RUHR-UNIVERSITÄT BOCHUM

RUB

Progress on Light Hadron Spectroscopy

Marc Pelizäus
Ruhr-Universität Bochum
(on behalf of the BES III Collaboration)

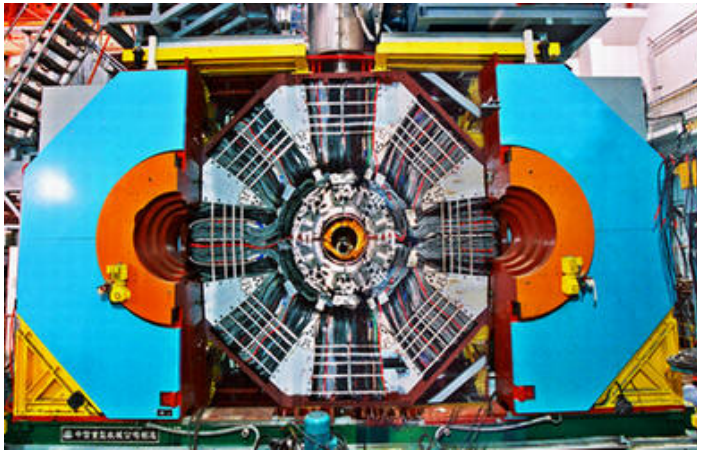
DIS 2016
April 11-15, 2015
DESY, Hamburg

DFG

BESIII

BESIII Physics Program

- Light Hadrons
  - Meson and baryon spectroscopy
  - Search for exotic hadrons, e.g. glueballs, hybrids, tetraquarks
  - Light meson decays ($\eta^{(\prime)}$, ω)
- Charmonium Physics
  - X, Y, and Z states
  - Decays and transitions
- Open Charm Physics
  - D meson decays
  - $D\bar{D}$ mixing
  - CP violation in the charm sector
- And many further topics
  - e.g. tau and two-photon physics

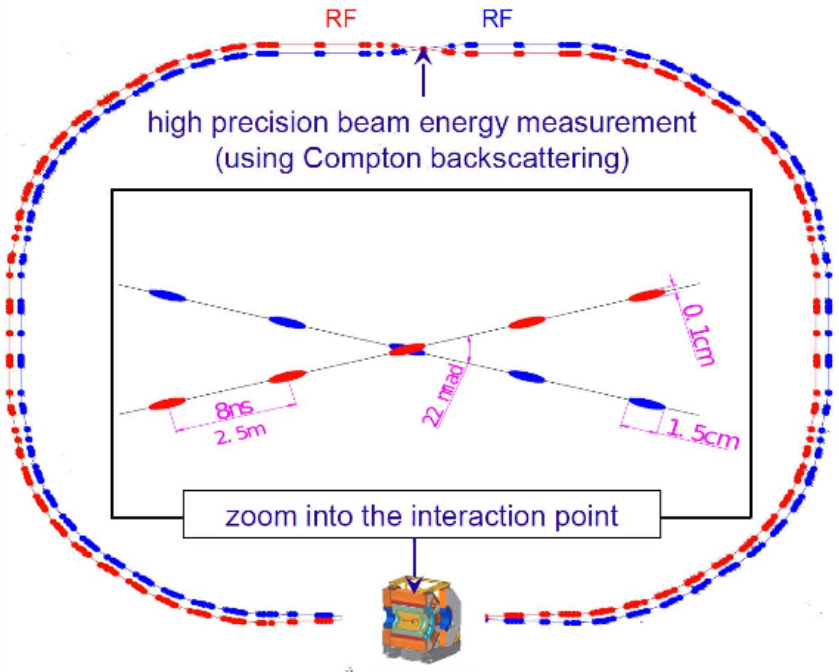


Further BESIII presentations at this workshop

WG 4 Heavy Flavors (Tue.)
Y. Zhang, Charm Physics at BES III

WG 4 Heavy Flavors (Wed.)
A. Guo, XYZ Studies at BES III

BESIII at BEPC II



Symmetric electron-positron collider BEPC II

- Energy range: $\sqrt{s}$ = 2.0-4.6 GeV
- Design luminosity achieved: 1×10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$)
- Energy spread: ~5×10^{-4}
- Operating since March 2008

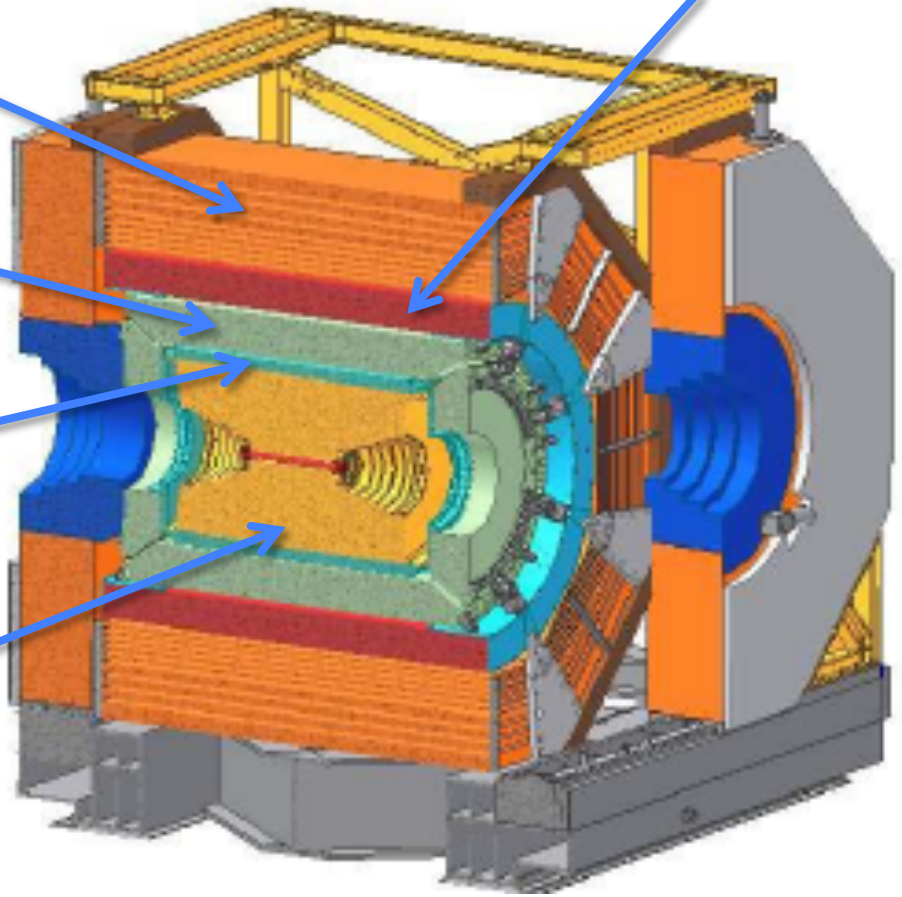
The BESIII Detector

RPC Muon Detector

8 layers (end caps), 9 layers (barrel)

$\delta R_\phi = 1.4 - 1.7\,\mathrm{cm}$

Superconducting Solenoid (1 T)



Electromagnetic CsI(Tl) Calorimeter

$\sigma_E/E < 2.5\%/\sqrt{E}$

$\sigma_{z,\phi} = 0.5 - 0.7\,\mathrm{cm}/\sqrt{\mathrm{E}}$

Time of Flight System

$\sigma_t = 90\,\mathrm{ps}$ (barrel)

$\sigma_t = 110\,\mathrm{ps}$ (end caps)

Drift Chamber

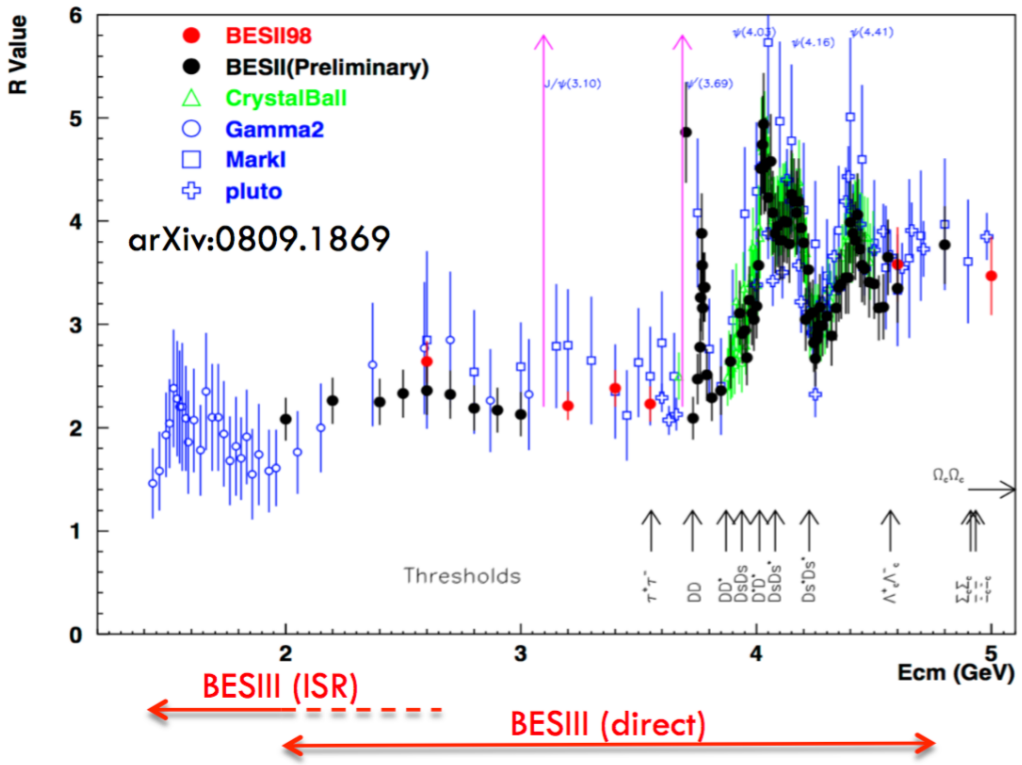
$\sigma_{(dE/dx)} = 6\%$

$\sigma_{p_t}/p_t = 0.5\%$

Data Samples

From 2009 to 2014/15:

- 1.3×10^9 J/ψ
- 5×10^8 ψ(2S)
- 2.9 fb^{-1}at ψ(3770)
- 0.5 fb^{-1}at ψ(4040)
- 2.3 fb^{-1}at 4230 / 4260 MeV
- 0.5 fb^{-1}at 4360 MeV
- 0.5 fb^{-1}at 4600 MeV
- 1 fb^{-1} at ψ(4415)
- 0.1fb^{-1} at 4470 / 4530MeV
- 0.04 fb^{-1}around Λ_c threshold
- 1 fb^{-1} at 4420 MeV
- R scan:
  - ~0.5 fb^{-1} at 2-3 GeV, 19 points
  - ~0.8 fb^{-1} at 3.85-4.59 GeV, 104 points
- 24 pb^{-1} at 3554 MeV (τ mass measurment)
- 0.5 fb^{-1} at 4100-4400 MeV

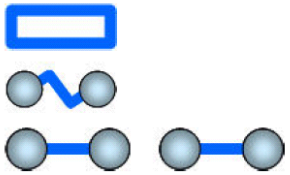


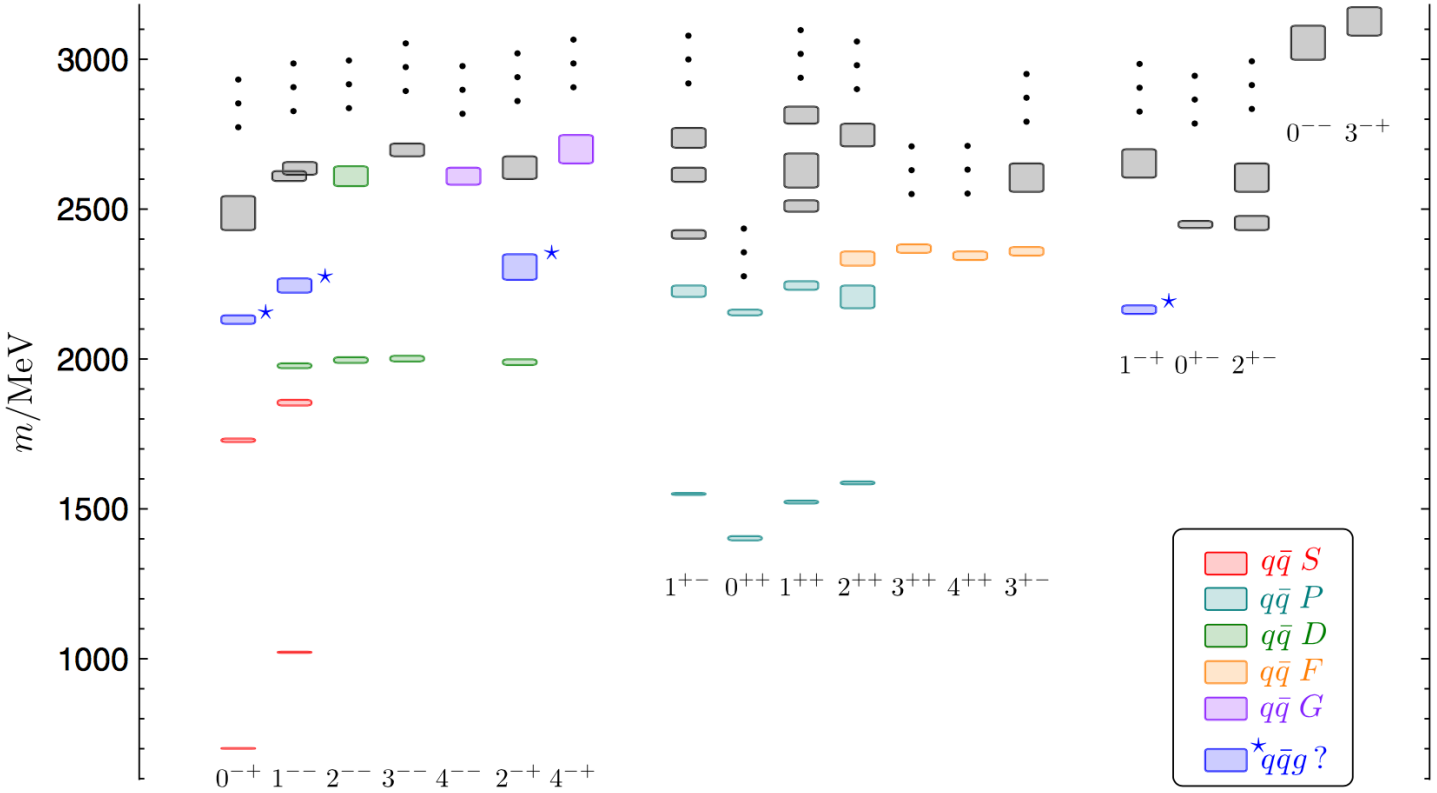
Light Meson Spectrum

Color-less $q\bar{q}$ states (q = u, d, s)
Multipletts of $q\bar{q}$ mesons with same J^{PC}

Additional color-less states:

- Glueballs: gg, ggg
- Hybrids: $q\bar{q}g$
- Tetraquarks: $(q\bar{q})(q\bar{q})$



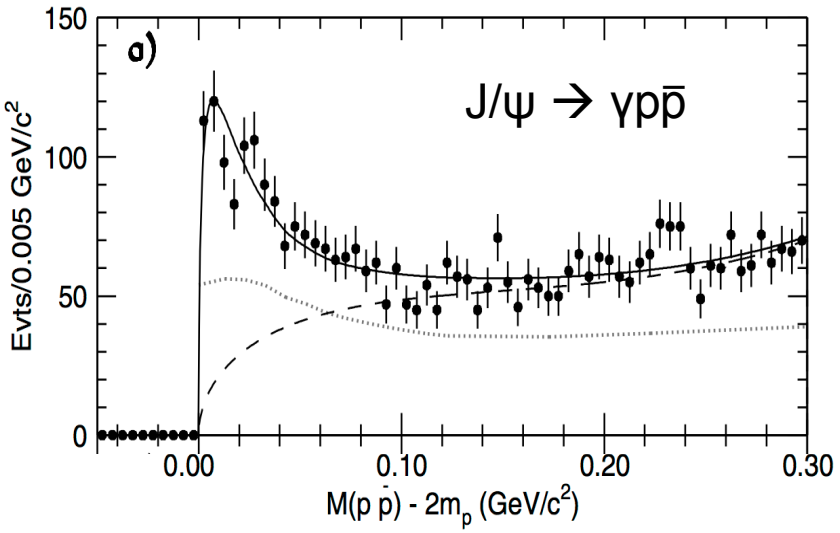


J. Dudek, Phys. Rev. D84 (2011) 074023

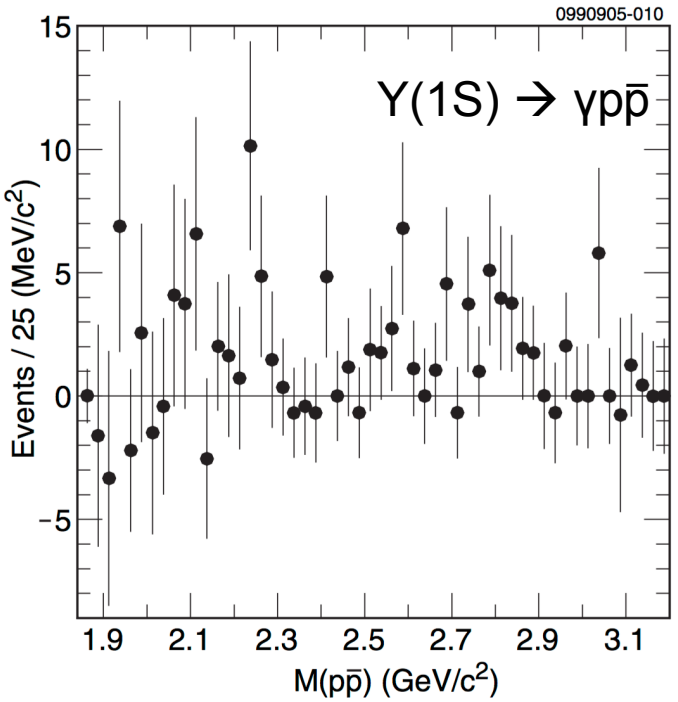
Enhancement at $p\bar{p}$ Threshold

- Enhancement at $p\bar{p}$ threshold observed in $J/\psi \rightarrow \gamma p\bar{p}$ by BESII (2003) and confirmed by CLEOc (2010)
- Enhancement not observed in related channel: $\Upsilon(1S) \rightarrow \gamma p\bar{p}$
- Nature still unclear
  - $p\bar{p}$ bound state (baryonium), multiquark state, FSI effect ?

BESII, Phys.Rev.Lett. 91 (2003) 022001



CLEOc, Phys. Rev. D73, 032001 (2006)



Radiative J/ψ and ψ' Decays

Partial Wave Analysis of J/ψ → γpp̄ and ψ' → γpp̄ in the mass region $m_{p\bar{p}} < 2.2$ GeV/c^2

J/ψ → γpp̄: Significant contributions of X(pp̄), $f_2(1920)$, $f_0(2100)$, and non-resonant 0^{++} pp̄ wave

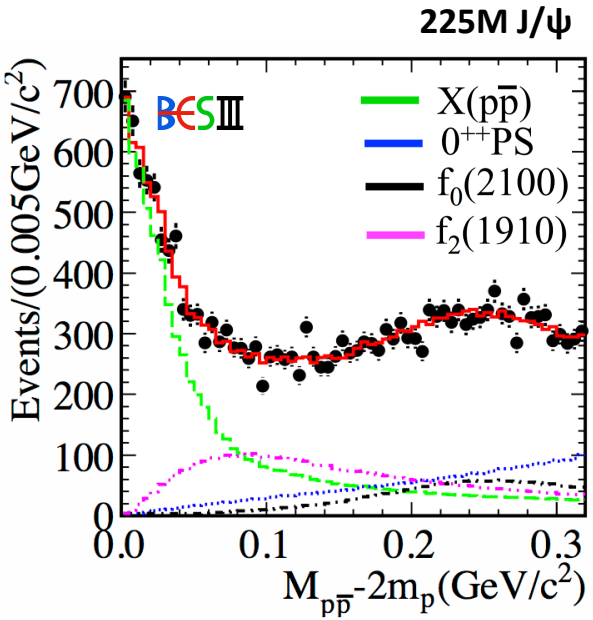
→ Structure at threshold X(pp̄): $J^{PC} = 0^{-+}$
Breit-Wigner parameterization:

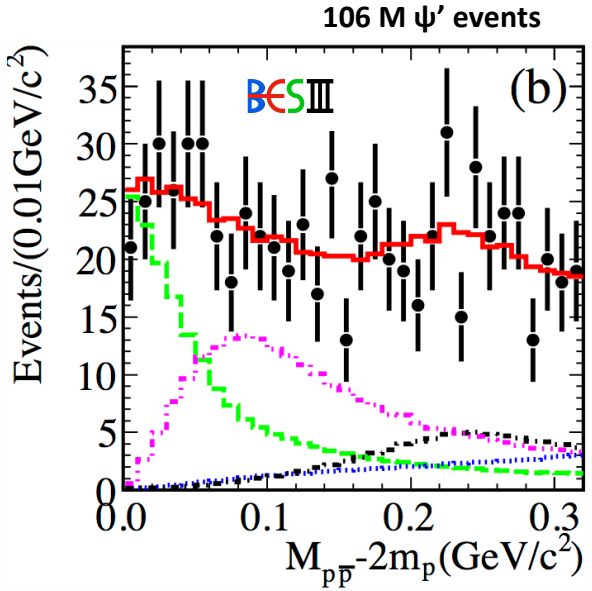
$$M = 1832^{+19}_{-5}(\text{stat})\ ^{+18}_{-17}(\text{syst}) \pm 19(\text{model})\ \text{MeV}/c^2$$

$$\Gamma = 13 \pm 39(\text{stat})\ ^{+10}_{-13}(\text{syst}) \pm 4(\text{model})\ \text{MeV}/c^2$$

$$BR_{[J/\psi\to\gamma X]\times BR[X\to p\bar{p}]} = (9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-5.0}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$

ψ' → γpp̄: X(pp̄) production is suppressed by a factor of ~20 compared to production in J/ψ → γpp̄





BESIII, Phys. Rev. Lett. 108,112003(2012)

Hadronic J/ψ Decays

Study of J/ψ → ωpp̄ and J/ψ → Φpp̄ may shed further light on the nature of X(pp̄)

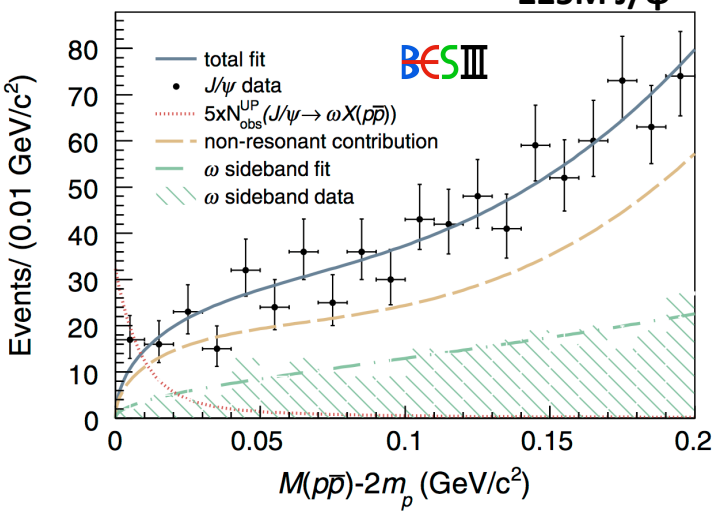
J/ψ → ωpp̄

B(J/ψ → ωX(pp̄) → ωpp̄) <3.7x10^{-6} (95% CL)

>10x suppressed compared to J/ψ →γX(pp̄)→γpp̄

BESIII, Phys. Rev. D87, 112004 (2013)

225M J/ψ



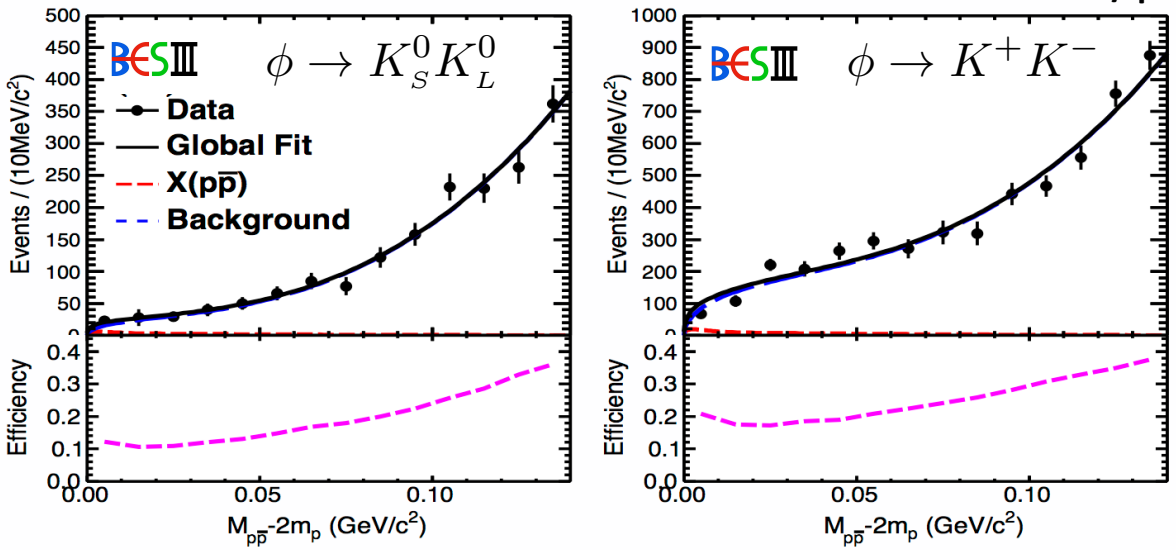
J/ψ → Φpp̄

B(J/ψ → ΦX(pp̄) → Φpp̄ <2x10^{-7} (90% CL)

>100x suppressed compared to J/ψ → γX(pp̄)→γpp̄

BESIII, Phys. Rev. D 93, 052010 (2016)

1310M J/ψ

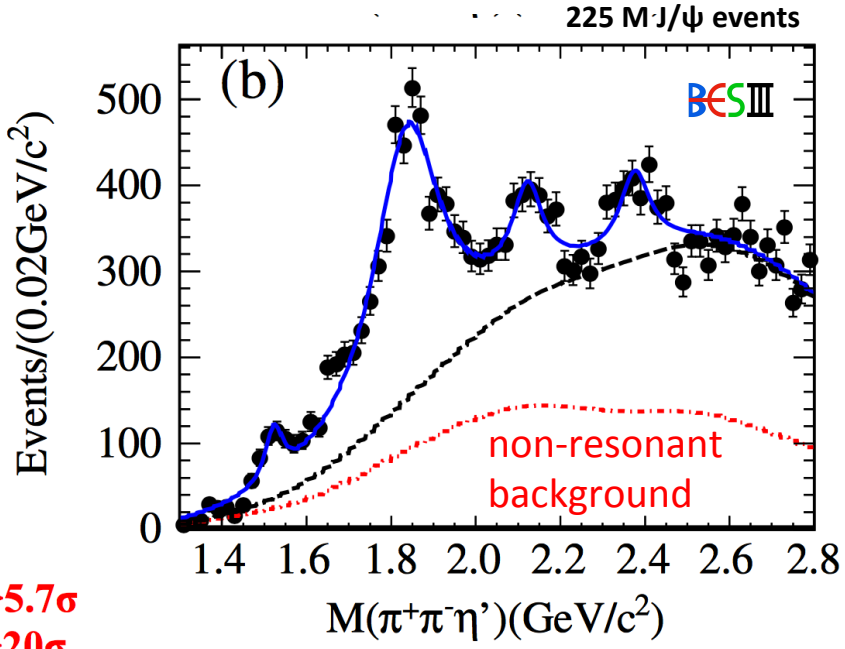


X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

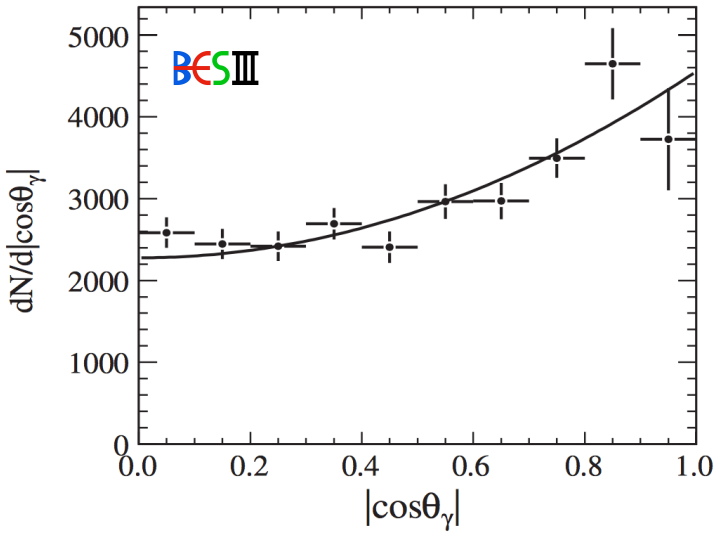
BESIII, Phys. Rev. Lett. 106, 072002 (2011)

- X(1835) previously observed at BES and BESII
- Nature unclear, interpretations include glueball, $\bar{p}p$ bound state, excited η meson
- Confirmed at BESIII with two additional structures above 2 GeV/c^2

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	
$f_1(1510)$	1522.7 ± 5.0	48 ± 11	>5.7σ
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0	>20σ
$X(2120)$	2122.4 ± 6.7	83 ± 16	>7.2σ
$X(2370)$	2376.3 ± 8.7	83 ± 17	>6.4σ



- X(1835) angular distribution consistent with pseudoscalar, but other spin-parity assignments not excluded



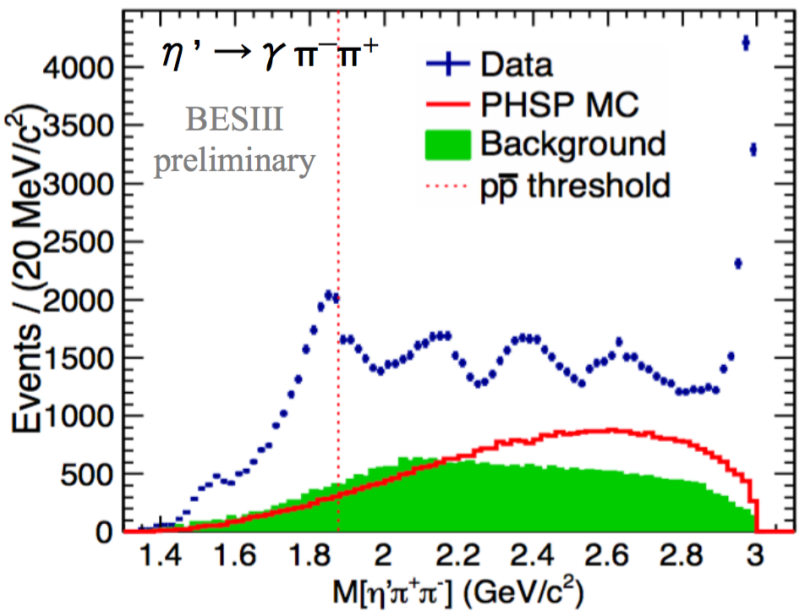
→ Systematic studies of X(1835) ongoing at BESIII (additional decay modes, production mechanisms, …)

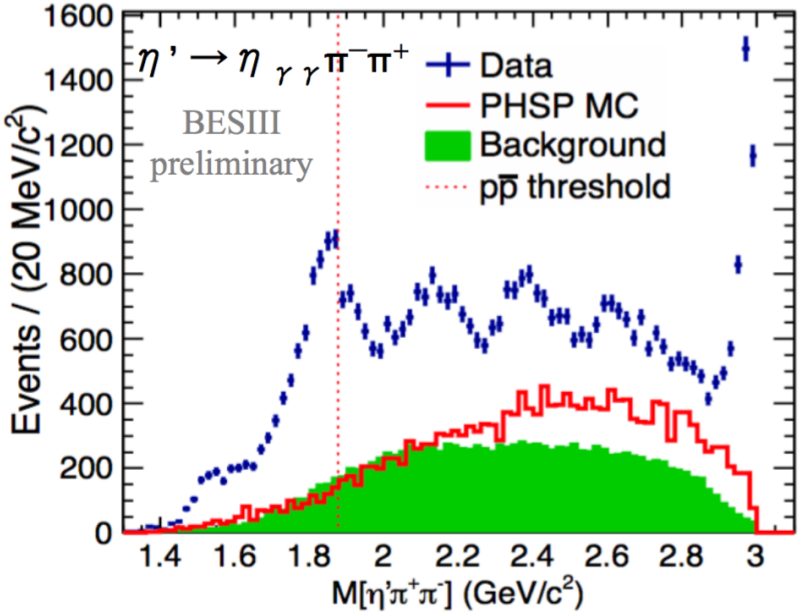
New: Connection of X(pp̄) and X(1835)

preliminary

- If X(1835) couples to pp̄, the lineshape would be affected at the pp̄ threshold
- Update of J/ψ → γπ⁺π⁻η' analysis with 1.09x10⁹ J/ψ events
  - Using η' → ηπ⁺π⁻ and η → γπ⁺π⁻
  - X(1835), X(2120), X(2370) and η_c signals; structure at ~2600 MeV/c²

1009M J/ψ events

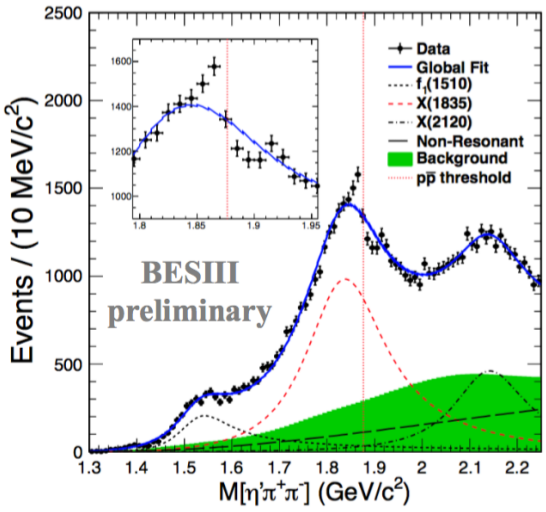


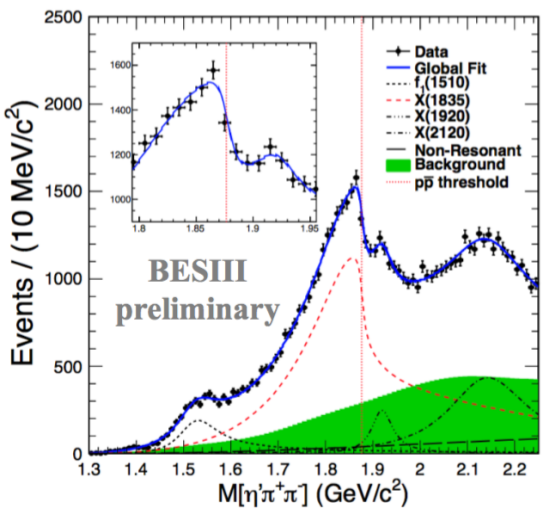


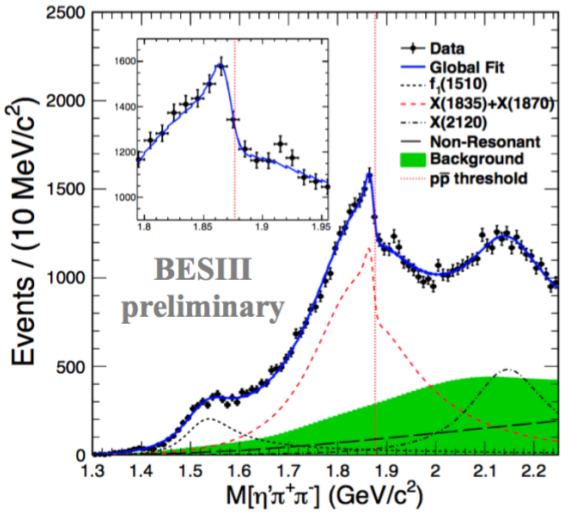
Drop of the X(1835) lineshape at the pp̄ threshold !

New: Connection of X(pp̄) and X(1835)

preliminary







Parameterization with single Breit-Wigner fails to describe the data

Model 1:
Flatte lineshape (strong coupling to pp̄) and one additional, narrow Breit-Wigner at ~1920 MeV/c^2

Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c^2

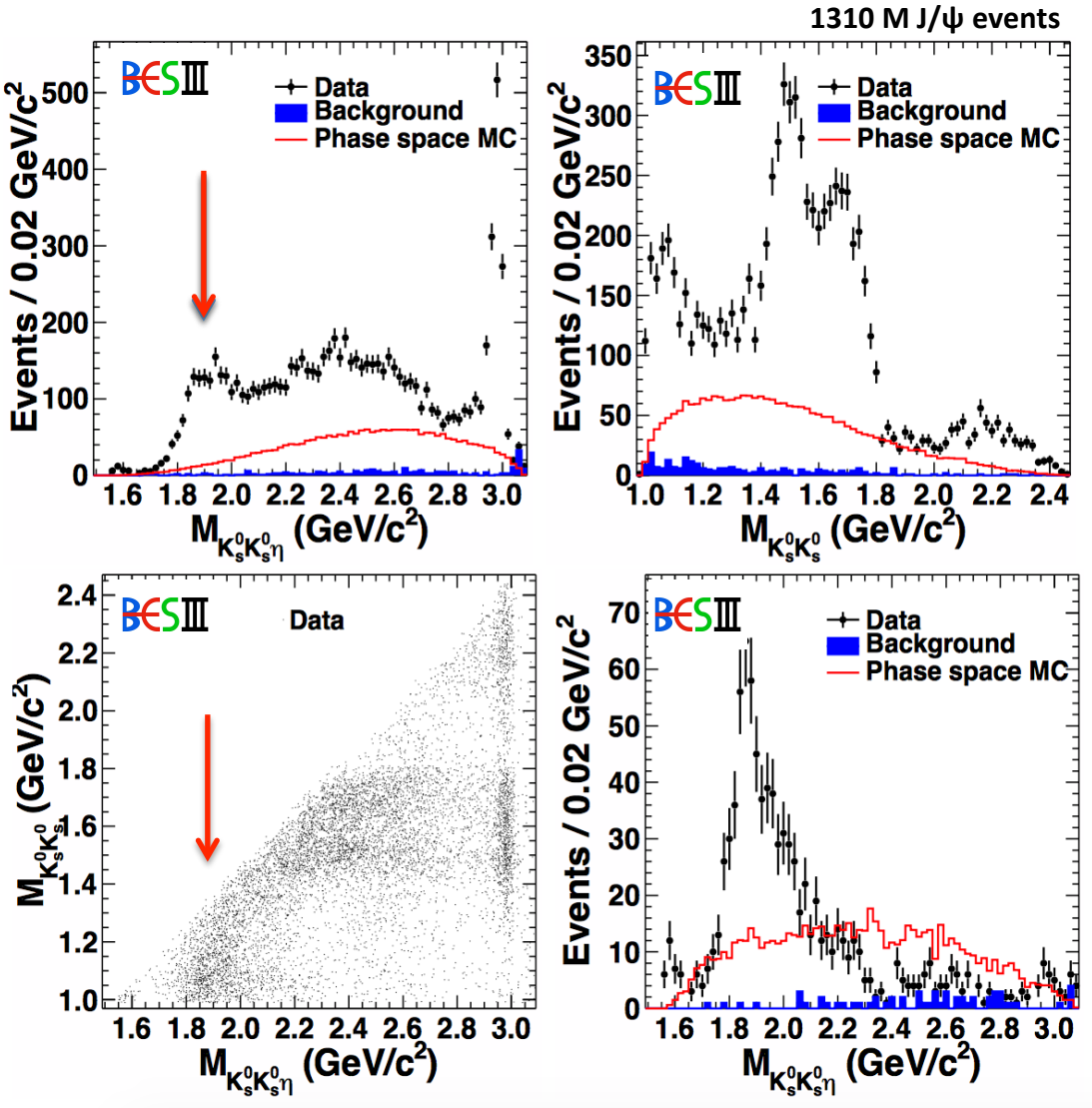
Model 1 and 2 yield almost equal fit quality
Both fits suggest two resonances:

- one broad resonance below threshold
- one narrow state very close to pp̄ threshold

X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

BESIII, Phys. Rev. Lett. 115, 091803 (2015)

- Structure in invariant $K_SK_S\eta$ mass at ~1.85 GeV/c^2
- Strong correlation with enhancement at K_SK_S mass threshold (interpreted as $f_0(980)$)
- Structure in $K_SK_S\eta$ is enhanced for $m(K_SK_S) < 1.1$ GeV/c^2



X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

BESIII, Phys. Rev. Lett. 115, 091803 (2015)

- Partial wave analysis for $m(K_S K_S) < 1.1$ GeV/c² and $m(K_S K_S \eta) < 2.8$ GeV/c²

- Two resonant pseudoscalar components (Breit-Wigner parameterization) required in best fit hypothesis

$X(1835) \to f_0(980)\eta$ (> 12.9σ)

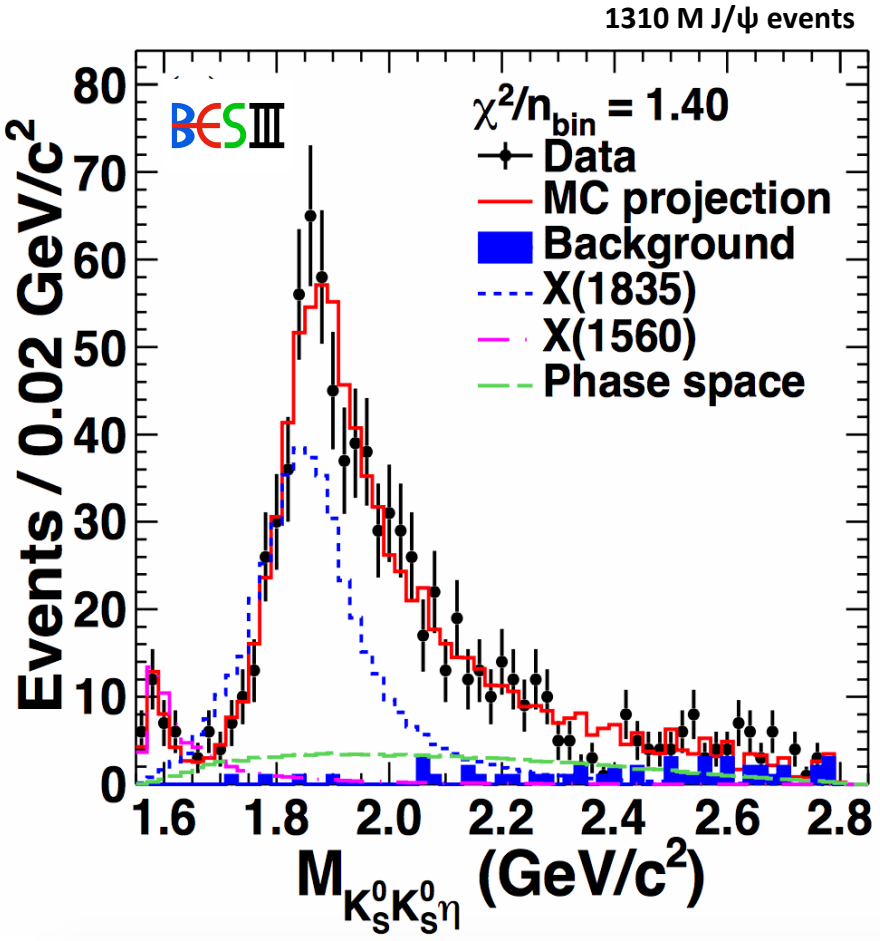
$$m = 1844 \pm 19^{+16}_{-25}\ \mathrm{MeV}/c^2$$

$$\Gamma = 192^{+20+62}_{-17-43}\ \mathrm{MeV}$$

$X(1560) \to f_0(980)\eta$ (> 8.9σ)

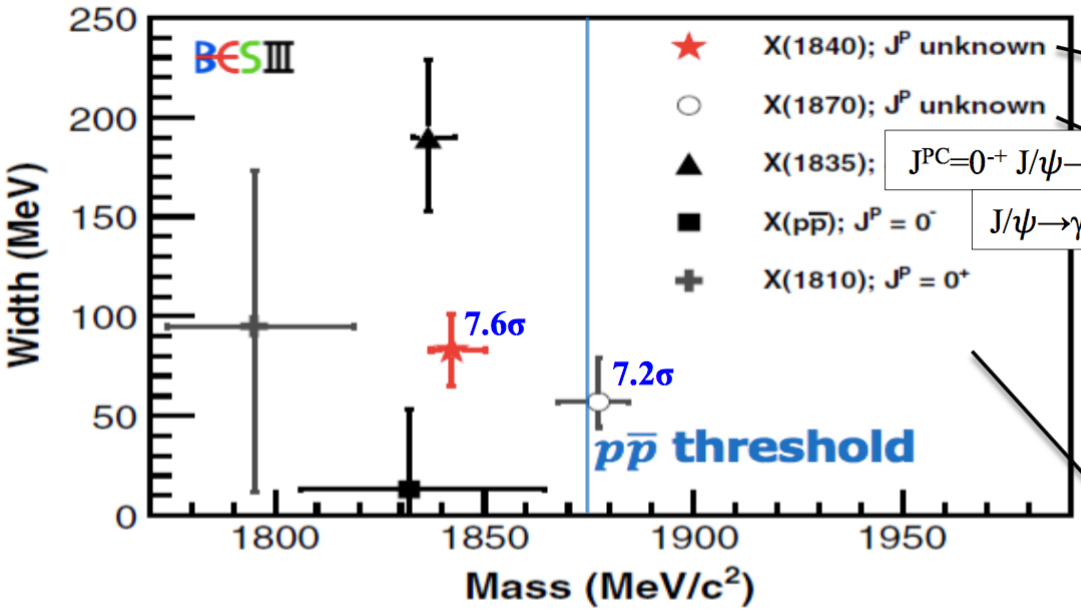
$$m = 1565 \pm 8^{+0}_{-63}\ \mathrm{MeV}/c^2$$

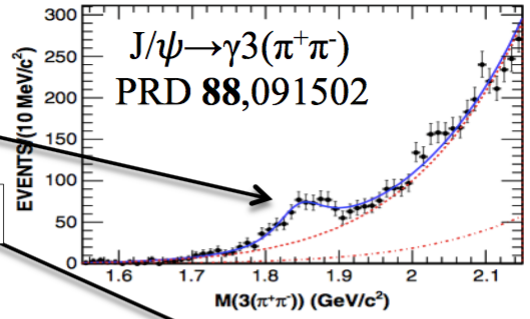
$$\Gamma = 45^{+14+21}_{-13-28}\ \mathrm{MeV}$$

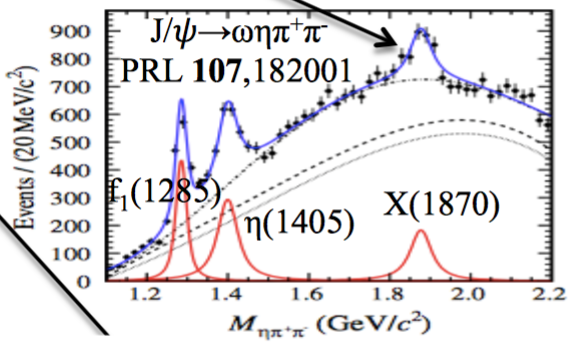


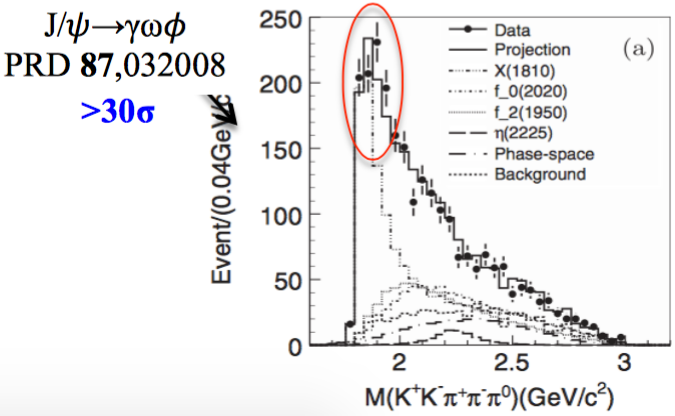
Values consistent with those of η(1405) / η(1475) at ~2σ
→ needs further investigations

Further Observations at $p\bar{p}$ Threshold









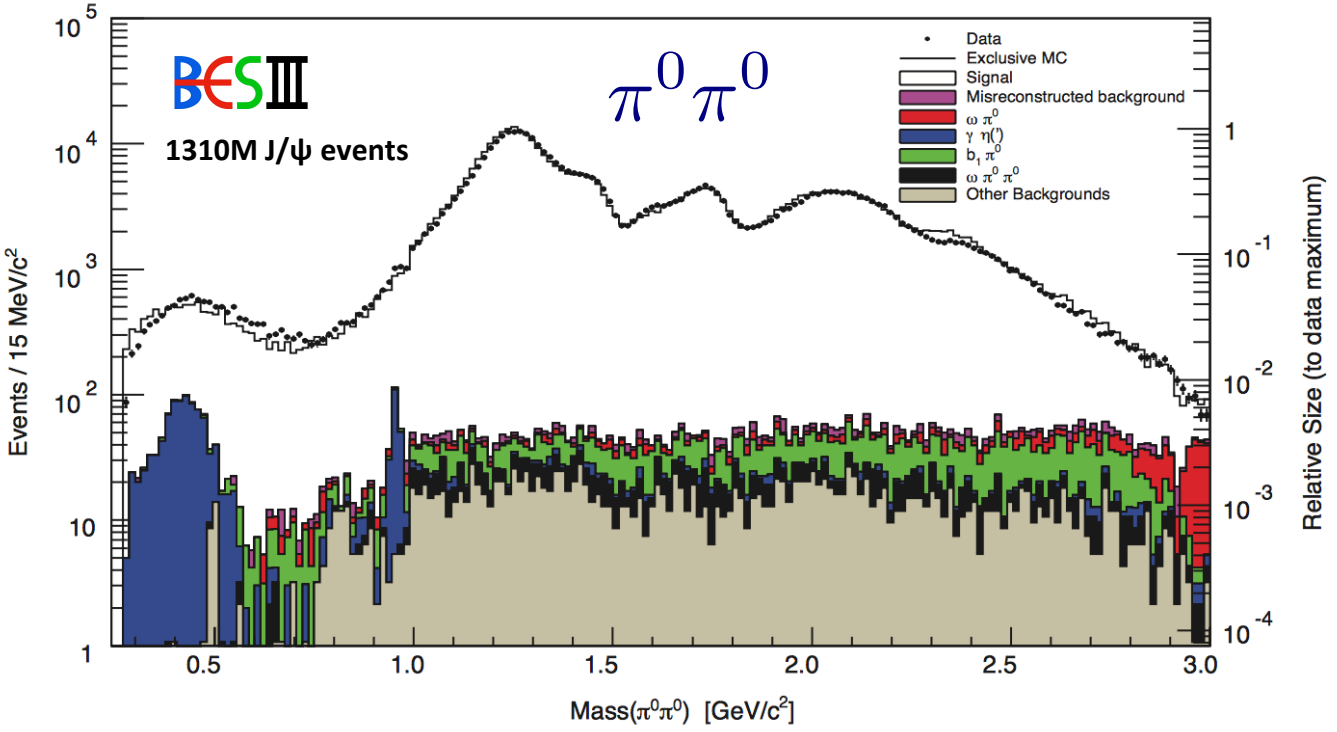
- Same origin?
- Further investigations required
  - J^{PC} not determined for all structures
  - Coupled channel analysis including various final states and production mechanisms needed

Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

- Radiative J/ψ decays into two pseudoscalar mesons (ππ, ηη, $K\bar{K}$)
  - Search for scalar and tensor glueballs (predicted at ~1.5 to ~2 GeV/c^2)
  - Many broad and overlapping resonances, many open channels
    → complex structure, parameterization challenging
- $\pi^0\pi^0$ system: Model Independent Partial Wave Analysis

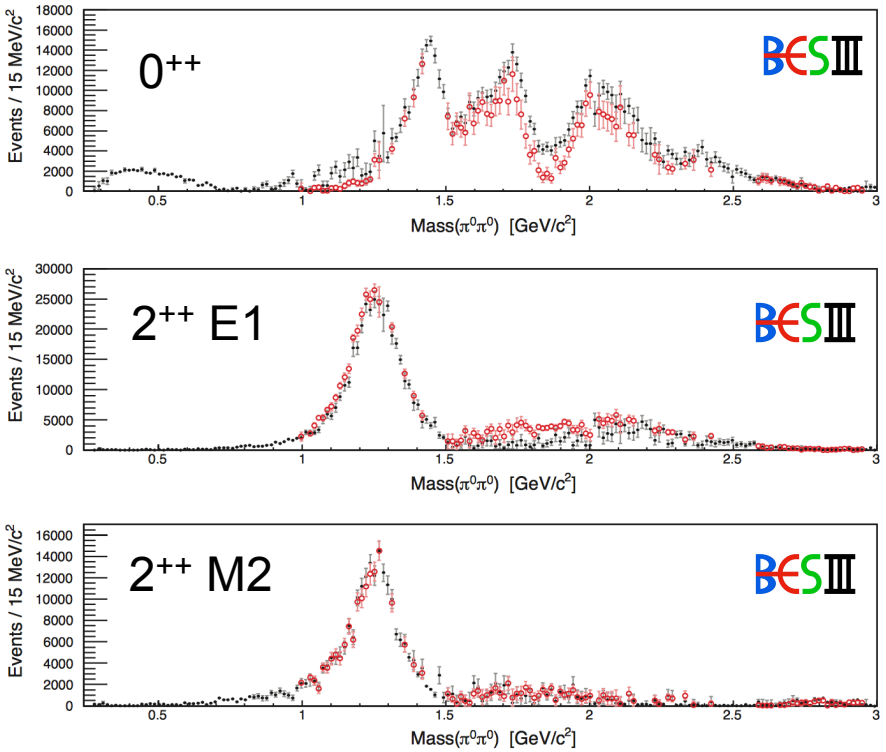
>440k reconstructed events
at a background level of 1.8%

BESIII, Phys.Rev. D92 052003 (2015)

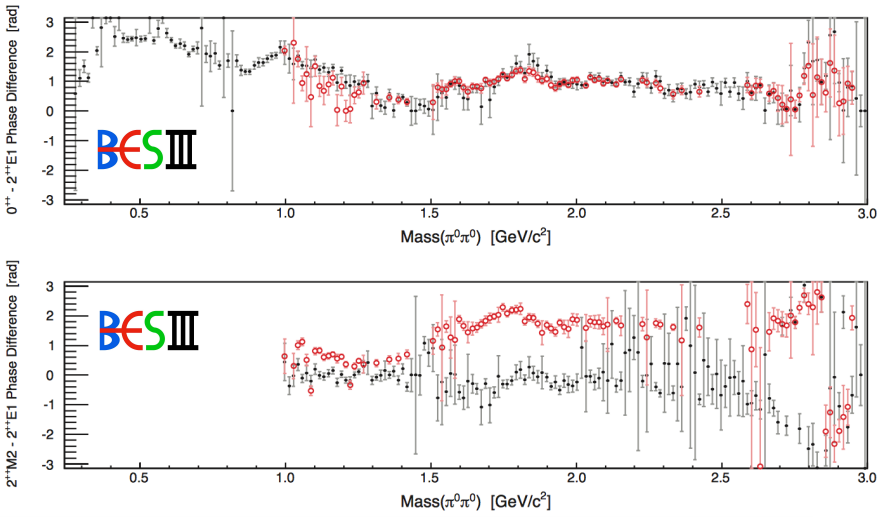


Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

Extracted Intensity



Relative Phase wrt/ 2^{++} E1 amplitude



nominal solution
ambigous solution

- Only 0^{++} and 2^{++} contribute significantly
- Ambiguities may be resolved in a model-dependent fit

Model independent approach is under investigation for other systems (e.g. ηη, $K\bar{K}$)
→ improves our understanding of the nature of the observed resonances

Partial Wave Analysis of $\chi_{c1} \rightarrow \eta\pi^+\pi^-$

- Spin-exotic 1^{-+} states
  - $\pi_1(1400) \rightarrow \eta\pi$, $\rho\pi$ (?) [GAMS, KEK, Crystal Barrel, E852]
  - $\pi_1(1600) \rightarrow \eta'\pi$, $f_1\eta'$, $b_1\pi$ [VES, E852, COMPASS, CLEOc]
    - recently seen in $\chi_{c1} \rightarrow \eta'\pi^+\pi^-$ by CLEOc

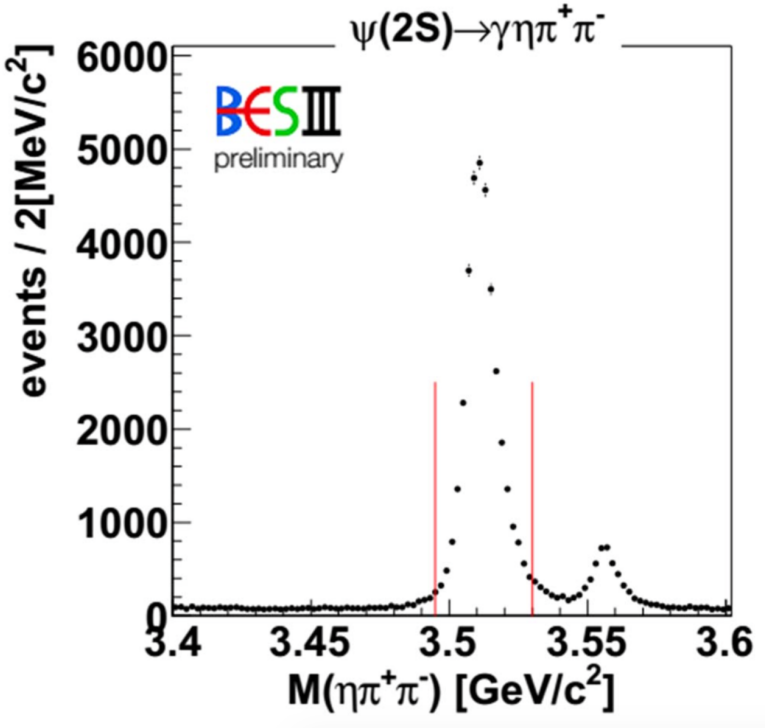
- $a_0(980)$
  - discovered four decades ago, nature still not resolved
  - $a_0(980) \rightarrow \eta'\pi$ only observed recently by CLEOc
  - $a_0(980) \rightarrow \eta\pi$ coupling poorly known
    - various experiments: $0.15 \pm 0.2 < g^2_{\eta\pi}$ [GeV^2] $< 0.36 \pm 0.04$

- BESIII: $\chi_{c1} \rightarrow \eta\pi^+\pi^-$
  - about 40M χ_{c1} produced from $\psi' \rightarrow \gamma\chi_{c1}$
  - clean environment to search for 1^{-+} states
  - determine $a_0(980)$ couplings $g^2_{\eta\pi}$ and $g^2_{\eta'\pi}$

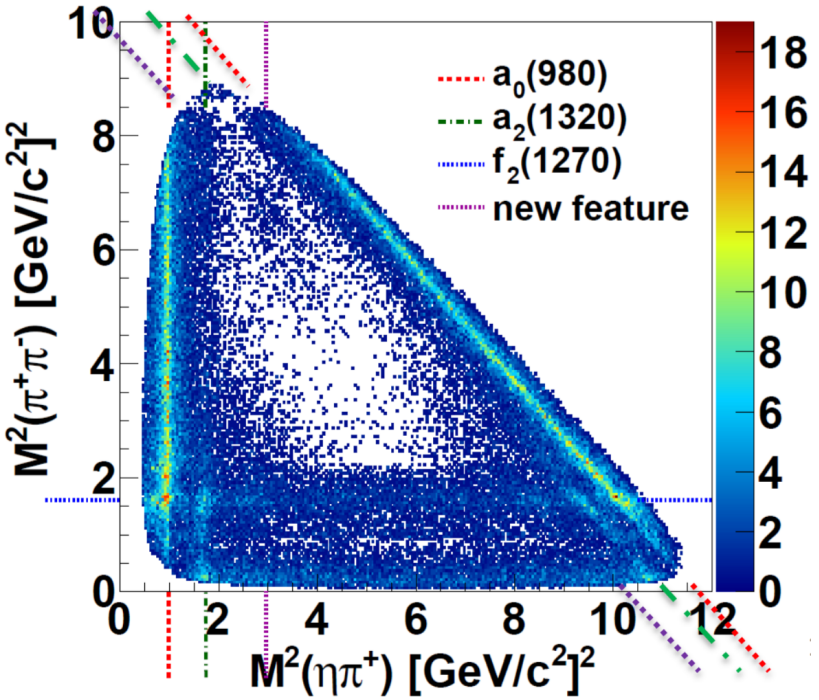
Partial Wave Analysis of $\chi_{c1} \rightarrow \eta\pi^+\pi^-$

preliminary

~35k reconstructed χ_{c1}
purity: ~99%

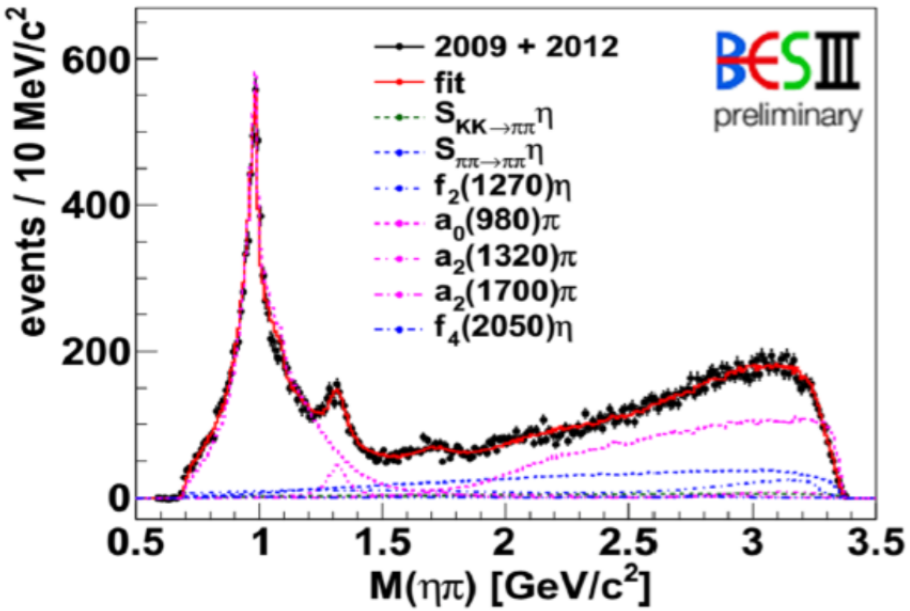


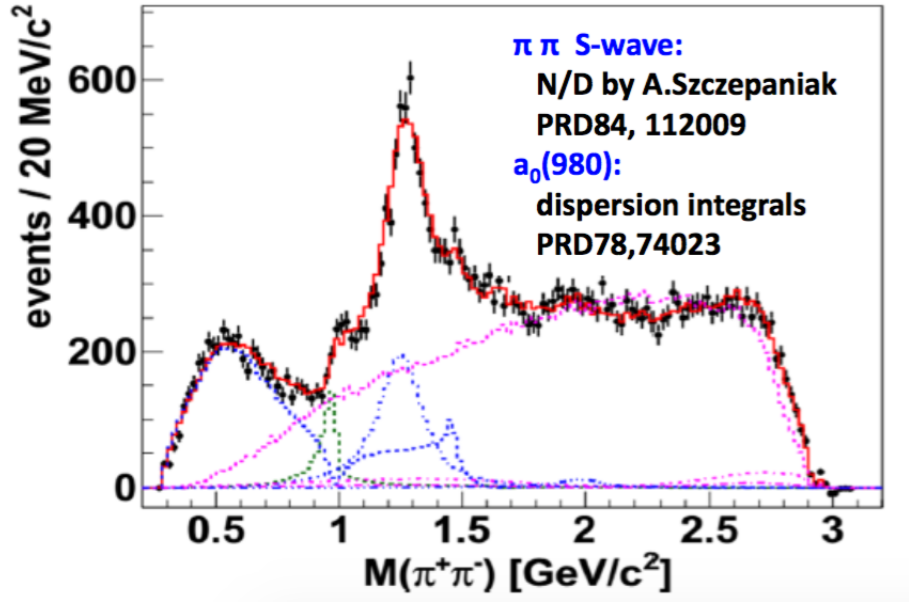
New feature compared to CLEOc results: consistent with $a_2(1700)$



Partial Wave Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$

preliminary





Clear evidence for $a_2(1700)$

Upper limits on $B(\chi_{c1} \to \pi_1\pi \to \eta\pi^+\pi^-)$ for 1^{-+} $\eta\pi$ wave

$\pi_1(1400)$: < 0.048 (90% CL)
$\pi_1(1600)$: < 0.016 (90% CL)
$\pi_1(2015)$: < 0.008 (90% CL)

Measurement of $a_0(980)$ couplings

Experiment	BESIII	CLEO-c[1]
m_0 [GeV/c^2]	995.5±2.4±6.5	998±16
$g^2_{\eta\pi}$ [GeV/c^2]	0.368±0.003±0.013	0.36±0.04
$g^2_{KK}/g^2_{\eta\pi}$	0.93±0.03±0.09	0.87±0.15
$g^2_{\eta'\pi}/g^2_{\eta\pi}$	0.49±0.05±0.10	0.00±0.17

Deviation from 0

Conclusions and Outlook

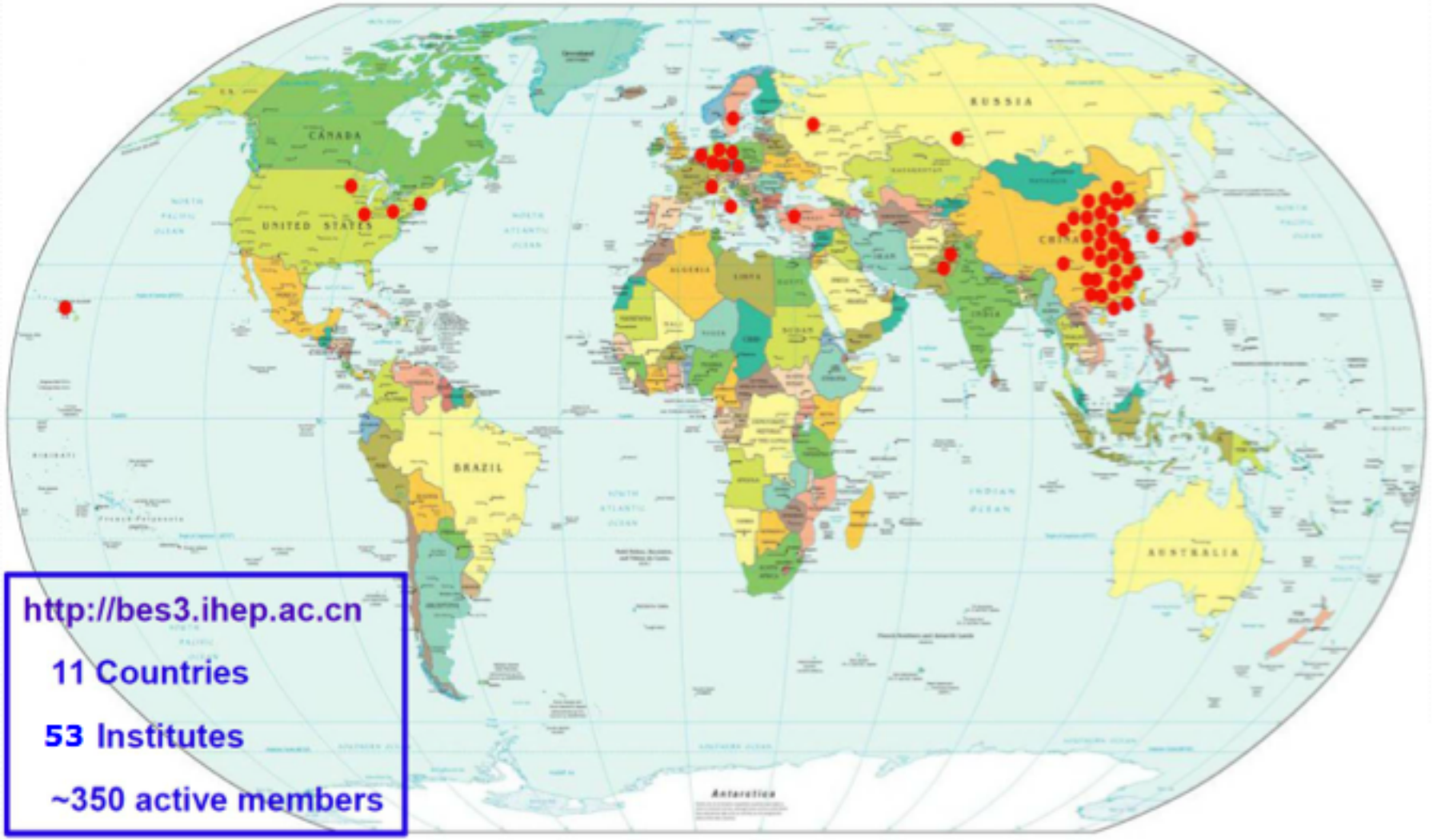
- BESIII is successfully operating since 2008
  - World's largest data sample at the J/ψ and ψ' resonance recorded
  - Clean and rich source for light hadron production

- Systematic studies to understand X(1835) and other structures observed near $p\bar{p}$ threshold
  - X(1835) nature unclear: $p\bar{p}$ bound state, glueball, excited η meson?

- Sophisticated Partial Wave Analyses well underway
  - $J/\psi \rightarrow \gamma\pi^0\pi^0$: model independent approach → rich structure in ππ
    - future: couple with other channels to reveal nature of observed resonances
  - $\chi_{c1} \rightarrow \eta\pi^+\pi^-$: further knowledge on exotic 1^{-+} states, $a_0(980)$ and $a_2(1700)$

Exciting times in light hadron spectroscopy with many important results and still more to come!

The BESIII Collaboration



http://bes3.ihep.ac.cn

11 Countries

53 Institutes

~350 active members