Initial State Radiation Physics at BaBar

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• ISR and BaBar

• Energy Dependence, Structure of
  • $e^+e^- \rightarrow p\bar{p}$
  • $e^+e^- \rightarrow \pi^+\pi^-\pi^0$
  • $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
  • $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$
  • $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$
  • $e^+e^- \rightarrow K^+K^-K^+K^-$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$
  • $e^+e^- \rightarrow J/\psi\pi^+\pi^-$, $J/\psi\gamma\gamma$, $D\bar{D}$
  • $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$

proton form factors
$\omega$ spectroscopy
contribution to $g_\mu - 2$
structure in $\phi f_0(980)$
resonance in $\omega\eta$
1st measurements
structure at 4260 MeV
structure at 4320 MeV

• Summary
Initial State Radiation in $e^+e^-$ Annihilations

- The radiator function $W$ is known to <1%

- Measure $\sigma(e^+e^- \to X)$ as a fcn. of $m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$

- Features:
  - access to wide $s'$ range
  - very small point-to-point systematic errors
  - $\gamma_{ISR}$ detected $\leftrightarrow$ hadron system contained
  - measure all the way down to threshold

- Disadvantages:
  - mass resolution $>$ beam-E spread
  - requires very high luminosity

$e^+e^- \to \gamma_{ISR}e^+e^- \to \gamma_{ISR}\gamma^* \to \gamma_{ISR}X$

$X$ is any allowed hadronic system, e.g. a resonance with $J^{PC} = 1^{--}$

Cross section:

$$\frac{d\sigma(s,s',\theta_\gamma)}{ds'd\cos\theta_\gamma} = W(s,s',\theta_\gamma) \cdot \sigma(s')$$

$\gamma_{ISR}$ detected $\leftrightarrow$ hadron system contained
$e^+e^- \rightarrow \text{hadrons}$ Cross Section:

- Has been measured over a rather broad range

- Recent, precise measurements from KLOE, VEPP-II, BES, LEP

- Perturbative QCD works at high $E_{\text{CM}}$; lots of structure at lower $E_{\text{CM}}$

- Regions around 2, 4 GeV especially interesting

- Theoretical $g_\mu-2$, $\alpha(M_Z)$ need integral, better data for $E_{\text{CM}}<10$ GeV
What do we measure?

- First, pick a specific final state $X$ and isolate it.
- Then measure the cross section, $\sigma(m)$
  → ...and $R_X = \sigma_X(m)/\sigma_{\mu\mu}(m)$
  → spectroscopy, BF of $1^{--}$ states
  → discover new $1^{--}$ states
  → extract form factors if $X=h\bar{h}$
  → tests of QCD in $m$-dependence
  $\leftrightarrow g_\mu-2$, $\alpha(m_Z)$
  see K.Yi’s talk to follow

- Then study the resonant substructure
  → some quantum #s through correlations, angular distributions
  → extract cross sections, form factors for “exclusive” submodes
  → discover new resonances

- Then more general substructure
  → general features might expose interesting dynamics
  → at what $E_{CM}$ do the events become “jetty”
  → ....
The ISR program at BaBar:

- Measure exclusive final states up to ~4.5 GeV, inclusive to ~7 GeV

- Published: \( \mu^+\mu^- \), \( pp \), \( \pi^+\pi^-\pi^0 \), \( \pi^+\pi^-\pi^+\pi^- \), \( K^+K^-\pi^+\pi^- \), \( K^+K^-K^+K^- \), \( \pi^+\pi^-\pi^+\pi^-\pi^+\pi^- \), \( \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0 \), \( K^+K^-\pi^+\pi^-\pi^+\pi^- \), \( J/\psi\pi^+\pi^- \)

- Today: these plus \( K^+K^-\pi^0\pi^0 \), \( f_0(980) \), \( J/\psi\gamma\gamma \), \( D\bar{D} \), \( \psi(2S)\pi^+\pi^- \)

- In progress: \( \pi^+\pi^- \), \( K^+K^- \), \( K^+K^-\pi^0 \), \( K^+K^0\pi^- \), \( K^0K^-\pi^+ \), \( \pi^+\pi^-\pi^0\pi^0 \), \( \pi^+\pi^-\pi^+\pi^-\pi^0 \), \( \psiK^+K^- \), \( \Lambda\bar{\Lambda} \), inclusive, ...
The BaBar Experiment

- \(e^+e^-\) collisions, \(\sim 10.6\) GeV
- Different beam energies:
  \(- E_{e^-} = 9.0\) GeV
  \(- E_{e^+} = 3.1\) GeV
  \(- \) c.m.-lab boost, \(\gamma\beta=0.55\)
- Asymmetric detector
  \(-\) c.m. frame acceptance
    \(- 0.9 \sim \cos\theta^* \sim 0.85\)
    \(- \text{wrt } e^- \text{ beam}\)
  \(-\) detects \(\sim 15\%\) of ISR \(\gamma\)
  \(-\) contains \(\sim 50\%\) of evts with fwd/bwd \(\gamma_{\text{ISR}}\)
- with excellent performance
  \(-\) Good tracking, mass resolution
  \(-\) Good \(\gamma, \pi^0\) recon.
  \(-\) Full \(e,\mu,\pi,K,p\) ID
- High luminosity:
  \(-\) \(\sim 390\) fb\(^{-1}\) accumulated
  \(-\) \(89\)–\(298\) fb\(^{-1}\) used here
  \(-\) \(0.3\)–\(1.1\) billion \(e^+e^- \rightarrow q\bar{q}\) evts.
  \(-\) \(3\)–\(10\) million \(e^+e^- \rightarrow \gamma_{\text{ISR}}J/\psi\)
  \(-\) \(2\)–\(7\) million \(e^+e^- \rightarrow \gamma_{\text{ISR}}\rho^0\)
The equivalent ISR Luminosity:

- Can be calculated from the measured luminosity or derived for our $\gamma_{\text{ISR}}$ acceptance using $e^+e^-\rightarrow\gamma_{\text{ISR}}\mu^+\mu^-$ events.

- In each 100 MeV window near 1 GeV, we expect to accumulate $\sim 8$ pb$^{-1}$
- In the 3 GeV region, $\sim 26$

- This mode also gives a nice constraint on the $J/\psi$ width:
  - $89$ fb$^{-1}$, PDG $B_{ee}$, $B_{\mu\mu}\rightarrow\Gamma_{J/\psi} = 93.7\pm3.5$ keV;
  - with CLEO $96.1\pm3.2$ keV, dominate world avg.
\[ \text{e}^+\text{e}^- \rightarrow \text{pp} \]\[ \quad 240 \text{ fb}^{-1} \quad \text{PRD 73, 012005 (06)} \]

- **Selection:**
  - events with exactly two tracks, ID’d as p and \( \bar{p} \), and a hard \( \gamma \)
  - kinematic fits, imposing 4-momentum conservation
  - select events with good \( \chi^2_{pp\gamma} \)

- **Evaluate and subtract backgrounds from**
  - \( \pi^+\pi^-\gamma \), \( K^+K^-\gamma \), using: measured cross sections, events with ID’d \( \pi, K \), and \( \chi^2_{KK\gamma}, \chi^2_{\pi\pi\gamma}, \ldots \)
  - \( \text{e}^+\text{e}^- \rightarrow \text{pp}\pi^0 \) from MC normalized to \( \pi^0 \) peak in data (\(~6\%)\)

![Graphs showing distributions for pp\gamma, K\bar{K}\gamma, J/\psi, and \( \psi(2S) \) events.](image-url)
• calculate the cross section
  → threshold to 4.5 GeV in one experiment
  → 5→10% systematic, not shown
  → consistent with previous results
  → easier to see structure
  → ...e.g. sharp drops at 2.25, 3 GeV

• described in terms of electric, magnetic form factors
  \[ \sigma(s) \propto |G_M(s)|^2 + 2m_p^2 |G_E(s)|^2 / s \]
  → full coverage allows separation via production angle distribution
  → \( G_E > G_M \) at low \( E_{CM} \)
  → but consistent at high \( E_{CM} \)
  → inconsistent with PS170
• define the effective form factor, $F$
  
  $\sigma(s) \propto (1 + 2m_p^2/s) |F|^2$

→ compare with $pp \rightarrow e^+e^-$
→ consistent with pQCD at high $s$
→ steep rise near threshold
→ ...similar to features seen in $B$, $J/\psi$ decays; all need to be understood
\[ e^+e^- \rightarrow \pi^+\pi^-\pi^0 \]

89 fb\(^{-1} \)  
PRD 70, 072004 (04)

- **Selection:**
  - events with exactly two tracks, a hard \( \gamma \), at least 2 more \( \gamma \)
  - kinematic fits, including \( \pi^0 \) mass constraint

- **Cross section**

  \[ M_{3\pi} \text{ (GeV/c}^2) \]

  \[ \text{Events / (4 MeV/c}^2) \]

  \[ \text{Cross section (nb)} \]

  → dominated by resonances: \( \omega, \phi, J/\psi \), ...plus excited \( \omega \)?

  → consistent with previous, precise data in \( \omega/\phi \) region

  → inconsistent with DM2 data at 1.35–2 GeV
• fit to cross section with $\phi$, $\omega$, $\omega'$, $\omega''$ resonances

→ “best” measurements of $\omega'$, $\omega''$
→ ...though relative phases must be assumed

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV/c$^2$)</th>
<th>$\Gamma$ (MeV)</th>
<th>$B_{ee \times B_{3\pi}} \times 10^{-6}$</th>
<th>$\phi - \phi_\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>782</td>
<td>8.7</td>
<td>67.0 ±2.8</td>
<td>–</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1019</td>
<td>4.3</td>
<td>43.0 ±2.2</td>
<td>163°</td>
</tr>
<tr>
<td>$\omega'$</td>
<td>1350±28</td>
<td>450±98</td>
<td>0.82±0.08</td>
<td>180°</td>
</tr>
<tr>
<td>$\omega''$</td>
<td>1660±10</td>
<td>230±36</td>
<td>1.30±0.14</td>
<td>0°</td>
</tr>
</tbody>
</table>

fixed to world average values
fitted
fixed to assumed values
\( e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- \)

- Selection: \( \rightarrow \) four good tracks, a hard \( \gamma \), kinematic fits

- Cross section
  \( \rightarrow \) threshold \( \rightarrow 4.5 \text{ GeV} \) in one experiment
  \( \rightarrow \) interesting structure
  \( \rightarrow \) this represents \( \sim \)half the total hadronic \( \sigma \) at 1.5 GeV
  \( \rightarrow \) 5\% systematic over most of range improves the error on \( g_\mu^{-2} \)

- Substructure
  \( \rightarrow \) main peak mostly \( a_1(1260)\pi \)
  \( \rightarrow f_0(1370)\rho^0 \) seen, could \( \leftrightarrow \) structure at \( \sim 2 \text{ GeV} \)
  \( \Rightarrow \) with more data, can study substructure in \( E_{\text{CM}} \) bins
Comparison with previous results:

- near threshold
  - consistent with prev. results
  - the best measurement for $E_{CM} < 0.75$ GeV, 12% relative systematic error

- main peak
  - the best/first measurement for $E_{CM} > 1.4 / 2$ GeV
  - a study of the $\pi^+\pi^-\pi^0\pi^0$ final state is in progress
\[ e^+e^- \rightarrow K^+K^-\pi^+\pi^- \text{, } K^+K^-\pi^0\pi^0 \]

- Cross sections

\[ \sigma(K^+K^-\pi^\mp) \text{ (nb)} \]

- huge improvement for \( K^+K^-\pi^+\pi^- \), first for \( K^+K^-\pi^0\pi^0 \)
- rich substructure dominated by \( K^*(892)K\pi \), with substantial \( K_1(1270)^+K^- \), \( K_1(1400)^+K^- \), \( \phi\pi^+\pi^- \), \( \rho^0K^+K^- \), and more
- several hints of structure, e.g. at \( \sim 2 \text{ GeV} \leftrightarrow \phi_0(980) \) threshold
- since \( \phi \), \( \phi_0(980) \) are both narrow, this submode can be studied...
• The $\phi f_0(980)$ submode:
  → visible in $m_{KK}$ vs. $m_{\pi\pi}$ scatter plots
  → extract yield by fitting the $m_{KK}$ distribution in each $E_{CM}$ bin in a $m_{\pi\pi}$ slice around the $f_0$ mass

  → background from $\phi \pi \pi <10$
  → threshold behavior inconsistent with a typical, smooth function
• Convert to cross sections
  → behavior near threshold unchanged
  → \( \pi^+\pi^- \) and \( \pi^0\pi^0 \) modes give consistent results
  → can be described by adding a resonance; a fit yields:
    \[ m = 2175 \pm 18 \text{ MeV}/c^2 \]
    \[ \Gamma = 58 \pm 26 \text{ MeV} \]
    \[ \phi = -36 \pm 56^\circ \]
    wrt non-res
    5.6\( \sigma \) significance
  → very interesting mass region, just below \( \Lambda\bar{\Lambda} \) threshold
  → is this a new state?
  → is it analogous to the \( Y(4260) \)?
  → need more data, other modes to understand structure in detail
**Cross sections**

- Large improvements in both measurements
- Dips at ~1950 MeV confirmed; also seen by FOCUS
- The 6-charged mode has very little substructure, ~1 η per event
- ...but the 4-charged mode has a rich substructure, including \(\omega\eta\), \(\omega\pi^+\pi^-\pi^0\), \(\eta\pi^+\pi^-\pi^0\) submodes, signals for \(\rho^\pm\), \(\rho^0\), \(f_0(980)\), ...
• The $2(\pi^+\pi^-)\pi^0\pi^0 : 3(\pi^+\pi^-)$ ratio
  → is flat and ...
  → =4 except where the $\omega\eta$ submode contributes
  → a challenge to understand
  → will keep studying, do a coupled-channel analysis

• The $\omega\eta$ submode
  → is easy to isolate, use sidebands to subtract background
  → the cross section is dominated by two resonances, $J/\psi$ and something with
    $m = 1645 \pm 8$ MeV/$c^2$
    $\Gamma = 114 \pm 14$ MeV
  ⇒ is it the $\omega(1650)$? ($\Gamma=315$)
    ...or the $\phi(1680)$?
    ...or something new...?
• What is causing the dip at 1950 MeV?
→ we don’t know, so let’s fit a resonance

→ fitted parameter values for our two modes are consistent
→ combined:
  \[ m = 1870 \pm 20 \text{ MeV/c}^2, \quad \Gamma = 150 \pm 20 \text{ MeV}, \quad \delta \phi = 9 \pm 15^\circ \]
→ the width is significantly larger than seen by FOCUS,
  \[ m = 1910 \pm 10 \text{ MeV/c}^2, \quad \Gamma = 37 \pm 13 \text{ MeV} \]
$e^+e^- \rightarrow K^+K^-K^+K^-$

$e^+e^- \rightarrow K^+K^-\pi^+\pi^-\pi^+\pi^-$

- Cross sections

$\sigma(K^+K^-K^+K^-) (\text{nb})$

$E_{CM}$ (GeV)

- First measurements
- The $K^+K^-K^+K^-$ mode has a strong $\phi$, but no other substructure
- The $K^+K^-\pi^+\pi^-\pi^+\pi^-$ mode has a complex substructure with a strong $K^*(890)$, but a weak $\phi$
$e^+e^- \rightarrow J/\psi \pi^+\pi^-$

233 fb$^{-1}$ PRL 95, 142001 (05)

• Selection:
  → ID’d $e^+e^-$ or $\mu^+\mu^-$ pair, ID’d $\pi^+\pi^-$ pair, no more tracks
  → **NO**, hard $\gamma$ required as $J/\psi$ signal is fairly clean
  → use prominent $\psi(2S)$ signal to choose cuts, evaluate efficiency
  → also use missing mass, $p_t$ to suppress bkgs

• Evaluate backgrounds from
  → all non-$J/\psi$ sources using events with $m_{ee,\mu\mu}$ in $J/\psi$ sidebands
  → $J/\psi X$ sources from missing mass, $p_t$ (very small)
• $E_{CM}$ distribution of selected events
  → is there non-resonant production?  → inconclusive
  → do heavy $\psi$ states decay this way?  → inconclusive
  → are there new (charmonium) state(s)  → yes! (maybe)

⇒ single resonance: $M \sim 4260$ MeV/$c^2$, $\Gamma \sim 90$ MeV
⇒ such a wide state above $D\bar{D}$ threshold shouldn’t decay to $J/\psi\pi\pi$
⇒ there is a dip in R at this energy...
⇒ is there is more than one state? What are they?
• Further studies of the Y(4260)
  → searches in B decays
  → ISR studies of J/ψγγ
  → inconclusive PRD 73, 011101 (06)
  → no signal hep-ex/0608004
  → ISR studies of D̅D
  → no signal hep-ex/0607083
  → all above ISR modes (e.g. φππ, pp)
  → no signal
  → several more studies in progress
$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$

298 fb$^{-1}$    hep-ex/0610057    submitted to PRL

- Selection:
  → Rec’d $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ candidate, ID’d $\pi^+\pi^-$ pair, no more tracks, no $\pi^0$ or $\eta$ candidates
  → **NO**, hard $\gamma$ required as the $\psi(2S)$ signal is very clean
  → cuts on missing mass and $p_t$, lepton helicity angle

- Yield and cross section

→ interesting structure near threshold...
→ ...but it’s NOT the Y(4260) $M \sim 4325$ MeV/c$^2$, $\Gamma \sim 170$ MeV
⇒ this is fun! And there’s more fun to come...
J/ψ and ψ(2S) Branching Fractions

- Observed in all/many of the above studies: 
  \[ \rightarrow \text{measure } BF(\psi \to f) \times \Gamma_{ee}, \text{ use PDG } \Gamma_{ee} \text{ to obtain} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>BaBar BF (%)</th>
<th>PDG 2004</th>
<th>Other since 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ→pp</td>
<td>0.222±0.016</td>
<td>0.217±0.008</td>
<td></td>
</tr>
<tr>
<td>J/ψ→π⁺π⁻π⁰</td>
<td>2.18 ±0.19</td>
<td>1.50 ±0.20</td>
<td>2.09 ±0.12 BES</td>
</tr>
<tr>
<td>J/ψ→π⁺π⁻π⁺π⁻</td>
<td>0.361±0.037</td>
<td>0.40 ±0.10</td>
<td>0.353±0.031 BES</td>
</tr>
<tr>
<td>J/ψ→K⁺K⁻π⁺π⁻</td>
<td>0.609±0.073</td>
<td>0.720±0.230</td>
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<tr>
<td>J/ψ→π⁺π⁻π⁺π⁻π⁺π⁻</td>
<td>0.440±0.041</td>
<td>0.40 ±0.20</td>
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<tr>
<td>J/ψ→π⁺π⁻π⁺π⁻π⁰π⁰</td>
<td>1.65 ±0.21</td>
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<tr>
<td>J/ψ→ωπ⁺π⁻π⁰</td>
<td>0.40 ±0.07</td>
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</tr>
<tr>
<td>J/ψ→ψ(2S)→K⁺K⁻K⁺K⁻</td>
<td>0.67 ±0.14</td>
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</tr>
<tr>
<td>J/ψ→ψ(2S)→π⁺π⁻π⁺π⁻π⁰π⁰</td>
<td>0.509±0.055</td>
<td>0.31 ±0.13</td>
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</tr>
<tr>
<td>J/ψ→ψ(2S)→φπ⁺π⁻</td>
<td>0.177±0.037</td>
<td>0.160±0.032</td>
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</tr>
</tbody>
</table>

- useful
- competitive
- best
- dominant
Summary

• The very high luminosity of the B factories has (re)opened several interesting areas of elementary particle physics

• At BaBar we have exploited initial state radiation to
  → study $e^+e^-$ annihilations at $E_{CM}$ from threshold to $\sim 5$ GeV
  → improve our knowledge of $R$, $g_{\mu-2}$, $\alpha(M_Z)$
  → improve spectroscopy of $\omega$ states
  → study proton form factors, find $G_E > G_M$ at low $E_{CM}$
  → discover new states/structures at $m\sim 2175, 4260, 4400$ MeV
  → improve measurement of an $\omega/\phi$ state at $1645$ MeV

• In the future, many new, improved studies planned
  → update current results with full data set
  → additional exclusive modes under study or consideration
  → in particular, hope to reach 1% uncertainty on $e^+e^- \rightarrow \pi^+\pi^-$
  → inclusive measurements