# Physics at BESIII

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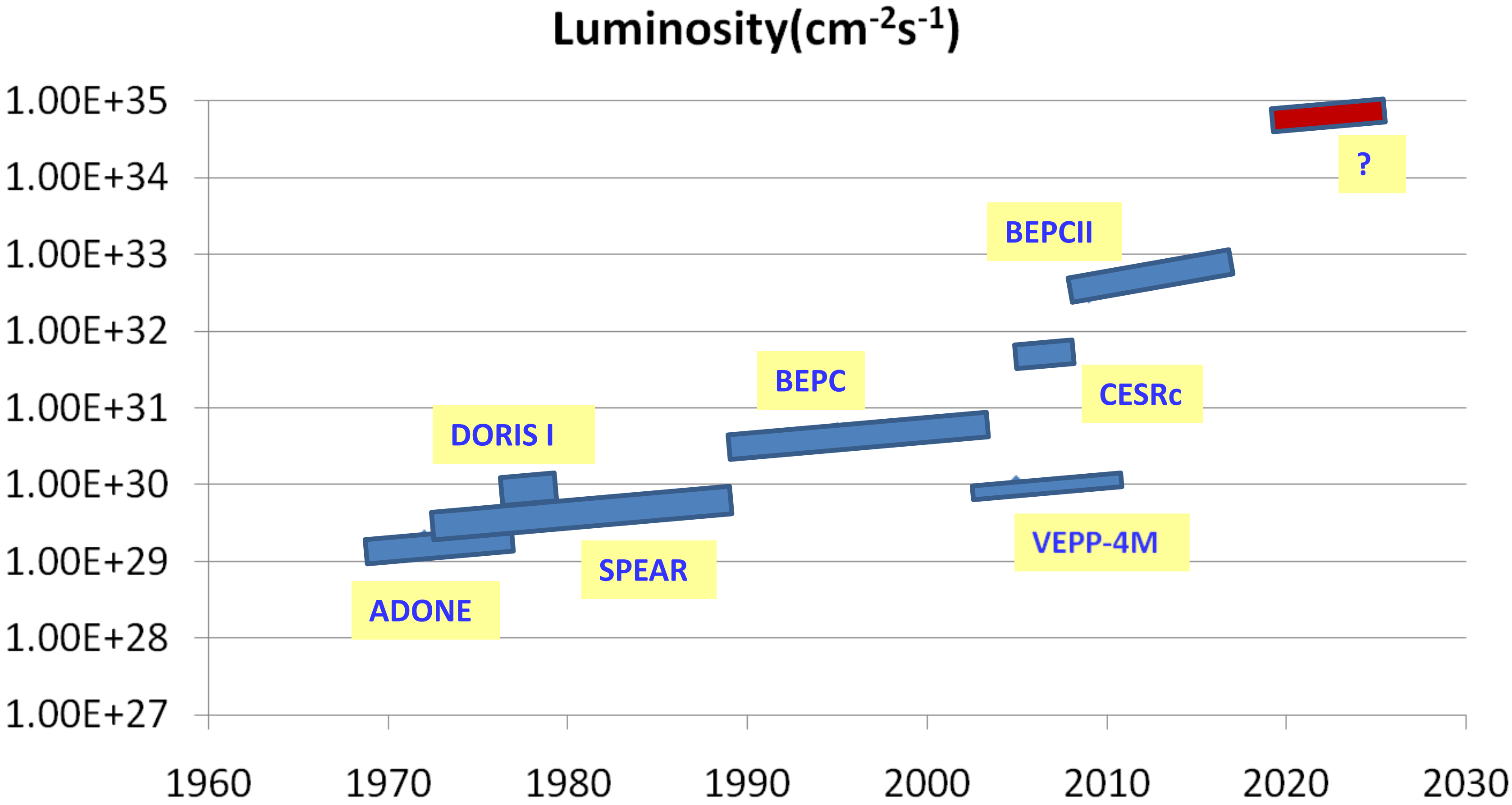
**Institute of High Energy Physics**

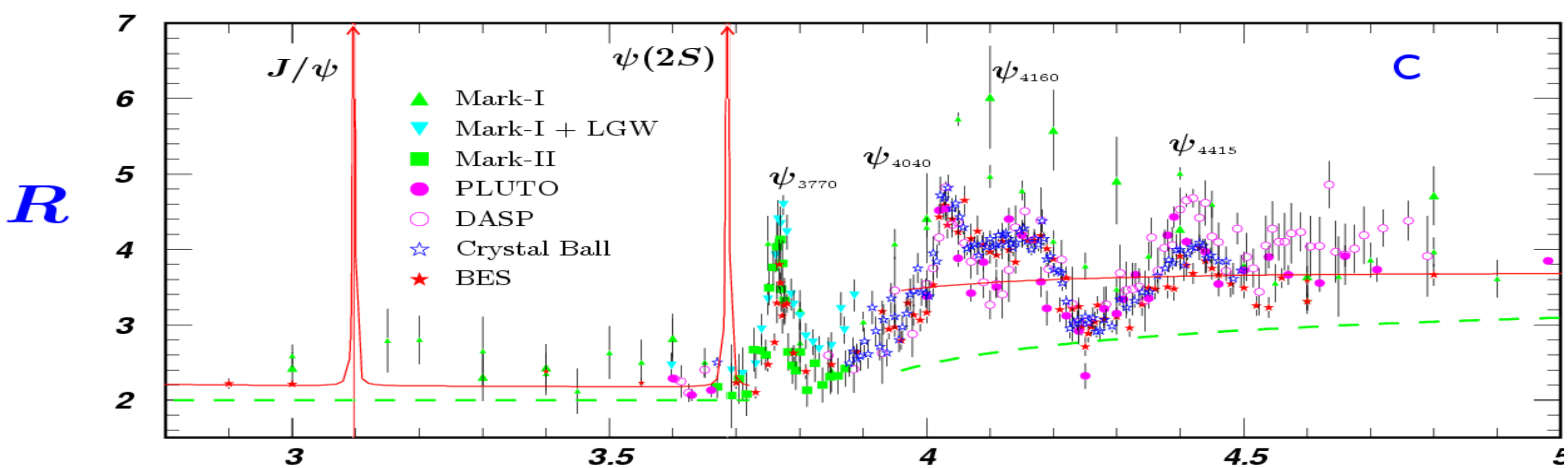
# Beijing Electron Positron Collider (BEPC)

# A long history of $e^+e^-$ colliders at the Tau-Charm energy region



# BESIII data taking status & plan

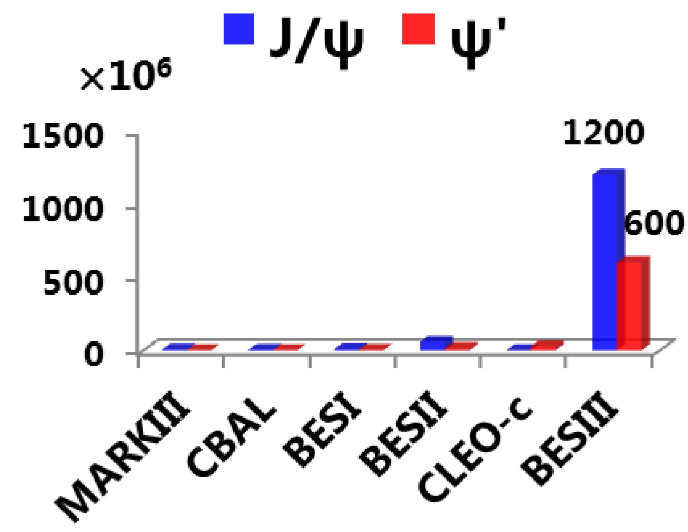
| | Previous data | BESIII present & future | Goal |
|---|---|---|---|
| J/ψ | BESII 58M | 1.2 B 20* BESII | 10 B |
| ψ' | CLEO: 28 M | 0.5 B 20* CLEOc | 3B |
| ψ" | CLEO: 0.8 /fb | 2.9/fb 3.5*CLEOc | 20 /fb |
| ψ(4040)/ψ(4160)/ ψ(4260) /ψ(4360) | CLEO: 0.6/fb @ ψ(4160) | 2011:0.4/fb @ ψ(4040)<br>2013: 1/fb@4260, 4360 | 5-10 /fb |
| R scan & Tau | BESII | 2012: 12/pb@2.23,2.4,2.8,3.4<br>25/pb tau<br>2013, 2014: high mass R, tau | |

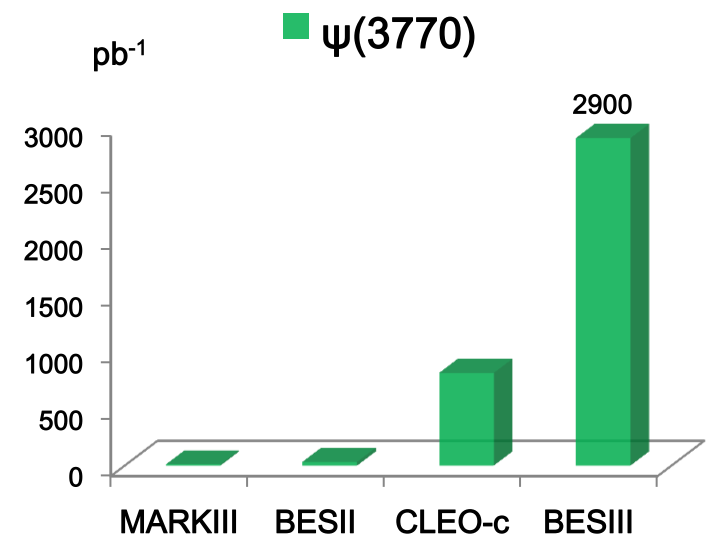


# BESIII results

- **Charmonium physics**
  - Charmonium spectroscopy
  - Transitions and decays
- **Light hadron spectroscopy**
  - Meson & baryon spectroscopy
  - Search for unconventional hadrons – glueballs, hybrids, multi-quark states
- **Charm physics**
  - Decay constant $f_D$
  - CKM matrix elements: *Vcd, Vcs*

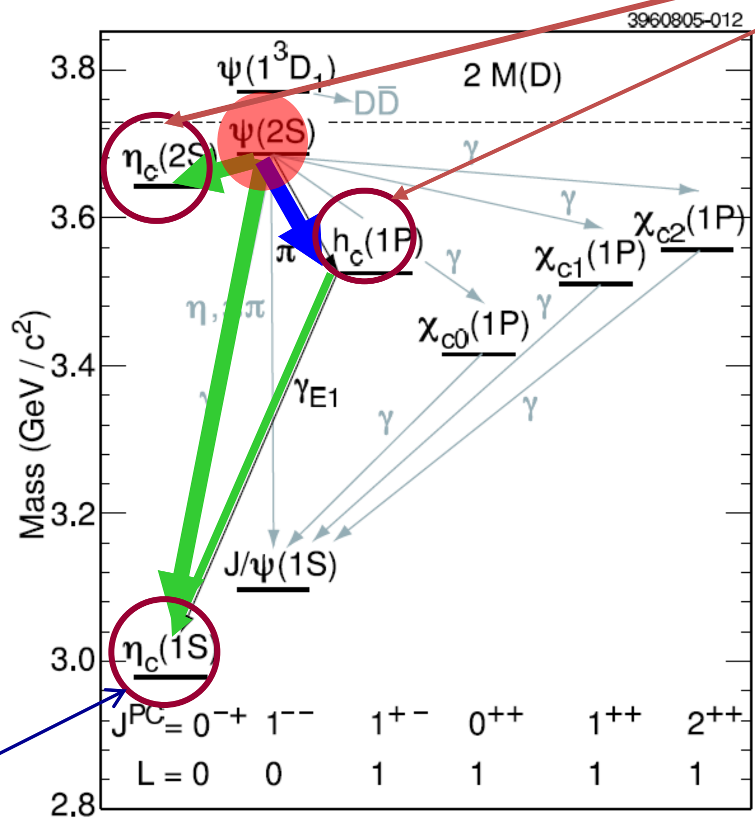
38 papers published/submitted



# Charmonium states
# $\psi'$, $h_c(^1P_1)$, $\eta_c(1S)$, $\eta_c(2S)$

Properties not well known




Problems with mass and width measurements

# Y.P. Kuang's contribution to BES: heavy quarkonium transitions and decays:

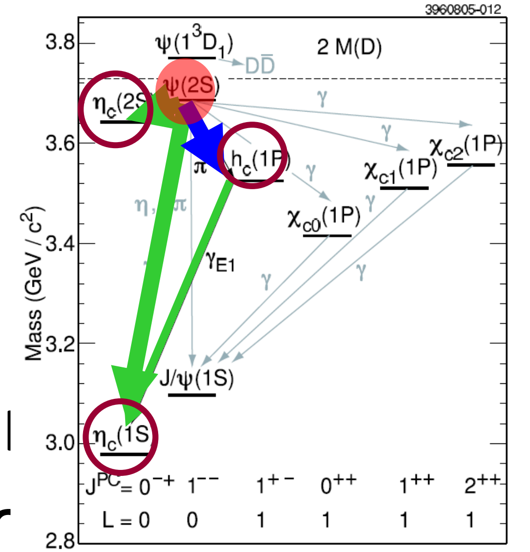
**(1) Hadronic transition – QCD multipole expansion**
**(2) Coupled channel effect**
**(3) 2S-1D mixing for $\psi(3770)$ –non-DDbar decays**
**(4) improved potential model for charmonium decays**

- In fact, Prof. Kuang is the main player in early days of BES for charmonium physics
- Theoretical support for the study at BES on charmonium transitions
- BESIII yellow book on hadronic transitions of charmonium
- Proposed the study of $\chi_{c1} \rightarrow \eta_c \pi\pi$ at BESIII
- Many other suggestions to BESIII…

# Incomplete list of Kuang's papers on the BESIII physics

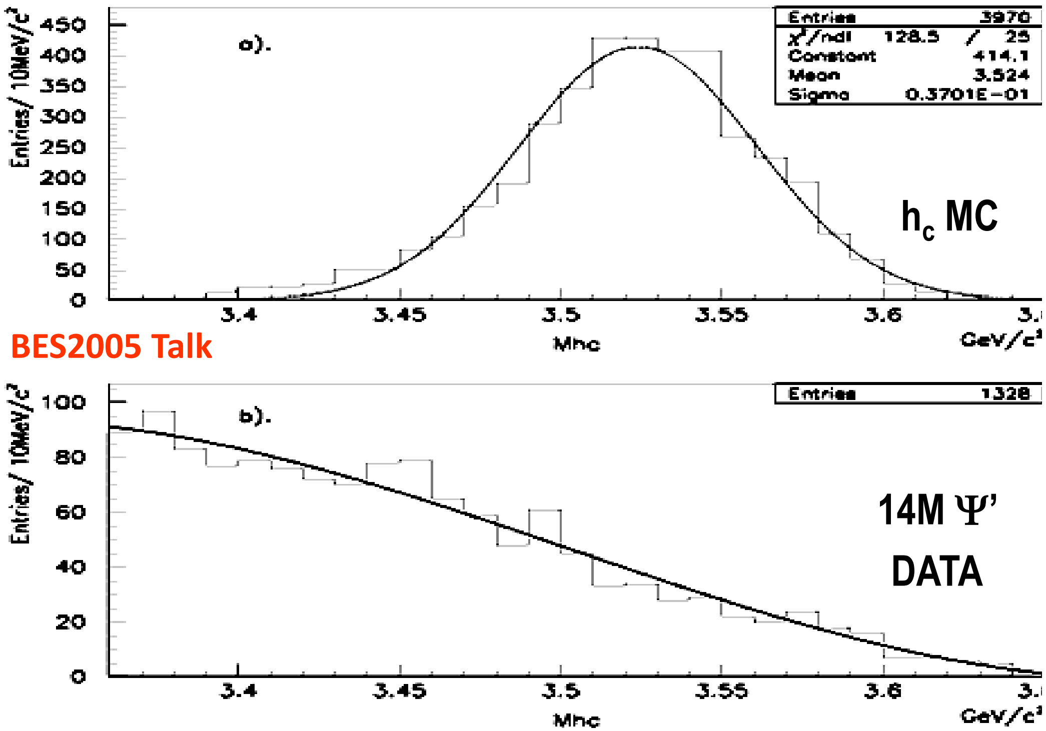
| | |
|---|---|
| Y.-P. Kuang et al, | Phys.Rev. D85 (2012) 114010 |
| Q. Lu and Y.-P. Kuang, | Phys.Rev. D75 (2007) 054019 |
| Y.-P. Kuang, | Front.Phys.China 1 (2006) 19-37 |
| Y.-P Kuang, | Phys.Rev. D65 (2002) 094024 |
| Y.-P. Kuang et al, | Phys. Rev.D37 (1998) 1210 |
| Y.Q. Chen, et al, | Phys.Rev. D52 (1995) 264-270 |
| Y.Q. Chen et al, | Z.Phys. C67 (1995) 627-632 |
| Y.Q. Chen et al, | Phys.Rev. D46 (1992) 1165 |
| H.Y. Zhong and Y.-P. Kuang, | Phys.Rev. D44 (1991) 756-769 |
| Y.-P. Kuang et al, | Phys.Rev. D42 (1990) 2300-2308 |
| Y.-P. Kuang et al, | Phys.Rev. D37 (1988) 1210-1219 |
| Y.-P. Kuang and T.M.Yan, | Phys.Rev. D41 (1990) 155 |
| Y.-P. Kuang and T.M.Yan, | Phys.Rev. D24 (1981) 2874 |

# $h_c(^1P_1)$




- Physics motivation even at BES I
- Prof. Kuang gave the first calculation of $\psi' \rightarrow \pi^0 h_c$ in 1988 , updated in 200
- Unfortunately, BES I and BESII did not have the capability due to the poor energy resolution (~20%) of EM calorimeter
- After 20 years, CLEOc observed the signal for the first time right before the BESIII, thanks to its crystal EM calorimeter(~2.5%)

# Impossible at BES I, nor at BESII




BES2005 Talk

## Search for $h_c(^1P_1)$ at BESII


LU Feng , DU ShuXian


June 14, 2005

BESII Memo

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**Abstract**

$h_c$ searches by the chains of $\psi' \longrightarrow h_c\pi^0$, $h_c \longrightarrow \eta_c+\gamma$, $\eta_c \to 4\pi$, $K_s^0K^+\pi^-$+c.c, 4K and $2K2\pi$ channels have beed presented, no clear $h_c$ signals are observed in the $\gamma\eta_c$ invariant mass spectra at BESII 14M $\psi'$ decays. 90% C. L. upper limits are set: $Br(\psi' \to \pi^0 h_c) \times Br(h_c \to \gamma\eta_c) < 3.3 \times 10^{-3}$ by $\eta_c \to 4\pi$ channel, $4.3 \times 10^{-3}$ by $\eta_c \to K_s^0K^+\pi^-$ + c.c. channel and $15.4 \times 10^{-3}$ by $\eta_c \to 4K$ channel respectively.


### 1 Introduction

$h_c$, P-wave spin singlet charmonium state ($^1P_1$), due to the $c\bar{c}$ system relativistic and other effects are less important than the light quarkonia system because of heavy charm quark mass, is extremely important to determine spin-dependent component of the $q\bar{q}$ confinement potential by $^1P_1$-$^3P_{cog}$ mass splitting for lattice QCD and NRQCD. With scalar confinement, $h_c$ should be degenerate in mass with the center of gavity of the $\chi_{cJ}(^3P_J)$ states [1]:

$$M_{cog} = \frac{m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2})}{9} = (3525.30 \pm 0.12) MeV/c^2 \quad (1)$$

The measurement of the deviation of the $h_c$ mass from $M_{cog}$ is a good test of Lorentz nature of the confining potential. Therefore searching $h_c$ and measuring its

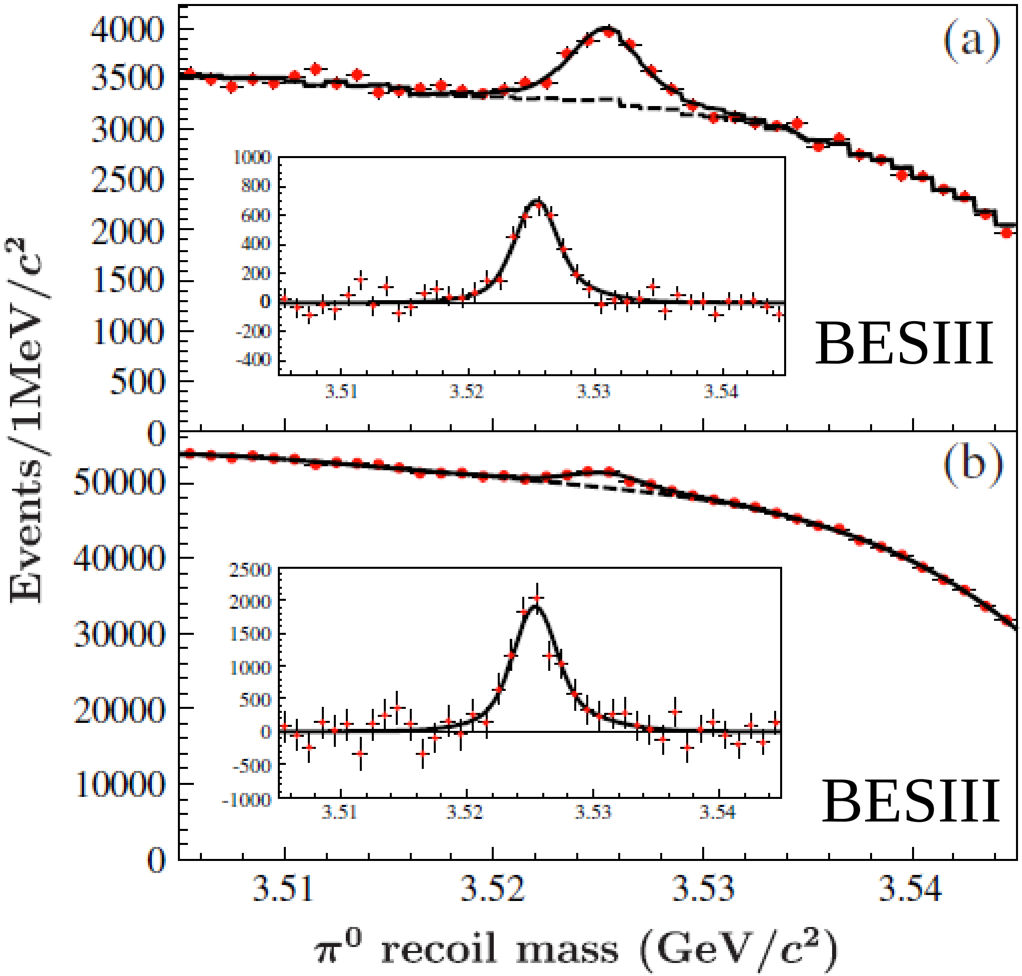
1

**Search for $h_c$ via $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to 4\pi/\eta_c \to k_s k\pi$ from 14M Ψ’ at BESII:**

$Br(\Psi' \to \pi^0 h_c) \times Br(h_c \to \gamma\eta_c) < 3.3 \times 10^{-3}$ (90% C.L.)

A memo was written but no paper was published since CLEO-c observed the signal

# First BESIII PRL paper: $\psi(2S) \rightarrow \pi^0 h_c$




**BESIII: PRL 104, 132002 (2010)**
**Mass: 3525.40±0.13±0.18 MeV**
**Width: 0.73±0.45±0.28 MeV**
**(<1.44 MeV @ 90% C.L.)**

**CLEOc: PRL101, 182003 (2008)**
**Mass: 3525.28±0.19±0.12 MeV**
**Width: fixed to 0.9 MeV**

**$\Delta M_{hf}$= <M($^3P_J$)>-M($^1P_1$)**
**Agrees with zero within ~0.5 MeV**

**Information on spin-spin interaction.**

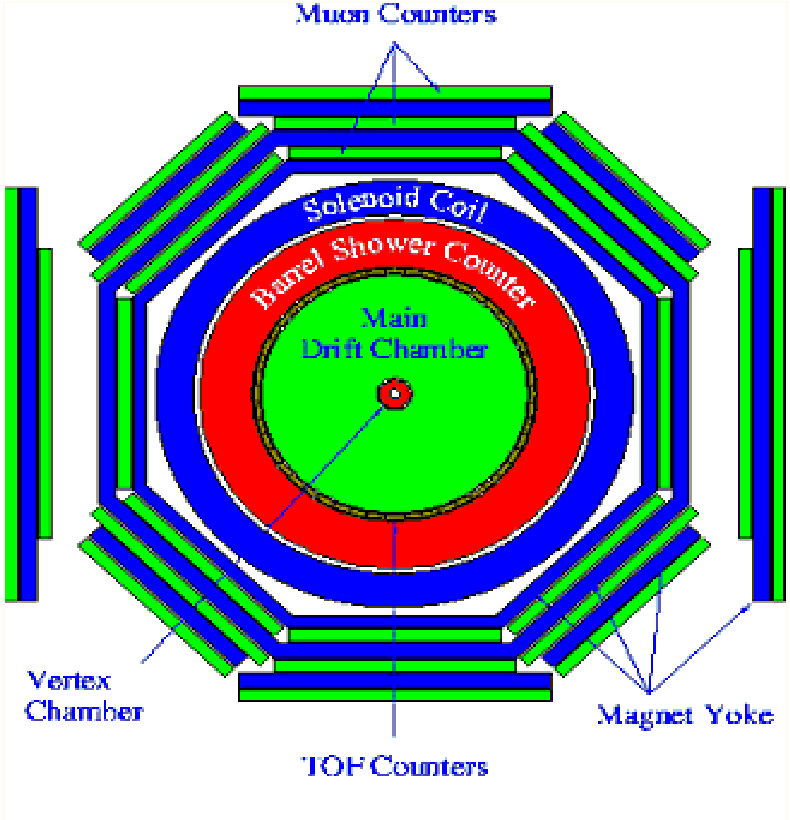
Combined inclusive and E1-photon-tagged spectrum (First measurements)

$B(\psi' \rightarrow \pi^0 h_c)$ = [ 8.4±1.3(stat.) ±1.0(syst.)]×$10^{-4}$
$B(h_c \rightarrow \gamma \eta_c)$ = [54.3±6.7(stat.) ±5.2(syst.)] %

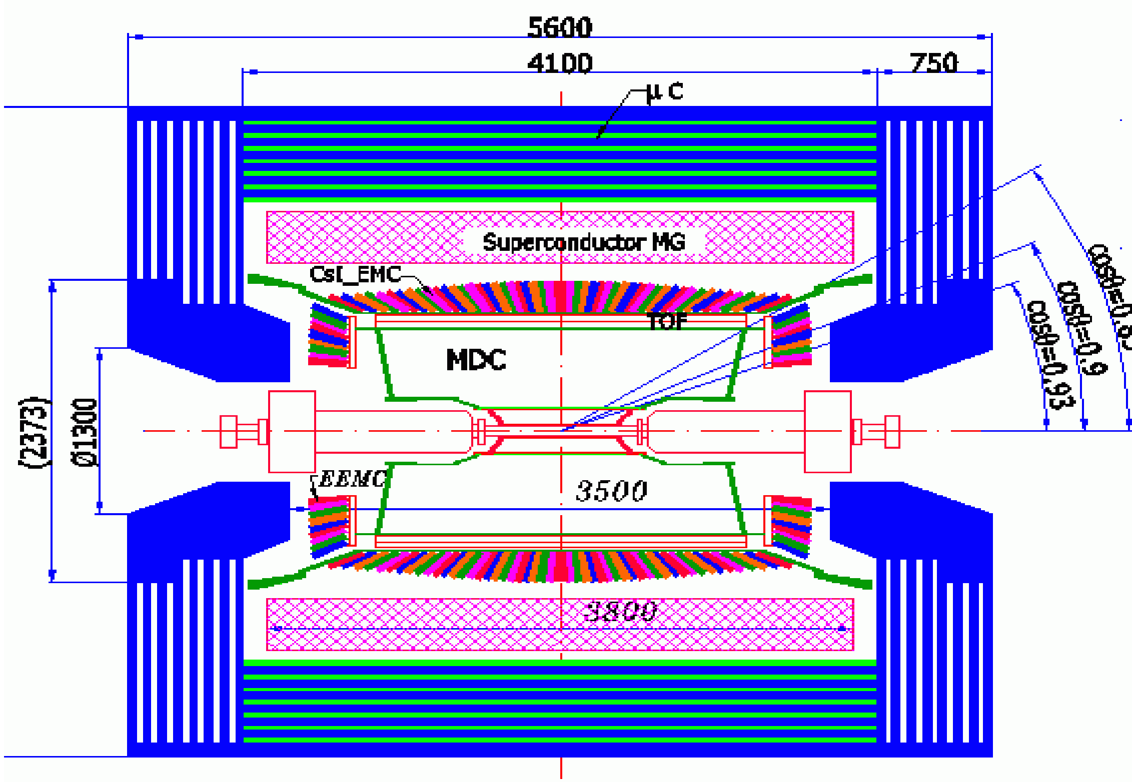
Agree with predictions of Kuang, Godfrey, Dudek, et al.

# BESII

# BESIII

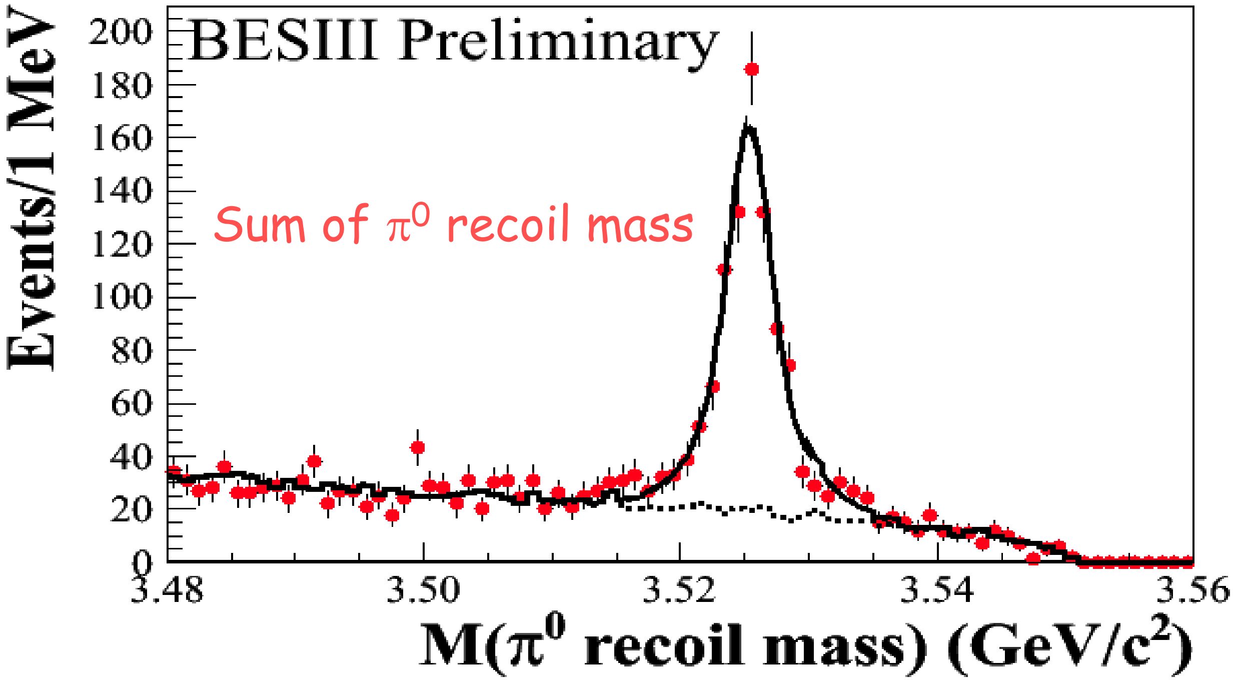



End view of the BES detector




没有钱是万万不行的！

# $h_c(1P1)$ in $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to X_i$ (exclusive)




Simultaneous fit to $\pi^0$ recoiling mass in 106M $\psi'$ sample (preliminary results):

$M(h_c) = 3525.31 \pm 0.11_{(stat)} \pm 0.15_{(sys)}$ MeV/$c^2$
$\Gamma(h_c) = 0.70 \pm 0.28_{(stat)} \pm 0.25_{(sys)}$ MeV
$N = 832 \pm 35$
$\chi^2$/d.o.f. = 32/46

Accepted for publication at PRD

Consistent with BESIII inclusive Results: PRL104,132002(2010)

CLEOc exlusive results:
$M(h_c) = 3525.21 \pm 0.27 \pm 0.14$ MeV/$c^2$
PRL101, 182003(2008)

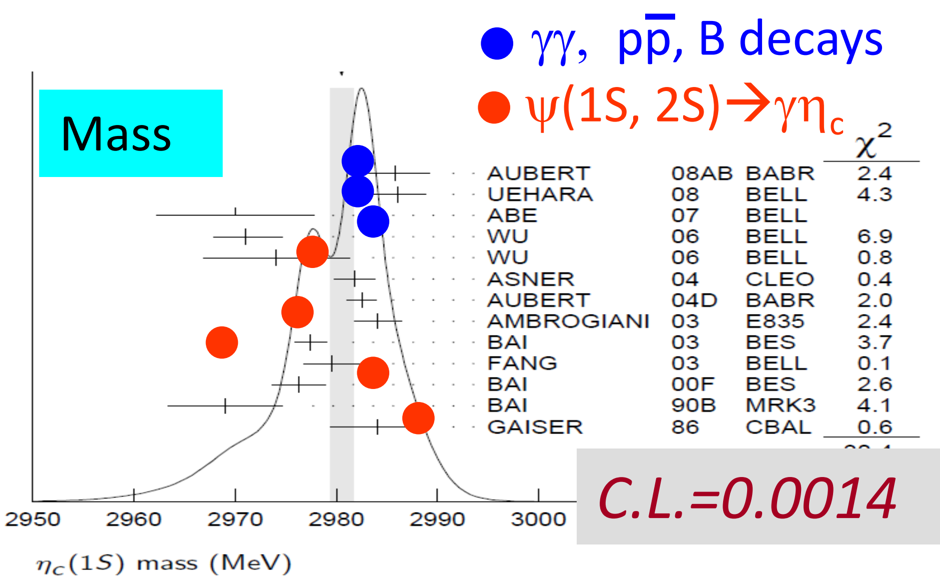
# $\eta_c(1S)$

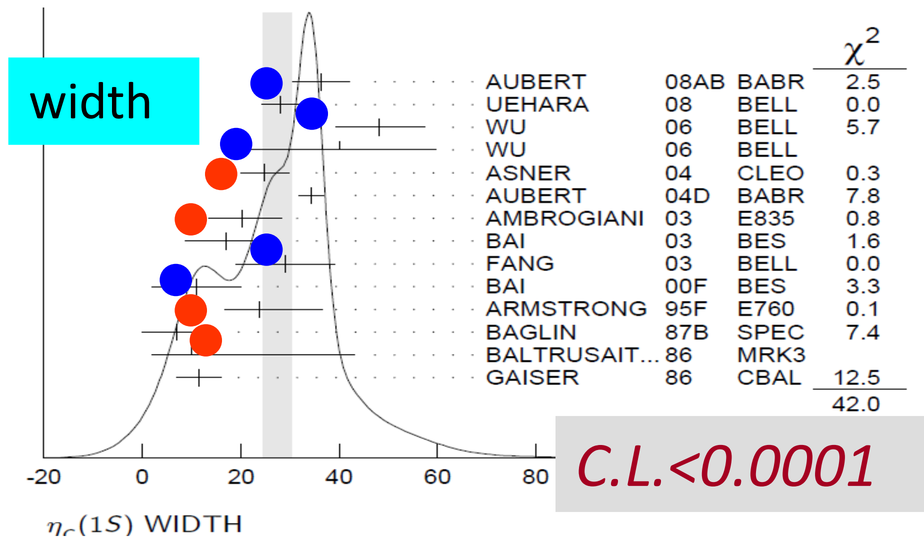
- **The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII. Confusion properties:**

  **Charmonium radiative transition: M ~ 2978.0MeV/$c^2$, $\Gamma$ ~ 10MeV**

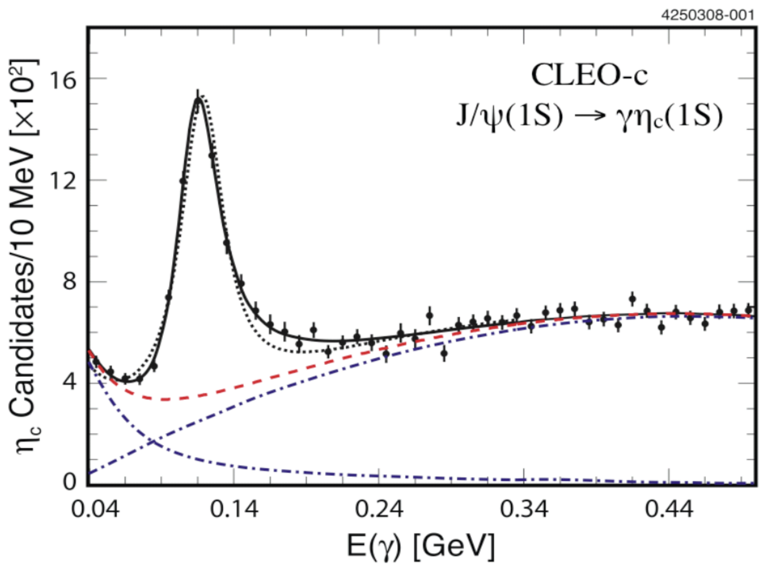
  **$\gamma\gamma$ process: M = 2983.1 ± 1.0 MeV/$c^2$, $\Gamma$ = 31.3 ± 1.9 MeV**

- **CLEOc found the distortion of the $\eta_c$ line shape in $\psi'$ decays.**
- **$c\bar{c}$ hyperfine splitting M(J/$\psi$)-M($\eta_c$(1S)) is the important exp. input to test LQCD, but is dominated by error on M($\eta_c$(1S)).**

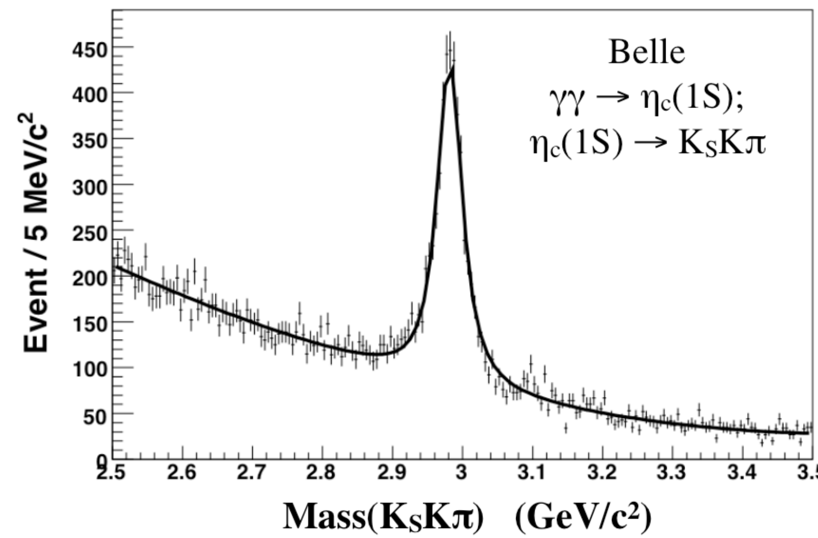


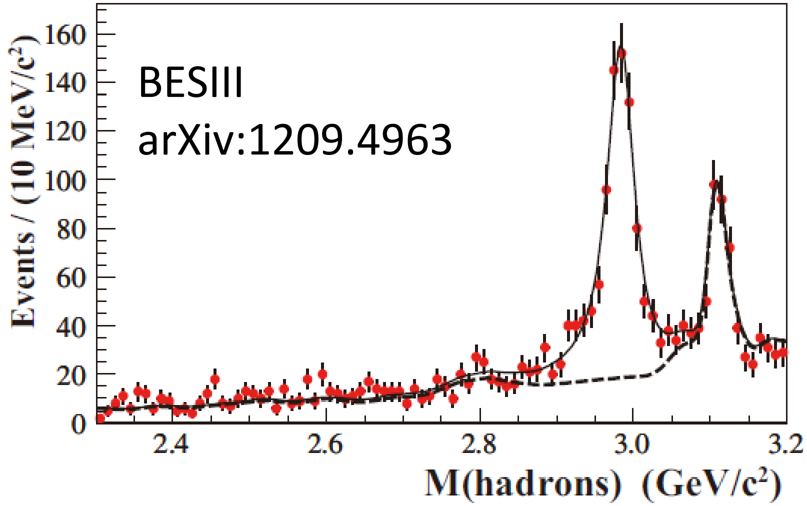
Asymmetric lineshape in J/ψ decay

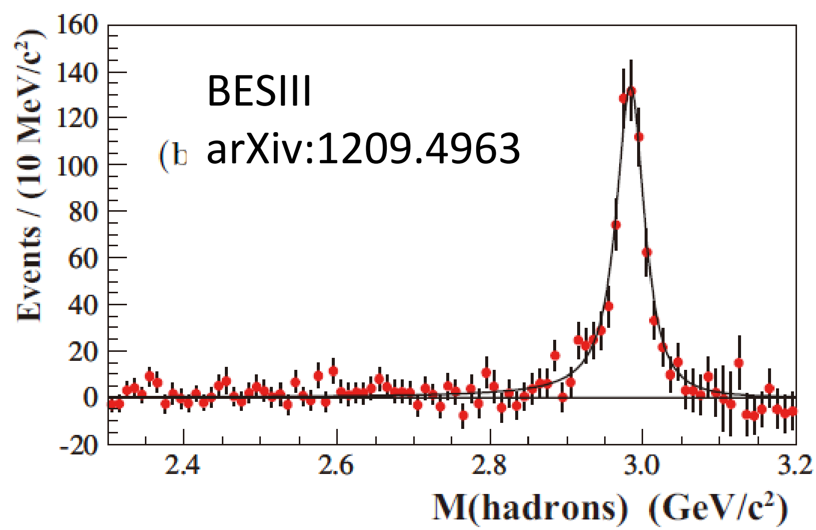



Symmetric lineshape in γγ production




**Symmetric $\eta_c$ lineshape from $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$**

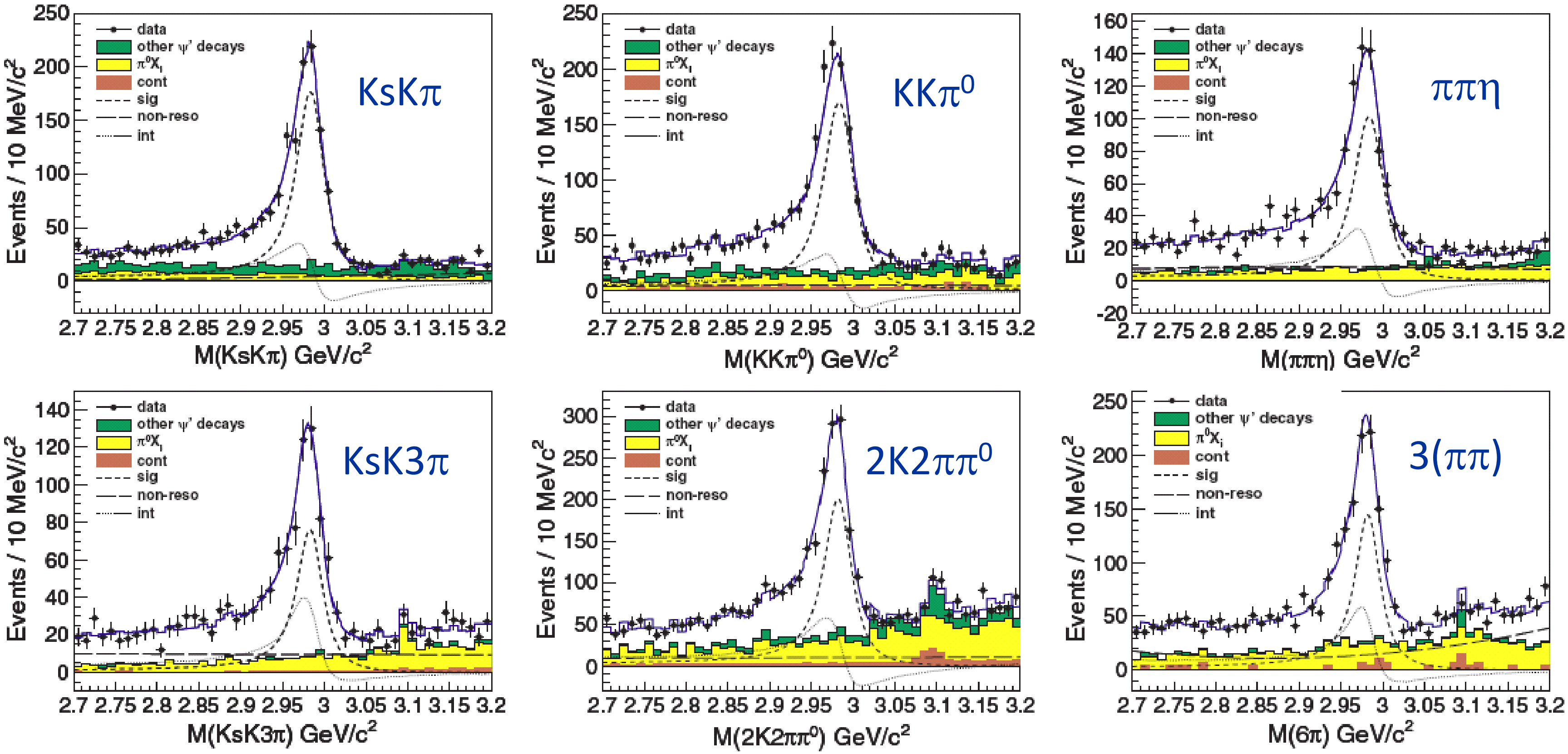


# $\eta_c$ resonance parameters from $\psi' \to \gamma\eta_c$ at BESIII

***Interference taken into account***

PRL 108 (2012) 222002




Relative phase $\phi$ values from each mode are consistent within $3\sigma$.

➔ use a common phase value in the simultaneous fit.

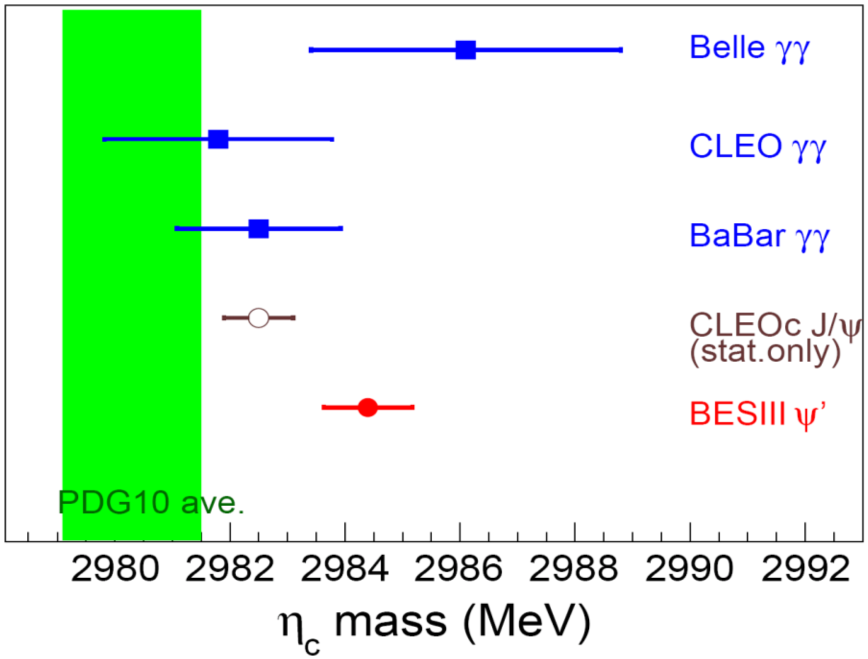
mass: $2984.3 \pm 0.6_{stat} \pm 0.6_{sys}$ MeV/$c^2$

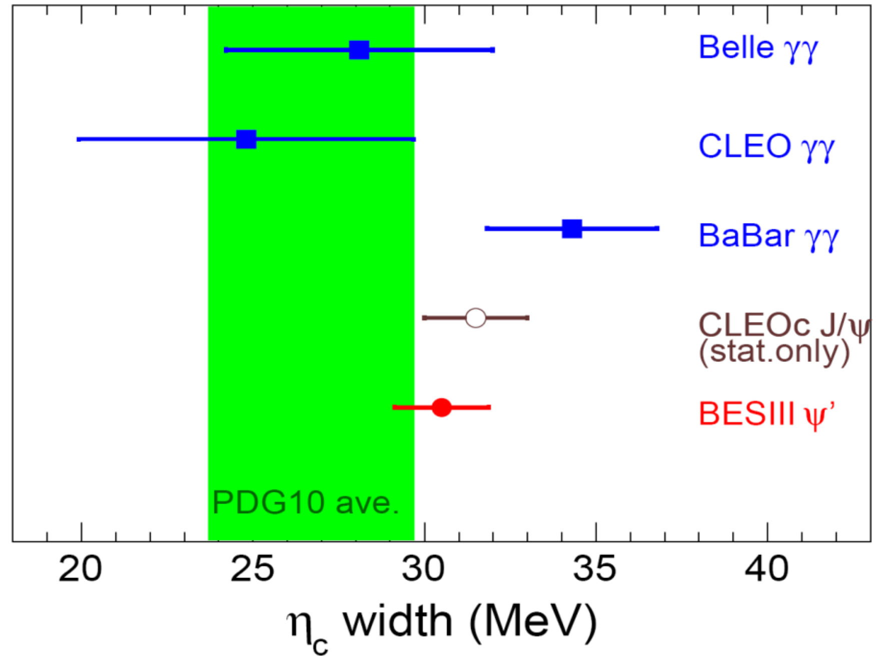
width: $32.0 \pm 1.2_{stat} \pm 1.0_{sys}$ MeV

$\phi$: $2.40 \pm 0.07_{stat} \pm 0.08_{sys}$ rad (constructive)

or $4.19 \pm 0.03_{stat} \pm 0.09_{sys}$ rad (destructive)

# Comparison of the mass and width for $\eta_c(1S)$

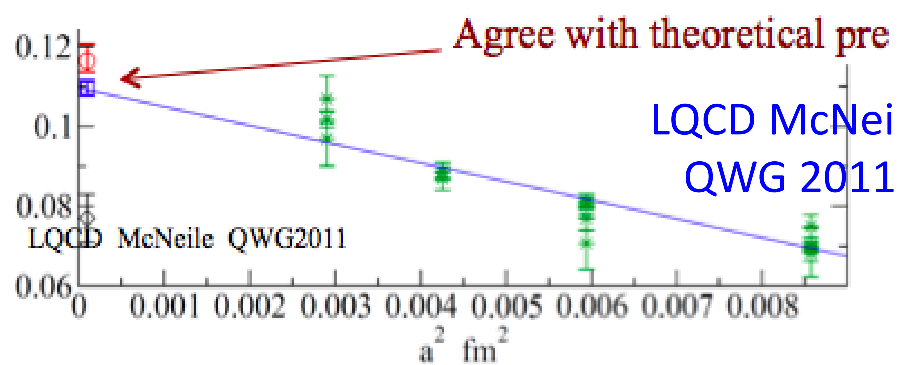



Mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/$c^2$

Width = $32.0 \pm 1.2 \pm 1.0$ MeV

- The most precise measurement
- Agree well with LQCD calculation.




LQCD McNeile
QWG 2011

# $\eta_c(2S)$

- Crystal Ball's "first observation" of $\psi' \to \gamma X$ never been confirmed

  PRL 48 70 (1982)

- Observed in different production mechanisms
  - $B \to K\eta_c(2S)$
  - $\gamma\gamma \to \eta_c(2S) \to KK\pi$
  - double charmonium production

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

| Experiment | $M$ [MeV] | $\Gamma$ [MeV] | Process |
|---|---|---|---|
| Belle [1] | $3654 \pm 6 \pm 8$ | — | $B^\pm \to K^\pm \eta_c(2S), \eta_c(2S) \to K_S K^\pm \pi^\mp$ |
| CLEO [2] | $3642.9 \pm 3.1 \pm 1.5$ | $6.3 \pm 12.4 \pm 4.0$ | $\gamma\gamma \to \eta_c(2S) \to K_S K^\pm \pi^\mp$ |
| BaBar [3] | $3630.8 \pm 3.4 \pm 1.0$ | $17.0 \pm 8.3 \pm 2.5$ | $\gamma\gamma \to \eta_c(2S) \to K_S K^\pm \pi^\mp$ |
| BaBar [4] | $3645.0 + 5.5^{+4.9}_{-7.8}$ | — | $e^+e^- \to J/\psi c\bar{c}$ |
| PDG [5] | $3638 \pm 4$ | $14 \pm 7$ | — |

- CLEOc did not find signals in 25M $\psi'$ M1 transition $\psi' \to \gamma\eta_c(2S)$

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

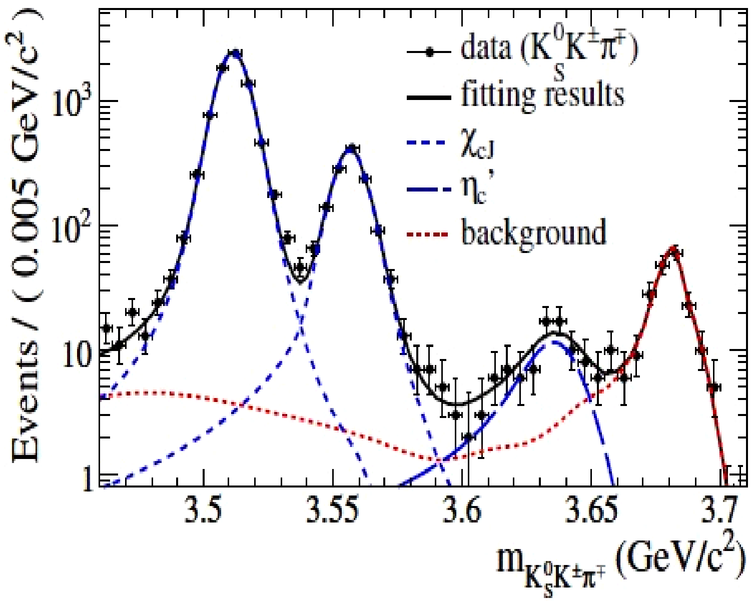
Experimental challenge : detect photons of 50 MeV

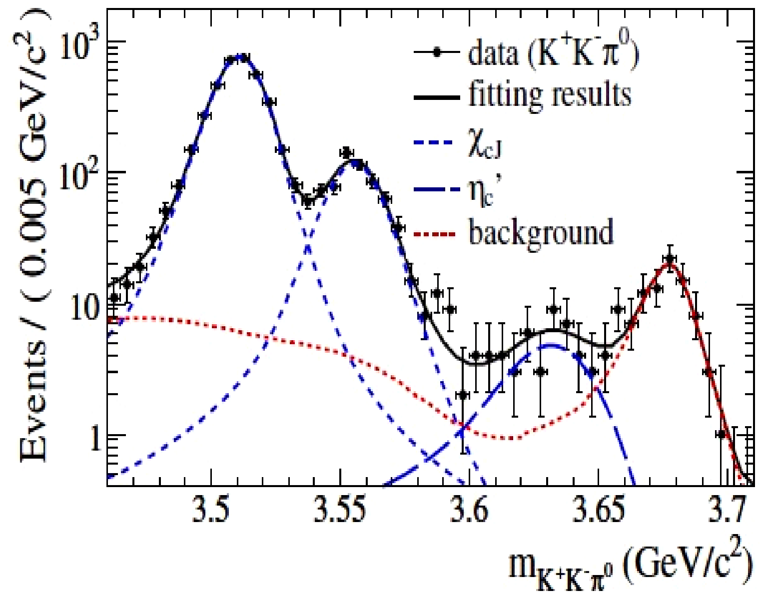
# First observation of $\psi' \rightarrow \gamma\eta_c(2S)$

Statistical significance >10 $\sigma$

New discovery! Great effort since BESI

BESIII: PRL109, 042003 (2012)



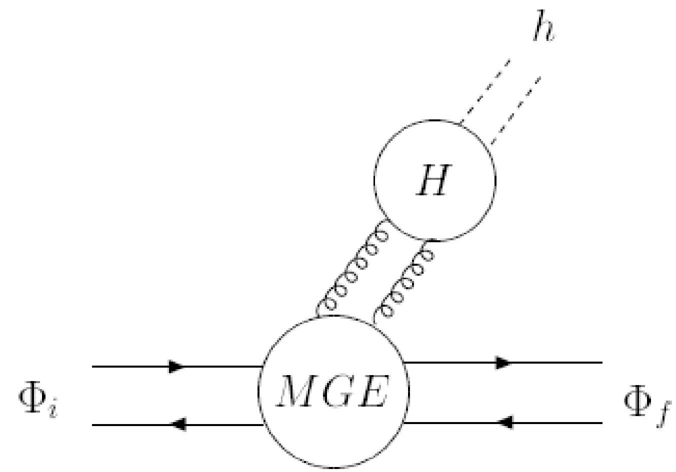




- Observed signal in $K_sK^+\pi^-$+c.c.， found evidence in $K^+K^-\pi^0$
- First measured $Br(\psi' \rightarrow \gamma\eta_c(2S))=(6.8\pm1.1\pm4.5)\times10^{-4}$

Potential model expectation: $(0.1\text{-}6.2)\times10^{-4}$ PRL 89 162002 (2002)

CLEOc: $<7.6\times10^{-4}$ PRD 81 052002 (2010)

# Kuang's QCDME model: Heavy quakonium hadronic transition




$$\Gamma\left(\psi(3770) \to J/\psi\ \pi\pi\right) = |C_1|^2 \left[ \sin^2\theta\ G(\psi')\ |f^{111}_{2010}(\psi')|^2 + \frac{4}{15}\left|\frac{C_2}{C_1}\right|^2 \cos^2\theta\ H(\psi'')\ |f^{111}_{1210}(\psi'')|^2 \right]$$

Y.P. Kuang's prediction：  $\Gamma[\psi(1^3D \rightarrow 1^3D\ \pi\pi)]=[11\sim160]$ keV

PRD41 (1990) 155

M.B. Voloshin's prediction：  $\Gamma[\psi(1^3D \rightarrow 1^3D\ \pi\pi)]<0.1$ keV

# Non-$\bar{D}D$ decay of ψ(3770) : discovered at BESII

$$BF(\psi(3770) \to J/\psi\pi^+\pi^-) = (0.34 \pm 0.14 \pm 0.09)\%$$

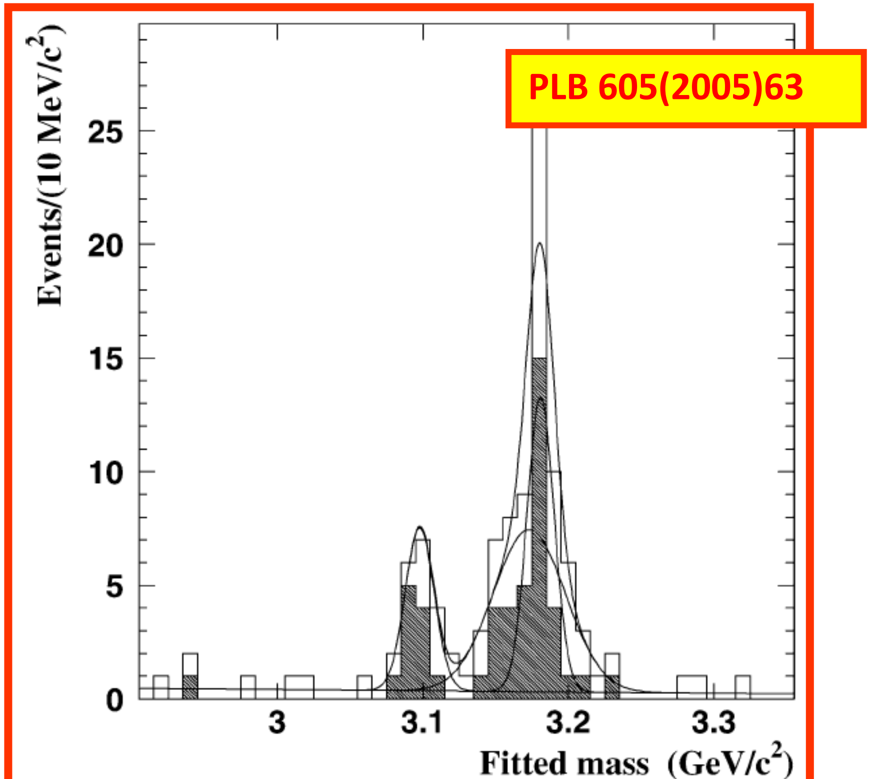
**Kuang's QCDME prediction:**

**BF[ψ(3770)→J/ψ$\pi^+\pi^-$]=(0.1-- 0.7)%**

**M.Voloshin's QCDME prediction:**

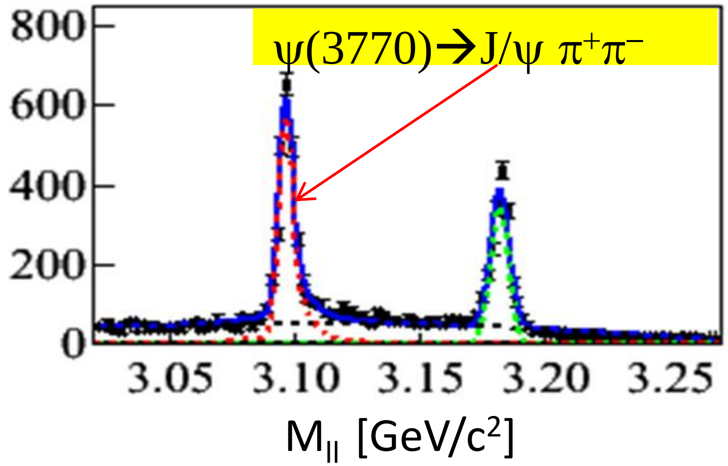
**BF[ψ(377J/ψ$\pi^+\pi^-$]<0.001%**

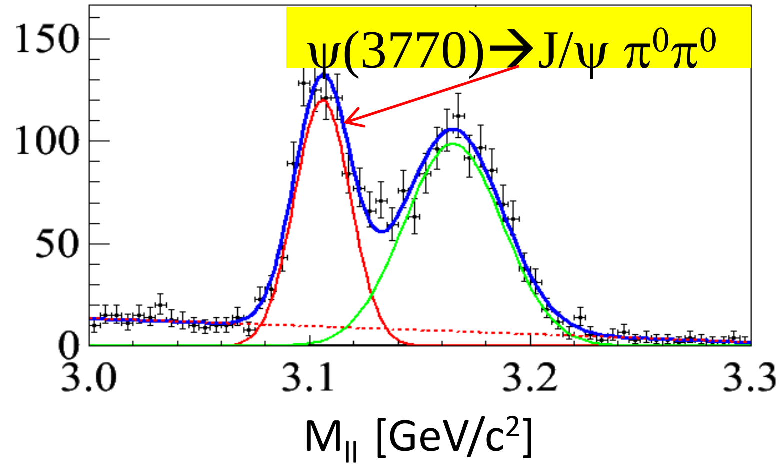
**Results from BES-II in agreement with Kuang's prediction. Observation later confirmed by CLEOc**



# D-wave charmonium hadronic transition at BES-III

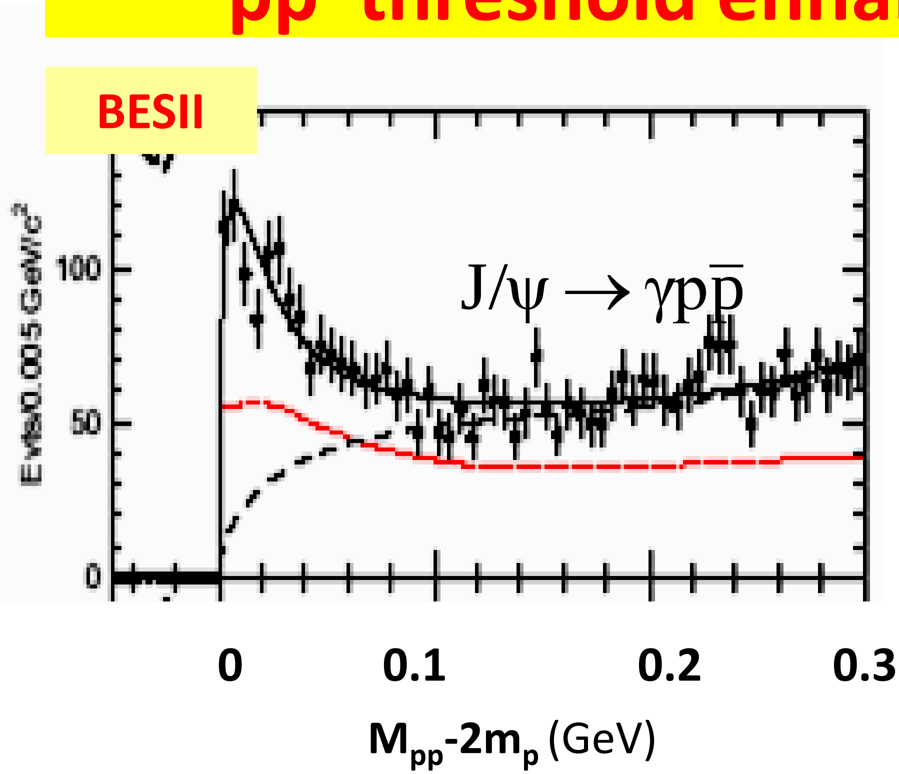
- ✓ **Branching ratio and decay width of the following process:**
  - $\psi(3770) \rightarrow J/\psi\, \pi^+\pi^-$ , $J/\psi\, \pi^0\pi^0$
  - $\psi(3770) \rightarrow J/\psi\, \pi^0$
  - $\psi(3770) \rightarrow J/\psi\, \eta$
- ✓ **S-D mixing angle $\theta_{mix}$**
- ✓ **$\pi\pi$ invariant mass spectrum from $\psi(3770) \rightarrow J/\psi\, \pi\pi$ for parameters $c_1$ and $c_2$ in the Kuang's QCDME model**



# Light hadron physics

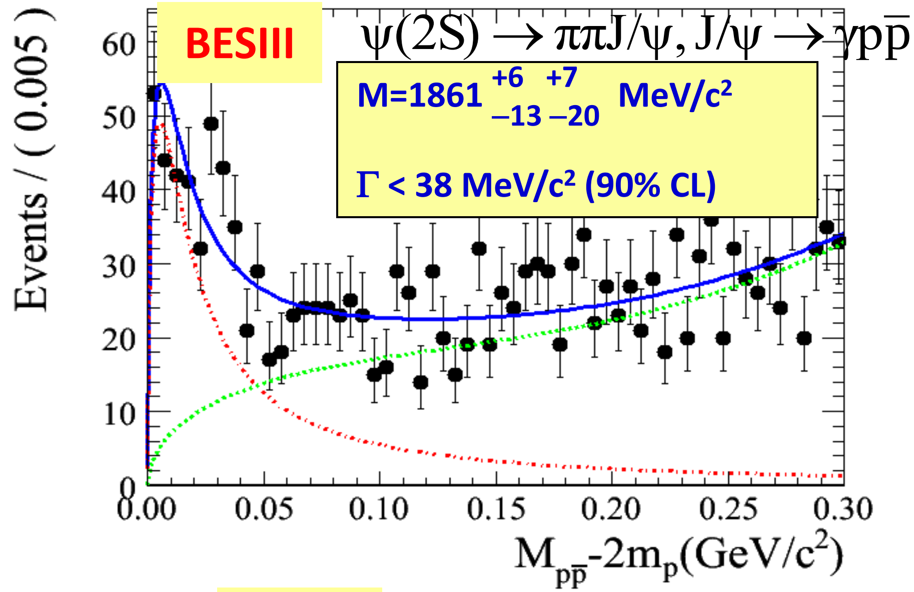
# Confirmation of the BESII observation: $p\bar{p}$ threshold enhancement in $J/\psi$ decays

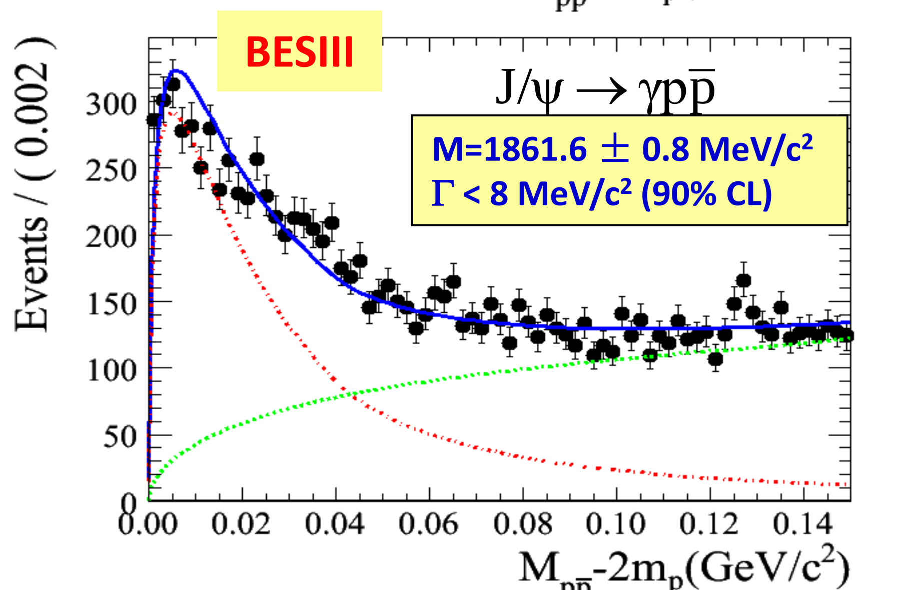



$M=1859^{+3\ +5}_{-10\ -25}$ MeV/c²

$\Gamma < 30$ MeV/c² (90% CL)

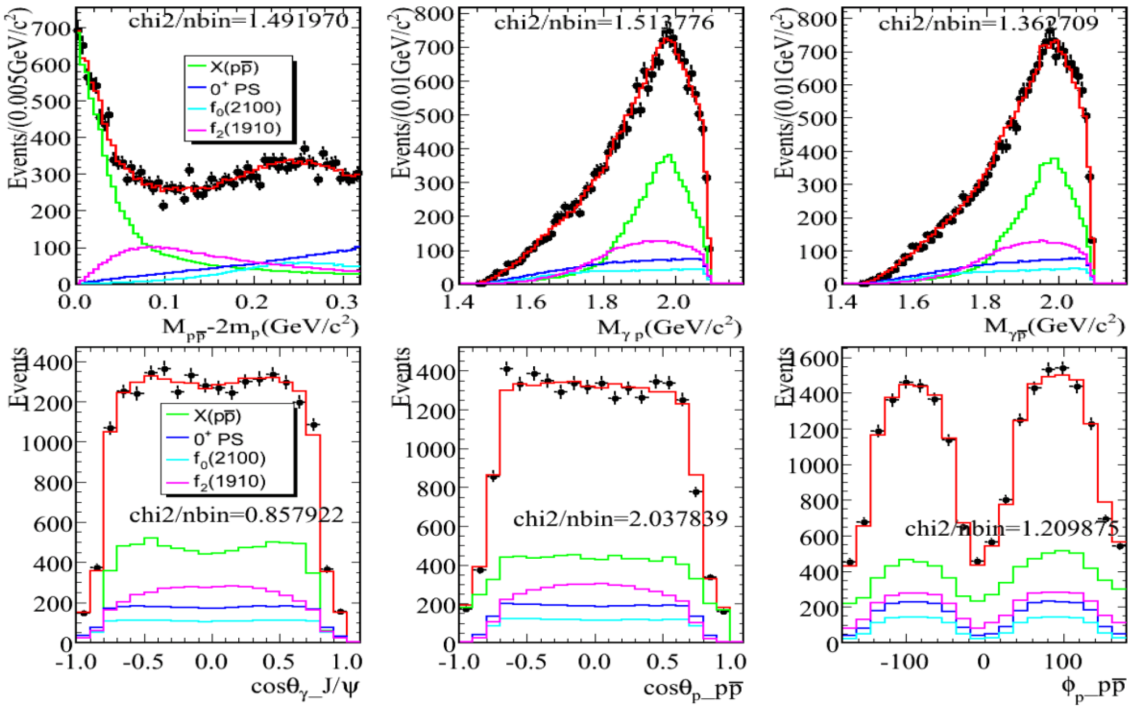
arXiv:1001.5328, accepted by Chinese Phys. C



# PWA of $J/\psi\to\gamma p\bar{p}$ @ BESIII

BESIII: PRL 108, 112003 (2012)




$f_0(2100)$ / $f_2(1910)$ fixed to PDG.
Sig. of X(ppbar) >>30σ

- The fit with a BW and S-wave FSI(I=0) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 ⇒ 7.1σ.

$$J^{PC} = 0^{-+}$$

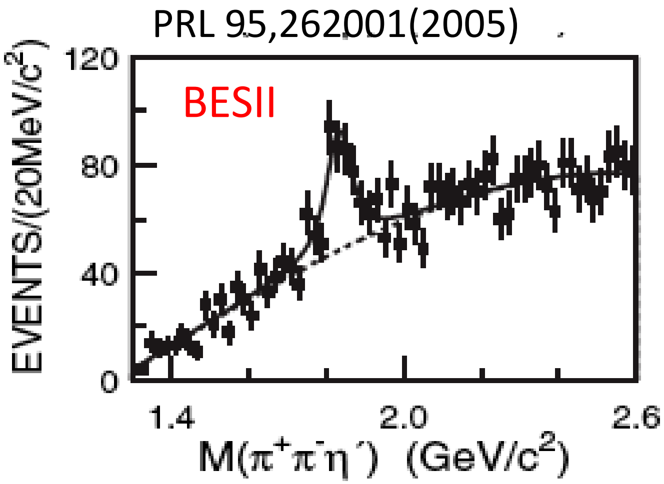
$$M = 1832^{+10}_{-5}(\text{stat.})^{+18}_{-17}(\text{syst}) \pm 19(\text{model})\ \text{MeV}/c^2$$

$$\Gamma = 13 \pm 39(\text{stat.})^{+10}_{-13}(\text{syst}) \pm 4(\text{model})\ \text{MeV}/c^2 (\Gamma < 60\text{MeV}/c^2 @ 90\text{C.L.})$$

$$\text{Br}(J/\psi \to \gamma X)\text{Br}(X \to p\bar{p}) = (9.0^{+0.4}_{-1.1}(\text{stat.})^{+1.5}_{-5.0}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$

Different FSI models → Model dependent uncertainty

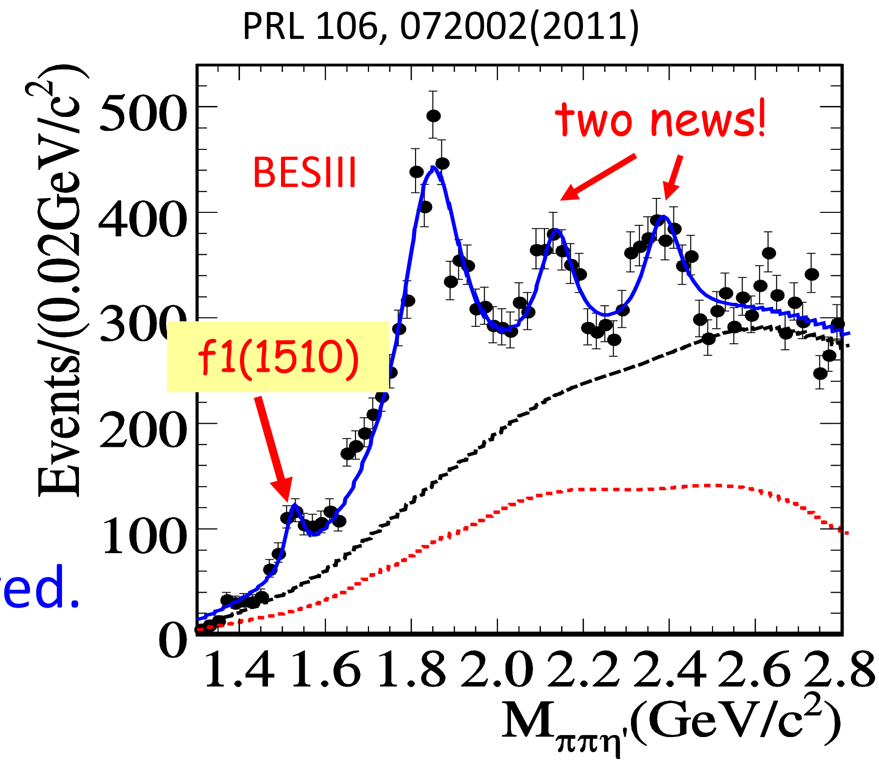
# X(1835) and two new structures




$$BESII\ result(\text{Stat. sig.} \sim 7.7\sigma):$$

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

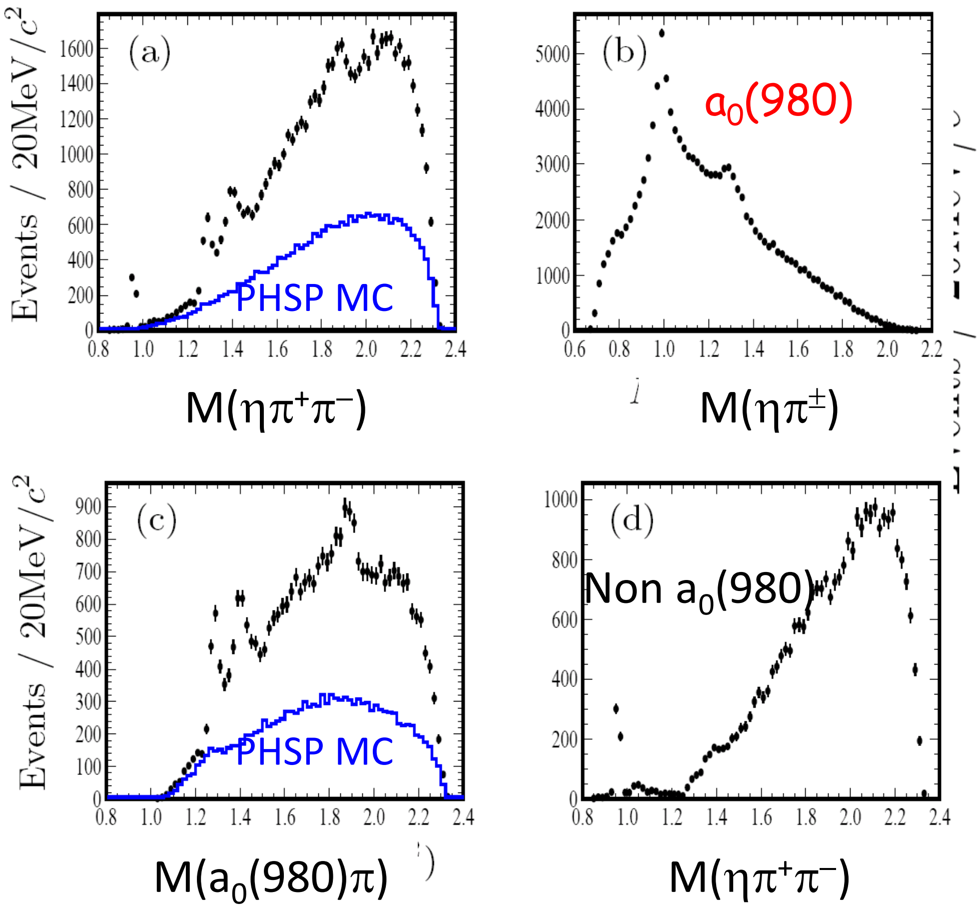
$$\Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst})\text{MeV}$$



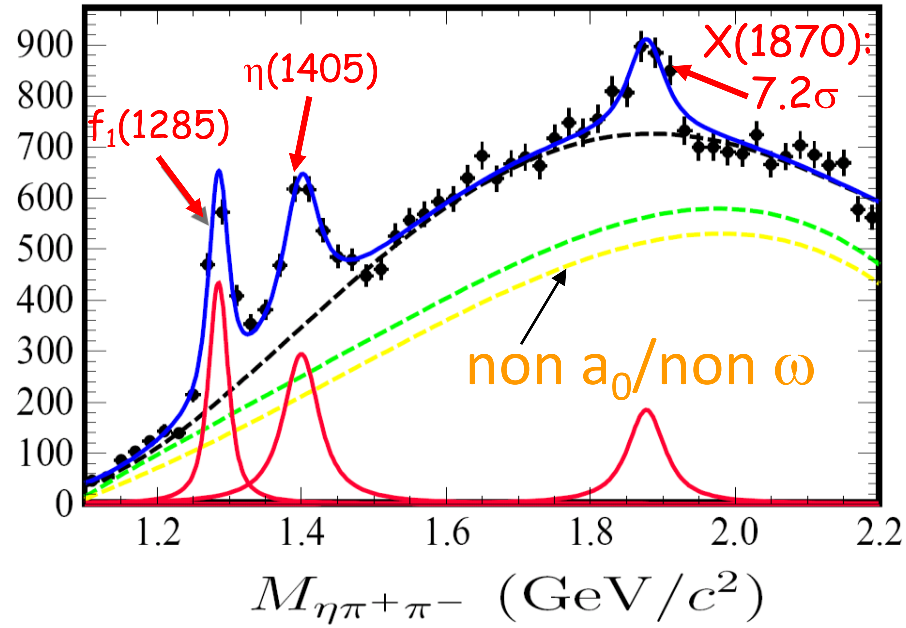

- X(1835) was observed in $J/\psi \to \gamma\eta'\pi\pi$ at BESII.
- X(1835) is confirmed at BESIII with 225 M $J/\psi$.
- Two new structures are observed.

BESIII: PRL 106 (2011) 072002

# X(1870) in $J/\psi \to \omega X$, $X \to a_0(980)\pi\pi$




PRL 107(2011)182001




| Resonance | Mass (MeV/$c^2$) | Width (MeV/$c^2$) | Branch ratio ($10^{-4}$) |
|---|---|---|---|
| $f_1(1285)$ | $1285.1 \pm 1.0^{+1.6}_{-0.3}$ | $22.0 \pm 3.1^{+2.0}_{-1.5}$ | $1.25 \pm 0.10^{+0.19}_{-0.20}$ |
| $\eta(1405)$ | $1399.8 \pm 2.2^{+2.8}_{-0.1}$ | $52.8 \pm 7.6^{+0.1}_{-7.6}$ | $1.89 \pm 0.21^{+0.21}_{-0.23}$ |
| $X(1870)$ | $1877.3 \pm 6.3^{+3.4}_{-7.4}$ | $57 \pm 12^{+19}_{-4}$ | $1.50 \pm 0.26^{+0.72}_{-0.36}$ |

New particle？

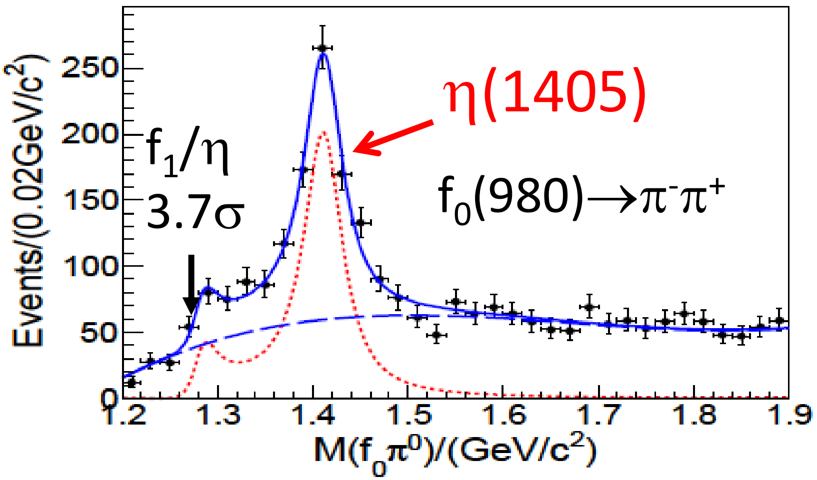
$\eta_2(1870)$ ？

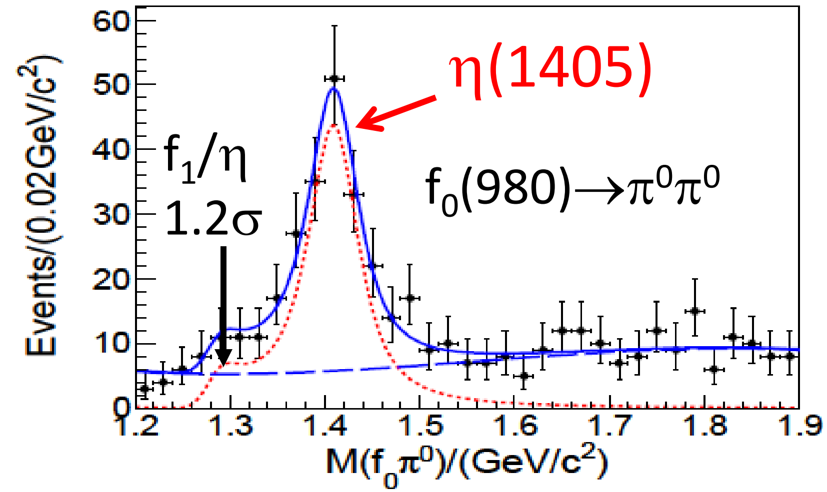
X(1835)?

# $J/\psi \to \gamma 3\pi$

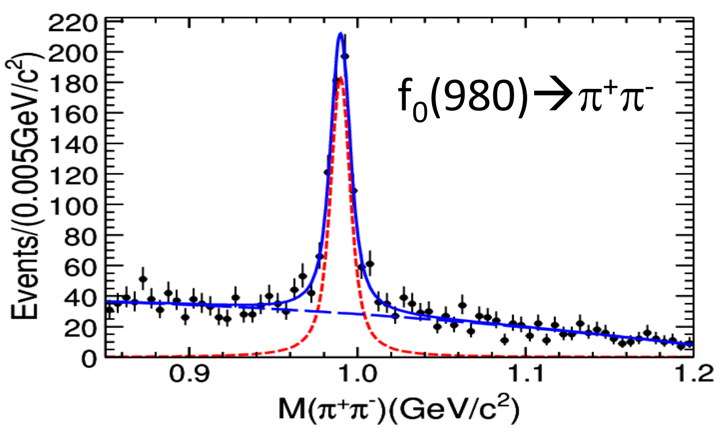
BESIII: PRL 108 (2012) 182001

- First observed large isospin breaking : $\eta(1405) \to f_0(980)\pi^0$

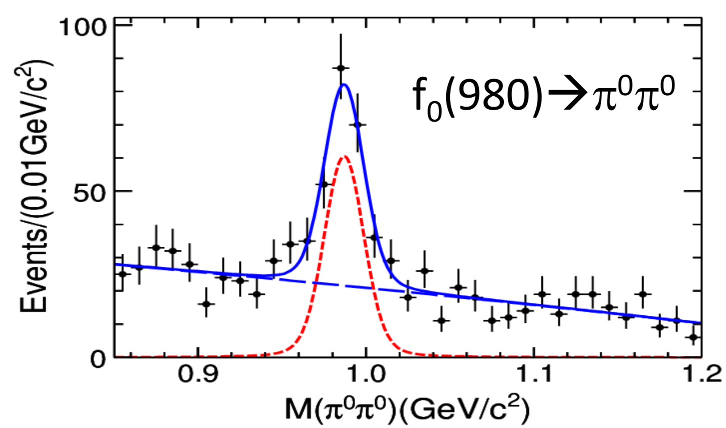



- observed narrow $f_0(980)$ – much narrow than PDG value




$M = 989.9 \pm 0.4$ MeV
$\Gamma = 9.5 \pm 1.1$ MeV




$M = 987.0 \pm 1.4$ MeV
$\Gamma = 4.6 \pm 5.1$ MeV

General speaking， the isospin breaking in hadronic decays < 1% or at 0.1% level.

For example：

$$\frac{BR(\psi'\to\pi^0 J/\psi)}{BR(\psi'\to\eta J/\psi)} = 0.2\% \times \frac{|P_\pi|^3}{|P_\eta|^3}, \quad \frac{BR(\eta'\to\pi^+\pi^-\pi^0)}{BR(\eta'\to\pi^+\pi^-\eta)} = 0.9\%$$

However:

$$\boxed{\frac{BR(\eta(1405)\to f_0(980)\pi^0)}{BR(\eta(1405)\to a_0(980)\pi)} \approx (17.9 \pm 4.2)\%}$$

How to understand? Stimulated many theoretical speculations.

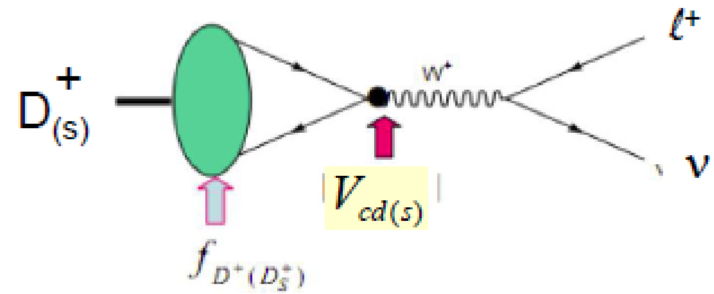
J.J.Wu et al, PRL 108, 081803(2012)

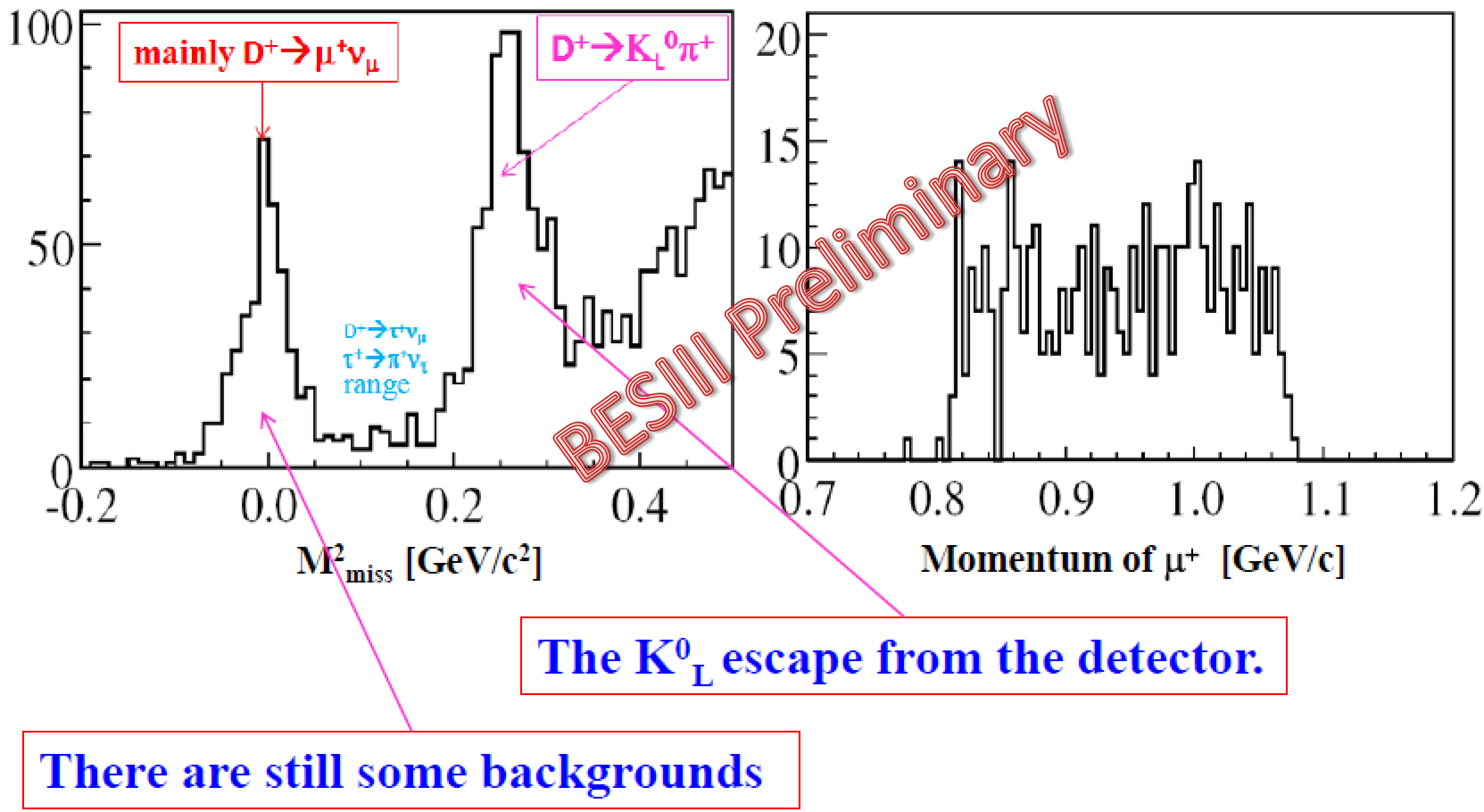
# Charm Physics

# Preliminary study of $D^+ \to \mu\nu$ at BESIII

- 9 singly $D^-$ tag modes

$$N_{D^-}^{tag} = (1.566 \pm 0.002) \times 10^6 \text{ in } 2.9\ fb^{-1}$$



Results: $N(D^+ \to \mu^+ \nu) = 377.3 \pm 19.4$
$BF(D^+ \to \mu^+ \nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4}$

$$\Gamma(D^+ \to l^+ \upsilon_l) = \frac{G_F^2 f_{D^+}^2}{8\pi} |V_{cd}|^2 m_l^2 m_{D^+} \left(1 - \frac{m_l^2}{m_{D^+}^2}\right)^2$$

$f_{D+} = (203.91 \pm 5.72 \pm 1.97)$ MeV
$|V_{cd}| = (0.222 \pm 0.006 \pm 0.005)$



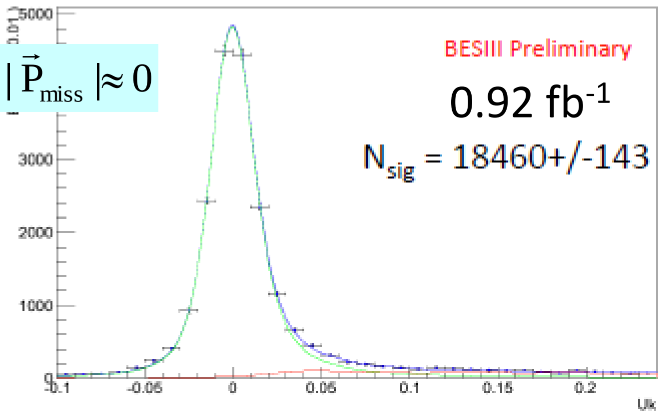
| Experiment | $B(D^+ \to \mu^+ \nu_\mu)$ ($\times 10^{-4}$) | Average |
|---|---|---|
| CLEO-c | $(3.82 \pm 0.32 \pm 0.09)$ | $(3.76 \pm 0.18)$ |
| BES-III(PRLMNRY) | $(3.74 \pm 0.21 \pm 0.06)$ | |

| Experiment | $f_D$ (MeV) | Average |
|---|---|---|
| CLEO-c | $(205.8 \pm 8.5 \pm 2.5)$ | $(204.5 \pm 5.0)$ |
| BES-III(PRLMNRY) | $(203.91 \pm 5.72 \pm 1.97)$ | |

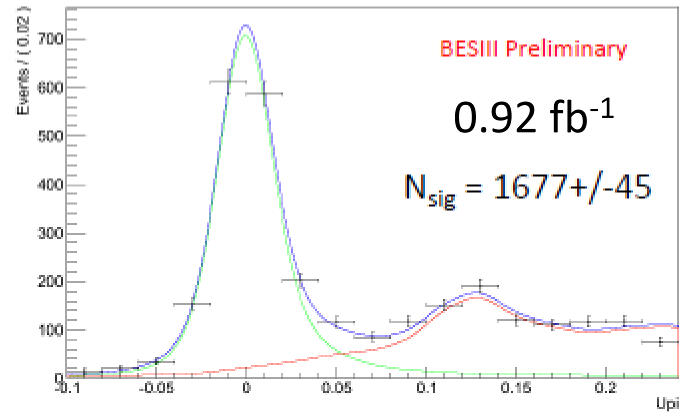
The error is still statistical dominated.

# Preliminary study of $D^0 \to \pi e \nu$ and $K e \nu$

$$U = E_{miss} - |\vec{P}_{miss}| \approx 0$$




$D^0 \to K e \nu$




$D^0 \to \pi e \nu$

Fit U distribution: BESIII Preliminary

| Mode | measured branching fraction(%) | PDG | CLEOc |
|---|---|---|---|
| $\bar{D}^0 \to K^+ e^- \bar{\nu}$ | $3.542 \pm 0.030 \pm 0.067$ | $3.55 \pm 0.04$ | $3.50 \pm 0.03 \pm 0.04$ |
| $\bar{D}^0 \to \pi^+ e^- \bar{\nu}$ | $0.288 \pm 0.008 \pm 0.005$ | $0.289 \pm 0.008$ | $0.288 \pm 0.008 \pm 0.003$ |

- Systematic uncertainties are preliminary
- Good consistency with CLEO-c, statistical precision comparable with only 1/3 data analyzed

# Summary

- BESIII collected
  - 1 billion $J/\psi$, 0.5 billion $\psi'$ data
  - R scan between 2.4 – 3.6 GeV
  - tau mass measurement (25/pb)
  - Phase measurement and J/psi lineshape
- Next physics run：
  - ~500 $pb^{-1}$ at 4260 MeV
  - ~500 $pb^{-1}$ at 4360 MeV
  - R scan at high mass region
- A lot of physics results. More are coming

Happy birthday,
Prof. Kuang.
I learned a lot from
you since 1986.
Thanks