Measurements of $\gamma^*\gamma \to \pi^0$ and $\gamma^*\gamma \to \eta_c$ transition form factors at BABAR

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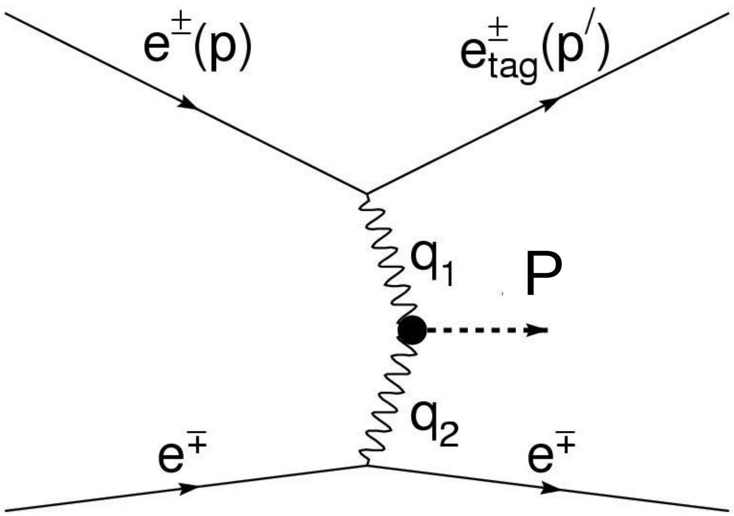
for BaBar Collaboration

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)

Single-tag mode:

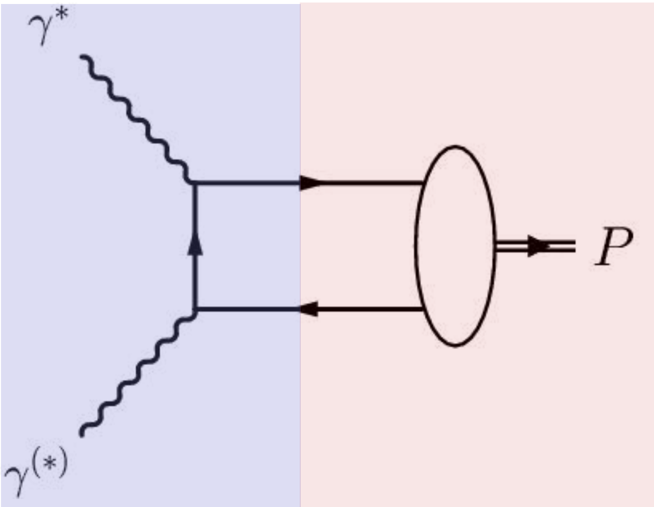
✓one of electrons is detected

✓$Q^2=-q_1^2=2EE^{/}(1-\cos\theta)$,

✓ $d\sigma/dQ^2 \sim 1/ Q^6$ for π^0

✓$F(Q^2,0)$

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

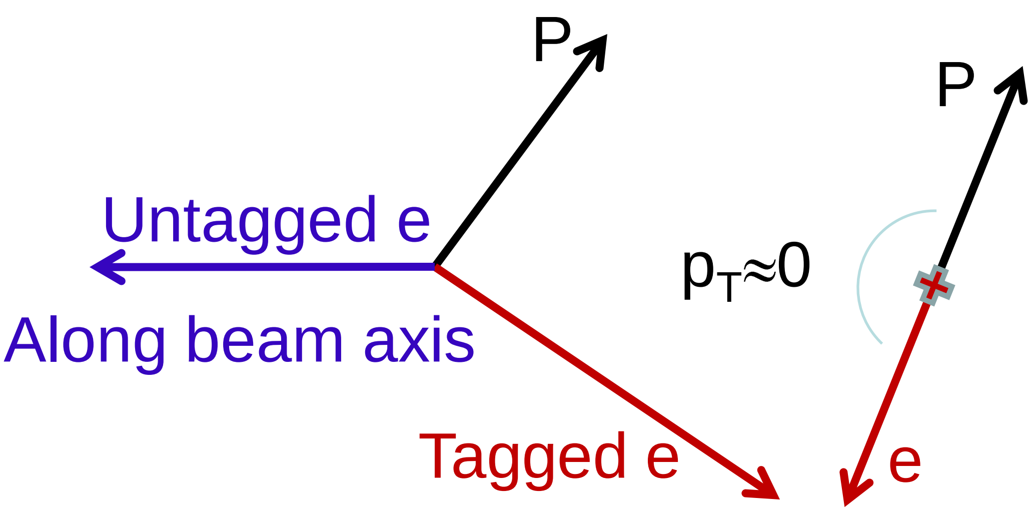


$$F(Q^2) = \int T(x,Q^2)\,\varphi(x,Q^2)\,dx$$

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

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

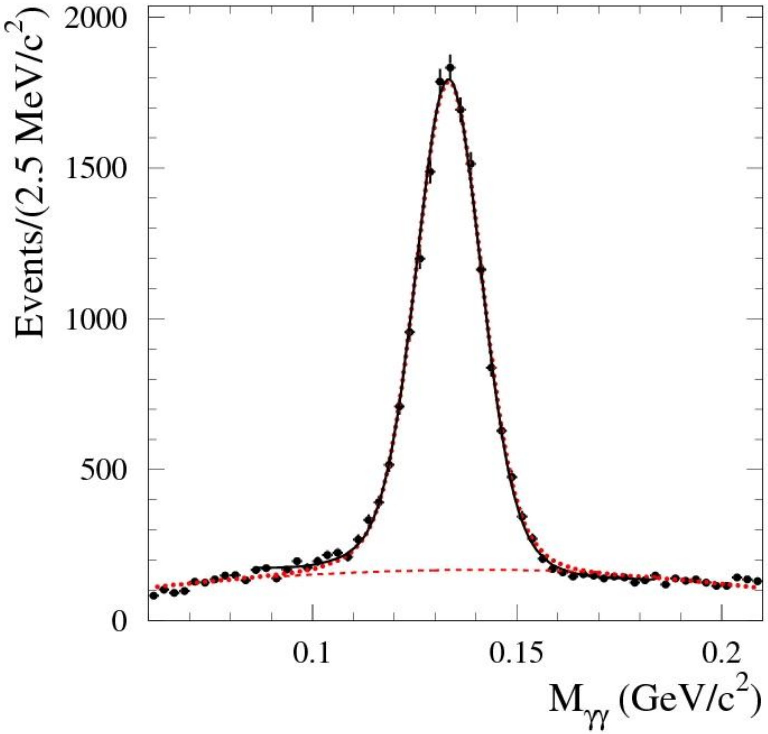
x is the fraction of the meson momentum carried by one of the quarks



- ✓electron is detected and identified
- ✓π^0 or η_c are detected and fully reconstructed
- ✓electron + meson system has low $p_\perp$
- ✓missing mass in an event is close to zero

$e^+e^- \to e^+e^-\pi^0$

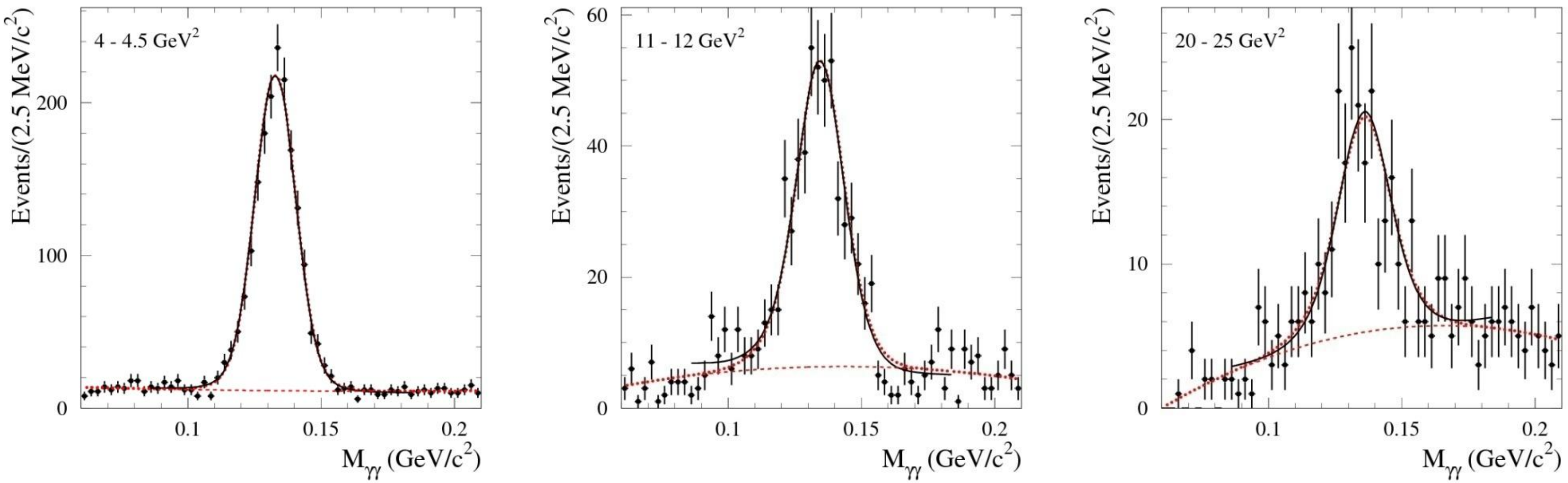
B.Aubert et al., Phys. Rev. D80, 052002 (2009)



- The main non-resonant background is virtual Compton scattering, the process $e^+e^- \to e^+e^-\gamma$ with one of the final electrons directed along the beam axis.
- The peaking background comes $e^+e^- \to e^+e^-\pi^0\pi^0$, about 10% of signal events.

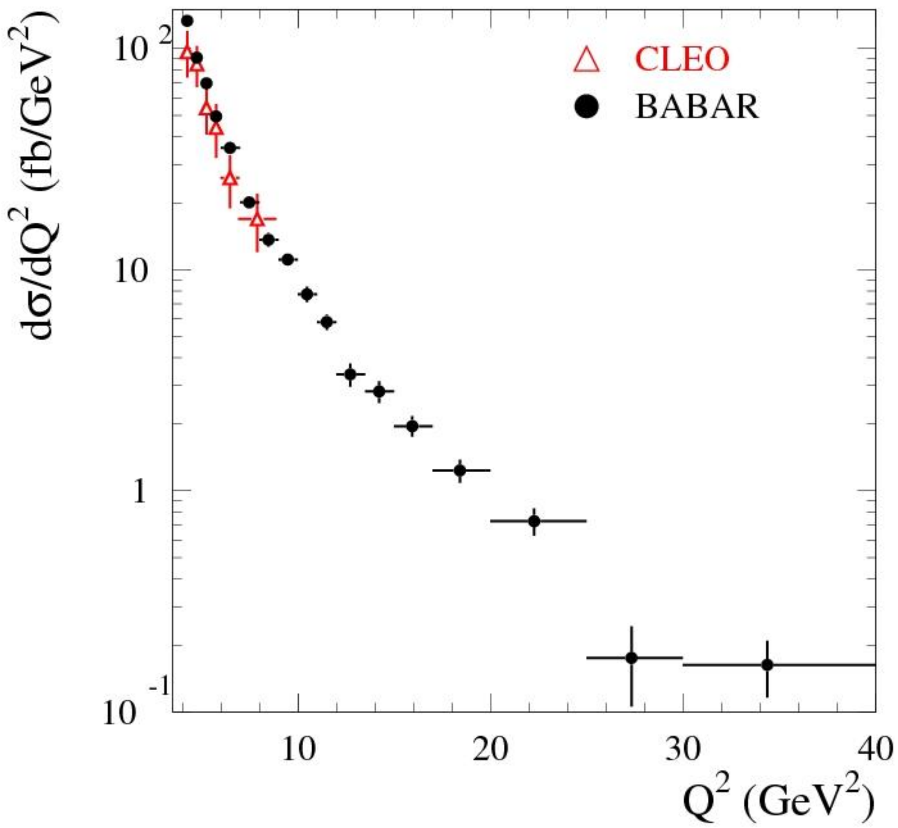
Detector	Q^2, GeV^2	Events	Year
CELLO	0.7-2.2	127	1991
CLEO	1.6-8.0	1219	1998
BABAR	4-40	13200	2009

$e^+e^- \to e^+e^-\pi^0$



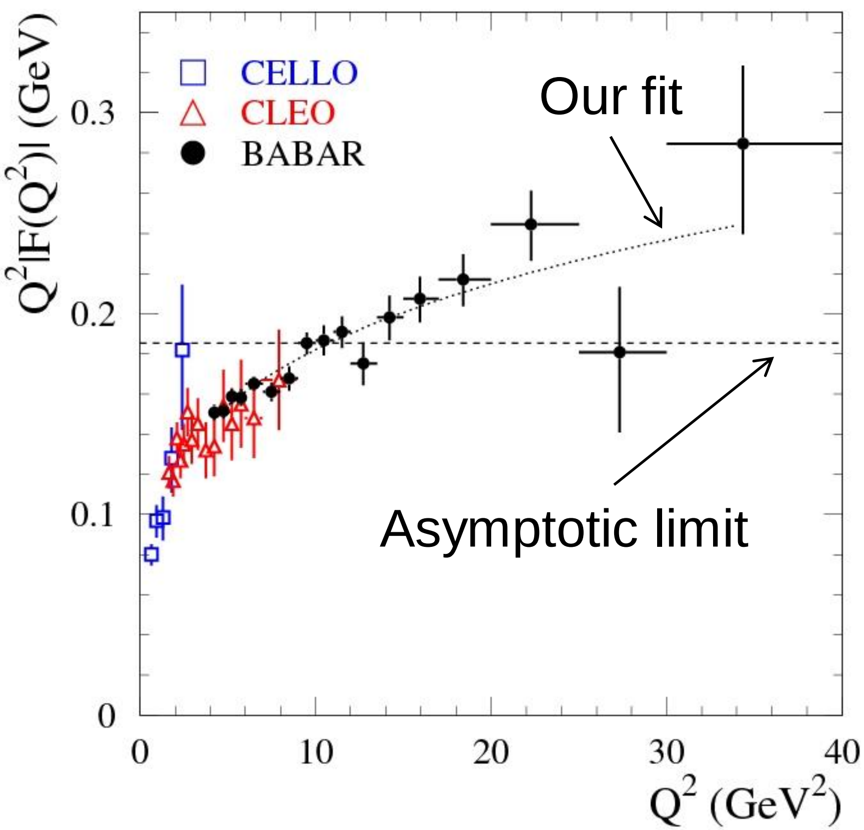
The data were divided into 17 Q^2 intervals.

$e^+e^- \to e^+e^-\pi^0$, cross section



Systematic uncertainty independent on Q^2 is 3%.

$e^+e^- \to e^+e^-\pi^0$, form factor



Systematic uncertainty independent on Q^2 is 2.3%.

✓ 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. Most models for the pion distribution amplitude give form factors approaching the limit from below.

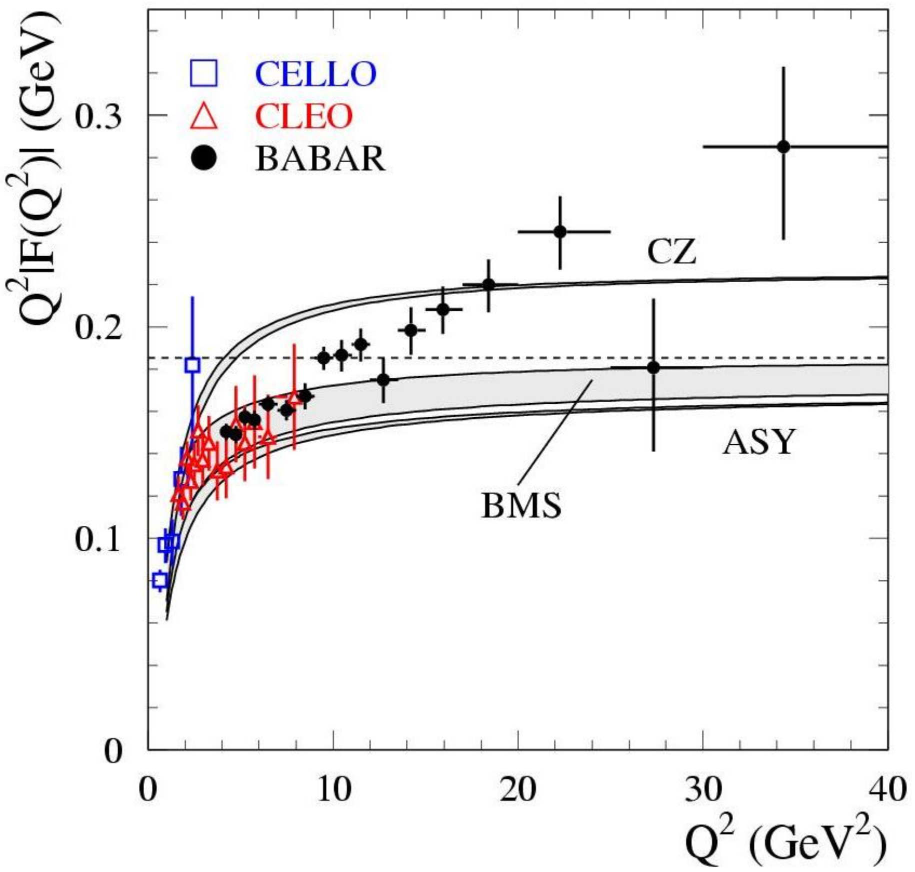
✓ Our data in the range 4-40 GeV^2 are well described by the formula

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

with A=0.182±0.002 GeV and β=0.25±0.02, i.e. $F\sim 1/Q^{3/2}$.

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

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



✓ 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.

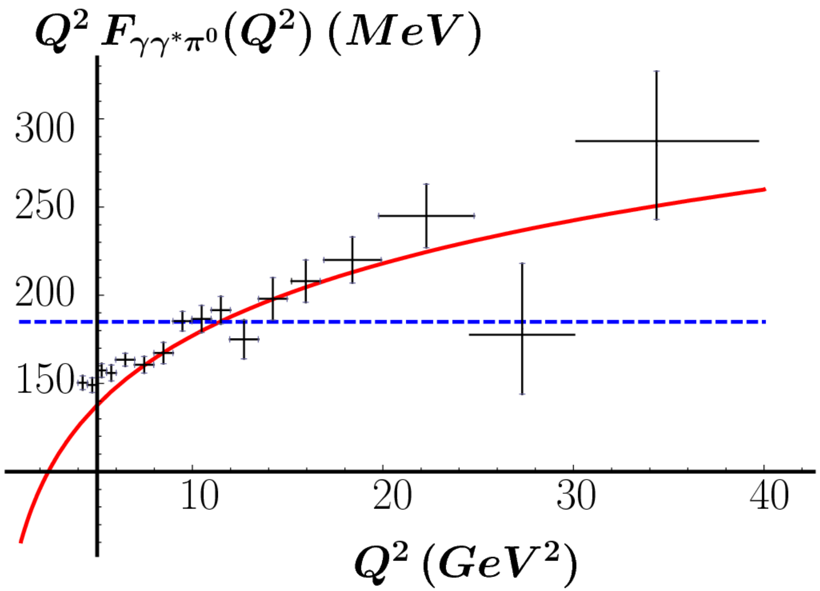
✓ $Q^2<20$ GeV^2 : large difference between the data and the theory in Q^2 dependence . The models are inadequate for $Q^2<15$ GeV.

✓ $Q^2 > 20$ GeV^2 : theoretical uncertainties are expected to be smaller. Our data lie above the asymptotic limit and are consistent with the CZ model.

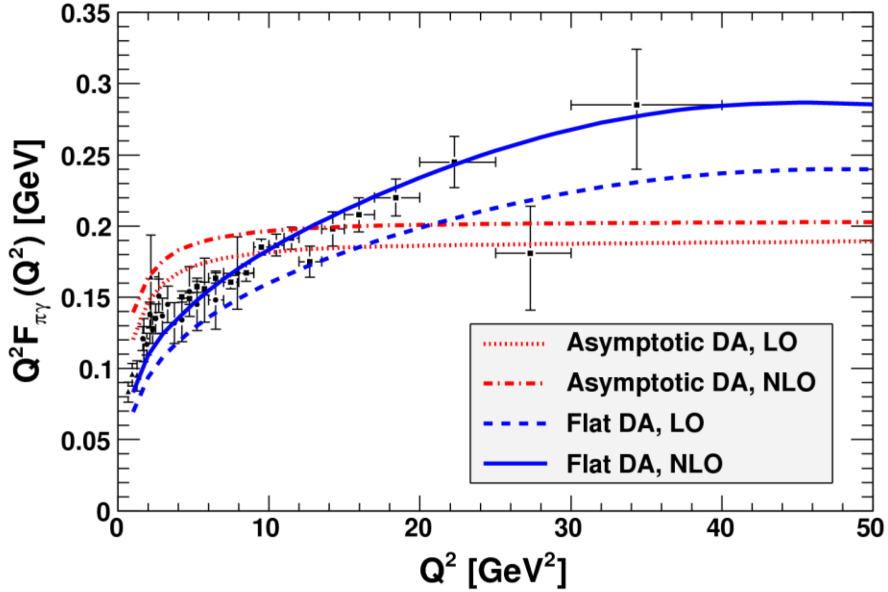
$e^+e^- \to e^+e^-\pi^0$, after publication

- S.V.Mikhailov and N.G.Stefanis, Nucl. Phys. B821, 291 (2009), the growth of the form factor in Q^2 range 10-20 GeV^2 cannot be explained by NNLO pQCD and power corrections
- A.V. Radyuskin, arXive:0906.0323; M.V.Polyakov, arXive:0906.0538; H.N.Li and S.Mishima, arXive:0907.0166. A flat pion distribution amplitude is used to reproduce Q^2 dependence of BABAR data.

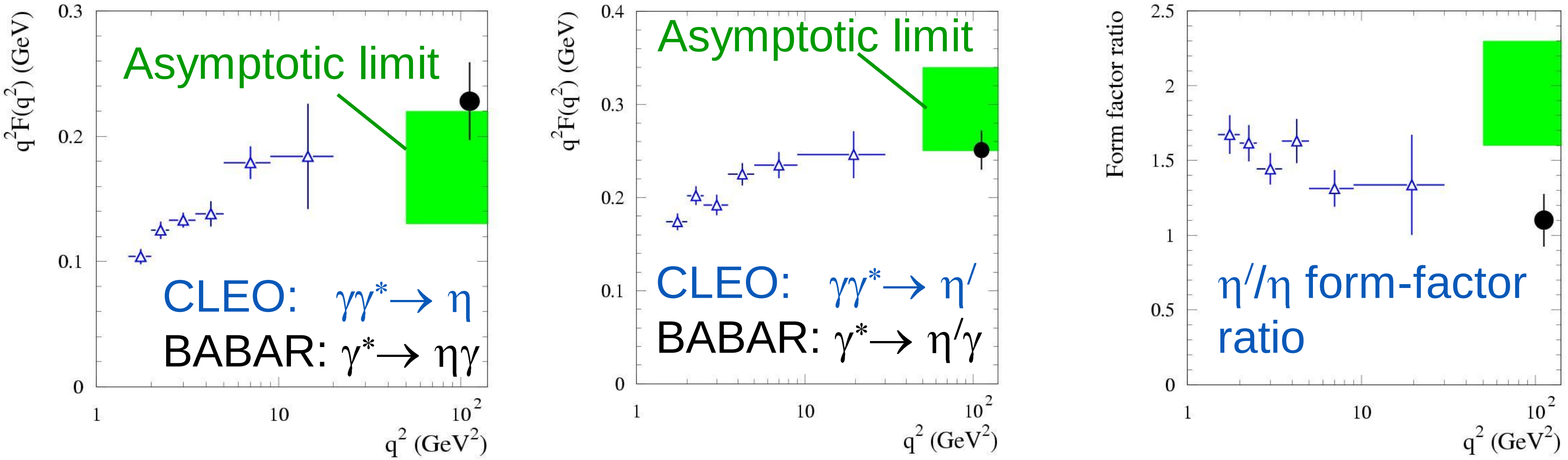
A.V. Radyuskin



H.N.Li and S.Mishima



$\gamma\gamma^* \to \eta, \eta^\prime$ form factors

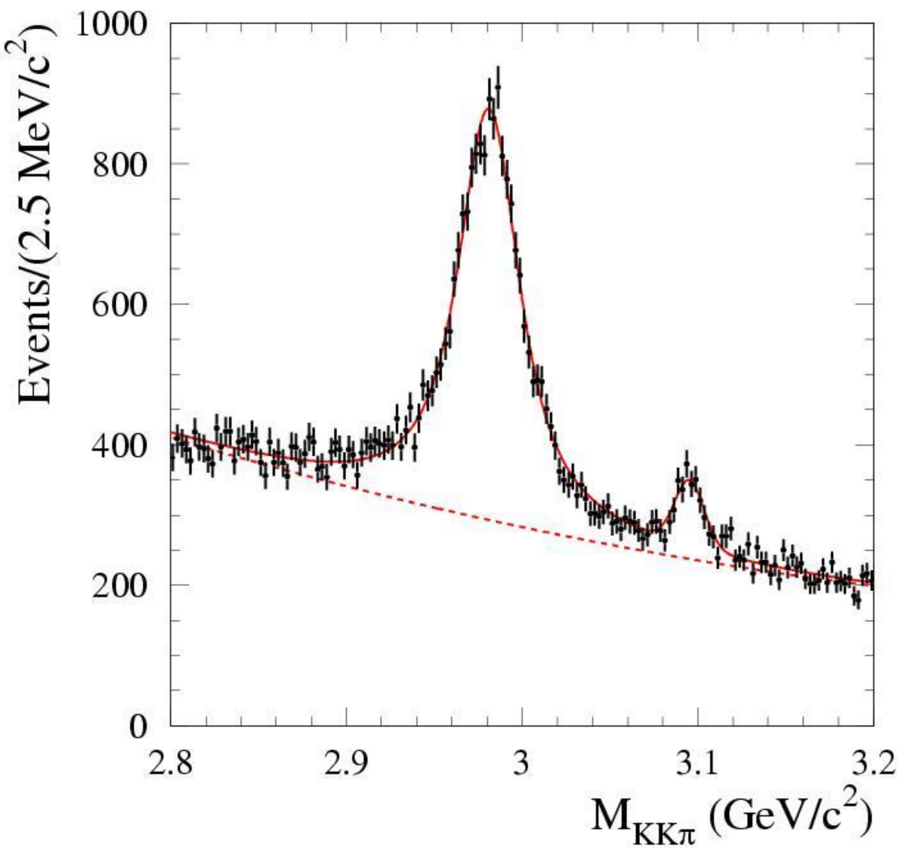


- ✓ BABAR (Phys.Rev.D74, 012002 (2006)) measured the time-like form factors in $e^+e^- \to \eta\gamma, \eta^\prime\gamma$ reactions at the c.m. energy 10.6 GeV.
- ✓ Asymptotic limits are calculated taking into account η-$\eta^\prime$-mixing and have large model uncertainties.
- ✓ The large deviation from the asymptotic value (by a factor of 1.5-2) is observed for the form-factor ratio. The deviation from the asymptotic value for the π^0 form factor at large Q^2 is about 30%.
- ✓ The analysis of BABAR data on two-photon η and $\eta^\prime$ production is in progress. We expect to cover Q^2 interval from 4 to 60 GeV^2.

$\gamma\gamma^* \rightarrow \eta_c$ form factor

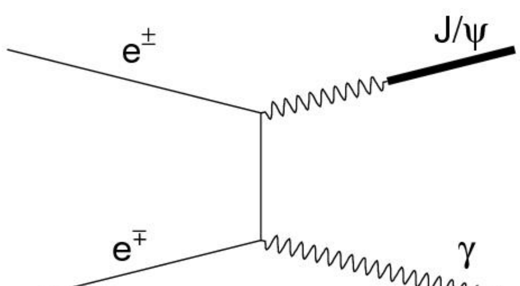
- pQCD: Due to relatively large c-quark mass, the η_c form factor is rather insensitive to the shape of η_c distribution amplitude. The form factor Q^2 dependence is expected to be described by the monopole form $F(0)/(1+Q^2/\Lambda)$ with $\Lambda \approx 10$ GeV^2.
- The η_c is observed via the $\eta_c \rightarrow K_S K^+ \pi^-$ decay.
- The η_c two-photon width and branching fractions are not well measured.
- No-tag data are also studied to measure the product $\Gamma(\eta_c \rightarrow \gamma\gamma)B(\eta_c \rightarrow KK\pi)$ and normalize the $F(Q^2)$ to $F(0)$.
- The high no-tag statistics allow to perform accurate measurement of the η_c mass and total width.

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

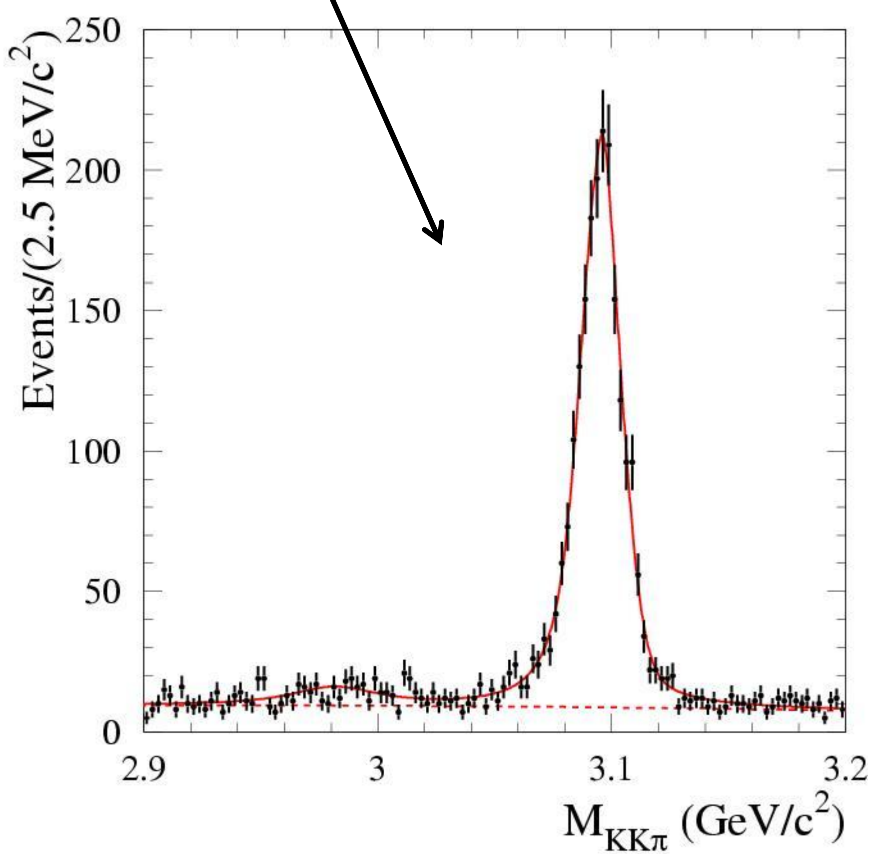


Part of ISR events can be separated using the condition:

$$p^*/(1 - M^2_{KK\pi}/s) > 5.1 \text{ GeV}/c,$$



(a)



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

- The sources of non-resonant background are two-photon and ISR processes.
- The peaking background is $e^+e^- \to J/\psi\gamma$, $J/\psi \to \eta_c\gamma \to K_S K^+ \pi^- \gamma$.

It is calculated from the fitted number of $J/\psi \to K_S K^+ \pi$ events. 4%.

	Mass, MeV	Width,MeV
PDG	2980.3±1.2	26.7±3.0
BABAR(88 fb^{-1})	2982.5±1.1±0.9	34.3±2.3±0.9
BABAR(470 fb^{-1}), preliminary	2982.2±0.4±1.5	31.7±1.2±0.8

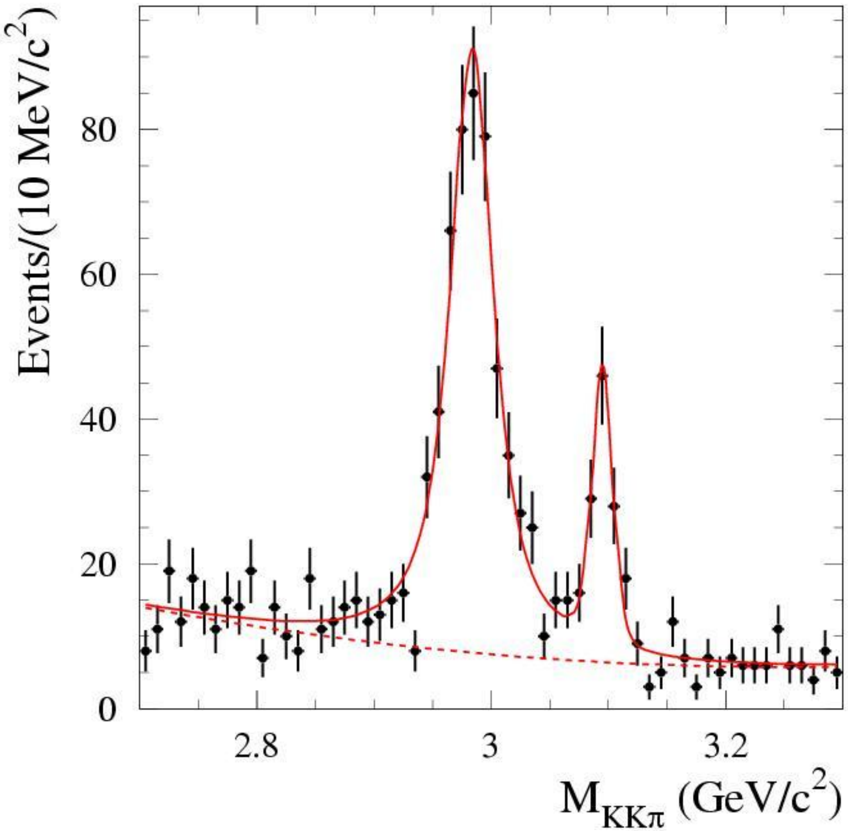
Main sources of systematic uncertainties are unknown background shape and possible interference η_c and non-resonant two-photon amplitudes.

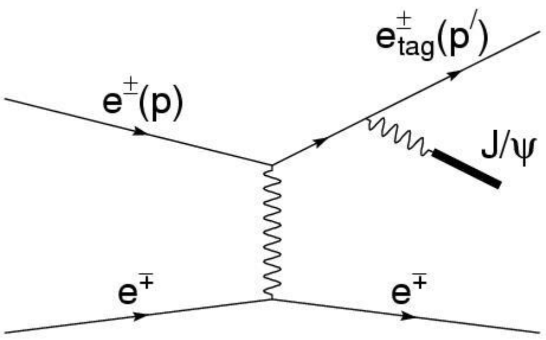
$N(\eta_c)=13890\pm320\pm670$

BABAR preliminary: $\Gamma(\eta_c \to \gamma\gamma)B(\eta_c \to KK\pi) = 0.379\pm0.009\pm0.031$ keV

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

$e^+e^- \to e^+e^- \eta_c$, single-tag mode

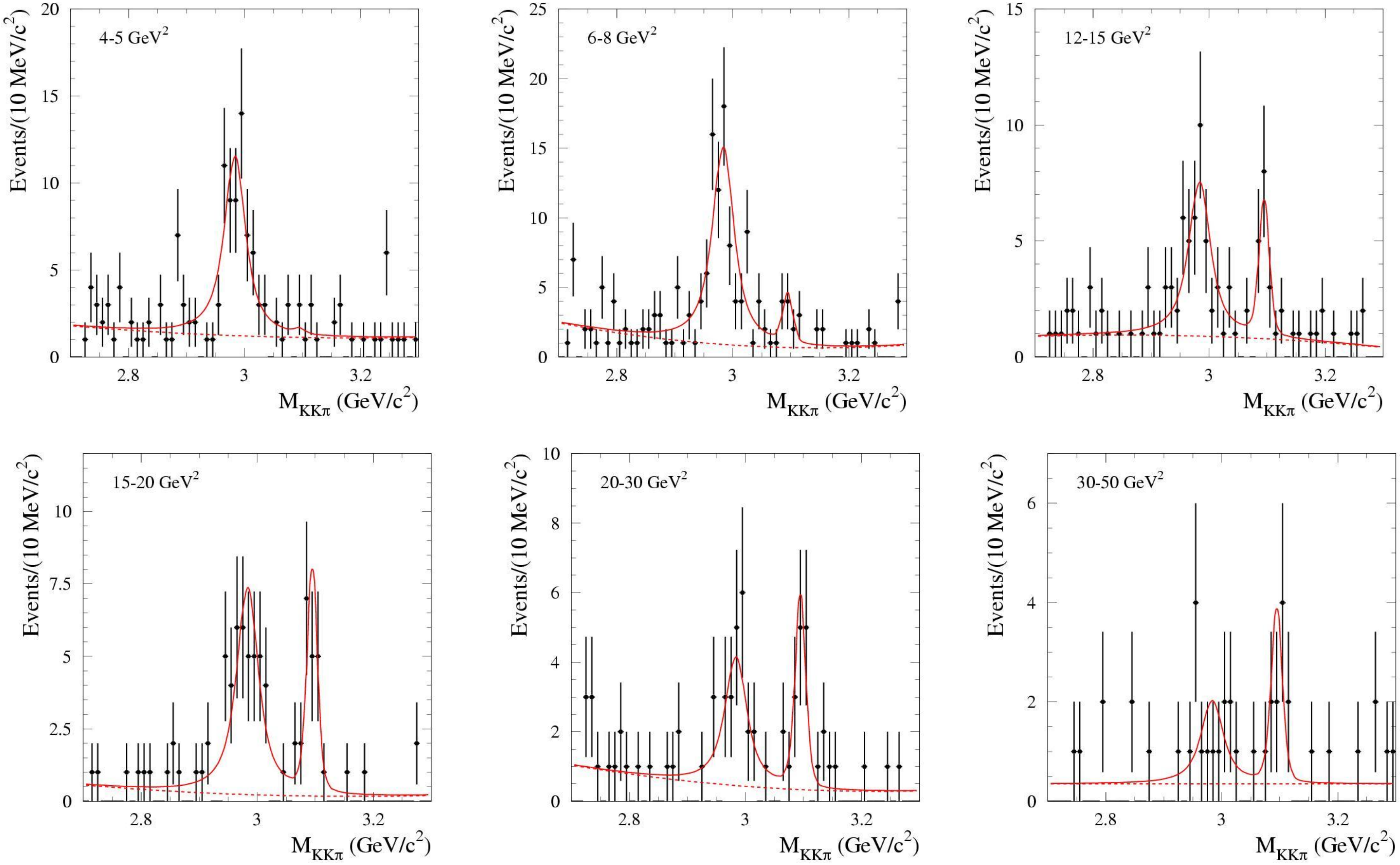




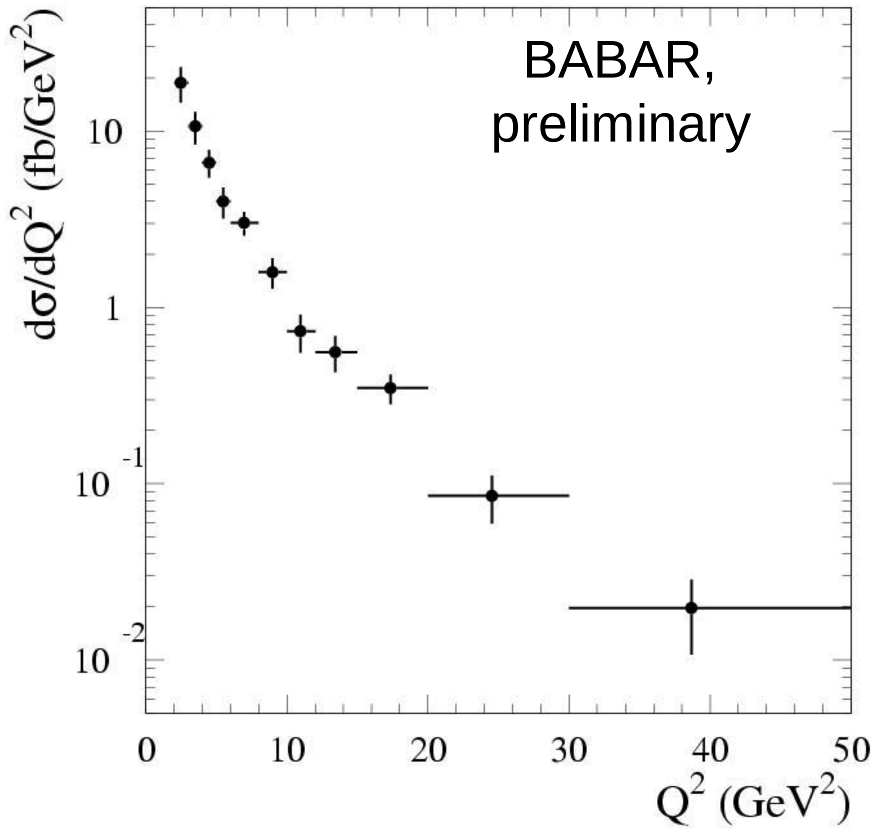
$m=2985.7\pm2.0$ MeV/c^2
$\Gamma=31.9\pm4.3$ MeV
$N=530\pm41\pm17$

Peaking background from $e^+e^- \to e^+e^- J/\psi$, $J/\psi \to \eta_c\gamma \to K_SK^+\pi^-\gamma$ is calculated from the fitted number of $J/\psi \to K_SK^+\pi^-$ events. It varies from about 1% at $Q^2<10$ GeV^2 to about 5% at $Q^2\approx30$ GeV^2

$e^+e^- \rightarrow e^+e^- \eta_c$, *single-tag mode*

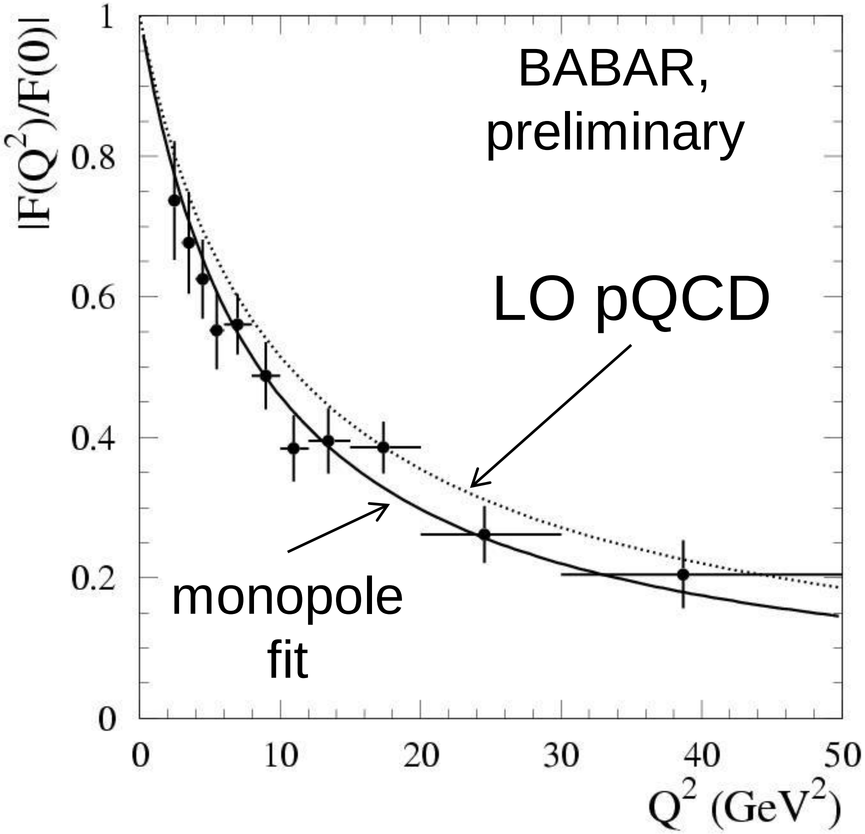


$e^+ e^- \to e^+ e^- \eta_c$, cross section



Systematic uncertainty independent on Q^2 is 6.7%.

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



Systematic uncertainty independent on Q^2 is 4.3%.

- The form factor is normalized to F(0) obtained from no-tag data.
- We fit the function

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

to the form factor data. The result

$\Lambda = 8.5 \pm 0.6 \pm 0.7$ GeV^2

does not contradict the vector dominance model with

$\Lambda = m^2_{J/\psi} = 9.6$ GeV^2.

and lattice QCD (J.J.Dudek, R.G.Edwards, Phys. Rev. Lett. 97, 172001 (2006))

$\Lambda = 8.4 \pm 0.4$ GeV^2

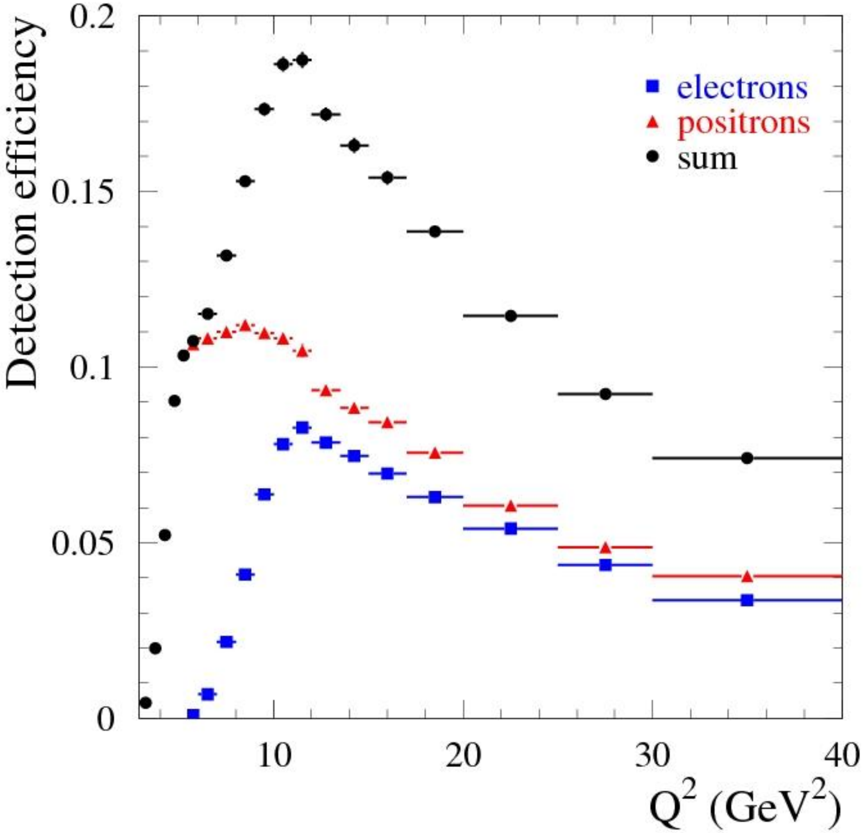
- Our data lie below a leading-order pQCD calculation (T. Feldmann, P.Kroll, Phys. Lett. B413, 410 (1997))

Summary

- The $\gamma^*\gamma\to\pi^0$ transition form factor has been measured for Q^2 range from 4 to 40 GeV^2
- The unexpected Q^2 dependence of the form factor is observed for $Q^2>10$ GeV^2. The data lie above the asymptotic limit. This indicates that pion distribution amplitude is wide.
- This measurement stimulated development of new models for form-factor calculations.
- The $\gamma^*\gamma\to\eta_c$ form factor has been measured for Q^2 range from 2 to 50 GeV^2
- The form factor data are well described by the monopole form with $\Lambda=8.6\pm0.6\pm0.7$ GeV^2.The data are in reasonable agreement with both QCD and VDM predictions.

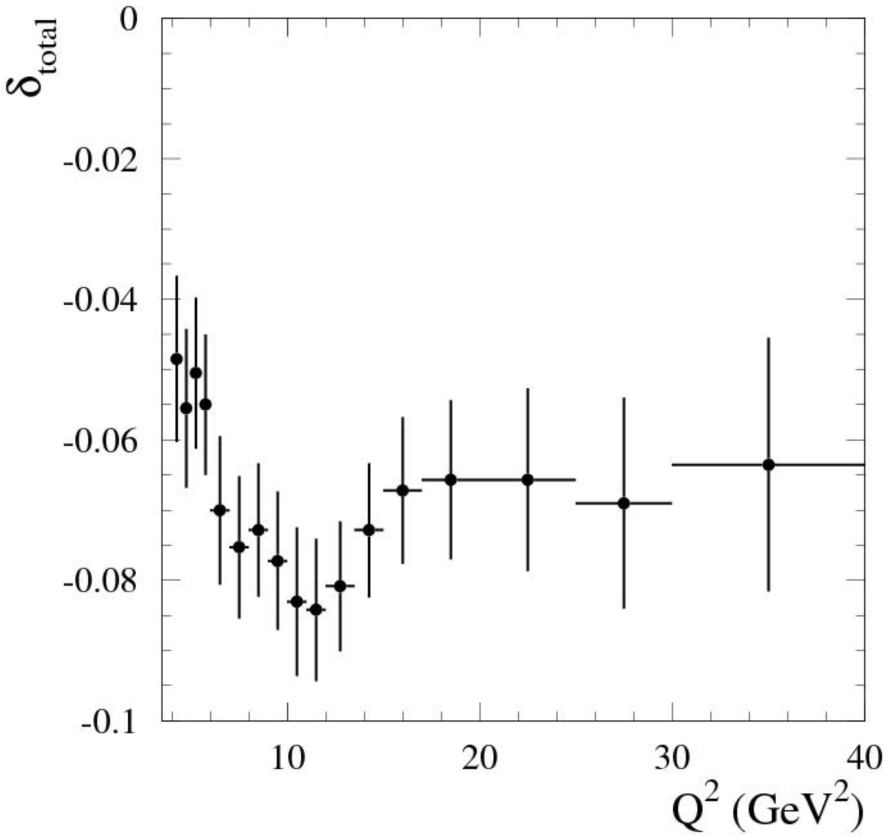
BACKUP SLIDES

$e^+e^- \to e^+e^-\pi^0$, detection efficiency



- Due to asymmetry of e^+e^- collision the Q^2 region below 7 GeV^2 is measured only with positron tag
- We measure the cross section from $Q^2 > 4$ GeV^2 to avoid possible systematic error due to data-MC difference near the edges of the detector
- The average π^0 energy grows with Q^2. This leads to decrease of the detection efficiency for $Q^2 > 10$ GeV^2

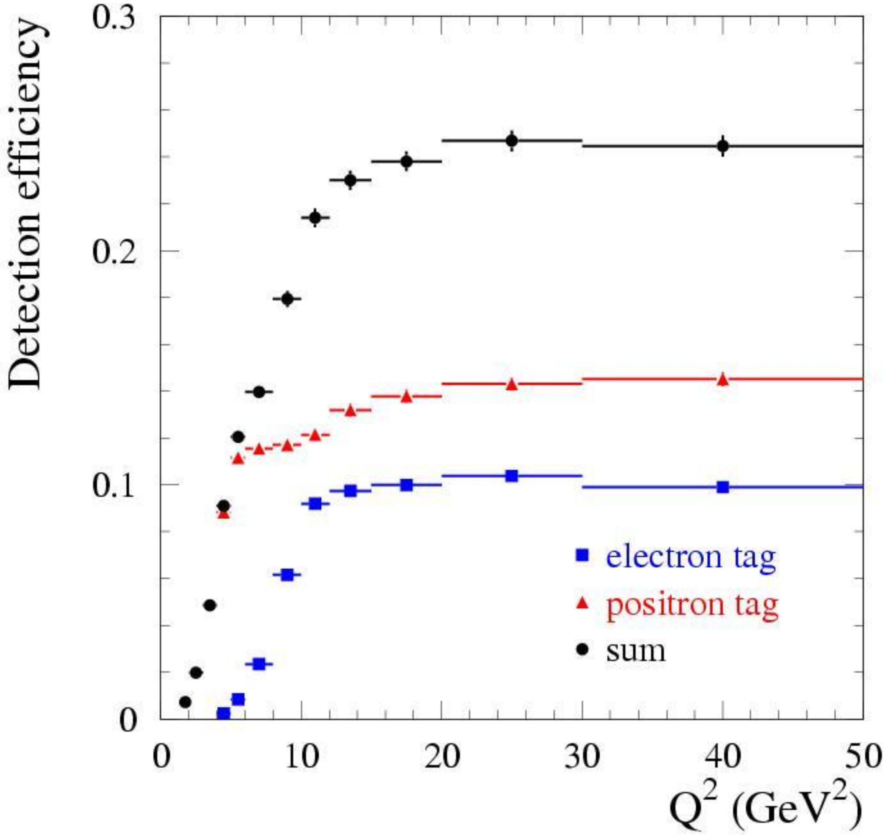
$e^+e^- \to e^+e^-\pi^0$, total efficiency correction



Total systematic error independent on Q^2 is 2.5% and includes

- 1% - π^0 losses,
- 2% - trigger efficiency,
- 1% - $\cos\theta_{e\pi}$ cut.

$e^+e^- \to e^+e^-\eta_c$, *detection efficiency*



- Due to asymmetry of e^+e^- collision the Q^2 region below 6 GeV^2 is measured only with positron tag
- We measure the cross section from Q^2 = 2 GeV^2 where the efficiency is about 2%.
- For no-tag events the efficiency is (14.5±0.2)%
- Data Dalitz plot distribution is used to reweight MC events. The shift of efficiency is small, (-1.1±1.6)%.

$e^+e^- \to e^+e^-\eta_c$, systematic uncertainty

Source	No-tag, %	Single-tag, %
trigger, filters	1.2	–
η_c selection	5.9	5.7
track reconstruction	1.4	1.5
$K^\pm$ identification	0.4	0.5
$e^\pm$ identification	–	1.0
total	6.2	6.0

- To estimate systematic uncertainty due to selection criteria we change
  - K_S mass window: o.4875-0.5075 $\Rightarrow$ 0.475-0.52
  - Limit on transverse momentum: 0.25 $\Rightarrow$ 0.5
  - $0.387<\theta<2.4$ for kaon and pions
  - $-0.02<r<0.03 \Rightarrow -0.02<r<0.06$
- The significant (~6%) effect is observed for change of angular restrictions.