Review of h_c, η_c and $\eta_c(2S)$

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BESIII
05-14-2012

CHARM2012, Hawaii

Introduction: Importance and Challenges of Charmonium

- **Great Lab for precision tests of quark mode**
- **Mysteries, e.g., "$\rho\pi$ puzzle"**
- **h_c, η_c, $\eta_c(2S)$**
  - **Predicted after J/ψ discovery**
  - **Technically challenging: statistic, low energy photon detection, interference, EM hinder effects…**
  - **Observed through various processes, but properties need to be understood**

In this talk:

h_c – mostly recently discovered charmonium state

– new measurements of production and properties

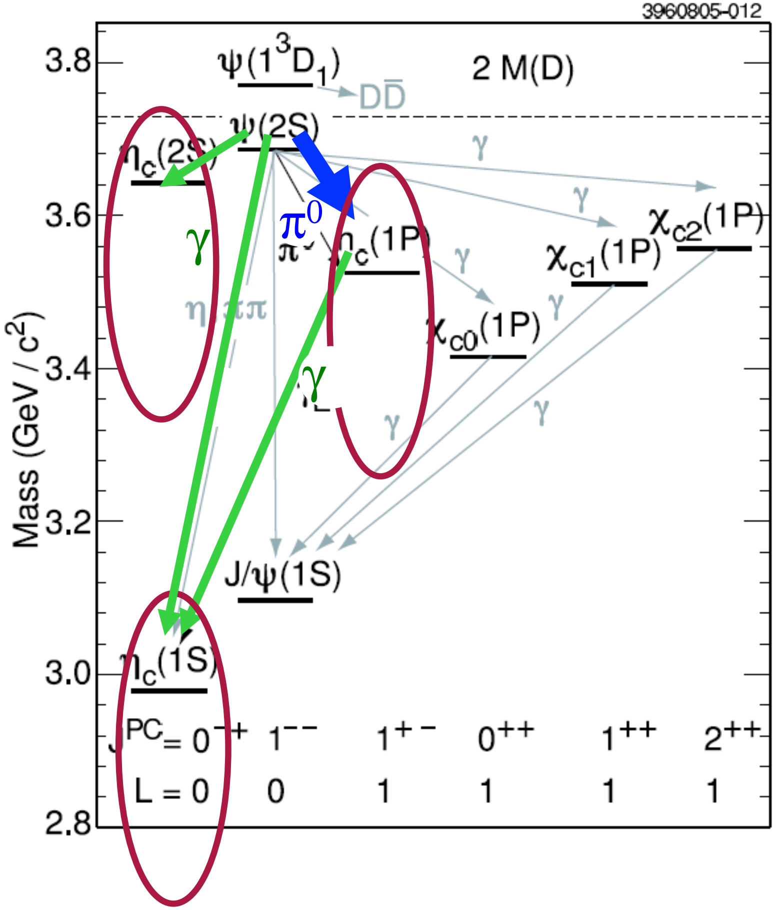
η_c – mass, width, distorted lineshape

$\eta_c(2S)$ – observed in charmonium transitions at last!

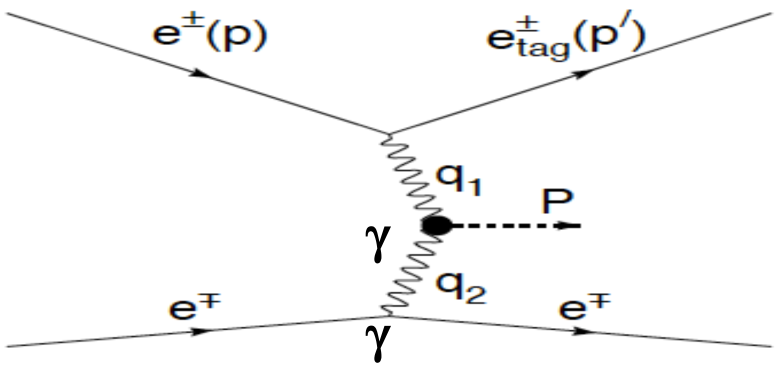
Experimental Approaches

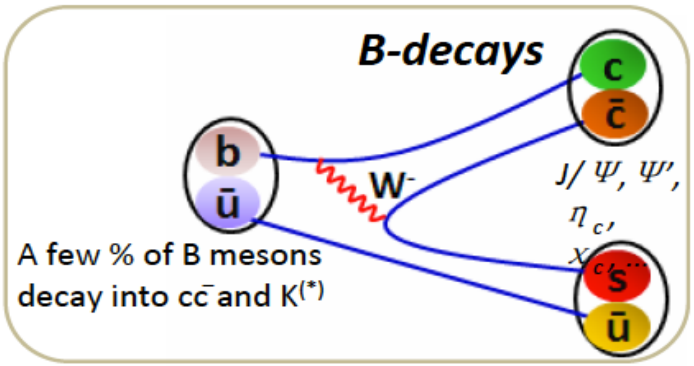
BESIII, CLEO-c:
From ψ' decays and e^+e^- annihilation near DDbar threshold
→ very clean and simple environment

BaBar, Belle:
From $\gamma\gamma$ and B decay
→ large production rate.

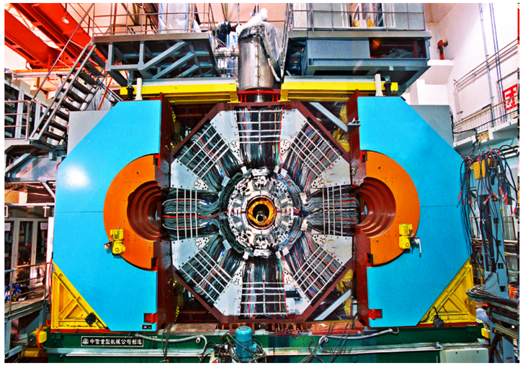


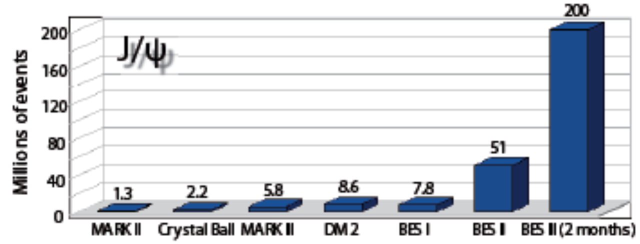
Two-Photon process

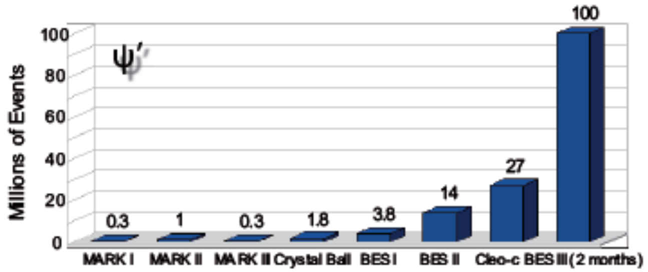




BEPCII/BESIII







BESIII Detector

Large luminosity

BEPCII

- Beam energy:
  $\sqrt{s}$=2.0 – 4.6 GeV
- Optimum energy:
  $\sqrt{s}$= 3.7 GeV
- Beam crossing
  angle:22 mrad
- Designed luminosity:1.0×10^{33}
- Record
  luminosity 0.57×10^{33}
- Energy spread: $5.16\text{x}10^{-4}$

He-based drift chamber:
$\delta p/p$=0.58%,
dE/dx~6%@1 GeV
CsI EM calorimeter:
δE~2.5%,
TOF: 80 ps (barrel), 100 ps(endcap)
1T Superconducting magnet
Muon system :
9 layers of RPC

BESIII has a comparable detector to CLEO-c with a much larger luminosity.

$h_c(^1P_1)$

- Spin singlet *P* wave (S=0, L=1)

- Potential model: if non-zero *P*-wave spin-spin interaction,

$\Delta M_{hf}(1P) = M(h_c) - \langle m(1\ ^3P_J)\rangle \neq 0$

where $\langle m(1\ ^3P_J)\rangle = [(M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9$,

- CLEO-c 1st observed h_c in $e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$

$\Delta M_{hf}(1P)=0.08\pm0.18\pm0.12$ MeV/c^2

Consistent with 1P hyperfine splitting = 0.

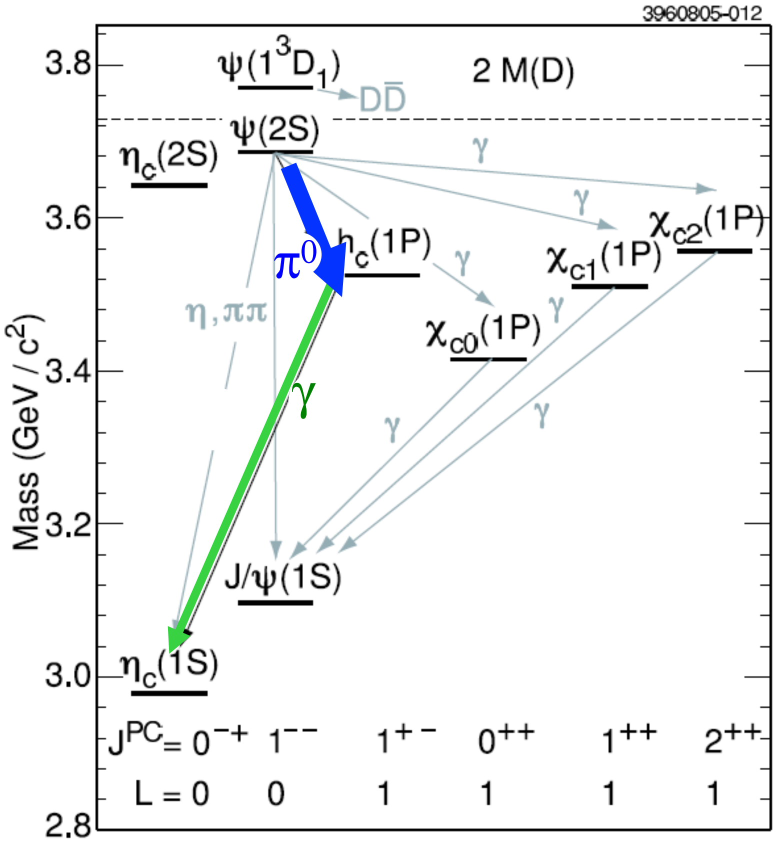
<u>Theoretical predictions:</u>

$BF(\psi(2S) \rightarrow \pi^0 h_c) = (0.4\text{-}1.3)\times10^{-4}$
$BF(h_c \rightarrow \gamma\eta_c)$ =48% (NRQCD)
$BF(h_c \rightarrow \gamma\eta_c)$ =88% (PQCD)
Kuang, PR D65 094024 (2002)

$BF(h_c \rightarrow \gamma\eta_c)$ =38%
Godfrey and Rosner, PR D66 014012(2002)

Different theoretical approaches give a wide range of predictions and that we've been waiting for experiment to resolve it.

Methods for studying the h_c in ψ' decays



Only detect the π^0 → "inclusive"
(compute M_{h_c} from kinematics)

$$Rate \propto Bf(\psi' \to \pi^0 h_c)$$

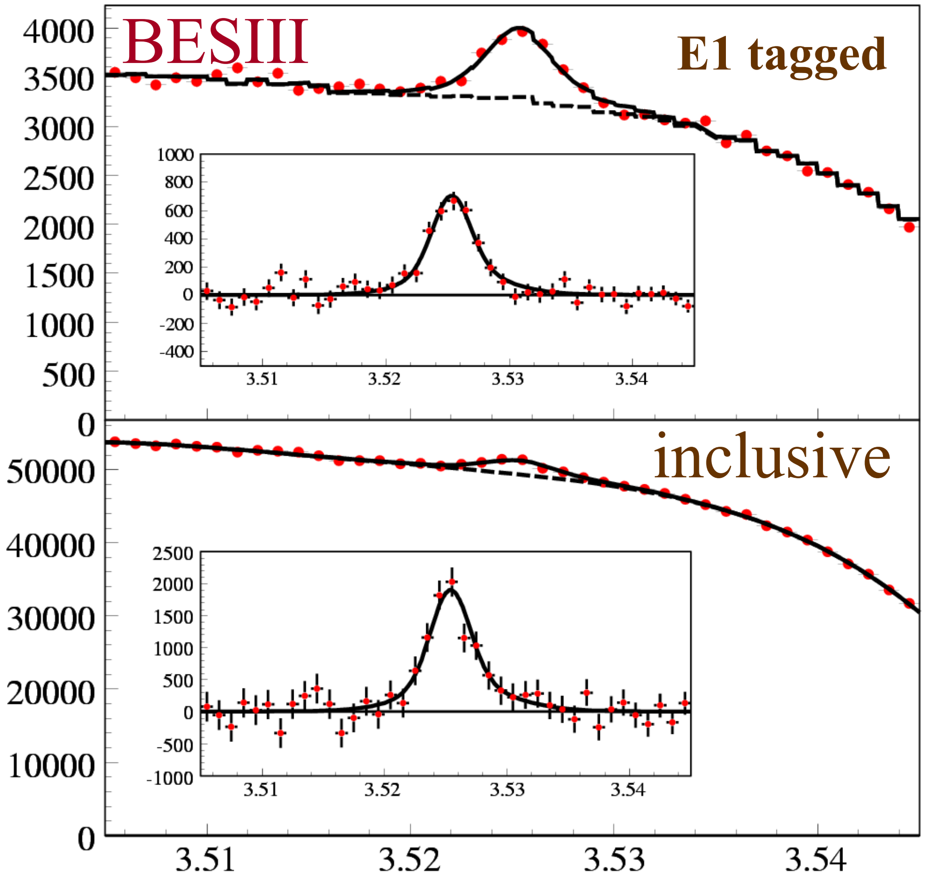
Detect the π^0 & γ → "E_1-tagged"
(compute M_{h_c} from kinematics)

$$Rate \propto Bf(\psi' \to \pi^0 h_c) \times Bf(h_c \to \gamma\eta_c)$$

Detect the π^0 , γ & *all* η_c → X_i decay products → "exclusive"
(compute M_{h_c} from 4-C kinematic fit)

$$Rate \propto Bf(\psi' \to \pi^0 h_c) \times Bf(h_c \to \gamma\eta_c) \times Bf(\eta_c \to X_i)$$

$\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ at BESIII



BESIII: 106M ψ' :
PRL 104 132002 (2010)

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

<1.44 MeV @90%

CLEO-c: PRL 101 182003 (2008)

Mass = **3525.28±0.19±0.12** MeV

Width: fixed at 0.9 MeV

Hyperfine mass splitting

$\Delta M_{hf}(1^1P) = M(h_c) - \langle m(1^3P_J)\rangle$

BESIII: **0.10±0.13±0.18** MeV/c^2

CLEO-c: **0.02±0.19±0.13 MeV/c^2**

By combining inclusive results with E1-photon tagged results

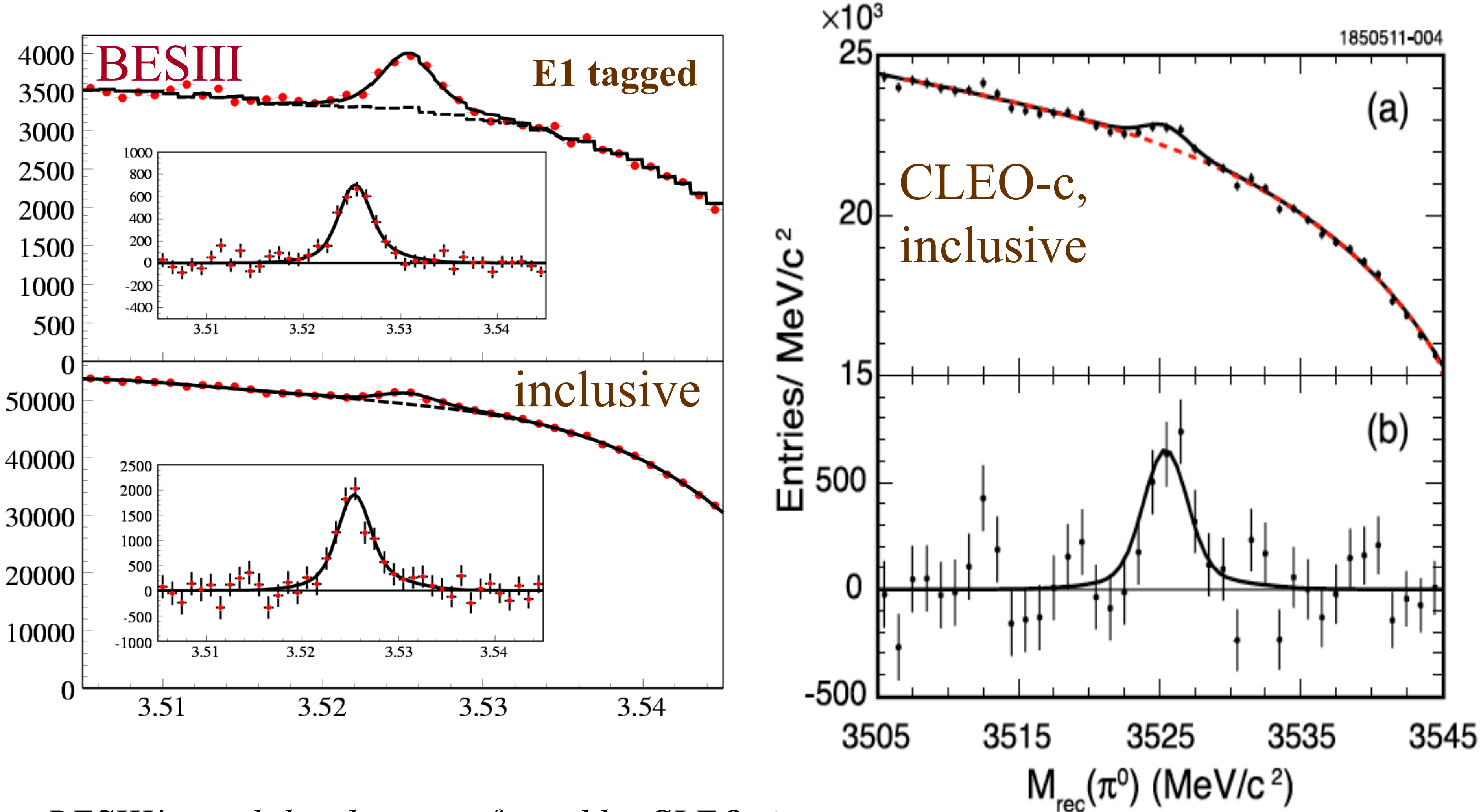
$BF(\psi' \to \pi^0 h_c)$ = **(8.4±1.3±1.0) ×10^{-4}**

$BF(h_c \to \gamma\eta_c)$ = **(54.3±6.7±5.2)%**

Agrees with prediction from Kuang, Godfrey, Dude et al.

Make it possible to extract absolute h_c cross sections.

Inclusive $\psi' \to \pi^0 h_c$ at CLEO-c

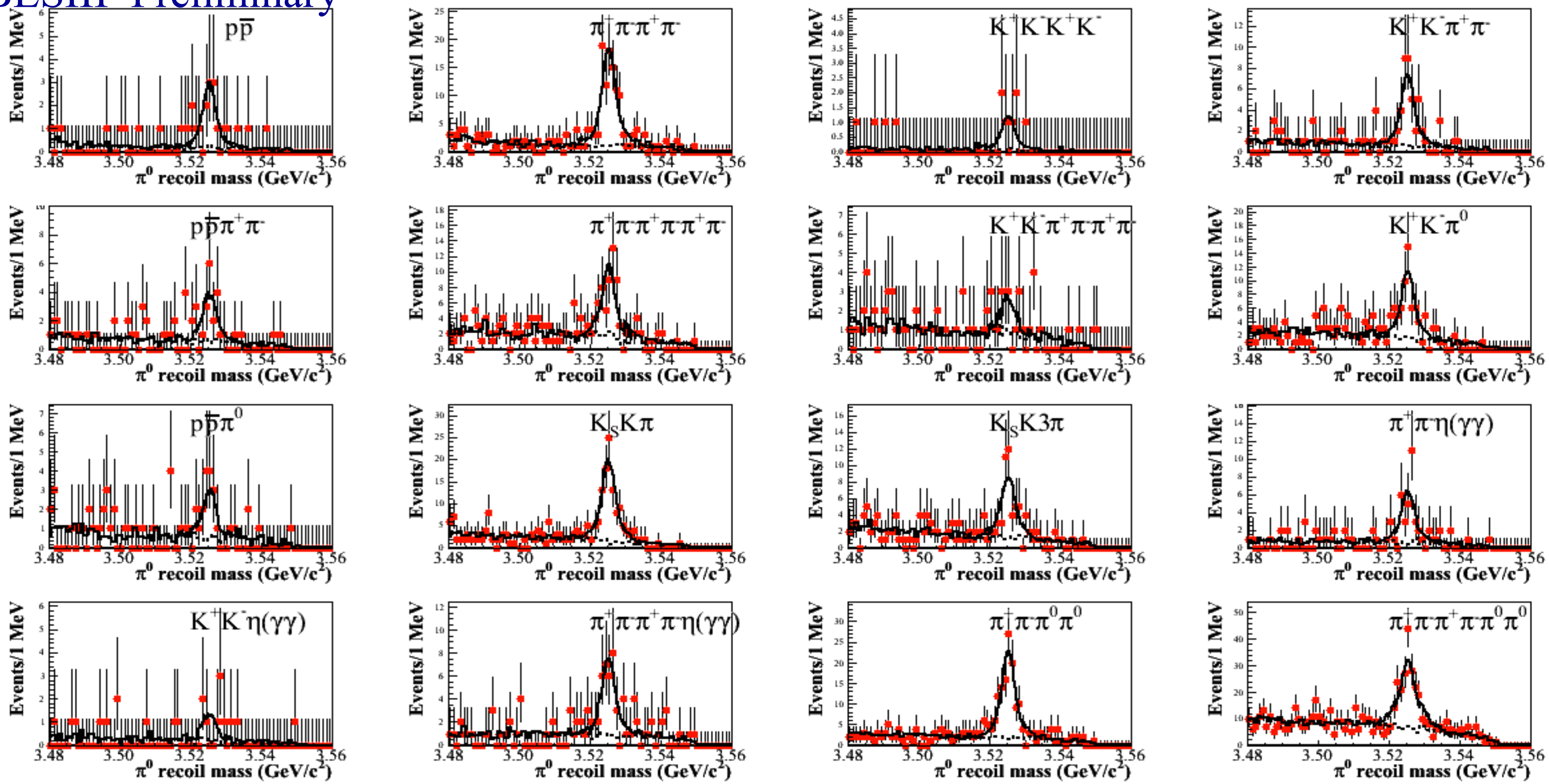


BESIII's result has been confirmed by CLEO-c

BF$(\psi' \to \pi^0 h_c)$ = **(9.0±1.5±1.3) ×10^{-4}** **Phys.Rev. D84 (2011) 032008**

$\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$, η_c exclusive decays at BESIII

BESIII Preliminary



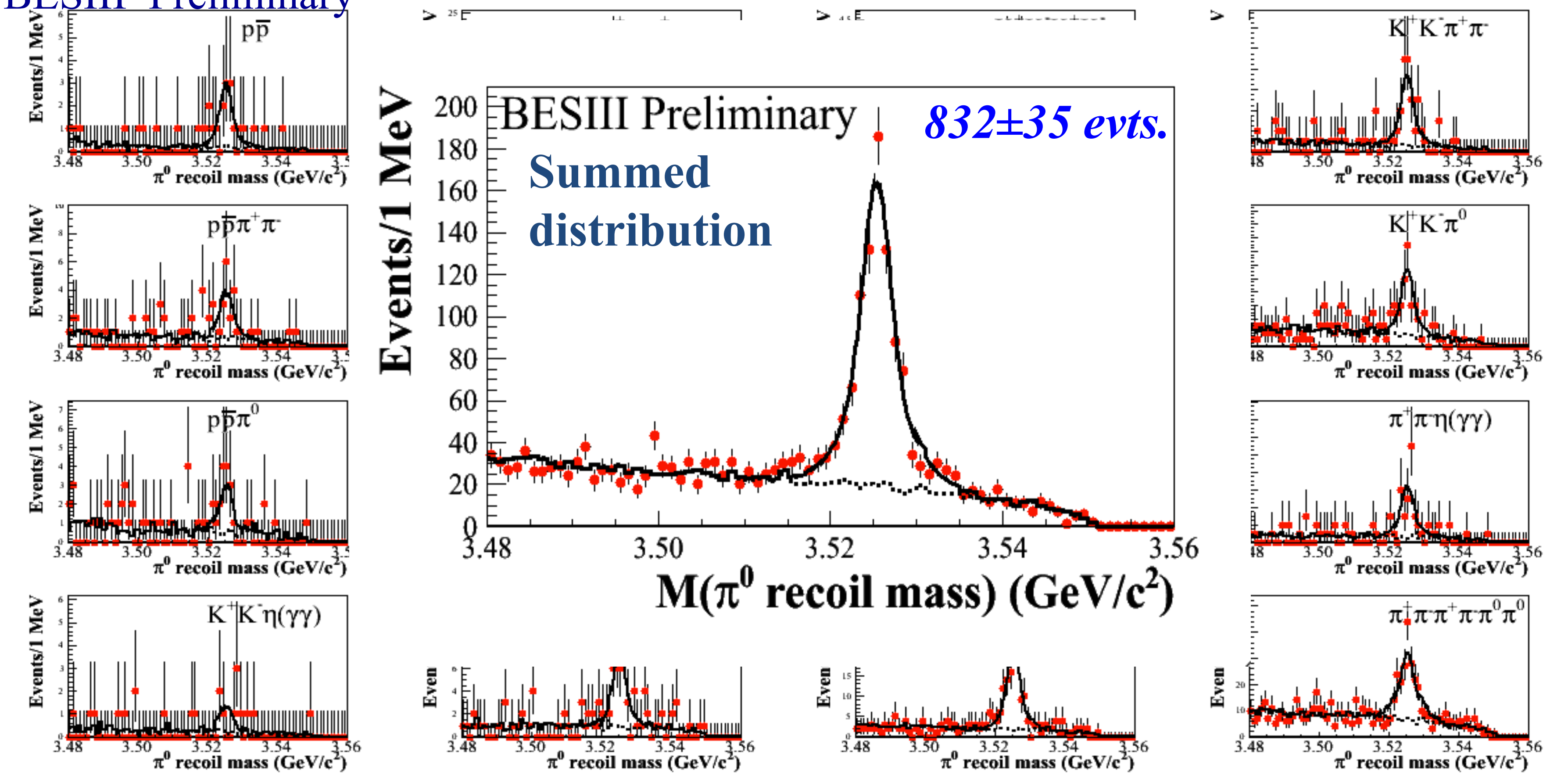
16 different η_c decay channels

Simultaneous fit to π^0 recoiling mass
χ^2/d.o.f. = 32/46
Mass = **3525.31 ± 0.11 ± 0.15** MeV/c^2
Width = **0.70 ± 0.28 ± 0.25** MeV

consistent with BESIII E_1-tagged results

$\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, η_c exclusive decays at BESIII

BESIII Preliminary



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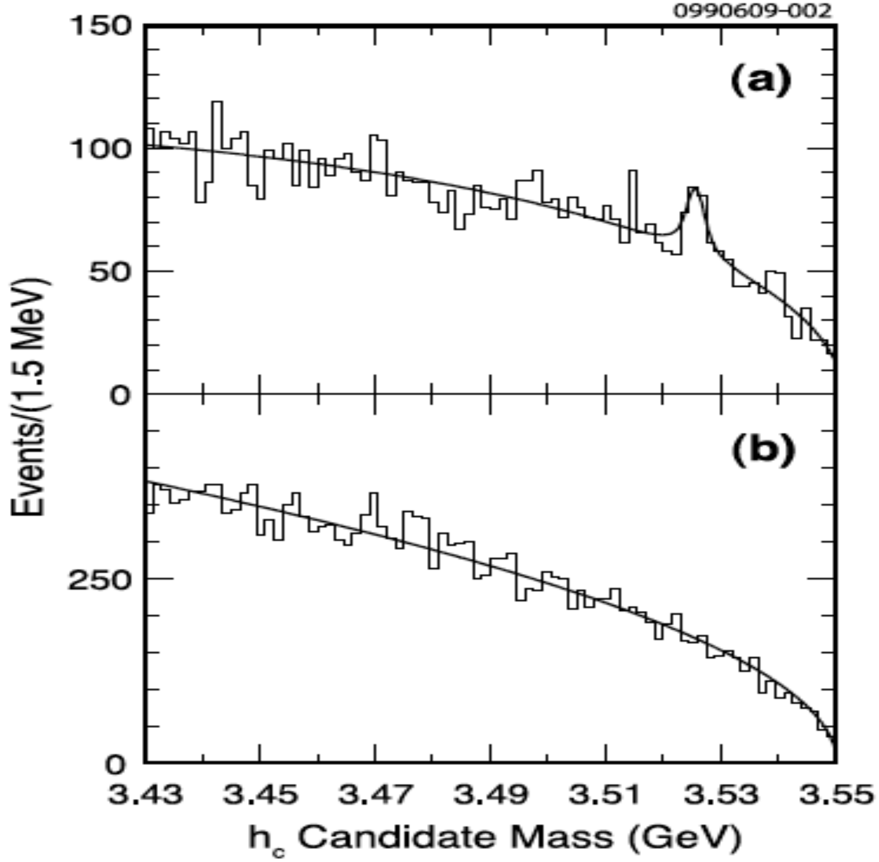
h_c hadronic decays at CLEO-c

Because the Br($h_c \rightarrow \gamma\eta_c$) = (54.3+-8.5)% (BESIII), the remaining hadronic decays should be large enough to be observed. CLEO-c has searched for odd pions decays and found the evidence of $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$.

$B(\psi' \rightarrow \pi^0 h_c) \times Br(h_c \rightarrow 2(\pi^+\pi^-)\pi^0)$
$= 1.88_{-0.45}^{+0.48}$ (stat.) $_{-0.30}^{+0.47}$ (syst.) $\times 10^{-5}$
Yield: $92_{-0.22}^{+23}$
Significance: 4.4σ

The main part of the remaining 45% hadronic decays is still unclear…

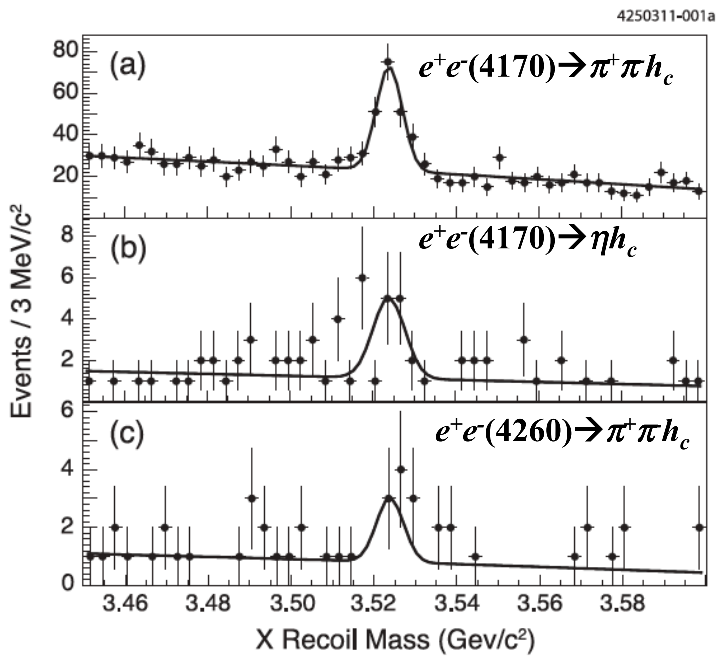
PRD80, 051106(R) (2009)



Invariant mass plots for $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$. for (a) data, and (b) non-h_c MC events.

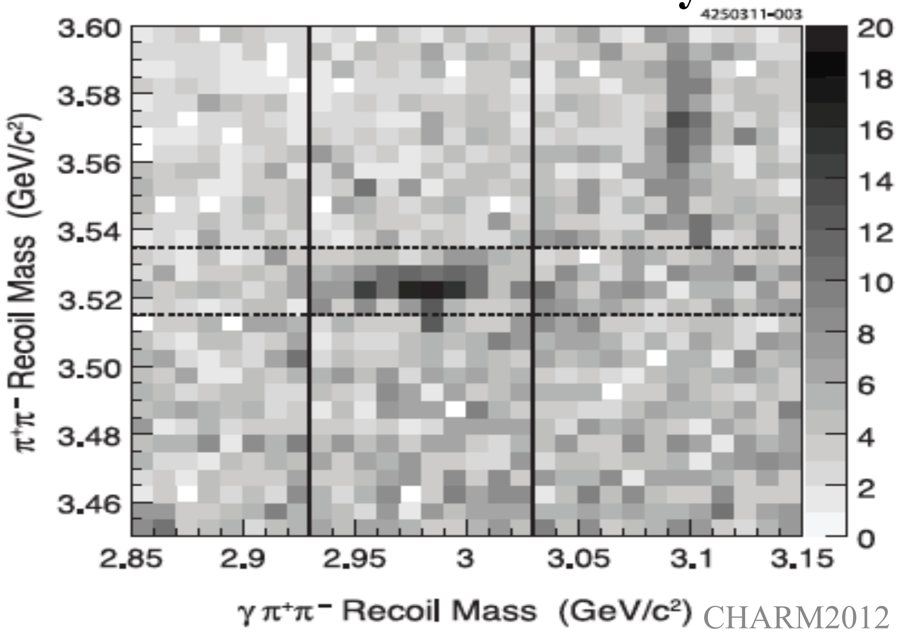
New h_c production mode found at CLEO-c

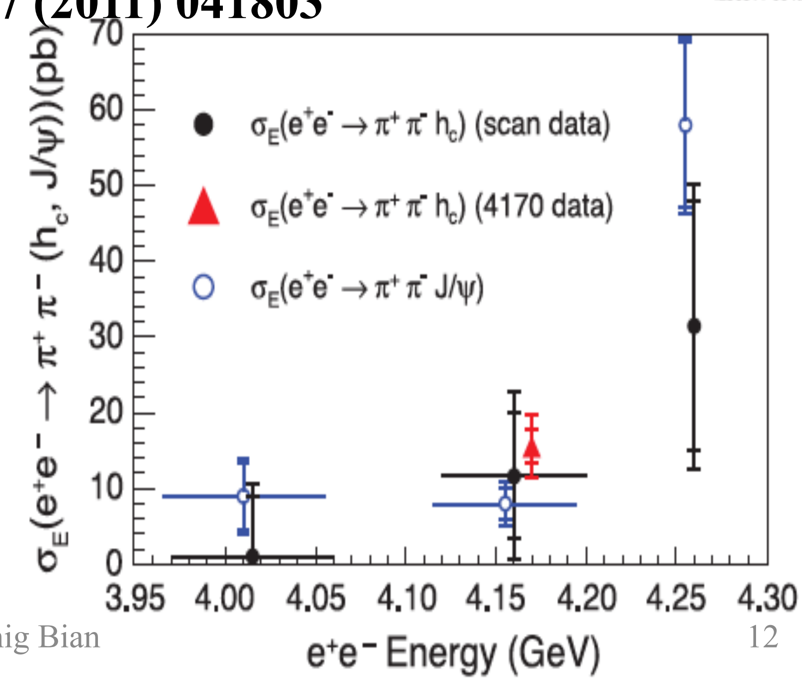
CLEO-c has discovered a prolific new source (~10σ) of h_c from e+e- annihilation at $\sqrt{s}$=4170MeV:
$e^+e^-(4170) \rightarrow \pi^+\pi^- h_c(1P)$
with $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$12 decay modes.



This discovery of the population of h_c in e^+e^- annihilations above the DD threshold of charmonium has led the Belle collaboration to search for $h_b(1P, 2P)$ in e^+e^- annihilations at $\sqrt{s}$ = 10.685 GeV using the same technique.

Phys.Rev.Lett. 107 (2011) 041803



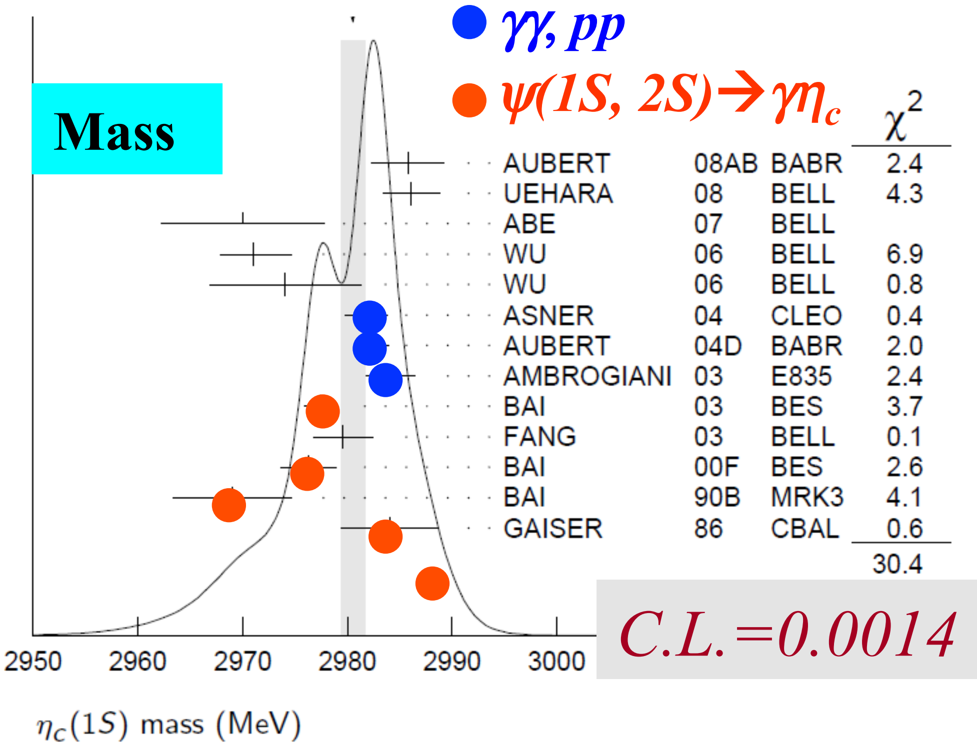


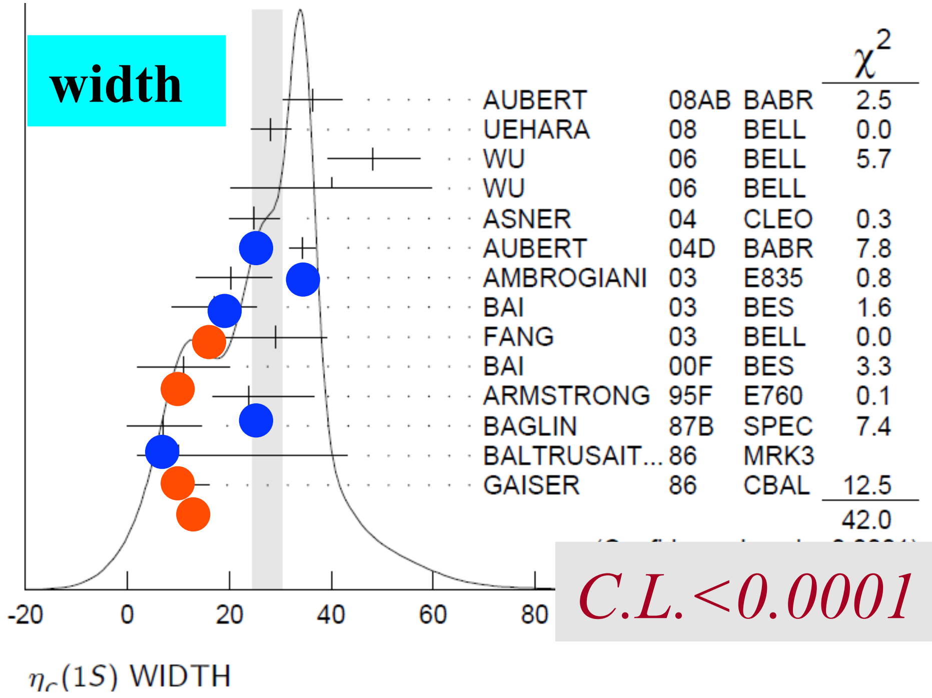
$\eta_c(1S)$

- The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII
- Parameters:

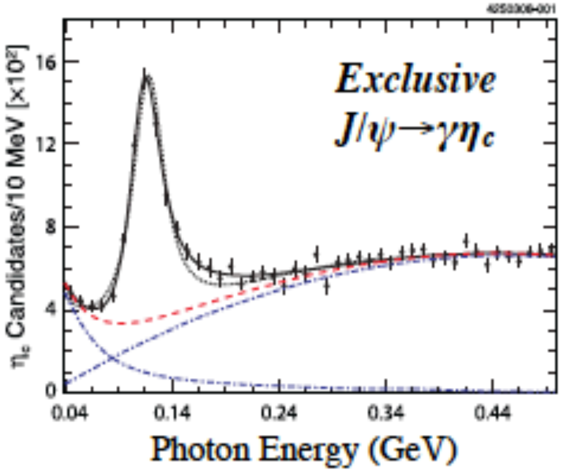
J/ψ, ψ' radiative transition: M ~ 2978.0MeV/c^2, Γ ~ 10MeV

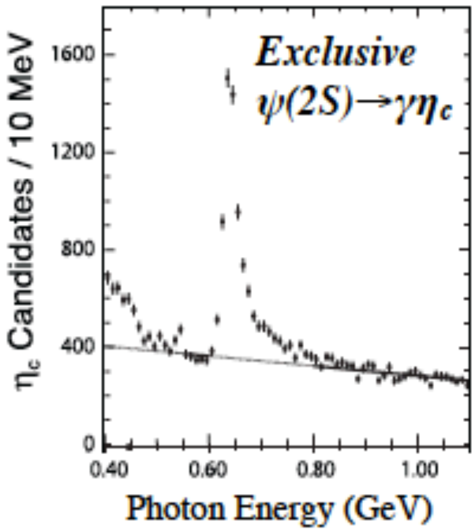
$\gamma\gamma$ process: M = 2983.1±1.0 MeV/c^2, Γ = 31.3±1.9 MeV





$\psi' \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ exclusive decays at CLEO-c



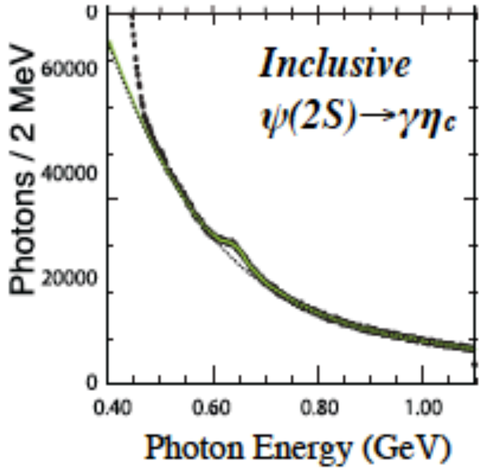


Three Measurements of M1 Transitions:

A. $B(\psi(2S)\rightarrow\gamma\eta_c) = (4.32\pm0.16\pm0.60)\times10^{-3}$ *from inclusive η_c decays.*

B. $B(J/\psi\rightarrow\gamma\eta_c) / B(\psi(2S)\rightarrow\gamma\eta_c)$ *using exclusive η_c decays.*

C. $B(J/\psi\rightarrow\gamma\eta_c) = (1.98\pm0.09\pm0.30)\%$ *taking A×B.*

× 

$= B(J/\psi\rightarrow\gamma\eta_c)$

Slide from Ryan Mitchell

PRL 106, 159903

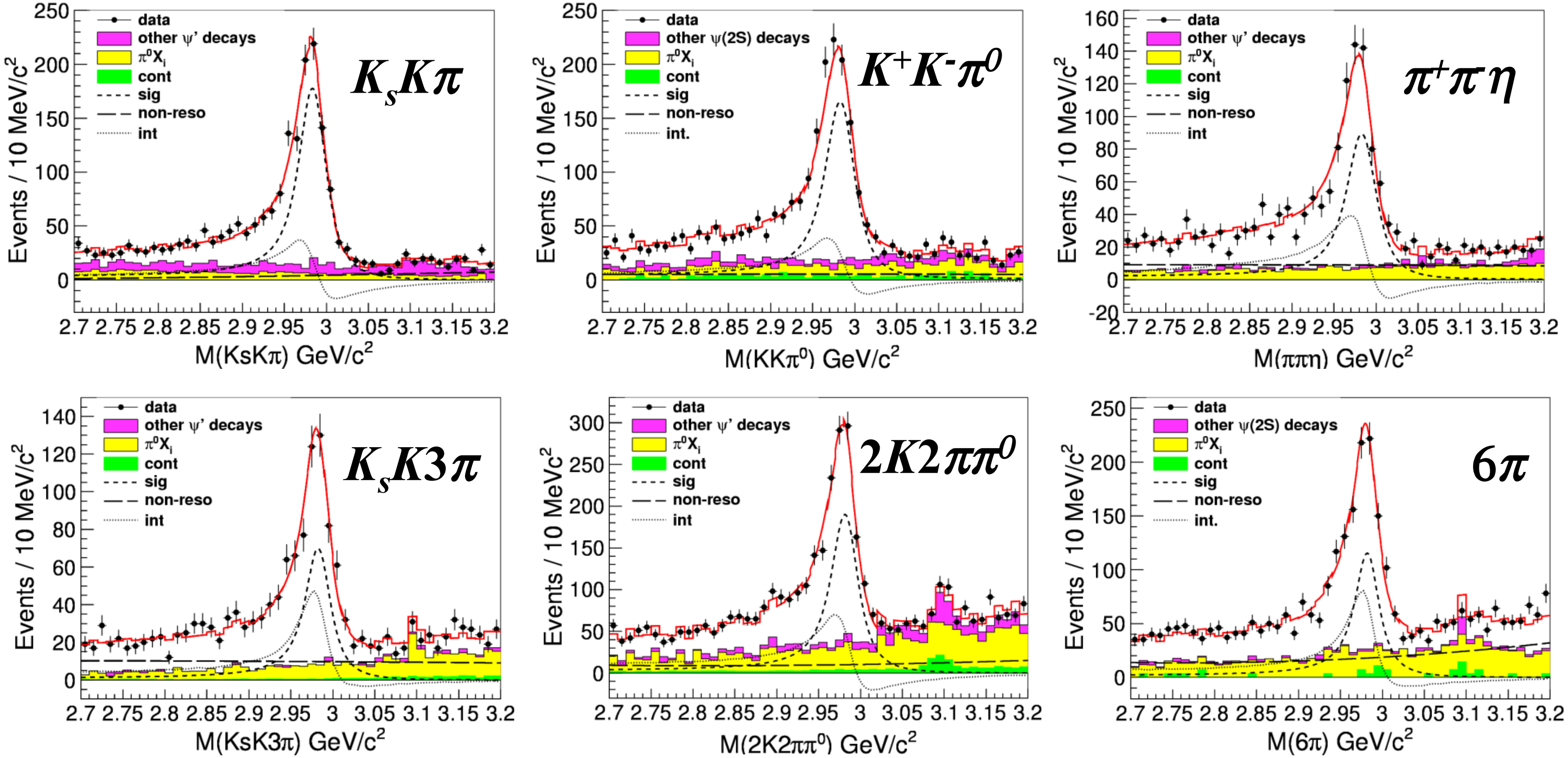
- One "surprise" was the non-trivial line-shape of the η_c.
- Recent Lattice QCD Results (**Dudek et al, PRD73,07450(2006)**) predict $\Gamma_{\gamma\eta c} = (2.0\pm0.1\pm0.4)$ keV
$\Rightarrow B(J/\psi\rightarrow\gamma\eta_c) = (2.1\pm0.1\pm0.4)\%$

The experimental value of $B(J/\psi\rightarrow\gamma\eta_c)$ is now in line with theoretical expectations.

The distortion of the η_c line shape in ψ' decays inspires BESIII's η_c study.

$\psi' \to \gamma\eta_c$, $\eta_c \to$ exclusive decays at BESIII

interference with non-resonant background is significant!!



Relative phase ϕ values from each mode are consistent within 3σ,

➔ *use a common phase value in the simultaneous fit.*

M: 2984.4 ± 0.5 ± 0.6 MeV

Γ: 30.5 ± 1.0 ± 0.9 MeV

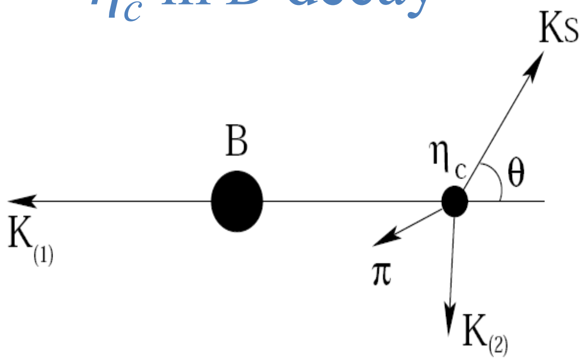
ϕ: 2.35 ± 0.05 ± 0.04 rad

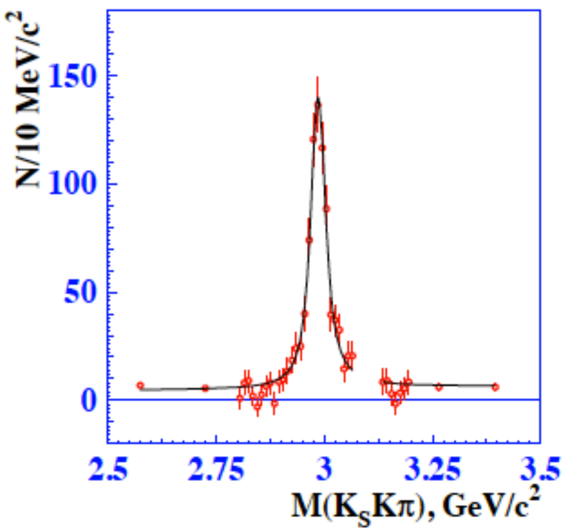
BESIII arXiv:1111:0398
accepted by PRL

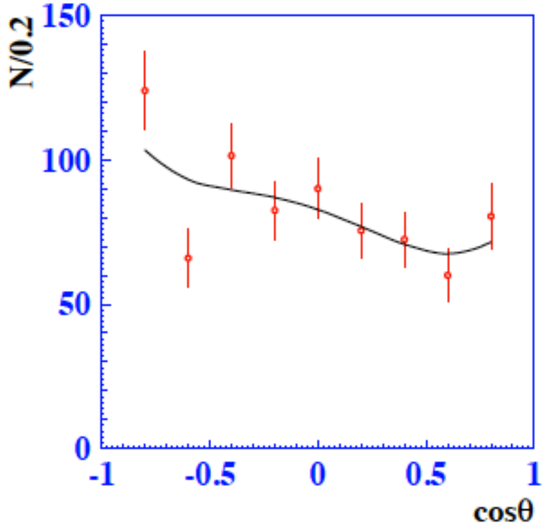
New mass and width measurement for η_c in B decays at Belle

$B^+ \to K^+ \eta_c, \eta_c \to K_S K^{+-} \pi^+$ **535 million BBbar-meson pairs**

η_c in B decay







Phys.Lett. B706 (2011) 139-149

2-dim fit of angle($K^+ K_S$) vs. M($K_S K \pi$)

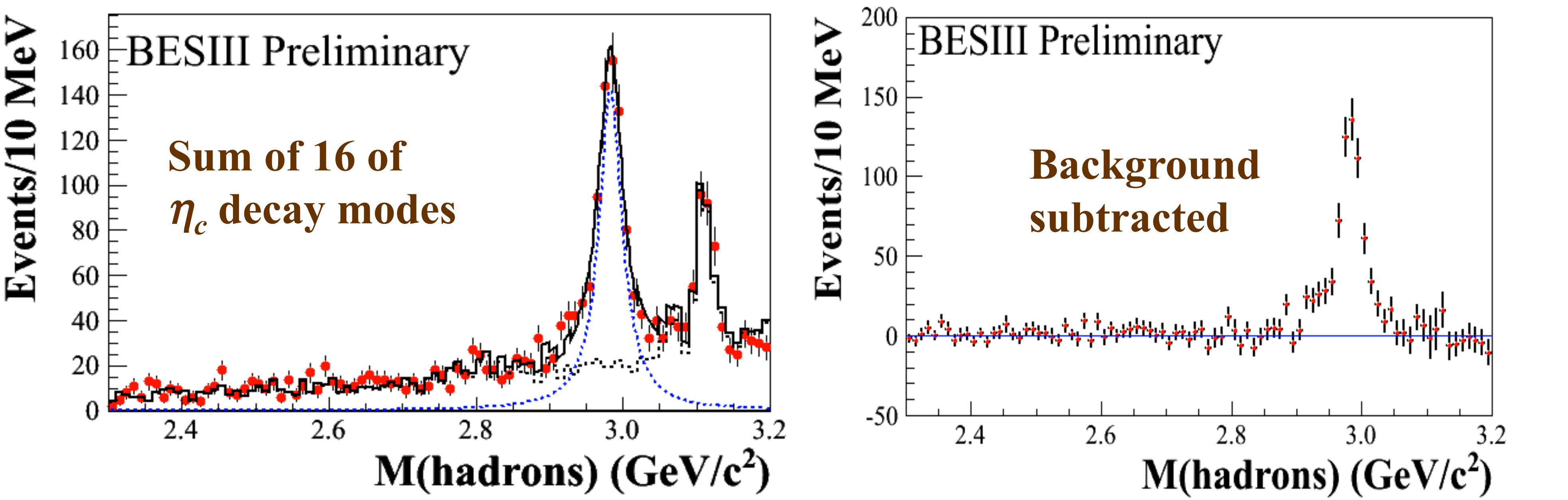
M = 2985.4 ± 1.5 $_{-2.0}^{+0.5}$ MeV

Γ = 35.1 ± 3.1 $_{-1.6}^{+1.0}$ MeV

Agreement with BaBar result in $\gamma\gamma \to \eta_c$

Agreement with BESIII result in $\psi' \to \gamma\eta_c$

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



The η_c lineshape in $h_c \rightarrow \gamma\eta_c$ is not as distorted as in $\psi' \rightarrow \gamma\eta_c$ decays because the non-resonant interfering bkg is small (B($h_c \rightarrow \gamma\eta_c$)=54%, B($\psi' \rightarrow \gamma\eta_c$)=0.34%). Ultimately, this channel will be best suited to determine η_c resonance parameters.

Yesterday's search → today's discovery → tomorrow's calibration

$\eta_c(2S)$

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

PRL 48 70 (1982)

"Seen" $\eta_c(2S)$ from inclusive photon spectrum of ψ' decays.

Branch ratios and parameters are far from modern measurements.

Observed in different processes other than radiative transition,

1. $B \to K\eta_c(2S)$
2. $\gamma\gamma \to \eta_c(2S) \to KK\pi$
3. double charmonium production

Belle: PRL 89 102001 (2002)
CLEO: 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)

M1 transition $\psi' \to \gamma\eta_c(2S)$

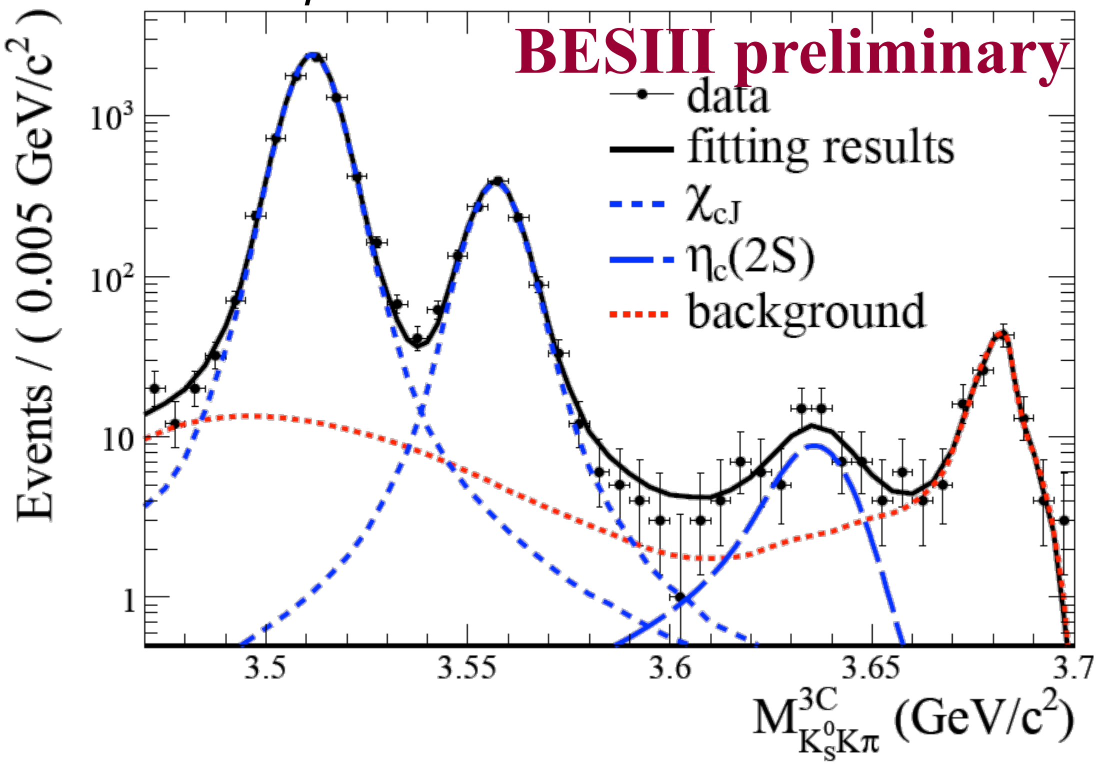
CLEO found no signals in 25M ψ'.

$BF(\psi' \to \gamma\eta_c(2S)) < 7.6\times10^{-4}$ CLEO: PRD 81 052002 (2010)

Experimental challenge : search for photons of 50 MeV

Observation of $\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma(K_sK\pi)$ at BESIII

106M ψ'



Width fixed to 12 MeV (world ave.)

Events: 50.6±9.7; Significance >6.0σ!

Mass = 3638.5±2.3±1.0 MeV/c^2

$BF(\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma K_sK\pi)$
=(2.98±0.57±0.48)×10^{-6}

$BF(\eta_c(2S) \rightarrow \bar{K}K\pi)$=(**1.9±0.4±1.1**)%
BaBar: PR D78 012006 (2008)

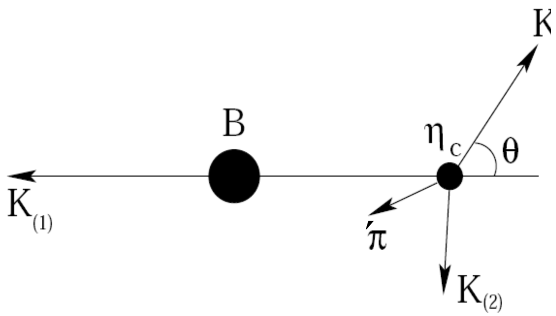
$BF(\psi' \rightarrow \gamma\eta_c(2S))$
= (4.7±0.9±3.0)×10^{-4}

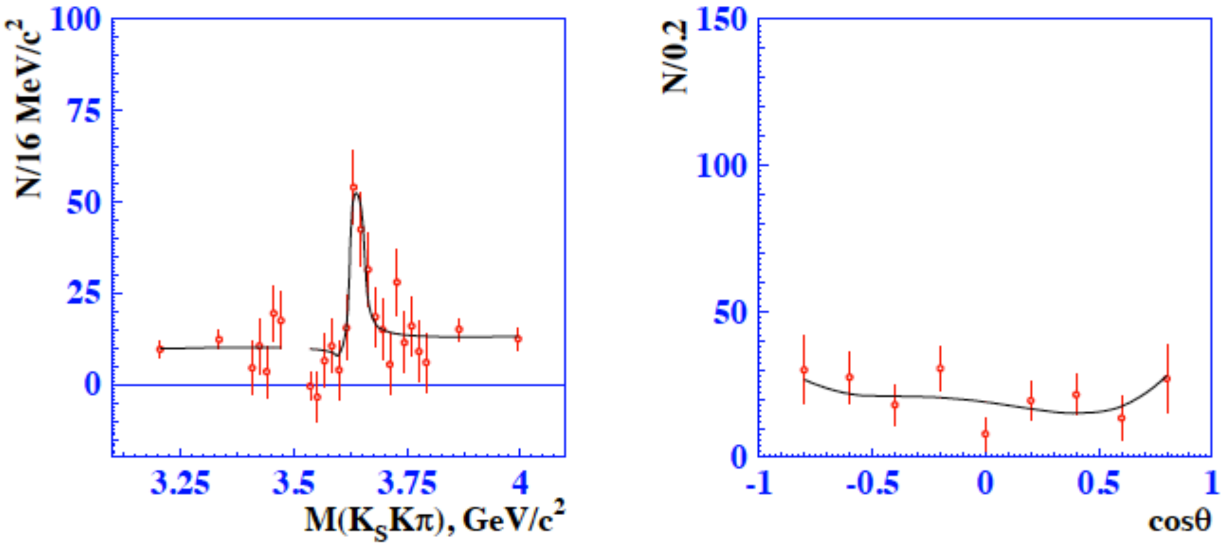
CLEO-c: <**7.6*10^{-4}**
PR D81 052002 (2010)

Potential model predicts
(0.1~ 6.2)*10^{-4}
PRL 89 162002 (2002)

New mass and width measurement of $\eta_c(2S)$ in B decays at Belle

$B^+ \to K^+ \eta_c(2S)$, $\eta_c(2S) \to K_S K^\pm \pi^\mp$





Phys.Lett. B706 (2011) 139-149

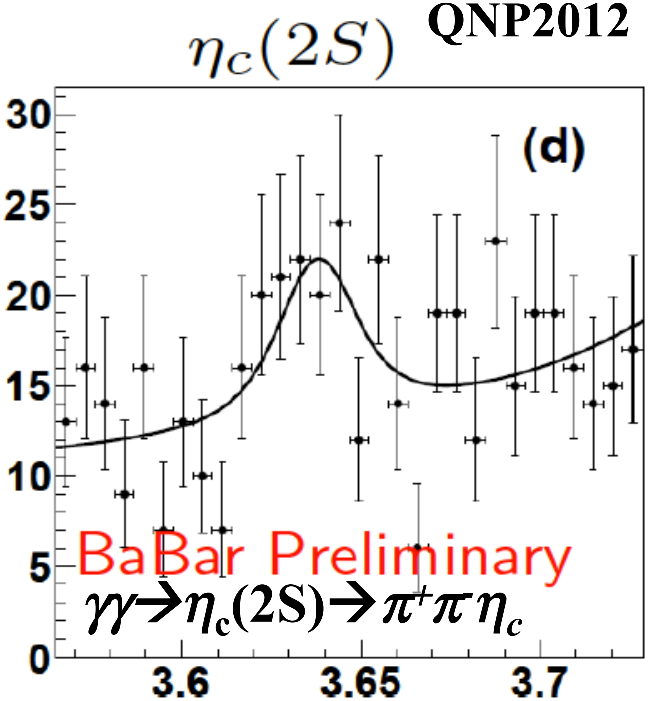
Interference of signal and non-resonant background important

fit with interference $\Gamma = 6.6_{-5.1}^{+8.4}$(stat.+model)$_{-0.9}^{+2.6}$(syst.) MeV

fit w/o interference $\Gamma = 41.1 \pm 12.0$(stat.)$_{-10.9}^{+6.4}$(syst.) MeV

$\eta_c(1S)$ & $\eta_c(2S)$ new BaBar results

QNP2012



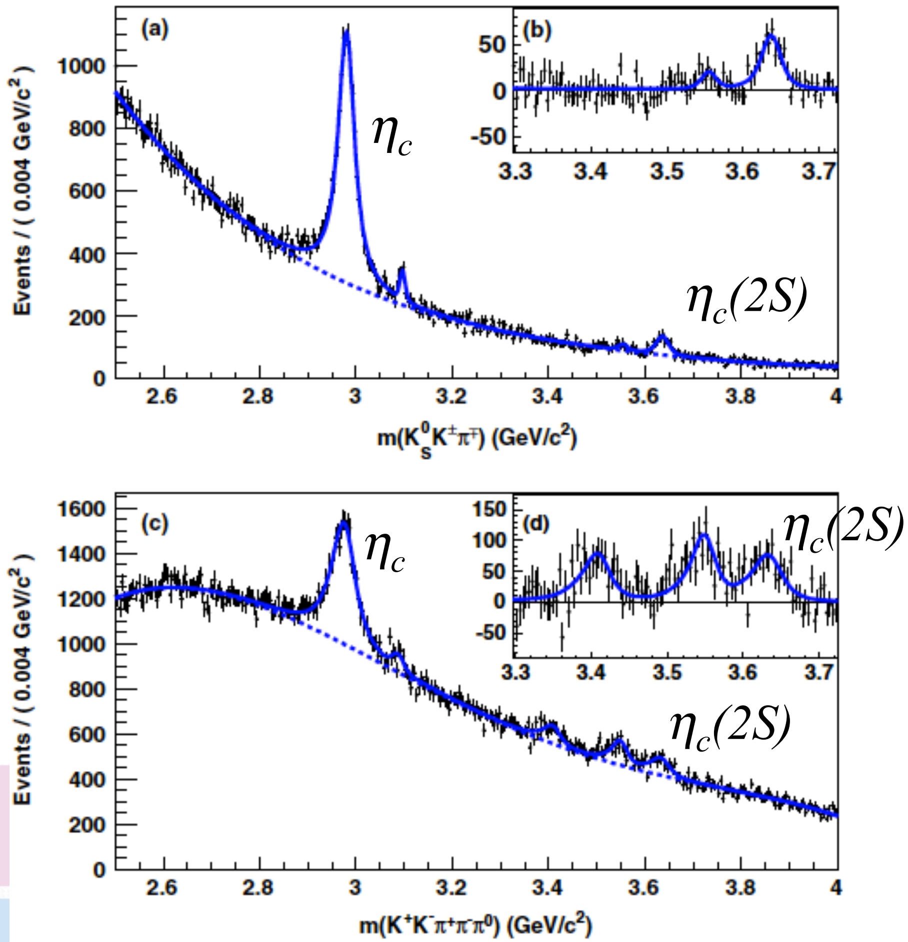
$\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$

(compatible with prediction $< 2.2\%$)

$m(\eta_c(1S))=2982.5\pm0.4\pm1.4$ MeV/c²
$\Gamma(\eta_c(1S))=32.1\pm1.1\pm1.3$ MeV

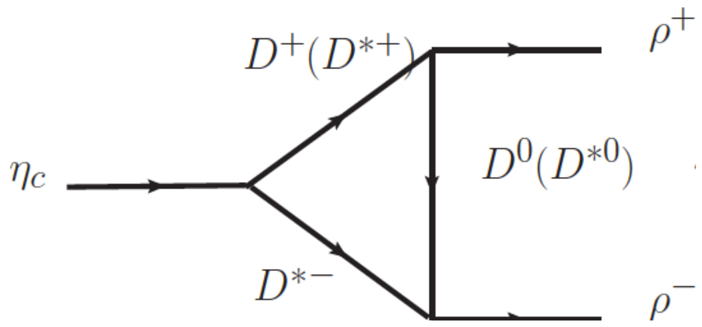
$m(\eta_c(2S))=3638.5\pm1.5\pm0.8$ MeV/c²
$\Gamma(\eta_c(2S))=13.4\pm4.6\pm3.2$ MeV

PRD 84, 012004 (2011)
519.2fb^{-1} near the Υ(n)s (n=2, 3, 4)



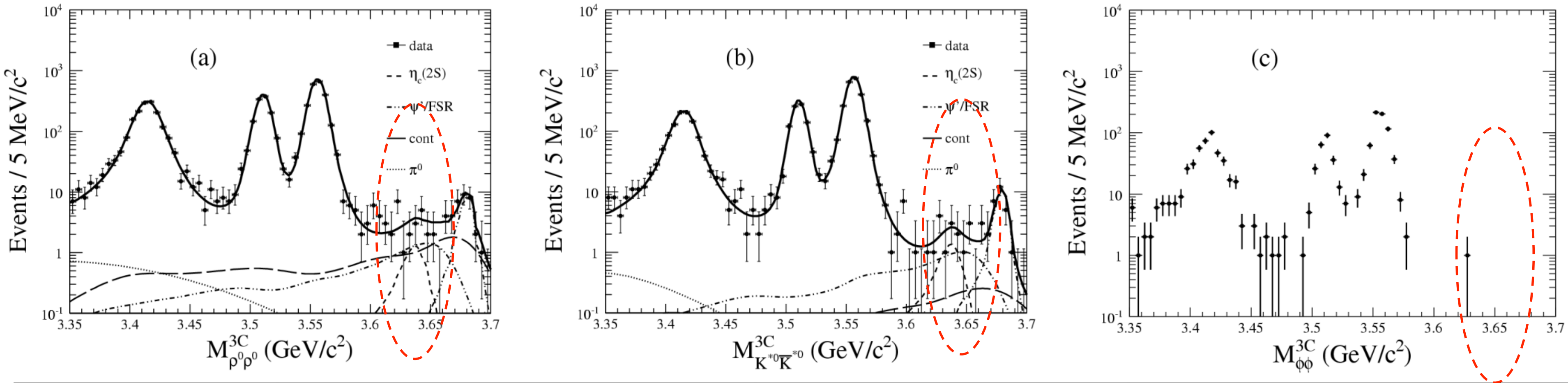
$\gamma\gamma \rightarrow \eta_c, \eta_c(2S) \rightarrow K_S K^\pm \pi^\mp$
$\gamma\gamma \rightarrow \eta_c, \eta_c(2S) \rightarrow K^+K^-\pi^+\pi^-\pi^0$ (5.3σ)

Search for $\eta_c(2S) \to VV$ at BESIII



Test for the "Intermediate charmed meson loops" to evade HSR

Phys. Rev. D 84, 091102 (2011)

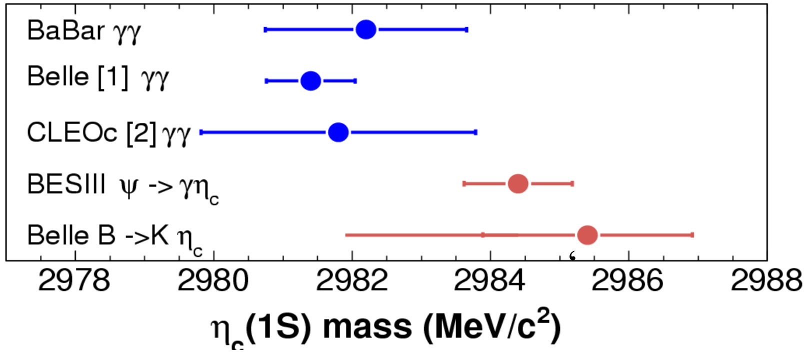


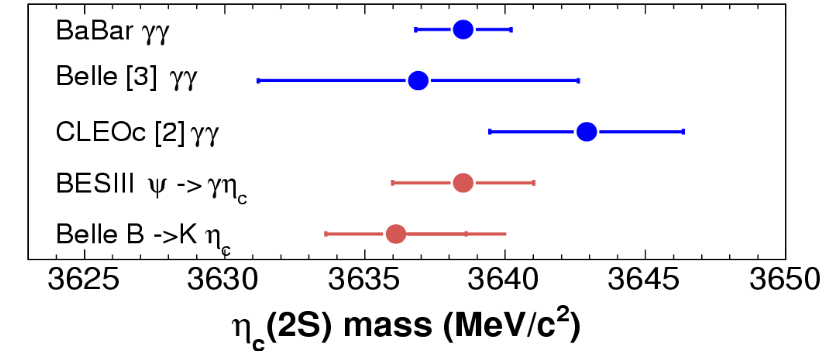
	BF($\psi' \to \gamma\eta_c(2S) \to \gamma VV$) ($10^{-7}$)	BF($\eta_c(2S) \to VV$) (10^{-3})	Theory BF($\eta_c(2S) \to VV$) (10^{-3})
$\rho^0\rho^0$	<11.4	<3.1	6.4 ~ 28.9
$K^{*0}K^{*0}$	<19.4	<5.3	7.9 ~ 35.8
$\phi\phi$	<7.8	<2.0	2.1 ~ 9.8

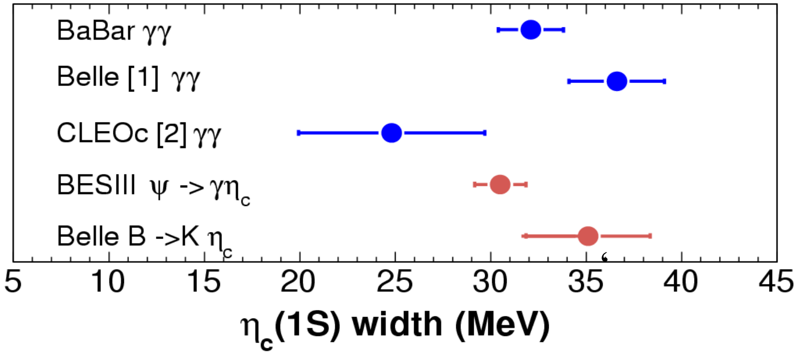
arxiv1010.1343

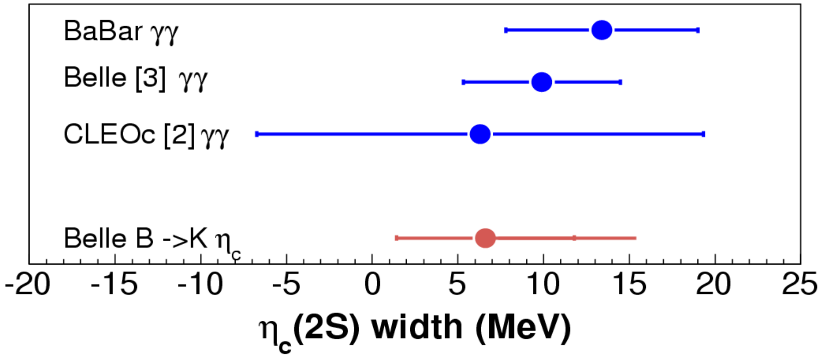
No signals observed in $\eta_c \to \rho\rho$, $K^{*0}K^{*0}$, $\phi\phi$; more stringent UL's are set.

Summary of recent η_c, $\eta_c(2S)$ results



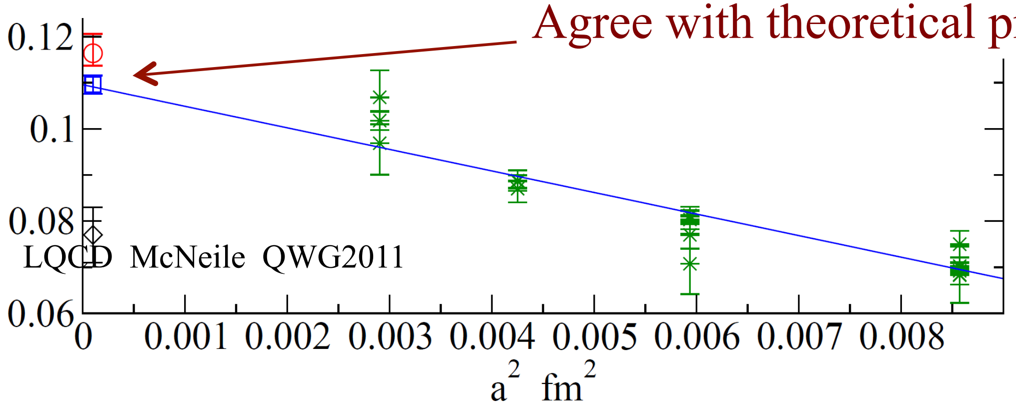






Hyperfine splitting: $\Delta M(1S)$ = **112.5 ± 0.8** MeV (earlyer results: ~**117MeV**)

Agree with theoretical prediction better



Slide from Steven Olsen

Summary

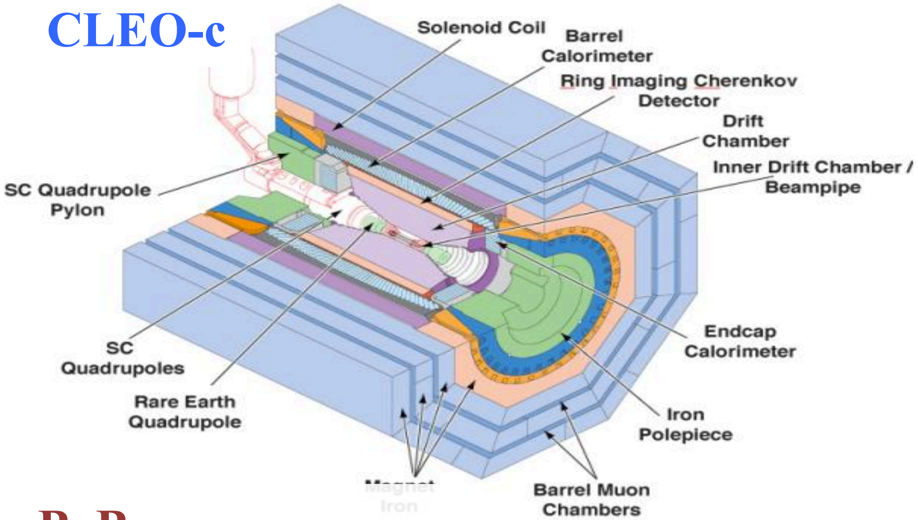
- $h_c(1P)$:
  - Nailed down key branching ratios $\psi' \to \pi^0 h_c$ and $h_c \to \gamma\eta_c$, so the absolute h_c cross sections/branching ratios are available.
  - New prolific production mode found: $e^+e^- \to \pi^+\pi^- h_c$.
- $\eta_c(1S)$:
  - Mass and width are more consistent in ψ decays, B decays and $\gamma\gamma$ production than previously.
  - $h_c \to \gamma\eta_c$ can provide an interference free lab for η_c lineshape study. (BESIII collected ~0.4b ψ' data this year, making this approach possible)
- $\eta_c(2S)$:
  - First observed in ψ' decays.
  - Decay modes other than $KK\pi$ are observed.

Thank you!

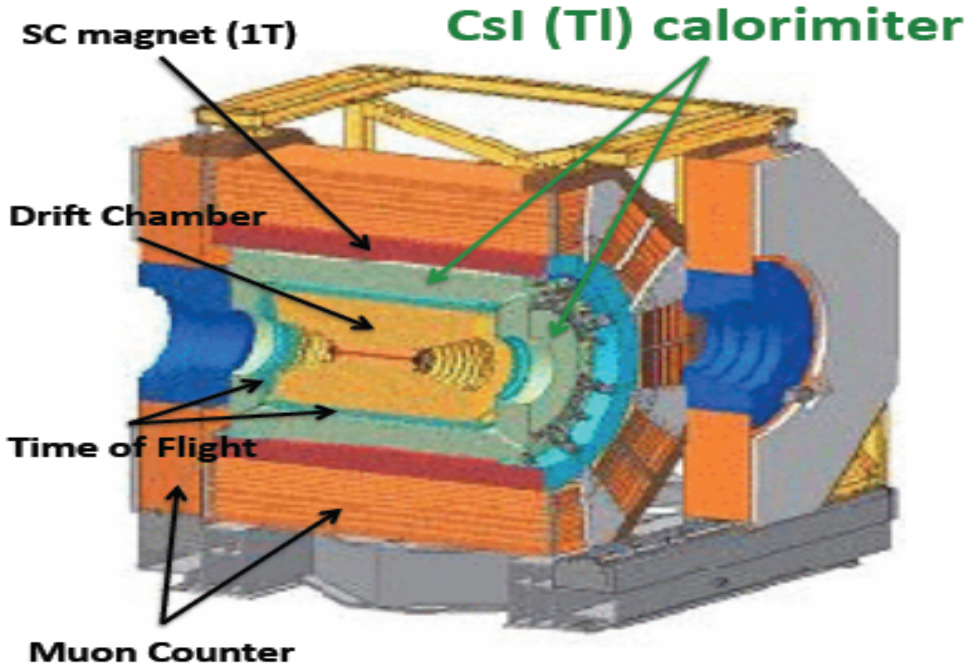
Backup

Detectors

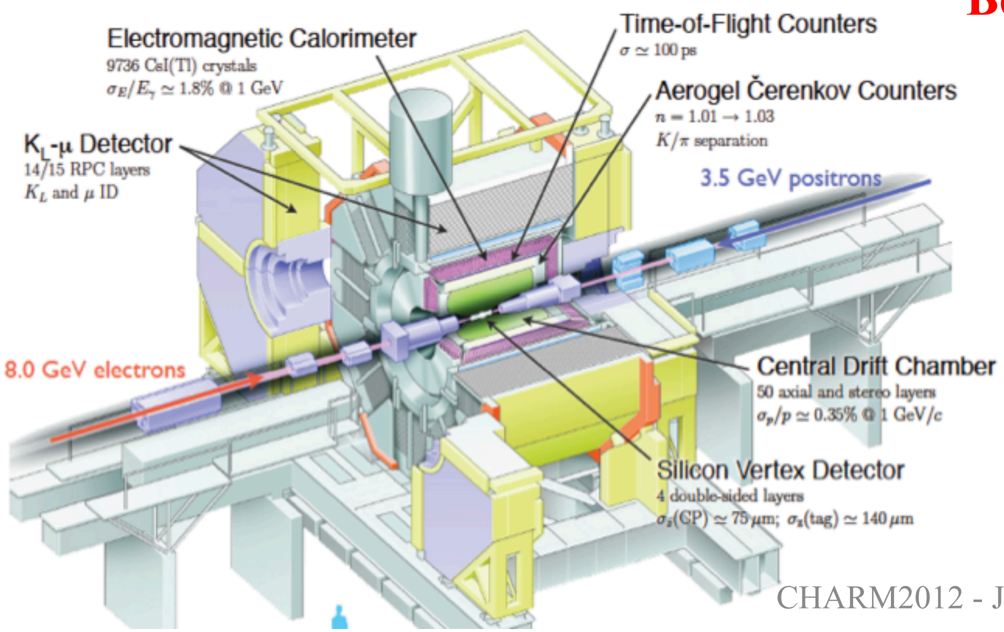
CLEO-c



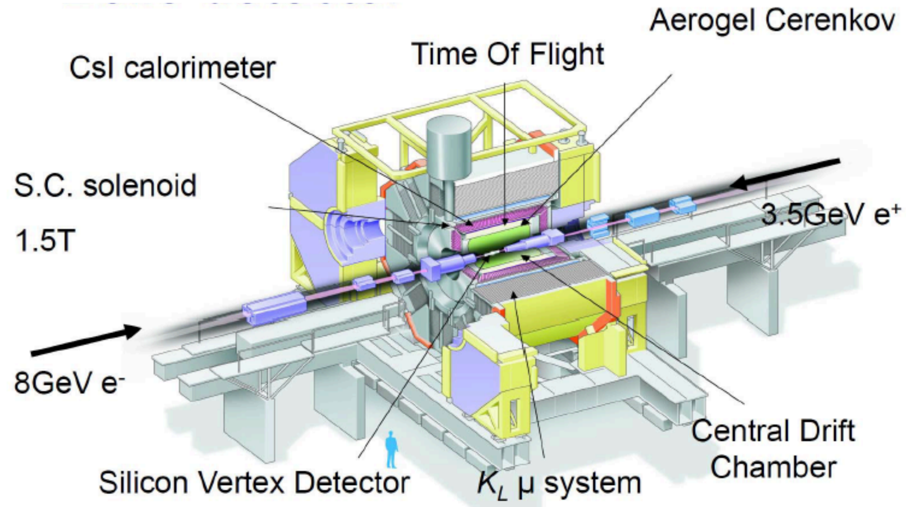
BESIII



BaBar



Belle



An example of intermediate charmed meson loops

arxiv1010.1343

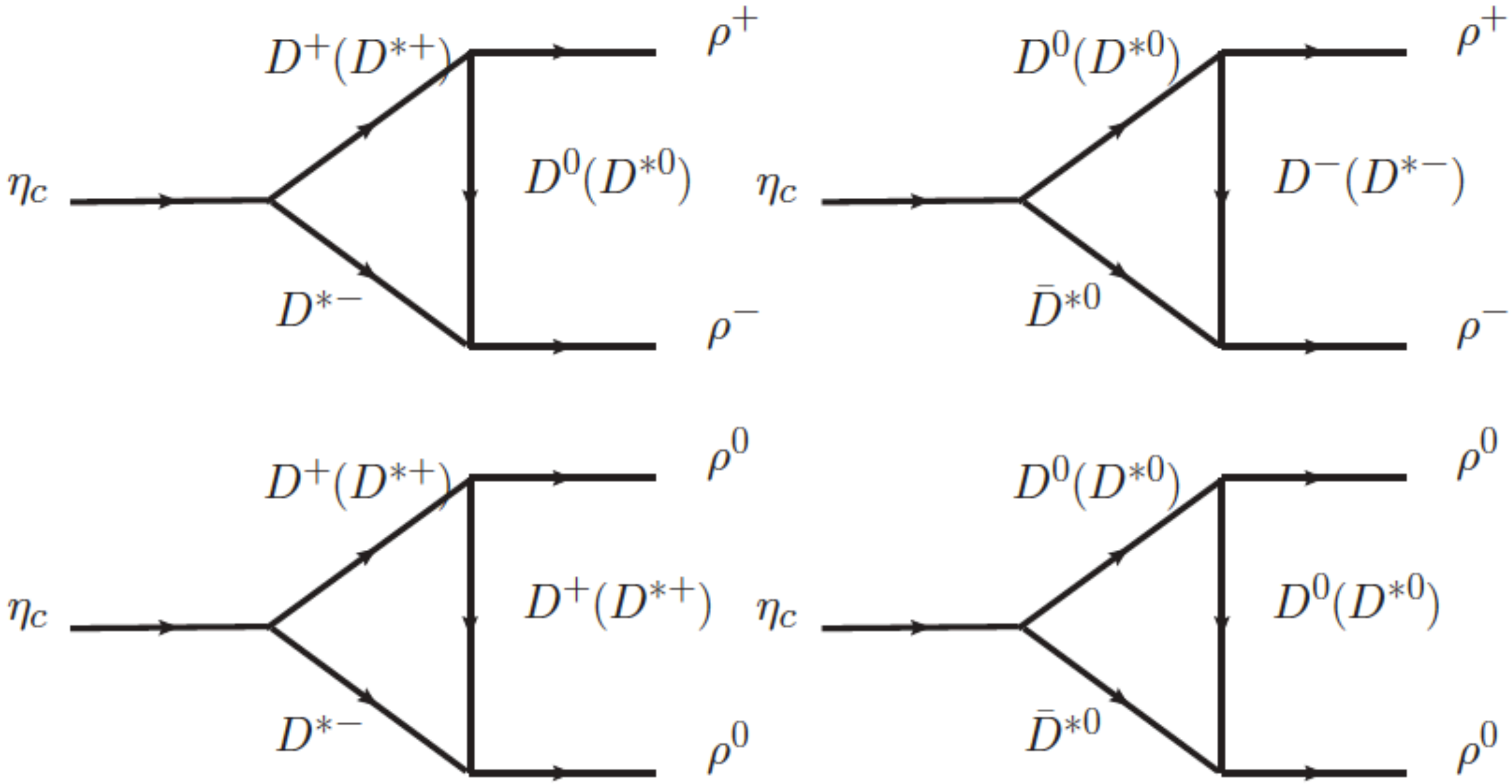


FIG. 1: Feynman diagrams for $\eta_c \to \rho\rho$ via intermediate charmed meson loops.

$\eta_c(\eta_c(2S))$ fitting formula at Belle

Phys.Lett. B706 (2011) 139-149

The fitting function can be represented as the square of the absolute value of the sum of the signal and non-resonant amplitudes integrated over all variables except $M(K_S K\pi)$ and $\cos\theta$:

$$F(s,x) = \int\int\int\int_{x-\frac{\delta}{2}}^{x+\frac{\delta}{2}}\int_{s-\frac{\Delta}{2}}^{s+\frac{\Delta}{2}} (1+\varepsilon_1 x' + \varepsilon_2 x'^2) \cdot \left| \left(\frac{\sqrt{N}}{s' - M^2 + iM\Gamma} A_\eta(q_1^2, q_2^2) + \alpha A_S(q_1^2, q_2^2) \right) S(x') + \beta A_P(q_1^2, q_2^2) P(x') + \gamma A_D(q_1^2, q_2^2) D(x') \right|^2 ds' dx' dq_1^2 dq_2^2 d\phi, \quad (1)$$

where $x = \cos\theta$, $s = M^2(K_S K\pi)$; q_1^2 and q_2^2 are Dalitz plot variables; ε_1 and ε_2 are constants that characterize the efficiency dependence on x and are

$\eta_c(\eta_c(2S))$ fitting formula at Belle

determined from MC; δ and Δ are the bin widths in $\cos\theta$ and $M(K_S K\pi)$ invariant mass, respectively; M and Γ are mass and width of the η_c ($\eta_c(2S)$) meson; N is the η_c ($\eta_c(2S)$) signal yield; α, β, γ are the relative fractions of the S-, P-, and D-waves, respectively; $S = \frac{1}{\sqrt{2}}$, $P = \sqrt{\frac{3}{2}}x$, $D = \frac{3}{2}\sqrt{\frac{5}{2}}(x^2 - \frac{1}{3})$ are the functions characterizing the angular dependence of the S-, P-, and D-waves, respectively; A_η is the signal S-wave amplitude, $A_{S,P,D}$ are the background S-, P-, and D-wave amplitudes, respectively. The absolute values of the amplitudes squared are normalized to unity:

$$\int\int\int |A_{\eta,S,P,D}(q_1^2, q_2^2)|^2 dq_1^2 dq_2^2 d\phi = 1. \quad (2)$$

To account for the momentum resolution, Eq. (1) is convolved with a Gaussian detector resolution function that is determined from the MC and calibrated from the J/ψ (χ_{c1}) width in data.