Hadron spectroscopy at BESIII

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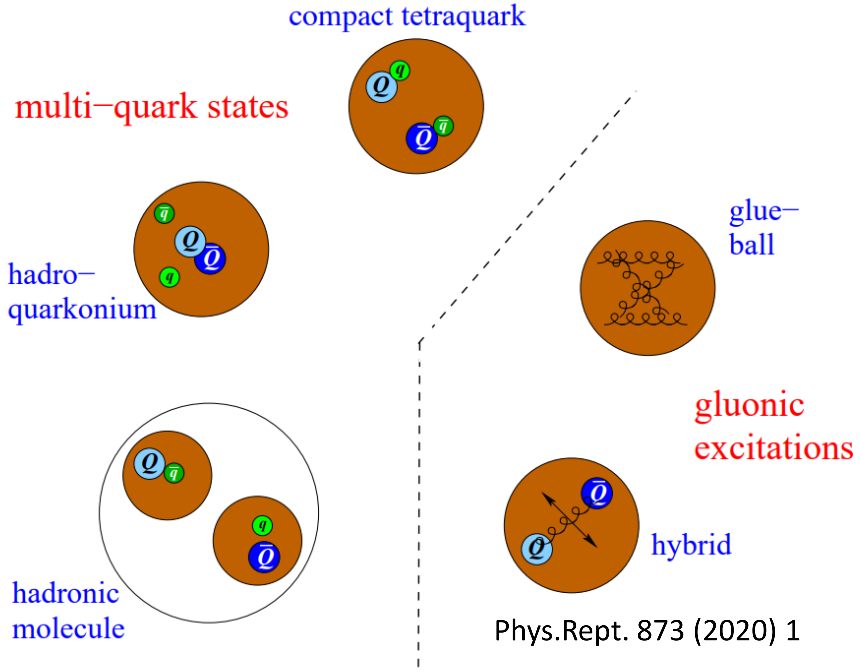
(On behalf of the BESIII collaboration)

International Workshop on Hadron Structure and Spectroscopy (IWHSS-2023), June 26-28, 2023, Prague

Hadron spectroscopy

- **How does QCD give rise to hadrons?**
  - **Quark model seems to work really well. Why?**
- **Key things to search for: additional degree of freedom**
  - Strong evidences for multi-quark in heavy quark sector
  - **Evidence for gluonic excitations remains sparse**

QCD exotics: configurations beyond QM



Phys.Rept. 873 (2020) 1

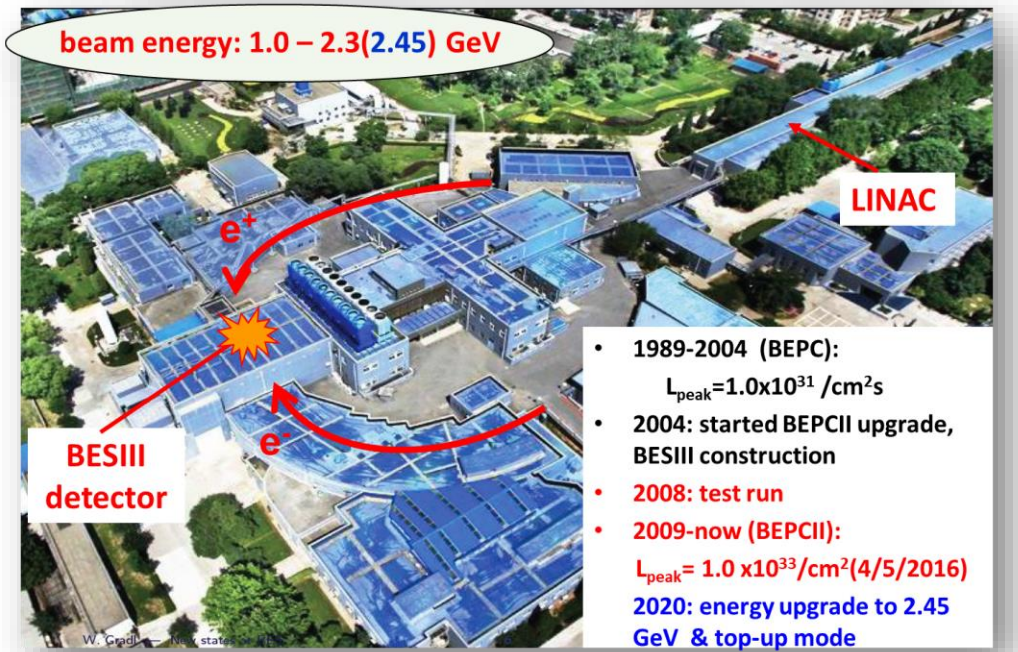
- **Role of gluons:**
  - Gluons mediate the strong force
  - **Hadron constituent: Mass? Quantum numbers? …**
  - Gluons' unique self-interacting property

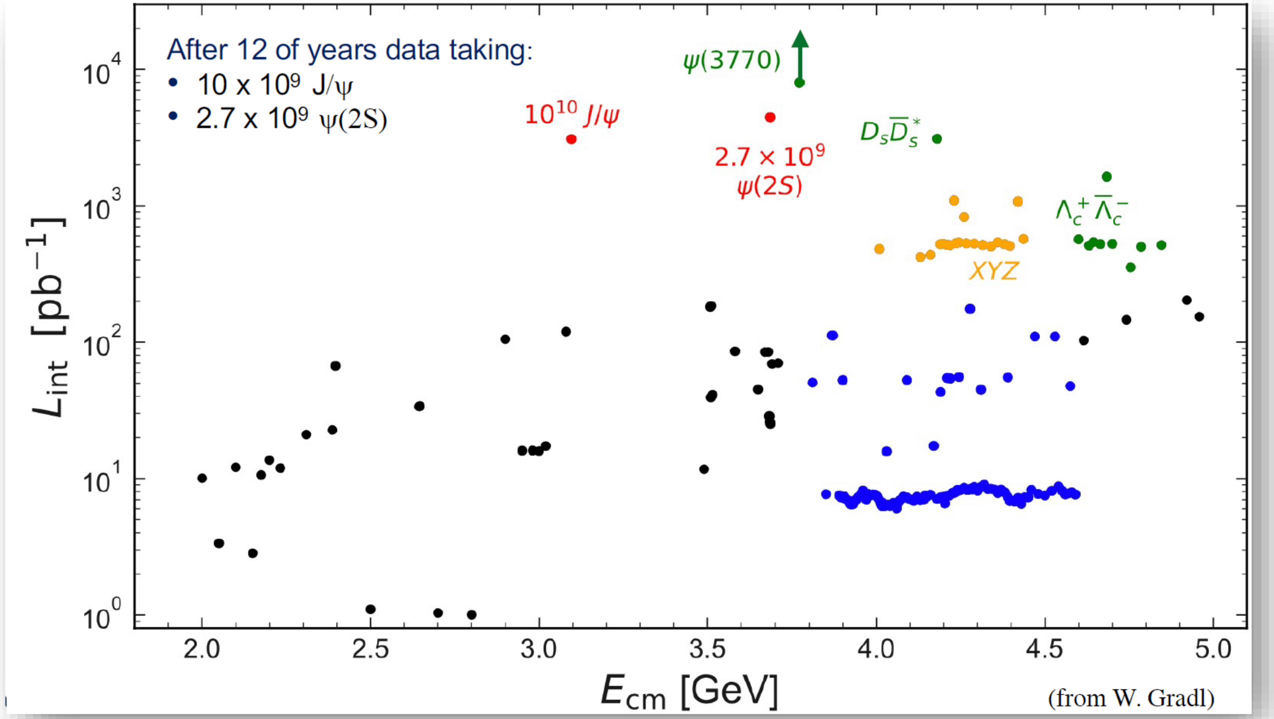
    → **New form of matter: glueballs, hybrids**
  - **Gluonic Excitations provide measurements of the QCD potential**

Critical to confinement and mass dynamical generation

World's largest $\tau-\mathrm{charm}$ data sets in e^+e^- annihilation

Beijing Electron Positron Collider (BEPCII)

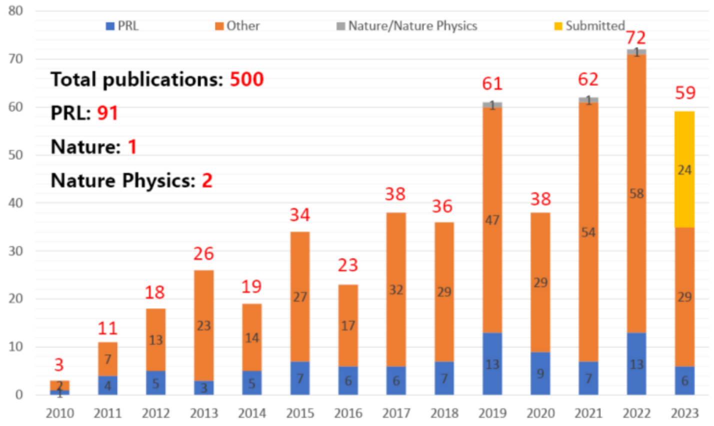


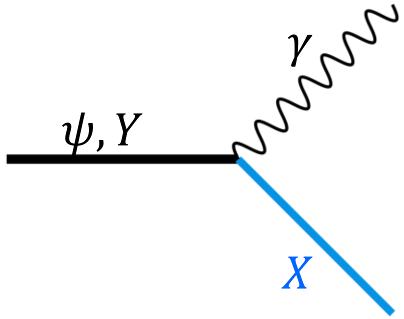


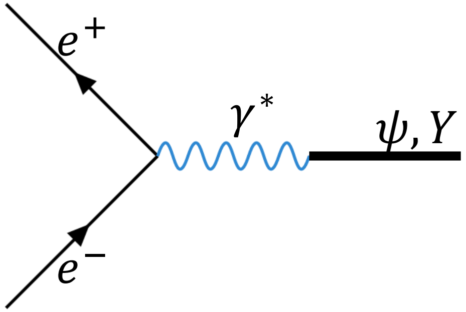
Rich physics programs:

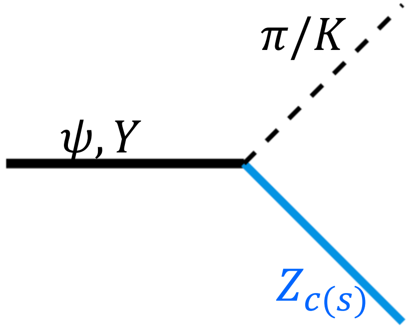
- light hadron spectroscopy & decays,
- charmonium spectroscopy,
- charm physics,
- precision measurements (R-value, TFF, ……)

BESIII publications (May 9, 2023)



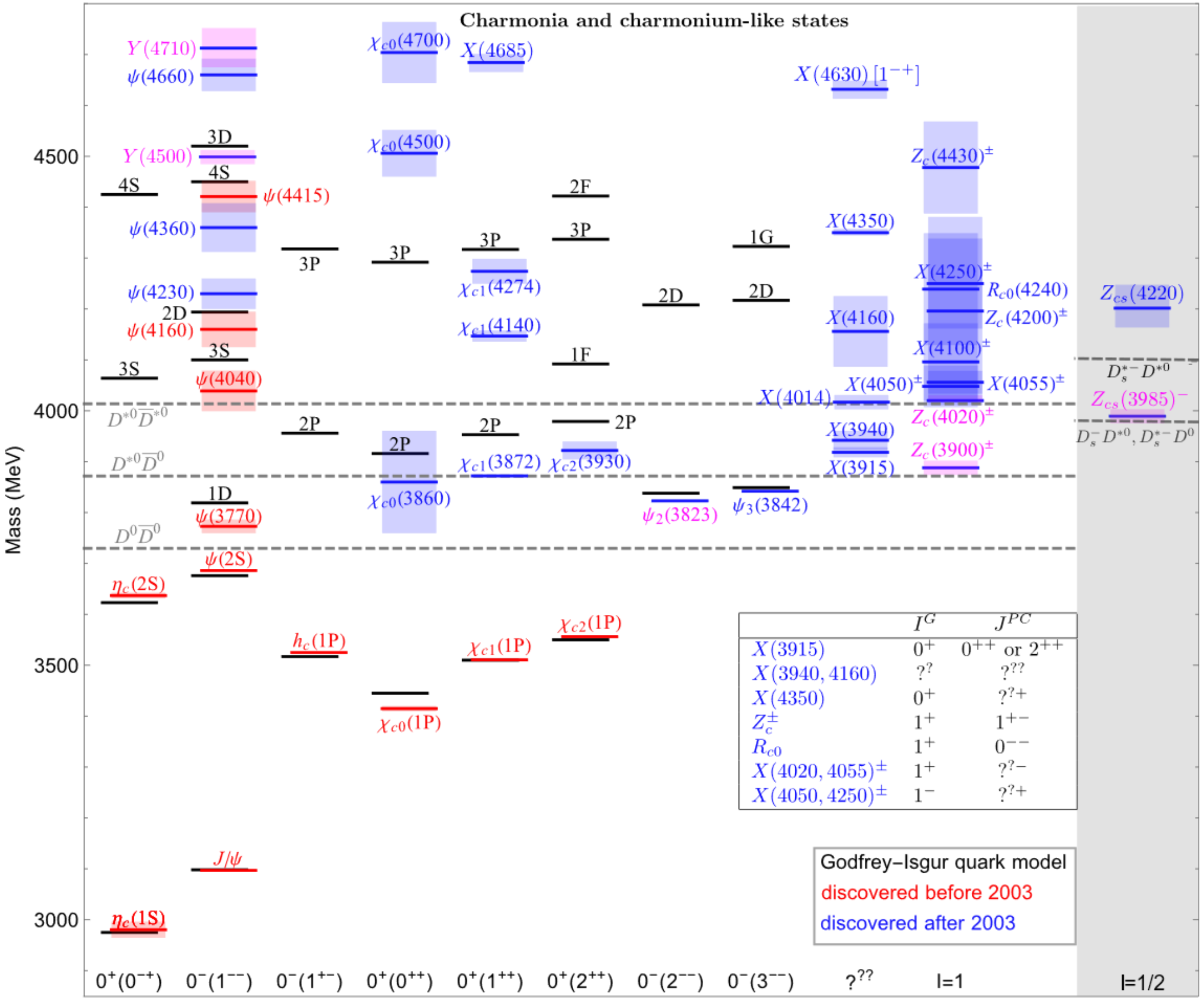






Charmonium(-like) Spectroscopy

Charmonium-like states



arXiv:2203.08290

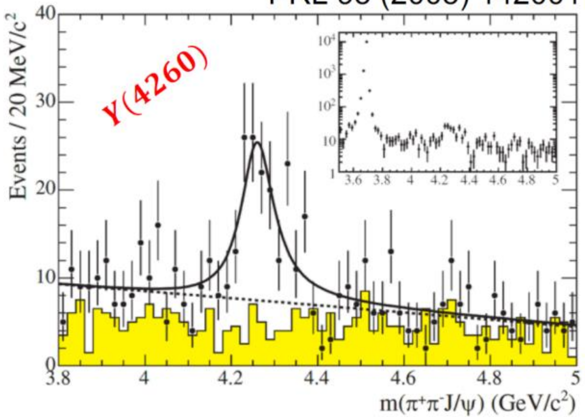
- Conventional $c\bar{c}$ meson fit well with potential model
- Abundance of new states with various probes
  - b-hadron decays
  - hadron/heavy-ion collisions
  - $\gamma\gamma$ processes
  - e^+e^- collisions
    - BESIII: dominant for vectors and states produced from vector decays

Vector states: Y(4260) → new Y states

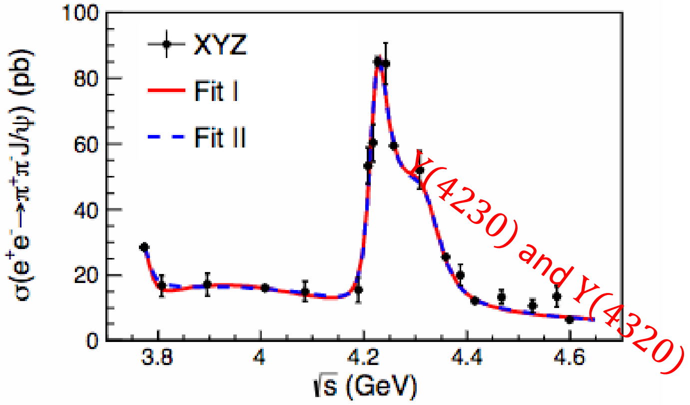
- Y(4260) firstly seen by BaBar
  - Inconsistent with simple $c\bar{c}$ scenario
  - Candidates for exotics:
    - Hybrid ($gc\bar{c}$)?
    - Hadronic molecule ?
    - Tetraquark ?

- Afterwards splits into Y(4230) and an additional resonance by BESIII

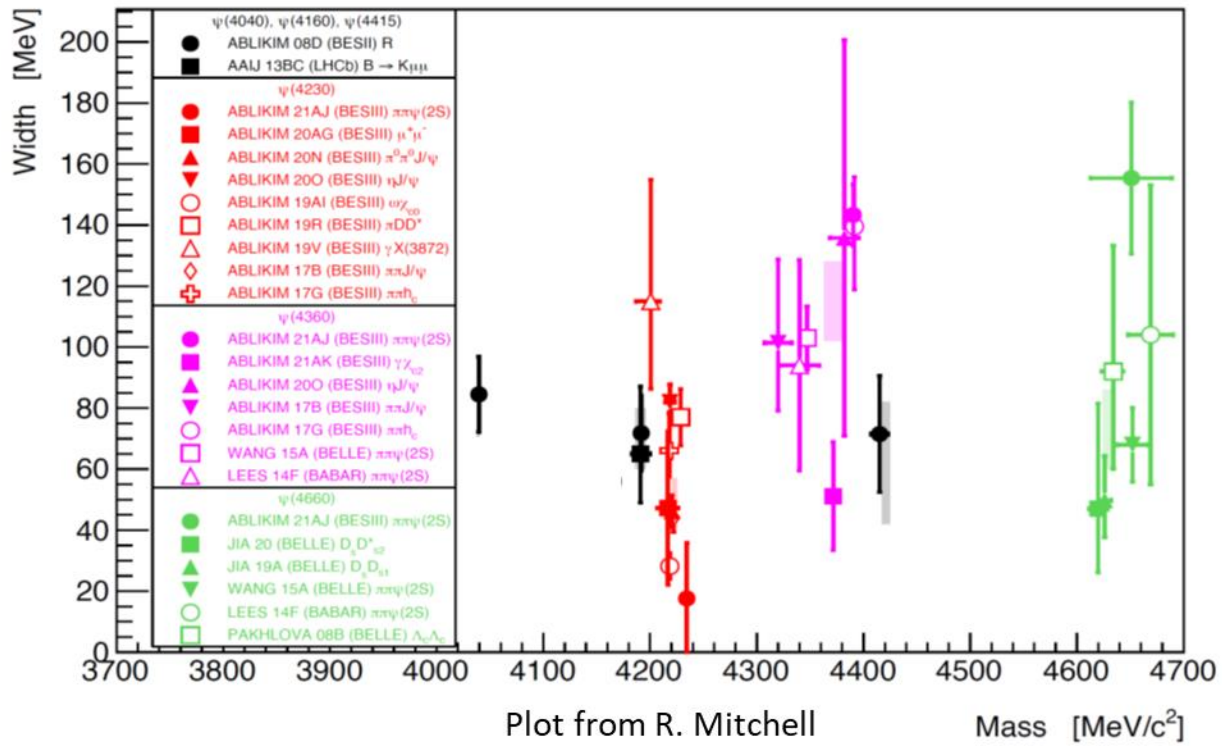
BaBar PRL 95 (2005) 142001



BESIII PRL 188(2017) 092001



PDG 2022 ψ States

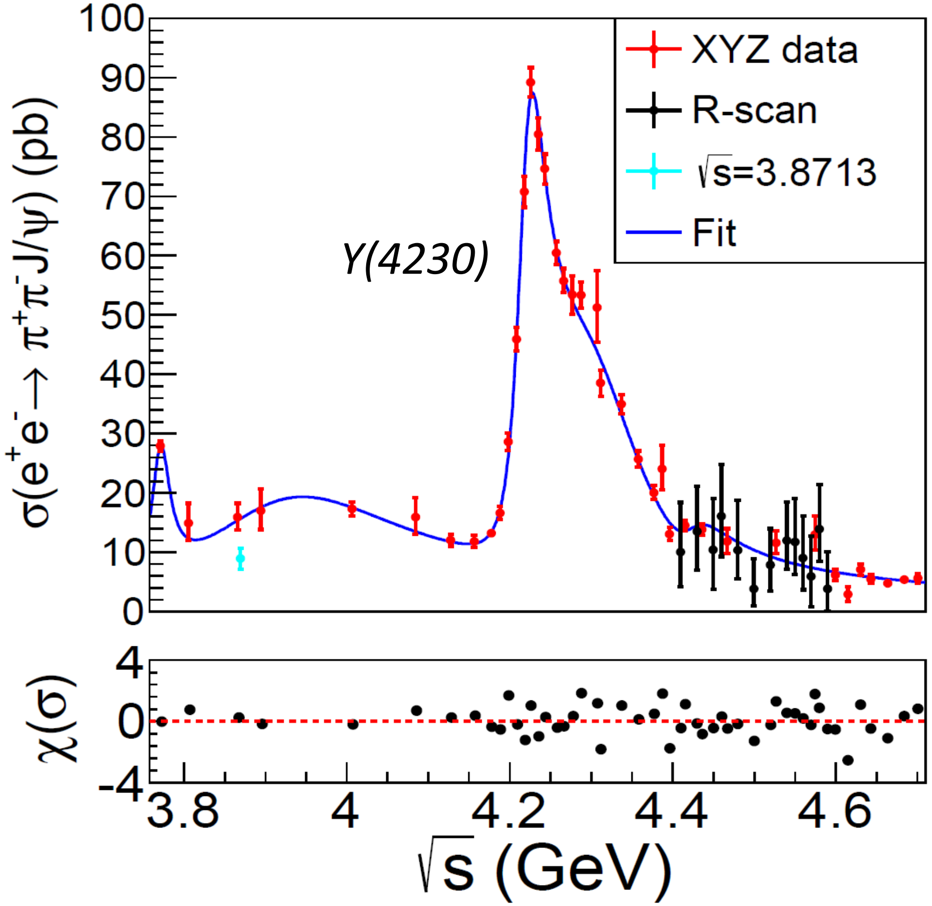


Plot from R. Mitchell

Y states

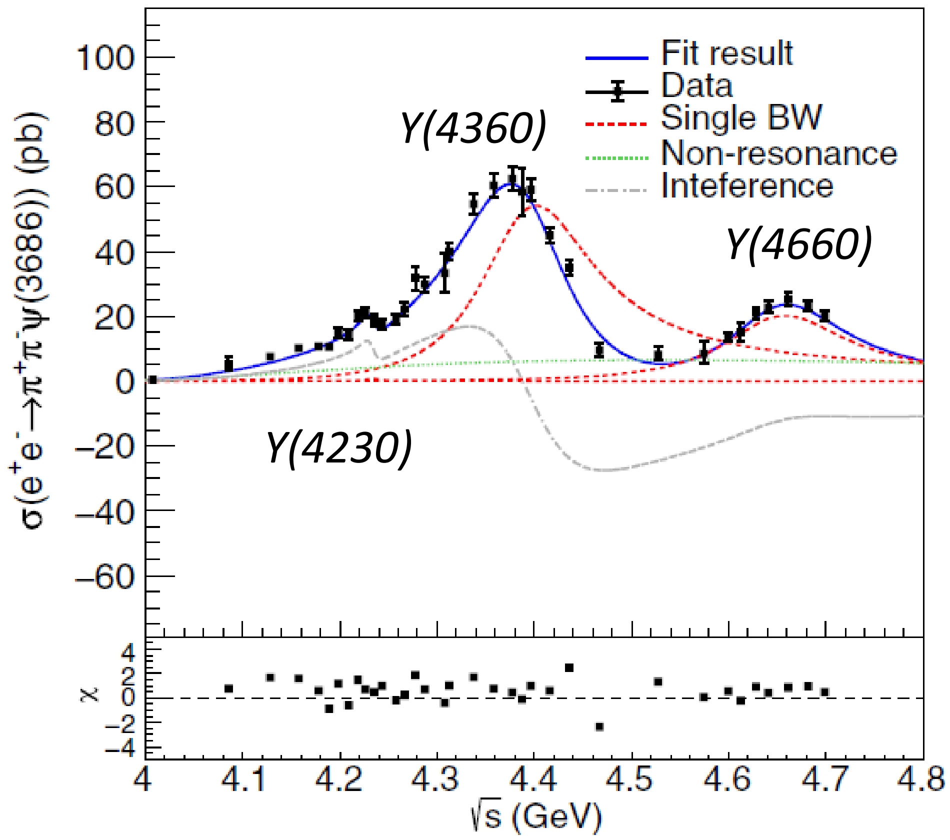
$e^+e^- \to \pi^+\pi^- J/\psi$

PRD 106 , 072001(2022)



$e^+e^- \to \pi^+\pi^- \psi(2S)$

PRD 104,052012(2021)

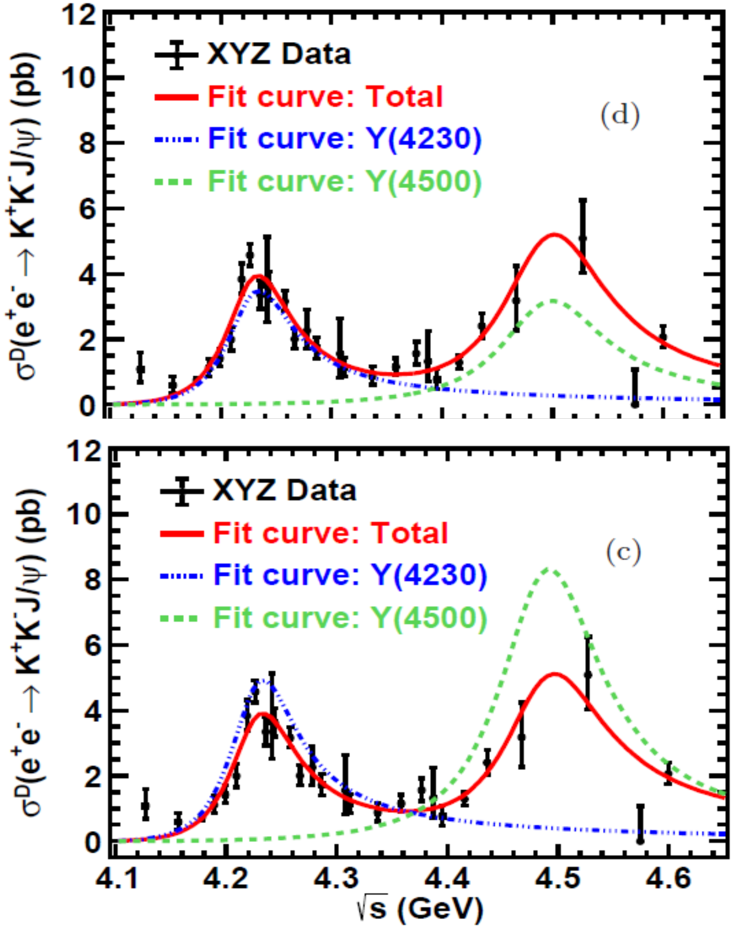


Significantly inconsistent with a single BW of the Y(4260)

Additional structure at ~4.5 GeV (3σ)

$e^+e^- \to K^+K^-J/\psi$ CPC 46, 111002 (2022)

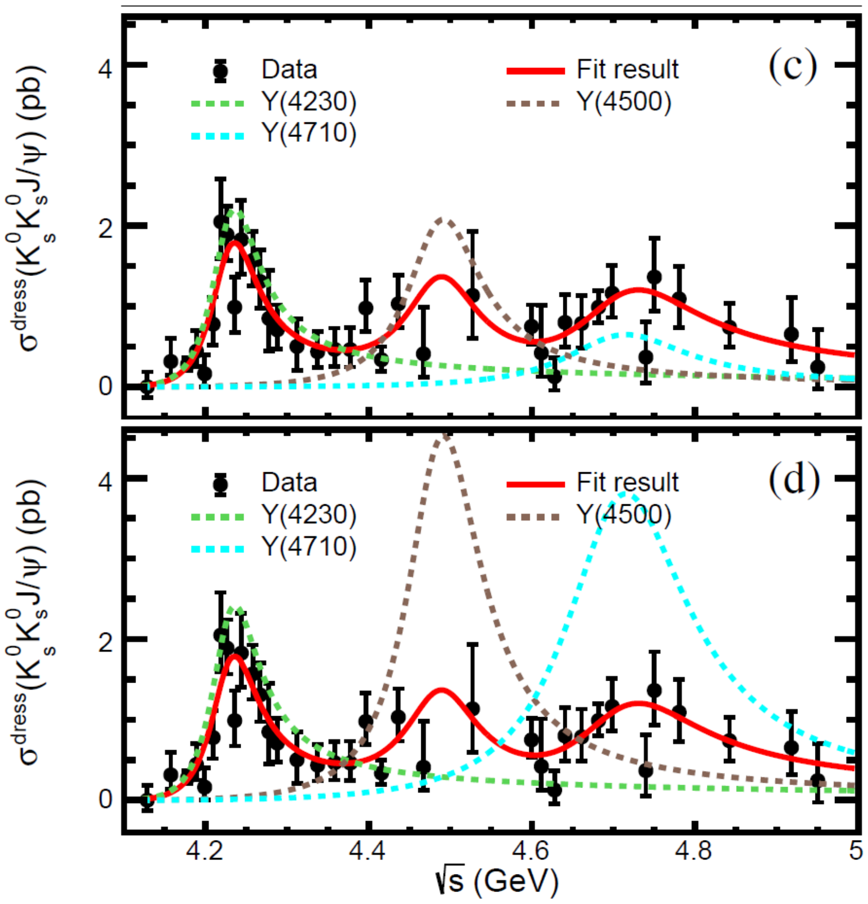
Data samples from 4.13 to 4.60 GeV(15.6 fb^{-1})



Y(4230) and Y(4500) observed (29σ / 8σ)

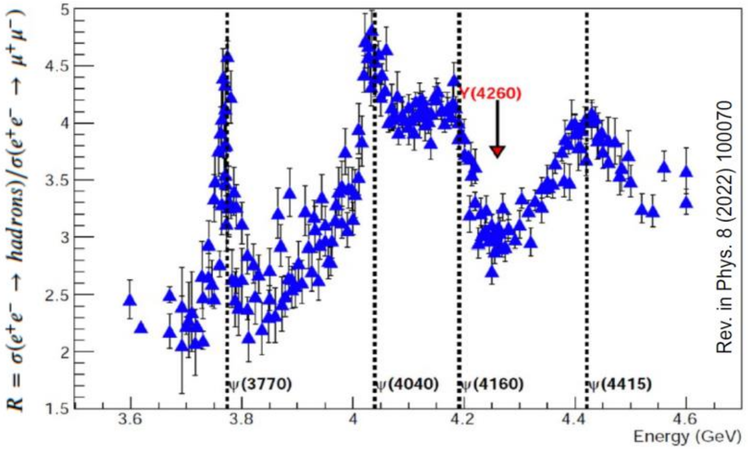
$e^+e^- \to K_S K_S J/\psi$ PRD 107, 092005 (2023)

Data samples from 4.13 to 4.95 GeV(21.2 fb^{-1})



Evidence for Y(4710) (4.0σ)

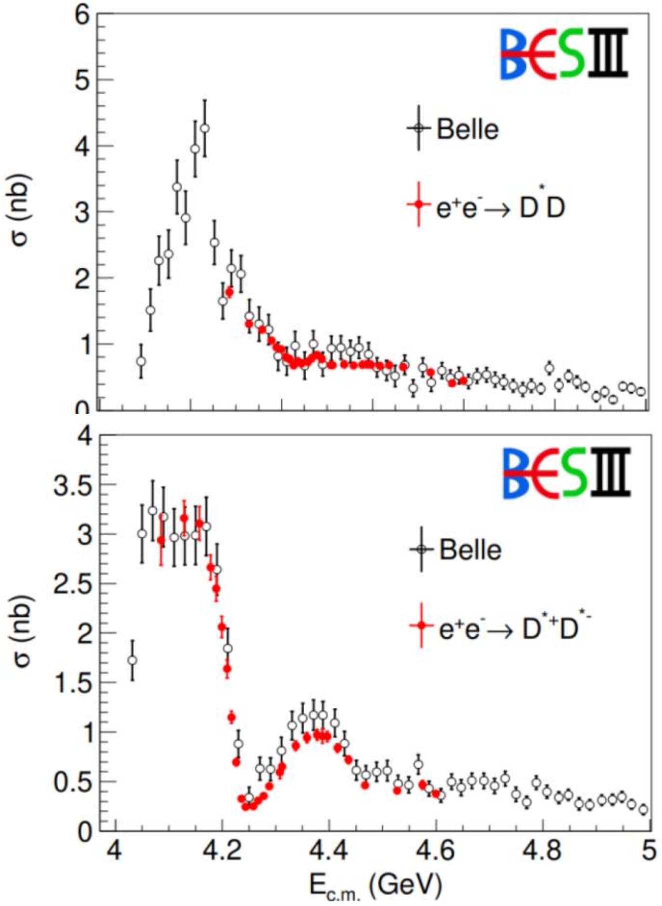
Open-charm production



The lineshape of inclusive cross section agrees well with conventional charmonium

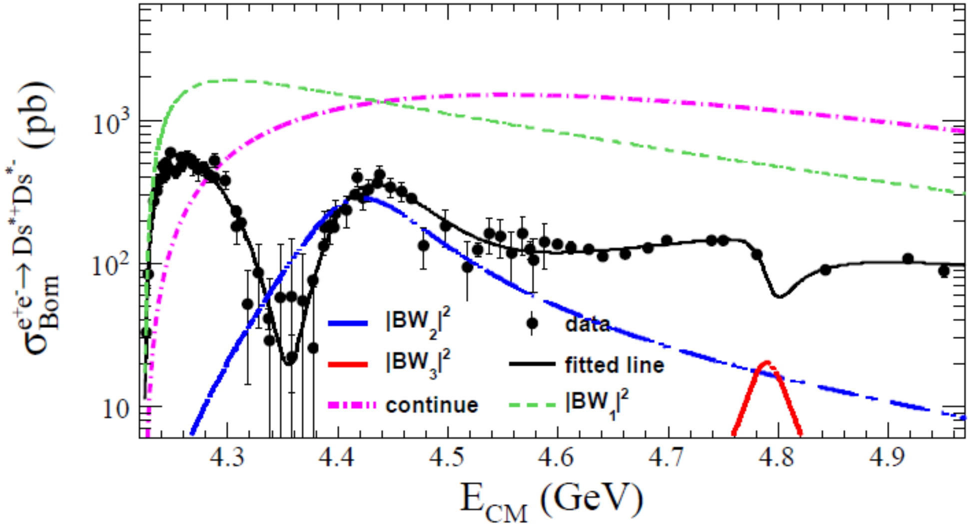
$e^+e^- \rightarrow D^{*+}D^{(*)-}$

JHEP 05 155 (2022)



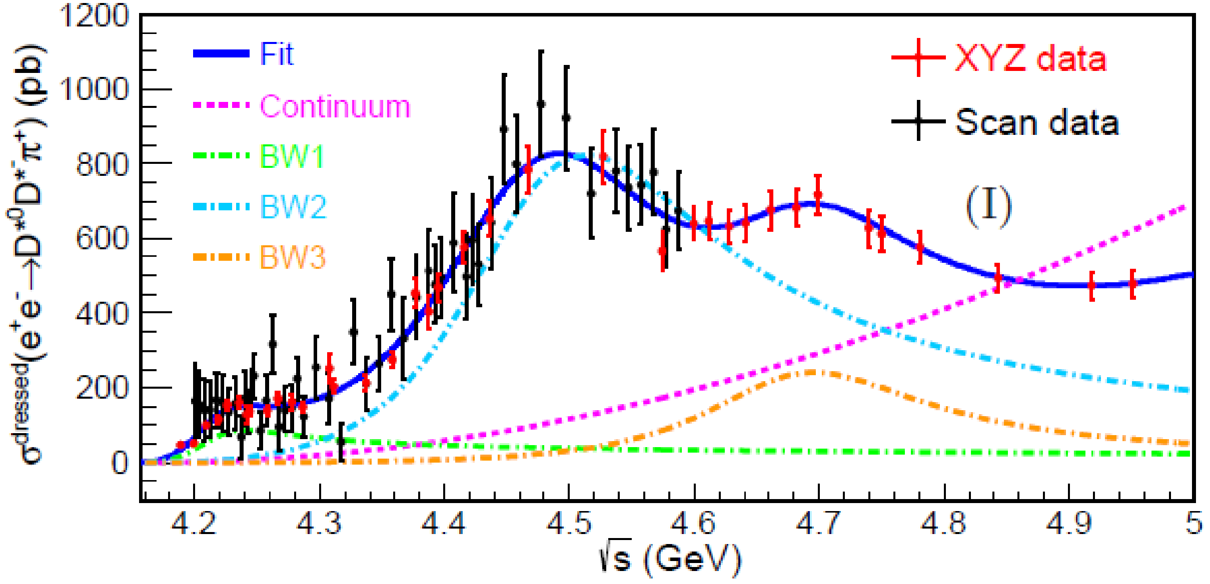
$e^+e^- \rightarrow D_s^{*+}D_s^{*-}$

arXiv:2305.10789



$e^+e^- \to D^{*0}D^{*-}\pi^+ + c.c.$

PRL 130, 121901 (2023)



Y(4230):

- $M = (4209.6 \pm 4.7 \pm 5.9)$ MeV/c²
- $\Gamma = (81.6 \pm 17.8 \pm 9.0)$ MeV

Y(4500):

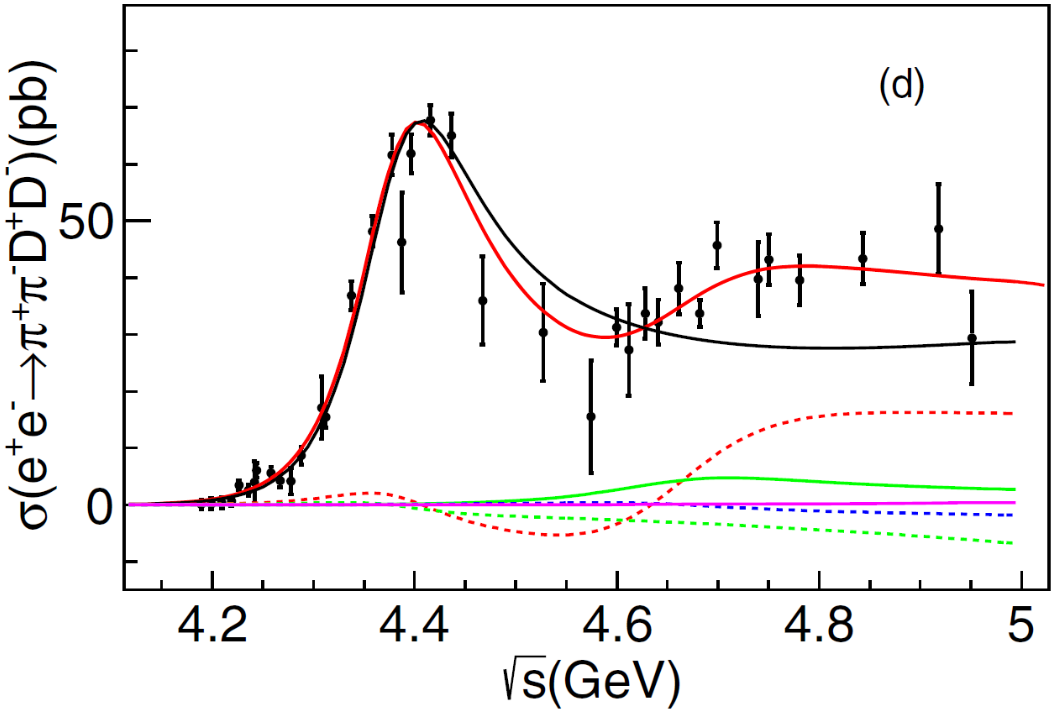
- $M = (4469.1 \pm 26.2 \pm 3.6)$ MeV/c²
- $\Gamma = (81.6 \pm 17.8 \pm 9.0)$ MeV

Y(4660):

- $M = (4675.3 \pm 29.5 \pm 3.5)$ MeV/c²
- $\Gamma = (218.2 \pm 72.9 \pm 9.3)$ MeV

$e^+e^- \to D^+D^-\pi^+\pi^-$

PRD 106, 052012 (2022)



A resonance agrees with the ψ(4360) or Y(4390) state, with an evidence for an addition resonance of 4.2 σ

More information on X(3872)

Open-charm decays and radiative transitions

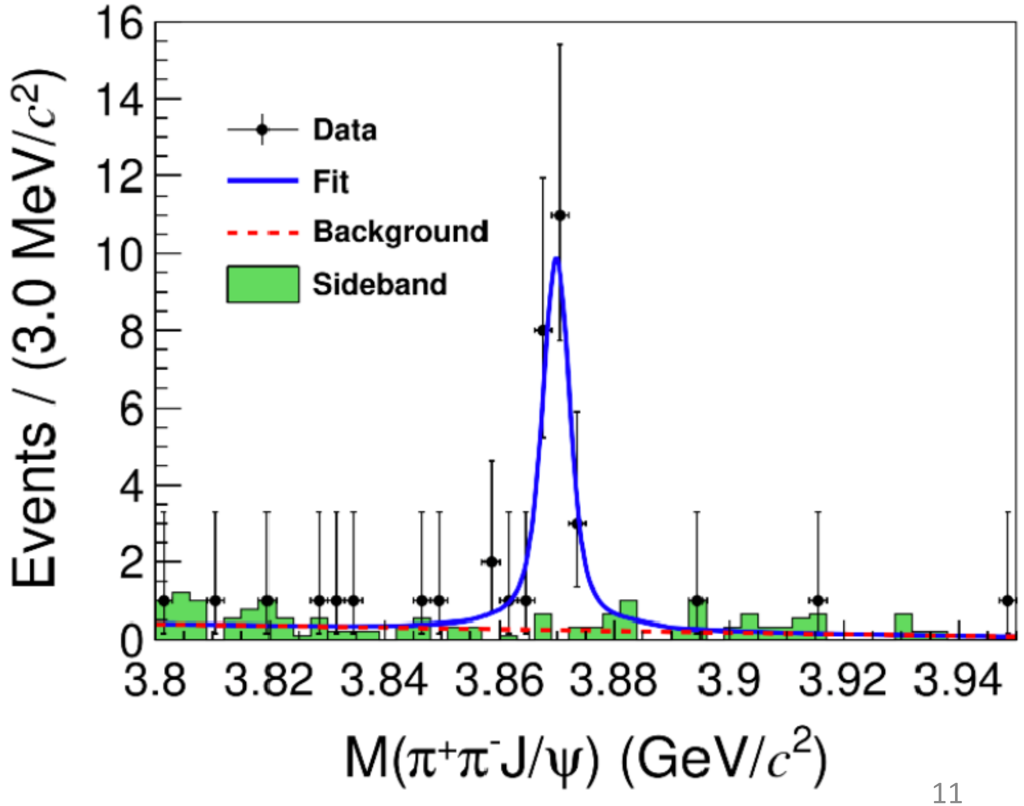
PRL 124, 242001 (2020)

mode	ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	-
$\gamma\psi'$	-0.03 ± 0.22	< 0.42
$\gamma D^0\bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0\bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0}\bar{D}^0 + c.c.$	11.77 ± 3.09	-
γD^+D^-	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	-
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [31]	-

A new production mechanism

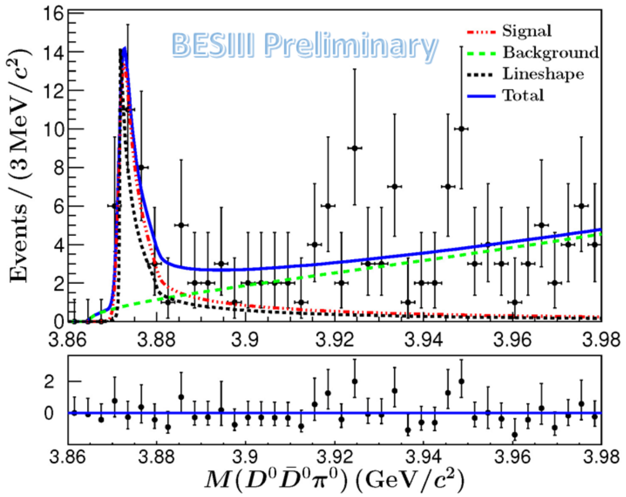
$e^+e^- \to \omega X(3872)$ at E_{CM} between 4.66 and 4.95 GeV

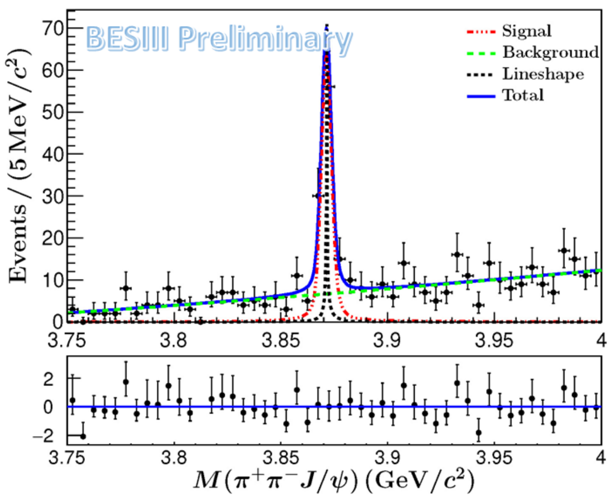
PRL 130, 151904 (2023)



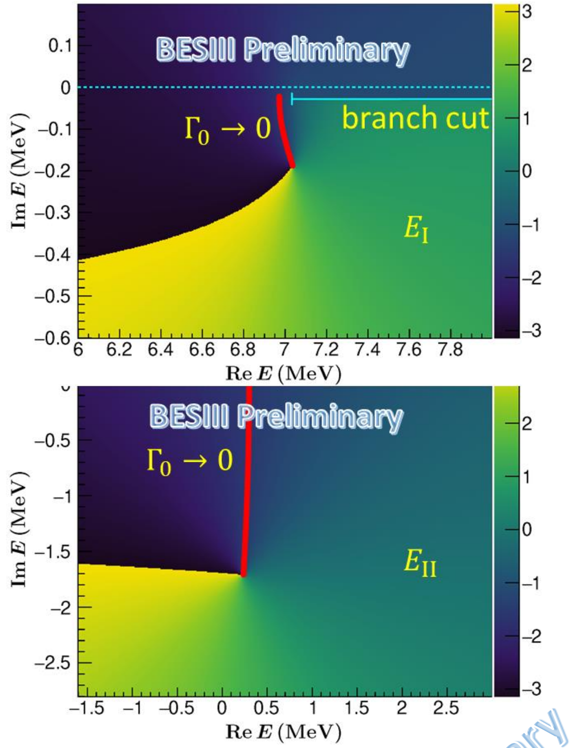
A coupled channel analysis of the X(3872) lineshape

$e^+e^- \to \gamma X(3872), X(3872) \to D^0\bar{D}^0\pi^0$ and $\pi^+\pi^- J/\psi$

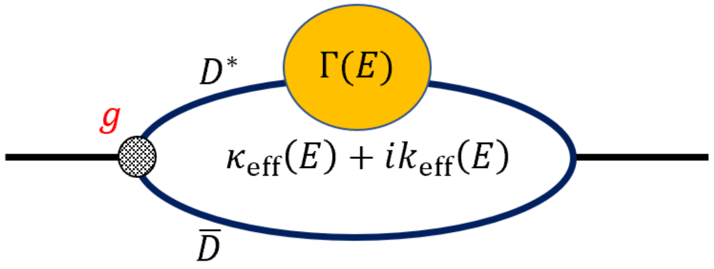




Two poles are found



Lineshape parameterization based on [C. Hanhart, etc., PRD 81, 094028 (2010)] , with the effect of D* width taken into account



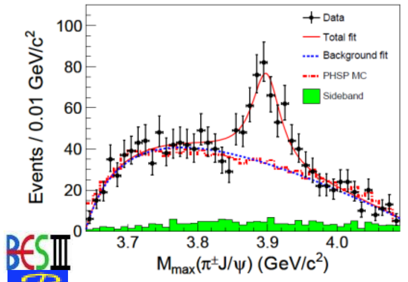
Parameters	g	Γ_0 (MeV)	M_X (MeV)
Fit results	0.16 ± 0.10	2.67 ± 1.77	3871.63 ± 0.13
g	1.00	0.30	−0.60
Γ_0		1.00	−0.29
M_X			1.00

BESIII Preliminary

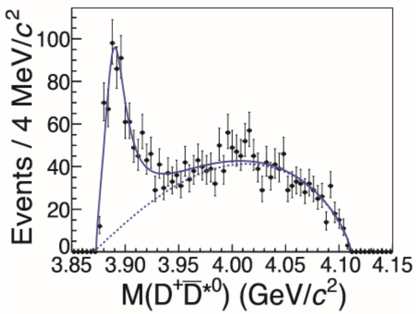
- $E_I = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV
- $E_{II} = (0.26 \pm 5.74^{+5.14}_{-38.32}) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV

BESIII Preliminary

The Zc Family at BESIII

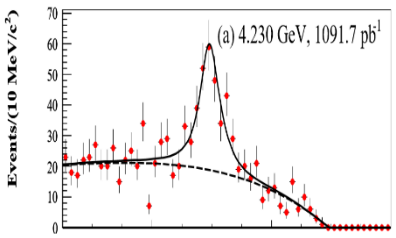


$e^+e^- \to \pi^+ \pi^- J/\psi$

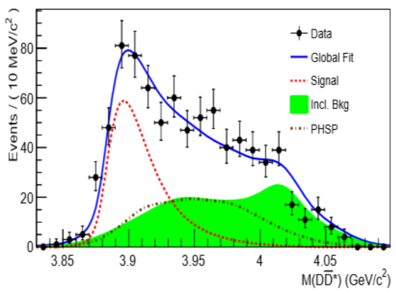


$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

$Z_c(3900)^{\pm}$

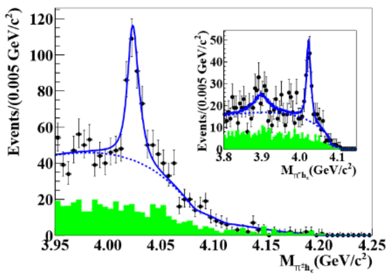


$e^+e^- \to \pi^0 \pi^0 J/\psi$

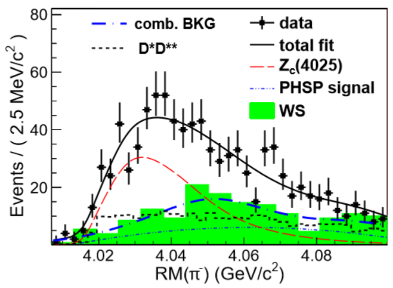


$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^0$

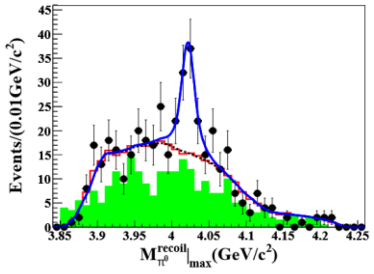


$e^+e^- \to \pi^+ \pi^- h_c$

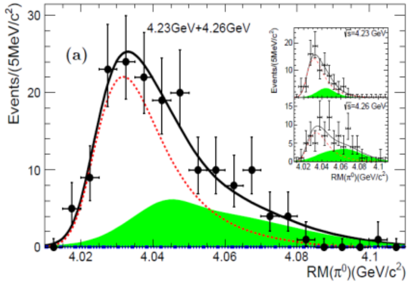


$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

$Z_c(4020)^{\pm}$



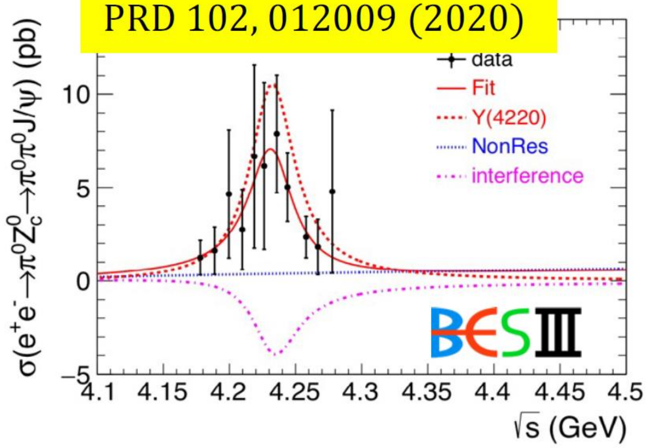
$e^+e^- \to \pi^0 \pi^0 h_c$



$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

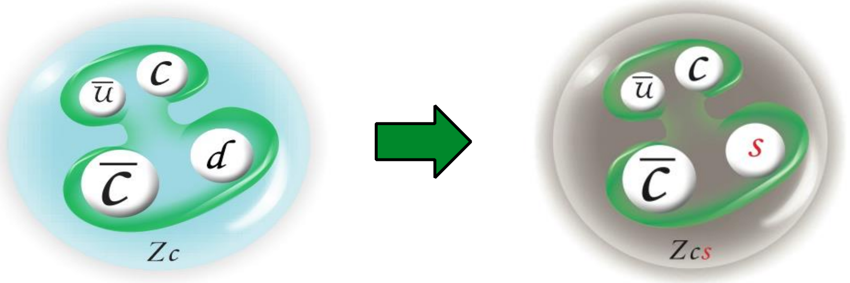
$Z_c(4020)^0$

PRD 102, 012009 (2020)



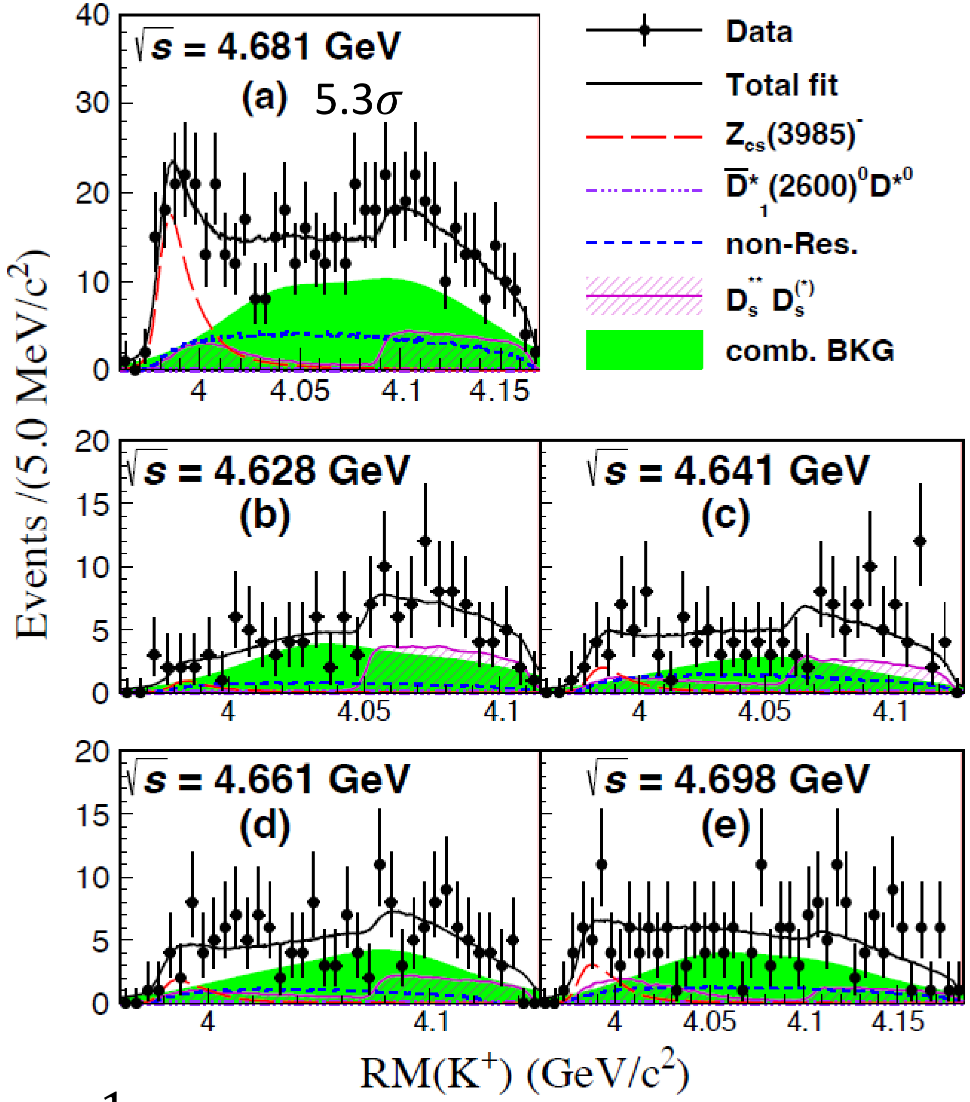
$I = 1\ Z_c(3900)$ near $D\bar{D}^*$ threshold

$I = 1\ Z_c(4020)$ near $D^*\bar{D}^*$ threshold



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

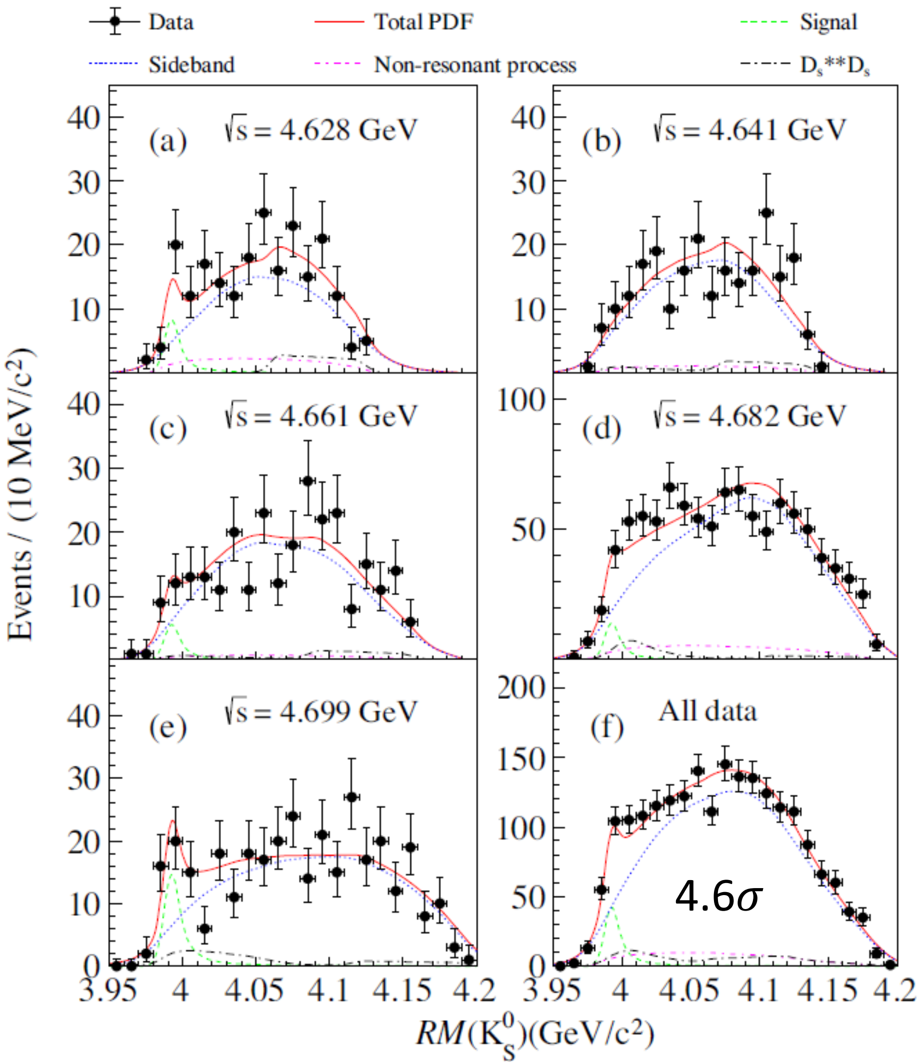
PRL126, 102001 (2021)



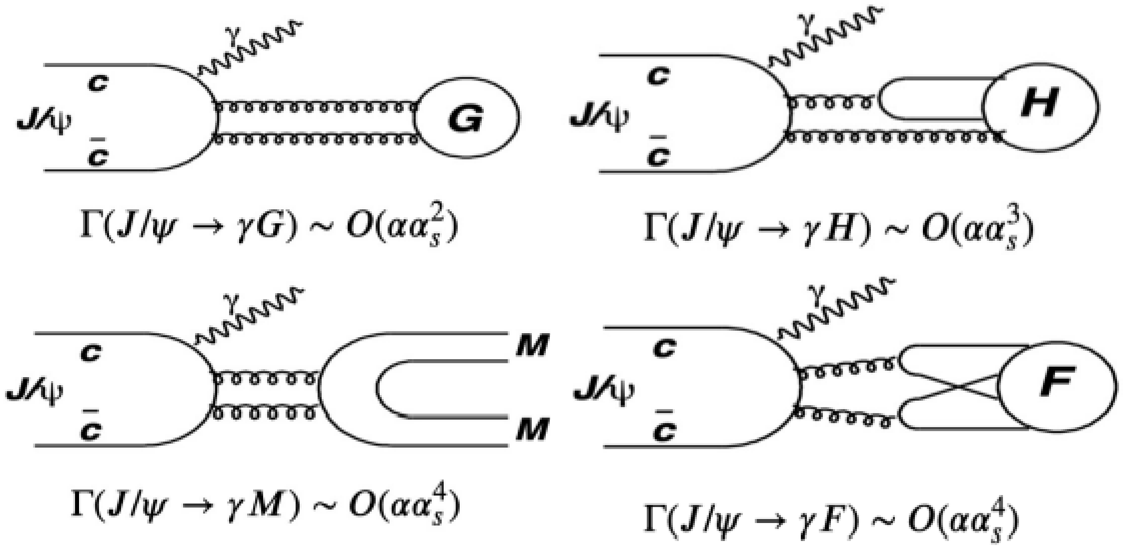
$I = \frac{1}{2}$ $Z_{cs}(3985)$ near $D_s D^*$ threshold

$$e^+e^- \to K_S(D_s^- D^{*+} + D_s^{*-} D^+)$$

PRL 129, 112003 (2022)



Evidence for the neutral $Z_{cs}(3985)$



“Gluon-rich” process

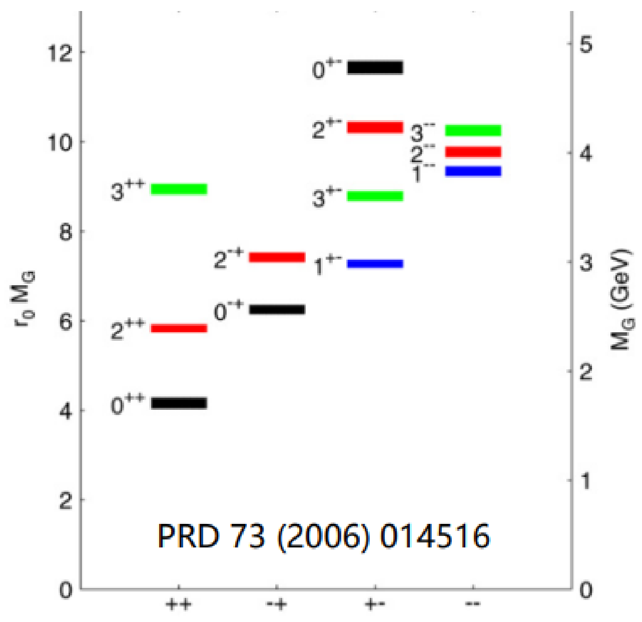
Light Hadron Spectroscopy

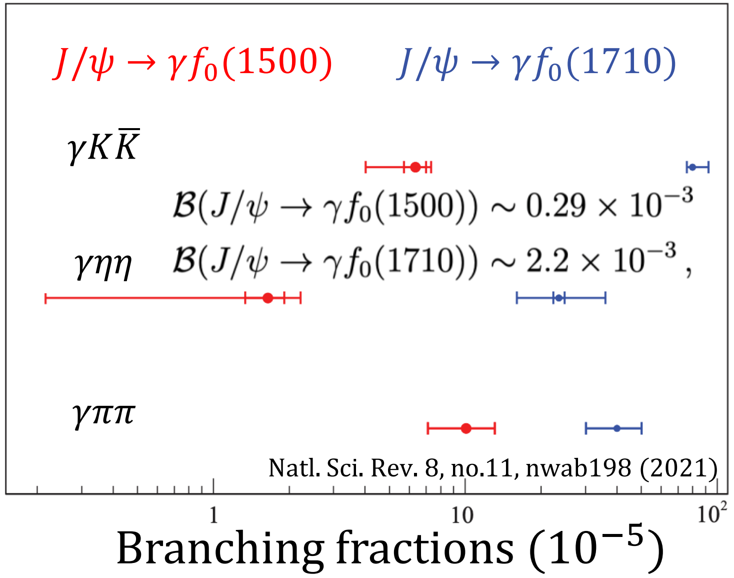
Glueballs

- Low-lying glueballs with ordinary J^{PC} → mixing with $q\bar{q}$ mesons
  - ➢ Non-$\mathbf{q\bar{q}}$ nature difficult to be established: *Cryptoexotic*
    - ➢ Supernumerary states
    - ➢ Unusual pattern of production and decay
- **Scalar glueball is expected to have a large production in J/ψ radiative decays**: $B(J/\psi \to \gamma G_{0+}) = 3.8(9) \times 10^{-3}$ by Lattice QCD
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$
  - ➢ BESIII: $f_0(1710)$ largely overlapped with scalar glueball

BESIII PRD 87 092009 (2013)
BESIII PRD 92 052003 (2015)
BESIII PRD 98 072003 (2018)

LQCD prediction of glueball spectrum

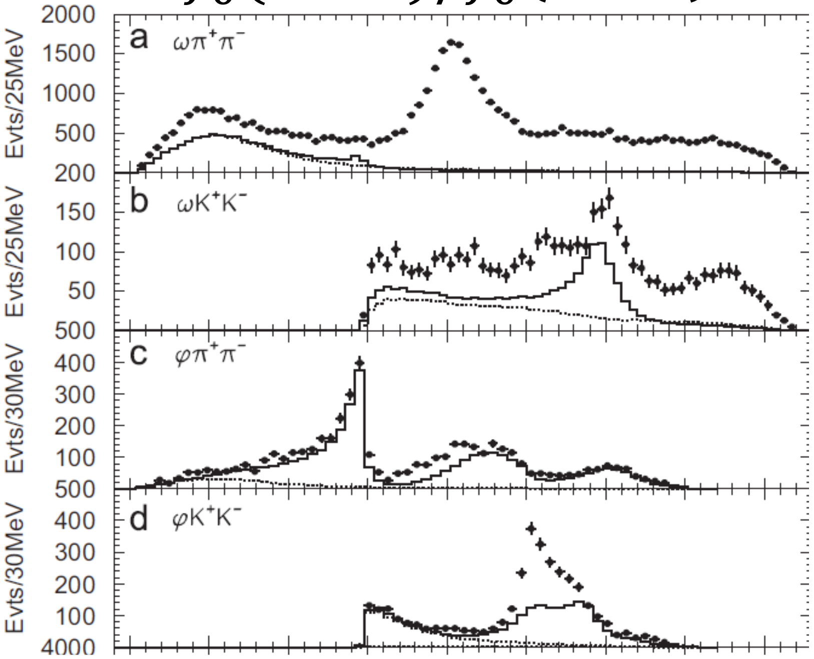




phenomenology studies of coupled channel analysis with BESIII results:
PLB 816, 136227 (2021), EPJC 82, 80 (2022)

More scalars

$f_0(1710)/f_0(1790)$?



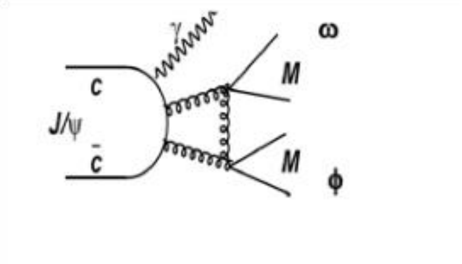
ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

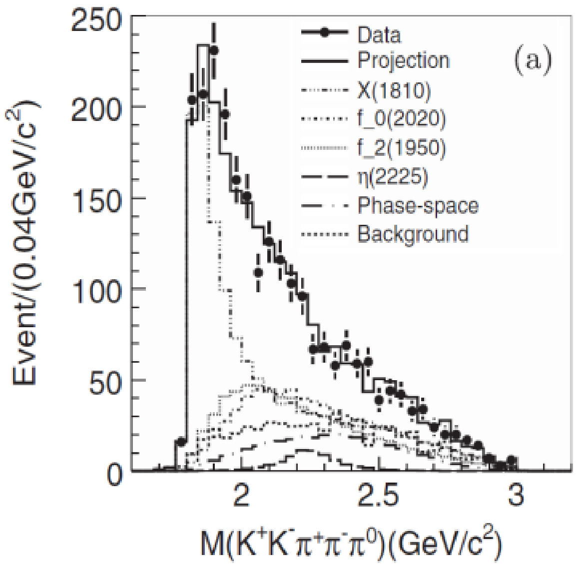
ϕK^+K^- ➜ No peak around 1700 MeV/c^2

$f_0(1800)$

PRD 87, 032008(2013)



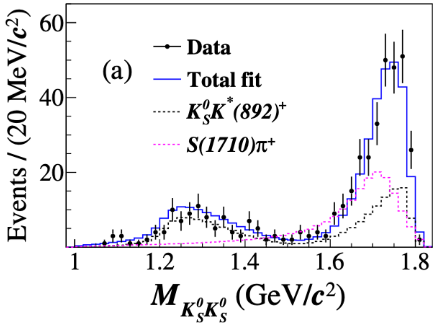
$J/\psi \to \gamma\omega\phi$ **(DOZI)**



$a_0(1710)/a_0(1817)$?

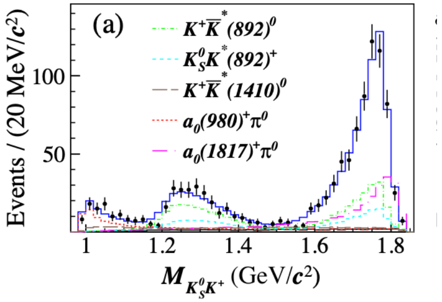
PRD105, L051103 (2022)

$D_s^+ \to K_S^0 K_S^0 \pi^+$



PRL129, 182001 (2022)

$D_s^+ \to K^0_S K^+ \pi^0$

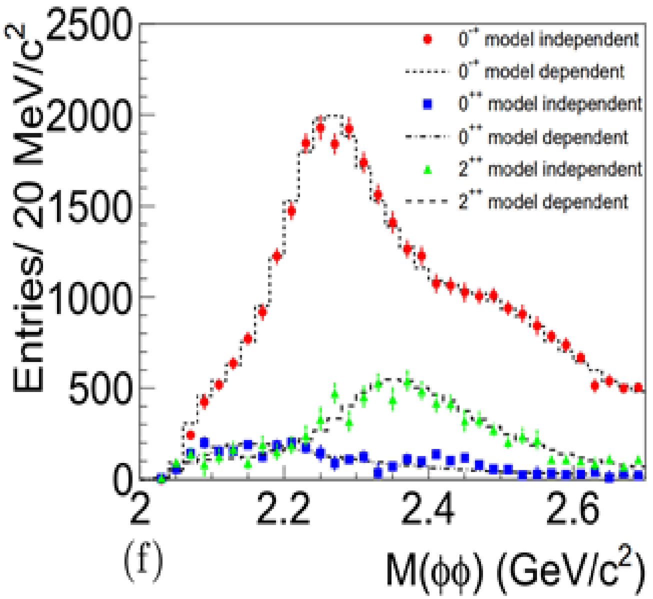


Tensor glueball candidate

$$\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22)keV$$
$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

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

BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ



Experimental results

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}}$$

BESIII PRD 87,092009 (2013)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}}$$

BESIII PRD 93, 112011 (2016)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = (5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}}$$

BESIII PRD 98,072003 (2018)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = (8.67 \pm 0.70^{+0.16}_{-1.67}) \times 10^{-6}}$$

BESIII PRD 105,072002 (2022)

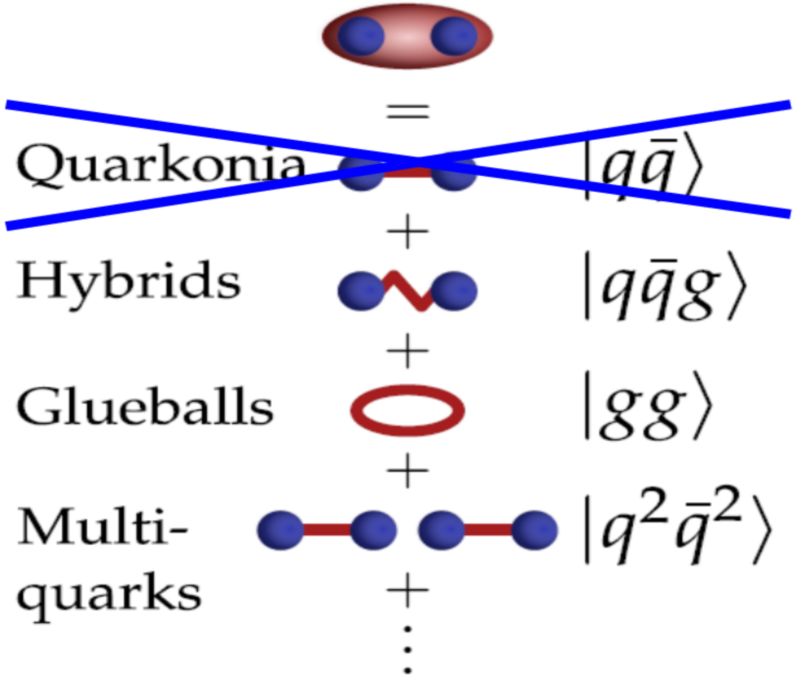
$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$

Consist with WA102@CERN

It is desirable to search for more decay modes

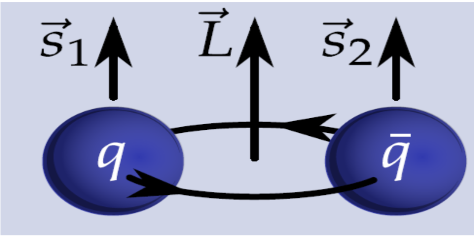
Light hadrons with exotic quantum numbers

- **Unambiguous signature for exotics**
  - Light Flavor-exotic hard to establish
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**
      $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$



Various probes:

- **Hadroproduction:** E852, VES, COMPASS, GAMS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX
- **Photoproduction:** GlueX(2017-), CLAS



$\vec{\mathbf{J}} = \vec{\mathbf{L}} + \vec{\mathbf{S}}$ $\quad \mathbf{P = (-1)^{L+1}}$ $\quad \mathbf{C = (-1)^{L+S}}$

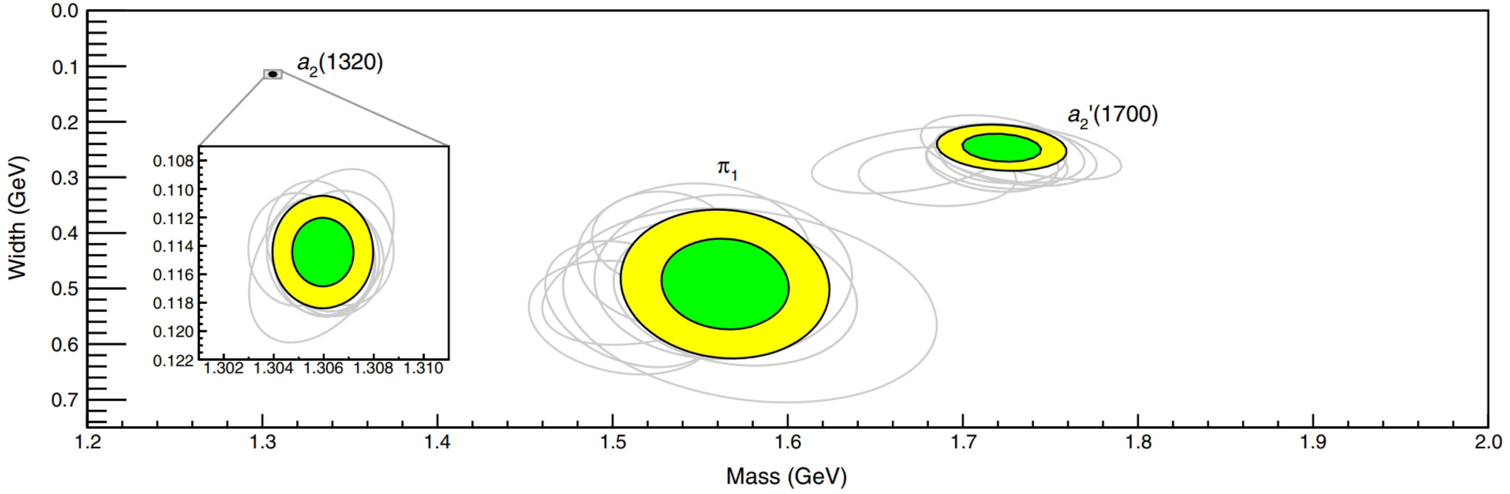
Allowed $\mathbf{J^{PC}: 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

Image Courtesy to B. Grube

Spin-exotic mesons

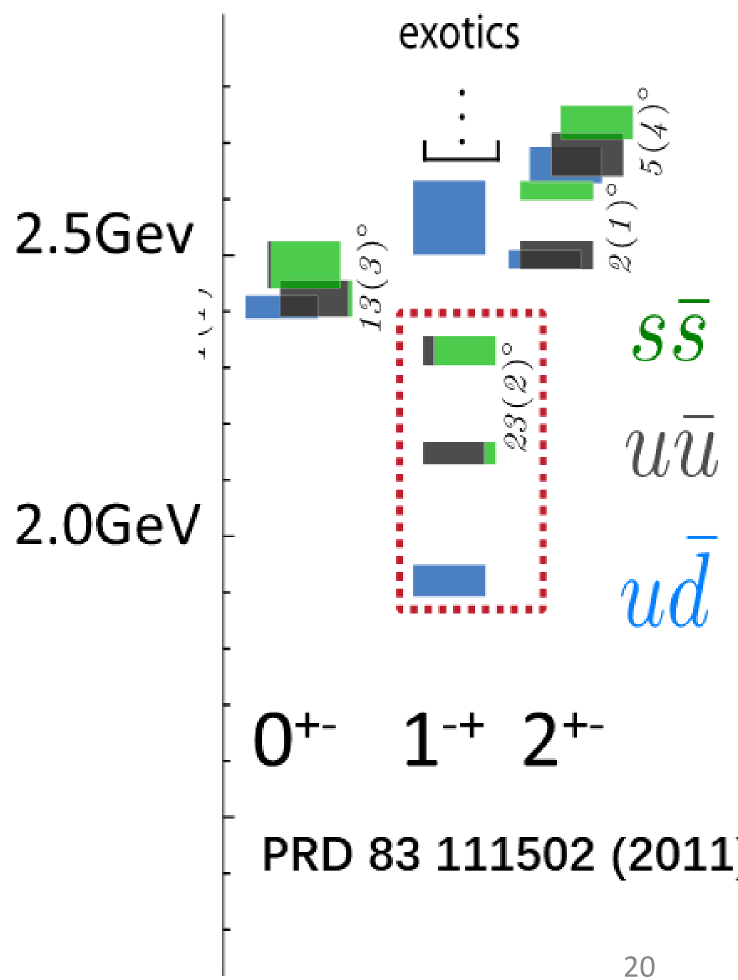
- **Only 3 candidates so far: All 1^{-+} isovectors**
  - Experimental and interpretational issues
  - $\pi_1(1400)$ & $\pi_1(1600)$ can be explained as one pole
  - **Most popular interpretation: hybrid**

PRL 122, 042002 (2019)



Confirmed by EPJC 81, 1056 (2021)

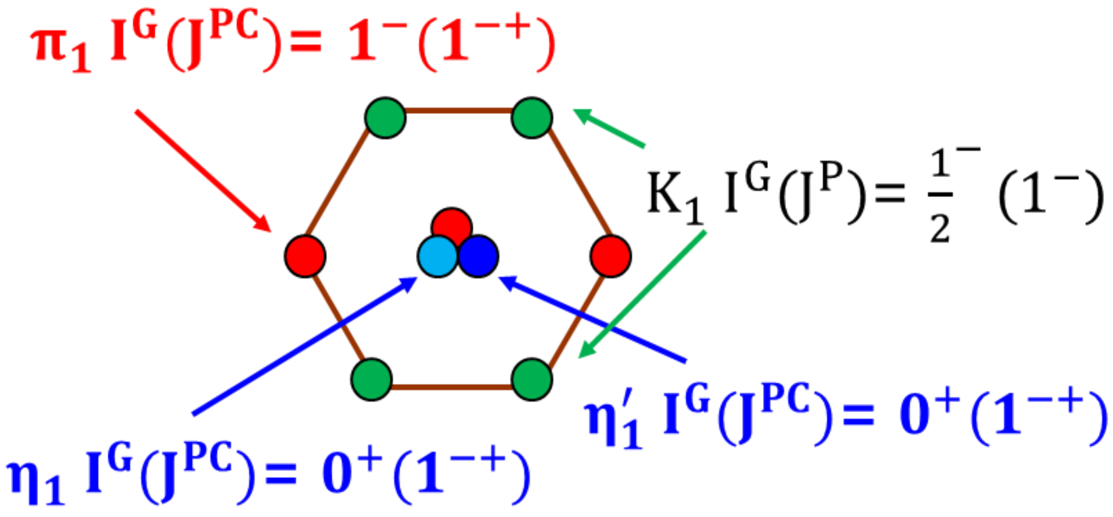
Lattice QCD Predictions:



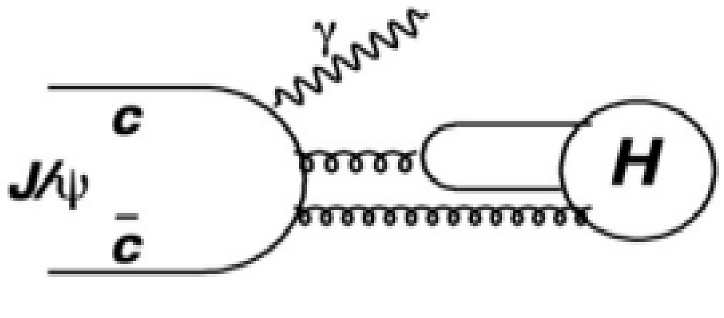
PRD 83 111502 (2011)

1^{-+} Hybrids

- **Isoscalar 1^{-+} is critical to establish the hybrid nonet**
  - **Can be produced in the gluon-rich charmonium decays**
  - **Can decay to $\eta\eta'$ in P-wave**



PRD 83,014021 (2011), PRD 83,014006 (2011), EP.J.P 135, 945(2020)



$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

→ Search for η_1 (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

Observation of An Isoscalar 1^{-+} State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

Phys. Rev. Lett. 129, 192002 (2022), Phys. Rev. D 106, 072012 (2022)

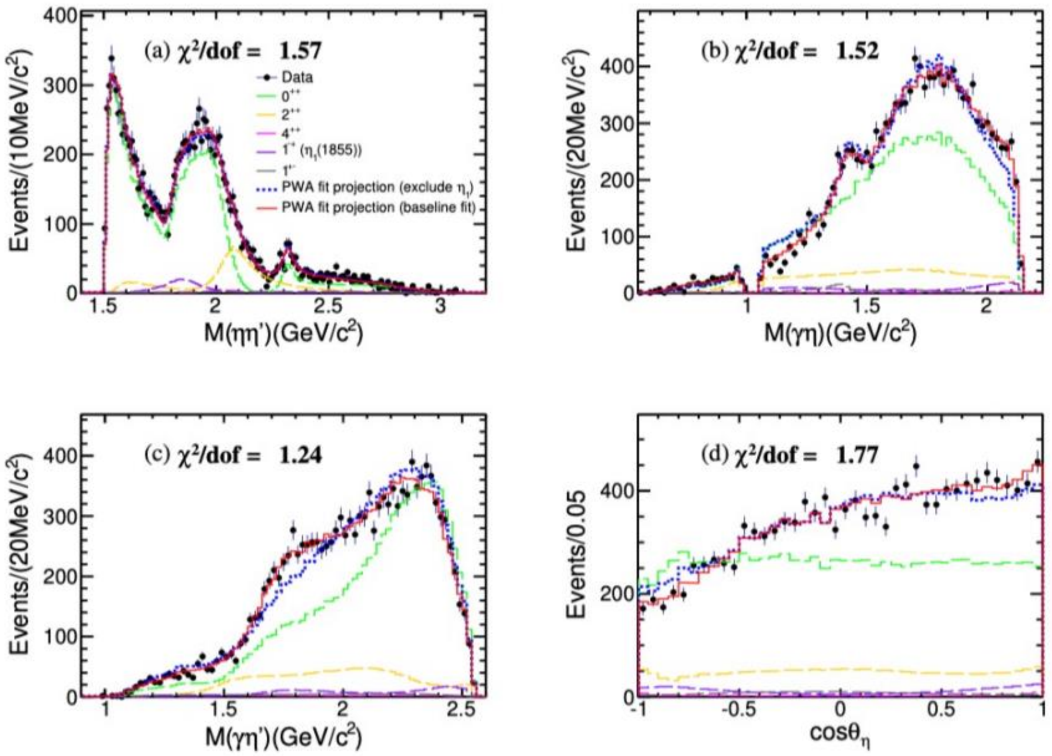
- The η' is reconstructed from $\gamma\pi^+\pi^-$ & $\eta\pi^+\pi^-$, η from $\gamma\gamma$
- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor formalism and GPUPWA*

World's first PWA framework with GPU acceleration

- **An isoscalar 1^{-+}, $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

$$\mathbf{M} = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2,\ \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$$

$$\mathrm{B}(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$



- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid ($1.7 \sim 2.1\ \mathrm{GeV}/c^2$)**
  - **Hybrid? Molecule? Tetraquark?**

Observation of An Isoscalar 1^{-+} State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

- Angular distribution as a function of $M(\eta\eta')$ expressed **model-independently**

$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(cos\theta_\eta^i)$$

- Related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

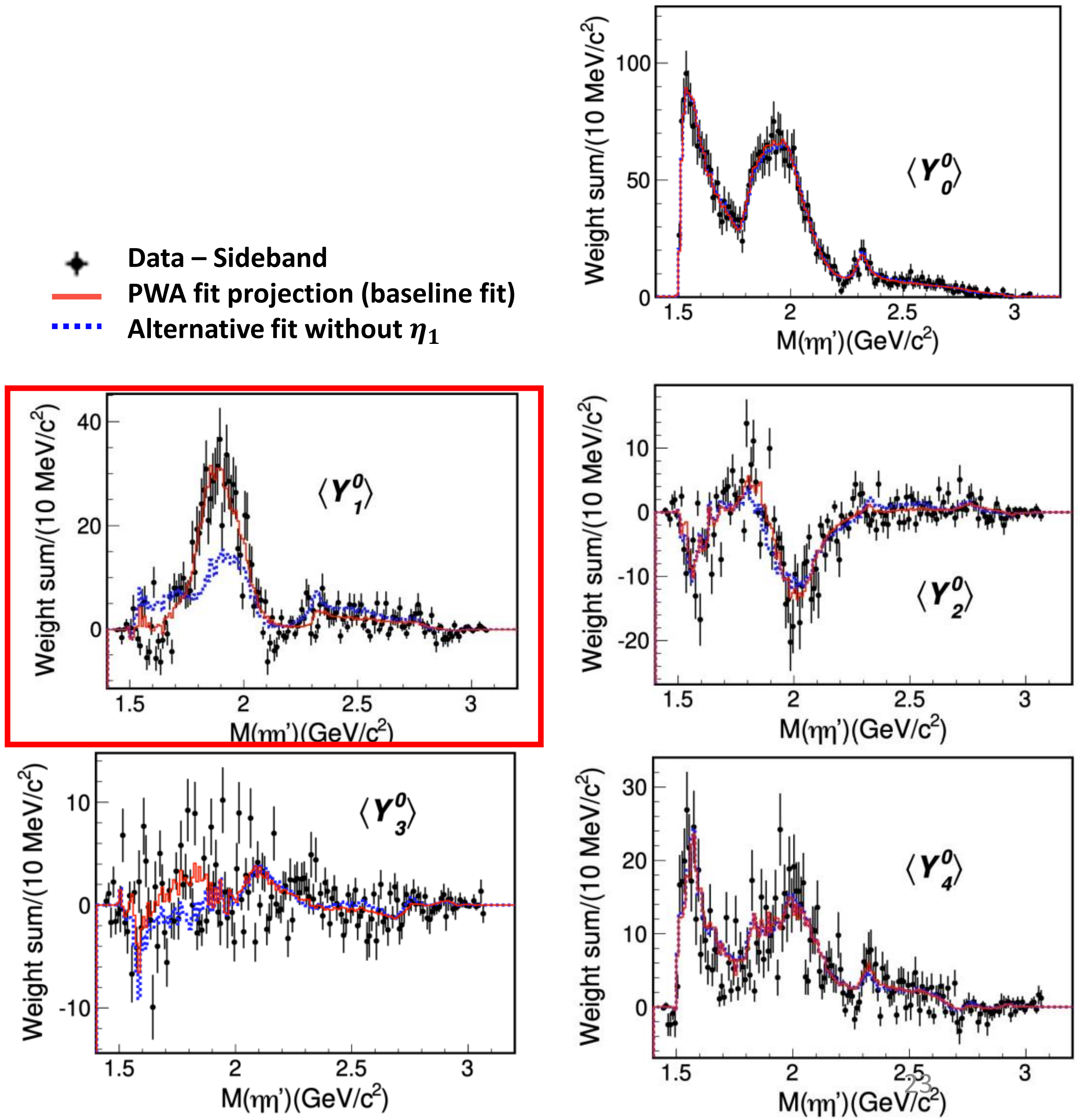
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0\cos\phi_{D_0},$$

$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

- **Narrow structure** in $\langle Y_1^0 \rangle$
  - ➢ **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**



Discussions about $f_0(1500)$ & $f_0(1710)$ in $J/\psi \to \gamma\eta\eta'$

- Significant $f_0(1500)$

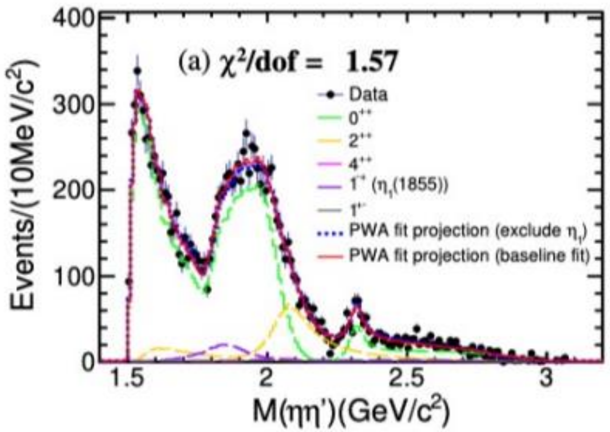
$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

consistent with PDG

- **Absence of $f_0(1710)$**

$$\frac{B(f_0(1710) \to \eta\eta')}{B(f_0(1710) \to \pi\pi)} < 2.87 \times 10^{-3} \text{ @90\% C. L.}$$

➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$

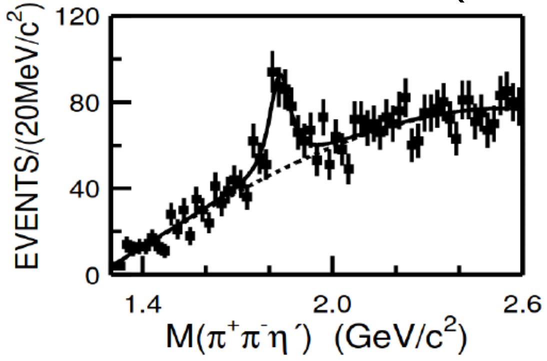


Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

New states in $J/\psi \to \gamma\pi^+\pi^-\eta'$

58 M J/ψ

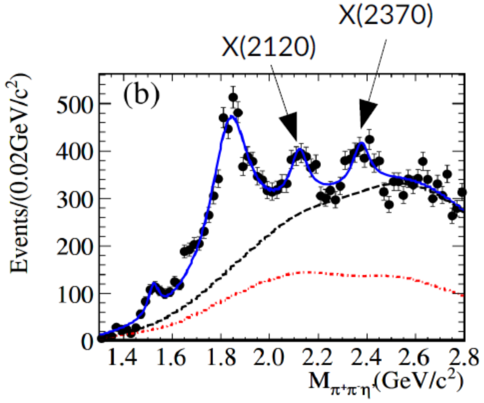
BESII PRL 95 262001(2005)



Observation of X(1835)

225M J/ψ

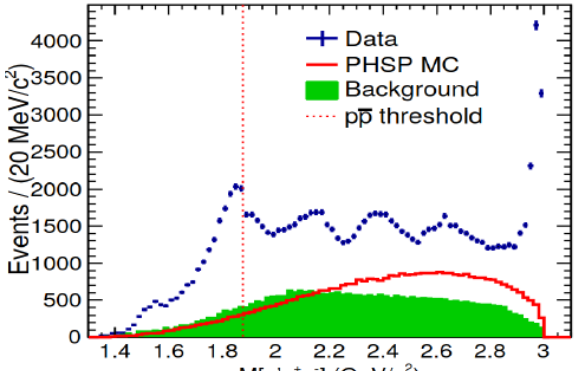
BESIII PRL 106 072002(2011)



Observation of X(2120), X(2370)

1.3B J/ψ

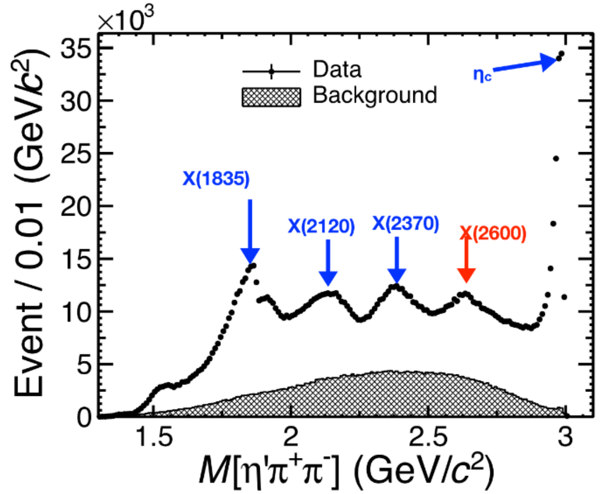
BESIII PRL 117 042002(2016)



Anomalous line shape near $p\bar{p}$ threshold

10B J/ψ

BESIII PRL 129, 042001 (2022)

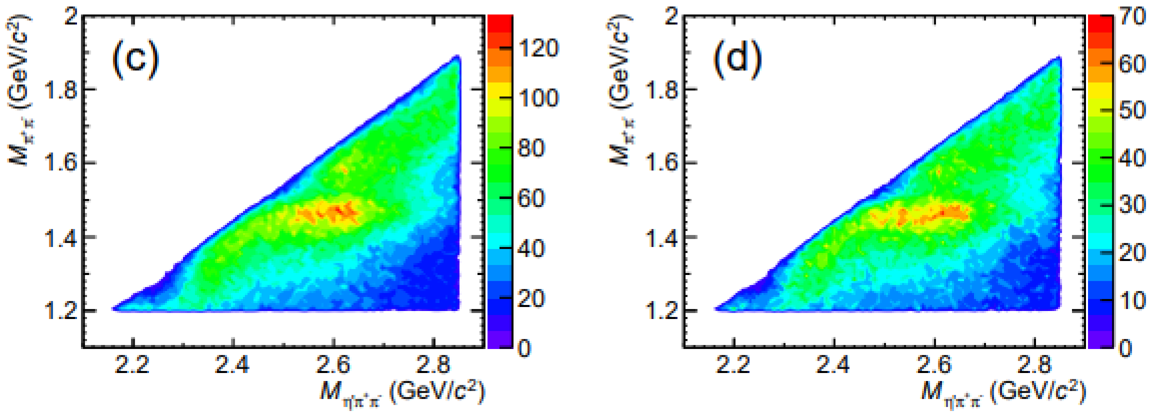


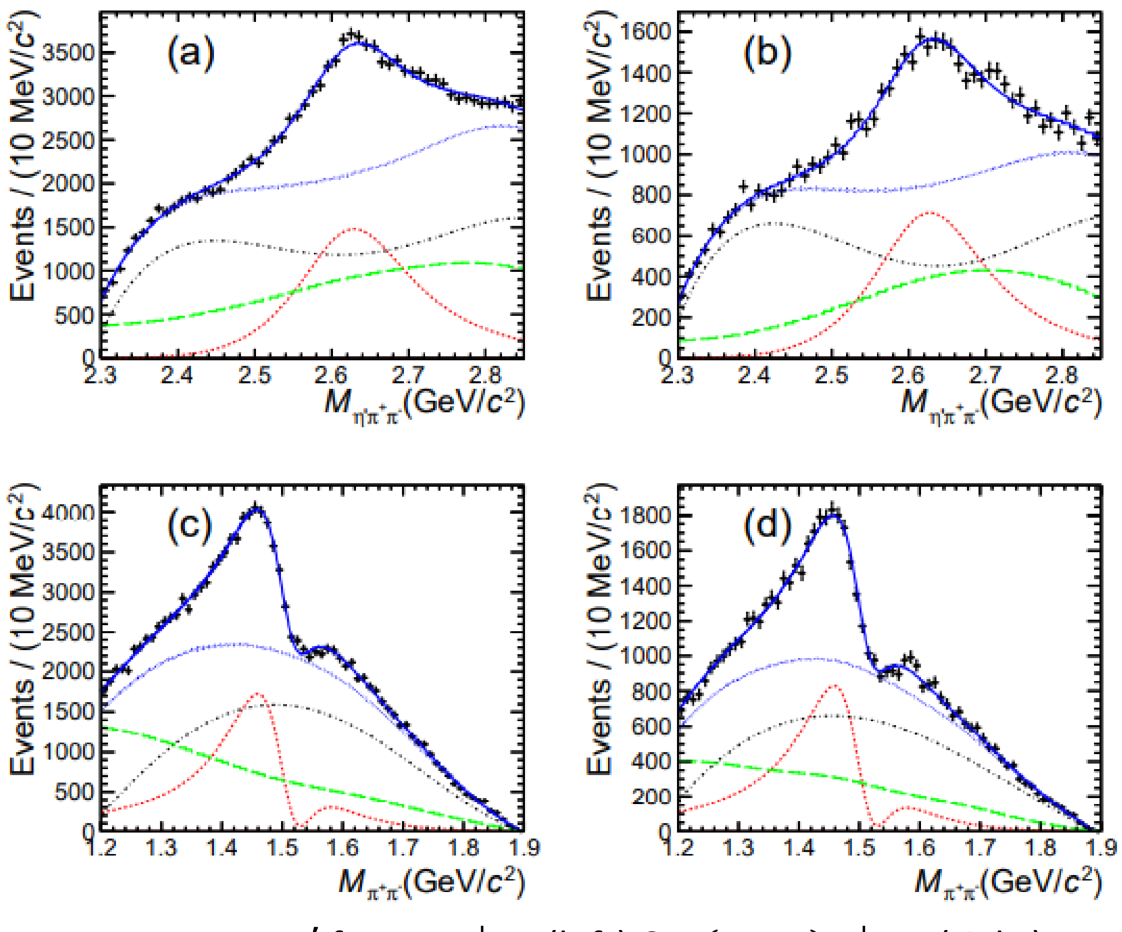
Observation of X(2600)

A New State $X(2600)$ Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 129, 042001 (2022)

- To study $X(2600)$ parameters, a simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ is performed
- The structure in $M(\pi^+\pi^-)$ well described with the interference between $f_0(1500)$ and $X(1540)$





reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

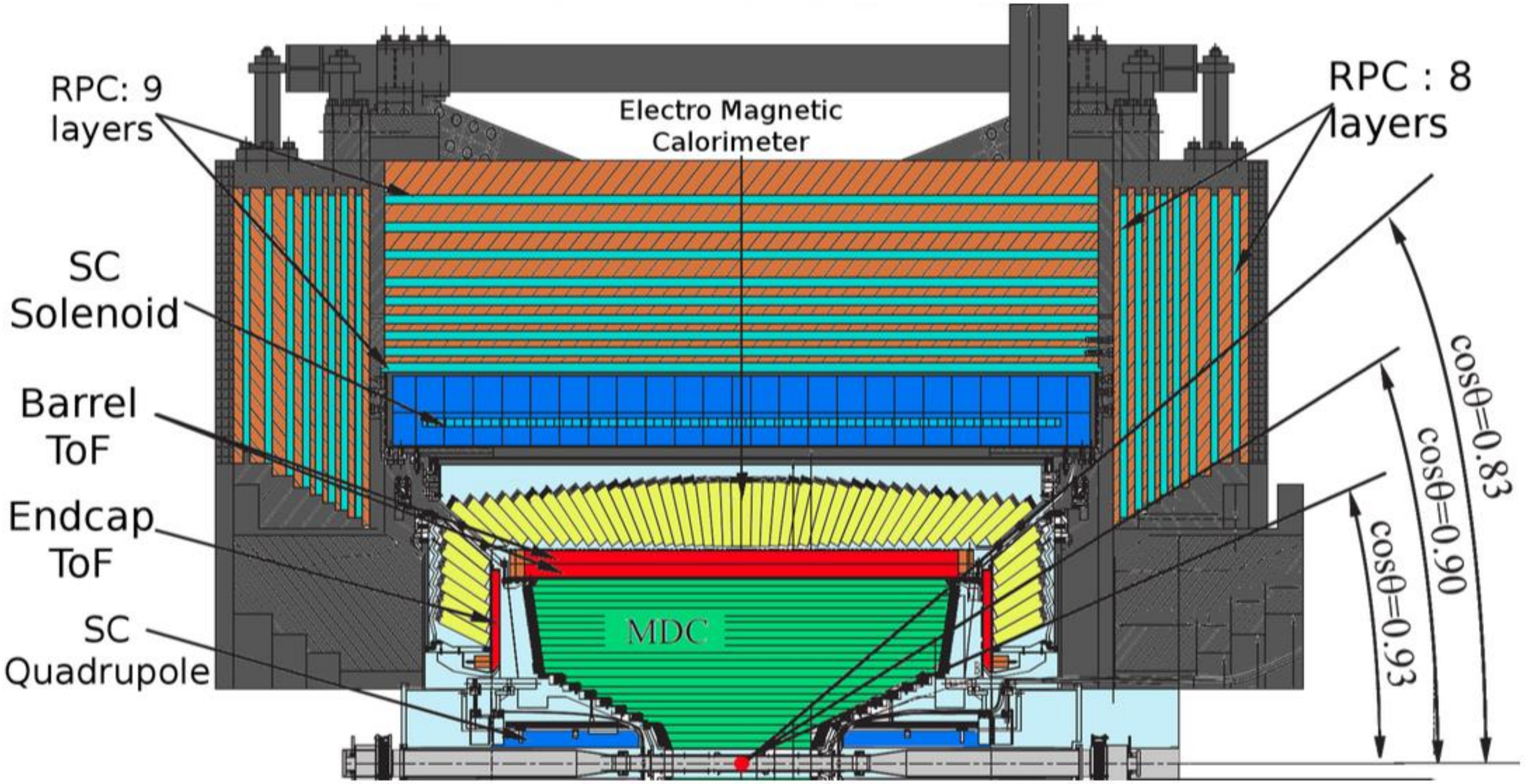
Summary

- **Exciting results from new J/ψ and XYZ data are presented**
  - **Mapping out non-trivial structures of Y states**
  - **Further information on X(3872)**
  - **The Z_c family has expanded with the strange Z_{cs}**
  - **Spin exotics state: $\eta_1(1855)$**
  - **New state X(2600) in J/ψ radiative decays**
- **Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030**
- **BESIII is in good status, inner detector upgrade in progress; High-lumi. fine scan between 3.8 GeV and 5.6 GeV is planned**

  ➔ BEPCII-U: 3x upgrade on luminosity; Ecms expanded to 5.6 GeV (summer 2024)

Thank you for your attention

Beijing Spectrometer(BESIII) Experiment

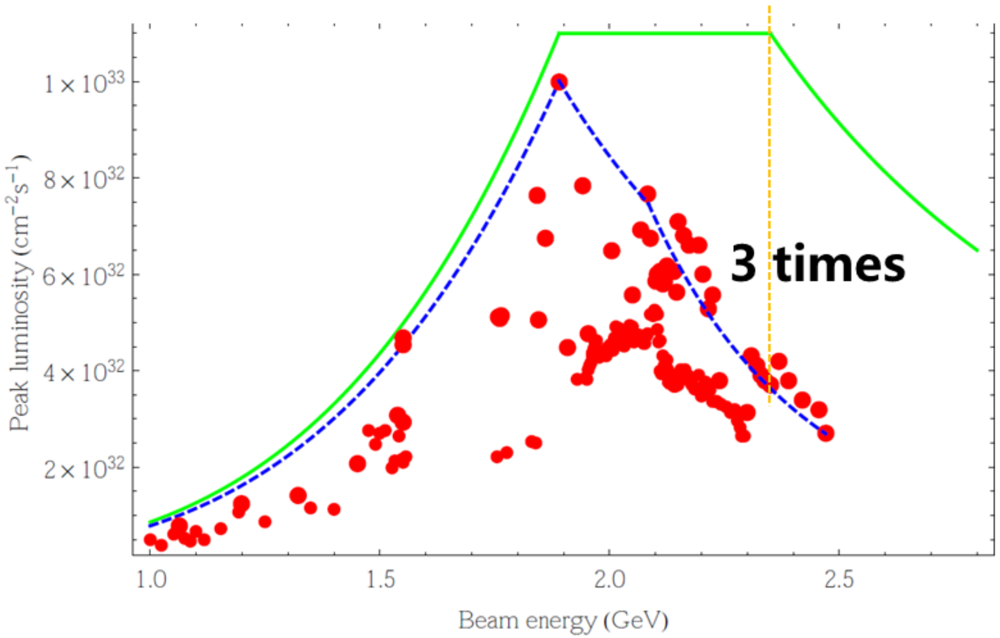


- Main Drift Chamber (MDC)
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dX} = 5.0\%$
- Time-of-flight (TOF)
  - $\sigma(t)$ = 68ps (barrel)
  - $\sigma(t)$ = 65ps (endcap)
- Electro Magnetic Calorimeter (EMC)
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{z,\phi}(E)$ = 0.5 – 0.7 cm
- RPC MUON Detector
  - $\sigma(xy) < 2$ cm

Beam Energy：2.35GeV

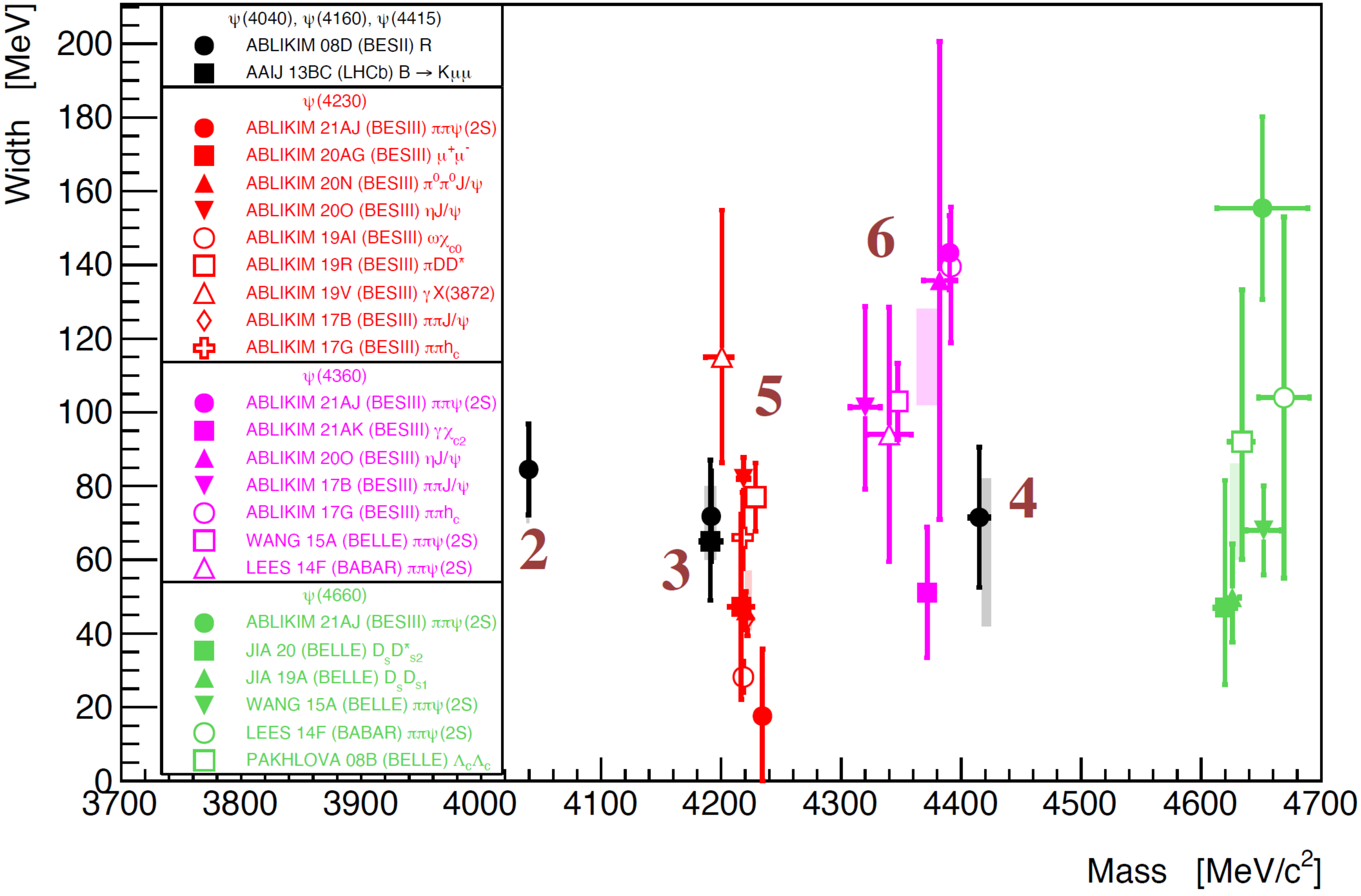
	BEPCII	BEPCII-U
Lum [$10^{32}cm^{-2}s^{-1}$]	3.5	11
β_y^* [cm]	1.5	1.3
Bunch Current [mA]	7.1	7.5
Bunch Num	56	120
SR Power [kW]	110	250
$\xi_{y,\mathrm{lum}}$	0.029	0.036
Emittance [nmrad]	147	152
Coupling [%]	0.53	0.35
Bucket Height	0.0069	0.011
$\sigma_{z,0}$ [cm]	1.54	1.04
σ_z [cm]	1.69	1.3
RF Voltage	1.6 MV	3.3 MV

BEPCII-U vs BEPCII



- **Luminosity is increased by a factor of 3 @2.35GeV**
- **Maximum beam energy is increased from 2.1GeV to 2.8GeV.**

PDG 2022 ψ States



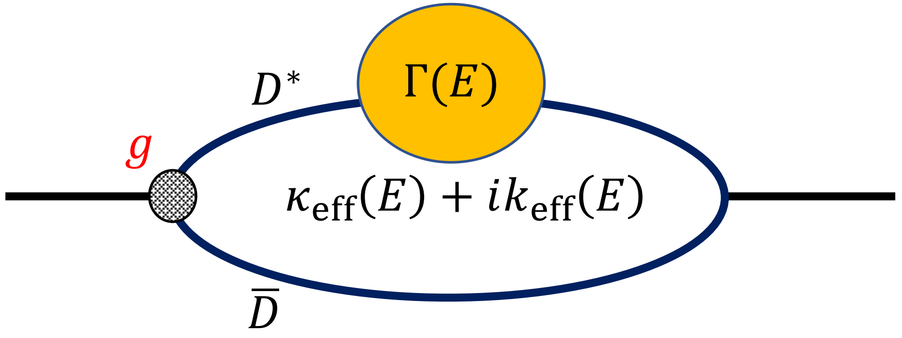
Plot from R. Mitchell

Lineshape parameterization

$$\frac{d\mathrm{Br}\left(D^0\bar{D}^0\pi^0\right)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2}\times\mathrm{Br}\left(D^{*0}\to D^0\pi^0\right)$$

$$\frac{d\mathrm{Br}(\pi^+\pi^- J/\psi)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

[C. Hanhart, PRD 81, 094028 (2010)]



$$D(E) = E - E_X + \frac{1}{2}g * \left(\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E) + \kappa_{\mathrm{eff}}^c(E) + ik_{\mathrm{eff}}^c(E)\right) + \frac{i}{2}\Gamma_0$$

$$k_{\mathrm{eff}}(E) = \sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}+E-E_R}$$

$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}-E+E_R}$$

$$+\sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2+\Gamma_X^2/4}-E_X+E_R}$$

$$\Gamma_0 = \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$$E_X = M_X - (m_{D^0} + m_{\bar{D}^0} + m_{\pi^0})$$

$\boldsymbol{B}$: the global normalization

Key features:

- Model independent
- Including the $D^*\bar{D}$ self energy terms
- Including the width of D^*
- Including the coupled channel effect
- Fit parameters: g, $\Gamma_{\pi^+\pi^- J/\psi}$, M_X

* superscript c: charged $D^{*+}D^-$
* Due to the limited statistics, $\boldsymbol{\Gamma_{unknown}/\Gamma_{\pi^+\pi^- J/\psi}}$ is fixed [Chunhua Li, Chang-Zheng Yuan, PRD 100(2019) 094003]

Correlate the expected numbers of signals

$$2\ Im[D(E)] = g * (k_{\text{eff}}+k_{\text{eff}}^{c}) + \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

The produced numbers of events in a fitting range (E_{min}, E_{max}) are:

$$\mu_{X(3872)}^{prod} = \int_{E_{min}}^{E_{max}} dE\ \frac{B}{2\pi} * \frac{2\ Im[D(E)]}{|D(E)|^2}$$

$$\mu_{D^0\bar{D}^0\pi^0}^{prod} = \text{Br}\left(D^{*0} \to D^0\pi^0\right) \times \int_{E_{min}}^{E_{max}} dE\ \frac{B}{2\pi} * \frac{g * k_{\text{eff}}}{|D(E)|^2}$$

$$\mu_{\pi^+\pi^- J/\psi}^{prod} = \int_{E_{min}}^{E_{max}} dE\ \frac{B}{2\pi} * \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

$$\mu_{D^0\bar{D}^0\pi^0} = \epsilon_{D^0\bar{D}^0\pi^0} \times R_{D^0\bar{D}^0\pi^0} \times \mu_{X(3872)}^{prod}$$

$$\mu_{\pi^+\pi^- J/\psi} = \epsilon_{\pi^+\pi^- J/\psi} \times R_{\pi^+\pi^- J/\psi} \times \mu_{X(3872)}^{prod}$$

ϵ : efficiency and branching fractions correction

$$R_{D^0\bar{D}^0\pi^0} = \text{Br}\left(D^{*0} \to D^0\pi^0\right) \times \frac{\int_{E_{min}}^{E_{max}} dE\ \frac{g * k_{\text{eff}}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE\ \frac{2\ Im[D(E)]}{|D(E)|^2}}$$

$$R_{\pi^+\pi^- J/\psi} = \frac{\int_{E_{min}}^{E_{max}} dE\ \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE\ \frac{2\ Im[D(E)]}{|D(E)|^2}}$$

Only one new parameter $\mu_{X(3872)}^{prod}$

Compare with LHCb

	LHCb	This work
g	$0.108 \pm 0.003^{+0.005}_{-0.006}$	$0.16 \pm 0.10^{+1.12}_{-0.11}$
$Re[E_I]$ [MeV]	7.10	$7.04 \pm 0.15^{+0.07}_{-0.08}$
$Im[E_I]$ [MeV]	-0.13	$-0.19 \pm 0.08^{+0.14}_{-0.19}$
$\frac{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)}{\Gamma(X(3872) \to D^0\bar{D}^{*0})}$	0.11 ± 0.03	$0.05 \pm 0.01^{+0.01}_{-0.02}$
FWHM (MeV)	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$	$0.44^{+0.13}_{-0.35}{}^{+0.38}_{-0.25}$
Z	0.15	0.18

The inclusion of the D^+D^{*-} term in the model lengthens the tail of the lineshape in the $D^0\bar{D}^0\pi^0$ channel and results in a larger signal yield.

Lineshape parameterization

$$\frac{d\mathrm{Br}\left(D^0\bar{D}^0\pi^0\right)}{dE} = \boldsymbol{B}\,\frac{1}{2\pi} \times \frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2} \times \mathrm{Br}\left(D^{*0} \to D^0\pi^0\right)$$

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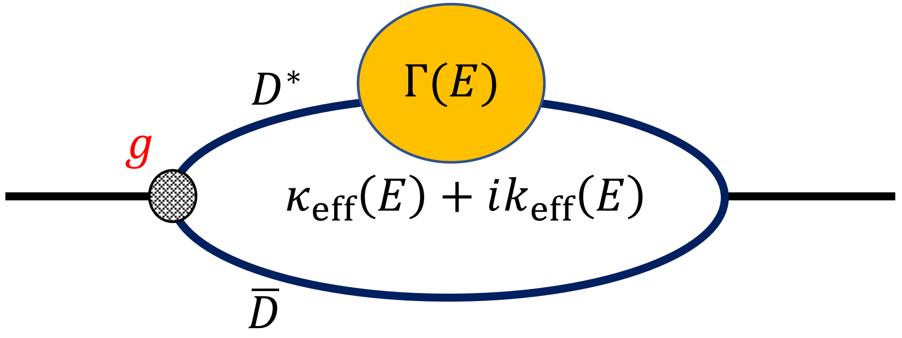

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$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2/4} - E + E_R}$$

$$+\sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2 + \Gamma_X^2/4} - E_X + E_R}$$

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⁎ superscript c: charged $D^{*+}D^-$

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[Chunhua Li, Chang-Zheng Yuan, PRD 100(2019) 094003]

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$$\mu^{prod}_{\pi^+\pi^- J/\psi} = \int_{E_{min}}^{E_{max}} dE \, \frac{B}{2\pi} * \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

$$\mu_{D^0\bar{D}^0\pi^0} = \epsilon_{D^0\bar{D}^0\pi^0} \times R_{D^0\bar{D}^0\pi^0} \times \mu^{prod}_{X(3872)}$$

$$\mu_{\pi^+\pi^- J/\psi} = \epsilon_{\pi^+\pi^- J/\psi} \times R_{\pi^+\pi^- J/\psi} \times \mu^{prod}_{X(3872)}$$

ϵ : efficiency and branching fractions correction

$$R_{D^0\bar{D}^0\pi^0} = \text{Br}\left(D^{*0} \to D^0\pi^0\right) \times \frac{\int_{E_{min}}^{E_{max}} dE \, \frac{g * k_{\text{eff}}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE \, \frac{2\,Im[D(E)]}{|D(E)|^2}}$$

$$R_{\pi^+\pi^- J/\psi} = \frac{\int_{E_{min}}^{E_{max}} dE \, \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE \, \frac{2\,Im[D(E)]}{|D(E)|^2}}$$

Only one new parameter $\mu^{prod}_{X(3872)}$

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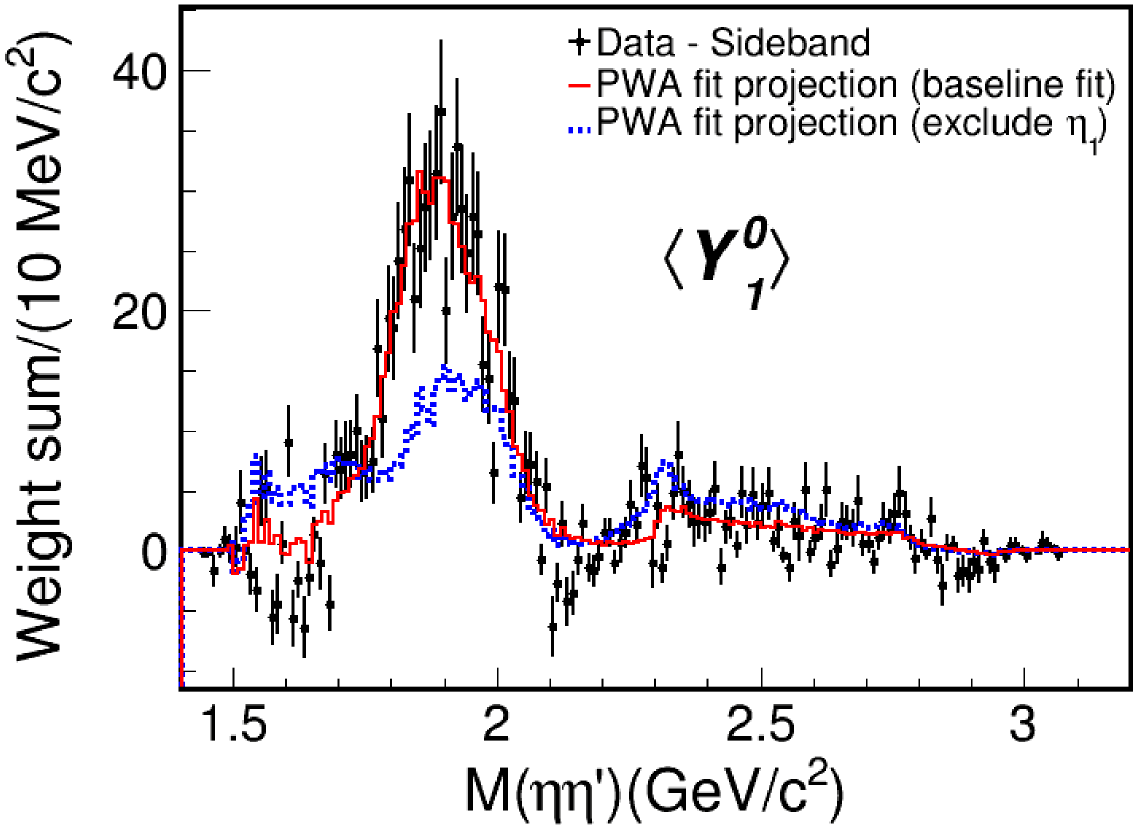
$Re[E_I]$ [MeV]	7.10	$7.04 \pm 0.15^{+0.07}_{-0.08}$
$Im[E_I]$ [MeV]	-0.13	$-0.19 \pm 0.08^{+0.14}_{-0.19}$
$\frac{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)}{\Gamma(X(3872) \to D^0\bar{D}^{*0})}$	0.11 ± 0.03	$0.05 \pm 0.01^{+0.01}_{-0.02}$
FWHM (MeV)	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$	$0.44^{+0.13}_{-0.35}{}^{+0.38}_{-0.25}$
Z	0.15	0.18

The inclusion of the D^+D^{*-} term in the model lengthens the tail of the lineshape in the $D^0\bar{D}^0\pi^0$ channel and results in a larger signal yield.

Angular moments without contribution from D wave and F wave

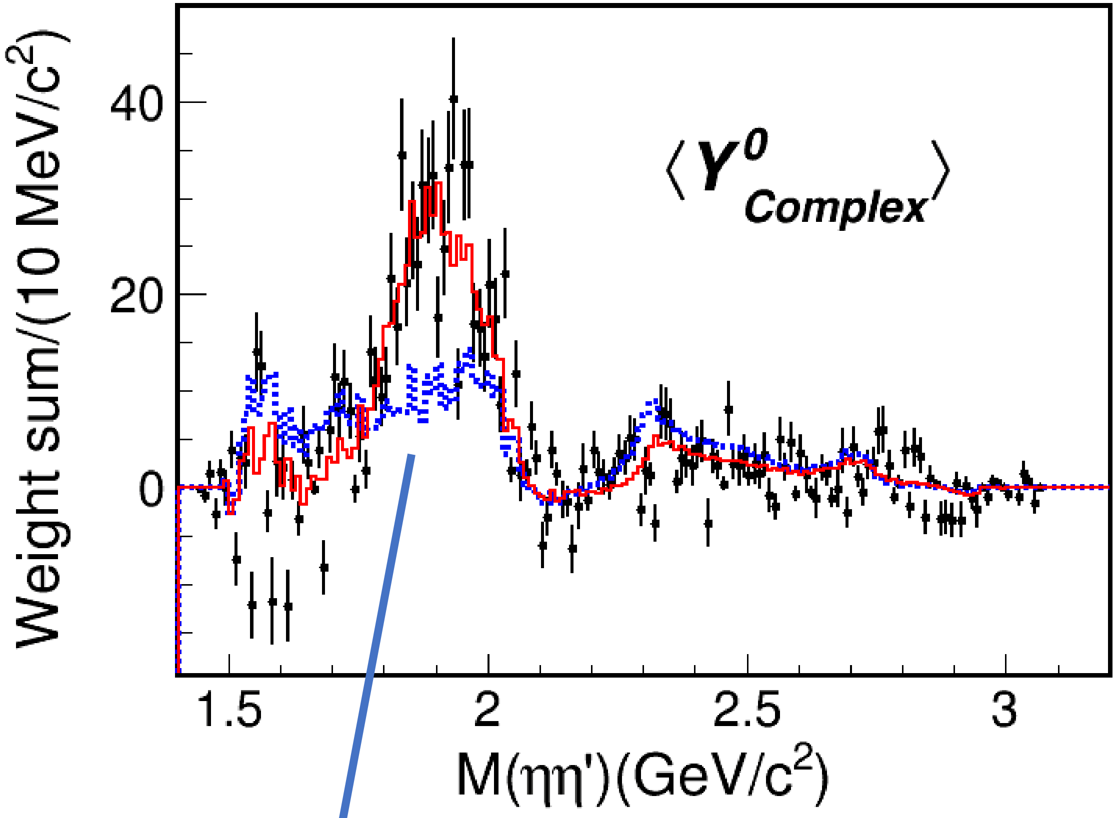
P wave

$$< Y_1^0 > \propto \boxed{\frac{2}{\sqrt{3}} SPcos(\phi_P) + \frac{4}{\sqrt{15}} PD\cos(\phi_P - \phi_D)} + \frac{6}{\sqrt{35}} DF\cos(\phi_D - \phi_F)$$



P wave

$$< Y_1^0 > - \frac{14}{9} < Y_3^0 > - \frac{308}{225} < Y_5^0 > = \boxed{\frac{2}{\sqrt{3}} SPcos(\phi_P)}$$

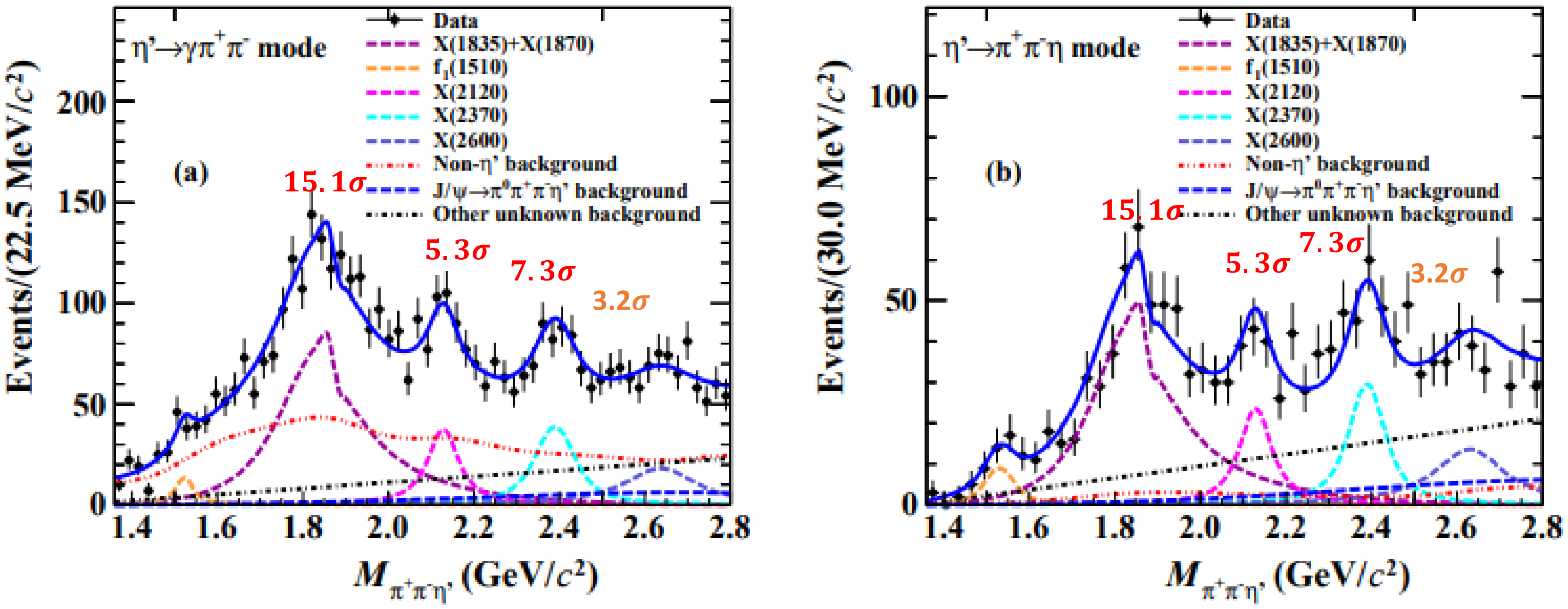


The blue line becomes flat from a peak structure

Observation of X(1835), X(2120) and X(2370) in J/ψ EM Dalitz Decays

$J/\psi \rightarrow \mathbf{e^+e^-}\pi^+\pi^-\eta'$

- **Confirmation** of $\mathbf{X(1835), X(2120), X(2370)}$ previously observed in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$



10 billion J/ψ
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reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\rightarrow\gamma\gamma)\pi^+\pi^-$ (right)

Observation of X(1835), X(2120) and X(2370) in J/ψ EM Dalitz Decays

$$J/\psi \rightarrow e^+e^-\pi^+\pi^-\eta'$$

- Measurement of the **Transition Form Factor** of $J/\psi \rightarrow e^+e^-X(1835)$
  - ➢the structure-dependent partial width can be modified by transition form factor, which provides information of the EM structure

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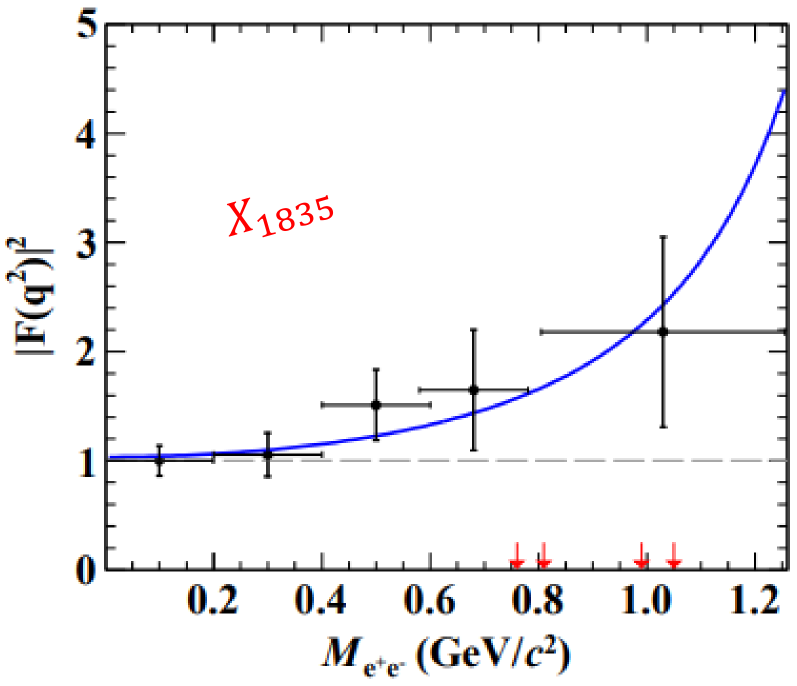
$$\frac{d\Gamma(J/\psi \rightarrow X(1835)e^+e^-)}{dq^2\Gamma(J/\psi \rightarrow X(1835)\gamma)} = |F(q^2)|^2 \times [QED(q^2)]$$

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

$$\Lambda = 1.75 \pm 0.29 \pm 0.05\ GeV/c^2$$

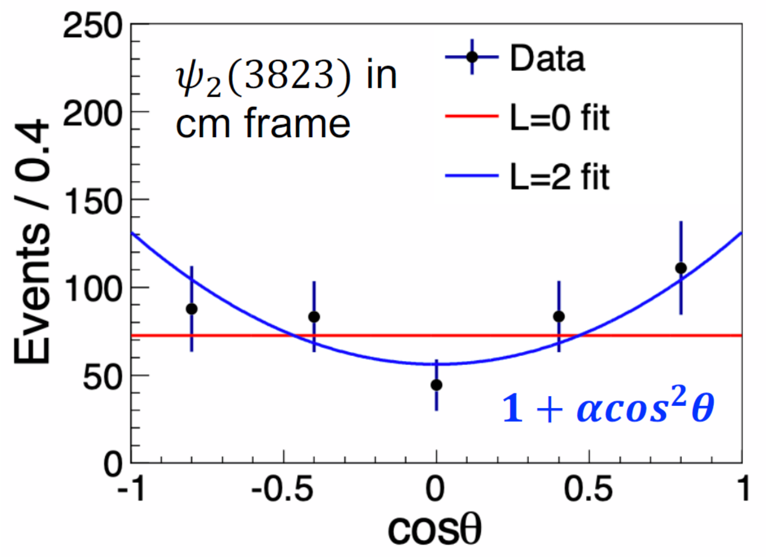


$\psi_2(3823)$-the $\psi(1^3D_2)$ state?

$e^+e^- \to \psi_2(3823)\pi^+\pi^-$, $\psi_2(3823) \to \gamma\chi_{c1}$

PRL 129, 103003(2022)

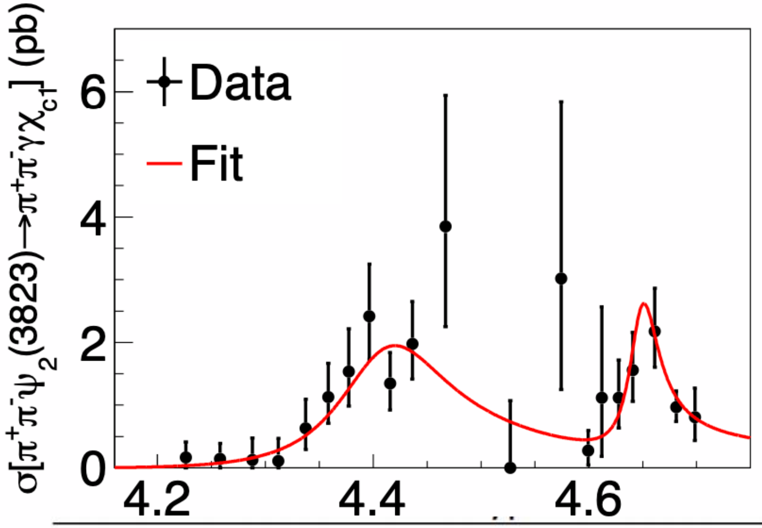
first observation of vector Y states decaying to D-wave charmonium state



L = 2 slightly favored over L = 0

$M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13$ MeV/c^2
$\Gamma[\psi_2(3823)] < 2.9$ MeV at 90% C.L.

Most precise to date!



Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

- ✓ Two-BW hypothesis:
  - Consistent with $Y(4360)$ and $Y(4660)$
- ✓ $\frac{\Gamma[\psi(4660)\to\pi^+\pi^-\psi_2(3823)]}{\Gamma[\psi(4660)\to\pi^+\pi^-\psi(2S)]} \sim 20\%$
  - Inconsistent with many interpretations of Y(4660):
    - $f_0(980)\psi(2S)$ hadron molecule (PLB 665, 26 (2018))
    - $\Sigma_c^0\bar{\Sigma}_c^0$ baryonium (J. Phys. G 35, 075008 (2008))
    - excitation of Y(4260) (PRD 89, 114010 (2014))