Partial wave analysis of $K^*\bar{K}$ events in GlueX

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The E/ι puzzle

Pseudoscalar in $\bar{p}p$ annihilation at rest

In 1963, peak at $1425\ \mathrm{MeV}$ seen in $K\bar{K}\pi$ mass spectrum with $J^{PC} = 0^{-+}$ dubbed E meson [1].

E and ι separate particles

Different quantum numbers for different production mechanisms from spin-parity analysis, specifically the E meson 0^{-+} and the ι meson 1^{++} [1].

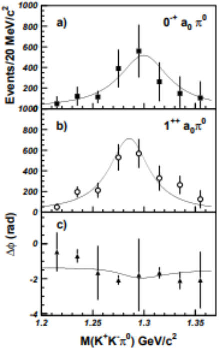
The 1998 PDG

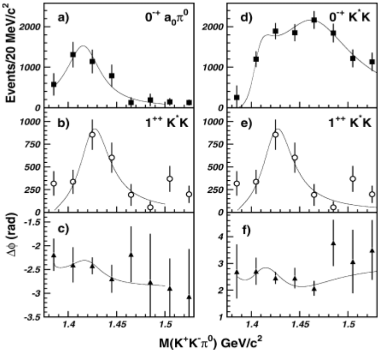
The 1998 PDG reports an axial vector $f_1(1420)$ and pseudoscalar $\eta(1440)$ as the ι and E, respectively [2].

Two pseudoscalar mesons in $1400\ \mathrm{MeV}$ mass region

- J/ψ decays in MARKIII and DM2.
- $p\bar{p}$ annihilation at rest by OBELIX.
- $\gamma\gamma$ collisions by L3 only provided evidence of $\eta(1475)$.

E852 at Brookhaven PWA results





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

Evidence of $\eta(1295)$ and $f_1(1285)$ decay $a_0(980)\pi^0$ left. Evidence of $\eta(1416)$ decay $a_0(980)\pi^0$ and $K^*\bar{K}$, and $\eta(1485)$ and $f_1(1420)$ decay $K^*\bar{K}$ right [3].

Interpretation of previous results and motivation

The $\eta(1295)$ and $\eta(1475)$ pseudoscalars

Assuming the $\eta(1295)$ exists, then it may be the first radial excitation of η and the $\eta(1475)$ is the first radial excitation of η'. The $\eta(1475)$ isoscalar would be the $s\bar{s}$ contribution to the 0^{-+} nonet.

The $\eta(1405)$ pseudoscalar

If two pseudoscalar mesons exist in the $1400\ \mathrm{MeV}$ region, the $\eta(1405)$ might be a 0^{-+} glueball. This is supported by the fact that it is not seen in $\gamma\gamma$ collisions in L3. This is not supported by lattice gauge theory, but is by the flux tube model [4].

Analysis of $X \to K^* \bar{K}$

What mesons states exist in the $1400\ \mathrm{MeV}$ region seen in production mechanisms: $\pi^- p$, radiative $J/\psi(1S)$ decay, and $\bar{p}p$ annihilation at rest?

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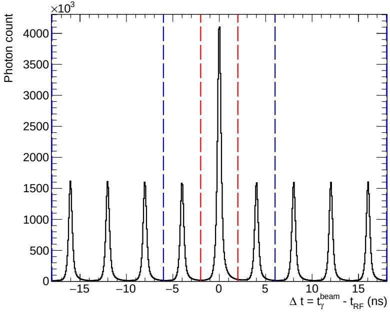
Event selection

Removal conditions
$\chi^2/n.d.f. > 5$
$\theta_\gamma < 1.5°$
$10.3° < \theta_\gamma < 11.5°$
$E^{min}_{BCAL} < 0.05$ GeV
Shower quality FCAL < 0.5
$d_{\gamma_1,\gamma_2} < 12.5$ cm
$MM^2 > 0.2$ GeV
$p_p^{recoil} < 0.45$ GeV
$52 \text{ cm} < z_{vertex} > 78 \text{ cm}$
$r_{vertex} > 1$ cm



Selection of combination

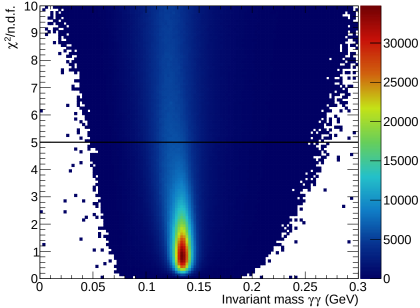
Select combination with best $\chi^2/n.d.f.$ and kaons detected in TOF or FCAL only.

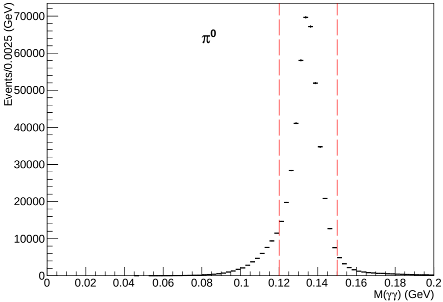
Accidentals

$-f/6$ weight for accidentals where f from CCDB.

Detector	Δt_p (ns)	$\Delta t_{K^\pm}$ (ns)	Δt_γ (ns)
BCAL	± 0.5	± 0.2	± 2.0
FCAL	± 1.0	± 0.5	± 2.0
TOF	± 0.3	± 0.15	NA
ST	None	None	NA
NULL	None	None	NA

$\pi^0 \to \gamma\gamma$

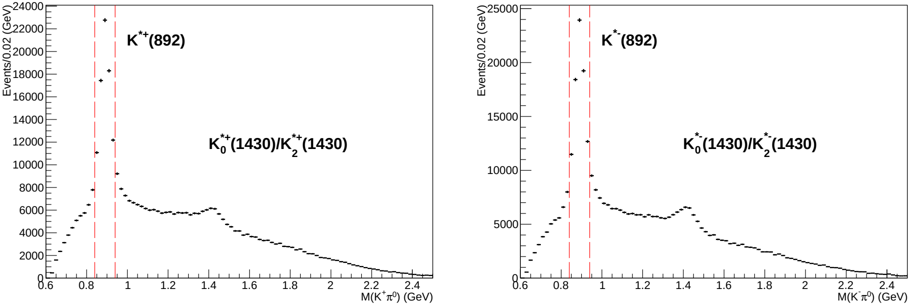




π^0 selection

From Gaussian with third degree polynomial fit, π^0 mesons is selected using 2σ from center, $0.12 - 0.15$ GeV as shown by dashed lines.

$K^*(892) \to K\pi^0$



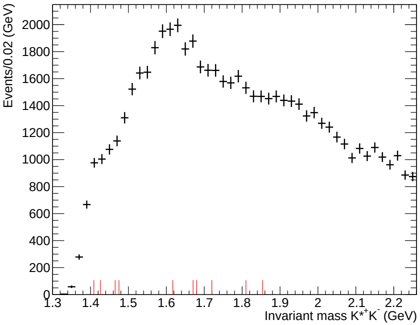
$K^*(892)$ selection

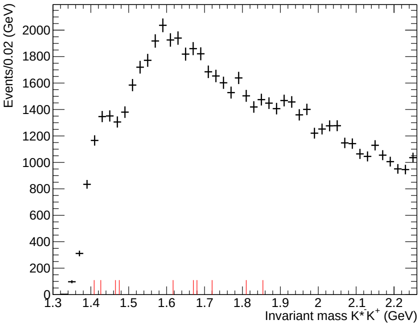
From Gaussian with third degree polynomial fit, $K^*(892)$ mesons is selected using 2σ from center, $0.84 - 0.94$ GeV as shown by dashed lines.

Excited K^*

A peak for excited K^* mesons near ~ 1.4 GeV is visible. This may include $K_1^*(1410)$, predicted to be an η_1' hybrid meson candidate decay product.

$X \to K^{*\pm}(892)K^{\mp}$

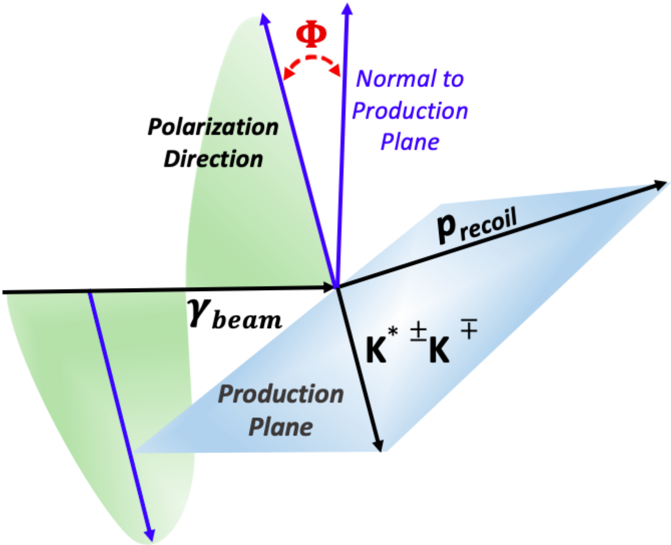




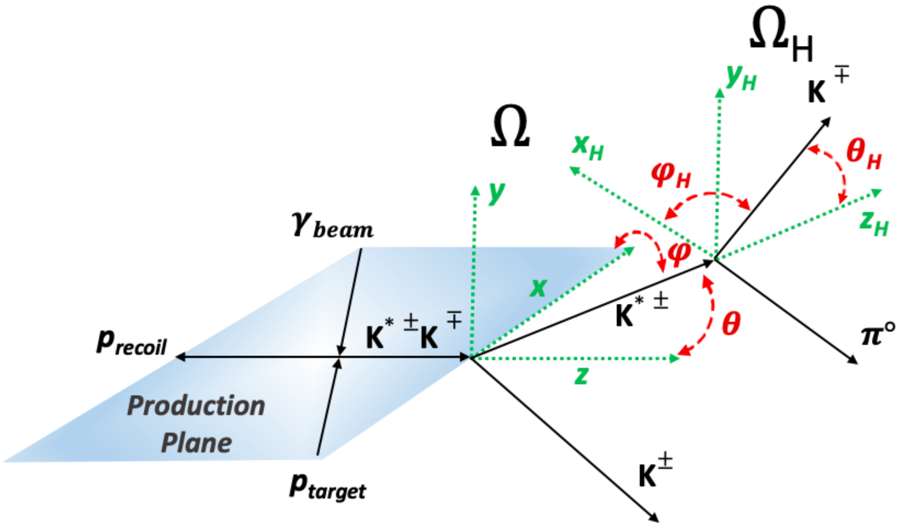
Possible meson states

Visible peak near ~ 1.4 GeV for both distributions. This is consistent with $\eta(1405)$, $f_1(1420)$, $\rho(1450)$, and $\eta(1475)$. Difficult to make any other conclusions for higher mass peaks without PWA.

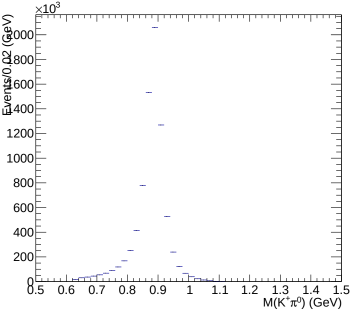
Angular distributions

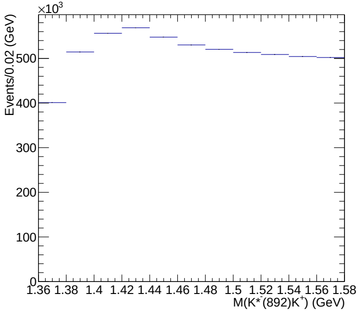


Angular distributions cont.



$K^*\bar{K}$ Monte Carlo

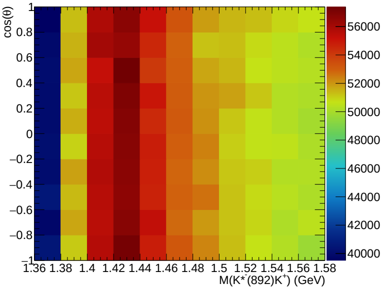


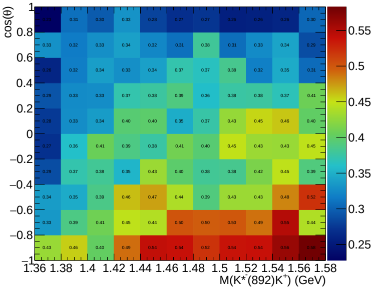


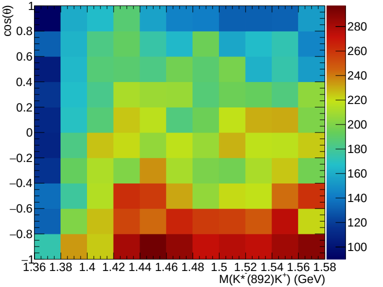
Generator and simulation

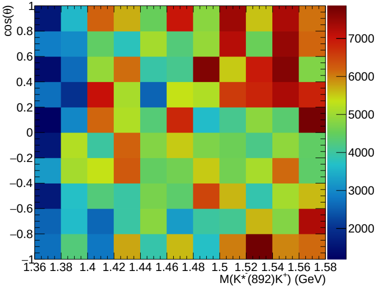
- Randomly generate samples of $K^*\bar{K}$ isotropically through phase space.
- Pass generated events through simulation of GlueX spectrometer.
- Flat incident photon beam energy from $8.2 - 8.6$ GeV.
- The K^* mass distribution is given a Breit-Wigner shape.
- t-slope$= 1.3/\mathrm{GeV}^2$

$K^*\bar{K}$ Monte Carlo cont.









Partial wave analysis

Intensity function in reflectivity basis requiring positive reflectivity

Obtain fit parameters $[J_i^P]^{(\epsilon)}_{m,k}$ for different wave contributions with fits to the angular distributions using the intensity function:

$$I(\Omega, \Omega_H, \Phi) = 2\kappa \sum_k [(1 - P_\gamma)[| \sum_{i_N, m} [J_i^N]^{(+)}_{m,k} Im(Z)|^2 + | \sum_{i_U, m} [J_i^U]^{(+)}_{m,k} Re(Z)|^2]$$

$$+ (1 + P_\gamma)[| \sum_{i_U, m} [J_i^U]^{(+)}_{m,k} Im(Z)|^2 + | \sum_{i_N, m} [J_i^N]^{(+)}_{m,k} Re(Z)|^2]],$$

$$Z = e^{-i\Phi} \sum_{m_2''} \sum_{m'} D^{J_i *}_{mm'}(\Omega) \langle Jm' | j_1 m_1 j_2 m_2'' \rangle D^{j_2 *}_{m_2'', m_2}(\Omega_H) [5].$$

Wave conditions

- Require positive reflectivity.
- $J = 0$, 1, and 2 for spin projections M from $-J$ to J.
- Orbital angular momentum of the decay is restricted to P, S, and D waves.

Fit constraints

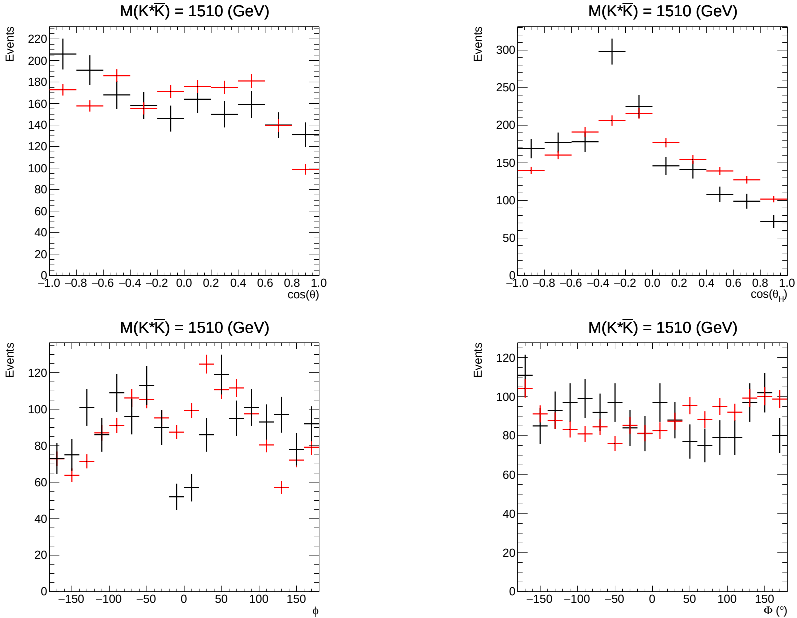
Between coherent sums

- Four fit parameters, two $[J_i^N]^{(+)}$ and two $[J_i^U]^{(+)}$.
- Identical fit parameters constrained.

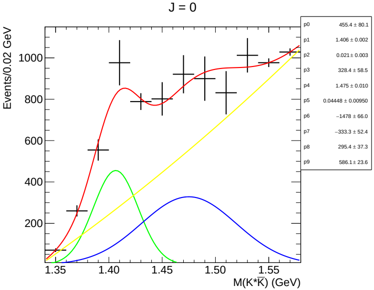
Simultaneous fit

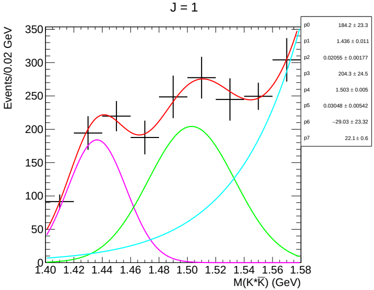
- Data broken into eight subsets with meson resonance deacys $K^{*+}K^-$ and $K^{*-}K^+$ for each polarization.
- Identical fit parameters between the eight subsets are constrained.
- $J = 0$ with P-wave forced to real.
- Number of fit parameters reduced from 192 to 10.
- Simultaneous fit between these subsets of the data reduces statistical uncertainty.

PWA fit results for



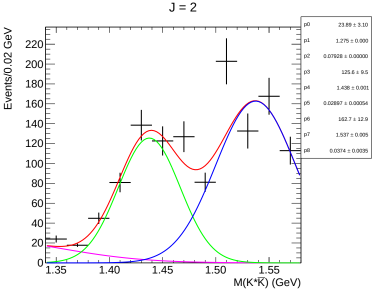
$K^*\bar{K}$ invariant mass for each total angular momentum





Results of PWA

- $J = 0$: $\eta(1405)$ and $\eta(1475)$.
- $J = 1$: $f_1(1420)$ and $f_1(1510)$.
- $J = 2$: $f_2(1430)$ and $f_2(1530)$.



Invariant mass fit results

Results of PWA

- $J = 0$: $\eta(1405)$ and $\eta(1475)$.
- $J = 1$: $f_1(1420)$ and $f_1(1510)$.
- $J = 2$: $f_2(1430)$ and $f_2(1530)$.

J	PID	PDG center (MeV)	PDG width (MeV)	Fit center (MeV)	Fit width (MeV)
0	$\eta(1405)$	1408.8 ± 2.0	50.1 ± 2.6	1406 ± 2	49.46 ± 7.07
0	$\eta(1475)$	1475 ± 4	90 ± 9	1475 ± 10	104.8 ± 2.24
1	$f_1(1420)$	1426.3 ± 0.9	54.5 ± 2.6	1436 ± 11	48.40 ± 4.17
1	$f_1(1510)$	1518 ± 5	73 ± 25	1503 ± 5	71.78 ± 12.76
2	$f_2(1430)$	~ 1430	NA	1438 ± 1	68.22 ± 1.27
2	$f_2(1525)$	1517.4 ± 2.5	86 ± 5	1537 ± 5	88.10 ± 8.24

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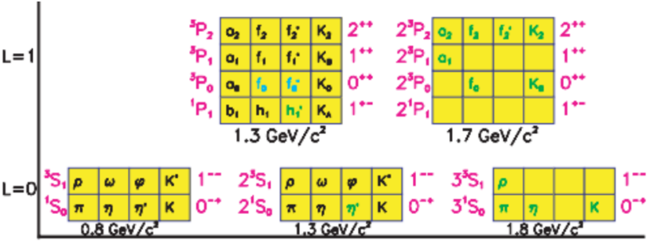
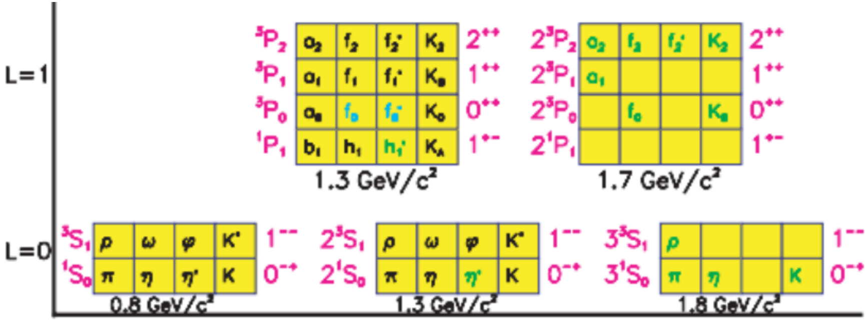
Motivation revisited

Analysis of $X \to K^* \bar{K}$

What mesons states exist in the $1400\ \mathrm{MeV}$ region seen in production mechanisms: $\pi^- p$, radiative $J/\psi(1S)$ decay, and $\bar{p}p$ annihilation at rest?



Resolving the nonets



How can this be resolved?

The K_L would help establish the $s\bar{s}$ meson contributions to the pseudoscalar, axial vector, and tensor meson nonets. The extraneous states would require glueball, hadronic molecule, or tetraquark explanations.

Discussion

Completed

- Possibly have multiple states in the $1400 - 1500$ MeV mass region.
- These states are consistent with past results.
- Consistent pattern between the three nonets.

Future

- Update the MC to change t-slope for each mass bin.
- Future work will move up the $K^*\bar{K}$ mass spectrum.
- Look at the other meson resonance decays, $a_0\pi^0$ and $K^+K^-\pi^0$.
- Look to simultaneously fit each decay mode.

Partial wave analysis cont.

Quantum numbers

- J and M are the total angular momentum and spin projection of the meson resonance.
- L and m_L are the orbital angular momentum and spin projection of the meson resonance's decay, for which a P
- S and m_S are the spin and spin projection of the vector meson.

Wave conditions

- Require positive reflectivity.
- $J = 0$, 1, and 2 for spin projections M from $-J$ to J are included for the four coherent sums.
- To reduce fit parameters, the orbital angular momentum of the decay L is restricted to P, S, and D waves for each J, respectively.
- To conserve total angular momentum $M = m_L + m_S$.

J	M	L	m_L	S	m_S
0	0	1	-1	1	1
0	0	1	0	1	0
0	0	1	1	1	-1
1	-1	0	0	1	-1
1	0	0	0	1	0
1	1	0	0	1	1
2	-2	2	-2	1	0
2	-2	2	-1	1	-1
2	-1	2	-2	1	1
2	-1	2	-1	1	0
2	-1	2	0	1	-1
2	0	2	-1	1	1
2	0	2	0	1	0
2	0	2	1	1	-1
2	1	2	0	1	1
2	1	2	1	1	0
2	1	2	2	1	-1
2	2	2	1	1	1
2	2	2	2	1	0

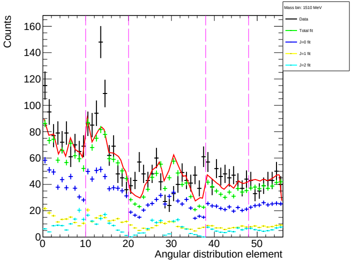
Uncertainty determination

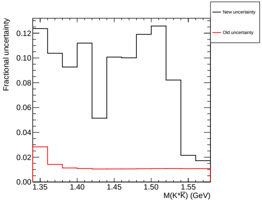
Fit

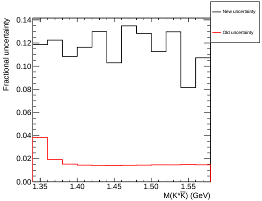
Plot $\cos\theta$, $\cos\theta_H$, ϕ, and Φ of PWA fit results for all subsets. Fit histograms to the data. Extract fractional uncertainties of the coefficients.

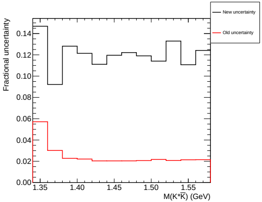
$$h_{tot} = a_0 h_0 + a_1 h_1 + a_2 h_2 + C$$

$$\sigma_m = \frac{\sigma_{a_n}}{a_n} m$$









LQCD hybrid predictions

Masses

0^{+-} $\sim 2.3 - 2.5$ GeV
1^{-+} $\sim 2.0 - 2.4$ GeV
2^{+-} $\sim 2.4 - 2.6$ GeV

Widths

Γ $\sim 0.1 - 0.5$ GeV
$\Gamma_{1^{-+}} \approx \Gamma_{2^{+-}} < \Gamma_{0^{+-}}$

J^{PC}	Particle	Decays
0^{+-}	b_0	$\pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta$
	h_0	$b_1\pi,\ h_1\eta$
	h_0'	$K_1(1270)\bar{K},\ K(1410)\bar{K},\ h_1\eta$
1^{-+}	π_1	$\rho\pi,\ b_1\pi,\ f_1\pi,\ \eta\pi,\ \eta'\pi,\ a_1\eta$
	η_1	$f_1\eta,\ a_2\pi,\ f_1\eta,\ \eta'\eta,\ \pi(1300)\pi,\ a_1\pi$
	η_1'	$K^*\bar{K},\ K(1270)\bar{K},\ K(1410)\bar{K},\ \eta'\eta$
2^{+-}	b_2	$\omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi,\ h_1\pi,\ b_1\eta$
	h_2	$\rho\pi,\ b_1\pi,\ \omega\eta,\ f_1\omega$
	h_2'	$K_1(1270)\bar{K},\ K(1410)\bar{K},\ K_2\bar{K},\ \phi\eta,\ f_1\phi$

[1] C. Meyer *et al.*, [arXiv:1004.551].

Partial wave analysis

The intensity of a meson states production is defined in terms of the differential cross section:

$$I(\Omega, \Omega_H, \Phi) \equiv \frac{d\sigma}{dt\ dm_{K^*\bar{K}}\ d\Omega\ d\Omega_H\ d\Phi}.$$

In terms of phase rotated decay amplitudes
$\tilde{A}_{\pm}(\Omega, \Omega_H, \Phi) = e^{\mp i\Phi} A_{\pm}(\Omega, \Omega_H, \Phi)$ in a reflectivity basis

$$I(\Omega, \Omega_H, \Phi) = 2\kappa \sum_k [(1-P_\gamma)[|\sum_{i_N,m} [J_i^N]^{(+)}_{m,k} Im(Z) + \sum_{i_U,m} [J_i^U]^{(-)}_{m,k} Im(Z)|^2$$
$$+|\sum_{i_N,m} [J_i^N]^{(-)}_{m,k} Re(Z) + \sum_{i_U,m} [J_i^U]^{(+)}_{m,k} Re(Z)|^2] + (1+P_\gamma)[|\sum_{i_N,m} [J_i^N]^{(-)}_{m,k} Im(Z)$$
$$+\sum_{i_U,m} [J_i^U]^{(+)}_{m,k} Im(Z)|^2 + |\sum_{i_N,m} [J_i^N]^{(+)}_{m,k} Re(Z) + \sum_{i_U,m} [J_i^U]^{(-)}_{m,k} Re(Z)|^2]].$$

$$A_\lambda = \sum_i \sum_m T^i_{\lambda,m} \sum_\lambda D^{J_i*}_{m,\lambda}(\Omega) F^i_\lambda D^{1*}_{m,\lambda}(\Omega_H), \qquad (1)$$

PDG and experimental results possible states

Particle	$I^G(J^{PC})$	Decays	Mass (MeV)	Width (MeV)
$b_1(1235)$	$1^+(1^{+-})$	$K^{*\pm}K^{\mp}\dagger$	1229.5 ± 3.2	142 ± 9
$a_1(1260)$	$1^-(1^{++})$	$KK\pi\dagger/K^*K\dagger$	1230 ± 40	$250 - 600$
$f_2(1270)$	$0^+(2^{++})$	$K^0K^-\pi^+ + c.c.$	1275.5 ± 0.8	$186.7 \pm 2.2/2.5$
$f_1(1285)$	$0^+(1^{++})$	$KK\pi/K^*K\star/a_0(980)\pi(E852)$	1281.9 ± 0.5	22.7 ± 1.1
$\eta(1295)$	$0^+(0^{-+})$	$a_0(980)\pi(E852)$	1294 ± 4	55 ± 5
$\eta(1405)$	$0^+(0^{-+})$	$KK\pi\dagger/K^*K^\dagger/a_0(980)\pi(E852)$	1408.8 ± 1.8	51.0 ± 2.9
$f_1(1420)$	$0^+(1^{++})$	$KK\pi\ddagger/K^*K\ddagger$	1426.4 ± 0.9	54.9 ± 2.6
$\rho(1450)$	$1^+(1^{--})$	$K^*K + c.c.*$	1476 ± 4	85 ± 9
$\eta(1475)$	$0^+(0^{-+})$	$KK\pi\dagger/K^*K\dagger/a_0(980)\pi\dagger$	1475 ± 4	90 ± 9
$\eta_2(1645)$	$0^+(2^{-+})$	$KK\pi\dagger/K^*K\dagger$	1617 ± 5	181 ± 11
$\pi_2(1670)$	$1^-(2^{-+})$	$K * K + c.c.$	1672.2 ± 3.0	260 ± 9
$\phi(1680)$	$0^-(1^{--})$	$K^*K + c.c.\ddagger/K^0_SK\pi\dagger$	1680 ± 20	150 ± 50
$\rho_3(1690)$	$1^+(3^{--})$	$K\bar{K}\pi$	1688.8 ± 2.1	161 ± 10
$\rho(1700)$	$1^+(1^{--})$	$K^*K + c.c.\dagger$	1720 ± 20	250 ± 100
$\pi(1800)$	$1^-(0^{-+})$	$K^*_0(1430)K^-\dagger/K^*K^-\star$	$1810 \pm 9/11$	$215 \pm 7/8$
$\phi(1850)$	$0^-(3^{--})$	$K^*K + c.c.\dagger$	1854 ± 7	$87 \pm 28/23$
(2170)	$0^-(1^{--})$	$K^{*0}K^\pm\pi^\mp\star$	2160 ± 80	125 ± 65

If no marker on the decay(s), has defined branching fraction.

$*$ - possibly seen

$\dagger$ - seen

$\ddagger$ - dominant

$\star$ - not seen

Work cited

[1] A. Bertin et al. (OBELIX), "E / iota decays to K anti-K pi in anti-p p annihilation at rest", Phys. Lett. B **361**, 187–198 (1995).

[2] P. D. Group et al., "Review of Particle Physics", Progress of Theoretical and Experimental Physics **2020**, 083C01, 10.1093/ptep/ptaa104 (2020).

[3] G. Adams et al., "Observation of pseudoscalar and axial vector resonances in p→k+k0n at 18 gev", Physics Letters B **516**, 264–272 (2001).

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[5] V. Mathieu et al., "Moments of angular distribution and beam asymmetries in 0 photoproduction at gluex", Physical Review D **100**, 10.1103/physrevd.100.054017 (2019).