$e^+e^- \to \pi^+\pi^- \text{ with ISR}$

and

the $R_b$ Scan

Francesco Renga

Università di Roma “La Sapienza” & INFN Roma

on behalf of the BaBar Collaboration
B-Factories showed an exciting capability for improving our experimental knowledge about *Hadronic Physics* (hadron production, mass spectra, hadron decays, ...);

Several fields involved:
- Quark models and quarkonia;
- QCD in the non-perturbative regime;
- ...

Impact on a wider range of fields:
- Measurement of SM parameters;
- Tests of SM;
- ...
Introduction

- B-Factories showed an exciting capability for improving our experimental knowledge about *Hadronic Physics* (hadron production, mass spectra, hadron decays,...);

- Several fields involved:
  - Quark models and quarkonia;
  - QCD in the non-perturbative regime;
  - ...

- Impact on a wider range of fields:
  - measurement of SM parameters;
  - Tests of SM;
  - ...

- $e^+e^- \rightarrow \pi^+\pi^-$ and the anomalous magnetic moment of the muon

- Bottomonium above the open beauty threshold
The BaBar Experiment

DIRC PID performances
$e^+e^- \rightarrow \pi^+\pi^- \text{ with ISR}$

(presented at TAU08)
$a_\mu = (g_\mu - 2) / 2$: SM & Experiment

\[ a_\mu^{\text{exp}} = 11\,659\,208.0(5.4)(3.3) \times 10^{-10} \]
SM predictions

\[ a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{EW} + a_{\mu}^{HLO} + a_{\mu}^{HHO}(\text{vp}) + a_{\mu}^{HHO}(\text{lbl}) \]

- Dominant contribution to the theoretical error;

- Require exp. measurement of \( e^+e^- \rightarrow \text{hadrons} \):
  - Direct measurement at \( e^+e^- \) colliders;
  - \( \tau \) hadronic decays.

QED Kernel (known function)

\[ a_{\mu}^{HLO} = \frac{1}{4\pi^3} \int_{4m_{\pi}^2}^{\infty} ds K(s) \sigma^{(0)}(s) \]

73% from \( e^+e^- \rightarrow \pi^+\pi^- \)

\( e^+e^- \rightarrow \text{hadrons} \) cross section \((s = m_{ee}^2)\)
The $e^+e^-$ Perspective

$$\frac{d\sigma_{\pi\pi\gamma}}{dx_sdcos\theta} = W(x_s',s,\theta)\sigma_{\pi\pi}(s')$$

**ISR production**

*automatic energy scan*

To be taken into account...
Analysis Strategy

• Measurement of the ratio of $e^+e^- \rightarrow \pi^+\pi^-(\gamma)\gamma_{\text{ISR}}$ and $e^+e^- \rightarrow \mu^+\mu^-(\gamma)\gamma_{\text{ISR}}$ productions:
  
  - Allows to remove common systematic uncertainties related to the ISR photon.

\[
\frac{dN_{\pi\pi\gamma(\gamma)}}{d\sqrt{s'}} / \frac{dN_{\mu\mu\gamma(\gamma)}}{d\sqrt{s'}} = \frac{\sigma^0_{\pi\pi(\gamma)}(\sqrt{s'})}{\sigma_{\text{pt}}(\sqrt{s'})} \cdot \kappa(\sqrt{s'}) \cdot \frac{4\pi\alpha^2}{3s'}
\]

DATA SAMPLES

• $\Upsilon(4S)$ data: ~513000 pion events, ~446000 muon events (231 fb$^{-1}$);

• MC samples for $e^+e^- \rightarrow \pi^+\pi^-(\gamma)\gamma_{\text{ISR}}$, $e^+e^- \rightarrow \mu^+\mu^-(\gamma)\gamma_{\text{ISR}}$, $e^+e^- \rightarrow qq$.

ISR/FSR simulation (AfkQED) includes LO ISR + LO FSR (PHOTOS) + interference + approx. additional ISR/FSR + corrections with Phokara
Selection (I)

**ISR photon**
- \( E > 3 \text{ GeV}; \)
- \( 0.35 < \theta < 2.4 \text{ rad}. \)

**μμ pair**
- 2 tracks:
  - opposite charge;
  - \( p_{\text{trk}} > 1 \text{ GeV}; \)
  - \( 0.40 < \theta_{\text{trk}} < 2.45 \text{ rad}. \)
  - PID based on IFR and EMC variables (\( \epsilon \sim 90\% \), muon-to-pion mis/ID \( \sim 10\% \));

**ππ pair**
- 2 tracks:
  - opposite charge;
  - \( p_{\text{trk}} > 1 \text{ GeV}; \)
  - \( 0.40 < \theta_{\text{trk}} < 2.45 \text{ rad}; \)
  - NOT SATISFYING either muon or kaon PID (\( \epsilon \sim 85-90\% \));
Selection (II)

- Further selection based on 2 kinematic fits:
  - “2C ISR” fit (assume a second undetected ISR photon);
  - “3C FSR” fit (if more than 1 reconstructed photon, assume that one of the non-ISR photons is FSR).

$\chi^2$'s used to define a background region (BG) from $\pi\pi$ data.
PID & Backgrounds

• Particle ID:
  - Efficiencies evaluated from data using $e^+e^- \rightarrow XX\gamma$ samples and evaluating the performances of the PID on one track after selecting the other one as a pion/muon/kaon.

• Background contamination:
  - From $e^+e^- \rightarrow pp\gamma$ (due to proton-to-pion mis-ID), $e^+e^- \rightarrow qq$, $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma_{ISR}$;
  - Estimated in the MC and corrected by data/MC comparisons;
\( \pi^+ \pi^- \) mass spectrum

- \( \pi\pi \) yields used to build the mass spectrum;
- **Unfolding** (transfer matrix method) to correct for resolution effects.

**Systematics (in 10^{-3})**

<table>
<thead>
<tr>
<th>sources</th>
<th>0.4–0.6</th>
<th>0.6–0.9</th>
<th>0.9–1.2</th>
<th>1.2–1.4</th>
<th>1.4–3.0</th>
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<tbody>
<tr>
<td>trigger/ filter</td>
<td>1.5</td>
<td>0.8</td>
<td>0.5</td>
<td>0.5</td>
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<td>tracking</td>
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<td>1.1</td>
<td>1.7</td>
<td>3.1</td>
<td>3.1</td>
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<tr>
<td>( \pi )-ID</td>
<td>5.2</td>
<td>2.4</td>
<td>4.2</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>background</td>
<td>5.2</td>
<td>0.4</td>
<td>1.0</td>
<td>7.0</td>
<td>12.0</td>
</tr>
<tr>
<td>acceptance</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>kinematic fit (( \chi^2 ))</td>
<td>1.8</td>
<td>0.7</td>
<td>1.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>correlated ( \mu\mu ) ID loss</td>
<td>3.0</td>
<td>1.3</td>
<td>2.0</td>
<td>3.0</td>
<td>10.0</td>
</tr>
<tr>
<td>sum ( \pi\pi )</td>
<td>7.5</td>
<td>3.3</td>
<td>5.5</td>
<td>13.4</td>
<td>19.1</td>
</tr>
</tbody>
</table>
Cross Section

\[ |F_{\pi'}|^2(s') = \frac{3s'}{\pi \alpha^2(0) \beta^3_{\pi}} \sigma_{\pi\pi}(s') \quad \text{and} \]

\[ a_\mu(SM) = (462.5 \pm 0.9 \pm 3.1) \times 10^{-10} \]

\[ a_\mu(\text{exp}) - a_\mu(SM) = (14.8 \pm 8.4) \times 10^{-10} \]

PRELIMINARY!
Comparisons \( (e^+e^-) \)

- SND (Scan)
- CMD2-2006 (Scan)
- CMD2-2004 (Scan)
- BaBar - \( F_\pi \)
- OTHER EXP. - \( F_\pi \)
- KLOE (ISR)

\[
\frac{|F_\pi|^2 (BaBar) - |F_\pi|^2 (OTHER EXP.)}{|F_\pi|^2 (BaBar)}
\]
Comparisons ($\tau$)

$$\frac{|F_\pi|^2 (\text{BaBar}) - |F_\pi|^2 (\text{OTHER EXP.})}{|F_\pi|^2 (\text{BaBar})}$$
$R_b$ Scan above $\Upsilon(4S)$

arXiv:0809.4120 [hep-ex]
Motivations

- A "new" charmonium spectroscopy emerged from the discovery of new resonances that does not fit in the "standard" charmonium model;
- Is there a "new" bottomonium spectroscopy?

\[ m(\text{bottomonium}) = m(\text{charmonium}) + m(Y(1S)) - m(J/\Psi) \]

*Works fine for standard bottomonium!*

\[ Y(4260) \rightarrow Y_b(10620)??? \]
\[ Y(4350) \rightarrow Y_b(10710)??? \]
\[ Y(4660) \rightarrow Y_b(11020)??? \]
Energy Scan

- New bottomonium resonances can be searched for with an energy scan above the \( \Upsilon(4S) \) resonance;

- **Inclusive approach:**
  - Search for unexpected structures in the inclusive hadronic cross section:

\[
R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma_{\mu\mu}^0(s)}
\]

\[s = m_{ee}^2\]
New bottomonium resonances can be searched for with an energy scan above the $\Upsilon(4S)$ resonance;

**Inclusive approach:**

- Search for unexpected structures in the inclusive hadronic cross section:

\[
R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}
\]

**WARNING!**

- Not corrected for radiative effects!
- $e^+e^- \rightarrow \Upsilon(nS)\gamma_{\text{ISR}}$ (n = 1, 2, 3) treated as a SIGNAL CONTRIBUTION
Previous Measurements


BaBar Scan

- BaBar performed a 10 days long energy scan starting on March 28\textsuperscript{th}, 2008:
  - Steps of 5 MeV from 10.54 to 11.20 GeV;
  - about 25 pb\textsuperscript{-1} per step (3.3 fb\textsuperscript{-1} total);
  - 8 additional steps in the $\Upsilon(6S)$ region (10.96 to 11.10 GeV) corresponding to 600 pb\textsuperscript{-1}.

30 times more luminosity and
4 times finer steps w.r.t. CESR scan
For each point and for a “reference” point (10.54 GeV) we select:

- bb-enriched sample, according to a multi-hadron selection (see later);
- \(\mu\mu\) sample (see later);

At the “reference” point:

- Estimate of backgrounds, scaled to other energies according to the expected \(s\) dependence;

Across the scan:

- \(R_b\) extracted from a combination of the bb and \(\mu\mu\) yields, subtracting the non-bb background.
Selection

- **bb-enriched sample:**
  - > 3 tracks;
  - reconstructed energy > 4.5 GeV;
  - Cut on the ratio of $0^{th}$ and $2^{nd}$ Fox–Wolfram moments: $R_2 < 0.2$ (spherical event);

- **$\mu\mu$ events given by 2 tracks with:**
  - $m_{\mu\mu} > 7.5$ GeV;
  - $\theta < 0.7485$ in the center-of-mass frame;
  - collinearity better than $10^\circ$.

$\mu\mu$ sample also used to have a precise measurement of the CM energy (tuned with $Y(3S)$ scan data).
Background

• \( e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- X_h \) (two-photon events):
  - cross-section estimated at the reference point and scaled according to \( \log(s) \);
  - efficiency supposed flat across the scan;

• \( e^+e^- \rightarrow qq \):
  - cross-section estimated at the reference and scaled according to \( \sqrt{s} \);
  - efficiency, estimated from MC simulations for different energies, follows a slow linear trend in \( \sqrt{s} \).
Results & Interpretation

- Region explored with unprecedented detail;
- Interpretation of structures made difficult by threshold effects.

N. Törnqvist (1984) predicted structures between $\Upsilon(4S)$ and $\Upsilon(5S)$ and an asymmetric $\Upsilon(5S)$ shape with NO NEW RESONANCES!

\( \Upsilon(5S) \) and \( \Upsilon(6S) \)

- Thresholds and interferences make also difficult the extraction of the \( \Upsilon(5S) \) and \( \Upsilon(6S) \) parameters;

- We tried with a fit including \( \Upsilon(5S) \), \( \Upsilon(6S) \) and continuum, interfering among them, plus a non-interfering continuum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \Upsilon(10860) )</th>
<th>( \Upsilon(11020) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass (GeV)</td>
<td>( 10.876 \pm 0.002 )</td>
<td>( 10.996 \pm 0.002 )</td>
</tr>
<tr>
<td>width (MeV)</td>
<td>( 43 \pm 4 )</td>
<td>( 37 \pm 3 )</td>
</tr>
<tr>
<td>( \phi ) (rad)</td>
<td>( 2.11 \pm 0.12 )</td>
<td>( 0.12 \pm 0.07 )</td>
</tr>
<tr>
<td>PDG mass (GeV)</td>
<td>( 10.865 \pm 0.008 )</td>
<td>( 11.019 \pm 0.008 )</td>
</tr>
<tr>
<td>PDG width (MeV)</td>
<td>( 110 \pm 13 )</td>
<td>( 79 \pm 16 )</td>
</tr>
</tbody>
</table>

\( \sqrt{s} \) [GeV]
Comparison with PDG

PDG: CLEO + CUSB

CLEO

BABAR
BELLE Statement:

DISAGREEMENT of $Y(5S)$ mass and width between exclusive (Belle) and inclusive (PDG) analysis

But...

$Y(5S)$ width

BaBar (Incl.): 
(43 ± 4) MeV

Belle (Excl.): 
(54.7$^{+8.5}_{-7.2}$ ±2.5) MeV

arxiv:0810.3829
Conclusions

- B-Factories allow to significantly boost the experimental knowledge on Hadronic Physics;

- I presented two recent results from BaBar:
  - $e^+e^- \rightarrow \pi^+\pi^-$ with ISR;
    - New contribution to the SM prediction of the anomalous magnetic moment of the muon
  - $R_b$ scan above the $Y(4S)$;
    - New estimate of the $Y(5S)$ and $Y(6S)$ shapes & improved knowledge of the open beauty threshold region

NEXT STEP: EXCLUSIVE ANALYSIS
Backup
$S/B \text{ in } e^+e^- \rightarrow \pi^+\pi^-$
Yield extraction

- Once data are selected and background is subtracted, $\pi\pi$ and $\mu\mu$ yields are extracted taking into account PID cross-feed:

$$N'_{\pi\pi'} = N^{(0)}_{\mu\mu} \epsilon_{\mu\mu \to \pi\pi'} + N^{(0)}_{\pi\pi} \epsilon_{\pi\pi \to \pi\pi'} + N^{(0)}_{KK} \epsilon_{KK \to \pi\pi'} + N_{ee'} \epsilon_{\pi\pi'}$$  

$$N'_{\mu\mu'} = N^{(0)}_{\mu\mu} \epsilon_{\mu\mu \to \mu\mu'} + N^{(0)}_{\pi\pi} \epsilon_{\pi\pi \to \mu\mu'} + N^{(0)}_{KK} \epsilon_{KK \to \mu\mu'}$$

Observed events in the PID category $\mu\mu$

Probability of a $\mu\mu$ pair to be identified as $\mu\mu$

Probability of a $\pi\pi$ pair to be identified as $\mu\mu$

measured from data
A new charm spectroscopy

- New charmonium-like resonances, recently discovered, do not fit in the “standard” $c\bar{c}$ charmonium schema;

- Masses far from predicted states;
- Widths too small;
- Unusual decay rates.

Tetraquarks $[qq][\bar{q}\bar{q}]$?
Hybrids $q\bar{q}g$?
Molecules $[q\bar{q}][q\bar{q}]$?
Scan Systematics

- Uncorrelated Systematics: **NO** point-by-point correlation;
- Correlated Systematics: **FULL** point-by-point correlation.

\[
V_{ij} = \left[ \sigma_{stat}(s_i) + \sigma_{unc}(s_i) \right] \delta_{ij} + \sigma_{corr}(s_i) \sigma_{corr}(s_j)
\]

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu\mu) MC statistics</td>
<td>0.2</td>
</tr>
<tr>
<td>(\mu\mu) radiative corrections</td>
<td>1.4</td>
</tr>
<tr>
<td>(\epsilon_{\mu})</td>
<td>1.3</td>
</tr>
<tr>
<td>(\epsilon_{B})</td>
<td>1.3</td>
</tr>
<tr>
<td>(\epsilon_{cont})</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td>(\epsilon_{ISR})</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td>(\sigma_{\gamma\gamma}\epsilon_{\gamma\gamma})</td>
<td>&lt; 0.2</td>
</tr>
</tbody>
</table>
Comparison with Belle (II)

<table>
<thead>
<tr>
<th></th>
<th>BaBar (Inclusive)</th>
<th>Belle (Exclusive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(5S)</td>
<td></td>
<td></td>
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<td>54.7^{+8.5}_{-7.2} ± 2.5</td>
</tr>
</tbody>
</table>
Comparison with Belle (III)

- A bias in the mass measurement in BaBar or Belle?
  - Try fitting Belle data with BaBar parameters + a mass shift.

\[
\text{shift} = (11.2 \pm 1.8) \text{ MeV}
\]