Measurement of $\pi^0 \to e^+e^-e^+e^-$ Branching Ratio and Study of the $\pi^0\gamma^*\gamma^*$ Form Factor using $K_L \to \pi^0\pi^0\pi^0$ Decays at KTeV.

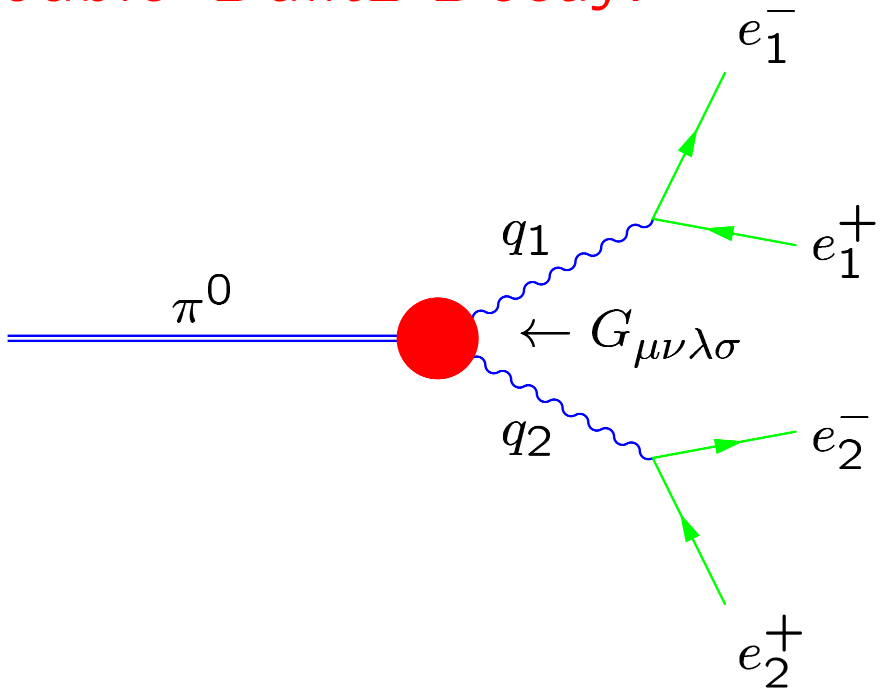
Patrick Toale
University of Colorado

DPF2002
May 27, 2002

KTeV Collaborating Institutions:

* University of Arizona
* University of California, Los Angeles
* University of California, San Diego
* University of Campinas, Brazil
* University of Chicago
* University of Colorado
* Elmhurst College
* Fermi National Accelerator Laboratory
* Osaka University, Japan
* Rice University
* Rutgers University
* University of São Paulo, Brazil
* University of Virginia
* University of Wisconsin, Madison

The Double–Dalitz Decay:



$$G_{\mu\nu\lambda\sigma} \sim F_{ps}\ \epsilon_{\mu\nu\lambda\sigma} + F_s \left[g_{\mu\lambda} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\lambda} \right]$$

- Final State angular distribution sensitive to Scalar/Pseudoscalar coupling
- Form Factor affects Distribution of ee Masses:

$$F\left(q_1^2, q_2^2\right) = F_0 \cdot f\left(q_1^2, q_2^2\right)$$

where

$$f\left(q_1^2, q_2^2\right) = 1 + \frac{a}{M_\pi^2}\left(q_1^2 + q_2^2\right) + \mathcal{O}\left(q_i^2 q_j^2\right)$$

Previous Measurement:

N. P. Samios, *et al*, Phys. Rev. **126**, 1844 (1962). Based on 146 Events :

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.18 \pm 0.30) \times 10^{-5}$$

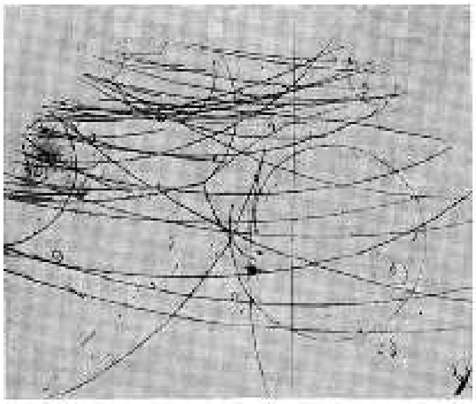


FIG. 1. Photograph of a typical double internal conversion.

$$\frac{\partial \Gamma}{\partial \phi} \sim 1 + \alpha\,(\cos 2\phi + C \sin 2\phi)$$

$\phi \sim$ Angle b/w ee planes

$$\begin{aligned} \alpha &= -0.12 \pm 0.15 \\ C &= 0.77 \pm 0.53 \end{aligned}$$

Experimental Method:

Signal Mode (DD):

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

Normalization Mode (2D):

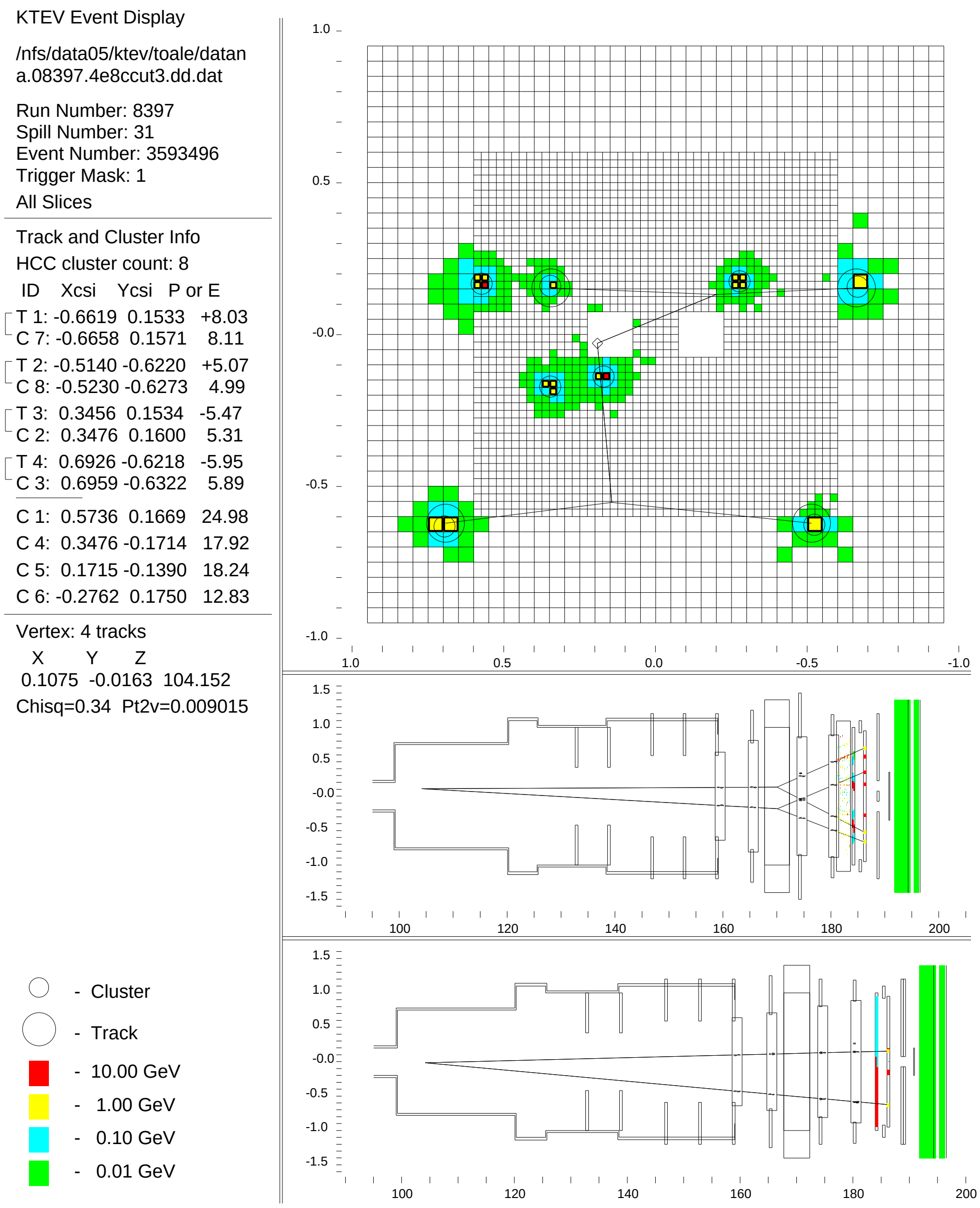
$$K_L \to \begin{cases} \pi^0 \to e^+e^-\gamma \\ \pi^0 \to e^+e^-\gamma \\ \pi^0 \to \gamma\gamma \end{cases}$$

$$\begin{aligned} N_{DD} &= 3 \cdot F_K \cdot B(K_L \to 3\pi^0) \cdot B(\pi^0 \to 4e) \cdot B(\pi^0 \to \gamma\gamma)^2 \\ N_{2D} &= 3 \cdot F_K \cdot B(K_L \to 3\pi^0) \cdot B(\pi^0 \to ee\gamma)^2 \cdot B(\pi^0 \to \gamma\gamma) \end{aligned}$$

$$\frac{B(\pi^0 \to 4e)}{B(\pi^0 \to \gamma\gamma)} = \frac{N_{DD}}{N_{2D}} \cdot \left[\frac{B(\pi^0 \to e^+e^-\gamma)}{B(\pi^0 \to \gamma\gamma)}\right]^2$$

$$\frac{B(\pi^0 \to 4e)}{B(\pi^0 \to e^+e^-\gamma)^2} = \frac{N_{DD}}{N_{2D}} \cdot \left[\frac{1}{B(\pi^0 \to \gamma\gamma)}\right]$$

Typical Double–Dalitz Event:



Analysis Overview:

- $\diamond$ Good 4–track Vertex
- $\diamond$ 8 Clusters
- $\diamond$ Well Separated Tracks
- $\diamond$ Consistent with DD or 2D

$$\chi^2_{DD} = \left(\frac{M_{4e} - M_{\pi^0}}{\sigma_{4e}}\right)^2 + \left(\frac{M^1_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\gamma\gamma}}\right)^2 + \left(\frac{M^2_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\gamma\gamma}}\right)^2$$

$$\chi^2_{2D} = \left(\frac{M^1_{ee\gamma} - M_{\pi^0}}{\sigma_{ee\gamma}}\right)^2 + \left(\frac{M^2_{ee\gamma} - M_{\pi^0}}{\sigma_{ee\gamma}}\right)^2 + \left(\frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\gamma\gamma}}\right)^2$$

Backgrounds:

External Photon Conversions:

$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow e^+e^-\gamma \\ \pi^0 \rightarrow \gamma\gamma \\ \pi^0 \rightarrow \gamma\gamma \end{cases} \quad + 1\ \gamma N \rightarrow e^+e^-N\ \text{(1C)}$$

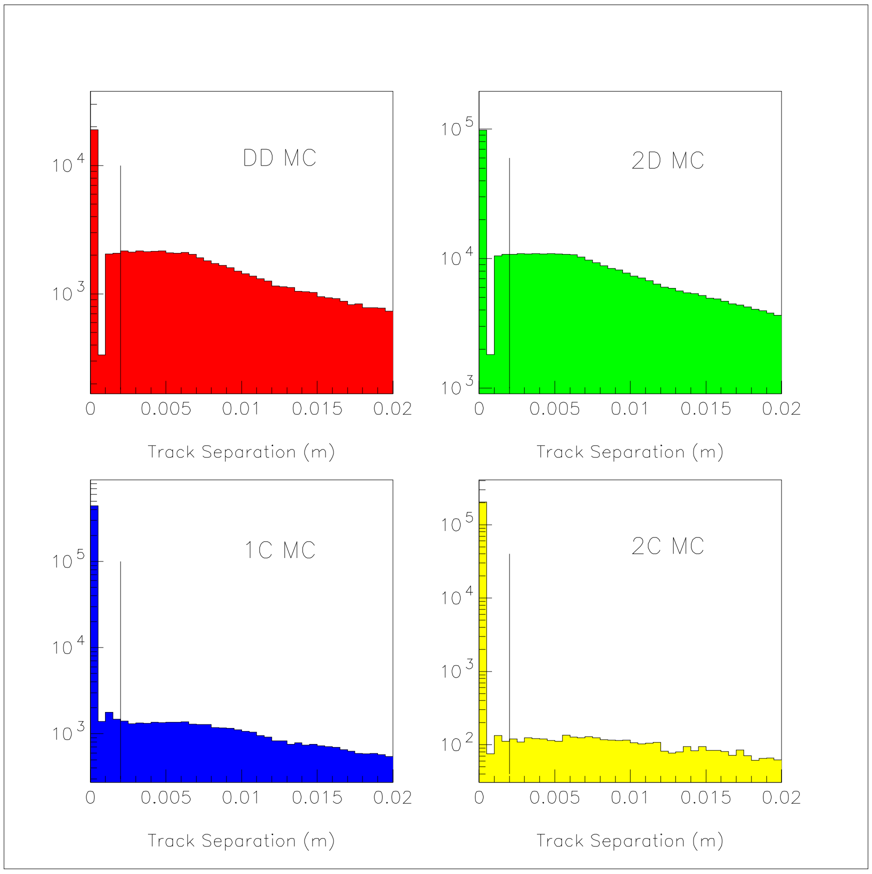
$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^0 \rightarrow \gamma\gamma \\ \pi^0 \rightarrow \gamma\gamma \end{cases} \quad + 2\ \gamma N \rightarrow e^+e^-N\ \text{(2C)}$$

Reconstruction Crossover (XO):

- $\chi^2_{2D} < \chi^2_{DD}$ for DD Events
- $\chi^2_{DD} < \chi^2_{2D}$ for 2D Events

Conversion Reduction:

- Require 2mm Track Separation at DC1
- 90% of Conversions fail cut
- 75% of Signal passes cut



Background Subtraction:

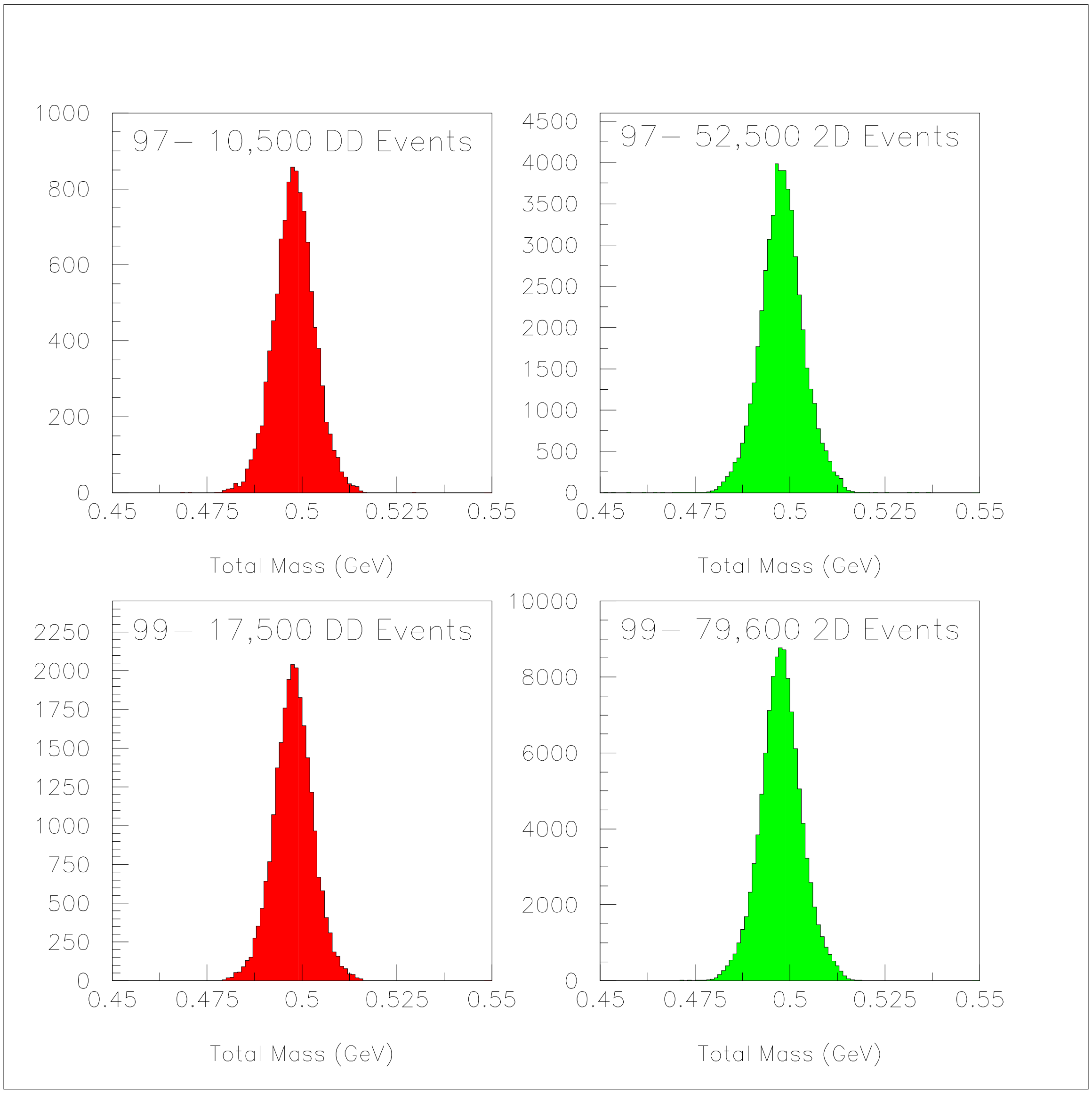
97 Data Set:

	DD	2D
Candidates	10,738	53,667
1C	177	1,050
2C	5	52
XO	50	119
Total BG	232	1,221
Signal	10,506	52,446

99 Data Set:

	DD	2D
Candidates	17,923	81,990
1C	367	2,027
2C	18	108
XO	90	215
Total BG	475	2,350
Signal	17,448	79,640

Event Sample:



Combined Result:

	DD	2D
97	10,506	52,446
99	17,448	79,640
Combo	27,954	132,086

97:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2277 \pm 0.0024$$

99:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2233 \pm 0.0019$$

Combined:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015$$

Systematic Studies:

Category	Source	Error
Theory:	$4e(\gamma)$	1.70%
	$f(x_1, x_2)$	
Acceptance:	Cut Variation	1.72%
	DC Res.	0.84%
	Material	0.16%
	Backgrounds	0.09%
	DC Ineff.	0.04%
	CsI Res.	0.02%
MC Stat:		0.39%
Total Int:		2.60%
External:	$B(\pi^0 \to ee\gamma)$	5.44%
Total:		6.03%

Combined Result:

Old 97 Preliminary Result:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.228 \pm 0.003 \pm 0.006$$

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.31 \pm 0.04 \pm 0.22)\times 10^{-5}$$

New Combined Preliminary Result:

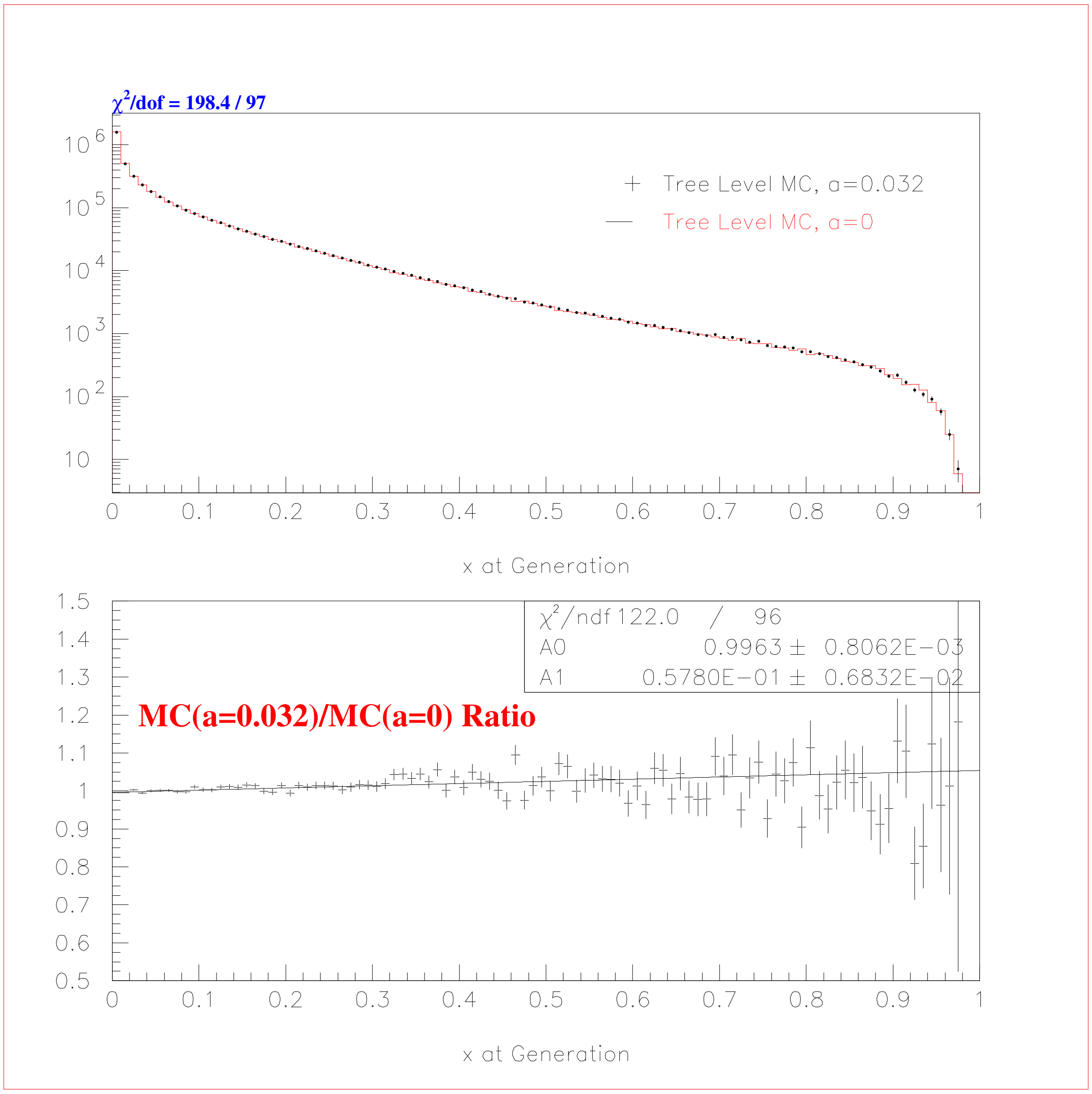
$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$$

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.274 \pm 0.022 \pm 0.197)\times 10^{-5}$$

$\pi^0\gamma^*\gamma^*$ Form Factor:

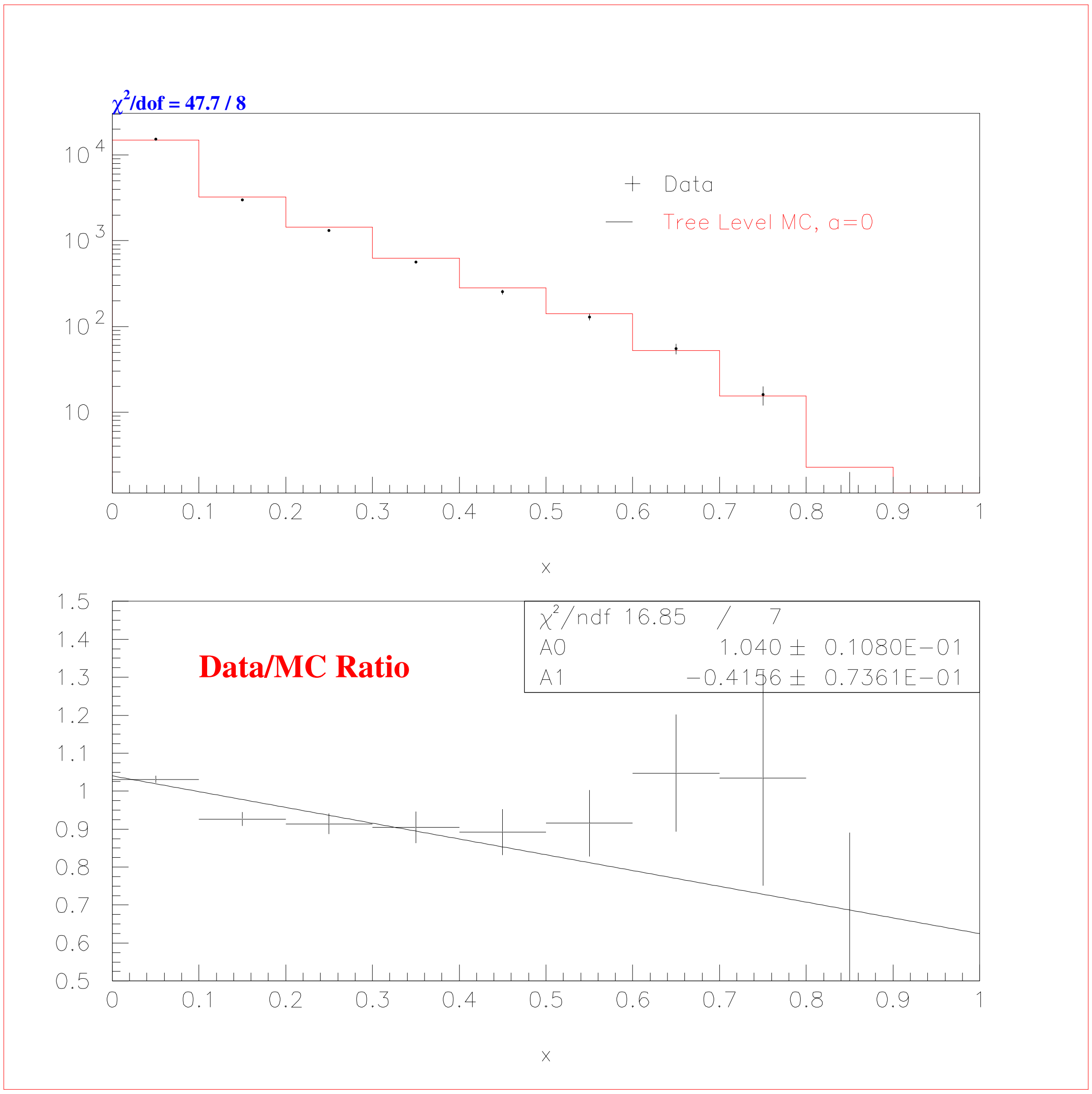
- $x_i = (q_i^2/M_\pi^2)$
- $f(x_1, x_2) = 1 + a \cdot (x_1 + x_2) + \mathcal{O}(x_i x_j)$
- Theoretical Expectation:
  $a \sim (M_\pi/M_\rho)^2 \sim 0.031$
- CELLO 91: $a = 0.0326 \pm 0.0026 \pm 0.0026$
  - Based on fit to Vector–meson Pole at large, negative q^2
- SINDRUM I 91: $a = 0.025 \pm 0.014 \pm 0.026$
  - Best Direct Measurement
- Radiative Corrections also a function of x

MC Distribution of x at Generation:



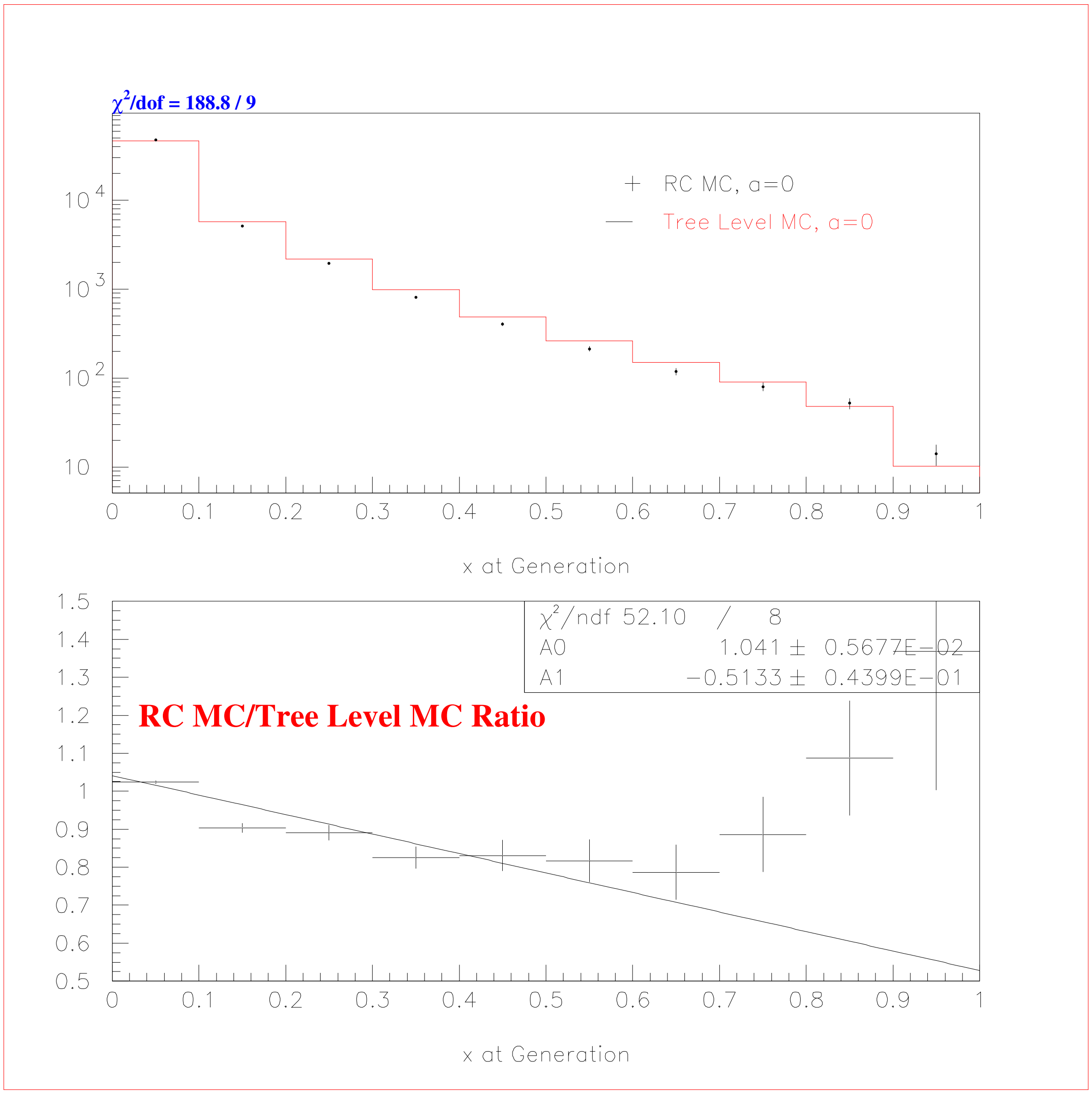
$$\Gamma \sim f(x_1, x_2)^2 = 1 + 2\ a \cdot (x_1 + x_2)$$

Data vs Tree–Level MC($a = 0$):



Our best fit: $a = -0.21 \pm 0.04$.

Tree–Level vs $\mathcal{O}(\alpha^3)$:

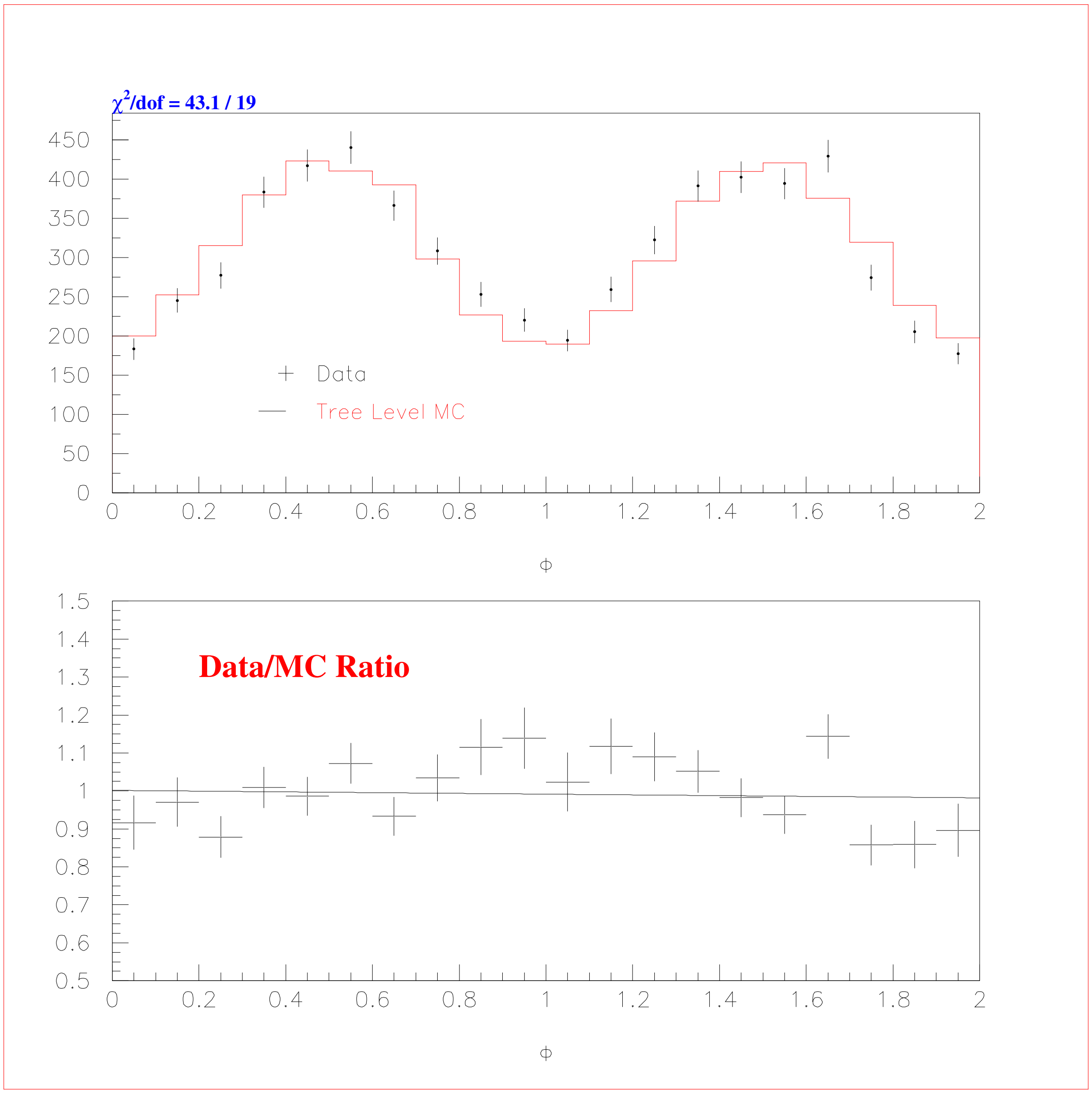


Radiative Corrections are large and negative at large x. The effect is about the right size to explain Data/MC disagreement.

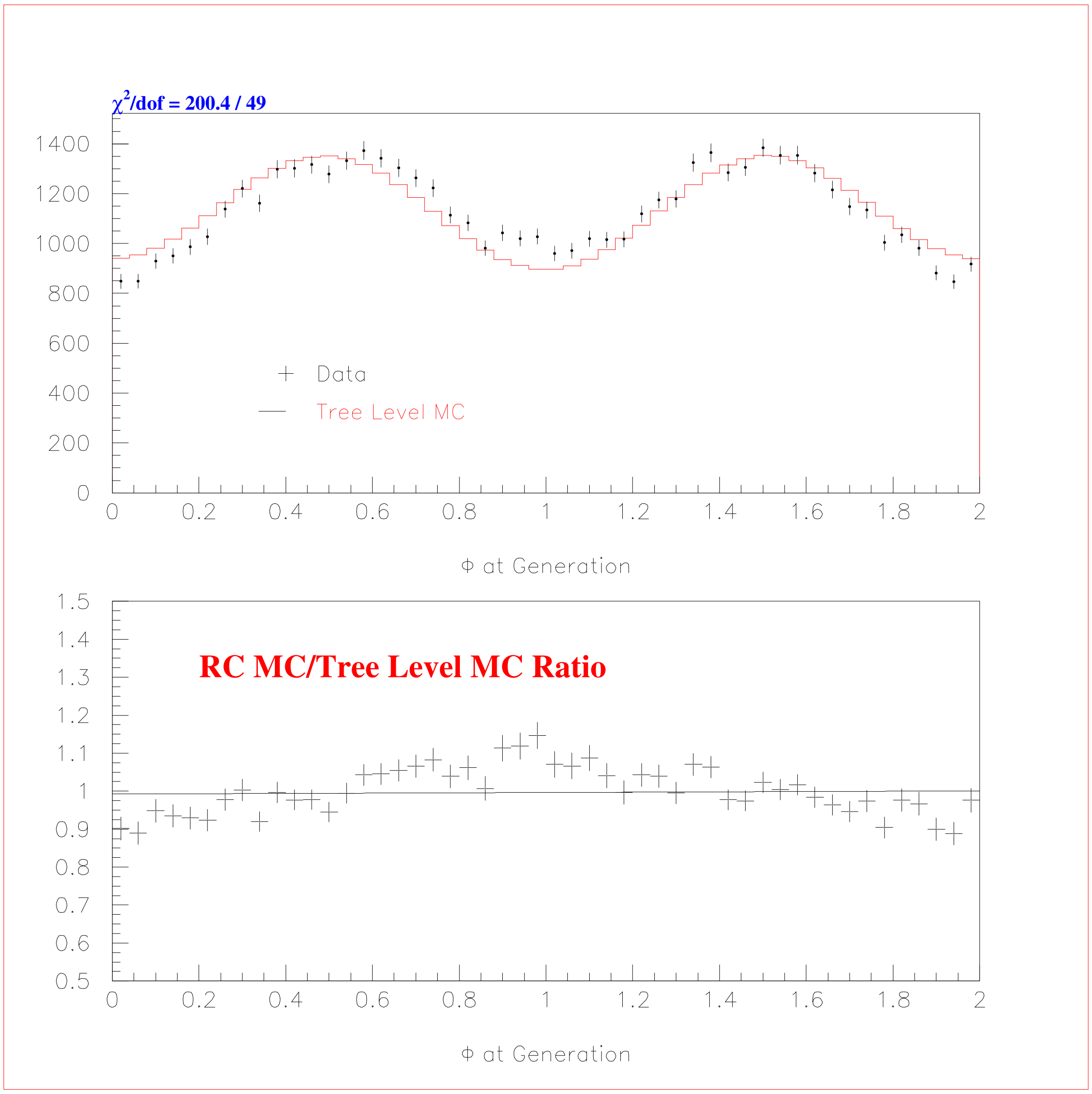
Parity Analysis of $\pi^0\gamma^*\gamma^*$ Coupling:

- ϕ is Angle between ee planes
- $\partial\Gamma/\partial\phi \sim 1 + \alpha\,(\cos 2\phi + C \sin 2\phi)$
- SM expectation: $\alpha = -0.18$, $C = 0$
- Radiative Corrections also a function of ϕ

Data vs Tree–Level MC:



Tree–Level vs $\mathcal{O}(\alpha^3)$:



Conclusions:

- Branching Ratio:
  - $\frac{B(\pi^0 \to 4e)}{B(\pi^0 \to ee\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$
  - Agrees with expectations
  - Radiative Corrections are now available
  - Systematic error can be reduced with further work
- Form Factor:
  - Radiative Corrections are a larger effect
  - Corrections will be included soon
- ϕ Distribution:
  - Tree–Level MC predicts general features of ϕ distribution in Data
  - No indication of CP violation