Single- and Two-Photon-Induced Processes at the B Factories

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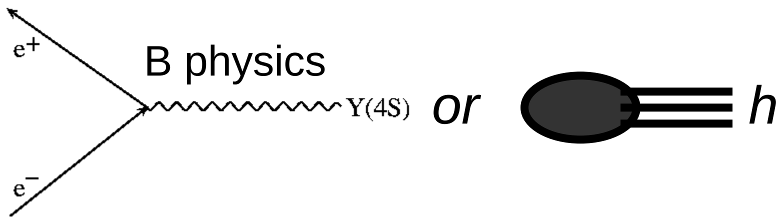
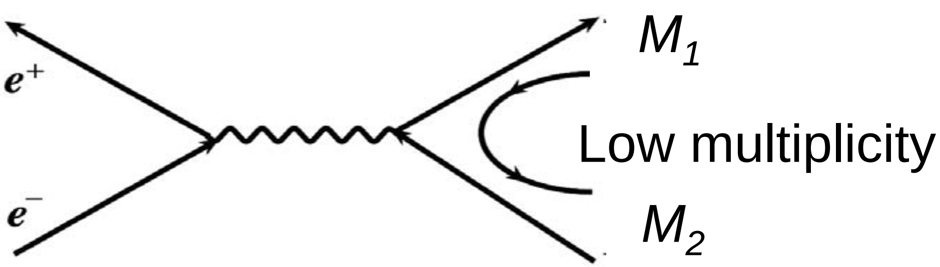
Possible Processes at the B Factories

One-photon processes C=−



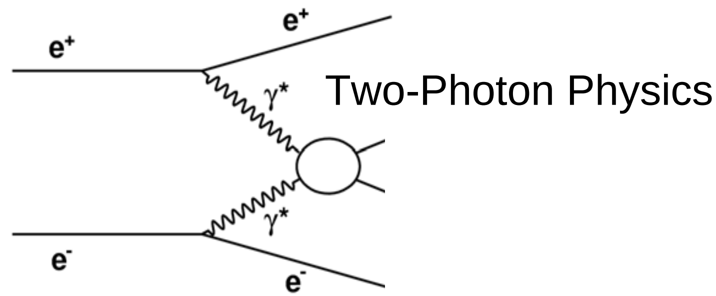
σ~nb

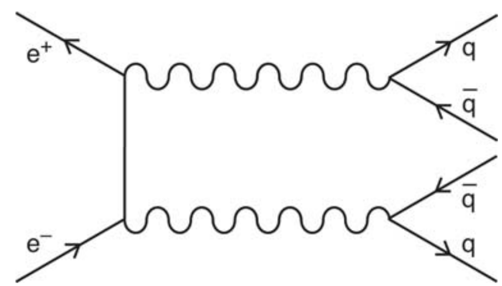


σ~fb

A subset of $e^+e^-\to q\bar{q}$ processes;
$e^+e^-\to M_1 M_2$ can also be studied via ISR;
Excellent test ground for QCD

Two-photon processes C=+

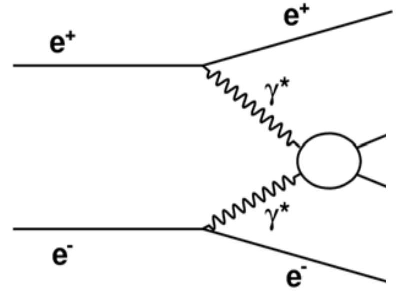




Two-Virtual-Photon-Annihilation (TVPA)

Outline

- Two-photon physics:



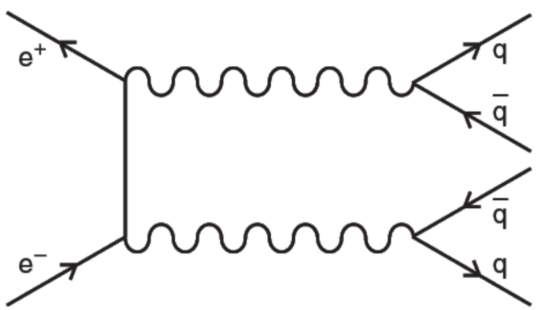
$\gamma\,\gamma \to \pi^0\pi^0$ (both γ's quasi-real)

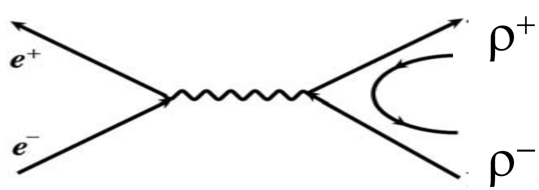
$\gamma\,\gamma^* \to \pi^0$ (one γ highly virtual)

- One- or two-photon-induced **e**$^+$ **e**$^-$ processes:

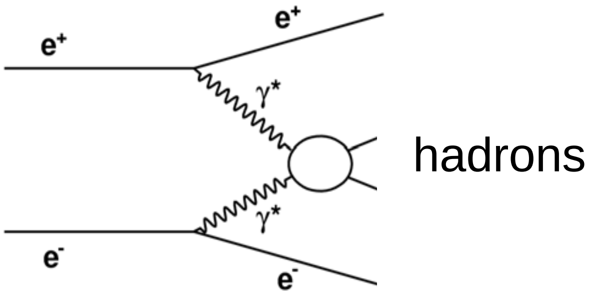
e$^+$ **e**$^-$ $\to \rho^0\rho^0$, **e**$^+$ **e**$^-$ $\to \phi\rho^0$

e$^+$ **e**$^-$ $\to \rho^+\rho^-$





Two-Photon Physics

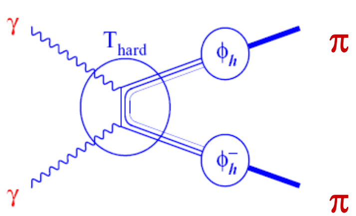


Possible Hadron Production Mechanisms in $\gamma\gamma$

- Vector Meson Dominance (VMD) model
  - The photons turn into vector mesons before interacting
- Quarks and partons
  - Particle production in $\gamma\,\gamma$ interaction is primarily due to the production of quark-pairs (point-like $q\bar{q}$ coupling)

pQCD hard-scattering

Phys. Rev. D24, 1808 (1981)



Amplitudes factor into two parts:

(1) Calculable hard-scattering amplitude T_{hard} for $\gamma\gamma \to q\,\bar{q}$

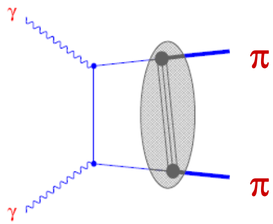
(2) Nonperturbative two-pion distribution amplitude ϕ_h for $q\,\bar{q} \to \pi\,\pi$

$$\frac{d\sigma(\pi\pi)}{d|\cos\theta^*|} \propto W_{\gamma\gamma}^{-6}\left\{\frac{F'(\theta^*)}{(1-\cos^2\theta^*)^2} + F''(\theta^*)\right\}$$

$$\frac{\sigma(\gamma\gamma\to\pi^0\pi^0)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} = 0.1$$

Handbag contribution

Phys. Lett. B532, 99 (2002)



A power correction to the asymptotically leading perturbative contribution.

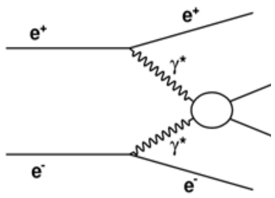
$$\frac{d\sigma(\pi\pi)}{d|\cos\theta^*|} \propto \frac{|R_{2M}(s)|^2}{s\,(1-\cos^2\theta^*)^2}$$

$$\frac{\sigma(\gamma\gamma\to\pi^0\pi^0)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} = 0.5$$

Note: isospin invariance for pure I=0 also gives 0.5

Three Different Kinematical Conditions

- Double-tag: the scattered e^+ and e^- are both detected
  - Full kinematic information available
  - Ideal for two-photon physics
  - Lack of experimental data



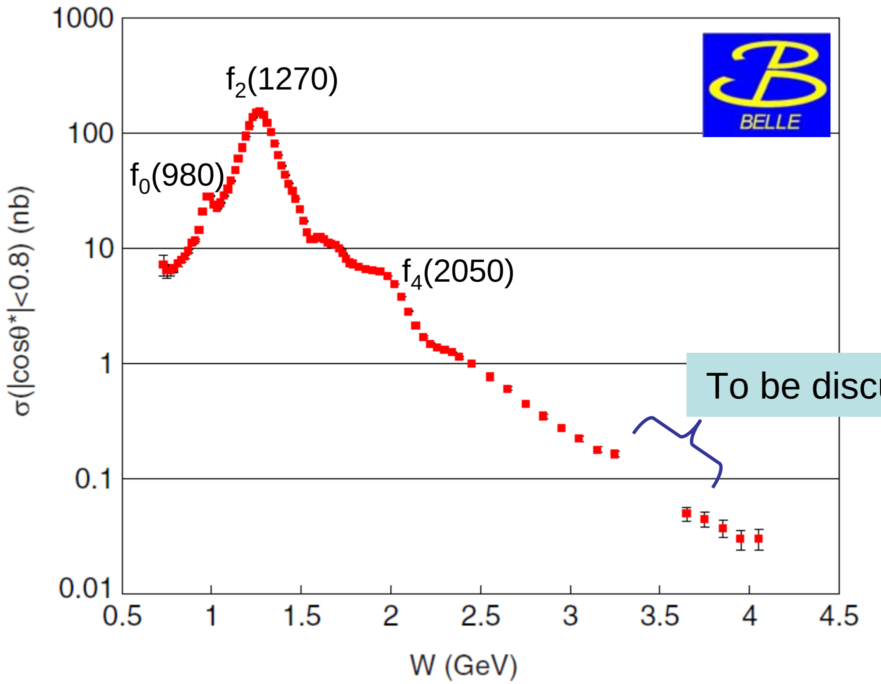
- Single-tag: only one scattered e^+ or e^- is detected
  - Determination of the Q^2 dependence of resonance couplings or of the total cross section
  - Trade off between statistics and kinematic info; The B factories yield large data samples
- No-tag: neither the e^+ nor the e^- is detected
  - Preferentially small total transverse momentum Σp_T of the detected particles $\Rightarrow$ restrict both Q^2 values to be small
  - Large missing mass since final state e^+ and e^- are not detected
  - The B factories yield very large data samples

An Analysis of $\gamma\gamma \to \pi^0\pi^0$

- Study the process $e^+ e^- \to e^+ e^- \gamma \gamma$, where $\gamma \gamma \to \pi^0\pi^0$ in a no-tag mode (i.e. quasi-real photons)
- Test QCD models: pQCD vs "handbag model" for hadron pair production
- **Why now:**
  - The virtual photon flux falls off rapidly at increasing center of mass energy W, so it had been difficult to use the two-photon reaction to study high-mass final states.
  - But, the high luminosity at the B factories makes this possible.

223 fb^{-1}

$\sigma(\gamma \gamma \to \pi^0\pi^0)$ for $|\cos\theta^*|<0.8$:



PRD79, 05229 (2009)

Differential Cross Section at Low Energy

Partial Wave Analysis:

+ Data

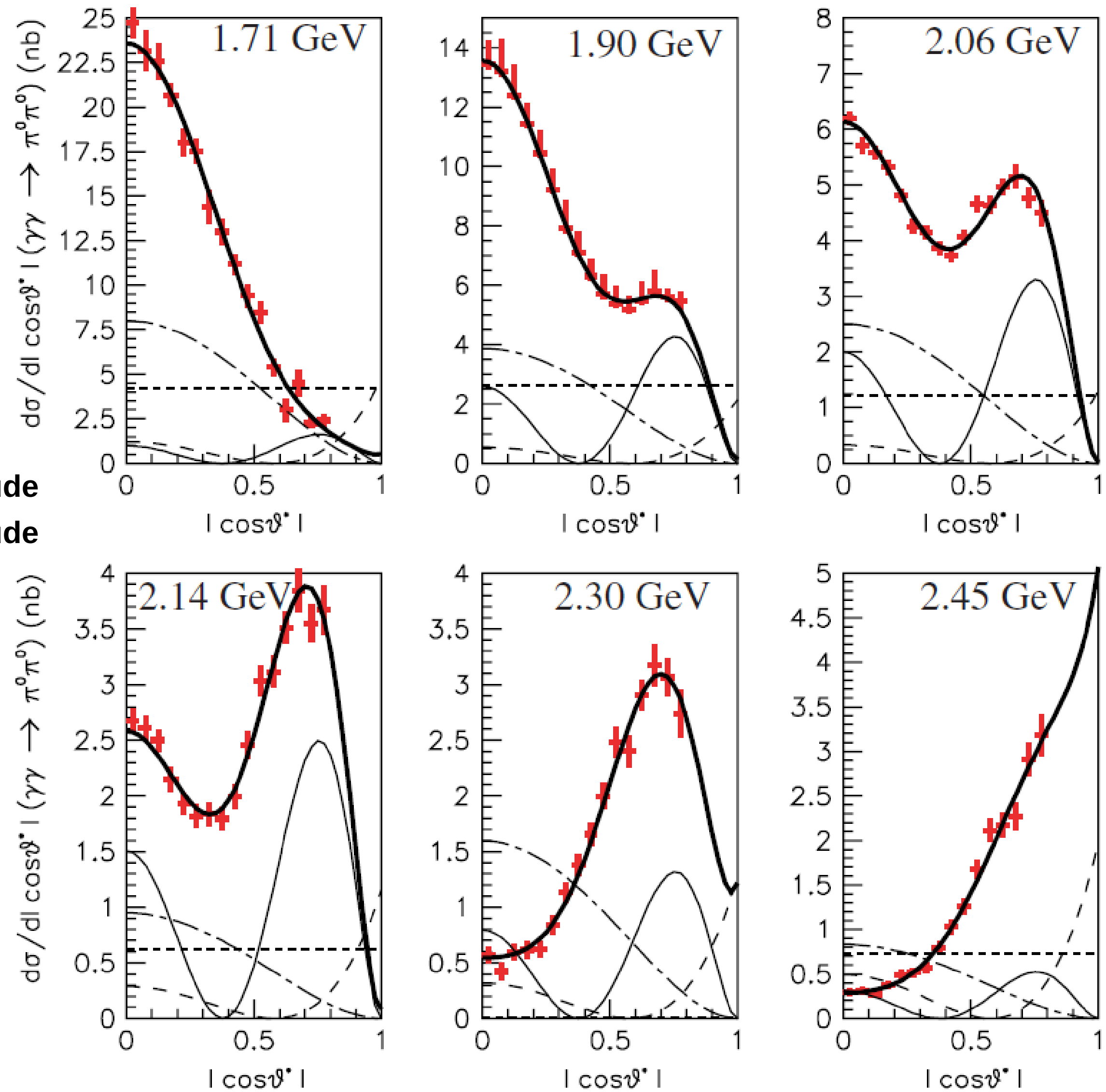
—— Fit to data using coherent superposition of S, D_0, D_2 and G_2 amplitudes

······ $|S|^2$

– – – $4\pi|D_0Y_2^0|^2$

–·–· $4\pi|D_2Y_2^2|^2$ ← Include $f_2(1950)$ amplitude

—— $4\pi|G_2Y_4^2|^2$ ← Include $f_4(2050)$ amplitude



θ*: the π^0 scattering angle in the γγ CM frame

Total Cross Section at Low Energy

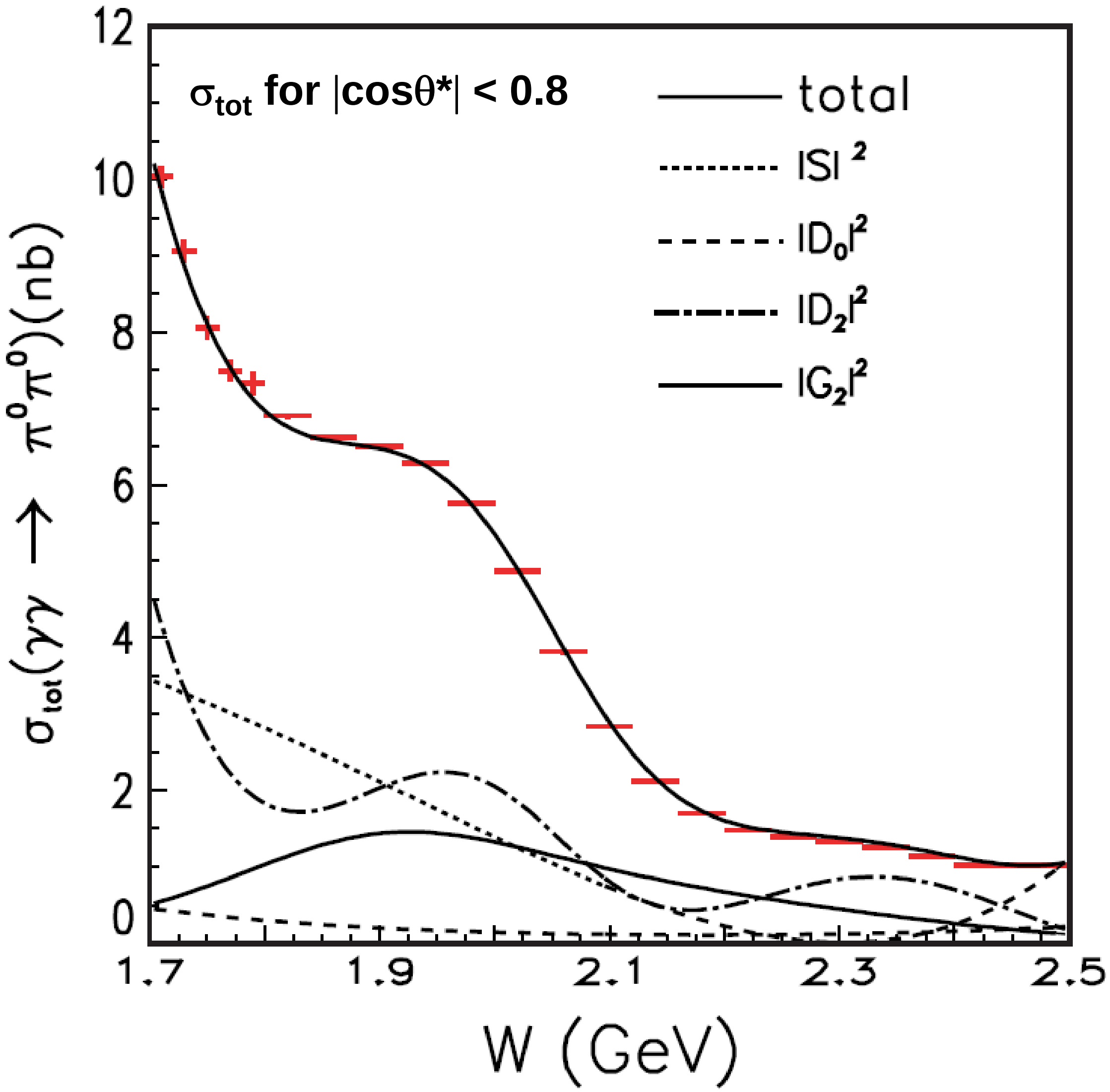
Partial Wave Analysis:

- **Helicity-2 production of the $f_4(2050)$ is favored.**

- **An enhancement at ~2.35 GeV is seen in the $|D_2|^2$ term.**

Conclusions drawn from including $f_2(2300)$ in a fit:

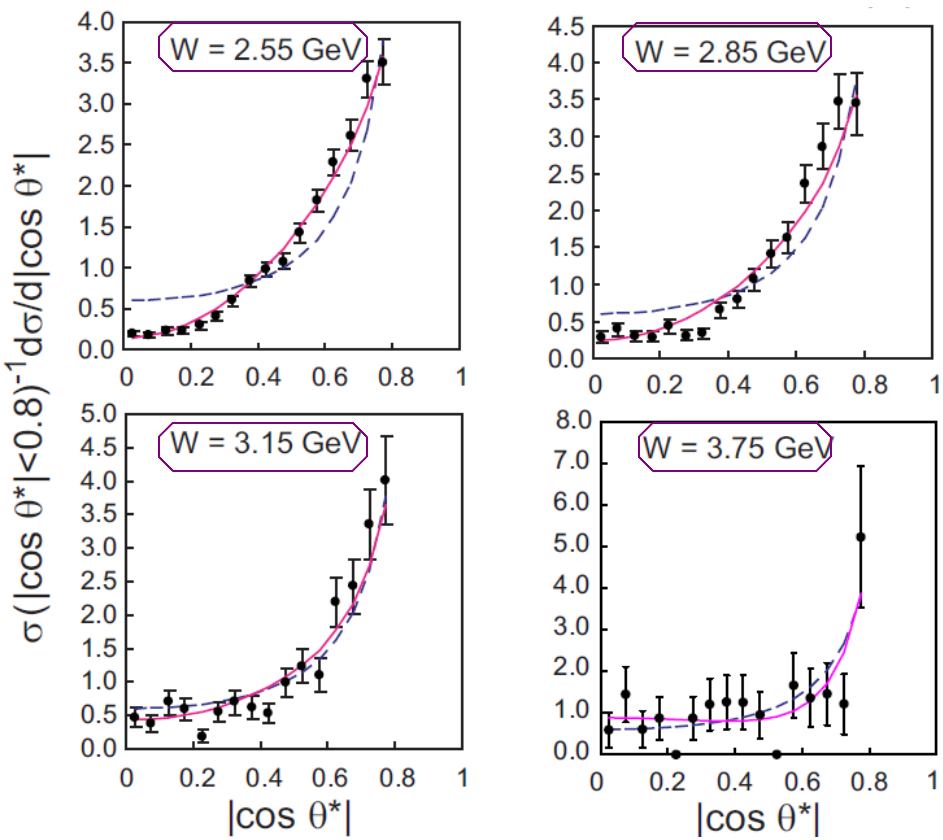
- **No sensitivity**
- **The enhancement arises from the $f_2(1950)$ and its interference with the G_2 wave and underlying continuum.**



Differential Cross Section at High Energy

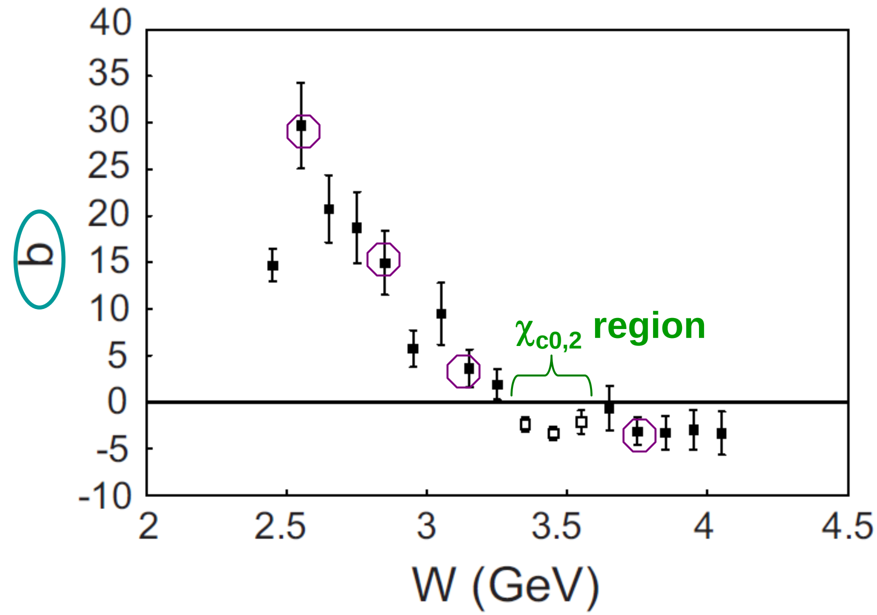
The fit function is parameterized as:

$$d\sigma/d|\cos\theta^*| = a(\sin^{-4}\theta^* + b\cos^2\theta^*)$$



- - b is fixed to 0

— b is free in the fit



⬡ Points correspond to fits shown on the left

- **The angular distribution of the differential cross section approaches ~ $\sin^{-4}\theta^*$ for W>3.1 GeV**

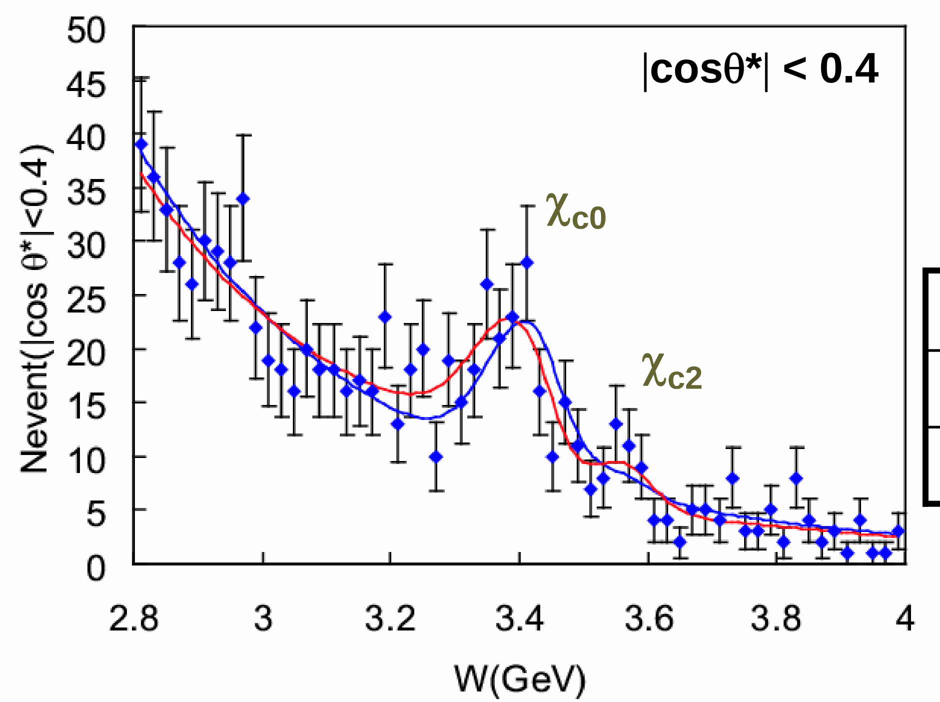
Predictions:

$$\frac{d\sigma(\pi\pi)}{d|\cos\theta^*|} \propto W_{\gamma\gamma}^{-6}\left\{\frac{F'(\theta^*)}{(1-\cos^2\theta^*)^2} + F''(\theta^*)\right\} \quad \text{(pQCD)}$$

$$\frac{d\sigma(\pi\pi)}{d|\cos\theta^*|} \propto \frac{|R_{2M}(s)|^2}{s\ (1-\cos^2\theta^*)^2} \quad \text{(Handbag model)}$$

The χ_{c0} and χ_{c2} Region

Charmonium production: $\gamma\gamma \rightarrow \chi_{c0}, \chi_{c2} \rightarrow \pi^0\pi^0$



Fits with and without an interference between χ_{c0} and continuum

Statistical significance of the resonances:

	w/ interference	w/o interference
χ_{c0}	7.6 σ	7.3 σ
χ_{c2}	2.6 σ	1.3 σ

	Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c0})$ (eV)	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2})$ (eV)
$\pi^0\pi^0$	Without	$9.7 \pm 1.5 \pm 1.2$	$0.18^{+0.15}_{-0.14} \pm 0.08$
	With	$9.9^{+5.8}_{-4.0} \pm 1.6$	$0.48 \pm 0.18 \pm 0.07 \pm 0.14$
$\pi^+\pi^-$	Without	$15.1 \pm 2.1 \pm 2.3$	$0.76 \pm 0.14 \pm 0.11$

stat. syst. interference

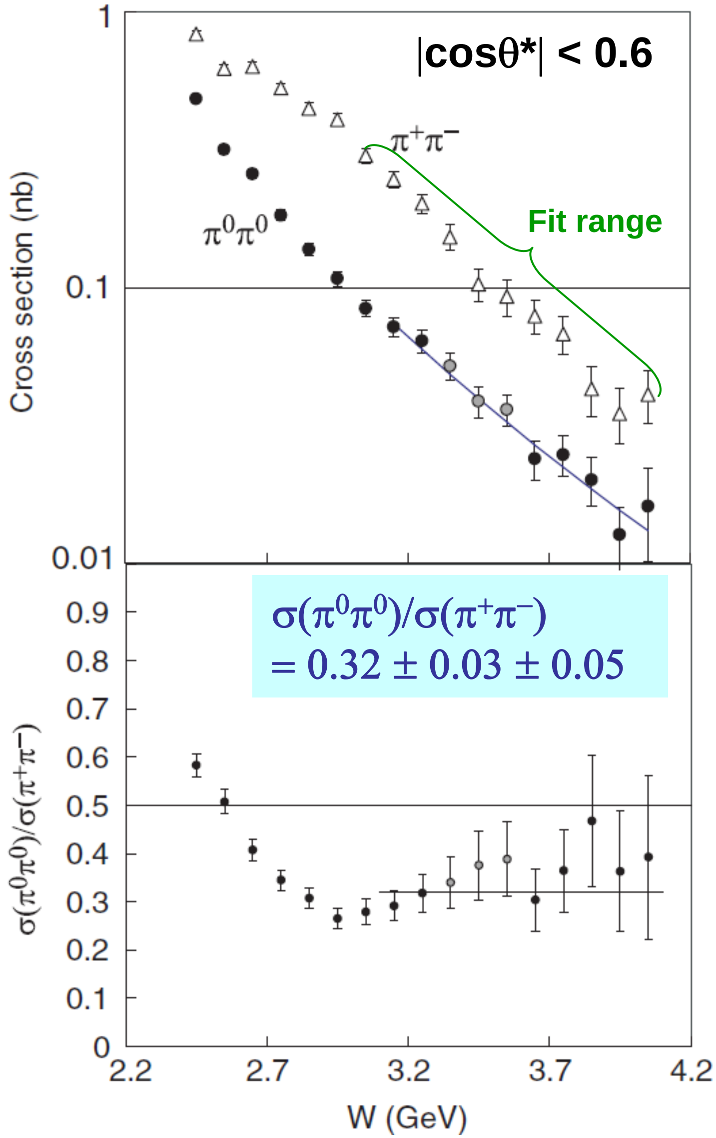
PRD79, 05229 (2009)

Phys. Lett. B615, 39 (2005)

Expectation from isospin invariance:
$\pi^0\pi^0 : \pi^+\pi^- = 1 : 2$

Cross Section at High Energy

223 fb^{-1}



PRD79, 05229 (2009)

- Fit the cross section with $\sigma \sim W^{-n}$

$\pi^0\pi^0$: $n = 6.9 \pm 0.6 \pm 0.7$	(3.1 < W < 4.1 GeV, exclude 3.3 < W < 3.6 GeV)
$\pi^+\pi^-$: $n = 7.9 \pm 0.4 \pm 1.5$	(3.0 < W < 4.1 GeV)

- pQCD prediction: $\sigma \sim W^{-6}$

- The ratio of the cross section is almost constant for W > 3.1GeV

← **Expectation from isospin invariance for pure I = 0**

Theoretical predictions for $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$:

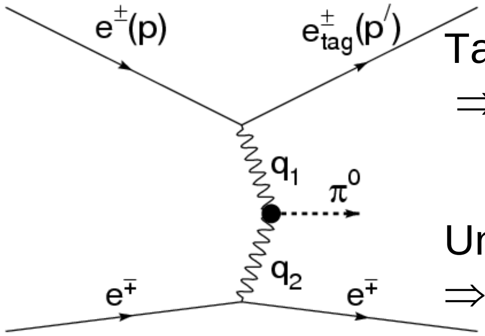
0.03-0.07 (Leading term QCD) **Nucl. Phys. B329, 285 (1990)**

0.1 (pQCD) **Phys. Rev. D24, 1808 (1981)**

0.5 (“handbag”) **Phys. Lett. B532, 99 (2002)**

An Analysis of $\gamma\,\gamma^* \rightarrow \pi^0$

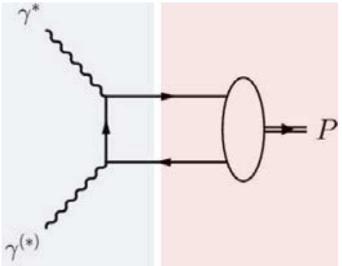
- We study the process $e^+ e^- \rightarrow e^+ e^- \gamma\,\gamma^*$, where $\gamma\,\gamma^* \rightarrow \pi^0$ in the single-tag mode:



Tagged: momentum transfer $Q^2 = -q_1^2 = -(p - p')^2 > 3$ GeV^2
$\Rightarrow$ Highly virtual photon

Untagged: momentum transfer $q^2 = -q_2^2 \sim 0$ GeV^2
$\Rightarrow$ Quasi-real photon

- The differential cross section for this process depends on only one form factor $F(Q^2) = \int T(x,Q^2)\ \phi_\pi(x, Q^2)\ dx$.



Calculable hard-scattering amplitude for $\gamma\gamma \rightarrow q\ \bar{q}$

Nonperturbative pion distribution amplitude (DA) for $q\ \bar{q} \rightarrow \pi$

(x = fraction of the π^0 momentum carried by one of the quarks)

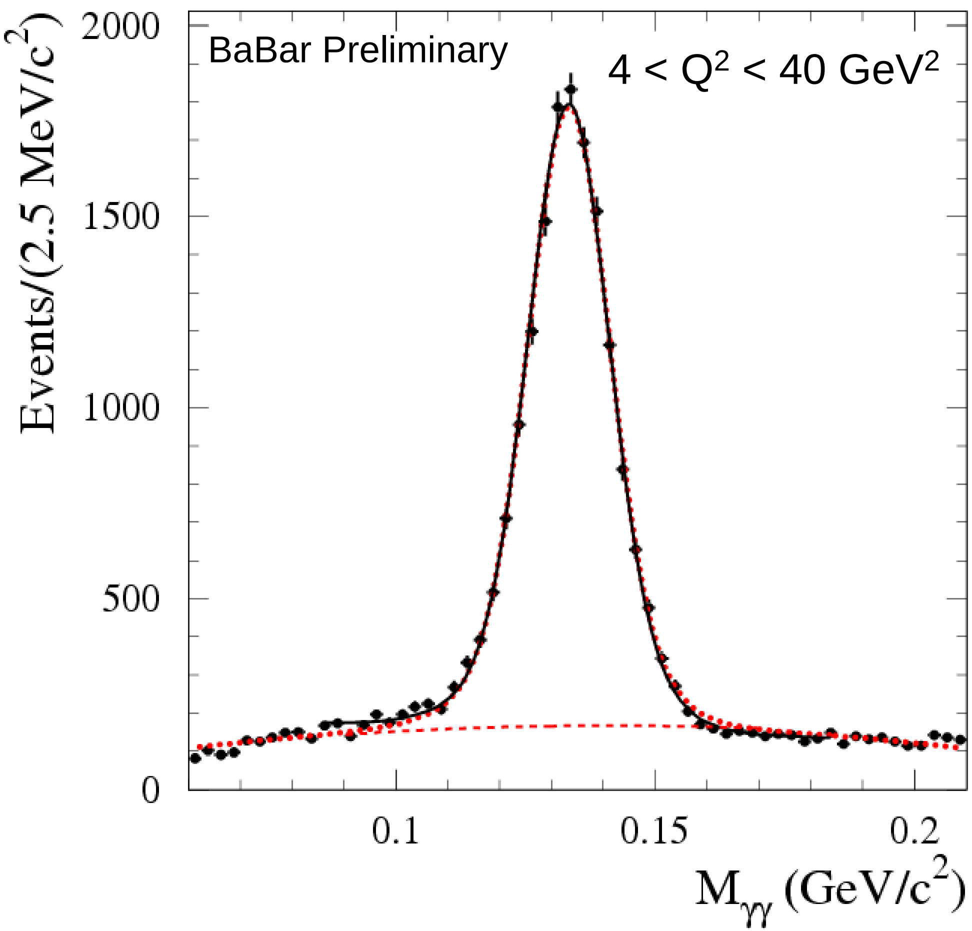
- Experimental data on $F(Q^2)$ help determine the unknown dependence on x for $\phi_\pi(x, Q^2)$.

$$\text{In lowest order QCD}: Q^2 F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int_0^1 \frac{dx}{x} \phi_\pi\left(x, Q^2\right) + O(\alpha_s) + O\left(\frac{\Lambda^2_{\text{QCD}}}{Q^2}\right)$$

The Final State γγ Mass Spectrum

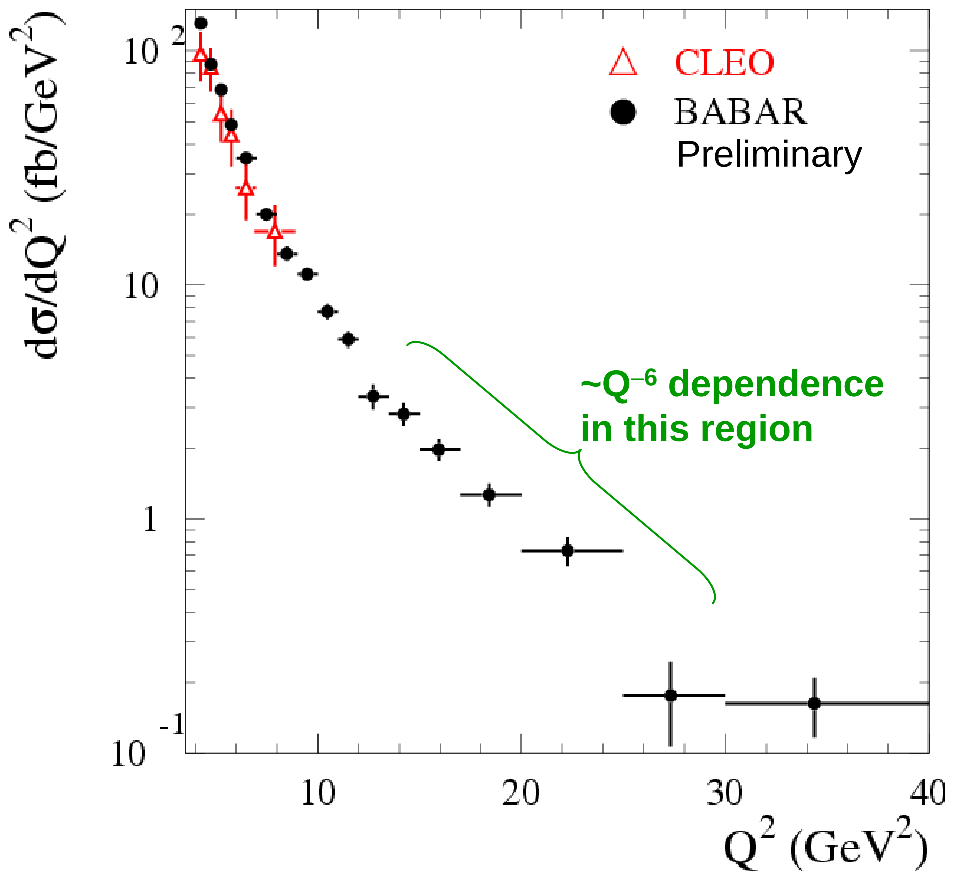
442 fb^{-1}

- The fit function is a sum of signal + background distributions:
  - Signal: convolution of Gaussian and exponential distribution
  - Background: A 1st order polynomial (black curve) or a 2nd Order polynomial (red dotted)



- N≈14000±140(stat)±170 (syst)
- σ=7.5 ± 0.1 MeV
- Similar fitting procedure is applied in each of the 17 Q^2 intervals to obtain the Q^2 dependence of the cross section.

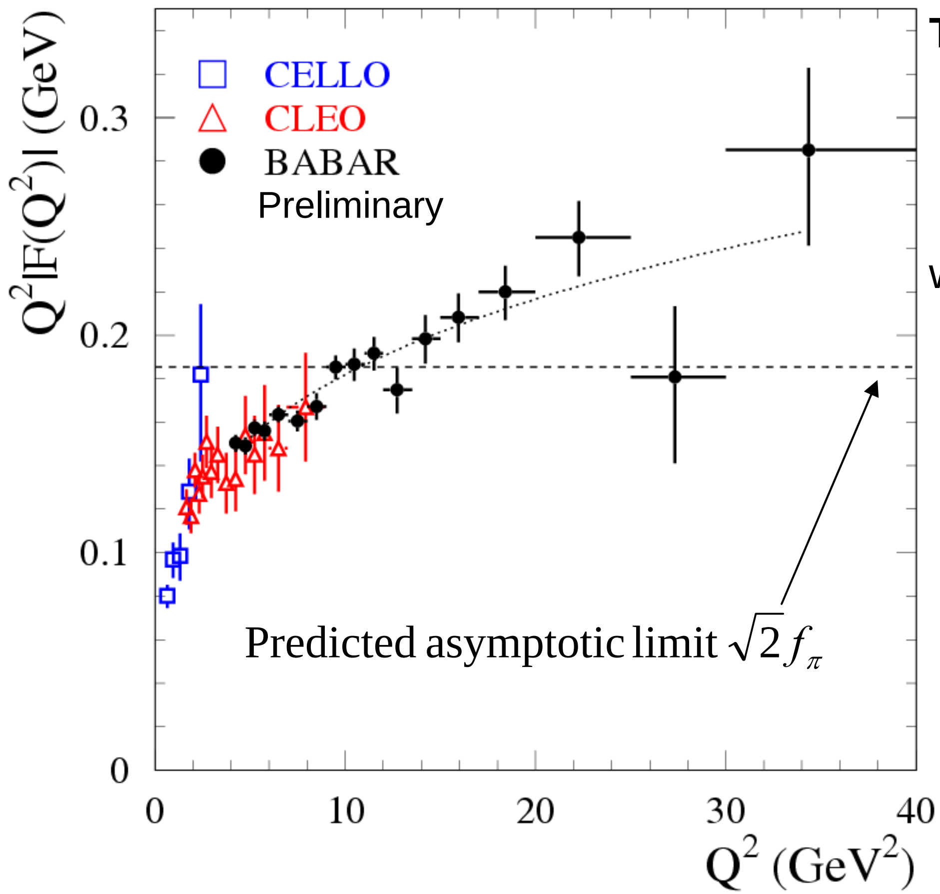
The Differential Cross Section



The Q^2-independent systematic error is 3% which includes:

- Efficiency correction: 2.5%
- Radiative correction factor: 1%
- Integrated luminosity: 1%

The π^0 Transition Form Factor



The form factor multiplied by Q^2 is fit with:

$$Q^2 |F(Q^2)| = A \left(\frac{Q^2}{10\,\mathrm{GeV}^2} \right)^{\beta}$$ for $4<Q^2<40$ GeV^2,

where A=0.182±0.002 GeV and β=0.25±0.02.

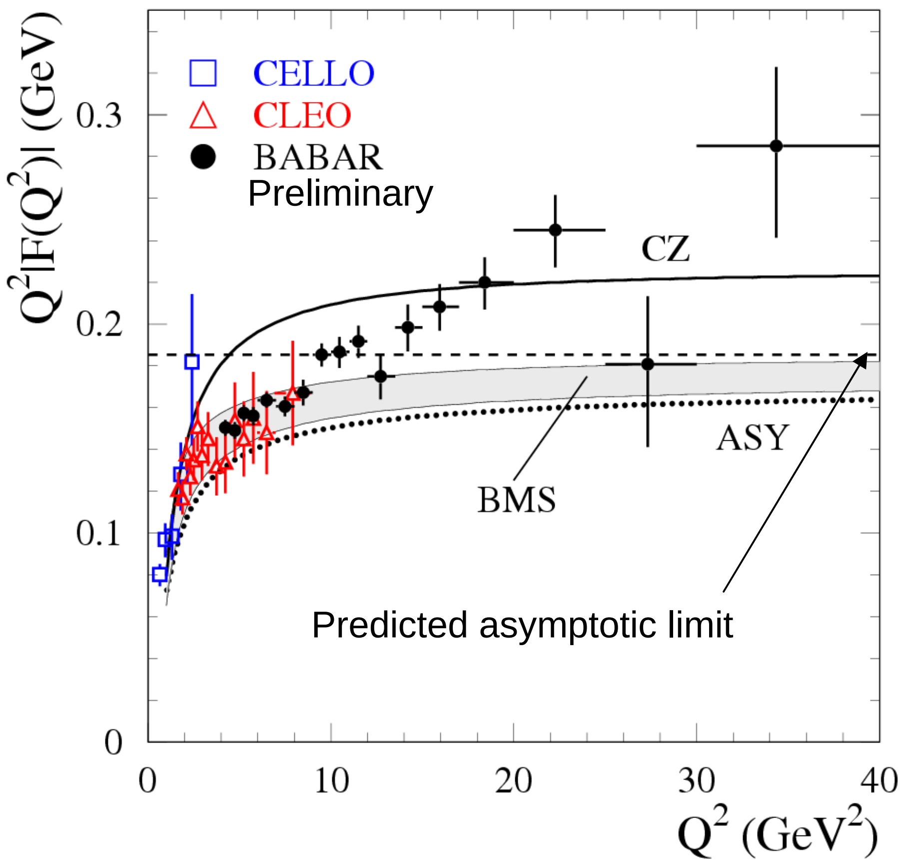
Data: $Q^2|F(Q^2)| \sim Q^{1/2}$
Leading order pQCD: $Q^2|F(Q^2)| \sim$ const.
(in the asymptotic limit)

$\Rightarrow$ Higher order pQCD and power corrections are needed in the Q^2 region under study.

The Q^2-independent systematic error: 2.3%

To be submitted to PRD

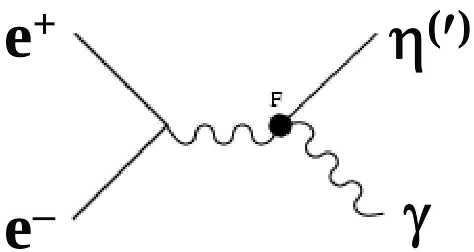
Comparison of the π^0 Transition Form Factor with Theoretical Models



The measured form factor exceeds the asymptotic limit for $Q^2 > 10$ GeV^2, and contradicts most models for the pion DA.

- The Chernyak-Zhitnitsky DA (CZ) — Nucl. Phys. B201, 492 (1982)
- The asymptotic DA (ASY) — Phys. Lett. B87, 359 (1979)
- The DA derived from QCD sum rules with non-local condensates (BMS) — Phys. Lett. B508, 279 (2001)

The η and η′ Transition Form Factors

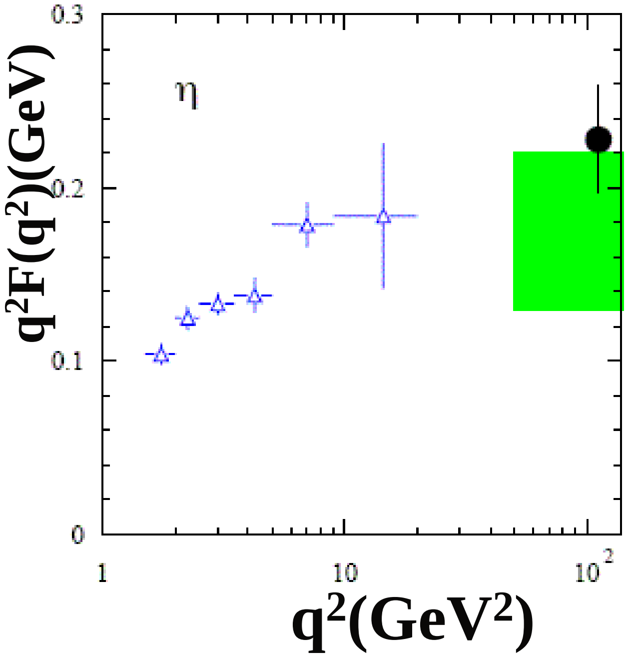


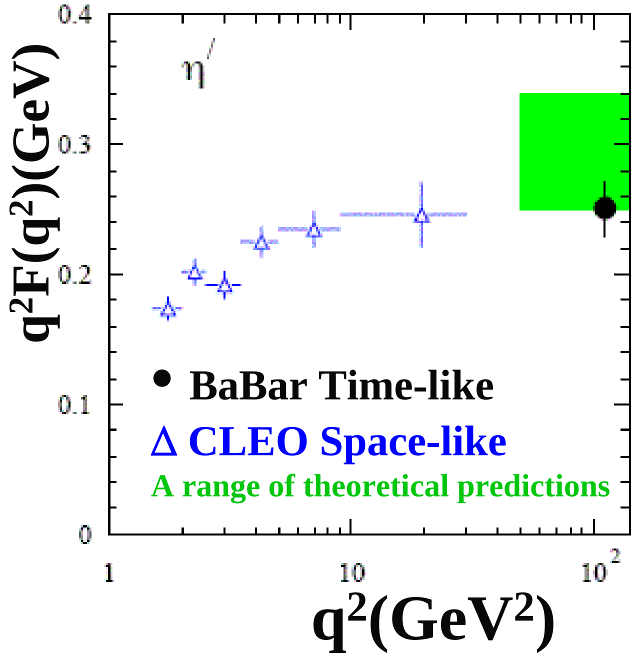
$$e^+e^- \to \gamma^* \to \eta\gamma \text{ or } \eta'\gamma$$

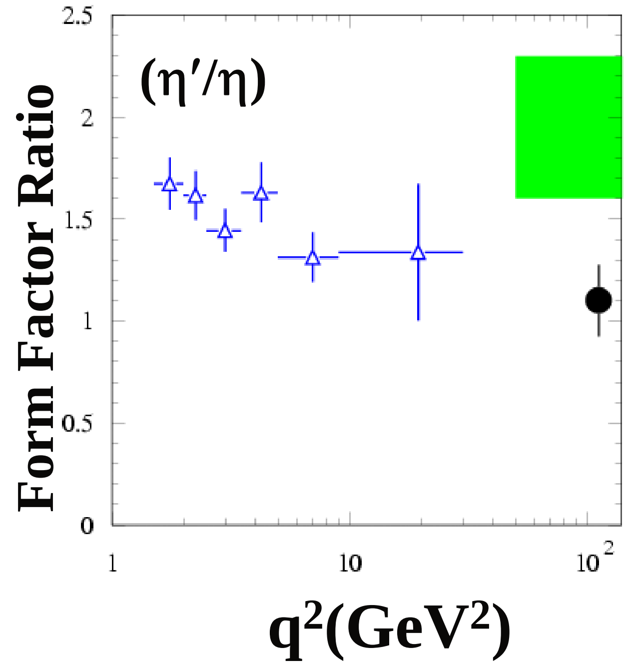
232 fb^{-1}

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

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







PRD 74, 012002 (2006)

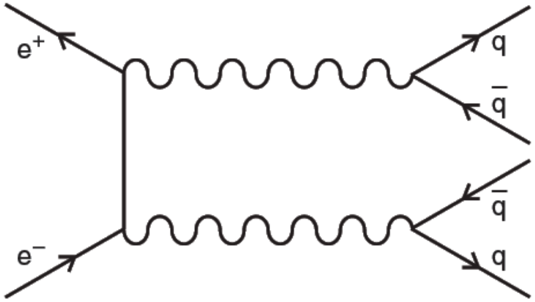
Note: Not two-photon physics processes!

Selective $e^+ e^-$ Processes from Single-Photon and/or Two-Photon

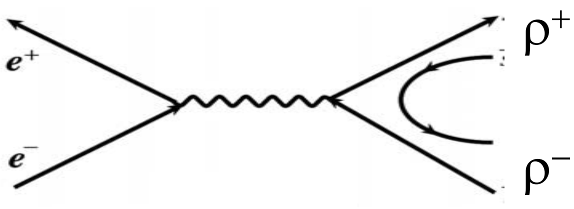
Exclusive Hadron Production at 10.58 GeV

Possible production mechanisms for $e^+e^- \to$ hadrons:

- Two-Virtual-Photon-Annihilation (TVPA) $\Rightarrow$ C=+1 final states
  - First observation in $e^+e^- \to \rho^0\rho^0$, $\phi\rho^0$ PRL 97, 112002 (2006)

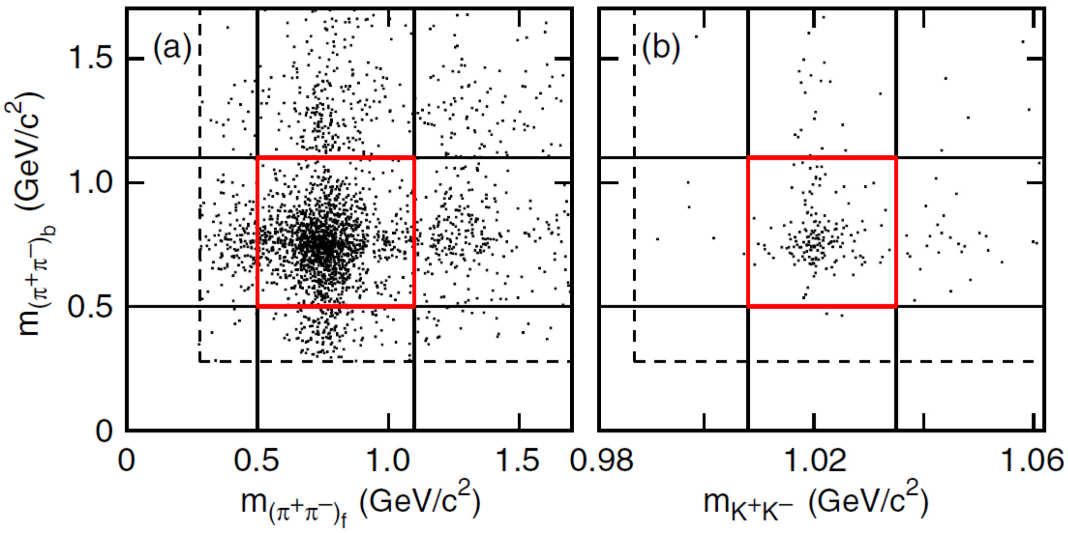


- Single-Virtual-Photon-Annihilation $\Rightarrow$ C=–1 final states
  - $e^+e^- \to \rho^+\rho^-$ PRD 78, 071103 (2008)



BABAR $e^+e^- \to \rho^0\rho^0$ and $e^+e^- \to \phi\rho^0$ at 10.58 GeV

(a) $\rho^0\rho^0$ (b) $\phi\rho^0$



225 fb^{-1}

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

	Yield	Significance
$\rho^0\rho^0$	1243 ± 43	$>> 5\sigma$
$\phi\rho^0$	147 ± 13	$>> 5\sigma$

For $|\cos\theta^*|<0.8$:

$\sigma(\rho^0\rho^0)=20.7\pm0.7(stat)\pm2.7(syst)$ fb

$\sigma(\phi\rho^0)=5.7\pm0.5(stat)\pm0.8(syst)$ fb

Reminder:

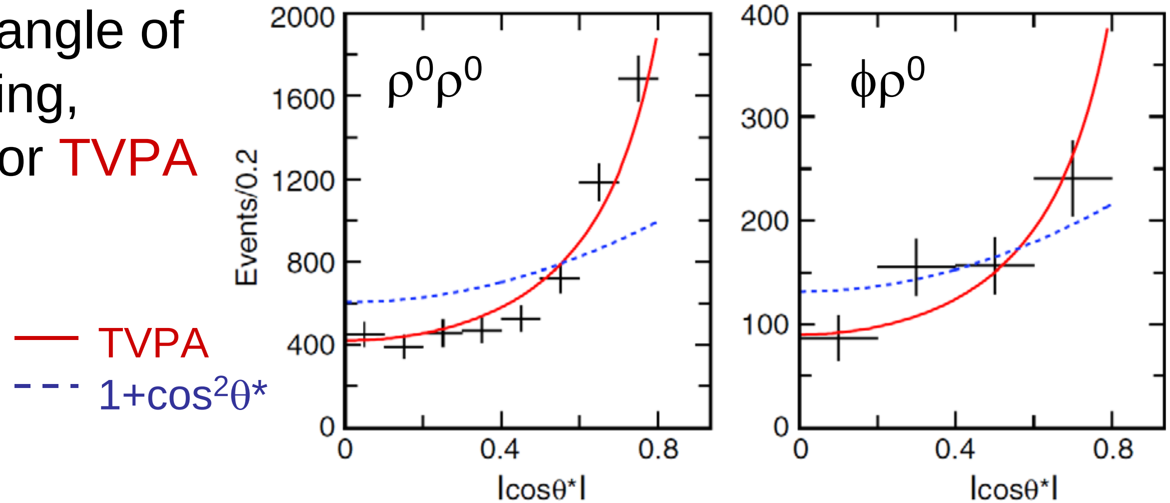
$\sigma(e^+e^-\to$hadrons @10 GeV) ~ 3 nb

PRL 97, 112002 (2006)

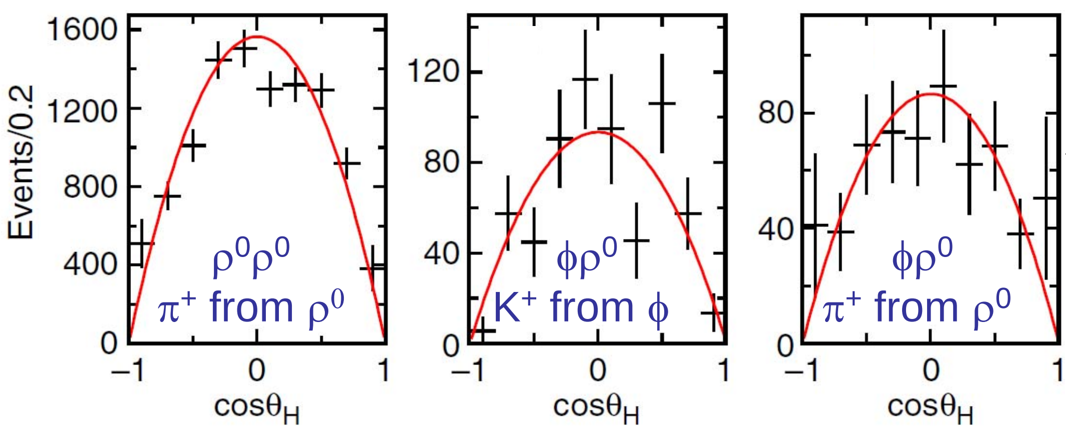
Angular Analysis of $e^+e^- \to \rho^0\rho^0, \phi\rho^0$

Production angle θ^*: polar angle of ϕ or ρ in CM is forward peaking, consistent with expectation for TVPA

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



Helicity angle θ_H: angle between π^+ (K^+) and the recoil ρ^0 direction in the ρ^0 (ϕ) rest frame



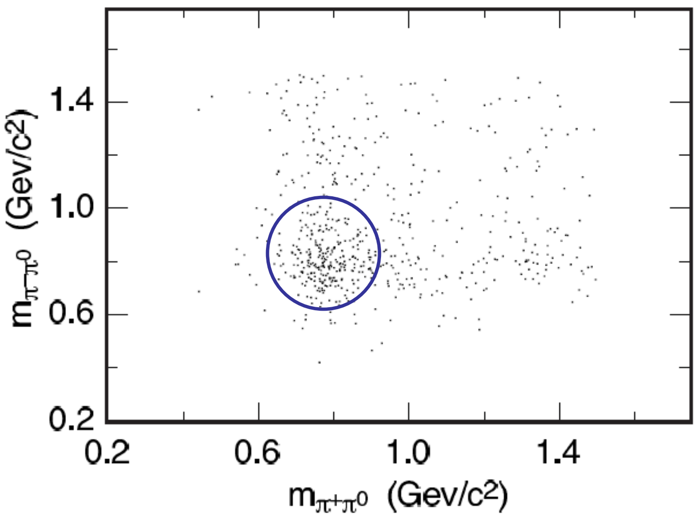
Consistent with the **$\sin^2\theta_H$** TVPA expectation for quasi-real photons

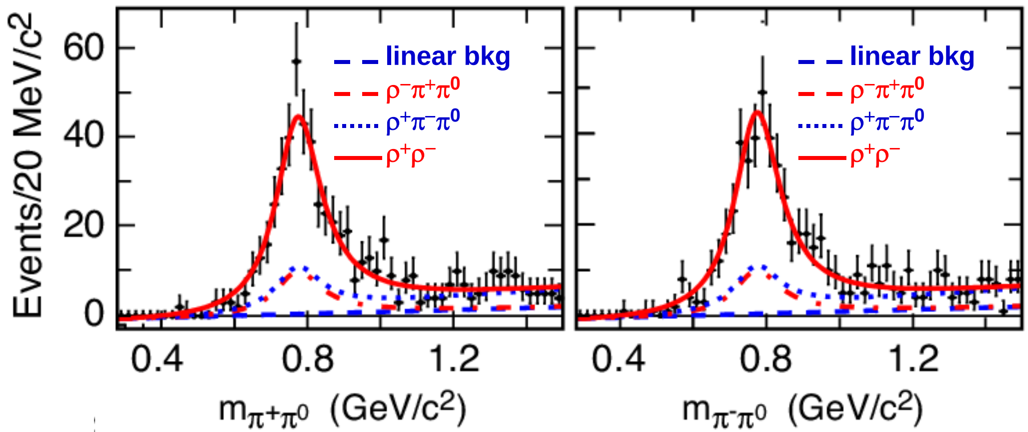
PRL 97, 112002 (2006)

BABAR Observation of $e^+e^- \to \rho^+\rho^-$

379 fb^{-1}

- $e^+e^- \to \rho^+\rho^-$ is allowed via single γ^* annihilation.





2D fits yield 357 ± 29 events

- Assuming from 1 γ^* production:

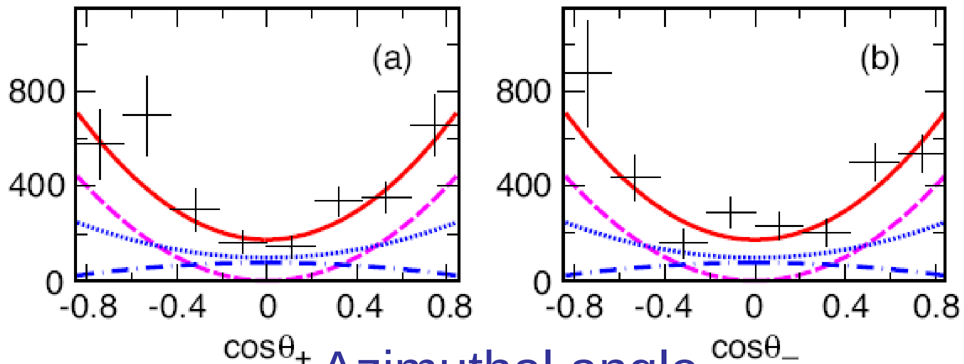
$$\sigma(e^+e^- \to \rho^+\rho^-) = 8.3 \pm 0.7(\text{stat}) \pm 0.8(\text{syst})\ \text{fb}$$ (for $|\cos\theta^*| < 0.8$, $|\cos\theta_H| < 0.85$)

$$\sigma(e^+e^- \to \rho^+\rho^-) = 19.5 \pm 1.6(\text{stat}) \pm 3.2(\text{syst})\ \text{fb}$$ (extrapolated to the full angular range)

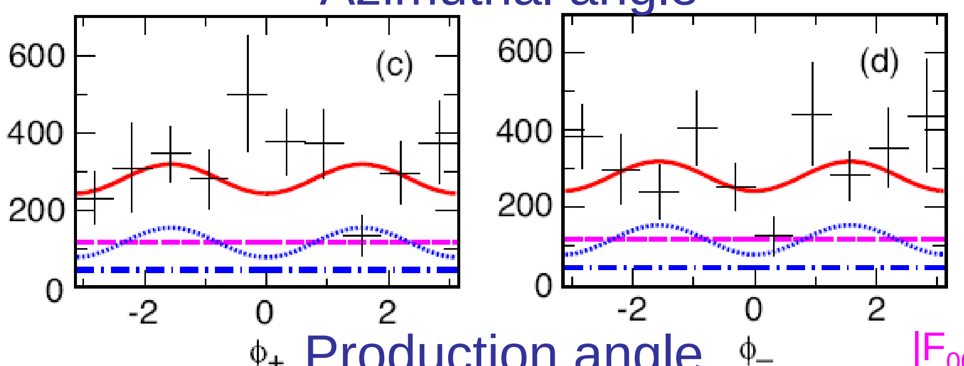
PRD 78, 071103 (2008)

Amplitude Studies for $e^+e^- \to \rho^+\rho^-$

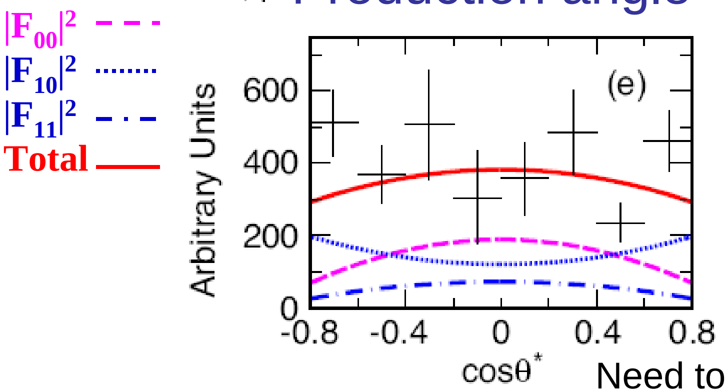
Helicity angle



Azimuthal angle



Production angle



- Simultaneous fit with normalization constraint:

$$|F_{00}|^2 + 4|F_{10}|^2 + 2|F_{11}|^2 = 1$$

- F_{00} cannot explain all
- pQCD predicted $|F_{00}| \approx 1$

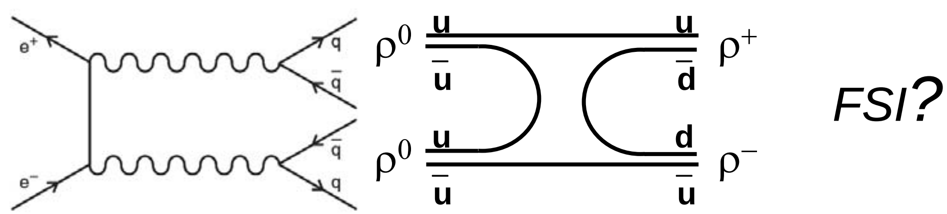
Fit results:

$$|F_{00}|^2 = 0.51 \pm 0.14(stat) \pm 0.07(syst)$$

$$|F_{10}|^2 = 0.10 \pm 0.04(stat) \pm 0.01(syst)$$

$$|F_{11}|^2 = 0.04 \pm 0.03(stat) \pm 0.01(syst)$$

$|F_{00}| \ll 1$. Are we seeing two-virtual-photon annihilation + final-state interactions? If so, how about $B \to \rho^0\rho^0/\rho^+\rho^-$, α angle!



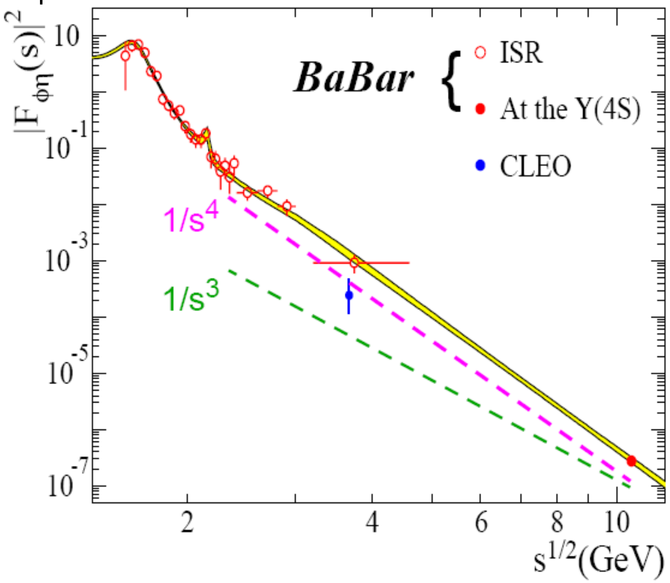
Need to measure s-dependence of the cross section for each amplitude

PRD 78, 071103 (2008)

Another Test of QCD

- Studies of low multiplicity final states can provide an excellent test ground for QCD.
- $e^+e^- \to \rho^+\rho^-$ via ISR will give a measurement of energy-dependence.
- An example: combine results from
  - ❖ measurement of $e^+e^- \to \phi\eta$ via ISR **PRD 77, 092002 (2008)**
  - ❖ exclusive production of $e^+e^- \to \phi\eta$ at 10.58 GeV **PRD-RC 74, 111103 (2006)**

  $\Rightarrow$ a test of QCD prediction: data consistent with $1/s^4$ asymptotic behavior for $|FF|^2$



Summary and Conclusions

- The high luminosity from the B factories has (re)opened several interesting areas of hadronic physics.

- Two-Photon Physics
  - Belle measured the cross section and its angular dependence for $\gamma\gamma \to \pi^0\pi^0$ in the kinematic range $0.6 < W < 4.1$ GeV and $|\cos\theta^*| < 0.8$ in a no-tag analysis.
  - BaBar measured the $\gamma\gamma \to \pi^0$ transition form factor in a single-tag analysis.
- Other Single- and two-photon induced e^+e^- processes
  - BaBar measured the cross sections and angular amplitudes for
    - $e^+e^- \to \rho^0\rho^0$, $e^+e^- \to \phi\rho^0$ (first observation of Two-Virtual-Photon-Annihilation)
    - $e^+e^- \to \rho^+\rho^-$ (should be a one virtual photon process, but amplitude results suggested potential interference effects).

- Other possible final states should be explored to make use of the large datasets available at the B factories.