Production of exotic states in central production

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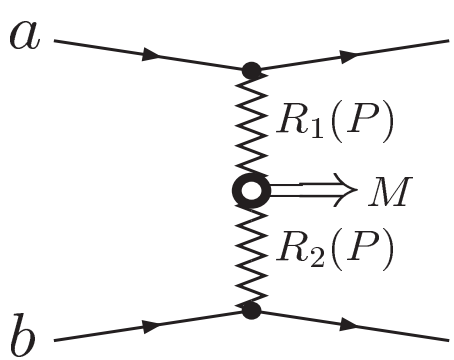
Why spectroscopy ?

1. The spectrum of bound states and resonances of a system reveals the underlying symmetries and forces
2. Examples:
   the hydrogen atom and the development of quantum mechanics
   the baryon octet and decuplet ground states and SU(3)
   the charmonium family of states and the potential model
3. The potential model (and other models) lead to a rich phenomenology. Not only $q\bar{q}$ mesons should exist but also
   glueballs, states without constituent glue, short-hand notation gg
   hybrids should exist, $q\bar{q}g$
   multiquark states should exist, $q\bar{q}q\bar{q}$
   Molecules should exist, e.g. $K\bar{K}$
4. Question: do these exist as independent entities ? Specifically, are there 2, 3, 4, or 5 scalar states, $q\bar{q}$, $q\bar{q}g$, $q\bar{q}q\bar{q}$, gg, $K\bar{K}$? Or just one with a (q^2 dependent) Fock space expansion ?

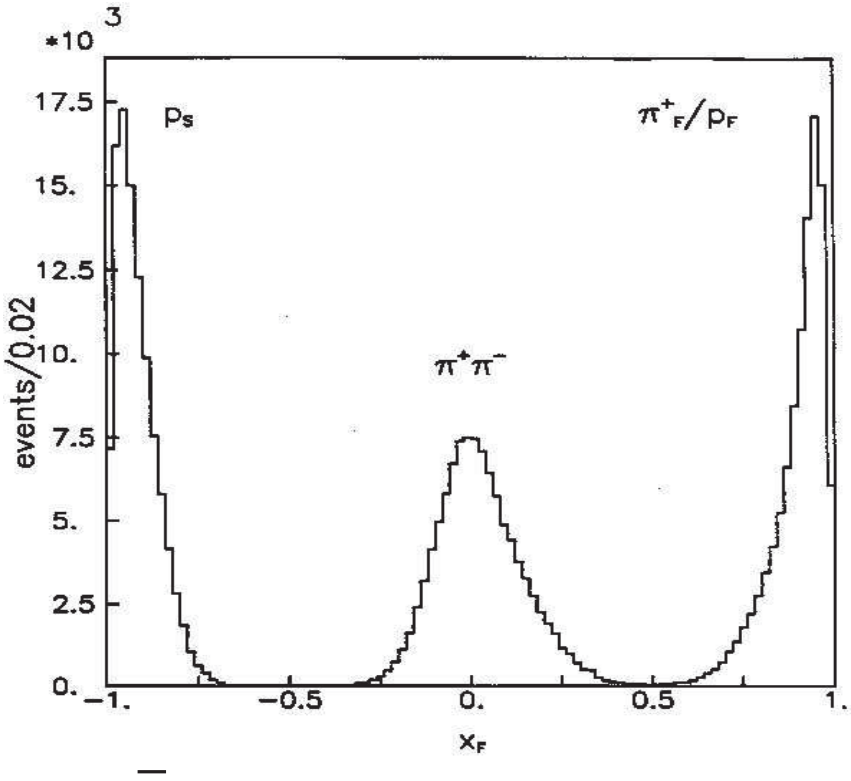
What is central production ?

In central production, two hadrons at a large energy scatter, keeping their identity and loosing a small fraction of their energy. In a fixed target experiment, a hadron h_{beam} scatters off a target proton p_{target} and produces a particle or system of particles X

$$h_{\mathrm{beam}}\, p \;\rightarrow\; h_{\mathrm{fast}}\, X\, p_{\mathrm{slow}} \tag{1}$$



Central production of a system X. The momentum transfer is defined by $q_i = (p_i - p_i')$ where p_i, p_i' are the in- and outgoing momenta of the two hadrons. ω_i are the energies transferred to X.

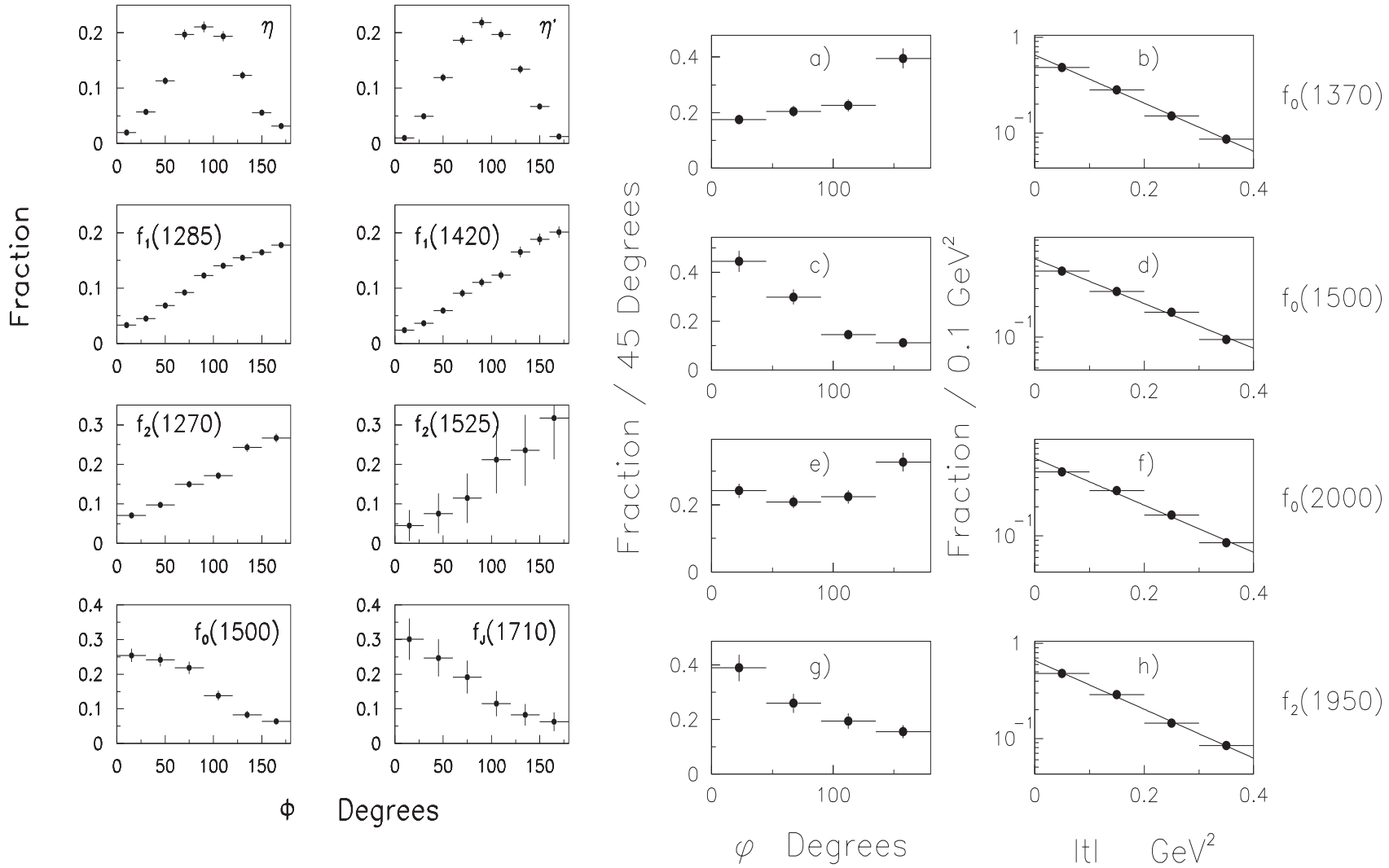


The target-proton is slow in the laboratory system. Two virtual particles collide producing a particle or system of particles X with mass $M \sim \sqrt{s(1-x_1)(1-x_2)}$ where s is the squared centre-of-mass energy.

For $\sqrt{s} \sim 27$ GeV/c^2 and $1-x_1, 1-x_2$ in the range from 0.0 to0.1 the available phase space is limited to about 2.7 GeV/c^2.Scattered hadron and targetproton keep a large fraction x_F of their total energy. The two scattering particles transfer a four-momenta t to the central system. The $\pi^+\pi$ pair is slow in the centre-of-mass system.

Most data from Barberis et al. (WA102), Phys. Lett. (1997-2001).

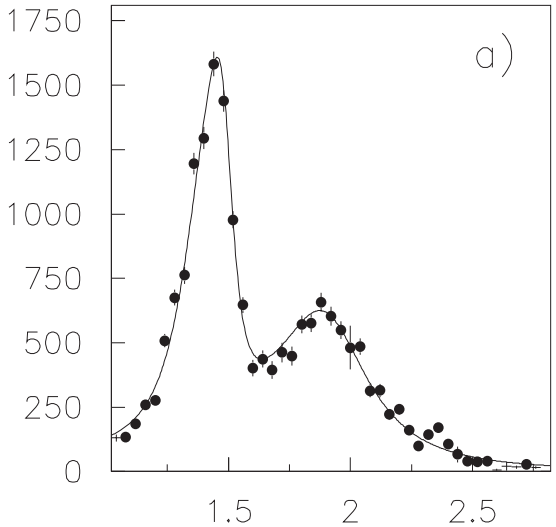
The Close-Kirk glueball filter $dP_t=|p_t-q_t|$ Phys. Lett B397 (1997) 333



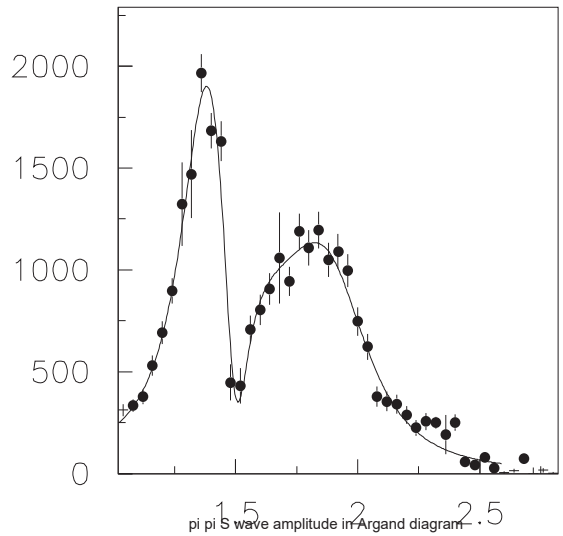
The azimuthal angle between two protons ϕ for various resonances.

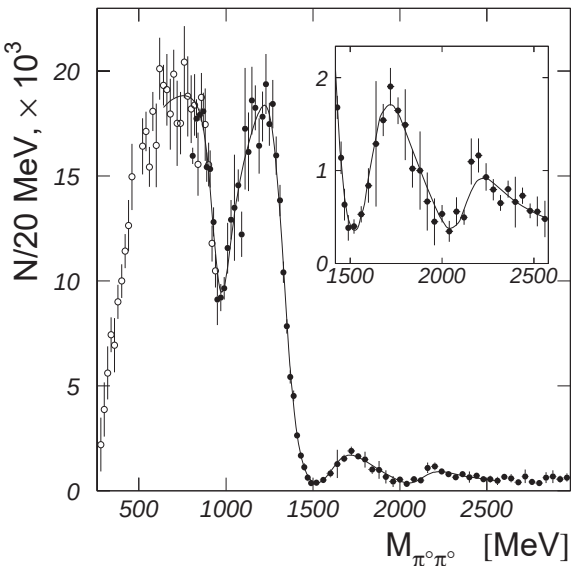
4 production for different P_T BNL:

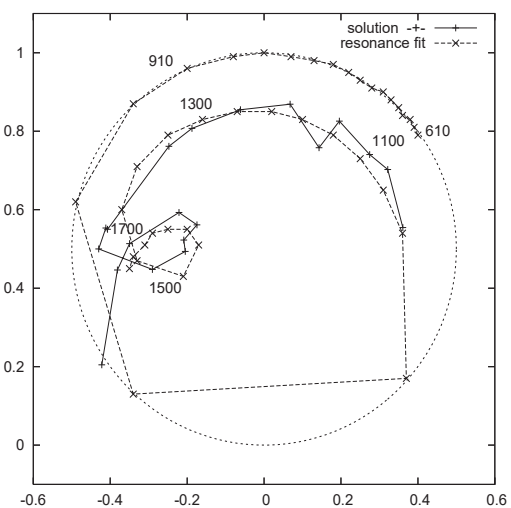
High P_T

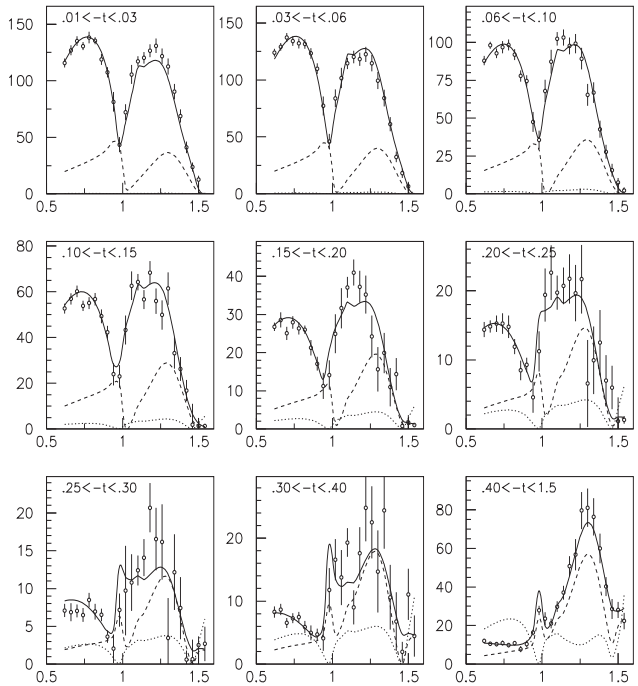


Low P_T



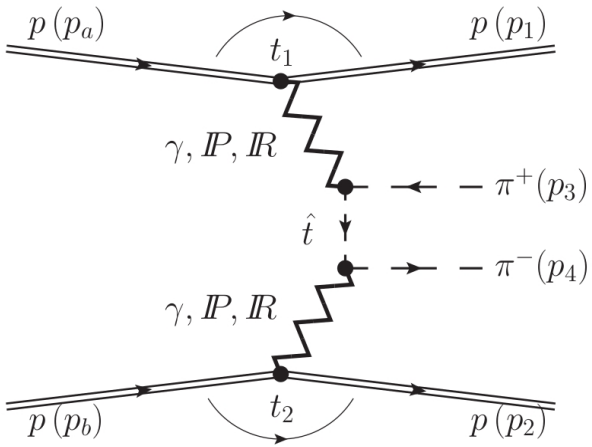




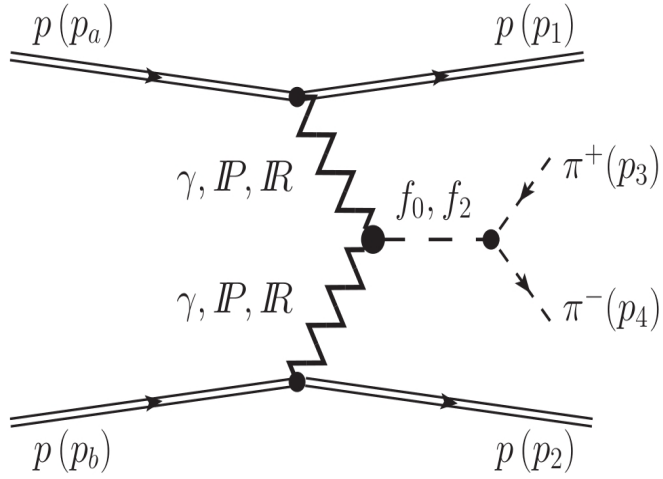


2 production in CEX (GAMS) and Argand diagram (W. Ochs)

However it could be not only double Pomeron exchange

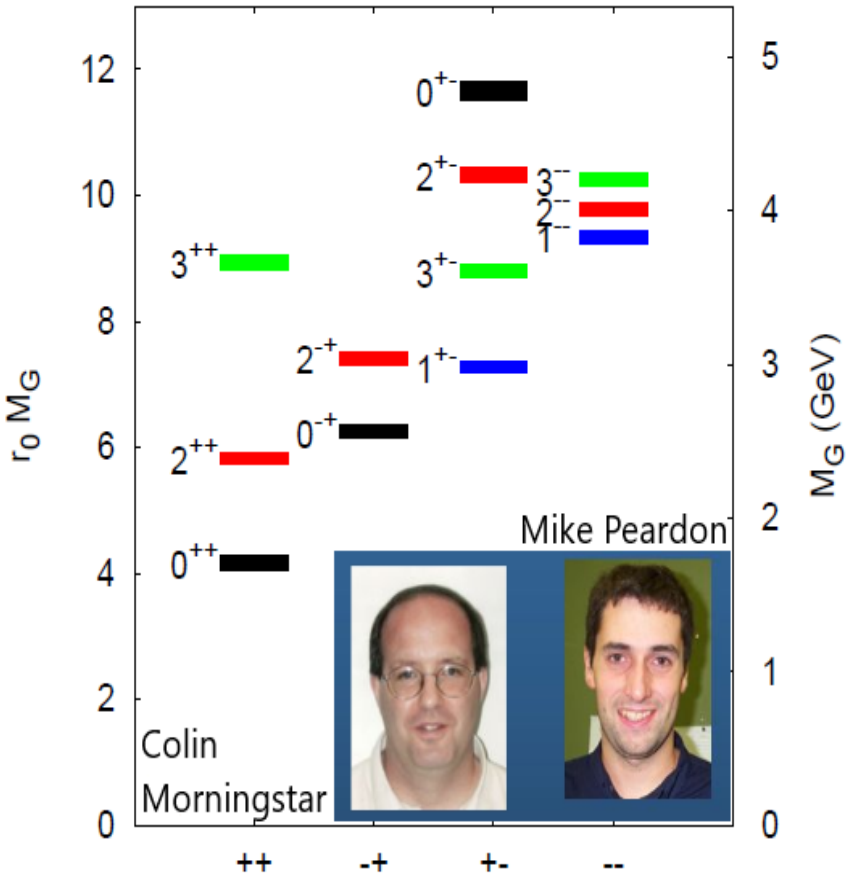


Non resonant production of 2 pions



Resonance production of 2 pions

1.3 Glueballs:



The scalar glueball is expected in the mass range

from 1700 to 2000 MeV

0^{++}	$1710 \pm 50 \pm 80$ MeV
2^{++}	$2390 \pm 30 \pm 120$ MeV
0^{-+}	$2560 \pm 35 \pm 120$ MeV

Y. Chen *et al.* "Glueball spectrum and matrix elements on anisotropic lattices," Phys. Rev. D 73, 014516 (2006).

0^{++}	1980 MeV	1920 MeV
2^{++}	2420 MeV	2371 MeV
0^{-+}	2220 MeV	

A. P. Szczepaniak and E. S. Swanson, "The Low lying glueball spectrum," Phys. Lett. B 577, 61-66 (2003).

M. Rinaldi and V. Vento, "Meson and glueball spectroscopy within the graviton soft wall model," Phys. Rev. D 104, no.3, 034016 (2021).

0^{++}	1850 ± 130 MeV
0^{-+}	2580 ± 180 MeV

M. Q. Huber, C. S. Fischer and H. Sanchis-Alepuz, "Spectrum of scalar and pseudoscalar glueballs from functional methods," Eur. Phys. J. C 80, no.11, 1077 (2020).

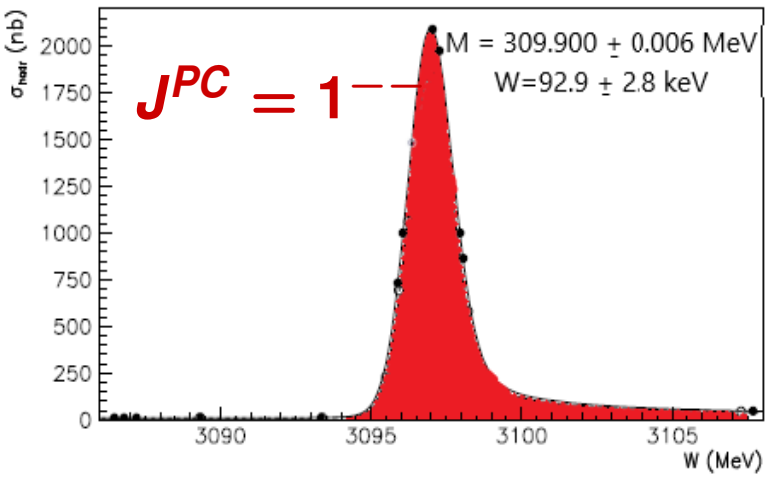
Glueballs in radiative J/ψ decays

1974: Extremely narrow resonance discovered: J/ψ

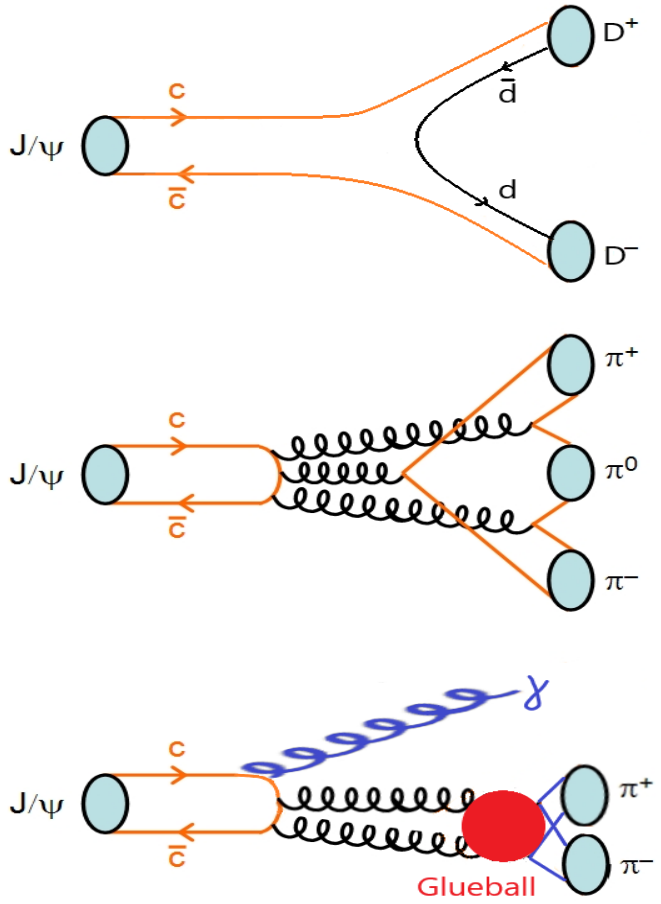
New quark: charm

$$J/\psi = c\bar{c} \rightarrow c\bar{d} + \bar{c}d$$

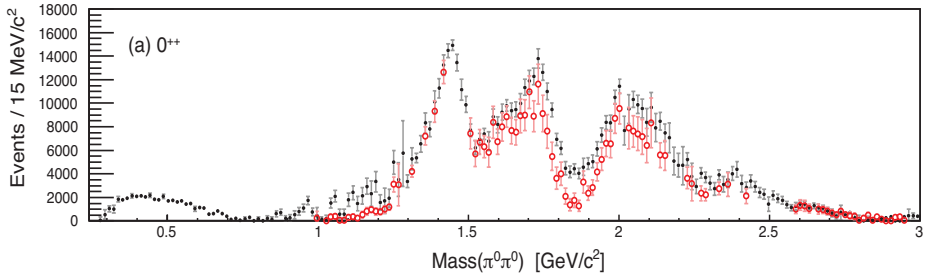
energetically forbidden!

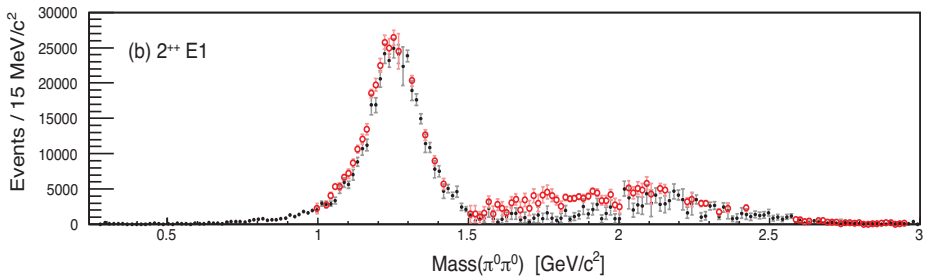


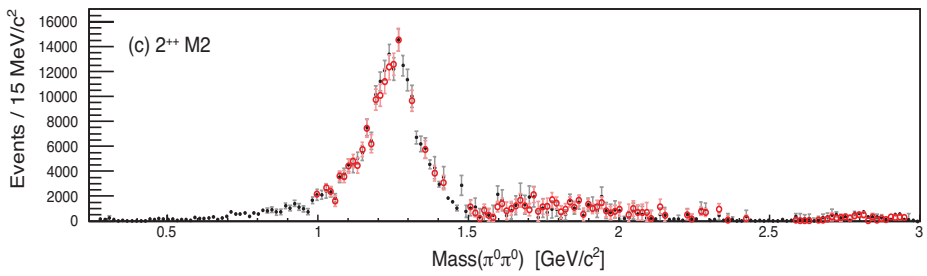
Today: Data from BESIII, $1.3 \cdot 10^9$ J/ψ decays

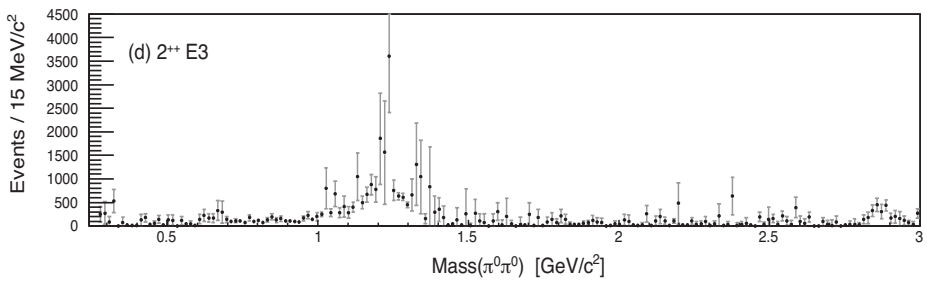


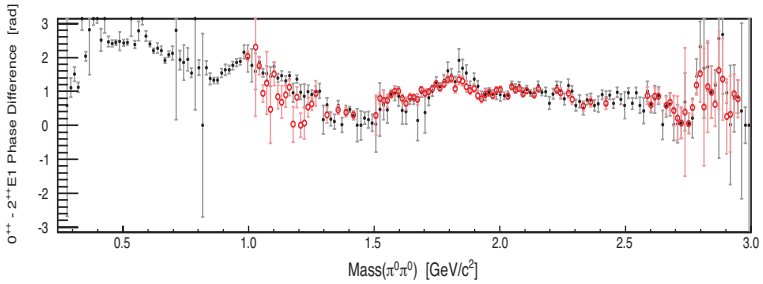
Energy independent analysis for $J/\Psi \to \gamma\pi^0\pi^0$

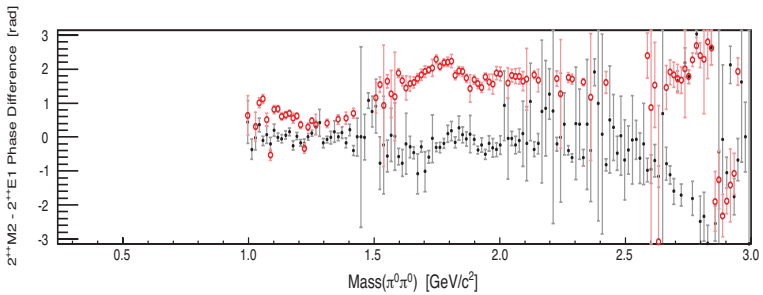


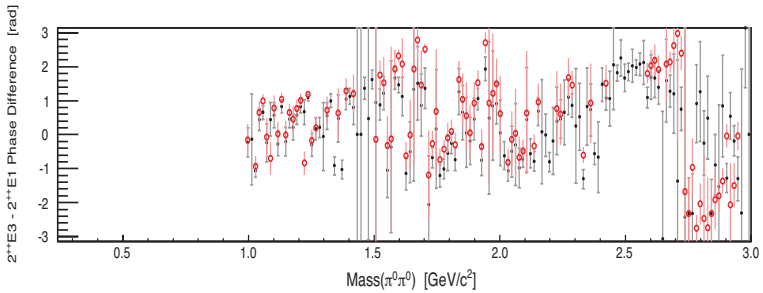






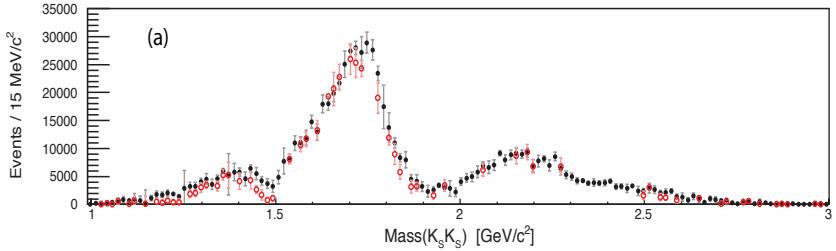


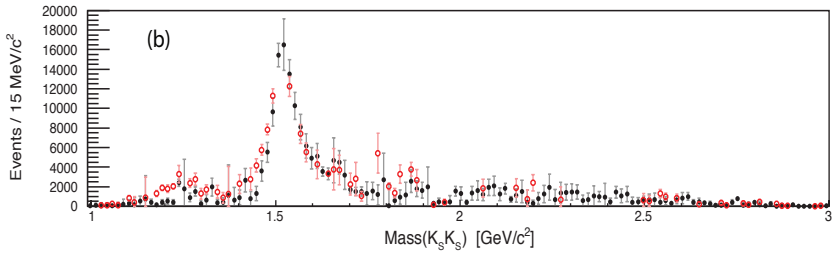


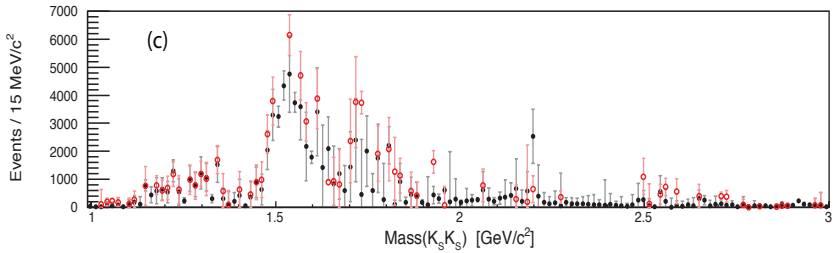


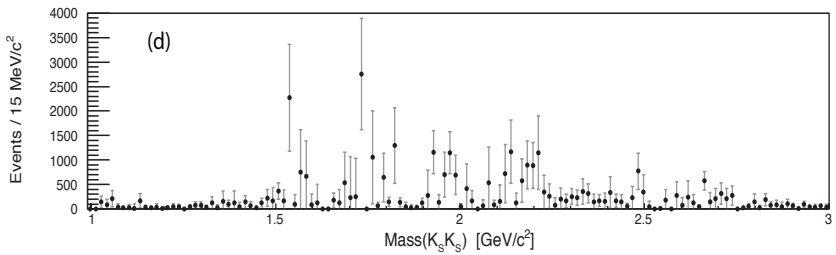
BESIII, A. P. Szczepaniak, P. Guo1 Phys. Rev. D 92 no.5, 052003 (2015)

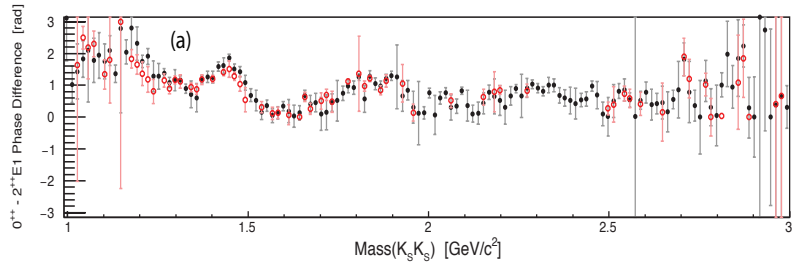
Energy independent analysis for $J/\Psi \to \gamma K_s K_s$

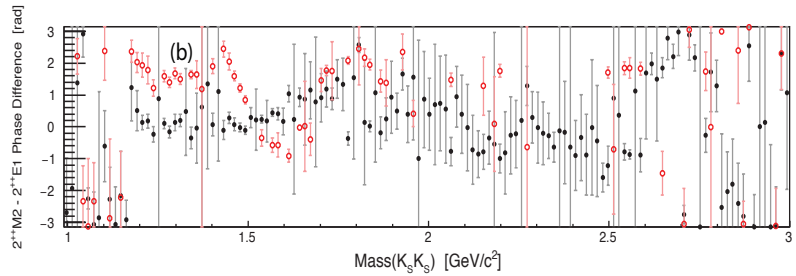


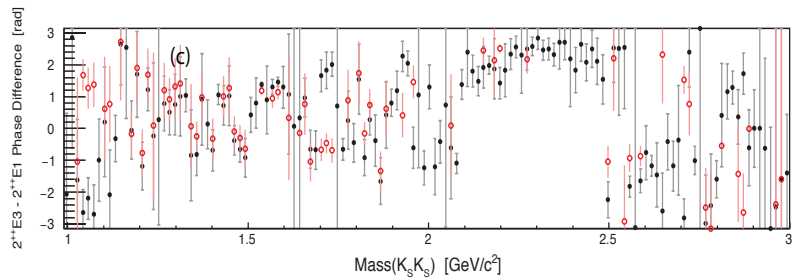






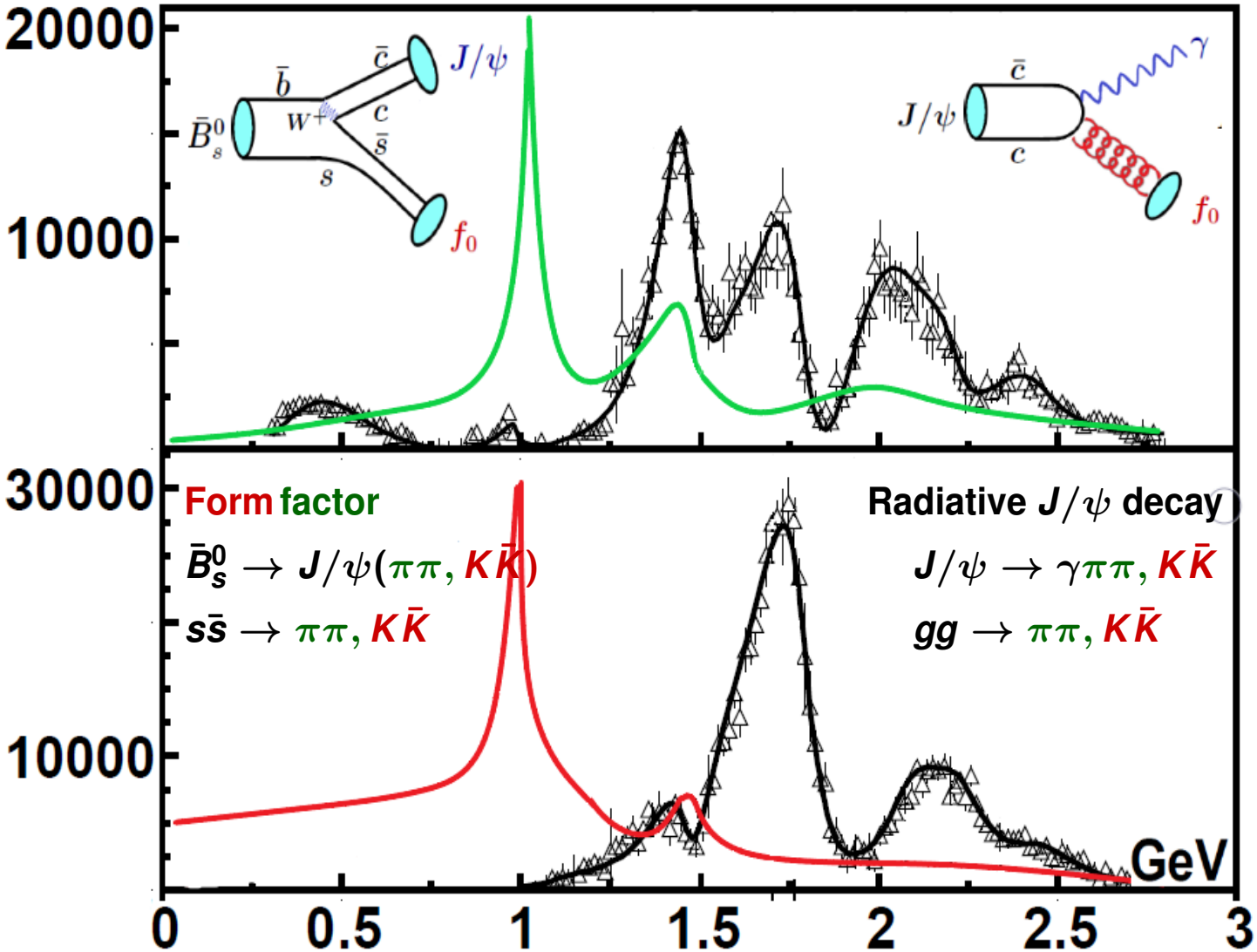






BESIII, Phys. Rev. D 98, no.7, 072003 (2018)

3.4 Evidence for strong glue-glue interactions



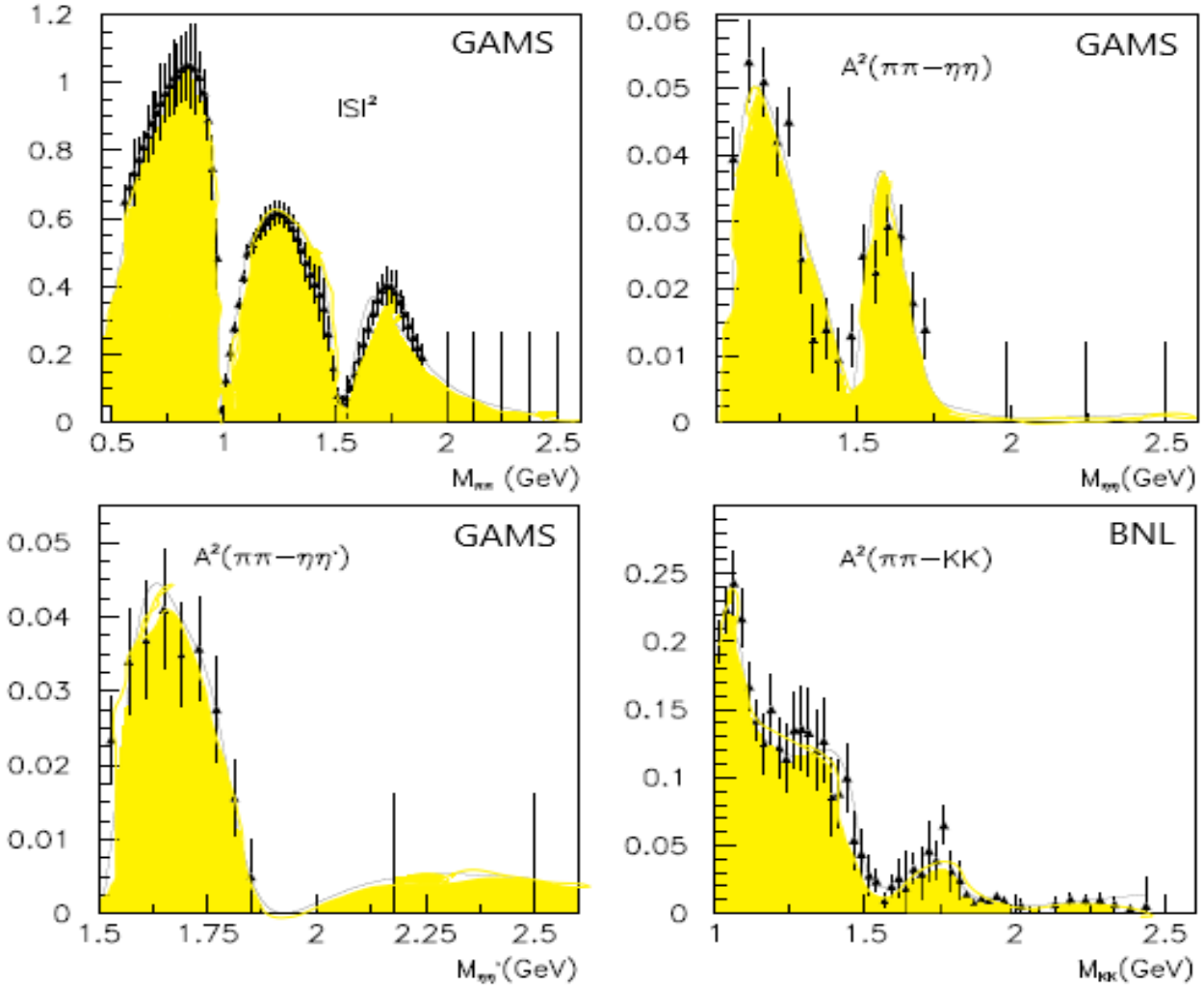
S. Ropertz, C. Hanhart and B. Kubis, Eur. Phys. J. C 78, no.12, 1000 (2018).
R. Aaij *et al.* [LHCb], Phys. Rev. D 89, R. Aaij *et al.* [LHCb], JHEP 08, 037 (2017).

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).

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

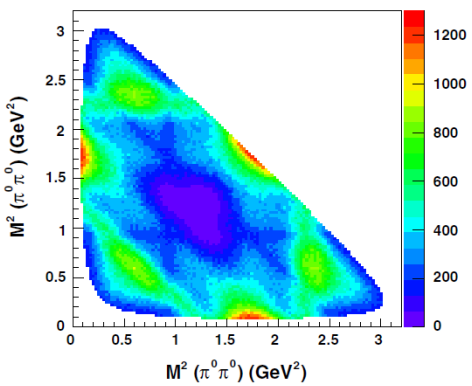
GAMS and BNL data on pion-induced reactions

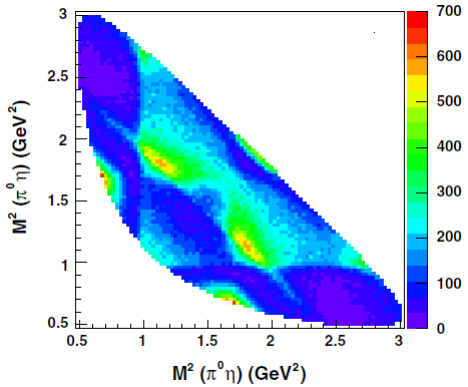


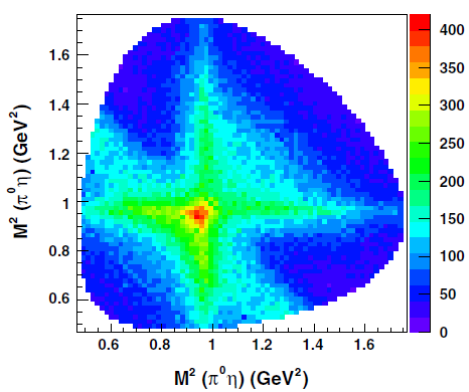
GAMS: D. Alde *et al.*, "Study of the $\pi^0\pi^0$ system with the GAMS-4000 spectrometer at 100 GeV/c," Eur. Phys. J. A 3, 361 (1998).

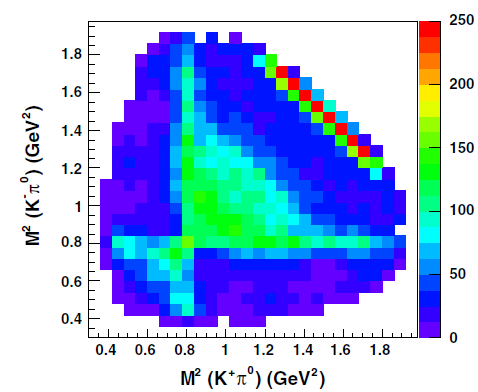
BNL: S. J. Lindenbaum and R. S. Longacre, "Coupled channel analysis of $J^{PC} = 0^{++}$ and 2^{++} isoscalar mesons with masses below 2 GeV," Phys. Lett. B 274, 492 (1992).

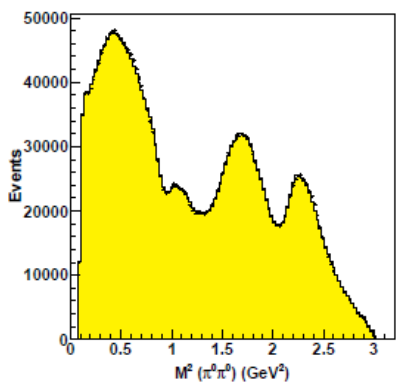
The Crystal Barrel data



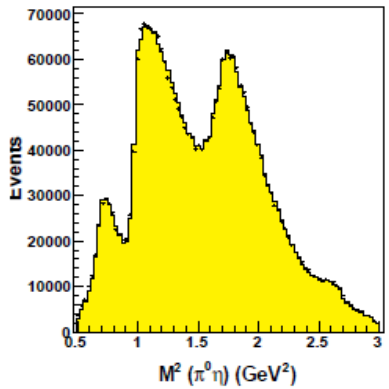




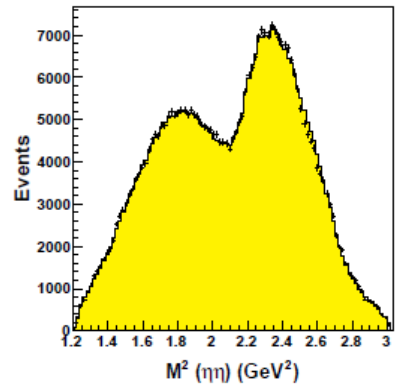




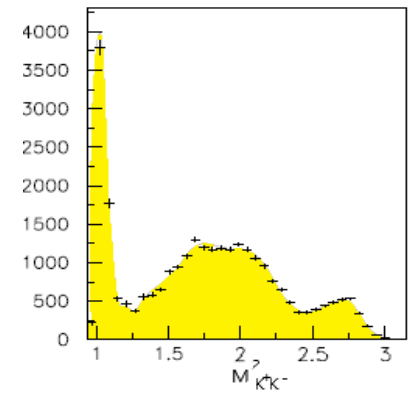
$\pi^0\pi^0\pi^0$



$\pi^0\pi^0\eta$



$\pi^0\eta\eta$



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

· · · and further Dalitz plots.

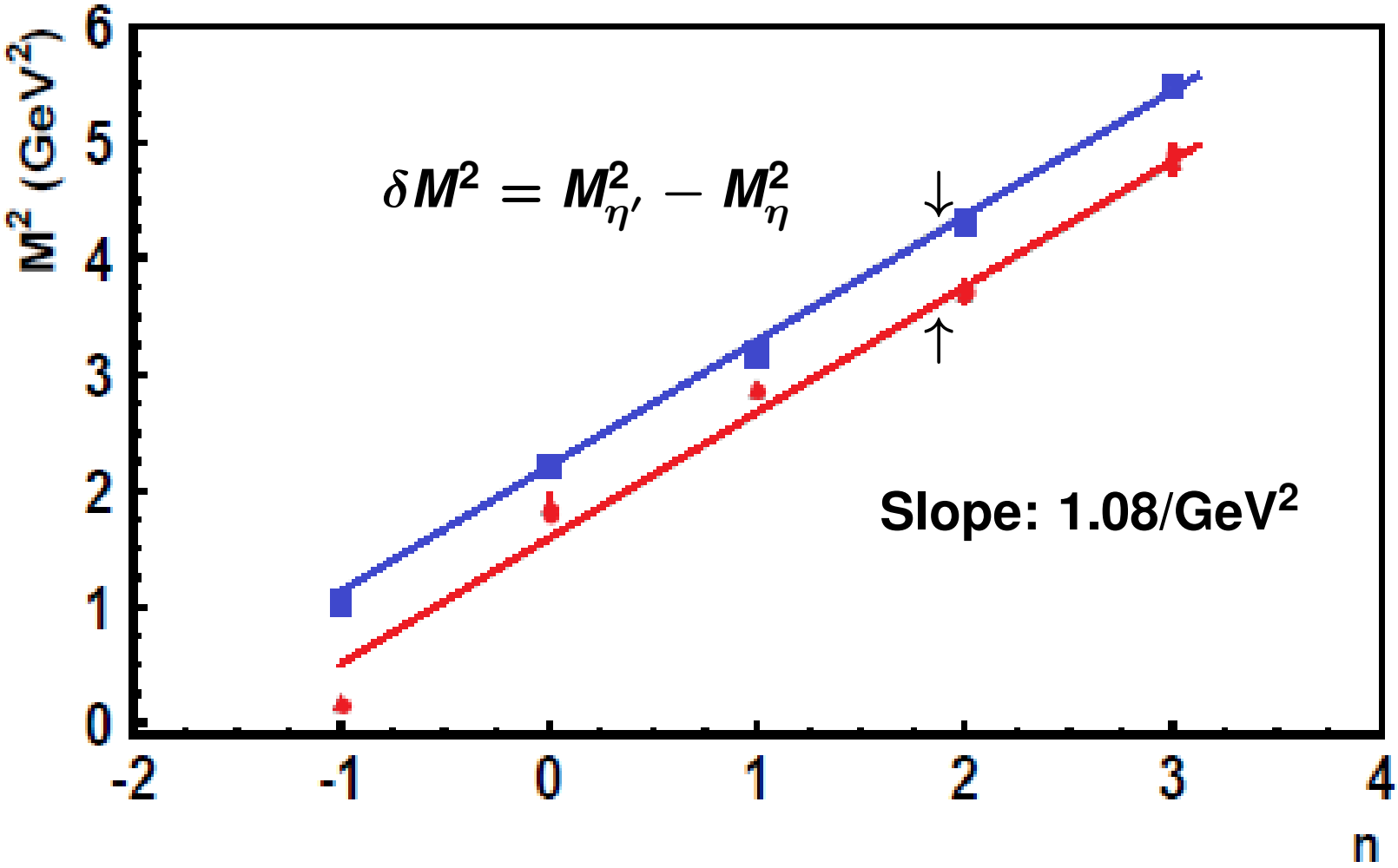
Results and interpretation

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 $400 \to 550$	1370 ± 40 $1200 \to 1500$	1700 ± 18 1704 ± 12	1925 ± 25 1992 ± 16	2200 ± 25 2187 ± 14
Γ	480 ± 30 $400 \to 700$	390 ± 40 $100 \to 500$	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 $10 \to 100$	116 ± 12 112 ± 9	180 ± 20	260 ± 25 284^{+60}_{-32}	165 ± 25 250 ± 20

(M^2, n) trajectories of scalar mesons



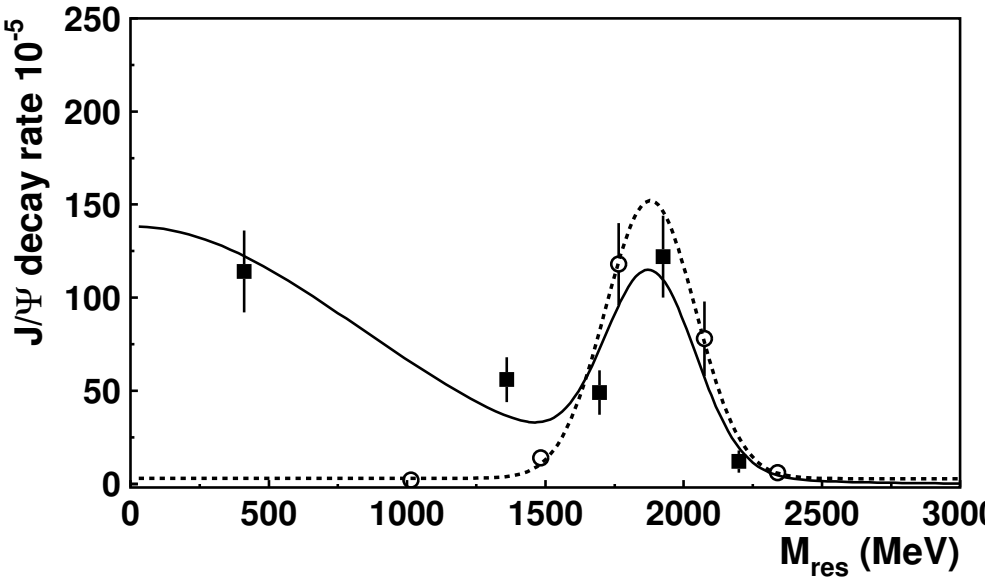
· · · and where is the scalar glueball ?

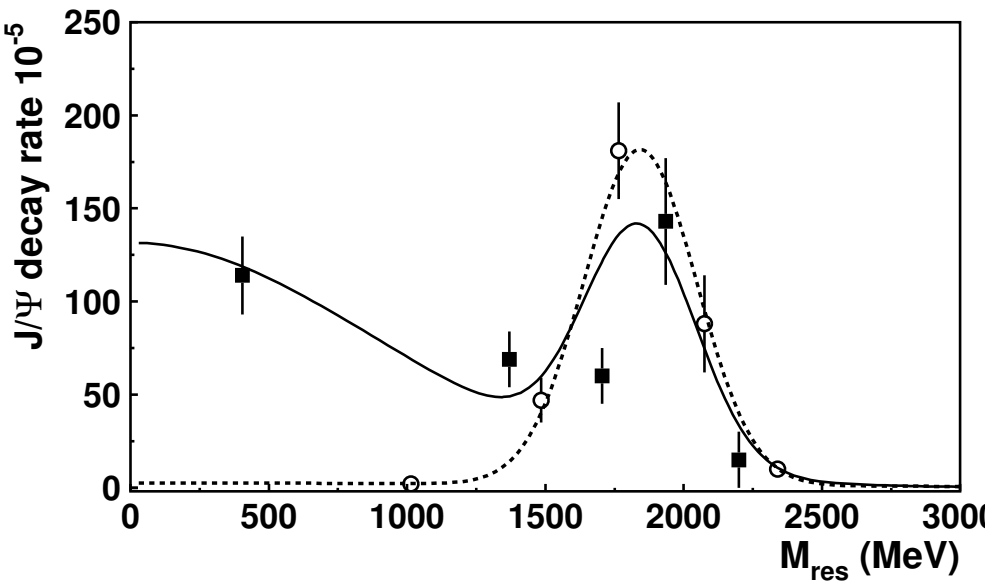
The fragmented glueball

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

Is this the scalar glueball?



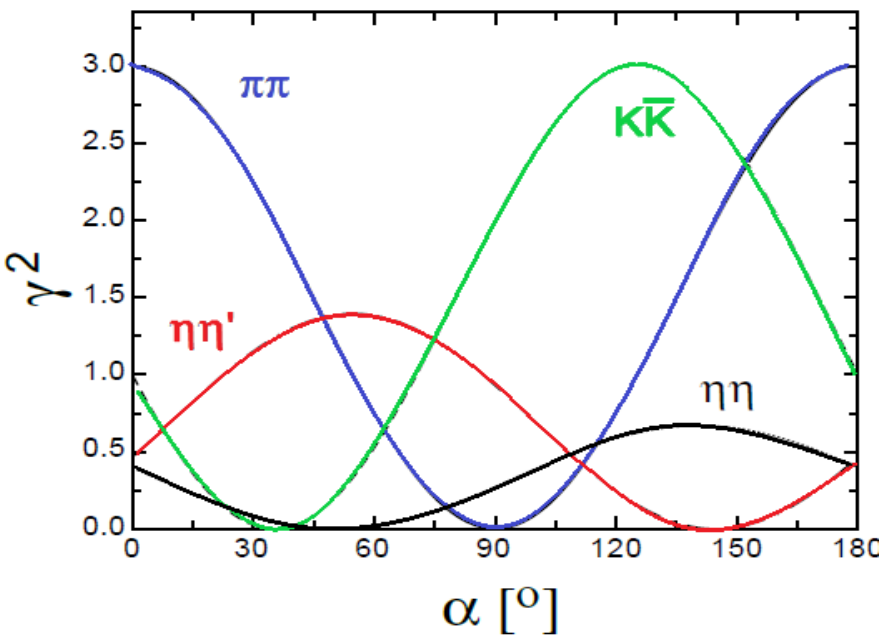


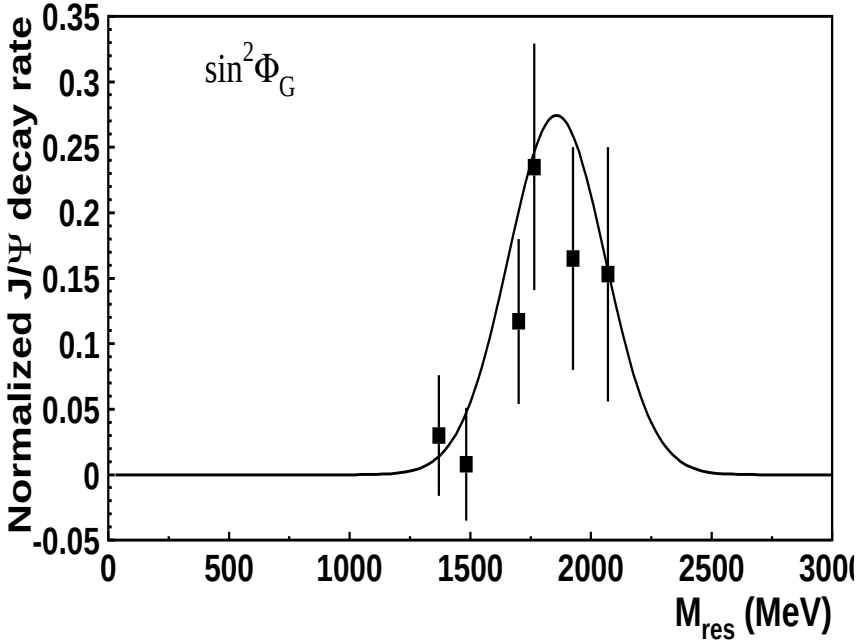
$M = 1865 \pm 25^{+10}_{-30}$ MeV

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

3.5 Glueball content of scalar mesons

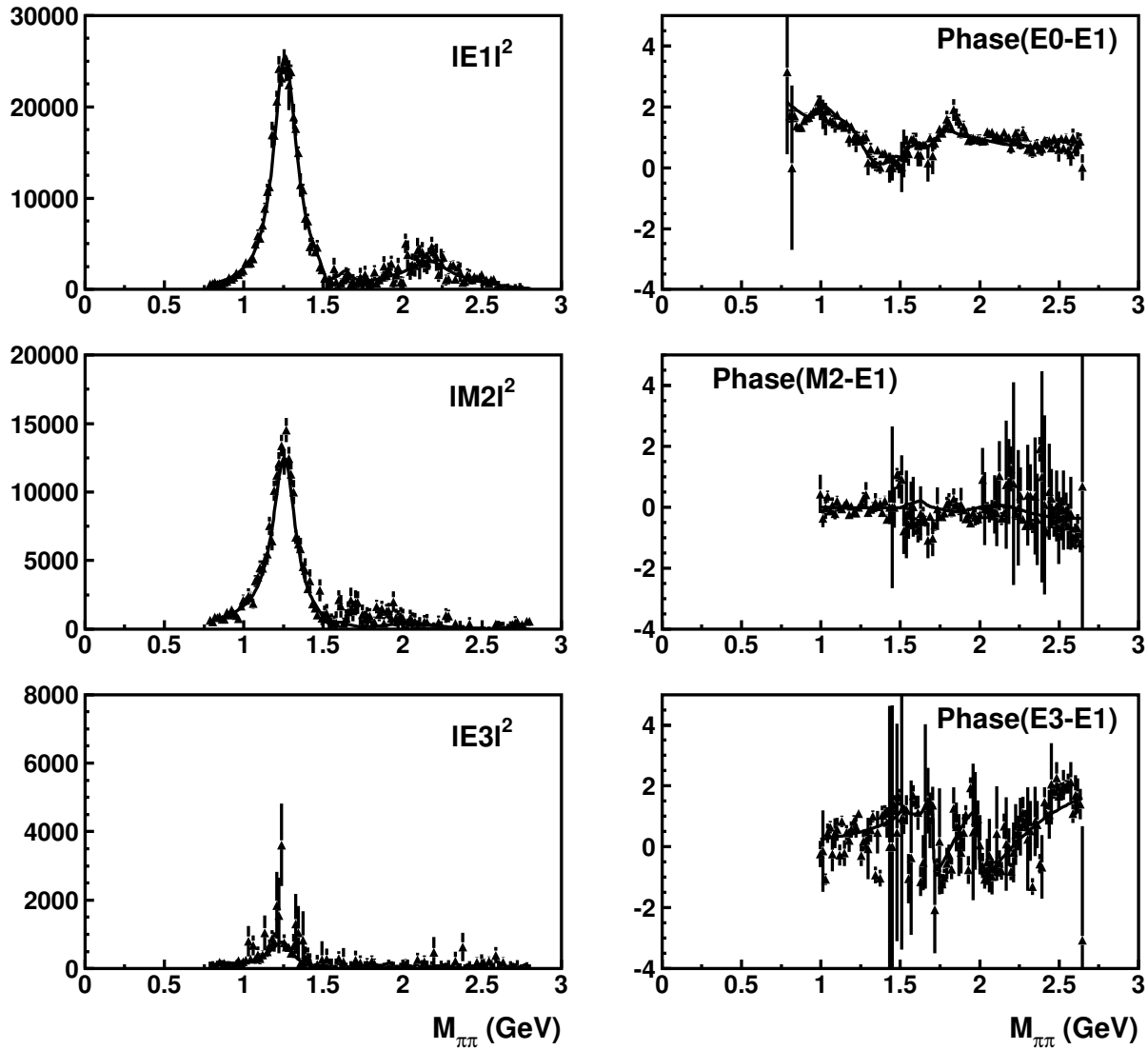
$$|f_0(1770)>= \cos\phi_g(n\bar{n}\cos\alpha - s\bar{s}\sin\alpha)\gamma_{q\bar{q}} + \sin\phi_g\gamma_1$$
$$|f_0(1710)>= \cos\varphi_g(n\bar{n}\sin\alpha + s\bar{s}\cos\alpha)\gamma_{q\bar{q}} + \sin\varphi_g\gamma_1$$



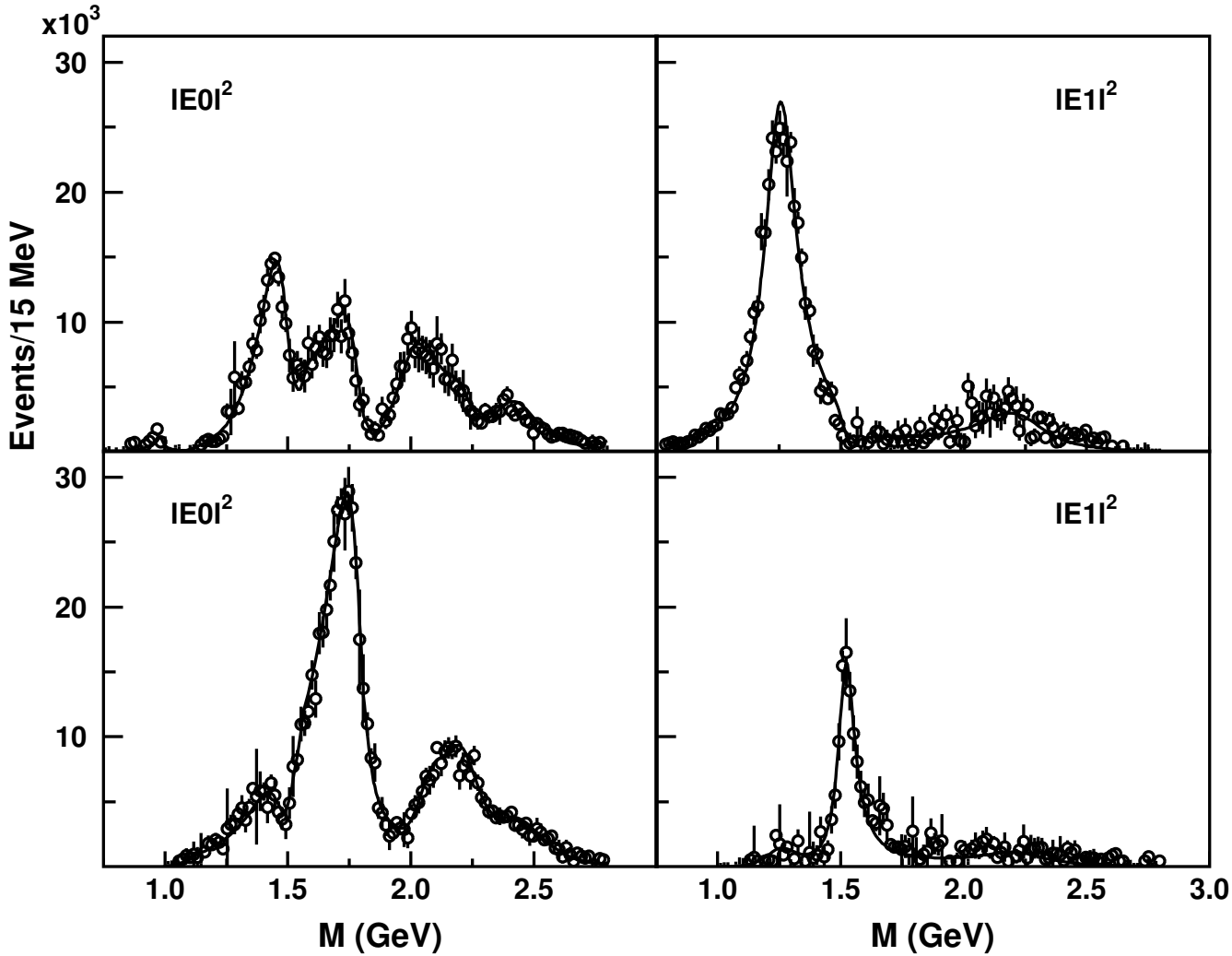


Glueball content from J/ψ radiative production is (nearly) consistent with glueball content from the decays of scalar mesons!

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



The comparison of the production scalar and tensor states in the reaction $J/\Psi \to \gamma\pi\pi$ and $J/\Psi \to \gamma KK$.



Summary

- There is a strong indication for the existence of the scalar glueball in the mass region 1850 MeV. The production intensities of the scalar mesons in this region has the Breit-Wigner like distribution with $M = 1865 \pm 25^{+10}_{-30}$ MeV and $\Gamma = 370 \pm 50^{+30}_{-20}$ MeV.
- The analysis reveals 10 scalar states which fall onto linear (n, M^2)-trajectories. No additional state was observed.
- Only the ground states of the tensor mesons are strongly produced. There is some indication for the state with mass $M = 2210 \pm 40$ MeV and $\Gamma = 355^{+60}_{-30}$ MeV.
- The central production can provide a crucial information about nature of the observed states due to specific production mechanism. Especially in the channels with 4 pions or two vector mesons in the final state.
- The Close-Kirk filter can help to extract the signal from the gluon-reach states