TWENTY-FIRST LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

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MOSCOW STATE UNIVERSITY

Light QCD exotics at BESIII

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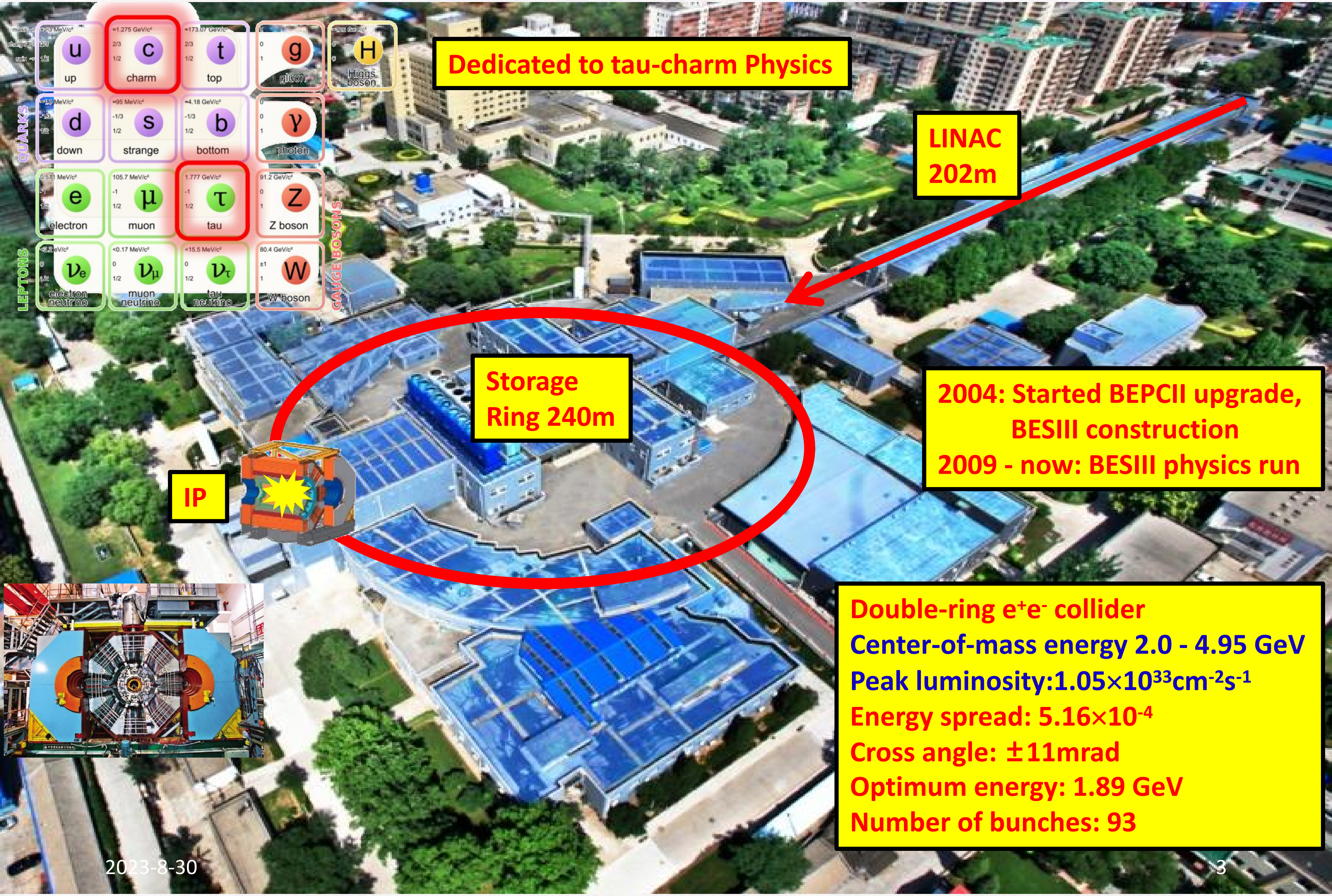
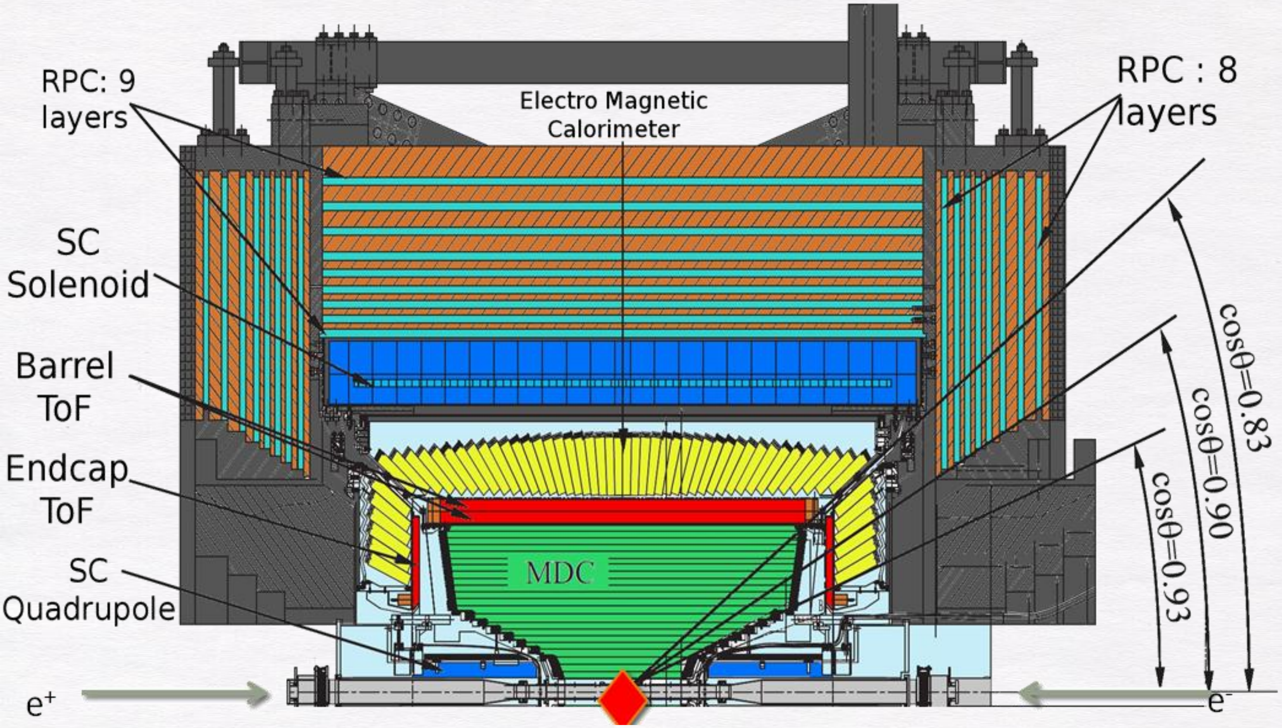
OUTLINE

- The BESIII experiment @ BEPCII
- Hadron spectroscopy
- Recent results @ BESIII
- Summary

Beijing Electron Positron Collider II



BESIII Detector



Main Drift Chamber:
$\sigma(p)/p = 0.5\%$ @ 1 GeV
$\sigma(dE/dx) = 6\%$

Time of Flight:
σ_t = 68 ps (barrel)
σ_t = 110(60) ps (endcap,upgrade)

Electromagnetic Calorimeter:
CsI(Tl) crystal;
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (endcap)
$\sigma_{xy} = (6mm)/\sqrt{E}$ @ 1 GeV

Magnet: 1T superconducting

Muon Counter:
Resistive Plate Chamber
$\sigma(xy) < 2$ cm

Total weight 730 tons,
~40,000 read-out channels,
Data rate: 5kHz, 50Mb/s

In full operation since 2008, still in very good status now!

BESIII physics program

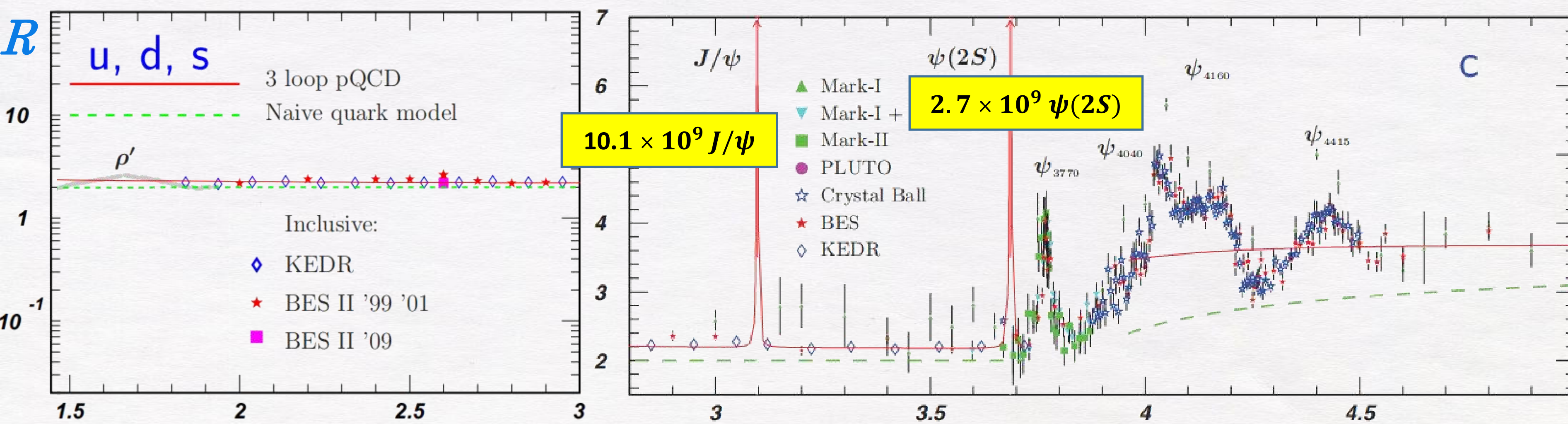
- ✓ R value
- ✓ τ physics
- ✓ Hadron form factors
- ✓ Light vector mesons

- ✓ “exotic” hadrons
- ✓ η/η' decays
- ✓ Baryon spectrum
- ✓ Meson spectrum
- ✓ Hyperon physics

- ✓ XYZ states
- ✓ charmonium transitions
- ✓ ...

- ✓ $D(D_S^{(*)})$ decays
- ✓ D^0-$\bar{D}^0$ mixing
- ✓ Strong phases
- ✓ CKM matrix
- ✓ Charm baryons

- ✓ Dark matter
- ✓ Rare decay
- ✓ ...



World’s largest J/ψ and $\psi(2S)$ data samples directly collected,

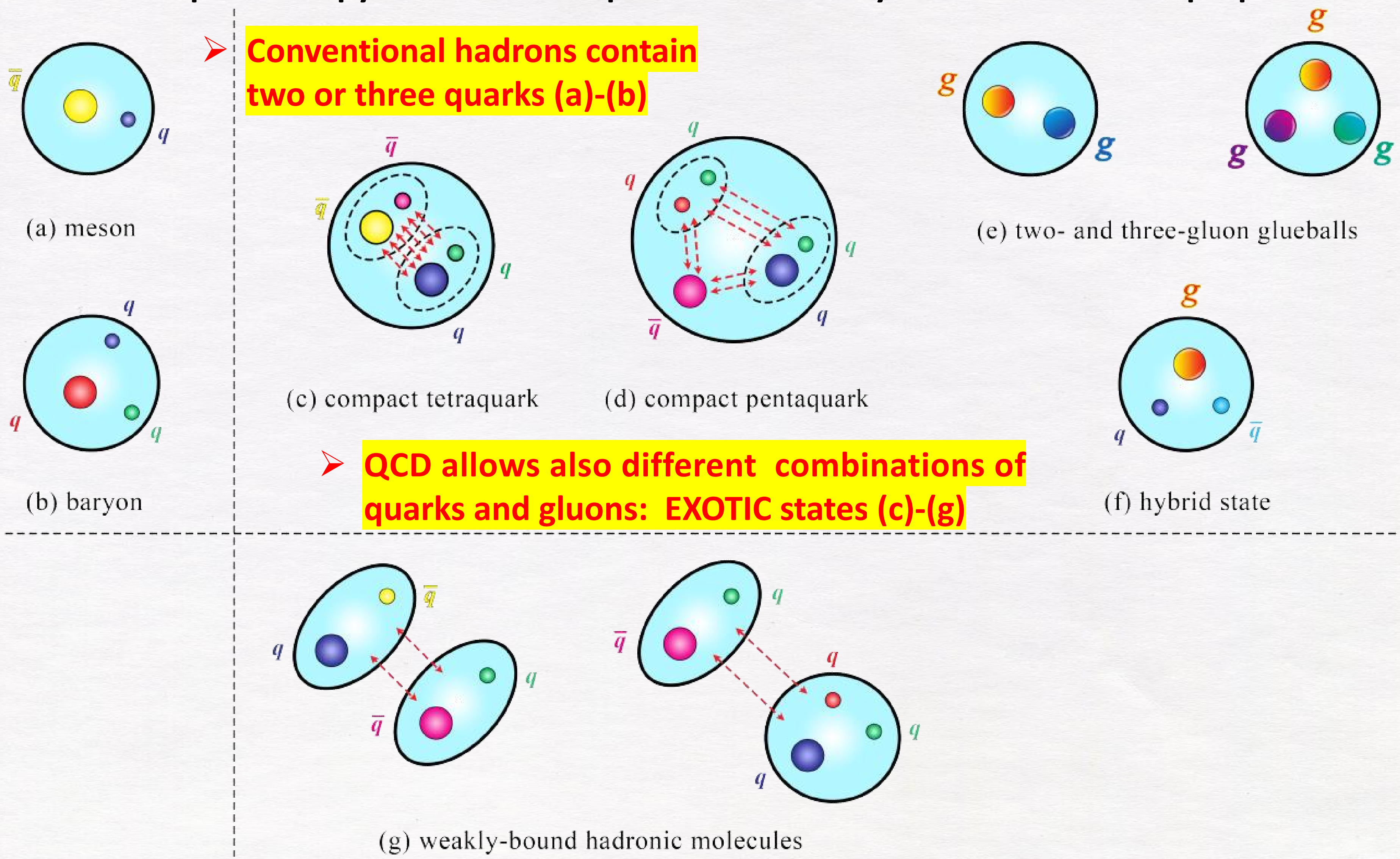
~40fb^{-1} data in E_{cm} = 2-4.95 GeV.

An excellent opportunity for studying light hadron physics!

Hadron spectroscopy

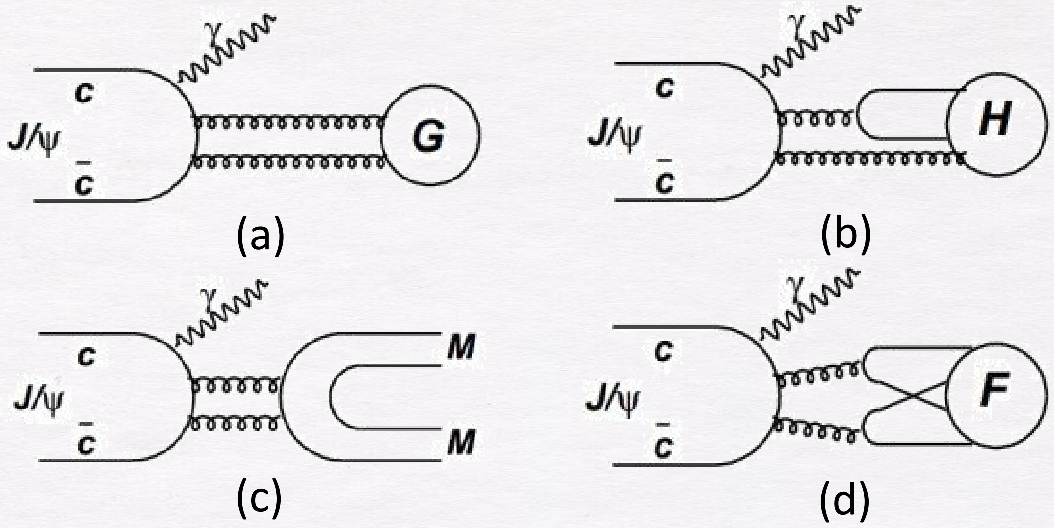
Hadron spectroscopy: Establish the spectrum and study the exotic hadrons properties.

- Conventional hadrons contain two or three quarks (a)-(b)
- QCD allows also different combinations of quarks and gluons: EXOTIC states (c)-(g)



Many exotic states have been observed, but their nature is still far from being understood!

Searches for exotic states



$\Gamma(J/\psi \to \gamma gg) \cong 6\%\Gamma_{J/\psi}$

- $\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$
- $\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$
- $\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4)$
- $\Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

Charmonium radiative decays provide an ideal laboratory for exotic states studies

- **High statistics** data samples.
- Well defined initial and final states (**clean**).
  - ✓ Kinematic constraints
  - ✓ I(J^{PC}) filter
- "**Gluon-rich**" environment. $\Gamma(J/\psi \to \gamma G) > \Gamma(J/\psi \to \gamma H) > \Gamma(J/\psi \to \gamma M) \geq \Gamma(J/\psi \to \gamma F)$

Searches for exotic states

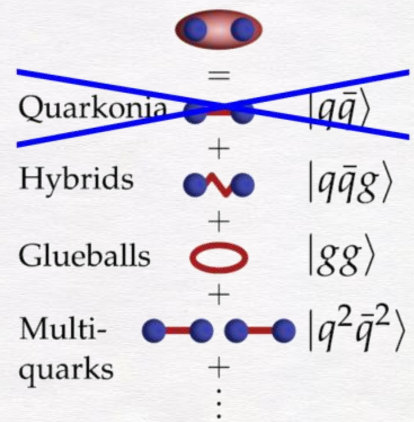
Manifest exotic

- Quark contents more than $q\bar{q}$ or qqq.
- Quantum number not reachable for ordinary mesons or baryons.

Ambiguous exotic

- Overpopulation of states.
- Mass/width not fit in spectra.
- Production incompatible with standard mesons/baryons.

- Light-flavor exotic states are hard to establish.
- Exotic quantum numbers are forbidden by $q\bar{q}$ configuration.
- Focus on spin-exotic states $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$.



J^{PC}	0^{++}	0^{+-}	0^{-+}	0^{--}	1^{++}	1^{+-}	1^{-+}	1^{--}	2^{++}	2^{+-}	2^{-+}	2^{--}	3^{++}	3^{+-}	3^{-+}	3^{--}
$q\bar{q}$	✓	×	✓	×	✓	✓	×	✓	✓	×	✓	✓	✓	✓	×	✓
$q\bar{q}q\bar{q}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$q\bar{q}g$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
gg	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×

Searches for exotic states

Glueball searches

- Provide critical information on the gluon field.
- Obtain quantitative understanding of confinement.
- 0^{++}, 0^{-+} and 2^{++} glueballs predicted by LQCD:

  Mass under 3.0 GeV.

Exotic hybrids

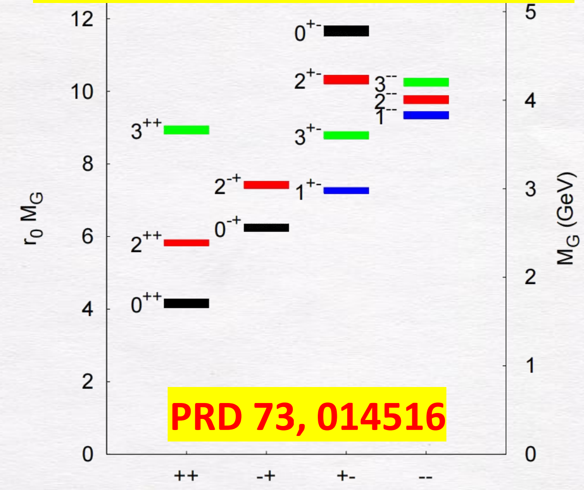
- Some low-order hybrids have exotic quantum numbers

  1^{-+}, 0^{+-}, 2^{+-} which are forbidden by $q\bar{q}$ configuration.

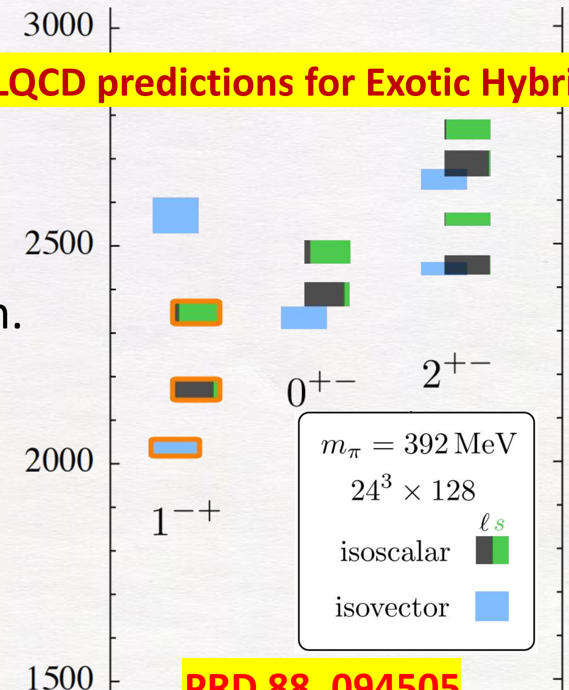
- 1^{-+} hybrids predicted by LQCD: **Mass around 2.0 GeV**.

An excellent opportunity for studying them using J/ψ or $\psi(2S)$ data samples!

LQCD predictions for Glueballs



LQCD predictions for Exotic Hybrids



Searches for exotic states

Exotic hybrids

- **1^{-+} nonet of hybrids is predicted to be the lightest.**
- **Isovector 1^{-+} have been observed including $\pi_1(1400)$, $\pi_1(1600)$ and $\pi_1(2015)$.**
  - Hybrid is the most popular interpretation.
  - $\pi_1(1400)$ and $\pi_1(1600)$ can be explained as one pole.

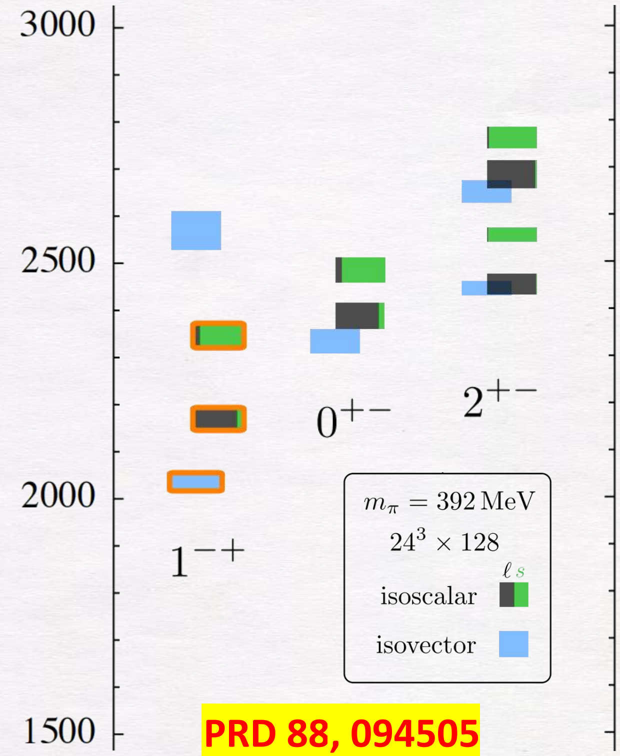
(PRD 105, 012005)

- **Isoscalar 1^{-+} is critical for establishing the hybrid nonet**
  - Can be produced in the gluon-rich J/ψ radiative decays.
  - Can decay to $\eta\eta'$ in P-wave.

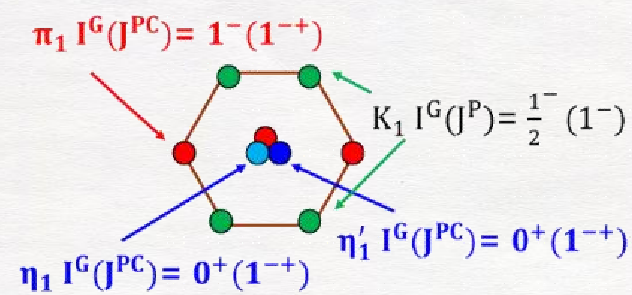
(PRD 83, 014021; PRD 83, 014006; EPJP 135, 945)

Observation of states with exotic quantum numbers, such as 1^{-+}, has been of great experimental interest!

LQCD predictions for Exotic Hybrids



PRD 88, 094505



Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

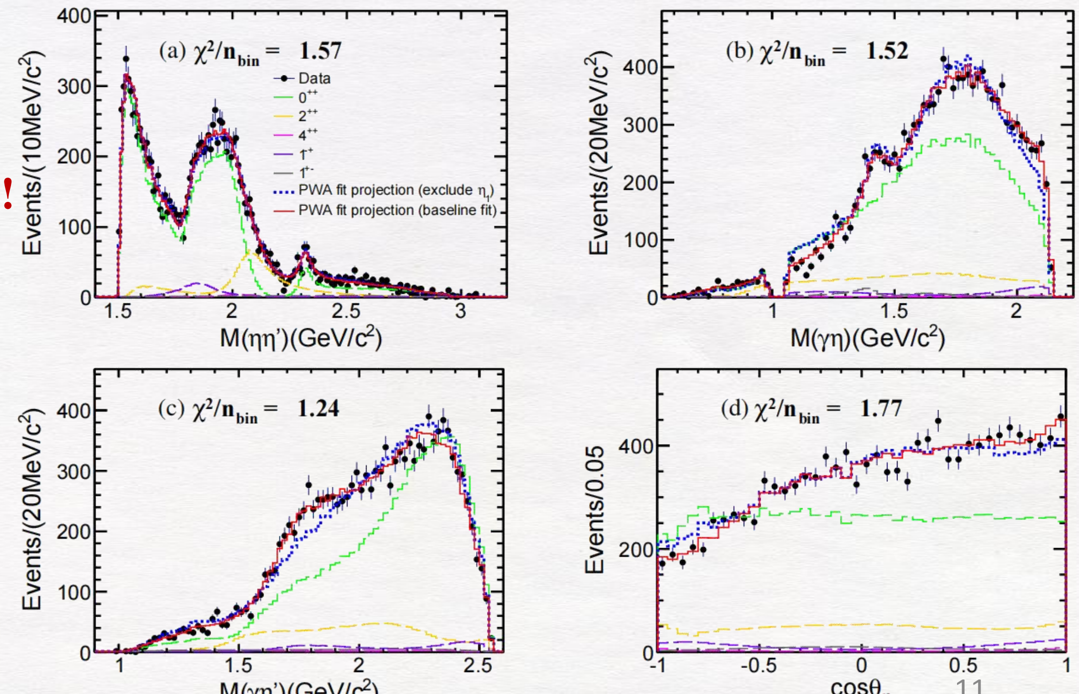
PWA of $J/\psi \to \gamma\eta\eta'$ using 10 Billion of J/ψ data @ BESIII

PRL 129, 192002 (2022)
PRD 106, 072012 (2022)

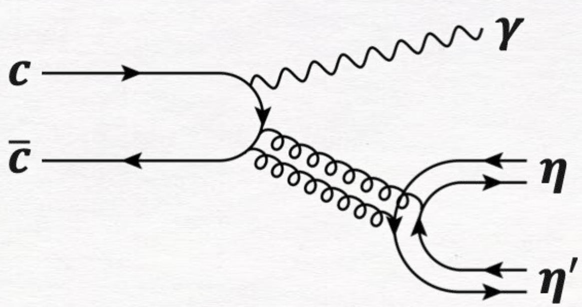
- $\eta \to \gamma\gamma$ and $\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$.
- **An isoscalar 1^{-+} state, $\eta_1(1855)$,** has been observed with statistical significance **larger than 19σ**.
- **Consistent with LQCD calculation for 1^{-+} hybrid** (Mass 1.7 – 2.1 GeV).

EPJA 16, 537

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	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	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



Critical to establish the 1^{-+} hybrid nonet !

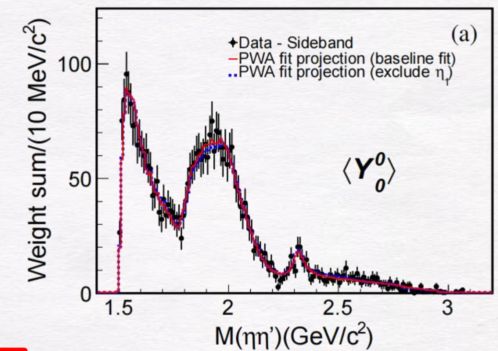


Further checks on the 1^{-+} state $\eta_1(1855)$

- The $\cos(\theta_\eta)$ distribution can be expressed as an expansion in terms of Legendre polynomials; **the coefficients (unnormalized moments of expansion) characterize the spin of the $\eta\eta'$ resonances**. The moment for the kth bin of $M(\eta\eta')$ is:

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

PRL 129, 192002 (2022)
PRD 106, 072012 (2022)



- The moments are related to the spin-0(S), spin-1(P) and spin-2(D) amplitudes by:

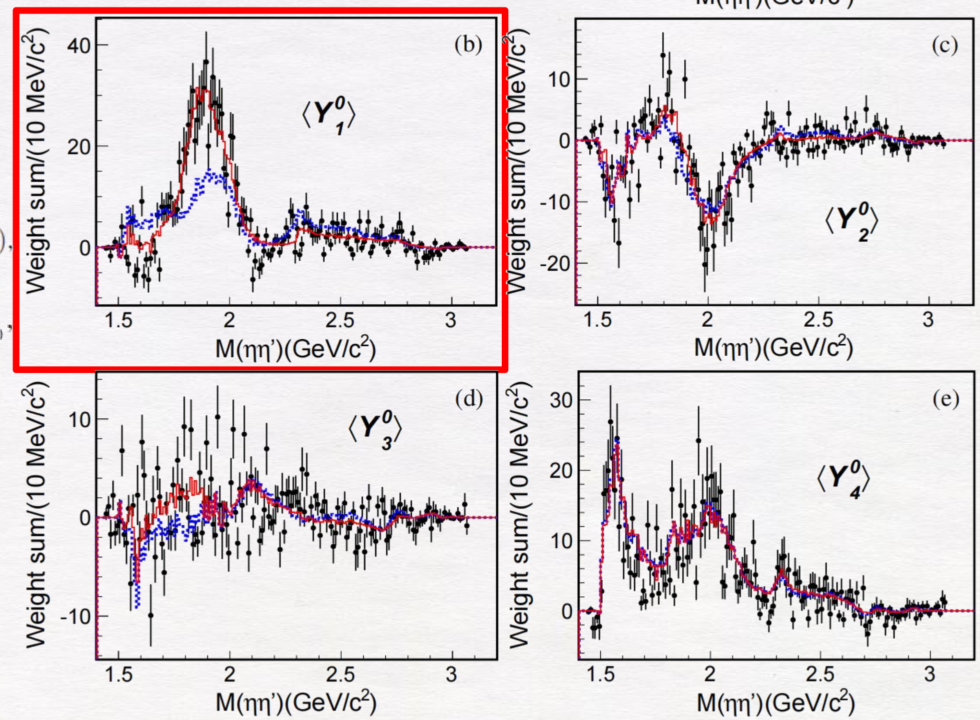
$$\sqrt{4\pi}\langle Y_0^0 \rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

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

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

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

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

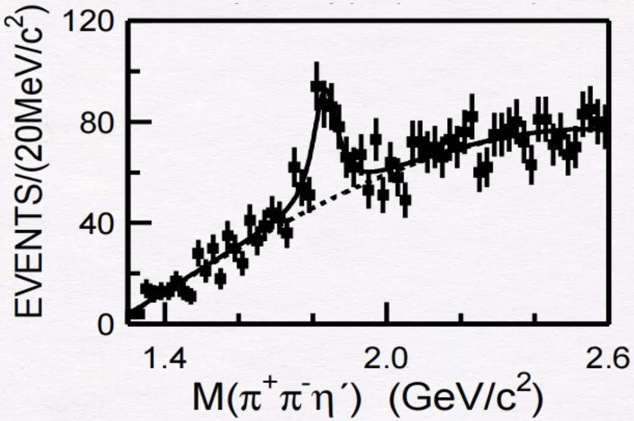


- **$< Y_1^0 >$ indicates significant P-wave.**
- In $\eta\eta'$ system, the **narrow structure should be $\eta_1(1855)$** P-wave component.

Good agreement between the PWA fit results and data.

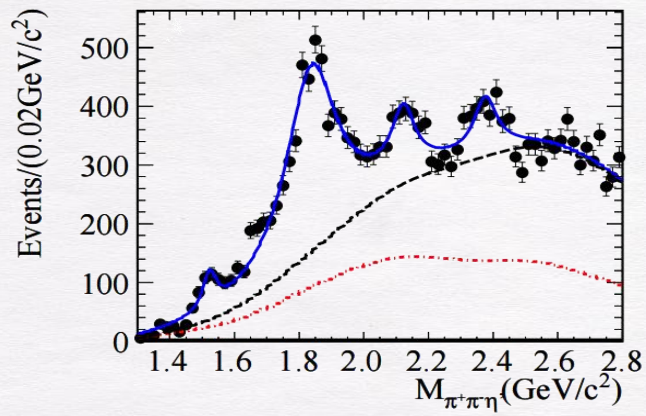
States in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 95, 262001 (2005) 58M J/ψ



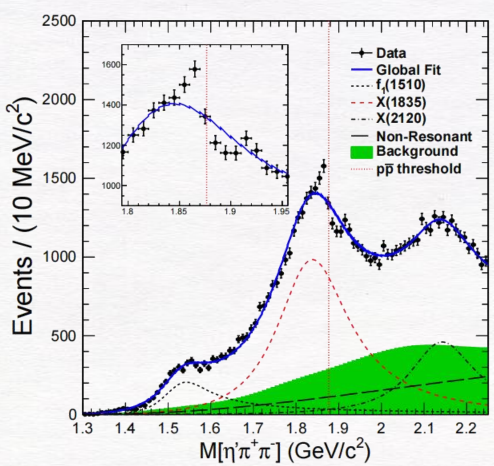
Observation of X(1835)

PRL 106, 072002 (2011) 225M J/ψ

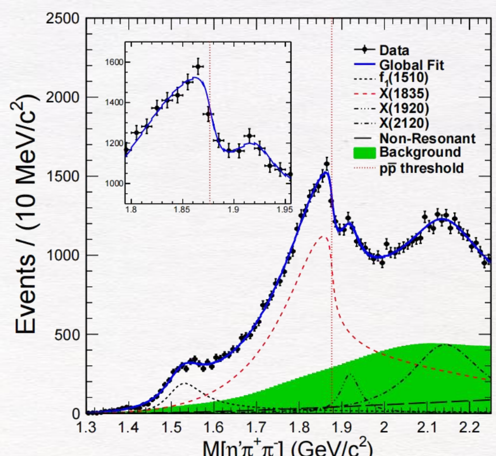


Observation of X(2120) and X(2370)

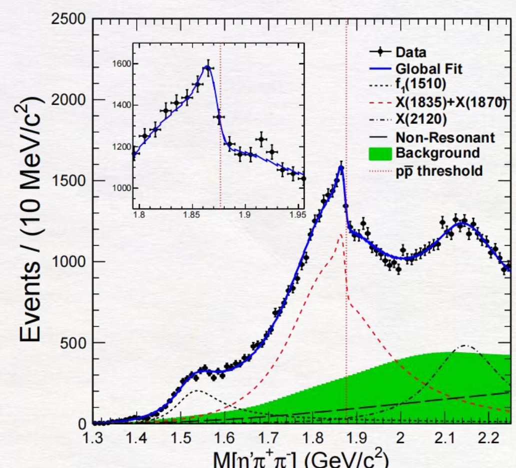
PRL 117, 042002 (2016) 1.3B J/ψ



Observation of anomalous line shape



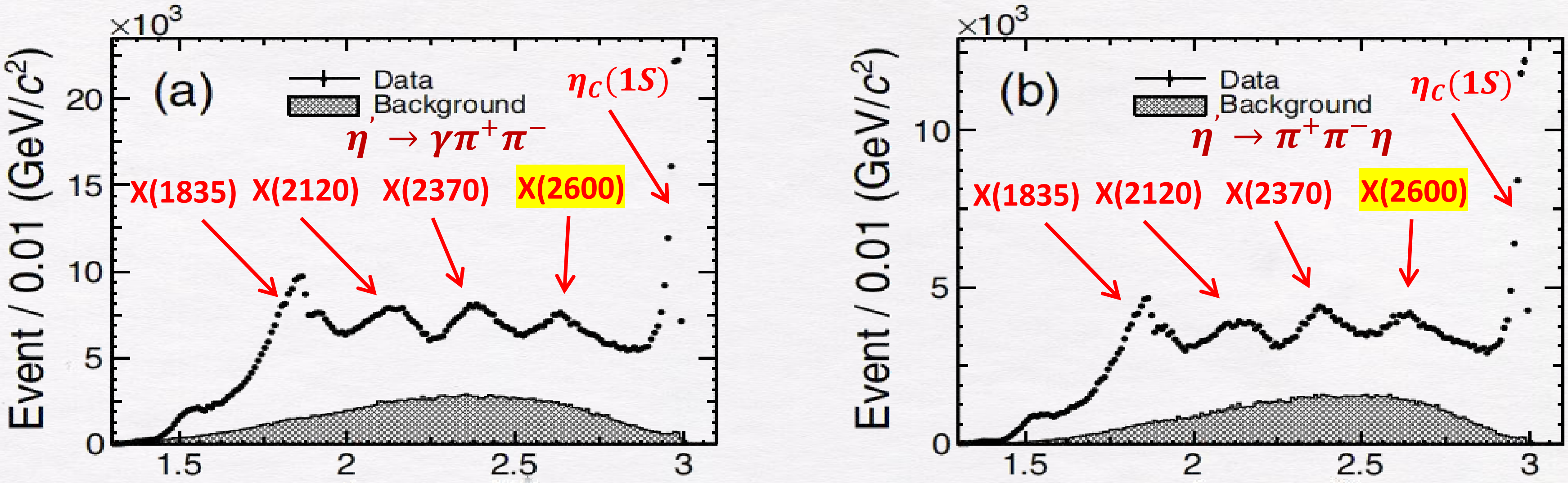
Sum of Flatte X(1835) at ppbar and BW X(1920)



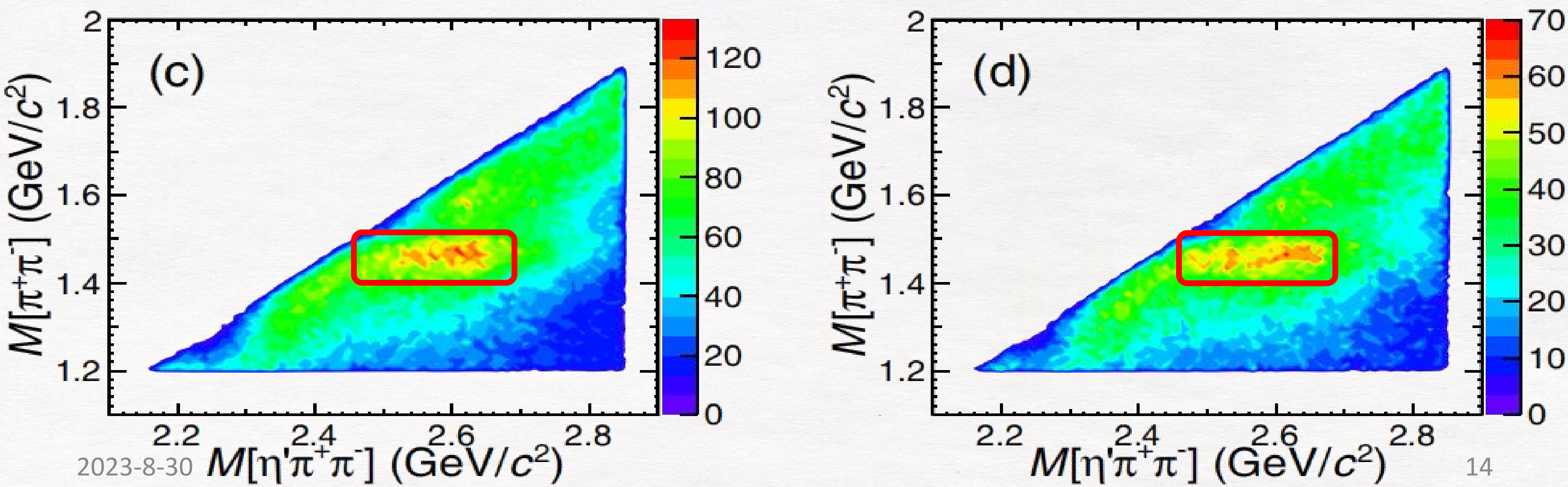
Coherent sum of BW X(1835) and BW X(1870) at ppbar

Observation of a new state X(2600) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

Study $J/\psi \to \gamma\pi^+\pi^-\eta'$ using **10 Billion** of J/ψ data @ BESIII **PRL 129, 042001 (2022)**

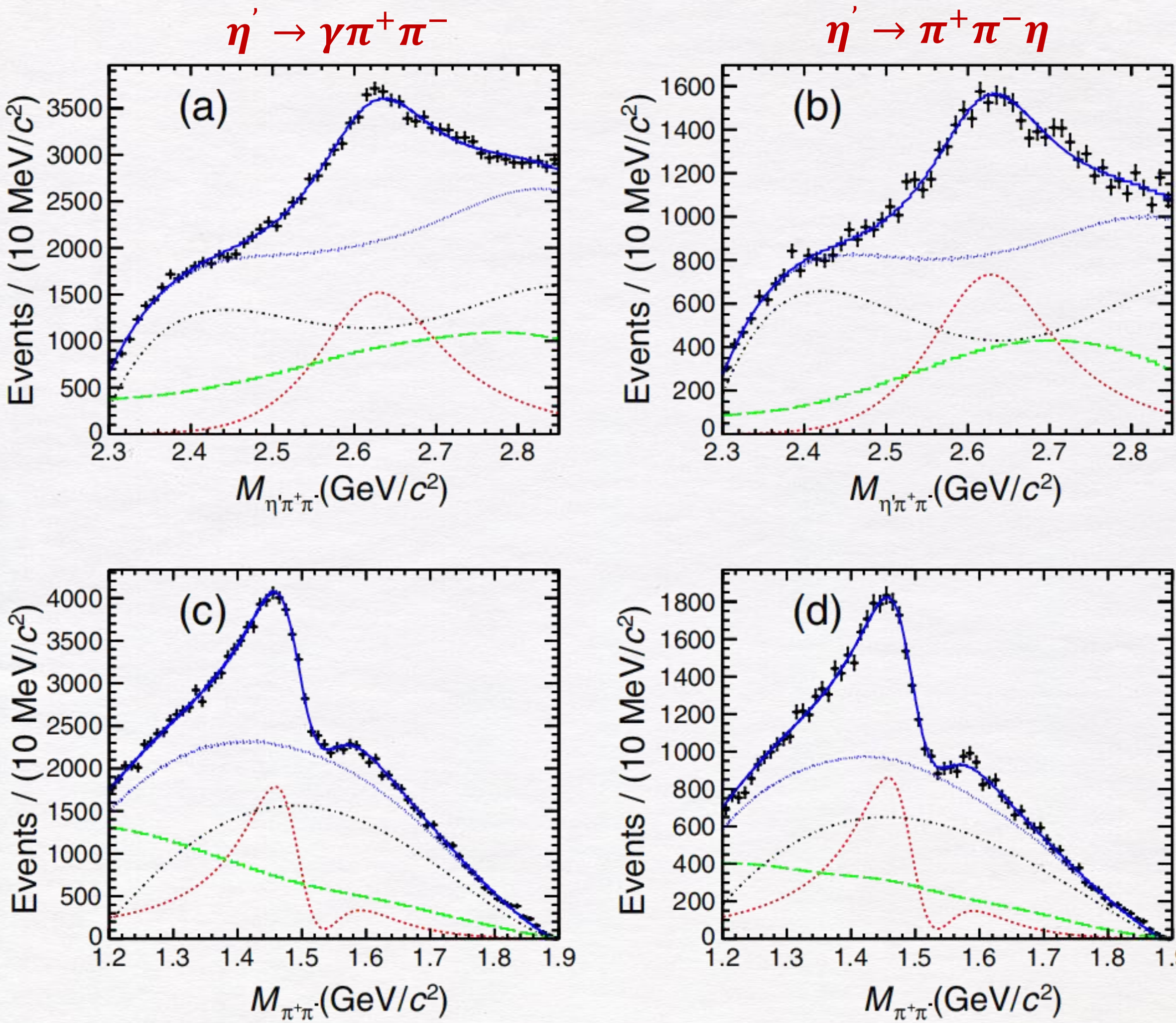


- **A new state in M($\pi^+\pi^-\eta'$) invariant mass is observed around 2.6 GeV, which is correlated to a structure in M($\pi^+\pi^-$) at 1.5 GeV.**



Observation of a new state X(2600) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 129, 042001

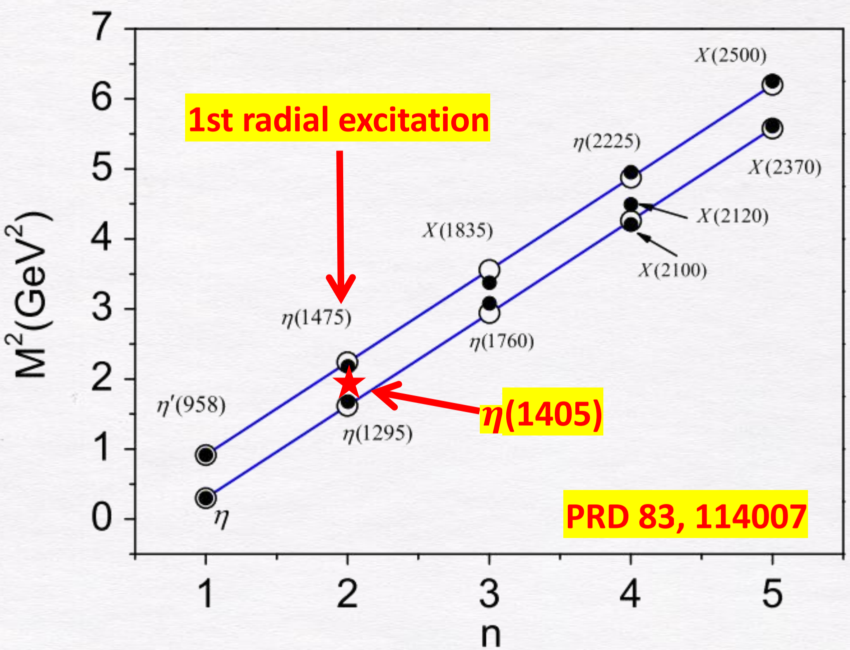


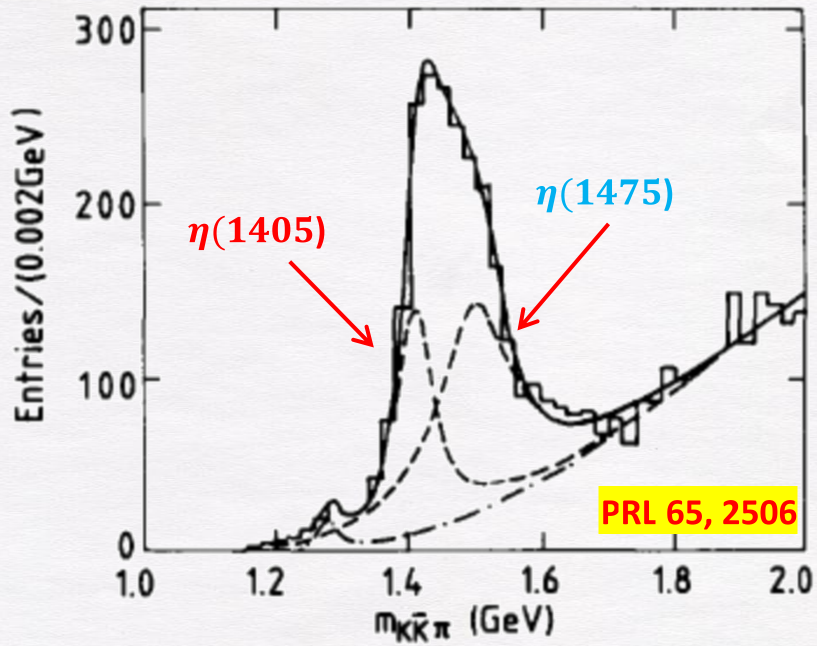
- **Simultaneous fit** to $\pi^+\pi^-\eta'$ and $\pi^+\pi^-$ mass spectra is performed.
- **X(2600)** observed for the first time with a statistical significance **greater than 20σ**.
- The structure in M($\pi^+\pi^-$) around **1.5 GeV** can be well described with the interference between **$f_0(1500)$ and X(1540)**.
- **0^{-+} or 2^{-+}** is favored for X(2600).

Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

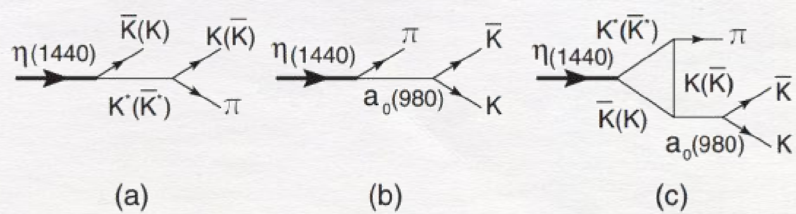
η radial excitation?
an exotic hadron?
J^{PC}?

"$\eta(1405/1475)$" Confusion / "ι" Puzzle





PRL 108, 081803



- A structure is first observed by MARK II, J^P is 0^{-+}, the "single structure" is named "ι".
- Mark III suggested there should **exist two 0^{-+} structures called $\eta(1405)$ and $\eta(1475)$**.
- $\eta(1405/1475)$ Confusion:

Long standing puzzle!

- Two states or just one? (**Triangle Singularity Mechanism**)
- Their nature? **Glueball / 1st radial excitation states of η'**?

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

PWA of $J/\psi \to \gamma K_s K_s \pi^0$ using 10 Billion of J/ψ data @ BESIII **JHEP 03(2023)121**

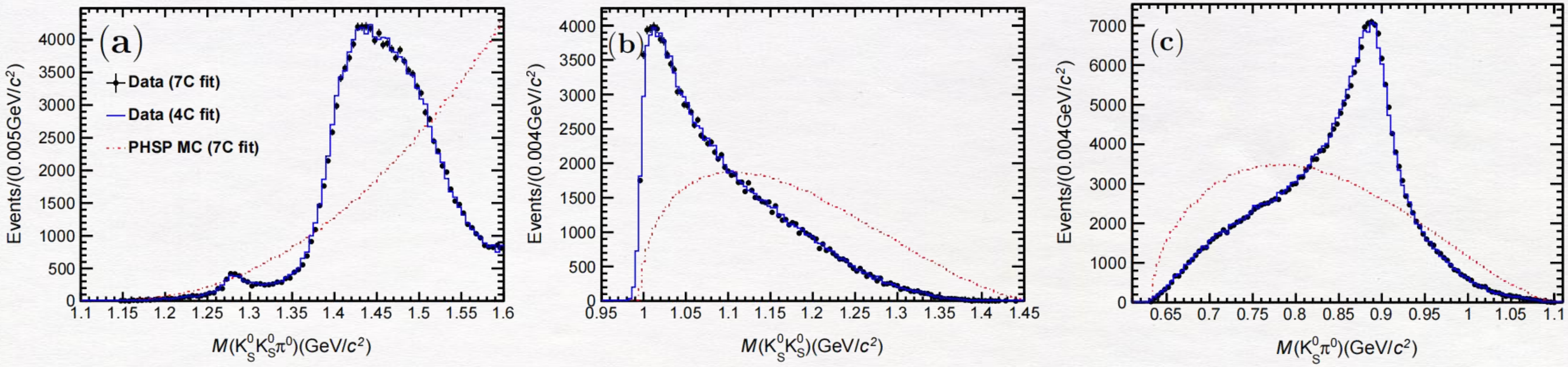
- $\pi^0 \to \gamma\gamma$ and $K_S^0 \to \pi^+\pi^-$.
- Study of $\eta(1405)$ and $\eta(1475)$.
- **Prominent structure around 1.45 GeV and a clear bump around 1.28 GeV.**

Mass Dependent PWA:

Extract the resonance parameters of the intermediate states by choosing particular dynamic models.

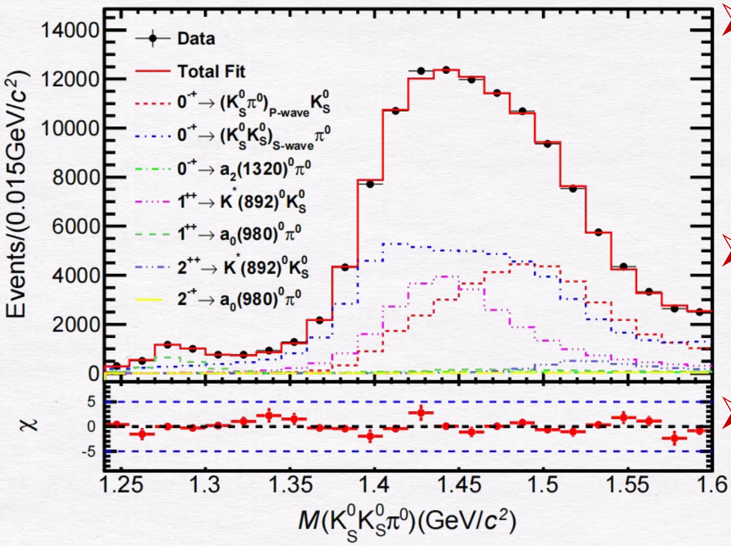
Mass Independent PWA:

Explore the lineshape of $K_s K_s \pi^0$ invariant mass for the different decay modes, and minimize bias from particular dynamic models of the intermediate states.



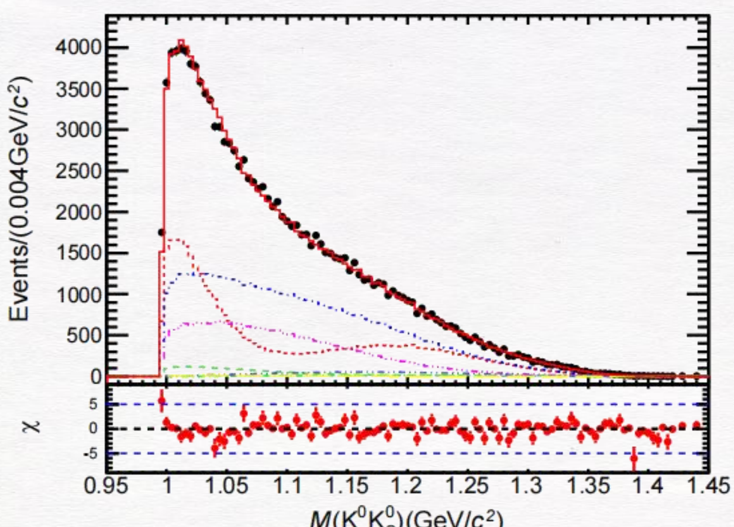
$J/\psi \to \gamma K_s K_s \pi^0$ - Mass Dependent PWA

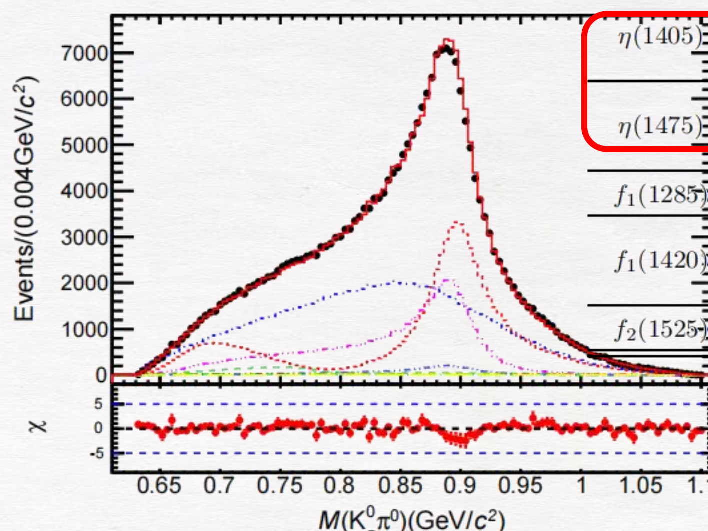
JHEP 03(2023)121



- **The pseudoscalar** components: **two states** are needed in MD-PWA using **relativistic BW model**, and both of them can decay by $(K_sK_s)_{\mathrm{S-wave}}\pi^0$ and $(K_s\pi^0)_{\mathrm{P-wave}}K_s$ modes.
- $f_1(1285)$, $f_1(1420)$ and $f_2(1525)$ are observed for the first time in this process.
- **TSM** and **one 0^{-+} state assumptions:** the description of $K_sK_s\pi^0$ invariant mass spectrum **deteriorates significantly**.

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$



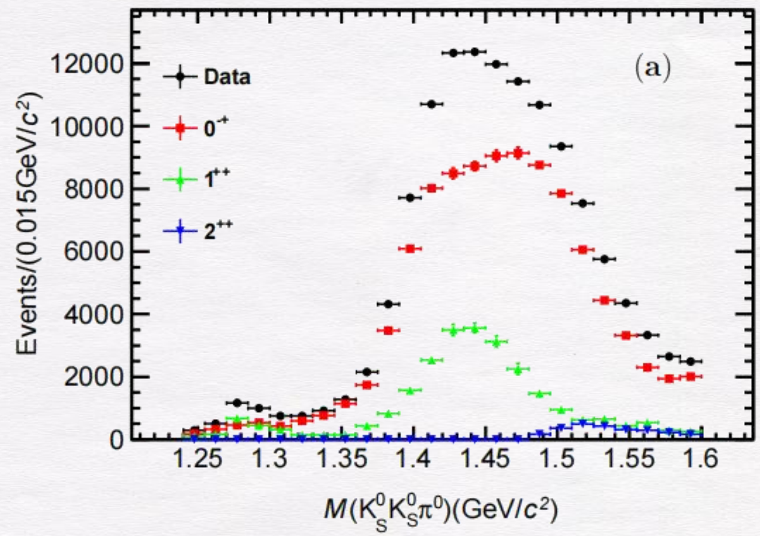


$J/\psi \rightarrow \gamma K_s K_s \pi^0$ - Mass Independent PWA

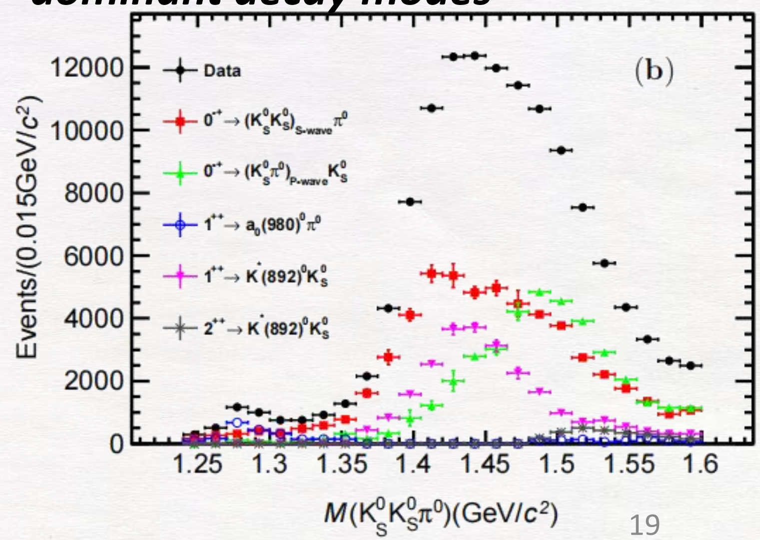
JHEP 03(2023)121

- Datasets of MI-PWA: dividing **$M(K_s K_s \pi^0)$** from **1.24GeV to 1.6GeV** into 24 bins, the width of each bin is **15MeV.**
- MI-PWA in each bin: **the dynamic function of $M(K_s K_s \pi^0)$** in each bin is approximate to be a **constant**. Perform PWA in each bin and extract components with **significance greater than 5σ**.
- The 0^{-+} component is the dominant contribution:
  - The **relatively flat lineshape** around 1.4 GeV **rules out one standard resonance parameterization**.
  - $(K_s K_s)_{S-wave}\pi^0$ & $(K_s \pi^0)_{P-wave} K_s$ waves are of **comparable magnitudes**, but with **different lineshape and peaks**.

dominant spin components



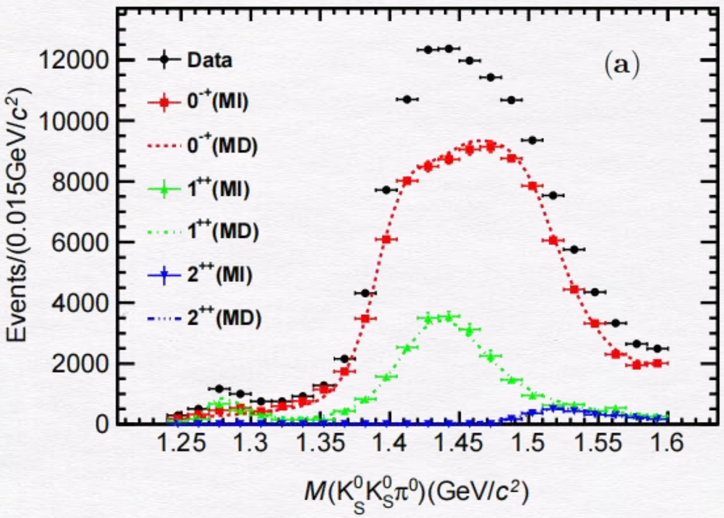
dominant decay modes



$J/\psi \to \gamma K_s K_s \pi^0$ - Mass Independent PWA

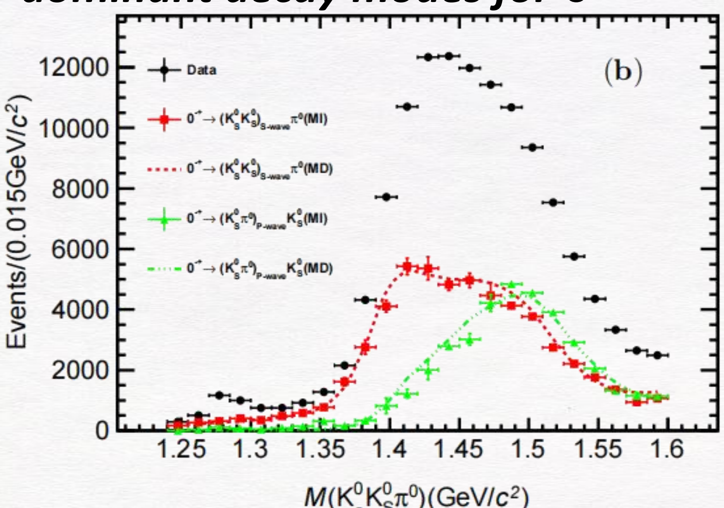
JHEP 03(2023)121

dominant spin components

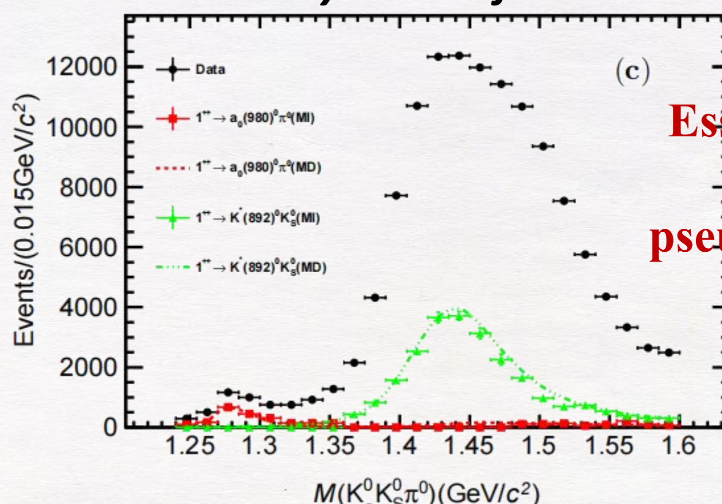


- **Axial vector** component at **1.28 GeV** and **1.42 GeV** in MI-PWA corresponding to $f_1(1285)$ and $f_1(1420)$ in MD-PWA clearly. The **first one decays by $a_0(980)\pi^0$** and the **second one decays by $K^{*0}(892)K_s$**.
- **Tensor** component around **1.52 GeV** decays by $K^{*0}(892)K_s$ in MI-PWA corresponding to $f_2(1525)$ in MD-PWA clearly.
- **Consistency between MI and MD results**.

dominant decay modes for 0^{-+}



dominant decay modes for 1^{++}

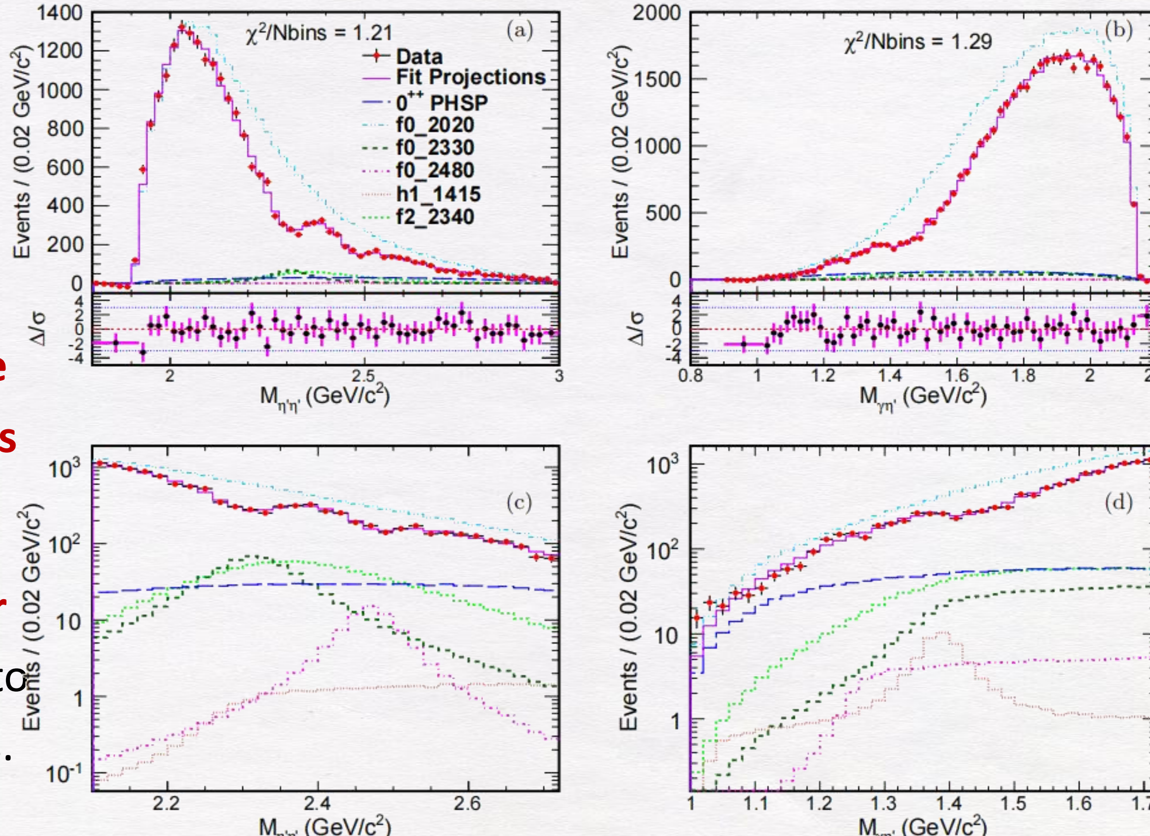


Essential for studying the dynamics of pseudoscalar structure!

Partial Wave Analysis of $J/\psi \to \gamma\eta'\eta'$

PWA of $J/\psi \to \gamma\eta'\eta'$ using 10 Billion of J/ψ data @ BESIII **PRD 105, 072002(2022)**

- $\eta \to \gamma\gamma$ and $\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$.
- $J^{PC} = 0^{++}, 2^{++}, 4^{++}$ in $\eta'\eta'$.
- $J^{PC} = 1^{+-},\ 1^{--}$ in $\gamma\eta'$.
- **$f_2(2340)$ observed in $\eta'\eta'$ mode for the first time, its significance is 16.1σ.**
- **$f_2(2340)$** is one **potential tensor glueball candidate** which is close to LQCD prediction for 2^{++} glueballs.



$\Gamma(J/\psi \to \gamma f_2(2340)) \sim 3.0 \times 10^{-4}$ including:

- $J/\psi \to \gamma K_S K_S$ **PRD 87, 092009**
- $J/\psi \to \gamma\eta\eta$ **PRD 98, 072003**
- $J/\psi \to \gamma\phi\phi$ **PRD 93, 112011**

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

PRL 111, 091601

Partial Wave Analysis of $J/\psi \to \gamma\eta'\eta'$

- **$f_0(2020)$, $f_0(2330)$ observed in $\eta'\eta'$ mode for the first time.**
- **$f_0(2480)$: new scalar state observed.**
- $f_0(2020)$:

PRD 87, 092009 PRD 98, 072003

- Production compatible with that of **$f_0(2100)$** in $J/\psi \to \gamma\eta\eta$ and **$f_0(2200)$** in $J/\psi \to \gamma K_S K_S$.
- Its large production rate in radiative J/ψ decay suggest a large **overlap with scalar glueball**.
- Consistent with previous analysis results, but its mass is **lower than the mass of the first excitation of scalar glueball** from the LQCD prediction. PLB 309, 378 PRD 60, 034509

PRD 105, 072002(2022)

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.		Significance (σ)
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	dominant	≫25
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	components	16.3
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$	new 0^{++} state	5.2
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$		5.3
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$		16.1
0^{++} PHSP	⋯	⋯	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$		15.7

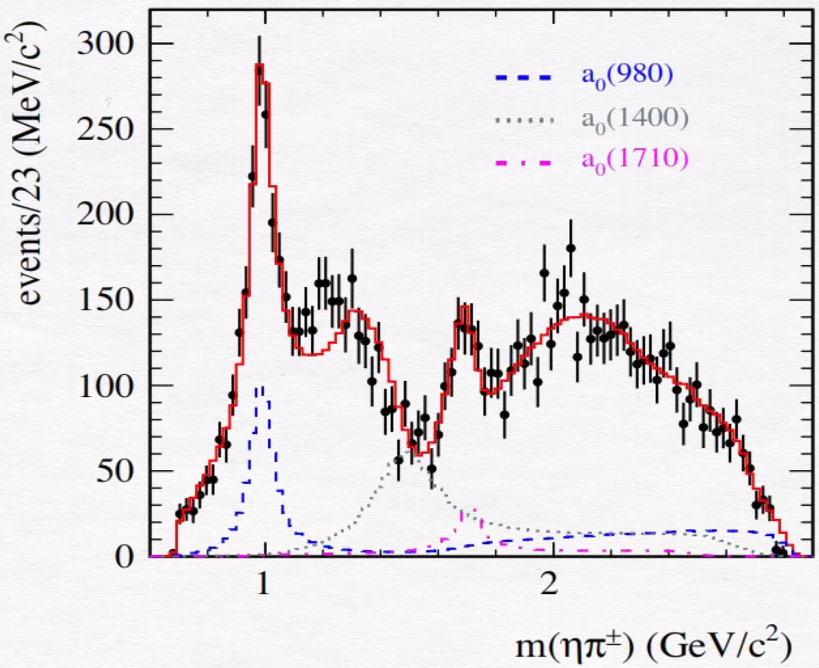
Light hadrons in open-charm decays

0^{++} ground state
- I=0: $f_0(500)$, $f_0(980)$
- I=1: $a_0(980)$

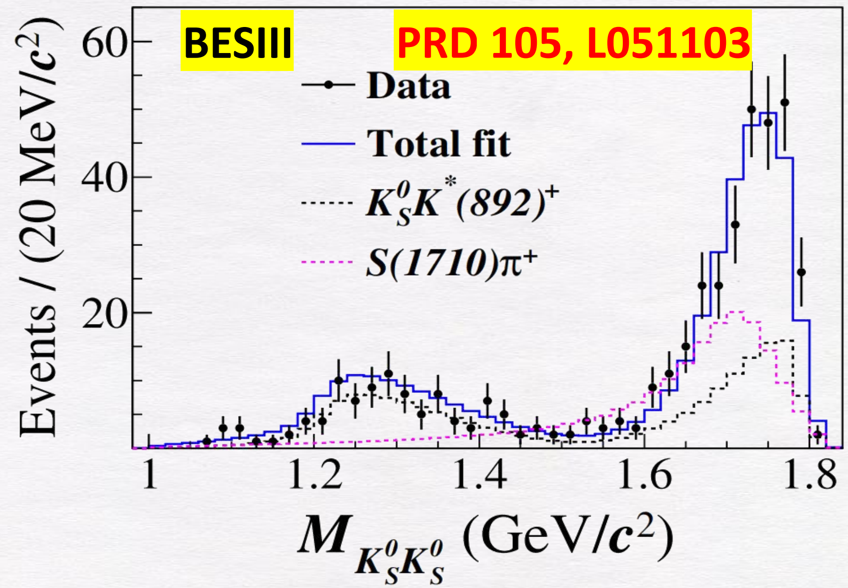
0^{++} radially excited states
- I=0: $f_0(1370)$, $f_0(1500)$
- I=1: $a_0(1450)$

0^{++} higher set of excitations
- I=0: $f_0(1710)$, $f_0(1770)$
- I=1: **$a_0(1710)/a_0(1817)$?**

BABAR **PRD 104, 072002**



$$m(a_0(1700)) = 1704 \pm 5_{\text{stat}} \pm 2_{\text{sys}} \ \text{MeV}/c^2,$$
$$\Gamma(a_0(1700)) = 110 \pm 15_{\text{stat}} \pm 11_{\text{sys}} \ \text{MeV}/c^2.$$



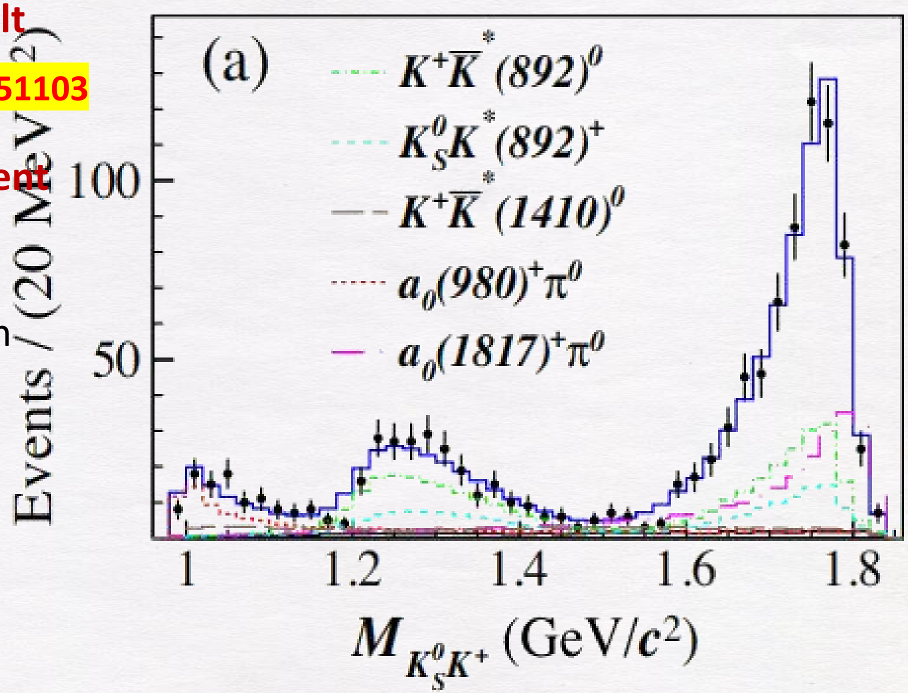
$$\mathcal{B}(D_s^+ \to S(1710)\pi^+) = (0.31 \pm 0.03 \pm 0.01)\%$$
$$(1.723 \pm 0.011_{\text{stat}} \pm 0.002_{\text{syst}}) \ \text{GeV}/c^2$$
$$(0.140 \pm 0.014_{\text{stat}} \pm 0.004_{\text{syst}}) \ \text{GeV}/c^2$$

- ➢ Suppression attributed to the **destructive interference between $a_0(980)$ and $f_0(980)$**.
- ➢ One order of magnitude larger than the expectation.
- ➢ **Constructive interference between $f_0(1710)$ and its isospin=1 partner**.

Light hadrons in open-charm decays

- Amplitude analysis of Cabibbo-favored $D_S^+ \to K_S K^+ \pi^0$.
- Together with BESIII analysis $D_S^+ \to K_S K^+ \pi^0$, **this result support the existence of a new a_0 triplet.** **PRD 105, L051103**
- BF of $D_S^+ \to a_0^+ \pi^0$ with $a_0^+ \to K_S K^+$ is **roughly consistent with the prediction.** **EPJC 82, 225**
- M(a_0) about 100 MeV/c2 greater than the expectation for $a_0(1710)$. **$\text{Mass} = 1.817 \pm 0.008 \pm 0.020$ GeV/c2** **$\text{Width} = 0.097 \pm 0.022 \pm 0.015$ GeV/c2**
- **$a_0(1817)$ could be the isospin=1 partner of the $f_0(1800)$ [X(1812)].** **PRD 105, 114014**
- The possibility of the **$f_0(1710)$ as the scalar glueball still cannot be excluded**.

PRL 129, 182001



Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0 (fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1817)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

Summary

- **The BESIII experiment is an excellent laboratory to study light hadron physics, while the charmonium provides an unique opportunity to search for glueball and exotic states.**
- **Selection of latest physics results on light exotic states are presented:**
  - First observation of exotic isoscalar 1^{-+} state $\boldsymbol{\eta_1(1855)}$ in $J/\psi \to \gamma\eta\eta'$. **PRL 129, 192002 (2022)** **PRD 106, 072012 (2022)**
  - **X(1835)**, **X(2120)** and **X(2370)** are confirmed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ and **X(2600)** is observed for the first time. **PRL 129, 042001 (2022)**
  - Two states of $\boldsymbol{\eta(1405)}$ and $\boldsymbol{\eta(1475)}$ are needed in $J/\psi \to \gamma K_s K_s \pi^0$ and both MD-PWA and MI-PWA results have been povided. **JHEP 03(2023)121**
  - The tensor glueball candidate $\boldsymbol{f_2(2340)}$ is observed in $\eta'\eta'$ mode for the first time in $J/\psi \to \gamma\eta'\eta'$ and a new scalar state $\boldsymbol{f_0(2480)}$ is observed as well. **PRD 105, 072002(2022)**
  - Light hadron $\boldsymbol{a_0(1817)}$ is observed for the first time in open-charm decays. **PRD 105, L051103** **PRL 129, 182001**
- **The BESIII detector is still in very good status, more surprises at BESIII are expected!**

Thanks for your attention!

Backup slide (I)

	0+	2+	0−
$J/\psi \to \gamma PP$	$J/\psi \to \gamma\eta\eta$ (PRD87,092009) $J/\psi \to \gamma\pi^0\pi^0$ (PRD92,052003) $J/\psi \to \gamma K_S K_S$ (PRD98,072003) $J/\psi \to \gamma\eta\eta'$ (PRL129,192002) $J/\psi \to \gamma\eta'\eta'$ (PRD105,072002)		
$J/\psi \to \gamma VV$		$J/\psi \to \gamma\omega\phi$ (PRD87,032008) $J/\psi \to \gamma\phi\phi$ (PRD93,112011) $J/\psi \to \gamma\omega\omega$ (PRD100,052012)	
$J/\psi \to \gamma PPP$			$J/\psi \to \gamma\eta'\pi\pi$ (PRL106,072002, noPWA) $J/\psi \to \gamma K_S K_S \eta$ (PRL115,091803) $J/\psi \to \gamma K_S K_S \pi^0$ (JHEP 03,121)

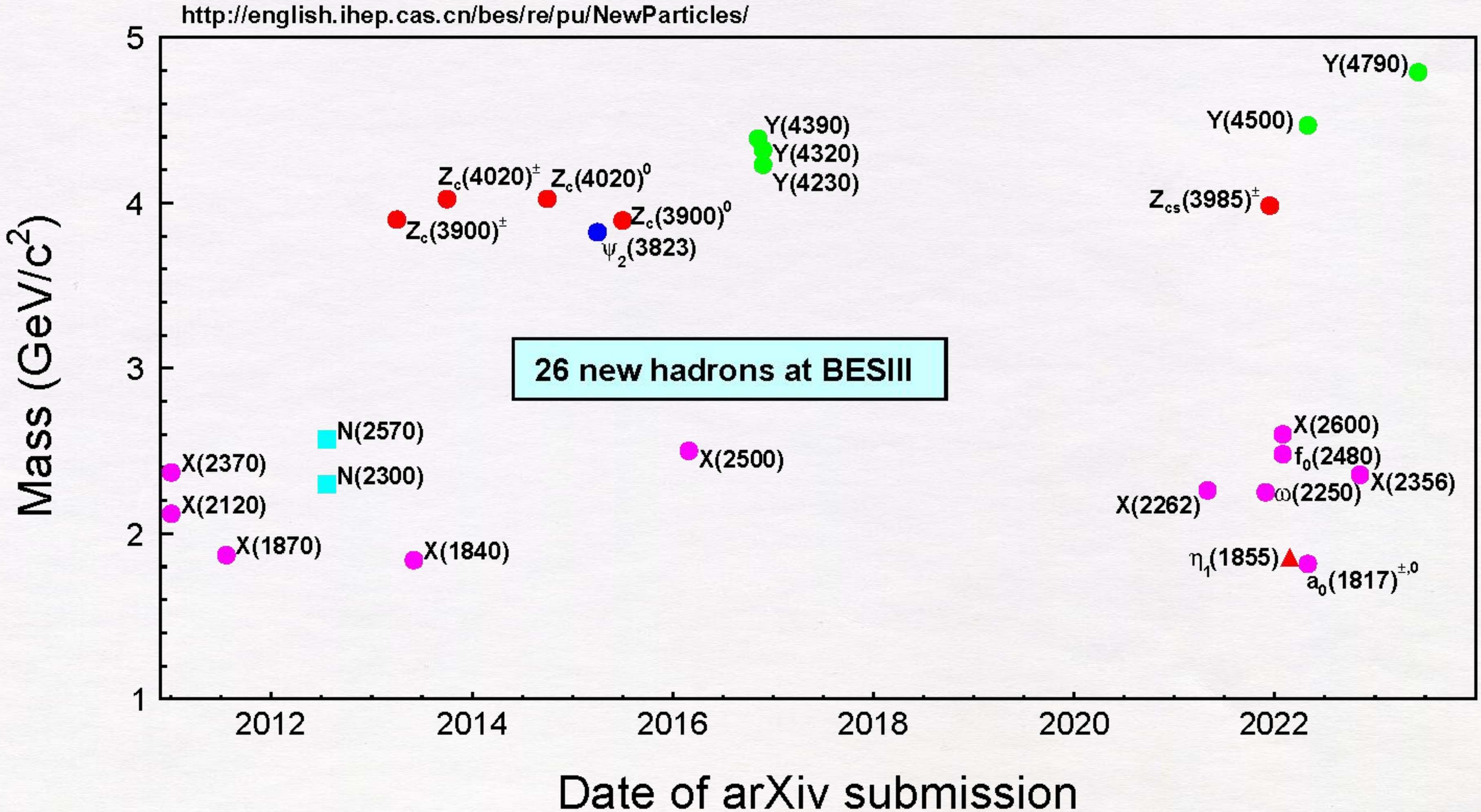
- **$J/\psi \to \gamma PP$: 0^{++}, 2^{++}, …**
- **$J/\psi \to \gamma PPP$, γVV: 0^{-+}**
- Neutral channel is much cleaner than the charged ones

Amplitude Analysis: toll to extract the complex amplitudes from experimental data

- Models with free parameters
- Consider the kinematic of final states particles
- Vary the parameters to maximize the likelihood

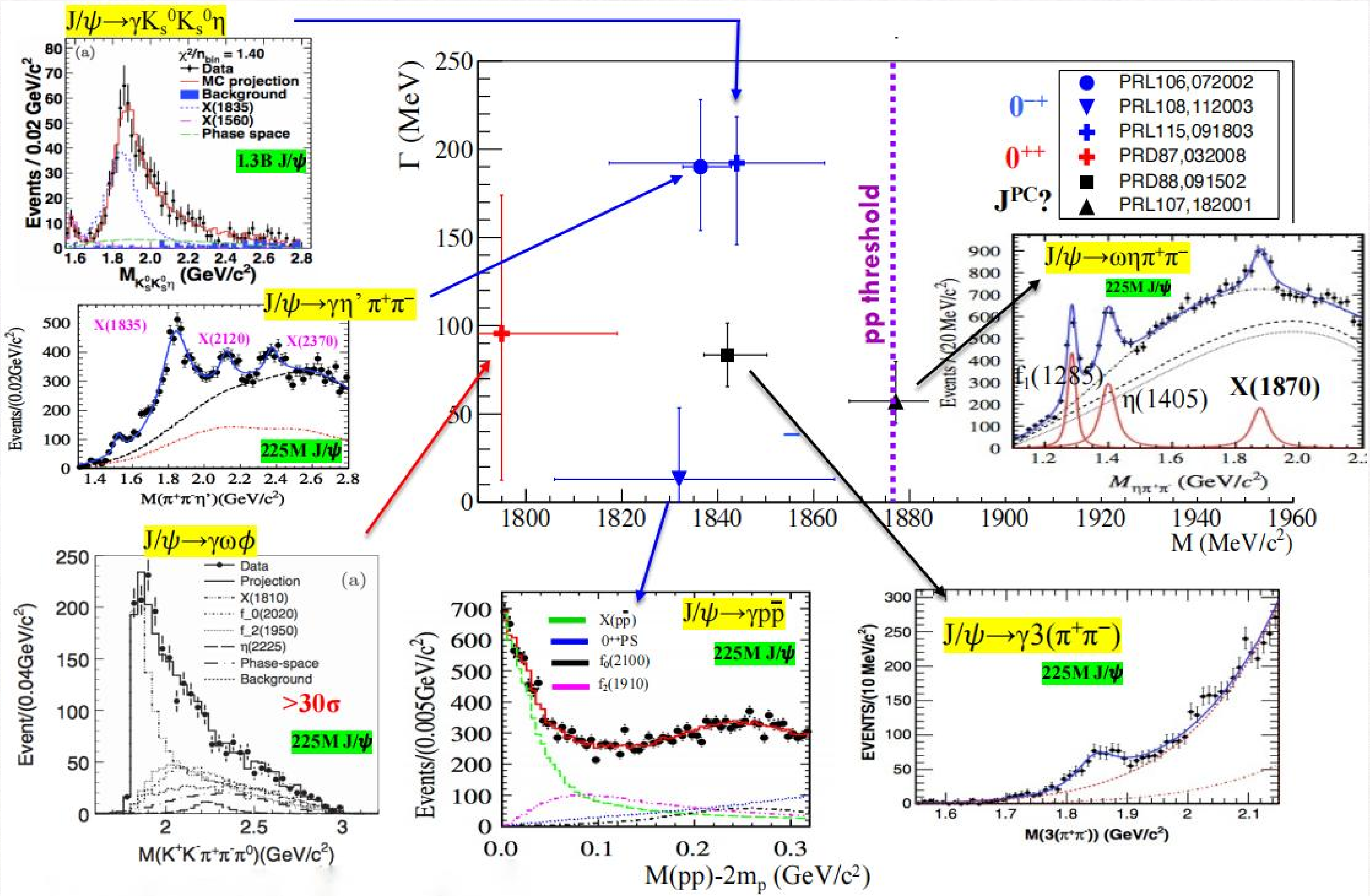
- **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
- **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (JHEP 03,121 (2023))

Backup slide (II)

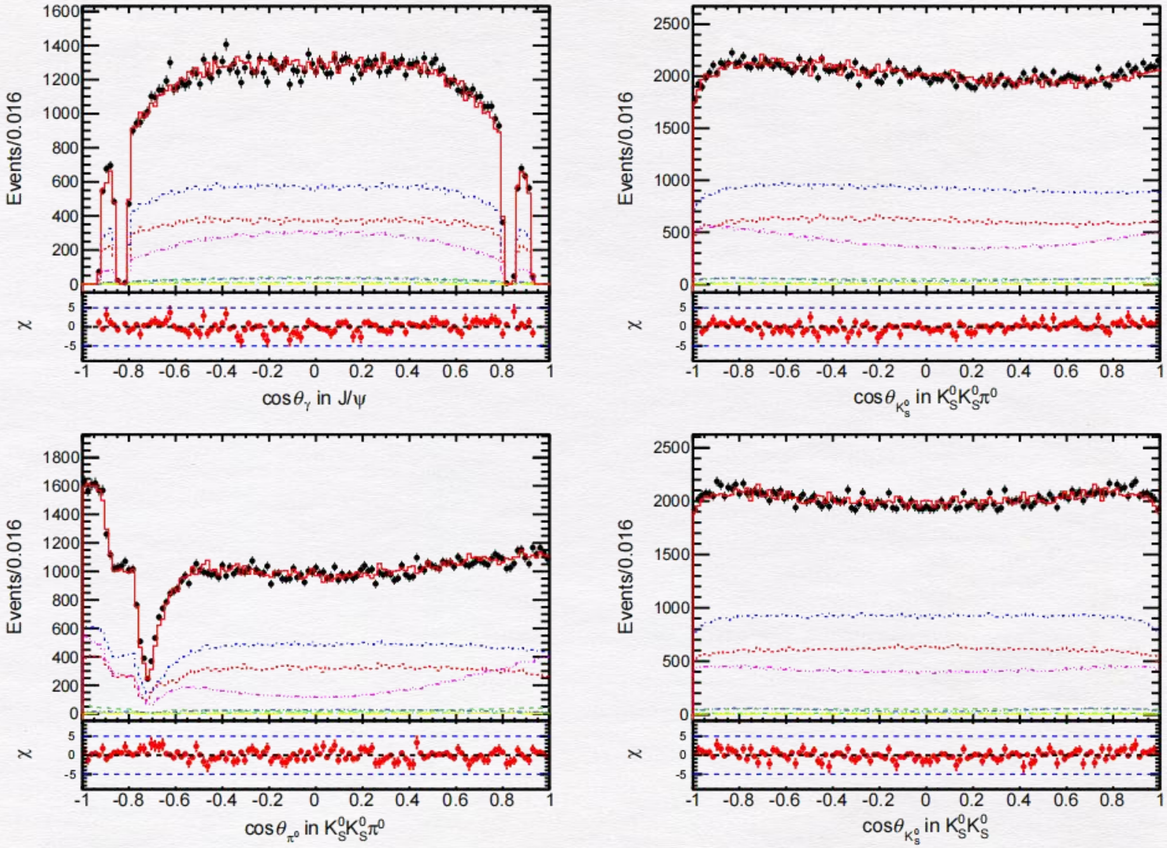


Backup slide (III)

X(18xx) between 1.8-1.9 GeV



Backup slide (IV)



Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	Decay Mode	B.F.	Sig.(σ)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$	$J/\psi \to \gamma\eta(1405) \to \gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$	$(5.84 \pm 0.12^{+2.03}_{-3.36}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma\eta(1405) \to \gamma(K_S^0 K_S^0)_{\text{S-wave}}\pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(2.88 \pm 0.04^{+1.64}_{-0.38}) \times 10^{-5}$	18.4
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$	$J/\psi \to \gamma\eta(1475) \to \gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$	$(6.58 \pm 0.12^{+3.98}_{-2.82}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma\eta(1475) \to \gamma(K_S^0 K_S^0)_{\text{S-wave}}\pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(3.99 \pm 0.09^{+0.41}_{-0.66}) \times 10^{-5}$	$\gg 35$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$	$J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0\pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(8.55 \pm 0.41^{+3.42}_{-1.04}) \times 10^{-6}$	$\gg 35$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$	$J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(7.25 \pm 0.12^{+0.73}_{-1.25}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0\pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(4.62 \pm 0.36^{+2.36}_{-1.94}) \times 10^{-6}$	17.8
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$	$J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(9.47 \pm 0.43^{+1.51}_{-0.66}) \times 10^{-6}$	23.8

Backup slide (V)

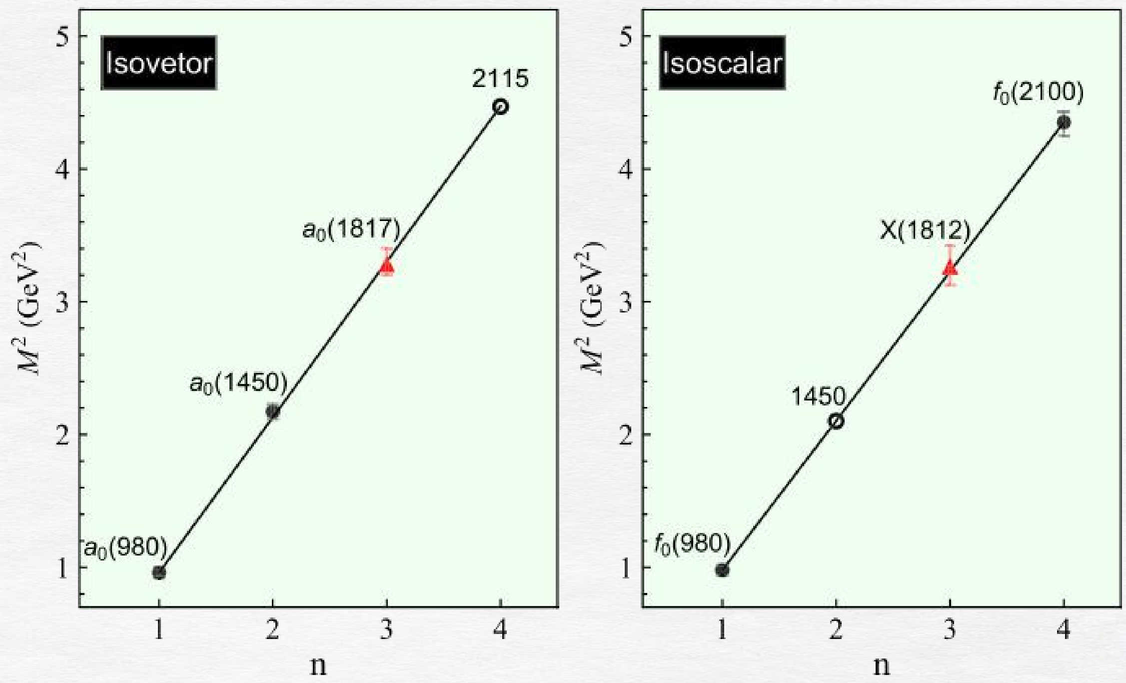


FIG. 1. Two Regge trajectories for the isovector and isoscalar scalar states. Here, the red triangles denote the $a_0(1817)$ and $X(1812)$, while the solid points and empty circles are the experimental and predicted states, respectively. Except the $a_0(1817)$, $X(1812)$ and predicted $a_0(2115)$, $f_0(1450)$, the masses of the other scalar states are taken from PDG. Here, the established states are marked by the black solid points, while the predicted states are denoted by the black circles. The error bars present total experimental uncertainties.