Light-Meson Spectroscopy
A Selection of Recent Results

Boris Grube

Physik-Department E18
Technische Universität München,
Garching, Germany

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Introduction

Scalar Mesons

$J^{PC} = 1^{-+}$ spin-exotic mesons

Narrow states around 1.4 GeV $/c^2$

The light $X$ states

Conclusions and outlook
1. Introduction

2. Scalar Mesons

3. $J^{PC} = 1^{--} \text{ spin-exotic mesons}$

4. Narrow states around 1.4 GeV / $c^2$

5. The light $X$ states

6. Conclusions and outlook
Mesons in the Constituent Quark Model (CQM)

Mesons

- Color-singlet $|qq'\rangle$ states, grouped into $SU(3)_{\text{flavor}}$ multiplets

Spin-parity rules for bound $q\bar{q}$ system

- Quark spins couple to total intrinsic spin $S = 0$ or $1$

- Relative orbital angular Momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$

- Parity $P = (-1)^{L+1}$

- Charge conjugation $C = (-1)^{L+S}$

- Forbidden $J^{PC}$: $0^{--}$, even$^{++}$, odd$^{--}$
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Constituent Quark Model

Light-quark Meson Spectrum

\[ v = n + L - 1 \]

\[ \frac{1}{2}S_0 = 0^{--} \]

\[ \frac{3}{2}S_1 = 1^{--} \]

\[ \frac{1}{2}S_0 = 0^{-+} \]

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\[ \frac{1}{2}S_0 = 0^{-+} \]

\[ \frac{3}{2}S_1 = 1^{--} \]

\[ 3^1P_0 = 0^{++} \]

\[ 3^1P_1 = 1^{++} \]

\[ 3^3P_2 = 2^{++} \]

\[ 3^1P_1 = 1^{++} \]

\[ 2S + 1 \]

\[ nL_j = J^{PC} \]

\( Amsler \ et \ al., \ Phys. \ Rept. \ 389 \ (2004) \ 61 \)
Constituent Quark Model
Light-quark Meson Spectrum

\[ v = n + L - 1 \]

- \( \pi(1800) \)
- \( K(1830) \)
- \( \eta(1760) \)
- \( a_2(1320) \)
- \( K_2^*(1980) \)
- \( f_2(2010) \)
- \( f_2(1950) \)
- \( a_1(1640) \)
- \( K_1 \)
- \( f_1(1285) \)
- \( f_1(1420) \)
- \( a_0(1450) \)
- \( K_0^*(1430) \)
- \( f_0(1370) \)
- \( f_0(1710) \)
- \( b_1(1235) \)
- \( K_{1b} \)
- \( h_1(1170) \)
- \( h_1(1380) \)

**“Light-meson frontier”**

- Many missing and disputed states in mass region \( m \approx 2 \text{ GeV}/c^2 \)
  - Identification of higher excitations becomes exceedingly difficult
    - Wider states + higher state density
    - More overlap and mixing

Constituent Quark Model

Light-quark Meson Spectrum

\[ \nu = n + L - 1 \]

\[
\begin{array}{c|c|c|c|c}
\pi(1800) & K(1830) & \eta(1760) \\
1 & 2 & \frac{1}{2} S_0 = 0^{--} & \frac{3}{2} S_1 = 1^{--} \\
\pi(1300) & K(1460) & \eta(1295) & \eta(1440) \\
1 & 1 & \frac{1}{2} S_0 = 0^{--} & \frac{3}{2} S_1 = 1^{--} \\
\pi & K & \eta & \eta' \\
0 & 0 & \frac{1}{2} P_0 = 0^{++} & \frac{1}{2} P_1 = 1^{++} \\
\end{array}
\]

\[ a_2(1700) \]
\[ f_2(1950) \]
\[ K_2^*(1980) \]
\[ f_2(2010) \]
\[ \rho_3(1690) \]
\[ \phi_3(1850) \]
\[ K_2(1820) \]

\[ a_1(1640) \]
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\[ \eta_2(1450) \]
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\[ 2S+1 \]
\[ nL_J = J^{PC} \]
Possible New Forms of Matter

**Hybrids** \(|q\bar{q}g\rangle\): states with **excited gluonic fields**
- Glue component contributes to quantum numbers
  - *All* \(J^{PC}\) allowed
- Lightest predicted hybrid: **spin-exotic** \(J^{PC} = 1^{-+}\)

**Glueballs** \(|gg\rangle\): states with **no valence quarks**
- Lightest predicted glueball: ordinary \(J^{PC} = 0^{++}\)
  - Will strongly mix with nearby conventional \(J^{PC} = 0^{++}\) states

**Multi-quark states**
- Tetraquarks \(|qq\bar{q}\bar{q}\rangle\): **compact**
- Molecules \(|q\bar{q}qq\rangle\): **extended**

**Physical states defined by quantum numbers**
- Linear superpositions of *all* allowed basis states: \(|q\bar{q}\rangle, |q\bar{q}g\rangle, |gg\rangle, |q^2\bar{q}^2\rangle, \ldots\); amplitudes not directly observable
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Connection to QCD

QCD in the confinement regime: $\alpha_s = \mathcal{O}(1)$

- QCD Lagrangian not calculable using perturbation theory

Frist-principles numerical method: Lattice QCD

- Simulation of QCD on finite discreet space-time lattice using Monte Carlo techniques
- Challenge: extrapolation to physical point
  - Heavier $u$ and $d$ quarks than in reality
  - Extrapolation to physical quark masses
  - Extrapolation to infinite volume $L \to \infty$
  - Extrapolation to zero lattice spacing $a \to 0$
  - Rotational symmetry broken due to cubic lattice
- Tremendous progress in past years
  - Finer lattices: spin-identified spectra
  - Larger operator bases: many excited states
  - Access to gluonic content of calculated states
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Light-Meson Spectrum in Lattice QCD

State-of-the-art Calculation

[Dudek et al., PRD 88 (2013) 094505]

\[ P = - \]

\[ P = + \]

Exotics

\[ m_{\pi} = 392 \text{ MeV} \]

\[ 24^3 \times 128 \]

isoscalar

isovector

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Light-Meson Spectroscopy
Reproduces mainly the quark-model pattern

Calculations not reliable yet for $J^{PC} = 0^{++}$ sector
Additional non-\(q\bar{q}\) states

- Set of hybrid mesons with \(0^{-+}, 1^{--}, 2^{-+}\) and spin-exotic \(1^{-+}\)
Resonance widths and decay modes still very difficult
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Nature of $J^{PC} = 0^{++}$ states still unclear

- **Data:** heavy-meson decays + production and formation experiments
- **Extraction of resonances from data difficult**
  - Some states have large widths
  - Distortions of line shapes due to openings of additional channels (e.g. $K\bar{K}, \eta\eta, \ldots$)
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Scalar Mesons with Isospin $I = 0$

Most complex sector

- At least 5 established states: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$

Isoscalar scalars above 1 GeV/$c^2$

- $f_0(1370)$ and $f_0(1500)$ decay mainly into pions (2π or 4π)
- $f_0(1710)$ mainly into $K\bar{K} \rightarrow$ large $s\bar{s}$ component
- Quark-model nonet:
  - $f_0(1370)$, $a_0(1450)$, $K^*_0(1430) + f_0(1710)$
- $q\bar{q}$ assignment for $f_0(1500)$ difficult
- $f_0(1500)$ mainly glue? Would imply
  - Weak coupling to $\gamma\gamma$
  - Enhanced production in “gluon-rich” reactions
    - Central production
    - Radiative $J/\psi$ decays

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Radiative $J/\psi$ Decays

$e^+ \rightarrow J/\psi \rightarrow \gamma (\eta \eta)$ ideal channel to look for scalar and tensor glueballs

- $\eta \eta$ final state: only $I = 0$ and $J^{PC} = \text{even}^{++}$ allowed
- "Gluon-rich" environment
  - Glueball production should be enhanced
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Decomposition into $J^P$ states: *partial-wave analysis* (PWA)

- Sequential decay: calculable quasi-two-body amplitudes
- Intermediate resonance $X$ described by Breit-Wigner propagator
- Same initial and final state $\implies$ different $X$ interfere
- Magnitudes, phases and parameters of $X$ determined from kinematic distribution of final-state particles
J/ψ → γ(ηη) at BESIII

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PWA of $J/\psi \rightarrow \gamma (\eta \eta)$ at BESIII

$\begin{align*}
\text{Events / 20 MeV/c}^2 & \quad \text{Events / 20 MeV/c}^2 & \quad \text{Events / 20 MeV/c}^2 \\
M_{\text{mm}}(\text{GeV/c}^2) & \quad M_{\text{mm}}(\text{GeV/c}^2) & \quad M_{\text{mm}}(\text{GeV/c}^2) \\
\text{Events / 20 MeV/c}^2 & \quad \text{Events / 20 MeV/c}^2 & \quad \text{Events / 20 MeV/c}^2 \\
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\end{align*}$

$\begin{align*}
f_0(1500) & \quad f_0(1710) & \quad f_0(2100) \\
f_2'(1525) & \quad f_2(1810) & \quad f_2(2340) \\
0^{++} \text{ PS} & \quad \text{Total } 0^{++} & \quad \text{Total } 2^{++} \\
\end{align*}$

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Light-Meson Spectroscopy
Result

- Largest signals from $f_0(1710)$ and $f_0(2100)$
- Clear but smaller $f_0(1500)$ signal
- No $f_0(1370)$ signal

$B(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$ of $f_0(1710)$ 10× larger than that of $f_0(1500)$

- $B(J/\psi \rightarrow \gamma f_0(1710)) \approx 2$ to $3 \cdot 10^{-3}$
- $B(J/\psi \rightarrow \gamma f_0(1500)) \approx 1$ to $3 \cdot 10^{-4}$

- (Quenched) lattice QCD prediction for pure gauge scalar glueball:

$B(J/\psi \rightarrow \gamma G_{0^{++}}) = 3.8(9) \cdot 10^{-3}$ [Gui et al., PRL 110 (2013) 021601]

- $f_0(1500)$ production rate much smaller
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- $\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$ of $f_0(1710)$ is $10 \times$ larger than that of $f_0(1500)$
  - $\mathcal{B}(J/\psi \rightarrow \gamma f_0(1710)) \approx 2 \text{ to } 3 \cdot 10^{-3}$
  - $\mathcal{B}(J/\psi \rightarrow \gamma f_0(1500)) \approx 1 \text{ to } 3 \cdot 10^{-4}$

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Source of mesons with even C-parity

Gives access to two-photon coupling $\Gamma_{\gamma \gamma}$ of $X$

For glueball $\Gamma_{\gamma \gamma} \ll 1 \text{ eV} / c^2$ expected
Data taken at energies around Υ(2S), Υ(4S), and Υ(5S) (total 972 fb⁻¹)

Study production of $f_J (I = 0)$ and $a_J (I = 1)$ mesons with even spin $J$

- Peaks near 1.3, 1.5, and 1.8 GeV/$c^2$
- Additional enhancements at 2.3 and 2.6 GeV/$c^2$
Scalar Mesons in $\gamma\gamma \rightarrow K_S^0 \bar{K}_S^0$ at Belle

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**Graph:**
- $\sigma$ (nb) vs. $M_{KK}$ (GeV)
- Systematic uncertainty

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Light-Meson Spectroscopy
PWA of $\gamma\gamma \to K_S^0\bar{K}_S^0$ at Belle

**Spin-parity decomposition** of mass spectrum based on **angular distribution** of final-state particles

- Range $1.2 < M_{KK} < 2.0$ GeV/$c^2$ fitted by **$S$- and $D$-waves**
- Data described best by **$S$-wave with $f_0(1710)$ + non-resonant contribution**
PWA of $\gamma \gamma \rightarrow K_S^0 \overline{K}_S^0$ at Belle

No signal for $f_0(1500)$

- Consistent with glueball interpretation
PWA of $\gamma\gamma \rightarrow K_S^0 \overline{K}_S^0$ at Belle

First measurement of $\Gamma_{\gamma\gamma} \mathcal{B}(K_S^0 \overline{K}_S^0)$

- $12^{+3+227}_{-2-8}$ eV/$c^2$ for $f_0(1710)$
- For glueball $\Gamma_{\gamma\gamma} \ll 1$ eV/$c^2$ expected
  - $f_0(1710)$ unlikely to be glueball
  - Favors interpretation of $f_0(1710)$ as $s\bar{s}$ state
PWA of $\gamma \gamma \rightarrow K_S^0 \bar{K}_S^0$ at Belle

- Range $2.0 < M_{KK} < 3.0$ GeV/$c^2$ fitted by $S$-, $D$-, and $G$-waves
- Data described best by including $f_0(2540)$ into $S$-wave
- First time this state is seen:
  $M = 2539 \pm 14^{+38}_{-14}$ MeV/$c^2$, $\Gamma = 274^{+77+126}_{-61-163}$ MeV/$c^2$
- Needs confirmation
Scalar Mesons in Central Production

$p_{\text{beam}}$ → $p_{\text{target}}$ → $X^0$ → $p_{\text{fast}}$ → $\pi^+ \pi^0 K^+ \ldots$

$\pi^- \pi^0 K^- \ldots$

"Glue rich" process

- Glueball production should be enhanced
COMPASS

S-wave intensity in $K^+K^-$

- Phase information available
- Working on improved analysis model

[PoS(Bormio 2013)014]
Central Production: Upcoming Data

**COMPASS**

*S-wave intensity in $K^+K^-$*

![Graph showing S-wave intensity for COMPASS 2009](image)

*Intensity of S0 wave*

*Phase information available*  
*Working on improved analysis model*

**ALICE**

*$\pi^+\pi^-$ invariant mass spectrum*

![Graph showing ALICE result](image)

*pp @ $\sqrt{s} = 7$ TeV*

*V0-FMD-SPD-TPC Double gaps*  
*Counts / (20 MeV/c²)*  
*Like sign*  
*Unlike sign*

*ALICE Performance*  
*13/04/2011*

*[PoS(Bormio 2013)014]*  
*[arXiv:1110.3693]*
Outline

1 Introduction

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3 $j^{PC} = 1^{-+}$ spin-exotic mesons

4 Narrow states around 1.4 GeV/$c^2$

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6 Conclusions and outlook
Meson Production in High-Energy Scattering

$\pi^- \pi^+ \pi^-$ Production with 190 GeV/c $\pi^-$ Beam at COMPASS

- Soft scattering of beam particle off target via strong interaction
  - Small momentum and energy transfer to target
  - Target particle stays intact
- Beam particle gets excited into intermediate resonance $X$
- Decay of $X$ into 3 forward-going pions
  - Measured by spectrometer
- Same final state $\implies$ interference of different $X$

COMPASS: $50 \cdot 10^6 \pi^- \pi^+ \pi^-$ events

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PWA assumption: $X^-$ decays via intermediate $\pi^+ \pi^-$ resonances
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$\pi^-$ Beam

Bachelor

Isobar

$\rho_{\text{target}}$

$\rho_{\text{recoil}}$

$\rho_{\text{target}}$

$\rho_{\text{recoil}}$

$\rho_{\text{target}}$

$\rho_{\text{recoil}}$

Bachelor

PWA assumption: $X^-$ decays via intermediate $\pi^+ \pi^-$ resonances
\( J^{PC} = 1^{-+} \) Spin-Exotic Mesons

The Checkered History of \( \pi_1(1600) \rightarrow 3\pi \)

BNL E852 analyses: 18 GeV/c \( \pi^- \) beam on \( p \) target

\[ [\text{PRL 81 (1998) 5760}] \]

- 250,000 events
- \( 0.1 < t' < 1.0 \) (GeV/c\(^2\))
- Model with 21 waves
\[ J^{PC} = 1^{--} \text{ Spin-Exotic Mesons} \]

The Checkered History of \( \pi_1(1600) \rightarrow 3\pi \)

**BNL E852 analyses: 18 GeV/c \( \pi^- \) beam on \( p \) target**

- [PRL 81 (1998) 5760]
- [PRD 73 (2006) 072001]

---

1500
1000
500

\( M(\pi^+\pi^-\pi^-) \) (GeV)

- 250 000 events
- \( 0.1 < t' < 1.0 \) (GeV/c)^2
- Model with 21 waves

---

0.1

1.0

1.5

2.0

\( M[3\pi] \) GeV/c^2

- 2.6 \( \cdot 10^6 \) events
- \( 0.1 < t' < 0.5 \) (GeV/c)^2
- Model with 21/36 waves
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS
Spin-Exotic Signal with $I = 1$ and $J^{PC} = 1^{-+}$ in $\rho(770)\pi$ Decay Channel

- **190 GeV/c** $\pi^-$ beam on $p$ target
- **50 \cdot 10^6** events
- **0.1 < t' < 1.0 \text{ (GeV/c)}^2**
- Largest model used up to now: **88 waves**
- Broad intensity bump
- Similar in both channels

\[
\begin{align*}
\pi^- \pi^0 \pi^0 \\
\pi^- \pi^+ \pi^- \text{ scaled}
\end{align*}
\]
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS

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$\pi^- \pi^0 \pi^0$

$\pi^- \pi^+ \pi^-$ scaled

COMPASS 2008 ($\pi^- p \rightarrow (3\pi)^- p$)

$1^+1^+ \rho(770) \pi P$

$\pi^- \pi^0 \pi^0$, $\pi^- \pi^- \pi^+$ (scaled)

$0.100 < t' < 1.000$ GeV$^2$/c$^2$

(incoherent sum)

Preliminary
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS

Analysis in $t'$ bins

"Low" $t' \approx 0.1 \text{ (GeV/c)}^2$

- Strong modulation of mass spectra with $t'$
- Dominant non-resonant contribution
- Needs to be understood in order to extract resonances

"High" $t' \approx 0.8 \text{ (GeV/c)}^2$

1$^{+}1^{+}$ $\rho(770)\pi P$

$0.100 \leq t' \leq 0.113 \text{ GeV}^2/c^2$

0.96%

$0.724 \leq t' \leq 1.000 \text{ GeV}^2/c^2$

0.66%

1$^{+}1^{+}$ $\rho(770)\pi P$

Intensity (20 MeV/c²) vs. Mass of the $\pi\pi\pi^+$ System (GeV/c²)
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS

Model for Non-Resonant Component

Deck effect

- MC pseudodata generated according to Deck amplitude
- Analyzed like real data
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS

Deck-Model for Non-Resonant Component

“Low” $t' \approx 0.1 \ (\text{GeV}/c)^2$

$p_{\pi\pi\pi\pi} \rightarrow p_{\pi\pi\pi\pi} (\text{COMPASS 2008})$

0.66%

$1^+1^+ \rho(770) \pi P$

$0.100 \leq t' \leq 0.113 \ (\text{GeV}^2/c^2)$

“High” $t' \approx 0.8 \ (\text{GeV}/c)^2$

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0.96%

$1^+1^+ \rho(770) \pi P$

$0.724 \leq t' \leq 1.000 \ (\text{GeV}^2/c^2)$

- **Deck MC** scaled to $t'$-integrated intensity
- Include amplitude in PWA?
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PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$ at COMPASS

Unexpected $I = 1$ Signal with $J^{PC} = 1^{++}$ in $f_0(980)\pi$ Decay Channel

- PWA model with 88 partial waves
- Peak around 1.4 GeV/$c^2$
- Small intensity: $\approx 0.25\%$

\[ \pi^- \pi^0 \pi^0 \]
\[ \pi^- \pi^+ \pi^- \text{ scaled} \]
Consistent with Breit-Wigner resonance

- $a_1(1420)$:
  - $M_0 = 1414^{+15}_{-13}$ MeV/$c^2$
  - $\Gamma_0 = 153^{+8}_{-23}$ MeV/$c^2$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$ at COMPASS

Consistent with Breit-Wigner resonance

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Consistent with Breit-Wigner resonance

\( a_1(1420): \)

\[ M_0 = 1414^{+15}_{-13} \text{ MeV} / c^2 \]

\[ \Gamma_0 = 153^{+8}_{-23} \text{ MeV} / c^2 \]
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$ at COMPASS

Nature of $a_1(1420)$ unclear

- No quark-model states expected at 1.4 GeV/$c^2$
- Ground state $a_1(1260)$ very close and wider
- Seen only in $f_0(980)\pi$ decay mode
- Isospin partner of narrow $f_1(1420)$?
- Suspiciously close to $K\bar{K}^*$ threshold
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$ at COMPASS

$1^{++} f_0(980) \pi P$

$0.1 < t' < 1.0 \ (\text{GeV/c})^2$

(1) Mass-dependent fit
(2) Resonance
(3) Non-resonant term

Several proposed explanations

- Re-scattering corrections in Deck process [Basdevant et al., arXiv:1501.04643]
- Branching point in triangle diagram [Mikhasenko et al., arXiv:1501.07023]
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First observation of decay $\eta(1405) \rightarrow f_0(980)\pi^0$

Large isospin breaking:

$$\frac{\mathcal{B}(\eta(1405) \rightarrow f_0(980)\pi^0)}{\mathcal{B}(\eta(1405) \rightarrow a_0^*(980)\pi^0)} = (17.9 \pm 4.2)\%$$

Anomally narrow $f_0(980): \Gamma_0 \approx 10 \text{ MeV}/c^2$
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Anomalously narrow $f_0(980)$: $\Gamma_0 \approx 10$ MeV / c^2
Proposed explanation

- Only one state \( \eta(1440) \) instead of \( \eta(1405) \) and \( \eta(1475) \)
- Different mass spectra in \( 3\pi, \eta\pi\pi, \) and \( K\bar{K}\pi \) due to triangle singularity, e.g.
Outline

1. Introduction
2. Scalar Mesons
3. $J^{PC} = 1^{--}$ spin-exotic mesons
4. Narrow states around 1.4 GeV / $c^2$
5. The light $X$ states
6. Conclusions and outlook
Threshold Enhancement $X(p\bar{p})$ at BESIII

- Seen in $J/\psi \to \gamma (p\bar{p})$
  - First observed by BESII; confirmed by CLEO
- PWA: Breit-Wigner for $X + p\bar{p}$ final-state-interaction model
  - $J^{PC} = 0^{-+}$, sub-threshold mass, width $< 76 \text{ MeV}/c^2$ at 90% C.L.
- Seen in $\psi(2S) \to \gamma (p\bar{p})$ with 5.08% of the rate in $J/\psi$
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- $p\bar{p}$ baryonium?
- Multi-quark state?
- Pure final-state-interaction (FSI) effect?
  - Unlikely: FSI model included in fit + no threshold enhancement in
    - $Y(1S) \rightarrow \gamma (p\bar{p})$ [CLEO, PRD 73 (2006) 032001]
    - $J/\psi \rightarrow \pi^0 (p\bar{p})$ [BESIII, PRL 91 (2003) 022001]
    - $J/\psi \rightarrow \omega (p\bar{p})$ [BESIII, PRD 87 (2013) 112004]

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Threshold Enhancement $X(p\bar{p})$ at BESIII

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    - $J/\psi \to \omega(p\bar{p})$ [BESIII, PRD 87 (2013) 112004]
$X(1810)$ in $J/\psi \rightarrow \gamma (\omega \phi)$ at BESIII

- $\omega \phi$ final state doubly-OZI suppressed
- Anomalous threshold enhancement
  - Tetraquark, hybrid, glueball?
  - Rescattering effect?
  - $f_0(1710)$ below threshold?

![Graph showing event distribution](image-url)
**PWA assuming sequential decay chain:** $J/\psi \rightarrow \gamma X, \ X \rightarrow \omega \phi$

- $X$ parametrized by simple Breit-Wigner
- $S$- and $P$-waves included; $D$-waves suppressed at threshold
- $J^{PC} = 0^{++}$ preferred by data
- $f_0(1710)$ as bound system of 2 vector mesons?
- $\omega \phi$ final-state-interaction effect not excluded
$M_0 = 1842.2 \pm 4.2^{+7.1}_{-2.6} \text{ MeV} / c^2, \Gamma_0 = 83 \pm 14 \pm 11 \text{ MeV} / c^2$

- New state or decay mode of other $X$?
- PWA needed to determine $J^P$
At least two different $J^P$

Common origin?

Need $J^P$ for all states

Study more decay modes and production channels
X-States around $p\bar{p}$ Threshold seen by BESIII

- At least **two different** $J^P$
- **Common origin?**
- **Need** $J^P$ **for all states**
- **Study more decay modes and production channels**

---

**Graphical Information:**

- **$X(1840)$** $J^P$ = $?$, $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$: PRD 88 (2013) 091502(R)
- **$X(1870)$** $J^P$ = $?$, $J/\psi \rightarrow \omega (\eta\pi\pi)$: PRL 107 (2011) 182001
- **$X(1835)$** $J^P$ = $0^-$, $J/\psi \rightarrow \gamma (\eta'\pi\pi)$: PRL 106 (2011) 072002
- **$X(p\bar{p})$** $J^P$ = $0^-$, $J/\psi \rightarrow \gamma (p\bar{p})$: PRL 108 (2012) 112003
- **$X(1810)$** $J^P$ = $0^+$, $J/\psi \rightarrow \gamma (\omega\phi)$: PRD 87 (2013) 032008

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[PRD 88 (2013) 091502(R)]
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Conclusions and Outlook

Light-meson spectroscopy is an active field

- Large data sets reveal ever new details; many still puzzling
- Pattern similar to heavy-meson sector: narrow enhancements at thresholds
  - Common mechanism?
- High-precision data require improved analysis tools
  - Strong collaboration between theory and experiment indispensable

Hadrons reflect workings of QCD at low energies

- Measurement of hadron spectra and hadron decays gives valuable input to theory and phenomenology
- Also input for measurement of CP-violation in multi-body decays of heavy mesons

New data sets keep on coming

- BESIII (BEPCII) and VES (IHEP Protvino) will take more data
- GlueX + CLAS12 (Jlab), and Belle II (KEK) will start soon
- Panda (FAIR) in somewhat further future
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