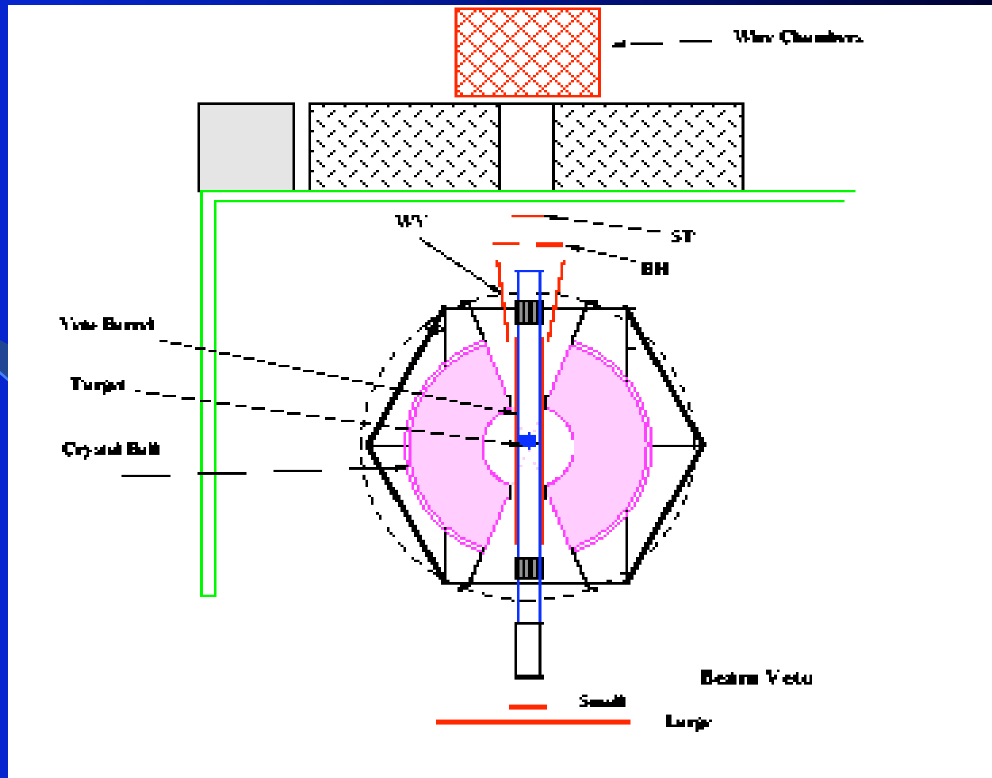
Partial Width of the □□ □^{0}□□ Decay

Crystal Ball Collaboration



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Frascati, May 21, 2003

Outline

- General Comments on Symmetry
- Chiral Symmetry and Perturbation
- The □ meson
- The Crystal Ball at Brookhaven
- Analysis Procedure
  - Cuts
  - Binned Maximum Likelihood Method
- Partial Width Result

Symmetry and Conservation Laws

$$i\hbar\frac{d\psi}{dt} = H\psi, [H, F] = 0 \Rightarrow \frac{d<F>}{dt} = 0$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = 0, \dot{p} - \frac{\partial L}{\partial q} = 0$$

- Translation: linear momentum
- Rotation: angular momentum
- Isotopic spin: nuclear force
- Space-time: speed of light

Symmetry Breaking/Hiding

- Rotation, Reflection
- Electro-weak force: **SU(2)xU(1)**
- Strong nuclear force: **SU(3)xSU(2)xU(1)**
- Supersymmetry

- Mass generation
- True vacuum (ground state)
- Symmetry is still there

Chiral Symmetry

- Not incomprehensible, nor a theorist's theory, nor just used for superstrings, nor just another model.
- Direct consequence of QCD.
- Rigorous calculations at low energy region.
- At low energies, processes are constrained by symmetry.
- Symmetry leads to non-trivial dynamics and predictions.
- Phenomenological input.

So, what is it?

- Pretend u, d, s quarks are massless.
- Each has a L- and R-handed helicity.
- QCD does not flip the helicity, so the symmetry is $SU(3)_L \times SU(3)_R$.
- Massive quarks: symmetry breaks; look at the field ψ=(u d s) $SU(3)_{L+R=V}$

$$\square_L = \frac{1}{2}\left[1 + \gamma_5\right];\ \square_R = \frac{1}{2}\left[1 - \gamma_5\right]$$

$$\psi_L = \square_L \psi;\ \psi_R = \square_R \psi;\ \psi = \psi_L + \psi_R$$

ψ_L and ψ_R have left- and right-handed chirality!

Noether says…

- 16 conserved currents and charges:
  - 8 vector currents - $SU(3)_V$
  - 8 new axial charges
  - Particles appear in multiplets
- $H|P> = E_p|P>$, single particle state:

$$H\left(e^{iQ_5^j}|P\rangle\right) = e^{iQ_5^j} H|P\rangle = E_p\left(e^{iQ_5^j}|P\rangle\right)$$

$$\left[H, Q_5^j\right] = 0$$

- Explicit (mass difference), spontaneous (dynamics) symmetry breaking.

Chiral Perturbation Theory (□PT)

- Small deviations: we can perturbe!
- Write L_{eff} consistent with **□S**.
- Calculate all possible diagrams.
- Renormalize all L_{eff} parameters from experiment.
- Apply at low and medium energies.
- Use matrix field U, with **U□ LUR**$^{+}$ (retains □S).
- L_{eff} has i=2,4,6,… derivatives like $\partial_{□}U\partial^{□}U^{+}$
- Perform energy expansion: $M=Aq^2+Bq^4+Cq^6$

What role does the □ play?

- The **□-meson** is a massive vacuum.
- J=Q=I=s=b=c=B=L=0, P=-1, i.e. we have transitions with no flavor change.
- Mass=547.4±0.2 MeV, □=1.2 keV
- Physical **□-meson** state:octet-singlet mixing, with □= -19.5^{0}.

$$|\square\rangle = [\cos\square]\square_8 \,\square\, [\sin\square]\square_1 = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} \,\square\, s\bar{s}\right)$$

Large no. of rare □ decays

- 3□, 3□^{0}□, 2□^{0}□: test of C-invariance
- 4□^{0}, 2□^{0}: test of CP-invariance
- 3□^{0}: slope; chiral perturbation test
- □^{0}□□: chiral perturbation test:
  - Third order in the momentum expansion for the □^{0}□□ decay

The interest in the □□ □^{0}□□ Decay

- It is a window on high order □PT effects.
  - Leading ***0(p^2)*** term and ***0(p^4)*** tree contribution absent: □does not couple directly to □^{0}, □^{0}.
  - ***0(p^4)*** and ***0(p^6)*** loops are suppressed by heavy intermediate states or G-parity.
  - □ Main ***0(p^6)*** contribution is Vector Meson Exchange.
- □ □□ □^{0}□□needed to understand semi-leptonic □□ □$^0 l^+ l^-$ decay; forbidden as a single-photon process by C-parity.
- □ □□ □^{0}□□needed to understand K^0_L□ □$^0 l^+ l^-$; direct signal of CP-violation.

The □ decay channels

Total neutral modes	**72.0±0.5%**
□□ □□	39.43±0.26%
□□ 3□^{0}	32.51±0.29%
□□ □^{0}□□	**(7.2±1.4)x10^{-4}**
Total charged modes	**28.0±0.5%**
□□ □$^+$□$^□$□^{0}	22.6±0.4%
□□ □$^+$□$^□$□	4.68±0.11%
Etc.	

The Status Quo of $\eta \to \pi^0\gamma\gamma$

- **Experimental:**
  - GAMS2000: (0.84±0.18) eV
- **Theoretical:**
  - VMD model: (0.30 ±0.15) eV
  - χPT theory: (0.42 ±0.20) eV
  - C-odd axial vectors: (0.47 ±0.20) eV
  - Quark boxes: (0.70 ±0.12) eV

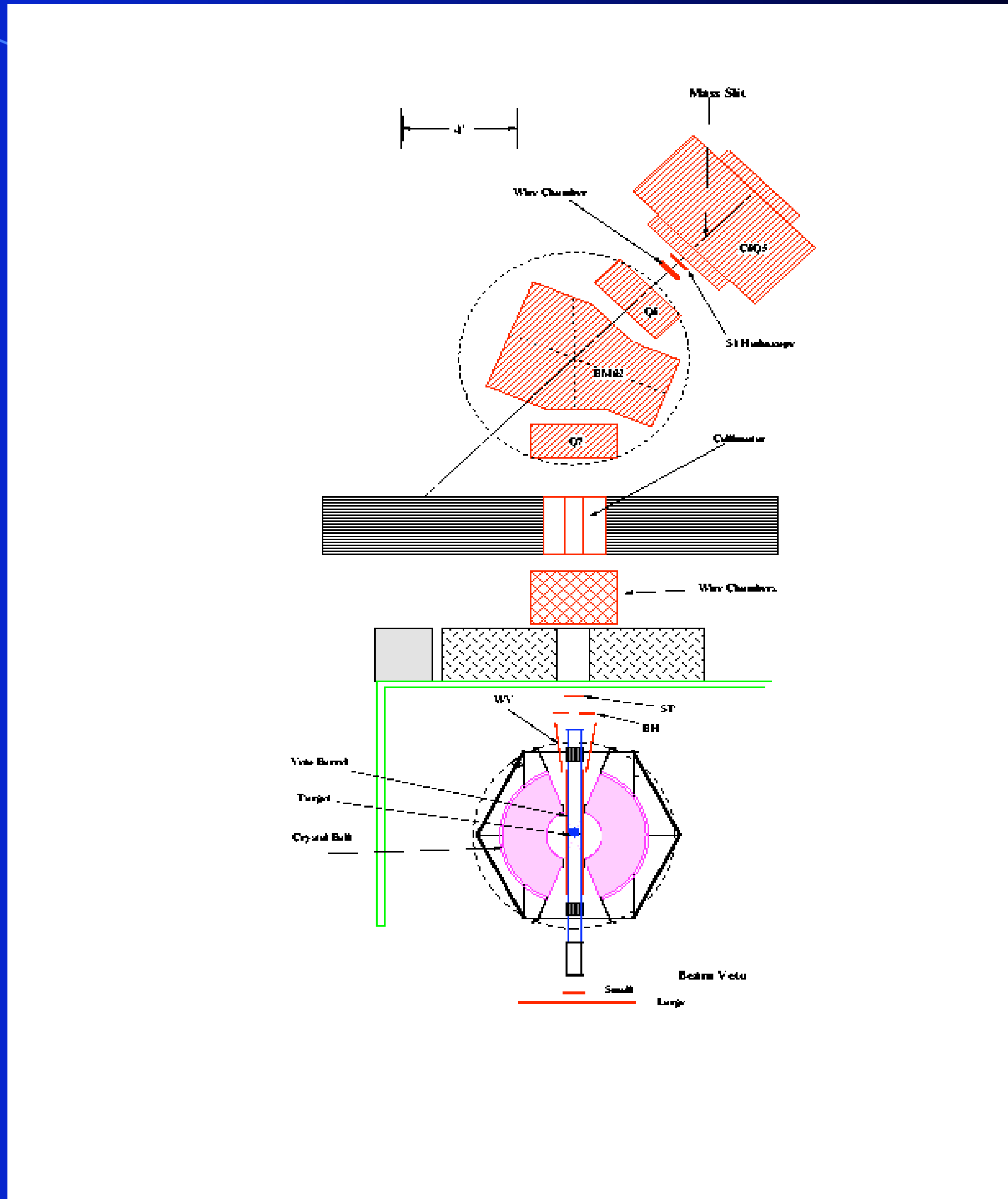
Measure the partial width with confidence!

Previous Measurements

	GAMS2000 (Serpukov)	SND (Novosibirsk)
Reference	Alde et al. Z. Phys. **C25** (1984) 225	Achasov et al., NP **B600** (2001) 3.
Production Reaction	$\square^{\square}$p$\square$ $\square$n @ 30 GeV/c	$e^{+}e^{\square}$$\square$ $\square^{0}$$\square$ $\square\square$@ 1044 MeV Collider
Detector	1538 38x38mm^2 Pb-Glass counters @12m	1630 Na(Tl) crystals; 90% of 4$\square$
$\square$ Sample	600,000 produced	258,000 detected
Complications	Misidentification of $\square\square$ 3$\square^{0}$ due to overlaps in the EM shower	Extra $\square$from primary $\square\square$ $\square^{0}$$\square\square$reaction is not unique
Result	$\square$=(0.84±0.17) eV	$\square$< 0.99 eV

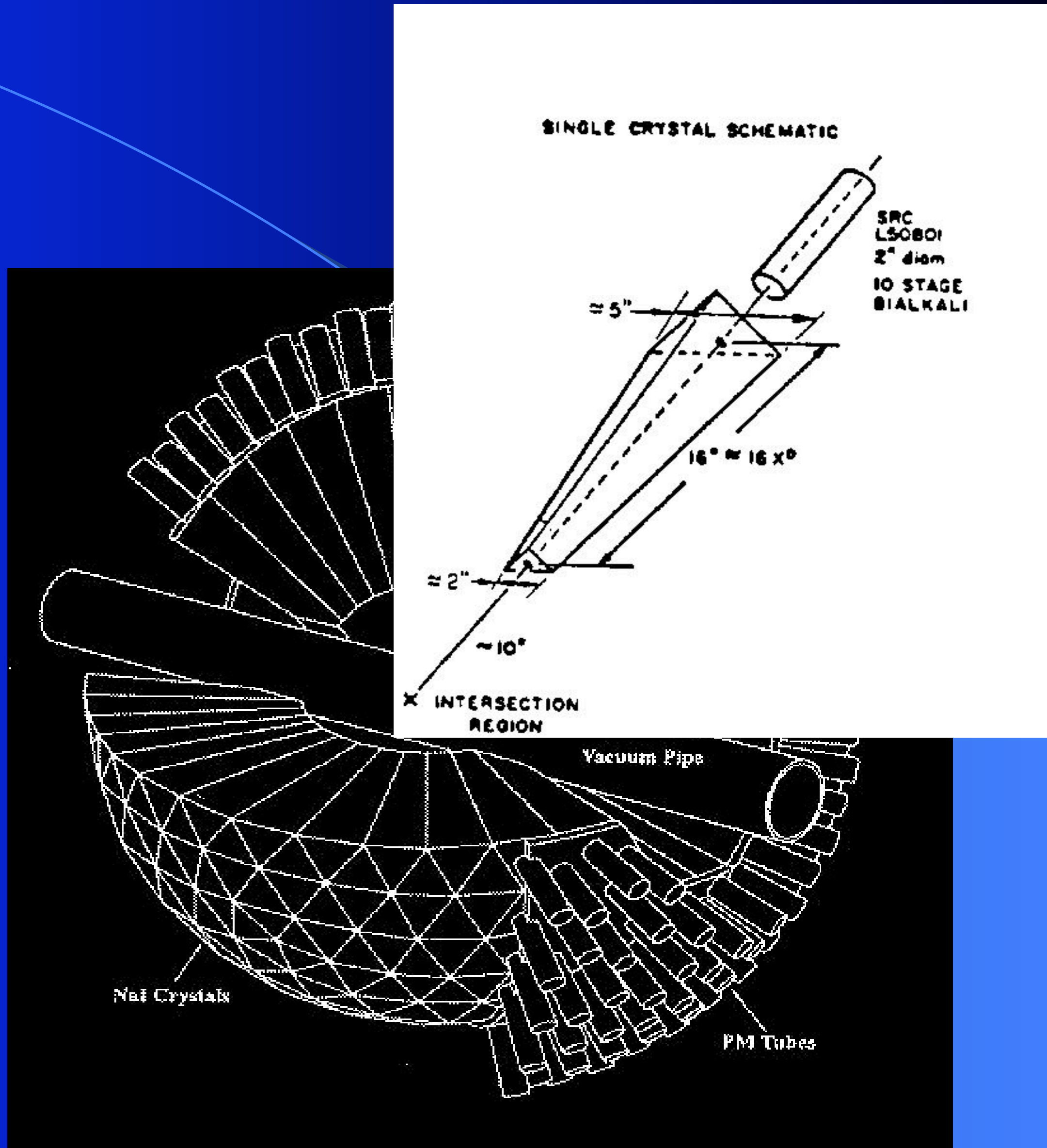
The Crystal Ball at BNL

- C6 beam line of AGS @ BNL
- **$\pi^- p \to \eta n$** reaction
- 720 MeV/c
- LH_2 target
- 3 x 10^7 η mesons produced
- Crystal Ball: NaI crystals



The Detector

- SLAC/DESY
- 672 optically isolated NaI crystals with PMTs at rear
- 2 hemispheres
- Beam pipe
- Trigger: total energy in ball > 400 MeV
- Veto Barrel (neutrals)
- Enclosed in dry room



Background: 4-Cluster Event Types

□□ □^{0}□□should produce 4 photon clusters in the CB

- □$^-$p□ n2□^{0}□ n4□: Initially □3000 for every □□ □^{0}□□
  - Suppressed with unique reconstruction of a single □^{0} and $m_{□□}$ > ($m_{□^0}$+4□)
- □$^-$p□ n□□ n3□^{0}□ n6□: Initially □1200 for every □□ □^{0}□□
  - 2 missing clusters turn it into a 4-cluster event

- A. Two photons escape through beam tunnel
  - Suppressed with Missing Mass=m_n and Invariant Mass=$m_□$ criteria
- B. Overlapping clusters
  - All energy is recovered so Missing Mass=m_n and Invariant Mass=$m_□$
  - 4 observed clusters reconstruct to a single □^{0} and two clusters

Background imitates □□ □^{0}□□!!

Analysis Overview

- Generate MC simulations using data dynamics to reproduce the data
- Apply likelihood analysis to achieve optimal separation between signal and background
- Subtract normalized background distributions and integrate in regions with good signal-to-noise background ratio
- Compare number of □□ $\square^0$□□events found to MC and number of □□ $3\square^0$ to arrive at:

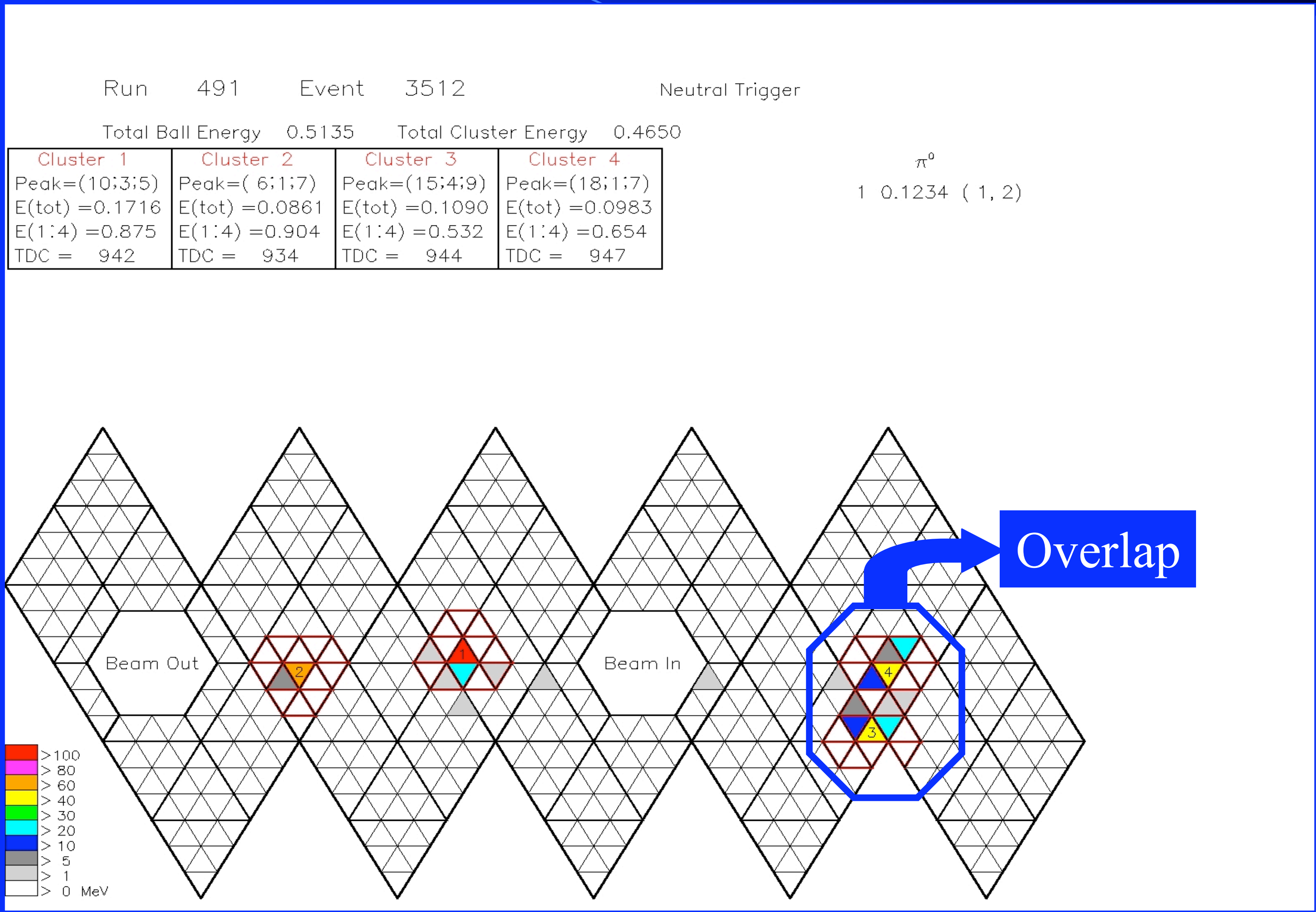
$$\frac{\square(\square\ \square\ \square^0\square\square)}{\square(\square\ \square\ 3\square^0)}$$

Get BR(□□ $\square^0$□□) through the PDG value of BR(□□ $3\square^0$)

Cluster Finding Algorithm

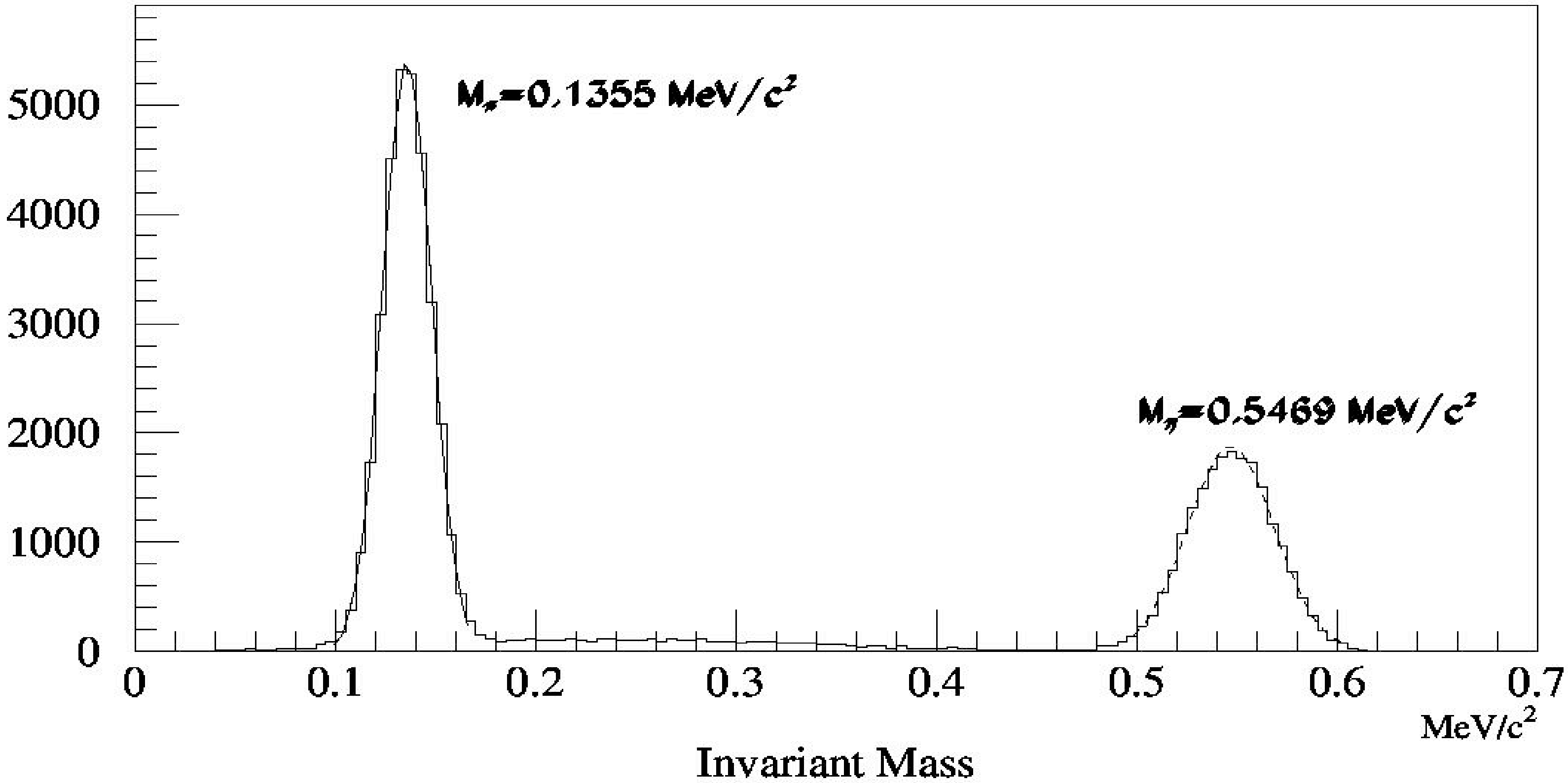
- 98% of a photon's energy is deposited in a cluster composed of a crystal and its 12 adjacent neighbors (eliminate guard crystals first)
- Crystal threshold: 2 MeV
- Cluster threshold: 20 MeV
- Identify "peak crystal" (most energetic)
- Identify cluster
- Remove all these crystals
- Iterate until all clusters have been assigned

Cluster Overlap



Calibration: p n

0



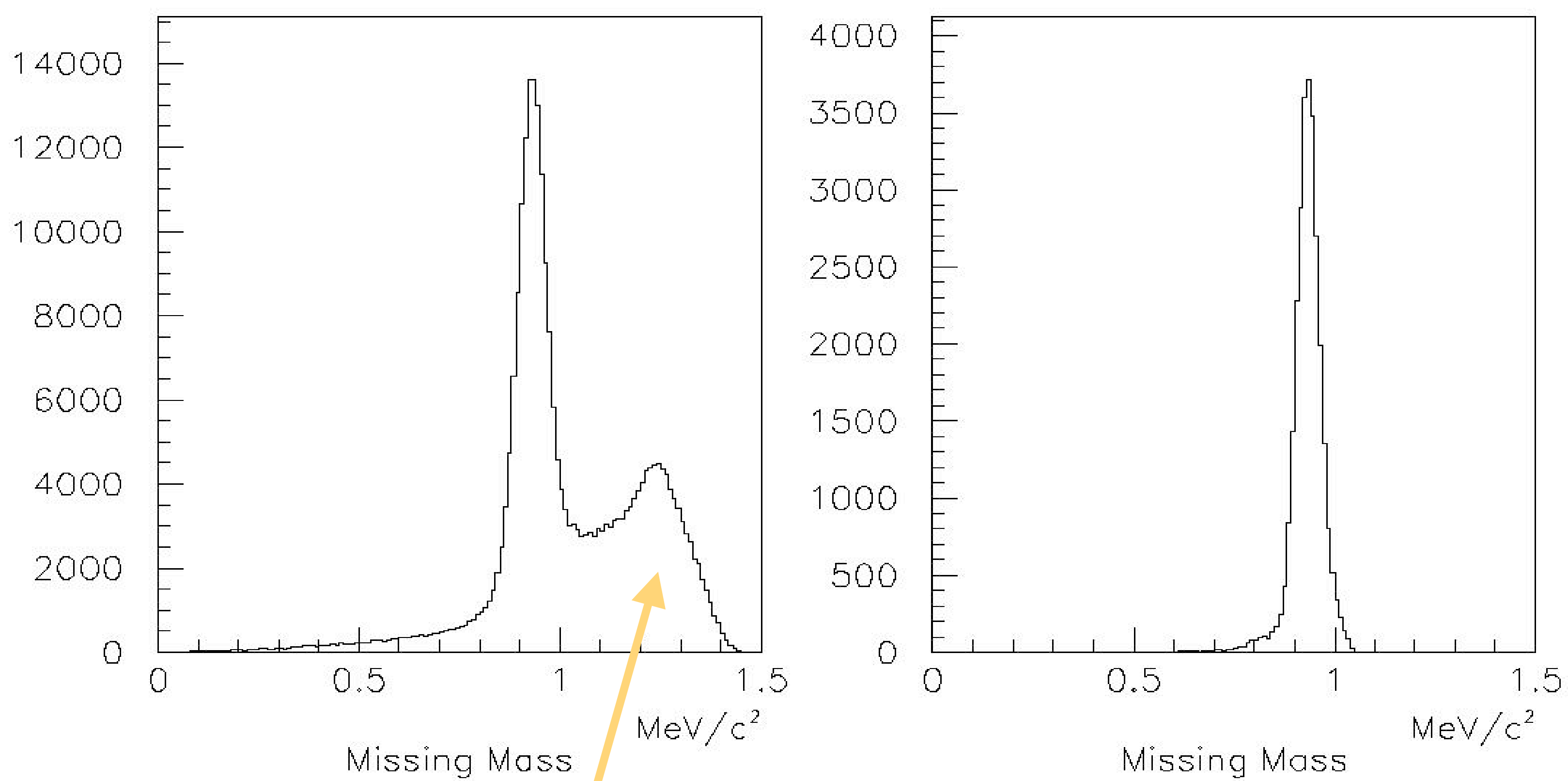
Excellent gain coefficient fitting:
Minimization to simultaneously fit both peaks

Reconstruction of Events

- Sort events based on:
  - Trigger type
  - Number of clusters
  - Missing Mass
  - Invariant Mass
  - Number of reconstructed pions

- **For this analysis:**
  - **Neutrals**
  - **Four clusters (±1, ±2)**
  - **Neutron Mass**
  - **Eta Mass**
  - **Unique π^0 (± 2σ)**

Cleanup: 2-cluster events



Missing photon

Condition: IM=m▯

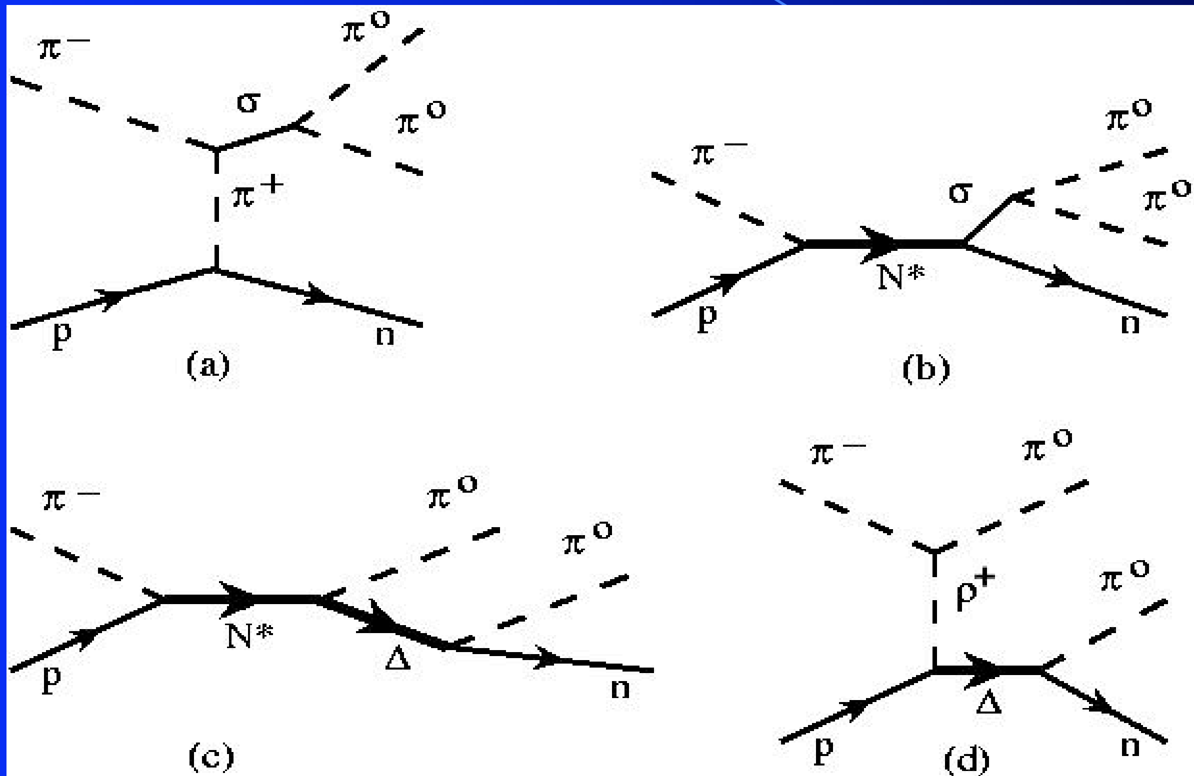
MC Generation

- Aim for agreement between MC and data:
  - Signal
  - Backgrounds
- Input:
  - Experimental distributions
  - Fundamental Physics information
- Simulate Crystal Energy Deposition
- Use the same **Analyzer** code

Physics Distribution Input

- Simulate three reactions:
  - □□p□ □n□ □^{0}□□n (Signal)
  - □□p□ □n□ 3□^{0}n (Background)
  - □□p□ 2□^{0}n (Background)
- All these contribute to 4-cluster events
- Distributions obtained from literature and our own data samples under different conditions (e.g. 6-cluster events for the □)

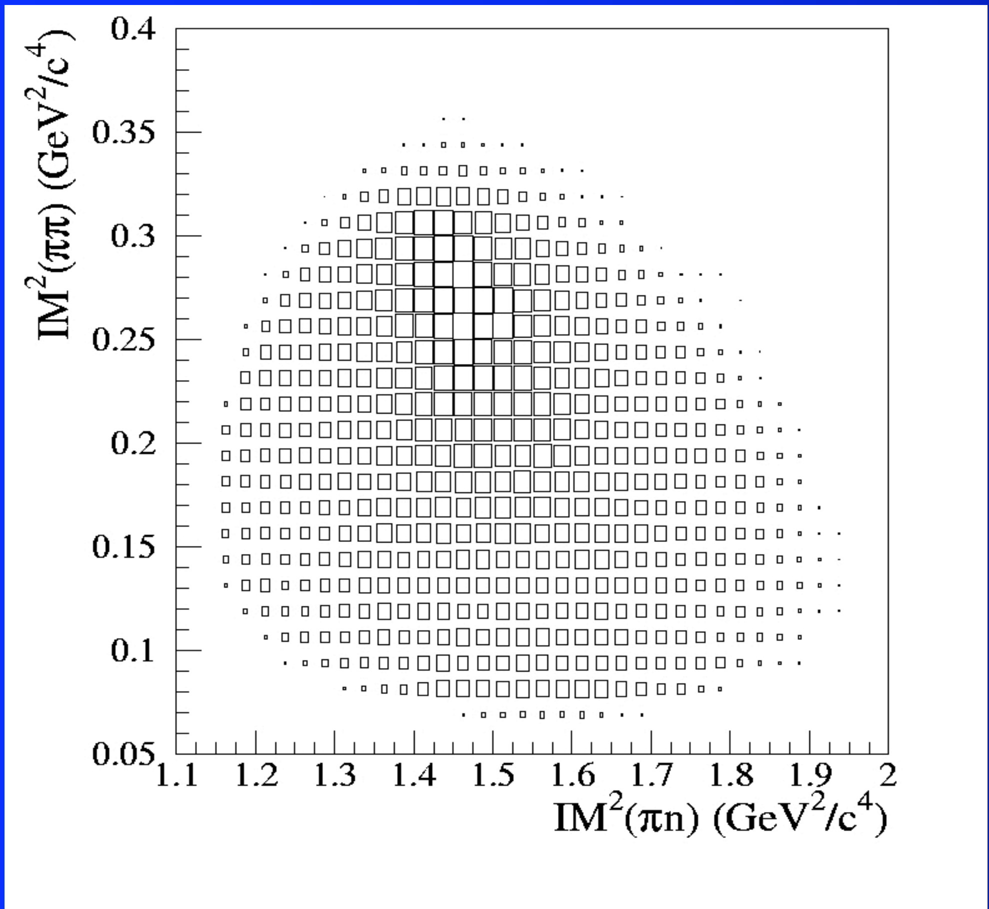
Physics channels of $\pi^- p \to 2\pi^0 n$

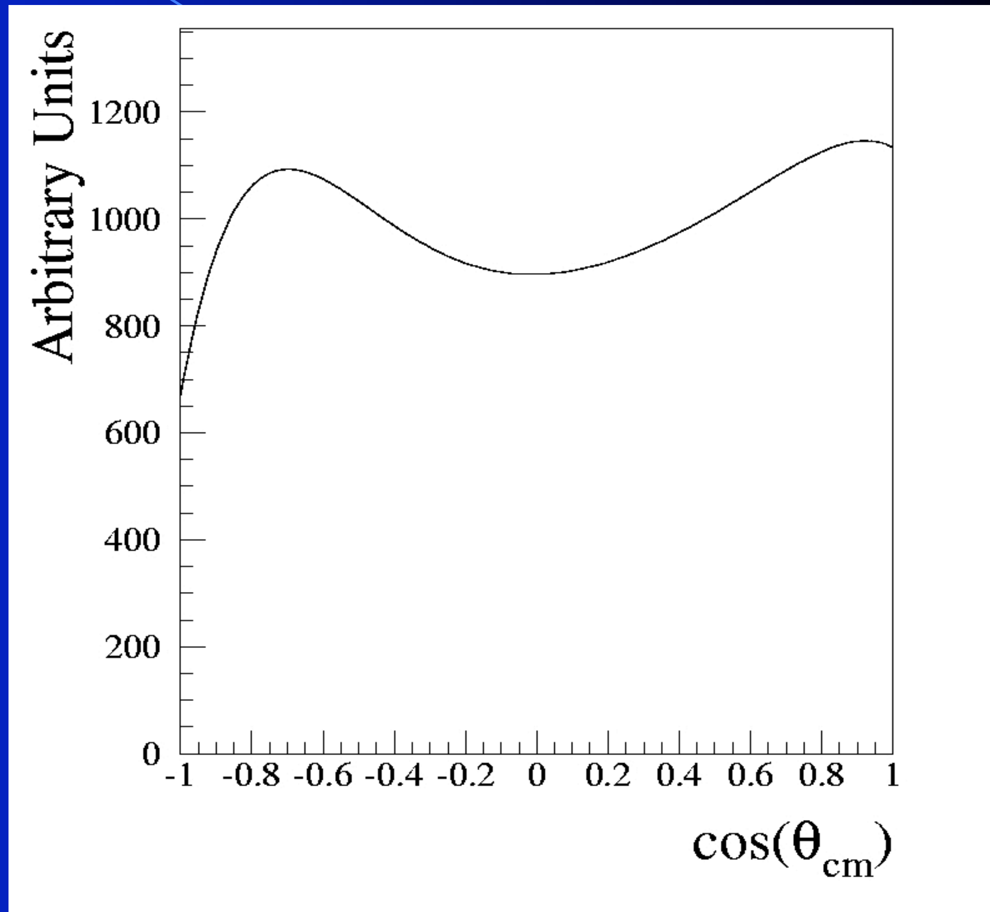


Studied in detailed by collaborators

Monte Carlo of $\gamma p \to 2\pi^0 n$ from Data

(Employ cuts: MM, $2\pi^0$s, CB threshold)

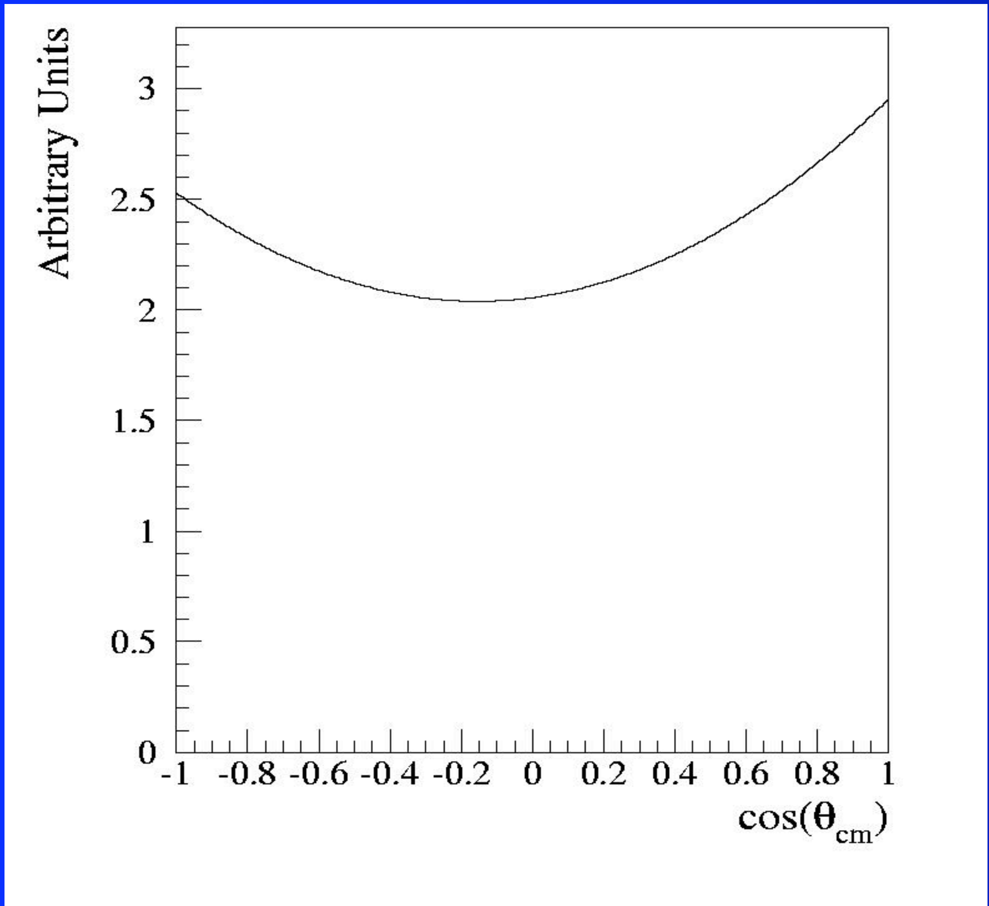


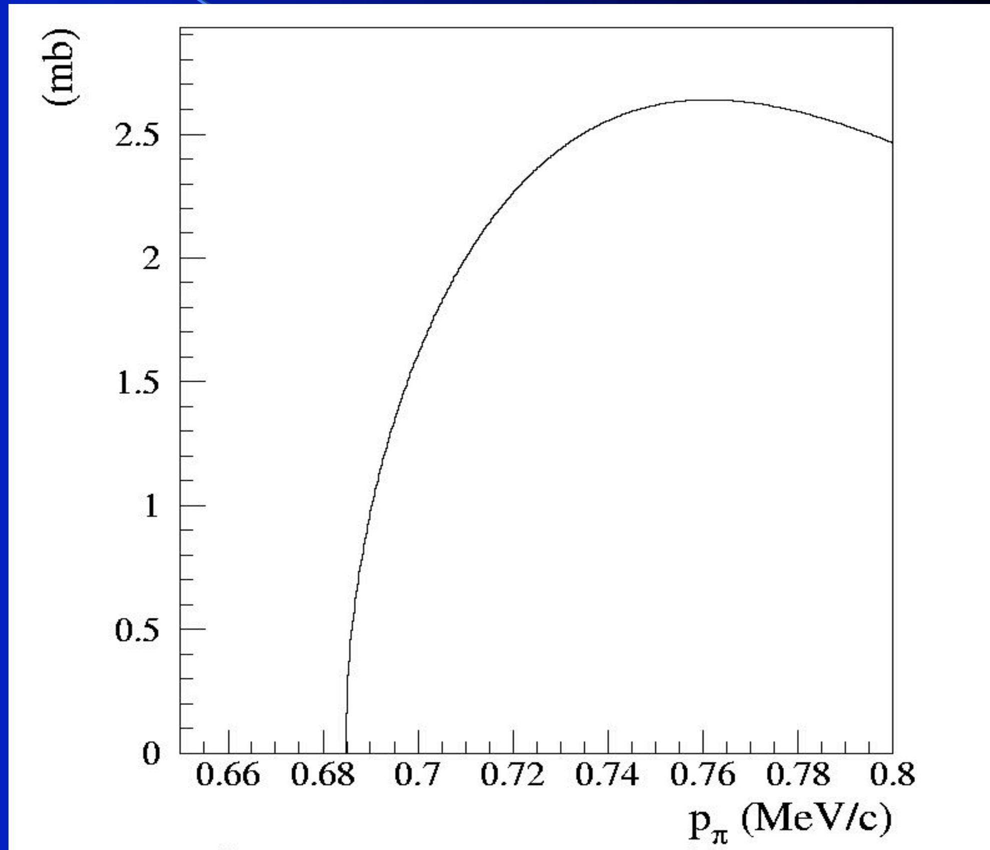


Iterative 3-D fitting: $IM_{\pi\pi}$ vs. $IM_{\pi n}$ vs. θ_{CM}

Monte Carlo for $\pi^- p \to \eta n$

(Two-body kinematics, $\eta \to 3\pi^0$)



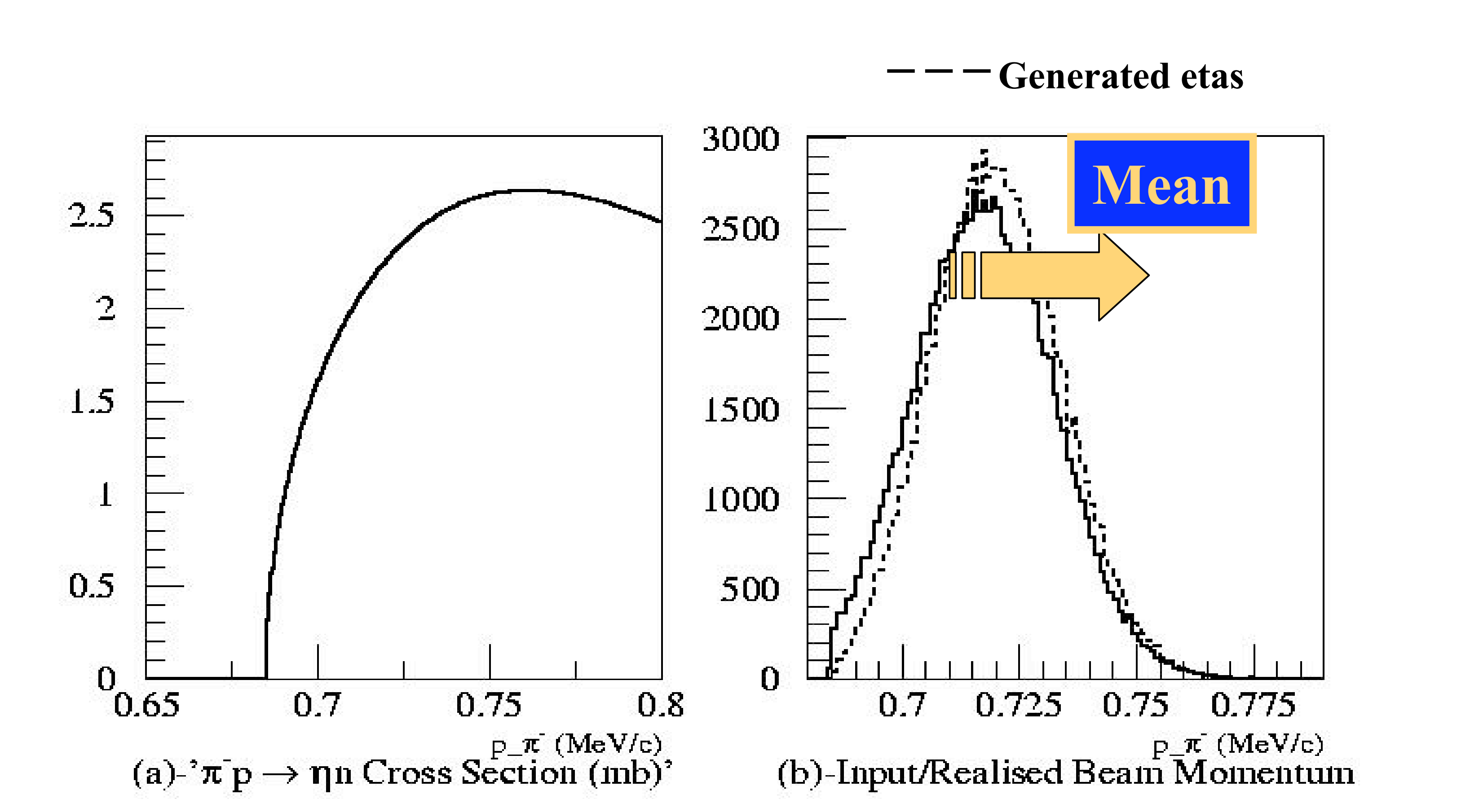


$\pi^- p \to \eta n$ Cross Section (mb)

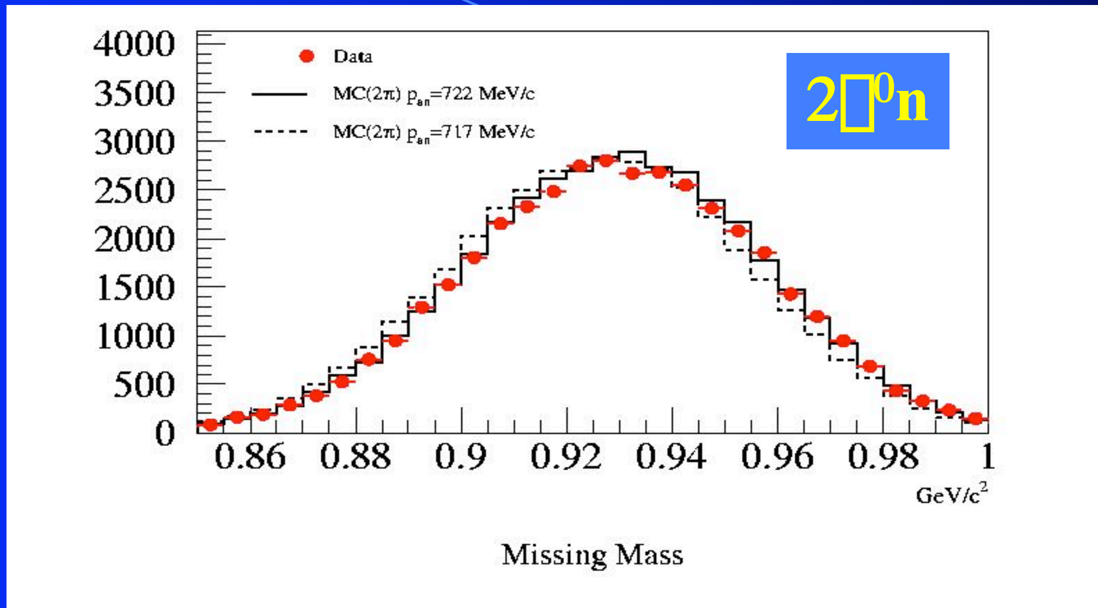
Straight forward

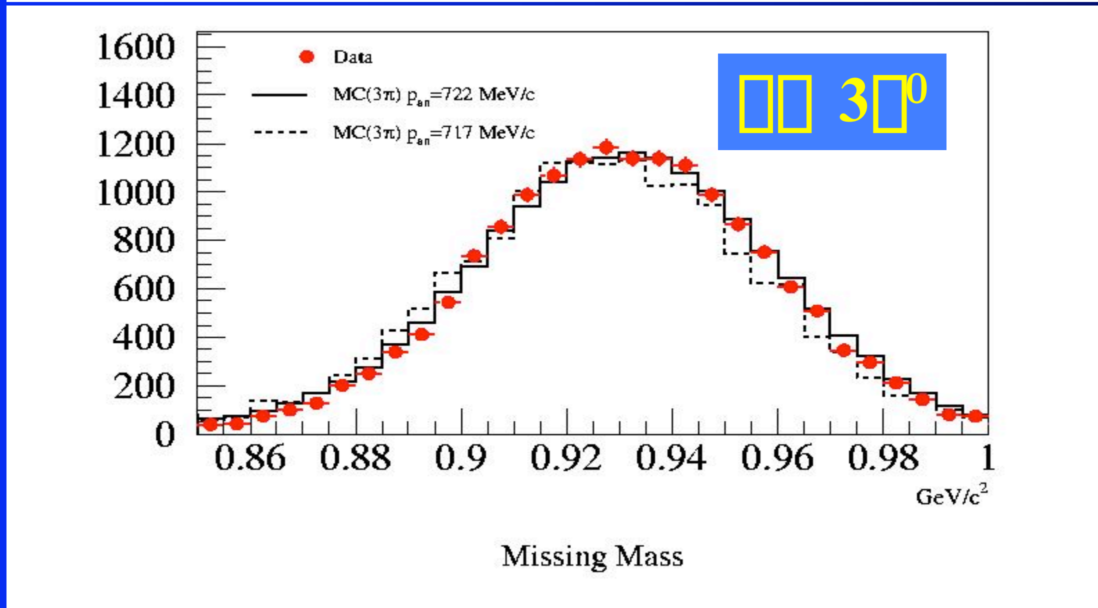
Experimental Distributions

- Beam properties: chambers in beam line
- Pedestals, pile-up, dead time

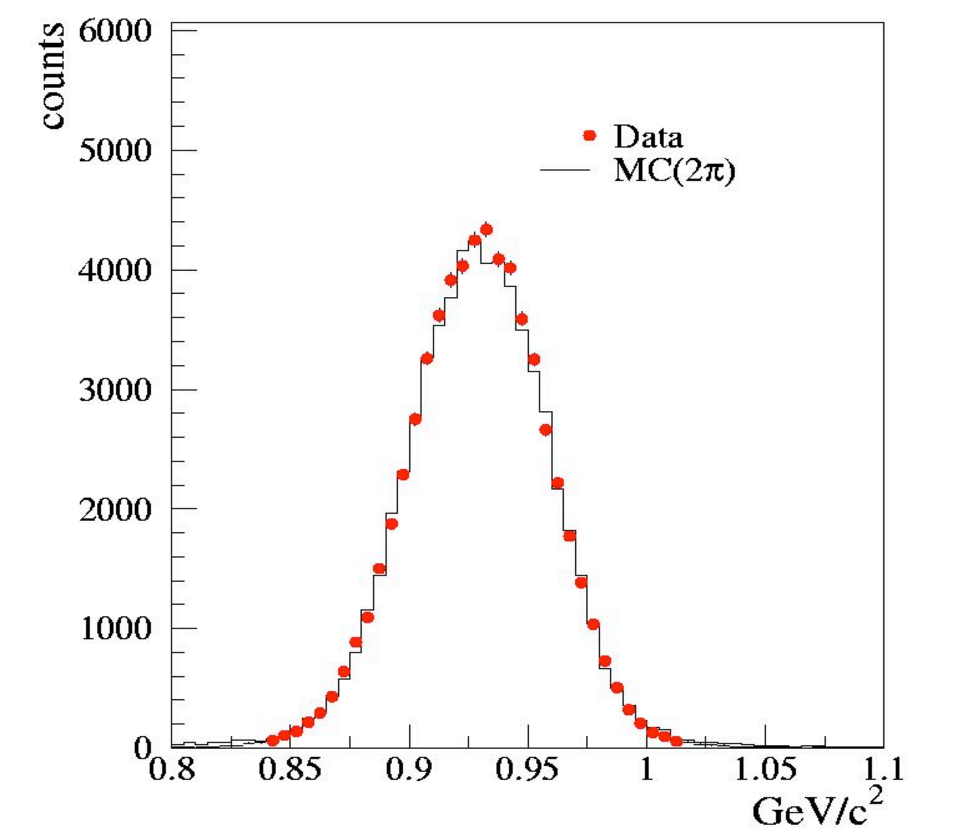


MC Momentum Adjustment

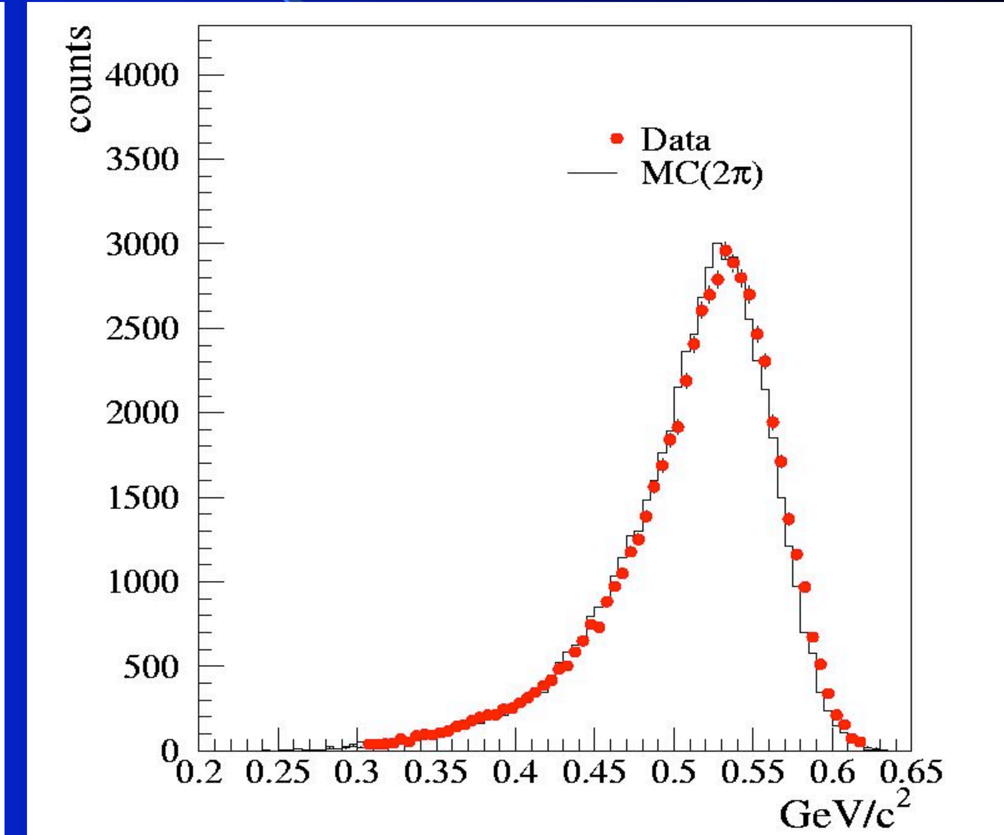




MC Reproduction of Data for $\pi^- p \to 2\pi^0 n$

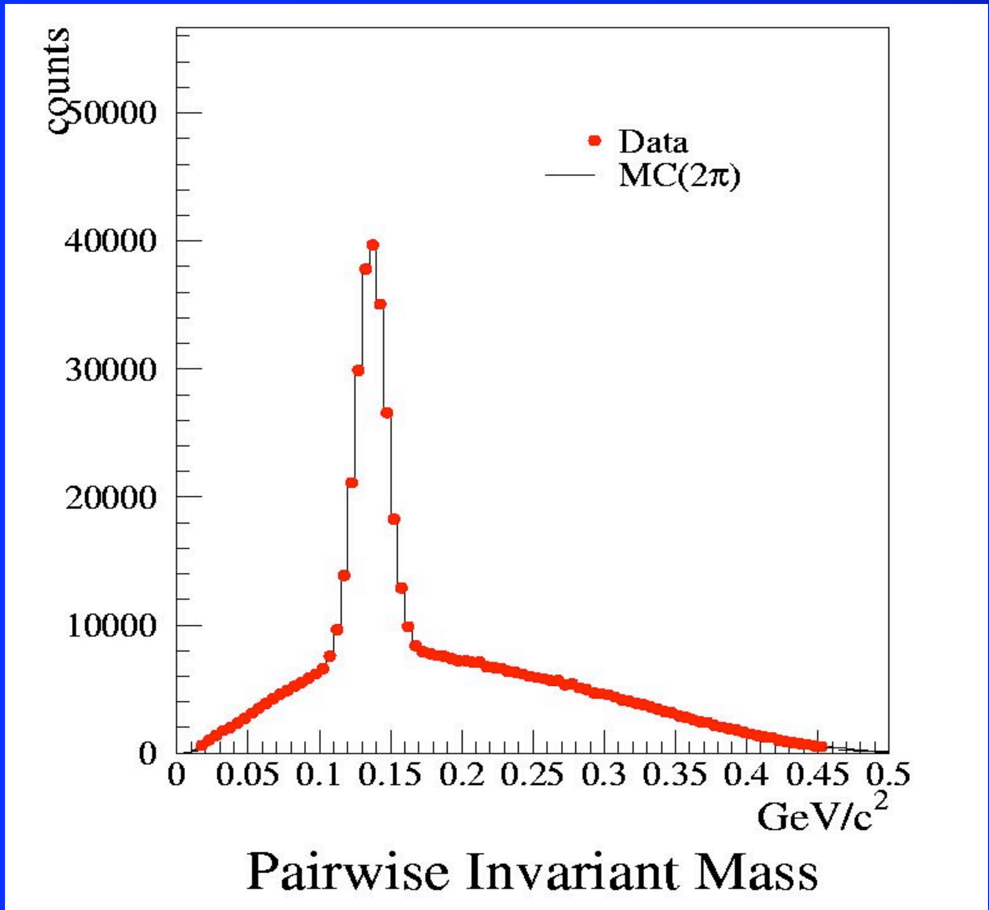


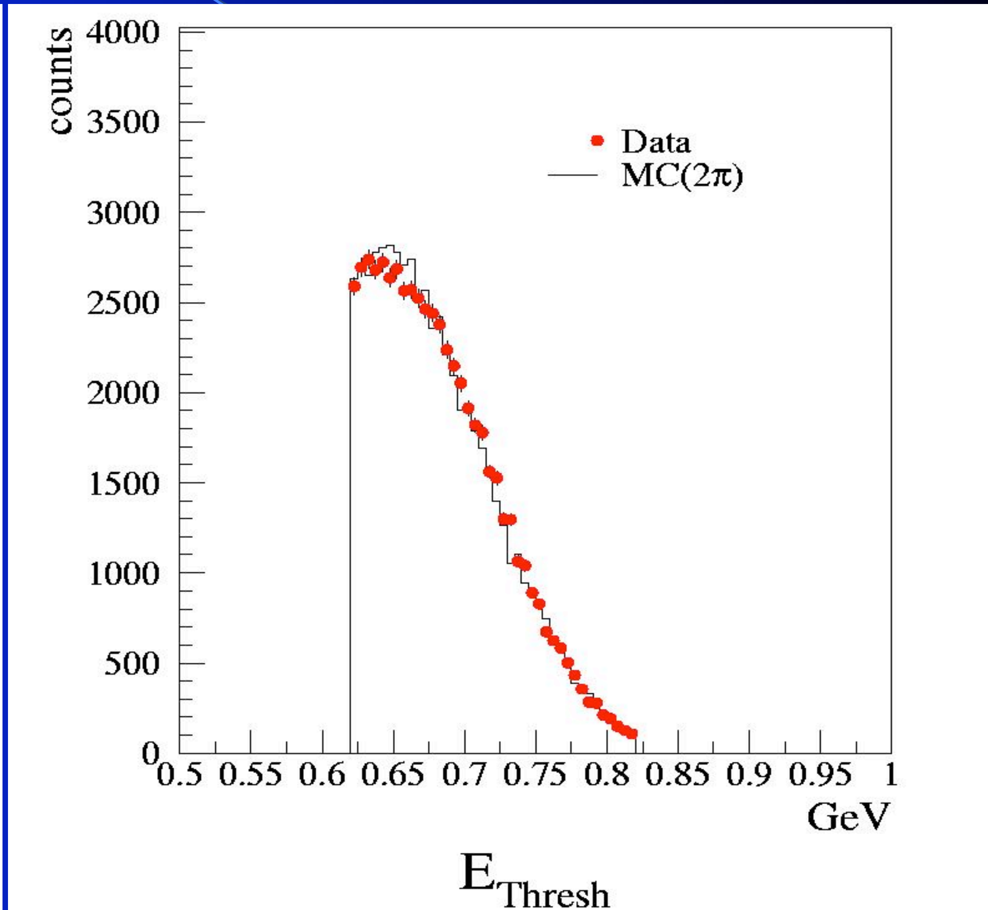
Missing Mass



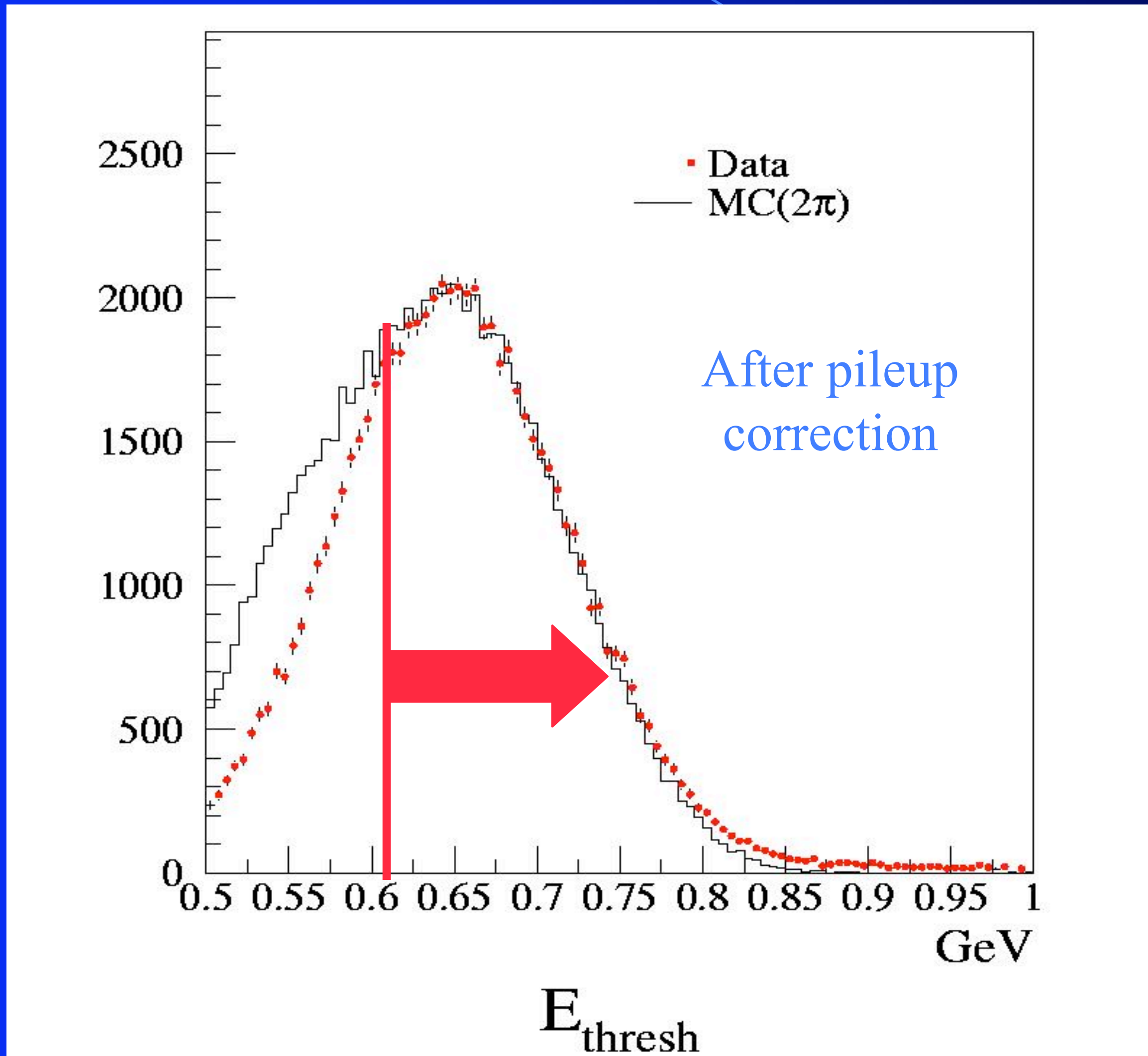
Invariant Mass

MC Reproduction of Data for p 20n





MC Reproduction of Data for $\pi^- p \to 2\pi^0 n$



Primary Cuts

- Four clusters
- No connected regions (suppresses overlaps)
- Peak crystal not a guard crystal
- Missing mass that of a neutron (suppresses $2□^0$)
- Invariant mass > 0.5 GeV/c^2 (suppresses $2□^0$)
- CB threshold between 0.62-0.80 GeV
- Unique $□^0$ (suppresses $2□^0$)
- $M_{□□}$ (suppresses $2□^0$)
- Radial energy spread ratio

These eliminate 99.9% of background and leave 35.6% of signal events: $3□^0/2□^0/□^0□□$: 925/340/35000

Probability Density Variables

$$IM = \sqrt{\sum_{i=1}^{k} E_i^2 - \sum_{i=1}^{k} \vec{p}_i \cdot \vec{p}_i}$$

Invariant Mass

$$MM = \left[E_{beam} - \sum_{i=1}^{k} E_i \right]^2 - \left[\vec{p}_{beam} - \sum_{i=1}^{k} \vec{p}_i \right]^2$$

Missing Mass

$$R = \frac{E_{cluster} - E_{peak}}{E_{cluster}}$$

R-cut: suppresses $3\pi^0$

(radial energy spread)

$$TPD = \min(t_{ij} + t_{kl}), i \neq j \neq k \neq l$$

$$t_{ij} = \frac{\left| IM_{ij} - m_{\pi^0} \right|}{m_{\pi^0}}$$

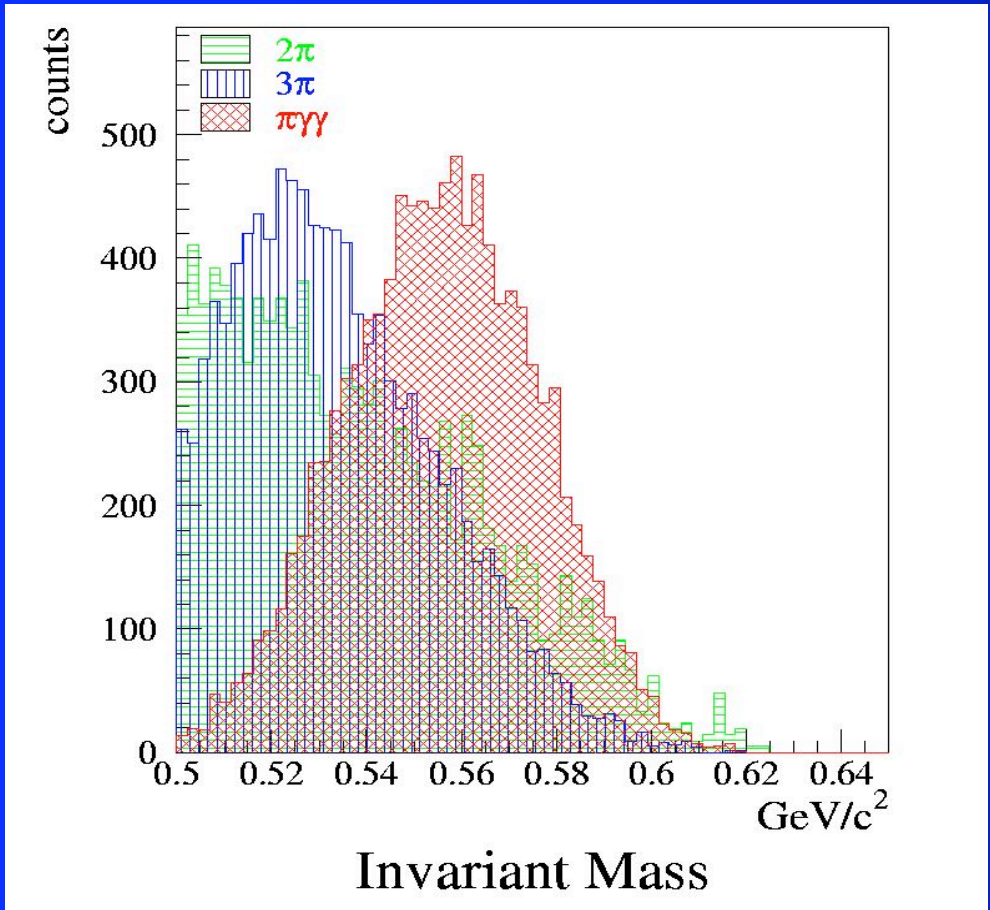
TPD-cut: suppresses $2\pi^0$

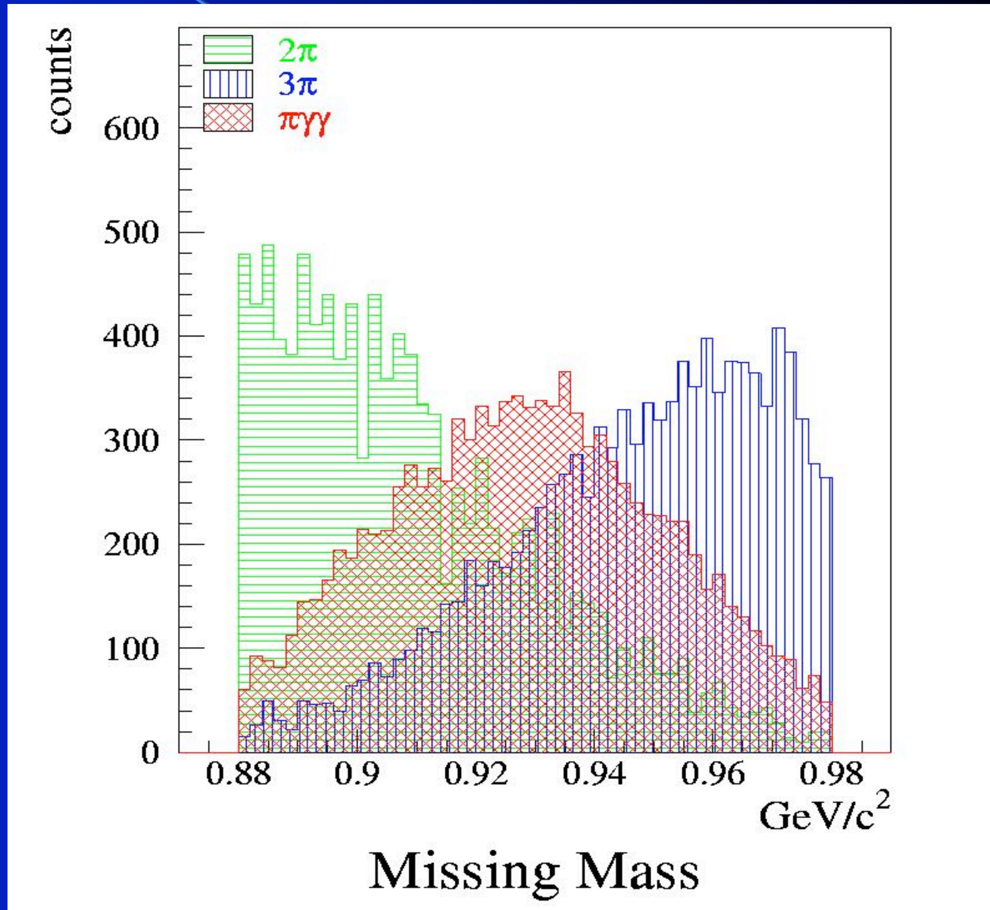
(fractional two-pion mass difference)

$$p_T = \sum_i \vec{p}_i \times \hat{z}$$

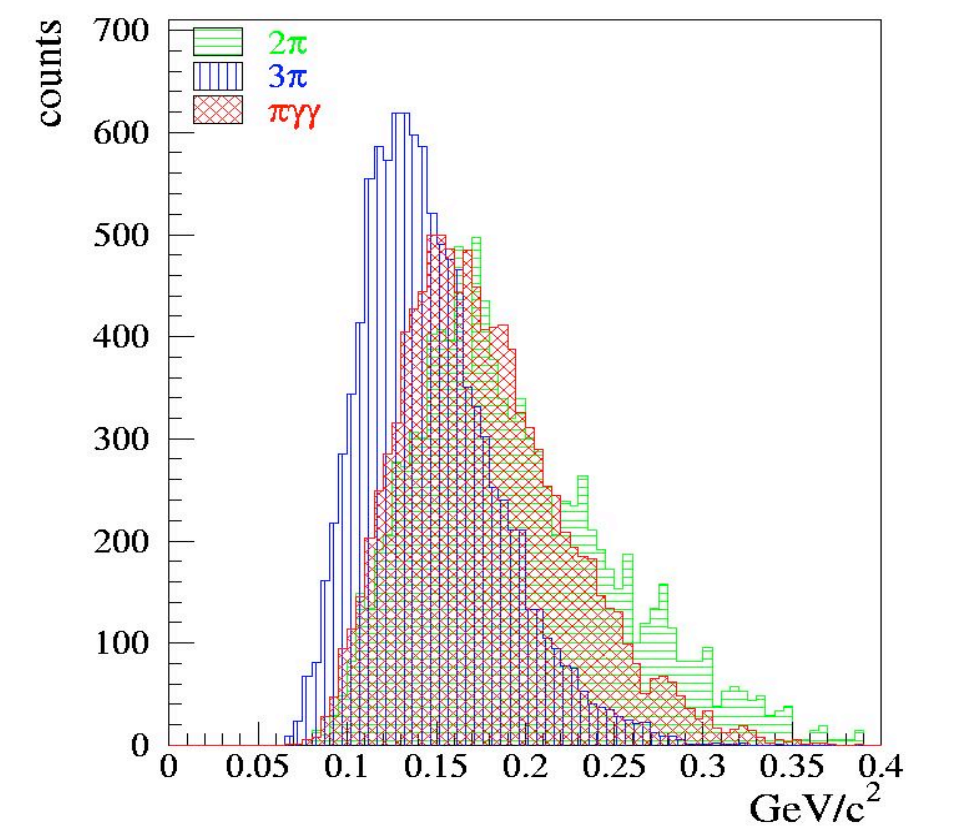
Transverse Momentum: suppresses $3\pi^0$

Probability Density Distributions

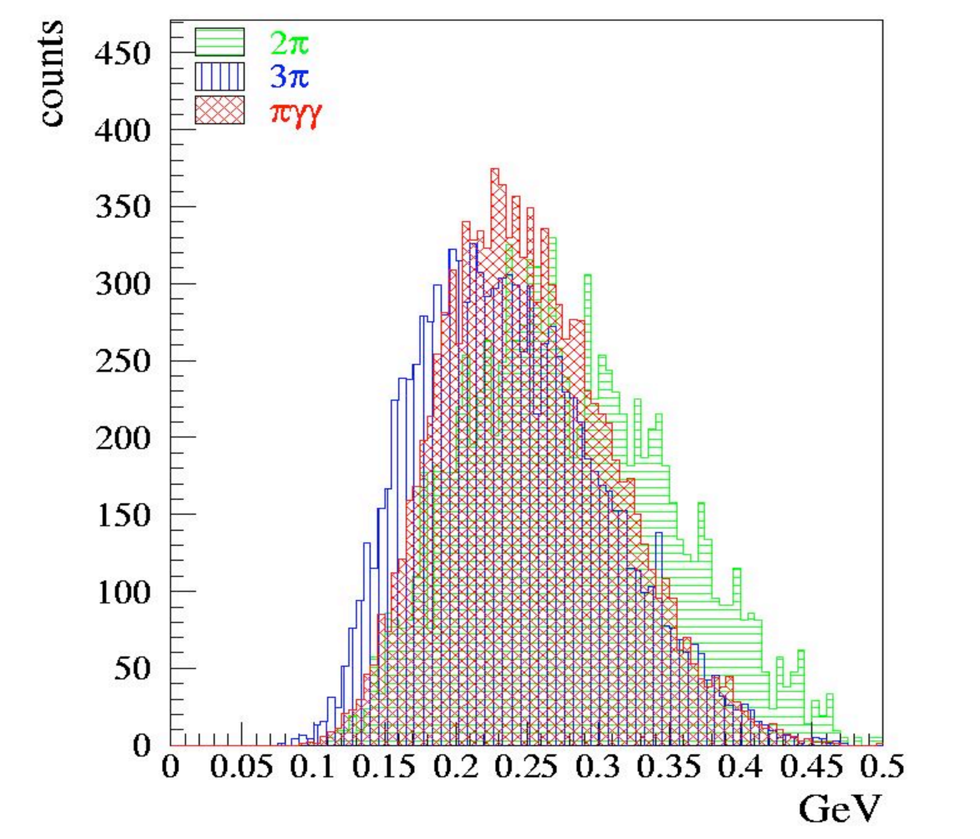




Probability Density Distributions

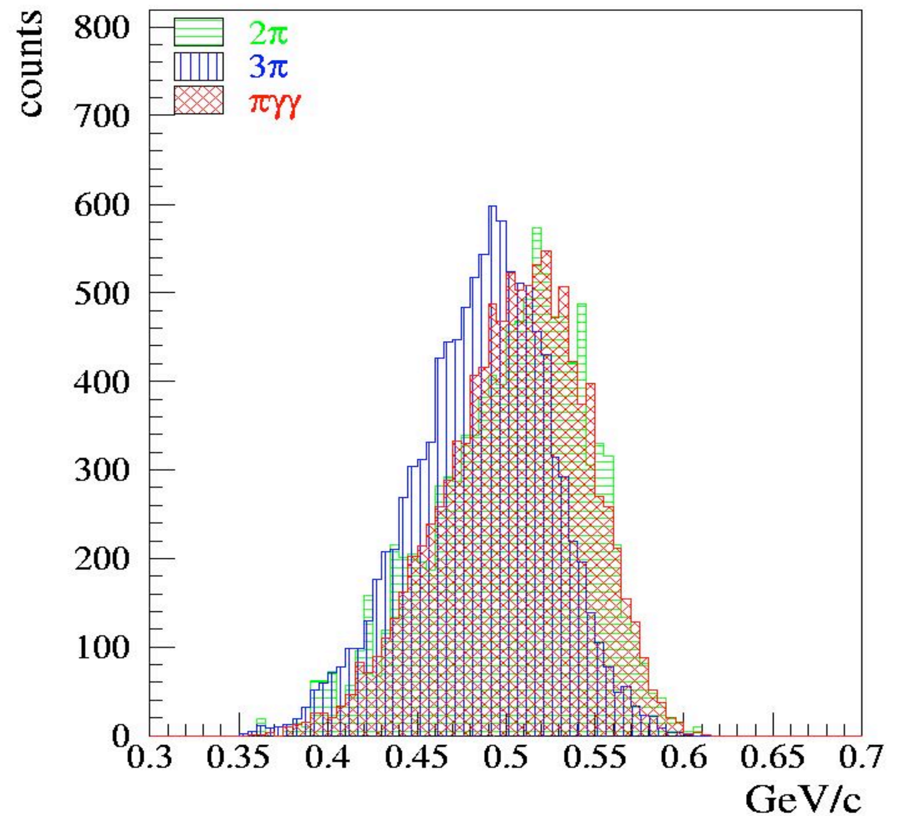


$E_{peak}(1)$

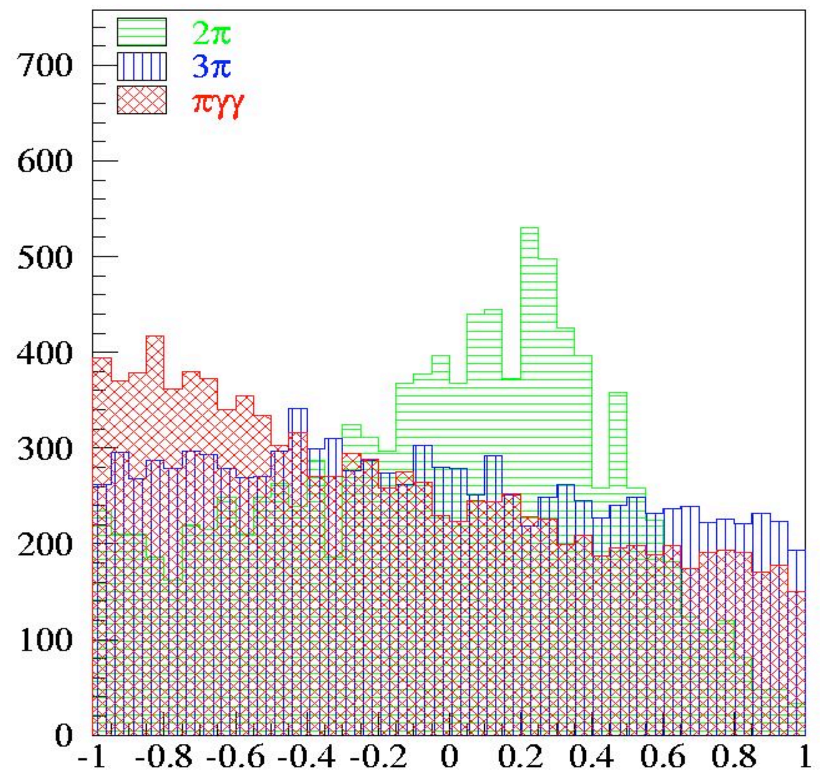


$E_{cl}(1)$

Probability Density Distributions

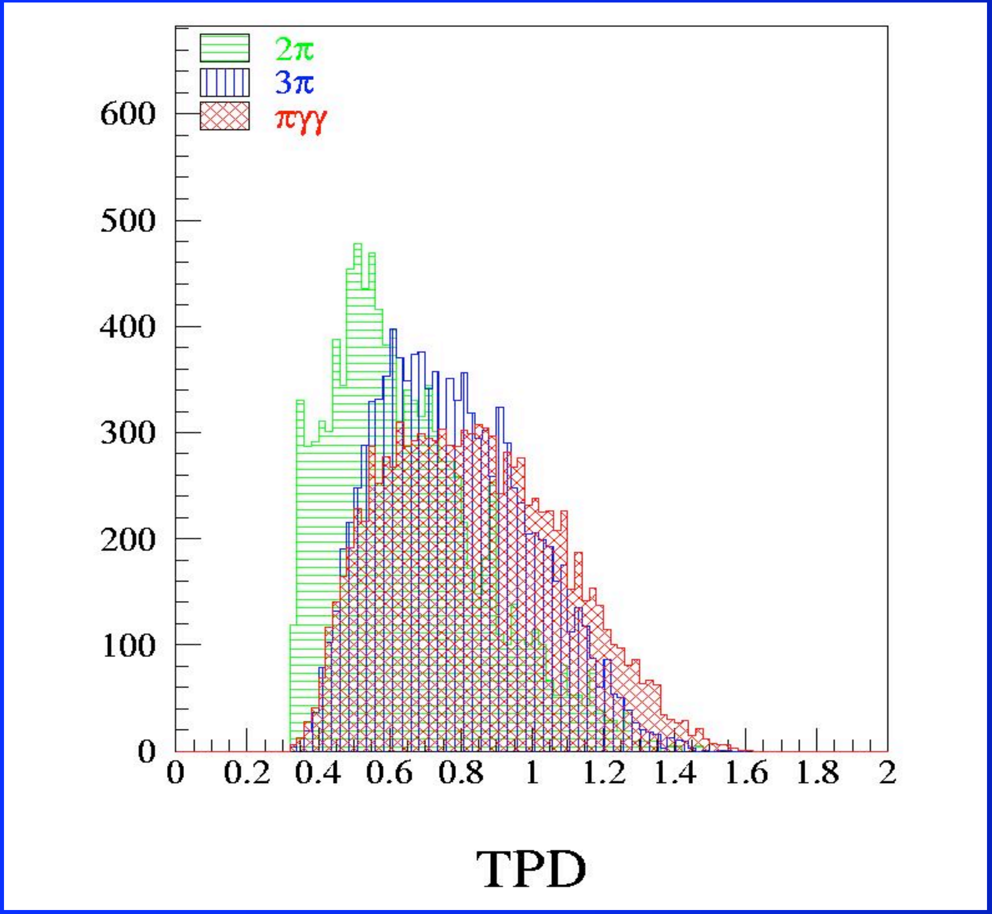


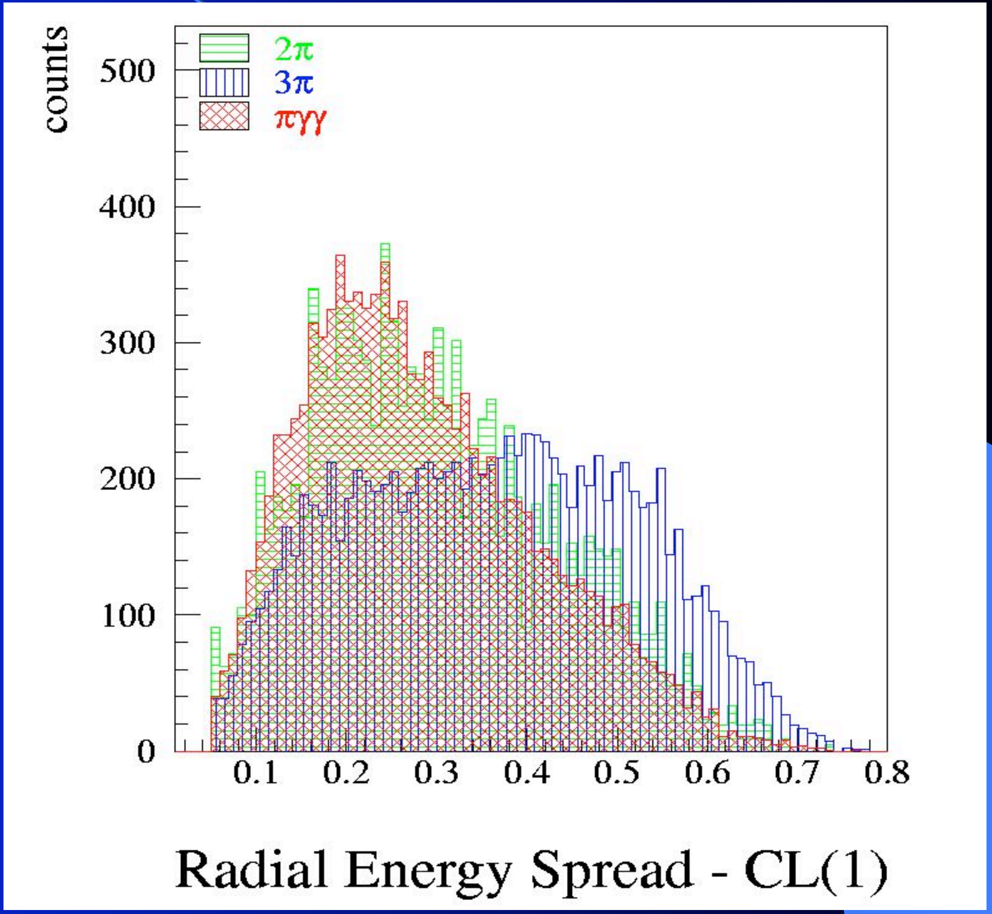
Transverse Momentum



$\cos(\theta_{cm})$

Probability Density Distributions





Likelihood Analysis to Separate $\eta \to \pi^0\gamma\gamma$ from Background

- Use the shapes of *probability distributions* to separate the three channels.
- Generate likelihood functions that compare relative probability of an event being a $\pi^0\gamma\gamma$ or to one of the background processes.

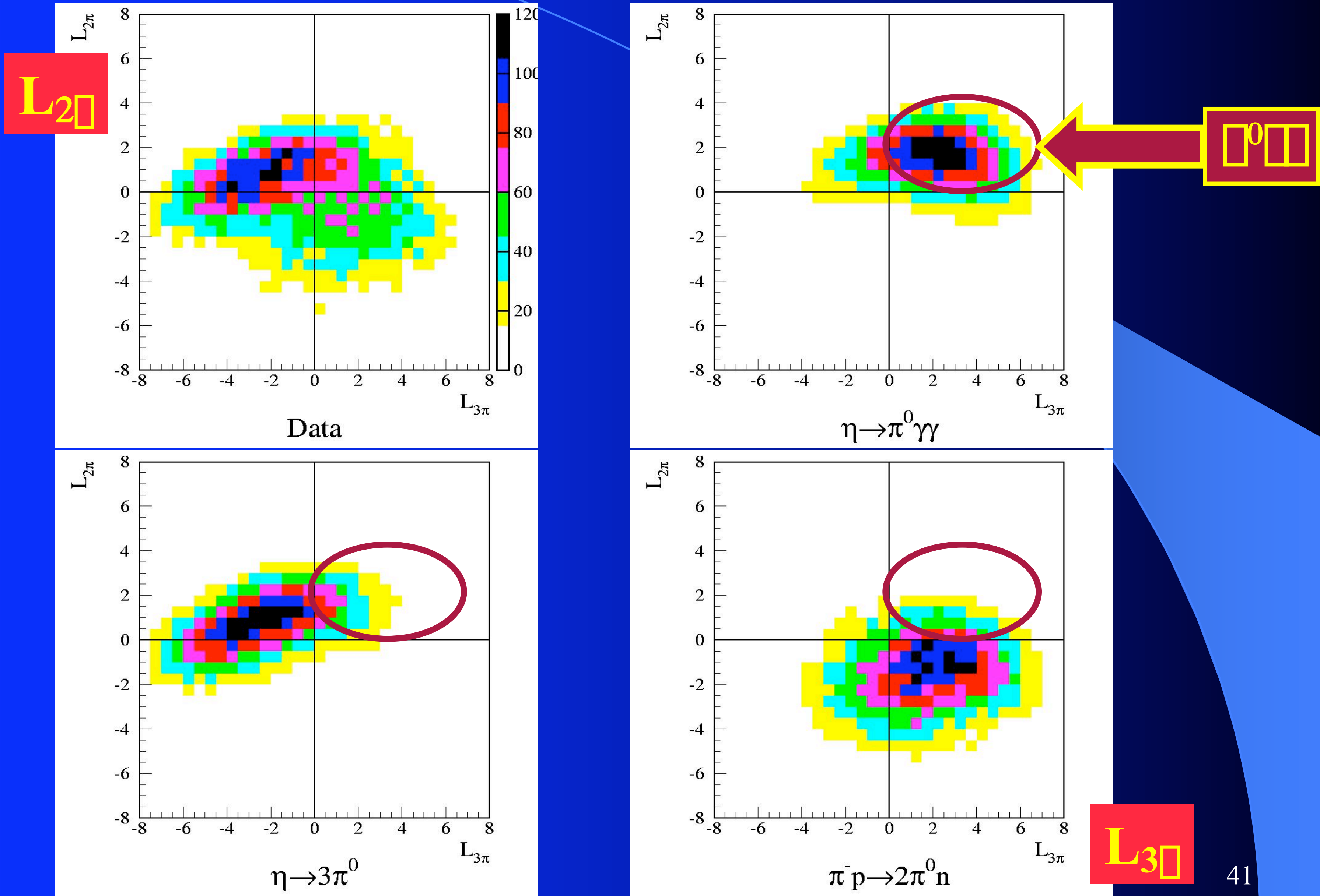
$$L_{2\pi} = \sum \ln\left(\frac{P[X_i = X(\eta \to \pi^0\gamma\gamma)]}{P[X_i = X(\pi^- \mathbf{p} \to 2\pi^0\mathbf{n})]}\right)$$

$$L_{3\pi} = \sum \ln\left(\frac{P[X_i = X(\eta \to \pi^0\gamma\gamma)]}{P[X_i = X(\eta \to 3\pi^0)]}\right)$$

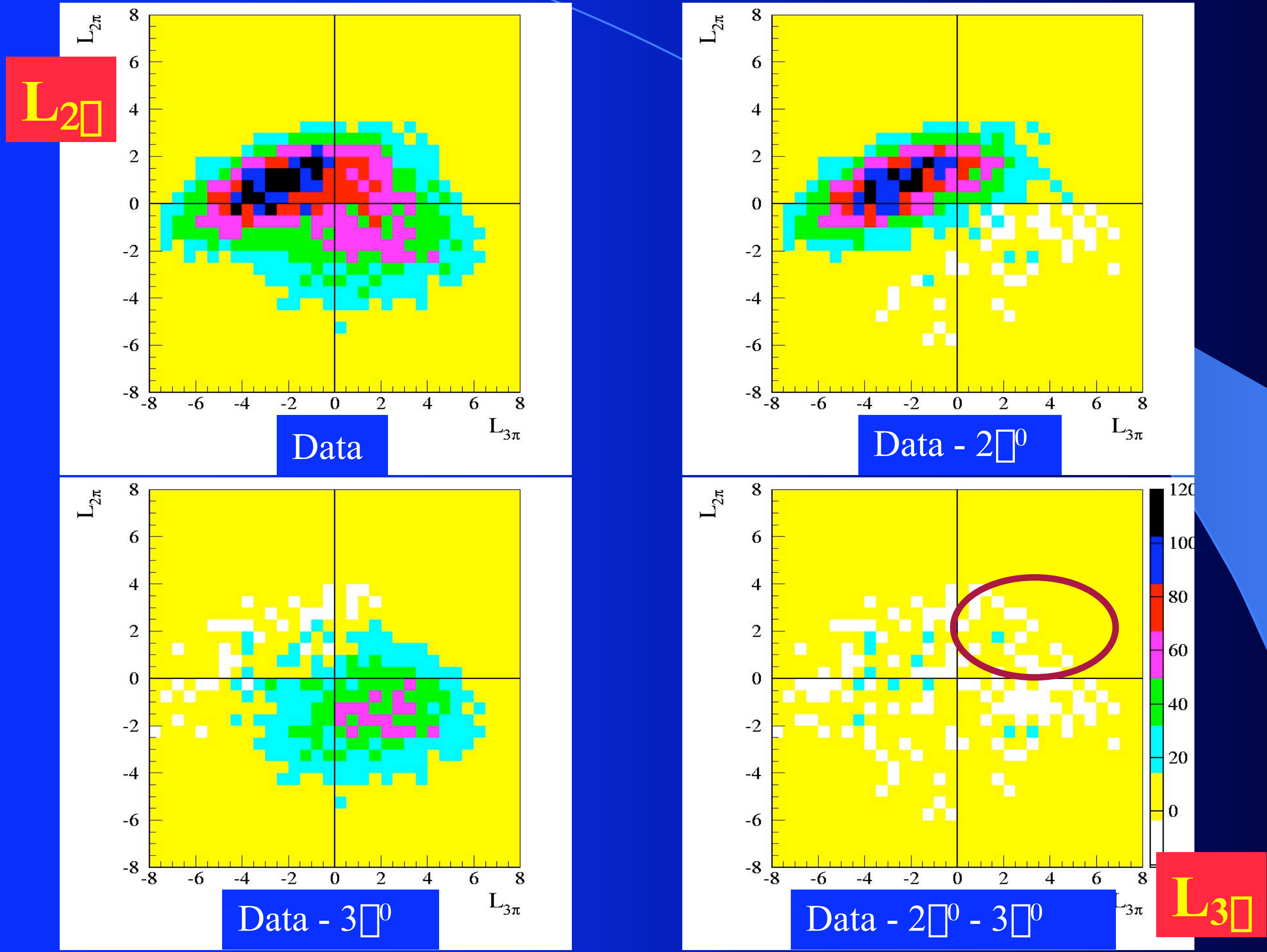
$L_{3\pi} = 0$: Equally likely $\eta \to \pi^0\gamma\gamma$ and $\eta \to 3\pi^0$ with 2 missing clusters.
$L_{3\pi} > 0$: Relatively more likely $\eta \to \pi^0\gamma\gamma$ than $\eta \to 3\pi^0$.

- Sum is over thirteen physical observables including invariant mass, cluster energies, etc.
- The likelihood variables are calculated on an event-by-event basis for both the experiment data and the MC simulated data.

Likelihood Islands

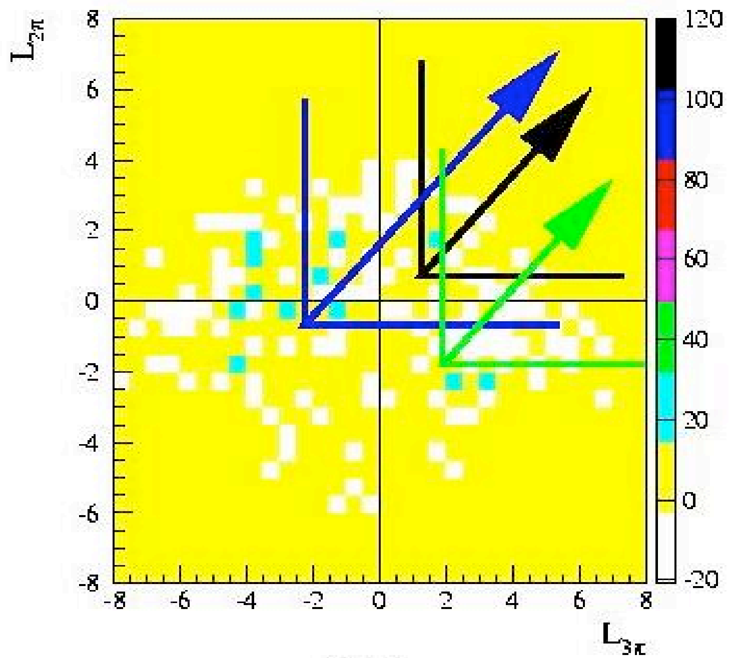


Normalized Background Subtraction



Results

- Normalizations performed and background MC simulation subtracted from data.
- Examined multiple integration regions that satisfy:
  - ⇒ Number of $\eta \to \pi^0\gamma\gamma$ events found is statistically significant above background to 3 σ, to ensure the region is large enough to be meaningful.
- Different integration choices were considered to ensure final result was not sensitive to choice of integration region ($\pm 10\%$).



Data

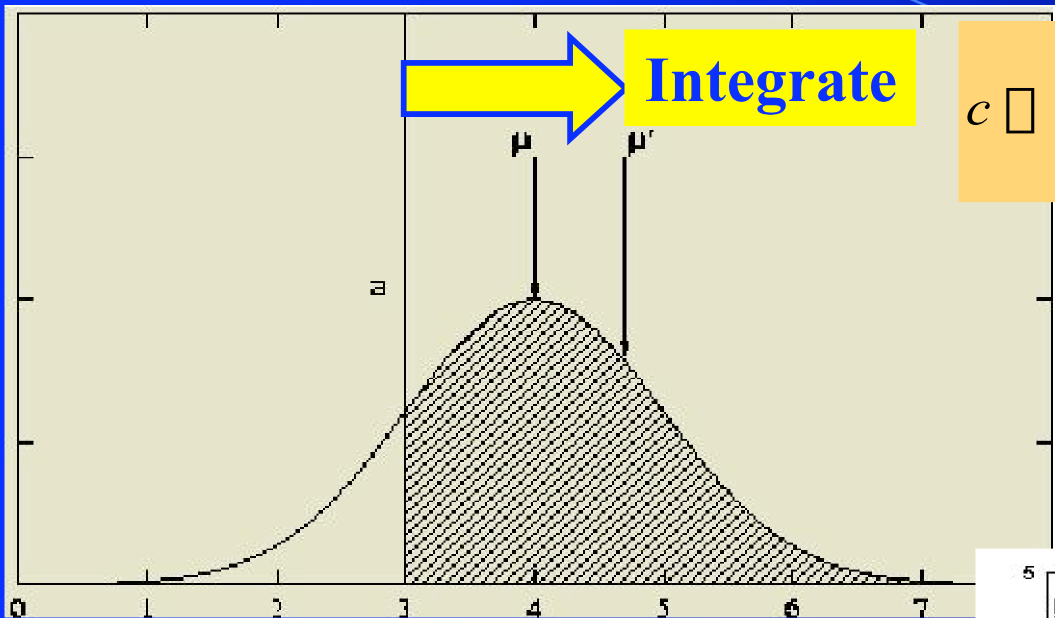
Identified : 120 ± 40 $\eta \to \pi^0\gamma\gamma$ events.

$\mathrm{BR} = 2.7 \pm 0.9 \times 10^{-4}$ (stat)

$$\sigma = \sqrt{\sigma_{tot}^2 + \sigma_{2\pi}^2 + \sigma_{3\pi}^2}$$

$$\sigma_{tot} = \sqrt{N_{tot}}$$

Correction to Method

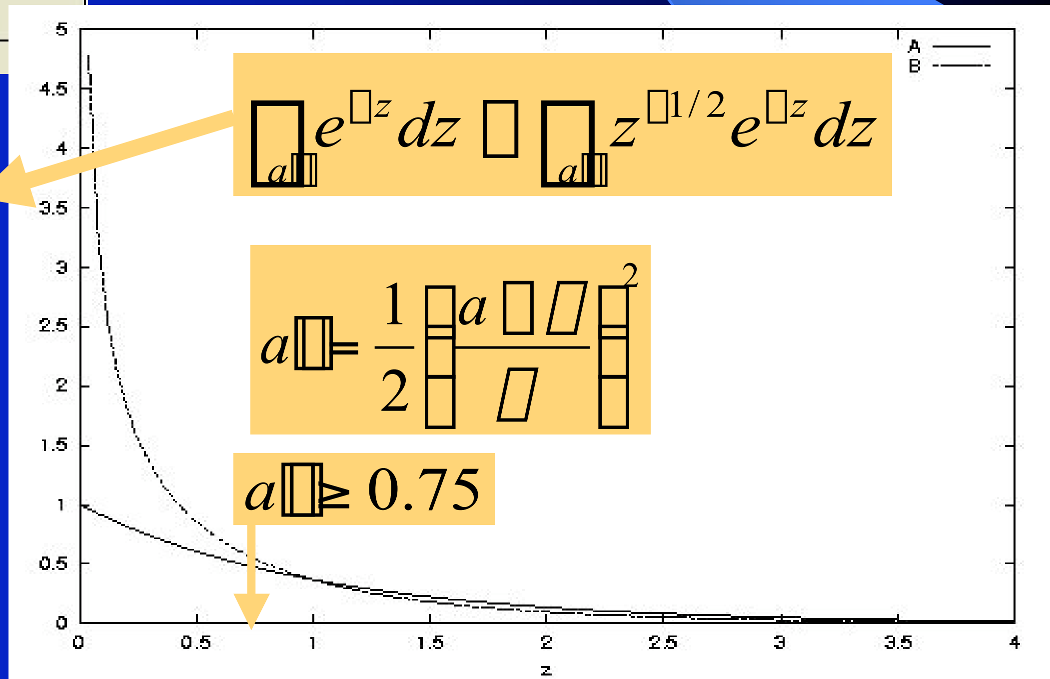


$$c \propto c' = \rho(\mu') = \int_a^{\infty} \frac{x\,dx}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{(x-\mu)}{\sigma}\right)^2\right]$$

μ' - weighted average

μ - true average

$$c = \rho(\mu') \approx 2\frac{\sigma}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{(x-\mu)}{\sigma}\right)^2\right]$$



$$\int_{a'}^{\infty} e^{-z}\,dz \ll \int_{a'}^{\infty} z^{-1/2} e^{-z}\,dz$$

$$a' = \frac{1}{2}\left(\frac{a-\mu}{\sigma}\right)^2$$

$$a' \geq 0.75$$

c=0.29 x 10^{-4}
(to 2%)

Error Considerations

• The statistical uncertainty is:	$\sim 30\%$
• Normalization was performed on multiple regions of the data and Analysis parameters were varied:	$\left.\right\} \sim 20\%$
• The 3 σ cutoff introduces a correction of $\sim$ 10% and uncertainty of:	$< 10\%$
• Uncanceled acceptance systematics were estimated to be:	$< 10\%$
• Sensitivity to simulated distribution of $\eta \rightarrow \pi^0\gamma\gamma$ decay products was:	$< 1\%$
• The systematic uncertainty is:	$\sim 30\%$

The GAMS-2000 Result

- GAMS had $\sim \frac{1}{50}$ our number of η's.
  - $\Rightarrow$ We were considerably more aggressive in our cuts aimed at achieving a high confidence background subtraction.
- Handling of $\eta \to 3\pi^0$ with double overlap?
  - $\Rightarrow$ MC $\to$ GAMS used 150k "real" γ-showers to simulate 600 k (?) η's.
    $\to$ Statistically limited simulation of BG.
  - $\Rightarrow$ Kin. Fit $\to$ Good at eliminating BG around the peak.
    $\to$ How much BG is under the peak?
- Error estimate?
  - $\Rightarrow$ Impact of limited MC stats. on errors?
  - $\Rightarrow$ Total error (from unspecified sources) in reanalysed result (with fewer identified signal events) is similar to stat. error from original analysis:
    - $*$ Were systematic errors included?

Summary and Conclusions

- The $\eta \to \pi^0\gamma\gamma$ decay is a sensitive test of χPT to third order in the momentum expansion
- The Crystal Ball result:
  - **$\Gamma(\eta \to \pi^0\gamma\gamma)$ = (0.32 ±0.10±0.11) eV**
- Main Limitation: CB crystal granularity
- More accurate measurements require perhaps a segmented e-m calorimeter