RUHR-UNIVERSITÄT BOCHUM

RUB

Recent Achievements of BESIII

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Ruhr-Universität Bochum
(on behalf of the BESIII Collaboration)

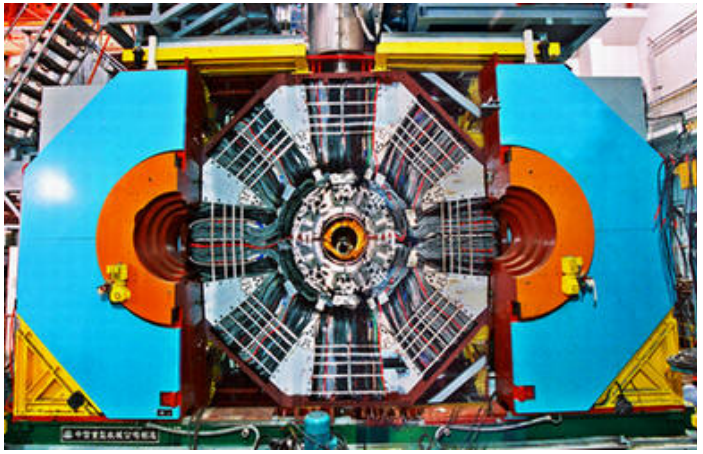
MESON 2021
May 17-20, 2021

DFG

BESIII

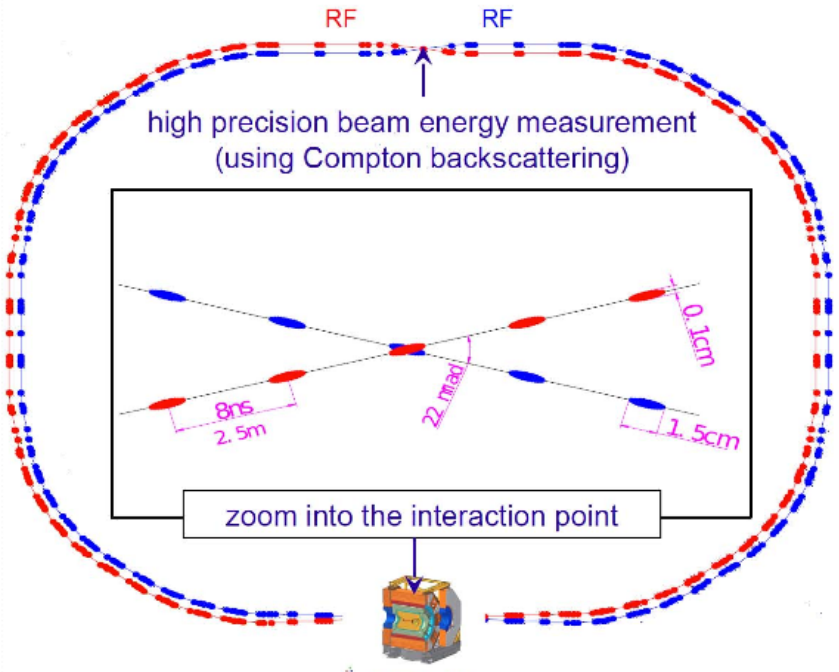
BESIII Physics Program

- Light Hadrons
  - Meson and baryon spectroscopy
  - Search for exotic hadrons, e.g. glueballs, hybrids, tetraquarks
  - Light meson decays ($\eta^{(\prime)}$, ω)
- Charmonium Physics
  - X, Y, and Z states
  - Decays and transitions
- Open Charm Physics
  - D meson decays
  - $D\bar{D}$ mixing
- And many further topics
  - e.g. tau and two-photon physics



Today: Recent highlights from light hadron and (exotic) charmonium spectroscopy

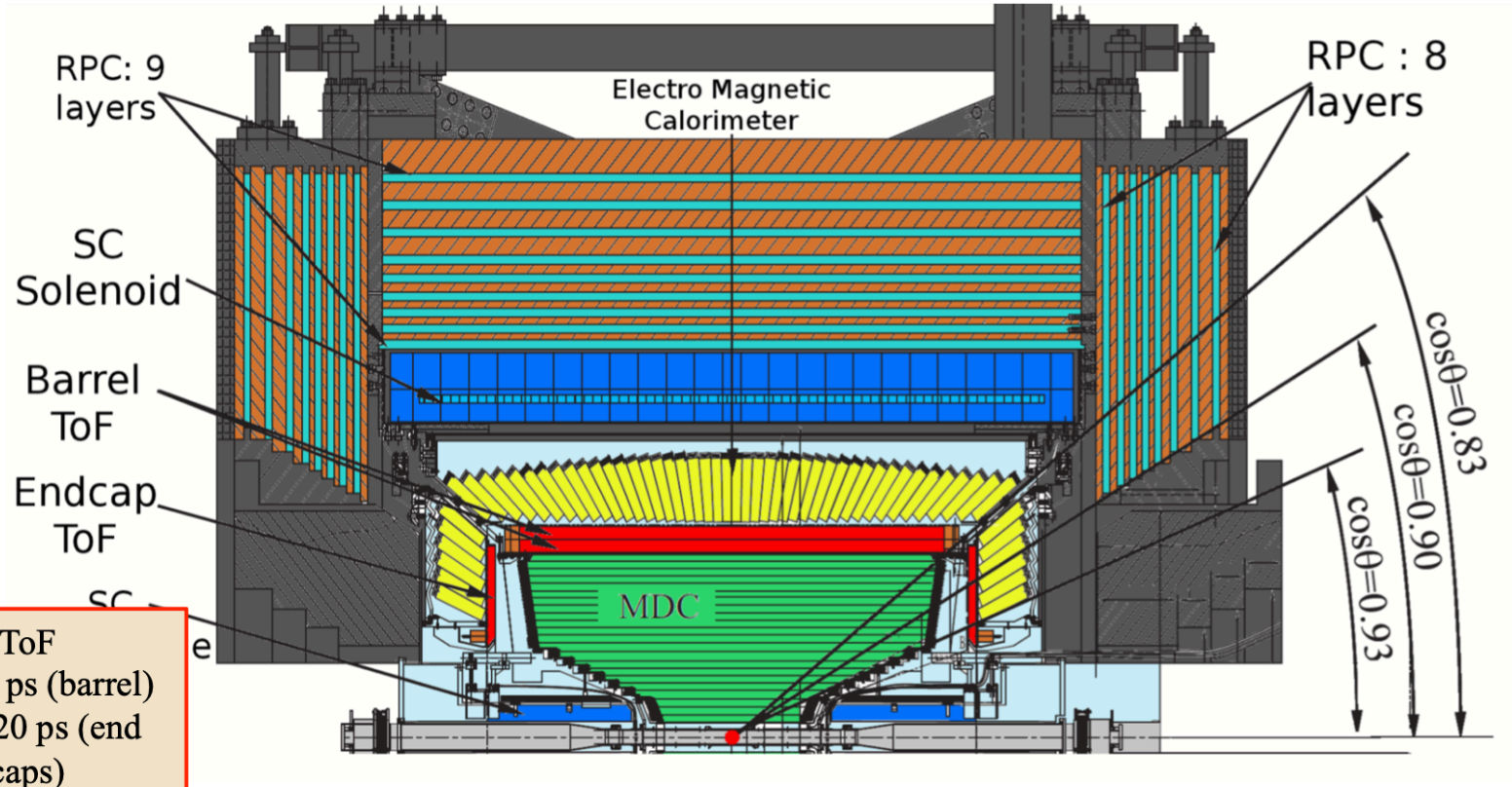
BESIII at BEPC II



Symmetric electron-positron collider BEPC II

- Energy range: $\sqrt{s}$ = 2.0 - 4.6 GeV (~5 GeV since summer 2019)
- Design luminosity achieved: 1x10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$)
- Energy spread: ~5x10^{-4}
- Operating since March 2008

The BESIII Detector



ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

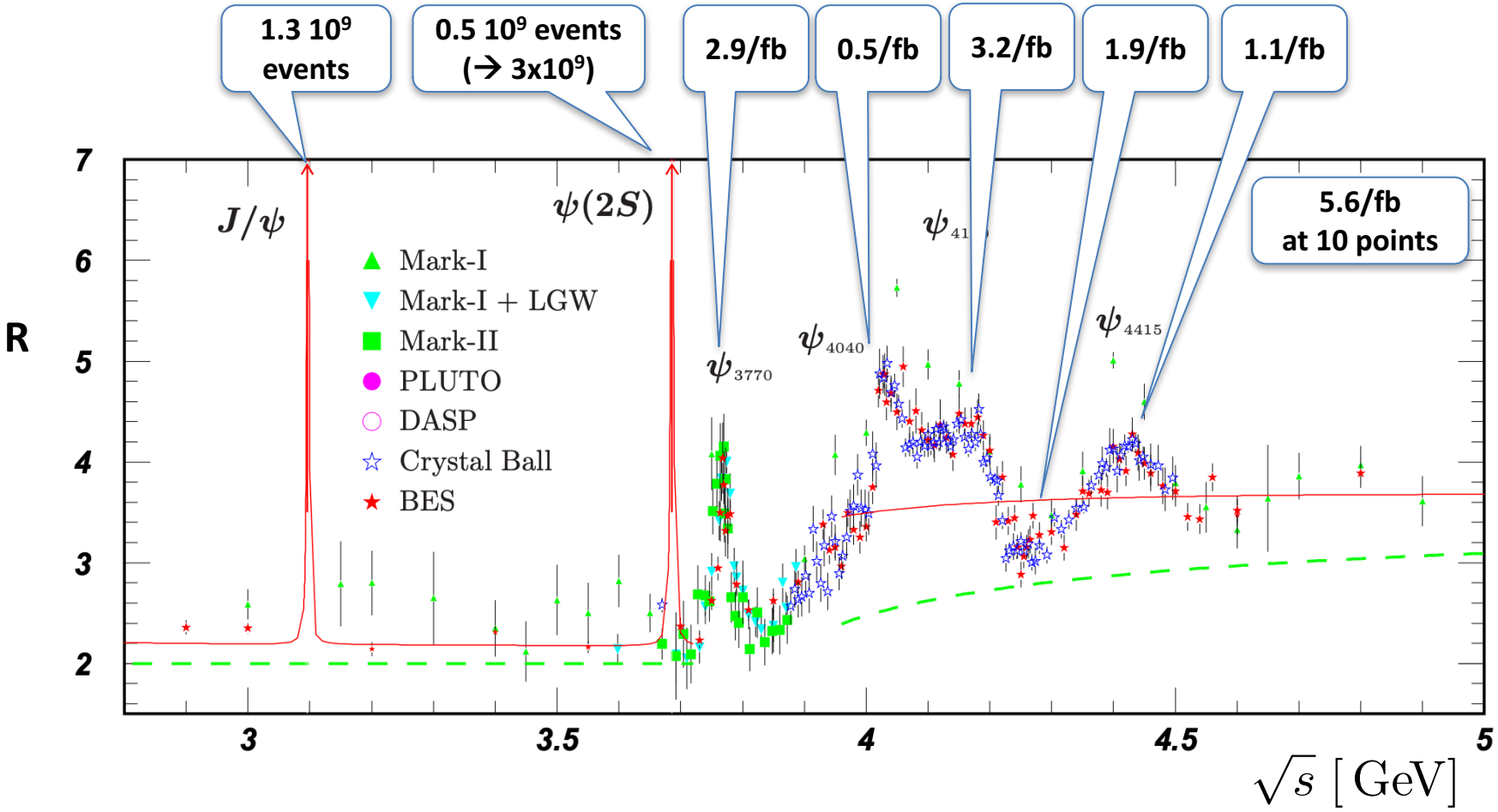
Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

Data Samples

World's largest τ-charm data samples in direct e^+e^- annihilations

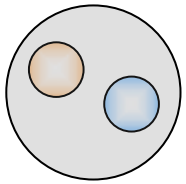


Clean environment, complementary to hadron machines

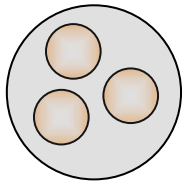
QCD Bound States

Conventional hadrons

mesons: $q\bar{q}$

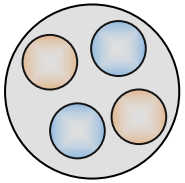


baryons: qqq

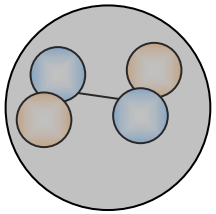


Exotic hadrons (other color-neutral configurations)

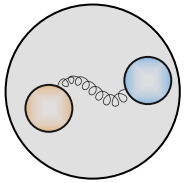
tetraquarks: $qq\bar{q}\bar{q}$



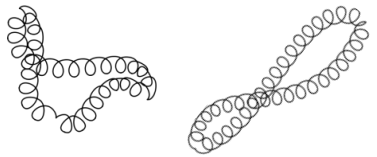
molecules: $[q\bar{q}][q\bar{q}]$



hybrids: $q\bar{q}g$



glueballs: gg, ggg



Candidates for exotic hadrons exist
Nature of these states is far from being understood

Glueballs

- Lattice predictions
  - 0^{++}: m ~ 1710 MeV
  - 2^{++}: m ~ 2390 MeV
  - 0^{-+}: m ~ 2560 MeV

- Production in (gluon-rich) radiative J/ψ decays

  large BFs predicted

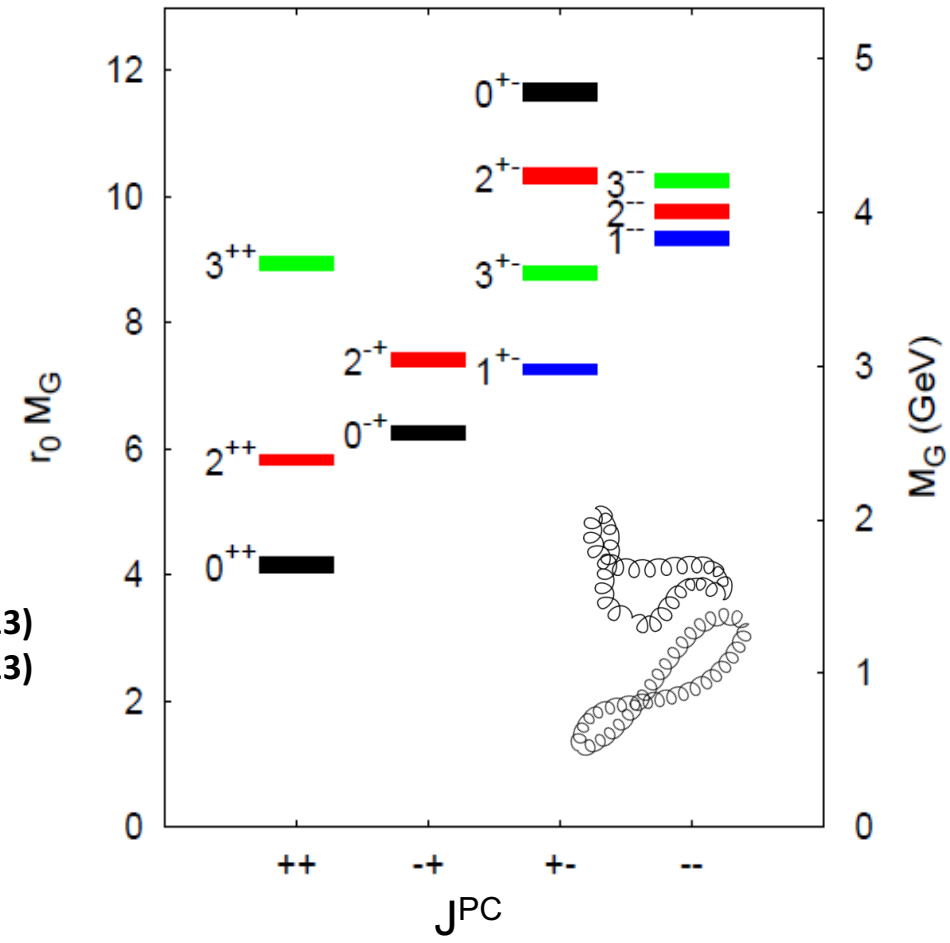
$$\Gamma(J/\psi \to \gamma G_{0^{++}}) = 3.8(9) \times 10^{-3}$$

$$\Gamma(J/\psi \to \gamma G_{2^{++}}) = 1.1(2)(1) \times 10^{-2}$$

  CLQCD, Phys. Rev. Lett. 110, 021601 (2013)
  CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

- Mixing with nearby $q\bar{q}$ states complicates the clear identification

Glueball Spectrum
(Lattice QCD)

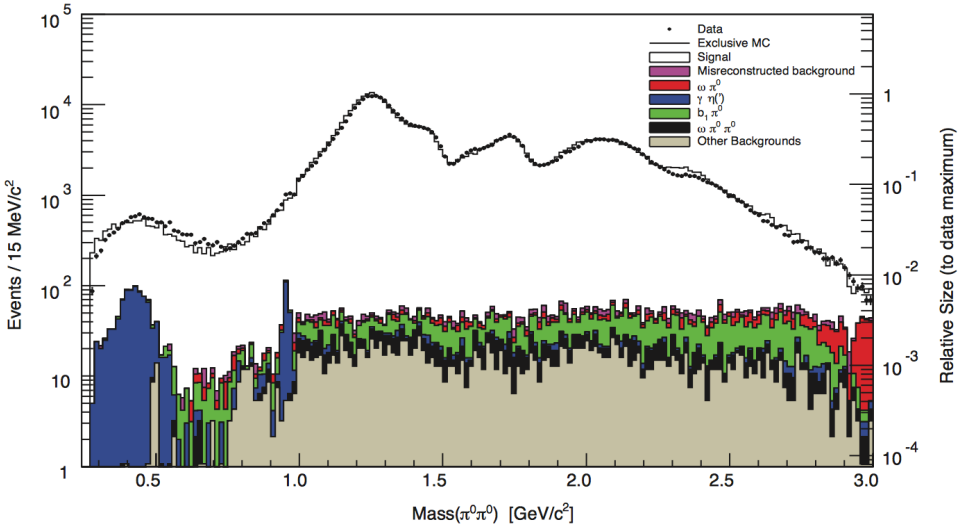


Y. Chen et al., Phys. Rev. D73, 014516 (2006)

Partial Wave Analyses

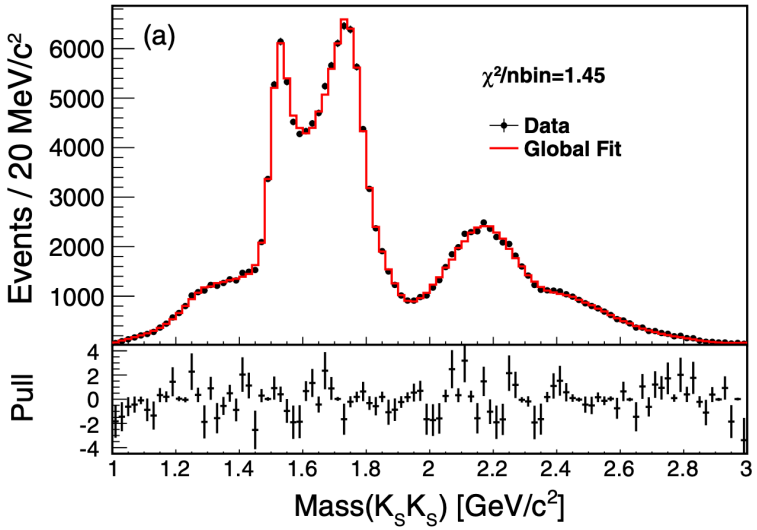
- Partial Wave Analyses of $J/\psi \to \gamma\pi^0\pi^0, \eta\eta, K_S^0 K_S^0$
  - many broad and overlapping resonances, many open channels
  - complex structure, parameterization challenging
- Approach: Model Independent Partial Wave Analysis
  - do not parameterize mass-dependent kinematics of the amplitudes

$J/\psi \to \gamma\pi^0\pi^0$



Phys.Rev. D92 052003 (2015)

$J/\psi \to \gamma K_S^0 K_S^0$

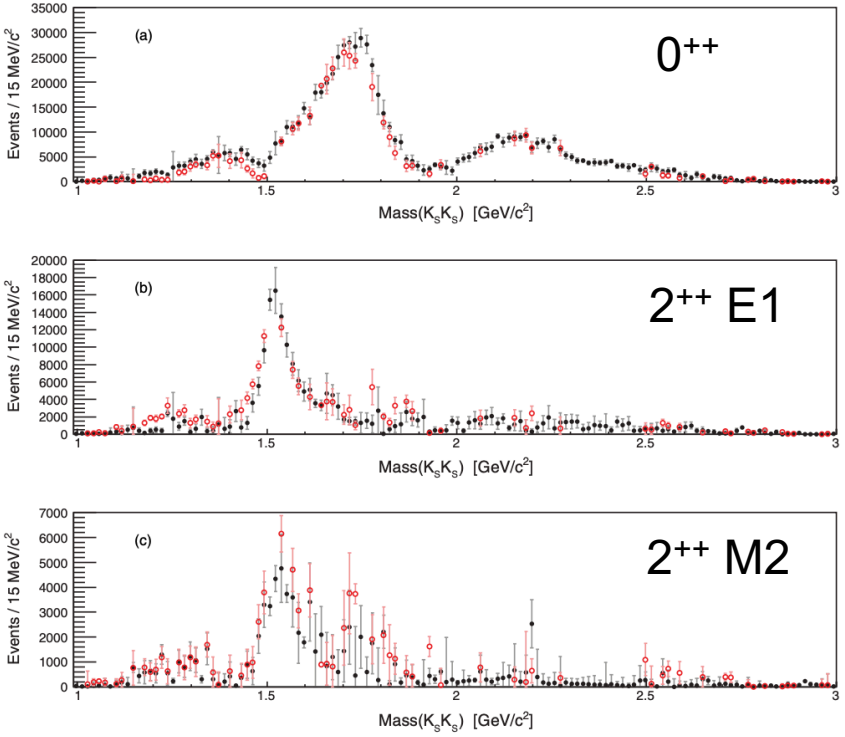


Phys. Rev. D 98, 072003 (2018)

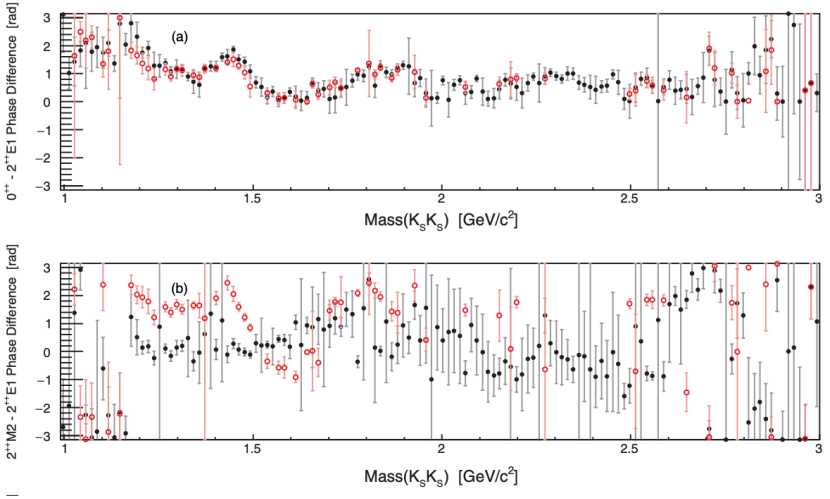
Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0$

Phys. Rev. D 98, 072003 (2018)

Extracted Intensity



Relative Phase wrt/ 2^{++} E1 amplitude



nominal solution

ambigous solution

- Only 0^{++} and 2^{++} contribute significantly
- Ambiguities are resolved in a model-dependent fit

Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0$

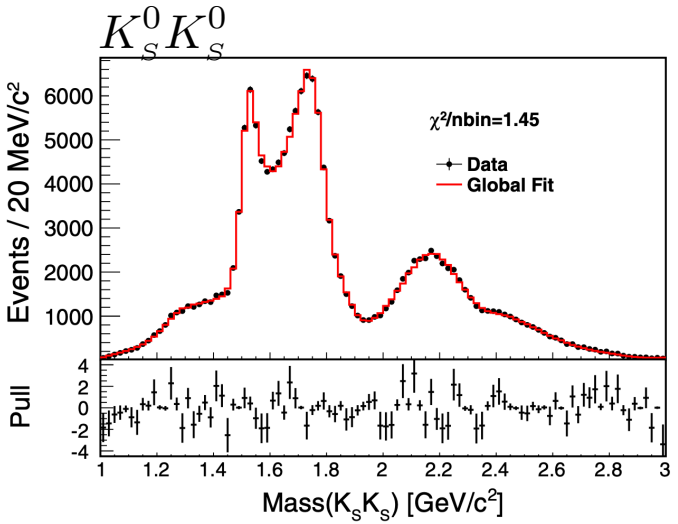
Parameterization:

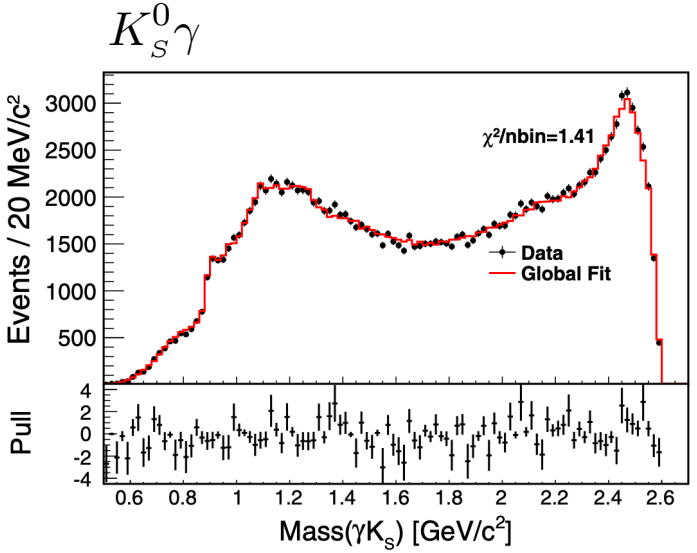
7 contributions 0^{++} $K_S^0 K_S^0$

4 contributions 2^{++} $K_S^0 K_S^0$

K*(892) and $K_1(1270)$ in $K_S^0\gamma$

Resonance	M (MeV/c^2)	Γ (MeV/c^2)	Branching fraction
$K^*(892)$	896	48	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$
$K_1(1270)$	1272	90	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	$231 \pm 21^{+28}_{-48}$	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$
$f_0(1500)$	1505	109	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	$146 \pm 3^{+7}_{-1}$	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$146 \pm 14^{+7}_{-15}$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	$364 \pm 9^{+4}_{-7}$	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$349 \pm 18^{+23}_{-1}$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$
$f_2(1270)$	1275	185	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$
$f_2'(1525)$	1516 ± 1	$75 \pm 1 \pm 1$	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	$507 \pm 37^{+18}_{-21}$	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$
0^{++} PHSP	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$
2^{++} PHSP	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$

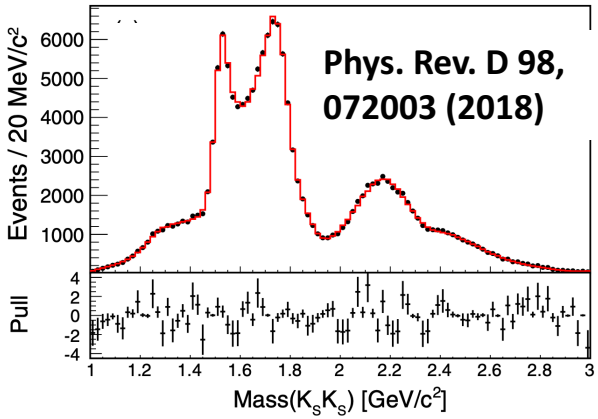




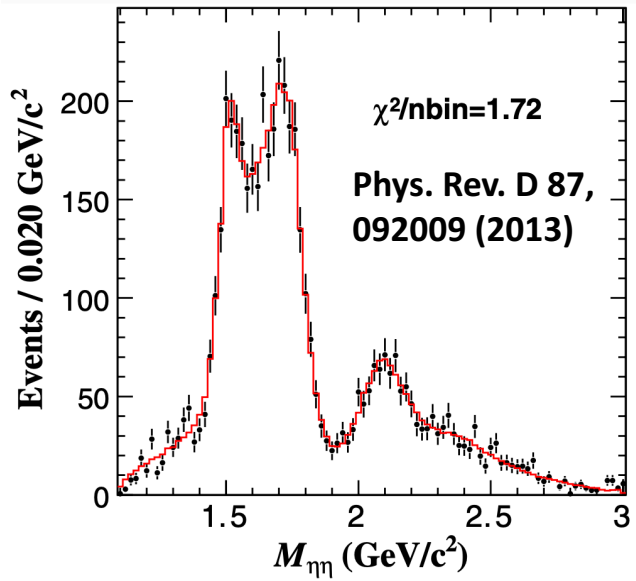
Phys. Rev. D 98, 072003 (2018)

Partial Wave Analysis of $J/\psi \to \gamma K^0_S K^0_S/\eta\eta$

$J/\psi \to \gamma K^0_S K^0_S$



$J/\psi \to \gamma\eta\eta$



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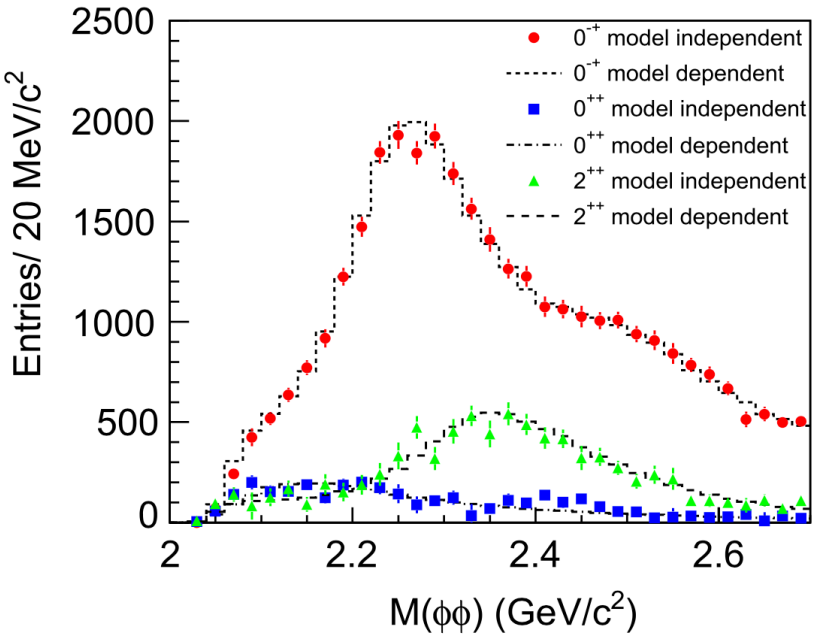
0^{++} PHSP	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$
2^{++} PHSP	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$

10x larger BF for $f_0(1710)$ compared to $f_0(1500)$ observed in both channels

Partial Wave Analysis of $J/\psi \to \gamma\phi\phi$

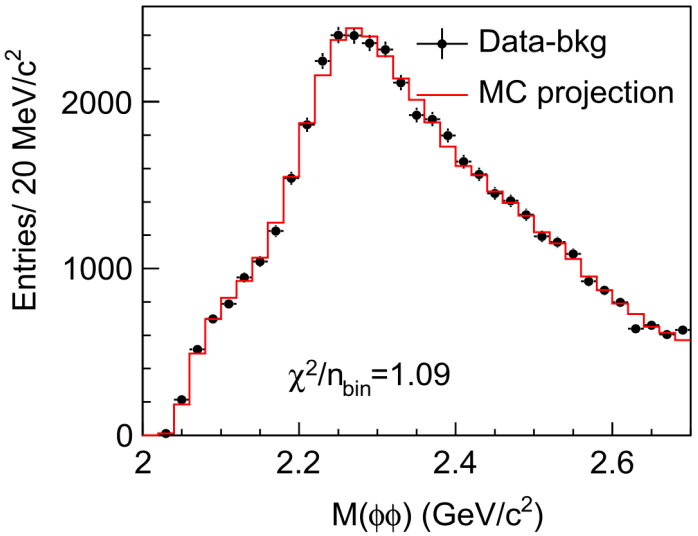
Phys. Rev. D 93, 112011 (2016)



dominant 0^{-+} component

broad 2^{++} component at ~2.3 GeV
$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$
previously observed in πN scattering

Phys. Lett. B 201, 568 (1988)

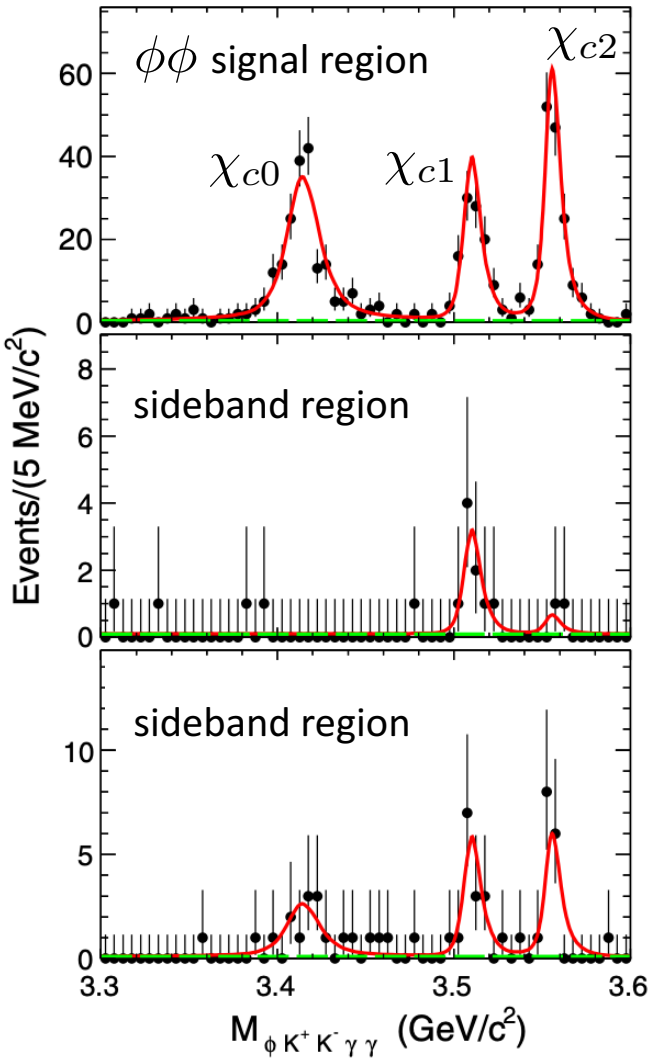


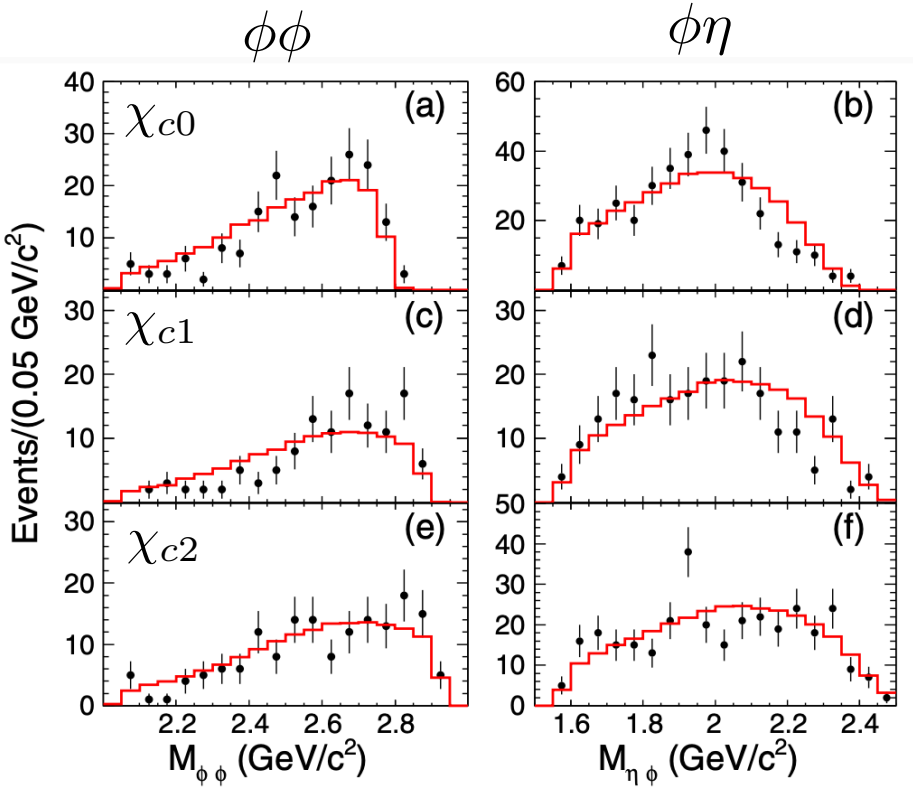
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$

First Observation of $\chi_{cJ} \to \phi\phi\eta$

Phys. Rev. D 101, 012012 (2020)

Study of $\chi_{cJ} \to \phi\phi\eta$ produced in $\psi(2S) \to \gamma\chi_{cJ}$





No significant deviation from phasespace distributions

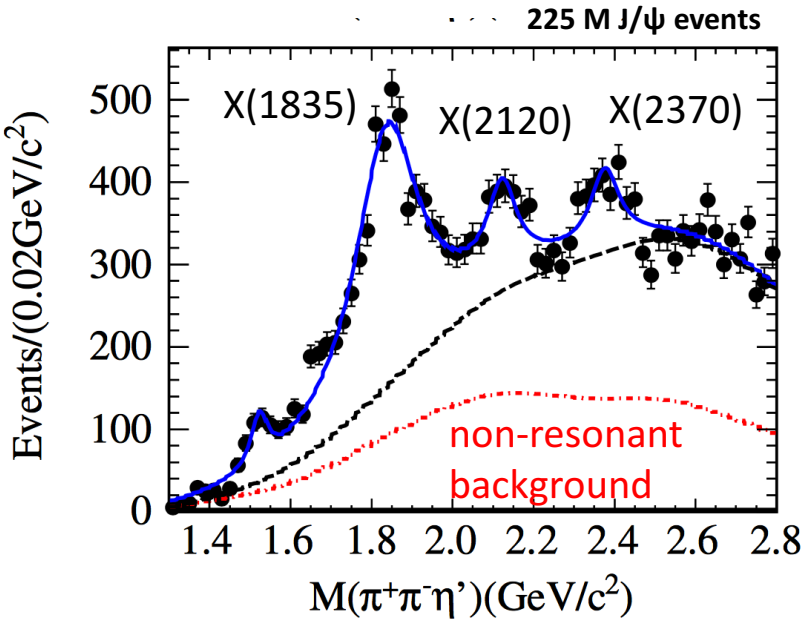
X(1835)

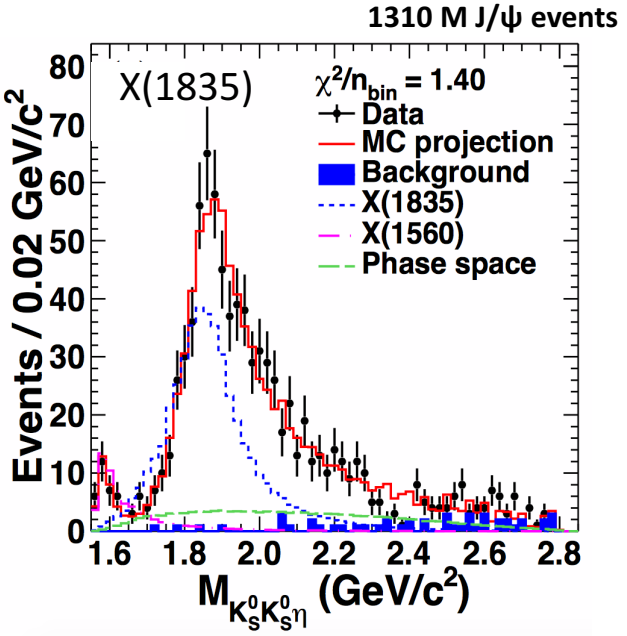
Phys. Rev. Lett. 106, 072002 (2011)
Phys. Rev. Lett. 115, 091803 (2015)

- Systematic study of X(1835) at BESIII with large statistics
  - previously observed at BES and BESII
- J^{PC} consistent with 0^{-+}
- observed in
  $J/\psi \rightarrow \gamma\pi^+\pi^-\eta', \gamma K_S^0 K_S^0 \eta$

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$
$f_1(1510)$	1522.7 ± 5.0	48 ± 11
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0
$X(2120)$	2122.4 ± 6.7	83 ± 16
$X(2370)$	2376.3 ± 8.7	83 ± 17

Nature of X(1835) unclear, interpretations include glueball, $p\bar{p}$ bound state, excited η meson



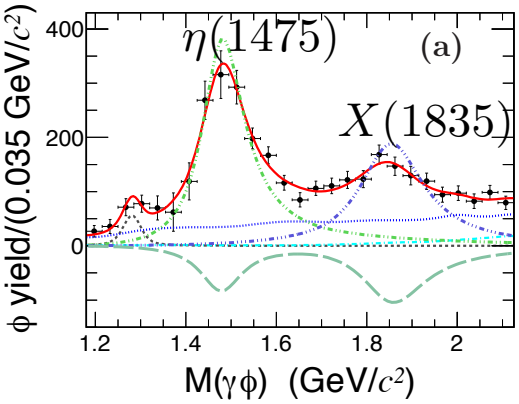


Studies of X(1835)

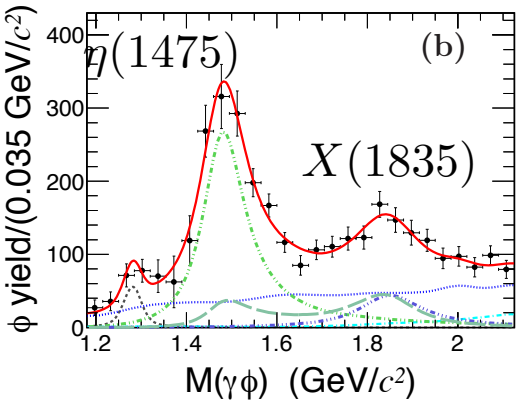
First observation of $J/\psi \to \gamma X(1835) \to \gamma\gamma\phi$

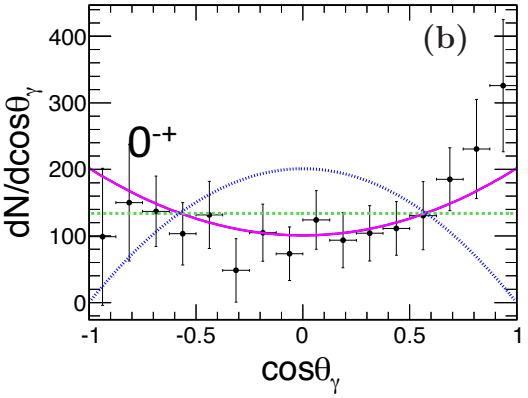
Phys. Rev. D 97, 051101 (2018)

Constructive interference



Destructive interference



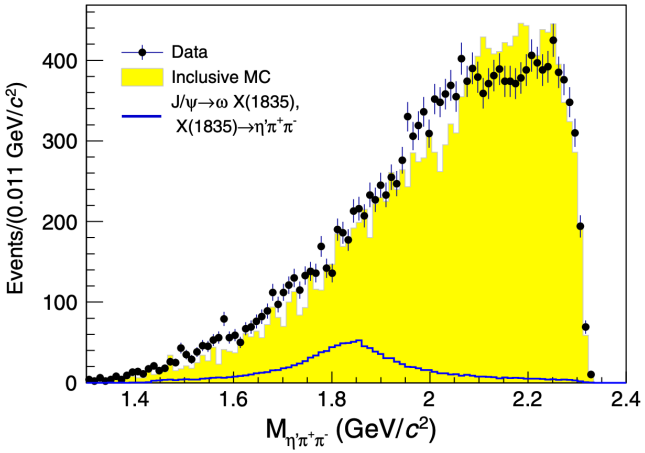


Search for X(1835) in $J/\psi \to \omega\pi^+\pi^-\eta'$

$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$

$$\mathcal{B}(J/\psi \to \omega X(1835))\mathcal{B}(X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5} \quad \text{(at 90\% CL)}$$

Phys. Rev. D 99, 071101 (R) (2019)

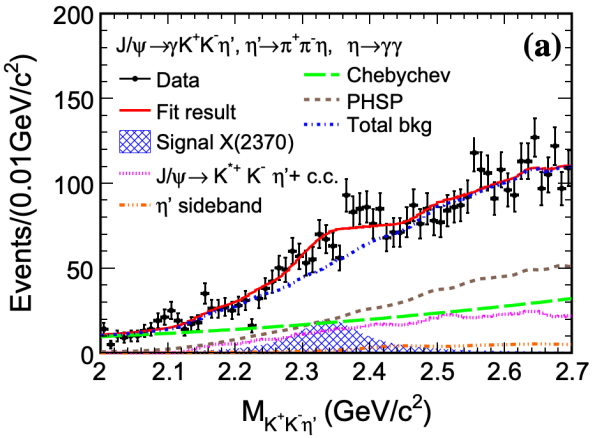


Study of X(2120) and X(2370)

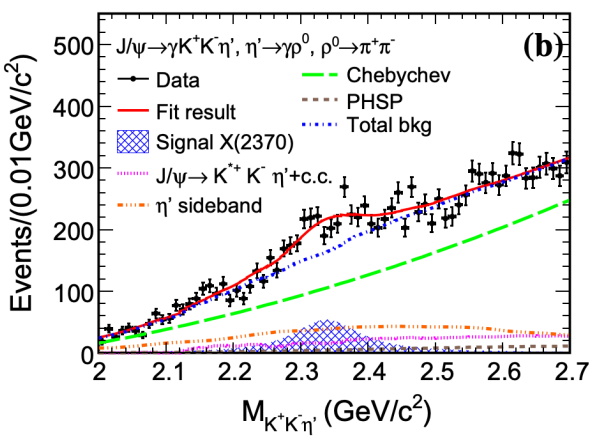
Eur. Phys. J. C 80:746 (2020)

$J/\psi \to \gamma K^+ K^- \eta'$

$\eta' \to \eta\pi^+\pi^-$



$\eta' \to \gamma\pi^+\pi^-$



Combined fit to the four data samples

No significant X(2120) observed

First observation (8.3σ) of $X(2370) \to K\bar{K}\eta'$

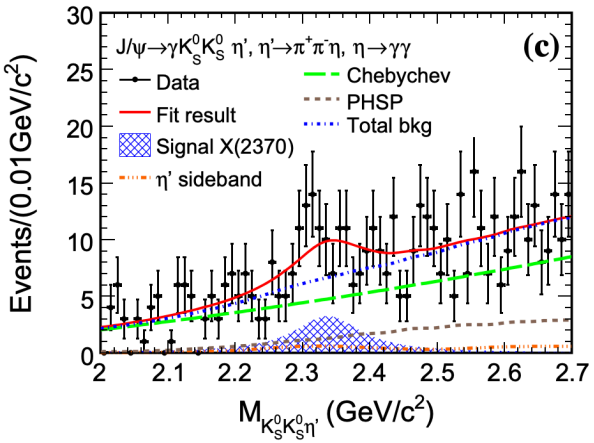
m(X(2370))=

$2341.6 \pm 6.5 \pm 5.7\,\mathrm{MeV}/c^2$

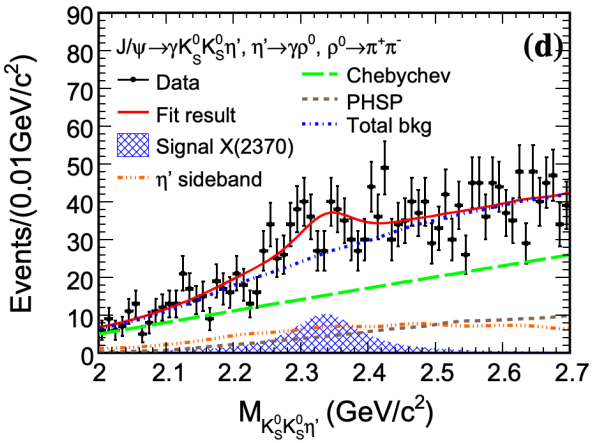
$\Gamma = 117 \pm 10 \pm 8\,\mathrm{MeV}$

$J/\psi \to \gamma K_S^0 K_S^0 \eta'$

$\eta' \to \eta\pi^+\pi^-$



$\eta' \to \gamma\pi^+\pi^-$

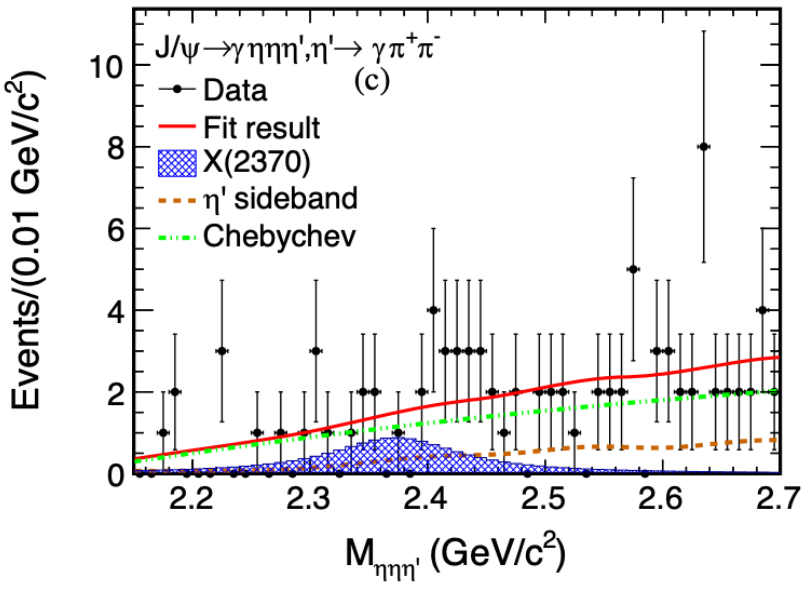


Study of X(2370)

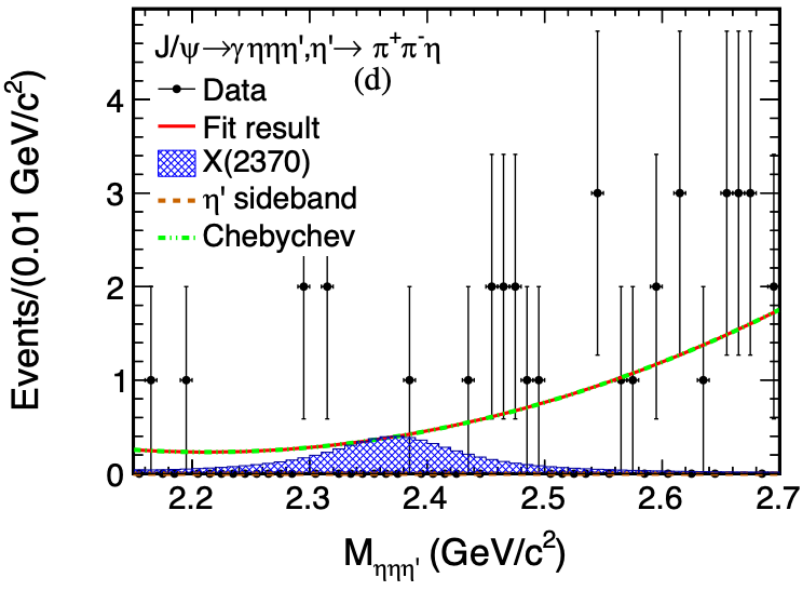
Phys. Rev. D 103, 012009 (2021)

Search for X(2370) in $J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta'$

$\eta' \to \gamma\pi^+\pi^-$



$\eta' \to \eta\pi^+\pi^-$



$\mathcal{B}(J/\psi \to \gamma X)\mathcal{B}(X \to \eta\eta\eta') < 9.2 \cdot 10^{-6}$ (at 90% CL)

does not contradict calculation for X(2370) as 0^{-+} glueball:

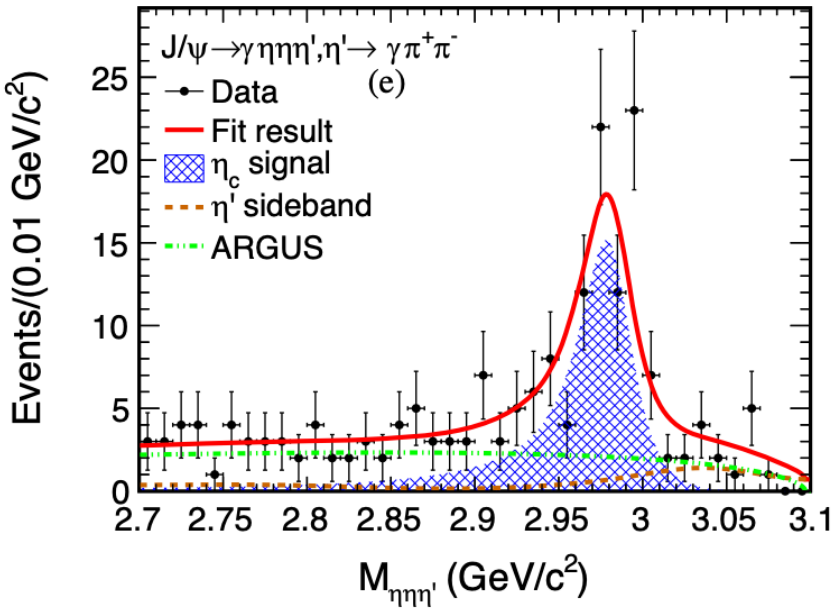
$\mathcal{B}_{\eta\eta\eta'}/\mathcal{B}_{K\bar{K}\eta'} \approx 0.075$

W. I. Eshraim, S. Janowski, F. Giacosa, and D. H. Rischke, Phys. Rev. D 87, 054036 (2013)

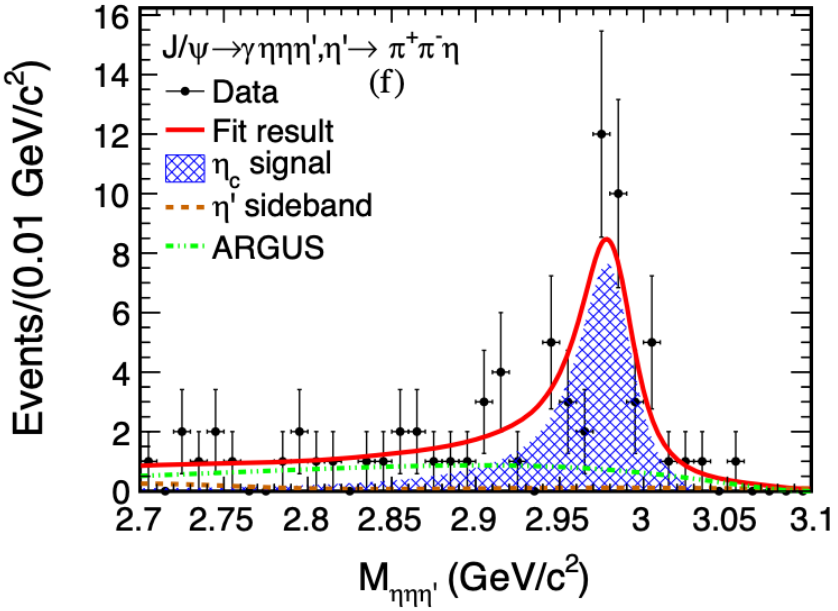
First Observation of $\eta_c \to \eta\eta\eta'$

Phys. Rev. D 103, 012009 (2021)

$\eta' \to \gamma\pi^+\pi^-$



$\eta' \to \eta\pi^+\pi^-$



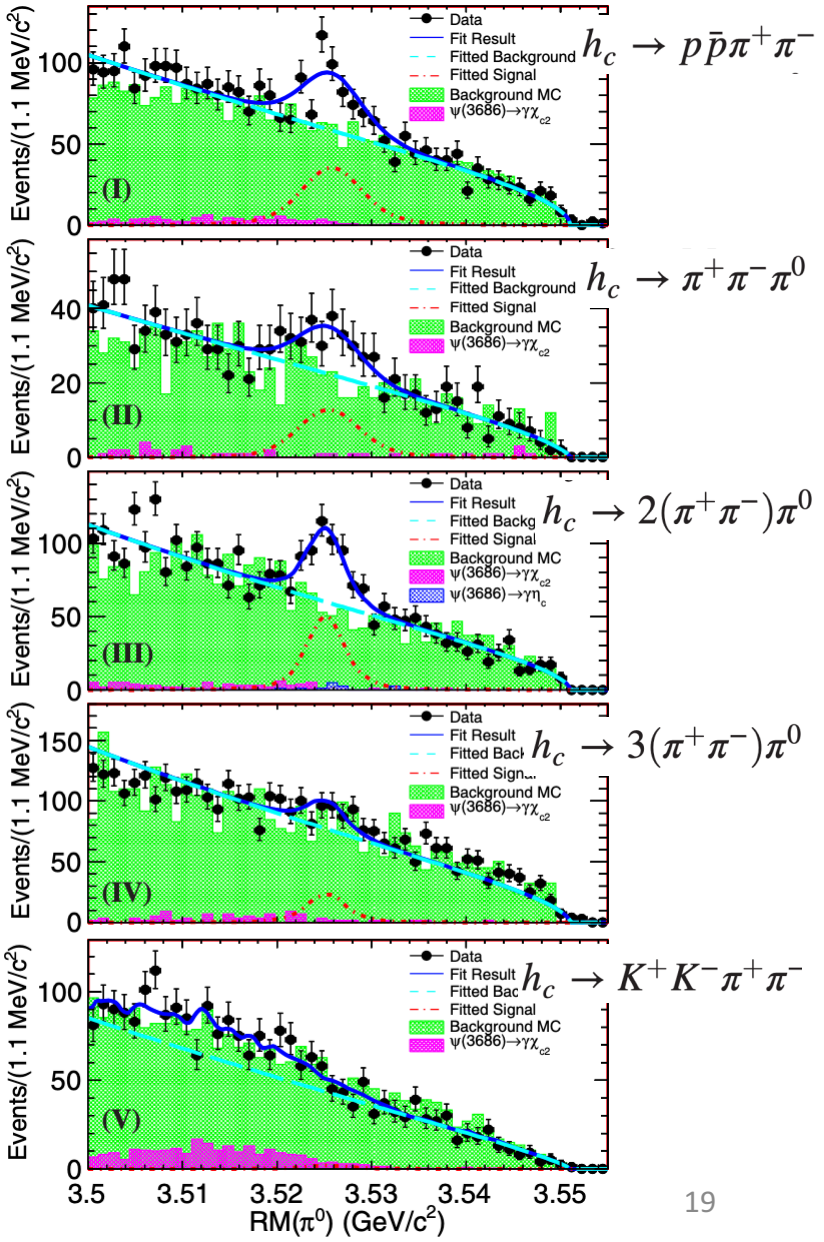
$$\mathcal{B}(J/\psi \to \gamma\eta_c)\mathcal{B}(\eta_c \to \eta\eta\eta') = (4.86 \pm 0.63_{\rm stat} \pm 0.45_{\rm sys}) \cdot 10^{-5}$$

Light Hadron Decays of h_c

Phys. Rev. D 99, 072008 (2019)

- Knowledge on h_c decay modes is still sparse
  - $\mathcal{B}(h_c \to \gamma\eta_c) \approx 0.5$
  - search for decays into light hadrons
- Access via $\psi(2S) \to \pi^0 h_c$
  - fully reconstruct events and inspect recoil mass of π^0

decay mode	$\mathcal{B}_{h_c}(10^{-3})$
$h_c \to p\bar{p}\pi^+\pi^-$	$2.89 \pm 0.32 \pm 0.55$
$h_c \to \pi^+\pi^-\pi^0$	$1.60 \pm 0.40 \pm 0.32$
$h_c \to 2(\pi^+\pi^-)\pi^0$	$7.44 \pm 0.94 \pm 1.52$
$h_c \to 3(\pi^+\pi^-)\pi^0$	$4.65 \pm 2.17 \pm 1.08$
	<8.7
$h_c \to K^+K^-\pi^+\pi^-$	<0.6

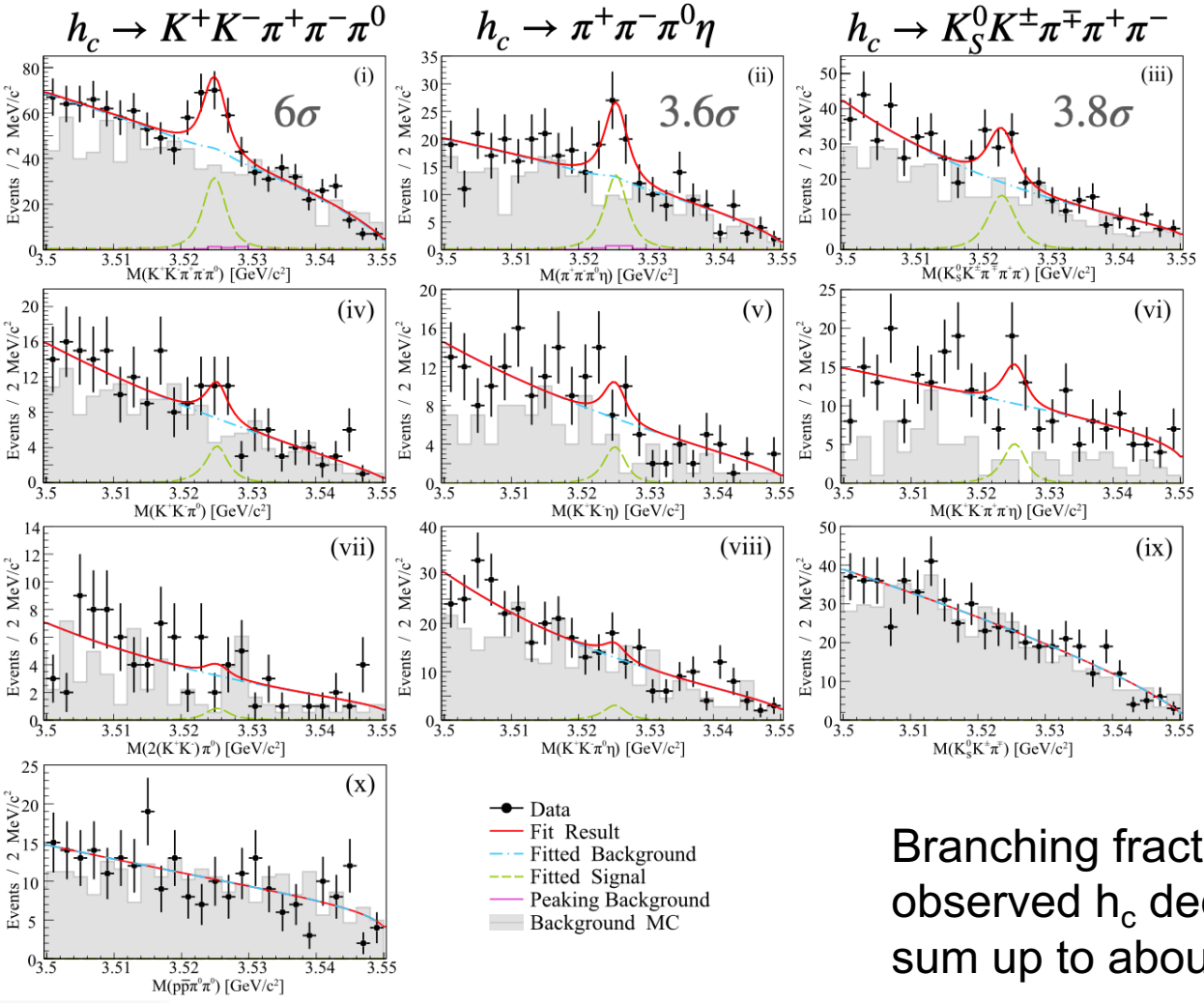


Light Hadron Decays of h_c

Phys. Rev. D 102, 112007 (2020)

observed for the first time

$$\mathcal{B}(h_c \to K^+K^-\pi^+\pi^-\pi^0) = (3.3 \pm 0.6 \pm 0.6) \times 10^{-3}$$



Significance

$< 3\sigma$

$< 3\sigma$

Branching fractions of the five observed h_c decays into light hadrons sum up to about 2% only

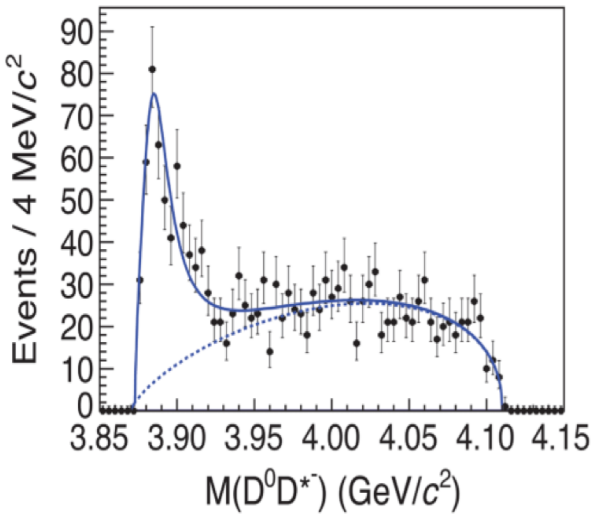
Charged Charmonium-like States

- BESIII has established isospin triplets of charmonium-like $Z_c(3900)$ and $Z_c(4020)$ seen in $e^+e^- \to (J/\psi\,, h_c)\pi\pi$

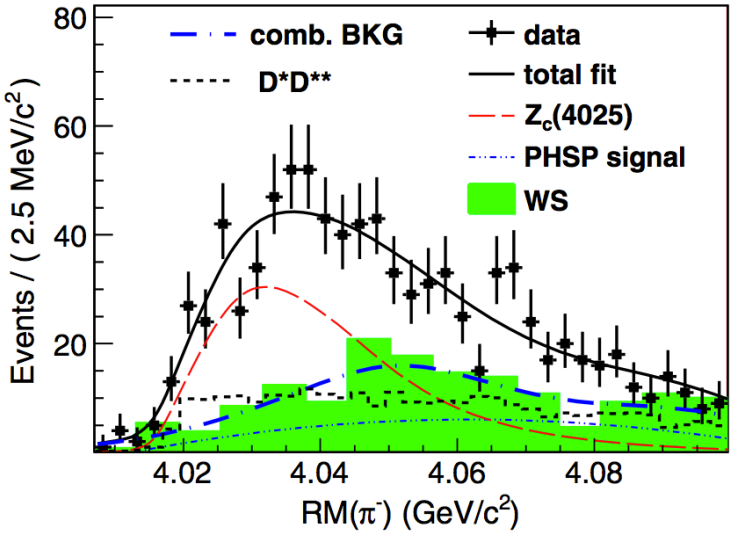
- $Z_c(3885)$ seen in $e^+e^- \to (D\bar{D}^*)^+\pi^-$
  $Z_c(4025)$ seen in $e^+e^- \to (D^*\bar{D}^*)^+\pi^-$

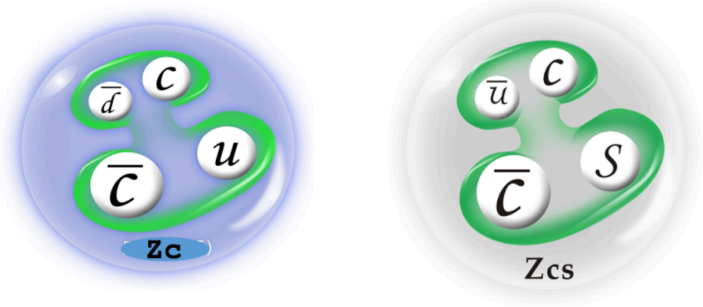
- Nature is unclear: tetraquarks, hadronic molecules, threshold effects, …?
- Do strange partners exist?

Phys. Rev. Lett. 112, 022001 (2014)



Phys. Rev. Lett. 112, 132001 (2014)



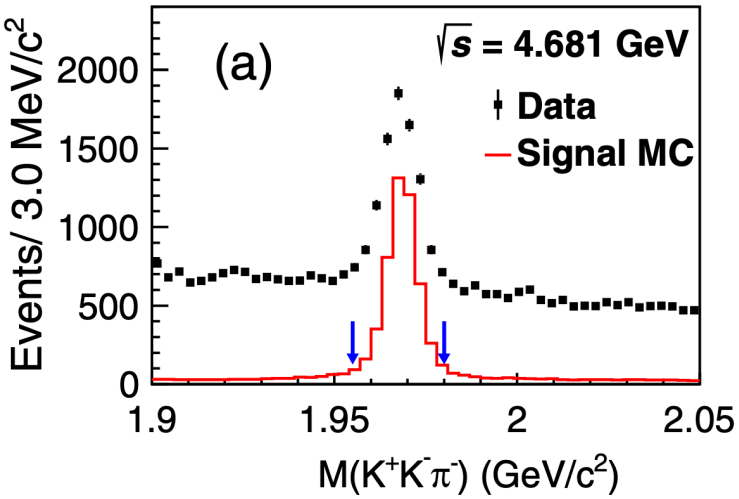


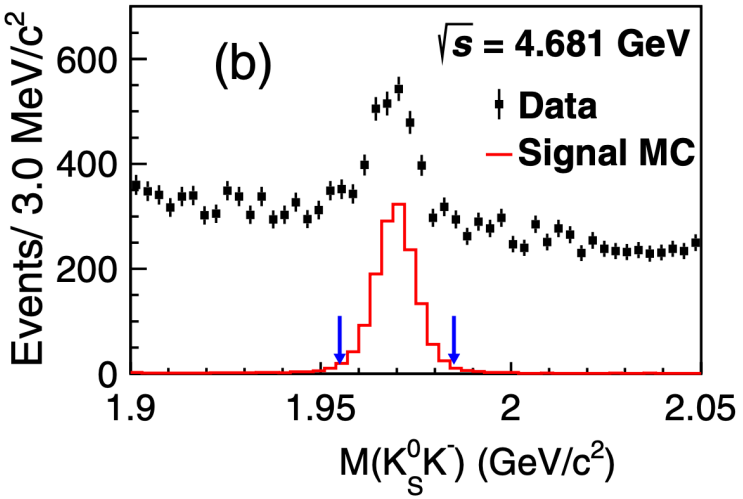
More on exotic charmonium at BESIII in Frank Nerling's talk

Search for strange $c\bar{c}$-like states

Phys. Rev. Lett. 126, 102001 (2021)

- Study $e^+e^- \to K^+ D_s^- D^{*0}, K^+ D_s^{*-} D^0$
  - at cms energies of 4.628, 4.641, 4.661, 4.681, and 4.698 GeV
  - total integrated luminosity: 3.7 / fb (~1.6 / fb at 4.681 GeV)
  - 2/3 of the data recorded at 4.681 GeV was blinded
- Partial event reconstruction: $D_s^- \to K^+K^-\pi^-, K_S^0K^-$ and K^+
- Identify signal in recoil system



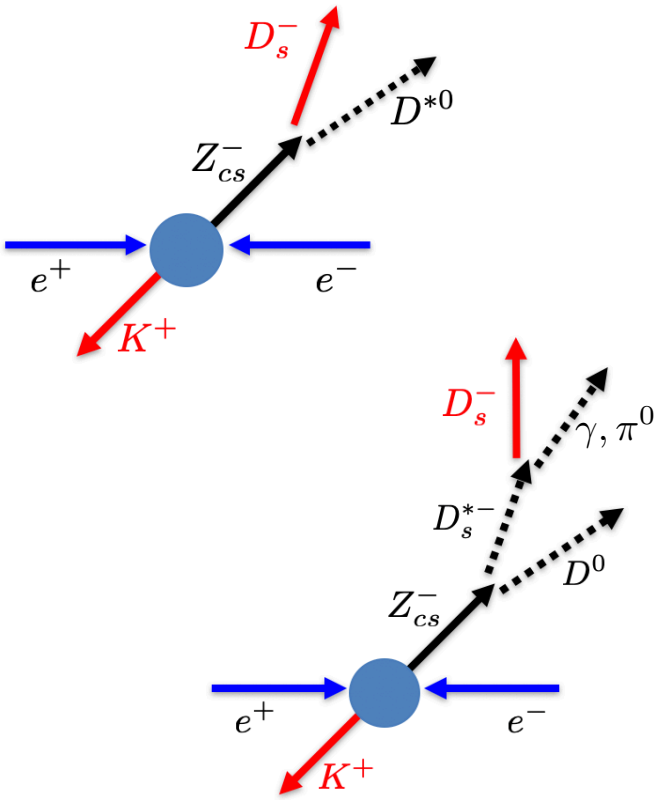


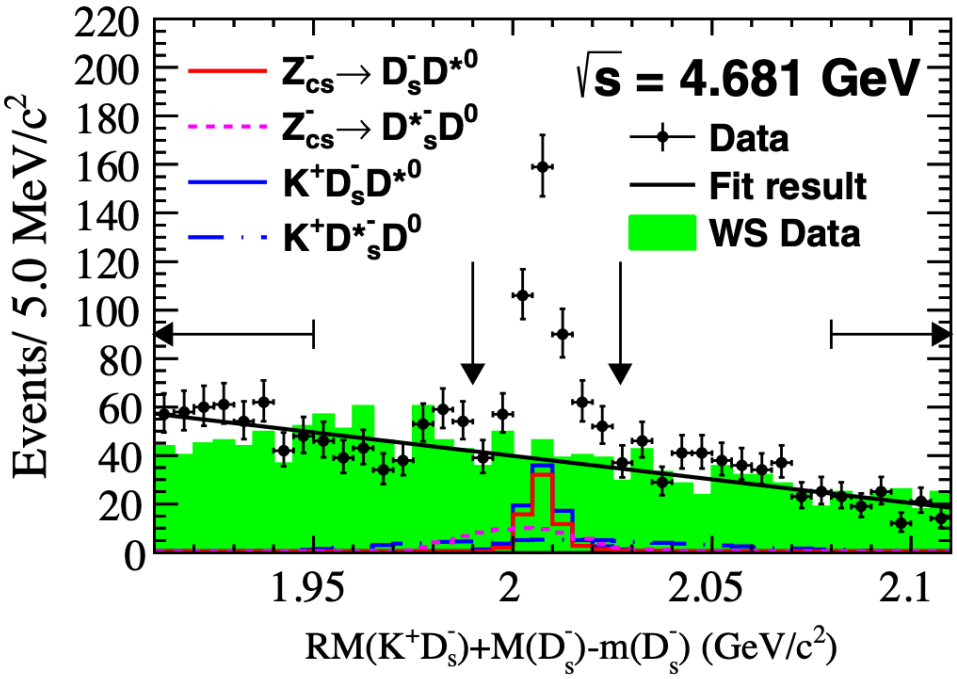
Search for strange $c\bar{c}$-like states

Phys. Rev. Lett. 126, 102001 (2021)

Signal in the recoil mass in the D^{*0} mass region

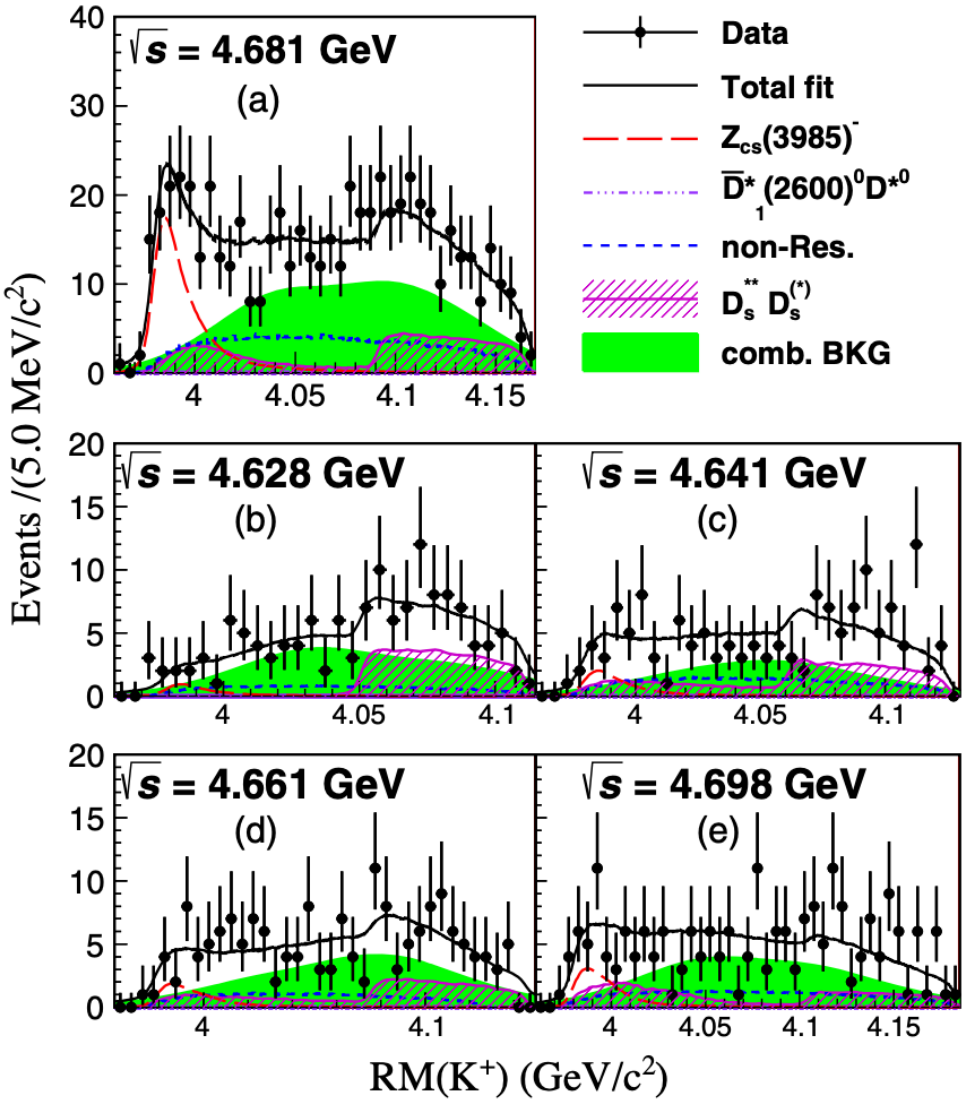
$$e^+e^- \to K^+ D_s^- D^{*0}, K^+ D_s^{*-} D^0$$





First Observation of $Z_{cs}(3985)$

Phys. Rev. Lett. 126, 102001 (2021)



Backgrounds from open charm channels estimated from control data samples

Significant (5.3σ) enhancement at threshold over estimated backgrounds at 4.681 GeV

→ Breit-Wigner parameterization

mass $(3985.2^{+2.1}_{-2.0} \pm 1.7)\ \mathrm{MeV}/c^2$

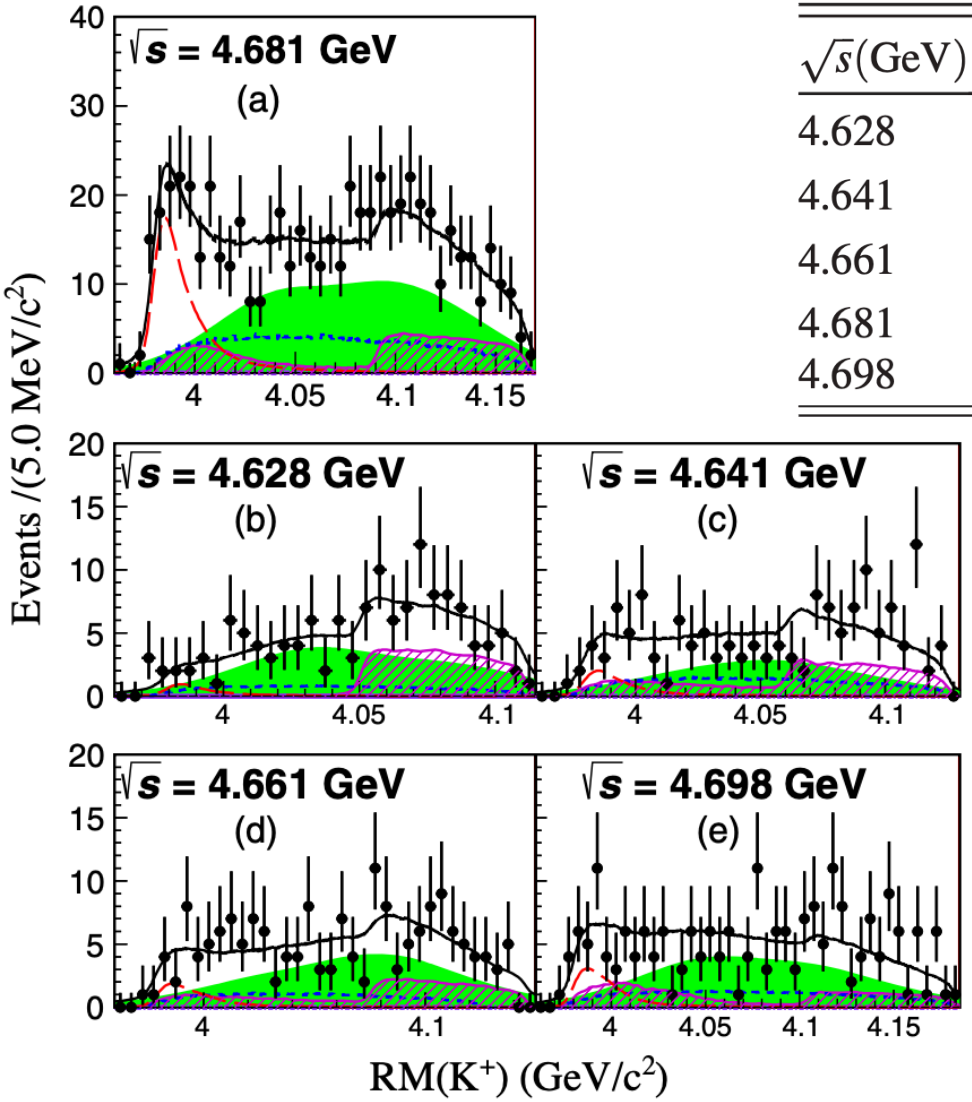
width $(13.8^{+8.1}_{-5.2} \pm 4.9)\ \mathrm{MeV}$

Signals $c\bar{c}s\bar{u}$ quark content of new $Z_{cs}(3985)^-$

Is this connected to the 10x broader $Z_{cs}(4000) \to J/\psi K^+$ observed by LHCb in B decays?

$Z_{cs}(3985)$ Cross Sections

Phys. Rev. Lett. 126, 102001 (2021)



$\sqrt{s}$(GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$n_{\rm sig}$	$\sigma^B \cdot \mathcal{B}$ (pb)
4.628	511.1	$4.2^{+6.1}_{-4.2}$	$0.8^{+1.2}_{-0.8} \pm 0.6 (< 3.0)$
4.641	541.4	$9.3^{+7.3}_{-6.2}$	$1.6^{+1.2}_{-1.1} \pm 1.3 (< 4.4)$
4.661	523.6	$10.6^{+8.9}_{-7.4}$	$1.6^{+1.3}_{-1.1} \pm 0.8 (< 4.0)$
4.681	1643.4	$85.2^{+17.6}_{-15.6}$	$4.4^{+0.9}_{-0.8} \pm 1.4$
4.698	526.2	$17.8^{+8.1}_{-7.2}$	$2.4^{+1.1}_{-1.0} \pm 1.2 (< 4.7)$

Summary

- BESIII is successfully operating since 2008 and is collecting large data samples in electron-positron annihilation for the next years

- Excellent laboratory for hadron spectroscopy, complementary to hadron machines
  - light and charm quark mass region
  - low backgrounds

- Light hadrons: Systematic studies of glueball candidates
  - scalar, tensor states, X(1835), and X(2370)
- Conventional charmonium: new decay modes of η_c and h_c
- Exotic charmonium: further exploration of X, Y, states → Frank Nerling's talk
  - first observation of $Z_{cs}(3985)$ in $e^+e^- \to K^+D_s^-D^{*0}, K^+D_s^{*-}D^0$

- Studies in all areas are ongoing with more exciting results to come

The BESIII Collaboration