New Physics with the Crystal Ball

J. R. Comfort
Arizona State University

Participating Institutions

Abilene Christian University
Argonne National Laboratory
Arizona State University
Brookhaven National Laboratory
George Washington University
Karlsruhe University
Kent State University
Petersburg Nuclear Physics Institute
Rudjer Bo_kovi_ Institute, Aagreb, Croatia
University of California, Los Angeles
University of Colorado
University of Maryland
University of Regina
Valpariso University

Outline

_ Goals of the Crystal Ball Program

_ Baryon Spectroscopy Program

_ Special Interests

_ _ Meson Decays

_ Summary and Conclusions

Issues

1. What are the *effective* low-energy degrees of freedom?

2. What are the symmetries?
   * C, P, T
   * Chiral Symmetry
   * Geometrical

3. What are the most effective models?
   * 3 quarks in a “bag” confined by a potential
   * Rotating or vibrating flux tubes
   * Quark-diquark models

Need <u>precision</u> tests of models of QCD at low energies.

Impact Issues

CKM quark-mixing matrix

QCD has unitarity constraints. There is some evidence of failure.

Value of $\_{s}$, and energy dependence

The precision in determining $\_{s}$ is limited by hadronic (non-perturbative) and quark-mass corrections.

Energy scale dependence of $\_{e}$

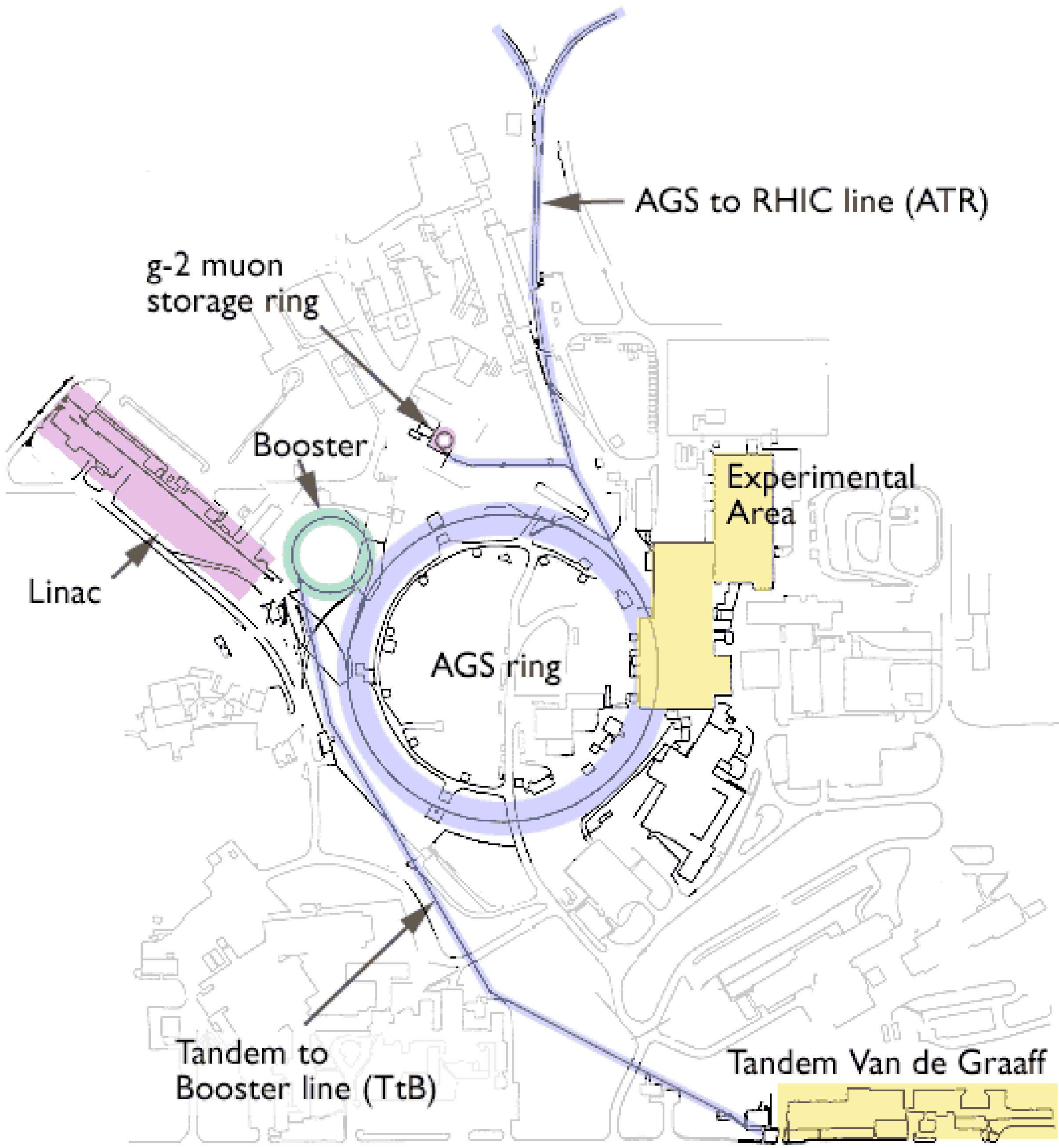
The theoretical understanding of $\_{e}$ is limited by non-perturbative QCD contributions to vacuum polarization.

Publications

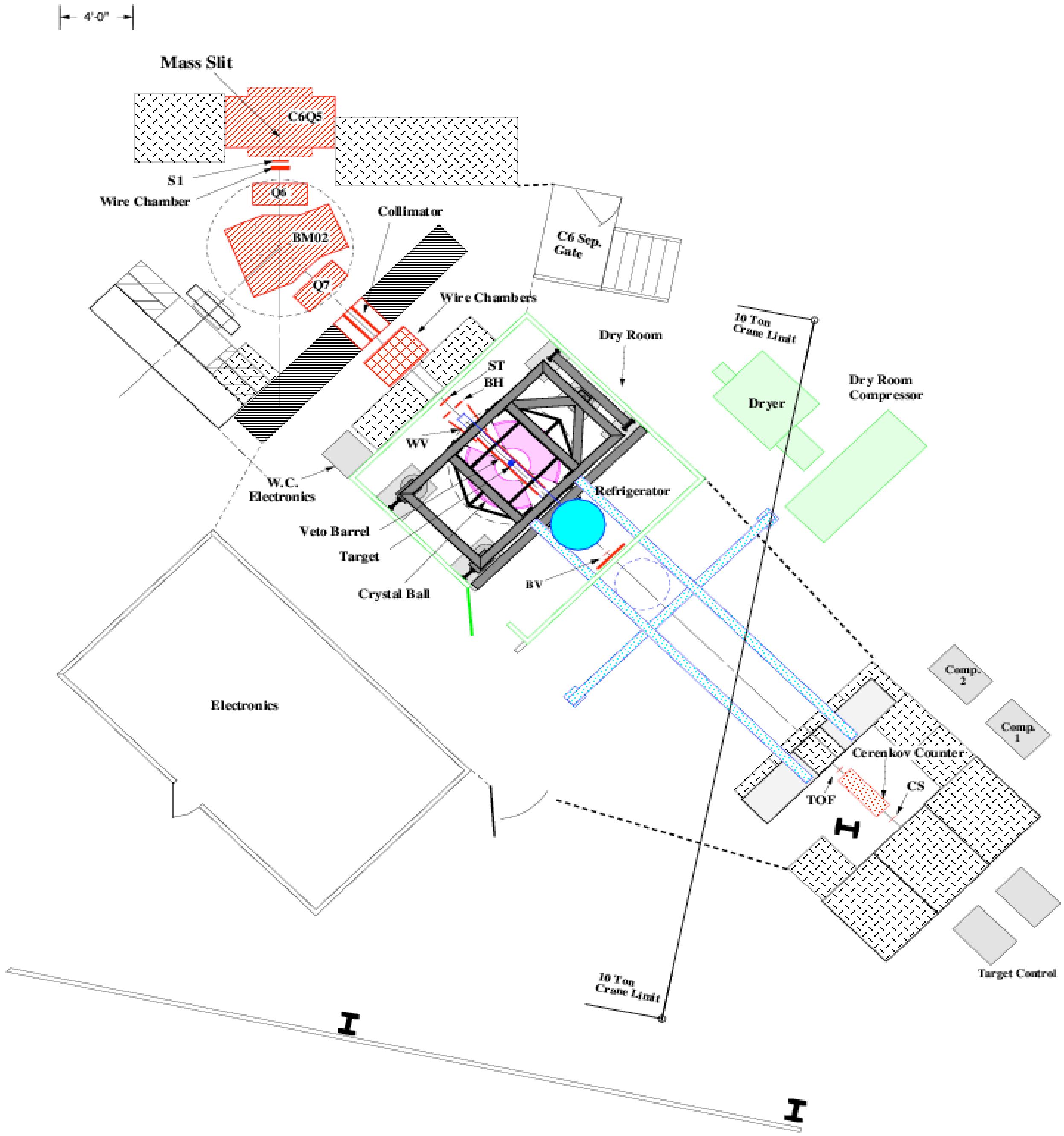
Physical Review Letters	5
Physical Review	10
Physics Letters	2
Nuclear Instruments Methods	1
Other	2

More to come

BNL Accelerator Complex



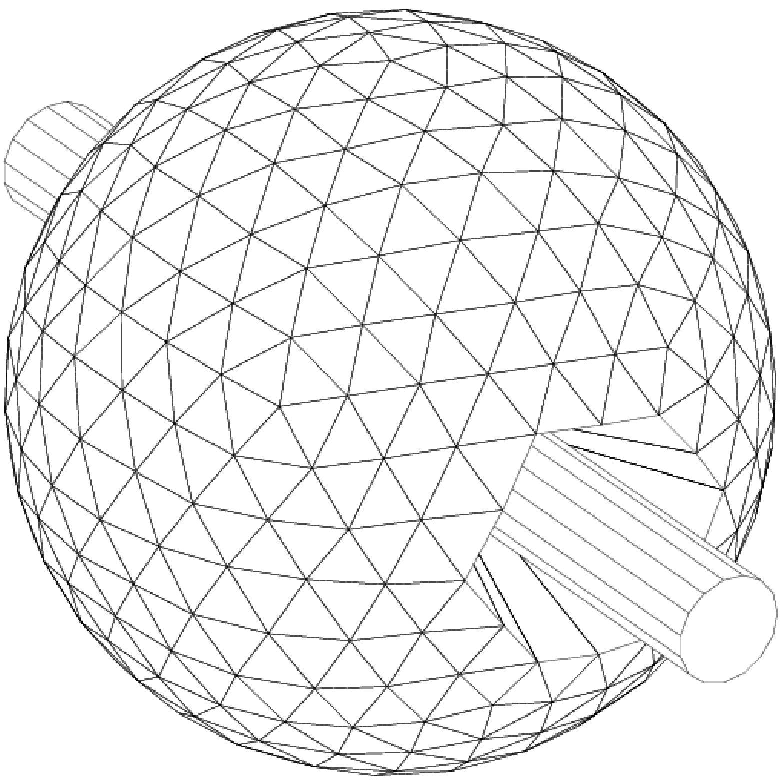
C6 Beamline


4'-0"
Mass Slit
C6Q5
S1
Wire Chamber
Q6
BM02
Q7
Collimator
C6 Sep. Gate
Wire Chambers
Dry Room
10 Ton Crane Limit
ST
BH
Dryer
Dry Room Compressor
WV
Refrigerator
W.C. Electronics
Veto Barrel
Target
Crystal Ball
BV
Electronics
Comp. 2
Comp. 1
Cerenkov Counter
CS
TOF
Target Control
10 Ton Crane Limit

Crystal Ball

Crystal Ball

Multi-photon Spectrometer

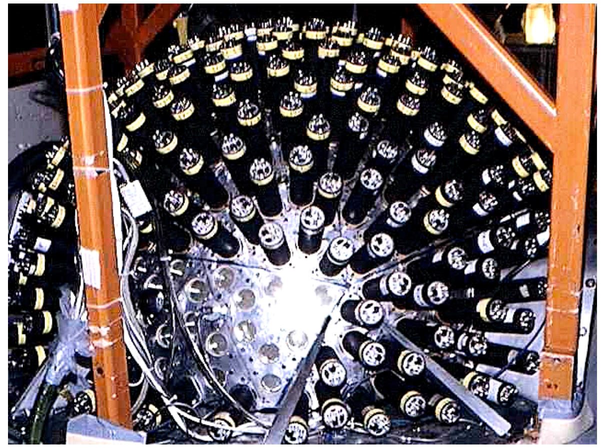


672 separate NaI(Tl) crystals

94% solid angle; with endcaps ~98%

$\sigma/E = 2.7\% \times E^{-1/4}$ (E in GeV)

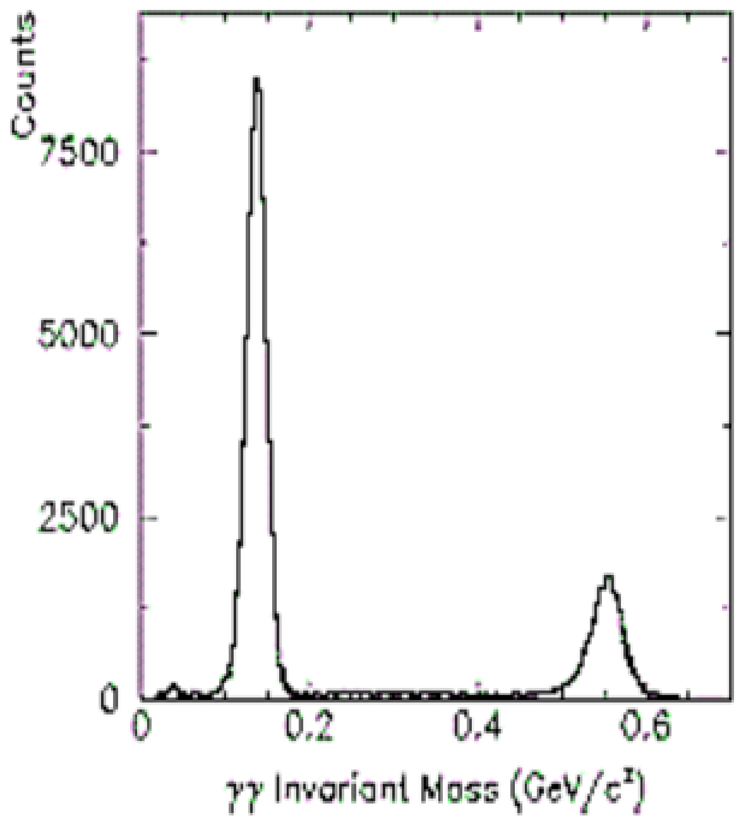
$\varnothing_{ext} = 1.32$ m, $\varnothing_{cavity} = 0.50$ m, $\sigma_\theta \approx 2° - 3°$, $\sigma_\phi = 2°/\sin\theta$, $t = 16X_0$



Reaction List

$$
\begin{array}{lllllll}
\pi^- \ \mathrm{p} & \to & \mathrm{n}\ \gamma & & & & \\
 & & \mathrm{n}\ \pi^0 & \to & \mathrm{n}\ 2\gamma & & \\
 & & \mathrm{n}\ \eta & \to & \mathrm{n}\ 2\gamma & & \\
 & & \mathrm{n}\ \pi^0\ \pi^0 & \to & \mathrm{n}\ 4\gamma & & \\
 & & \text{etc.} & & & & \\
 & & & & & & \\
K^- \ \mathrm{p} & \to & \Lambda\ \gamma & \to & \mathrm{n}\ \pi^0\ \gamma & \to & \mathrm{n}\ 3\gamma \\
 & & \Lambda\ \pi^0 & \to & \mathrm{n}\ \pi^0\ \pi^0 & \to & n\ 4\gamma \\
 & & \Lambda\ \eta & \to & \mathrm{n}\ \pi^0\ \eta & \to & n\ 4\gamma \\
 & & \Lambda\ \pi^0\ \pi^0 & \to & \mathrm{n}\ 3\pi^0 & \to & n\ 6\gamma \\
 & & \text{etc.} & & & & \\
 & & & & & & \\
 & & \Sigma^0\ \gamma & \to & \Lambda\ \gamma\ \gamma & \to & \mathrm{n}\ 4\gamma \\
 & & \text{etc.} & & & &
\end{array}
$$

Invariant Mass



π-N Physics of Special Interest

Pion Single Charge Exchange (E958)

(Darko Mekterovic Dissertation, RBI Zagreb)

2 π^0 Production

Kelly Craig Ph.D. Dissertation, ASU

π-N Isospin Relations

$\boxed{\pi^{\pm} N \text{ data}} \Longrightarrow \boxed{\text{Phase-shift Analysis}}$

$\Downarrow$

$\boxed{\text{SCX Amplitudes}}$

Compare to:

$\boxed{\text{SCX data}} \Longrightarrow \boxed{\text{Phase-shift Analysis}}$

$\Downarrow$

$\boxed{\text{SCX Amplitudes}}$

Differences $\leq$ 7% in S waves, below 100 MeV.

Excellent and improving $\pi^{\pm}$ data.

Limited and poor SCX data.

Existing π-N Data Base

Process	Δ Region	Low Energy
$\pi^{\pm}$ Elastic $d\sigma/d\Omega$	Excellent	Very Good
$\pi^{\pm}$ Elastic A_y	Excellent	Very Good
SCX $d\sigma/d\Omega$	Excellent	Poor
SCX A_y	Excellent	None

Getting at Quark Masses

$$\begin{aligned}\Delta\mathcal{L} &= -(m_u\bar{u}u + m_d\bar{d}d)\\ &= -\left[\frac{1}{2}(m_u+m_d)(\bar{u}u+\bar{d}d) + \frac{1}{2}(m_u-m_d)(\bar{u}u-\bar{d}d)\right]\end{aligned}$$

"Sigma" Term Isospin Violation

Quark-Mass Term:

$$\mathcal{L}^{(1)}_{qm} = -\frac{\delta m_N}{2}\left(N^\dagger\tau_3 N - \frac{1}{2Df_\pi^2}N^\dagger\pi_3\,\boldsymbol{\pi}\cdot\boldsymbol{\tau}N\right)$$

Hard-Photon Exchange:

$$\mathcal{L}^{(-1)}_{hp} = -\frac{\bar{\delta}m_N}{2}\left(N^\dagger\tau_3 N + \frac{1}{2Df_\pi^2}N^\dagger(\pi_3\,\boldsymbol{\pi}\cdot\boldsymbol{\tau} - \boldsymbol{\pi}^2\tau_3)N\right)$$

Sum:

$$\delta m_N + \bar{\delta}m_N = m_p - m_n = -1.3\text{ MeV}$$

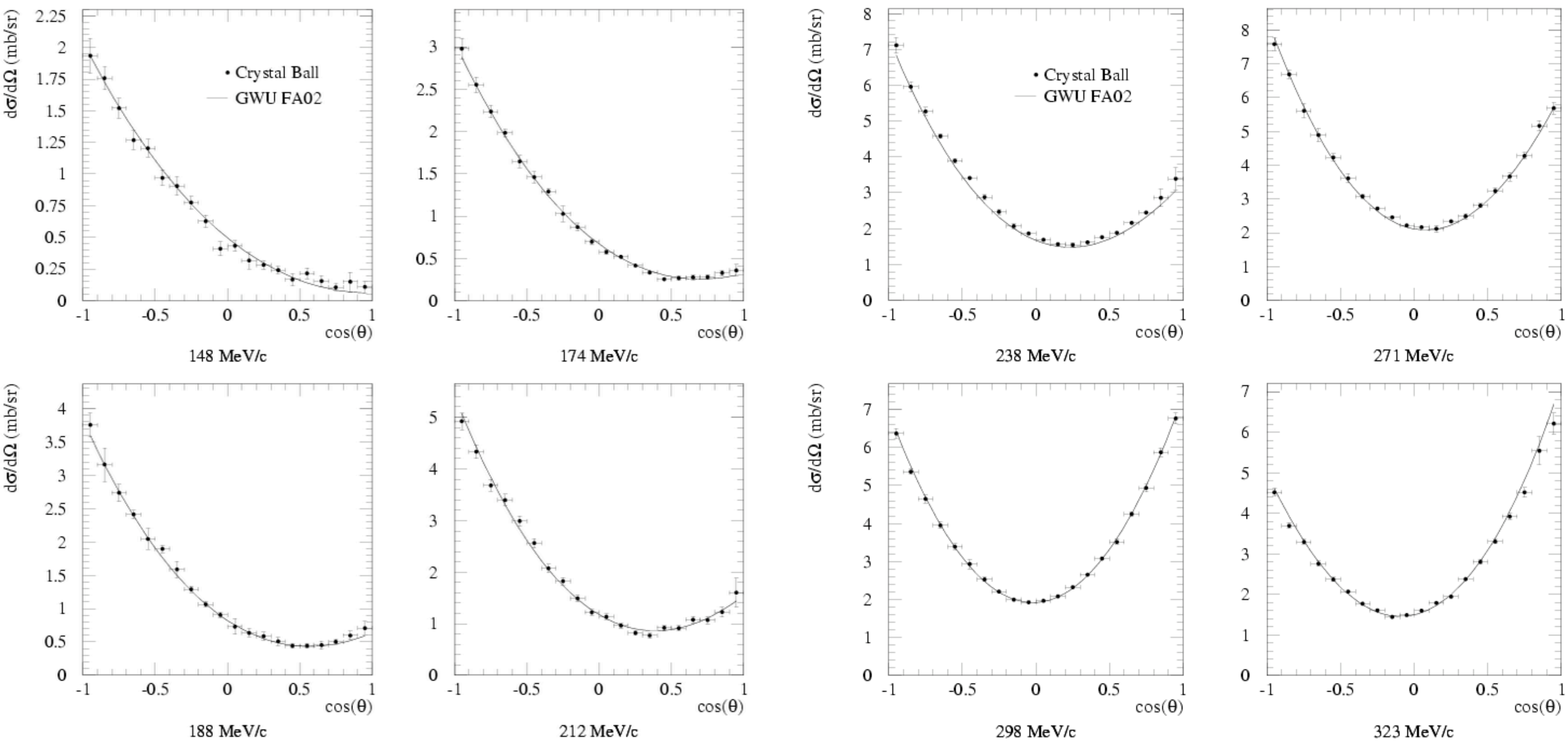
Difference:

$$\frac{\delta m_N - \bar{\delta}m_N}{2m_\pi} \simeq 2\,\frac{T_+ - T_- - \sqrt{2}T_0}{T_+ - T_- + \sqrt{2}T_0}$$

[$T_+ = T(\pi^+ p \to \pi^+ p)$, etc.]

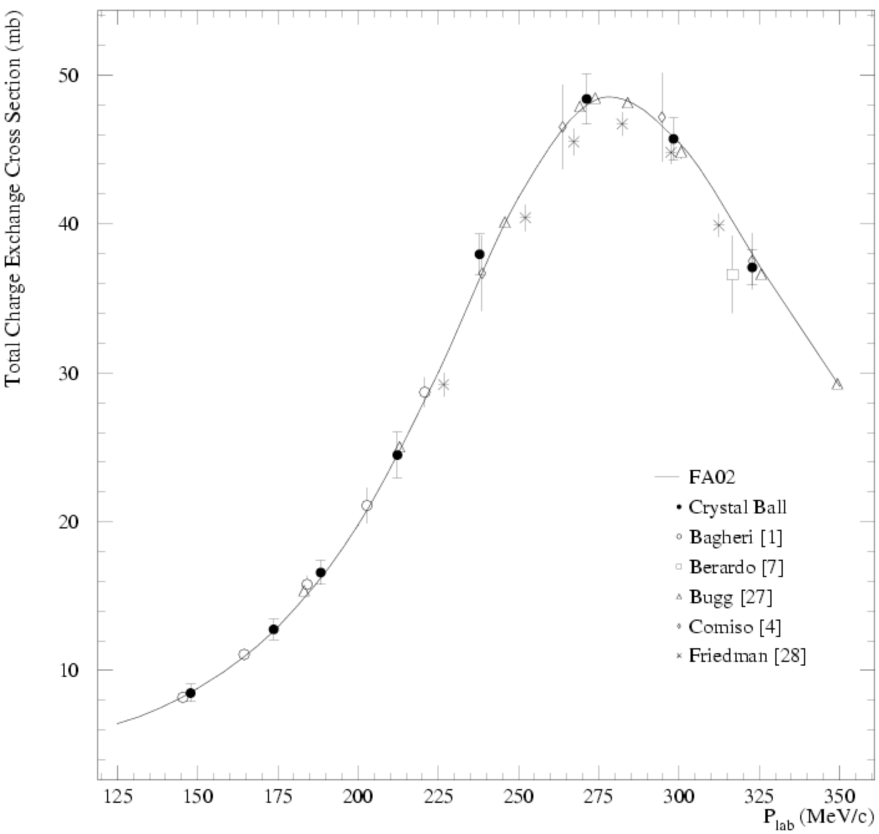
van Kolck, Niskanen & Miller, Phys. Lett. **B493**, 65 (2000)

SCX Cross Sections, _ Resonance



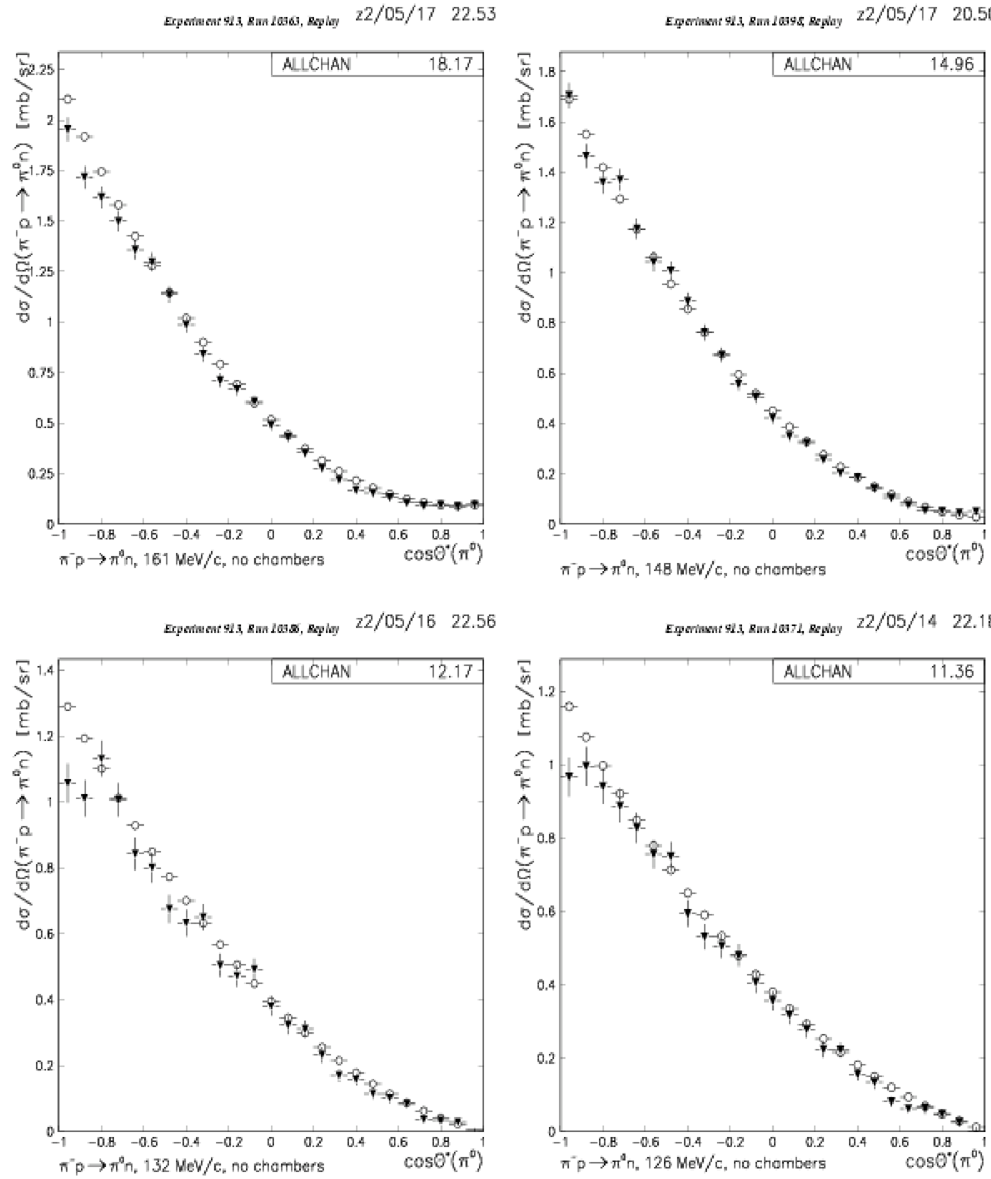
May 2002 'On-Line' Results

E913

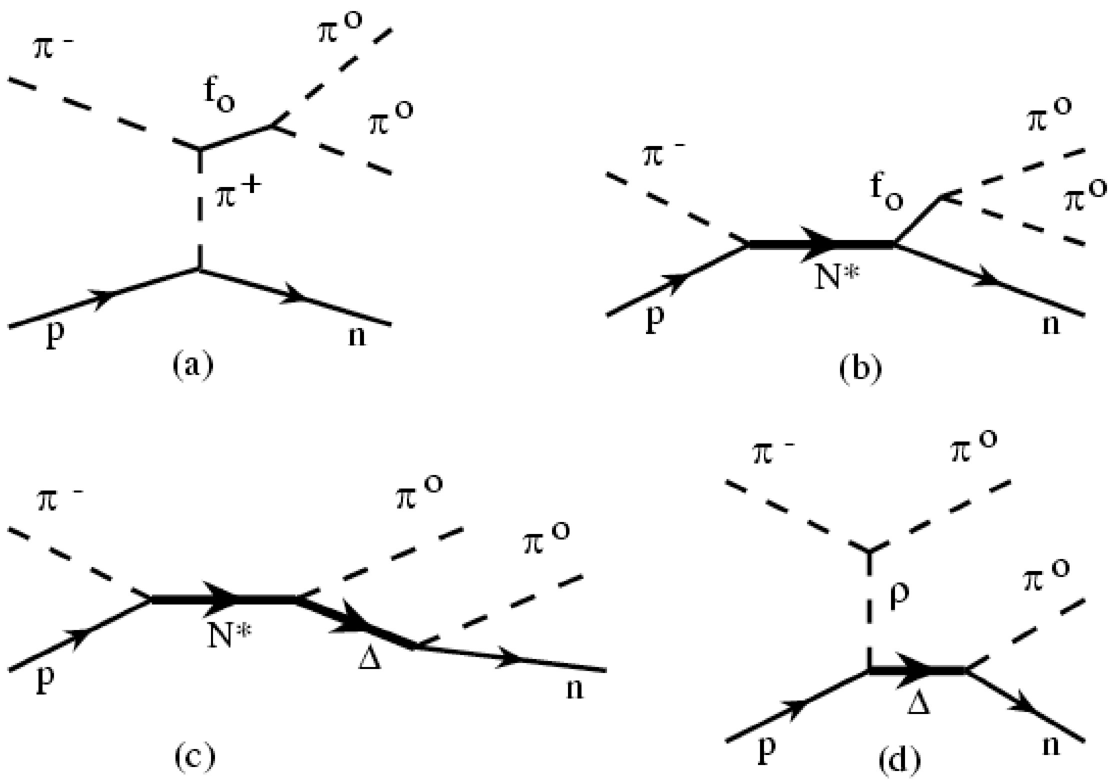


50 MeV 100 MeV

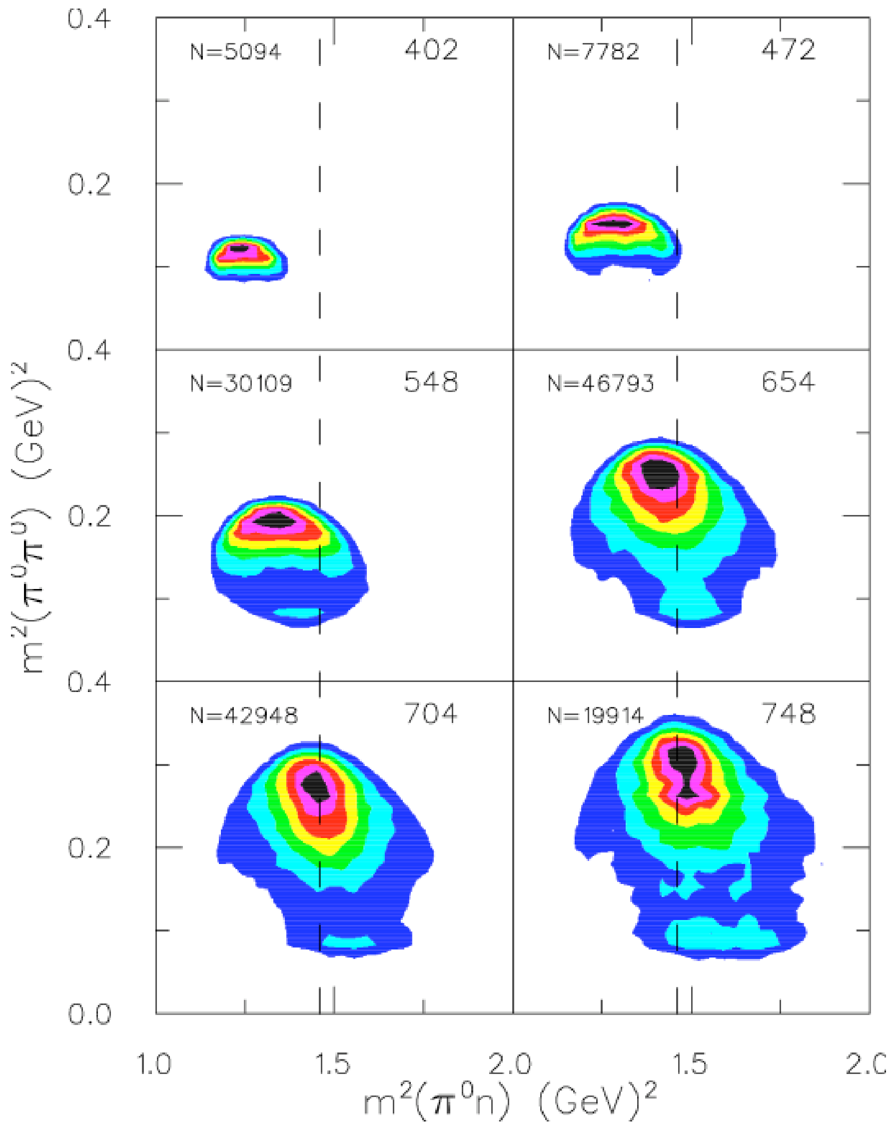
E958

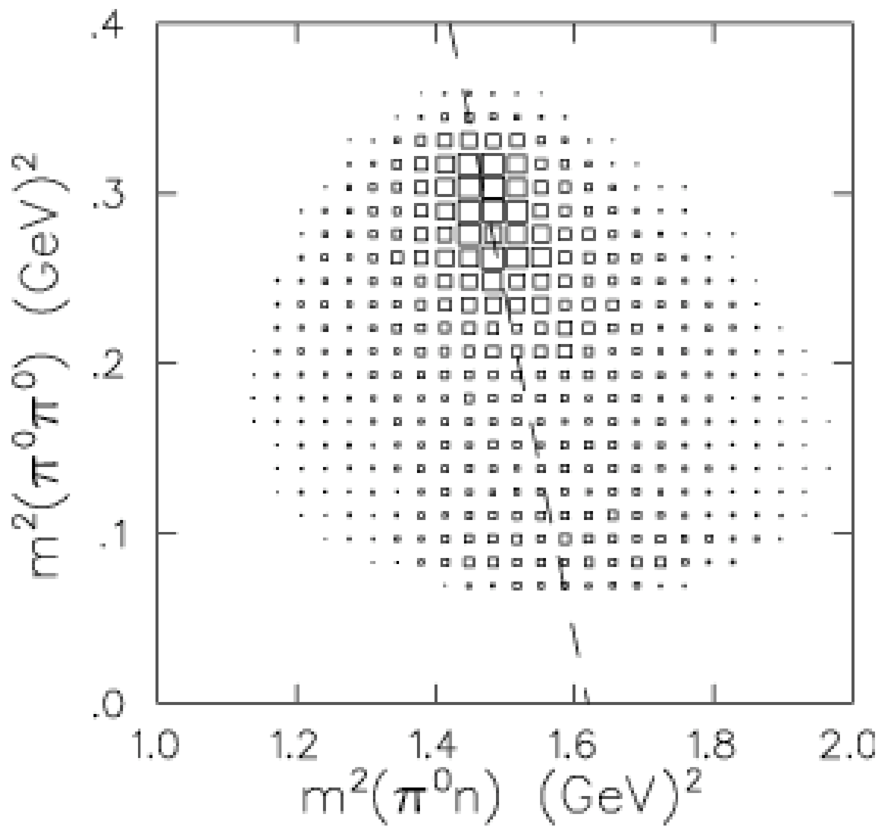


$\pi^- p$ _ $\pi^0 \pi^0 n$

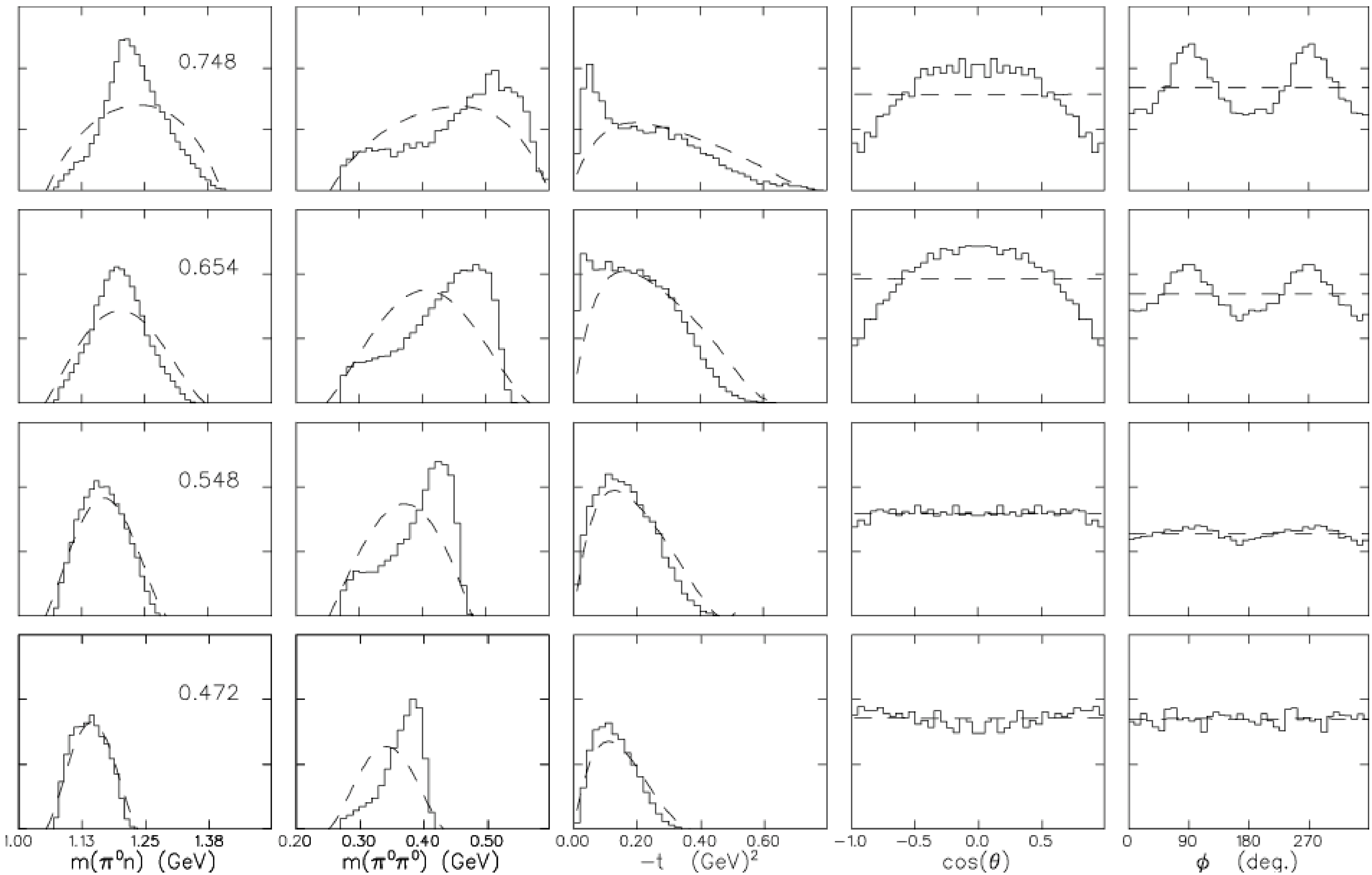


Dalitz Distributions





Data Distributions



Multipole Analysis

Amplitude

$$A = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \alpha_{\ell m} Y_{\ell}^{m}(\theta, \phi)$$

Intensity

$$\begin{aligned} I(s,t,M,\theta,\phi) &\equiv \frac{\partial^4 \sigma}{\partial t\, \partial M\, \partial(\cos\theta)\, \partial\phi} \\ N &\equiv 4\pi \langle I \rangle = \frac{\partial^2 \sigma}{\partial t\, \partial M} \\ W(\theta,\phi) &\equiv \frac{1}{N} I(\theta,\phi) \\ &= \sum_{L=0}^{\infty} \sum_{M=-L}^{L} a_{LM}\, \Re Y_L^M(\theta,\phi) \end{aligned}$$

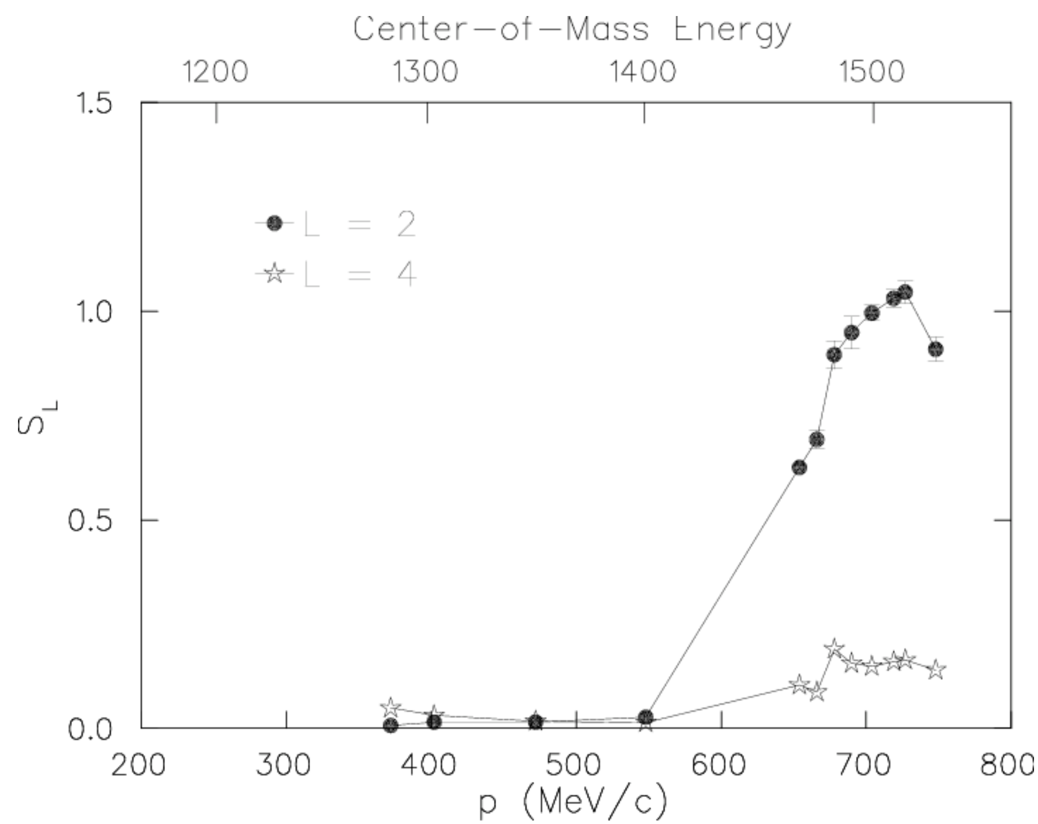
where $a_{00} = (4\pi)^{-\frac{1}{2}}$.

$L_{\max} = 2\,\ell_{\max}$

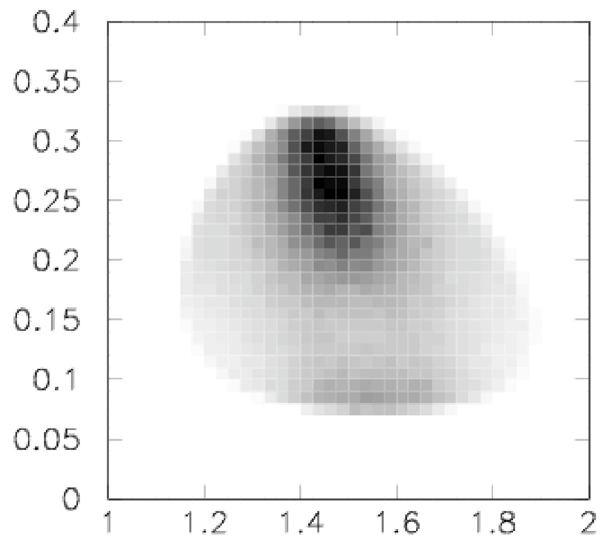
L =even only for decay of $\pi^0\pi^0$.

A measure of multipole strength:

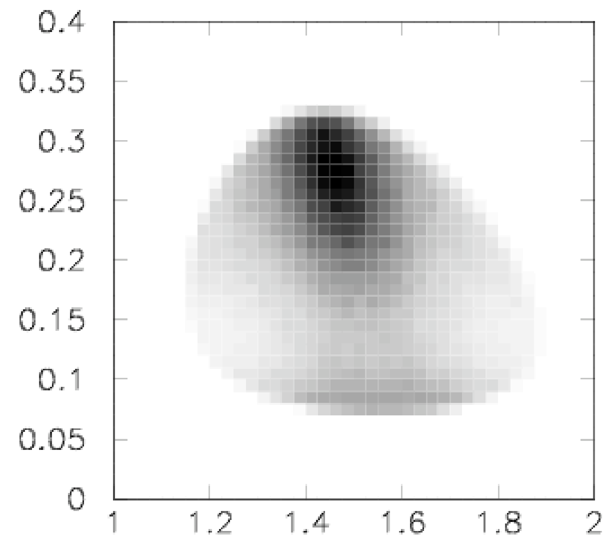
$$S_L = (2L+1) \sum_{M=-L}^{L} \left(\frac{a_{LM}}{a_{00}}\right)^2$$



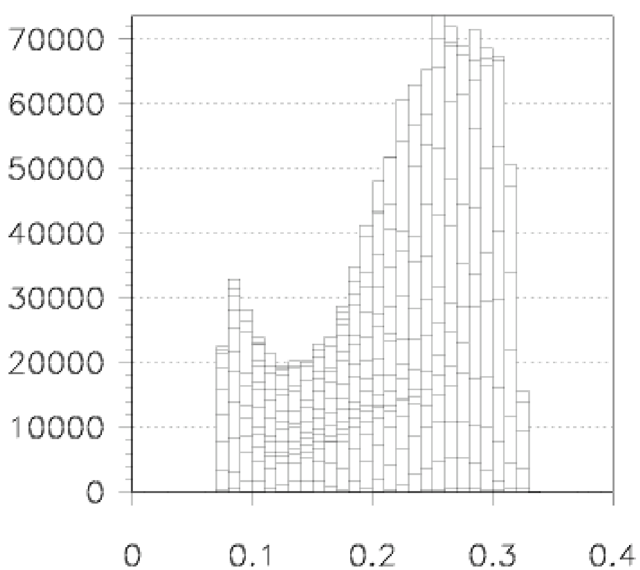
$\pi^- p$ _ π^0 _^{0} _ $\pi^0\pi^0$ n



Em2(2pi0) vs Em2(pi0n), noworm, Pbm=.705-.73



Em2(2pi0) vs Em2(pi0n), Pbm=.705-.73



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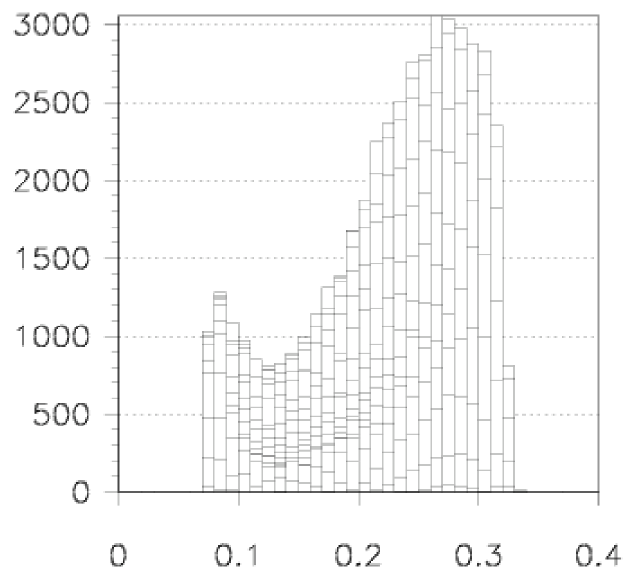


Em2(2pi0) vs Em2(pi0n), Pbm=.705-.73

_ Meson Decays

Symmetry Operators

Operator	η	π^0	γ
Charge Conjugation	$+1$	$+1$	-1
Parity	-1	-1	-1

$\eta \rightarrow n\,\pi^0$

n = even: No (P and CP)

n = odd: Violates G (=CR) parity

$\eta \rightarrow n\,\gamma$

n = even: OK

n = odd: No (C)

(Note: n = odd includes $\eta \rightarrow m\pi^0\gamma$)

_ _ 4 π^0

_ _ 3 π^0

_ _ π^0 _ _

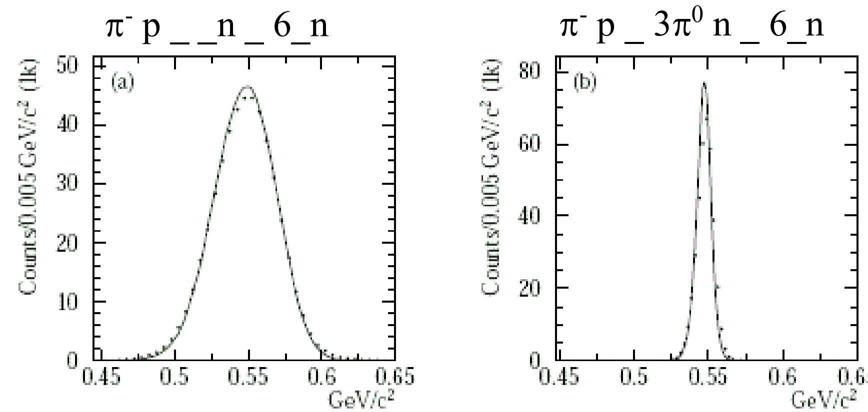
_ _ 3 _

Antonio Ramirez
Ph.D. Dissertation, ASU

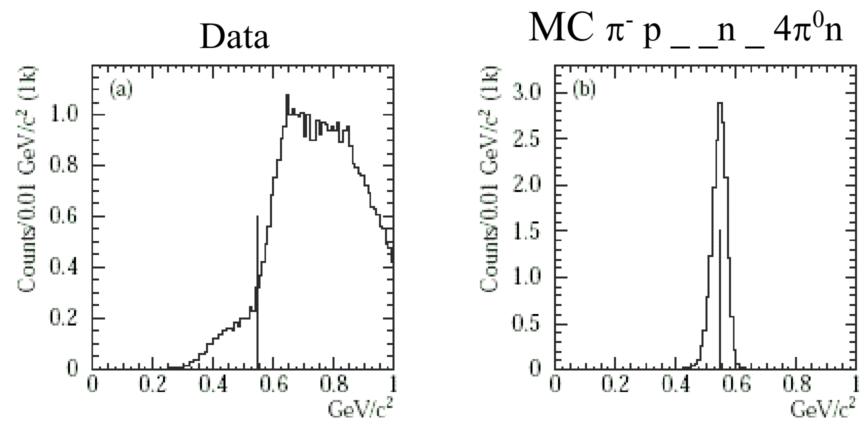
_ _ 4 π^0

- Violates CP.
- Measure $\mathcal{B} \leq 6.9 \times 10^{-7}$ ($\Gamma \leq 8.3 \times 10^{-4}$ eV).
- Use a model for phase-space corrections, involving $2\pi^0$ and $4\pi^0$ decays of $f_0(1500)$.
- Estimate $< 2\%$ violation in quark-family-conserving interactions.

Kinematic Fit



8_ Events



_ _ 3 π^0

- Violates G parity.

- Decay amplitude depends on $m_u - m_d$.

- Parameterize M.E. $|M|^2 \propto 1 + 2\alpha z$, $z = \rho^2/\rho^2_{\rm max}$. ($\rho$ is dist. from center of Dalitz plot.)

- Theory —

  α term arises at $\mathcal{O}(p^6)$

  Kambor *et al.*, (1996); dispersive

  α = -0.014 to -0.007

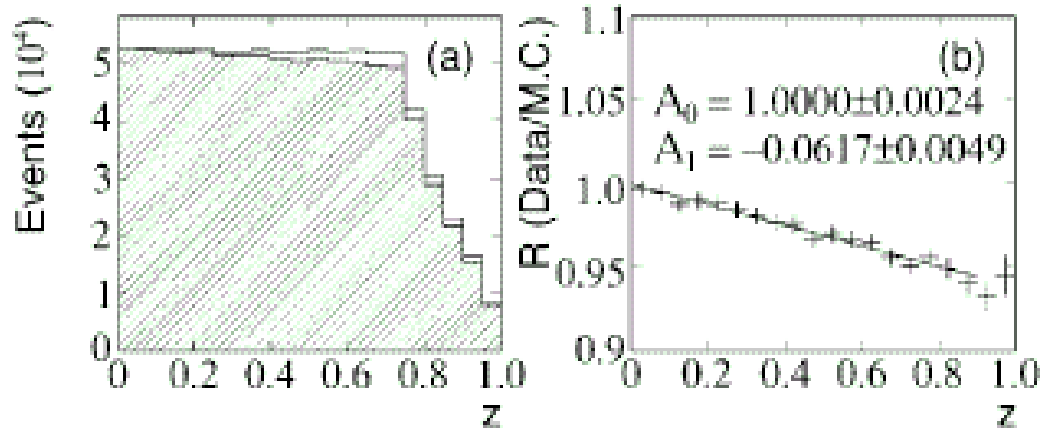
- Prior Experiment —

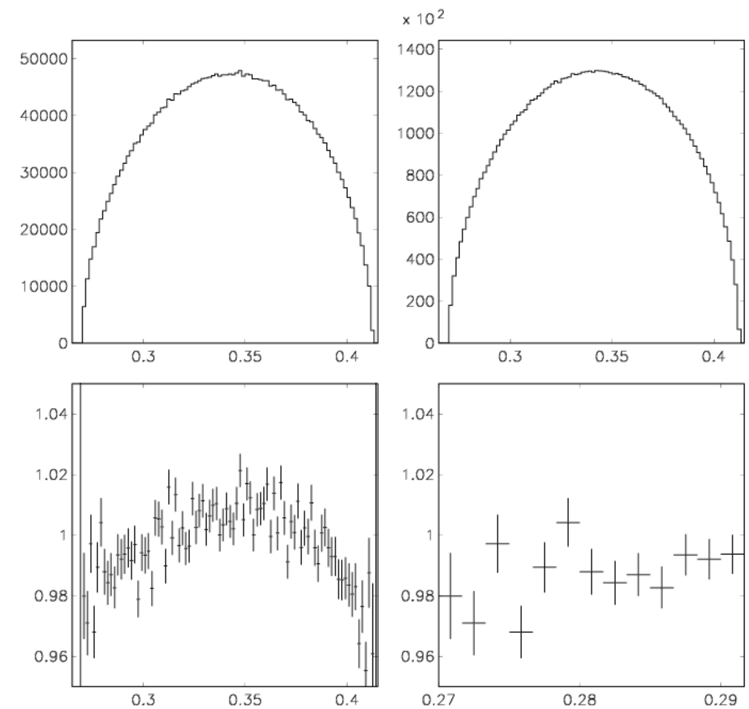
  -0.022 ± 0.023 GAMS 2000 (1984)

  -0.052 ± 0.02 Crystal Barrel (1998)

- Our Result —

  $\alpha = -0.031 \pm 0.004$





IM ($2\pi^0$)

Regina Analysis Criteria

Channels Considered

π^- p _ _n _ π^0 __ n

π^- p _ _n _ $3\pi^0$ n

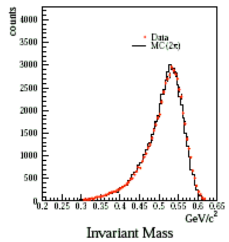
π^- p _ $\pi^0 \pi^0$ n

Cuts

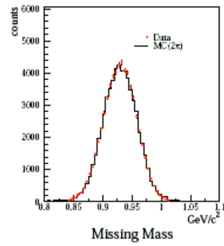
4 clusters
4 connected regions
Exclude events with cluster center on a guard crystal
Miss. Mass: $0.88 < m_n < 0.98$ GeV
Inv. Mass > 0.5 GeV
$0.62 < E_{thresh} < 0.80$ GeV
One and only one π^0
m > 0.19 GeV
Non-peak energy ratio > 0.05 for each of 4 clusters

MC/Data Comparison

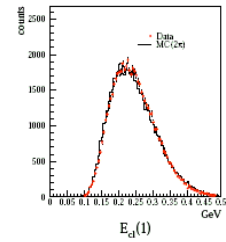
π^{-} p _ $\pi^{0}\pi^{0}$ n



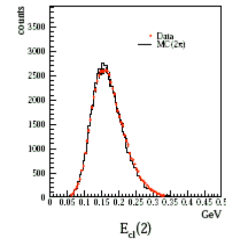
(a) Invariant Mass



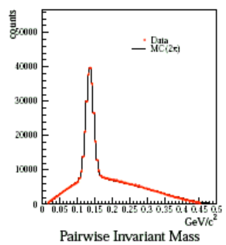
(b) Missing Mass



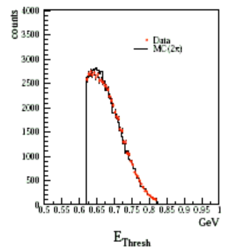
(a) Cluster #1



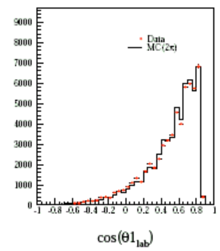
(b) Cluster #2



(c) Pairwise Invariant Mass − m_{π^0}



(d) Threshold Energy



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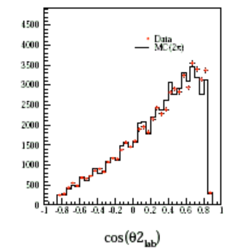
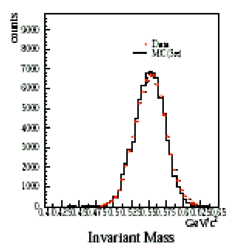


(b) Cluster #2

π^{-} p _ $3\pi^{0}$ n



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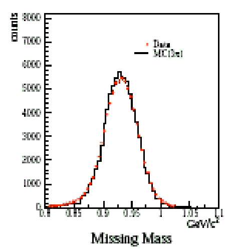
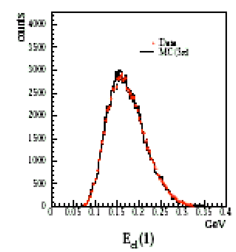


(b) Missing Mass



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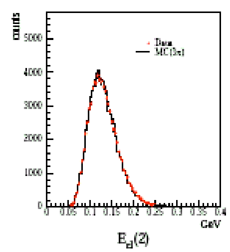
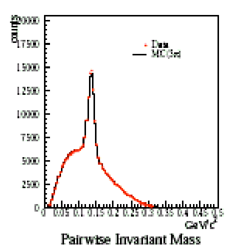


(b) Cluster #2



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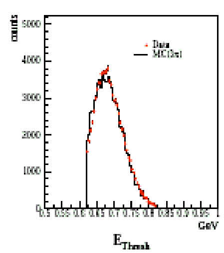
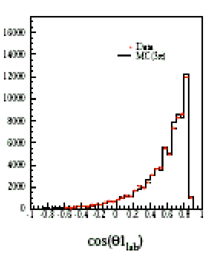


(d) Threshold Energy



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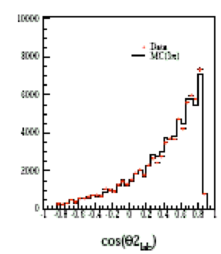
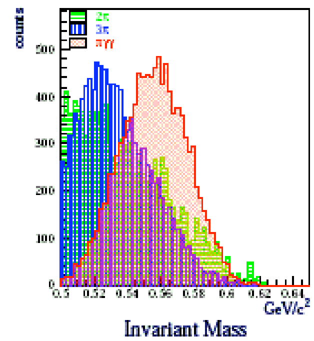


(b) Cluster #2

Likelihood Analysis

Likelihood Variables

Invariant Mass
Missing Mass
CM angle of combined
 4-photon system
Non-peak energy ratio for
 each of 4 clusters
Fractional 2-pion mass
 difference
Transverse Momentum
Peak crystal energy in each
 of 4 clusters



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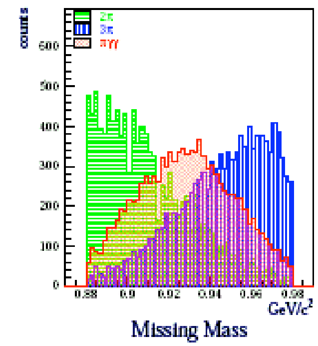
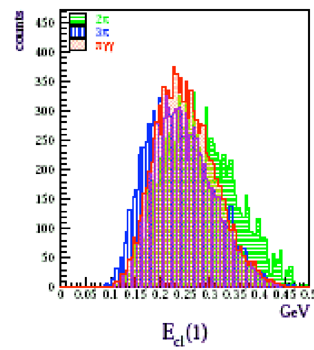


(b) Missing Mass



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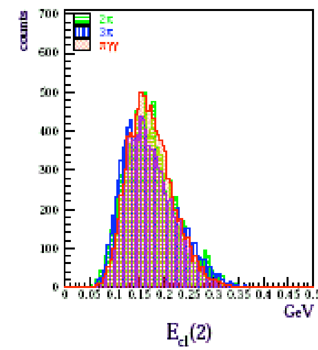
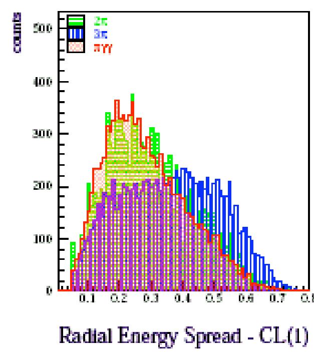


(b) Cluster #2



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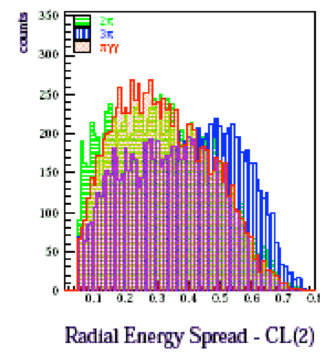
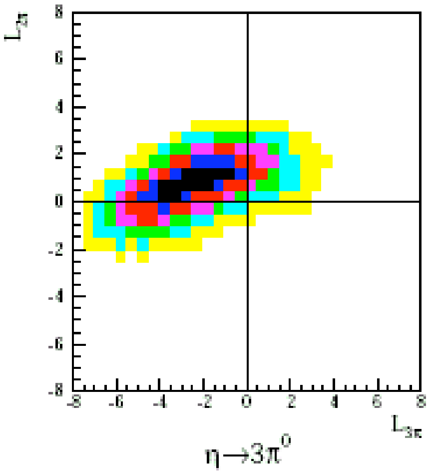


(b) Cluster #2

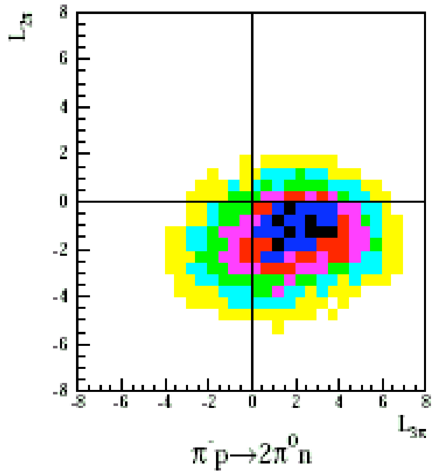
Data Analysis

MC

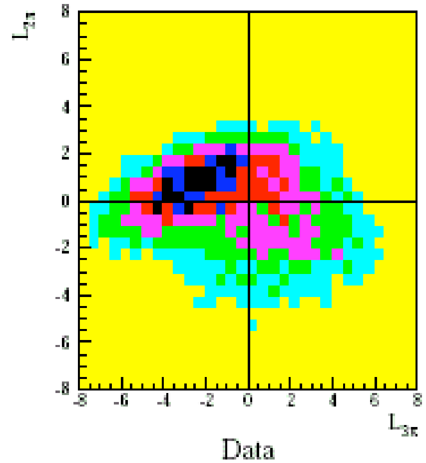
Data



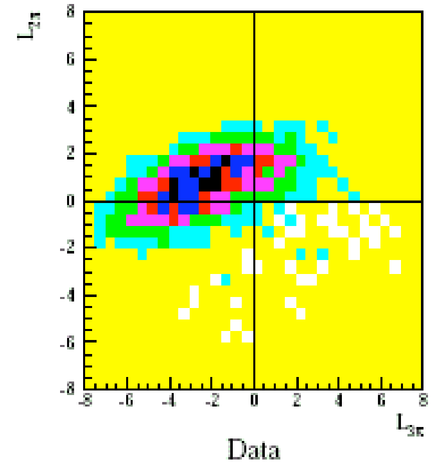
(a) MC – $\eta \to 3\pi^0$



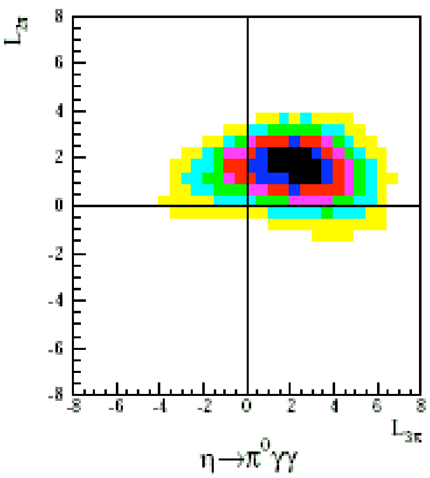
(b) MC – $\pi^- p \to \pi^0\pi^0 n$



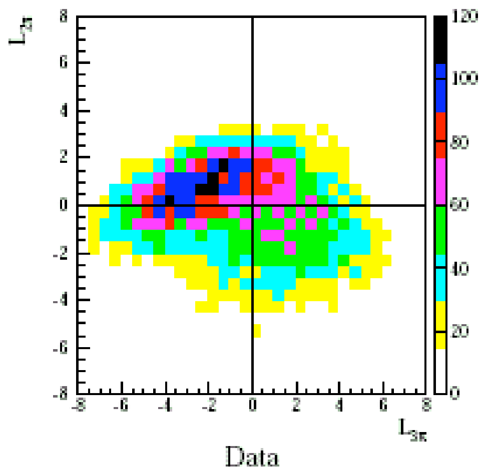
(a) Data



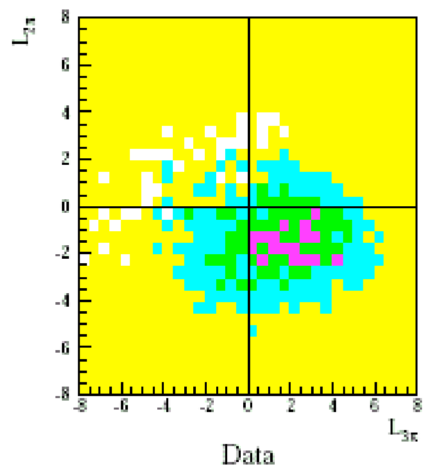
(b) Data-MC($\pi^- p \to \pi^0\pi^0 n$)



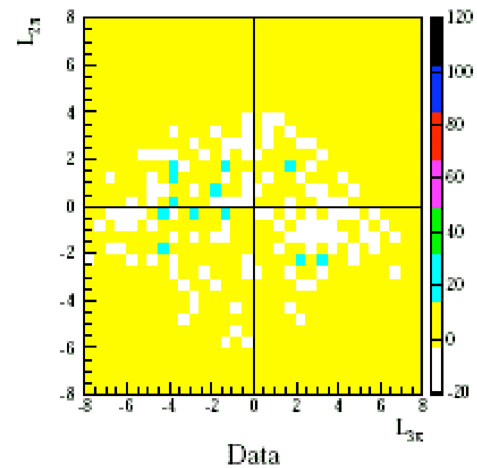
(c) MC – $\eta \to \pi^0\gamma\gamma$



(d) Data



(c) Data-MC($\eta \to 3\pi^0$)



(d) Data - MC($\pi^- p \to \pi^0\pi^0 n + \eta \to 3\pi^0$)

UCLA Analysis

Similar channels to Regina analysis
   Added _ _ 2_ (with double splitoffs)

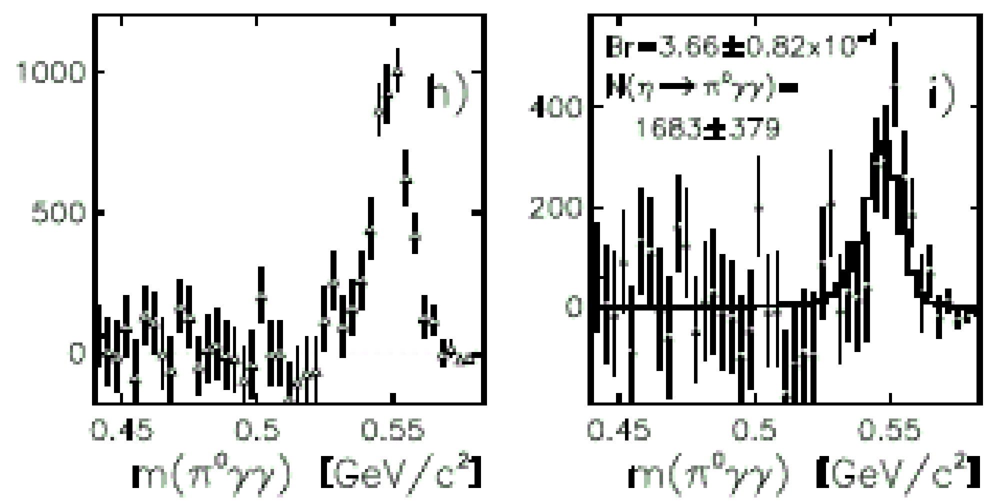
Kinematic fit analysis
   Target Z position is fitting variable

Better beam treatment; many more events

Good MC reproduction of various reaction data

Cluster radius is a cut parameter

Subtract MC from data



π^- p _ _n _ π^0 __ n Results

Regina

$$BR = (2.7 \pm 0.7_{stat.} \pm 0.8_{syst.}) \text{ x } 10^{-4}$$

_ = 0.32 ± 0.14 eV

UCLA

$$BR = (3.5 \pm 0.7_{stat.} \pm 0.6_{syst.}) \text{ x } 10^{-4}$$

_ = 0.41 ± 0.08 eV

Analysis and Reactions

Neural Network

$2\pi^0 n$

2_X

$3\pi^0 n$

π^0 __ n

$\pi^0 n$

Cuts

Neutral Trigger

Beam tracking cut

Target cut

Veto counter cut

Worm cuts

Near-edge cuts

Event has 3 clusters

CB thresthold cut

Joint cut on Miss. Mass and Inv. Mass

No electronics error flags; ADC overflows

_ _ 3 _ Results

'Traditional'	$(2.26 \pm 0.21) \times 10^{-2}$
ANN (all)	$(6.23 \pm 0.37) \times 10^{-3}$
ANN (> 0)	$(5.61 \pm 0.31) \times 10^{-3}$
GAMS	$< 5 \times 10^{-4}$
UCLA	4×10^{-5}

Summary and Conclusions

The Crystal Ball Program has been successful.

Fundamental physics has been probed with precision experiments.

High-quality data are being provided for pion SCX. Possible sensitivity to $m_u - m_d$.

$2\pi^0$ data has little evidence for f_0 (_) production.

Several decay modes are providing new lower limits on P, C, and CP.