Light hadron spectroscopy at BESIII

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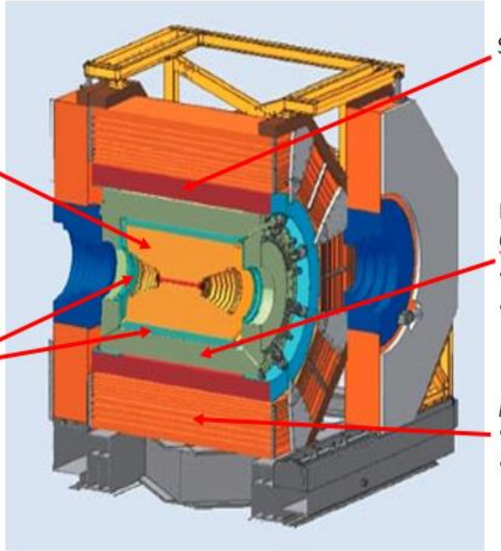
Meson2018

Outline

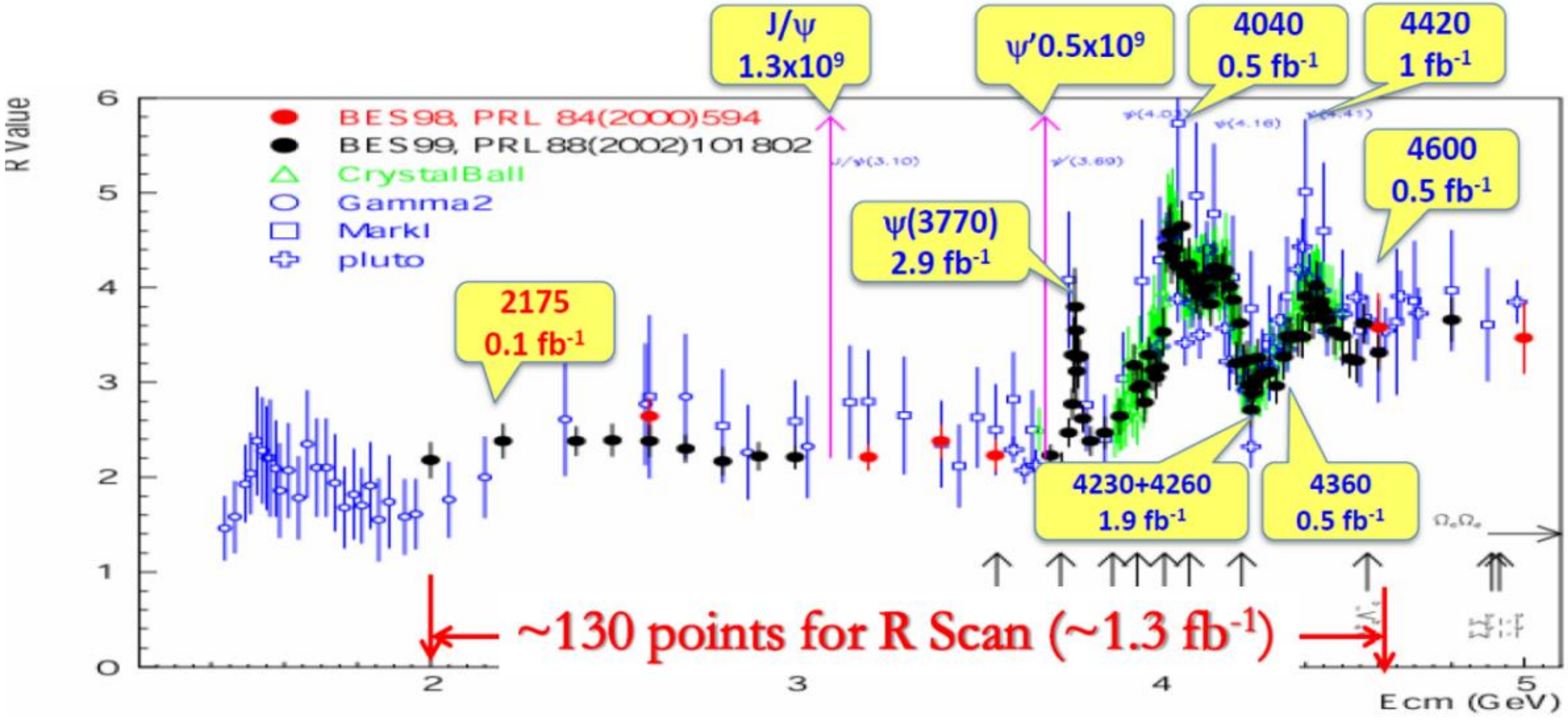
- **BEPCII and BESIII**
- **Gluonic states**
  - Observation of $\eta(1475)$ and X(1835) in $J/\psi \to \gamma\gamma\phi$
  - Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$
- **Strangeonium(like) states**
  - Observation of $e^+e^- \to \eta Y(2175)$ at √s > 3.7 GeV
  - Search for Z_s at 2.125GeV
  - Observation of $h_1(1380)$ in $J/\psi \to \eta' K\bar{K}\pi$
- **Summary**

The BESIII Detector



- 2004:start BEPCII construction
- 2008:test run of BEPCII
- 2009-now:data taking
- Beam energy:1.0-2.3GeV
- Max luminosity: $10^{33} cm^{-2} s^{-1}$ (reached in April 5th,2016)

BESIII data samples



World largest $J/\psi, \psi(3686), \psi(3773), \psi(4160), Y(4260)$, …
Produced directly from e^+e^- annihilation: an ideal factory to study hadron spectroscopy

Light hadron spectroscopy

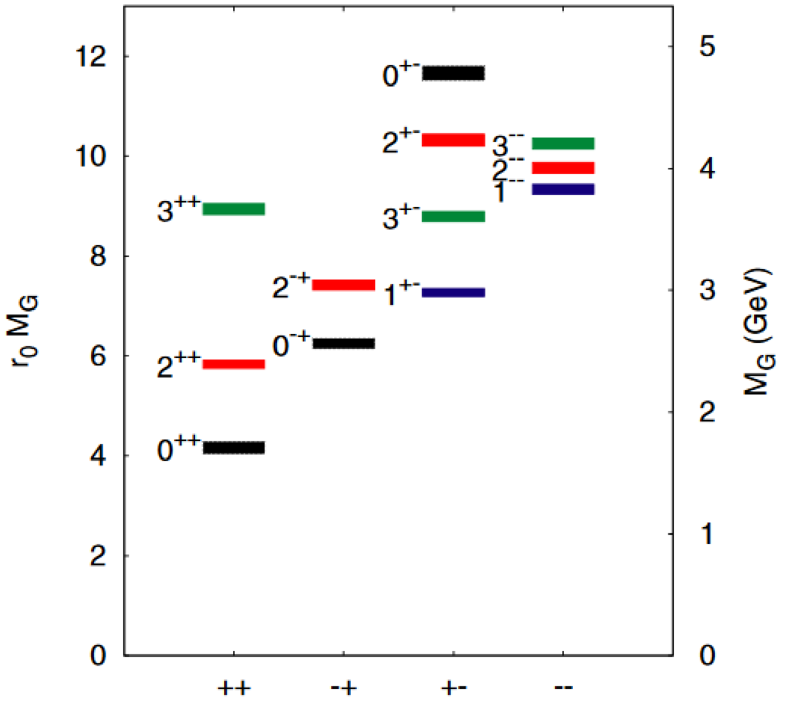
- Conventional hadrons:
  - Meson: $q\bar{q}$
  - Bayron:qqq
- QCD allowed other forms:
  - Multi-quark state : ≥ 4 quarks
  - Glueball :gg, ggg,…
  - Hybrid: $q\bar{q}g, qqqg, \ldots$
- Hadron spectroscopy is a key tool to investigate QCD

Not unambiguously established yet

Glueball search

- **Charmonium radiative decay:**
  An ideal hunting ground for light glueballs:
  - "Gluon-rich" process
  - Clean high statistics data sample
  - $I(J^{pc})$ filter in strong decays of charmonium
- **LQCD:**
  - 0^{++} ground state: 1.5-1.7 GeV/c²
  - 2^{++} ground state: 2.3-2.4 GeV/c²
  - 0^{-+} ground state: 2.3-2.6 GeV/c²
- **Clean environment for searching 0^{-+} glueball:**
  - Only η, η' excitations in quark model

LQCD



Phys. Rev. D73 (2006) 014516

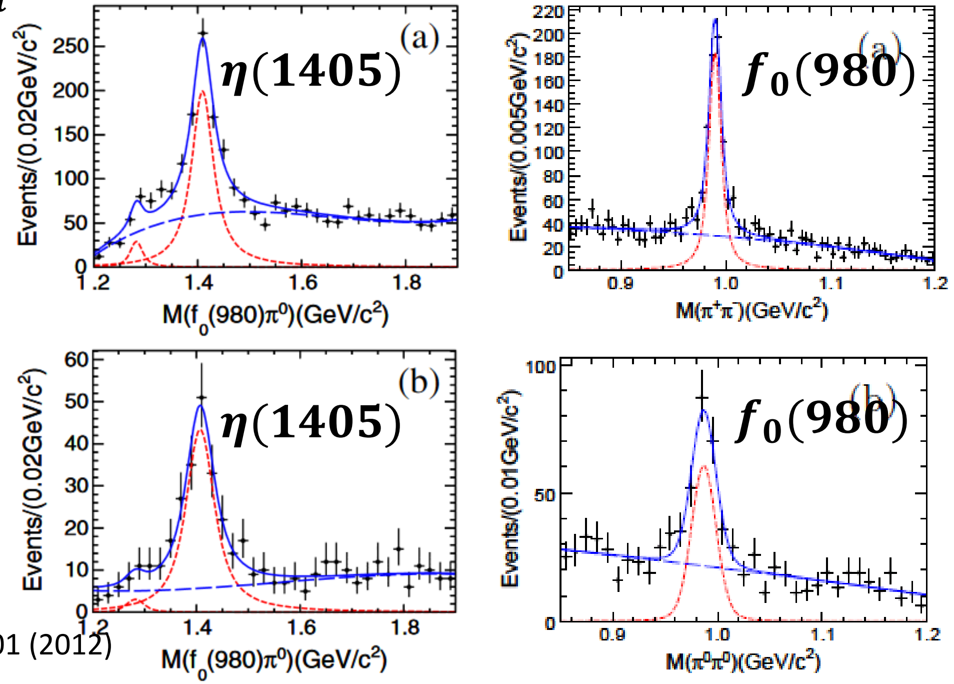
$\eta(1405)/\eta(1475)$ puzzle

- **Mark III reported two pseudoscalar states in the 1400 MeV/c² region in radiative J/ψ decays ($a_0(980)\pi$ and K^*K), confirmed by Crystal Barrel and Obelix**
- **0^{-+} glueball in the fluxtube model: ~1.4 GeV/c²**
  - **No observation by L3 on $\eta(1405)$. Negative results on both states by CLEO**
  - **First observation of $\eta(1405) \to f_0(980)\pi^0$ at BESIII, with narrow $f_0(980)$ and large isospin violation**

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

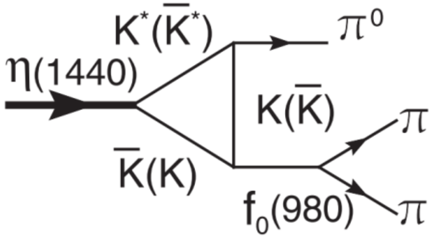
$\pi^+\pi^-$ mode

$\pi^0\pi^0$ mode



PRL 108, 182001 (2012)

- **Triangle Singularity was proposed to explain the anomalies[1]. $\eta(1405)$ and $\eta(1475)$ could be one state appeared as different line shape in different channel**

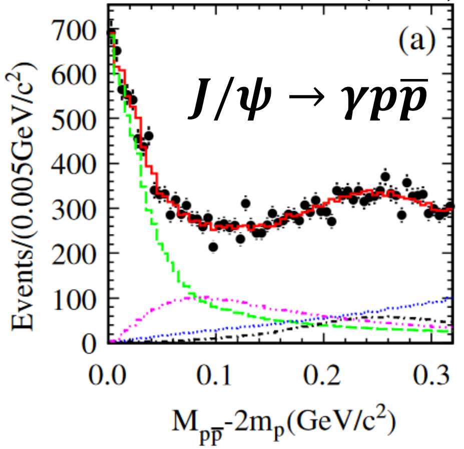


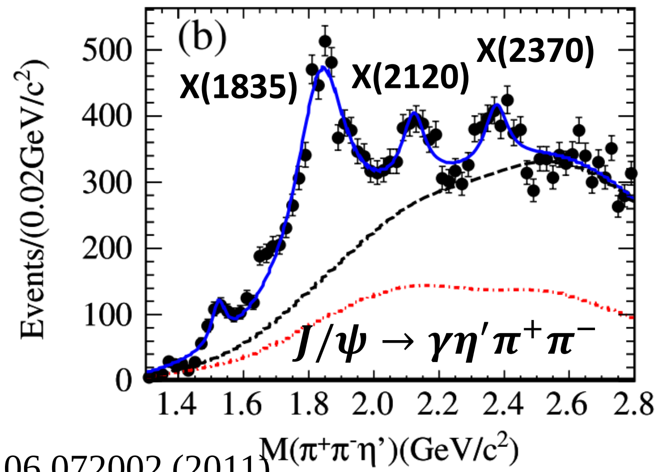
[1]PRL 108, 081803 (2012)

$X(1835)$

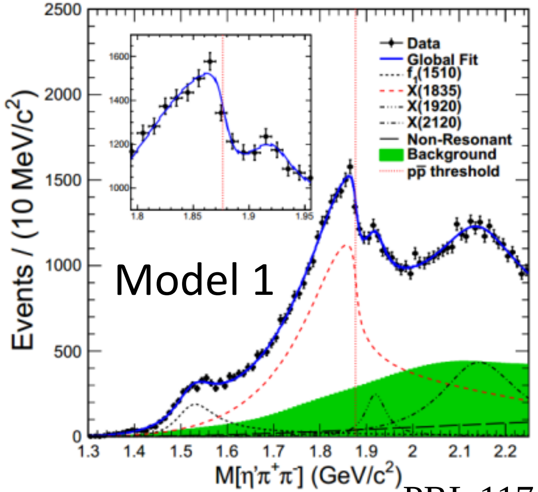
- X($p\bar{p}$) J^{pc} = 0^{-+} : discovered by BESII in $J/\psi \to \gamma p\bar{p}$
- X(1835), X(2120) and X(2370) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$
- X(1835) J^{pc} = 0^{-+} : determined in $J/\psi \to \gamma K_S^0 K_S^0 \eta$
- Anomalous X(1835) line shape in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - One broad state with strong coupling to $p\bar{p}$ (flatte)
  - One narrow state below to the $p\bar{p}$ mass threshold interfering with X(1835)

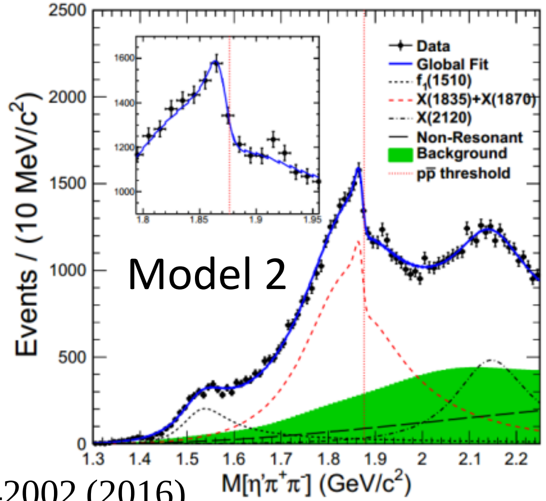
PRL 108,112003 (2012)



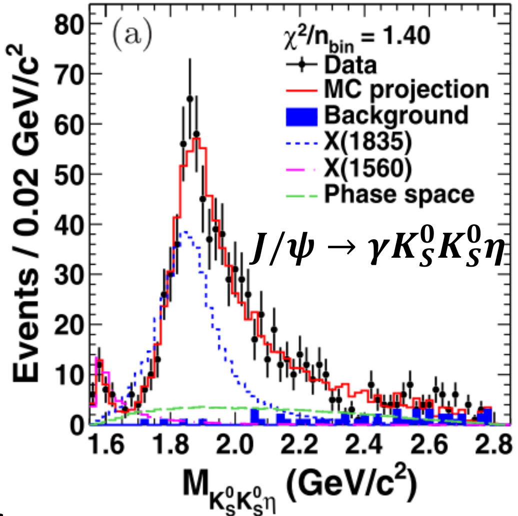


PRL 106,072002 (2011)





PRL 117,042002 (2016)



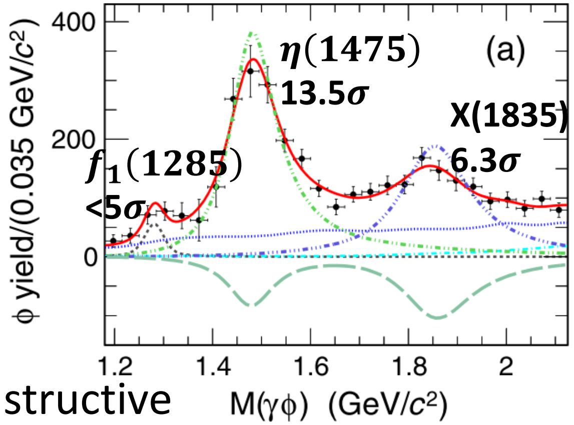
PRL 115,091803 (2015)

- Possible interpretation: $N\bar{N}$ bound state; pseudoscalar glueball; second radial excitation of the η'; η_c-glueball mixture; …

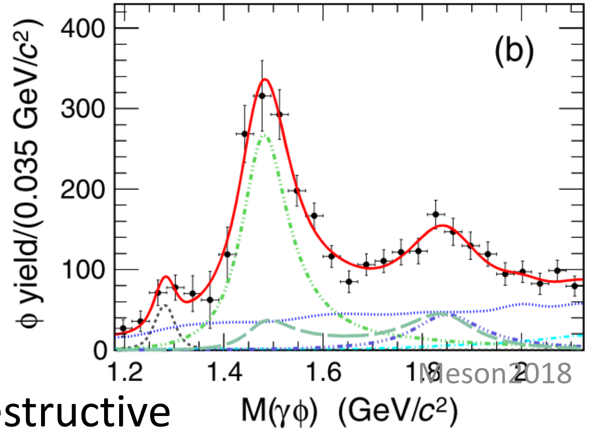
Observation of $\eta(1475)$ and X(1835) in $J/\psi \to \gamma\gamma\phi$

Phys. Rev. D97 (2018) no.5, 051101

- **Two structures observed in the $\mathrm{M}(\gamma\phi)$:**
  - **Angular distribution favored as 0^{-+}**
  - **M and Γ are consistent with $\eta(1475)$ and the X(1835)**
- **Observation of $\eta(1475), \mathrm{X}(1835) \to \gamma\phi$:**
  - **Sizable $s\bar{s}$ component**
  - **One state assumption: Ratio $\frac{\Gamma_{\eta(1405/\eta(1475)\to\gamma\rho)}}{\Gamma_{\eta(1405/\eta(1475)\to\gamma\phi)}}$ is slightly larger than the prediction [1]**
  - **Two states assumption: $\eta(1475)$ could be the radial excitation of the η'**

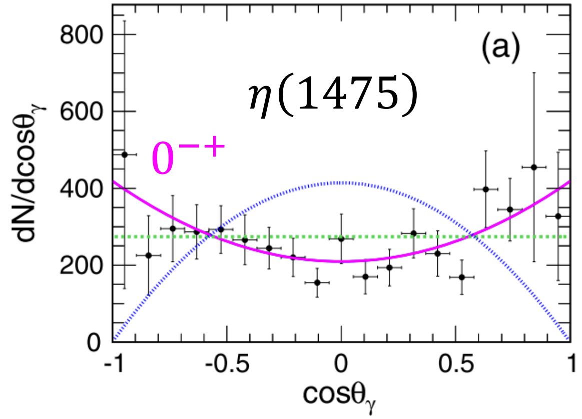


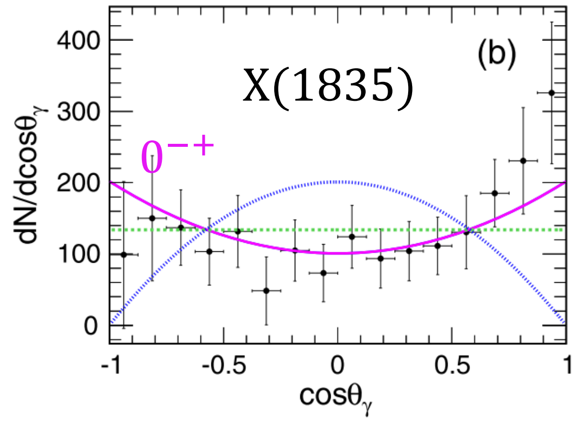
constructive



destructive

- **$\eta(1475)(MeV)$:**
  M=1477 $\pm$ 7 $\pm$ 13
  Γ=118 $\pm$ 22 $\pm$ 17
- **X(1835)(MeV):**
  M=1839 $\pm$ 26 $\pm$ 26
  Γ=175 $\pm$ 57 $\pm$ 25



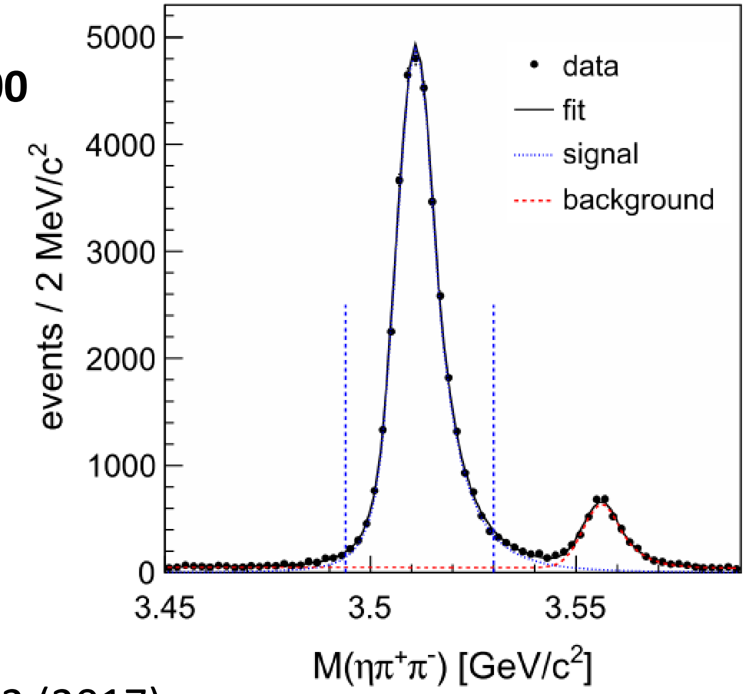


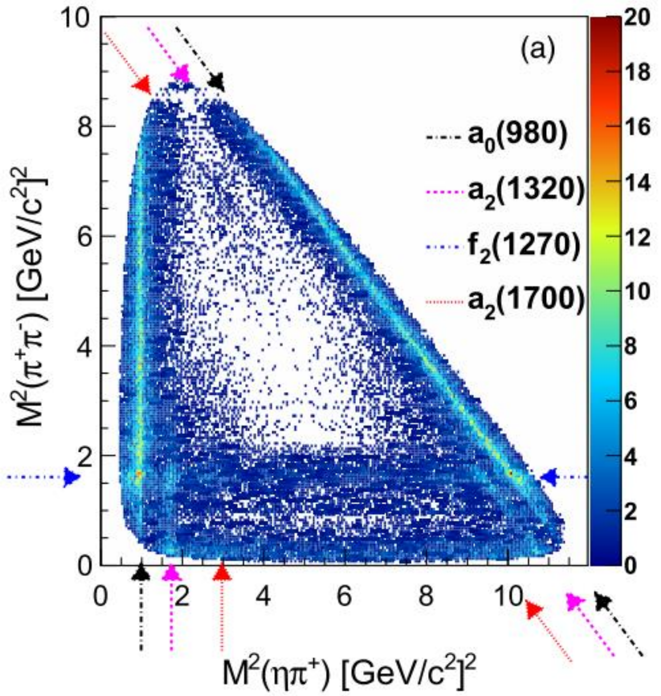
[1]Phys. Rev. D87, 014023 (2013)

Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$ using $\psi(3686) \to \gamma\chi_{c1}$

- **The $\chi_{c1} \to \eta\pi^+\pi^-$ decay is suitable for studying the production of 1^{-+}**
  - $\pi_1(1600)$ studied in χ_{c1} decays by CLEO-c [1]
  - $\pi_1(1400)$ reported only in $\eta\pi$ final states [2,3,4,5]
- **Use 448×10^6 $\psi(3686)$ events**
  - $\psi(3686) \to \gamma\chi_{c1} \to \gamma\eta\pi^+\pi^-$

$N(\chi_{c1})$~35000



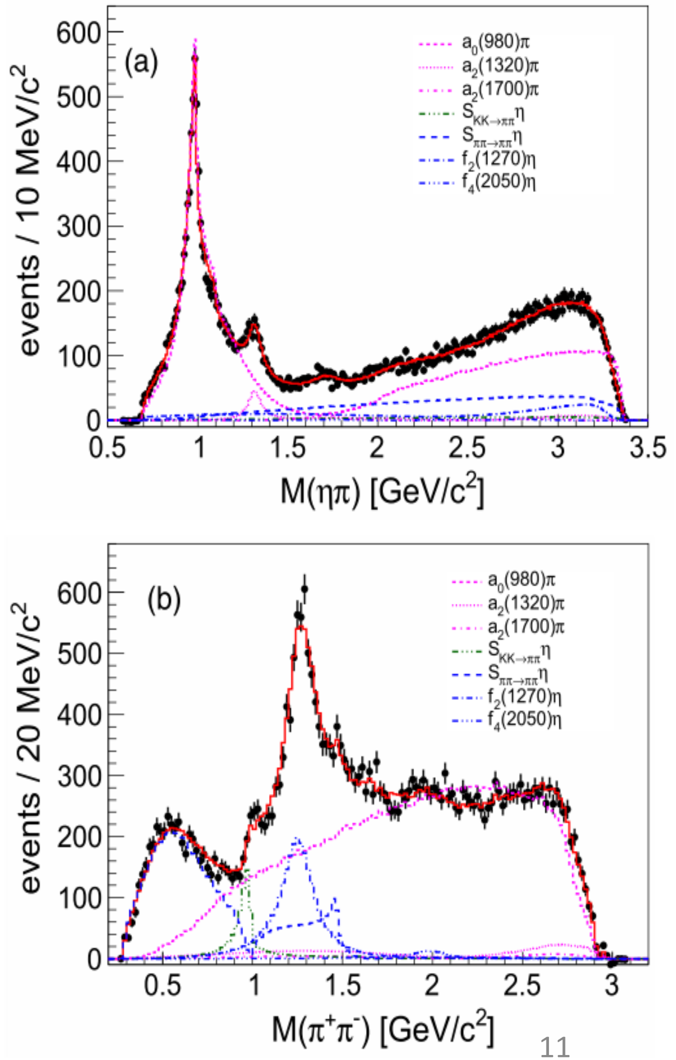


Phys.Rev. D95, 032002 (2017)

[1]Phys.Rev. D84,112009 (2011)
[2] Phys. Lett. B 205, 397 (1988)
[3] Phys. Lett. B 314, 246 (1993)
[4] Phys. Lett. B423, 175 (1998); 446, 349 (1999)
[5] Phys. Lett. B 657, 27 (2007)

Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$ using $\psi(3686) \to \gamma\chi_{c1}$

- **Main dominant contribution is from $a_0(980)\pi$**
- **First observation of $g'_{\eta'\pi} \neq 0$ from $a_0(980) \to \eta\pi$**
- **Observed $\chi_{c1} \to a_2(1700)\pi$ for the first time ($> 17\sigma$)**
- **Measured upper limits for $\pi_1(1^{-+})$ in 1.4-2.0 GeV/c² region**

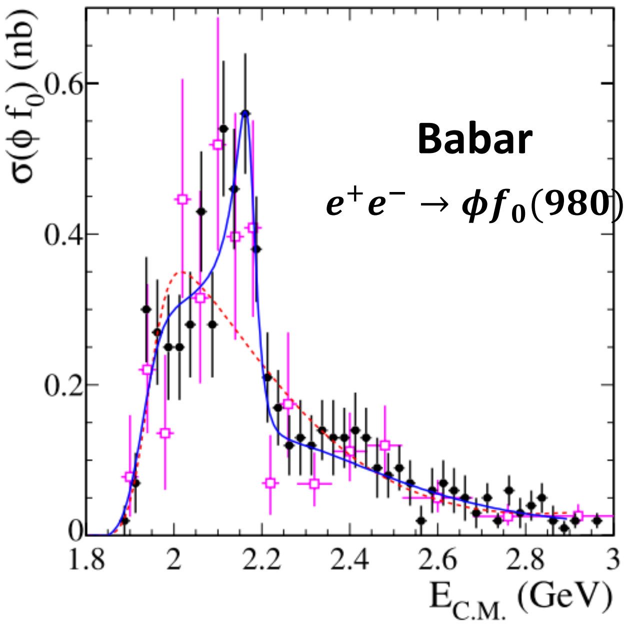


Decay	$\mathcal{F}$ [%]	Significance [σ]	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-)$ [10^{-3}]
$\eta\pi^+\pi^-$	...	...	$4.67 \pm 0.03 \pm 0.23 \pm 0.16$
$a_0(980)^+\pi^-$	$72.8 \pm 0.6 \pm 2.3$	>100	$3.40 \pm 0.03 \pm 0.19 \pm 0.11$
$a_2(1320)^+\pi^-$	$3.8 \pm 0.2 \pm 0.3$	32	$0.18 \pm 0.01 \pm 0.02 \pm 0.01$
$a_2(1700)^+\pi^-$	$1.0 \pm 0.1 \pm 0.1$	20	$0.047 \pm 0.004 \pm 0.006 \pm 0.002$
$S_{K\bar{K}}\eta$	$2.5 \pm 0.2 \pm 0.3$	22	$0.119 \pm 0.007 \pm 0.015 \pm 0.004$
$S_{\pi\pi}\eta$	$16.4 \pm 0.5 \pm 0.7$	>100	$0.76 \pm 0.02 \pm 0.05 \pm 0.03$
$(\pi^+\pi^-)_S\eta$	$17.8 \pm 0.5 \pm 0.6$	...	$0.83 \pm 0.02 \pm 0.05 \pm 0.03$
$f_2(1270)\eta$	$7.8 \pm 0.3 \pm 1.1$	>100	$0.36 \pm 0.01 \pm 0.06 \pm 0.01$
$f_4(2050)\eta$	$0.6 \pm 0.1 \pm 0.2$	9.8	$0.026 \pm 0.004 \pm 0.008 \pm 0.001$
Exotic candidates			U.L. [90% C.L.]
$\pi_1(1400)^+\pi^-$	0.58 ± 0.20	3.5	<0.046
$\pi_1(1600)^+\pi^-$	0.11 ± 0.10	1.3	<0.015
$\pi_1(2015)^+\pi^-$	0.06 ± 0.03	2.6	<0.008

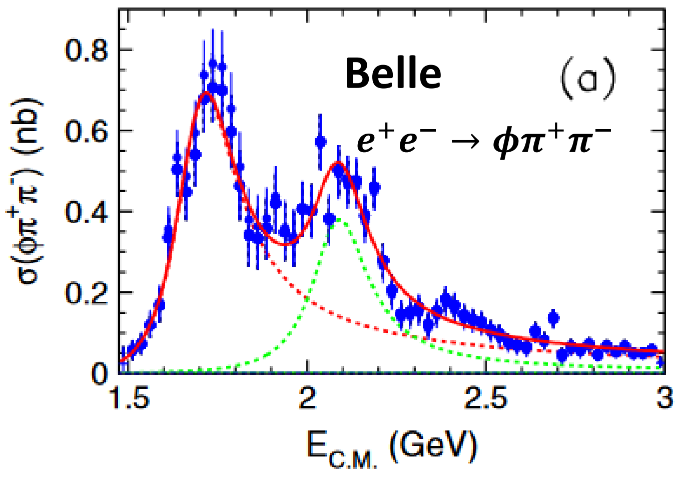
Phys.Rev. D95, 032002 (2017)

Search for strangeonium-like Z_s

- Y(2175) observed by BaBar, confirmed by Belle, BESII and BESIII
  - A candidate for a tetraquark state, a strangeonium hybrid state, or a conventional $s\bar{s}$ state
- Unique place to search for the Zs:
  - Y(2175) is regarded as strangeonium-like state analogied to Y(4260)
  - $Z_c(3900) \rightarrow \pi^{\pm}J/\psi$? $Z_s \rightarrow \pi^{\pm}\phi$

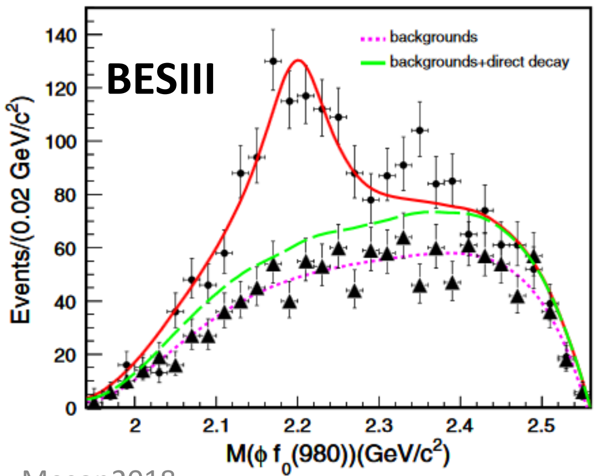


Phys.Rev. D74, 091103(R) (2006)



Phys.Rev. D80, 031101(R) (2009)

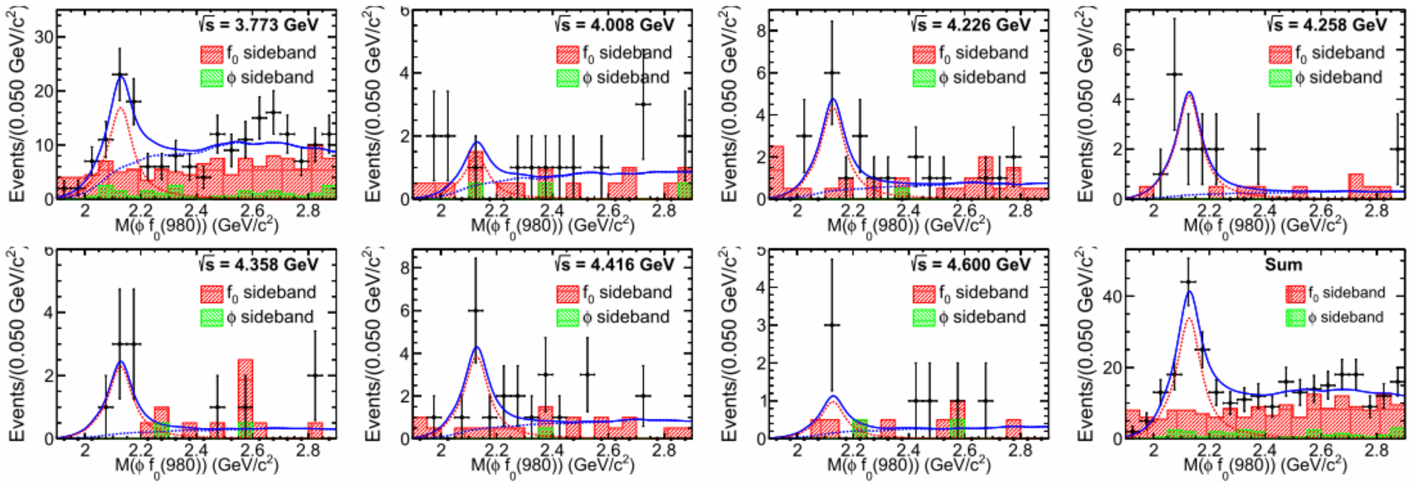
$J/\psi \rightarrow \eta\phi\pi^+\pi^-$



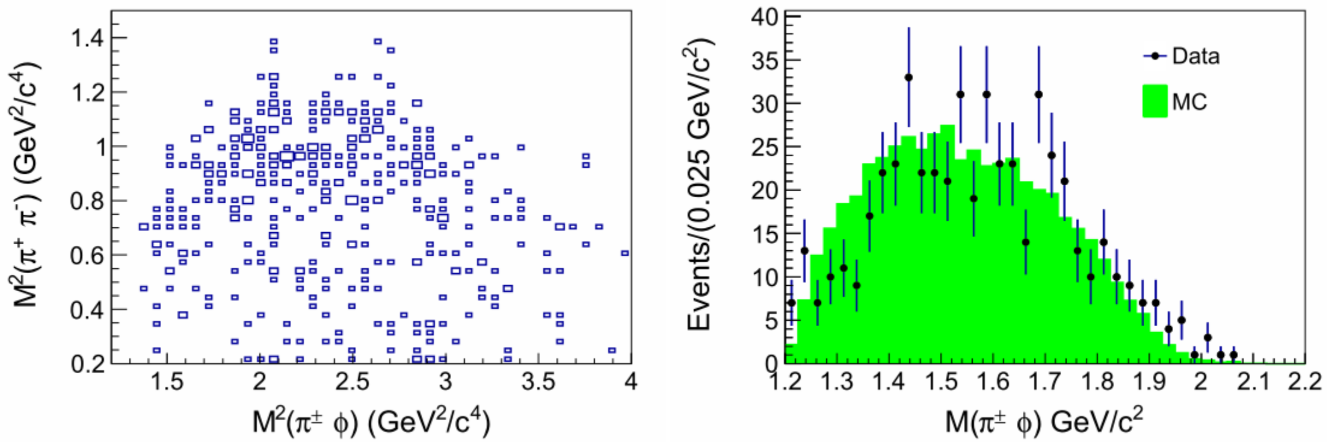
Phys.Rev. D91,052017 (2015)

Observation of $e^+e^- \to \eta Y(2175)$ at √s > 3.7 GeV

- **The joint statistical significance of the Y(2175) is larger than 10σ**



- **No significant Zs signal can be seen in $\phi\pi^\pm$ invariant mass spectrum**



arXiv:1709.04323, Submitted to PRD

Search for Z_s at 2.125GeV

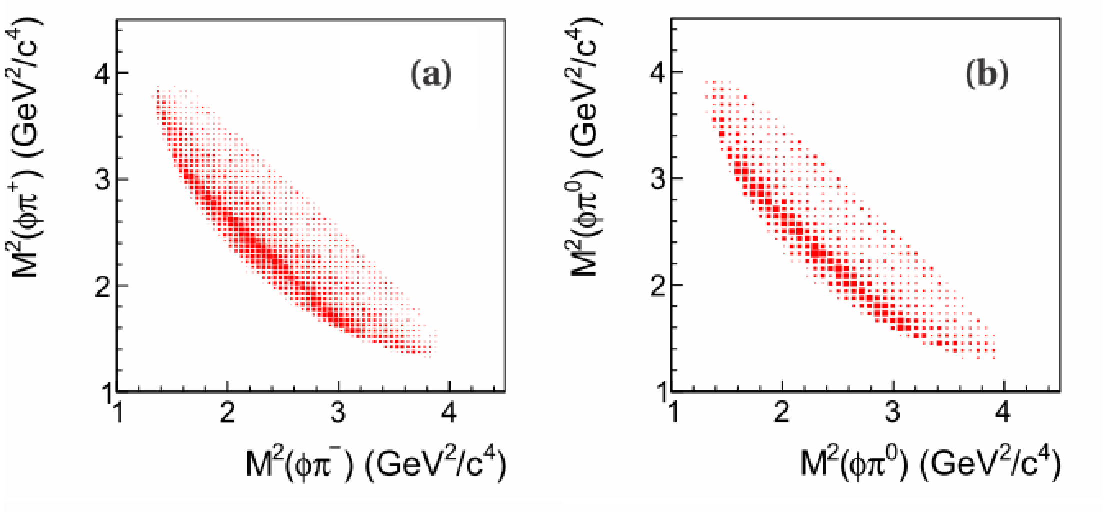
$$e^+e^- \rightarrow \phi\pi^+\pi^-(\phi\pi^0\pi^0)$$

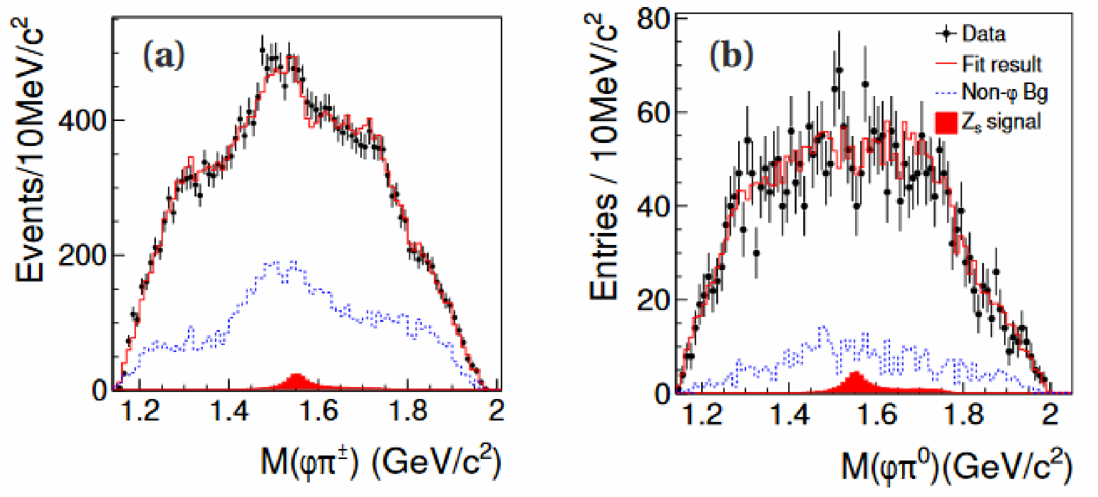
- **108 pb^{-1} e^+e^- collision data collected at collision energy of 2.125GeV**

- **No clear Z_s signal is observed in the φπ mass spectrum around 1.4 GeV/c²**

- **PWA is performed:**
  - $\phi\sigma$
  - $\phi f_0(980)$
  - $\phi f_0(1370)$
  - $\phi f_2(1270)$
  - $Z_s\pi$

Assumption:
$J^P(Z_s)=1^+$
$M(Z_s) = 1.5\mathrm{GeV/c^2}$
$\Gamma(Z_s) = 0.05\mathrm{GeV}$



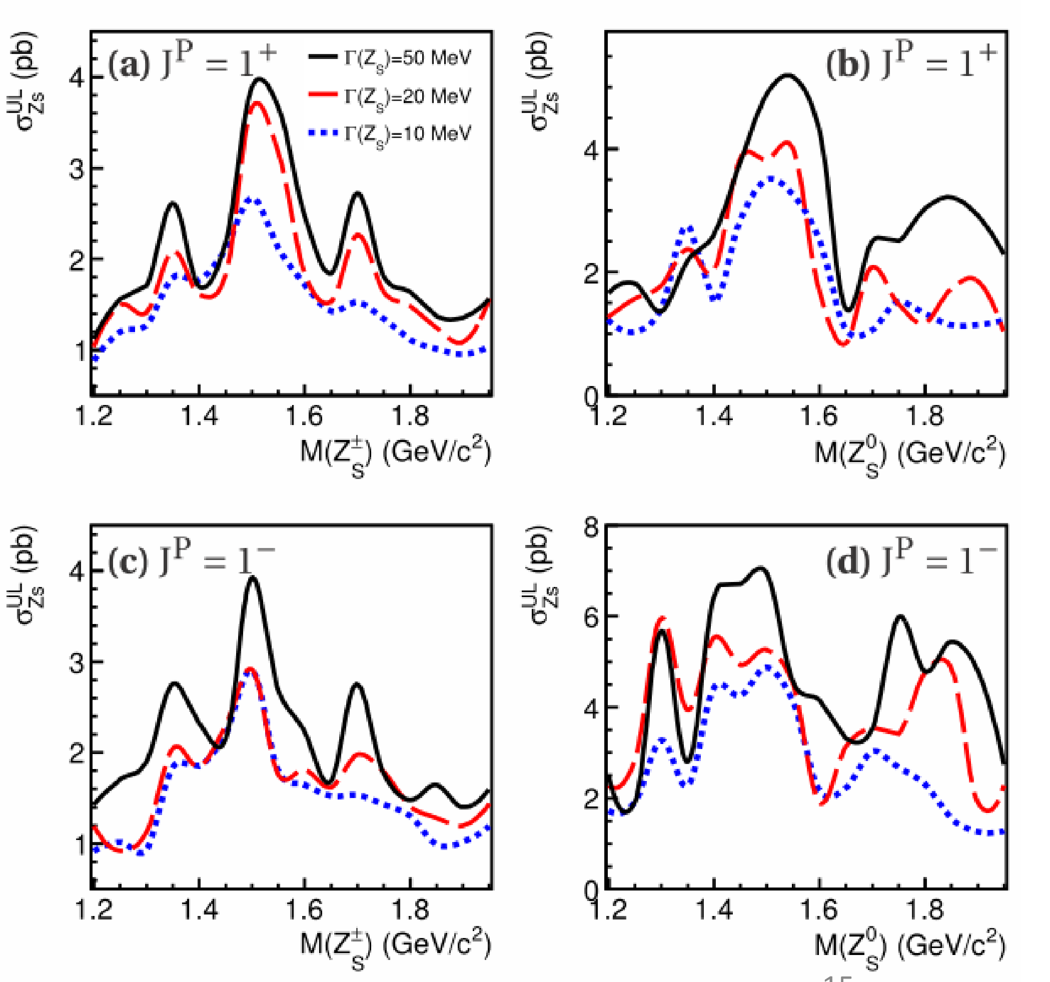


arXiv:1801.10384 , Submitted to PRL

Search for Z_s at 2.125GeV

$$e^+e^- \to \phi\pi^+\pi^-(\phi\pi^0\pi^0)$$

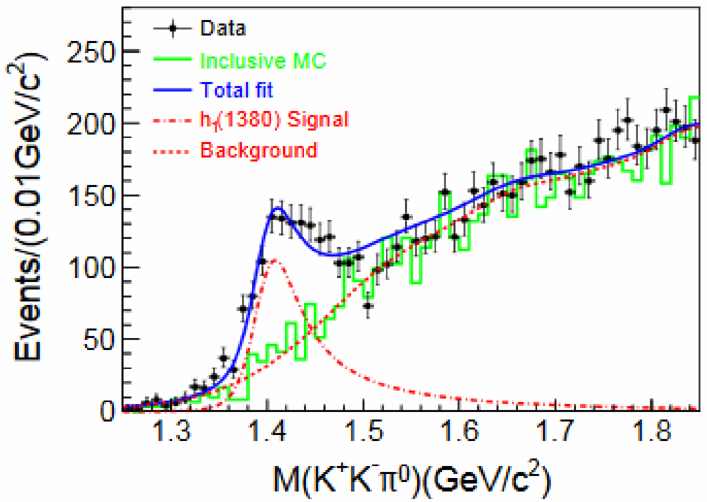
- **Upper limits on the cross sections for Z_s production are determined:**
  - **Different assumptions with M, Γ and J^p of Z_s**
- **In addition, the cross sections of $e^+e^- \to \phi\pi^+\pi^-$ and $e^+e^- \to \phi\pi^0\pi^0$ are measured to be $(343.0 \pm 5.1 \pm 25.1)$pb and $(208.3 \pm 7.6 \pm 13.5)$pb**

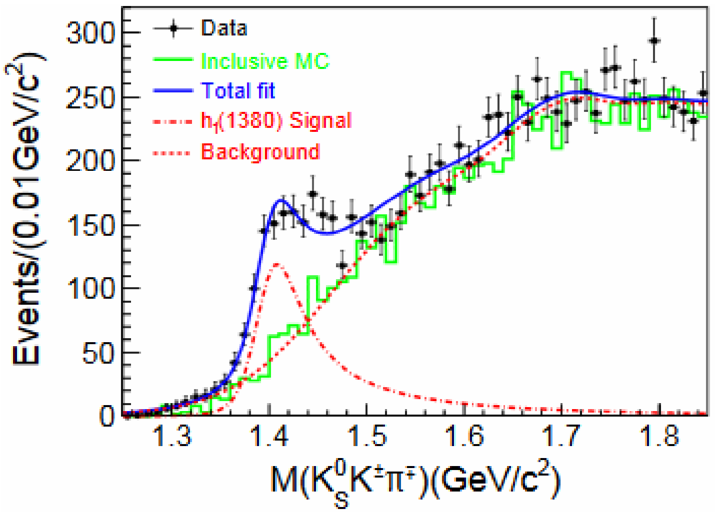


arXiv:1801.10384 , Submitted to PRL

Observation of $h_1(1380)$ in $J/\psi \to \eta' K\bar{K}\pi$

- $h_1(1380)$ observed by LASS and Crystal Barrel
- Simultaneous fit is performed to the $M(K^*(892)\bar{K})$ in $K^+K^-\pi^0$ and $K_S^0K^{\pm}\pi^{\mp}$ modes
- $h_1(1380)$ observed in $J/\psi \to \eta' h_1(1380)$ (>10σ)
- The quark contents of the $h_1(1380)$ is predominantly $s\bar{s}$:
  - mixing angle results between $h_1(1170)$ and $h_1(1380)$: $35.9^{\circ} \pm 2.6^{\circ}$
- The branching fraction:
  - $B(J/\psi \to \eta' h_1(1380) \to \eta' K^*(892)^+ K^- + \text{c.c.}) = (1.51 \pm 0.09 \pm 0.21) \times 10^{-4}$
  - $B(J/\psi \to \eta' h_1(1380) \to \eta' K^*(892)\bar{K} + \text{c.c.}) = (2.16 \pm 0.12 \pm 0.29) \times 10^{-4}$





M=$(1423.2 \pm 2.1 \pm 7.3) MeV/c^2$
Γ=$(90.3 \pm 9.8 \pm 17.5) MeV$

arXiv:1804.05536 , Submitted to PRD

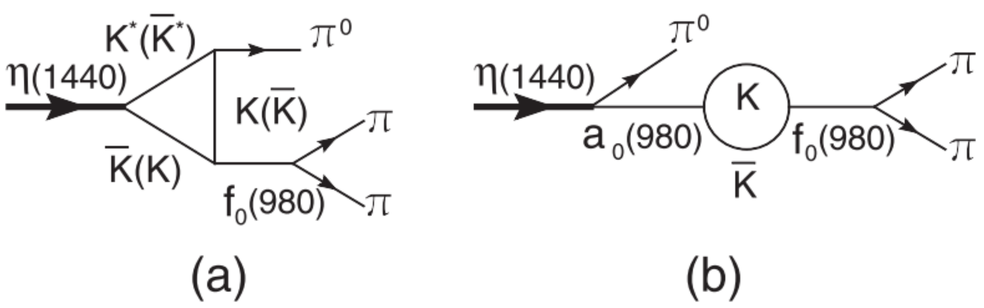
Summary

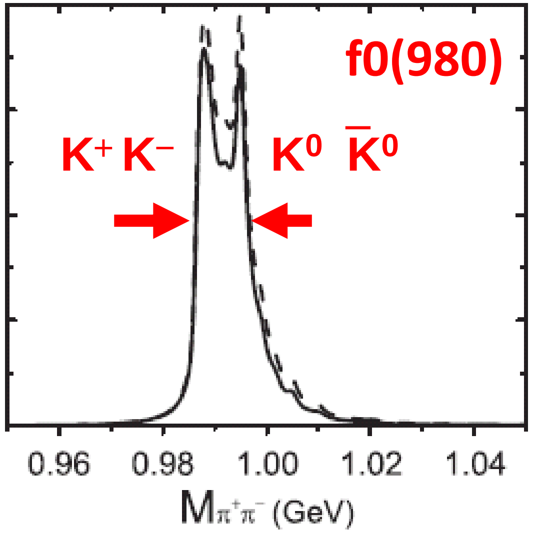
- Highlights of latest results in light hadron spectroscopy from BESIII
  - $\eta(1475)$ and X(1835) in $J/\psi \to \gamma\gamma\phi$
    - Sizable $s\bar{s}$ component
  - Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$
    - Clear evidence for $a_2(1700)$ and no evidence for π_1
  - Observation of $e^+e^- \to \eta Y(2175)$ at √s > 3.7 GeV
    - Significant Y(2175) signal but no evident Z_s
  - Search for Z_s at 2.125GeV
    - No Z_s signal observed, upper limit is given
  - Observation of $h_1(1380)$ in $J/\psi \to \eta' K\bar{K}\pi$
    - Predominantly $s\bar{s}$ component
- BESIII is taking larger J/ψ dataset in 2018, more results are expected in the future

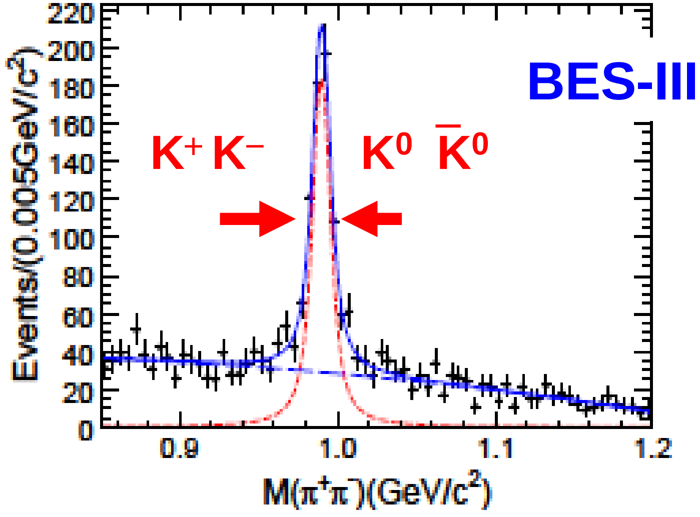
Thanks for your attention!

$\eta(1405)/\eta(1475)$ puzzle

- The contributions from the "Triangle Singularity" mechanism can shift the peak positions in different channels.
- **The intermediate on-shell KK*+c.c. pair can exchange an on-shell kaon and then rescatter to the isospin-violating $f_0(980)\pi$**







$X(1835)$

- X(1835) line shape in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - One broad state with strong coupling to $p\bar{p}$ (flatte)
  - One narrow state below to the $p\bar{p}$ mass threshold interfering with X(1835)

Anomalous line shape of η′π⁺π⁻ near $p\bar{p}$ mass threshold in J/ψ→γη′π⁺π⁻

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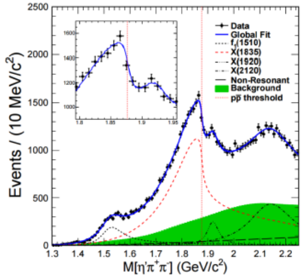
Phys. Rev. Lett. 117, 042002

- Use the Flatté formula for the line shape
  - $T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2 \rho_k}$
  - $\sum_k g_k^2 \rho_k \simeq g_0^2(\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2}\rho_{p\bar{p}})$
  - $g_{p\bar{p}}^2/g_0^2$ is the ratio between the coupling strength to the $p\bar{p}$ channel and the sum of all other channels

The state around 1.85 GeV/c^2	
$\mathcal{M}$ (MeV/c^2)	$1638.0\,^{+121.9}_{-121.9}\,^{+127.8}_{-254.3}$
g_0^2 ((GeV/c^2)^2)	$93.7\,^{+35.4}_{-35.4}\,^{+47.6}_{-43.9}$
$g_{p\bar{p}}^2/g_0^2$	$2.31\,^{+0.37}_{-0.37}\,^{+0.83}_{-0.60}$
M_{pole} (MeV/c^2) *	$1909.5\,^{+15.9}_{-15.9}\,^{+9.4}_{-27.5}$
Γ_{pole} (MeV/c^2) *	$273.5\,^{+21.4}_{-21.4}\,^{+6.1}_{-64.0}$
Branching Ratio	$(3.93\,^{+0.38}_{-0.38}\,^{+0.31}_{-0.84}) \times 10^{-4}$

* The pole nearest to the $p\bar{p}$ mass threshold

A $p\bar{p}$ molecule-like state?



$\log\mathcal{L}$ = 630549.5

Significance of $g_{p\bar{p}}^2/g_0^2$ being non-zero is larger than 7σ

X(1920) is needed with 5.7σ

Anomalous line shape of η′π⁺π⁻ near $p\bar{p}$ mass threshold in J/ψ→γη′π⁺π⁻

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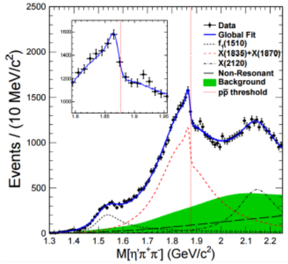
Phys. Rev. Lett. 117, 042002

- Use coherent sum of two Breit-Wigner amplitudes
  - $T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta \cdot e^{i\theta} \cdot \sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$

X(1835)	
M (MeV/c^2)	$1825.3\,^{+2.4}_{-2.4}\,^{+17.3}_{-2.4}$
Γ (MeV/c^2)	$245.2\,^{+14.2}_{-12.6}\,^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01\,^{+0.17}_{-0.17}\,^{+0.26}_{-0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72\,^{+0.21}_{-0.21}\,^{+0.18}_{-0.35}) \times 10^{-4}$

X(1870)	
M (MeV/c^2)	$1870.2\,^{+2.2}_{-2.3}\,^{+2.3}_{-0.7}$
Γ (MeV/c^2)	$13.0\,^{+7.1}_{-5.5}\,^{+2.1}_{-3.8}$
B.R. (constructive interference)	$(2.03\,^{+0.12}_{-0.12}\,^{+0.43}_{-0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57\,^{+0.09}_{-0.09}\,^{+0.49}_{-0.86}) \times 10^{-5}$

A $p\bar{p}$ bound state?



$\log\mathcal{L}$ = 630540.3

Significance of X(1870) is larger than 7σ

X(1920) is not significant

From Min's talk in FPCP

Observation of $\eta(1475)$ and X(1835) in $J/\psi \to \gamma\gamma\phi$

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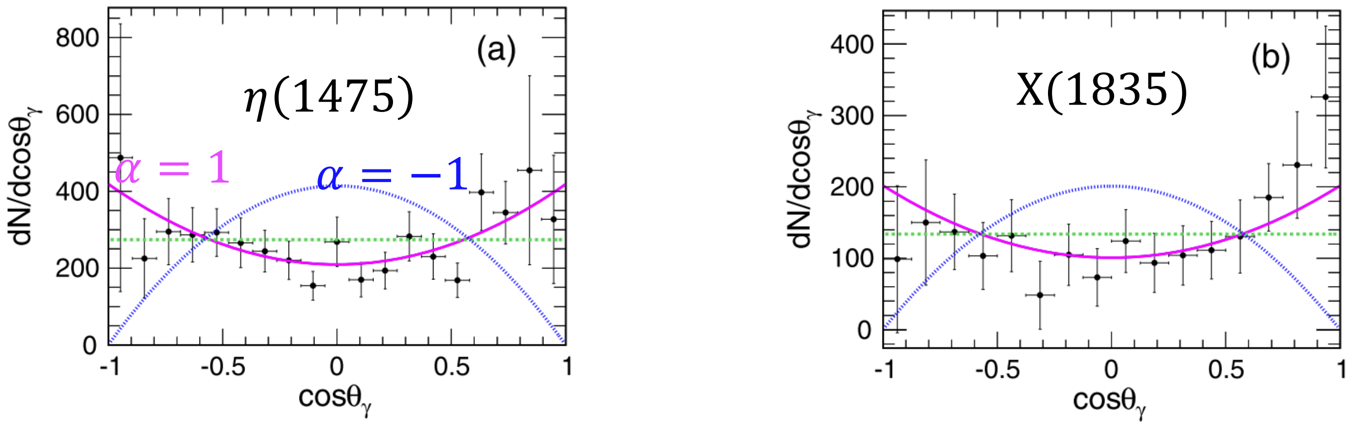
- **Angular distribution : with the assumption with $\alpha = -1, 0, 1$**

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \times cos^2\theta$$



Amplitude Analysis of $\chi_{c1} \to \gamma\eta\pi^+\pi^-$ using $\psi(3686) \to \gamma\chi_{c1}$

- **Parameterization of $a_0(980)$: dispersion relation**

$$D_a(s) = m_0^2 - s - \sum_{ch} \Pi_{ch}(s),$$

$$\mathrm{Im}\Pi_{ch}(s) = g_{ch}^2 \rho_{ch}(s) F_{ch}(s), \qquad \mathrm{Re}\Pi_{ch}(s) = \frac{1}{\pi} P \int_{s_{ch}}^{\infty} \frac{\mathrm{Im}\Pi_{ch}(s')ds'}{(s'-s)}.$$

Phys.Rev. D95, 032002 (2017)

Observation of $h_1(1380)$ in $J/\psi \to \eta' K\bar{K}\pi$

- LASS: PWA in $K\bar{K}\pi$, h1(1380) with 1+- is observed.
- Crystal Barrel: $p\bar{p} \to K_L K_S \pi^0 \pi^0$ PWA
- Theory prediction:
  - M=1468 by meson-mixing models
  - M=1386, 1470, 1499 by quark models.
- Fit:$\Gamma(m)$:mass dependent, q:phase space factor ,convolving with K* mass distribution

$$\left|\frac{\sqrt{m\Gamma(m)}}{m^2 - m_0^2 + i \times m\Gamma(m)}\right|^2 \times q$$

arXiv:1804.05536 , Submitted to PRD