Observation of Exclusive Hadronic Processes at 10.6 GeV: $e^+e^-\to\rho^0\rho^0,\phi\rho^0,\gamma\eta,\gamma\eta',\phi\eta$

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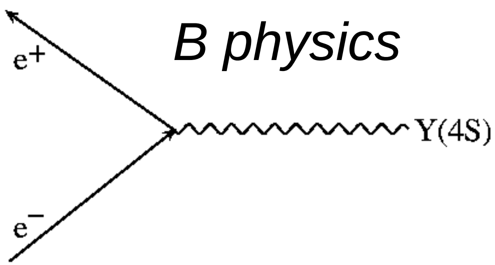
Outline

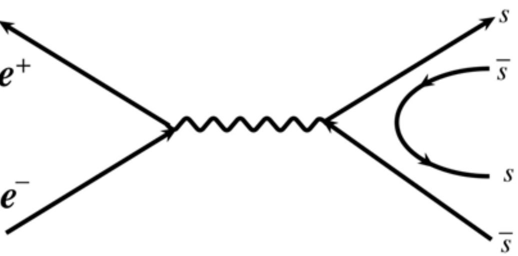
- *Introduction*
- *First Observation of positive C parity hadronic final states in the reactions $e^+e^- \rightarrow \rightarrow \rho^0\rho^0, \phi\rho^0$*
- *Observation of $e^+e^- \rightarrow \gamma\eta, \gamma\eta'$ (C=–1) and the time-like transition form factor at 10.6 GeV*
- *Observation of $e^+e^- \rightarrow \phi\eta$ (C=–1 final state)*
- *Summary and Outlook*

Introduction—possible processes at B factories

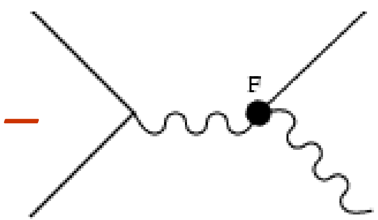
One photon related process

B physics





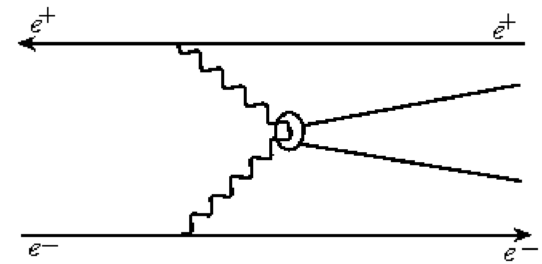
C=−



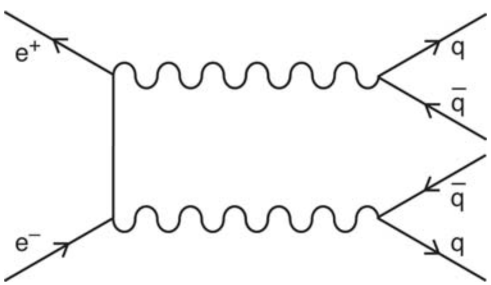
A test ground for QCD

Two photon interaction processes

Two Photon TP



C=+



Two-Virtual-Photon-Annihilation, TVPA; new observation at BaBar

Today's topic

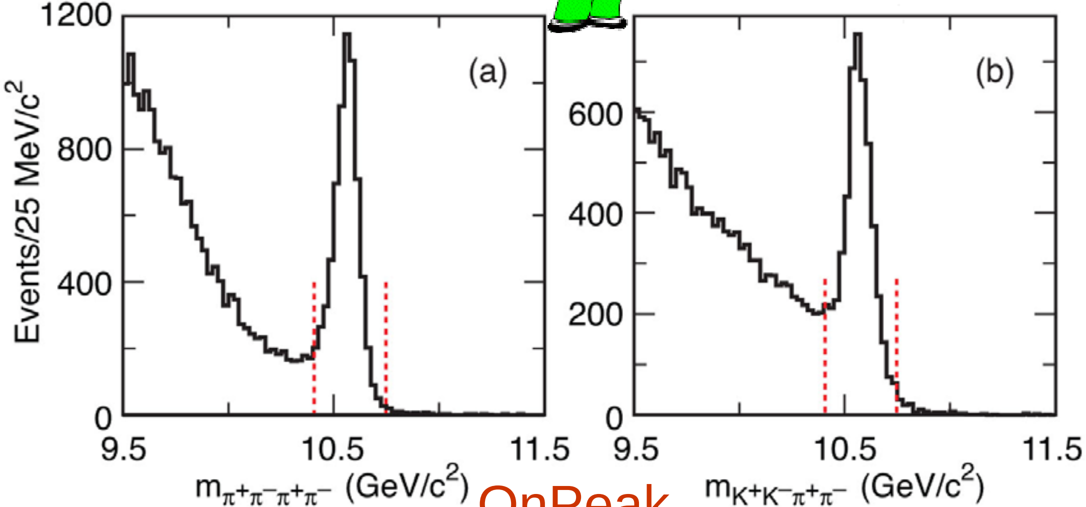
Introduction

- B factories are desired to study the following process:
  $e^+e^- \to \gamma^* \to \Upsilon(4S) \to B\,\bar{B}$

- The high integrated luminosity at B factories also provides a new window on other e^+e^- physics :
  I. Two-virtual-photon-annihilation (TVPA) yielding hadronic final states
  --Different from well-known TP
  --Speculated to be significant but not observed for double charmonium production
  --First time observation
  II. one photon to exclusive hadronic final states
  -- $e^+e^- \to$hadronic states are studied everywhere, exclusive is special
  cross section very small @10.6 GeV, test s dependence
  III. Interference between these processes

- Very large integrated luminosity at interesting s values!
  ~205 fb^{-1} @10.58 GeV (OnPeak), 20 fb^{-1} @10.54 GeV (OffPeak)
  Can explore new opportunities; much more to be analyzed!

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)



OnPeak

--4 well-reconstructed charged tracks ($K^+K^-\pi^+\pi^-/\pi^+\pi^-\pi^+\pi^-$)

--identified kaons or pions

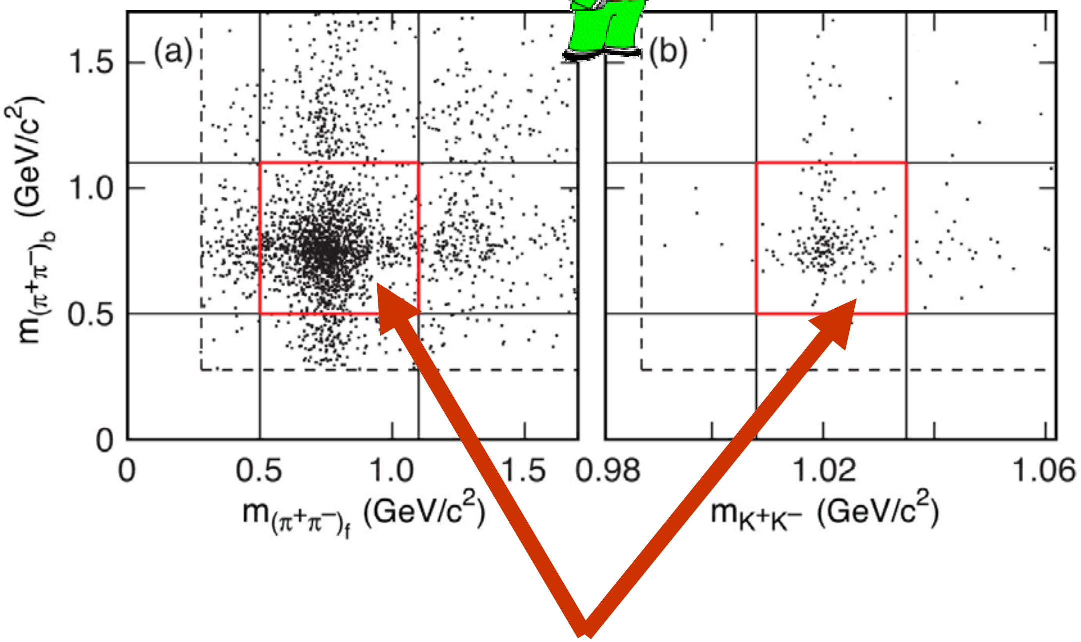
--Vertex Constraint $p(\chi^2)>0.1\%$

--$p_K>800$ MeV/c, $p_\pi>600$ MeV/c to reduce QED background

Select events of invariant mass of 4 track system ($K+K-\pi+\pi-/\pi+\pi-\pi+\pi-$) within 170 MeV of c.m. energy.

PRL 97, 112002 (2006)

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)



Scatter plots of :

m_{KK} vs $m_{\pi\pi}$ $(KK\pi\pi)$

$m_{(\pi\pi)f}$ vs $m_{(\pi\pi)b}$ $(\pi\pi\pi\pi)$

Only one entry in the $\pi^+\pi^-\pi^+\pi^-$ scatter plot out of two possible combinations (no ambiguity)

Use binned log-likelihood fit over 9 tiles to extract signal

Define signal tiles:

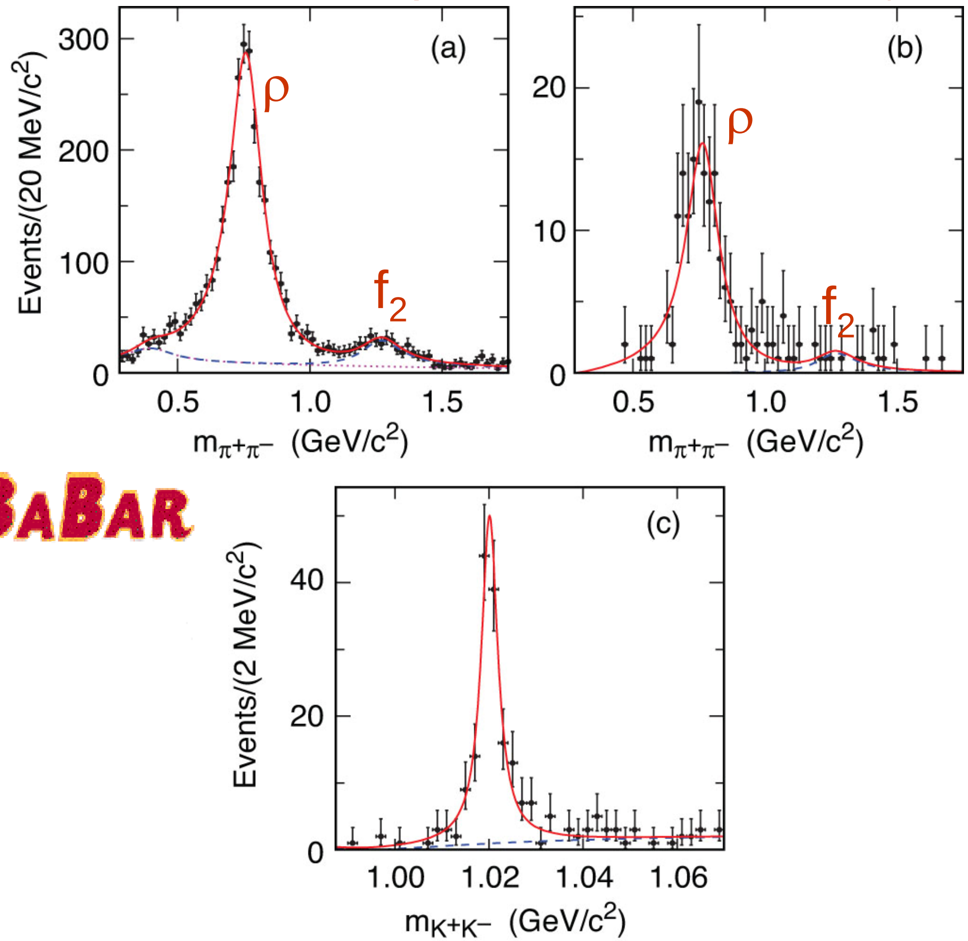
$0.5 < m_{\pi\pi} < 1.1$ GeV/c^2 & $1.008 < m_{KK} < 1.035$ GeV/c^2

"ρ" "ϕ"

Use adjacent tiles to subtract background

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)

ππ against "ρ" ππ against "ϕ"



KK against "ρ"

Mass projections for *selected events*

Clean ϕ and ρ^0 signals

Relativistic Breit-Wigner lineshapes used in the fit

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)

The extracted signals:

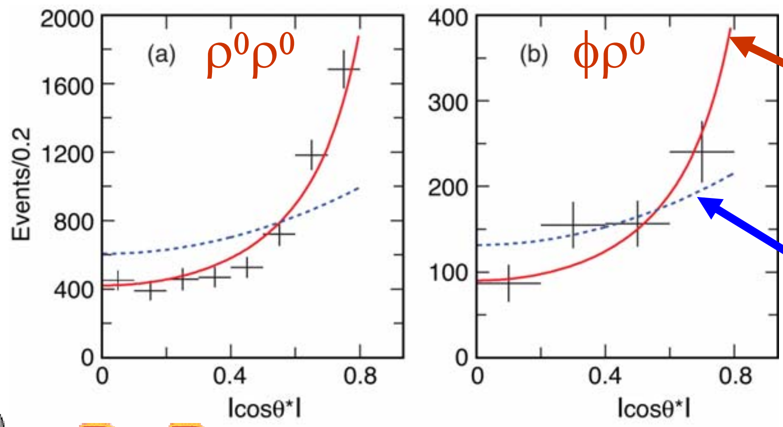
	On+OffPeak		*OnPeak Yield*	*OffPeak Yield*	*OffPeak expected (continuum)*
	Yield	significance			
$\rho\rho$	*1243±43*	$>> 5\sigma$	*1138± 42*	*104± 14*	*112 ±4*
$\phi\rho$	*147±13*	$>> 5\sigma$	*135± 13*	*14± 4*	*13± 1*

consistent

Y(4S) production does not contribute because of C parity violation.
The yields are consistent with continuum production
Signals large enough that can investigate the angular distributions

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)

Efficiency corrected distributions

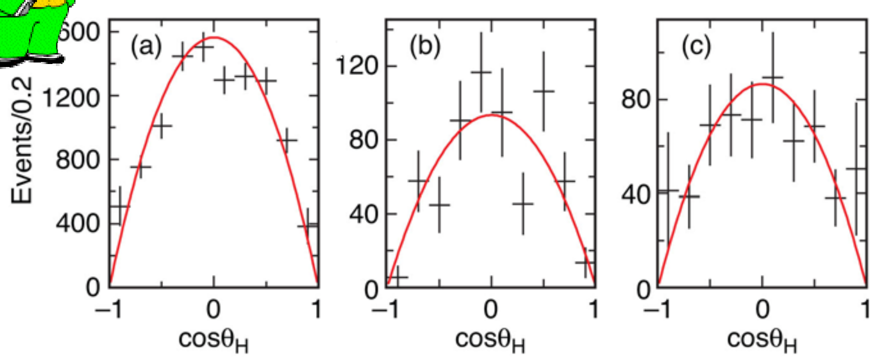


Production angle θ^*–polar angle of ϕ or $\rho_{forward}$ in CM
Expectation for TVPA:

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{1+\cos^2\theta^*}{k^2-\cos^2\theta^*}$$ with $k^2 \sim 1$

where k depends on the vector meson masses and $\sqrt{s}$:

$1+\cos^2\theta^*$ for one photon annihilation (for comparison)



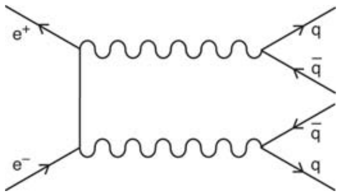
ρ from $\rho\rho$ *ϕ from $\phi\rho$* *ρ from $\phi\rho$*

$\sin^2\theta_H$ distributions

All angular distributions are consistent with TVPA expectation

Observation of $e^+e^- \to \rho^0\rho^0/\phi\rho^0$ (C=+1)

These are the first observations of $e^+e^- \to$ C=+1 exclusive hadronic final states
Arguments to support TVPA production:



- *C parity*
- *Consistency of the yield between OnPeak and OffPeak*
- *Observed angular distributions*

Define $1.008<m_\phi<1.035$ GeV and $0.5<m_\rho<1.1$ GeV (reduce uncertainty); the cross sections for these mass regions and $|\cos\theta^*|<0.8$ are:

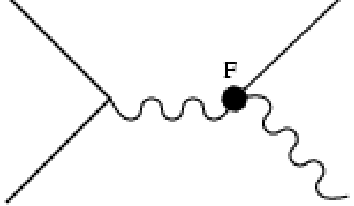
$\sigma(\rho\rho)=20.7\pm0.7(stat)\pm2.7(syst)$ fb — *$21.4\pm0.7/17.7\pm0.6$ fb (Theory)*

$\sigma(\phi\rho)=5.7\pm0.5(stat)\pm0.8(syst)$ fb — *$6.0\pm0.1/\ 5.6\pm0.2$ fb (Theory)*

[note: $\sigma(e^+e^- \to$ hadrons at Ecm=10 GeV) ~ 3 nb]

The corresponding contribution to muon g-2 from TVPA is small; this removes a possible uncertainty source in the g-2 calculation

$e^+e^- \to \eta\gamma$, $e^+e^- \to \eta'\gamma$



- *The cross section of* $e^+e^- \to \gamma^* \to P\gamma$ *(P = η or η'):*

$$\sigma\left(e^+e^- \to P\gamma\right) = \frac{2}{3}\pi^2\alpha^3\left|F_P\left(q^2\right)\right|^2$$

transition form factor

$F_P(q^2)$ can be calculated using pQCD:

$$-q^2F_P\left(q^2\right) = \sqrt{2}f_P\left(1 - \frac{5}{3}\frac{\alpha_s\left(q^2\right)}{\pi}\right) \text{for } q^2 >> 1\,\text{GeV}^2$$

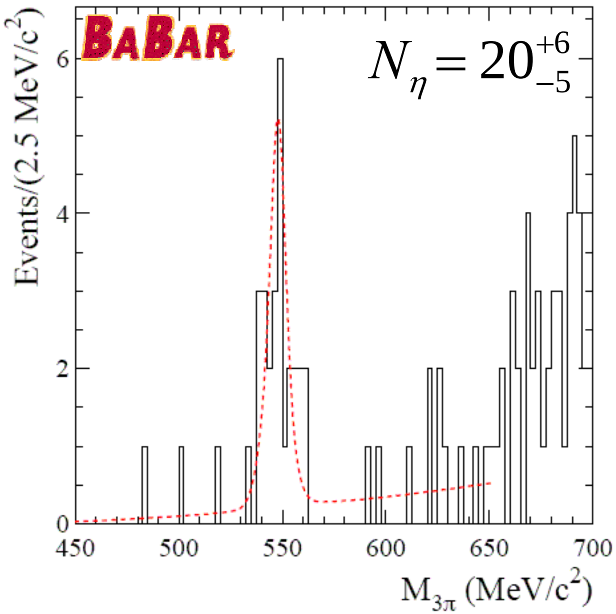
effective decay constant

- *Measurement of form factors at high q^2 is needed to test phenomenological models.*
  - *Previous measurements from $\gamma^*\gamma^* \to \eta^{(\prime)}$ measure up to $q^2 \approx 20$ GeV^2.*
  - *We measure the transition form factor at q^2 = 112 GeV^2, i.e. much closer to the asymptotic region.*

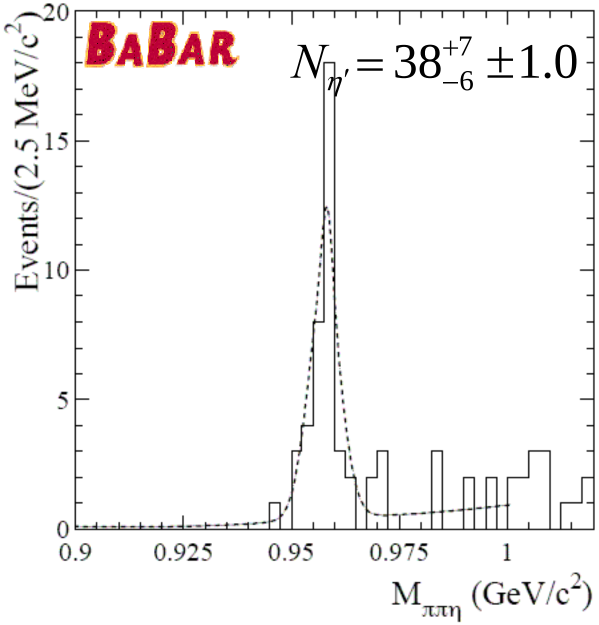
$e^+e^- \to \eta\gamma$, $e^+e^- \to \eta'\gamma$

- *Very rare but clean two-body final states:*

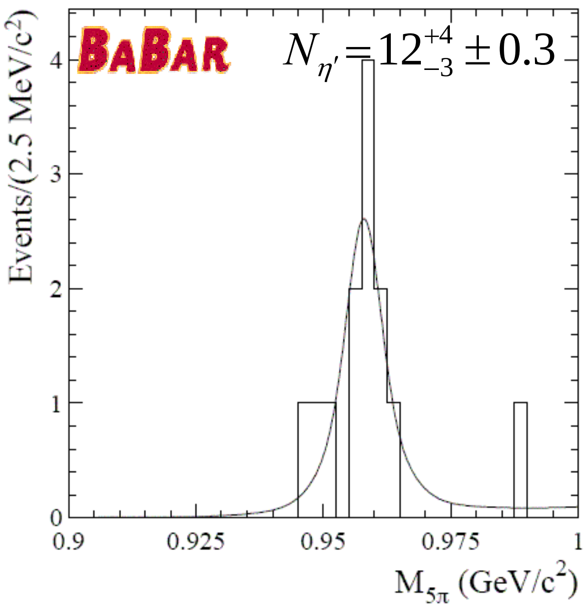
$e^+e^- \to \eta\gamma \to 3\pi\gamma$



$e^+e^- \to \eta'\gamma \to 2\pi3\gamma$



$e^+e^- \to \eta'\gamma \to 5\pi\gamma$



$$\sigma\left(e^+e^- \to \eta\gamma\right) = 4.5^{+1.2}_{-1.1} \pm 0.3\ fb$$
$$\sigma\left(e^+e^- \to \eta'\gamma\right) = 5.4 \pm 0.8 \pm 0.3\ fb$$

PRD 74:012002 (2006)

$e^+e^- \to \eta\gamma$, $e^+e^- \to \eta'\gamma$

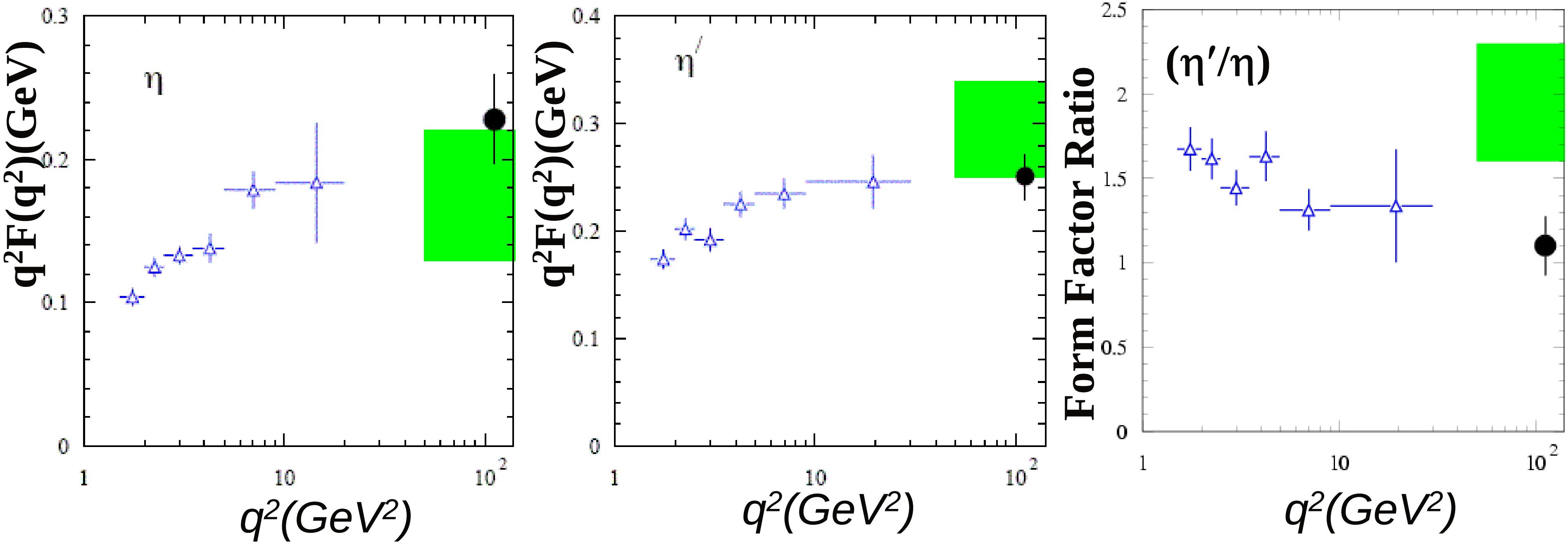
q^2=112 GeV^2	BaBar Data	Predictions
$q^2F(\eta')$	$0.251 \pm 0.019 \pm 0.008$	$0.25 - 0.34$
$q^2F(\eta)$	$0.229 \pm 0.030 \pm 0.008$	$0.11 - 0.22$
Ratio (η'/η)	1.10 ± 0.17	$1.56 - 2.27$

The Transition Form Factors

- **BaBar**

Δ CLEO

Theoretical predictions



Observation of $e^+e^- \to \phi\eta$ at ~10.6 GeV

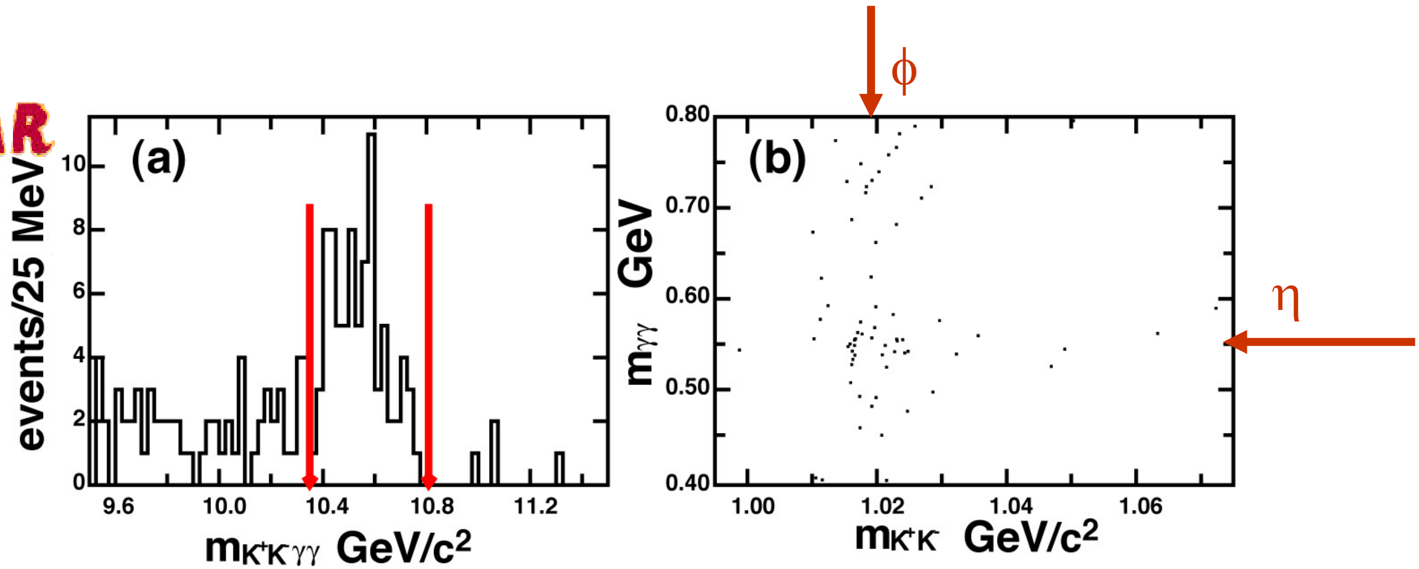
To be submitted to PRD

- *$e^+e^- \to \phi\eta$ is analogous to $e^+e^- \to J/\psi\eta_c$ in the s quark sector*
  need relativistic treatment, η--not pure s-sbar pair

- *Provide information on s-dependence by combining with a CLEO measurement at lower energy*

Basic requirements (similar to $\phi\rho$:
--2 well-reconstructed tracks
-- at least 2 good photons (E_γ>500 MeV)
--identified kaons
--Vertex constraint, $p(\chi^2)$ >0.001
--m_{KK}<1.1 GeV/c^2, 0.4<$m_{\gamma\gamma}$<0.6 GeV/c^2
--Invariant mass of 4 particle ($K^+K^-\gamma\gamma$)
within 230 MeV of c.m. energy.

Observation of $e^+e^- \to \phi\eta$ at ~10.6 GeV



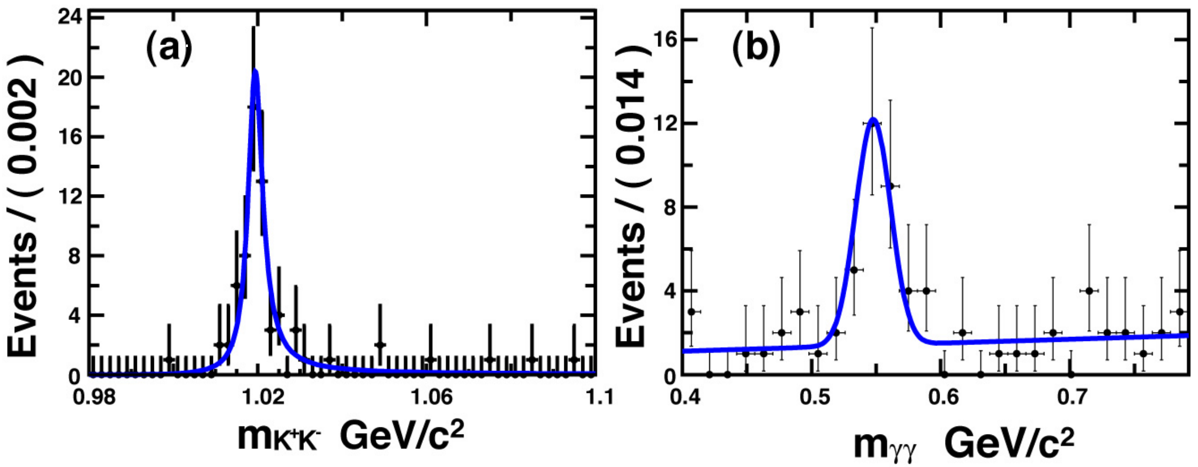
Y(4S) data Y(4S)+Off peak data

We see $\phi\eta$ correlation. Define $1.008 < m_\phi < 1.035\ GeV/c^2$

use a two-dimensional log-likelihood fit to extract signals
P-wave relativistic Breit-Wigner for ϕ
Gaussian resolution function for η

fix the mass and width of the ϕ and the mass of the η to PDG 2004 values
fix the r.m.s value of the η Gaussian to the MC resolution value (13.6 MeV/c^2).

Observation of $e^+e^- \to \phi\eta$ at ~10.6 GeV



Mass projections

Yield in the defined mass window:
On+Off: 24±5 On: 20±5 Off: 3±2

Significance: 6.5 σ

U.L. for Y(4S) decay @90% CL based on -10 ± 21 events: $2.5X10^{-6}$

Observation of $e^+e^- \to \phi\eta$ at ~10.6 GeV

The full angular distribution, assuming one-photon production, is given by:

$$\frac{dN}{d\cos\theta^* d\cos\theta_\phi d\varphi_\phi} \propto \sin^2\theta_\phi (1 + \cos^2\theta^* + \cos 2\varphi_\phi \sin^2\theta^*)$$

Projections:

$$\frac{dN}{d\cos\theta^*} \propto (1 + \cos^2\theta^*)$$

$$\frac{dN}{d\cos\theta_\phi} \propto \sin^2\theta_\phi$$

$$\frac{dN}{d\varphi_\phi} \propto (2 + \cos 2\varphi_\phi)$$

θ^*: polar angle in c.m.

θ_ϕ: ϕ helicity angle

φ_ϕ: azimuthal angle of the decay plane ϕ w.r.t. production plane normal in the c.m. frame

Distributions in data are consistent with predictions with limited statistics

We re-weight MC angular distributions as above for efficiency estimation.

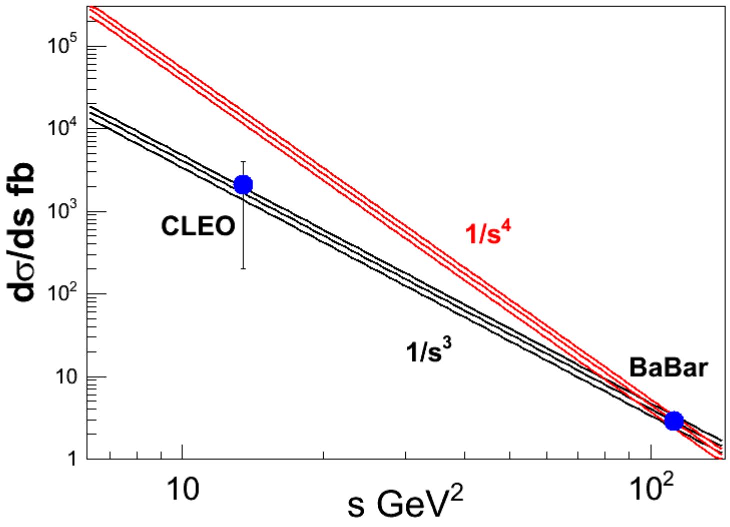
Observation of $e^+e^- \to \phi\eta$ at ~10.6 GeV

Define $1.008 < m_\phi < 1.035$ GeV/c^2 and $0.5 < m_\rho < 1.1$ GeV/c^2. After radiative corrections, the restricted cross section ($|\cos\theta^*| < 0.8$) are measured as:

$\sigma(\phi\eta) = 2.1 \pm 0.4(stat) \pm 0.1(syst)$ fb

Extend to ($|\cos\theta^*| <= 1.0$ by assuming $1 + \cos^2\theta^*$ distribution:

$\sigma(\phi\eta) = 2.9 \pm 0.5(stat) \pm 0.1(syst)$ fb



Combine with CLEO measurement at lower energy; $1/s^3$ energy dependence favored over $1/s^4$, assuming continuum production

A direct comparison with theoretical calculation is interesting. Another puzzle?

Analysis in Initial State Radiation data is ongoing, will provide more information on the s dependence

Summary and Outlook

At BaBar we have:

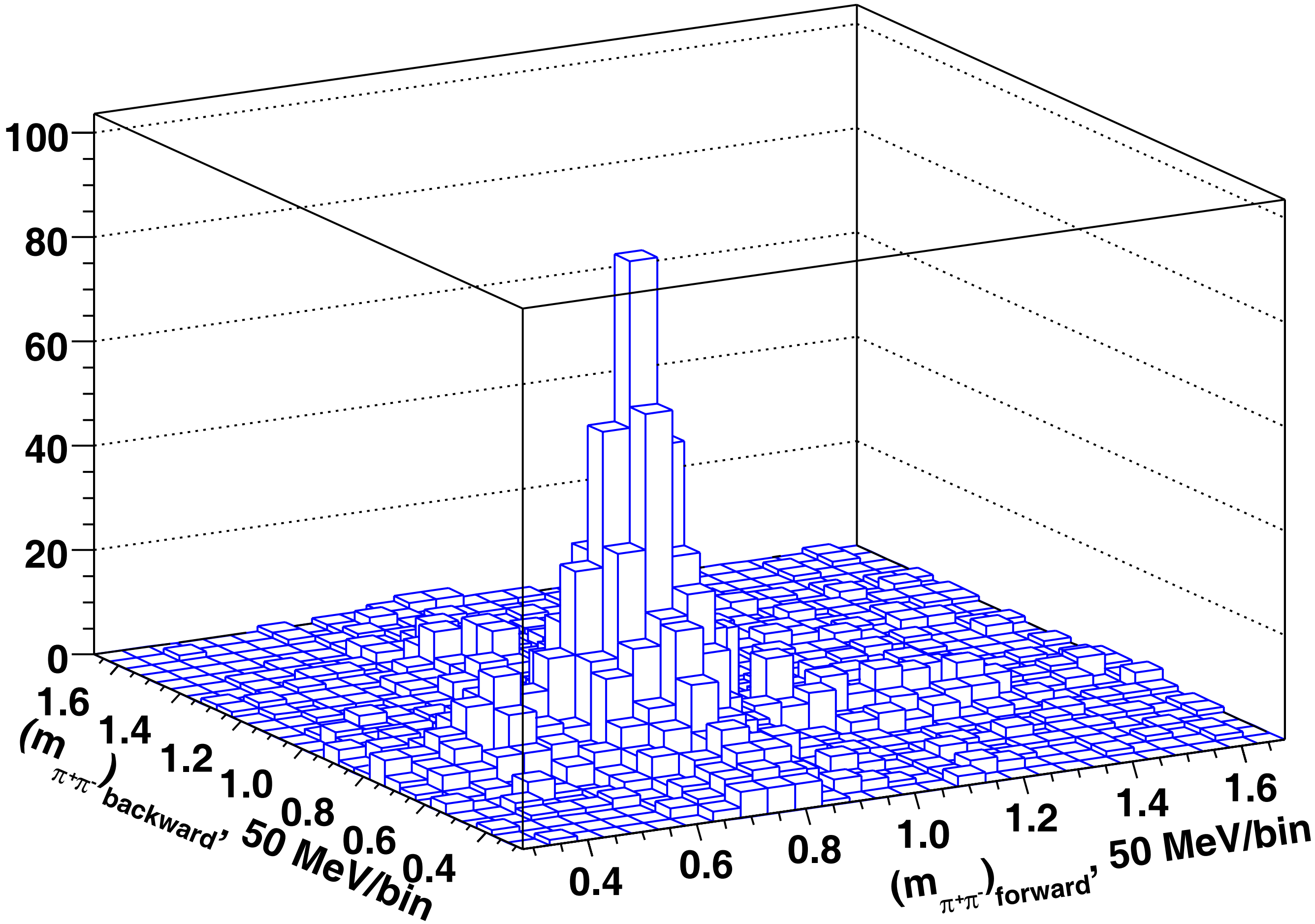
- Made the first observations of the TVPA hadronic processes:
  $e^+e^-\to\rho^0\rho^0$ and $e^+e^-\to\phi\rho^0$

- Measured the η and η' transition form factors at high q^2 (~112 GeV^2)

- Observed the process $e^+e^- \to\phi\eta$ and measured the cross section; this provides an interesting test of QCD prediction of the energy dependence, assuming continuum production.

We plan to use the high integrated luminosity at BaBar to investigate other interesting low-multiplicity exclusive final states in the near future!

Backup plots



Nine Tile likelihood fit Method

A binned likelihood fit based on nine-tiles is designed to extract signal yield in order to handle possible nonlinear background in $e^+e^- \rightarrow \phi\rho^0$ and $e^+e^- \rightarrow \rho^0\rho^0$ which is described in Chapter 7. The likelihood of obtaining the events observed in each tile n_i is given by

$$L = \prod_i e_i^{-m_i} \frac{m_i^{n_i}}{n_i!} \tag{2}$$

where m_i is the number of events expected for a given choice of the parameters, and n_i is the number seen. For purposes of fitting it is convenient to take the log and drop terms that do not depend on the parameters through the m_i's. This yields

$$lnL = \sum(-m_i + n_i ln m_i) \tag{3}$$

The parameters are the number of signal events S, the number of ϕ-only background events B_ϕ, the number of ρ-only background events B_ρ and B the number of events with neither a ϕ nor ρ.

By combining Monte Carlo, mass projectiion fit, and other assumptions, we can specify the fraction of events of each type that contribute to each tile – f_i^X. Thus the contributions to each tile are given by

$$m_i = f_i^S S + f_i^\phi B_\phi + f_i^\rho B_\rho + f_i B \tag{4}$$

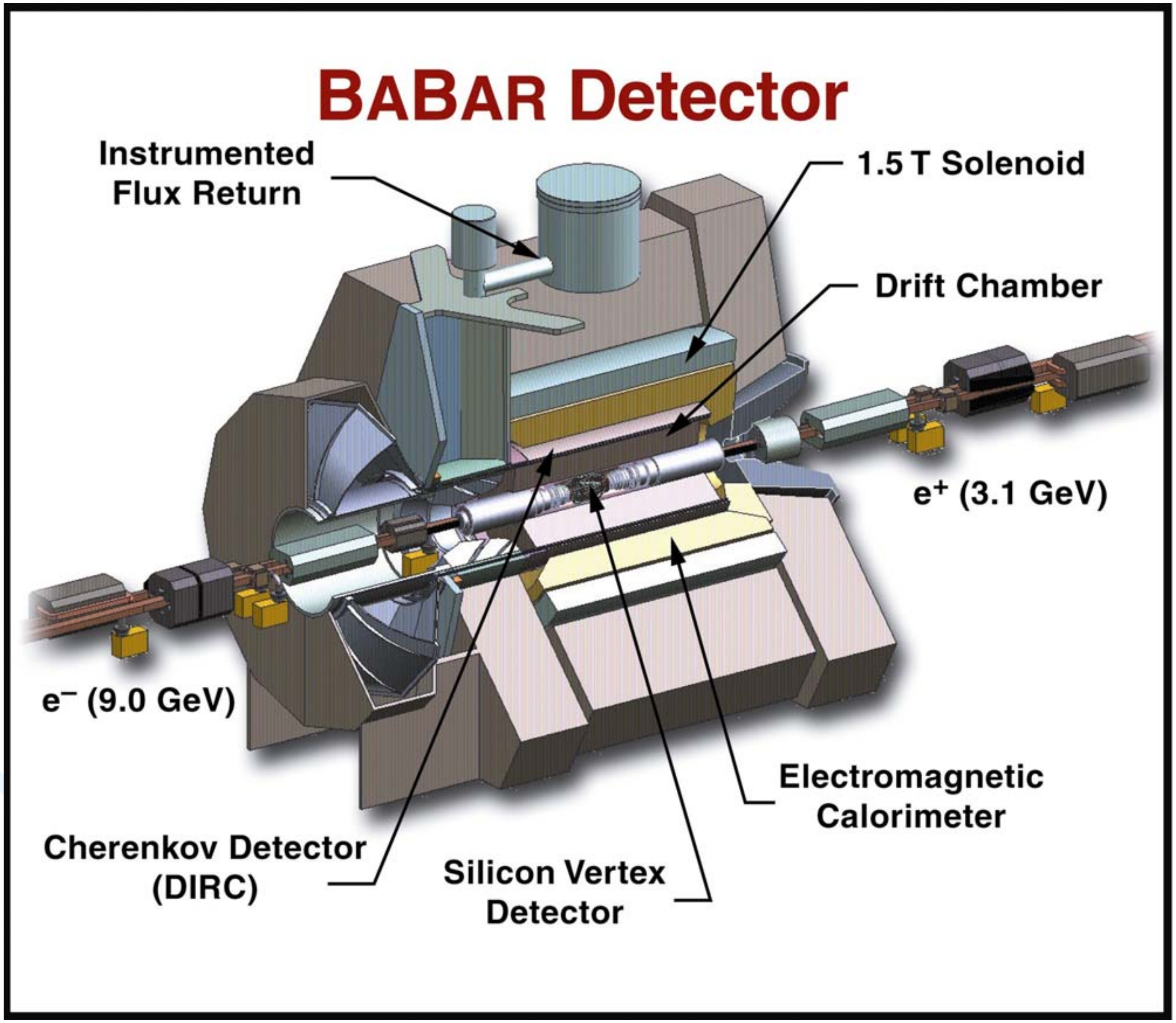
where the subscript (or lack thereof) indicates the component.

N_1	N_2	N_3
N_4	N_5	N_6
N_7	N_8	N_9

f_i^S—from Monte Carlo

f_i^ρ, f_i^ϕ—from mass projection fit

f_i^B—float slopes assuming linear


BABAR Detector
Instrumented
Flux Return
1.5 T Solenoid
Drift Chamber
e⁺ (3.1 GeV)
e⁻ (9.0 GeV)
Electromagnetic
Calorimeter
Cherenkov Detector
(DIRC)
Silicon Vertex
Detector

Radiative Corrections

Assuming ϕ and η decaying branching ratios to be 1 and ignoting other correction factors first, the visible cross section and the Born cross section have the following relation due to the radiation of soft photons[3]:

$$\sigma_{visible} = \frac{N_{observe}}{L} = \int_0^{x_{max}} \sigma_B(s(1-x)) * \epsilon(x) * W(s,x)dx \tag{12}$$

where $N_{observe}$ is the number of observed signal events, $\mathcal{L}$ is the integrated luminosity, $s = 10.58^2$ GeV^2, $x = E_\gamma/(\sqrt{s}/2)$ is the normalized radiated photon energy, $\epsilon(x)$ is the detection efficiency for certain x, $W(s,x)$ (See Appendix B) is the QED radiator function [20], and $\sigma_B(s(1-x))$ is the Born cross section at $q^2 = s(1-x)$. Assuming σ_B has a $1/s^n$ dependence, then $\sigma_B(s(1-x)) = \sigma_B(s)(\frac{s}{s(1-x)})^n = \sigma_B(s) * \frac{1}{(1-x)^n}$ which has a $1/s^n$ dependence, equation 12 can be rewritten as:

$$\sigma_{visible} = \sigma_B(s) * \epsilon(x=0) * (1+\delta) \tag{13}$$

where δ is the radiative correction, and

$$(1+\delta) = \int_0^{x_{max}} (\frac{1}{1-x})^n * \frac{\epsilon(x)}{\epsilon(x=0)} * W(s,x)dx \tag{14}$$

The $\epsilon(x)$ is obtained from MC simulation, and the angular distributions are re-weighted by equa-