Light-Meson Spectroscopy

A Selection of Recent Results

Boris Grube

Physik-Department E18
Technische Universität München,
Garching, Germany

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Outline

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Mesons in the Constituent Quark Model (CQM)

Mesons

- Color-singlet $|q\bar{q}'\rangle$ states, grouped into $\mathrm{SU}(3)_{\mathrm{flavor}}$ 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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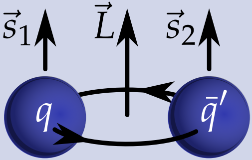

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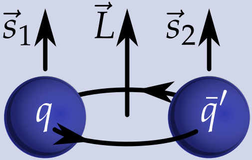
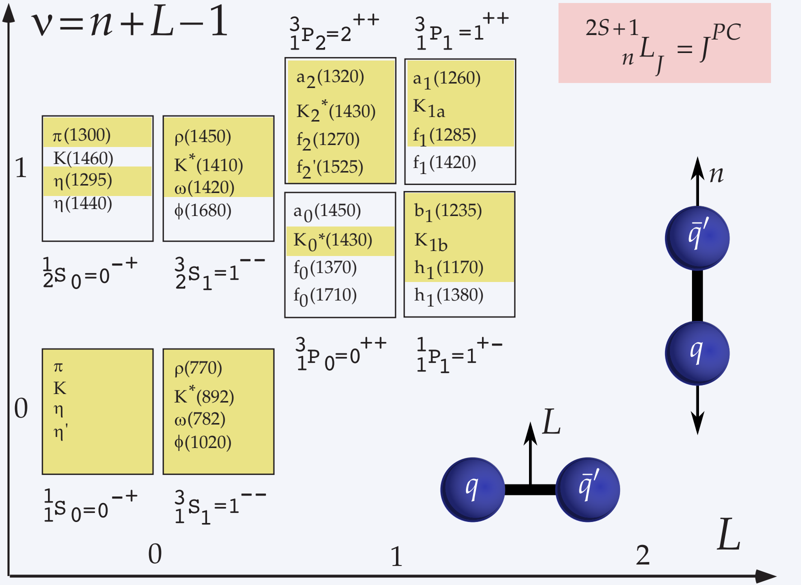


Constituent Quark Model

Light-quark Meson Spectrum



Amsler *et al.*, Phys. Rept. **389** (2004) 61

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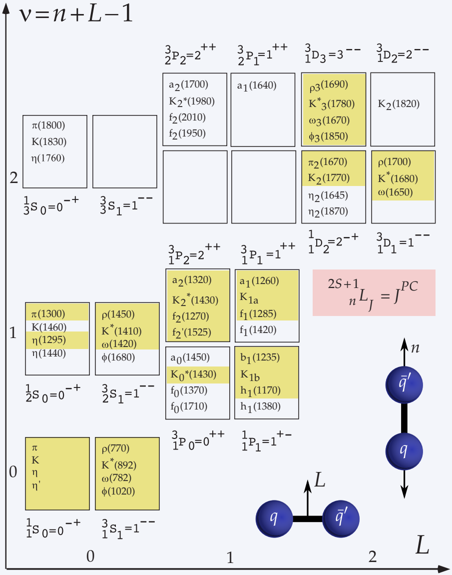

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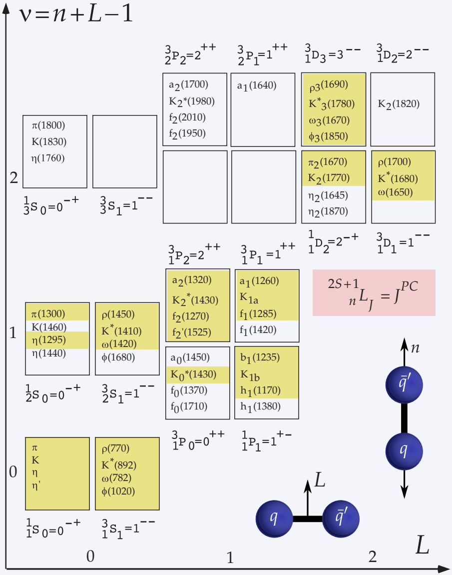
"Light-meson frontier"

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



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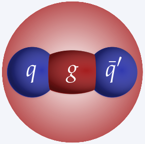
Possible New Forms of Matter

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 $|q\bar{q}\,q\bar{q}\rangle$: 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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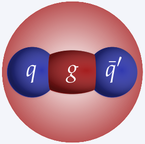

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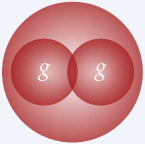

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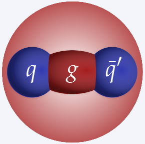

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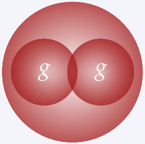

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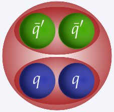

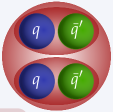

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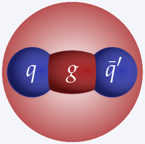

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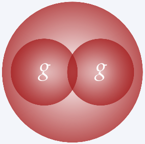

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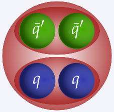

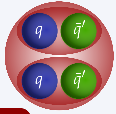

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Connection to QCD

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 $\Longrightarrow$ 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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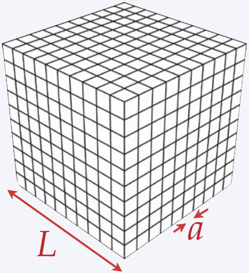

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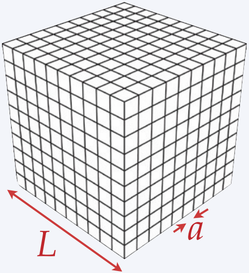

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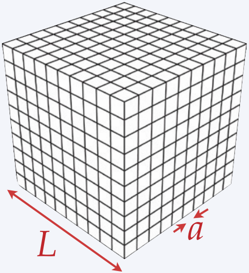

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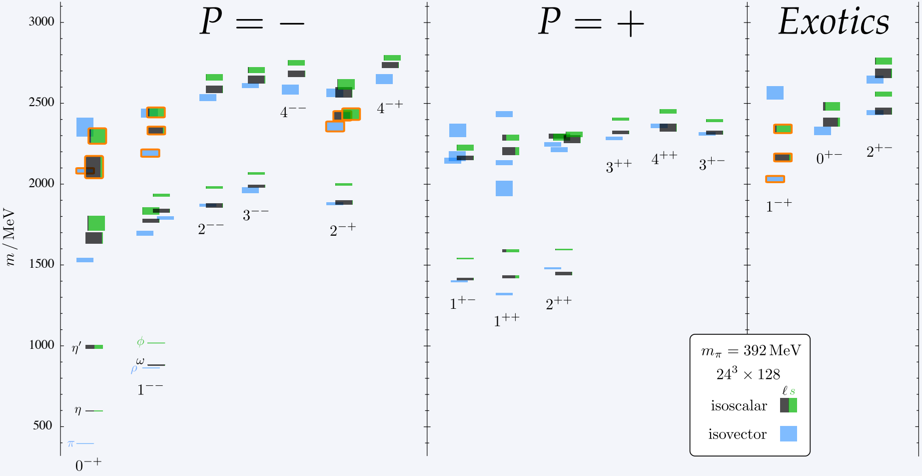
Light-Meson Spectrum in Lattice QCD

State-of-the-art Calculation

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



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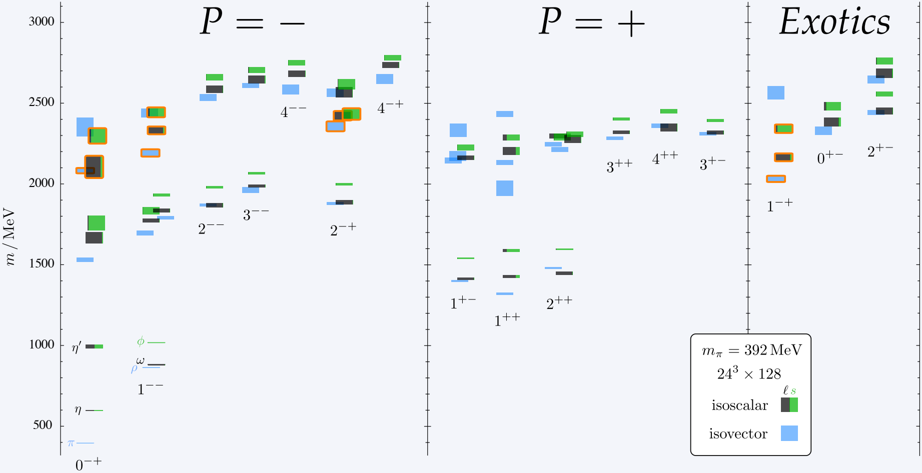

- Reproduces mainly the quark-model pattern
- Calculations not reliable yet for $J^{PC} = 0^{++}$ sector

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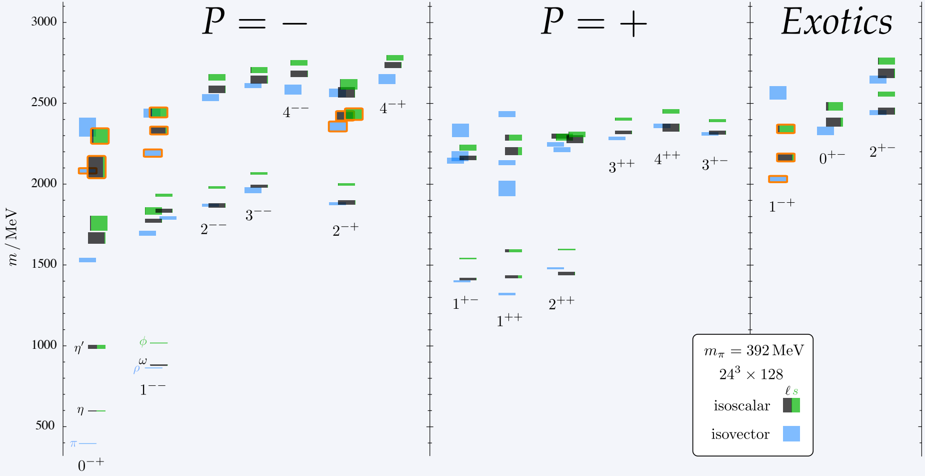
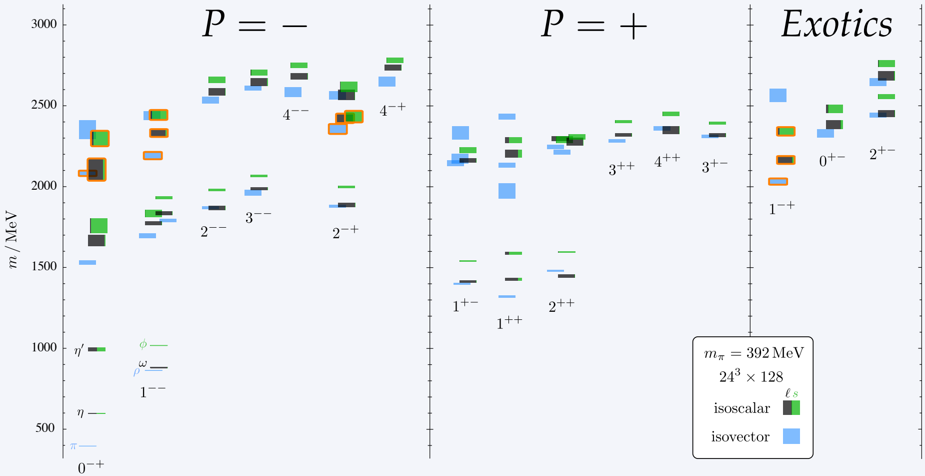


- Additional non-$q\bar{q}$ states
  - Set of hybrid mesons with 0^{-+}, 1^{--}, 2^{-+} and spin-exotic 1^{-+}



- Resonance widths and decay modes still very difficult

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

Scalar Mesons

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 $K\bar{K}$ $\implies$ 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/ψ decays

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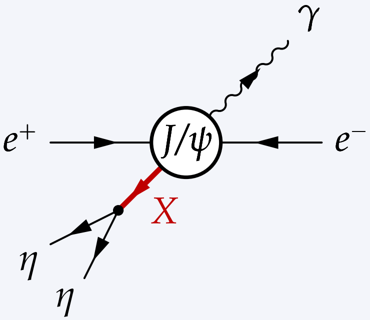
Radiative J/ψ Decays



- $\eta\eta$ final state: only $I = 0$ and $J^{PC} = \text{even}^{++}$ allowed
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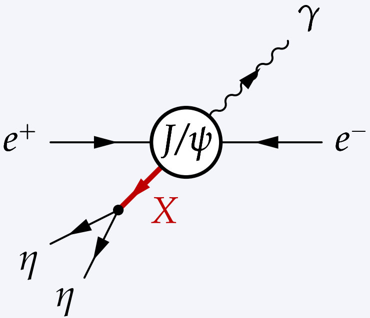

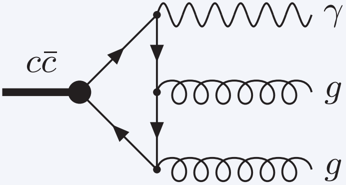

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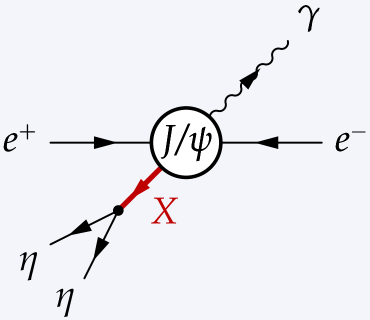
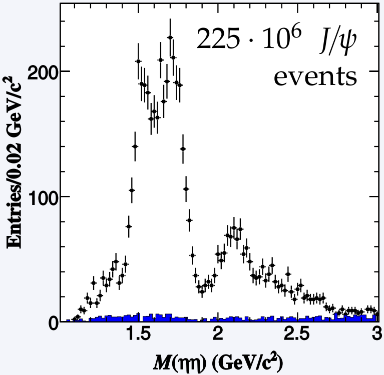
$J/\psi \to \gamma\,(\eta\eta)$ at BESIII

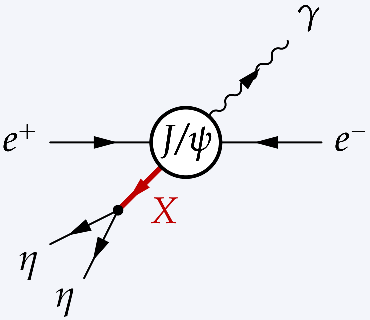


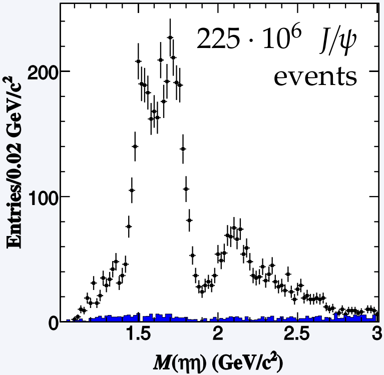


Decomposition into J^P states: *partial-wave analysis* (PWA)

- Sequential decay: calculable quasi-two-body amplitudes
- Intermediate resonance X described by Breit-Wigner propagator
- Same initial and final state $\Longrightarrow$ different X interfere
- Magnitudes, phases and parameters of X determined from kinematic distribution of final-state particles

$J/\psi \to \gamma\,(\eta\eta)$ at BESIII





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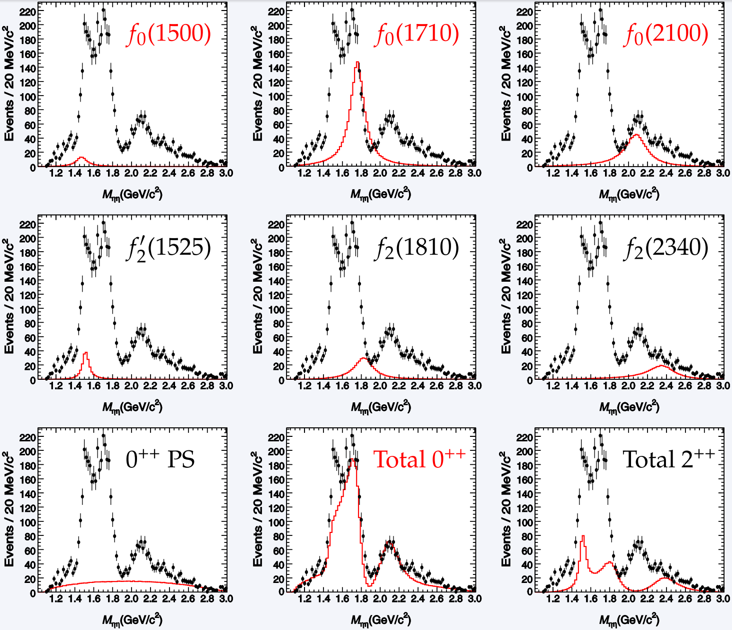
[PRD 87 (2013) 092009]



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

Result

- Largest signals from $f_0(1710)$ and $f_0(2100)$
- Clear but smaller $f_0(1500)$ signal
- No $f_0(1370)$ signal
- $\mathcal{B}(J/\psi \to \gamma\, X \to \gamma\, \eta\eta)$ of $f_0(1710)$ $10\times$ larger than that of $f_0(1500)$
  - $\mathcal{B}(J/\psi \to \gamma\, f_0(1710)) \approx 2$ to $3 \cdot 10^{-3}$
  - $\mathcal{B}(J/\psi \to \gamma\, f_0(1500)) \approx 1$ to $3 \cdot 10^{-4}$
- (Quenched) lattice QCD prediction for pure gauge scalar glueball: $\mathcal{B}(J/\psi \to \gamma\, G_{0^{++}}) = 3.8(9) \cdot 10^{-3}$ [Gui *et al.*, PRL 110 (2013) 021601]
  - $f_0(1500)$ production rate much smaller
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PWA of $J/\psi \to \gamma\,(\eta\eta)$ at BESIII

[PRD 87 (2013) 092009]

Result

- Largest signals from $f_0(1710)$ and $f_0(2100)$
- Clear but smaller $f_0(1500)$ signal
- No $f_0(1370)$ signal
- $\mathcal{B}(J/\psi \to \gamma\, X \to \gamma\,\eta\eta)$ of $f_0(1710)$ $10\times$ larger than that of $f_0(1500)$
  - $\mathcal{B}(J/\psi \to \gamma\, f_0(1710)) \approx 2 \text{ to } 3 \cdot 10^{-3}$
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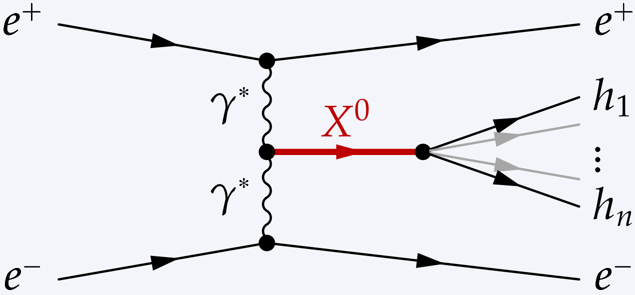
Meson Production in Two-Photon Collisions



- Source of mesons with even C-parity
- Gives access to two-photon coupling $\Gamma_{\gamma\gamma}$ of X
  - For glueball $\Gamma_{\gamma\gamma} \ll 1\ \mathrm{eV}/c^2$ expected

Scalar Mesons in $\gamma\gamma \to K_S^0 \bar{K}_S^0$ at Belle

[PTEP (2013) 123C01]

- Data taken at energies around $\Upsilon(2S)$, $\Upsilon(4S)$, and $\Upsilon(5S)$ (total $972\,\mathrm{fb}^{-1}$)
- Study production of f_J $(I = 0)$ and a_J $(I = 1)$ mesons with even spin J

- Peaks near 1.3, 1.5, and $1.8\,\mathrm{GeV}/c^2$
- Additional enhancements at 2.3 and $2.6\,\mathrm{GeV}/c^2$

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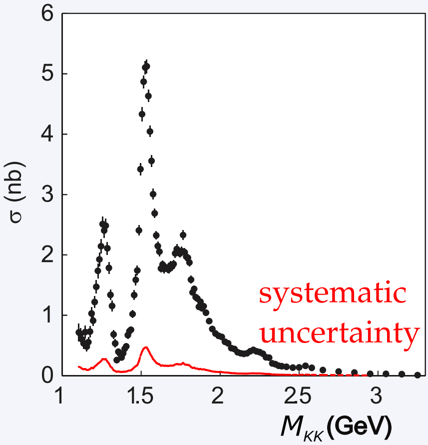

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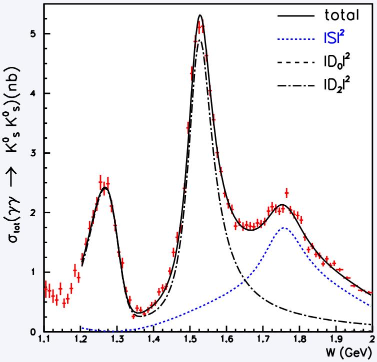
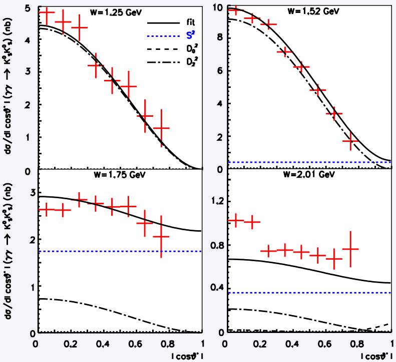
PWA of $\gamma\gamma \to K^0_S \bar{K}^0_S$ at Belle

[PTEP (2013) 123C01]

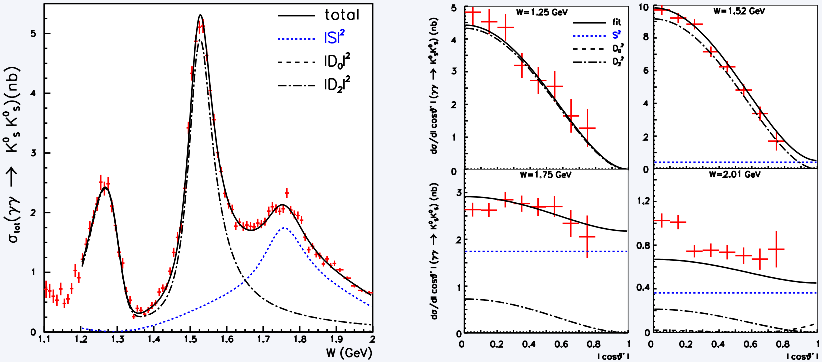




- Spin-parity decomposition of mass spectrum based on angular distribution of final-state particles
- Range $1.2 < M_{KK} < 2.0$ GeV$/c^2$ fitted by S- and D-waves
- Data described best by S-wave with $f_0(1710)$ + non-resonant contribution

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

[PTEP (2013) 123C01]

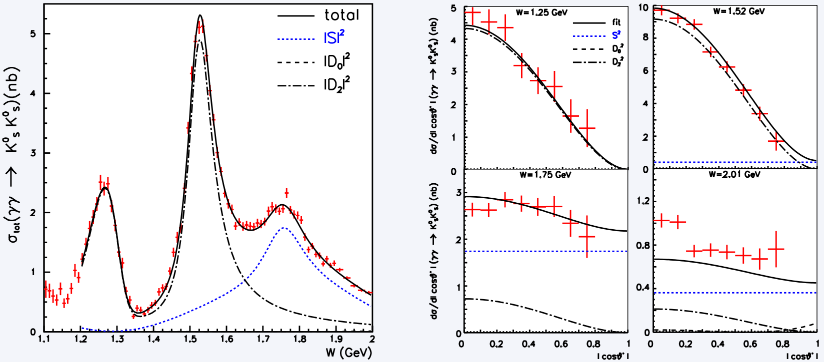


No signal for $f_0(1500)$

- Consistent with glueball interpretation

PWA of $\gamma\gamma \to K^0_S \bar{K}^0_S$ at Belle

[PTEP (2013) 123C01]

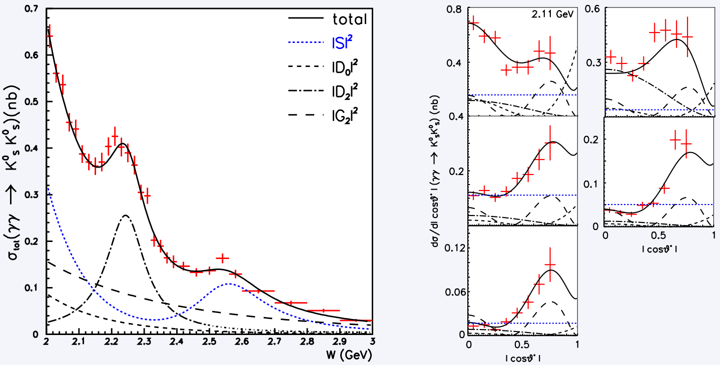


First measurement of $\Gamma_{\gamma\gamma}\,\mathcal{B}(K^0_S \bar{K}^0_S)$

- 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

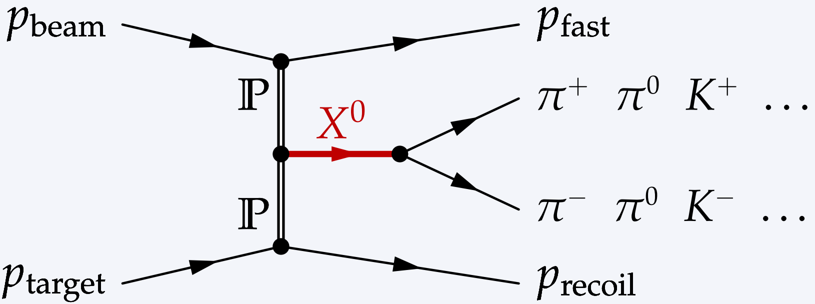
PWA of $\gamma\gamma \to K_S^0 \bar{K}_S^0$ at Belle

[PTEP (2013) 123C01]



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

Scalar Mesons in Central Production

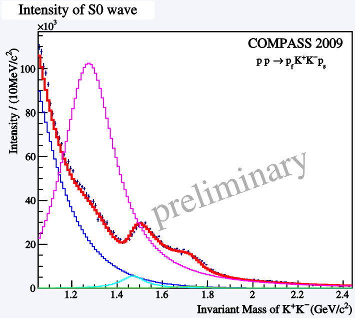


- "Glue rich" process
  - Glueball production should be enhanced

Central Production: Upcoming Data

COMPASS

S-wave intensity in K^+K^-



[PoS(Bormio 2013)014]

- Phase information available
- Working on improved analysis model

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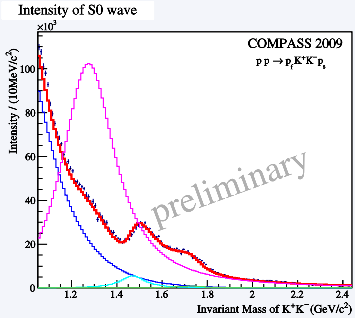
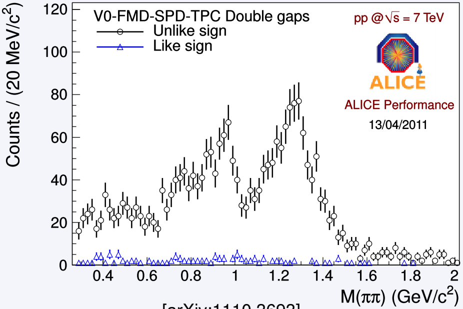


[PoS(Bormio 2013)014]

ALICE

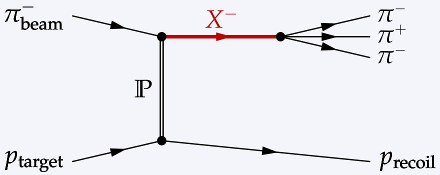
$\pi^+\pi^-$ invariant mass spectrum



[arXiv:1110.3693]

- Phase information available
- Working on improved analysis model

Outline

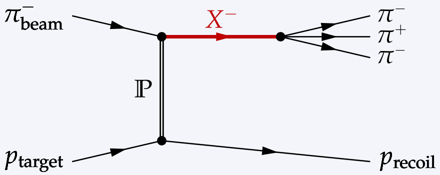


- Soft scattering of beam particle off target via strong interaction
  - Small momentum and energy transfer to target
  - Target particle stays intact
- Beam particle gets excited into intermediate resonance X
- Decay of X into 3 forward-going pions
  - Measured by spectrometer
- Same final state $\Longrightarrow$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

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

Meson Production in High-Energy Scattering

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



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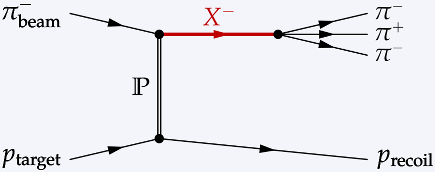

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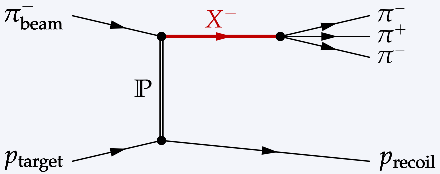

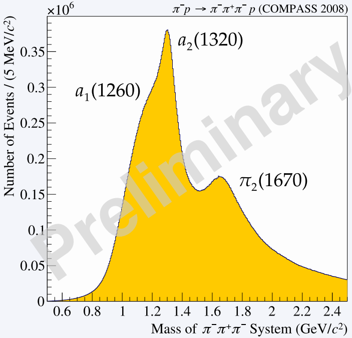

PWA assumption: X^- decays via intermediate $\pi^+\pi^-$ resonances

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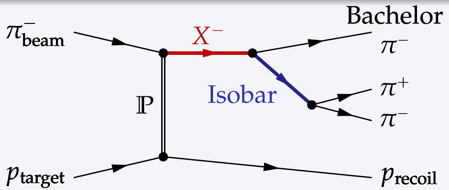
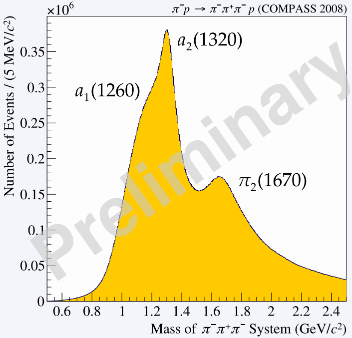
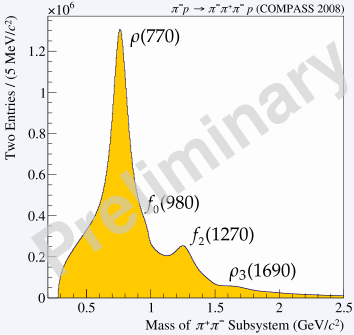


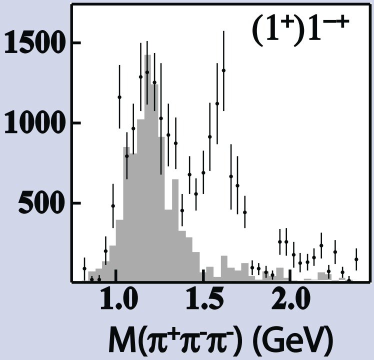




PWA assumption: X^- decays via intermediate $\pi^+\pi^-$ resonances

BNL E852 analyses: 18 GeV$/c$ π^- beam on p target

[PRL 81 (1998) 5760]



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

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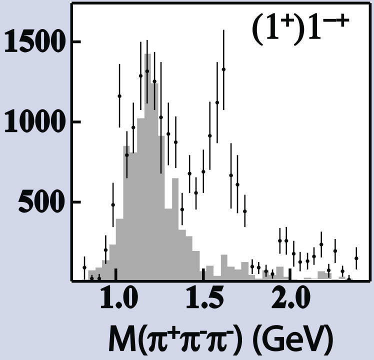
[PRL 81 (1998) 5760]



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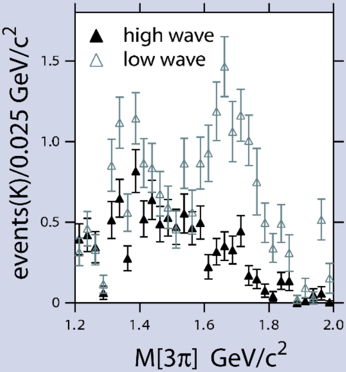
- Model with 21 waves

[PRD 73 (2006) 072001]



- $2.6 \cdot 10^6$ events
- $0.1 < t' < 0.5\,(\text{GeV}/c)^2$
- Model with 21/36 waves

- $190\,\text{GeV}/c$ π^-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

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

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

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

Spin-Exotic Signal with $I = 1$ and $J^{PC} = 1^{-+}$ in $\rho(770)\pi$ Decay Channel

- 190 GeV/c π^-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
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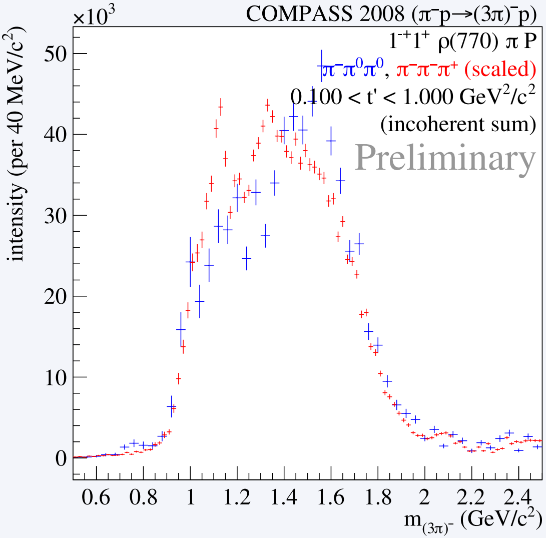

$\pi^-\pi^0\pi^0$

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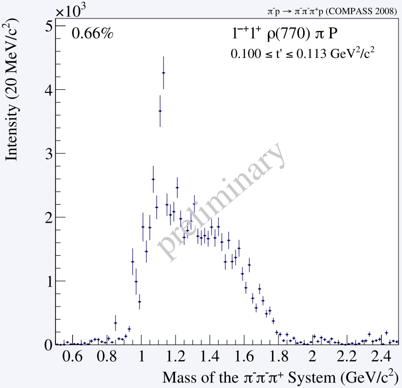
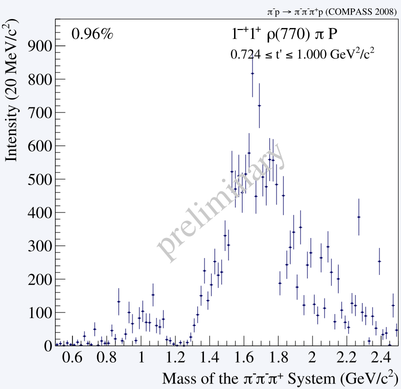
PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$ at COMPASS

Analysis in t' bins

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

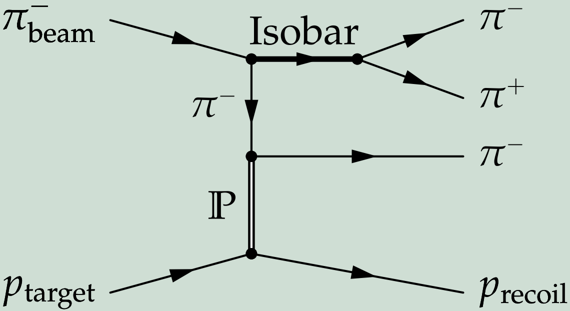


"High" $t' \approx 0.8\,(\text{GeV}/c)^2$



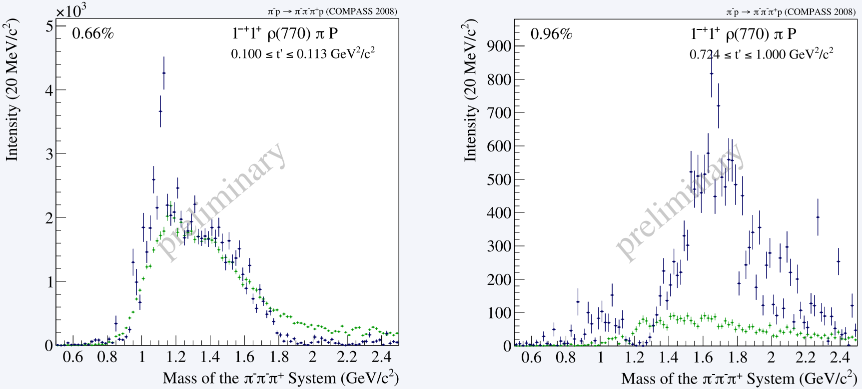
- Strong modulation of mass spectra with t'
- Dominant non-resonant contribution
  - Needs to be understood in order to extract resonances

Deck effect



- MC pseudodata generated according to Deck amplitude
- Analyzed like real data

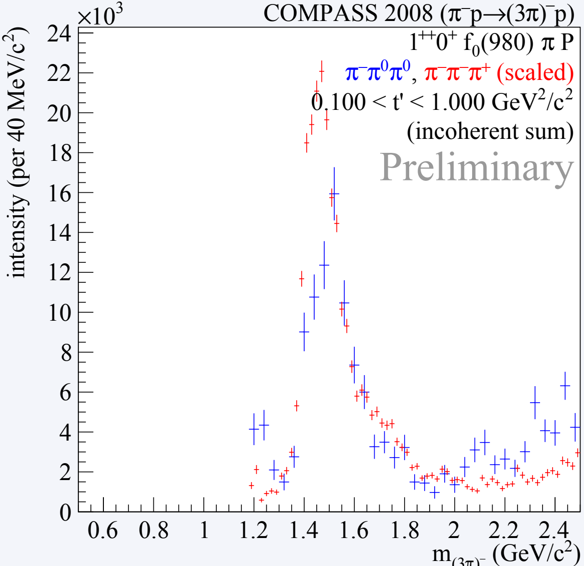
“Low” $t' \approx 0.1\ (\text{GeV}/c)^2$ “High” $t' \approx 0.8\ (\text{GeV}/c)^2$



- Deck MC scaled to t'-integrated intensity
- Include amplitude in PWA?

Outline

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



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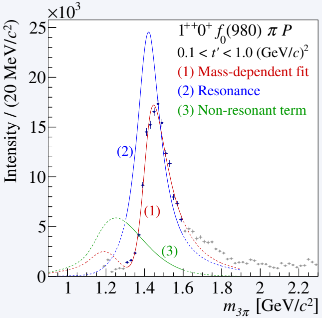
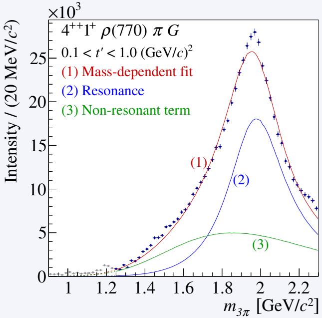
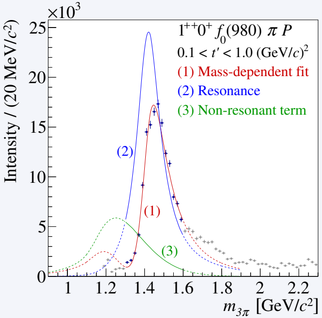


- Consistent with Breit-Wigner resonance
- $a_1(1420)$:
  $M_0 = 1414^{+15}_{-13}\ \text{MeV}/c^2$
  $\Gamma_0 = 153^{+8}_{-23}\ \text{MeV}/c^2$

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$ at COMPASS [arXiv:1501.05732]





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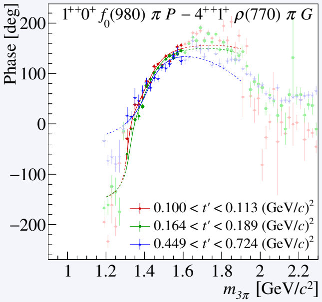

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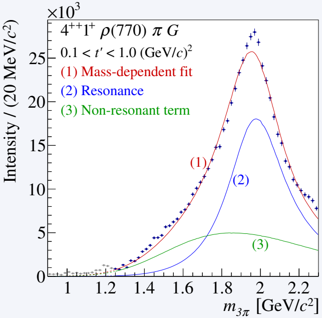

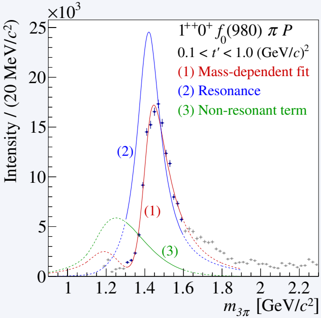

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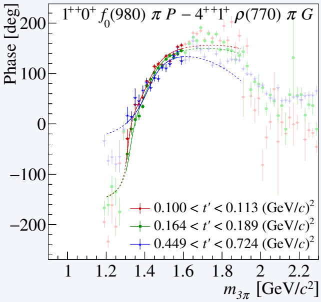

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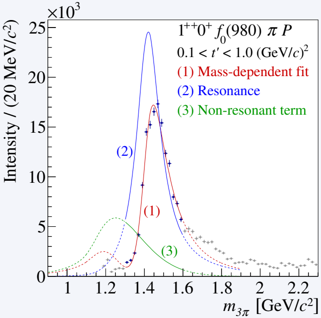
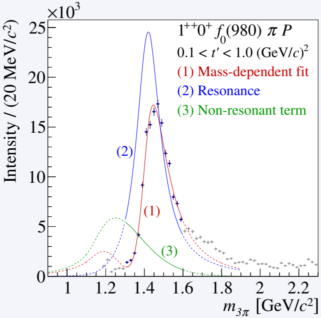


Nature of $a_1(1420)$ unclear

- 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

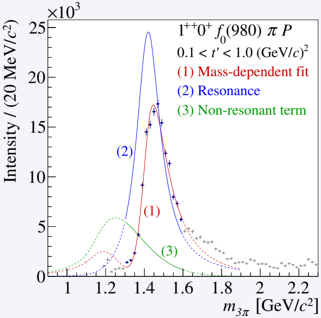
PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$ at COMPASS [arXiv:1501.05732]

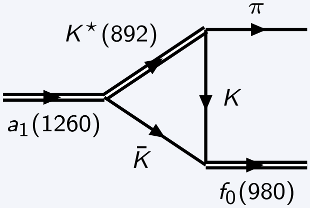


Several proposed explanations

- Two-quark-tetraquark mixed state [Wang, arXiv:1401.1134]
- Re-scattering corrections in Deck process [Basdevant *et al.*, arXiv:1501.04643]
- Branching point in triangle diagram [Mikhasenko *et al.*, arXiv:1501.07023]

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$ at COMPASS [arXiv:1501.05732]





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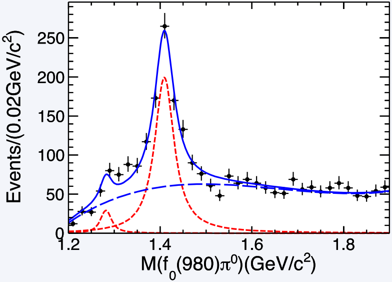
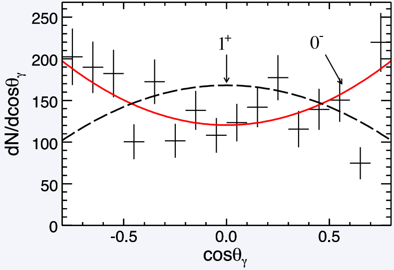
$\eta(1405)$ in $J/\psi \to \gamma\,(3\pi)^0$ at BESIII

[PRL 108 (2012) 182001]





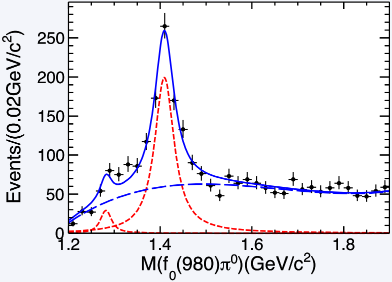
- First observation of decay $\eta(1405) \to f_0(980)\pi^0$
- Large isospin breaking:

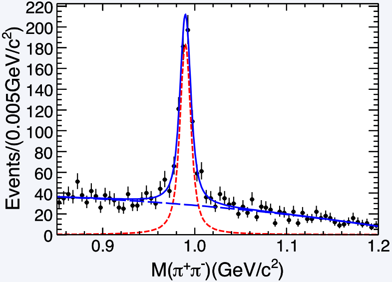
$$\frac{\mathcal{B}(\eta(1405) \to f_0(980)\pi^0)}{\mathcal{B}(\eta(1405) \to a_0^0(980)\pi^0)} = (17.9 \pm 4.2)\%$$

- Anomalously narrow $f_0(980)$: $\Gamma_0 \approx 10\,\mathrm{MeV}/c^2$

$\eta(1405)$ in $J/\psi \to \gamma\,(3\pi)^0$ at BESIII

[PRL 108 (2012) 182001]





- First observation of decay $\eta(1405) \to f_0(980)\pi^0$
- Large isospin breaking:

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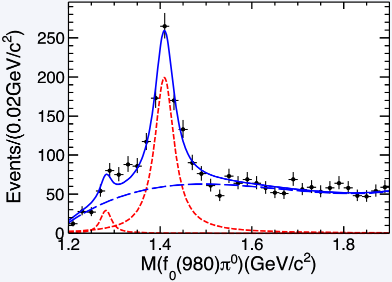
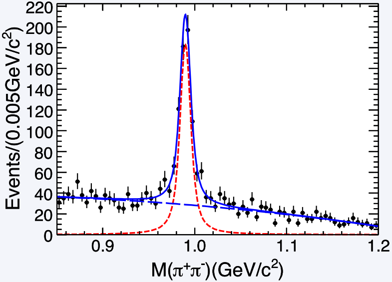
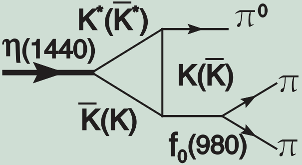




Proposed explanation

[Wu *et al.*, PRL 108 (2012) 081803; PRD 87 (2013) 014023]

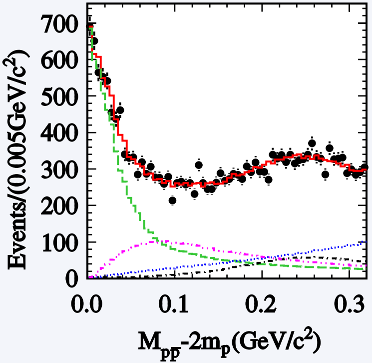
- Only one state $\eta(1440)$ instead of $\eta(1405)$ and $\eta(1475)$
- Different mass spectra in 3π, $\eta\pi\pi$, and $K\bar{K}\pi$ due to triangle singularity, e.g.



Outline

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

[PRL 108 (2012) 112003]



- 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 $< 76\,\mathrm{MeV}/c^2$ at 90% C.L.
- Seen in $\psi(2S) \to \gamma\,(p\bar{p})$ with 5.08% of the rate in J/ψ

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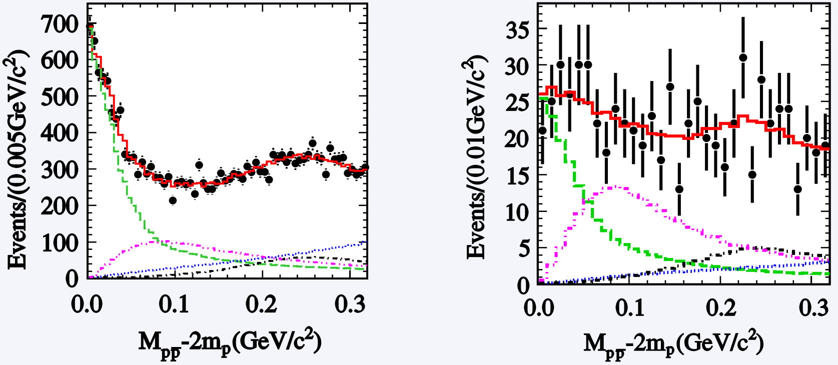

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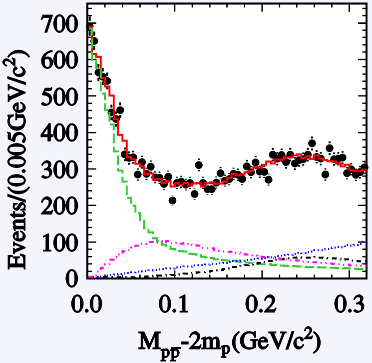

- $p\bar{p}$ baryonium?
- Multi-quark state?
- Pure final-state-interaction (FSI) effect?
  - Unlikely: FSI model included in fit + no threshold enhancement in
    - $\Upsilon(1S) \to \gamma\,(p\bar{p})$ [CLEO, PRD 73 (2006) 032001]
    - $J/\psi \to \pi^0\,(p\bar{p})$ [BESIII, PRL 91 (2003) 022001]
    - $J/\psi \to \omega\,(p\bar{p})$ [BESIII, PRD 87 (2013) 112004]

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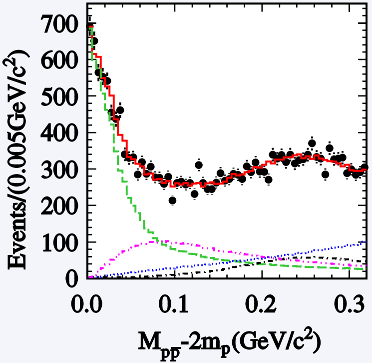

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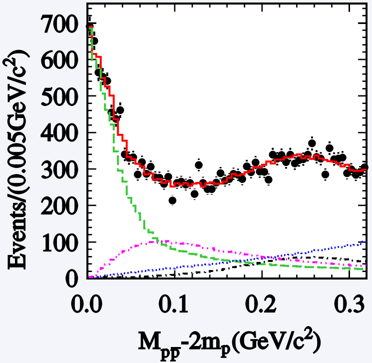

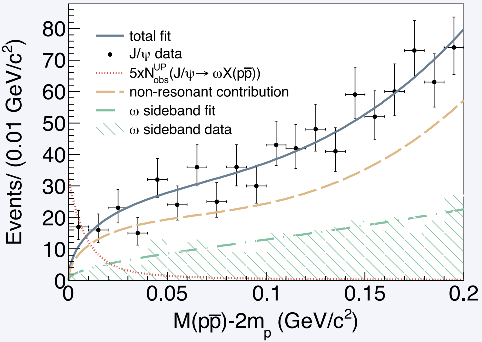

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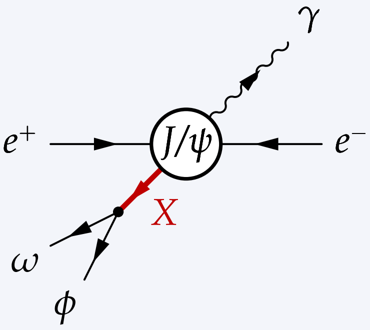
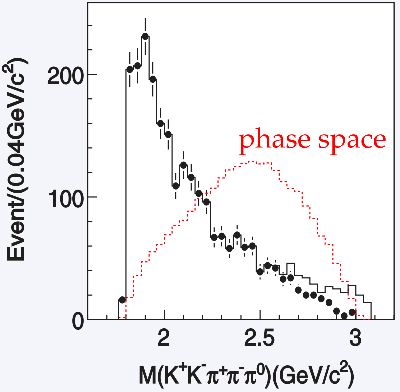
$X(1810)$ in $J/\psi \to \gamma\,(\omega\phi)$ at BESIII

[PRD 87 (2013) 032008]

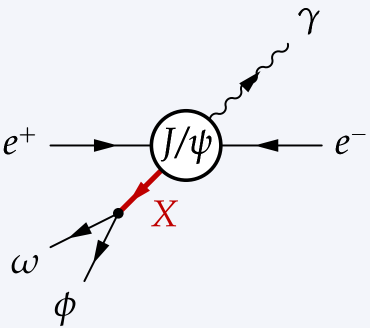


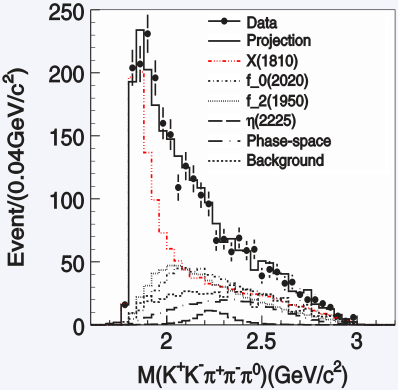


- $\omega\phi$ final state doubly-OZI suppressed
- Anomalous threshold enhancement
  - Tetraquark, hybrid, glueball?
  - Rescattering effect?
  - $f_0(1710)$ below threshold?

$X(1810)$ in $J/\psi \to \gamma\,(\omega\phi)$ at BESIII

[PRD 87 (2013) 032008]

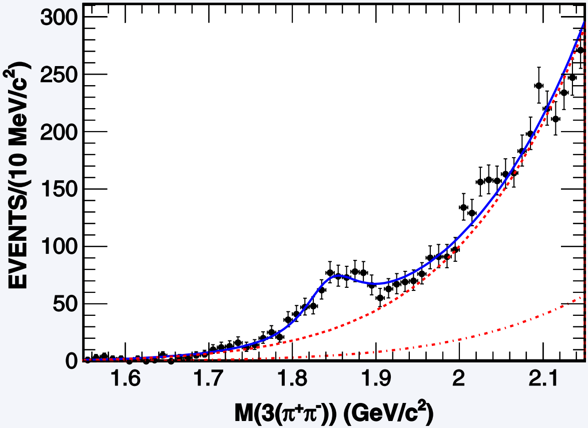




- PWA assuming sequential decay chain: $J/\psi \to \gamma\, X$, $X \to \omega\phi$
  - X parametrized by simple Breit-Wigner
  - S- and P-waves included; D-waves suppressed at threshold
- $J^{PC} = 0^{++}$ preferred by data
  - $f_0(1710)$ as bound system of 2 vector mesons? [PRD 87 (2013) 096006]
  - $\omega\phi$ final-state-interaction effect not excluded

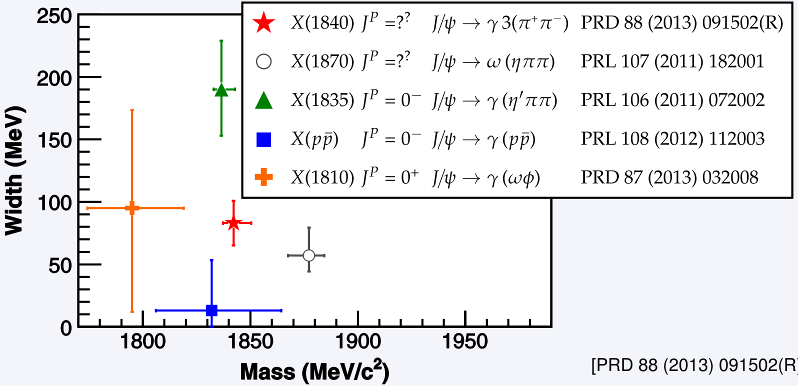
$X(1840)$ in $J/\psi \to \gamma\, 3(\pi^+\pi^-)$ at BESIII

[PRD 88 (2013) 091502(R)]



- $M_0 = 1842.2 \pm 4.2^{+7.1}_{-2.6}\,\mathrm{MeV}/c^2$, $\Gamma_0 = 83 \pm 14 \pm 11\,\mathrm{MeV}/c^2$
- New state or decay mode of other X?
- PWA needed to determine J^P

X-States around $p\bar{p}$ Threshold seen by BESIII



[PRD 88 (2013) 091502(R)]

- At least two different J^P
- Common origin?
- Need J^P for all states
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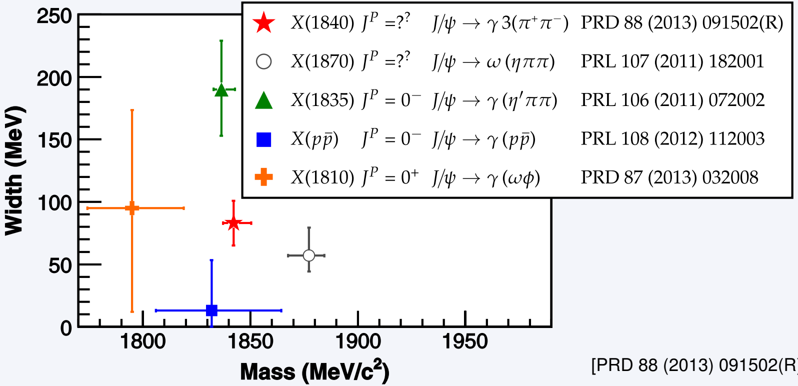

[PRD 88 (2013) 091502(R)]

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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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