

# Study of $e^+e^-$ Annihilations into

$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$  ,  $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$ ,

$\pi^+\pi^-\pi^0\pi^0\pi^0\eta$  and  $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\eta$

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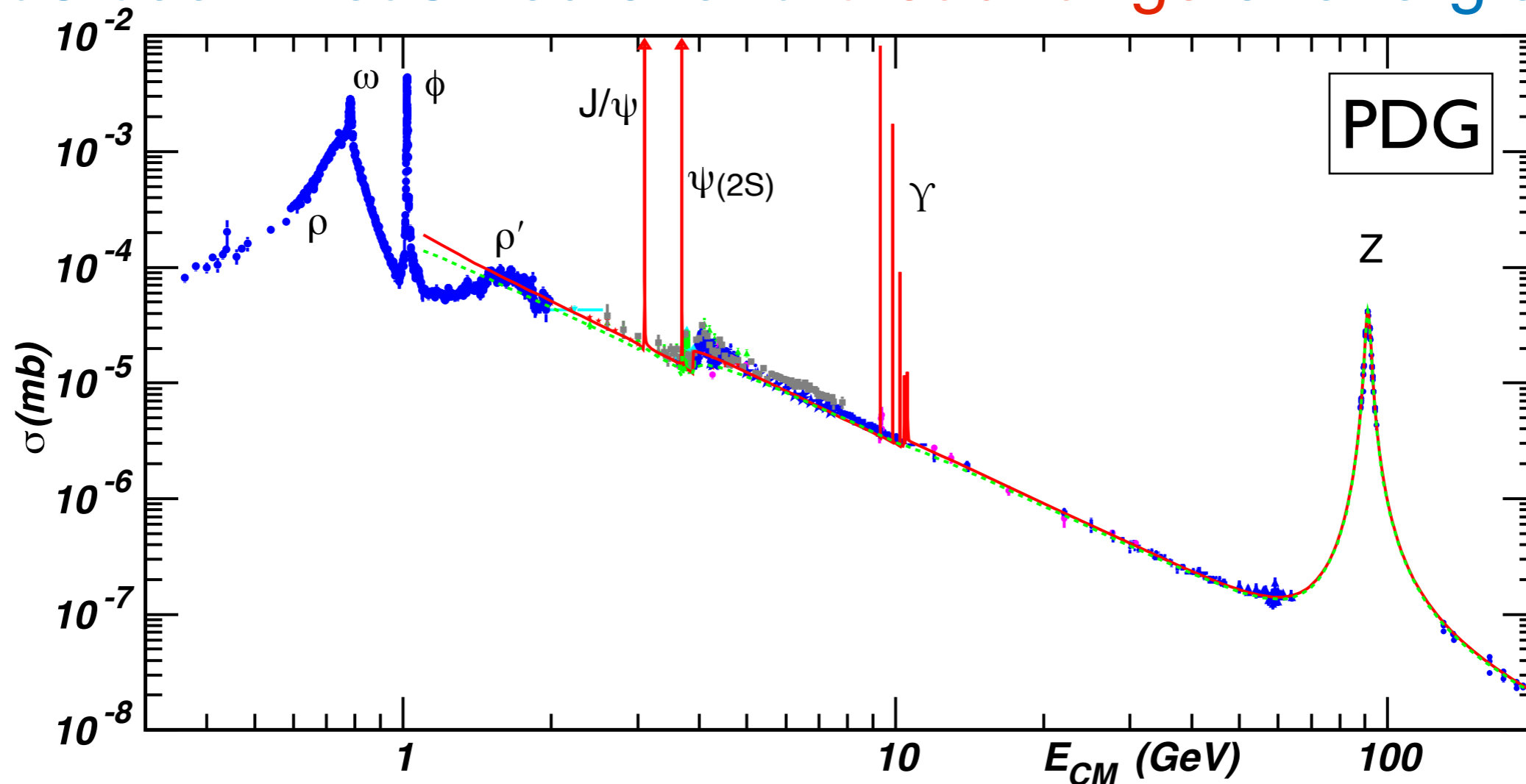
**representing the BaBar collaboration**

XXI International Conference on High-Energy Physics  
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- **Introduction**
- **The Initial-State Radiation (ISR) Method**
- **Event Selection and Cross Sections**
- **Internal Structure**
- **$J/\psi$ ,  $\psi(2S)$  Branching Fractions**
- **Summary**

# The $e^+e^- \rightarrow$ hadrons Cross Section

- has been measured over a **broad range** of energies

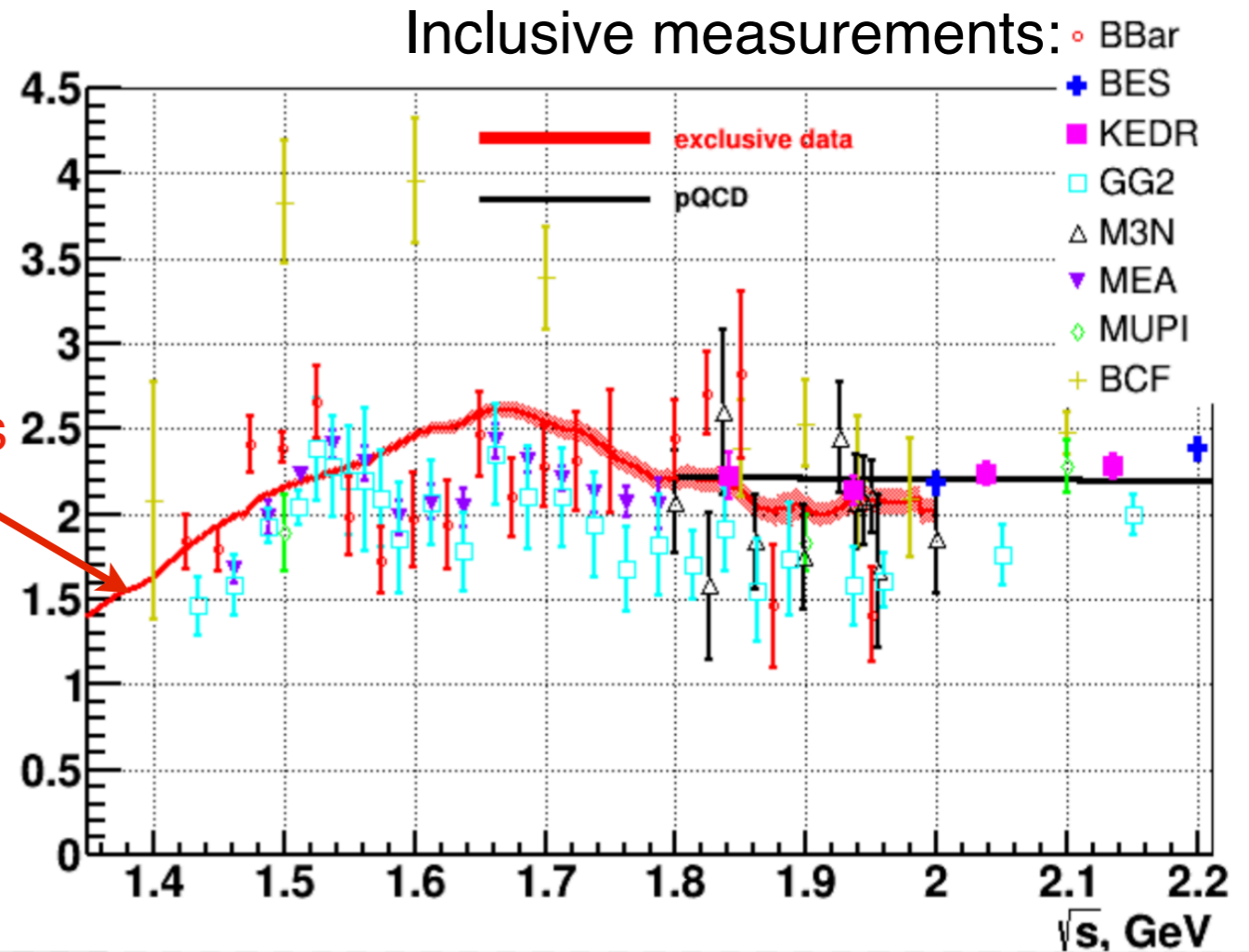


- at **high** energies: well described by perturbative QCD  
 $e^+e^- \rightarrow q\bar{q}(g) \rightarrow$  jets of hadrons
- **below**  $\sim 1.2$  GeV: a few  $J^{PC}=1^{--}$  resonances dominate plus some (quasi-)2-body processes quite well measured

- but in between, there is much to be understood

$$R = \frac{\sigma_{\text{had}}}{\sigma_{\mu\mu}}$$

Sum of exclusive modes



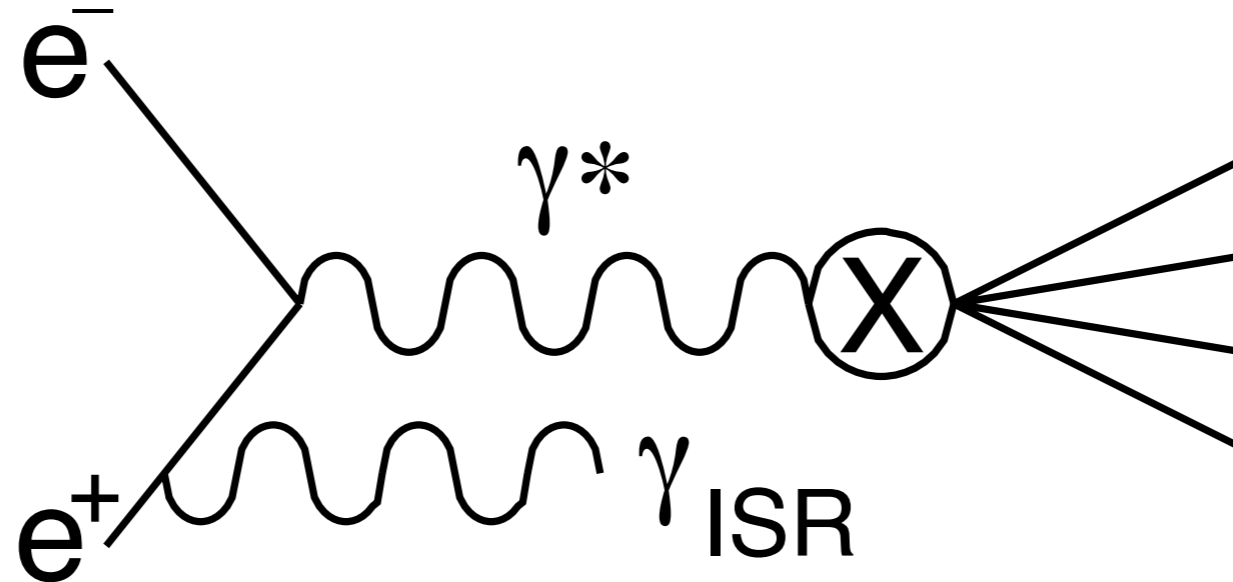
- many processes contribute

- much spectroscopy to be done
- transition toward (into?) multi-jet structure

where does PQCD become good (enough)?

- theoretical predictions for  $g_{\mu}-2$ ,  $\alpha(M_Z)$  rely on  $\sigma_{\text{had}}$ 
  - isospin relations, other assumptions used
  - this region contributes substantially to the uncertainty on both quantities

# Initial-State Radiation in $e^+e^-$ Annihilations



- $e^+e^- \rightarrow \gamma_{\text{ISR}}e^+e^- \rightarrow \gamma_{\text{ISR}}\gamma^* \rightarrow \gamma_{\text{ISR}}X$
- $X$  is any allowed final state at the **reduced energy**  
 $\rightarrow \sqrt{s'} = m = m_{\gamma^*} = m_X = E_{\text{CM}}$
- the cross section:  $d\sigma(s, s', \theta_\gamma)/ds' d\cos \theta_\gamma = W(s, s', \theta_\gamma)\sigma(s')$   
 $\rightarrow$  the radiator function  $W$  is known to  $\sim 1\%$
- **ISR accesses a continuous, wide  $s'$  range in a single experiment**  
 $\rightarrow$  **very small point-to-point systematic errors**

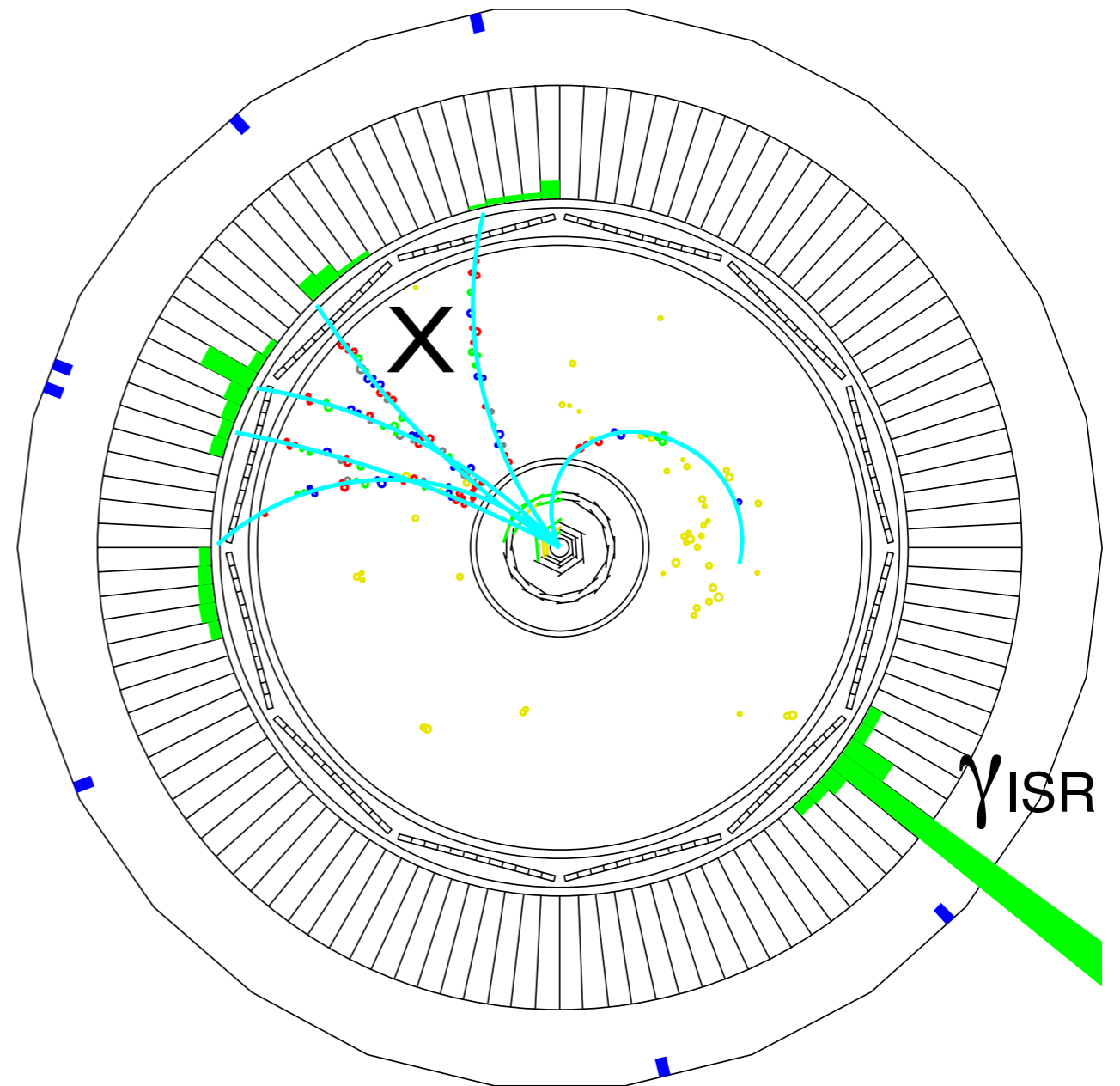
- if the  $\gamma_{\text{ISR}}$  is detected then the system  $X$  is well contained in the detector

→  $\sim$ full acceptance

→ good measurements of full angular distributions, other internal variables

- the hadronic system  $X$  is boosted

→ good efficiency and resolution all the way down to threshold



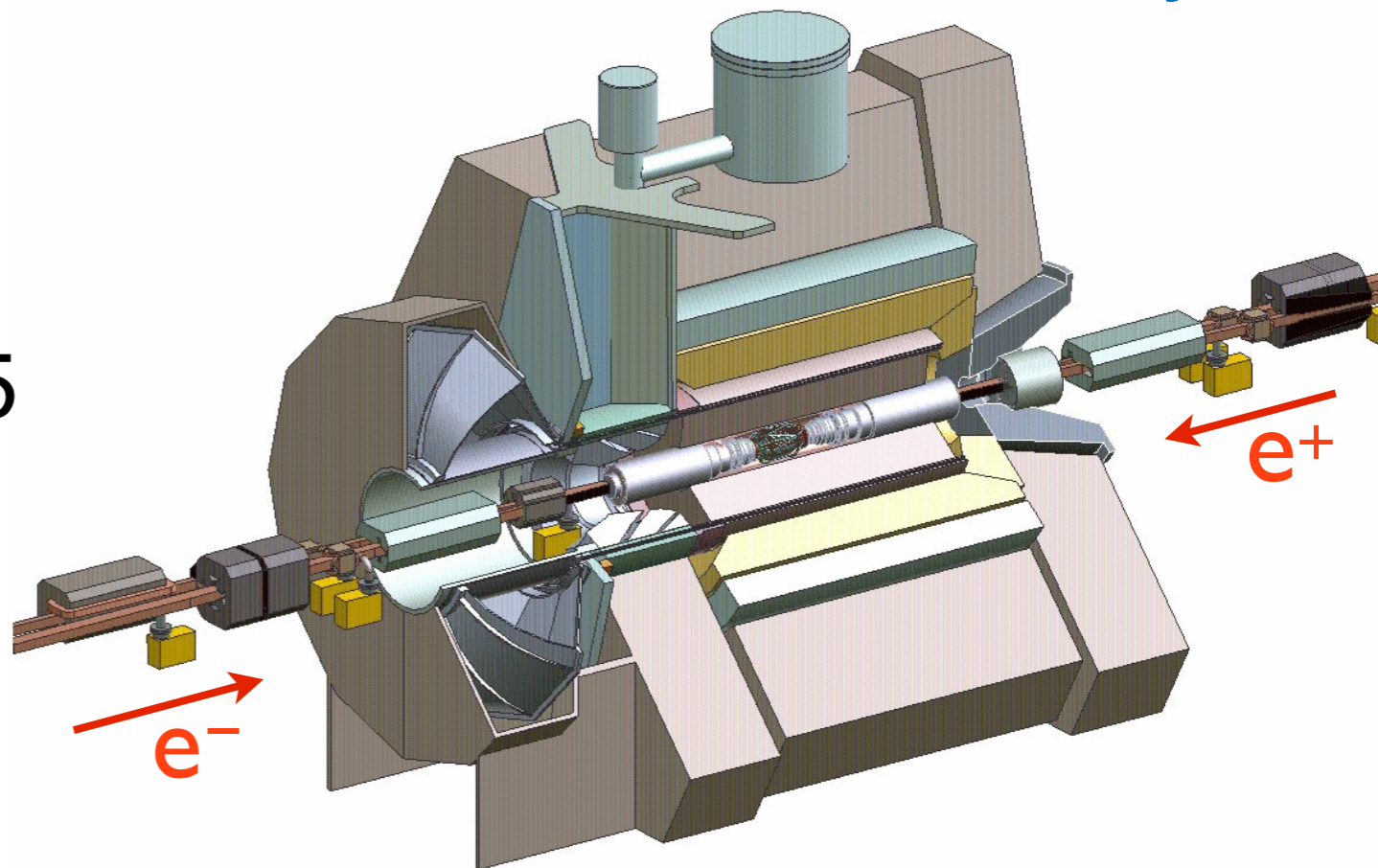
- tradeoffs

→ mass resolution worse than collider  $E_{\text{CM}}$  spread

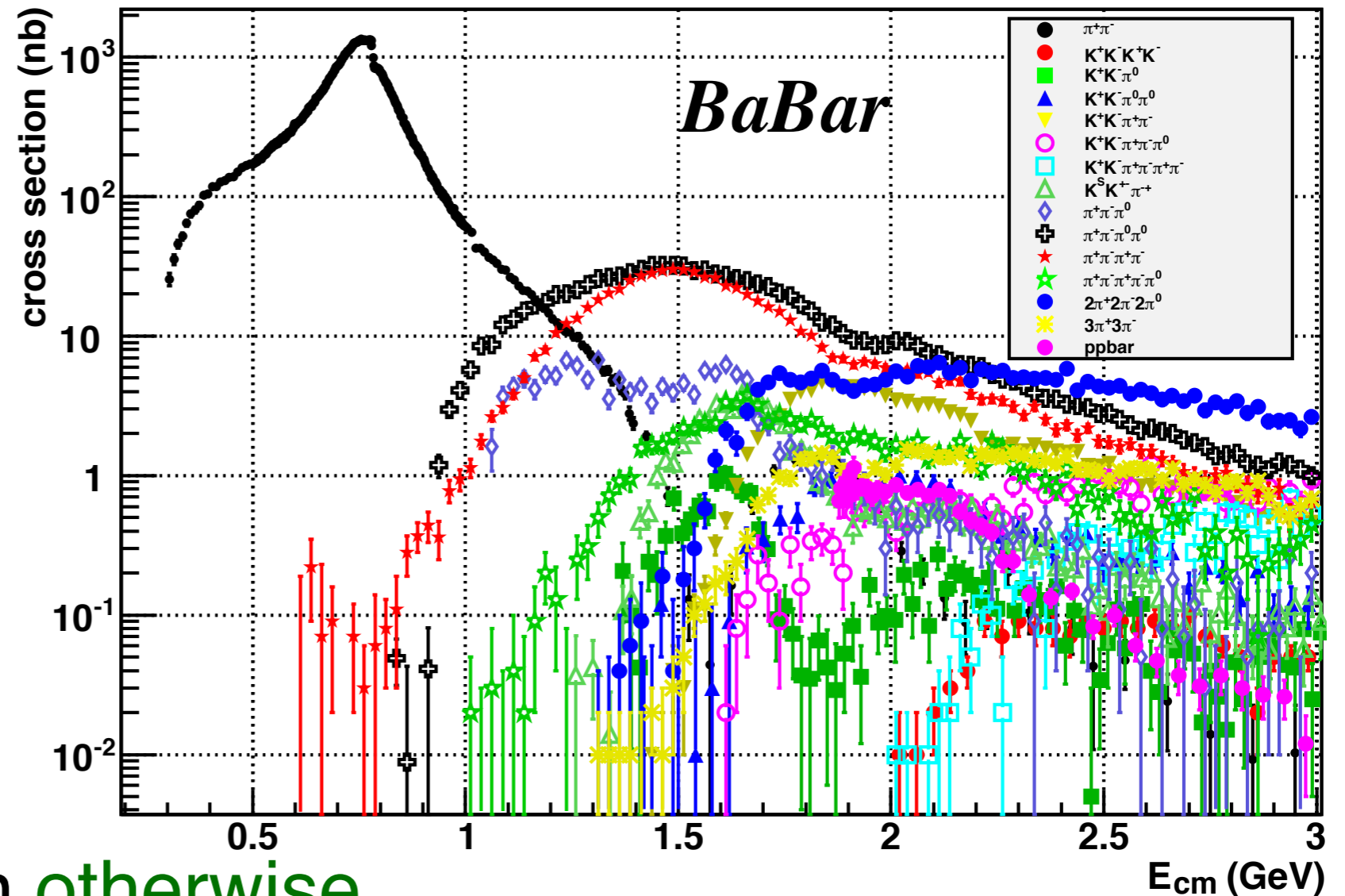
→ need very high luminosity at the nominal  $E_{\text{CM}}$

# The BaBar Experiment

- $e^+e^-$  collisions at  $E_{\text{CM}} = 10.6 \text{ GeV}$ ,  
designed for CP violation in B decays
- different beam energies
  - $E_{e^-} = 9.0 \text{ GeV}$
  - $E_{e^+} = 3.1 \text{ GeV}$
  - c.m.-lab boost,  $\beta\gamma=0.55$
- asymmetric detector
  - c.m. frame acceptance  
 $-0.9 \sim \cos\theta^* \sim 0.85$   
wrt  $e^-$  beam
- with excellent performance
  - good tracking, mass resolution
  - good  $\gamma$ ,  $\pi^0$  recon.
  - full  $e, \mu, \pi, K, p$  ID
- high luminosity
  - $\sim 520 \text{ fb}^{-1}$  accumulated
  - ↔ 1.7 billion  $e^+e^- \rightarrow q\bar{q}$  events
  - ↔ 12 million  $e^+e^- \rightarrow \gamma_{\text{ISR}}\rho^0$
  - ↔ 1 million  $e^+e^- \rightarrow \gamma_{\text{ISR}}\phi$



- BaBar has a program to measure **all** individual modes
  - including  $\pi^\pm, \pi^0, \eta, K^\pm, K_S, K_L, \rho, \Lambda^0, \Sigma^0$
  - 45 modes measured to date
  - precision  $<1\%$  on  $\pi^+\pi^-, K^+K^-$ ; 1-2% / hadron otherwise
  - recent  $K_S K_L(\pi(\pi)), K_S K^+\pi^-(\pi^0)$  complete the 2-, 3-, 4-meson final states
  - have measured  $6\pi^\pm, 4\pi^\pm 2\pi^0, 4\pi^\pm 2K^\pm$ , adding  $2\pi^\pm 4\pi^0$
  - beginning to look at 7-hadron final states

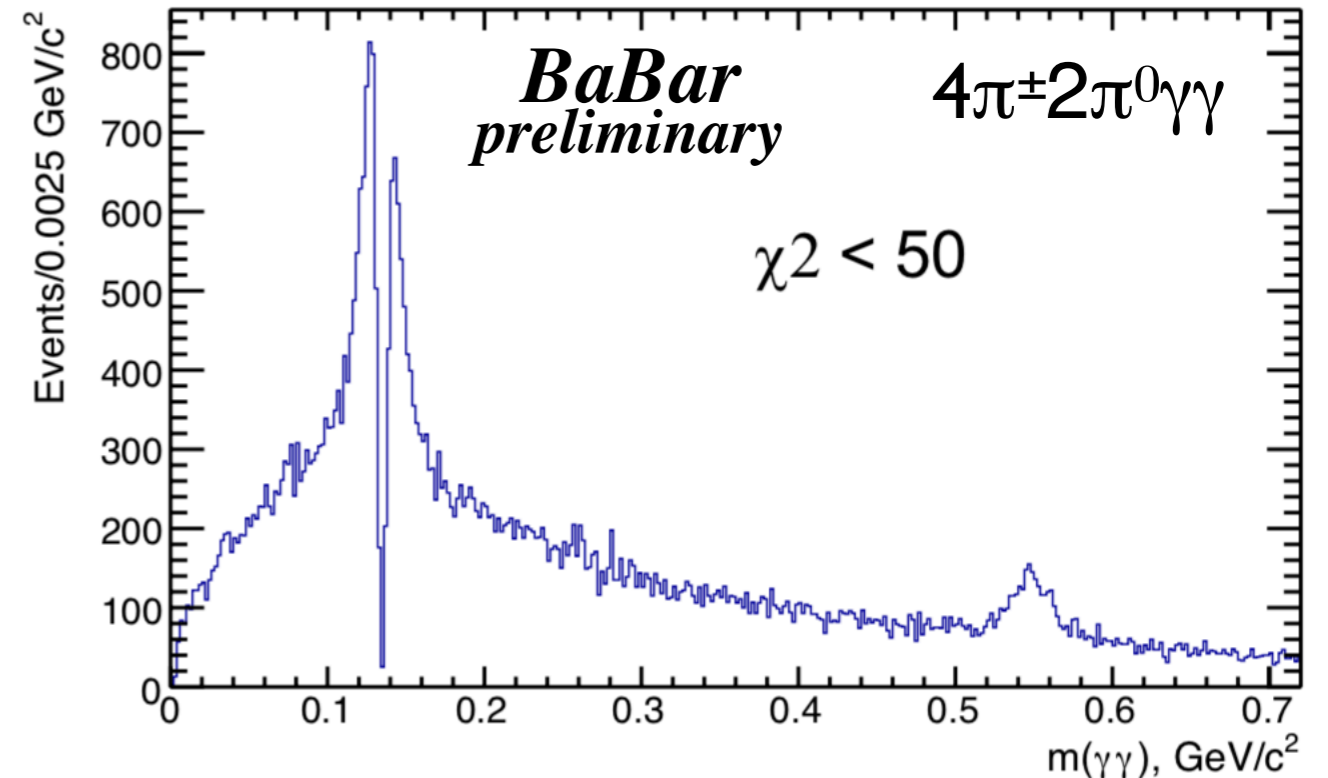
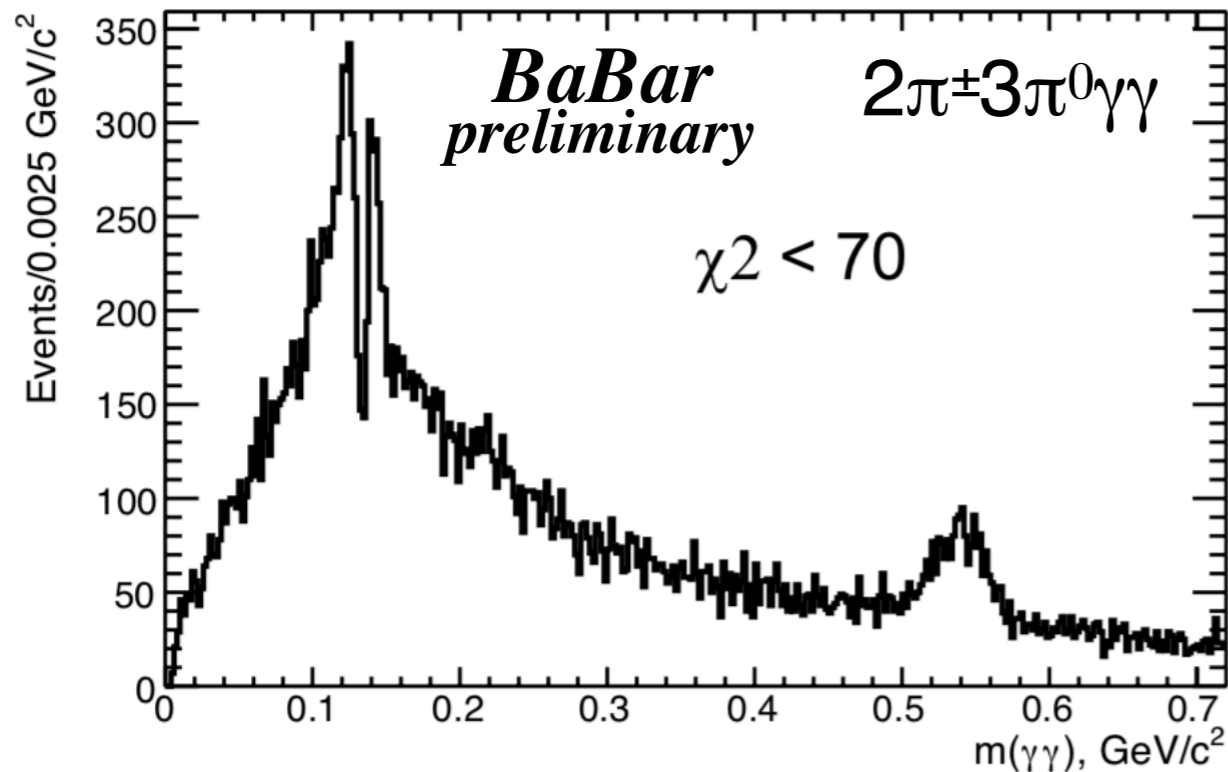


# Event Selection

for  $e^+e^- \rightarrow \pi^+\pi^-3\pi^0 \pi^0/\eta$   $2(\pi^+\pi^-\pi^0)\pi^0/\eta$

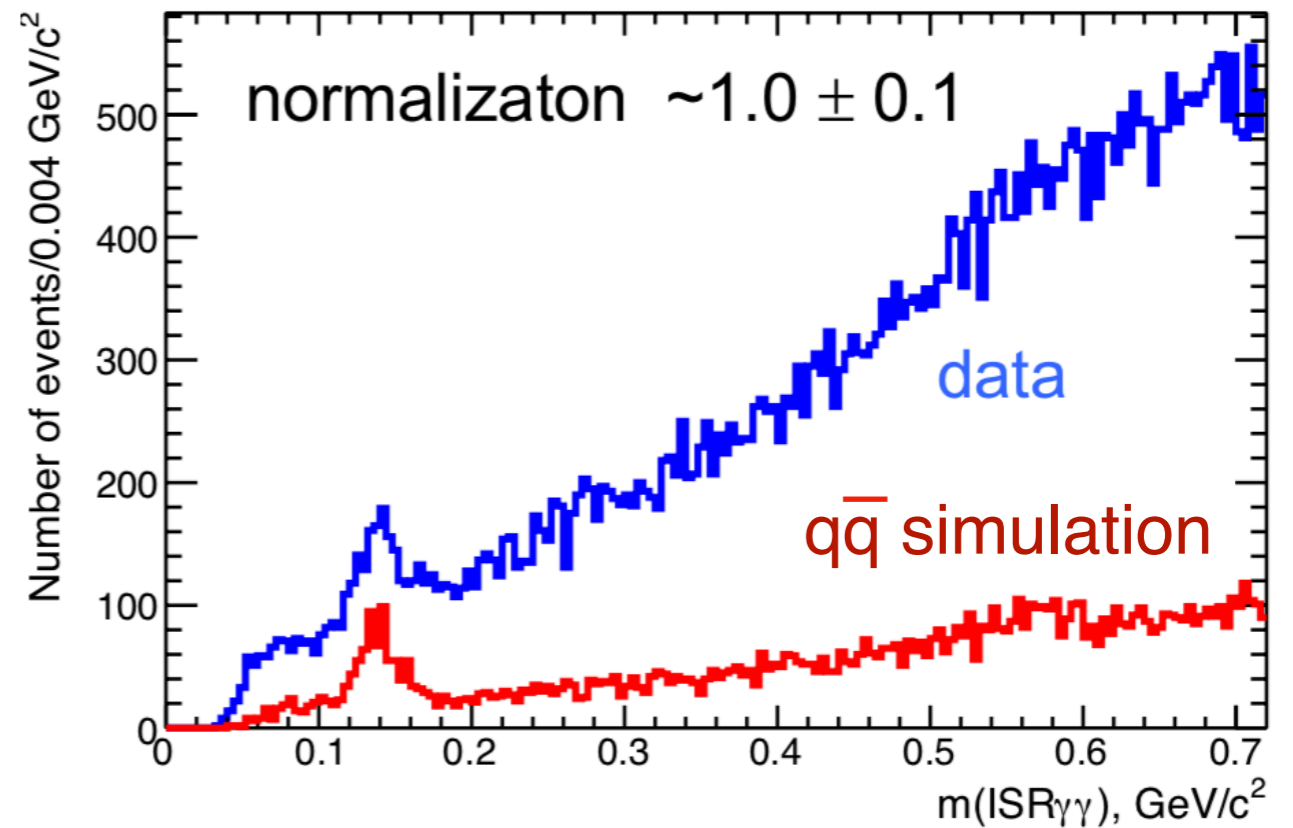
- **require:**
  - a high energy  $\gamma_{\text{ISR}}$ ,  $E_{\text{ISR}} > 3 \text{ GeV}$
  - exactly 2 (4) good charged tracks
  - at least 6 (8) additional photons,  $E_\gamma > 20 \text{ MeV}$
- **combine photons to form  $\pi^0$  candidates**
  - consider all with  $m_{\gamma\gamma}$  within  $35 \text{ MeV}/c^2$  of the  $\pi^0$  mass
- **perform 6C (7C) kinematic fits to the  $2\pi^\pm 3\pi^0 \gamma\gamma\gamma_{\text{ISR}}$  ( $4\pi^\pm 2\pi^0 \gamma\gamma\gamma_{\text{ISR}}$ ) hypothesis**
  - $\pi^0$  masses constrained
  - test all combinations of non-overlapping  $\pi^0, \gamma$
  - accept that with the best  $\chi^2$ , if  $\chi^2 < 70$  (50)
  - test other hypotheses, reject events with good  $\chi^2_{\text{other}}$
  - use higher- $\chi^2$  regions,  $\chi^2_{\text{other}}$  distributions as controls
  - misc. additional cuts

- resulting distributions of the invariant mass of the **unconstrained  $\gamma\gamma$**  pair

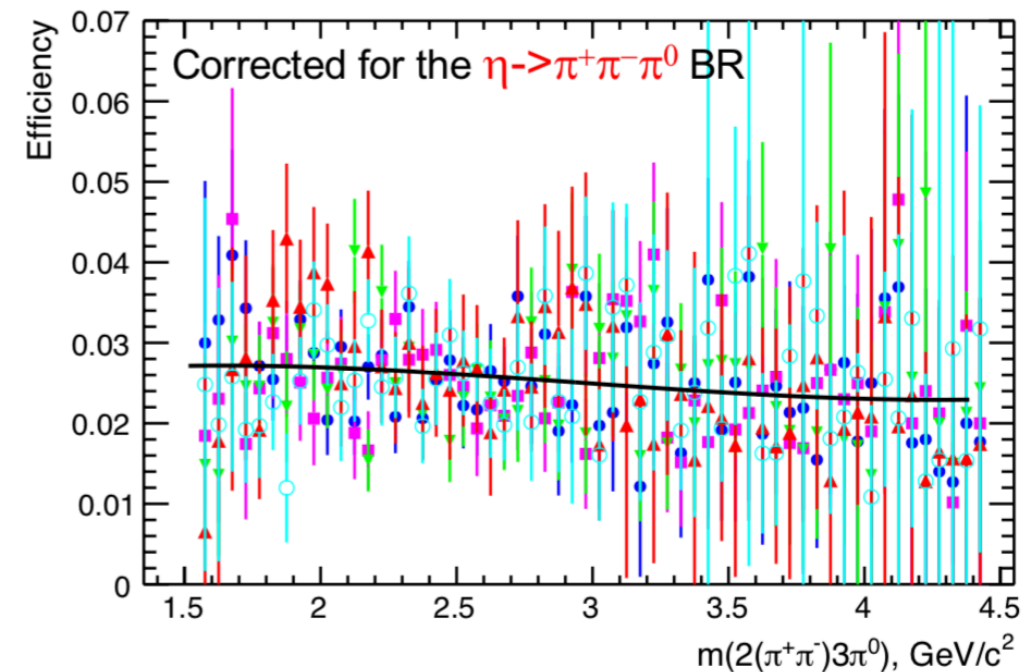
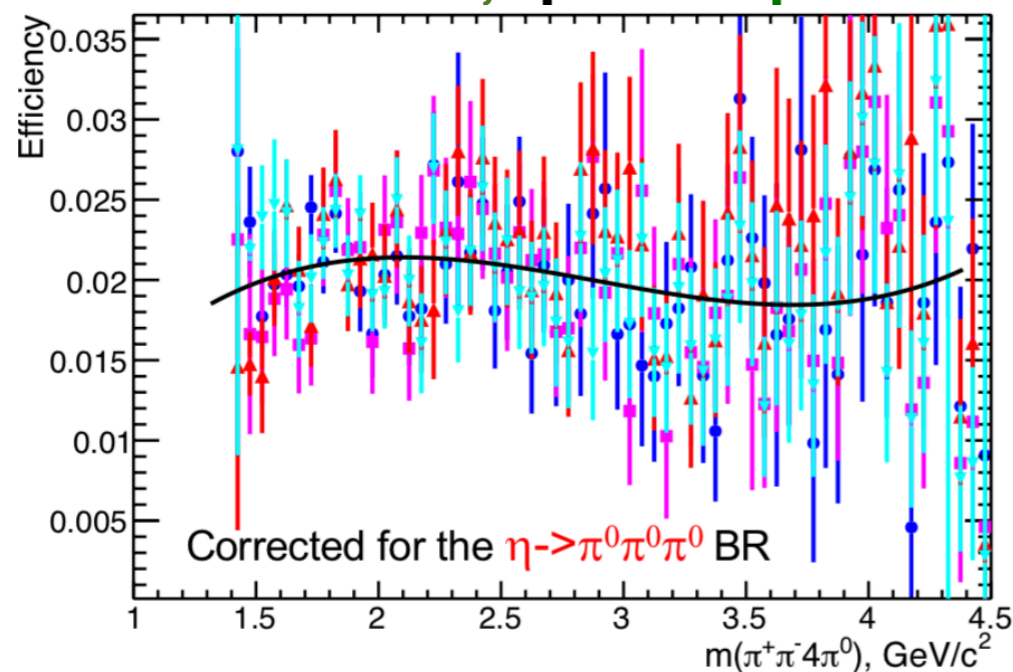


- clear signals for  $\pi^0$ ,  $\eta$
- structure in the  $\pi^0$  peak is an artifact of the selection
- fit these distributions to determine the **number of detected events** in appropriate bins
  - removes all backgrounds except,  $e^+e^- \rightarrow q\bar{q} \rightarrow \pi^0 X$  where an energetic  $\pi^0$  decays asymmetrically to mimic a  $\gamma_{\text{ISR}}$

- calibrate the simulation of this background using the  $\pi^0$  peak in the  $\gamma\gamma_{\text{ISR}}$  mass distributions
  - try all extra photons
  - use simulated structure



- the efficiency may depend on the internal structure
  - compare simulations of different sub-processes
  - also use  $\omega, \eta \rightarrow 3\pi$  peaks in data

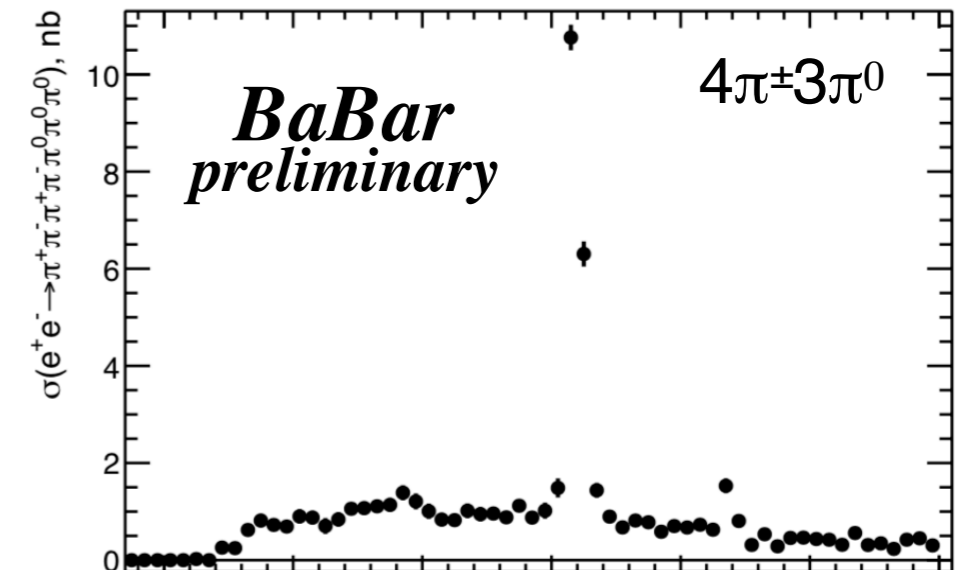
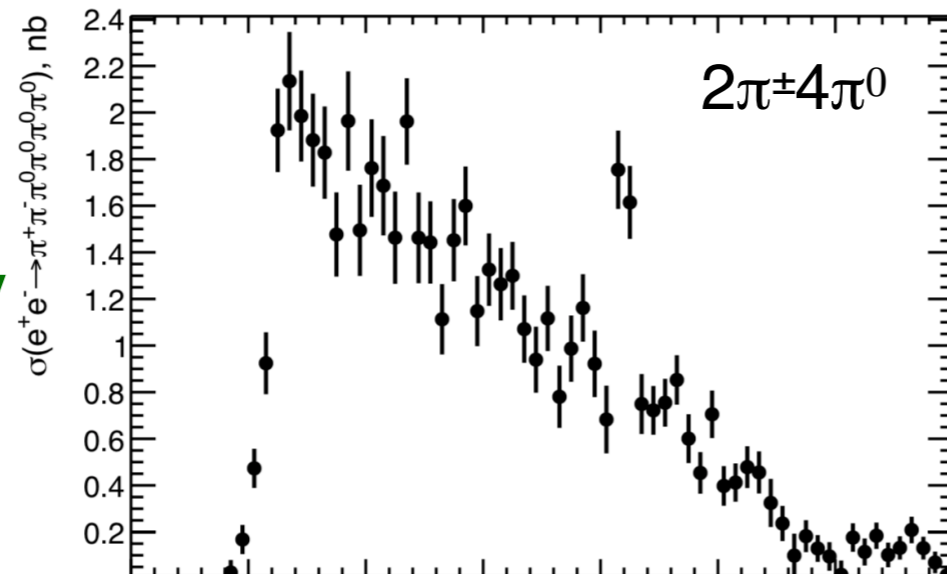


→ use empirical fits to all points

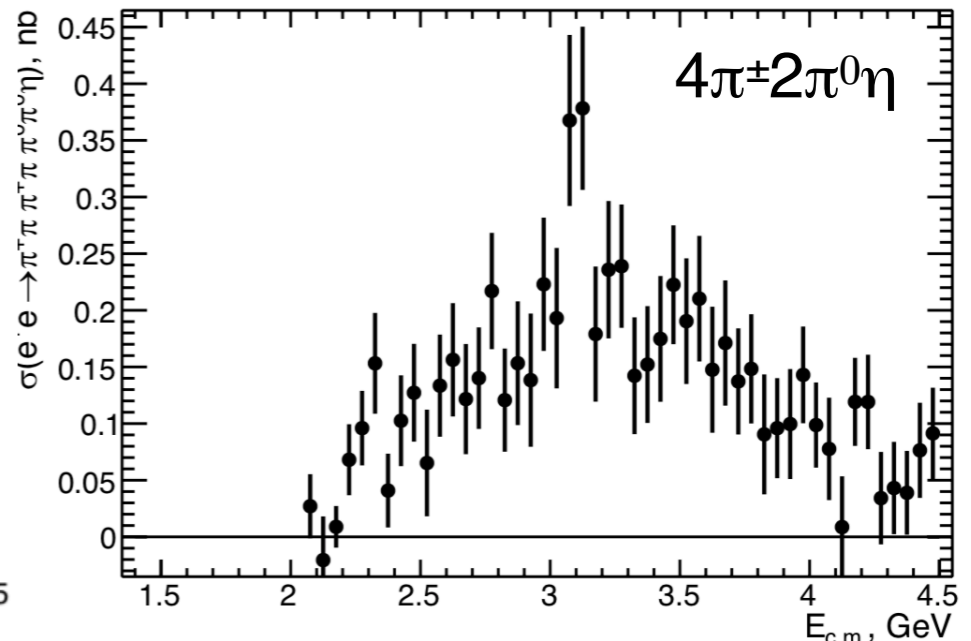
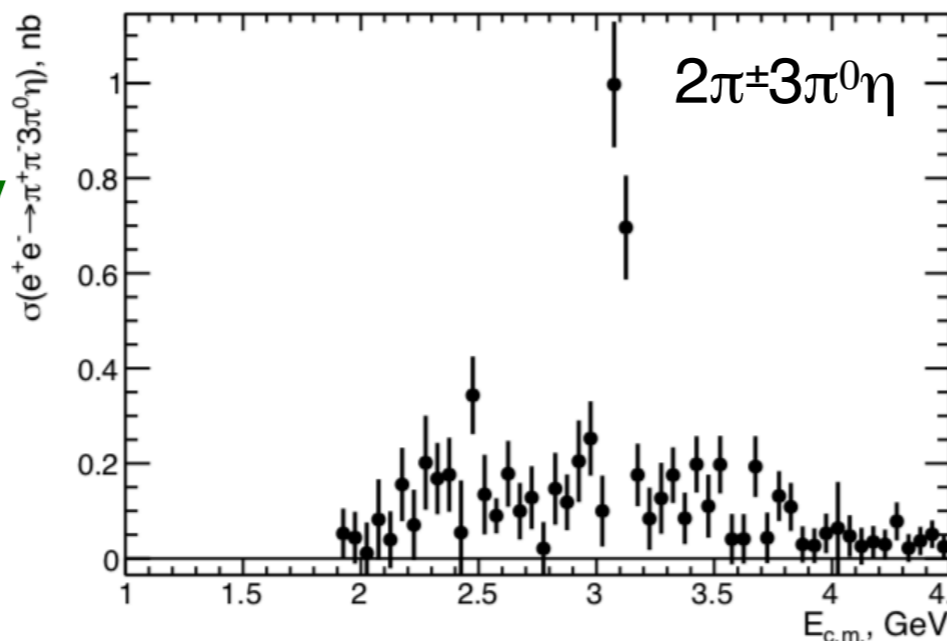
# Cross Sections

- first measurements; systematic uncertainty  $\sim 10\%$

→ very small below 1.5 GeV

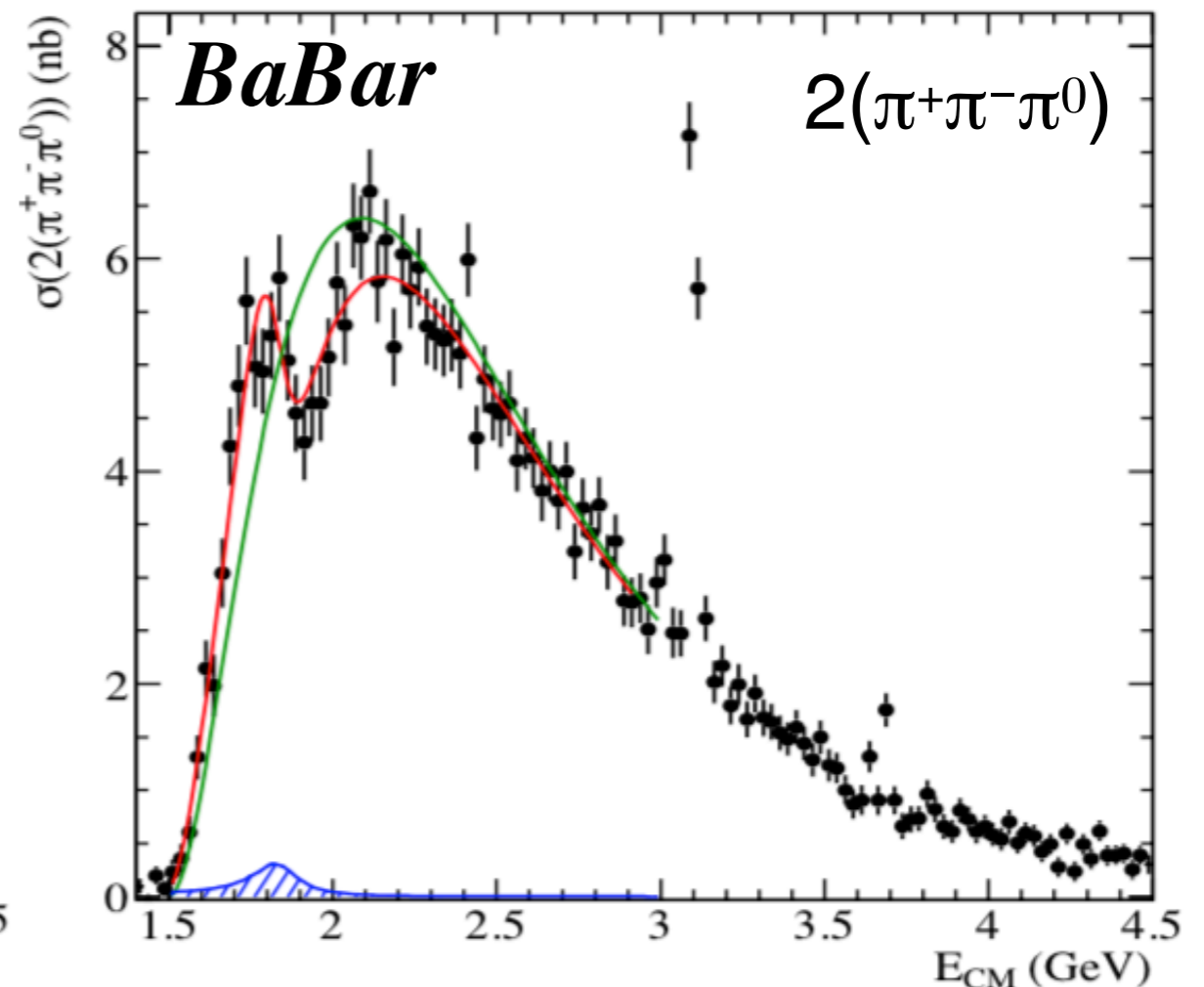
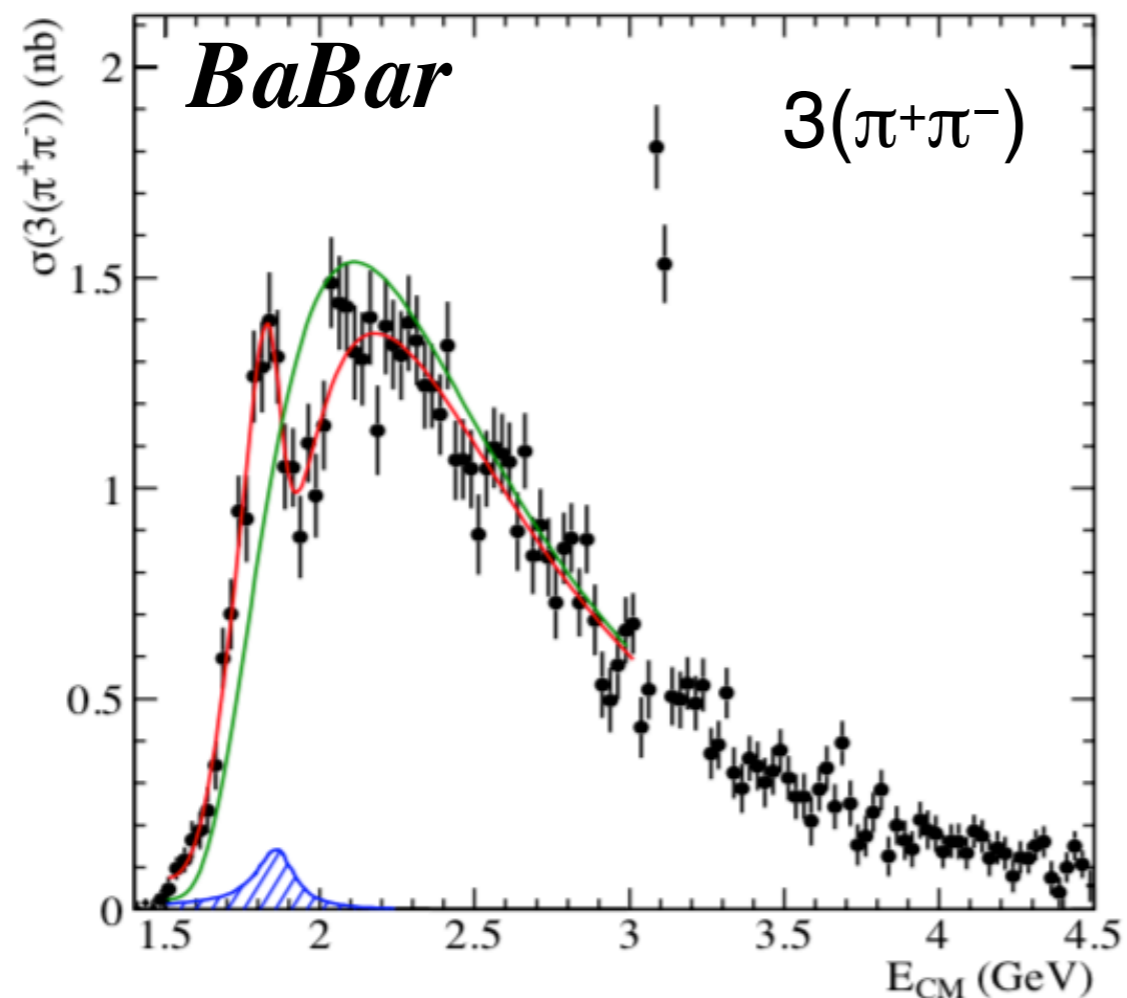
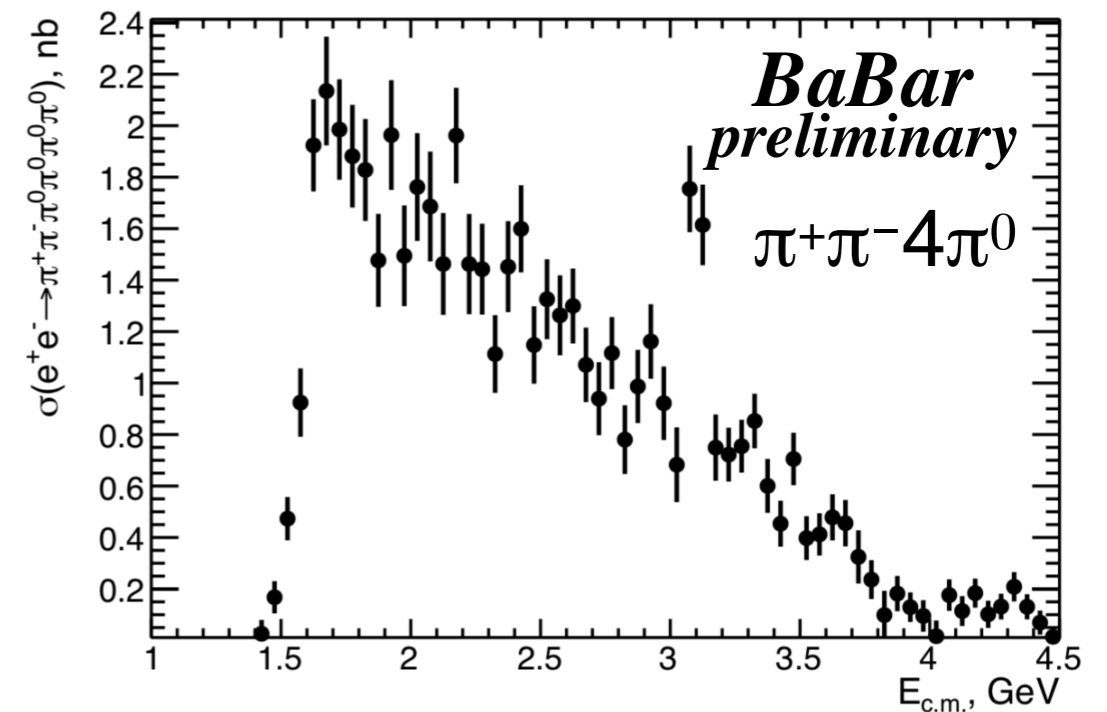


2.0 GeV



- substantial contributions of up to 2 nb
- some clear  $J/\psi$ ,  $\psi(2S)$  signals
- useful input into  $g_\mu - 2$ ,  $\alpha(M_Z)$  calculations

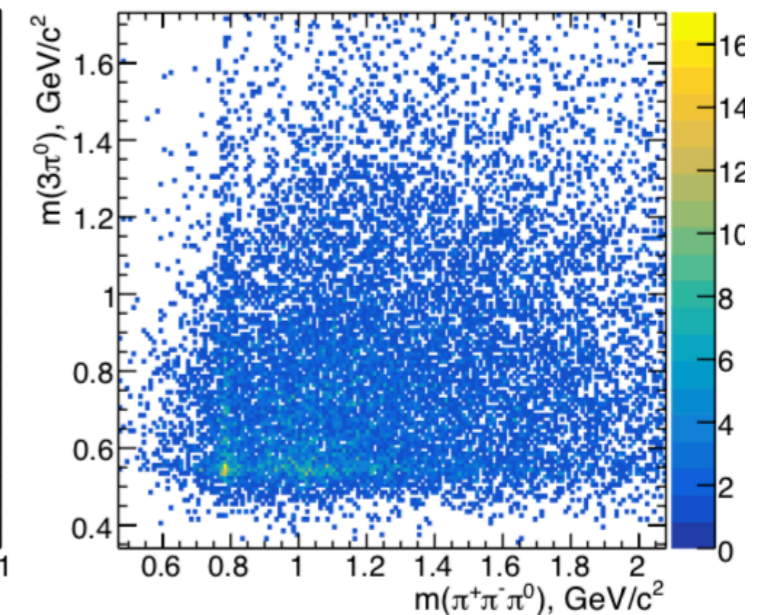
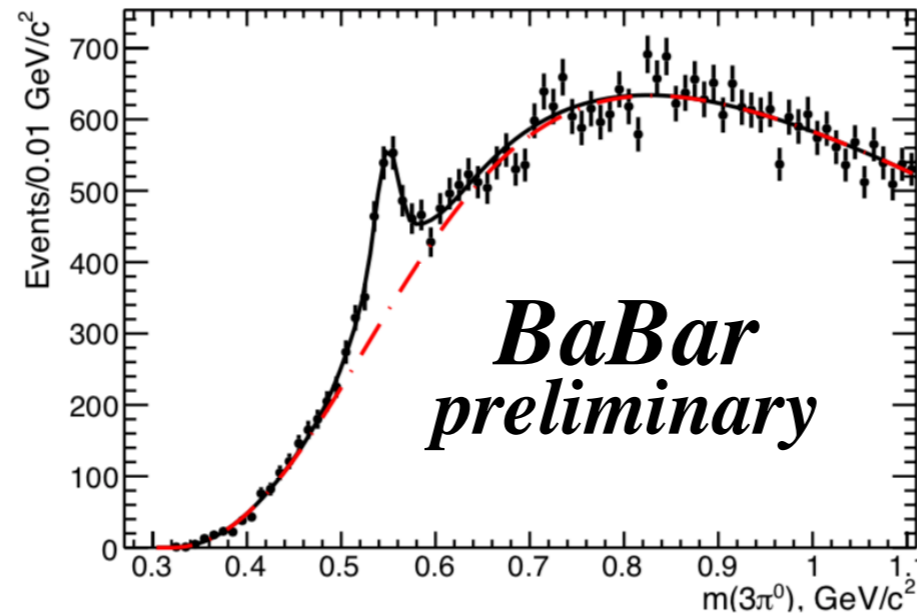
- the  $2\pi^\pm 4\pi^0$  cross section does not show the dip seen previously in the  $6\pi^\pm$  and  $4\pi^\pm 2\pi^0$  cross sections
- near 1.8 GeV, just below  $p\bar{p}$  threshold



# Internal Structure in $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$

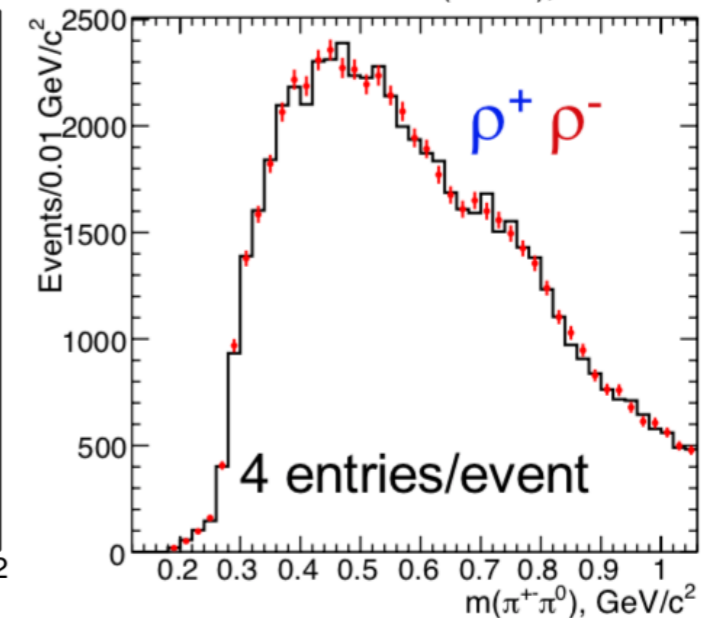
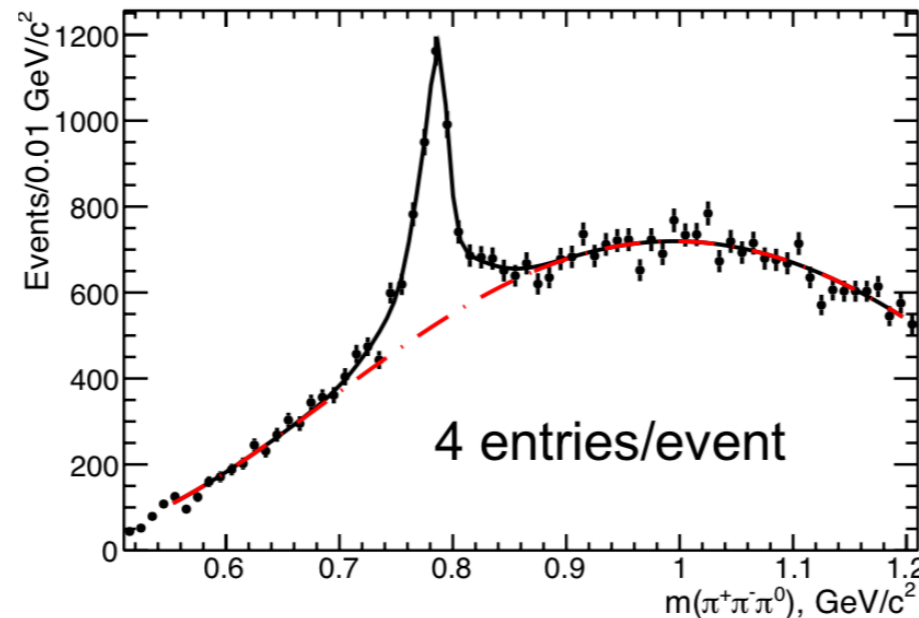
- observe clear signals for  $e^+e^- \rightarrow$

- $\rightarrow \eta\pi^+\pi^-\pi^0$
- $\rightarrow \omega\pi^0\pi^0\pi^0$
- $\rightarrow \phi\pi^0\pi^0\pi^0$
- $\rightarrow \eta\omega$
- $\rightarrow \rho^\pm\pi^\mp\pi^0\pi^0\pi^0$



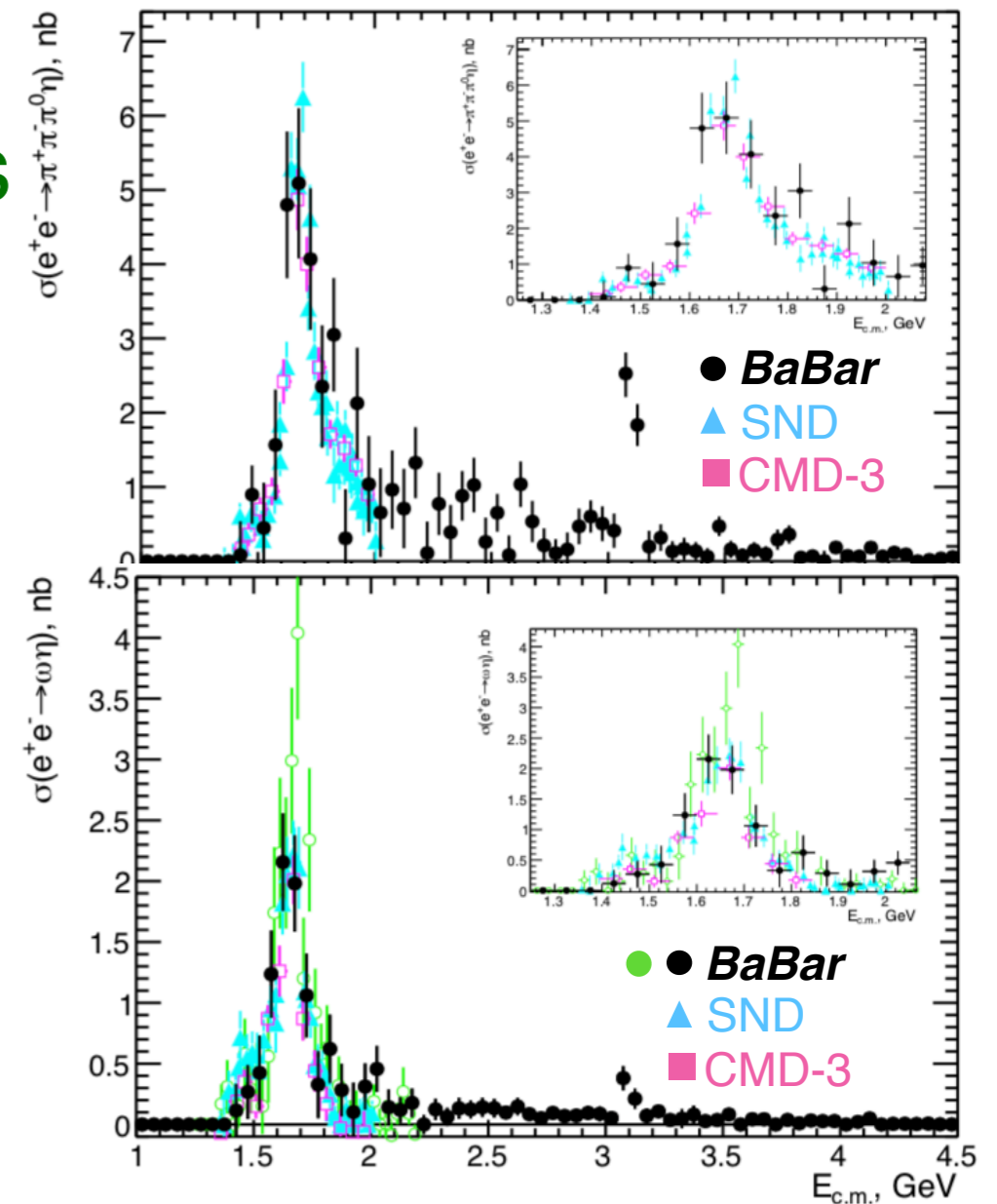
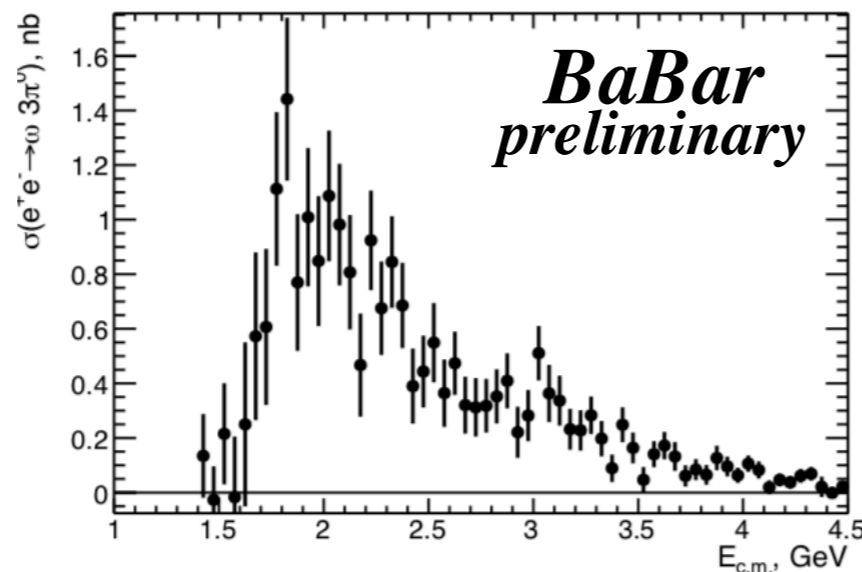
- also evidence for

- $\rightarrow \rho^\pm\pi^\mp\eta$
- $\rightarrow \rho^+\rho^-\pi^0\pi^0$   
(mostly in  $J/\psi$  decays)



- structure is as rich as in the  $4\pi^\pm 2\pi^0$  mode, and far richer than in the  $6\pi^\pm$  mode

- we can extract cross sections for:
  - $\eta\pi^+\pi^-\pi^0$ : consistent w/ previous measurements in  $\eta\rightarrow\gamma\gamma$ , extending the range
  - $\omega\eta$ : cons. w/, extending prev. measurements in  $\eta\rightarrow\pi^+\pi^-\pi^0$
  - $\omega\pi^+\pi^-\pi^0$ : first measurement



- the  $\rho^\pm\pi^\mp 3\pi^0$  mode is important above 2 GeV
  - systematic uncertainty is >20%, no x-section quoted
- these  $\sim$ saturate the  $2\pi^\pm 4\pi^0$  cross section up to 2.9 GeV
  - these do not look like jetty events
  - ... or do these jets have very low primary multiplicity?

# Internal Structure in $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$

- observe clear signals for  $e^+e^- \rightarrow$

$\rightarrow \eta\pi^+\pi^-\pi^+\pi^-$ ,  
 via  $\eta\rho^0\pi^+\pi^-$ ,  
 $\eta a_1^\pm \pi^\mp$

$\rightarrow \omega\pi^+\pi^-\pi^0\pi^0$ ,  
 $\eta\pi^+\pi^-\pi^0\pi^0$

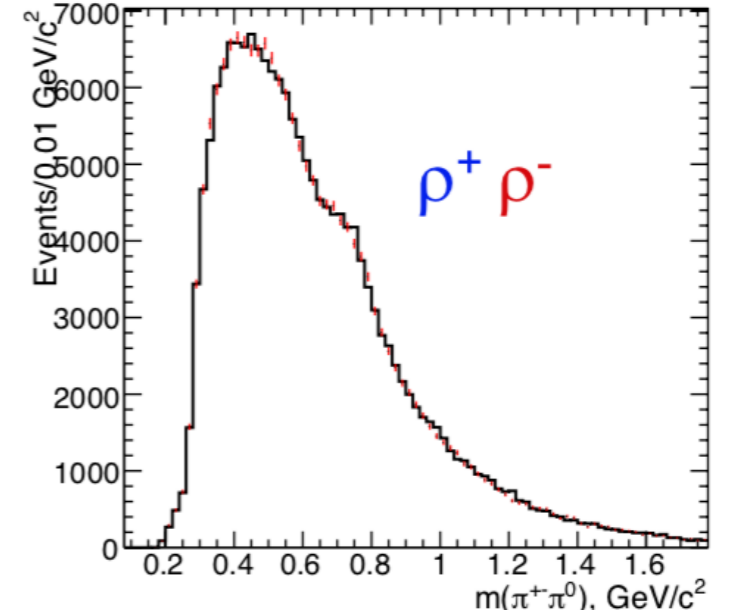
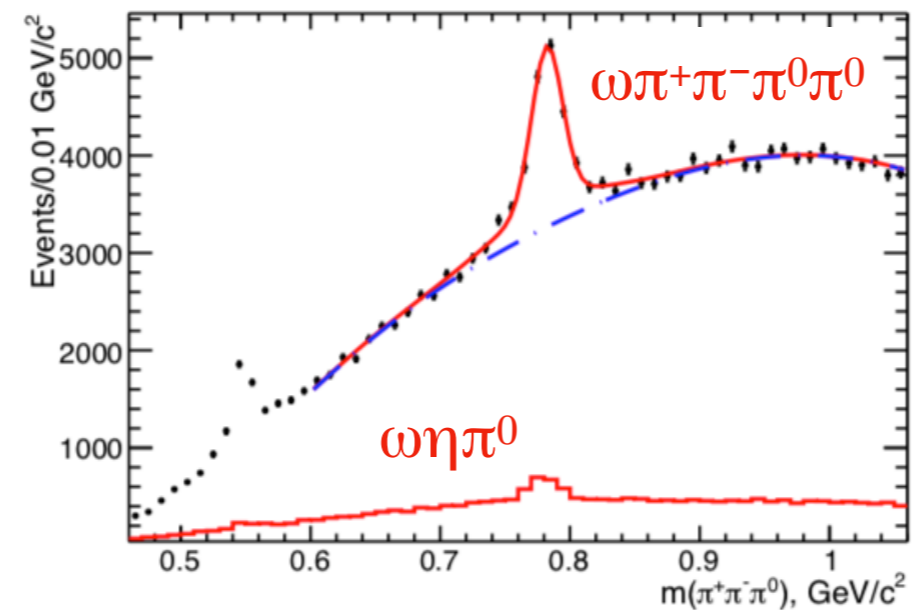
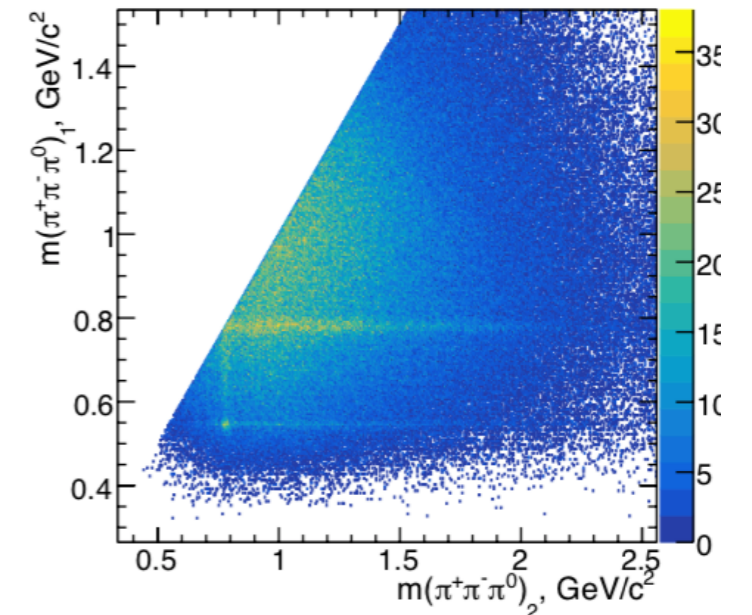
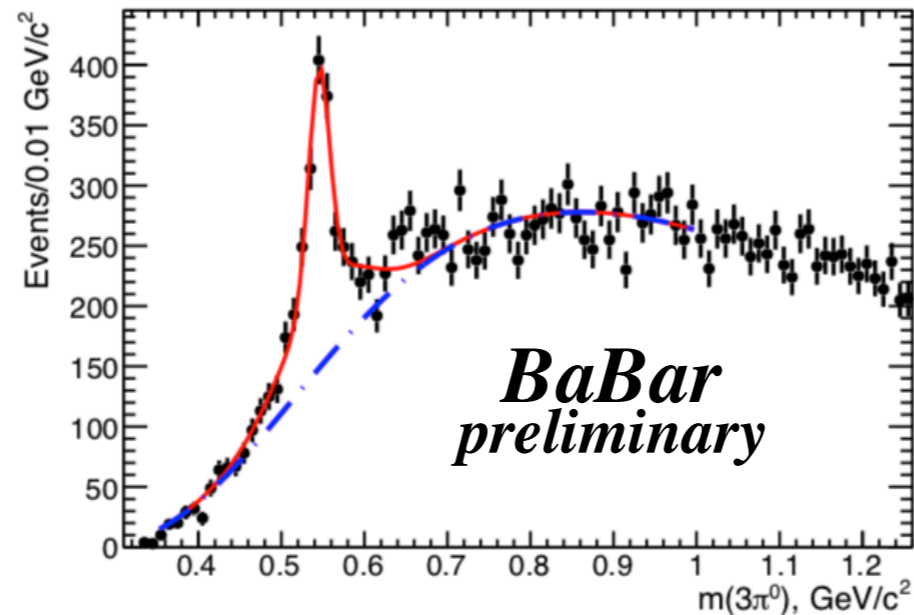
$\rightarrow \omega\eta\pi^0$

$\rightarrow \rho^\pm\pi^\mp\pi^0\pi^0\pi^0\pi^0$

- also evidence for

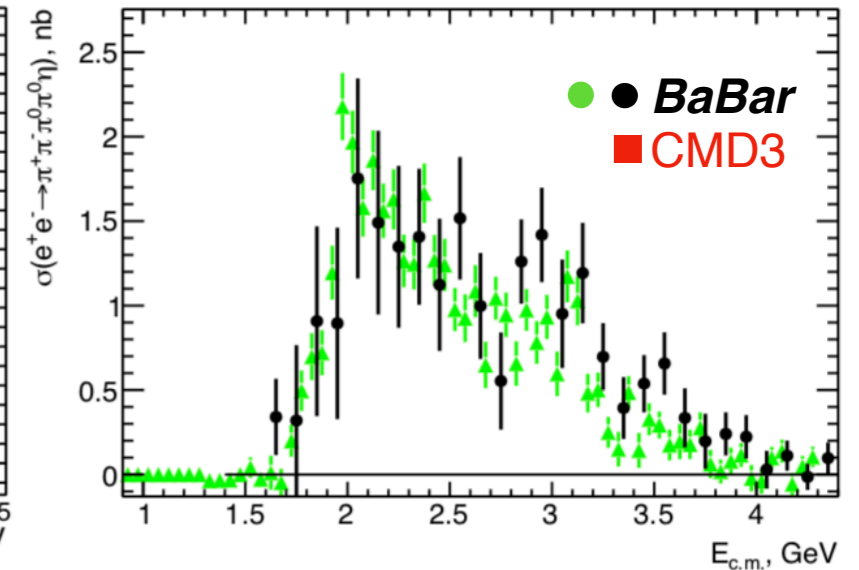
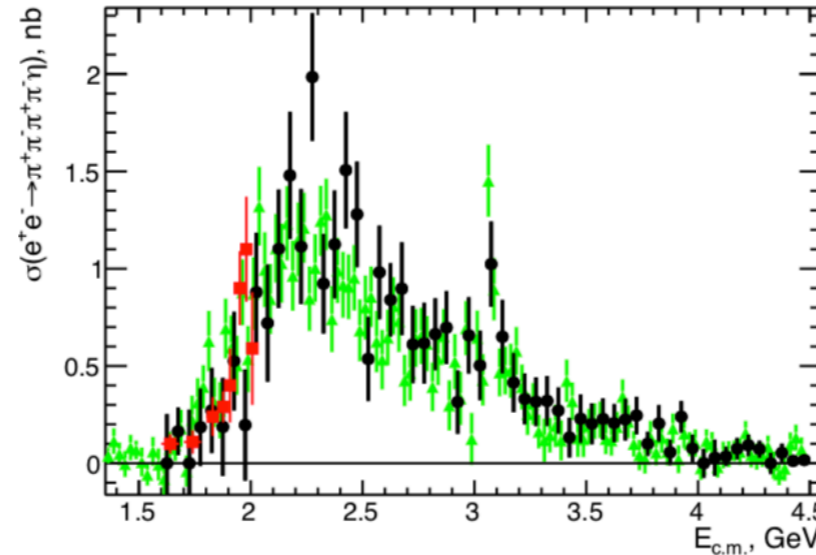
$\rightarrow \rho^+\rho^-3\pi^0$   
 mostly in  $J/\psi$  decays

- again, very rich structure



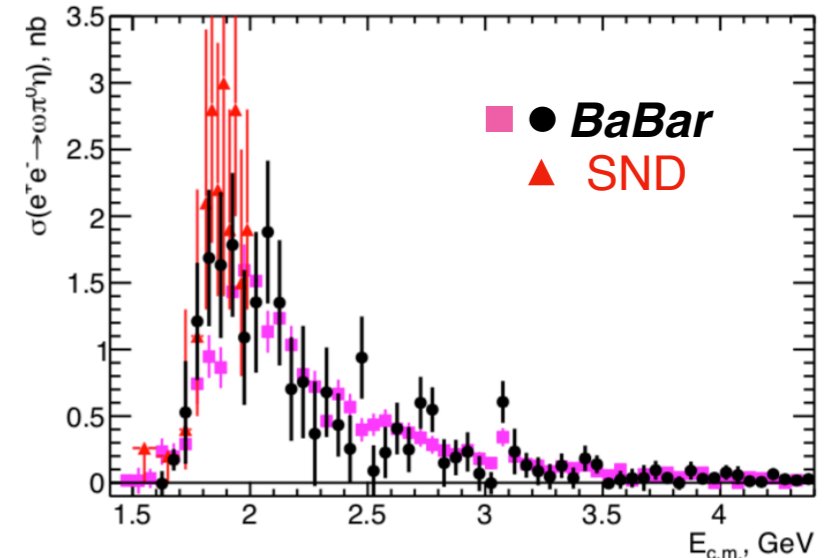
- we can extract cross sections for:

→  $\eta 4\pi^\pm, \eta 2\pi^\pm 2\pi^0$ : consistent with previous measurements in  $\eta \rightarrow \gamma\gamma$

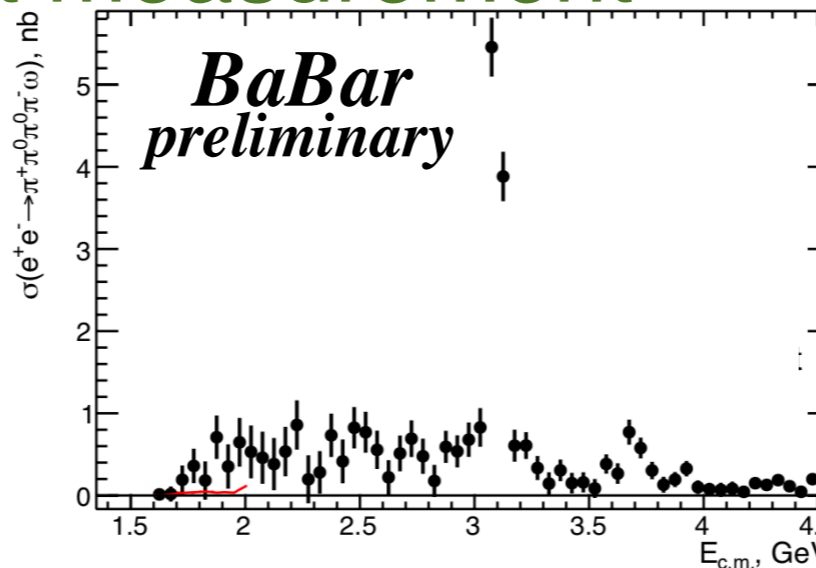


→  $\omega \eta \pi^0$ : consistent with prev. msmts. in  $\eta \rightarrow \pi^+ \pi^- \pi^0$

→  $\omega \pi^+ \pi^- \pi^0 \pi^0$ : first measurement



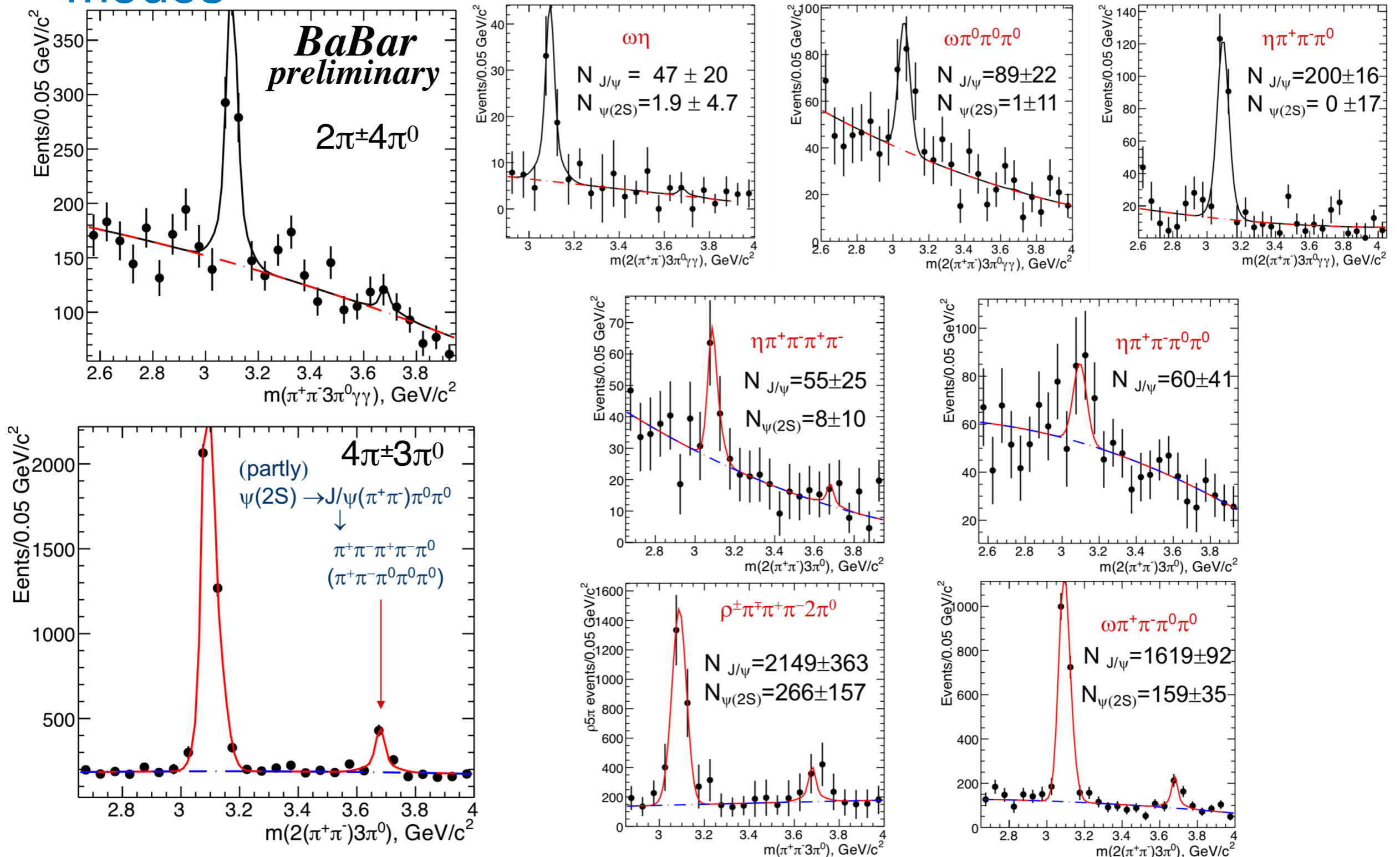
- $\rho^\pm \pi^\mp \pi^+ \pi^- 2\pi^0$  is important above  $\sim 1.7$  GeV



- these  $\sim$ saturate the  $4\pi^\pm 3\pi^0$  cross section below 3 GeV
- only slightly more jetty events

# The Charmonium Region

- We observe  $J/\psi$  and/or  $\psi(2S)$  signals in many of these modes



- Measure the product of:
  - the  $J/\psi$  or  $\psi(2S)$  branching fraction
  - the  $J/\psi$  or  $\psi(2S)$  electronic width,  $\Gamma_{ee}$
  - any relevant internal branching fractions
- use PDG  $\Gamma_{ee}$  and internal BFs to obtain

Mode	$J/\psi$ BF ( $10^{-3}$ )		$\psi(2S)$ BF ( $10^{-3}$ )	
	this work	PDG	this work	PDG
$2\pi^{\pm}4\pi^0$	$6.5 \pm 0.8 \pm 1.0$	—	$1.4 \pm 1.0 \pm 0.2$	—
$\eta\pi^+\pi^-\pi^0$	$11.9 \pm 0.9 \pm 2.3$	—	$< 3.5$	—
$\omega\eta$	$3.0 \pm 1.3 \pm 0.5$	$1.74 \pm 0.20$	$< 1.4$	$< 0.11$
$\omega 3\pi^0$	$1.9 \pm 0.5 \pm 0.3$	—	$< 0.8$	—
$\pi^+\pi^-3\pi^0\eta$	$4.9 \pm 0.8 \pm 0.8$	—	$< 2.0$	—
$4\pi^{\pm}3\pi^0$	$62.0 \pm 2.0 \pm 9.0$	—	$14.0 \pm 2.0 \pm 2.0$	—
$\omega 2\pi^{\pm}2\pi^0$	$33.0 \pm 2.0 \pm 5.0$	—	$8.7 \pm 1.9 \pm 1.5$	—
$\eta 2\pi^{\pm}2\pi^0$	$4.8 \pm 3.2 \pm 0.8$	$2.3 \pm 5.0$		
$\eta 4\pi^{\pm}$	$2.6 \pm 1.2 \pm 0.5$	$2.26 \pm 0.28$	$< 2.3$	$1.2 \pm 0.6$
$\rho^{\pm}\pi^{\mp}\pi^+\pi^-2\pi^0$	$28.0 \pm 4.7 \pm 6.6$	—		
$\rho^+\rho^-2\pi^{\pm}\pi^0$	$5.7 \pm 2.4 \pm 2.7$	—		
$4\pi^{\pm} 2\pi^0\eta$	$4.2 \pm 1.2 \pm 0.6$	—	$< 1.9$	—
$J/\psi 4\pi^{\pm}\pi^0$			$34.7 \pm 6.1 \pm 5.2$	$33.7 \pm 2.6$
$J/\psi 2\pi^{\pm}3\pi^0$			$23.8 \pm 5.6 \pm 3.6$	$27.1 \pm 2.9$

# Summary

- BaBar continues to make large contributions to hadron physics via initial state radiation
  - $e^+e^-$  annihilations at low energy
  - meson and baryon form factors
  - discovery of new states and spectroscopy of others
  - improved understanding of  $R$ ,  $g_{\mu-2}$ ,  $\alpha(M_Z)$
- new measurements from threshold to 4.5 GeV of
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$ ,  $\pi^+\pi^-\pi^0\pi^0\pi^0\eta$
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$ ,  $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\eta$
- including lots of substructure
  - $J/\psi$  and  $\psi(2S)$  BFs
- much more is possible

# Backup Slides

# BaBar cross sections with ISR

$e^+e^- \rightarrow$	threshold to $E_{cm} =$	latest Ref.
$\pi^+\pi^-$	4.5 GeV	PRD 86, 032013 (2012)
$\pi^+\pi^-\eta$	4.5 GeV	PRD 97, 052007 (2018)
$\pi^+\pi^-\pi^0$	4.5 GeV	PRD 70, 072004 (2004)
$\pi^+\pi^-\pi^0\pi^0$	4.5 GeV	PRD 96, 092009 (2017)
$\pi^+\pi^-\pi^+\pi^-$	4.5 GeV	PRD 85, 112009 (2012)
$\pi^+\pi^-\pi^+\pi^-\pi^0/\eta, K^+K^-\pi^+\pi^-\pi^0/\eta$	4.5 GeV	PRD 76, 092005 (2007)
$\pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\eta$	4.5 GeV	PRD 98, 112015 (2018)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$		
$K^+K^-$	8.0 GeV	PRD 92, 111101 (2015)
$K_S K_L, K_S K_L \pi^+\pi^-, K_S K_S \pi^+\pi^-, K_S K_S K^+K^-$	4.5 GeV	PRD 89, 092002 (2014)
$K_S K_L \pi^0, K_S K_L \eta, K_S K_L \pi^0\pi^0$	4.5 GeV	PRD 95, 052001 (2017)
$K_S K^+\pi^-\pi^0, K_S K^+\pi^-\eta$	4.5 GeV	PRD 95, 092005 (2017)
$K^+K^-\pi^+\pi^-\pi^+\pi^-$	4.5 GeV	PRD 73, 052003 (2006)
$K^+K^-\pi^0, K^+K_S\pi^-, K^+K^-\eta$	2.6 GeV	PRD 77, 092002 (2008)
$K^+K^-\pi^+\pi^-, K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-$	4.5 GeV	PRD 86, 012008 (2012)
$pp$	6.0 GeV	PRD 88, 072009 (2013)
$\Lambda^0\Lambda^0, \Lambda^0\Sigma^0, \Sigma^0\Sigma^0$	3.0 GeV	PRD 76, 092006 (2007)
$J/\psi\pi^+\pi^-$	5.5 GeV	PRD 86, 051102 (2012)
$J/\psi\pi^+\pi^-\pi^0, J/\psi K^+K^-\pi^0, J/\psi K_S K^+\pi^-$	5.5 GeV	PRD 86, 051102 (2012)
$D^{(*)}D^{(*)}$	6.0 GeV	PRD 79, 092001 (2009)
$D_S^{(*)}+D_S^{(*)-}$	6.0 GeV	PRD 82, 072004 (2010)
$\psi(2S)\pi^+\pi^-$	5.5 GeV	PRD 89, 111103 (2014)