# BESIII Overview

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on behalf of the BESIII Collaboration

Ruhr-Universität Bochum
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LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE
Results and Perspectives in Particle Physics, La Thuile
March 8, 2017

RUHR UNIVERSITÄT BOCHUM

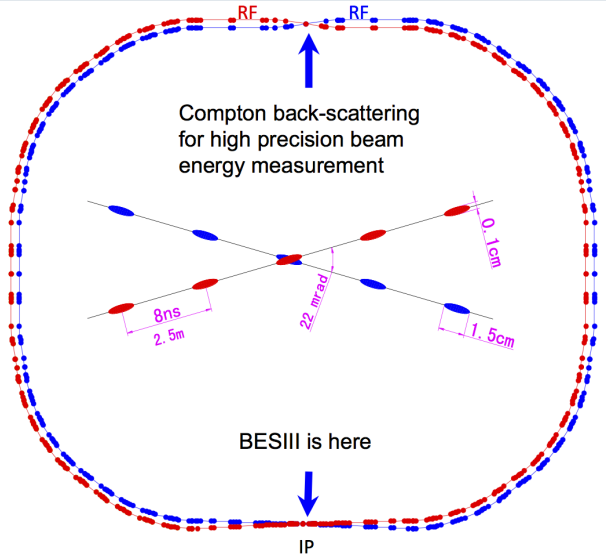
RUB

BESIII

# Outline

- The BESIII Experiment at BEPCII
- BESIII Highlights from 2016/17
- Towards an understanding of the "XYZ" states
- Selected Topics and Recent Results from Charmonium/XYZ studies and Light Hadron Spectroscopy
- Summary

# The BESIII Experiment at BEPCII



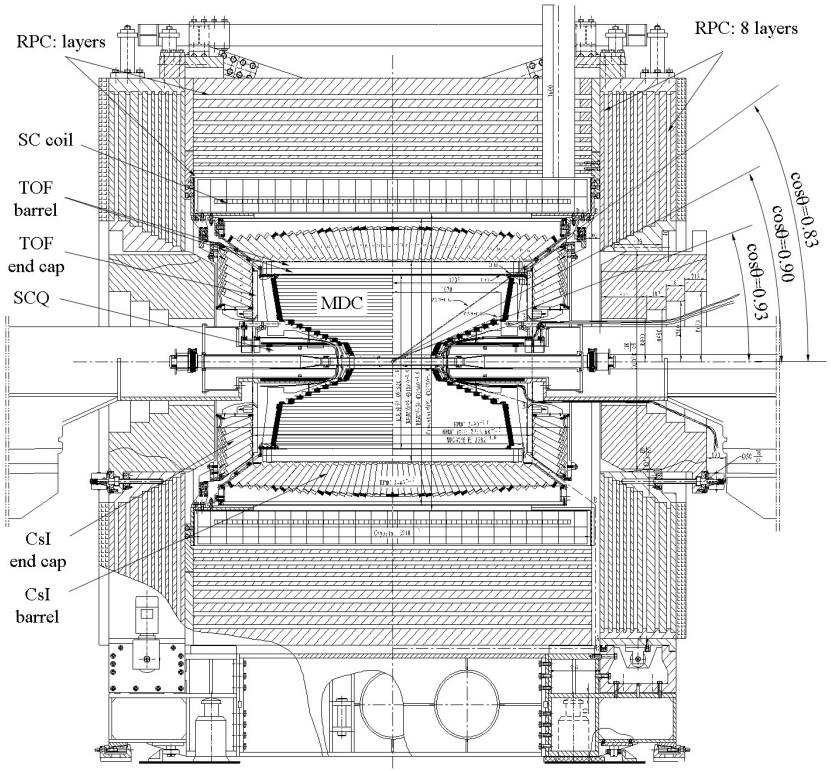


- Symmetric electron-positron collider
- Energy range: $\sqrt{s} = 2.0 - 4.6\,\text{GeV}$
- Design Luminosity: $\mathcal{L} = 1 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$ (at $\psi(3770)$)

$\rightarrow$ Achieved in 04/2016!

- Energy spread $\approx 5 \cdot 10^{-4}$
- Operating since March 2008

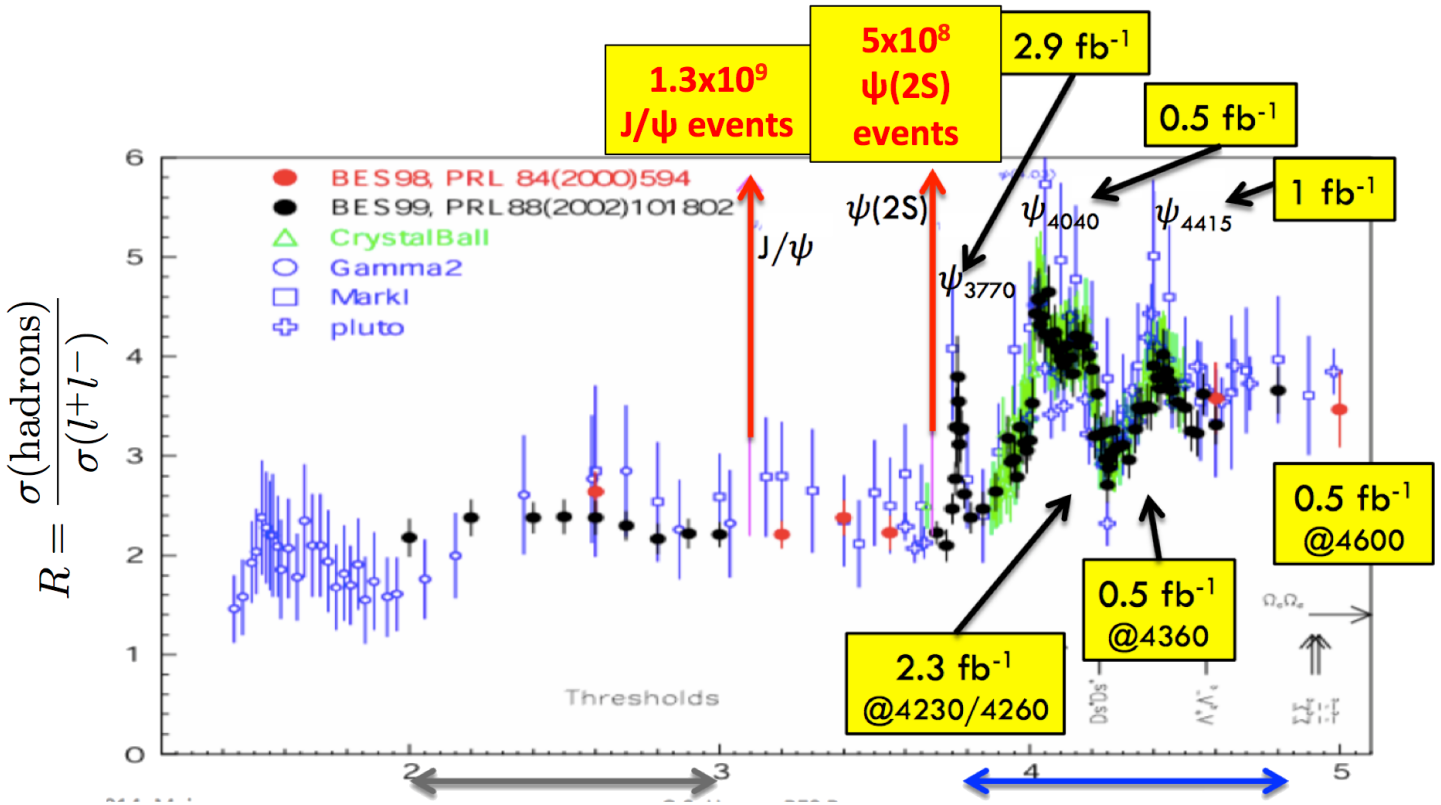
# The BESIII Detector





- Main Drift Chamber (MDC): $\sigma_{dE/dx} = 6\%$ $\frac{\sigma_{p_t}}{p_t} = 0.5\%$
- Time of Flight System (TOF): $\sigma_{t,\text{barrel}} = 80\,\text{ps}$ $\sigma_{t,\text{endcaps}} = 110\,\text{ps}$
- Electromagnetic CsI(Tl) Calorimeter: $\frac{\sigma_E}{E} < \frac{2.5\%}{\sqrt{E}}$ $\sigma_{z,\phi} = \frac{0.5-0.7\text{cm}}{\sqrt{E}}$
- Superconducting Solenoid $B = 1\,\text{T}$
- RPC muon chambers: 8-9 layers $\delta R_\phi = 1.4 - 1.7\,\text{mm}$

# Data Samples



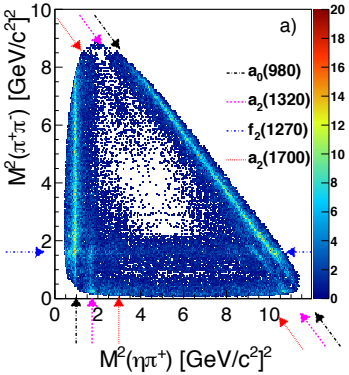

R scan: 2-3 GeV, 20 points, ~0.5 fb$^{-1}$; 3.85-4.59 GeV, 104 points, ~0.8 fb$^{-1}$

plus 24/pb at τ mass threshold and
0.5/fb in the region 4100-4400 MeV

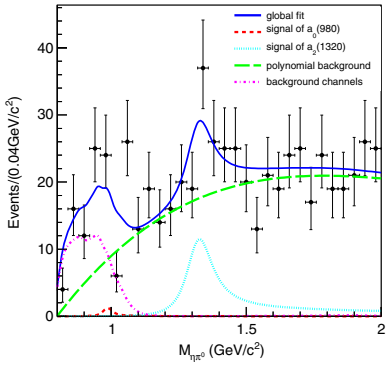
## Physics program:

- Meson and baryon spectroscopy
- Search for exotic hadrons
- Charmonium physics
- XYZ-states
- Open Charm physics
- Two-photon physics
- *R*-value measurements
- ... and many more topics

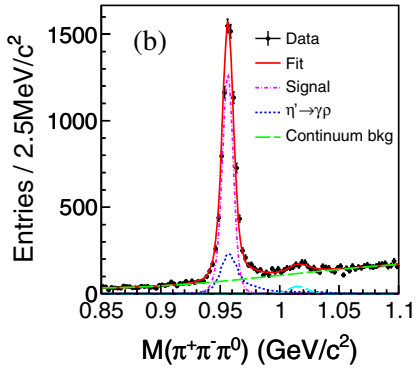
# Highlights since last years La Thuile Conference



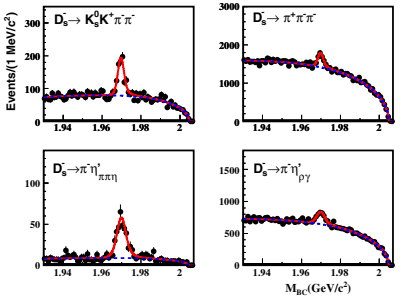

PWA of $\chi_c 1 \to \gamma\eta\pi\pi$
Acc. by PRD



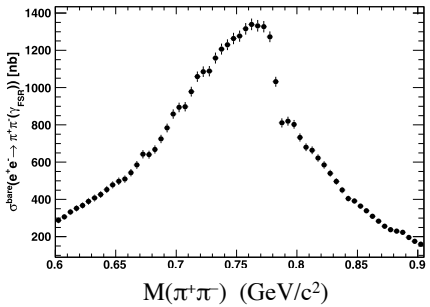

Obs. of $J/\psi \to \gamma\eta\pi^0$
PRD94, 072005(2016)



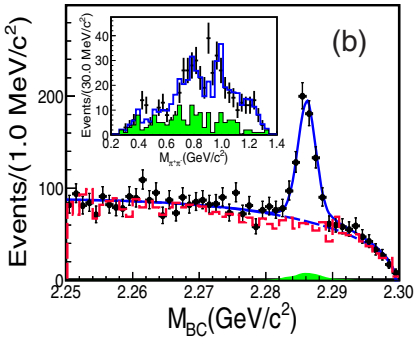

PWA of $\eta' \to 3\pi$
PRL118, 012001(2017)




$D_s \to l^+\nu$
PRD94, 072004(2016)




$e^+e^- \to \pi^+\pi^-$
PLB753, 629(2016)




$\Lambda_c \to pK^+K^-$
PRL117, 232002(2016)

## Physics program:

- Meson and baryon spectroscopy
- Search for exotic hadrons
- Charmonium physics
- XYZ-states
- Open Charm physics
- Two-photon physics
- $R$-value measurements
- ... and many more topics

+ Many more (new physics searches, .....)

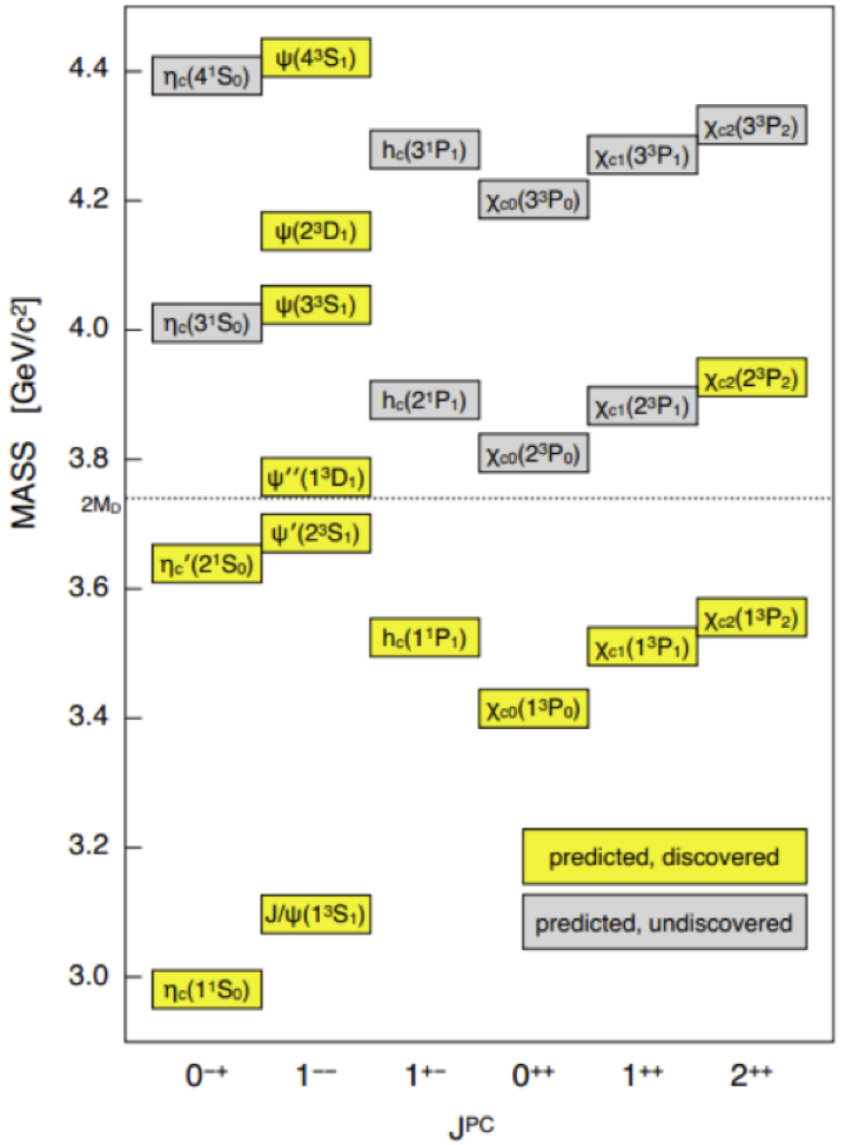
# The Charmonium System

- Discovery of the $J/\psi$ in 1974 triggered investigations in charmonium region:
- $c\overline{c}$ states can be described using potential models

→ Extremely successful approach: All predicted states below the $D\overline{D}$ threshold have been found!

→ Properties are in agreement with predictions

- Clean environment to search for exotic states



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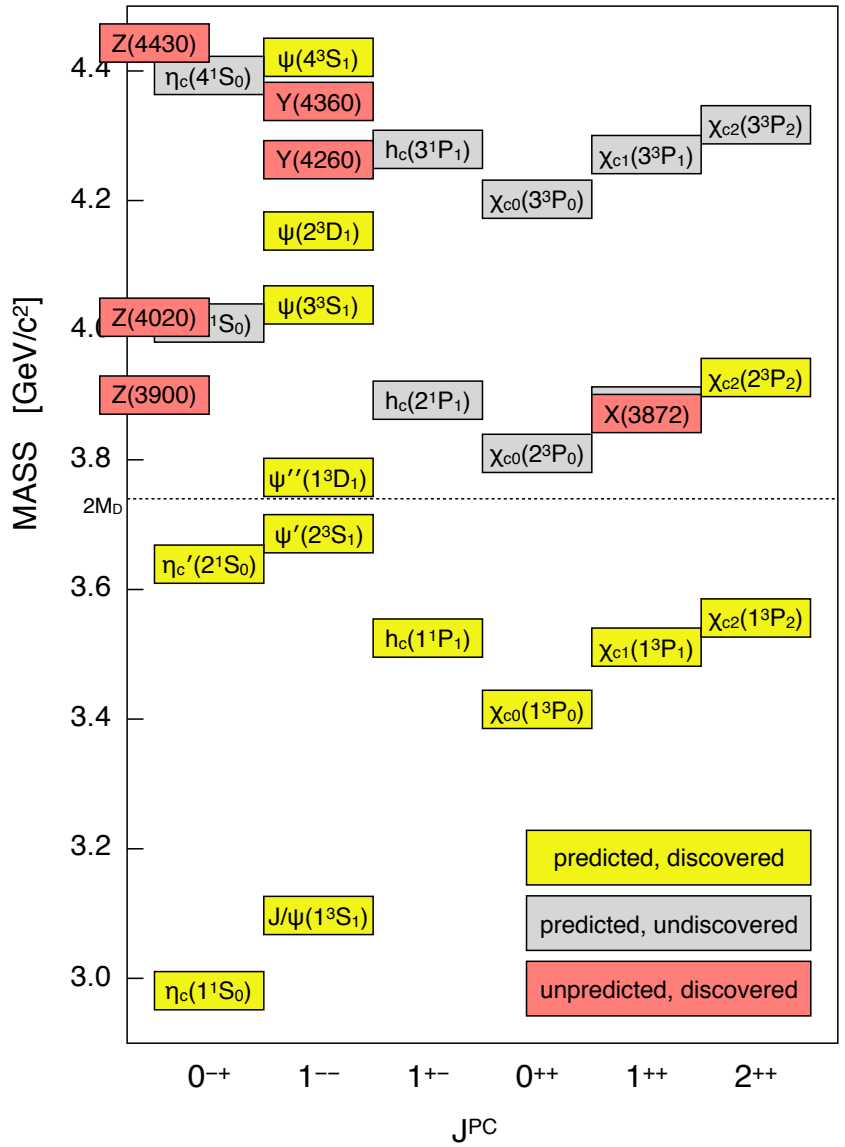
- Clean environment to search for exotic states
- Big surprise: Many **unpredicted** states were reported above the $D\overline{D}$ threshold, called "$XYZ$" states



# The "XYZ" States

"X"

- Neutral, $J^{PC} \neq 1^{--}$
- Observed e.g. in radiative or hadronic transitions from Y

"Y":

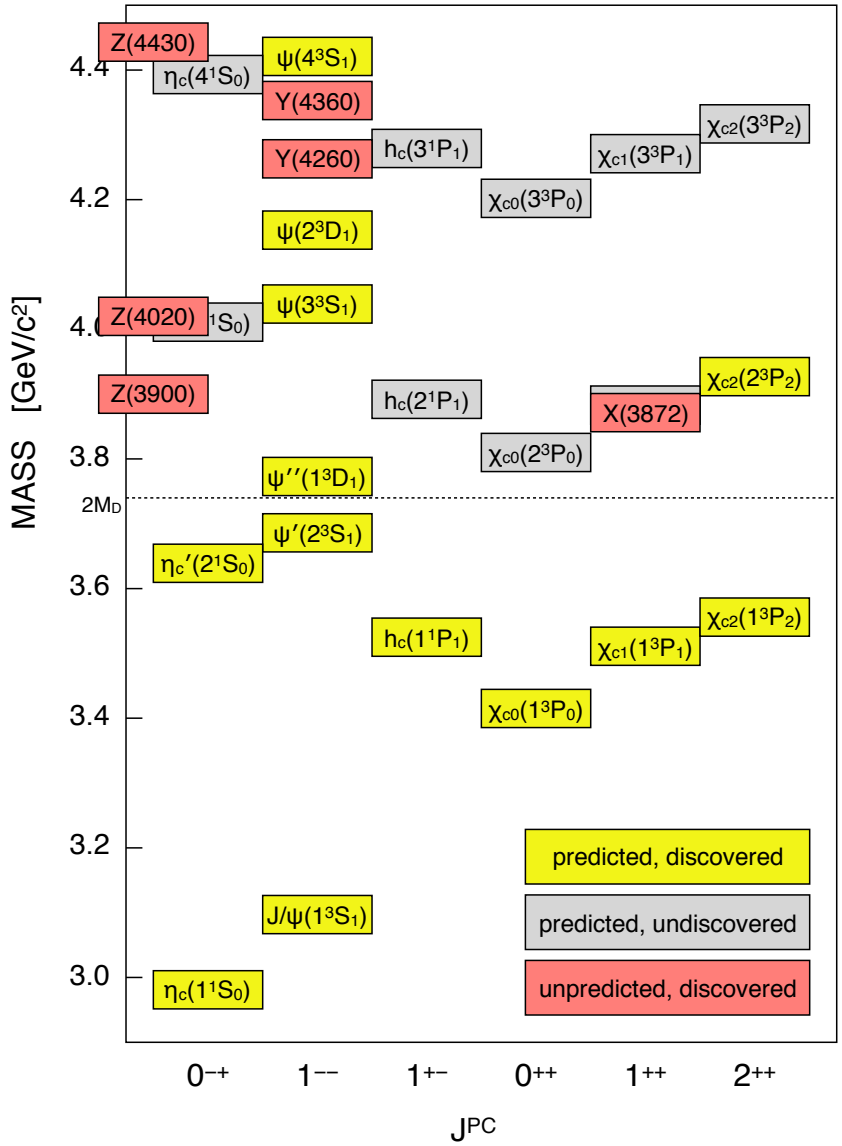
- Neutral, $J^{PC} = 1^{--}$
  Direct access in $e^+e^-$ annihilation!

"Z"

- Charged, Isospin triplets
- Must contain $c\bar{c}$ and a light $q\bar{q}$ pair $\Rightarrow$ Undoubtedly exotic
- Observed e.g. in hadronic transitions from Y

- BESIII is perfectly suited to act as a "$Y(4260)$ factory"

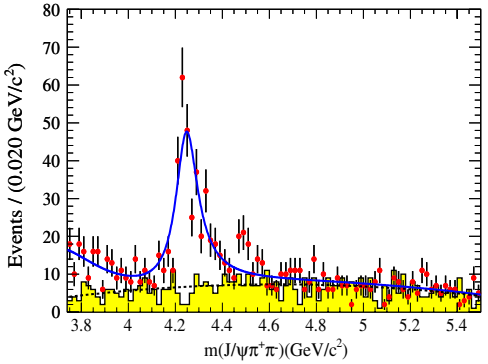
$\rightarrow$ We can map out the connections between X, Y and Z states!



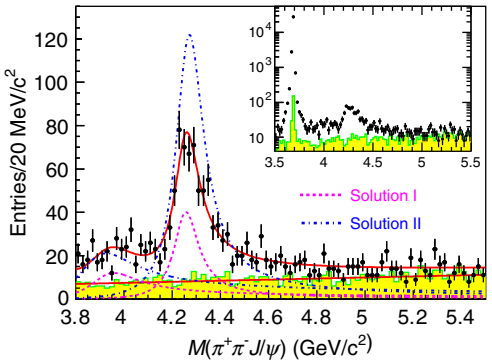
# The $Y$ states: $e^+e^- \to \pi^+\pi^- J/\psi$

- $Y(4260)$ discovered in 2005 by BaBar
- Confirmed by Belle
- Recent studies show asymmetric line shape / additional low mass peak ($Y(4008)$?)

$e^+e^- \to \pi^+\pi^- J/\psi$ using ISR at BaBar
*PRD 86, 051102(R) (2012)*




$e^+e^- \to \pi^+\pi^- J/\psi$ using ISR at Belle
*PRL 110, 252002 (2013)*



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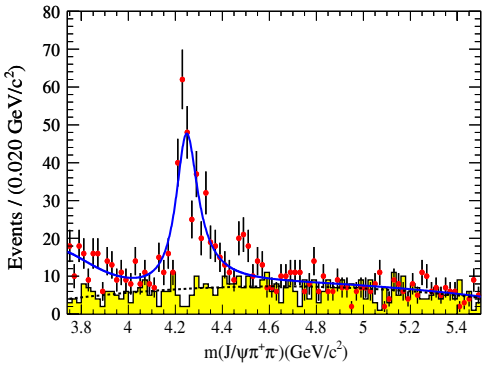


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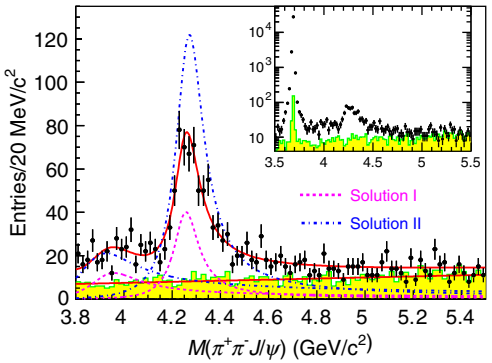
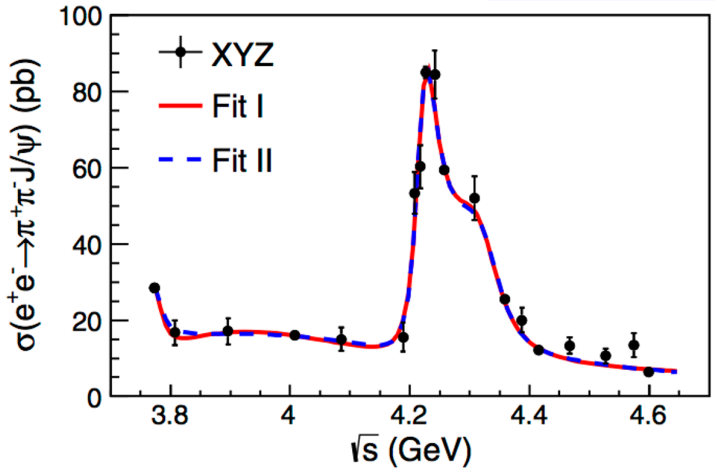
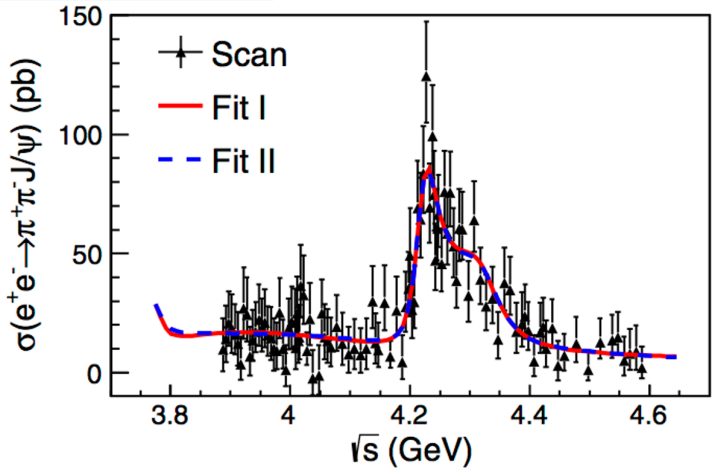



$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)
PRL118, 092001(2017) NEW!

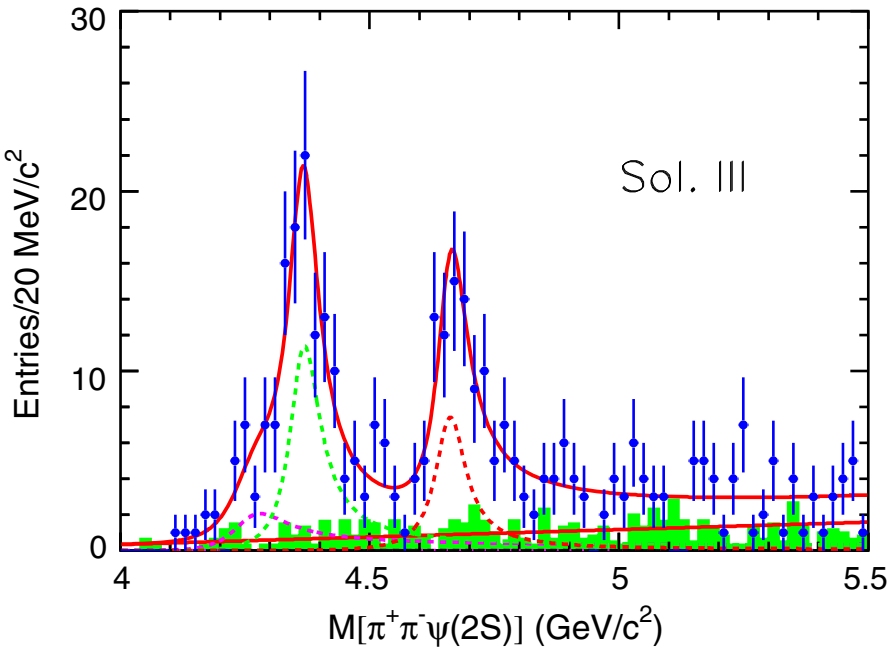



**Conclusion 1**: Cross section is inconsistent with a single peak for the $Y(4260)$ (Significance $> 7\sigma$)
**Conclusion 2**: $Y(4008)$ is not needed to describe BESIII data

# The $Y$ states: $e^+e^- \to \pi^+\pi^-\psi(2S)$

$e^+e^- \to \pi^+\pi^-\psi(2S)$ using ISR at Belle
*PRD 91, 112007 (2015)*




- No evidence for the $Y(4260)$, but...
- Clear signals at $\approx 4360$ MeV/$c^2$ and $\approx 4660$ MeV/$c^2$!

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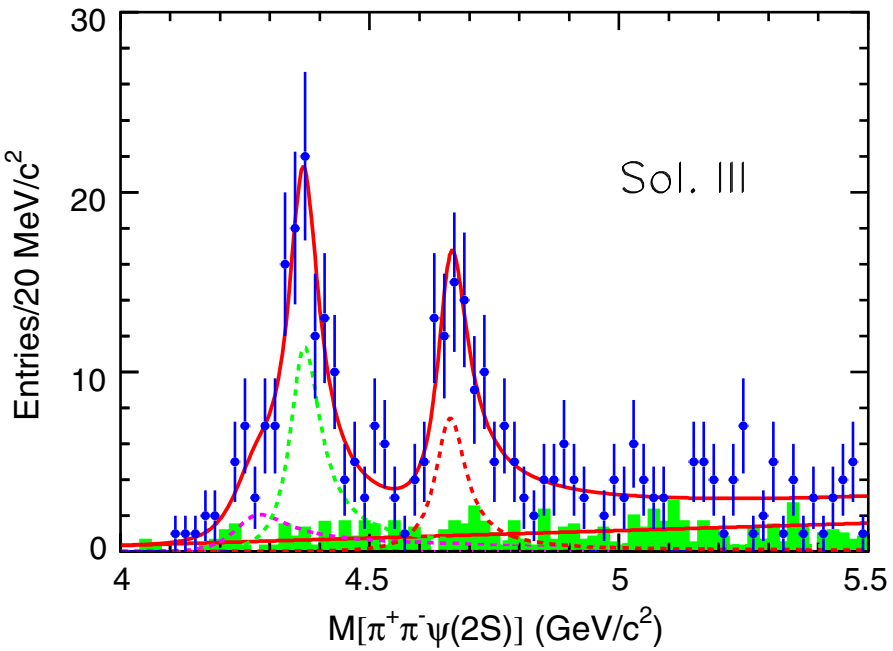


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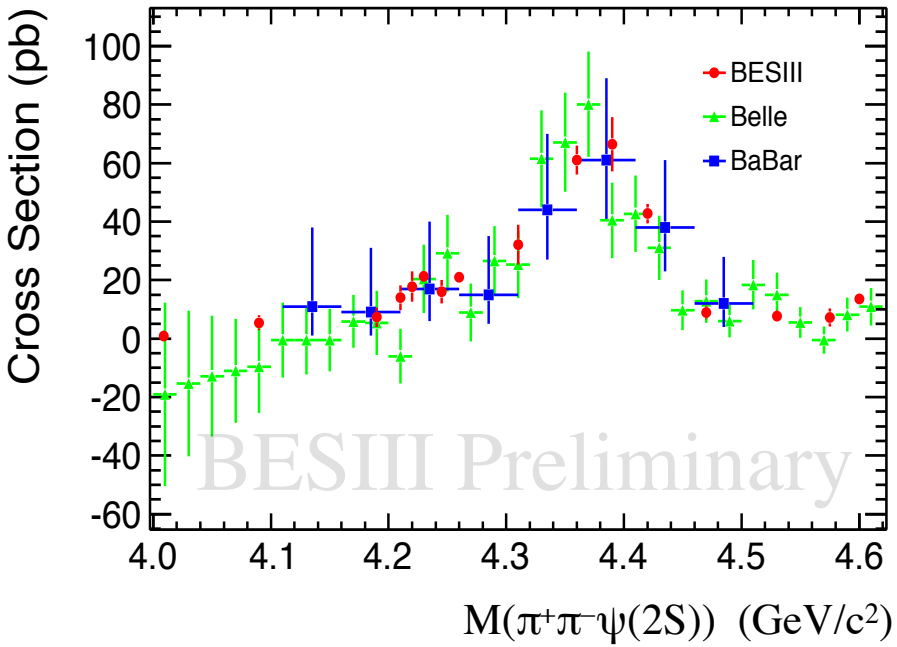
$e^+e^- \to \pi^+\pi^-\psi(2S)$ at BESIII (direct)
*BESIII Preliminary (NEW!)*

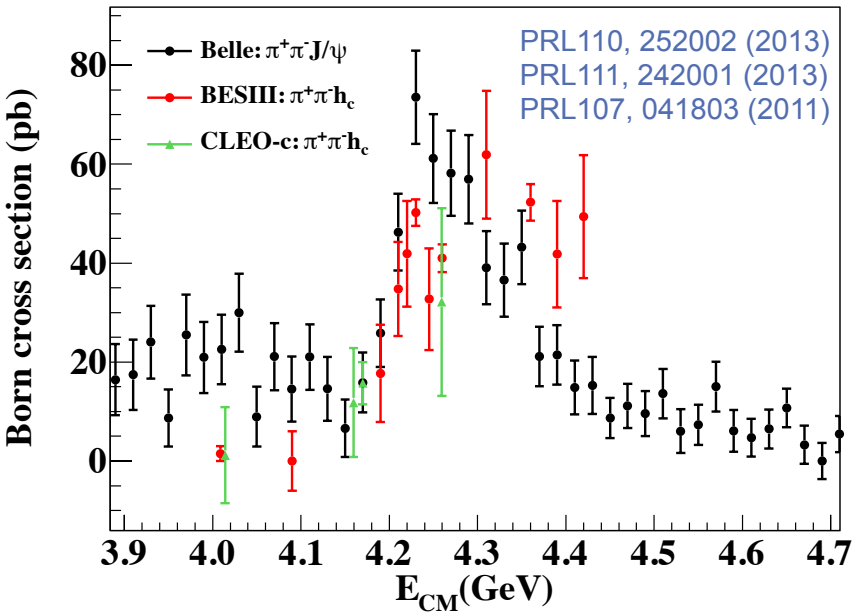



- BESIII confirms $Y(4360)$ line shape
- More data in the region $4.3 - 4.6$ GeV is being taken
- **Analysis of the $\pi^\pm\psi(2S)$ substructure will be reported in the following talk by Yateng Zhang**

# The $Y$ states: $e^+e^- \to \pi^+\pi^- h_c$

$e^+e^- \to \pi^+\pi^- h_c$ at CLEO and BESIII and $\pi^+\pi^- J/\psi$ at Belle

*PRL 107, 041803 (2011)*
*PRL 111, 242001 (2013)*
*PRD 110, 252002 (2013)*

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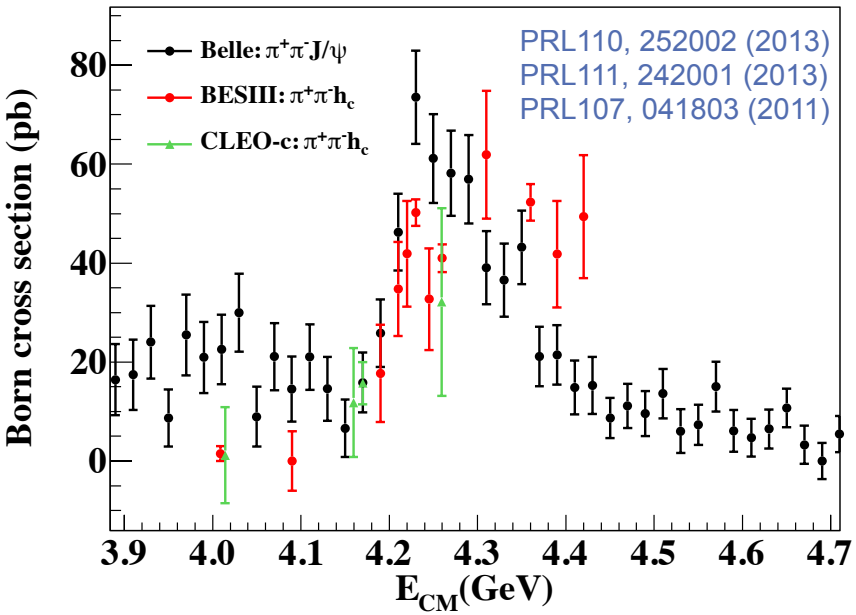


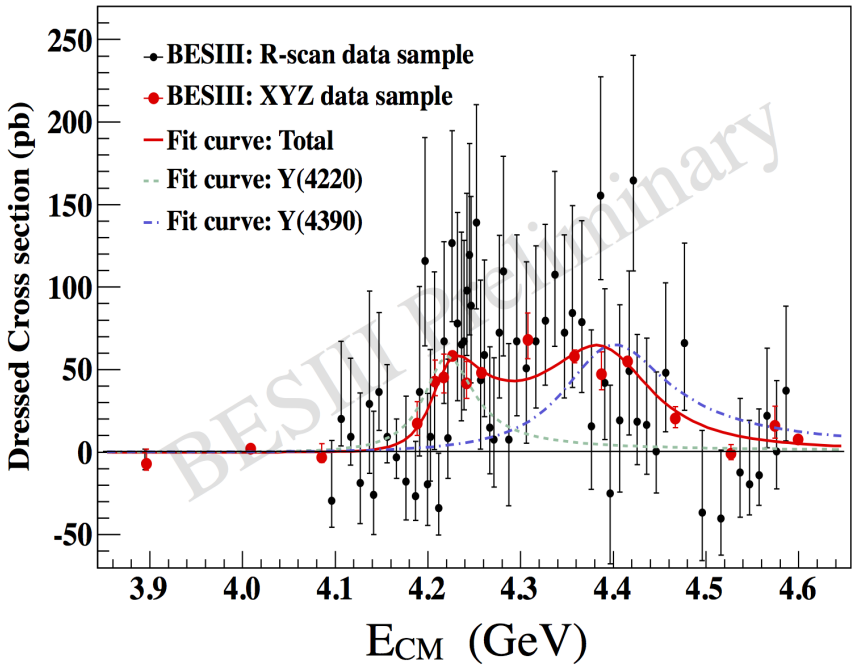

- Clear difference visible between $\pi^+\pi^- h_c$ and $\pi^+\pi^- J/\psi$ shapes

→ More investigations are needed to sort out these exclusive cross sections...

$e^+e^- \to \pi^+\pi^- h_c$ at BESIII (direct)

*BESIII Preliminary (arXiv:1610.07044)*

**Submitted to PRL**




- Two peaks are visible!
- $M = (4218.4 \pm 4.0 \pm 0.9)\,\mathrm{MeV}/c^2$, $\Gamma_{\mathrm{tot.}} = (66.0 \pm 9.0 \pm 0.4)\,\mathrm{MeV}/c^2$
- $M = (4391.6 \pm 6.3 \pm 1.0)\,\mathrm{MeV}/c^2$, $\Gamma_{\mathrm{tot.}} = (139.5 \pm 16.1 \pm 0.6)\,\mathrm{MeV}/c^2$

# The $X$ states: $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$

- The $X(3872)$ was discovered by Belle in 2003 in $B \to K(\pi^+\pi^- J/\psi)$ and confirmed by various other experiments [PRL91, 262001(2003)]

$\to$ First discovered and best-studied "XYZ" state ($J^{PC} = 1^{++}$)

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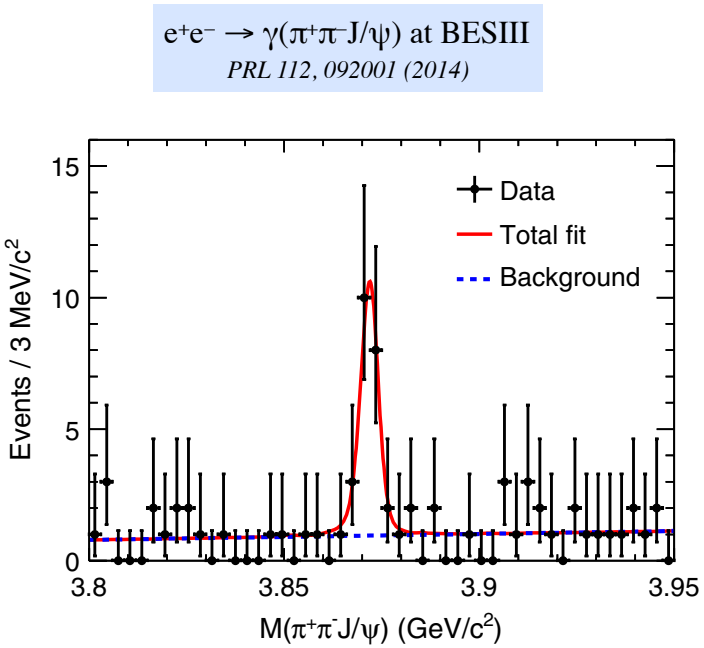
- BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma(\pi^+\pi^- J/\psi)$:
  - Significance: $6.3\sigma$
  - $M = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$, $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)



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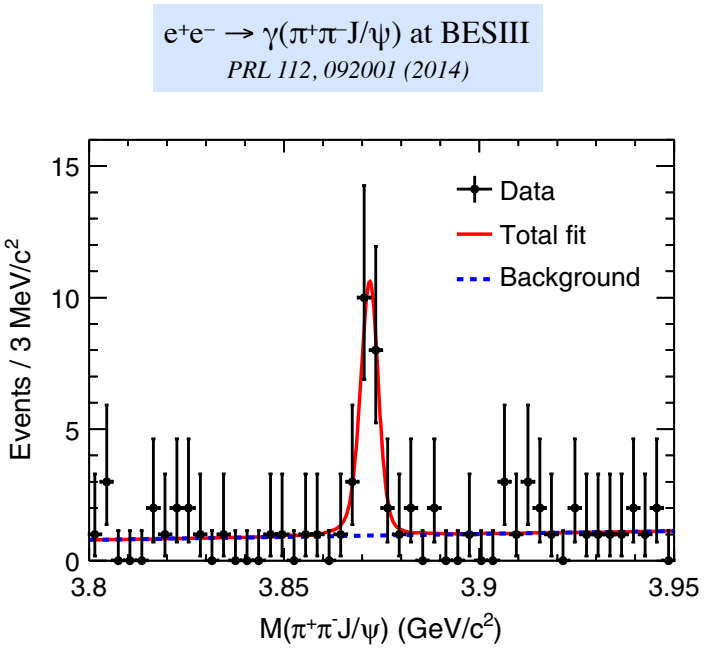
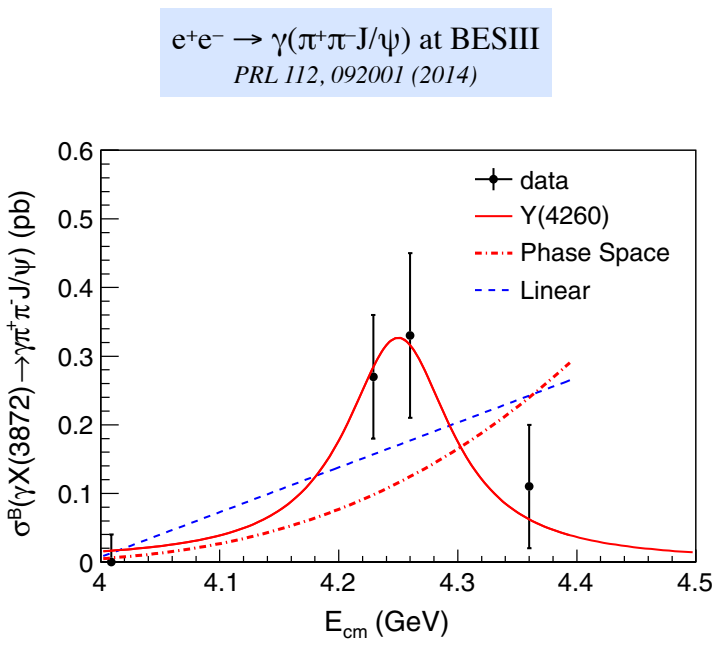
  - $M = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$, $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)
- Cross section measured at $\sqrt{s} = 4009, 4229, 4260, 4360\,\mathrm{MeV}$ hints towards production of the $X(3872)$ through a $Y$, but more data is needed

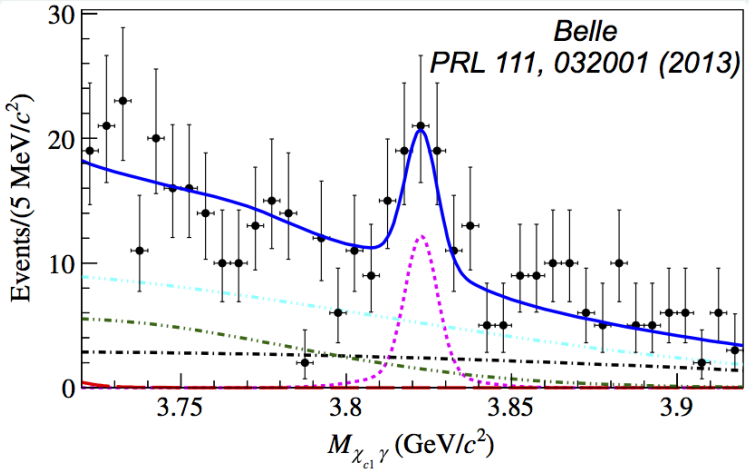


# The $X$ states: $e^+e^- \to \gamma\pi^+\pi^-\chi_{c1,2}$

- Another state found by Belle: The $X(3823)$
- $M = (3823.1 \pm 1.8 \pm 0.7)\,\mathrm{MeV}/c^2$, Significance: $3.8\sigma$

$\to$ Consistent with potential model predictions for the yet unobserved $\psi_2(1^3D_2)$ state!



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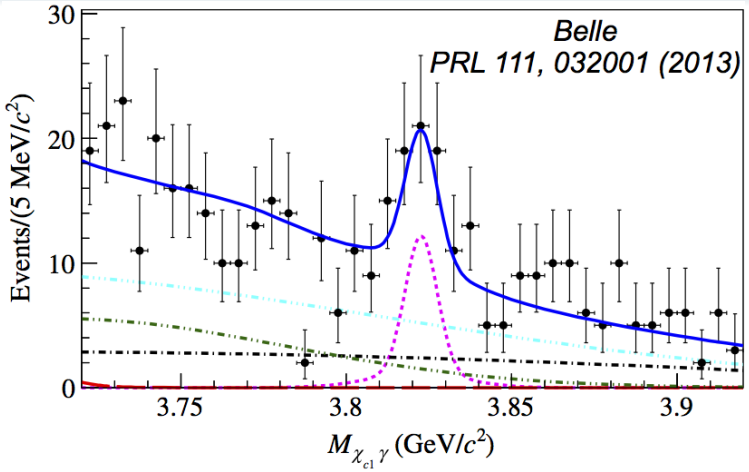
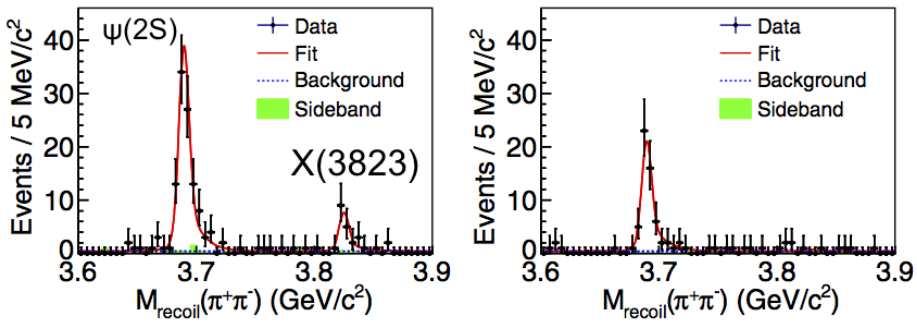
- Confirmed by BESIII with a significance of $6.2\sigma$

  [PRL115, 011803(2015)]

- based on data taken at $\sqrt{s} = 4230, 4260, 4360, 4420$ and $4600\,\mathrm{MeV}$



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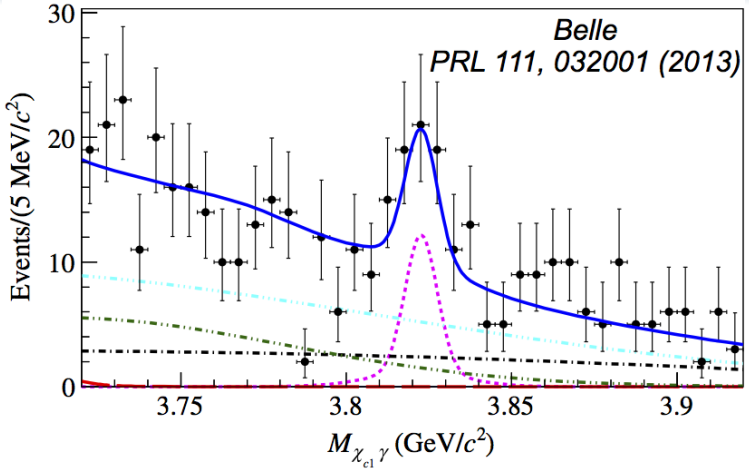
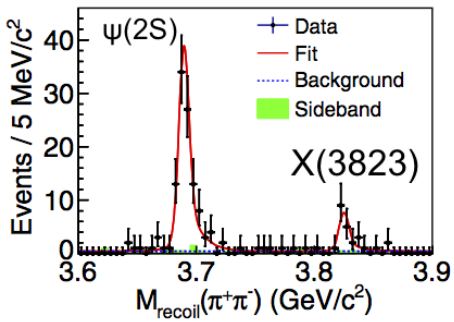
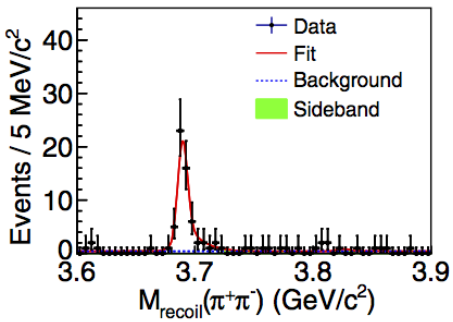
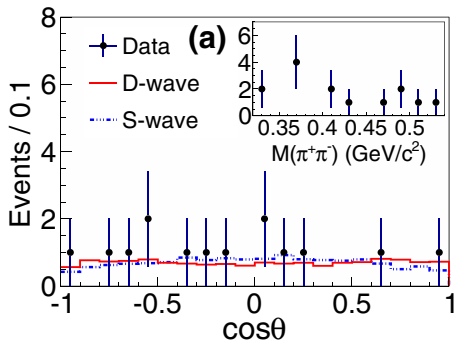
  [PRL115, 011803(2015)]

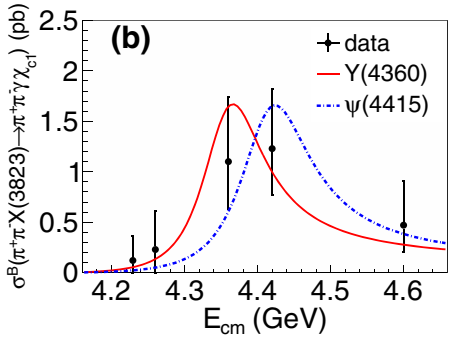
- based on data taken at $\sqrt{s} = 4230, 4260, 4360, 4420$ and $4600\,\mathrm{MeV}$
- Fits to energy dep. cross section consistent with $Y(4360)$ and $\psi(4415)$ hypotheses (expectation: $D$-wave)



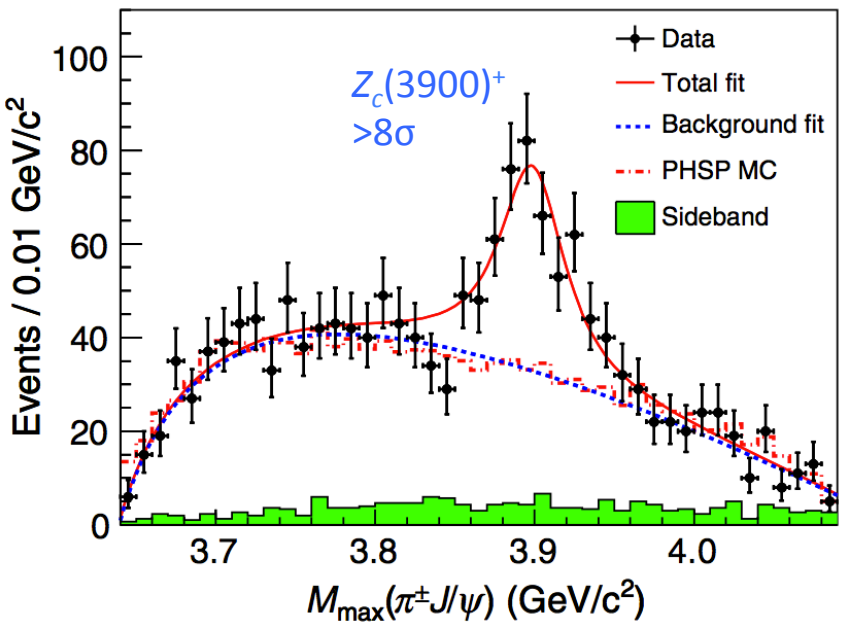
# The $Z$ states: Discovery of the $Z_c(3900)$

- 2013: Discovery of a resonant structure decaying to $J/\psi\pi^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII [PRL110, 252001(2013)]
- $M = (3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$, $\Gamma = (46 \pm 10 \pm 20)\,\mathrm{MeV}$

$\to$ Decays to $J/\psi \Rightarrow$ contains $c\bar{c}$

$\to$ Electrically charged $\Rightarrow$ contains $u\bar{d}$

$\to$ Very close to the $D\overline{D^*}$ threshold



# The $Z$ states: Discovery of the $Z_c(3900)$

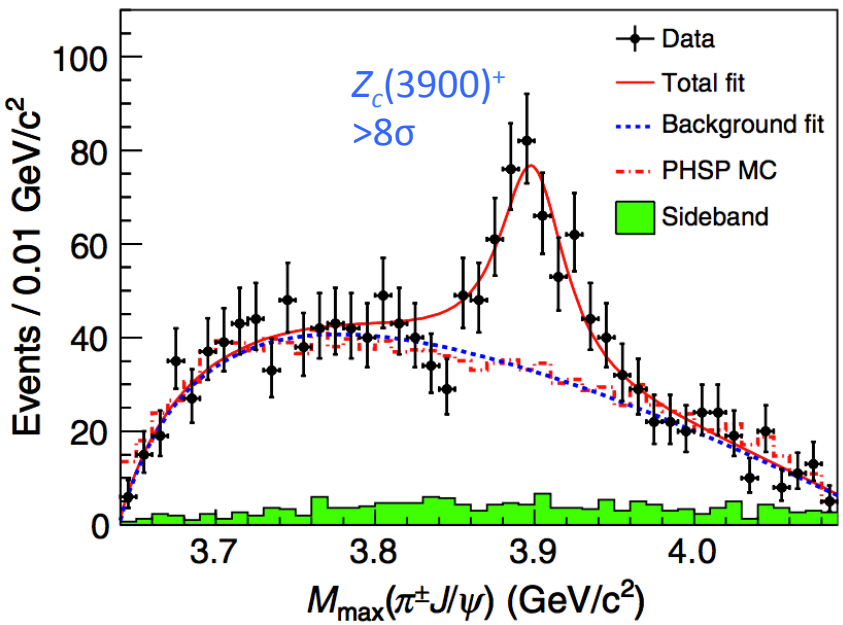
- 2013: Discovery of a resonant structure decaying to $J/\psi\pi^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII [PRL110, 252001(2013)]
- $M = (3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$, $\Gamma = (46 \pm 10 \pm 20)\,\mathrm{MeV}$

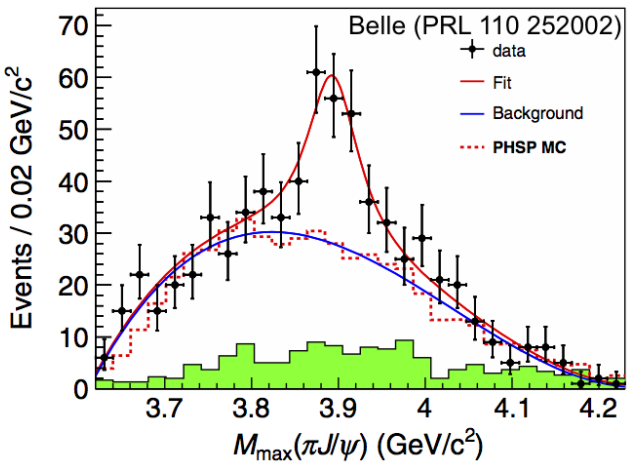
→ Decays to $J/\psi \Rightarrow$ contains $c\bar{c}$

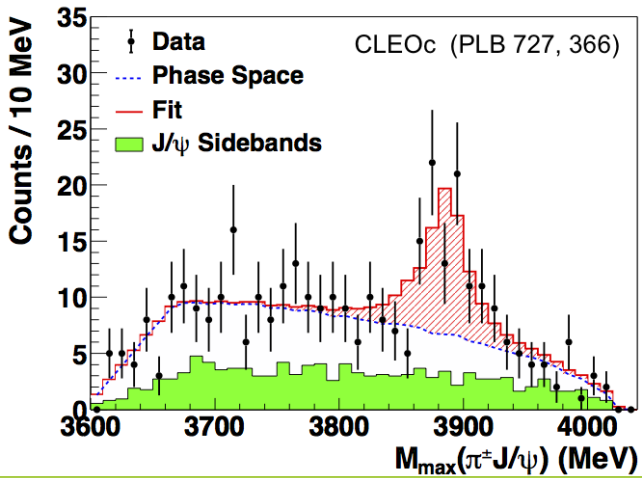
→ Electrically charged $\Rightarrow$ contains $u\bar{d}$

→ Very close to the $D\overline{D^*}$ threshold

- Confirmed by Belle and CLEO-c
- First observation of a four-quark state! (by $>1$ experiment)



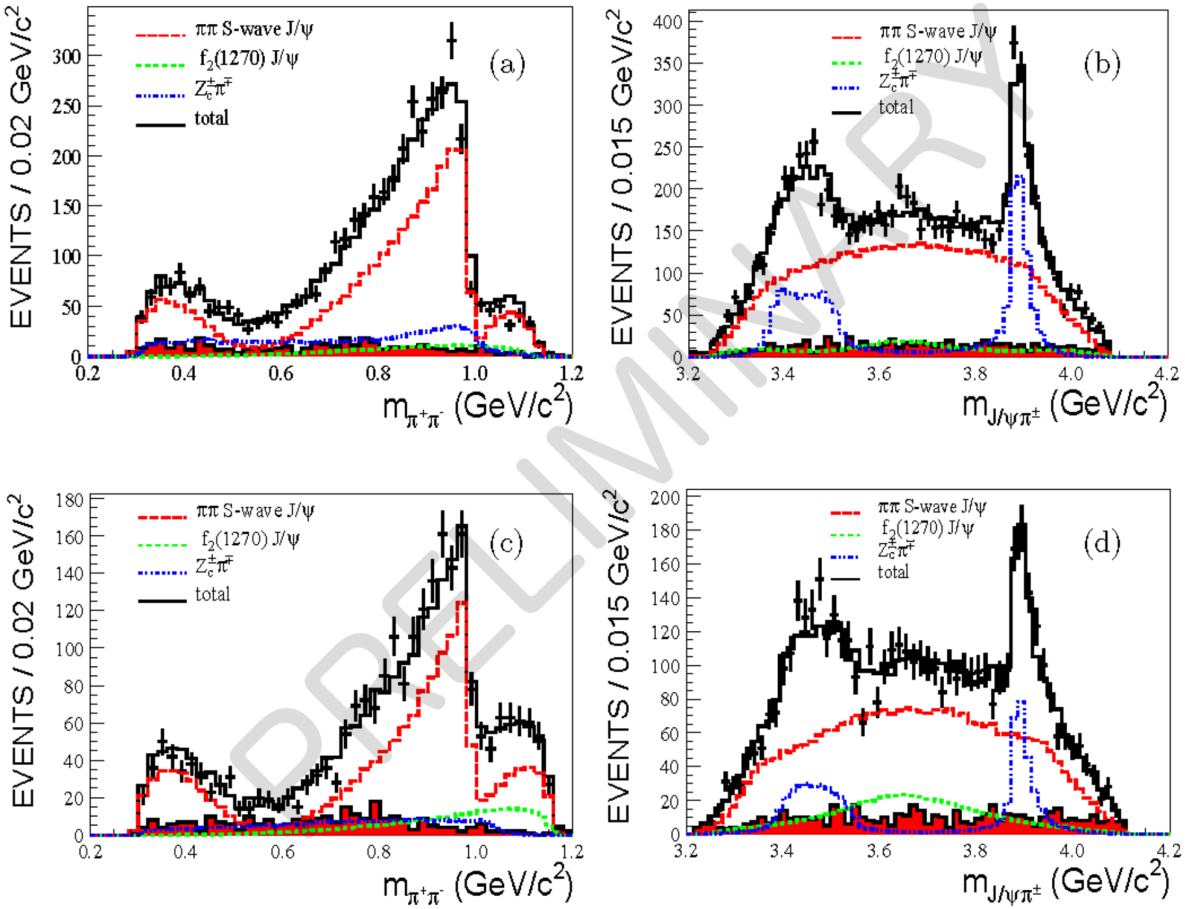



# The $Z$ states: Quantum Numbers of the $Z_c(3900)$

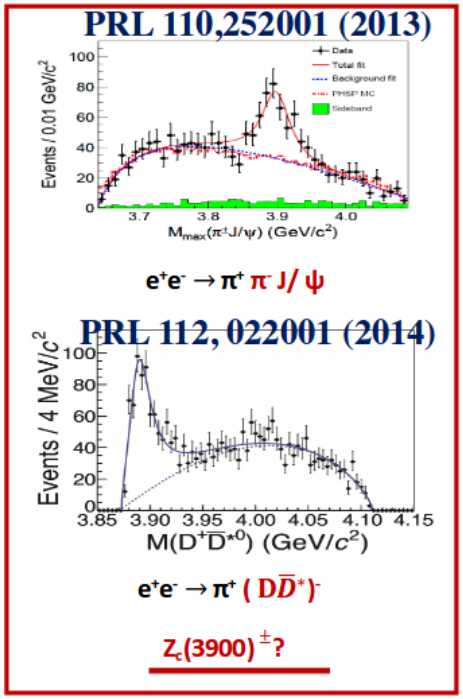
- Determination of the spin-parity of the $Z_c(3900)$ is performed using a partial wave analysis
- Using data recorded at $\sqrt{s} = 4230$ and 4260 MeV
- $Z_c$ is parameterized with a Flatté-like line shape

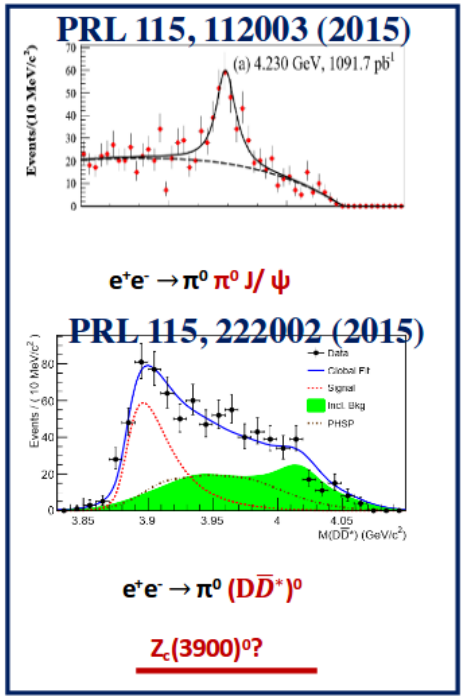
→ Hypothesis $J^P = 1^+$ is preferred with a stat. significance $> 7.3\sigma$ over other quantum number assignments

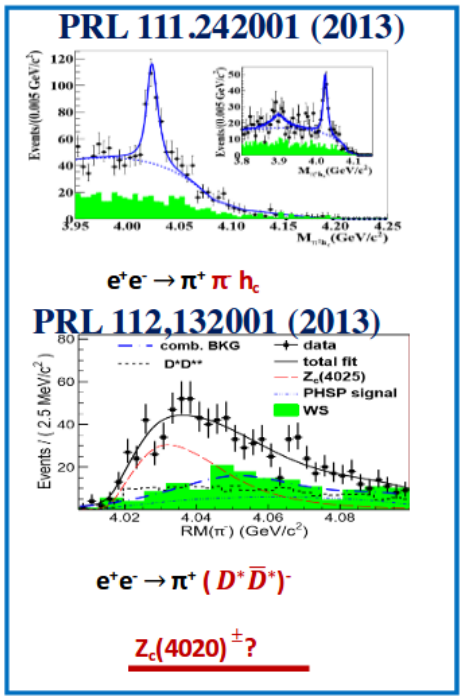


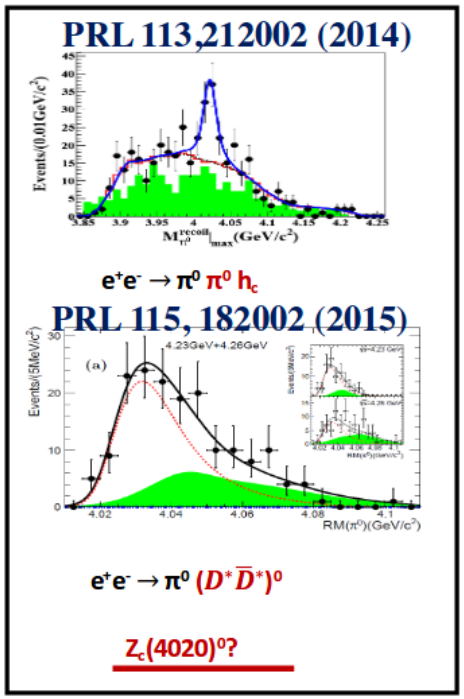

| Hypothesis | $\Delta(-\ln L)$ | $\Delta(ndf)$ | significance |
|---|---|---|---|
| $1^+$ over $0^-$ | 44.5 | 4×2+5 | $7.3\sigma$ |
| $1^+$ over $1^-$ | 107.0 | 4×2+5 | $> 8.0\sigma$ |
| $1^+$ over $2^-$ | 51.8 | 4×2+5 | $> 8.0\sigma$ |
| $1^+$ over $2^+$ | 193.5 | 4×2+5 | $> 8.0\sigma$ |

# Summary of the $Z$ states at BESIII



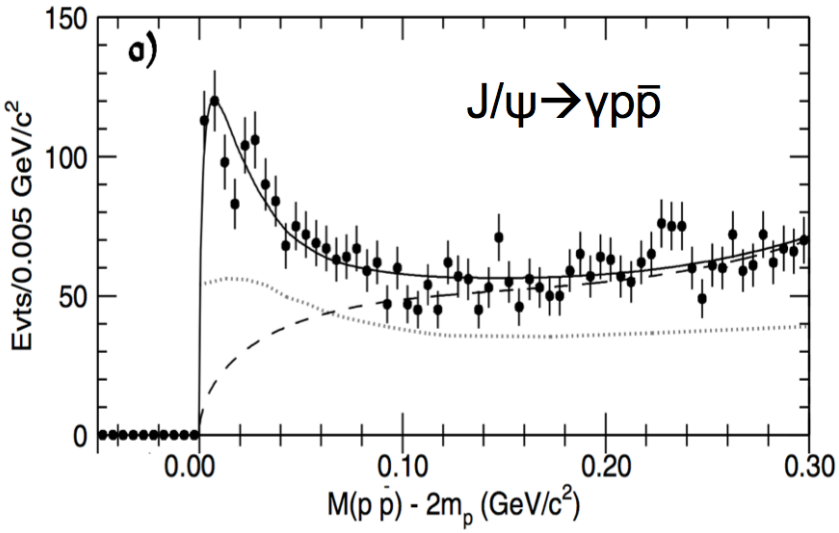

Two isospin-triplets of charged, charmonium-like four-quark states have been established!

# Light Hadron Sector: The $p\bar{p}$ Threshold Enhancement

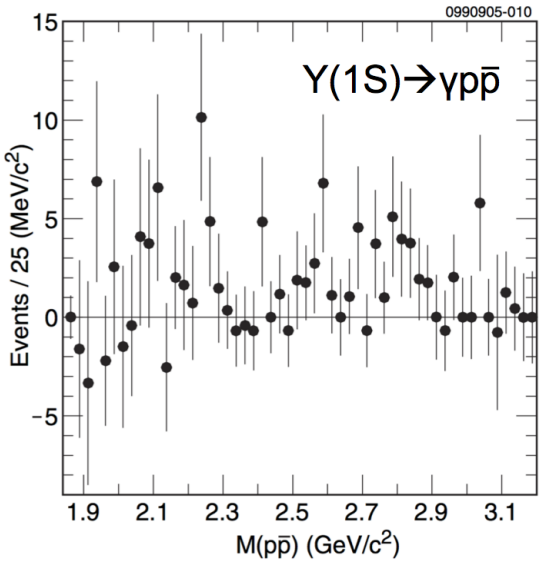
- An enhancement at the $p\bar{p}$ threshold was observed in $J/\psi \to \gamma p\bar{p}$ by BESII in 2003, confirmed by CLEOc in 2010
- **No evidence** in related channel $\Upsilon(1S) \to \gamma p\bar{p}$

$\to$ Nature unclear: Baryonium? Multiquark state? FSI effect?

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




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



# Light Hadron Sector: The $p\bar{p}$ Threshold Enhancement

- Recent achievements:

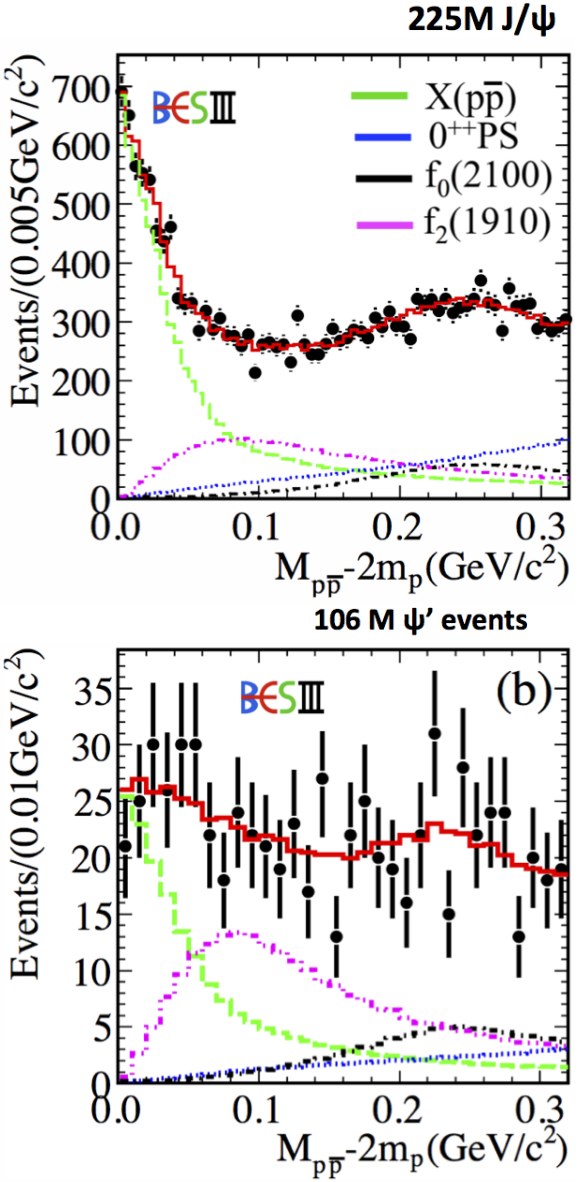
  **[BESIII, Phys.Rev.Lett. 108,112003(2012)]**
- Partial wave analysis in the mass region $m(p\bar{p}) < 2.2\,\mathrm{GeV}/c^2$ of...
- $J/\psi \to \gamma p\bar{p}$ **decay**:
  - Significant contributions of $X(p\bar{p})$, $f_2(1910)$, $f_0(2100)$, non-resonant $0^{++}$ contribution
  - $X(p\bar{p})$ structure: $J^{PC} = 0^{-+}$
  - Breit-Wigner parameterization:

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

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

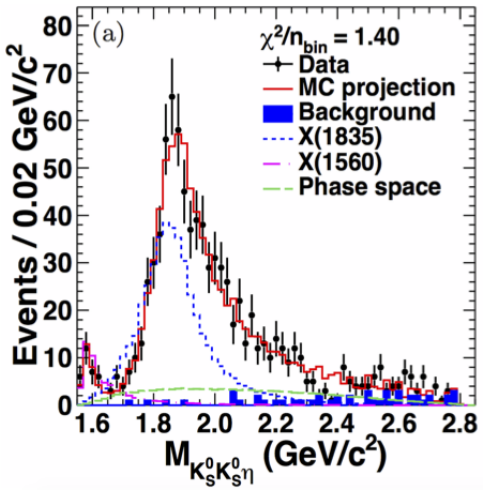
    $\mathcal{B}(J/\psi \to \gamma X) \cdot \mathcal{B}(X \to p\bar{p}) =$
    $(9.0^{+0.4}_{-1.1}(\mathrm{stat})^{+1.5}_{-5.0}(\mathrm{syst}) \pm 2.3(\mathrm{model})) \cdot 10^{-5}$

- $\psi' \to \gamma p\bar{p}$ **decay**:
  - Production of the $X(p\bar{p})$ in $\psi'$ decays is suppressed by a factor of $\approx 20$ over $J/\psi \to \gamma X(p\bar{p})$



# Many More Oberservations at the $p\bar{p}$ Threshold

- $X(1835) \to f_0(980)\eta$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$ [Phys.Rev.Lett. 115, 091803(2015)]
- $X(1840) \to 3(\pi^+\pi^-)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$ [Phys.Rev.D 88, 091502(2013)]
- $X(1870) \to \eta\pi^+\pi^-$ in $J/\psi \to \omega\eta\pi^+\pi^-$ [Phys.Rev.Lett. 107, 192001(2011)]
- Enhancement at the $\phi\omega$-threshold in $J/\psi \to \gamma\omega\phi$ [Phys.Rev.D 87, 032008(2013)]



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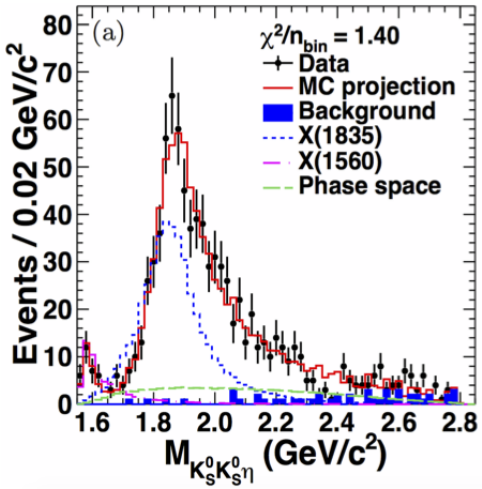

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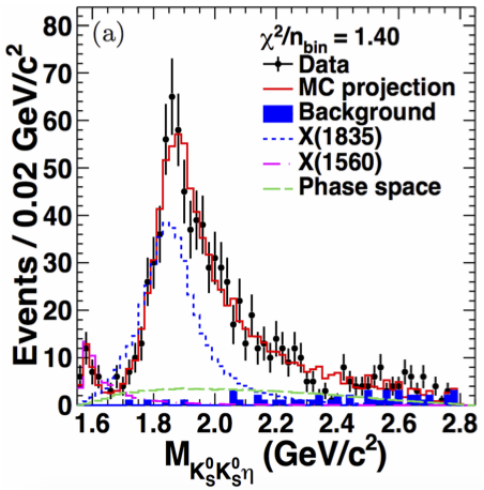


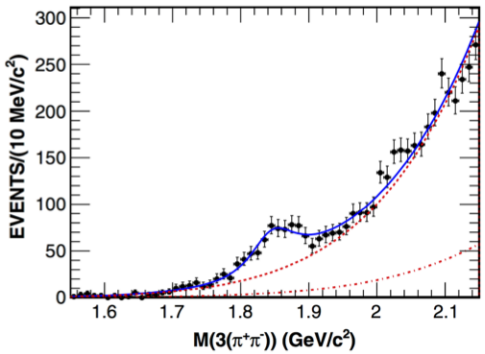


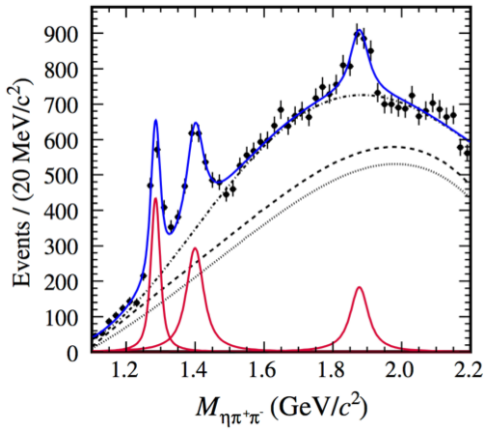

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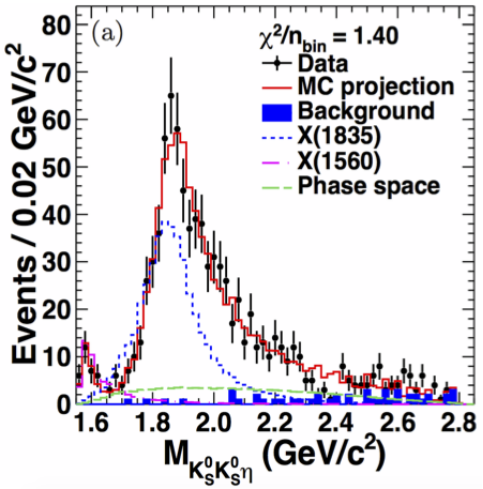
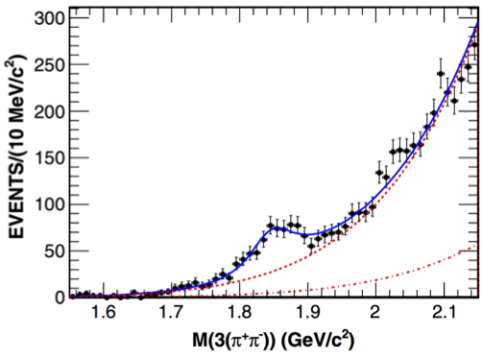
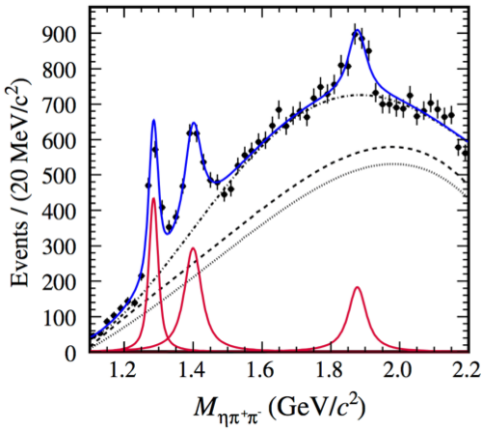
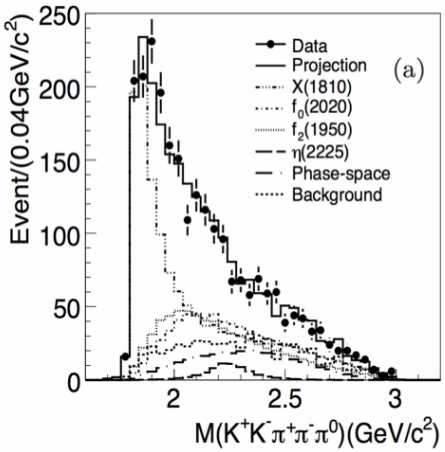


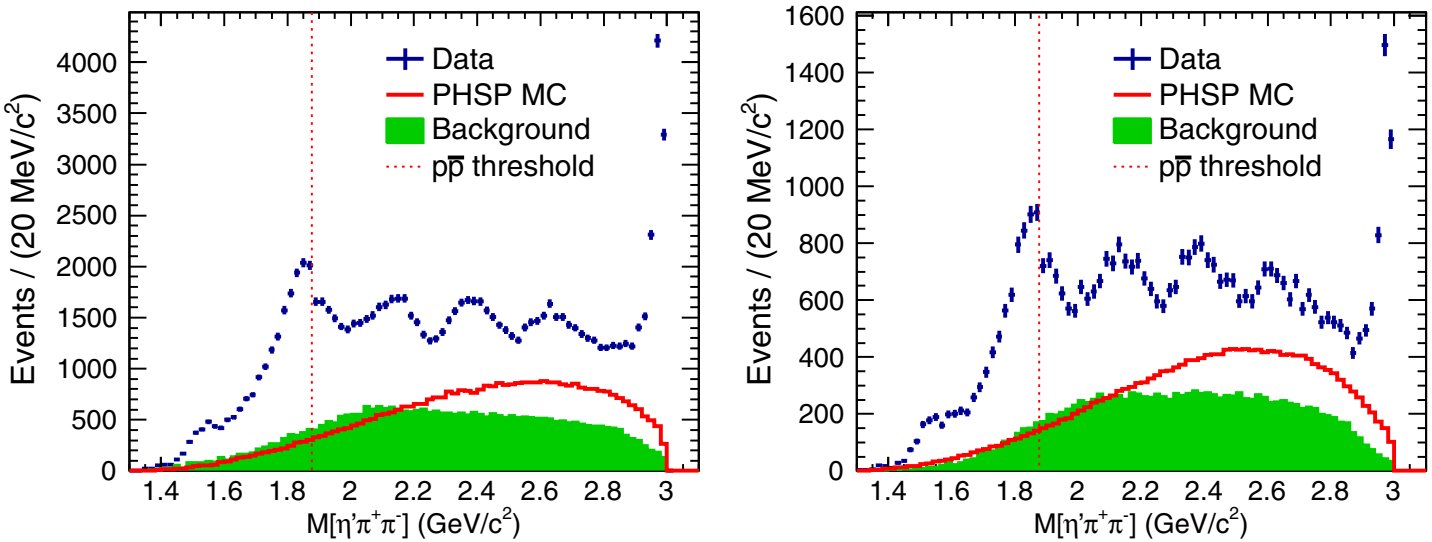



# $X(1835)$ in $J/\psi \to \gamma\eta'\pi^+\pi^-$ [PRL117, 042002(2016)]

- Two decay modes of $\eta'$ analyzed
- Observations in $\eta'\pi^+\pi^-$ mass:
  - Apart from $X(1835)$, three additional structures and a clear signal of the $\eta_c$ become apparent
  - Additionally: **Significant distortion of the line shape in the vicinity of the $p\bar{p}$ threshold!**
- Nature of $X(1835)$ unclear: Glueball? $p\bar{p}$ bound state? Excited $\eta$ meson?
- Is there a connection to the $p\bar{p}$ threshold enhancement?

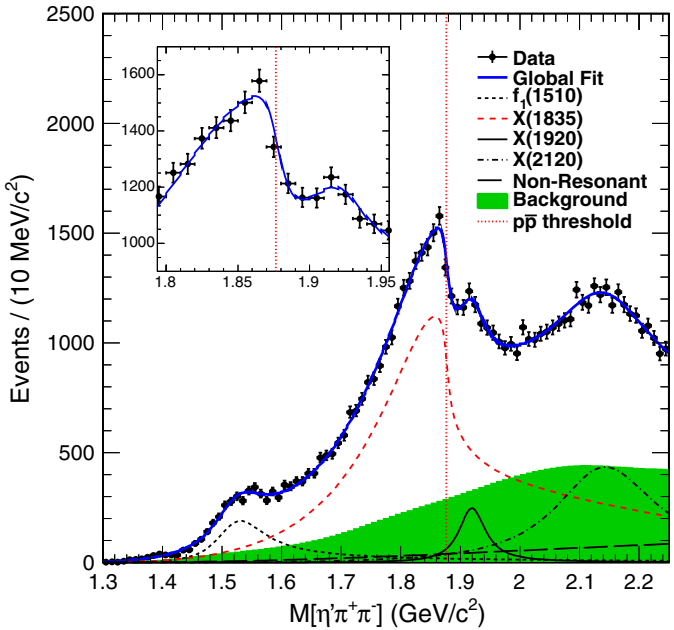


# $X(1835)$ Line Shape

[PRL117, 042002(2016)]

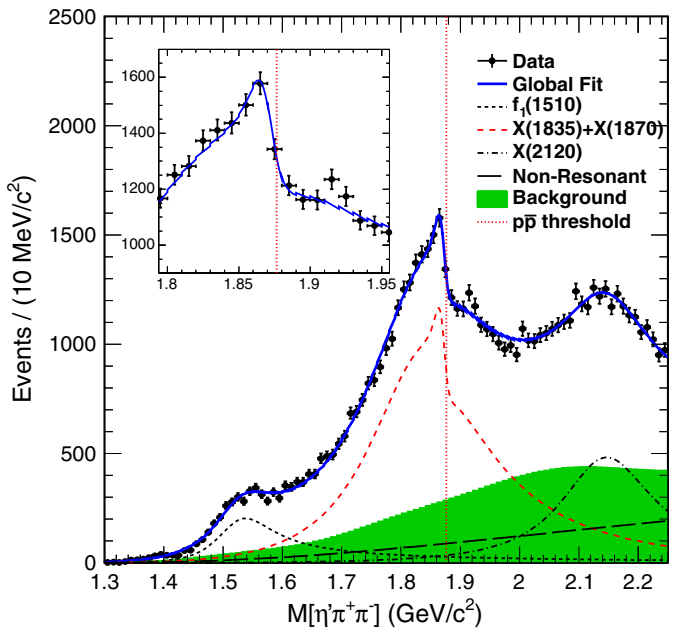
## Fit Model 1:

Flatté line shape (strong coupling to $p\bar{p}$) and one **additional**, narrow Breit-Wigner at $m \approx 1920\,\mathrm{MeV}/c^2$




## Fit Model 2:

Coherent sum of two Breit-Wigners ($X(1835)$ and additional narrow resonance at $m \approx 1870\,\mathrm{MeV}/c^2$




Almost equal fit quality, but both models suggest a **broad resonance below**, and a **narrow state very close to the $p\bar{p}$ threshold**

# Conclusions and Outlook

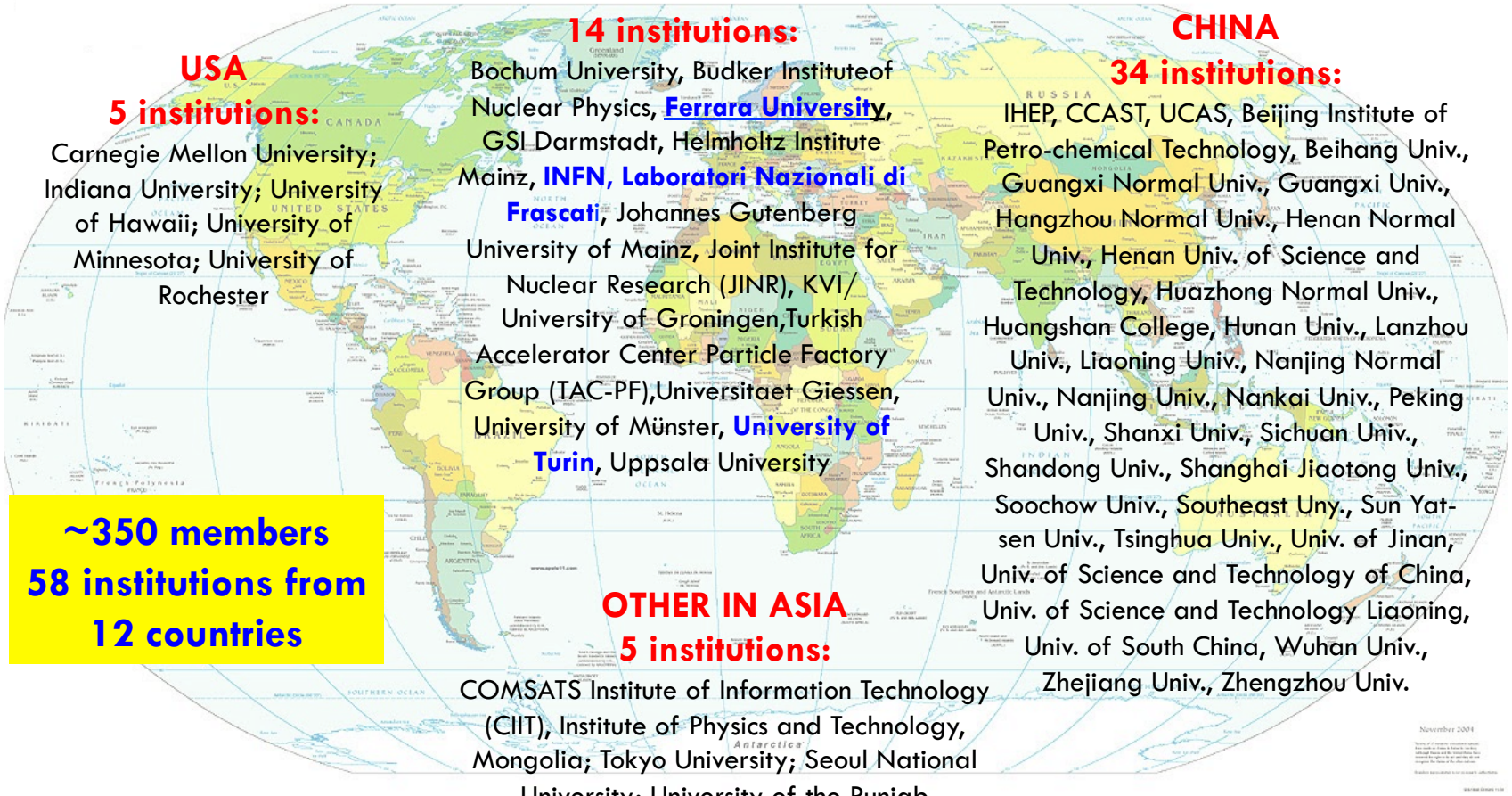
- BESIII operating successfully since 2008
  - Collected large data samples in the $\tau$-charm mass region
- Study of $X$, $Y$ and $Z$ states
  - BESIII is ideally suited to explore transitions and decays of $Y$ states and thus to map the $XYZ$-spectrum
  - Established isospin triplet states $Z_c(3900)$ and $Z_c(4020)$
- Light Hadron spectroscopy in charmonium decays
  - Benefit from world's largest $J/\psi$ and $\psi'$ data sets

  $\rightarrow$ Clean environment and high statistics
  - Understanding structures near $p\bar{p}$ threshold
  - Sophisticated partial wave analyses ongoing

Exciting times in hadron spectroscopy
with many more results not covered in this talk!

**Thank you for your attention**

# The BESIII Collaboration



**EUROPE**
**14 institutions:**
Bochum University, Budker Instituteof Nuclear Physics, Ferrara University, GSI Darmstadt, Helmholtz Institute Mainz, INFN, Laboratori Nazionali di Frascati, Johannes Gutenberg University of Mainz, Joint Institute for Nuclear Research (JINR), KVI/ University of Groningen,Turkish Accelerator Center Particle Factory Group (TAC-PF),Universitaet Giessen, University of Münster, University of Turin, Uppsala University

**USA**
**5 institutions:**
Carnegie Mellon University; Indiana University; University of Hawaii; University of Minnesota; University of Rochester

**CHINA**
**34 institutions:**
IHEP, CCAST, UCAS, Beijing Institute of Petro-chemical Technology, Beihang Univ., Guangxi Normal Univ., Guangxi Univ., Hangzhou Normal Univ., Henan Normal Univ., Henan Univ. of Science and Technology, Huazhong Normal Univ., Huangshan College, Hunan Univ., Lanzhou Univ., Liaoning Univ., Nanjing Normal Univ., Nanjing Univ., Nankai Univ., Peking Univ., Shanxi Univ., Sichuan Univ., Shandong Univ., Shanghai Jiaotong Univ., Soochow Univ., Southeast Uny., Sun Yat-sen Univ., Tsinghua Univ., Univ. of Jinan, Univ. of Science and Technology of China, Univ. of Science and Technology Liaoning, Univ. of South China, Wuhan Univ., Zhejiang Univ., Zhengzhou Univ.

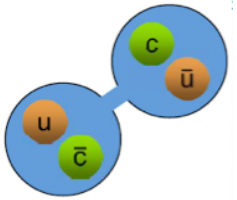
**~350 members**
**58 institutions from 12 countries**

**OTHER IN ASIA**
**5 institutions:**
COMSATS Institute of Information Technology (CIIT), Institute of Physics and Technology, Mongolia; Tokyo University; Seoul National University; University of the Punjab

**http://bes3.ihep.ac.cn**

# Backup

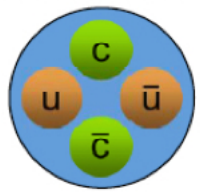
# Nature of the XYZ States




**Molecular state**

Loosely bound state of a pair of mesons. The dominant binding mechanism should be pions exchange

NA Tornqvist PLB 590, 209 (2004)
ES Swanson PLB 598,197 (2004)
E Braaten & T Kusunoki PRD 69 074005 (2004)
CY Wong PRC 69, 055202 (2004)
MB Voloshin PLB 579, 316 (2004)
F Close & P Page PLB 578,119 (2004) …..



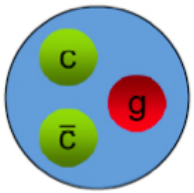

**Tetraquark**

L Maiani et al PRD 71,014028 (2005)
T-W Chiu & TH Hsieh PRD 73, 111503 (2006)
D Ebert et al PLB 634, 214 (2006)
…

Bound state of four quarks, i.e. diquark-antidiquark

Distinctive feature of multi-quark picture with respect to charmonium:

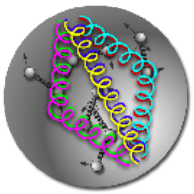
- Prediction of many new states
- Possible existence of new states with nonzero charge, strangeness, or both




**Charmonium hybrids**

Bound states with a pair of quarks and one excited gluon; Lattice and model predictions found that the lowest charmonium hybrids lies around 4200 MeV

P Lacock et al (UKQCD) PLB 401, 308 (1997)
SL Zhu PLB 625, 212 (2005)
FE Close, PR Page PLB 628, 215 (2005)
E Kou, O Pene PLB 631, 164 (2005)
…



**Glueball**

Bound states of gluons

Heavy quarkonium: progress, puzzles, and opportunities
N. Brambilla et. All, Eur.Phys.J.C71:1534,2011