Light meson spectroscopy at BESIII

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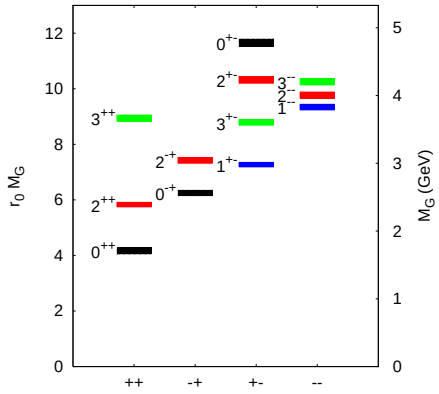
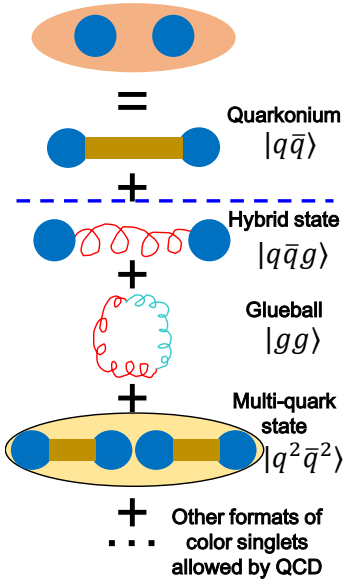
Outline

Glueball

- Light meson spectroscopy
  - Key tool to study/develop QCD in non-perturbative region
- Conventional quark model: Meson($q\bar{q}$), Baryon(qqq)
- Exotic hadronic state predicted by QCD
  - Glueball(gg, $ggg\cdots$)
  - Hybrid state($q\bar{q}g$, $qqqg$)
  - Multi-quark state($N_{q(\bar{q})} \geq 4$)
- Searching for those states helps study gluon field and understand color confinement
- Lattice QCD(LQCD) predicted the glueball spectrum and their quantum numbers

Phys.Rev.D 73 (2006) 014516



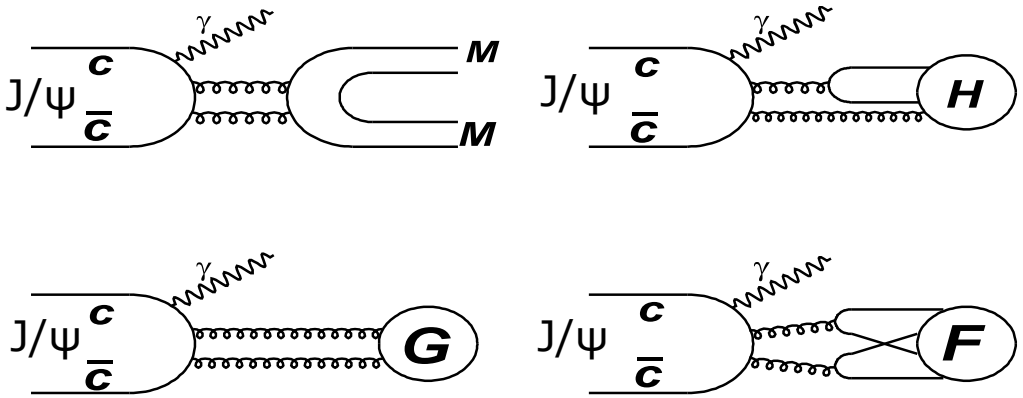


- Glueball with ordinary quantum number can be mixed with nearby $q\bar{q}$ states
  - Systematical study needed in the identification

Glueball

BESIII's advantages

- Gluon-rich process
- Clean, high-statistics data samples directly from e^+e^- collisions
- I, J^{PC} filter



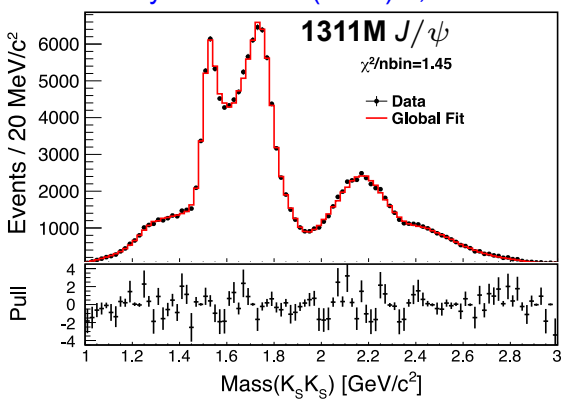
Glueball

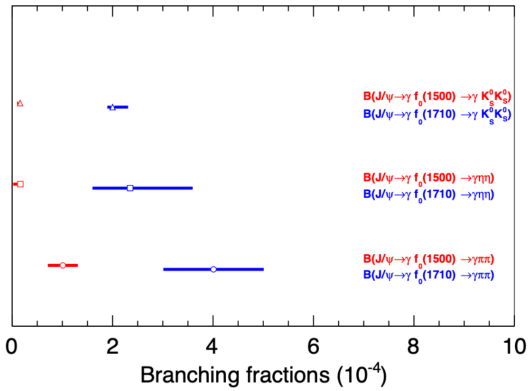
Amplitude analysis of $J/\psi \to \gamma K_S K_S$

LQCD prediction of scalar glueball

- Mass: 1.5∼1.7 GeV [Phys.Rev.D 87 (2013) 9, 092009]
- Production in radiative J/ψ decay: $\mathcal{B}(J/\psi \to \gamma G_{0^+}) = 3.8(9) \times 10^{-3}$ [Phys.Rev.Lett. 110 (2013) 2, 021601]

Phys.Rev.D 98 (2018) 7, 072003





- Dominant amplitudes include the $f_0(1710)$, $f_0(2200)$, $f_2'(1525)$
- $f_0(1710)$ ∼10 times larger production than $f_0(1500)$ in $J/\psi \to \gamma\eta\eta$ [Phys.Rev.D 87 (2013) 9, 092009] and $J/\psi \to \gamma K_S K_S$
  - Measured mass ∼1.7 GeV
  - Production of $f_0(1710)$ in radiative J/ψ decay ($> 1.7 \times 10^{-3}$) close to theoretical prediction of scalar glueball

Glueball

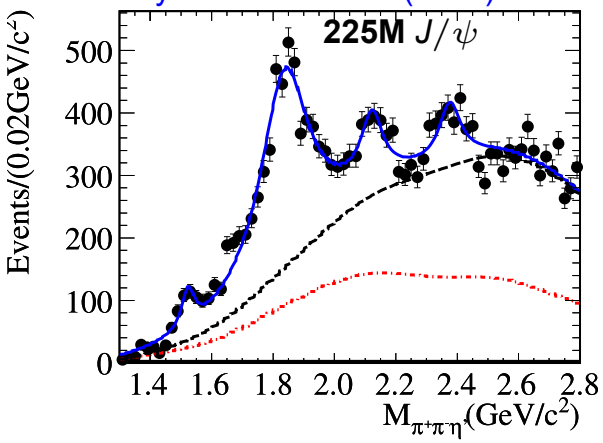
Pseudo-scalar glueball candidate

LQCD prediction of Pseudo-scalar glueball

- Mass: 2.3∼2.6 GeV [Phys.Rev.D 73 (2006) 014516]
- Production in radiative J/ψ decay: $\mathcal{B}(J/\psi \to \gamma G_{0^{-+}}) = 2.31(80) \times 10^{-4}$ [Phys.Rev.D 100 (2019) 5, 054511]

- $X(2370)$ firstly observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$
  - Measured mass: $2376.3 \pm 8.7(\text{stat.})^{+3.2}_{-4.3}(\text{sys.})\ \text{MeV}$
  - Consistent with LQCD prediction to pseudo-scalar glueball

Phys.Rev.Lett. 106 (2011) 072002



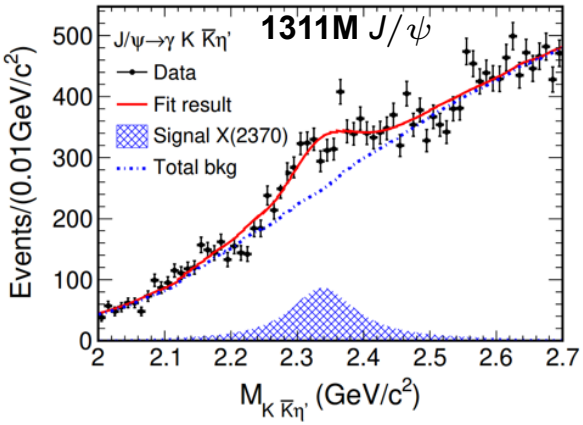
Glueball

Search of $X(2370)$

Chiral effective Lagrangian calculation [Phys.Rev.D 87 (2013) 5, 054036]

- For pseudo-scalar glueball mass of 2.37 GeV,
  $\mathcal{B}(G \to \eta\eta\eta')$, $\mathcal{B}(G \to KK\eta')$, $\mathcal{B}(G \to \pi\pi\eta')$=0.00082, 0.011, 0.090

Eur.Phys.J.C 80 (2020) 8, 746

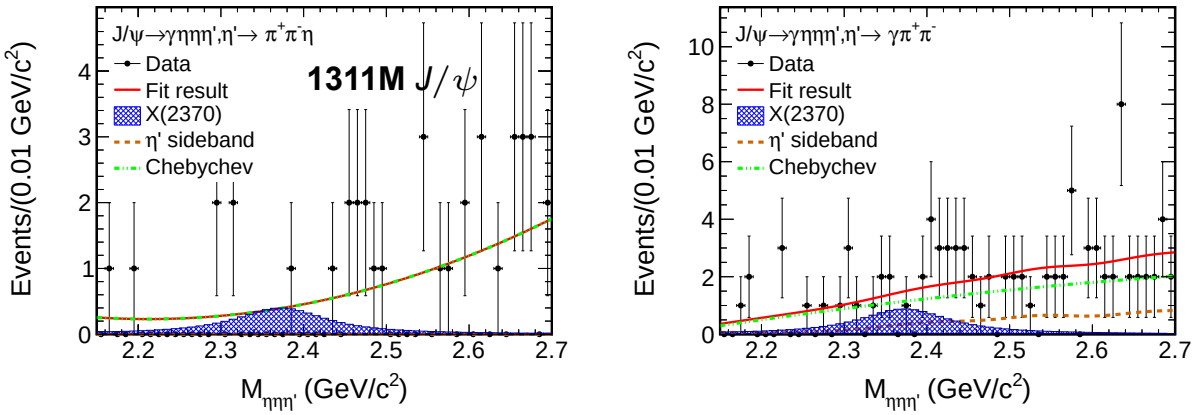


- $X(2370)$ is observed in $J/\psi \to \gamma K\bar{K}\eta'$
  - Measured mass: $2341.6 \pm 6.5(\text{stat.}) \pm 5.7(\text{sys.})$ MeV
  - $\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta')$: $1.79 \pm 0.23(\text{stat.}) \pm 0.65(\text{sys.}) \times 10^{-5}$

Glueball

Search of $X(2370)$

Phys.Rev.D 103 (2021) 1, 012009



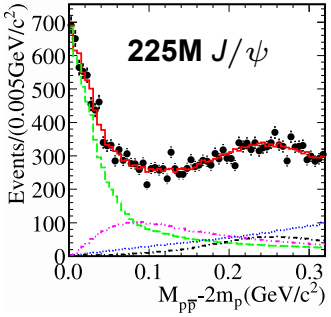
- No $X(2370)$ signal in $J/\psi \to \gamma\eta\eta\eta'$, $\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta')$ $< 9.2 \times 10^{-6}$ at 90% C.L.
  - No contradiction to the calculation for $X(2370)$ as 0^{-+} glueball
- Search $X(2370)$ in more decays with high statistics J/ψ data to determine its J^{PC}

Structure near $p\bar{p}$ threshold

$X(1835)/X(p\bar{p})$

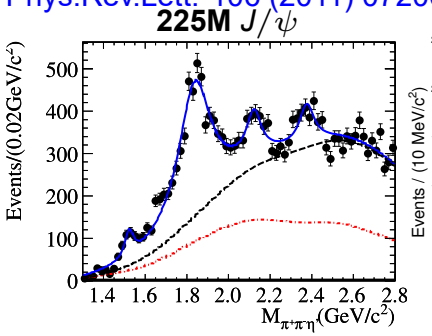
- $X(p\bar{p})$
  - Anomalous strong enhancement structure at $p\bar{p}$ threshold in $J/\psi \to \gamma p\bar{p}$, firstly observed by BES, J^{PC} favor 0^{-+}

Phys.Rev.Lett. 108 (2012) 112003

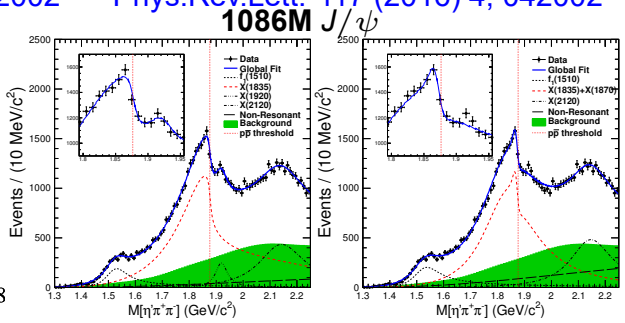


- $X(1835)$
  - Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$(BESII, BESIII), J^{PC} favor 0^{-+}
  - Anomaly line shape near $p\bar{p}$ threshold
  - ? $p\bar{p}$ molecule state or bound state

Phys.Rev.Lett. 106 (2011) 072002



Phys.Rev.Lett. 117 (2016) 4, 042002

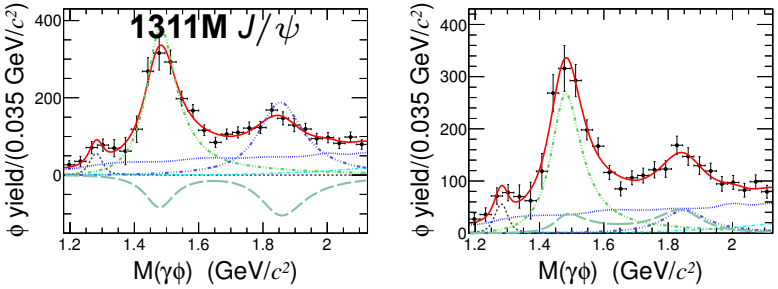


Structure near $p\bar{p}$ threshold

Search of $X(1835)$

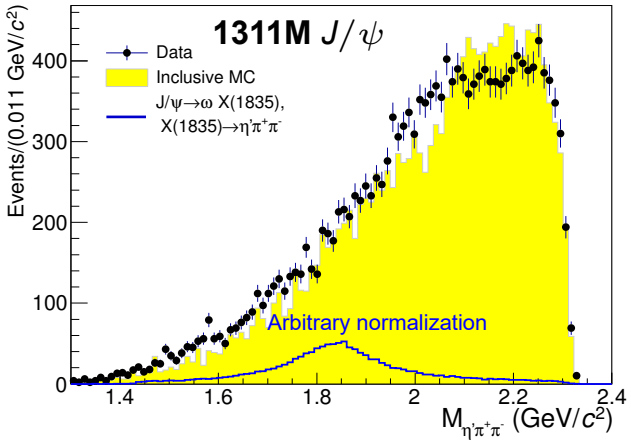
- $J/\psi \to \gamma\gamma\phi$
  - Flavor filter
  - First observation of $\eta(1475)/X(1835) \to \gamma\phi$, J^{PC} favor 0^{-+}
    - Sizable $s\bar{s}$ components
  - $X(1835)$ seems unlikely to be a pure $N\bar{N}$ bound state

Phys.Rev.D 97 (2018) 5, 051101



- $J/\psi \to \omega\pi^+\pi^-\eta'$
  - Provide information on $q\bar{q}$ or gluon component of $X(1835)$
  - No evident signal of $X(1835)$
  - $\mathcal{B}(J/\psi \to \omega X(1835) \to \omega\pi^+\pi^-\eta') < 6.2\times10^{-5}$ at 90% C.L.

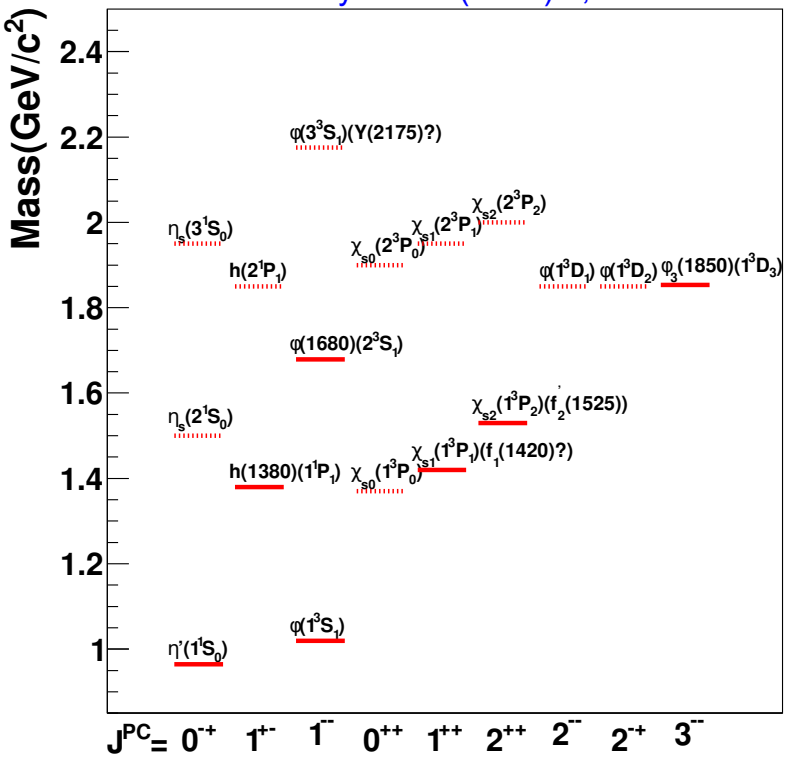
Phys.Rev.D 99 (2019) 7, 071101



Strange quarkonium($s\bar{s}$)

- Strangeonium spectroscopy is not well understood experimentally
  - Only 7 states in the expected spectrum assigned to the observed mesons(marked with red solid lines)
- Study of the strangeonium mesons is of particular interest
  - Bridge between light u, d quark and heavy c, b quark
  - Helps to identify the exotics

Chin.Phys.C 39 (2015) 8, 082001

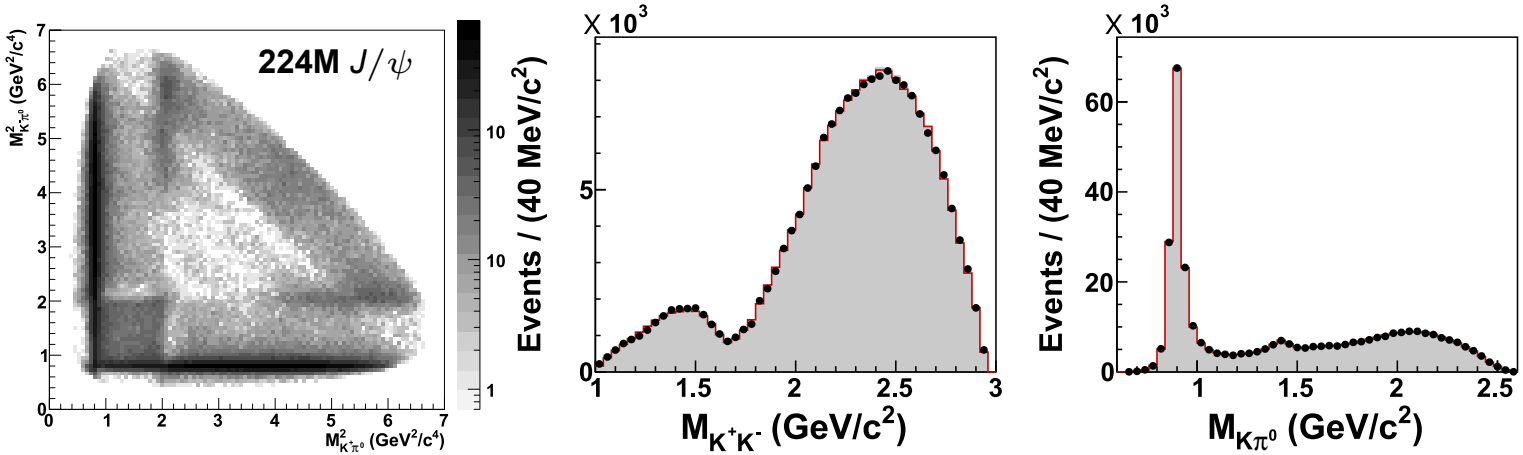


Strange quarkonium($s\bar{s}$)

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

- Reveal signals not observed before due to low statistics [Phys.Rev.Lett. 97 (2006) 142002]
- Precisely determine properties of intermediate states

Phys.Rev.D 100 (2019) 3, 032004



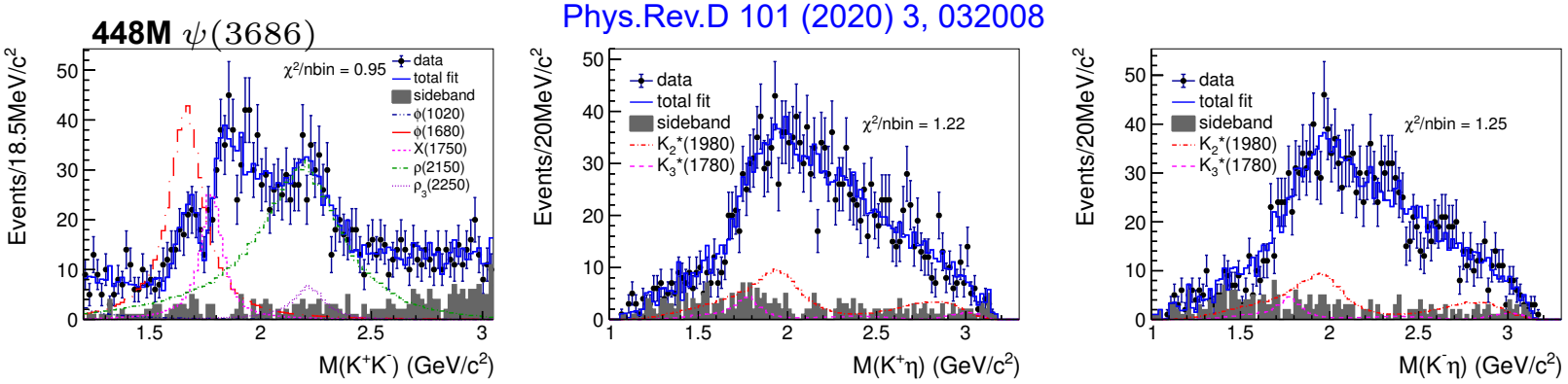
- $K\pi^0$
  - Dominated by $K^*(892)^\pm$
  - Observe $K_2^*(1980)^\pm$ and $K_4^*(2045)^\pm$ for the first time in J/ψ decays
- K^+K^-
  - Two broad 1^{--} structures in K^+K^-
    - Possibly assigned to $\omega(1650)$ and $\rho(2150)$
    - Further studies on $J/\psi \to K_S K\pi$ and $J/\psi \to K^+K^-\eta$ needed

Strange quarkonium($s\bar{s}$)

Partial wave analysis of $\psi(3686) \to K^+K^-\eta$

- Large statistics allows re-examine previous analysis [Phys.Rev.D 86 (2012) 072011] and study of K^* states

Phys.Rev.D 101 (2020) 3, 032008



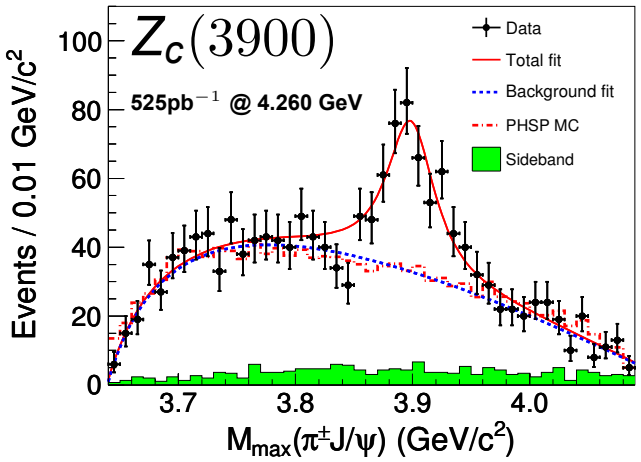
- K^+K^-
  - Observe $\phi(1680)$ and another 1^{--} state, which consistent with $X(1750)$ reported by FOCUS
  - Broad structure around 2.2 GeV contributed from:
    - 1^{--}: $\phi(2170)/\rho(2150)$ or both
    - 3^{--}: $\rho_3(2250)$
  - Difficult to distinguish these excited ρ and ϕ states due to limited statistics
    - Need help from other decays, e.g. $\psi(3686) \to \pi^+\pi^-\eta$
- $K^\pm\eta$
  - Dominated by $K_2^*(1980)^\pm$ and $K_3^*(1780)^\pm$

Strange quarkonium($s\bar{s}$)

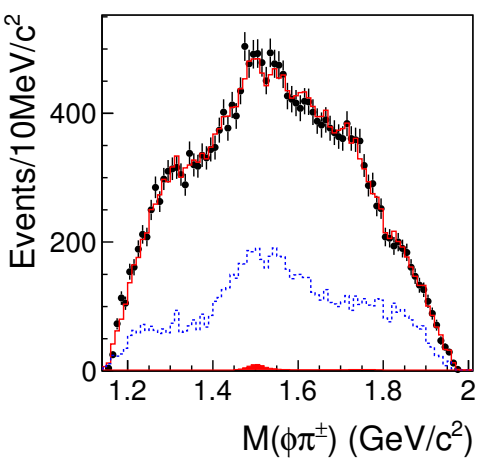
Strangeonium-like Z_s

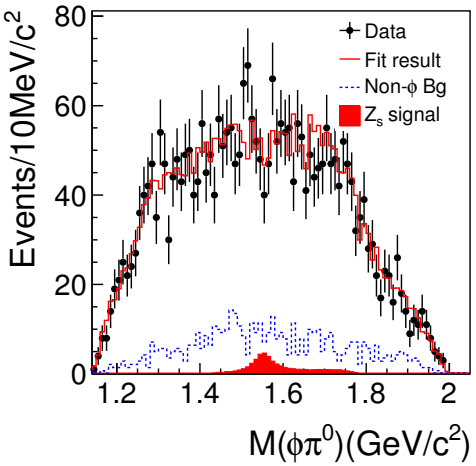
- Replace $c\bar{c}$ with $s\bar{s}$ in Z_c
  - Analogous structure: Z_s
- Search Z_s in $\pi^{\pm}\phi$ around $K^*\bar{K}$ threshold
- Amplitude analysis on $e^+e^- \to \phi\pi\pi$
  - Can be described by $\phi\sigma$, $\phi f_0(980)$, $\phi f_0(1370)$, $\phi f_2(1270)$
  - Upper limit on the cross section of Z_s at 90% C.L. for different mass/width hypotheses determined

Phys.Rev.Lett. 110 (2013) 252001



Phys.Rev.D 99 (2019) 1, 011101





108.49 pb^{-1}@ 2.125 GeV

Summary

- Glueball
  - Production of $f_0(1710)$ ~10 times larger than $f_0(1500)$ in radiative J/ψ decays
    - $f_0(1710)$ largely overlap with scalar glueball
  - $X(2370)$ observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$, $\gamma K\bar{K}\eta'$, and no signal in $J/\psi \to \gamma\eta\eta\eta'$
- Structure near $p\bar{p}$ threshold
  - $\eta(1475)/X(1835)$ observed in $J/\psi \to \gamma\gamma\phi$
  - No $X(1835)$ signal in $J/\psi \to \omega\pi^+\pi^-\eta'$
- Strangeonium
  - $X(1750)$ and possible $\phi(2170)$ observed in $\psi(3686) \to K^+K^-\eta$
  - Two 1^{--} structures, possibly $\omega(1650)$ and $\rho(2150)$, observed in $J/\psi \to K^+K^-\pi^0$
  - Upper limit of Z_s determined in $e^+e^- \to \phi\pi\pi$

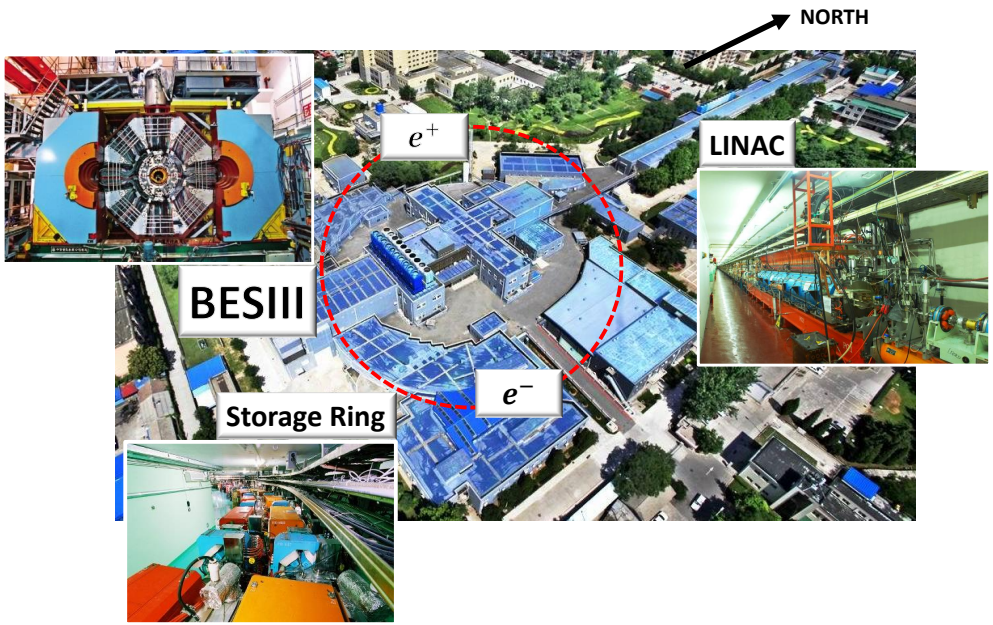
- BESIII already collected $\sim$10B J/ψ, $\sim$3B $\psi(3686)$ and going to run for another 10 years

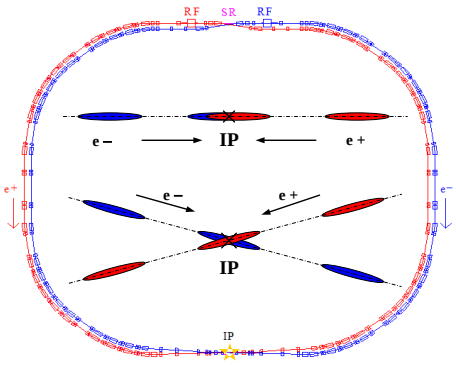
⋆ Using the unprecedented high statistics data, more fascinating results in light meson spectroscopy are expected

谢谢！

BACK UP

Beijing Electron Positron Collider(BEPC)





- Start construction since 1984
- E_{cm}: $2 \sim 4.6$ GeV
  (5.0 GeV since summer 2019)

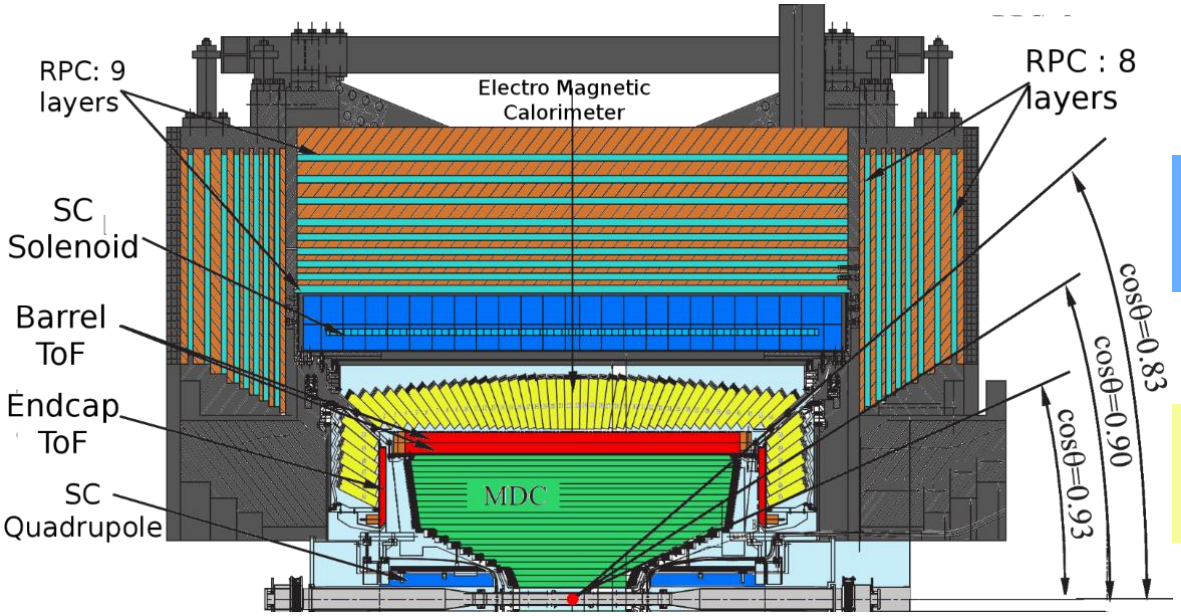
BEPC(1989-2005)

- $L_{\text{peak}} = 1.0 \times 10^{31} (cm^2 \cdot s)^{-1}$

BEPCII(2008-now)

- $L_{\text{peak}} = 1.0 \times 10^{33} (cm^2 \cdot s)^{-1}$
  (April 5, 2016)

BESIII detector



- Super Conducting Solenoid
  - 1.0 T (2009)
  - 0.9 T (2012)

- Electromagnetic Calorimeter
  - CsI(Tl)
  - $\sigma_E/E < 2.5\%$ @ $1GeV$

- Main Drift Chamber
  - σ_{xy}= 120μm
  - $\sigma_p/p < 0.5\%$ @ 1GeV/c
  - Build and replacement of Inner Chamber with CGEM-IT is ongoing

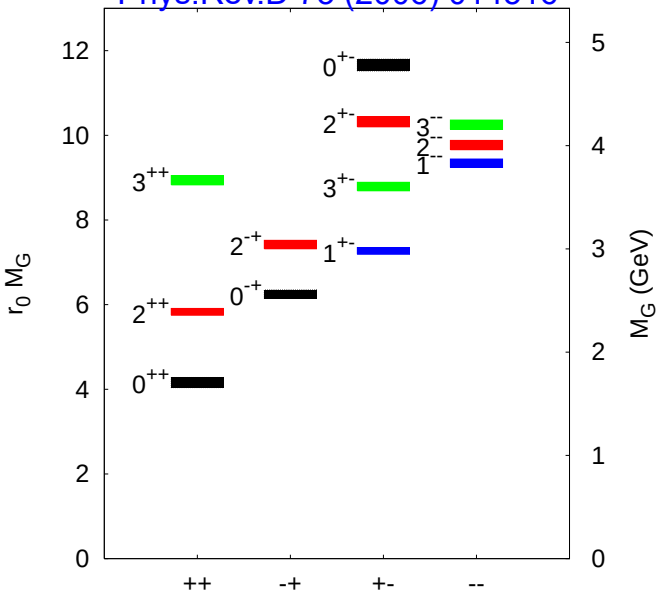
- Time Of Flight
  - σ_T= 70 ps (Barrel)
  - σ_T= 60 ps (End Cap)

Glueball spectrum

Lattice QCD(LQCD) predictions of lightest glueballs

J^{PC}	Mass	$\mathcal{B}(J/\psi \to \gamma G)$
0^{++}	1.5~1.7 GeV	$3.8(9) \times 10^{-3}$ [Phys.Rev.Lett. 110 (2013) 2, 021601]
2^{++}	2.3~2.4 GeV	$1.1(2)(1) \times 10^{-2}$ [Phys.Rev.Lett. 111 (2013) 9, 091601]
0^{-+}	2.3~2.6 GeV	$2.31(80) \times 10^{-4}$ [Phys.Rev.D 100 (2019) 5, 054511]

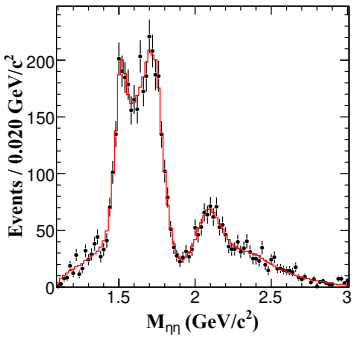
Phys.Rev.D 73 (2006) 014516



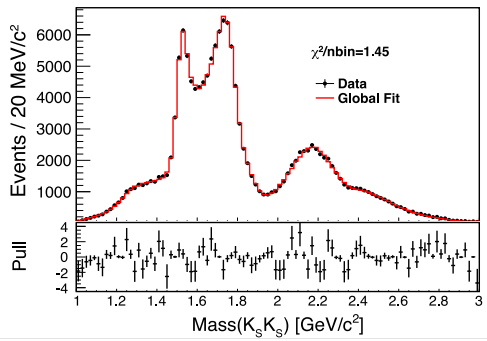
- Those states with ordinary quantum number can be mixed with nearby $q\bar{q}$ states
  - Systematical study needed in the identification

Scalar glueball candidate

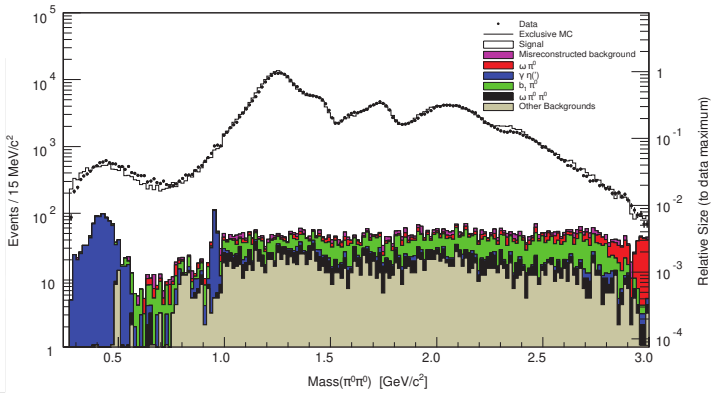
Phys.Rev.D 87 (2013) 9, 092009



Phys.Rev.D 98 (2018) 7, 072003



Phys.Rev.D 92 (2015) 5, 052003



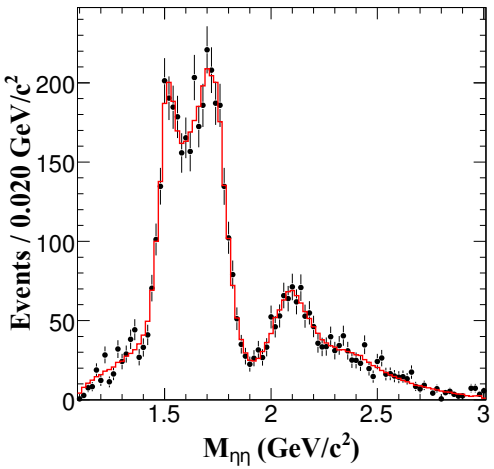
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

Resonance	M (MeV/c^2)	$M_{\rm PDG}$ (MeV/c^2)	Γ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$\cdots$	$349 \pm 18^{+23}_{-1}$	$\cdots$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

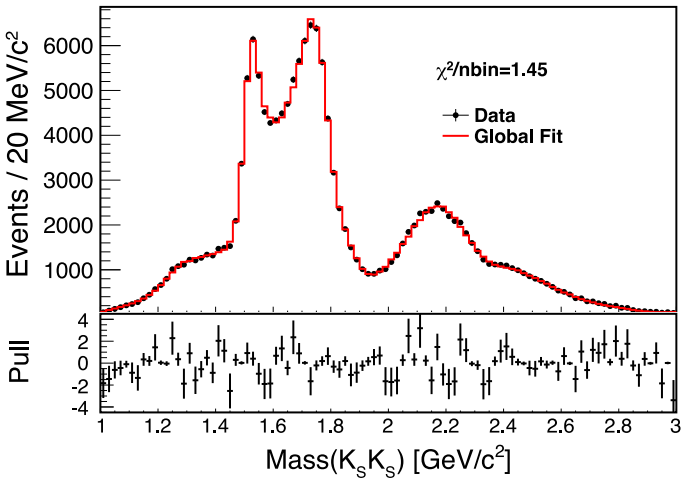
- $f_0(1710)$ ~10 times larger production than $f_0(1500)$ in $J/\psi \to \gamma\eta\eta,\ \gamma K_S K_S$
  - Production of $f_0(1710)$ in radiative J/ψ decay ($> 1.7 \times 10^{-3}$) close to theoretical prediction of scalar glueball (3.8×10^{-3})
- Broad scalar contribution $\sim$2.1 GeV observed in $J/\psi \to \gamma\eta\eta,\ \gamma K_S K_S$, also seen in $J/\psi \to \gamma\pi^0\pi^0$

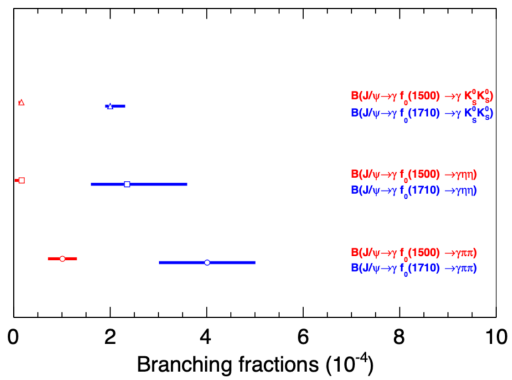
Scalar glueball candidate

Phys.Rev.D 87 (2013) 9, 092009



Phys.Rev.D 98 (2018) 7, 072003



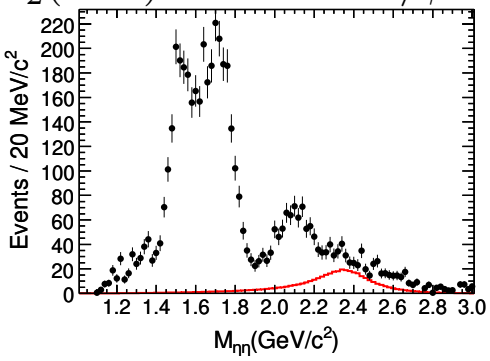


LQCD prediction	Experimental results
Mass: 1.5∼1.7 GeV $\mathcal{B}(J/\psi \to \gamma G_{0+})$= $3.9(9) \times 10^{-3}$	$\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$ $\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0 \pm 1.0) \times 10^{-4}$ $\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1 \pm 1.0) \times 10^{-4}$ $\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$ $\Longrightarrow \mathcal{B}(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$
$f_0(1710)$ largely overlapped with scalar glueball	

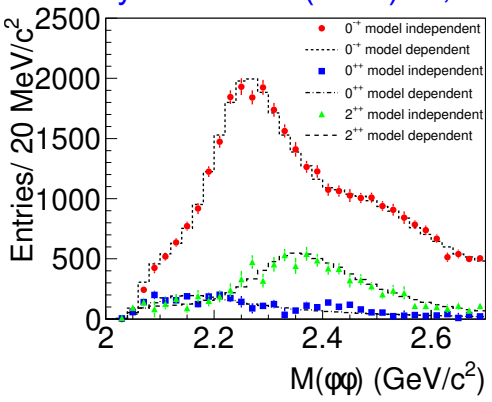
Tensor glueball candidate

Phys.Rev.D 87 (2013) 9, 092009

$f_2(2340)$ contribution in $J/\psi \to \gamma\eta\eta$



Phys.Rev.D 93 (2016) 11, 112011



Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

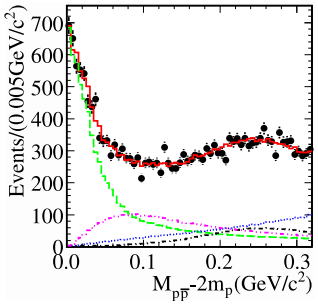
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

- $f_2(2340)$: a good tensor glueball candidate
  - largely produced in $J/\psi \to \gamma\eta\eta,\ \gamma\phi\phi$, significant tensor contribution $\sim$2.4 GeV also seen in $J/\psi \to \gamma\pi^0\pi^0,\ \gamma K_S K_S$
  - Measured mass close to LQCD prediction of tensor glueball(2.3$\sim$2.4 GeV)
- Production of $f_2(2340)$ in radiative J/ψ decay is much lower than LQCD prediction(1.1×10^{-2})
  - More measurements needed

$X(1835)/X(p\bar{p})$

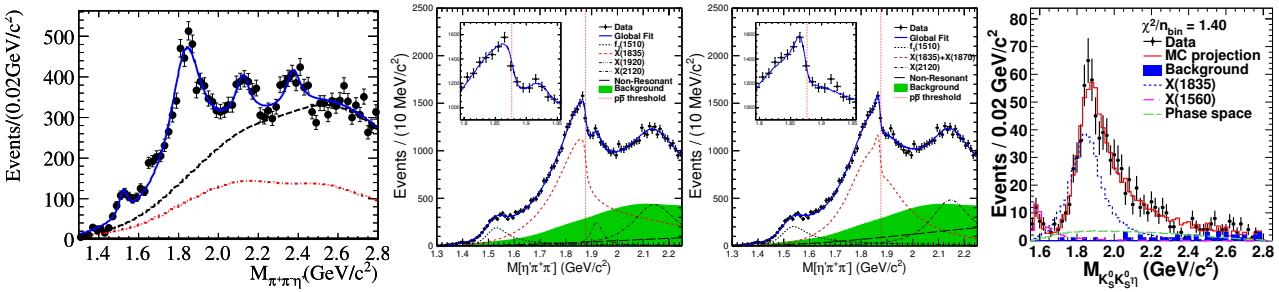
- $X(p\bar{p})$
  - Anomalous strong enhancement structure at $p\bar{p}$ threshold in $J/\psi \to \gamma p\bar{p}$, firstly observed by BES, J^{PC} favor 0^{-+})

Phys.Rev.Lett. 108 (2012) 112003



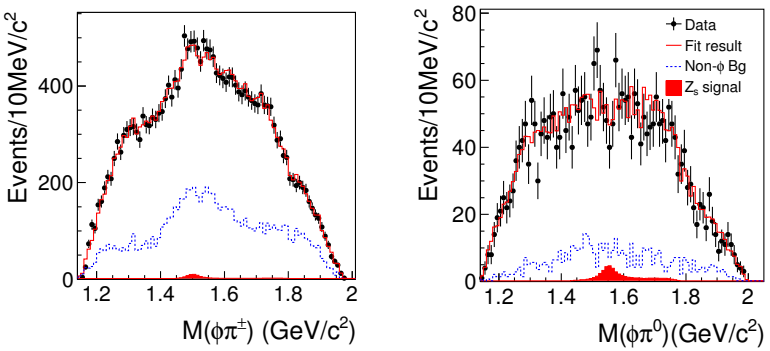
- $X(1835)$
  - Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$(BESII, BESIII), J^{PC} favor 0^{-+}
  - Anomaly line shape near $p\bar{p}$ threshold
  - ? $p\bar{p}$ molecule state or bound state
  - Also seen in $J/\psi \to \gamma K_S K_S \eta$ (J^{PC} determined to be 0^{-+})

Phys.Rev.Lett. 106 (2011) 072002 Phys.Rev.Lett. 117 (2016) 4, 042002 Phys.Rev.Lett. 115 (2015) 9, 091803



Search of Z_s in $e^+e^- \to \phi\pi\pi$

Phys.Rev.D 99 (2019) 1, 011101



- Amplitude analysis performed
  - Well described by $\phi\sigma$, $\phi f_0(980)$, $\phi f_0(1370)$, $\phi f_2(1270)$
  - No Z_s signal
  - Upper limit on the cross section of Z_s at 90% C.L. for different mass/width hypotheses determined