university of groningen

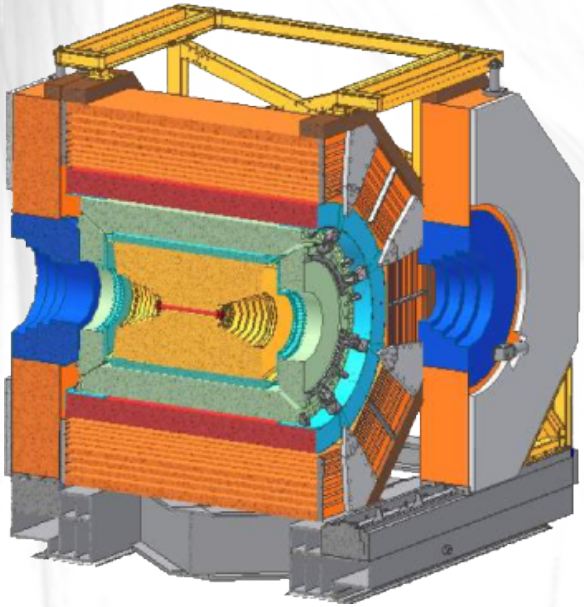
kvi - center for advanced radiation technology

Recents results on charmonium-like states at BESIII: Collecting Pieces of the "Exotic-matter" Puzzle

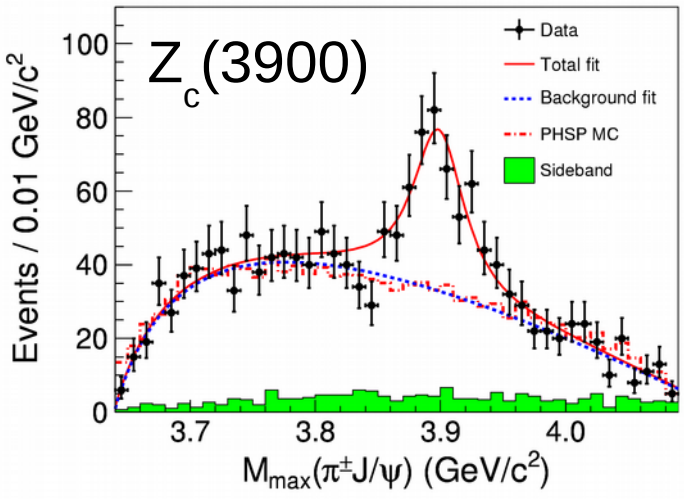
Myroslav Kavatsyuk

KVI – Center for Advanced Radiation Technology, University of Groningen

For the BESIII collaboration



- **Hadron landscape and the BESIII**
- **Exotic hadron matter at BESIII**

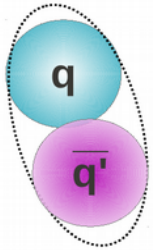


Hadron Matter

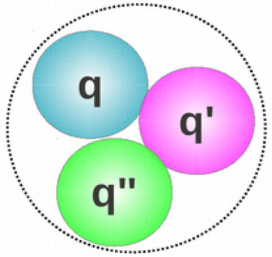
Colour-neutral states allowed by QCD

Conventional matter

Pions, charmonium, etc



Meson

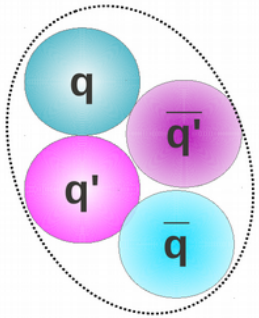


Baryon

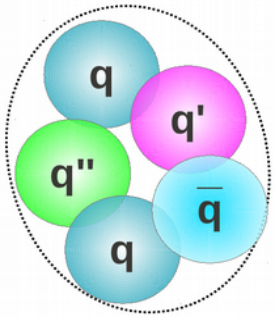
Protons, neurons, etc

Exotic matter

Z_c and Z_b states



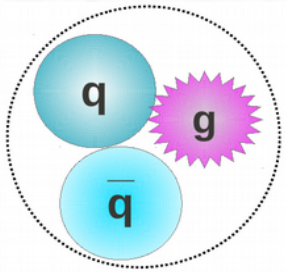
Four-quark state



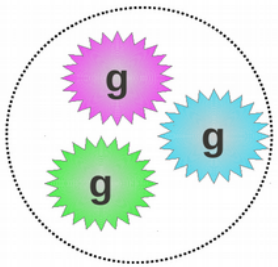
Five-quark state

Pentaquark?

XY states?



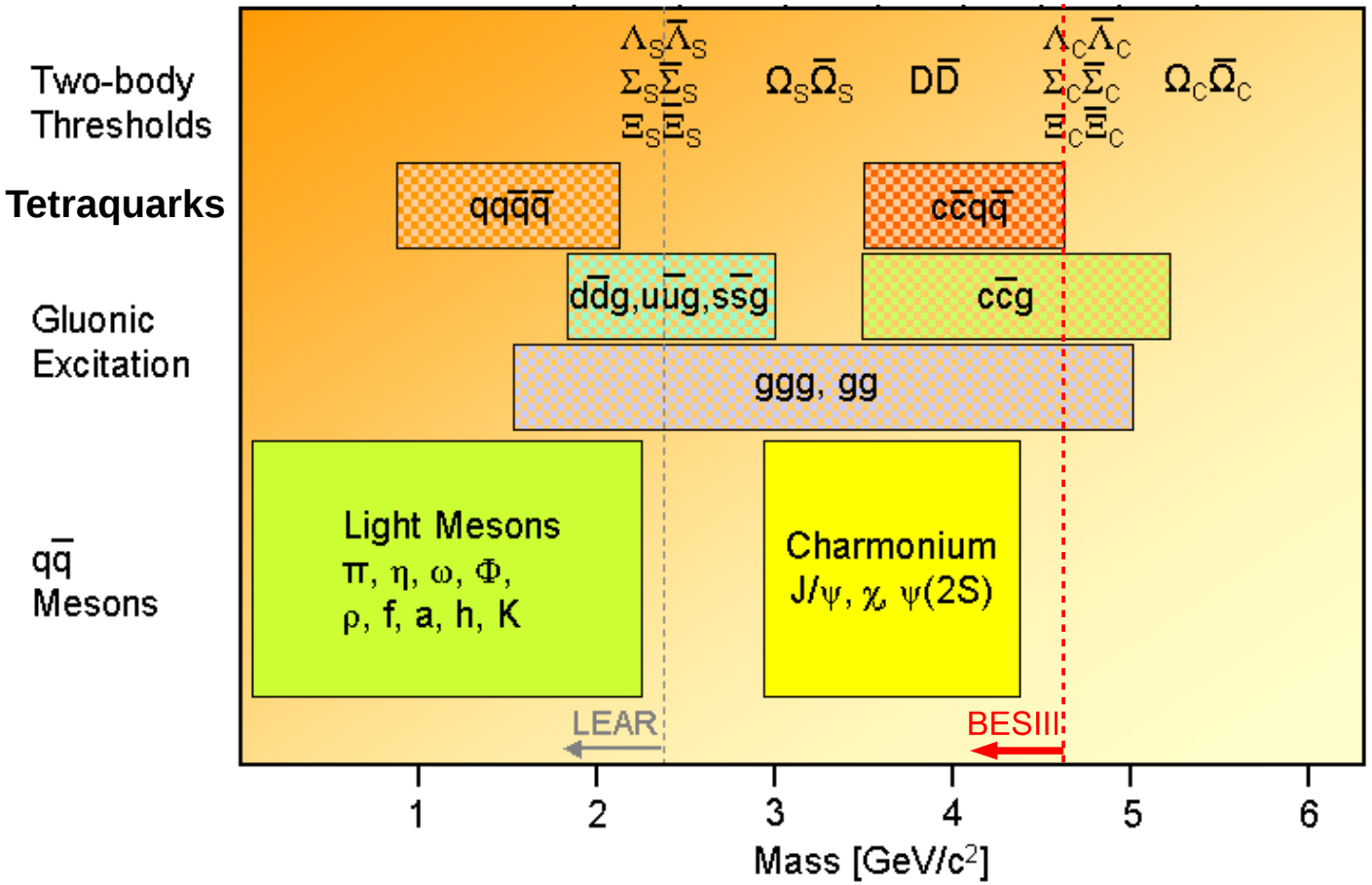
Hybrid



Glueball

$f_0(1500)$?
$f_0(1500)$?
XY states?
...

Hadron Landscape



Hadron-physics challenges:

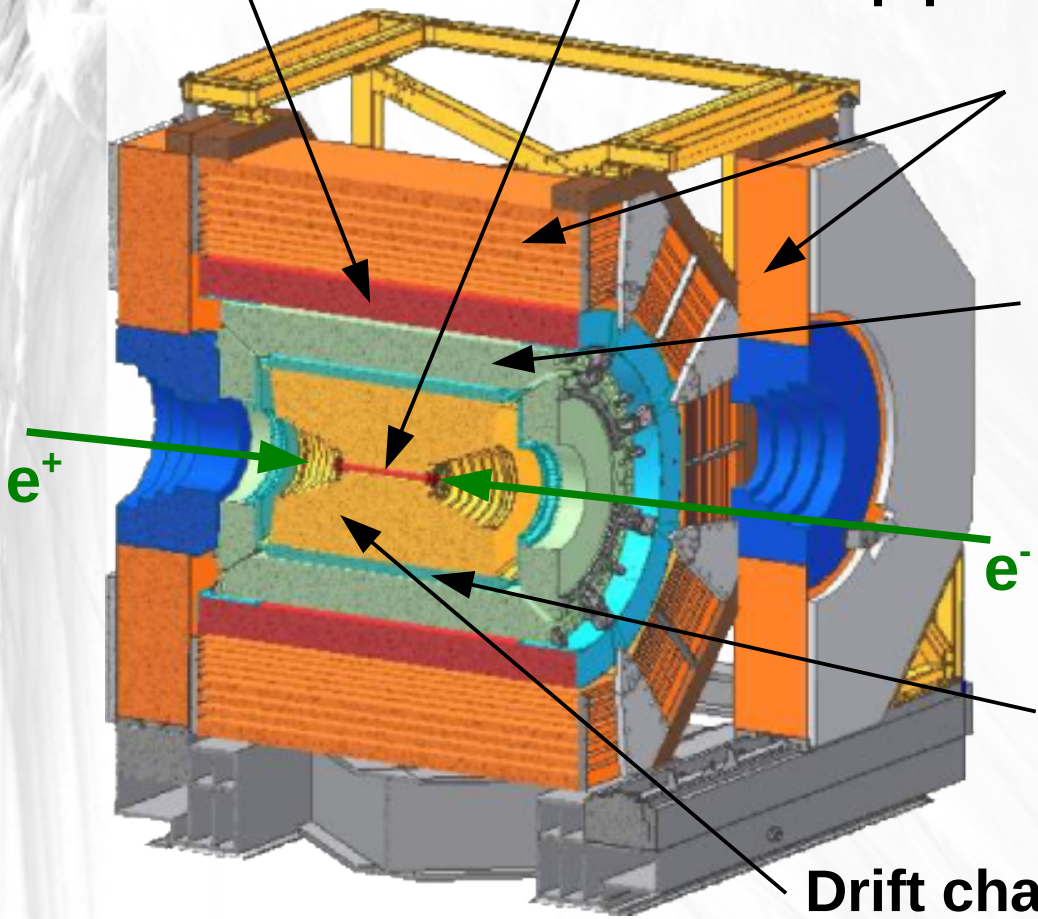
- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

Clean environment and high luminosity are required for resolving puzzle of exotic matter

BESIII Detector

1.0 Tesla **super-conducting magnet**

Be beam pipe



Muon counters:
9/8 RPC layers (barrel/endcaps)
Cut-off momentum: 0.4 GeV/c

CsI(Tl) **ElectroMagnetic Calorimeter:**
σ_E/E (at 1 GeV): 2.5 %
$\sigma_{z,\phi}$ (at 1 GeV): 6 mm

Time Of Flight (TOF):
σ_T: 100/110 ps (barrel/endcaps)

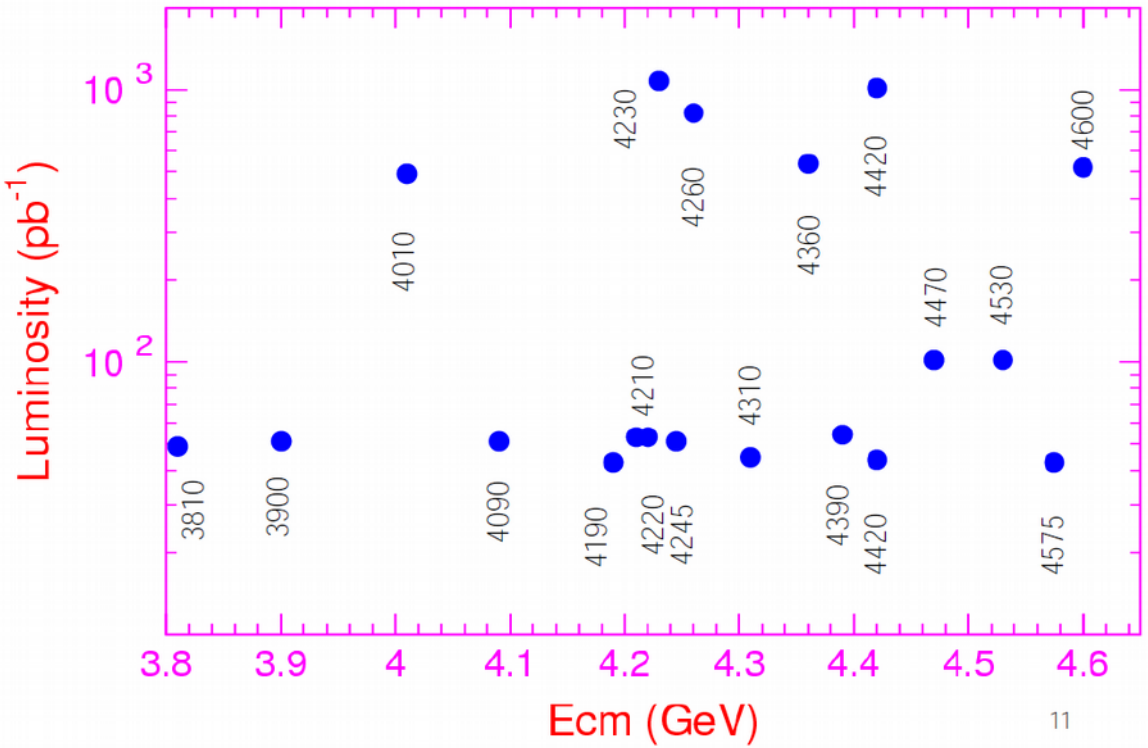
Drift chambers (MDC):
σ_p/p (at 1 GeV): 0.5 %
$\sigma_{dE/dx}$: 6 %

M. Ablikim *et al.*, Nucl. Instr. and Meth. **A 614** (2010) 345–399

BESIII: Collected Data

July 18, 2008: First $e^+ e^-$ collision event in BESIII

~ 0.6 B	Ψ' events	~ 24×CLEO-c
~ 1.2 B	J/Ψ events	~ 21×BESII
~ 42pb^{-1}	at 3.65 GeV	
~ 2.9fb^{-1}	Ψ''	~ 11×CLEO-c
~ 70pb^{-1}	scanning of the Ψ'' region	



- 104 energy points between **3.85** and **4.6 GeV**
- ~20 energy points between **2.0** and **3.1 GeV**

Record Luminosity so far:

8.5×10^{32} cm^{-2} s^{-1}

(design value: 10^{33} cm^{-2} s^{-1})

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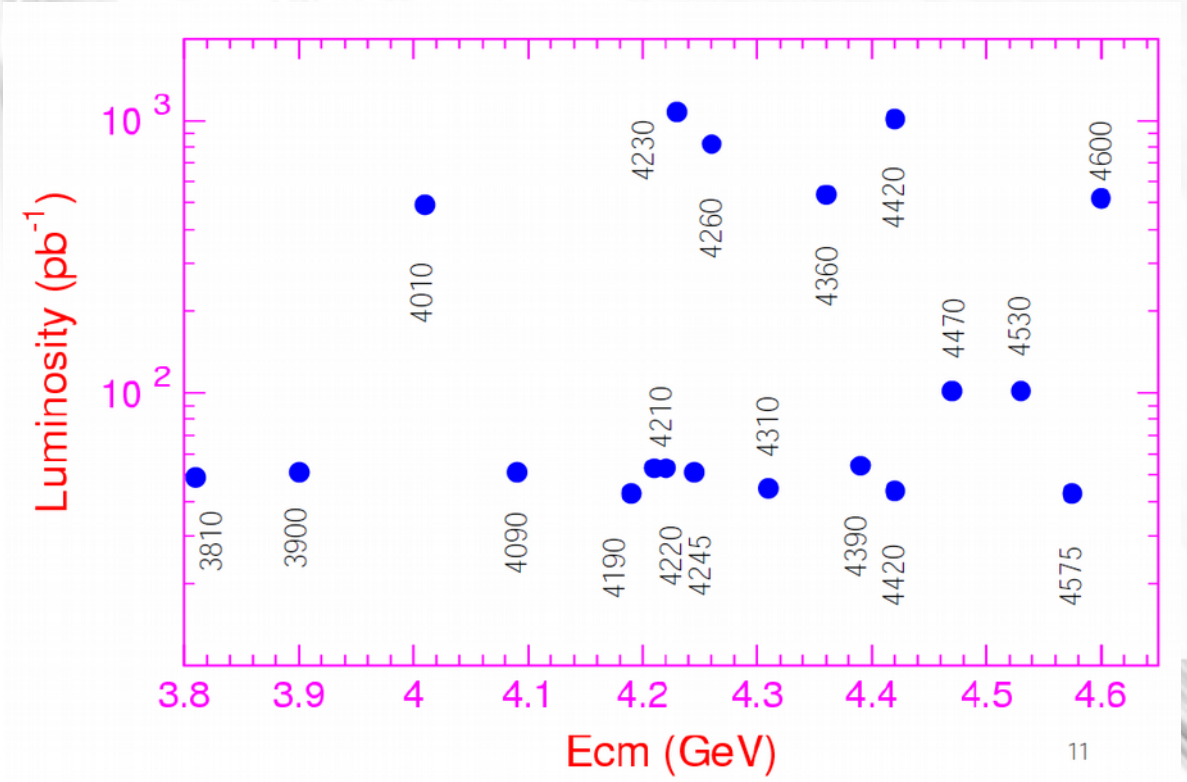
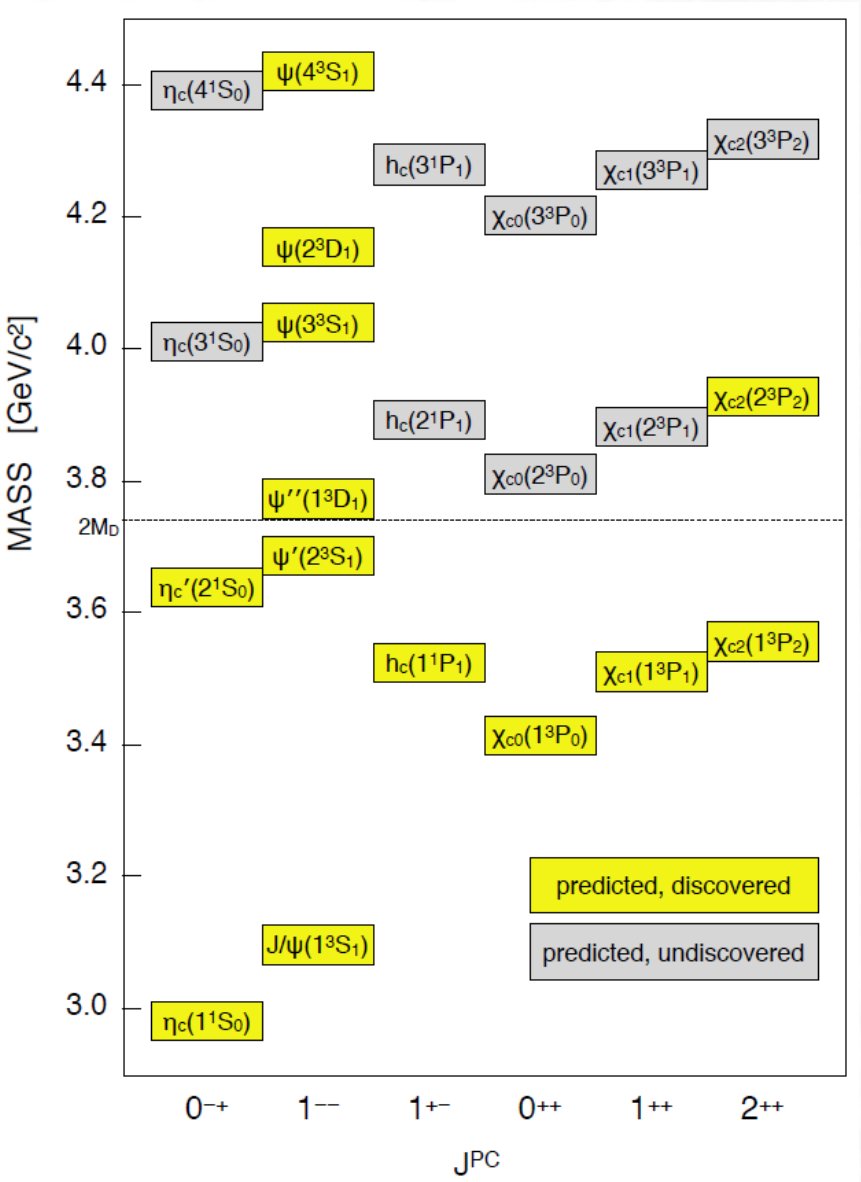


High luminosity,
clean environment

Access to precise measurements of rare processes:

Key to understanding of exotic matter

Charmonium Region



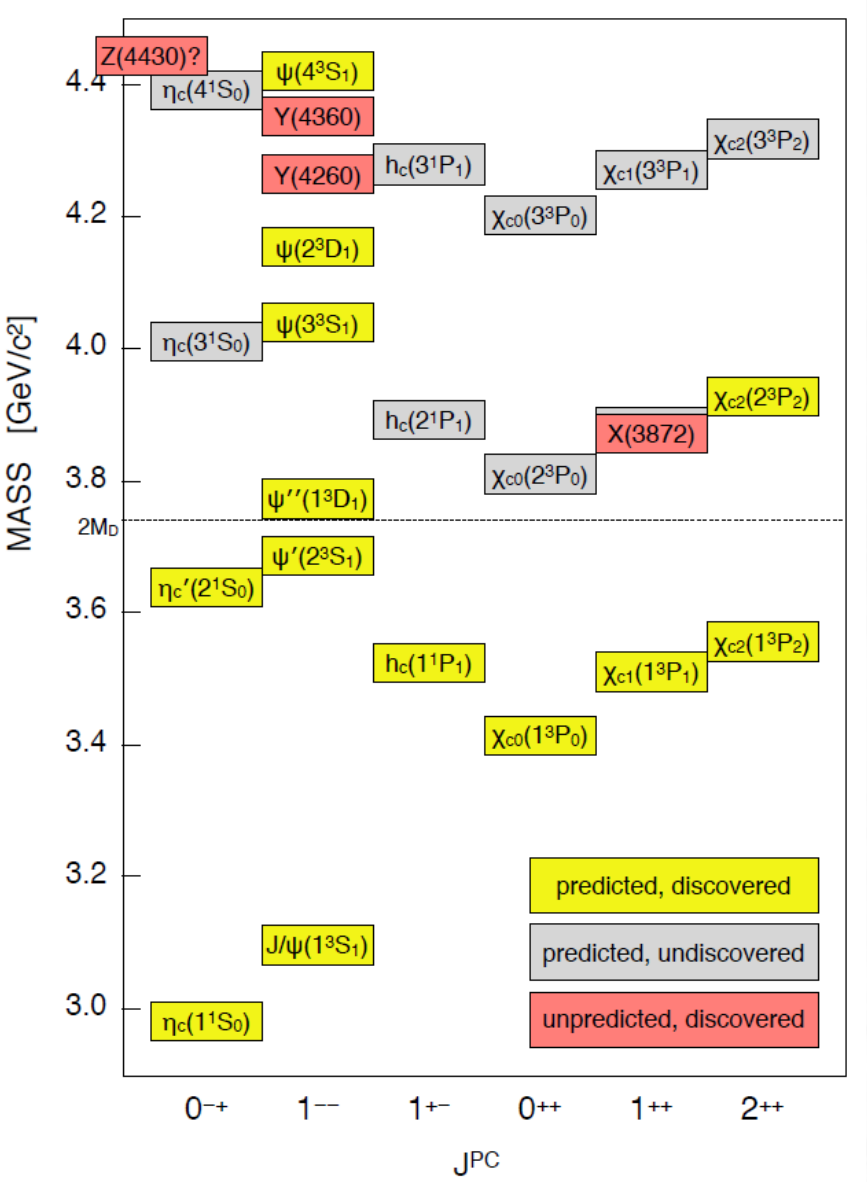
Hidden-charm region of the spectrum is well understood,

however,

in the open-charm region there are predicted states, but not yet seen...

Moreover...

Charmonium Region



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Moreover...

In the last decade there were found not-predicted charmonium-like states with unexpected properties

Mysterious XYZ States…

… unexpectedly narrow for mesons in the open-charm region, strongly coupled to charmonium: What is their nature?

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (<2.2)	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^- J/\psi)$ $p\bar{p}\to(\pi^+\pi^- J/\psi)+\ldots$ $B\to K(\omega J/\psi)$ $B\to K(D^{*0}\bar{D}^0)$ $B\to K(\gamma J/\psi)$ $B\to K(\gamma\psi(2S))$	Belle [85, 86] (12.8), *BABAR* [87] (8.6) CDF [88–90] (np), DØ [91] (5.2) Belle [92] (4.3), *BABAR* [93] (4.0) Belle [94, 95] (6.4), *BABAR* [96] (4.9) Belle [92] (4.0), *BABAR* [97, 98] (3.6) *BABAR* [98] (3.5), Belle [99] (0.4)	2003	OK
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B\to K(\omega J/\psi)$ $e^+e^-\to e^+e^-(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19) Belle [102] (7.7)	2004	OK
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$ $e^+e^-\to J/\psi\ (\ldots)$	Belle [103] (6.0) Belle [54] (5.0)	2007	NC!
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$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$ $e^+e^-\to(\pi^+\pi^- J/\psi)$ $e^+e^-\to(\pi^0\pi^0 J/\psi)$	*BABAR* [108, 109] (8.0) CLEO [110] (5.4) Belle [104] (15) CLEO [111] (11) CLEO [111] (5.1)	2005	OK
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
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[EPJ C71, 1534 (2011)]

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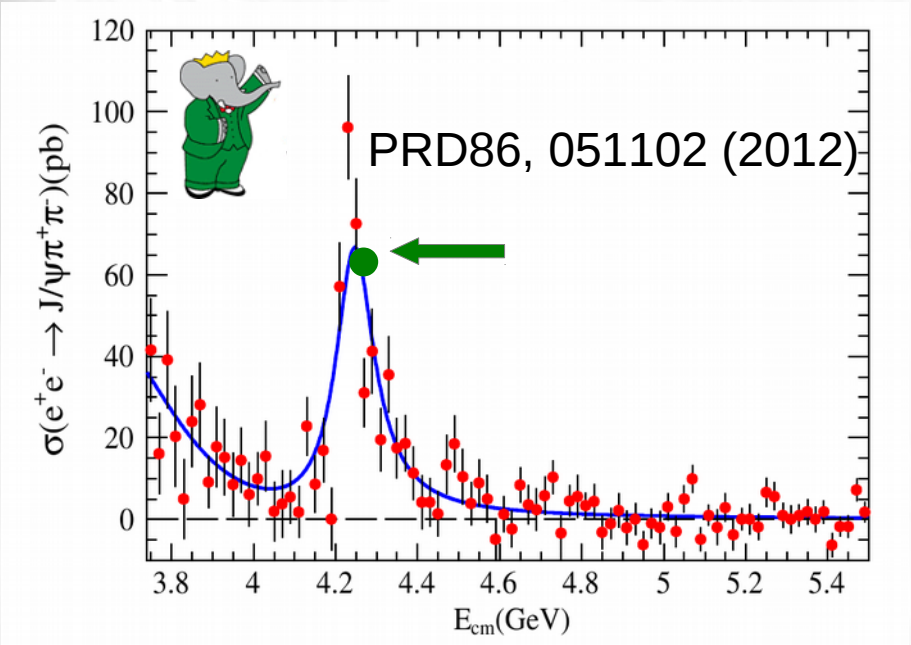
Systematic studies at BESIII of Y(4260), Y(4360)

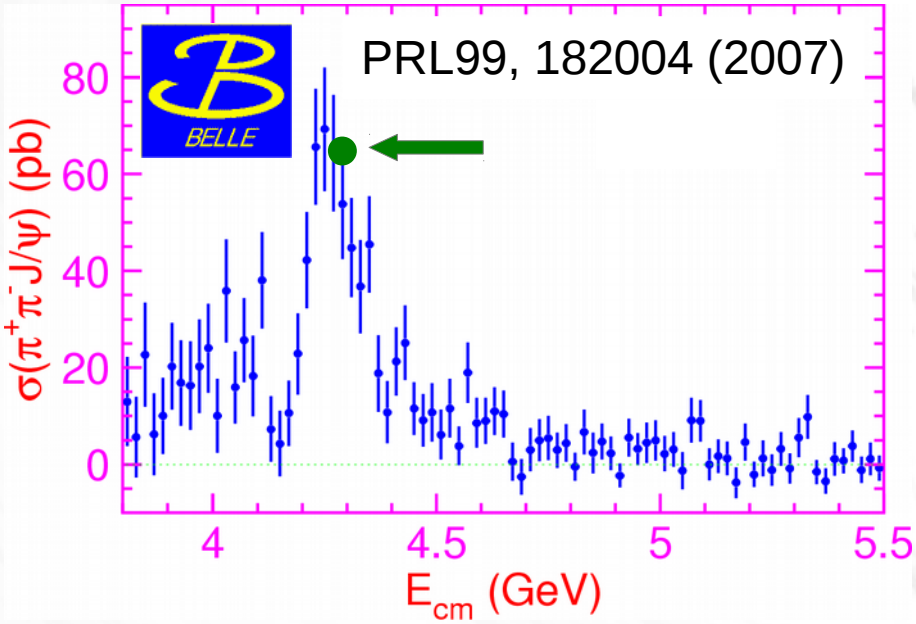
[EPJ C71, 1534 (2011)]

Studies of Y(4260) at BESIII

Y(4260):

- Does not fit any potential model.
- Has a small coupling to open charm
- $J^{PC} = 1^{--}$
- A hybrid candidate according to Lattice QCD calculations!
  [JHEP 1207, 126 (2012)]

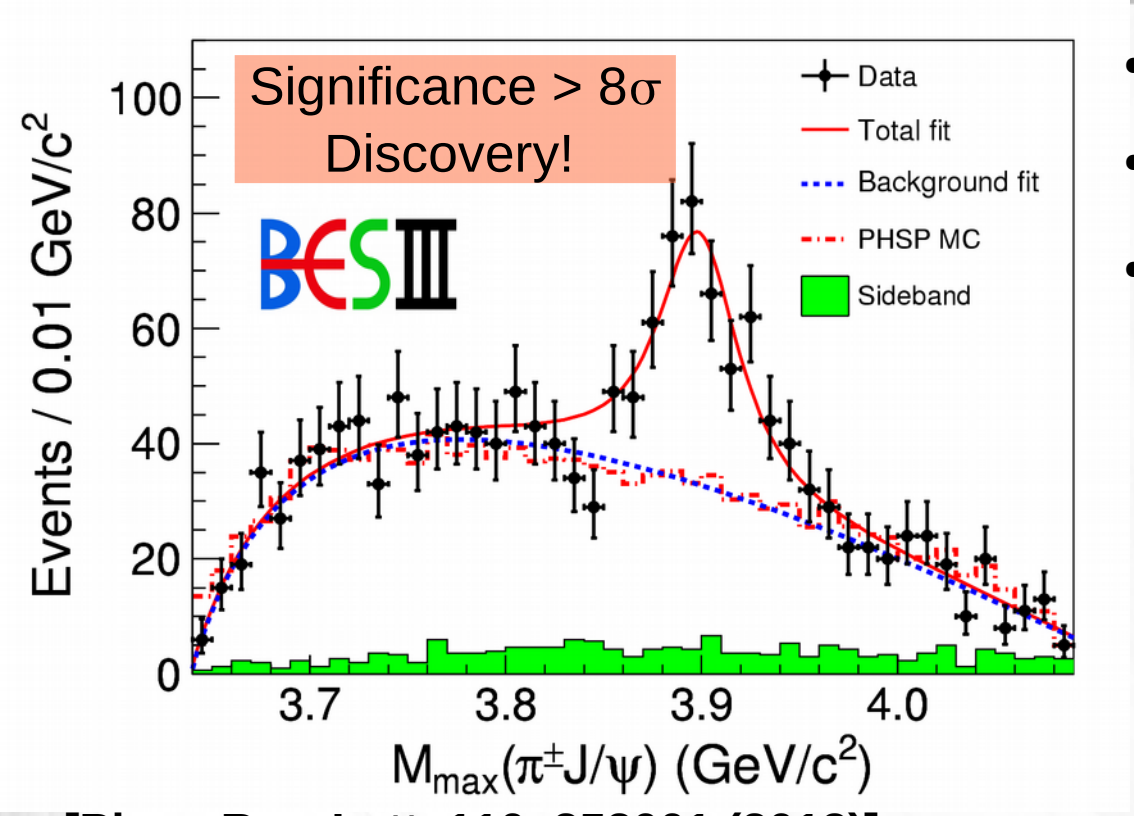




BESIII: $\sigma^B = 62.9 \pm 1.9 \pm 3.7$ pb

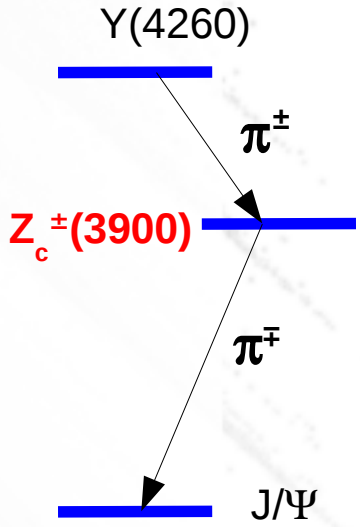
[Phys. Rev. Lett. 110, 252001 (2013)]

The $Z_c(3900)^{\pm}$

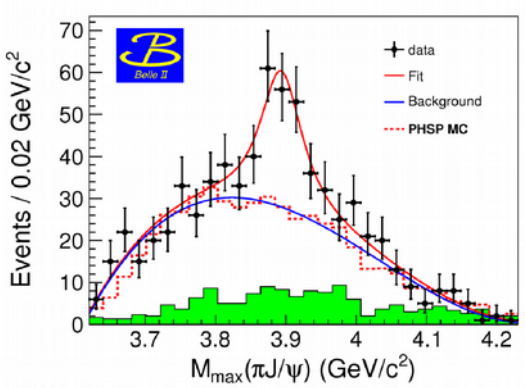


[Phys. Rev. Lett. 110, 252001 (2013)]

- Fit with S-wave Breit-Wigner
- **M = (3899.0±3.6±4.9) MeV/c^2**
- **Γ = (46±10±20) MeV**



Discovered by BESIII, promptly confirmed by:



Belle: [Phys. Rev. Lett. 110, 252002 (2013)]

M = 3894.5 ± 6.6 ± 4.5 MeV/c^2

Γ = 63 ± 24 ± 26 MeV

CLEO-c: [Phys. Lett. B 727, 366 (2013)]

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$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

$Z_c(3900)$ – first confirmed Z state!

[EPJ C71, 1534 (2011)]

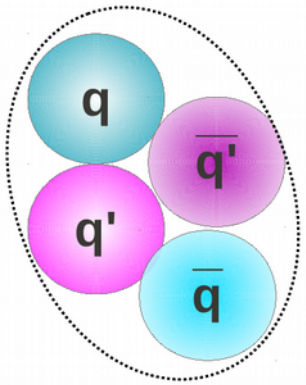
$Z_c(3900)$ Structure?

… **unexpectedly narrow for mesons in the open-charm region, strongly coupled to charmonium: What is their nature?**

Z states:

- Charged states
- Strongly coupled to charm

→ **can not be conventional mesons**

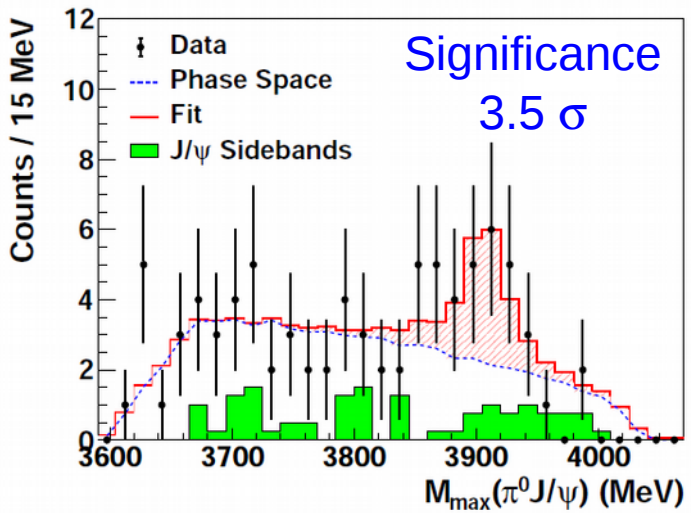


Four-quark state

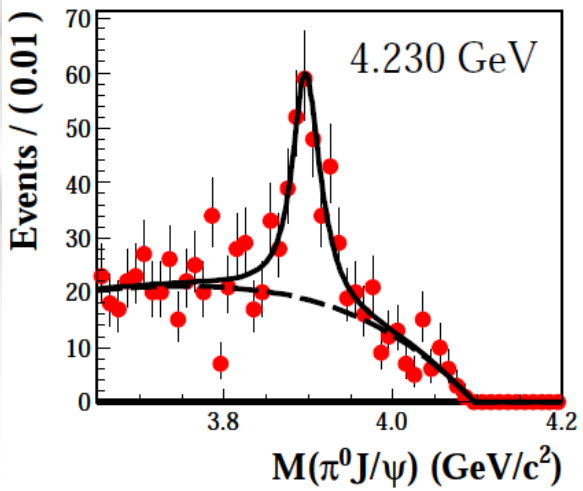
?

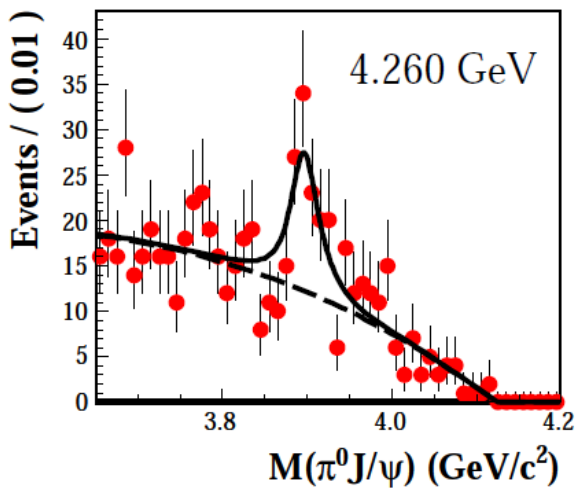
Does a neutral partner $Z_c(3900)^0$ exists?

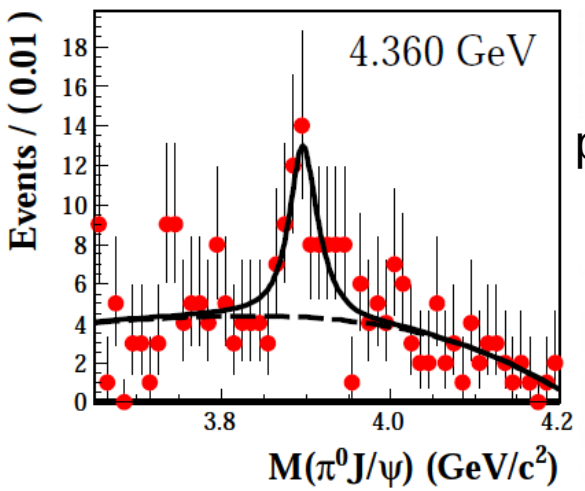
The $Z_c(3900)^0$



Evidence for $Z_c(3900)^0$
is seen by the CLEO-c
[Phys. Lett. B 727, 366 (2013)]







preliminary

Structure is seen in $\pi^0 J/\Psi$ (10σ significance):

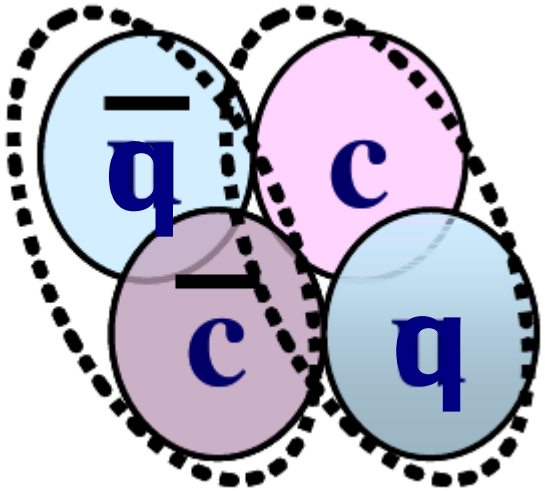
- **M = (3894.0±2.3±2.7) MeV/c^2**
- **Γ = (29±8.2±8.2) MeV**

$Z_c(3900)$ – four-quark isospin triplet?

Nature of the $Z_c(3900)$

Most popular models

Tetraquark

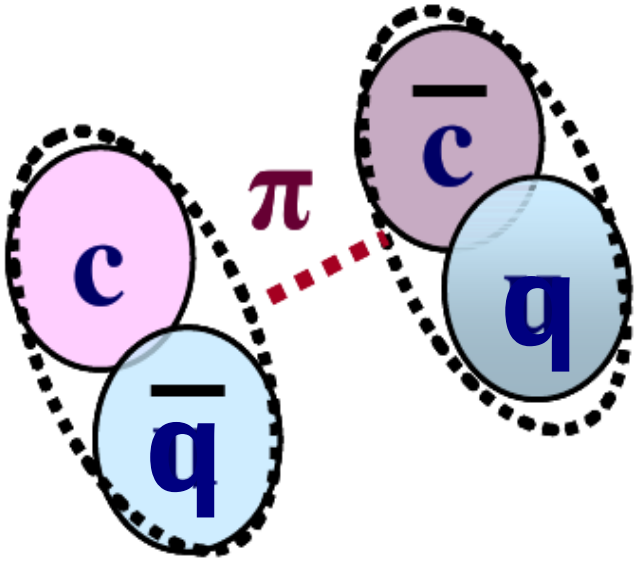


Interact by gluonic color force

[PRD 87, 111102(R) (2013)]
[arXiv:1304.0345, 1304.1301]

[arXiv: 1304.0380]

Hadronic molecule



2 color-neutral mesons
Interact by pion exchange

[PRD 88, 054007 (2013)]
[Phys. Lett. B726, 326 (2013)]
[arXiv:1304.1850]

Other models:

- Meson loop **[arXiv: 1303.6355, 1304.4458]**
- Initial State Pion Emission (ISPE) model

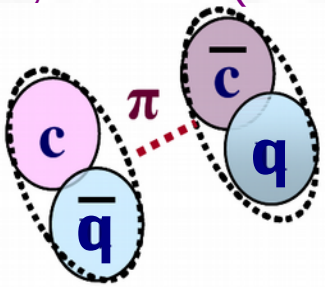
[PRL 110, 232001 (2013), PRD 88, 036008 (2013)]

- Hadro-charmonium **[M. B. Voloshin]**

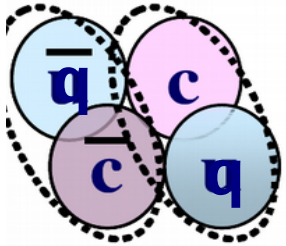
Nature of the $Z_c(3900)$

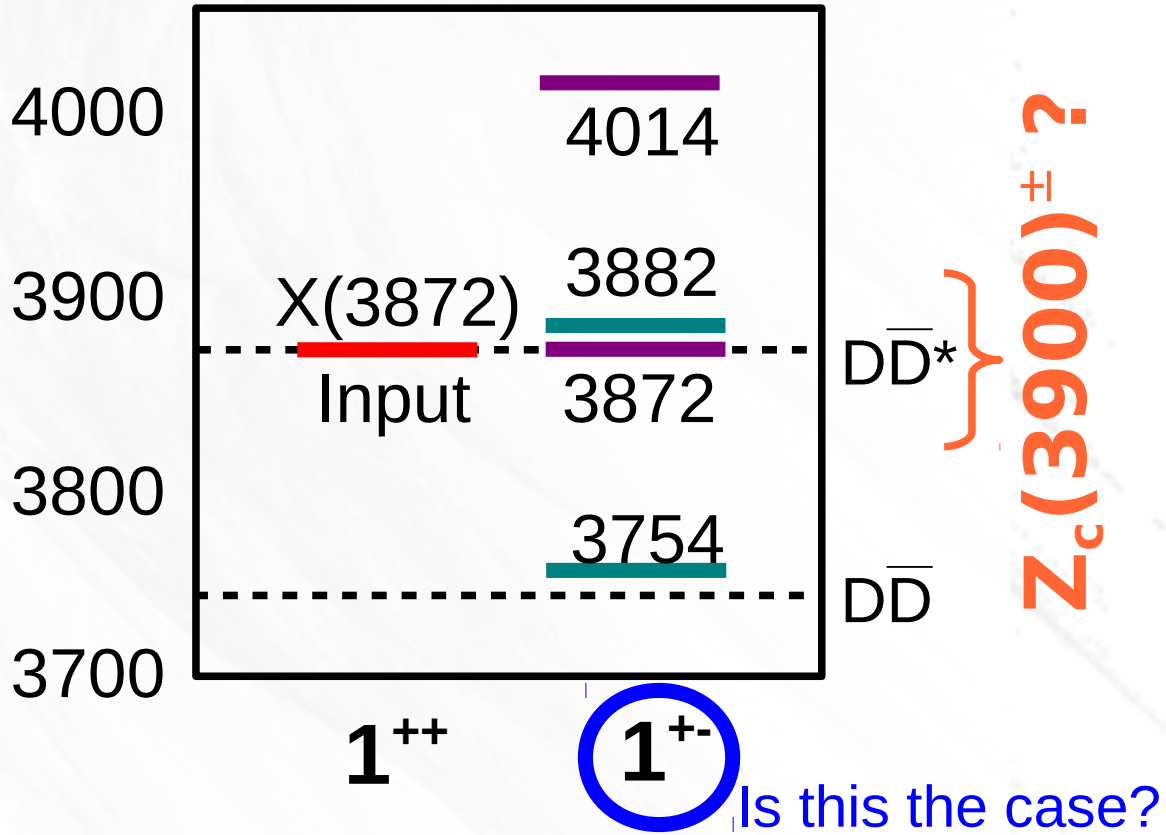
Sensitive probes?

- **Heavier/lighter states**
  - Hadronic molecule
    [PRD 77, 014029 (2008)]



  - Tetraquark
    [PRD 87, 111102(R) (2013)]





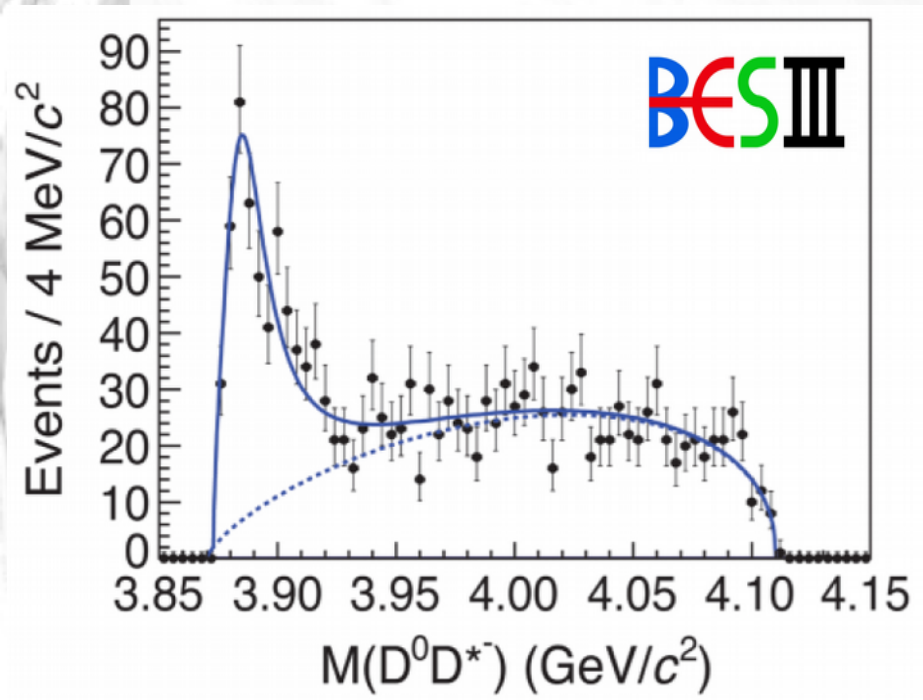
- **Decay modes and rates**
  - Hadronic molecule:
    decays mainly to its constituents
  - Tetraquark: **$\Gamma(Z_c^+ \to \pi^+ J/\psi) \approx 29$ MeV**
    $\Gamma(Z_c^+ \to D^+\bar{D}^{*0}, \bar{D}^0 D^{*+}) \approx 4$ MeV

Can we find missing puzzle pieces with BESIII ?

$Z_c(3900)$ Decay Rates

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

$\sqrt{s} = 4.26$ GeV



- **M = (3883.9±1.5±4.2) MeV/c^2**
- **Γ = (24.8±3.3±11) MeV**

[Phys. Rev. Lett. 112, 022001 (2014)]

Reconstruction method:

- Reconstruct π^+ and $D^0 \rightarrow K^-\pi^+$
- Infer D^{*-}
- Analyse as well $\pi^+D^-D^{*0}$

- **Is found structure** (referred as $Z_c(3885)$) **different decay mode of the $Z_c(3900)$?**

  $Z_c(3900)^{\pm}$ properties:
  - M = (3899.0±3.6±4.9) MeV/c^2
  - Γ = (46±10±20) MeV

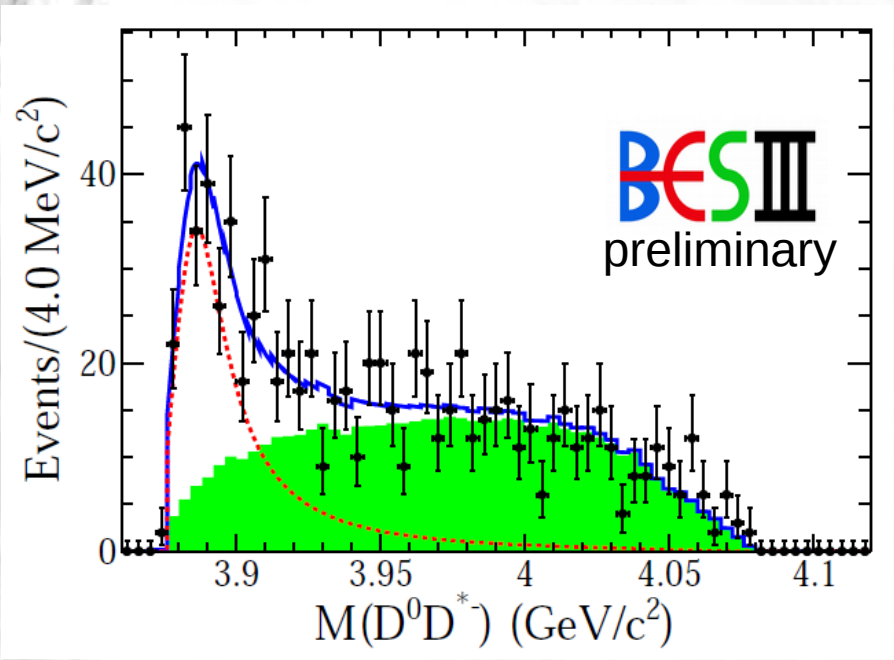
- Assuming it is, the partial width ratio:
  $\Gamma(Z_c \rightarrow DD^*)/\Gamma(Z_c \rightarrow \pi J/\Psi)$ = 6.2±1.1±2.7

Tetraquark model disfavoured ?

$Z_c(3900)$ Quantum Numbers

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

$\sqrt{s}$ = 4.23 and 4.26 GeV

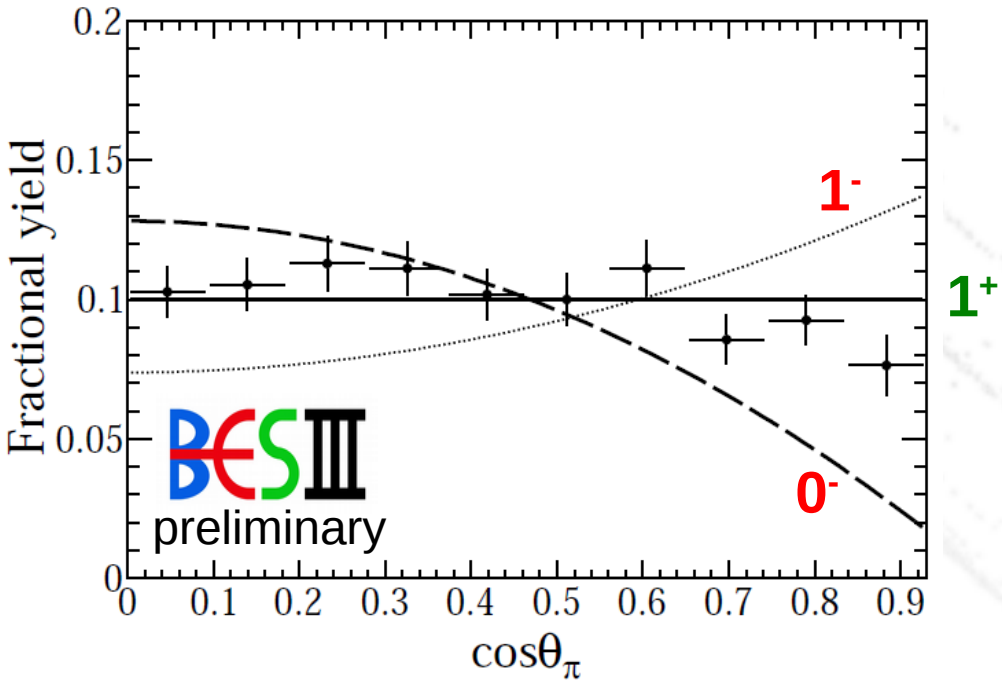


- M = (3884.3±1.2±1.8) MeV/c^2
- Γ = (23.8±2.1±2.6) MeV

Reconstruction method:

- Complete reconstruction of decay

Fits to |cosθ| distributions for $\pi^+ D^0 D^0$ – tagged events



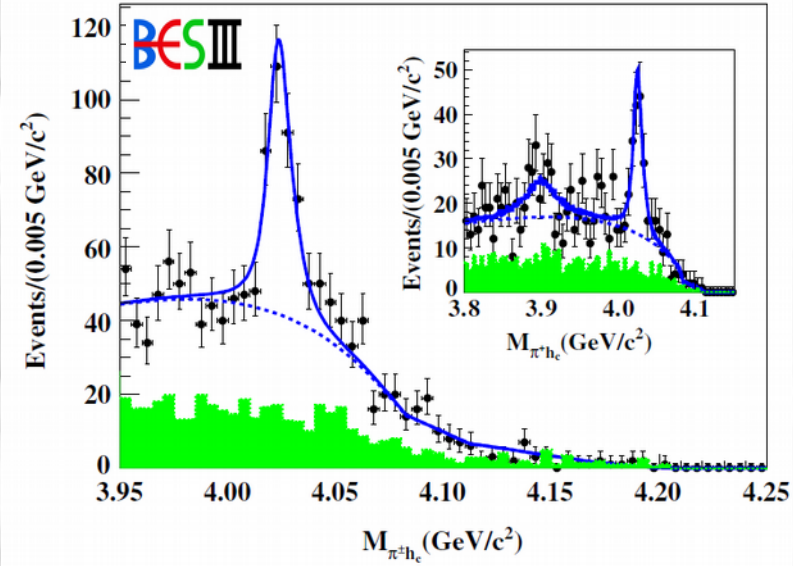
Spin-parity of $Z_c(3895)$ 1^+

Confirms expectations!

$Z_c(4020)^{\pm}$ seen by the BESIII

$e^+e^- \to \pi^-\pi^+h_c$

$\sqrt{s}$ = 3.9 – 4.42 GeV

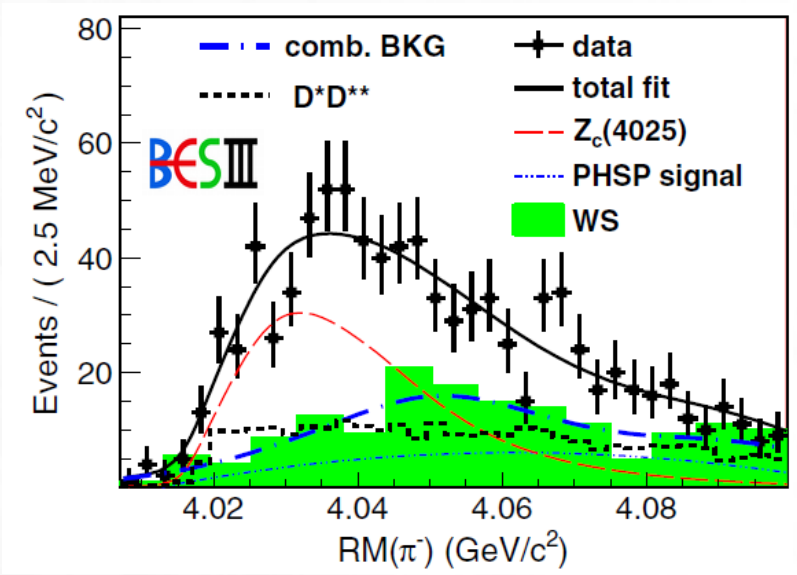


- M = (4022.9±0.8±2.7) MeV/c^2
- Γ = (7.9±2.7±2.6) MeV

[Phys. Rev. Lett. 111, 242001 (2013)]

$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$

$\sqrt{s}$ = 4.26 GeV



- M = (4026.3±2.6±3.7) MeV/c^2
- Γ = (24.8±5.6±7.7) MeV

[Phys. Rev. Lett. 112, 132001 (2014)]

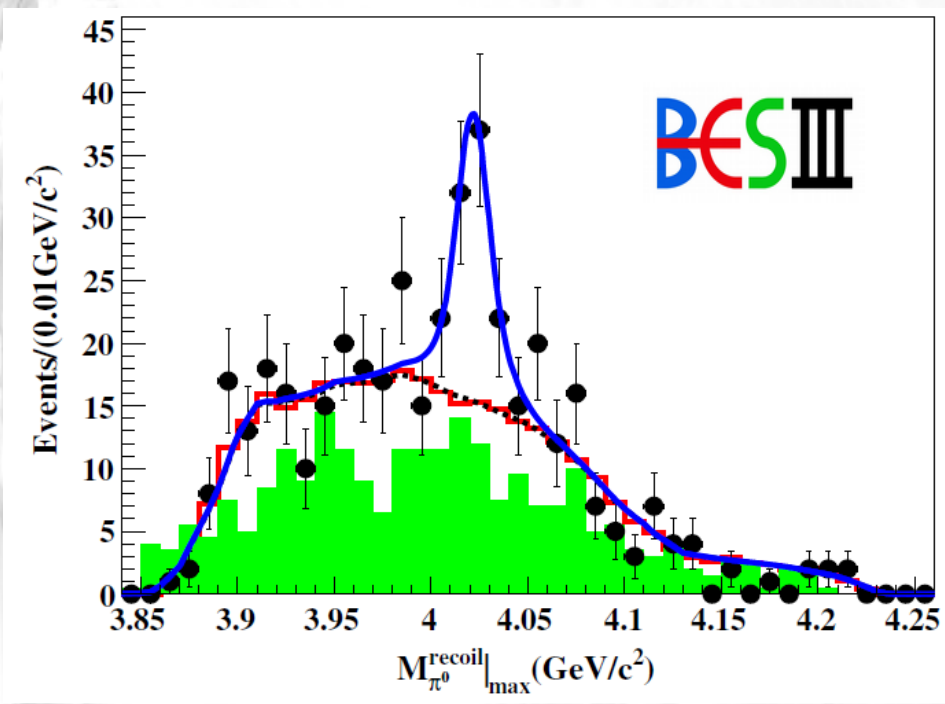
Assuming found structures correspond to the same state the open-charm decay-mode is favoured but suppressed in comparison with established open-charm states, e.g. Ψ(4040)

Is there a neutral partner?

$Z_c(4020)^0$ seen by the BESIII

$e^+e^- \rightarrow \pi^0\pi^0 h_c$

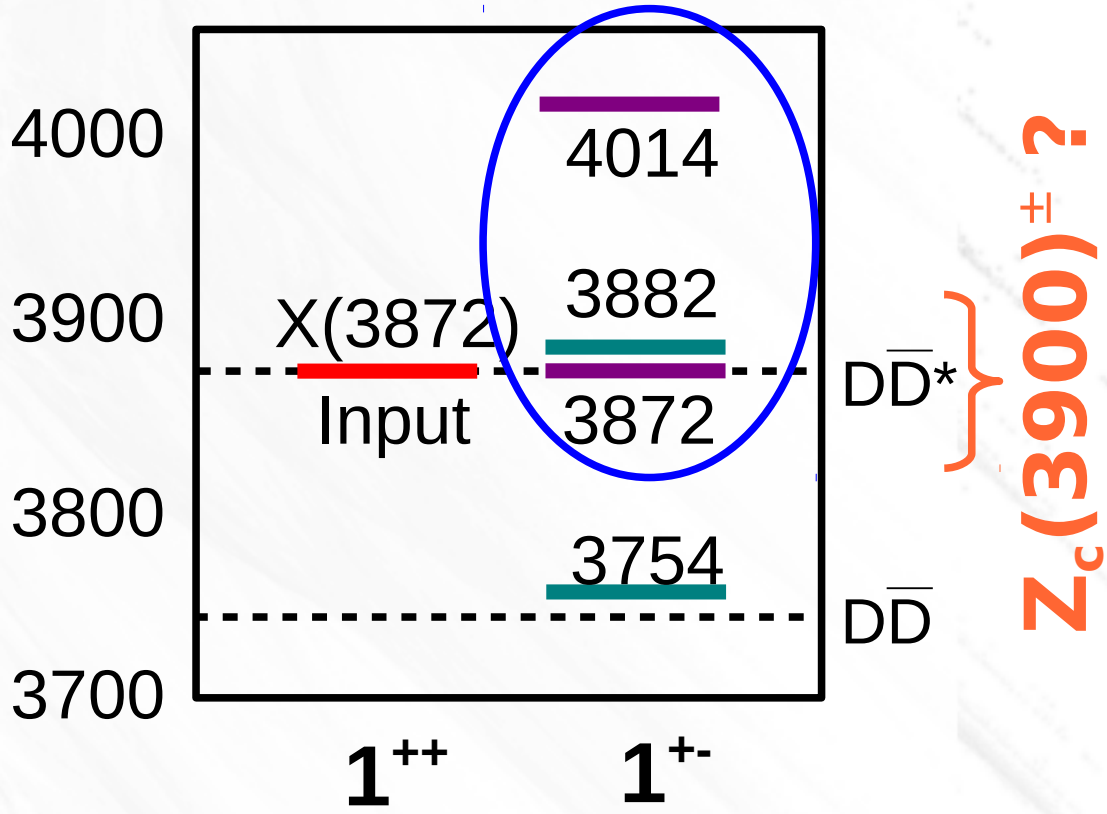
$\sqrt{s}$ = 4.23 – 4.36 GeV



- M = (4023.9±2.2±3.8) MeV/c^2

[Phys. Rev. Lett. 113, 212002 (2014)]

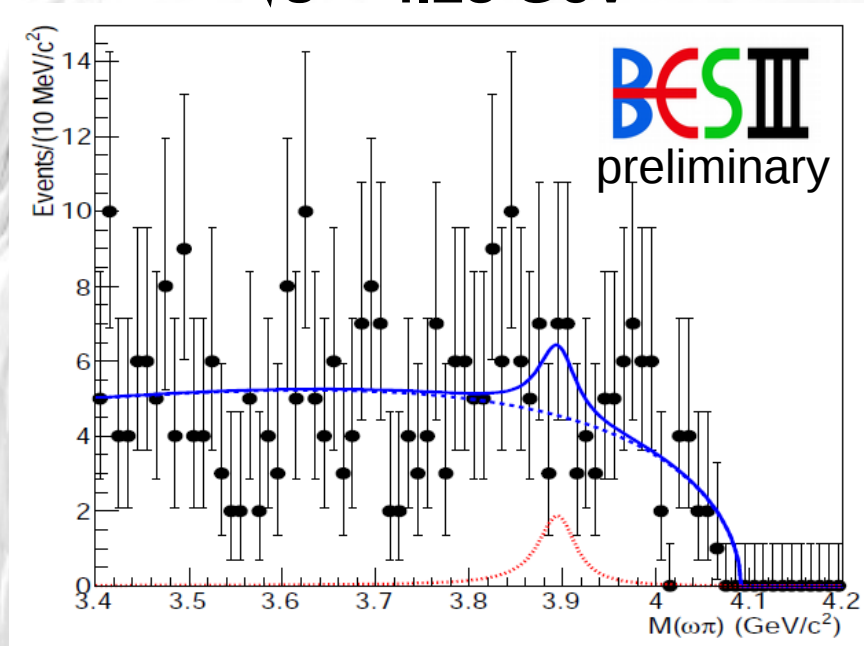
$Z_c(4020)$ – another four-quark isospin triplet found?



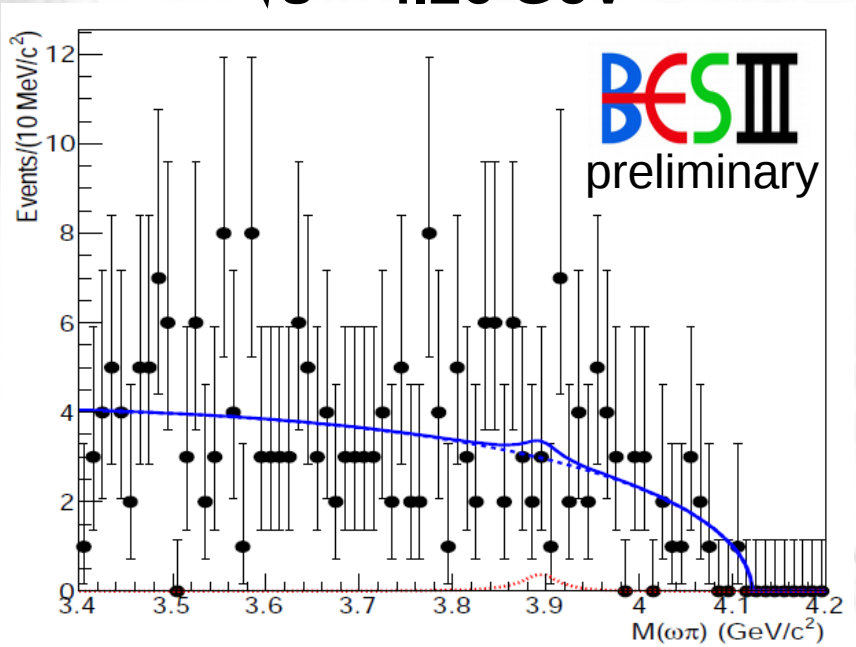
Is $Z_c(4020)$ – a partner state to $Z_c(3900)$, predicted by the hadronic-molecule model?

More Mysteries of $Z_c(3900)$

$\sqrt{s}$ = 4.23 GeV



$\sqrt{s}$ = 4.26 GeV



Search for $Z_c(3900) \rightarrow \pi^{\pm}\omega$

There are three important decay modes for charmonium-like states:

- the fall-apart to open charm mesons;
- the cascade to hidden charm mesons;
- decays to light hadrons via intermediate gluons.

Since **$Z_c(3900)$** decays to $J/\Psi\pi$, a sizeable annihilation rate could be expected with $\bar{c}c$ in S − wave (as for χ_c)

No significant signal observed:

$\Gamma(Z_c(3900) \rightarrow \omega\pi) < 0.2\% \Gamma(Z_c(3900))$

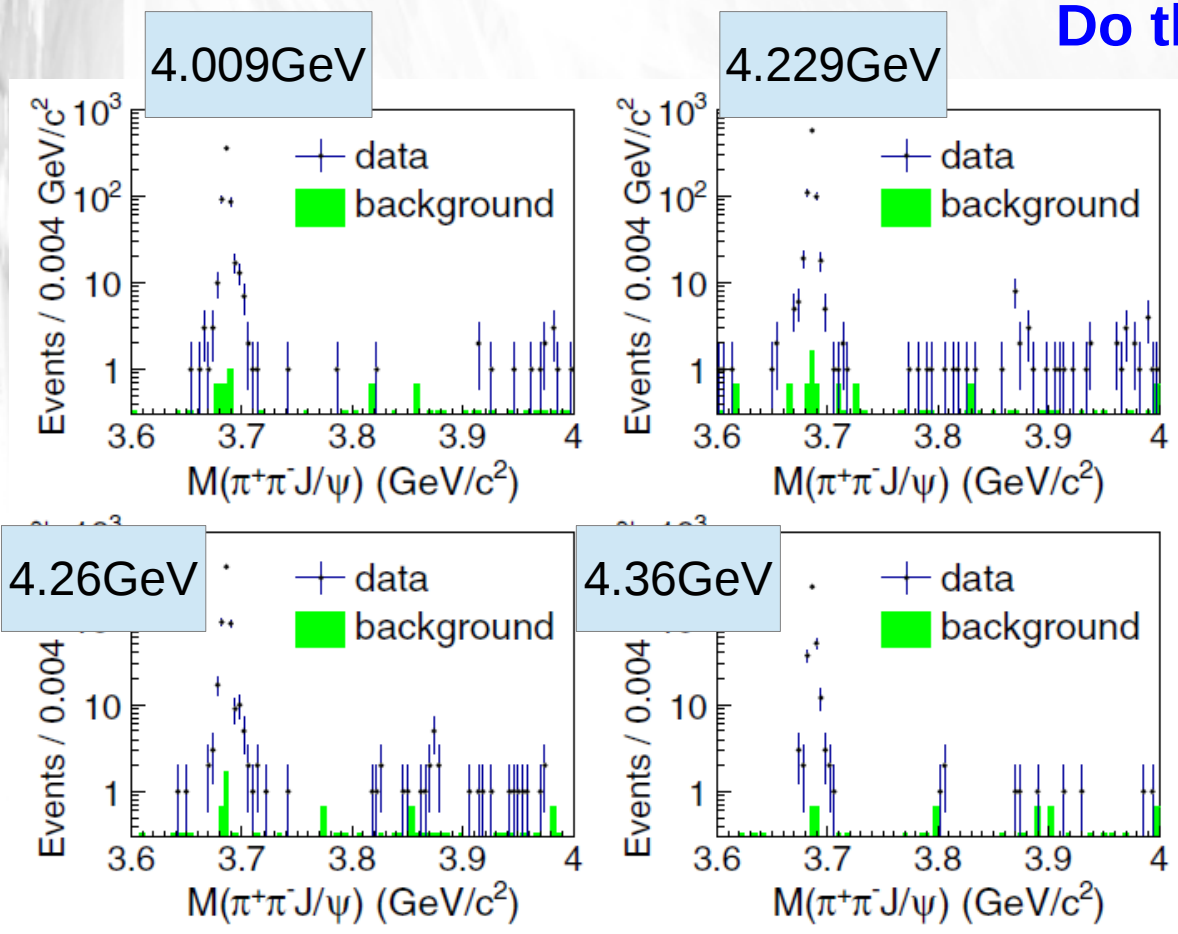
Annihilation to $\bar{c}c$ is suppressed?

Shedding Light on X(3872)

X(3872) – the first discovered unconventional charmonium-like state so far seen in B-meson decays of hadron collisions:

- $J^{PC} = 1^{++}$, measured by LHCb and CDF
- Interpreted as a candidate for a tetraquark or hadronic molecule
- Most probably Y(4260) and Y(4360) couple with exotic Z_c states

Do they couple with X(3872)?

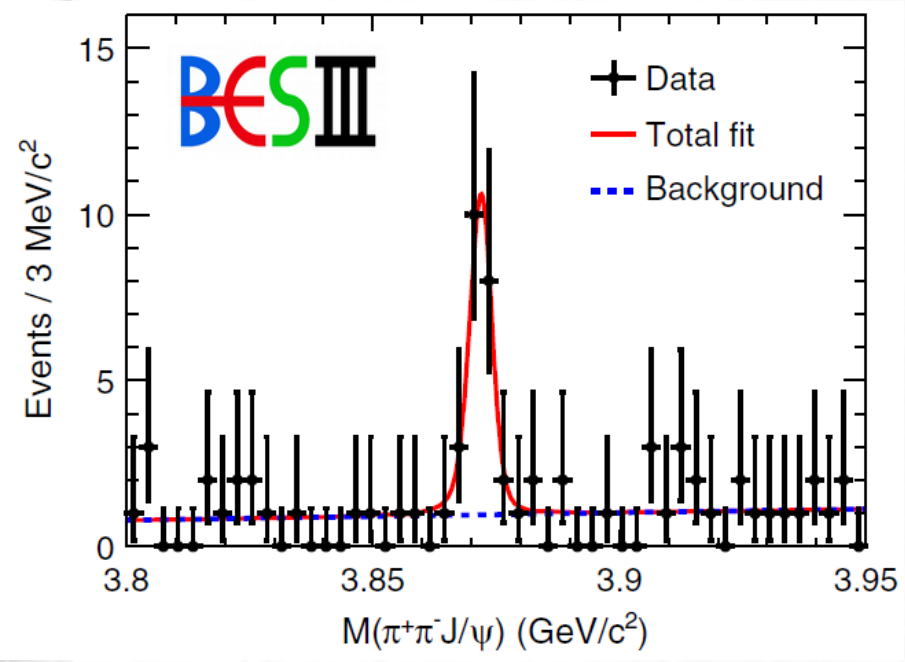


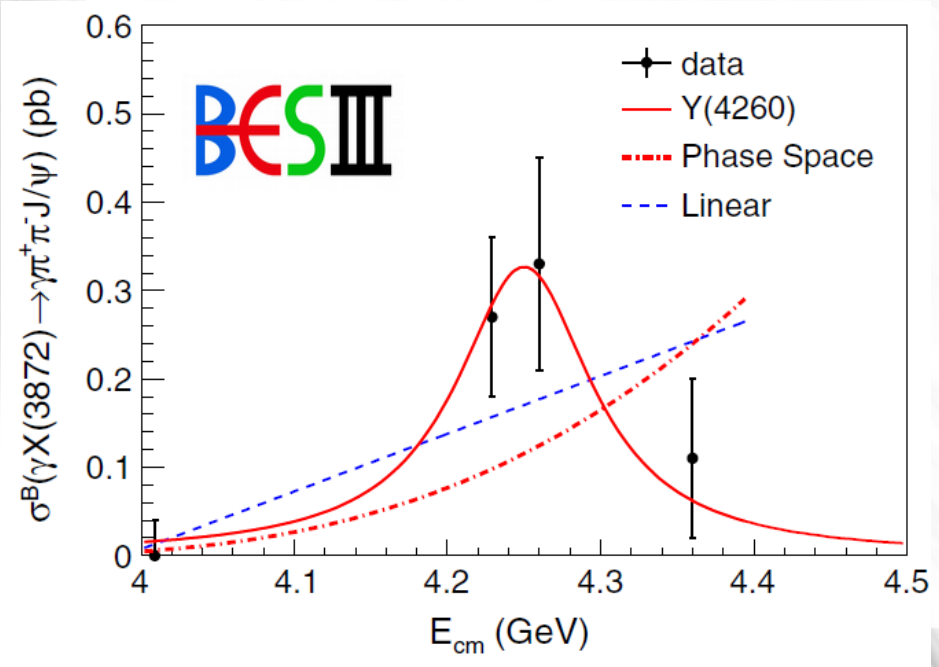
$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma J/\Psi\pi^+\pi^-$

Ψ` signal is used for analysis validation

[Phys. Rev. Lett. 112, 092001 (2014)]

Shedding Light on X(3872)





- **The X(3872) signal is clearly observed: significance 6.3σ**
- **Cross-section hints radiative transition between Y(4260) and X(3872)**
- **Existence of transitions between Y(4260) X(3872) and Zc states suggest that there might be some commonality in the nature of these three different states**

Systematic studies of unexpected states allows BESIII to collects pieces of "exotic-matter" puzzle

[Phys. Rev. Lett. 112, 092001 (2014)]

A lot of interesting results are already published by the BESIII collaboration

New exciting results are coming soon!

Summary

- BESIII is operational since 2008
  and already has world's largest data samples of various Y and charmonium states in a clean environment (e^+e^- annihilation)

- BESIII – an ideal tool for precision studies of suppressed channels:
  - clean environment
  - well controlled systematics

- A lot of interesting results have been obtained:
  - Precise measurements of resonance properties
  - Discovery of unexpected states
  - Systematic studies of XYZ states in charmonium region

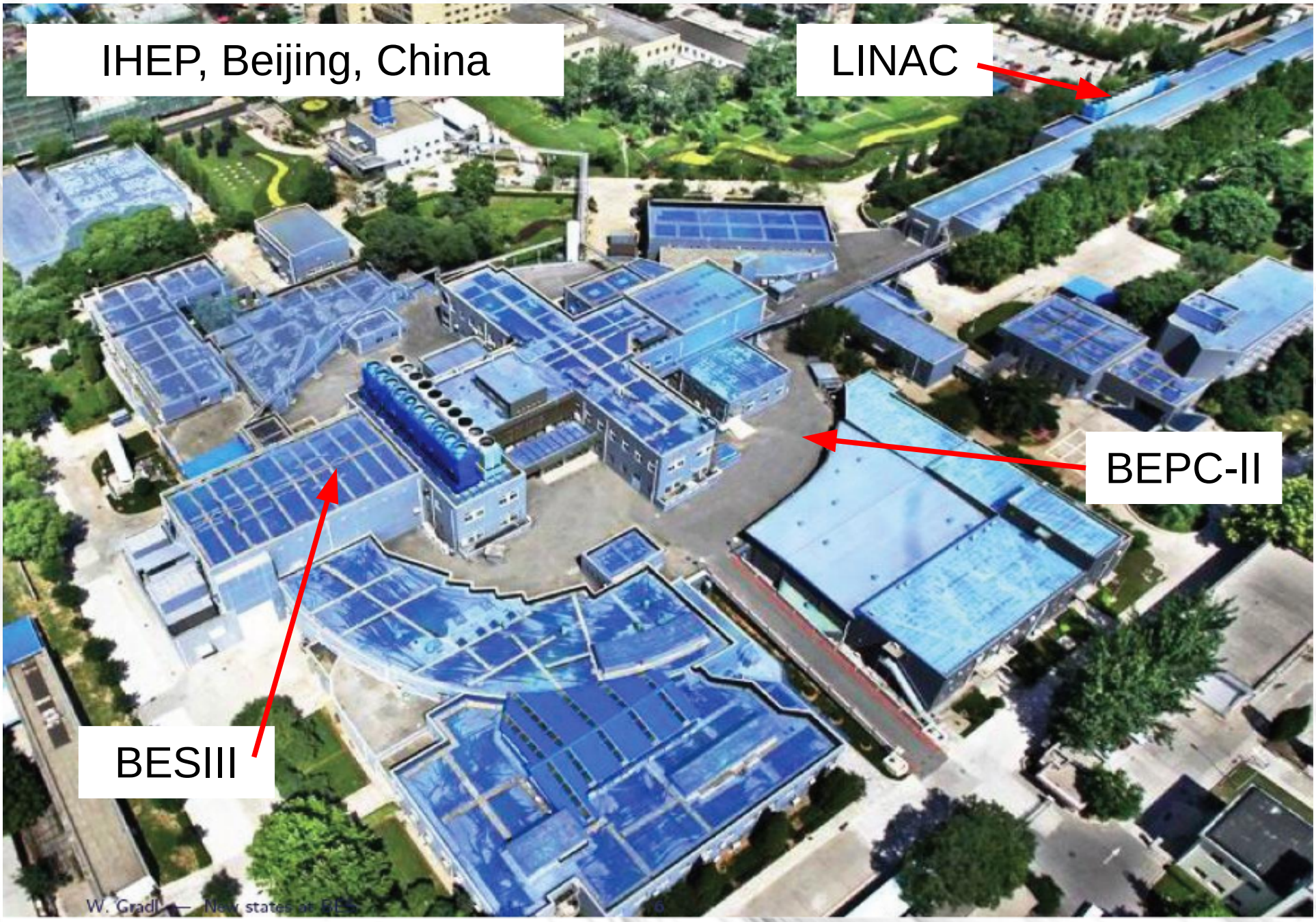
- ... and we are looking forward to the future:
  - More data available than presented in current analysis

Stay tuned!

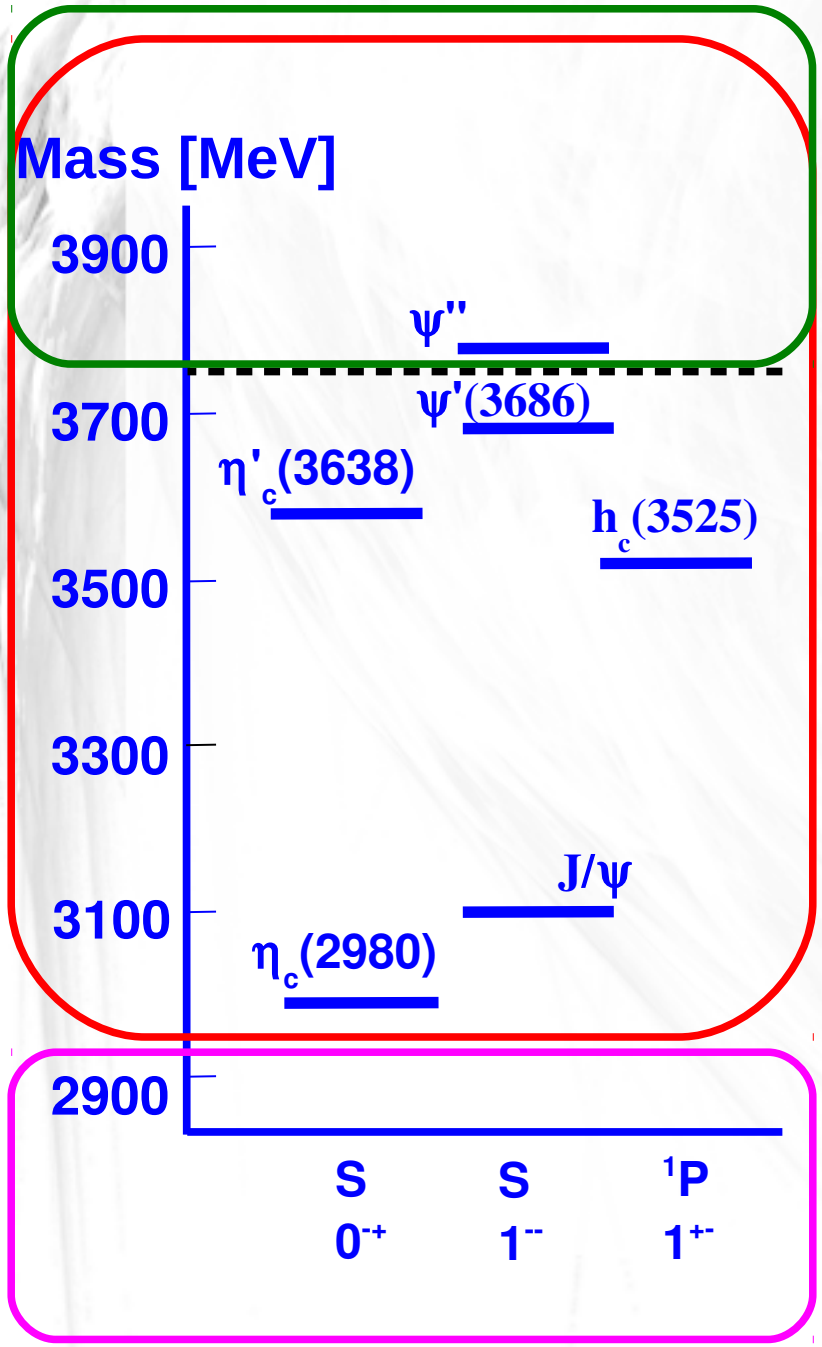
Thank you for your attention and to the BESIII collaboration!

BESIII collaboration: >360 members in 53 institutions from 11 countries

BESIII at BEPC-II



Physics at BESIII



Charm physics:

- (semi)leptonic + hadronic decays
- decay constant, form factors
- CKM matrix: Vcd, Vcs
- D_0-D_0 mixing and CP violation
- rare/forbidden decays

Charmonium physics:

- transitions and decays
- spectroscopy of exotic states

Light hadron physics:

- meson & baryon spectroscopy
- glueball & hybrid
- two-photon physics
- e.m. form factors of nucleon

Tau physics:

systematics under control → high precision

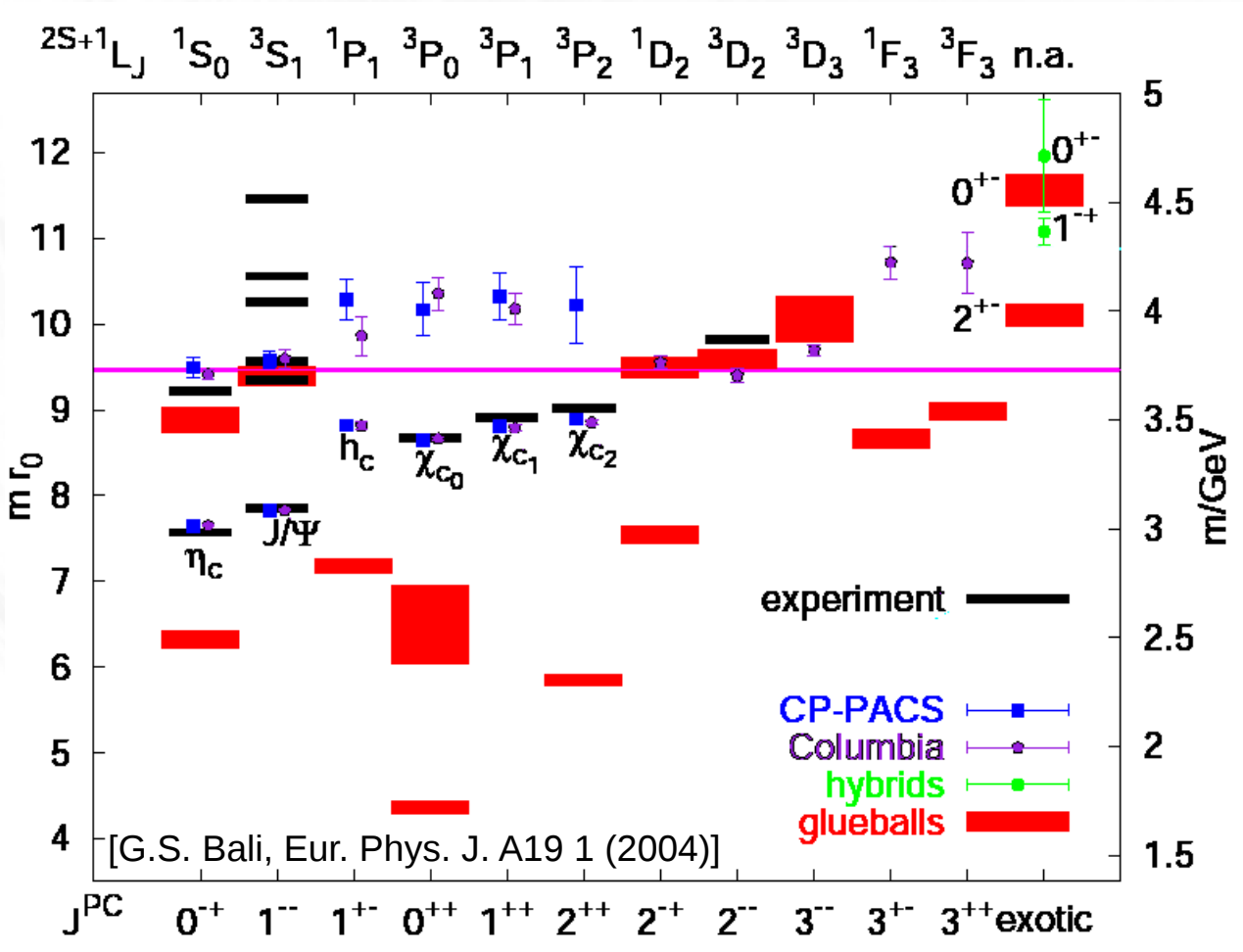
- tau decays near threshold
- tau mass scan

Other QCD Exotic Objects

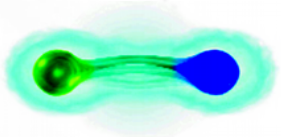
QCD predicts exotic objects:

- hybrids (resonances of quark-antiquark and excited glue)
- glueballs (excited states of glue)

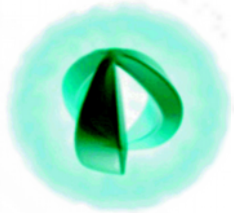
D $\overline{\text{D}}$ threshold →



$|\bar{c}\,c\rangle$



$|\bar{c}\,c\,g\rangle$



$|g\,g\,g\rangle$

Glueballs and hybrids properties are determined by the long-distance features of QCD

→ Insight into QCD vacuum