# *Recent results on two-photon physics at BABAR*

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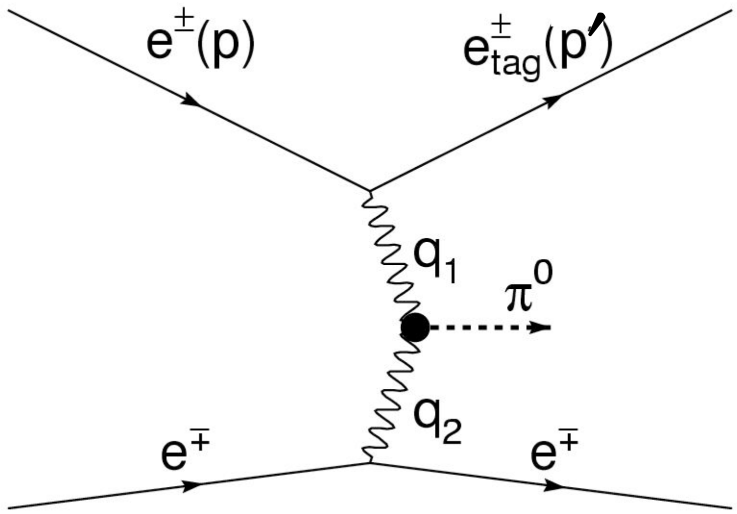
I. $\gamma^{*}\gamma \to \pi^{0}$
II. $\gamma^{*}\gamma \to \eta_{c}$

BABAR™

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

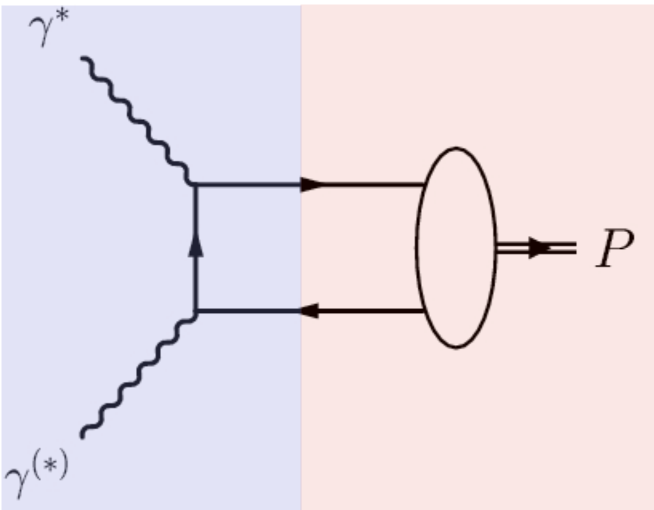



- Electrons are scattered predominantly at small angles.
- For pseudoscalar meson production the cross section depends on a form factor $F(q_1^2, q_2^2)$, which describes the $\gamma^*\gamma^* \to P$ transition.

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 $\pi^0$
✓$F(Q^2,0)$

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

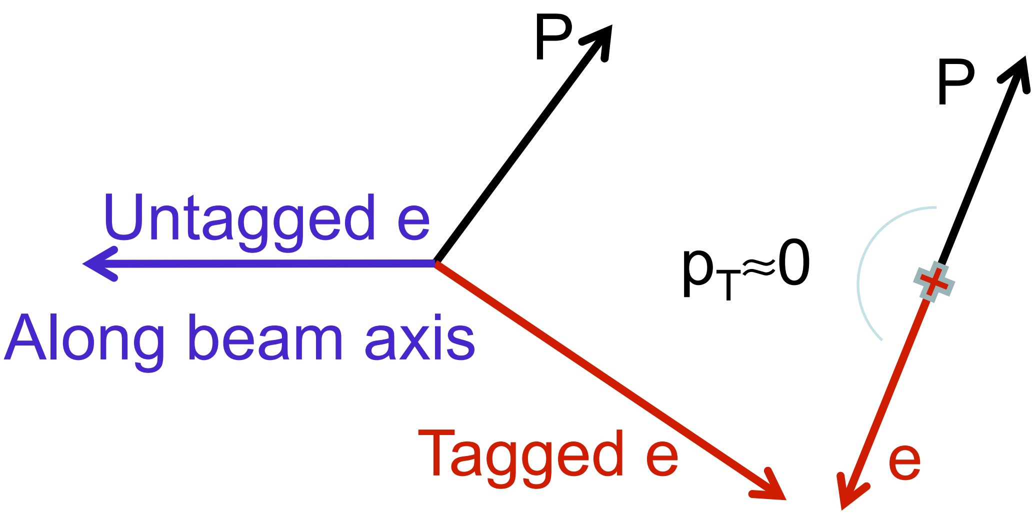



$$F(Q^2) = \int T(x,\mu^2)\,\varphi(x,\mu^2)\,dx$$

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

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

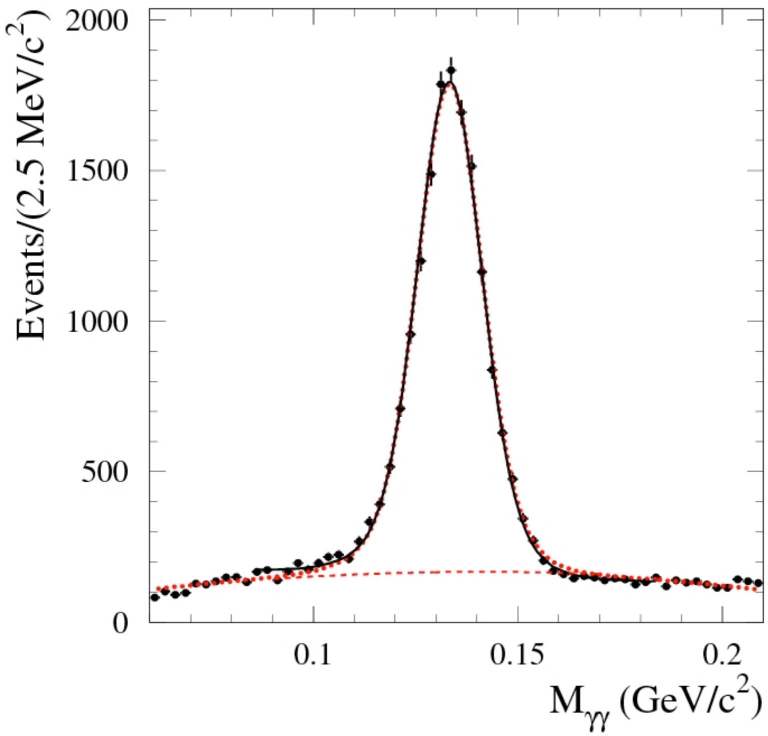
$x$ is the fraction of the meson momentum carried by one of the quarks in the infinite momentum frame




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

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

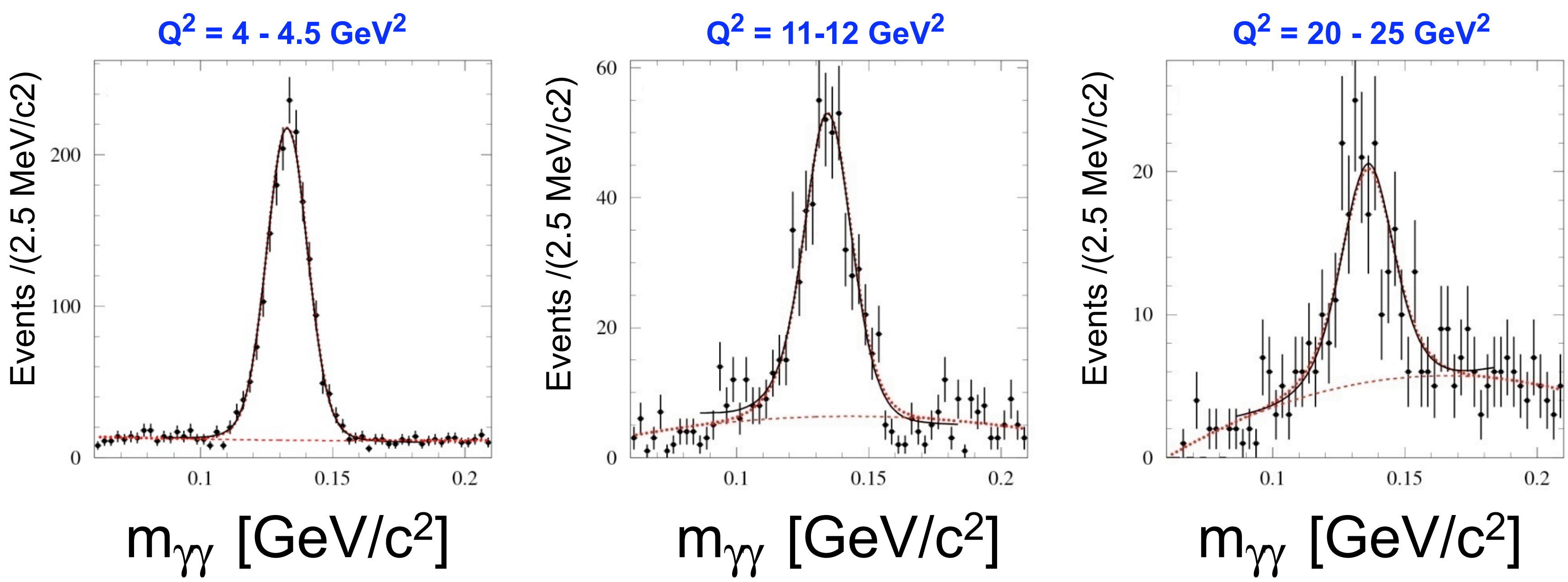
B.Aubert et al., arXiv:0905.4778, submitted to PRD




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

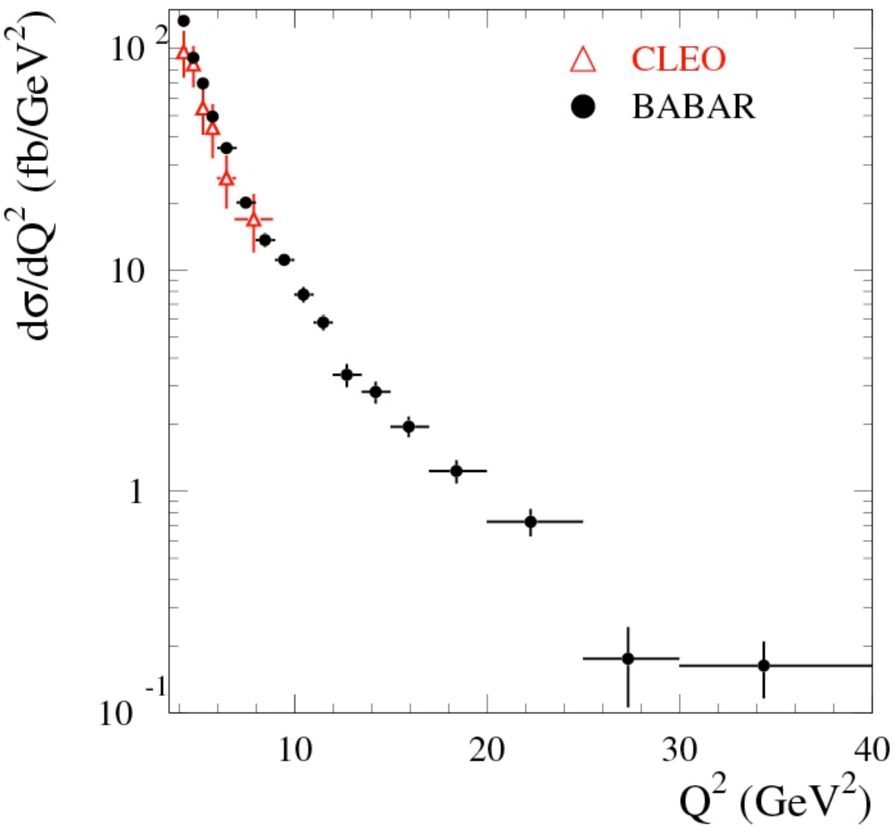
| Detector | $Q^2$, $GeV^2$ | Events | Year |
|---|---|---|---|
| CELLO | 0.7-2.2 | 127 | 1991 |
| CLEO | 1.6-8.0 | 1219 | 1998 |
| BABAR | 4-40 | 13200 | 2009 |

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




Data from 3 of 17 $Q^2$ intervals studied

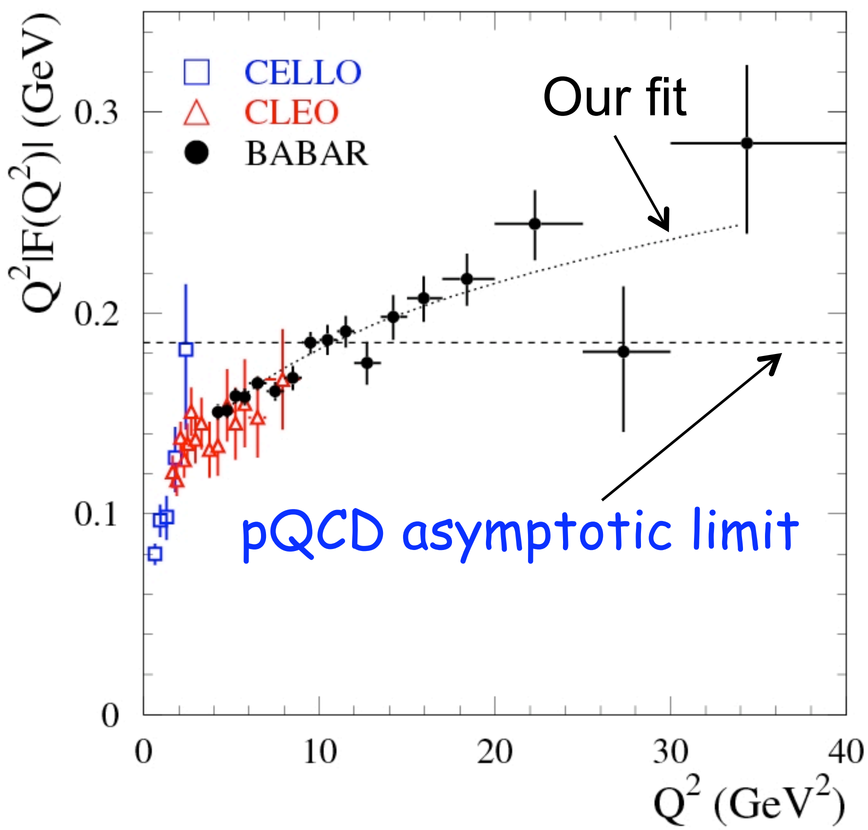
# $e^+e^- \to e^+e^-\pi^0$, cross section




**Systematic uncertainty independent of $Q^2$ is 3%.**

- **Efficiency correction ~ 2.5%**
- **Radiative correction ~ 1%**
- **Luminosity uncertainty ~ 1%**

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




**Systematic uncertainty independent of $Q^2$ is 2.3%.**

- **cross section**
- **model uncertainty**

✓ 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 amlitude give form factors approaching the limit from below.

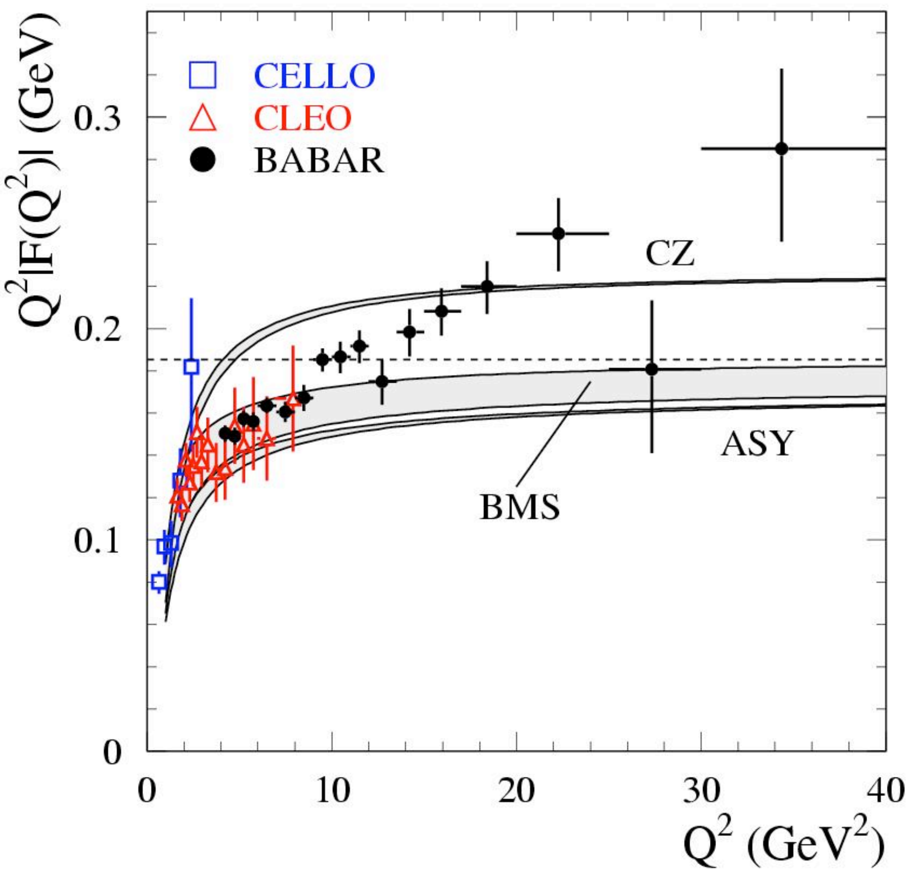
✓ Our data in the range 4-40 $GeV^2$ are well described by the formula

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

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

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

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

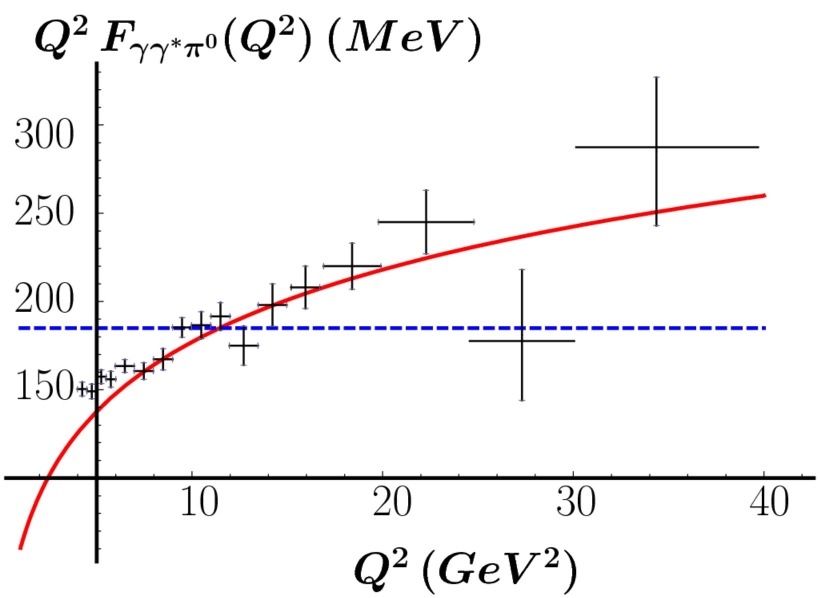



- ✓ A.P.Bakulev, S.V.Mikhailov, N.G.Stefanis, Phys. Rev. D 67, 074012, light-cone sum rule method at NLO pQCD+twist-4 power corrections.
- ✓ $Q^2<20$ GeV$^2$ : large difference between the data and the theory in $Q^2$ dependence . For $Q^2<15$ GeV$^2$, none of the models describes the $Q^2$ dependence well.
- ✓ $Q^2 > 20$ GeV$^2$ : theoretical uncertainties are expected to be smaller. Our data lie above the asymptotic limit at high $Q^2$, as does the prediciton of theChernyak-Zhitnitsky (CZ) model, Nucl. Phys. B **201**, 492(1982) [Erratum – ibid B 214, 547 (1983) ]

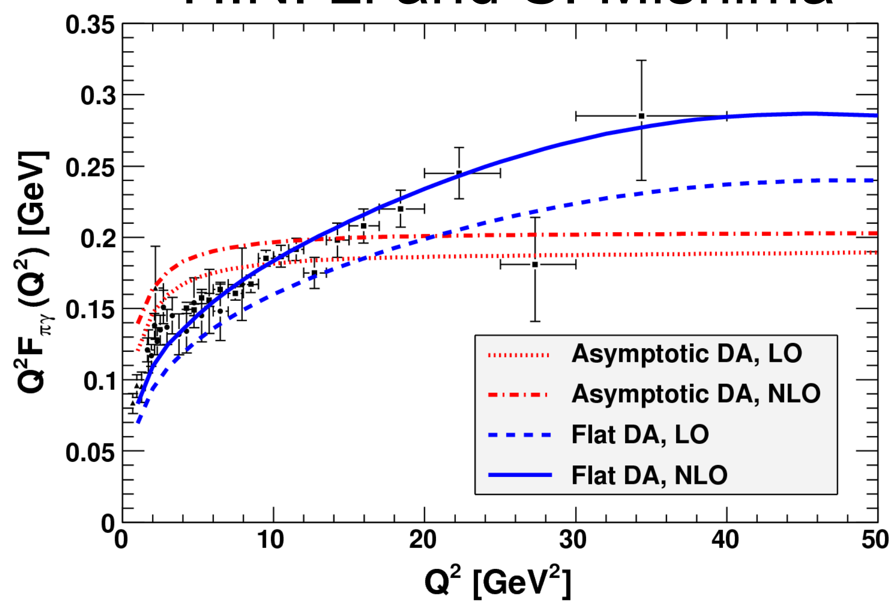
# $e^+e^- \to e^+e^-\pi^0$ calculations, after public release

- S.V. Mikhailov and N.G.Stefanis, arXiv:0905.4004, the growth of the form factor cannot be explained by NNLO pQCD corrections and power corrections
- A.V. Radyuskin, arXiv:0906.0323; M.V. Polyakov, arXive:0906.0538; H.N. Li and S. Mishima, arXiv:0907.0166. A flat pion distribution amplitude is used to reproduce the $Q^2$ dependence of BABAR data.

A.V. Radyuskin

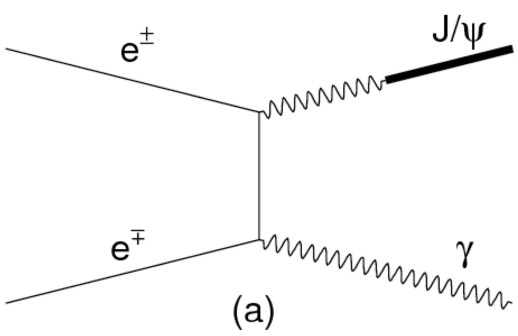


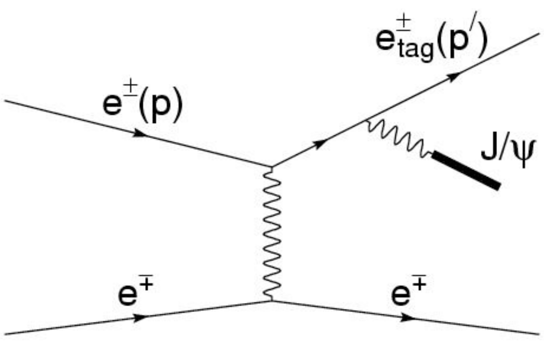

H.N. Li and S. Mishima



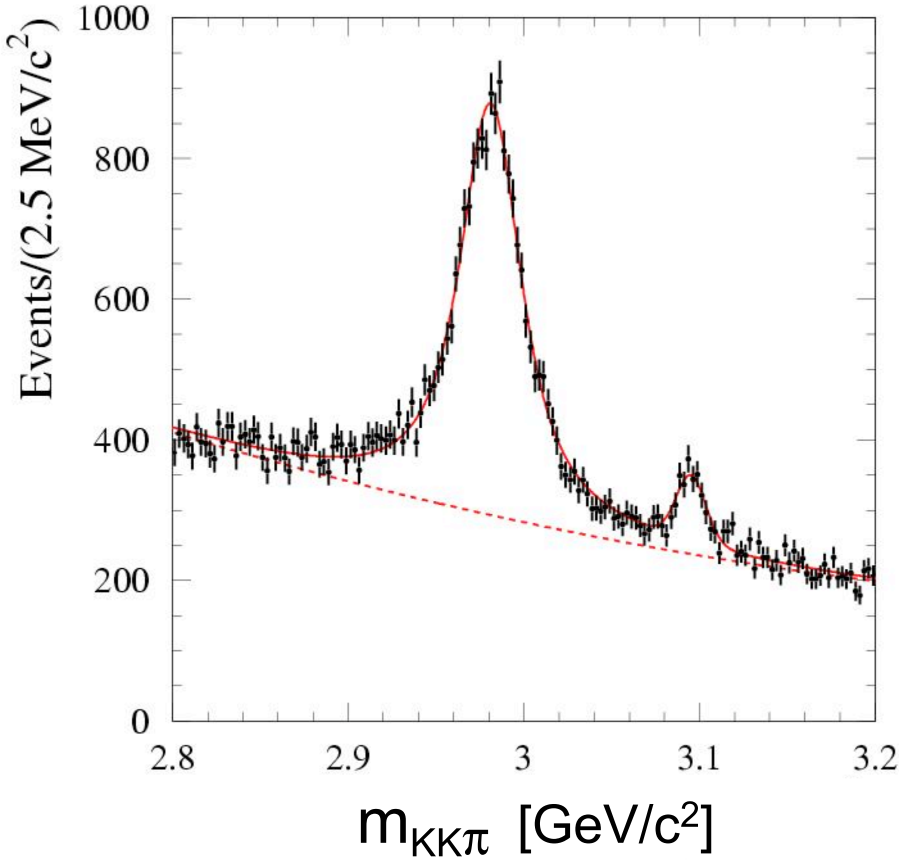
# $\gamma^* \gamma \rightarrow \eta_c$

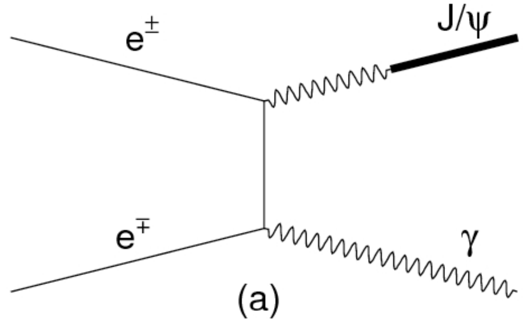
- $e^+e^- \rightarrow e^+e^- \eta_c$
- $\eta_c \rightarrow K_S K^+ \pi$
- *no-tag mode - used for single-tag form factor normalization; also extract mass and width*
  - *background from* $e^+e^- \rightarrow J/\psi\, \gamma$, $J/\psi \rightarrow \eta_c \gamma$
- *single-tag mode - extract form factor*
  - *background from* $e^+e^- \rightarrow e^+e^- J/\psi$, $J/\psi \rightarrow \eta_c \gamma$



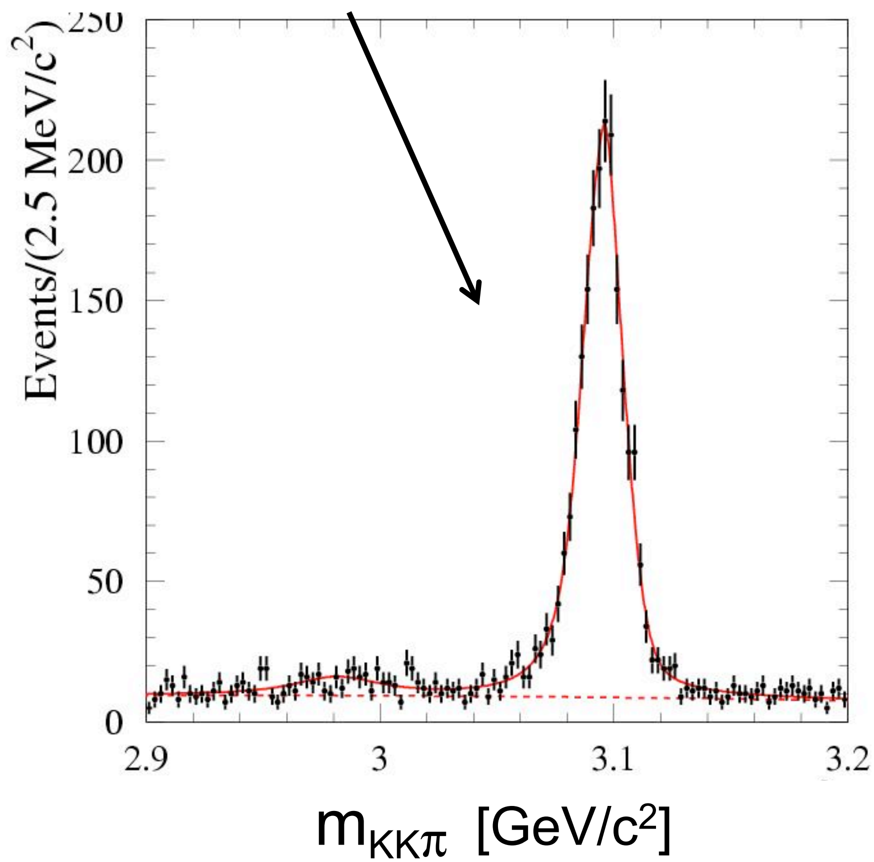
# $e^+e^- \rightarrow e^+e^-\eta_c$ , $\eta_c \rightarrow K_S K^+\pi^-$, *no-tag*




ISR events can be separated from two-photon events using the kinematic criterion:

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



# $e^+e^- \rightarrow e^+e^-\eta_c$ , no-tag mode

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

It is calculated from the fitted number of $J/\psi \rightarrow K_S K^+\pi$ 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 |

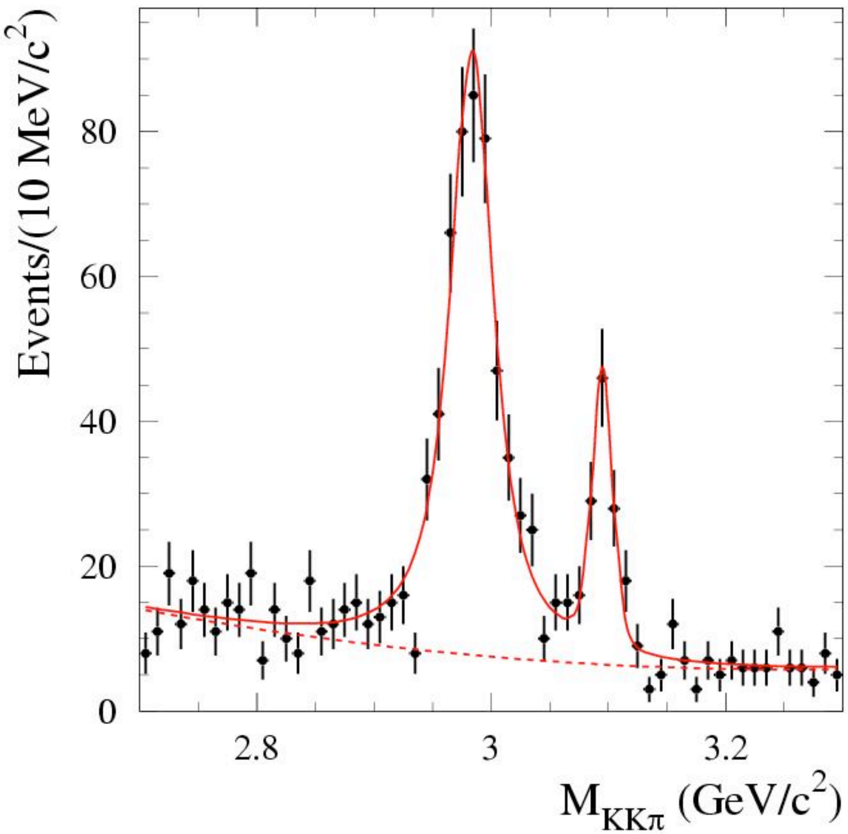
Main sources of systematic uncertainties are unknown background shape and possible interference between $\eta_c$ and non-resonant two-photon amplitudes.

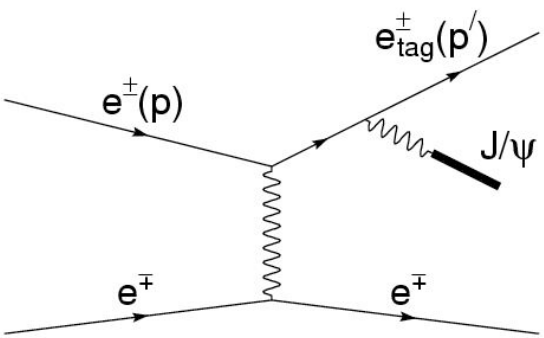
$N(\eta_c)=13890\pm320\pm670$

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

PDG: $0.44\pm0.04$ keV, CLEO: $0.407\pm0.022\pm0.028$ keV

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

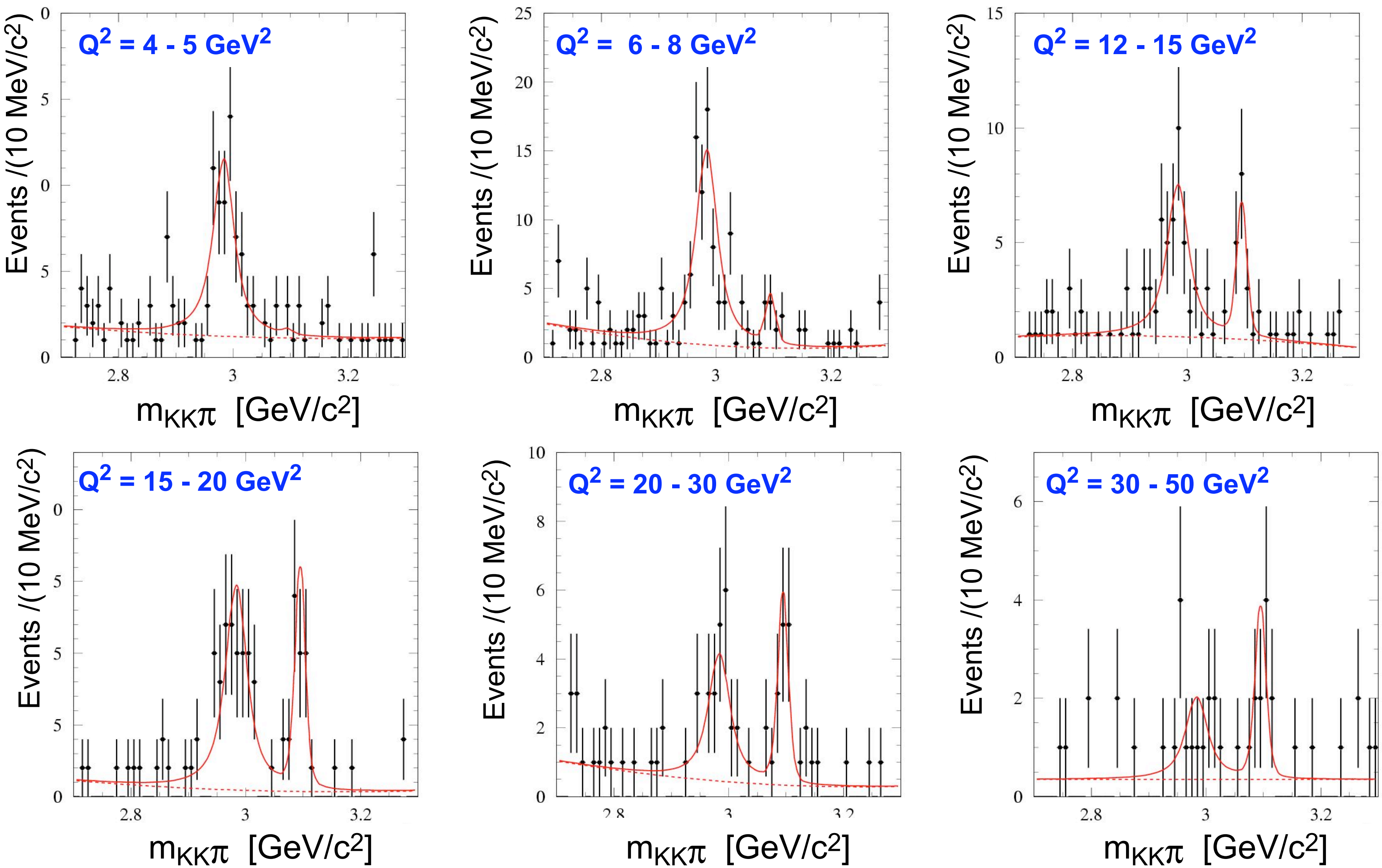


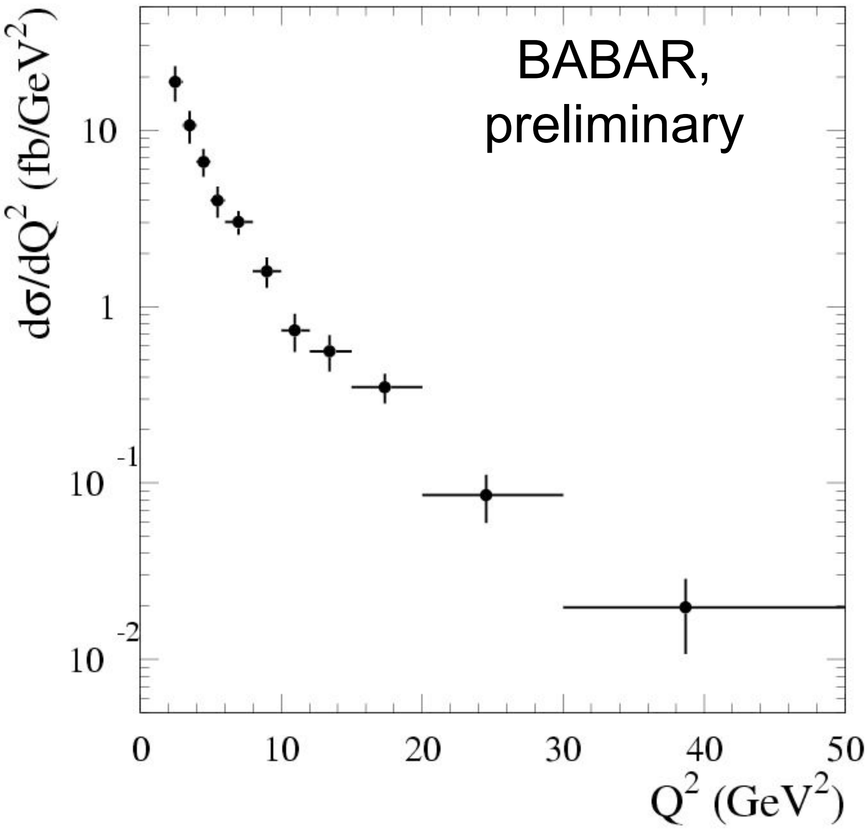

$m=2985.7\pm2.0$ MeV/c$^2$
$\Gamma=31.9\pm4.3$ MeV
$N=530\pm41\pm17$

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

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



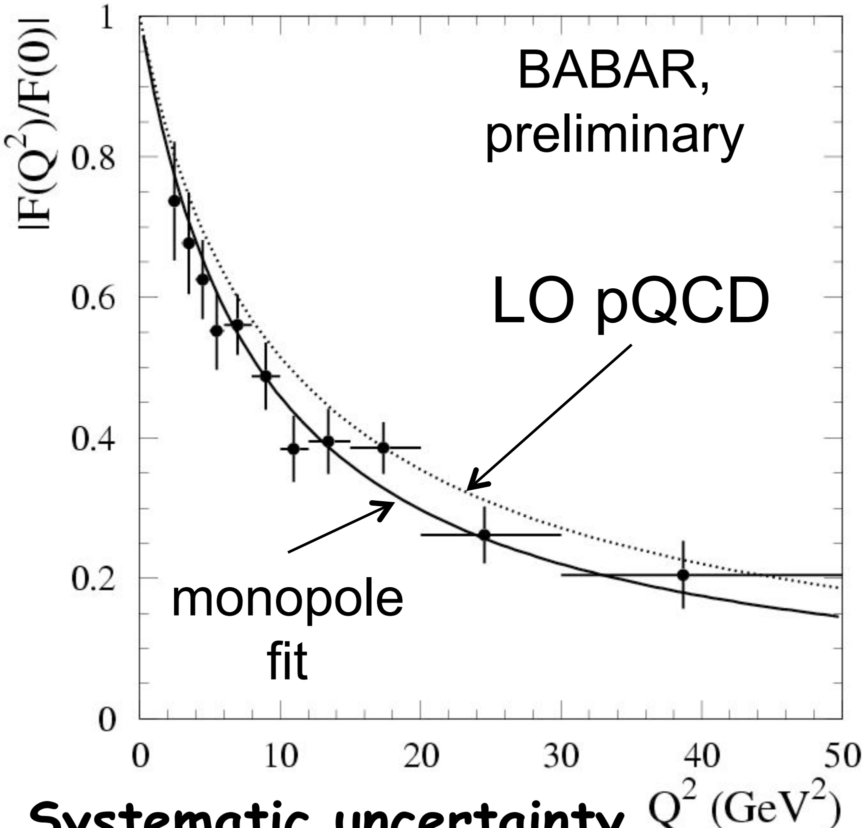
# $e^+ e^- \to e^+ e^- \eta_c$ cross section




**Systematic uncertainty independent of $Q^2$ is 6.7%.**

| | |
|---|---|
| • **detection efficiency** | **5.9%** |
| • **background subtraction** | **2.5%** |
| • **radiative corrections** | **1%** |
| • **luminosity** | **1%** |

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




✓ The form factor is normalized to F(0) obtained from no-tag data

✓ We fit the function

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

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$^2$.

✓ Our data lie below a leading-order pQCD calculation (T. Feldmann, P.Kroll, Phys. Lett. B 413, 410 (1997))

**Systematic uncertainty independent of $Q^2$ is 4.3%.**

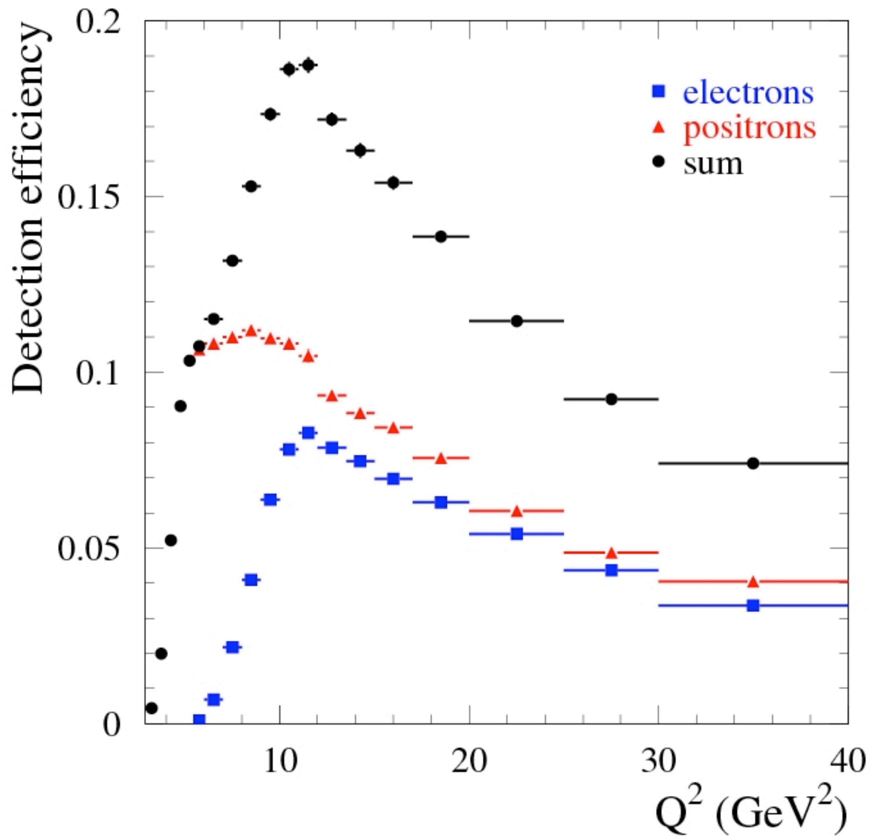
- **detection efficiency**
- **number of no-tag events**
- **stat. error on no-tag efficiency**
- **background subtraction**
- **radiative correction uncertainty**

# *Summary*

- The $\gamma^*\gamma\to\pi^0$ transition form factor has been measured for $Q^2$ range from 4 to 40 $GeV^2$
- An unexpected $Q^2$ dependence of the $\pi^0$ transition form factor is observed for $Q^2>10$ $GeV^2$. The data lie above the pQCD asymptotic limit. This indicates that the 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 the $Q^2$ 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.

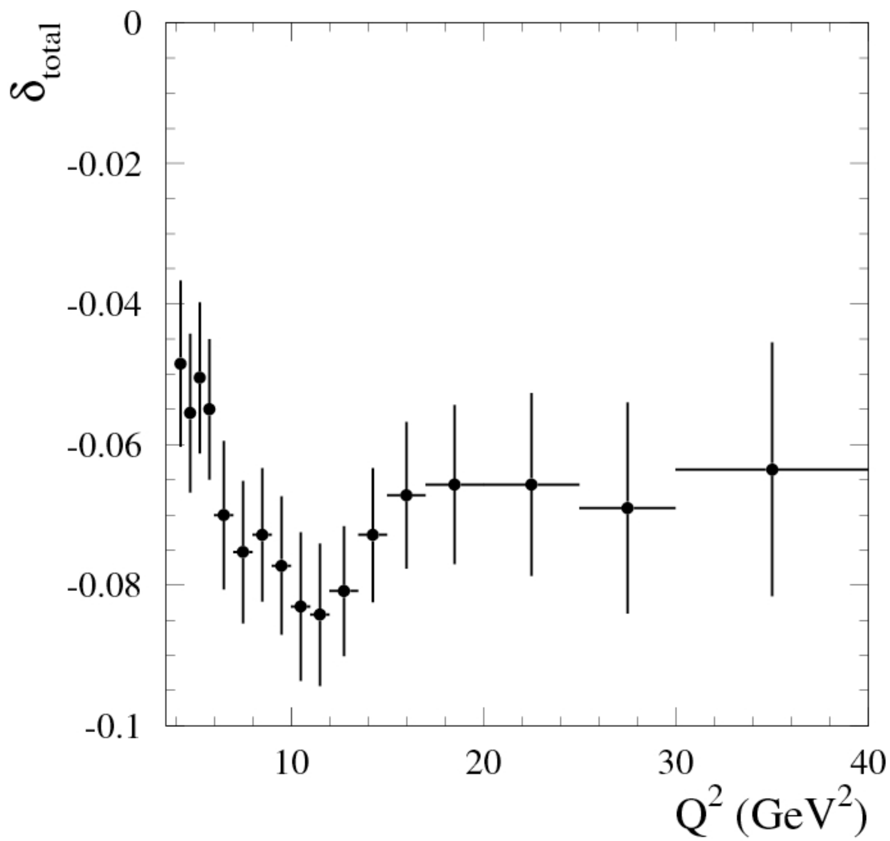
# BACKUP SLIDES

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




- Due to the energy asymmetry of our $e^+e^-$ collisions, the $Q^2$ region below 7 $GeV^2$ is measured only with positron tags.
- We measure the cross section above $Q^2 = 4\ GeV^2$ to avoid possible systematic error due to data-MC differences near the edges of the detector
- The average $\pi^0$ energy grows with $Q^2$. This leads to a decrease of the detection efficiency for $Q^2 > 10\ GeV^2$

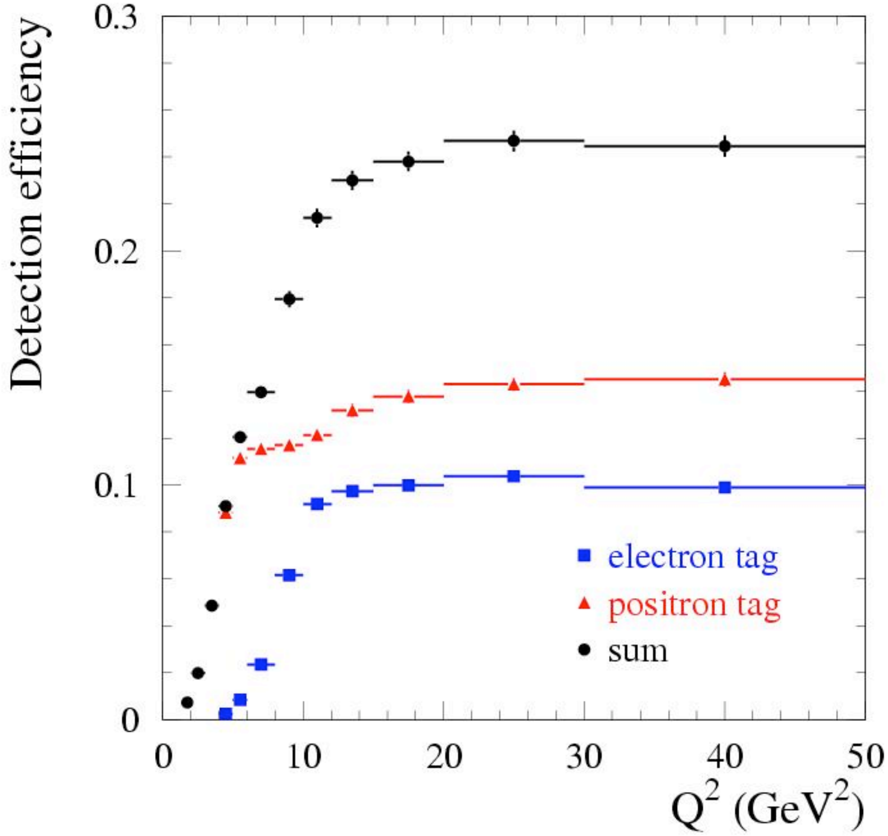
# $e^+e^- \to e^+e^-\pi^0$, total efficiency correction




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

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

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




• Due to the energy asymmetry of our $e^+e^-$ collisions, the $Q^2$ region below 6 GeV$^2$ is measured with positron tags only.

• We measure the cross section above $Q^2 = 2$ GeV$^2$ where the efficiency is about 2%.

•For no-tag events, the efficiency is (14.5±0.2)%

•The 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 | – |
| $\eta_c$ 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 uncertainties due to selection criteria we vary
  - $K_S$ mass window: o.4875-0.5075 ⇒ 0.475-0.52
  - Limit on transverse momentum: 0.25 ⇒ 0.5
  - 0.387<θ<2.4 for kaon and pions
  - -0.02<r<0.03 ⇒ -0.02<r<0.06
- The most significant effect (~6%) is observed for the change of angular restrictions.