SLAC-WP-060

Initial State Radiation Studies at the Upsilon(4S)

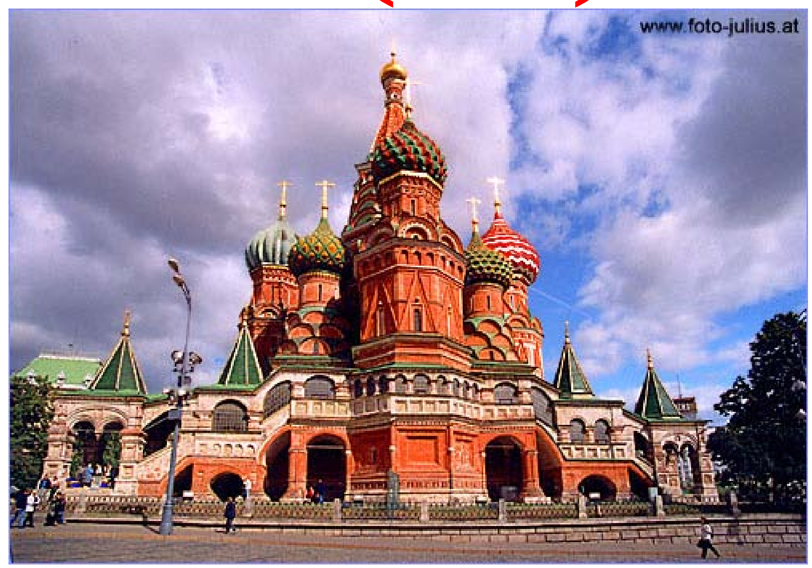
J. McKenna for the BaBar Collaboration

Presented at 11th Lomonosov Conference on Elementary Particle Physics,
08/21/2003--8/27/2003, Moscow, Russia

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported by Department of Energy contract DE–AC03–76SF00515.

Initial State Radiation studies at $\Upsilon(4S)$



Lomonosov Conference August 2003

Janis McKenna
University of British Columbia
Representing the BaBar Collaboration

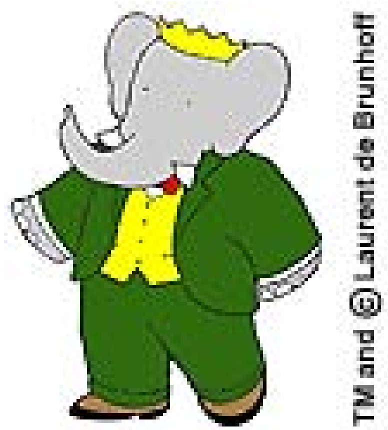
Outline

Initial State Radiation at an e^+e^- collider

- Why we are investigating initial state radiation at PEP-II with BABAR

BABAR Initial State Radiation Analyses

- $e^+ e^- \to \mu^+ \mu^- \gamma$ J/ψ production via ISR



- Many other ISR channels in progress: $e^+ e^- \to$ hadrons γ

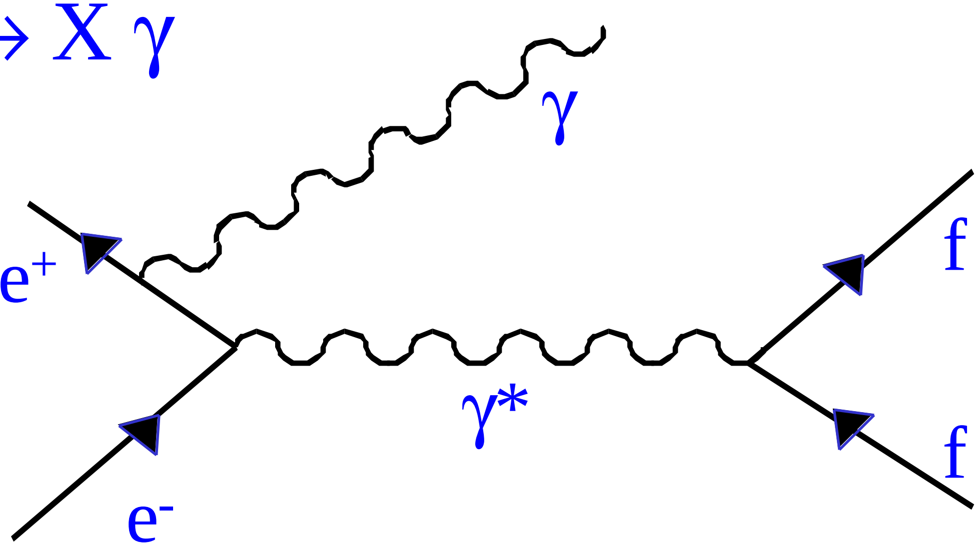
  including:

  $K^+ K^- \gamma$ $\pi^+ \pi^- \gamma$ $p\, p\, \gamma$

Summary & Conclusions

Initial State Radiation

$e^+ e^- \rightarrow X\gamma$



Lepton pair or hadronic system

•Radiative processes effectively give us a variable E_{CM} energy e^+e^- collider without actually varying beam energies.

$\rightarrow$ $e^+e^- \rightarrow f\bar{f}\gamma$ with ISR in order to study $e^+e^- \rightarrow f\bar{f}$ at lower effective E_{CM}

•Hard photon must be detected and well measured.

Acceptance & efficiency for hard ISR photon is typically ~10%

Physics Motivations

•Low mass particle spectroscopy

Improve on branching ratio, mass and width measurements of low mass hadrons

B Factory luminosity → competitive with or better than PDG world averages

•Contribute to critical tests of the Standard Model

Fundamental quantities critical to test the Standard Model:

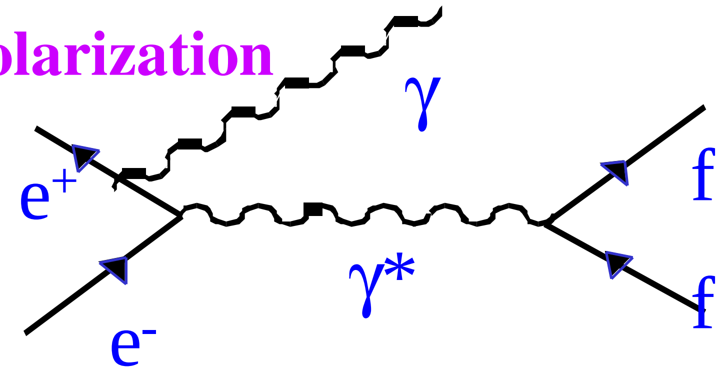
- muon anomalous magnetic moment, g_μ-2
- $\alpha(m_Z^2)$, QED running constant evaluated at Z pole

  (necessary for precise determination of Higgs mass)

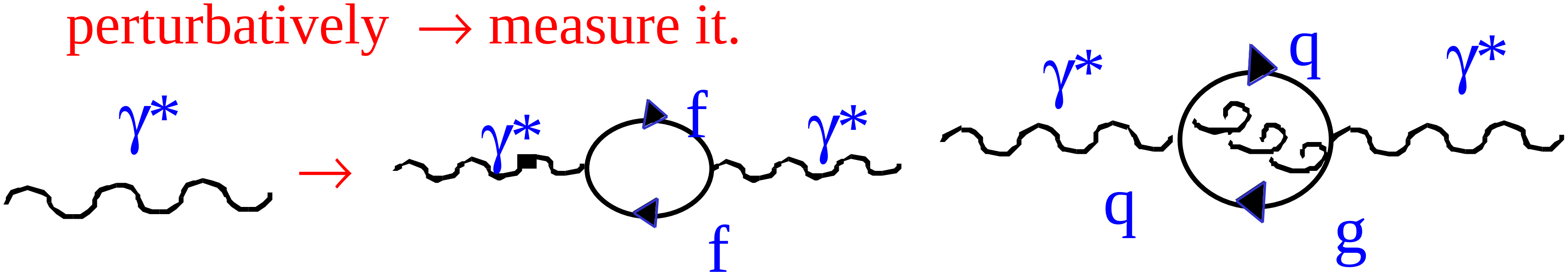
In both these cases, we need to "measure" the photon propagator (hadronic vacuum polarization)

Physics Motivations

Both g_μ-2 and $\alpha(m_Z^2)$ have dominant theoretical uncertainties arising from **hadronic vacuum polarization** which can't be calculated precisely at low energies.



When the fermions f are charged leptons, we can calculate this to high order in QED
When the fermions are quarks, can't calculate virtual photon perturbatively $\rightarrow$ measure it.



ISR studies - Tests of SM

We can use experimental data to measure these hadronic corrections by studying ISR decays either individually and summing all contributions, or inclusively by measuring *R(s′)*

$$R(s') = \frac{\sigma_{e^+e^- \rightarrow hadrons}(s')}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}(s')}$$

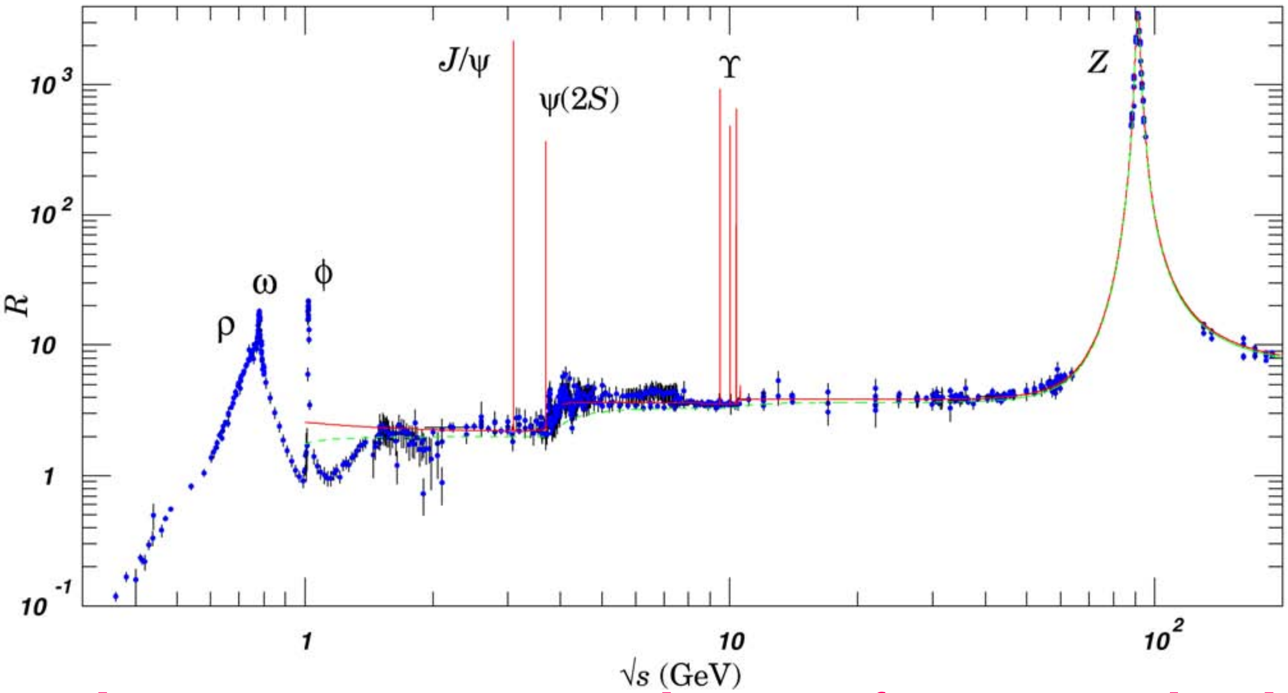
Inclusive method has larger uncertainty on effective E_{CM} resulting from photon energy resolution

s′: nominal/effective CMS energy

Need Improved R Measurement

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- for critical test of SM (g-2)
- Higgs mass limits (LEP)



Using ISR lets us measure R over wide range of energies, with only one experiment → no normalization uncertainties introduced, as when combining several experiments

Particularly low statistics in 1.4-3.4 GeV E_{CM} region

Muon Anomalous Magnetic Moment

• Precision measurement of **muon's** $a_\mu = \frac{g_\mu - 2}{2}$ provides critical test of Standard Model. Muon more sensitive to new physics in electroweak loops $\rightarrow$ sensitivity ~ $(m_\mu/m_e)^2$

Currently:

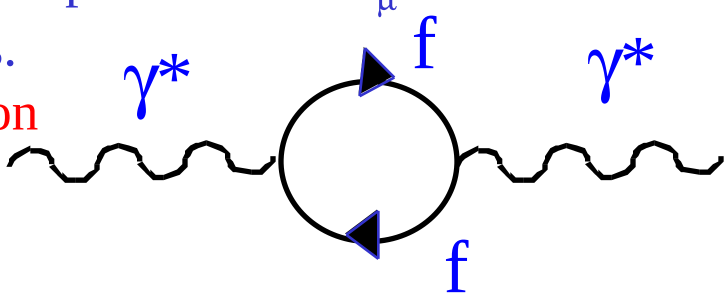
$$a_\mu^{exp} - a_\mu^{SM} = (10.3 \pm 10.7) \times 10^{-10} (e^+e^- \text{and} \tau \text{ decay data})$$

$$a_\mu^{exp} - a_\mu^{SM} = (35.5 \pm 11.7) \times 10^{-10} (e^+e^- \text{ data only})$$

•Recently, muon anomalous magnetic moment a_μ measured to .7 ppm and gave hints at deviations from Standard Model

•Largest contribution to uncertainty in theoretical prediction in a_μ is from hadronic contribution to vacuum polarization corrections.

Measuring ISR cross-sections gives us correction for this hadronic vacuum polarization:



→ **we urgently need to measure hadronic cross-sections**

'ENGINEERING NUMBERS' for critical test of SM in **g-2**

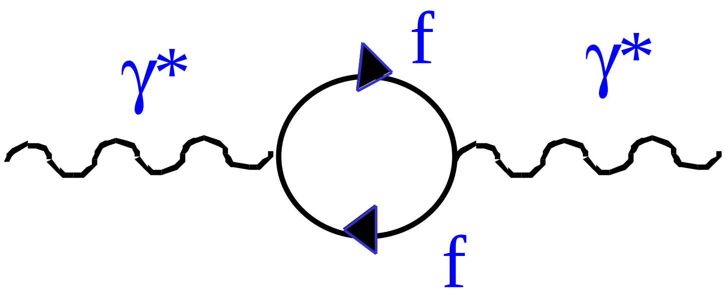
Improved Prediction of Higgs Mass

Precise knowledge of hadronic contributions (these same vacuum polarization corrections) to running α_{EM} is dominant contribution to the indirect determination of the SM Higgs mass.

To predict Higgs mass precisely, we need $\alpha_{EM}(m_Z)$

Goal: predict m_{HIGGS} indirectly, just as we did for the top quark mass using LEP precision electroweak data

Measuring ISR cross-sections gives us correction for this hadronic vacuum polarization:



→ **we urgently need to measure hadronic cross-sections**

"ENGINEERING NUMBERS" for SM Higgs mass

Initial State Radiation

GREAT TOOL!

Most low energy $e^+ e^-$ collider data is from the VEPP machines at BINP (very high statistics up to 1.4 GeV CMS energies)

$\rightarrow$ BABAR can contribute significantly to a large number of exclusive cross-sections and eventually an inclusive R measurement at and just above these energies, in particular, in the 1.4 - 3.4 GeV E_{CMS} region

BABAR 2 prong + γ ISR Analysis

88-90 fb^{-1} of BABAR data used in all analyses

- continuum and ϒ(4S) running

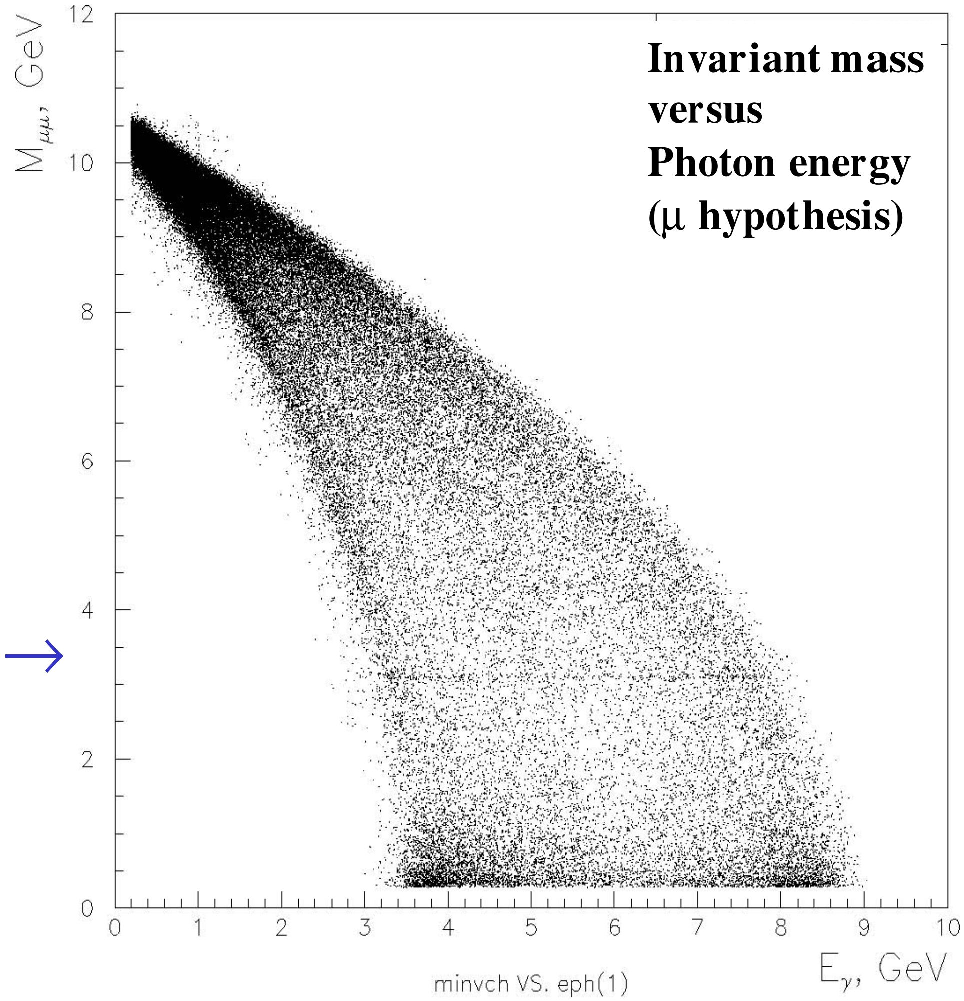
EVENT SELECTION:

- $E_{\gamma CM}$ >3 GeV , photon in well measured detector region
- 2 'good' oppositely charged tracks (well measured, from IP, p_t>.1GeV/c)
- No electrons in final state (no radiative bhabhas: p >.5 GeV/c, E_{EMC}< 0.4 GeV)
- Large angular separation between γ + charged track ($\cos\theta^*_{\gamma\text{-trk}} < 0.5$) (reduces FSR events)
- Cut on angle between photon and dimuon recoil "missing" momentum

MC simulation of data includes ISR, FSR, structure fcns

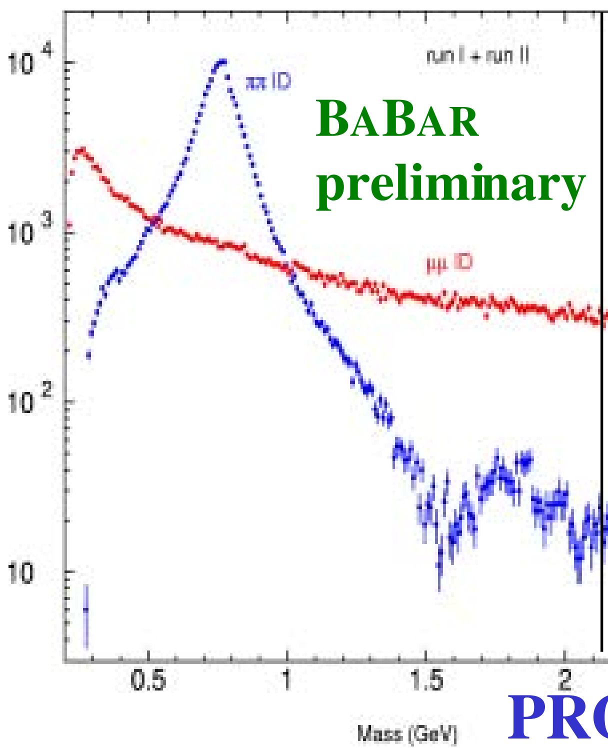
$e^+ e^- \rightarrow$ 2 prong + γ

J/ψ (more on this later) →

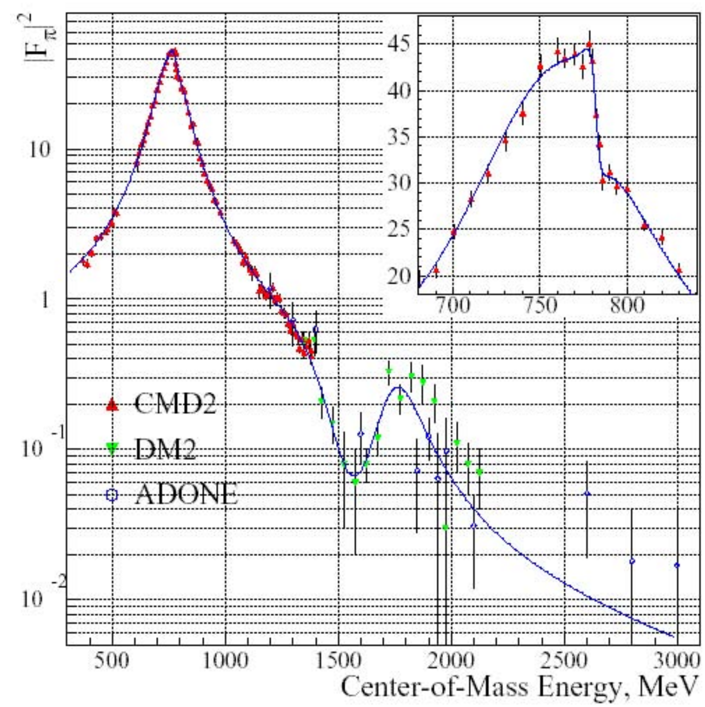


$e^+ e^- \to \pi^+ \pi^- \gamma$

Examine e $N_{\pi\pi}$ using
1C-fit with $\pi^+ \pi^-$ hypothesis



Compare BABAR statistics with Results from **VEPP and DCI**



PROMISING! Lumi, radcorr, efficiencies cancel in ratio

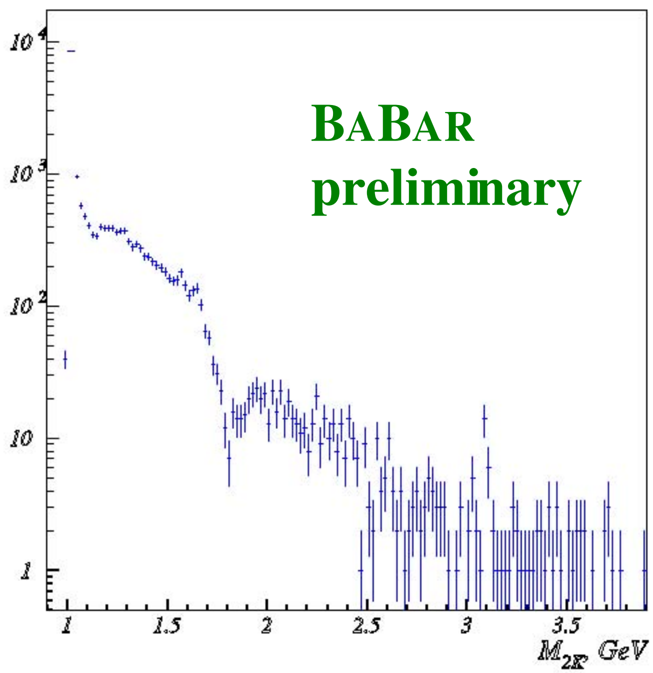
VERY IMPORTANT FOR g-2 hadronic contributions

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

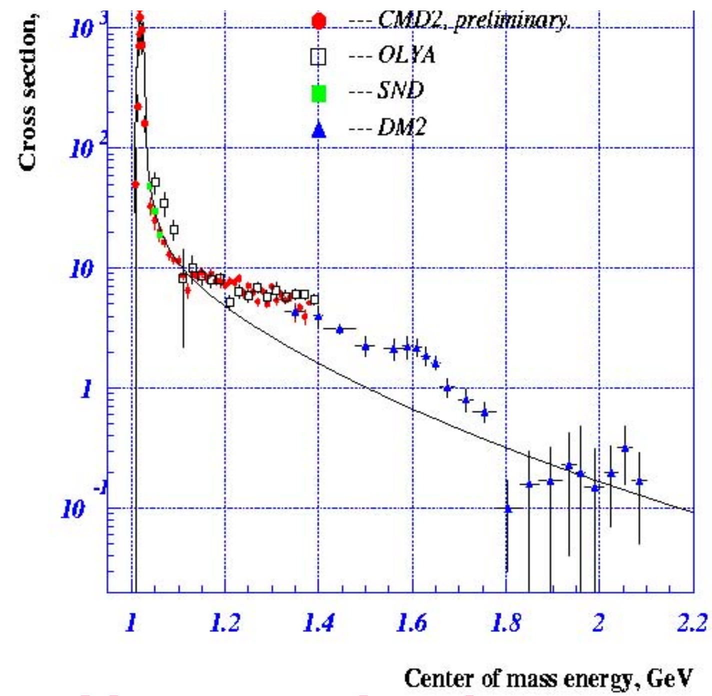
use same technique as for $\pi^+ \pi^-$

but require:

- 2 ID'd K's, opposite charge
- 1C-fit with $K^+ K^-$ hypothesis



Compare BABAR statistics with Results from **VEPP and DCI**



Could use more data above 1.4 GeV, → BABAR will help here

Effective Luminosity determination

Use $e^+ e^- \to \mu^+ \mu^- \gamma$ events to determine ISR **"effective luminosity"** to normalize hadronic cross section measurements.

$$\sigma_{e^+e^- \to ff}(s') = \frac{dN_{ff\gamma} \cdot \varepsilon_{\mu\mu} \cdot (1+\delta^{\mu\mu}_{rad})}{dN_{\mu\mu\gamma} \cdot \varepsilon_{ff} \cdot (1+\delta^{ff}_{rad})} \cdot \sigma_{e^+e^- \to \mu^+\mu^-}(s')$$

where $s' = s(1-x)$ (effective E_{CM}, i.e. after ISR photon gone),
$\varepsilon_{\mu\mu}$ and ε_{ff} are detection efficiencies, and $1+\delta^{\mu\mu}_{rad}$ and $1+\delta^{ff}_{rad}$ are final state photon radiation corrections.
The Born cross-section is used for $\sigma_{e^+e^- \to \mu^+\mu^-}(s')$

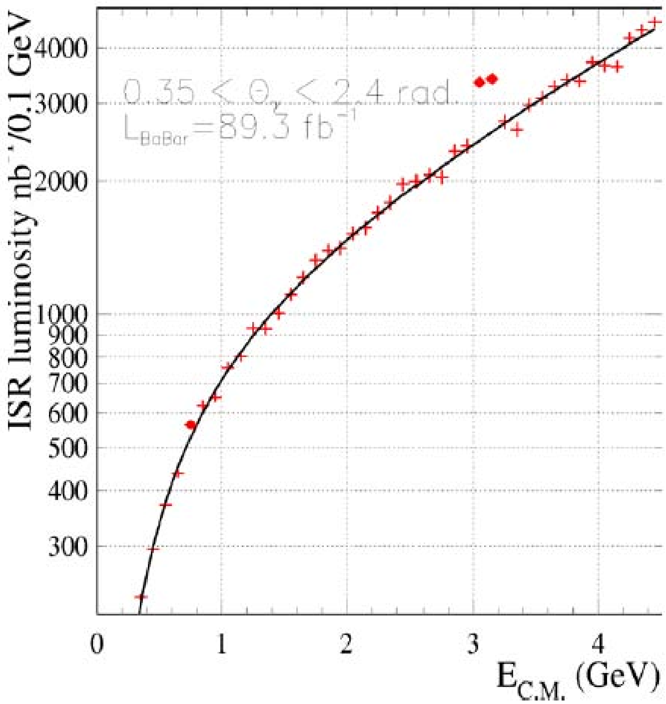
Advantage of ratio: radiative corrections to the initial state & acceptance for ISR photon and some systematic errors cancel

$e^+ e^- \rightarrow \mu^+ \mu^- \gamma$

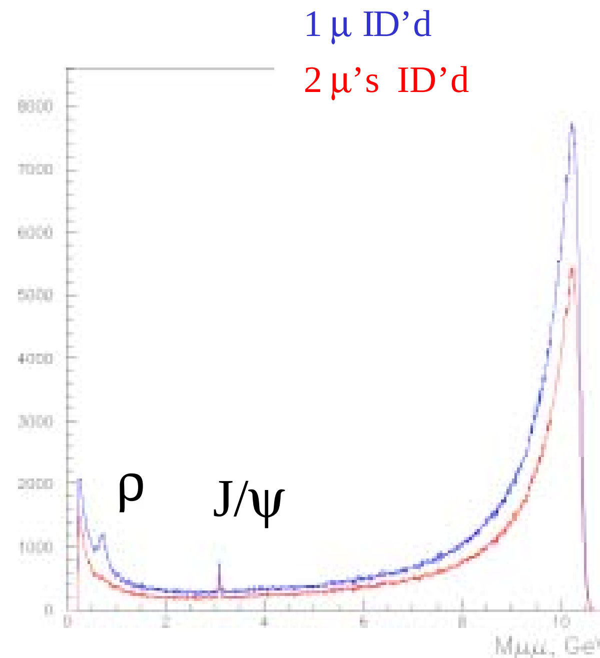
Luminosity from dimuon events:

•Cross-check: correct for efficiencies, lumi agrees with BaBar lumi to 2% (subtract $\pi^+ \pi^-$ and $K^+ K^-$ backgrounds)

•Can calculate equivalent e^+e^- lumi for given E_{CM}



Dimuon mass



⇐ Babar's 90 fb^{-1} is equivalent to e^+e^- lumi:

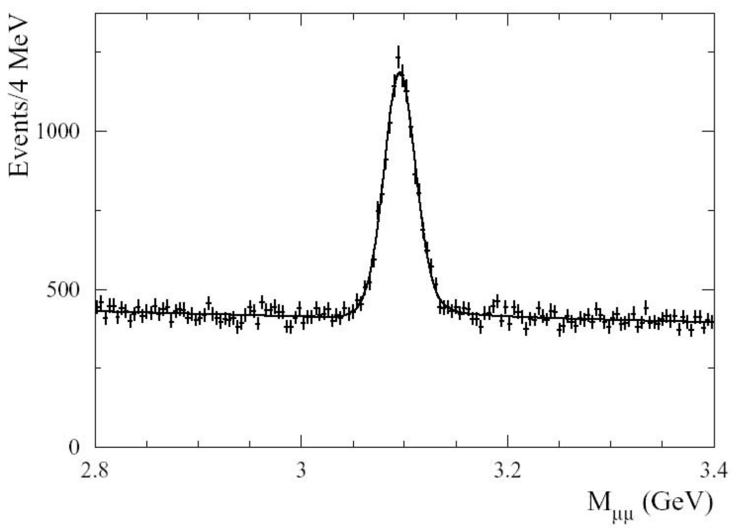
~700 nb^{-1}/.1GeV at 1 GeV

~ 2 pb^{-1}/.1GeV at 2.5 GeV

~ 4 pb^{-1}/.1GeV at 4 GeV

$e^+ e^- \to \mu^+ \mu^- \gamma$

J/ψ serves to study mass resolution in other ISR studies



- 1-C fit: recoil against $\mu^+\mu^-$ has zero mass
  - ~70,000 dimuon pairs,
  - ~7800 J/ψ events in peak
    - mass resolution 8 MeV

Generic ISR Cross Section

The first order ISR cross-section to particular final state is related to the e^+e^- collision cross-section σ_f by:

$$\frac{d\sigma_{ISR}(s,x)}{dx} = W(s,x)\cdot\sigma_f\left(\, s(1-x)\,\right) \qquad x = \frac{2E_\gamma}{\sqrt{s}}$$

- σ_f is Born cross-section for final state f
- E_γ is photon energy in the CM
- $W(s,x)$ is the energy spectrum of the radiated ISR photon and takes into account vertex and self energy corrections.

$$W(s,x) = \frac{2\alpha}{\pi x}\cdot\left(2\ln\frac{\sqrt{s}}{m_e} - 1\right)\cdot\left(1 - x + \frac{x^2}{2}\right)$$

$J/\psi \to \mu^+ \mu^-$

The Born cross-section for $e^+ e^- \to J/\psi \to \mu^+ \mu^-$ production can be written as a Breit-Wigner:

$$\sigma_f(s) = \frac{12\pi B_{ee} B_{\mu\mu}}{m^2} \cdot \frac{m^2\Gamma^2}{\left(s - m^2\right)^2 + m^2\Gamma^2}$$

where $B_{ee} = B(J/\psi \to e^+e^-)$ $\quad B_{\mu\mu} = B(J/\psi \to \mu^+\mu^-)$

For narrow $J/\psi \to \mu^+\mu^-$ production via ISR, pop Born cross-section into ISR differential:

$$\frac{d\sigma_{ISR}(s,x)}{dx} = W(s,x) \cdot \sigma_f\left(s(1-x) \right) \qquad x = \frac{2E_\gamma}{\sqrt{s}}$$

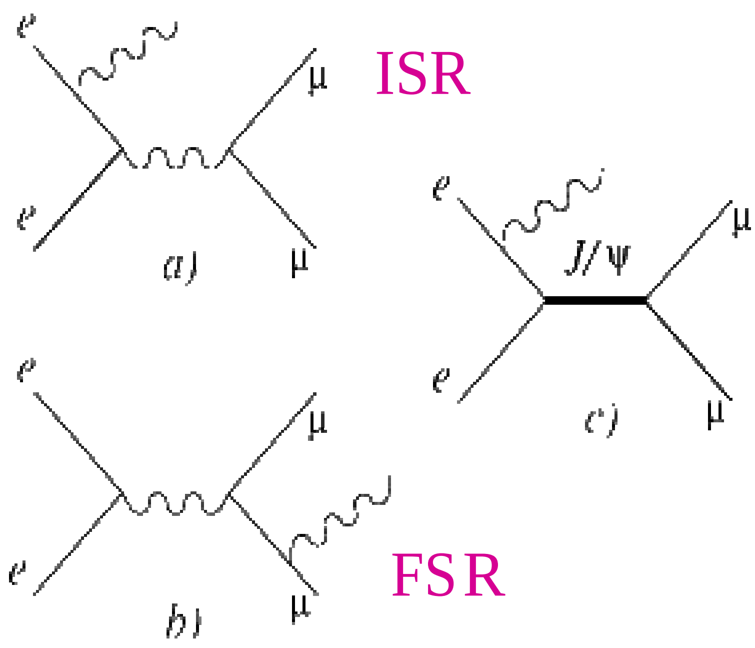
integrate to get:

$$\sigma_{J/\psi\ ISR}(s) = \frac{12\pi^2 \Gamma_{ee} B_{\mu\mu}}{m \cdot s} \cdot W(s, x_0) \qquad x_0 = 1 - \frac{m^2}{s}$$

Only unknown in Born approximation is product $\Gamma_{ee} B_{\mu\mu}$ →

Count events in J/ψ peak to get this product

$e^+ e^- \to \mu^+ \mu^- \gamma$

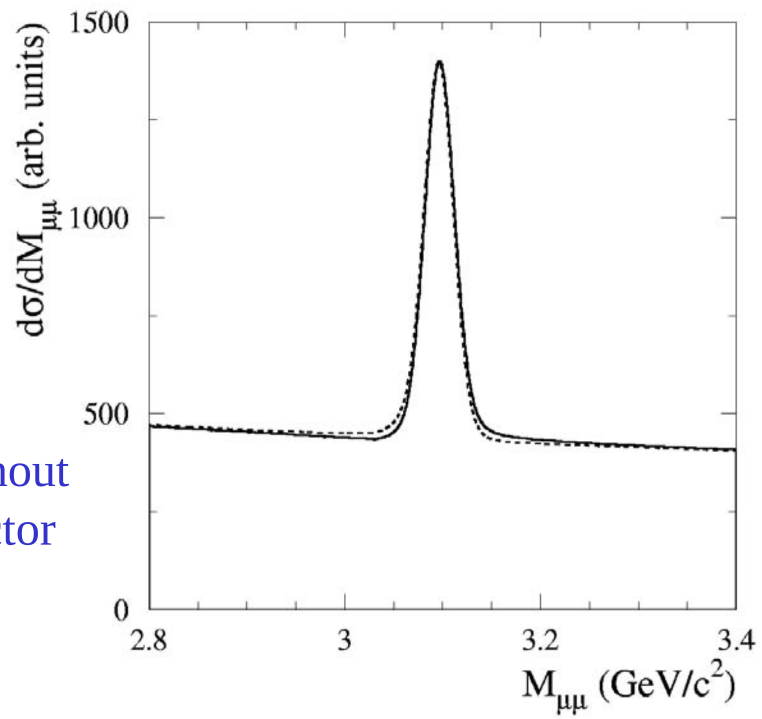


ISR

FSR

But real life is a little more complicated: ISR is not whole story. Must include FSR, resonance and interference.

ISR + J/ψ production



Calculated dimuon distribution with (solid) without (dashed) resonant J/ψ - QED interference (detector resolution included)

Used to estimate sensitivity to shape assumptions

J/ψ production in $e^+e^- \to \mu^+\mu^-\gamma$

Backgrounds: ISR events with 2 body hadronic final states - only background that peaked under the J/ψ is $\pi^+\pi^-\gamma$ final state. Backgrounds from higher multiplicity ISR final states estimated using MC

Systematic Errors

statistical error of K factor	0.9%
systematic error of K factor	1.3%
background uncertainty	0.5%
simulation of J/ψ line shape	1.4%
interference effect	0.3%
total	2.2%

Fit and obtain $\Gamma(J/\psi \to e^+e^-) \cdot B(J/\psi \to \mu^+\mu^-) = 0.3301 \pm 0.0077 \pm 0.0073\,\mathrm{keV}$

Use world average for $B(J/\psi \to e^+e^-)$ and $B(J/\psi \to \mu^+\mu^-)$

to deduce electronic and total width:

$\mathbf{\Gamma_{ee}=5.61 \pm 0.20\ keV}$ and $\mathbf{\Gamma_{J/\psi}=94.7 \pm 4.4\ keV}$

Babar agrees with **and improves on** PDG world values:

$\mathbf{\Gamma_{ee}=5.27 \pm 0.37\ keV}$ and $\mathbf{\Gamma_{J/\psi}=87 \pm 5\ keV}$

Many ISR analyses underway

$e^+ e^- \rightarrow p\ p\ \gamma$ use same technique as for $\mu^+\mu^-$ but require:

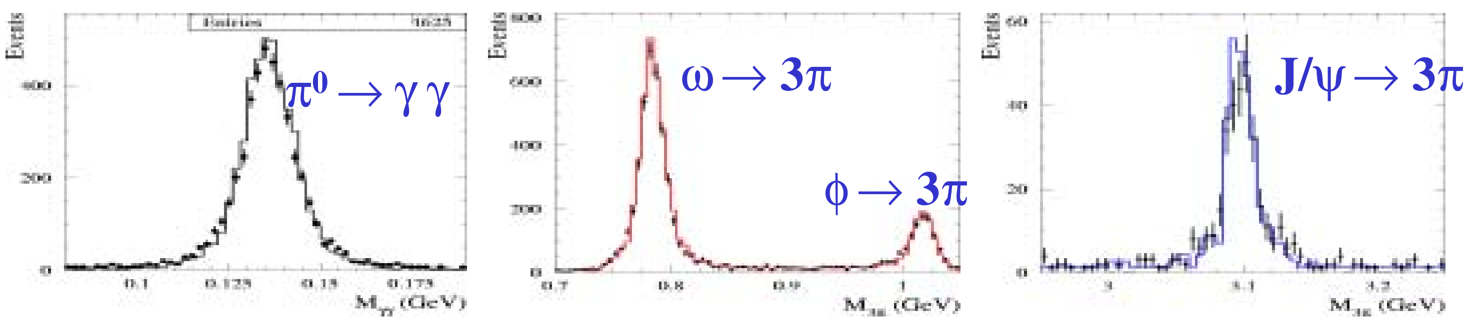
- 2 ID'd p's, opposite charge
- 1C-fit with p p hypothesis

$e^+ e^- \rightarrow \pi^+ \pi^- \pi^0\ \gamma$ use same technique as for $\pi^+\pi^-$ but require:

- 2 photons (forming π^0)
- 3C-fit with $\pi^+ \pi^- \pi^0$ hypothesis

Data and MC agree well, backgrounds under investigation

($K^+ K^- \pi^0$, $\pi^+ \pi^- \gamma$, $\pi^+ \pi^- \pi^0 \pi^0$, τ pairs, other hadron combinations)



$e^+ e^- \rightarrow$ 4 charged hadrons γ

require:

- 4 charged tracks, charge sum zero
- hard photon: $E_{\gamma CM}$ >3 GeV
- 1C-fit with ($\pi^+\pi^- \pi^+\pi^-$) final state hypothesis

  ($\pi^+\pi^-$ **K^+K^-**) if one or two K's ID'd

  (**$K^+K^- K^+K^-$**) if three or four K's ID'd

High statistics:

BABAR will have significant improvement on PDG world average branching ratios for these three **$J/\psi \rightarrow$ 4 hadron** final states

Summary and Conclusions

A B- Factory is good for more than just B's

ISR luminosity high & efficiencies reasonably understood at BABAR

Initial state radiation great tool for examining low energy hadronic cross-sections - variable energy machine
(essential for g-2 hadronic corrections, m_{Higgs} indirect limits)

New results in hadron spectroscopy

Best yet determination of electronic and total J/ψ widths

Many more channels possible

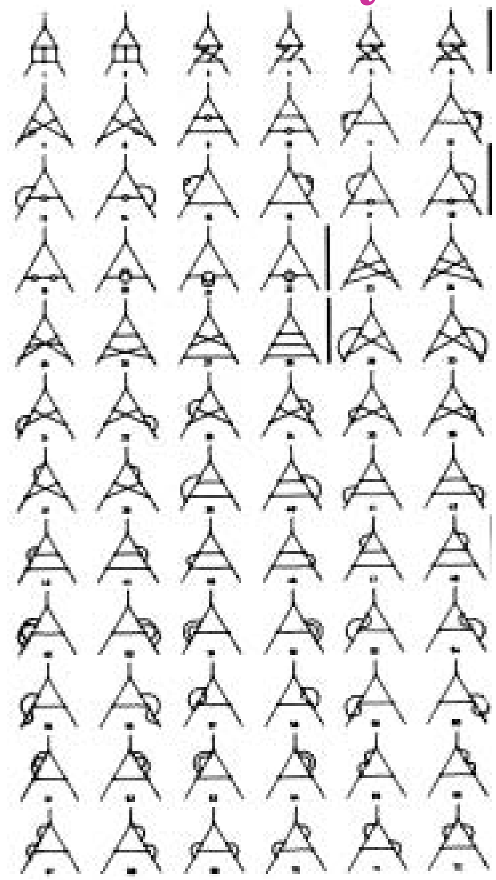
Extras

Lepton Anomalous Magnetic Moment, g-2

Dirac theory: gyromagnetic ratio of a lepton is exactly 2.

Deviations from 2. are caused by radiative corrections to the lepton-photon vertex due to quantum field fluctuations.

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} \qquad \text{anomaly:} \quad a = \frac{g-2}{2}$$



Precision measurements of **electron's** anomalous magnetic moment (and hyperfine structure and Lamb shift) drove development of QED. Now a_e measured to **4 parts per billion**!

3rd order corrections shown,

$\rightarrow$ calculated to 4th order