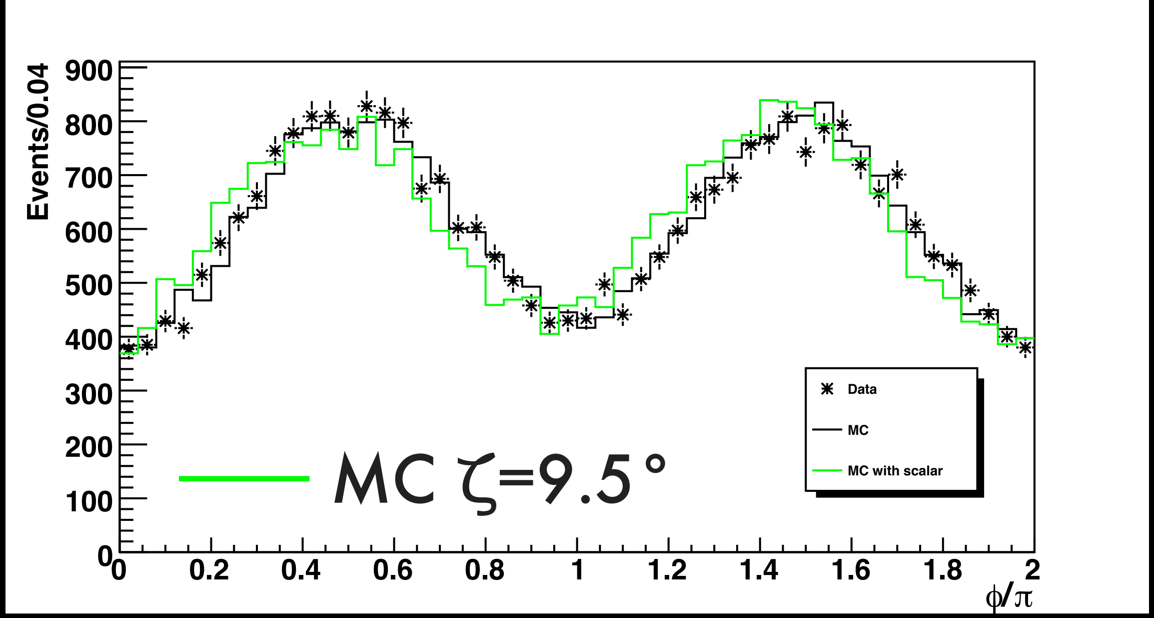
Note: pairs defined such that $x_1 < x_2$.

Parity fit

$$C \propto f(x_1, x_2)[P\cos\zeta + Se^{i\delta}\sin\zeta]$$

- Pure pseudoscalar MC (ζ=0) describes data very well
- Scalar pion: ζ=90° completely excluded (no surprise!)
- Fit yields 90% CL limit on ζ with and without assuming CPT (δ=0):
  - CPT constraint: ζ<1.9°
  - CPTV allowed: ζ<6.9°

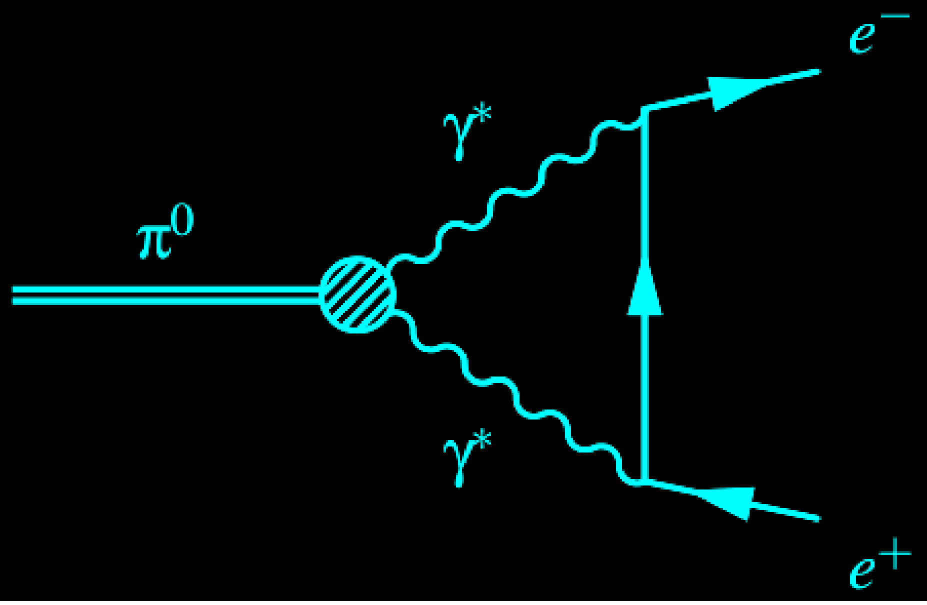




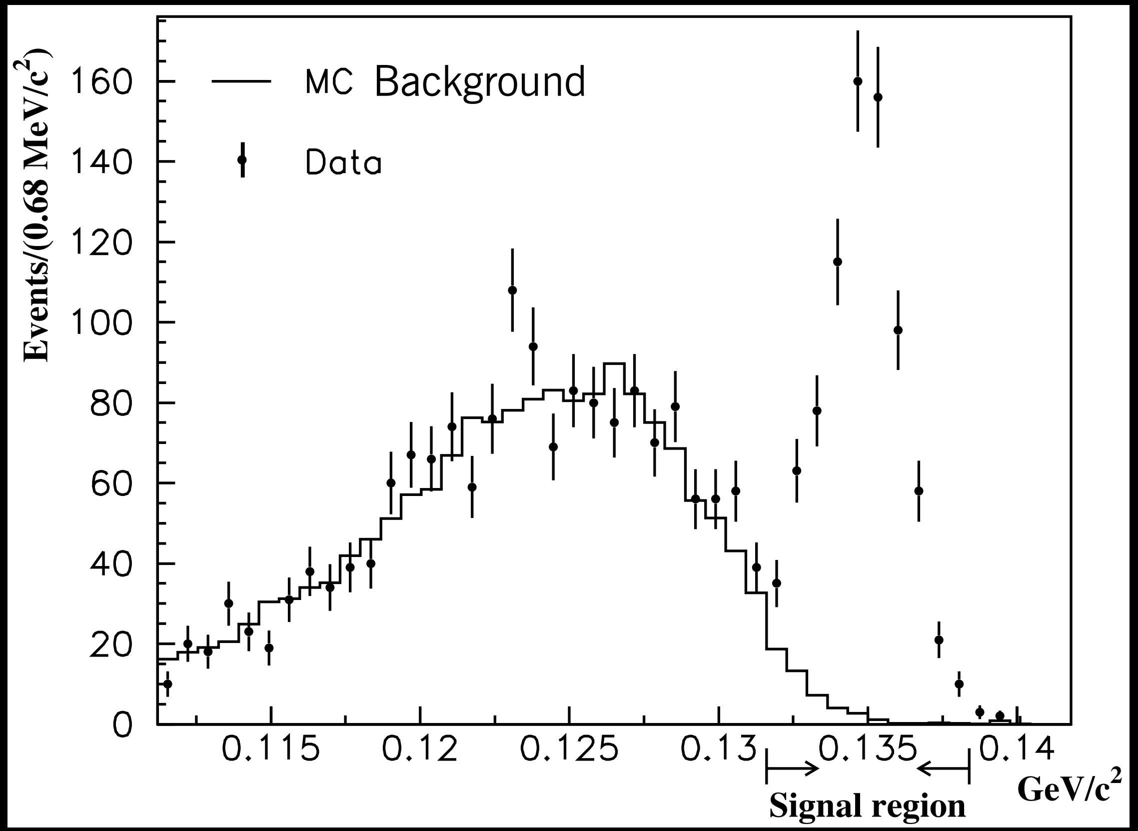
KTeV result: arXiv:0802.2064 [hep-ex]

The rare decay $\pi^0 \to e^+e^-$

- Helicity suppressed decay; proceeds via loop at lowest order



- Probe of $\pi^0\gamma^*\gamma^*$ coupling
- KTeV result published: *Phys. Rev.* D**75** 012004 (2007)
  - $B(\pi^0 \to e^+e^-, x>0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$



The rare decay $\pi^0 \to e^+e^-$

- New calculation predicts rate: Dorokhov and Ivanov, Phys Rev **D75** 114007 (2007)
  - Prediction is $(5.25 \pm 0.08) \times 10^{-8}$ for $x > 0.95$
  - This is 3σ below our result
- Kahn, Schmitt, and Tait (arXiv:0712.0007 [hep-ph]): MeV-scale dark matter could explain the excess…

Lepton Flavor Violation

- KTeV (E799) has good sensitivity to several lepton flavor violating modes:
  - $K_L \to \pi^0 \mu e$
  - $K_L \to \pi^0 \pi^0 \mu e$
  - $\pi^0 \to \mu e$ (from $K_L \to 3\pi^0$)

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

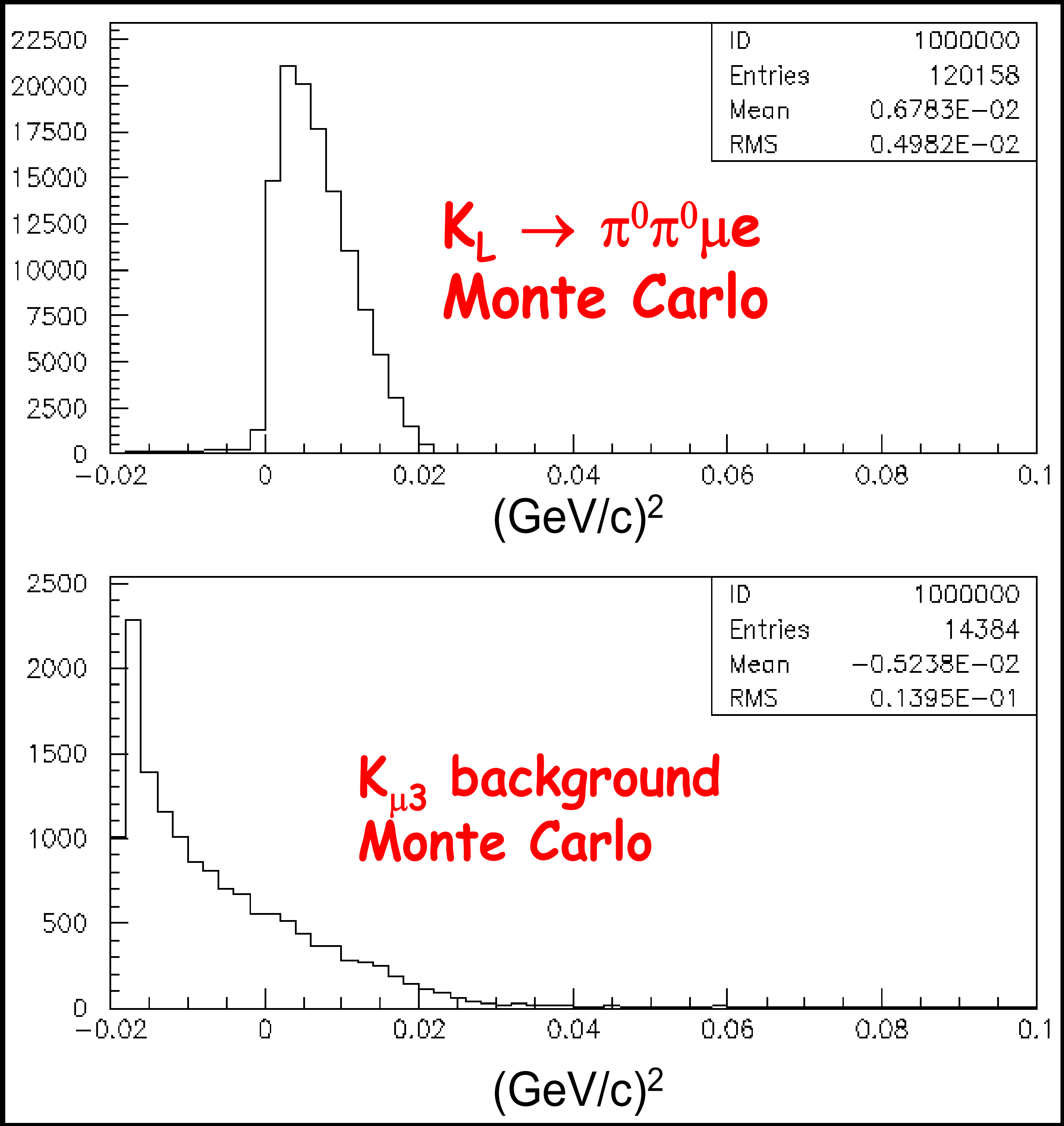
- Full reconstruction of signal final state
- Backgrounds are:
    - $K_L \to \pi^+ \pi^- \pi^0$ with two particles misidentified
    - K_{e4} ($K_L \to \pi^\pm \pi^0 e^\mp \nu$) with pion misidentified and soft neutrino
    - K_{e3} ($K_L \to \pi^\pm e^\mp \nu$) with pion misidentified and accidental $\gamma\gamma$

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

- Major improvements since preliminary result of 2003
  - Replaced cuts on p_T^2 and invariant mass with signal likelihood variable to optimize use of information
  - Better use of beam-hole photon veto to reduce accidental losses
  - Improved model of K_{e4} form factor
- No events observed; $B(K_L \to \pi^0 \mu e) < 7.6 \times 10^{-11}$ (90% CL)

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

- Lower background than $K_L \to \pi^0\mu e$ due to reconstruction of second π^0 (eliminates $K_L \to \pi^+\pi^-\pi^0$ as background)
- Can require that charged and neutral vertices agree
- The square of the π^0 momentum in the K_L rest frame is a good discriminator against remaining backgrounds:
  - $K_L \to \pi^\pm\mu^\mp\nu$ ($K_{\mu3}$) with 4 accidental photons
  - $K_L \to \pi^\pm e^\mp\nu$ (K_{e3}) with 4 accidental photons and π misidentified



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

- Additional particle ID cuts use calorimeter, TRD to reject electrons from π^0 Dalitz decays.
- Also make additional cuts on a likelihood variable similar to $K_L \to \pi^0 \mu e$ analysis
- Use data to estimate rejection factors (don't trust MC at the 10^{-10} level)
- No events observed within signal region
- $\pi^0 \to \mu e$ analysis: just add cut on $m_{\mu e}$

Summary of LFV searches

- $B(K_L \to \pi^0 \mu e) < 7.6 \times 10^{-11}$ (90% CL)
- $B(K_L \to \pi^0 \pi^0 \mu e) < 1.7 \times 10^{-10}$ (90% CL)
- $B(\pi^0 \to \mu e) < 3.6 \times 10^{-10}$ (90% CL)

- Publication accepted by PRL, in press.

Summary of π^0 decay measurements

- Preliminary result: $\Gamma(\pi^0 \to e^+e^-\gamma)/\Gamma(\pi^0 \to \gamma\gamma) = (1.1539 \pm 0.0045 \pm 0.0152) \times 10^{-2}$
- Submitted: $B(\pi^0 \to e^+e^-e^+e^-) = (3.26 \pm 0.18) \times 10^{-5}$
- Published: $B(\pi^0 \to e^+e^-) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$
- *Second and third result (and many others in PDG) will improve when $\pi^0 \to e^+e^-\gamma$ result is published.*

Some of KTeV's coming attractions

- Search for $K_L \to \pi^0 \pi^0 \mu\mu$ (E871 anomaly)
- Search for $K_L \to \pi^0 \pi^0 \gamma$ soon to appear in Phys. Rev. D
- New $\Re(\epsilon'/\epsilon)$ measurement: see talk tomorrow morning