Studies of $\sigma(e^+e^- \rightarrow hadrons)$ at BABAR using Initial State Radiation (ISR)

Wenfeng Wang
Laboratoire de l'Accélérateur Linéaire, Orsay
for the BABAR Collaboration

XII International Conference on Hadron Spectroscopy 8-13 October, 2007, Frascati

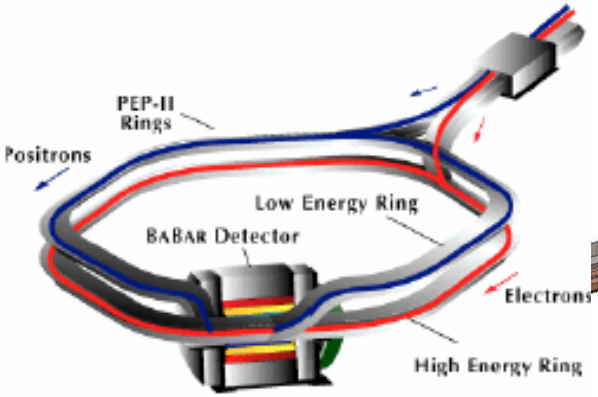
Outline

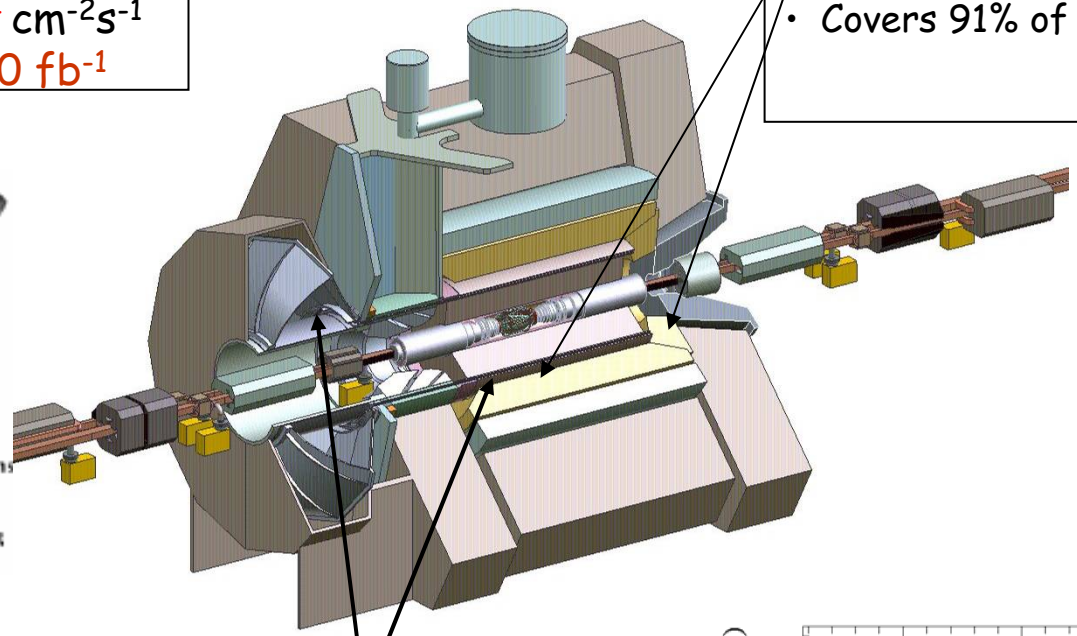
- Introduction
- ISR method at BABAR
- Exclusive Analyses
- Inclusive analysis
- Summary

BaBar/PEP-II

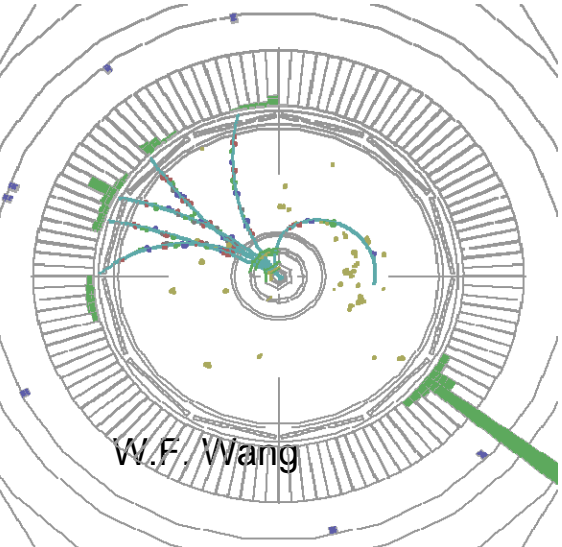
- **PEP-II** is an asymmetric e^+e^- collider with a CM energy of $\Upsilon(4S)$.
- Peak luminosity = $1.17 * 10^{34}$ $cm^{-2}s^{-1}$
- Integrated luminosity = 500 fb^{-1}

BaBar EMC:
- 6580 CsI(Tl) crystals, E resolution ~1-2 % at high E.
- Covers 91% of solid angle.

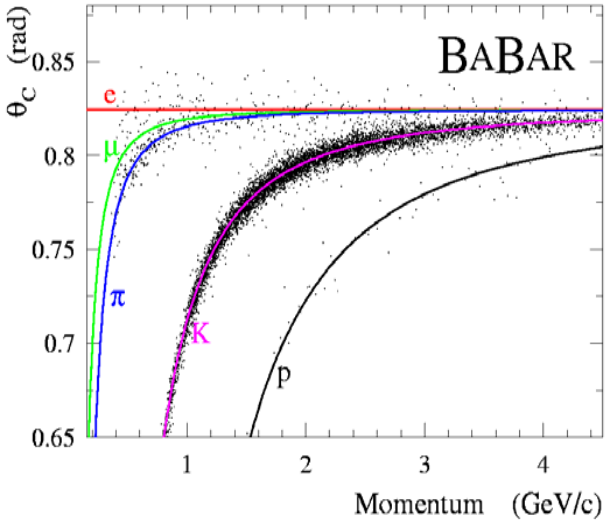




BaBar DIRC
- Covers 80% of solid angle
- Particle ID up to 4-5 GeV/c



R measurements at BaBar-ISR

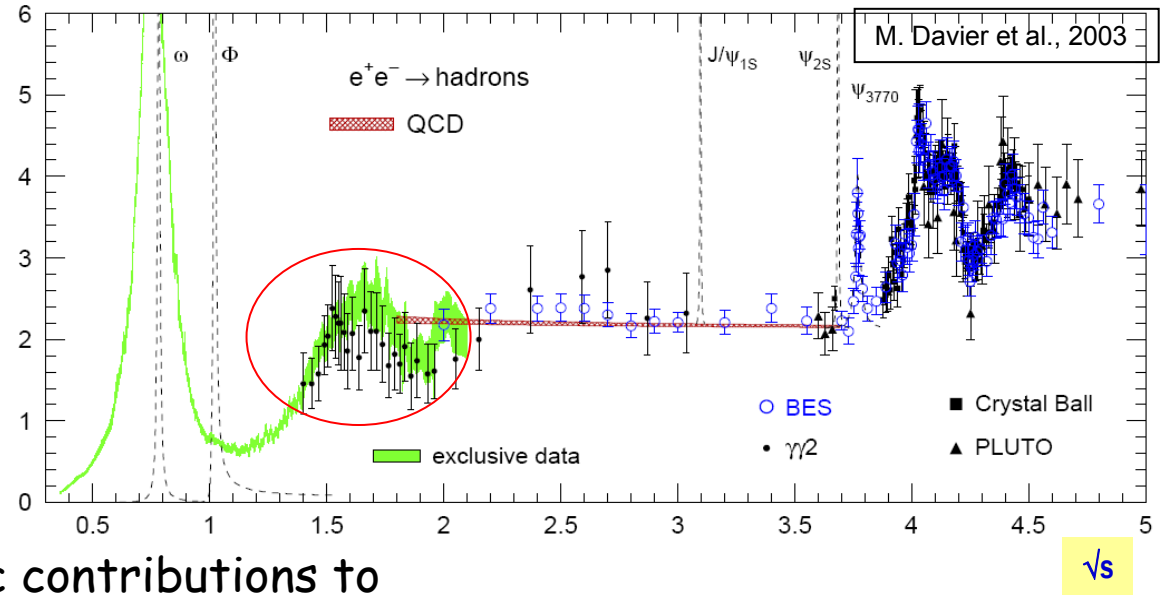


Objective

Precise measurements of cross section for all significant processes, $e^+e^- \rightarrow$hadrons, from threshold to ~4-5GeV

- Summing up exclusive cross sections ==>Improve the precision of R
- Study spectroscopy of $J^{PC}=1^{--}$ states and their decays

$$R(s) = \frac{\sigma_0(e^+e^- \rightarrow \text{hadrons}\ (\gamma))}{\sigma_{pt}(e^+e^- \rightarrow \mu^+\mu^-)}$$



R(s): crucial input for hadronic contributions to

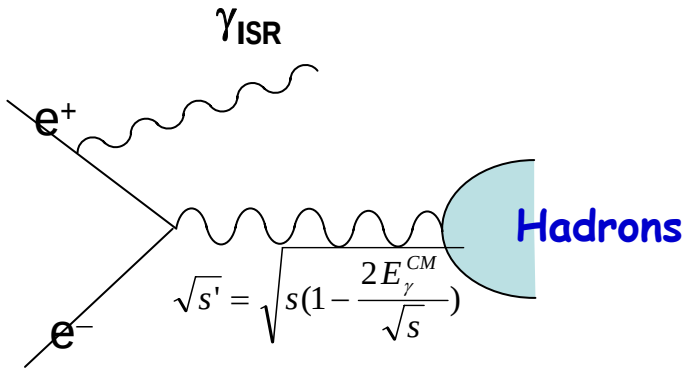
- Muon anomalous magnetic moment (a_μ) -----dispersion integrals

$$a_\mu^{had,LO} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} R(s)\frac{K(s)}{s}ds$$

K(s) known QED kernel

- Running of α_{QED} (for SM fits $\Rightarrow$ Higgs Mass).

ISR at Υ(4S) Energies

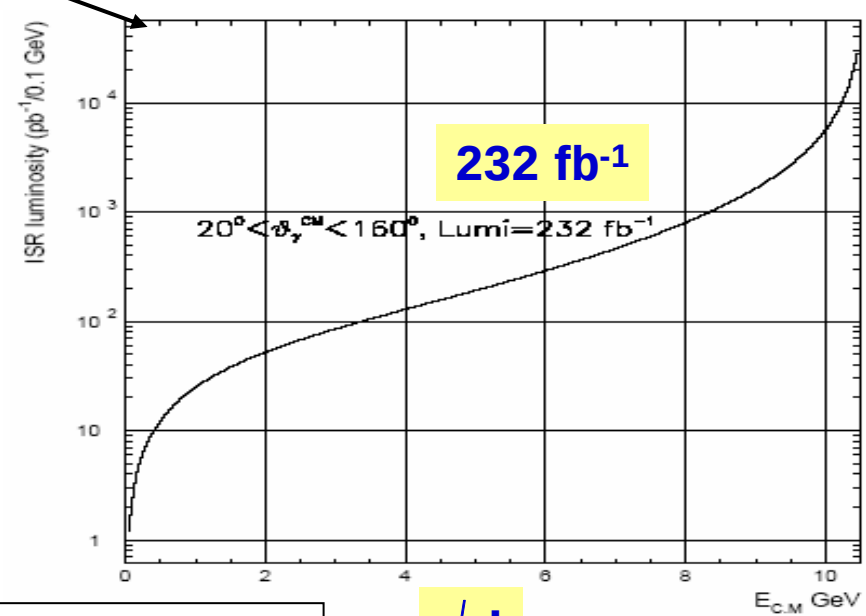


Born cross-section:

$$\frac{d\sigma(s')}{dx} = W(s,x).\sigma_0(s'), \qquad s' = s(1-x)\,,\ x \equiv \frac{2E_\gamma^{CM}}{\sqrt{s}}$$

$$W(s,x,\theta_\gamma^{CM}) \cong \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma^{CM}} - \frac{x^2}{2}\right)$$

- Whole √s' spectrum from threshold to ~4-5GeV with tagged photon; high transverse momentum, high acceptance
- Obtained in one experiment, as opposed to scan experiments: point-to-point uncertainties greatly reduced
- High PEP-II luminosity and BABAR detector performance allow to be competitive with low energy e^+e^- machines

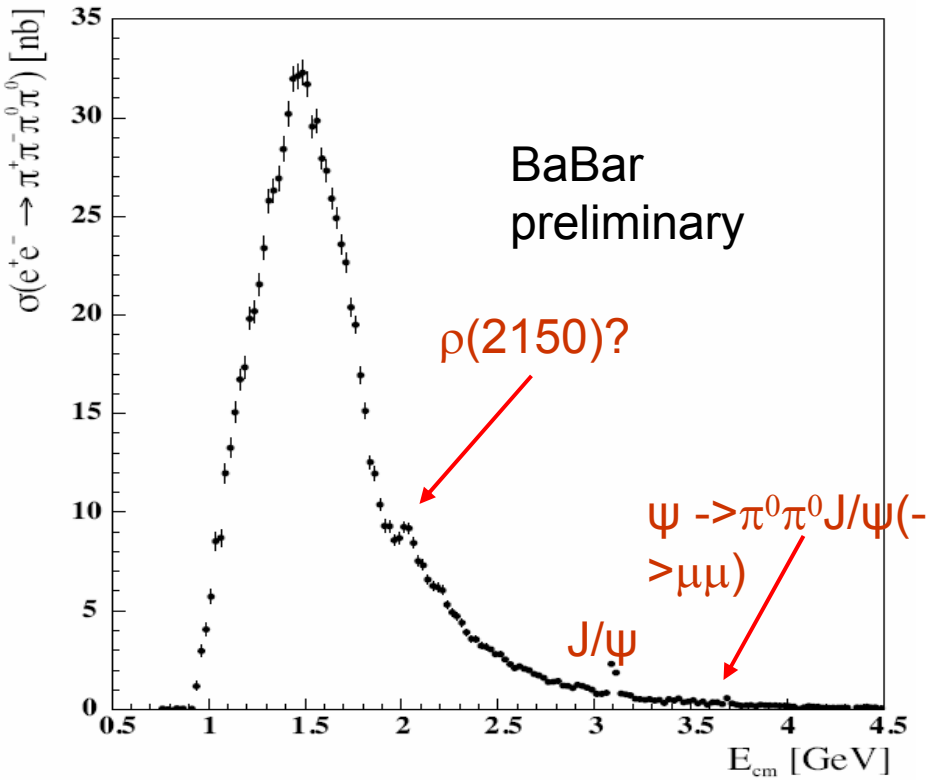


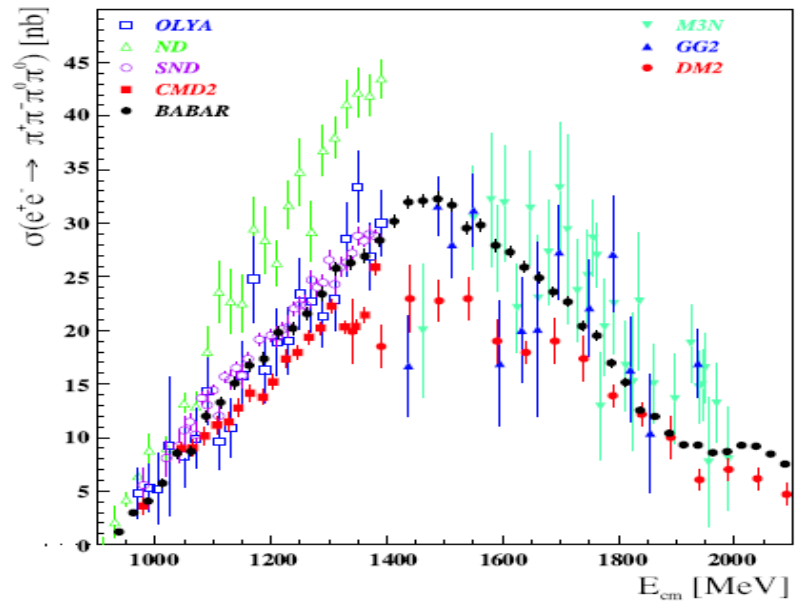
MC simulation (AfkQed) uses Born-level ISR + FSR + Interference, + Structure functions for soft photons; precision ~1%

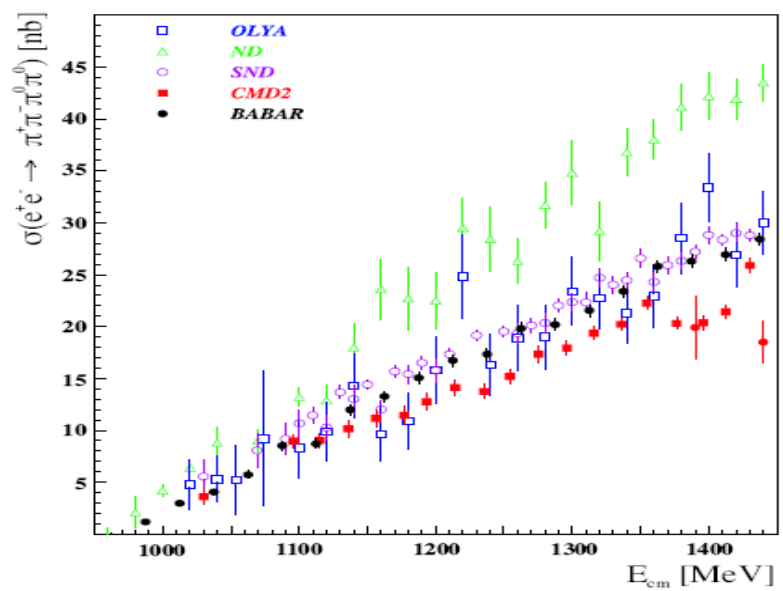
BaBar ISR: $e^+e^- \rightarrow$ hadrons

- Reactions for which results have been published :
  - $p\bar{p}$ — PRD 73, 012005 (2006)
  - $\pi^+\pi^-\pi^0$ — PRD 70, 072004 (2004)
  - $2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$, — PRD 71, 052001 (2005)
  - $K^+K^-\pi^+\pi^-$ $K^+K^-\pi^0\pi^0$, $2K^+2K^-$ — PRD 76, 012008 (2007)
  - $3\pi^+3\pi^-$, $2\pi^+2\pi^-\pi^0\pi^0$, $K^+K^-2\pi^+2\pi^-$ — PRD 73, 052003 (2006)
- New results presented in this meeting :
  - $K^+K^-\pi^0$, $K_SK^-\pi^+$, $K^+K^-\eta$, — BaBar Preliminary
  - $\Lambda\Lambda$, $\Lambda\Sigma^0$, $\Sigma^0\Sigma^0$ — Submitted to PRD e-Print: **arXiv:0709.1988** [hep-ex]
  - $\pi^+\pi^-\pi^0\pi^0$ — BaBar Preliminary
  - $2\pi^+2\pi^-\pi^0$, $2\pi^+2\pi^-\eta$, $KK\pi^+\pi^-\pi^0$, $KK\pi^+\pi^-\eta$ — Submitted to PRD e-Print: **arXiv:0708.2461** [hep-ex]
- Work in progress on :
  - $\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-3\pi^0$
  - Inclusive R

BaBar ISR: $\pi^+\pi^-\pi^0\pi^0$



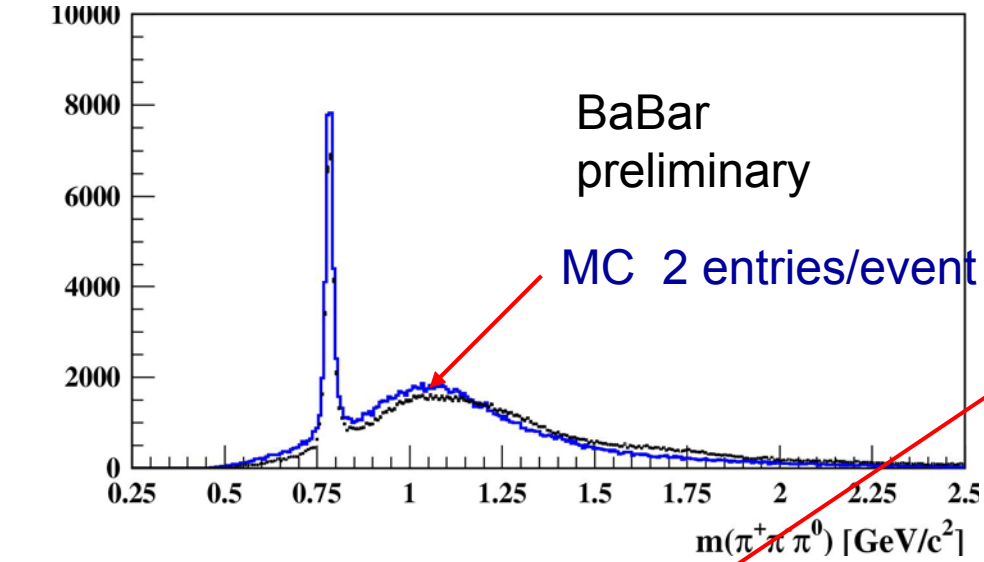




- Important mode for a_μ and α_{QED}
- Preliminary precision: 8% in peak ➡ 5%
- Good agreement with SND <1.4 GeV
- Huge improvement >1.4 GeV
- First measurement >2.5 GeV

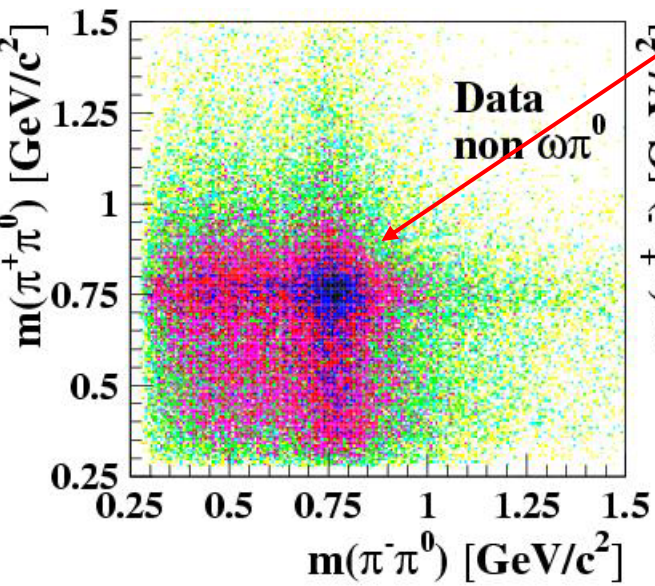
BaBar ISR: $\pi^+\pi^-\pi^0\pi^0$

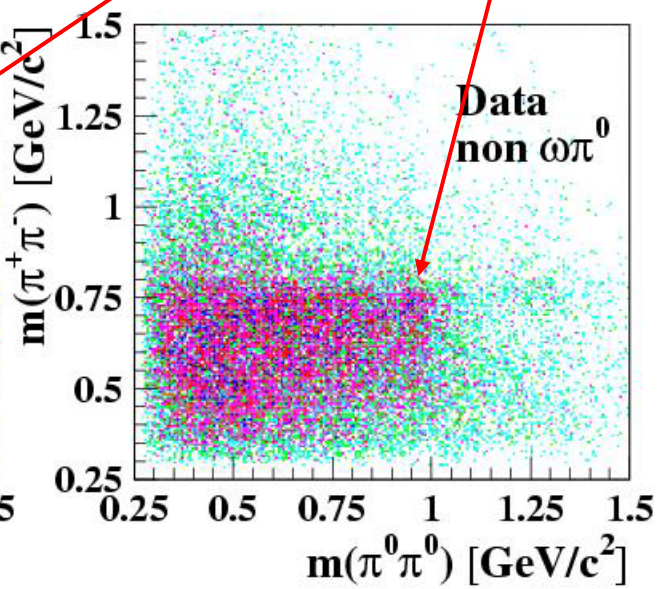
--substructure

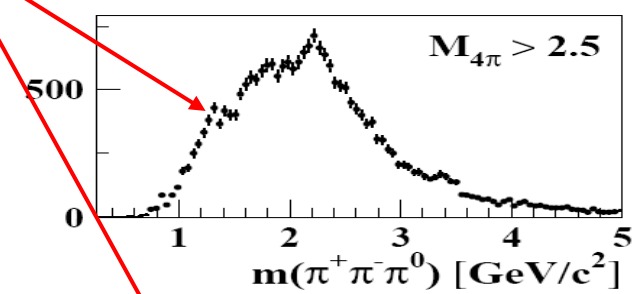


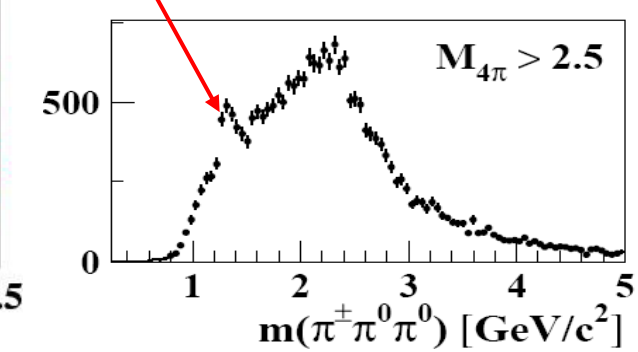
Intermediate states:

- $\omega\pi^0$
- $\rho^+\rho^-$ large and 1st seen
- $\rho^0 f_0(980)$
- $a_1(1260)\pi$





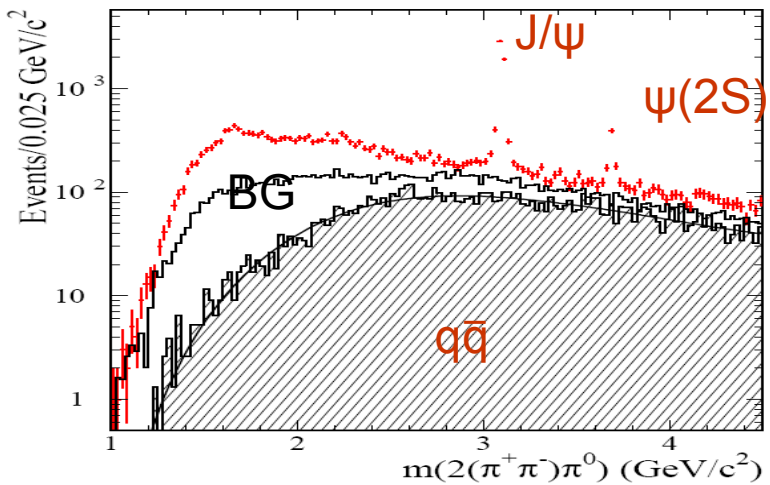


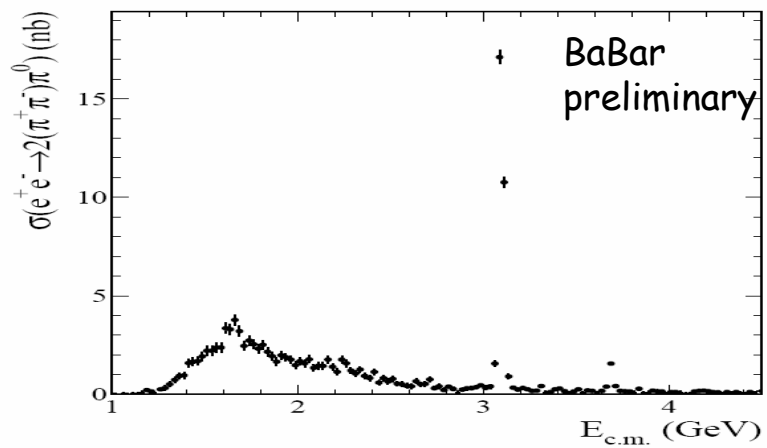


BaBar ISR: $\pi^+\pi^-\pi^+\pi^-\pi^0$

- ~30,000 events => allow to study details
  - Lower mass : 20% bg.
  - ~4.5GeV : 60-80% bg.

- Wider energy region
- ~4.0 nb at 1.65 GeV, generally decrease except for J/ψ and ψ(2S)
- systematic error~7% at peak.





Only statistical errors in plot,

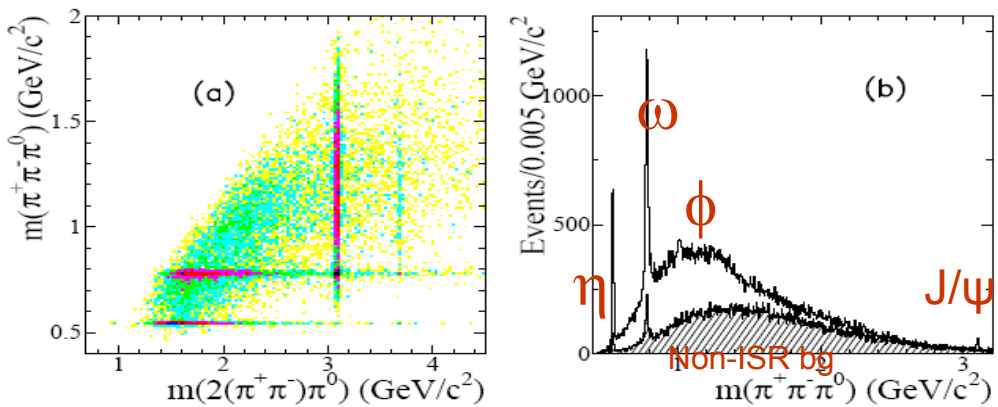
BaBar ISR: $\pi^+\pi^-\pi^+\pi^-\pi^0$ --substructure

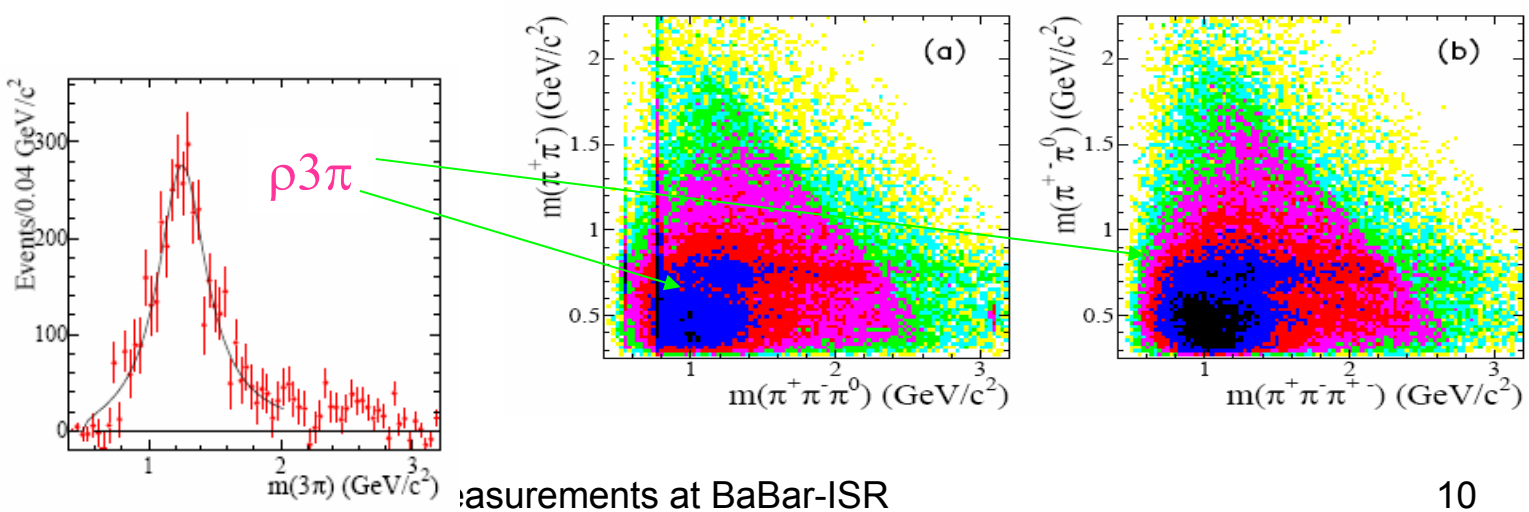
Rich internal structure:

- $\eta\pi^+\pi^- \approx \eta\rho^0$
- $\omega\pi\pi$
- $\rho X = \rho^{\pm} 3\pi + \rho^0 3\pi$

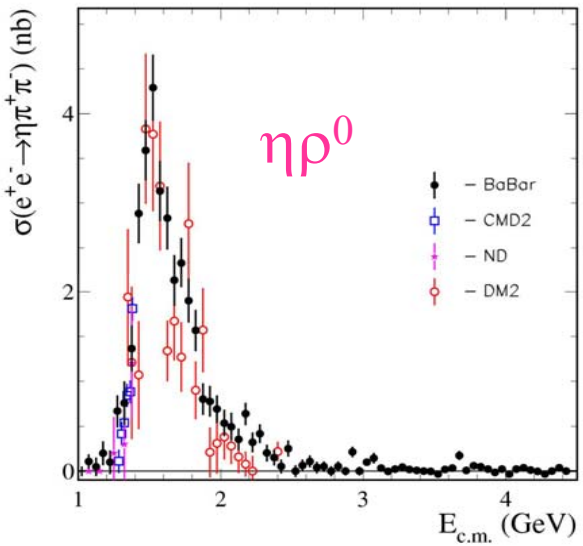
  $X = \pi(1300)$ or $a_1(1260)$

  inconsistent with $a_2(1320)$





BaBar ISR: $\pi^+\pi^-\pi^+\pi^-\pi^0$ --sub-modes

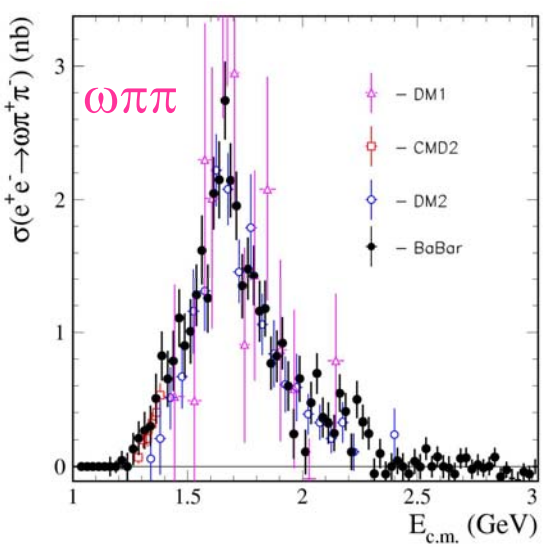


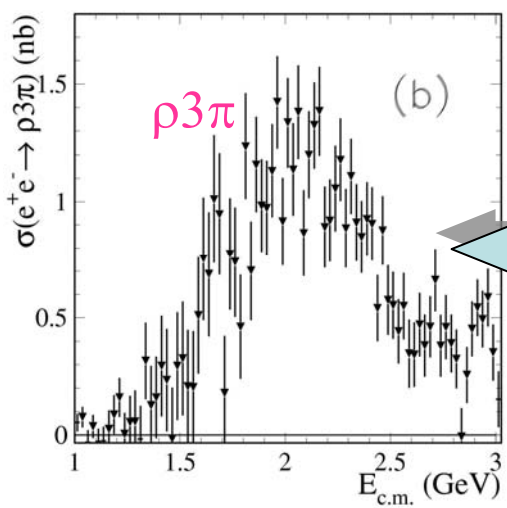
Cross sections of sub-mode:

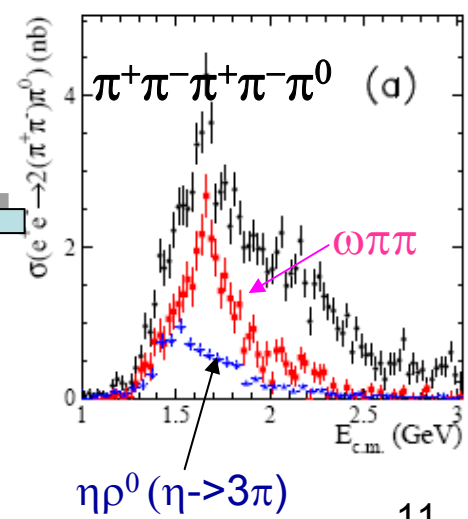
$\eta\pi^+\pi^- \approx \eta\rho^0$

$\omega\pi\pi$

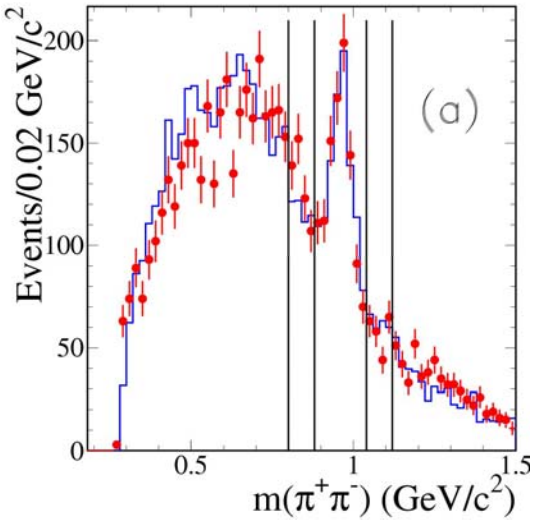
$\rho X = \rho^{\pm} 3\pi + \rho^0 3\pi$: from subtraction $\omega\pi\pi/\eta\pi^+\pi^-$

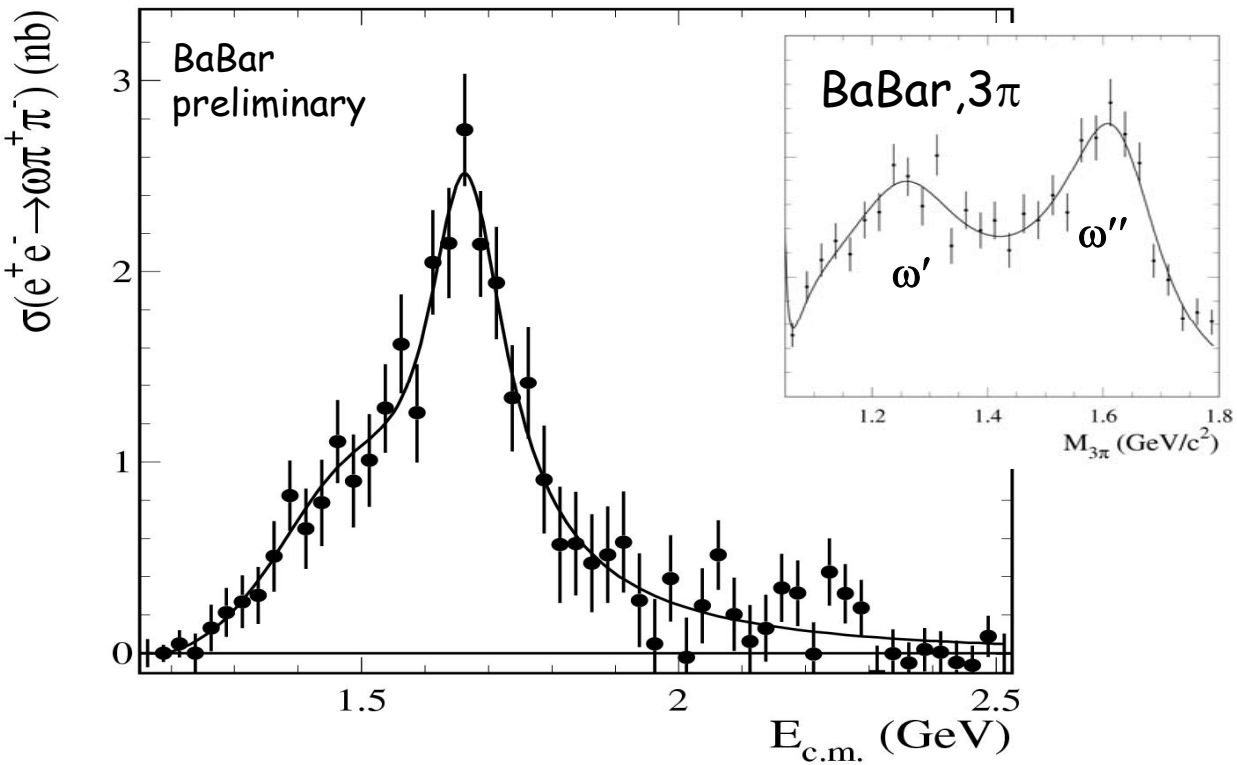


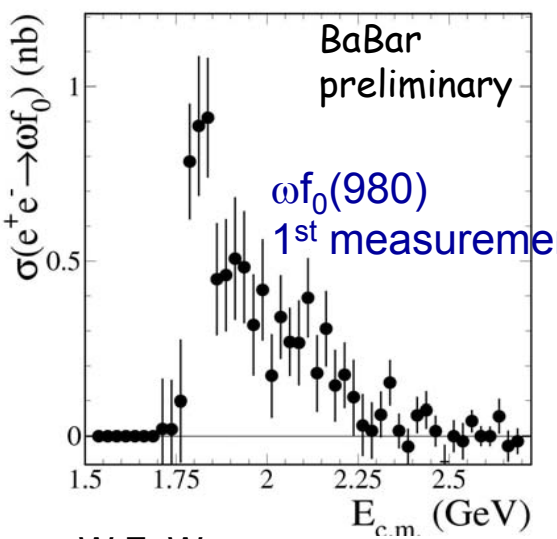




BaBar ISR: $\omega\pi^+\pi^-$





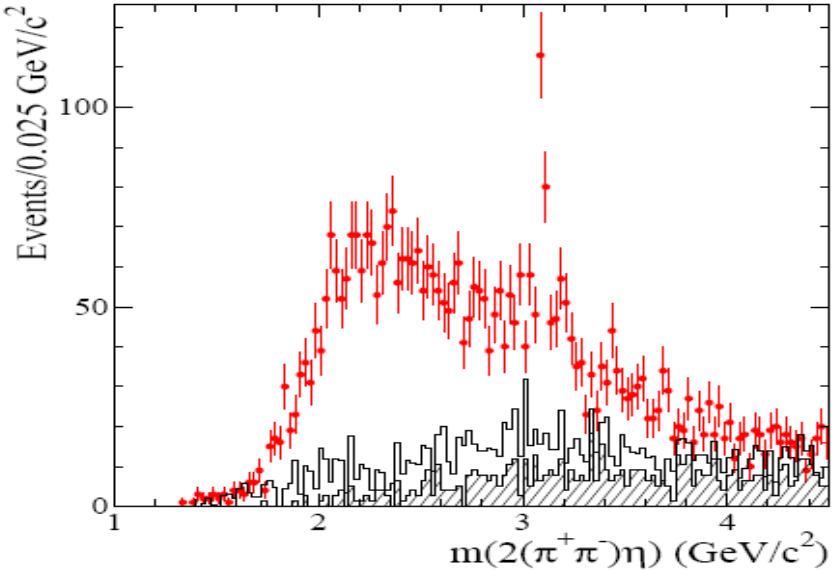


$\omega f_0(980)$
1st measurement

$$m_{\omega(1420)} = 1.38 \pm 0.02 \pm 0.07 \ \text{GeV}/c^2,$$
$$\Gamma_{\omega(1420)} = 0.13 \pm 0.05 \pm 0.10 \ \text{GeV},$$
$$m_{\omega(1650)} = 1.667 \pm 0.013 \pm 0.006 \ \text{GeV}/c^2,$$
$$\Gamma_{\omega(1650)} = 0.222 \pm 0.025 \pm 0.020 \ \text{GeV}.$$

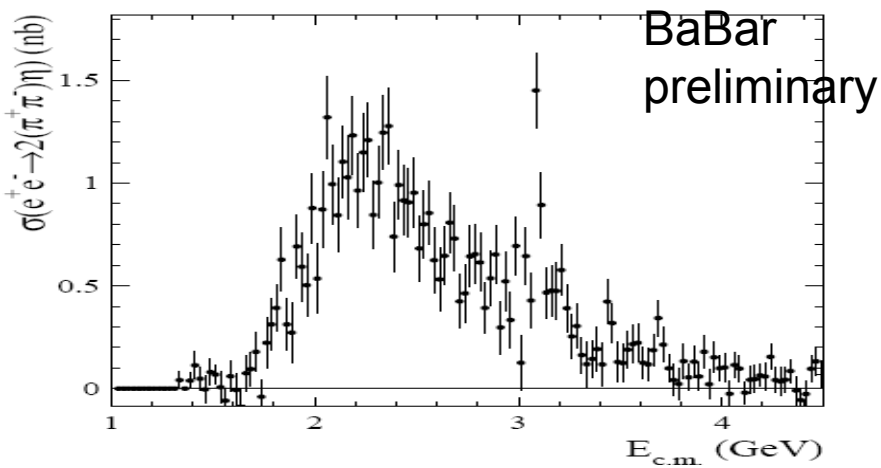
1.35 ± 0.03	BaBar,3π
0.45 ± 0.14	
1.66 ± 0.01	
0.22 ± 0.04	

BaBar ISR: $\pi^+\pi^-\pi^+\pi^-\eta$

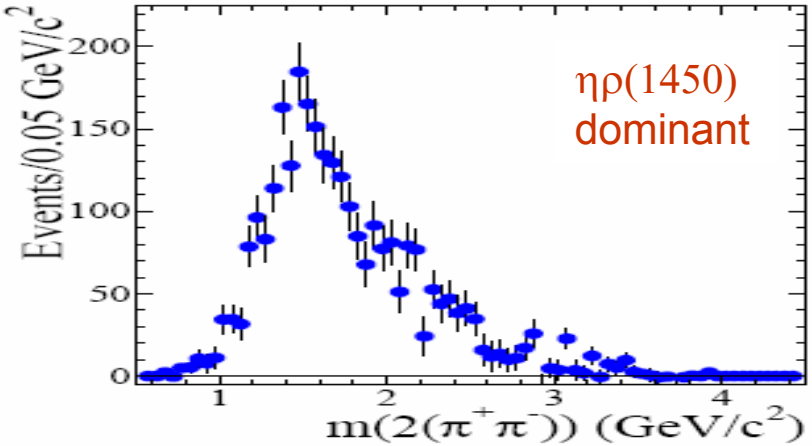


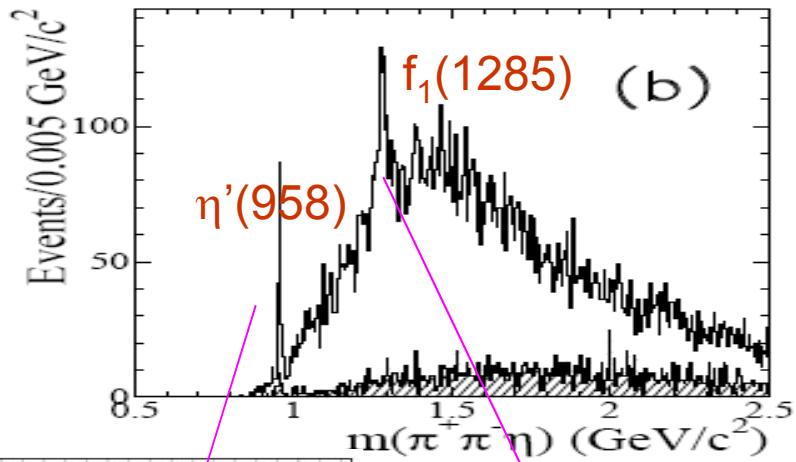
- ~4,300 events selected, J/ψ seen,
  - Lower mass <20% bg
  - Higher mass 50-80% bg

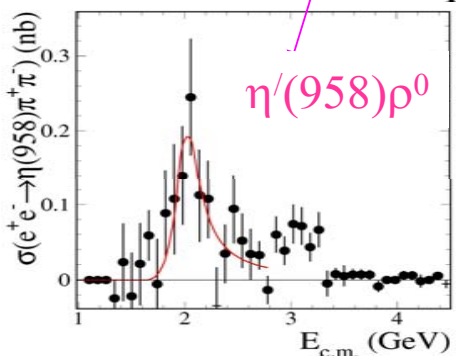
- First measurement of cross section
- Peak 1.2 nb at 2.2 GeV
- 10% systematic error below 3 GeV

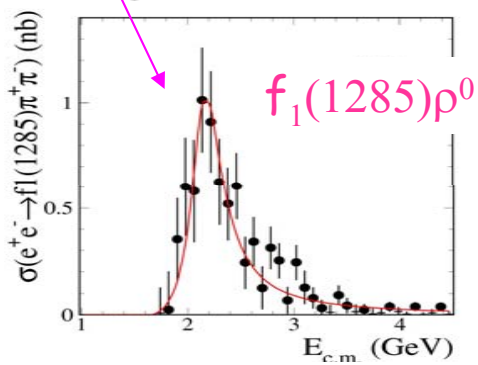


BaBar ISR: $\pi^+\pi^-\pi^+\pi^-\eta$ --substructure









Internal structure:

$\eta\pi^+\pi^-\pi^+\pi = \eta\rho(1450)$

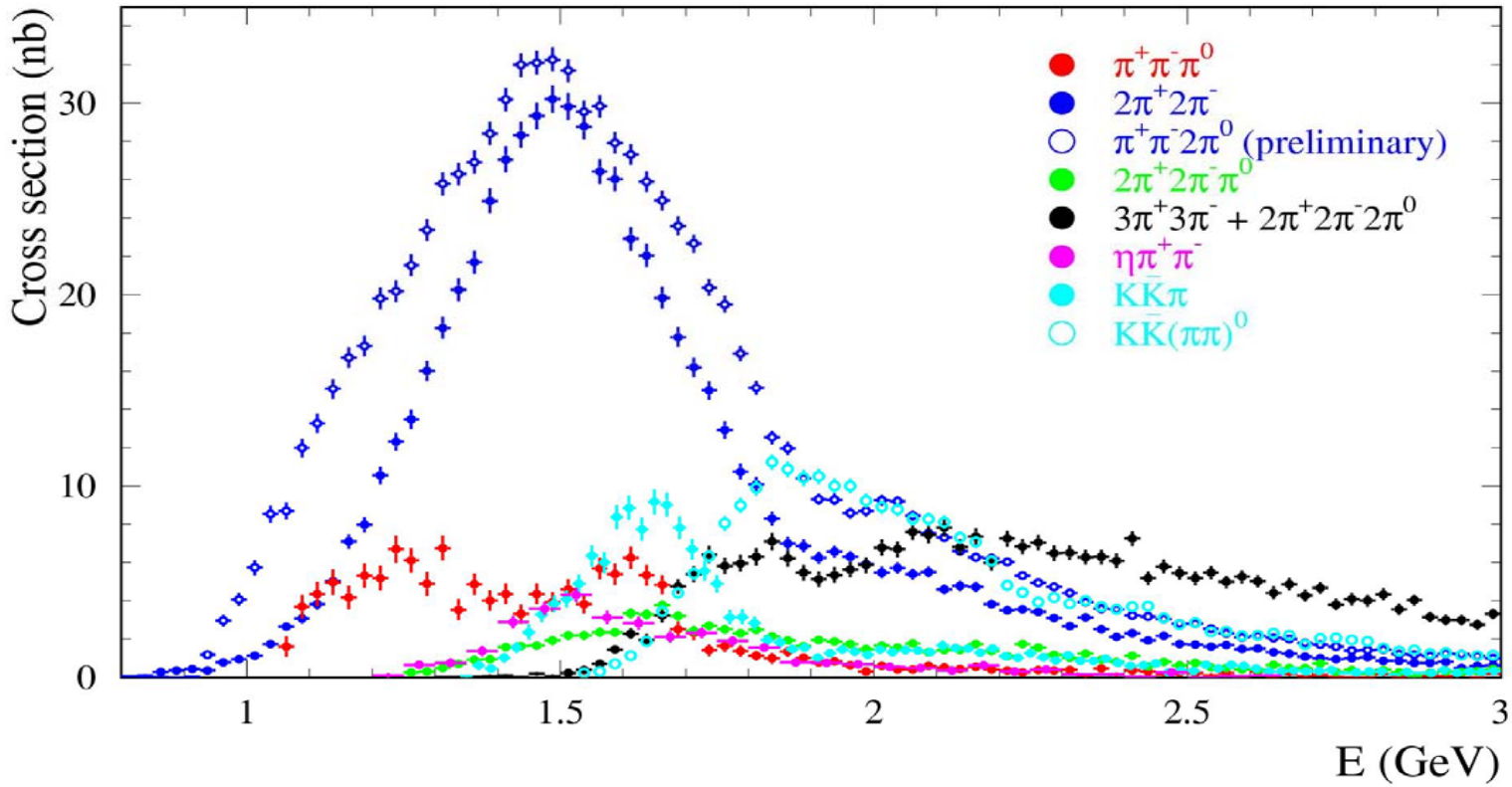
$\eta'(958)\pi\pi = \eta'(958)\rho^0$

$f_1(1285)\pi\pi = f_1(1285)\rho^0$

} m=2.15±0.04±0.05 GeV
Γ=0.35±0.04±0.05 GeV

ρ (2150)?

BaBar measurement summary



To calculate R in the energy range 1-2 GeV the processes $\pi^+\pi^-$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, K^+K^-, K_SK_L, $K_SK_L\pi\pi$, $K_SK^+\pi^-\pi^0$ must be measured.

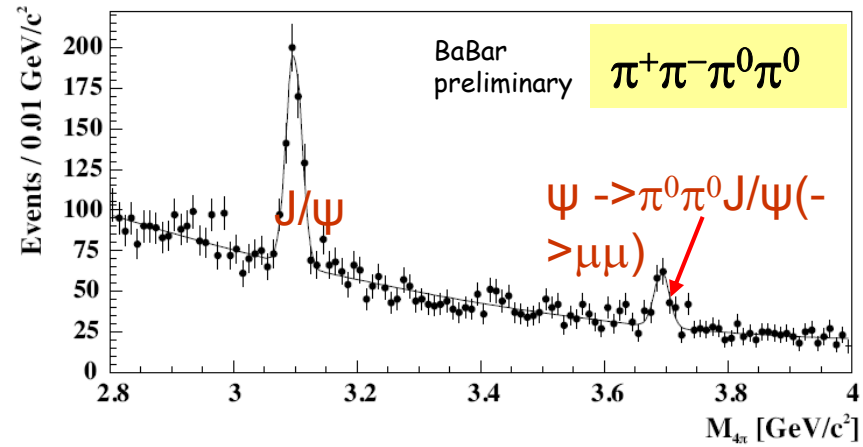
J/ψ and ψ(2S) decays @BaBar

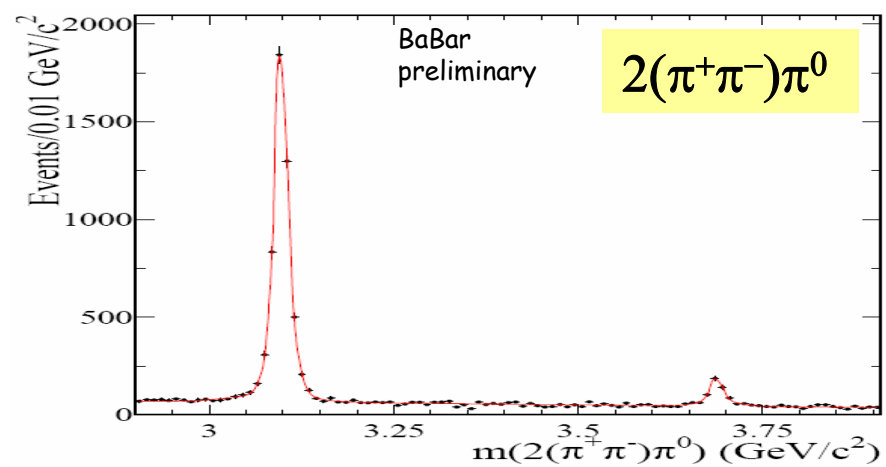
- J/ψ and ψ(2S) used to monitor mass scale and resolution
- byproduct but important: measure Γ_{ee}x B(J/ψ–>f) => B(J/ψ–>f)

Mode	BaBar (10^{-3})	PDG2006 (10^{-3})
$J/\psi \to \pi^+\pi^-\pi^0\pi^0$	**5.74±0.74**	-------
$J/\psi \to 2(\pi^+\pi^-)\pi^0$	**54.6±0.9±3.4**	**33.7±2.6**
$J/\psi \to \omega\pi^+\pi^-$	**9.7±0.6±0.6**	**7.2±1.0**
$J/\psi \to 2(\pi^+\pi^-)\eta$	**2.35±0.39±0.20**	**2.26±0.28**
$\psi(2S) \to 2(\pi^+\pi^-)\pi^0$	**12.0±0.9±0.7**	**2.66±0.29**
$\psi(2S) \to 2(\pi^+\pi^-)\eta$	**1.2±0.6±0.1**	**--------**

Part of results, more seen in papers.

$\pi^+\pi^-$ J/ψ included



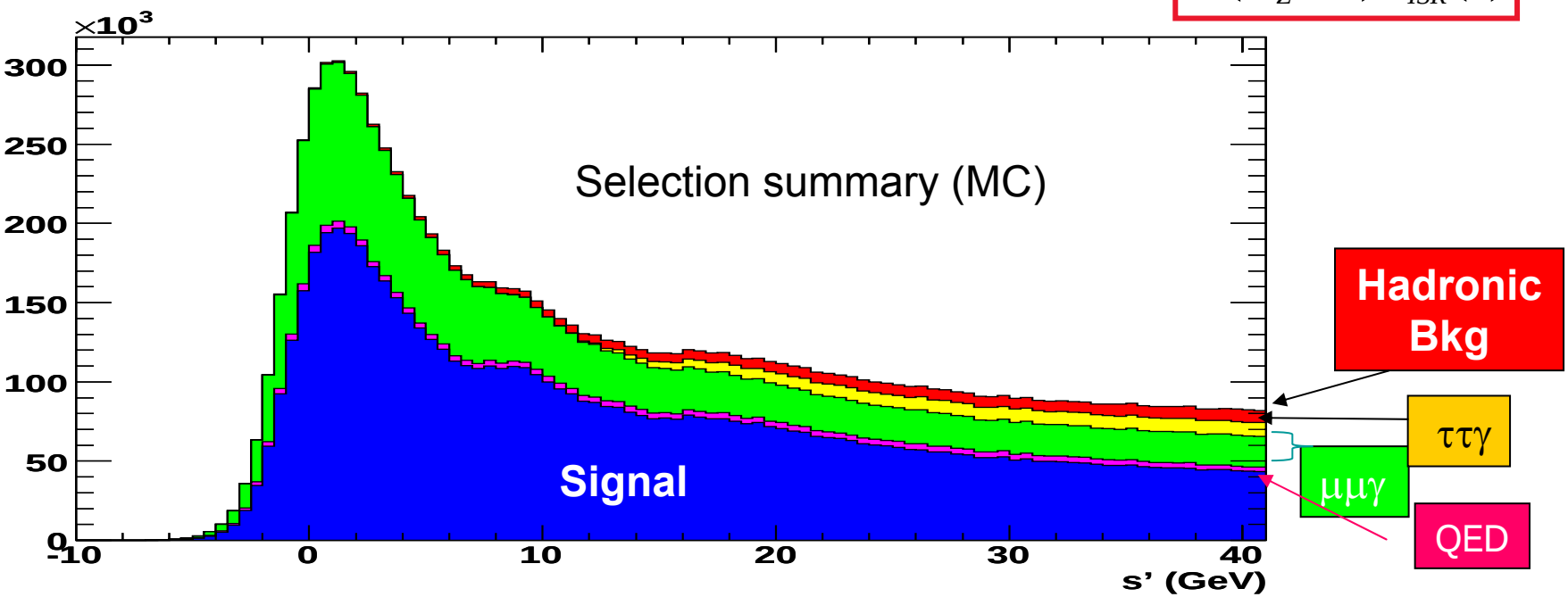


Inclusive R: Analysis Technique

- Select events with a high-energy photon in a region with good energy resolution.
- Primary background: QED events with a high-E photon
  - Remove/subtract: $e^+e^-\gamma$, $\gamma\gamma$; $\tau^+\tau^-\gamma$ and $\mu^+\mu^-\gamma$ ...
- Compute the integral:

Taken from MC

$$\Delta\alpha_{Had}(m_Z^2, s_{Max}) = \frac{\alpha m_Z^2}{3\pi}\int_{4m_\pi^2}^{s_{Max}} \frac{d\sigma(e^+e^- \to \gamma\,\text{hadrons})}{\boxed{s(m_Z^2 - s)\sigma_{ISR}^0(s)}}$$



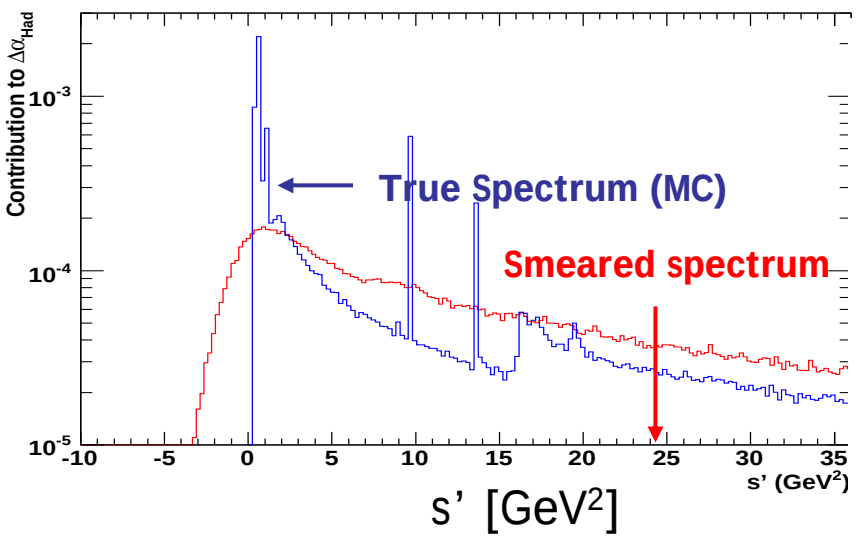
Inclusive R: Energy Resolution effects

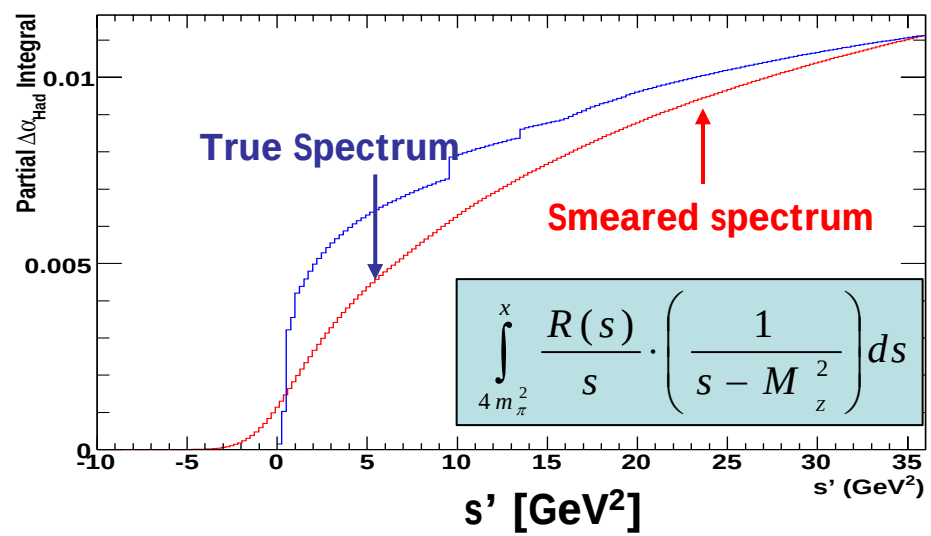
- Energy resolution ~2%, affects the spectrum, especially at low s′:
- Fortunately, we measure an **integral** of R(s)/s, not R(s)/s itself:

$$\Delta\alpha^{had}(M_Z^2) \propto \int_{4m_\pi^2}^{\infty} \frac{R(s)}{s}\cdot\left(\frac{1}{s-M_Z^2}\right)ds \qquad \frac{\delta s'}{s'} \sim \frac{s}{s'}\frac{\delta E_\gamma}{E_\gamma}$$

- Smearing ⇒ events move in s′; Problem only if weight function is non-uniform.
  - **OK for $\Delta\alpha^{Had}$**
  - **Does not work for a_μ**

$$a_\mu^{had} \propto \int_{4m_\pi^2}^{\infty} \frac{R(s)}{s}\cdot\left(\frac{K(s)}{s}\right)ds,$$





- **The region <5 GeV dominates overall uncertainty ~ 3.2%**
- **Preliminary systematic uncertainty 4.4% -->3.6% , improve overall precision**

Summary

- *BaBar* continues study of low energy e^+e^- cross section using ISR
  - Results published: $p\bar{p}$, $\pi^+\pi^-\pi^0$, $2\pi^+2\pi^-$, $2K^+2K^-$, $3\pi^+3\pi^-$, $2\pi^+2\pi^-\pi^0\pi^0$, $K^+K^-2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$
  - Preliminary results: $\pi^+\pi^-\pi^0\pi^0$, $2\pi^+2\pi^-\pi^0$, $2\pi^+2\pi^-\eta$, $K^+K^-\pi^0$, $K_SK^-\pi^+$, $K^+K^-\eta$, $\Lambda\Lambda$, $\Lambda\Sigma^0$, $\Sigma^0\Sigma^0$, $KK\pi^+\pi^-\pi^0$, $KK\pi^+\pi^-\eta$
  - Obtained data allow to determine parameters of excited ρ-, ω-, φ-states. Simultaneous fit of all channels?
- Work in progress: $\pi^+\pi^-$, K^+K^-, $K\bar{K}(\pi,\eta)$, $\pi^+\pi^-\pi^0\pi^0$, inclusive-R…

BABAR providing high statistics measurements of exclusive hadronic cross sections with ~5-10% syst. uncertainties

==> large improvement over the existing data in the lower mass range!

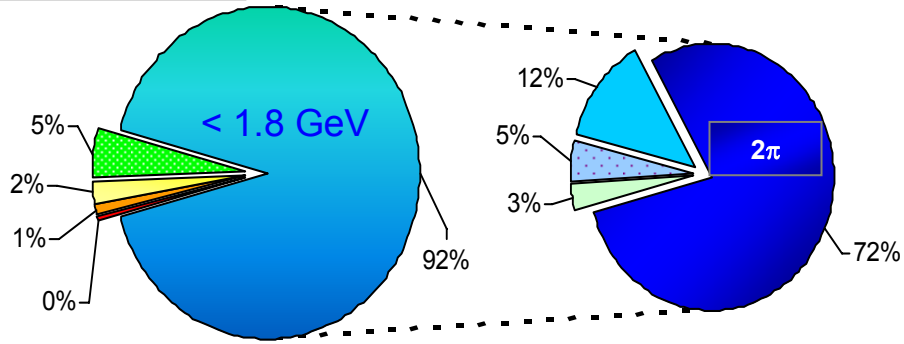
Backup Slides

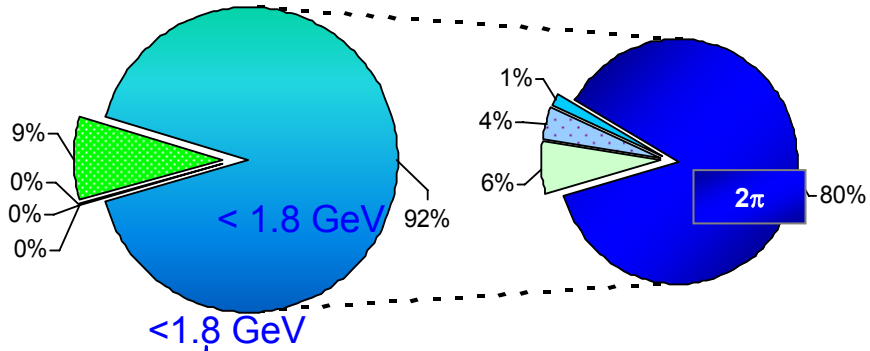
Relevance of precision of R measurements

Contributions to $a_\mu^{had,LO}$:
low-s region crucial

Contributions to $\Delta\alpha^{had}$
sensitive to full accessible range
(1-5) GeV has dominant uncertainties

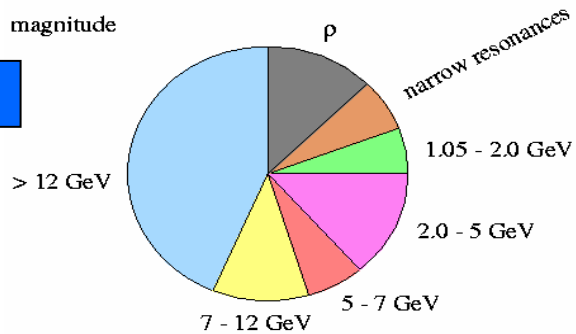
Davier-Eidelman-Höcker-Zhang 2006



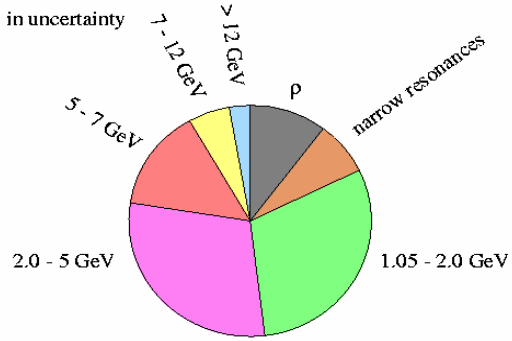


Burkhardt & Pietrzyk 2001

magnitude



errors

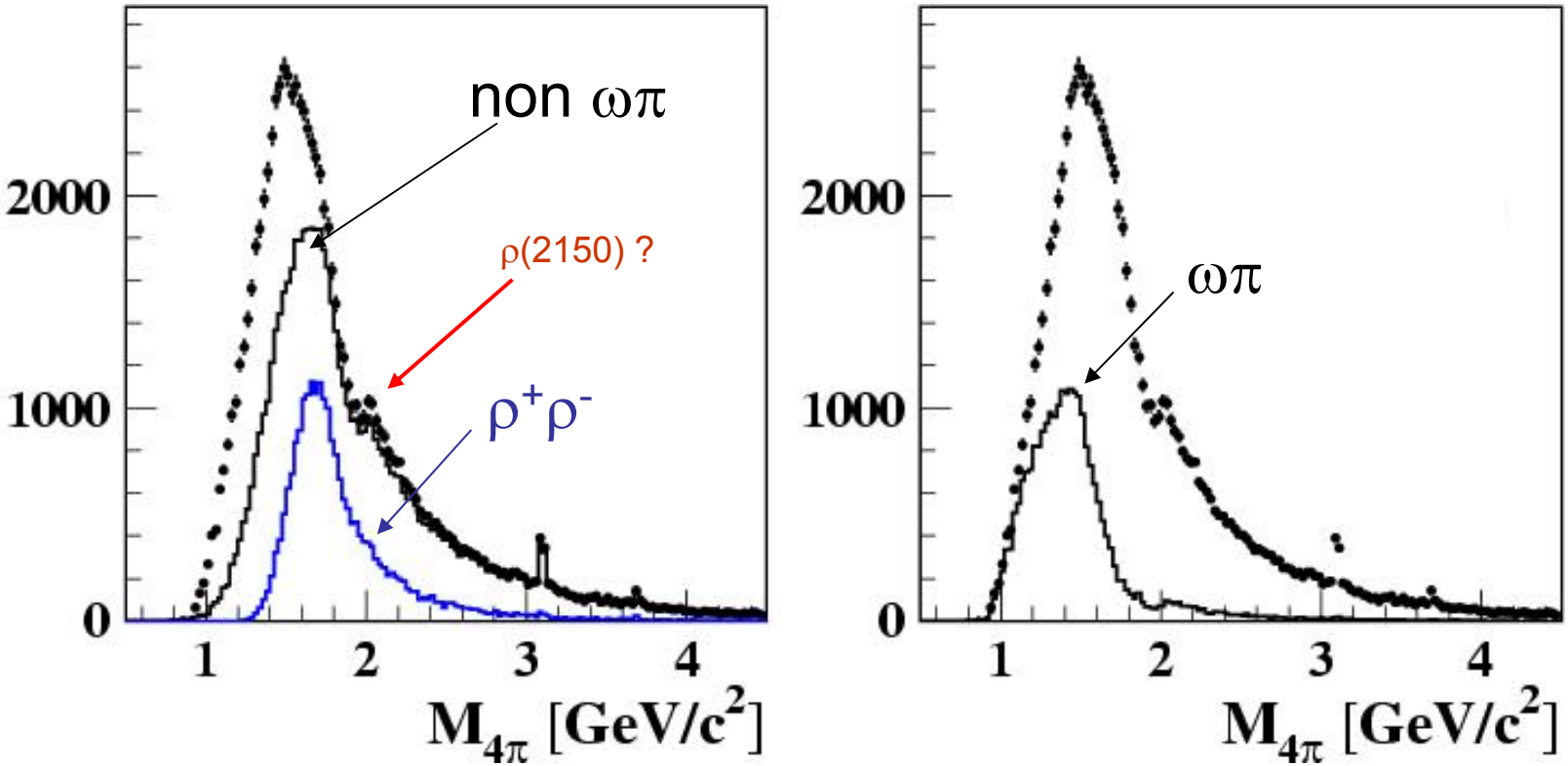


W.F. Wang

R measurements at BaBar-ISR

2π	3π (+ω,ϕ)	4π	> 4π (+KK)	1.8 - 3.7	3.7 - 5 (+J/ψ, ψ)	5 - 12 (+ϒ)	12 - ∞

BaBar ISR: $\pi^+\pi^-\pi^0\pi^0$



J/ψ and ψ(2S) decays @BaBar

- J/ψ and ψ(2S) used to monitor mass scale and resolution
- byproduct but important: measure Γ_{ee}x B(J/ψ->f) => B(J/ψ->f)

BaBar preliminary

Measured Quantity	Measured Value (eV)	J/ψ or $\psi(2S)$ Branching Fraction (10^{-3}) Calculated, this work	PDG2006
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to 2(\pi^+\pi^-)\pi^0}$	303. ± 5 ± 18	54.6 ± 0.9 ± 3.4	33.7 ± 2.6
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to\omega\pi^+\pi^-} \cdot \mathcal{B}_{\omega\to 3\pi}$	47.8 ± 3.1 ± 3.2	9.7 ± 0.6 ± 0.6	7.2 ± 1.0
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to\eta\pi^+\pi^-} \cdot \mathcal{B}_{\eta\to 3\pi}$	0.51 ± 0.22 ± 0.03	0.40 ± 0.17 ± 0.03	0.193 ± 0.023
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to 2(\pi^+\pi^-)\eta}$	5.16 ± 0.85 ± 0.39	2.35 ± 0.39 ± 0.20	2.26 ± 0.28
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to K^+K^-\pi^+\pi^-\pi^0}$	107.0 ± 4.3 ± 6.4	19.2 ± 0.8 ± 1.5	12.0 ± 3.0
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to\phi\eta} \cdot \mathcal{B}_{\phi\to K^+K^-} \cdot \mathcal{B}_{\eta\to 3\pi}$	0.84 ± 0.37 ± 0.05	1.4 ± 0.6 ± 0.1	0.74 ± 0.08
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to\omega K^+K^-} \cdot \mathcal{B}_{\omega\to 3\pi}$	3.3 ± 1.3 ± 0.2	1.36 ± 0.50 ± 0.10	1.9 ± 0.4
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi\to K^+K^-\pi^+\pi^-\eta}$	10.2 ± 1.3 ± 0.8	4.7 ± 0.6 ± 0.4	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to 2(\pi^+\pi^-)\pi^0}$	29.7 ± 2.2 ± 1.8	12.0 ± 0.9 ± 0.7	2.66 ± 0.29
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-} \cdot \mathcal{B}_{J/\psi\to 3\pi}$	18.6 ± 1.2 ± 1.1	23.6 ± 1.6 ± 1.6	20.2 ± 1.4
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to\omega\pi^+\pi^-} \cdot \mathcal{B}_{\omega\to 3\pi}$	2.69 ± 0.73 ± 0.16	1.22 ± 0.33 ± 0.07	0.66 ± 0.17
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to J/\psi\eta} \cdot \mathcal{B}_{\eta\to 3\pi} \cdot \mathcal{B}_{J/\psi\to\mu^+\mu^-}$	1.11 ± 0.33 ± 0.07	33.4 ± 9.9 ± 2.0	30.9 ± 0.8
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to 2(\pi^+\pi^-)\eta}$	1.13 ± 0.55 ± 0.08	1.2 ± 0.6 ± 0.1	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to K^+K^-\pi^+\pi^-\pi^0}$	4.4 ± 1.3 ± 0.3	1.8 ± 0.5 ± 0.1	1.24 ± 0.10
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to K^+K^-\pi^+\pi^-\eta}$	1.2 ± 0.7 ± 0.1	1.3 ± 0.7 ± 0.1	no entry