Proton-Antiproton Annihilation into Three Pseudoscalar Mesons at 900 MeV/*c*

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CRYSTAL BARREL Collaboration

Quark Model

strong interaction
hadrons

mesons	baryons
spin 0,1,2 ...	spin $\frac{1}{2},\frac{3}{2},\frac{5}{2}$ ...
$q\bar{q}$	qqq
$\pi^+ = u\bar{d}$	$p = uud$

$$q = u, d, s, c, b, t$$

the quarks are bound by gluons:

$$S = 0, 1$$
$$L = 0, 1, 2, \ldots$$

$$n^{2S+1}L_J = nJ^{PC}$$

n	principal quantum number	
J	spin of meson	$\vec{J} = \vec{L} + \vec{S}$
P	parity	$P(q\bar{q}) = -(-1)^L$
C	charge parity	$C(q\bar{q}) = -(-1)^{L+S}$

$^1\mathrm{S}_0$	0^{-+}	pseudo scalar	$^3\mathrm{S}_1$	1^{--}	vector
$^3\mathrm{P}_1$	0^{++}	scalar	$^3\mathrm{P}_2$	2^{++}	tensor

Light Quarks

$$u, d, s \quad (\bar{u}, \bar{d}, \bar{s})$$

9 possible $q\bar{q}$ combinations for each J^{PC}

nonet

isospin I:	u	$I = +\frac{1}{2}$
	d	$I = -\frac{1}{2}$
	s	$I = 0$

$I = 0$:	$f_J(....)$	e.g. $f_0(1500)$	J	spin
$I = 1$:	$a_J(....)$	e.g. $a_2(1320)$	....	mass

other possibilities:	gg	glueballs
	$q\bar{q}g$	hybrids
	$q\bar{q}q\bar{q}$	molecules

which are the nonet members ?

0^{++} Nonet

- too many 0^{++} mesons:

$f_0(980)$ 1	$a_0(980)$ 3	$f_0(1370)$ 1	$K_0^*(1430)$ 4
$a_0(1450)$ 3	$f_0(1500)$ 1	$f_0(1710)$ 1	$\sum$ 14

- lightest glueball (predicted by lattice QCD):

  0^{++}
  I = 0 (observed as $f_0(....)$)
  m = 1500 - 1700 MeV/c^2

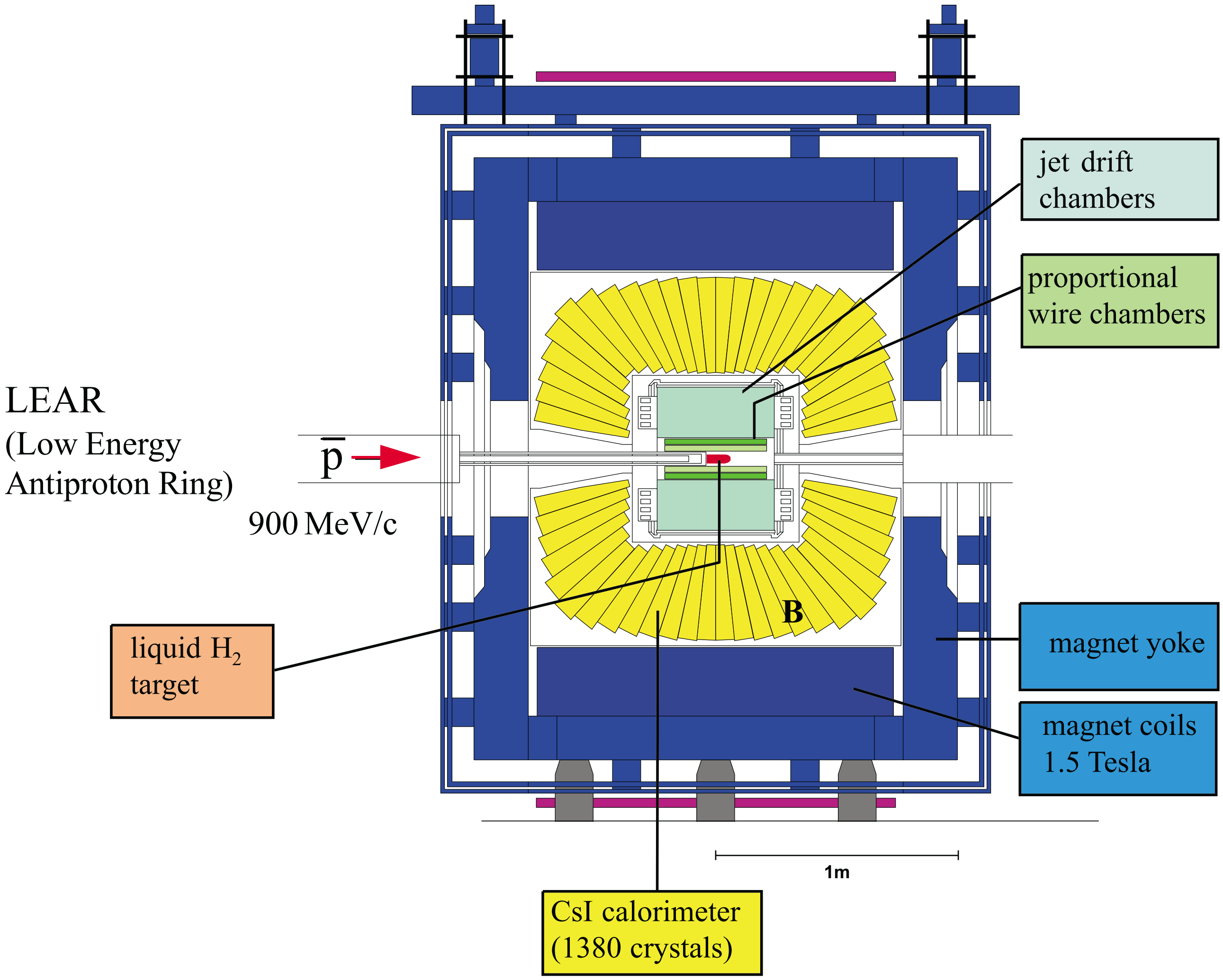
- which is the $s\bar{s}$ member ? $f_0(1500) \Leftrightarrow f_0(1710)$?

search for the decay of the $f_0(1710)$ into $\pi\pi$ and $\eta\eta$

$$\bar{p}p \rightarrow \pi^0 \; f_0(1710) \rightarrow \pi^0\pi^0\pi^0$$
$$\rightarrow \pi^0\eta\eta$$

Crystal Barrel Experiment (CERN)

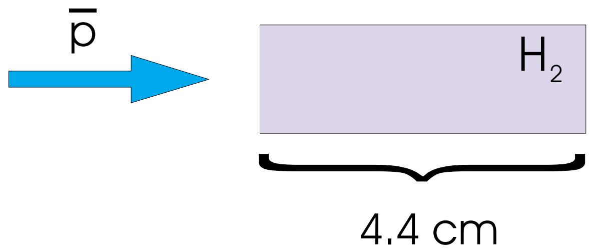
1989 - 1996



- highly efficient detection of charged and neutral particles
- good energy and momentum resolution of final state particles
- solid angle coverage: 97% 4π neutral particles
95 – 64% 4π charged particles
- efficient hard- and software trigger (e.g. 'all neutral')

<u>Data Selection</u>

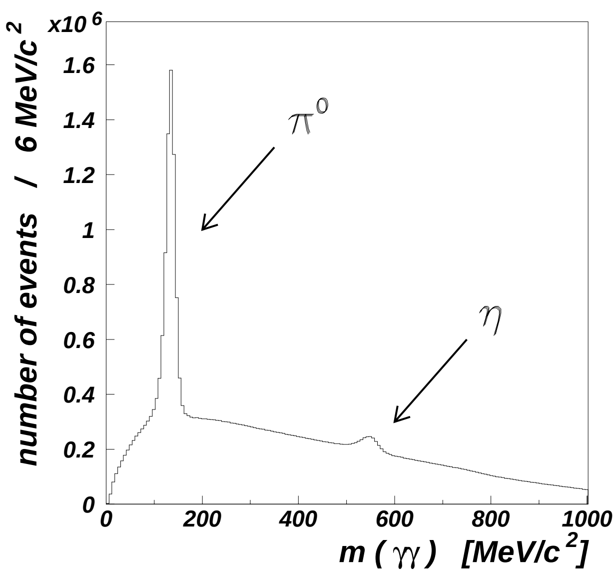
- $\bar{p}p$ annihilation in-flight at 900 MeV/c



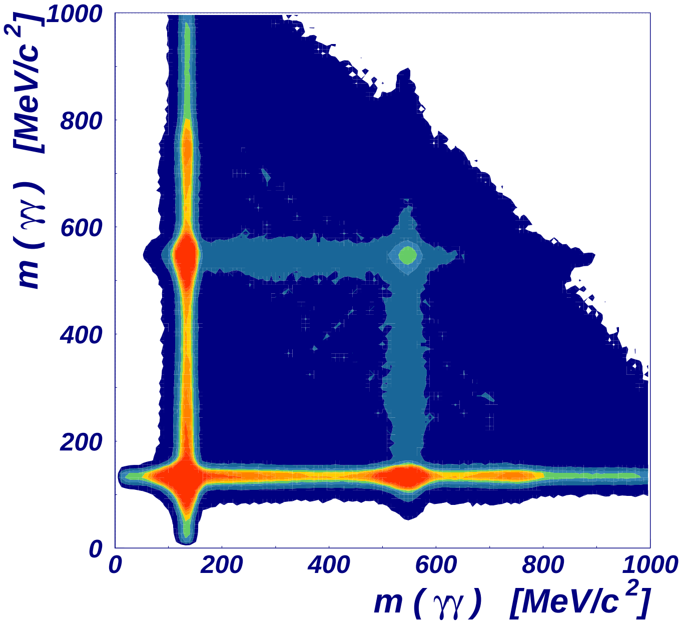
- 6 photon final states,
  selected from 17.8 M 'all neutral' triggered events on tape

$\pi^0\pi^0\pi^0$		
$\pi^0\pi^0\eta$	$\pi^0 \to \gamma\gamma$	$(99\ \% \to \gamma\gamma)$
	$\eta \to \gamma\gamma$	$(39\ \% \to \gamma\gamma)$
$\pi^0\eta\eta$		

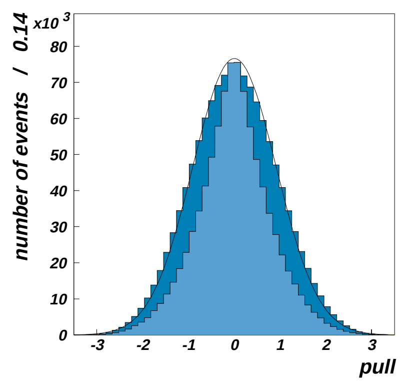
- all possible 15 $\gamma\gamma$ combinations of 6 photons:



- 4γ combinatorics:
  $(+\ \pi^0 \to \gamma\gamma)$



- kinematic fit:
  - energy/momentum conservation
  - masses of π^0/η
  - free annihilation vertex along z



- anti-cuts against: crosstalk
  background (e.g. $\omega\omega$)

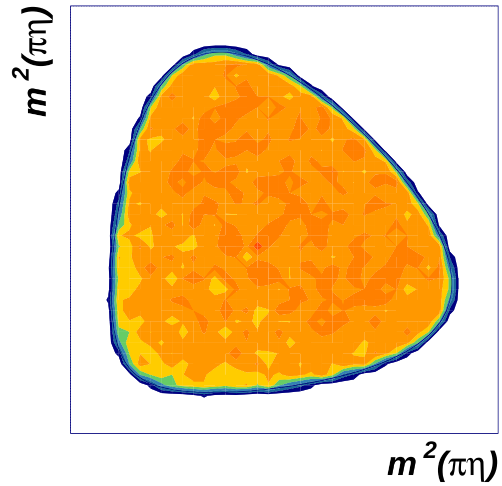
600'962	$\pi^0\pi^0\pi^0$	events
156'886	$\pi^0\pi^0\eta$	
16'081	$\pi^0\eta\eta$	

- same selection chain for Monte Carlo simulated events
  (efficiencies ~ 26 %)

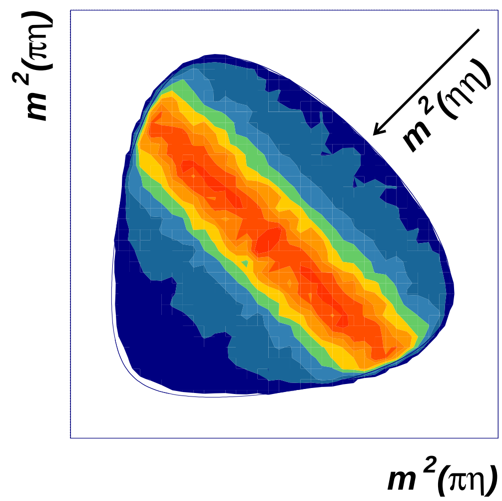
Dalitzplot

invariant mass squares: $m_{ij}^2 = (E_i + E_j)^2 - (\vec{p}_i + \vec{p}_j)^2$

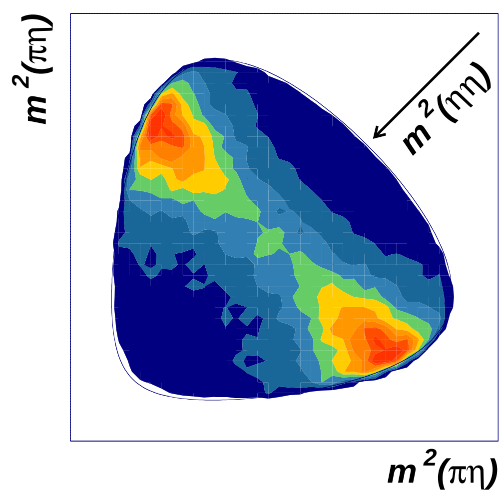
no resonance (phase space):
Dalitzplot homogenously populated



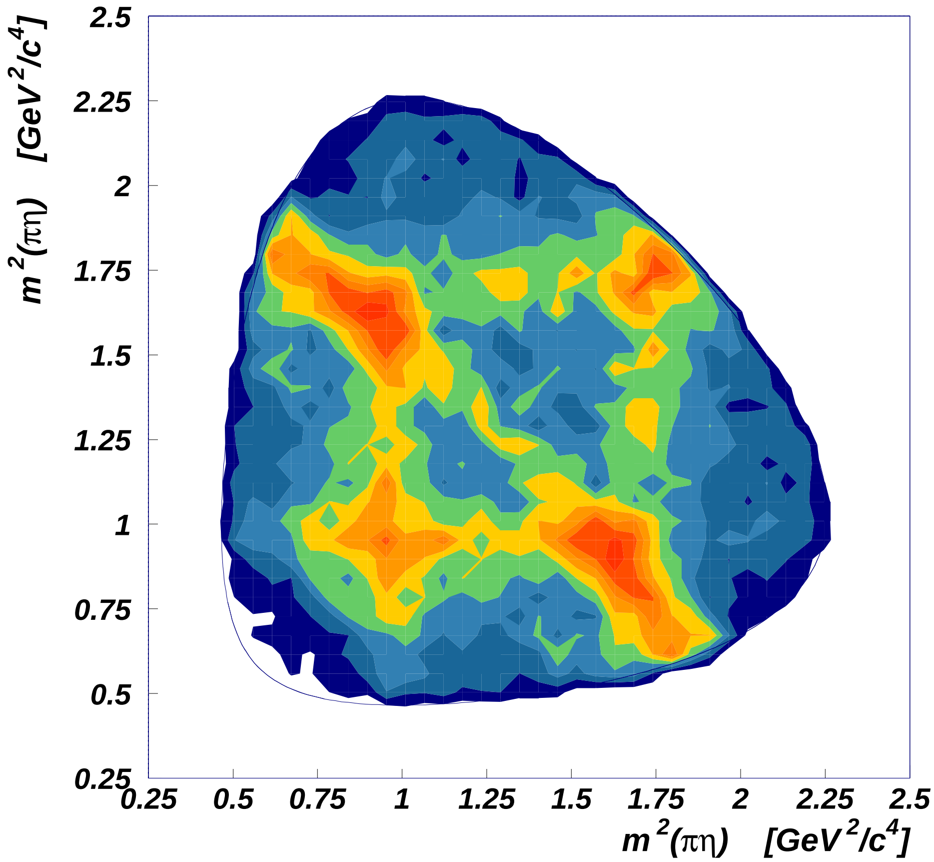
resonance (no spin):
band in Dalitzplot



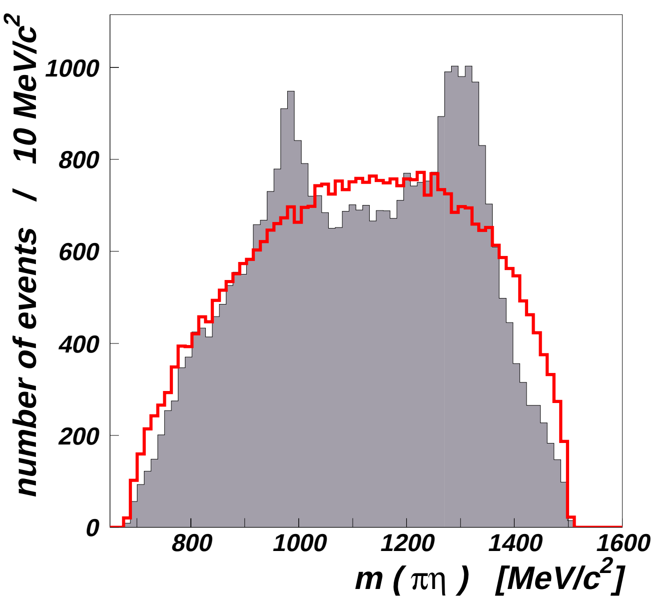
resonance (with spin):
band with angular distribution

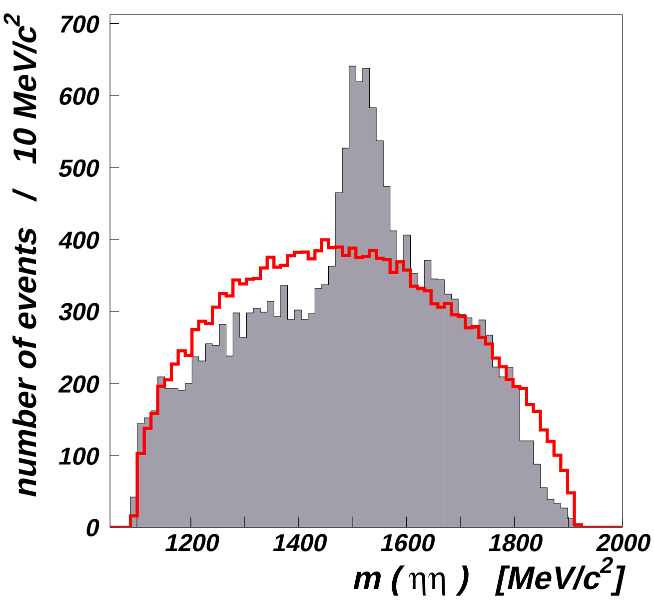


$\pi^0\eta\eta$ Data



$\pi^0\eta\eta$ Dalitzplot





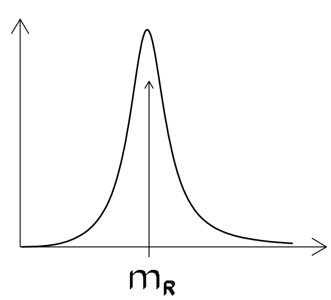
Projections of the Dalitzplot

Partial Waves

$\overline{p}p$	J	total spin of the $\overline{p}p$ system
	M	helicity (projection of spin onto z-axis)
$f_2\ \pi^0$	Ω	production angles of the resonance
	l	angular momentum between resonance and spectator
$\eta\eta\ \pi^0$	$\Omega^{'}$	decay angles of the resonance
	s	spin of the resonance
	λ	helicity of the resonance

$$A_M^{J^{PC}} = \alpha_{l,s}^{J^{PC}} \cdot H_M^{J^{PC}} \cdot f_M^{l,s,\lambda}(\Omega,\Omega^{'}) \cdot \widehat{F}(m)$$

$\alpha_{l,s}^{J^{PC}}$	resonance production strength
$H_M^{J^{PC}}$	$\overline{p}p$ production amplitude
$f_M^{l,s,\lambda}(\Omega,\Omega^{'})$	helicity amplitude
$\widehat{F}(m)$	dynamical function, K-matrix or Breit-Wigner function



Partial Wave Analysis

weight of i^{th} event $\propto$ probability :

$$w_i = |\sum A^{S=0}_{M=0}|^2 + |\sum A^{S=1}_{M=-1}|^2 + |\sum A^{S=1}_{M=0}|^2 + |\sum A^{S=1}_{M=1}|^2$$

maximise likelihood of the n events :

$$\mathcal{L} = n! \prod_{i=1}^{n} P_i = n! \prod_{i=1}^{n} \frac{w_i}{\sum w_j^{MC}}$$

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high statistics data sets:

- recalculate w_i in every iteration step for every event (data and Monte Carlo) ($\sim$ 1'000'000 events for $\pi^0\pi^0\pi^0$)
- typically 100'000 - 200'000 iterations per fit

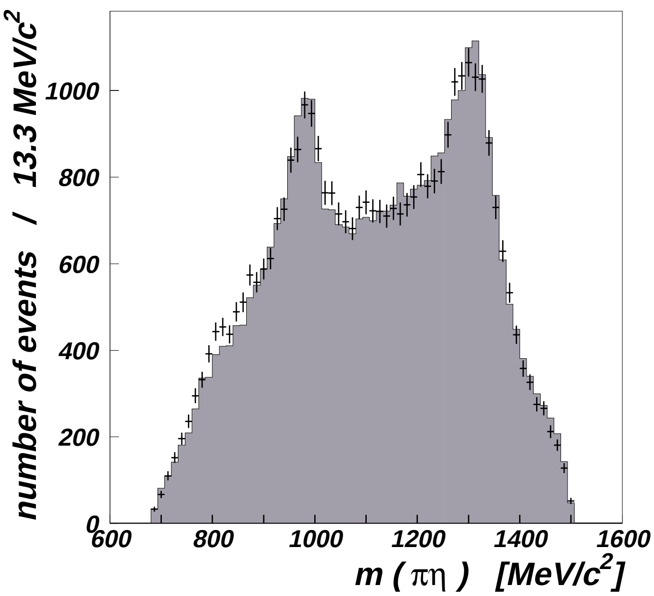
therefore:

- optimisation of the algorithms
- high performance hardware ($\sim$ 40 - 50 times faster than PC)

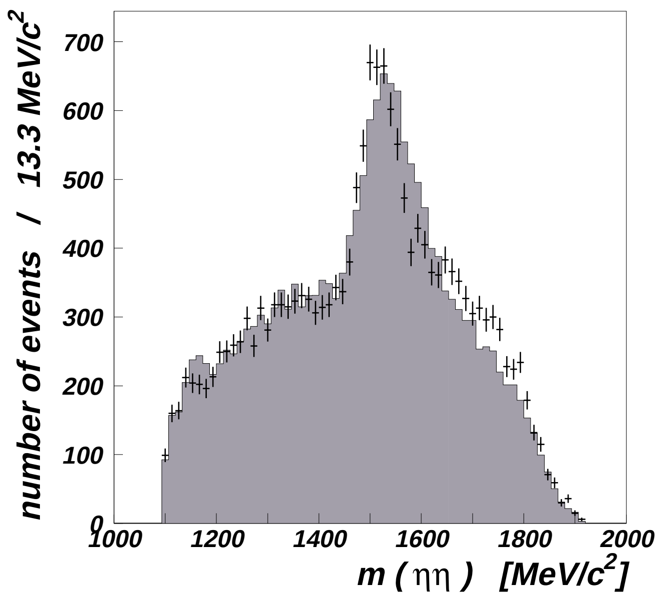
$\Rightarrow$ each fit lasted 10 - 20 hours

Basic Hypothesis for $\pi^0\eta\eta$

$$\bar{p}p \to f_0(1370) \quad \pi^0$$
$$\bar{p}p \to f_0(1500) \quad \pi^0$$
$$\bar{p}p \to a_0(980) \quad \eta$$
$$\bar{p}p \to a_0(1450) \quad \eta$$
$$\bar{p}p \to a_2(1320) \quad \eta$$



$m(\pi^0\eta)$



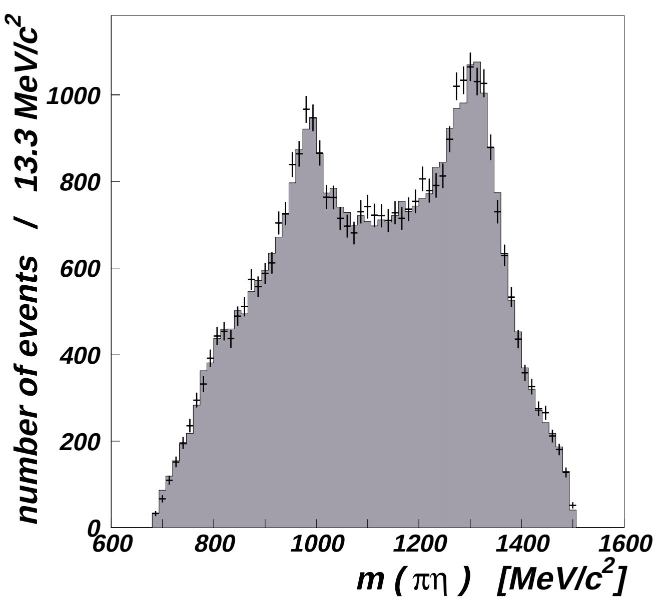
$m(\eta\eta)$

$$N_{parameter} = 45$$
$$\chi^2/\ dof = 1466/770 = 1.90 \quad \text{(Dalitz plot)}$$

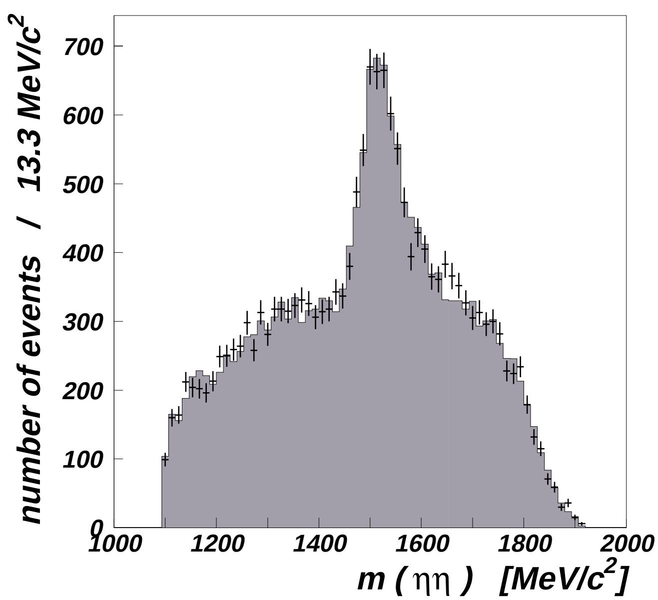
Best Hypothesis for $\pi^0\eta\eta$

$\bar{p}p \to f_0(1370)\ \pi^0$	$\bar{p}p \to a_0(1450)\ \eta$
$\bar{p}p \to f_0(1500)\ \pi^0$	$\bar{p}p \to f_2'(1525)\ \pi^0$
$\bar{p}p \to a_0(980)\ \eta$	$\bar{p}p \to f_2(1820)\ \pi^0$
$\bar{p}p \to a_2(1320)\ \eta$	no $f_J(1710)$

$m_{f_2} = 1820 \,{}^{+\,57}_{-\,10}\ \mathrm{MeV}/c^2 \qquad \Gamma_{f_2} = 358 \pm 42\ \mathrm{MeV}/c^2$



$m(\pi^0\eta)$



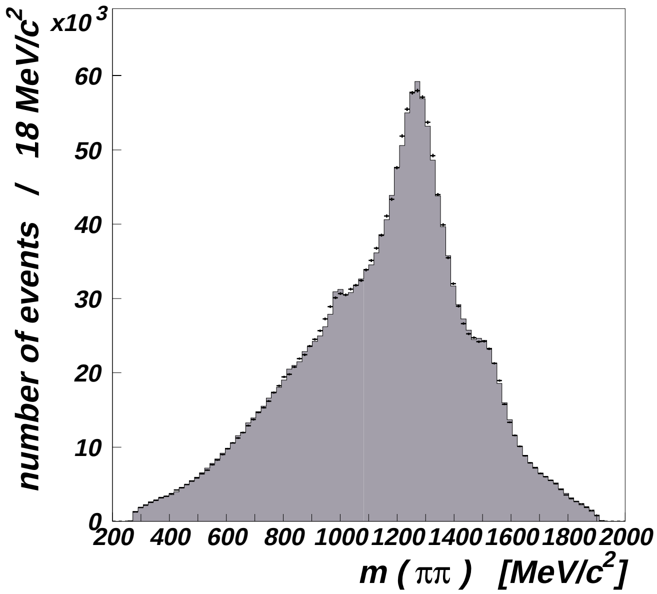
$m(\eta\eta)$

$N_{parameter} = 101$

$\Delta \log(\mathcal{L}) = 1'783$

$\chi^2/\ dof = 855/770 = 1.11$ (Dalitz plot)

Best Hypothesis for $\pi^0\pi^0\pi^0$



requires a $f_2(1880)$ with: $m = 1877 \pm 30$ MeV$/c^2$

$\Gamma = 318 \pm 55$ MeV$/c^2$

no $f_J(1710)$

is the $f_2(1880)$ the same object as in $\pi^0\eta\eta$ with
$m = 1820 \,^{+\,57}_{-\,10}$ MeV$/c^2, \Gamma = 358 \pm 42$ MeV$/c^2$?

$\Rightarrow$ coupled fit of $\pi^0\eta\eta$ and $\pi^0\pi^0\pi^0$

some parameters are the same in both data sets,
e.g. mass and width of the $f_2(1880)$

$\Rightarrow$ good simultaneous description of both data sets

Results

$f_2(1870)$

- ◇ first observation of a broad 2^{++} state around 1900 MeV/c^2 decaying into $\pi^0\pi^0$ and $\eta\eta$
- ◇ mass: 1867 ± 46 MeV/c^2
  width: 385 ± 58 MeV/c^2
- ◇ $$\frac{\gamma^2(f_2(1870) \to \eta\eta)}{\gamma^2(f_2(1870) \to \pi\pi)} = 0.20 \pm 0.07$$
- ◇ member of a radial excitation of the tensor nonet ?

$a_2(1660)$

- ◇ first definitive observation in the $\pi^0\pi^0\eta$ final state
- ◇ mass: 1698 ± 44 MeV/c^2
  width: 265 ± 55 MeV/c^2
- ◇ parameters in good agreement with previous measurement
- ◇ radial excitation ?

$f_J(1710)$

- ◇ not seen in $\pi^0\pi^0\pi^0$ and $\pi^0\eta\eta$ (upper limits)
  $\Rightarrow$ $f_J(1710)$ has a large $s\bar{s}$ content
- ◇ other experiments: $J = 0$, mostly $s\bar{s}$
- $\Rightarrow$ very likely the $s\bar{s}$ member of the 0^{++} nonet
- $\Rightarrow$ $f_0(1500)$ supernumerary:
  further evidence for the $f_0(1500)$ being the ground state glueball

Conclusions

- complete description of the $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$ and $\pi^0\eta\eta$ data sets at 900 MeV/c
- coupled fit of $\pi^0\pi^0\pi^0$ and $\pi^0\eta\eta$

- first observation of the $f_2(1870)$ in the $\pi^0\pi^0\pi^0$ and $\pi^0\eta\eta$ data sets
- first definite observation of the $a_2(1660)$ in $\pi^0\pi^0\eta$
- the $f_2(1565)$ is also required in $\overline{p}p$ annihilation in-flight
- high contribution of the $f_2^{'}(1525)$ to $\pi^0\eta\eta$