Rare Decays of the η and η' Mesons at CLEO II

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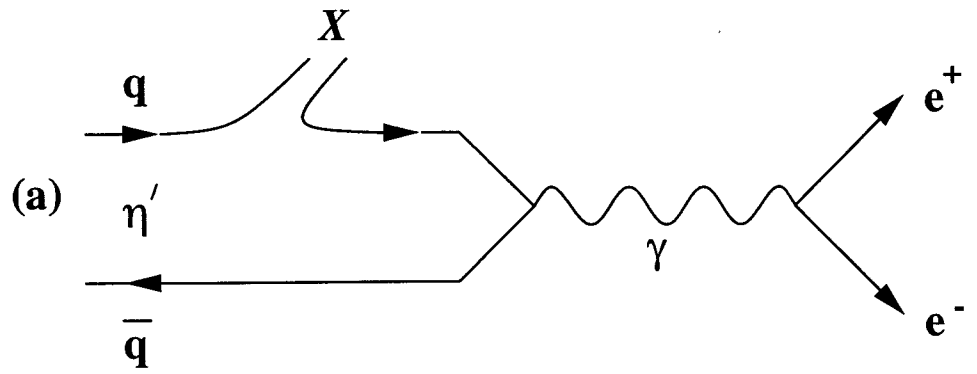
- **Theoretical Motivation**
- **The CLEO II Detector**
- **Rare Decay Searches:**
  - $\eta \to e^+e^-$
  - $\eta' \to e^+e^-\eta$
  - $\eta' \to e^+e^-\pi^0$
  - $\eta' \to e^+e^-\gamma$
  - $\eta' \to e\mu$
- **Future Experiments**

The η and η' Mesons

- **Both η and η' are spin-0 pseudoscalar mesons**
- **Masses:**
  - $\eta = 547\ \mathrm{MeV}/c^2$
  - $\eta' = 958\ \mathrm{MeV}/c^2$
  - proton $= 938\ \mathrm{MeV}/c^2$ by comparison
- **Common η decays:**
  - $\gamma\gamma$ – $(39.2 \pm 0.3)\%$
  - $3\pi^0$ – $(32.2 \pm 0.4)\%$
  - $\pi^+\pi^-\pi^0$ – $(23.1 \pm 0.5)\%$
- **Common η' decays:**
  - $\pi^+\pi^-\eta$ – $(43.8 \pm 1.5)\%$
  - $\rho^0\gamma$ – $(30.2 \pm 1.3)\%$
  - $\pi^0\pi^0\eta$ – $(20.7 \pm 1.3)\%$
- **Both mesons are produced in $e^+e^- \rightarrow$ hadron events as well as other reactions**

Symmetry Violation

- η and η' are odd eigenstates of P and CP, allowing us to study CP violation through decays to two π's
- Both mesons are even eigenstates of C, so we can search for C violation in decays to an odd number of photons:
  - $\eta \to 3\gamma$
  - $\eta \to 3\pi^0\gamma$
- We can also look for evidence of C violation in decays to $l^+l^-\pi^0$ or $l^+l^-\eta$ (l is a lepton), which can progress through one virtual photon:



Other Physics Topics

- **Leptoquarks – The branching ratio of the decay $\eta \to e^+e^-$ can constrain the leptoquark mass and its coupling to the s quark**

- **Chiral perturbation theory – The shape of the $\eta \to \pi^0\gamma\gamma$ signal is influenced by the p^6 term**

- **Lepton family violation – Both $\eta \to e\mu$ and $\eta' \to e\mu$ can give evidence of this violation**

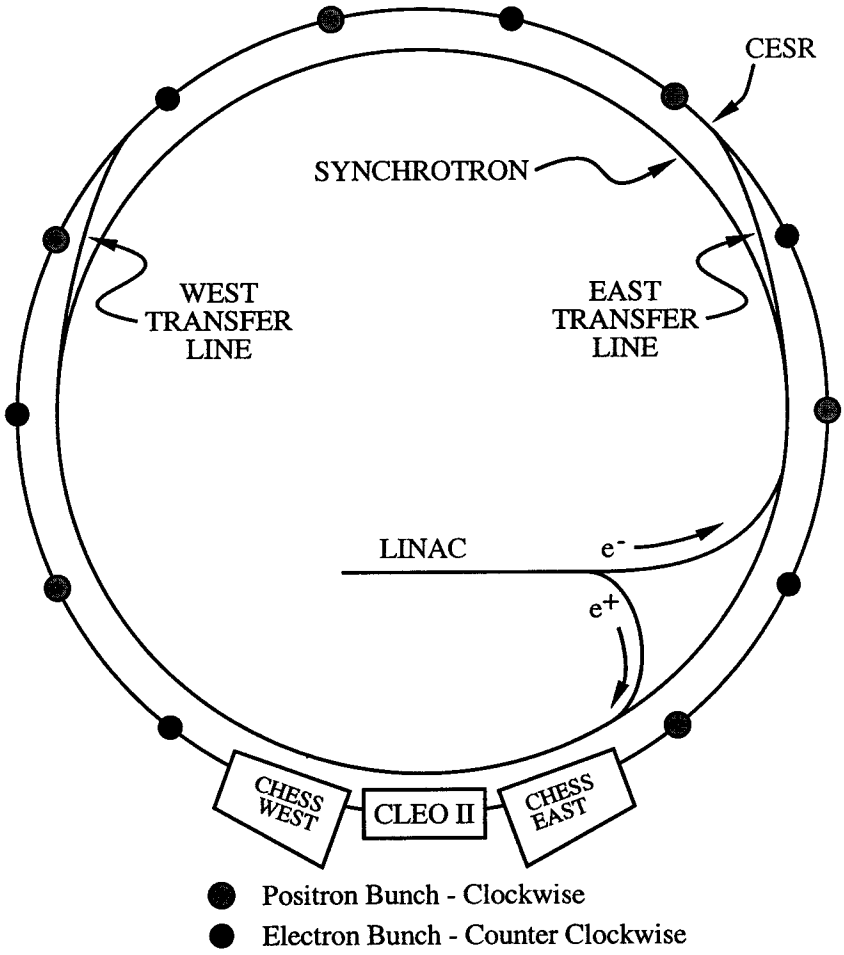
- **Glueballs – Shape of $\eta' \to \pi^+\pi^-\eta$ Dalitz plot can give information about gluon content of η'**

Current Upper Limits

Decay	Physics	Upper Limit
$\eta \to \pi^+\pi^-$	CP violation	9×10^{-4}
$\eta \to 3\gamma$	C violation	5×10^{-4}
$\eta \to \pi^0 e^+ e^-$	C violation	4×10^{-5}
$\eta \to \pi^0 \mu^+ \mu^-$	C violation	5×10^{-6}
$\eta \to e^+ e^-$	Leptoquarks	3×10^{-4}
$\eta \to e\mu$	Lepton family violation	6×10^{-6}
$\eta' \to \pi^+\pi^-$	CP violation	2.0%
$\eta' \to e^+ e^- \eta$	C violation	1.1%
$\eta' \to e^+ e^- \pi^0$	C violation	1.3%
$\eta' \to e\mu$	Lepton family violation	None

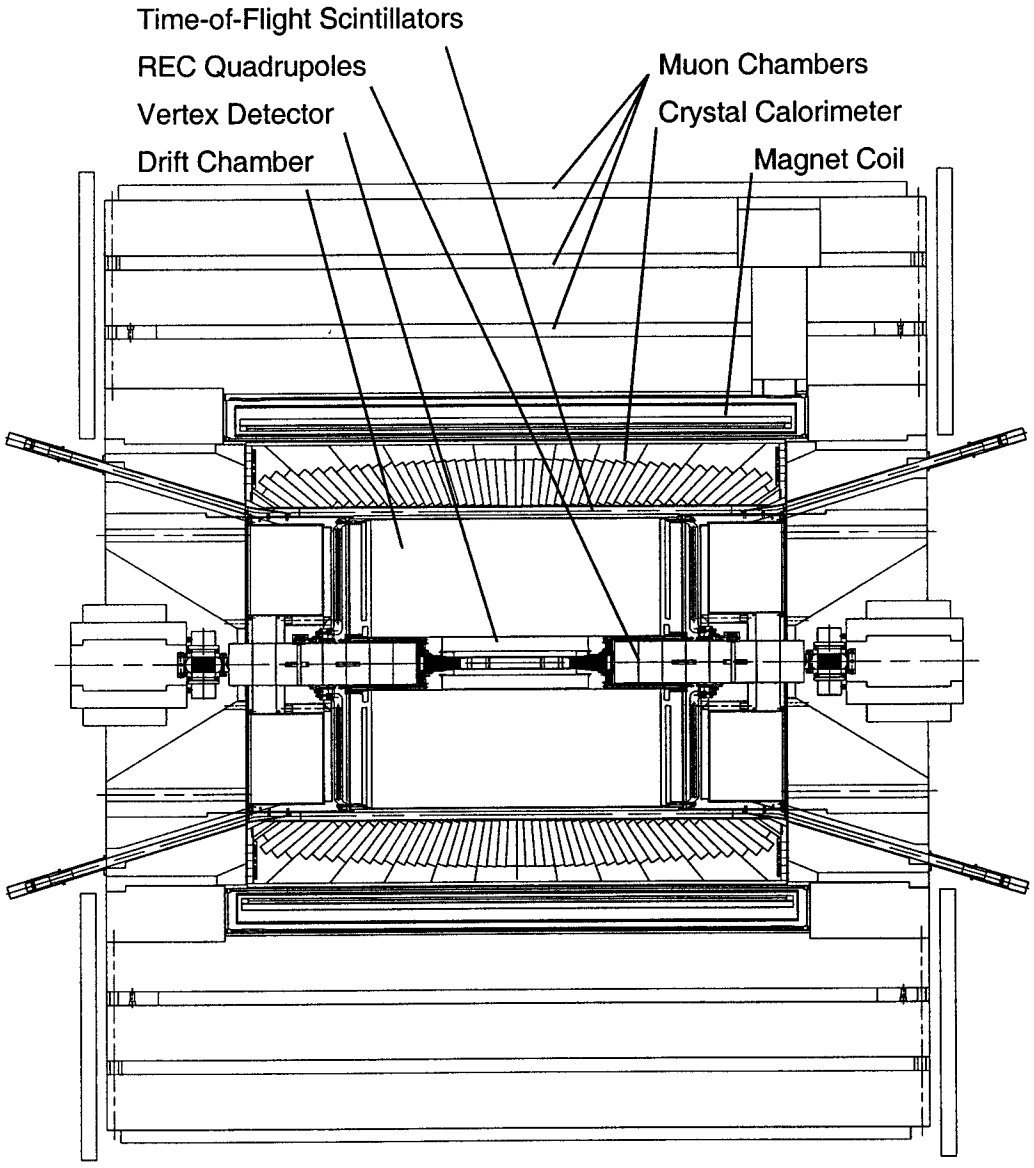
- **Some of these limits can be improved by searching the large data sample from CLEO II**

Cornell Electron Storage Ring (CESR)



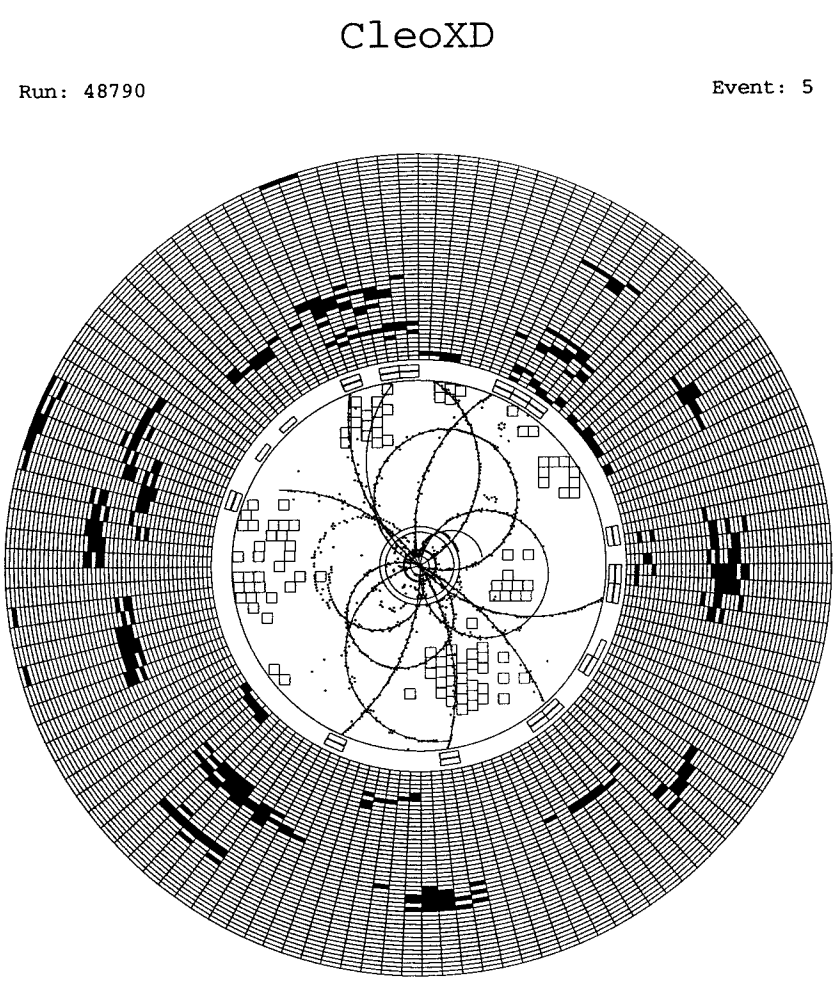
- **4.8 fb^{-1} of data at or just below Υ(4S) resonance:**
  - 3.1 fb^{-1} on-resonance (10.58 GeV)
  - 1.7 fb^{-1} off-resonance (10.53 GeV)
  - Approximately 2.6×10^7 candidate hadron events

The CLEO II Detector



- **Excellent electron identification above 0.4 GeV/c (90+% efficiency, 0.5% fake rate from pions)**

Combinatoric Background



- **Large potential background from random combinations of charged pions and photons**
- **Lepton multiplicity smaller, but muon momentum threshhold is high (1.0 GeV/c)**

Physics Goals

- **We choose to oncentrate on decays involving electrons to minimize combinatoric background**

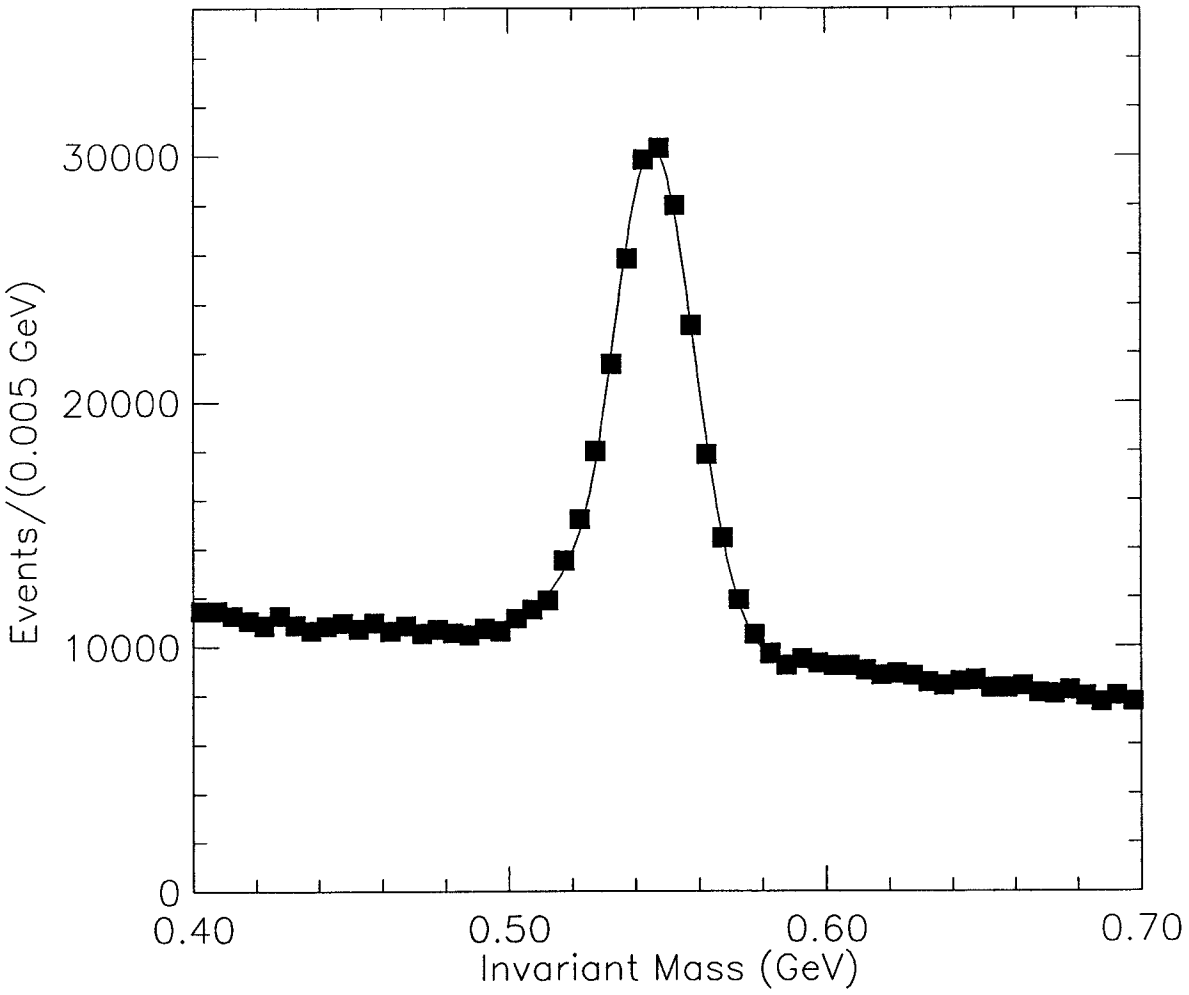
- **We search for the following decays:**
  - $\eta \to e^+e^-$ **– Leptoquarks**
  - $\eta' \to e^+e^-\eta$ **– C violation**
  - $\eta' \to e^+e^-\pi^0$ **– C violation**
  - $\eta' \to e^+e^-\gamma$ **– Unobserved Dalitz decay**
  - $\eta' \to e\mu$ **– Lepton family violation**

- **Normalize measurements to common decays $\eta \to \gamma\gamma$ and $\eta' \to \pi^+\pi^-\eta$ $(\eta \to \gamma\gamma)$ to cancel some systematic errors**

Selection criteria for $\eta \to \gamma\gamma$

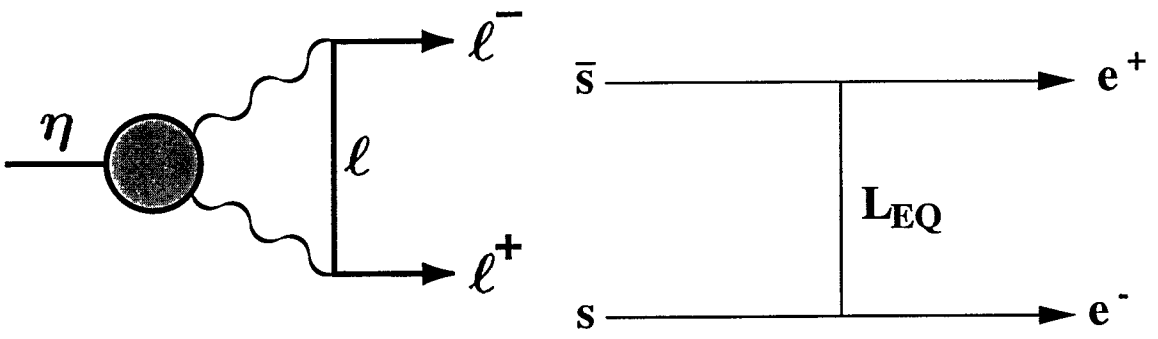
- **Event cuts:**
  - **At least five charged tracks**
  - **Not a beam-wall or beam-gas interaction**
  - **Not a $B\bar{B}$ decay based on event shape**
- **Photon identification:**
  - **$E_\gamma \geq 0.4$ GeV**
  - **Region of best energy resolution in calorimeter**
  - **No overlap with charged tracks**
  - **No shower fragments or overlaps**
  - **Veto photon pairs with invariant mass within 12.5 MeV/c^2 of the π^0 mass**
- **Other cuts:**
  - **$p_\eta \geq 0.8$ GeV/c**

$\eta \to \gamma\gamma$ Results



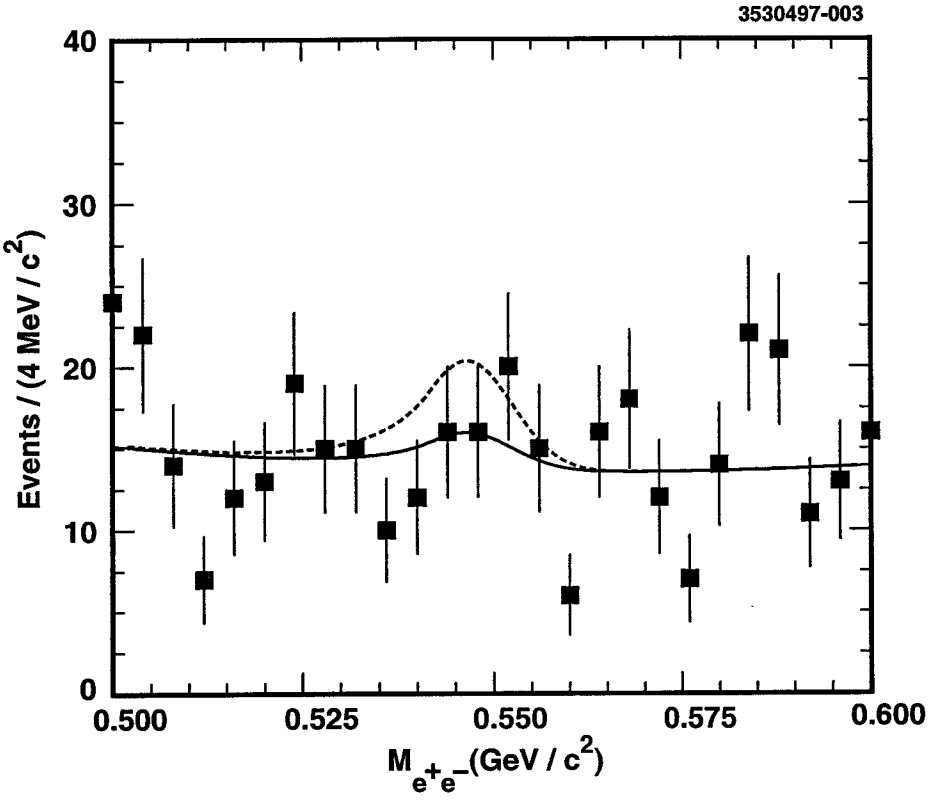
- $\varepsilon(\eta \to \gamma\gamma) = (4.80 \pm 0.05\%)$
- 1.4×10^5 **signal events**
- **Approximately** 7.5×10^6 η **mesons in data sample**

Search for $\eta \to e^+e^-$



- Due to helicity suppression, decay expected at 10^{-9} level
- Also provides severe constraint on leptoquark couplings at 10^{-9} level
- Electron identification:
  - Electron momentum greater than 0.4 GeV/c
  - Region of best energy resolution in calorimeter
  - Distance of closest approach to interaction point less than 5mm
  - Identified as electron by CLEO algorithm combining E/p, shower shape, and specific ionization rate

Results for $\eta \to e^+e^-$



- **Solid curve represents MC parameter fit to data**
- $\varepsilon(\eta \to e^+e^-) = (5.22 \pm 0.31\%)$
- **90% confidence upper limit of 27.1 signal events (dashed curve)**

Final Numbers for $\eta \to e^+e^-$

Table 1: Summary of Systematic Uncertainty

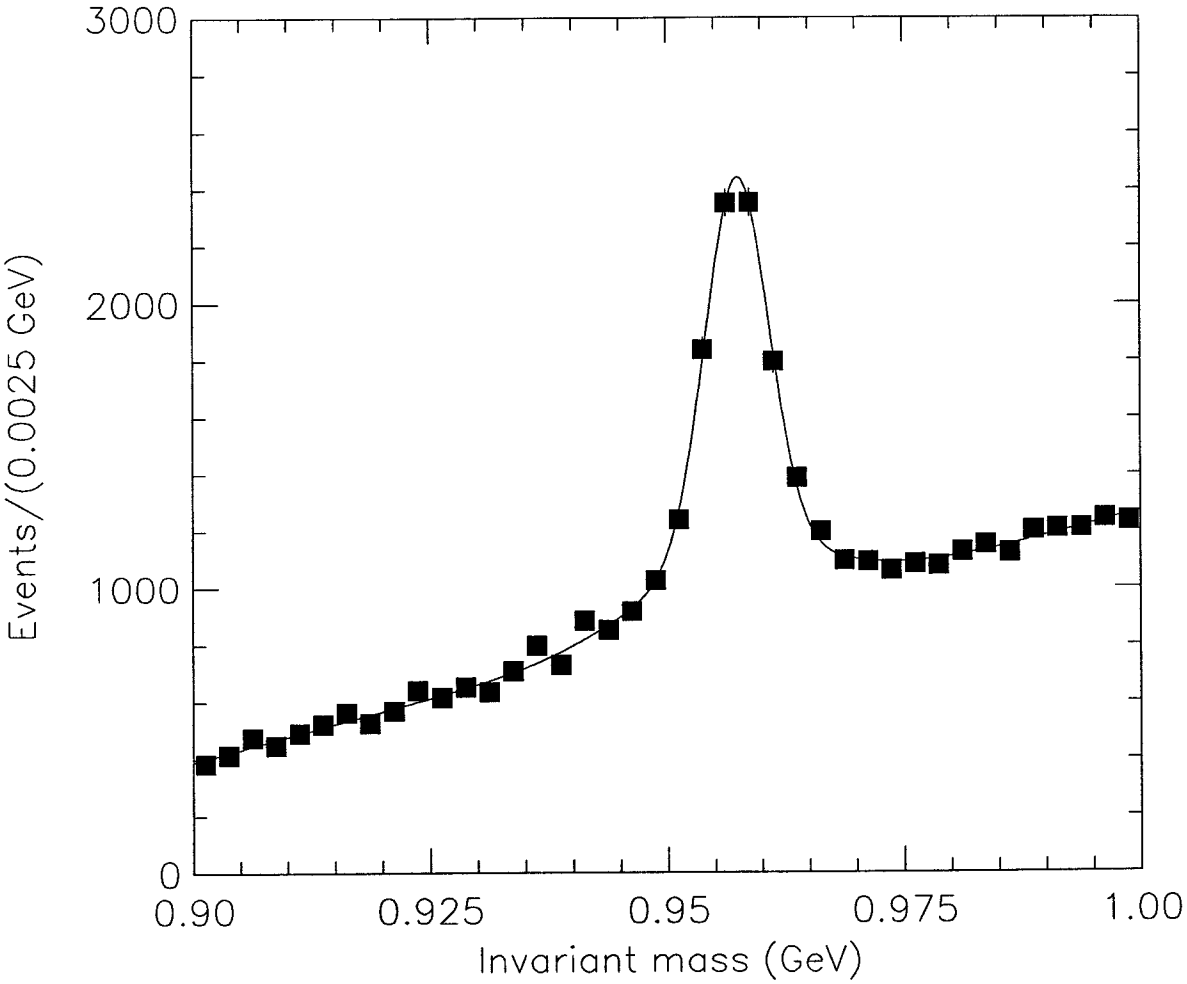
Source	Uncertainty
Tracking efficiency	1% per e candidate
Electron ID efficiency	3% per electron
Photon detection efficiency	3% per photon
$N_{\eta\to\gamma\gamma}$ (stat.)	1.4%
$\varepsilon_{\eta\to\gamma\gamma}$ (stat.)	1.0%
$\varepsilon_{\eta\to e^+e^-}$ (stat.)	6.0%
$B(\eta \to \gamma\gamma)$	0.7%
Total	10.7%

- **Include systematics by increasing signal limit by this amount**
- **Normalize to $\eta \to \gamma\gamma$ to yield final limit:**
  - $B(\eta \to e^+e^-) < 7.7 \times 10^{-5}$
- **T.E. Browder *et al.*, Phys. Rev. D56, 5359 (1997)**

Cuts for $\eta' \to \pi^+\pi^-\eta\ (\eta \to \gamma\gamma)$

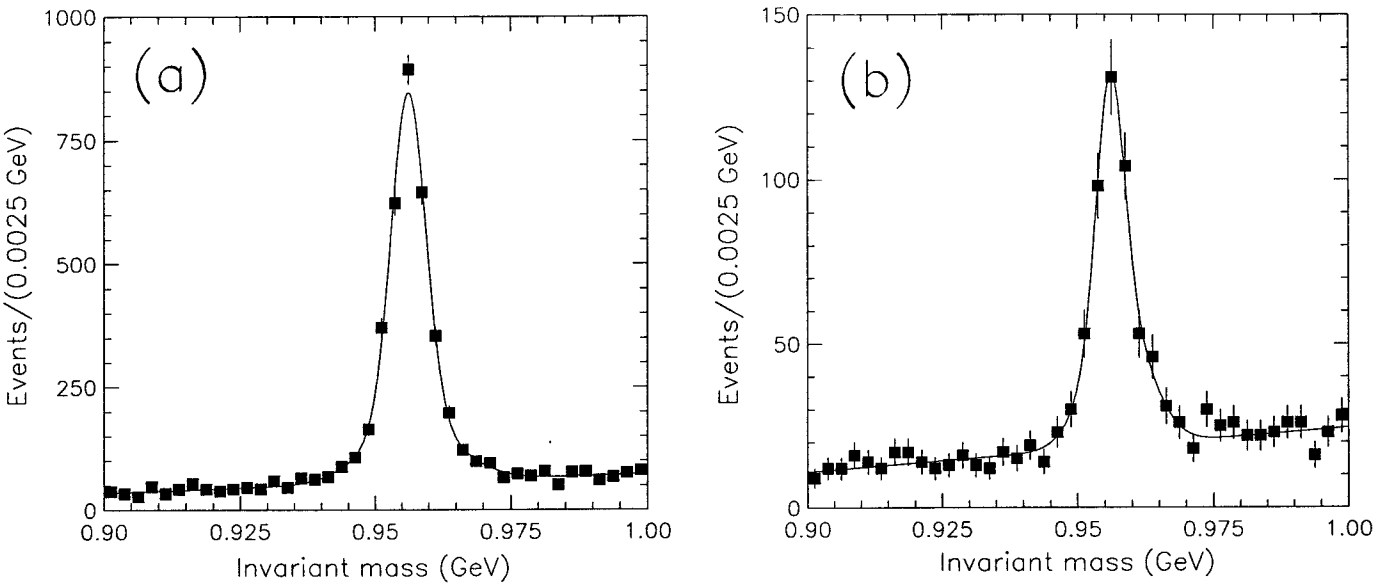
- Event cuts:
  - At least five charged tracks
  - Not a beam-wall or beam-gas interaction
- Photon identification:
  - $E_\gamma \geq 0.2$ GeV
  - Region of best energy resolution in calorimeter
  - No overlap with charged tracks
  - Veto photon pairs with invariant mass within 12.5 MeV/c^2 of the π^0 mass
- Pion identification:
  - Lepton veto
  - Region of best energy resolution in calorimeter
  - Must not be a gamma conversion
- Other cuts:
  - Kinematic fit to η mass must have $\chi^2 \leq 10$
  - $p_\eta \geq 0.6$ GeV/c
  - $p_{\eta'} \geq 1.0$ GeV/c

$\eta' \to \pi^+\pi^-\eta$ in Data



- **6704 ± 244 events in peak**

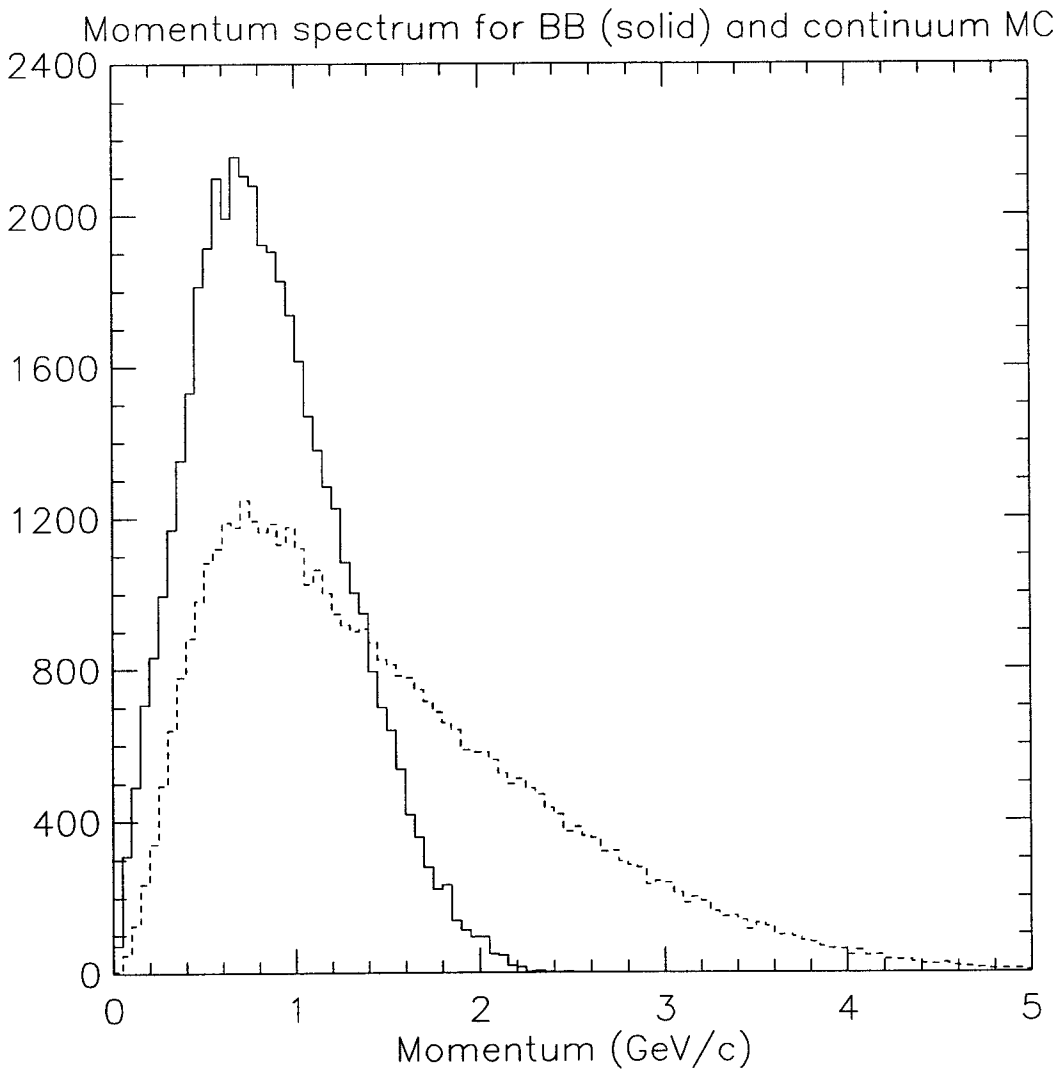
$\eta' \to \pi^+\pi^-\eta$ in Monte Carlo



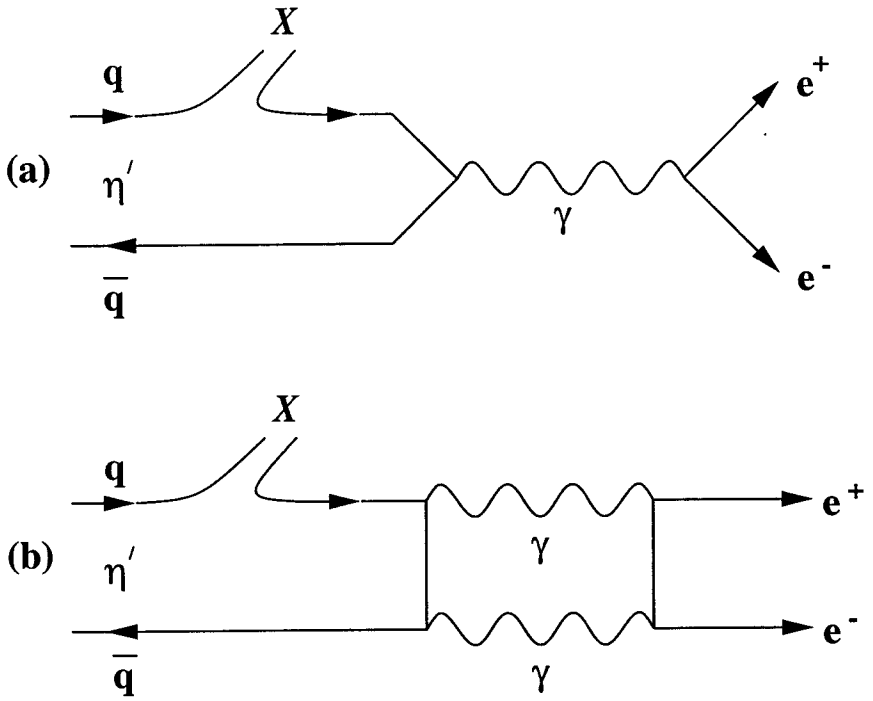
$\eta' \to \pi^+\pi^-\eta$ $(\eta \to \gamma\gamma)$ invariant mass spectrum from (a) continuum and (b) $B\bar{B}$ Monte Carlo

- $\varepsilon(\text{continuum}) = (3.24 \pm 0.08)\%$
- $\varepsilon(B\bar{B}) = (1.39 \pm 0.09)\%$
- **Difference is due to η' momentum spectrum**
- **Use known production rate to determine weighted-mean efficiencies**

η' Momentum Comparison



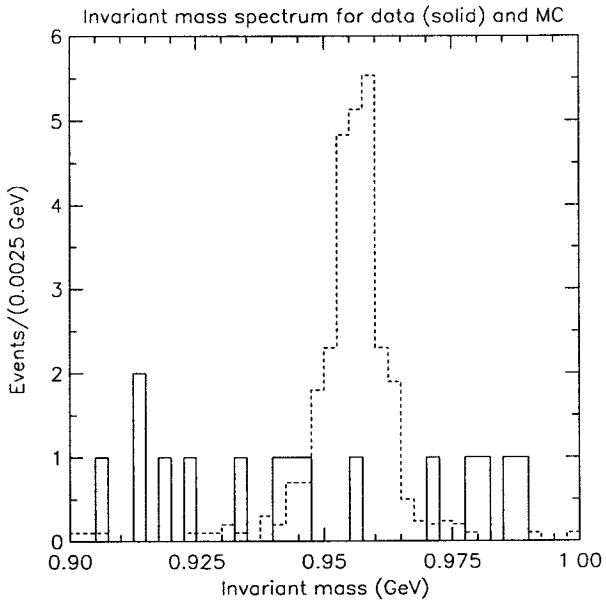
C Violation in $\eta' \to e^+e^-X$

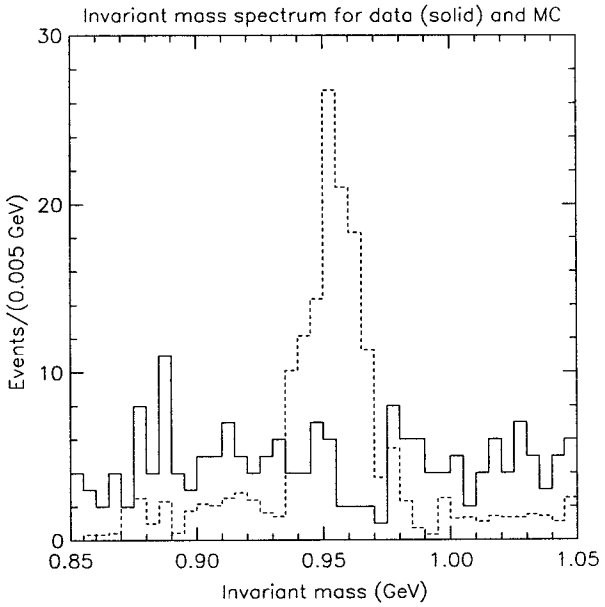


(a) C-violating and (b) C-conserving contributions to the decay $\eta' \to e^+e^-X$, where X is an η or π^0.

- $B(\eta' \to \pi^0\gamma\gamma) < 8 \times 10^{-4}$; **the rate for e^+e^-X should be orders of magnitude smaller.**
- **Cuts are identical to normalizing mode except for addition of electron identification**

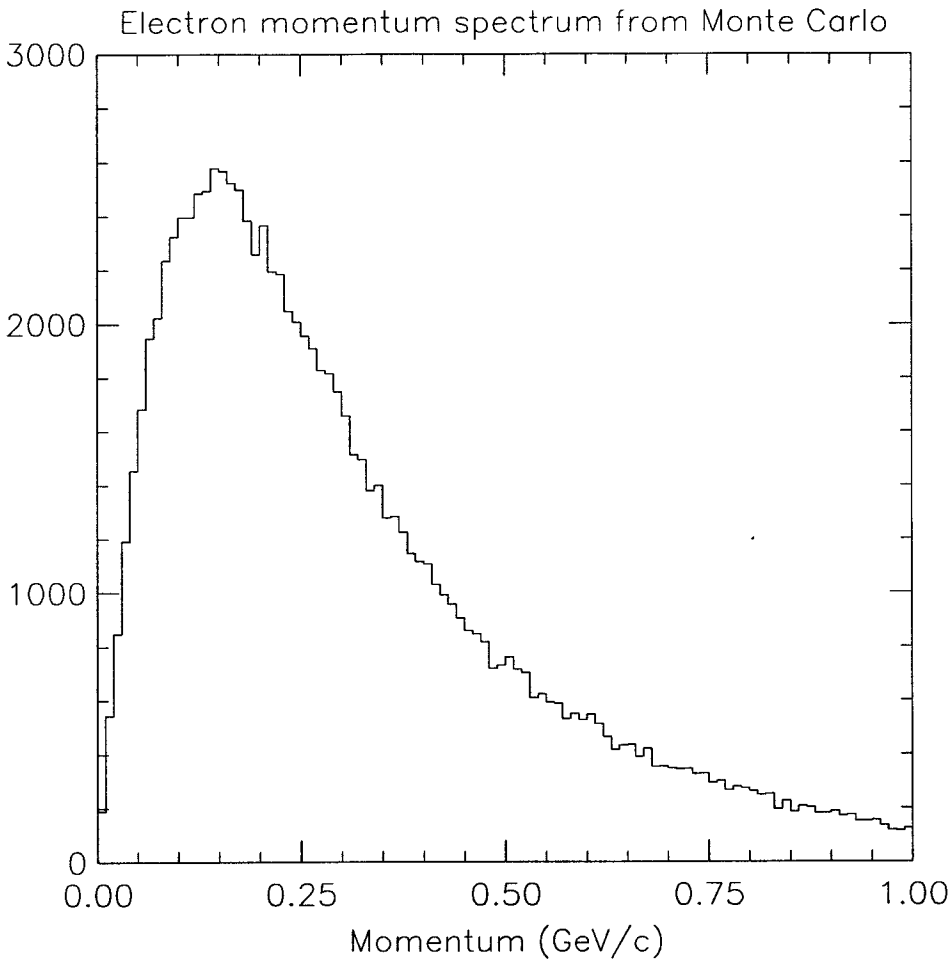
Results for $\eta' \to e^+e^-X$ $(X \to \gamma\gamma)$





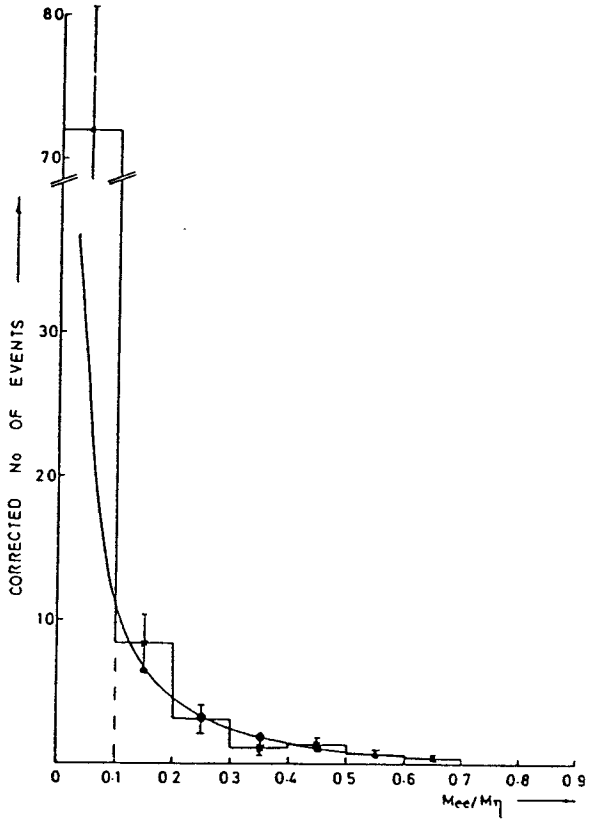
- **For $\eta' \to e^+e^-\eta$:**
  - $\varepsilon = (0.27 \pm 0.02)\%$
  - **90% confidence upper limit of 2.8 signal events**
- **For $\eta' \to e^+e^-\pi^0$:**
  - $\varepsilon = (0.37 \pm 0.02)\%$
  - **90% confidence upper limit of 6.2 events**

$e^{\pm}$ Momentum Spectrum



- **Poor efficiency due to implicit momentum cut in electron ID**
- **$\sim$30% of electrons have momentum > 0.4 GeV/c**

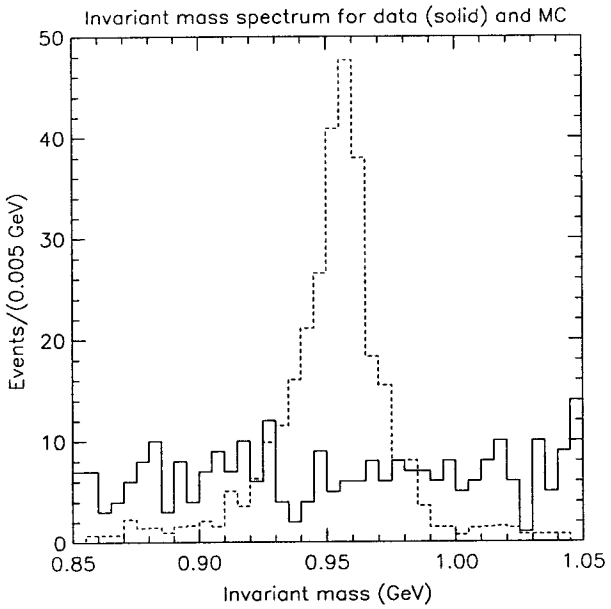
Alternate Matrix Element



- Phase space may not be appropriate for the C-violating mode (one virtual photon).
- The m_{ee} distribution has been measured for the η Dalitz decay [M.R. Jane *et al.*, Phys. Lett. 59B, 103 (1975)].
- Second Monte Carlo sample using this matrix element gives efficiencies ~20% less. We use mean value and introduce the discrepancy as a systematic error.

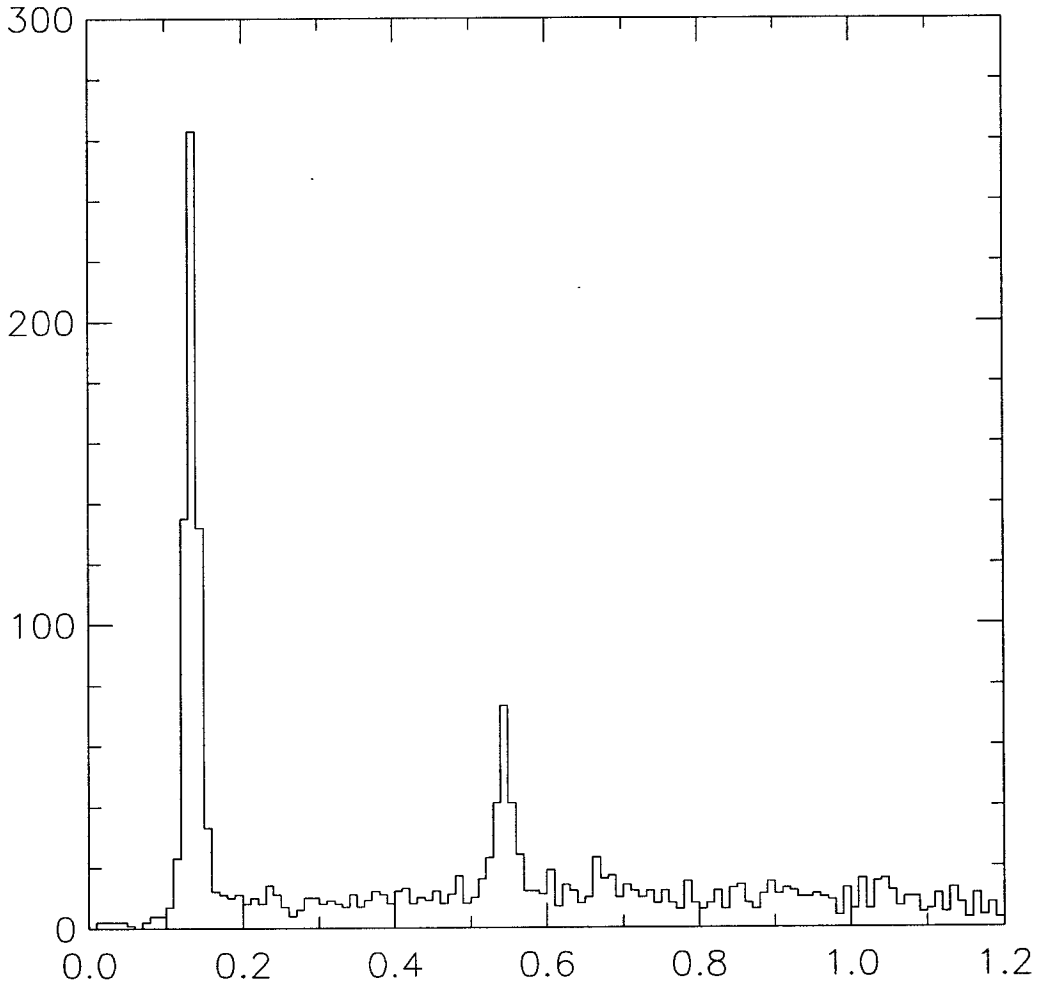
Dalitz Decay $\eta' \to e^+e^-\gamma$

- **The Dalitz decay rates for the π^0 and η are two orders of magnitude smaller than the $\gamma\gamma$ modes for each meson.**
- **$B(\eta' \to \gamma\gamma) < (2.11 \pm 0.13)\%$, so we may expect the Dalitz decay at the 10^{-4} level.**
- **Additional search criteria:**
  - **Photon energy > 0.6 GeV/c**
  - **Veto events with $e^+e^-\gamma$ combination near η or π^0 mass**



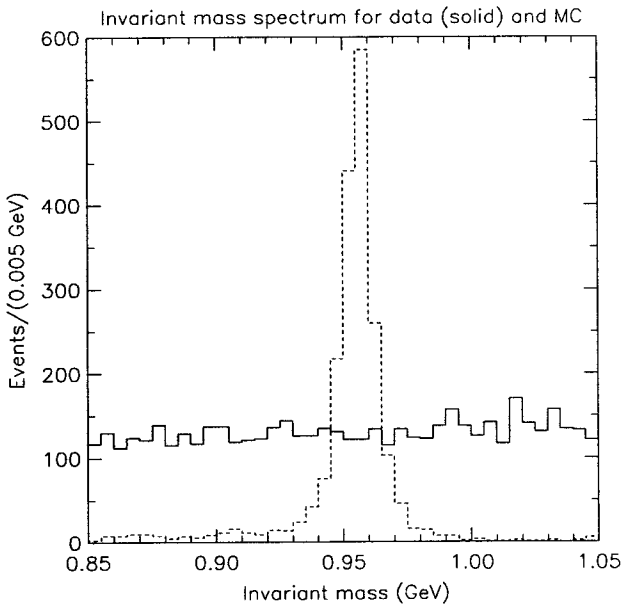
- **$\varepsilon(\eta' \to e^+e^-\gamma) = (1.01 \pm 0.06\%)$**
- **90% confidence upper limit of 11.7 signal events**

Dalitz Decay Background



Lepton Family Violation ($\eta' \to e\mu$)

- The decays $\eta' \to e^+\mu^-$ and $\eta' \to e^-\mu^+$, with no accompanying neutrinos, are examples of lepton family violation.
- Experiments on $\mu^- \to e^-$ conversion in heavy nuclei suggest an upper bound of 10^{-11}.
- Muon tracks must penetrate three interaction lengths of material outside the calorimeter.

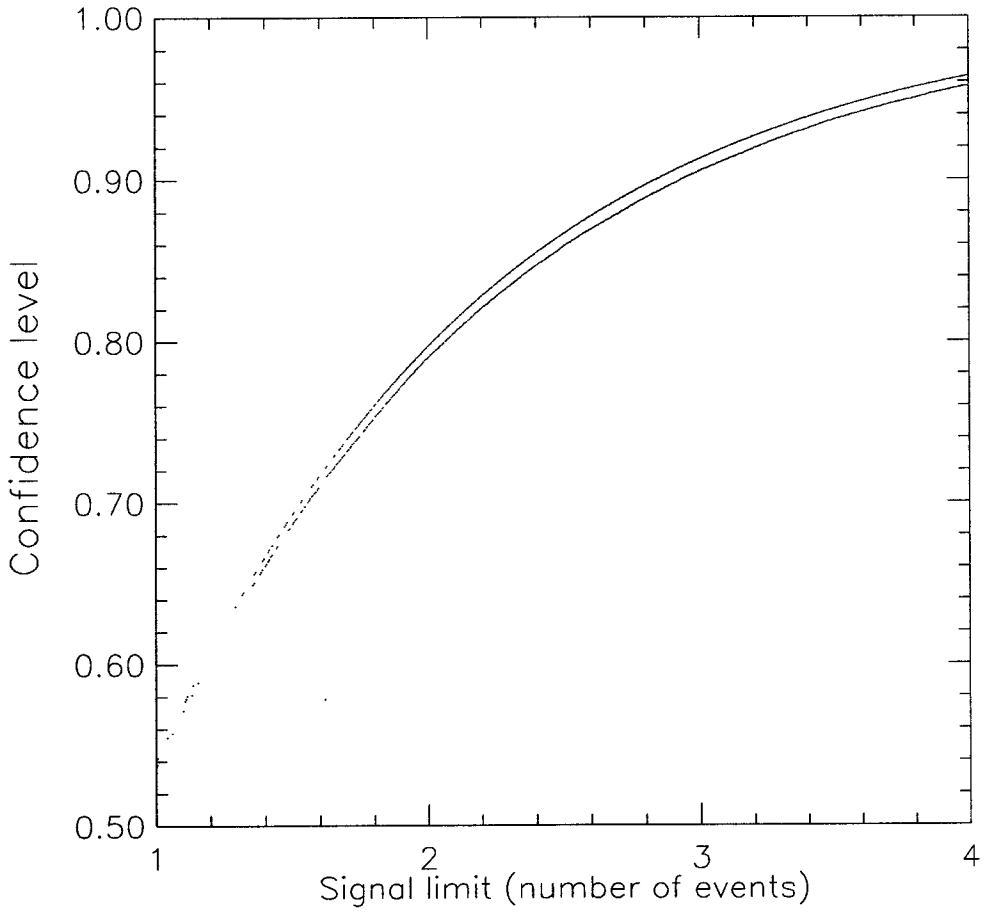


- $\varepsilon(\eta' \to e\mu) = (4.92 \pm 0.15)\%$
- 90% confidence upper limit of 30.1 signal events

Systematics for η' decays

Source	$e^+e^-\eta$	$e^+e^-\pi^0$	$e^+e^-\gamma$	$e\mu$
Photon detection efficiency	—	—	3.0%	6.0%
Electron ID efficiency	6.0%	6.0%	6.0%	3.0%
Muon ID efficiency	—	—	—	0.5%
$B(\eta' \to \pi^+\pi^-\eta)$	0.7%	0.7%	0.7%	0.7%
$B(\eta \to \gamma\gamma)$	—	3.4%	3.4%	3.4%
$N_{\eta' \to \pi^+\pi^-\eta}$ (fit to data)	3.6%	3.6%	3.6%	3.6%
$\varepsilon_{\eta' \to \pi^+\pi^-\eta}$ (MC stat)	2.5%	2.5%	2.5%	2.5%
ε(rare decay) (MC stat)	8.3%	5.9%	5.5%	3.1%
Choice of MC model	12.5%	8.8%	—	—
$B\bar{B}$ contribution	1.6%	1.1%	0.6%	0.7%
Total	16.8%	13.4%	10.3%	9.3%

Confidence Level Distribution



- **Assign random Gaussian error to each point in Poisson probability distribution**
- **"Smeared" distribution gives corrected 90% confidence upper limit on signal size**

Final η' Numbers

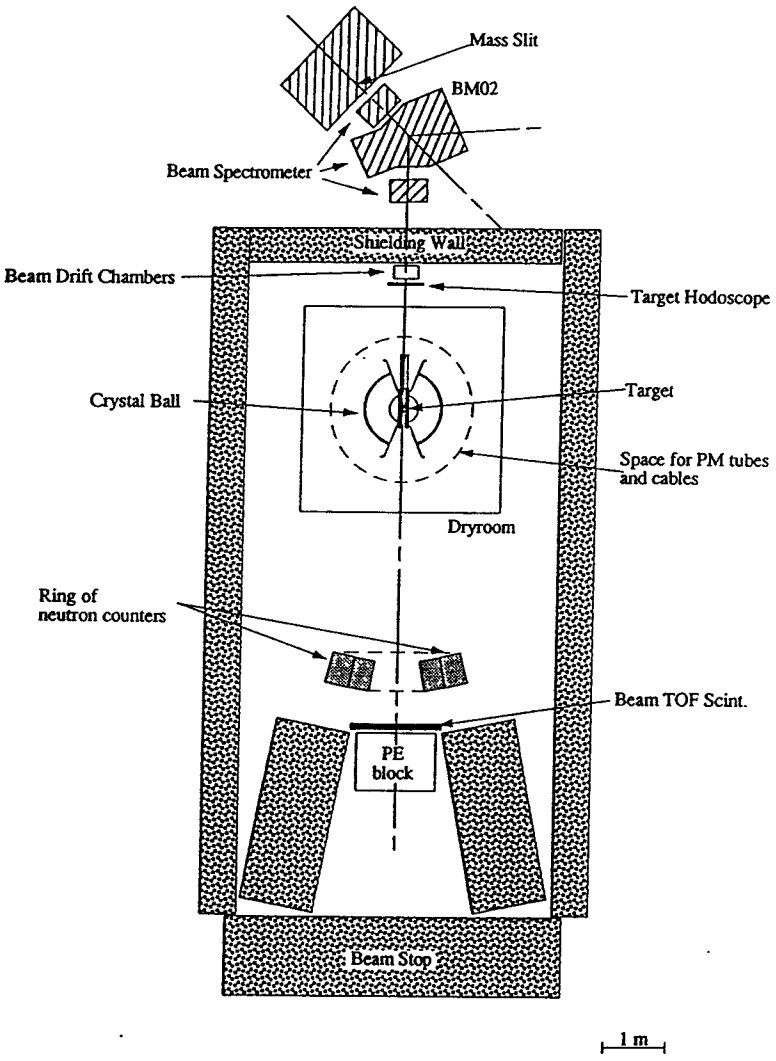
Normalizing to $\eta' \to \pi^+\pi^-\eta$ gives these 90% confidence upper limits (preliminary):

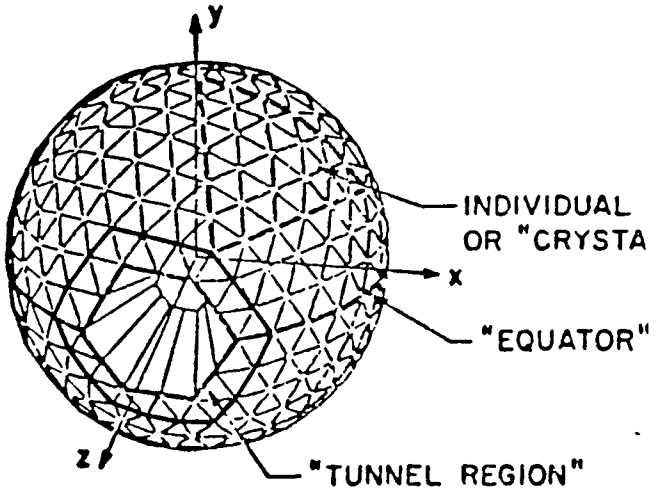
Decay	CLEO Limit	Old Limit
$\eta' \to e^+e^-\eta$	2.4×10^{-3}	1.1%
$\eta' \to e^+e^-\pi^0$	1.4×10^{-3}	1.3%
$\eta' \to e^+e^-\gamma$	0.9×10^{-3}	**None**
$\eta' \to e\mu$	4.7×10^{-4}	**None**

Future Experiments

- **High-energy colliders are limited by low statistics and large backgrounds**
- **Some potential from lower-energy machines:**
  - VEPP-2M at Novosibirsk (ρ, ω, ϕ)
  - KLOE at Frascati (rare K decays)
- **Need high-luminosity, clean "η factory"**
  - $\pi^- p \to n\eta$
  - $pd \to {}^3\mathrm{He}\ \eta$
  - SATURNE (Saclay, France) uses pd reaction to study η decays involving muons

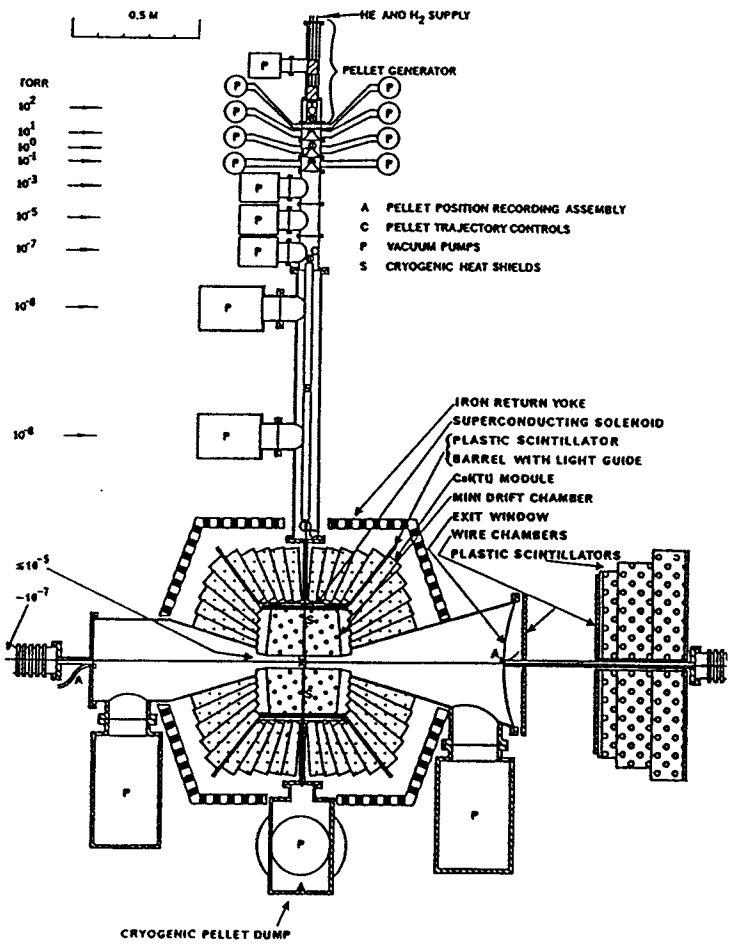
Crystal Ball at AGS





- Uses $\pi^- p \to n\eta$ with 710 MeV π^- beam
- 98% of solid angle covered for neutral decays
- 2×10^7 η decays recorded in 1997

Wide Angle Shower Apparatus (WASA)



- Uses $pd \rightarrow {}^3\mathrm{He}\ \eta$ with frozen hydrogen pellet target
- 10^8 η/day running expected by end of 1999

Summary

- η and η' rare decays allow the study of CP violation, C violation, lepton family violation, leptoquarks, and a host of other topics

- We have searched the CLEO II data set for rare η and η' decays, and have established the following 90% confidence upper limits:
  - $B(\eta \to e^+e^-) < 7.7 \times 10^{-5}$
  - $B(\eta' \to e^+e^-\eta) < 2.4 \times 10^{-3}$
  - $B(\eta' \to e^+e^-\pi^0) < 1.4 \times 10^{-3}$
  - $B(\eta' \to e^+e^-\gamma) < 0.9 \times 10^{-3}$
  - $B(\eta' \to e\mu) < 4.7 \times 10^{-4}$

- Dedicated "η factories" such as WASA and AGS/Crystal Ball will push our experimental understanding to the 10^{-10} level by the year 2001