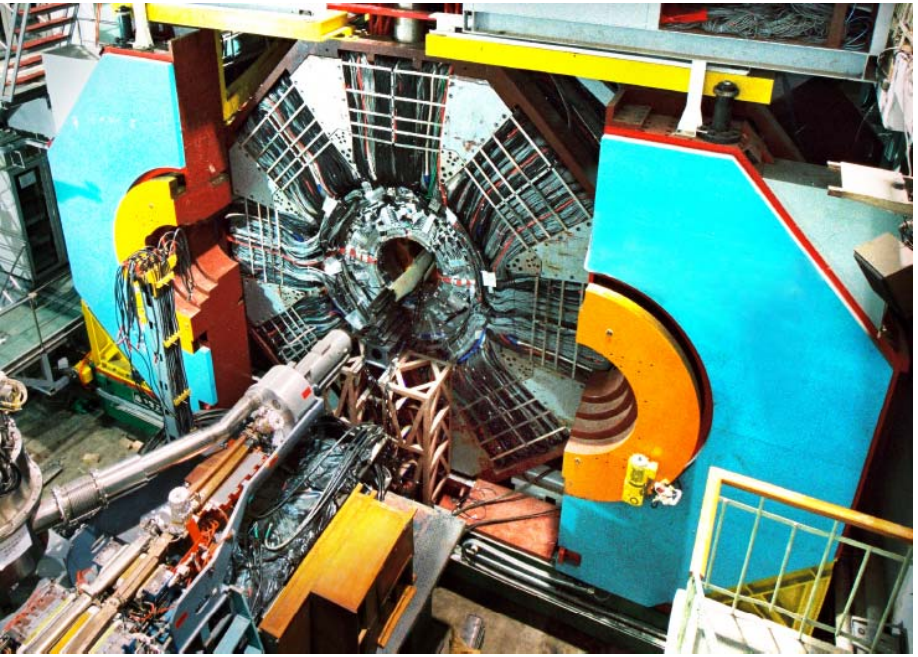
Recent Results on Hadron Spectroscopy from BESIII



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2010, May 31-June 4,

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Outline

- **Confirmation of $p\bar{p}$ mass threshold enhancement at BESIII**
- **Confirmation of X(1835) at BESIII**
- **Observation of h_c**
- **Summary**

What can we do @BESIII

IJMP A V24 No 1 (2009) supp

- **Light hadron spectroscopy**
  - **Full spectra: normal & exotic hadrons** **QCD**
  - **How quarks form a hadron?** **Non-pQCD**
- **Charm physics**
  - **CKM matrix elements** **SM & beyond**
  - **D $\bar{D}$ mixing & CPV** **SM & beyond**
- **Charmonium physics**
  - **Spectroscopy & transition** **pQCD & non-pQCD**
  - **New states above open charm thresholds** **exotic hadrons ?**
  - **pQCD: rhopi puzzle** **a probe to non-pQCD or ?**
- **Tau physics & QCD**
  - **Precision measurement of the tau mass & R value**
- **Search for rare & forbidden decays**

Why can we do @BESIII

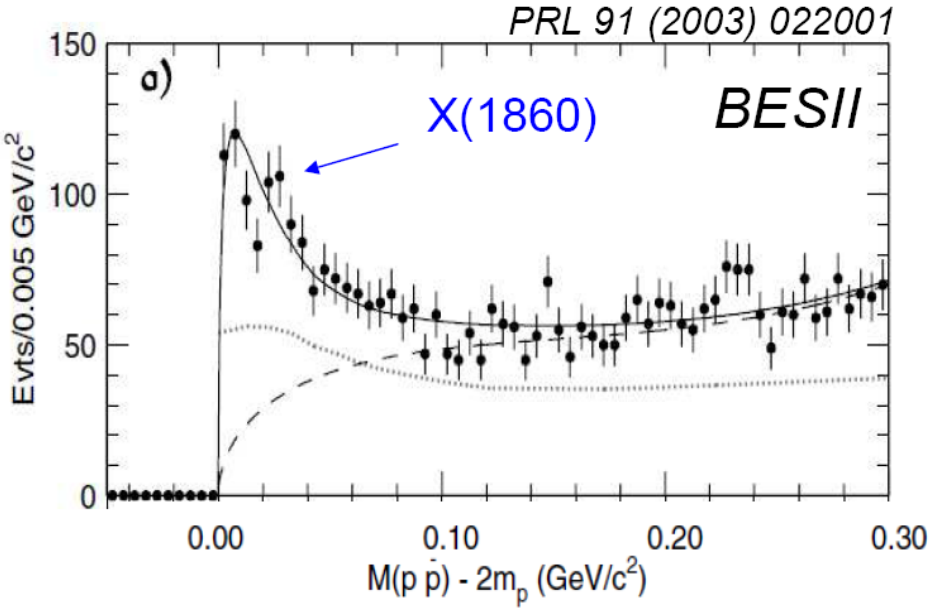
- **Gluon rich**
- **Kinematics favorable**
- **Clean environment, no combinatoric background**
- **Important J^{PC} filter, and isospin filter**

- **High statistics: high luminosity machine**
- **Small systematic error: high quality detector.**

a good platform to study precision charm physics & search for new physics.

Confirmation of $p\bar{p}$ mass threshold enhancement at BESIII

Observation of $p\bar{p}$ threshold enhancement in $J/\psi \to \gamma p\bar{p}$ @ BESII



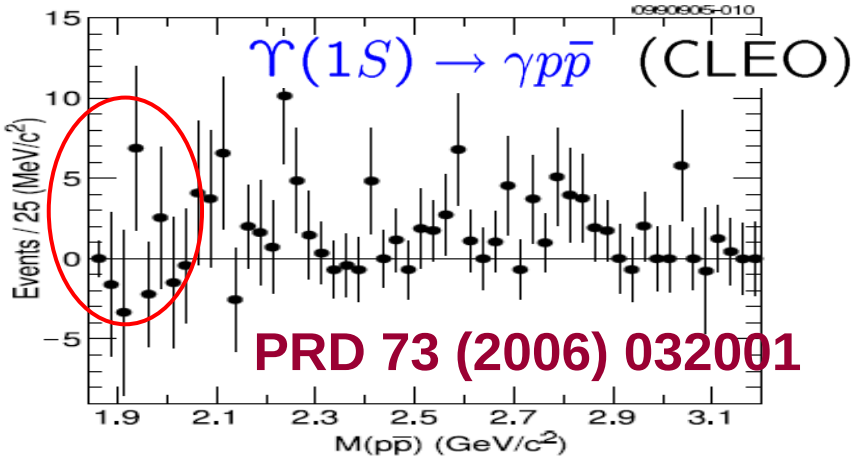
$M = 1859^{+3}_{-10}{}^{+5}_{-25}$ MeV/c²

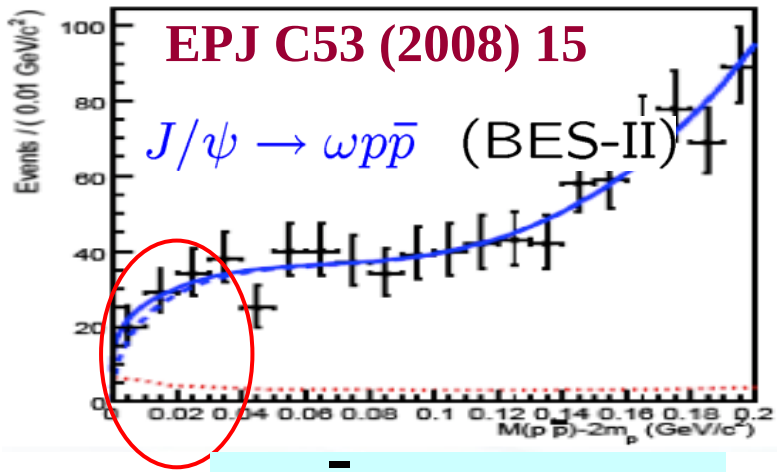
$\Gamma < 30$ MeV/c² (90% CL)

theoretical speculation:

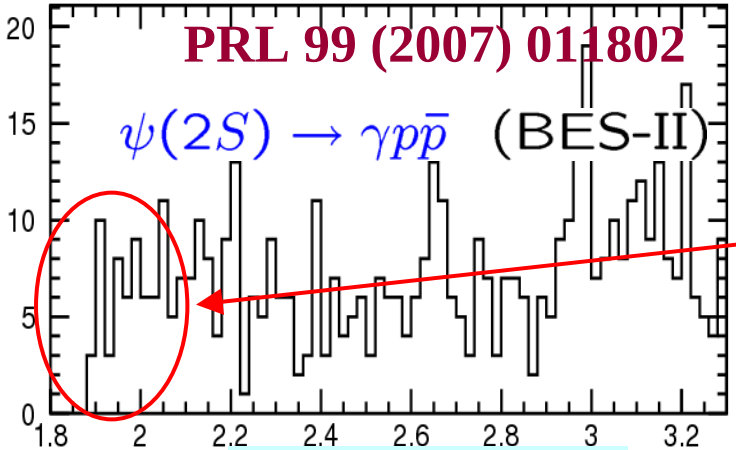
- $p\bar{p}$ bound state (baryonium)
- FSI effects
- ……

Non-observation of X(1860) at $p\bar{p}$ mass threshold@ BESII





$M(p\bar{p})-2m_p$ (GeV/c²)



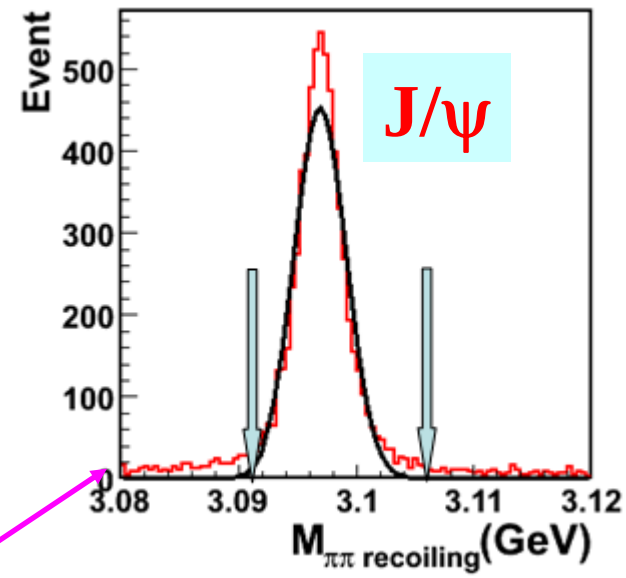
$M(p\bar{p})$ (GeV/c²)

No significant signal of X(1860) found
(only 2σ statistic significance)

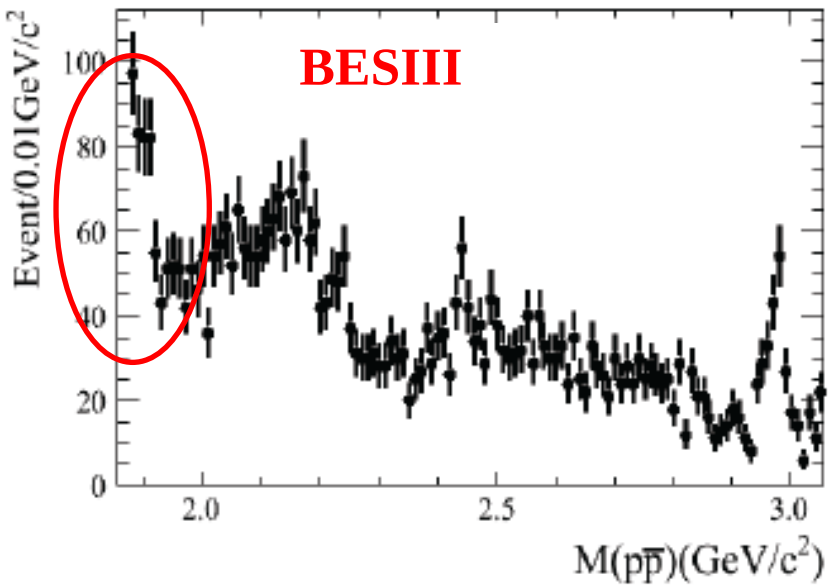
$p\bar{p}$ mass threshold enhancement in $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$ @BESIII

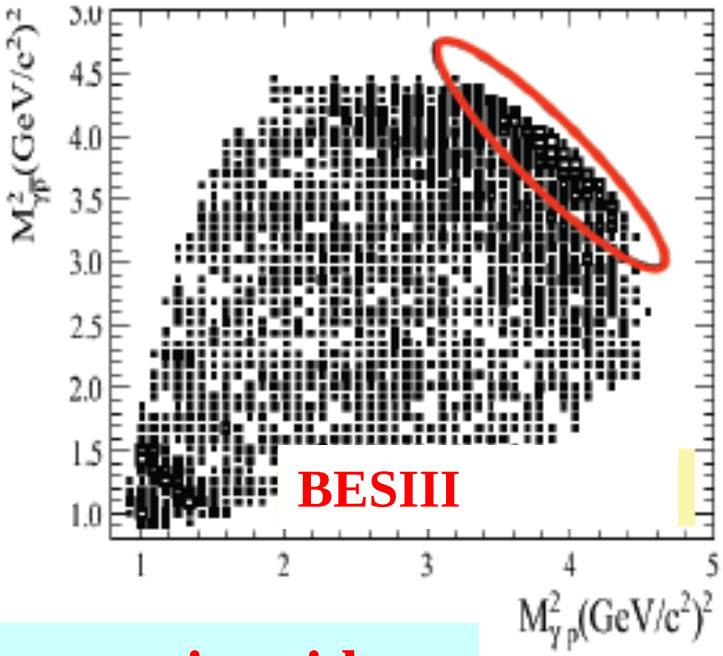
Event selection

- Initial Selection Criteria:
  - $N_{charged}=4$, $N_\gamma>=1$
  - Particle ID: $n_p = 1, n_{\bar{p}} = 1$
  - $\chi^2_{4C}(\gamma\pi^+\pi^- p\bar{p})<100$
- Final Selection Criteria:
  - Reconstruction of J/Ψ: $\left|M_{\pi\pi\_recoiling} - M_{J/\psi}\right| < 6MeV$
  - $\left|U_{miss}\right| < 0.04$
  - $P^2_{t\gamma} < 0.0005$
  - $M_{\pi^+\pi^- p\bar{p}} < M_{\psi'} - 15MeV$



$p\bar{p}$ mass spectrum and Dalitz plot



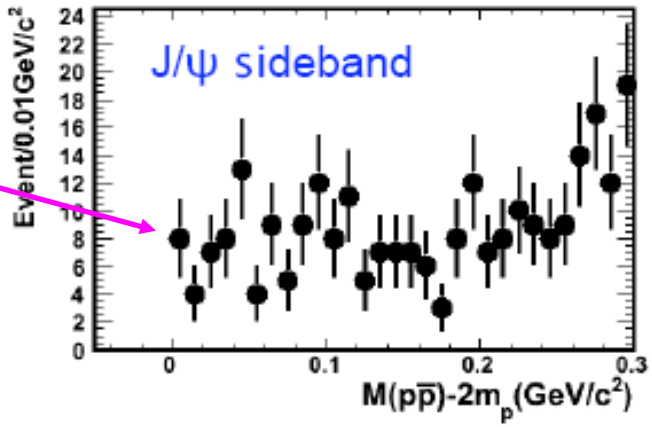


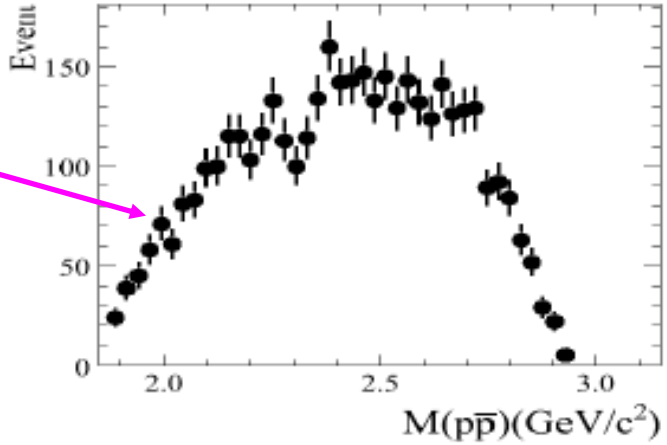
The mass threshold enhancement is evident in $p\bar{p}$ mass spectrum

Background study

- **J/ψ sideband estimation**
  - **~2%**
- **Inclusive MC sample**
  - $\psi(2S) \to \pi\pi J/\psi(J/\psi \to \pi^0 p\bar{p})$
- **Main background**

from $\psi(2S) \to \pi\pi J/\psi(J/\psi \to \pi^0 p\bar{p})$





No mass threshold enhancement observed from background

Mass spectrum fitting method

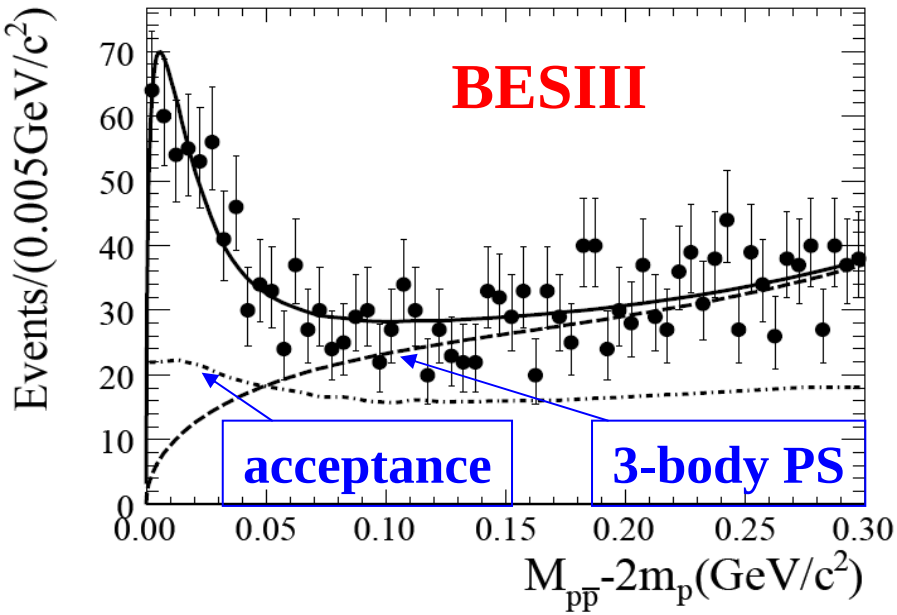
$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$

- Fit function:
  - signal: acceptance weighted S-wave BW function: $BW(M) \propto \frac{q^{(2l-1)}k^3}{(M^2 - M_0^2)^2 + M^2\Gamma^2}$
    - q : the proton momentum in cms of ppb
    - k : the photon momentum
    - ***l:*** the ppb orbital angular momentum
  - background shape: $f_{bkg}(\delta) = \delta^{1/2} + a_1\delta^{3/2} + a_2\delta^{5/2}$

a_1 and a_2 are obtain from uniform phase space MC sample

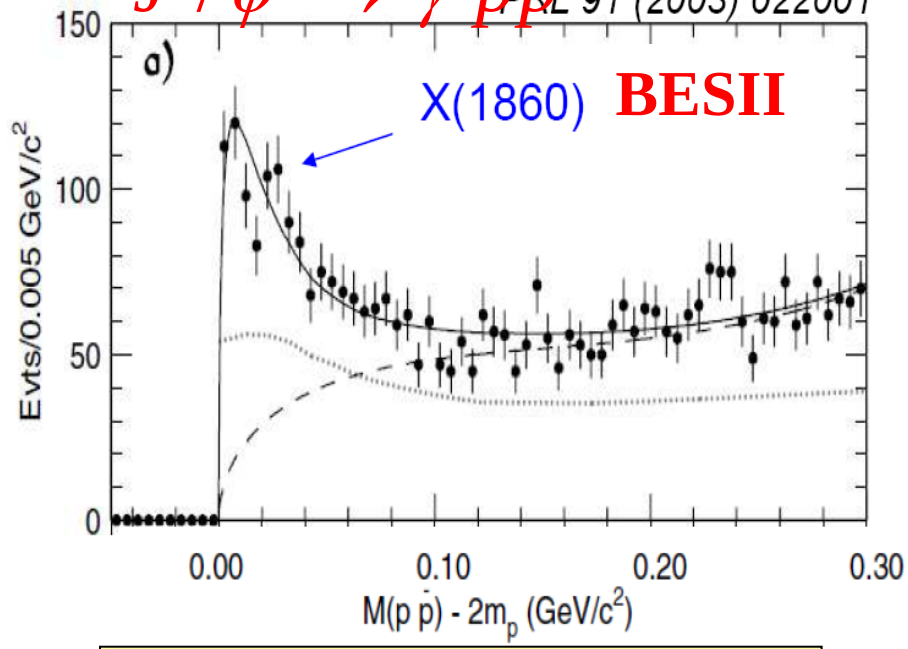
confirmation of $p\bar{p}$ mass threshold enhancement

$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$



$J/\psi \to \gamma p\bar{p}$

PRL 91 (2003) 022001



$M = 1865 \pm 5$ MeV/c²

$\Gamma < 33$ MeV/c² (90% CL)

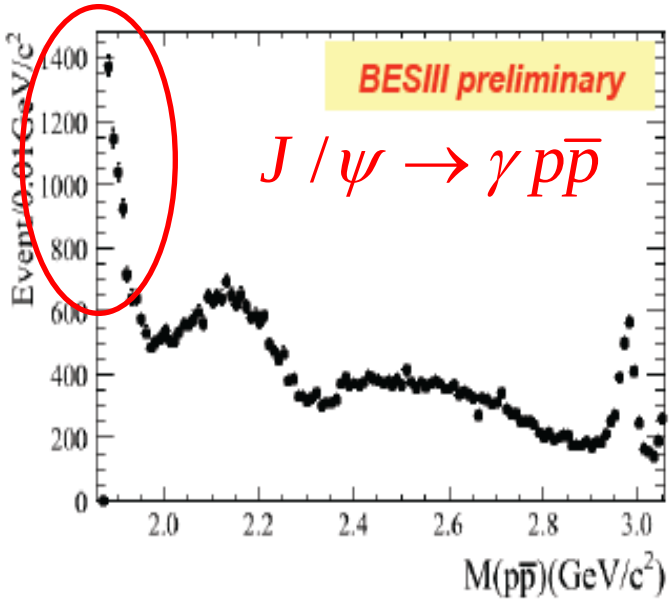
$M = 1859^{+3}_{-10}{}^{+5}_{-25}$ MeV/c²

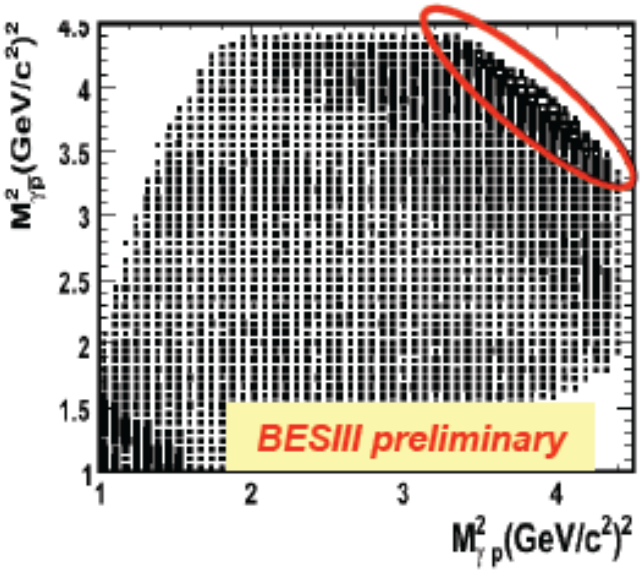
$\Gamma < 30$ MeV/c² (90% CL)

Published in Chinese Physics C 34(2010)421

Confirmed at BESIII, the mass and width are consistent with those from BESII.

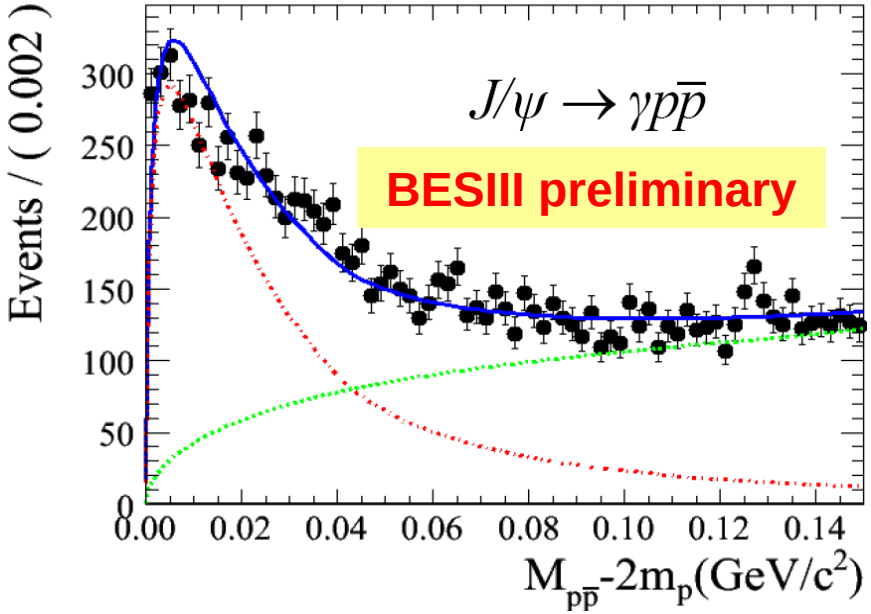
$p\bar{p}$ mass threshold enhancement in $J/\psi \to \gamma p\bar{p}$ @BESIII

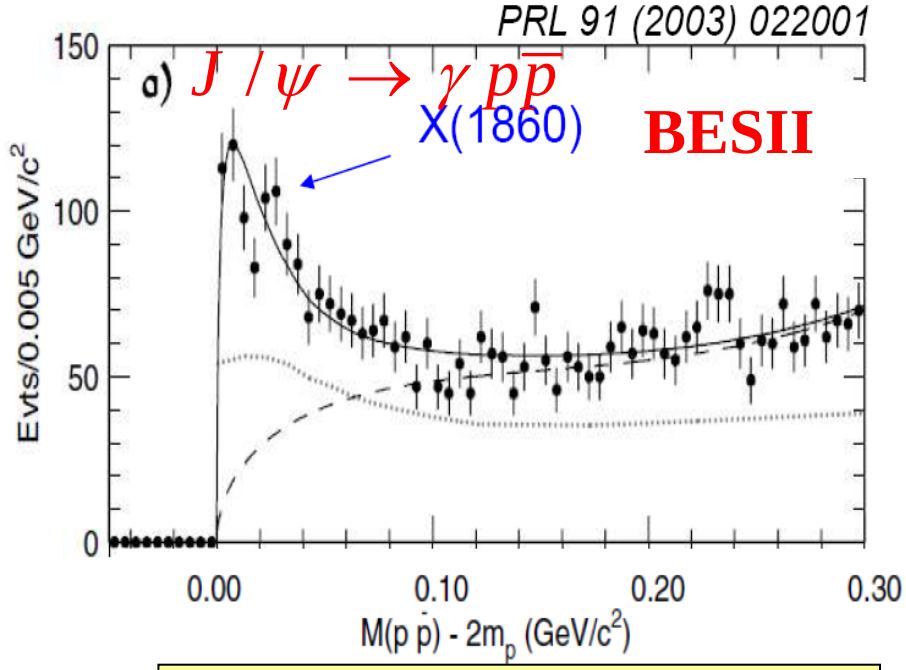




The $p\bar{p}$ mass threshold enhancement is evident in $p\bar{p}$ mass spectrum

Fitting $p\bar{p}$ mass threshold enhancement





$M = 1861.6 \pm 0.8$ MeV/c^2

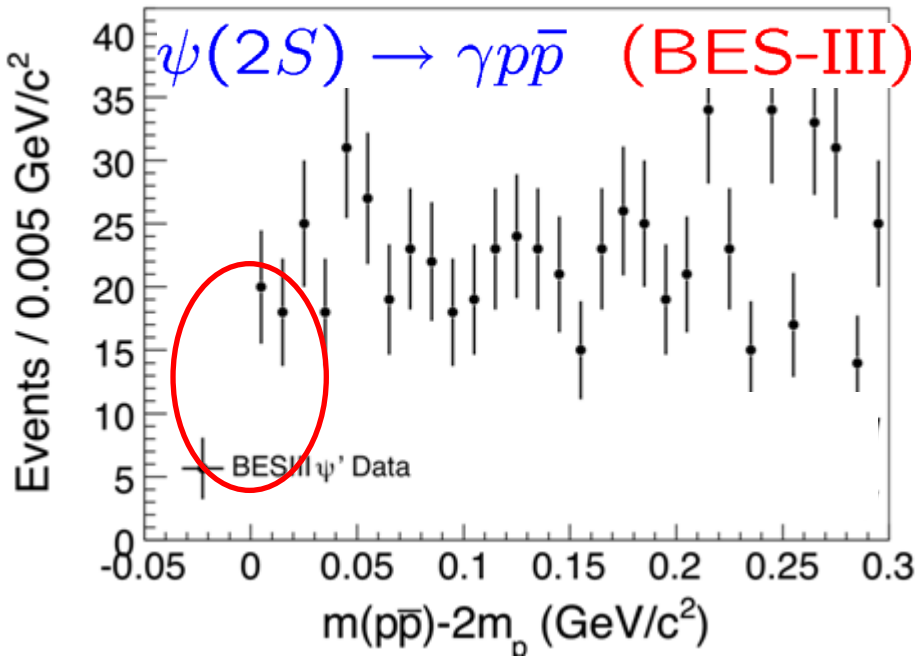
$\Gamma < 8$ MeV/c^2 (90% CL)

$M = 1859^{+3}_{-10}{}^{+5}_{-25}$ MeV/c^2

$\Gamma < 30$ MeV/c^2 (90% CL)

Consistent results at BESIII

Non-observation of mass enhancement in $\psi(2S)\to\gamma p\bar{p}$ @BESIII



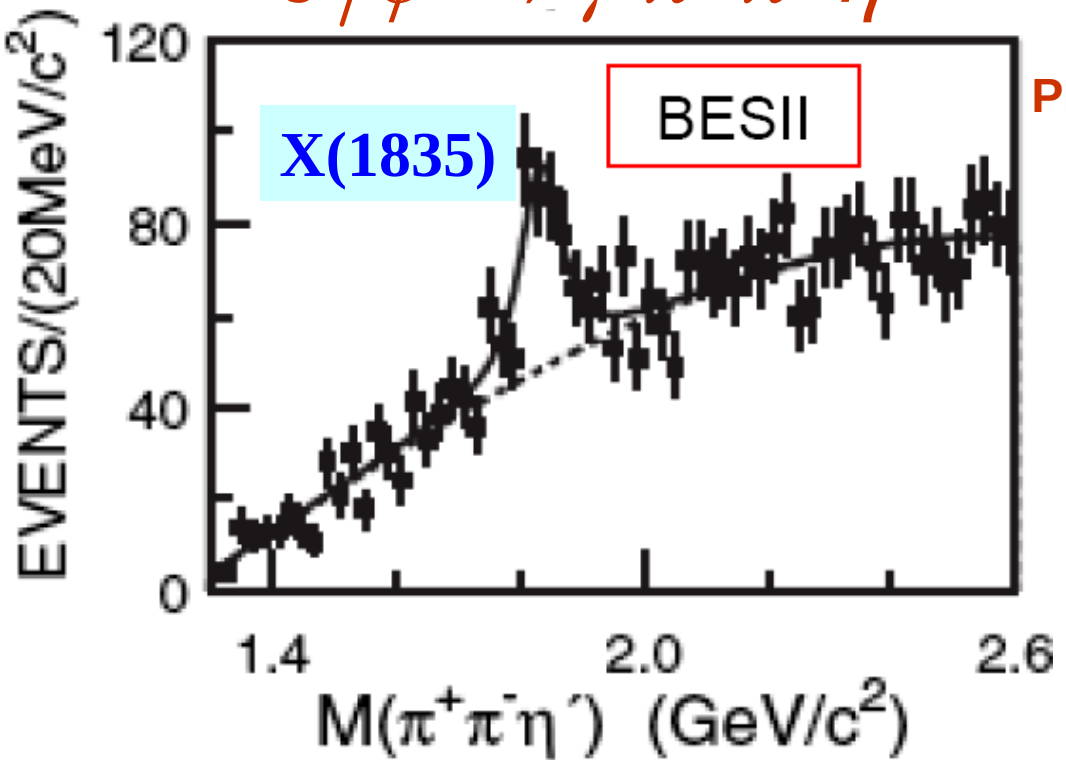
Confirmation of non-observation of enhancement in $\psi(2S)$ channel!

⇒pure FSI effect unlikely

Confirmation of X(1835) at BESIII

Observation of X(1835) @BESII

$$J/\psi \to \gamma \pi^+ \pi^- \eta'$$



PRL 95,262001(2005)

It's necessary to confirm X(1835) at BESIII with high statistic J/ψ data sample

X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \gamma\rho$) at BESIII

Event selection

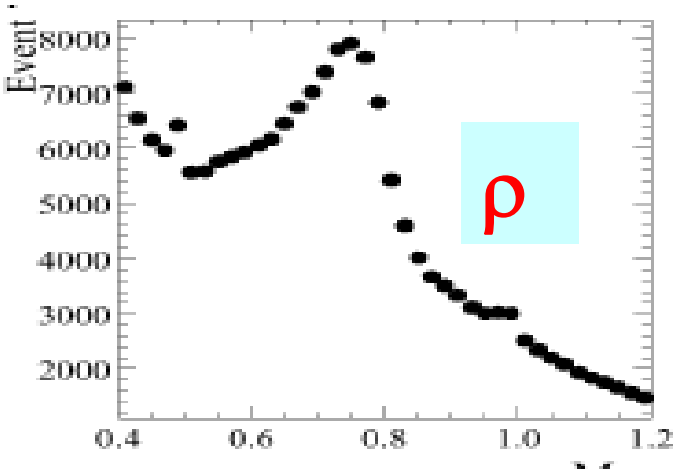
- Initial selection criteria:
  - $N_{charged}=4$, $N_\gamma >= 2$
  - $N_\pi > 2$
  - Kinematic fit(4C):
    $\chi^2_{4C}(\gamma\gamma\pi^+\pi^-\pi^+\pi^-) < 40$
    $\chi^2_{4C}(\gamma\gamma\pi^+\pi^-\pi^+\pi^-) < \chi^2_{4C}(\gamma\gamma K^+K^-\pi^+\pi^-)$
- Final selection criteria:
  - Reduce background from $\pi^0\pi^+\pi^-\pi^+\pi^-$:

$$\left|m_{\gamma\gamma} - m_\pi\right| < 0.04GeV$$

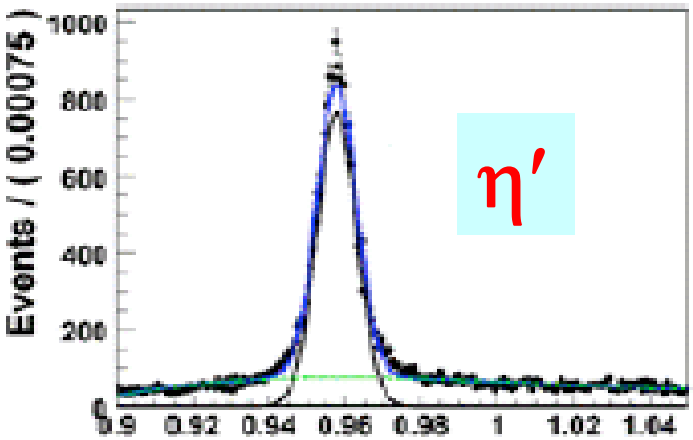
$$\left|m_{\gamma\gamma} - m_\eta\right| < 0.03GeV$$

$$0.72GeV < m_{\gamma\gamma} < 0.82GeV$$

X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \gamma\rho$) @BESIII



$M(\pi^+\pi^-)$

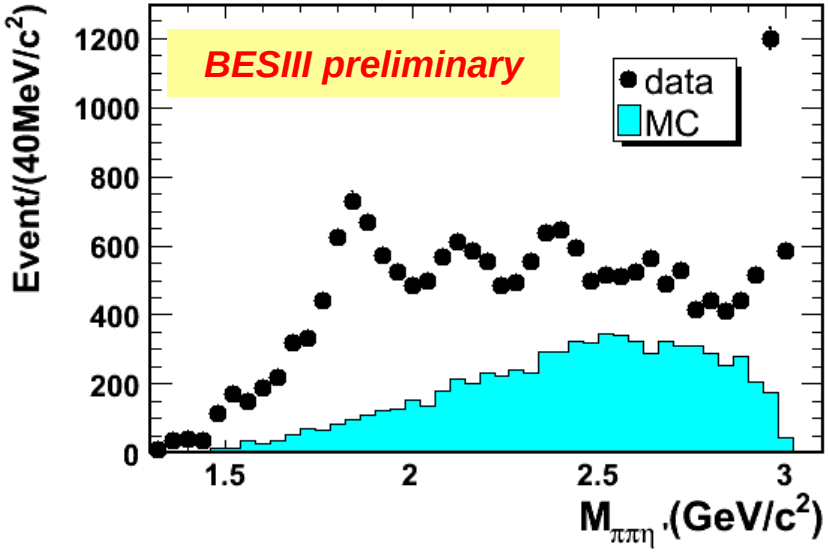


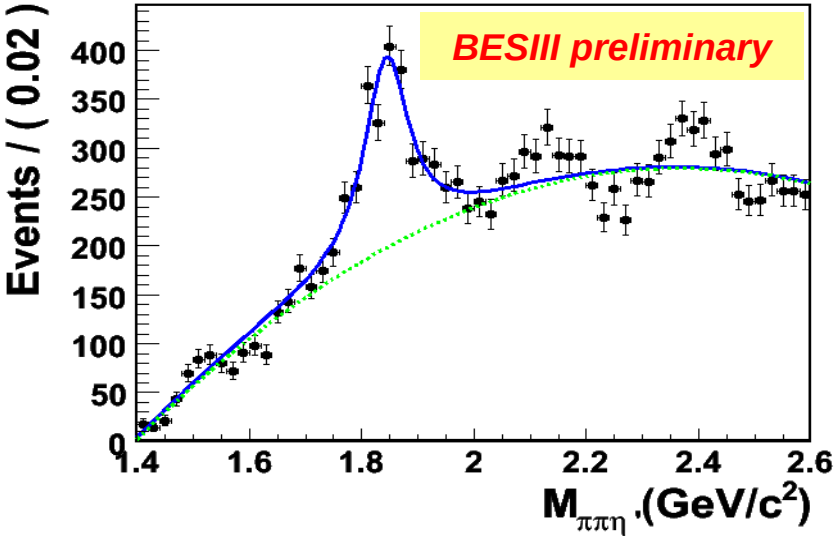
$M(\gamma\pi+\pi-)$

$|M(\pi^+\pi^-)-m_\rho|<0.2GeV$

$|M(\gamma\pi^+\pi^-)-m_{\eta'}|<0.018GeV$

Observation X(1835) in the mass spectrum of $\eta'\pi^+\pi^-$ ($\eta'\to\gamma\rho$)





- Significant peak at M~1835MeV
- Statistical significance of X(1835) is about **18 σ @BESIII**
  6 σ @BESII

X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \eta\pi^+\pi^-$) @BESIII

Event selection

- $N_{charged}=4$, $N_\gamma >= 3$
- $N_\pi > 2$
- Kinematic fit(4C,5C):

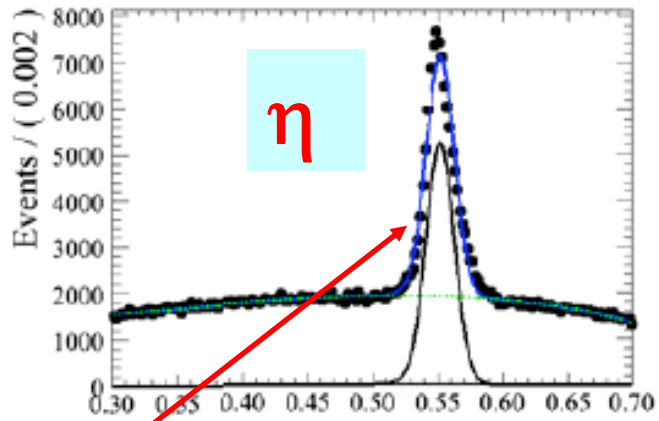
$$\chi^2_{4C}(\gamma\gamma\pi^+\pi^-\pi^+\pi^-) < 40$$

$$\chi^2_{5C}(\gamma\eta\pi^+\pi^-\pi^+\pi^-) < 40$$

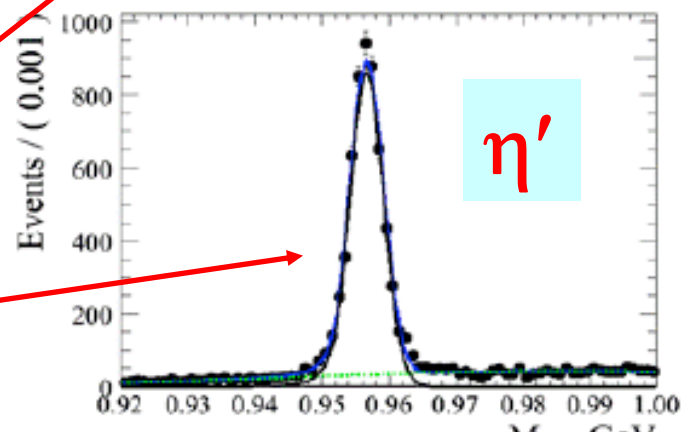
- selection for η and η' signal:

$$|M_{\gamma\gamma} - m_\eta| < 0.03\,\mathrm{GeV}$$

$$|M_{\pi\pi\eta} - m_{\eta'}| < 0.01\,\mathrm{GeV}$$

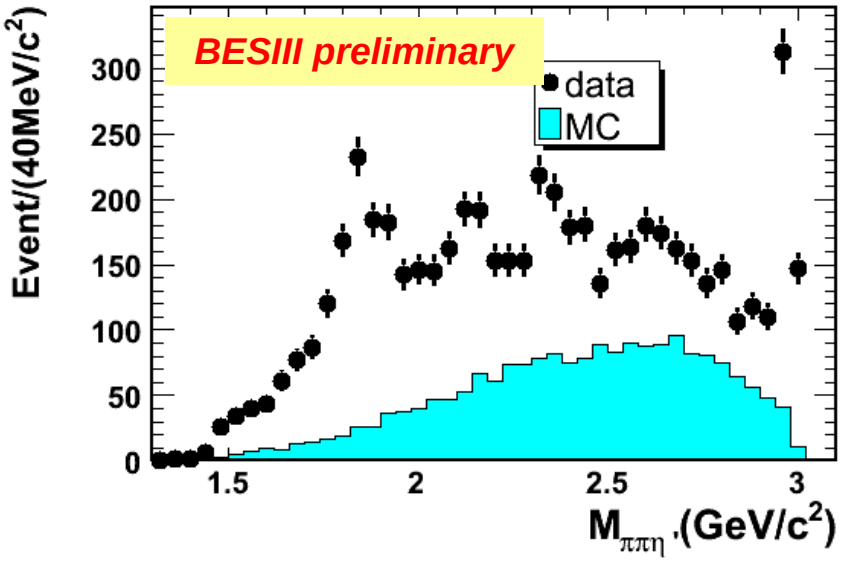


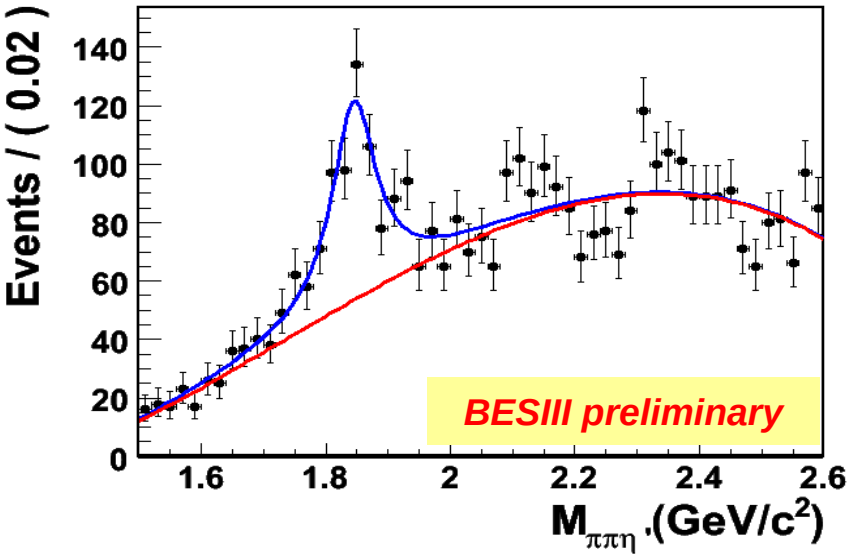
M(γγ)



M(ηπ+π-)

Observation of X(1835) in the mass sepctrum of $\eta'\pi^+\pi^-$ ($\eta' \to \eta\pi^+\pi^-$)





- **Significant peak at M~1835MeV**
- **Statistic significance of X(1835) is about 9 σ @BESIII**

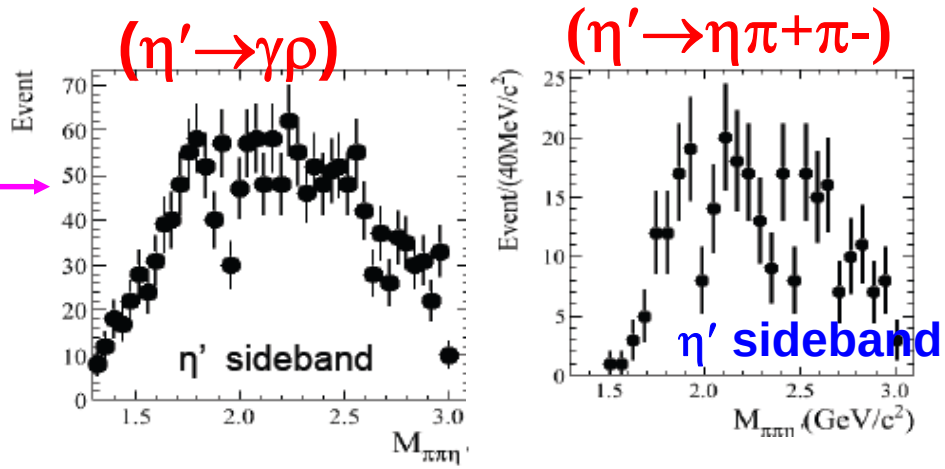
5.1 σ @BESII

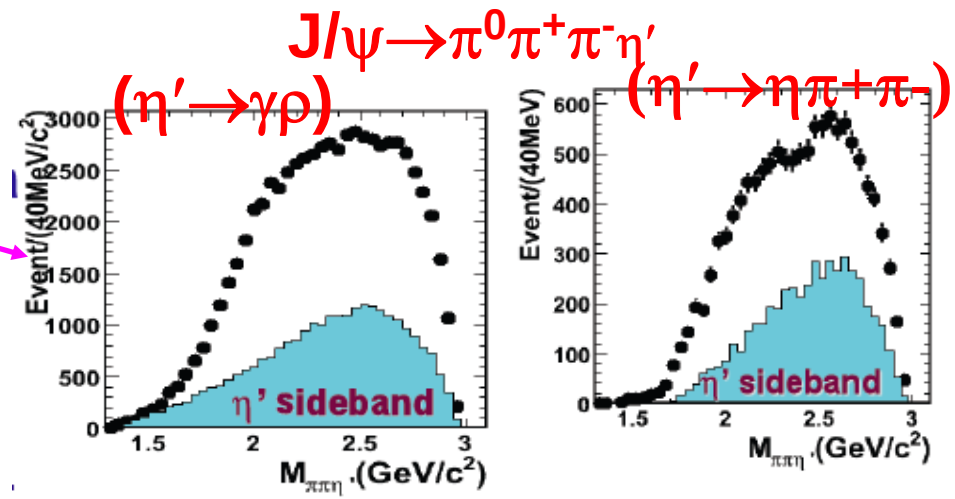
Background study for $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \gamma\rho$ & $\eta' \to \eta\pi^+\pi^-$)

- η' sideband:
  - No clear peak at M~1835MeV
- Inclusive sample
  - main background channel:

$$J/\psi \to \rho\pi\eta'$$

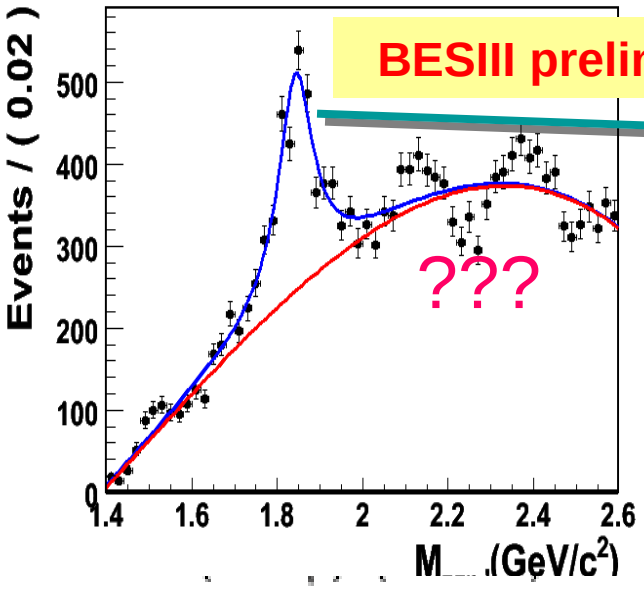
- Analysis of $J/\psi \to \pi^0\pi^+\pi^-\eta'$ in data





No peak at M~1835MeV

Combined mass spectrum of the two decay modes



Statistic significance ~21σ@BESIII

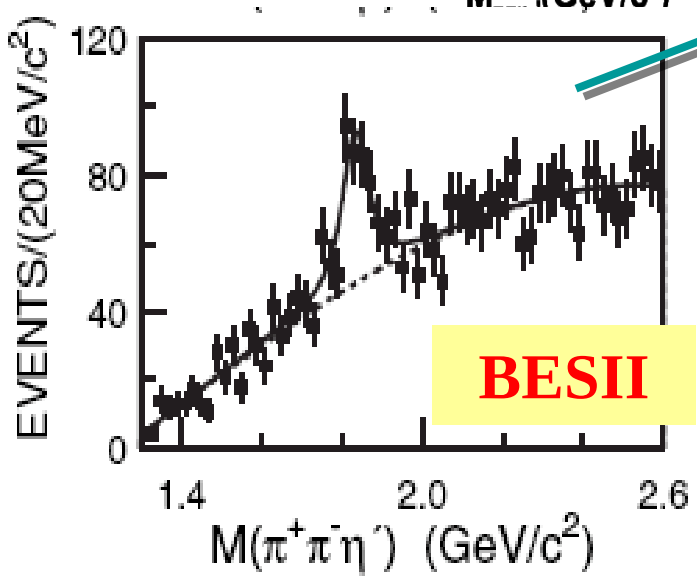
$$M = 1842.4 \pm 2.8(stat) MeV$$

$$\Gamma = 99.2 \pm 9.2(stat) MeV$$

Statistic significance 7.7 σ@BESII

$$M = 1833.7 \pm 6.1(stat) \pm 2.7(syst) MeV$$

$$\Gamma = 67.7 \pm 20.3(\mathrm{stat}) \pm 7.7(\mathrm{syst}) \mathrm{MeV}$$



- **X(1835) is confirmed in BESIII and the significance increases as statistics increases**
- **The possibility that there are two new resonances is under further study.**

Observation of h_c

$h_c(^1P_1)$ in charmonium family

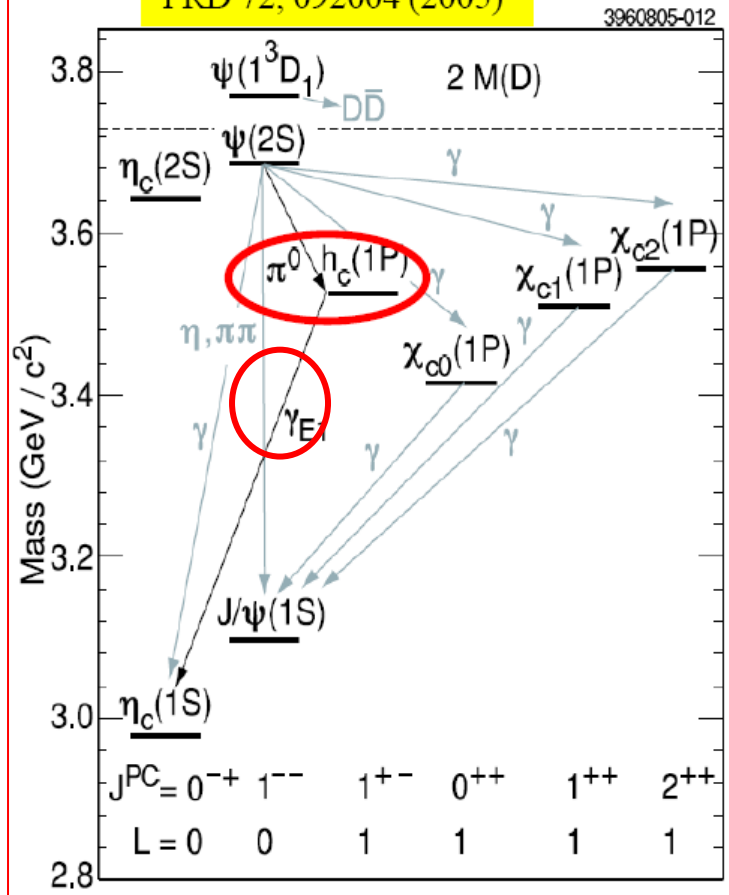
- **Although the charmonium family has been studies for many years, knowledge is limited on the $c\bar{c}$ P wave spin-singlet state $h_c(^1P_1)$.**
- **In 2008, h_c was observed by CLEOc**

✓ **In the charmonium decays, h_c can only be observed in the process of $\psi(2S) \rightarrow \pi^0 h_c$**

✓ **The main decay mode of h_c is the E1 transition $h_c \rightarrow \gamma \eta_c$.**

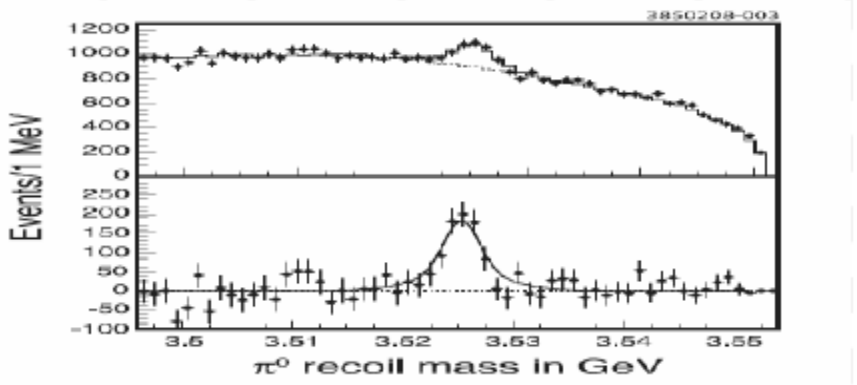
✓ **$M(h_c)$ is very close to $M(1^3P) \approx 3525$MeV**
$\Delta M_{hf} = M<1^1P_1> - M(1^3P) \sim 0.08 \pm 0.18 \pm 0.12$MeV
consistent to 1P hypefine splitting of 0

PRD 72, 092004 (2005)

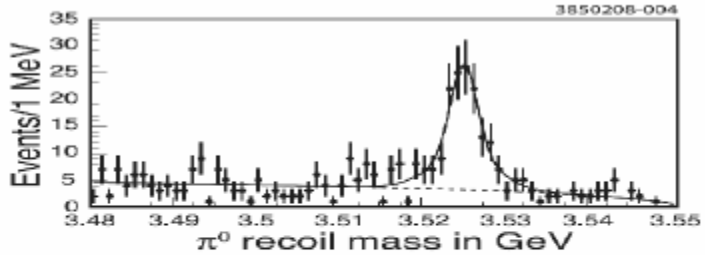


h_c @CLEOc

CLEOc's Result –$\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, E1-tagged



CLEOc's Result – $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ exlusive

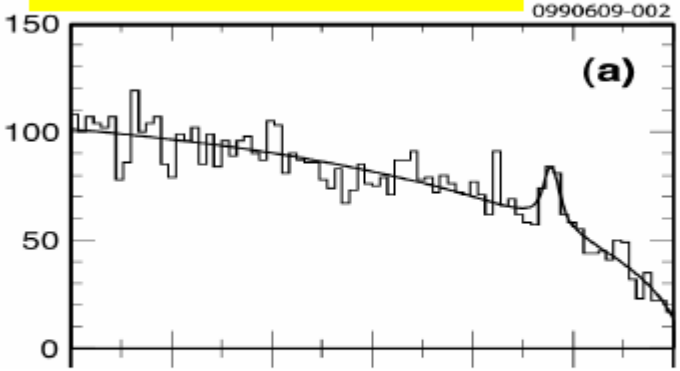


	Inclusive	Exclusive
Counts	1146 ± 118	136 ± 14
Significance	10.0σ	13.2σ
$M(h_c)$ (MeV)	$3525.35 \pm 0.23 \pm 0.15$	$3525.21 \pm 0.27 \pm 0.14$
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$	$4.22 \pm 0.44 \pm 0.52$	$4.15 \pm 0.48 \pm 0.77$

PRL101,182003(2008)

CLEOc's Result – $\psi' \to \pi^0 h_c$, $h_c \to 2(\pi^+\pi^-)\pi^0$

PRD80, 051106(2009).



Mode	efficiency (%)	Yield	$B_1 \times B_2 \times 10^5$
$\pi^+\pi^-\pi^0$	27.0	$1.6^{+6.7}_{-5.9}$	< 0.19
$2(\pi^+\pi^-)\pi^0$	18.8	92^{+23}_{-22}	$(1.88^{+0.48+0.47}_{-0.45-0.30})$
$3(\pi^+\pi^-)\pi^0$	11.5	35 ± 26	$(1.2 \pm 0.9 \pm 0.3)$ (< 2.5)

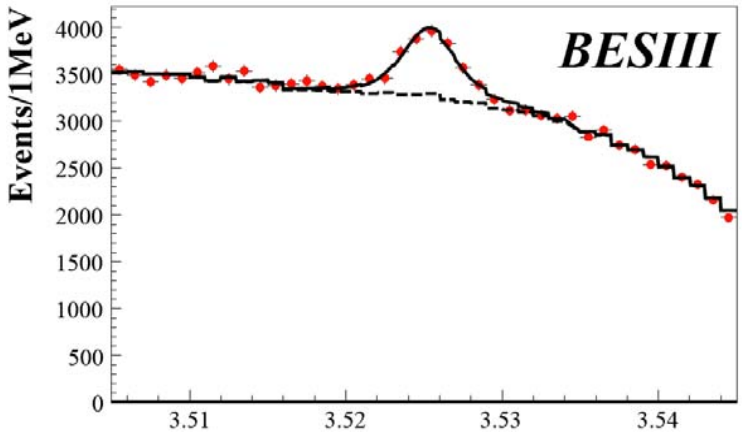
In previous experiments, the absolute branching ratios of $\psi' \to \pi^0 h_c$ and $h_c \to \gamma\, \eta_c$ have not been measured

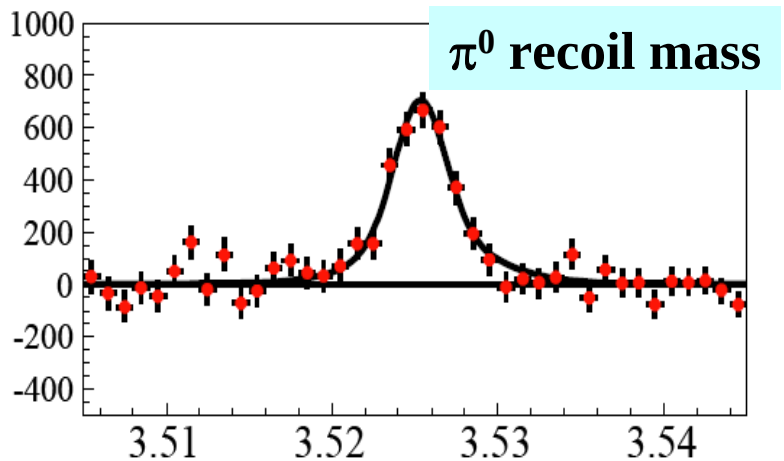
h_c in E1-tagged $\psi(2S)\to\pi^0 h_c$, $h_c\to\gamma\eta_c$ @BESIII

Event selection

- **Select inclusive π^0 ($\psi'\to\pi^0 h_c$)**
  - Photon polar angle: $|\cos\theta|<0.8$
  - Photon energy: $E_\gamma>40$MeV
  - Each photon belongs to only one π^0
  - $M_{\gamma\gamma}\in[0.12,0.145]$GeV/$c^2$
  - Do 1C fit for each π^0 candidate (no cut on χ^2)
- **Select E1-photon γ to tag $h_c\to\gamma\,\eta_c$**
  - 450MeV$<E_\gamma<$540MeV
  - Not belonging to π^0 (0.10-0.145GeV/c^2) and η(0.53-0.56GeV/c^2)
- **Background veto**
  - $\pi^+\pi^-J/\psi$: $|M^{rec}(\pi^+\pi^-)-3.097|>0.007$GeV/$c^2$
  - $\pi^0\pi^0J/\psi$: $|M^{rec}(\pi^0\pi^0)-3.097|>0.03$GeV/$c^2$

E1-tagged $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$





- **A fit of double-Gaussian ⊗ BW signal + E1-photon sideband background yield**

Significance=18.6σ

$N(h_c)$=3679±319

$M(h_c)$=3525.40±0.13MeV

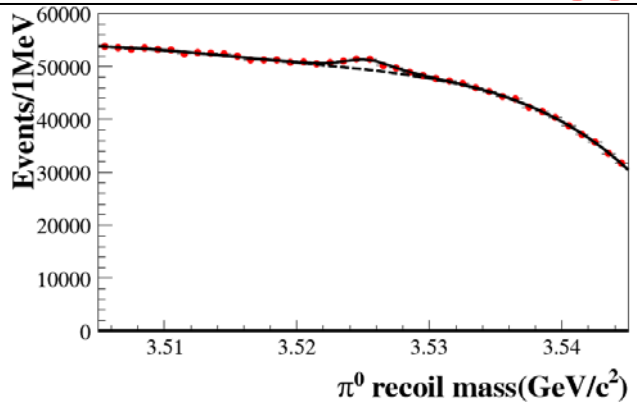
$\Gamma(h_c)$=0.73±0.45MeV

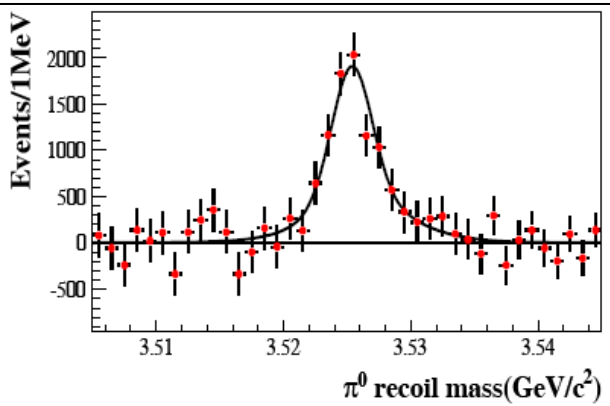
χ^2/d.o.f=33.5/36

For the first time

$Br(\psi' \to \pi^0 h_c) \times Br(h_c \to \gamma\eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$

h_c in inclusive $\psi' \to \pi^0 h_c$
(untagged E1- photon)





- **Select inclusive π^0 ($\psi' \to \pi^0 h_c$)**
- **Untagged E1-photon**
- **A fit of D-Gaussian ⊗ BW signal + 4th Poly. BG yeild. mass and width is fixed as tagged measurement**

Combined with tagged results, we measured for the first time :

- **Br($\psi' \to \pi^0 h_c$) =(8.4±1.3±1.0) ×10^{-4}**
- **Br($h_c \to \gamma \eta_c$) =(54.3±6.7±5.2)%**

BES Collaboration, PRL 104, 132002 (2010)

Summary for h_c analysis

	BESIII	CLEOc	theoretical prediction
$Br(\psi' \to \pi^0 h_c) \times Br(h_c \to \gamma \eta_c)$ $[10^{-4}]$	$4.58 \pm 0.40 \pm 0.50$	$4.19 \pm 0.32 \pm 0.45$	-
M [MeV/c^2]	$3525.40 \pm 0.13 \pm 0.18$	$3525.80 \pm 0.19 \pm 0.12$	-
Γ [MeV]	$0.73 \pm 0.45 \pm 0.28$ <1.44 @ 90%CL	-	1.1 (NRQCD) Kuang 0.51 (PQCD) Kuang
$\Delta M_{hf}(1P)$ [MeV/c^2]	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$	
$Br(\psi' \to \pi^0 h_c)$ $[10^{-4}]$	$8.4 \pm 1.3 \pm 1.0$	-	4 - 13
$Br(h_c \to \gamma \eta_c)$	$54.3 \pm 6.7 \pm 5.2$	-	41 (NRQCD) Kuang 88 (PQCD) Kuang 38 Godfrey, Rosner

CLEO-c Collaboration, Phys.Rev.Lett.101:182003,2008
BES Collaboration, PRL 104, 132002 (2010)
Theoretical predictions: PRD65, 094024 (2002) & PRD 66, 014012 (2002).

Summary

- $p\bar{p}$ mass threshold enhancement has been confirmed in $\psi' \to \pi^+\pi^- J/\psi(J/\psi \to \gamma p\bar{p})$ and $J/\psi \to \gamma p\bar{p}$ and no significance mass enhancement is observed in $\psi' \to \gamma p\bar{p}$ at BESIII
- X(1835) is confirmed in the two decay modes ($\eta' \to \gamma\rho$ and $\eta' \to \eta\pi^+\pi^-$) for $J/\psi \to \gamma\eta'\pi^+\pi^-$
- From inclusive and E1-tagged analysis, we observed h_c and measured

  $\Gamma(h_c) = 0.89 \pm 0.57 \pm 0.23$ MeV

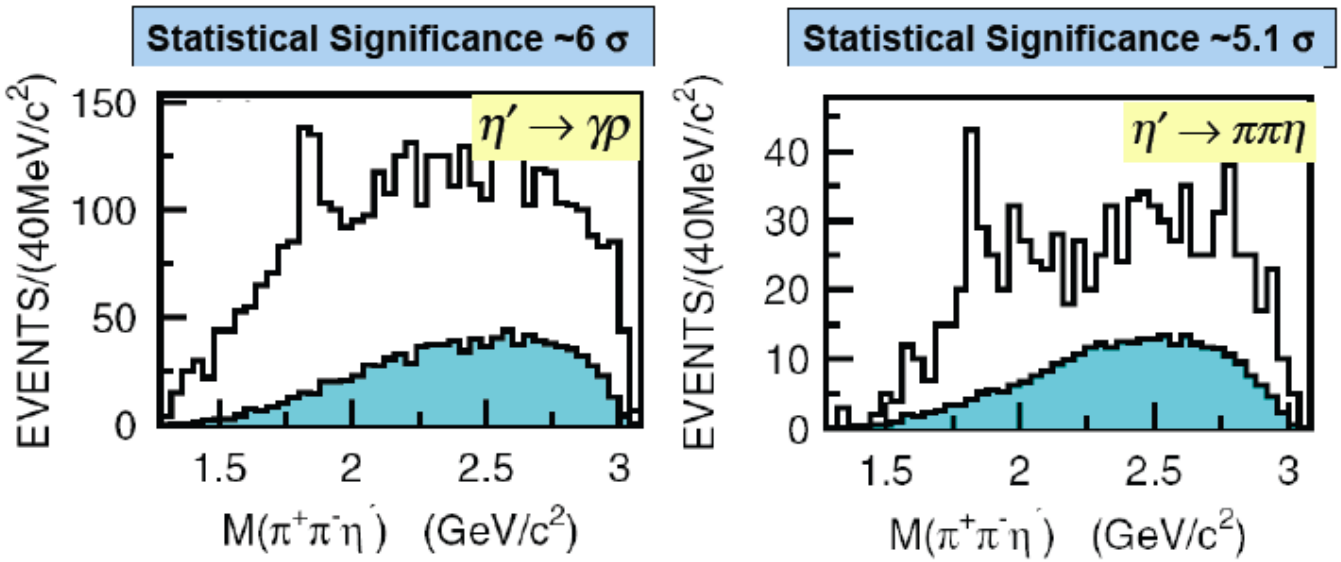
  $B_1(\psi' \to \pi^0 h_c) = (8.42 \pm 1.29(\text{stat.})) \times 10^{-4}$ and

  $B_2(h_c \to \gamma\eta_c) = (55.7 \pm 6.3(\text{stat.}))\%$ for the first time.
- More Exciting results are expected in the coming years.

Back up

Back up

Observation of X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$ at BESII



PRL 95,262001(2005)

speculation for X(18**)

- **The strong and narrow $p\bar{p}$ mass threshold enhancement has only been observed in J/ψ radiative decay, not in any other place so far.**

- **Any model trying to interpret the mass threshold enhancement should also answer why it is not observed in other places, especially in ψ(2S) and Υ(1S) radiative decays as well as in $J/\psi \to \omega\, p\bar{p}$ process.**

✧ Whether X(1860) and X(1835) are the same resonance, still needs further study.

h_c: spin-spin interaction

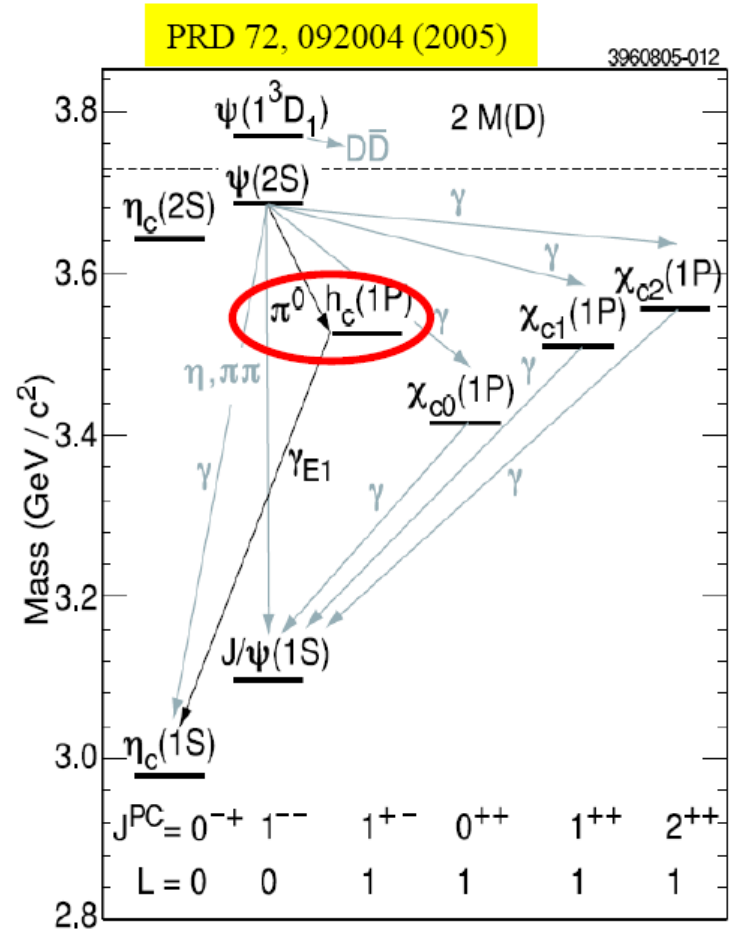
The cc singlet state hc was predicted by theory long time ago.

In 2008, hc was observed by CLEO_c in charmonium decays

hc can only be observed in the process of y(2S)→p0hc

the main decay mode of hc:

the E1 transition hc→γhc.



- **Test of QCD and potential model spin-spin-interaction tells us:**

$$\Delta M_{hf}(1P) = m(h_c) - \frac{1}{9}\left(m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2})\right)$$

h_c in CleOc and E853

data were done. In the *inclusive analysis* h_c decays were identified by loose constraints on either the energy of the electric dipole (E1) photon from h_c decay, or the mass of η_c. In the *exclusive analysis* no constraint was placed on $E(\gamma)$. Instead, η_c events were reconstructed in seven different hadronic decay channels of η_c. The combined significance level of the h_c observation was $>6\sigma$, and the quoted mass was $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV.

The Fermilab E835 measurement [3] made scans of antiproton energy for the reaction, $\bar{p}p \rightarrow h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow \gamma\gamma$. The results from the year 1997 scan and the year 2000 scan were combined to obtain $M(h_c) = 3525.8 \pm 0.2 \pm 0.2$ MeV. The significance level of h_c observation was $\sim 3\sigma$. No evidence was found for h_c in the previously reported reaction $\bar{p}p \rightarrow h_c \rightarrow \pi^0 J/\psi$ [5].

Event selection for the inclusive π^0 and E1-tagged analysis

- **Inclusive analysis of $\psi(2S) \rightarrow \pi^0 h_c$**
  - Identify the h_c signal by searching for an enhancement in the inclusive recoiling mass spectrum of π^0

- **E1-tagged analysis of $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$**
  - Tag the E1 photon(~503MeV) emitted in $h_c \rightarrow \gamma_{E1} \eta_c$. No further constrains on the final states of the η_c are imposed. The h_c signal in π^0 recoil mass spectrum will be improved significantly.

- **Exclusive analysis of $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$**
  - Fully reconstruct the exclusive final states of η_c

Event selection for the inclusive π^0 and E1-tagged analysis

Good charged track

- IP region: $|R_{xy}| \leqslant 1cm$, $|Rz| \leqslant 10cm$
- Momentum: $p<2.0GeV$
- Polar angle: $|\cos\theta|<0.93$
- $N_{charge} \geqslant 2$, $N_{good} \geqslant 1$

Good photon

- $|\cos\theta|<0.8$: $E_\gamma > 25MeV$
- $0.84<|\cos\theta|<0.92$: $E_\gamma > 50MeV$
- Angle between charged track and neutral track: Dang<20°
- EMC time: $0 \leqslant t \leqslant 14$ ($\times$50ns)

Event selection for the inclusive π^0 and E1-tagged analysis

signal π^0 candidate selection

- Photon polar angle: $|\cos\theta|<0.8$
- Photon energy: $E_\gamma>40$MeV
- Each photon belongs to only one π^0
- $M_{\gamma\gamma}\in[0.12,0.145]$GeV/$c^2$
- Do 1C fit for each π^0 candidate (no cut on χ^2)

Tag E1 photon in $h_c\rightarrow\gamma_{E1}\eta_c$

- 450MeV$<E_\gamma<$540MeV
- Not belonging to π^0 (0.10-0.145GeV/c^2) and η(0.53-0.56GeV/c^2)

Background Veto

- $\pi^+\pi^-J/\psi$: $|M^{rec}(\pi^+\pi^-)-3.097|>0.007$GeV/$c^2$
- $\pi^0\pi^0J/\psi$: $|M^{rec}(\pi^0\pi^0)-3.097|>0.03$GeV/$c^2$

Systematic error for h_c analysis

source	$M(h_c)(\mathrm{MeV}/c^2)$	$\Gamma(h_c)(\mathrm{MeV})$	$\mathcal{B}_1(10^{-4})$	$\mathcal{B}_1 \times \mathcal{B}_2(10^{-4})$	$\mathcal{B}_2(\%)$
Background shape and fit range	0.11	0.23	0.4	0.22	4.4
Energy scale, position reconstruction and 1-C fit	0.13	0.06	0.5	0.10	2.1
Energy resolution	0.00	0.15	0.2	0.03	1.0
Background veto	0.05	0.03	0.0	0.03	0.3
π^0 efficiency	0.00	0.00	0.3	0.14	0.0
$E1$ photon efficiency	0.00	0.00	0.0	0.10	1.2
Number of π^0	0.00	0.00	0.6	0.35	0.6
Number of charged tracks	0.00	0.00	0.1	0.06	0.1
$N(\psi')$	0.00	0.00	0.4	0.19	0.0
$M(\psi')$	0.03	0.02	0.0	0.00	0.0
$M(\eta_c)$ and $\Gamma(\eta_c)$	0.00	0.00	0.0	0.01	0.3
Total systematic error	0.18	0.28	1.0	0.50	5.2

Hyperfine mass spiltting

The CLEO average mass in Eq. (6) leads to

$$\Delta M_{hf}(1P) = +0.08 \pm 0.18(\text{stat.}) \pm 0.12(\text{syst.})\text{MeV}.$$

These results are consistent with the lowest order expectation of $1P$ hyperfine splitting being zero. We notice that the triplet mass used above was obtained as $\langle M(^3P_J)\rangle = [M(^3P_0) + 3M(^3P_1) + 5M(^3P_2)]/9$, which is the evaluation of $M(^3P)$ in the lowest order, when the spin-orbit splitting is perturbatively small. It has been pointed out [4] that with $[M(^3P_2) - M(^3P_0)] \approx 140$ MeV, the validity of the perturbative determination of $M(^3P)$ is questionable. Indeed, the perturbative prediction that $M(^3P_1) - M(^3P_0) = \frac{5}{2}[M(^3P_2) - M(^3P_1)] = 113.9 \pm 0.3$ MeV disagrees with the experimental result, 95.9 ± 0.4 MeV, by 18 MeV. This necessarily implies that the true $M(^3P)$ is different from the centroid value $\langle M(^3P_J)\rangle$. Since $\Delta M_{hf}(1P)$ is expected to be small ($\sim$ few MeV), if not identically zero, it is important that higher order effects should be taken into account in deducing $M(^3P)$ from the known masses of ^3P_J states [4], so that a true measure of $\Delta M_{hf}(1P)$ can be obtained. Only then can the present measurement of $M(h_c)$ be used to distinguish between the different potential model calculations, whose predictions for $\Delta M_{hf}(1P)$ vary over a large range because of the different assumptions they make about relativistic effects, the Lorentz nature of the confinement potential, and smearing of the spin-spin contact potential [12]. Although the presently available lattice calculations do not have the required precision [13], it may be expected that future unquenched lattice calculations will resolve these problems.