Do we see NFF in $e^+e^- \to$ hadrons in ISR study at BaBar?

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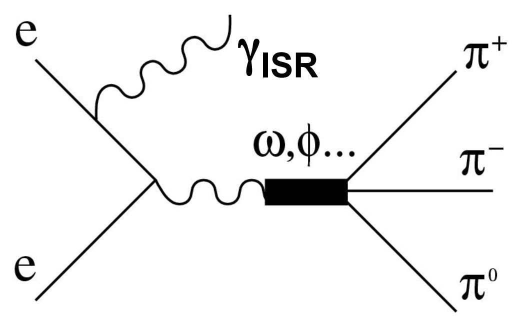
Representing BaBar collaboration

$$\frac{d\sigma(s,x)}{dx\,d(\cos\theta)} = W(s,x,\theta)\cdot\sigma_0\left(s(1-x)\right),$$

$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$



Motivation

- Low energy e^+e^- cross section dominates in hadronic contribution to g-2 of muon
- Poor direct e^+e^- data in 1.4 - 2.5 GeV region
- New information for hadron spectroscopy at low masses
  - dip at 1.9 GeV observed by FOCUS and DM2
- Access to charmonium region (J/ψ, $\psi(2S)$ decays)

- ISR at BaBar gives competitive statistic
- BaBar has excellent capability for ISR study
- All major hadronic processes are under study

$e^+e^- \to 2\mu\gamma, 2\pi\gamma, 2K\gamma, 2p\gamma, 2\Lambda\gamma$

$e^+e^- \to 3\pi\gamma$

$e^+e^- \to 2(\pi^+\pi^-)\gamma, K^+K^-\pi^+\pi^-\gamma, 2(K^+K^-)\gamma$

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma, \pi^+\pi^-\pi^0\pi^0\pi^0\gamma, K^+K^-\pi^0\pi^0\gamma, \pi^+\pi^-\pi^0\eta\gamma$ ...

$e^+e^- \to K^+K^-\pi^0\gamma, K^+K^-\eta\gamma$ ($KK^*\gamma, \phi\pi^0\gamma, \phi\eta\gamma$ ...)

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0\gamma, \pi^+\pi^-\pi^+\pi^-\eta\gamma, K^+K^-\pi^+\pi^-\pi^0\gamma$ ...

$e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\gamma$, $3(\pi^+\pi^-)\gamma$, $K^+K^-2(\pi^+\pi^-)\gamma$ – new results, this talk

Analysis procedure for $3(\pi^+\pi^-)$

- 232 fb^{-1} of BaBar data from "Raw" ISR Ntuples
- 400k of MC simulation (phase space for $e^+e^-\to 6\pi\gamma$ and $\rho 4\pi\gamma$)
- 100k of MC simulation (phase space for $e^+e^-\to 2K4\pi\gamma$)
- NLO radiative processes are included
- Background processes (from MC, normalized and subtracted):

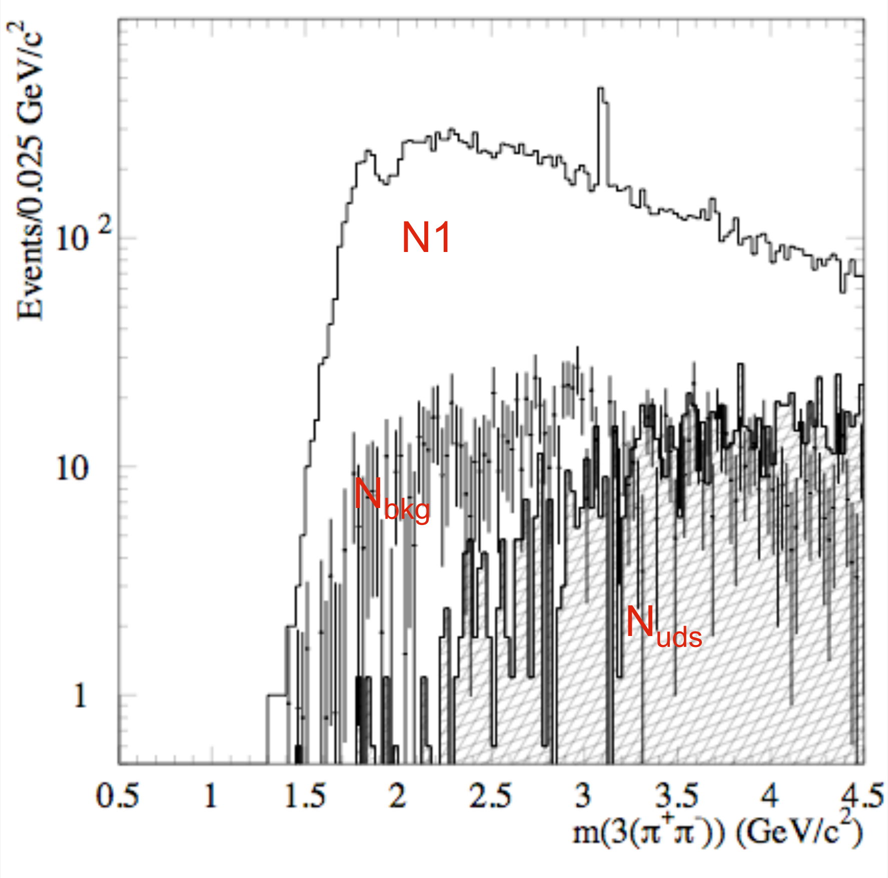
  $e^+e^- \to \tau^+\tau^-$

  $e^+e^- \to qq$ (q = u,d,s,c) - major background is from $e^+e^- \to 6\pi\pi^0$

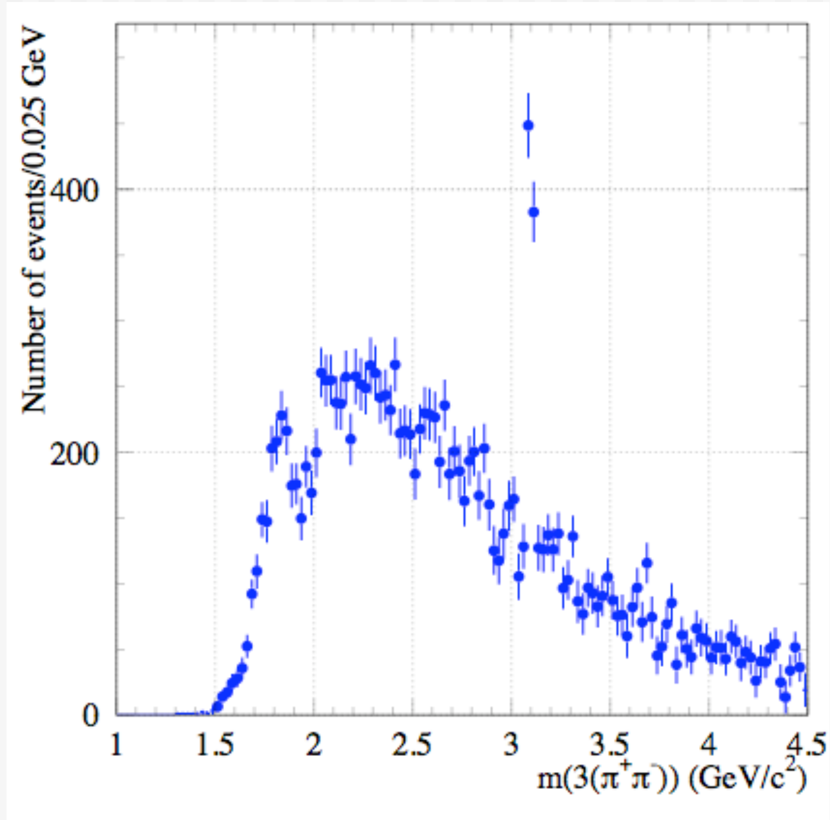
- 1C fit for events with ntrk=4; ISR photon is detected but not used in fit
- "ISR-type" background is subtracted using χ^2 side band
- If 1 or 2 kaon ID - $2K4\pi\gamma$ hypothesis is used.
- All procedures are the same as for $e^+e^-\to 4\pi\gamma$ analysis

  (published in Phys. Rev. D71 052001 (2005).

Signal events



N1 = 19683 events are selected



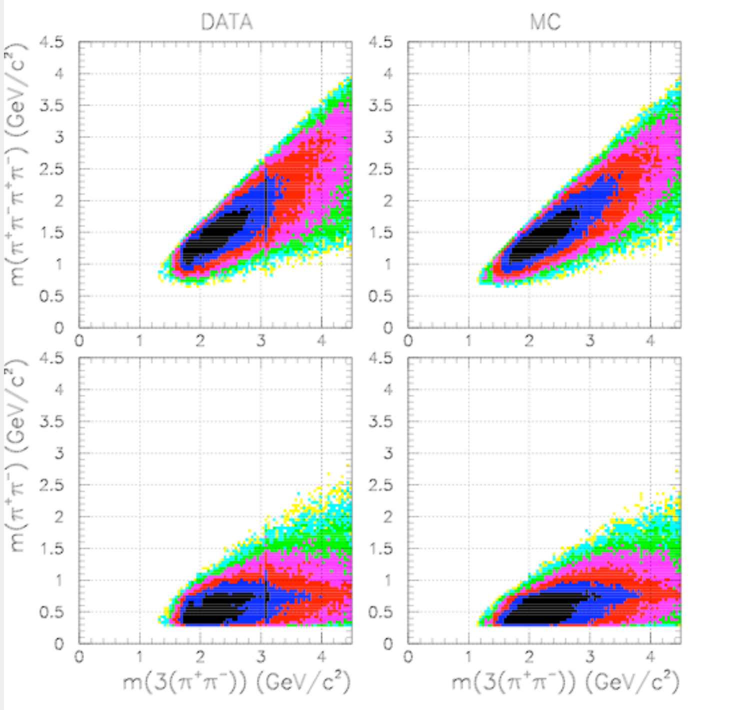
After background subtraction

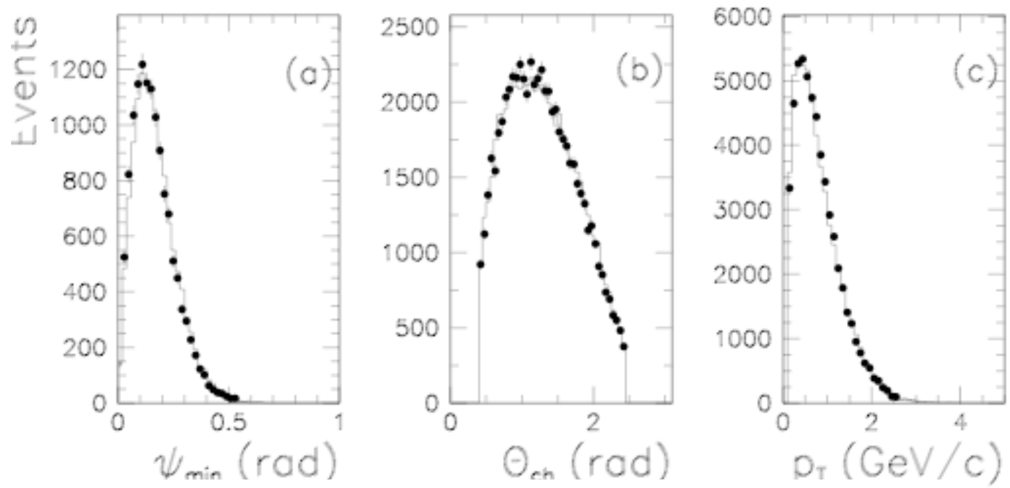
We estimate contribution of background:

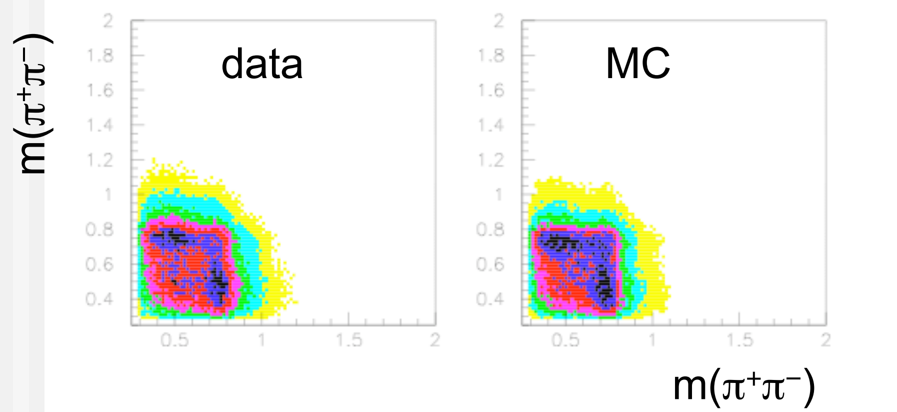
10 ± 3% in 1.5-3.0 GeV range

20 ± 5% in 3.0-4.5 GeV range

Comparison with MC simulation





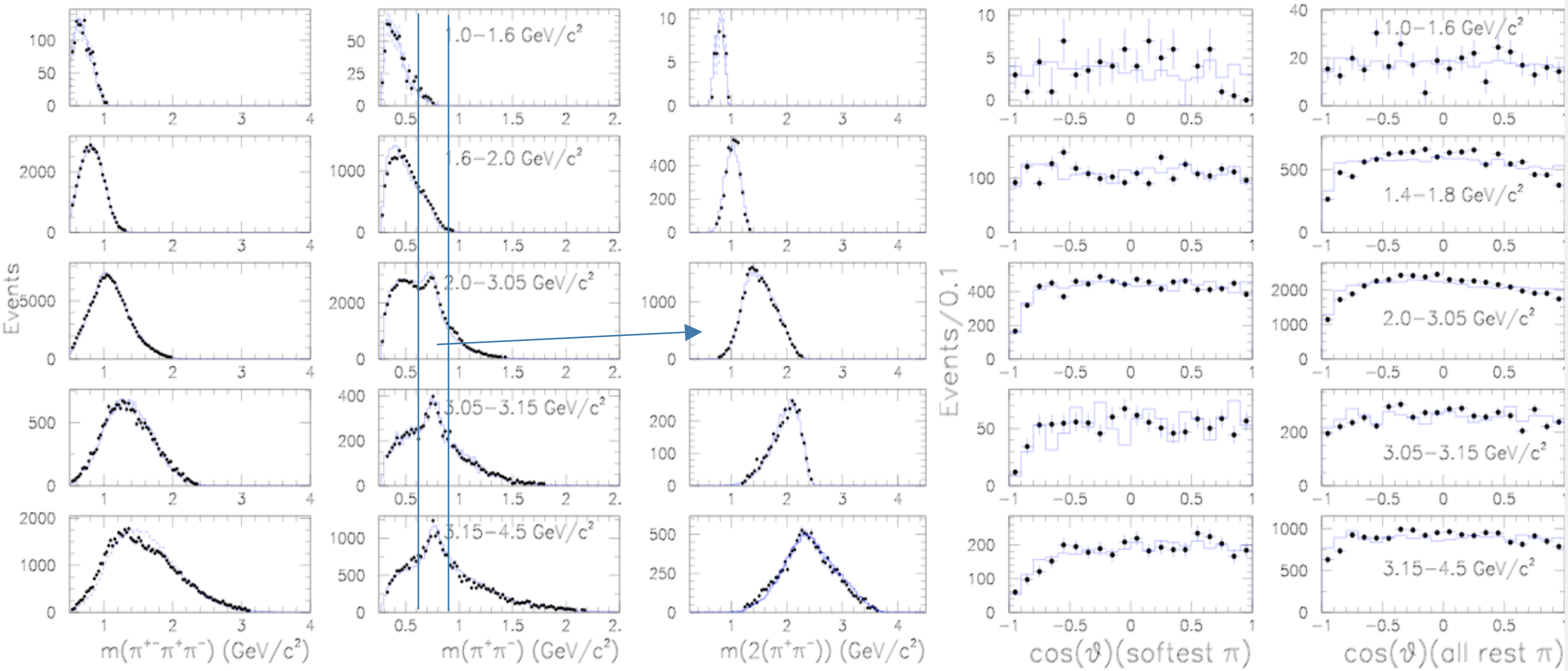


Generator with 1 ρ/event $e^+e^- \to \rho 4\pi \to 6\pi$ relatively good describes observables

Detail comparison

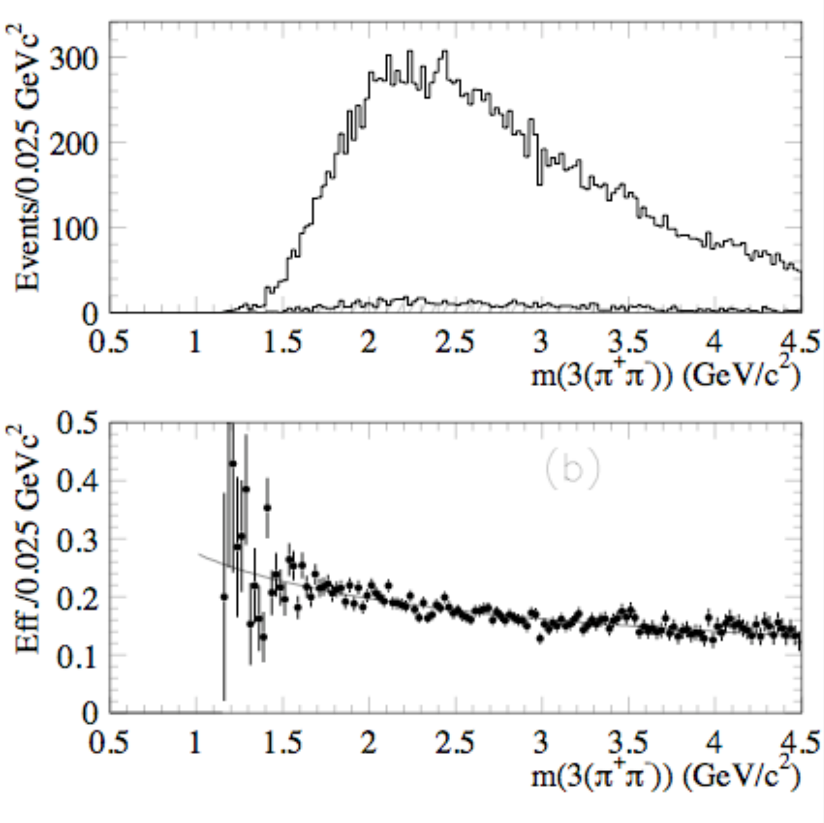
Mass distributions in comparison with MC

Angular distributions in c.m. frame



Relatively good Data-MC agreement. Uncertainty in acceptance should not be larger 3% (using experience from 4π study and comparison with phase space MC).

Efficiency from MC



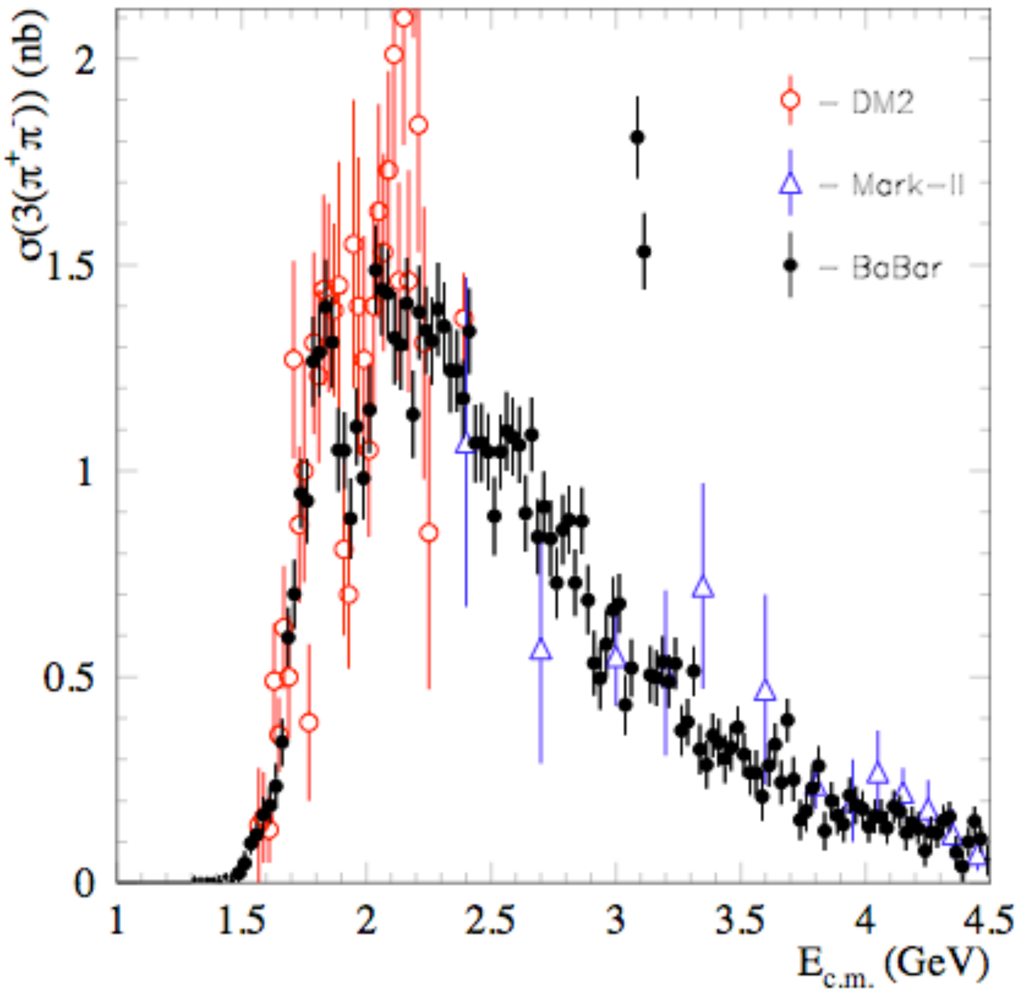
19980 of MC events are selected

We are unable to reproduce trick with 1 lost track to determine tracking efficiency for data - background too big.

But for MC this procedure is performed and gives exactly the same value as for 4π final state (BAD831).

We use the same 0.8%/track correction for 6π final state what gives +5±3% overall correction to efficiency.

Cross section for $e^+e^- \rightarrow 3(\pi^+\pi^-)$



Systematic errors:

Background subtraction	-- 3-5%
Tracking efficiency	-- 3%
ISR luminosity	-- 3%
Acceptance	-- 3-5%
χ^2 cut uncertainty	-- 3%
Total	-- 6-8%

Analysis procedure for $2(\pi^+\pi^-)\pi^0\pi^0$

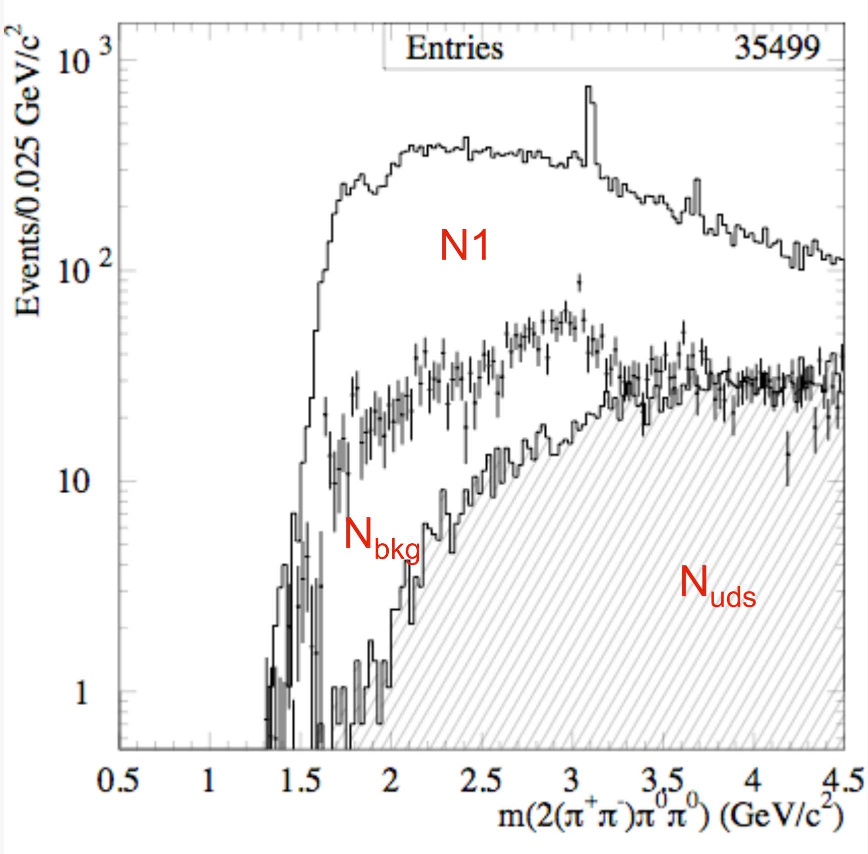
- 232 fb^{-1} of BaBar data from "Raw" ISR Ntuples
- 400k of MC simulation (phase space for $e^+e^- \to 4\pi 2\pi^0\gamma$)
- NLO radiative processes are included
- Background processes (from MC, normalized and subtracted):

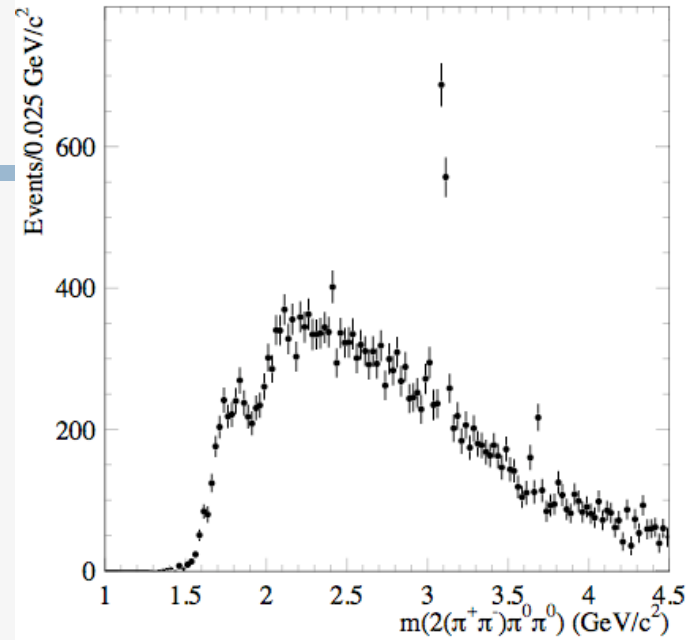
  $e^+e^- \to \tau^+\tau^-$

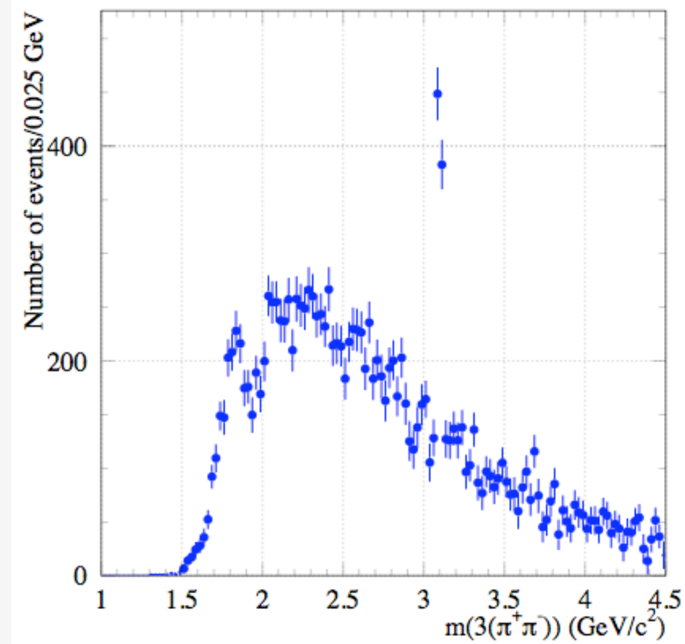
  $e^+e^- \to qq$ (q = u,d,s,c) - major background is from $e^+e^- \to 4\pi 3\pi^0$

- 5C fit for events with ntrk = 4 and nphot ≥ 5
- Best χ^2 form all 2 pair combinations in 25 MeV windows of π^0 mass
- Masses of π^0 are used as constraints, energy of ISR photon is not
- If 1 or 2 kaon ID - $2K2\pi 2\pi^0\gamma$ hypothesis is used.
- Contribution from other ISR processes is subtracted using χ^2 side band

Signal events







After background subtraction

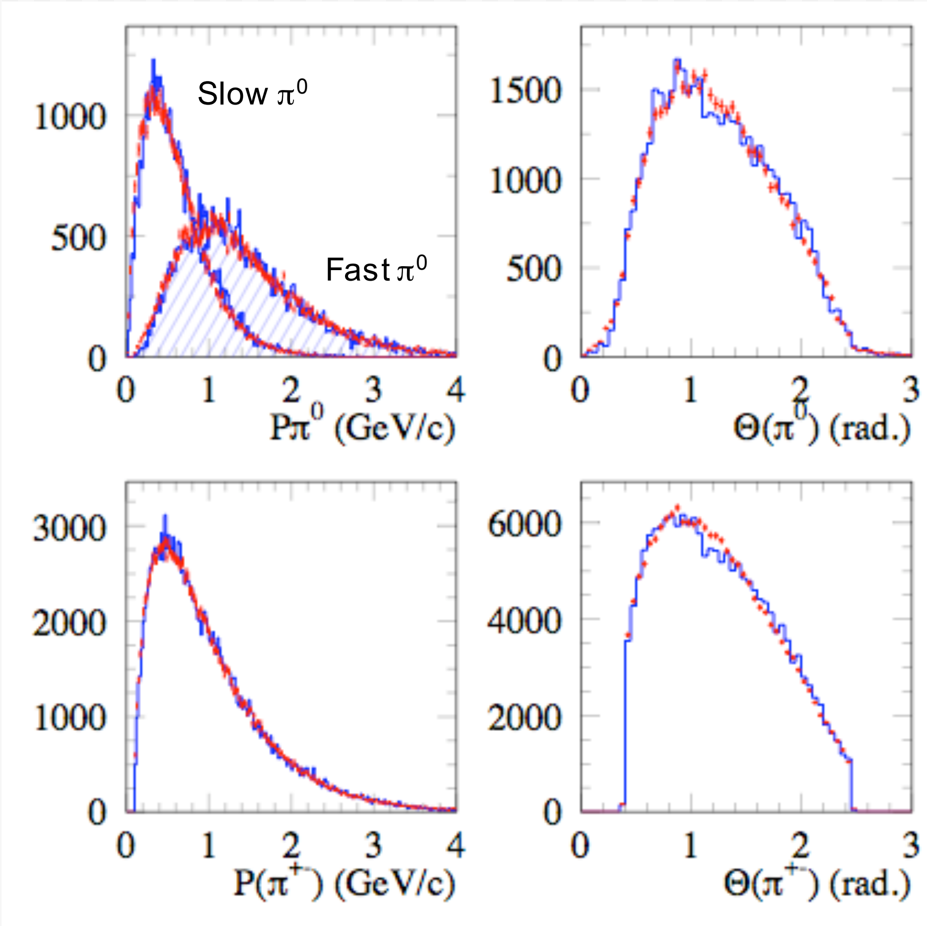
We estimate contribution of background:

15 ± 3% in 1.5-3.0 GeV range

20 ± 5% in 3.0-4.5 GeV range

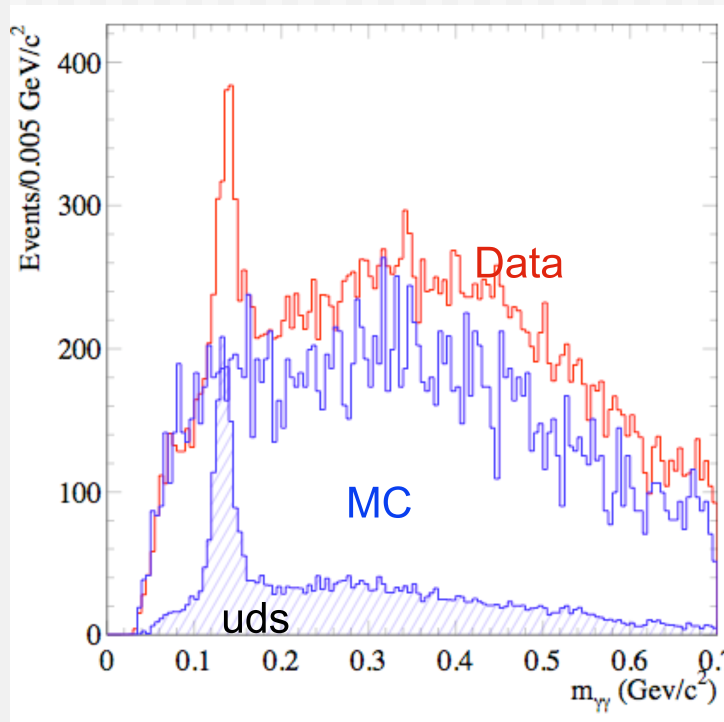
N1 = 35499

How good are MC distributions?



Good agreement only after
uds and ISR background subtraction!

UDS background normalized by π^0 peak (~80%)

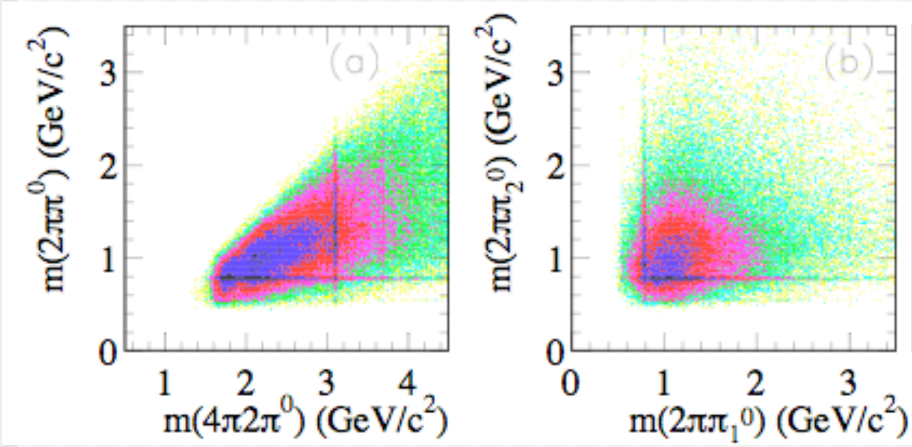


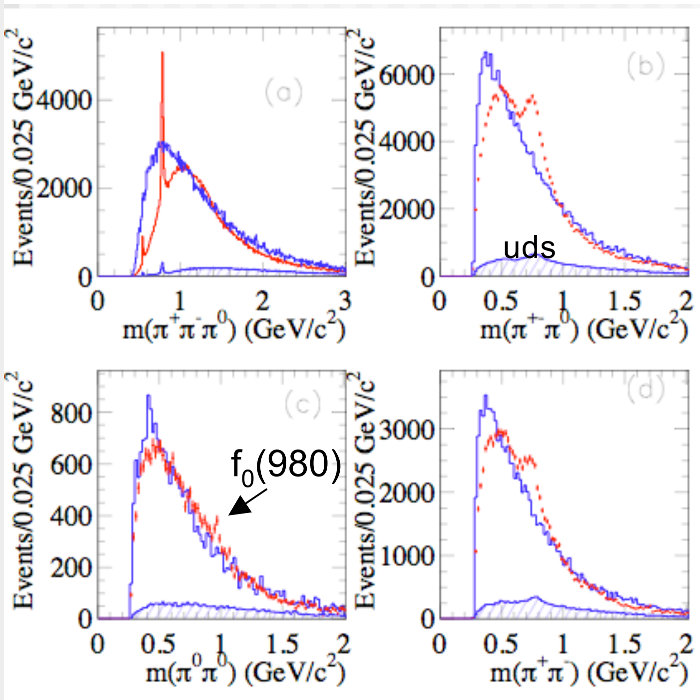
ISR photon + best another photon, close to π^0 mass

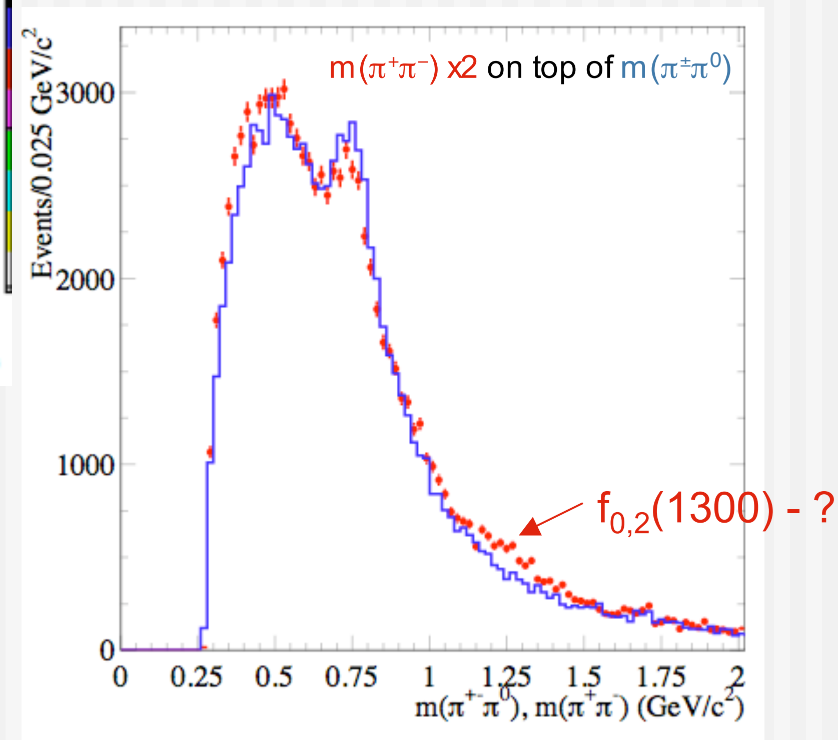
Generator with phase space relatively good describes observables

Comparison with MC simulation

Data



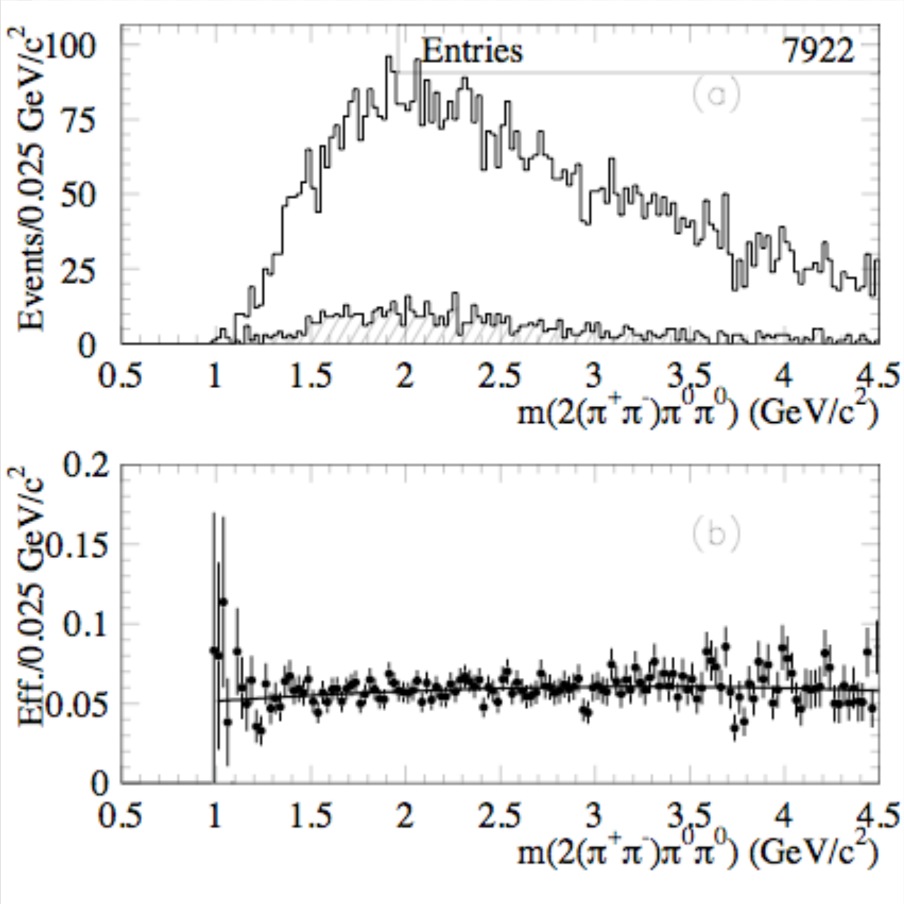




5C fit gives better resolution - ω and η peaks are higher.

Generator with phase space NOT good for masses.

Efficiency from MC



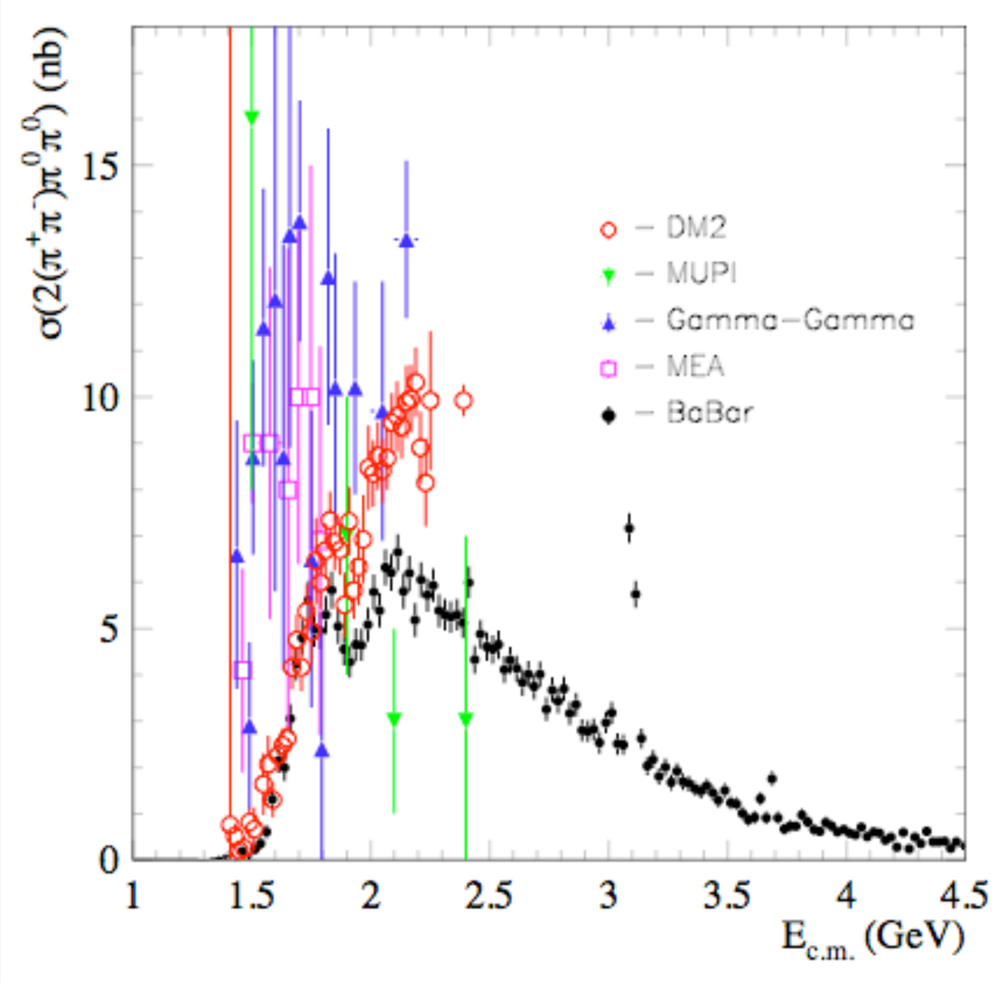
7922 events are selected; efficiency ~6% with 5C fit (+cuts)

We are unable to reproduce trick with 1 lost track to determine tracking efficiency for data - background too big.

We use the same 0.8%/track correction as for 4π final state what gives +3±2% overall correction to number of experimental events.

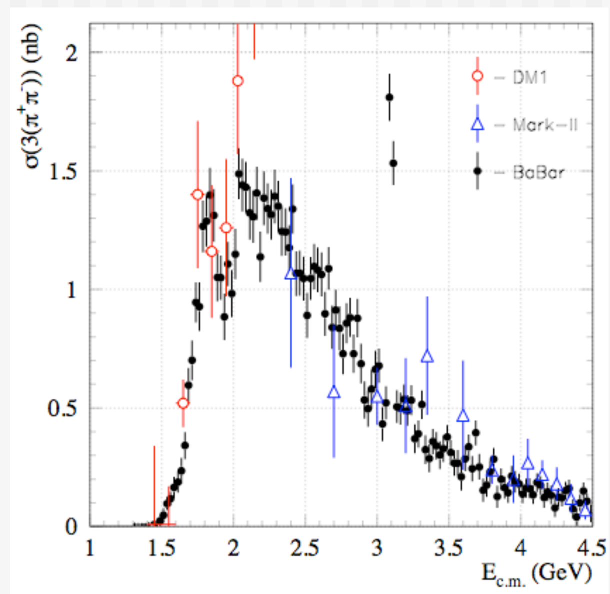
π^0 efficiency correction was studied with $\pi^+\pi^-\pi^0\pi^0$ events (BAD1163) and was found to be +2.8 ± 1.5%. For two π^0 correction is taken as ~ +6 ± 3%.
Momentum dependence used as weight for all hists .

Cross section for $e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0$

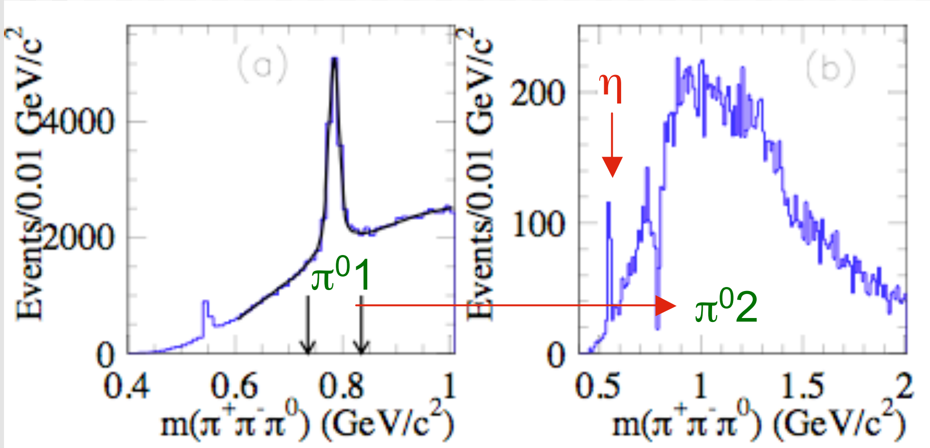


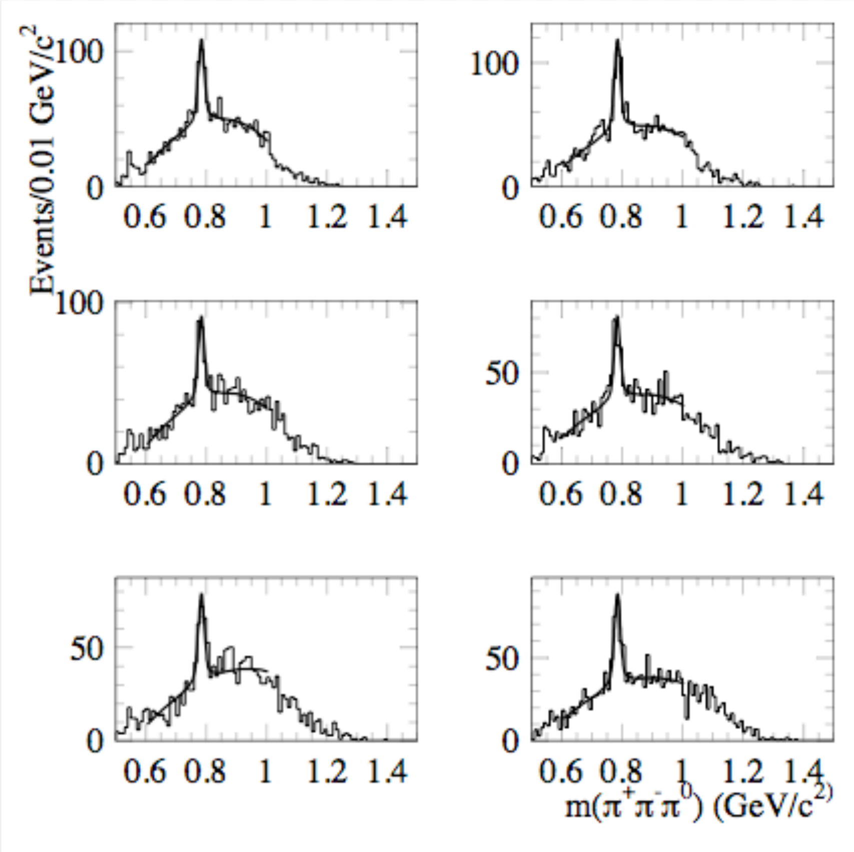
Systematic errors:

Background subtraction	--	3-5%
Tracking efficiency	--	3%
Luminosity	--	3%
Acceptance	--	3-5%
χ^2 cut uncertainty	--	6%
π^0 efficiency	--	3%
Total	--	11%



How big is ω(782) contribution?





Fit gives 9899±158 of ω3π events
And 770 ± 40 of η3π events

η selection from $\pi^0 2$ distribution in correlation with ω in $\pi^0 1$ distribution :

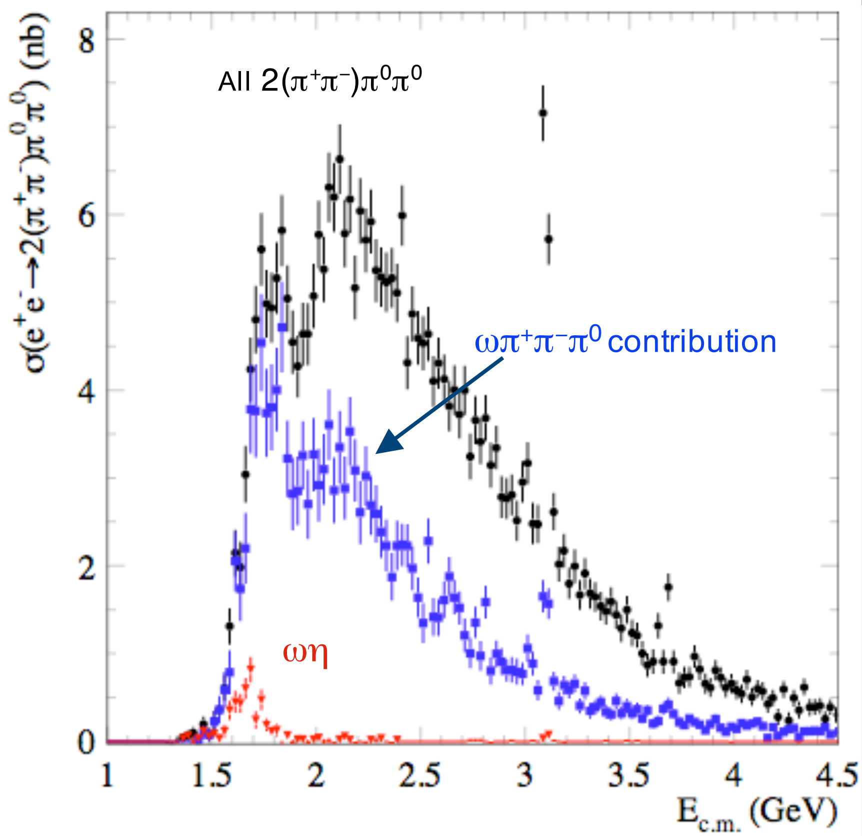
$|m_{3\pi}-m_\eta|<0.02$ - signal events
$0.02<|m_{3\pi}-m_\eta|<0.04$ - bkg. Events

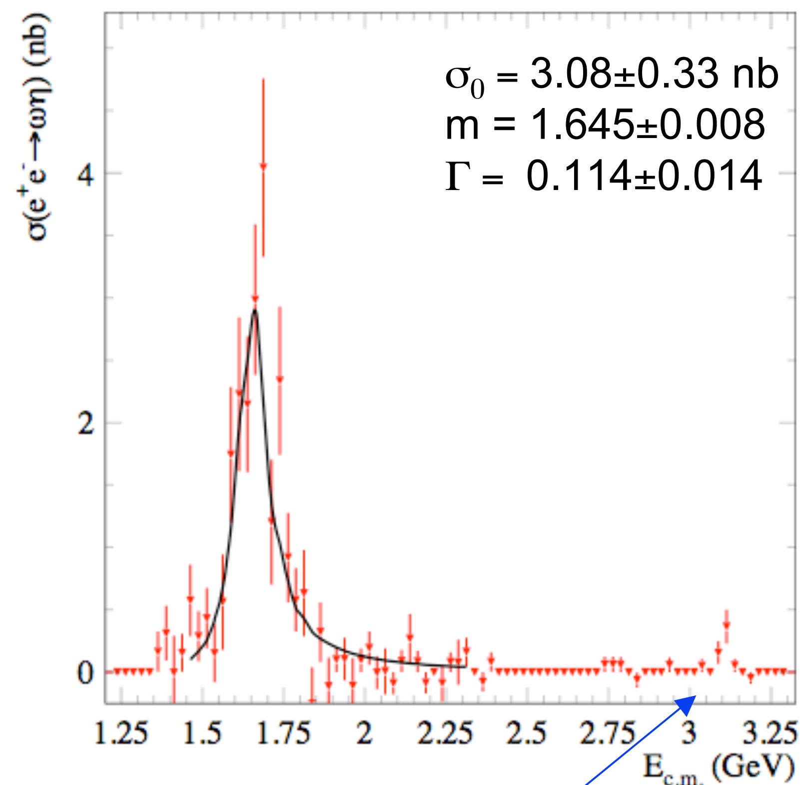
~ 200 of ω η events are selected

Fit to number of ω for 0.025 GeV/c^2 bin
In $2(\pi^+\pi^-)\pi^0\pi^0$ mass (128 bins in1.3-4.5 GeV/c^2)
(example for ~2 GeV region)

How big is ω(782) contribution?

Corrected on B(ω,η→3π)





PDG2004 $\phi(1680)$
m = 1.680±0.020
Γ = 0.150±0.050

13 events are from $J/\psi \to \omega\eta$ with less than 0.5 events of background

Cross section ratio

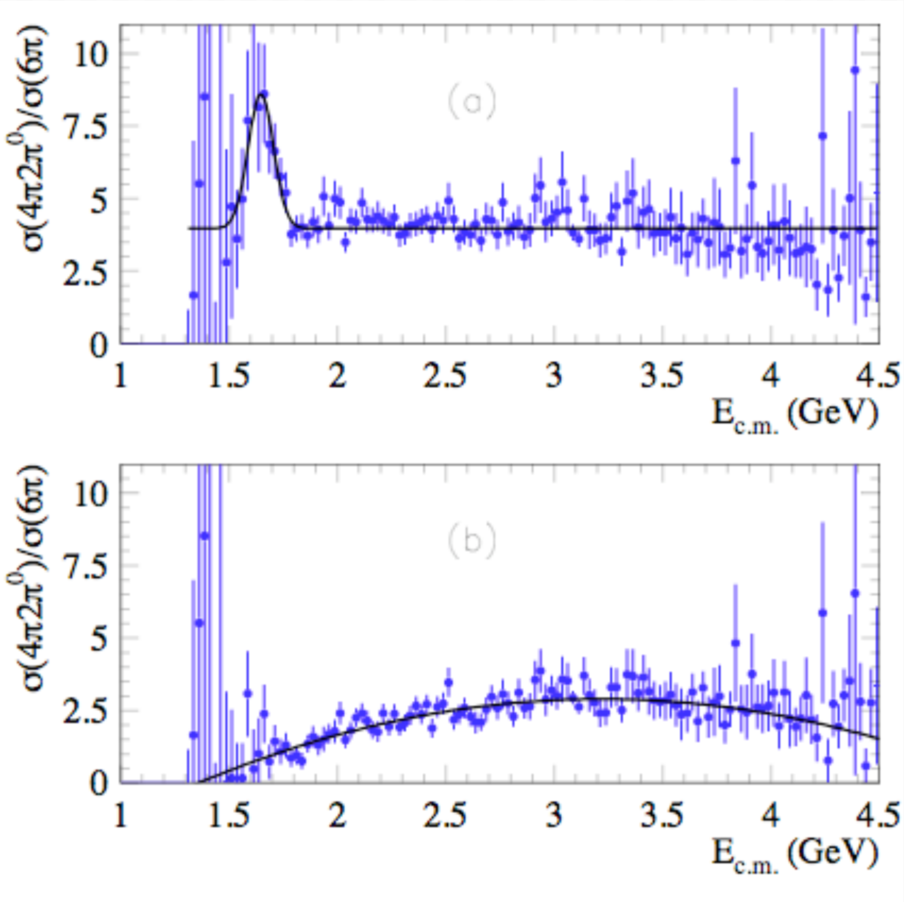
$\omega(1650),\phi(1680)$?

Gaussian fit gives:

$m = 1.65 \pm 0.02$ GeV/c^2

$W = 0.12 \pm 0.02$ GeV

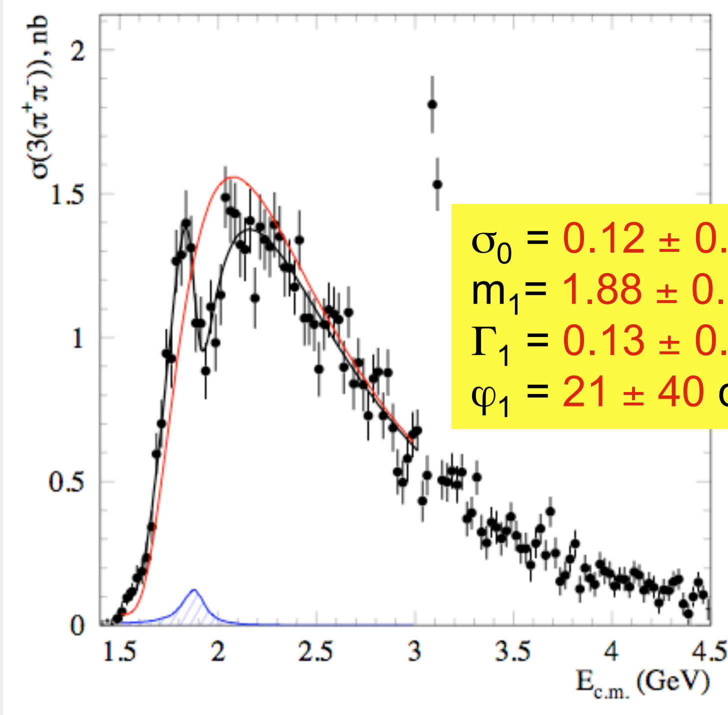
$R = 3.98 \pm 0.06$



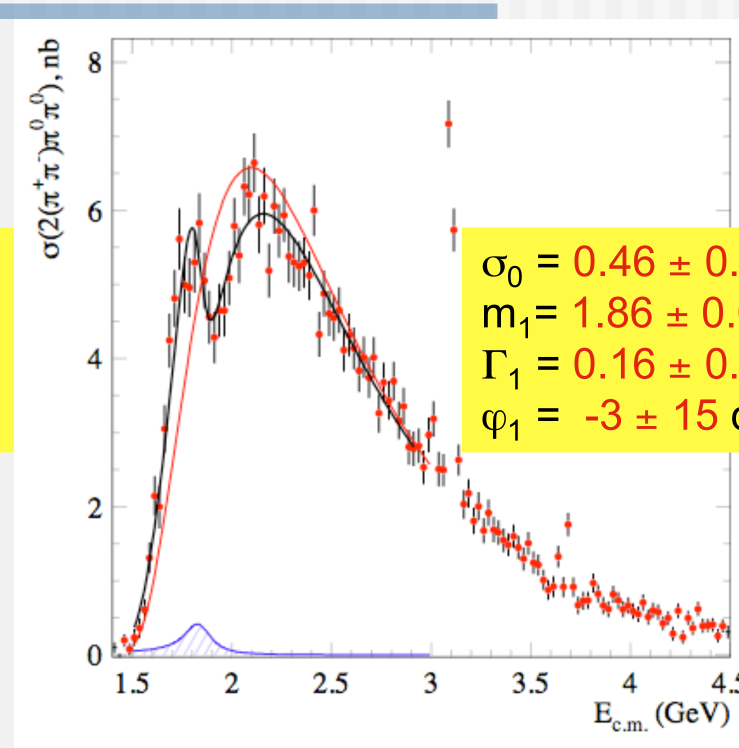
If ω contribution is excluded

No narrow resonances allowed in $2(\pi^+\pi^-)\pi^0\pi^0$ and not allowed in $3(\pi^+\pi^-)$ are seen.

Cross section fit for $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0\pi^0$



σ_0 = 0.12 ± 0.03 nb
m_1= 1.88 ± 0.05 GeV/c^2
Γ_1 = 0.13 ± 0.03 GeV
φ_1 = 21 ± 40 deg.



σ_0 = 0.46 ± 0.10 nb
m_1= 1.86 ± 0.02 GeV/c^2
Γ_1 = 0.16 ± 0.02 GeV
φ_1 = -3 ± 15 deg.

Cross section is described as:
(N.N.Achasov, hep-ph/9609216)

$$\sigma\left(e^+e^- \to V_1 + V_2\right) = \frac{4\pi\alpha^2}{s^{3/2}}\left(\frac{g m_1^2 e^{i\varphi}}{m_1^2 - s - i\sqrt{s}\Gamma_1} + A_{V_1}(s)\right)^2$$

$$A_{V_1}(s) = c_0 + c_1 \frac{e^{\frac{-\beta}{\sqrt{s}-m_0}}}{(\sqrt{s}-m_0)^{2-\alpha}}$$

A_{V1} - Jacob-Slansky model for the continuum.

The dip is not well described by single BW !

FOCUS data

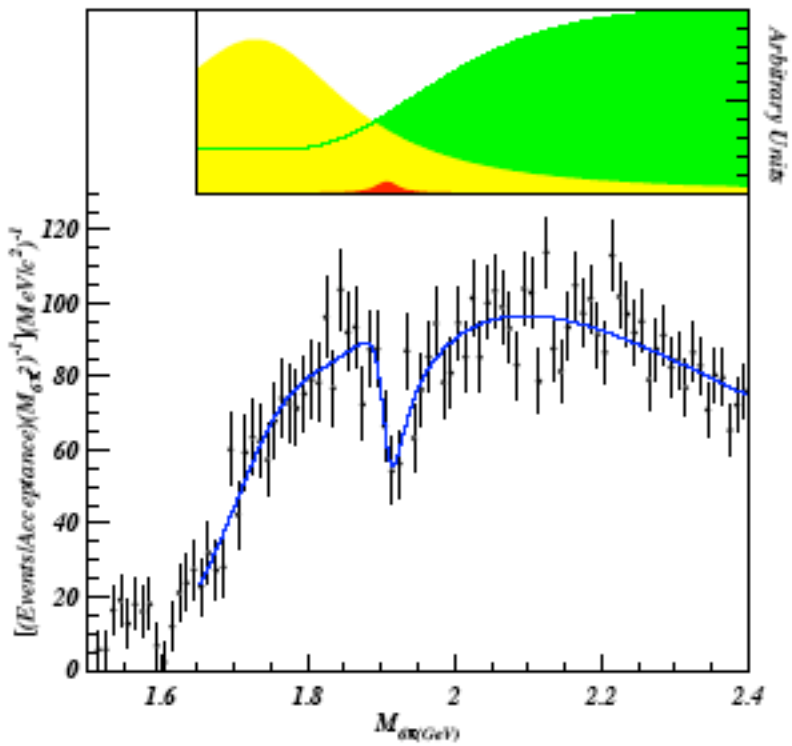
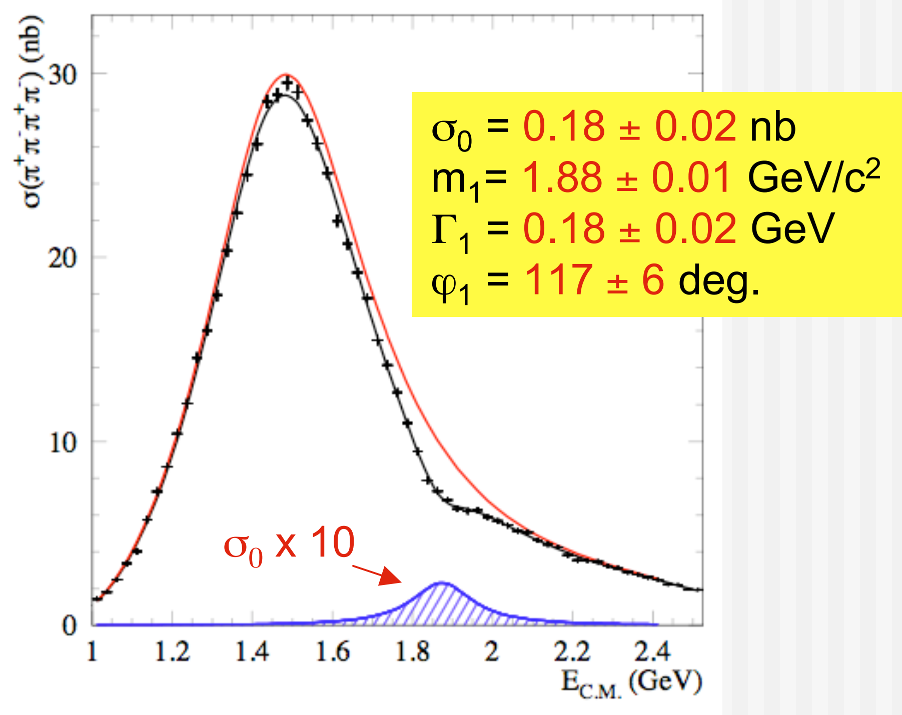
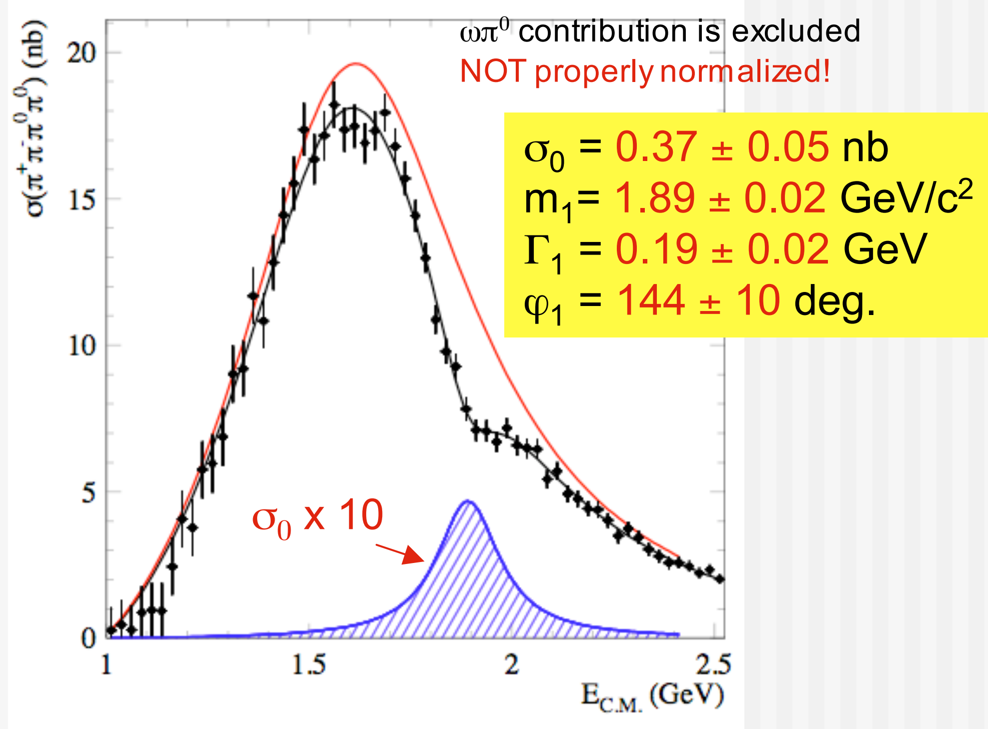


Figure 2: E687 $3\pi^+3\pi^-$ invariant mass distribution. Continuous line: fit with two resonances and Jacob-Slansky continuum (parameters in Tab. 1). Inset: relative fraction of each amplitude without interference.

m_1= 1.91 ± 0.01 GeV/c^2
Γ_1 = 0.037 ± 0.013 GeV
φ_1 = 10 ± 30 deg.

How about 4π final states?





Two (red and blue) BWs fit with free relative phase

Nothing is seen in 3π or 5π final states !

Summary table

Experiment	Reaction	m, GeV/c^2	Γ, MeV	φ, d.eg	σ_0, nb
DM2	$3(\pi^+\pi^-)$	1.93±0.03	35 ± 20		
FOCUS	$3(\pi^+\pi^-)$	1.91±0.01	37 ± 13	10 ± 30	
BaBar	$3(\pi^+\pi^-)$	1.88±0.05	130 ± 30	21 ± 40	0.12 ± 0.03
BaBar	$2(\pi^+\pi^-)\pi^0\pi^0$	1.86±0.02	160 ± 20	-3 ± 15	0.46 ± 0.10
BaBar	$2(\pi^+\pi^-)$	1.88±0.01	180 ± 20	117 ± 6	0.18 ± 0.02
BaBar	$\pi^+\pi^-\pi^0\pi^0$	1.89±0.02	190 ± 20	144 ± 10	0.37 ± 0.05

Summary

- $e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-)\pi^0\pi^0$ cross sections have been measured with 6-11% syst. errors using ISR at BaBar - publication is in preparation (PRD).
- $\sigma(2(\pi^+\pi^-)\pi^0\pi^0)/\sigma(3(\pi^+\pi^-)) = 3.98 \pm 0.06$, $\omega(782)$ contribution is demonstrated.
- Structure at 1.9 GeV is seen but wider than in DM2 and FOCUS.
- The same (?) structure is demonstrated in $e^+e^- \to 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$ reactions and cross section is estimated
- BW fit gives $m = 1.88$ GeV/c^2 and $\Gamma = 0.13$-0.18 GeV for this structure and distructive interference with continuum.
- No evidence of the structure is in odd number of pions
- We need a theoretical input for proper description of the dip and extracting correct parameters to identify a nature of it.