



Light meson spectroscopy: experimental status

Alessandra Filippi
INFN Torino



GHP 2025
Anaheim, March 14-16, 2025

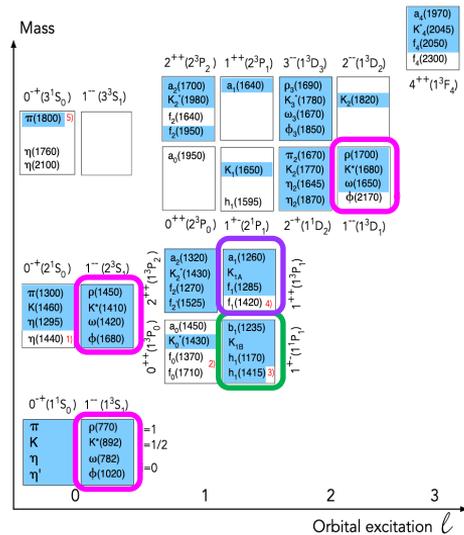
Outline of the talk

- ◀ General features of light mesons
- ◀ Investigation methods
- ◀ News on non-strange exotic candidates
 - ◀ Search for hybrid mesons and glueballs
- ◀ Conclusions

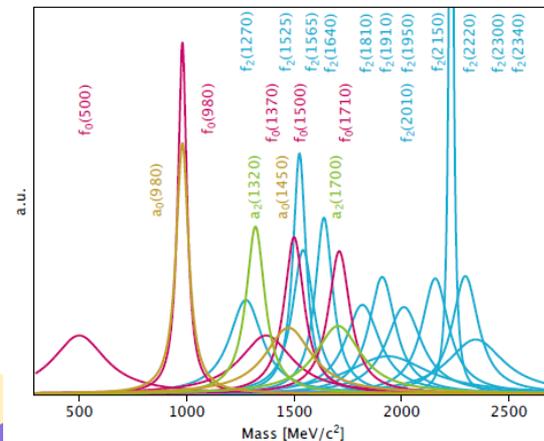
A plethora of new observations made in the recent years
Only a selection will be reported

Light mesons features

- Light meson mass region (below ~ 2.2 GeV) very packed
- Several (mostly broad) resonances with the same quantum numbers
 - Interfering
 - Overlapping
 - (possibly) mixing
 - Decays in the same and/or different channels
- Difficult identification
 - Resonances do not always appear as peaks
 - Peaks are not always generated by a resonance!
- The analysis of a single channel is usually not enough to disentangle and identify states unambiguously
- More tools and experimental inputs needed
 - Important to exploit as many experimental information as possible!



spectrum of well established states



Hadrons beyond the Constituent Quark Model



ordinary mesons



ordinary baryons

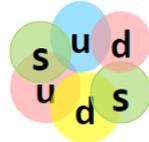
non- $q\bar{q}$ & non- qqq color-singlet combinations



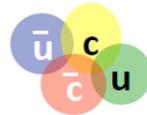
pentaquarks



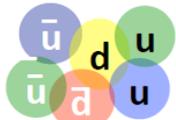
glueballs



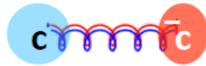
H-dibaryon



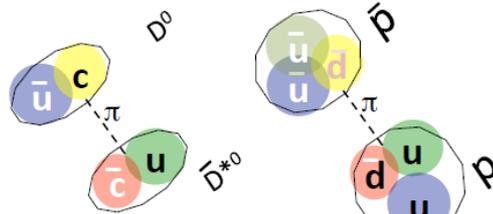
diquark-diantiquarks



heptaquarks



hybrids



deusons

molecules

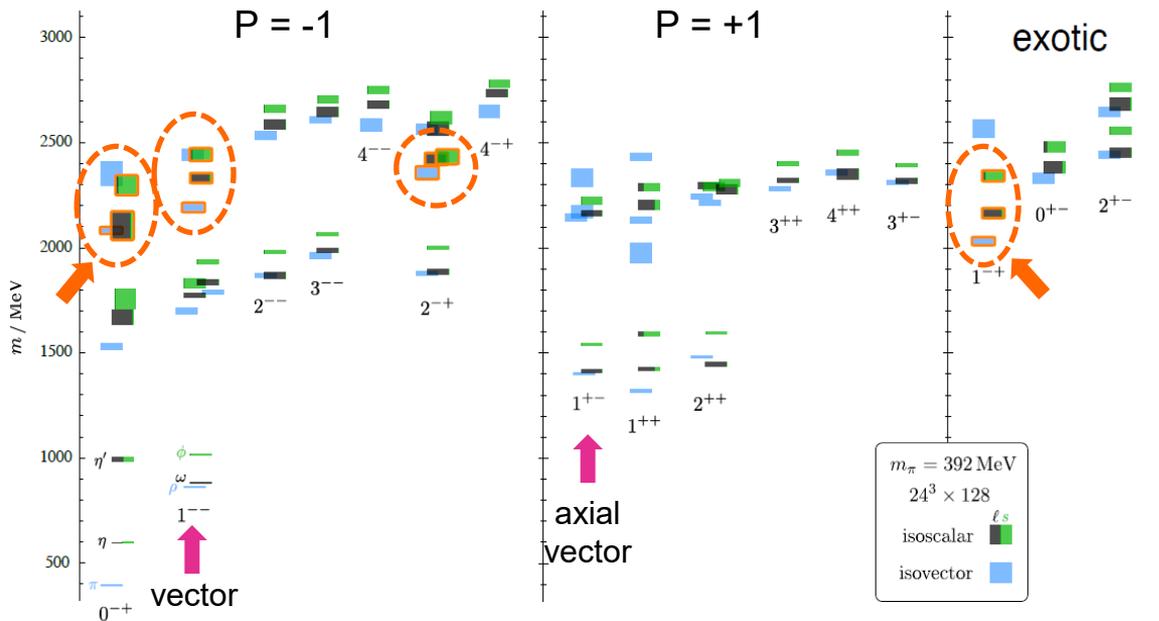
protonium

- QCD intrinsically allows for the existence of hadrons formed by gluons only, or a mixture of quarks and gluons
 - Their quantum numbers may be the same as for ordinary $q\bar{q}$ pairs... but they can also be forbidden combinations!



exotics

The meson spectrum from Lattice QCD



[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

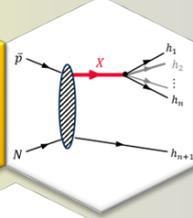
- ▶ State-of-art calculations with $m_\pi = 391 \text{ MeV}/c^2$
- ▶ Expectations for masses in overall agreement with observations
 - ▶ Towers of excited states similar to quark models
 - ▶ May include gluonic contributions
- ▶ Additional hybrid meson supermultiplet
- ▶ Lightest $|q\bar{q}g\rangle$ hybrid state: isovectors with exotic $J^{PC} = 1^{-+}$
- ▶ First predictions for hybrid partial widths
 (Woss et al. PRD **103**(2021), 054502)

Meson production mechanisms

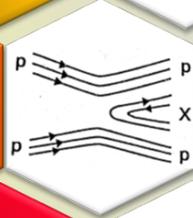
Hadronic processes

$\bar{N}N$ annihilation,
at rest and in-flight

Gluon rich process

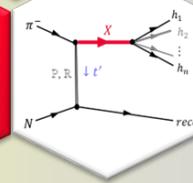


pp central production



$pp/\pi N$ diffractive (peripheral) production

Pomeron and Reggeons exchange



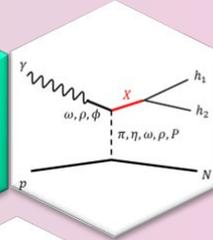
Quarkonium radiative decays

All reactions induced by hadronic probes are gluon-rich processes

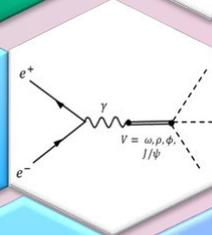
Electromagnetic processes

Diffractive photoproduction
 $\gamma N \rightarrow N' X$

Production of spin 1 lightest hybrids



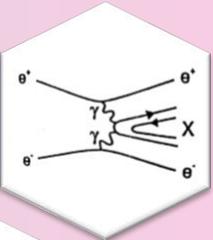
single photon (VDM): 1^{--} meson production



e^+e^- annihilation

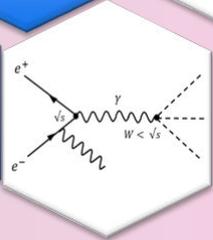
two photons:
 $e^+e^- \rightarrow \gamma\gamma \rightarrow e^+e^-X$

- Tagged vs untagged
- Spin 1 production strongly suppressed: possible only with one virtual γ
- $C = +1, J^{PC} = 0^{++}, 2^{++}, \dots$



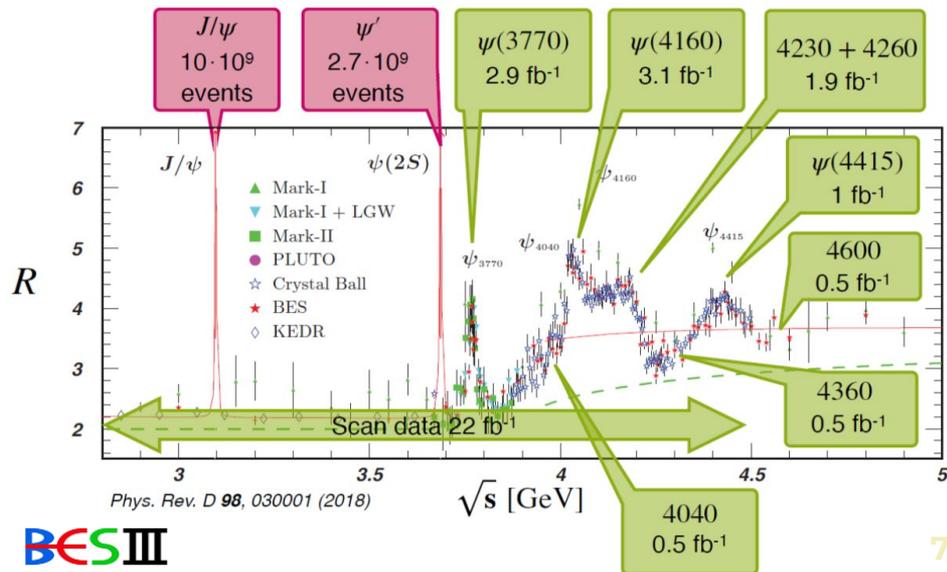
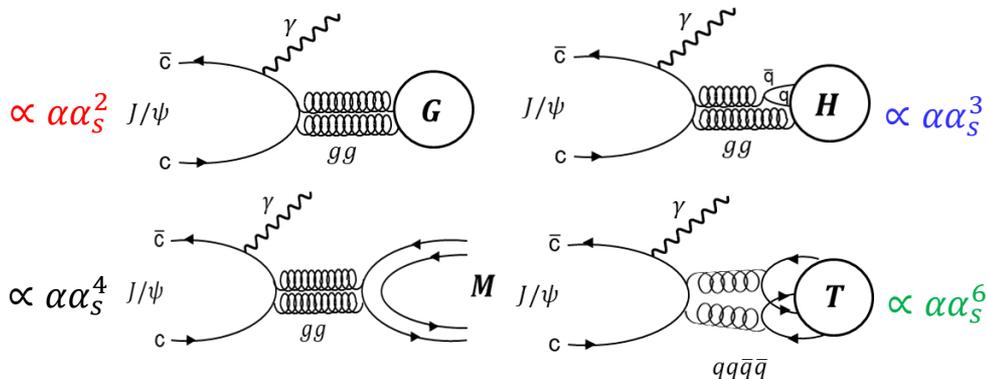
With ISR radiation:
 $e^+e^- \rightarrow e^+e^-\gamma$

Control the c.m. energy of the e^+e^- pair



Charmonium radiative decays

- ◀ Ideal environment for glueball searches
- ◀ Glueball production rates could be higher than in normal mesons
 - ◀ Processes mediated by 2- or 3g
- ◀ **Isospin filter**: final states dominated by $I=0$ processes
 - ◀ OZI rule
- ◀ **Spin parity filter: $C = +1$**
 - ◀ $J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}$
- ◀ Clean environment in e^+e^- collisions
 - ◀ BESIII accumulated so far 10 B J/ψ , and 3B $\psi(2S)$
 - ◀ World largest data samples of charmonium resonances



Search for exotic- spin resonances: hybrids

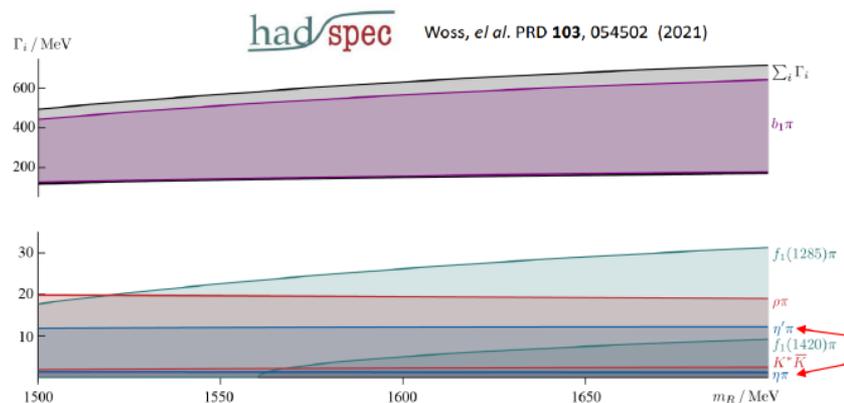


- The case of the $\pi(1600)$
 - Diffractive dissociation at COMPASS
 - Photoproduction at GluEx
- Observation of a new isoscalar at BESIII

Sticky fellows: hybrids



- Formed by quarks, anti-quarks and excitation gluon fields
- Low lying hybrids can have exotic quantum numbers 1^{+-} , 1^{-+} , 2^{+-} forbidden by $\bar{q}q$ configuration
- LQCD prediction: **lightest exotic 1^{-+} nonet in the mass range 1.7-2.1 GeV/c²**
- Preferred decays: S+P wave mesons**
 - Main mode: $b_1(1235)\pi \rightarrow \omega\pi\pi$
 - Other decays expected to be suppressed: $\rho\pi, \eta\pi, \eta'\pi$
- Some indications for isovector 1^{-+} : $\pi_1(1400), \pi_1(1600), \pi_1(2015)$
- 1^{-+} isoscalar?
 - Can be produced in J/ψ radiative decays
 - Can decay to $\eta\eta'$ in P-wave



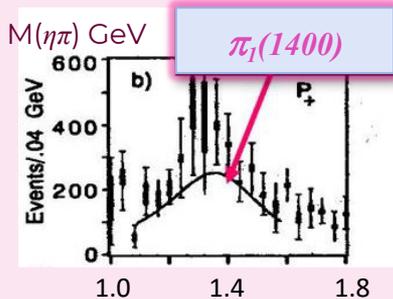
The $\pi_1(1400)/\pi_1(1600)$ case in a nutshell

Hints for spin exotics since the 80's

Two signals observed:

- ◀ $\pi_1(1400) \rightarrow \eta\pi$
 - ◀ 350-400 MeV broad
 - ◀ E852 (1997, 2007)
 - ◀ Crystal Barrel (1998)
- ◀ $\pi_1(1600) \rightarrow \eta'\pi, \rho\pi$
 - ◀ COMPASS (2010)
 - ◀ E852 (2001)
 - ◀ VES (1993)

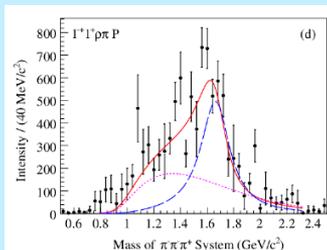
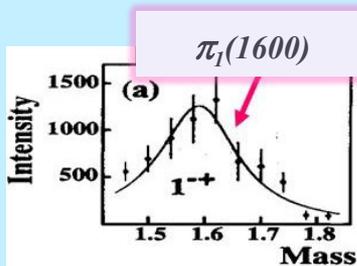
E852: $\pi^-p \rightarrow \pi^- \eta p$ and
 $\pi^-p \rightarrow \pi^0 \eta n$ @ 18 GeV/c



Observed as interference between $L=1$ and $L=2$ $\eta\pi$ amplitudes

State reported in $\eta'\pi$ and $\rho\pi$ channels, NO $\eta\pi$

$\pi^-p \rightarrow \pi^- \pi^+ \pi^+ p$ (COMPASS) and
 $\pi^-p \rightarrow \pi^- \eta' p$ (E852)



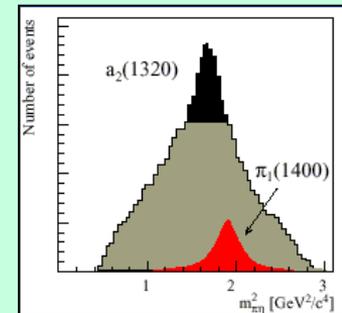
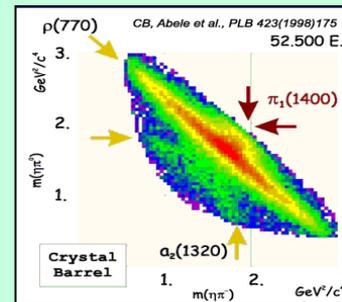
CRYSTAL BARREL: $\bar{N}N$ annihilations at rest

$\bar{p}n \rightarrow \pi^- \pi^0 \eta$
 $\bar{p}n \rightarrow \pi^0 \pi^0 \eta$

$\sigma, \rho \rightarrow \pi\pi$ and
 $a_2(1320) \rightarrow \eta\pi$ decays do not describe the data correctly

The presence of a $\pi_1(1400)$ meson decaying into $\eta\pi$ is needed

$\pi_1(1400)$



Novel observations of $\pi_1(1600)$ from COMPASS

$b_1(1235)\pi \rightarrow \omega\pi\pi$ spectroscopy:

$\pi^-p \rightarrow \omega\pi^- \pi^0$ @190 GeV

States observed in the $b_1(1235)\pi$ channel (+others in $\rho^-\omega$)

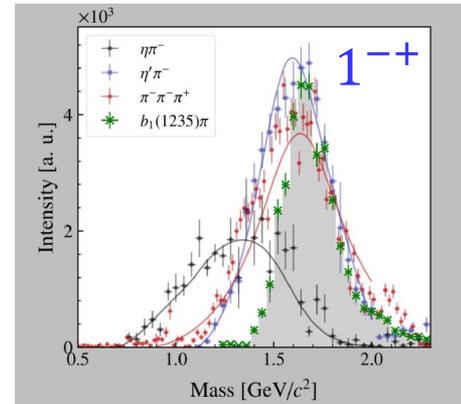
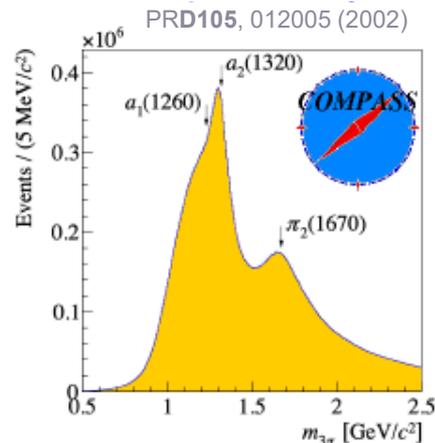
- ▶ 1^{-+} : $\pi_1(1600) \rightarrow b_1(1235)\pi$
- ▶ 2^{++} : $a_2(1320), a_2'(1700) \rightarrow b_1(1235)\pi$
- ▶ Possible additional signals from
 - ▶ 3^{++} : $a_3(1320)$
 - ▶ 4^{++} : $a_4(1970)$

$\eta^{(\prime)}\pi$ spectroscopy: $\pi^-p \rightarrow \eta^{(\prime)}\pi^0$ @190 GeV

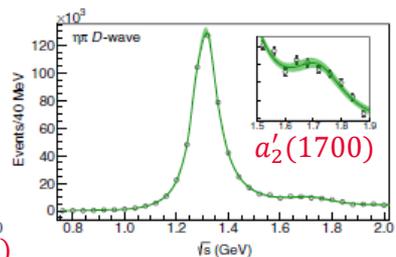
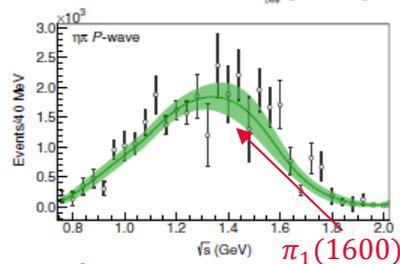
▶ $\pi_1(1400) \rightarrow \eta\pi$

▶ $\pi_1(1600) \rightarrow \eta'\pi$

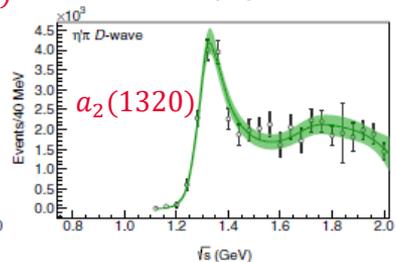
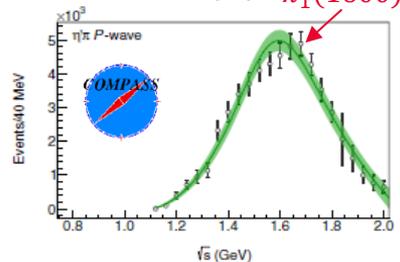
- ▶ Coupled channel analysis compatible with a **single pole at high mass**
- ▶ **Single pole hypothesis also compatible with coupled channel COMPASS+Crystal Barrel data analysis** (EPJ **C80**(2020),453)



NC 47C (2024), 150



JPAC



PRL122, 042002 (2019)

Novel observations of $\pi_1(1600)$ from GluEx

- Photoproduction reaction with polarized photons

$\eta\pi$ spectroscopy

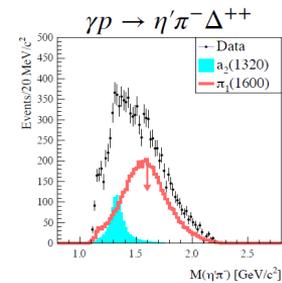
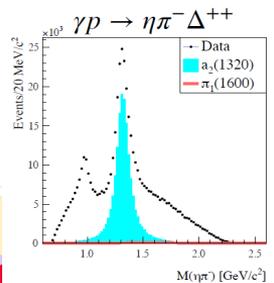
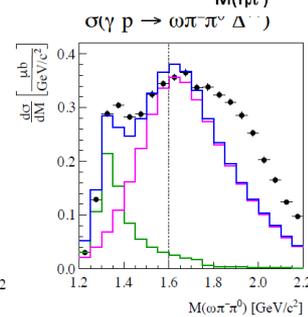
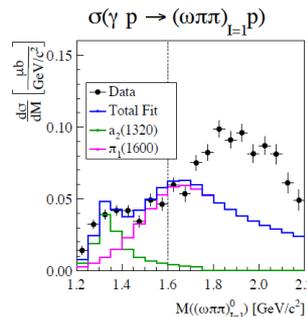
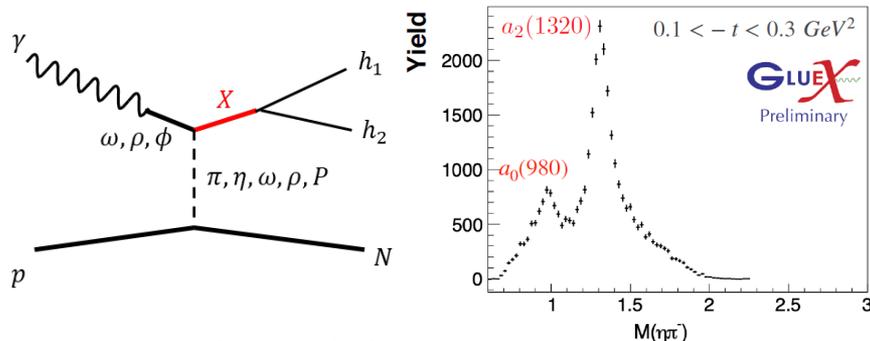
- Dominant $a_0(980)$ and $a_2(1320)$

$b_1(1235)\pi$ spectroscopy

- No clear signal observed for $\pi_1(1600)$: upper limit set

- Use the upper limit to assess a limit for the relative production to $a_2(1320)$ in $\eta^{(\prime)}\pi$

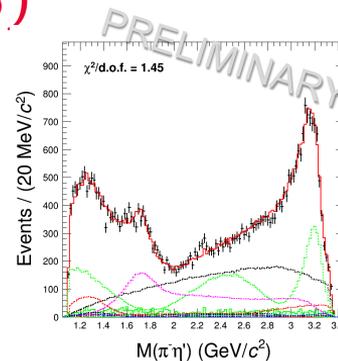
- $\pi_1(1600)$ could be significant in $\eta'\pi$
- Largely excluded in $\eta\pi$



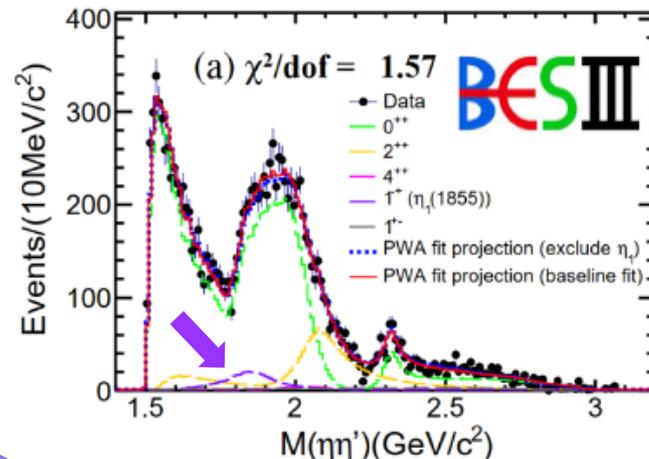
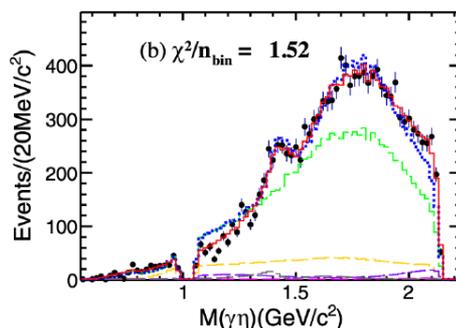
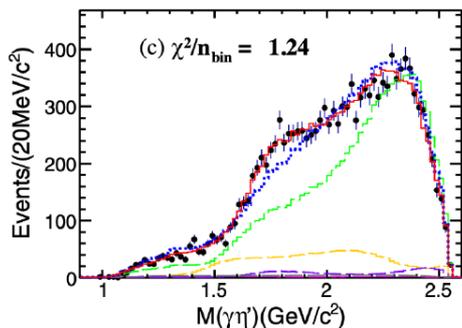
PRL133 (2024), 261903

A new hybrid candidate from BESIII: $\eta_1(1855)$

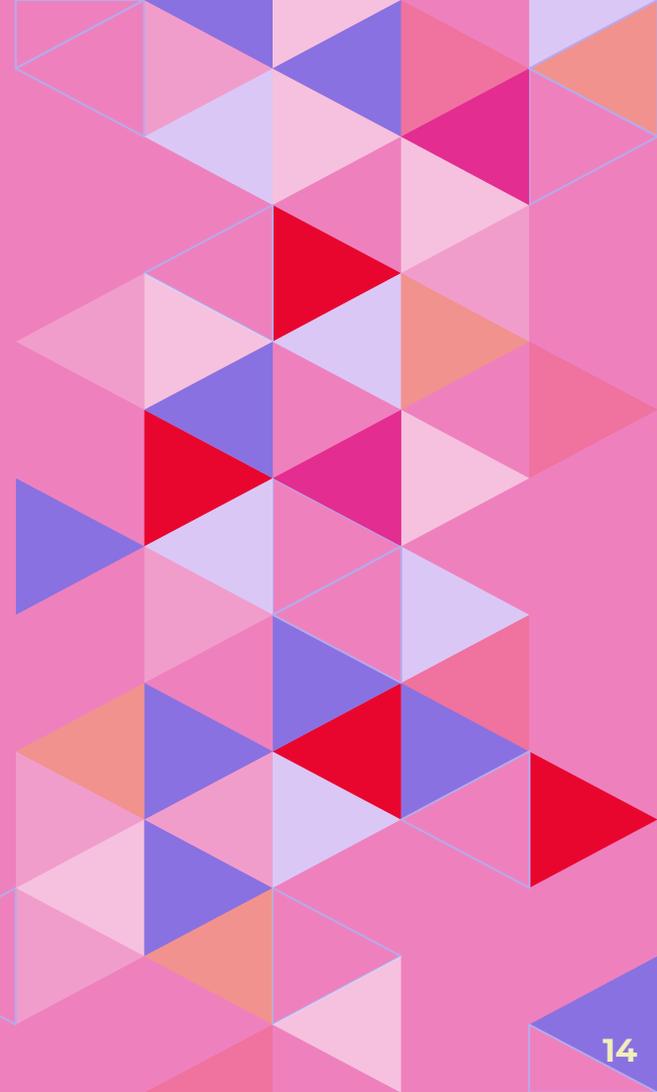
- Evidence of isovector $1^{-+} \pi_1(1600)$ in $\psi' \rightarrow \gamma \chi_{c1} (\chi_{c1} \rightarrow \pi^+ \pi^- \eta')$ [10σ]
 - Analysis in progress
- Evidence for a **new isoscalar $1^{-+} \eta_1(1855)$** in $J/\psi(1S) \rightarrow \gamma \eta' \eta$ [$>19\sigma$]
 - $m = (1855 \pm 9_{-1}^{+6})$ MeV, $\Gamma = (188 \pm 18_{-8}^{+3})$ MeV, decay in $\eta' \eta$
 - Isoscalar partner of $\pi_1(1600)$ in 1^{-+} nonet?
 - Signature of a tetraquark or molecule?
 - Agreement with LQCD expectations



PRL129 (2022), 192002
PRD106 (2022), 072012



The scalar and
pseudoscalar
sectors:
glueballs
footprints?



Sticky fellows: glueballs

- Unique particles with self-interactions
- No valence quark content, gluons only
- Strongly produced in gluon-rich processes
- Glueball decays:



- Flavor blindness**

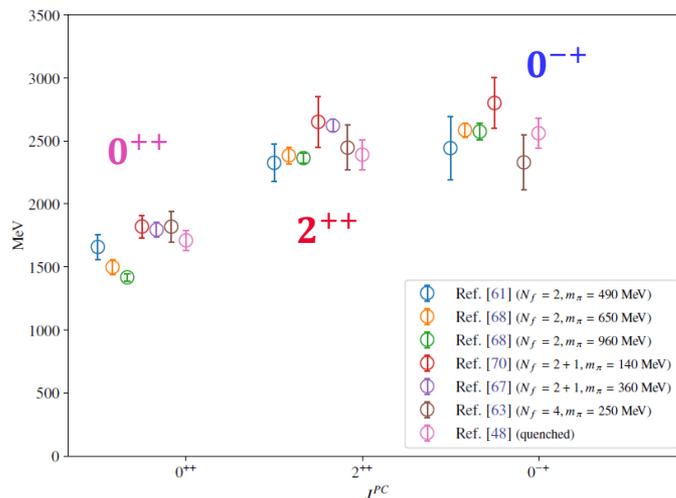
- $\Gamma(G \rightarrow \pi\pi: K\bar{K}: \eta\eta: \eta'\eta') = 3: 4: 1: 0: 1$

- $\eta'\eta'$ decay suppressed: important information from $J/\psi \rightarrow \gamma\eta\eta'$ radiative decay

- 1^{--} could decay like charmonium
- 0^{-+} could decay like $\eta_c \rightarrow \gamma\pi\pi$
 - Good place to search: $J/\psi \rightarrow \gamma\pi\pi\eta'$

- LCQD expectations:

- 0^{++} ground state: 1.5-1.7 GeV/c²
- 2^{++} ground state: 2.3-2.4 GeV/c²
- 0^{-+} ground state: 2.3-2.6 GeV/c²

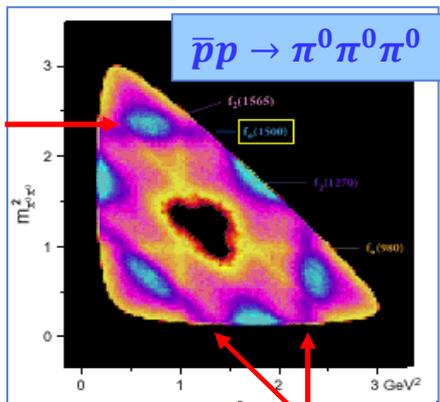


The scalar glueball: a bit of history

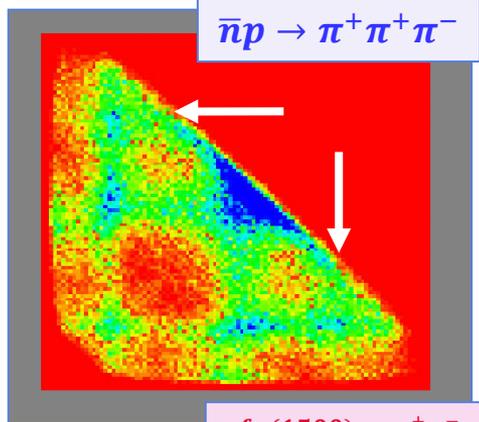
- Lightest glueball candidate until the y2000: **scalar state**
- $f_0(1500)$ observed by **Crystal Barrel** and **OBELIX** in $\bar{N}N$ @LEAR-CERN

- Three observed isoscalars $f_0(1370)$, $f_0(1500)$, $f_0(1710)$:
 - one appears to be supernumerary
- $f_0(1500)$
 - Compatible with a $\bar{n}n$ structure
 - Enhanced production in central collisions
 - Observed in multiple decay channels

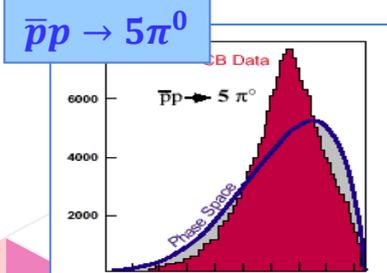
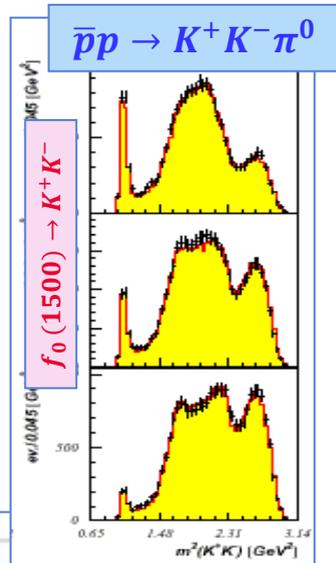
$f_0(1710)$ mostly $\bar{s}s$



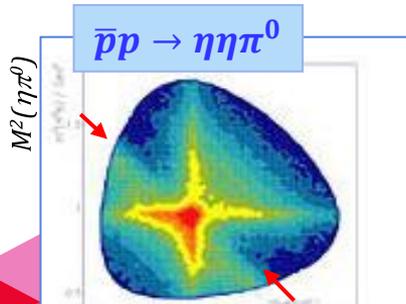
$f_0(1500) \rightarrow \pi^0 \pi^0$



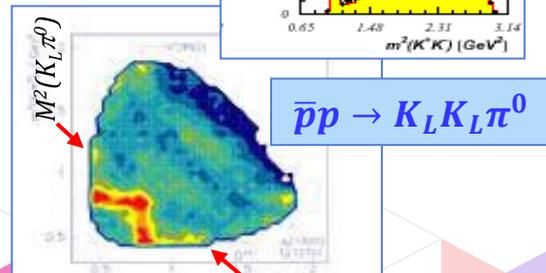
$f_0(1500) \rightarrow \pi^+ \pi^-$



$f_0(1500) \rightarrow 4\pi^0$



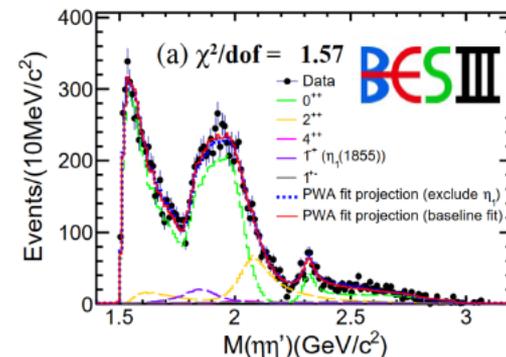
$f_0(1500) \rightarrow \eta \eta$



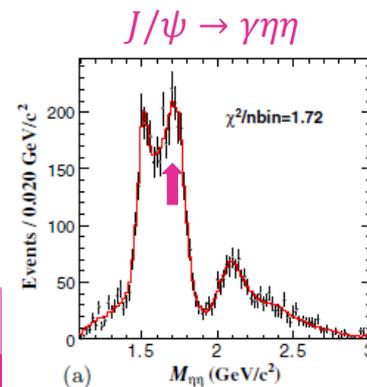
$f_0(1500) \rightarrow K_L K_L$

$f_0(1500)$ and $f_0(1710)$ at BESIII

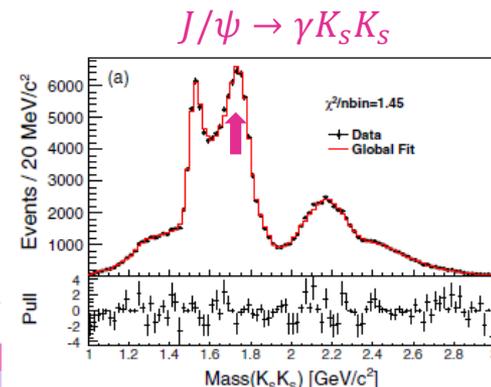
- ▶ $J/\psi \rightarrow \gamma\eta\eta'$
 - ▶ $f_0(1500) \rightarrow \eta\eta'$: significant contribution
 - ▶ $f_0(1710) \rightarrow \eta\eta'$: not observed
- ▶ $J/\psi \rightarrow \gamma\eta'\eta'$, $J/\psi \rightarrow \gamma K_S K_S$, $J/\psi \rightarrow \gamma\pi^0\pi^0$
 - ▶ Large $f_0(1710)$ production (assuming $f_0(1810)$ is the same object)



- ▶ $f_0(1710)$ can have a large gluonic content or a sizeable overlap with the ground state scalar glueball



PRD87 (2013), 092009



PRD98 (2018), 072003

The pseudoscalar and axial vector sectors: the old $E/1$ puzzle

- Long standing problem since the 70's: superimposition of several pseudoscalar and axial states in the (1.3-1.5) GeV mass region, decaying to $\bar{K}K\pi$
 \Rightarrow “ $E/1$ puzzle”
- The $\bar{K}K\pi$ decay channel is only possible for $J^P = (\text{odd})^+ \text{ or } (\text{even})^-$

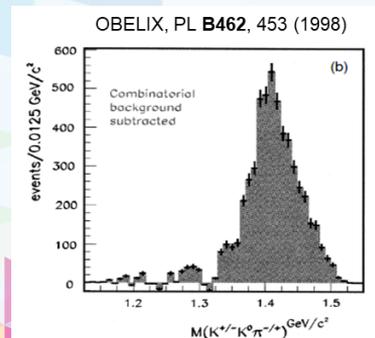
Pseudoscalar states 0^{-+}

- All of them decay to $a_0(980)\pi$, K^*K , $\bar{K}K\pi$
- $\eta(1275)$: First η' radial excitation?
- $\eta(1440)$: likely split in two states
 - $\eta(1405)$: true gluonium candidate?
 - Not observed in $\gamma\gamma$ collisions, large production in gluon rich environments (J/ψ decays, peripheral production, $\bar{p}p$ annihilation)
 - $\eta(1475)$: radially excited $\bar{s}s$ state in $K^*\bar{K}$?
 - Observed in $\gamma\gamma$ collision
 - Not seen in K^-p collisions

Axial states 1^{++}

- $f_1(1285)$: does not decay to $K^*\bar{K}$
- $f_1(1420)$: hybrid $\bar{q}qg$? 4-quark state? $K^*\bar{K}$ molecule?
- $f_1(1510)$: not established yet
- + isovector $a_1(1420)$ (COMPASS)

$$\bar{p}p \rightarrow K^0 K^\pm \pi^\mp \pi^+ \pi^-$$



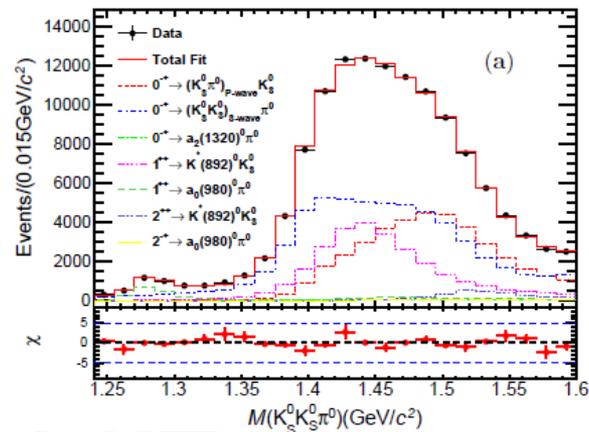
$\eta(1405)/\eta(1475)$ puzzle: BESIII recent results

- $J/\psi \rightarrow \gamma K_S K_S \pi^0$
 - Prominent structures around 1.45 GeV
 - Clear bump about 1.28 GeV
 - Two isoscalar states $\eta(1405)/\eta(1475)$ can fit well the data

- $J/\psi \rightarrow \gamma\gamma\phi$
 - Clear observation of $\eta(1405)$ [18.9σ]
 - $\eta(1475)$ cannot be excluded

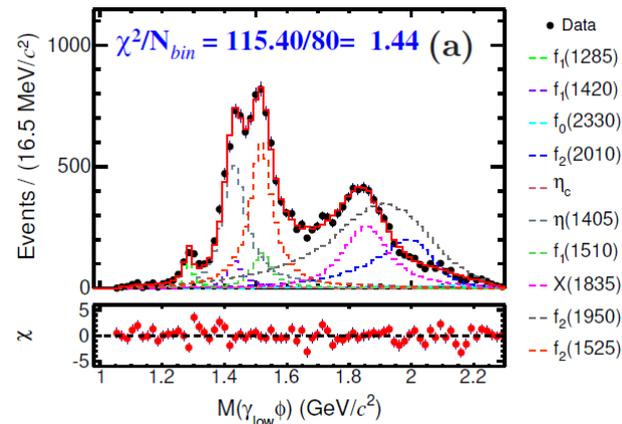
- The nature of $\eta(1405)$ is still unclear

JHEP03 (2023). 121



BESIII

ArXiv:2401.00918



X(2370): a pseudoscalar glueball?

◀ A wealth of pseudoscalar “X” states observed by BESIII, starting from the 10B $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ sample

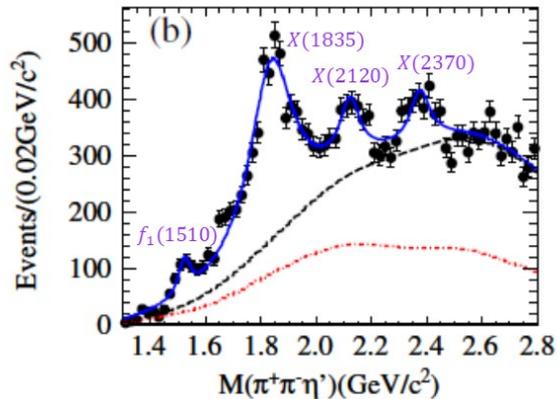
◀ **X(2370)** observed in several gluon-rich decay channels:

- ◀ $\eta'\pi^+\pi^-$, $\eta'K^+K^-$, $\eta K_S K_S$, $\pi^0 K_S K_S$, $\eta\pi^0\pi^0$, $a_0(980)\pi^0$
- ◀ Analog to η_c decay pattern

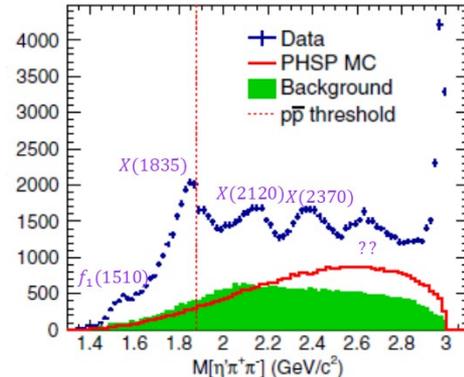
◀ $J^{PC} = 0^{-+}$

◀ Mass and production rates consistent with LQCD expectations for the **lightest pseudoscalar glueball**

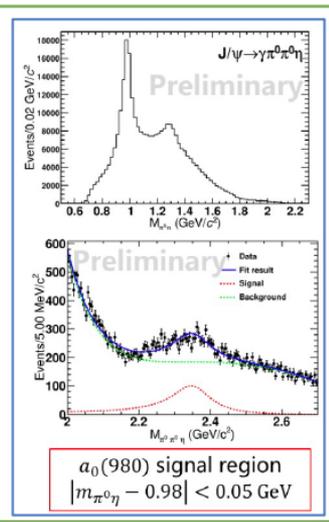
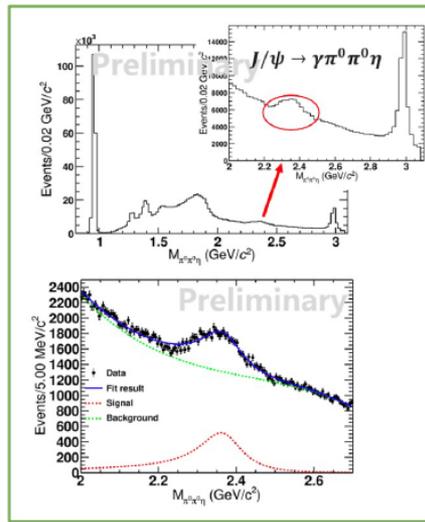
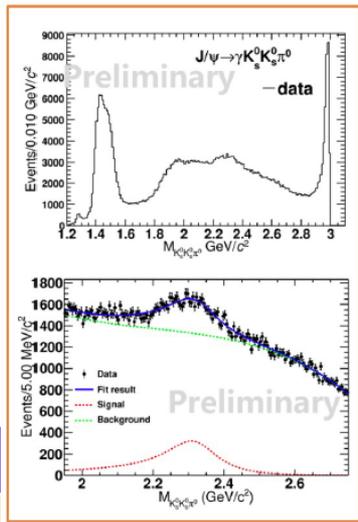
PRL106 (2011), 072002



PRL117 (2016), 042002



Lyu, ICHEP2024



Conclusions

- ◀ Over the last 30 years a significant amount of data was collected and analyzed, but **still many unsolved questions**
 - ◀ Lots of broad and overlapping signals observed
 - ◀ A complete and unambiguous identification of all the component of $\bar{q}q$ multiplets is still missing
- ◀ **More sophisticated approaches needed for light mesons coupled to different production and decay channels**
 - ◀ unitarity is violated by simple single-channel approach
- ◀ **Most significant recent observation: spin exotic 1^{-+} wave**
 - ◀ $\eta\pi$ @ 1.4 GeV, $\eta'\pi$ @ 1.6 GeV in pion diffraction, observed also in photoproduction and J/ψ decays
- ◀ **Mostly important:** **match and combine observations** for high statistics experiments in as many production and decay channels as possible

Backup slides



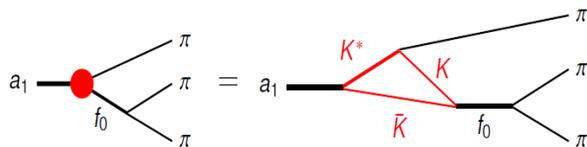
“Fake” resonance: the $a_1(1420)$ case



◀ $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ @ 190 GeV

◀ Clear peak at 1.4 GeV: $a_1(1420)$

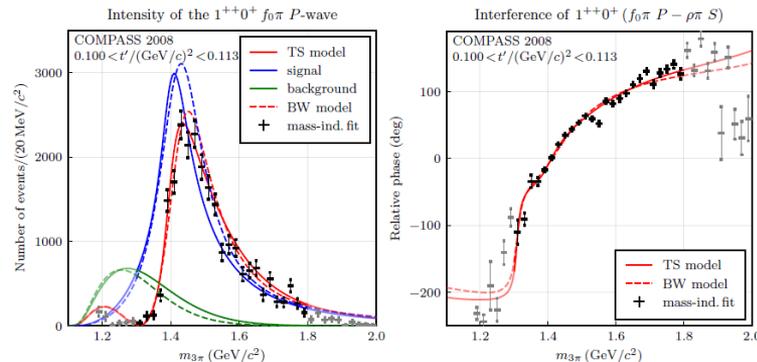
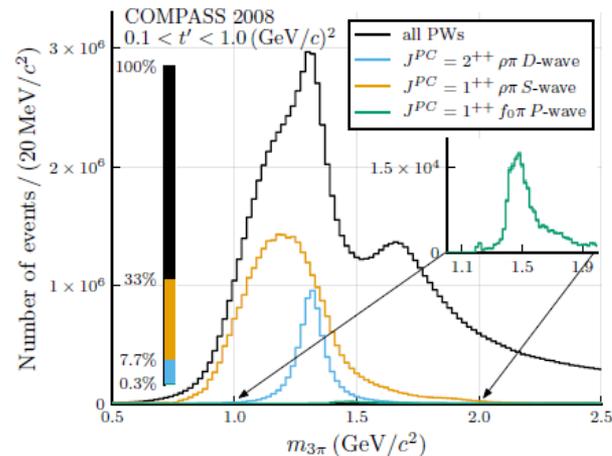
- ◀ exotic $J^{PC} = 1^{++}$ in $f_0(980)\pi$
- ◀ Resonant behavior (also correct phase motion!)
- ◀ Not an ordinary meson
 - ◀ Small width, narrower than the ground state ($a_1(1260)$: $\Gamma \sim 500$ MeV)
 - ◀ Too close to ground state: 400 MeV expected from radial excitation trajectories
 - ◀ Seen only in one channel: $f_0(980)\pi$



◀ It can be better explained by a three body rescattering effect: triangle-singularity mechanism

◀ $a_1(1260) \rightarrow K^*(\rightarrow \pi K)\bar{K} +$ rescattering to $f_0(980)$

PRL127 (2021), 082501



Indications for tensor glueballs

◀ $f_2(1950)$

- ◀ Observed by several experiments, beyond the known $f_2(1270)$ ($\bar{n}n$) and $f_2(1525)$ ($\bar{s}s$)
 - ◀ GAMS (1995): $f_2(1950) \rightarrow \pi\pi$
- ◀ Ground state of the Pomeron?

◀ $f_2(2340)$

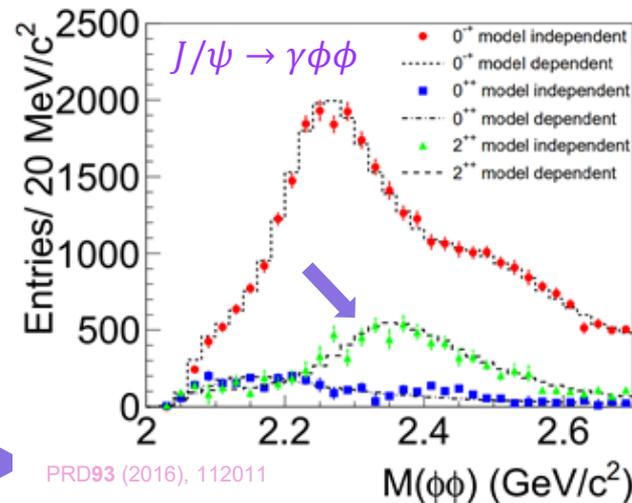
- ◀ Large $\bar{p}p \rightarrow \phi\phi$ production (JETSET)
- ◀ Large cross section in $\pi^-p \rightarrow \phi\phi n$
- ◀ Observed by BESIII in $J/\psi \rightarrow \gamma\phi\phi$
 - ◀ Relatively narrow
 - ◀ Several decay channels
 - ◀ Mass substantially lower than LQCD predictions

- ◀ Expected decay width:

$$\Gamma(J/\psi \rightarrow \gamma G_{2+}) = 1.01(22) \text{ keV}$$

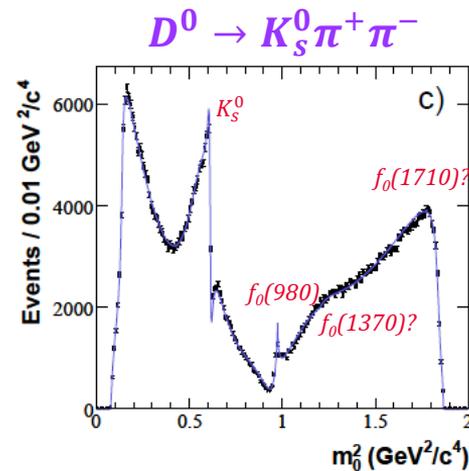
- ◀ $J/\psi \rightarrow \gamma f_2(2340)$ decay modes:

- ◀ $f_2(2340) \rightarrow \eta\eta$
- ◀ $f_2(2340) \rightarrow \phi\phi$
- ◀ $f_2(2340) \rightarrow K_S K_S$
- ◀ $f_2(2340) \rightarrow \eta'\eta'$



The scalar sector in a nutshell

- Since the 90's: too many observed states to be fit into the scalar nonet
 - The “isoscalar ($\pi\pi$) S-wave puzzle”**
- Three “confirmed” f_0 mesons and a couple of suspects
 - $f_0(980)$, $f_0(1300)$, $f_0(1590)$
 - $f_0(1500)$, $f_0(1370)$

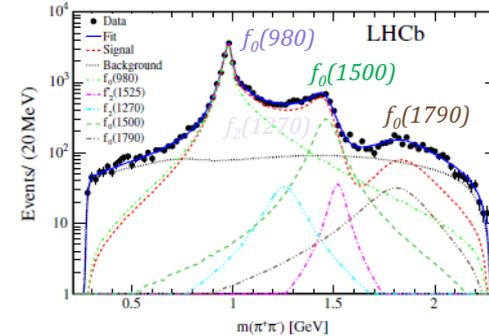
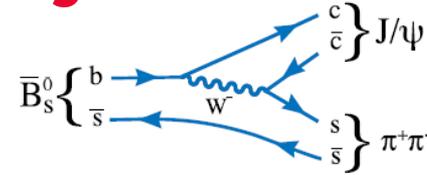


BaBar, PRD78(2008), 034023

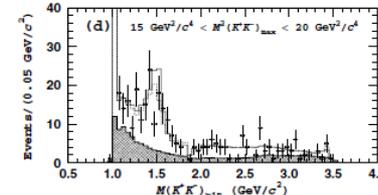
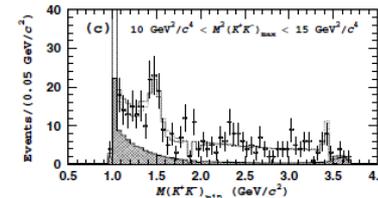
- Experimental facts:
 - The first radial excitation should be 2-300 MeV heavier than the ground state
 - $f_0(1500)$ could be OK as hidden strange component of the nonet whose ground state is the $f_0(1370)$
 - $f_0(1500)$ almost degenerate with $f_2'(1525)$, sound D-wave $\bar{s}s$ candidate
- Open questions:
 - $f_0(1500)$ as glueball candidate?
 - Is $f_0(980)$ (aka κ) the $\bar{s}s$ partner of $f_0(1370)$?

$f_0(1500)$ observations in B decays

- B decays are flavor filters:
 - $B^0 \rightarrow J/\psi(1S)X$ filters out $X \bar{d}d$ component
 - $B_s^0 \rightarrow J/\psi(1S)X$ filters out $X \bar{s}s$ component
 - Very similar to D_s^+ decay
- Indications on $J=even$ mesons features from $B_S^0 \rightarrow J/\psi(1S)X_{J=0,2}$
 - LHCb (2014): $B_S^0 \rightarrow J/\psi(1S)\pi^+\pi^-$
 - Largest component by $f_0(980)$, $f_0(1500)$ one order of magnitude smaller
 - Belle (2008): absence of $f_0(1500)$ in $\gamma\gamma$ collisions
- Indications for $f_0(1500)$ found in $B^+ \rightarrow K^+K^-K^+$ decay
 - Belle (2005)
 - not confirmed by BaBar (2006)



PRD89 (2014), 092206



PRD71 (2005), 092203

