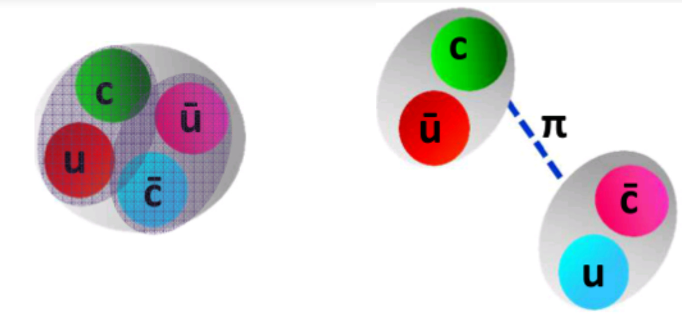
Recent Highlights from BES III

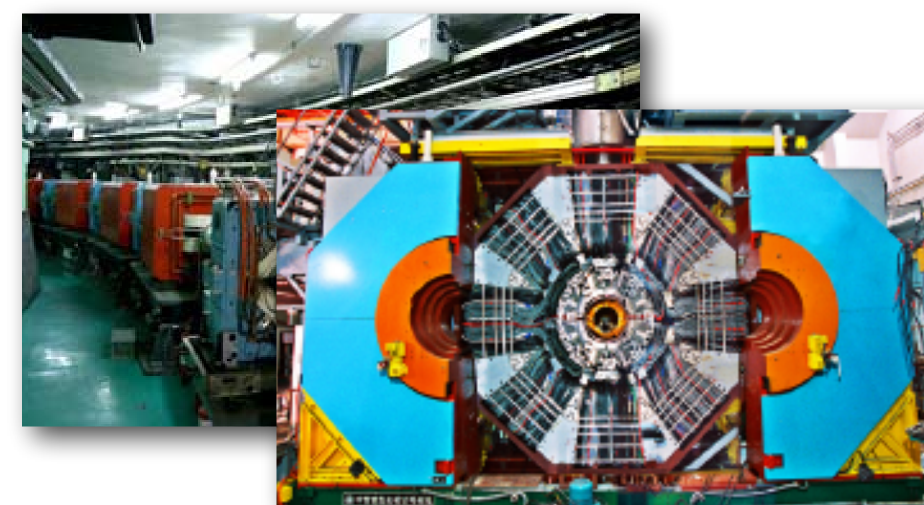
Wolfgang Kühn, JLU Giessen (BES III Collaboration)

Outline

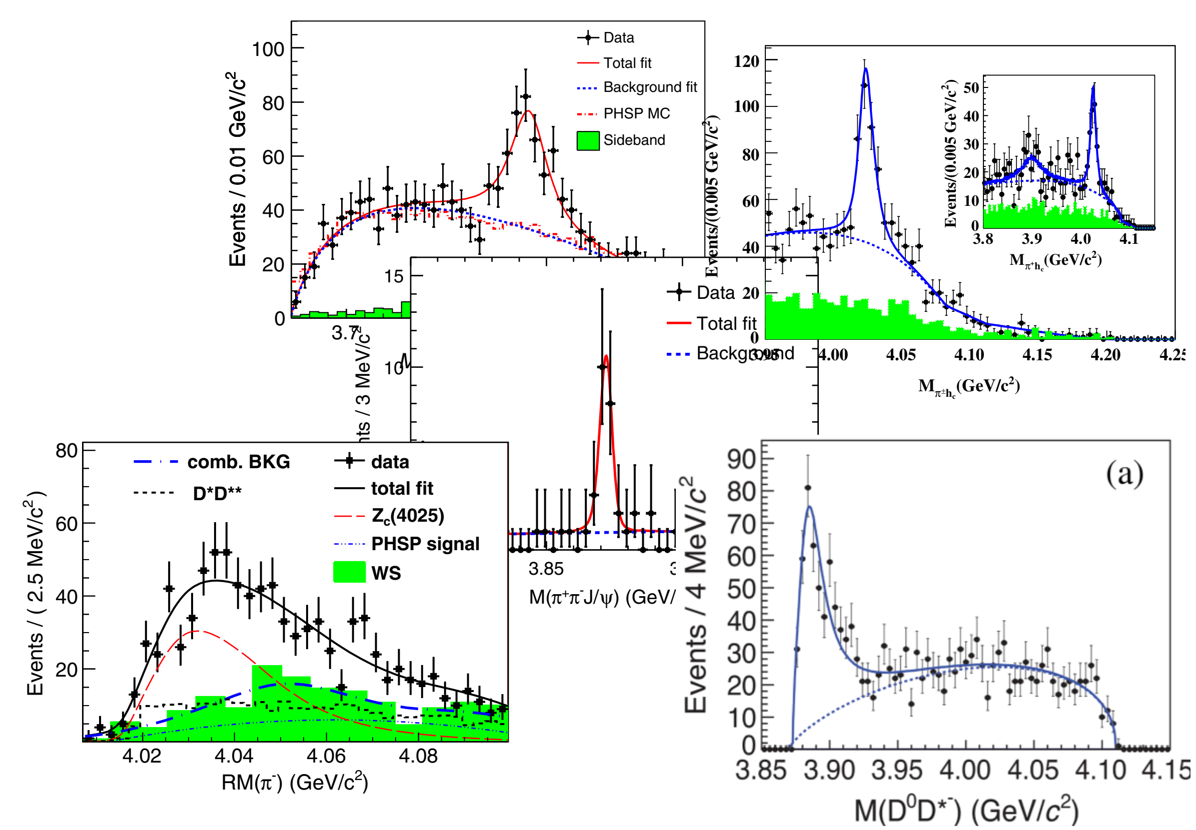
- Introduction: Hadrons, Charmonium and XYZ states



- BEPCII collider and BES III detector



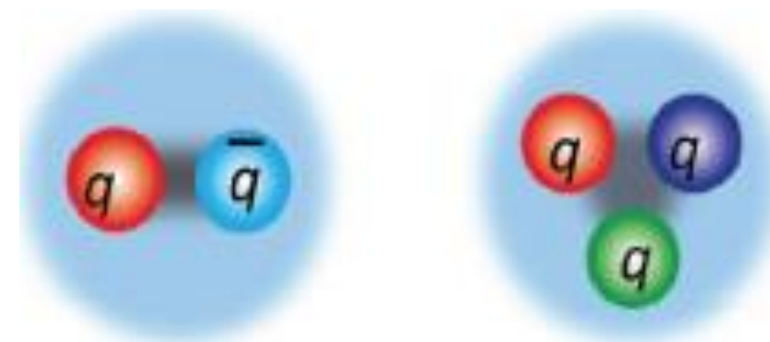
- Data sets and BES III Physics Program
- Focus for today:
    - **New exotic charmonium-like states**
        - Z(3900), Z(4020), …



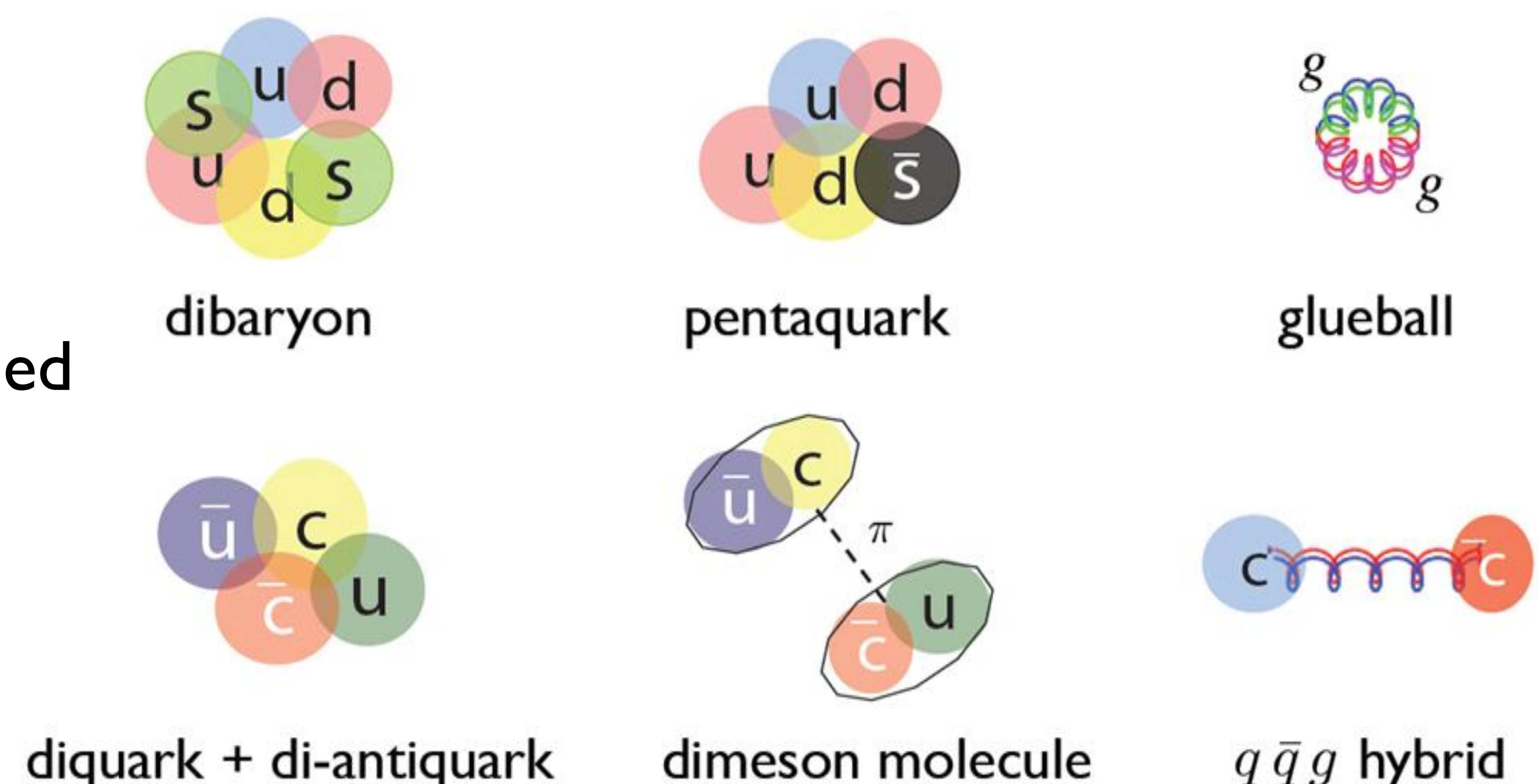
- Conclusions and outlook

Reminder: Hadrons

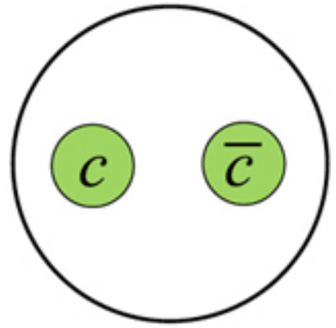
- Hadrons are the **bound states of QCD**
- All hadrons are **color singlets**
- Well established hadrons
  - **Mesons** (quark/antiquark states)
  - **Baryons** (3-quark states)



- However: **QCD allows more configurations:**
  - Experimentally not well established

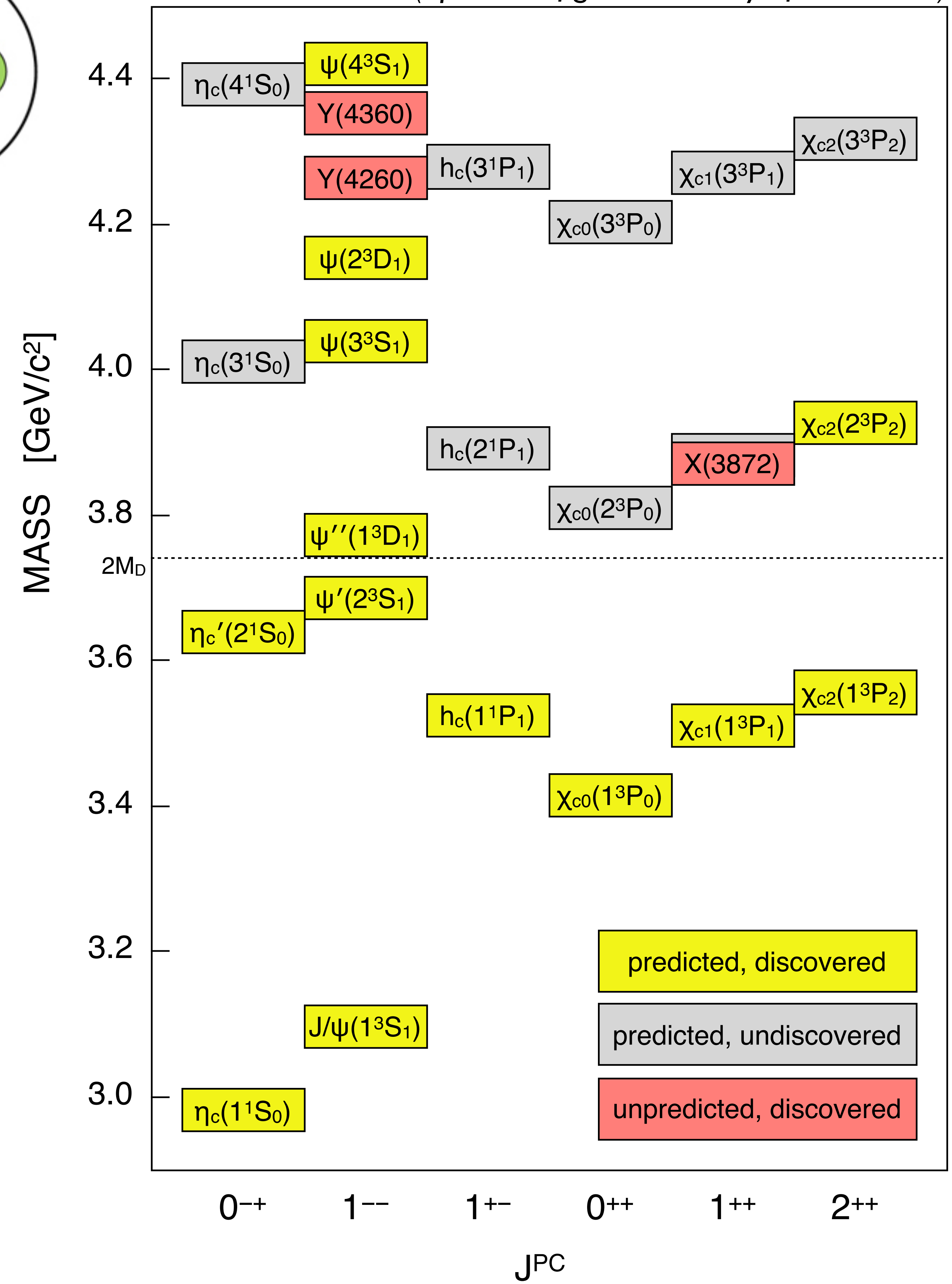


Charmonium and Charmonium-like States



- Charmonium in QCD is like positronium in QED
  - Bound states of charm/anti-charm quarks
- **Levels below the open charm threshold** (“ionization”) well understood
  - Experiment and theory agree well
- **Above the open charm threshold,** situation more complex
  - Some of the predicted states have been found, many have not yet been observed
  - New unpredicted states have been found with properties that are not consistent with conventional charmonium states => **“XYZ states”**

(Spectrum figures courtesy of R. Mitchell)



Prediction: Barnes, Swanson, and Godfrey, PRD 72, 054026 (2005)

XYZ - Physics

- **X** : neutral charmonium - like states with quantum numbers other than 1^{--} (vector)

- **Y** : neutral charmonium - like states with 1^{--} (vector) quantum number

  - Can be directly formed in an $e+e^-$ collision

- **Z** : charged charmonium-like states

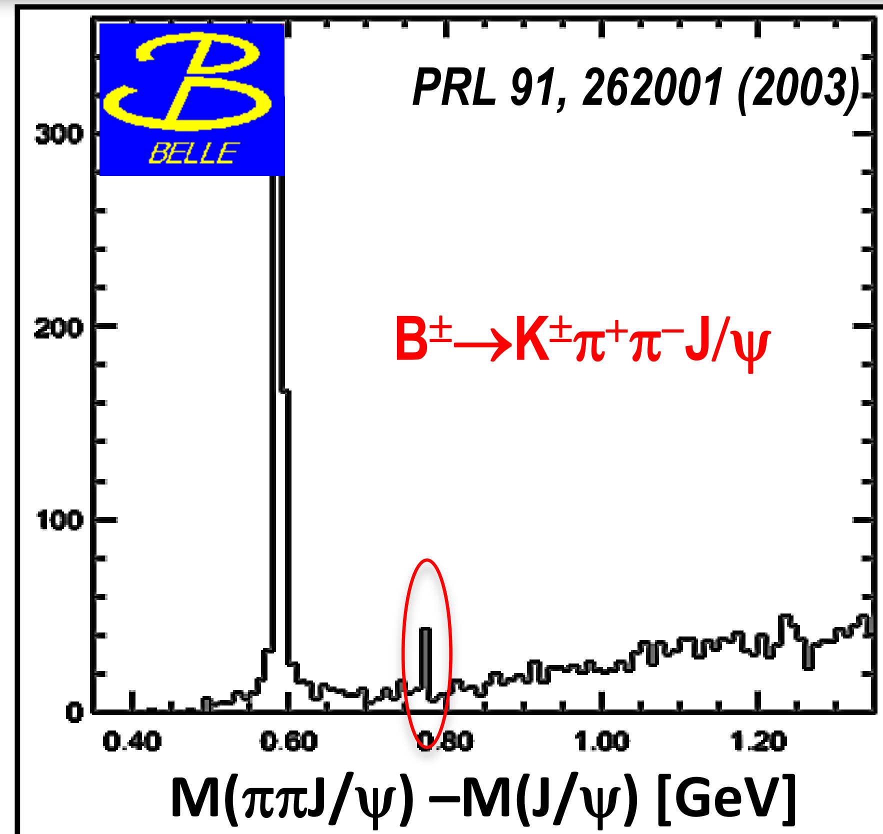
  - Such a state must consist of at least 2 quarks and 2 antiquarks

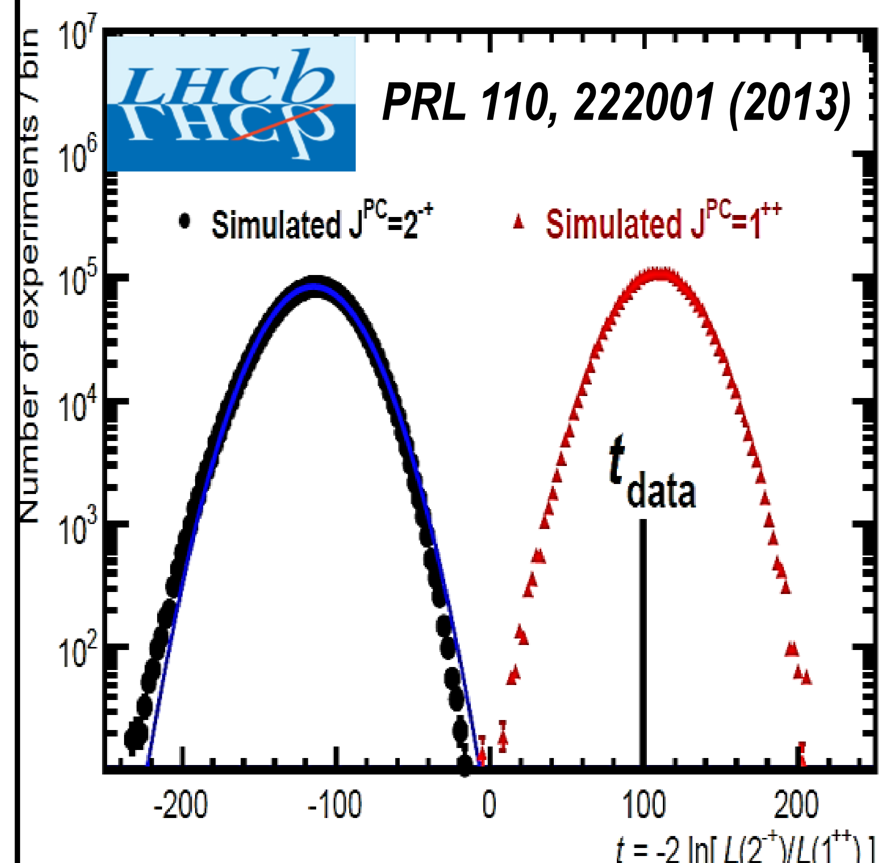
X(3872) - the first XYZ state discovered in 2003

- First X - state discovered in B decays at Belle
- Extremely narrow resonance at 3872 MeV
  - Mass(D^0)+mass(D^{*0})=3871.84±0.28 MeV ? ?
  - Width < 1.2 MeV
    - compare ψ(3770) : Γ = 27.2 MeV
- Seen in many other experiments
- Peculiar decay modes:

Γ_i	Mode	Fraction (Γ_i / Γ)
Γ_1	$X(3872) \to e^+e^-$	
Γ_2	$X(3872) \to \pi^+\pi^- J/\psi(1S)$	>2.6 %
Γ_3	$X(3872) \to \rho^0 J/\psi(1S)$	
Γ_4	$X(3872) \to \omega J/\psi(1S)$	>1.9 %
Γ_5	$X(3872) \to D^0 \overline{D}^0 \pi^0$	>3.2 $\times 10^{-1}$
Γ_6	$X(3872) \to \overline{D}^{*0} D^0$	>2.4 $\times 10^{-1}$

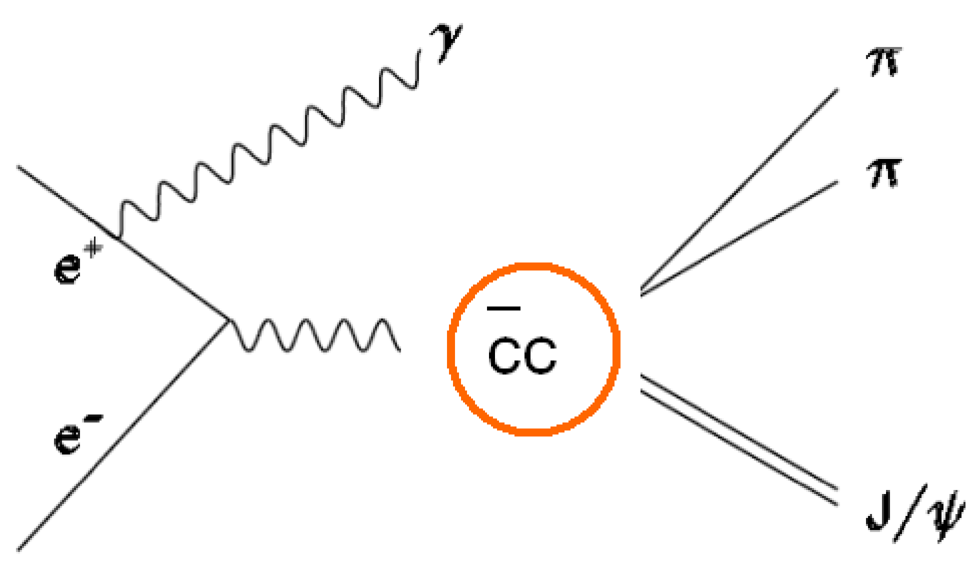
- Recently, LHCb has determined the quantum numbers to be $J^{PC} = 1^{++}$





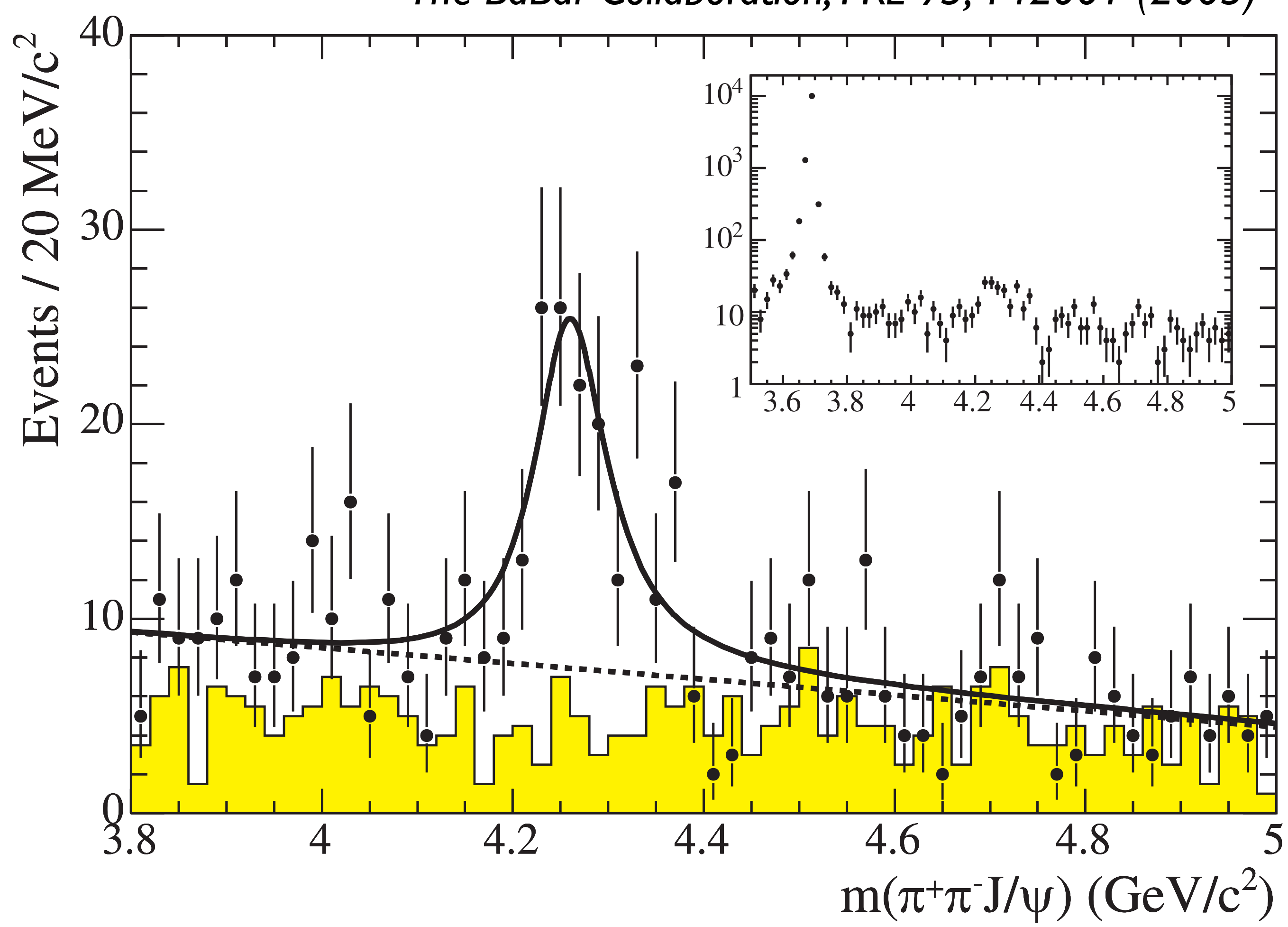
The first exotic 1^{--} state: Y(4260), discovered by BaBar

- Discovered in **initial state radiation:**



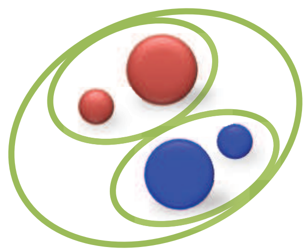
$$e^+e^- \rightarrow \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

The BaBar Collaboration, PRL 95, 142001 (2005)



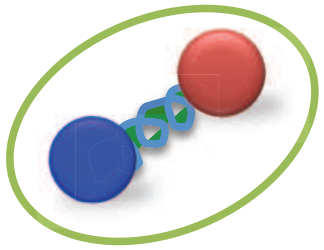
- Why is this no conventional charmonium state ?
  - Does not fit predicted spectrum of vector states, overpopulation of 1^{--} states
  - Peculiar decay pattern: $$\frac{\mathcal{B}(Y(4260) \rightarrow D\bar{D})}{\mathcal{B}(Y(4260) \rightarrow \pi\pi J/\psi)} < 4$$
    - Compare to ψ(3770) : ratio is ≈ 500 ! (open charm decays dominant)

What are these states ?



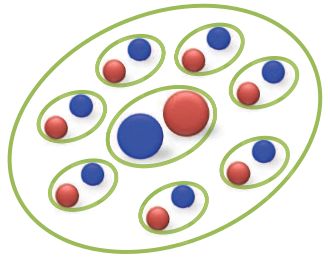
Tetraquark

→ Compact object formed from (Qq) and $(\bar{Q}\bar{q})$



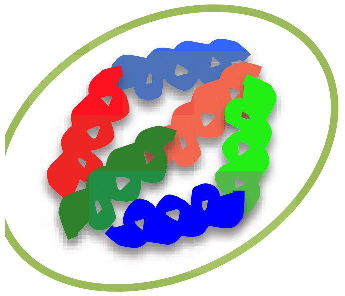
Hybrid

→ Compact with active gluons and $\bar{Q}Q$



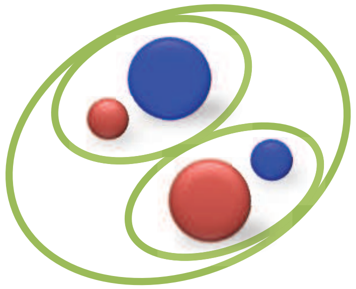
Hadro-Quarkonium

→ Compact $(\bar{Q}Q)$ surrounded by light quarks



Glueball

→ Compact object just made off gluons



Hadronic-Molecule

→ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

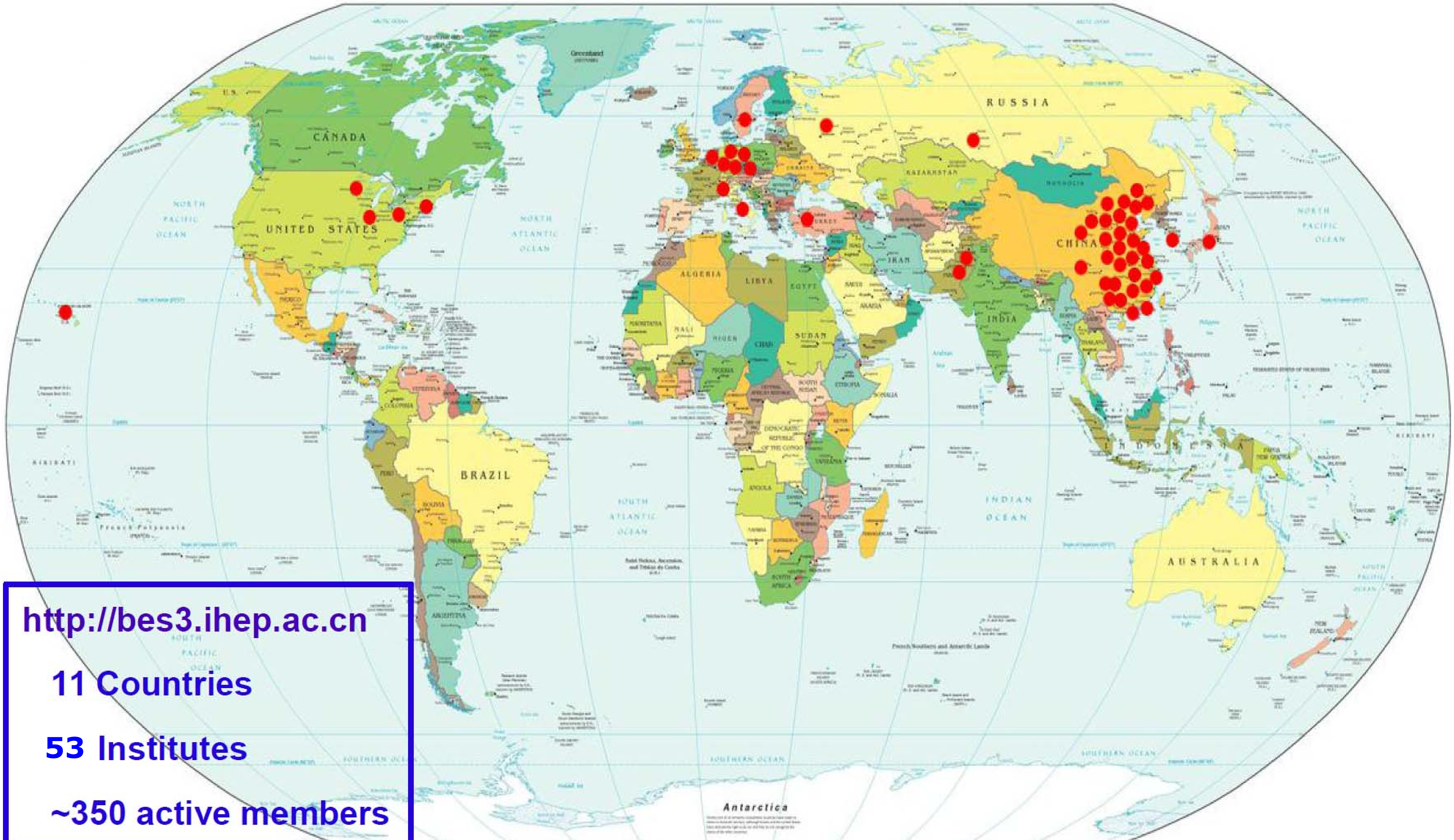
....or...mixtures of such configurations with/without conventional charmonium states

(Slide stolen from Christoph Hanhart)

How to make progress ?

- Many theoretical models, no firm conclusion
- How about charged charmonium like states (“Z”-type) ?
  - **Such states must at least contain for 2 quarks and 2 anti-quarks !!!**
- Strategy:
  - Search for more XYZ states: establish the spectroscopy
    - Determine quantum numbers and decay patterns
  - Search for transitions between XYZ states
    - Of particular interest: radiative transitions

The BES-III Collaboration



http://bes3.ihep.ac.cn

11 Countries

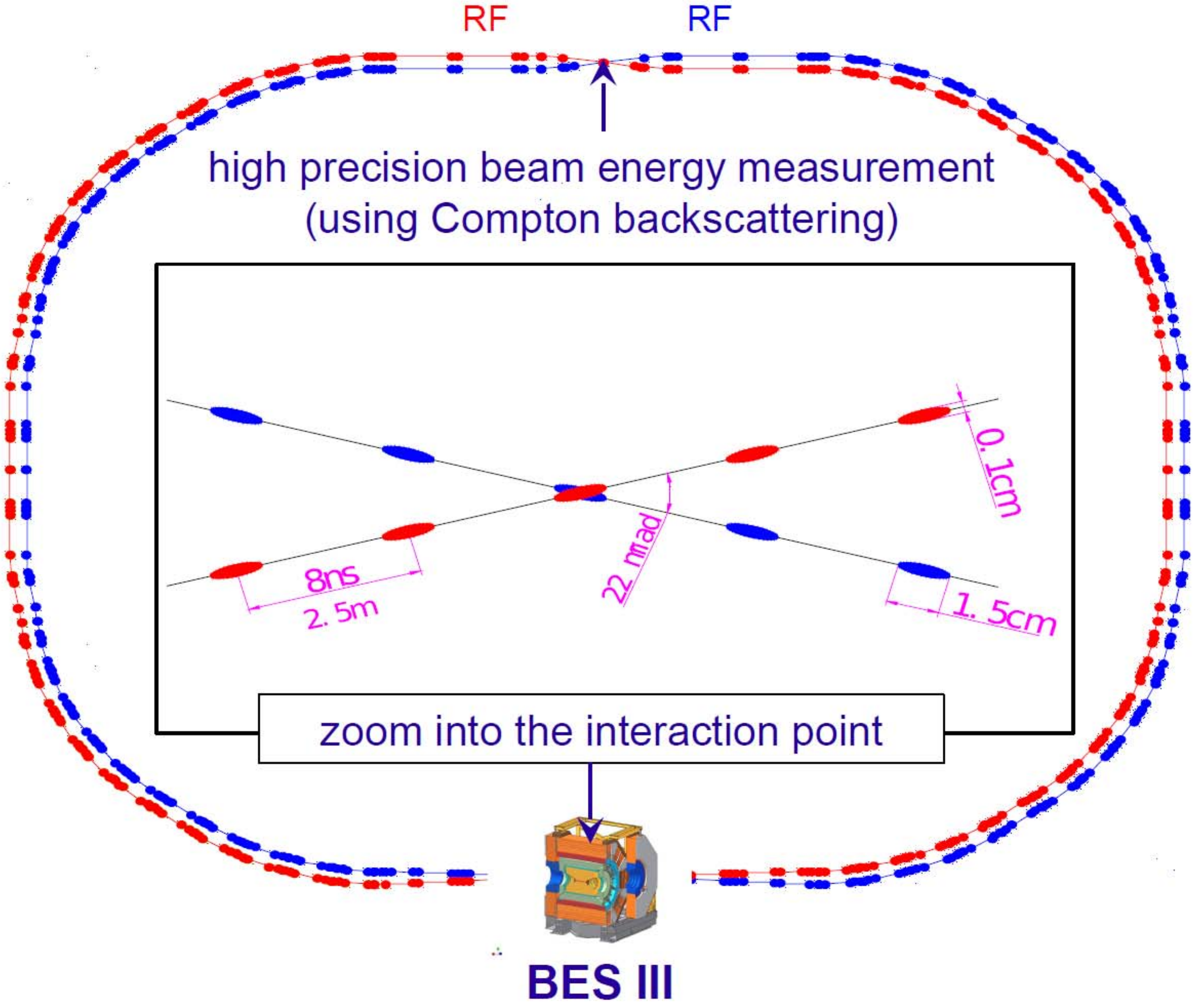
53 Institutes

~350 active members

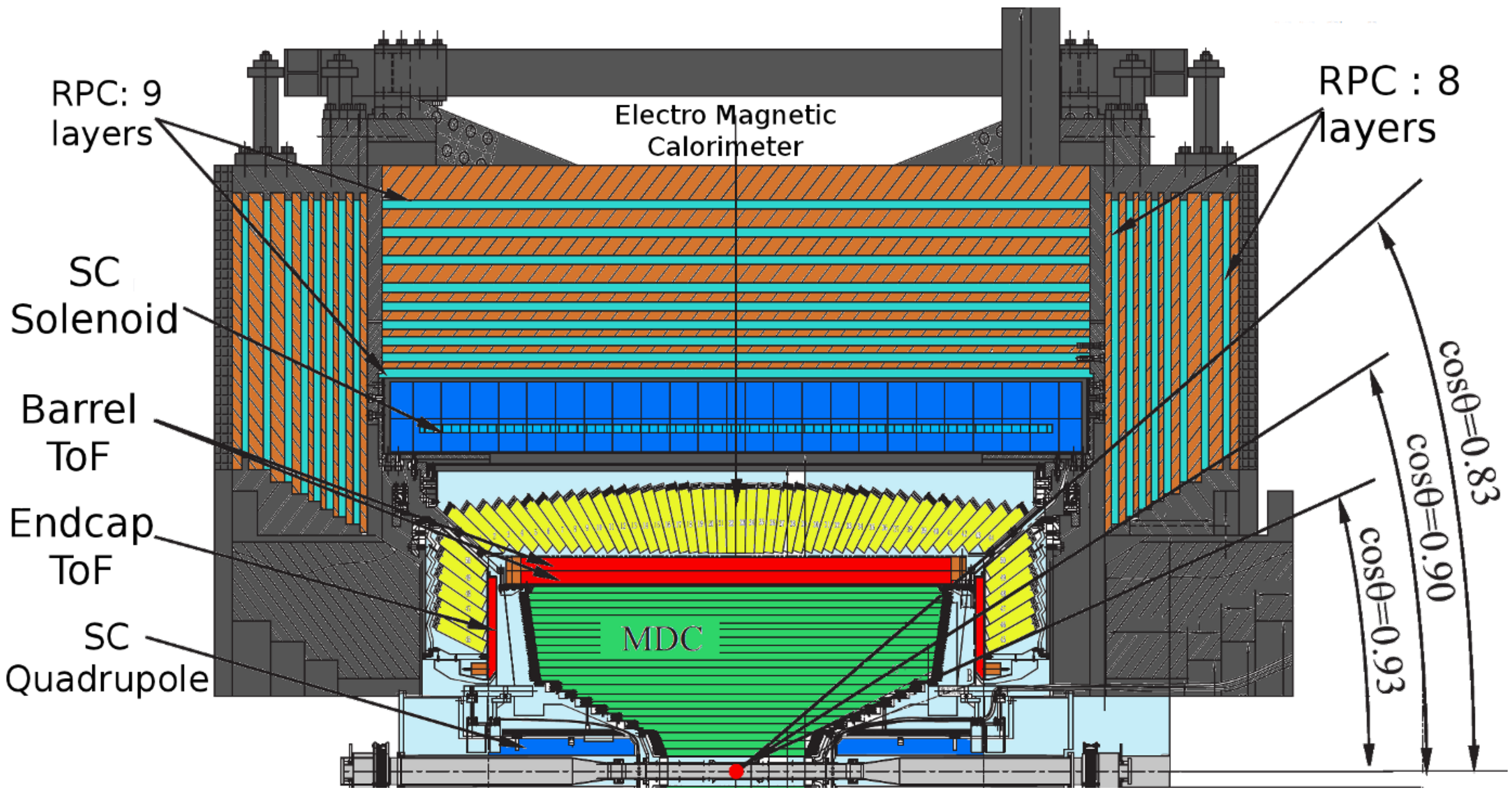
The BEPC II Collider at IHEP Beijing

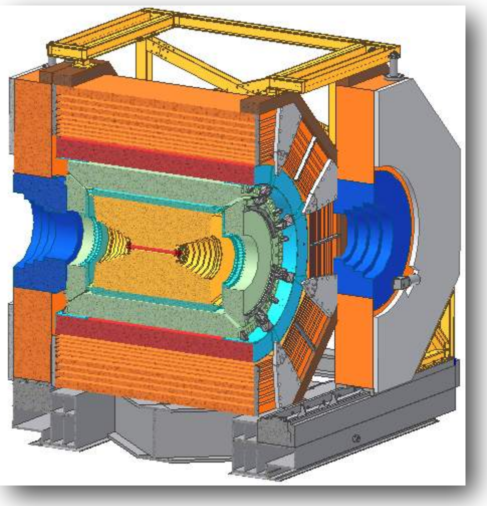
- $\sqrt{s}$: 2.0 - 4.6 GeV
- Energy spread ≈ $5x10^{-4}$
- Design Luminosity:

  $1x10^{33}$ /cm^2/s @ ψ(3770)
- Achieved: $0.7x10^{33}$ /cm^2/s



BES III - Detector





Muon Chambers
- 8 – 9 layers of RPC
- p>400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

Superconducting Magnet
- 1 T magnetic field

EMC
- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{Z,\Phi}(E) = 0.5 – 0.7$ cm

Mini Drift Chamber (MDC)
- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$

Time-of-flight system (TOF)
- σ(t) = 80ps (barrel)
- σ(t) = 110ps (endcap)

The Available Data

BESIII

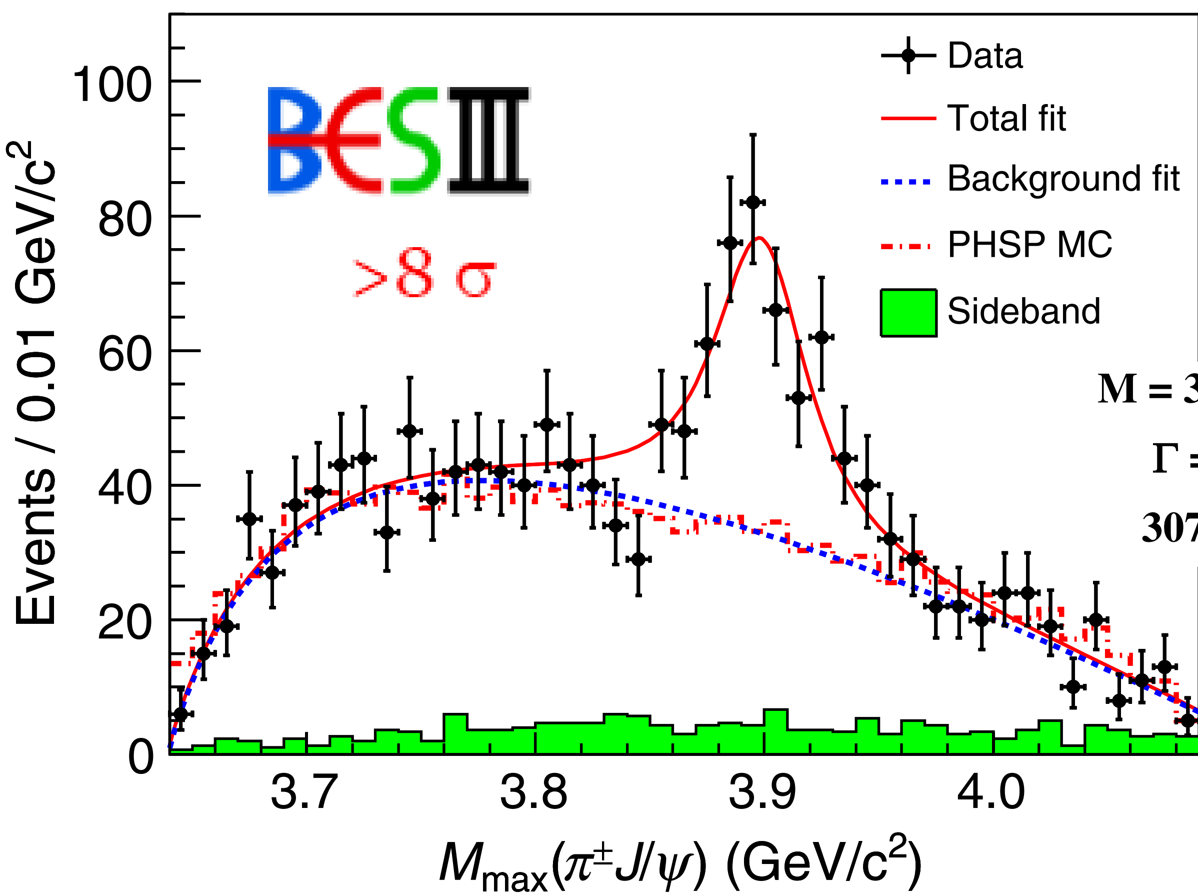
Data sets collected by BESIII since 2009

Energy & physics	*L* or *N*	Physics Topics
3097 MeV: J/ψ	1.3×10^9	light hadron spectroscopy
3686 MeV: ψ’	0.5×10^9	charmonium transitions; light hadron spectroscopy
ψ(3770)	2.9 fb^{-1}	*D* decays; precision flavor physics
ψ(4040)	0.5 fb^{-1}	charmonium spectroscopy
3554 MeV	0.024 fb^{-1}	precision determination of τ mass
4230 MeV - 4260 MeV	1.9 fb^{-1}	charmonium spectroscopy; study of **Y(4260)**
4360 MeV	0.5 fb^{-1}	charmonium spectroscopy; study of *Y*(4360)
4100 MeV - 4400 MeV	0.5 fb^{-1}	coarse scan; *Y* spectroscopy
3850 MeV - 4590 MeV	0.8 fb^{-1}	fine scan; R measurement; *Y* spectroscopy
4600 MeV	0.5 fb^{-1}	charmonium spectroscopy

(Red: partial or full data sets for the analyses presented today)

Z(3900): Discovery of a charged Charmonium-Like State

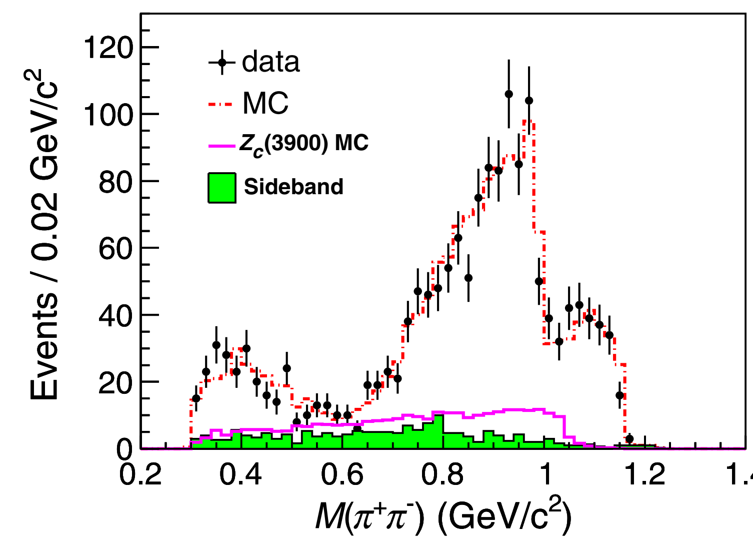
- Idea: Y(4260) seems exotic - let's look at its decay products
- Strong decay to J/ψ $\pi^+\pi^-$
- Analyze Dalitz plot, understand structures in $\pi^+\pi^-$ mass spectrum (scalar mesons)



M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

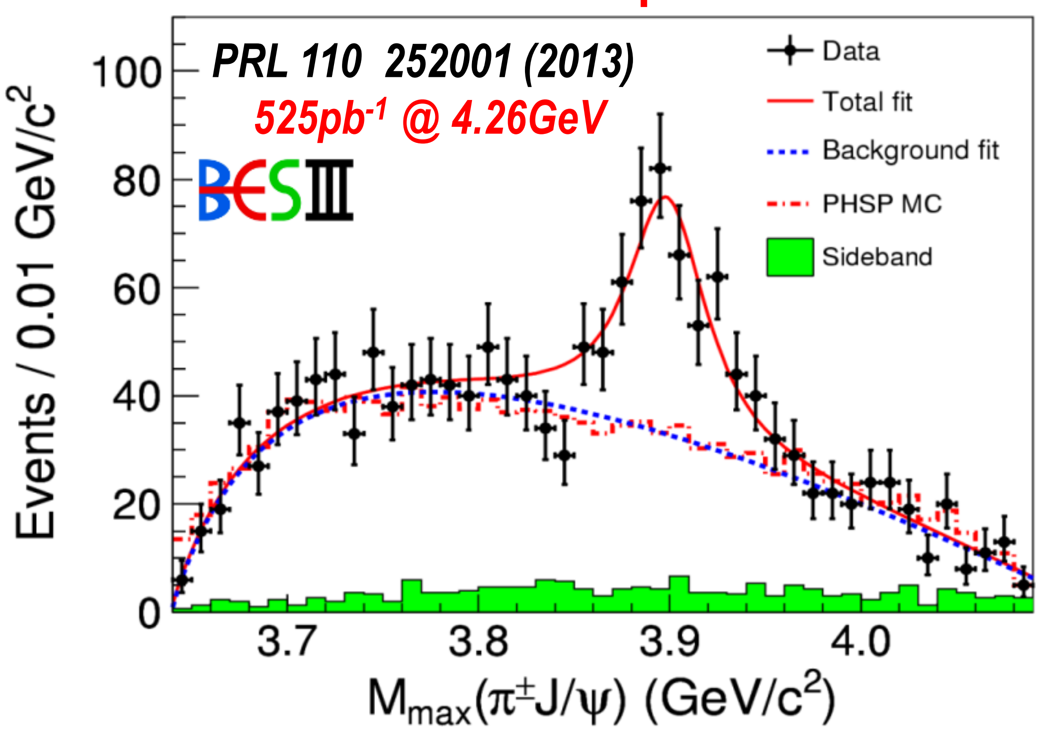
307 ± 48 events, >8σ

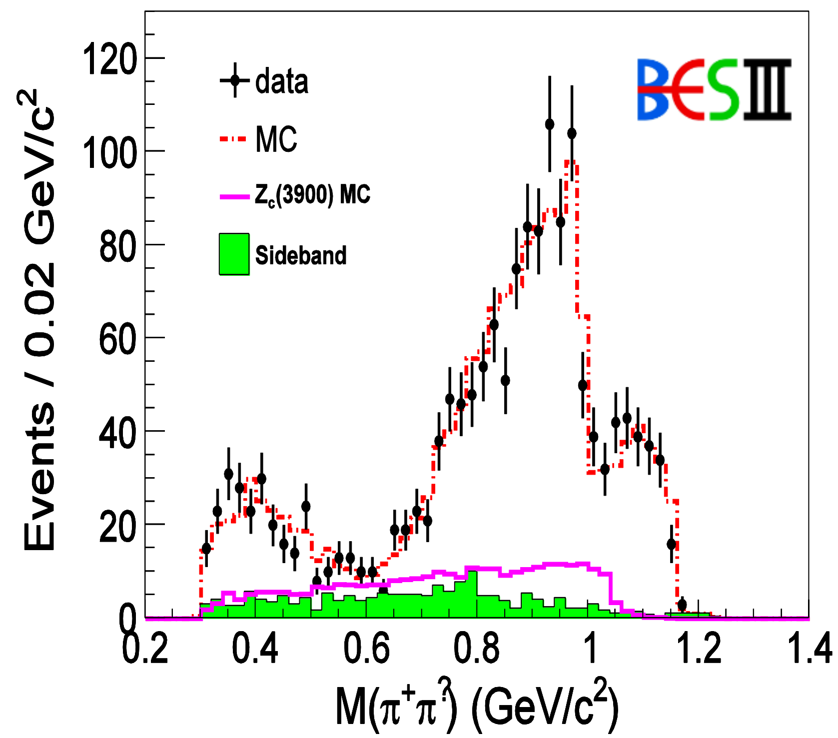


- **Clear evidence for a charged charmonium-like state !**

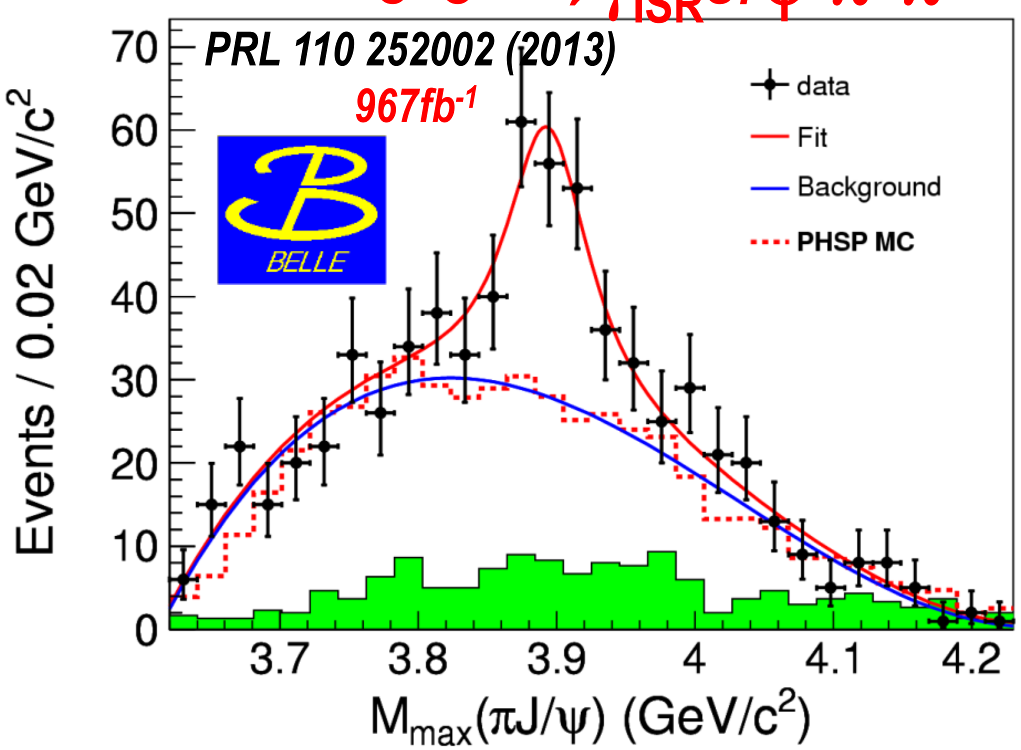
Z(3900): Confirmation by Belle and CLEO-c-Data

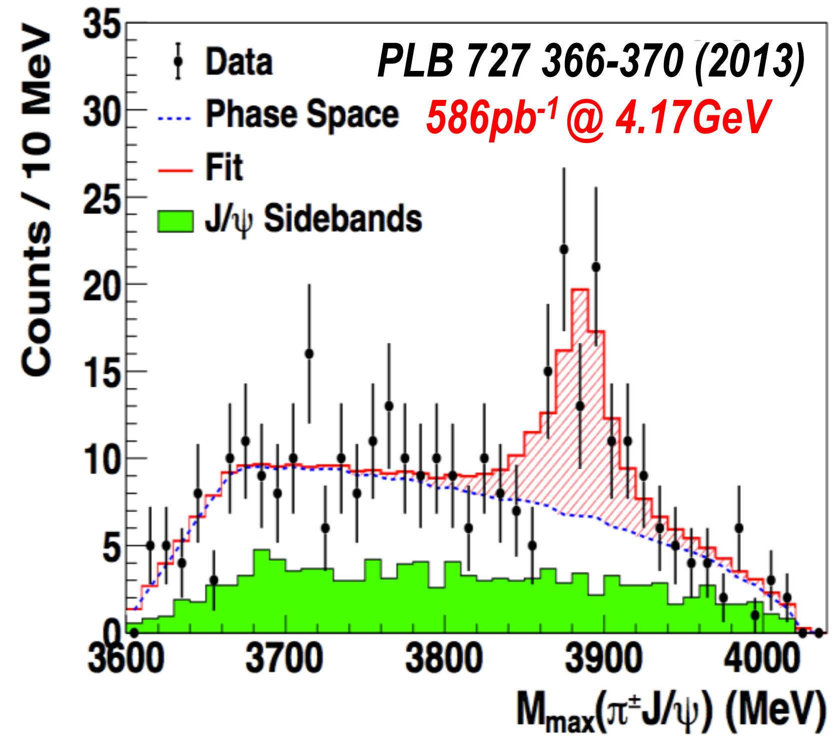
$e^+e^- \to J/\psi\, \pi^+\pi^-$





$e^+e^- \to \gamma_{ISR} J/\psi\, \pi^+\pi^-$





BESIII

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307 ± 48 events, >8σ

BELLE

M = 3894.5±6.6±4.5 MeV

Γ = 63±24±26 MeV

159 ± 49 events, >5.2σ

CLEO-c Data

M = 3886±4±2 MeV

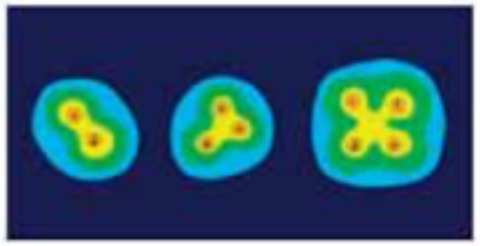
Γ = 37±4±8 MeV

81 ± 16 events, >5σ

Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

PHYSICS VIEWPOINT



New Particle Hints at Four-Quark Matter

Published 17 June 2013

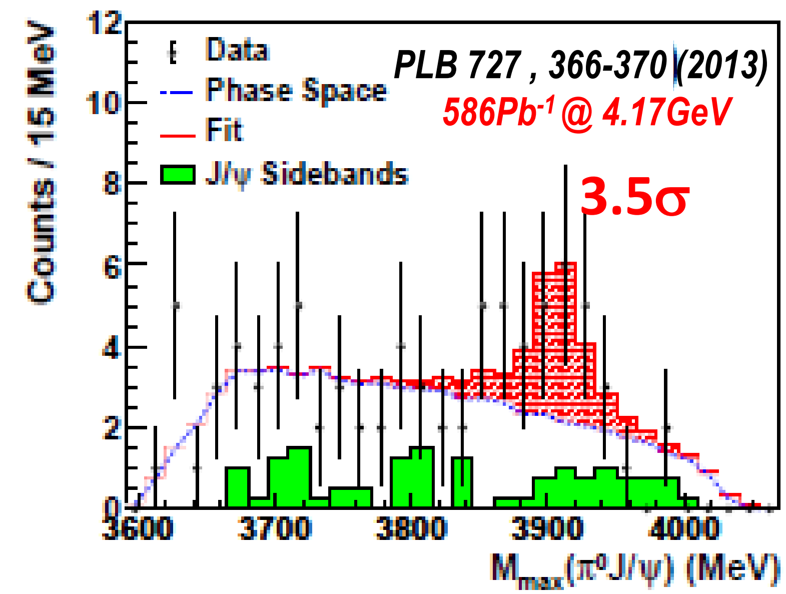
Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before.

This is the first charged Z state observed by 2 experiments!

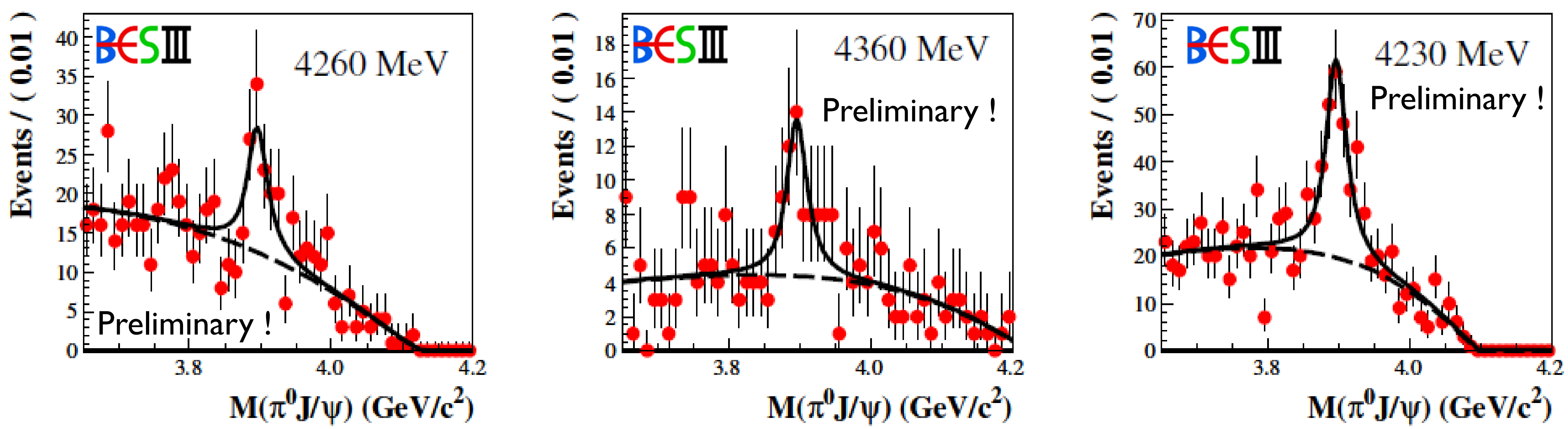
named „APS Highlight of the year 2013"
among others, e.g. extra-solar neutrinos by IceCube

How about a neutral isospin partner ?

- We have seen $Z^+(3900)$ and $Z^-(3900)$
  - Is there a $Z^0(3900)$?
- First hint from CLEO-c data



- New BES III analysis (**preliminary !!**)

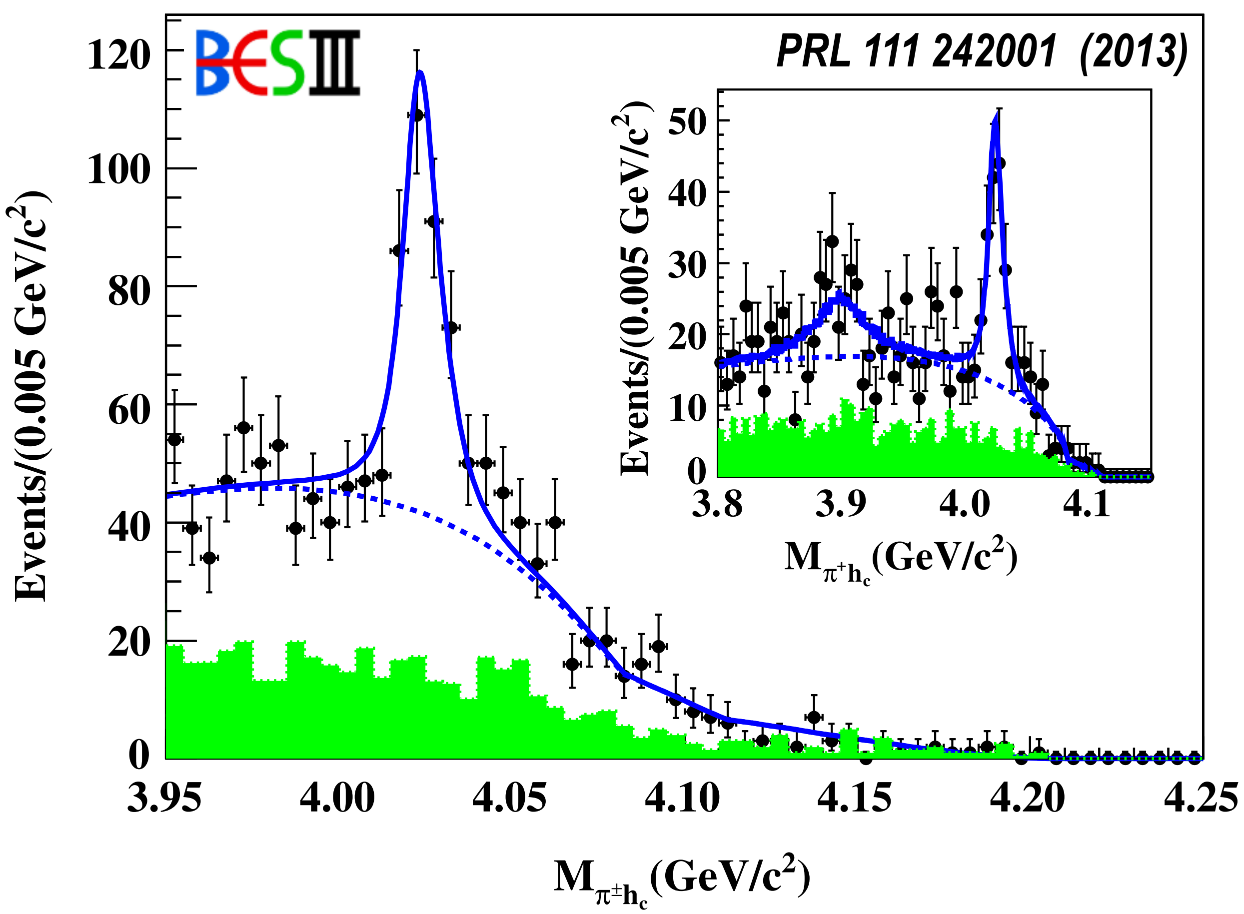


  - **M= 3894.8 ± 2.3 MeV, Γ = 29.6 ± 8.2 MeV**
  - **Significance = 10.4 σ**

This establishes an isospin triplet Z(3900)

More charged Z states ?

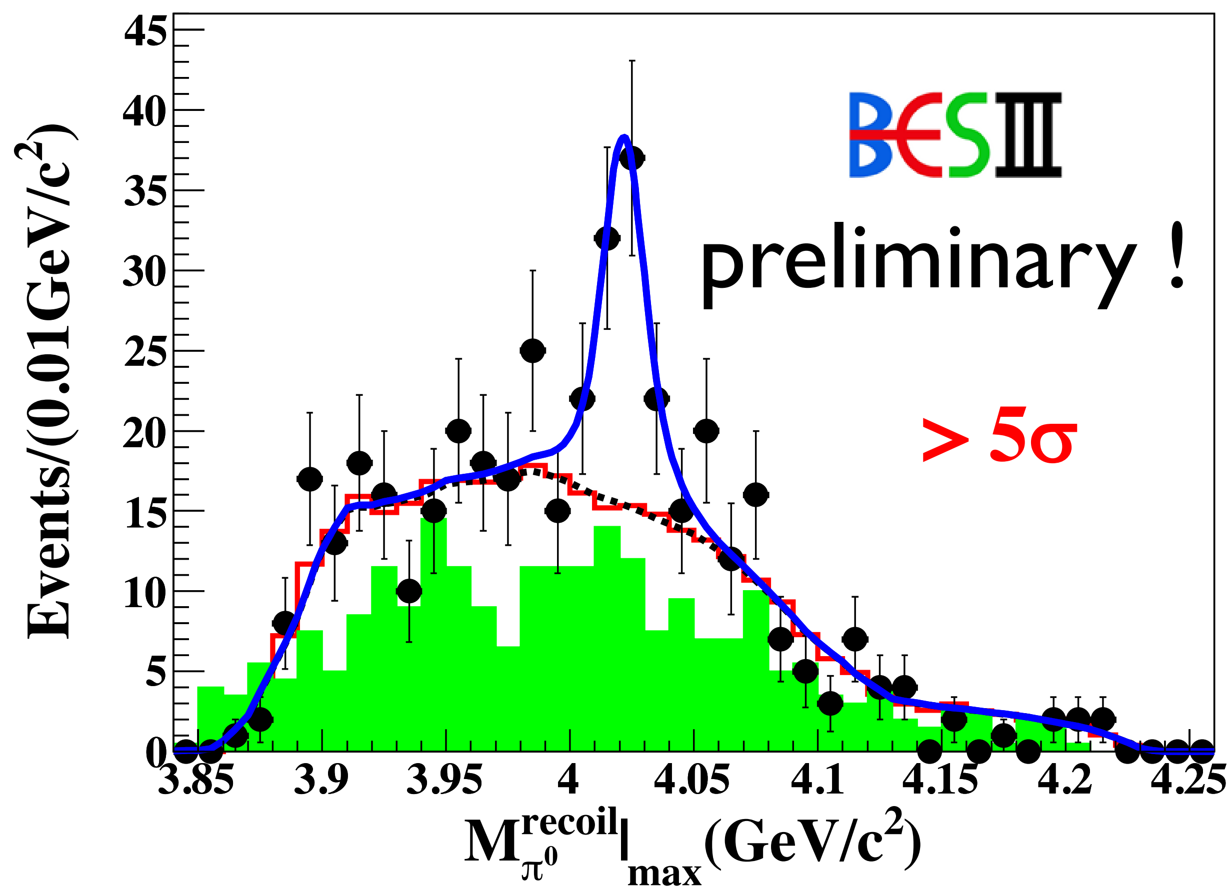
- How about $e^+e^- \Rightarrow h_c \pi^+\pi^-$
  - Detect $h_c \Rightarrow \gamma\, \eta_c$
  - Difficult (reconstruct η_c via 16 hadronic decay channels)



- Result: observation of Z(4020)
  - M = 4022.9±0.8±2.7 MeV
  - Γ= 7.9±2.7±2.6 MeV
  - Significance : 8.9σ

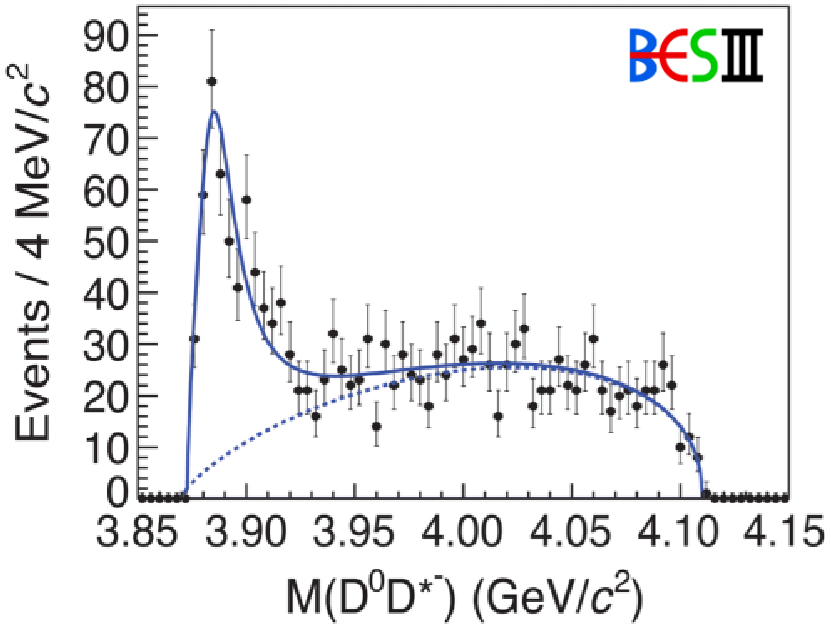
... and there is also the neutral isospin partner !

- Select events with $\pi^0\pi^0 h_c$ final state:
  - reconstruct h_c
    - h_c ➠ $\gamma\ \eta_c$
    - η_c ➠ 16 exclusive hadronic channels
  - Look at distribution of π^0 recoil mass after event selection



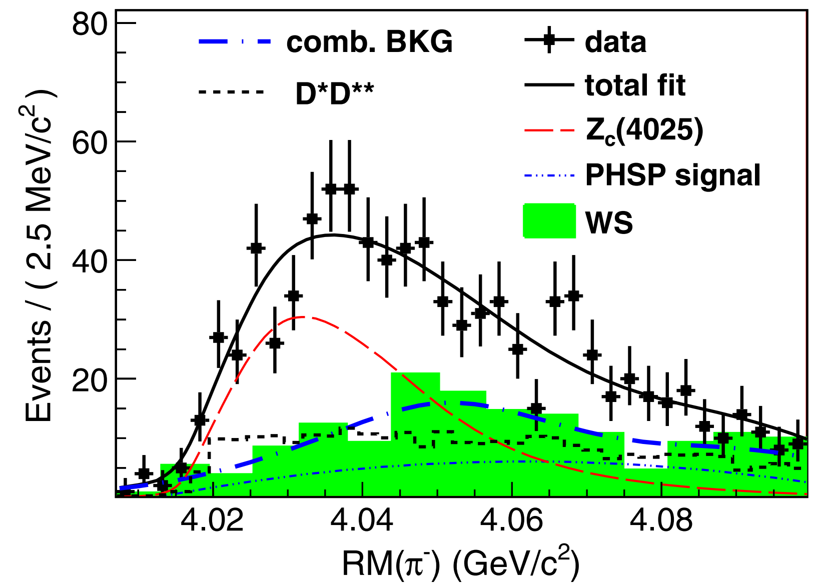
- Evidence for a neutral partner of the Z(4020)
- M=(4023.6 ± 2.2 ± 3.8) MeV/c²

Are there charged charmonium-like states decaying into open charm ?



e$^+$e$^-$→π$^\pm$(DD*)$^\mp$ **@4.26GeV**

PRL **112,** 022001 (2014)



$e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$ **@4.26GeV**

PRL **112,** 132001 (2014)

- **Charged charmonium like structure found:**

	$Z_c(3885) \rightarrow D\bar{D}^*$	$Z_c(3900) \rightarrow \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899.0 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$

- **Very similar parameters as Z(3900), possibly same state !**

- Signal line shape and angular distribution agree with $J^P=1^+$

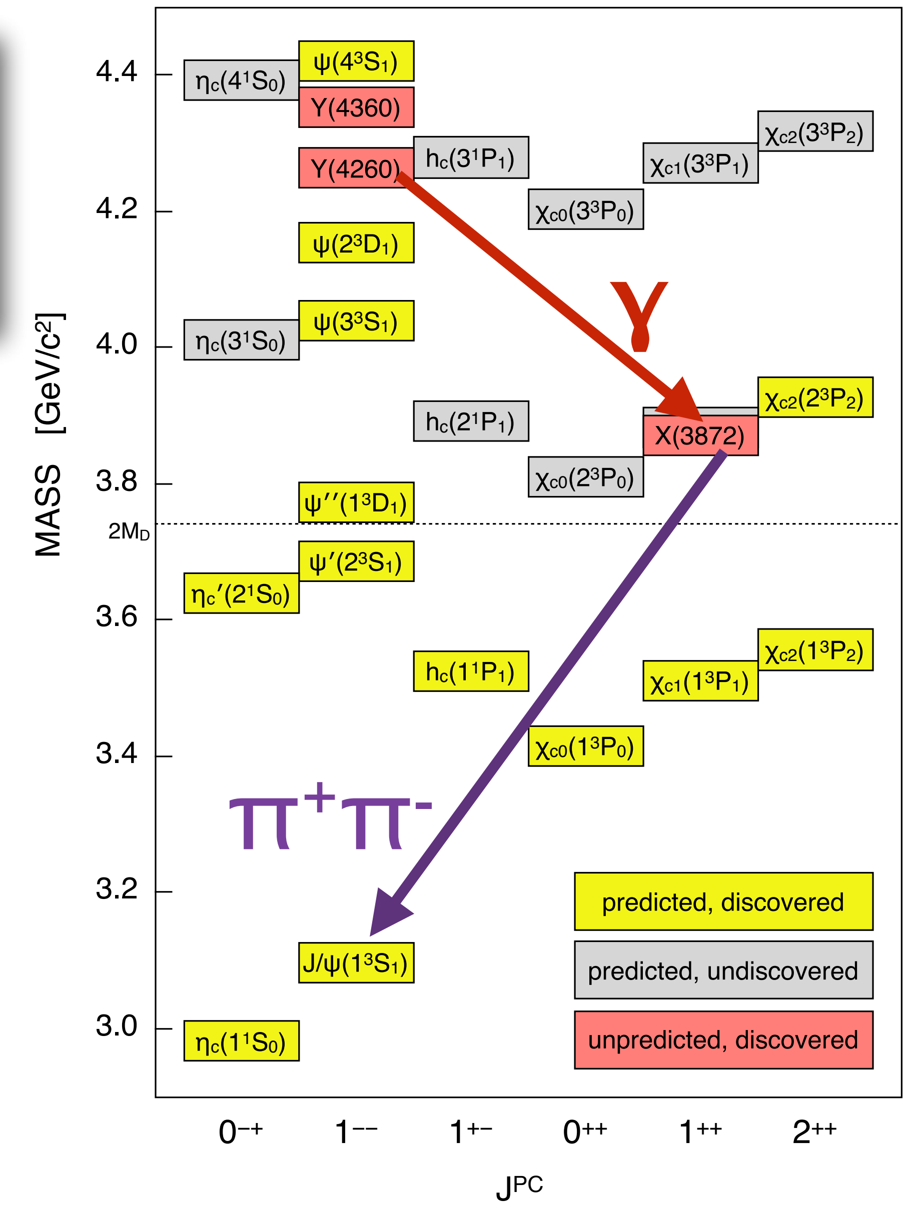
- **Charged charmonium like structure found:**

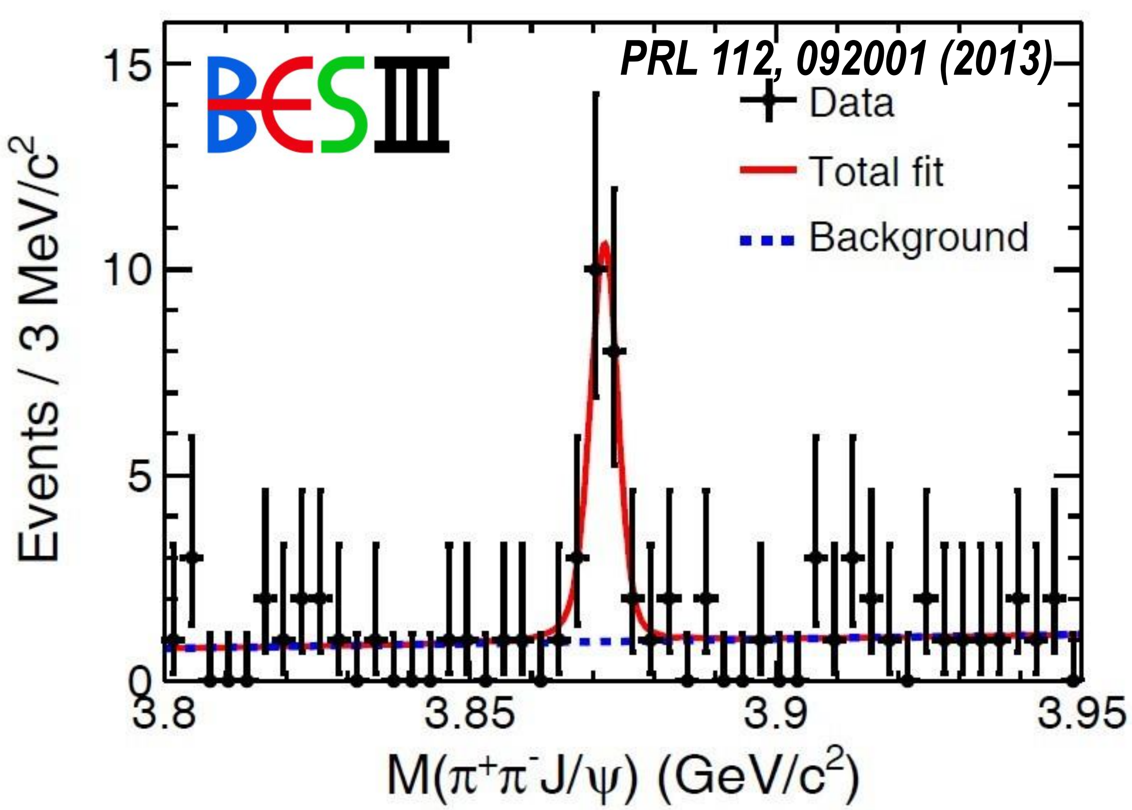
$$m(Z_c^+(4025)) = (4026.3 \pm 2.6)\ \mathrm{MeV}/c^2,$$
$$\Gamma(Z_c^+(4025)) = (24.8 \pm 5.6)\ \mathrm{MeV}.$$

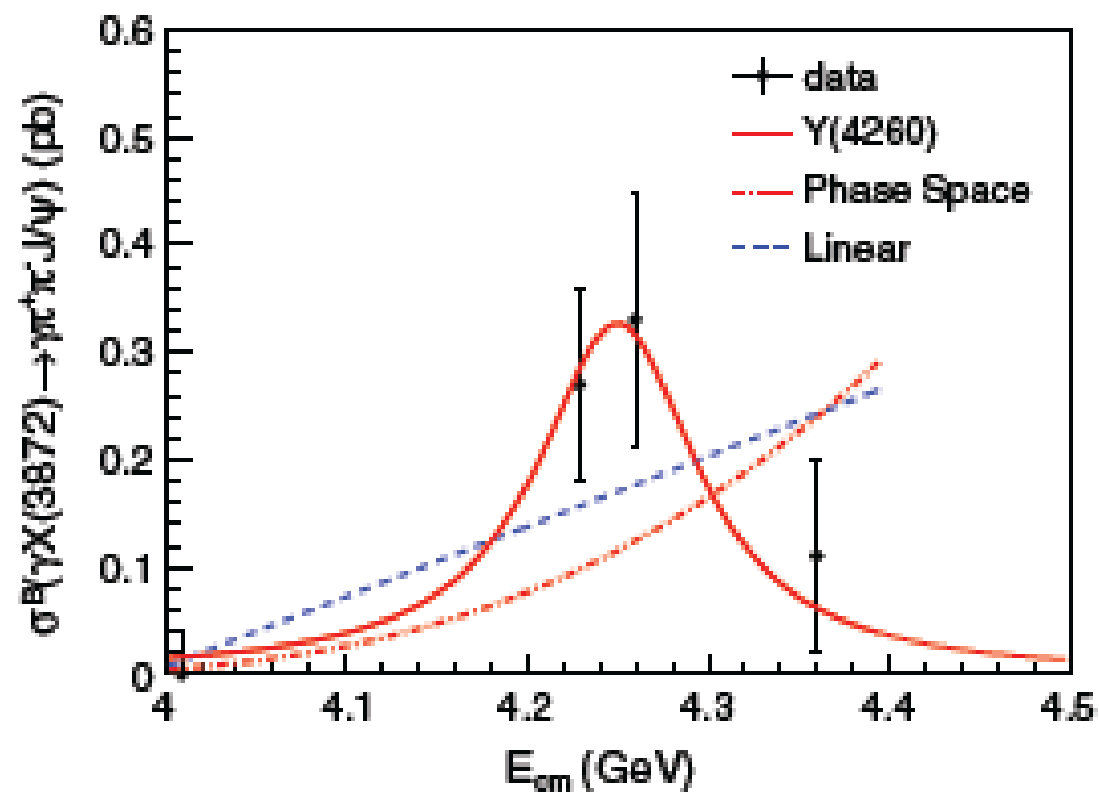
- **Very similar parameters as Z(4020), possibly same state !**

How about radiative transitions between XYZ states ?

- Y(4260) is a 1^{--} state
- X(3872) is a 1^{++} state
  - Look for gamma ray transition:
    - Y(4260) ➟ γ X(3872) ➟ γ J/ψ $\pi^+\pi^-$







Summary and Outlook

- Charmonium is an excellent probe to study QCD in the transition between the perturbative and non-perturbative regime
- Within the last 10 years, a whole new class of charmonium -like states has been discovered that have properties which cannot be understood in terms of conventional charmonium states
  - **The structure of these states is not well understood**
    - Many models exist
    - We really need to work hard in order to understand the strong interaction !
    - Remarkable feature: many X, Z - states close to open charm thresholds
- We know today, that there are **charged states that must contain at least 2 quark / anti-quark pairs**
  - This is the first solid proof that QCD has to offer more types of bound states than just mesons and baryons
    - Tetraquarks, meson molecules, ….. ???
- The currently running experiments (BES III, LHCb) and the future experiments (Belle II, PANDA) will hopefully solve the puzzle of the XYZ states, together with refined models and more fundamental calculations (LQCD, effective field theories, Dyson-Schwinger, …)