Scalar and tensor mesons from a coupled-channel analysis

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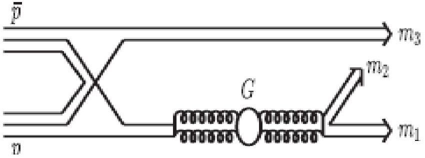
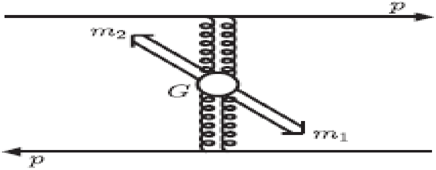
How to search for glueballs

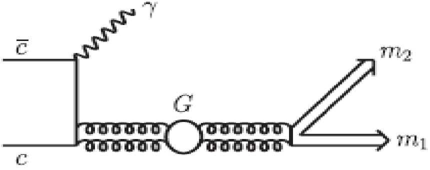
$\bar{N}N$ **annihilation**



Central production



Radiative J/ψ **decays**



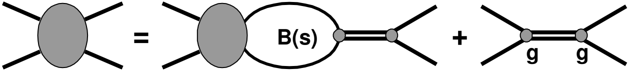
2. Coupled channel analysis

A. V. Sarantsev, I. Denisenko, U. Thoma and E. Klempt,
"Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays,"
Phys. Lett. B 816, 136227 (2021).

$\pi^+\pi^-$	$\rightarrow$	$\pi^+\pi^-$	$\pi^0\pi^0$	$\eta\eta$	$\eta\eta'$	K^+K^-
$\chi^2/N, N$		1.32; 845	0.89; 110	0.67; 15	0.23; 9	1.06; 35
		CERN-Munich		GAMS		BNL
$\bar{p}p$	$\rightarrow$	$3\pi^0$	$\pi^0\pi^+\pi^-$	$2\pi^0\eta$	$\pi^0\eta\eta$	CB (liq. H_2)
$\chi^2/N, N$		1.40; 7110	1.24, 1334	1.23; 3475	1.28; 3595	
$\bar{p}p$	$\rightarrow$	$3\pi^0$		$2\pi^0\eta$	$\pi^0\eta\eta$	CB (gas. H_2)
$\chi^2/N, N$		1.38; 4891		1.24; 3631	1.32; 1182	
$\bar{p}p$	$\rightarrow$	$K_LK_L\pi^0$	$K^+K^-\pi^0$	$K_SK^\pm\pi^\mp$	$K_LK^\pm\pi^\mp$	CB (liq. H_2)
$\chi^2/N, N$		1.08; 394	0.97; 521	2.13; 771	0.76; 737	
$\bar{p}n$	$\rightarrow$	$\pi^+\pi^-\pi^-$	$\pi^0\pi^0\pi^-$	$K_SK^-\pi^0$	$K_sK_S\pi^-$	CB (liq. D_2)
$\chi^2/N, N$		1.39; 823	1.57; 825	1.33; 378	1.62; 396	
J/ψ	$\rightarrow$	$\gamma\pi^0\pi^0$	γK_SK_S	$\gamma\eta\eta$	$\gamma\omega\phi$	BESIII
$\chi^2/N; N$		1.28; 167	1.21, 121	0.8; 21	0.2; 17	

N/D-based approach to the description of the scattering amplitude

The scattering amplitude is found by solving the following equation:



$$A_{ij}(s,s) = \sum_m \int\limits_{(m_1+m_2)^2}^{\infty} \frac{ds}{\pi} \frac{A_{im}(s,s')\rho_m(s')K_{mj}(s',s)}{s'-s-i\varepsilon} + K_{ij}(s,s)$$

Here $i, m, j = \pi\pi, KK, \eta\eta, \eta\eta', \omega\phi, \ldots$ **and** $K(s)$ **is an interaction kernel:**

$$K_{ij} = \sum_\alpha \frac{g_i^\alpha g_j^\alpha}{M_\alpha^2 - s} + f_{ij}(s)\,.$$

where f_{ij} **is nonresonant transition part.**

P-vector approach

$$T_j(s,s) = \sum_i \int\limits_{(m_1+m_2)^2}^{\infty} \frac{ds}{\pi} \frac{P_i(s,s')\rho_i(s')A_{ij}(s,s')}{s'-s-i\varepsilon} + P_j(s,s)$$

The P-vector of the initial interaction has the form:

$$P_j = \sum_\alpha \frac{\Lambda_\alpha g_j^\alpha}{M_\alpha^2 - s} + F_j(s)$$

Here F_j is a nonresonant production term.
The same set of Λ_α production couplings should describe all final states. For example the same P-vector describes the reactions:

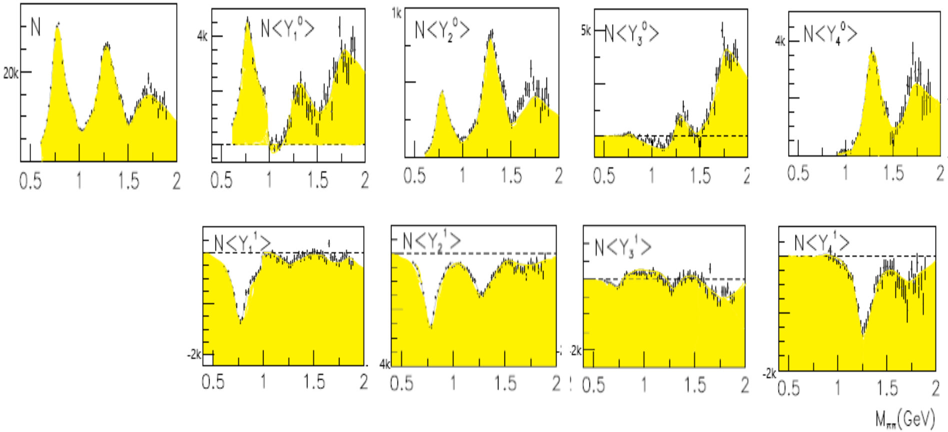
$$\bar{p}p \to \pi^0\pi^0\pi^0, \eta\eta\pi^0, KK\pi$$

Here the Λ_α and F_j parameters can be complex numbers due to rescattering.
The same P-vector should describe the J/Ψ decay:

$$J/\Psi \to \gamma\pi\pi, \gamma KK, \gamma\eta\eta, \gamma\eta\eta', \gamma\omega\phi$$

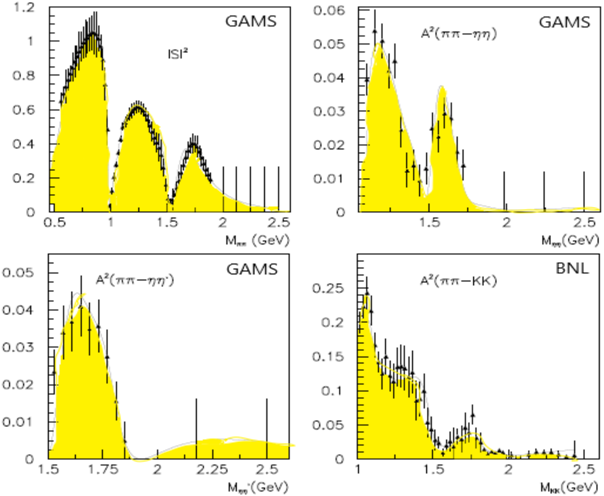
Here one can expect that Λ_α and F_j parameters are real numbers.

The CERN-Munich data on $\pi\pi \to \pi\pi$ elastic scattering



The CERN-Munich data have different PWA solutions. The ambiguity is resolved by the GAMS data on $\pi^- p \to \pi^0\pi^0 n$ (at 200 GeV/c pion momenta).

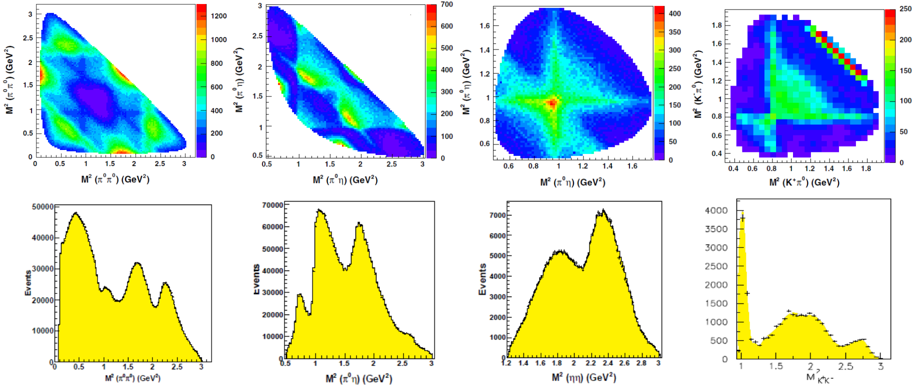
GAMS and BNL data on pion-induced reactions



GAMS: D. Alde *et al.*, "Study of the $\pi^0\pi^0$ system with the GAMS-4000 spectrometer at 100 GeV/c," Eur. Phys. J. A 3, 361 (1998).

BNL: S. J. Lindenbaum and R. S. Longacre, "Coupled channel analysis of $J^{PC} = 0^{++}$ and 2^{++} isoscalar mesons with masses below 2 GeV," Phys. Lett. B 274, 492 (1992).

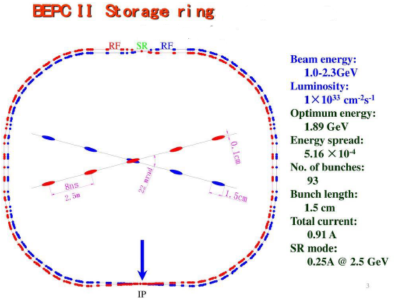
The Crystal Barrel data

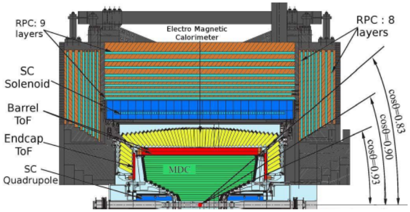


$\pi^0\pi^0\pi^0$ $\pi^0\pi^0\eta$ $\pi^0\eta\eta$ $K^+K^-\pi^0$

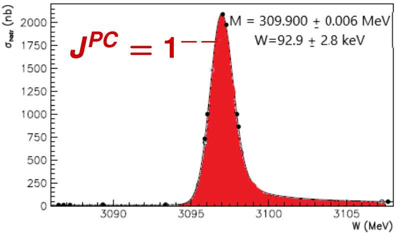
$\cdots$ **and further Dalitz plots.**

Data from BESIII

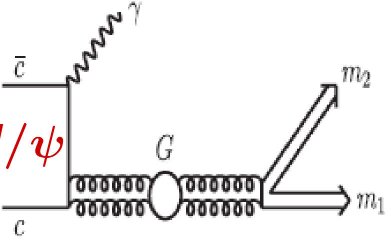




M. Ablikim *et al.* [BESIII],"Design and Construction of the BESIII Detector," Nucl. Instrum. Meth. A 614, 345-399 (2010).



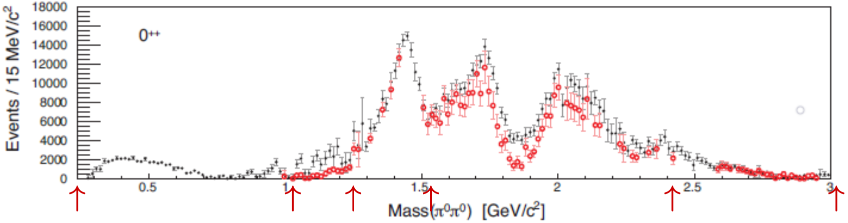
$J^{PC} = 1^{--}$



J/ψ

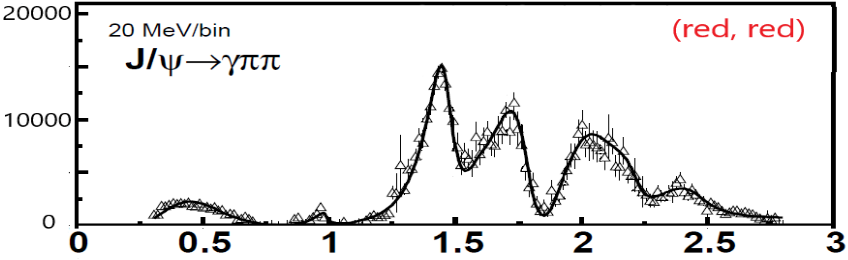
V. V. Anashin *et al.* "Final analysis of KEDR data on J/ψ and $\psi(2S)$ masses," Phys. Lett. B 749, 50-56 (2015).

Partial waves from $J/\psi \to \pi^0\pi^0$ in slices of the $2\pi^0$ mass

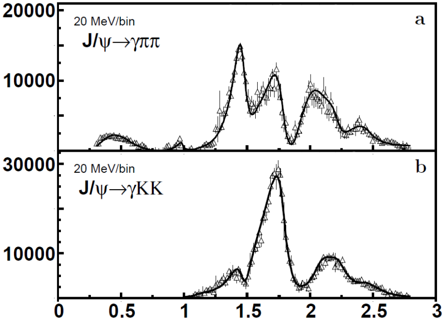


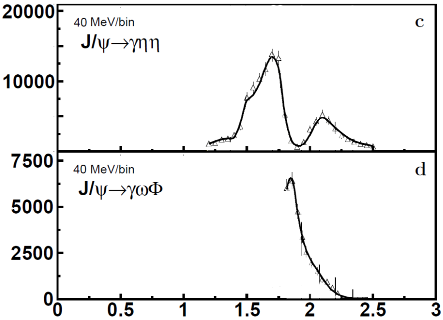
$\leftarrow \mathbf{I}_{\text{identical}} \rightarrow$ $\mathbf{II}_{\text{amb}}$ $\mathbf{III}_{\text{id}}$ $\leftarrow \mathbf{IV}_{\text{ambiguous}} \rightarrow \leftarrow \mathbf{V}_{\text{identical}} \rightarrow$

M. Ablikim *et al.* [BESIII], and A.P. Szczepaniak, P. Guo,
"Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92, no.5, 052003 (2015).



$J/\psi \to \gamma$ $\pi^0\pi^0$ and K_sK_s $\eta\eta$ and $\omega\phi$





$1.3 \cdot 10^9$ events

$0.225 \cdot 10^9$ events

PWA in slices of energy

Amplitude fit to data

M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92 no.5, 052003 (2015).
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the K_SK_S system produced in radiative J/ψ decays," Phys. Rev. D 98 no.7, 072003 (2018).
M. Ablikim et al. [BESIII Collaboration], "Partial wave analysis of $J/\psi \to \gamma\eta\eta$,"
Phys. Rev. D 87, no. 9, 092009 (2013).
M. Ablikim *et al.* [[BESIII Collaboration], "Study of the near-threshold $\omega\phi$ mass enhancement in doubly OZI-suppressed' $J/\psi \to \gamma\omega\phi$ decays," Phys. Rev. D 87 no.3, 032008 (2013).

The tensor amplitudes in the spin-orbital momentum basis $A_2(SL)$:

$$
\begin{aligned}
A_2(20) &= \epsilon^{\Psi}_{\mu}\epsilon^{\gamma}_{\nu}\tilde{a}_{20}(s)Z_{\mu\nu}(k) \\
A_2(02) &= (\epsilon^{\Psi}\epsilon^{\gamma})X^{(2)}_{\mu\nu}(k_1^{\perp})\tilde{a}_{02}(s)Z_{\mu\nu}(k) \\
A_2(12) &= \frac{3}{2}(\epsilon^{\Psi}k_1^{\perp})\epsilon^{\gamma}_{\mu}k^{\perp}_{1\nu}\tilde{a}_{12}(s)Z_{\mu\nu}(k)
\end{aligned}
$$

The correspondence to the helicity basis:

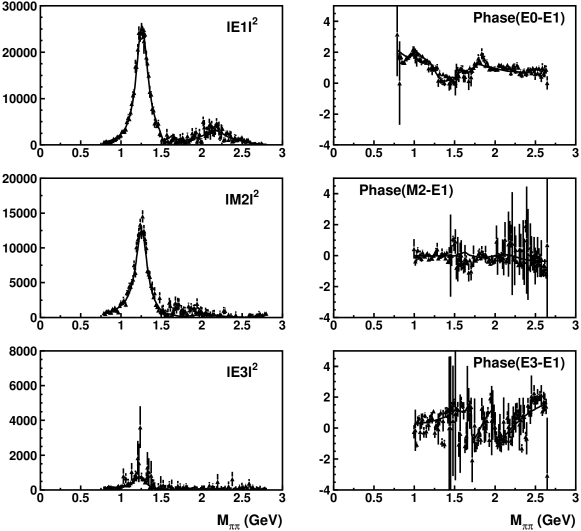
$$
\begin{aligned}
E_1 &= \frac{1}{\sqrt{5}}\left(\tilde{a}_{02}+\sqrt{3}\tilde{a}_{12}+\tilde{a}_{20}\left(7+3\frac{P_0}{\sqrt{s}}\right)\right) \\
M_2 &= \frac{\sqrt{5}}{3}\left(\sqrt{3}\tilde{a}_{02}+\tilde{a}_{12}-\sqrt{3}\tilde{a}_{20}\left(1-\frac{P_0}{\sqrt{s}}\right)\right) \\
E_3 &= \frac{2\sqrt{7}}{3\sqrt{5}}\left(\sqrt{3}\tilde{a}_{02}-2\tilde{a}_{12}+2\sqrt{3}\tilde{a}_{20}\left(1-\frac{P_0}{\sqrt{s}}\right)\right)
\end{aligned}
$$

At high masses:

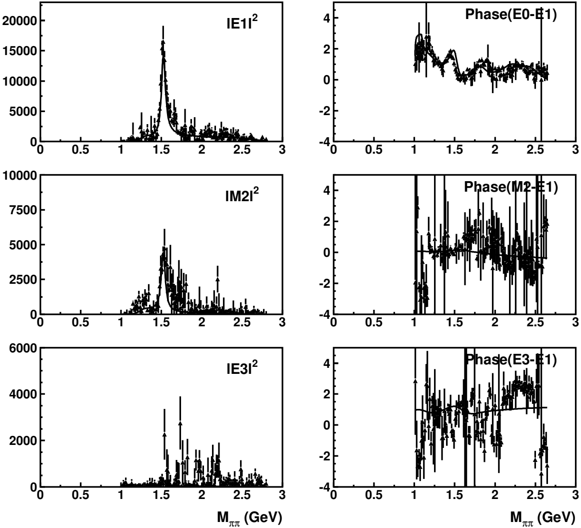
$$
\frac{P_0}{\sqrt{s}} \to 1 \qquad E_1 >> M_2 \qquad E_1 >> E_3
$$

if $\tilde{a}_{20}(s)$ is a dominant partial wave.

The description of the tensor states in the reaction $J/\Psi \to \gamma\pi\pi$: only ground states are strongly produced.



The description of the tensor states in the reaction $J/\Psi \to \gamma KK$: only ground states are strongly produced.

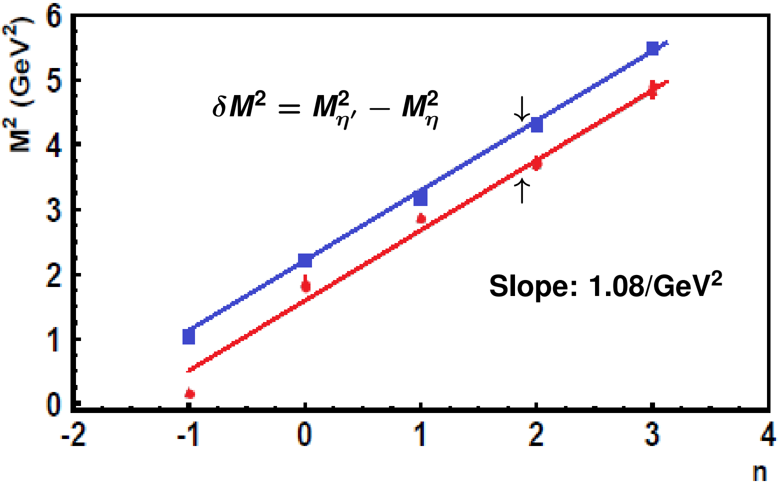


Results and interpretation

Pole masses and widths (in MeV) of scalar mesons. The RPP values are listed as small numbers for comparison.

Name	$f_0(500)$	$f_0(1370)$	$f_0(1710)$	$f_0(2020)$	$f_0(2200)$
M	410 ± 20 $400\to550$	1370 ± 40 $1200\to1500$	1700 ± 18 1704 ± 12	1925 ± 25 1992 ± 16	2200 ± 25 2187 ± 14
Γ	480 ± 30 $400\to700$	390 ± 40 $100\to500$	255 ± 25 123 ± 18	320 ± 35 442 ± 60	150 ± 30 ~ 200
Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M	1014 ± 8 990 ± 20	1483 ± 15 1506 ± 6	1765 ± 15	2075 ± 20 2086^{+20}_{-24}	2340 ± 20 ~2330
Γ	71 ± 10 $10\to100$	116 ± 12 112 ± 9	180 ± 20	260 ± 25 284^{+60}_{-32}	165 ± 25 250 ± 20

(M^2, n) trajectories of scalar mesons



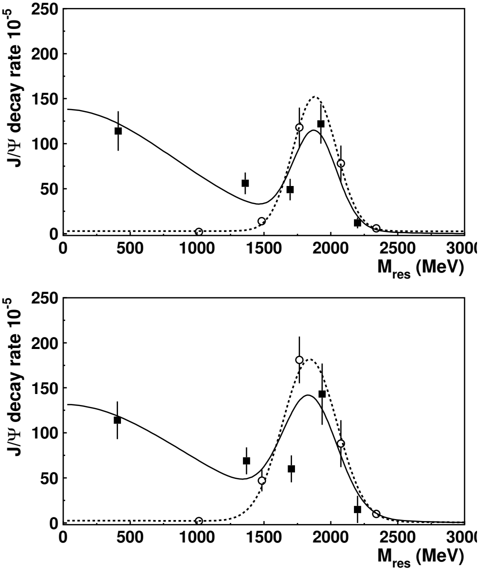
··· and where is the scalar glueball ?

The fragmented glueball

Yields in radiative J/ψ decays (in units of 10^{-5})

$BR_{J/\psi\to\gamma f_0\to}$	$\gamma\pi\pi$	$\gamma K\bar{K}$	$\gamma\eta\eta$	$\gamma\eta\eta'$	$\gamma\omega\phi$	missing		total
						$\gamma 4\pi$	$\gamma\omega\omega$	
$f_0(500)$	105±20	5±5	4±3	∼0	∼0	∼0		114±21
$f_0(980)$	1.3±0.2	0.8±0.3	∼0	∼0	∼0	∼0		2.1±0.4
$f_0(1370)$	38±10	13±4	3.5±1	0.9±0.3	∼0	14±5		69±12
		42±15				27±9		
$f_0(1500)$	9.0±1.7	3±1	1.1±0.4	1.2±0.5	∼0	33±8		47±9
	10.9±2.4	2.9±1.2	$1.7^{+0.6}_{-1.4}$	$6.4^{+1.0}_{-2.2}$		36±9		
$f_0(1710)$	6±2	23±8	12±4	6.5±2.5	1±1	7±3		56±10
$f_0(1770)$	24±8	60±20	7±1	2.5±1.1	22±4	65±15		181±26
$f_0(1750)$	38±5	99^{+10}_{-6}	24^{+12}_{-7}		25±6	97±18	31±10	
$f_0(2020)$	42±10	55±25	10±10			(38±13)		145±32
$f_0(2100)$	20±8	32±20	18±15			(38±13)		108±25
$f_0(2200)$	5±2	5±5	0.7±0.4			(38±13)		49±17
$f_0(2100)/f_0(2200)$	62±10	109^{+8}_{-19}	$11.0^{+6.5}_{-3.0}$			115±41		
$f_0(2330)$	4±2	2.5±0.5	1.5±0.4					8±3
		20±3						

Is this the scalar glueball?



$$M = 1865 \pm 25^{+10}_{-30} \text{ MeV}$$

$$\Gamma = 370 \pm 50^{+30}_{-20} \text{ MeV}$$

Summary

- We have performed the combined analysis of the J/Ψ radiative decay data together with $\pi\pi$ scattering data and the LEAR data from the anti-proton nucleon annihilation at rest.
- The P-vector analysis reveals 10 scalar states which fall onto linear (n, M^2)-trajectories
- Only the ground states of the tensor mesons are strongly produced. There is some indication for the states in the mass region 1800-2100 MeV. The tensor states are produced dominantly with the orbital momentum $L = 0$ as well as the scalar states.
- The only relevant explanation for the enhanced production of scalar mesons in the mass range 1700 - 2100 MeV and a strong suppression for the production of the tensor states is the mixture of the scalar states with a scalar glueball.
- The intensity for the production of the scalar states reveal the lowest scalar glueball.