Measurement of the $e^+e^- \rightarrow \text{hadrons}$ cross-section with ISR at BaBar

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Initial state radiation (ISR) method

\[ \frac{d\sigma(s,x)}{dx d(\cos \theta)} = W(s,x,\theta) \cdot \sigma_0(s(1-x)), \]

\[ W(s,x,\theta) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2 \theta} - \frac{x^2}{2} \right), \quad x = \frac{2E_\gamma}{\sqrt{s}} \]

Motivation

- High PEP-II luminosity at $\sqrt{s} = 10.58$ GeV
- Improved hadron spectroscopy
- Input to $(g_{\mu} - 2)$ and $\alpha_{em}$ calculations.
- Few previous data in the 1.4-3.0 GeV range.
- Wide energy range in one experiment
- Small exclusive XS - no FSR
- Comprehensive program at BaBar.

Two approaches:

1. Detection of all particles
   - flat acceptance, dynamic independent
   - better mass resolution (Kin.Fit)
   - $\sim 10\%$ efficiency
   - background $e^+e^- \rightarrow uds, \pi^0$ imitate $\gamma$
2. ISR photon is not detected
   - $x3-5$ higher statistic above $\sim 3$GeV
   - no background from uds
   - background from $e^+e^- \rightarrow e^+e^- \gamma\gamma$
   - greater for charm region
R, the definition

R(s) is defined as:

\[ R(s) = \frac{\sigma^{(0)}(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma^{(0)}(e^+e^- \rightarrow \mu^+\mu^-)} \]

R(s) is one of the most fundamental quantities in high energy physics:

- its global structure reflects number of quarks and their colors; used for QCD tests and as a source of QCD parameters
- plays special role in precision measurements:

\[ \alpha^\text{had}_\mu (l.o.) = \left( \frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s^2} R(s) \]

\[ \Delta \alpha^\text{had}_{M_Z^2} = \frac{\alpha(0)M_Z^2}{3\pi} \text{Re} \int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s - M_Z^2) - i\epsilon} \]
\[ \sigma(e^+e^- \rightarrow \text{hadrons}) \]

**Contribution to \( \Delta \alpha_{\text{had}} \)**

- **Value**
  - \( \rho \)
  - \( > 12 \text{ GeV} \)
  - \( 7 - 12 \text{ GeV} \)
  - \( 5 - 7 \text{ GeV} \)
  - \( 2.0 - 5 \text{ GeV} \)
  - \( 1.05 - 2.0 \text{ GeV} \)

- **Error**
  - \( \rho \)
  - \( > 12 \text{ GeV} \)
  - \( 7 - 12 \text{ GeV} \)
  - \( 5 - 7 \text{ GeV} \)
  - \( 2.0 - 5 \text{ GeV} \)
  - \( 1.05 - 2.0 \text{ GeV} \)

\[ R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma_0(e^+e^- \rightarrow \mu^+\mu^-)} \]
Current/Future activities in R

- BaBar ISR
- VEPP-2000
- VEPP-4M
- CLEO-c
- KLOE
- BES-III
- VEPP-2M

Diagram:
- Exclusive data (green)
- QCD (red)
- BES (circles)
- Crystal Ball (dark squares)
- PLUTO (triangles)
- e^+e^- → hadrons
- e^+e^- → QCD

Graphs:
- √s (GeV)
- R

- Experimental data points
- Theoretical predictions
\[ a_\mu \text{ [had]} [ee] = (693.4 \pm 5.3 \pm 3.5) \times 10^{-10} \]

\[ a_\mu [ee] = (11 659 182.8 \pm 6.3_{\text{had}} \pm 3.5_{\text{LBL}} \pm 0.3_{\text{QED+EW}}) \times 10^{-10} \]

Hadronic contribution from higher order:
\[ a_\mu \text{ [had]} [(\alpha/\pi)^3] = - (10.0 \pm 0.6) \times 10^{-10} \]

Hadronic contribution from LBL scattering:
\[ a_\mu \text{ [had]} [\text{LBL}] = + (12.0 \pm 3.5) \times 10^{-10} \]

BNL E821 (2004):
\[ a_\mu \text{ [exp]} = (11 659 208.0 \pm 5.8) \times 10^{-10} \]

Observed Difference with Experiment:
\[ a_\mu \text{ [exp]} - a_\mu \text{ [SM]} = (25.2 \pm 9.2) \times 10^{-10} \]

\[ 2.7 \text{ „standard deviations“} \]

M. Davier talk at tau04

References:
- Melnikov-Vainshtein, hep-ph/0312226
• **PEP-II** is an asymmetric $e^+e^-$ collider with a CM energy of 10.58 GeV.
  • Peak luminosity = $10.8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  • Integrated luminosity = 350 fb$^{-1}$

**BaBar EMC:**
• 6580 CsI(Tl) crystals
• Covers 91% of solid angle
• Resolution ~2 % at high E.

**BaBar DIRC**
• Quartz Cherenkov radiator
• Covers 80% of solid angle
• Particle ID up to 4-5 GeV/c
ISR data analysis status with BaBar

\[ \sqrt{s} \ [\text{GeV}] \]

R Units

\[ \pi^+ \pi^- \]

\[ \pi^+ \pi^- \pi^0 \]

\[ K^+ K^- K^0 S K^0 L \]

\[ \pi^+ \pi^- \pi^0 \pi^0 \]

\[ K^+ K^- \pi^0 \pi^0 \]

\[ 5\pi \]

\[ 2K3\pi \]

\[ K^+ K^- / \eta \]

\[ K^0 K\pi \]

\[ 6\pi \]

\[ 2K4\pi \]

\[ DD^* \]

\[ \psi(2S) \]

\[ pp \]

\[ \Lambda \Lambda \]

\[ J/\psi \]
\[ e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \gamma \]

**Event selection:**
- Isolated ISR photon with \( E_{cm} > 3 \text{ GeV} \)
- At least 2 good photons with \( E_\gamma > 0.1 \text{ GeV} \)
- Two good, non-K tracks from IP

**Kinematic fit:**
- Energy and momentum balance enforced
- Mass of two soft photons constrained to \( \pi^0 \)
- \( \chi^2 < 40 \) for fit in \( \pi^+ \pi^- \pi^0 \gamma \) hypothesis selects signal events
- Reject events with extra photons if \( \chi^2 < 40 \) for \( \pi^+ \pi^- \pi^0 \pi^0 \gamma \) hypothesis
Background for $3\pi\gamma$

Most dangerous backgrounds:
\[ e^+ e^- \rightarrow K^+ K^- \pi^0 \gamma, \quad e^+ e^- \rightarrow q\bar{q} \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \]

Other backgrounds:
\[ e^+e^- \rightarrow 2\pi\gamma, \; 4\pi\gamma, \; 5\pi\gamma, \ldots, \; \tau^+\tau^-, \; \tau^\pm \rightarrow \pi^\pm\pi^0\nu \]

Two methods of background subtraction:
1. background mass distribution measured in data, subtracted bin-by-bin from signal mass distribution
2. taken from simulation, corrected to real experimental distribution

Total background level:
- (0.5 - 1.5)% in $\omega$, $\phi$ regions
- (15 - 50)% at higher masses
- accuracy in background level ~25% up to 2 GeV
Detection efficiency for $3\pi\gamma$

The detection efficiency $\varepsilon(m)$:

- determined from a Monte Carlo simulation that includes additional corrections extracted from special control event-samples
- quite uniform in $0.5 < m < 3$ GeV/c$^2$
- systematic error currently $\sim 4\%$ - will be improved with more data
Fit of the $\pi^+\pi^-\pi^0$ mass spectrum

\[
\left( \frac{dN}{dm} \right)_{\text{th}} = \sigma_{3\pi}(m) \frac{dL}{dm} \cdot \varepsilon(m) \cdot R(m),
\]

\[
\left( \frac{dN}{dm} \right)_{\text{exp}} = \left( \frac{dN}{dm'} \right)_{\text{th}} \otimes f(m,m')
\]

- $\sigma_{3\pi}(m)$ - Born cross section of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$
  
  is a coherent sum of 4 resonances: $\omega$, $\phi$, $\omega'$, $\omega''$

- $R(m)\sim1$ - radiative correction function from calculation

- $dL/dm$ - ISR luminosity taken from total integrated luminosity and photon radiator function $W(s,x)$; (checked with $\mu\mu\gamma$ events)

- $f(m,m')$ - detector resolution taken from simulation
  
  (with floating extra Gaussian smearing)

- Fix $\omega$, $\phi$ widths to PDG values

- Fix $\omega-\phi$ relative phase to experimental value $(163\pm7)^\circ$

- Fix $\omega-\omega'$ relative phase to $180^\circ$, $\omega' - \omega''$ to $0^\circ$
Fit results: $\omega - \phi$ region

$\chi^2$/d.f. = 146/148

consistent with known properties of these resonances
($\omega, \phi$ widths fixed to PDG values)

The resolution is about 6, 7, 9 MeV/c$^2$ at $\omega$, $\phi$, J/$\psi$ masses.

Fitted resolution smearing is $\sim$1 MeV/c$^2$

BaBar Preliminary

$B(\omega \rightarrow ee)B(\omega \rightarrow 3\pi) = (6.70 \pm 0.06 \pm 0.27) \cdot 10^{-5}$

$B(\phi \rightarrow ee)B(\phi \rightarrow 3\pi) = (4.30 \pm 0.08 \pm 0.21) \cdot 10^{-5}$

PDG

$(6.35 \pm 0.11) \cdot 10^{-5}$

$(4.59 \pm 0.14) \cdot 10^{-5}$
Fit results: higher mass region

- Good fit obtained for the range up to 1.8 GeV/c².
- Extending the fit to masses above 1.8 GeV/c² may require a more complicated fitting function taking into account non-resonant 3π production.
- Mass and width parameters are dependent upon our assumed phases - interference effect is strong

\[ B(\omega'\to ee)B(\omega'\to 3\pi) = (0.82 \pm 0.05 \pm 0.06) \times 10^{-6} \]
\[ \Gamma(\omega') = 450 \pm 70 \pm 70 \text{ MeV} \]
\[ M(\omega') = 1350 \pm 20 \pm 20 \text{ MeV/c}^2 \]
\[ B(\omega''\to ee)B(\omega''\to 3\pi) = (1.3 \pm 0.1 \pm 0.1) \times 10^{-6} \]
\[ \Gamma(\omega'') = 230 \pm 30 \pm 20 \text{ MeV} \]
\[ M(\omega'') = 1660 \pm 10 \pm 2 \text{ MeV/c}^2 \]

PDG

- 1400 - 1450
- 180 - 250
- 1670 ± 30
- 315 ± 35
Normalization to $\mu\mu\gamma$ events

Cross-section to final state $f$:

$$\sigma_f(s') = \frac{dN_{f'}}{dN_{\mu\mu\gamma}} \cdot \varepsilon_{\mu\mu} \cdot (1 + \delta_{\mu\mu}^{rad}) \cdot \sigma_{e^+e^-\rightarrow\mu^+\mu^-}(s')$$

Detection efficiencies

Corrections for final state radiation

"effective c.m. energy squared"

ISR luminosity

Detection efficiencies

$$\sigma(e^+e^-\rightarrow\mu\mu\gamma) : \frac{\text{Exp}}{\text{Theory}} = -1.8 \pm 0.5\%$$

Graph showing $0.35 < \theta < 2.4$ rad, $L_{\text{Bar}=89.3 \text{ fb}^{-1}}$
$e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ cross section

- coverage of wide region in this experiment - no point-to-point normalization problems
- consistent with SND data $E_{\text{c.m.}} < 1.4$ GeV
- inconsistent with DM2 results
- overall normalization error $\sim 5\%$ up to 2.5 GeV

$$\sigma_{3\pi}(m) = \frac{(dN/dm)}{\varepsilon(m) \cdot R(m) \cdot dL/dm}$$
\[ e^+ e^- \rightarrow 2\pi^+ 2\pi^- \gamma, \ K^+ K^- \pi^+ \pi^- \gamma, \ 2K^+ 2K^- \gamma \]

**Event selection:**
- Isolated ISR photon with \( E_{cm} > 3 \) GeV
- At least four good tracks from IP

**Kinematic fit:**
- Energy and momentum balance enforced
- Energy and angles of hard ISR photon are not used - 1C fit
- Fit in 3 hypotheses:
  - \( 4\pi \) for all events
  - \( 2K2\pi \) if 1 or 2 identified kaons
  - \( 4K \) if 2, 3 or 4 identified kaons

**Background subtraction:**
- Other ISR processes (5\( \pi \gamma \), ...) – using difference in \( \chi^2 \) distributions
- \( e^+ e^- \rightarrow qq \) – using JETSET simulation
$e^+e^- \rightarrow 2\pi^+ 2\pi^- \text{ cross section}$

**Systematic errors:**
- 12% for $m_{4\pi} < 1$ GeV,
- 5% for $1 < m_{4\pi} < 3$ GeV,
- 16% for higher masses
- best measurement above 1.4 GeV

**Coverage of wide region in one experiment**
No point-to-point normalization problems

**Intermediate states:**
- $a_1(1260)\pi$ - dominant, structure which may be $f_0(1370)\rho$ final state is seen.
- For detailed study, a simultaneous analysis of $2\pi^+2\pi^-$ and $\pi^+\pi^-2\pi^0$ final states is required.
\[ e^+ e^- \rightarrow 2\pi^+ 2\pi^- \] cross section

Good agreement with direct \( e^+ e^- \) measurements
Most precise result above 1.4 GeV
$\pi^+\pi^-\pi^+\pi^-$ substructures

BaBar

MC generator:
- Includes $a_1(1260)\pi$ and $f_0(1370)\rho$
- Does not include $J/\psi$

$\rho(770)$

$f_0(1370)$

$J/\psi$

$a_1(1260)$
$e^+ e^- \rightarrow K^+ K^- \pi^+ \pi^-$

Systematic error – 15% (model dependence, kaon identification)

Substantial resonance sub-structures observed:
- $K^*(890)K\pi$ dominant
- $\phi\pi\pi$, $\rho KK$ contribute strongly
- $K^*_2(1430)K\pi$ seen.

Systematic error – 8%

Much more precise than previous measurement.
$K^+ K^- \pi^+ \pi^-$ substructures

K*(890)K\pi dominated

No studies in previous $e^+ e^-$ experiments!

K*K\pi\gamma MC generators are not available yet

K* regions excluded

No signal from $\phi f_0(980)$ yet

Connection to $\phi \rightarrow f_0(980) \gamma$ ?

(we have it with 232 fb^{-1} !!)
$$e^+ e^- \rightarrow 2K^+ 2K^-$$

First measurement

Overall normalization systematic error – 25% (model dependence, kaon identification)

BaBar

$89 \text{ fb}^{-1}$
Signal 6h events

We estimate contribution of background:

- 10 ± 3% in 1.5-3.0 GeV range
- 20 ± 5% in 3.0-4.5 GeV range

- 15 ± 3% in 1.5-3.0 GeV range
- 20 ± 5% in 3.0-4.5 GeV range
Comparison with MC simulation

Generator with $1 \rho$/event $e^+e^- \rightarrow \rho 4\pi \rightarrow 6\pi$ (charged) relatively good describes observables.
Cross section $e^+e^- \rightarrow 3(\pi^+\pi^-), 2(\pi^+\pi^-)\pi^0\pi^0$

Background subtraction -- 3-5%
Tracking efficiency -- 3%
ISR luminosity -- 3%
Acceptance -- 3-5%
$\chi^2$ cut uncertainty -- 3%
Total -- 6-8%

Background subtraction -- 3-5%
Tracking efficiency -- 3%
Luminosity -- 3%
Acceptance -- 3-5%
$\chi^2$ cut uncertainty -- 6%
$\pi^0$ efficiency -- 3%
Total -- 11%
How big is $\omega(782)$ contribution?

$\sigma_0 = 3.08 \pm 0.33$ nb
$m = 1.645 \pm 0.008$
$\Gamma = 0.114 \pm 0.014$

13 events are from $J/\psi \rightarrow \omega \eta$ with less than 0.5 events of background
$\sigma(e^+e^- \rightarrow p\bar{p}) = \frac{4\pi\alpha^2\beta C}{3m^2} \left( |G_M|^2 + \frac{2m_p^2}{m^2} |G_E|^2 \right)$

- Cross section depends on two form factors - magnetic and electric.
- Form factor ratio can be extracted from angular distributions of proton in c.m. system of $p\bar{p}$-pair $\theta_p$.
- Form factors are well known in the space-like region $(e^-p \rightarrow e^-p)$, few data exist in the time-like energy region $(e^+e^- \rightarrow p\bar{p}, \ p\bar{p} \rightarrow e^+e^-)$.

**ISR advantages:**
- Efficiency has small dependence on mass
- Mass resolution at the threshold is $\sim 1$ MeV
- Cross section can be measured from the threshold
- Efficiency has small dependence on proton angle - model-independent cross section and $|G_E/G_M|$
\[ \frac{d\sigma(G_M)}{d\cos\theta_p} \sim 1 + \cos^2 \theta_p \quad \frac{d\sigma(G_E)}{d\cos\theta_p} \sim \sin^2 \theta_p \]

BaBar results:

- At the threshold \(|G_E/G_M|\) is higher than 1 (at the threshold = 1).
- In agreement with space-like region
- Disagreement with LEAR results

**Proton Helicity Angle**

- \(1.877 < m_{\bar{p}p} < 1.950 \text{ GeV} \)
- \(2.100 < m_{\bar{p}p} < 2.200 \text{ GeV} \)
- \(1.950 < m_{\bar{p}p} < 2.025 \text{ GeV} \)
- \(2.200 < m_{\bar{p}p} < 2.400 \text{ GeV} \)
- \(2.025 < m_{\bar{p}p} < 2.100 \text{ GeV} \)
- \(2.400 < m_{\bar{p}p} < 3.000 \text{ GeV} \)
Cross section $e^+e^- \rightarrow \bar{p}p$

- Good agreement with previous experiments
- Cross section is not zero at the threshold
- «Steps» at 2.2 and 3 GeV
\[ |F| = \sqrt{|G_M|^2 + \frac{2m_p^2}{m_{pp}}|G_E|^2} \sqrt{1 + \frac{2m_p^2}{m_{pp}}} \]
Structure in $e^+e^- \rightarrow 6\pi$ cross section

- Under-threshold $p\bar{p}$-resonance should be seen in multihadron cross sections
- Structure at 1.9 GeV was observed in photoproduction (FOCUS) and $e^+e^-$-annihilation (DM2, FENICE)
- BABAR confirms the structure, but width is wider than FOCUS observed.

$m_1 = 1.91 \pm 0.01$ GeV/c$^2$
$\Gamma_1 = 0.037 \pm 0.013$ GeV
$\phi_1 = 10 \pm 30$ deg.
J/ψ production in e⁺e⁻ → γ J/ψ

For the narrow states such as J/ψ:

\[ \sigma_{J/ψ}^{tot}(s) = \frac{12\pi^2 \Gamma_{ee}}{m \cdot s} \cdot W(s, x_0), \quad x_0 = (1 - \frac{m^2}{s}) \]

Total J/ψ ISR production cross section is 0.036 nb for s= (10.58)^2 GeV^2

\(~10^7\) of J/ψ for 250 fb⁻¹ of BaBar luminosity
(acceptance for ISR photon is 0.1)

For the final state \(f\):

\[ \sigma_{J/ψ}^{f}(s) = \frac{12\pi^2 \Gamma_{ee} B_f}{m \cdot s} \cdot W(s, x_0), \quad x_0 = (1 - \frac{m^2}{s}) \]

\(W(s,x_0)\) can be calculated with <1% accuracy

Number of detected events is proportional to \(\Gamma_{ee} B_f\)
The idea is to measure $R$ - ratio of $J/\psi$ signal to QED continuum (excluding FSR) in 4 MeV bin - many uncertainties are canceled.

According to simulation, the FSR correction factor $K = 1.08$ for our selections procedure.
Results for $\Gamma_{ee}$ and $\Gamma$ of $J/\psi$

$K \cdot R = 21.03 \pm 0.49 \pm 0.46 \quad \rightarrow \quad \sigma_{J/\psi} = (2124 \pm 49 \pm 47) \text{ fb}$

$\Gamma_{ee} \cdot B_{\mu\mu} = 0.3301 \pm 0.0077 \pm 0.0073$ keV

$B_{\mu\mu} = (5.88 \pm 0.10)\%$

$B_{ee} = (5.93 \pm 0.10)\%$

Our result

$\Gamma_{ee} = 5.61 \pm 0.20$ keV

$\Gamma = 94.7 \pm 4.4$ keV

Derived using PDG

PDG2002:

$87 \pm 5$ keV

$5.26 \pm 0.37$ keV

Hsuch 1992

E760 1993

BES 1995

PDG 2002

This work

CLEO2006

PDG2004

85.5±6.0

99±13

84.4±8.9

87±5

94.7±4.4

95.5±3.5

91.0±3.2
The $J/\psi$ meson is narrow - clean signal

After sideband subtraction - $N_{J/\psi} = 920 \pm 34$

Detection efficiency - $\varepsilon = (9.2 \pm 0.6)\%$

The result: $\Gamma(J/\psi \rightarrow ee) \cdot B(J/\psi \rightarrow 3\pi) = 0.122 \pm 0.005 \pm 0.08 \text{ keV}$

We previously measured ($\mu\mu\gamma$) $\Gamma(J/\psi \rightarrow ee) = 5.61 \pm 0.20 \text{ keV}$

![Histogram of $M_{3\pi}$ with sidebands](Image)

$B(J/\psi \rightarrow 3\pi) = (2.18 \pm 0.19)\%$

- BaBar
- (1.50 \pm 0.20)\% PDG
- (2.10 \pm 0.12)\% BES 2003
\( J/\psi \) and \( \psi(2S) \) decays

**BaBar \((89 fb^{-1})\)**

\[ B(J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-) = (3.61 \pm 0.26 \pm 0.26) \cdot 10^{-3} \]

\[ B(J/\psi \rightarrow K^+K^-\pi^+\pi^-) = (6.09 \pm 0.50 \pm 0.53) \cdot 10^{-3} \]

\[ B(J/\psi \rightarrow K^+K^-K^+K^-) = (6.7 \pm 1.1 \pm 1.0) \cdot 10^{-4} \]

\[ B(\psi(2S) \rightarrow J/\psi \pi^+\pi^-) = 0.361 \pm 0.015 \pm 0.028 \]

**PDG2004**

\[ B(J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-) = (4.0 \pm 1.0) \cdot 10^{-3} \]

\[ B(J/\psi \rightarrow K^+K^-\pi^+\pi^-) = (7.2 \pm 2.3) \cdot 10^{-3} \]

\[ B(J/\psi \rightarrow K^+K^-K^+K^-) = (9.2 \pm 3.3) \cdot 10^{-4} \]

\[ B(\psi(2S) \rightarrow J/\psi \pi^+\pi^-) = 0.317 \pm 0.011 \]
**J/ψ and ψ(2S) decays to 6h**

<table>
<thead>
<tr>
<th>Decay</th>
<th>BaBar (232fb⁻¹)</th>
<th>PDG2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ → 3(π⁺π⁻)</td>
<td>$(4.40 \pm 0.29 \pm 0.29) \times 10^{-3}$</td>
<td>$(4.0 \pm 2.0) \cdot 10^{-3}$</td>
</tr>
<tr>
<td>J/ψ → K⁺K⁻2(π⁺π⁻)</td>
<td>$(5.09 \pm 0.42 \pm 0.35) \times 10^{-3}$</td>
<td>$(3.1 \pm 1.3) \cdot 10^{-3}$</td>
</tr>
<tr>
<td>J/ψ → 2(π⁺π⁻)π⁰π⁰</td>
<td>$(1.65 \pm 0.10 \pm 0.18) \times 10^{-2}$</td>
<td>---</td>
</tr>
<tr>
<td>ψ(2S) → K⁺K⁻2(π⁺π⁻)</td>
<td>$(2.1 \pm 1.0 \pm 0.2) \times 10^{-4}$</td>
<td>---</td>
</tr>
<tr>
<td>ψ(2S) → 2(π⁺π⁻)π⁰π⁰</td>
<td>$(5.3 \pm 1.6 \pm 0.6) \times 10^{-3}$</td>
<td>---</td>
</tr>
</tbody>
</table>
## J/ψ decay rate ratio to continuum

<table>
<thead>
<tr>
<th>J/ψ decay mode (f)</th>
<th>$\sigma_{\text{int}} \cdot B_{J/ψ \rightarrow f}/\sigma_{\text{ee} \rightarrow f}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\mu^-\gamma$</td>
<td>84.1 ± 0.7</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0\gamma$</td>
<td>2558 ± 640</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>85.1 ± 7.9</td>
</tr>
<tr>
<td>$K^+K^-\pi^+\pi^-$</td>
<td>166 ± 19</td>
</tr>
<tr>
<td>$K^+K^-K^+K^-$</td>
<td>138 ± 32</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$</td>
<td>106 ± 10</td>
</tr>
<tr>
<td>$K^+K^-\pi^+\pi^-\pi^+\pi^-$</td>
<td>122 ± 10</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$</td>
<td>99.1 ± 6.5</td>
</tr>
</tbody>
</table>

Confirmation, that J/ψ decays to even number of pions dominate by one photon exchange.
If $X(3872)$ has $J^{PC} = 1^{--}$ it can be seen in $e^+e^- \rightarrow X\gamma$ - the same way as $\psi(2S)$ with the decay to $J/\psi \pi\pi \rightarrow \mu\mu\pi\pi$.

Using muon ID and asking $3.05 < m(\mu\mu) < 3.15 $ GeV/$c^2$ only 1 event candidate has been found (with 1.4 estimated background) compare to 358 $\psi(2S)$ events.

The upper limit

$B_{X(3872) \rightarrow J/\psi \pi\pi \Gamma_{\text{Xee}}} < 6.2$ eV at 90% CL

has been set.
\[ e^+ e^- \rightarrow Y(4260) \gamma \rightarrow \pi^+ \pi^- J/\psi \gamma \]

ISR photon is not detected

Statistical significance - 8σ

**Y(4260)**
- 125 ± 23 events
- Mass - 4258±8 MeV
- Width - 88±23 MeV
- \( \sigma_{\text{max}} \sim 50 \) pb

- Not seen in total hadron cross section \( \Rightarrow \) small, compare with \( \psi^- \) mesons, electron width, but \( \Gamma(\pi^+ \pi^- J/\psi) \) is large
- Exotic structure: 4q, hybrid, meson or barion molecule
- Plans: search for light quark similar structures (\( \phi \pi \pi \)).
**J/ψ region for φ π⁺π⁻**

In $m_Y \pm 0.1$ GeV/c² zone we have

\[ N_{\text{signal}} - N_{\text{bkg}} = 10 - 9.2 = 0.8 \pm 3.3 \text{ events} \]

$N_{\text{bkg}}$ estimated in 3.8 - 5 GeV/c² region

\[ N(Y(4260) \rightarrow \phi \pi^+\pi^-) < 5 \text{ ev. } 90\% \text{ C.L.} \]

\[ \Gamma_{ee} \cdot B_{\phi 2\pi} < 0.4 \text{ eV} \quad \text{compare with} \]

\[ \Gamma_{ee} \cdot B_{J/ψ 2\pi} = (5.5 \pm 1.0 \pm 0.8) \text{ eV} \]

**CLEO-c hep-ex/0602034:**

\[ \sigma(Y \rightarrow J/ψ\pi^+\pi^-) = 58^{+12}_{-10} \pm 4 \text{ pb}; \quad \sigma(Y \rightarrow φ\pi^+\pi^-) < 5 \text{ pb} \]

**BaBar**

\[ B(J/ψ \rightarrow φ\pi^+\pi^-) = (9.8 \pm 1.1 \pm 0.7) \times 10^{-4} \]

**PDG**

\[ (8.0 \pm 1.2) \times 10^{-4} \]
Summary

- Using ISR method the cross sections of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$, $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $2K^+2K^-$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0\pi^0$, $K^+K^-2(\pi^+\pi^-)$ reactions have been measured from threshold to 4.5 GeV.
- These are the most precise measurements to date for c.m. energies greater than 1.4 GeV.
- ISR provides an overview. Detailed XS study require e+e- machine !!
- Examples: contributions to $a_\mu^{\text{had}} (\times 10^{-10})$ from $2\pi^+ 2\pi^-$ (0.56 – 1.8 GeV)
  - from all e$^+$ e$^-$ exp. $14.21 \pm 0.87_{\text{exp}} \pm 0.23_{\text{rad}}$
  - from all $\tau$ data $12.35 \pm 0.96_{\text{exp}} \pm 0.40_{\text{SU(2)}}$
  - from BaBar $12.95 \pm 0.64_{\text{exp}} \pm 0.13_{\text{rad}}$
  - from $\pi^+ \pi^- \pi^0$
  - from all e$^+$ e$^-$ exp. $2.45 \pm 0.26_{\text{exp}} \pm 0.03_{\text{rad}}$
  - from BaBar $3.31 \pm 0.13_{\text{exp}} \pm 0.03_{\text{rad}}$

- Several B(J/$\psi$ -> X) measurements better than current world average
- More modes to come; aim for systematic errors $\leq 1\%$ (in $\pi^+\pi^-$)
- More interesting spectroscopy results are under analysis now. - Moscow?
\[ \pi^+ \pi^- \gamma \]

**Pion Form Factor with \( \rho - \omega \) interference**

**Very encouraging agreement!**

Hard work! <1% systematic error is needed for g-2