# Charmonium decays into light hadrons at BESIII

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# Introduction

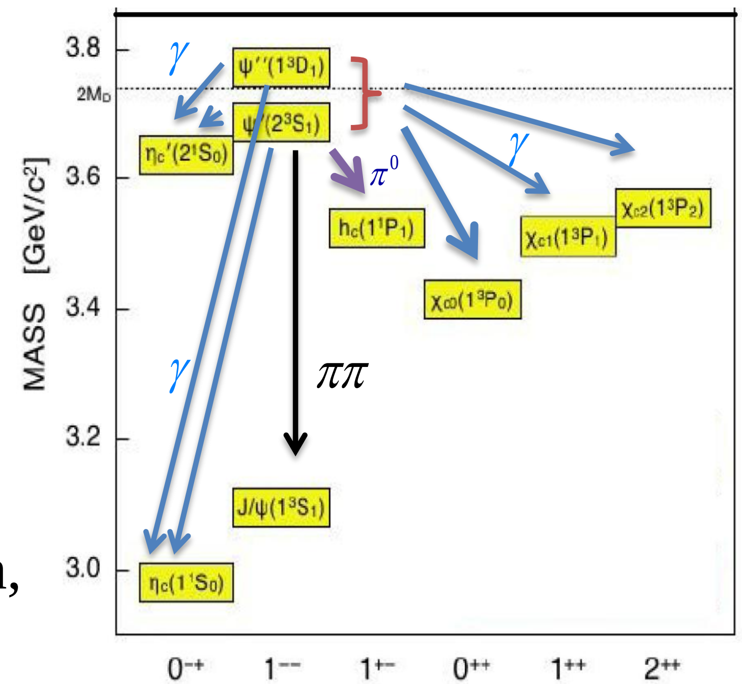
- Vector charmonium data sets

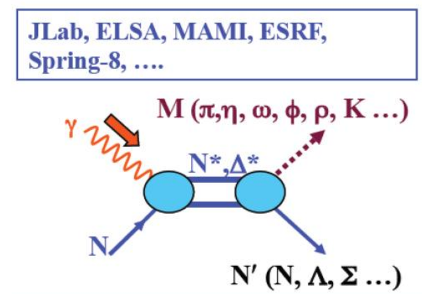
| Vector charmonium | Previous data | BESIII now | Goal |
|---|---|---|---|
| $J/\psi$ | BESII: 58 M | 1.2B(20×BESII) | 10 B |
| $\psi(3686)$ | CLEO: 28 M | 0.5B(20×CLEO) | 3 B |
| $\psi(3770)$ | CLEO: 0.8 $fb^{-1}$ | 2.9$fb^{-1}$(3.5×CLEO) | 20 $fb^{-1}$ |

- $\eta_c, \eta_c(2S), \chi_{cJ}$ are available via $\gamma$ transition, and $h_c$ available via pion transiton.

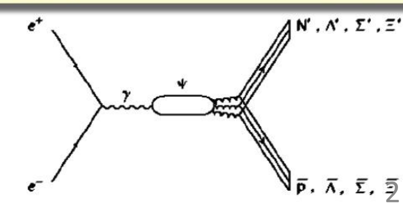
- charmonium physics
  - $\rho\pi$ puzzle, and violation of the 12% rule
  - non-$D\bar{D}$ decays of $\psi(3770)$
  - charmonium structure and properties

- light hadron spectroscopy




$J/\psi(\psi') \to \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$



$$\psi(3770) \to B\bar{B}(\mathrm{B} = \Sigma, \Xi), \Lambda\bar{\Lambda}\pi^+\pi^-, \Lambda\bar{\Lambda}\pi^0, \Lambda\bar{\Lambda}\eta, p\bar{p}\pi^0$$

- $\psi(3770)$ decays are dominated by DD mode

$$\text{PDG 2014: } Br[\psi(3770) \to D\bar{D}] = 93^{+8}_{-9}\%$$

- Non DD decay measurements

$$Br[\psi(3770) \to \text{light hadrons}] =$$

$(14.7 \pm 3.2)\%$ : BESII: Phys. Lett. B641, 145 (2006)

$(-3.3 \pm 1.4^{+6.6}_{-1.8})$ : CLEO: Phys. Rev. Lett., 96, 092002 (2006)

- No significant light hadron decay modes are exclusively established in experiment so far .

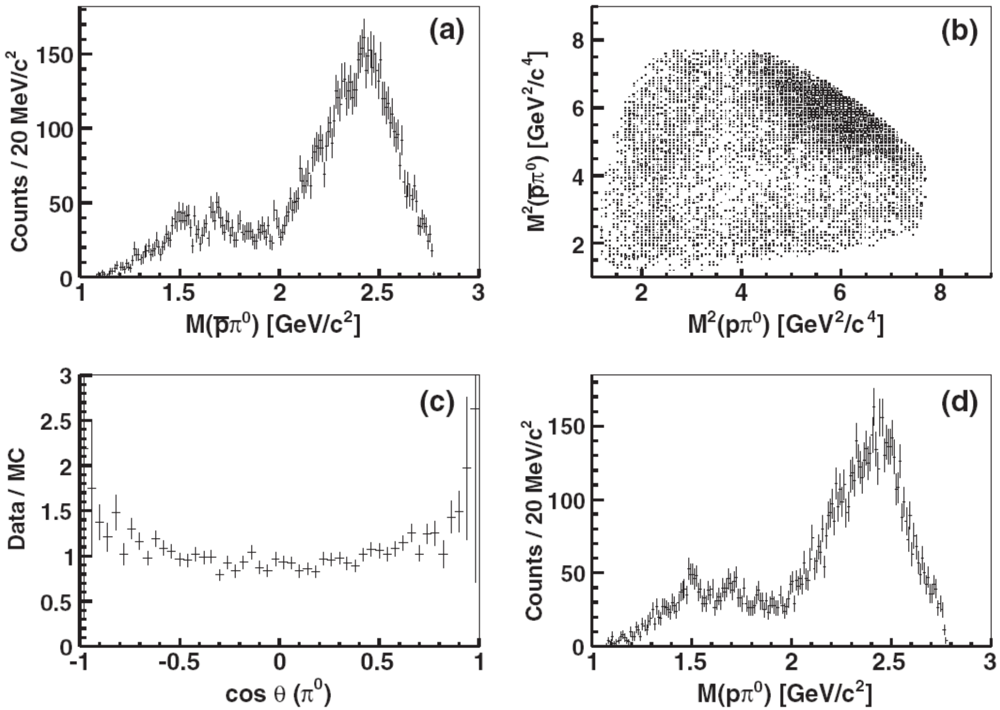
- NRQCD calculation yields upper limits of 5% for light hadron decays (PRL101, 112001), while other phenomenological model, e.g., hadron loops give large fractions(PRL102, 172001).

- Using 2.9 $fb^{-1}$ taken at 3.773 GeV.
- Continuum backgrounds are subtracted using 44 $pb^{-1}$ data taken at 3.65 GeV.
- No significant events are observed .

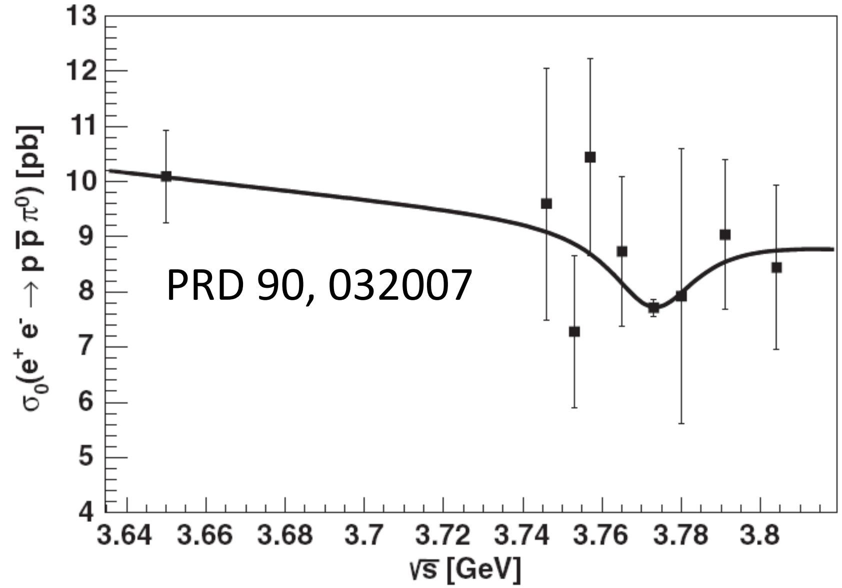
| Mode $f$ | $N^f_{\rm obs}$ (3.773) | $N^f_{\rm B}$ (3.773) | $N^{\rm up}_{\psi(3770)\to f}$ | $\epsilon$ | $\Delta_{\rm sys}$ | $\mathcal{B}_{\psi(3770)\to f}$ [$\times 10^{-4}$] | $\mathcal{B}^{\rm up}$ [$\times 10^{-4}$] |
|---|---|---|---|---|---|---|---|
| $\Lambda\bar{\Lambda}\pi^+\pi^-$ | $844.0 \pm 33.6$ | 5.2 | 481.2 | 0.1321 | 8.0 | $1.80^{+1.74}_{-2.30} \pm 0.40$ | $<4.7$ |
| $\Lambda\bar{\Lambda}\pi^0$ | $124.9 \pm 14.4$ | 3.4 | 83.6 | 0.1694 | 8.0 | $-1.28^{+0.67}_{-1.51} \pm 0.15$ | $<0.7$ |
| $\Lambda\bar{\Lambda}\eta$ | $74.0 \pm 9.5$ | 0.9 | 87.7 | 0.1518 | 8.1 | $-1.22^{+1.44}_{-3.21} \pm 0.19$ | $<1.9$ |
| $\Sigma^+\bar{\Sigma}^-$ | $100.5 \pm 11.9$ | 0.7 | 96.0 | 0.1975 | 8.0 | $-0.21^{+0.63}_{-1.56} \pm 0.05$ | $<1.0$ |
| $\Sigma^0\bar{\Sigma}^0$ | $43.5 \pm 6.7$ | 0.0 | 56.6 | 0.1752 | 8.0 | $0.30^{+0.05}_{-0.58} \pm 0.05$ | $<0.4$ |
| $\Xi^-\bar{\Xi}^+$ | $48.5 \pm 7.0$ | 0.0 | 119.7 | 0.1060 | 8.1 | $0.31^{+0.66}_{-1.32} \pm 0.05$ | $<1.5$ |
| $\Xi^0\bar{\Xi}^0$ | $43.5 \pm 6.6$ | 1.3 | 60.7 | 0.0581 | 8.2 | $-0.80^{+1.03}_{-2.72} \pm 0.14$ | $<1.4$ |

PRD 87, 112011 (2013)

# $\psi(3770) \to p\bar{p}\pi^0$




$$\sigma(s) = \left| \sqrt{\sigma_{\text{con}}} + \sqrt{\sigma_\psi}\,\frac{m\Gamma}{s - m^2 + im\Gamma}\exp(i\phi) \right|^2$$

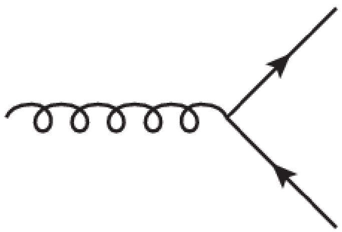



Data sets: 2.9 $fb^{-1}$ @ 3.773 GeV, 44.5 $pb^{-1}$ @ 3.65 GeV

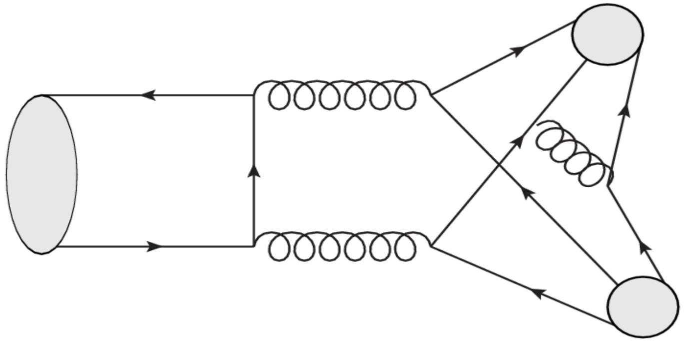
| Solution | $\sigma_0^{\psi(3770)\to p\bar{p}\pi^0}$ [pb] | $\phi_{\text{Fit}}$ [$^\circ$] | $\sigma_0^{p\bar{p}\to\psi(3770)\pi^0}$ [nb] at 5.26 GeV |
|---|---|---|---|
| 1 | $< 0.22$ | $269.8^{+52.4}_{-48.0} \pm 11.0$ | $< 0.79$ |
| 2 | $33.8 \pm 1.8 \pm 2.1$ | $269.7 \pm 2.3 \pm 0.3$ | $122 \pm 10$ |

# $\eta_c(2S), h_c, \chi_{cJ} \to p\bar{p}$

- These decays are suppressed by helicity selection rule.



$\eta_c(2S), \eta_c,$
$h_c, \chi_{c0}$



Helicity: $\bar{u}_{\uparrow}\gamma^{\mu}v_{\uparrow} = \bar{u}_{\downarrow}\gamma^{\mu}v_{\downarrow} \propto$ quark mass

suppressed by quark mass

helicity amplitude: $H_{\uparrow\uparrow}, H_{\downarrow\downarrow}, \lambda_p = \lambda_{\bar{p}} = \pm\frac{1}{2}$

Nucl. Phys. B 201, 492: $Br[\psi(\lambda) \to h_1(\lambda_1)h_2(\lambda_2)] \sim \left(\frac{\Lambda_{QCD}^2}{m_c^2}\right)^{|\lambda_1+\lambda_2|+2}$

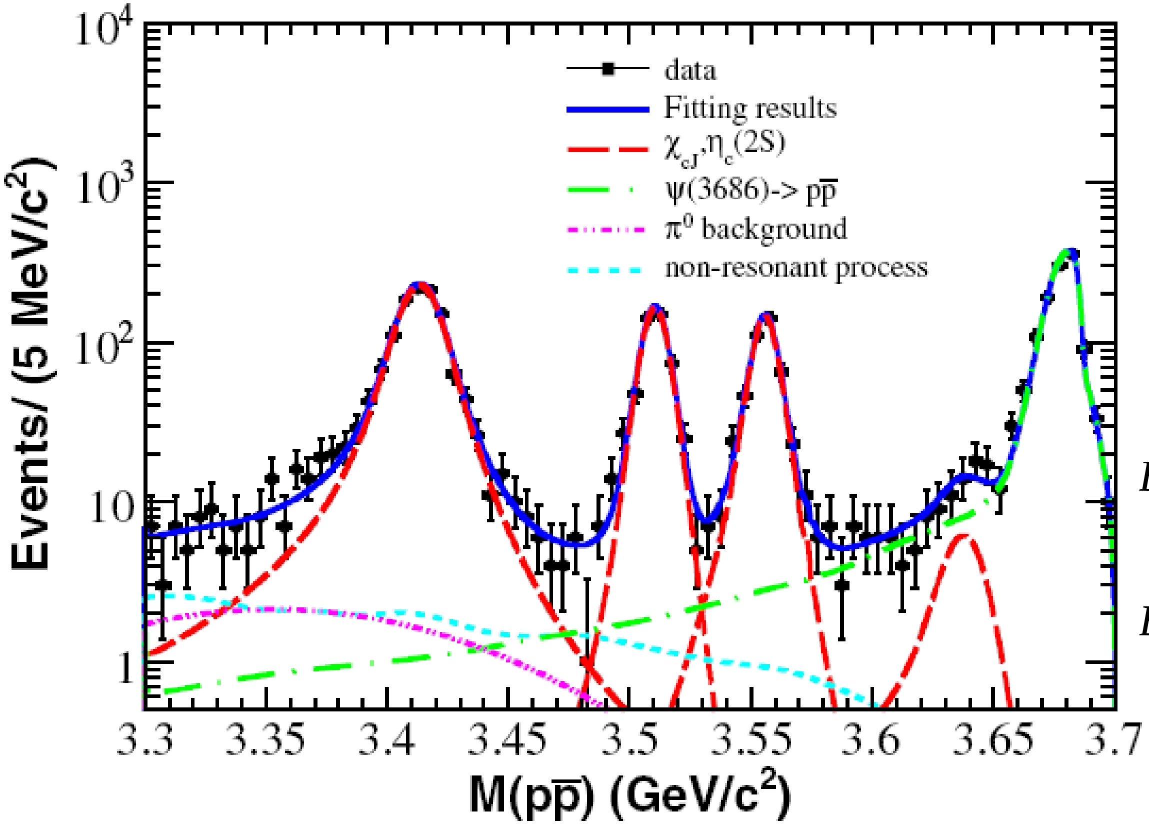
- However, measured branching fractions

$$Br[\chi_{c0} \to p\bar{p}]=(2.23\pm0.13)\times10^{-4}$$

$$Br[\eta_c \to p\bar{p}] = (1.41\pm0.17)\times10^{-3}$$

- Theoretical estimation:

$$Br[h_c \to p\bar{p}] \sim 10^{-3}$$ (PRD 86, 034011)




- 106 million $\psi(3686)$ decays are used.
- No significance for $\eta_c(2S)$ and $h_c$ signals are observed.
- Upper limit is set to be:

$$Br(\psi(3686) \to \gamma\eta_c(2S))Br(\eta_c(2S) \to p\bar{p}) < 1.4\times10^{-6} \text{ @ 90\% CL},$$

$$Br(\psi(3686) \to \pi^0 h_c)Br(h_c \to p\bar{p}) < 1.3\times10^{-7} \text{ @ 90\% CL}.$$

PRD 88, 112001 (2013)

| Channels | $\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) \times \mathcal{B}(\chi_{cJ} \to p\bar{p})(\times10^{-5})$ | $\mathcal{B}(\chi_{cJ} \to p\bar{p})(\times10^{-5})$ |
|---|---|---|
| $\chi_{c0}$ | $2.37 \pm 0.08 \pm 0.09$ | $24.5 \pm 0.8 \pm 1.3$ |
| $\chi_{c1}$ | $0.79 \pm 0.04 \pm 0.03$ | $8.6 \pm 0.5 \pm 0.5$ |
| $\chi_{c2}$ | $0.73 \pm 0.04 \pm 0.03$ | $8.4 \pm 0.5 \pm 0.5$ |

# $\psi(3686) \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c, \quad \omega K^+K^-$

BESIII

- pQCD “12% rule” and long existing $\rho\pi$ puzzle

$$Q_h = \frac{\mathcal{B}_{\psi(3686)\to h}}{\mathcal{B}_{J/\psi\to h}} \approx \frac{\mathcal{B}_{\psi(3686)\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} = 12.7\% \qquad Q_{\rho\pi} = (1.89 \pm 0.73)\times 10^{-3}$$

- Mass spectrum of $\bar{\Sigma}^{\pm}\pi^{\mp}$ may indicate the $\Lambda^* / \Sigma^*$ hints

- **Large uncertainty for branching fraction of $\psi(3686) \to \omega K^+K^-$**

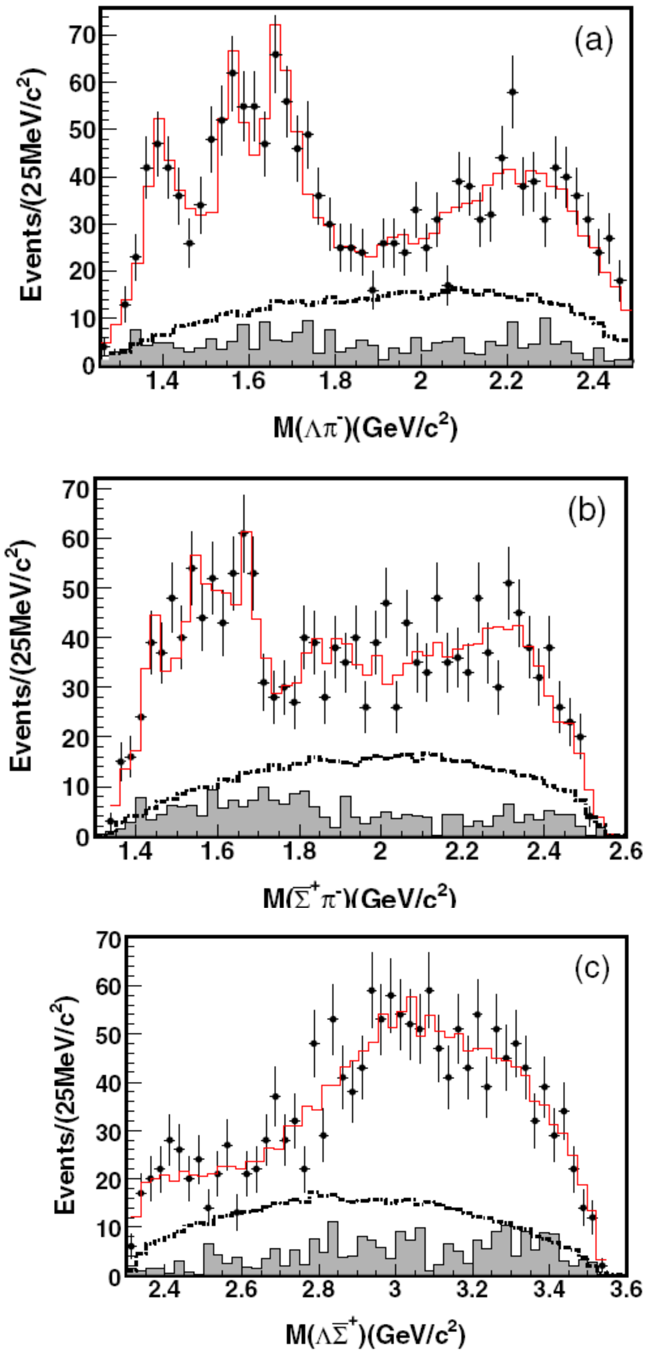
$$B(\psi(3686) \to \omega K^+K^-) = (1.85 \pm 0.25)\times 10^{-4}$$

with uncertainty ~13%, and

$$Q_{\omega K^+K^-} = (21.8 \pm 5)\%$$

PRD 88, 112007

# $\psi(3686) \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c$




- 106 million $\psi(3686)$ decays are used.
- $\Sigma$ ( $\bar{\Sigma}$) is reconstructed with $n\pi$ ( $p\pi$) mode.
- For determine detection efficiency, a preliminary partial wave analysis is performed.

$\Lambda(1810)$, $\Lambda(1800)$, $\Lambda(1670)$, $\Lambda(1600)$, $\Lambda(1405)$, $\Lambda(1116)$, $\Lambda(2325)$, $\Lambda(1890)$, $\Lambda(1690)$, $\Lambda(1520)$, $\Lambda(1830)$, $\Lambda(1820)$, $\Sigma(1660)$, $\Sigma(1670)$, $\Sigma(1580)$ and $\Sigma(1385)$

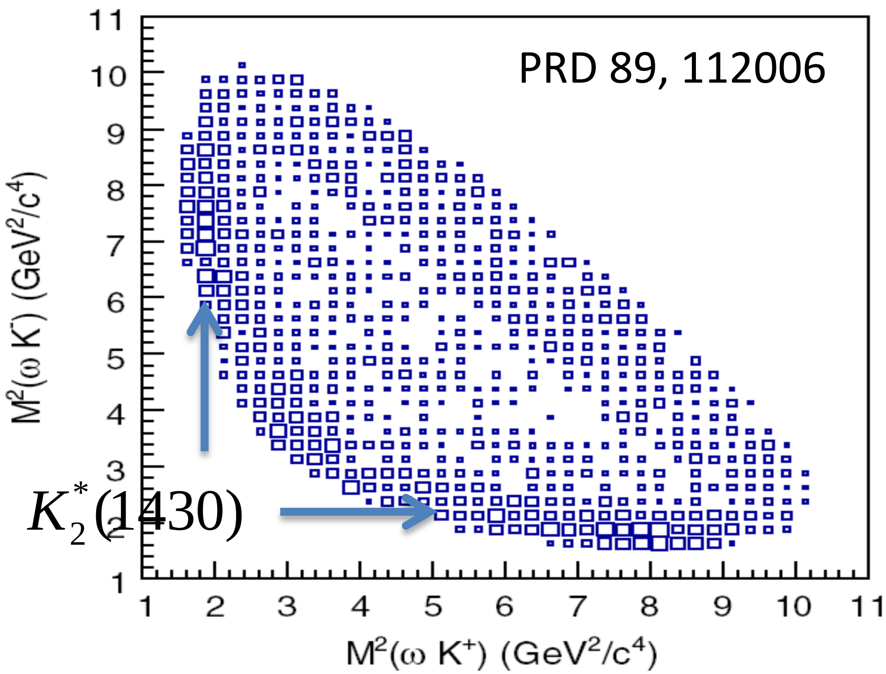
$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{+}\pi^{-} + \text{c.c.}) = (1.40 \pm 0.03 \pm 0.13) \times 10^{-4},$$

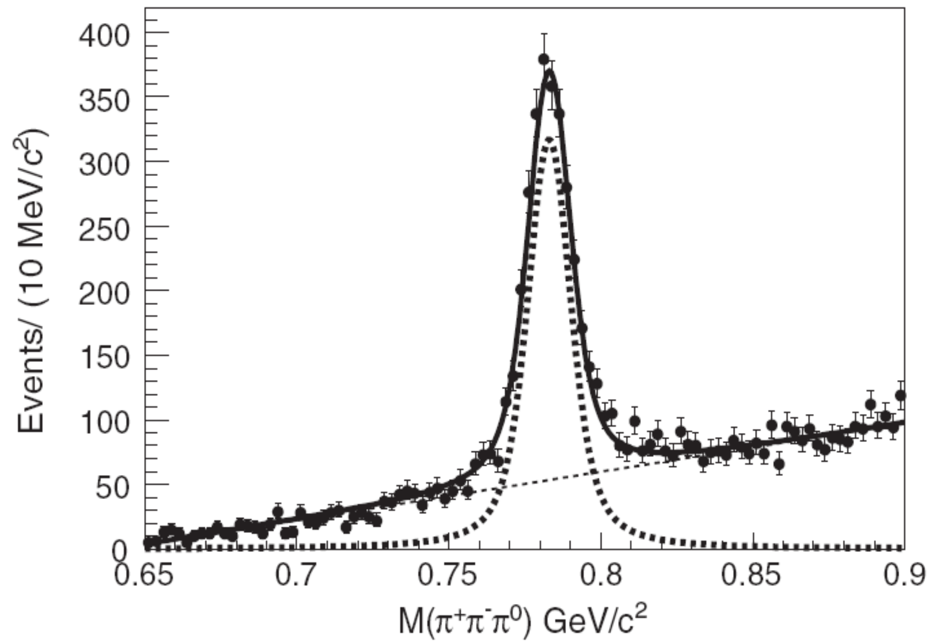
$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+} + \text{c.c.}) = (1.54 \pm 0.04 \pm 0.13) \times 10^{-4},$$

$$Q_{\Lambda\bar{\Sigma}^{-}\pi^{+}} = \frac{\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+})}{\mathcal{B}(J/\psi \to \Lambda\bar{\Sigma}^{-}\pi^{+})} = (9.3 \pm 1.2)\%,$$

- To resulve $\Lambda^{*}/\Sigma^{*}$ contribution, PWA is desirable.

# $\psi(3686) \to \omega K^+K^-$



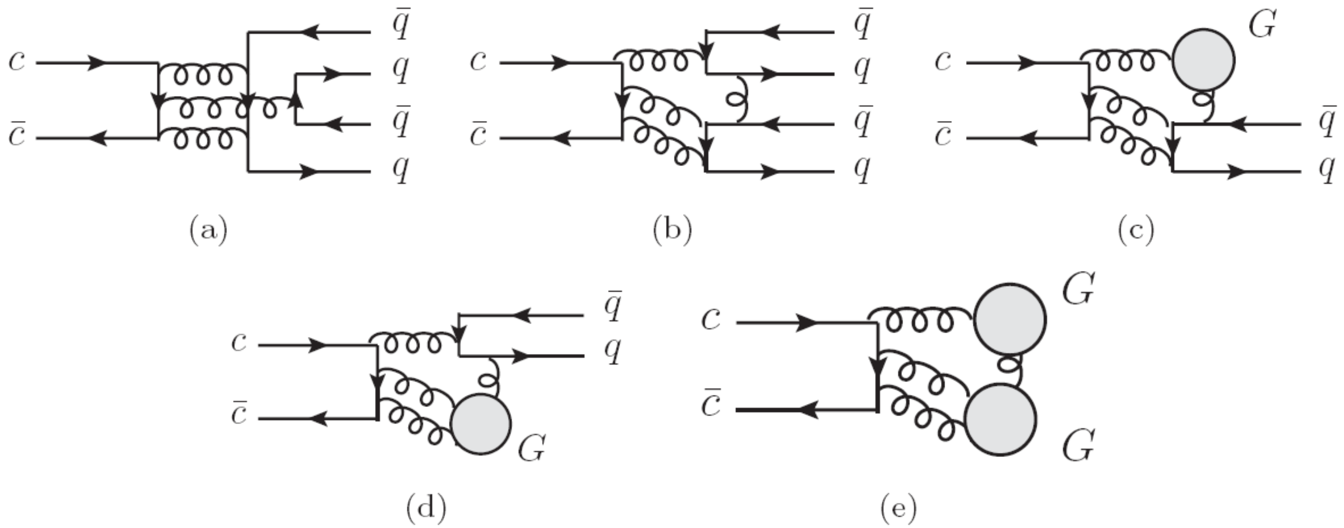

**106 million $\psi(3686)$ decays**

| Branching fraction | Source |
|---|---|
| $(1.56 \pm 0.04 \pm 0.11) \times 10^{-4}$ | this analysis |
| $(2.38 \pm 0.37 \pm 0.29) \times 10^{-4}$ | BESII [20] |
| $(1.9 \pm 0.3 \pm 0.3) \times 10^{-4}$ | CLEO [21] |
| $(1.5 \pm 0.3 \pm 0.2) \times 10^{-4}$ | BES [22] |
| $(1.85 \pm 0.25) \times 10^{-4}$ | PDG [5] |

$Q_{\omega K^+K^-} = (18.4 \pm 3.7)\%$

# $\chi_{cJ} \to \eta' K^+ K^-$

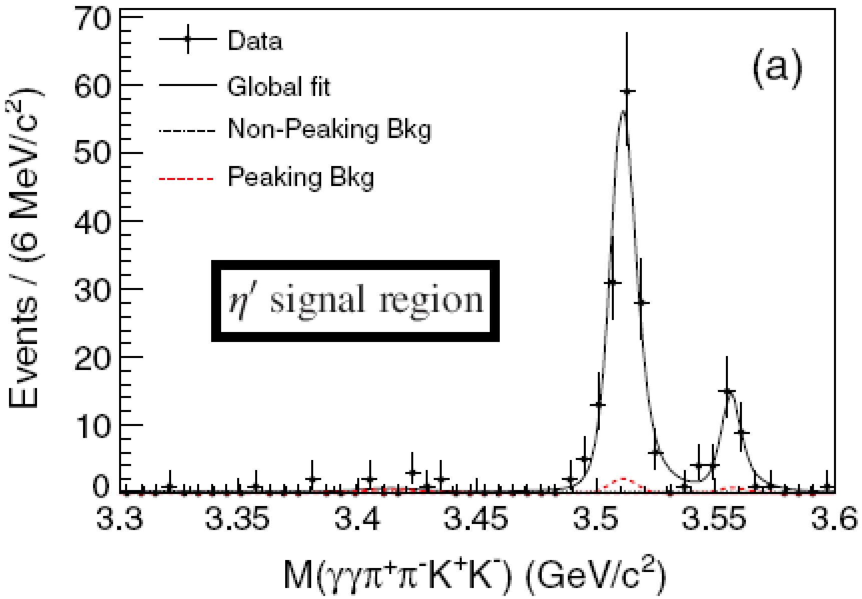
- Compared to J/$\psi$ and $\psi(3686)$ decays, relatively little is known about $\chi_{cJ}$ decays.
- Look for scalar states, e.g. $f_0$(1370), $f_0$(1500), and so on, and test the glueball-qqbar mixing relations (Int.J.Mod.Phys.27,1250135).

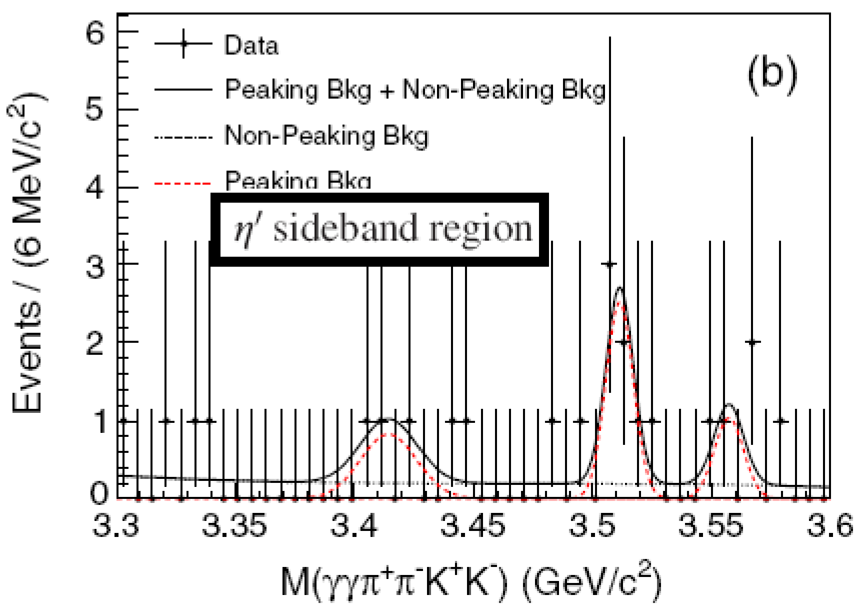



The schematic Feynman diagrams of $\chi_{c1} \to PS$ via three-gluon annihilations.

- Looking for $K^*_0(1430) \to \eta' K$

PRD 89, 074030



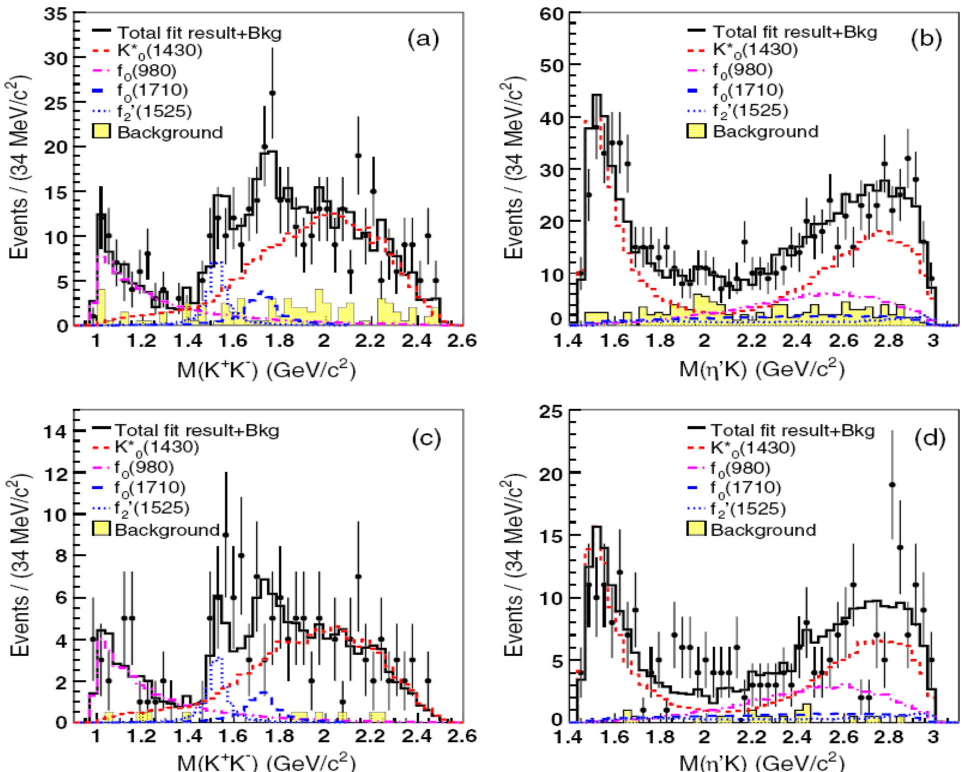




- **Use 106 million $\psi(3686)$ decays**
- $\eta'$ is reconstructed with decays

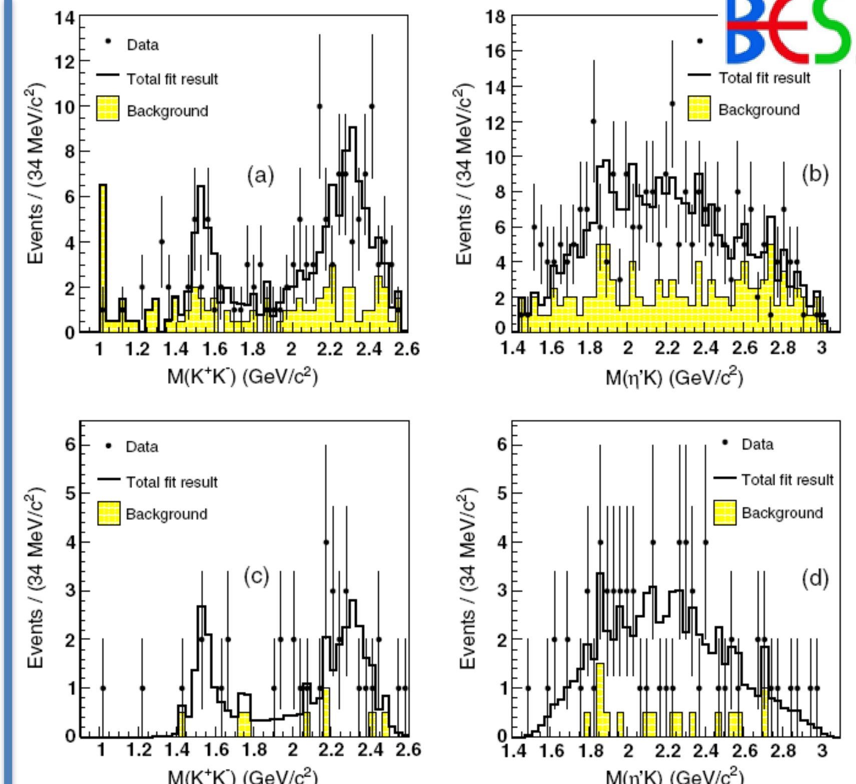
$$\eta' \to \gamma\rho^0 \to \gamma\pi^+\pi^- \quad \text{and}$$

$$\eta' \to \eta\pi^+\pi^- \to \gamma\gamma\pi^+\pi^-$$

| Process | $\mathcal{B}(\times 10^{-4})$ |
|---|---|
| $\mathcal{B}(\chi_{c1} \to \eta' K^+ K^-)$ | $8.75 \pm 0.87$ |
| $\mathcal{B}(\chi_{c2} \to \eta' K^+ K^-)$ | $1.94 \pm 0.34$ |




$\chi_{c1} \rightarrow \eta' K^+ K^-$




$\chi_{c2} \rightarrow \eta' K^+ K^-$

where (a) (b) for mode I, and (c) (d) for mode II

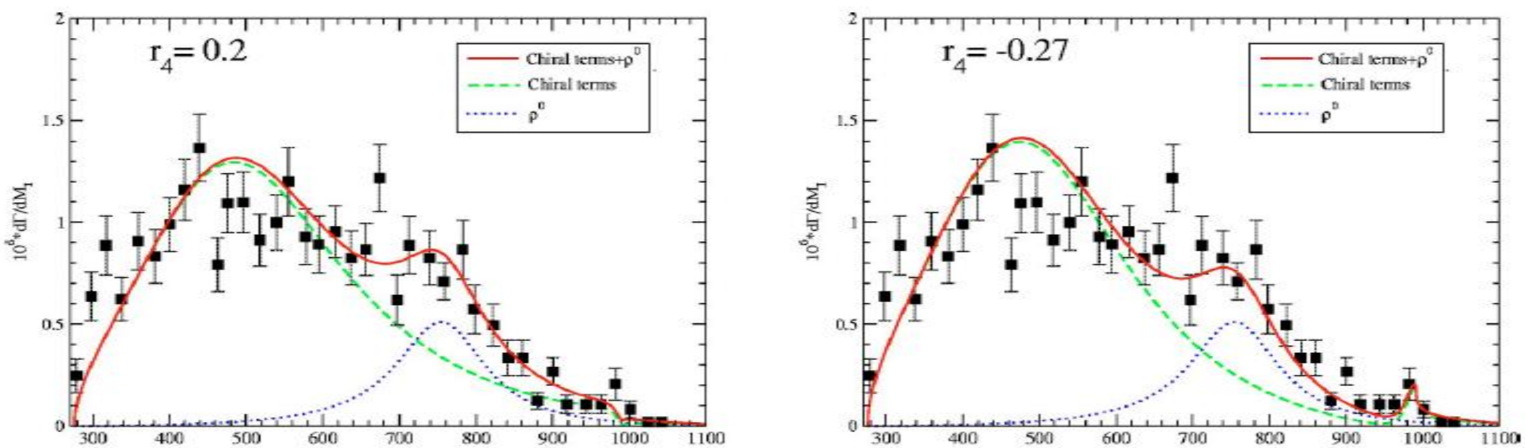
PRD 89, 074030

| Process | $\mathcal{B}(\times 10^{-4})$ |
|---|---|
| $\chi_{c1} \rightarrow K_0^*(1430)^{\pm} K^{\mp},\ K_0^*(1430)^{\pm} \rightarrow \eta' K^{\pm}$ | $6.41 \pm 0.57^{+2.09}_{-2.71}$ |
| $\chi_{c1} \rightarrow \eta' f_0(980),\ f_0(980) \rightarrow K^+ K^-$ | $1.65 \pm 0.47^{+1.32}_{-0.56}$ |
| $\chi_{c1} \rightarrow \eta' f_0(1710),\ f_0(1710) \rightarrow K^+ K^-$ | $0.71 \pm 0.22^{+0.68}_{-0.48}$ |
| $\chi_{c1} \rightarrow \eta' f_2'(1525),\ f_2'(1525) \rightarrow K^+ K^-$ | $0.92 \pm 0.23^{+0.55}_{-0.51}$ |

# $J/\psi \to p\bar{p}a_0(980)$

- The nature of $a_0(980)$ and $f_0(980)$ is a long-standing problem of physics
- The measurement of $J/\psi \to p\bar{p}a_0(980)$ will provide an additional constraint to any model describing $a_0(980)$ formation and decays.
- $\chi$PT provides a description of $J/\psi \to N\bar{N}MM$ process, yet to be test experimentally.

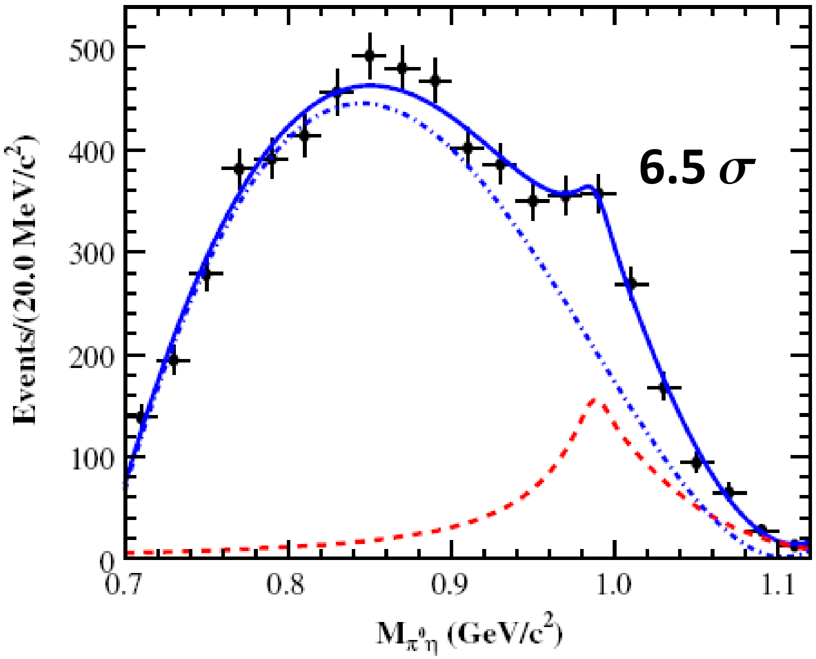
PRC **69**, 015201




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

- **225 million J/$\psi$ decays**

PRD 90, 052009




$J/\psi \to p\bar{p}a_0(980),$

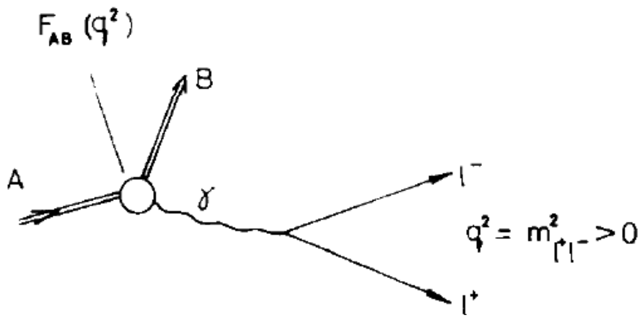
$a_0(980) \to \pi^0\eta$

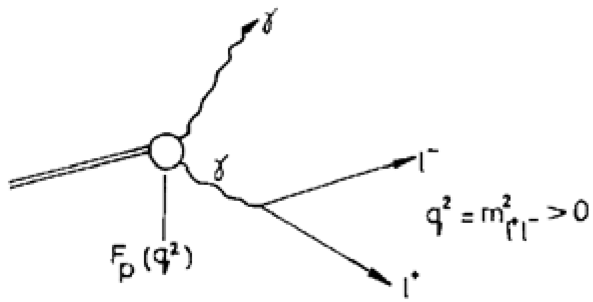
is observed for the first time.

- $Br(\mathrm{J}/\psi \to p\bar{p}a_0(980) \to p\bar{p}\pi^0\eta) = (6.8 \pm 1.2 \pm 1.3) \times 10^{-5}$.
- Interference with $N^*$ states is not taken into account.
- Comparison with $Br(\mathrm{J}/\psi \to p\bar{p}\pi^+\pi^-)$ from the PDG shows preference $r_4$=0.2 in ChPT .

# $J/\psi \to Pe^+e^- \quad (P = \eta'/\eta/\pi^0)$

- Electromagnetic decays are suggested as an important probe to reveal the structure of hadrons.

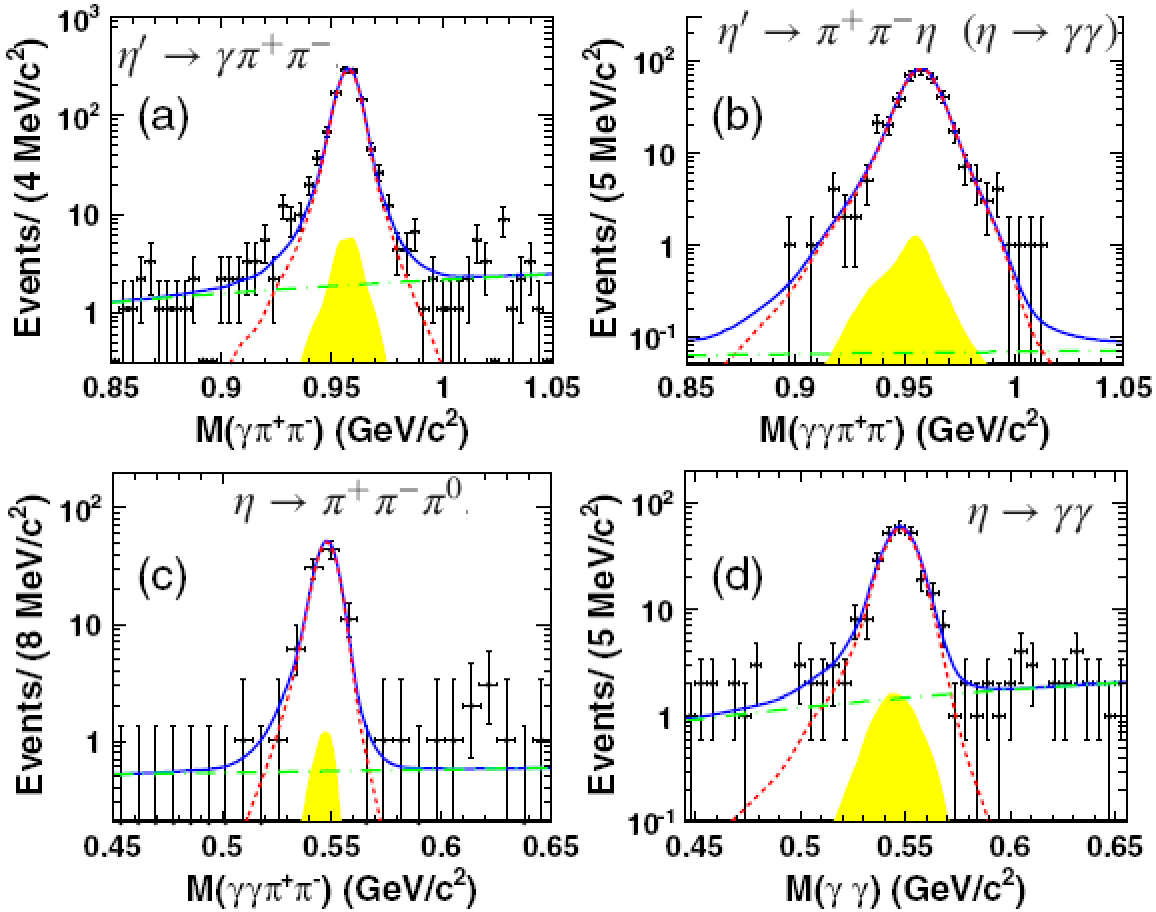


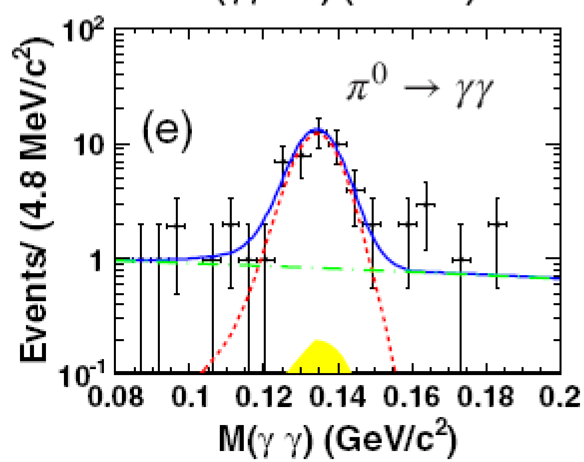




$$\frac{d\Gamma(V \to Pe^+e^-)}{dq^2\Gamma(V \to P\gamma)} = |F_{VP}(q^2)|^2 \times [\mathrm{QED}(q^2)], \quad |F_{VP}(q^2)| = \frac{1}{(1 - q^2/\Lambda^2)}$$

Pointlike QED part

- Measurements of EM decays for $\rho, \omega, \phi$ mesons have been performed at CMD2, CLOE and so on.
- The branching fractions and form factors for $\phi \to \eta e^+e^-$, $\omega \to \pi^0 e^+e^-$ are consistent with VMD model prediction, but for decay $\omega \to \pi^0\mu^+\mu^-$, measured $\Lambda^{-2}$ significantly deviates from VDM.




PRD 89, 092008

- **Using 225 million J/$\psi$ decays**
- **$\gamma$-conversion backgrounds from J/$\psi \to$ P$\gamma$ are subtracted.**
- **Backgrounds from J/$\psi \to$ P$\phi/\omega$ are subtracted.**
- **Non-peaking backgrounds are carefully checked with MC simulation.**

Signal yield and peaking BG.

| Modes | $N_S$ | $N_B$ | $\epsilon$ |
|---|---|---|---|
| $J/\psi \to \eta' e^+e^-(\eta' \to \gamma\pi^+\pi^-)$ | $983.3 \pm 33.0$ | $27.4 \pm 1.0$ | 24.8% |
| $J/\psi \to \eta' e^+e^-(\eta' \to \pi^+\pi^-\eta)$ | $373.0 \pm 19.9$ | $8.5 \pm 0.3$ | 17.6% |
| $J/\psi \to \eta e^+e^-(\eta \to \pi^+\pi^-\pi^0)$ | $84.2 \pm 9.6$ | $5.3 \pm 0.3$ | 14.9% |
| $J/\psi \to \eta e^+e^-(\eta \to \gamma\gamma)$ | $235.5 \pm 16.4$ | $8.7 \pm 0.3$ | 22.7% |
| $J/\psi \to \pi^0 e^+e^-(\pi^0 \to \gamma\gamma)$ | $39.4 \pm 6.9$ | $1.1 \pm 0.1$ | 23.4% |

PRD 89, 092008

| Mode | Branching fraction | Combined result | Theoretical prediction |
| --- | --- | --- | --- |
| $J/\psi \to \eta' e^+ e^- (\eta' \to \gamma\pi^+\pi^-)$ | $(6.01 \pm 0.20 \pm 0.34) \times 10^{-5}$ | | |
| $J/\psi \to \eta' e^+ e^- (\eta' \to \pi^+\pi^-\eta)$ | $(5.51 \pm 0.29 \pm 0.32) \times 10^{-5}$ | $(5.81 \pm 0.16 \pm 0.31) \times 10^{-5}$ | $(5.66 \pm 0.16) \times 10^{-5}$ |
| $J/\psi \to \eta e^+ e^- (\eta \to \pi^+\pi^-\pi^0)$ | $(1.12 \pm 0.13 \pm 0.06) \times 10^{-5}$ | | |
| $J/\psi \to \eta e^+ e^- (\eta \to \gamma\gamma)$ | $(1.17 \pm 0.08 \pm 0.06) \times 10^{-5}$ | $(1.16 \pm 0.07 \pm 0.06) \times 10^{-5}$ | $(1.21 \pm 0.04) \times 10^{-5}$ |
| $J/\psi \to \pi^0 e^+ e^- (\pi^0 \to \gamma\gamma)$ | $(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$ | $(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$ | $(3.89^{+0.37}_{-0.33}) \times 10^{-7}$ |

- Measured branching fraction for $J/\psi \rightarrow \eta' e^+e^-$, $\eta e^+e^-$ are consistent with the VMD predictions.
- But for $J/\psi \rightarrow \pi^0 e^+e^-$, there is about 2.5 standard deviation from the VMD prediction.
- Further improvement of the theoretical calculation are needed.

# Summary

By using BESIII data sets taken at J/$\psi$, $\psi$(3686) and $\psi$(3770) peak, a lot of results on the light hadron decays are obtained.

- No significant non $D\bar{D}$ decays of $\psi(3773)$ are observed.
- No significant $\eta_c(2S), h_c \to p\bar{p}$ decays are observed.
- Measured Br. for $\psi(3686) \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c, \omega K^+K^-$.
- Perfomred PWA analysis for $\chi_{cJ} \to \eta' K^+K^-$.
- Observed $J/\psi \to p\bar{p}a_0(980)$.
- Observed $J/\psi \to \eta' e^+e^-$, $\eta e^+e^-$ and $\pi^0 e^+e^-$.

**A more interesting light hadron decays of charmonium will come soon!**