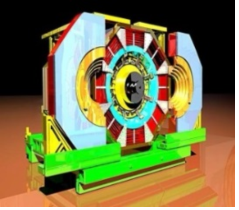

Charmonium hadronic transitions at BESIII

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(on behalf of the BESIII Collaboration)

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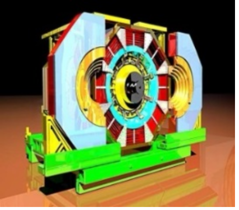
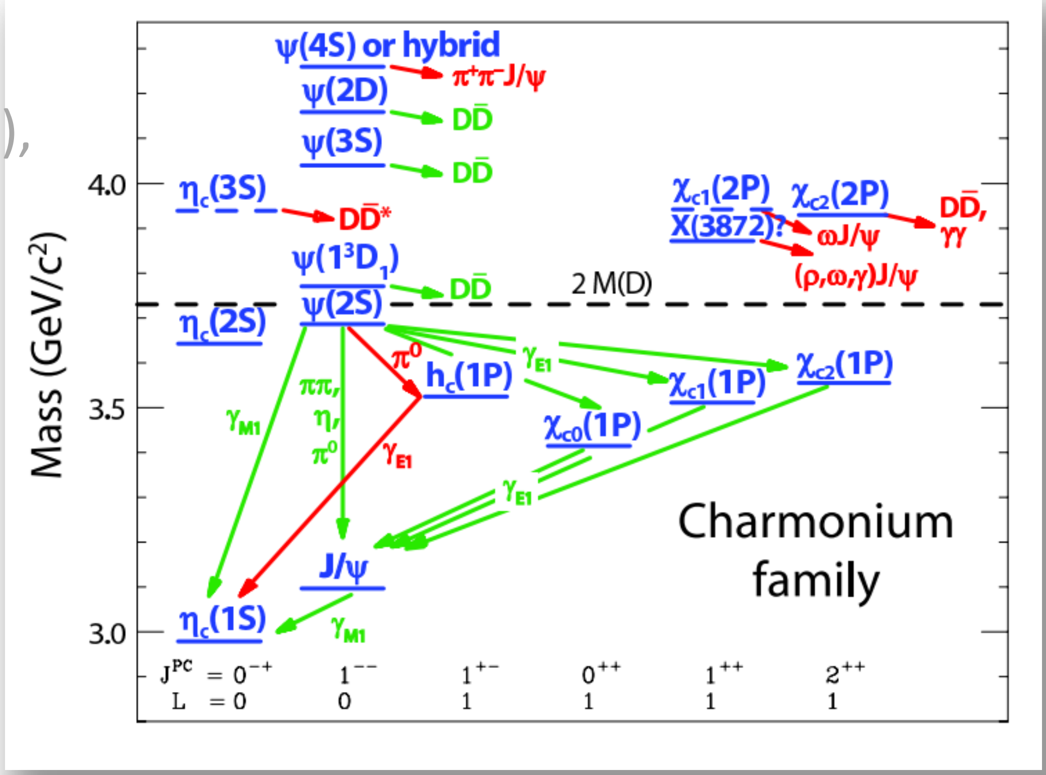
QWG 2014 CERN Nov. 12th, 2014

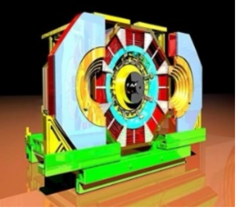


Charmonium physics overview

- Charmonium spectroscopy
  - η_c, J/ψ, h_c, χ_{cJ}, $\eta_c(2S)$, $\psi(3686)$, $\psi(3770)$ …
- Charmonium transitions
  - ✓ Radiative transitions
  - ✓ Hadronic transitions
- Charmonium decays
  - ✓ $X_{c0,2} \to \gamma\gamma$, $J/\psi \to \gamma\gamma$, $\eta_c \to \gamma\gamma$
  - ✓ Light hadron decays
  - ✓ Baryonic decays
- Hunt for XYZ or exotic charmonium-like states



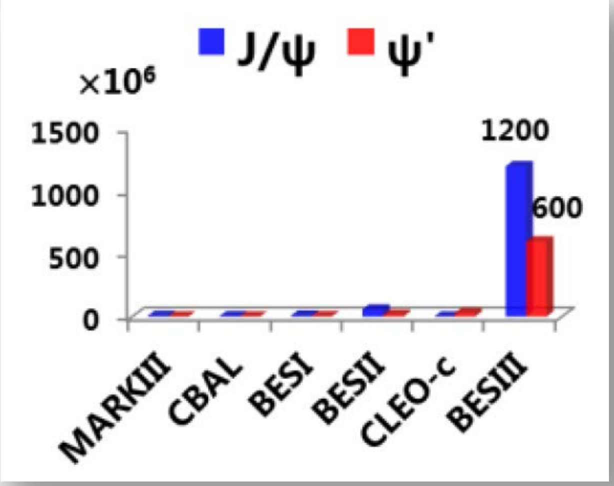
The quark model describes most of charmonium remarkably well especially those below open-charm threshold.



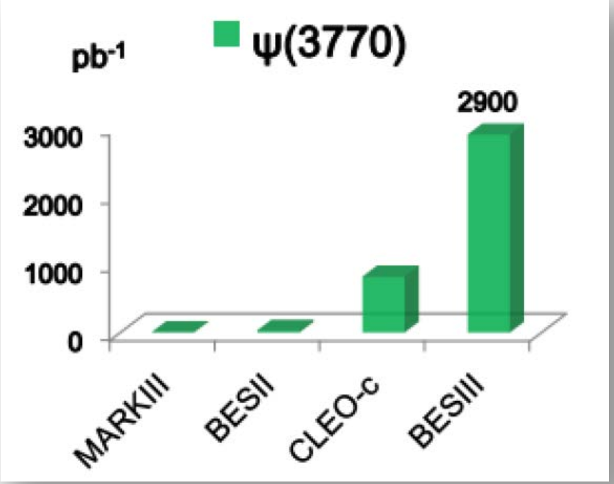
Charmonium hadronic transitions

- Hadronic transitions are important decay modes of heavy quarkonia
  - ✓ e.g. Br(ψ(3686)→ππJ/ψ) is approximately 50%
- Characterized as the emission of two soft gluons from the heavy quarks and the conversion of gluons into light hadrons
- Strong and EM transitions if mass difference is large enough to produce one or more π's, or η
- Only hadronic transitions of the ψ(3686) have been well studied experimentally, including $\pi^+\pi^-J/\psi$, $\pi^0\pi^0J/\psi$, ηJ/ψ and π^0J/ψ, other possible transitions need to be studied
- Many theoretical calculations were done, multipole expansion can make quite successful predictions for many hadronic transitions
- Mass difference between charmonium states are not large, light hadrons with low momentum, experimental challenge

BESIII data sets for charmonium study

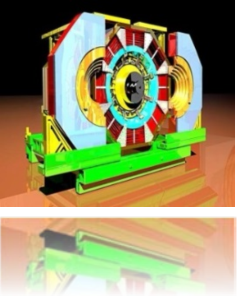


	Previous data	BEIII present
J/ψ	BESII: 58 M	1.3 B 20×BESII
ψ(3686)	CLEO: 28 M	0.5 B 20×CLEO-c
ψ(3770)	CLEO: 0.8 /fb	2.9 /fb 3.5×CLEO-c



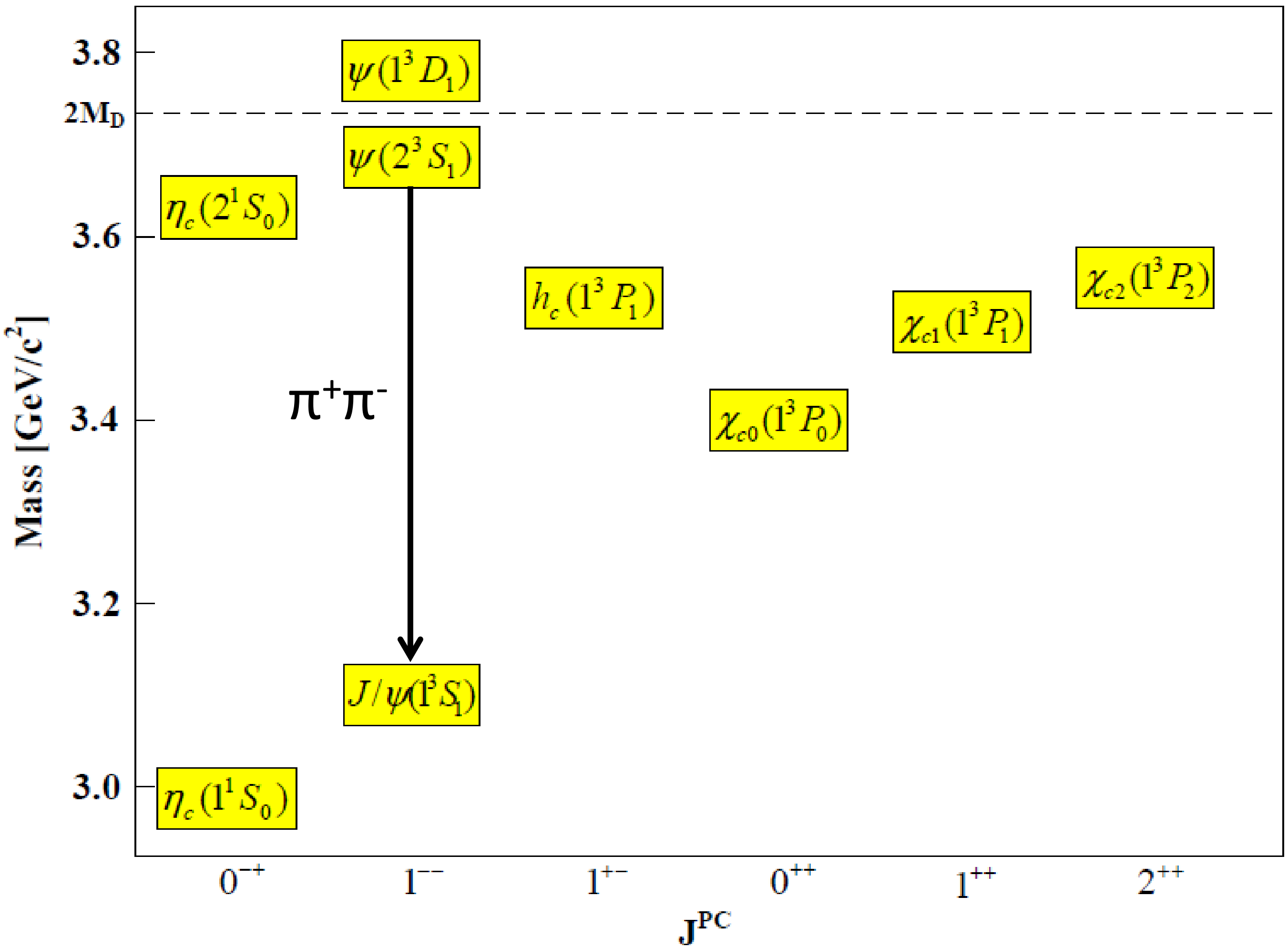
- Ψ(3686)
  - ✓ 106 M in 2009 → results shown in this talk
  - ✓ 400 M in 2012 analysis in progress

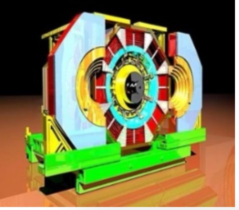
Vector ψ/Υ states can be produced directly.
C-even states can be produced from radiative transitions.



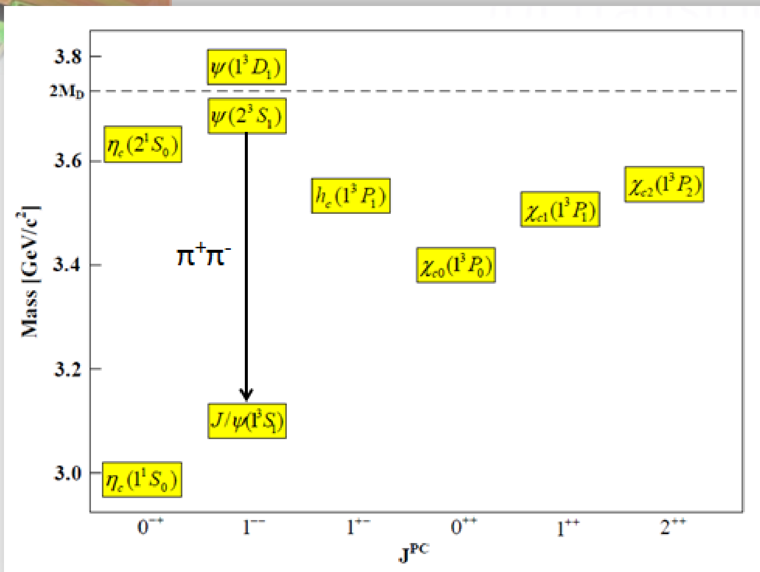
Hadronic transitions beteen S-wave charmonia

ππ transitions





ψ(3686)→$\pi^+\pi^-$J/ψ



Branching fraction

CLEO-c: PRD 78, 011102 (2008)

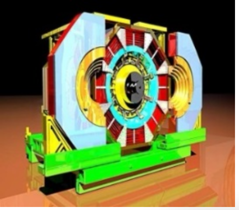
$\mathscr{B}$(ψ(3686)→$\pi^+\pi^-$J/ψ) = (35.04±0.8)%

BESII: PLB 550, 24 (2002)

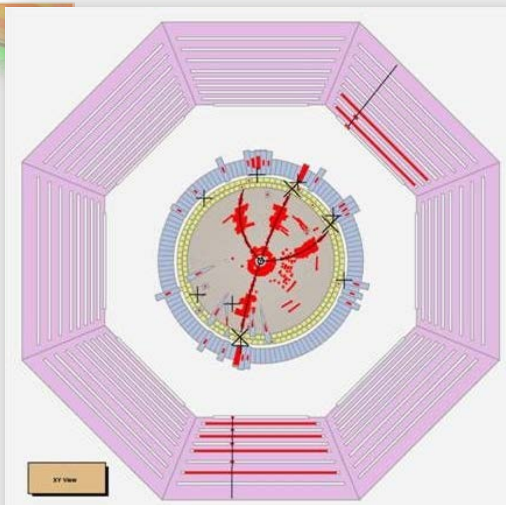
$\mathscr{B}$(ψ(3686)→$\pi^+\pi^-$J/ψ) = (32.3±1.4)%

Demands additional, high-precision measurements

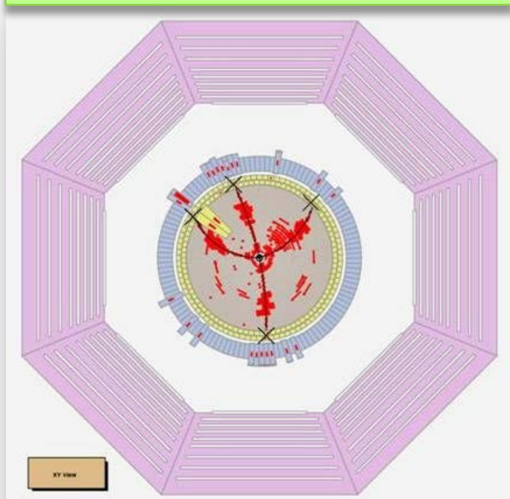
- The largest branching fraction in ψ(3686) decays, still remains interesting
- $\mathscr{B}$($\pi^+\pi^-$J/ψ) is crucial for relevant measurements in charmonium decays and in searches for new particles (using $M^{rec}_{\pi^+\pi^-}$ to identify J/ψ)
- Relates to the interaction between heavy quarks and gluons, excellent testing ground for some theoretical predictions (QCD multiple expansion and chiral symmetry)



$\psi(3686)\to\pi^+\pi^- J/\psi$



$J/\psi\to\mu^+\mu^-$



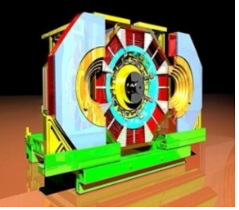
$J/\psi\to e^+e^-$

- Measure the $\mathcal{B}(\psi(3686)\to\pi^+\pi^- J/\psi)$ and $\mathcal{B}(J/\psi\to l^+l^-)$
- Advantage: no interference with Bhabha or dimuon production
- Extract signal yields by looking at the recoiling mass distribution against the dipion system
- Calculate the equations

$$\mathcal{B}_{\pi\pi J/\psi} = \frac{N_{\pi\pi J/\psi}}{\epsilon_{\pi\pi J/\psi}\times N_{\rm tot}}$$

$$\begin{aligned}\mathcal{B}_{ll} &= \frac{\mathcal{B}_{\pi\pi J/\psi}\times\mathcal{B}_{ll}}{\mathcal{B}_{\pi\pi J/\psi}}\\ &= \frac{N_{ll}/(\epsilon_{ll}\times N_{\rm tot})}{N_{\pi\pi J/\psi}/(\epsilon_{\pi\pi J/\psi}\times N_{\rm tot})}\\ &= \frac{N_{ll}/\epsilon_{ll}}{N_{\pi\pi J/\psi}/\epsilon_{\pi\pi J/\psi}}.\end{aligned}$$

Independent of $N_{\psi(3686)}$, one of the major sources of systematic uncertainties



$\psi(3686)\to\pi^+\pi^- J/\psi$

PRD 88, 032007 (2013)

Branching fraction

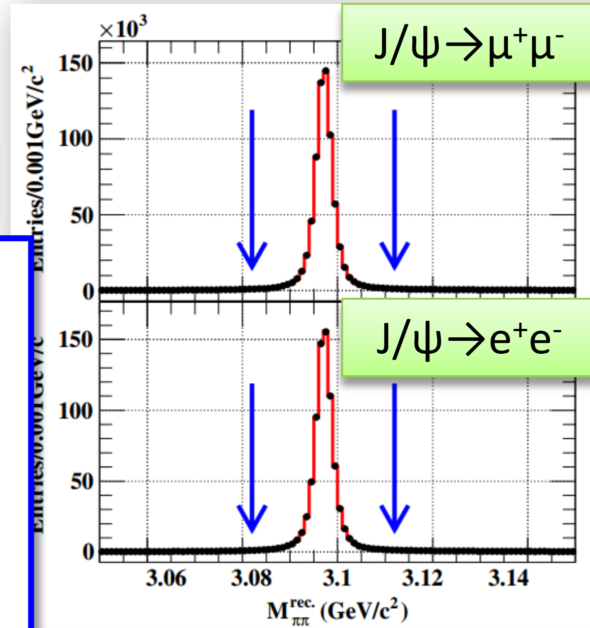
$\mathcal{B}(\psi(3686)\to\pi^+\pi^- J/\psi)$ =
$(34.98 \pm 0.02 \pm 0.45)\%$

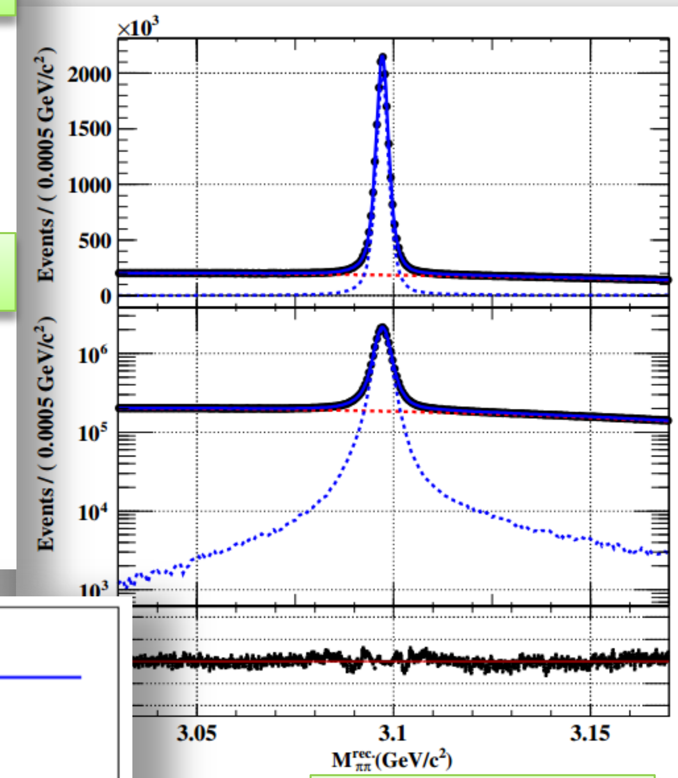
$\mathcal{B}(J/\psi\to\mu^+\mu^-)$ =
$(5.973 \pm 0.007 \pm 0.038)\%$

$\mathcal{B}(J/\psi\to e^+e^-)$ =
$(5.983 \pm 0.007 \pm 0.037)\%$

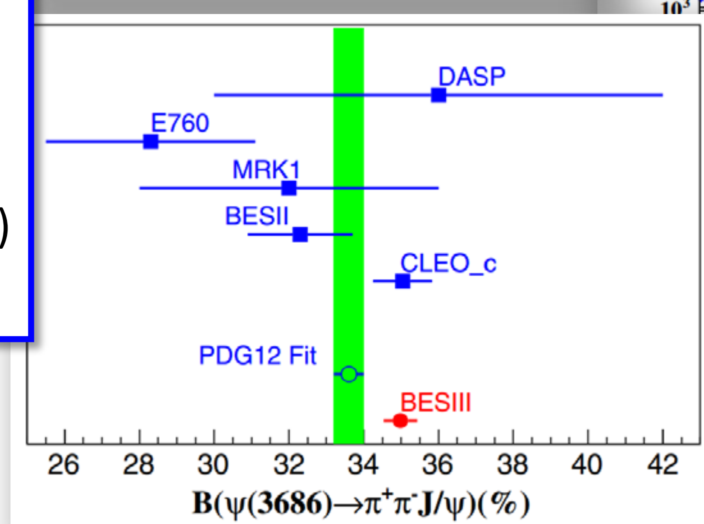
$\mathcal{B}(J/\psi\to l^+l^-)$ =
$(5.978 \pm 0.005 \pm 0.040)\%$

$\mathcal{B}(J/\psi\to e^+e^-)/\mathcal{B}(J/\psi\to\mu^+\mu^-)$
= $1.0017 \pm 0.0017 \pm 0.0033$

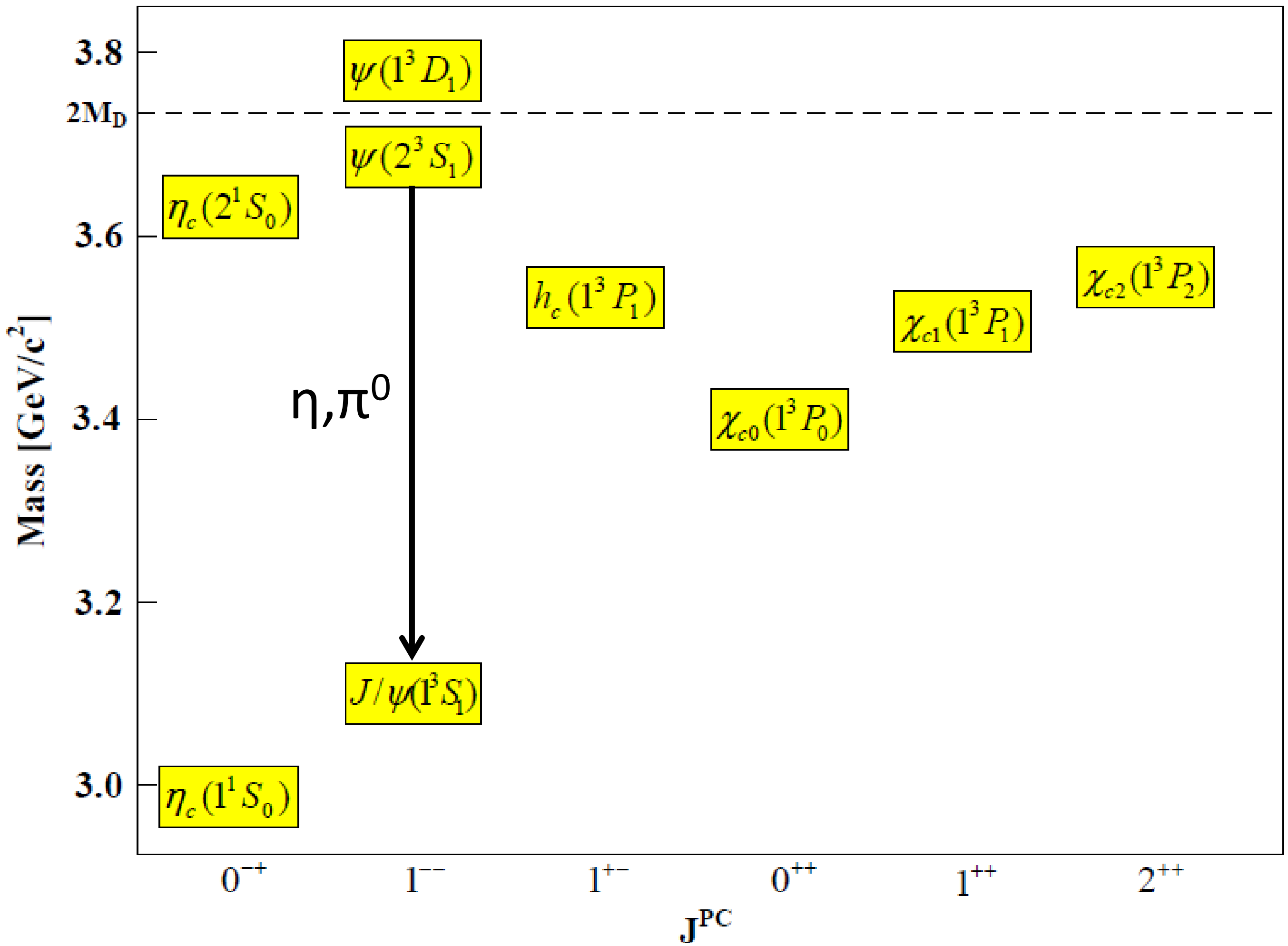


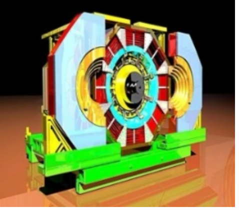


J/ψ→anything

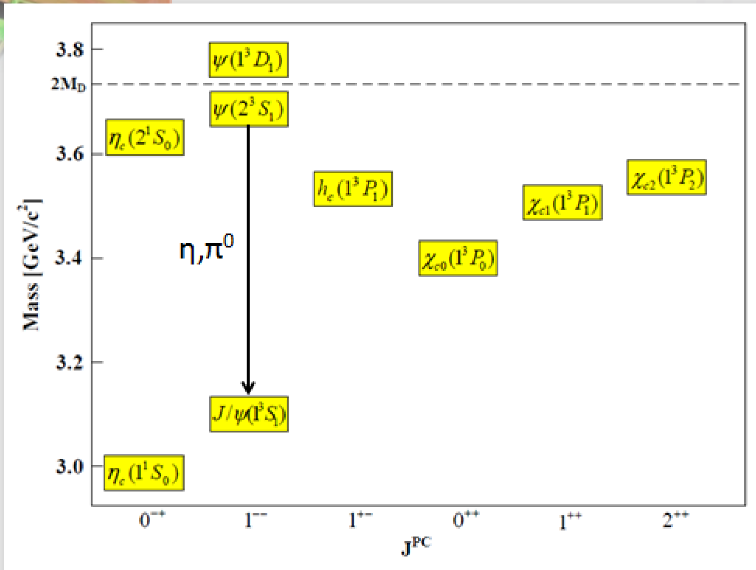


η, π^0 transitions





$\psi(3686)\to\eta J/\psi,\ \pi^0 J/\psi$



- $\psi(3686)\to\pi^0 J/\psi$ is isospin-violating transition
- $R = \frac{\mathcal{B}(\psi'\to\pi^0 J/\psi)}{\mathcal{B}(\psi'\to\eta J/\psi)}$ can be used to measure the light-quark mass ratio m_u/m_d
- Previous measurements

  R=0.040 ± 0.004 PRD 86, 010001 (2012)
- Large discrepancy between theory and experiment, has to be resolved, need more precise measurement

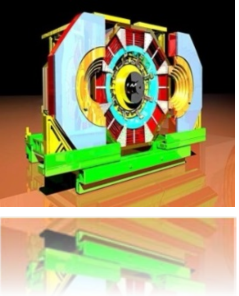
- Theoretical predictions
  - ✓ Based on the QCD multi-pole expansion and axial anomaly

$$R \equiv \frac{M(s)-M}{M(d)-M(u)}, \quad M=(M(d)+M(u))/2$$

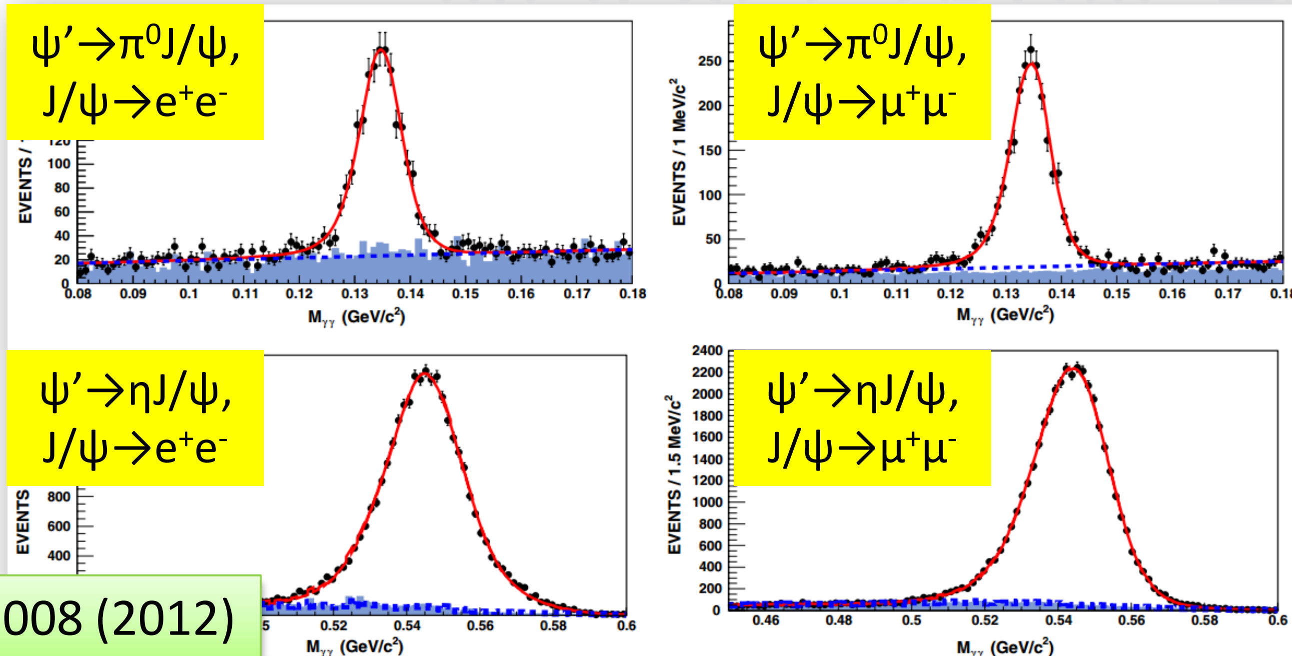
R=0.016 Phys. Rep. 194, 1 (1990)

  - ✓ Using chiral-perturbation theory, considering charmed-meson loop mechanism

R=0.11 ± 0.06 PRL 103, 082003 (2009)



$\psi(3686)\rightarrow\eta J/\psi$, $\pi^0 J/\psi$



PRD 86, 092008 (2012)

<u>Our results</u>

$\mathscr{B}(\psi(3686)\rightarrow\pi^0 J/\psi) = (1.62\pm0.02\pm0.03)\times10^{-3}$

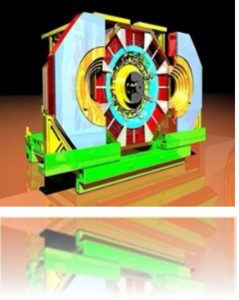
$\mathscr{B}(\psi(3686)\rightarrow\eta J/\psi) = (33.75\pm0.17\pm0.86)\times10^{-3}$

$R = (3.74\pm0.06\pm0.04)\%$

<u>Consistent with CLEO-c's</u>

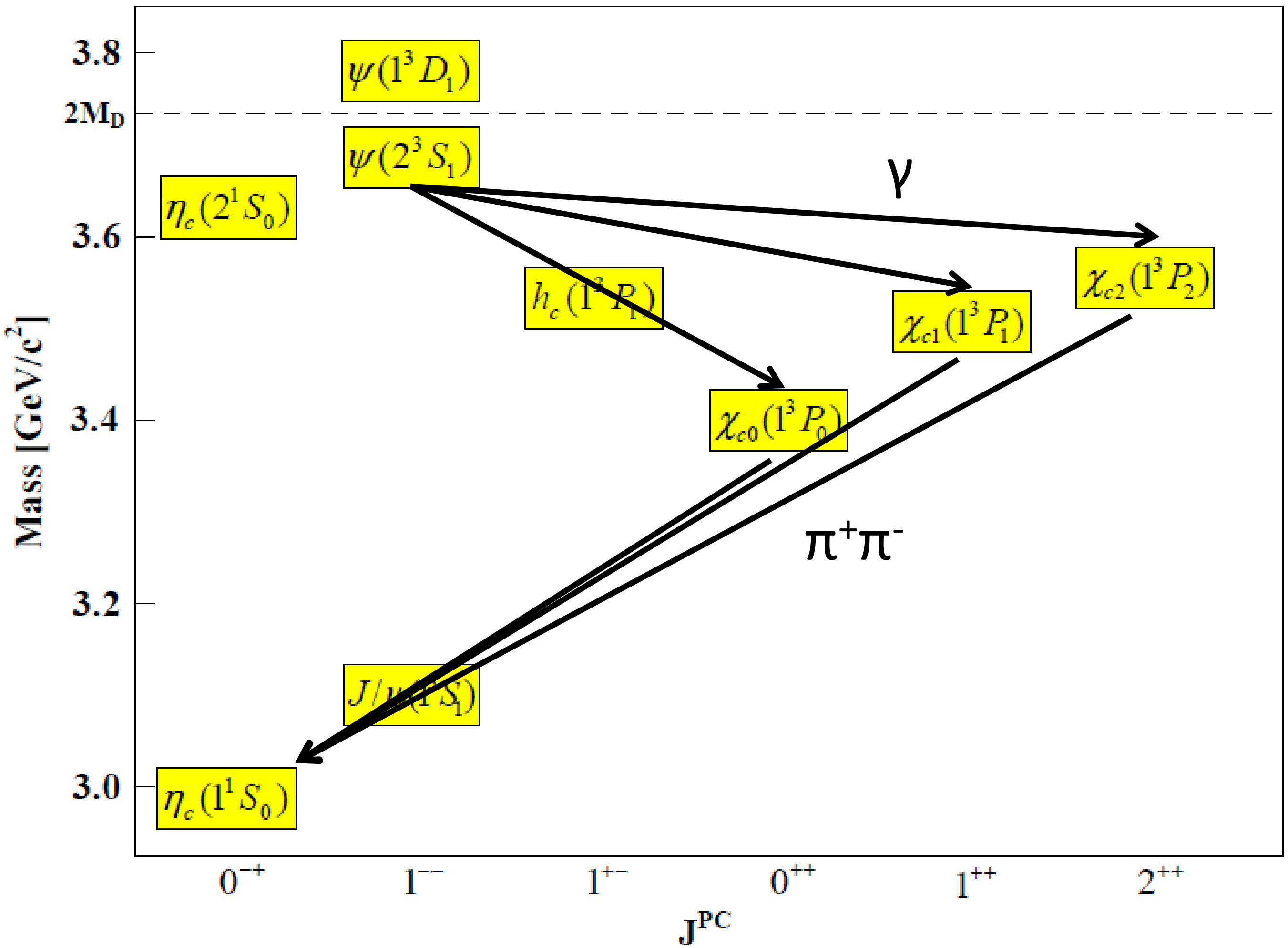
$R = (3.88\pm0.23\pm0.05)\%$

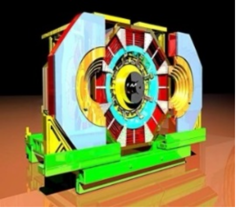
- The most precise measurement so far!
- The axial anomaly does not adequately explain the observed isospin violation, charmed meson loops would be a possible mechanism



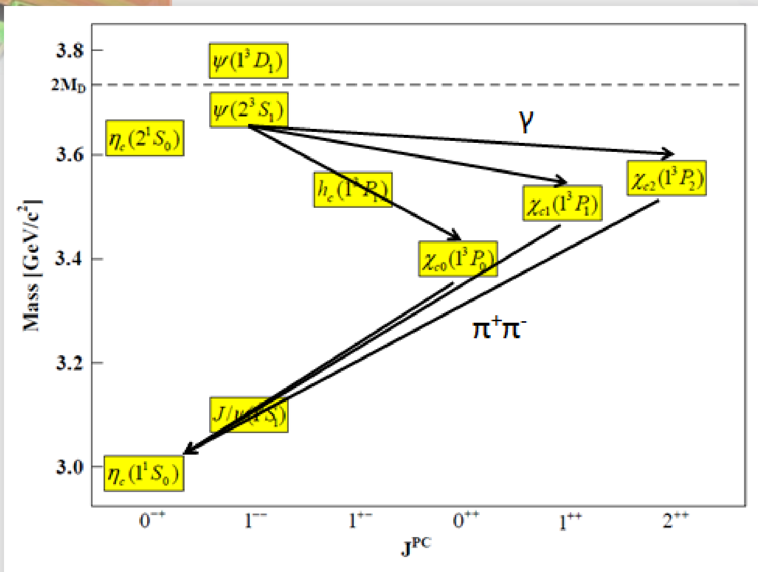
Hadronic transitions of P-wave charmonia

ππ transitions of χ_{cJ}





Search for $\chi_{cJ} \to \eta_c \pi^+ \pi^-$



- Hadronic transitions of ^3P_J states are seldom explored
- BABAR reported an upper limit

  $\mathcal{B}(\chi_{c2} \to \eta_c \pi^+ \pi^-) < 2.2\%$ @90% C.L.

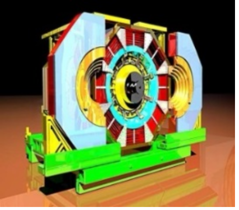
  PRD 86, 092005 (2012)

- The process $\chi_{c1} \to \eta_c \pi\pi$, dominated by an E1-M1 transition, calculated in the multipole expansion formalism

  $\mathcal{B}(\chi_{c1} \to \eta_c \pi\pi) = (2.72 \pm 0.39)\%$

  PRD 75, 054019 (2007)

- The process $\chi_{c0} \to \eta_c \pi^+ \pi^-$ is suppressed by spin-parity conservation

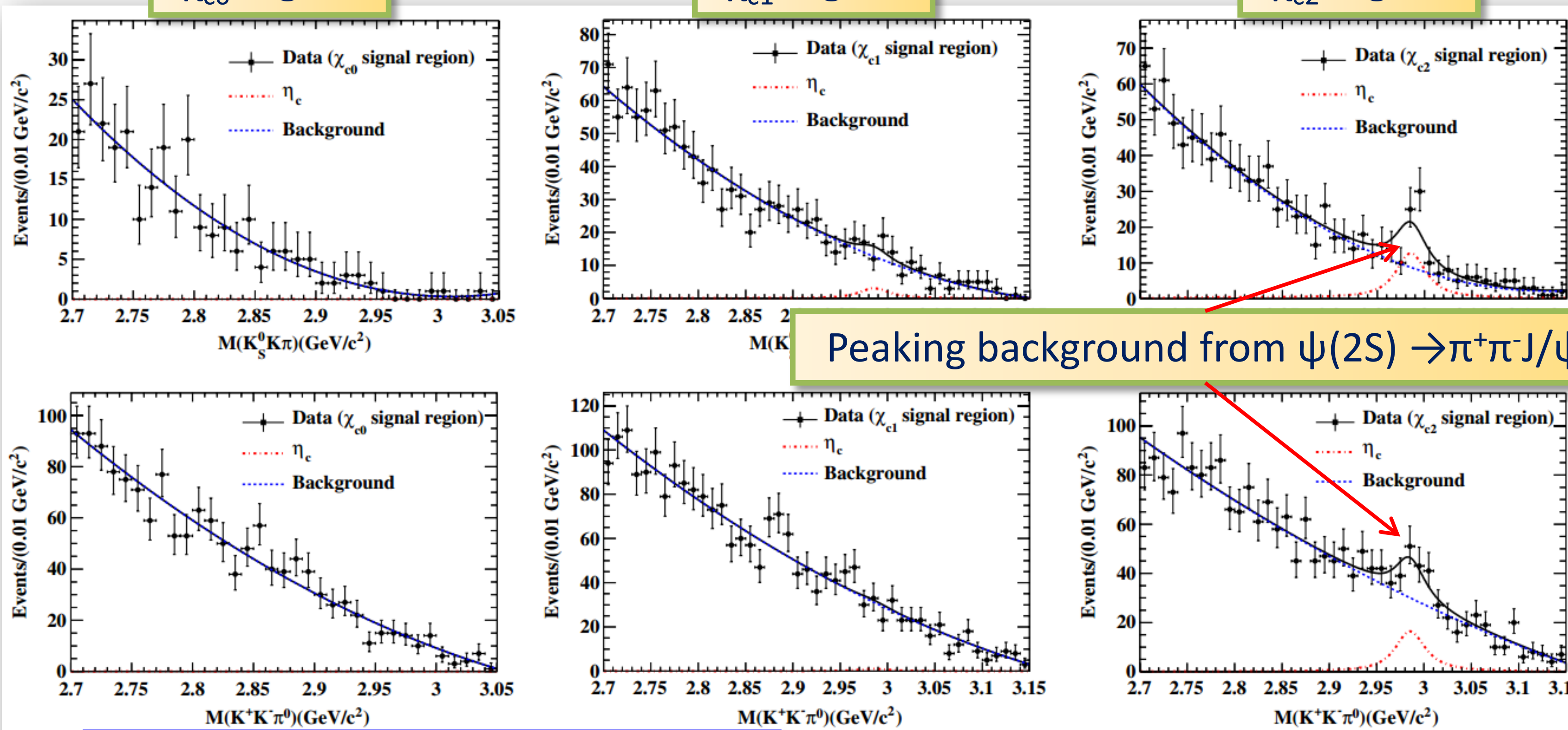


Search for $\chi_{cJ} \to \eta_c \pi^+ \pi^-$

χ_{c0} region

χ_{c1} region

χ_{c2} region



Peaking background from $\psi(2S) \to \pi^+\pi^- J/\psi$

$\mathcal{B}(\chi_{c0}(1P) \to \pi^+\pi^- \eta_c(1S)) < 0.07\%$

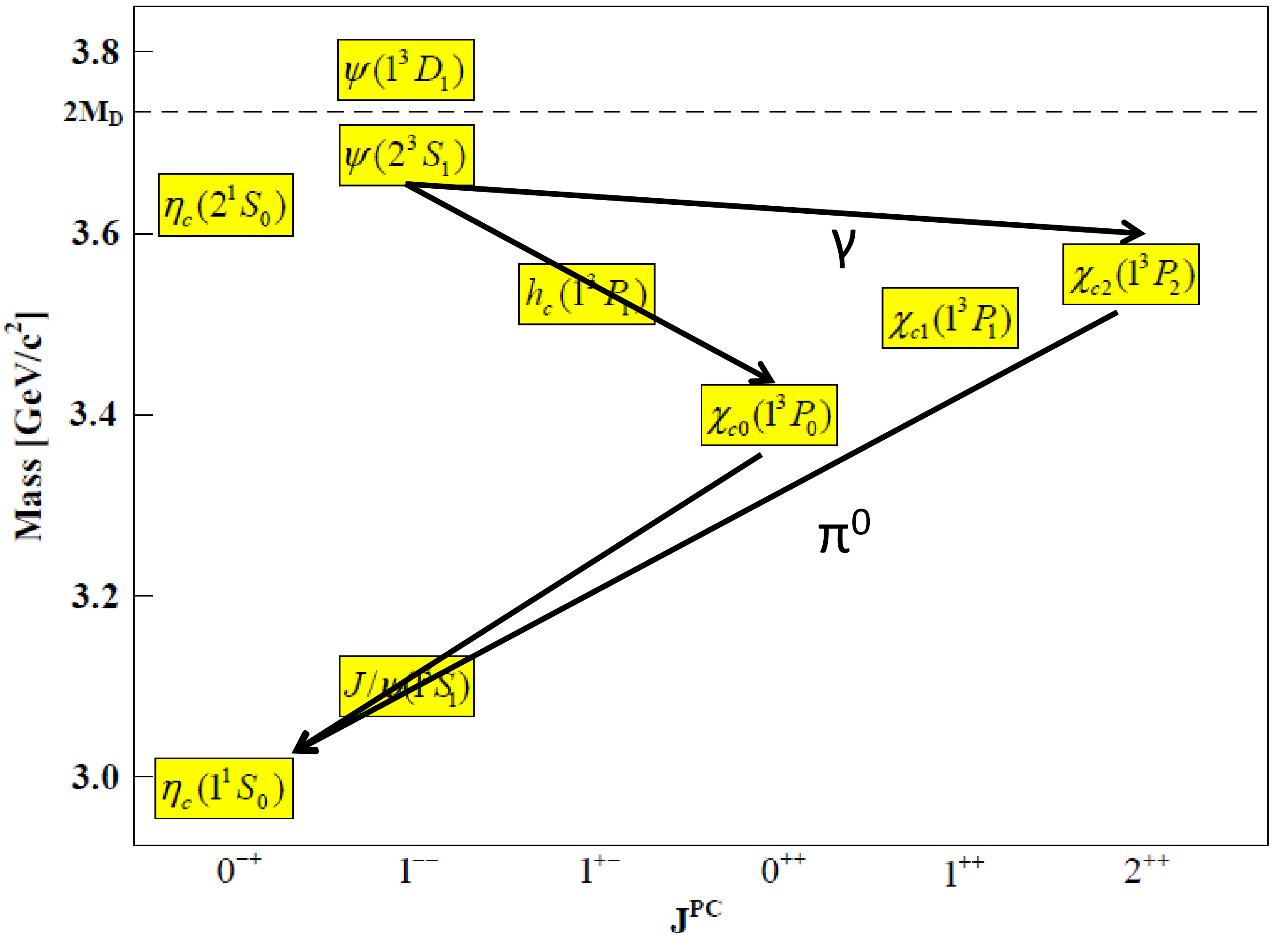
$\mathcal{B}(\chi_{c1}(1P) \to \pi^+\pi^- \eta_c(1S)) < 0.32\%$

$\mathcal{B}(\chi_{c2}(1P) \to \pi^+\pi^- \eta_c(1S)) < 0.54\%$

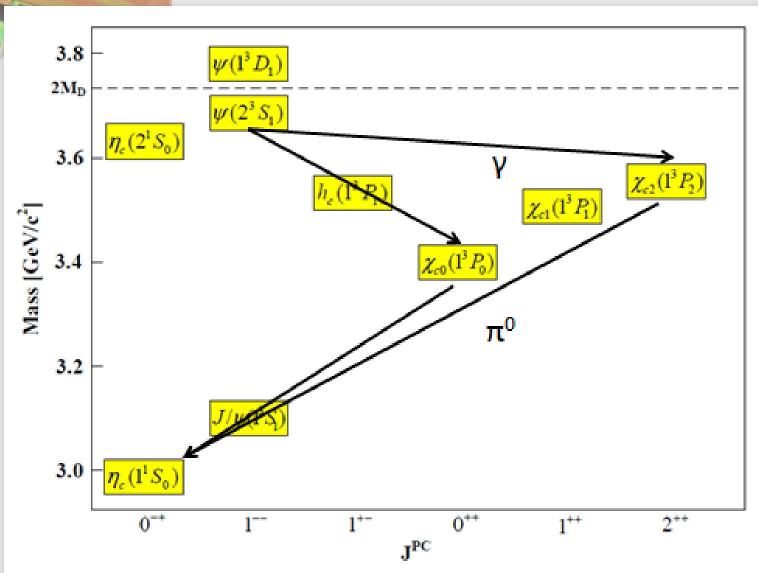
PRD 87, 012002 (2013)

- Using the process $\psi(3686) \to \gamma \chi_{cJ}$, $\chi_{cJ} \to \eta_c \pi^+ \pi^-$, $\eta_c \to K\bar{K}\pi$
- Set stringent upper limit on the $\chi_{cJ} \to \eta_c \pi^+ \pi^-$ branching fraction

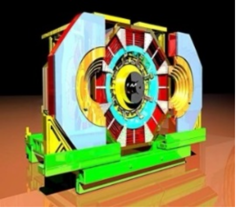
π^0 transitions of $\chi_{c0,c2}$



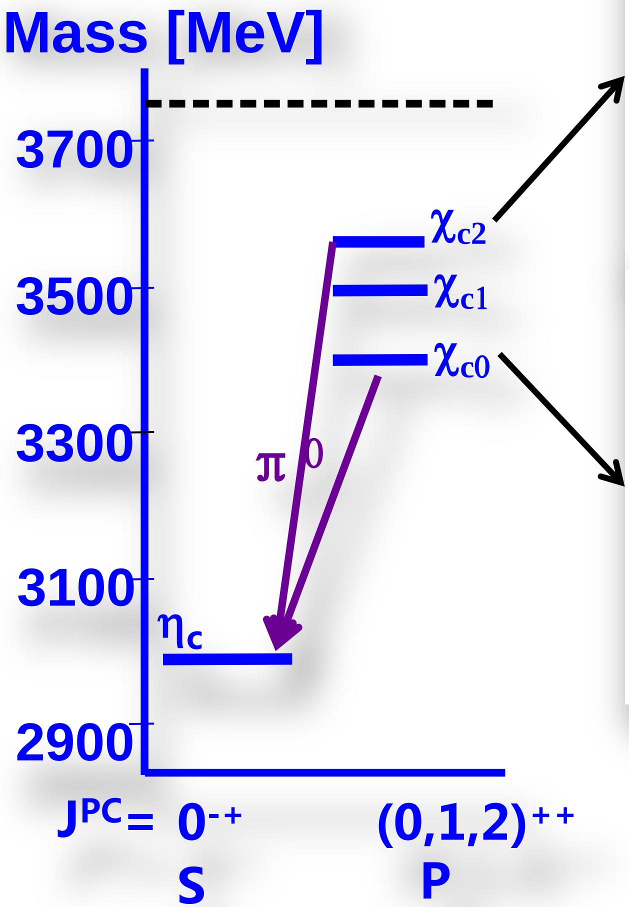
Search for $\chi_{c0,2} \to \pi^0 \eta_c$

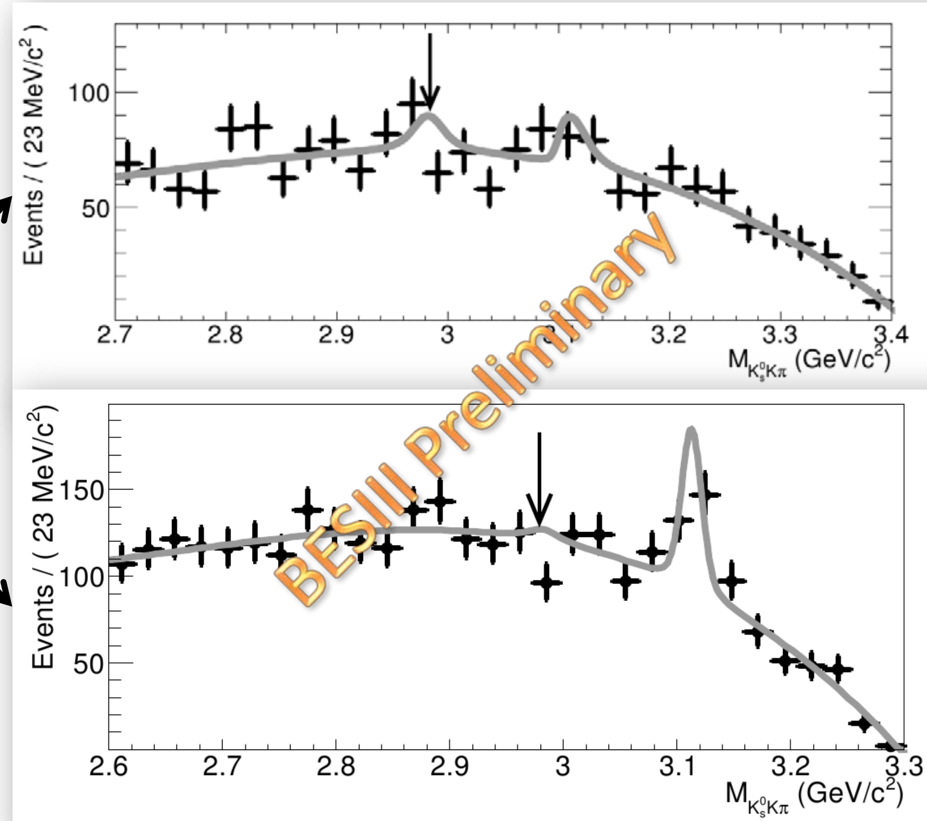


- Isospin-suppressed transition of the charmonium P-waves
- The process $\chi_{c1} \to \pi^0 \eta_c$ violates spin-parity conservation
- The dimensionless suppression factor for the loops in $\chi_{c0} \to \pi^0 \eta_c$ is 0.2, smaller than in the process $\psi(2S) \to \pi^0 J/\psi$ PRD 82, 034025 (2010)
- However, meson loops may give a significant contribution through the interference with the tree-level amplitute and cannot be neglected



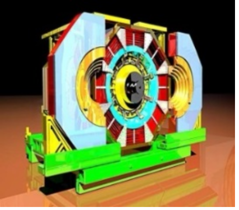
Search for $\chi_{c0,2}\rightarrow\pi^0\eta_c$



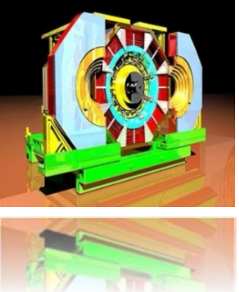


- Using the process $\psi(3686)\rightarrow\gamma\chi_{c0,2}$, $\chi_{c0,2}\rightarrow\pi^0\eta_c$, and the golden channel $\eta_c\rightarrow K^0{}_S K\pi$
- 90% C.L. upper limit on the branching fractions are set for the first time

$\mathcal{B}(\chi_{c0}\rightarrow\pi^0\eta_c) < 3.3\times10^{-3}$, $\mathcal{B}(\chi_{c2}\rightarrow\pi^0\eta_c) < 1.6\times10^{-3}$

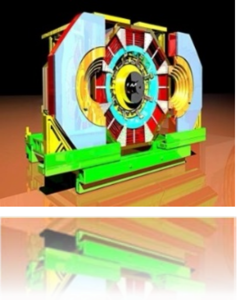


Other opportunities in BESIII



Other opportunities in BESIII

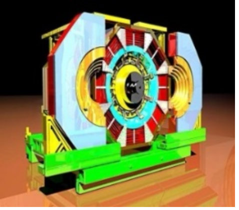
- $\psi(3770)\to\pi\pi J/\psi$, $\eta J/\psi$, $\pi^0 J/\psi$
  - ✓ BESII reported the first sighting of a $\psi(3770)$ non-DD decay $\mathcal{B}(\psi(3770)\to\pi^+\pi^- J/\psi) = (0.34\pm0.14\pm0.09)\%$ PLB 605, 63 (2005)
  - ✓ Confirmed by CLEO-c with $\mathcal{B}(\psi(3770)\to\pi^+\pi^- J/\psi) = (0.189\pm0.020\pm0.020)\%$ and $\mathcal{B}(\psi(3770)\to\pi^0\pi^0 J/\psi) = (80\pm25\pm16)\times10^{-5}$, $\mathcal{B}(\psi(3770)\to\eta J/\psi) = (87\pm33\pm22)\times10^{-5}$
  - ✓ We may improve the results using 2.9 fb^{-1} $\psi(3770)$ data of BESIII
- $h_c\to\pi\pi J/\psi$, $\pi^0 J/\psi$
  - ✓ $h_c\to\pi\pi J/\psi$: E760 found no evidence in $p\bar{p}$ annihilation PRL 69, 2337 (1992)
  - ✓ $h_c\to\pi^0 J/\psi$: G-violation, EM decays
- $\psi(3686)\to\pi^+\pi^-\pi^0\eta_c$
  - ✓ Expected to be produced at 1% level or larger PLB 628, 211 (2005)
  - ✓ $\mathcal{B}(\psi(3686)\to\pi^+\pi^-\pi^0\eta_c) < 1.0\times10^{-3}$ @ 90% C.L. by CLEO-c using 3M $\psi(3686)$ data PRD 75, 011102 (2007)
  - ✓ search for it using ~500M $\psi(3686)$ data



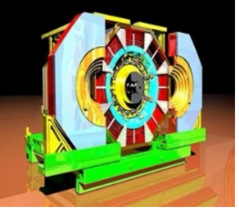
Summary

- Precise measurements are made on hadronic transitions of $\psi(3686)$ including $\pi^+\pi^- J/\psi$, $\eta J/\psi$ and $\pi^0 J/\psi$
  - ✓ Consistent with other experiments
  - ✓ The most precision in the world
- Searches for the hadronic transition of P-wave charmonia
  - ✓ $\chi_{cJ} \rightarrow \eta_c \pi^+ \pi^-$
  - ✓ $\chi_{c0,2} \rightarrow \eta_c \pi^0$
- More charmonium hadronic transition results with larger data set coming soon

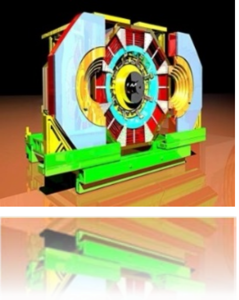
Thank you for your attention!



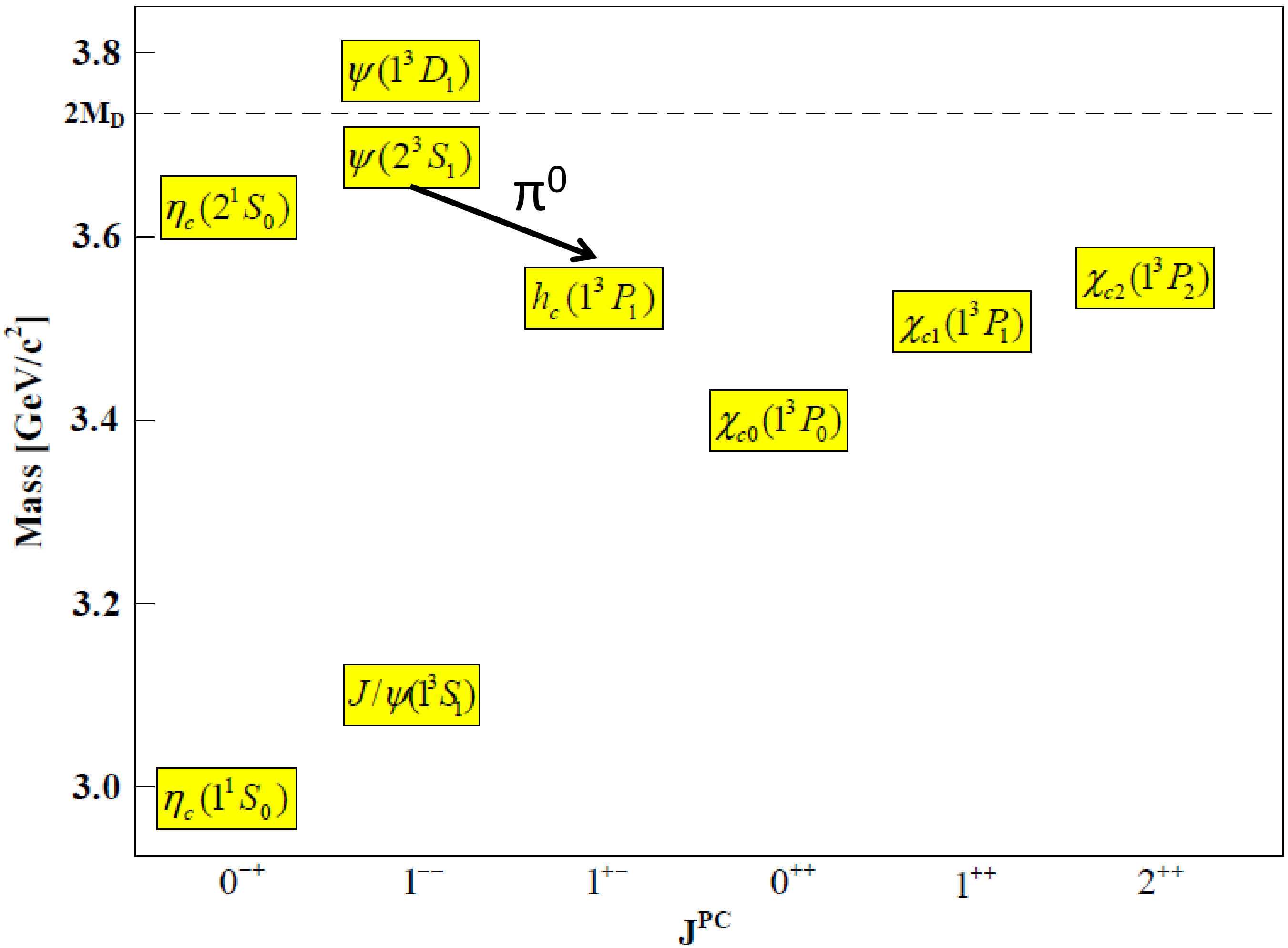
BACK UP

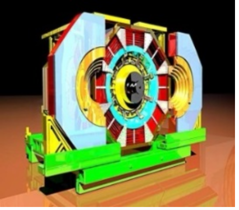


Studying the h_c state

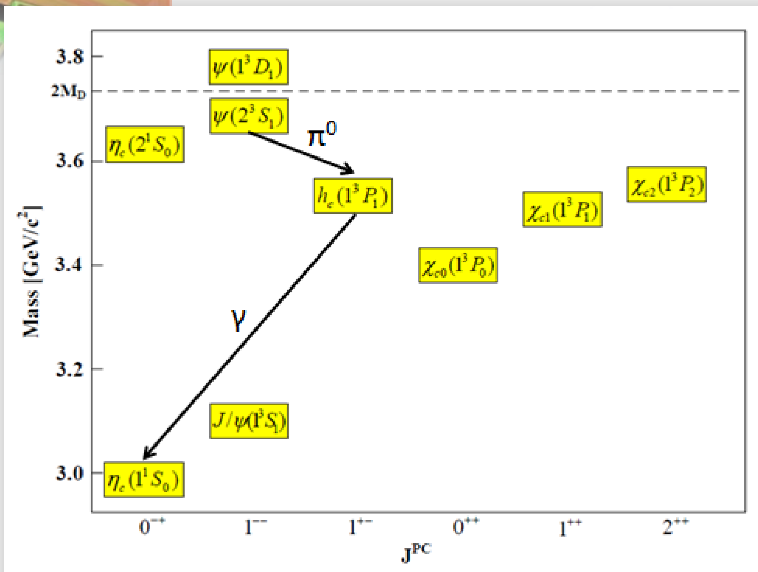


$\psi(2S) \to \pi^0 h_c$





$\psi(2S) \to \pi^0 h_c$



- Spin-singlet P-wave state h_c
- Potential model: if non-vanishing

P-wave spin-spin interaction,

$$\Delta m_{hf}(1P) = m(1\,^1P_1) - \langle m(1^3P_J) \rangle \neq 0$$

$$\text{with } \langle m(1^3P_J) \rangle = \frac{1}{9}\left(m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2})\right)$$

Hyperfine splitting

<u>"inclusive"</u> (published in 2011)

only detect the **π^0**

Rate $\propto \mathcal{B}(\psi(2S) \to \pi^0 h_c)$

<u>"E1 tagged"</u> (published in 2011)

detect the **π^0** & **γ**

Rate $\propto \mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c)$

<u>"exclusive"</u> (published in 2012)

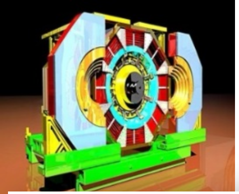
detect the **π^0**, **γ** & **$h_c \to X_i$** decay

Rate $\propto \mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma \eta_c) \times \mathcal{B}(h_c \to X_i)$

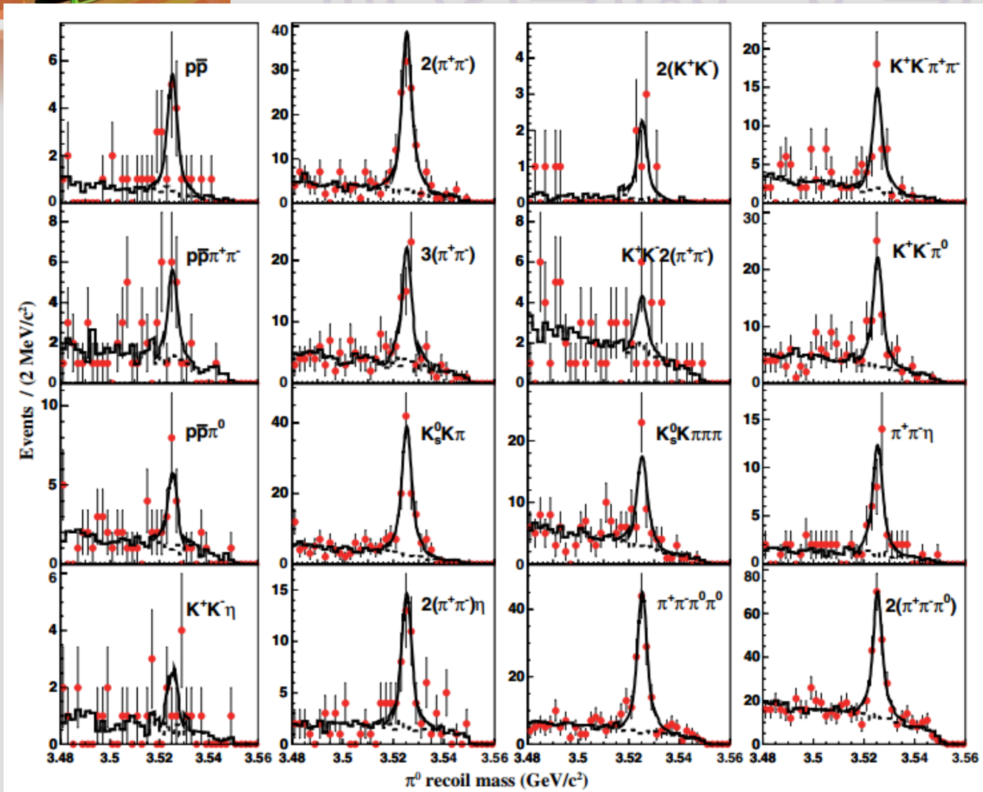
PRD 65, 094024 (2002)

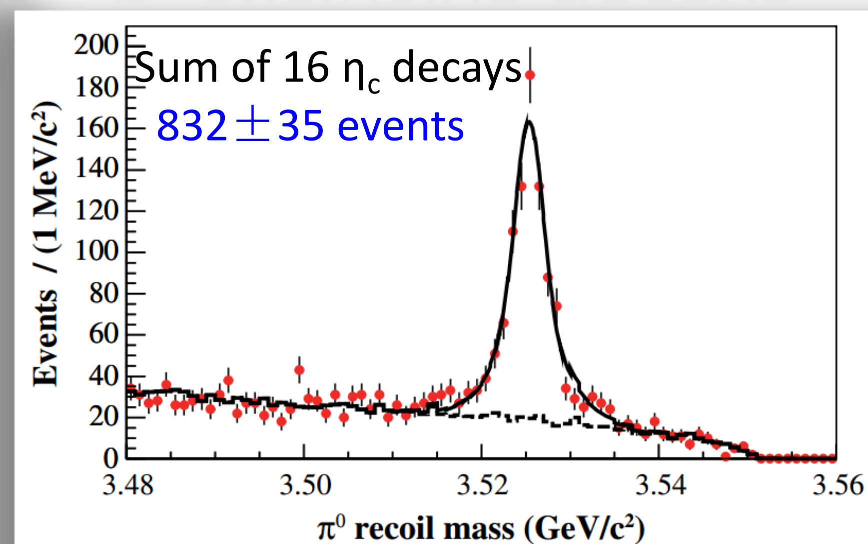
PRL 104, 132002 (2010)

- First observation by CLEO-c in cascade process $e^+e^- \to \psi(3686) \to \pi^0 h_c$, $h_c \to \gamma \eta_c$
  $\Delta M_{hf}(1P) = \mathbf{0.08 \pm 0.18 \pm 0.12}$ MeV/c^2
- Theoretical prediction: $\mathcal{B}(\psi(2S) \to \pi^0 h_c) = (0.4\text{-}1.3) \times 10^{-3}$
- Previous BESIII measurement: $\mathcal{B}(\psi(2S) \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-3}$



$\psi(2S)\to\pi^0 h_c$, $h_c\to\gamma\eta_c$, η_c exclusive decays





Simultaneous fit to π^0 recoiling mass:

Mass = **3525.31±0.11±0.14** MeV/c²

Width = **0.70±0.28±0.22** MeV

$\Delta M_{hf}(1P)$ = **-0.01±0.11±0.15** MeV/c²

BESIII: PRD 86, 092009 (2012)

Consistent with BESIII inclusive results:

Mass = **3525.40±0.13±0.18** MeV/c²

Width = **0.73±0.45±0.28** MeV

$\Delta M_{hf}(1P)$ = **-0.10±0.13±0.18** MeV/c²

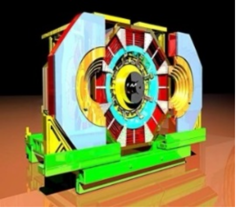
BESIII: PRL 104, 132002 (2010)

CLEO-c exclusive results:

Mass = **3525.21±0.27±0.14** MeV/c²

$\Delta M_{hf}(1P)$ = **0.08±0.18±0.12** MeV/c²

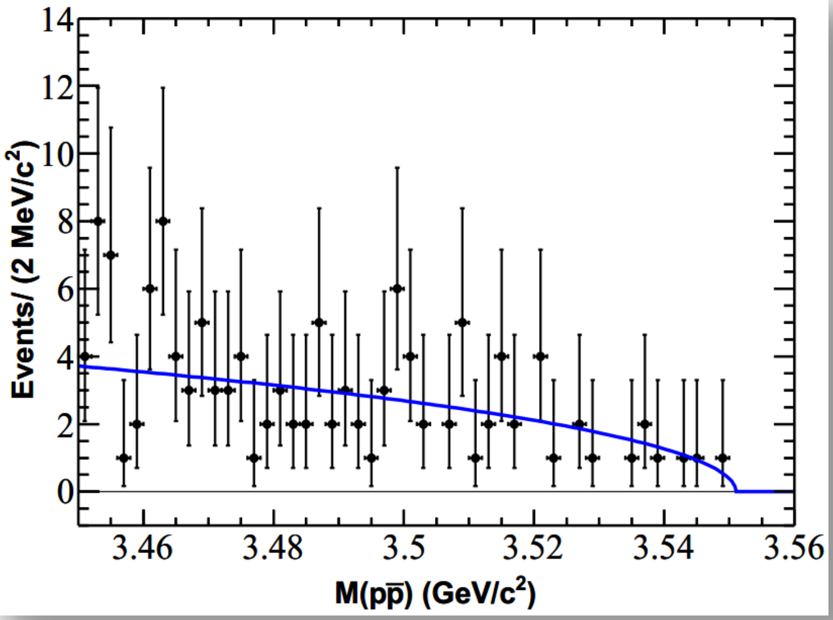
CLEO-c: PRL 101, 182003 (2008)



Search for $\psi(2S)\to\pi^0 h_c$, $h_c\to p\bar{p}$

PRD 88, 112001 (2013)

- No clear signal for $\psi(2S)\to\pi^0 h_c$, $h_c\to p\bar{p}$ is observed. UL on BF is set at 90% C.L.



Branching fraction

$BF(\psi(2S)\to\pi^0 h_c\to\pi^0 p\bar{p}) < 1.3\times10^{-7}$

Using BESIII measurement:

$BF(\psi(2S)\to\pi^0 h_c) = (8.4\pm1.3\pm1.0)\%$

PRD 78, 012006 (2008)

$BF(h_c\to p\bar{p}) < 1.7\times10^{-4}$

Theoretical predictions

$BF(h_c\to p\bar{p}) = (1.52\text{-}1.93)\times10^{-3}$ X.H. Liu and Q. Zhao, J. Phys. G 38, 035007 (2011)

$BF(h_c\to p\bar{p}) = (3.2\pm0.5)\times10^{-3}$ S. Barsuk, J. He, E. Kou and B. Viaud, PRD 86, 034011 (2012)