Experimental overview of charmonium spectroscopy

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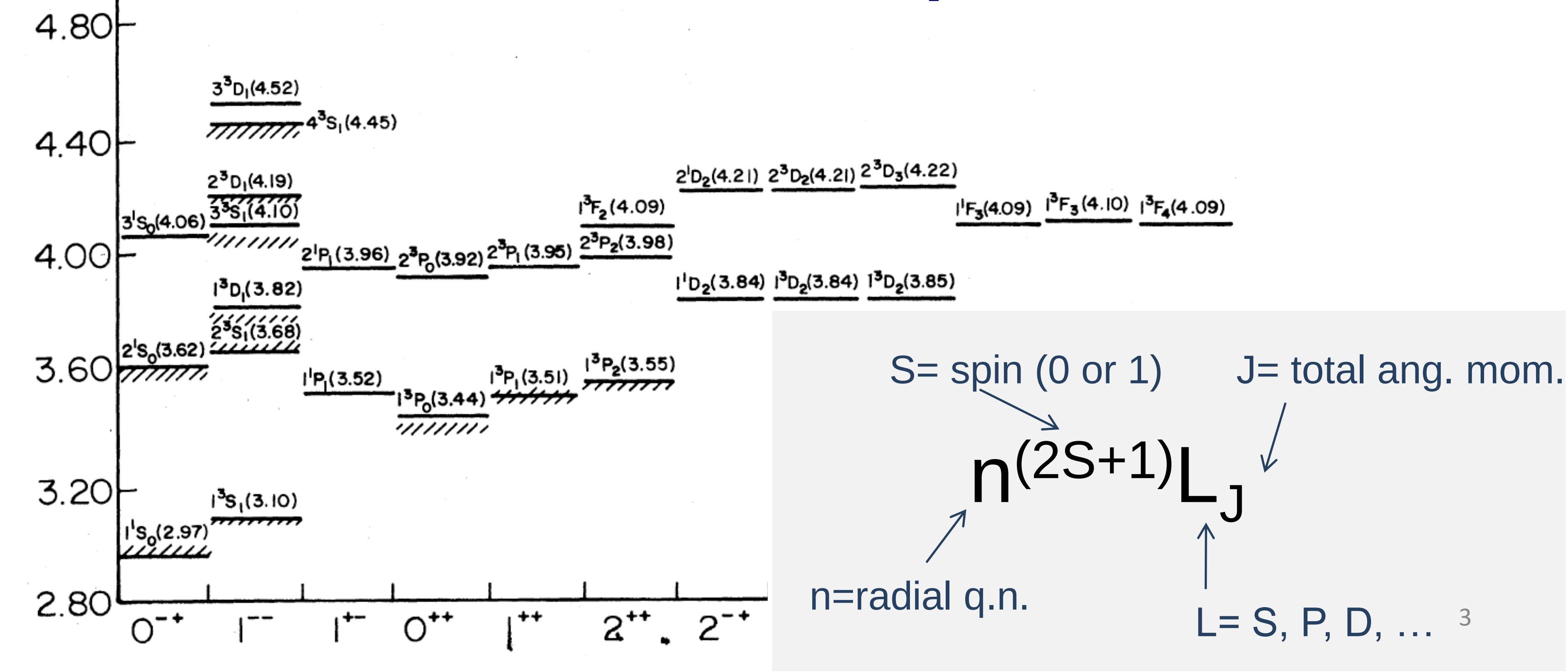
Charmonium

- Charmed-quark($\boldsymbol{c}$) anticharmed-quark($\bar{\boldsymbol{c}}$) bound states.

- Has been a powerful tool for the understanding of the strong interaction
  - QCD is well tested at high energies
  - In low-energy regime, many aspects are not understood
  - Charmonium sector is in an important position to test QCD and improve our limited understanding of QCD

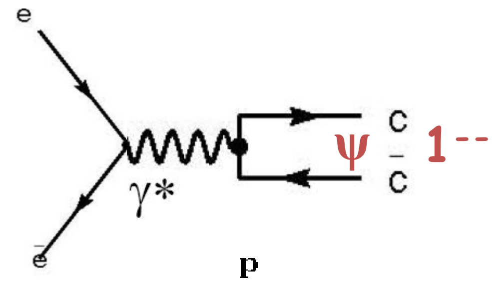
Charmonium

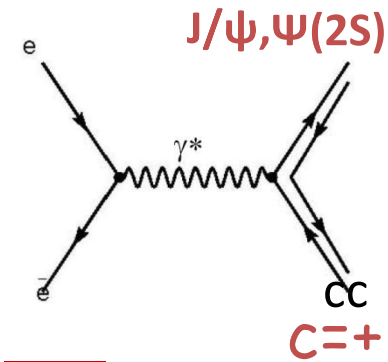
- $m_c \sim 1.5$ GeV/c^2, $v^2 \sim 0.3$ ➔ the system is non-relativistic.
- In quark potential model, **the energy levels** can be solved with
  - non-relativistic SchÖdinger eqution
  - *color Coulomb + linear potential*



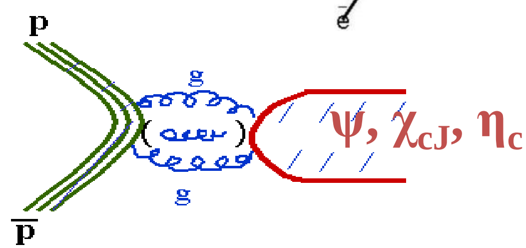
Production

1. e^+e^- annihilation (including ISR/double charmonium)

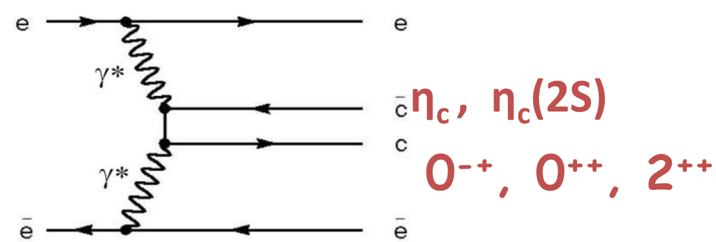




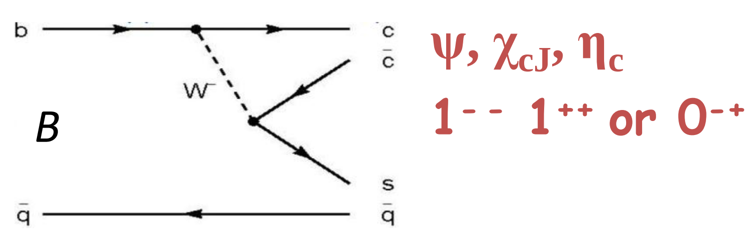
2. $p\bar{p}$ annihilation



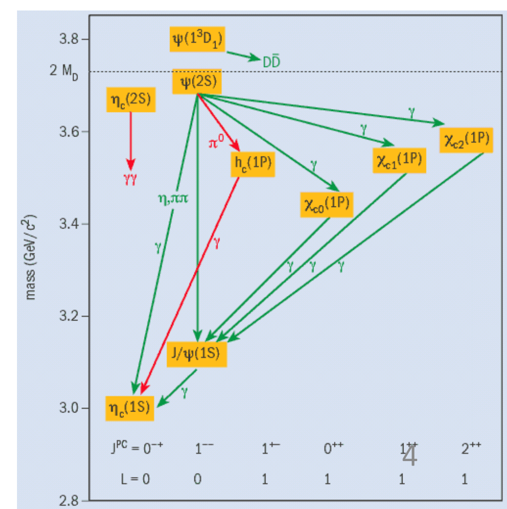
3. Two-photon process



4. B decays

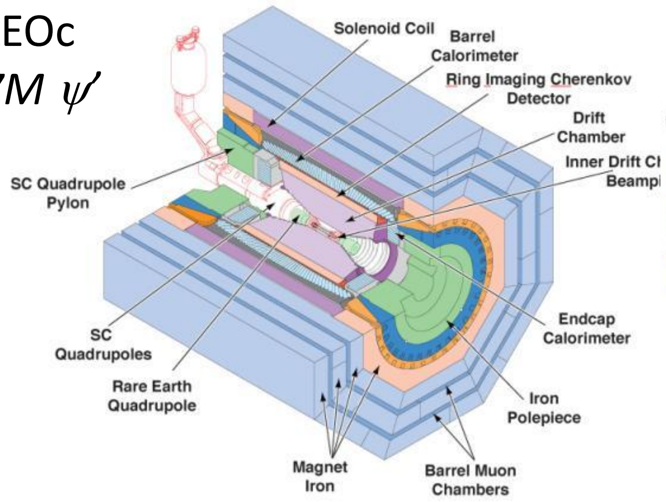


5. Charmonium transition

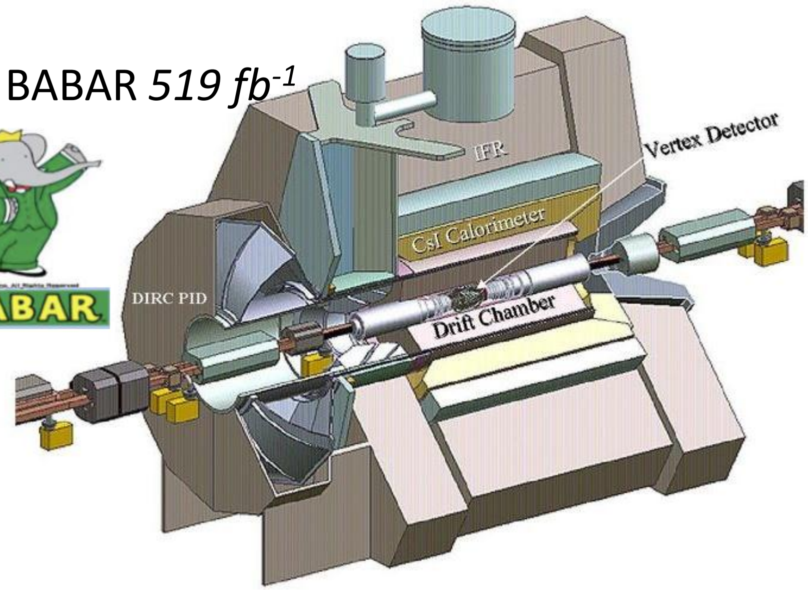


Experiments

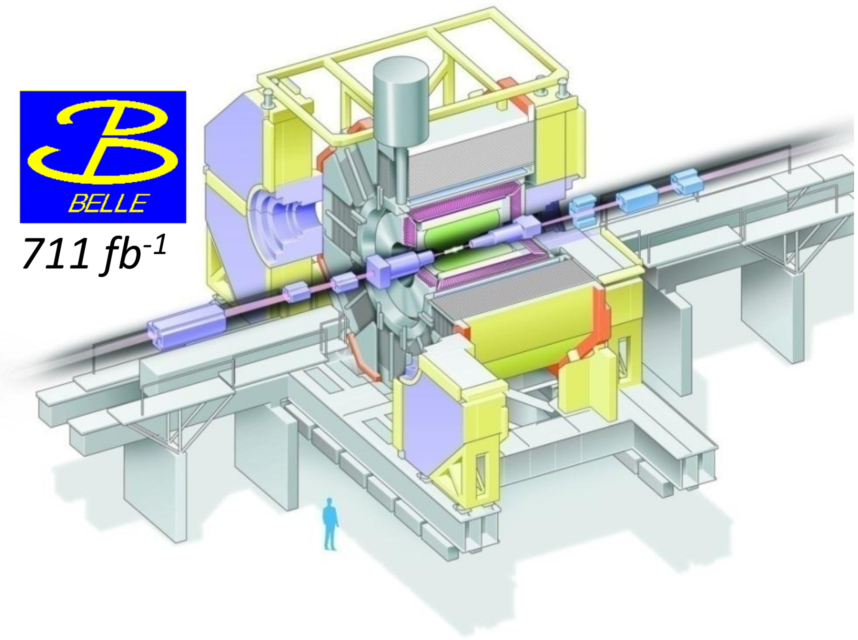
CLEOc
27M ψ'

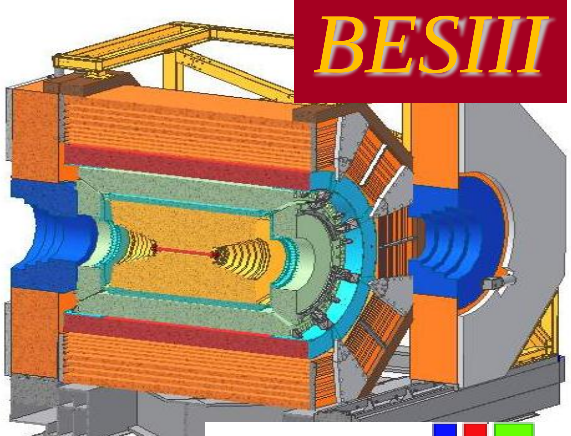


BABAR *519* fb^{-1}



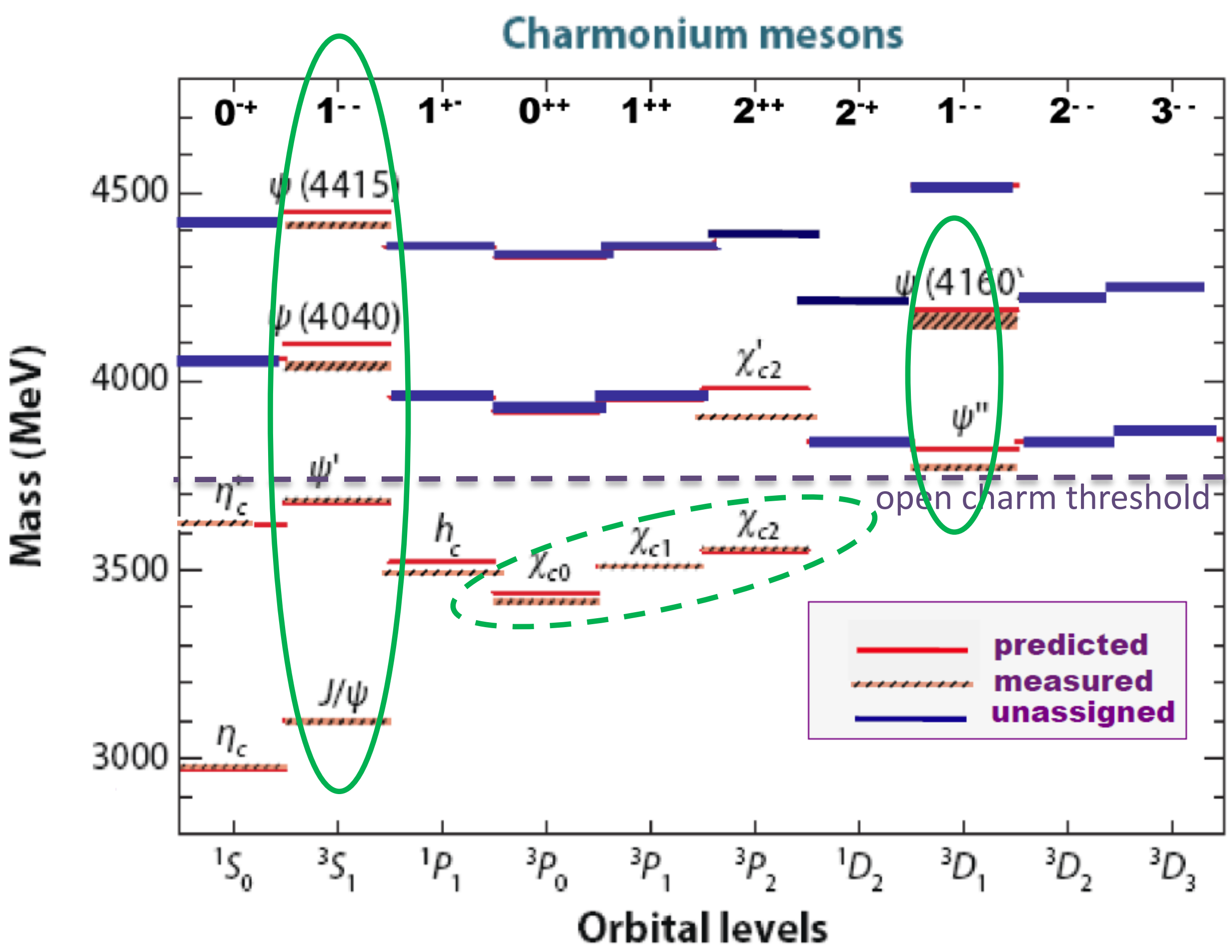
711 fb^{-1}





1^{--} states: J/ψ, ψ', ψ'', $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

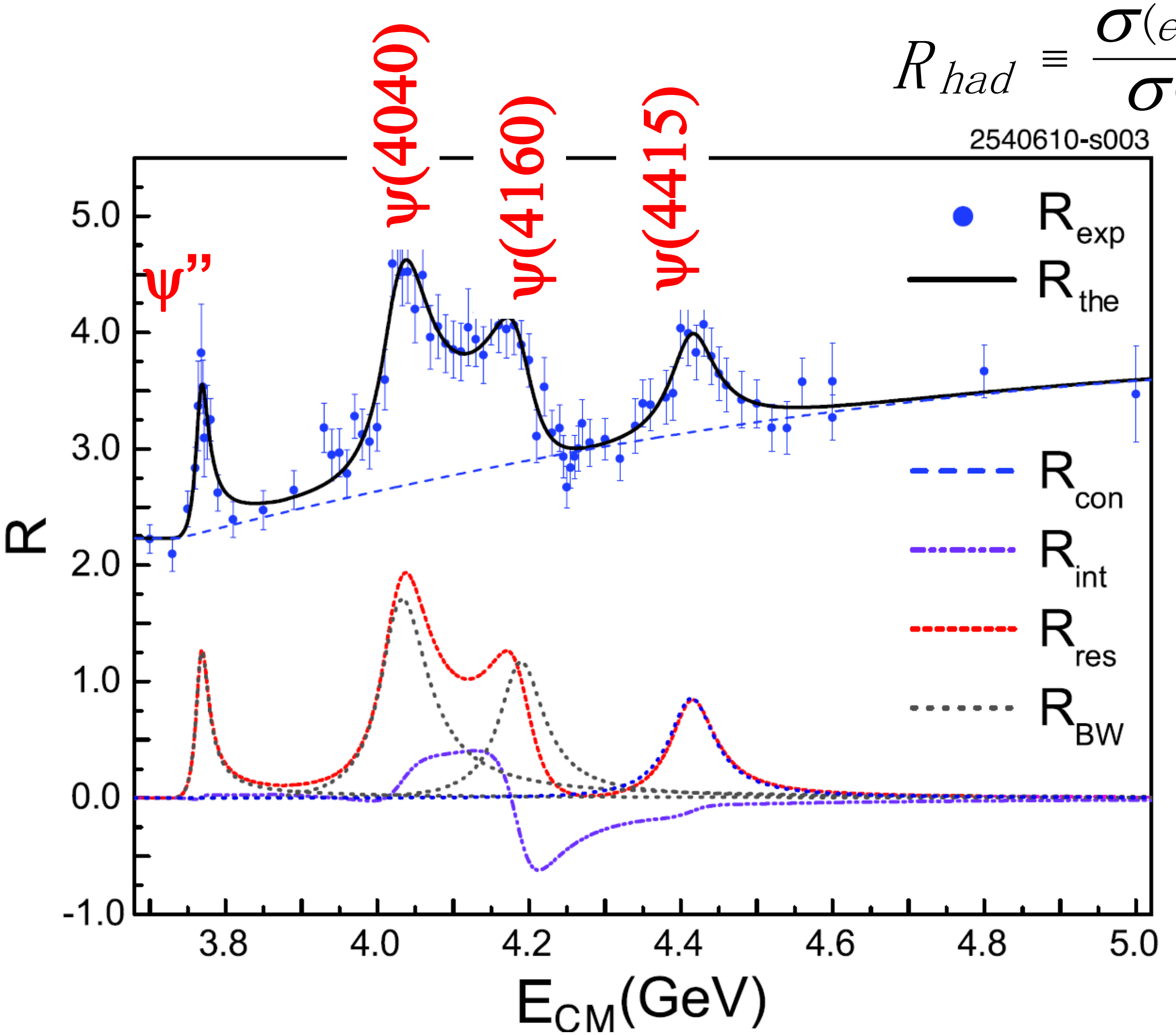
- Abundantly produced from e^+e^-, $p\bar{p}$ collsions
- Observed in 1970's
- Above DD threshold, those states present themself as enhancement in the total hadronic X-section.



$J^{PC} = 1^{--}$ states produce peaks in R_{had}

Extraction of resonance parameters from R measurement

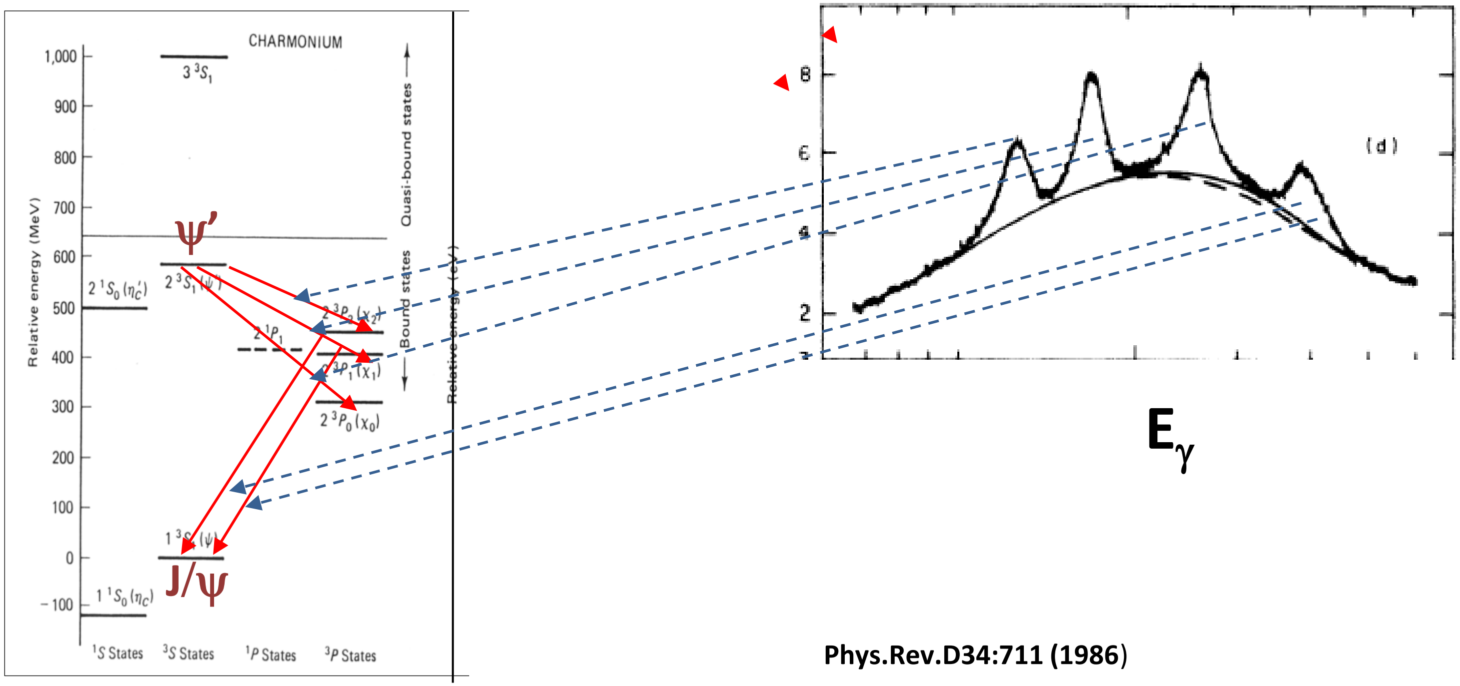
$$R_{had} \equiv \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



BES II PL B660, 315 (2008)

P wave triplet $\chi_{c0}, \chi_{c1}, \chi_{c2}$

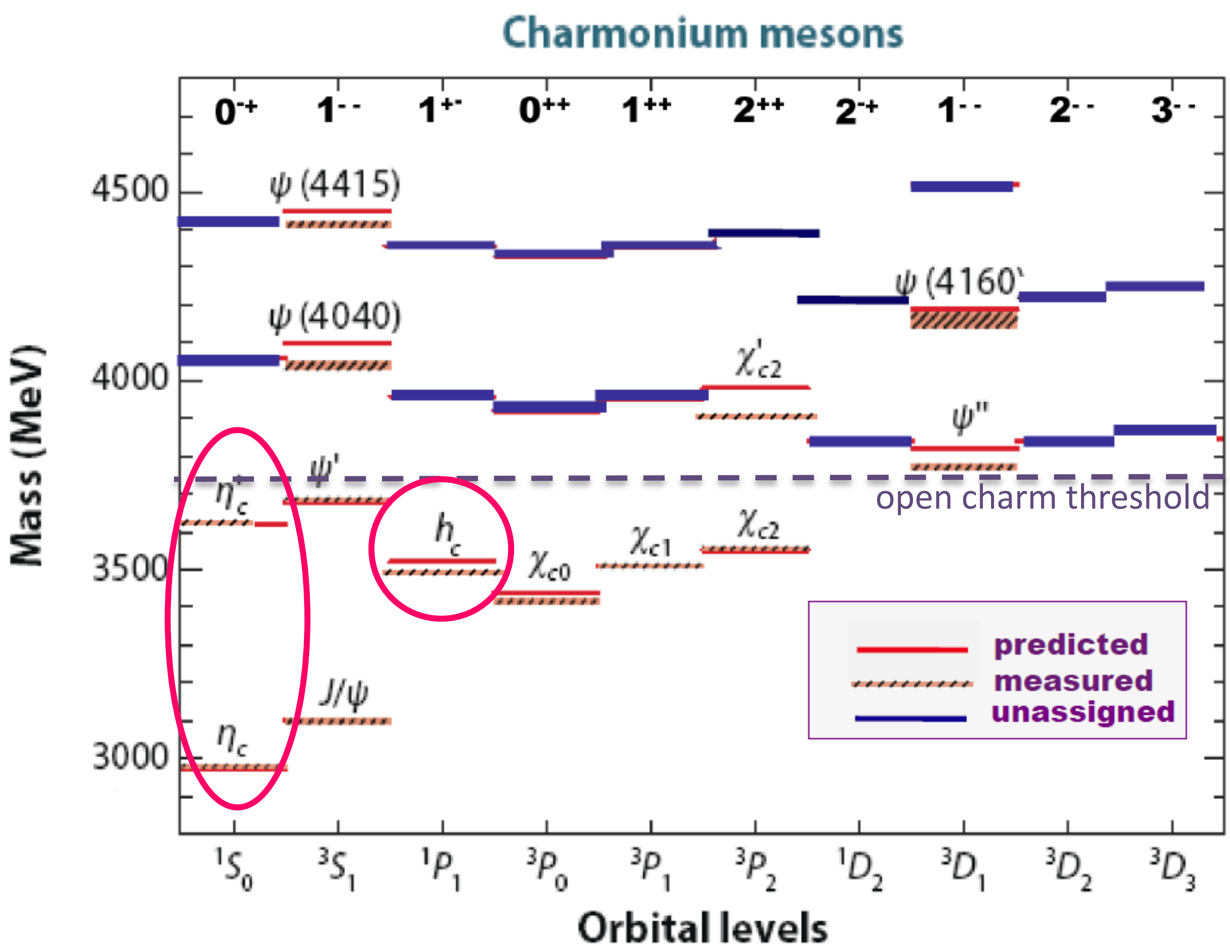
- Large event samples can be produced through E1 transition of the ψ'
- The mass/width has been measured precisely (< 0.5 MeV), dominated by the results from E835 $p\bar{p}$ anhilation



Phys.Rev.D34:711 (1986)

Spin singlet states: η_c , $\eta_c(2S)$, h_c

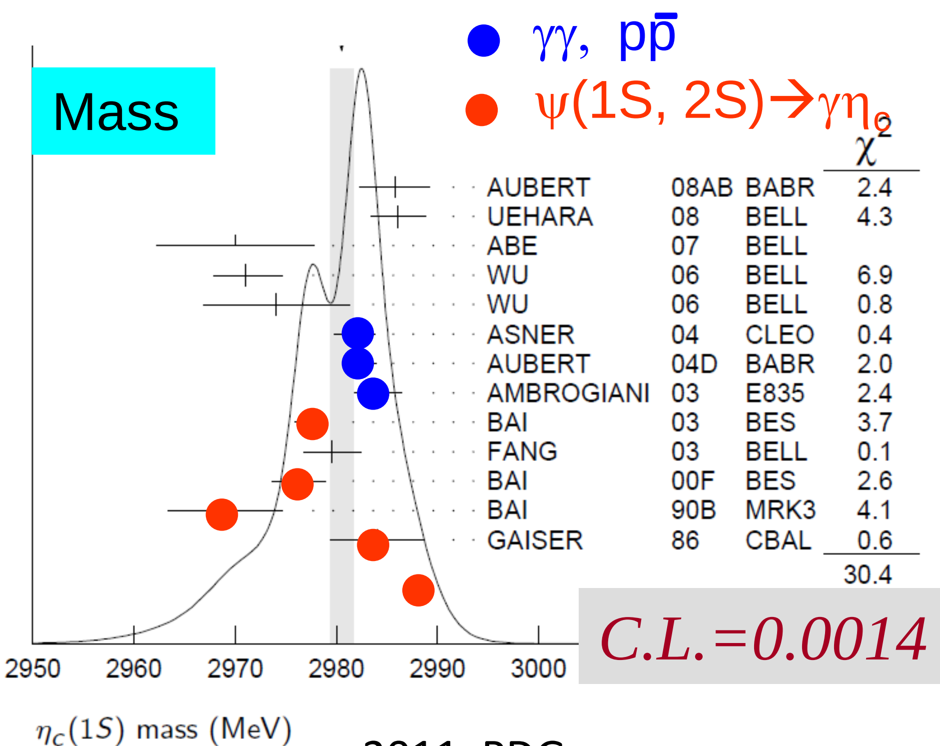
- Be produced in $\gamma\gamma$ process, B decay, $p\bar{p}$ collision, ..
- Least-understood states below the DD threshold



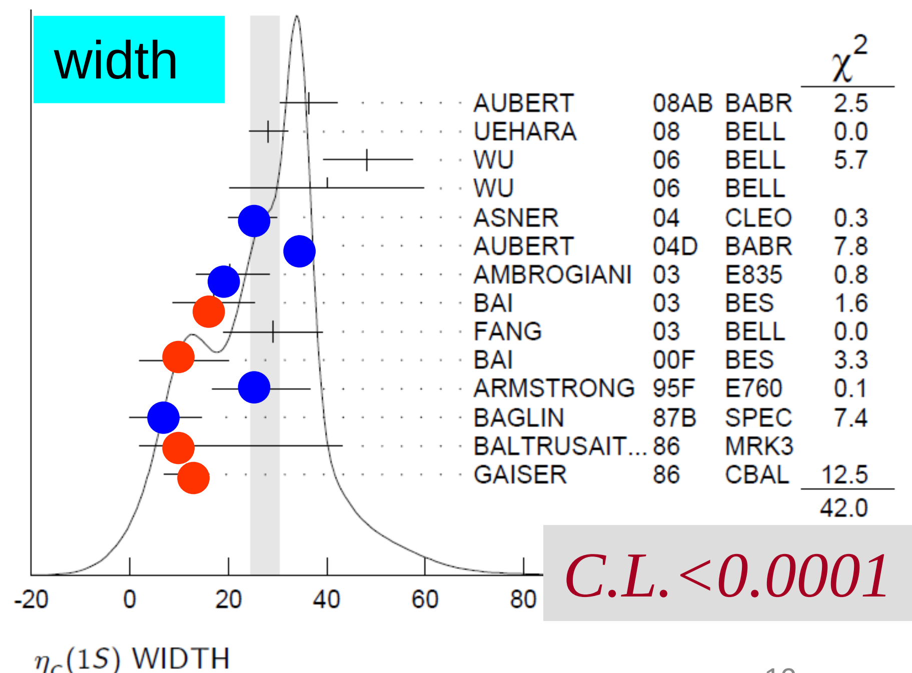
$\eta_c(1S)$

- S-wave spin-singlet ground state, first found by MarkII in 1980
  PRL 45, 1146 (1980)

- The mass & width
  J/ψ radiative transition: M ~ 2978.0MeV/c^2, Γ ~ 10MeV
  γγ process: M = 2983.1 ± 1.0 MeV/c^2, Γ = 31.3 ± 1.9 MeV



2011 PDG



$\eta_c(2S)$

Crystal Ball's "first observation" of $\psi' \to \gamma X$ never been confirmed
PRL 48 70 (1982); *until 2002, Belle found it in* $B \to K\eta_c$.

<u>Observed in different production mechanisms,</u>

1. $B \to K\eta_c(2S)$
2. $\gamma\gamma \to \eta_c(2S) \to KK\pi$
3. double charmonium production
4. <u>M1 transition</u> $\psi' \to \gamma\eta_c(2S)$
   CLEO found no signals in 25M ψ'.

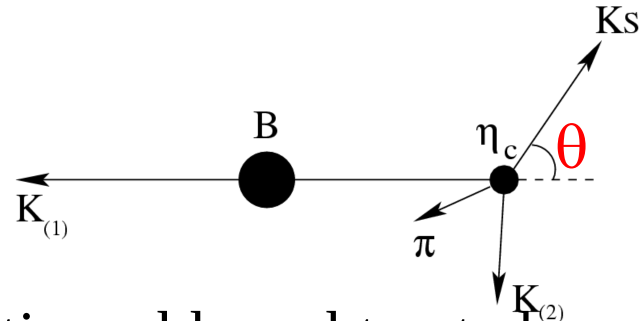
Belle: PRL 89 102001 (2002)
CLEOc: PRL 92 142001 (2004)
Belle: NPPS.184 220 (2008); PRL 98 082001(2007)
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
BaBar: PR D84 012004 (2011)

$BF(\psi' \to \gamma\eta_c(2S)) < 7.6 \times 10^{-4}$ *PRD 81 052002 (2010)*

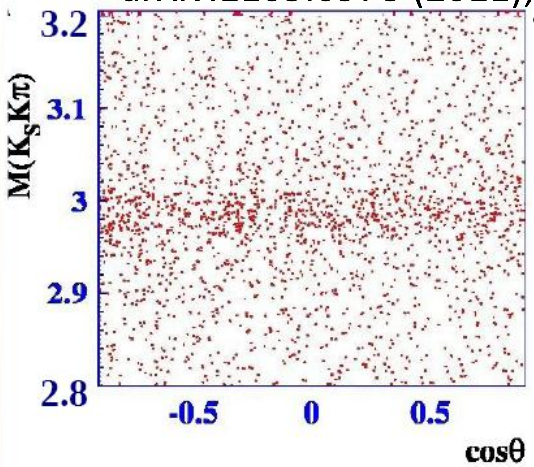
Experimental challenge : search for photons of 50 MeV

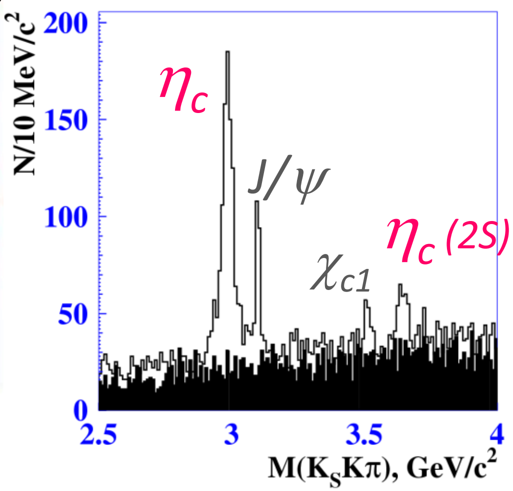
$B \to K\eta_c(1S,2S) \to K(K_sK\pi)$

- Perform a $M(K_sK\pi)$ & $\cos\theta$ 2D fit
- ***Interference btw signal & NR considered***

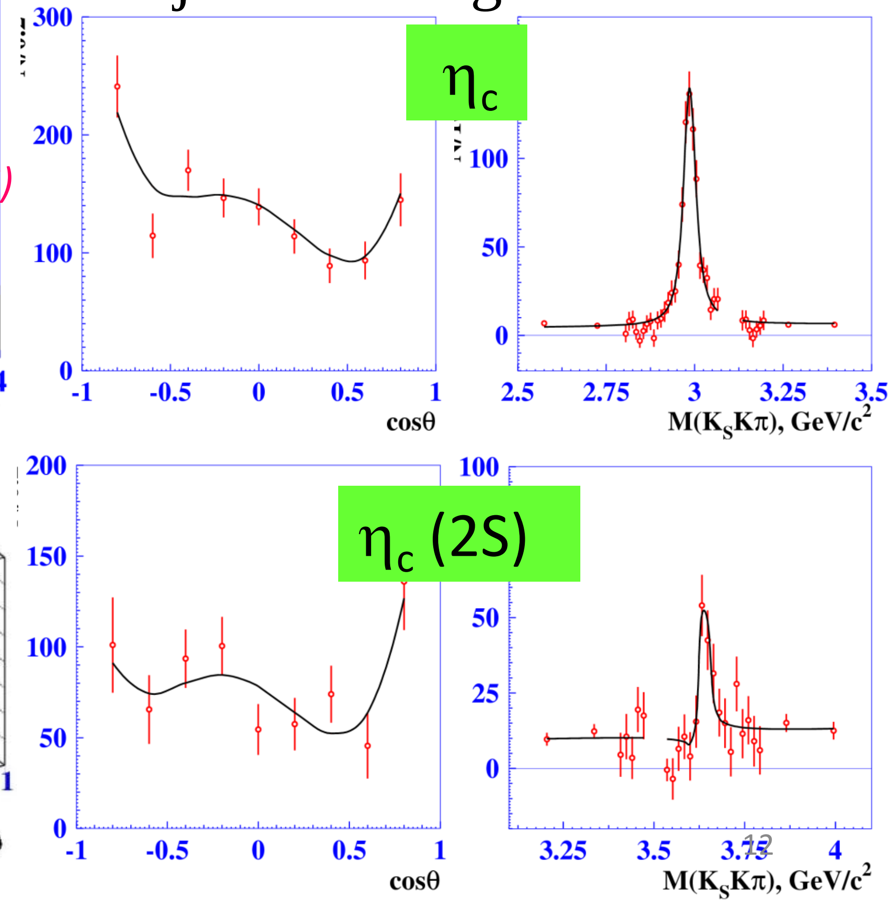


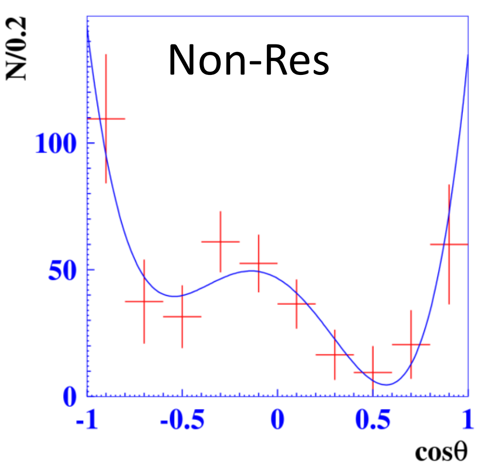
arXiv:1105.0978 (2011); 535M *BB*

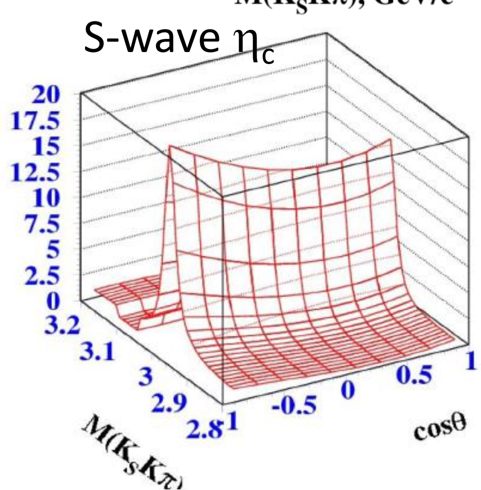




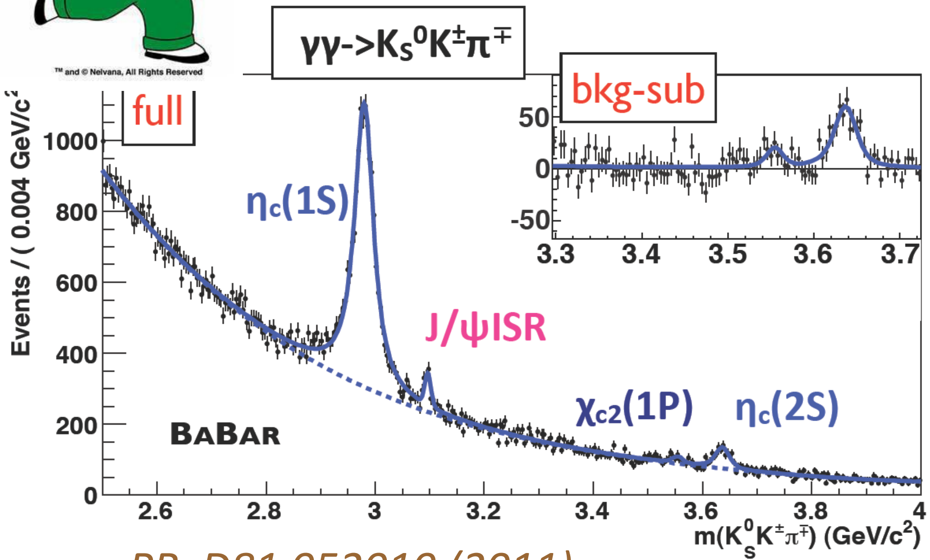
Projections: bkg subtracted



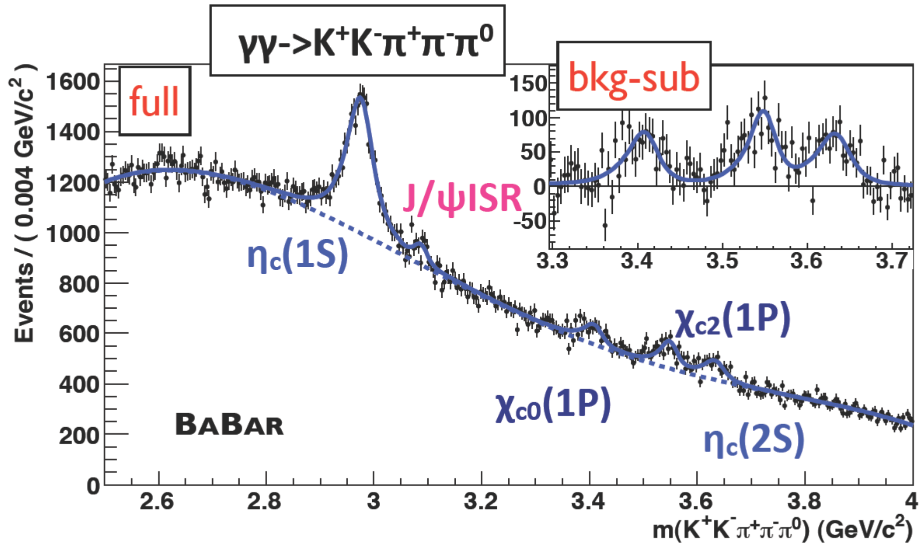




$\gamma\gamma \rightarrow \eta_c(1S/2S) \rightarrow K_s K\pi;\ KK3\pi$

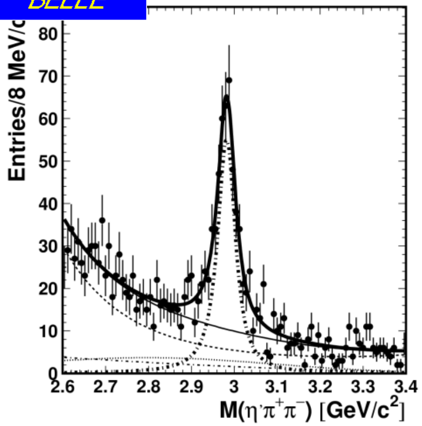


PR D81 052010 (2011)



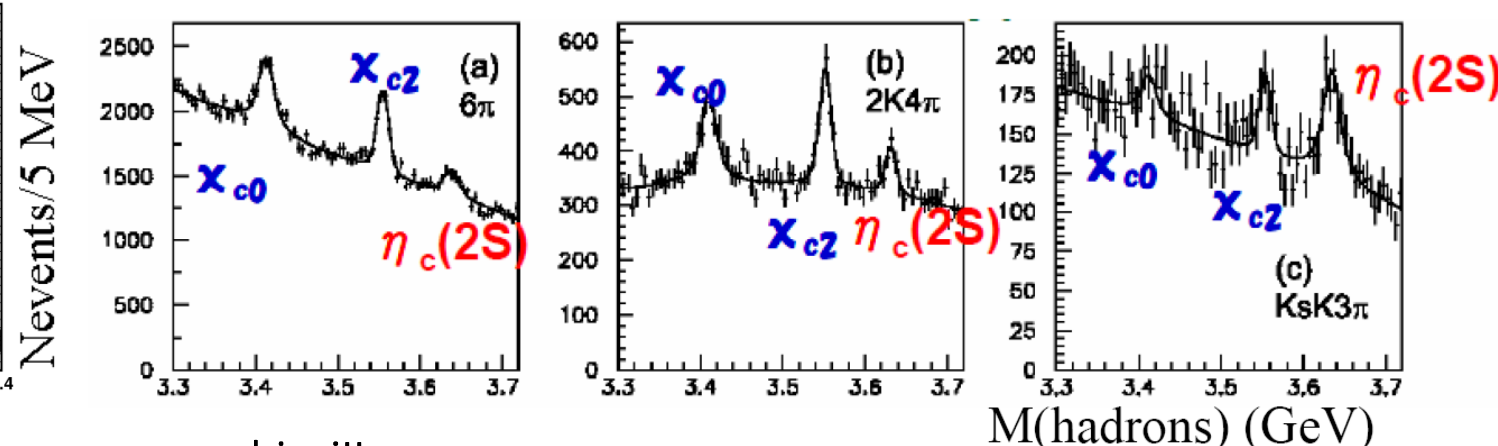
PR D84 012004 (2011)

$\eta_c \rightarrow \eta' \pi\pi$



arXiv:1206.5087

6π(π⁺π⁻π⁺π⁻π⁺π⁻) **2K4π**(K⁺K⁻π⁺π⁻π⁺π⁻) **KsK3π**(K_SK^±π^∓π⁺π⁻)

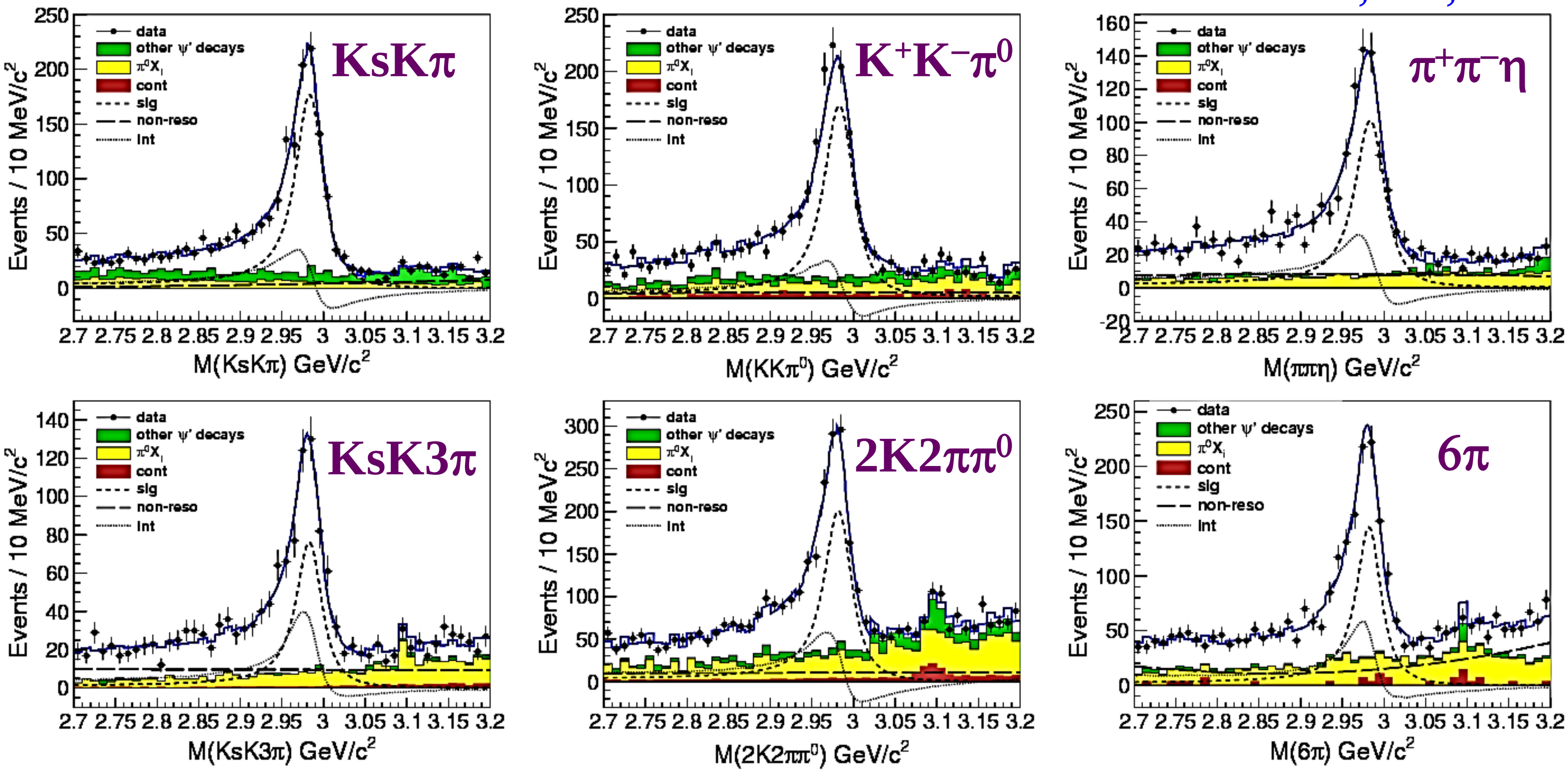


phipsiII

BESIII

Measure η_c in $\psi'\to\gamma\eta_c$

PRL,108,22202



The interference between η_c and non-resonant is significant.

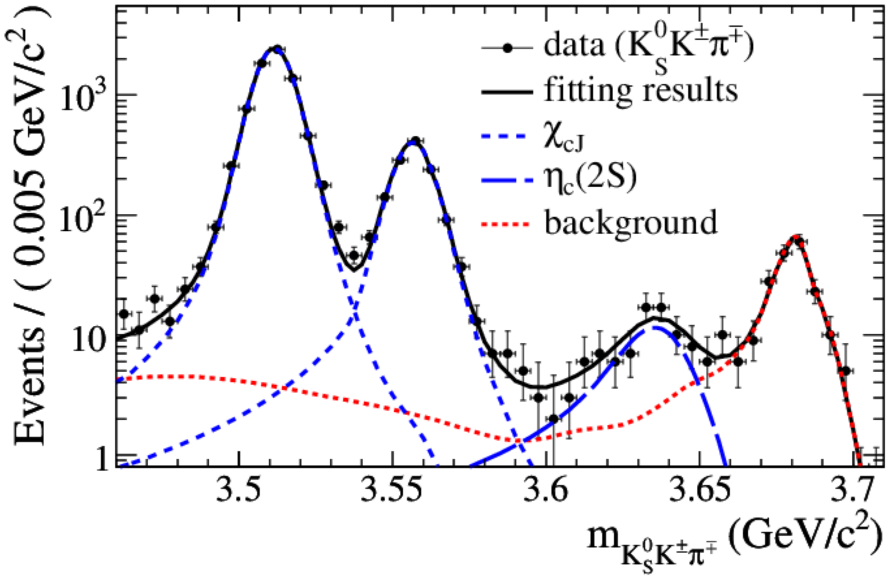
Simultaneous fit to 6 modes,

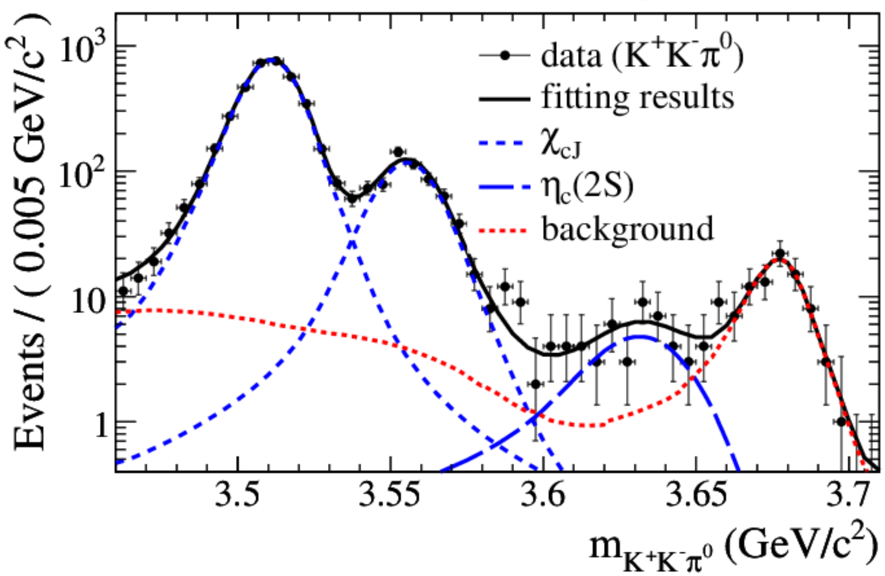
Mass = 2984.3 ± 0.6 ± 0.6 MeV/c²

Width = 32.0 ± 1.2 ± 1.0 MeV

BESIII Observation of $\psi' \to \gamma\eta_c(2S) \to \gamma(KK\pi)$

PRL,109, 042003





Mass = $3638.5 \pm 2.3 \pm 1.0$ MeV/c^2
$\Gamma(\eta_c')$ = $16.9 \pm 6.4 \pm 4.8$ MeV

BF($\psi' \to \gamma\eta_c(2S) \to \gamma KK\pi$))
= $(1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$

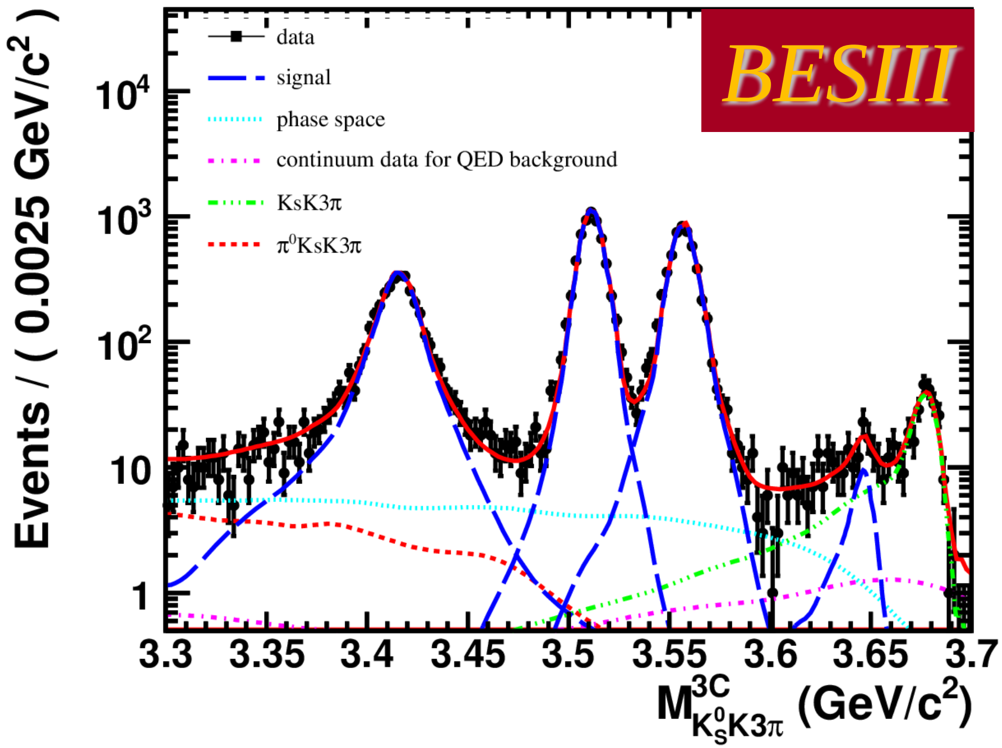
BF($\eta_c(2S) \to KK\pi$)=$(1.9 \pm 0.4 \pm 1.1)$%
BaBar: PR D78 012006 (2008)

BF($\psi' \to \gamma\eta_c(2S)$)
=$(6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

CLEOc: $<7.6\times10^{-4}$ PR D81 052002 (2010)
Potential model predicts:
$(0.1$” $6.2)\times10^{-4}$ PRL 89 162002 (2002)

Evidence of $\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma(K_S K 3\pi)$

PRD 87, 052005 (2013)

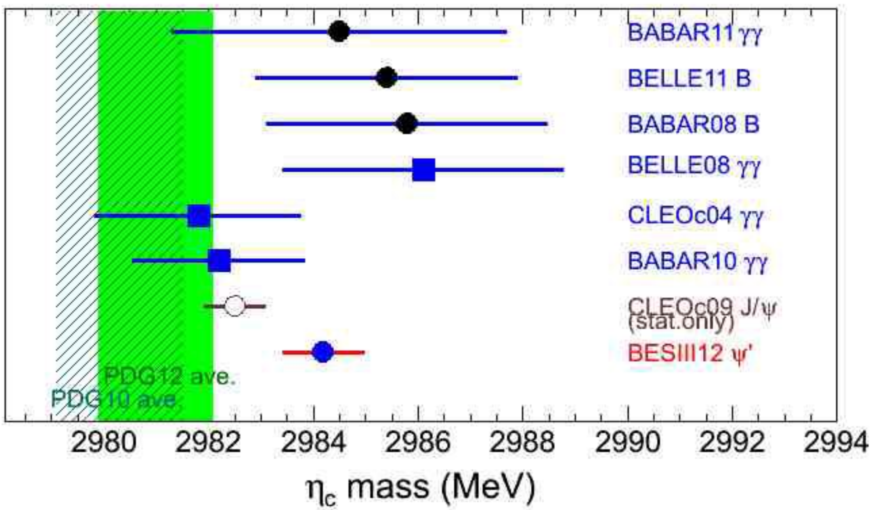


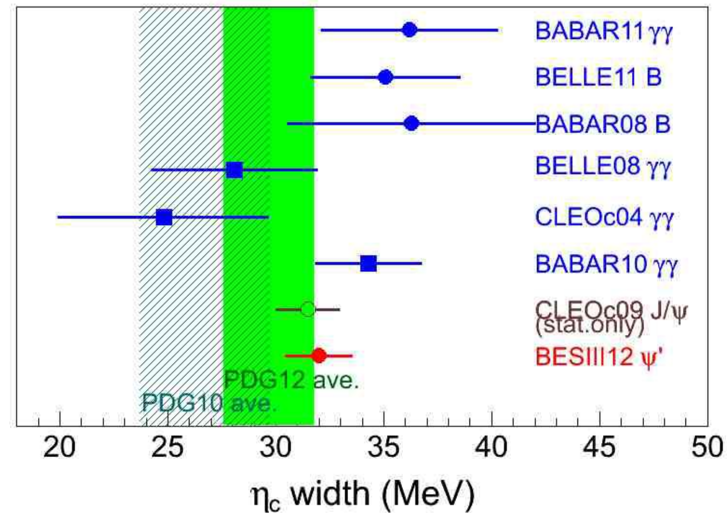
Significance = **4.2σ**

Mass = 3646.9 ± 1.6±3.6 MeV/c^2

$\Gamma(\eta_c')$ = 9.2±4.8±2.9 MeV

Summary for η_c

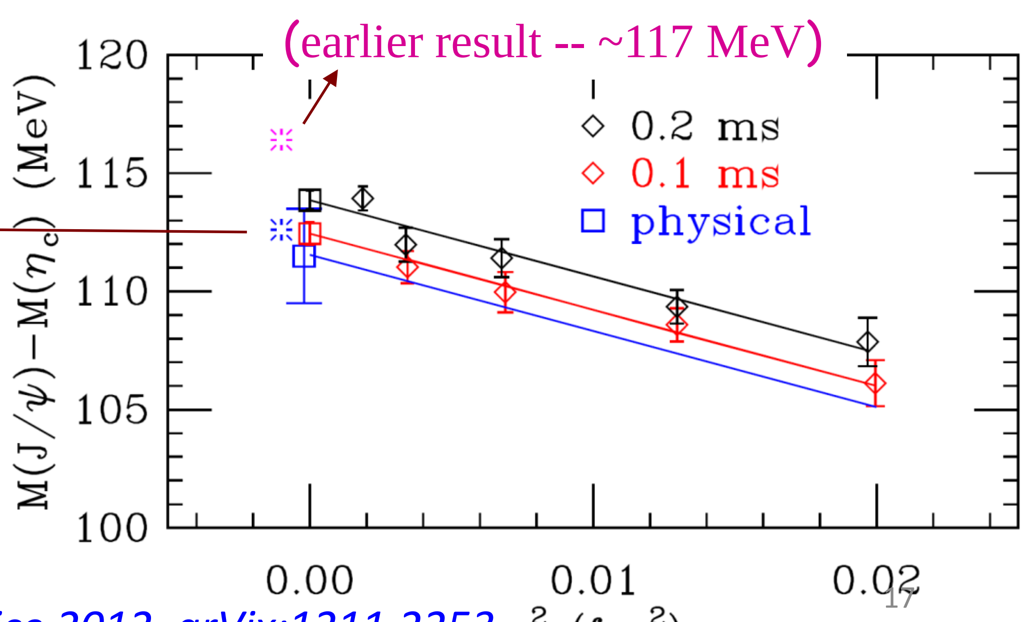




Hyperfine splitting (BESIII alone)

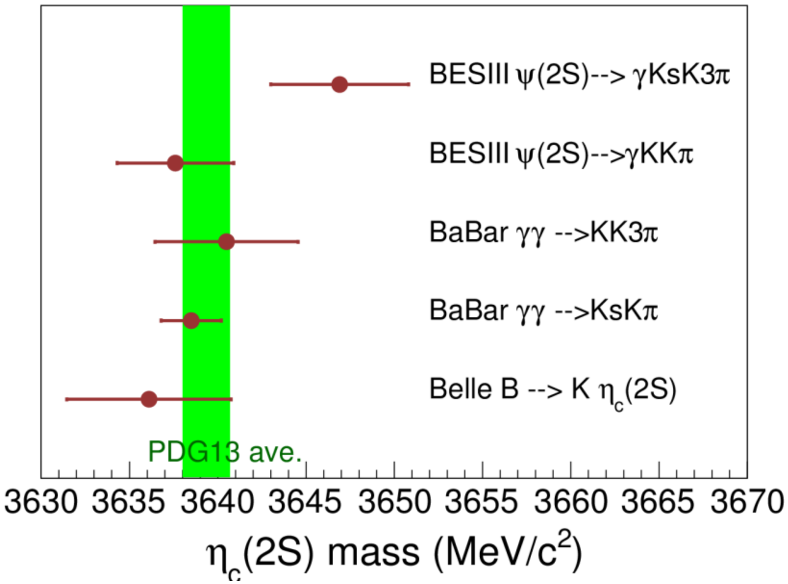
$\Delta M(1S)$ = **112.5±0.8** MeV

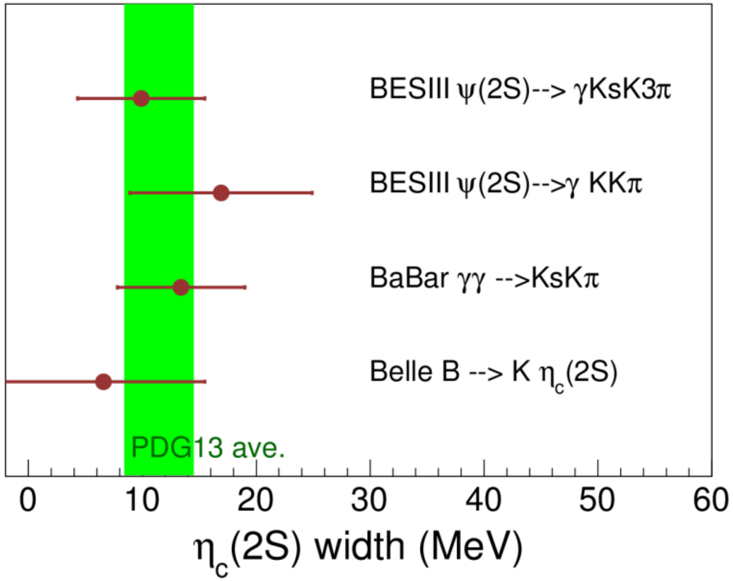
Closer to prediction than earlier result



Lattice 2012, arVix:1211.2253

Summary for $\eta_c(2S)$





Hyperfine splitting: Exp: $\Delta M(2S)$ = 46.7 ± 1.3 MeV

Theory: $\Delta M(2S) \approx$ 68 MeV

$h_c(^1P_1)$

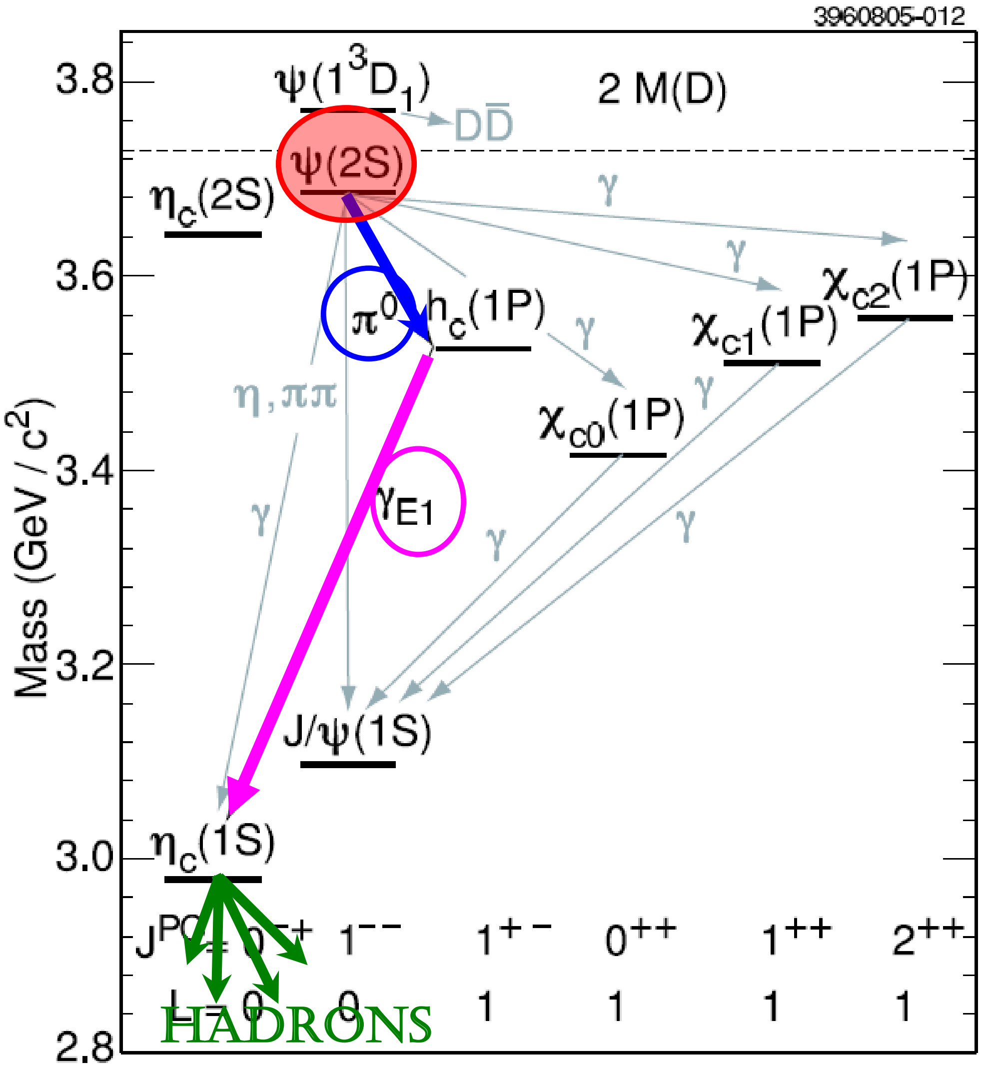
- Spin singlet P wave (S=0, L=1)
- Potential model: if non-vanishing P-wave spin-spin interaction, $\Delta M_{hf}(1P)=M(h_c)-\langle M(1\,^3P_J)\rangle \neq 0$,

  $\langle M(1\,^3P_J)\rangle \quad [M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9$
- Theoretical predictions:
  - $\mathcal{B}(\psi' \to \pi^0 h_c) = (0.4\text{-}1.3)\times 10^{-3}$, $\mathcal{B}(h_c \to \gamma\eta_c) = 41\%$ (NRQCD)

    $\mathcal{B}(h_c \to \gamma\eta_c) = 88\%$ (PQCD)

    Y. P. Kuang, PR D65, 094024 (2002)
  - $\mathcal{B}(h_c \to \gamma\eta_c) = 38\%$ *Godfrey and Rosner, PR D66, 014012 (2002)*
- First reported by E760 in decay $pp \to h_c \to J/\psi\pi^0$, not confirmed
  Evidence found by E835 in $pp \to hc \to \gamma\eta_c$ in 2005 (PR D72 032001)
- Observed by CLEO in $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ PRL 95 102003 (2005)
- Most recent results from BESIII

h_c analysis



"inclusive"

only detect the π^0

(compute M(h_c) from kinematic)

Rate $\propto \mathcal{B}(\psi' \to \pi^0 h_c)$

***"E1* tagged"**

detect the π^0 & γ

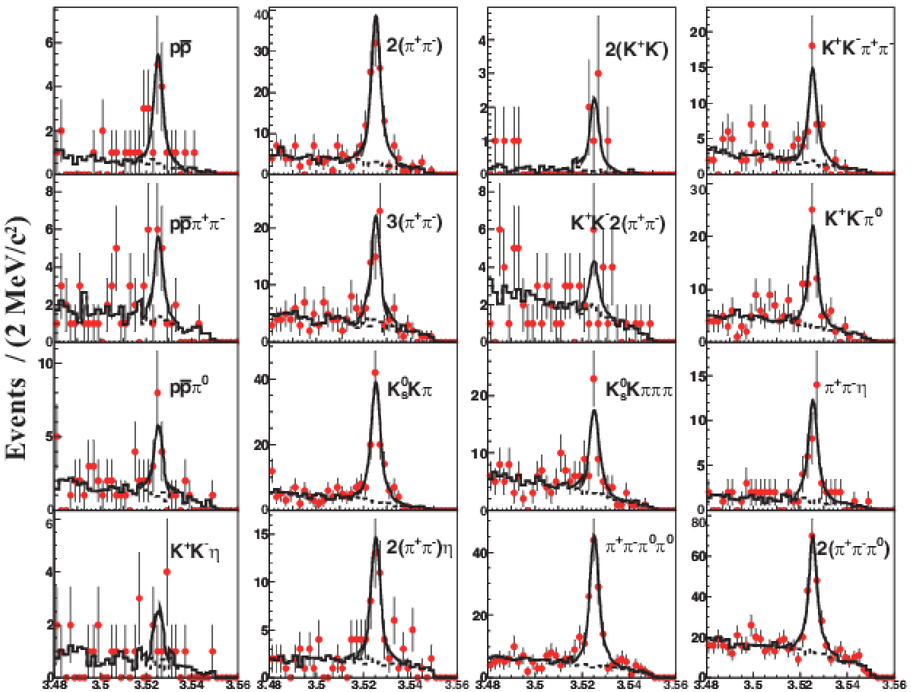
Rate $\propto \mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c)$

"exclusive"

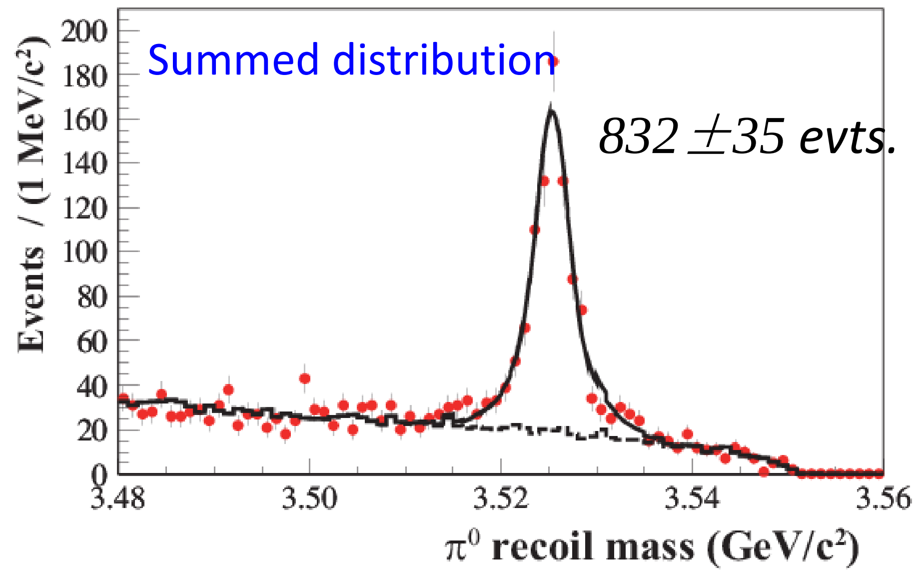
detect the π^0, γ & $\eta_c \to X_i$ decay products

Rate $\propto \mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c) \times \mathcal{B}(\eta_c \to Xi)$

BESIII 16 hadronic decays (~40% η_c decays)



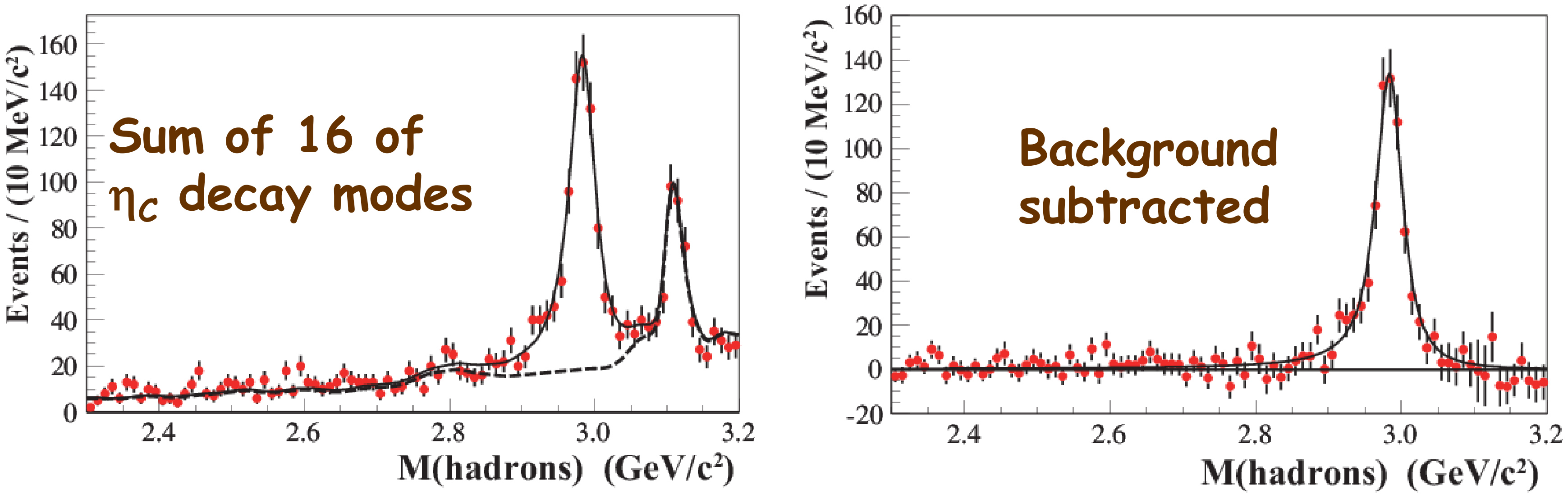
Phys. Rev. D 86, 092009 (2012)



(MeV)	BESIII Exclusive	BESIII Inclusive	CLEO
mass	$3525.31 \pm 0.11 \pm 0.14$	$3525.40 \pm 0.13 \pm 0.18$	$3525.21 \pm 0.27 \pm 0.14$
width	$0.70 \pm 0.28 \pm 0.22$	$0.73 \pm 0.45 \pm 0.28$	--
$\Delta M_{hf}(1P)$	$-0.01 \pm 0.11 \pm 0.15$	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$

BESIII: PRL 104 132002 (2010)
CLEOc: PRL 101 182003 (2008)

η_c lineshape from $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$



The η_c lineshape in $h_c \rightarrow \gamma\eta_c$ is not as distorted as in $\psi' \rightarrow \gamma\eta_c$ decays;
$\rightarrow$the non-resonant interfering bkg is smaller than $\psi' \rightarrow \gamma\eta_c$.
$\rightarrow$this channel will be best suited to determine η_c resonance parameters, $\mathcal{B}(\psi' \rightarrow \gamma\eta_c)$

η_c resonance parameters from $h_c \rightarrow \gamma\eta_c$ @BESIII

η_c Mass = 2984.49 ± 1.16 ± 0.52 MeV/c^2
η_c Width = 36.4 ± 3.2 ± 1.7 MeV

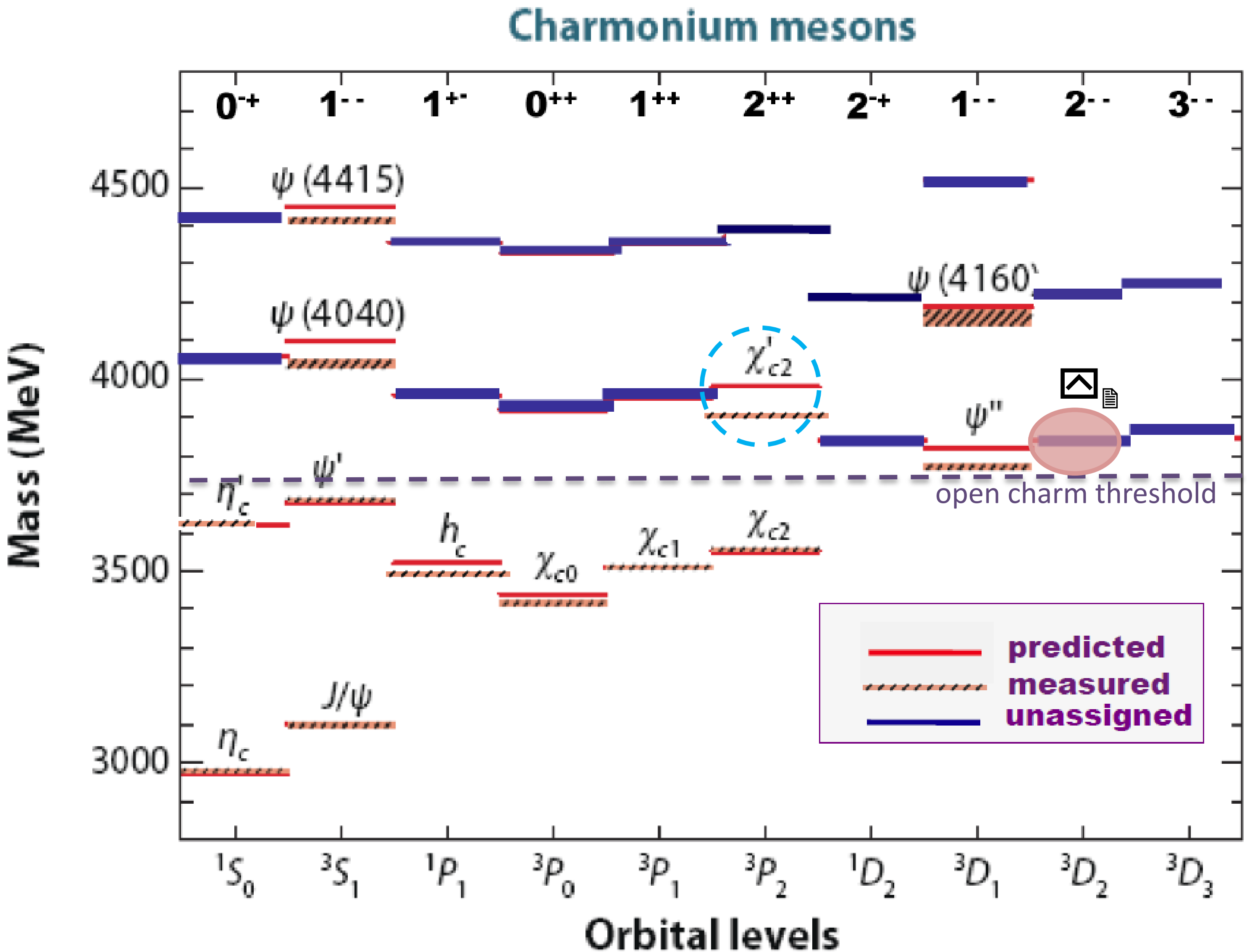
Compared with the reults from $\psi' \rightarrow \gamma\eta_c$

Mass = 2984.3 ± 0.6 ± 0.6 MeV/c^2

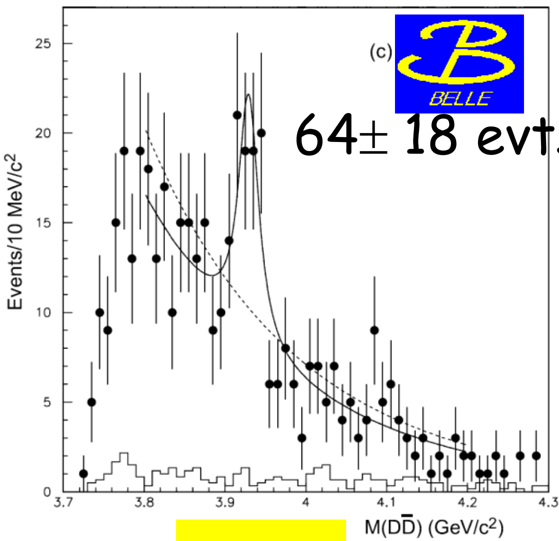
Width = 32.0 ± 1.2 ± 1.0 MeV

1. *Statistic errors are dominated, need more statistics.*
2. *Reults are consistent with those from $\psi' \rightarrow \gamma\eta_c$ decays within errors.*

Confirmation of χ_{c2}' and evidence for ψ_2

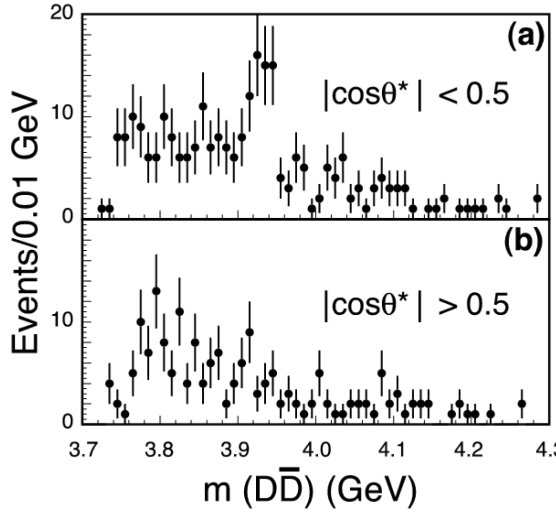


$\gamma\gamma \rightarrow \chi_{c2}(2P) \rightarrow D\bar{D}$

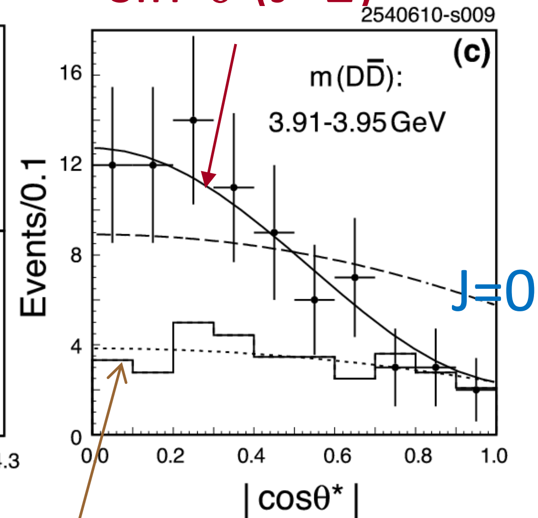


64± 18 evts

m(DD)

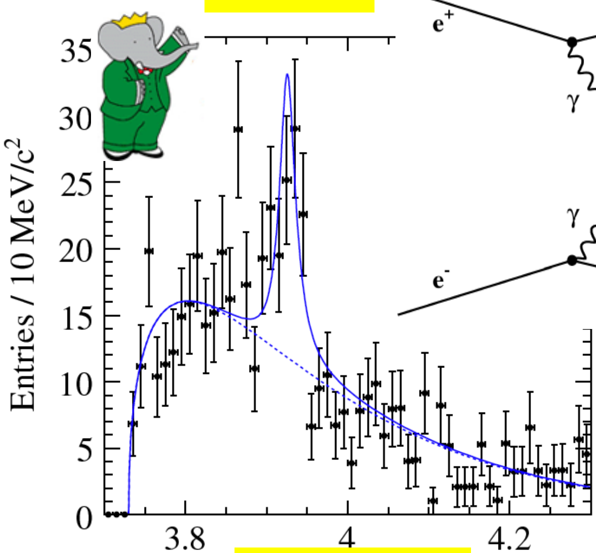


Expected $\sin^4\theta$ (J=2)

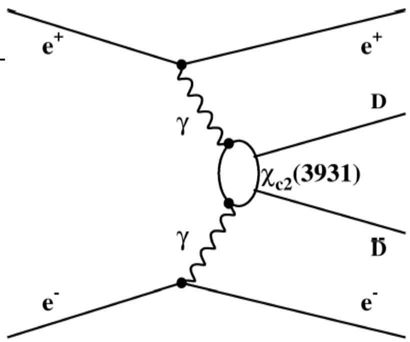


J=0

sideband



m(DD)



$J^{PC} = 0^{++}, 2^{++}$

Belle PRL 96 082003 (2005)

M=3929 ± 5 ± 2 MeV

Γ=29 ± 10 ± 2 MeV

BaBar: PRD 81, 092003(2010)

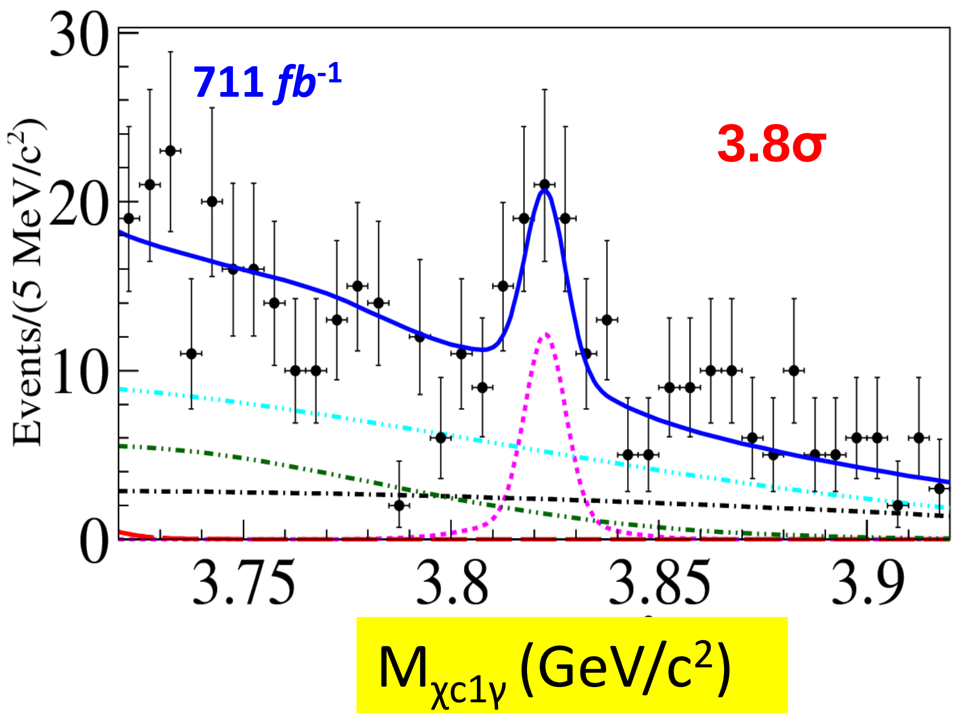
M = 3926.7 ± 2.7 ± 1.1 MeV

G = 21.3 ± 6.8 ± 3.6 MeV

$X(3823) \to \chi_{c1}\gamma$ in $B \to \chi_{c1}\gamma K$

Simultanous fit to $B^{\pm} \to \chi_{c1}\gamma K^{\pm}$ & $B^{0} \to \chi_{c1}\gamma K_S$

χ_{c1} reconstructed in $\gamma J/\psi$



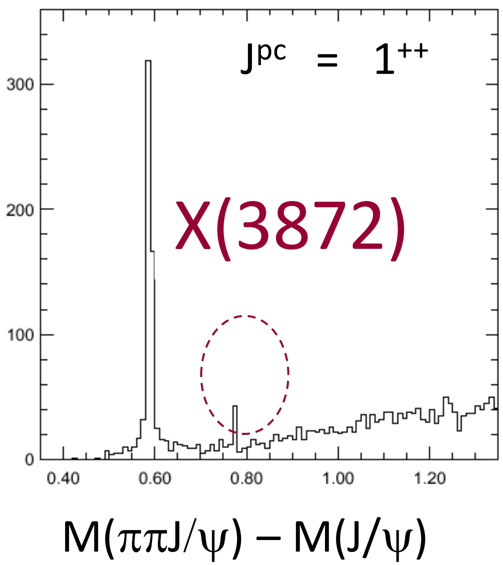
$$M_{X(3823)} = M^{meas}_{X(3823)} - M^{meas}_{\psi'} + M^{PDG}_{\psi'}$$
$$= 3823.1 \pm 1.8 \pm 0.7\, MeV$$

The measured mass and other properties are consistent with the missing $\psi_2(1\,^3D_2)$ state

PRL 111 032001(2013);

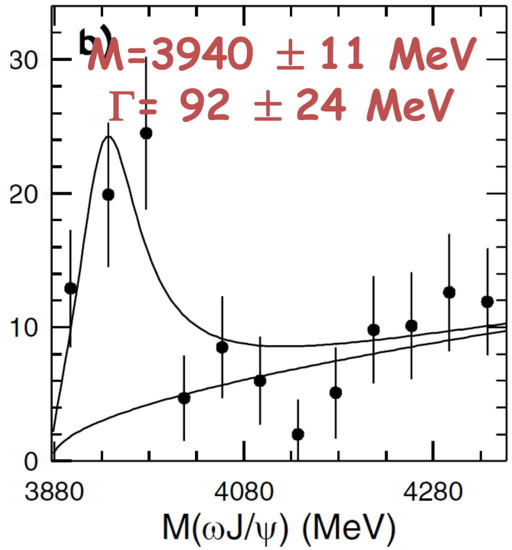
Resonances: quantum number is not assigned
Are those the missing charmonium states?

X(3872)→$\pi^+\pi^-$ J/ψ



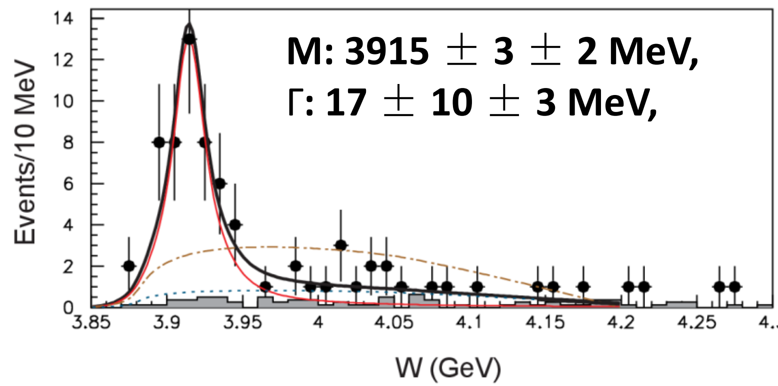
PRL 91, 262001 (2003)

Y(3940)→ ωJ/ψ
in B→K $\pi^+\pi^-\pi^0$ J/ψ



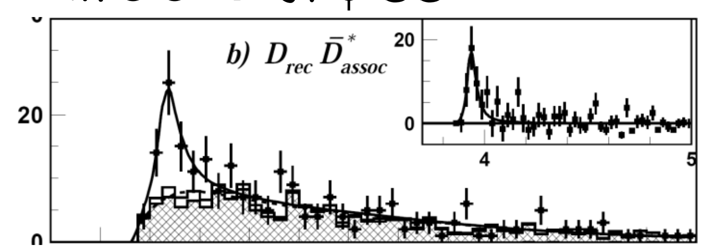
PRL94, 182002 (2005)

γγ→X(3915)→ ωJ/ψ



PRL 104, 092001 (2010)

X(3940)→ DD*
in e^+e^- → J/ψ DD*



PRL 100, 202001

Opportunities

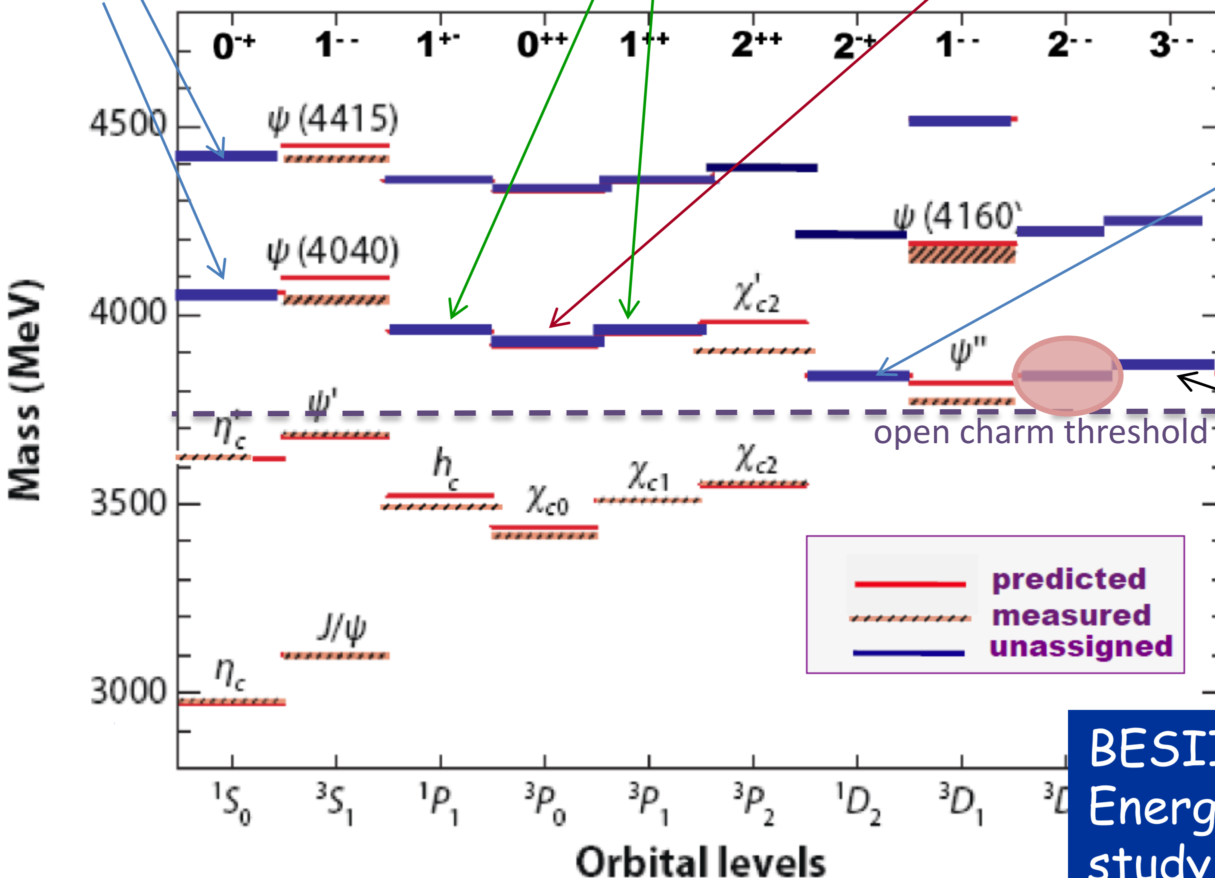
PRL94, 182002 (2005)

Might be seen in $\gamma\gamma$ or hadronic production

Decay to DD*
Produced in E1 transition

χ_{c0} ($^3p_0$ 0^{++}) = Y(3940)→ $\omega J/\psi$
Largely decays to DD,

η_{c2} ($^1D_2$ 2^{-+})
η_{c2}→DD violates P
→$\pi^+\pi^-\eta_c$~30%



From χ_{c1}'($^3p_2$ 2^{++}) E1 transition
Γ ~ 100keV

PRL 89, 162002 (2002)

BESIII has taken data at higher Energies around 4.26 GeV, to study Charmonium(-like) state
see Changzheng Yuan's talk

Summay

- Charmonium states provide a platform to study non-perturbative mechanism.
- Below the open-charm threshold: Spin-singlet states η_c , h_c , $\eta_c(2S)$ have been well measured
- Lots of discoveries, expected and unexpected
  - χ_{c2}' is assigned; X(3823) is consistent with $\psi_2(1\,^3D_2)$
  - Are the X/Y states really new? Or the missing charmonium states? What's their nature?
- Future potential model, Lattice QCD, sum rules, novel method
- BESIII and future experiments, Panda, BelleII, have good chance to establish not-yet-observed states.