Dalitz Decays of Pseudo-Scalar Mesons

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On behalf on the CLAS collaboration

Outline

Constituent Quark Model

Hadrons are colorless particle formed of quarks/anti-quarks that are held together by the strong force:

- Baryons
  - 3 valence quarks (qqq)
  - Half integer spin ($\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$....) particles (fermions)
- Mesons
  - 2 valence quarks($\mathrm{q}\overline{\mathrm{q}}$)
  - Integer spin (0, 1, 2...) particles (bosons)

Valence quarks in hadrons produce the quantum numbers J^P

- $J = L + S$
- $P = (-1)^{L+1}$

Constituent Quark Model

Table: Types of Mesons

Type	J	P	L	S	J^P
Pseudoscalar	0	-	0	0	0^-
Scalar	0	+	1	1	0^+
Vector	1	-	0	1	1^-
Axial Vector	1	+	1	0	1^+
Tensor	2	+	1	1	2^+

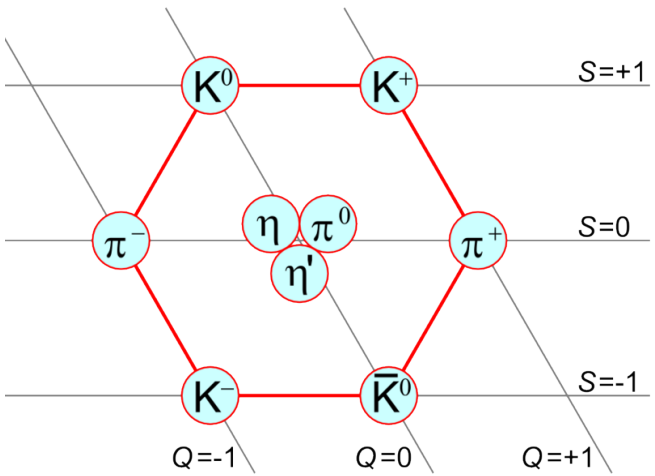


Figure: Nonet of Pseudoscalar Mesons

Constituent Quark Model

$$\pi^0 = \frac{1}{\sqrt{2}}(u\overline{u} - d\overline{d})$$

η and η' are linear combinations of the singlet and octet states.

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} -\sin\theta_{\text{mix}} & \cos\theta_{\text{mix}} \\ \cos\theta_{\text{mix}} & \sin\theta_{\text{mix}} \end{pmatrix} \cdot \begin{pmatrix} \eta_0 \\ \eta_8 \end{pmatrix}$$

$$\eta_0 \rightarrow \sqrt{\frac{1}{6}}(u\overline{u} + d\overline{d} + s\overline{s})$$

$$\eta_8 \rightarrow \sqrt{\frac{2}{3}}(u\overline{u} + d\overline{d} - 2s\overline{s})$$

$$\theta_{\text{mix}} = -16.54^\circ \pm 0.71$$

Form Factors

If a particle is not point-like, then:

$$\left.\frac{d\sigma}{dq^2}\right|_{\text{measured}} = \left[\frac{d\sigma}{dq^2}\right]_{\text{pointlike}} \left|F(q^2)\right|^2$$

- $q \rightarrow$ momentum transfer
- $F(q^2)$ is the form factor, which contains information about the electromagnetic structure of the hadron
- $F(q^2)$ is the ratio of the measured differential cross section to the Q.E.D. pointlike differential cross section

Neutral Mesons

A neutral meson is it's own antiparticle and has

- charge = 0
- magnetic moment = 0
- wave function is unaffected by charge conjugation or only reverses sign
- C(M) = M

Charge parity is conserved in strong and e&m processes

Particle Type	Charge Parity	Reason
γ	-	quanta of e $\&$m field
Pseudoscalar	+	can decay to $\gamma\gamma$
Vector	-	same quantum numbers as γ

Definition of Dalitz Decay

- Consider charge-conjugation parity of the radiative decay of neutral meson *A* to neutral meson *B*: $A \to B + \gamma$

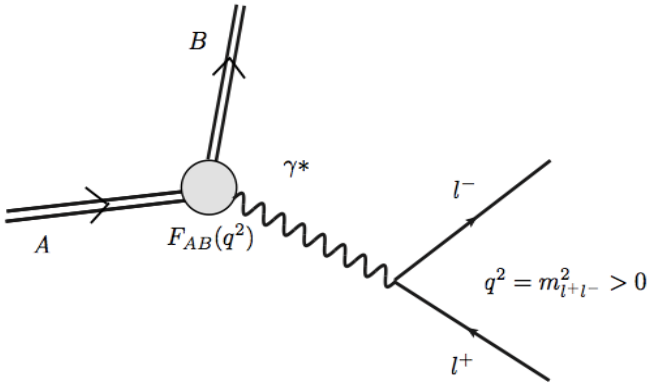
$$C\,|A\rangle \to C\,|B\rangle\,|\gamma\rangle$$

- By conservation of charge-conjugation

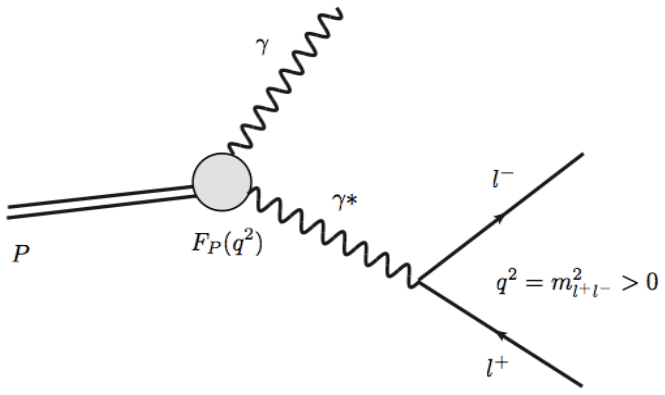
$$C_A = -C_B$$

- If γ is "off shell" γ^*, then Dalitz decay
  - $A \to B + \gamma^* \to B + e^+e^-$
  - $q^2 = m^2(\gamma^*) = m^2_{l^+l^-} > 0 \Rightarrow$ time-like
  - probability of emitting γ^* is caused by the cloud of virtual states in the region of *A*→*B*. This dynamic structure is encoded in the transition form factor.

Neutral Meson Dalitz Decays



Vector or Pseudoscalar meson decay



Pseudoscalar meson decay

Decay Amplitude:

$$M = 4\pi\alpha\imath[\underbrace{f_{AB}(q^2)\varepsilon^{\alpha\beta\gamma\delta}p_\alpha q_\beta \epsilon_\gamma}_{A\to B\gamma^*\ transition}] \quad \underbrace{\frac{1}{q^2}}_{photon\ propagator} \quad \underbrace{\bar{u}\gamma_\delta u}_{leptonic\ current}$$

Back to the Form Factor

For pseudoscalar meson $P \in \{\pi^0, \eta, \eta'\}$ Dalitz decay $P \to l^+ l^- \gamma$, the decay rate is proportional to the form factor

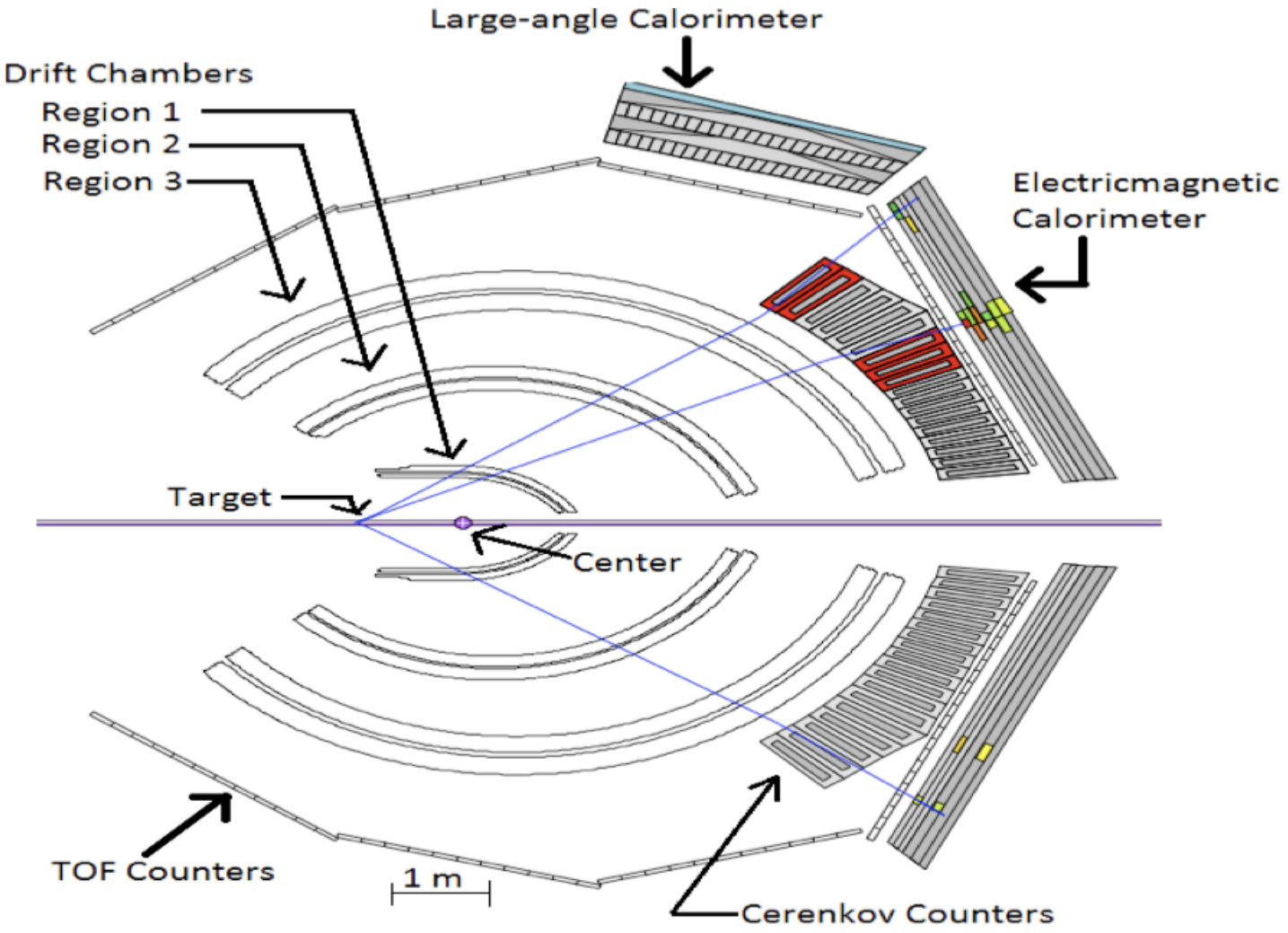
$$\frac{d\Gamma(P \to l^+ l^- \gamma)}{dq\Gamma(P \to \gamma\gamma)} = \frac{4\alpha}{3\pi q}\left[1 - \frac{4m_l^2}{q^2}\right]^{\frac{1}{2}}\left[1 + 2\frac{m_l^2}{q^2}\right]\left[1 - \frac{q^2}{m_P^2}\right]^3 \left|F(q^2)\right|^2$$

$F(q^2)$ can be fit to the dipole form: $F(q^2) = [1 - \frac{q^2}{\Lambda^2}]^{-1}$
In the limit of small momentum transfer

$$\lim_{q^2 \to 0} F(q^2) = 1 - \frac{1}{6}q^2\langle r^2 \rangle$$

Determining the transition form factor or the charge radius from Dalitz decay has been a challenge due to low statistics.....until now

Dalitz Event In



Dalitz event in CLAS detector

G12 Overview

- Data was taken in Hall B experiment G12
- Running Time: 04/2008 $\rightarrow$ 06/2008
- 44 Days of Beam Time
- 60 – 65 nA of 5.6–5.7 GeV e^-
- E_γ up to 5.5 GeV
- 126 TB Raw Data
- 40 cm ℓH_2 target
- gold radiator $10^{-4} X_0$
- Raw sensitivity of 53 pb^{-1}
- 26 x10^9 production triggers (3 x 10^6 triggers)
- Calorimeter + Čerenkov counter cleanly identify e^+e^- pairs ad reject $\pi^+\pi^-$ pairs by factor of 10^{-6}

Identifying p $e^{\pm}$ and γ events

For $e^{\pm}$, particle had to pass CC and EC cut

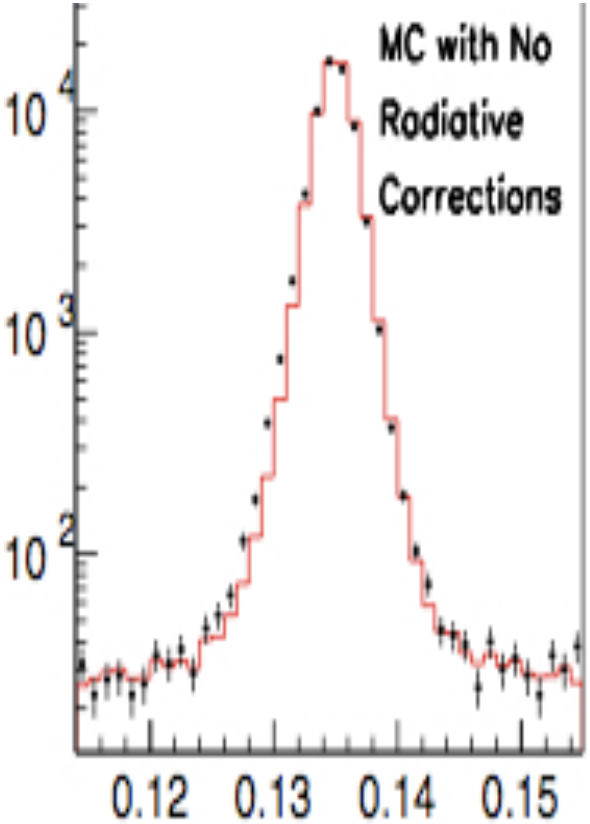
- Detect p, e^+ e^- γ for reaction p(γ, p, e^+ e^- γ)
- Identify e^+ e^- and reject $\pi^+\pi^-$ pairs by
  - # of Čerenkov counter photoelectrons $\geq$ 2.5 per particle
  - Calorimeter energy $\approx$ particle momentum
  - Geometric match in the azimuthal angle between the CC and a DC hits.
- Identify & measure γ
  - Energy deposition in EC
  - Time of flight
- No missing mass or missing energy
- Also look at p(γ, p, e^+ e^-) γ, identifying the γ with missing mass and energy

Many collaborations and η factories have produced results for TFF's

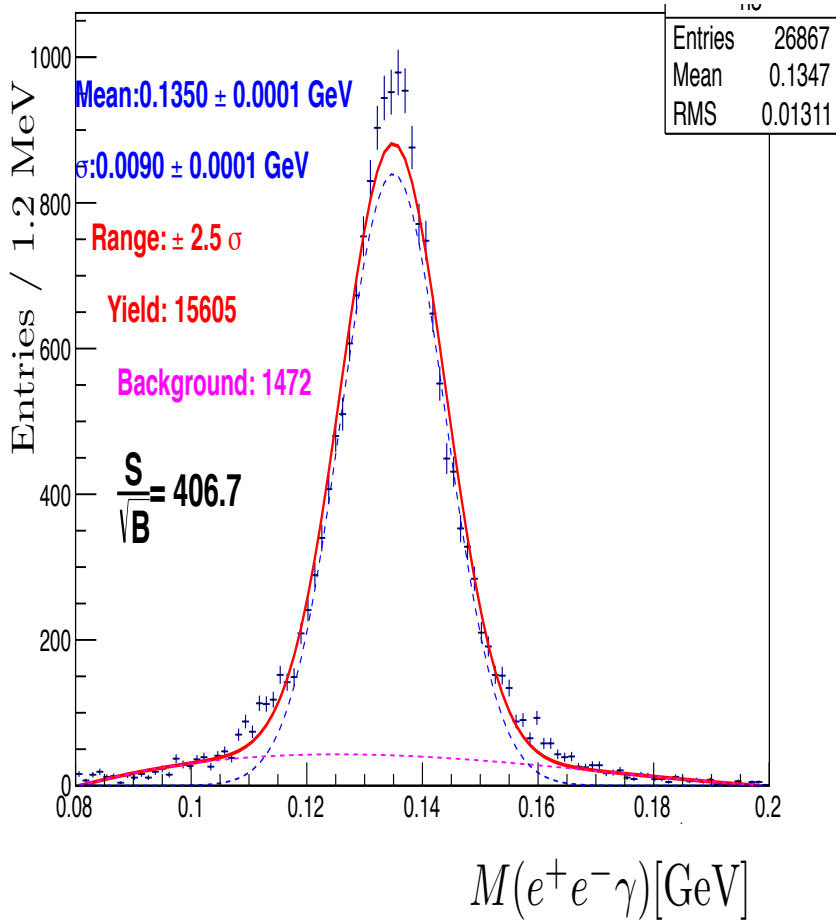
- For π^0
  - SINDRUM I: 53,955
  - FERMILAB: 63,693
- For η
  - WASA: 526 ± 25
  - TAPS: 1345 ± 59
- For η'
  - NONE

π^0 Dalitz Decay Statistics

FNAL E832 π^0 events



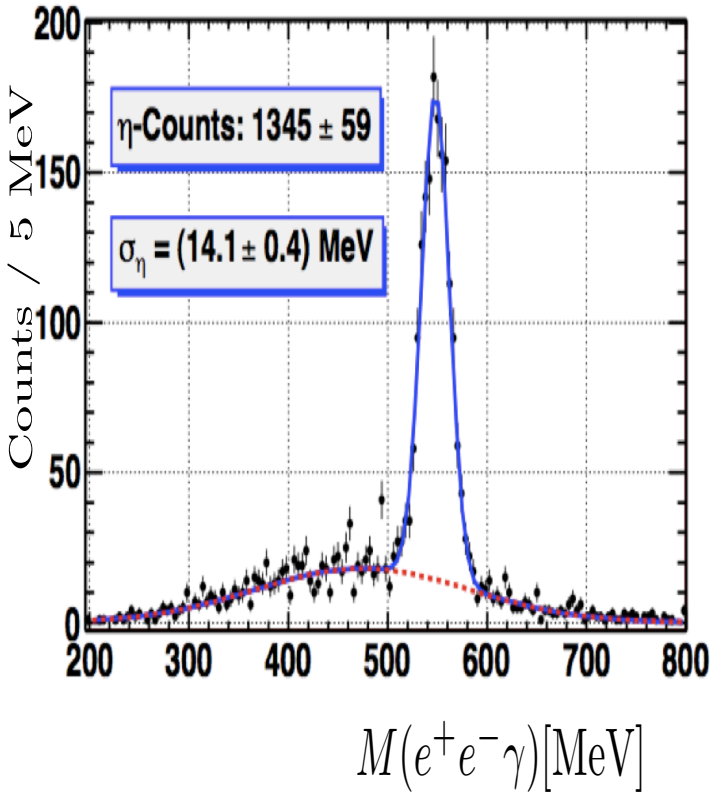
This experiment's $p(\gamma, pe^+e^-\gamma)$ π^0 events



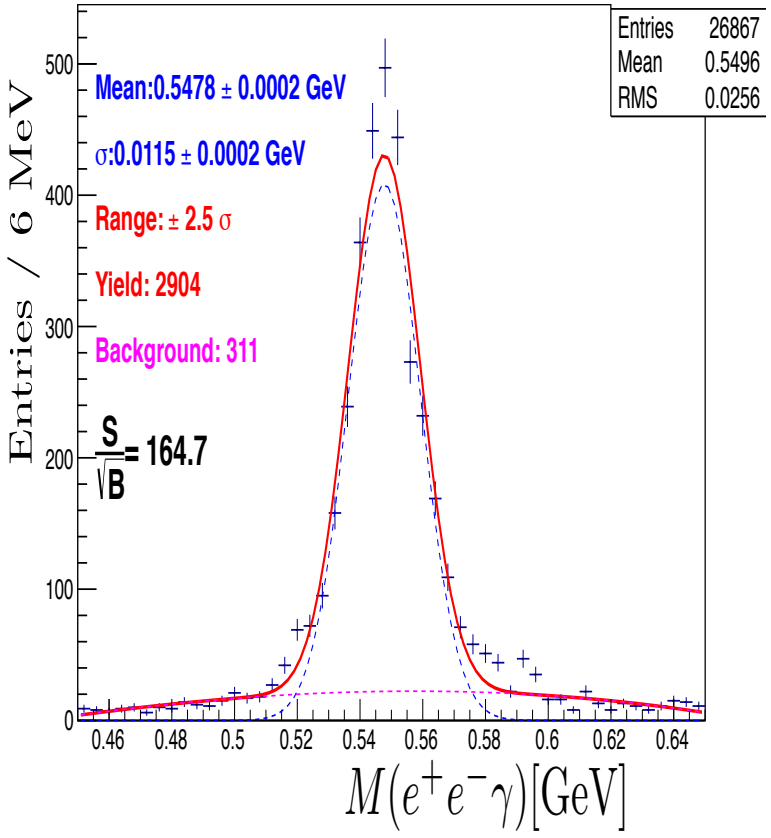
Comparison of FNAL π^0 Dalitz decay spectrum (left), to the CLAS G12 π^0 Dalitz decay spectrum (right)

η Dalitz Decay Statistics

TAPS η events

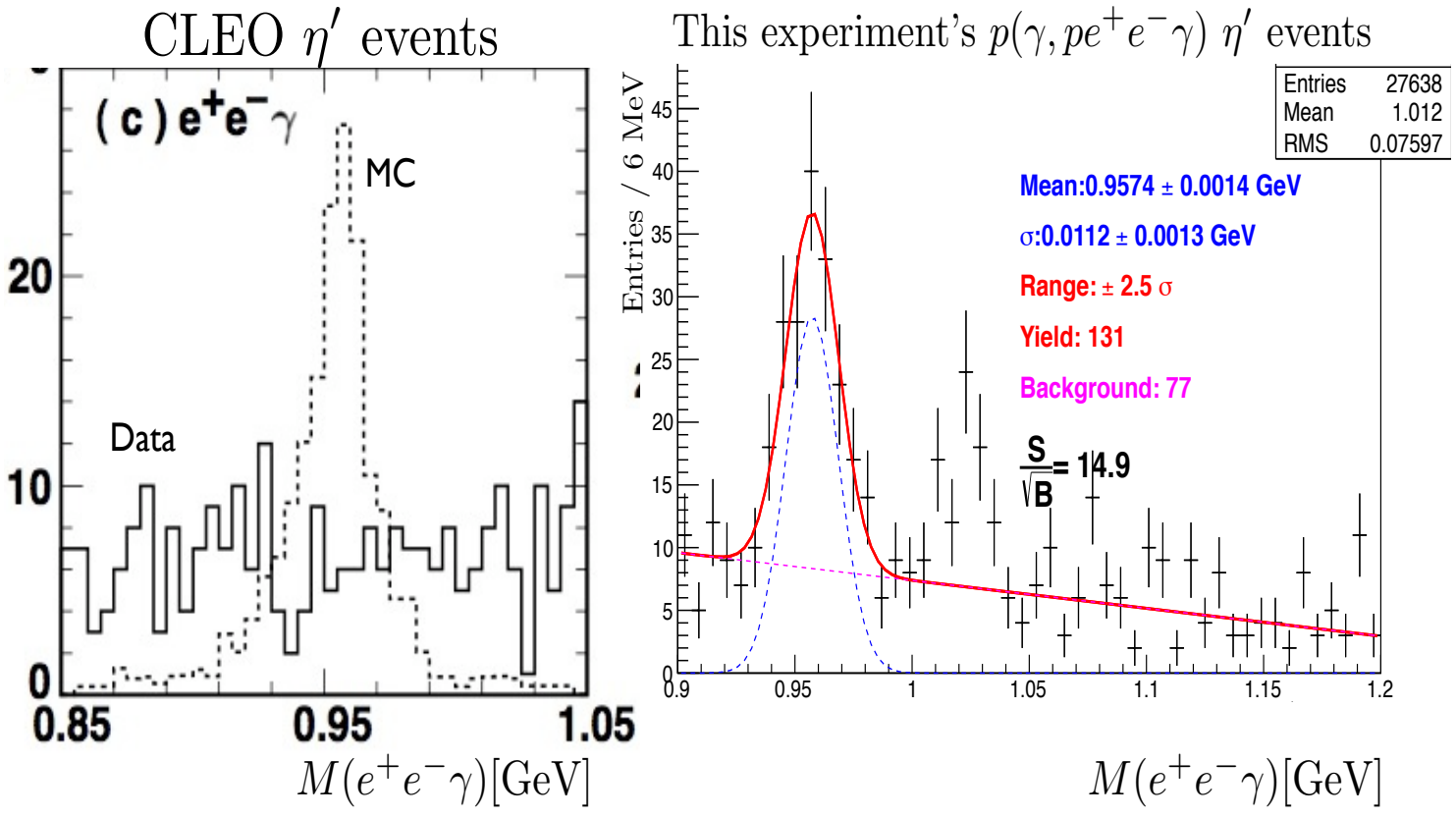


This experiment's $p(\gamma, pe^+e^-\gamma)$ η events



Comparison of TAPS η Dalitz decay spectrum (left), to the CLAS G12 η Dalitz decay spectrum (right)

η' Dalitz Decay Statistics



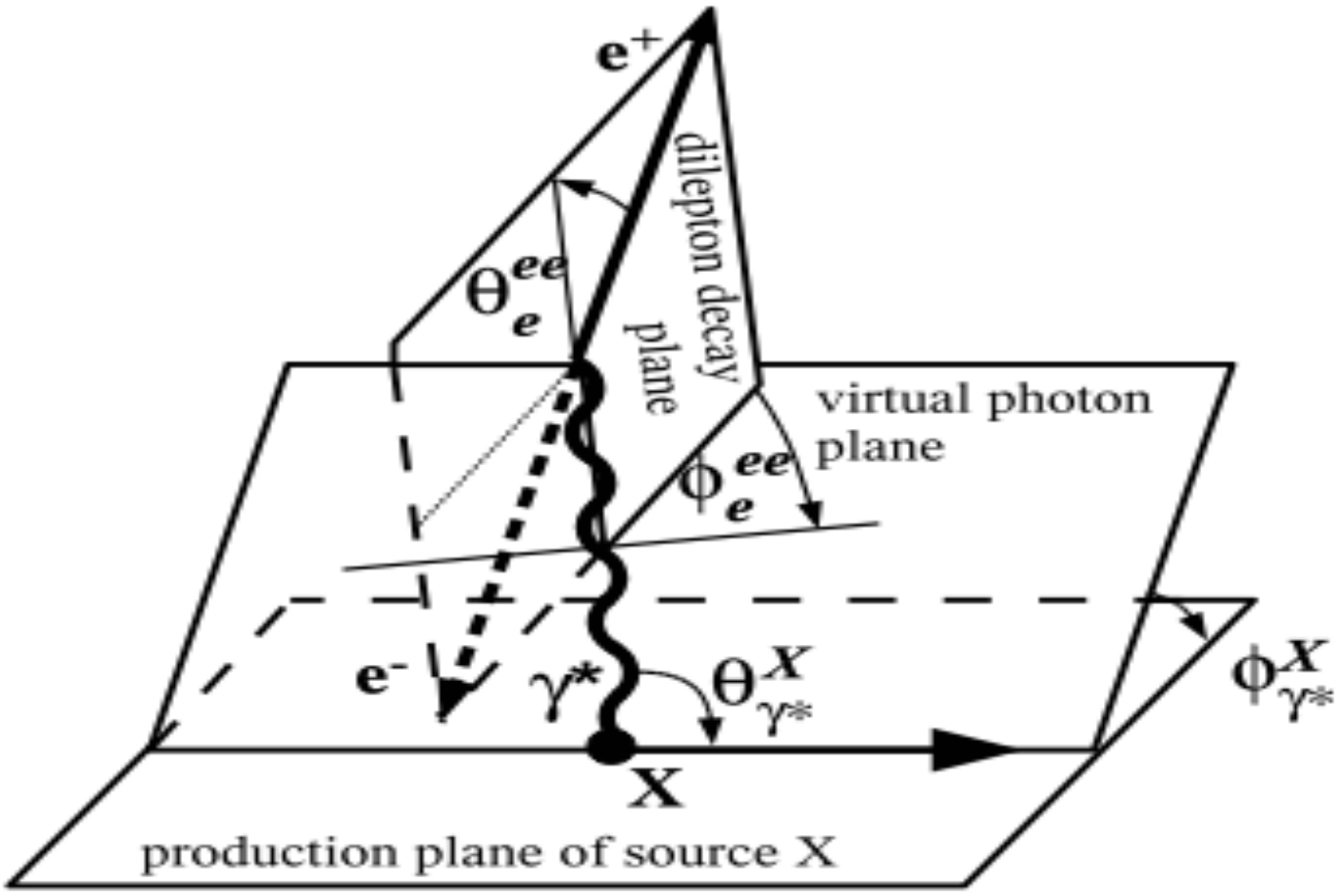
CLEO search of η'Dalitz decay (left),

First observation of η'Dalitz decay from

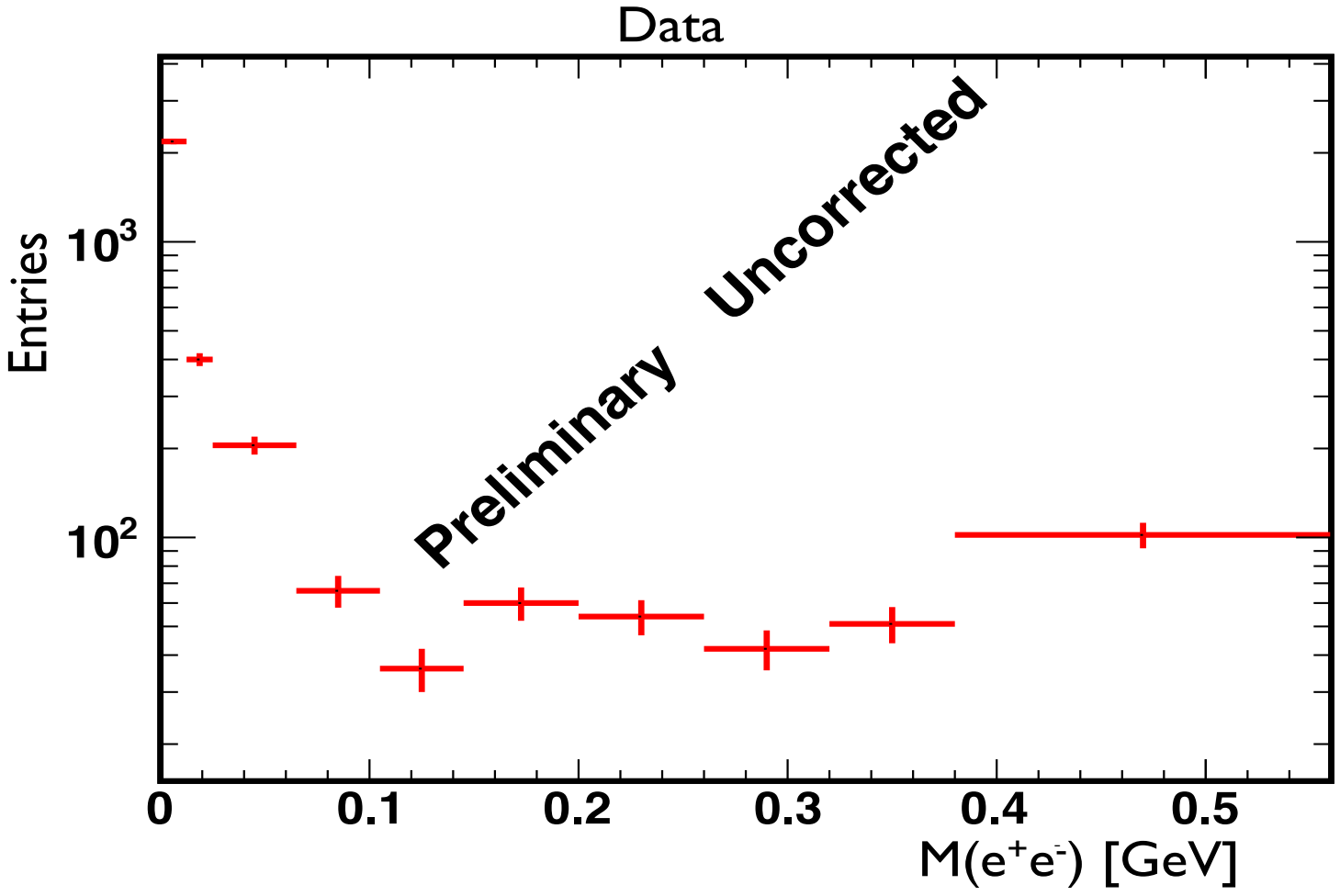
CLAS G12 experiment (right)

Simulation

- Acceptance is complete due to PLUTO event simulator, which I implemented for CLAS for Dalitz decays
  - Generates Dalitz spectrum using conserving production angles

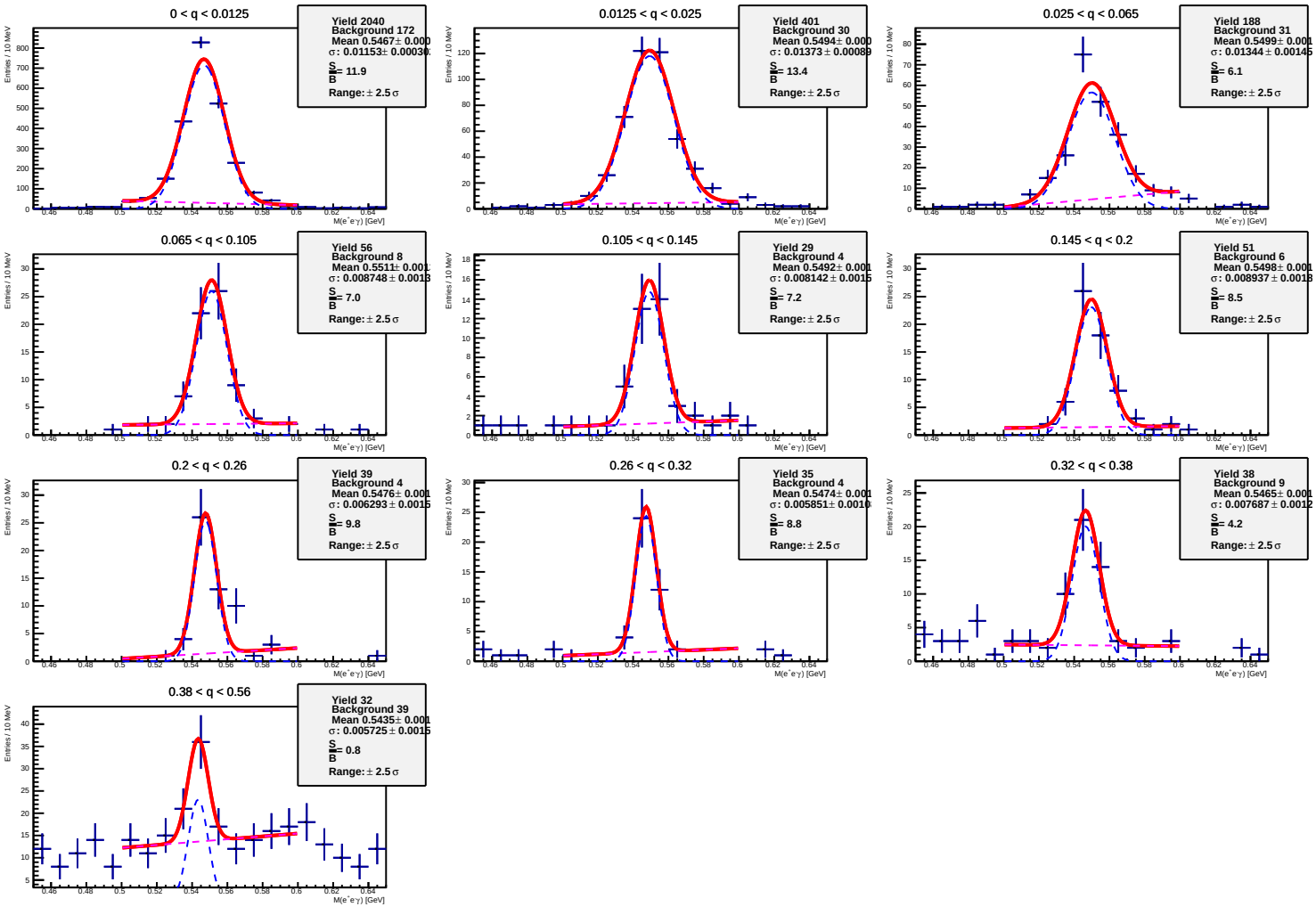


Results



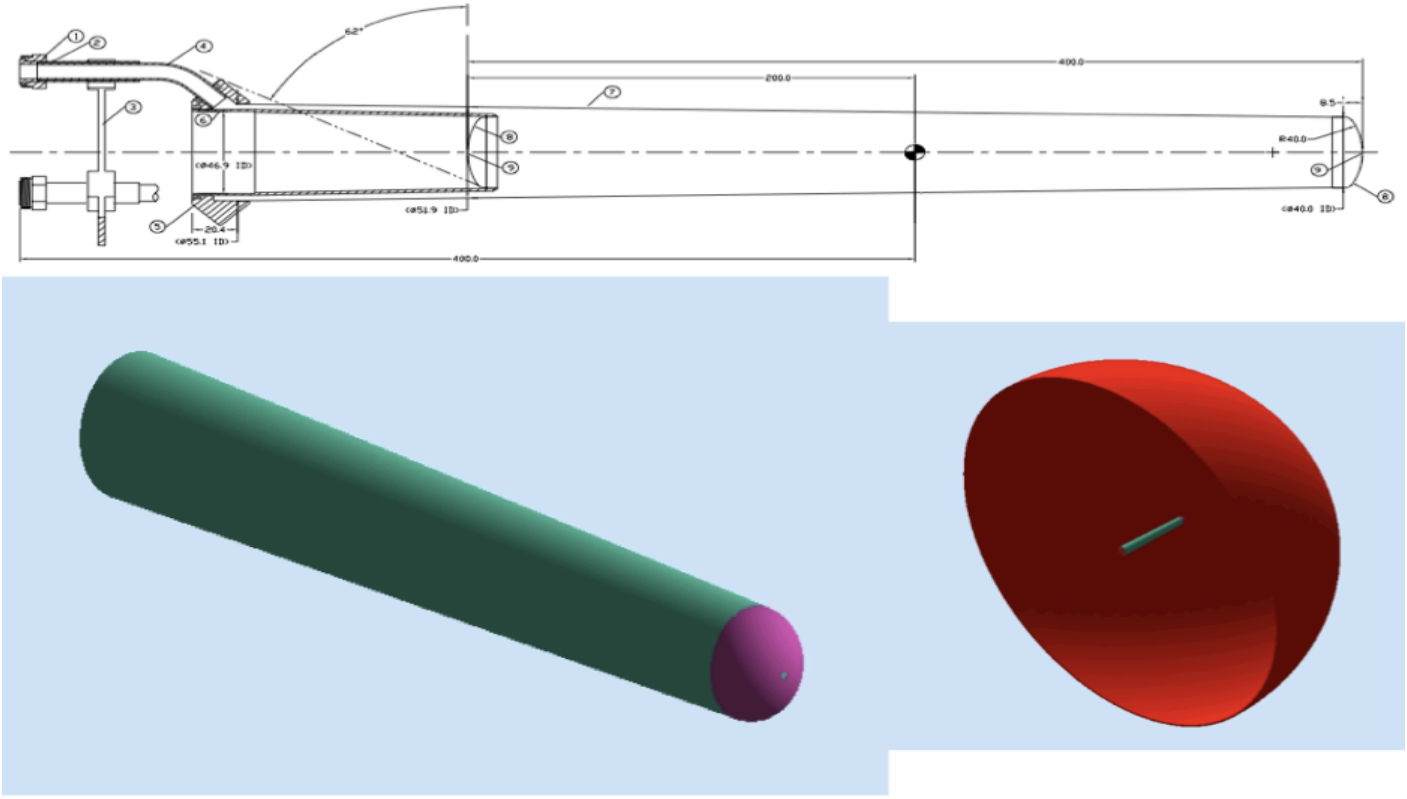
Problem: Anomalous point at $q^2 \sim 0$

Results


0 < q < 0.0125
Yield 2040
Background 172
Mean 0.5467± 0.000
σ: 0.01153± 0.00030
S/B = 11.9
Range: ± 2.5 σ
0.0125 < q < 0.025
Yield 401
Background 30
Mean 0.5494± 0.000
σ: 0.01373 ± 0.00089
S/B = 13.4
Range: ± 2.5 σ
0.025 < q < 0.065
Yield 188
Background 31
Mean 0.5499± 0.001
σ: 0.01344 ± 0.00145
S/B = 6.1
Range: ± 2.5 σ
0.065 < q < 0.105
Yield 56
Background 8
Mean 0.5511± 0.001
σ: 0.008748 ± 0.0013
S/B = 7.0
Range: ± 2.5 σ
0.105 < q < 0.145
Yield 29
Background 4
Mean 0.5492± 0.001
σ: 0.008142 ± 0.0015
S/B = 7.2
Range: ± 2.5 σ
0.145 < q < 0.2
Yield 51
Background 6
Mean 0.5498± 0.001
σ: 0.008937 ± 0.0013
S/B = 8.5
Range: ± 2.5 σ
0.2 < q < 0.26
Yield 39
Background 4
Mean 0.5476± 0.001
σ: 0.006293 ± 0.0015
S/B = 9.8
Range: ± 2.5 σ
0.26 < q < 0.32
Yield 35
Background 4
Mean 0.5474± 0.001
σ: 0.005851± 0.0010
S/B = 8.8
Range: ± 2.5 σ
0.32 < q < 0.38
Yield 38
Background 9
Mean 0.5465± 0.001
σ: 0.007687 ± 0.0012
S/B = 4.2
Range: ± 2.5 σ
0.38 < q < 0.56
Yield 32
Background 39
Mean 0.5435± 0.001
σ: 0.005725 ± 0.0015
S/B = 0.8
Range: ± 2.5 σ
Entries / 10 MeV
M(e⁺e⁻γ) [GeV]

Background @ $q^2 \sim 0$

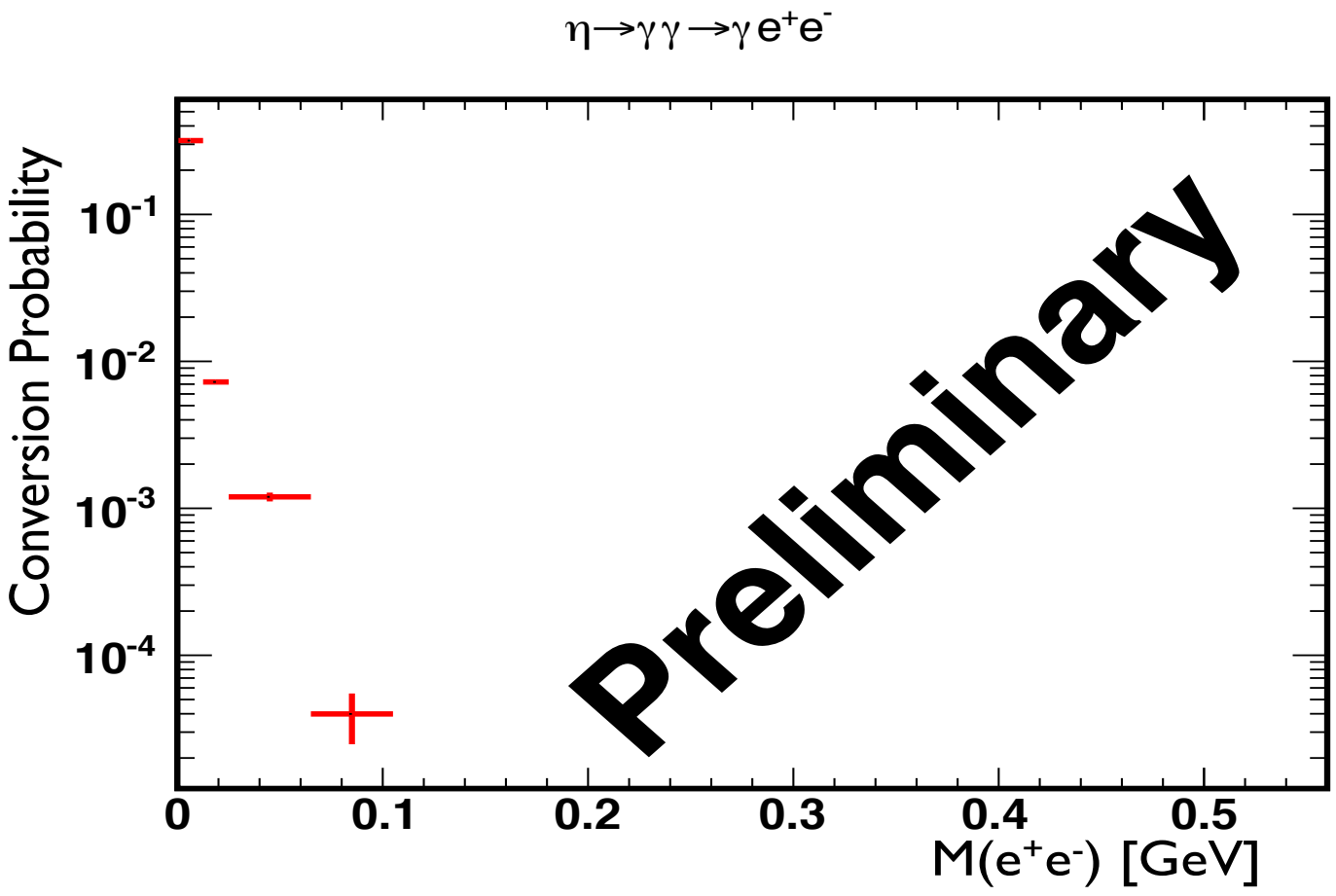
- Background due to $\eta \to \gamma\gamma$ and $\gamma \to e^+e^-$ in the target
- Solution simulate this process using GEMC, a GEANT4 based simulation



G12 target schematic (top); GEMC G12 target reconstruction (bottom)

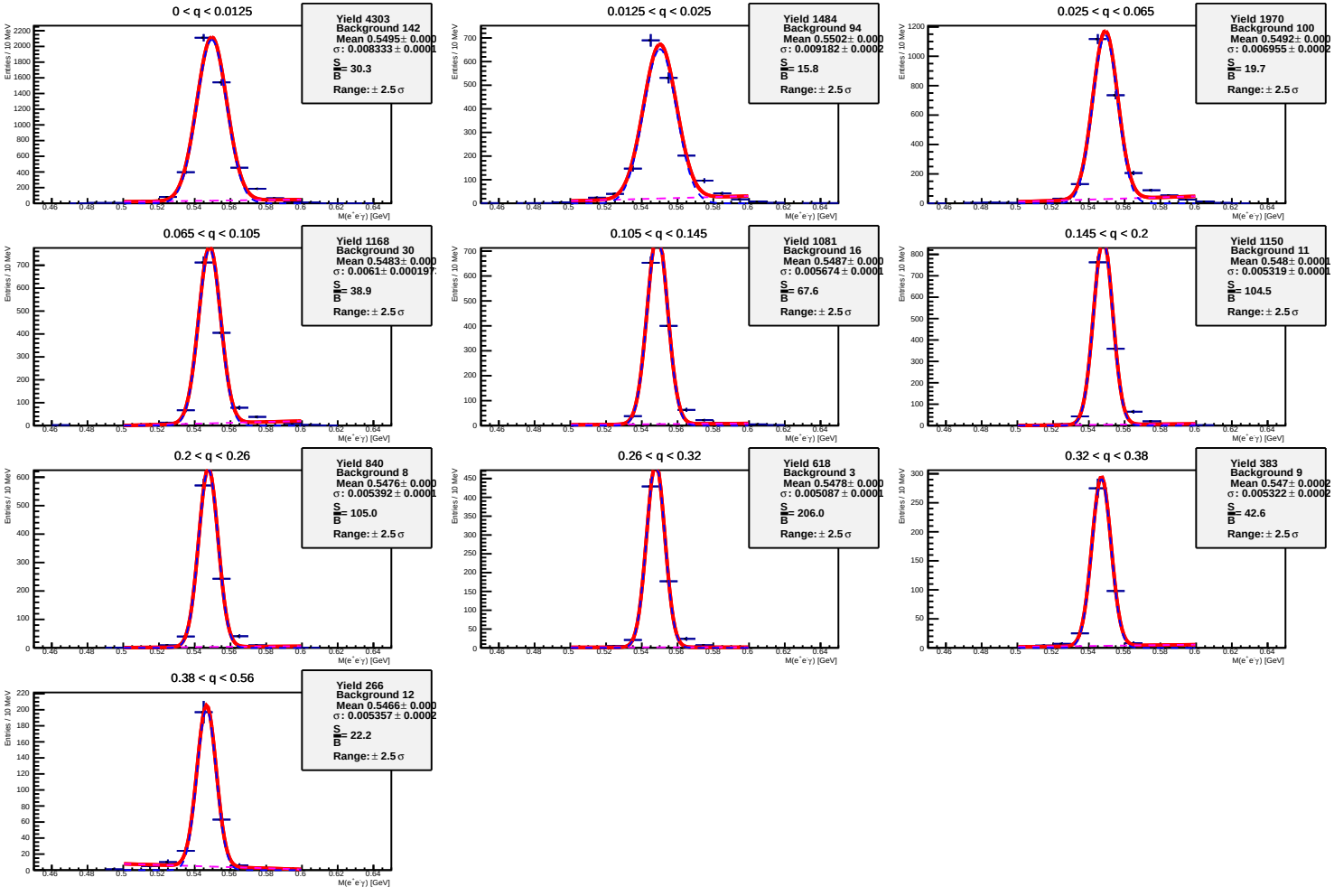
GEMC Simulation

- Used PLUTO++ to simulate $10^7 \eta \rightarrow \gamma\gamma$ events
- Smeared γ vertex to be uniformly distributed within GEMC target

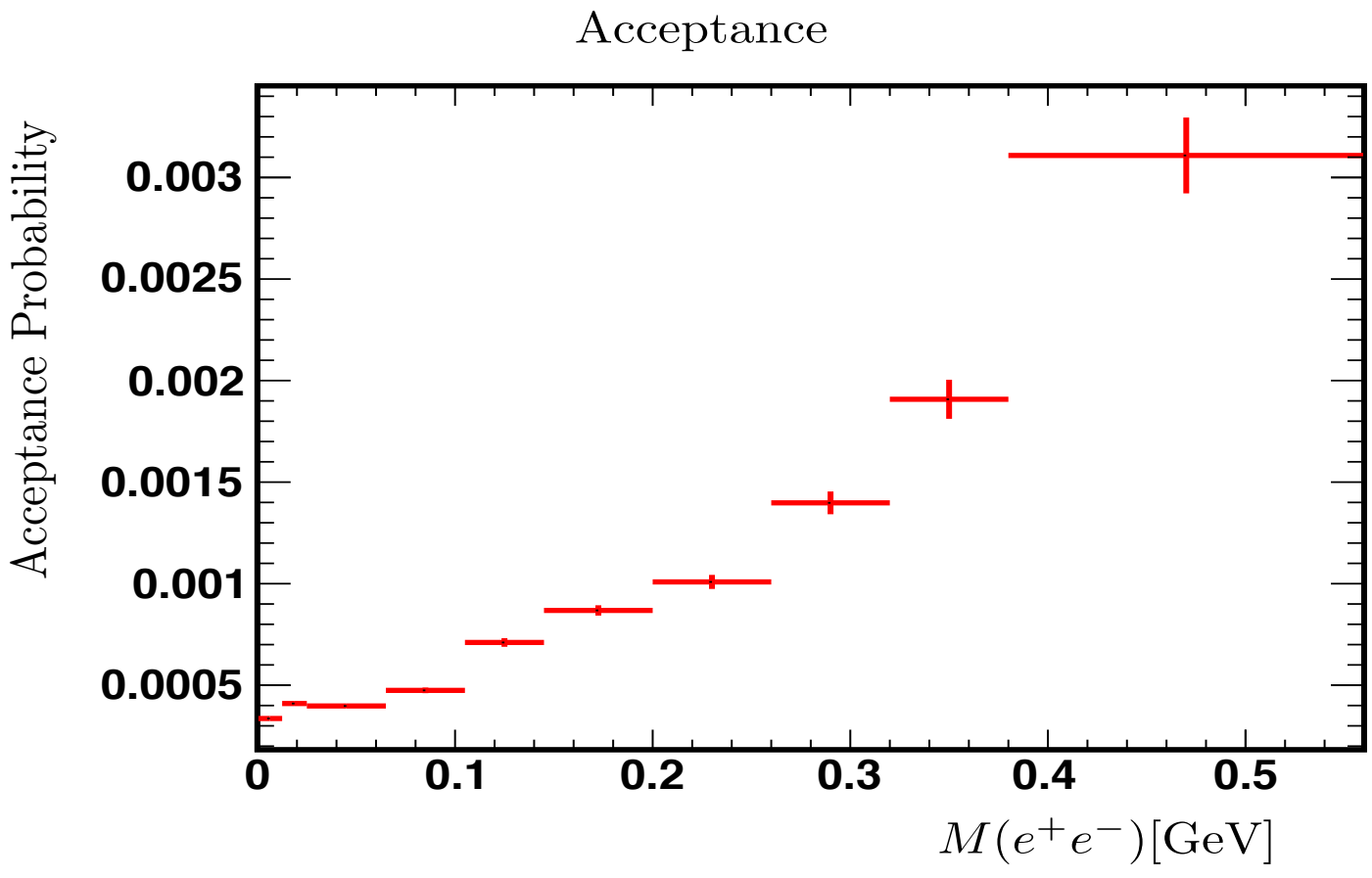


Acceptance

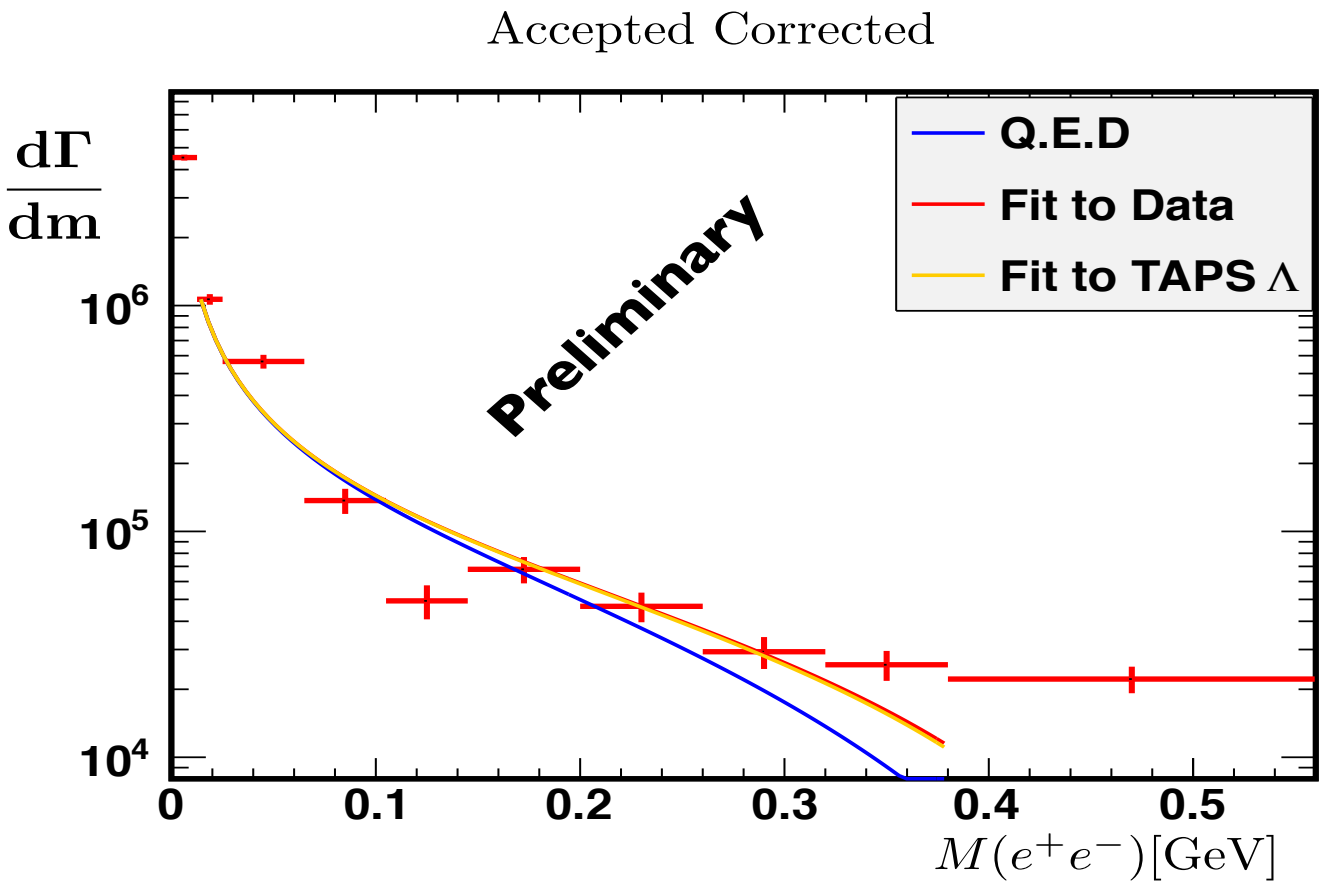
- Used PLUTO++ to simulate $50 \cdot 10^6$ $\eta \to e^+e^-\gamma$ Dalitz events
- Used same cuts and binning as data



Acceptance

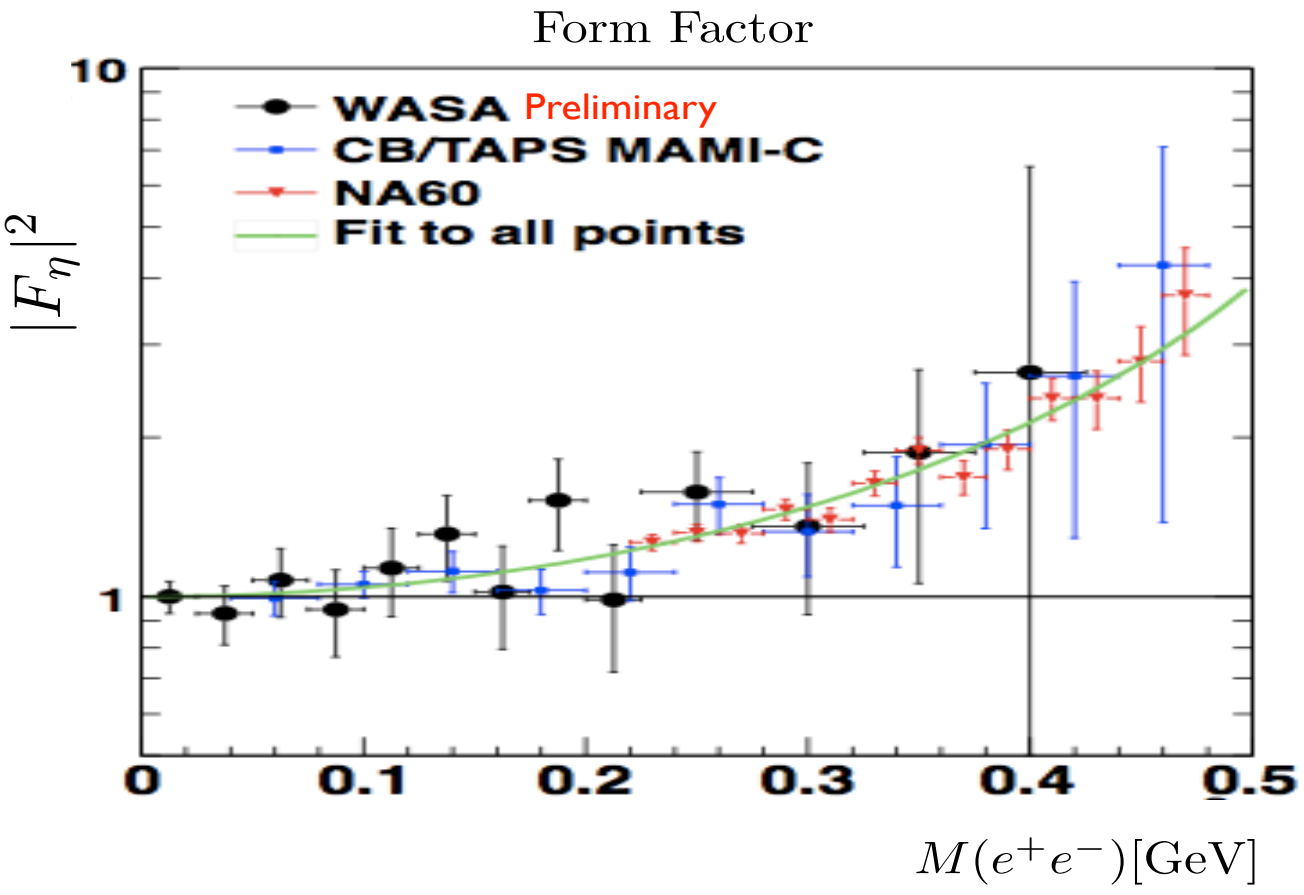

Acceptance
Acceptance Probability
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0.1
0.2
0.3
0.4
0.5
$M(e^+e^-)$[GeV]

Corrected Eta Dalitz Spectrum



- Anomalous points in bins 4 & 5
- Currently studying causes of these anomalies

What we will to contribute to



- Hope to update current picture with better error bars

Conclusion

- Works in Progress
  - Study anomalous points in data spectrum
  - Investigating acceptance corrections
- Invariant mass of $\mathrm{e}^+\mathrm{e}^-\gamma$ exceeds worlds statistics in $\mathrm{P}(\eta, \eta')$
- Dalitz decay of η' seen for first time
- A significant contribution will be made from this work