Recent results on Υ at BESIII

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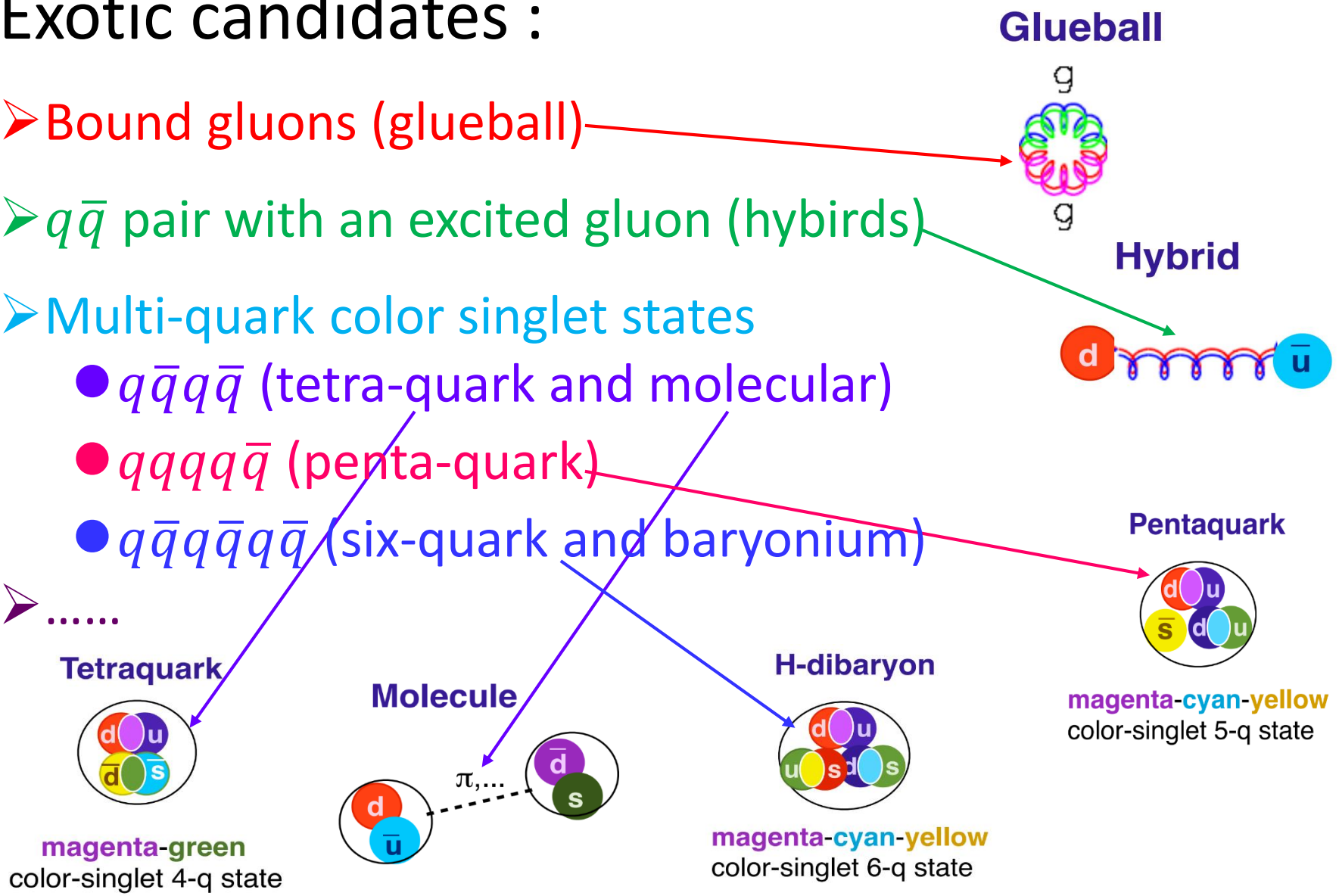
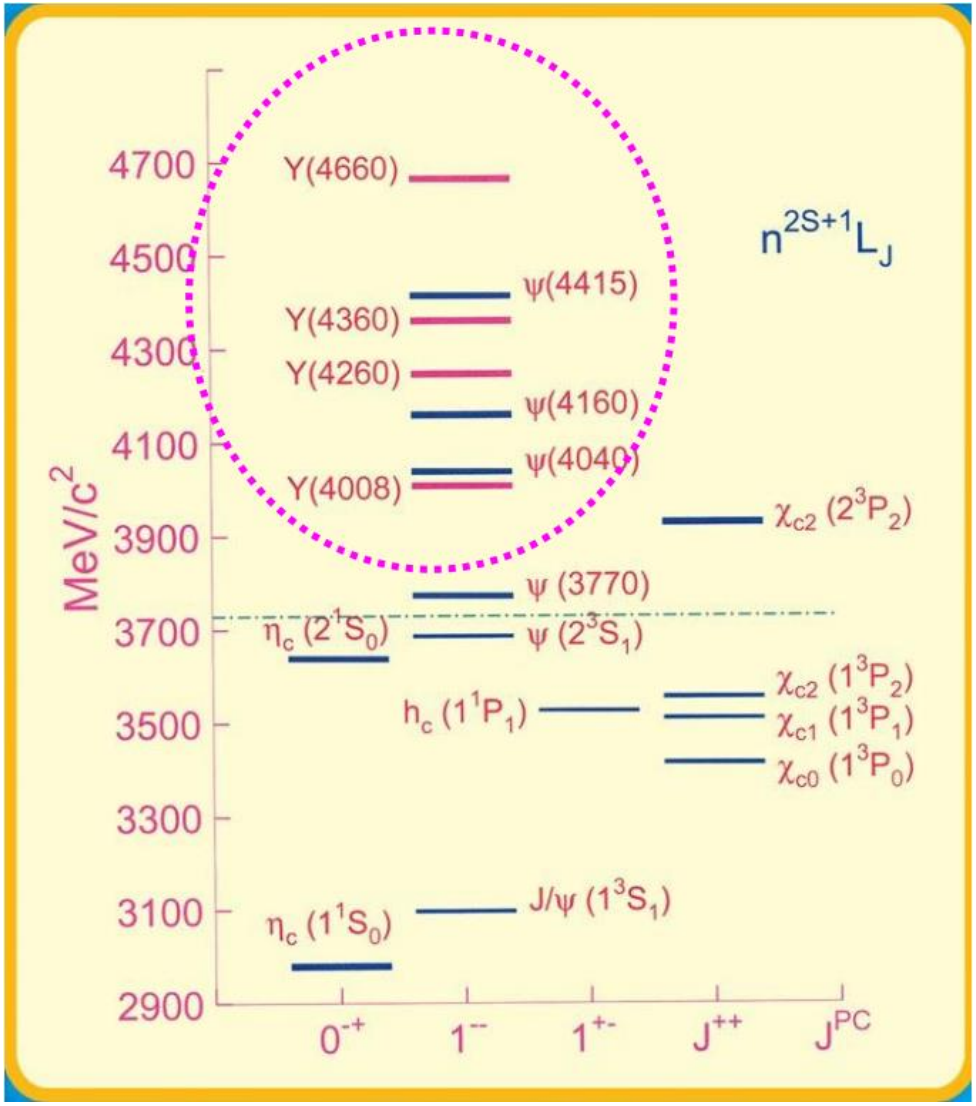
arXiv: 1403. 1254

Exotic candidates :

- Bound gluons (glueball)
- $q\bar{q}$ pair with an excited gluon (hybirds)
- Multi-quark color singlet states
  - $q\bar{q}q\bar{q}$ (tetra-quark and molecular)
  - $qqqq\bar{q}$ (penta-quark)
  - $q\bar{q}q\bar{q}q\bar{q}$ (six-quark and baryonium)
- ……

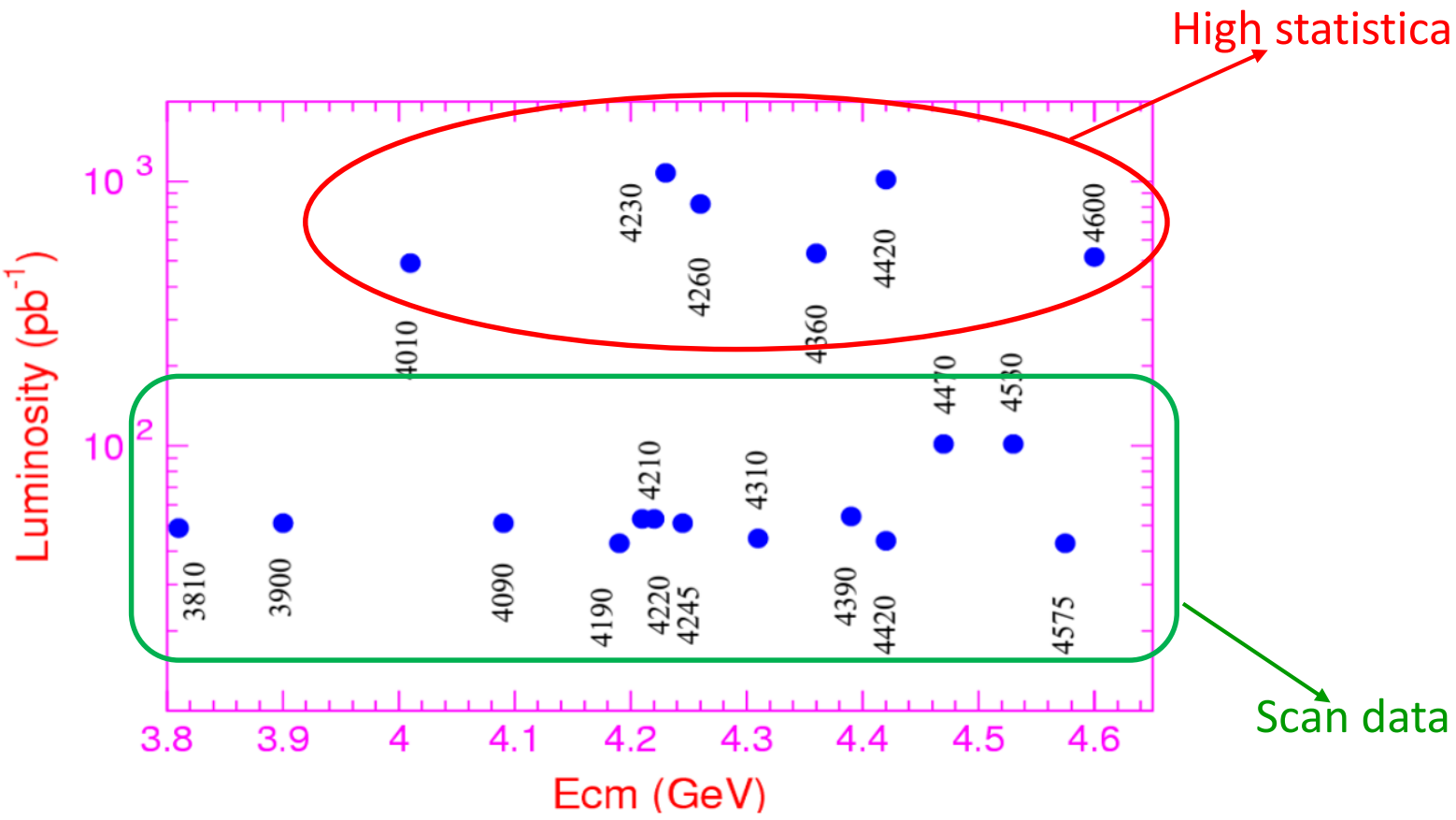


The 1^{--} Y states



- Between 4.0 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S); 7 states observed
- Hybrids are expected in this mass region
- Molecular states?
- Can't rule out threshold effect/FSI/…
- New decay modes ($\pi^+\pi^- h_c, \omega\chi_{c0}$) add complexity

The data set above 3.8 GeV at BESIII



What can we do with these data?

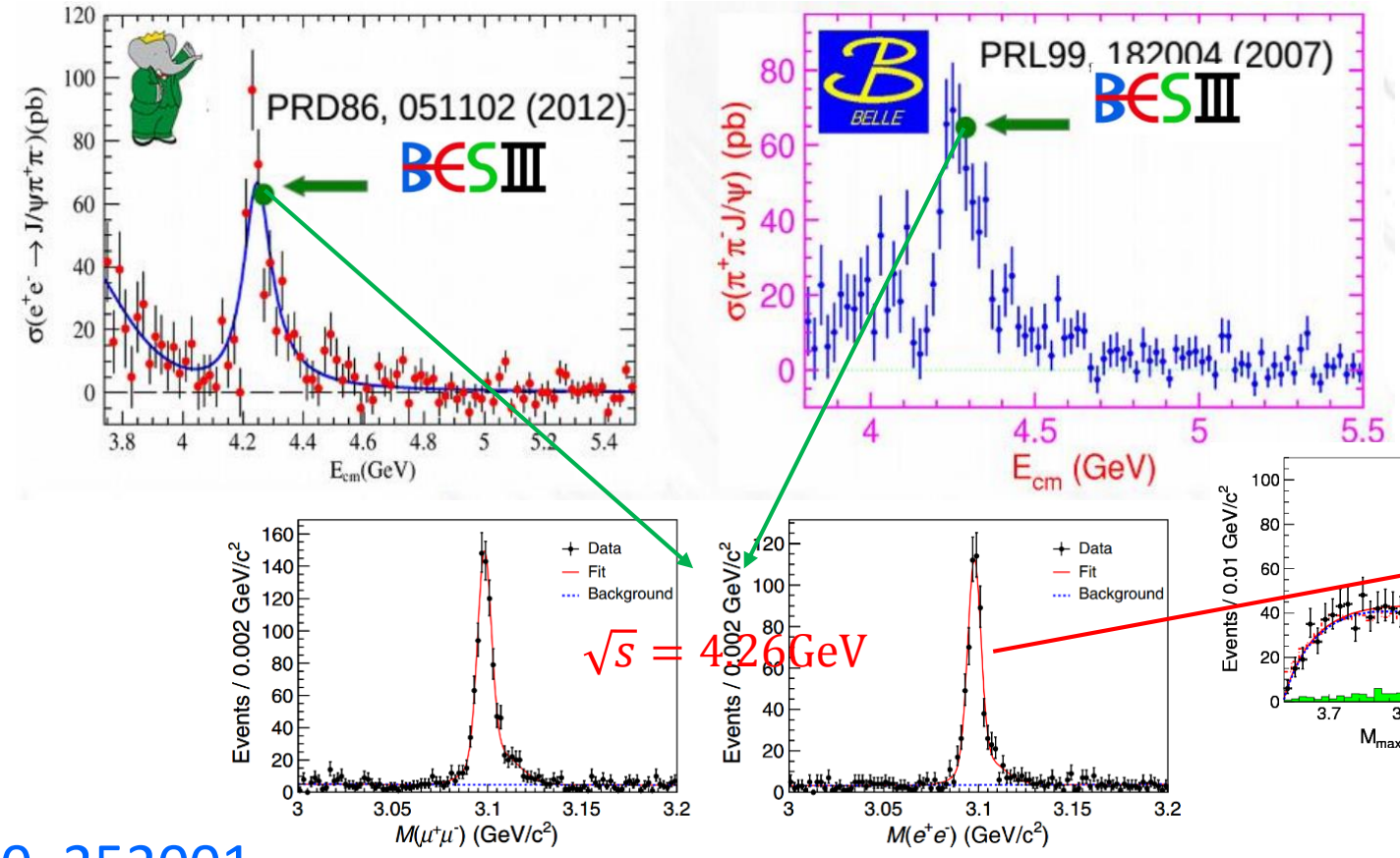
The results at BESIII

- Measurement of cross sections for $e^+e^- \to \pi\pi J/\psi$
- Measurement of cross sections for $e^+e^- \to \pi\pi h_c(1P)$
- Study of $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ from 4.21 to 4.42 GeV
- Measurement of cross sections for $e^+e^- \to \eta J/\psi$ and search for $e^+e^- \to \pi^0 J/\psi$
- Observation of $e^+e^- \to \eta' J/\psi$ from 4.19 to 4.60 GeV
- Search for $e^+e^- \to \gamma\chi_{cJ(J=0,1,2)}$
- Search for the isospin violating decay $Y(4260) \to J/\psi\eta\pi^0$

Measurement of cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$

$\hookrightarrow \mu^+\mu^-/e^+e^-$

BaBar and Belle results, and one month data at BESIII.



PRL 110, 252001

$$\sigma = (62.9 \pm 1.9 \pm 3.7)\text{pb}$$

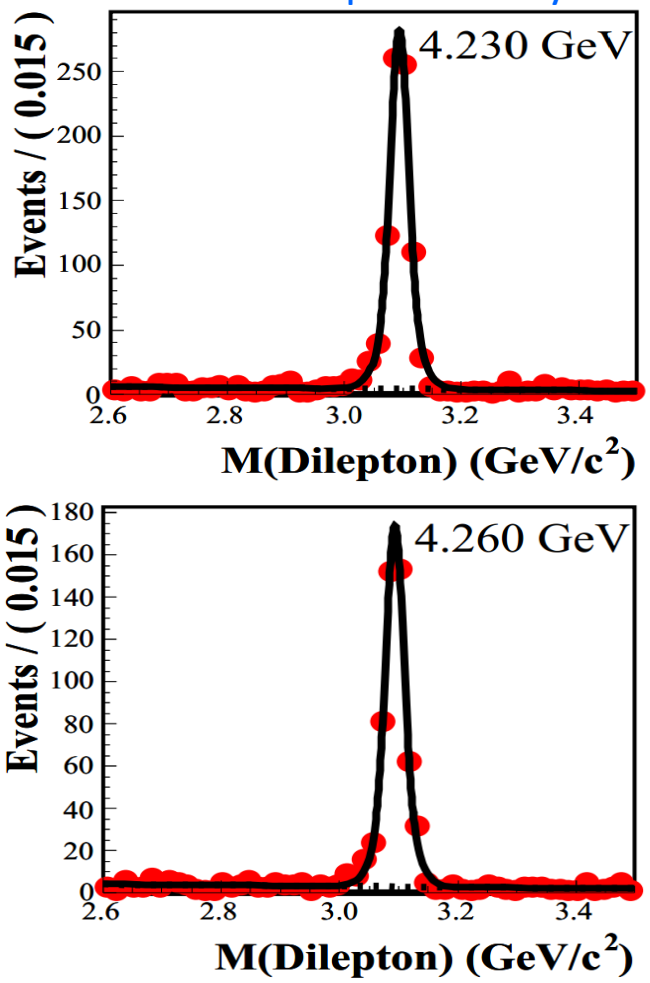
The line-shape analysis for $e^+e^- \to \pi^+\pi^- J/\psi$ is ongoing.

Measurement of cross sections for $e^+e^- \to \pi^0\pi^0 J/\psi$

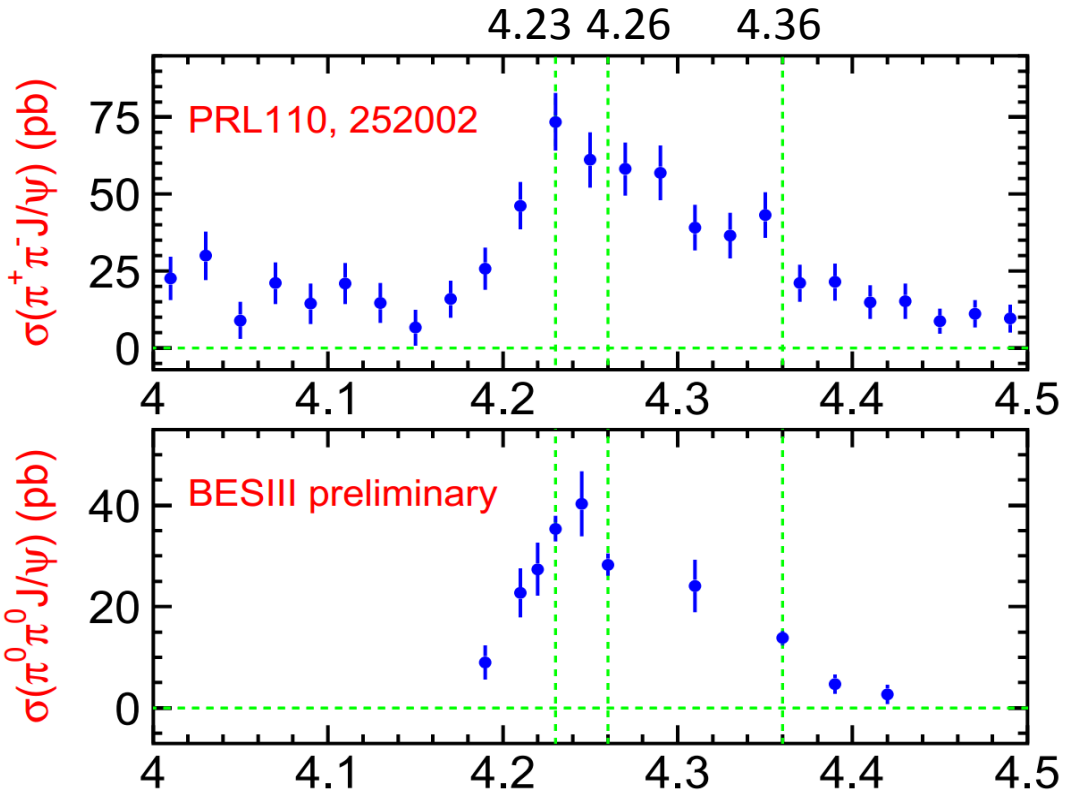
$\gamma\gamma$ ← $\pi^0\pi^0 J/\psi$ → $\mu^+\mu^-/e^+e^-$

Signal : a Breit-Wigner convoluted with a double Gaussian
Background : a first-order Chebyshev polynomial

BESIII preliminary



The efficiency $\varepsilon(\pi^0\pi^0 J/\psi)$ is the average for events with Z_c^0 and without Z_c^0.



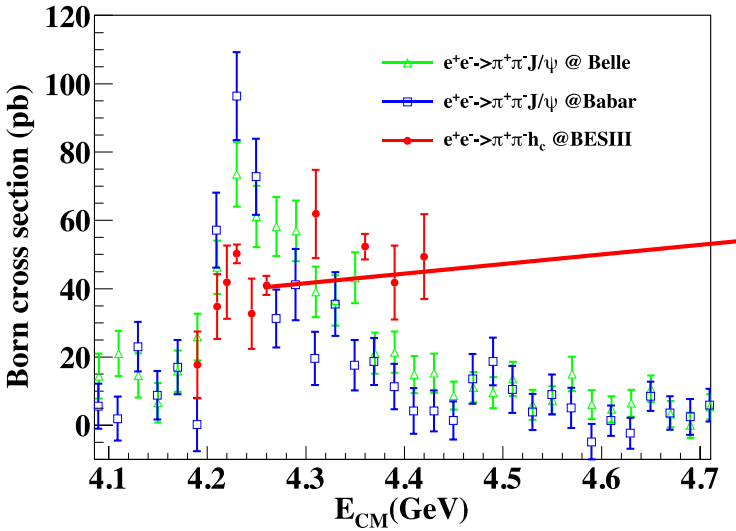
Measurement of cross sections for $e^+e^- \to \pi^+\pi^- h_c(1P)$

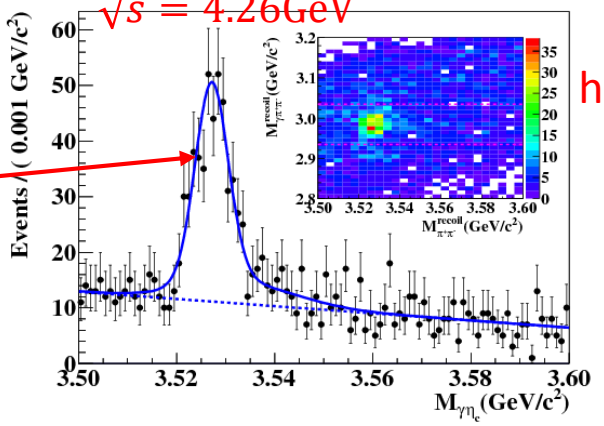
$\gamma\eta_c$

hadrons

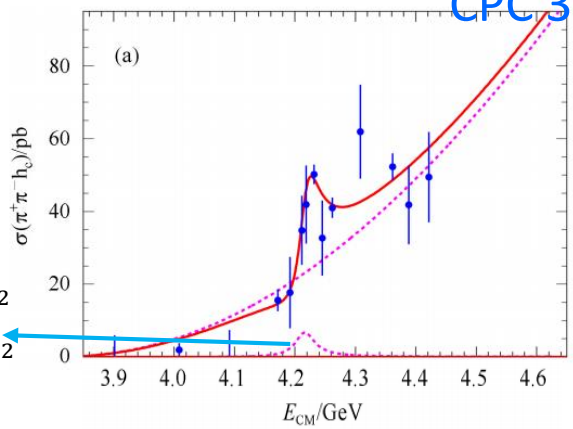
PRL 111, 242001

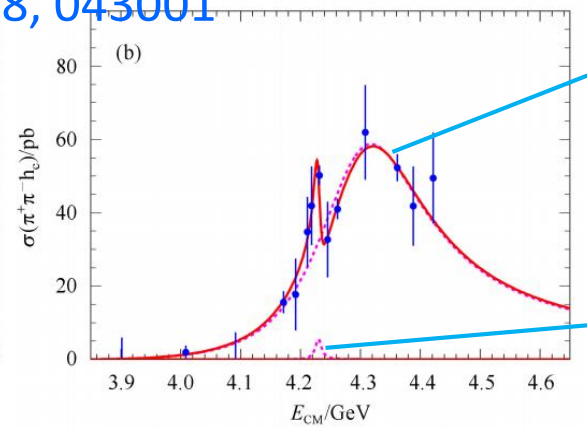
$\sqrt{s} = 4.26\text{GeV}$





CPC 38, 043001





$M^2 = (4293 \pm 9)\text{MeV}/c^2$

$\Gamma^2_{tot} = (222 \pm 67)\text{MeV}/c^2$

$M = (4216 \pm 7)\text{MeV}/c^2$

$\Gamma_{tot} = (39 \pm 17)\text{MeV}/c^2$

$M^1 = (4230 \pm 10)\text{MeV}/c^2$

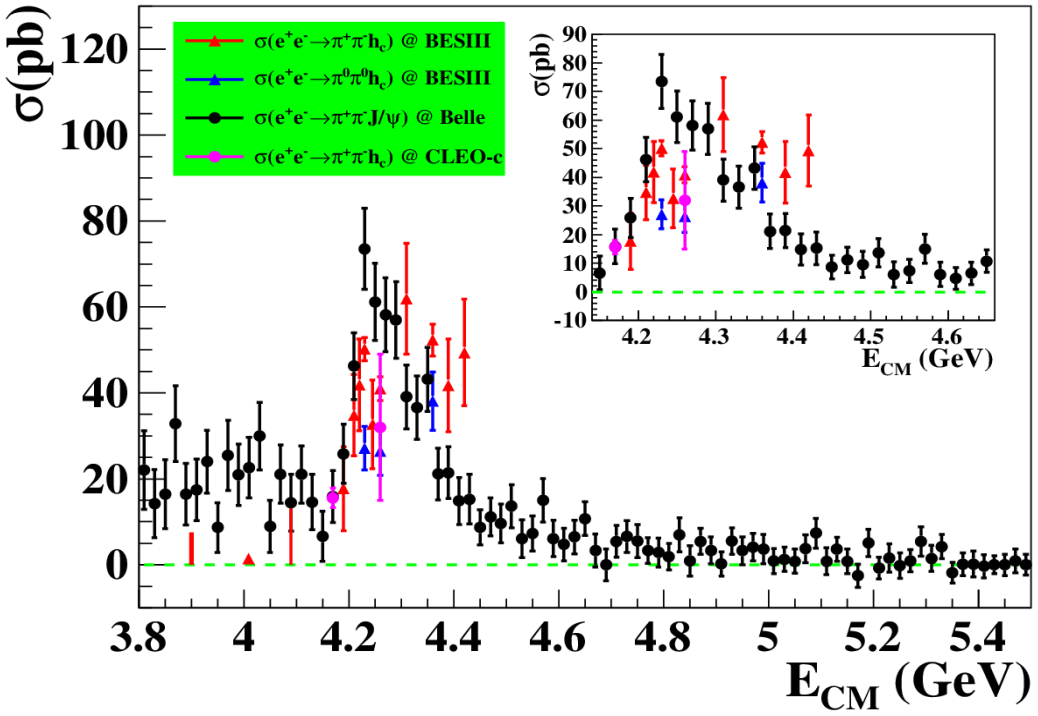
$\Gamma^1_{tot} = (12 \pm 36)\text{MeV}/c^2$

$$\sigma_a(m) = |c\sqrt{PS(m)} + e^{i\phi} BW(m)\sqrt{\frac{PS(m)}{PS(M)}}|^2 \quad \sigma_b(m) = |BW_1(m)\sqrt{\frac{PS(m)}{PS(M_1)}} + e^{i\phi} BW_2(m)\sqrt{\frac{PS(m)}{PS(M_1)}}|^2$$

Measurement of cross sections for $e^+e^- \to \pi^0\pi^0 h_c(1P)$

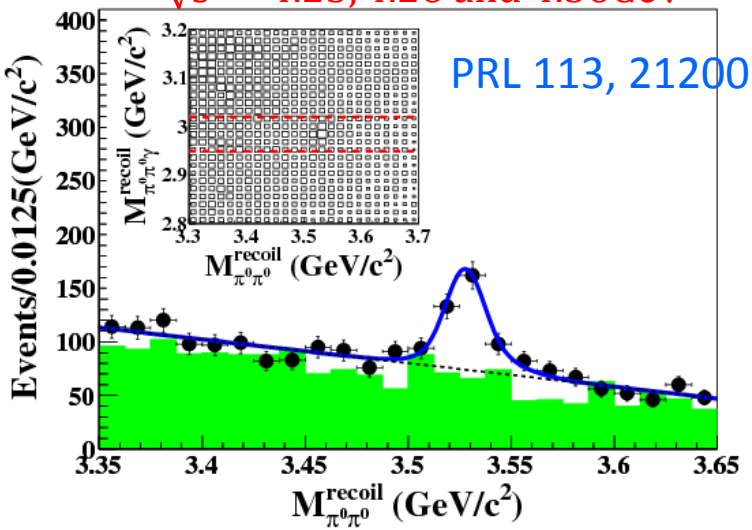
$\gamma\gamma$ ← $\pi^0\pi^0 h_c$ → $\gamma\eta_c$

hadrons



$\sqrt{s}$ = 4.23, 4.26 and 4.36GeV

PRL 113, 212002



$$\mathcal{R}_{\pi\pi h_c} = \frac{\sigma(e^+e^- \to \pi^0\pi^0 h_c)}{\sigma(e^+e^- \to \pi^+\pi^- h_c)}$$

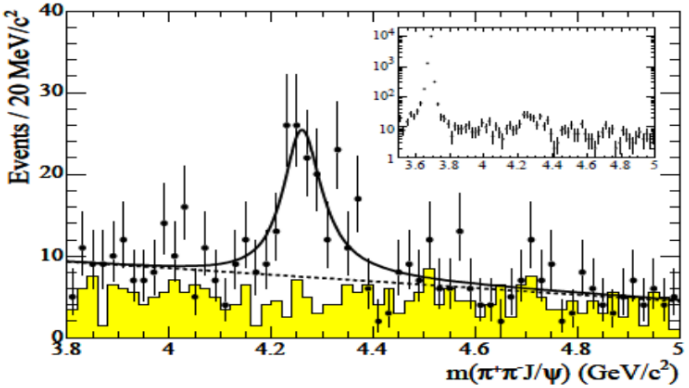
$\sqrt{s}$ (GeV)	$\sigma^{\rm B}(e^+e^- \to \pi^0\pi^0 h_c)$ (pb)	$\mathcal{R}_{\pi\pi h_c}$
4.230	$25.6 \pm 4.8 \pm 2.6 \pm 4.0$	$0.54 \pm 0.11 \pm 0.06$
4.260	$24.4 \pm 5.2 \pm 3.2 \pm 3.8$	$0.63 \pm 0.14 \pm 0.10$
4.360	$36.2 \pm 6.5 \pm 4.1 \pm 5.7$	$0.73 \pm 0.14 \pm 0.10$

No large isospin violation in $\pi\pi h_c$ system.

Study of $e^+e^- \to \omega\chi_{cJ}$ from 4.21 to 4.42 GeV

- Y(4260)
  - First observed in ISR process $\pi^+\pi^- J/\psi$ by BABAR, confirmed by CLEO and Belle.
  - Inconsistent with quark model prediction.

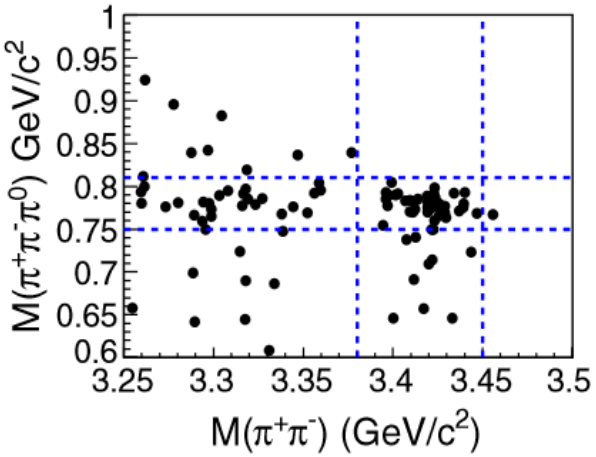
BABAR: PRL 95,142001

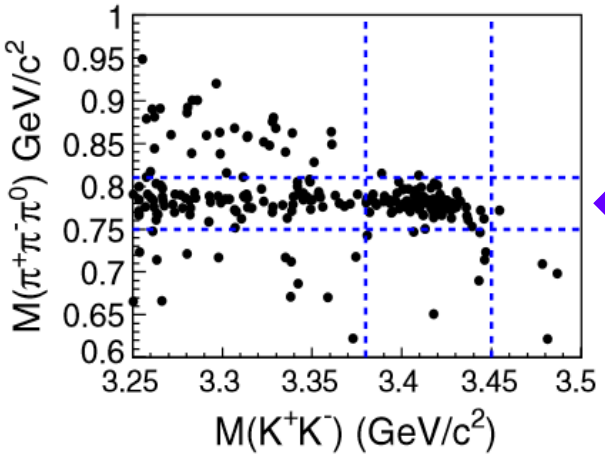


- arXiv: 1206.6911
  - Y(4260) is a ccbar state renormalized by $\omega\chi_{c0}$ continuum.
  - A sizable coupling between Y(4260) and $\omega\chi_{c0}$ predicted.
- PR B 660, 399 (2006)
  - Y(4260) is a $\omega\chi_{c1}$ molecule, and predict a large branching ratio of Y(4260)->$\pi^+\pi^-\pi^0\chi_{c1}$

Study of $e^+e^- \to \omega\chi_{c0}$ from 4.21 to 4.42 GeV

PRL 114, 092003

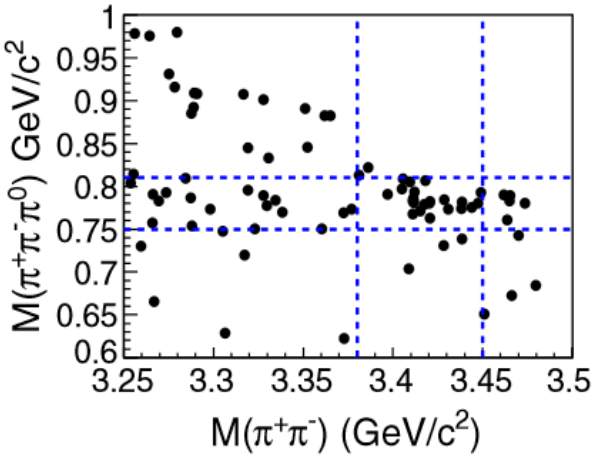


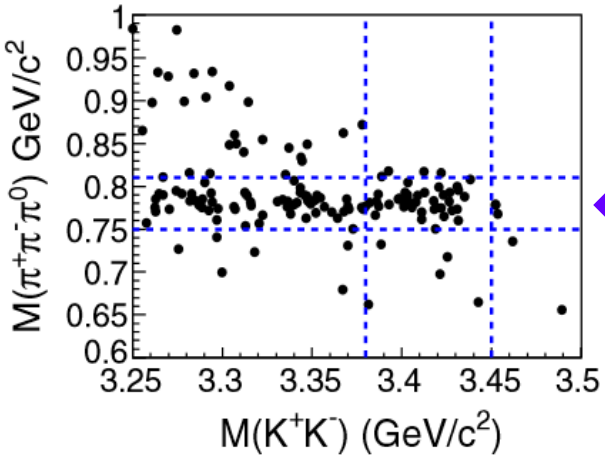


$\sqrt{s} = 4.23\text{GeV}$

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

$\chi_{c0} \to K^+K^-/\pi^+\pi^-$



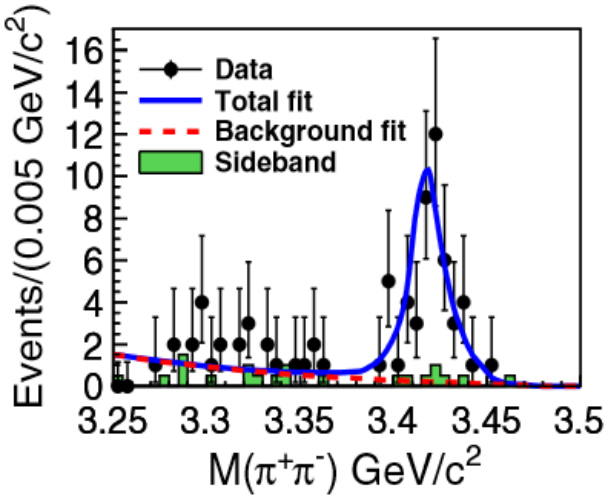


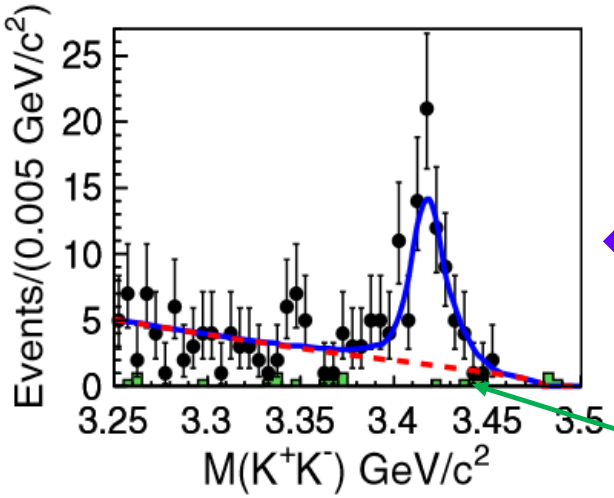
$\sqrt{s} = 4.26\text{GeV}$

Simultaneous unbinned maximum likelihood fit to $\pi^+\pi^-/K^+K^-$

Signal : MC-determined shape

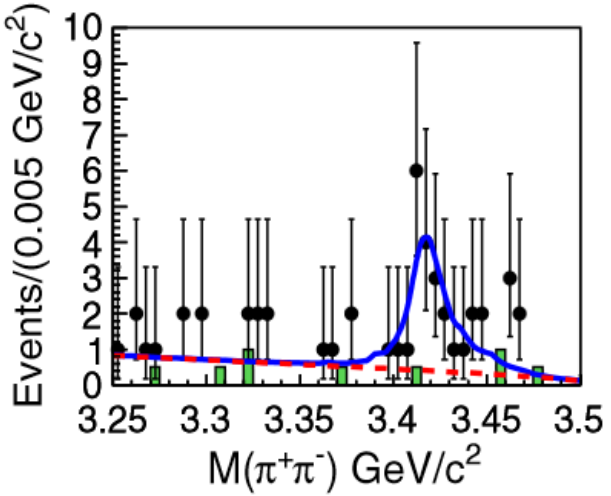
Background : an ARGUS function

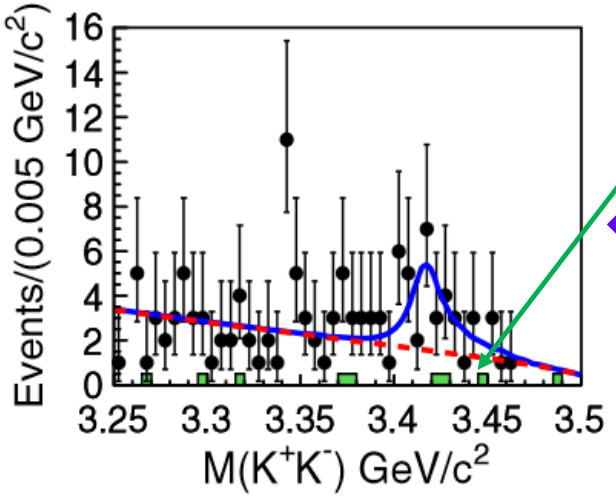




$\sqrt{s} = 4.23\text{GeV}$

ω sideband





$\sqrt{s} = 4.26\text{GeV}$

Maximum Likelihood fit to $\sigma(e^+e^- \to \omega\chi_{c0})$

Assuming that the $\omega\chi_{c0}$ signals come from a resonance, a phase-space modified Breit-Wigner function

$$\mathrm{BW}(\sqrt{s}) = \frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})\Gamma_t}{(s-M^2)^2+(M\Gamma_t)^2} \times \frac{\Phi(\sqrt{s})}{\Phi(M)}$$

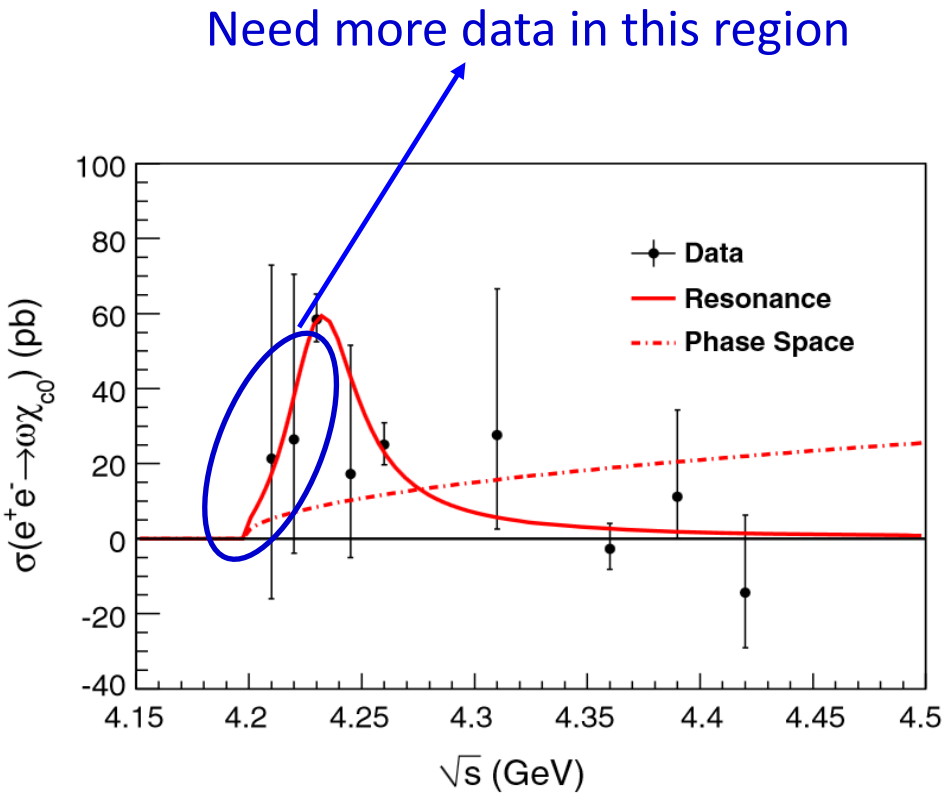
to fit $\sigma(e^+e^- \to \omega\chi_{c0})$

Statistical significance $> 9\sigma$

$\Gamma_{ee}\mathcal{B}(\omega\chi_{c0}) = (2.7 \pm 0.5 \pm 0.4)$ eV

$M(Y) = (4230 \pm 8 \pm 6)$ MeV/c^2

$\Gamma_t = (38 \pm 12 \pm 2)$ MeV



The line-shape is not consistent with the $Y(4260) \to \pi^+\pi^- J/\psi$

No significant signals are found for $e^+e^- \to \omega\chi_{c1,2}$

Measurement of cross sections for $e^+e^- \to \eta J/\psi$

$\gamma\gamma$ ← η → $\mu^+\mu^-/e^+e^-$

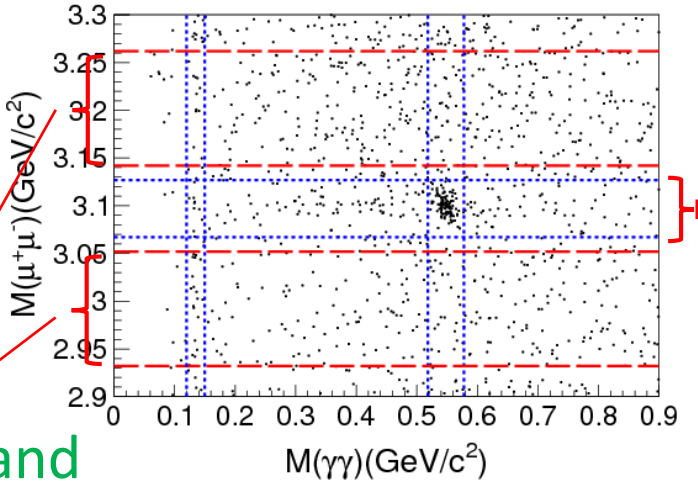
Signal : MC-determined shape convoluted with a Gaussian
Background : Polynomial function

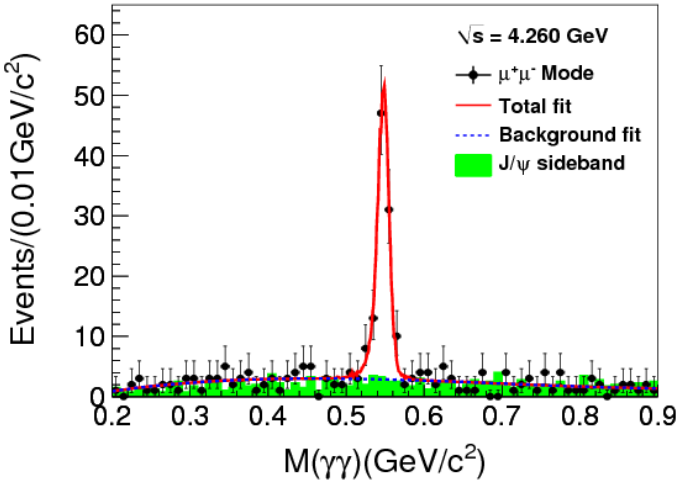
arXiv: 1503. 06644

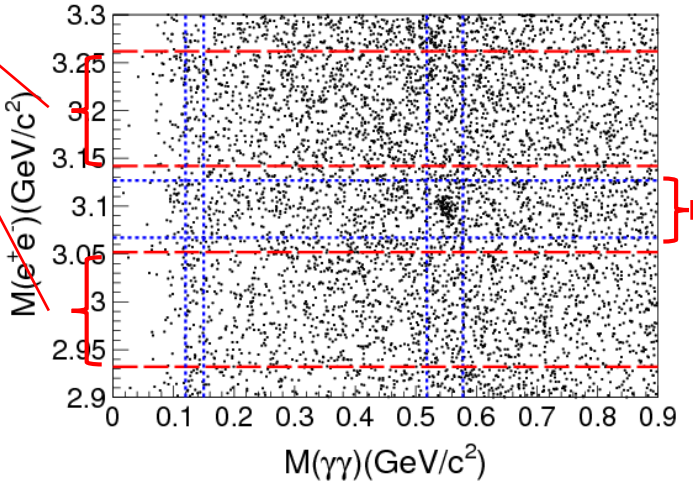
$\sqrt{s} = 4.26\text{GeV}$
$\mu^+\mu^-$ Mode

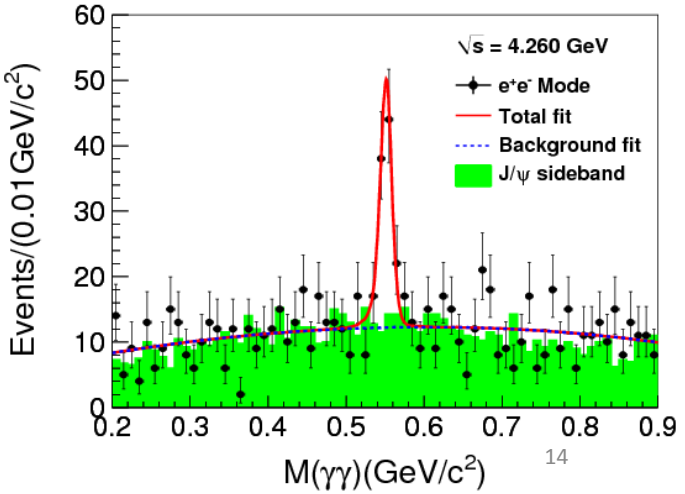
J/ψ sideband

$\sqrt{s} = 4.26\text{GeV}$
e^+e^- Mode







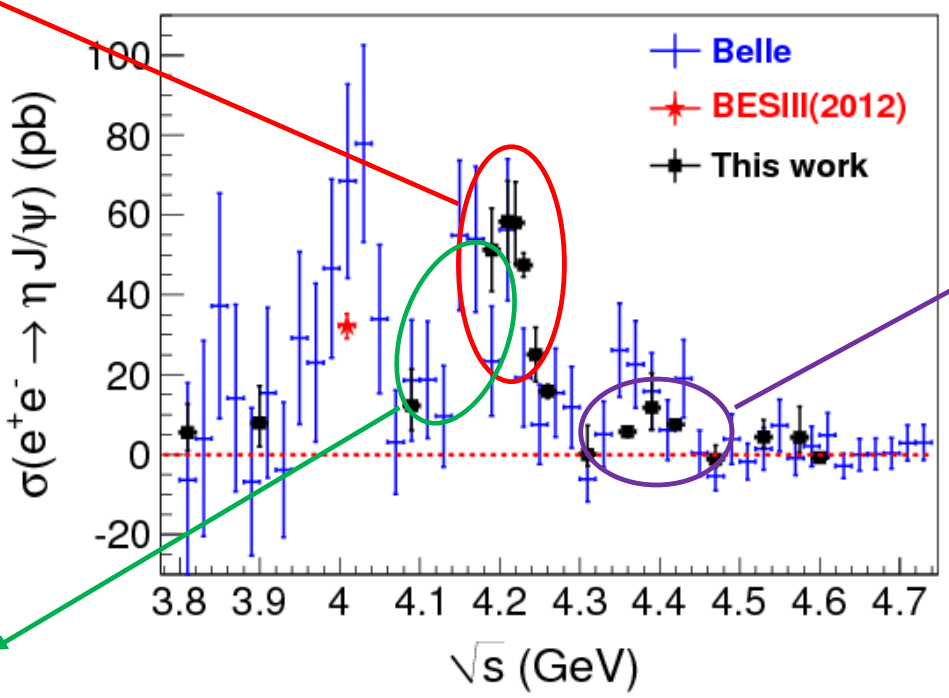


Born cross section for $e^+e^- \to \eta J/\psi$

$\psi(4160)$? or ?

Inconsistent with the $Y(4260) \to \pi^+\pi^- J/\psi$ and agree with Belle results

But similar with $e^+e^- \to \omega\chi_{c0}$



?

We need data in this region(4.1~4.2 GeV)

The measured $\sigma(e^+e^- \to \eta J/\psi)$ agrees with previous results but with improved accuracy.

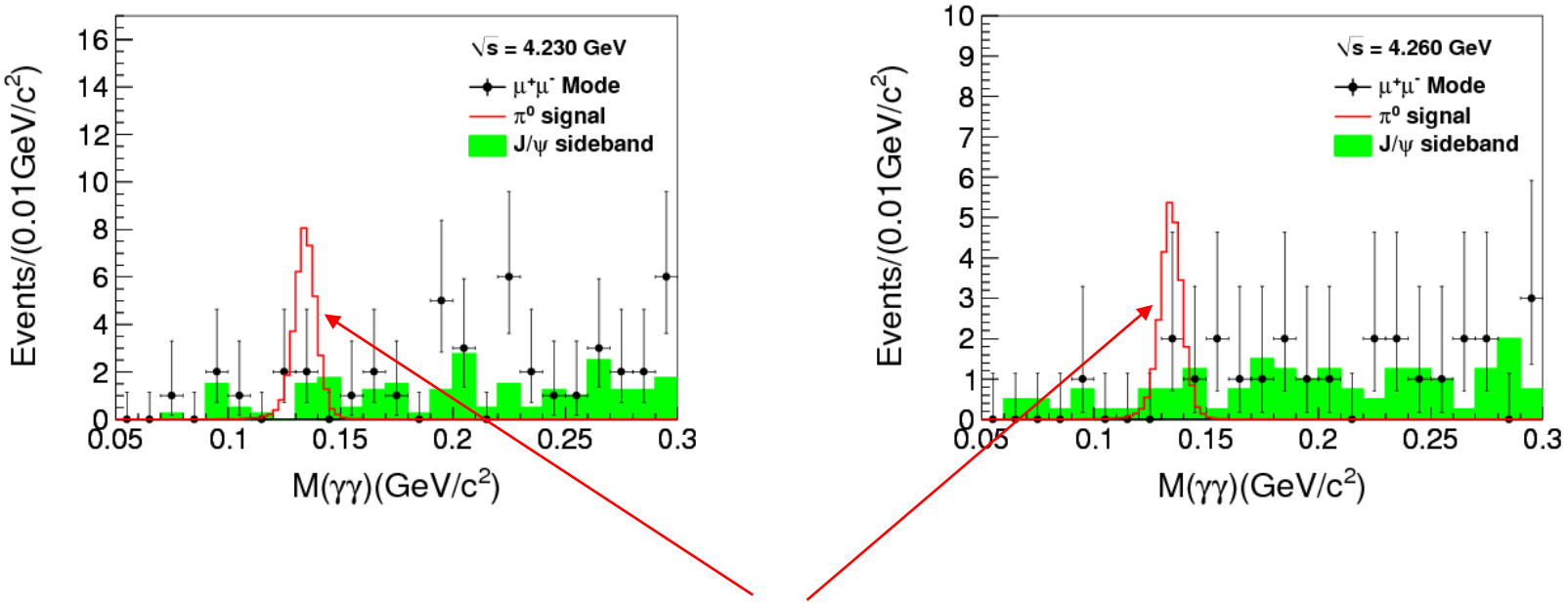
The cross section peaks around 4.2 GeV.

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

$\gamma\gamma$ ← π^0 , J/ψ → $\mu^+\mu^-$

arXiv: 1503. 06644

No significant signal



π^0 MC shape with arbitrary normalization

- Only use $J/\psi \to \mu^+\mu^-$ is used, $J/\psi \to e^+e^-$ is not used due to the large background of radiative Bhabha events.
- The obtained $\pi^0 J/\psi$ upper limits are higher by a factor of 50 than that of the theoretical prediction.

Observation of $e^+e^- \to \eta' J/\psi$ from 4.19 to 4.60 GeV

- The process $e^+e^- \to \eta J/\psi$ has been observed at a center-of-mass energy of 4.26 GeV, so we can infer that the mode $e^+e^- \to \eta' J/\psi$ should also exist but we haven't measured it .

- Based on the nonrelativistic QCD and the Light-Cone model, the cross section of $e^+e^- \to \eta' J/\psi$ has been estimated for $\sqrt{s}$ from 4.3 to 5.3 GeV. To check the model and search for potential resonance in this region, measurement of $e^+e^- \to \eta' J/\psi$ is needed.

Observation of $e^+e^- \to \eta' J/\psi$ from 4.19 to 4.60 GeV

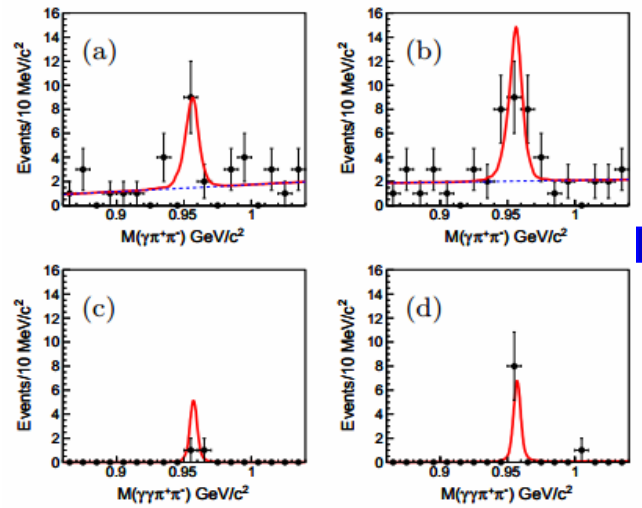
BESIII preliminary

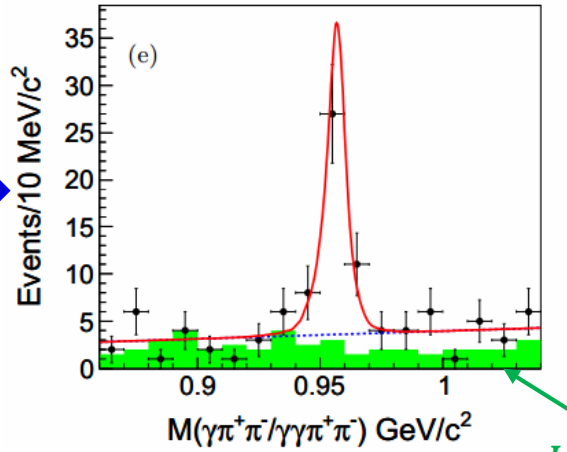
Simultaneous fit

$(a)\ \eta' \to \gamma\pi^+\pi^-$ and $J/\psi \to e^+e^-$ $(b)\ \eta' \to \gamma\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$

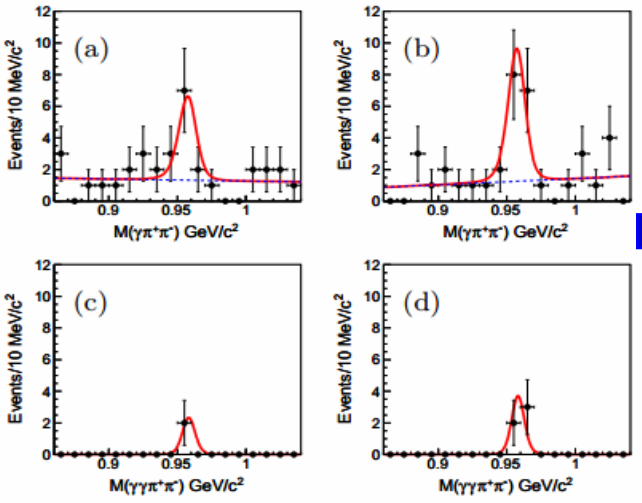
$(c)\ \eta' \to \eta\pi^+\pi^-$ and $J/\psi \to e^+e^-$ $(d)\ \eta' \to \eta\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$

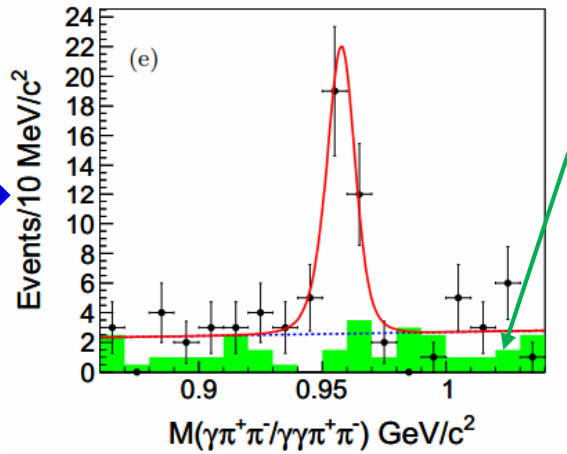
$\sqrt{s} = 4.23$ GeV





$\sqrt{s} = 4.26$ GeV

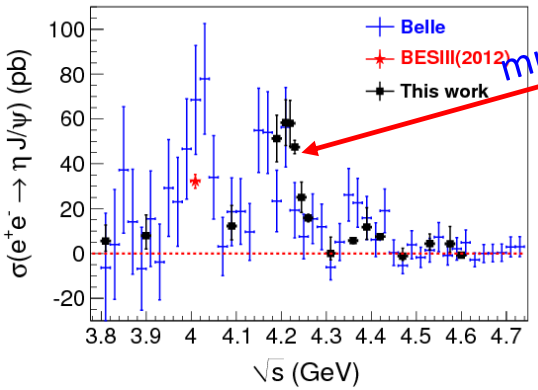




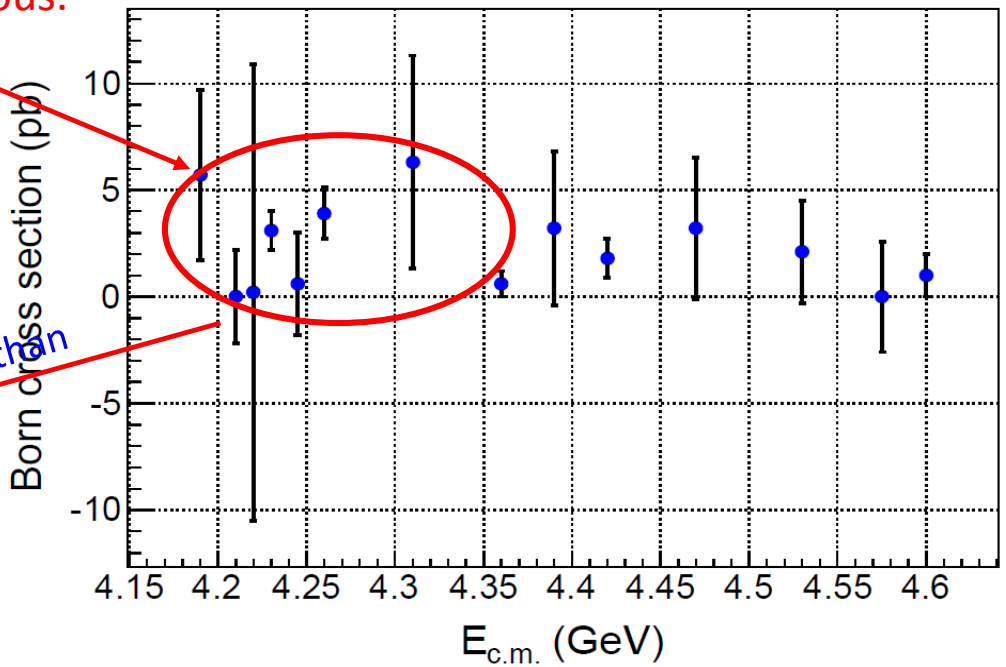
J/ψ sideband

The Born cross section for $e^+e^- \to \eta' J/\psi$

The line-shape's structure is not obvious.
$\psi(4160)$?
$Y(4260)$?
the same source with $\omega\chi_{c0}$?
or others?



much lower than

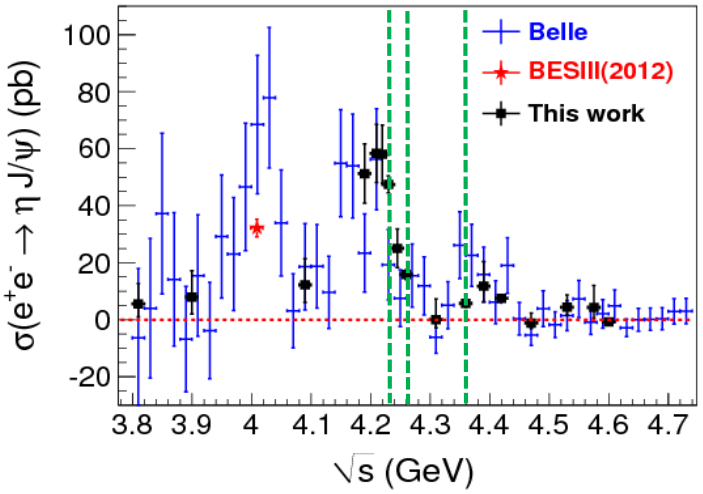


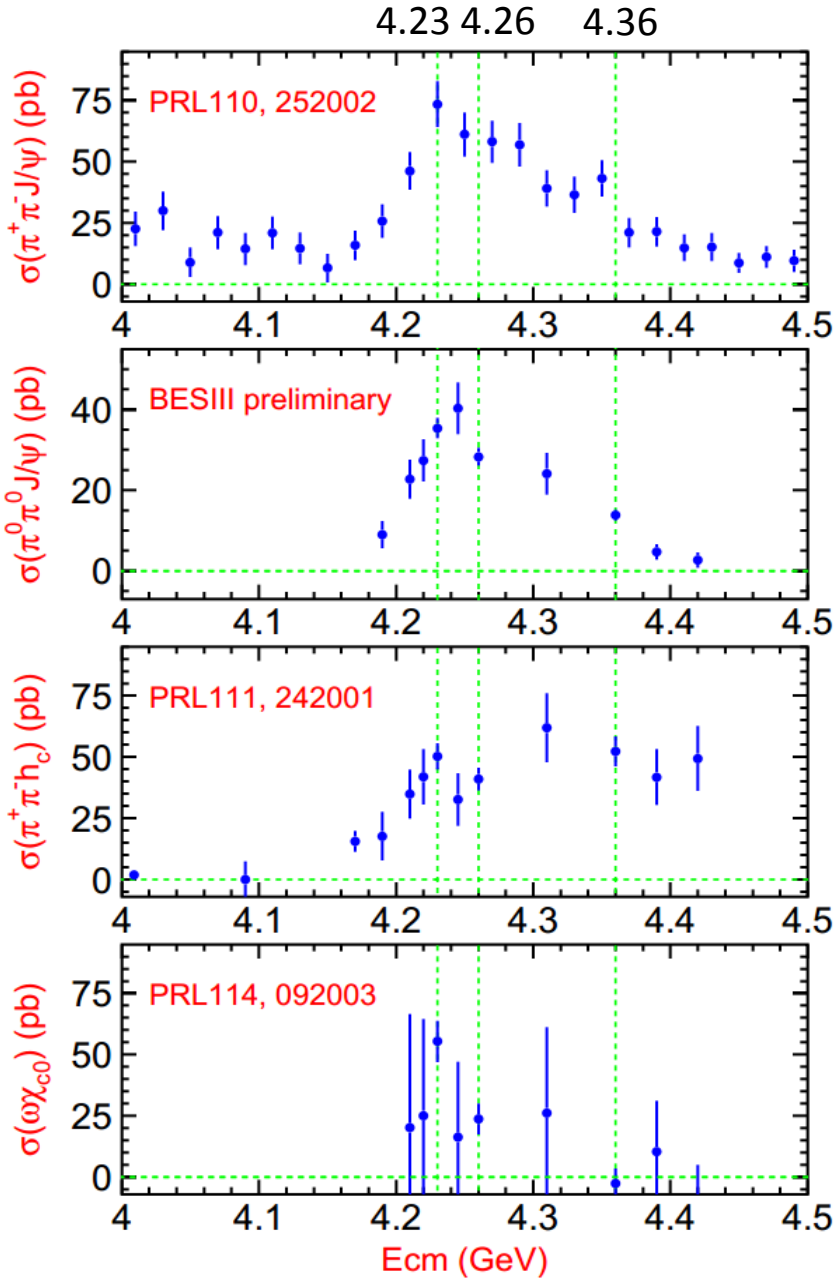
- Significant $\eta' J/\psi$ signals are observed at $\sqrt{s} = 4.23$ GeV and 4.26 GeV, and the upper limits are set for other energy points.
- The cross section of $e^+e^- \to \eta' J/\psi$ is much lower than $e^+e^- \to \eta J/\psi$, and is in contradiction to the calculation in the framework of NRQCD.

PRD 89, 074006 (2014)

There might be something around 4.23 GeV, only God knows the answer now!

So we need more data around 4.23 GeV to know what God knows.



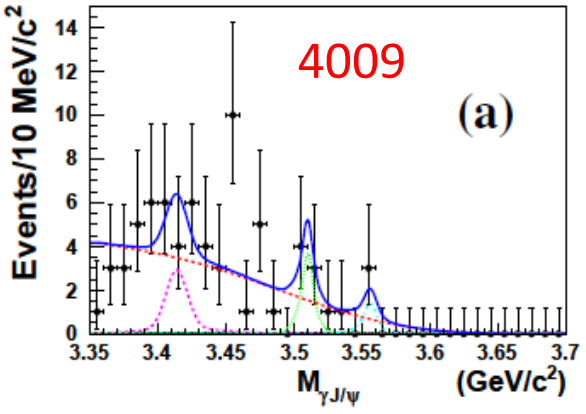


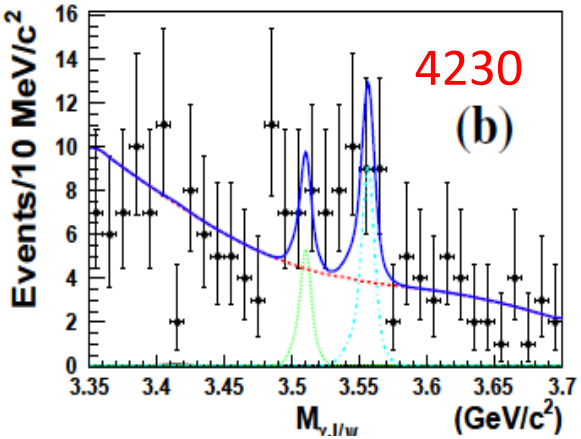
Search for $e^+e^- \to \gamma\chi_{cJ(J=0,1,2)}$

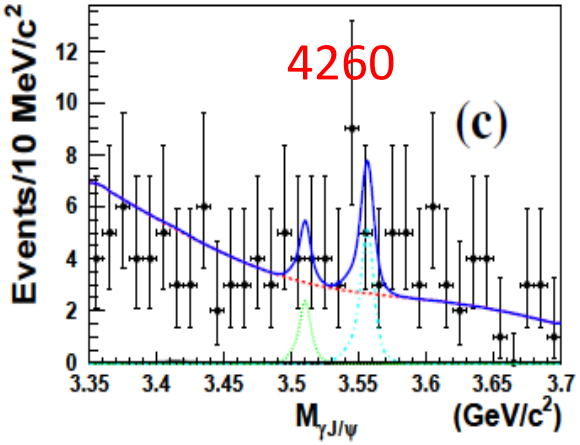
$\gamma J/\psi$

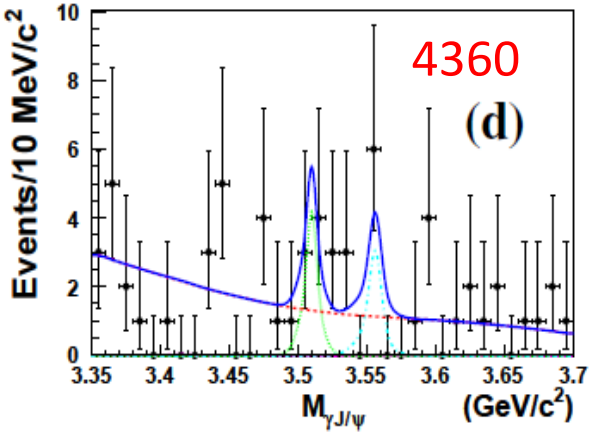
$\mu^+\mu^-$

CPC 39, 041001









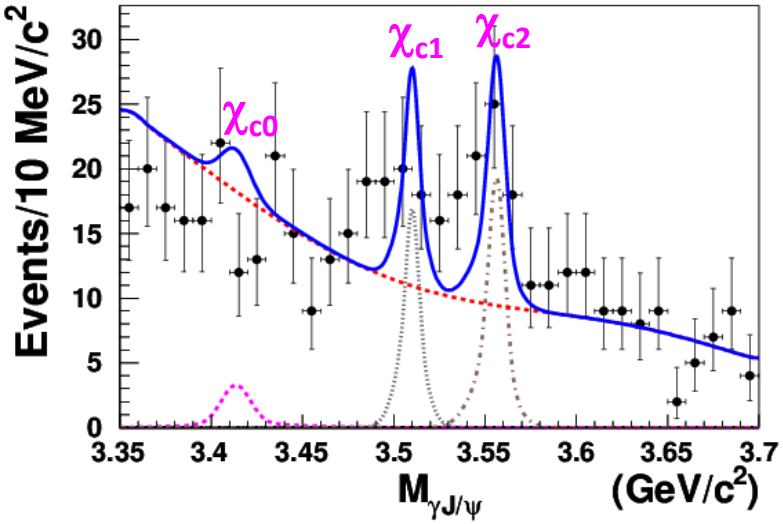
Signal : a double-Gaussian with shape parameters determined from signal MC at $\sqrt{s} = 4.26$ GeV

Background : radiative di-muon MC shape

- The decay $J/\psi \longrightarrow e^+e^-$ is not considered due to the huge background of Bhabha events.
- The remaining dominant background is from radiative di-muon events.

Combine all the data sets for $e^+e^- \to \gamma\chi_{cJ(J=0,1,2)}$

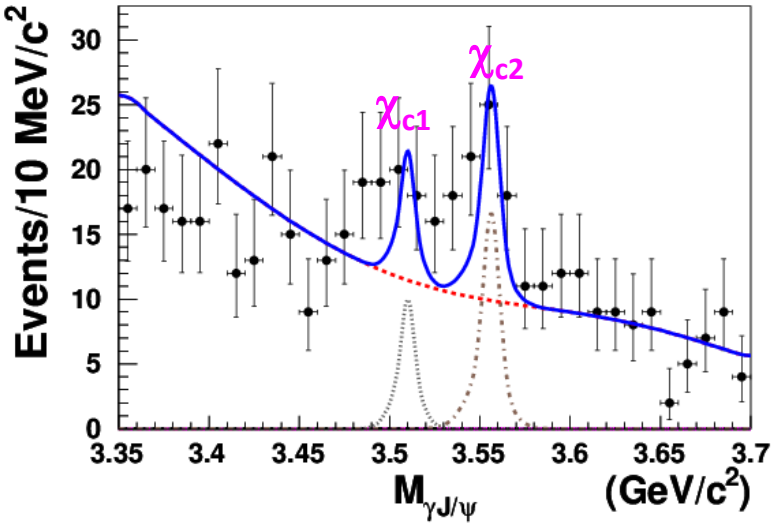
The same fit is applied to the sum of $M_{\gamma J/\psi}$ distributions of the four CME points.



The statistical significance for χ_{c0}, χ_{c1} and χ_{c2} are found to be 1.2σ, 3.0σ and 3.4σ, respectively.

Evidence for $e^+e^- \to \gamma\chi_{c1,2}$

A simultaneous fit to the $M_{\gamma J/\psi}$ distributions at four CME points with assuming the production $\sigma(e^+e^- \to \gamma\chi_{cJ})$ at different CME point follows the line-shape of the $Y(4260)$.



The statistical significance for χ_{c0}, χ_{c1} and χ_{c2} are found to be 0σ, 2.4σ and 4.0σ, respectively.

$$\Gamma_{ee} \cdot \mathcal{B}(Y(4260) \to \gamma\chi_{c1}) = (0.11 \pm 0.06)\text{eV}$$
$$\Gamma_{ee} \cdot \mathcal{B}(Y(4260) \to \gamma\chi_{c2}) = (0.33 \pm 0.11)\text{eV}$$

Search for the isospin violating decay $Y(4260) \to J/\psi\eta\pi^0$

- Y(4260) does not fit into 1^{--} quarkonium spectrum. Possible interpretations: D_1D molecule, hybrid charmonim etc.
- Recent observations at BESIII:
  - Coupling to $Z_c(3900)$ at 4.260 GeV is observed
  - Transition of e^+e^--> $\gamma X(3872)$ near Y(4260) is observed
- Search for the isospin violating decay of Y(4260) may shed a light on its nature.

Theoretical works:

- Hadro-charmonium of Z_b and Z_c:
  - Prediction of $\Upsilon(5S)$->$\eta\pi^0$+ bottomonium, M.Voloshin, PRD 86 034013
- Tetraquark interpretation of Z_b and Z_c:
  - Prediction of $\Upsilon(5S)$->$\Upsilon(1S)\eta\pi^0$, A. Ali et al., PRL 104 162001, PRL 106 092002
  - Proposed search of Z_c in Y(4260)->$J/\psi\eta\pi^0$, L. Maiani et al., PRD 87 111102
- D_1D molecule:
  - Prediction of Y(4260)->$J/\psi\eta\pi^0$, X. Wu et al., PRD 89, 054038

Search for the isospin violating decay $Y(4260) \to J/\psi\eta\pi^0$

arXiv: 1505. 00539

$\mu^+\mu^-/e^+e^-$ ← J/ψ → $\gamma\gamma$

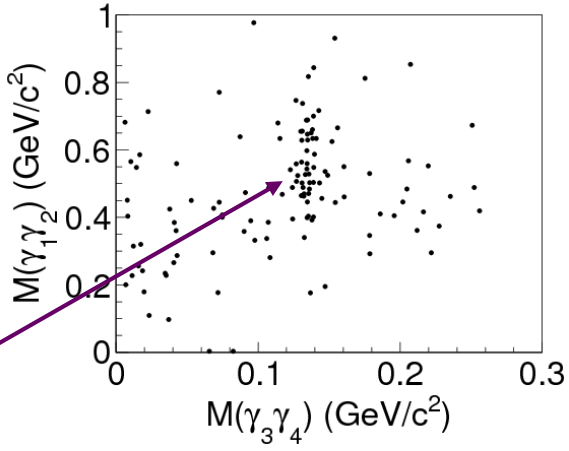
$\eta \to \gamma\gamma$

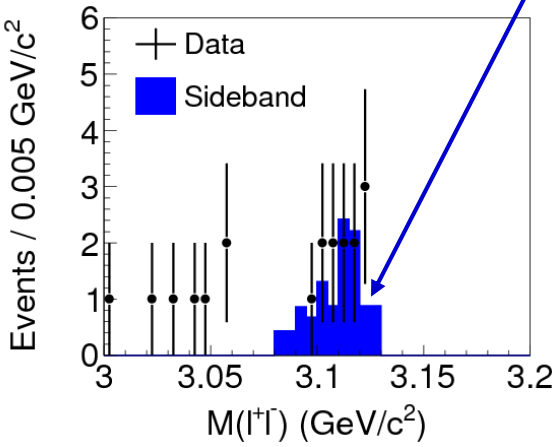
Choose the combination of photons by minimizing

$$\sqrt{\left|\frac{M(\gamma_1\gamma_2)-m_\eta}{\sigma_\eta}\right|^2+\left|\frac{M(\gamma_3\gamma_4)-m_{\pi^0}}{\sigma_{\pi^0}}\right|^2}$$

Normalized 2-dimensional $\eta\pi^0$ sideband

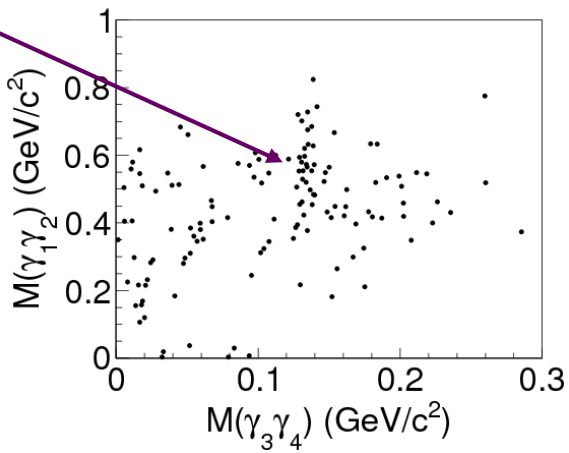
$\sqrt{s} = 4.23$ GeV

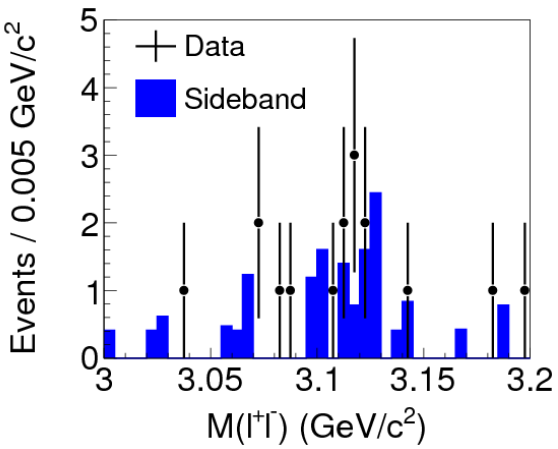




No obvious $J/\psi\eta\pi^0$ signal

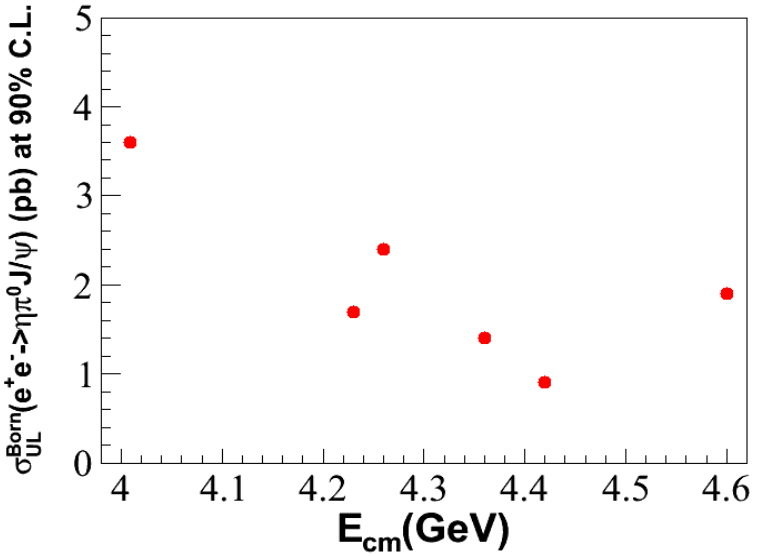
$\sqrt{s} = 4.26$ GeV





Cross section upper limits for $e^+e^- \to J/\psi\eta\pi^0$

No significant $J/\psi\eta\pi^0$ is observed, upper limits at 90% C.L. are given.



We also can get

$\sigma(e^+e^- \to Z_c^0\pi^0 \to J/\psi\eta\pi^0) < 1.3\text{pb at } \sqrt{s} = 4.23 \text{ GeV}$

$< 2.0\text{pb at } \sqrt{s} = 4.26 \text{ GeV}$

Compared to the measured cross section of $e^+e^- \to Z_c^0\pi^0 \to J/\psi\pi^0\pi^0$

$\frac{\mathcal{B}(Z_c^0\to J/\psi\eta)}{\mathcal{B}(Z_c^0\to J/\psi\pi^0)} < 0.15 \text{ at } \sqrt{s} = 4.23 \text{ GeV}$

$< 0.65 \text{ at } \sqrt{s} = 4.26 \text{ GeV}$

The cross section upper limits for $e^+e^- \to J/\psi\eta\pi^0$ are well above the prediction for that $Y(4260)$ is a $D_1\bar{D}$ molecule hadronic model.

Summary

- The line-shape of $e^+e^- \to \pi\pi J/\psi$ and $e^+e^- \to \pi\pi h_c(1P)$ are measured, No large isospin violation
- $e^+e^- \to \omega\chi_{c0}$ is observed, a new narrow state around 4.23 GeV
- The cross section of $e^+e^- \to \eta J/\psi$ is measured, interesting structure.
- $e^+e^- \to \eta' J/\psi$ is observed, need more data
- Search for $e^+e^- \to \gamma\chi_{cJ(J=0,1,2)}$, evidence for $e^+e^- \to \gamma\chi_{c1,2}$
- Search for the isospin violating decay $Y(4260) \to J/\psi\eta\pi^0$, but no obvious signal
- Maybe an unexpected narrow structure around 4.23 GeV (seen in $\pi^+\pi^- h_c(1P)$, $\omega\chi_{c0}$, $\eta J/\psi$)
- A high statistical scan data(4.0~4.6 GeV) will be very useful

Ongoing at BESIII

- $e^+e^- \to \pi\pi\psi'$
- $e^+e^- \to KKJ/\psi$
- $e^+e^- \to \gamma\eta_c$
- $e^+e^- \to \gamma\chi'_{c2}$
- $e^+e^- \to \gamma Y(3915)$

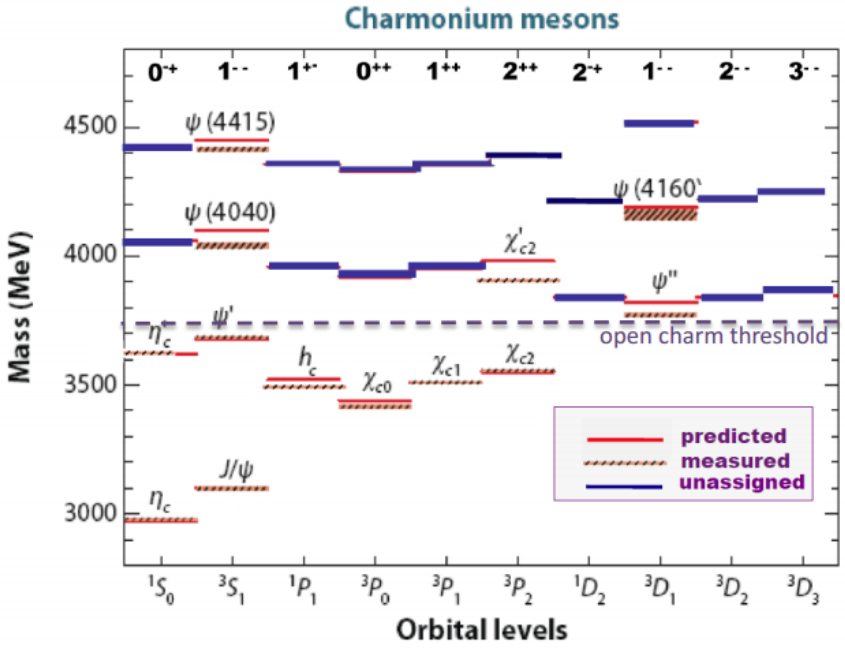
……

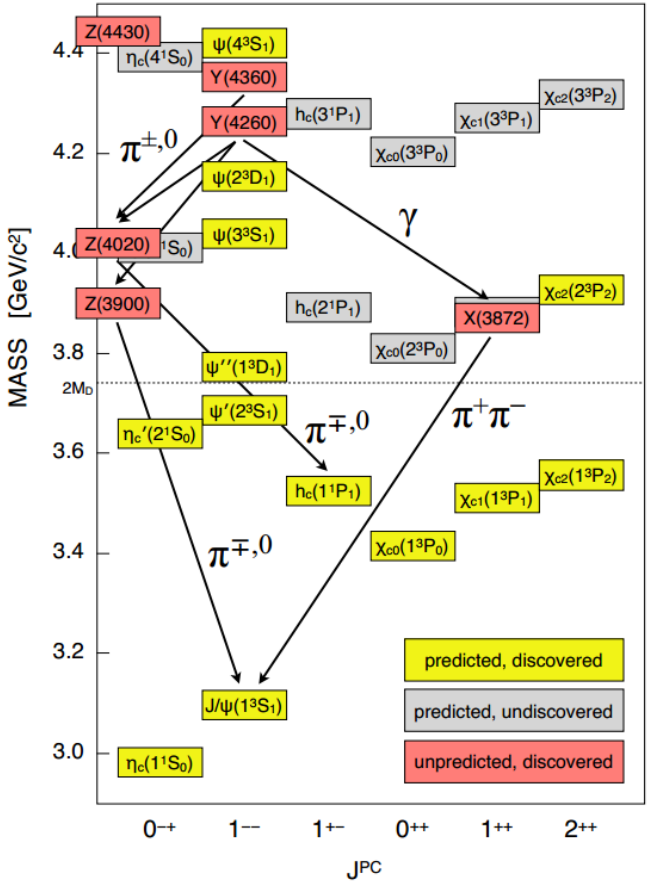
More results will come out !!!

BESIII will take data around 4.17 GeV for 3fb^{-1}, it is a good opportunity to study the nature of $\psi(4160)$ and supplement the low-end line-shape for many decay modes.

Thanks for your attention

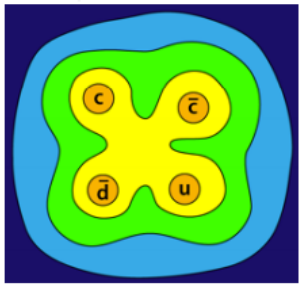
BACKUP


Charmonium mesons
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁺ 1⁻⁻ 2⁻⁻ 3⁻⁻
4500
4000
3500
3000
Mass (MeV)
ψ (4415)
ψ (4040)
ψ (4160)
χ'c2
ψ''
ψ'
ηc'
hc
χc0
χc1
χc2
J/ψ
ηc
open charm threshold
predicted
measured
unassigned
1S0 3S1 1P1 3P0 3P1 3P2 1D2 3D1 3D2 3D3
Orbital levels


Z(4430)
ηc(4¹S₀)
ψ(4³S₁)
Y(4360)
Y(4260)
hc(3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
π±,0
ψ(2³D₁)
γ
Z(4020)
ψ(3³S₁)
Z(3900)
hc(2¹P₁)
X(3872)
χc2(2³P₂)
χc0(2³P₀)
ψ''(1³D₁)
2MD
ψ'(2³S₁)
ηc'(2¹S₀)
π∓,0
π⁺π⁻
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
J/ψ(1³S₁)
ηc(1¹S₀)
predicted, discovered
predicted, undiscovered
unpredicted, discovered
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
MASS [GeV/c²]
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺
JPC

- Not an obvious charmonium state
- But charmonium in the final state
- XYZ or charmoniumlike particles

What are they ?



$Z_c(3900)$

X(3872)

Y(4260)

X(3915)
X(4160)
Y(4008)
Y(4140)
X(4350)
Y(4360)
Y(4660)

XYZ(3940)

Z(4430)
Z(4250)
Z(4050)

...

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...