

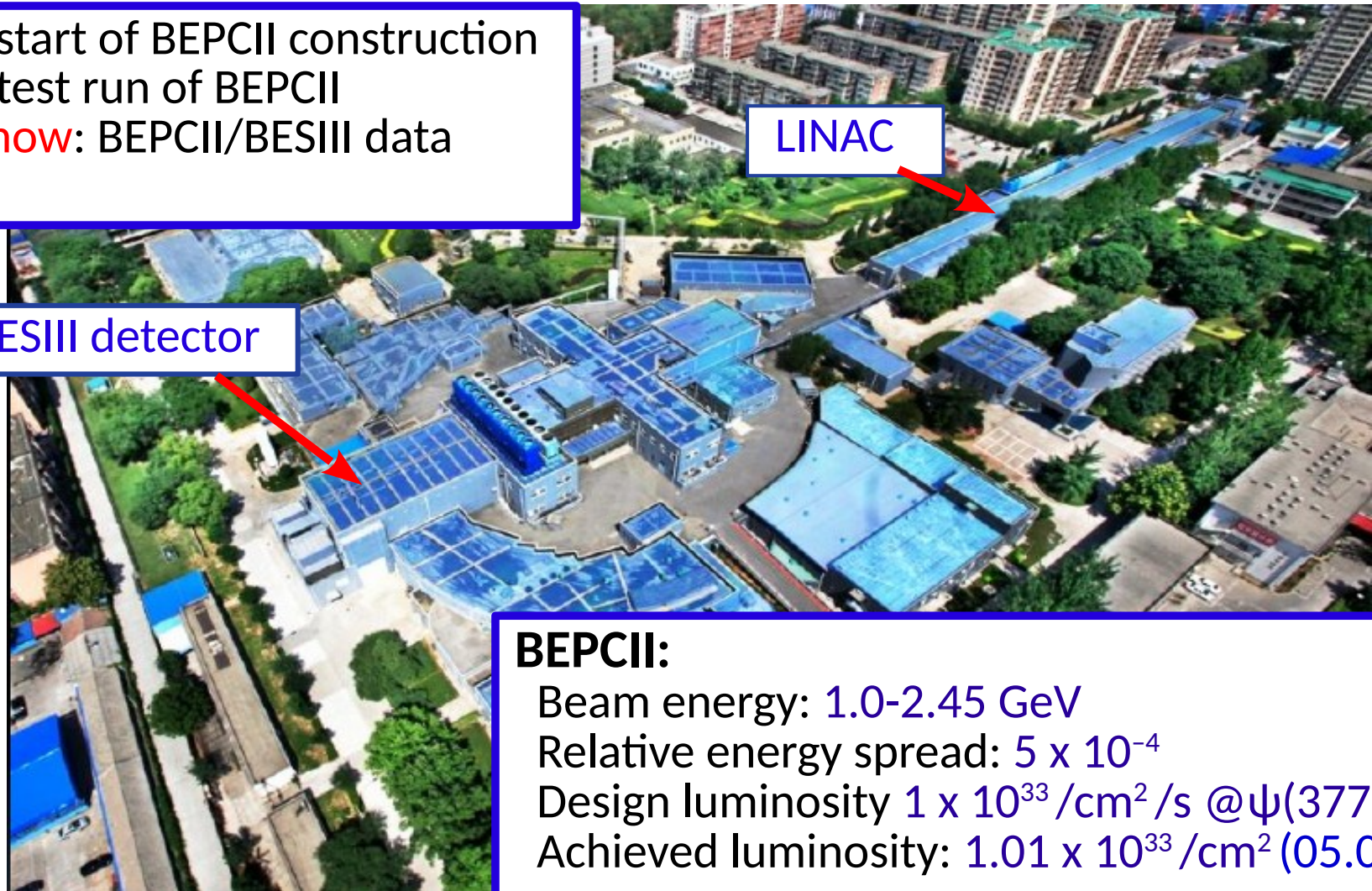
# Partial wave analysis of $J/\psi \rightarrow K^+K^-\pi^0$

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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:  $5 \times 10^{-4}$

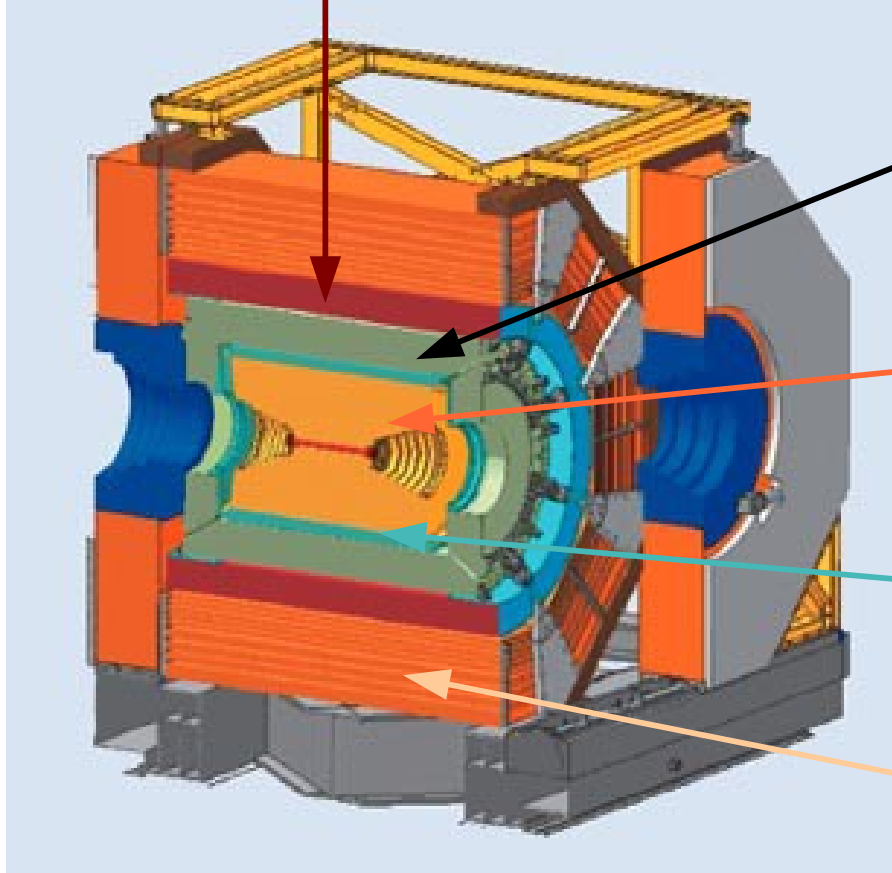
Design luminosity  $1 \times 10^{33} / \text{cm}^2 / \text{s}$  @  $\psi(3770)$

Achieved luminosity:  $1.01 \times 10^{33} / \text{cm}^2$  (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:  $\sigma_{xy} = 120\mu\text{m}$
- Momentum resolution: **0.5% @ 1GeV**
- **dE/dx** resolution: **6%**

**TOF (double/single layer scintillator):**

Time resolution: **80ps** (barrel)  
**110ps [60ps]** (endcaps)

**Muon ID:**

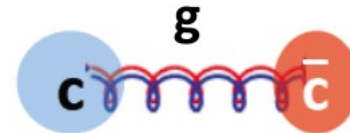
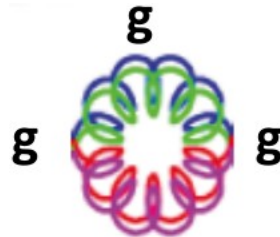
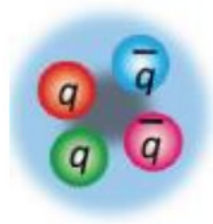
9 layers RPC (8 for endcaps) in the flux-return yoke

# 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 at BESIII

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

# $J/\psi \rightarrow K^+K^-\pi^0$ and light hadron spectroscopy

## $J/\psi \rightarrow K^+K^-\pi^0$

### Kaon spectroscopy:

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

### Meson decaying to $K^+K^-$ :

- Isovector states with  $JPC=1^{--}, 3^{--}, 5^{--}, \dots$  are allowed in strong decays ( $\rho(1450)$ ,  $\rho(1700)$ , ...)
- The same JPCs are allowed for isoscalars in EM decays
- Previously reported exotic  $X(1575)$

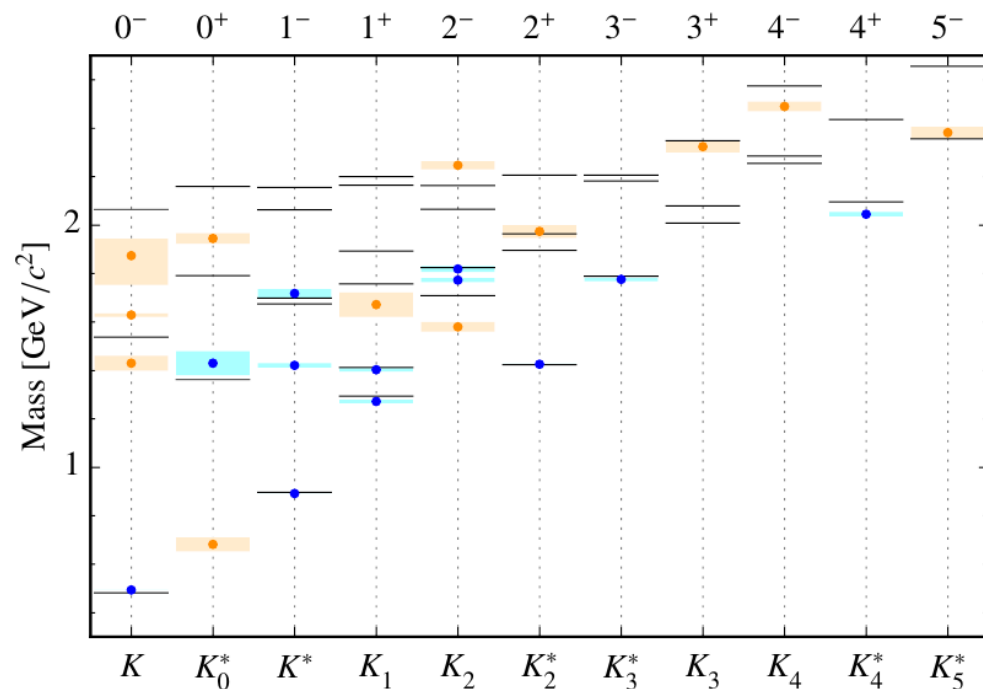


Figure from B. Grube, PKI2018 (arXiv:1804.06528)

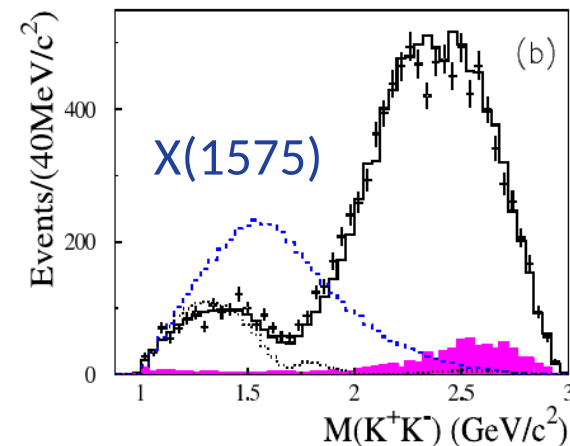
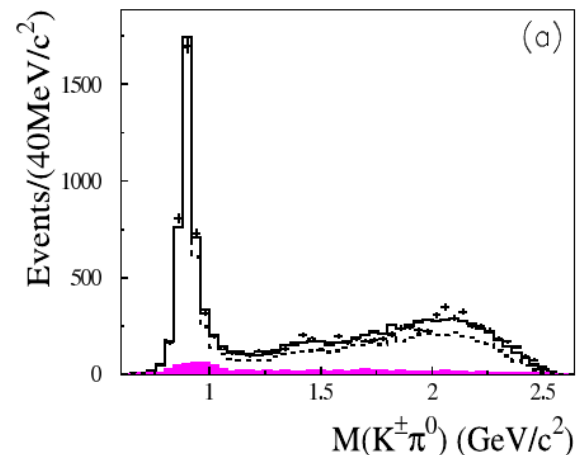
# X(1575) in $J/\psi \rightarrow K^+K^-\pi^0$

**BESII** (PRL97, 142002 (2006))

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

**X(1575):**

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





# BABAR: $J/\psi \rightarrow K^+K^-\pi^0$ , $J/\psi \rightarrow K_s K \pi$ and $J/\psi \rightarrow \pi^+\pi^-\pi^0$

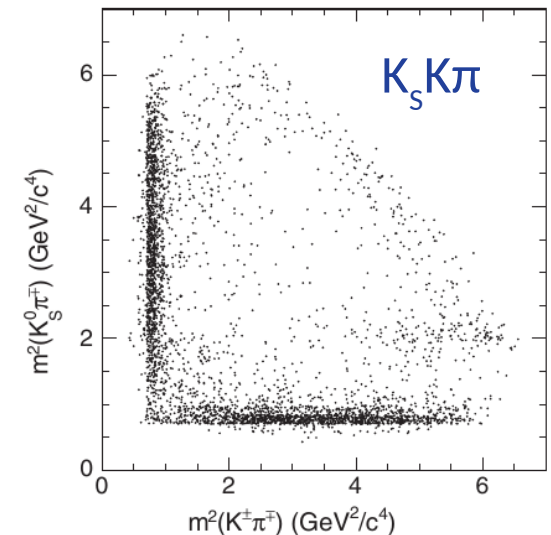
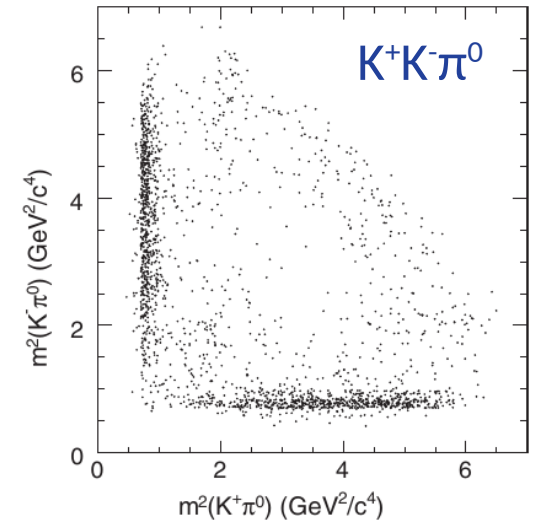
**BABAR (PRD95, 072007 (2017)):**

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

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

- Properties of  $\rho(1450)$

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





**Data at BESIII:**

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

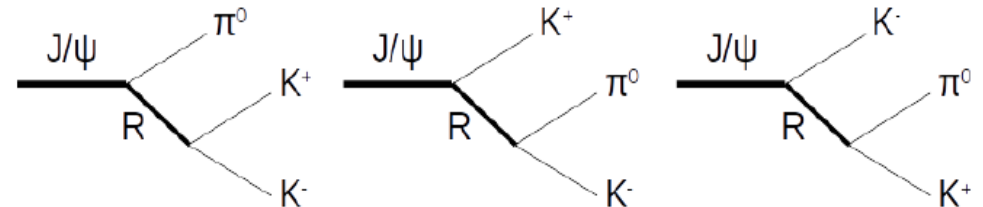
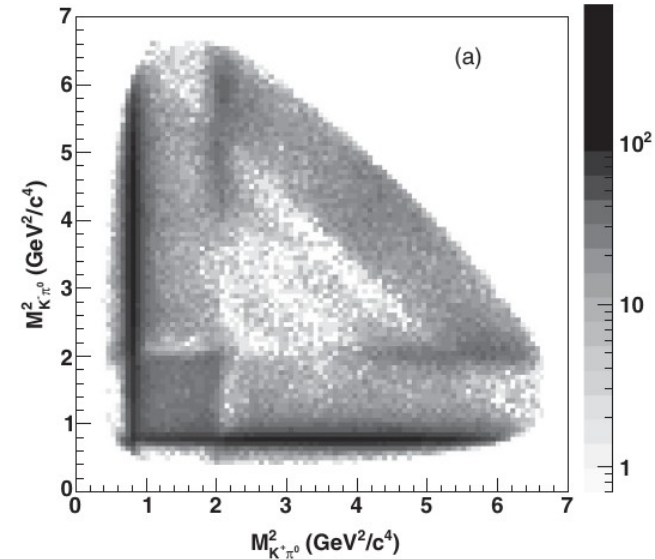
**Partial wave analysis:**

- 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  $JP=3^- K\pi$  wave



$K^\pm\pi^0$ channels						
$J^{PC}$	PDG	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$b(\%)$	$b^{+(-)}(\%)$	$\Delta\text{NLL}$
$1^-$	$K^*(892)^\pm$	$894.1 \pm 0.1$	$46.7 \pm 0.2$	$89.2 \pm 0.8$	$41.0 \pm 0.2$	—
$1^-$	$K^*(1680)^\pm$	$1677^*$	$205^*$	$0.59 \pm 0.04$	$0.25 \pm 0.02$	398
$2^+$	$K_2^*(1430)^\pm$	$1431.4 \pm 0.8$	$100.3 \pm 1.6$	$9.2 \pm 0.1$	$4.1 \pm 0.1$	—
$2^+$	$K_2^*(1980)^\pm$	$1817 \pm 11$	$312 \pm 28$	$0.44 \pm 0.05$	$0.17 \pm 0.02$	238
$3^-$	$K_3^*(1780)^\pm$	$1781^*$	$203^*$	$0.08 \pm 0.01$	$0.04 \pm 0.01$	83
$4^+$	$K_4^*(2045)^\pm$	$2015 \pm 7$	$183 \pm 17$	$0.16 \pm 0.02$	$0.07 \pm 0.01$	192
$K^+K^-$ channel						
$J^{PC}$	PDG	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$b(\%)$	$\Delta \ln L$	
$1^{--}$	$\rho(770)$	$771^*$	$150^*$	$1.8 \pm 0.2$	220	
$1^{--}$	$\rho(1450)$	$1465^*$	$400^*$	$1.2 \pm 0.2$	27	
$1^{--}$		$1643 \pm 3$	$167 \pm 12$	$1.1 \pm 0.1$	281	
$1^{--}$		$2078 \pm 6$	$149 \pm 21$	$0.15 \pm 0.03$	73	
$1^{--}$	non-resonant	—	—	$1.2 \pm 0.2$	34	
$3^{--}$	$\rho_3(1690)$	$1696^*$	$204^*$	$0.14 \pm 0.01$	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)

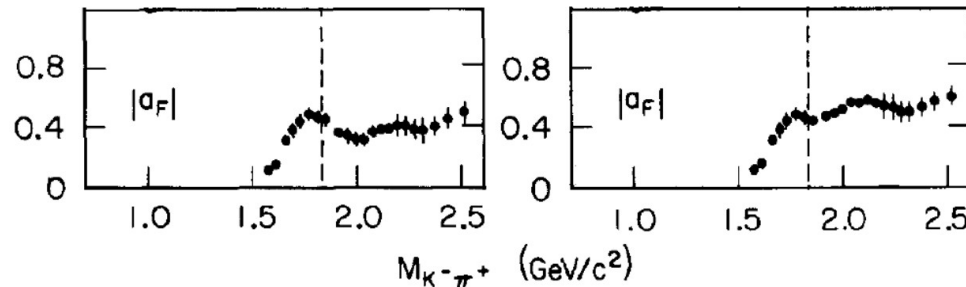
$K^\pm \pi^0$ channels						
$J^{PC}$	PDG	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$b(\%)$	$b^{+(-)}(\%)$	$\Delta\text{NLL}$
$1^-$	$K^*(892)^\pm$	$893.6 \pm 0.1^{+0.2}_{-0.3}$	$46.7 \pm 0.2^{+0.1}_{-0.2}$	$93.4 \pm 0.4^{+1.8}_{-5.8}$	$42.5 \pm 0.1^{+0.5}_{-1.7}$	—
$1^-$	$K^*(1410)^\pm$	1380*	176*	$0.26 \pm 0.04$	$0.11 \pm 0.02$	80
$1^-$	$K^*(1680)^\pm$	1677*	205*	$0.20 \pm 0.03$	$0.08 \pm 0.01$	56
$2^+$	$K_2^*(1430)^\pm$	$1432.7 \pm 0.7^{+2.2}_{-2.3}$	$102.5 \pm 1.6^{+3.1}_{-2.8}$	$9.4 \pm 0.1^{+0.8}_{-0.5}$	$4.2 \pm 0.1^{+0.3}_{-0.2}$	—
$2^+$	$K_2^*(1980)^\pm$	$1868 \pm 8^{+40}_{-57}$	$272 \pm 24^{+50}_{-15}$	$0.38 \pm 0.04^{+0.22}_{-0.05}$	$0.15 \pm 0.02^{+0.08}_{-0.02}$	192
$3^-$	$K_3^*(1780)^\pm$	1781*	203*	$0.16 \pm 0.02$	$0.07 \pm 0.01$	105
$4^+$	$K_4^*(2045)^\pm$	$2090 \pm 9^{+11}_{-29}$	$201 \pm 19^{+57}_{-17}$	$0.21 \pm 0.02^{+0.10}_{-0.05}$	$0.09 \pm 0.01^{+0.04}_{-0.02}$	212
$3^-$	non-resonant	—	—	$\sim 1.5\%$	$\sim 0.6\%$	629

$K^+ K^-$ channel					
$J^{PC}$	PDG	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$b(\%)$	$\Delta \ln L$
$1^{--}$		$1651 \pm 3^{+16}_{-6}$	$194 \pm 8^{+15}_{-7}$	$1.83 \pm 0.11^{+0.19}_{-0.17}$	796
$1^{--}$		$2039 \pm 8^{+36}_{-18}$	$193 \pm 23^{+25}_{-27}$	$0.23 \pm 0.04^{+0.07}_{-0.06}$	102

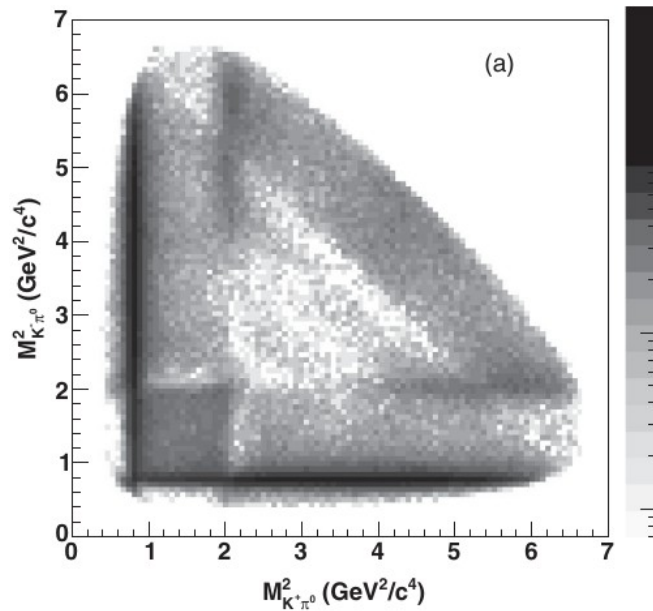
- Broad  $3^- K^\pm \pi^0$  contribution is added
- States contributing to NLL by more than 40 are included
- Systematic errors are determined from the uncertainties of PWA and the detector simulation

Nucl. Phys. B 296, 493 (1988)

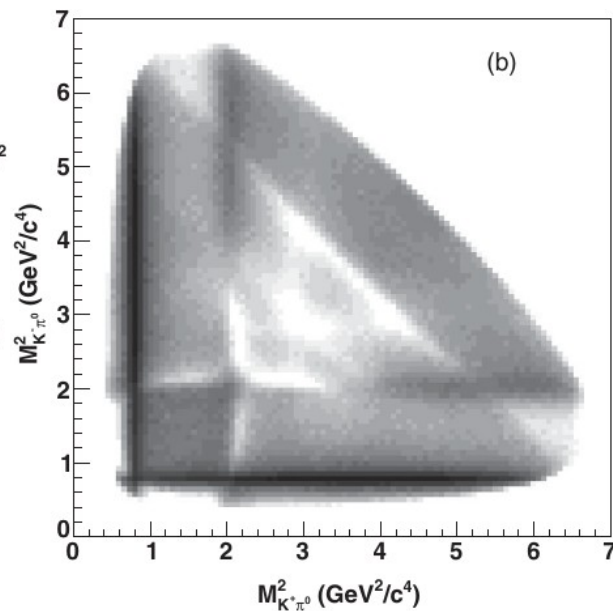


# Data description I

PRD100,032004(2019)

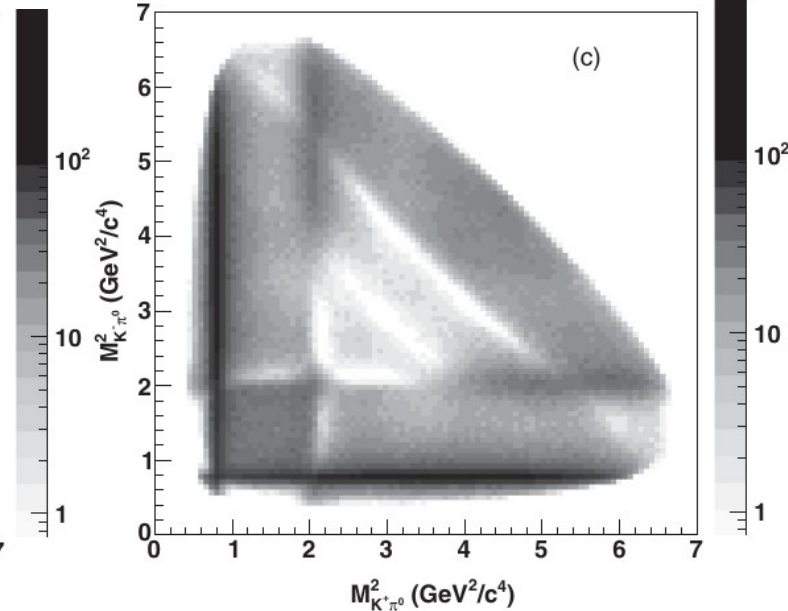


Data



PWA solution I

$\chi^2/\text{NDF} = 3314.8/2950$



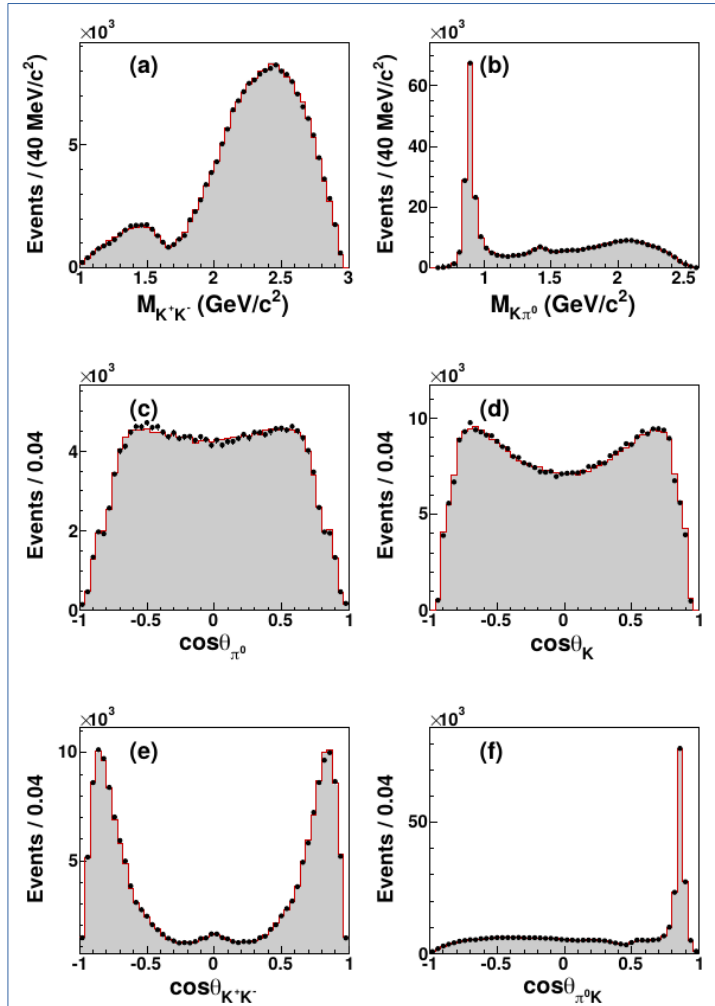
PWA solution II

$\chi^2/\text{NDF} = 3191.0/2950$

# Data description II

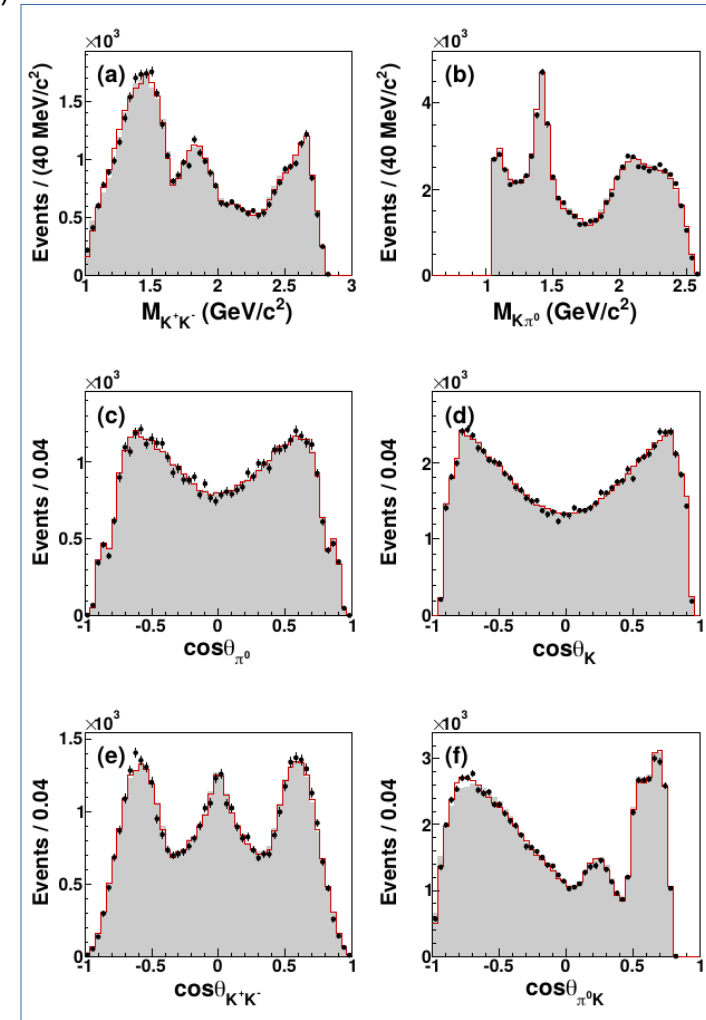
PRD100,032004(2019)

Full data set



Solution I  
Solution II

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



# Summary on the decay structure

PRD100,032004(2019)

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

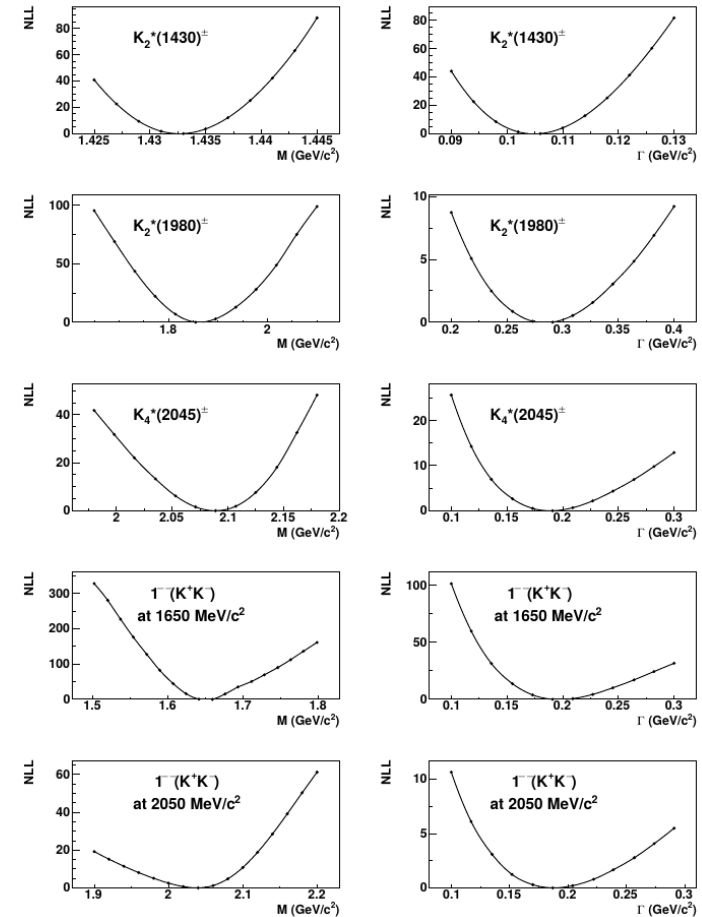
- $K^*(892)^\pm$
- $K_2^*(1430)^\pm$
- $K_2^*(1980)^\pm$
- $K_4^*(2045)^\pm$
- $1^{--}$  @ 1650 MeV/c<sup>2</sup>
- $1^{--}$  @ 2050 MeV/c<sup>2</sup>

Also

- There are no evidence for X(1575)
- $\rho(1450)$  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 <sup>2</sup> )	$\Gamma$ (MeV)
$\tau$ -decays (PDG aver.)	$895.47 \pm 0.20 \pm 0.74$	$46.2 \pm 0.6 \pm 1.2$
hadroproduction (PDG aver.)	$891.66 \pm 0.26$	$50.8 \pm 0.9$
$J/\psi \rightarrow K^+ K^- \pi^0$ (sol. II)	$893.6 \pm 0.1^{+0.2}_{-0.3}$	$46.7 \pm 0.2^{+0.1}_{-0.2}$

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

CHARGED ONLY, WITH FINAL STATE  $K\pi$

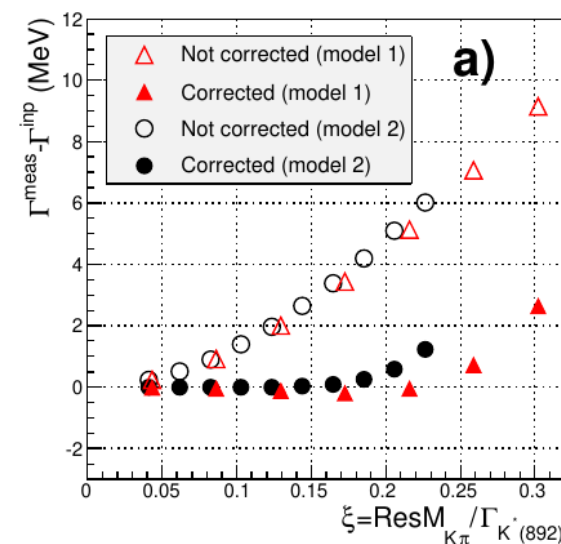
Mass

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

Width

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

JINST 10, P10028 (2015)



Approximations to calculate the  $R \circ \sigma$  convolution:

- use of the Taylor expansion for  $\sigma$ ,
- 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  $J/\psi$  decays.

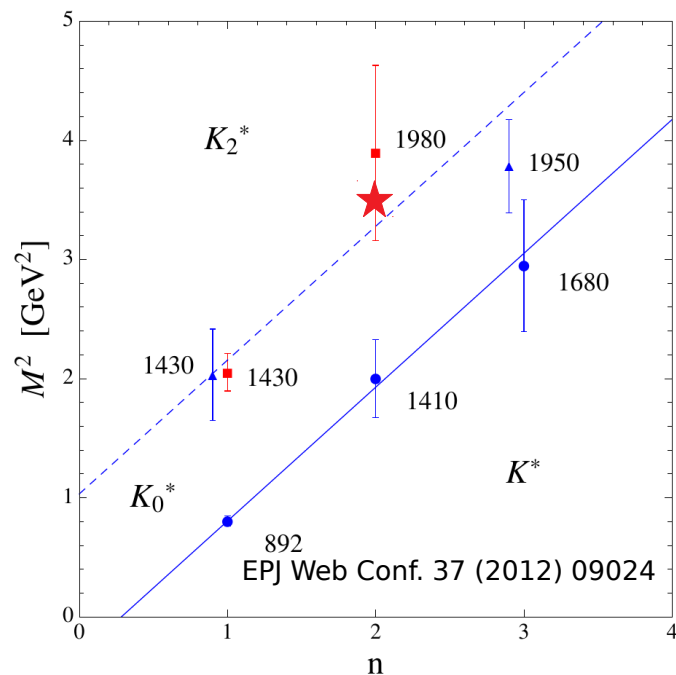
## $K_2^*(1980)$

$K_2^*(1980)$	Approximation II	PDG 2018
Mass (MeV/c <sup>2</sup> )	$1868 \pm 8_{-57}^{+40}$	$1974 \pm 26$
Width (MeV)	$272 \pm 24_{-15}^{+50}$	$376 \pm 70$

Consistent within  $2.2\sigma$

Potential models				
$n^{2S+1}L_J$	Mass (MeV/c <sup>2</sup> )			
	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  $(n, M^2)$  plain.



# Resonances in the $K^+K^-$ channel

PRD100,032004(2019)

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

$$M = 1651 \pm 3_{-6}^{+16} \text{ MeV}/c^2$$

$$\Gamma = 194 \pm 8_{-7}^{+15} \text{ MeV}/c^2$$

Possible interpretations:

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

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

$$M = 2039 \pm 8_{-18}^{+36} \text{ MeV}/c^2$$

$$\Gamma = 193 \pm 23_{-27}^{+25} \text{ MeV}/c^2$$

Possible interpretations:

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

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

## $\omega(1650)$ MASS

INSPIRE

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

## $\omega(1650)$ WIDTH

INSPIRE

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

# Branching fractions

PRD100,032004(2019)

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

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

The systematic uncertainties for  $K^*(892)^\pm$  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 $J/\psi \rightarrow K^+K^-\pi^0$

- 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  $J/\psi$  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<sup>2</sup> and 2050 MeV/c<sup>2</sup> 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.
- $B(J/\psi \rightarrow K^+K^-\pi^0)$  is measured with a high precision, branching fractions for decays through reliably identified states are reported.