Experimental review on light meson spectroscopy

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Outline of the talk

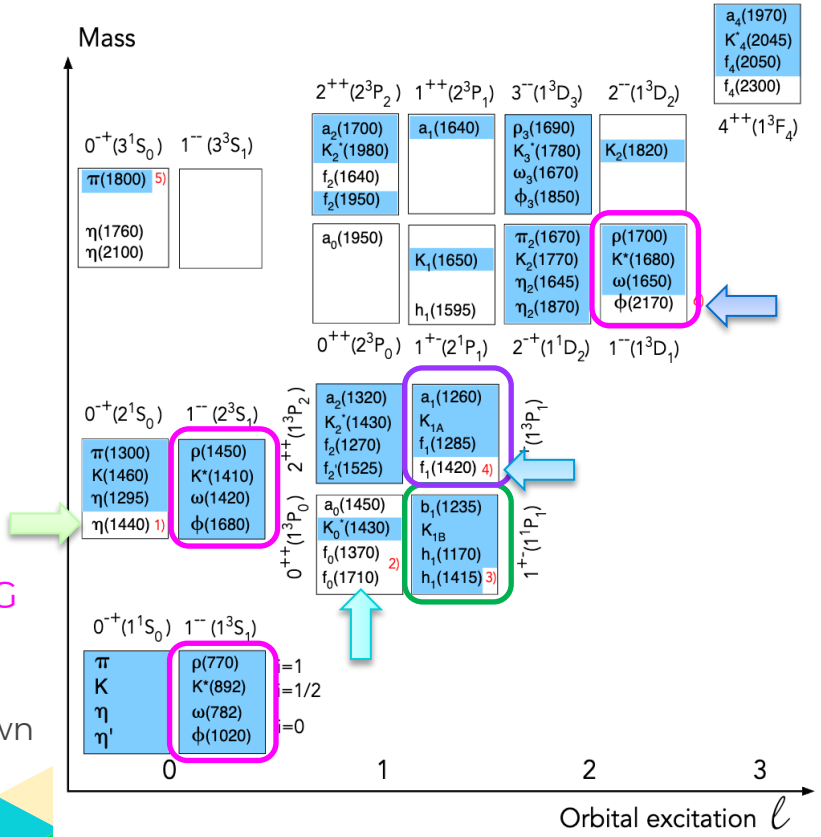
- The spectrum and general features of light mesons
- Experiments and investigation methods
- News on non-strange mesons: ordinary mesons and exotic candidates
  - Search for hybrid mesons and glueballs
  - New signals
- Conclusions

The meson spectrum as we know it

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

- **Meson spectroscopy target:**
  - Characterize observed structures assigning the correct quantum numbers
  - Disentangle states through angular distributions in their decays

- Much is known… but much more is not!
  - Three vector 1^{--} nonets established by PDG
  - One nonet established by PDG in 1^{++} and 1^{+-} sectors
    - The other axial-vector nonets largely unknown



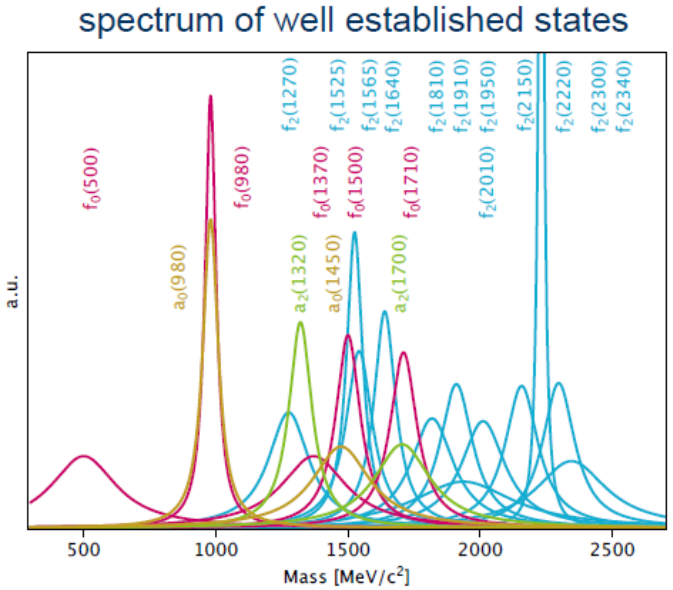
Light mesons features

- Light meson mass region (below ~2.2 GeV) very packed

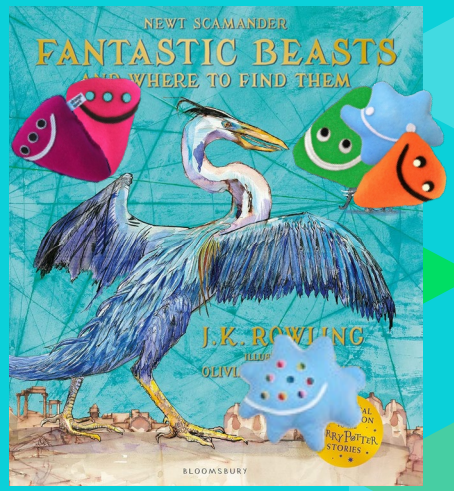
- Several (mostly broad) resonances with the same quantum numbers
  - Interfering
  - Overlapping
  - (possibly) mixing
  - Decays in the same and/or different channels

- 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!

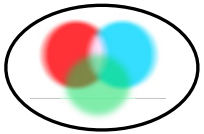


Fantastic hadrons... and where to find them



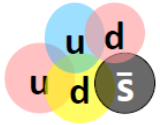
Hadrons beyond the Constituent Quark Model

ordinary mesons



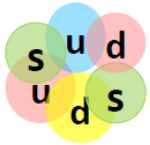
ordinary baryons

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

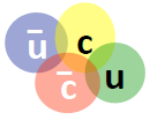


pentaquarks

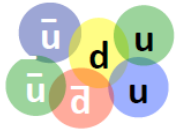
glueballs



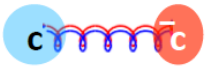
H-dibaryon



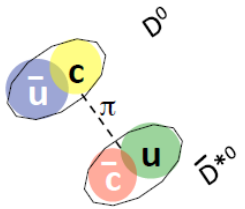
diquark-diantiquarks



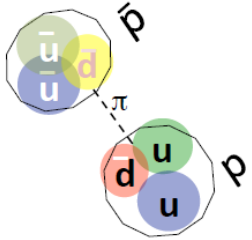
heptaquarks



hybrids



deusons

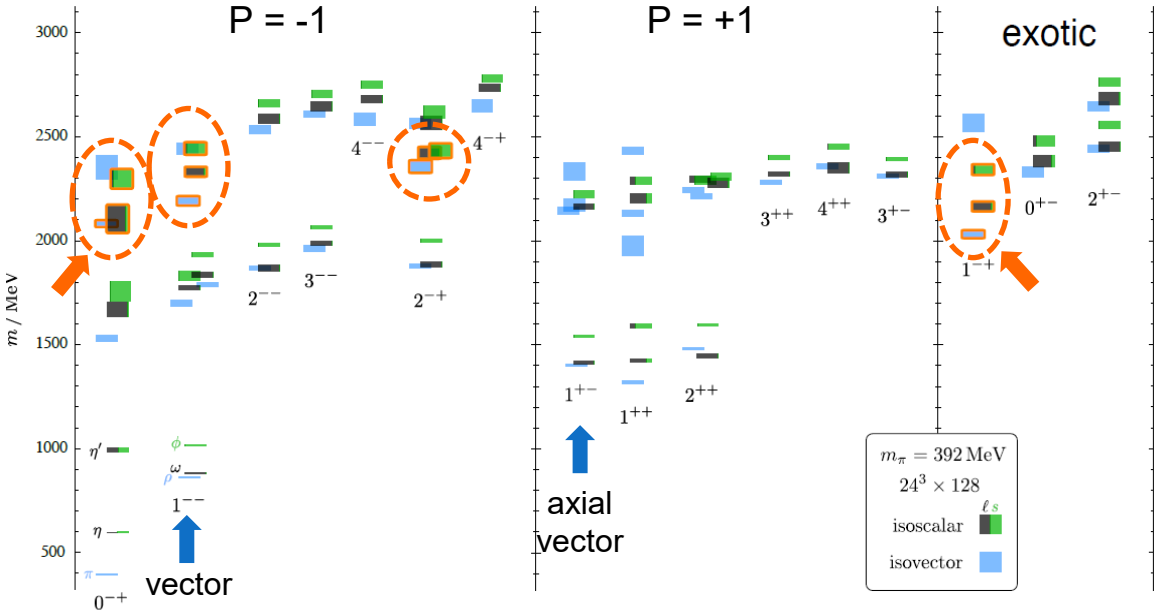


molecules

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 $\bar{q}q$ pairs… but they can also be forbidden combinations!

The meson spectrum from Lattice QCD



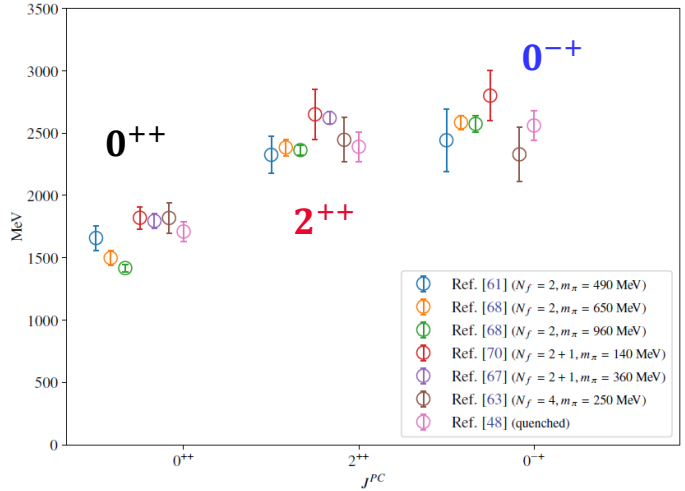
[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

- State-of-art calculations with m_π = 391 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 super-multiplet
- 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)

Sticky fellows: glueballs

- Unique particles with self-interactions
- No valence quark content, gluons only
- Strongly produced in gluon-rich processes
- Glueball decays:
  - **Flavor blindness**
    - $\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3 : 4 : 1 : 0 : 1$
      - $\eta\eta'$ **decay suppressed**: important information from $J/\psi \to \gamma\eta\eta'$ radiative decay
  - 1^{++} could decay like charmonium
  - 0^{-+} could decay like $\eta_c \to \gamma\pi\pi$
    - Good place to search: $J/\psi \to \gamma\pi\pi\eta'$
- 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



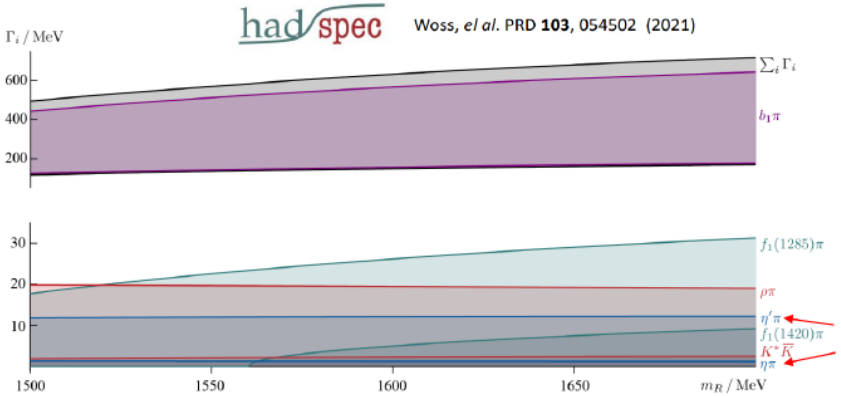
arXiv:2305.04869

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: $\rho\pi, \eta\pi, \eta'\pi$

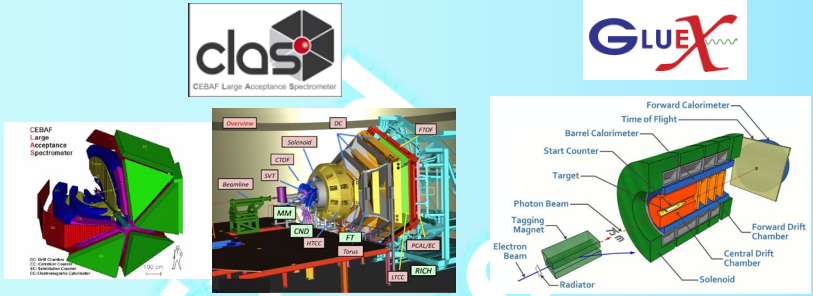


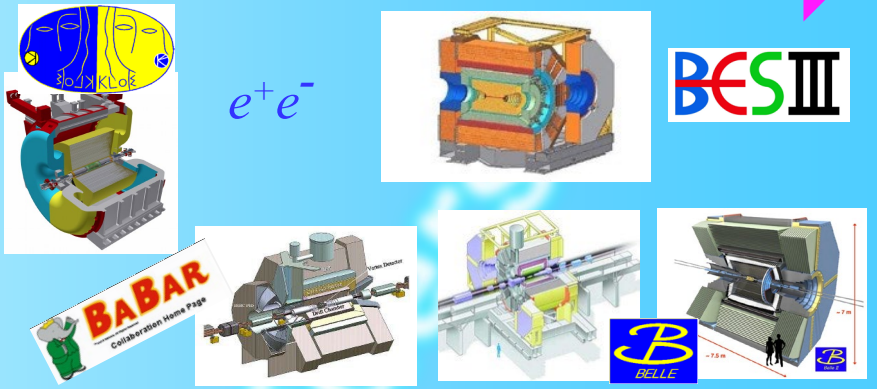
- Some indications for isovector 1^{-+}: $\pi_1(1400), \pi_1(1600), \pi_1(2015)$
- 1^{-+} isoscalar?
  - Can be produced in J/ψ radiative decays
  - Can decay to $\eta\eta'$ in P-wave

Experiments and investigation methods

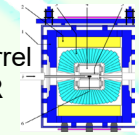
Experimental facilities for meson spectroscopy

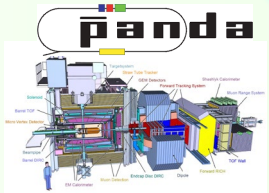
	Light quarks	Heavy quarks
Electromagnetic probes	$ep/\gamma p$	e^+e^-
Hadronic probes	$\bar{p}p$ pp πp	$\bar{p}p$ pp

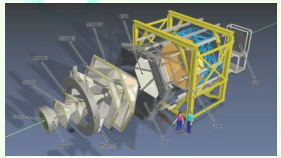


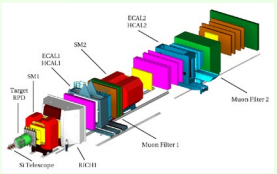


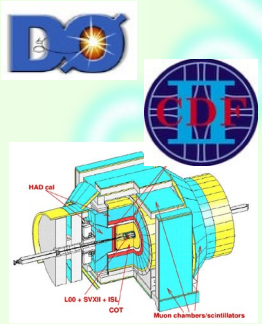
Crystal Barrel @LEAR

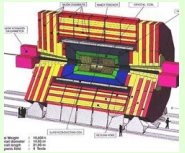


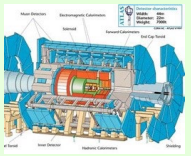


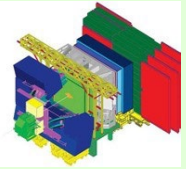




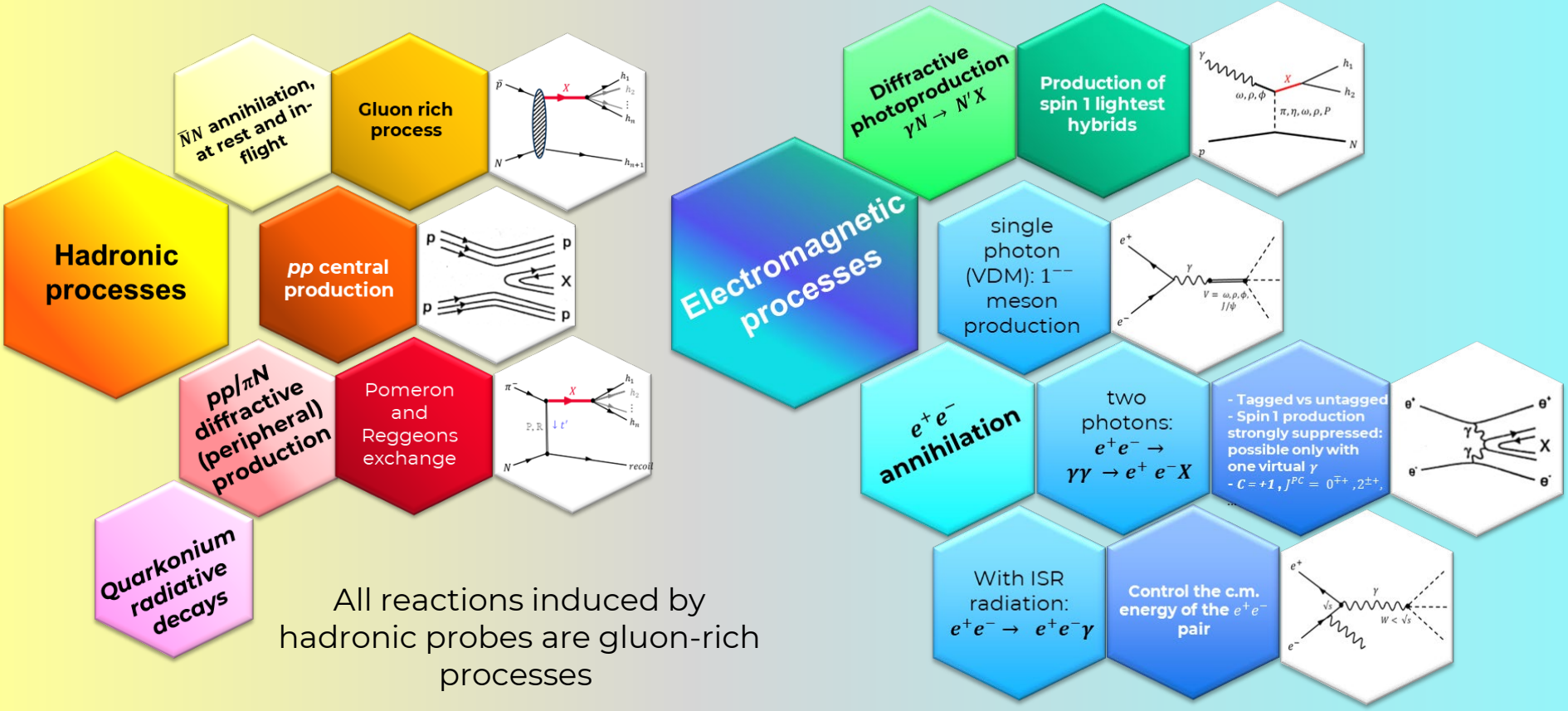








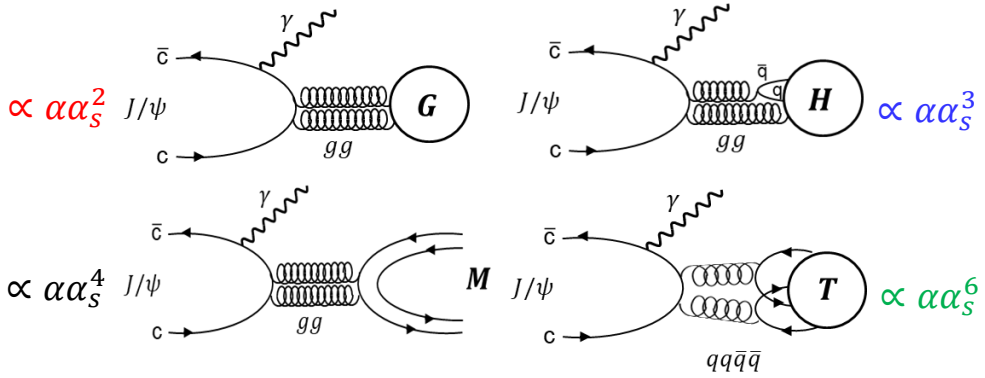
Meson production mechanisms

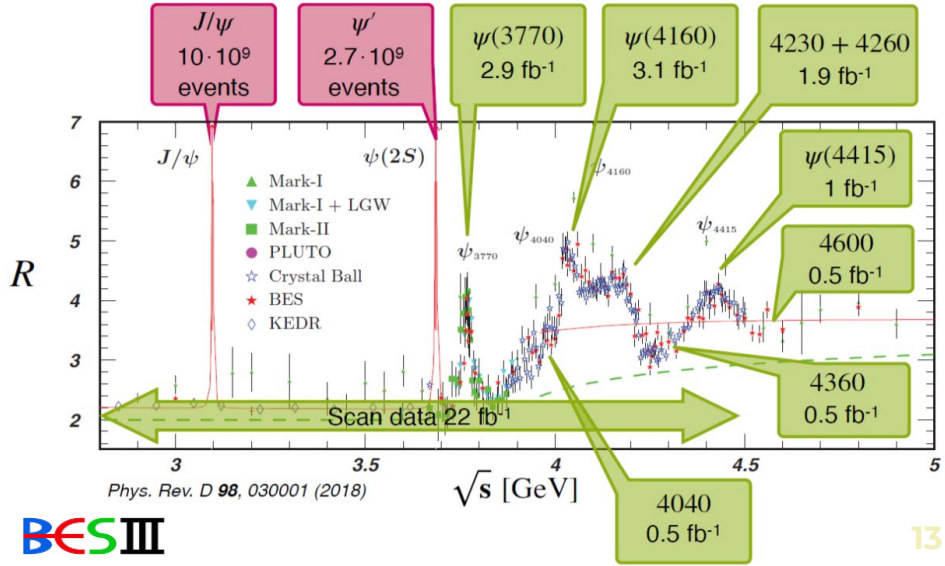


All reactions induced by hadronic probes are gluon-rich processes

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

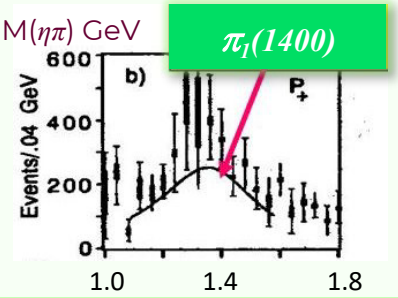
The $\pi_1(1400)/\pi_1(1600)$ case in a nutshell

Hints for spin exotics since the 80's

Two signals observed:

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

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

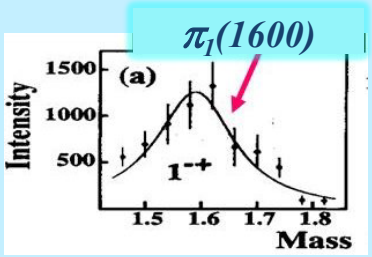


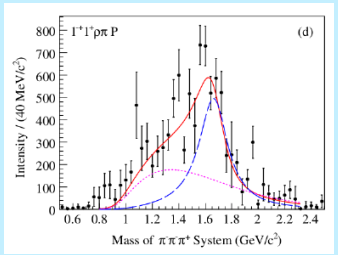
Observed as interference between *L=1* and *L=2* $\eta\pi$ amplitudes

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

$\pi^- p \to \pi^- \pi^+ \pi^+ p$ (COMPASS) and

$\pi^- p \to \pi^- \eta' p$ (E852)



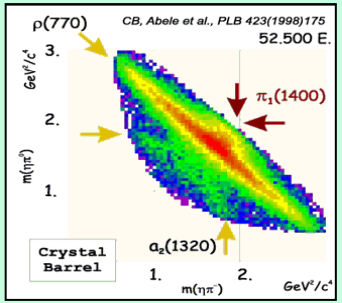


CRYSTAL BARREL: $\bar{N}N$ annihilations *at rest*

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

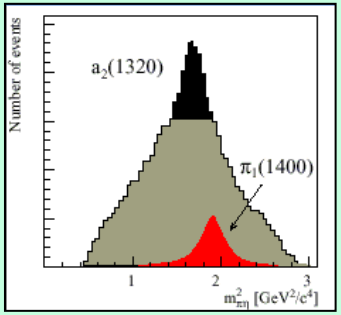
$\bar{p}n \to \pi^0\pi^0\eta$

$\pi_1(1400)$



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

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



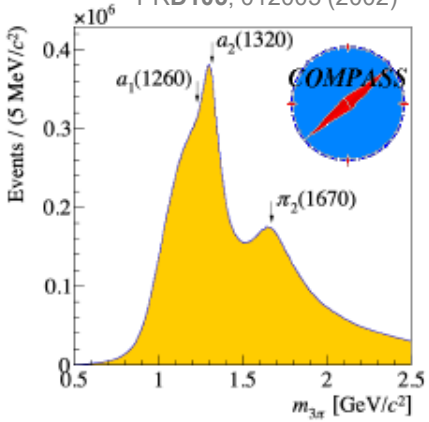
Novel observations of $\pi_1(1600)$ from COMPASS

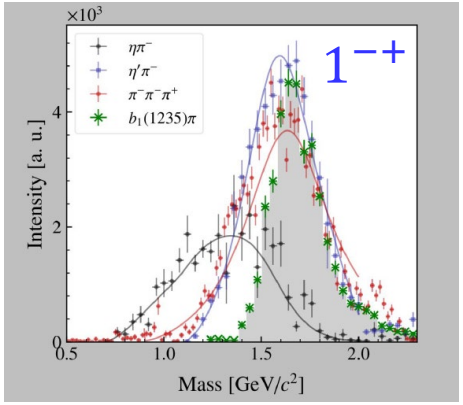
- **$b_1(1235)\pi \to \omega\pi\pi$ spectroscopy:**

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

  - States observed in the $b_1(1235)\pi$ channel (+others in $\rho^-\omega$)
    - $\mathbf{1^{-+}: \pi_1(1600) \to b_1(1235)\pi}$
    - $2^{++}: a_2(1320), a_2'(1700) \to b_1(1235)\pi$
    - Possible additional signals from
      - $3^{++}: a_3(1320)$
      - $4^{++}: a_4(1970)$

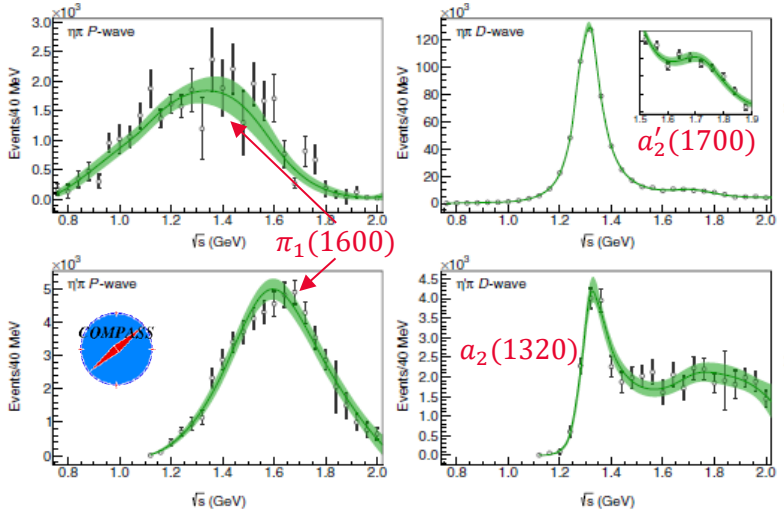
PRD**105**, 012005 (2002)





NC **47C** (2024), 150

- **$\eta^{(\prime)}\pi$ spectroscopy: $\pi^- p \to \eta^{(\prime)}\pi^0$** @190 GeV
  - $\pi_1(1400) \to \eta\pi$
  - $\boldsymbol{\pi_1(1600) \to \eta'\pi}$
    - 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)

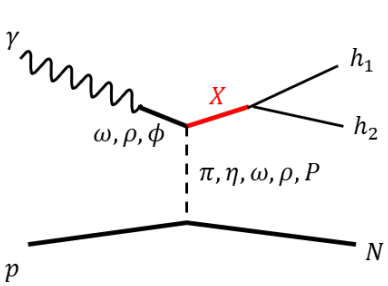


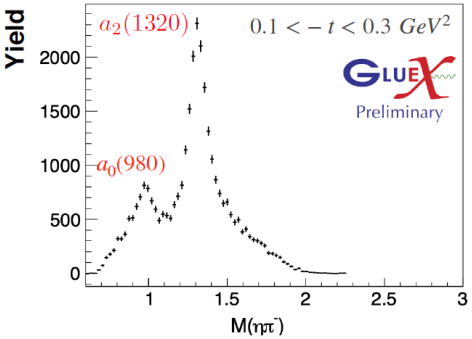
JPAC

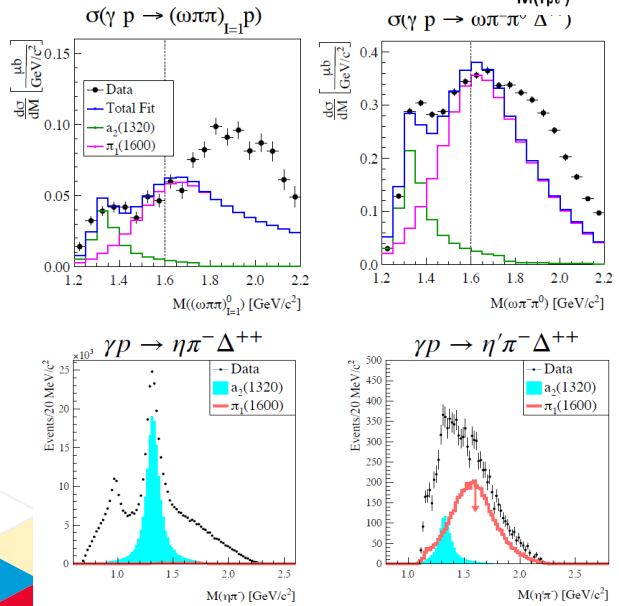
PRL**122**, 042002 (2019)

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 $\eta\pi$



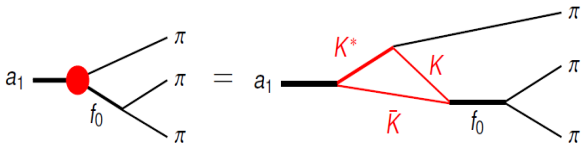




ArXiv:2407.03316

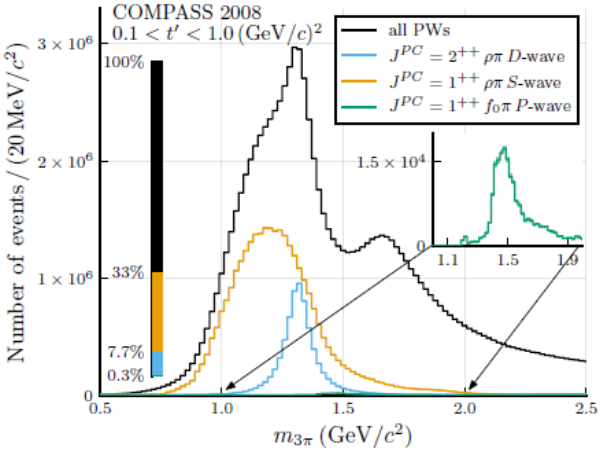
“Fake” resonance: the $a_1(1420)$ case

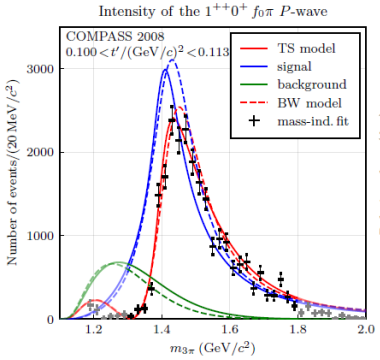
- $\pi^- p \to \pi^- \pi^- \pi^+ p$ **@ 190 GeV**
- Clear peak at 1.4 GeV: $a_1(1420)$
  - exotic $J^{PC} = 1^{++}$ in $f_0(980)\pi$
  - Resonant behavior (also correct phase motion!)
  - Not an ordinary meson
    - Small width, narrower than the ground state ($a_1(1260)$: Γ~500 MeV)
    - Too close to ground state: 400 MeV expected from radial excitation trajectories
    - Seen only in one channel: $f_0(980)\pi$

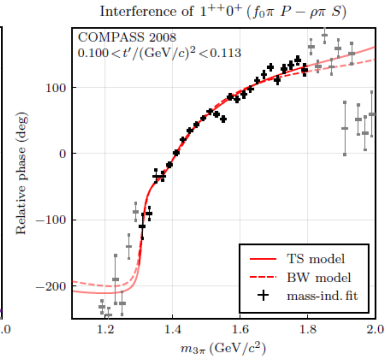


- It can be better explained by a three body rescattering effect: triangle-singularity mechanism
  - $a_1(1260) \to K^*(\to \pi K)\bar{K}$ + rescattering to $f_0(980)$

PRL**127** (2021), 082501



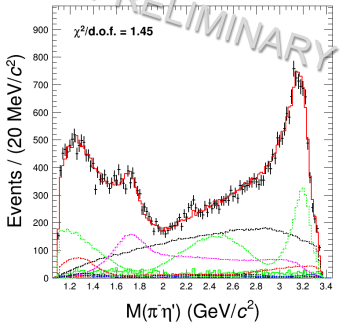




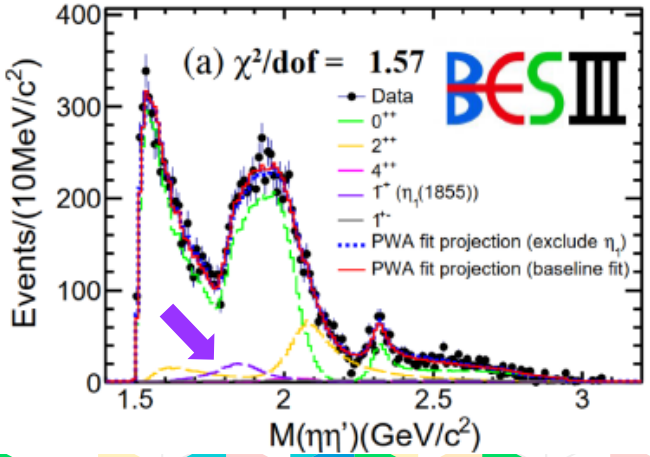
A new hybrid candidate from BESIII: $\eta_1(1855)$

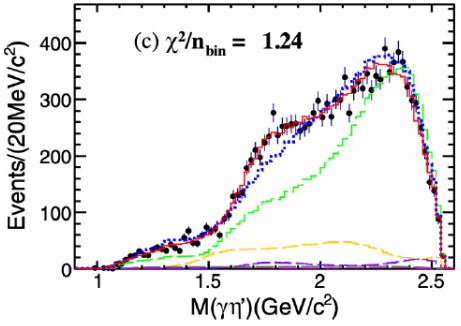
- Evidence of isovector 1^{-+} $\pi_1(1600)$ in $\psi' \to \gamma\chi_{c1}$ $(\chi_{c1} \to \pi^+\pi^-\eta')$ [10σ]
  - Analysis in progress

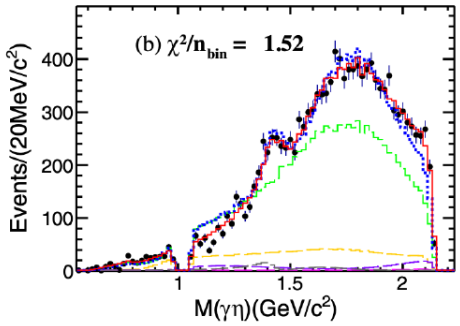
- Evidence for a ***new isoscalar*** $\mathbf{1^{-+}}$ $\boldsymbol{\eta_1(1855)}$ in $\boldsymbol{J/\psi(1S) \to \gamma\eta'\eta}$ [>19σ]
  - $m = (1855 \pm 9^{+6}_{-1})$ MeV, $\Gamma = (188 \pm 18^{+3}_{-8})$ MeV, decay in $\eta'\eta$
  - Isoscalar partner of $\pi_1(1600)$ in 1^{-+} nonet?
  - Signature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



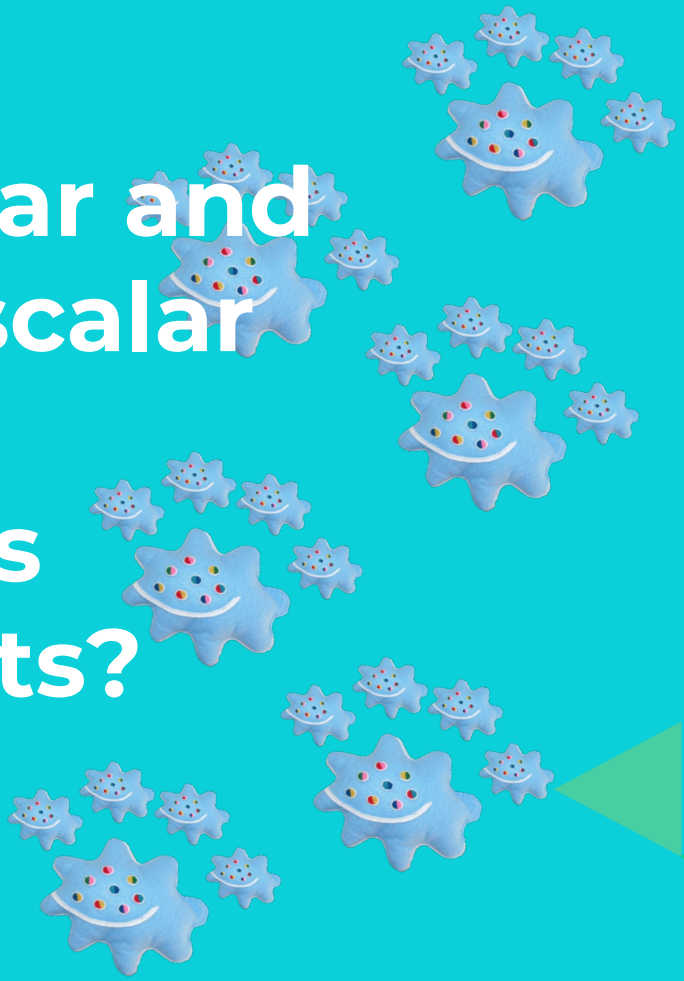
PRL**129** (2022), 192002
PRD**106** (2022), 072012







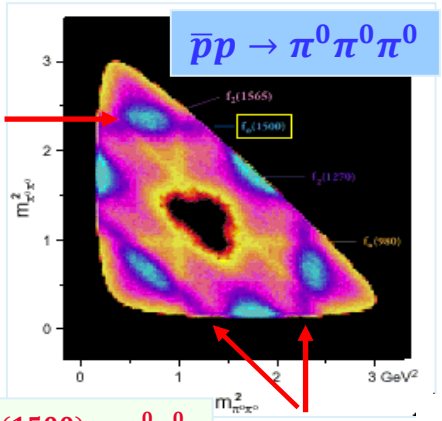
The scalar and pseudoscalar sectors: glueballs footprints?

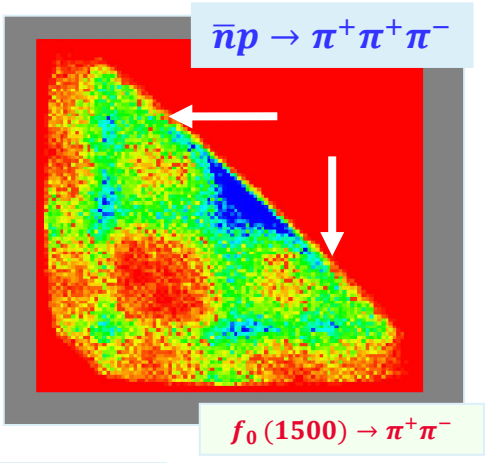


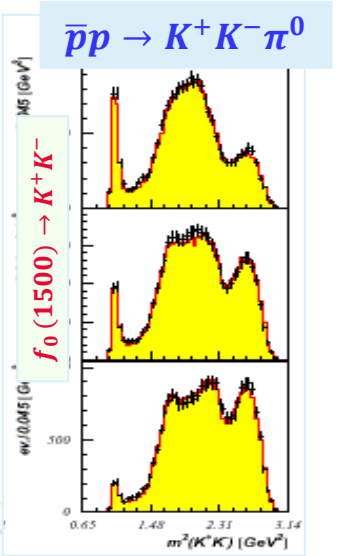
The scalar glueball: a bit of history

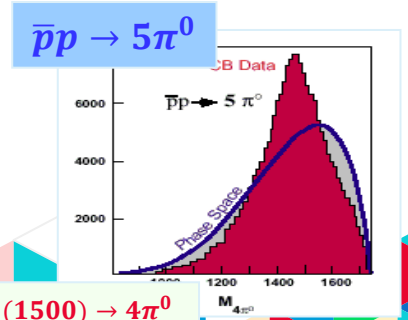
- Lightest glueball candidate until the y2000: ***scalar state***
- $f_0(1500)$ observed by **Crystal Barrel** and **OBELIX** in $\bar{N}N$ @LEAR-CERN

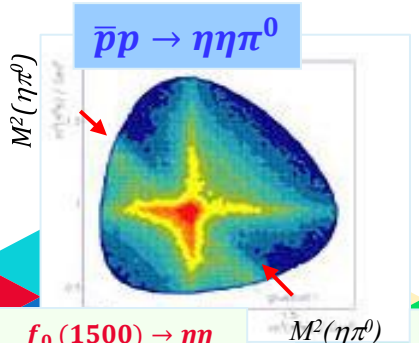
- Three observed isoscalars $f_0(1370)$ $f_0(1500), f_0(1710)$:
  - one appears to be supernumerary
- $f_0(1500)$
  - Compatible with a $\bar{n}n$ structure
  - Enhanced production in central collisions
  - Observed in multiple decay channels
- $f_0(1710)$ mostly $\bar{s}s$

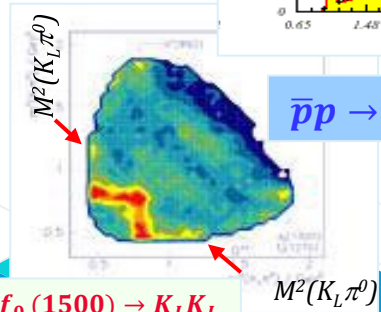








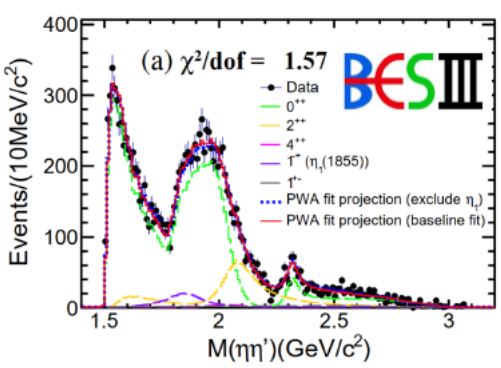




$f_0(1500)$ and $f_0(1710)$ at BESIII

- $J/\psi \to \gamma\eta\eta'$
  - $f_0(1500) \to \eta\eta'$: significant contribution
  - $f_0(1710) \to \eta\eta'$: not observed

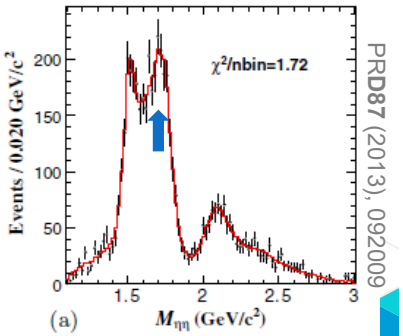
PRL**129** (2022), 192002
PRD**106** (2022), 072012



- $J/\psi \to \gamma\eta'\eta'$, $J/\psi \to \gamma K_S K_S$, $J/\psi \to \gamma\pi^0\pi^0$
  - Large $f_0(1710)$ production (assuming $f_0(1810)$ is the same object)

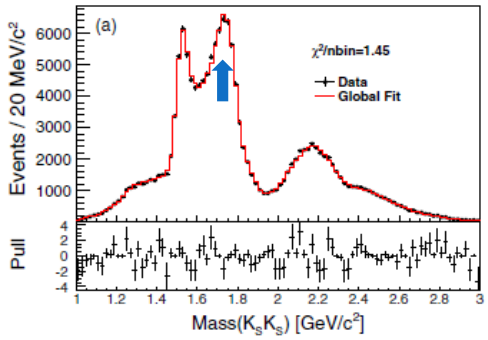
- $f_0(1710)$ can have a large gluonic content or a sizeable overlap with the ground state scalar glueball

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



PRD**87** (2013), 092009

$J/\psi \to \gamma K_S K_S$



PRD**98** (2018), 072003

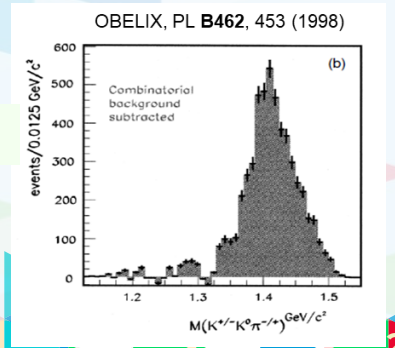
The pseudoscalar and axial vector sectors: the old E/ι puzzle

- 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 $\bar{K}K\pi$ ⇒ **"E/ι puzzle"**
- The $\bar{K}K\pi$ decay channel is only possible for $\boldsymbol{J^P = (odd)^+ \; or \; (even)^-}$

- **Pseudoscalar states 0^{-+}**
  - All of them decay to $a_0(980)\pi$, K^*K, $\bar{K}K\pi$
  - $\boldsymbol{\eta(1275)}$**:** First η' radial excitation?
  - $\boldsymbol{\eta(1440)}$**:** likely split in two states
    - $\boldsymbol{\eta(1405)}$: true gluonium candidate?
      - Not observed in $\gamma\gamma$ collisions, large production in gluon rich environments (J/ψ *decays*, peripheral production, $\bar{p}p$ annihilation)
      - Estimated glue content: ~76%
    - $\boldsymbol{\eta(1475)}$: radially excited $\bar{s}s$ state in $K^*\bar{K}$?
      - Observed in $\gamma\gamma$ collision
      - Not seen in K^-p collisions

- **Axial states 1^{++}**
  - $\boldsymbol{f_1(1285)}$: does not decay to $K^*\bar{K}$
  - $\boldsymbol{f_1(1420)}$: hybrid $\bar{q}qg$? 4-quark state? $K^*\bar{K}$ molecule?
  - $\boldsymbol{f_1(1510)}$: not established yet
  - + isovector $\boldsymbol{a_1(1420)}$ (COMPASS)

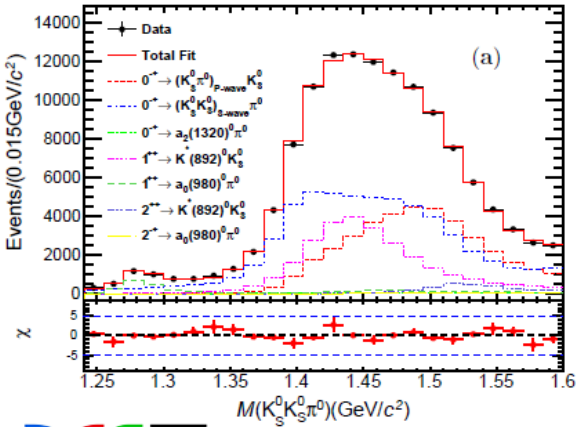
$\bar{p}p \rightarrow K^0K^{\pm}\pi^{\mp}\pi^+\pi^-$



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

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

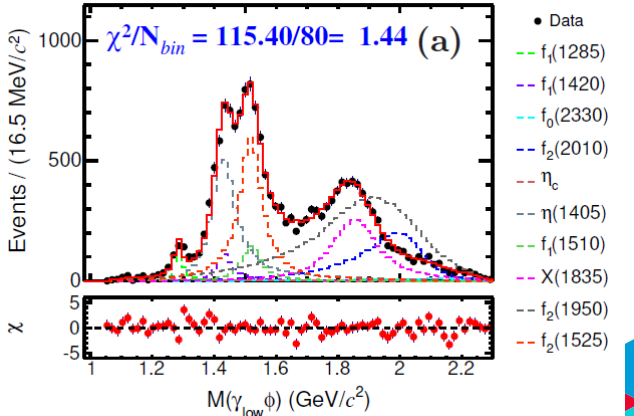
JHEP**03** (2023). 121



BESIII

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

ArXiv:2401.00918



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

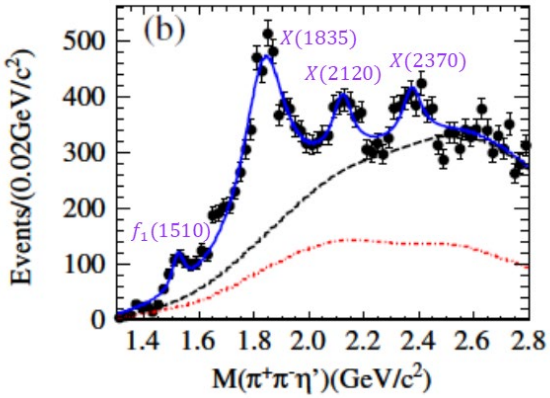
$X(2370)$: a pseudoscalar glueball?

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

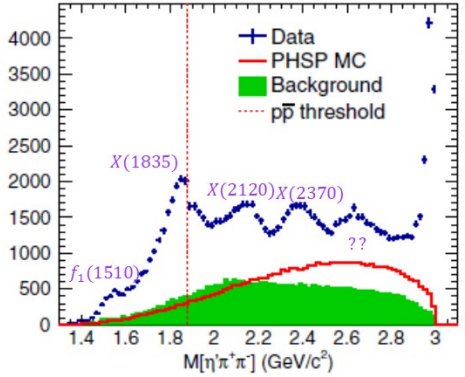
- $X(2370)$ observed in several gluon-rich decay channels:
  - $\eta'\pi^+\pi^-, \eta' K^+K^-, \eta K_S K_S, \pi^0 K_S K_S, \eta\pi^0\pi^0, a_0(980)\pi^0$
  - Analog to η_c decay pattern

- $J^{PC} = 0^{-+}$
  - Mass and production rates consistent with LQCD expectations for the lightest pseudoscalar glueball

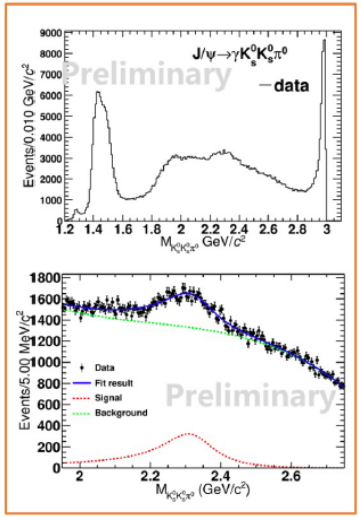
PRL**106** (2011), 072002

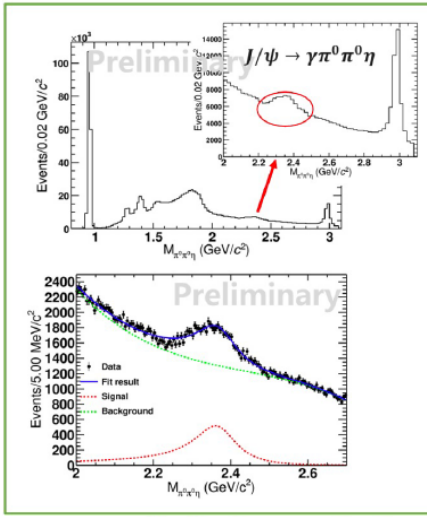


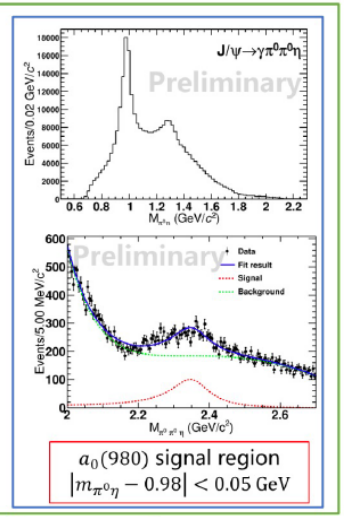
PRL**117** (2016), 042002



Lyu, ICHEP2024







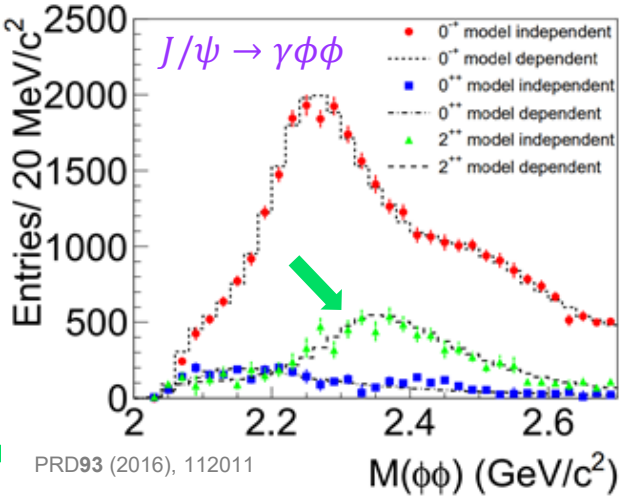
Indications for tensor glueballs

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

- Expected decay width:

  $\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22)$ **keV**
- $J/\psi \to \gamma f_2(2340)$ decay modes:
  - $f_2(2340) \to \eta\eta$
  - $f_2(2340) \to \phi\phi$
  - $f_2(2340) \to K_S K_S$
  - $f_2(2340) \to \eta'\eta'$

- $f_2(2340)$
  - Large $\bar{p}p \to \phi\phi$ production (JETSET)
  - Large cross section in $\pi^- p \to \phi\phi n$
  - Observed by BESIII in $J/\psi \to \gamma\phi\phi$
    - Relatively narrow
    - Several decay channels
    - Mass substantially lower than LQCD predictions



PRD**93** (2016), 112011

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