Charmonia and exotics from BESIII

CHARM 2015

Wayne State University
18 – 22 May, 2015

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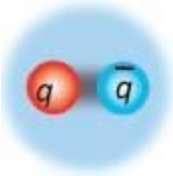
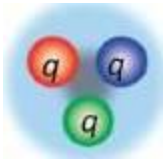
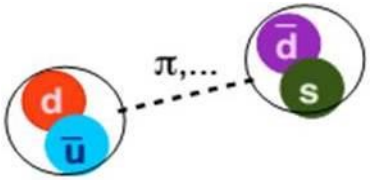
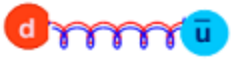
On behalf of BESIII Collaboration

Outline

- Introduction:
  - expected and unexpected, charmonium-like states
- Exotics @ BESIII: X, Y, Z
  - emerging connections
- Conclusions & Outlook

QCD bound states

- Usual: mesons(qq)  and baryons (qqq) 

- Allowed but unusual, or exotic:
  - **multi-quark**  or **molecules** 
  - **hybrids** 
  - **glueballs** 

$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

Exotic: any multi-quark meson,
or meson with $J^{PC} = 0^{--}, 0^{-+}, 1^{-+}, 2^{+-} \ldots$

Charmonium Laboratory

Potential models, and L-QCD, very **successful** in describing **spectra & onium properties!**

Example from Barnes, Godfrey, Swanson:

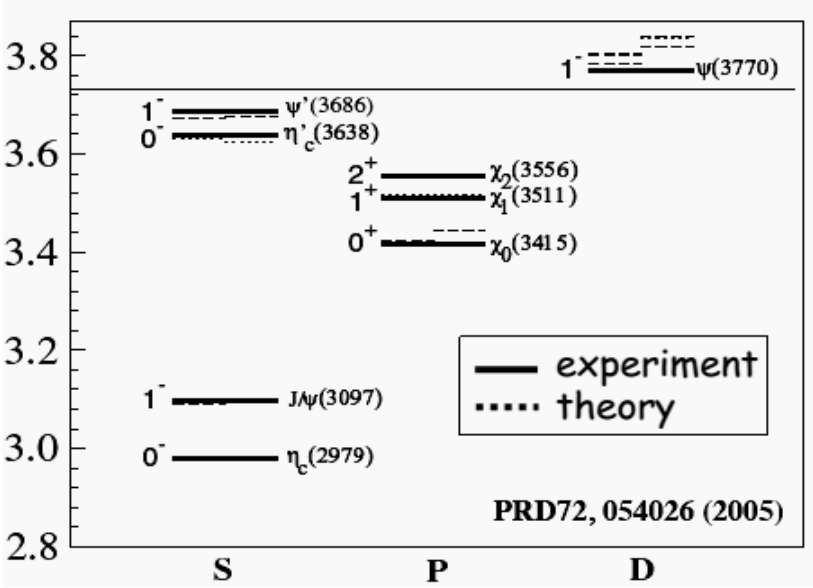
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

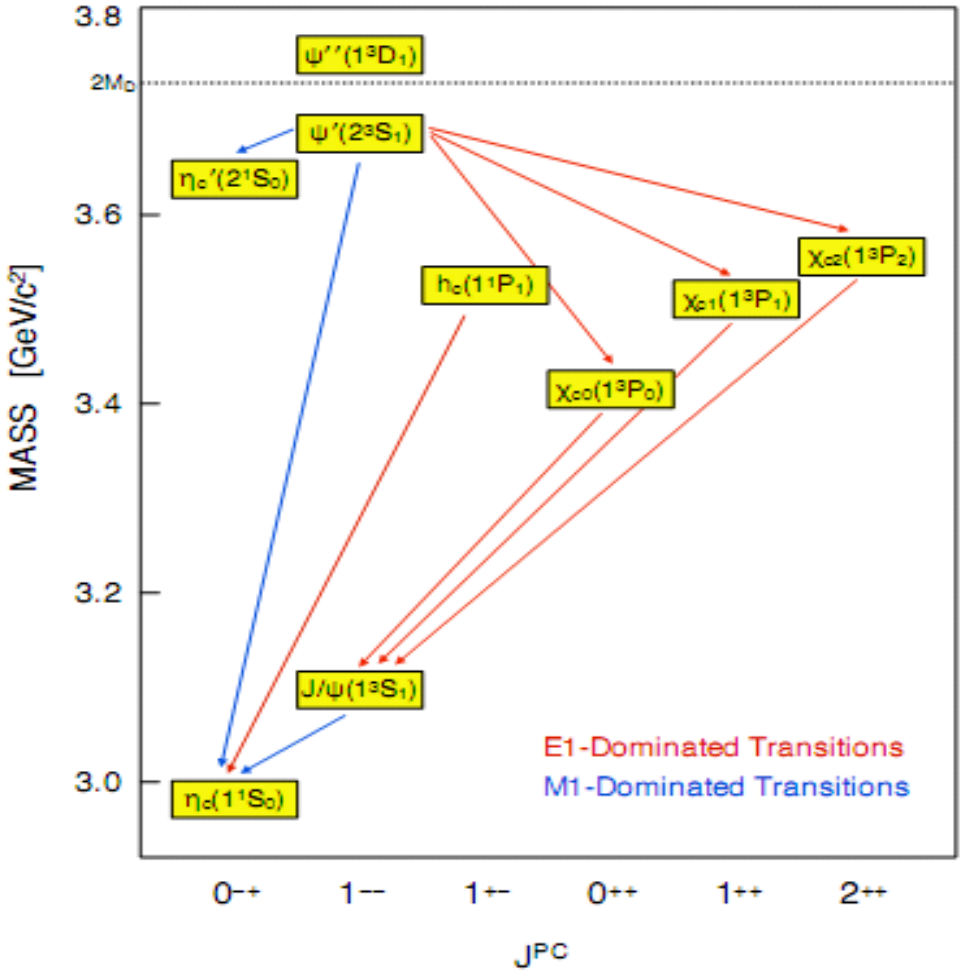
(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

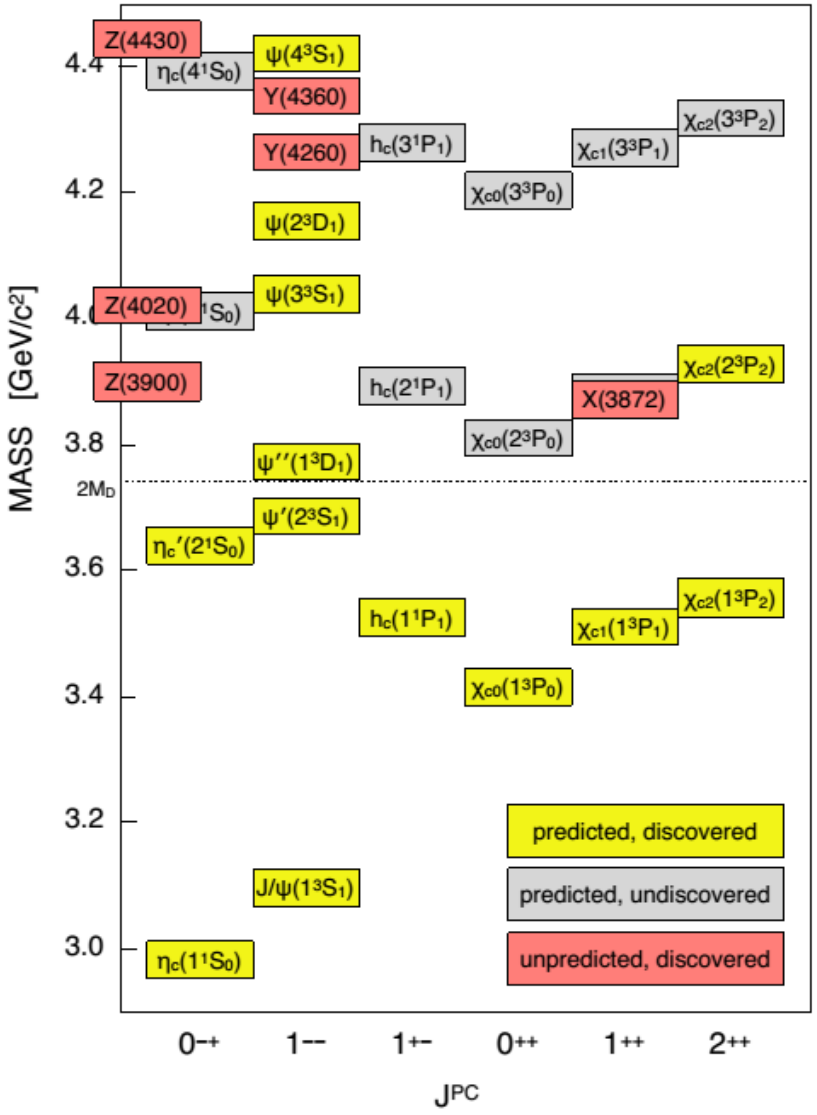
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)





XYZ: charmonium-like

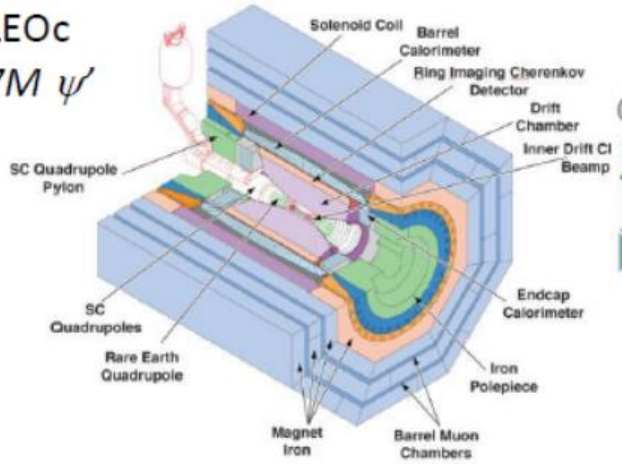


- Most note-worthy: **X(3872)**, **Y(4260)** & **Z_c(3900)** …
- XYZ: **not predicted** by potential models
- XYZ: **do not fit** into $q\bar{q}$-scheme
- **Challenge** for theory and experiment(s)
- > 20 new states, including $b\bar{b}$ sector!

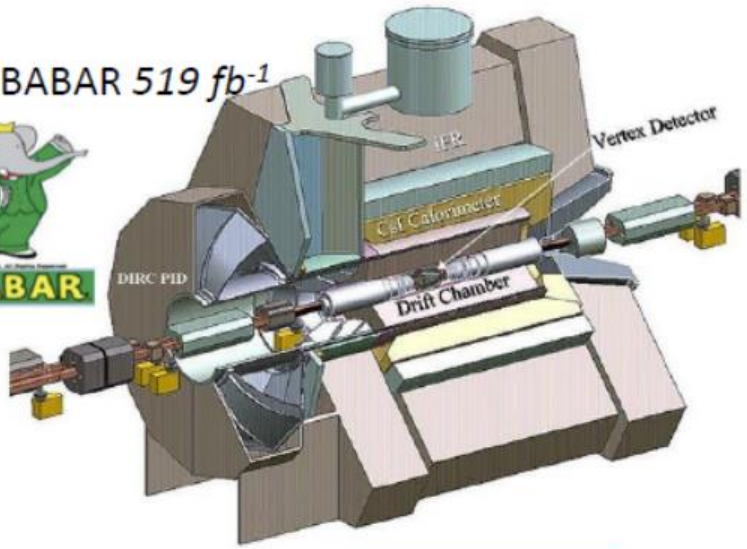
QWG report, Bodwin et al, arXiv: 1307.7424

Experiments

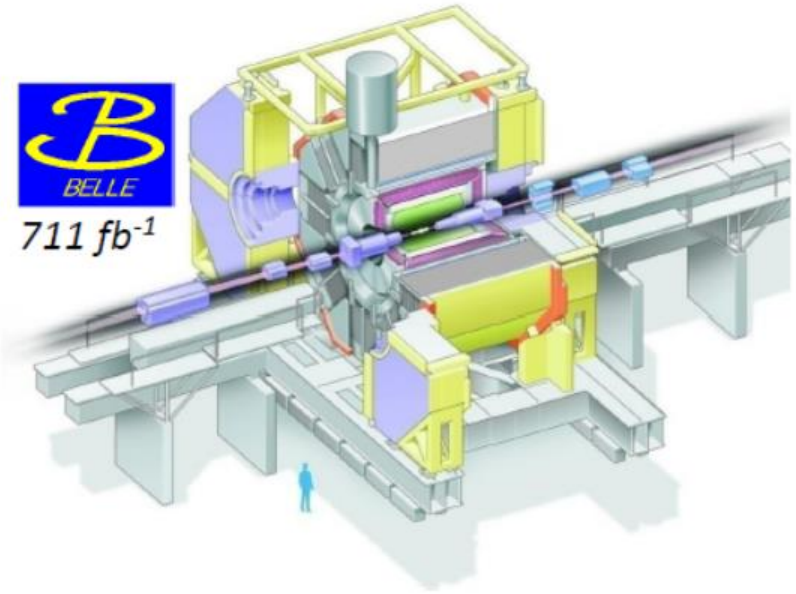
CLEOc
27M ψ'



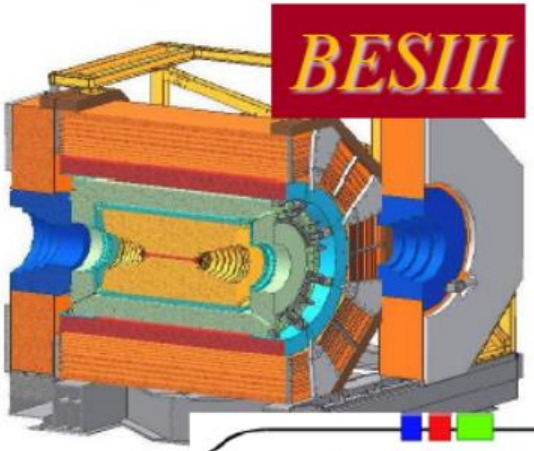
BABAR 519 fb^{-1}



BELLE
711 fb^{-1}



BESIII



LHCb

panda

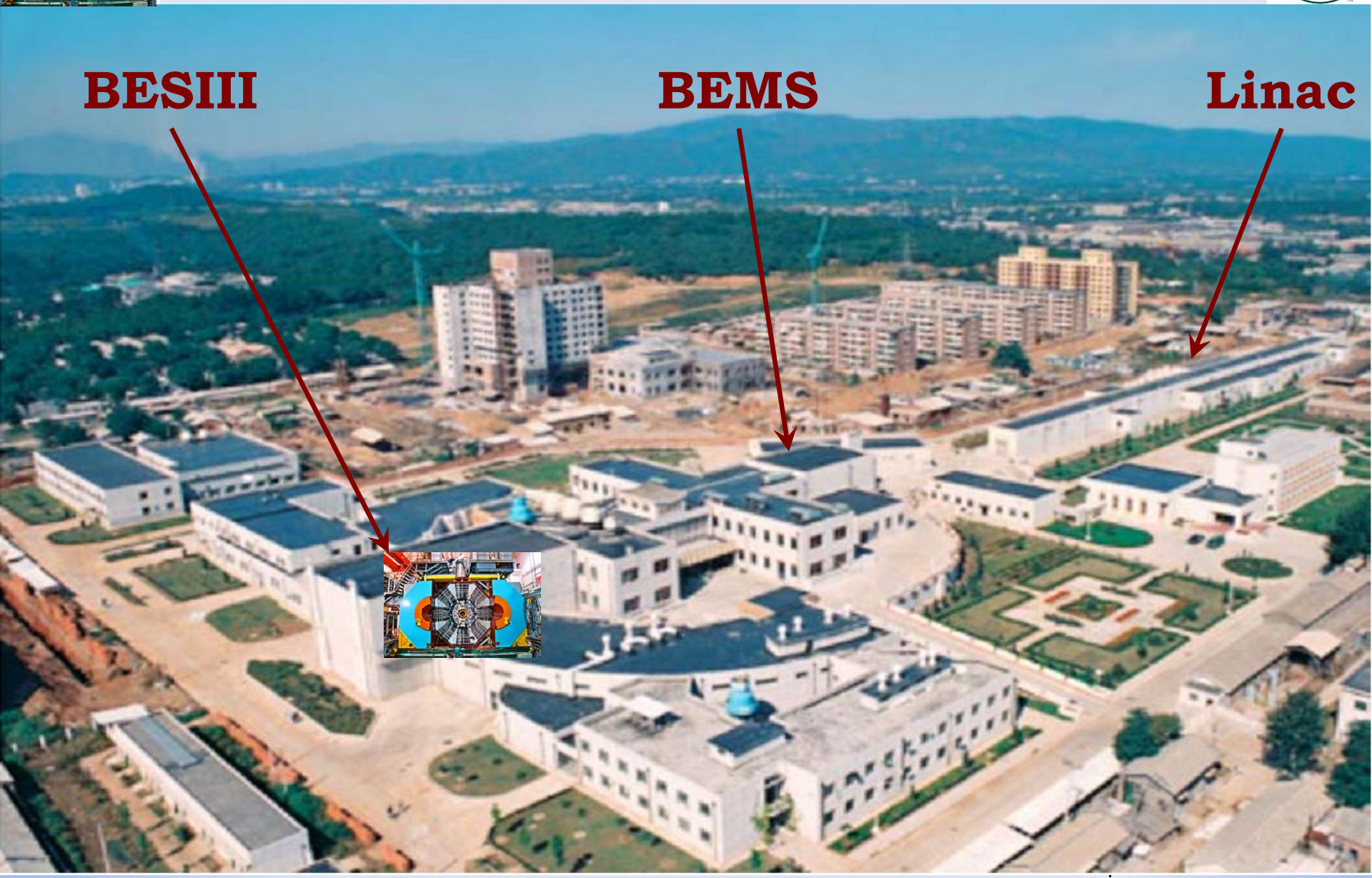
What can BESIII do?

BESIII Collaboration

- Over **50 institutions**, **~400 members** scattered in **11 countries**
- **τ – charm** physics with very rich program:
- **Charmonium** spectroscopy transitions and decays, dedicated to explore XYZ region (up to 4.6 GeV) …
- **Light hadron** program: XY_sZ_s, exotic mesons …
- **Charm physics**: precision phase …
- **τ - physics**: most precise τ-mass measurement

… and many more, several talks @ CHARM 2015!

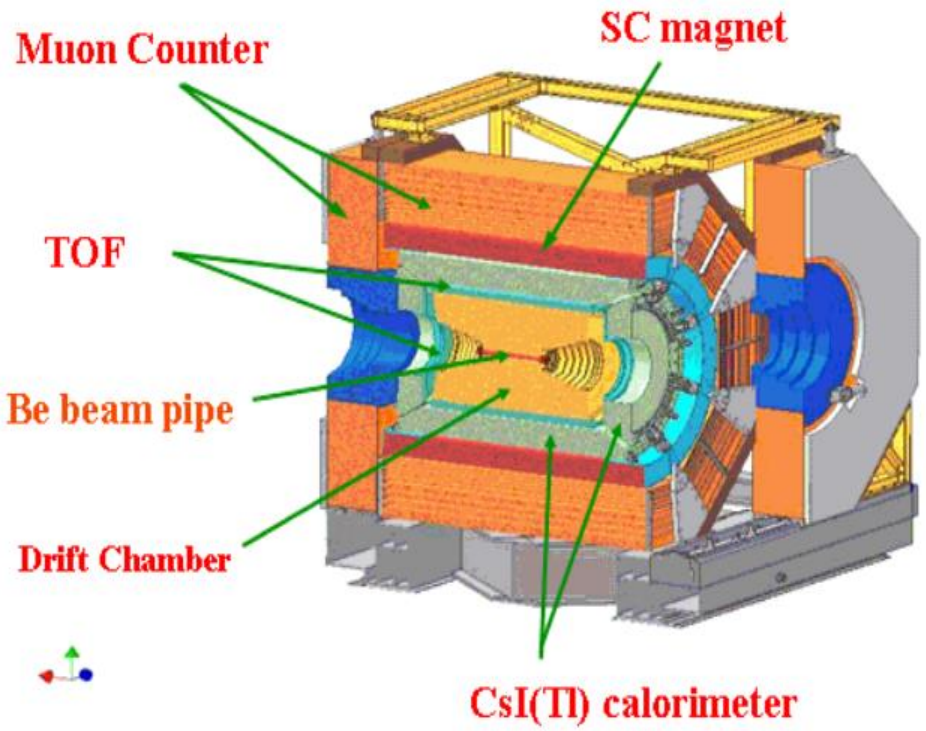
Beijing Electron Positron Collider II

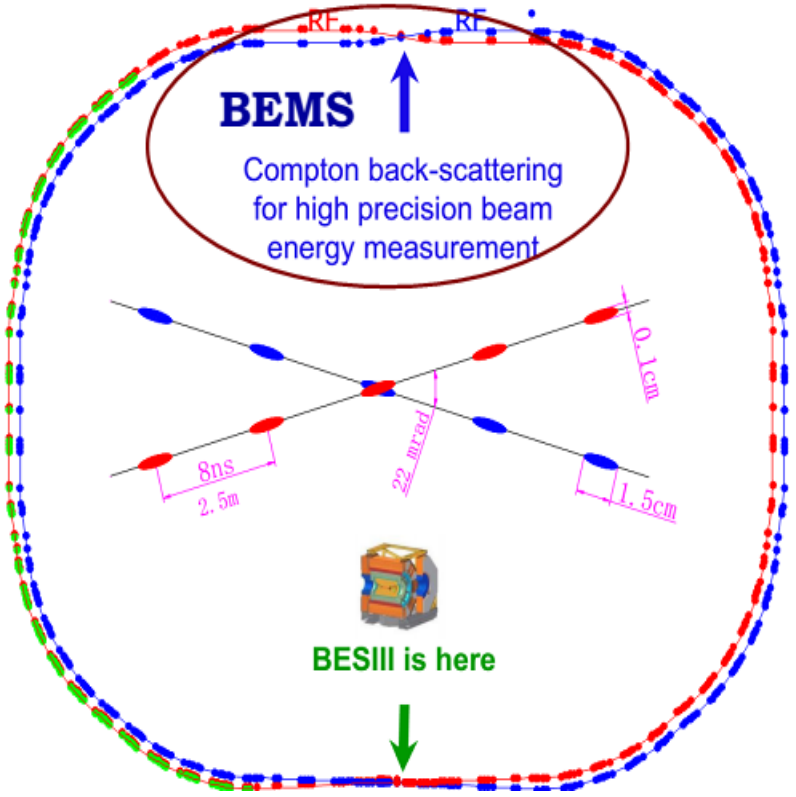


BESIII @ BEPCII

Excellent **tracking:** $\delta p/p = 0.5\%$ @1GeV
dE/dx=6%

Peak Luminosity **achieved**:
0.85×10^{33} cm^{-2}s^{-1}

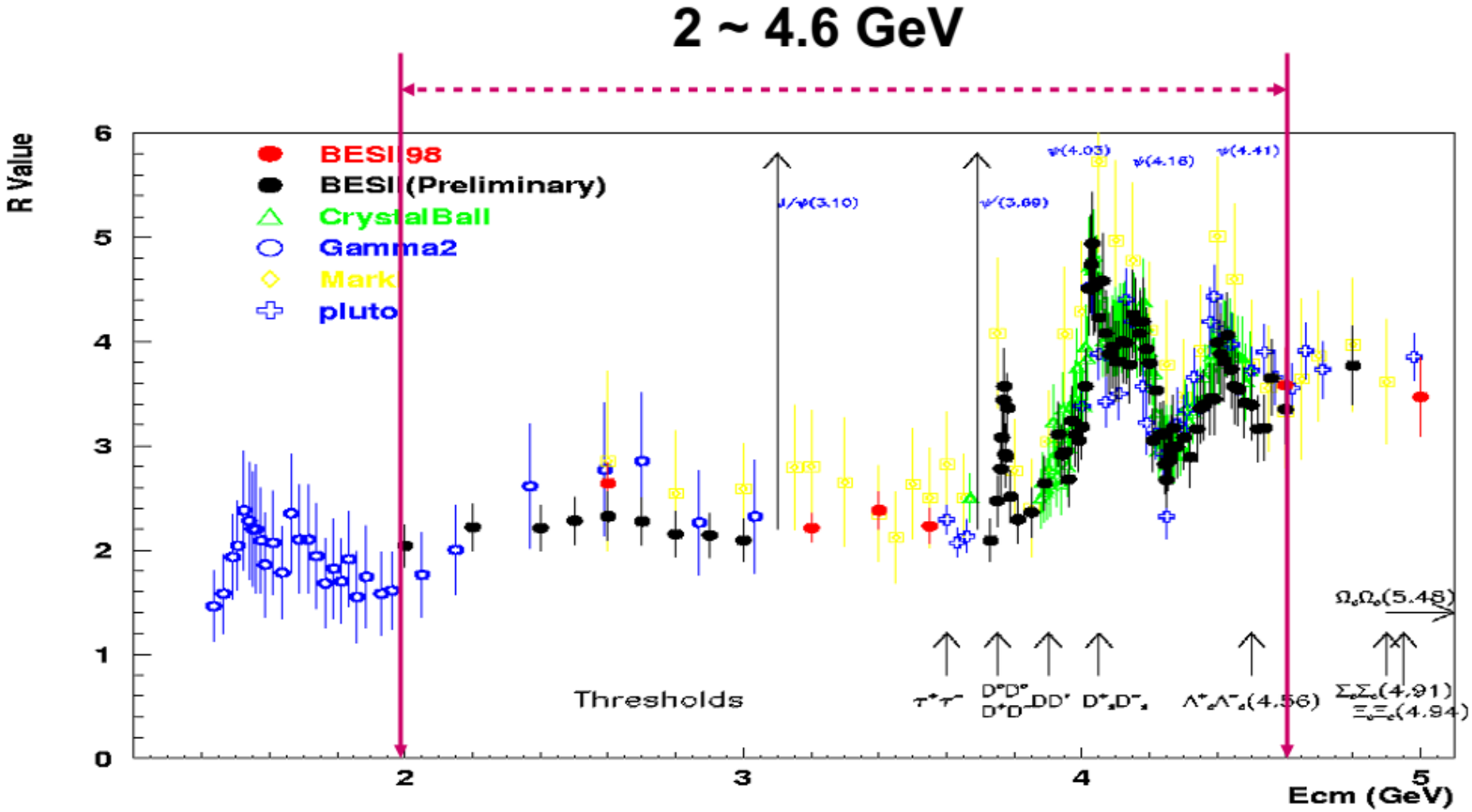




Shower reconstruction: $\Delta E/E = 2.5\%$ @1 GeV
$\sigma_{\varphi,z} = 0.5\sim0.7$ cm/$\sqrt{E}$

Optimal energy **1.89 GeV**

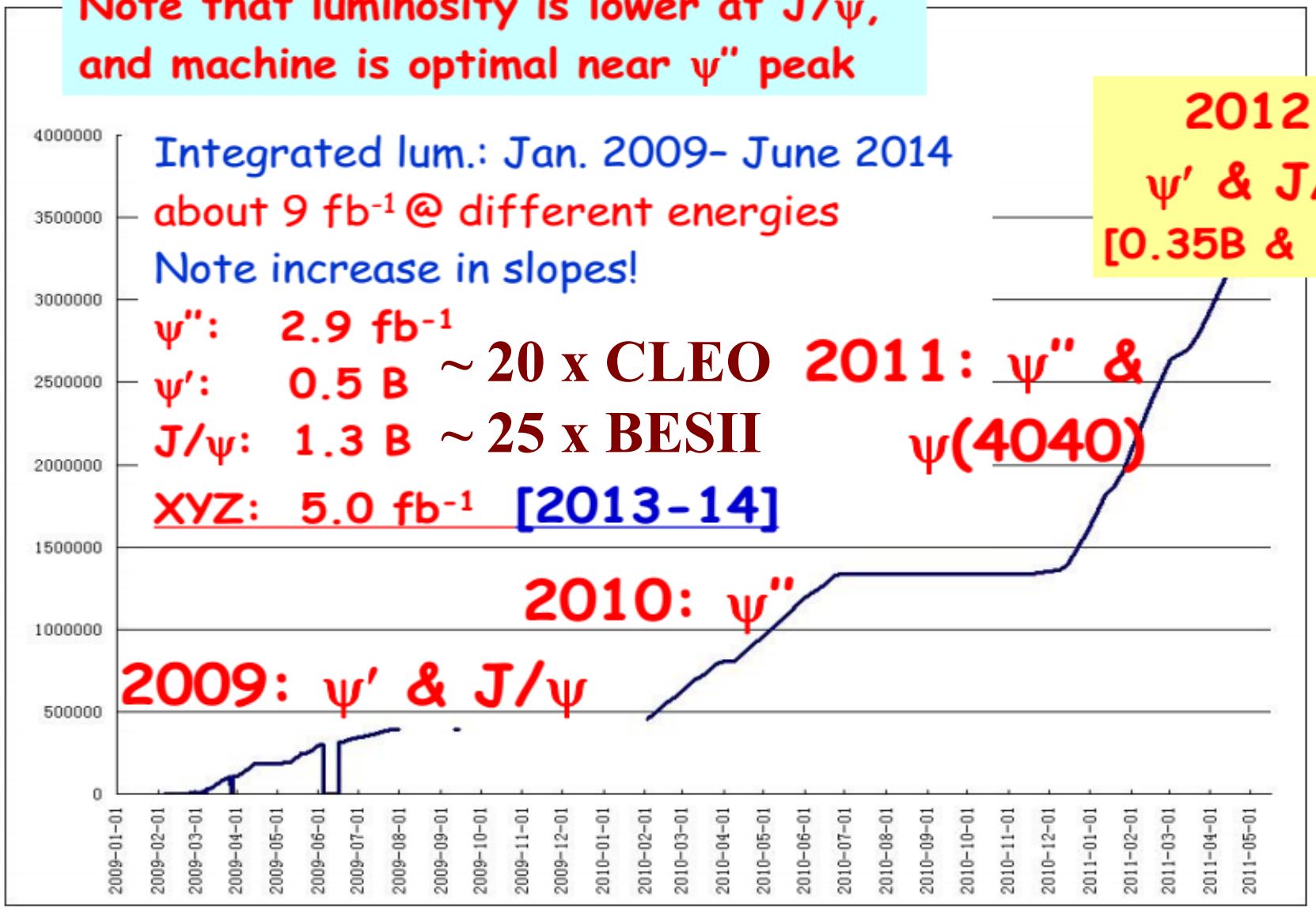
Energy range @ BEPCII



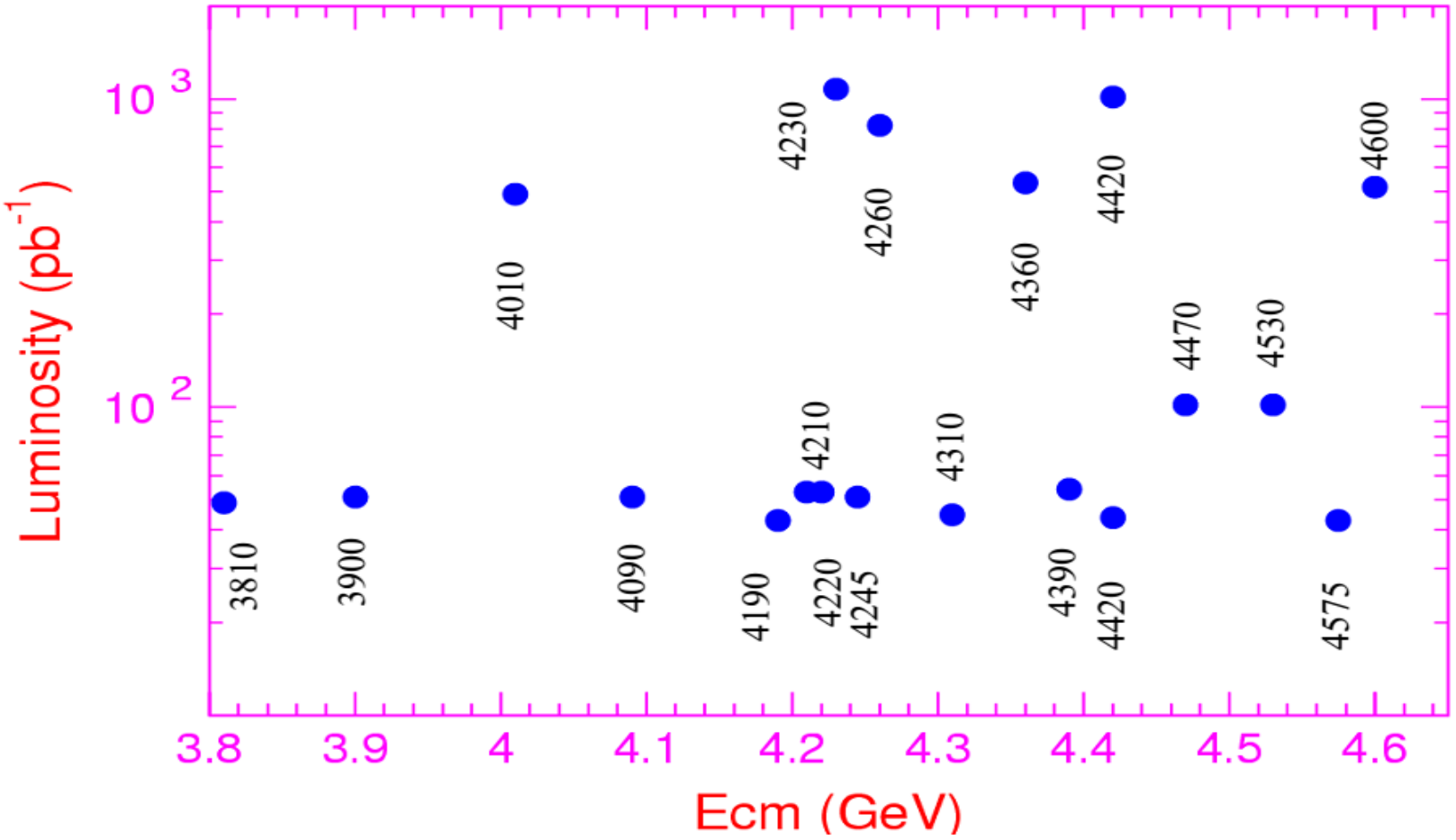
A lot of interesting thresholds, pay attention to Λ_c decays later…

Data collected over time

Note that luminosity is lower at J/ψ, and machine is optimal near ψ'' peak



Data for XYZ study (5/fb)

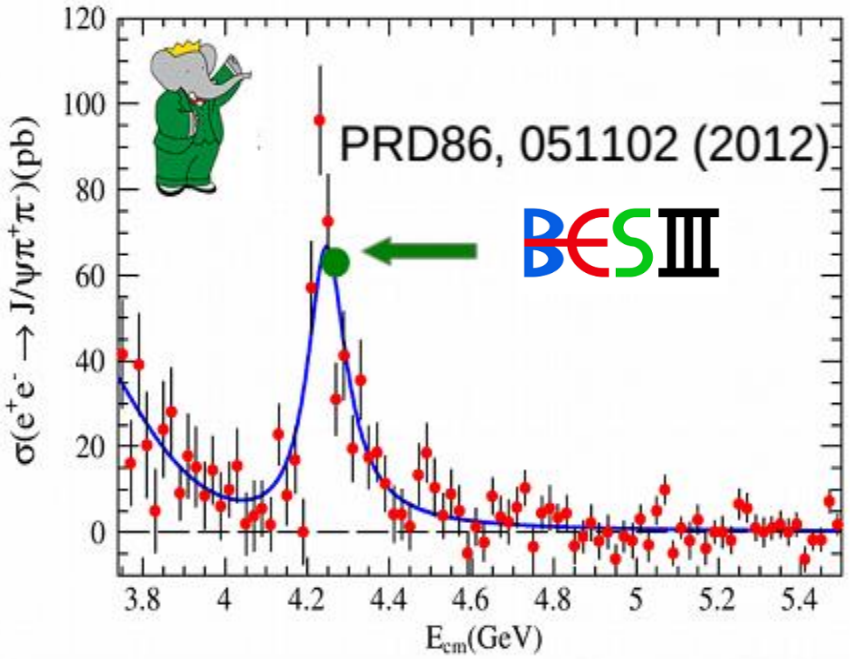


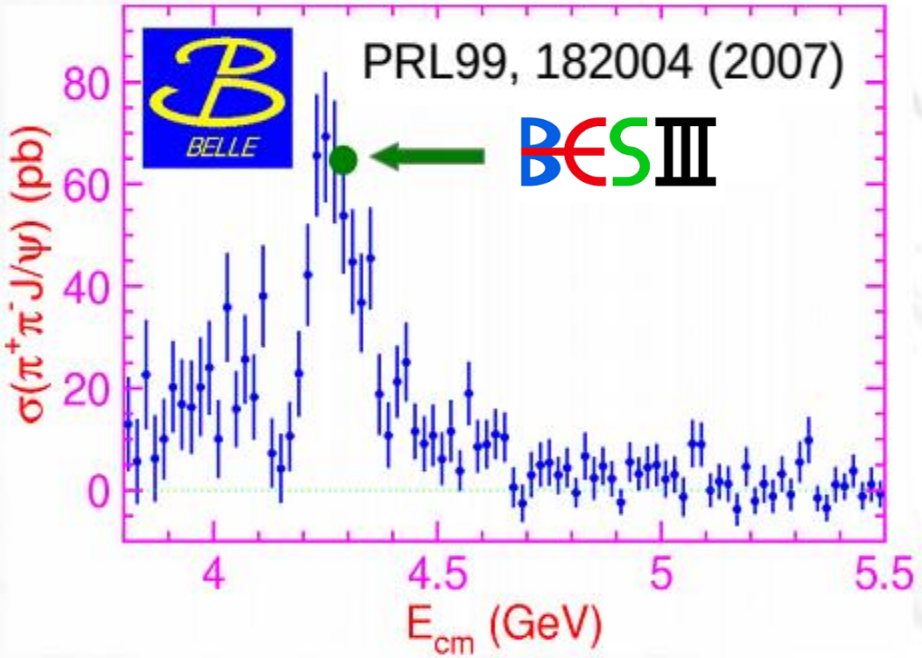
2015: running energy scan between 2 - 3 GeV

Start of XYZ @ BESIII:

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

Compare running at **Belle and BaBar,** with one month at **BESIII !**





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

PRL 110, 252001 (2013)

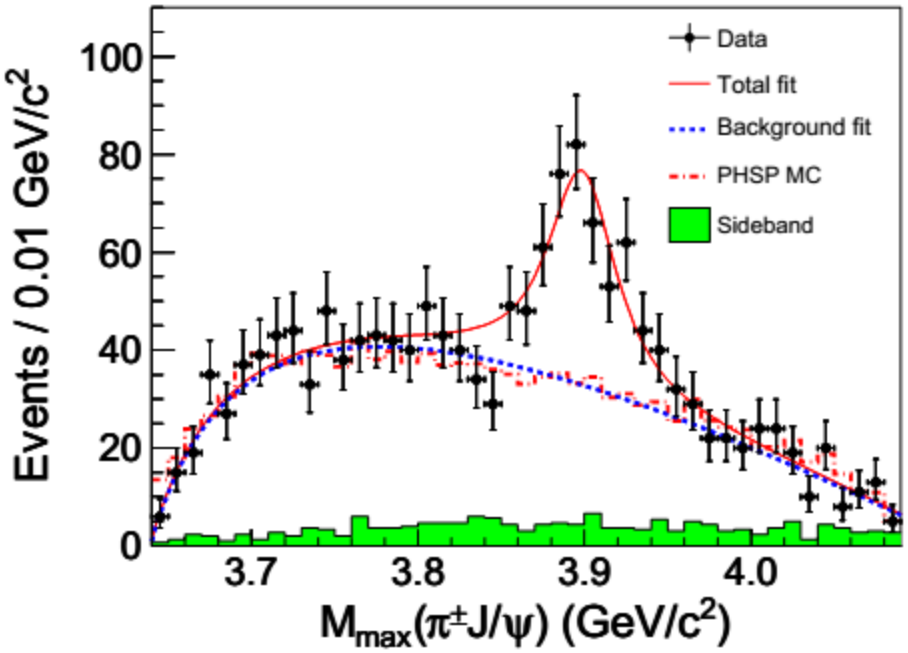
$Z_c(3900) \to \pi^{\pm}\, J/\psi$

- **Charged** charmonium-like structure: $e^+e^- \to \pi^{\mp}(\pi^{\pm} J/\psi)$

  manifestly exotic:

Significance > 8 σ

- couples to $c\bar{c}$
- has charge
- at least 4 quarks
- what is it ?



M: (3899.0 ± 3.6 ± 4.9) MeV/c^2

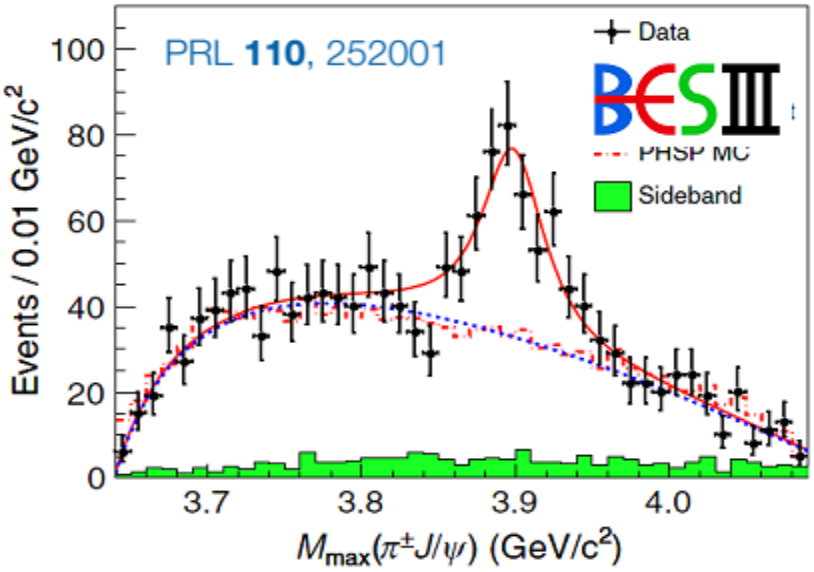
Γ: (46 ± 10 ± 20) MeV

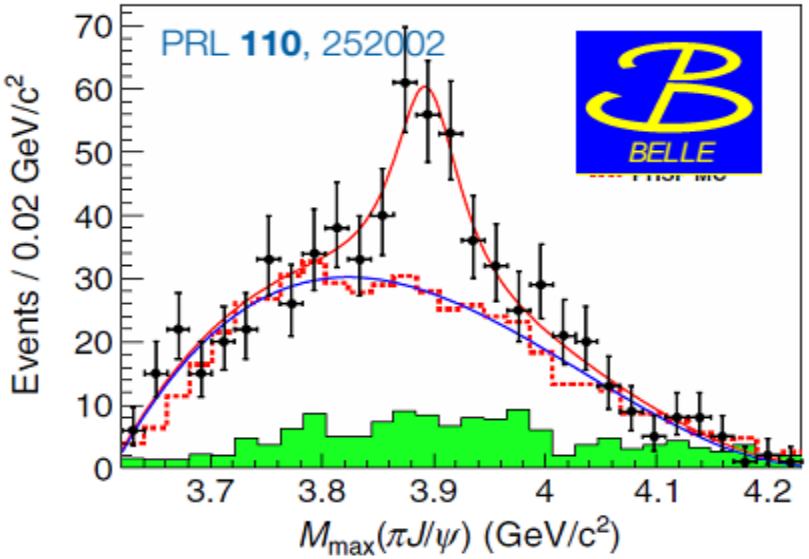
R: (21.5 ± 3.3 ± 7.8)%

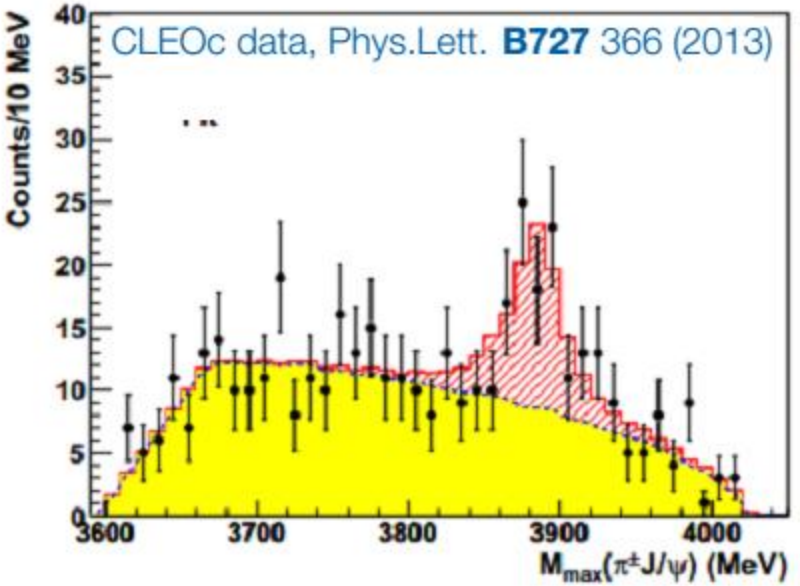
PRL 110, 252001 (2013)

The first Z_c confirmed

by data from three experiments!





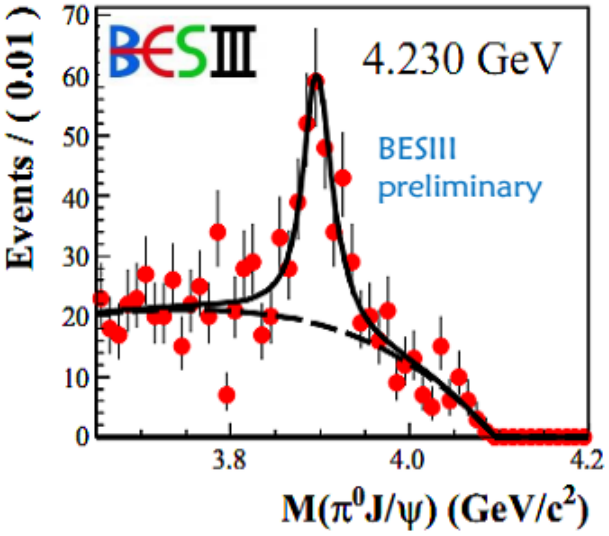


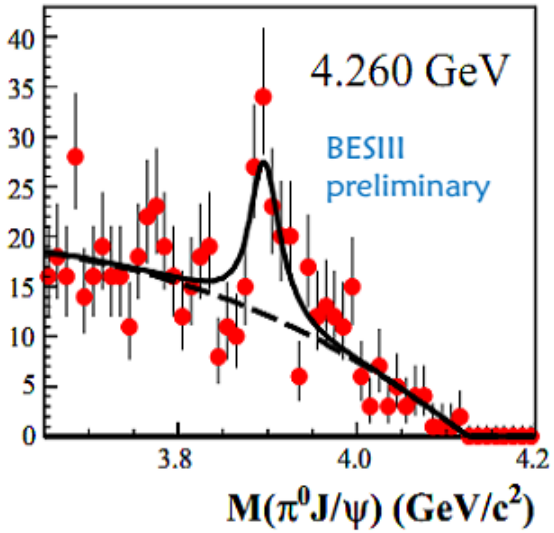
	m / MeV	Γ / MeV
BESIII	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
Belle	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$
CLEOc	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$

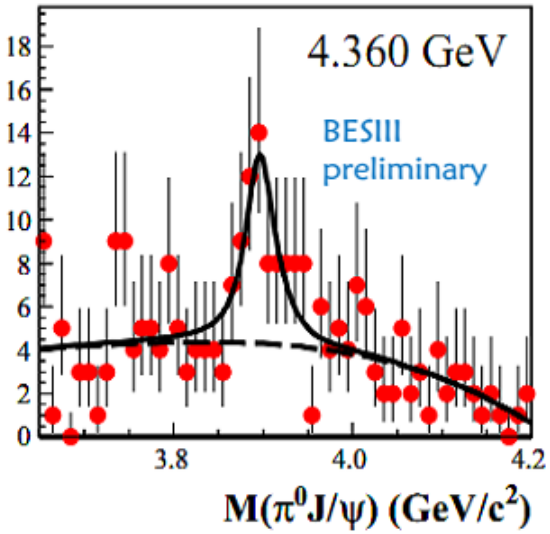
Belle: $e^+e^- \to \gamma_{ISR} J/\psi \pi^+\pi^-$,
in $Y(4260)$ region
CLEOc data: $\sqrt{s} = 4.170\,\text{GeV}$

Neutral partner!

Studying the $e^+e^- \to \pi^0\pi^0 J/\psi$ process at different $\sqrt{s}$







A structure in $\pi^0 J/\psi$ invariant mass is clearly evident:

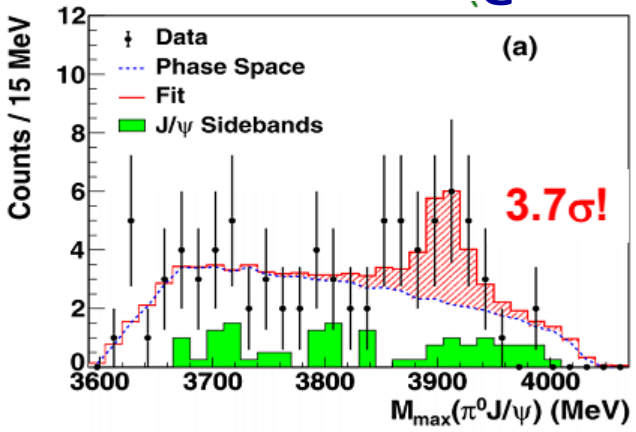
M: (3894.8 ± 2.3 ± 2.7) MeV/c²

Γ: (29.6 ± 8.2 ± 8.2) MeV

Significance = 10σ

Isospin triplet **established!**

NWU: CLEOc data @ 4.17 GeV



PLB 727, 366

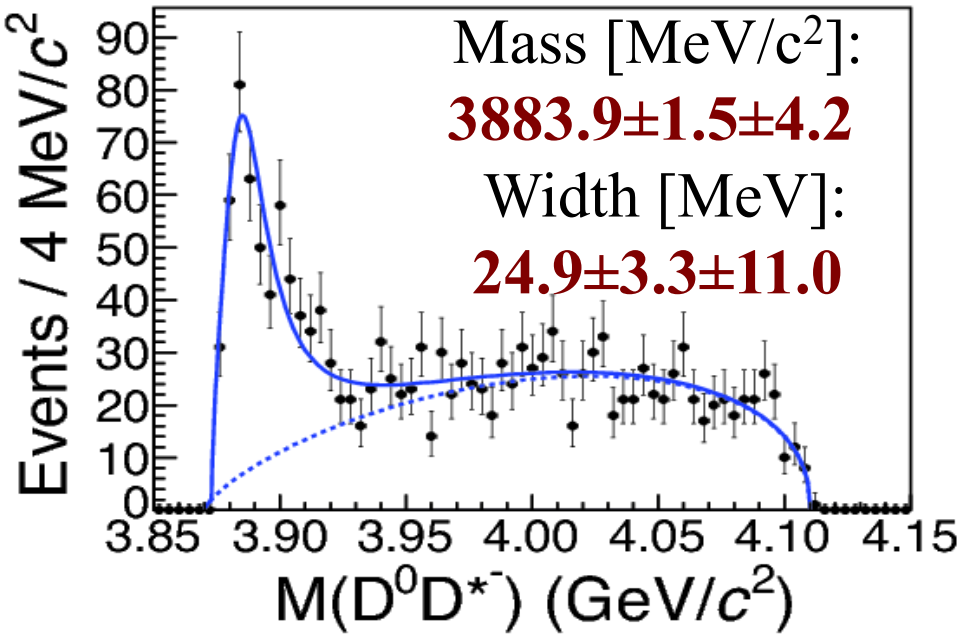
$Z_c(3900)$: close to D^*D threshold

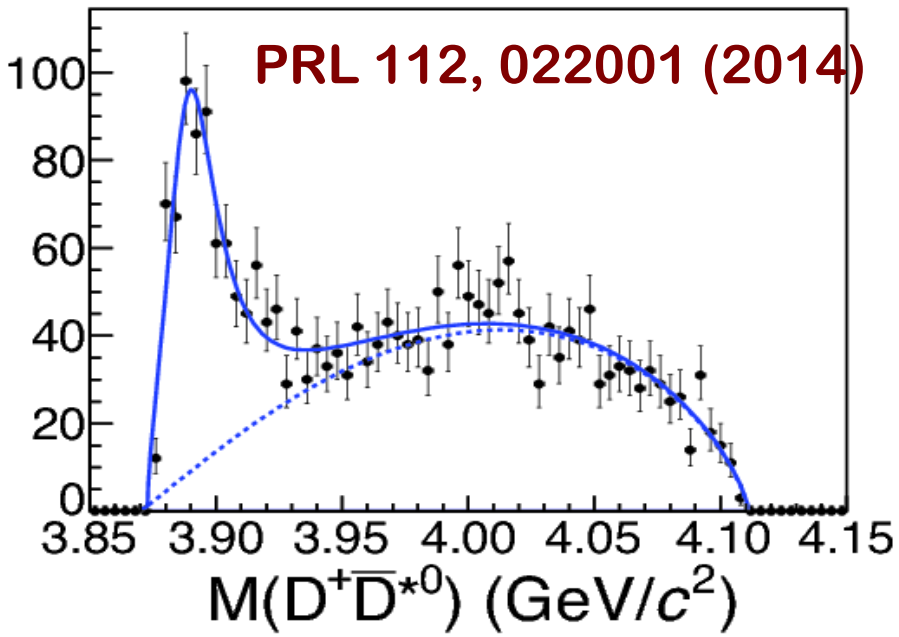
$e^+e^- \to \pi^+ D^0 D^{*-} + c.c.$ → $K^-\pi^+$

$e^+e^- \to \pi^+ D^- D^{*0} + c.c.$ → $K^-\pi^+\pi^+$

$\sqrt{s} = 4.26\ GeV$

Single D-tag: reconstruct π^+ and $D^0 \to K^-\pi^+$ and require that missing mass is consistent with D^*; (do the same for $\pi^+D^-D^{*0}$)





Enhancement in both $D\overline{D}^*$ modes, labeled $Z_c(3883)$

$Z_c(3883)$: angular analysis

PRL 112, 022001 (2014)

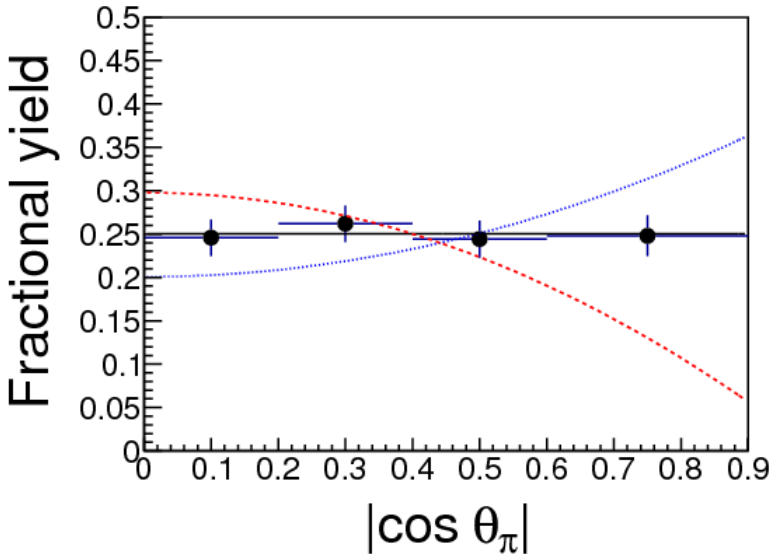
0^-, π in P-wave: $dN/\,d\,cos\theta_\pi \propto 1 - cos^2\theta_\pi$

1^-, π in P-wave: $dN/\,d\,cos\theta_\pi \propto 1 - cos^2\theta_\pi$

1^+, π in S-wave : $dN/\,d\,cos\theta_\pi \propto$ flat

(assuming D-wave small near threshold)

0^+: excluded by parity conservation



Data clearly favor $J^{PC} = 1^+$

If $Z_c(3900)$ and $Z_c(3883)$ are the same:

$$\frac{\mathcal{B}(Z_c \to D^* \bar{D})}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 6.2 \pm 1.1 \pm 2.7$$

Compare to:

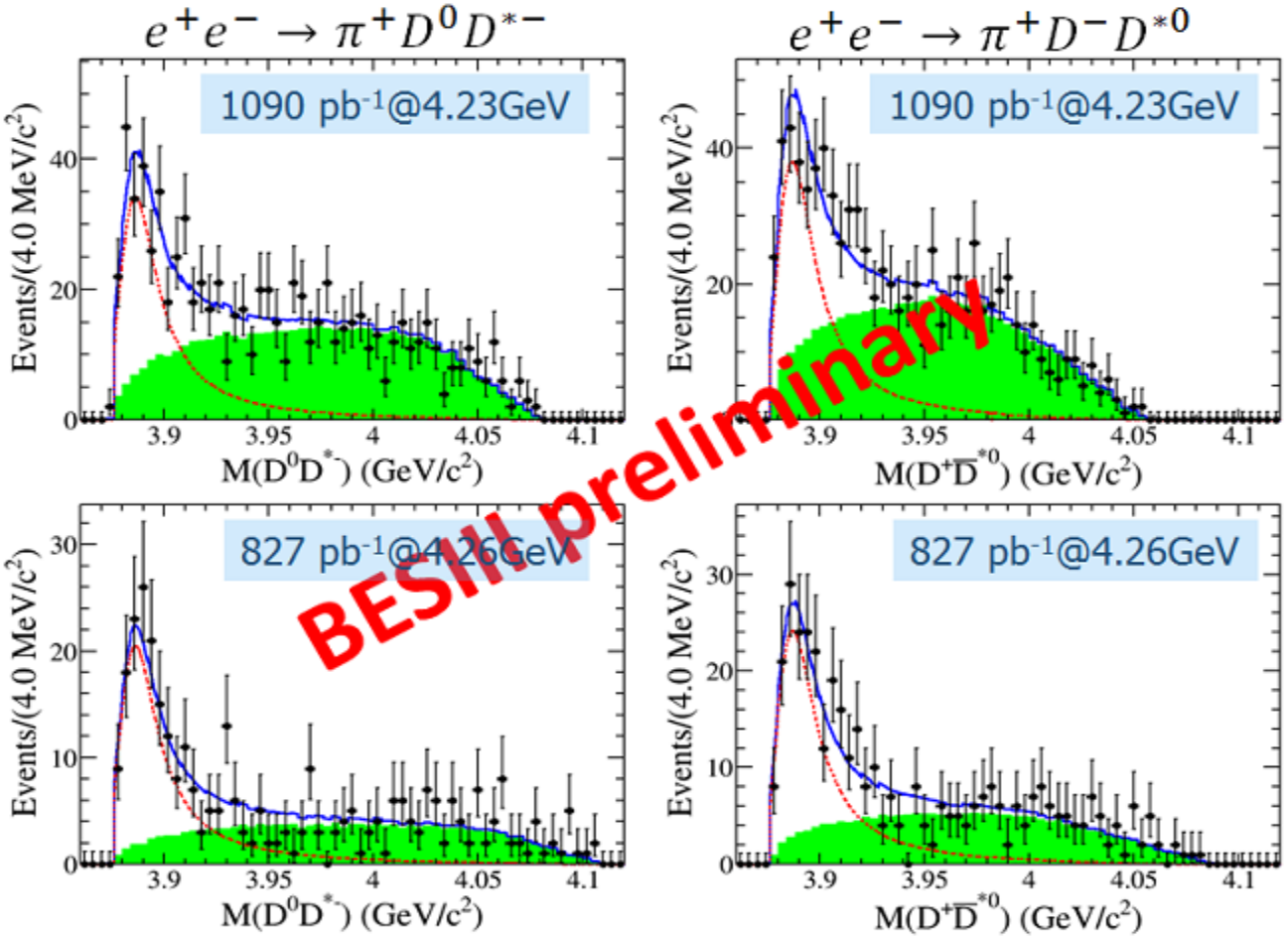
$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)} \bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

Open charm decays clearly suppressed: different dynamics in Y(4260) – $Z_c(3900)$ system!

$Z_c(3883)$: double tag D^*D analysis

Reconstruct π^+ and D^0, D^-, in 4 or 6 decay modes, plus require π in missing D* mass:

(new)



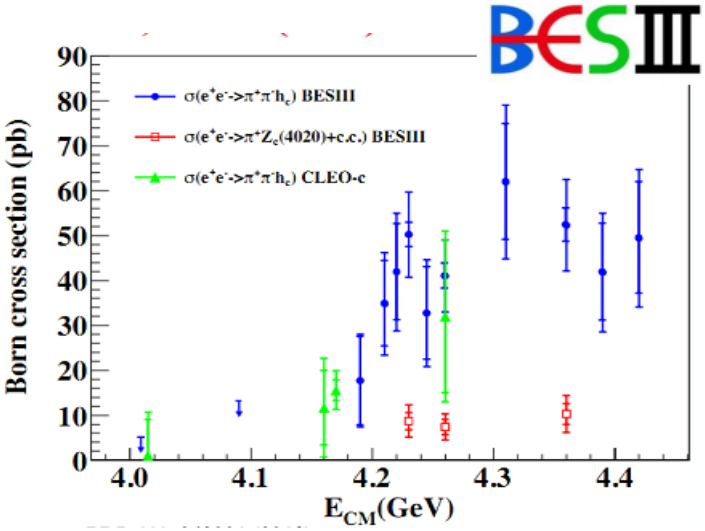
Mass [MeV/c^2]:
3884.3±1.2±1.5
Width [MeV]:
23.8±2.1±2.6

Compatible with single D-tag result, but much more precise!

$e^+e^- \to \pi^+\pi^- h_c(1P)$

$h_c \to \gamma\eta_c$; η_c in 16 decay channels @ 13 different energies!

Cross section line shape consistent with CLEO, but not trivial!



PRL 111, 242001 (2013)

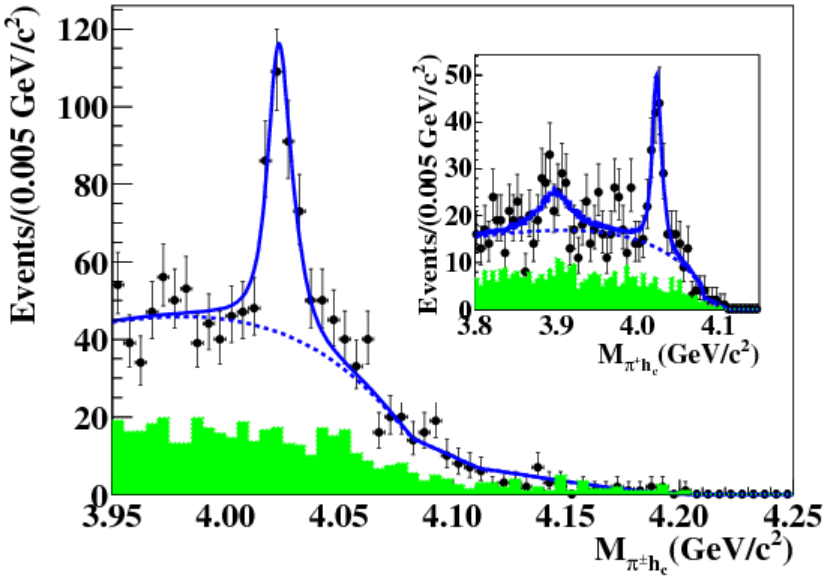
$\pi^\pm h_c$ structure observed:

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV/c^2

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

Yet another charmonium-like state, charged: $Z_c(4020)$

Note: a weak evidence for $Z_c(3090) \to \pi^\pm h_c$



Neutral partner !

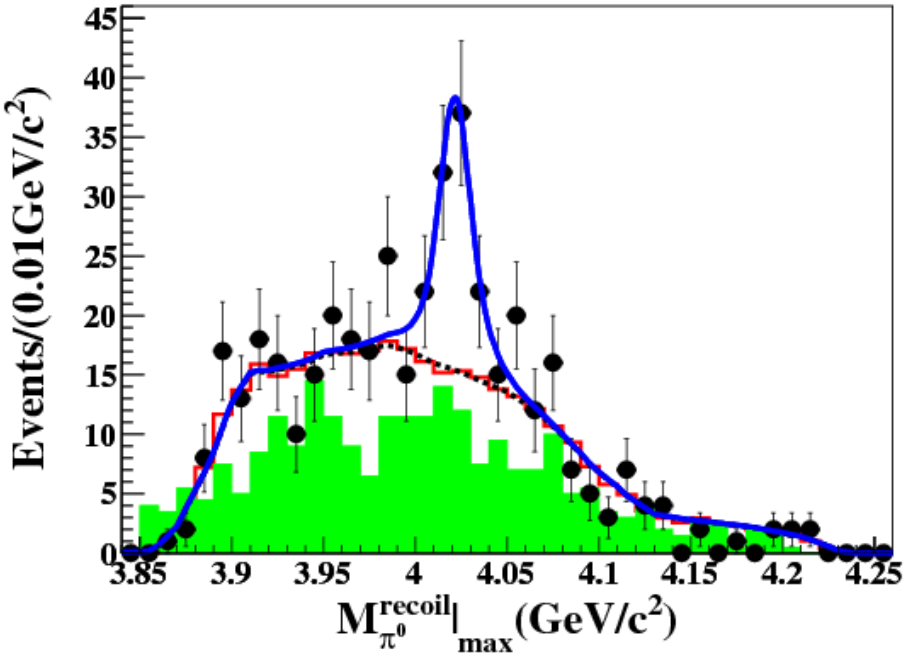
$$e^+e^- \to \pi^0\pi^0 h_c(1P)$$

$\pi^0 h_c$ structure observed:

M = **4023.9 ± 2.2 ± 3.8** MeV/c²

Γ - **fixed** to be the same as for its charged partner.

Another isospin triplet established!



PRL 113, 212002 (2014)

Note: cross sections for $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \pi^0\pi^0 h_c$

consistent with isospin conservation!

$Z_c(4020)$ close to D^*D^* threshold

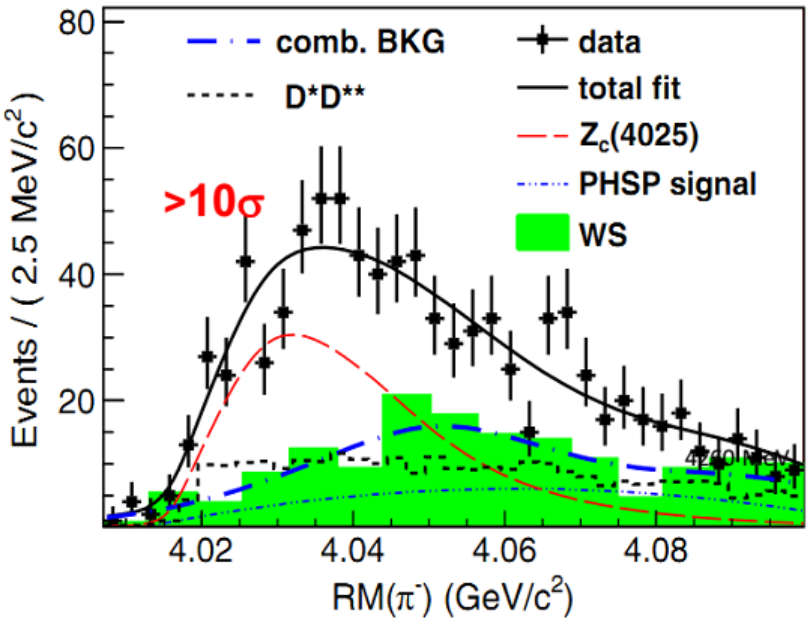
$e^+e^- \to \pi^- (D^*\overline{D^*})^+ + c.c.$ at $\sqrt{s} = 4.26\ GeV$

PRL 112, 132001 (2014)

Tag a D* and `bachelor` π^- :

look for recoil mass against π^-

after reconstructing π^0 to suppress the background.



$D^*\overline{D^*}$ structure observed $Z_c(4025)$:

$M = \mathbf{4026.3 \pm 2.6 \pm 3.7}$ MeV/c^2

$\Gamma = \mathbf{24.8 \pm 5.6 \pm 7.7}$ MeV

If $Z_c(4020)$ and $Z_c(4025)$ are the same, coupling to $D^*\overline{D^*}$ much stronger compared to πh_c:

$$\sigma[e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp] = 137 \pm 9 \pm 15 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^\pm Z_c(4025)^\mp \to (D^*\bar{D}^*)^\pm\pi^\mp]}{\sigma[e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp]} = 0.65 \pm 0.09 \pm 0.06$$

D^*D^* double-tag neutral mode!

$e^+e^- \to \pi^0 (D^* \bar{D}^*)^0$ @ 4.23 & 4.26 GeV

Similar strategy: tag D , $\bar{D}$ & select π^0

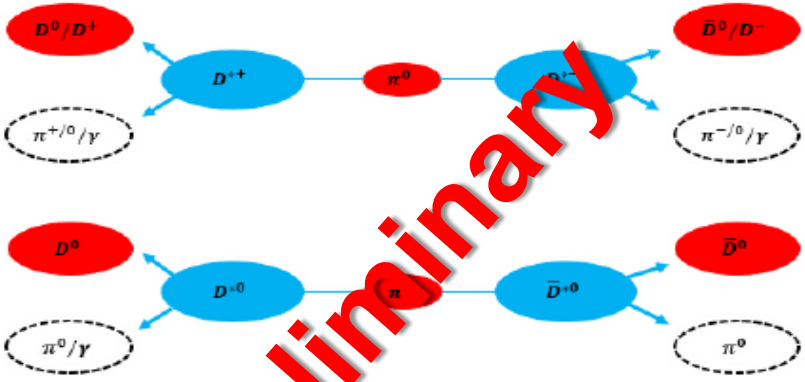
(new)

$D^0 \to K^- \pi^+ + c.c.$

$D^0 \to K^- \pi^+ \pi^0 + c.c.$

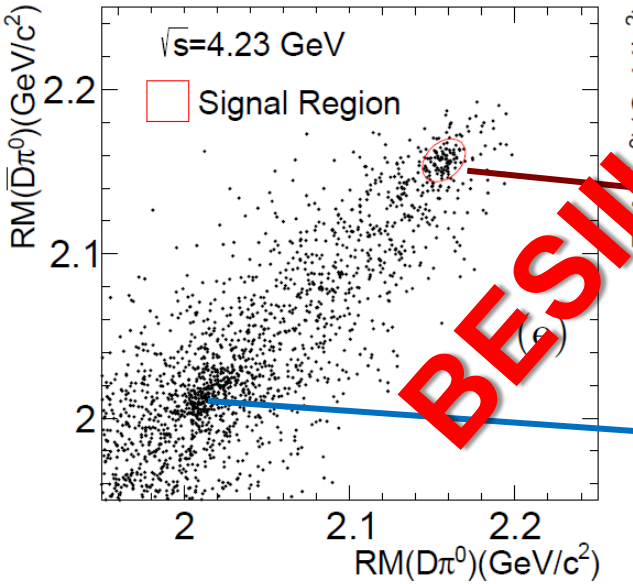
$D^0 \to K^- \pi^+ \pi^+ \pi^- + c.c.$

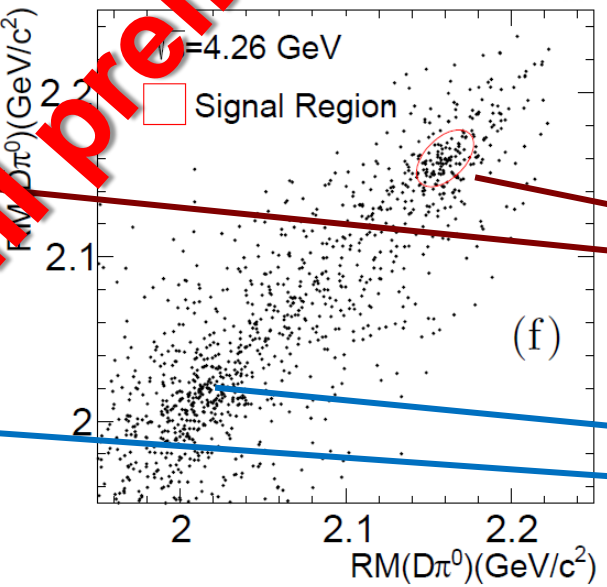
$D^+ \to K^- \pi^+ \pi^+ + c.c.$



detected

not detected





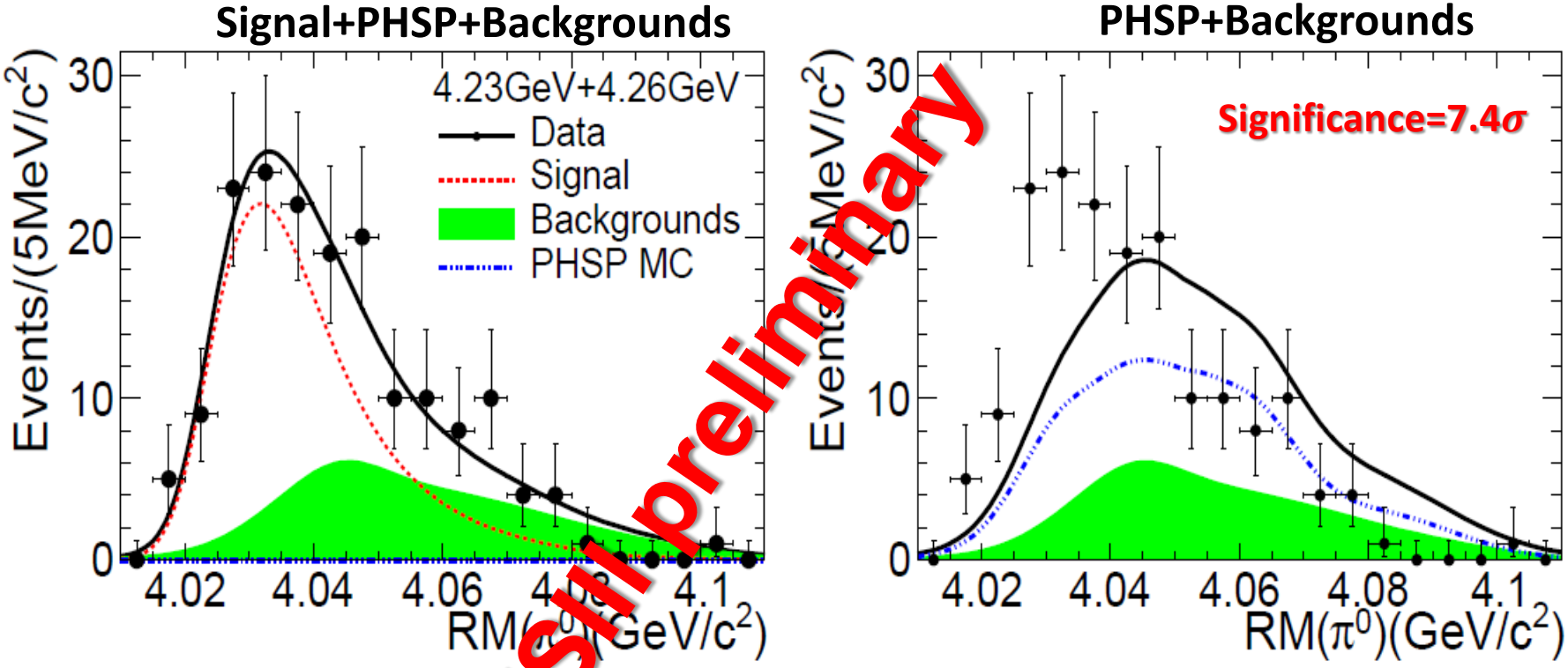
BESIII preliminary

signal regions:

$D^*D^*\pi^0$ process

$DD^*\pi^0$ process

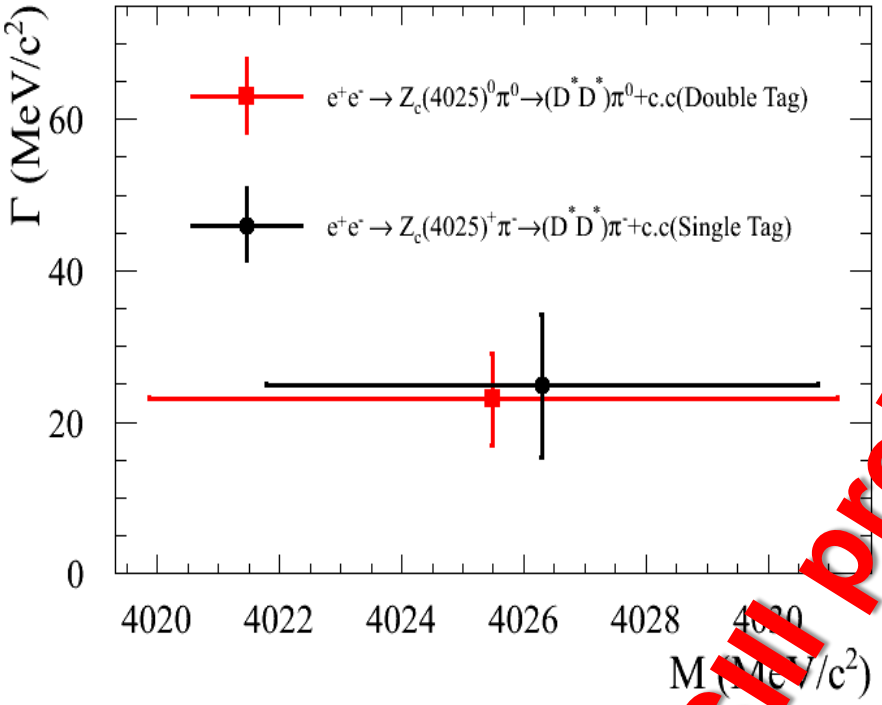
π^0 recoiling mass

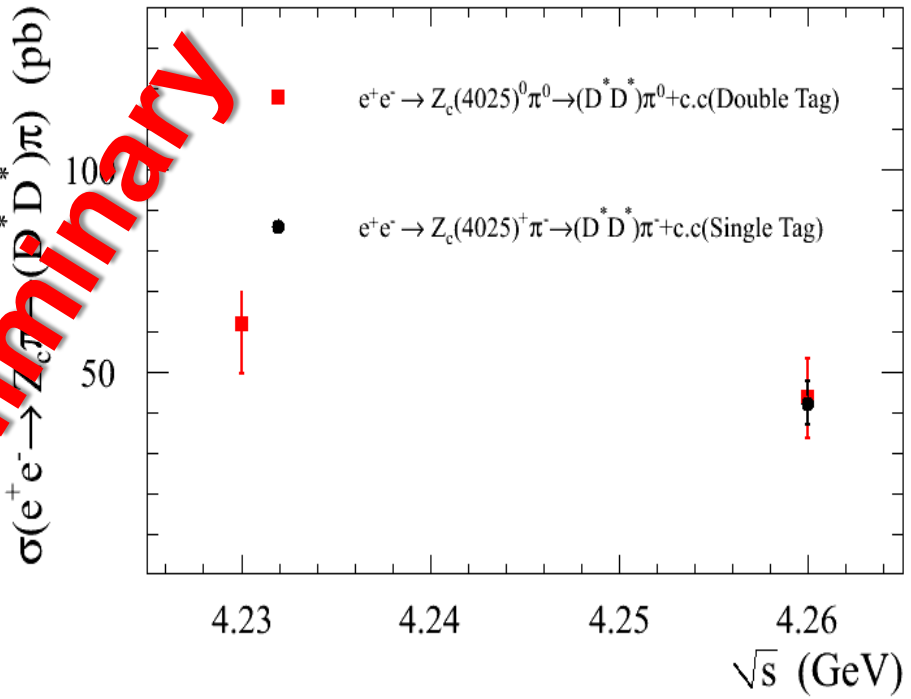


Data	Mass(MeV/c^2)	Width(MeV)	$\sigma(e^+e^- \to Z_c(4025)^0\pi^0 \to D^*\bar{D}^*\pi^0)$(pb)
@4.23GeV	$4025.5^{+2.0}_{-4.7}\pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$61.6 \pm 8.2 \pm 9.0$
@4.26GeV			$43.4 \pm 8.0 \pm 5.4$

Note: **consistency** between charged and neutral modes!

Comparison between $Z_c(4025)^0$ and $Z_c(4025)^+$





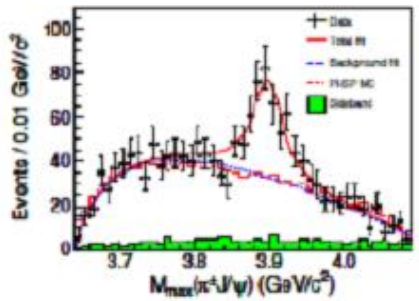
BESIII preliminary

	Mass(MeV/c^2)	Width(MeV)	$\sigma(e^+e^- \to Z_c(4025)\,\pi \to D^*\bar{D}^*\pi)$(pb) @4.26GeV
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$43.4 \pm 8.0 \pm 5.4$
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$42.2 \pm 2.8 \pm 4.6$

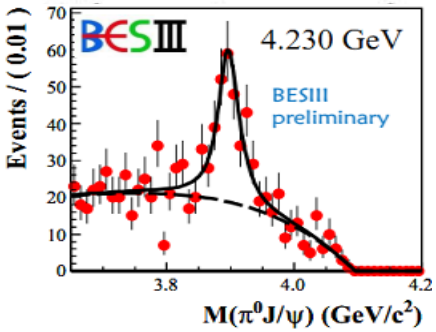
What do we know so far!

State	Mass(MeV)	Width(MeV)	Decay mode	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ [single D tag] $3884.3 \pm 1.2 \pm 1.5$ [double D tag]	$24.8 \pm 3.3 \pm 11.0$ [single D tag] $23.8 \pm 2.1 \pm 2.6$ [double D tag]	D^0D^{*-} D^-D^{*0}	$e^+e^- \to \pi^+ D^0 D^{*-}$ $e^+e^- \to \pi^+ D^- D^{*0}$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^{*0}D^{*-}$	$e^+e^- \to \pi^+ (D^* \bar{D}^*)^-$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$(D^*D^*)^0$	$e^+e^- \to \pi^0 (D^*D^*)^0$

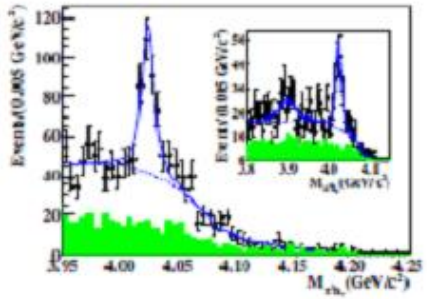
What do we know so far!



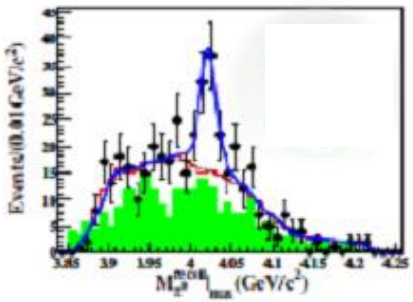
$e^+e^- \to \pi^-\pi^+ J/\psi$



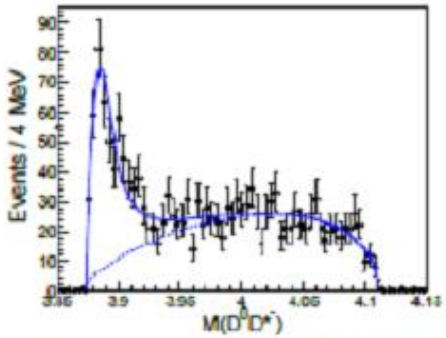
$e^+e^- \to \pi^0\pi^0 J/\psi$



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



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

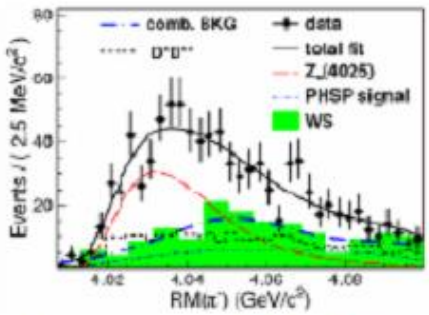


$e^+e^- \to \pi^- (D\bar{D}^*)^+$

$Z_c(3900)^+$?

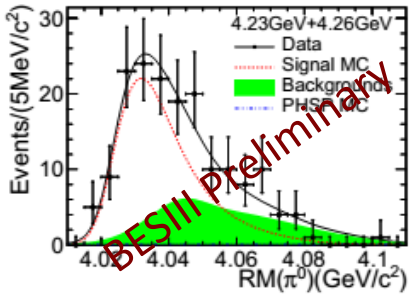
soon …

$Z_c(3900)^0$?



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

$Z_c(4020)^+$?



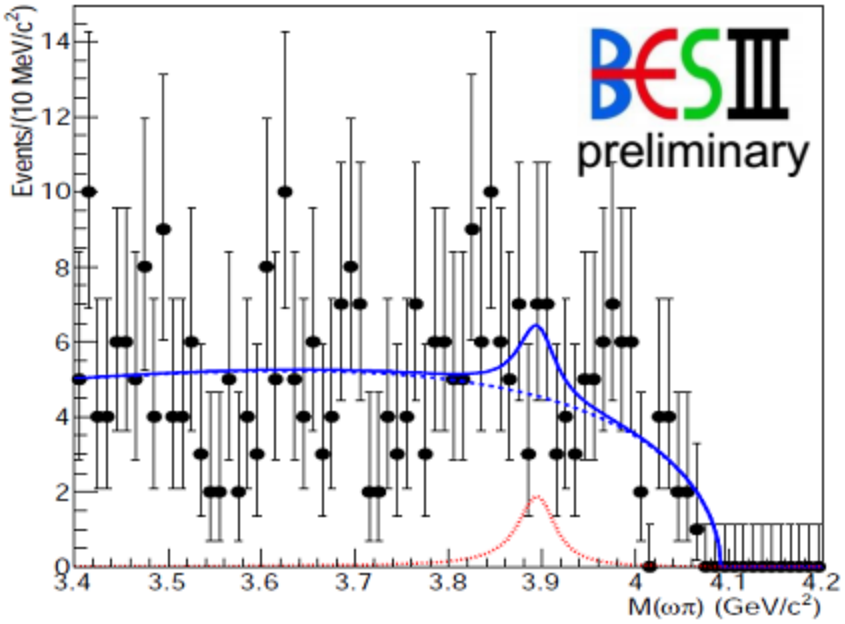
$e^+e^- \to \pi^0 (D^*\overline{D^*})^0$

$Z_c(4020)^0$?

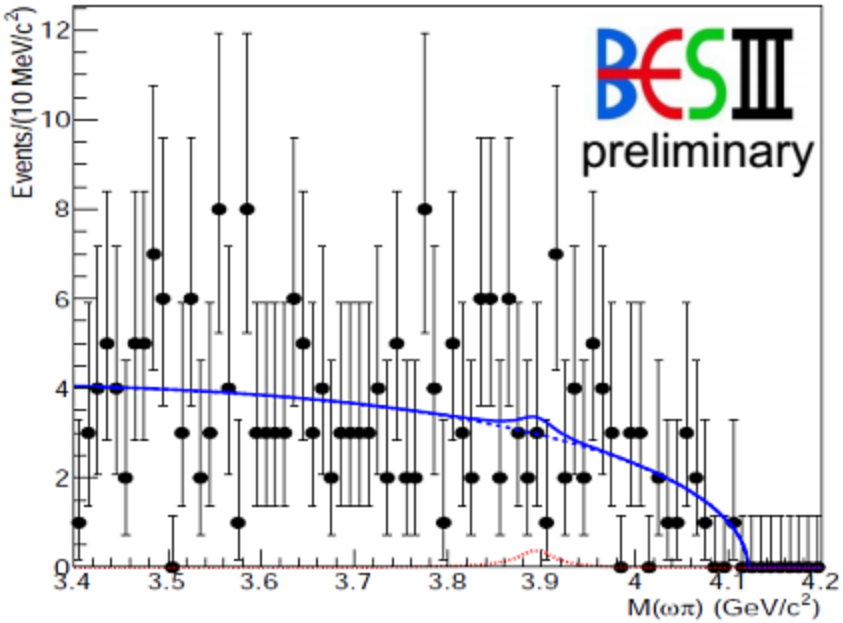
$e^+e^- \to \pi^+\pi^-\omega$ @ 4.23-4.26 GeV

$\omega \to \pi^+\pi^-\pi^0$

$\sqrt{s}$ = 4.23 GeV

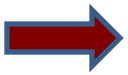


$\sqrt{s}$ = 4.26 GeV



No significant $\mathbf{Z_c(3900) \to \pi\omega}$ signal!

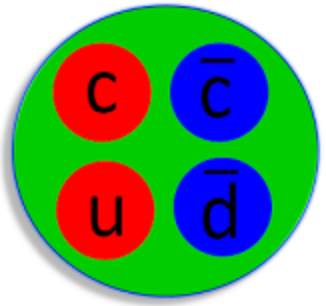
$\Gamma(Z_c(3900) \to \pi\omega) < \mathbf{0.2\ \%}\ \Gamma_{tot}(Z_c(3900))$



Indicates that $c\bar{c}$ annihilation **is suppressed!**

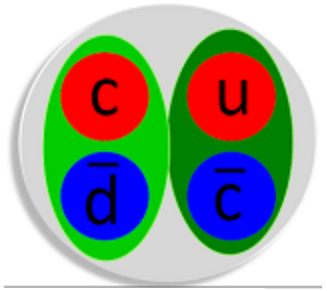
What is the nature of these Z_c?

- At least 4 quarks, not a conventional mesor
- Tetraquark state?



Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);
Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); etc

- $D^{(*)}\ \bar{D}^{(*)}$ molecule state?



Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)
Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

- **Threshold-effects?**

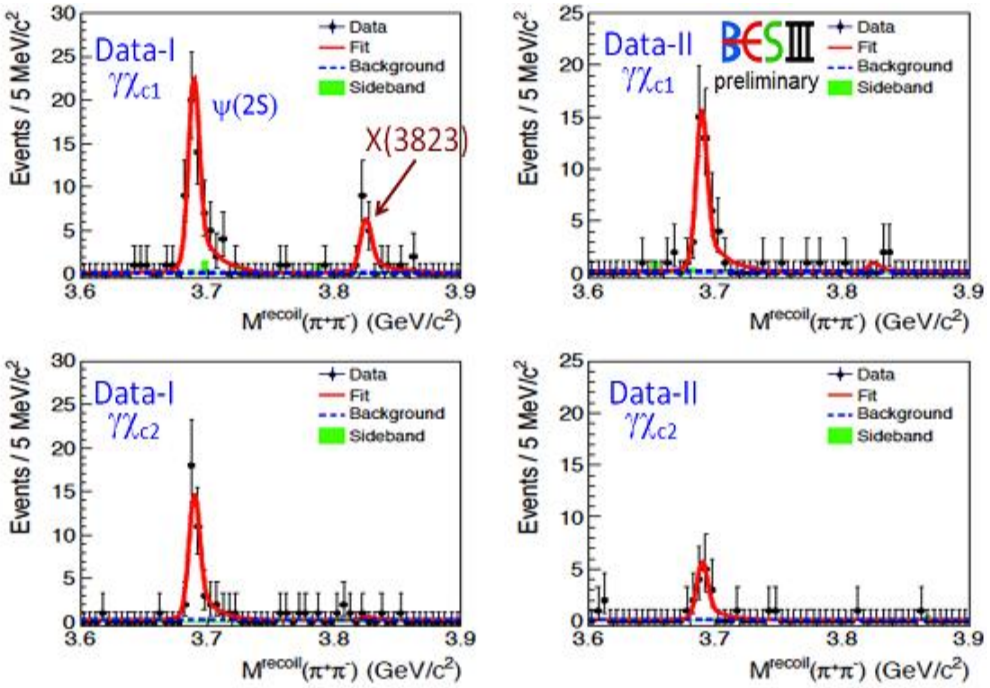
Rescattering near threshold due to interactions between two outgoing mesons,
both $Z_c(3900)$ & $Z_c(4020)$ suspiciously close to $D^{(*)}D^{(*)}$ **thresholds**!

X & Y @ BESIII

$e^+e^- \to \gamma\pi^+\pi^-\chi_c$ @ 4.2-4.6 GeV

preliminary
arXiv:1503.08203

Reconstruct $\chi_c \to \gamma\, J/\psi \to \gamma\, l^+l^-$
look for $\pi\pi$ recoil



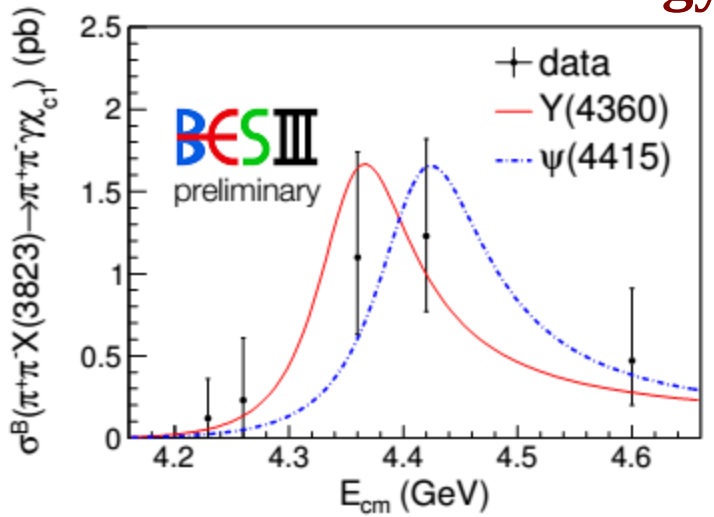
$M = 3821.7 \pm 1.3 \pm 0.7$ MeV, significance 6.7σ

$\Gamma < 16$ MeV at 90% C.L.

X(3823) candidate consistent with
$\psi(1^3D_2) \to \gamma\, \chi_c$

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_c$

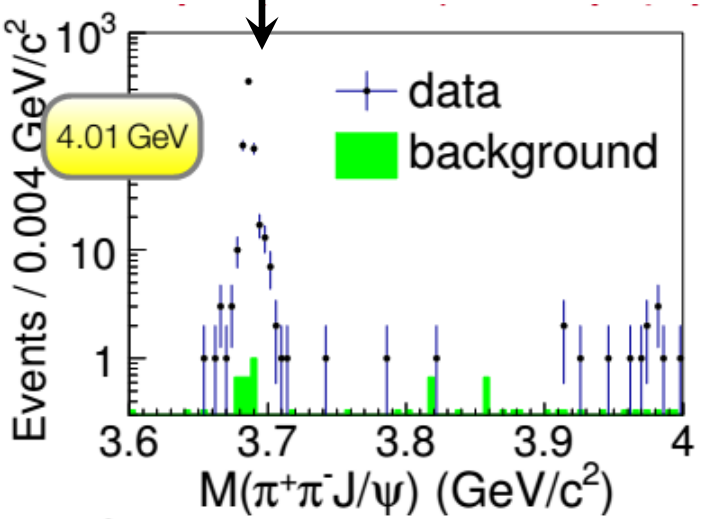
Cross-section v.s. energy

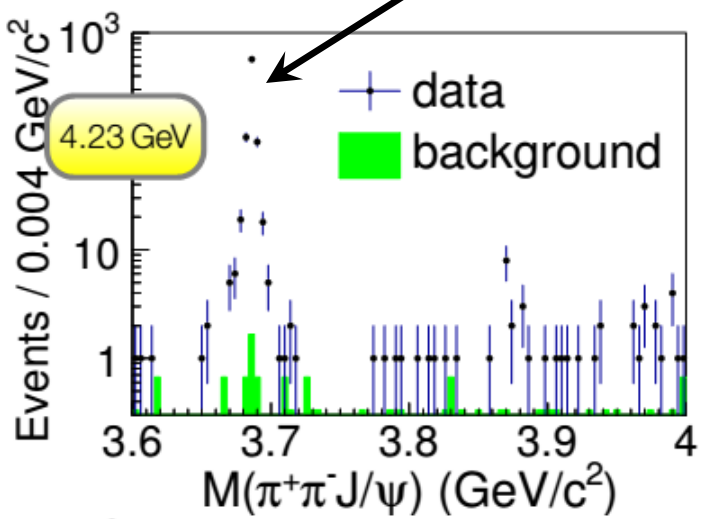


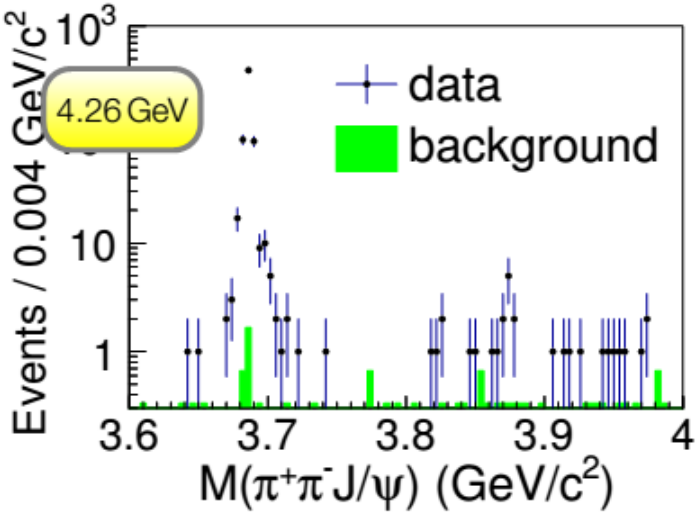
Line shape consistent with both Y(4260) & Y4360

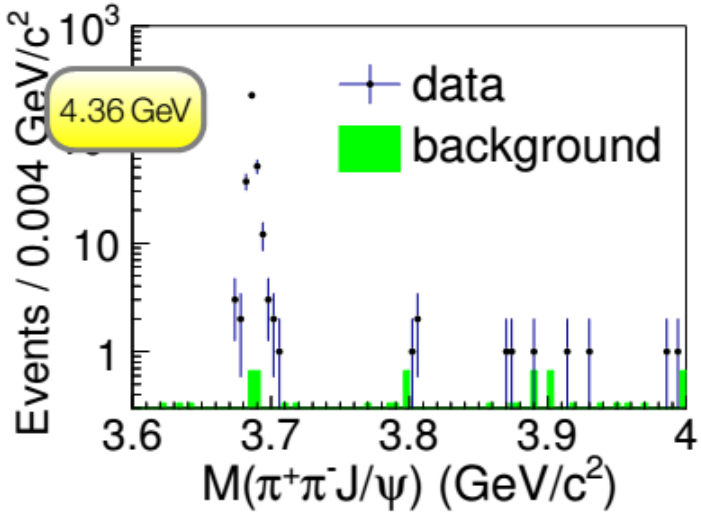
$e^+e^- \to \gamma\pi^+\pi^- J/\psi$

Clear ISR signal for validation: $e^+e^- \to \gamma\psi$







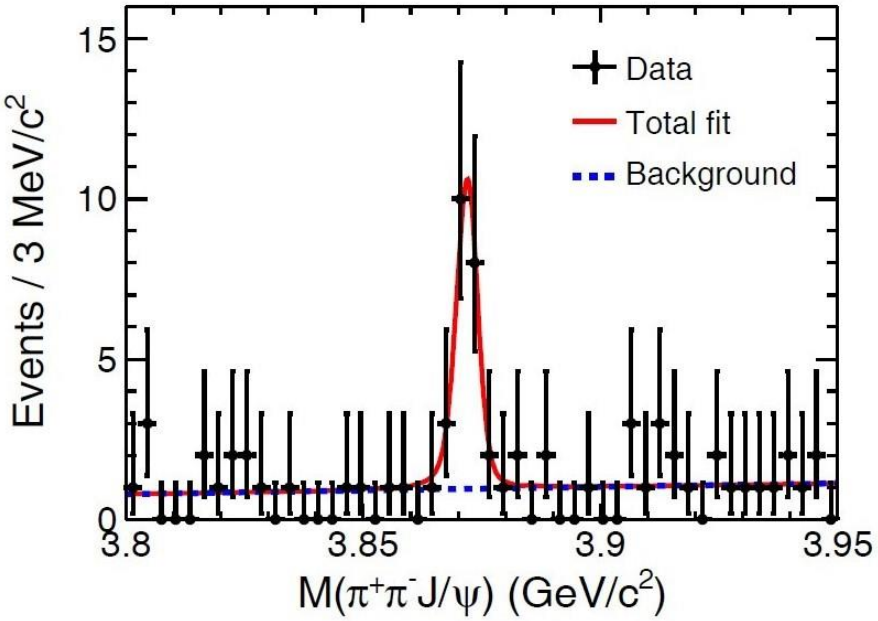


X(3872) @ BESIII

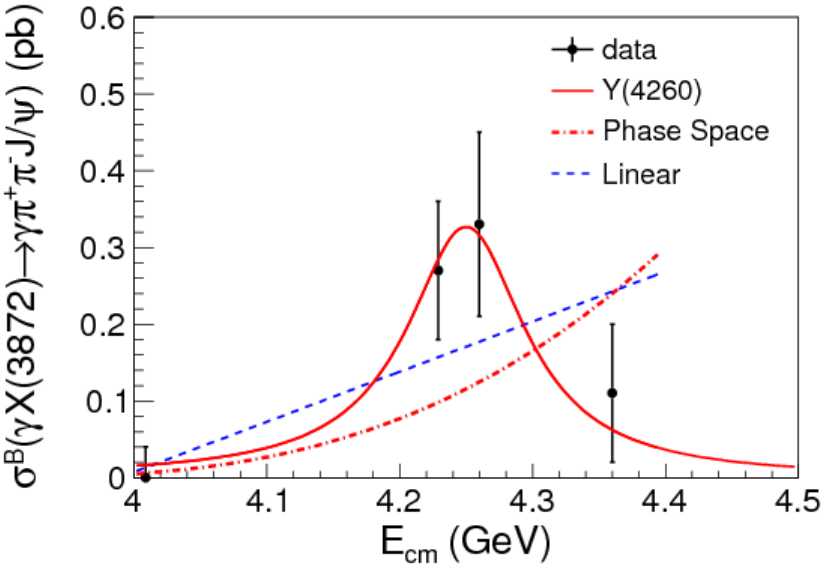
Strong evidence for
X(3872) → ππ J/ψ

PRL 112, 092001 (2014)

M = **3871.9 ± 0.7 ± 0.2** MeV/c²



Suggestive of
Y(4260) → γ X(3872)



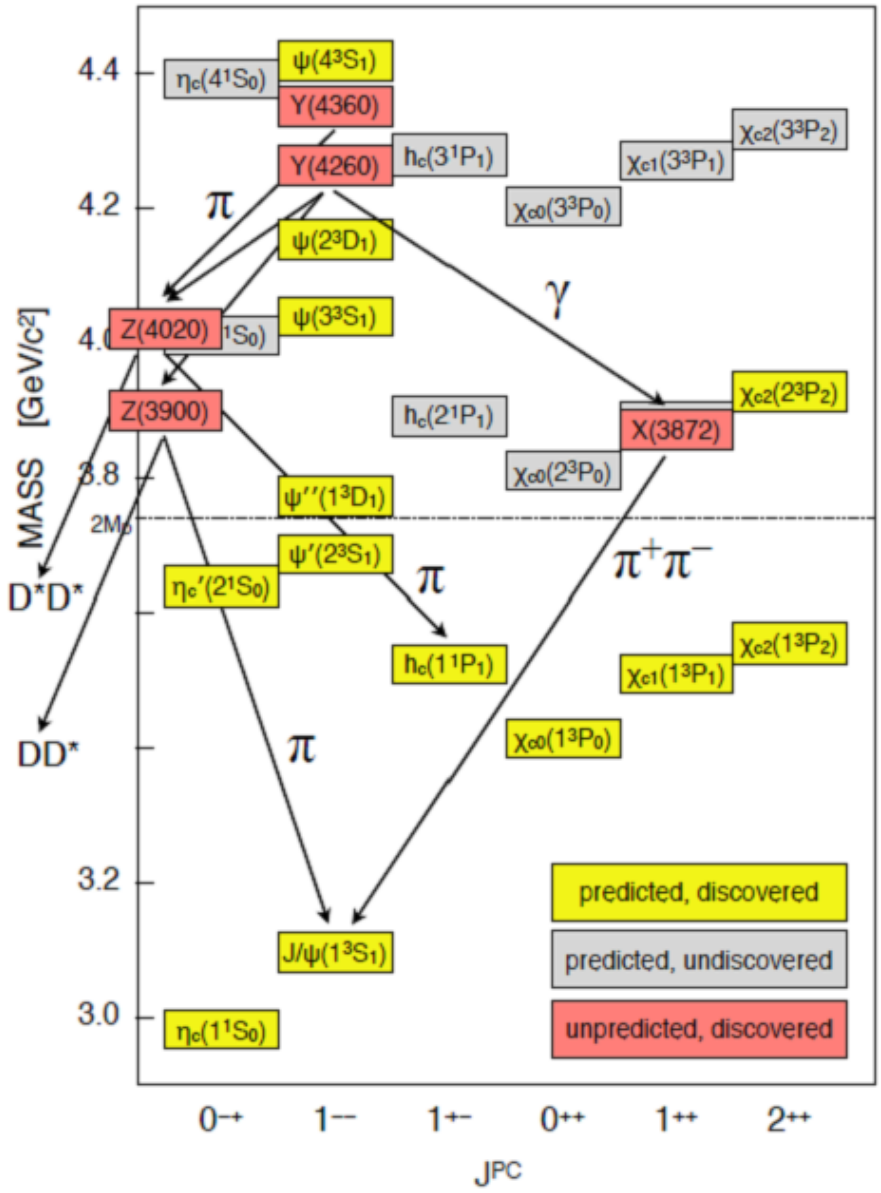
❖ **New mode of production of X(3872) and Y(4260) decay?**

Emerging connections?

Y(1^{--}) states @ BESIII

- Structures from $\pi^+\pi^- h_c$ Phys. Rev. Lett. 111, 242001
- Cross sections of $e^+e^- \to \omega\chi_{c0}$ is measured. No signal of $\omega\chi_{c1}$ or $\omega\chi_{c2}$ found. Disfavor $Y(4260)$ is a $\omega\chi_{c1}$ molecule.
- Cross section of $e^+e^- \to \eta J/\psi$ [preliminary]
- Cross section of $e^+e^- \to \pi^0\pi^0 J/\psi$ [preliminary]
- Cross section of $e^+e^- \to J/\psi\eta\pi^0$, no observation, only upper limit report. [preliminary]
- Cross section of $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ [preliminary]
- Cross section of $e^+e^- \to \eta' J/\psi$ [preliminary]
- $e^+e^- \to \gamma\phi J/\psi$, No significant Y(4140) signal. [preliminary]
- Cross section of $e^+e^- \to \gamma\chi_{cJ}$, no observation, only upper limit report. [preliminary]

XYZ @ BESIII summary



- Quark model works well for charmonium ($c\bar{c}$) states below DD threshold
- Several Z_c structures appear unexpected, pointing to non-conventional (exotic) mesons
- A number of transitions between different exotic states observed, starting to make connections!
- A model that can explain all new features needed!
- Expect more data from BESIII and watch for more BESIII talks!

…

Thank you