The exotic Y states via ISR at BaBar

Peter Lewis
Stanford University | SLAC
on behalf of the BaBar Collaboration

26 April 2013

QWG 2013
Beijing

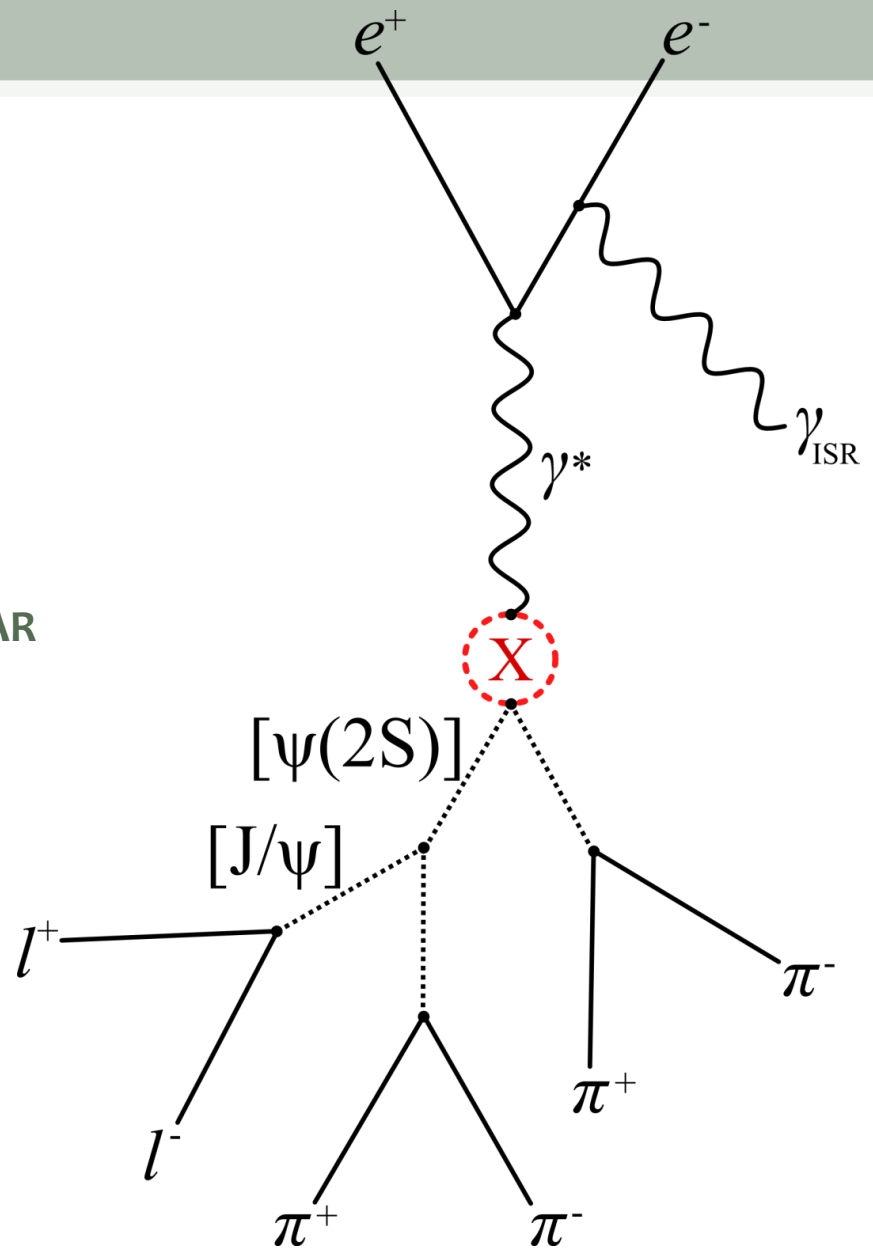
BaBar

SLAC

Outline

THE EXOTIC Y STATES

- **UPDATE OF THE $\pi^+\pi^- J/\psi$ ISR ANALYSIS AT BABAR**
  - Context
  - New $\pi^+\pi^- J/\psi$ results
  - Analysis of $\pi^+\pi^-$ in $\pi^+\pi^- J/\psi$
  - Summary
- **UPDATE OF THE $\pi^+\pi^-\psi(2S)$ ISR ANALYSIS AT BABAR**
  - Context
  - New $\pi^+\pi^-\psi(2S)$ results
  - Analysis of $\pi^+\pi^-$ in $\pi^+\pi^-\psi(2S)$
  - Summary



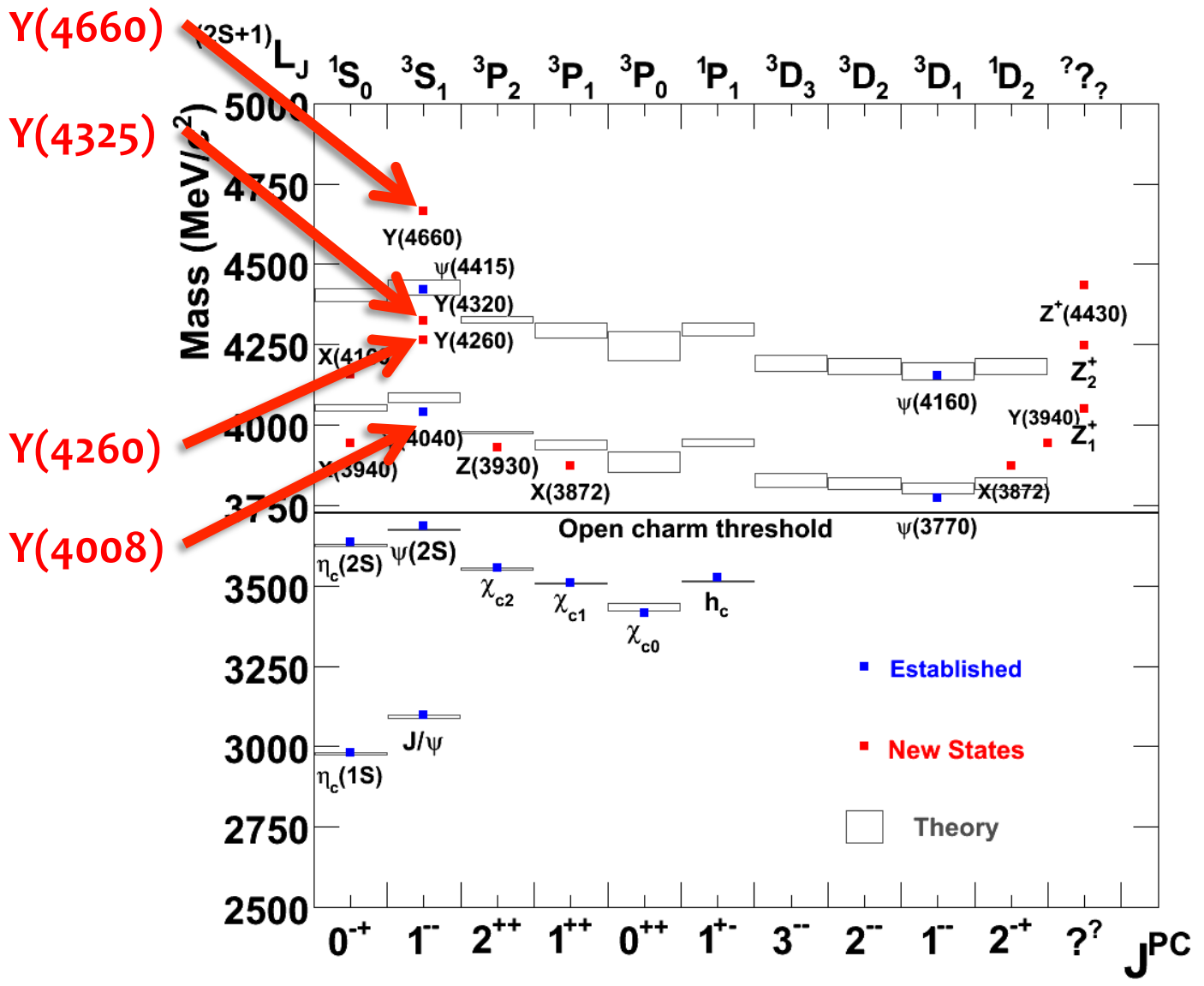
The exotic Y states

Exotic charmonium-like states above open-charm threshold

- Need no introduction here!
- Focus primarily on the "Y" candidates: $J^{PC} = 1^{--}$

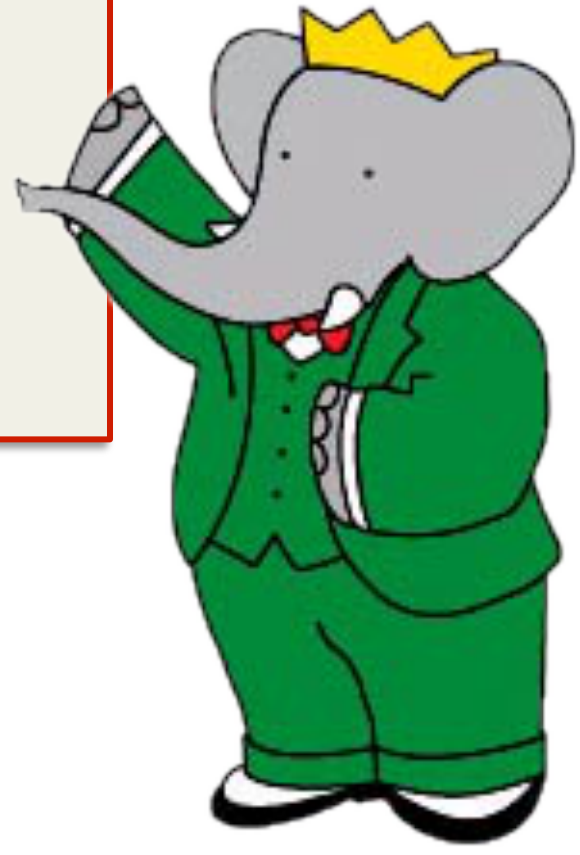
Production technique

- Pseudo-direct production in ISR events
- Look at strong decay modes strongly suppressed for charmonium above threshold [such as $Y \to \pi^+\pi^- J/\psi$]
- Previous BaBar analyses using the ISR method discovered the Y(4260) and Y(4325) but were based on partial datasets
- Re-analyze in ISR modes with full BaBar dataset



Update of the $\pi^+\pi^- J/\psi$ ISR analysis at BaBar

PRD-RC 86, 051102 (2012)



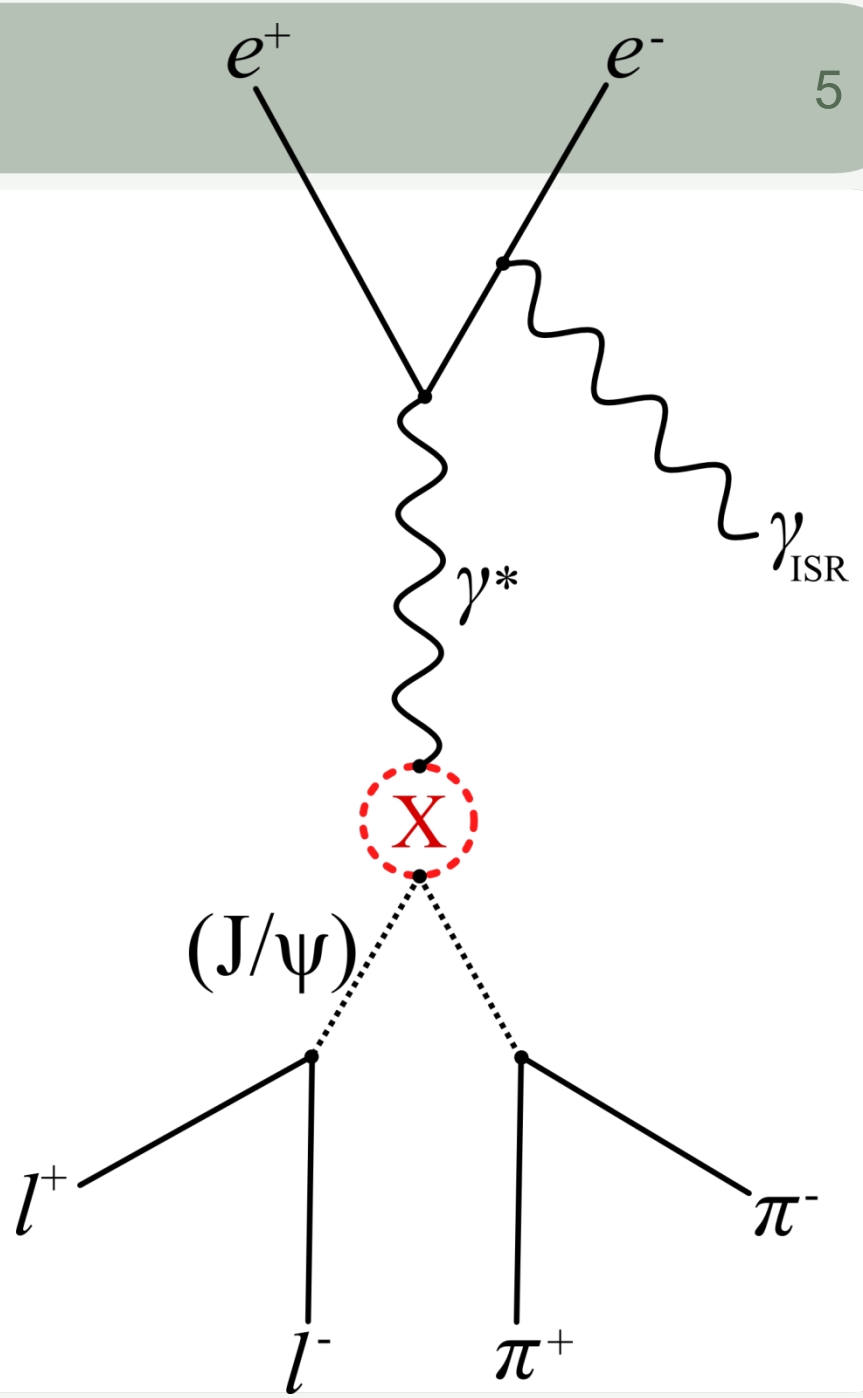
The $\pi^+\pi^-$ J/ψ mode in ISR

Radiative Return technique

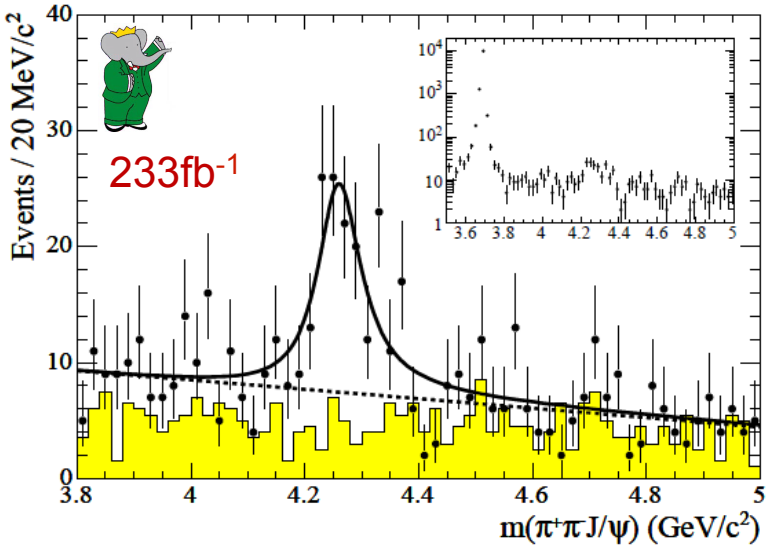
- *ee* collider operating at higher resonances
- ISR events lower CM energy of *ee* collision
- Direct production of $J^{PC}= 1^{--}$ states
- Existing data provide effective "scan" of energies at charmonium levels
- Explicit reconstruction of ISR photon not necessary

ISR production in charmonium region

- Direct production of any $J^{PC}= 1^{--}$ state X
- Plausible X decay modes include $X \to \pi^+\pi^- J/\psi$
- If X is charmonium, this mode is highly suppressed above the open-charm threshold:
  - $e^+e^- \to \gamma_{ISR}\, X$
  - $X \to \pi^+\pi^- J/\psi$
  - $J/\psi \to l^+l^-$
- Exotic state enhancements seen in this mode
- Remains one of the most fruitful analysis modes



Context: previous $\pi^+\pi^-$ J/ψ results



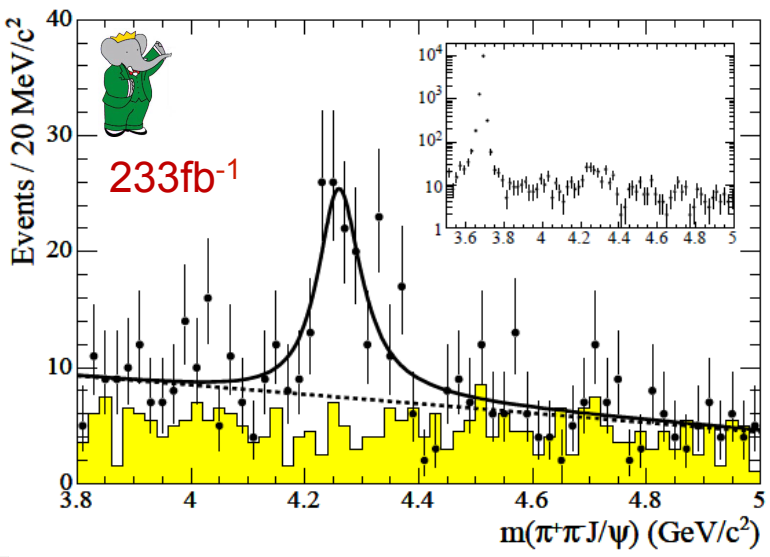
BaBar: Y(4260) observation

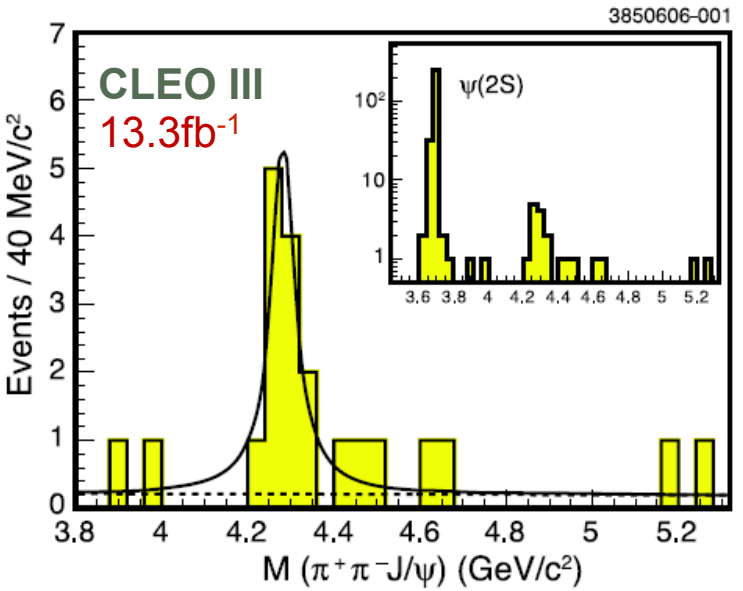
- PRL 95, 142001 (2005)
- 8σ enhancement with ISR method

$$m_{Y(4260)} = (4259 \pm 8^{+2}_{-6}) MeV/c^2$$

$$\Gamma_{Y(4260)} = (88 \pm 23^{+6}_{-4}) MeV$$

Context: previous $\pi^+\pi^-$ J/ψ results





BaBar: Y(4260) observation

- PRL 95, 142001 (2005)
- 8σ enhancement with ISR method

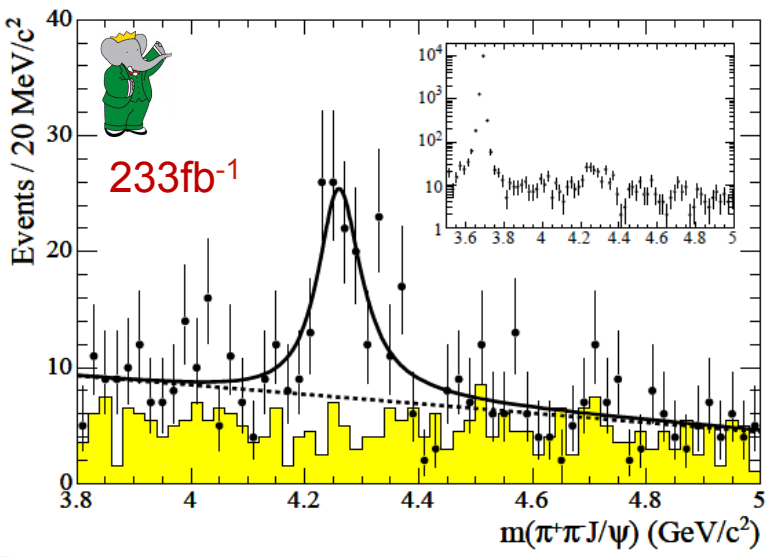
$$m_{Y(4260)} = (4259 \pm 8^{+2}_{-6})MeV/c^2$$
$$\Gamma_{Y(4260)} = (88 \pm 23^{+6}_{-4})MeV$$

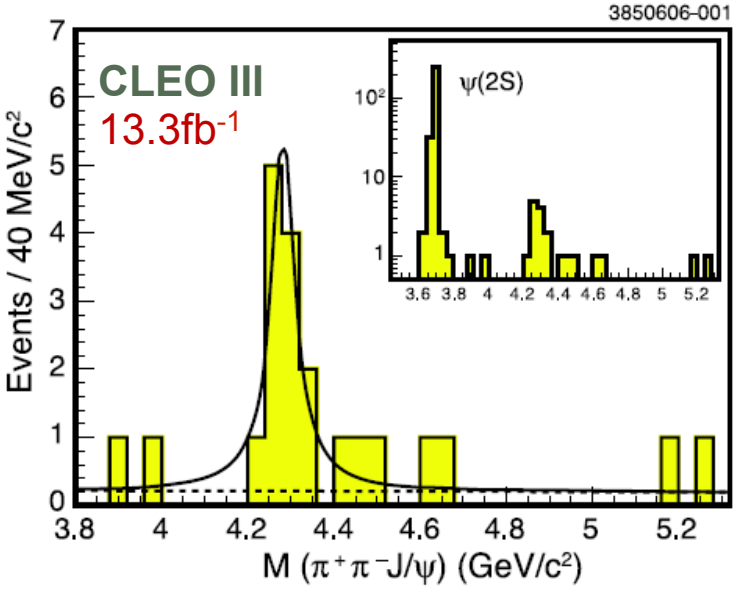
CLEO: Y(4260) confirmation

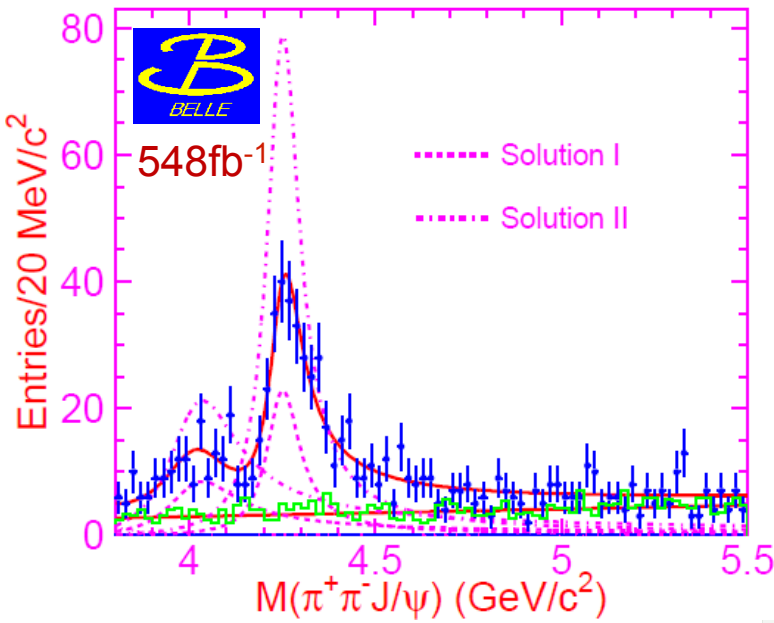
- CLEO III: ISR method [pictured]
- PRD 74, 091104(R) (2006)
- CLEO-c: scan/direct production
- PRL 96, 162003 (2006)
- $\pi^0\pi^0$ mode implies 0 isospin

$$m_{Y(4260)} = (4284 \pm 4^{+17}_{-16})MeV/c^2$$
$$\Gamma_{Y(4260)} = (73 \pm 5^{+39}_{-25})MeV$$

Context: previous $\pi^+\pi^-$ J/ψ results







BaBar: Y(4260) observation

- PRL 95, 142001 (2005)
- 8σ enhancement with ISR method

$$m_{Y(4260)} = (4259 \pm 8^{+2}_{-6})MeV/c^2$$
$$\Gamma_{Y(4260)} = (88 \pm 23^{+6}_{-4})MeV$$

CLEO: Y(4260) confirmation

- CLEO III: ISR method [pictured]
- PRD 74, 091104(R) (2006)
- CLEO-c: scan/direct production
- PRL 96, 162003 (2006)
- $\pi^0\pi^0$ mode implies 0 isospin

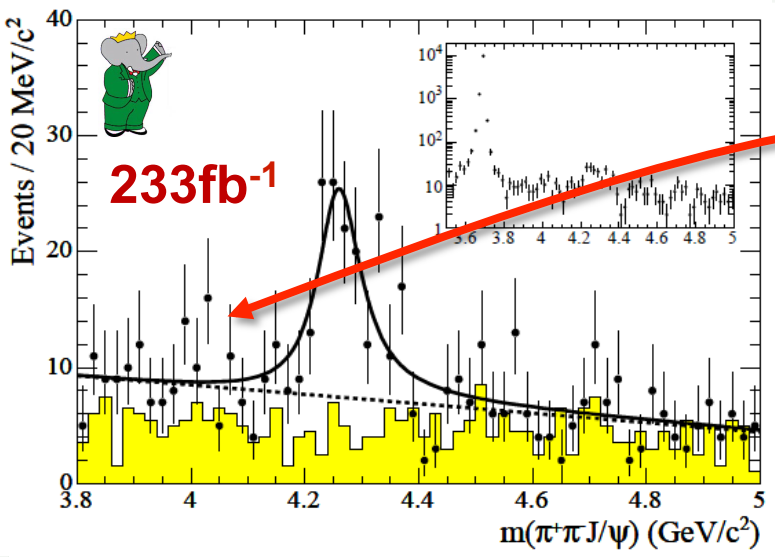
$$m_{Y(4260)} = (4284 \pm 4^{+17}_{-16})MeV/c^2$$
$$\Gamma_{Y(4260)} = (73 \pm 5^{+39}_{-25})MeV$$

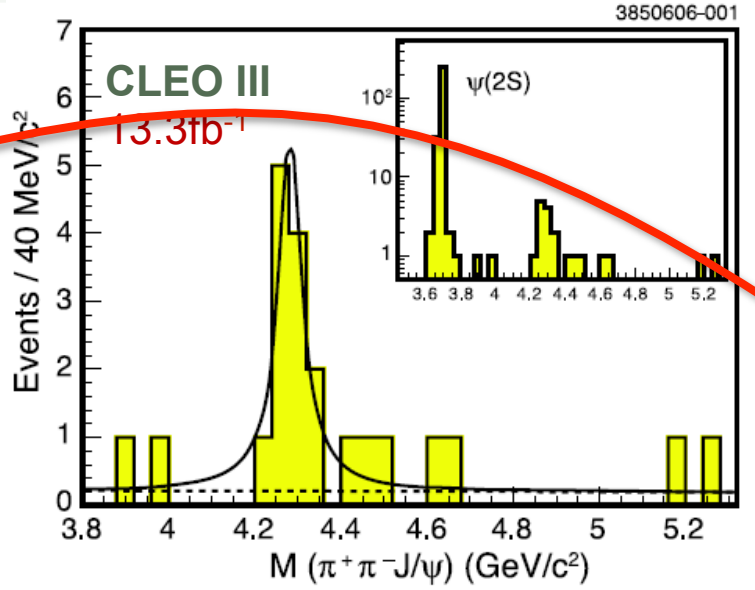
Belle: Y(4260) + Y(4008)

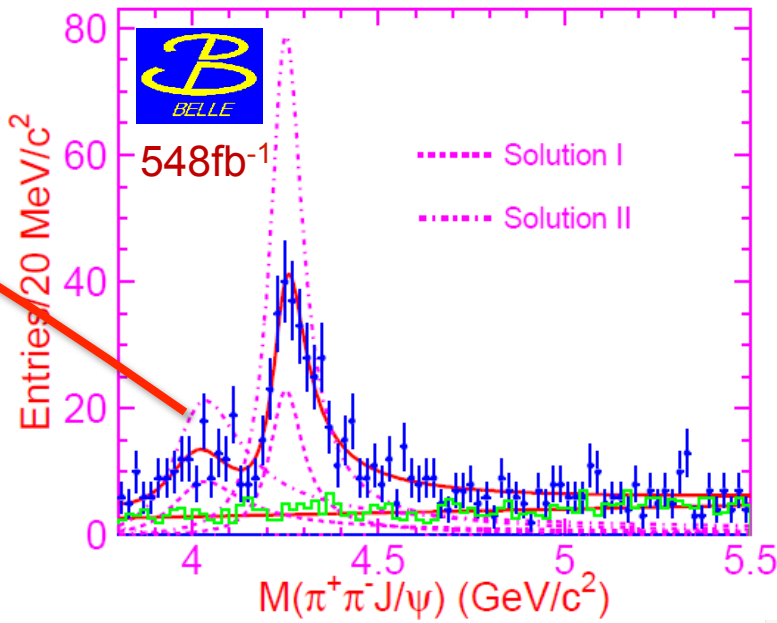
- ISR method
- PRD 99, 182004 (2007)
- Second enhancement Y(4008)

$$m_{Y(4260)} = (4247 \pm 12^{+17}_{-32})MeV/c^2$$
$$\Gamma_{Y(4260)} = (108 \pm 19 \pm 10)MeV$$
$$m_{Y(4008)} = (4008 \pm 40^{+114}_{-28})MeV/c^2$$
$$\Gamma_{Y(4008)} = (226 \pm 44 \pm 87)MeV$$

Context: previous $\pi^+\pi^-$ J/ψ results







BaBar: Y(4260) observation

- PRL 95, 142001 (2005)
- 8σ enhancement with ISR method

$$m_{Y(4260)} = (4259 \pm 8^{+2}_{-6})MeV/c^2$$
$$\Gamma_{Y(4260)} = (88 \pm 23^{+6}_{-4})MeV$$

CLEO: Y(4260) confirmation

- CLEO III: ISR method [pictured]
- PRD 74, 091104(R) (2006)
- CLEO-c: scan/direct production
- PRL 96, 162003 (2006)
- $\pi^0\pi^0$ mode implies 0 isospin

$$m_{Y(4260)} = (4284 \pm 4^{+17}_{-16})MeV/c^2$$
$$\Gamma_{Y(4260)} = (73 \pm 5^{+39}_{-25})MeV$$

Belle: Y(4260) + Y(4008)

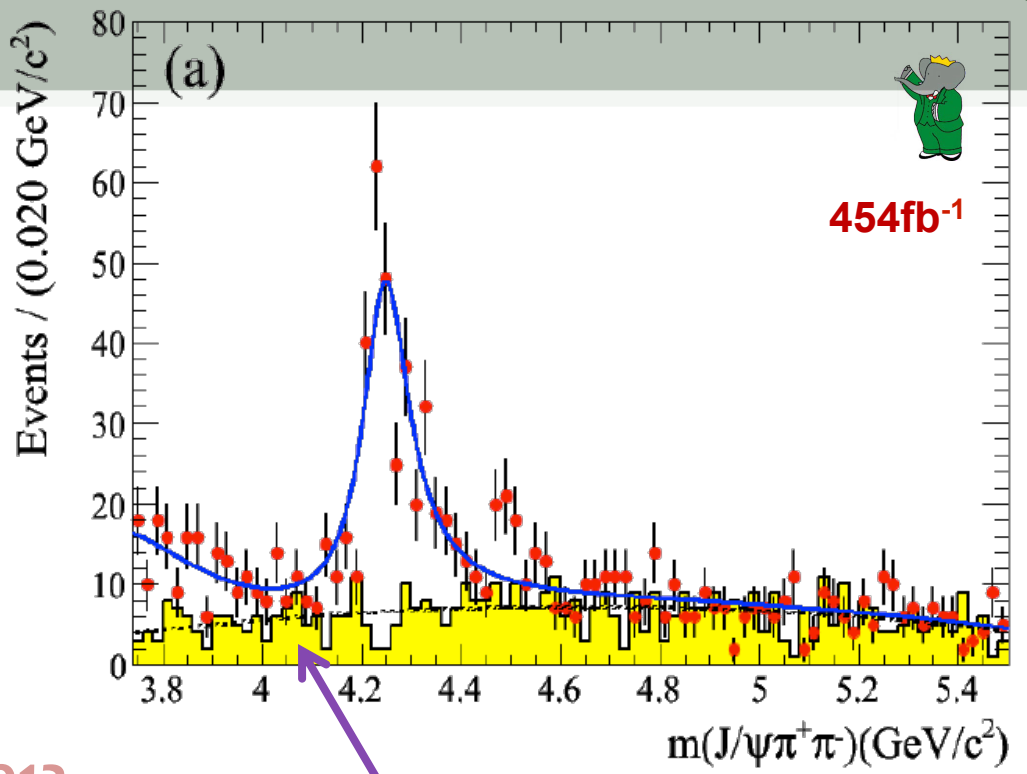
- ISR method
- PRD 99, 182004 (2007)
- Second enhancement Y(4008)

$$m_{Y(4260)} = (4247 \pm 12^{+17}_{-32})MeV/c^2$$
$$\Gamma_{Y(4260)} = (108 \pm 19 \pm 10)MeV$$
$$m_{Y(4008)} = (4008 \pm 40^{+114}_{-28})MeV/c^2$$
$$\Gamma_{Y(4008)} = (226 \pm 44 \pm 87)MeV$$

New $\pi^+\pi^- J/\psi$ results

$\pi^+\pi^- J/\psi$ invariant mass plot [right]

- Clear Y(4260) peak
- Background [yellow] is interpolated from J/ψ sidebands in m(l^+l^-) distribution
- **Where is the Y(4008)?**
- **What is the enhancement at the low end?**
- **Y(4260) results consistent with Belle**



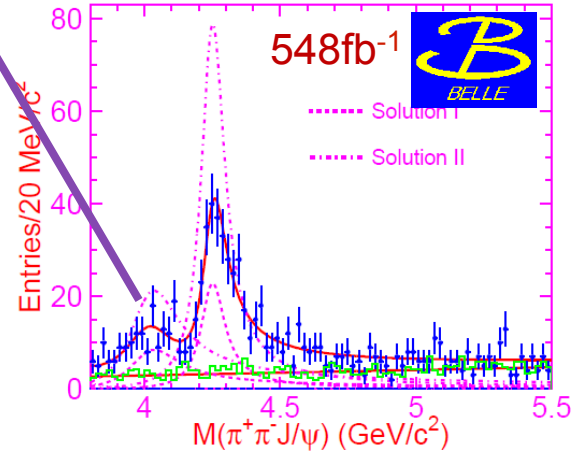
Belle 2007

$$m_{Y(4260)} = (4247 \pm 12^{+17}_{-32}) MeV/c^2$$
$$\Gamma_{Y(4260)} = (108 \pm 19 \pm 10) MeV$$

$$m_{Y(4008)} = (4008 \pm 40^{+114}_{-28}) MeV/c^2$$
$$\Gamma_{Y(4008)} = (226 \pm 44 \pm 87) MeV$$

BaBar 2012

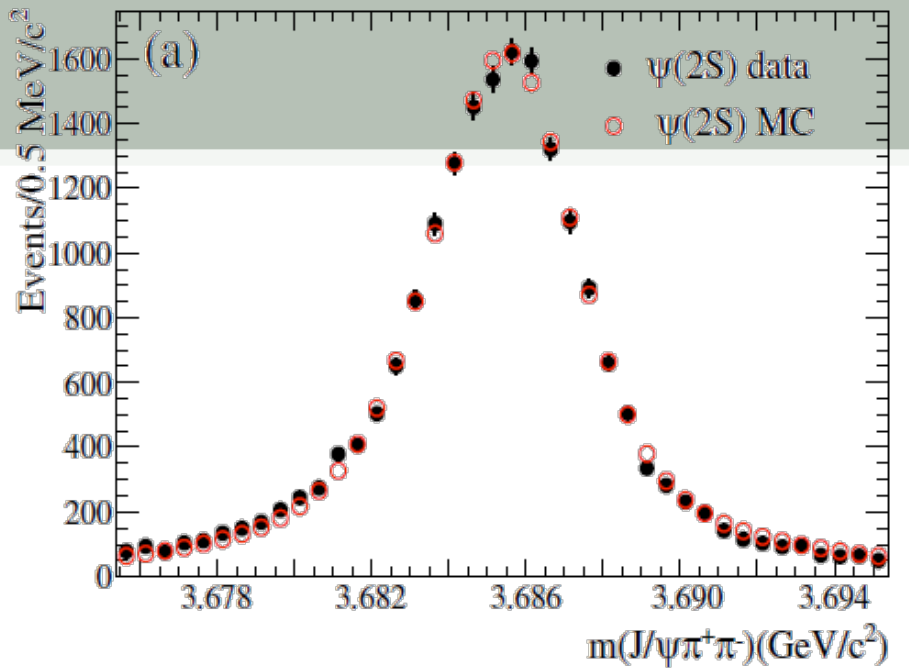
$$m_{Y(4260)} = (4244 \pm 5 \pm 4) MeV/c^2$$
$$\Gamma_{Y(4260)} = (114^{+16}_{-15} \pm 7) MeV$$

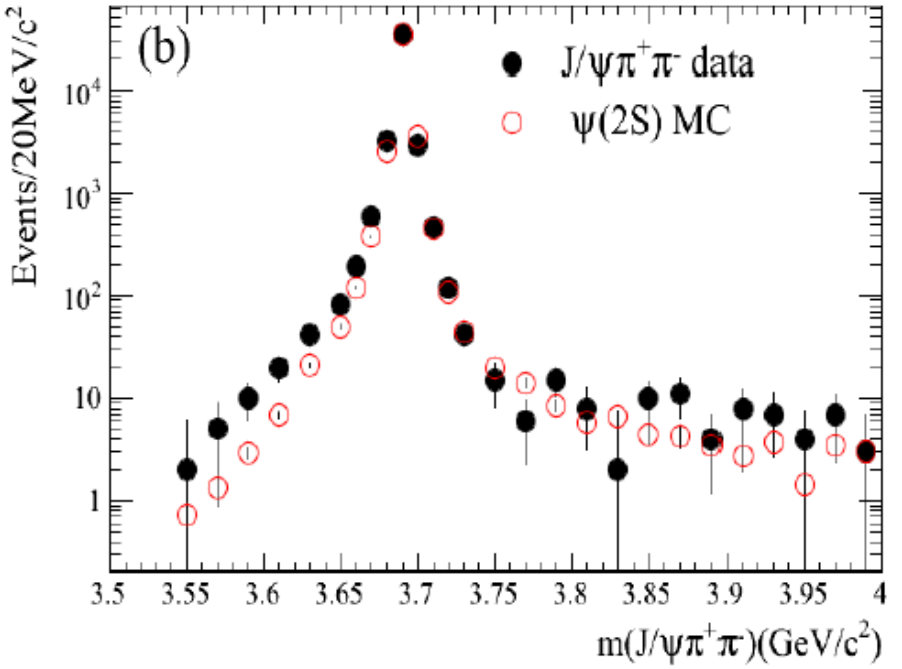


The excess

Could it be from the $\psi(2S)$ peak?

- Below ~3800MeV, the huge peak from $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ dominates; perhaps the excess is stray wing events from this process
- Use [corrected] MC to model contribution to $m(\pi^+\pi^- J/\psi)$ in the Y(4260) window
- [Top] MC/data correspondence in $\psi(2S)$ region, background-subtracted
- [Bottom] MC/data up to 4GeV
- $\psi(2S)$ tail appears to model data in high-E tail correctly, but disagreement in low-E region implies nonresonant contribution
- Extrapolation of BW lineshape to signal region is problematic
- **Continuum contribution to cross section seems to be missing**

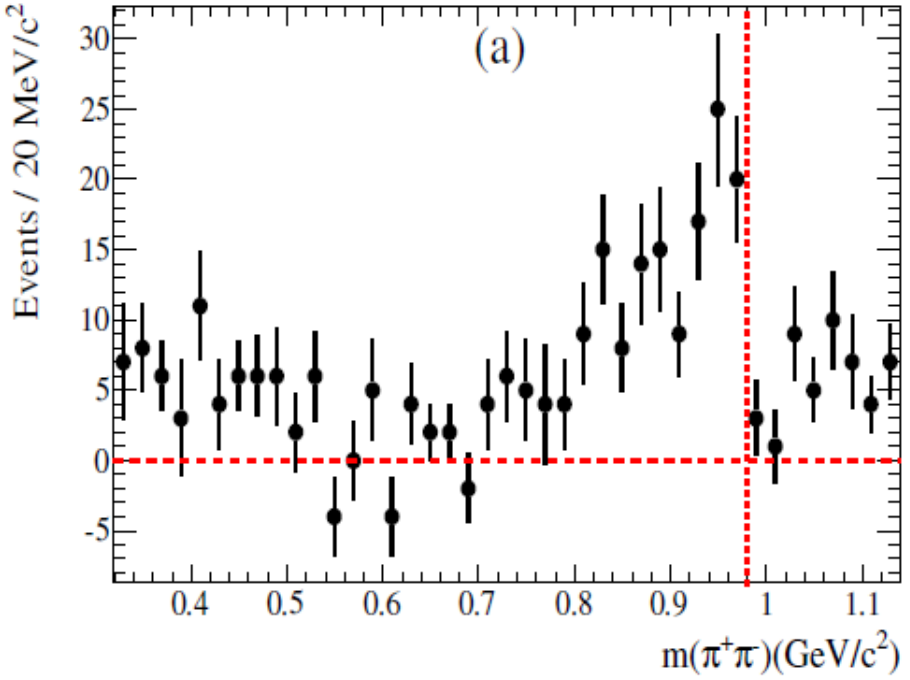


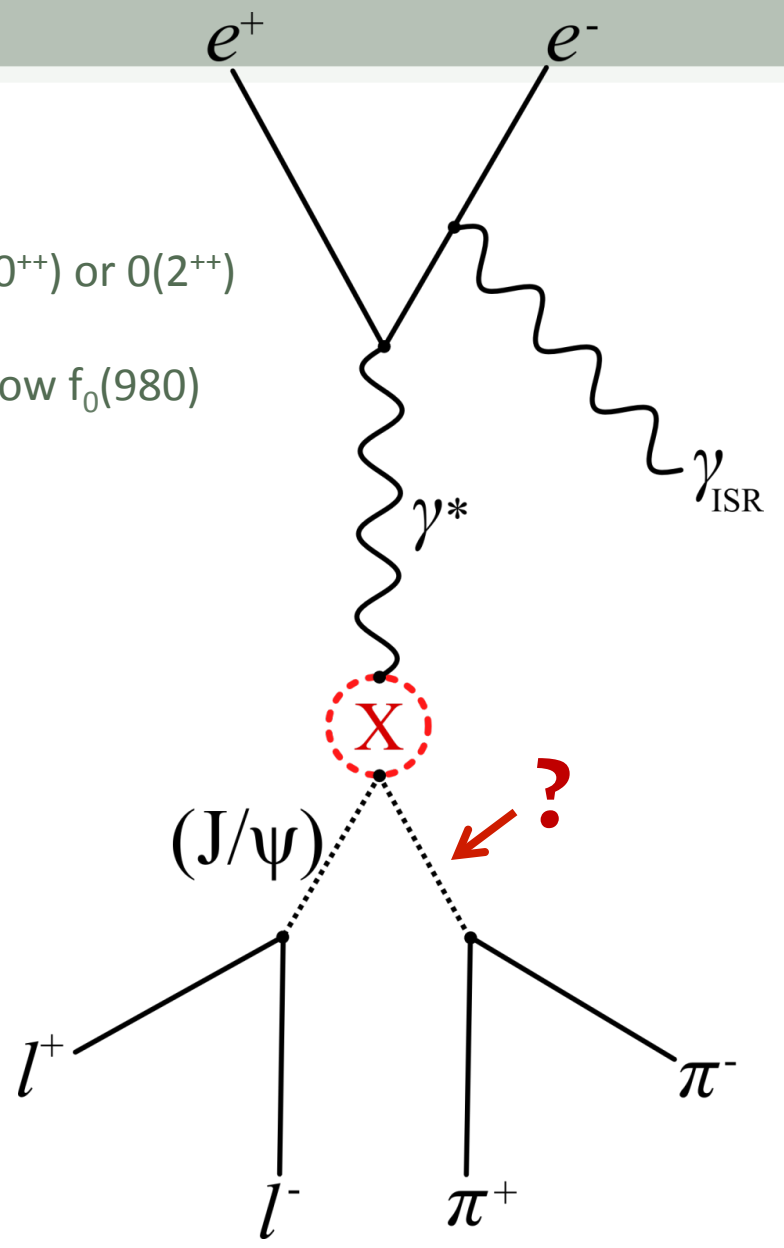


Analysis of $\pi^+\pi^-$ in $\pi^+\pi^- J/\psi$

What is the $\pi^+\pi^-$ mass structure in $Y(4260) \to \pi^+\pi^- J/\psi$?

- Width indicates strong decay
- Y(4260) has $I(J^{PC})=0(1^{--})$, same as J/ψ; $\pi^+\pi^-$ system must have $0(0^{++})$ or $0(2^{++})$
- Select Y(4260) peak: $4.15 < m(\pi^+\pi^- J/\psi) < 4.45$ GeV/c^2
- Background-subtracted $m(\pi^+\pi^-)$ distribution shows peak just below $f_0(980)$ $[0(0^{++})]$
- Odd-looking peak resembles interference effect

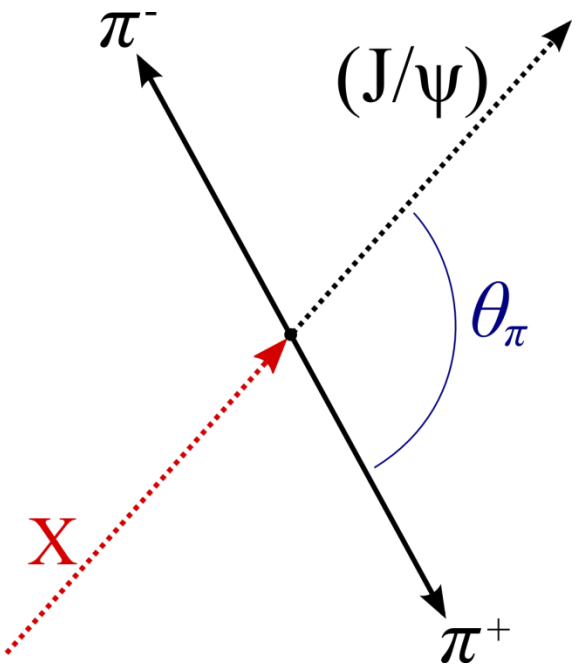


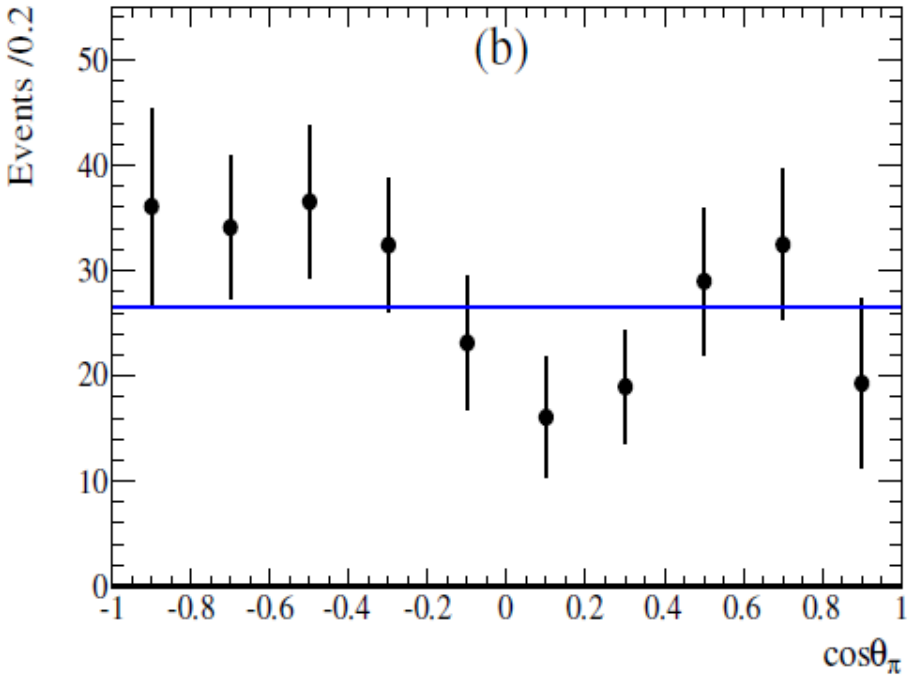


Analysis of $\pi^+\pi^-$ in $\pi^+\pi^- J/\psi$

Angular distribution

- Define θ_π as the angle between the π^+ and the recoil J/ψ both in the dipion rest frame [below]
- cos θ_π plot fitted with S-wave distribution (blue line)
- Consistent with S-wave hypothesis (χ^2/NDF = 12.3/9, probability = 19.7%)
- Consistent with $f_0(980)$





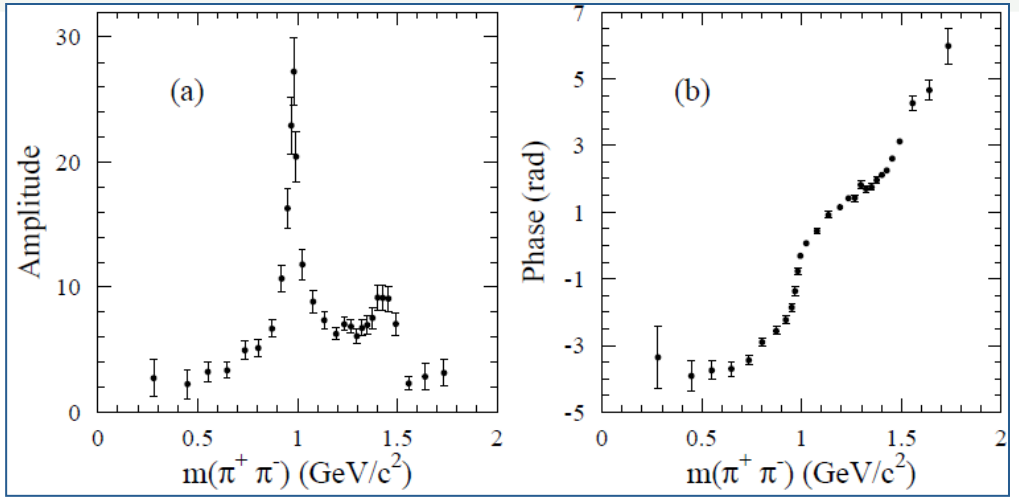
Analysis of $\pi^+\pi^-$ in $\pi^+\pi^- J/\psi$

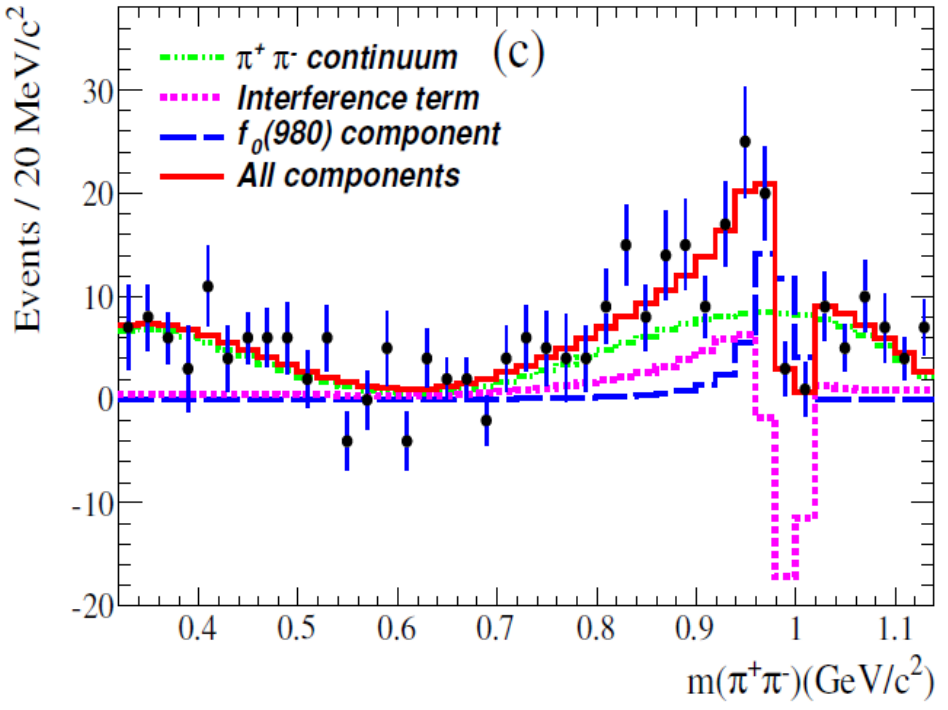
[PRD 79, 032003 (2009)]

Model $\pi^+\pi^-$ mass distribution

- Peak might be caused by interference between a resonant amplitude describing the $f_0(980)$ and $\pi^+\pi^-$ continuum
- Take mass dependence of $f_0(980)$ amplitude and phase from previous BaBar analysis
- Add nonresonant polynomial amplitude motivated by a QCD multipole expansion
- In fit, allow relative strength and phase of components to vary
- Resultant fit [BOTTOM] requires some $f_0(980)$ contribution but it is not the dominant source of the peak—**qualitatively consistent with BES results**

$$\frac{B(Y(4260) \to J/\psi\, f_0(980), f_0(980) \to \pi^+\pi^-)}{B(Y(4260) \to \pi^+\pi^- J/\psi)} = (17 \pm 13)\%$$





Summary of $\pi^+\pi^- J/\psi$

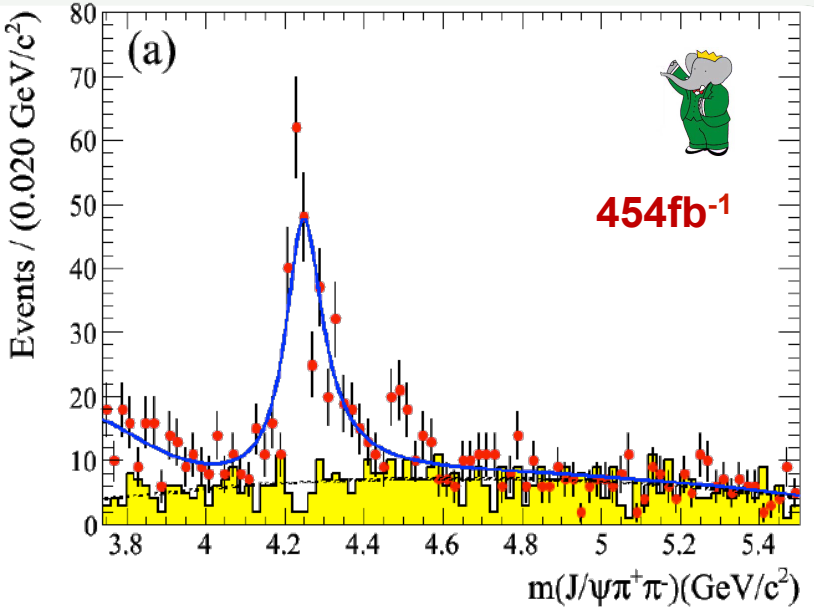
Y(4260) mass/width

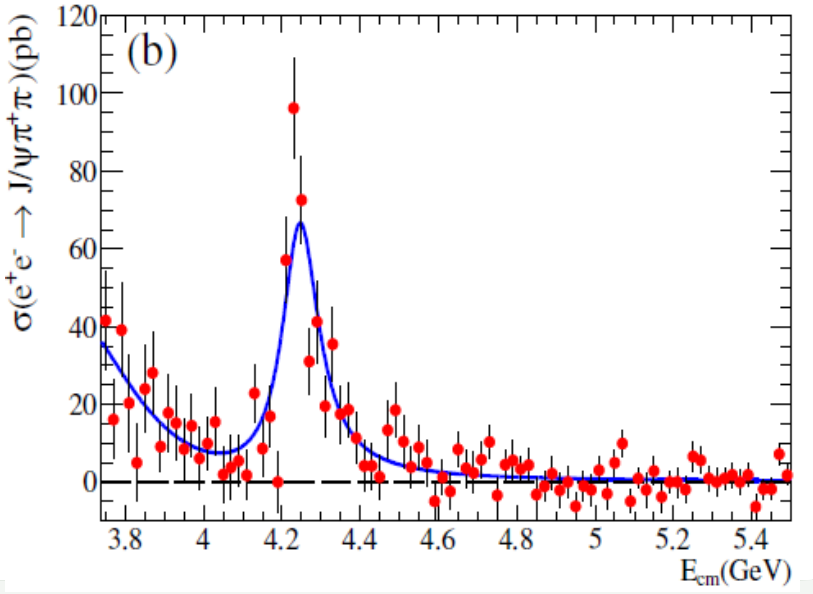
$$m_{Y(4260)} = (4244 \pm 5 \pm 4) MeV/c^2$$
$$\Gamma_{Y(4260)} = (114^{+16}_{-15} \pm 7) MeV$$

No evidence for Y(4008)

Cross-section enhancement at low energies that is not fully explained

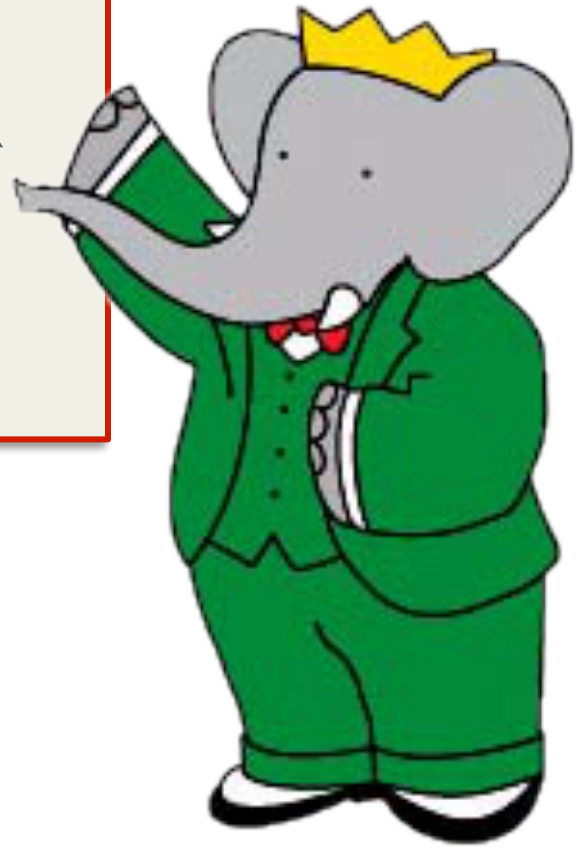
Some $f_0(980)$ component in Y(4260) $\rightarrow \pi^+\pi^- J/\psi$ decays present





Update of the $\pi^+\pi^-\psi(2S)$ ISR analysis at BaBar

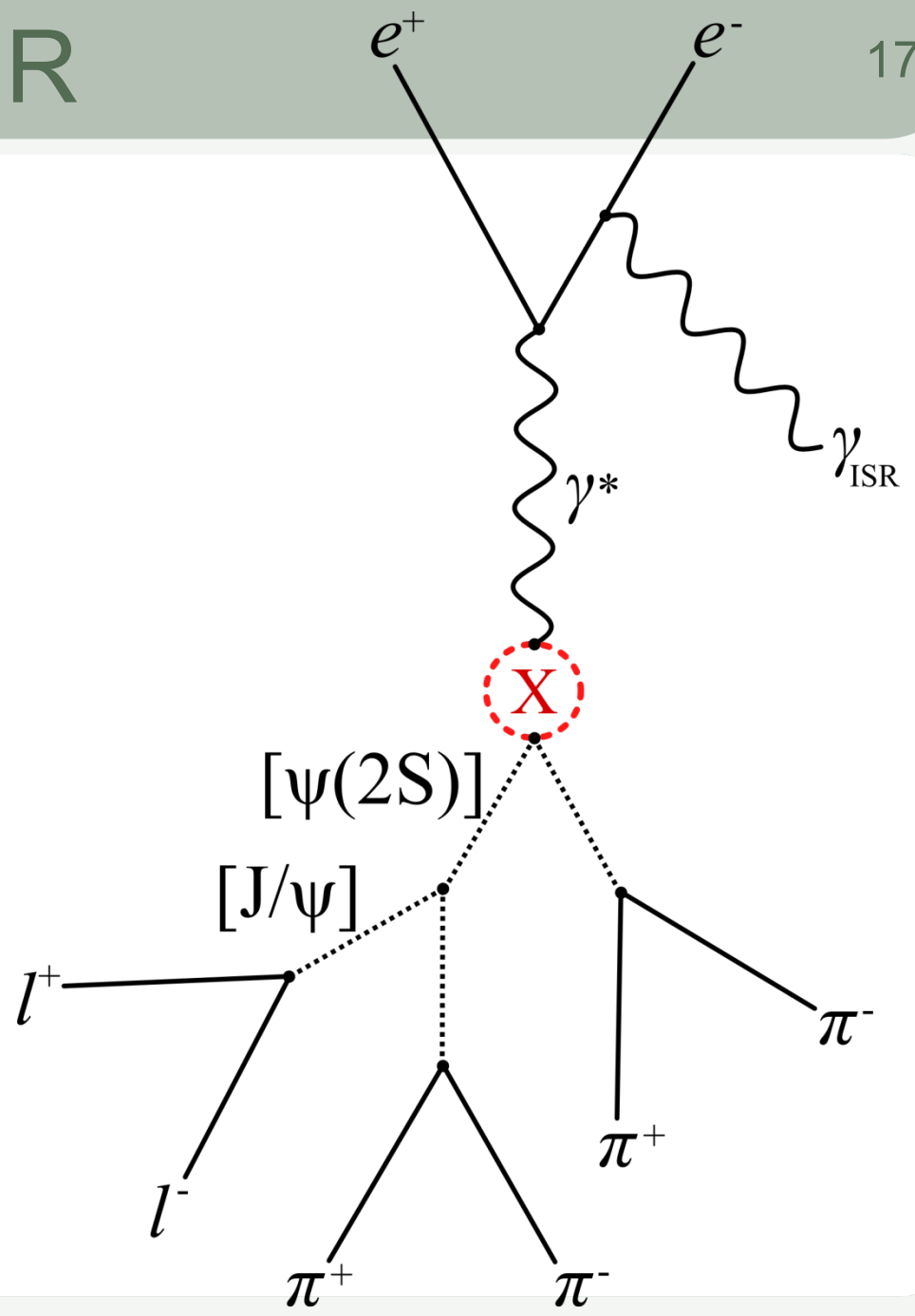
arXiv:1211.6271



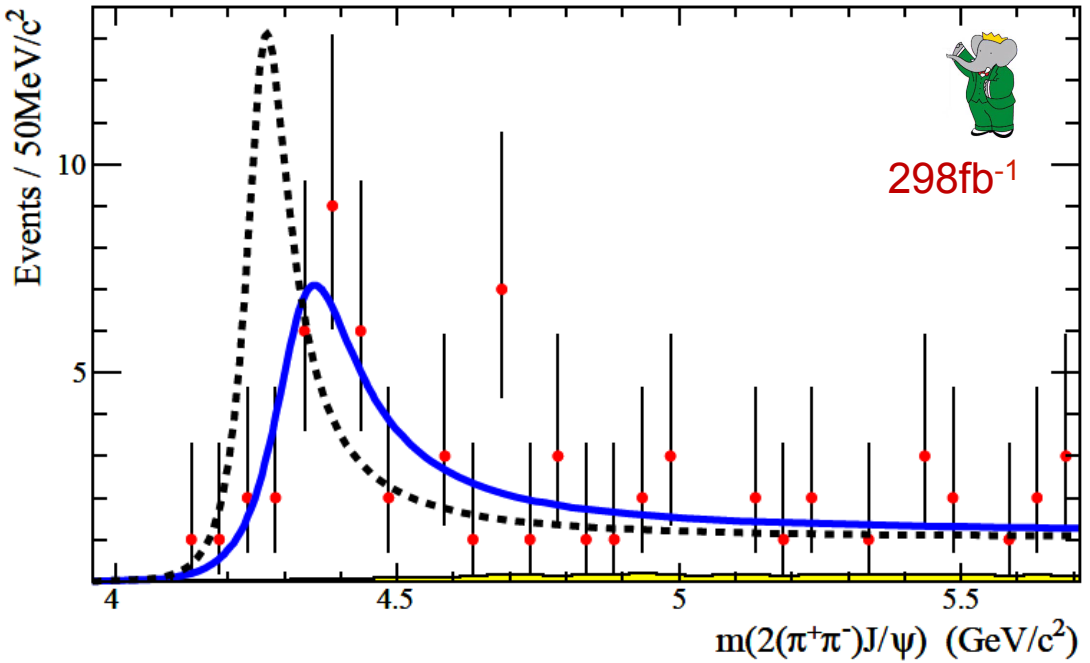
The $\pi^+\pi^-\psi(2S)$ mode in ISR

ISR production in charmonium region

- Analogous to $\pi^+\pi^- J/\psi$ with $X \to \pi^+\pi^-\psi(2S)$
- Plausible access to other exotic states
- Main decay mode:
  - $e^+e^- \to \gamma_{ISR}\, X$
  - $X \to \pi^+\pi^-\psi(2S)$
  - $\psi(2S) \to \pi^+\pi^- J/\psi$
  - $J/\psi \to l^+l^-$
- Additional mode:
  - $e^+e^- \to \gamma_{ISR}\, X$
  - $X \to \pi^+\pi^-\psi(2S)$
  - $\psi(2S) \to l^+l^-$



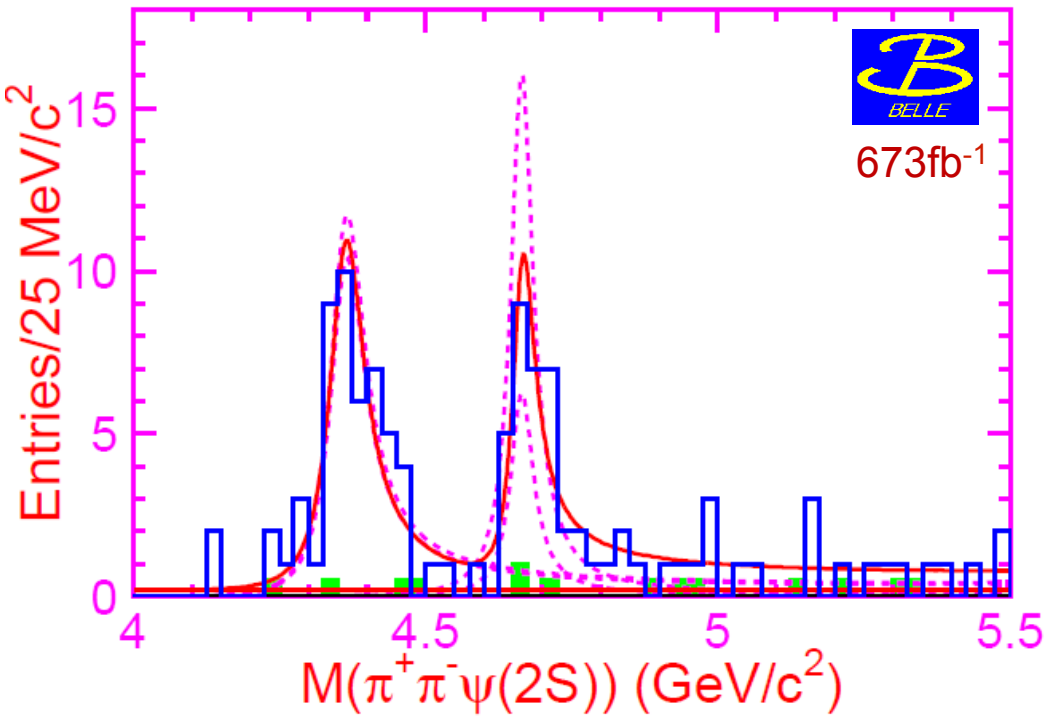
Context: previous $\pi^+\pi^-\psi(2S)$ results



BaBar: Y(4350) observation

- Search for Y(4260)
- Poor match to Y(4260) lineshape [dashed]
- Instead, Y(4325) observed
- PRL 98, 212001 (2007)

$$m_{Y(4325)} = (4324 \pm 24) MeV/c^2$$
$$\Gamma_{Y(4325)} = (172 \pm 33) MeV$$

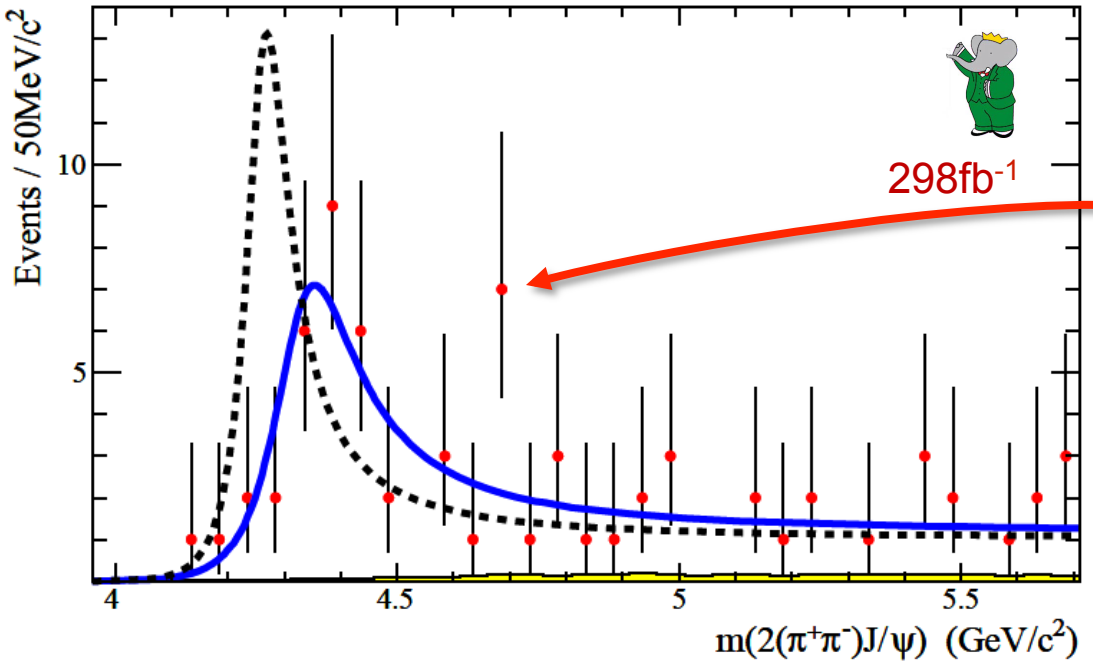


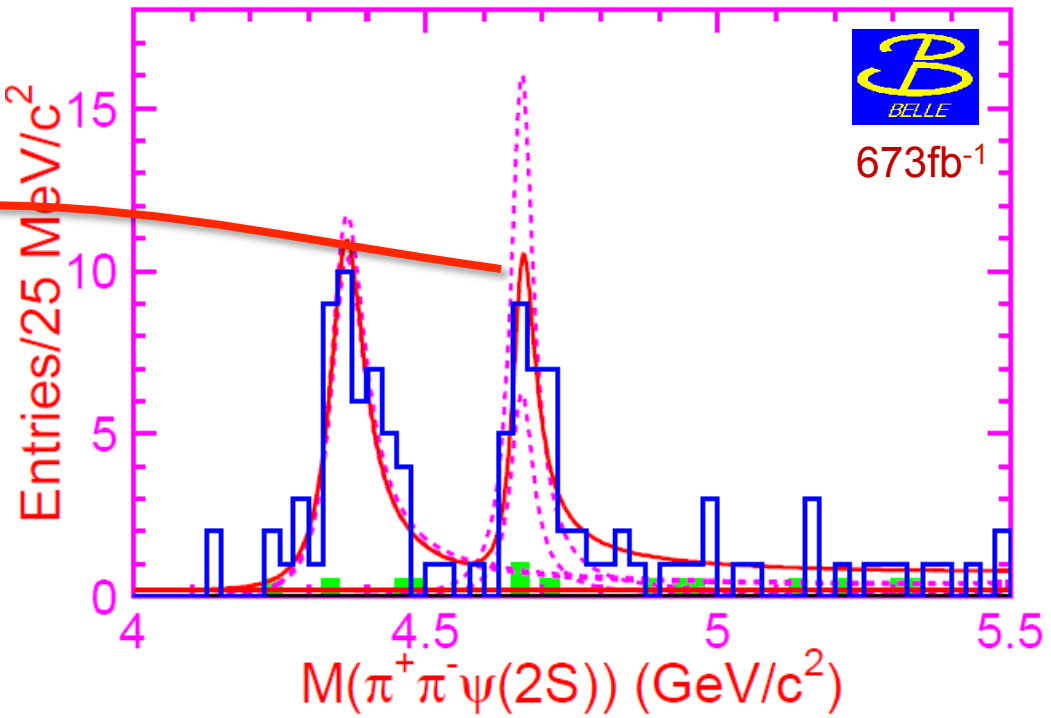
Belle: Y(4350) + Y(4660)

- PRD 99, 182004 (2007)

$$m_{Y(4325)} = (4361 \pm 9 \pm 9) MeV/c^2$$
$$\Gamma_{Y(4325)} = (74 \pm 15 \pm 10) MeV$$
$$m_{Y(4660)} = (4664 \pm 11 \pm 5) MeV/c^2$$
$$\Gamma_{Y(4660)} = (48 \pm 15 \pm 3) MeV$$

Context: previous $\pi^+\pi^-\psi(2S)$ results





BaBar: Y(4350) observation

- PRL 98, 212001 (2007)
- ISR method
- Poor match to Y(4260) [dashed]

$$m_{Y(4325)} = (4324 \pm 24) MeV/c^2$$
$$\Gamma_{Y(4325)} = (172 \pm 33) MeV$$

Belle: Y(4350) + Y(4660)

- PRD 99, 182004 (2007)

$$m_{Y(4325)} = (4361 \pm 9 \pm 9) MeV/c^2$$
$$\Gamma_{Y(4325)} = (74 \pm 15 \pm 10) MeV$$
$$m_{Y(4660)} = (4664 \pm 11 \pm 5) MeV/c^2$$
$$\Gamma_{Y(4660)} = (48 \pm 15 \pm 3) MeV$$

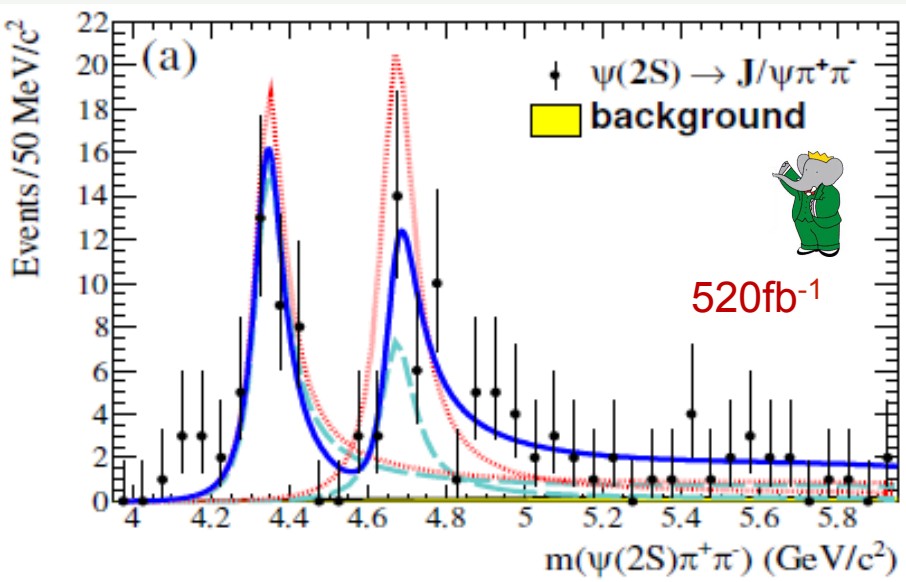
New $\pi^+\pi^-\psi(2S)$ results

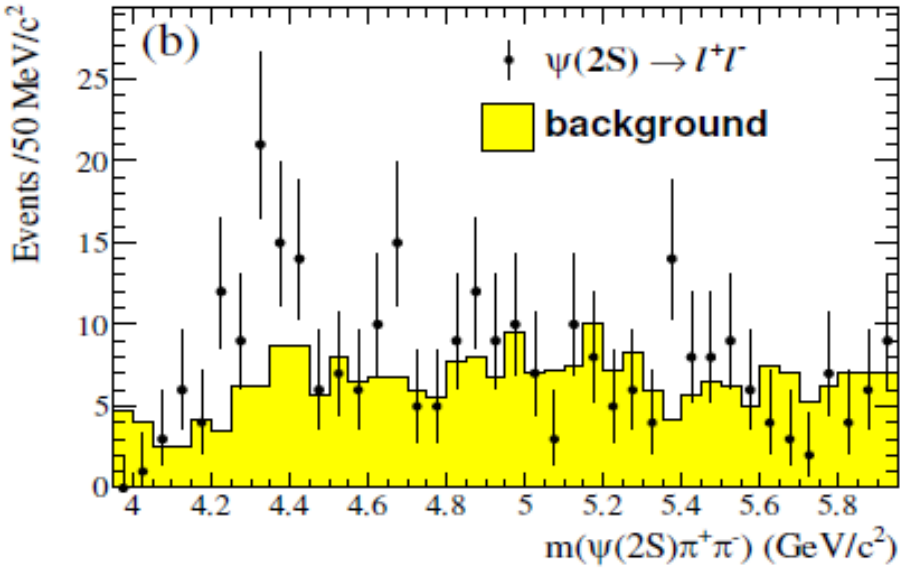
$\psi(2S) \to \pi^+\pi^- J/\psi$ [top]

- [added Υ(2,3S) runs]
- Very small background from $\psi(2S)$ sidebands
- **Υ(4660) confirmed**
- Overlapping peaks have identical *PC*; interference terms do not cancel in mass projection
- Branching fraction measurement depends on interference assumption: **constructive** and **destructive**

$\psi(2S) \to l^+l^-$ [bottom]

- More data
- Much more background
- [supports Υ(4660) but does not improve mass or width measurements]

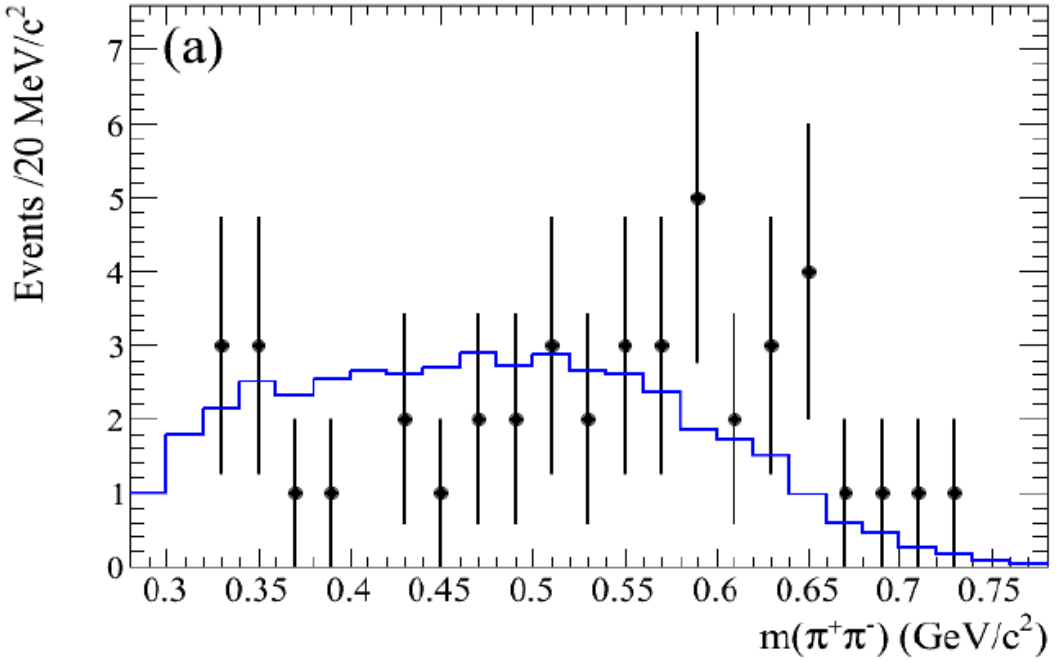


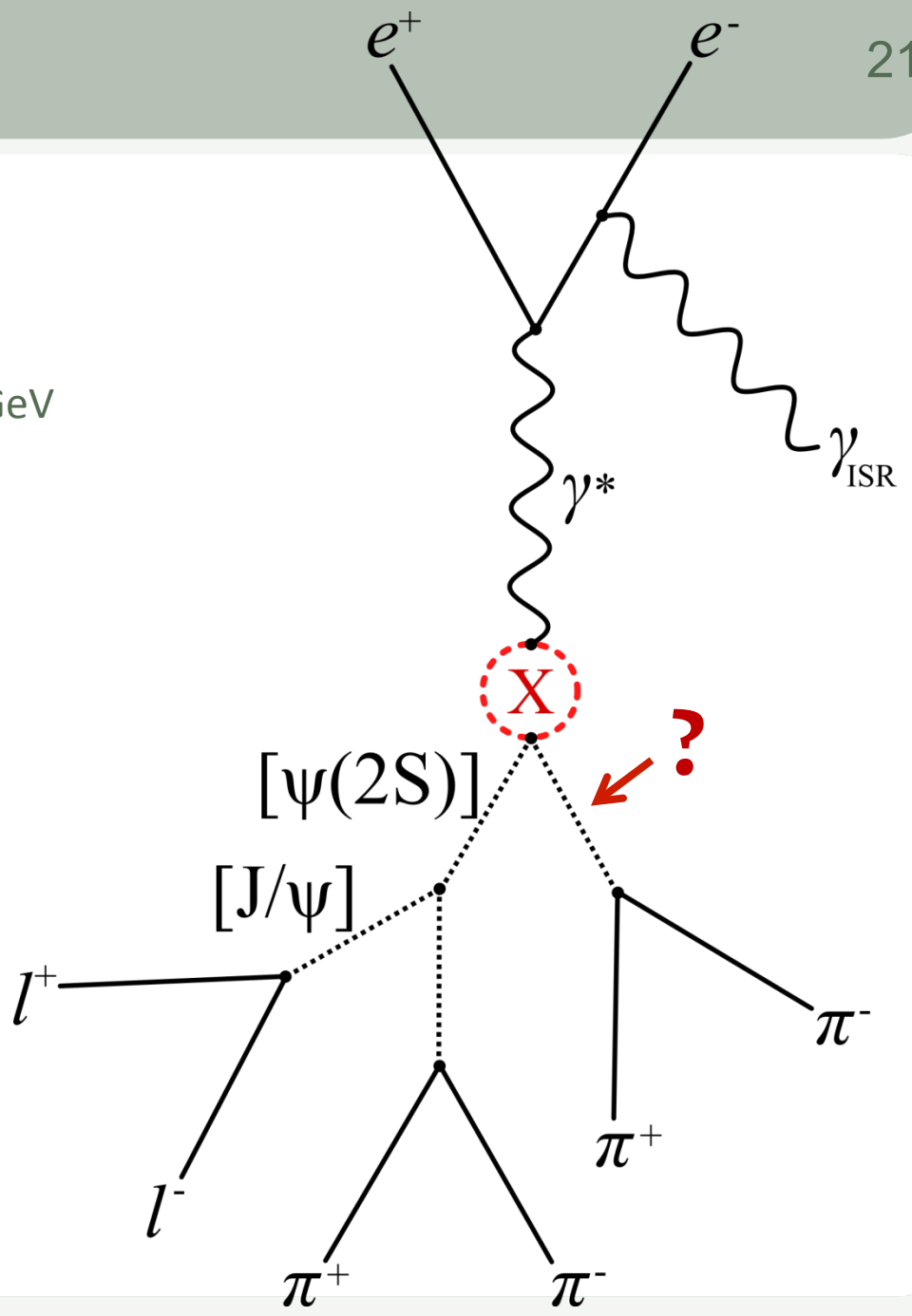


$Y(4360) \rightarrow \pi^+\pi^-\psi(2S)$

$\pi^+\pi^-$ Invariant mass plot [below]

- Very low statistics—41 events
- 4.0-4.5GeV region of the $m(\pi^+\pi^-\psi(2S))$ distribution
- Blue histogram is MC estimation given resonance at 4.36GeV based on phase space
- No conclusive disagreement
- [similar to Belle findings]

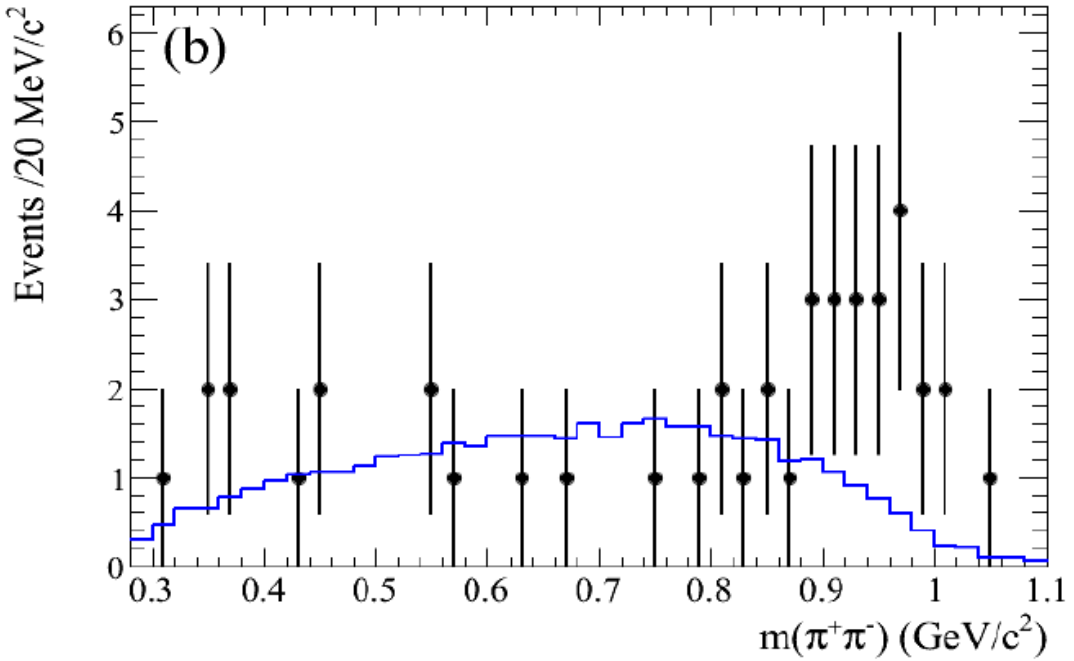


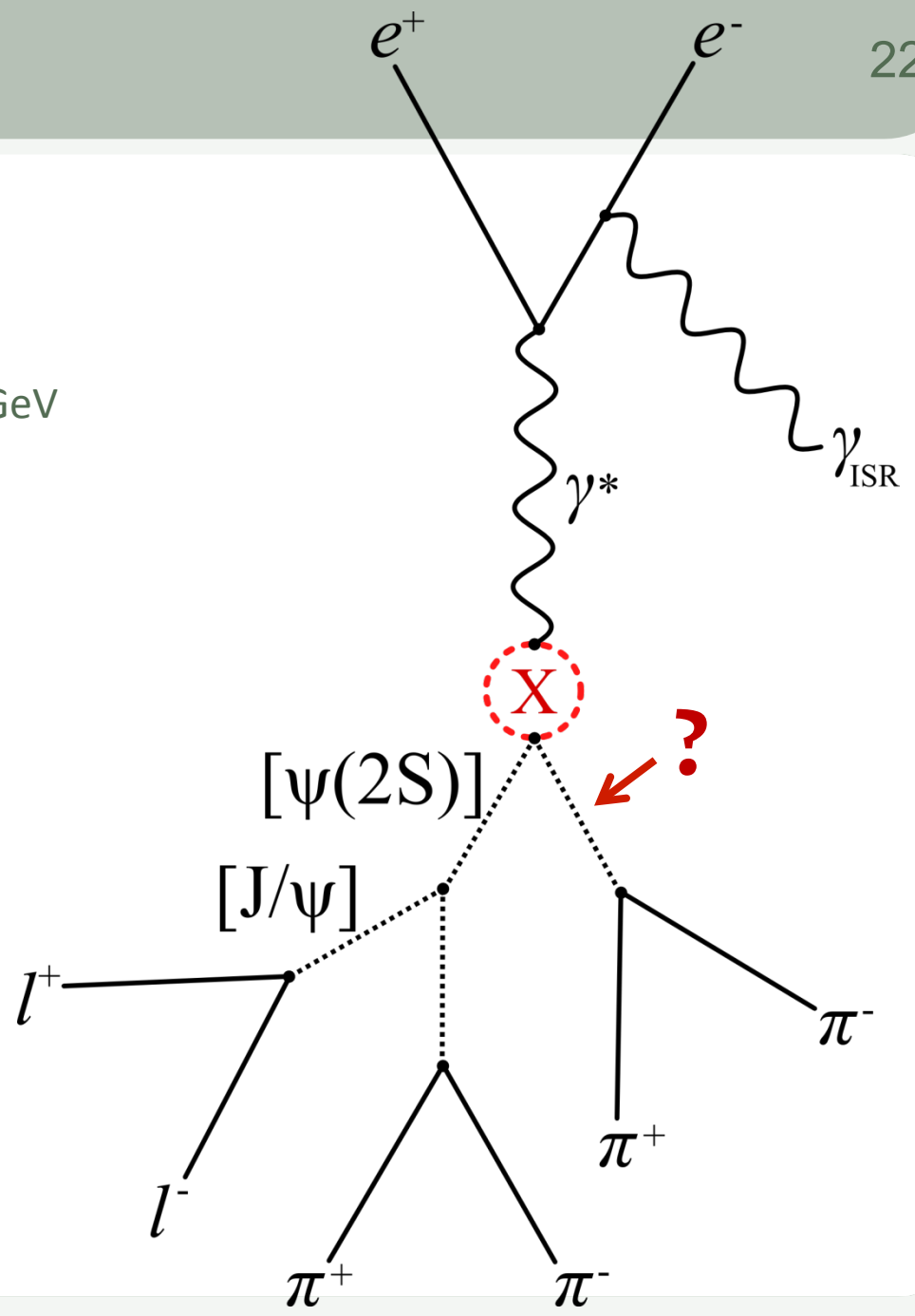


$Y(4660) \rightarrow \pi^+\pi^-\psi(2S)$

$\pi^+\pi^-$ Invariant mass plot [below]

- Very low statistics—42 events
- 4.5-4.9GeV region of the $m(\pi^+\pi^-\psi(2S))$ distribution
- Blue histogram is MC estimation given resonance at 4.66GeV based on phase space
- **Possible $f_0(980)$ contribution**





$\pi^+\pi^-\psi(2S)$ summary

BaBar/Belle

- Y(4360) seen with similar mass/width to Belle confirmation
- Y(4660) **confirmed** with consistent mass/width
- Invariant mass spectra are very similar [top]
- Combined spectrum [bottom]: 1.2ab^{-1}! Huge datasets required to get substantially better results from ISR method

Belle 2007

$$m_{Y(4325)} = (4361 \pm 9 \pm 9) MeV/c^2$$
$$\Gamma_{Y(4325)} = (74 \pm 15 \pm 10) MeV$$
$$m_{Y(4660)} = (4664 \pm 11 \pm 5) MeV/c^2$$
$$\Gamma_{Y(4660)} = (48 \pm 15 \pm 3) MeV$$

BaBar 2012

$$m_{Y(4325)} = (4340 \pm 16 \pm 9) MeV/c^2$$
$$\Gamma_{Y(4325)} = (94 \pm 32 \pm 13) MeV$$
$$m_{Y(4660)} = (4669 \pm 21 \pm 3) MeV/c^2$$
$$\Gamma_{Y(4660)} = (104 \pm 48 \pm 10) MeV$$

Y Decays

- Nothing conclusive from Y(4360)
- Y(4660) may have an $f_0(980)$ contribution