Exclusive Hadronic Final States in e<sup>+</sup>e<sup>-</sup> Interactions and in B Decays at *BABAR* 

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# Topics in this talk

- Ø The first observation of C=+1 hadronic final states in e<sup>+</sup>e<sup>-</sup> interactions (e<sup>+</sup>e<sup>-</sup>  $\rightarrow \rho^0 \rho^0$  and  $\rho^0 \phi$ )
- Ø Observation of the interactions  $e^+e^- \rightarrow \varphi \eta$  and  $\rho^+\rho^-$  at  $\sqrt{s} \sim 10.6 \text{ GeV}$
- Ø  $\eta$  and  $\eta'$  Transition Form Factors at  $q^2 = 112 \text{ GeV}^2$
- Ø The energy dependence of  $e^+e^- \rightarrow p\overline{p}$  via Initial State Radiation (ISR)
- ${\it {\it O}}$  B decays with  $p \overline{p}$  in the final state
- Ø Test of factorization in  $\overline{B}^0 \rightarrow D^{*+}\omega\pi^-$  decay



## $e^+e^- \rightarrow \rho^0 \rho^0 \& \phi \rho^0$ reactions at $\sqrt{s} \sim 10.6 \text{ GeV} (I)$

- $\emptyset$  We can see clear  $\rho$  and  $\varphi$  signals in the exclusive 4-charged-track samples.





- Ø Strong correlations can be seen for  $\rho\rho$  and  $\rho\phi$  which are forbidden in the usual single C = -1 virtual photon processes.



## $e^+e^- \rightarrow \rho^0 \rho^0 \& \phi \rho^0$ reactions at $\sqrt{s} \sim 10.6 \text{ GeV}$ (II)

 $\frac{1+\cos^2\theta}{1-\cos^2\theta}$ 

 $1 + \cos^2 \theta^*$ 

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q  $V(\rho)$ q  $V(\rho,\phi)$ 

Two-Virtual-Photon Annihilation (TVPA)

- Ø The C=+1 final states are consistent with production via 2 virtual photons:
- Ø The angular distributions of the  $\rho$  and  $\phi$  in CM frame are similar to  $e^+e^- \rightarrow \gamma\gamma$  as expected.
- Ø The distributions in cosine of helicity angle,  $\cos\theta_{\rm H}$ , are  $\sim \sin^2\theta_{\rm H}$  as expected for quasi-real photons.
- Ø BaBar preliminary cross section measurements (values agree with TVPA expectation):

$$\begin{array}{lll} \sigma_{\rm fid} \left( e^+ e^- \to \rho^0 \rho^0 \right) &=& 20.7 \pm 0.7 ({\rm stat}) \pm 2.7 ({\rm sys}) \ {\rm fb} \\ \sigma_{\rm fid} \left( e^+ e^- \to \phi \rho^0 \right) &=& 5.7 \pm 0.5 ({\rm stat}) \pm 0.8 ({\rm sys}) \ {\rm fb} \end{array}$$

 $fid = |\cos\theta^*| < 0.8$ 

 $0.5 < m(\rho) < 1.1 \text{ GeV/c}^2$ 

 $1.008 < m(\phi) < 1.035 \text{ GeV/}c^2$ 







# $e^+e^- \rightarrow \phi \eta$ reaction at $\sqrt{s} \sim 10.6 \text{ GeV} (I)$

- $\emptyset$  e<sup>+</sup>e<sup>-</sup> $\rightarrow \varphi \eta$  is a vector-pseudoscalar final state.
- Ø Production rate described by form factors predicted in QCD based models.

PRD 24, 2848 (1981) hep-ph/9906387 Phys. Lett. B 425, 365 (1998)



There is a discrepancy between theory and experiment for  $e^+e^- \rightarrow J/\psi \eta_c$  ( $\sigma$ 's in fb):

$$\sigma(e^+e^- \to J/\psi\eta_c(1S)) = 17.6 \pm 2.8^{+1.5}_{-2.1}$$
 fb BaBar  
 $\sigma(e^+e^- \to J/\psi\eta_c(1S)) = 2.31 \pm 1.09$  fb Theory

BaBar: PRD 72, 031101 (2005) Theory: Braaten & Lee, PRD 67, 054007 (2003)

> • Kaon momentum > 800 MeV/c •  $m_{KK} < 1.1 \text{ GeV/c}^2$ •  $0.4 < m_{\gamma\gamma} < 0.8 \text{ GeV/c}^2$ •  $\chi^2$  of vertex fit > 0.1% • data sample of 224 fb<sup>-1</sup>

## $e^+e^- \rightarrow \phi \eta$ reaction at $\sqrt{s} \sim 10.6$ GeV (II)



Ø Derived a 90% confidence level:

 $B(\Upsilon(4S) \rightarrow \phi \eta) < 2.5 \times 10^{-6}$ 

BaBar analysis at lower energies in progress using ISR production of φη

- Theory predicts 1/s<sup>4</sup> dependence
- BaBar and CLEO's favor a 1/s<sup>3</sup> dependence
- The disagreement is  $2\sigma$

# $e^+e^- \rightarrow \rho^+\rho^-$ reaction at $\sqrt{s} \sim 10.6 \text{ GeV} (I)$



- This is a vector-vector final state.
- Provides a test of QCD at the amplitude level using angular distributions.

Brodsky & Lepage, PRD 22, 2157 (1980) Chernyak & Zhitnitsky, Phys. Rept. 112, 173 (1984)

- Require  $|\cos\theta^*| < 0.8$  where  $\theta^*$  is the angle between  $\rho^+$  and  $e^-$  in c.m. frame
- $m(\pi^{\pm}\pi^{0}) < 1.5 \text{ GeV/c}^{2}$
- $\chi^2$  of vertex fit>0.1%
- data sample of 379 fb<sup>-1</sup>
- 308±25 signal events in the  $\rho^{\pm}$  mass window of [0.5,1.1] GeV/c<sup>2</sup>



## $e^+e^- \rightarrow \rho^+\rho^-$ reaction at $\sqrt{s} \sim 10.6 \text{ GeV}$ (II)

Assuming 1-photon ( $J^{PC}=1^{-}$ ) process, one can define three independent helicity amplitudes ( $F_{00}$ ,  $F_{10}$  and  $F_{11}$ ). The projected angular distributions for  $\rho^+\rho^-$  are:

$$\frac{dN}{d\cos\theta^{*}} \propto \frac{3}{4} [\sin^{2}\theta^{*} | F_{00} |^{2} + 2(1 + \cos^{2}\theta^{*}) | F_{10} |^{2} + 2\sin^{2}\theta^{*} | F_{11} |^{2}] \qquad (\textcircled{O} \theta^{*} \text{ is angle} between \rho^{-1} e^{-1} in c.m. f$$

$$\frac{dN}{d\cos\theta_{\pm}} \propto \frac{3}{2} [\cos^{2}\theta_{\pm} | F_{00} |^{2} + (1 + \cos^{2}\theta_{\pm}) | F_{10} |^{2} + \sin^{2}\theta_{\pm} | F_{11} |^{2}] \qquad (\textcircled{O} \theta_{\pm} \text{ is } \rho^{\pm} \text{ hell} angle)$$

$$\frac{dN}{d\varphi_{\pm}} \propto \frac{1}{2\pi} [| F_{00} |^{2} + (4 - \cos 2\varphi_{\pm}) | F_{10} |^{2} + 2 | F_{11} |^{2}] \qquad (\textcircled{O} \theta_{\pm} \text{ is angle} f \pi^{\pm} \text{ angle of } \pi^{\pm} \text{ rest frame})$$

between ρ<sup>+</sup> and e<sup>-</sup> in c.m. frame
θ<sub>±</sub> is ρ<sup>±</sup> helicity angle
φ<sub>±</sub> is azimuthal angle of π<sup>±</sup> in ρ<sup>±</sup> rest frame relative to the production plane of ρ.

Theory predicts:  $|F_{00}|^2 \sim 1/s^2$  PRD 22, 2157 (1980)  $|F_{10}|^2 \sim 1/s^3$  PRD 24, 2848 (1981)  $|F_{11}|^2 \sim 1/s^3$ 

ISR study gives info at low  $\sqrt{s}$  (work in progress)

 $|F_{10}|^2 \sim |F_{11}|^2 < 0.01 |F_{00}|^2$ (at B factory energies)

# $e^+e^- \rightarrow \rho^+\rho^-$ reaction at $\sqrt{s} \sim 10.6 \text{ GeV}$ (III)

- $\emptyset$  Fit for  $|F_{00}|^2$  and  $|F_{10}|^2$  with normalization constraint:

$$|F_{00}|^2 + 4 |F_{10}|^2 + 2 |F_{11}|^2 = 1$$
  
Expect: ~1 small small

Fit Results:

$$\begin{split} |F_{00}|^2 &= 0.51 \pm 0.14 \text{ (stat)} \pm 0.02 \text{ (syst)} \\ |F_{10}|^2 &= 0.10 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)} \\ |F_{11}|^2 &= 0.04 \pm 0.03 \text{ (stat)} \pm 0.00 \text{ (syst)} \end{split}$$

Inconsistent with  $F_{00}$  dominance at  $> 3\sigma$ 



## $e^+e^- \rightarrow \rho^+\rho^-$ reaction at $\sqrt{s} \sim 10.6 \text{ GeV} (IV)$

The cross section is derived from:  $\sigma = N_{sig}/(Luminosity \times \epsilon \times (1+\delta))$ 

Radiative correction  $(1+\delta) = 0.775$ M. Benayoun et. al. Mod. Phys. Lett. A 14, 2605 (1999)

The measured  $\sigma$  (in fb) for  $0.5 < m_0 < 1.1 \text{ GeV/c}^2$ ,  $|\cos\theta^*| < 0.8$  and  $|\cos\theta_{\pm}| < 0.85$ :

 $\sigma_{_{fid}}(e^+e^- \to \rho^+\rho^-) = 8.5 \pm 0.7(stat) \pm 1.5(syst)$  fb

Scaling from acceptance to the full angular ranges:

 $\sigma(e^+e^- \to \rho^+\rho^-) = 20.0 \pm 1.6(stat) \pm 3.6(syst) \pm 1.7(ampl)$  fb

Comparable to cross section for  $e^+e^- \rightarrow \rho^0 \rho^0$  at  $\sqrt{s} \sim 10.6 \text{ GeV}$ 

Upper limit on Y(4S) decay @ 90% confidence level:



#### $\eta$ and $\eta'$ Transition Form Factors (I)

- $\emptyset$  Previous measurements of  $e^+e^- \rightarrow \eta \gamma$  and  $e^+e^- \rightarrow \eta' \gamma$  only up to  $q^2 = 4 \text{ GeV}^2$ ; this analysis is performed at  $q^2 = 112 \text{ GeV}^2$ .
- Ø The BaBar measurements are considered to represent the asymptotic region; cross sections of a few fb expected.



$$\sigma(e^+e^- \to \eta\gamma) = 4.5^{+1.2}_{-1.1} \pm 0.3 \text{ fb} \qquad N(\eta\gamma) = 20^{+6}_{-5}$$
  
$$\sigma(e^+e^- \to \eta'\gamma) = 5.4 \pm 0.8 \pm 0.3 \text{ fb} \qquad N(\eta'\gamma) = 50^{+8}_{-7}$$







#### $\eta$ and $\eta'$ Transition Form Factors (II)

- Ø Problem with precise prediction due to some different uncertainties like the gluon content of  $\eta$  and  $\eta'$ .
- Ø Our data are at the upper and lower limits of the predicted ranges for  $\eta$  and  $\eta'$  respectively.



$$q^{2} |F_{\eta}(q^{2})| = 0.229 \pm 0.030 \pm 0.008$$
 GeV  
 $q^{2} |F_{\eta'}(q^{2})| = 0.251 \pm 0.019 \pm 0.008$  GeV

Our measurement of the ratio of the form factors is:

 $1.10\pm0.17$ 

The prediction is 1.6 - 2.3 for the  $\eta'$  to  $\eta$  ratio.

 $e^+e^- \rightarrow \gamma_{ISR} p\bar{p}$  (I)

Ø The cross section for  $e^+e^- \rightarrow p\bar{p}$  is parametrized by Electric (G<sub>E</sub>) and Magnetic (G<sub>M</sub>) form factors:  $\tau = \frac{4m_p^2}{m^2}$   $e^{\gamma_{ISR}} / P$ 

$$\sigma(m) = \frac{2\pi\alpha^2\beta C}{3m^2} (2 |G_M(m)|^2 + \tau |G_E(m)|^2)$$



Ø Only BABAR has measurements in the entire range  $1.875-4.5 \text{ GeV/c}^2$ 





## $e^+e^- \rightarrow \gamma_{ISR} p \overline{p}$ (III)



The BABAR results are obtained from ISR production and so do not suffer from the typical point-to-point uncertainties which affect other measurements obtained from e<sup>+</sup>e<sup>-</sup> colliders operating at individual c.m. energy values.

- Ø The dashed line in the top plot corresponds to the asymptotic QCD fit [PRL 43, 545, (1979)].
- $\emptyset$  The significant increase in the form factor as the pp threshold is approached may be a manifestation of a pp subthreshold resonance with negative C parity.
- Ø Similar behavior in  $J/\psi \rightarrow \gamma p\bar{p}$  (BES), but  $p\bar{p}$  has positive C parity.

#### B decay to final states containing pp



The phase-space-corrected pp invariant mass for  $B^0 \rightarrow \overline{D}{}^0 p \bar{p}$ ,  $B^0 \rightarrow \overline{D}^{*0} p \bar{p}, B^0 \rightarrow D^- p \bar{p} \pi^+$  and  $B^0 \rightarrow D^* p \bar{p} \pi^+$ 



correlations between p and  $\overline{p}$ 

#### Test of factorization in $\overline{B^0} \to D^{*+} \omega \pi^-$ (I)



Ligeti, Luke and Wise have proposed an elegant test of factorization based on data from  $\tau \rightarrow X\nu$  decay. (Phys. Lett. B507, 142 (2001) ).

The invariant mass spectrum of the  $\omega\pi$  system is found to be in agreement with expectations based on factorization and  $\tau$  decay data.



### Test of factorization in $\overline{B}^0 \rightarrow D^{*+}\omega\pi^-$ (II)

We find an enhancement for  $D^*\pi$ masses around 2.5 GeV. This could be due to color-suppressed decays into a broad  $D_1$  resonance followed by  $D_1 \rightarrow D^{*+}\pi^-$ .





Good agreement for the fraction of  $D^*$  longitudinal polarization in the region of  $\omega\pi$  mass between 1.1 and 1.9 GeV with predictions based on factorization and HQET.

$$\Gamma_L / \Gamma = 0.654 \pm 0.042(stat) \pm 0.016(sys)$$

### Conclusion

### With BaBar's huge data sample we have:

- ü First measurement of  $e^+e^-$  producing C=+1 hadronic final states
- $\ddot{u}$  New QCD tests using  $e^+e^- \rightarrow \phi \eta$  and  $\rho^+\rho^-$
- $\ddot{u}$  Measurements of  $\eta$  and  $\eta'$  Transition Form Factors  $~at~q^2$  =112  $GeV^2$
- $\ddot{u}$  Best measurements of  $e^+e^- \rightarrow p\bar{p}$  with insights onto  $G_E$  and  $G_M$
- $\ddot{u}$  New information on  $p\bar{p}$  threshold enhancement in exclusive B decays
- ü New test of factorization using a new channel  $\overline{B}^0 \rightarrow D^{*+} \omega \pi^-$