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***The Hadronic Light-by-Light Contribution to the Muon Anomaly***

# Meson Transition Form Factors at BaBar

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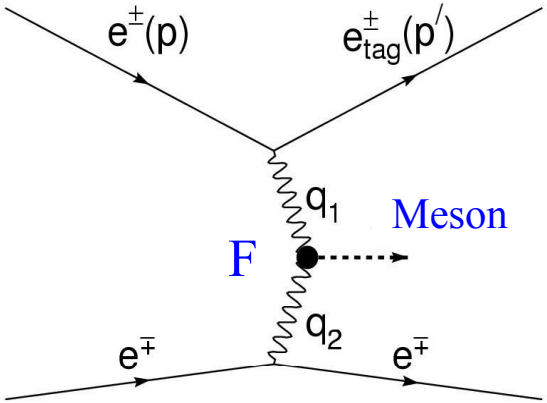
# *Outline*

- **Two-photon physics at BaBar**
- **Measurement of $\pi^0$ transition form factor**
- **Measurement of $\eta$ and $\eta'$ transition form factors**
- **Conclusions and Outlook**
  - ***Timelike FF from Meson Decays***
  - ***BES-III Perspectives***

# *Two Photon Physics at BaBar*




Study of $e^+e^- \to e^+e^-\gamma\gamma^*$ with $\gamma\gamma^* \to \pi^0, \eta, \eta', \eta_c$

BaBar: Test validity of pQCD at low and intermediate $Q^2$

## Meson Structure Physics

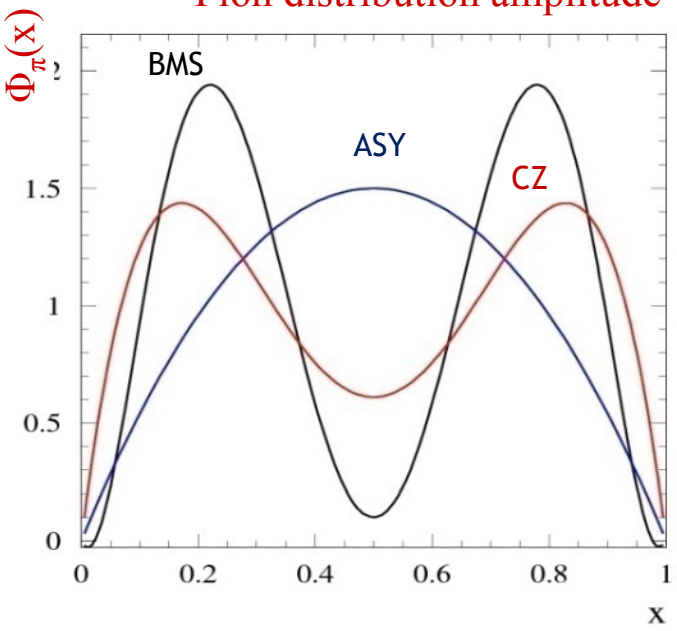
Transition form factors F give access to the meson distribution amplitudes (DA)

$\Phi(x,Q^2)$ important for many QCD processes

- $Q^2$ dependence can be calculated
- x dependence extracted from FF measurements

  (x: fraction of the meson momentum carried by one of the quarks)

Pion distribution amplitude




CZ: Chernyak-Zhitnitsky DA NPB201,492

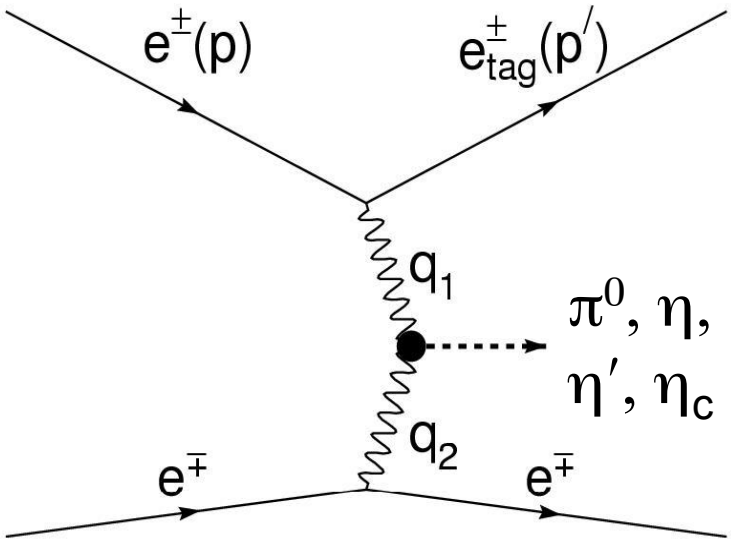
ASY: Asymptotic DA PLB87,359

BMS: Bakulev-Mikhailov-Stefanis DA PLB508,279

# *Single Tag Method*

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed
- Measured electron-meson system with low $p_t$
- Missing mass close to 0

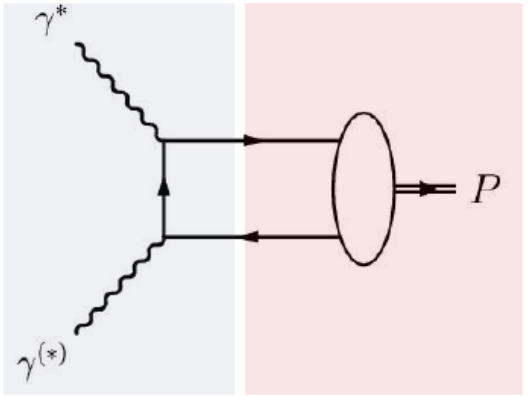



Momentum transfer

- tagged: $Q^2 = -q_1^2 = -(p - p')^2 > 3$ GeV$^2$,
  → Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0$ GeV$^2$,
  → Quasi-real photon

# *Meson Transition Form Factors*

Differential cross section for pseudoscalar meson production dependent only on one form factor $F(q_1^2,q_2^2)$




→ Single tag method: $F(q_1^2,q_2^2) \rightarrow F(Q^2)$

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

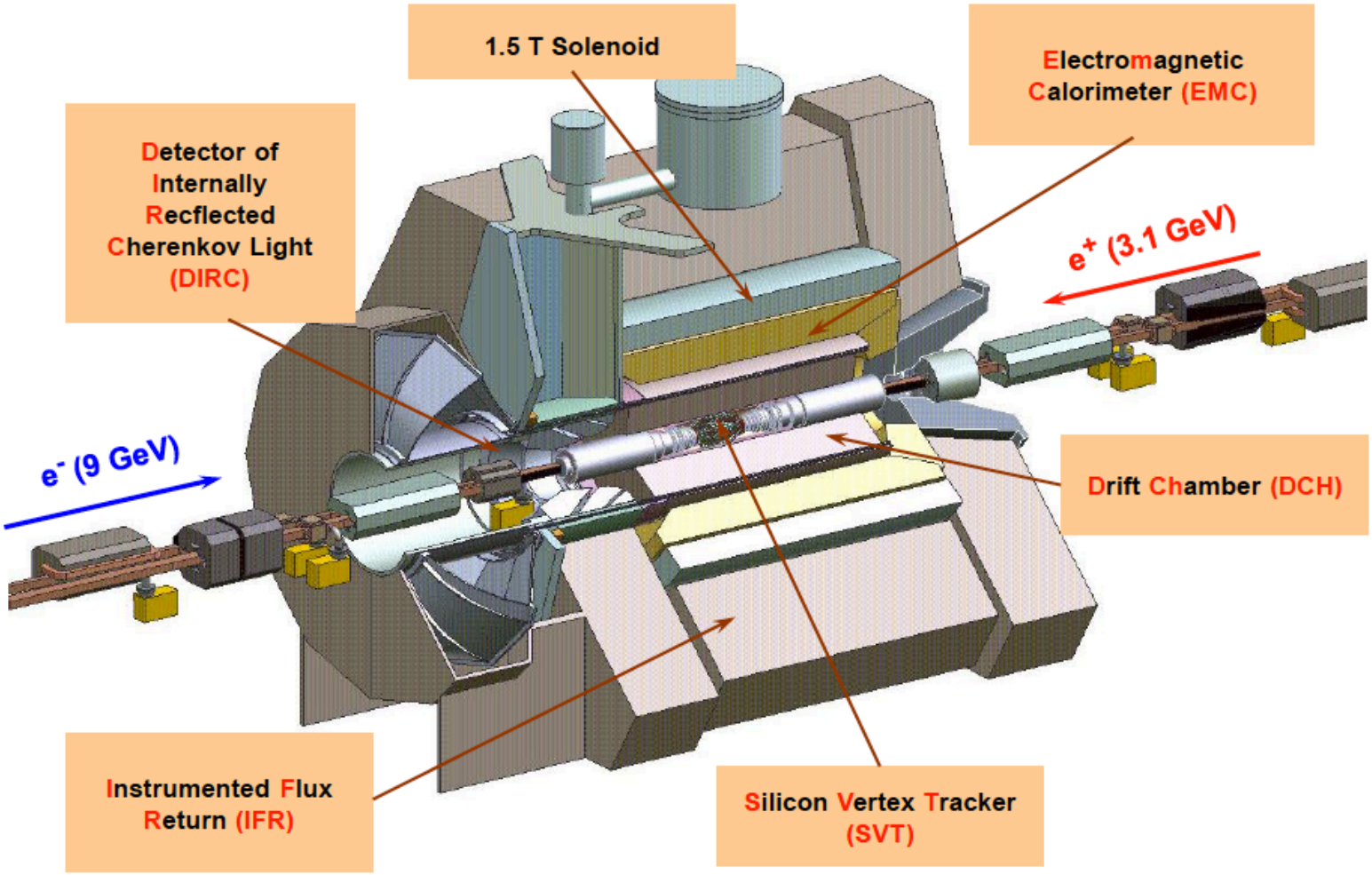
Calculable in pQCD, hard scattering amplitude for $\gamma\gamma \rightarrow q\bar{q}$

Nonperturbative meson distribution amplitude for $q\bar{q} \rightarrow \pi/\eta$

**Status**:

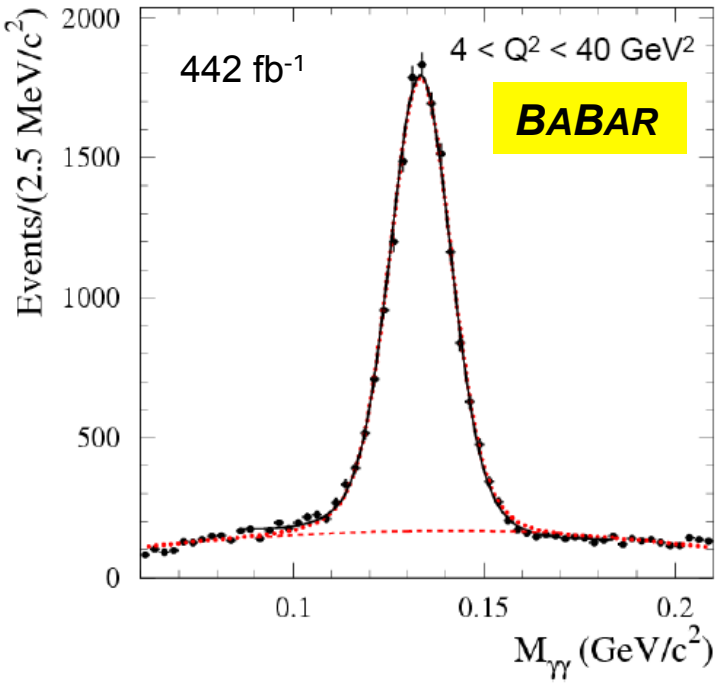
- Dependence on x for $\Phi(x,Q^2)$ not known, certain theoretical models
- Experimental data on $F(Q^2)$ needed

# The BABAR-Experiment



# Pion Production: $e^+e^- \to e^+e^-\pi^0$

## $\gamma\gamma$ mass spectrum



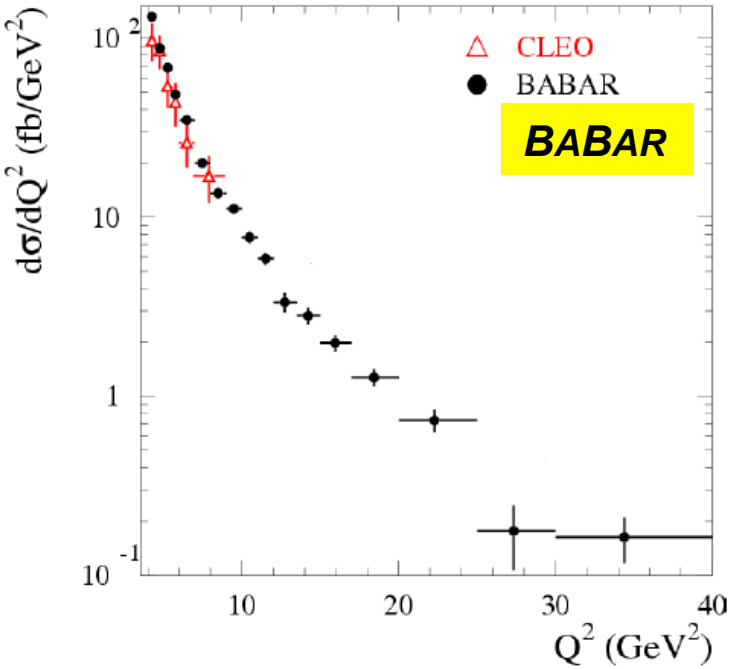

**Fit function: sum of signal+background**

**$N \approx 140.000 \pm 140 \pm 170$**

$\sigma = 7.5 \pm 0.1$ MeV/c$^2$

17 intervals in $Q^2$

## Differential cross section

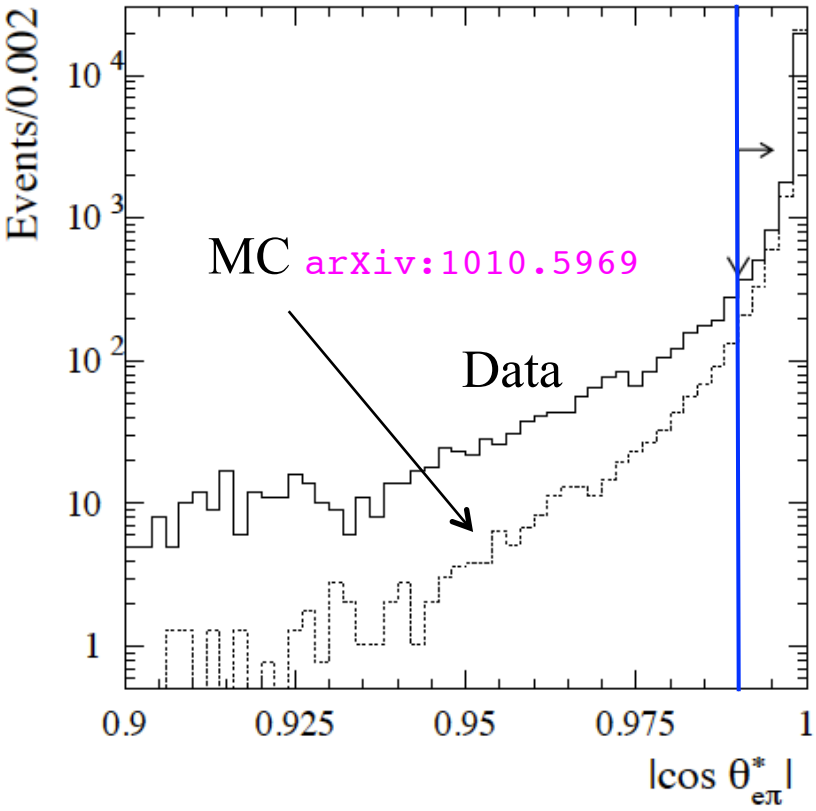



**Main background:**

- Compton Scattering
- Two-Photon-$2\pi^0$ ( ~10% )

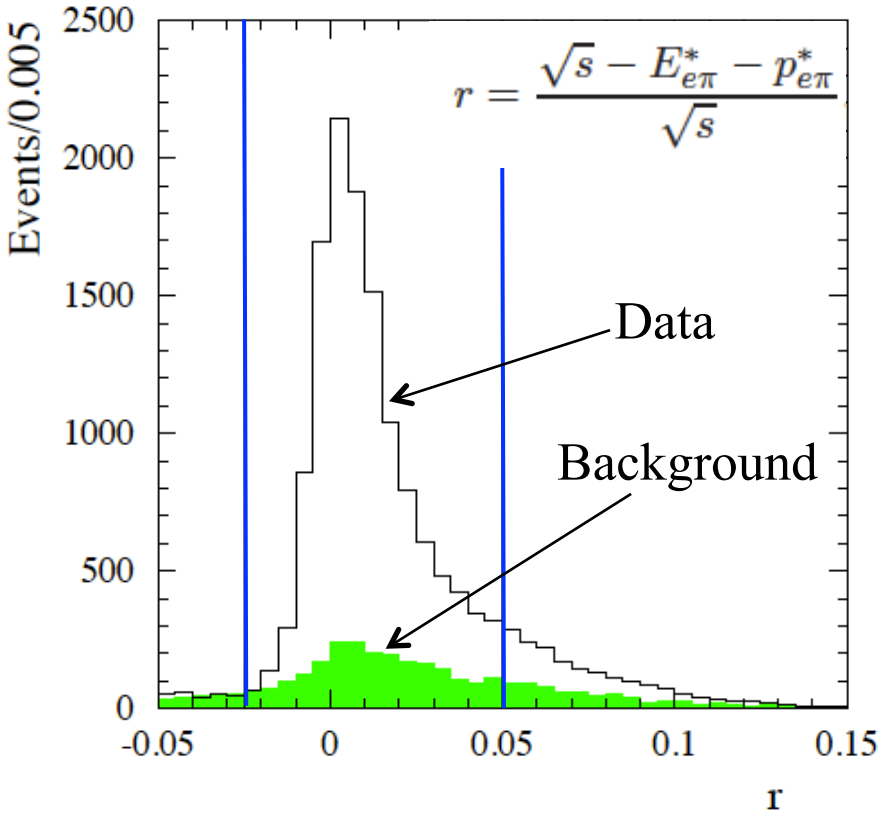
**$Q^2$ independent systematic err.: 3%**

# *Pion Production: $e^+e^- \to e^+e^-\pi^0$*




Helicity angle of tagged and hadronic system

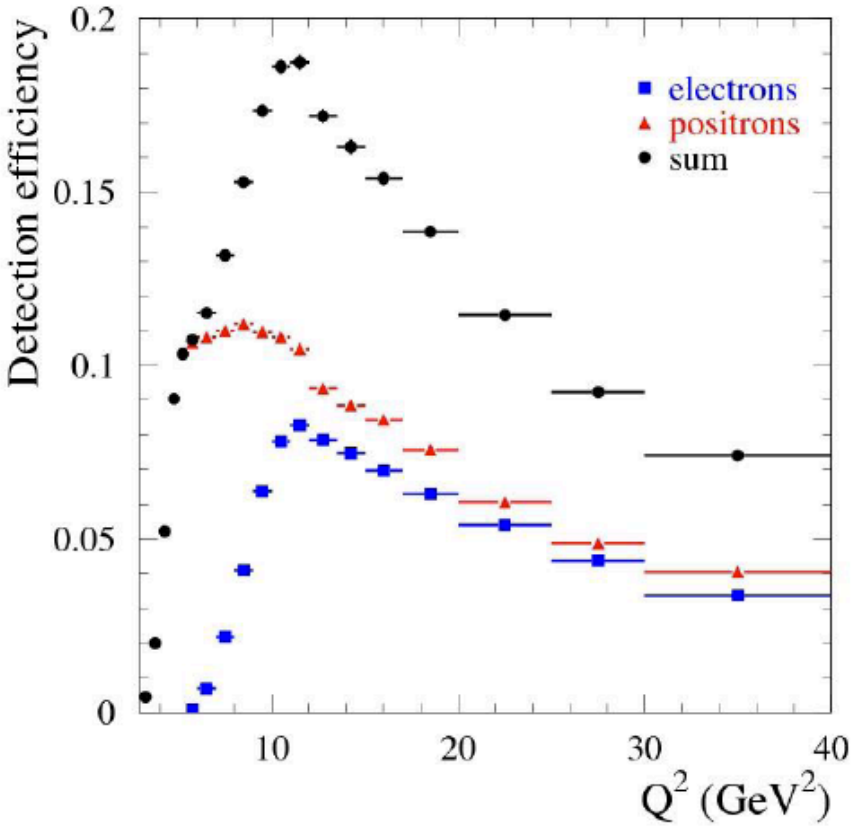
$\cos(\Theta_{e\pi})>0.99$



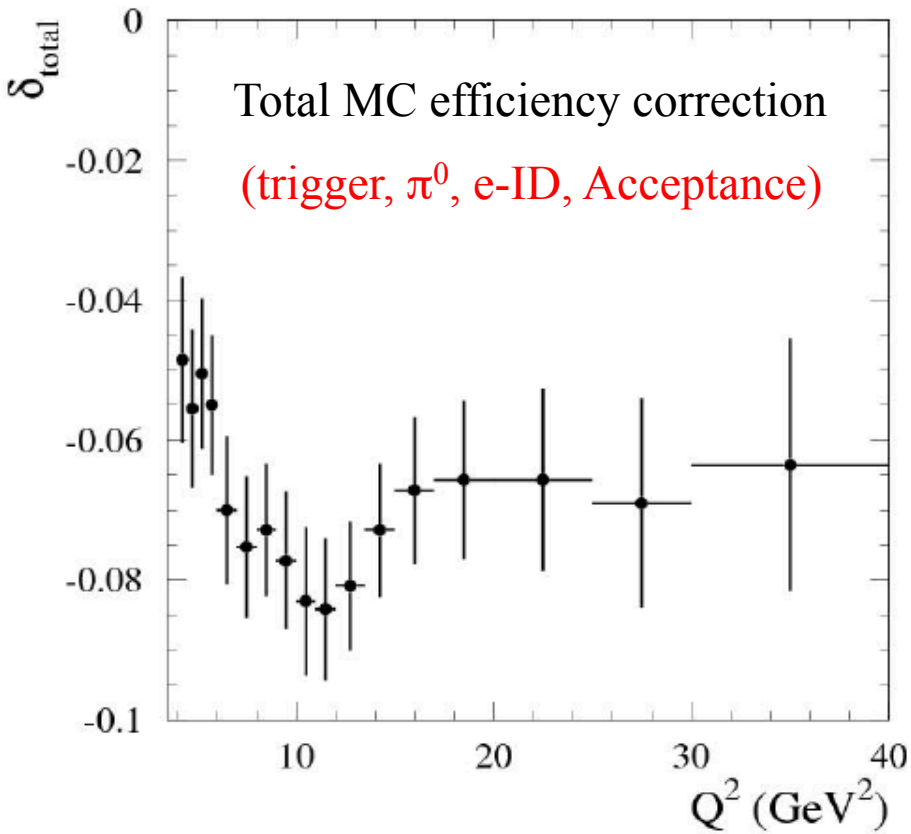

Parameter r cuts events with high-energetic ISR emission ➔ $Q^2_{meas} = Q^2_{true} \cdot (1+r)$

$-0.025 < r < 0.05$

# *Pion Production: $e^+e^- \rightarrow e^+e^-\pi^0$*



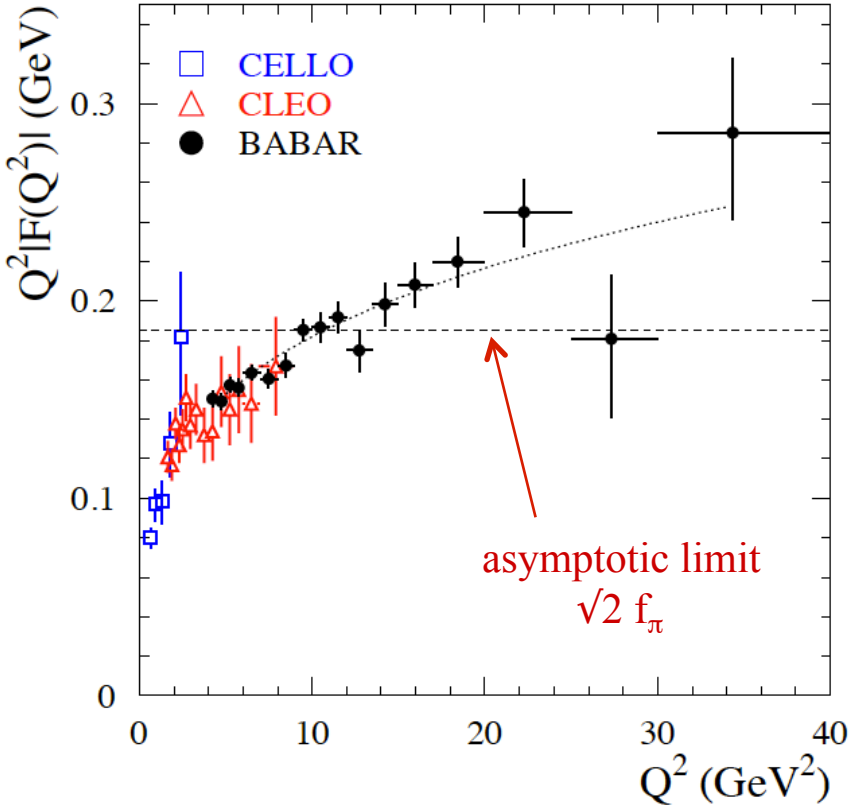

Detection efficiency for electron and positron tag




Measurement restricted to $Q^2 > 4$ GeV$^2$

# The $\pi^0$ Transition Form Factor

Comparison with world data set and QCD



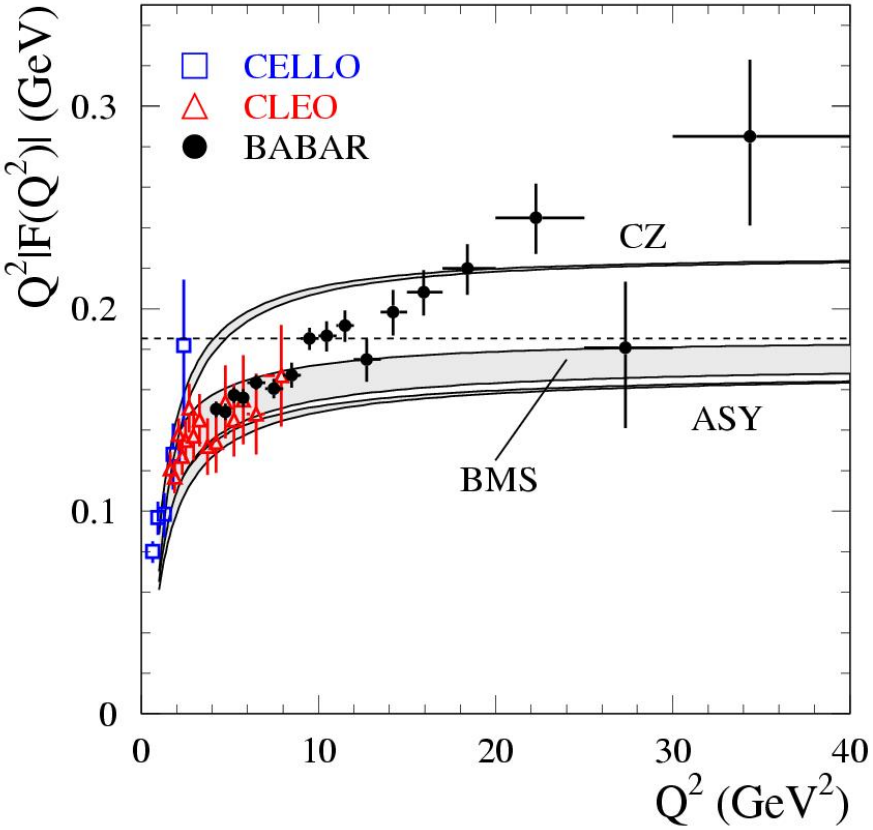

- In $Q^2$ range 4-9 GeV$^2$ BaBar results are in a reasonable agreement with CLEO and CELLO
- Expectation: >10 GeV$^2$ reach asymptotic limit for $Q^2\,F(Q^2) = \sqrt{2} f_\pi = 0.185$ GeV predicted by Brodsky-Lepage in 1979

PRD22,2157

Data exceed asymptotic limit $Q^2 > 10$ GeV$^2$

# The $\pi^0$ Transition Form Factor

Comparison with world data set and QCD




- Several DAs to confront theory vs. experiment:

  CZ: Chernyak-Zhitnitsky DA

  ASY: Asymptotic DA

  BMS: Bakulev-Mikhailov-Stefanis

Models for DA do not describe data

→ Is the DA for pions not known ?

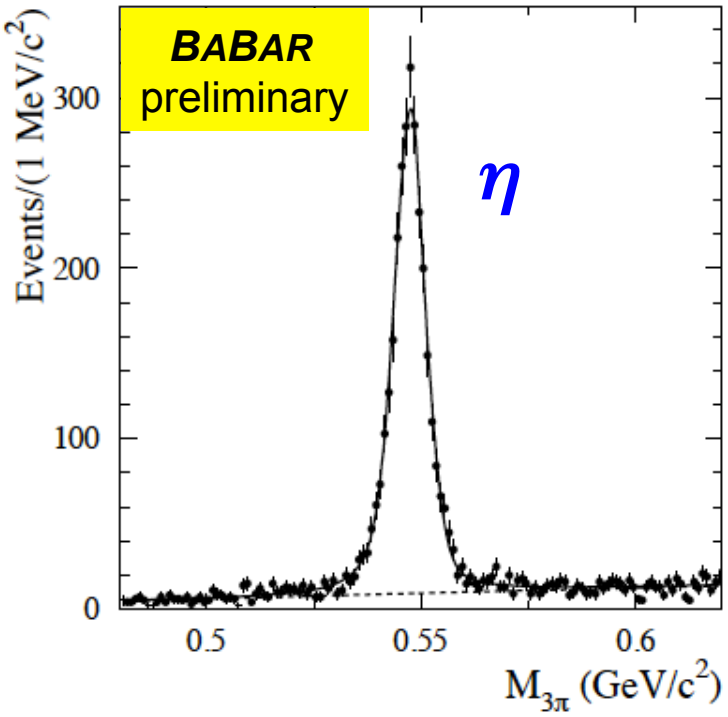
- Use Bakulev-Mikhailov-Stefanis light-cone sum rule theory at NLO pQCD + twist-4 power corrections PRD 67, 074012

Need for higher order pQCD corrections ?!

# $\eta$ and $\eta'$ Production: $e^+e^- \to e^+e^-\eta^{(\prime)}$

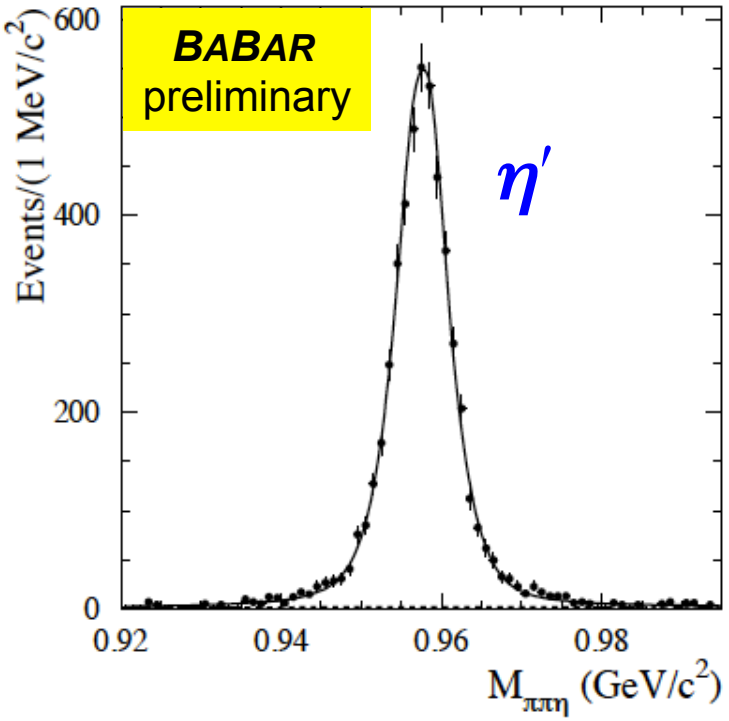
ArXiv:1101.1142
Submitted to PRD

$\pi^+\pi^-\pi^0 \to \pi^+\pi^-\gamma\gamma$ mass spectrum




N = 2760

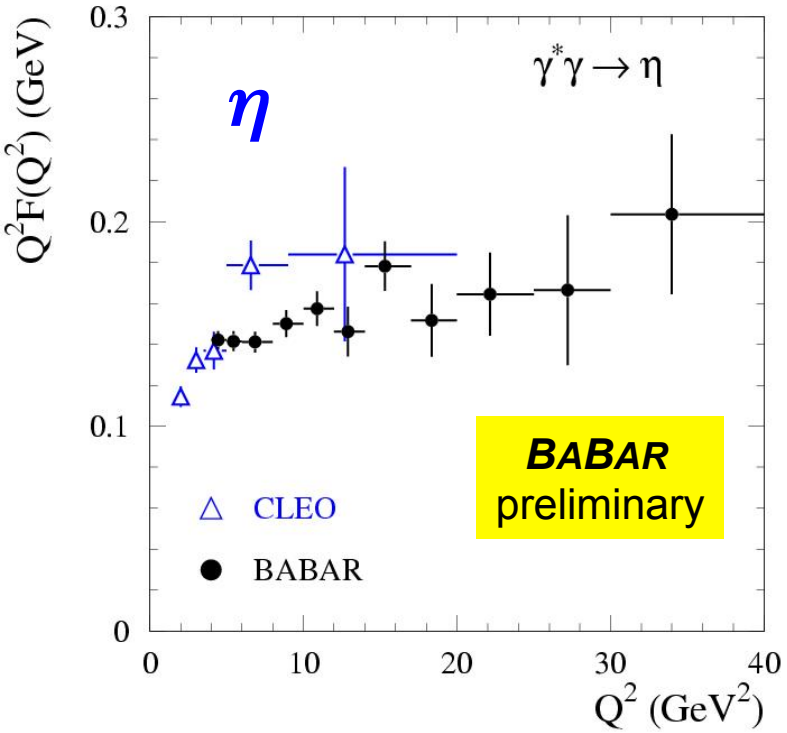
$\pi^+\pi^-\eta \to \pi^+\pi^-\gamma\gamma$ mass spectrum

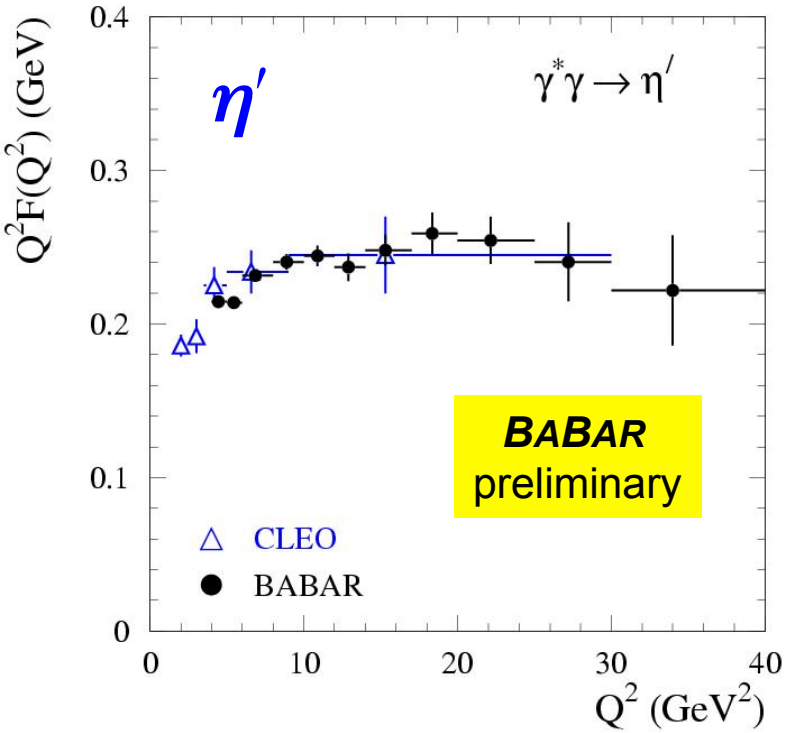



N = 4997

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

# The $\eta$ and $\eta'$ Transition Form Factors



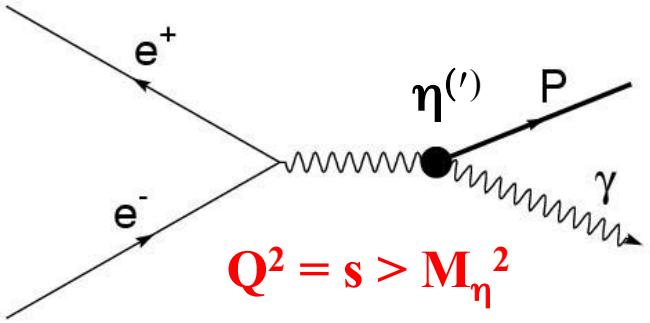

Again fair agreement with existing CLEO data set.
What about the slope at high $Q^2$ ?

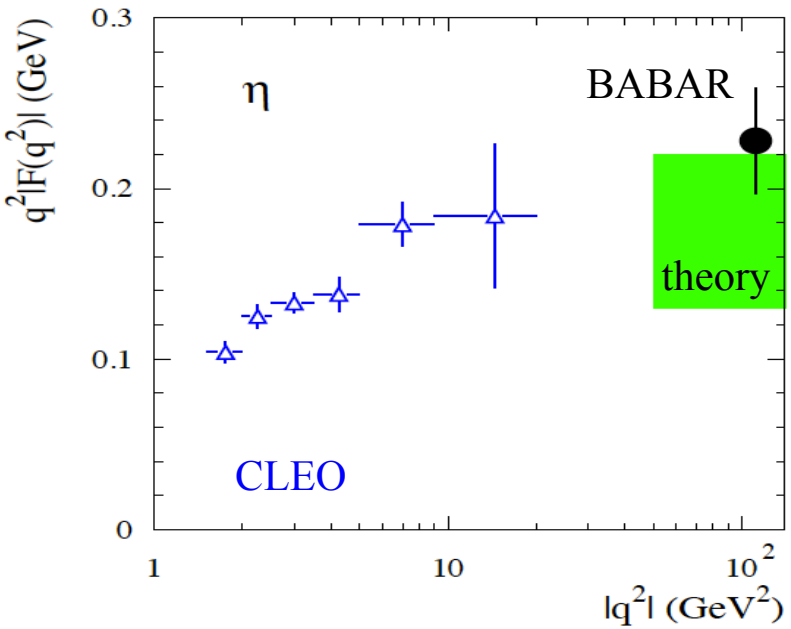
# *Timelike η (η′) Transition Form Factors*

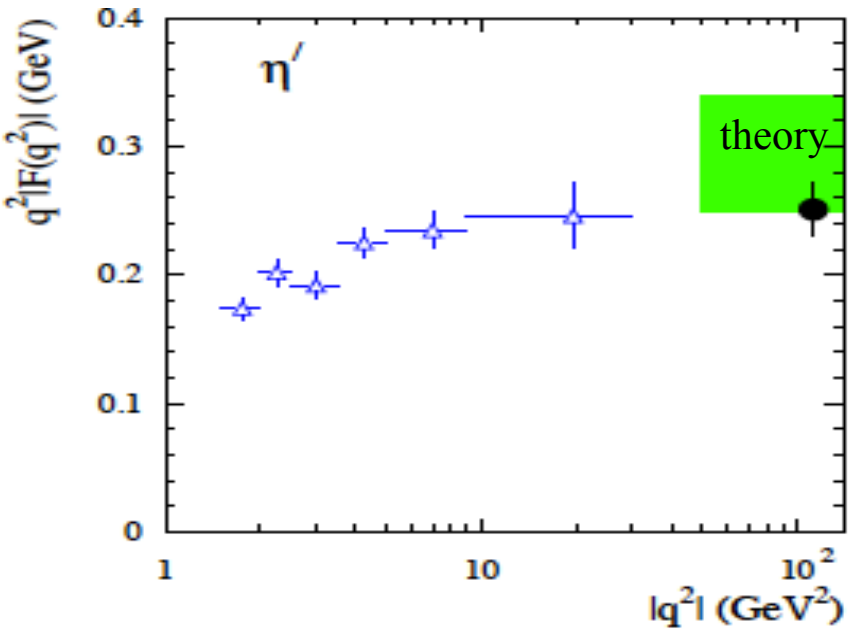
Annihilation Process

PRD74 012002

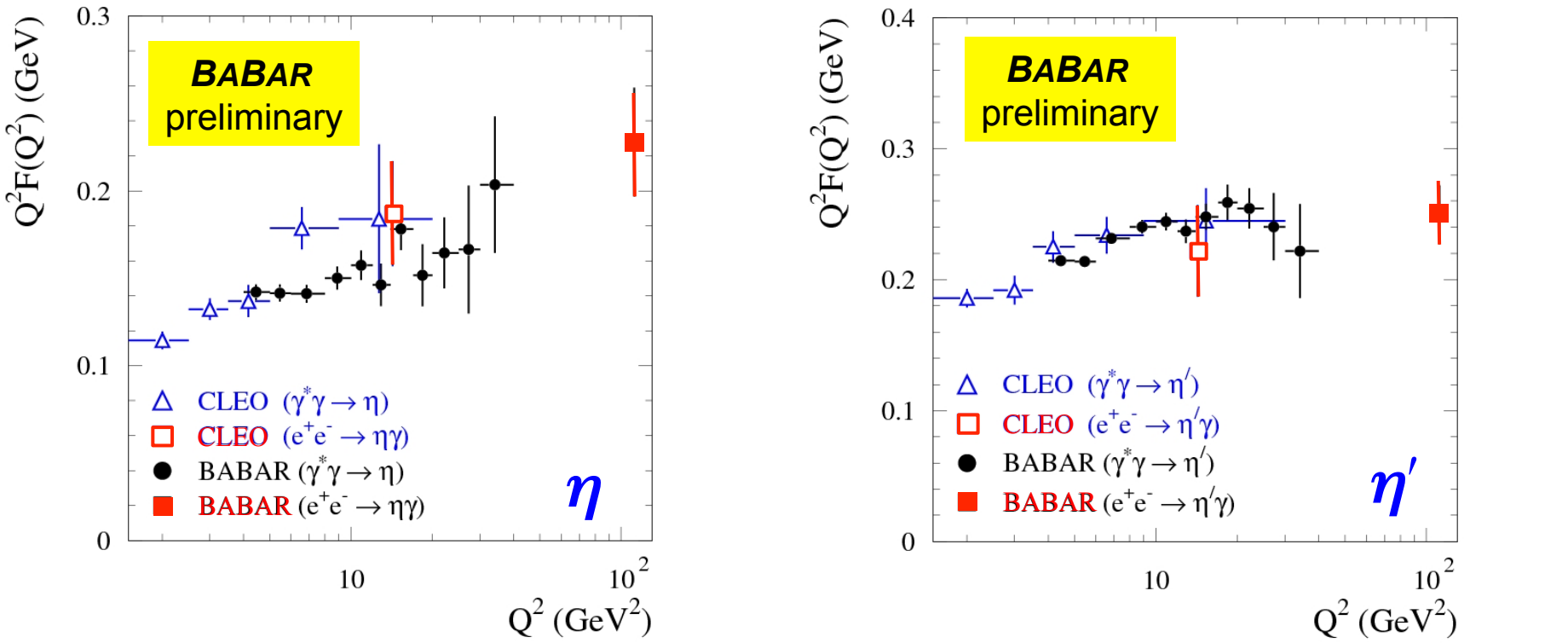
232 fb$^{-1}$



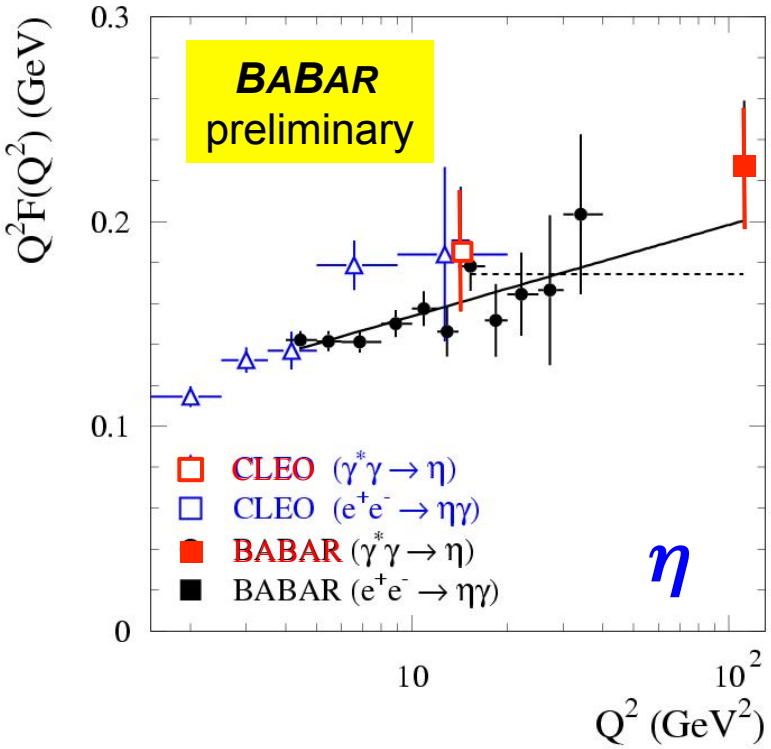
# Comparison with existing (time-like) Data

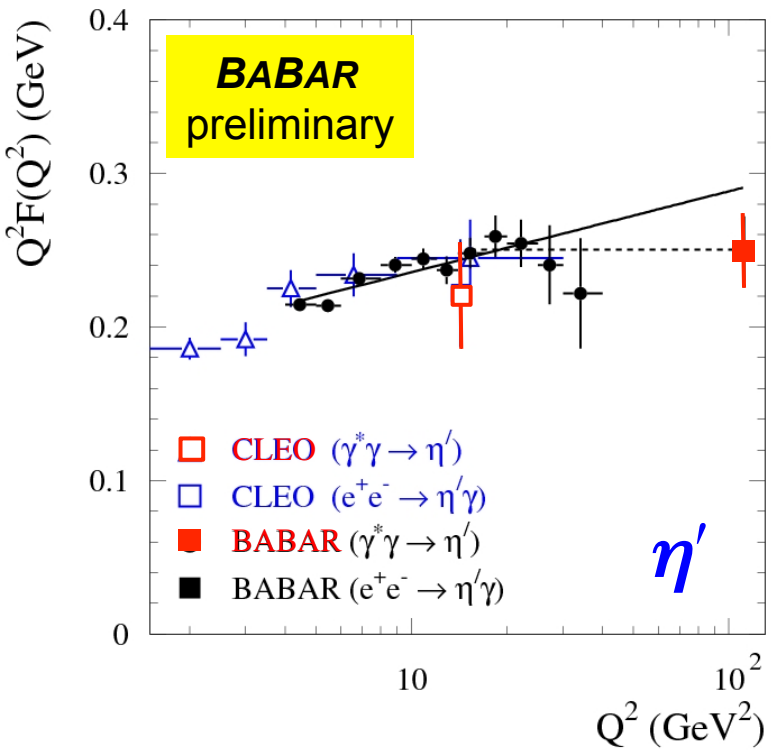



- BABAR time-like transition FF allow to extend the $Q^2$ region up to 112 $GeV^2$
- Additional CLEO point at $Q^2$=14.2 $GeV^2$

Time-like and space-like data seem to be equal at high $Q^2$ (as expected)

# Slope seen for η and η′ Form Factors ?




- The BABAR data are fitted 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 for η ($a \approx 0.2$ GeV$^2$) is about 3 times weaker than that for $\pi^0$

- A fit by a constant (dashed line) for $Q^2>15$ GeV$^2$ also gives reasonable quality
  with $\chi^2/n=5.6/5$ for η and 2.6/5 for η′

# $\eta$-$\eta'$ Mixing in the Quark Flavour Basis

Flavour decomposition needed to compare $\eta$ and $\eta'$ data with $\pi^0$!

$$|n\rangle = \frac{1}{\sqrt{2}}(|\bar{u}u\rangle + |\bar{d}d\rangle), \quad |s\rangle = |\bar{s}s\rangle, \qquad \phi \approx 41^\circ$$

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

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 the asymptotic limits

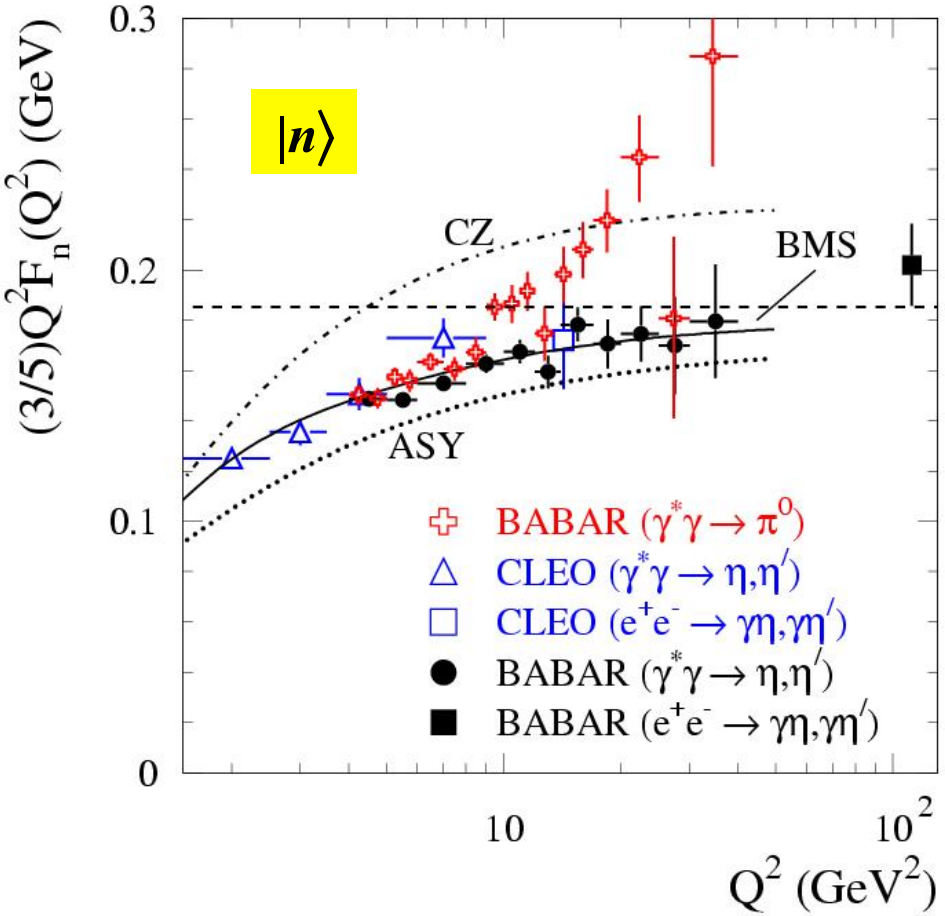
$$Q^2 F_s(Q^2) = \frac{2}{3} f_s, \quad Q^2 F_n(Q^2) = \frac{5\sqrt{2}}{3} f_n,$$

where the decay constants are expected to be $f_n = f_\pi$,
$f_s = (2f_K^2 - f_\pi^2)^{1/2} = 1.34\, f_\pi$

One can expect that the DA for the $|n\rangle$ state is close to the $\pi^0$ DA;
except factor of 3/5 coming from the quark charges.

# *Form Factor for $|n\rangle$ and $|s\rangle$ States*

Non-strange η FF in comparison with $\pi^0$ FF

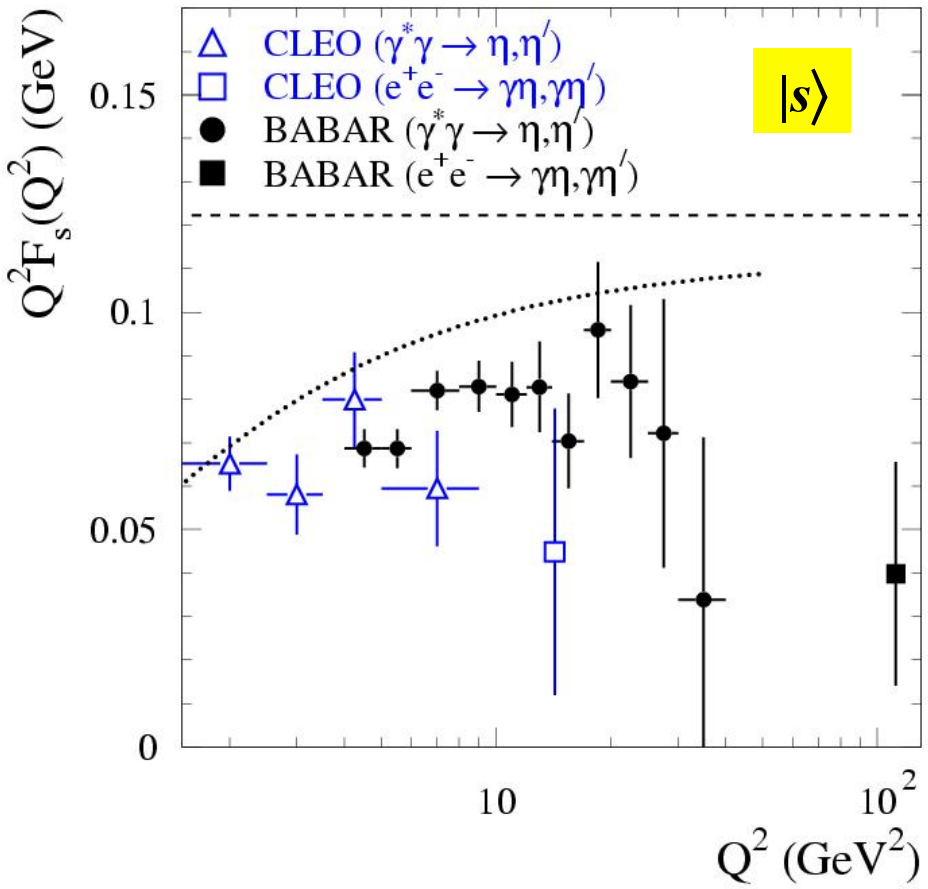



The $Q^2$ dependencies of the measured $|n\rangle$ and $\pi^0$ form factors are strongly different

- Data on the $|n\rangle$ form factor are described well by the model with the BMS DA
- Data slightly higher than the asymptotic DA prediction

# *Form Factor for $|n\rangle$ and $|s\rangle$ States*

Strange η FF




Result for $|s\rangle$ strongly depends on mixing parameters and on possible two-gluon content in η′

- For $|s\rangle$ all data points lie well below the pQCD prediction for the asymptotic DA
- Timelike FF distant from asymptotic limit

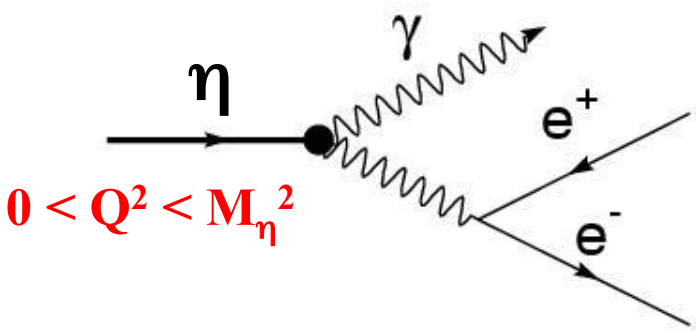
# *Conclusions*


- ✓ Babar results on two-photon physics in the intermediate energy range proves to be an important testing ground for QCD physics
- ✓ The $\gamma^*\gamma\rightarrow\pi^0$, $\eta$, $\eta'$ transition form factors have been measured for $Q^2$ range from 4 to 40 $GeV^2$.
- ✓ The unexpected $Q^2$ dependence of the $\gamma^*\gamma\rightarrow\pi^0$ form factor is observed. At $Q^2>10$ $GeV^2$ the data lie above the asymptotic limit and show no saturation.
- ✓ The measured $Q^2$ dependencies for the $\gamma\gamma^*\rightarrow\eta$ and $\gamma\gamma^*\rightarrow\eta'$ transition form factors strongly differ from that for $\gamma\gamma^*\rightarrow\pi^0$

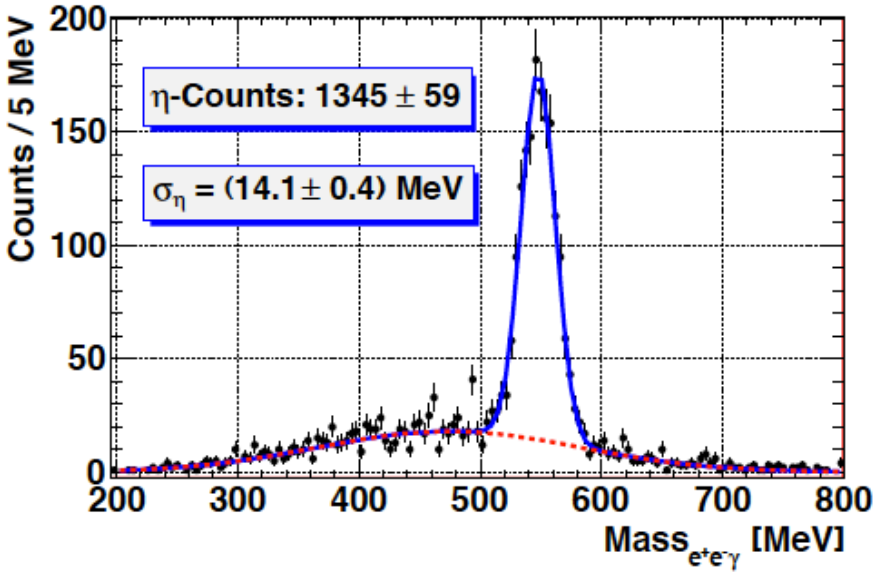
so-called "BaBar puzzle" ….
caused quite some interest/confusion in the theory community …
…. impact on $(g-2)_\mu$ probably limited due to high $Q^2$ range ….

# Meson Decays: Timelike Form Factors

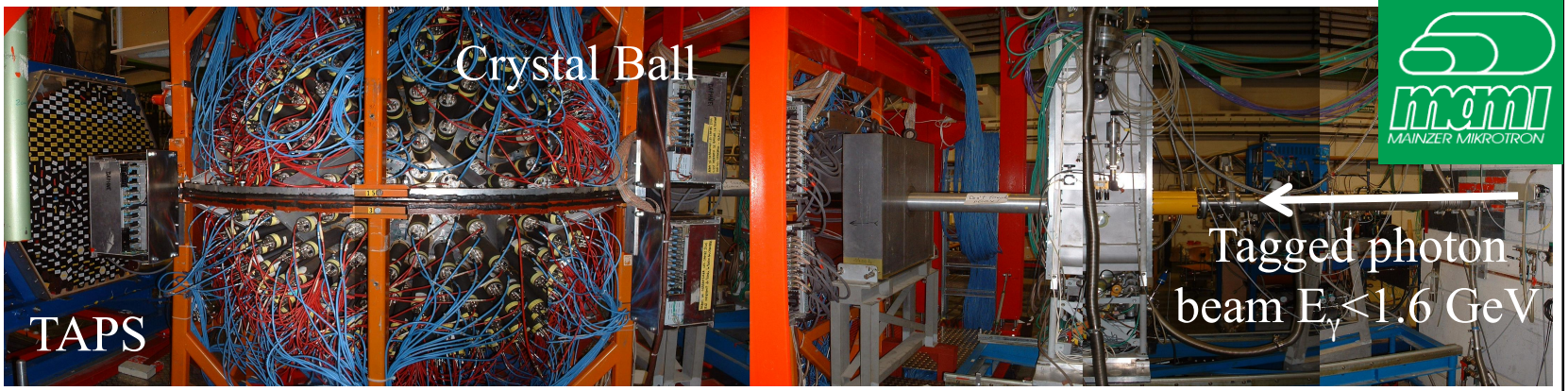
Meson Dalitz Decays



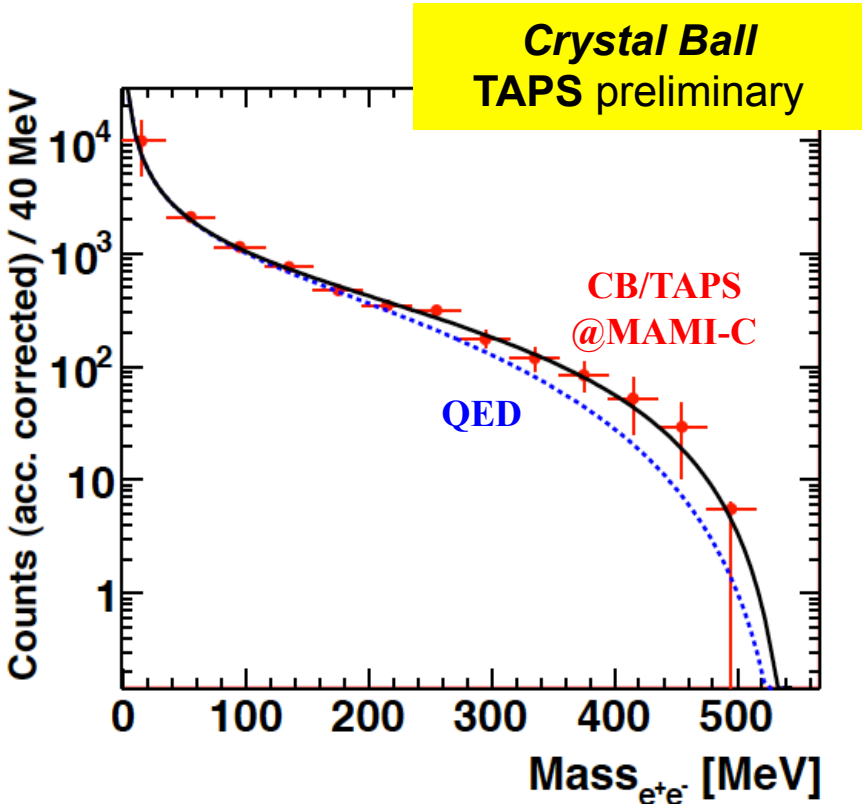

$0 < Q^2 < M_\eta^2$

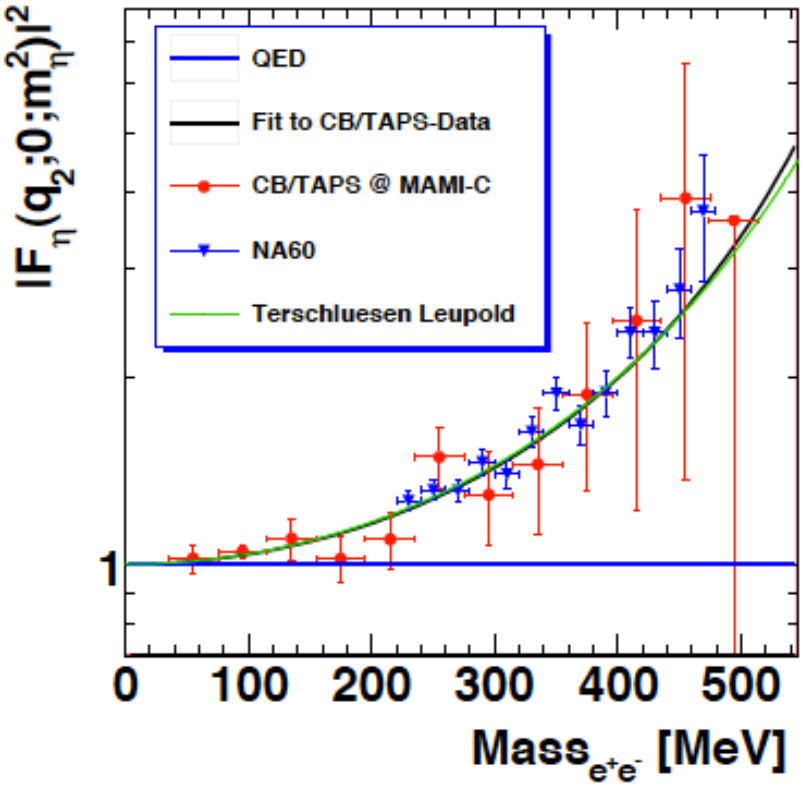



Produce mesons in photo production on target ( $>10^5$ / hour )



# *Meson Decays: Timelike Form Factors*




Fit to the event yield within VMD model

$$\Lambda = (738 \pm 64)\ \mathrm{MeV}$$

Transition FF