Light QCD exotics at BESIII

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中国科学院粒子物理前沿卓越创新中心第八次全体会议

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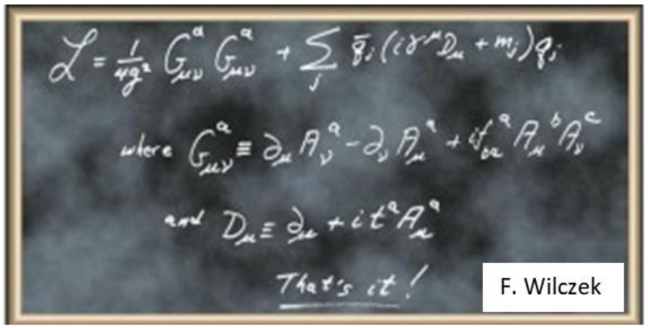
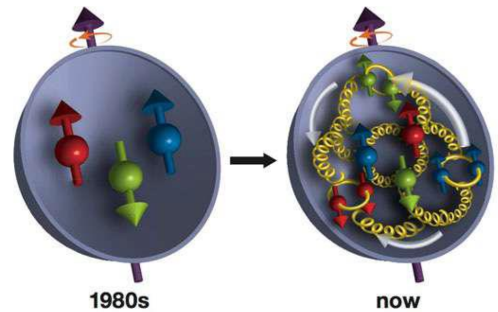
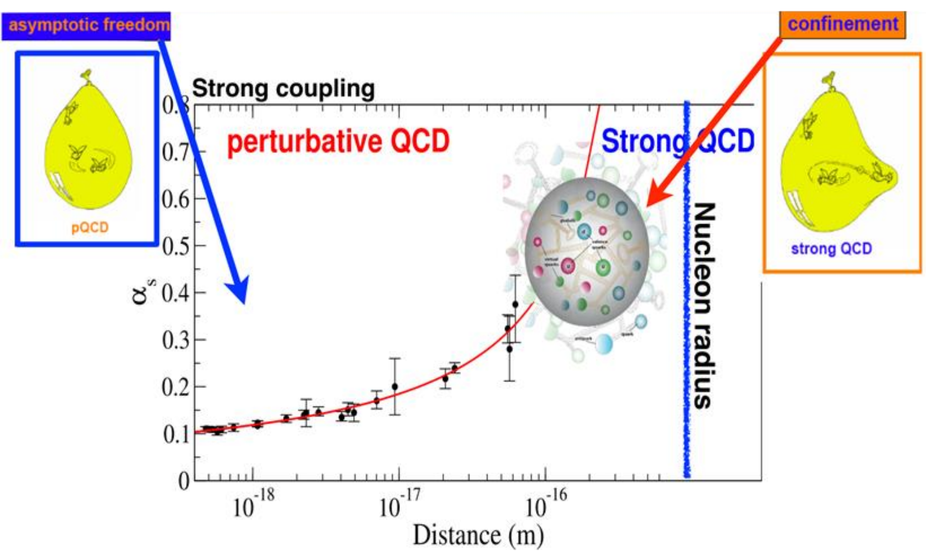
Non-Perturbative QCD

--how did the complex building blocks of our world come into being





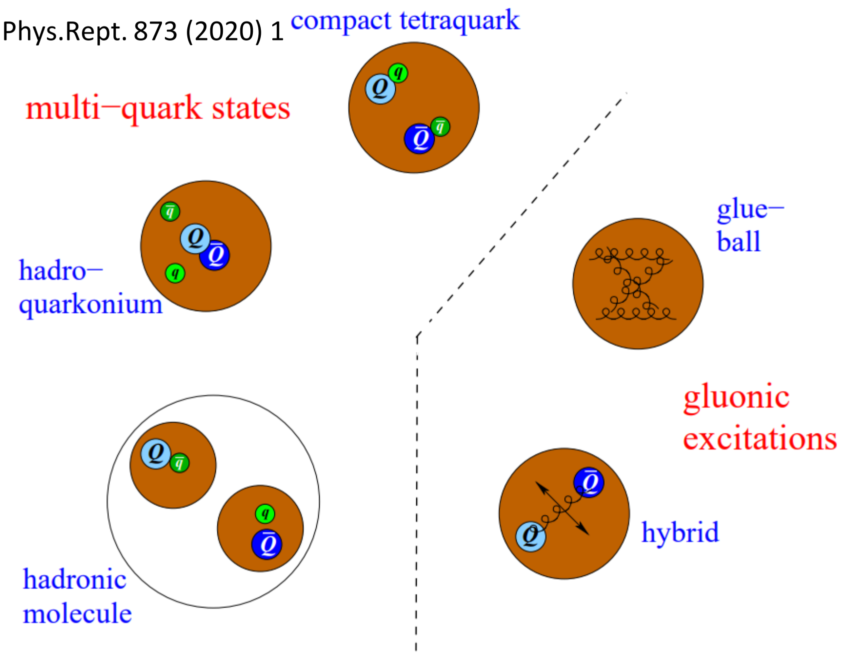


Quark model seems to work really well. But, how does QCD give rise to hadrons?

- What is the origin of confinement?
- How is the mass generated in QCD? How are confinement and chiral symmetry breaking connected?
- What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

QCD exotics

Phys.Rept. 873 (2020) 1



Two general approaches:

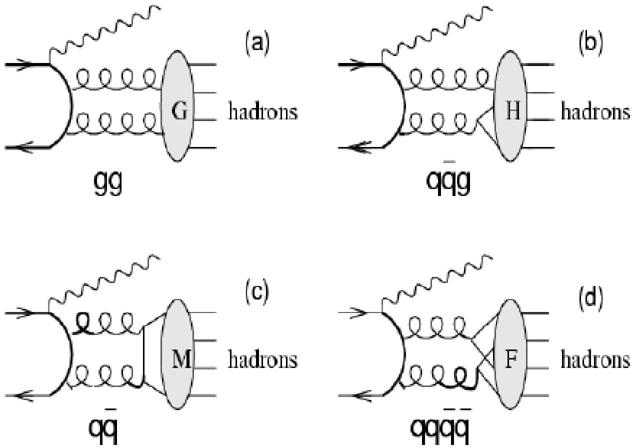
- Manifested exotics, e.g.
    - quantum numbers incompatible with QM states
    - flavor: Charged-charmonium
- With internal exotic structure, no model free signature
    - Outnumbering of conventional QM states
    - Abnormal masses & decay properties…

What are the properties of the predicted states beyond simple QM?
→Gluonic Excitations provide a measurement of the excited QCD potential

"Discovery experiment" with high precision

-- Need a well understood conventional hadron picture

Charmonium decays provide an ideal lab for light hadron physics

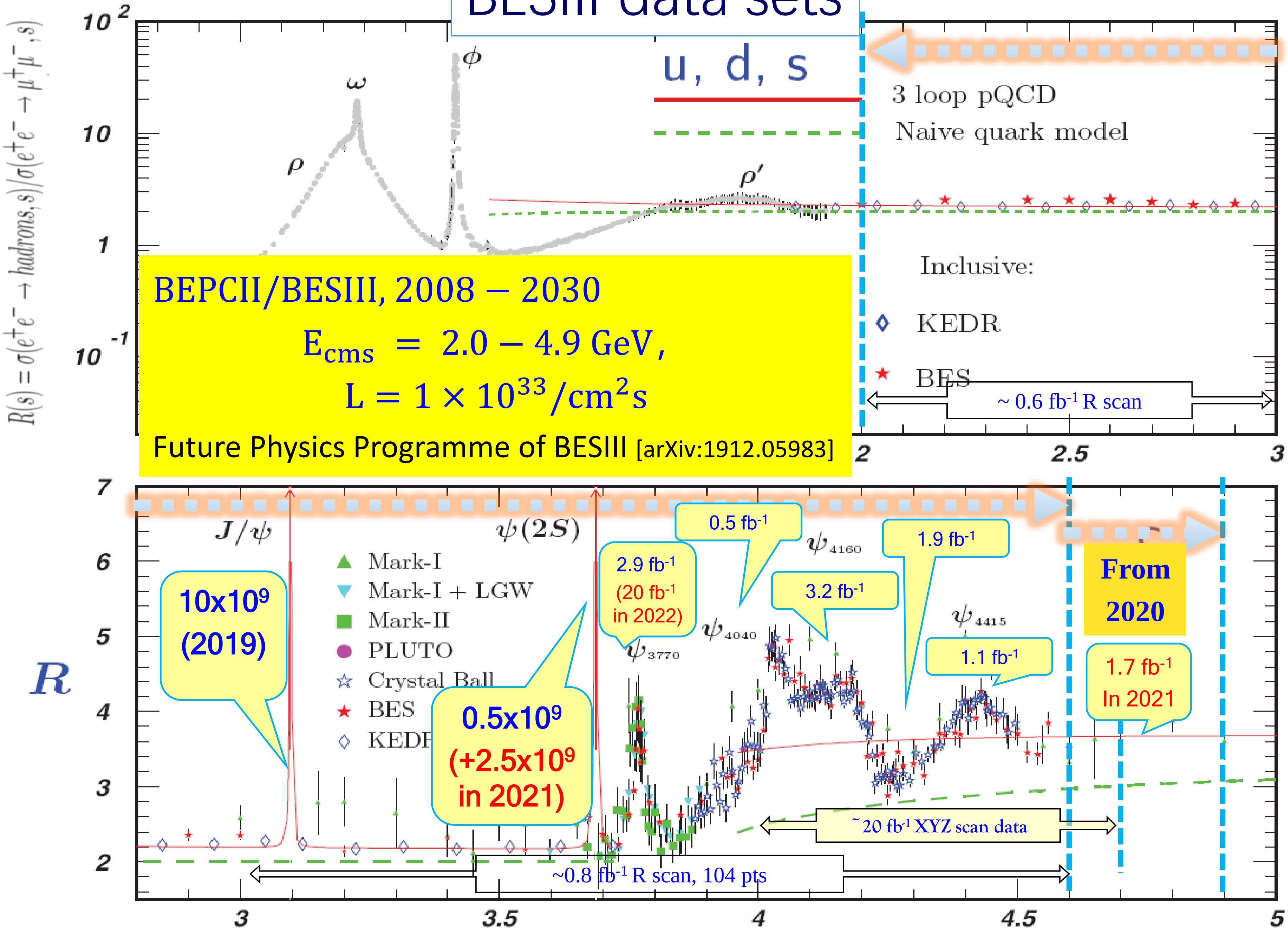


$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$

$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

- Clean high statistics data samples
- Well defined initial and final states
  - Kinematic constraints
  - $I(J^{PC})$ filter
- “Gluon-rich” process

BESIII data sets



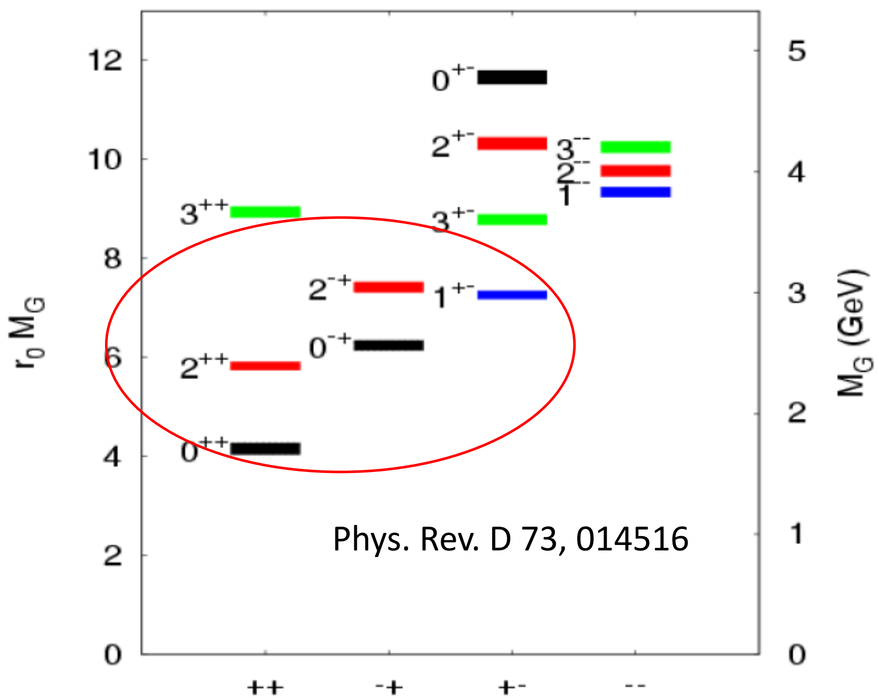
A few highlights

- Search for glueballs and hybrids

- Structures near $\mathrm{N\overline{N}}$ threshold
  - X($\mathrm{p\bar{p}}$) and X(1835)
- Scalars near $\mathrm{K\overline{K}}$ threshold
  - $\mathrm{a_0(980) - f_0(980)}$ mixing

Glueball

- Direct evidence of the most fascinating property of QCD -- gluon self interaction
- Critical information on the gluon field and the quantitative understanding of confinement



Glueballs from Lattice simulations in the pure gauge theory without quarks

	m_π (MeV)	$m_{0^{++}}$ (MeV)	$m_{2^{++}}$ (MeV)	$m_{0^{-+}}$ (MeV)
$N_f = 2$	938	1417(30)	2363(39)	2573(55)
	650	1498(58)	2384(67)	2585(65)
$N_f = 2+1$ [22]	360	1795(60)	2620(50)	—
quenched [13]	—	1710(50)(80)	2390(30)(120)	2560(35)(120)
quenched [14]	—	1730(50)(80)	2400(25)(120)	2590(40)(130)

Low lying glueballs with ordinary QN
→mixing with qqbar mesons

Systematic studies are required to solve the long standing puzzle

- Outnumbering of conventional QM states
- Abnormal properties

What we have learned so far

--from MarkIII, CLEO, BES(I, II), Crystal barrel, OBELIX, WA102, GAMS, E852, …

Scalar: overpopulation

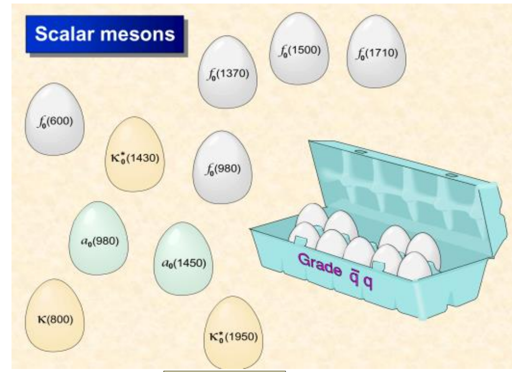
- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

Tensor: large uncertainty

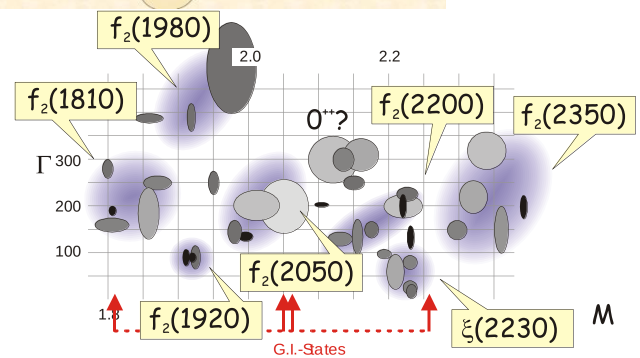
- LQCD: 2^{++}(2.3~2.4 GeV)

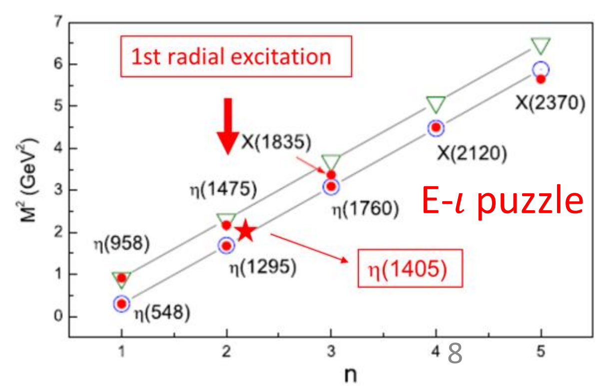
Pseudoscalar: very little known above 2 GeV, puzzles in low mass region

- LQCD: 0^{-+}(2.3~2.6 GeV)



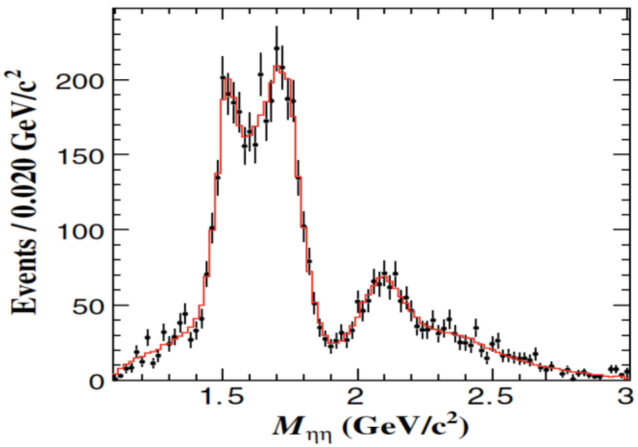
$f_0(1500)$ VS $f_0(1710)$





Amplitude analysis of $J/\psi \to \gamma\eta\eta/K_S^0K_S^0$

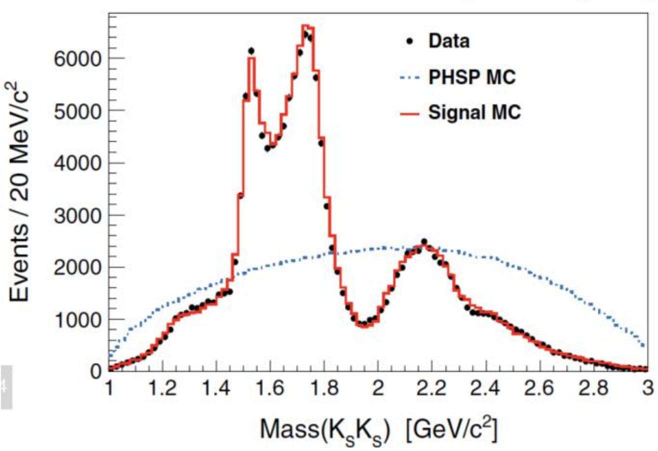
BESIII PRD 87, 092009 (2013)



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

Br of $f_0(1710)$ ~10x larger than $f_0(1500)$

BESIII PRD 98, 072003 (2018)



Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{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	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{[illegible]}_{-0.06-0.32}) \times 10^{-5}$	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

Scalar glueball candidate

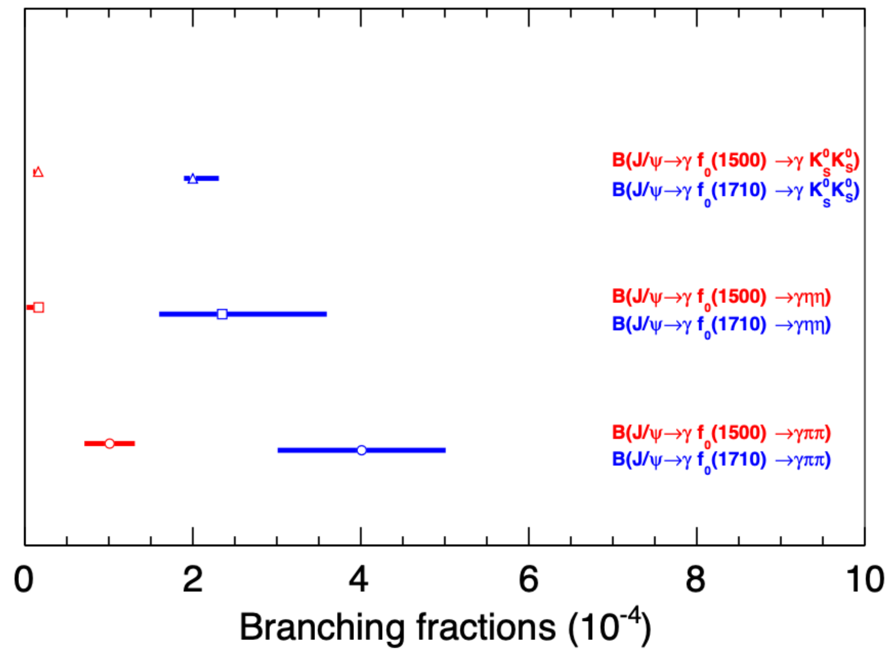
$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha \frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8)keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9) \times 10^{-3}$$

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

Experimental results

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$



$f_0(1710)$ largely overlapped with scalar glueball

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)

Experimental results

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

Phys.Rev. D87, 092009 (2013)

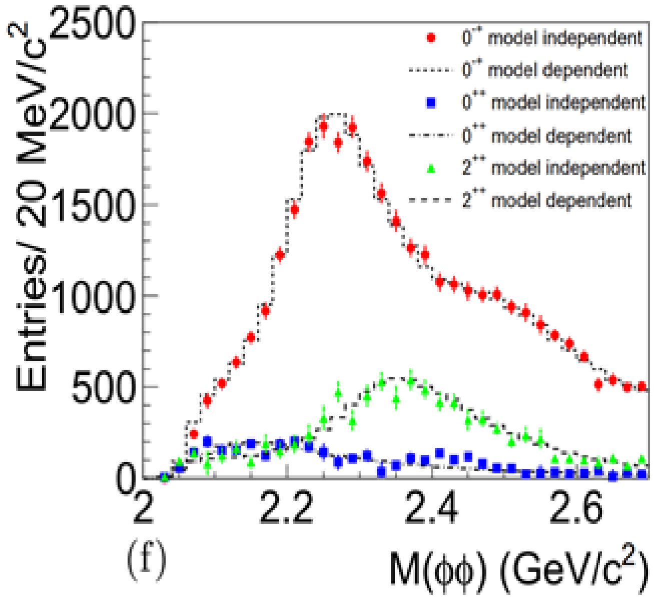
$$Br(J/\psi \to f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

Phys.Rev. D93, 112011 (2016)

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

Phys.Rev. D98, 072003 (2018)

BESIII $J/\psi \to \gamma\phi\phi$

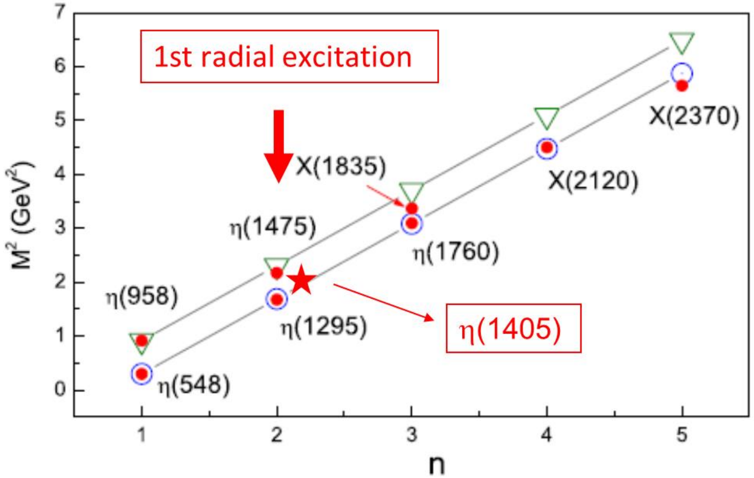


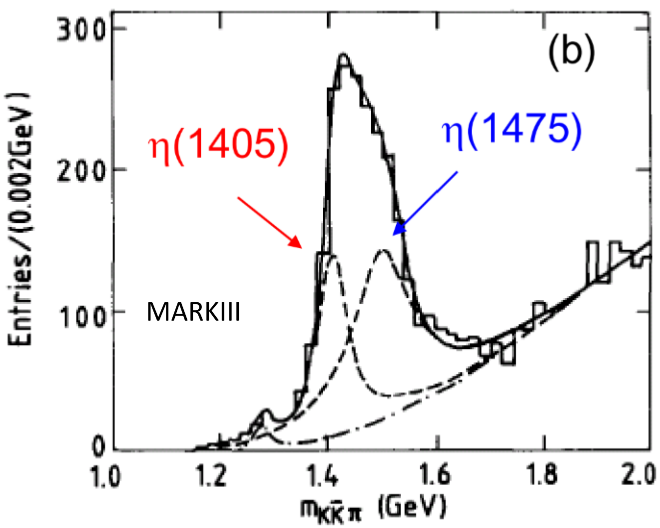
- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$
- Consist with central exclusion production in WA102

It is desirable to search for more decay modes

Pseudoscalar glueball

The small number of expected pseudoscalars in the quark model provide a clean and promising environment for the search of glueballs





Where is the 0^{-+} glueball

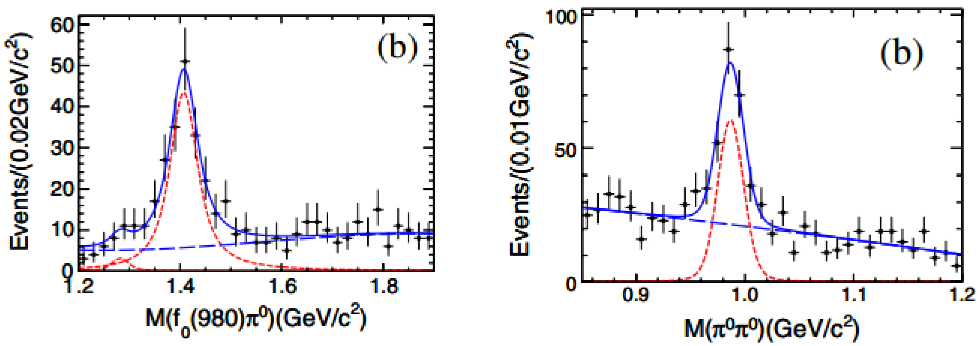
- LQCD: 0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- What's the nature of the outnumbered $\eta(1405)$?

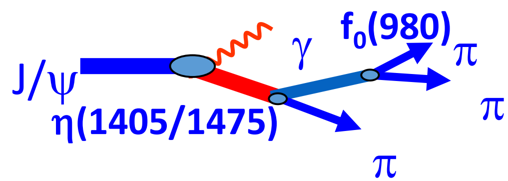
Long standing E-ι puzzle

$$M = 1416 \pm 8^{+7}_{-5};\ \Gamma = 91^{+67}_{-31}{}^{+15}_{-38}\ \mathrm{MeV}/c^2$$

$$M = 1490^{+14+3}_{-8-6};\ \Gamma = 54^{+37+13}_{-21-24}\ \mathrm{MeV}/c^2$$

Isospin-violating decay of $\eta(1405) \rightarrow f_0(980)\pi^0$





BESIII PRL 108 182001

f0(980) is extremely narrow: $\Gamma \cong$ 10 MeV.

PDG: Γ(f0(980)) $\cong$ 40~100 MeV.

Anomalously large isospin violation:

$$\frac{Br(\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\eta(1405) \rightarrow a_0^0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

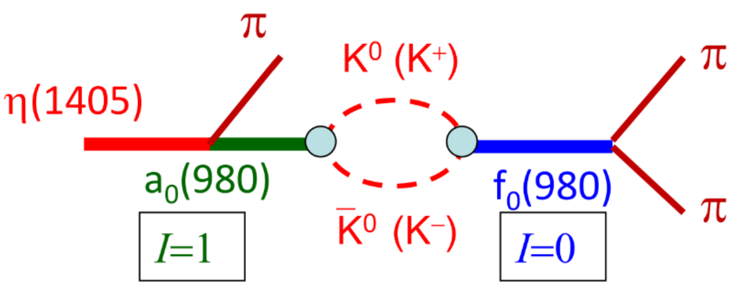
$$\xi_{af} = \frac{Br(\chi_{c1} \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} < 1\%(90\%\ C.L.)$$

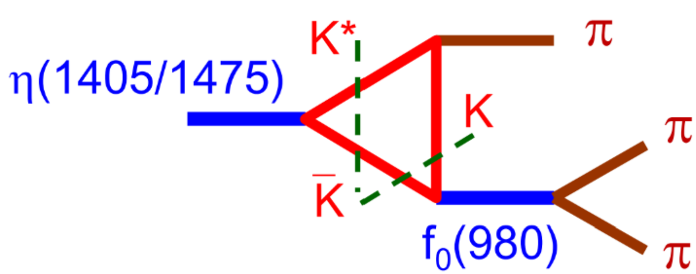
PRD, 83(2100)032003

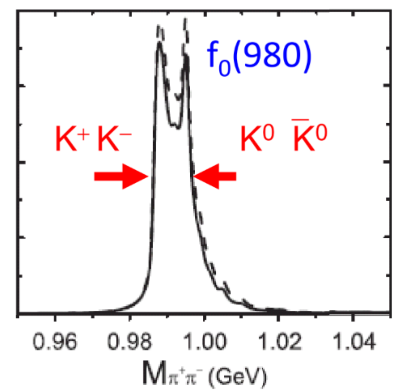
Isospin-violating decay of $\eta(1405) \rightarrow f_0(980)\pi^0$

Inspired by BESIII's observation, the triangle singularity mechanism plays an important role in the study of threshold phenomena

[Phys.Rev.Lett. 108 (2012) 081803]







→No need for two pseudoscalars around 1.4 GeV

→Look for pseudoscalar glueball in higher mass region

→Manifestations of triangle singularity in various process

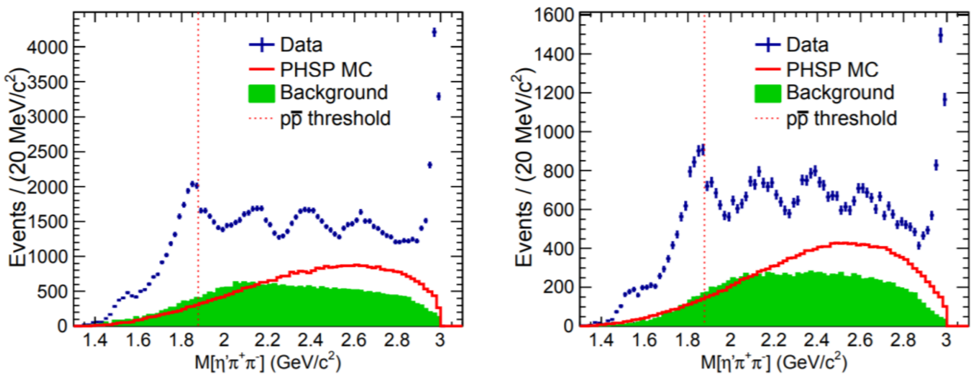
[e.g. Rev.Mod.Phys. 90 (2018) 015004, Prog.Part.Nucl.Phys. 112 (2020) 103757]

Structures >2 GeV

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

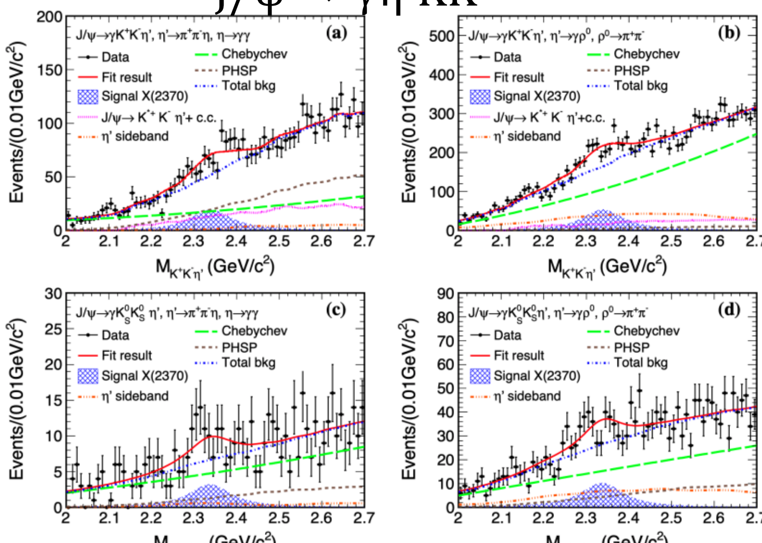
BESIII PRL 106, 072002, PRL 117, 042002

X(2370)



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

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



8.3σ

Landscape of glueballs has been updated with BESIII's inputs

Scalar: Overpopulation

- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

→

- ✓ **Strong production of $f_0(1710)/f_0(2100)$ in $J/\psi \to \gamma\, \eta\eta/KK/\pi\pi$**

Tensor: large uncertainty

- LQCD: 2^{++}(2.3~2.4 GeV)

→

- ✓ **Strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/KK/\pi\pi/\phi\phi$**

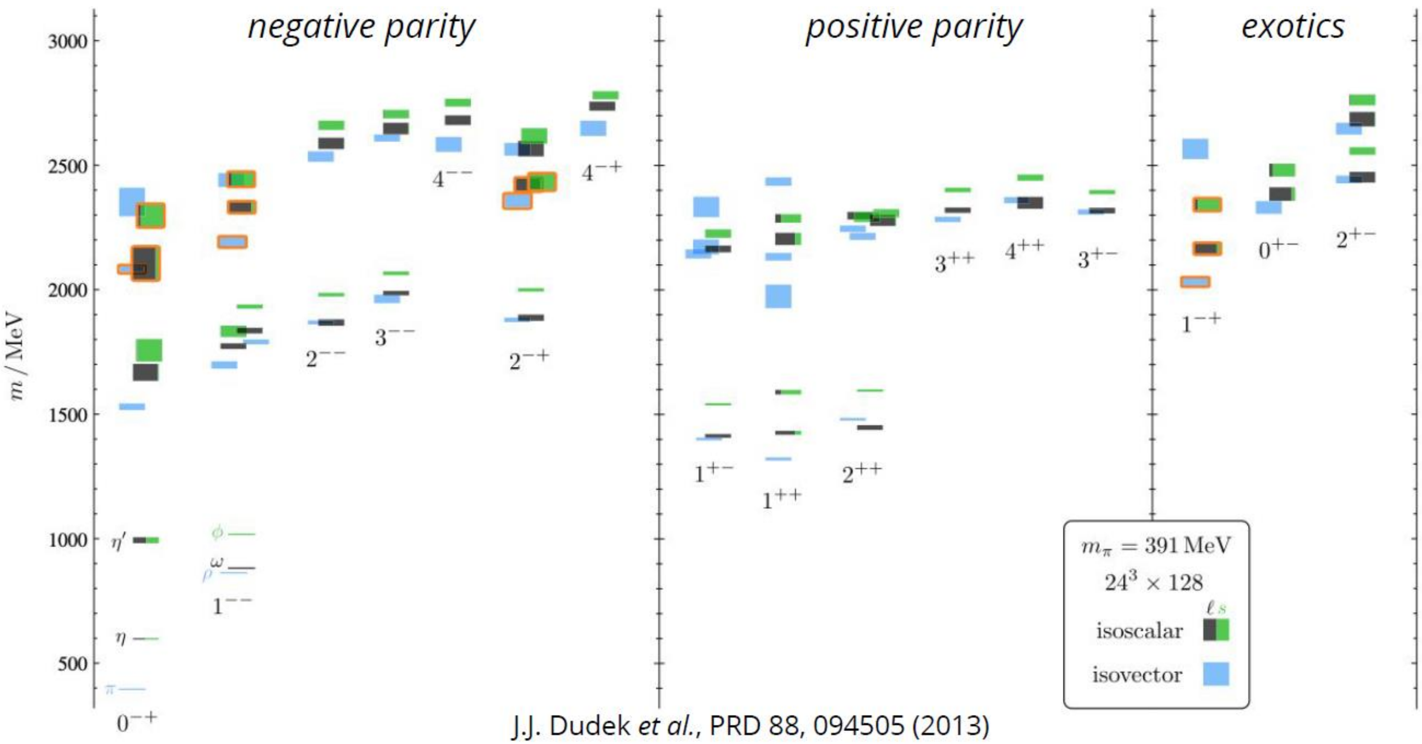
Pseudoscalar: very little known above 2 GeV, puzzles in low mass region

- LQCD: 0^{-+}(2.3~2.6 GeV)

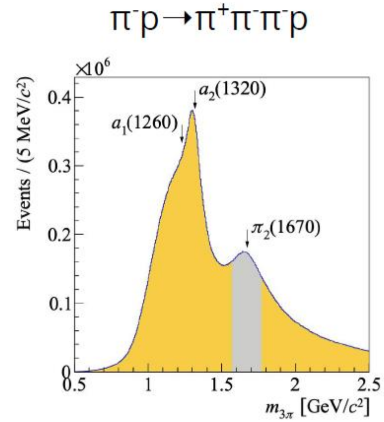
→

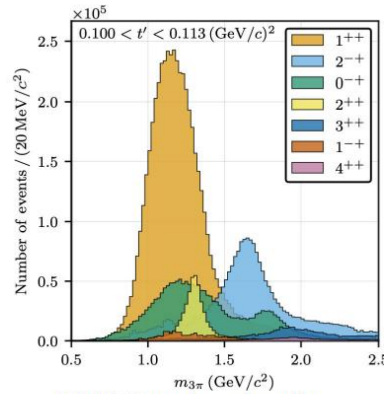
- ✓ **Trajectory**:
  - **η(1405) /η(1475) can be one resonance**
- ☐ **Above 2 GeV: X(2370)?**

Hybrids



J.J. Dudek *et al.*, PRD 88, 094505 (2013)





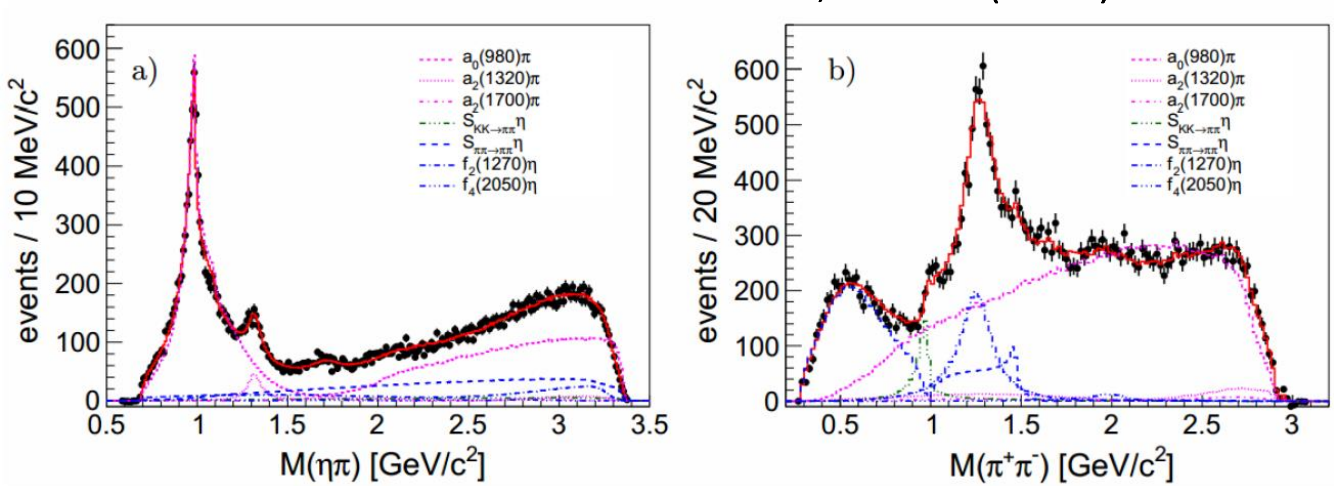
COMPASS results reviewed in:
B. Ketzer, B. Grube, and D. Ryabchikov, PPNP 113, 103755 (2020).

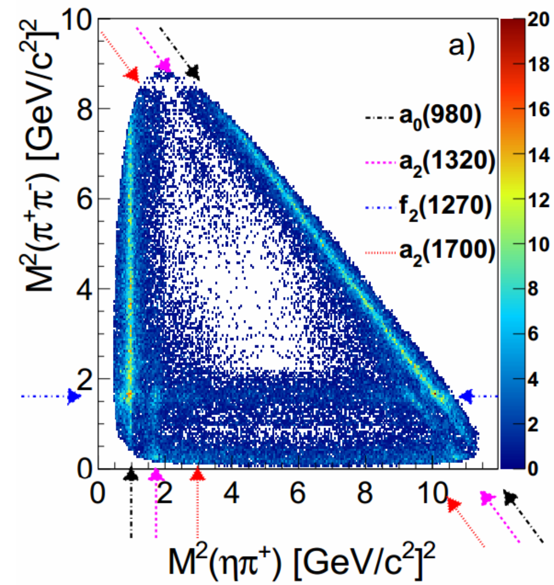
Only π_1 canditates are observed

Hybrids

- χ_{c1} **provides another suitable environment to look for 1^{-+}**
  - $\boldsymbol{\pi_1}$**(1600) studied in** $\chi_{c1} \to \eta' \pi^+ \pi^-$ **by CLEO-c** [PRD 84 112009(2011)]
  - **only** $\boldsymbol{\pi_1}$**(1400) has been reported decays to** $\boldsymbol{\eta\pi}$

$\chi_{c1} \to \eta \pi^+ \pi^-$ BESIII PR D95, 032002(2017)



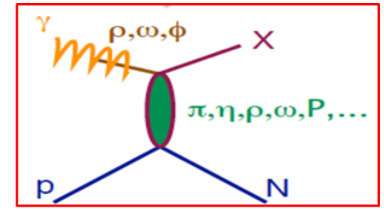


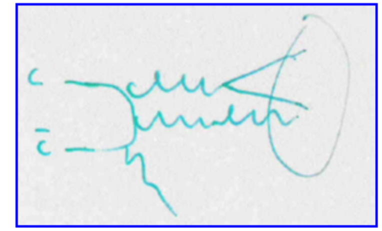
- **Clear evidence for a$_2$(1700) in χ_{c1}decays.**
- **First measurement of** $g'_{\eta'\pi} \neq 0$ **using** $a_0(980) \to \eta\pi$ **line shape.**
- **Measured upper limits for** $\pi_1(1^{-+})$ **in 1.4 - 2.0 GeV/c^2 region.**

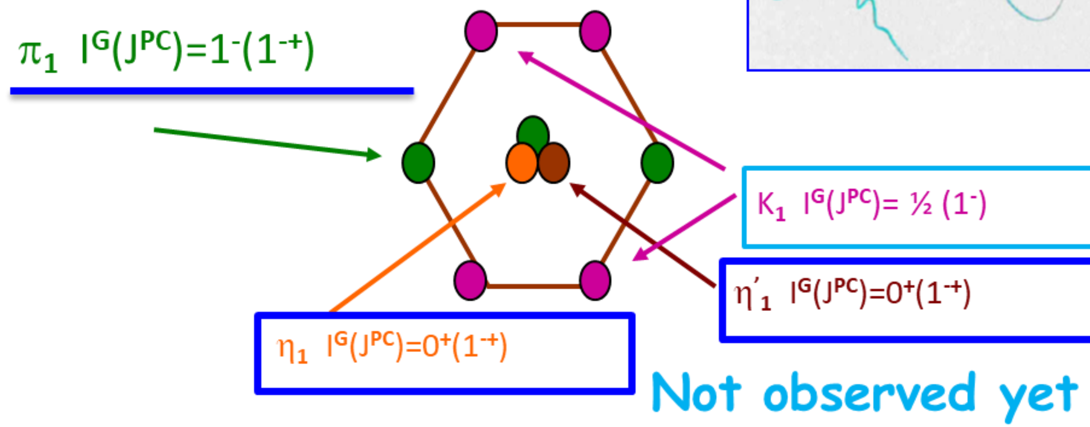
Hybrids

GlueX@JLab

BESIII







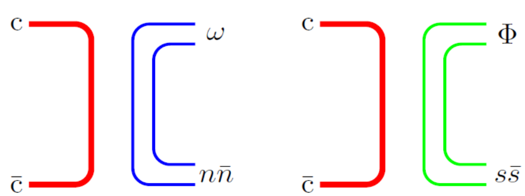
- Establishing a spectrum of hybrids is necessary. Isoscalar 1^{-+} is critical
- Isoscalar 1^{-+} is expected to be produced J/ψ radiative decays
  - $J/\psi \to \gamma + a_1\pi/\eta f_1/K_1K/\eta\eta'/\eta f_2$ /…,
- Synergies between other experiments

10B J/ψ and 3B ψ′ provide great opportunities to mapping the spectrum of light mesons and gluonic excitations

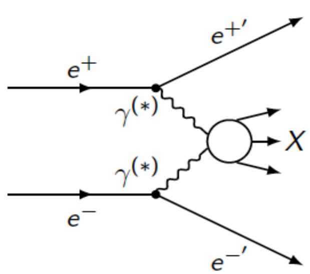
	0^+	2^+	0^-
J/ψ→γPP			
J/ψ→γVV			
J/ψ→γPPP			
J/ψ→γPPPP			

Flavor Filters：

J/ψ→γX →γ γ V　　J/ψ→ω/ϕ + X



Anti filter:



- 0^+, 2^+ : coupled channel analysis
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory >2 GeV, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V
- 1^{-+}
  - J/ψ→$\gamma\eta_1^{(\prime)}$
  - $\chi_{c1} \to \eta\eta_1^{(\prime)}, \pi\pi_1$

A few highlights

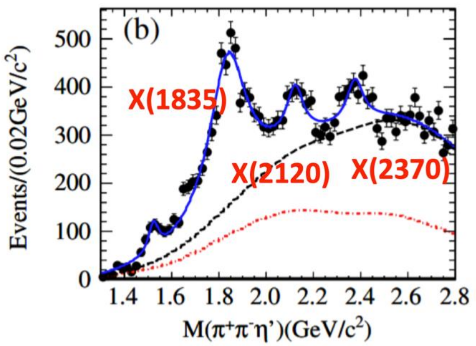
- Search for glueballs and hybrids

- Structures near $\mathrm{N\bar{N}}$ threshold
  - $\mathrm{X(p\bar{p})}$ and X(1835)
- Scalars near $\mathrm{K\bar{K}}$ threshold
  - $\mathrm{a_0(980) - f_0(980)}$ mixing

X(1835)/$X(p\bar{p})$'s structure at $p\bar{p}$ threshold

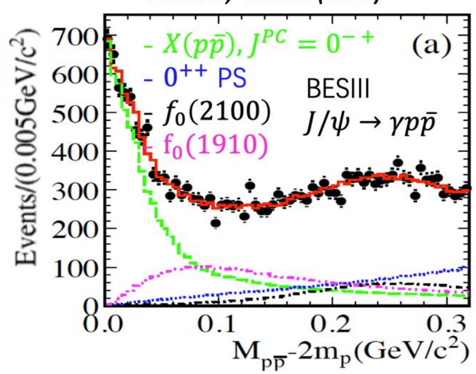
X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

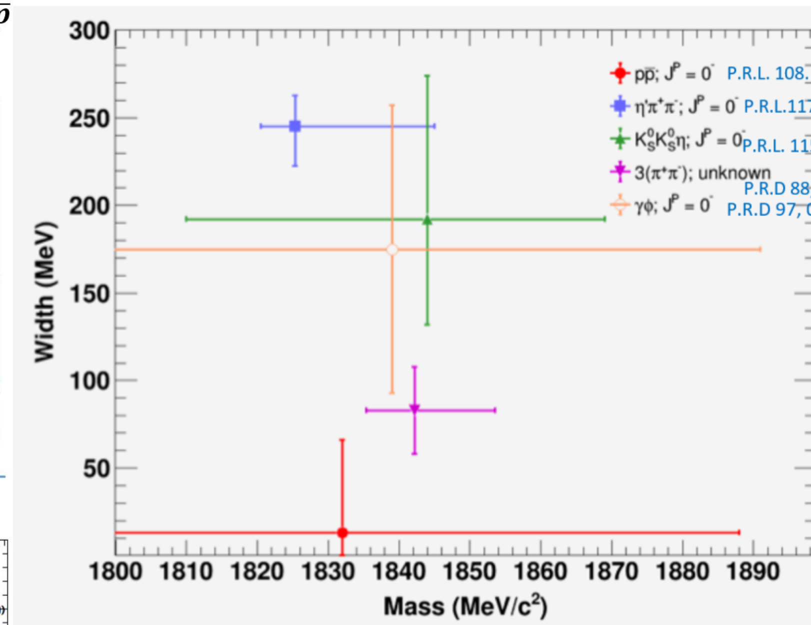
PRL 106, 072002(2011)



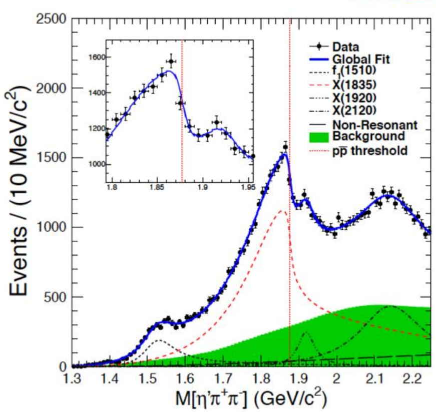
$X(p\bar{p})$ observed in $J/\psi \to \gamma p\bar{p}$

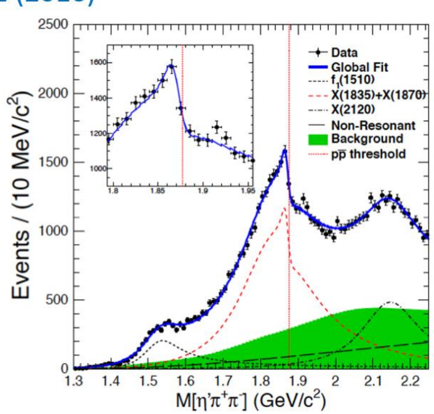
PRL 108, 112003 (2012)
PRL 115, 091803(2015)





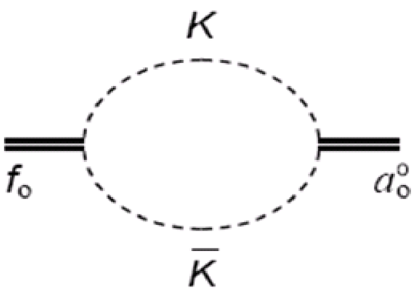
PRL 117, 042002 (2016)

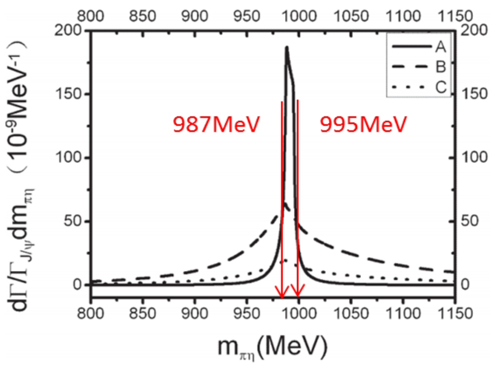


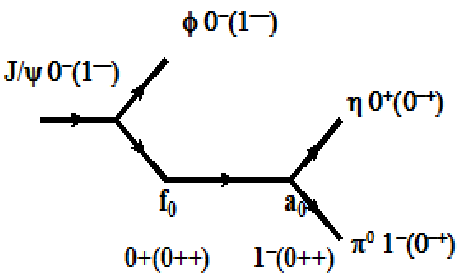


- Anomaly line shape of X(1835) is observed in $p\bar{p}$ threshold
- $p\bar{p}$ molecule-like state ? bound state ?

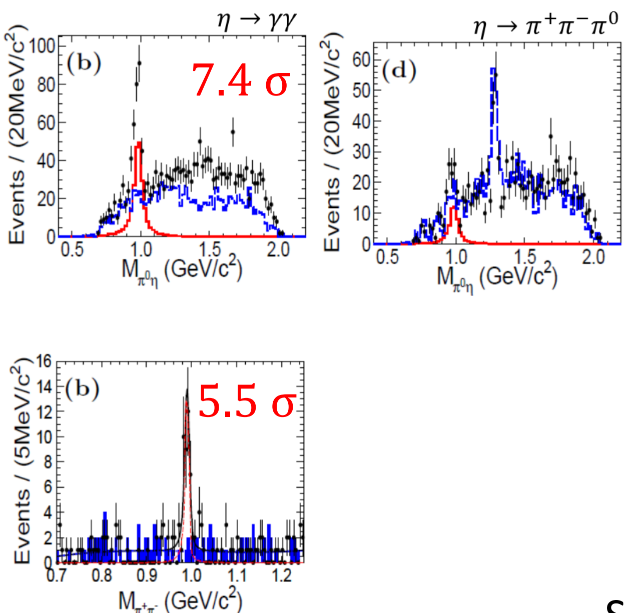
$a_0(980) - f_0(980)$ mixing

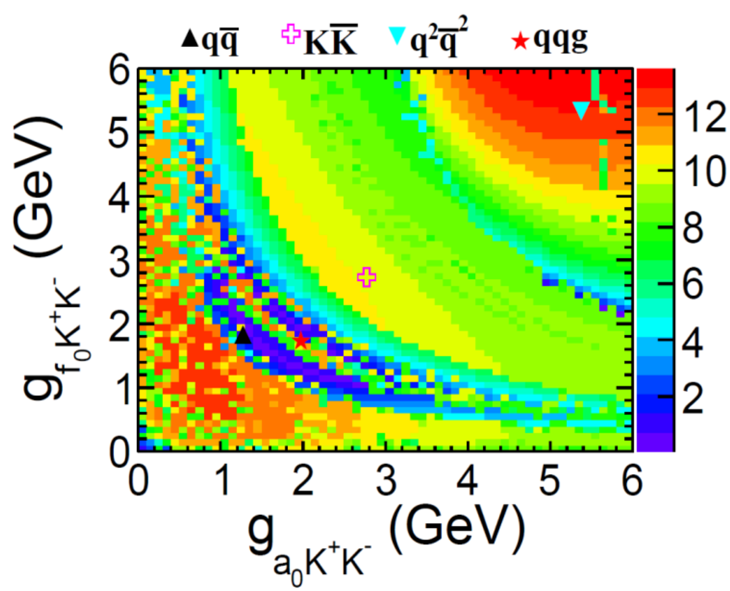






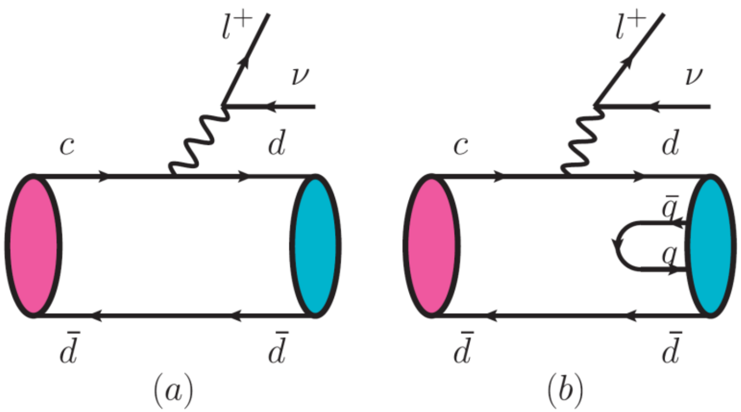
First direct measurement with > 5σ , [BESIII PRL 121 022001]





Significance of $a_0 - f_0$ mixing signal VS. coupling of $a_0(f_0) \to K\overline{K}$

Explore light hadrons with charmed meson decays

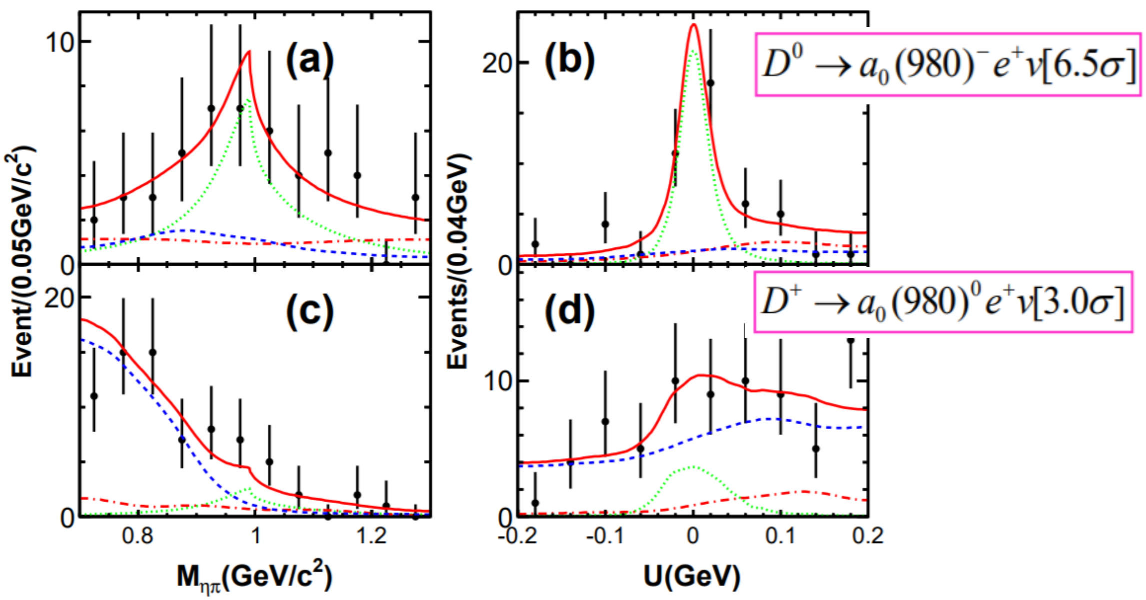


In the SU(3) symmetry limit,

PR D82, 034016 (2010)

$$R = \frac{\mathcal{B}(D^+ \to f_0(980) l^+ \nu) + \mathcal{B}(D^+ \to f_0(600) l^+ \nu)}{\mathcal{B}(D^+ \to a_0^0(980) l^+ \nu)}$$

$$= \begin{cases} 1 & \text{two quark} \\ 3 & \text{tetra-quark} \end{cases} .$$



BESIII measurements:

PRL 121, 081802 (2018)

PRL 122, 062001 (2019)

$R_{BESIII} > 2.7$ @ 90% C.L.

Summary

- Understanding how the strong interaction of quarks and gluons generate the structures and properties of hadrons remains an interesting (and important) question
  - The light quark sector is more complicated, but indispensable
  - Different experiments with complementary information are needed
- BESIII has a unique role to leading the efforts
  - Unprecedented high-statistics data sets of charmonia provide a gluon rich environment. Will continue to run for ~10 years
  - To fully explore the data sets, more advanced tools and closer experiment<->theory cooperation are needed

Thank you for your attention

Other information on scalars

Two photon couplings

"Stickness"

PDG2018

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$f_0(1710)$ Γ(i)Γ(γγ)/Γ(total)

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ **$\Gamma_1\Gamma_4/\Gamma$**

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
$12^{+3}_{-2}{}^{+227}_{-\ 8}$		UEHARA	13	BELL	$\gamma\gamma \to K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<480	95	ALBRECHT	90G	ARG	$\gamma\gamma \to K^+ K^-$
<110	95	[1] BEHREND	89C	CELL	$\gamma\gamma \to K^0_S K^0_S$
<280	95	[1] ALTHOFF	85B	TASS	$\gamma\gamma \to K \overline{K} \pi$

However, a scalar in $\gamma\gamma \to \pi^0\pi^0$

Belle PRD 78 052004

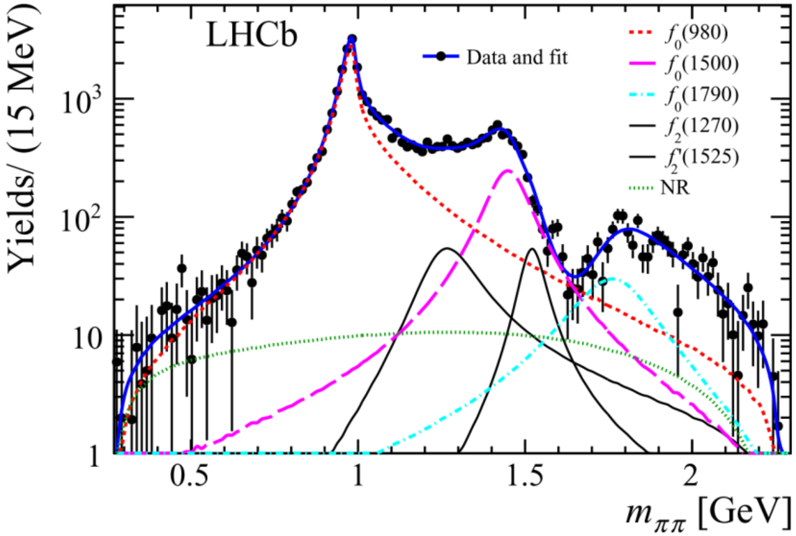
TABLE VI: Fitted parameters of the $f_0(Y)$

Parameter	Belle($\pi^0\pi^0$)	Crystal Ball	$f_0(1370)$(PDG)	$f_0(1500)$(PDG)	Unit
Mass	$1470\ ^{+6}_{-7}\ ^{+72}_{-255}$	1250	1200 - 1500	1507 ± 5	MeV/c^2
Γ_{tot}	$90\ ^{+2}_{-1}\ ^{+50}_{-22}$	268 ± 70	150 - 200	109 ± 7	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	$11\ ^{+4}_{-2}\ ^{+603}_{-7}$	430 ± 80	Unknown	Not seen	eV

$f_0(1370)$? $f_0(1500)$?

$B_s \to J/\psi f_0$ is selective for $s\bar{s}$

PLB 797 (2019) 134789



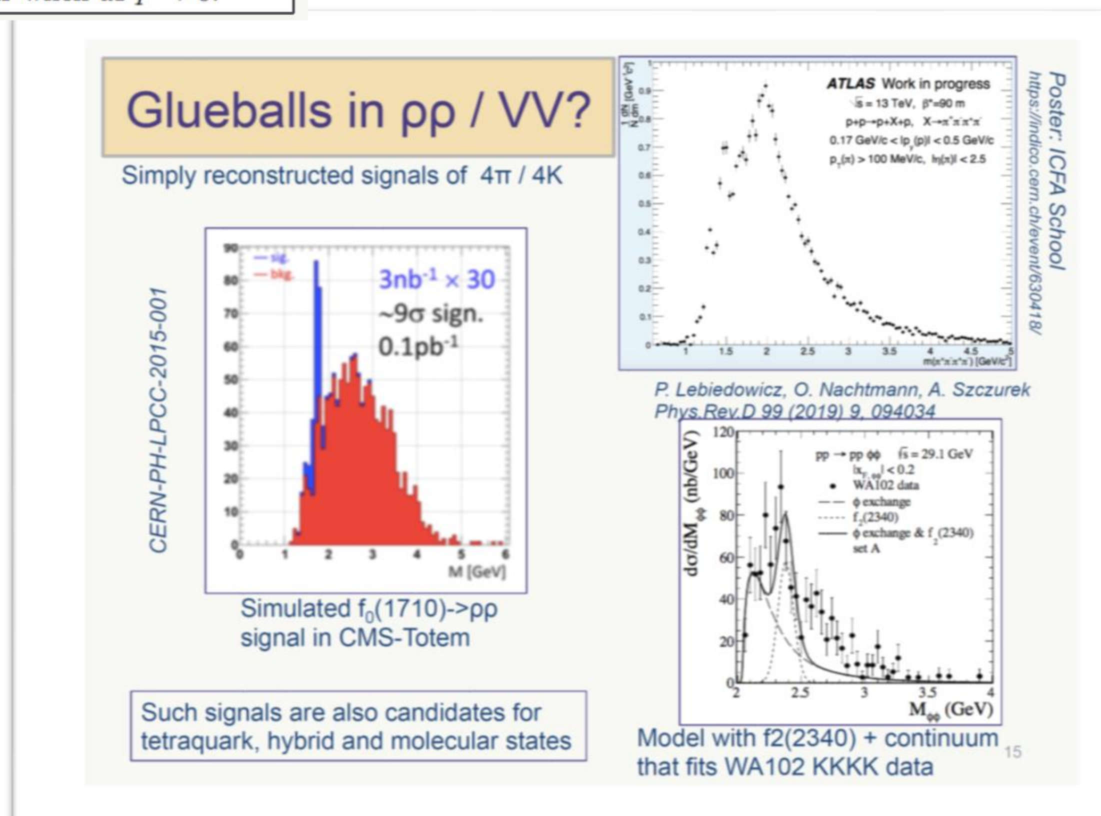
observation of $f_0(1500)$,
non-observation of $f_0(1710)$

Assignment requires further study with more sophisticated model

Central Exclusive Production

F. Close, A. Kirk, Phys.Lett.B397:333-338,1997

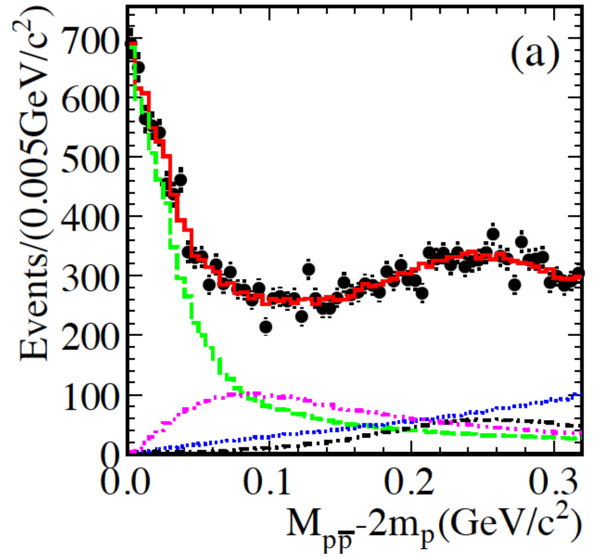
We shall suggest that it is driven primarily by the variable $dP_T \equiv |\vec{p_T} - \vec{q_T}|$ and that gg configurations are enhanced in kinematic configurations where the gluons can flow "directly" into the final state with only small momentum transfer, in particular when $dP_T \to 0$.



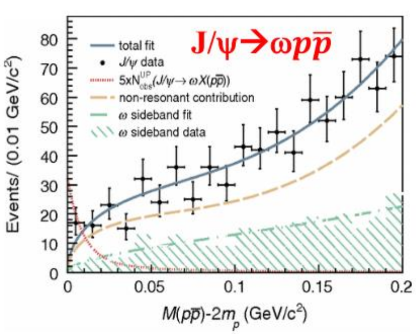
From R. McNulty, Snowmass2021 Workshop

$p\bar{p}$ threshold enhancement $X(p\bar{p})$

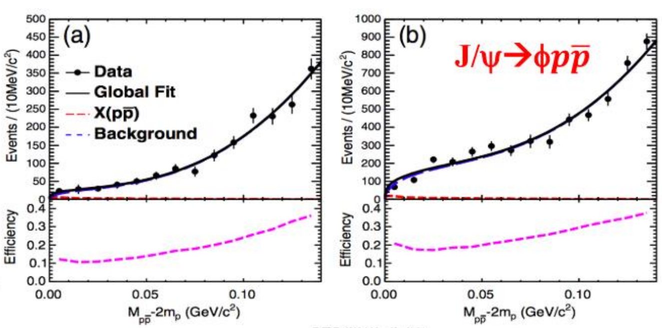
PRL 108 112003



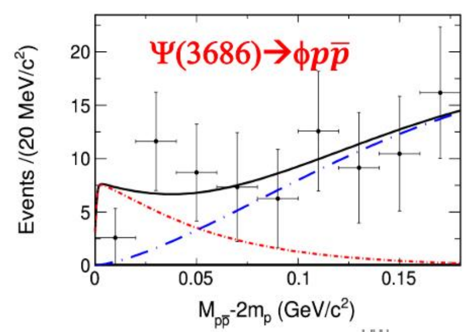
- First observed in $J/\psi \to \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \to \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure
- Non-observation in hadronic decays: not from pure FSI



PR D87 112014



PR D93 052010

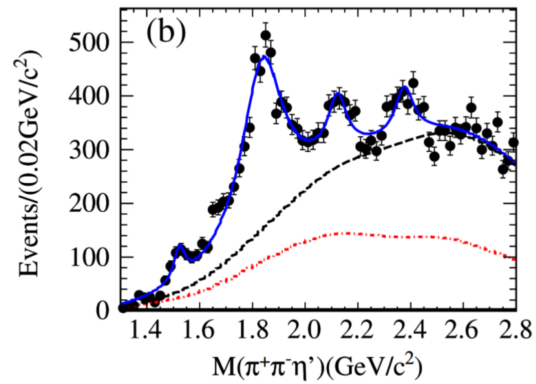


PR D99 112010

X(1835)

- Observed by BESII in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$, confirmed at BESIII
- PWA of $J/\psi \rightarrow \gamma K_s K_s \eta$
  - X(1835)→$K_S K_S \eta$ is observed (the $K_S K_S$ system is dominantly produced through the $f_0(980)$)
  - $J^{PC}=0^{-+}$

PRL 106 072002



PRL 115 091803