Measurements of the photon-meson transition form factors at BABAR

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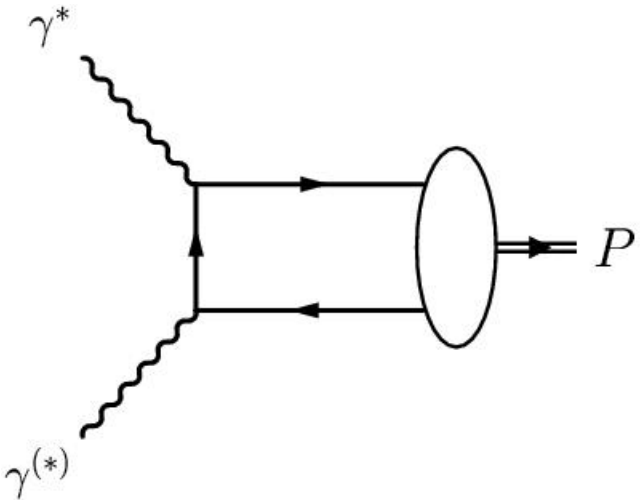
BABAR™

What is the $\gamma^*\gamma \to P$ form factor?



The amplitude of the $\gamma^*\gamma \to P$ transition

$$A = e^2 \varepsilon_{\mu\nu\alpha\beta} e_1^\mu e_2^\nu q_1^\alpha q_2^\beta F(q_1^2, q_2^2),$$

where P is a pseudoscalar meson, contains one unknown function, depending on the photon virtualities.

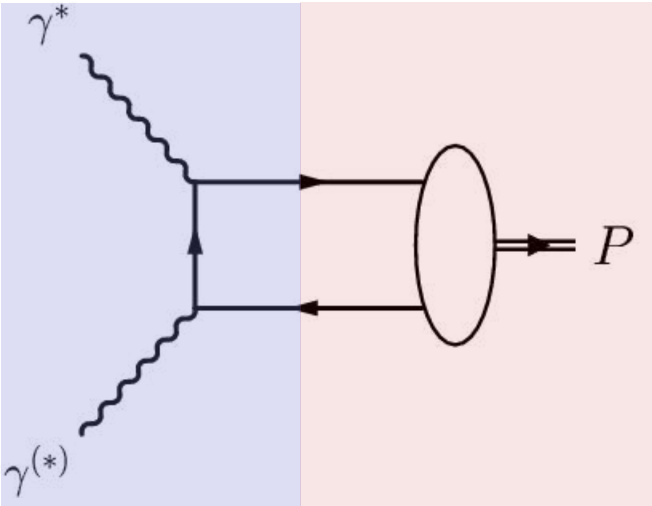
The form factor is usually measured as a function of $Q^2=|q_1|^2$. The second photon is real or almost real ($q_2^2 \approx 0$).

The form factor is known only for the two extreme cases. For π^0

$\lim_{Q^2\to 0} F(Q^2) = \sqrt{2}/(4\pi^2 f_\pi),$	from the axial anomaly in the chiral limit, prediction for $\Gamma(\pi^0 \to \gamma\gamma)$
$\lim_{Q^2\to\infty} Q^2 F(Q^2) = \sqrt{2} f_\pi.$	from perturbative QCD

$f_\pi \approx 0.131$ GeV is the pion decay constant

Why is the form factor interesting?



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

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

Nonperturbative meson distribution amplitude (DA) describing transition $P \to q\bar{q}$

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

✓ The meson DA $\varphi(x,Q^2)$ plays an important role in theoretical descriptions of many QCD processes ($\gamma^* \to \pi^+\pi^-$, $\gamma\gamma \to \pi\pi$, $\chi_{c,0,1} \to \pi^+\pi^-$, $B \to \pi l \nu$, $B \to \pi\pi$…)

✓ Its shape (x dependence) is unknown, but its evolution with Q^2 is predicted by pQCD

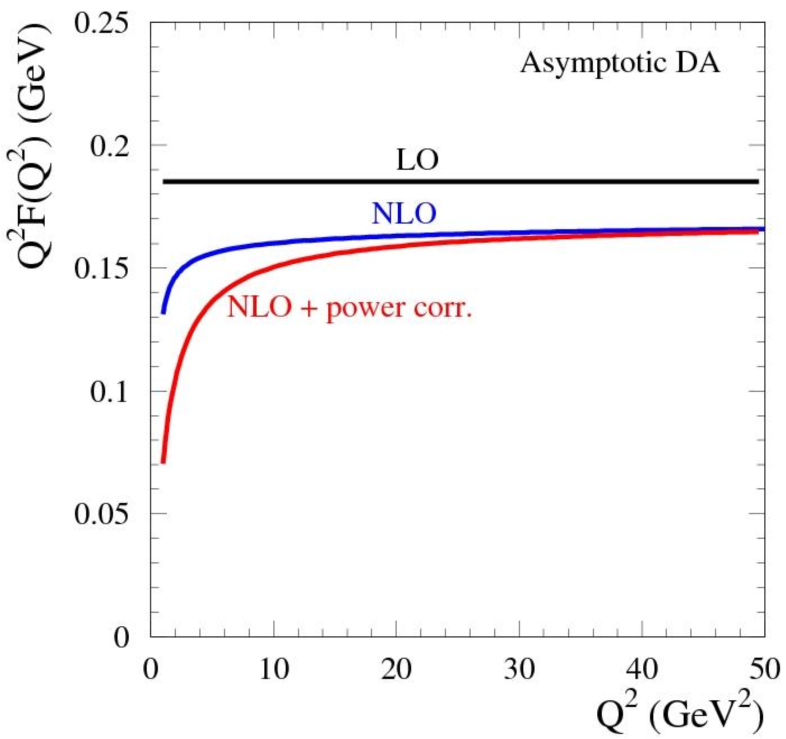
✓ The models for DA shape can be tested using data on the form factor Q^2 dependence

Calculation of the $\gamma^*\gamma \to \pi^0$ form factor

The leading contribution:

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

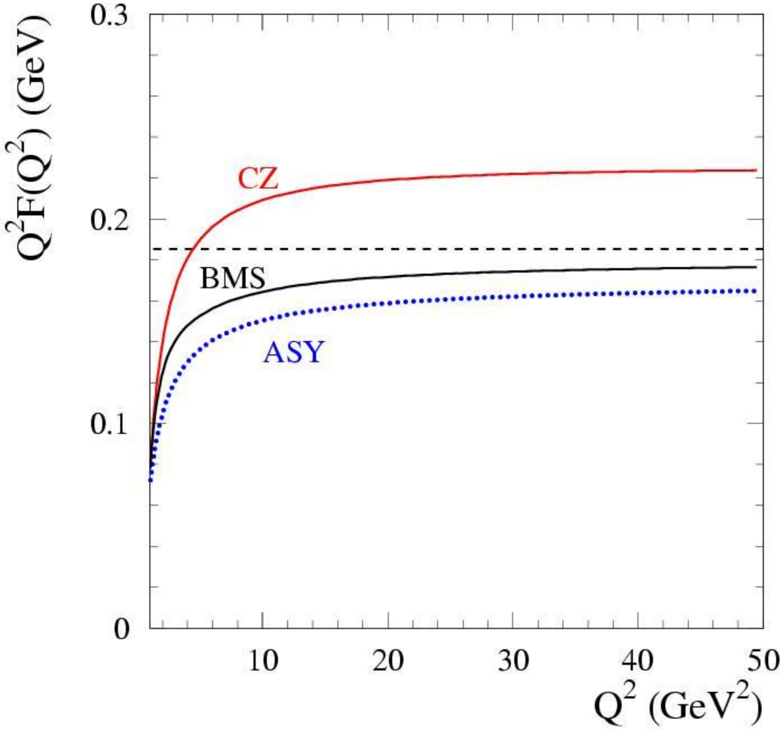
$$\varphi_{ASY} = 6x(1-x)$$ G.P.Lepage and S.J.Brodsky, Phys.Lett. B87, 359 (1979)



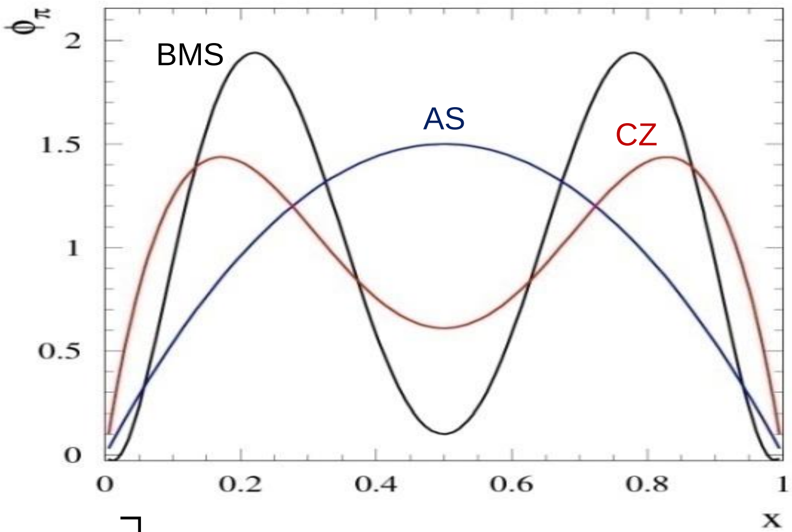
A.P.Bakulev, S.V.Mikhailov and N.G.Stefanis, Phys.Rev. D 67, 074012 (2003): light-cone sum rule method at NLO.

- NLO and power corrections are large: 30, 20,10 % at 4,10,50 GeV^2.
- Power corrections are 7% at 10 GeV^2 (twist-4 + due to hadronic component of a quasi-real photon).
- What is the model uncertainty of the power corrections?

Calculation of the $\gamma^*\gamma \to \pi^0$ form factor



CZ DA: V.L.Chernyak and A.R.Zhitnitsky, Nucl.Phys. B201, 492 (1982).
BMS DA: A.P.Bakulev, S.V.Mikhailov and N.G.Stefanis, Phys.Lett. B508, 279 (2001).



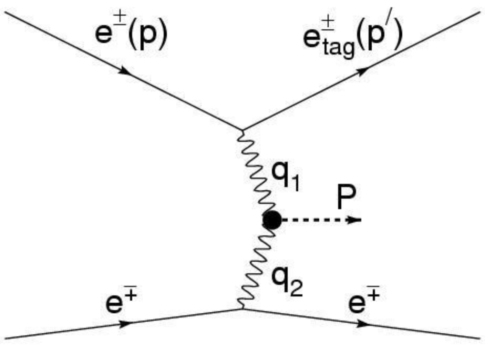
$$\varphi(x,Q^2) = \varphi_{ASY}\left[1 + \sum_{n\geq 1} a_{2n}(Q^2)\, C_{2n}^{3/2}(2x-1)\right],\ C_{2n}^{3/2} \text{ are Gegenbauer polynomials}$$

- The QCD evolution of the DA is very slow. The Q^2 needed to decrease the a_2 coefficient found at 1 GeV^2 by a factor of 3 is about 70000 GeV^2

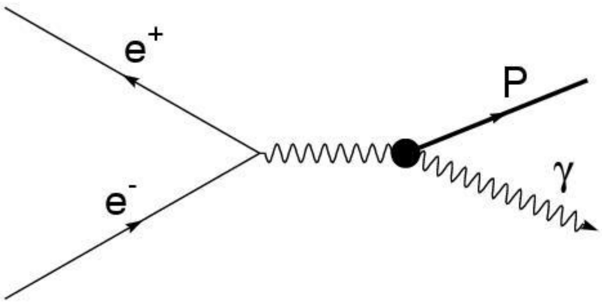
How can the form factor be measured?

- Two-photon production of the meson
  - $-S+M^2 < q_1^2 < 0,\ q_2^2 \approx 0, \quad Q^2 \equiv -q_1^2$
  - $d\sigma/dQ^2$ falls as $1/Q^6$
  - At $\sqrt{s}$=10.6 GeV for $e^+e^- \to e^+e^- \pi^0$

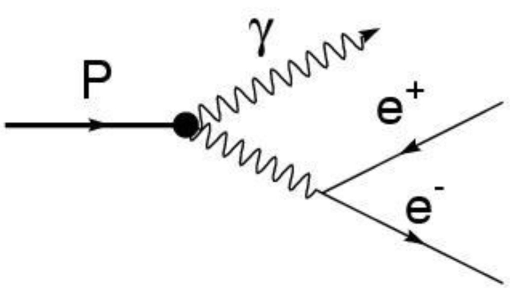
    $d\sigma/dQ^2(10\ \mathrm{GeV}^2) \approx 10\ \mathrm{fb/GeV}^2$



- Annihilation process $e^+e^- \to P\gamma$
  - $Q^2 = S > M^2$
  - $\sigma \propto 1/S^2$
  - $\sigma(e^+e^- \to \eta\gamma) \approx 5$ fb at $\sqrt{s}$=10.6 GeV



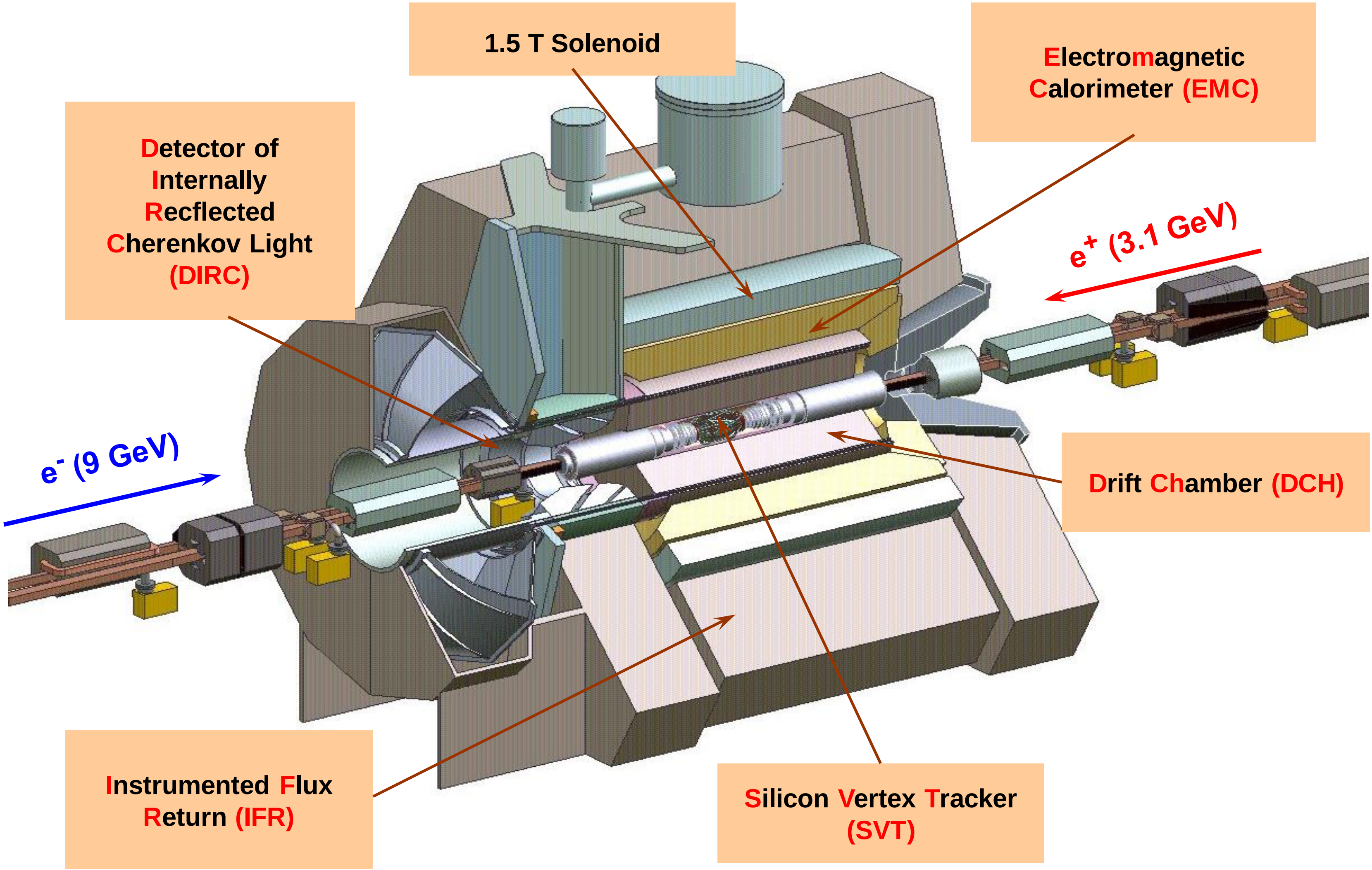
- Dalitz decay $P \to \gamma e^+e^-$
  - $0 < Q^2 < M^2$
  - $M^2 d\Gamma/dQ^2 \approx (2\alpha/\pi)\Gamma(P\to\gamma\gamma)$ at $Q^2/M^2 \approx 1/4$



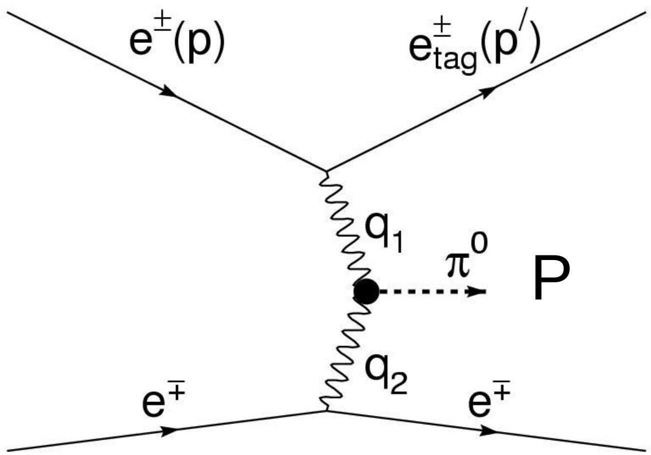
Available statistics

- ✓ The cross section studied is < 10 fb (10^{-38} cm^2)
- ✓ B-factory at SLAC and BABAR detector
  - peak luminosity is about 10^{34} cm^{-2}sec^{-1}
  - integrated luminosity collected during 8-year data taking period is about 450 fb^{-1}
- ✓ Expected number of events for the $\gamma^*\gamma\to\pi^0$ form factor measurement is $L\times\sigma\times\varepsilon = 450\times10\times0.15\approx700/\mathrm{GeV}^2$ at $Q^2=10$ GeV^2
- ✓ dN/dQ^2 falls with Q^2 increase as Q^{-6}
- ✓Previous CLEO measurement of the $\gamma^*\gamma \to \pi^0, \eta, \eta'$ transition form factors (J.Gronberg *et al*., Phys.Rev. D57, 33 (1998)) was based on 3 fb^{-1}

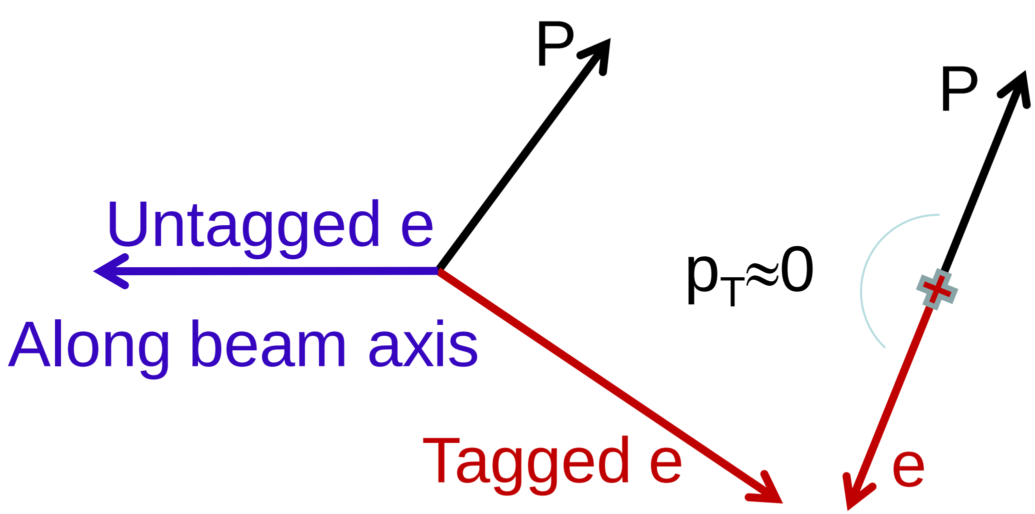
BABAR detector



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



- Electrons are scattered predominantly at small angles.
- Single-tag mode:
  - one of electrons is detected
  - $Q^2=-q_1^2=2EE^{/}(1-\cos\theta)$,
  - $q_2^2 \approx 0$
  - $F(Q^2,0)$



✓electron is detected and identified

✓meson P are detected and fully reconstructed

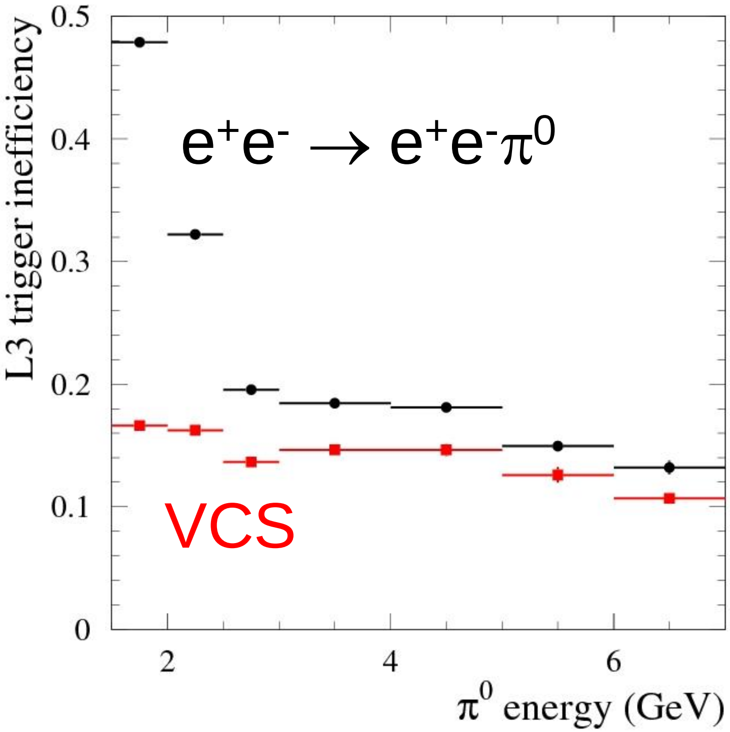
✓electron + meson system has low $p_{\perp}$

✓missing mass in an event is close to zero

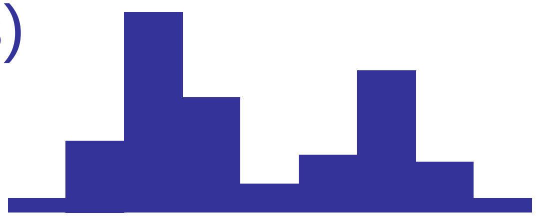
Specific features of $e^+ e^- \to e^+ e^- \pi^0$

- Low final particle multiplicity and only one charged particle (electron).
  - Such events are usually removed at the trigger and filter stages
  - Special trigger line should be designed to select $e^+ e^- \to e^+ e^- \pi^0$ events
- Large QED background
  - $e^+ e^- \to e^+ e^- \gamma\gamma$ in which one of the photons is emitted along the beam axis, and one of the electrons is soft
  - Virtual Compton scattering (VCS): $e^+ e^- \to e^+ e^- \gamma$ with one of the final electrons going along the collision axis
  - The photon from QED process together with a soft photon, for example, from beam background, may give the invariant mass close to the π^0 mass.

Trigger selection for $e^+e^- \to e^+e^-\pi^0$



- The $e^+e^- \to e^+e^-\pi^0$ events do not pass the standard BABAR trigger and background filters.
- Fortunately, a special trigger line was designed to select VCS events (electron+photon with zero recoil mass) for detector calibration.
- Two photons from the π^0 decay are close and usually form single cluster (with two bumps) in the detector calorimeter.



The VCS trigger treats this cluster as a photon.

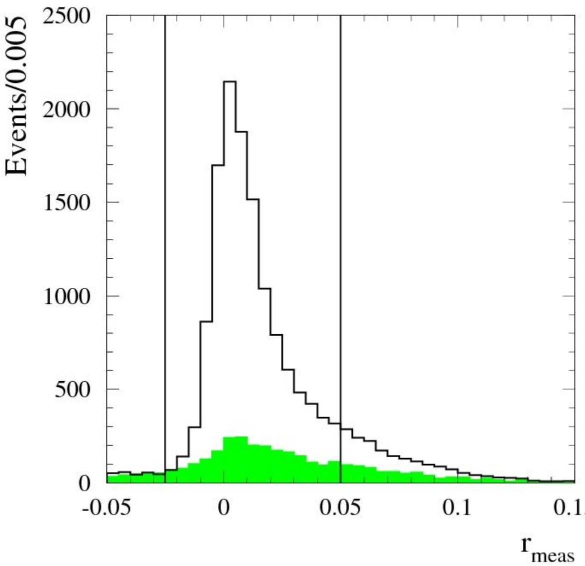
➡ **The $e^+e^- \to e^+e^-\pi^0$ events are efficiently selected by the VCS trigger.**

Selection criteria

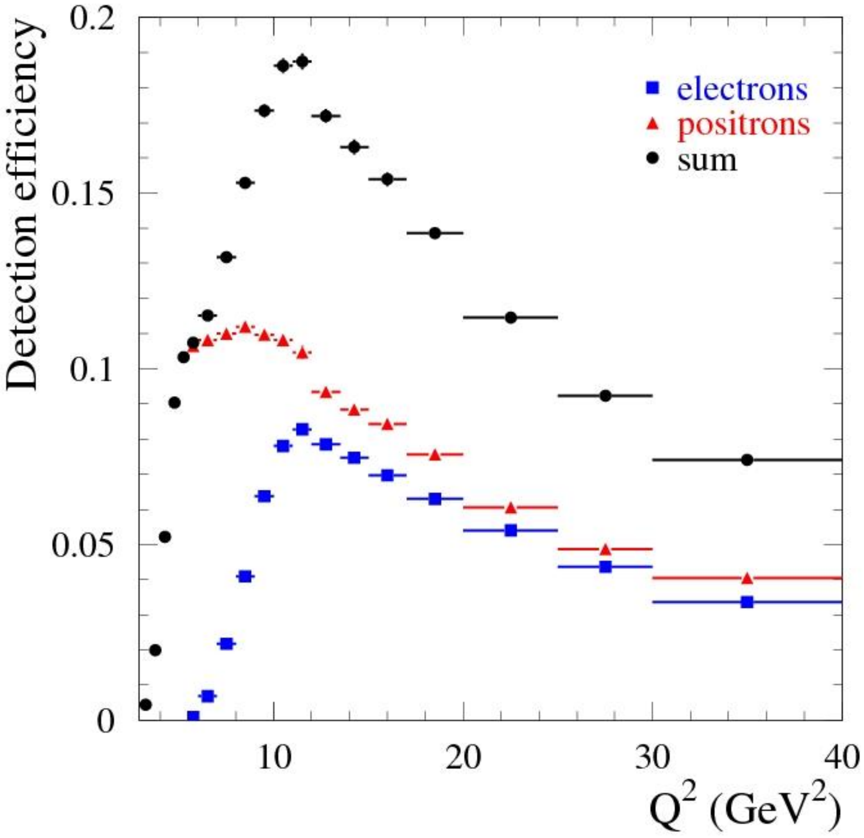
- ✓ VCS trigger
- ✓ Identified electron, $E_e > 2$ GeV
- ✓ π^0 formed from two photons, $E_\pi > 1.5$ GeV
- ✓ cuts to remove QED background ($|\cos\theta_\pi| < 0.8$, $|\cos\theta_h| < 0.8$, no extra tracks along π^0 direction, …)
- ✓ Momentum of $e\pi^0$ system is directed along beam axis: $|\cos\theta_{e\pi}| > 0.99$. This cut limits the q^2 range for untagged electron ($|q^2| < 0.2$ GeV^2).
- ✓

$$-0.025 < r = \frac{\sqrt{s} - E_{e\pi}^{CM} - p_{e\pi}^{CM}}{\sqrt{s}} < 0.05$$

This cut improves Q^2 resolution removing events with ISR photons.



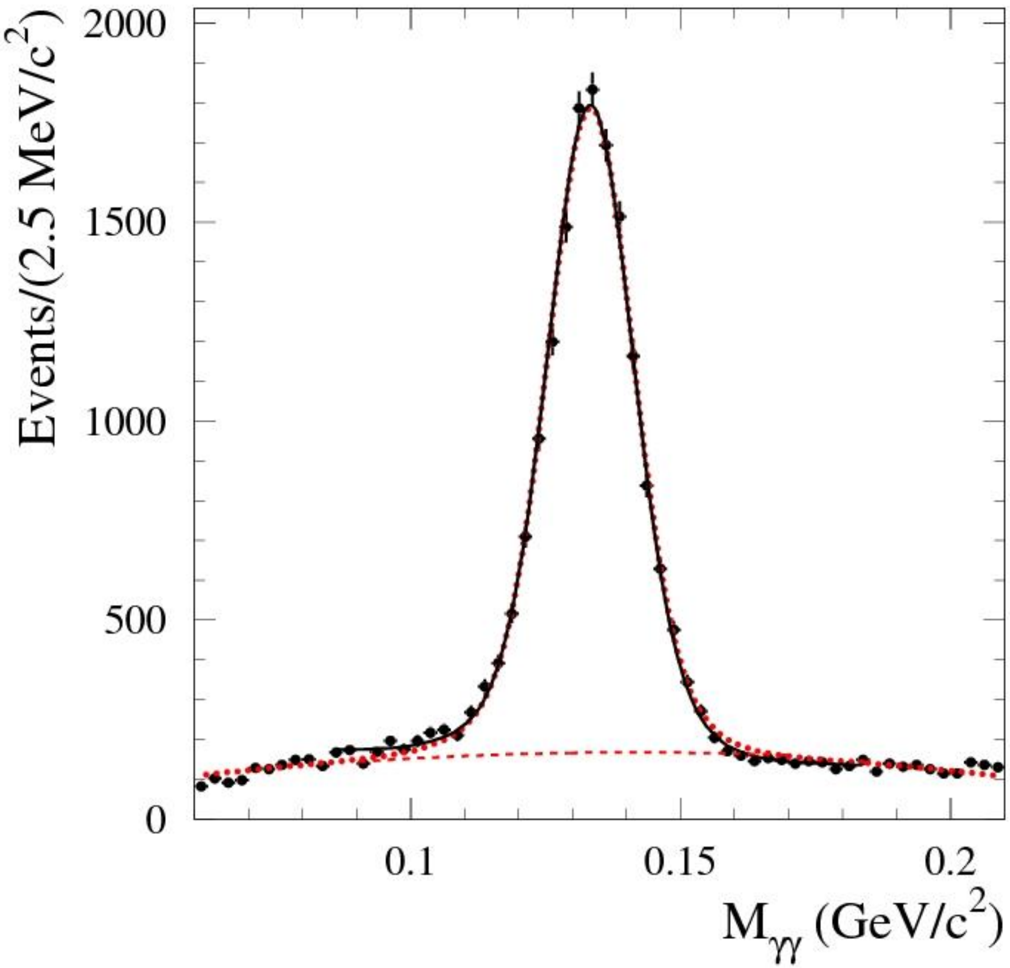
Detection efficiency from MC



- 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

Two-photon mass spectrum

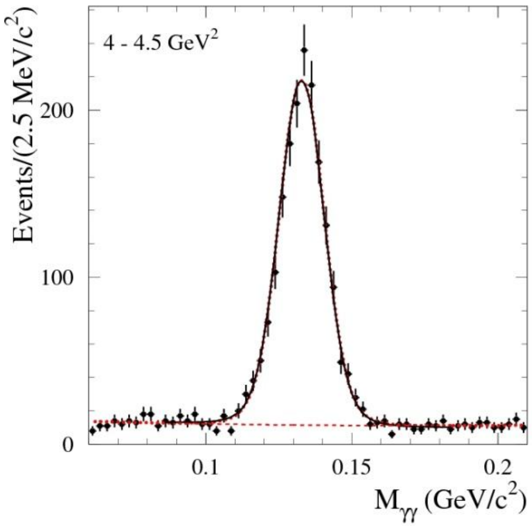
B.Aubert et al., Phys. Rev. D80, 052002 (2009)

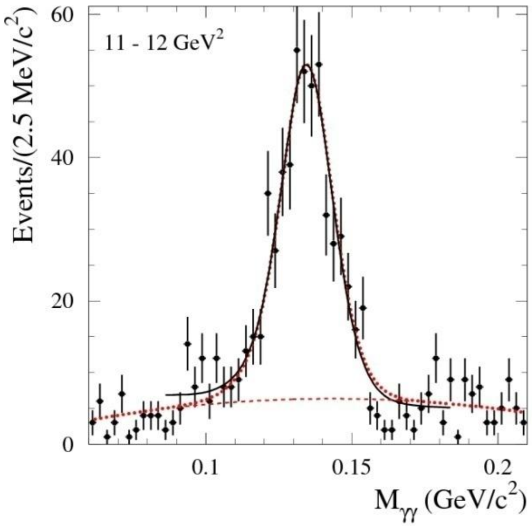


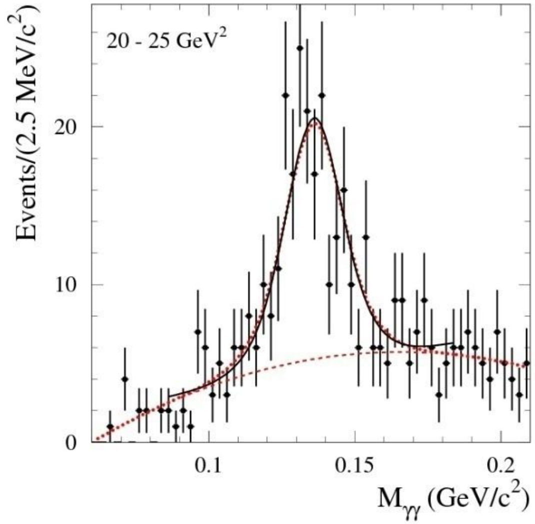
The two-photon invariant mass spectrum for data events with Q^2 = 4-40 GeV^2 fitted with a sum of signal (obtained using MC simulation) and background (a second order polynomial) distributions.

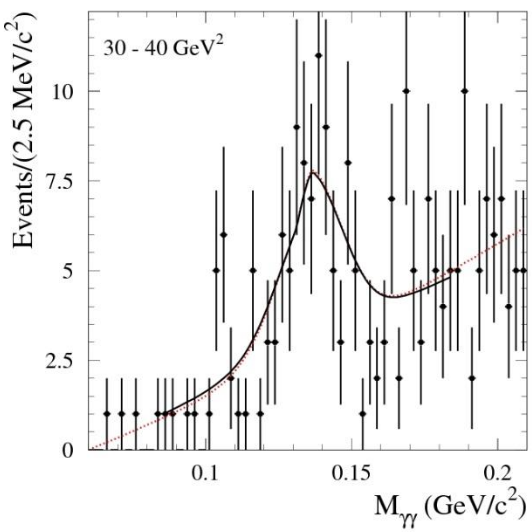
$N_\pi \approx 14000 \pm 140$

Two-photon mass spectrum



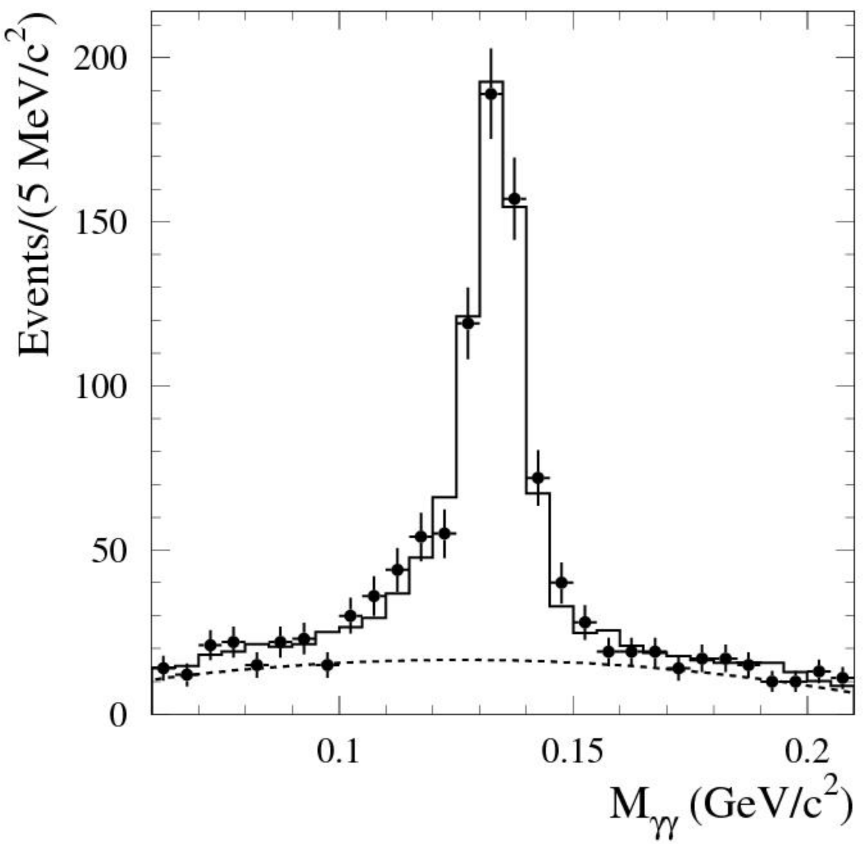






The data were divided into 17 Q^2 intervals. The size of the interval is increased with Q^2 growth.

Peaking background



The main source of the peaking background is $e^+e^- \to e^+e^- \pi^0\pi^o$.

It is seen as π^0 peak in the two-photon invariant mass spectrum for events with two extra photons.

To estimate and subtract background we select a clear sample of $2\pi^0$ events with special criteria.

The $2\pi^0$ background is found to be about 10% at $Q^2 < 10$ GeV^2 and 6-7% at higher Q^2.

Efficiency corrections

The transition form factor is determined from the ratio of Q^2 distributions for data and simulation events. The data distribution must be corrected to account for data-MC simulation difference in detector response:

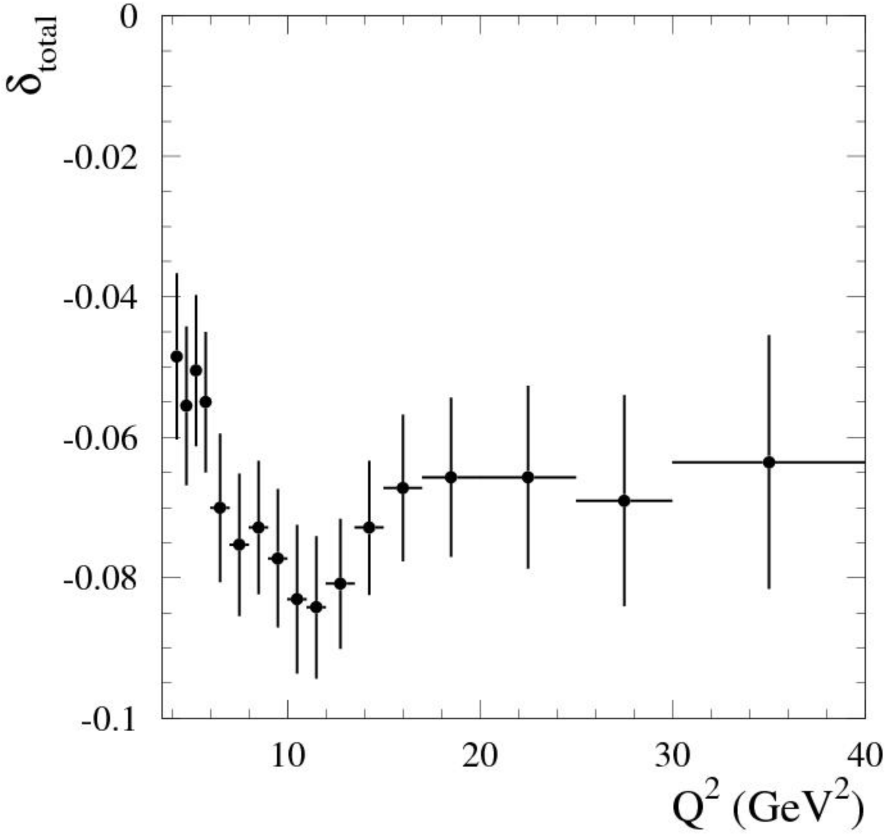
$$N_i^{corr} = N_i / \prod_i (1 + \delta_i)$$

We study the data-MC difference in:

- π^0 reconstruction efficiency
- PID efficiency
- trigger inefficiency
- effect of selection cuts on r and cos $\theta_{e\pi}$

The corrections are determined using specially selected samples of $e^+e^- \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$ and VCS events.

Total correction for data-MC difference

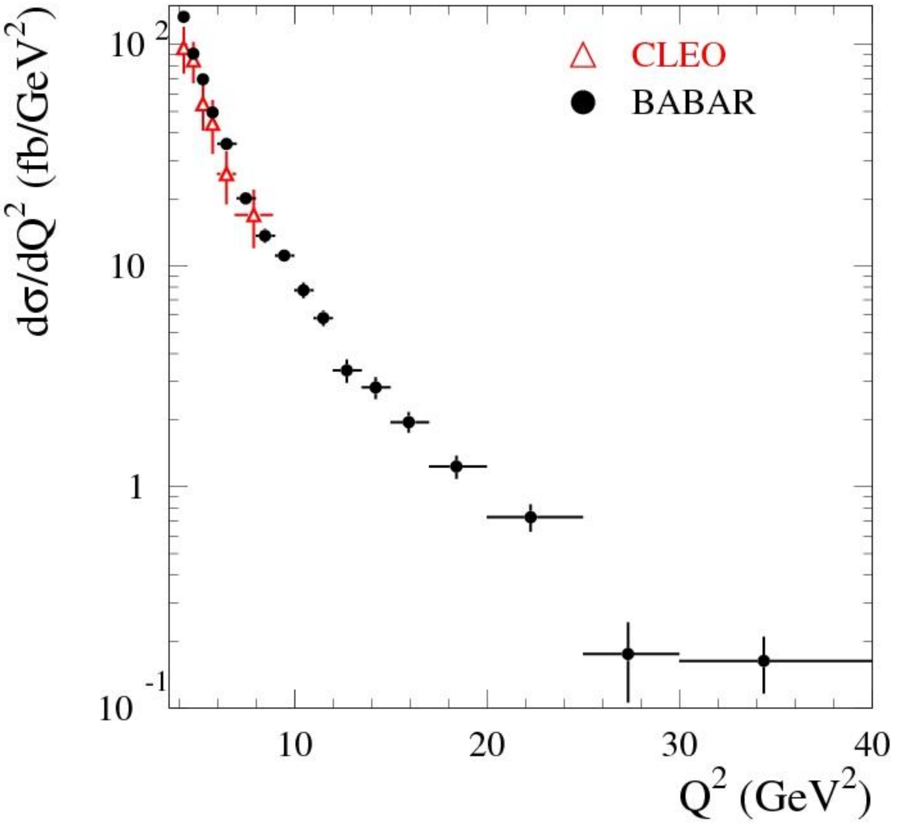


Total systematic error independent on Q^2 is 2.5% and includes

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

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

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

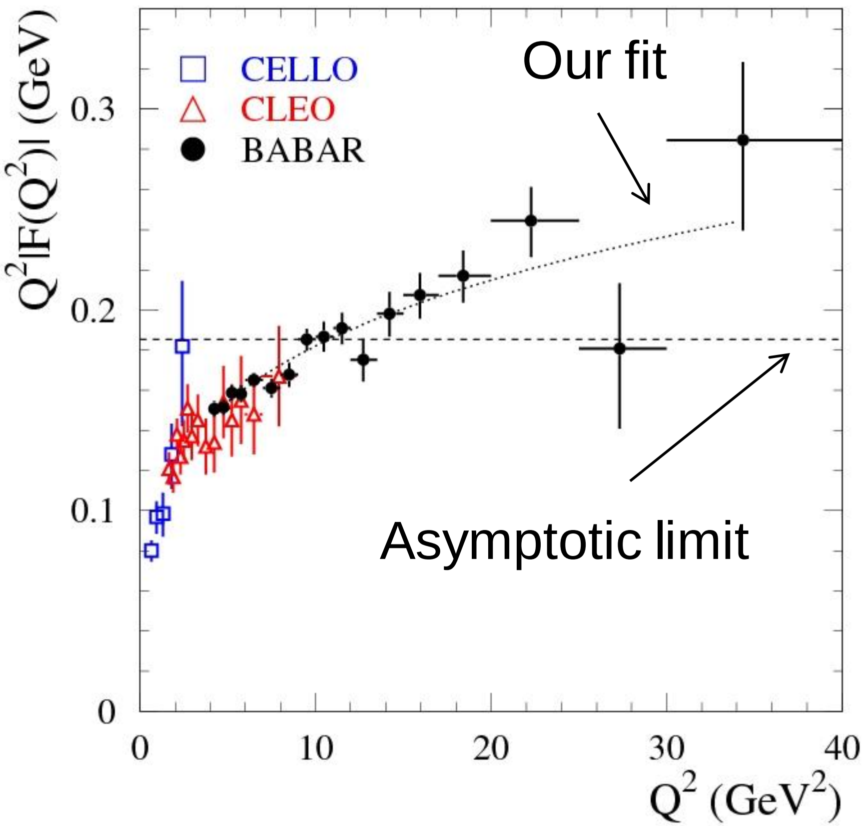


$$\frac{d\sigma}{dQ^2} = \frac{(dN/dQ^2)_{corr}}{\varepsilon R L}$$

Systematic uncertainty independent on Q^2 is 3%.

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

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

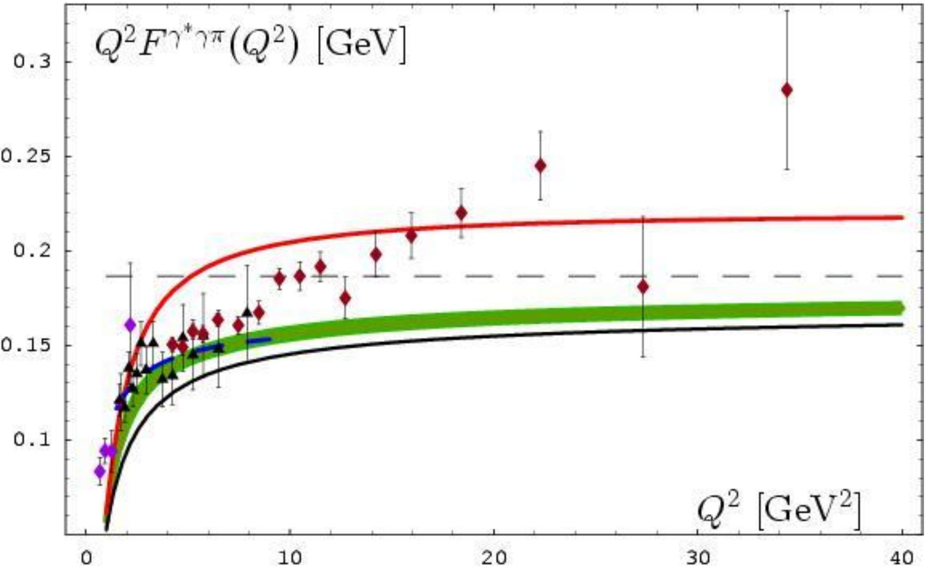
✓ Our data in the range 4-40 GeV^2 are well described by the formula

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

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

Systematic uncertainty independent on Q^2 is 2.3%.

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



S.V.Mikhailov, N.G.Stefanis, Nucl. Phys. B821, 291(2009); arXiv:0909.5128; arXiv:0910.3498.

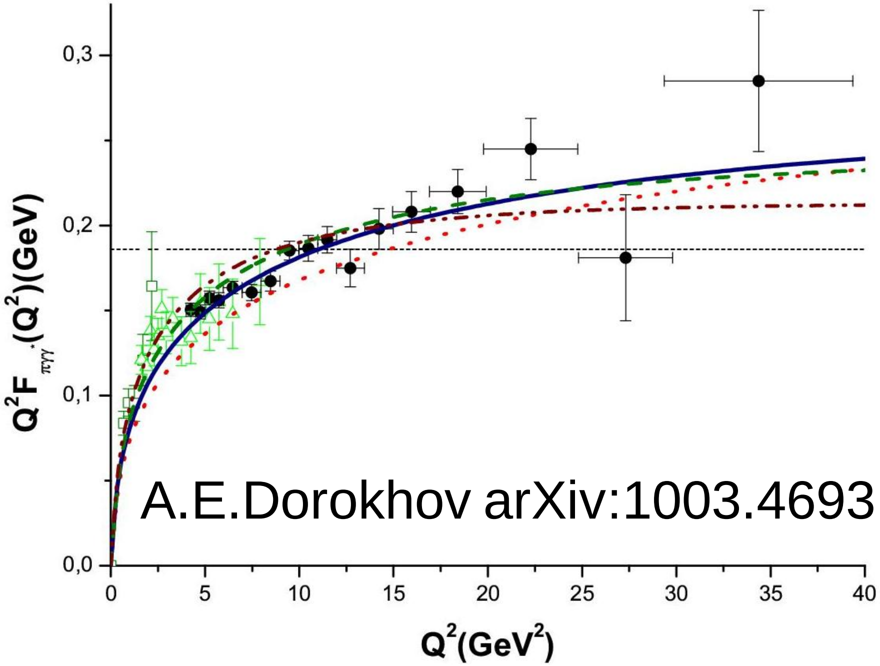
The NNLO pQCD corrections was partly taken into account. They was estimated to be about 5% at $Q^2 \sim 10$ GeV^2.

The BABAR data contradict the QCD factorization for any pion DA with the end points (x=0,1) behavior ~ x(1-x).

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

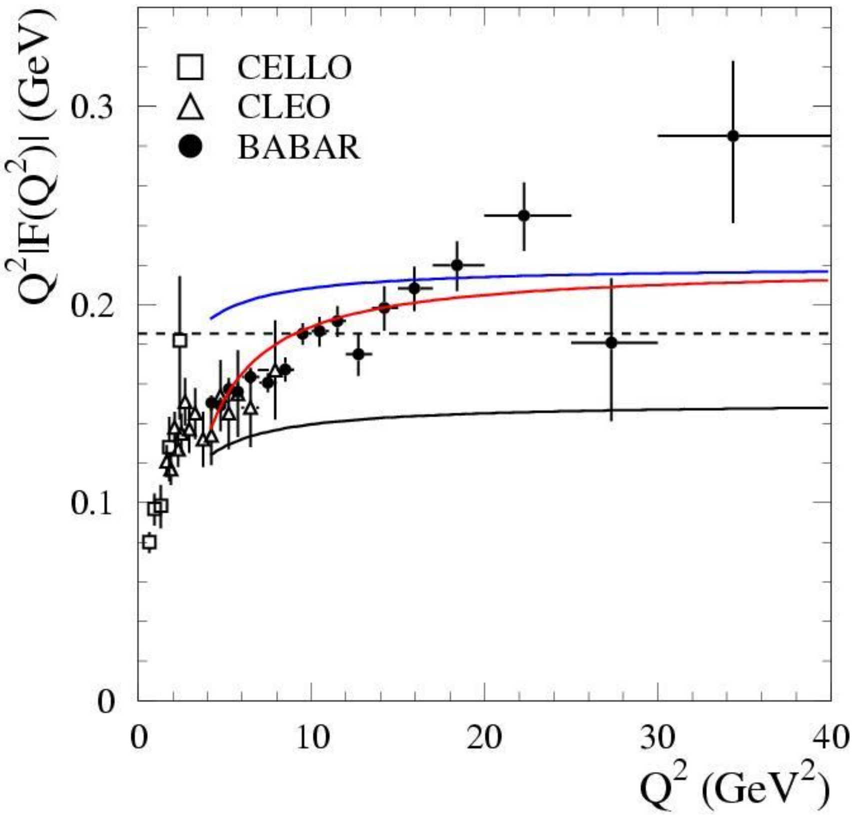
$$Q^2 F_{\pi\gamma}(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int_0^1 dx \, \frac{\phi_\pi(x,Q)}{x + m^2/Q^2}$$

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

$$Q^2 F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \ln\left(1 + \frac{Q^2}{m^2}\right)$$

with $m^2 \approx 0.6$ GeV^2.

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



V.L.Chernyak, arXiv:0912.0623

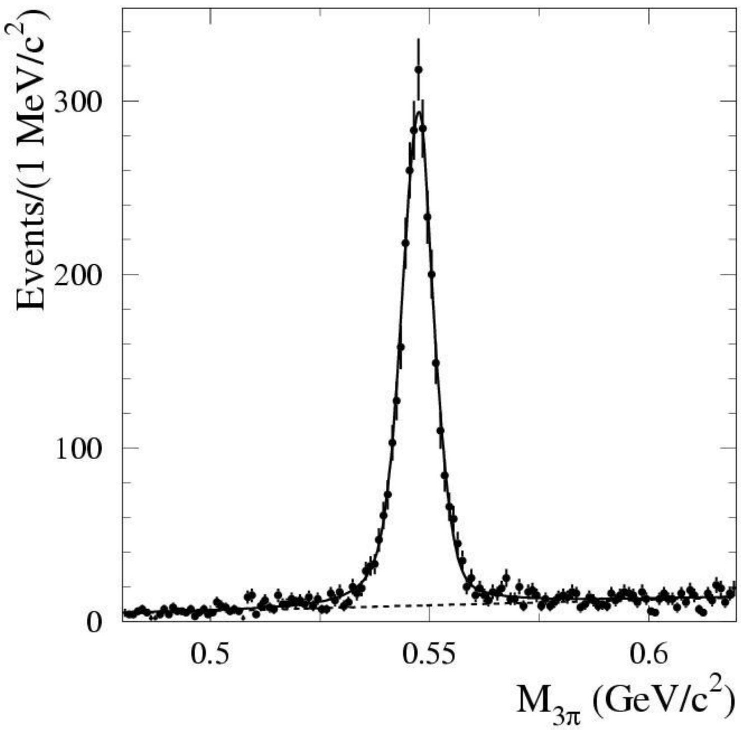
The twist-4 power correction, $\Delta F/F(Q^2) \sim -(0.6\ \mathrm{GeV}^2)/Q^2$, is only part of the total power correction.

Taking, for example, $\Delta F/F(Q^2) = -1.5/Q^2 - (1.2/Q^2)^2$ for CZ DA leads to good data description.

$e^+e^- \to e^+e^- \eta^{(/)}$, event selection

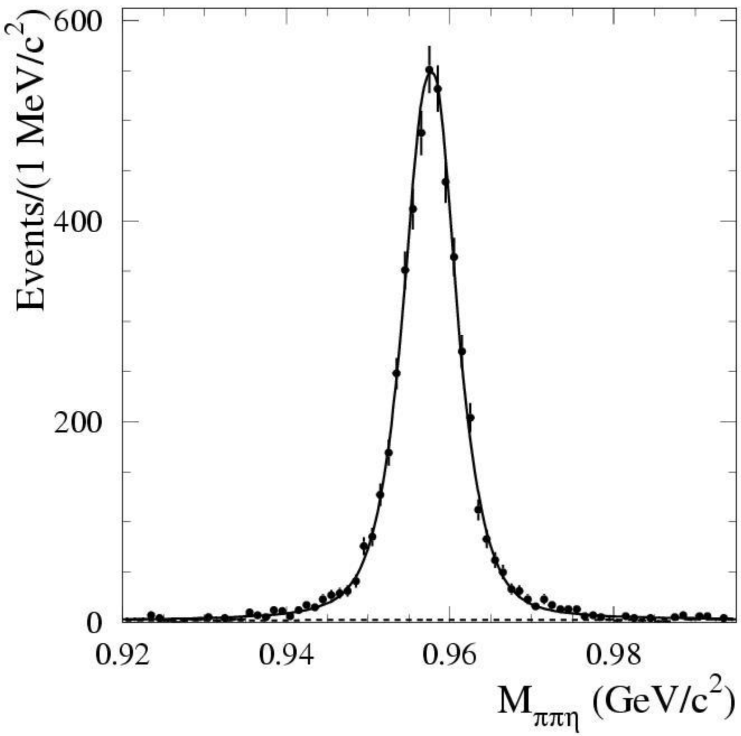
This work is not yet published.

$\eta \to \pi^+\pi^-\pi^0, \quad \pi^0 \to \gamma\gamma$



$N_s = 3060 \pm 70$

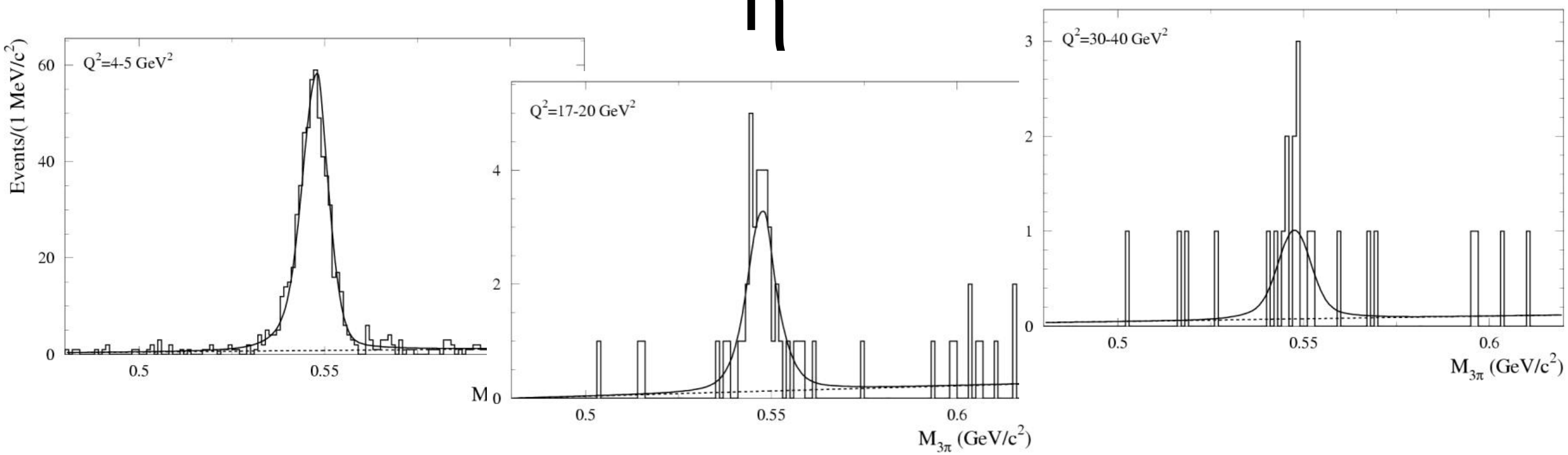
$\eta' \to \pi^+\pi^-\eta, \ \eta \to \gamma\gamma$



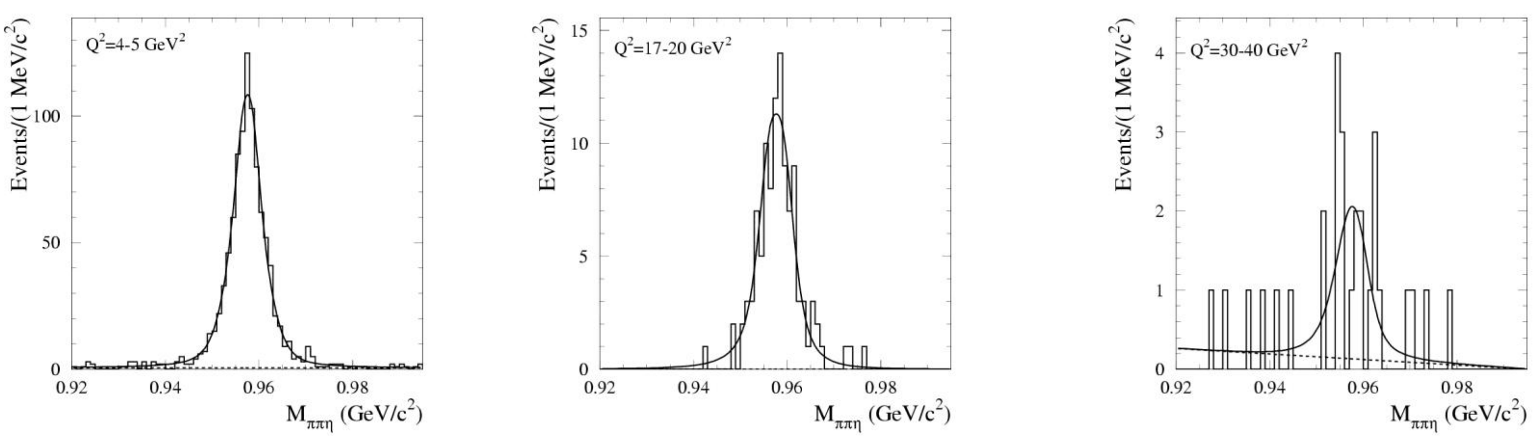
$N_s = 5010 \pm 90$

Mass spectra for η and η′ *events*

η

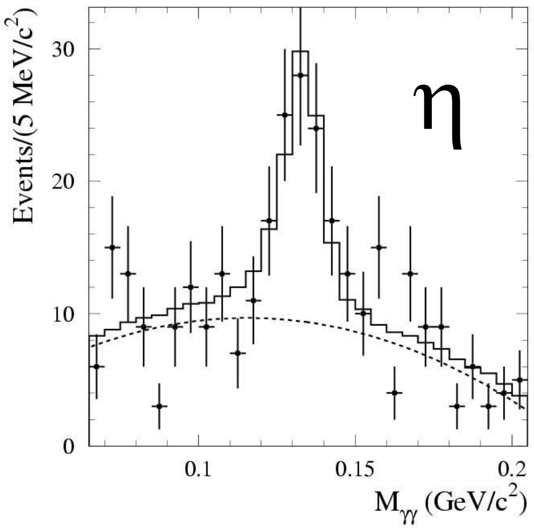


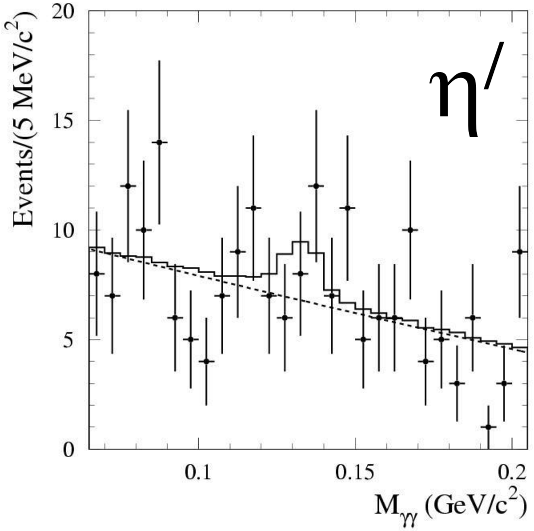
η′



The fit is performed in 11 Q^2 intervals.

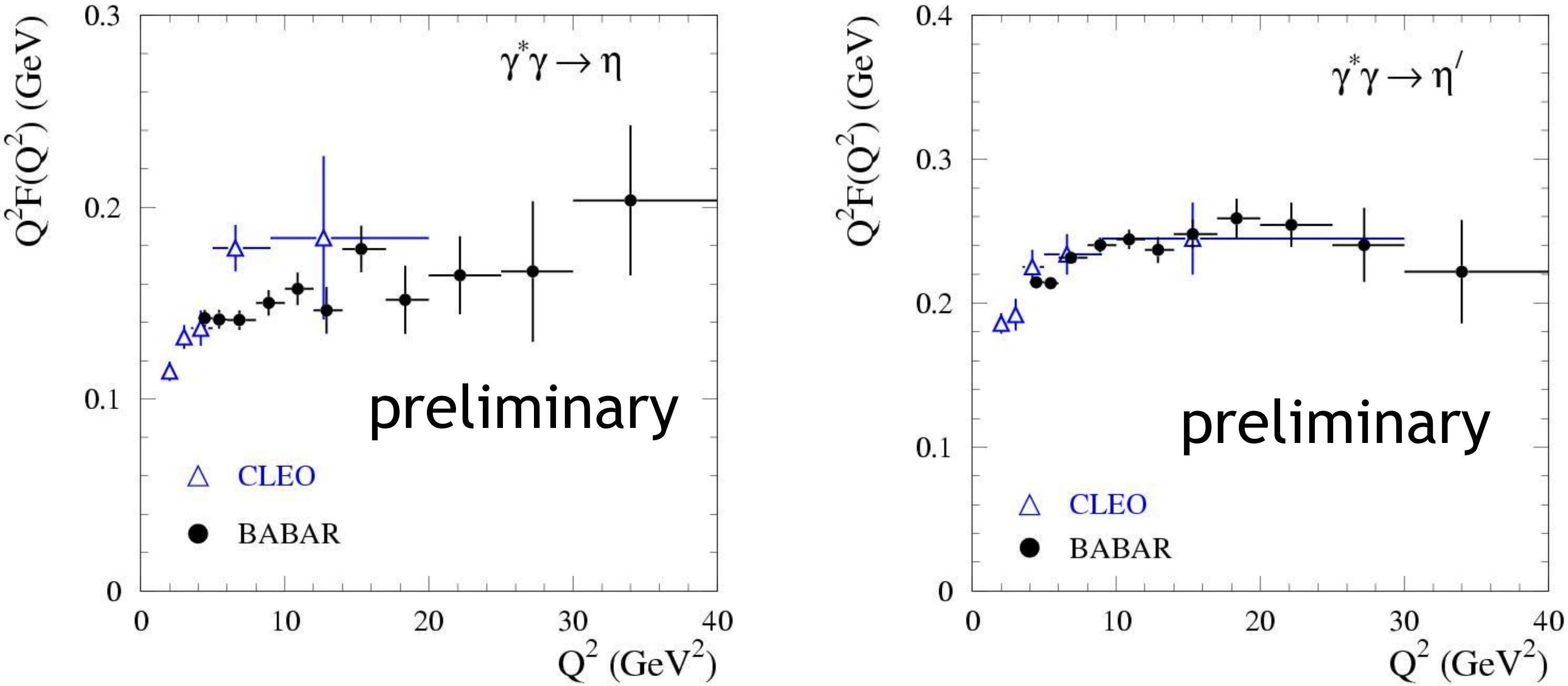
Two-photon background





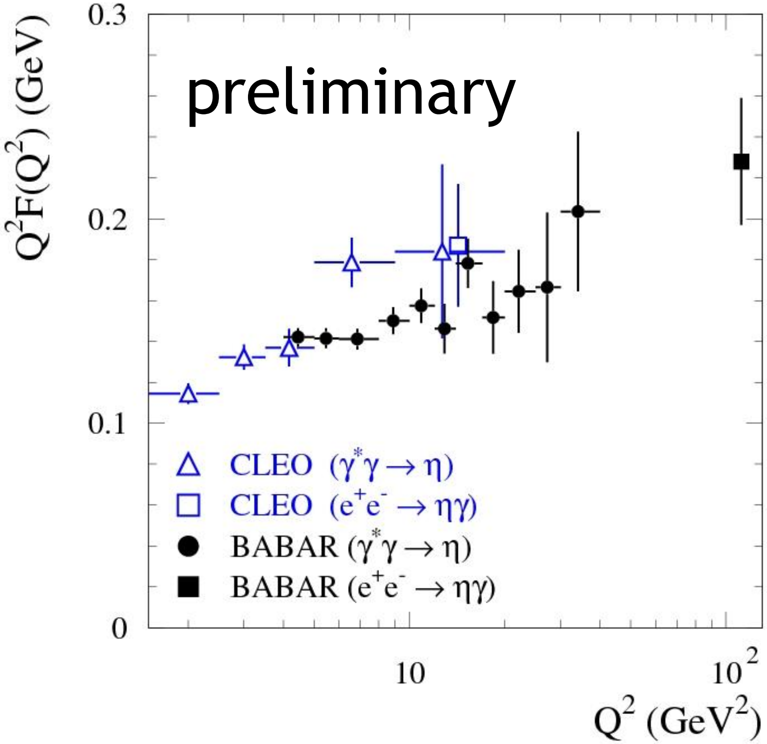
- In contrast to previous CLEO analysis we observe the background from the two photon process $e^+e^- \to e^+e^- \eta\pi^o$.
- It is seen as a π^0 peak in the two-photon invariant mass spectrum for events with 2 extra photons.
- For the $\eta^/$ sample the two-photon background does not exceed 1.6%.
- For the η sample the background is estimated to be about 10%.

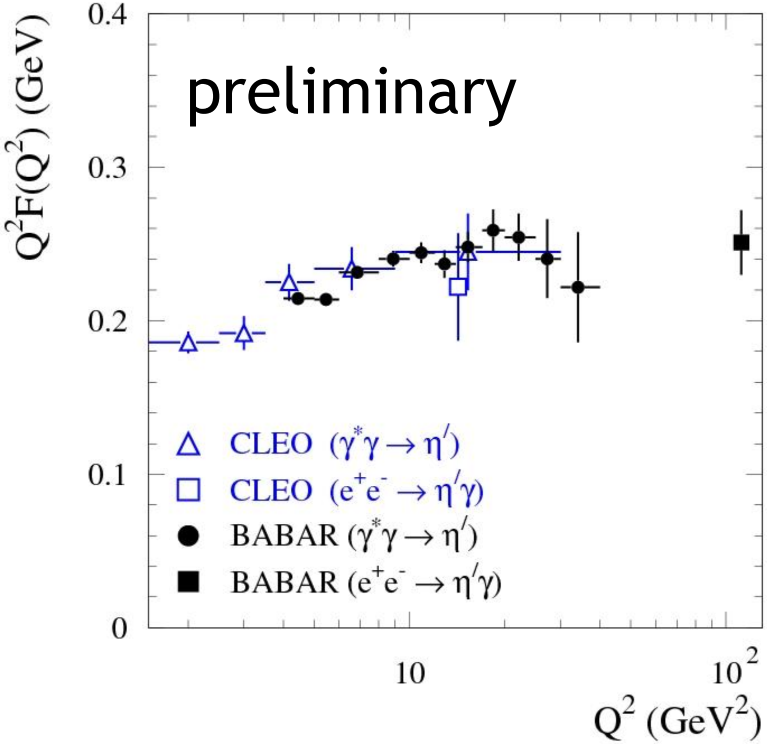
η *and* η' *form factors*



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

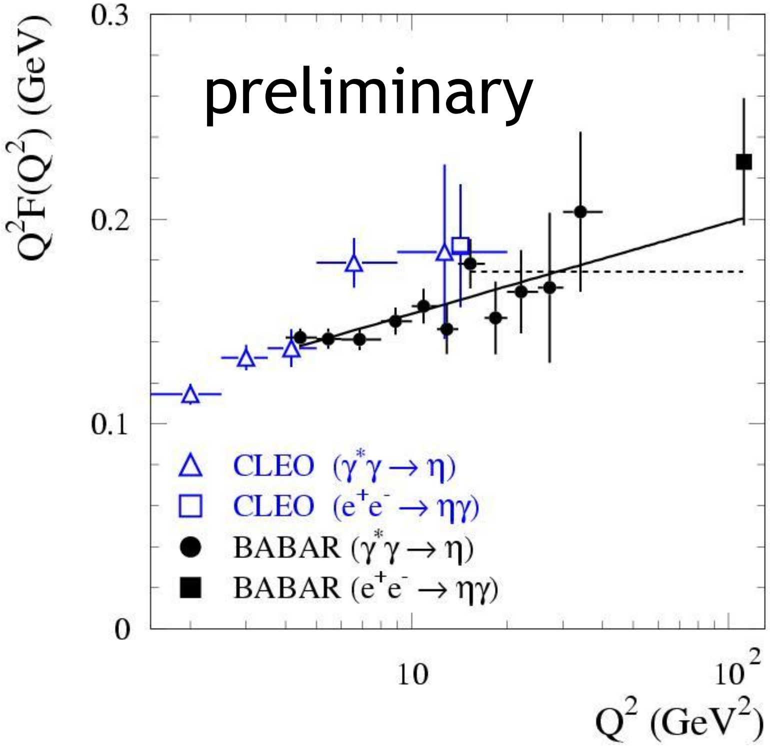
η *and* $\eta^{/}$ *form factors*

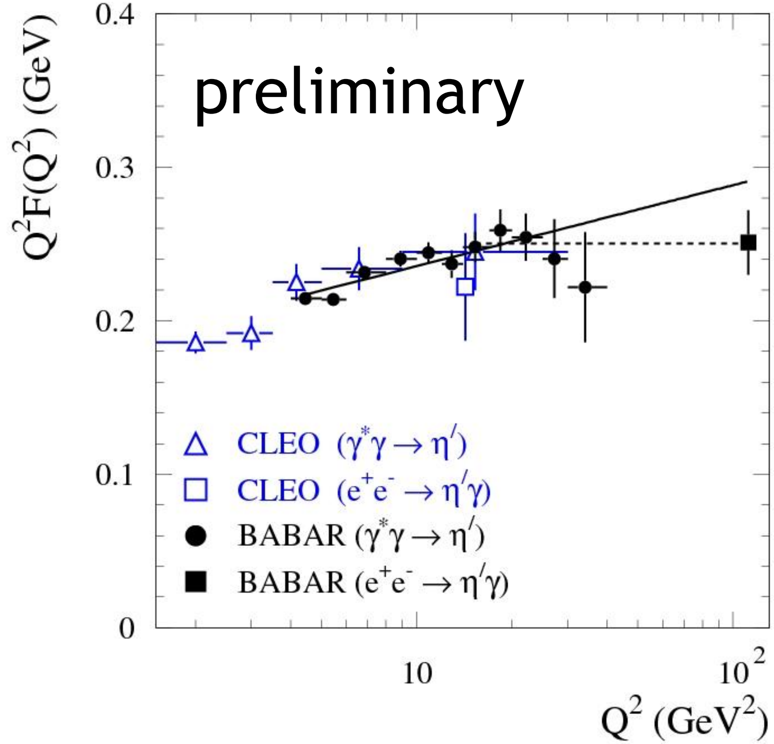




- CLEO (Phys. Rev. D79, 111101, 2009) and BABAR (Phys. Rev. D74, 012002, 2006) data on the time-like transition form factors are added.
- They are extracted from the $e^+e^- \to \eta^{(/)}\gamma$ cross section measurements at Q^2=14.2 GeV^2 (CLEO) and 112 GeV^2 (BABAR).
- At large Q^2 the time- and space-like 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≈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

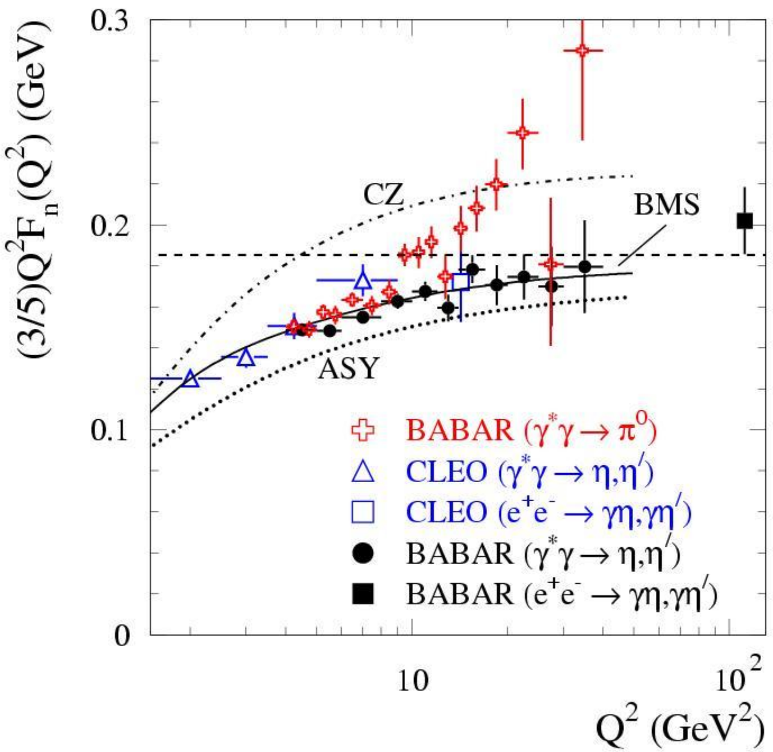
$$F_\eta = \cos\phi\,F_n - \sin\phi\,F_s, \quad F_{\eta'} = \sin\phi\,F_n + \cos\phi\,F_s,$$

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

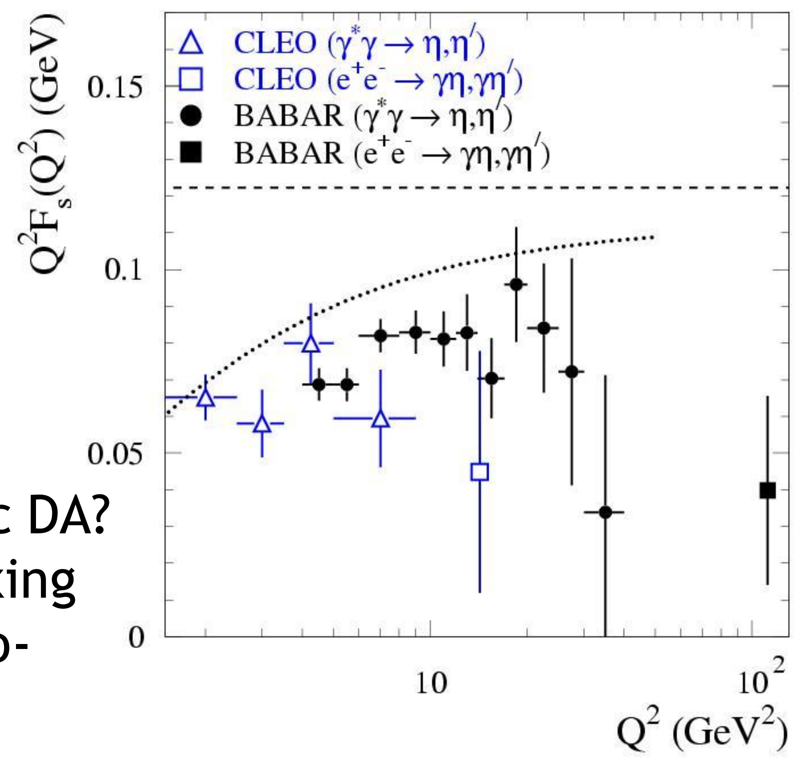
where decay constants is expected to be $f_n=f_\pi$, $f_s=1.34f_\pi$

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 $|n\rangle$ and $|s\rangle$ state



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



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

Concluding remarks

- After the CLEO publication on the photon-meson transition form factors in 1998 it was generally accepted that the pion DA is close to asymptotic form in near-end-point regions. Many theoretical works (predictions) using such near-asymptotic DAs were published.
- The BABAR measurement indicates that the pion DA is significantly wider than the asymptotic form. If the experiment is correct, many theoretical predictions should be revised.
- The next measurement of the pion-photon transition form factor confirming or refuting BABAR result will be performed at Super-B factories in 5-10 years.
- Therefore, study of other reactions sensitive to the DA shape and careful theoretical analysis of already measured reactions should be performed.

Concluding remarks

- The processes with pseudoscalars, which have already been measured and which theoretical description should be updated:
  - The $\gamma^*\gamma \to \eta^{(\prime)}$ transition form factors. There are new BABAR data.
  - The pion and kaon electromagnetic form factors. There are recent CLEO time-like measurements at Q^2=14 GeV^2
  - Belle measurements of the $\gamma\gamma \to \pi\pi$, KK, $\eta\pi$ cross sections for $W_{\gamma\gamma}$ up to 4.1 GeV
  - $\chi_{c,0}, \chi_{c,2} \to \pi\pi$, KK, $\eta\eta$, …(BELLE,CLEO,BES)
  - …

Concluding remarks

The processes sensitive to the pseudoscalar DA shape which can be measured using B-factory data

- $\gamma\gamma \to \eta\eta, \eta'\eta', \eta\eta'$
- single tag studies of $\gamma\gamma$ reactions: $\pi^+\pi^-$, $\eta\pi$, …
- update of the $e^+e^- \to \eta^{(\prime)}\gamma$ cross section measurements
- kaon electromagnetic form factor at 112 GeV^2
- $e^+e^- \to VP$
- …

$e^+e^- \to VP$ cross sections

$$F(\gamma^* \to VP) \sim \int_\delta^1 \frac{\varphi_P(x)}{x^2} dx \text{ with } \delta = \frac{m_0^2}{s},$$

$$\text{for } \varphi_P(x) \sim x(1-x): \ \sigma(e^+e^- \to VP) \sim \frac{\ln^2(s/s_0)}{s^4},$$

$$\text{for flat } \varphi_P(x): \quad \sigma(e^+e^- \to VP) \sim \frac{1}{s^2}$$

V.L.Chernyak, arXiv:0912.0623

The $\gamma^* \to$ VP form factors are highly sensitive to the end-point behavior of the pseudoscalar DA.

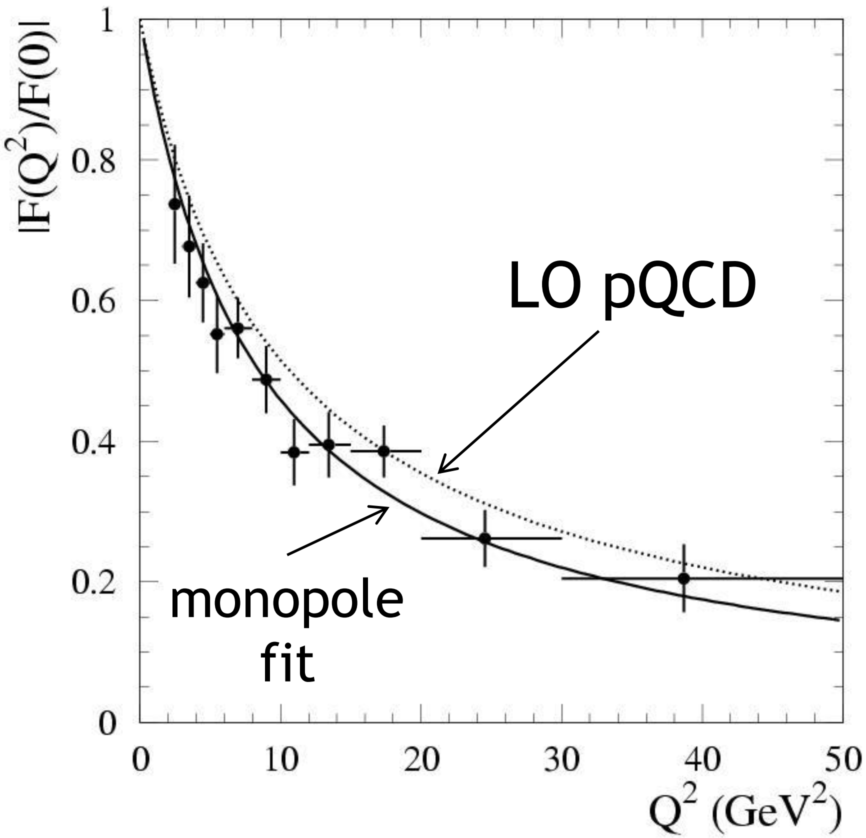
- The $e^+e^- \to VP$ cross sections have been measured by CLEO for $V=\rho,\omega,\phi$, and $P=\pi,\eta,\eta'$ at s=14 GeV^2.
- The BABAR and Belle have performed measurements for $\phi\eta^{(\prime)}$, $\rho\eta^{(\prime)}$ at 112 GeV^2. The cross section s dependencies reasonably agree with the QCD predictions for conventional DA's.
- The cross sections for all other VP combinations definitely can be measured at BABAR and Belle.
- The expected cross section for the $\omega\pi$ final state at 112 GeV^2 is about 4 fb for a conventional DA and 200 fb for flat DA.

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.
- ✓ The measured Q^2 dependencies for the $\gamma\gamma^*\to\eta$ and $\gamma\gamma^*\to\eta'$ transition form factors strongly differ from that for $\gamma\gamma^*\to\pi^0$.
- ✓ The η' data are in good agreement with the result of QCD calculation with a conventional DA.
- ✓ For η the agreement is worse. A mild logarithmic rise of $Q^2F(Q^2)$ is not excluded.
- ✓ There are many processes sensitive to the DA shape measured and not measured yet. The theoretical input is required to stimulate experimentalists.

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

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

- The result $\Lambda=8.5\pm0.6\pm0.7$ GeV² does not contradict to the vector dominance model with $\Lambda=m^2_{J/\psi}=9.6$ GeV².
- 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 GeV² (T. Feldmann, P.Kroll, Phys. Lett. B 413, 410 (1997)).
- Lattice QCD: $\Lambda=8.4\pm0.4$ GeV² (J.J.Dudek, R.G.Edwards, Phys. Rev. Lett. 97, 172001 (2006)).