Remember $\pi^0 \to e^+e^-e^+e^-$?

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for

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Outline

- $\pi^0 \to e^+e^-e^+e^-$ Branching Ratio Analysis:
  - Method and Selection
  - Result
- $\pi^0 \to e^+e^-e^+e^-$ Maximum Likelihood Fit:
  - Likelihood Function
  - Results

$\pi^0 \to e^+e^-e^+e^-$ BR Measurement

- Normalize $K_L \to \pi^0\pi^0\pi^0_{DD}$ to $K_L \to \pi^0\pi^0_D\pi^0_D$:

$$R = \frac{N_{DD}}{N_{2D}} \cdot \frac{\epsilon_{2D}}{\epsilon_{DD}} = \frac{B_{4e} \cdot B_{\gamma\gamma}}{B^2_{ee\gamma}}$$

- Trigger 1 Data:
  - 4TRACK output of 2e-nclus Crunch
  - Require exactly 8 hardware clusters, 4 of which match to tracks
- Same selection requirements applied to both modes
- Main background from $K_L \to \pi^0\pi^0\pi^0_D$ with external conversion before DC1

Analysis Cuts

Variable	Accepted Range
Minimum Cluster Energy	> 2 GeV
Total CsI Energy	$40 - 210$ GeV
Minimum Cluster Separation	> 5 cm
Minimum Track Momentum	> 2 GeV
E/p	$0.93 - 1.07$
χ^2_{vertex}	< 40
χ^2_{magnet}	< 100
z-Vertex Position	$94 - 157$ m
Total Mass	$480 - 515$ MeV
P_T^2	< 800 MeV^2
χ^2_{pairing}	< 12
Track Separation	< 2 mm

Backgrounds

- External Conversion upstream of Spectrometer:

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

  After all cuts: $0.2\,\%$ of signal and normalization

- Kinematic Misidentification:
  A small number of normalization events are identified as signal ($0.4\,\%$), and signal as normalization ($0.3\,\%$).

Double Ratio by Run Period

	Win97	Sum97	99
N_{DD}	5429	4152	20930
N_{2D}	26011	19879	95361
ϵ_{DD}	0.00196	0.00194	0.00321
ϵ_{2D}	0.00213	0.00212	0.00327
N_{DD}/N_{2D}	0.2087	0.2089	0.2195
$\epsilon_{2D}/\epsilon_{DD}$	1.087	1.093	1.019
δ_{BG}	0.9975	1.0025	0.9974
R	0.2263(34)	0.2289(39)	0.2231(17)

$$R = 0.2244 \pm 0.0014 \qquad \chi^2 = 2.2$$

Systematic Uncertainties

Category	Source	Error (%)
Theory	δ_{rad}	0.04
	$\mathcal{M}(\alpha, \zeta, \delta)$	0.01
Simulation	DC Res	0.84
	Material	0.15
	DC Ineff	0.04
	CsI Res	0.02
Analysis	MC Stat	0.26
	Cut Var	0.21
	Backgrounds	0.15
Total Uncertainty		0.93

Branching Ratios

Based on 30,315 BG-subtracted events:

$$\frac{B_{4e} \cdot B_{\gamma\gamma}}{B_{ee\gamma}^2} = 0.2244 \pm 0.0014(\text{stat}) \pm 0.0021(\text{syst})$$

$$\frac{B_{4e}(x_{4e} > 0.9)}{B_{\gamma\gamma}} = [3.30 \pm 0.04(\text{int}) \pm 0.18(\text{ext})] \times 10^{-5}$$

$$\frac{B_{4e(\gamma)}(\text{all } x_{4e})}{B_{\gamma\gamma}} = [3.50 \pm 0.04(\text{int}) \pm 0.19(\text{ext})] \times 10^{-5}$$

Comparisons

- Final KTeV Result: (pending new $\pi^0 \to e^+e^-\gamma$ measurement)

$$\frac{B_{4e}(x_{4e} > 0.9)}{B_{\gamma\gamma}} = (3.30 \pm 0.18) \times 10^{-5}$$

- 1962 Samios Result:

$$\frac{B_{4e}}{B_{\gamma\gamma}} = (3.18 \pm 0.30) \times 10^{-5}$$

- Barker *et al* Calculation:

$$\frac{B_{4e}(x_{4e} > 0.9)}{B_{\gamma\gamma}} = 3.331 \times 10^{-5}$$

$\pi^0\gamma^*\gamma^*$ Vertex

Interaction has the form:

$$\mathcal{L} \sim \left[\mathcal{F}_P \epsilon_{\mu\nu\rho\sigma} + \mathcal{F}_S (g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho})\right] F^{\mu\nu} F^{\rho\sigma} \Pi$$

where,

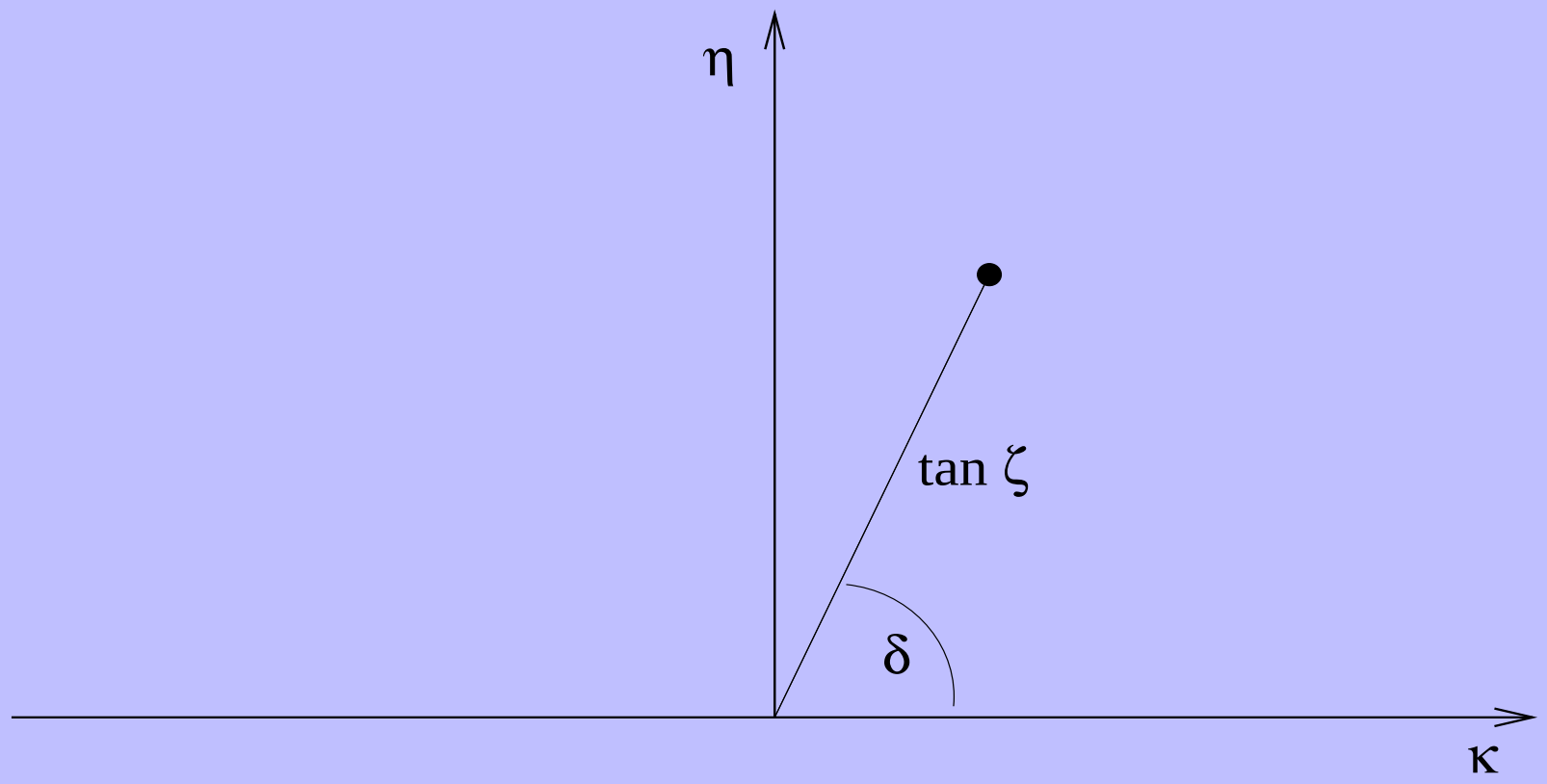
$$\boxed{\mathcal{F}_P = \tilde{g} f(x_1, x_2) \cos\zeta \qquad \mathcal{F}_S = \tilde{g} f(x_1, x_2) \sin\zeta \mathrm{e}^{\mathrm{i}\delta}}$$

- DIP Form Factor:

$$f_{\mathrm{DIP}}(x_1, x_2) = 1 - \alpha\mu \left(\frac{x_1}{1 - \mu x_1} + \frac{x_2}{1 - \mu x_2} \right) + \beta\mu^2 \frac{x_1 x_2}{(1 - \mu x_1)(1 - \mu x_2)}$$

- Coupling Strength: $\mathcal{F}_S / \mathcal{F}_P = \tan\zeta \mathrm{e}^{\mathrm{i}\delta} = \kappa + \mathrm{i}\eta$

The $\kappa - \eta$ Plane



$$\kappa = \tan\zeta\cos\delta \qquad \zeta = \tan^{-1}\sqrt{\kappa^2+\eta^2}$$

$$\eta = \tan\zeta\sin\delta \qquad \delta = \tan^{-1}\sqrt{\eta/\kappa}$$

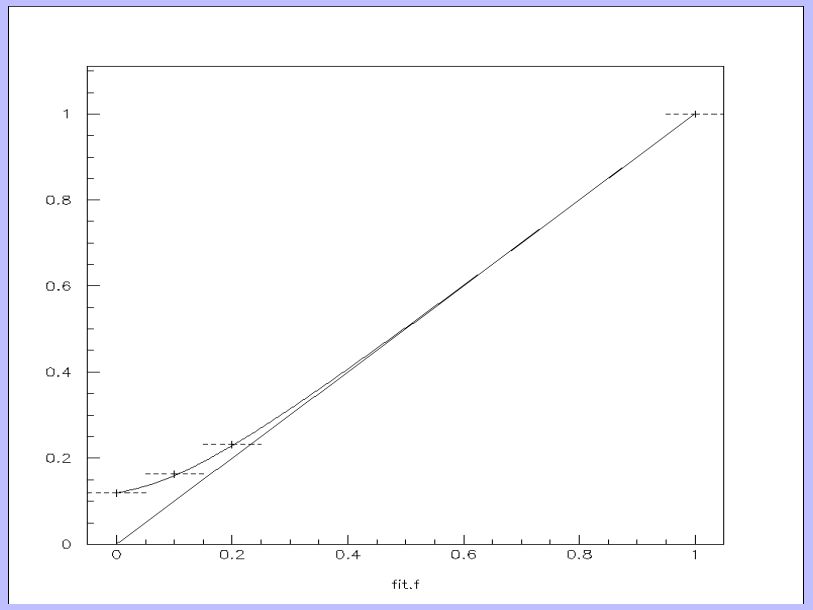
Resolution Bias

$$\frac{d\Gamma}{d\phi} \sim 1 + A\cos 2\phi + B\sin 2\phi$$

On the η-axis:

$$A \sim -0.19\,(1 - 2\eta^2)$$

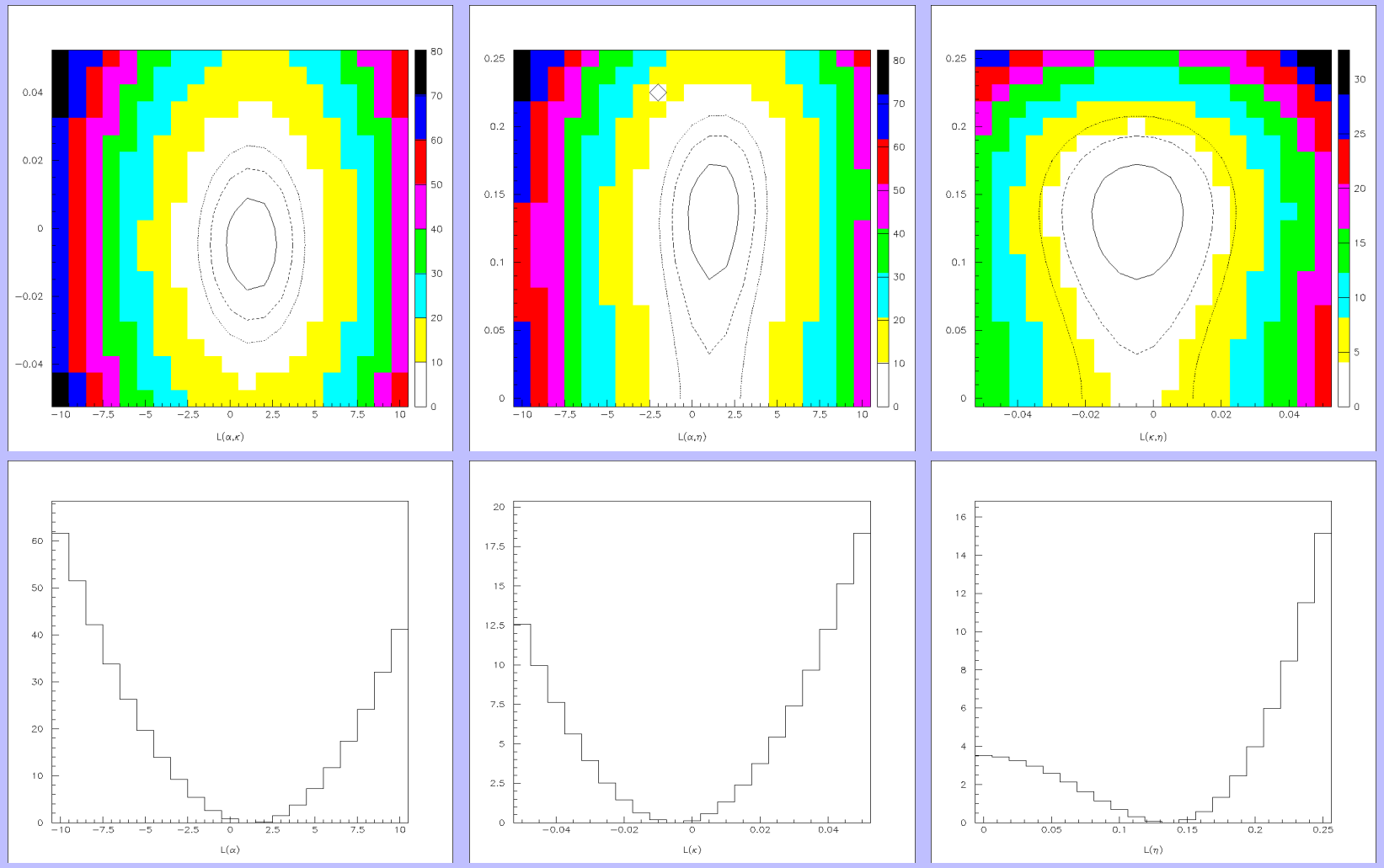
$$B \sim 0$$



Resolution on ϕ will reduce the amplitude, increasing η.

$$\eta_{\text{fit}} = \eta_{\text{gen}} + b\left(\frac{\mathrm{e}^{-m\eta_{\text{gen}}} - \mathrm{e}^{-m}}{1 - \mathrm{e}^{-m}}\right)$$

Likelihood Minimum



$\alpha = 1.3 \pm 1.0$ $\kappa = -0.008 \pm 0.009$ $\eta = 0.135 \pm 0.026$

$\pi^0\gamma^*\gamma^*$ Uncertainties

Source	α	κ	η
Statistical	1.0	0.009	0.026
Normalization	0.3	0.005	0.006
Cut Variation	0.9	0.010	0.006
ϕ Bias	-	-	0.087
Total Systematic	0.9	0.011	0.087
Total Error	1.3	0.014	0.091

Likelihood Results

Maximum Likelihood Estimate:

$$\alpha = 1.3 \pm 1.3$$

$$\kappa = -0.008 \pm 0.014$$

$$\eta = 0.051 \pm 0.087$$

Allowing CPT violation:

$$\eta < 0.200 \quad \text{implies} \quad \zeta < 11.3^\circ$$

Requiring CPT conservation:

$$|\kappa| < 0.031 \quad \text{implies} \quad \zeta < 1.72^\circ$$

Form Factor Comparison

- Previous Direct Measurements: (from $\pi^0 \to e^+e^-\gamma$)

$$a = +0.015 \pm 0.025$$

- Indirect Measurement: (from $e^+e^- \to \pi^0 e^+e^-$)

$$a = +0.033 \pm 0.004$$

- First $\pi^0 \to e^+e^-e^+e^-$ Result:

$$a = -0.040 \pm 0.040$$

Publication Plans

- One paper including $\pi^0 \rightarrow e^+e^-e^+e^-$ Branching Ratio and $\pi^0\gamma^*\gamma^*$ Vertex measurements
- Branching Ratio:
  - DC Resolution: reduces total error from 1.12% to 0.74%
  - Many small error sources crop up next
- $\pi^0\gamma^*\gamma^*$ Vertex:
  - ϕ Resolution Bias: only impacts limit without CPT conservation
  - Cut Variation: minimal improvement to form factor