Recent results on two-photon physics at BABAR

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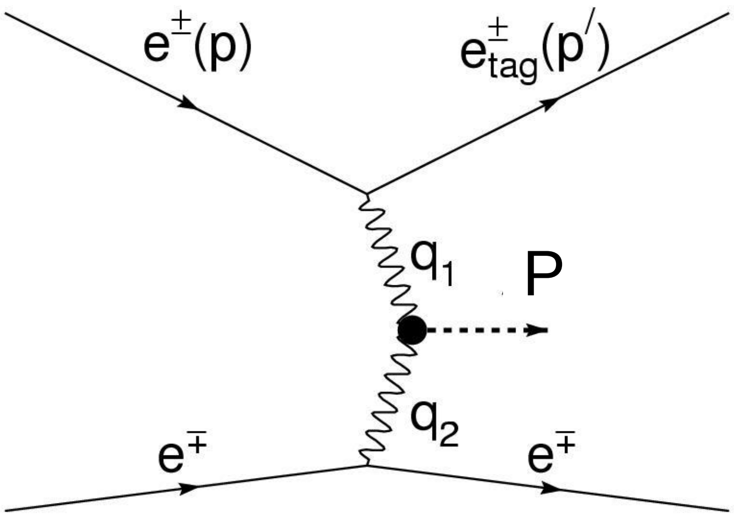
for BaBar Collaboration

ICHEP 2010 - Paris
July 23, 2010

BABAR™

Two-photon reaction $e^+ e^- \to e^+ e^- P$



- Electrons are scattered predominantly at small angles.
- For pseudoscalar meson production the cross section depends on only one form factor $F(q_1^2, q_2^2)$, which describes the $\gamma^*\gamma^*\to P$ transition.

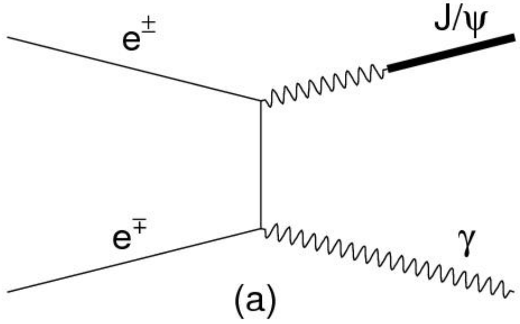
No-tag mode:
✓both electrons are undetected
✓q_1^2, $q_2^2 \approx 0$
✓$\Gamma\gamma\gamma$ or F(0,0)
✓Study of resonance parameters

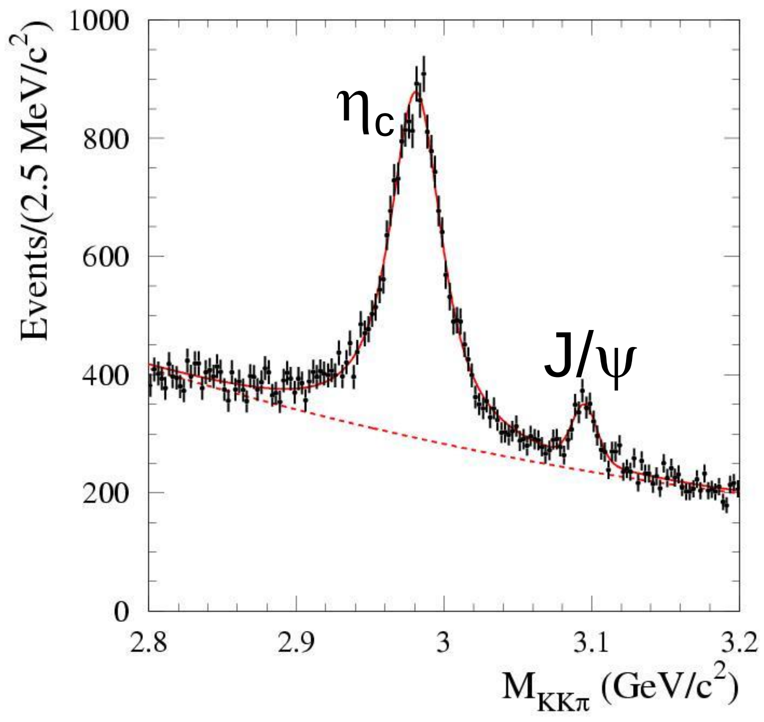
Single-tag mode:
✓one of electrons is detected
✓$Q^2=-q_1^2$
✓ $d\sigma/dQ^2 \sim 1/\ Q^6$ for light mesons
✓$F(Q^2,0)$

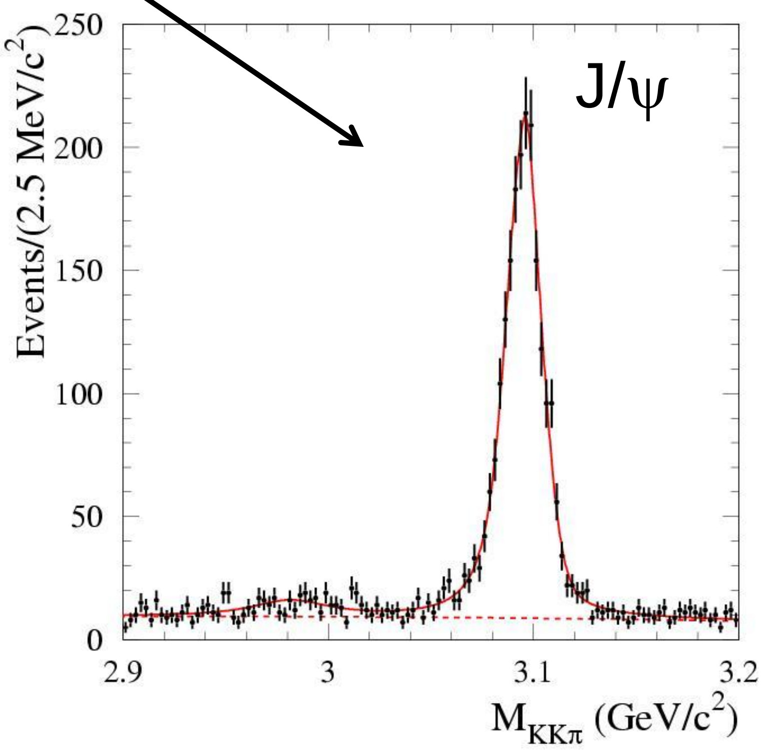
$e^+e^- \to e^+e^- \eta_c$, $\eta_c \to K_S K^+ \pi^-$, *no-tag*

J.P.Lees et al., Phys. Rev. D **81** 052010 (2010) [arXiv:1002:3000]

J/ψ's are produced in the ISR process.
ISR events can be separated using the condition $p^*/(1 - M^2_{KK\pi}/s) > 5.1\ \mathrm{GeV}/c,$







$e^+e^- \to e^+e^- \eta_c$, no-tag mode

J.P.Lees et al., Phys. Rev. D **81** 052010 (2010) [arXiv:1002:3000]

	Mass, MeV	Width,MeV
PDG	2980.5±1.2	27.4±2.9
BABAR(88 fb^{-1})	2982.5±1.1±0.9	34.3±2.3±0.9
BABAR(470 fb^{-1}),	2982.2±0.4±1.5	31.7±1.2±0.8

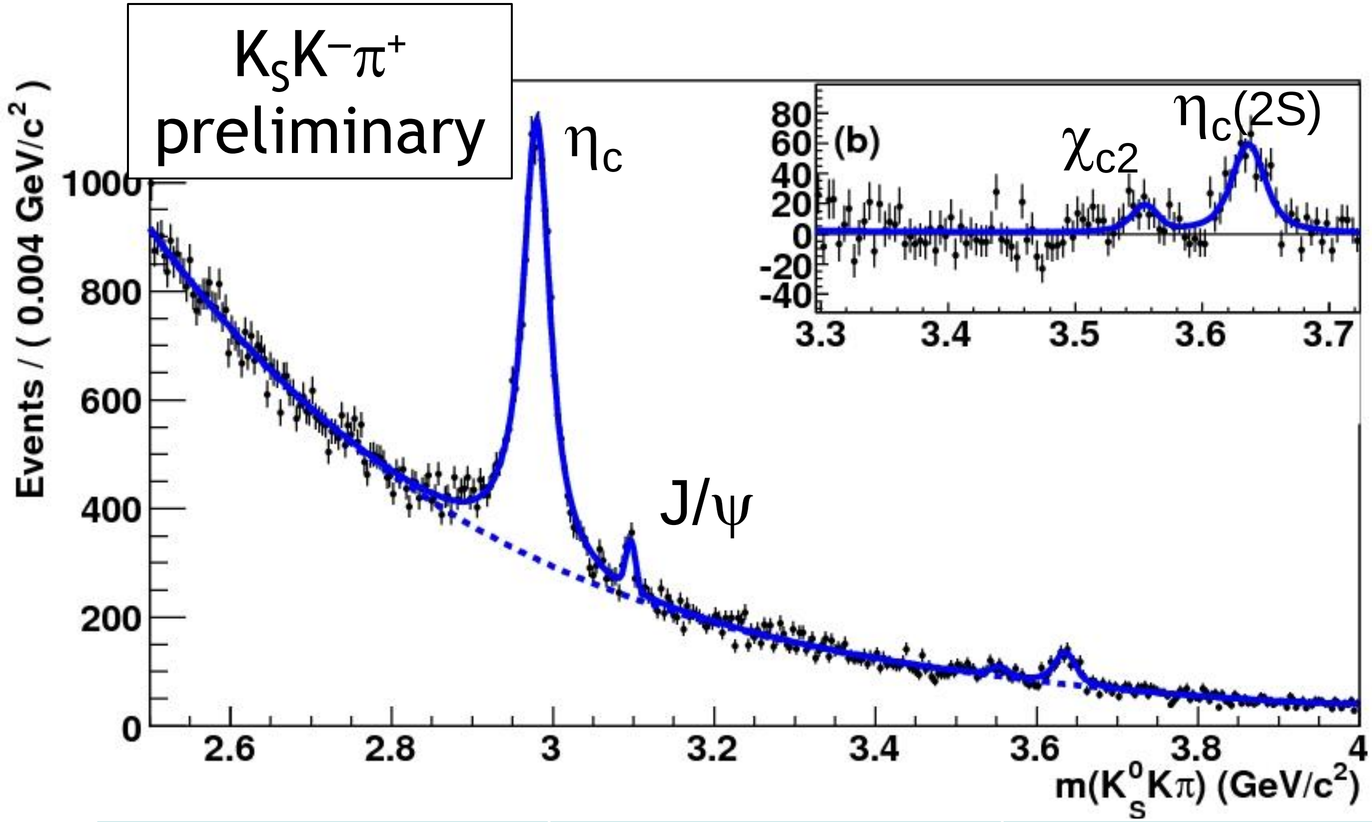
Main sources of systematic uncertainties are unknown background shape and possible interference between the η_c and non-resonant two-photon amplitudes.

$N(\eta_c)$=13890±320±670

BABAR: $\Gamma(\eta_c \to \gamma\gamma)B(\eta_c \to KK\pi)$ = 0.379±0.009±0.031 keV

PDG: 0.44±0.04 keV, CLEO: 0.407±0.022±0.028 keV

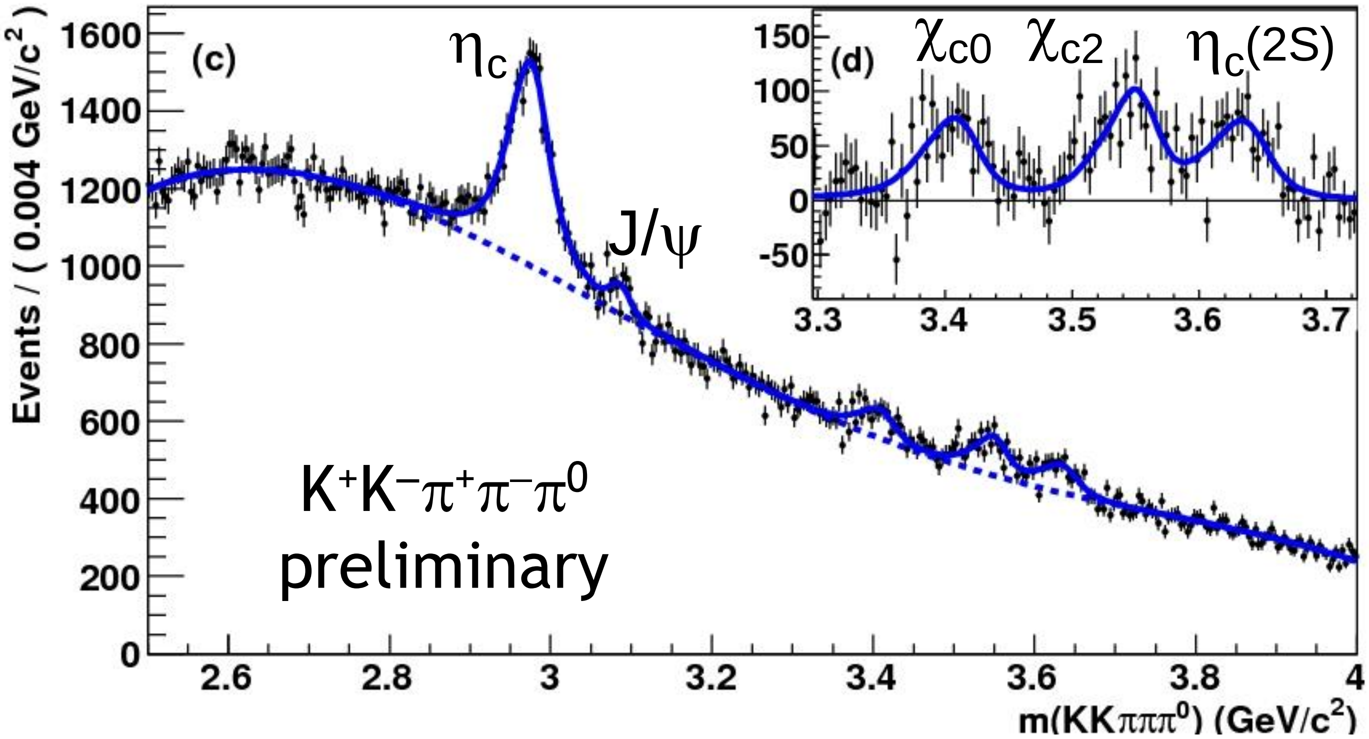
$e^+e^- \to e^+e^- \eta_c(2S)$, no-tag mode



620±70±30 $\eta_c(2S)$ events are observed.

	Mass, MeV	Width, MeV
PDG	3637±4	14±7
BABAR(88 fb^{-1})	3630.8±3.4±1.0	17.0±8.3±2.5
BABAR(521 fb^{-1}), preliminary	3638.3±1.5±0.5	14.2±4.4±2.5

$e^+e^- \to e^+e^- \eta_c(2S)$, no-tag mode



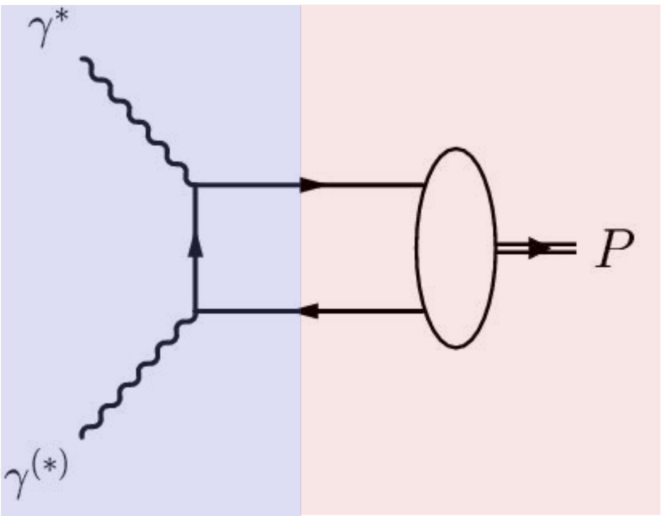
1190±130±180 $\eta_c(2S)$ events are observed.

$$\frac{B(\eta_c \to K^+K^-\pi^+\pi^-\pi^0)}{B(\eta_c \to K_S K^\pm \pi^\mp)} = 1.44 \pm 0.06 \pm 0.26,$$

$$\frac{B(\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0)}{B(\eta_c(2S) \to K_S K^\pm \pi^\mp)} = 2.2 \pm 0.4 \pm 0.5$$

$e^+ e^- \to e^+ e^- P$, single tag

$$F(Q^2) = \int T(x,\mu^2)\,\varphi(x,\mu^2)\,dx$$



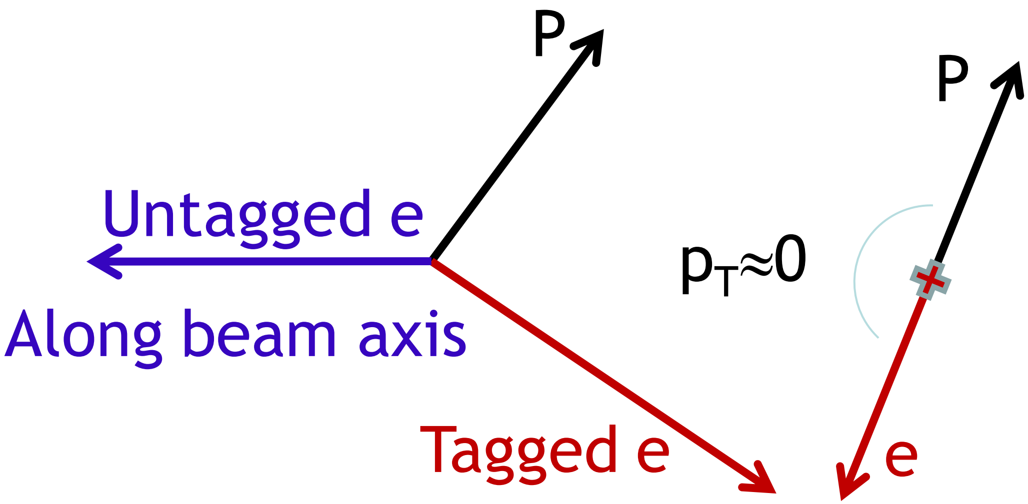
Hard scattering amplitude for $\gamma^*\gamma \to q\bar{q}$ transition which is calculable in pQCD

Nonperturbative pion distribution amplitude describing transition $P \to q\bar{q}$

x is the fraction of the meson momentum carried by one of the quarks

Data on the form factor are used to test phenomenological models for the meson distribution amplitude.

$e^+ e^- \to e^+ e^- P$, single tag

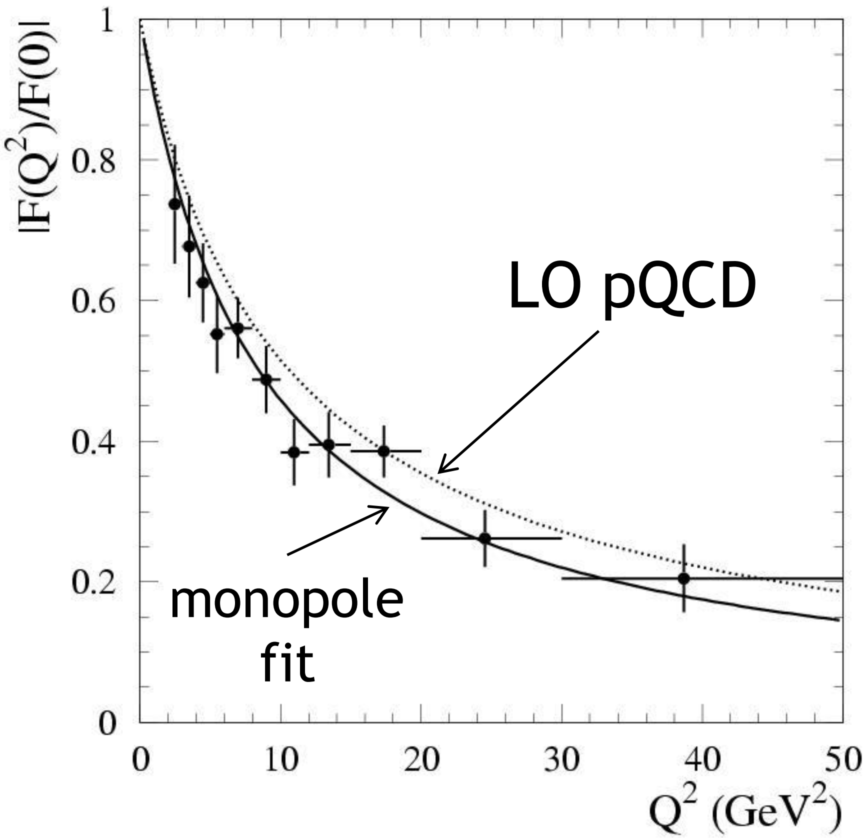


✓electron is detected and identified
✓meson decay products are detected and reconstructed
✓electron + meson system has low $p_\perp$
✓missing mass in an event is close to zero

$$dN/dQ^2 \Rightarrow d\sigma/dQ^2 \Rightarrow |F(Q^2)|$$

$e^+e^- \to e^+e^-\eta_c$, form factor

J.P.Lees et al., Phys. Rev. D **81** 052010 (2010)



Systematic uncertainty independent of Q^2 is 4.3%.

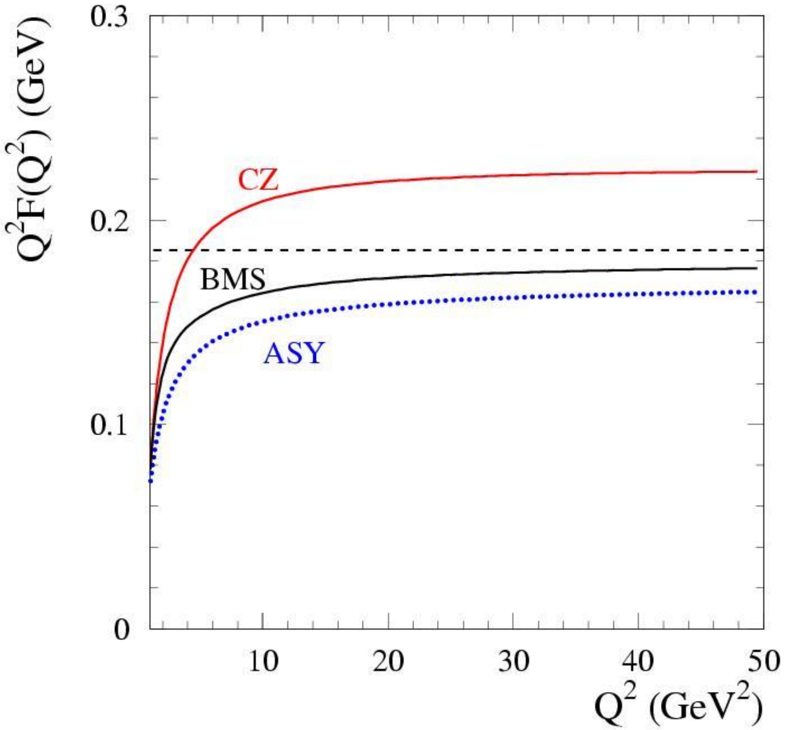
- The form factor is normalized to F(0) obtained from no-tag data
- The form factor data are fit with the monopole function

$$F(Q^2) = F(0) / (1 + Q^2/\Lambda)$$

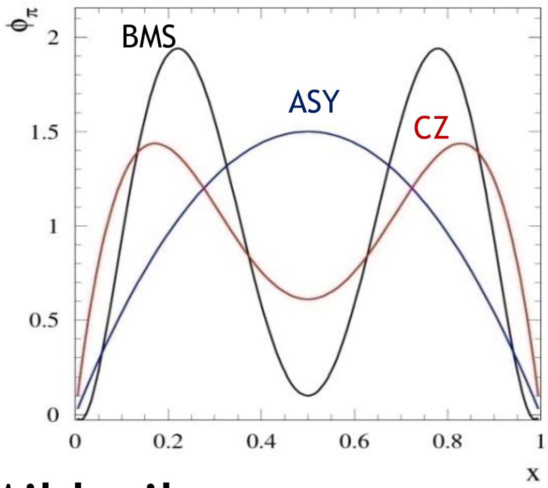
- The result Λ=8.5±0.6±0.7 GeV^2 does not contradict to the vector dominance model with $\Lambda = m^2_{J/\psi}$=9.6 GeV^2.
- pQCD: Due to relatively large c-quark mass, the η_c form factor is rather insensitive to the shape of the η_c distribution amplitude. Λ is expected to be about 10 GeV^2 (T. Feldmann, P.Kroll, Phys. Lett. B 413, 410 (1997)).
- Lattice QCD: Λ=8.4±0.4 GeV^2 (J.J.Dudek, R.G.Edwards, Phys. Rev. Lett. 97, 172001 (2006)).

$e^+e^- \to e^+e^-\pi^0$, *theory*

$$Q^2F(Q^2) = \frac{\sqrt{2}f_\pi}{3}\int_0^1 \frac{dx}{x}\varphi_\pi(x,Q^2) + O(\alpha_s) + O(\Lambda^2_{QCD}/Q^2)$$



$$\varphi_{ASY} = 6x(1-x)$$



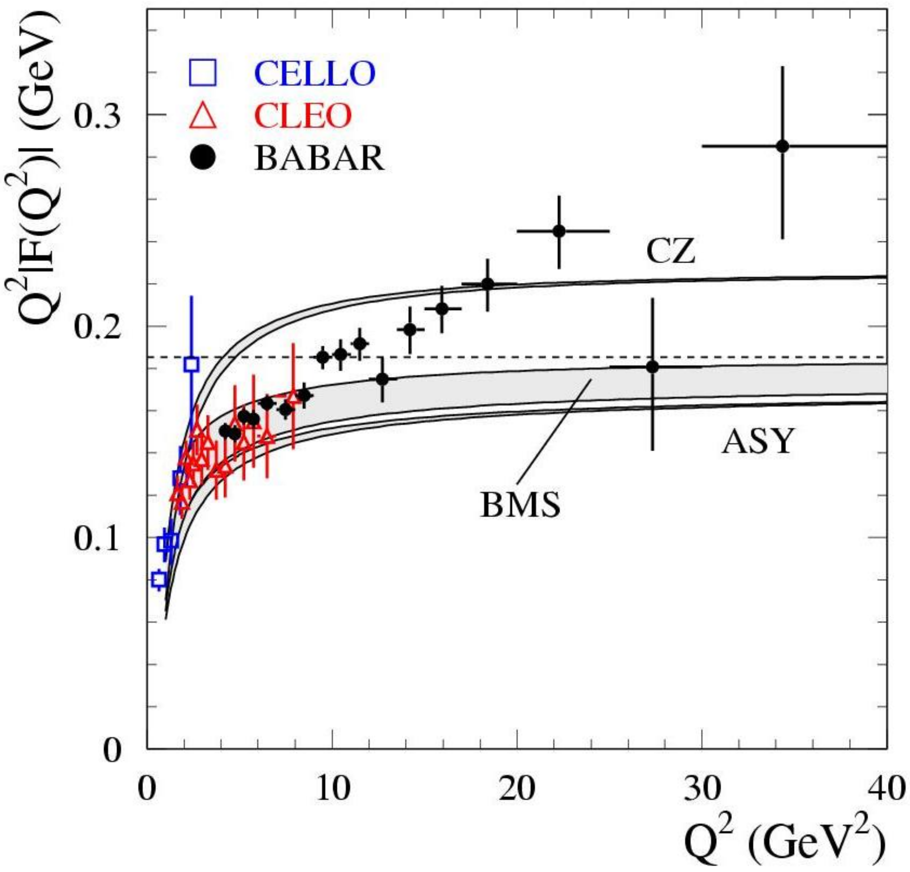
A.P.Bakulev, S.V.Mikhailov, N.G.Stefanis, Phys. Rev. D 67, 074012, light-cone sum rule method at NLO pQCD+twist-4 power corrections.

- NLO and power corrections are large: 30% at 4 GeV^2, 20% at 10 GeV^2, and 10% at 50 GeV^2

- The Q^2 evolution of the DA is very slow. As result the form factor Q^2 dependence is almost flat at Q^2 > 20 GeV^2.

$e^+e^- \to e^+e^-\pi^0$, comparison with theory

B.Aubert et al., Phys. Rev. D80, 052002 (2009)

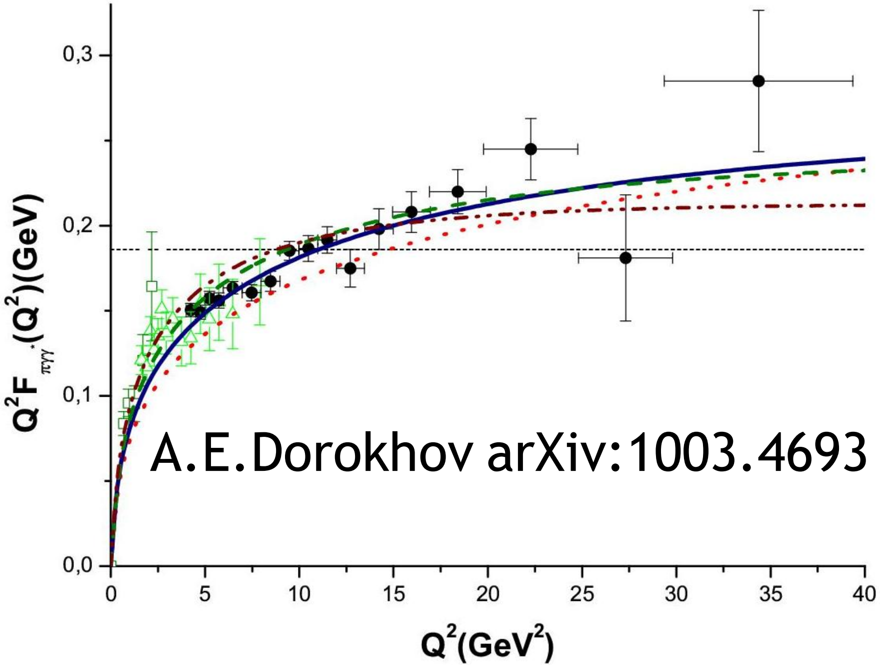


- ✓ In Q^2 range 4-9 GeV^2 our results are in a reasonable agreement with CLEO data but have significantly better accuracy.
- ✓ At Q^2>10 GeV^2 the measured form factor exceeds the asymptotic limit $\sqrt{2}f_\pi$=0.185 GeV.
- ✓ A.P.Bakulev, S.V.Mikhailov, N.G.Stefanis, Phys. Rev. D 67, 074012, light-cone sum rule method at NLO pQCD+twist-4 power corrections.

$e^+e^- \to e^+e^-\pi^0$, after publication

A.E.Dorokhov, arXiv:0905.4577, 1003.4693.
A.V. Radyuskin, arXiv:0906.0323. M.V.Polyakov, arXiv:0906.0538 …

A flat pion distribution amplitude $\varphi_\pi(x) \approx 1$ is used to reproduce Q^2 dependence of BABAR data.



A.E.Dorokhov arXiv:1003.4693

To avoid divergence the infrared regulator m^2 can be introduced

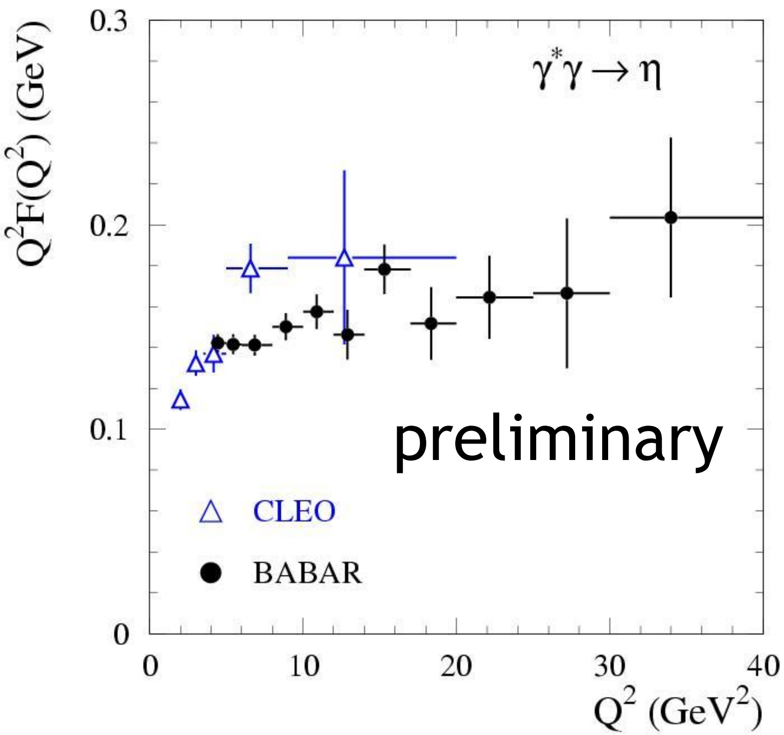
$$Q^2 F_{\pi\gamma}(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int_0^1 dx\, \frac{\phi_\pi(x,Q)}{x + m^2/Q^2}$$

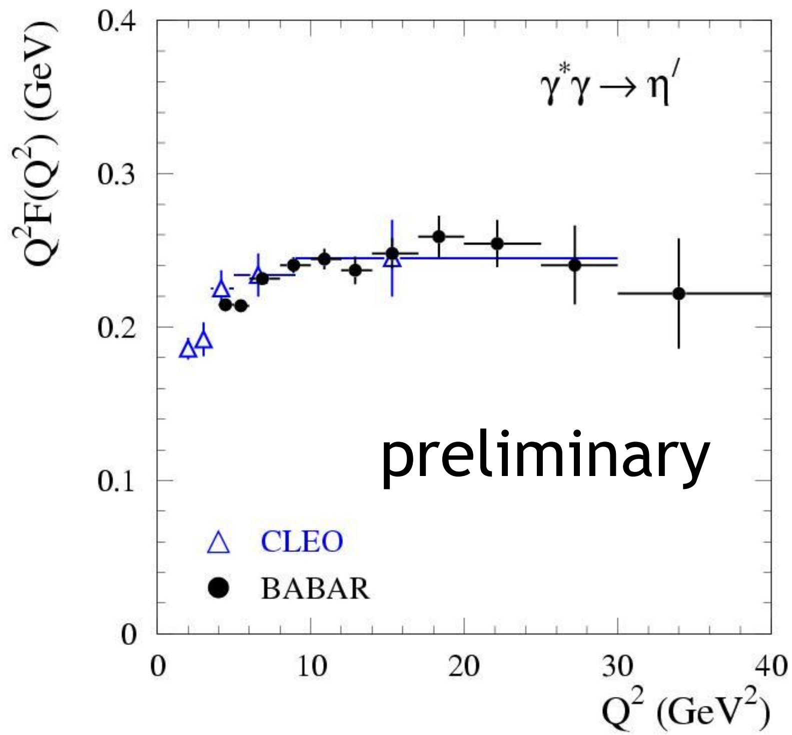
The result has a logarithmic rise with the Q^2 increase

$Q^2F(Q^2)=b+a \ln Q^2$ (GeV^2)

with $a \approx 0.06$ GeV^2

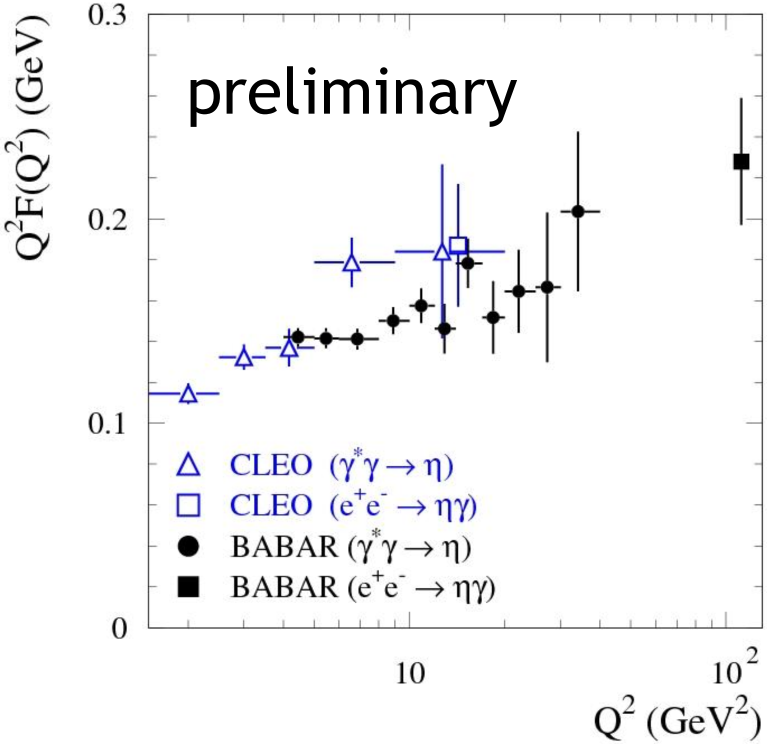
η and η' form factors

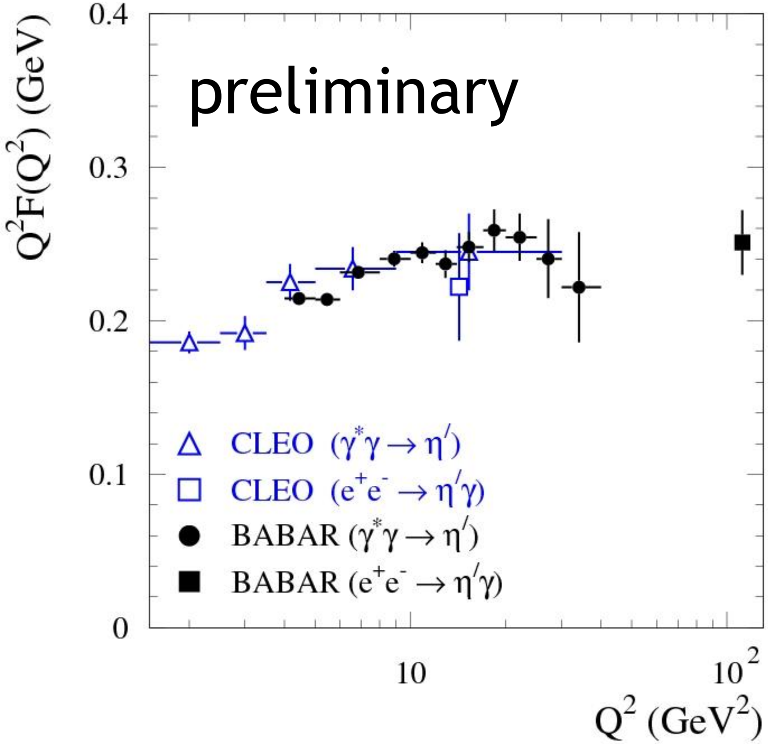




The systematic uncertainties independent of Q^2 are 2.9% for the η form factor and 3.5% for the η' form factor.

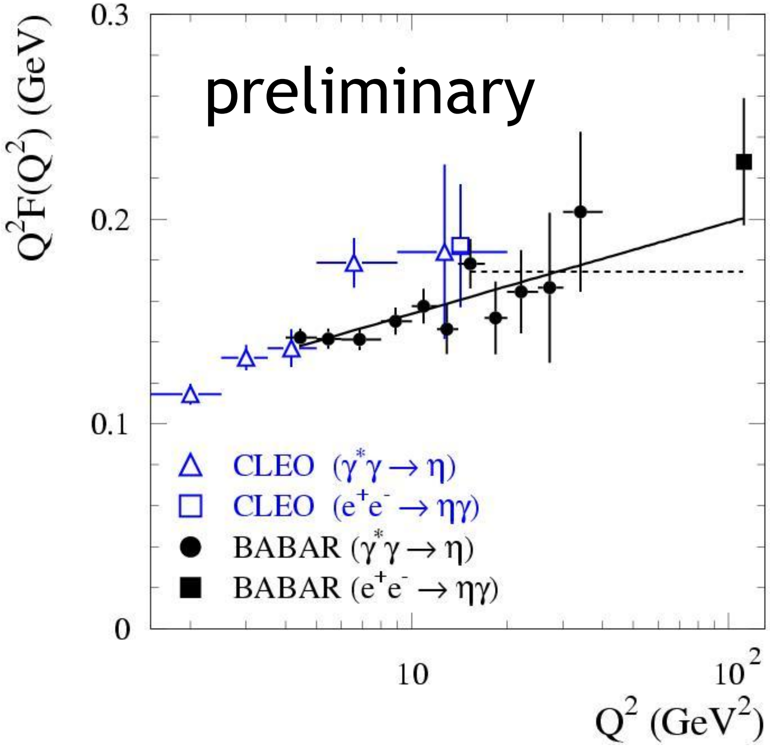
η *and* η' *form factors*

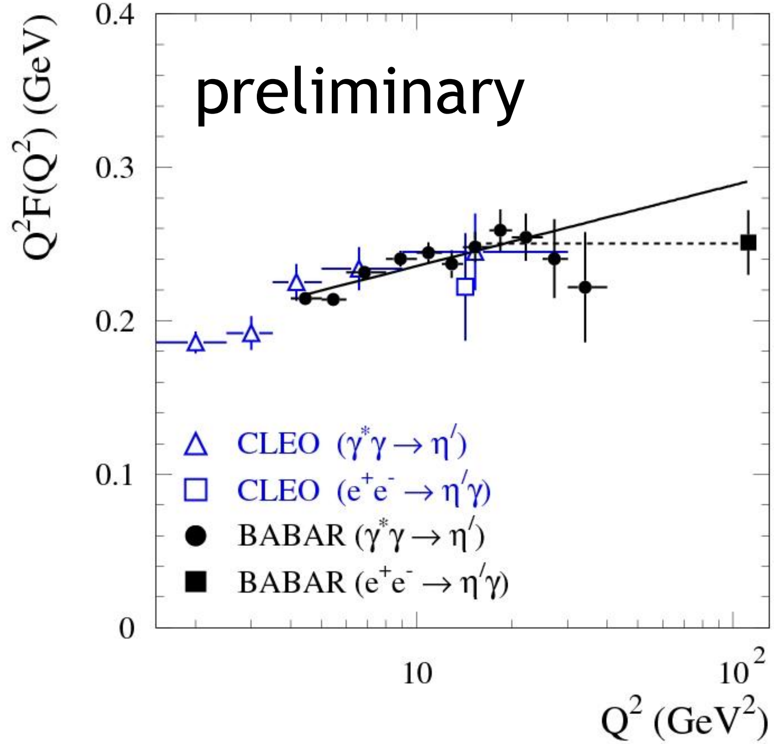




- CLEO and BABAR data on the time-like transition form factors are added.
- They are extracted from the $e^+e^- \to \eta^{(\prime)}\gamma$ cross section measurements at Q^2=14.2 GeV^2 (CLEO) and 112 GeV^2 (BABAR).
- At large Q^2 the time- and space-like values are expected to be close.
- This is confirmed by the CLEO result.
- The BABAR time-like data allow to extend the Q^2 region up to 112 GeV^2

Discussion: η and η' form factors





- The BABAR data are fit with $Q^2F(Q^2)=b+a\ln Q^2$ (GeV^2) with $\chi^2/n=6.7/10$ for η and $14.6/10$ for η'
- The fitted rise ($a\approx 0.2$ GeV^2) is about 3 times weaker than that for π^0.
- The fit by a constant for $Q^2>15$ GeV^2 also gives reasonable quality: $\chi^2/n=5.6/5$ for η and $2.6/5$ for η'.

η-η' mixing in the quark flavor basis

$$|n\rangle = \frac{1}{\sqrt{2}}(|\bar{u}u\rangle + |\bar{d}d\rangle), \quad |s\rangle = |\bar{s}s\rangle,$$

$\phi \approx 41°$

$$|\eta\rangle = \cos\phi\,|n\rangle - \sin\phi\,|s\rangle, \quad |\eta'\rangle = \sin\phi\,|n\rangle + \cos\phi\,|s\rangle.$$

The form factors for the $|n\rangle$ and $|s\rangle$ states are introduced

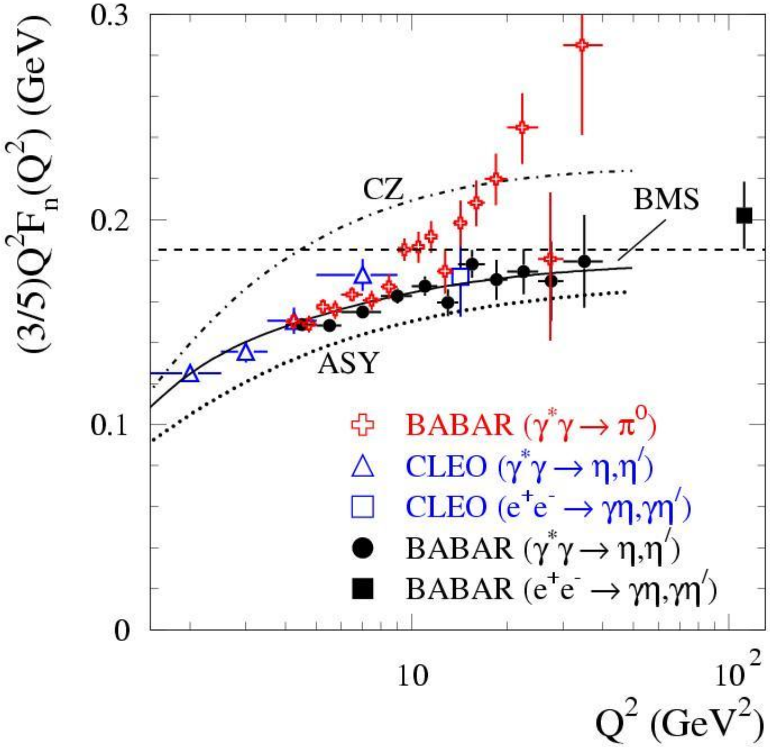
$$F_\eta = \cos\phi\,F_n - \sin\phi\,F_s, \quad F_{\eta'} = \sin\phi\,F_n + \cos\phi\,F_s,$$

with asymptotic limits $Q^2F_s(Q^2) = \frac{2}{3}f_s, \quad Q^2F_n(Q^2) = \frac{5\sqrt{2}}{3}f_n,$

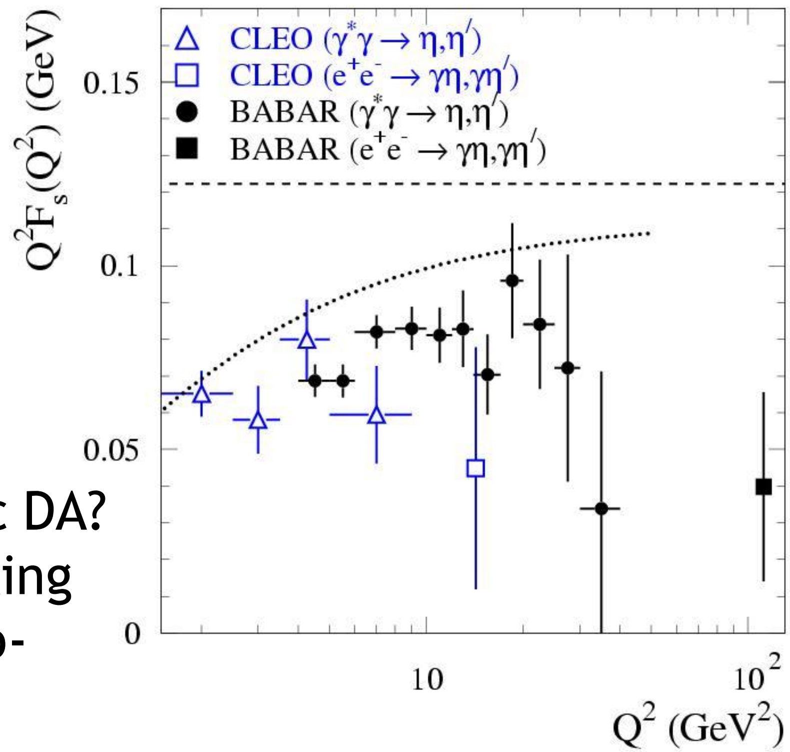
where decay constants is expected to be $f_n=f_\pi$, $f_s=1.34f_\pi$

One can expect that the DA for the $|n\rangle$ state is close to the π^0 DA. Under this assumption the only difference between the $|n\rangle$ and π^0 DAs is a factor of 3/5 coming from the quark charges.

Form factor for |n⟩ and |s⟩ state



- The Q^2 dependencies of the measured |n⟩ and π^0 form factors are strongly different.
- The data on the |n⟩ form factor are described well by the model with BMS DA.



- For |s⟩ all data points lie well below the pQCD prediction for the asymptotic DA.
- Is DA for |s⟩ narrower than the asymptotic DA?
- The result for |s⟩ strongly depends on mixing parameters, for example, on a possible two-gluon contents in η' .

Summary

- ✓ The new precise measurements of the η_c and $\eta_c(2S)$ masses and widths have been performed in the two-photon reaction.
- ✓ The new decay η_c and $\eta_c(2S)$ modes to $K^+K^-\pi^+\pi^-\pi^0$ have been observed.
- ✓ The $\gamma^*\gamma\to\eta_c$ form factor has been measured for Q^2 range from 2 to 50 GeV^2
- ✓ The η_c form factor data are in reasonable agreement with both QCD and VDM predictions.

Summary

- ✓ The $\gamma^*\gamma\to\pi^0$, η, η' transition form factors have been measured for Q^2 range from 4 to 40 GeV^2.
- ✓ The unexpected Q^2 dependence of the $\gamma^*\gamma\to\pi^0$ form factor is observed. At $Q^2>10$ GeV^2 the data lie above the asymptotic limit.
- ✓ The measured Q^2 dependencies for the $\gamma\gamma^*\to\eta$ and $\gamma\gamma^*\to\eta'$ transition form factors strongly differ from that for $\gamma\gamma^*\to\pi^0$ form factor.
- ✓ The η' data are in good agreement with the result of QCD calculation with a conventional DA, equal to zero at the end points.
- ✓ For η the agreement is worse. A mild logarithmic rise of $Q^2F(Q^2)$ is not excluded.
- ✓ We plan to update our measurements of $\gamma\gamma^*\to\eta$ and $\gamma\gamma^*\to\eta'$ time-like transition form factors at $Q^2=112$ GeV^2.