Partial wave analysis of $J/\psi \rightarrow K^+K^- \pi^0$

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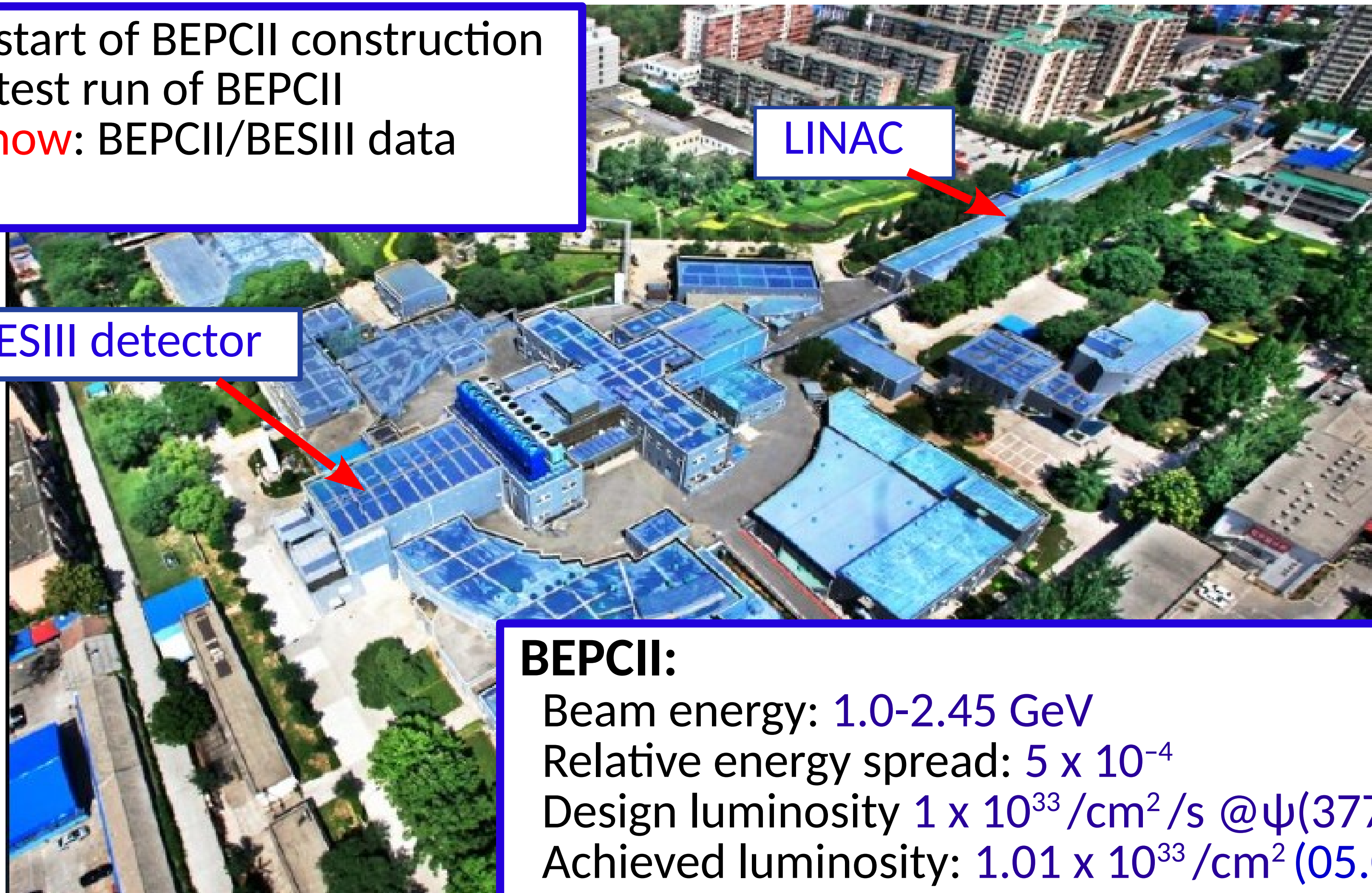
BESIII @BEPCII

2004: start of BEPCII construction
2008: test run of BEPCII
2009-now: BEPCII/BESIII data taking



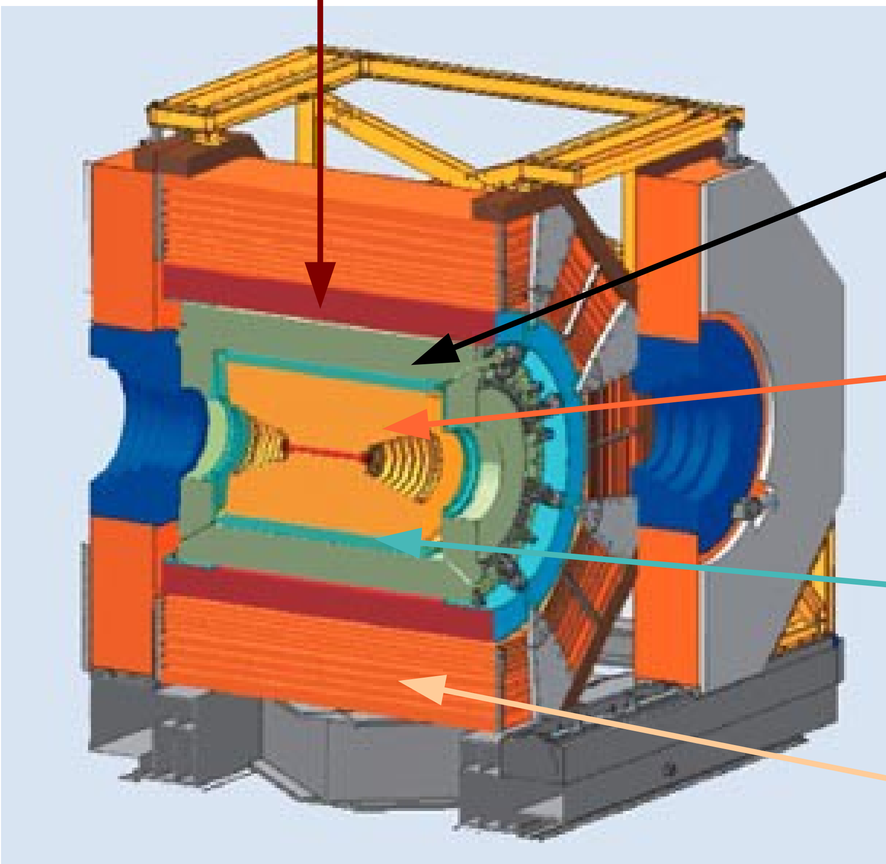
BEPCII:

- Beam energy: 1.0-2.45 GeV
- Relative energy spread: 5×10^{-4}
- Design luminosity 1×10^{33} /cm^2 /s @ψ(3770)
- Achieved luminosity: 1.01×10^{33} /cm^2 (05.04.2016)

The BESIII detector

Superconducting magnet: 1 T

NIM A614, 345(2010)



EMC: CsI cristal
- Energy resolution: **2.5% @1GeV**
- Spatial resolution: **6mm**

MDC:
- Spatial resolution: **σ_{xy} = 120µm**
- Momentum resolution:**0.5% @ 1GeV**
- **dE/dx** resolution: 6%

TOF (double/single layer scintillator):
Time resolution: **80ps** (barrel)
110ps [60ps] (endcaps)

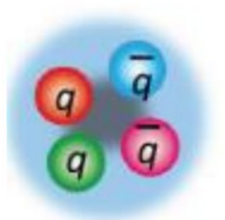
Muon ID:
9 layers RPC (8 for endcaps) in the flux-return yoke

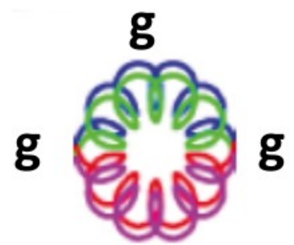
Hadron spectroscopy

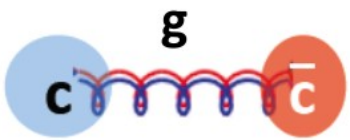
Hadron spectroscopy is widely believed to be a key to understand QCD in the strong coupling regime.

It is a testing ground for non-perturbative approaches to QCD like AdS/QCD models or lattice QCD.

Detailed understanding of the hadron spectra is crucial for identification of long predicted exotic particles.







Light hadron spectroscopy @BESIII

Light hadron spectroscopy at BESIII

- Clean e^+e^- environment
- Known quantum numbers of the initial state
- Gluon-rich decays
- Unprecedented statistics (10 billion J/ψ and 0.5 billion ψ' decays).
- Clean final states

J/ψ → $K^+K^-\pi^0$ and light hadron spectroscopy

J/ψ → $K^+K^-\pi^0$

Kaon spectroscopy:

- 13 established states, 12 need confirmation, much more predicted by potential models
- Natural parity states (JP=1-, 2+, 3-,…) with masses up 2.6 GeV/c^2 are allowed

Meson decaying to K^+K^-:

- Isovector states with JPC=1--, 3--,5--, … are allowed in strong decays (ρ(1450), ρ(1700), …)
- The same JPCs are allowed for isoscalars in EM decays
- Previously reported exotic X(1575)

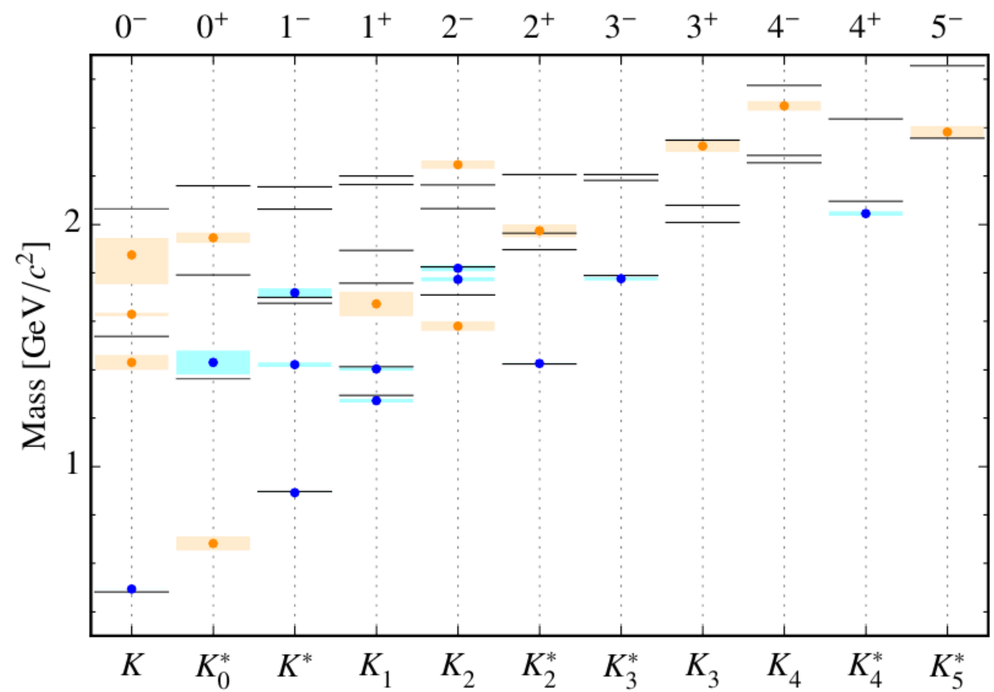


Figure from B. Grube, PKI2018 (arXiv:1804.06528)

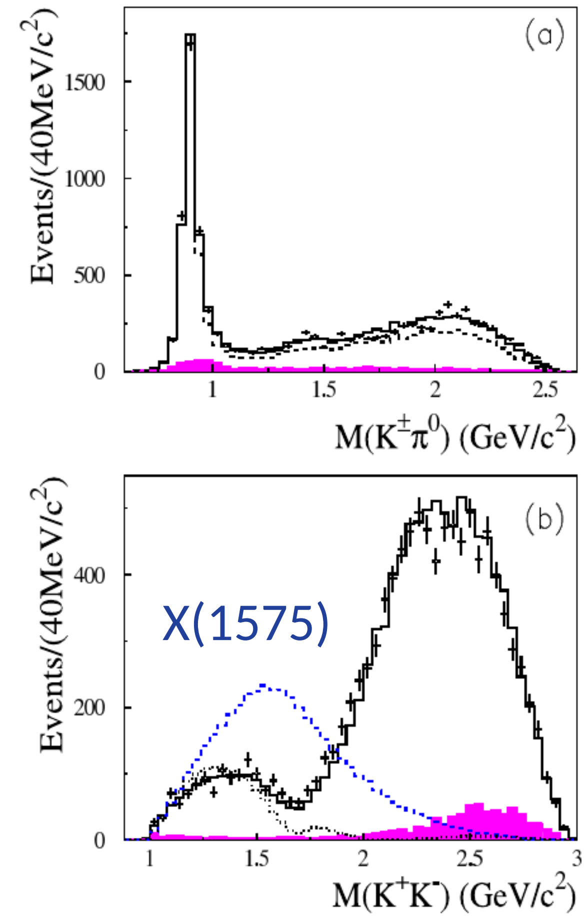
X(1575) in $J/\psi \to K^+K^-\pi^0$

BESII (PRL97, 142002 (2006))

- Analysis of 58M J/ψ decays
- PWA:
  - $K^*(892)^\pm$
  - $K^*(1410)^\pm$
  - X(1575) (K^+K^-)
  - ρ(1700)
  - flat JPC=1-- contribution (PHSP)

X(1575):

- M ~ 1570 MeV
- Γ ~ 800 MeV
- $B(J/\psi \to X(1575)\pi^0 \to K^+K^-\pi^0)) \sim 8.5\text{x}10^{-4}$
- Multiquark and molecular state interpretations were suggested (e.g. PRD74, 097503 (2006), PLB 643 (2006), …)



BABAR: $J/\psi \to K^+K^-\pi^0$, $J/\psi \to K_sK\pi$ and $J/\psi \to \pi^+\pi^-\pi^0$

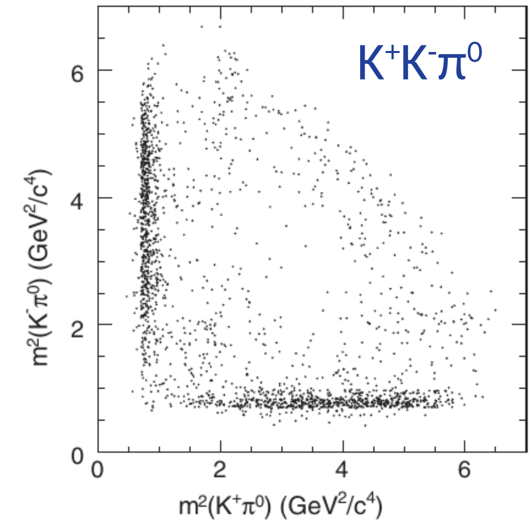
BABAR (PRD95, 072007 (2017)):

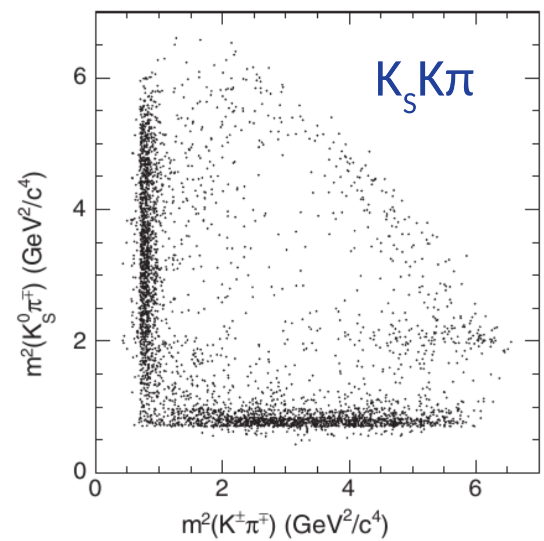
- Channels: $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, and $K_sK\pi$
- ISR technique
- Statistics: 2102 ($K^+K^-\pi^0$) and 3907 ($K_sK\pi$)
- Dalitz-plot analysis

Intermediate state	$b_{K^+K^-\pi^0}$ (%)	$b_{K_SK^\pm\pi^\mp}$ (%)
$K^*(892)$	$92.4 \pm 1.5 \pm 3.4$	$90.5 \pm 0.9 \pm 3.8$
$K_1^*(1410)$	$2.3 \pm 1.1 \pm 0.7$	$1.5 \pm 0.5 \pm 0.9$
$K_2^*(1430)$	$3.5 \pm 1.3 \pm 0.9$	$7.1 \pm 1.3 \pm 1.2$
$\rho(1450)$	$9.3 \pm 2.0 \pm 0.6$	$6.3 \pm 0.8 \pm 0.6$

- Properties of ρ(1450)

$$B(\rho(1450) \to K^+K^-)/B(\rho(1450) \to \pi^+\pi^-) = 0.307 \pm 0.084 \pm 0.082$$





PWA

PRD100,032004(2019)

Data at BESIII:

- ~183 thousands events collected from 223M J/ψ decays
- Background level of 0.3%

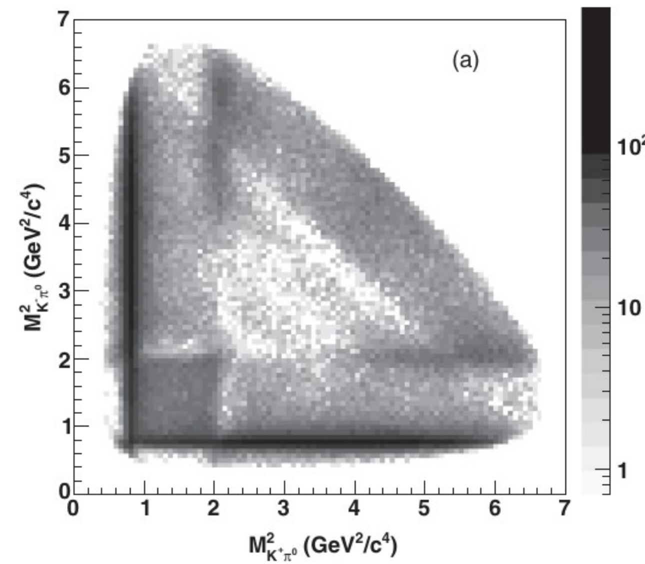
Partial wave analysis:

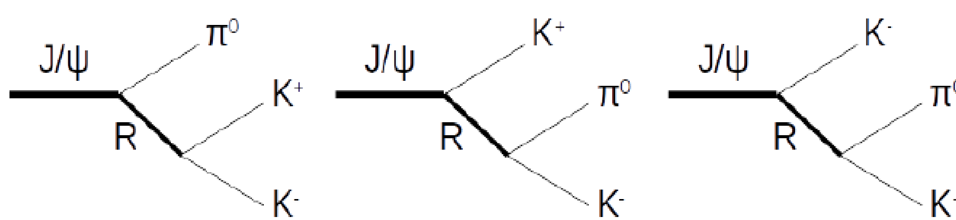
- Unbinned maximum likelihood method
- Isobar parameterization of the decay
- Resonances are parameterized with BW. In case of $K^*(892)^\pm$ and $K^*_2(1430)^\pm$

$$\Gamma(s_m, J_a) = \frac{\rho_J(s_m)}{\rho_J(M_a^2)}\Gamma_a,$$

$$\rho_J(s_m) = \frac{2q}{\sqrt{s_m}} \frac{q^{2J}}{F^2(q^2, r, J)}.$$

- Two solution reported: based on well-established states only and with a smooth parameterization in the JP=3- Kπ wave





PWA solution I

PRD100,032004(2019)

$K^\pm\pi^0$ channels						
J^{PC}	PDG	M(MeV/c^2)	Γ(MeV/c^2)	b(%)	$b^{+(-)}$(%)	ΔNLL
1^-	$K^*(892)^\pm$	894.1±0.1	46.7±0.2	89.2±0.8	41.0±0.2	–
1^-	$K^*(1680)^\pm$	1677*	205*	0.59±0.04	0.25±0.02	398
2^+	$K_2^*(1430)^\pm$	1431.4±0.8	100.3±1.6	9.2±0.1	4.1±0.1	–
2^+	$K_2^*(1980)^\pm$	1817±11	312±28	0.44±0.05	0.17±0.02	238
3^-	$K_3^*(1780)^\pm$	1781*	203*	0.08±0.01	0.04±0.01	83
4^+	$K_4^*(2045)^\pm$	2015±7	183±17	0.16±0.02	0.07±0.01	192

K^+K^- channel					
J^{PC}	PDG	M(MeV/c^2)	Γ(MeV/c^2)	b(%)	$\Delta \ln L$
1^{--}	$\rho(770)$	771*	150*	1.8±0.2	220
1^{--}	$\rho(1450)$	1465*	400*	1.2±0.2	27
1^{--}		1643±3	167±12	1.1±0.1	281
1^{--}		2078±6	149±21	0.15±0.03	73
1^{--}	non-resonant	– –	– –	1.2±0.2	34
3^{--}	$\rho_3(1690)$	1696*	204*	0.14±0.01	144

- No established states improve NLL by more than 17
- NLL can be still improved by up to 95 with smooth contributions (the largest in 3^- $K^\pm\pi^0$ wave)
- Not possible to consistently define systematic errors
- No evidence for X(1575)

PWA solution II

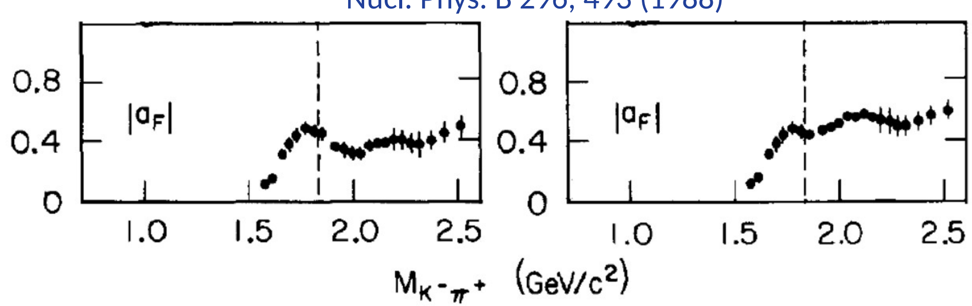
PRD100,032004(2019)

J^{PC}	PDG	M(MeV/c^2)	Γ(MeV/c^2)	b(%)	$b^{+(-)}$(%)	ΔNLL
			$K^{\pm}\pi^0$ channels			
1^-	$K^*(892)^{\pm}$	$893.6\pm0.1^{+0.2}_{-0.3}$	$46.7\pm0.2^{+0.1}_{-0.2}$	$93.4\pm0.4^{+1.8}_{-5.8}$	$42.5\pm0.1^{+0.5}_{-1.7}$	–
1^-	$K^*(1410)^{\pm}$	1380^*	176^*	0.26 ± 0.04	0.11 ± 0.02	80
1^-	$K^*(1680)^{\pm}$	1677^*	205^*	0.20 ± 0.03	0.08 ± 0.01	56
2^+	$K_2^*(1430)^{\pm}$	$1432.7\pm0.7^{+2.2}_{-2.3}$	$102.5\pm1.6^{+3.1}_{-2.8}$	$9.4\pm0.1^{+0.8}_{-0.5}$	$4.2\pm0.1^{+0.3}_{-0.2}$	–
2^+	$K_2^*(1980)^{\pm}$	$1868\pm8^{+40}_{-57}$	$272\pm24^{+50}_{-15}$	$0.38\pm0.04^{+0.22}_{-0.05}$	$0.15\pm0.02^{+0.08}_{-0.02}$	192
3^-	$K_3^*(1780)^{\pm}$	1781^*	203^*	0.16 ± 0.02	0.07 ± 0.01	105
4^+	$K_4^*(2045)^{\pm}$	$2090\pm9^{+11}_{-29}$	$201\pm19^{+57}_{-17}$	$0.21\pm0.02^{+0.10}_{-0.05}$	$0.09\pm0.01^{+0.04}_{-0.02}$	212
3^-	non-resonant	– –	– –	~ 1.5%	~ 0.6%	629

J^{PC}	PDG	M(MeV/c^2)	Γ(MeV/c^2)	b(%)	$\Delta \ln L$
			K^+K^- channel		
1^{--}		$1651\pm3^{+16}_{-6}$	$194\pm8^{+15}_{-7}$	$1.83\pm0.11^{+0.19}_{-0.17}$	796
1^{--}		$2039\pm8^{+36}_{-18}$	$193\pm23^{+25}_{-27}$	$0.23\pm0.04^{+0.07}_{-0.06}$	102

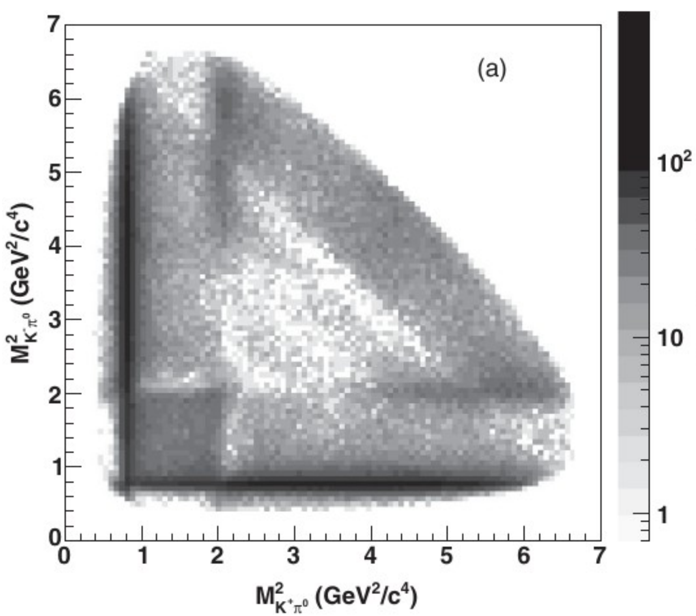
- Broad 3^- $K^{\pm}\pi^0$ contribution is added
- States contributing to NLL by more than 40 are included
- Systematic errors are determined from the uncertainties of PWA and the detector simulation

Nucl. Phys. B 296, 493 (1988)

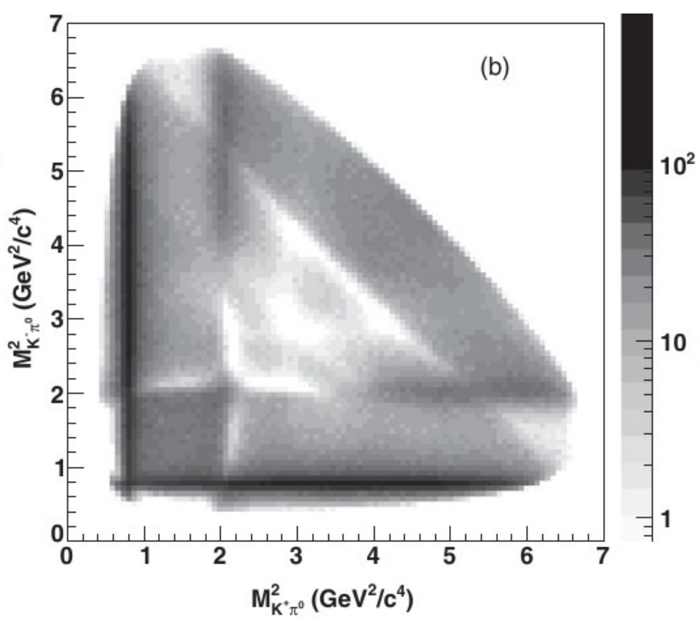


Data description I

PRD100,032004(2019)

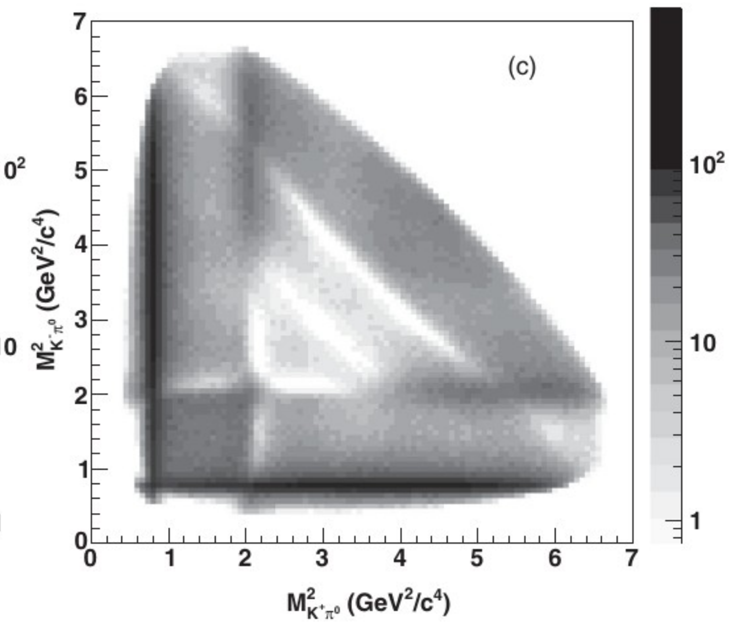


Data



PWA solution I

χ^2/NDF = 3314.8/2950



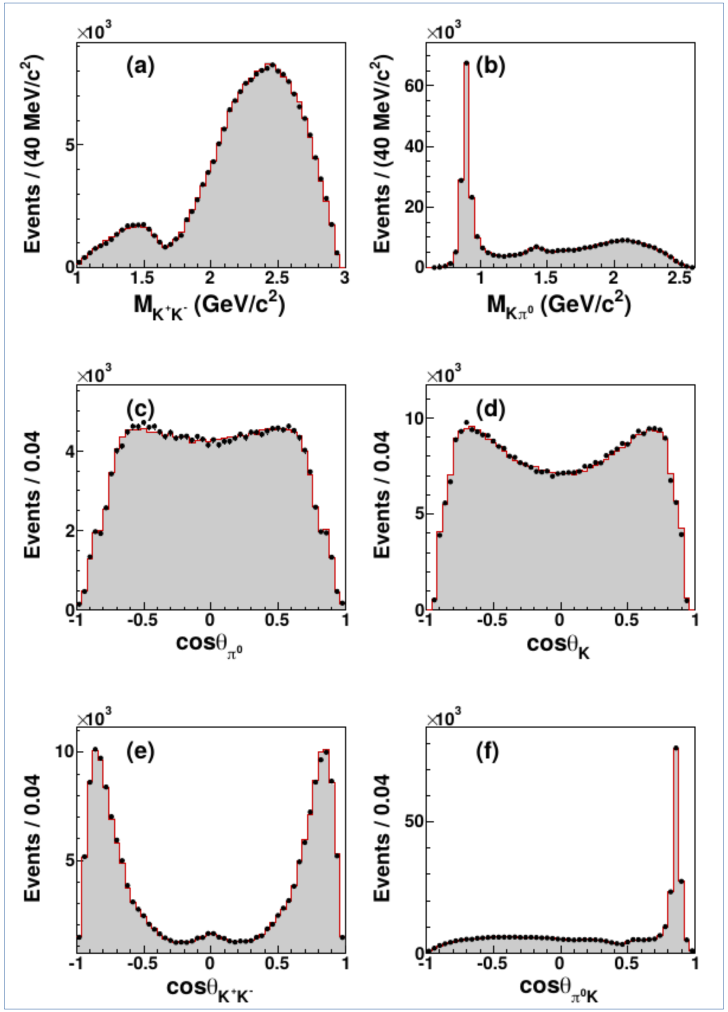
PWA solution II

χ^2/NDF = 3191.0/2950

Data description II

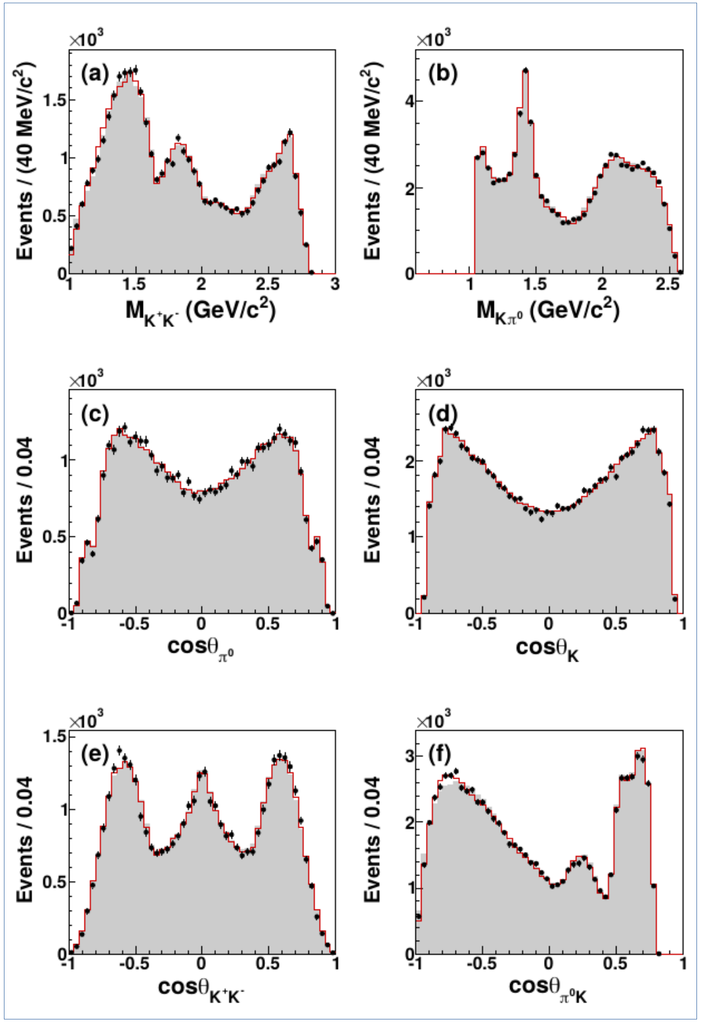
PRD100,032004(2019)

Full data set



Solution I
Solution II

M($K^{\pm}\pi^0$) > 1.05 GeV/c^2



Summary on the decay structure

PRD100,032004(2019)

There is a set of states (contributions) reliably identified in both solutions:

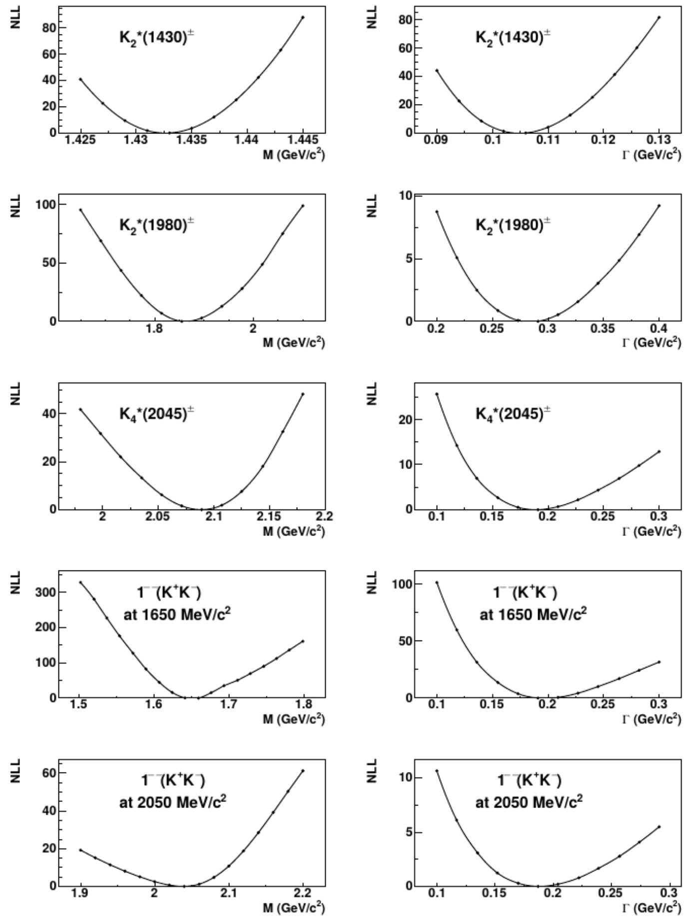
- $K^*(892)^\pm$
- $K^*_2(1430)^\pm$
- $K^*_2(1980)^\pm$
- $K^*_4(2045)^\pm$
- 1-- @1650 MeV/c^2
- 1-- @2050 MeV/c^2

Also

- The are no evidence for X(1575)
- ρ(1450) can not be reliably identified, but its production rate of the order of 1% does not contradict data

The results of the solution II are considered as final.

Solution II



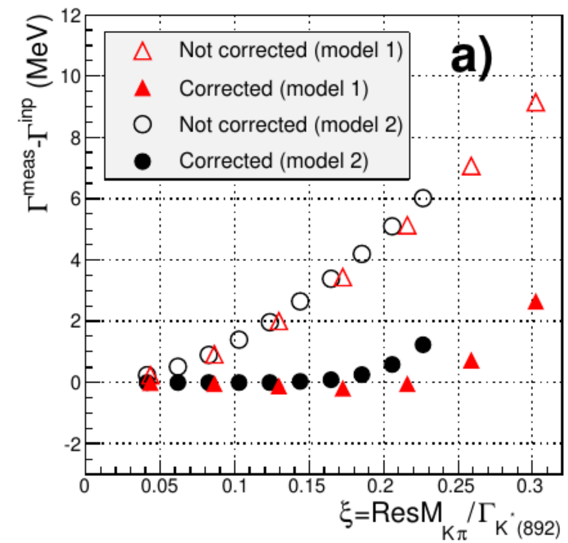
$K^*(892)^\pm$ and $K^*_2(1430)^\pm$

The most precise measurements of $K^*(892)^\pm$ and $K^*_2(1430)^\pm$ parameters

$K^*(892)^\pm$

	M (MeV/c^2)	Γ (MeV)
τ-decays (PDG aver.)	$895.47 \pm 0.20 \pm 0.74$	$46.2 \pm 0.6 \pm 1.2$
hadroproduction (PDG aver.)	891.66 ± 0.26	50.8 ± 0.9
$J/\psi \to K^+K^-\pi^0$ (sol. II)	$893.6 \pm 0.1^{+0.2}_{-0.3}$	$46.7 \pm 0.2^{+0.1}_{-0.2}$

JINST 10, P10028 (2015)



$K^*_2(1430)^\pm$

CHARGED ONLY, WITH FINAL STATE $K\pi$

Mass

VALUE (MeV)	EVTS	DOCUMENT ID	TECN
1427.3 ± 1.5	**OUR AVERAGE** Error includes scale factor of 1.3.		
$1432.7 \pm 0.7\,^{+2.2}_{-2.3}$	183k	ABLIKIM 2019AQ	BES
1420 ±4	1587	BAUBILLIER 1984B	HBC
1436 ±5.5	400	1, 2 CLELAND 1982	SPEC
1430 ±3.2	1500	1, 2 CLELAND 1982	SPEC
1430 ±3.2	1200	1, 2 CLELAND 1982	SPEC

Width

VALUE (MeV)	EVTS	DOCUMENT ID	TECN
100.0 ± 2.1	**OUR FIT**		
100.0 ± 2.2	**OUR AVERAGE** Error includes scale factor of 1.1.		
$102.5 \pm 1.6\,^{+3.1}_{-2.8}$	183k	ABLIKIM 2019AQ	BES
109 ±22	400	1, 2 CLELAND 1982	SPEC
124 ±12.8	1500	1, 2 CLELAND 1982	SPEC
113 ±12.8	1200	1, 2 CLELAND 1982	SPEC
85 ±16	935	TOAFF 1981	HBC

Approximations to calculate the R∘σ convolution:

- use of the Taylor expansion for σ,
- consider cross-section dependence on $M^2(K^+\pi^0)$ and $M^2(K^-\pi^0)$ only

$K^*_2(1980)^\pm$ and $K^*_4(2045)^\pm$

$K^*_2(1980)$ and $K^*_4(2045)$ are for the first time observed in J/ψ decays.

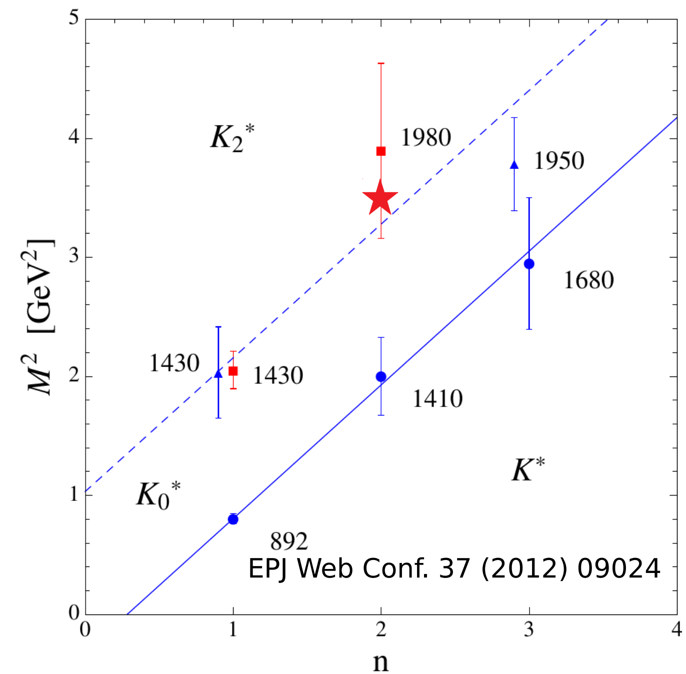
$K^*_2(1980)$

$K^*_2(1980)$	Approximation II	PDG 2018
Mass (MeV/c²)	$1868 \pm 8_{-57}^{+40}$	1974±26
Width (MeV)	$272 \pm 24_{-15}^{+50}$	376±70

Consistent within 2.2σ

Potential models				
$n^{2S+1}L_J$	Mass (MeV/c²)			
	Godfey et al, 1985	Barnes et al, 2002	Ebert et al, 2009	Pang et al, 2017
2^3P_2	1938	1850	1896	1870
1^3F_2	2151	2050	2093	1964

Better consistency with Regge trajectories in the (n,M²) plain.



Resonances in the K^+K^- channel

PRD100,032004(2019)

$J^{PC}=1^{--}$ @1650 MeV:

$$M = 1651 \pm 3^{+16}_{-6}\ MeV/c^2$$
$$\Gamma = 194 \pm 8^{+15}_{-7}\ MeV/c^2$$

Possible interpretations:

- $^3D_1$ isovector state,
- ω(1650),
- interference of these states.

Production of ϕ-resonances is strongly suppressed:
$B(J/\psi \to \phi\pi^0) \sim 10^{-6} - 10^{-7}$ (Phys. Rev. D91, 112001 (2015)).

$\omega(1650)$ MASS INSPIRE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1670 ± 30	**OUR ESTIMATE**			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1651 \pm 3\ ^{+16}_{-6}$	183k	1 ABLIKIM 2019AQ	BES	$J/\psi \to K^+K^-\pi^0$
$1673\ ^{+6}_{-7}$		ACHASOV 2019	SND	$e^+e^- \to \pi^+\pi^-\pi^0\eta$
$1671 \pm 6 \pm 10$	824	2 AKHMETSHIN 2017A	CMD3	$1.4 - 2.0\ e^+e^- \to \omega\eta$
1660 ± 10	898	3 ACHASOV 2016B	SND	$1.34 - 2.00\ e^+e^- \to \omega\eta$
1680 ± 10	13.1k	4 AULCHENKO 2015A	SND	$1.05 - 1.80\ e^+e^- \to \pi^+\pi^-\pi^0$
$1667 \pm 13 \pm 6$		AUBERT 2007AU	BABR	$10.6\ e^+e^- \to \omega\pi^+\pi^-\gamma$
1645 ± 8	13	AUBERT 2006D	BABR	$10.6\ e^+e^- \to \omega\eta\gamma$
$1660 \pm 10 \pm 2$		AUBERT,B 2004N	BABR	$10.6\ e^+e^- \to \pi^+\pi^-\pi^0\gamma$

$J^{PC}=1^{--}$ @2050 MeV:

$$M = 2039 \pm 8^{+36}_{-18}\ MeV/c^2$$
$$\Gamma = 193 \pm 23^{+25}_{-27}\ MeV/c^2$$

Possible interpretations:

- ρ(2150),
- vector-isovector state observed in $p\bar{p}$ annihilation (Phys. Lett. B 491, 47 (2000)).

$\omega(1650)$ WIDTH INSPIRE s

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
315 ± 35	**OUR ESTIMATE**			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$194 \pm 8\ ^{+15}_{-7}$	183k	1 ABLIKIM 2019AQ	BES	$J/\psi \to K^+K^-\pi^0$
95 ± 11		ACHASOV 2019	SND	$e^+e^- \to \pi^+\pi^-\pi^0\eta$
$113 \pm 9 \pm 10$	824	2 AKHMETSHIN 2017A	CMD3	$1.4 - 2.0\ e^+e^- \to \omega\eta$
110 ± 20	898	3 ACHASOV 2016B	SND	$1.34 - 2.00\ e^+e^- \to \omega\eta$
310 ± 30	13.1k	4 AULCHENKO 2015A	SND	$1.05 - 1.80\ e^+e^- \to \pi^+\pi^-\pi^0$
$222 \pm 25 \pm 20$		AUBERT 2007AU	BABR	$10.6\ e^+e^- \to \omega\pi^+\pi^-\gamma$
114 ± 14	13	AUBERT 2006D	BABR	$10.6\ e^+e^- \to \omega\eta\gamma$
$230 \pm 30 \pm 20$		AUBERT,B 2004N	BABR	$10.6\ e^+e^- \to \pi^+\pi^-\pi^0\gamma$

Branching fractions

PRD100,032004(2019)

$B(J/\psi \to K^+K^-\pi^0) = (2.88 \pm 0.01 \pm 0.12) \times 10^{-3}$ – currently the most precise measurement

Intermediate resonance in the $K\pi$ system		
$R_{K\pi}$	$B(J/\psi \to R^{\pm}_{K\pi} K^{\mp} \to K^+K^-\pi^0)$	$B(J/\psi \to R^{+}_{K\pi} K^{-} + c.c. \to K^+K^-\pi^0)$
$K^*(892)$	$(1.22 \pm 0.01^{+0.05}_{-0.07}) \times 10^{-3}$	$(2.69 \pm 0.01^{+0.13}_{-0.20}) \times 10^{-3}$
$K_2^*(1430)$	$(1.21 \pm 0.02^{+0.10}_{-0.08}) \times 10^{-4}$	$(2.69 \pm 0.04^{+0.25}_{-0.19}) \times 10^{-4}$
$K_2^*(1980)$	$(4.3 \pm 0.5^{+2.3}_{-0.6}) \times 10^{-6}$	$(1.1 \pm 0.1^{+0.6}_{-0.1}) \times 10^{-5}$
$K_4^*(2045)$	$(2.6 \pm 0.3^{+1.1}_{-0.6}) \times 10^{-6}$	$(6.2 \pm 0.7^{+2.8}_{-1.4}) \times 10^{-6}$
Intermediate resonance in the K^+K^- system		
R_{KK}	$B(J/\psi \to R_{KK}\pi^0 \to K^+K^-\pi^0)$	
$1^{--}(1650\ \mathrm{MeV}/c^2)$	$(5.3 \pm 0.3^{+0.6}_{-0.5}) \times 10^{-5}$	
$1^{--}(2050\ \mathrm{MeV}/c^2)$	$(6.7 \pm 1.1^{+2.2}_{-1.8}) \times 10^{-6}$	

The systematic uncertainties for K*(892)± production are larger than those reported by BABAR (PRD77,092002 (2008)) due to uncertainties of the PWA solution.

Summary

In the partial wave analysis of $J/\psi \to K^+K^-\pi^0$

- The structure of the decay is determined and found significantly different from what was previously reported by BESII and BABAR.

- The most precise measurements of $K^*(892)^\pm$ and $K_2^*(1430)^\pm$ parameters.

- The first observation of $K^*_2(1980)^\pm$ and $K^*_4(2045)^\pm$ in J/ψ decays. Results for $K^*_2(1980)^\pm$ much better agree with linear (n,M^2) trajectories with the standard slope.

- Two resonance contributions at 1650 MeV/c^2 and 2050 MeV/c^2 are identified, their interpretation is discussed.

- $\rho(1450)$ can not be reliably identified, no evidence are found for X(1575) with the decay rate reported previously.

- $B(J/\psi \to K^+K^-\pi^0)$ is measured with a high precision, branching fractions for decays through reliably identified states are reported.