

Charmonium decays into light hadrons at BESIII

Jake Bennett

Carnegie Mellon University

On behalf of the BESIII collaboration



Carnegie Mellon

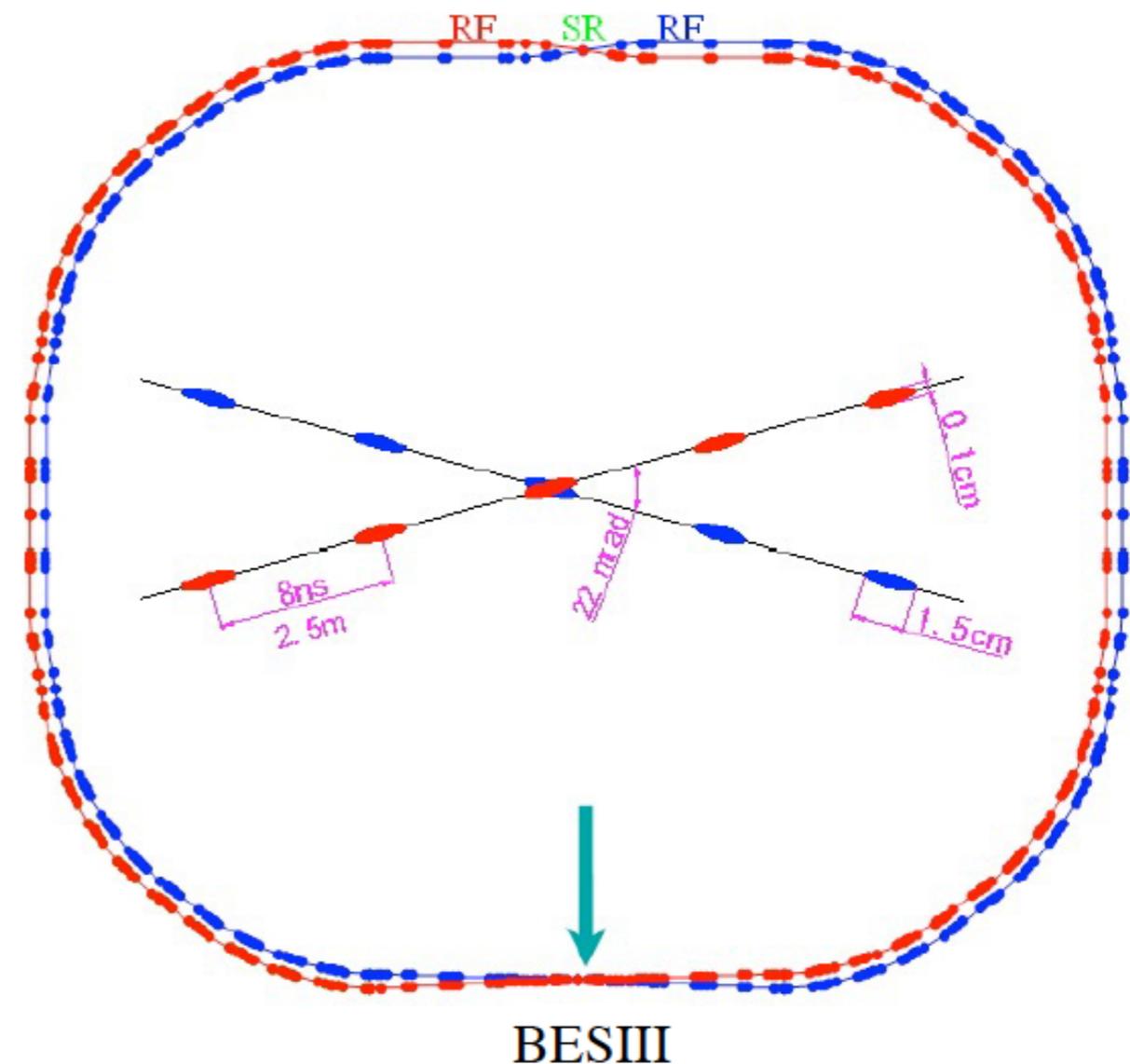
BESIII

BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
 - Light hadron spectroscopy, charm physics, τ physics, charmonium physics
- e^+e^- collisions in the charmonium region
 - Use the properties and decays of charmonium states to study QCD



BEPC-II e^+e^- Collider



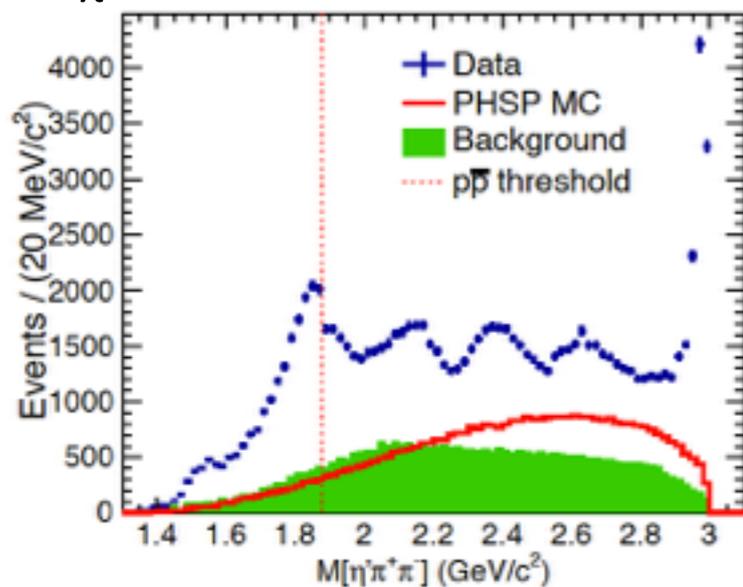
BESIII at BEPCII

See the other BESIII talks this week

- The physics goals of BESIII cover a diverse range:

Light hadron spectroscopy, charm physics, τ physics, charmonium physics

arXiv:1603.09653 Submitted to PRL



Connection between $X(1835)$ and $p\bar{p}$ threshold enhancement
 Suggestion of the existence of (1) a broad resonance below threshold and (2) a narrow state very close to $p\bar{p}$ threshold

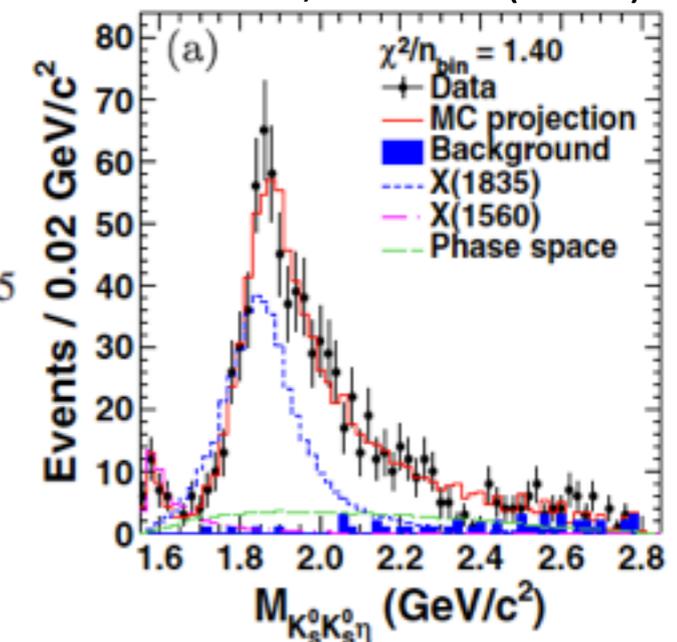
$X(1835)$ in $J/\psi \rightarrow \gamma\eta K_s K_s$

$$M = 1844 \pm 9(\text{stat})_{-25}^{+16}(\text{syst}) \text{ MeV}/c^2$$

$$\Gamma = 192_{-17}^{+20}(\text{stat})_{-43}^{+62}(\text{syst}) \text{ MeV}$$

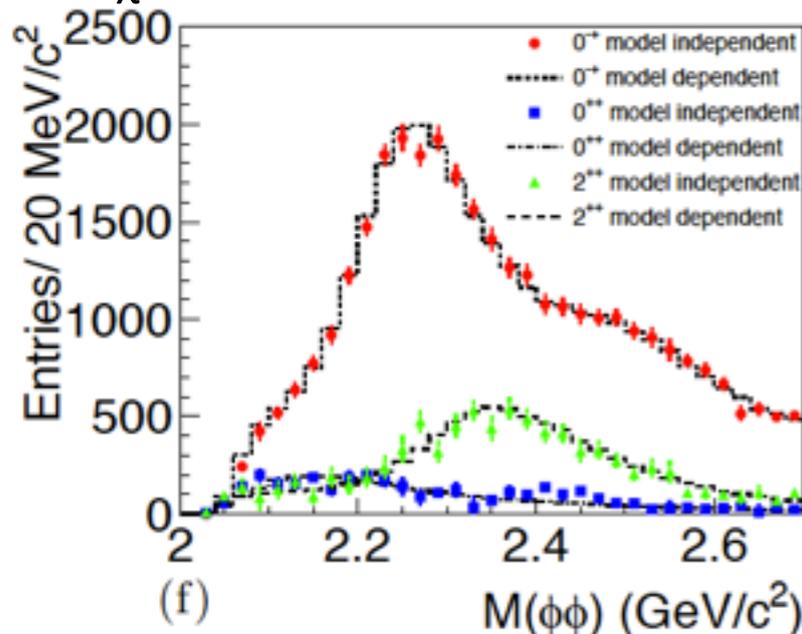
$$\mathcal{B}_{X(1835)} = [3.31_{-0.30}^{+0.33}(\text{stat})_{-1.29}^{+1.96}(\text{syst})] \times 10^{-5}$$

PRL 115, 091803 (2015)

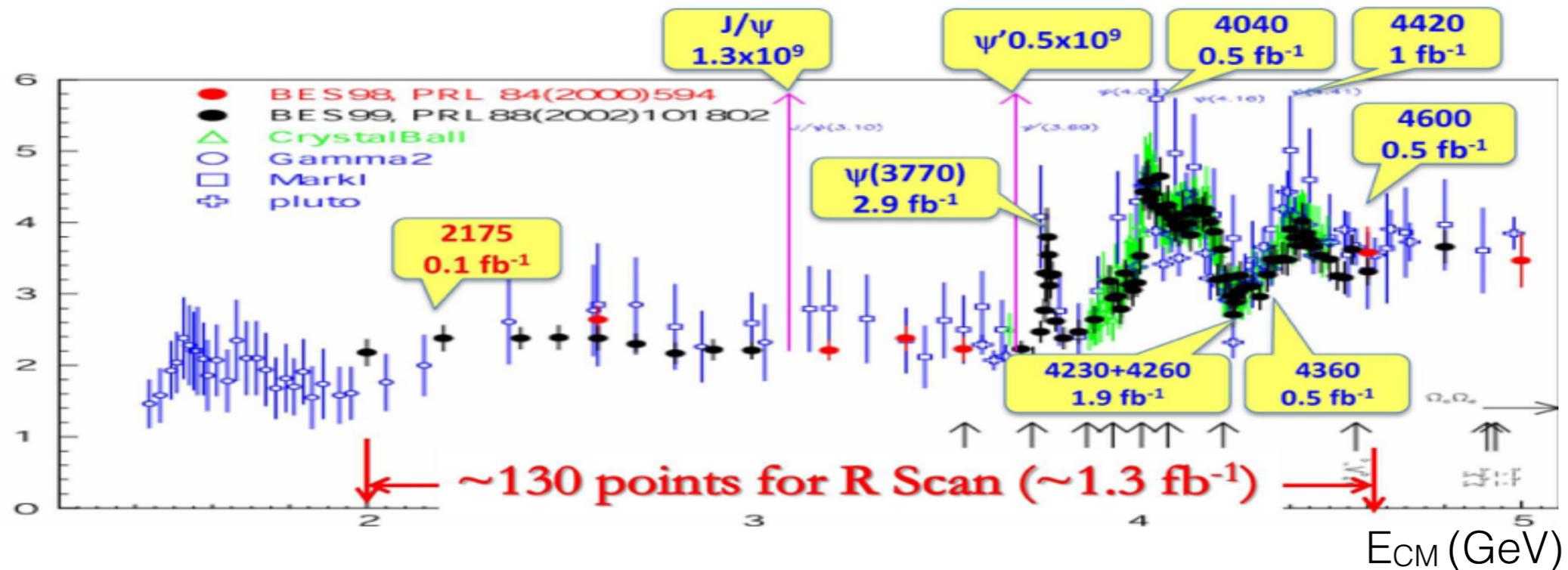


Partial Wave Analysis of J/ψ to $\gamma\phi\phi$
 Consistent model-dependent and model-independent results

arXiv:1602.01523 Submitted to PRL



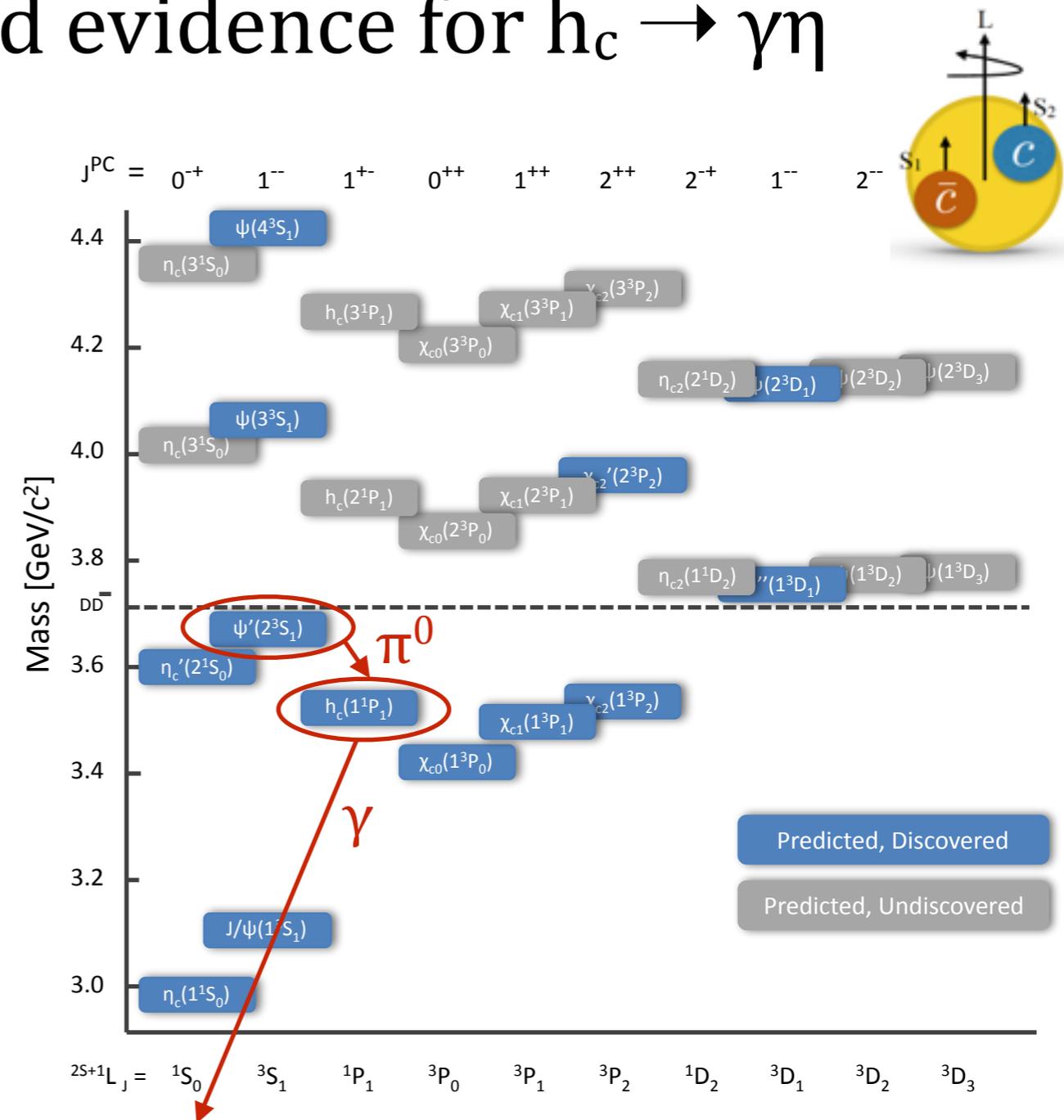
Charmonium decays to light hadrons



- Charmonium decay dynamics
 - Observation of $h_c \rightarrow \gamma\eta'$ and evidence for $h_c \rightarrow \gamma\eta$ Accepted by PRL
PRD 93, 072003 (2016)
 - $\rho\pi$ puzzle and violation of the 12% rule BESIII Preliminary
 - Helicity selection rule suppression processes
- XYZ physics in light quark sector
 - $Y(2175)$ as possible s-quark counterpart of $Y(4260)$ PRD 91, 052017 (2015)
- Opportunities for theory/experiment collaboration
 - Mass independent amplitude analysis of $\pi^0\pi^0$ system PRD 92, 052003 (2015)

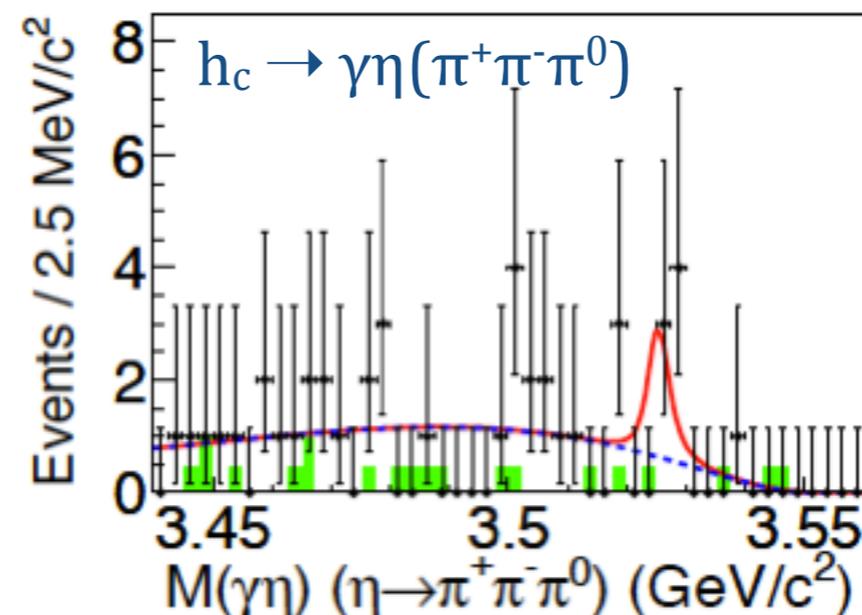
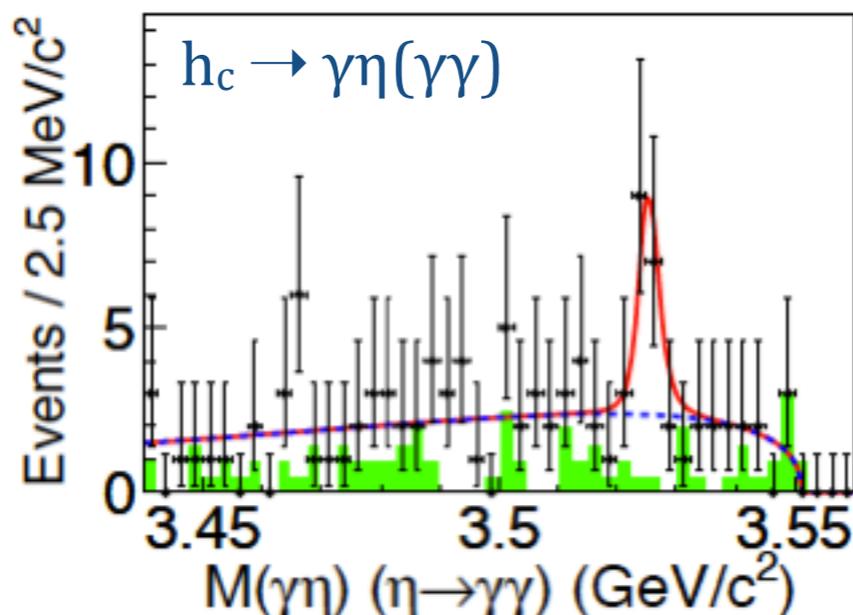
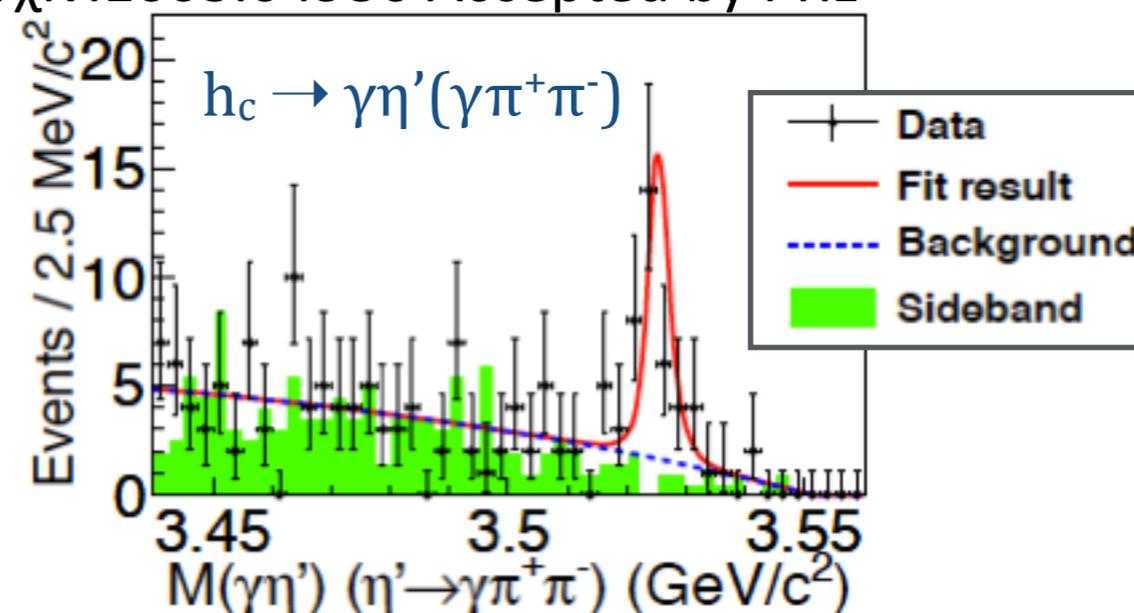
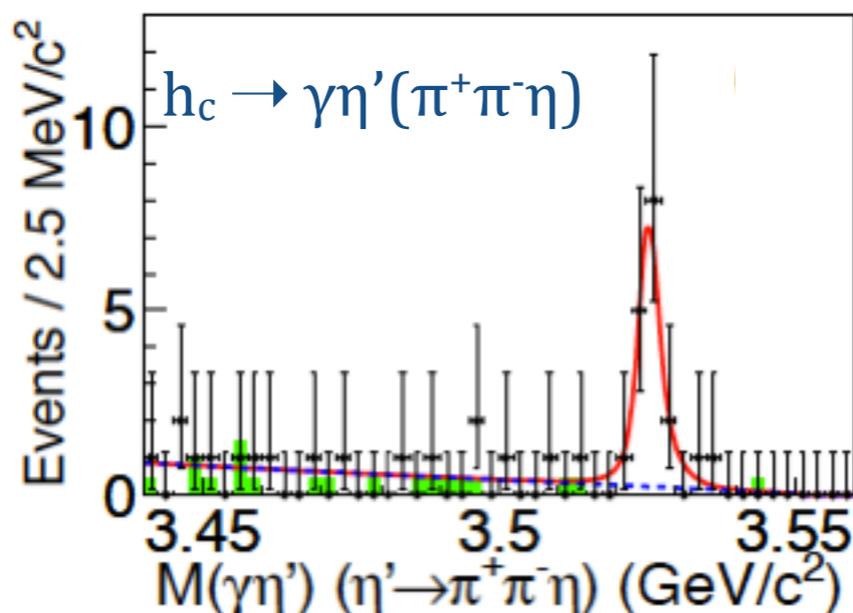
Observation of $h_c \rightarrow \gamma\eta'$ and evidence for $h_c \rightarrow \gamma\eta$

- **Goal:** Obtain a better understanding of charmonium and charmonium-like states
- **Method:** Study pattern of masses, transitions between states, etc.
- Below $D\bar{D}$ threshold, all states have been observed and are well described by $c\bar{c}$ potential models
- Knowledge of P-wave spin-singlet h_c rather sparse
 - Not produced in e^+e^- collisions - use hadronic transition $\psi' \rightarrow \pi^0 h_c$
 - Search for new decays modes with BESIII sample of $448 \times 10^6 \psi'$ events



Observation of $h_c \rightarrow \gamma\eta'$ and evidence for $h_c \rightarrow \gamma\eta$

arXiv:1603.04936 Accepted by PRL



Mode	$\mathcal{B}(h_c \rightarrow \gamma\eta'(\eta))$	Significance	$\frac{\mathcal{B}(h_c \rightarrow \gamma\eta)}{\mathcal{B}(h_c \rightarrow \gamma\eta')} (\%)$
$h_c \rightarrow \gamma\eta'$	$(1.52 \pm 0.27(\text{stat.}) \pm 0.29(\text{sys.})) \times 10^{-3}$	8.4σ	$30.7 \pm 11.3(\text{stat.}) \pm 8.7(\text{sys.})$
$h_c \rightarrow \gamma\eta$	$(4.7 \pm 1.5(\text{stat.}) \pm 1.4(\text{sys.})) \times 10^{-4}$	4.0σ	

Study of ψ decays to $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^+\bar{\Sigma}(1385)^-$

- pQCD predicts exclusive decays of J/ψ and ψ' into light hadrons should have widths proportional to the square of the wave function at the origin (the “12% rule”)

$$Q_h \equiv \frac{\mathcal{B}(\psi(3686) \rightarrow \text{hadrons})}{\mathcal{B}(J/\psi \rightarrow \text{hadrons})} \approx \frac{\mathcal{B}(\psi(3686) \rightarrow e^+e^-)}{\mathcal{B}(J/\psi \rightarrow e^+e^-)} \approx 12\%$$

- Current theoretical explanations of the $\rho\pi$ puzzle are unsatisfactory, especially for decays to baryon pairs

$$Q_{\rho\pi} = \frac{\mathcal{B}(\psi(2S) \rightarrow \rho\pi)}{\mathcal{B}(J/\psi \rightarrow \rho\pi)} = (0.13 \pm 0.05)\%$$

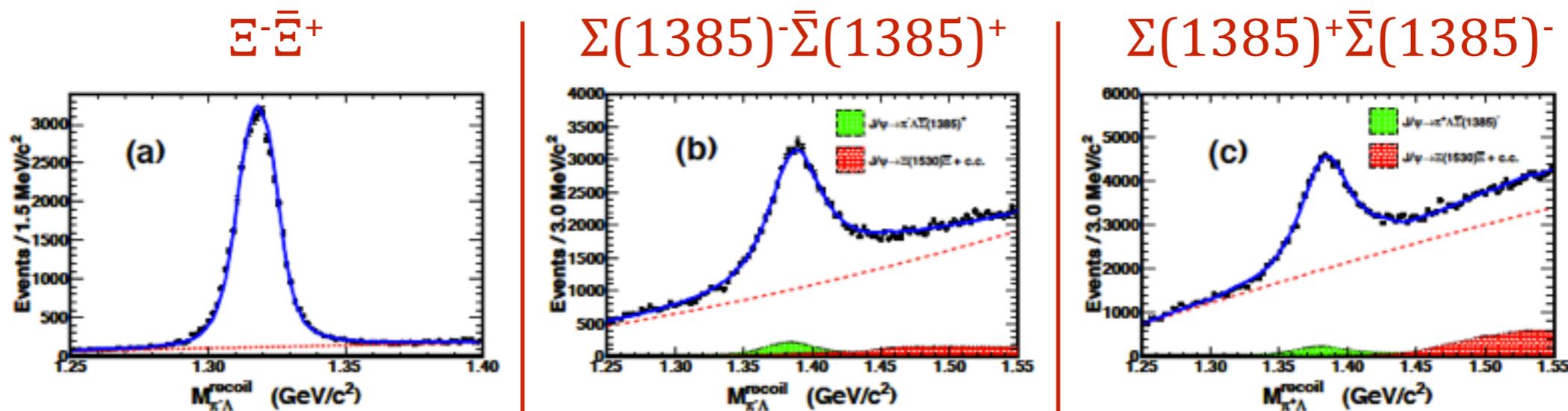
- More experimental measurements are desirable
- Use large BESIII charmonium samples to make precision measurements of J/ψ and ψ' decays to $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^+\bar{\Sigma}(1385)^-$

Study of ψ decays to $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^-\bar{\Sigma}(1385)^+$

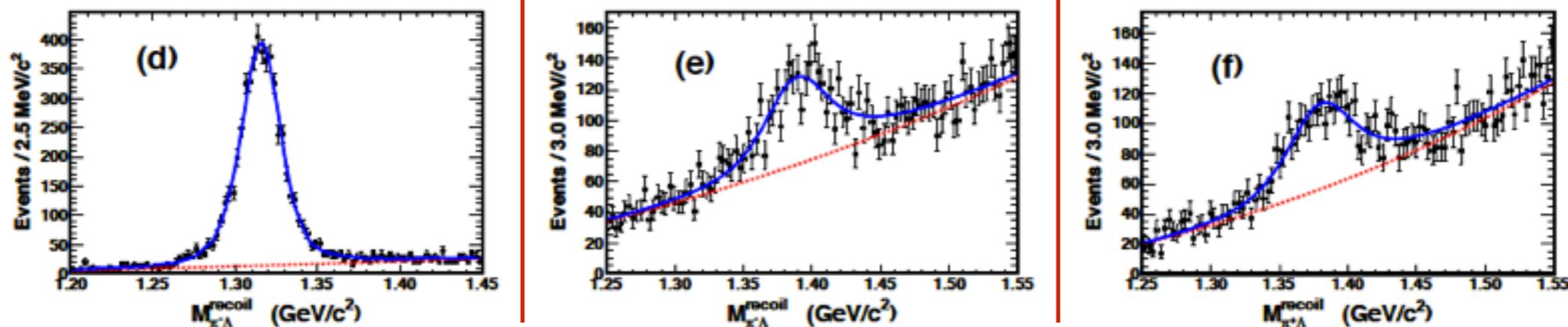
- Based on $(223.7 \pm 1.4) \times 10^6$ J/ψ and $(106.4 \pm 0.9) \times 10^6$ ψ' decays
- Avoid full reconstruction of both baryons (low efficiency)
 - Identify $\bar{\Xi}^+$ or $\bar{\Sigma}(1385)^+$ from recoil mass against $\pi^+\Lambda$

$$M_{\pi^+\Lambda}^{\text{recoil}} = \sqrt{(E_{CM} - E_{\pi^+\Lambda})^2 - \vec{p}_{\pi^+\Lambda}^2}$$

J/ψ



ψ'



Study of ψ decays to $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^{\mp}\bar{\Sigma}(1385)^{\pm}$

- Based on $(223.7 \pm 1.4) \times 10^6$ J/ψ and $(106.4 \pm 0.9) \times 10^6$ ψ' decays

Comparison of the branching fractions for $\psi \rightarrow \Xi^-\bar{\Xi}^+$, $\Sigma(1385)^{\mp}\bar{\Sigma}(1385)^{\pm}$ (in units of 10^{-4})

Source Mode	$J/\psi \rightarrow$			$\psi(3686) \rightarrow$		
	$\Xi^-\bar{\Xi}^+$	$\Sigma(1385)^-\bar{\Sigma}(1385)^+$	$\Sigma(1385)^+\bar{\Sigma}(1385)^-$	$\Xi^-\bar{\Xi}^+$	$\Sigma(1385)^-\bar{\Sigma}(1385)^+$	$\Sigma(1385)^+\bar{\Sigma}(1385)^-$
This work	$10.40 \pm 0.06 \pm 0.74$	$10.96 \pm 0.12 \pm 0.71$	$12.58 \pm 0.14 \pm 0.78$	$2.78 \pm 0.05 \pm 0.14$	$0.85 \pm 0.06 \pm 0.06$	$0.84 \pm 0.05 \pm 0.05$
MarkI [5]	14.00 ± 5.00	—	—	< 2.0	—	—
MarkII [6]	$11.40 \pm 0.80 \pm 2.00$	$8.60 \pm 1.80 \pm 2.20$	$10.3 \pm 2.4 \pm 2.5$	—	—	—
DM2 [7]	$7.00 \pm 0.60 \pm 1.20$	$10.00 \pm 0.40 \pm 2.10$	$11.9 \pm 0.4 \pm 2.5$	—	—	—
BESII [8, 12]	$9.00 \pm 0.30 \pm 1.80$	$12.30 \pm 0.70 \pm 3.00$	$15.0 \pm 0.8 \pm 3.8$	$3.03 \pm 0.40 \pm 0.32$	—	—
CLEO [9]	—	—	—	$2.40 \pm 0.30 \pm 0.20$	—	—
BESI [26]	—	—	—	$0.94 \pm 0.27 \pm 0.15$	—	—
PDG [3]	8.50 ± 1.60	10.30 ± 1.30	10.30 ± 1.30	1.80 ± 0.60	—	—

PRD 93, 072003 (2016)

$$\frac{\mathcal{B}(\psi(3686) \rightarrow \Xi^-\bar{\Xi}^+)}{\mathcal{B}(J/\psi \rightarrow \Xi^-\bar{\Xi}^+)} = (26.73 \pm 0.50 \pm 2.30)\%$$

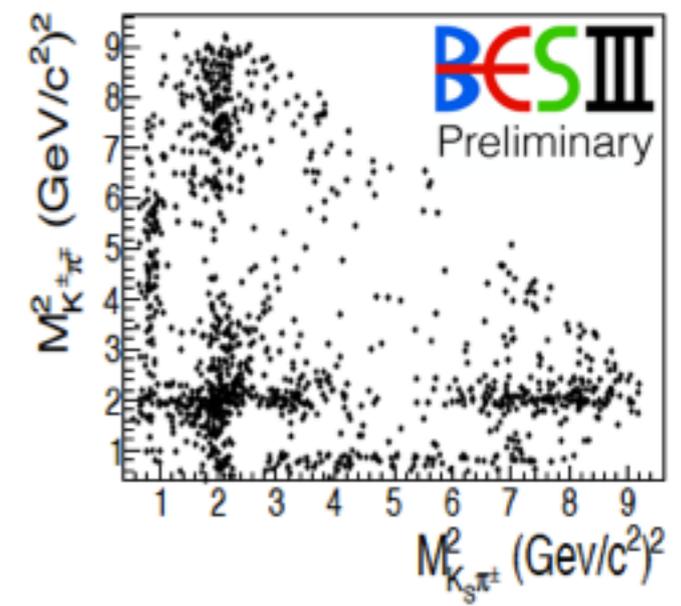
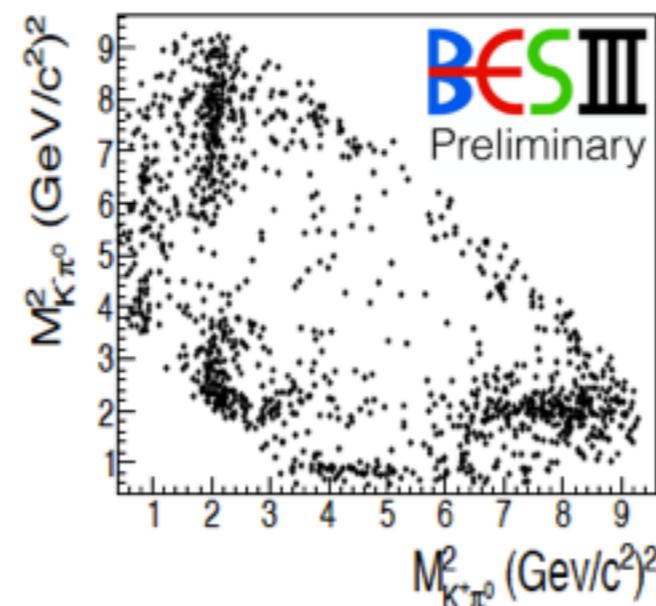
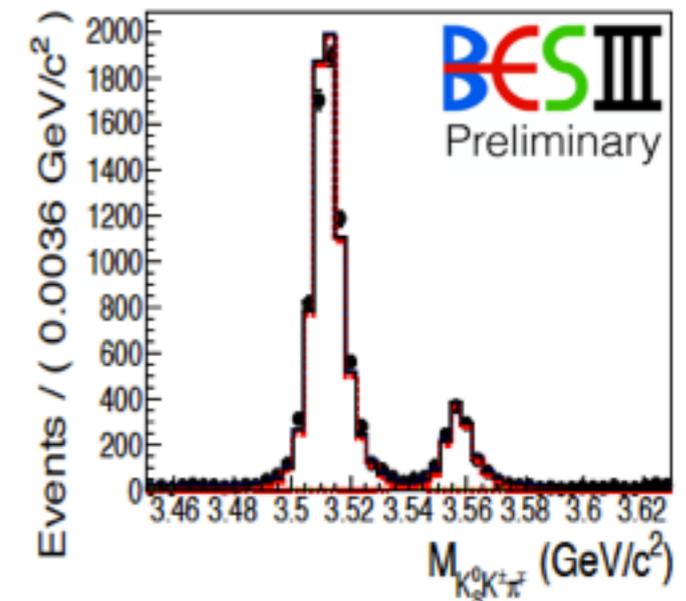
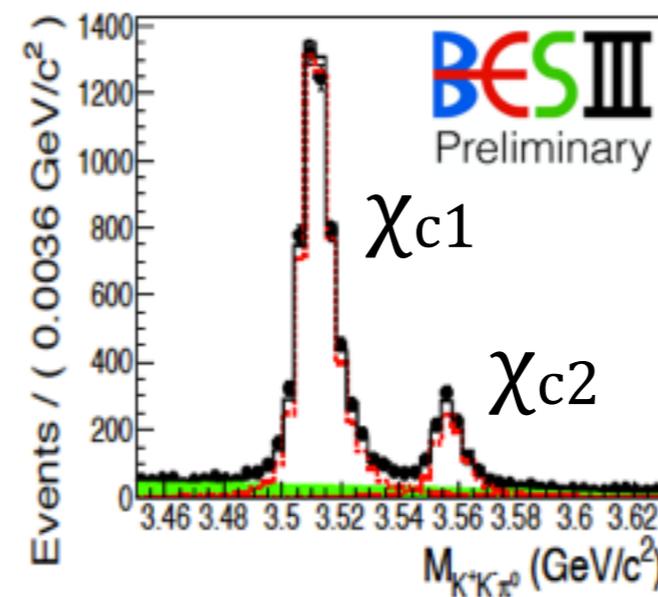
$$\frac{\mathcal{B}(\psi(3686) \rightarrow \Sigma(1385)^-\bar{\Sigma}(1385)^+)}{\mathcal{B}(J/\psi \rightarrow \Sigma(1385)^-\bar{\Sigma}(1385)^+)} = (7.76 \pm 0.55 \pm 0.68)\%$$

$$\frac{\mathcal{B}(\psi(3686) \rightarrow \Sigma(1385)^+\bar{\Sigma}(1385)^-)}{\mathcal{B}(J/\psi \rightarrow \Sigma(1385)^+\bar{\Sigma}(1385)^-)} = (6.68 \pm 0.40 \pm 0.50)\%$$

Not in agreement
with 12% rule

PWA on χ_{c2} decays to VP

- Precise measurements of Helicity Selection Rule suppressed processes are crucial for a better understanding of the underlying dynamics of the strong interaction
 - Charmonium hadronic decays could be useful to clarify mechanisms that may violate the leading pQCD results
- Use χ_{c2} decays to VP to quantify HSR-violating mechanisms
 - Intermediate meson loops may contribute sizable branching ratios for $\chi_{c2} \rightarrow K^*K + c.c.$
- Based on full ψ' sample $(448.1 \pm 2.9) \times 10^6$ events



PWA on χ_{c2} decays to VP

- PWA with relativistic Breit-Wigner lineshapes (masses and widths fixed at PDG values)
- BR rather sizable compared to HSR conserving channel

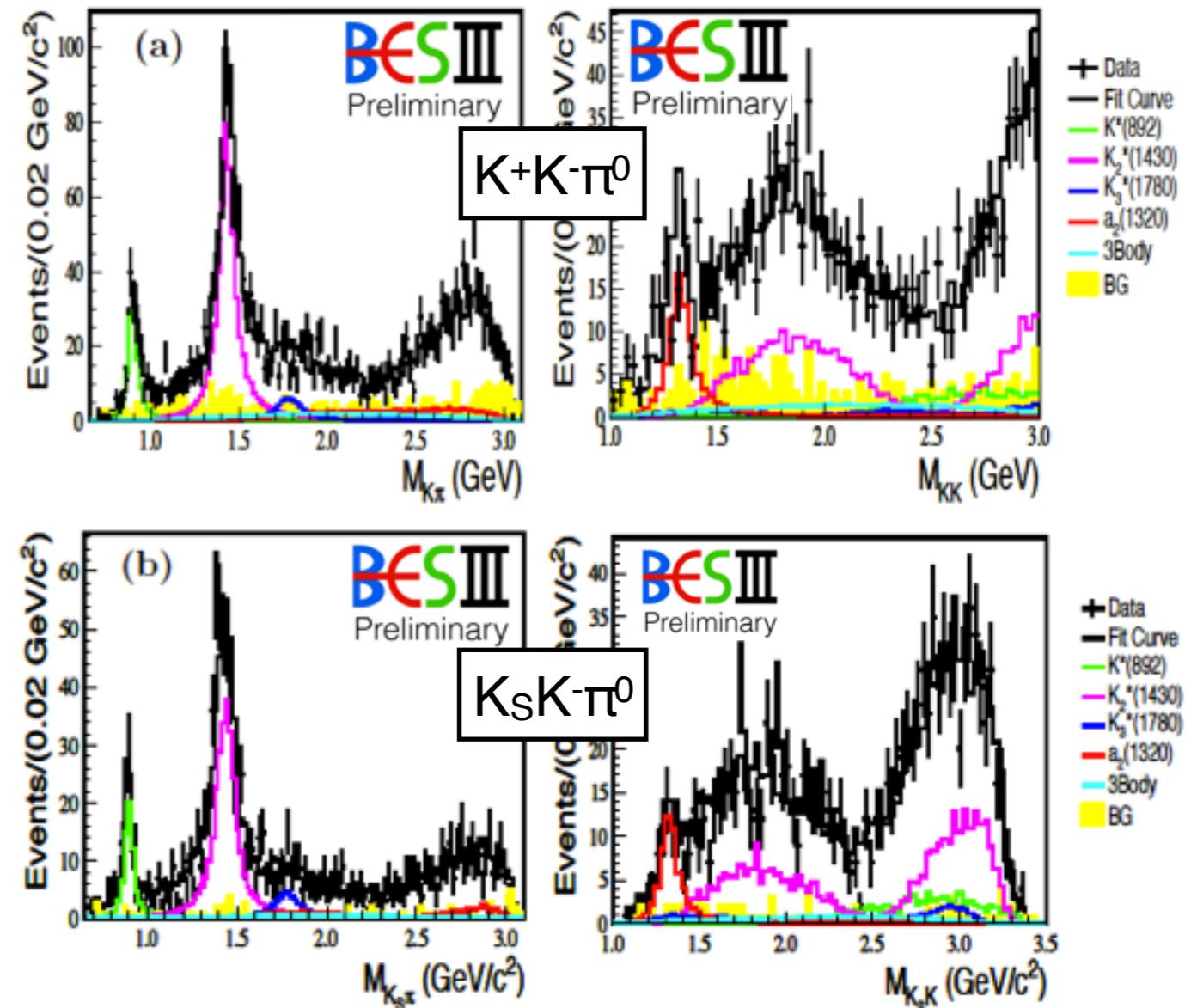
$$\mathcal{B}(\chi_{c2} \rightarrow K^*(892)^0 \bar{K}^*(892)^0) \\ (4.67 \pm 0.55 \pm 0.85) \times 10^{-3}$$

- Isospin conservation suppresses intermediate loop transitions?

$$\text{Br}(\chi_{c2} \rightarrow \rho^+ \pi^- + c.c.) \\ [(0.64 \pm 0.28 \pm 0.07) \times 10^{-5}]$$

$$\text{Br}(\chi_{c2} \rightarrow K^* K) \text{Br}(K^* \rightarrow K \pi) \text{ and } \text{Br}(\chi_{c2} \rightarrow a_2 \pi) \text{Br}(a_2 \rightarrow KK)$$

Mode	Charged ($\times 10^{-4}$)	Neutral ($\times 10^{-4}$)
$K^*(892)K$	$1.6 \pm 0.1 \pm 0.2$	$1.3 \pm 0.2 \pm 0.2$
$K_2^*(1430)K$	$8.0 \pm 0.3 \pm 0.6$	$6.5 \pm 0.5 \pm 0.9$
$K_3^*(1780)K$	$1.0 \pm 0.1 \pm 0.2$	$1.1 \pm 0.3 \pm 0.3$
$a_2(1320)\pi$	$0.90 \pm 0.16 \pm 0.23$	$0.66 \pm 0.08 \pm 0.12$



Prediction from intermediate meson loop transitions:

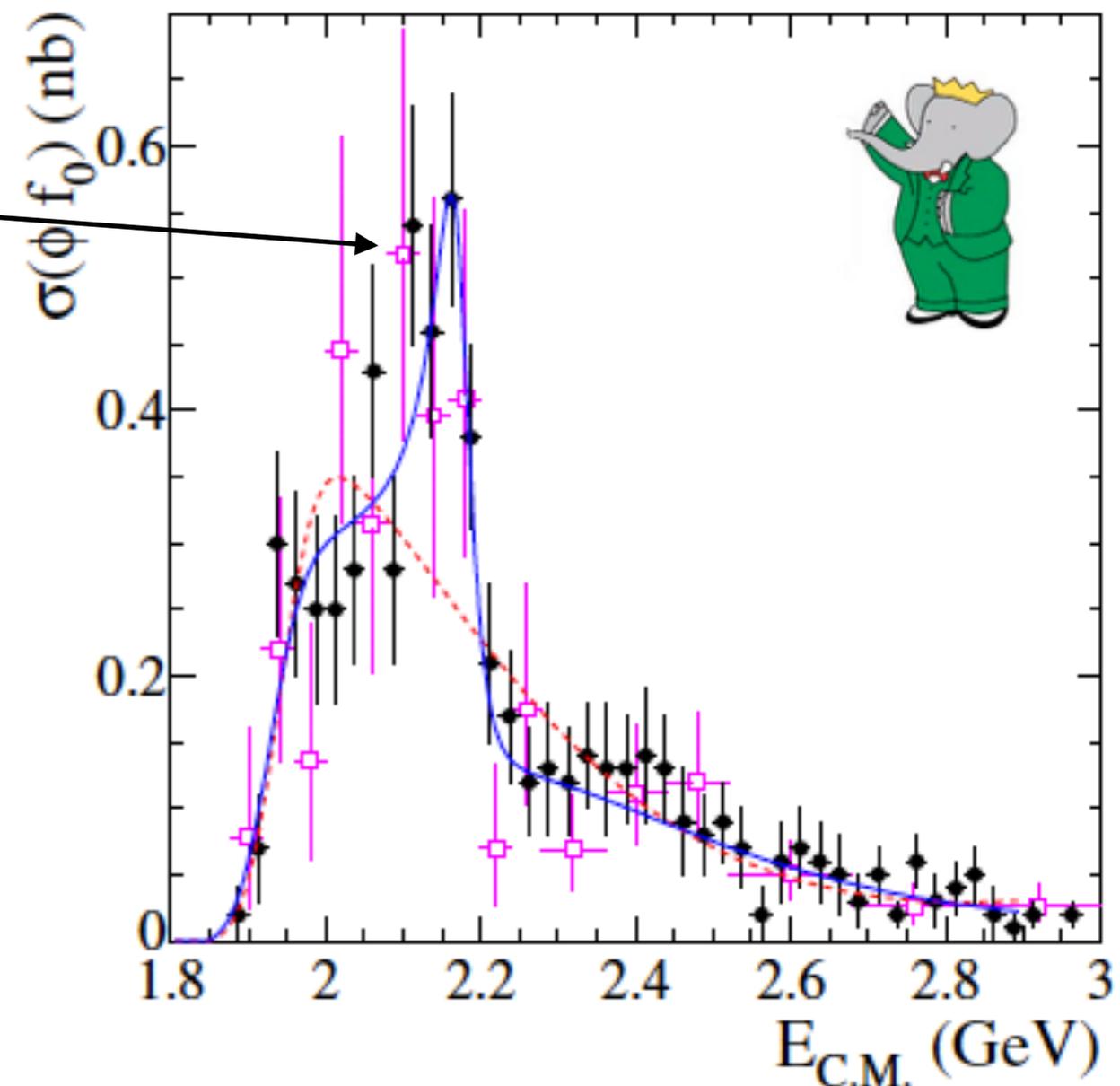
$$[(4.0 \sim 6.7) \times 10^{-5}]$$

PRD 81 014017 (2010)

Study of $J/\psi \rightarrow \eta\phi\pi^+\pi^-$

- $Y(2175)$ as possible s-quark counterpart of the $Y(4260)$
 - Observed by BaBar in $e^+e^- \rightarrow \gamma_{\text{ISR}}\phi f_0(980): J^{PC} = 1^{--}$
 - Confirmed by BES [$J/\psi \rightarrow \eta\phi f_0(980)$], and Belle [$e^+e^- \rightarrow \gamma_{\text{ISR}}\phi f_0(980)$]
 - Many possible interpretations predict masses consistent with experimental measurements: $s\bar{s}$ hybrid, excited ϕ state, tetraquark, $\Lambda\bar{\Lambda}$ bound state, FSI
- Based on $(225.3 \pm 2.8) \times 10^6$ J/ψ events

BaBar: PRD 74, 091103R (2006)

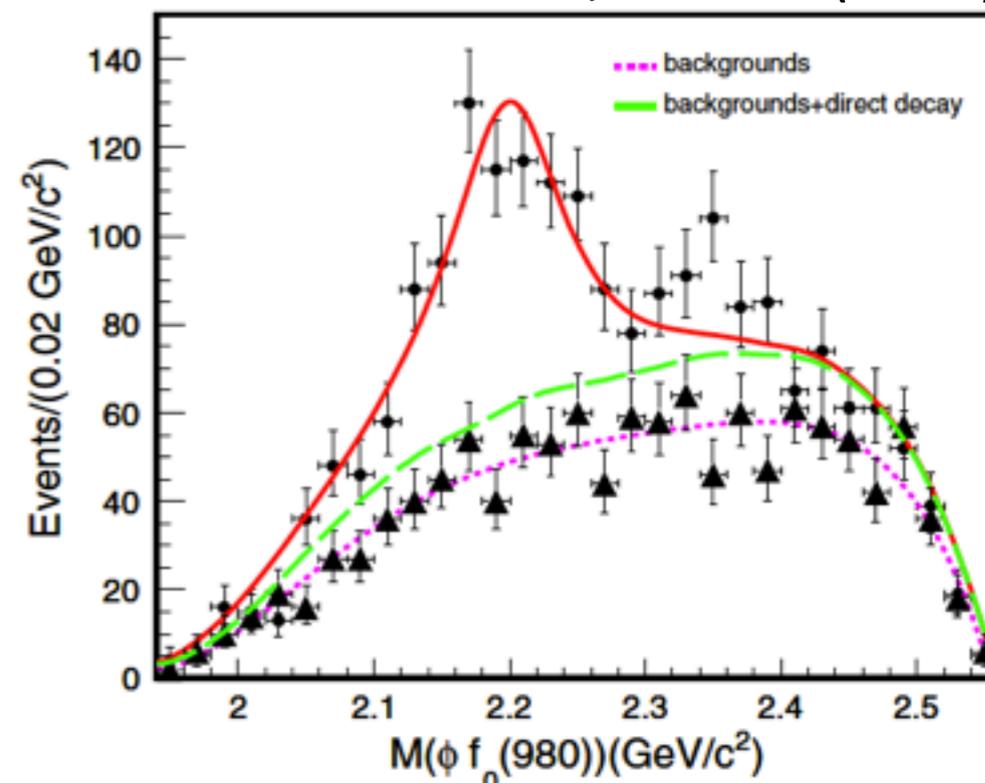


Study of $J/\psi \rightarrow \eta\phi\pi^+\pi^-$

- Based on $(225.3 \pm 2.8) \times 10^6$ J/ψ events
- $Y(2175)$ observed with significance $> 10 \sigma$

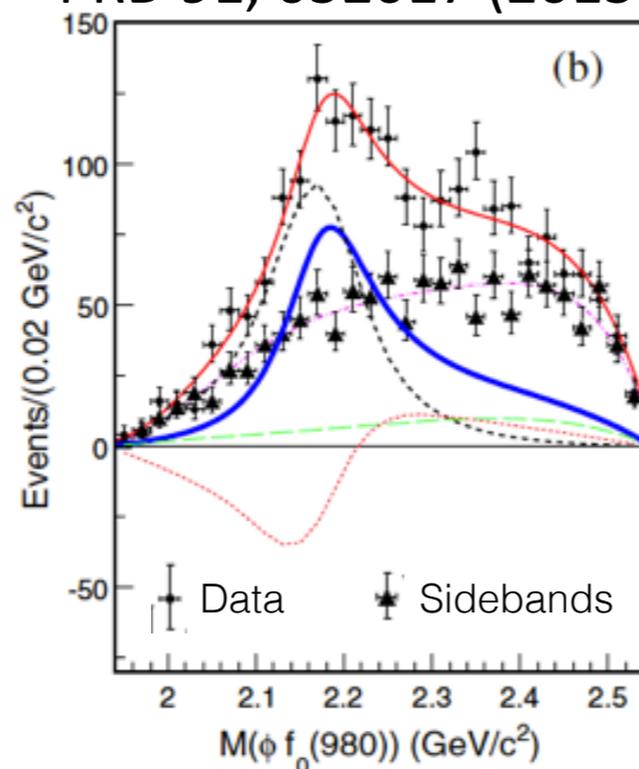
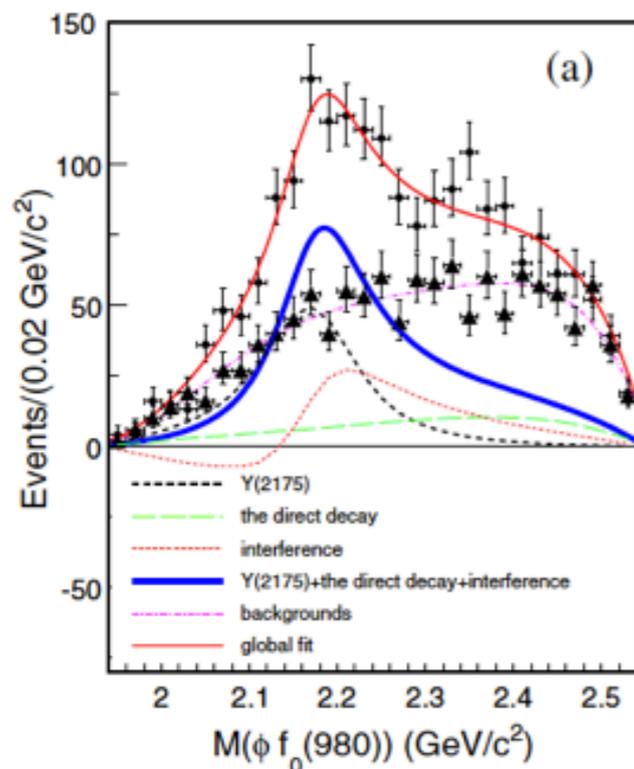
Collaboration	Process	M (MeV/c^2)	Γ (MeV)
BABAR [2]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BESII [3]	$J/\psi \rightarrow \eta\phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
BELLE [4]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2079 \pm 13^{+79}_{-28}$	$192 \pm 23^{+25}_{-61}$
BABAR (updated) [5]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2172 \pm 10 \pm 8$	$96 \pm 19 \pm 12$
BESIII	$J/\psi \rightarrow \eta\phi f_0(980)$	$2200 \pm 6 \pm 5$	$104 \pm 15 \pm 15$

PRD 91, 052017 (2015)



$$\mathcal{B}(J/\psi \rightarrow \eta Y(2175), Y(2175) \rightarrow \phi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-) = (1.20 \pm 0.14(\text{stat}) \pm 0.37(\text{syst})) \times 10^{-4}$$

PRD 91, 052017 (2015)

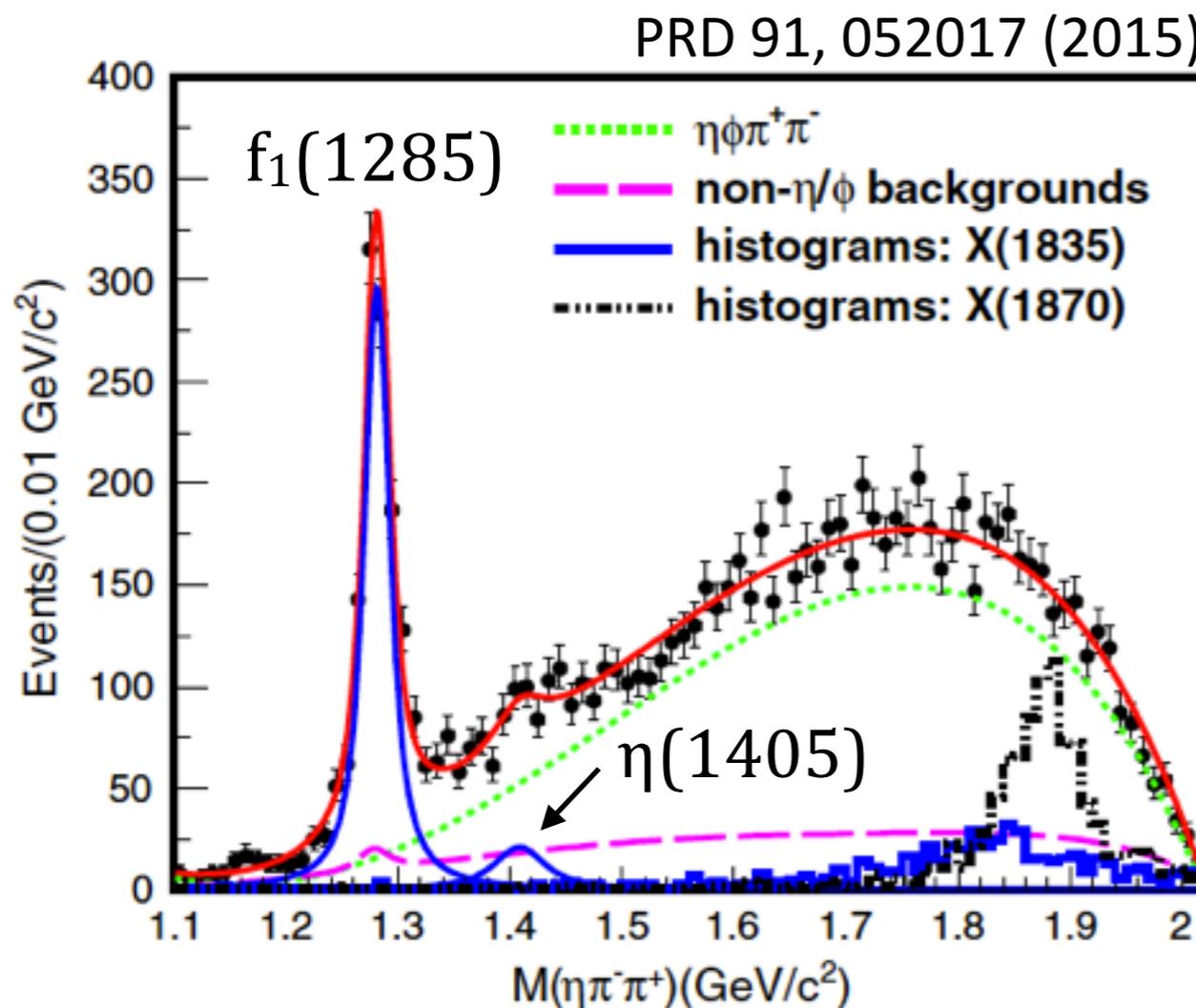


- Also repeat fit including interference between the $Y(2175)$ and the direct decay

Parameters	Constructive	Destructive
M (MeV/c^2)	2171 ± 10	2170 ± 9
Γ (MeV)	128 ± 26	126 ± 25
Signal yields	400 ± 167	744 ± 40
relative angle Φ (rad)	-0.51 ± 0.78	0.60 ± 0.64

Study of $J/\psi \rightarrow \eta\phi\pi^+\pi^-$

- Also provides a unique opportunity to investigate properties of other states: $f_1(1285)$, $\eta(1295)$, $\eta(1405)/\eta(1475)$, $X(1835)$, $X(1870)$



- Fit $\eta\pi\pi$ mass spectrum against the ϕ
- $\eta(1405)$ signal with 3.6σ significance
- No evidence of $X(1835)$ or $X(1870)$

$$B(J/\psi \rightarrow \phi f_1 \rightarrow \eta\phi\pi^+\pi^-) = (1.20 \pm 0.06 \pm 0.14) \times 10^{-4}$$

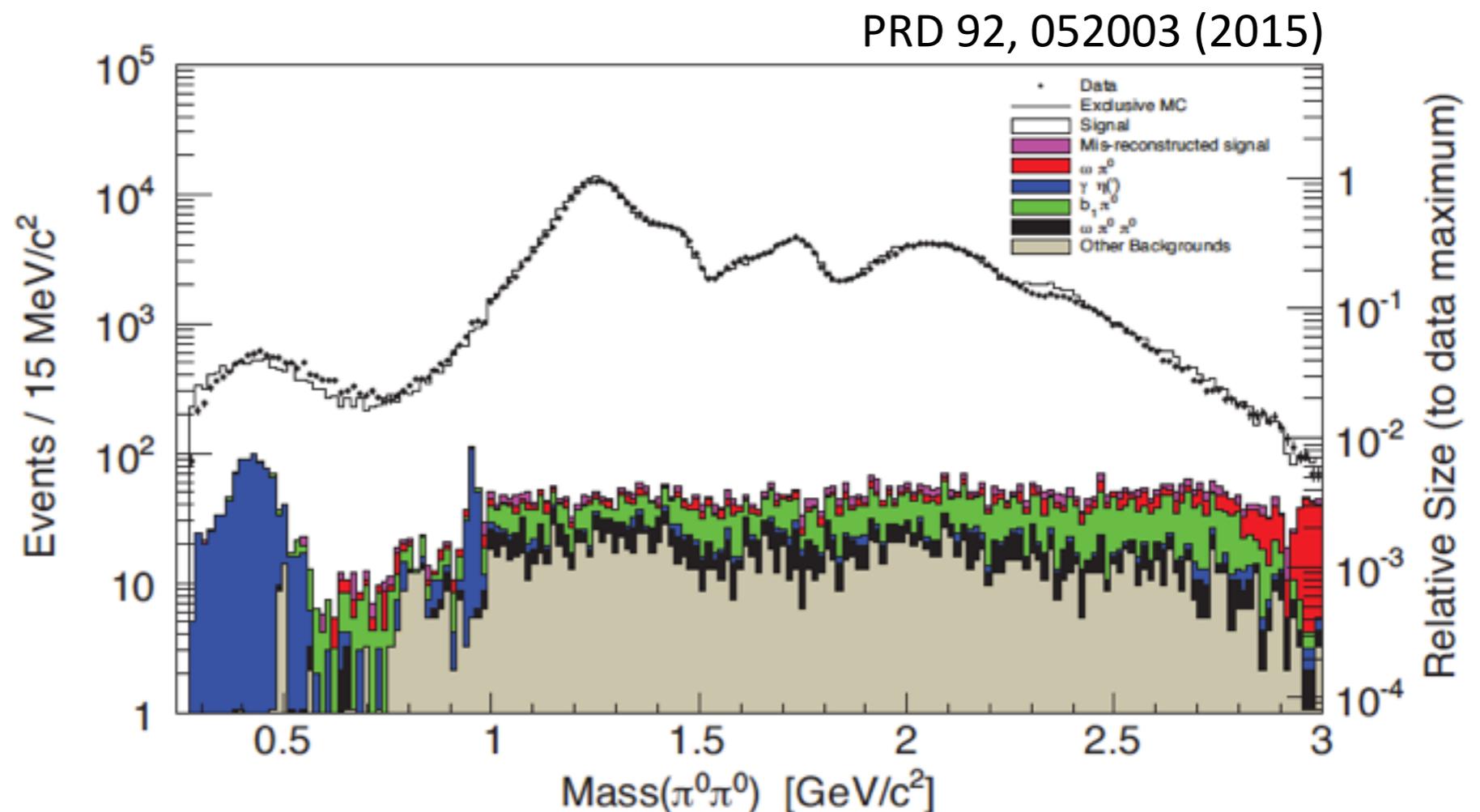
$$B(J/\psi \rightarrow \phi\eta(1405) \rightarrow \eta\phi\pi^+\pi^-) = (2.01 \pm 0.58 \pm 0.82) \times 10^{-4}$$

Amplitude analysis of the $\pi^0\pi^0$ system in radiative J/ψ decays

- Study scalar and tensor spectrum in radiative J/ψ decays into two pseudoscalar mesons
 - Only 0^{++} and 2^{++} amplitudes contribute significantly
 - Glueball states predicted in the region around 1.5 and 2 GeV/c^2
 - Presence of broad, overlapping states makes parameterization challenging

Full J/ψ sample
 $(1.311 \pm 0.011) \times 10^9$

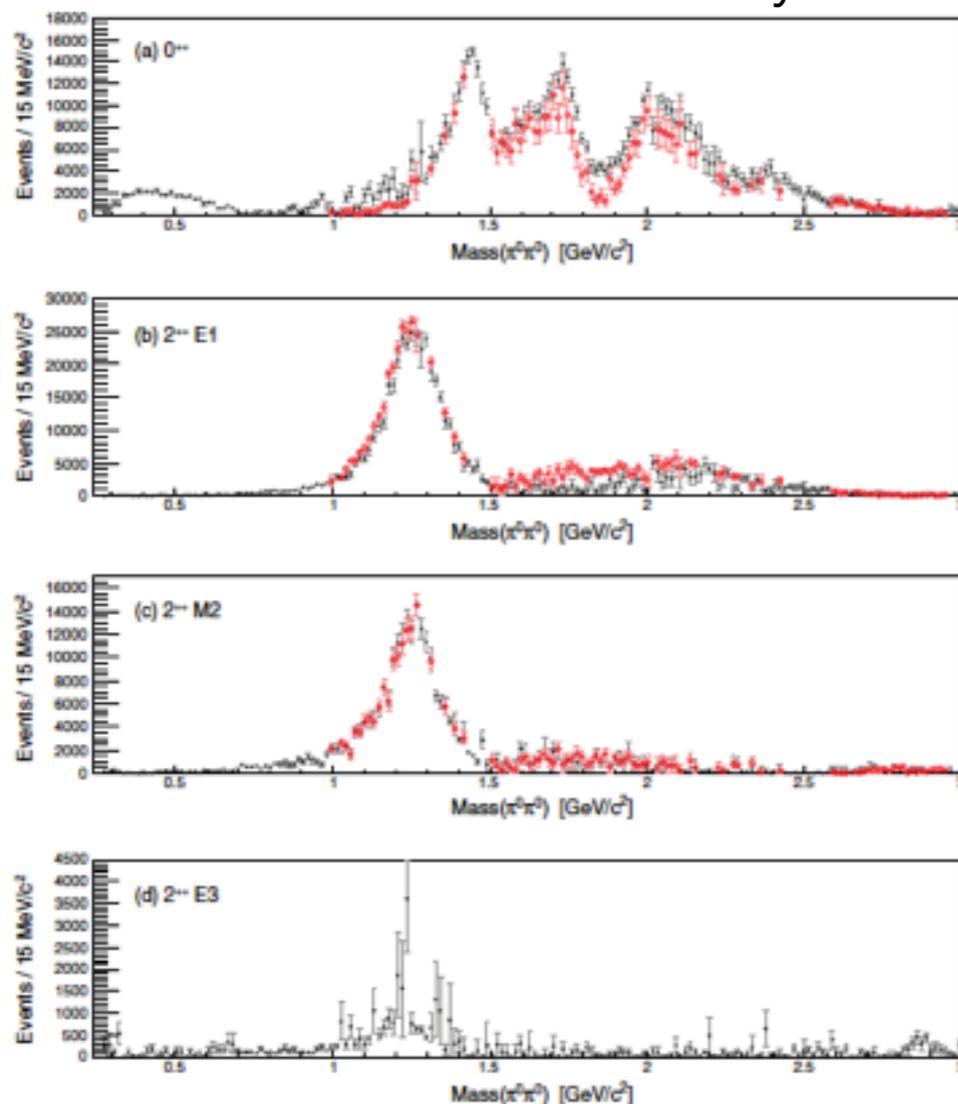
Very clean
 spectrum:
 $\sim 440\text{k}$ events with a
 background level
 less than 2%



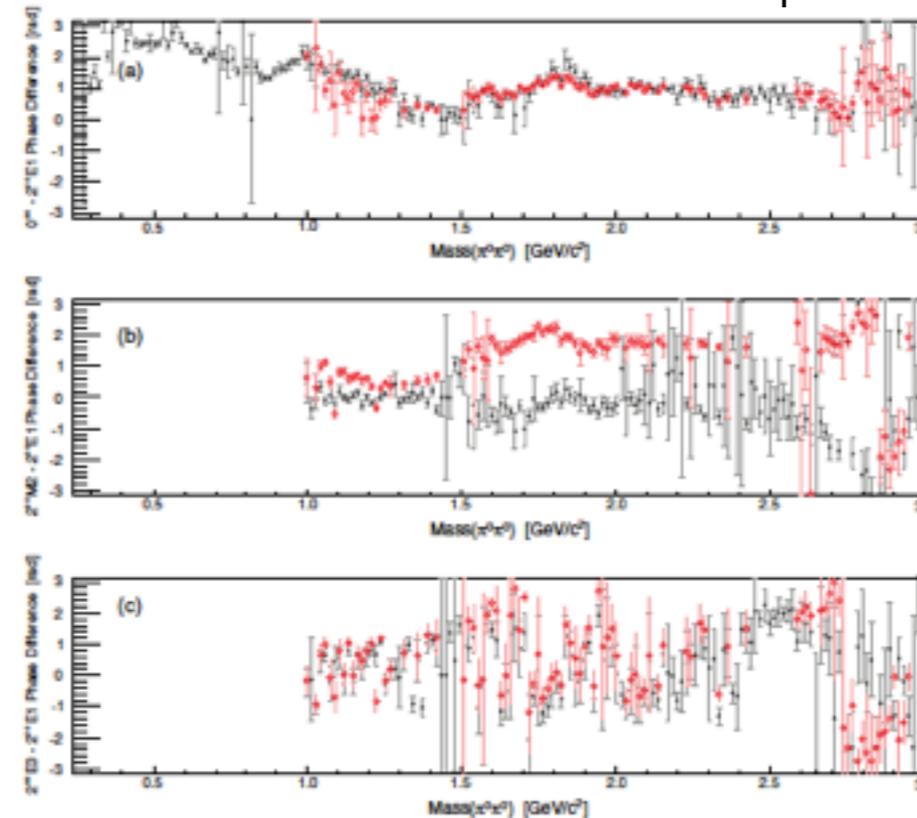
Amplitude analysis of the $\pi^0\pi^0$ system in radiative J/ψ decays

- Perform mass independent amplitude analysis
 - Useful for model development to describe hadronic interactions
 - **Great opportunity for collaboration between theory and experiment!**
 - Similar approach is under investigation for other systems (e.g. $K_S K_S$)

Extracted Intensity



Phase difference wrt E1 amplitude



nominal solution
ambiguous solution

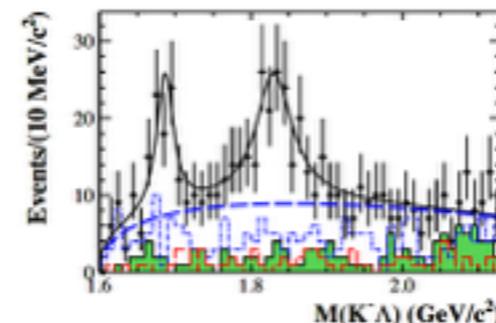
$$\mathcal{B}(J/\psi \rightarrow \gamma \pi^0 \pi^0) = (1.15 \pm 0.05) \times 10^{-3}$$

PRD 92, 052003 (2015)

Many more results in light hadron spectroscopy

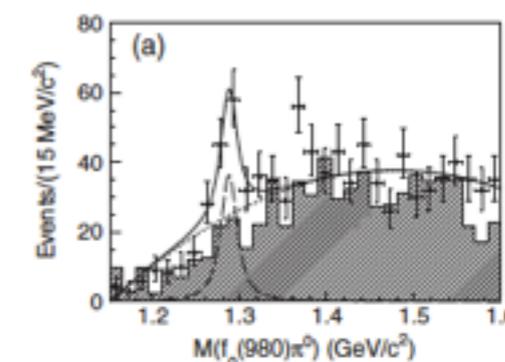
- Measurements of $\psi(3686) \rightarrow (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$

PRD 91, 092006 (2015)



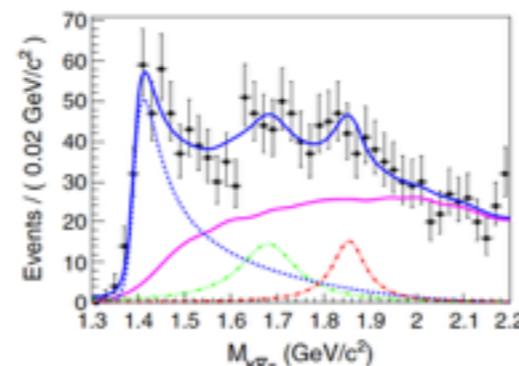
- Observation of the isospin-violating decay $J/\psi \rightarrow \phi\pi^0 f_0(980)$

PRD 92, 012007 (2015)



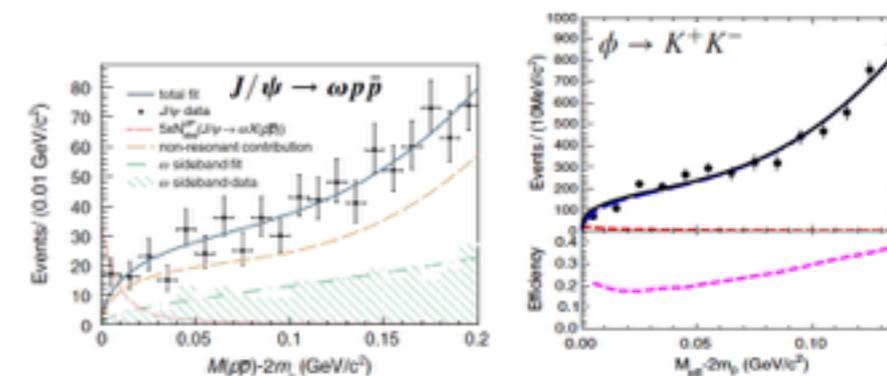
- Study of χ_{cJ} decaying into $\phi K^* \bar{K}$

PRD 91, 112008 (2015)

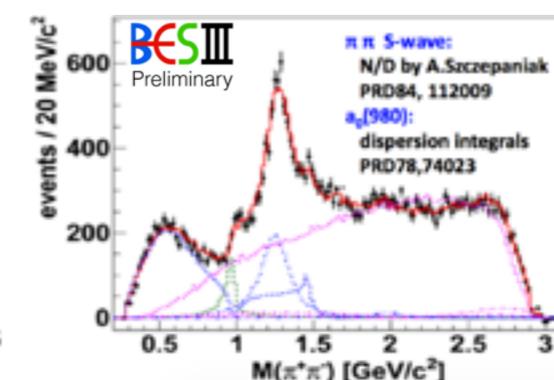
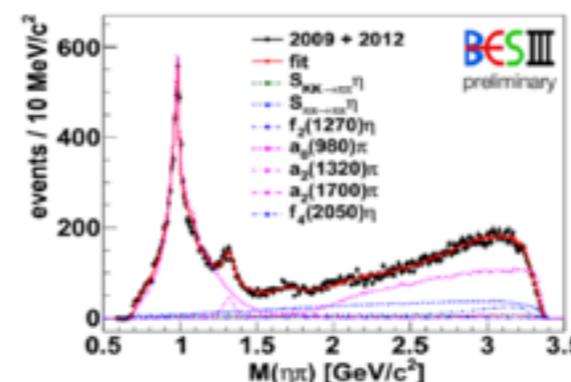


- Studies of the $p\bar{p}$ spectrum in hadronic J/ψ decays

PRD 87, 112004 (2013) PRD 93, 052010 (2016)



- Amplitude analysis of $\chi_{c1} \rightarrow \eta\pi^+\pi^-$



Conclusions

- High statistics charmonium data sets are producing many interesting results!
 - Observation of $h_c \rightarrow \gamma\eta'$ and evidence for $h_c \rightarrow \gamma\eta$
 - Tests of the 12% rule in ψ decays to $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^-\bar{\Sigma}(1385)^+$
 - Study of helicity selection rule suppressed process $\chi_{c2} \rightarrow VP$
 - $Y(2175)$ observed in J/ψ decays to $\eta\phi\pi^+\pi^-$
 - Mass independent amplitude analysis of $\pi^0\pi^0$ system
 - ... many more results in light hadron spectroscopy!
- Still more to come!