Study of the decay $\phi \rightarrow f_0(980)\gamma \rightarrow \pi^+\pi^-\gamma$

C.Bini, S.Ventura, *KLOE Memo 294*
03/2004 (upd. 06/2005)
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03/2005 (upd. 06/2005)

Outline

- Motivations of this analysis.
- The data sample: what we measure and how the data look like.
- Theory, KL, NS, SA,....
- The fits.
- Discussion of the results.
- Conclusion: what we learn from this analysis.

Motivations of this analysis

- Assess clearly the $\phi \rightarrow f_0(980)\gamma \rightarrow \pi^+\pi^-\gamma$ signal;
- determine the $f_0(980)$ parameters (coupling to the ϕ to KK and $\pi\pi$); assess the quark content of the f_0;
- any further meson is needed to describe the data ?
- Compare models.

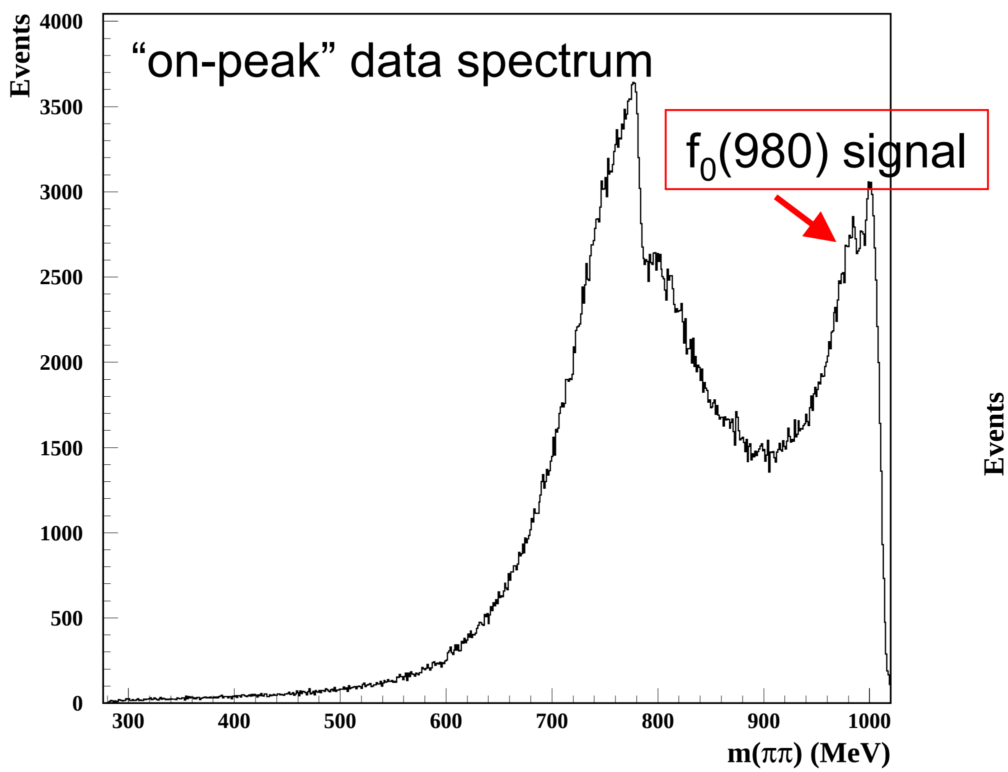
The data sample: the event selection

• drc stream	
• “vertex”:	R_v<8 cm; Z_v<15 cm;
• “2 tracks”:	+,-; $45^o<\theta^+,\theta^-<135^o$;
• “pion identification”	L_1 vs. L_2 cut (AND);
• “large angle”:	$45^o<\theta_{\pi\pi}<135^o$;
• “track mass”:	$129<M_T<149$ MeV;
• “photon matching”:	$E_{cl}>10$ MeV; $\theta_{cl}>22^o$
	$\Omega_\gamma<0.03+3/E_{cl}$
	$N_\gamma > 0$

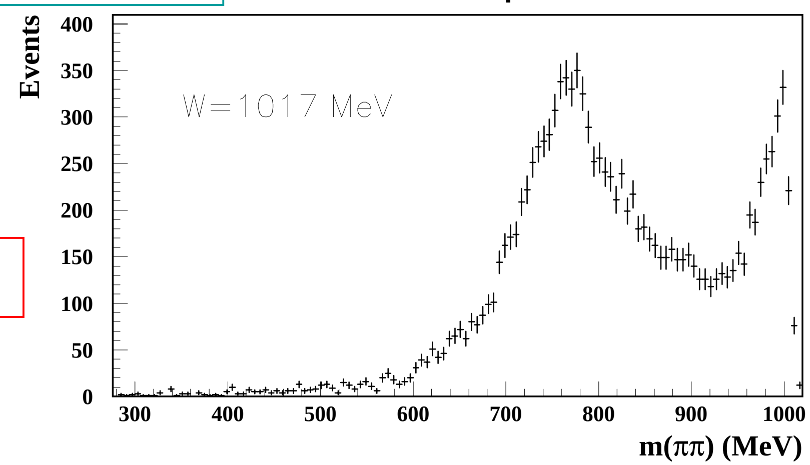
See Memo 294

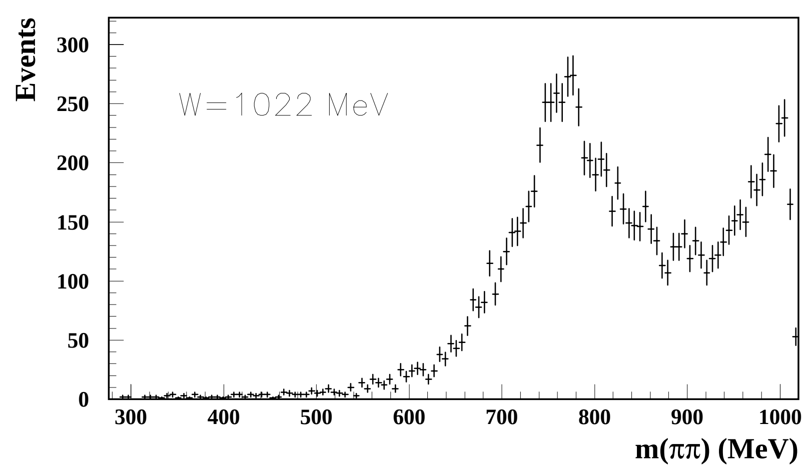
The data sample: dN/d*m*

- ➔ 6.7×10^5 events / 350 pb^{-1} "on-peak" data
- ➔ 1.2×10^4 events /6.58 pb^{-1} "off-peak" data 1017 MeV
- ➔ 1.0×10^4 events /4.93 pb^{-1} "off-peak" data 1022 MeV

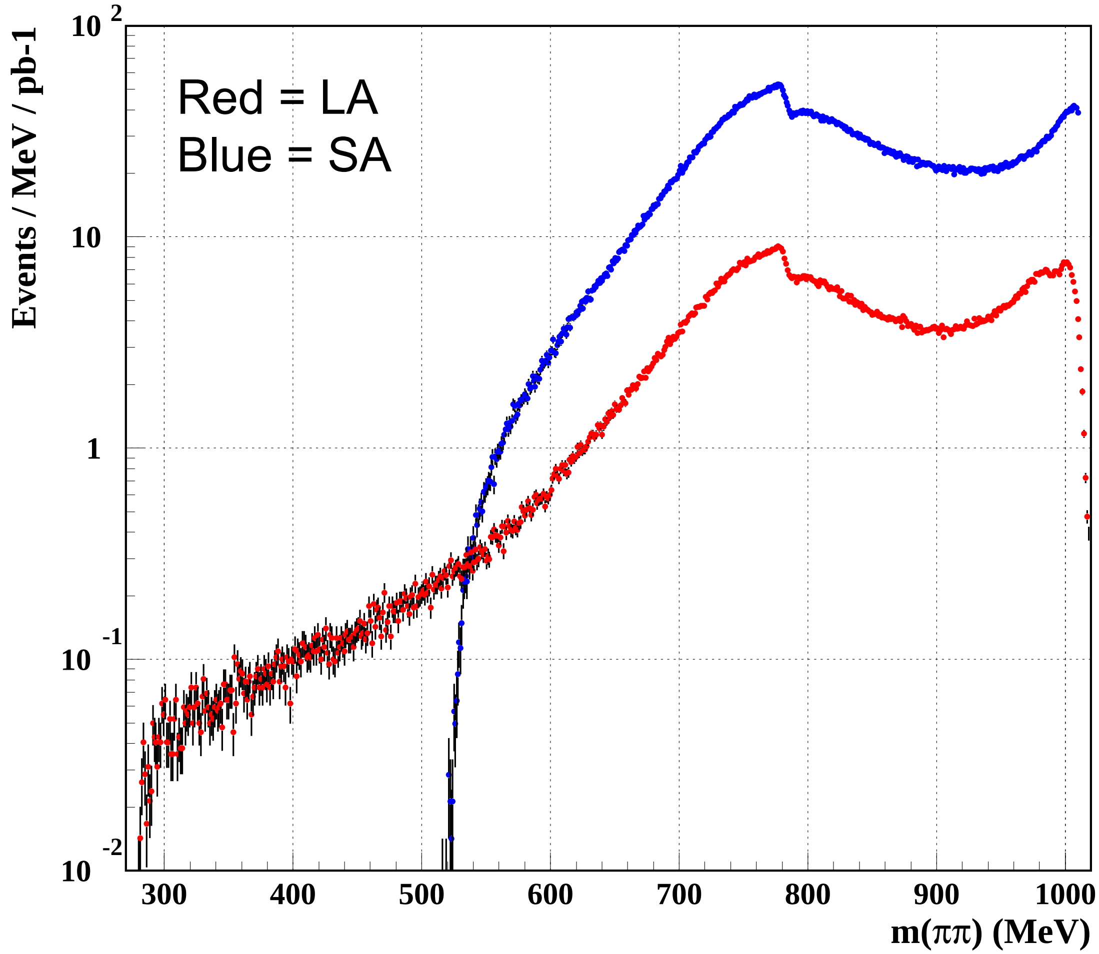


"off-peak" data





The data sample: large angle vs. small angle



f_0 signal in LA vs. SA events

$$\frac{\int_{LA} (1+\cos^2\theta)\, d\cos\theta}{\int_{SA} (1+\cos^2\theta)\, d\cos\theta} \approx 12$$

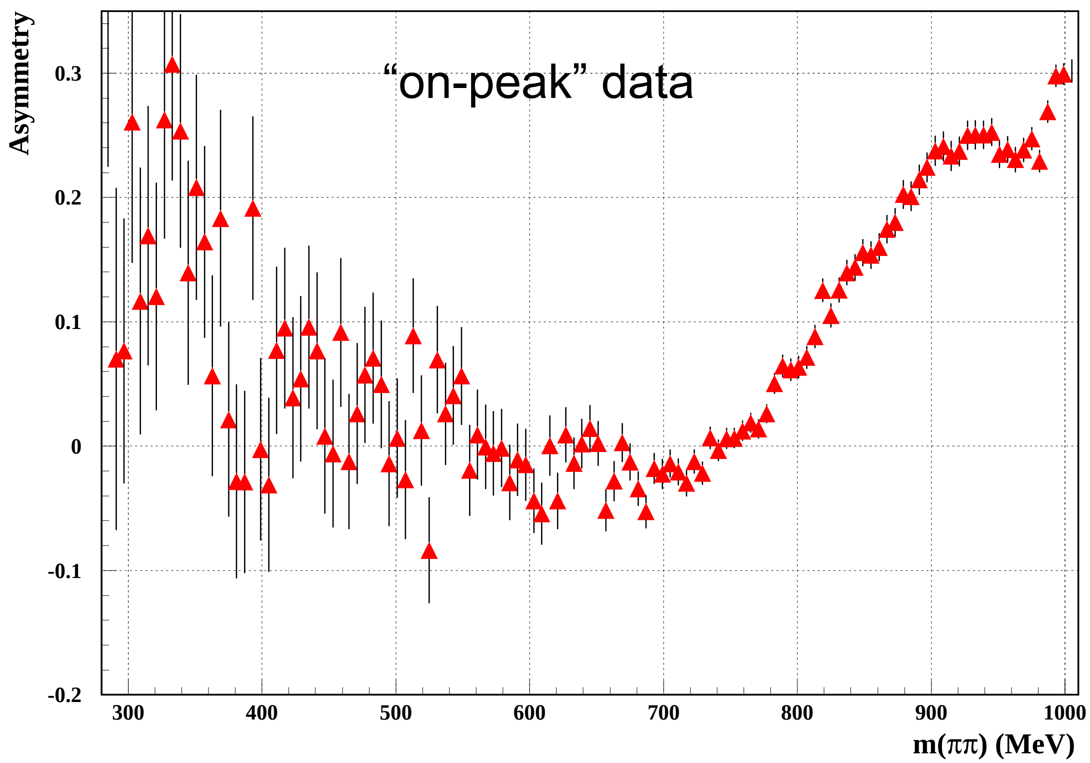
In the $f_0(980)$ region:
ISR(LA)/ISR(SA)~5

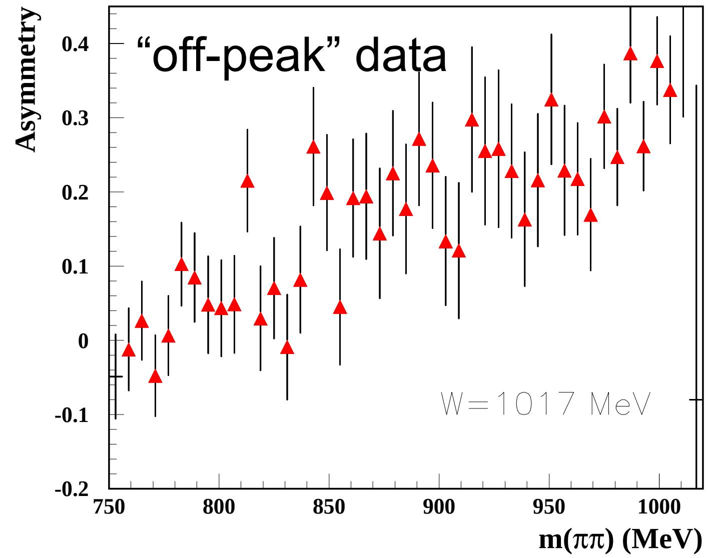
➔ $[S/B]_{LA}$ ~ 60 $[S/B]_{SA}$

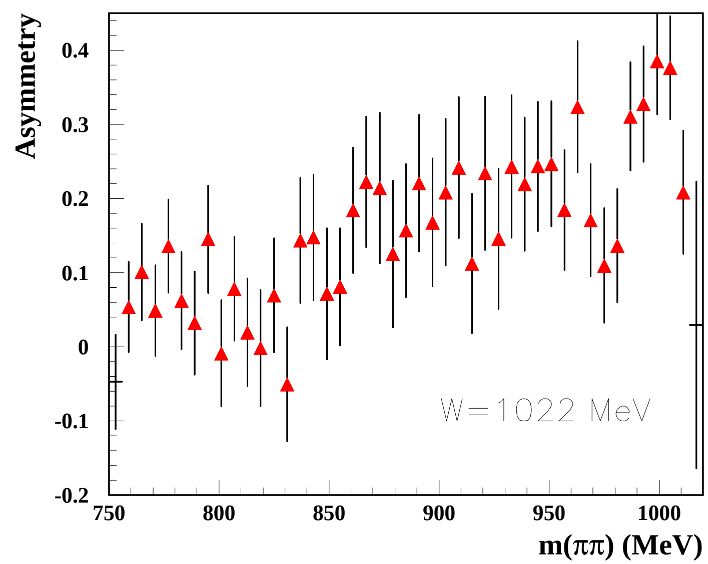
The data sample: A_c

Charge asymmetry A_c in bins of *m*

$$A_c = \frac{N(\theta^+ > 90^o) - N(\theta^+ < 90^o)}{N(\theta^+ > 90^o) + N(\theta^+ < 90^o)}$$

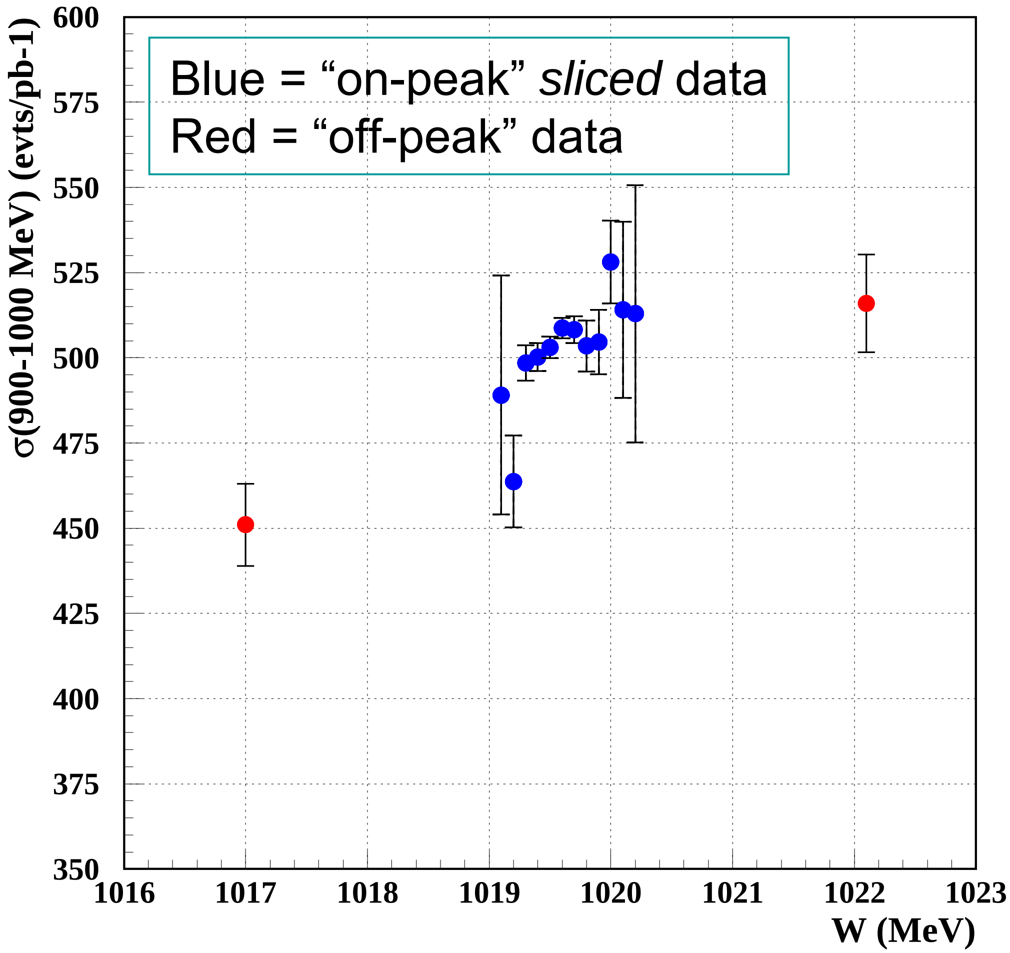






The data sample: √s dependence

$\sigma(900\text{-}1000\ \text{MeV}) = N(\text{events } 900<m<1000\ \text{MeV}) / L_{int}\ \varepsilon(m))$

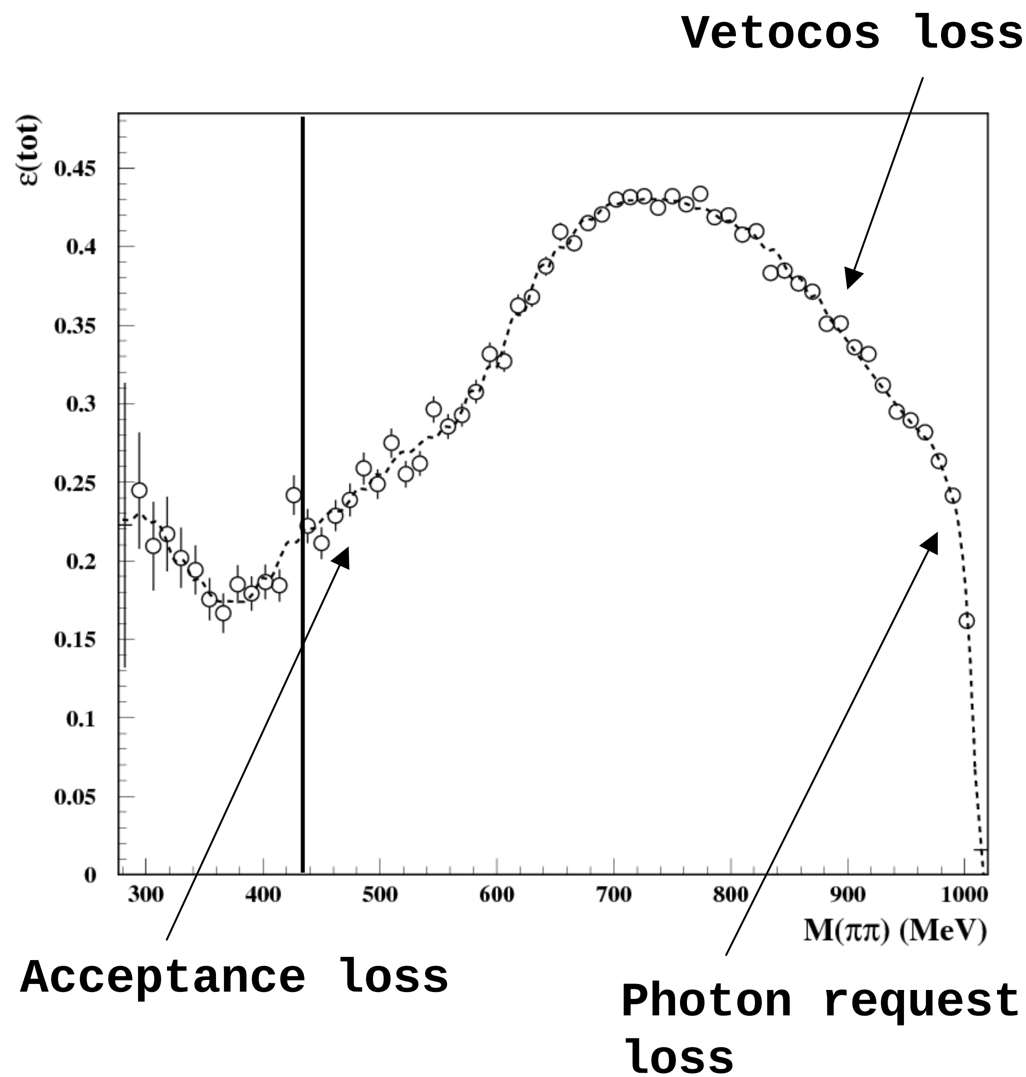


The data sample: detection efficiency

MC stream ppphvlag (ISR+FSR)
Sample size ~ data

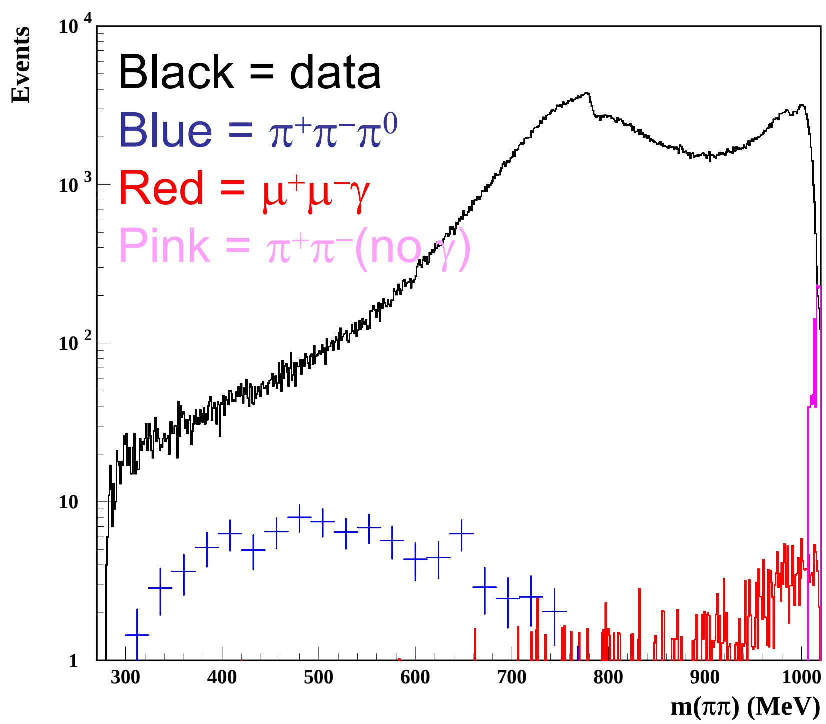
***All selection chain apart from*:**
Filfo
Vetocos
TCA+Likelihood
(taken from data)

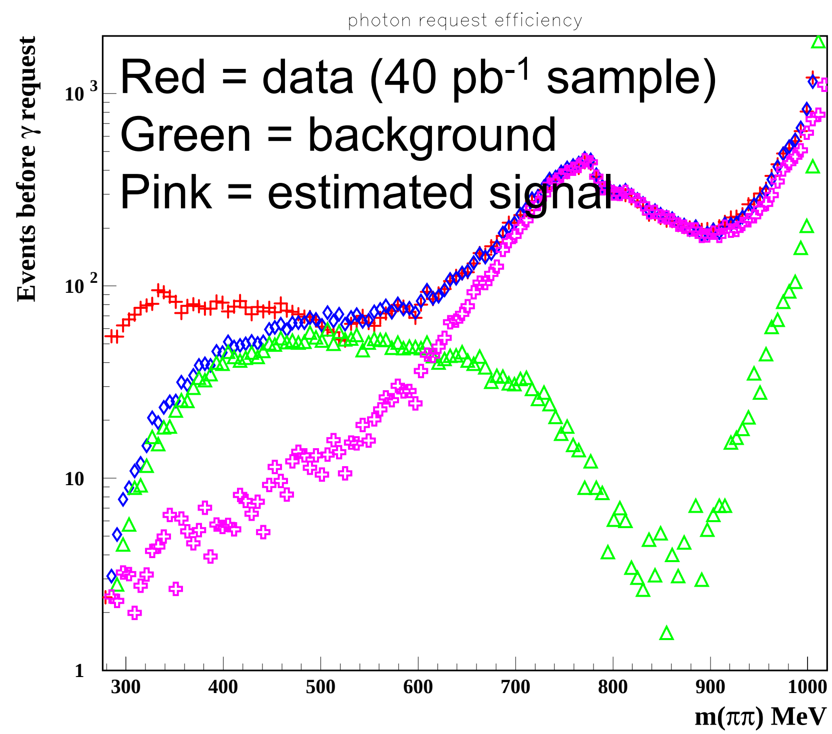
***Corrections from*:**
tracking efficiency
photon efficiency
(1-exp(-E/a)) a~8-10 MeV



The data sample: estimated background

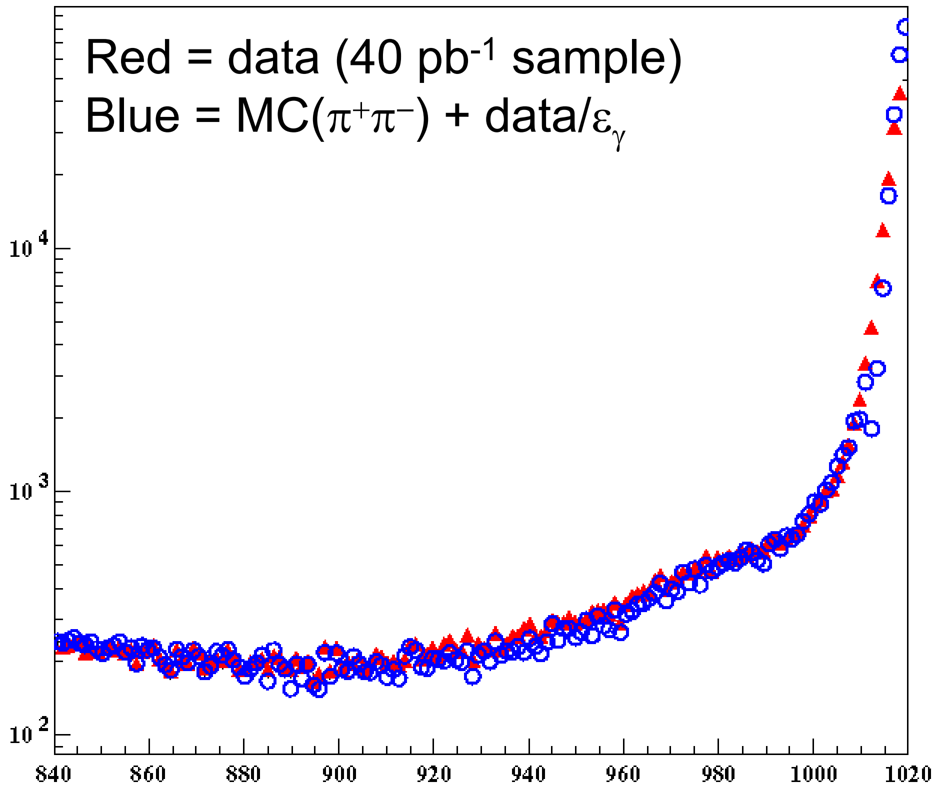
Dedicated MC generations of $\pi^+\pi^-\pi^0$, $\mu^+\mu^-\gamma$ and $\pi^+\pi^-$(no γ):
Check done “before photon request”: good agreement above 450 MeV



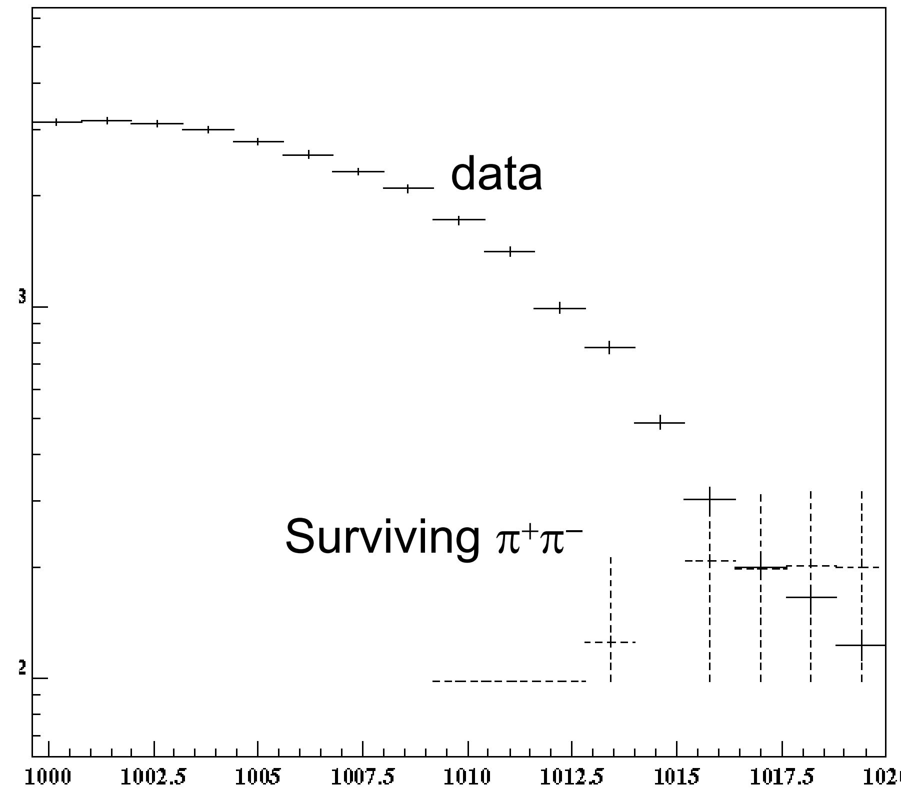


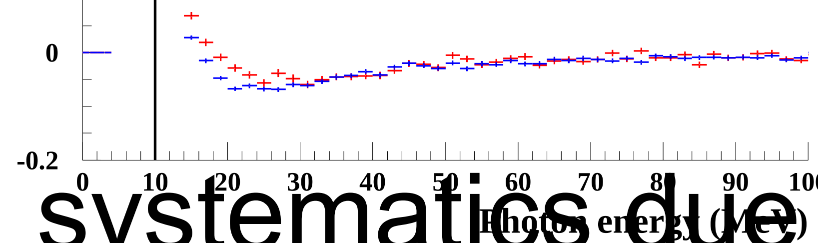
Zoom (signal region)

Before the photon request

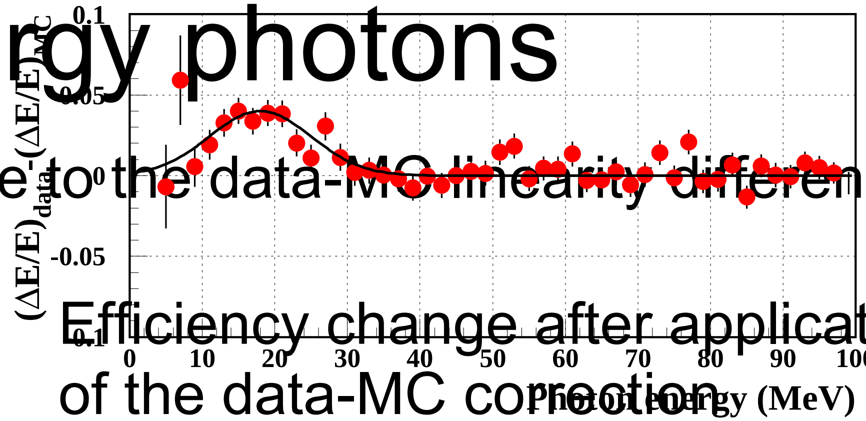


At the end of the selection

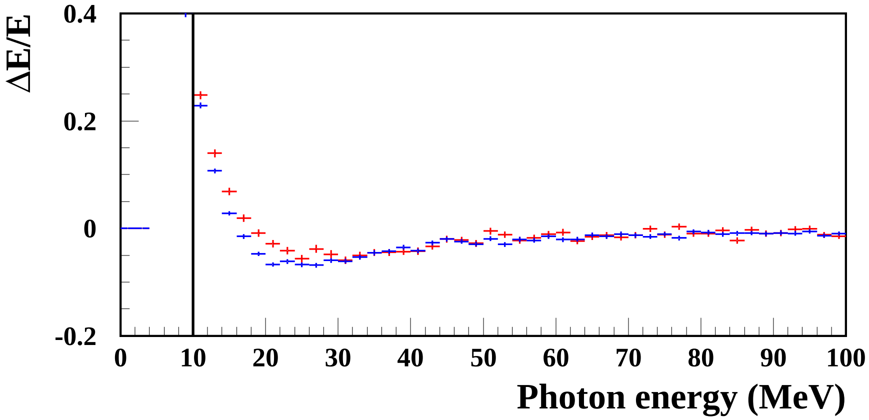




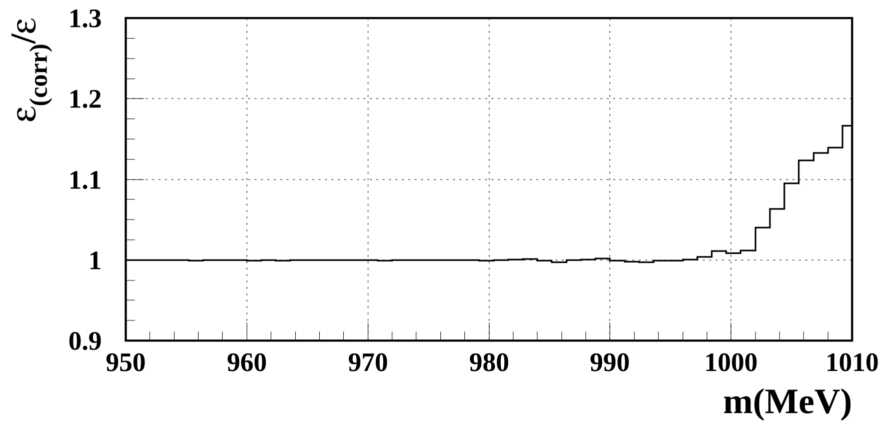
The data sample: systematics due to low energy photons

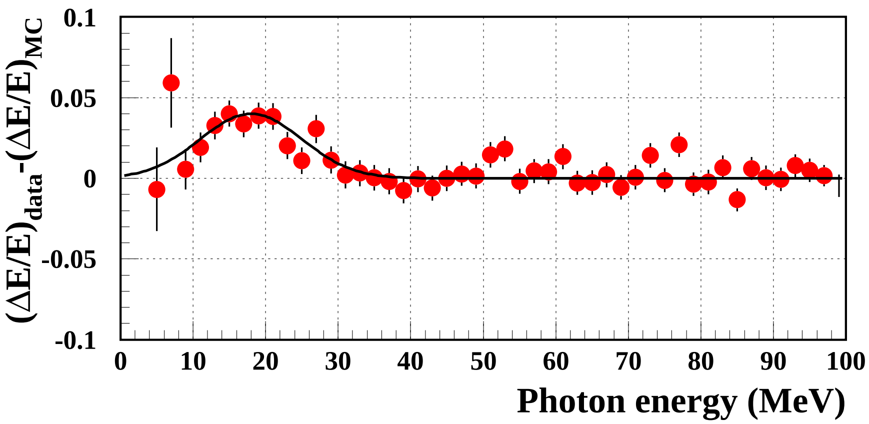


The larger systematic effect is due to the data-MC linearity difference

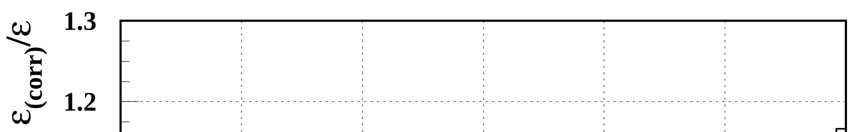


Efficiency change after application of the data-MC correction

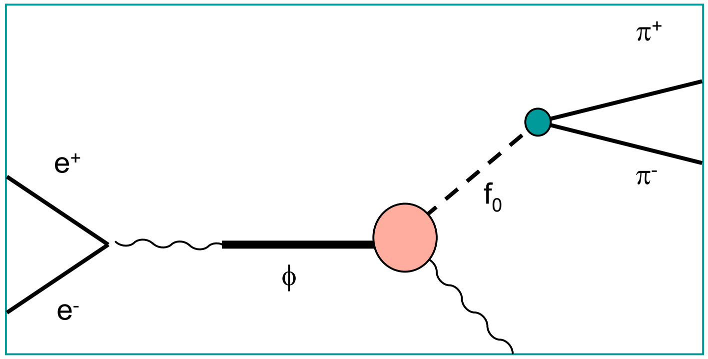




The difference is assumed as an uncertainty (quad. add to stat.).
(*) also tried ½ correct.+ ½ error



Theory: KL,NS,SA,....



$$A(e^+e^- \to \phi \to S\gamma \to \pi^+\pi^-\gamma) = -\frac{esm_\phi^2}{4 f_\phi D_\phi(s)}\{M\}$$

{M} has to rely on “some” model with “some” parameters

$$M_{KL} = 2g(m^2)e^{i\delta(m)}\sum_{S,S'}\left(g_{SKK}G^{-1}_{SS'}g_{S'\pi+\pi-}\right)$$

$$M_{NS} = (s-m^2)\left[\frac{g_{f\pi+\pi-}g_{\phi f\gamma}}{D'_f(m^2)} + \frac{a_0}{m_\phi^2}e^{ib_0\sqrt{m^2/4-m_\pi^2}} + a_1\frac{m^2-m_f^2}{m_\phi^4}e^{ib_1\sqrt{m^2/4-m_\pi^2}}\right]$$

$$M_{SA} = (m^2-m_o^2)(1-\frac{m^2}{s})\left[(a_1+b_1m^2+c_1m^4)T_{11} + (a_2+b_2m^2+c_3m^4)T_{12}\right]e^{i\lambda}$$

Theory: KL

(KL) by N.N.Achasov;

$$M_{KL} = 2g(m^2)e^{i\delta(m)}\sum_{S,S'}\left(g_{SKK}G^{-1}_{SS'}g_{S'\pi+\pi-}\right)$$

where:

$g(m)$ = kaon-loop function

$\delta(m)$ = phase shift (based on $\pi\pi$ scattering data)

$D_f(m)$ = f_0 propagator (finite width corrections)

$$G_{SS'}(m) = \begin{pmatrix} D_S(m) & -\Pi_{SS'}(m) \\ -\Pi_{S'S}(m) & D_{S'}(m) \end{pmatrix}$$

If only one meson (no σ included):

$$M_{KL} = 2g(m^2)e^{i\delta(m)}\frac{g_{fKK}g_{f\pi+\pi-}}{D_f(m)}$$

3 free parameters: **m_f, g_{fKK}, $g_{f\pi\pi}$**

Theory: NS

(NS) after several discussions with G.Isidori, L.Maiani and (recently) S.Pacetti;

$$M_{NS} = (s - m^2)\left[\frac{g_{f\pi^+\pi^-} g_{\phi f\gamma}}{D'_f(m^2)} + \frac{a_0}{m_\phi^2} e^{ib_0\sqrt{m^2/4 - m_\pi^2}} + a_1 \frac{m^2 - m_f^2}{m_\phi^4} e^{ib_1\sqrt{m^2/4 - m_\pi^2}}\right]$$

where the propagator (Flatte' revised) is:

$$D'_f(m) = m^2 - m_f^2 + im\Gamma(m)$$

$$\Gamma(m) = \left[g_{\pi\pi}\sqrt{m^2/4 - m_\pi^2} + g_{KK}\left(\sqrt{m^2/4 - m_{K0}^2} + \sqrt{m^2/4 - m_{K\pm}^2}\right)\right]\frac{m_f^2}{m^2}$$

with couplings

$$g_{f\pi\pi} = \sqrt{8\pi m_f^2 g_{\pi\pi}}; g_{f\pi+\pi-} = \sqrt{2/3}\, g_{f\pi\pi}$$

$$g_{fKK} = \sqrt{8\pi m_f^2 g_{KK}}$$

7 free parameters: **m_f, $g_{\phi f\gamma}$, g_{fKK}, $g_{f\pi\pi}$, a_0, a_1, b_1**

Theory: SA

(NS) by M.E.Boglione and M.R.Pennington;

$$M_{SA} = (m^2 - m_o^2)(1 - \frac{m^2}{s})\left[(a_1 + b_1 m^2 + c_1 m^4)T_{11} + (a_2 + b_2 m^2 + c_3 m^4)T_{12}\right]e^{i\lambda}$$

where $T_{11} = T(\pi\pi \rightarrow \pi\pi)$ and $T_{12} = T(\pi\pi \rightarrow KK)$:
$(1-m^2/s)$ satisfies gauge invariance requirement.
From the polynomials ➔ coupling $\mathbf{g_\phi}$ (GeV) residual at the f_0 pole.

8 free parameters: $\mathbf{m_0, a_1, b_1, c_1, a_2, b_2, c_2, \lambda}$

The fits.

491 bins, 1.2 MeV wide from 420 to 1009 MeV

$$\frac{dN}{dm} = \left\{ \begin{array}{l} \left(\frac{d\sigma}{dm}\right)_{ISR} + \left(\frac{d\sigma}{dm}\right)_{FSR} + \left(\frac{d\sigma}{dm}\right)_{\rho\pi} \\ + \left(\frac{d\sigma}{dm}(|\mathrm{A}|^2)\right)_{Scalar} + \left(\frac{d\sigma}{dm}(\mathrm{A})\right)_{\mathrm{int}.Scalar+FSR} \end{array} \right\} \times \varepsilon(m) \times \mathrm{L} + back(\pi^+\pi^-\pi^0 + \mu^+\mu^-\gamma)$$

Free parameters:

Background: m_ρ, Γ_ρ, α, β, $a_{\rho\pi}$

Signal: depending on the fit (3 for KL, 7 NS, 8 SA)

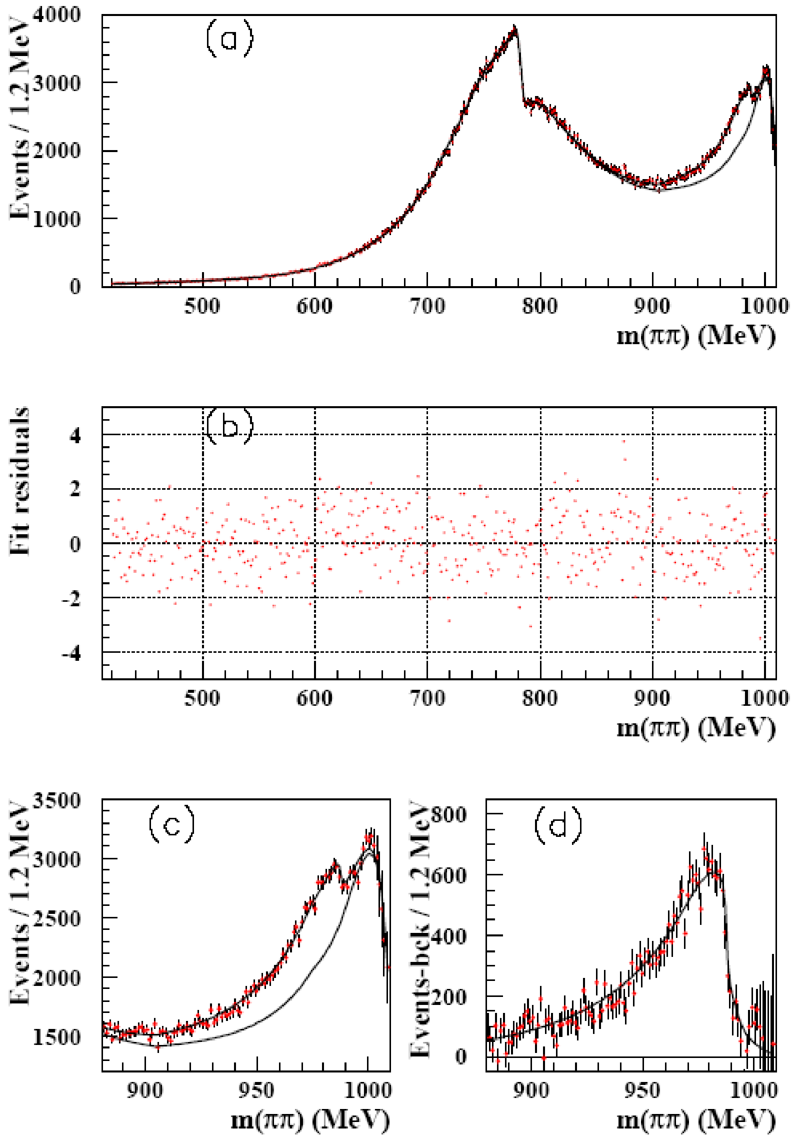
The fits: KL

(KL) $f_0(980)$ only:

χ^2/ndf	538/481 (3.7%)
$g^2_{f0KK}/4\pi$ (GeV^2)	2.76±0.13
R	2.66±0.10
m_{f0} (MeV)	983.0±0.6
m_ρ (MeV)	773.1±0.2
Γ_ρ (MeV)	144.0±0.3
α (x10^{-3})	1.65±0.05
β (x10^{-3})	-123±1
$a_{\rho\pi}$	0.0±0.6

Fit uncertainties. Covariance matrix of the 3 signal parameters:

1.0	0.56	0.0
	1.0	-0.36
		1.0



The fits: KL

Study of the systematics on the 3 $f_0(980)$ parameters:
The fits are repeated with fixed "non-scalar" part

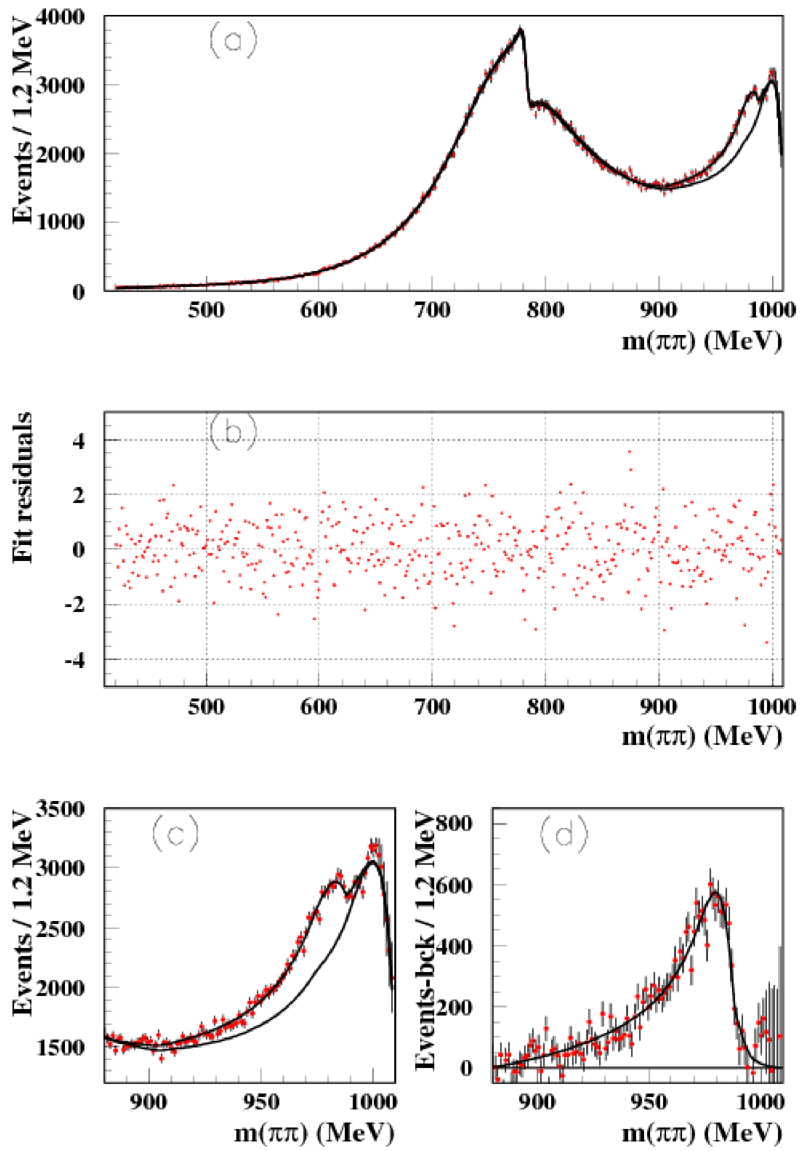
Fit	m_{f0} (MeV)	$g^2_{f0KK}/4\pi$ (GeV^2)	R
$\sqrt{s}$ +0.5 MeV	982.5	2.88	2.77
$\sqrt{s}$ -0.5 MeV	983.7	2.62	2.54
Abs.scale + 2%	985.2	2.52	2.64
Abs.scale - 2%	980.4	2.92	2.65
θ free ➔ $\theta = 2.3\pm0.2$	983.0	2.76	2.66
bin = 2.4 MeV	983.5	3.12	2.76
start = 492 MeV	983.2	2.85	2.69
start = 564 MeV	983.6	3.16	2.77
end= 1002 MeV	983.0	2.75	2.66
$\pi+\pi-\pi0$=0.47/2	983.5	3.06	2.74
$\pi+\pi-\pi0$=0.47*2	981.9	2.23	2.50
Full correction to low Eγ	982.8	2.78	2.70
(1-exp(-E/b)) b=11.6	982.9	3.15	2.95
(1-exp(-E/b)) b=7.6	982.9	2.50	2.47
Back NS	987.2	2.00	2.22

Summarizing: g^2_{fKK} has large systematic uncertainty

m_{f0} (MeV)	983.0 ± 0.6	$980 \div 987$
$g^2_{fKK}/4\pi$ (GeV^2)	2.76 ± 0.13	$2.0 \div 3.2$
$R = g^2_{fKK}/g^2_{f\pi+\pi-}$	2.66 ± 0.10	$2.5 \div 2.8$

The fits: NS

χ^2/ndf	533/477 (3.6%)
m_{f0} (MeV)	977.3±0.9
$g_{\phi f\gamma} \times g_{f\pi+\pi-}$	1.46±0.05
$g_{\pi\pi}$	0.062±0.002
g_{KK}	0.117±0.017
a_0	6.00±0.02
a_1	4.10±0.04
b_1 (rad/GeV)	3.13±0.05
m_ρ (MeV)	773.0±0.1
Γ_ρ (MeV)	145.1±0.1
α (x10^{-3})	1.64±0.04
β (x10^{-3})	-137±1
$a_{\rho\pi}$	1.5±1.4



The fits: NS

(NS) systematics 1: dependence on the shape of the background

fit	$P(\chi 2)$	m_{f0} (MeV)	$g_{\phi f\gamma} \times g_{f\pi+\pi-}$	$g_{\pi\pi}$	g_{KK}
no σ, b_0 constrained	4.6%	977.9	1.29	0.057	0.102
no σ, b_0 free	2.6%	978.1	1.17	0.055	0.093
no σ, $b_0 = b_1$	2.3%	978.9	1.12	0.053	0.077
no σ, $b_0 = 0$	1.2%	980.7	1.15	0.051	0.058
no σ, b_0 free $b_1 = 0$	2.3%	978.7	1.13	0.053	0.081
σ BES b_0 constrained	$\sim 10^{-7}$	983.2	0.76	0.034	<0.01
σ E791 b_0 constrained	$\sim 10^{-6}$	983.4	0.80	0.034	<0.01
σ BES b_0 free	0.1%	983.6	0.88	0.040	<0.02
σ E791 b_0 free	$\sim 10^{-5}$	983.4	0.81	0.035	<0.01

baseline fit

Polynomial background

Second pole background

The fits: NS

(NS) systematics 2: correlation between mass and couplings

fit	m_{f0} (MeV)	$g_{\phi S\gamma}$ (GeV^{-1})	$g_{f\pi+\pi-}$ (GeV)	g_{fKK} (GeV)
√s +0.5 MeV	979.0	1.56	1.00	1.73
√s -0.5 MeV	976.2	1.39	0.98	1.67
Abs.scale + 2%	981.4	1.23	0.89	0.97
Abs.scale - 2%	973.0	1.74	1.09	2.29
bin = 2.4 MeV	976.5	1.50	1.00	1.82
start = 492 MeV	978.4	1.46	0.98	1.60
start = 564 MeV	978.5	1.45	0.98	1.58
end= 1002 MeV	977.2	1.48	1.00	1.74
π+π−π0=0.47/2	976.9	1.49	1.00	1.78
π+π−π0=0.47*2	977.7	1.47	0.99	1.68
Full correction to low Eγ	977.3	1.48	0.99	1.72
(1-exp(-E/b)) b=11.6	972.9	1.48	1.05	2.07
(1-exp(-E/b)) b=7.6	970.0	1.47	1.08	2.27
Back KL	977.4	2.05	1.10	2.14

Summarizing....
In terms of couplings

m_{f0} (MeV)	977.3 ± 0.9	970 ÷ 981
$g_{\phi S\gamma}$ (GeV^{-1})	1.48 ± 0.06	1.2 ÷ 2.0
$g_{f\pi+\pi-}$ (GeV)	0.99 ± 0.02	0.9 ÷ 1.1
g_{fKK} (GeV)	1.73 ± 0.12	1.0 ÷ 2.3

Test of fit stability (on sub-samples);

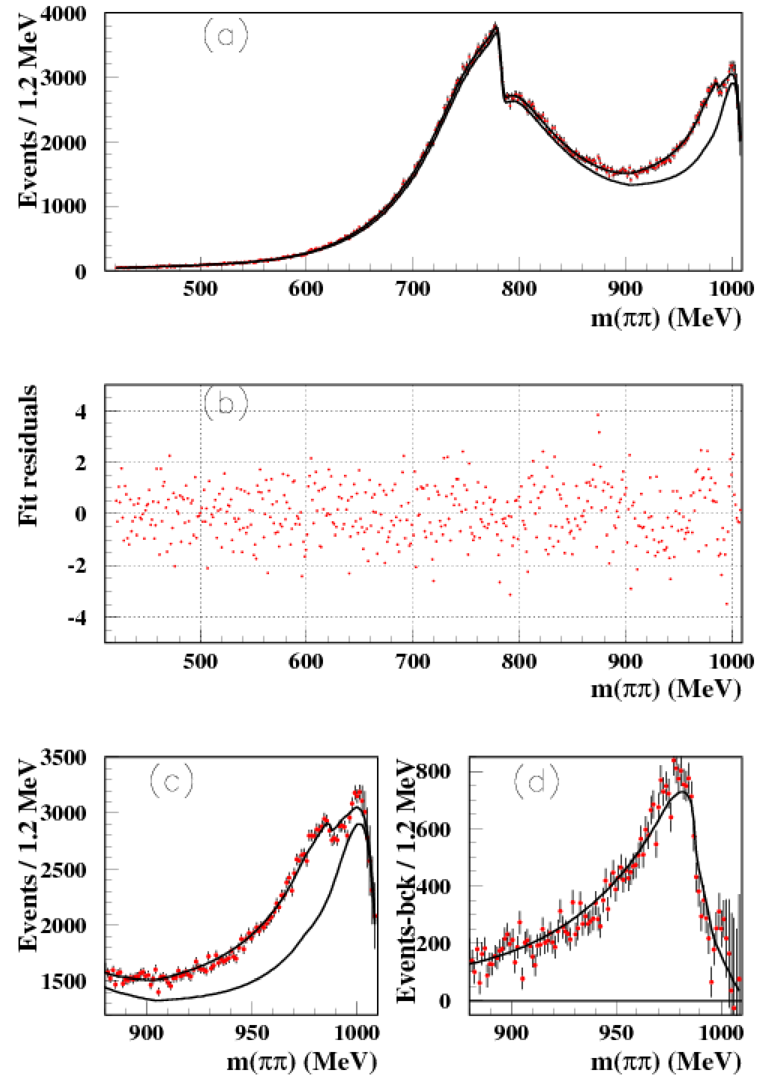
In red the results outside the ranges given before for the parameters

(1) Fit KL	$P(\chi 2)$	m_{f0} (MeV)	$g^2_{f0KK}/4\pi$ (GeV^2)	R
2001 data (115 pb-1)		979.3	1.44	2.17
2002 data ($234\ pb^{-1}$)		982.7	2.55	2.58
$\sqrt{s}$=1019.51 ($145\ pb^{-1}$)		981.4	2.18	2.54
$\sqrt{s}$=1019.67 ($108\ pb^{-1}$)		977.0	1.75	2.49

(2) Fit NS	$P(\chi 2)$	m_{f0} (MeV)	$g_{\phi S\gamma}$ (GeV^{-1})	$g_{f\pi+\pi-}$ (GeV)	g_{fKK} (GeV)
2001 data (115 pb-1)		982.8	1.27	0.91	0.83
2002 data ($234\ pb^{-1}$)		974.7	1.56	1.03	2.01
$\sqrt{s}$=1019.51 ($145\ pb^{-1}$)		978.3	1.54	0.99	1.72
$\sqrt{s}$=1019.67 ($108\ pb^{-1}$)		979.8	1.56	0.98	1.45

The fits: SA

χ^2/ndf	577/477 (0.11%)
a_1	11.9
b_1	3.3
c_1	-15.1
a_2	-14.7
b_2	-15.3
c_2	35.8
m_0	0.
λ (rad)	1.63
m_ρ (MeV)	774.4±0.2
Γ_ρ (MeV)	142.8±0.3
α (x10^{-3})	1.74±0.05
β (x10^{-3})	-100±18
$a_{\rho\pi}$	0±2



In collaboration with M.R.Pennington

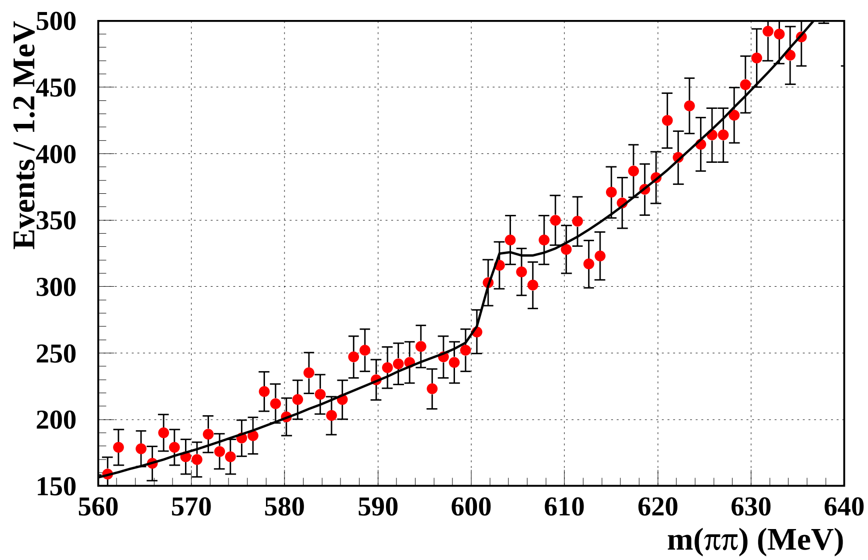
➔ g_ϕ = 6.6 ×10^{-4} GeV

The fits: try to include the σ

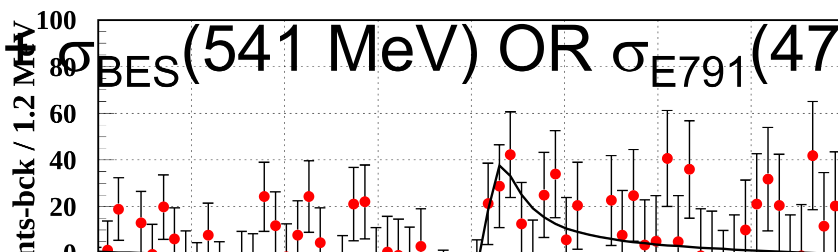
(KL) f_0(980) + σ_{BES}(541 MeV) σ coupling ~ 0 no change

(KL) f_0(980) + σ_{E791}(478 MeV) to f_0 parameters

(KL) f_0(980) + $\sigma_{free\ mass}$ ➔ found a solution with m=600 MeV



(NS) f_0(980) + σ_{BES}(541 MeV) OR σ_{E791}(478 MeV) ➔ bad fit

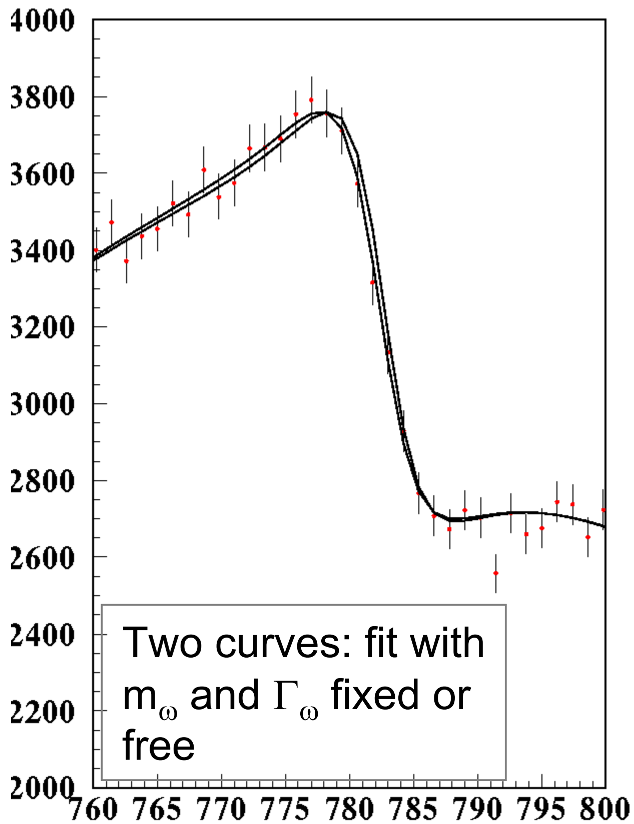


The fits: comment on the background

Use $\rho - \omega$ interference pattern to test mass scale and resolution

m_ω = 782.18 ± 0.58 MeV PDG value = 782.59 ± 0.11 MeV

Γ_ω = 8.87 ± 0.84 MeV PDG value = 8.49 ± 0.08 MeV



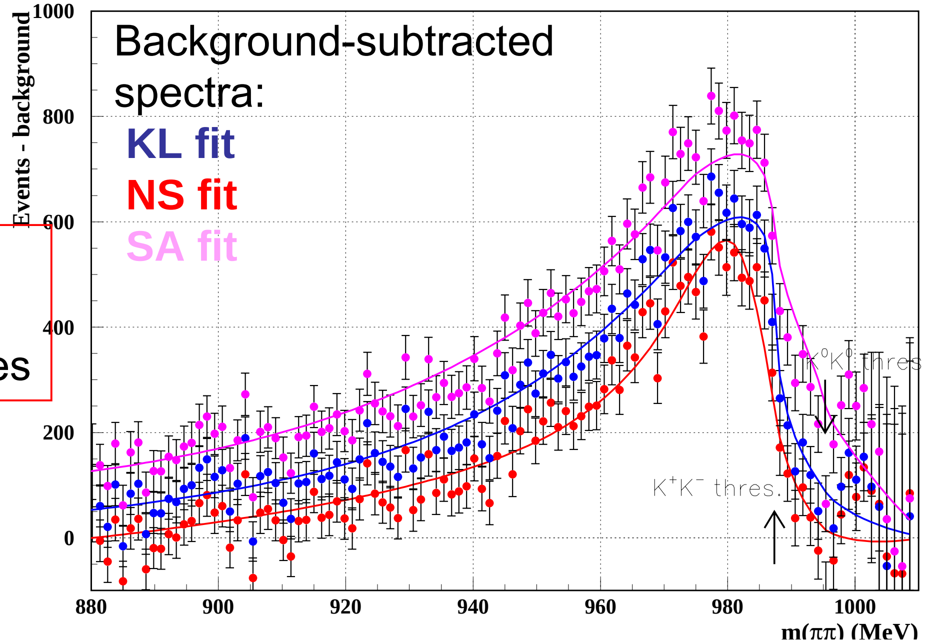
Background parameters: pion form factor (Kuhn-Santamaria parameters)

	Fit KL	Fit NS	Fit SA
m_ρ (MeV)	773.1	773.0	774.4
Γ_ρ (MeV)	144.0	145.1	142.8
α (x10^{-3})	1.65	1.64	1.74
β (x10^{-3})	-123	-137	-100

β determines the background level in the f_0(980) region ➔ the signal size: Difference up to 5% in the f_0 region.

Discussion of the results: the line-shape

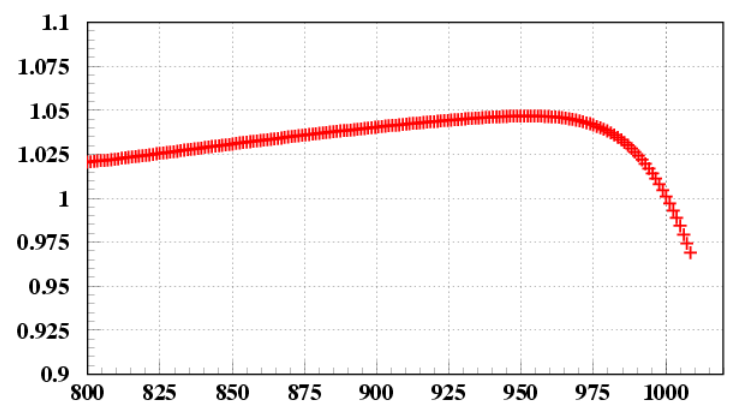
Different background parameters ➔ different signal shapes



Peak size:
KL fit → 25% of bck
NS fit → 24% of bck
SA fit → 33% of bck

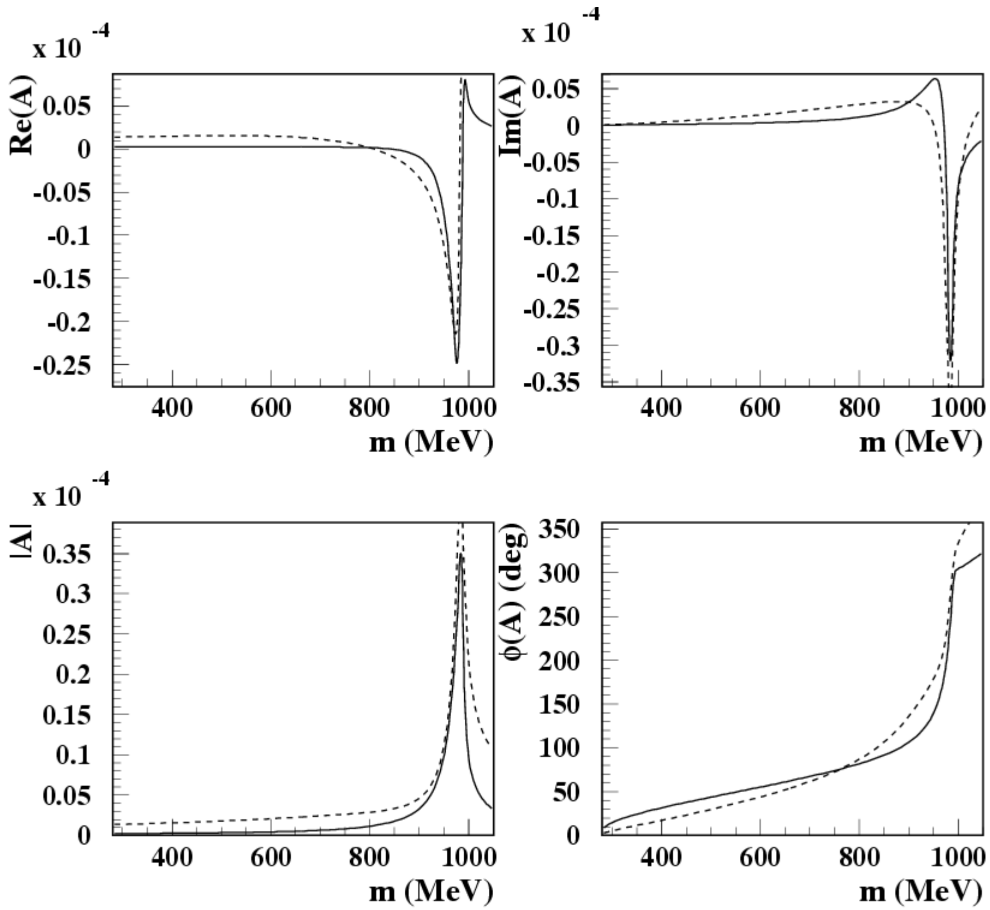
Peak FWHM:
KL fit → 37 MeV
NS fit → 30 MeV
SA fit → 45 MeV

Ratio between "non-scalar part" resulting from NS and KL fits.



Discussion of the results: the scalar amplitude

A is the scalar amplitude: Re(**A**), Im(**A**), |**A**|, ϕ(**A**) as functions of *m*:
KL (solid), NS (dashed)



ϕ(**A**) = 3/2 π @ f_0 pole
= π (resonance) + π/2
(kaon-loop, background)

Not enough sensitivity to the intermediate region

Discussion of the results: the f_0 parameters.

Summarizing...

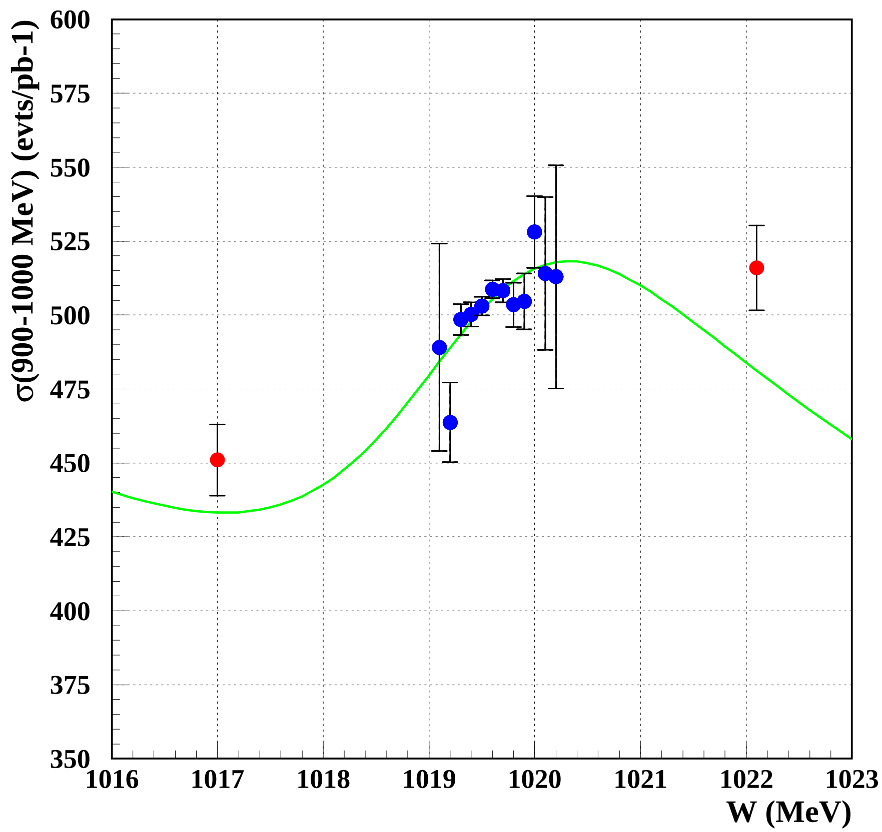
	KL	NS
m_{f0} (MeV)	983 [980 ÷ 987]	978 [970 ÷ 981]
g_{f0KK} (GeV)	5.9 [5.0 ÷ 6.5]	1.7 [1.6 ÷ 2.3]
$g_{f0\pi+\pi-}$ (GeV)	3.6 [3.3 ÷ 3.8]	1.0 [0.9 ÷ 1.1]
$R=(g_{f0KK} / g_{f0\pi+\pi-})^2$	2.7 [2.5 ÷ 2.8]	3.0 [2.6 ÷ 4.4]
$g_{\phi f0g}$ (GeV^{-1})	--	1.5 [1.2 ÷ 2.0]

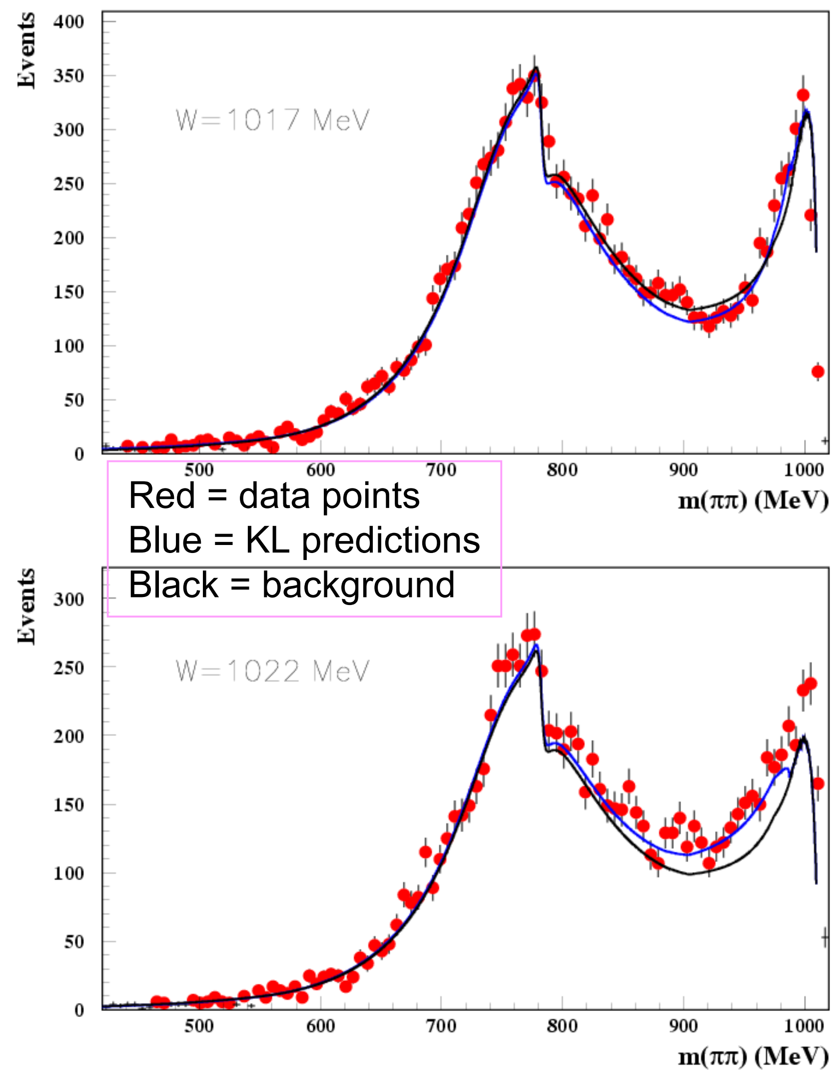
1. 5 ÷10 MeV mass difference: all within PDG 980 ±10 MeV.
2. Discrepancies due to a different interpretation of the line-shape: for KL *all is f_0*, for NS there is *background also*.
3. Agreement on R
4. $g_{\phi f0g}$ >> $g_{\phi Mg}$ with M any pseudoscalar meson (naïve statement)

Discussion of the results: extrapolation to “off-peak” data

Not a fit but an “absolute” prediction

Red and Blue = data points
Green = KL predictions



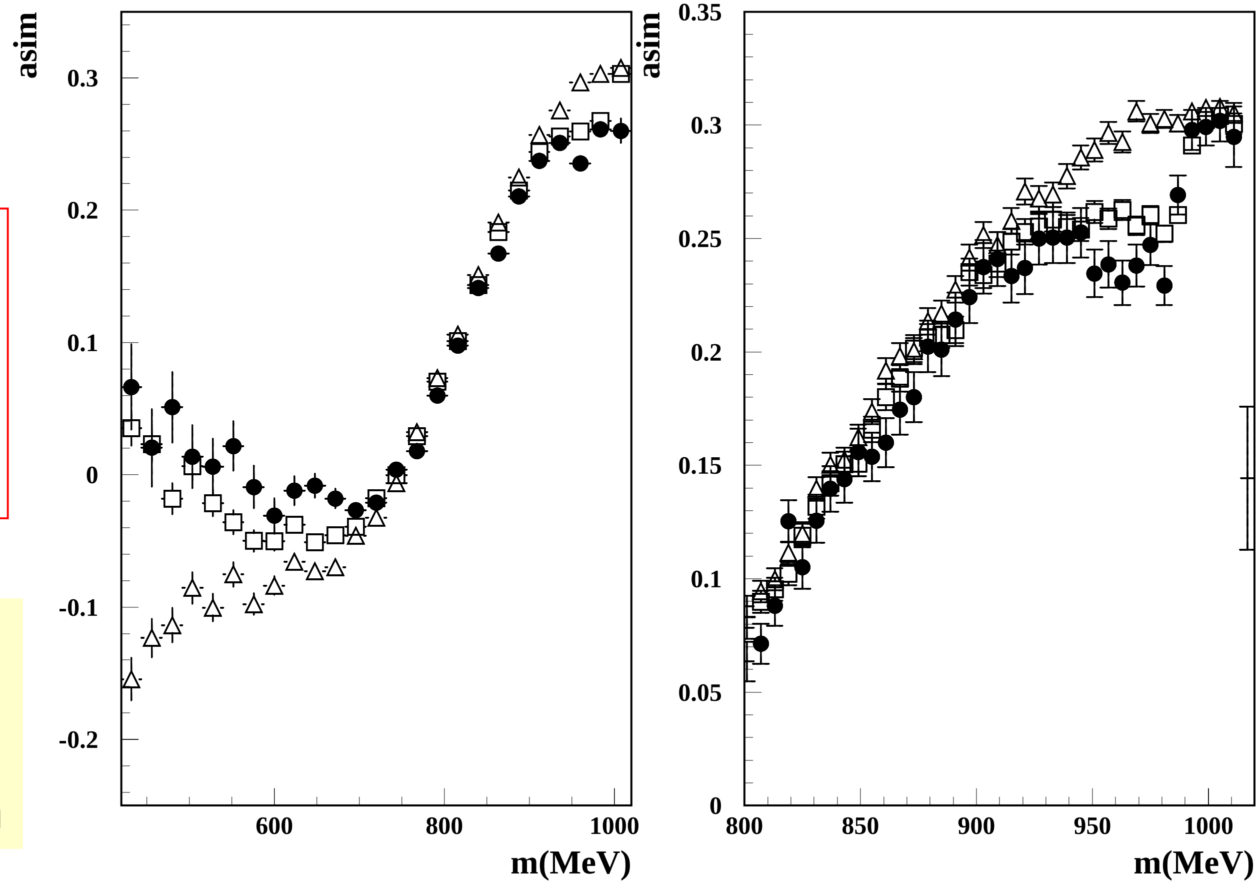


Discussion of the results: interpretation of the charge asymmetry

“Diluition” due to residual $\pi^+\pi^-\pi^0$ background is included. The effect is at m<600 MeV

Full = data points
traingles = predictions ISR+FSR
Squares = predictions ISR+FSR+f_0(KL)

➔KL amplitude is able to describe the observed behaviour ! Again: not a fit but an “absolute” prediction



Conclusion.

- Goto publication soon including KL and NS results (not SA).
- Main results of this analysis:
  - Observation of $\phi \rightarrow f_0(980)\gamma \rightarrow \pi^+\pi^-\gamma$;
  - Determination of $f_0(980)$ parameters;
  - Positive test of the kaon-loop model;
  - Model-Independent approach very difficult;
  - We have no sensitivity in the low mass region (we don't see any σ but this is not a good place to look for it).
- 2 fb^{-1} analysis to be done