ISR and Two-Photon results from BaBar

Miriam Fritsch

on behalf of the BaBar Collaboration

Institut für Kernphysik

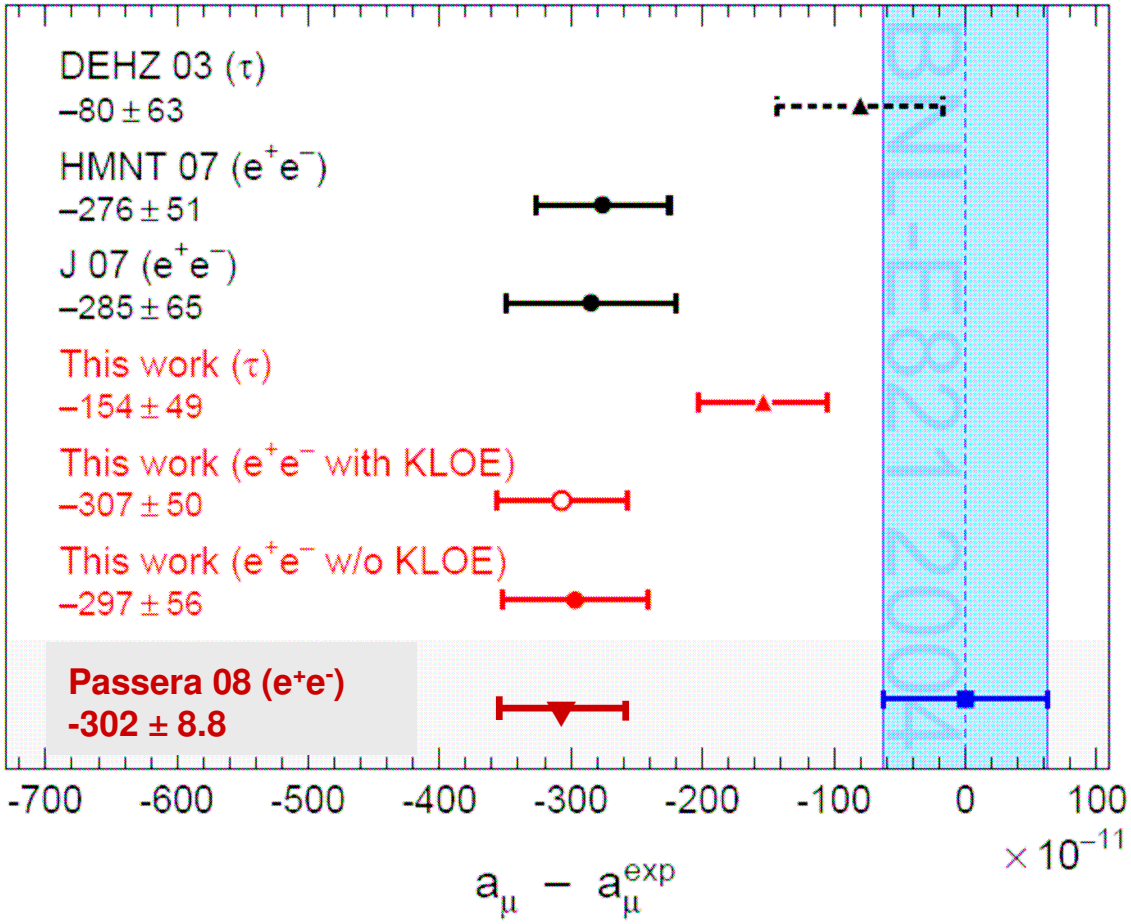
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Kazimierz

July 24 2009

$(g_\mu - 2)$: Comparison theory - experiment

M. Davier et al. arXiv:0906.5443
M. Passera et al. PRD 78 (2008) 013009



Anomalous Magnetic Moment of the Muon:

$a_\mu = (g_\mu - 2)/2$

$a_\mu^{exp} - a_\mu^{theo} = (30.2 \pm 8.8) \cdot 10^{-10}$

significance: **3.4 σ**

→ Is this a hint for physics beyond the standard model ?

Standard model prediction for (g_μ -2)

M. Passera et al. PRD 78 (2008) 013009

Data: 2π only KLOE, SND and CMD-2
τ-data not used for now

QED:	(11 658 471.810	±	0.016)	x 10^{-10}
Weak:	(15.4	±	0.2)	x 10^{-10}
Strong:				
vacuum polarization	(691.8	±	4.3)	x 10^{-10}
light by light scatt.	(11.0	±	4.0)	x 10^{-10}
SM prediction:	(11 659 177.8	±	6.1)	x 10^{-10}

→ Limitation for the theoretical precision of the SM:
Hadronic contribution

Standard model prediction for (g_μ -2)

M. Passera et al. PRD 78 (2008) 013009

Data: 2π only KLOE, SND and CMD-2
τ-data not used for now

QED:	(11 658 471.810	±	0.016)	x 10^{-10}
Weak:	(15.4	±	0.2)	x 10^{-10}
Strong:				
vacuum polarization	(691.8	±	4.3)	x 10^{-10}
light by light scatt.	(11.0	±	4.0)	x 10^{-10}
SM prediction:	(11 659 177.8	±	6.1)	x 10^{-10}

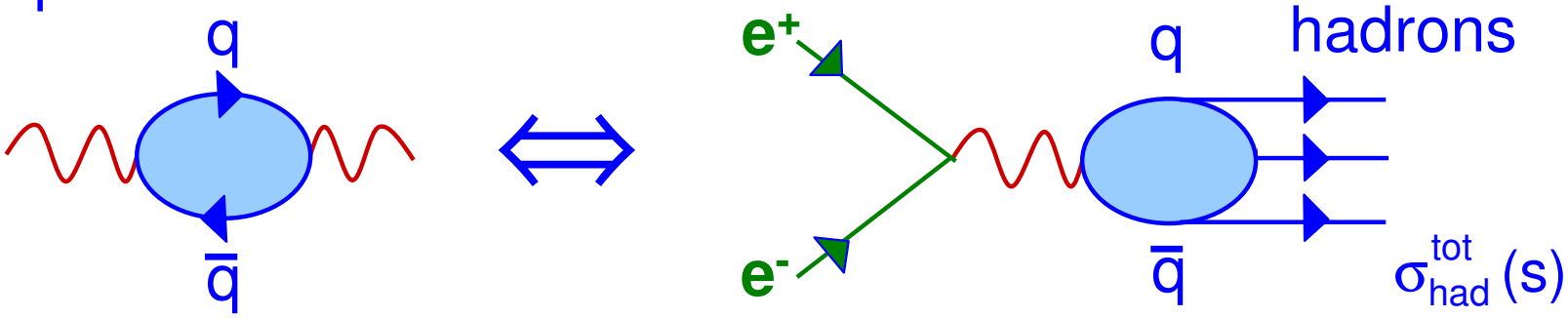
ISR physics

Two-Photon physics

→ Limitation for the theoretical precision of the SM:
Hadronic contribution

Hadronic contribution a_μ^{had}

Optical theorem:

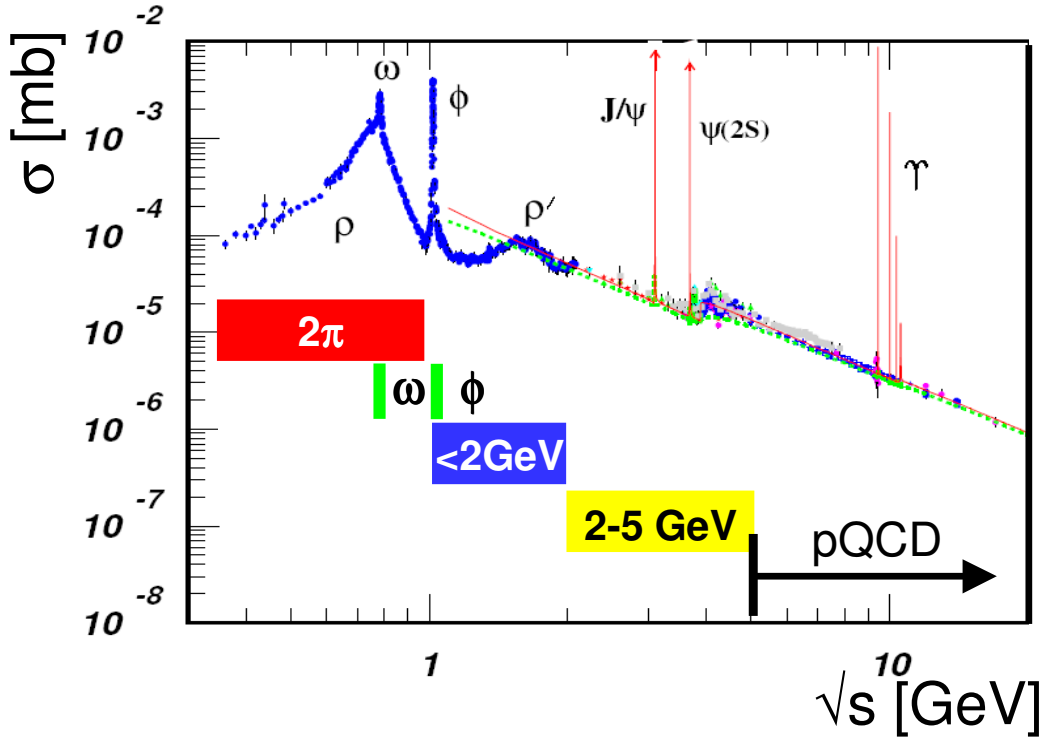


Dispersion integral:

$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\ \sigma_{had}(s)$$

Hadronic contribution: Sum over e^+e^--cross section data
(Hadronic τ-decays)

Hadronic cross section



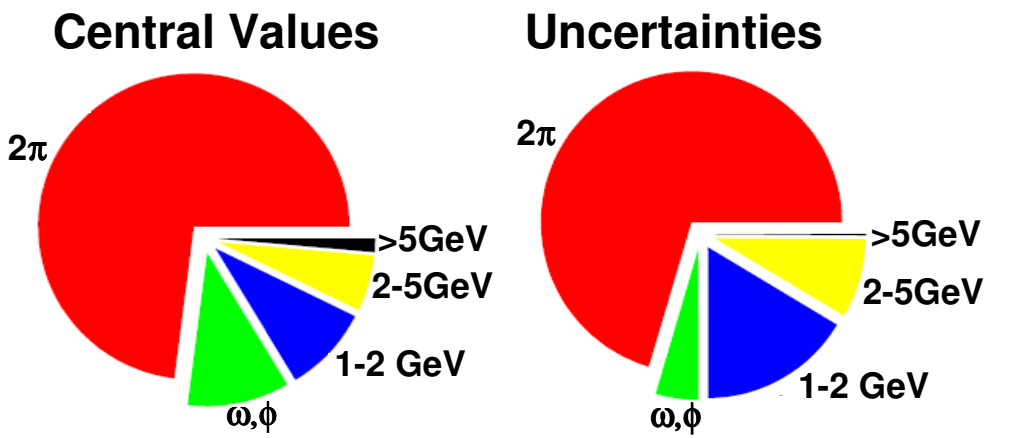
Dispersion integral:

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}(s)$$

$K(s) \sim 1/s^2$

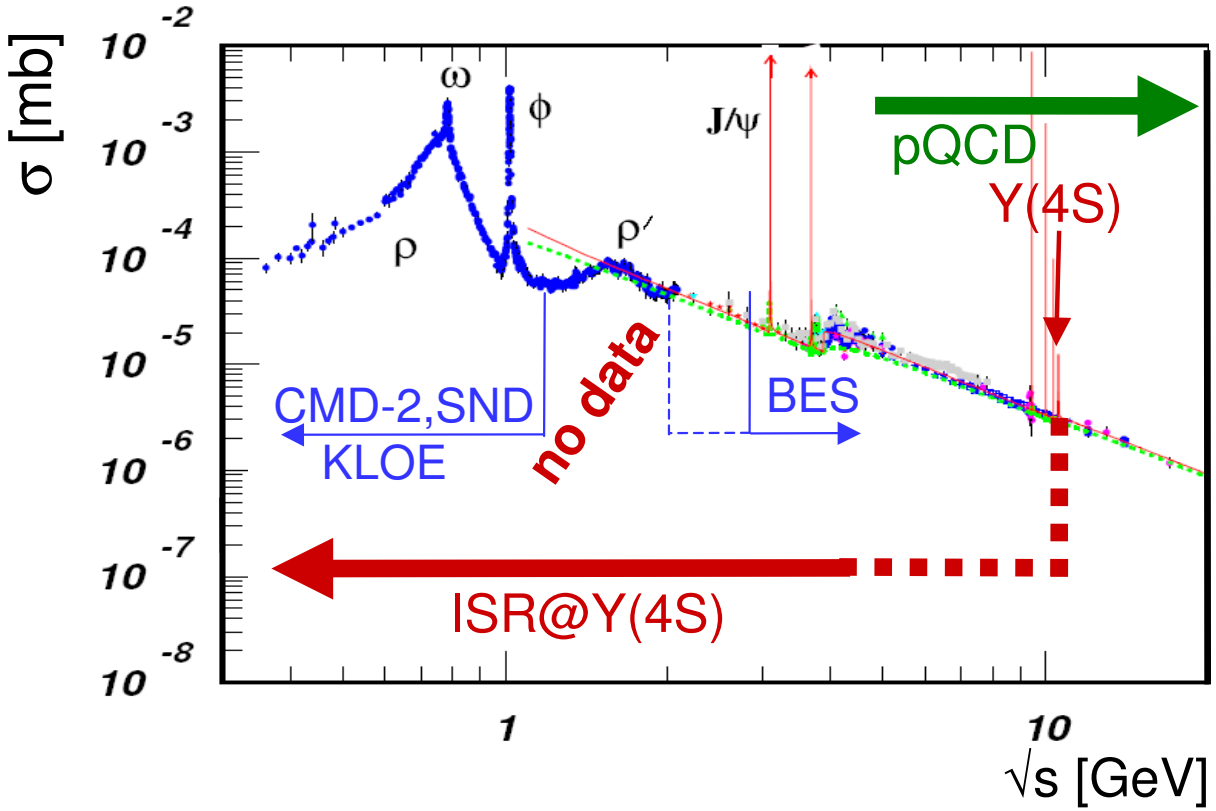
→ Low energy contributions very important

Experimental input into dispersion integral



from S. Eidelman

Experimental situation



- Energy Scan:
  $e^+e^- \rightarrow$ Hadrons
  CMD-2,SND, Novosibirsk
  BES, Bejing

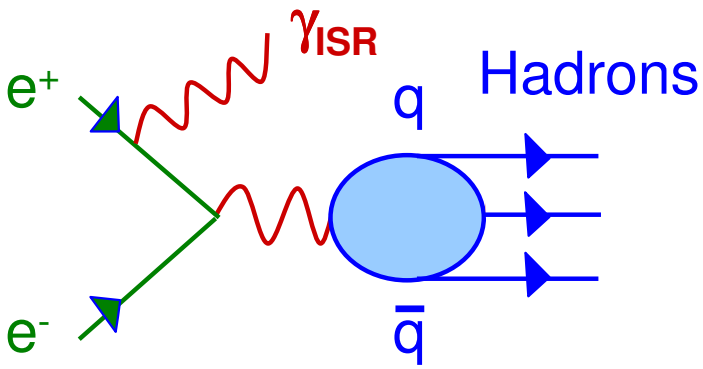
- Initial State Radiation:
  $e^+e^- \rightarrow \gamma_{ISR}$ + Hadrons
  KLOE, Frascati
  (Belle, KEK)
  BaBar, SLAC

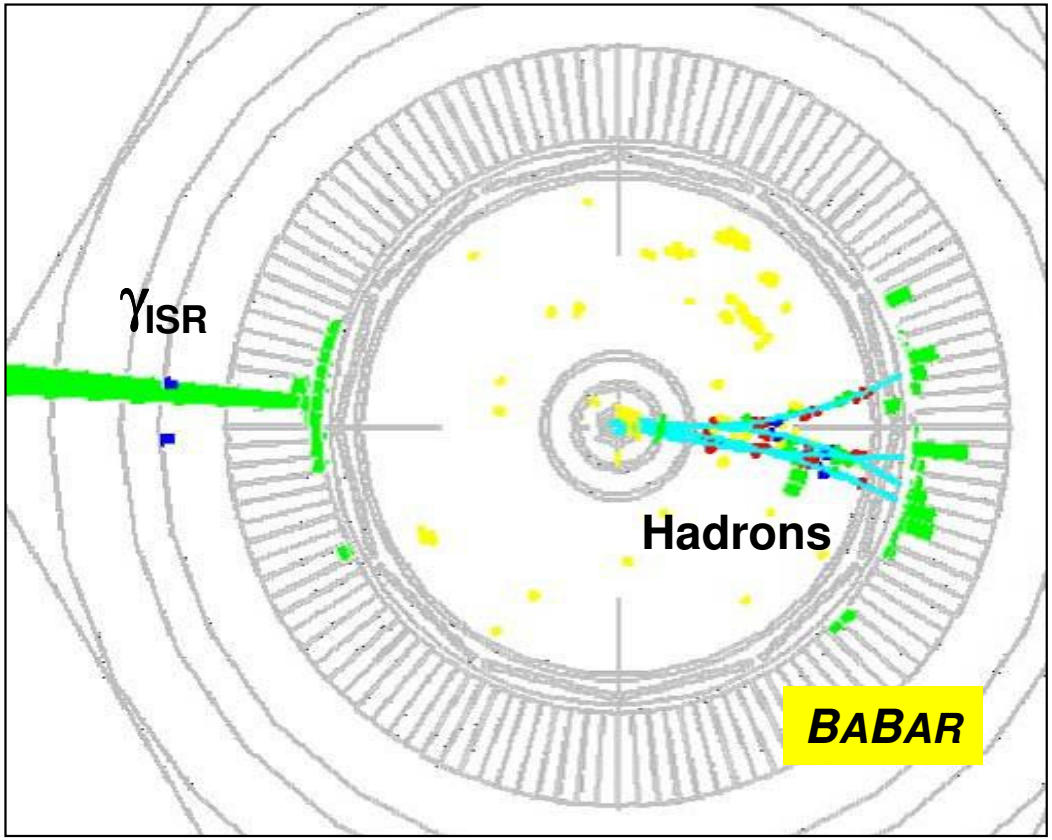
After including $\pi^+\pi^-$-data with high accuracy from KLOE, CMD-2 and SND to the a_μ^{had} calculation:

$\rightarrow$ Uncertainty of a_μ^{had} dominated by energy range 1-2 GeV

$\rightarrow$ 4π-channels

Using ISR events from BaBar





Selection criteria:

- Photon > 3 GeV for identification of ISR events (tagged method)
- Typical topology:
  $\gamma_{ISR} \leftrightarrow$ hadrons

- Excellent momentum resolution using kinematical fit
- Slow particles easier to get because of the boost in lab system
  $\rightarrow$ More precise measurement with higher efficiency near threshold !
- Simultaneous measurement from threshold up to 4.5 GeV/c^2, reduced point-to-point uncertainties

Extraction of σ ($e^+e^- \rightarrow$ hadrons)

dN(hadrons γ_{ISR}) / $dM_{hadrons}$
with acceptance cuts

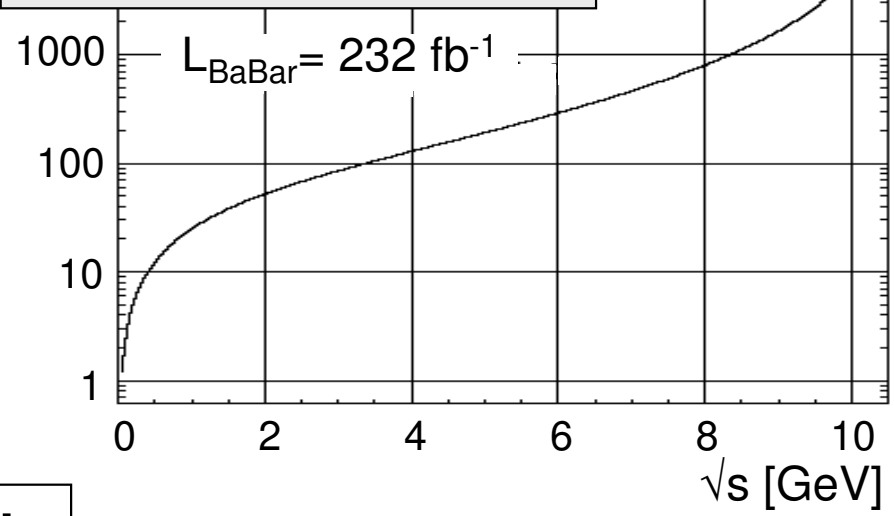
Efficiencies, background
functions dependent of $M_{hadrons}$

Normalization with **luminosity** and **radiator function** from $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$

Analysis

Total cross section
$\sigma(e^+e^- \rightarrow$ hadrons)

ISR Luminosity L^{ISR}
(pb^{-1} / 0.1 GeV)



Avoid problems with:

- ISR photon efficiency
- integrated luminosity
- radiator function (model dep.)
- additional ISR photons
- vacuum polarization

Syst. error: 2-3 % → <1%

Exclusive hadronic ISR channels

measured with BaBar

Published:

- 2 mesons: $e^+e^- \to \phi f_0(980)$
- 3 mesons: $e^+e^- \to \pi^+\pi^-\pi^0$, $K^+K^-\eta$, $K^+K^-\pi^0$, $K^0_S K^{+-}\pi^{-+}$ PRD 70 (2004) 072004 PRD 77 (2008) 092002
- 4 mesons: $e^+e^- \to 2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $2(K^+K^-)$
- 5 mesons: $e^+e^- \to 2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$
- 6 mesons: $e^+e^- \to 3(\pi^+\pi^-)$, $3(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$ PRD 76 (2007) 092005
- 2 baryons: $e^+e^- \to p\bar{p}$ PRD 73 (2006) 012005 PRD 73 (2006) 052003
- 2 hyperons: $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$ PRD 76 (2007) 092006

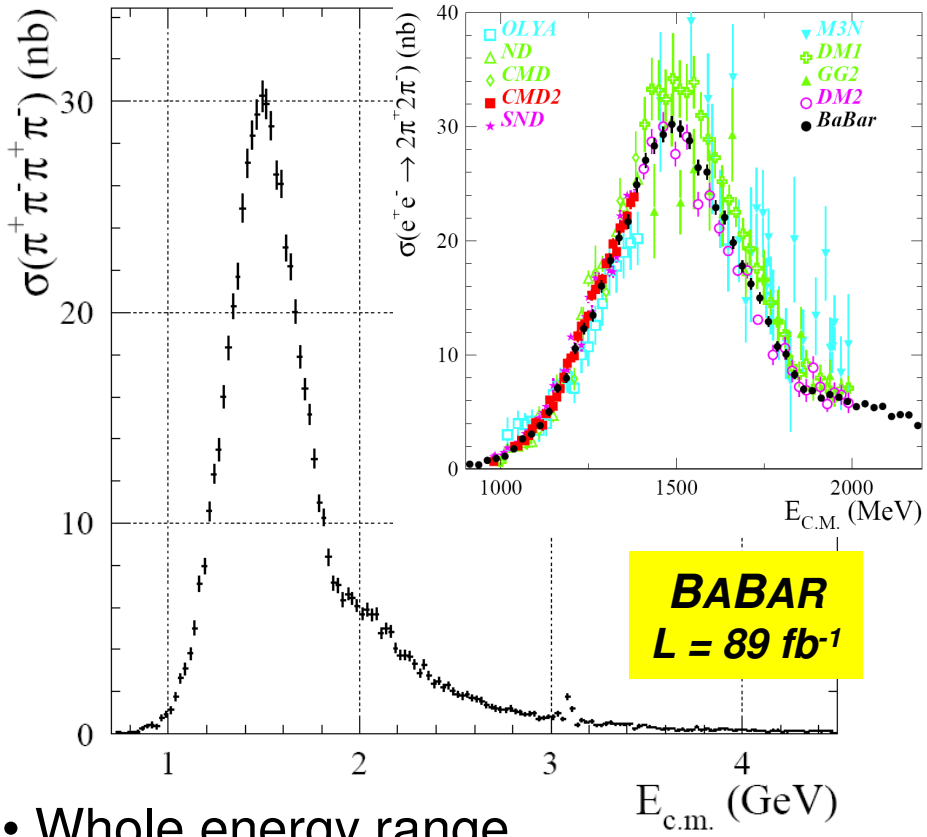
Preliminary analysis:

- 2 mesons: $e^+e^- \to \pi^+\pi^-$
- 4 mesons: $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ / $K^+K^-K^+K^-$

PRD 71 (2005) 052001
PRD 76 (2007) 012008

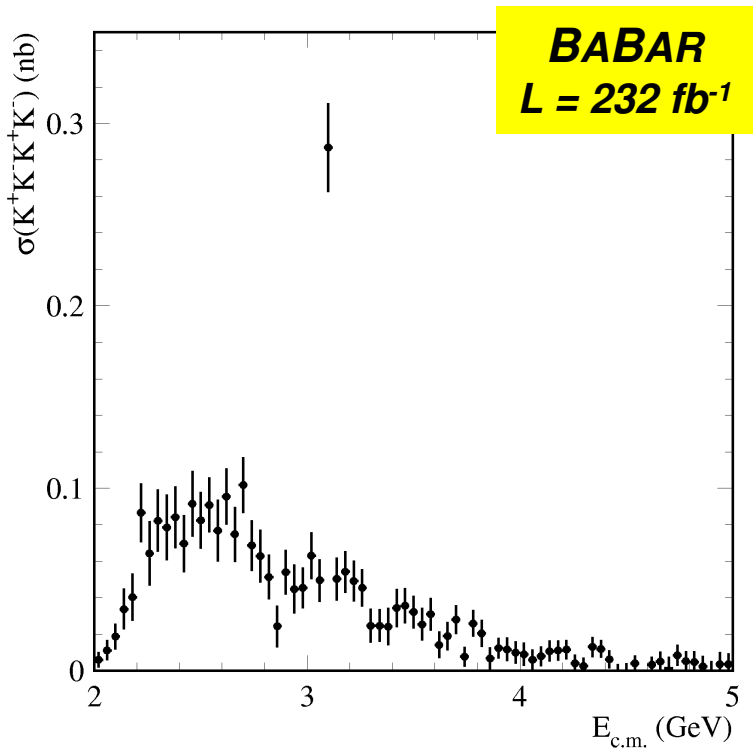
$\pi^+\pi^-\pi^+\pi^-$ final state



- Whole energy range
- Best measurement above 1.4 GeV
- Syst. err.: 5% ($1 < m_{4\pi} < 3$ GeV), 12% ($m_{4\pi} < 1$ GeV), 16% ($m_{4\pi} > 3$ GeV)
- Resolution 6.2 - 7.5 MeV/c²

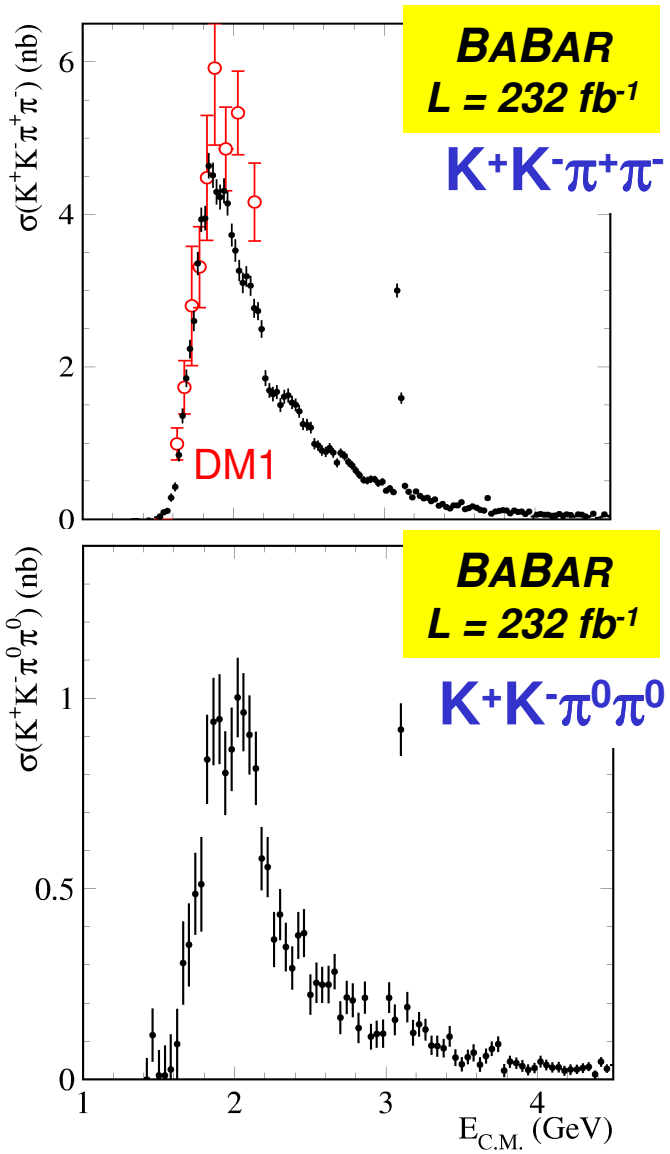
$K^+K^-K^+K^-$ final state

- First measurement
- Very good particle ID at BaBar
- Syst. err.: 9% - 13%
- Resolution 3.0 - 4.7 MeV/c²

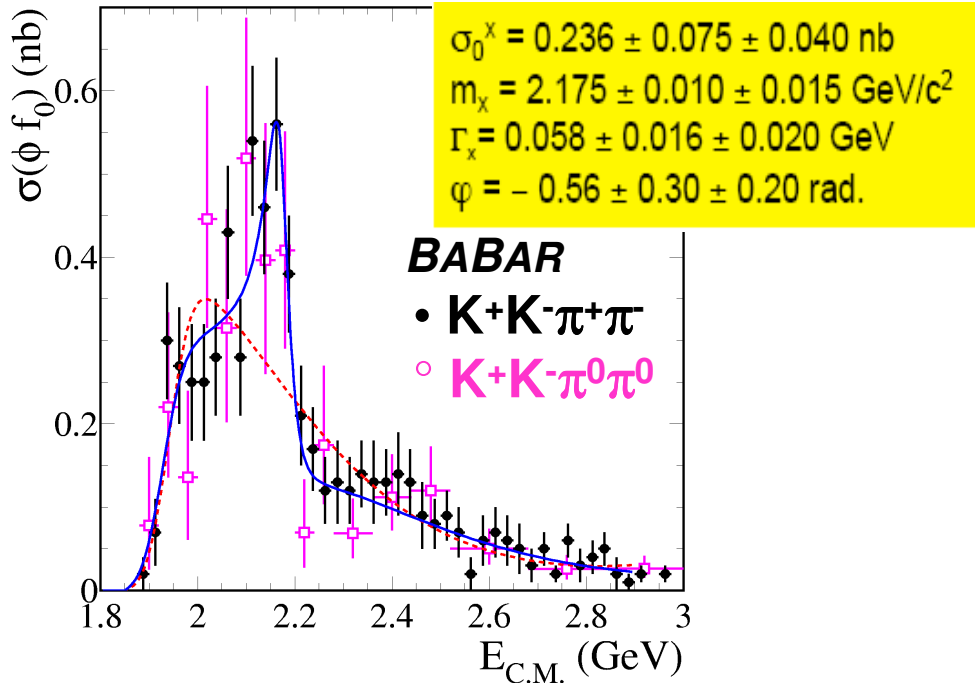


$e^+e^- \to K^+K^-\pi\pi$

PRD 74 (2006) 091103
PRD 76 (2007) 012008

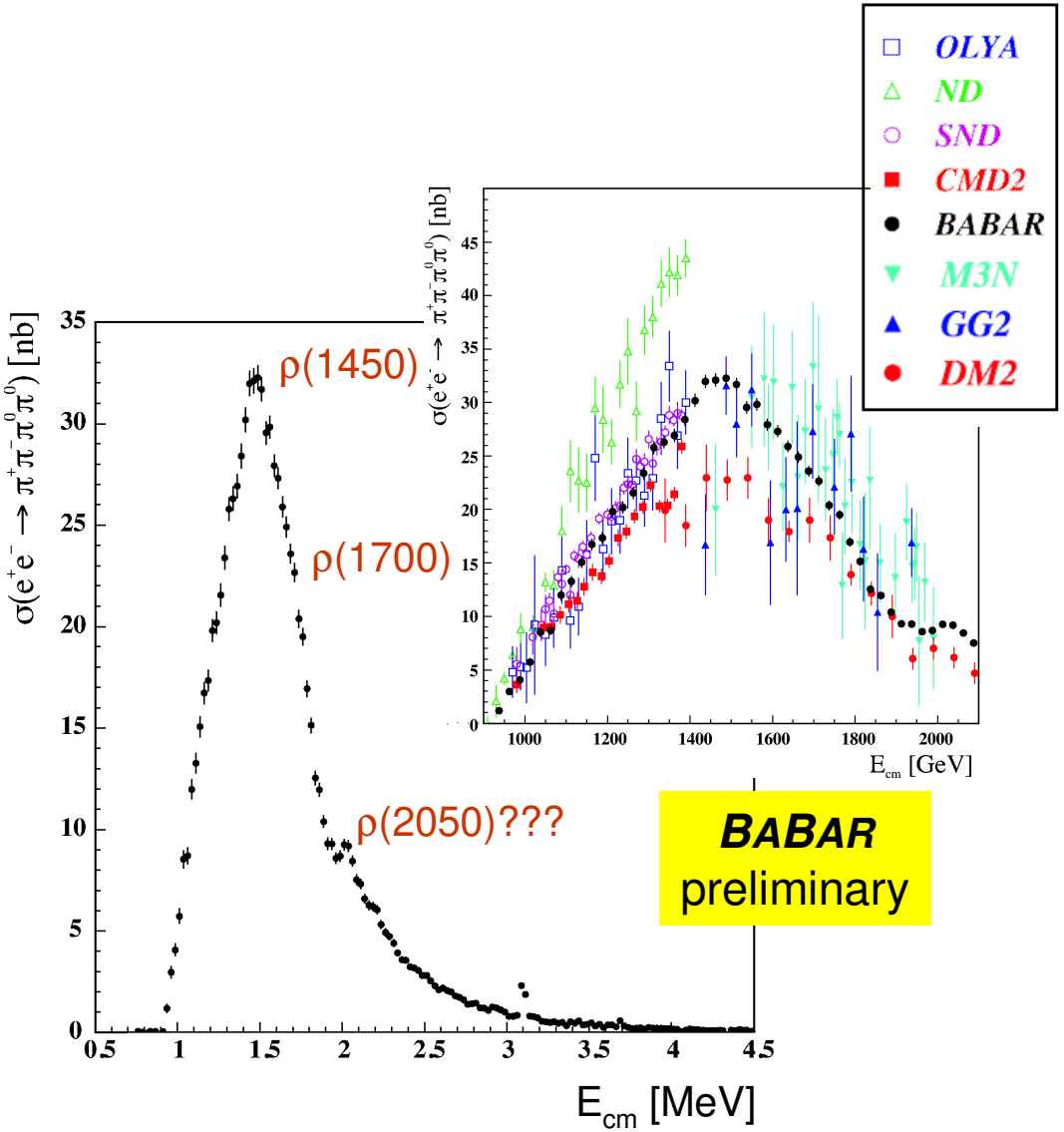


$e^+e^- \to \phi\, f_0(980) \to K^+K^-\pi\pi$



- New measurements with big energy range
- Syst. err.: 7-9% and 10-14%, resp.
- Resolution: 4.2-5.5 and 8.8-11.2 MeV/c^2, resp.
- New resonance found with $J^{PC} = 1^{--}$?
  mass: 2.175 GeV width: 58 MeV
  Strangeness partner of Y(4260) ?

$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ (preliminary)

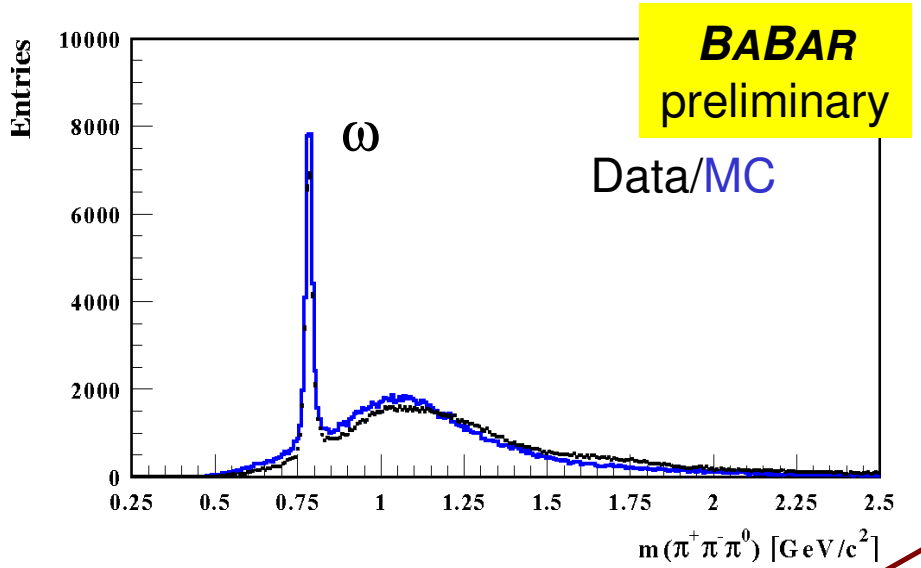


- Data from threshold up to 4.5 GeV
- Syst.err.: 8-10% (14% above 3 GeV)
- < 1.4 GeV: Good agreement with SND (syst. err. 10%)

  → New preliminary CMD-2 data: better agreement with BaBar/SND
- > 1.4 GeV: Better accuracy (DM2, 20%)
- > 2.4 GeV: First measurement

- Hints of ρ(1450) and ρ(1700)
- Peak at 2.05 GeV/c^2
- J/ψ and ψ(2S)

Invariant 3π masses



Approx. half of the events are $\omega\pi^0$

Non-$\omega\pi^0$ events:

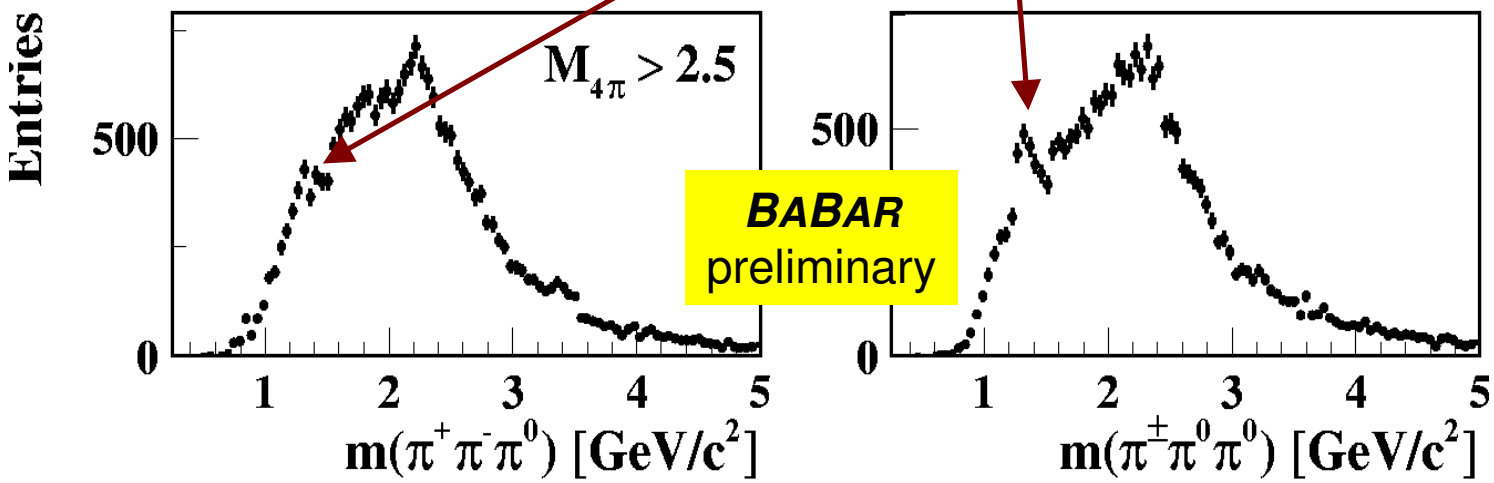
Bump at 1.3 GeV/c² for

$M_{4\pi} > 2.5$ GeV/c²

$m(\pi^+\pi^-\pi^0) \rightarrow a_1(1260)^0$

$m(\pi^\pm\pi^0\pi^0) \rightarrow a_1(1260)^\pm$

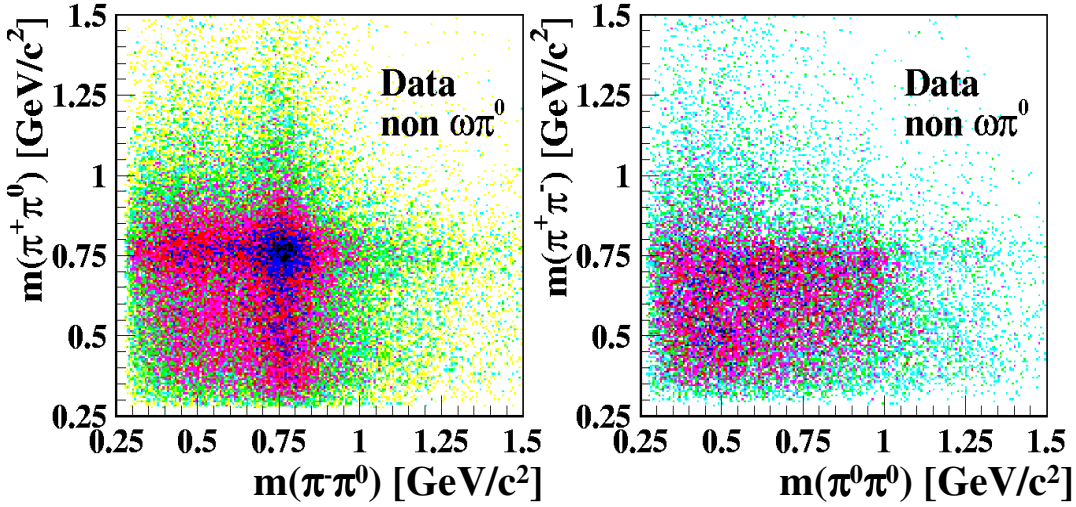
Non-$\omega\pi^0$ events:



Expectation from old experiments:

→ Non-$\omega\pi^0$ events dominated by $a_1^\pm$ resonance

Invariant 2π masses (non-$\omega\pi^0$ events)



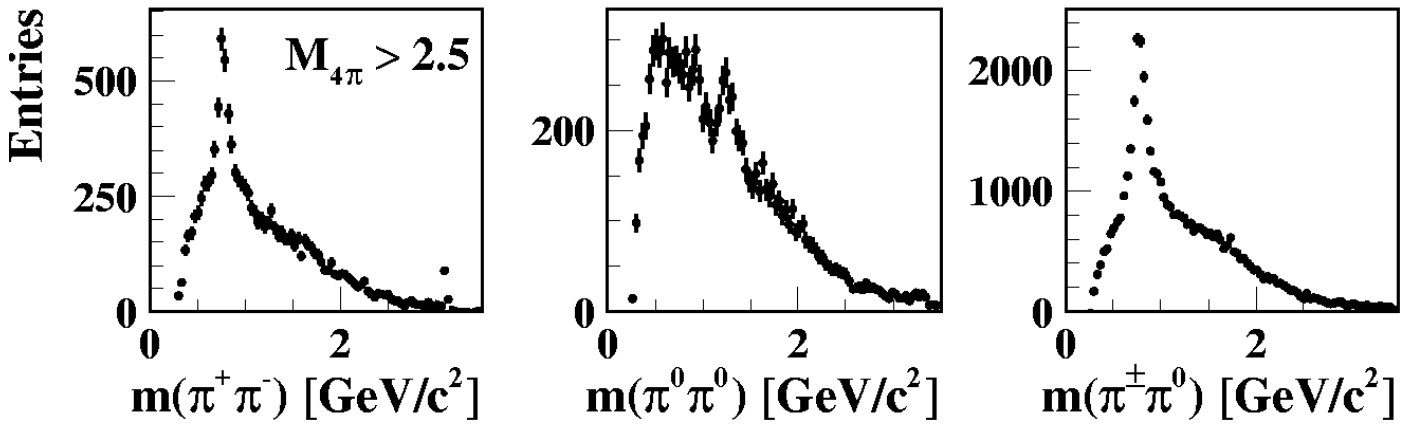
BABAR
preliminary

Scatter plot:

- Band of $\rho^\pm$, ρ^0 and $f_0(980)$
- Strong contribution of $\rho^+\rho^-$ (new!)
- $\rho^0 f_0(980)$ signal

Projections:

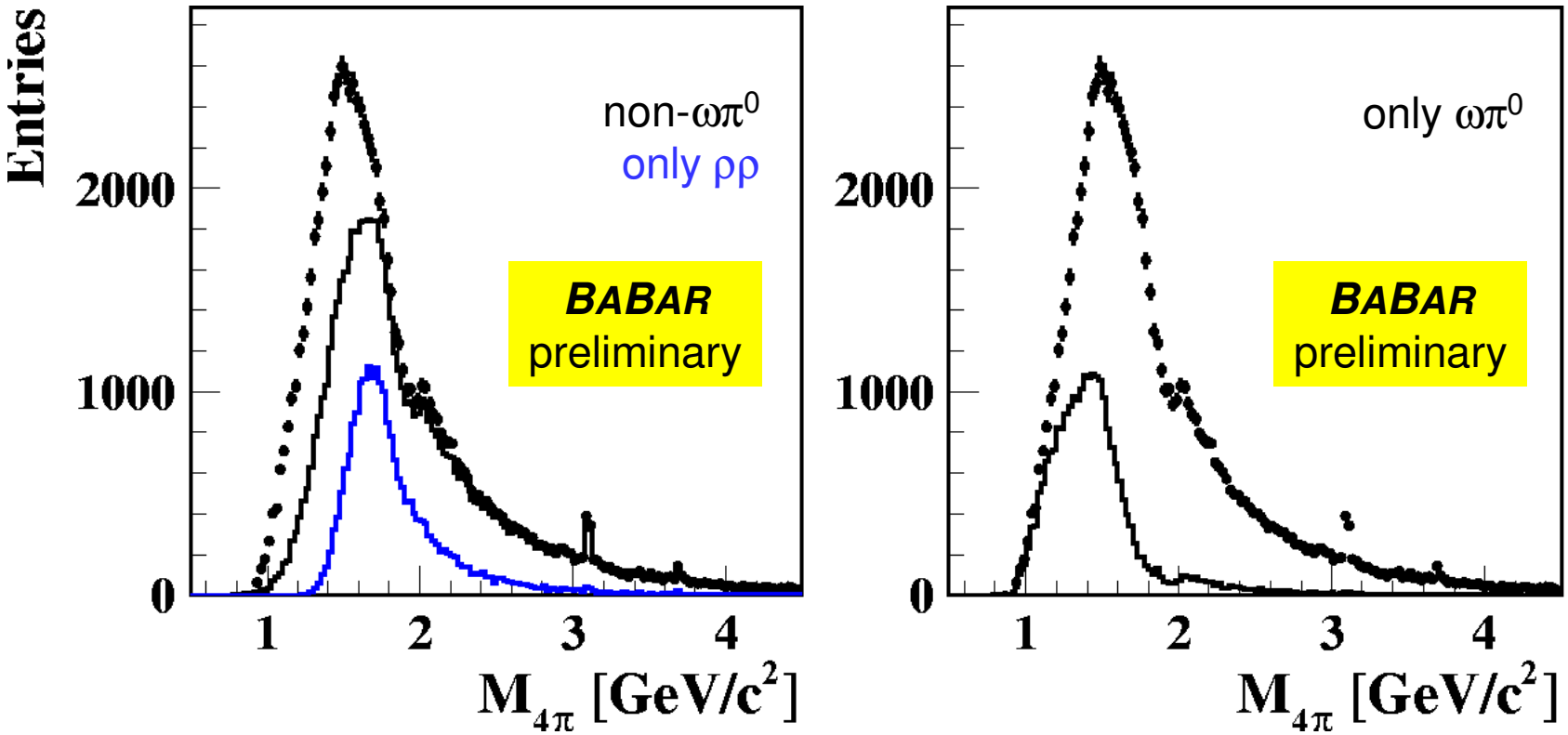
- Peaks of $\rho^\pm$, ρ^0, J/ψ and $f_2(1270)$
- $f_0(980)$ visible as a shoulder



Partial Wave Analysis needed !!

Invariant 4π mass

- non-$\omega\pi^0$ events shifted to large E_{cm}
- Strong $\rho\rho$ contribution (blue)
- $\omega\pi^0$ events shifted to low E_{cm}



$e^+e^- \rightarrow \pi^+\pi^-$ (preliminary)

- $\pi^+\pi^-$ contributes 73% of a_μ^{hadr}
- Dominant uncertainty, aim: precision < 1%

- Using data of integrated luminosity 230.8 fb^{-1}
- Many checks done, some are still missing (e.g. FSR in $\mu^+\mu^-\gamma_{ISR}$)
  → Systematic uncertainty at ρ-peak ~0.6%

- Experimental data: CMD-2 0.8%, SND 1.5% and KLOE (ISR) 0.8%

→ Wait for the final results !!

Two-Photon physics

Study of $e^+e^- \to e^+e^- \gamma\gamma^*$ with $\gamma\gamma^* \to \pi^0$ or $\gamma\gamma^* \to \eta_c$

→ Allows to test hadronic models needed for the hadronic Light-by-Light-contribution for g-2

→ Test of the validity of pQCD for low Q^2

Pion Distribution amplitudes $\Phi_\pi(x,Q^2)$ important for many QCD processes

- Q^2 dependence can be calculated
- x dependence can be extracted from form factor measurements

(x: fraction of the π^0 momentum carried by one of the quarks)

Test of models

- Vector Meson Dominance
- Perturbative QCD

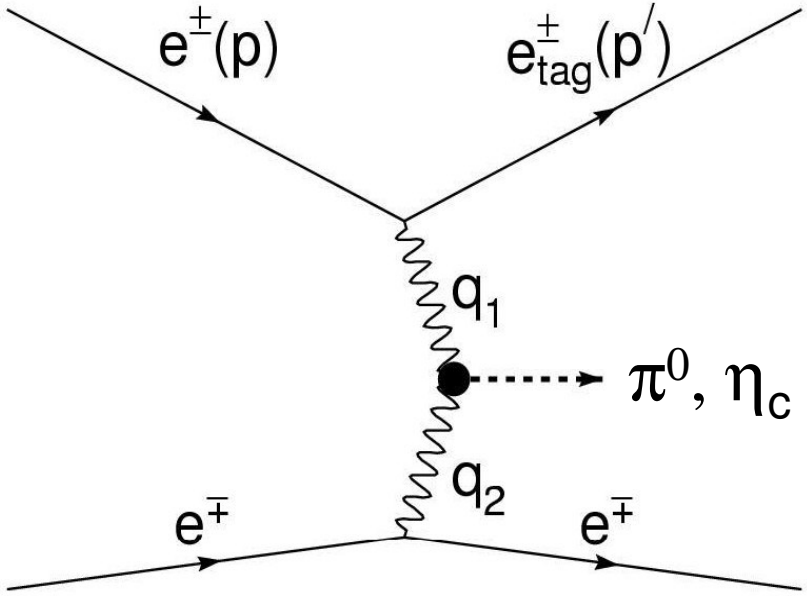
Single Tag Method

Selection criteria

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

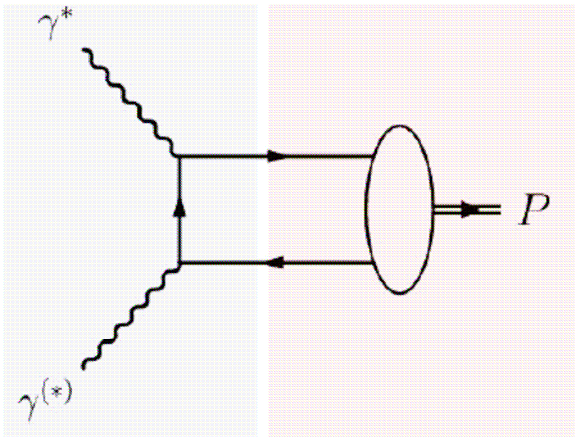
Momentum transfer

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



Differential cross section

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 pion distribution amplitude for $q\bar{q} \rightarrow \pi$

x: fraction of the π^0 momentum carried by one of the quarks

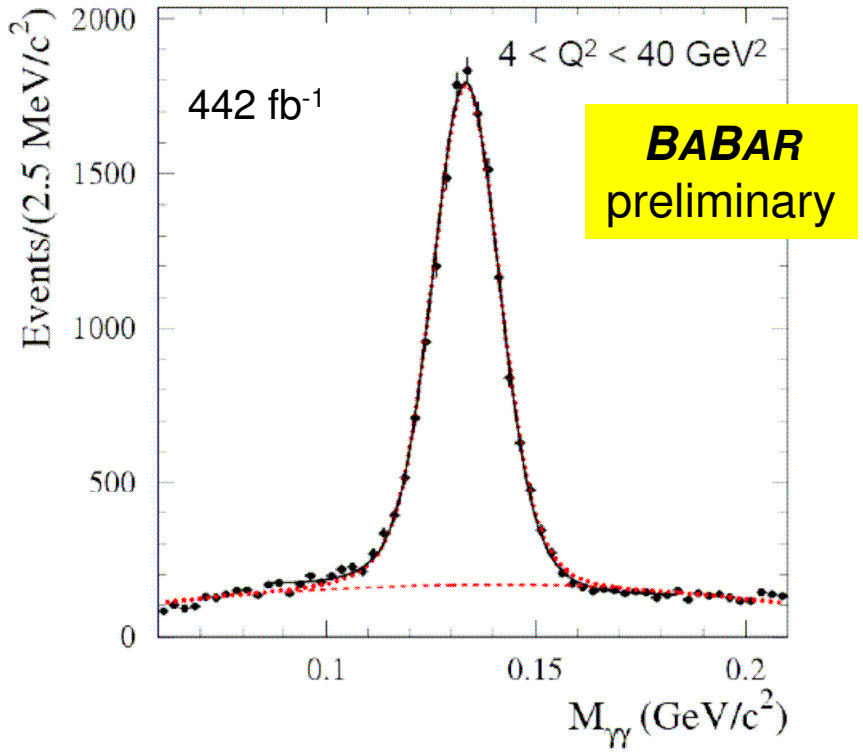
Status:

- Dependence on x for $\Phi_\pi(x,Q^2)$ unknown
- Experimental data on $F(Q^2)$ needed

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

arXiv:0905.4778
Submitted to PRD

$\gamma\gamma$ mass spectrum



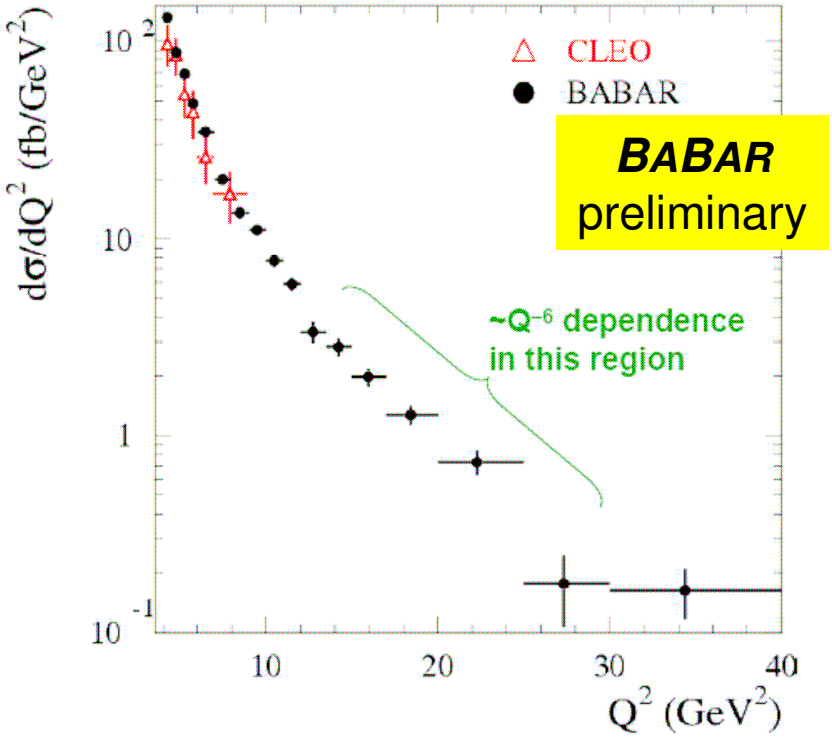
Fit function: sum of signal+background

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

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

17 intervals in Q^2

Differential cross section

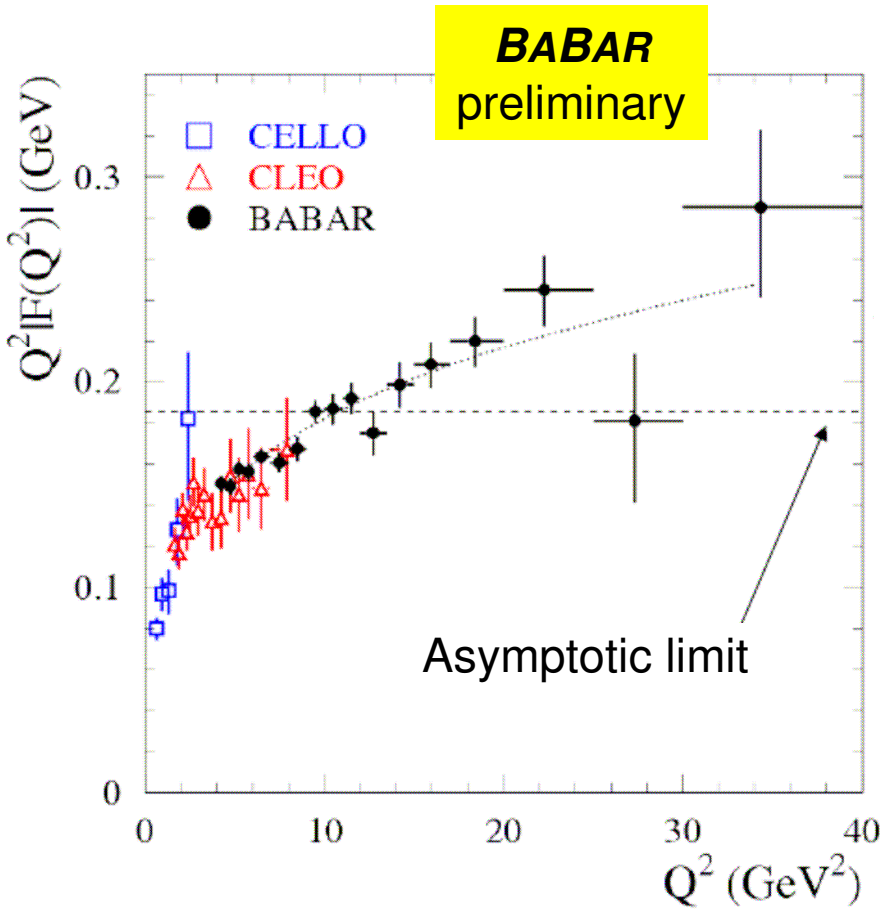


Main background:

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

Q^2 independent syst. err.: 3%

The π^0 Transition Form Factor



Systematic uncertainty: 2.3%

- Whole range of Q^2 from 4 - 40 GeV^2
- Reasonable agreement with old data
- Much better accuracy

Fit to the BaBar data:

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

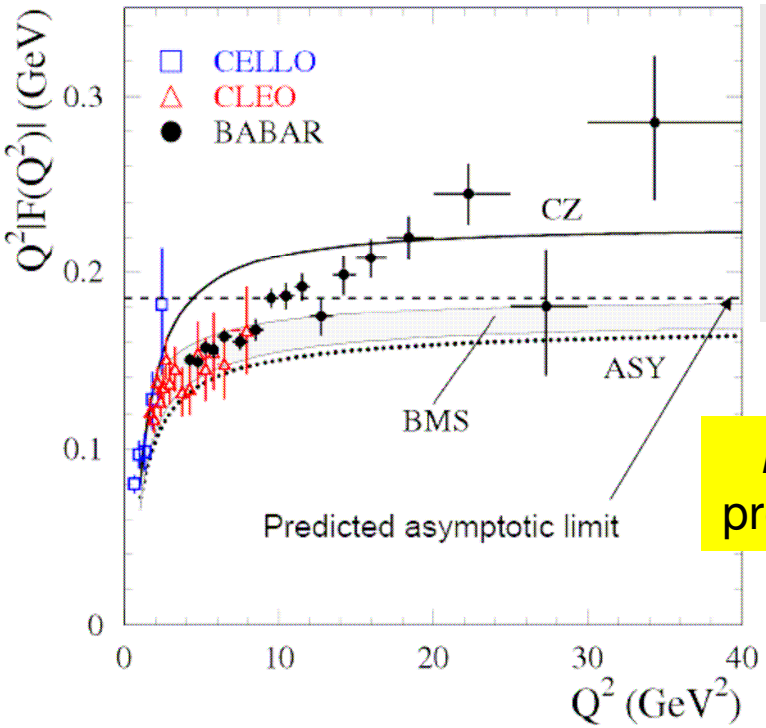
with

$A = 0.182 \pm 0.002$ GeV and
$\beta = 0.25 \pm 0.02$

→ Data: $Q^2|F(Q^2)| \sim 1/Q^2$
LO pQCD: $Q^2|F(Q^2)| \sim$ const.
in the asymptotic limit

Comparison with theoretical models

Before Publication



CZ: Chernyak-Zhitnitsky DA

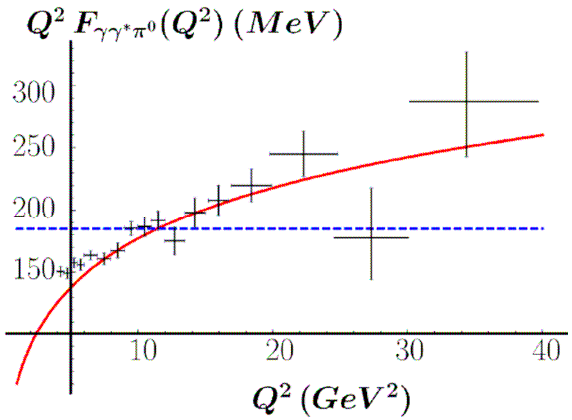
ASY: Asymptotic DA

BMS: DA from QCD sum roles with non-local condensates

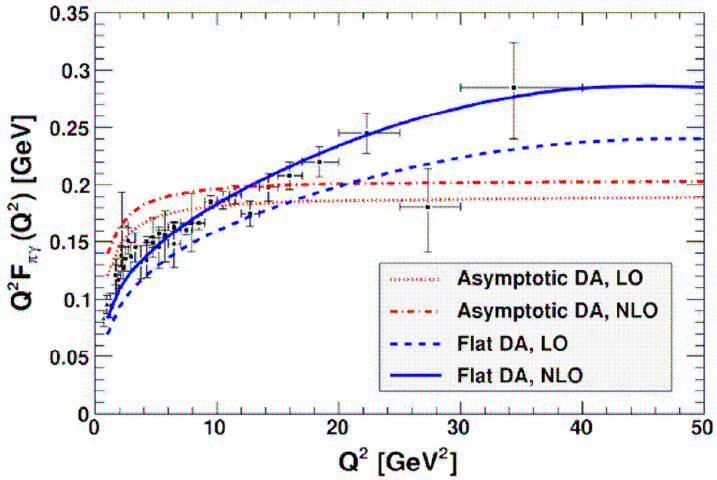
BABAR preliminary

After Publication

A.V. Radyuskin



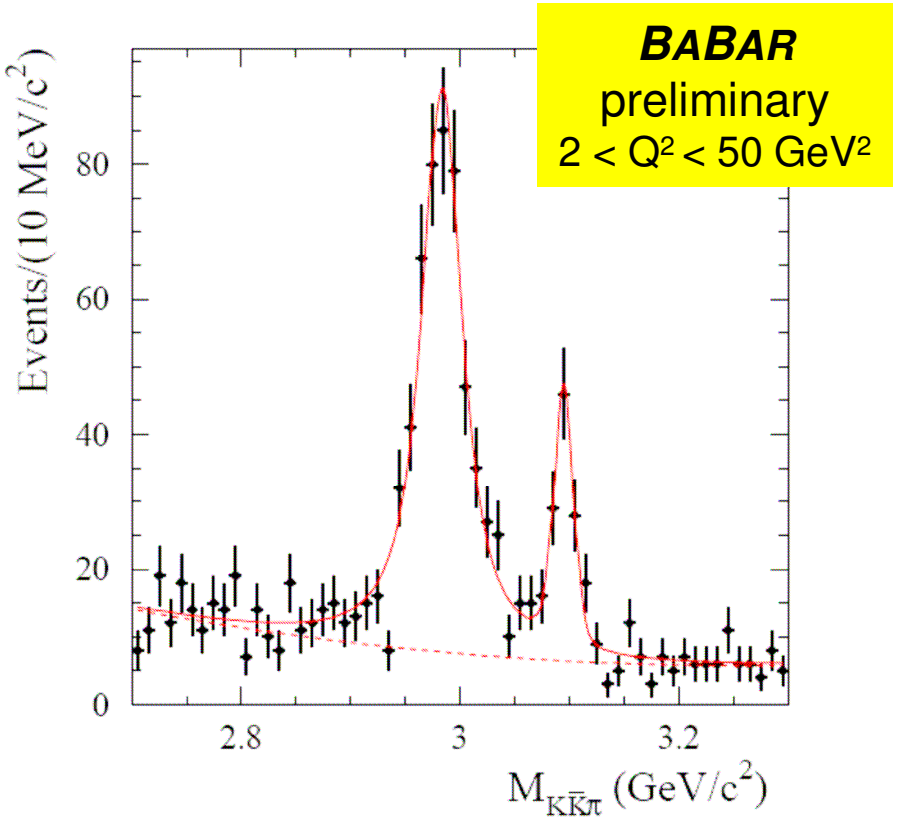
H.N.Li & S.Mishima



- Most models do not describe the data
- Data exceed the asymptotic limit for $Q^2 > 10$ GeV^2

→ Higher order pQCD and power corrections needed !!

$e^+e^- \to e^+e^-\eta_c$ with $\eta_c \to K_s K^+\pi^-$



N = 530 ± 41 ± 17

m = 2985.7 ± 2.0 MeV/c²

PDG: 2980.3 ± 1.2 MeV/c²

Γ = 31.9 ± 4.3 MeV/c²

PDG: 26.7 ± 3.0 MeV/c²

Single Tag Method

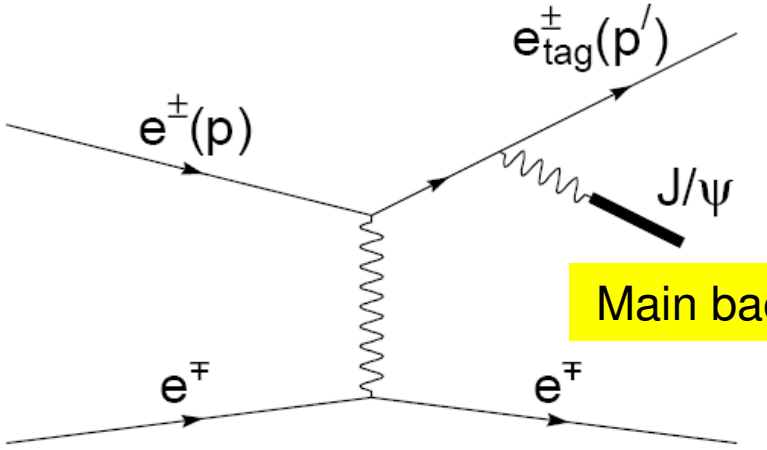
Peaking Background:

$e^+e^- \to e^+e^- J/\psi$ with

$J/\psi \to \eta_c \gamma \to K_s K^+\pi^- \gamma$

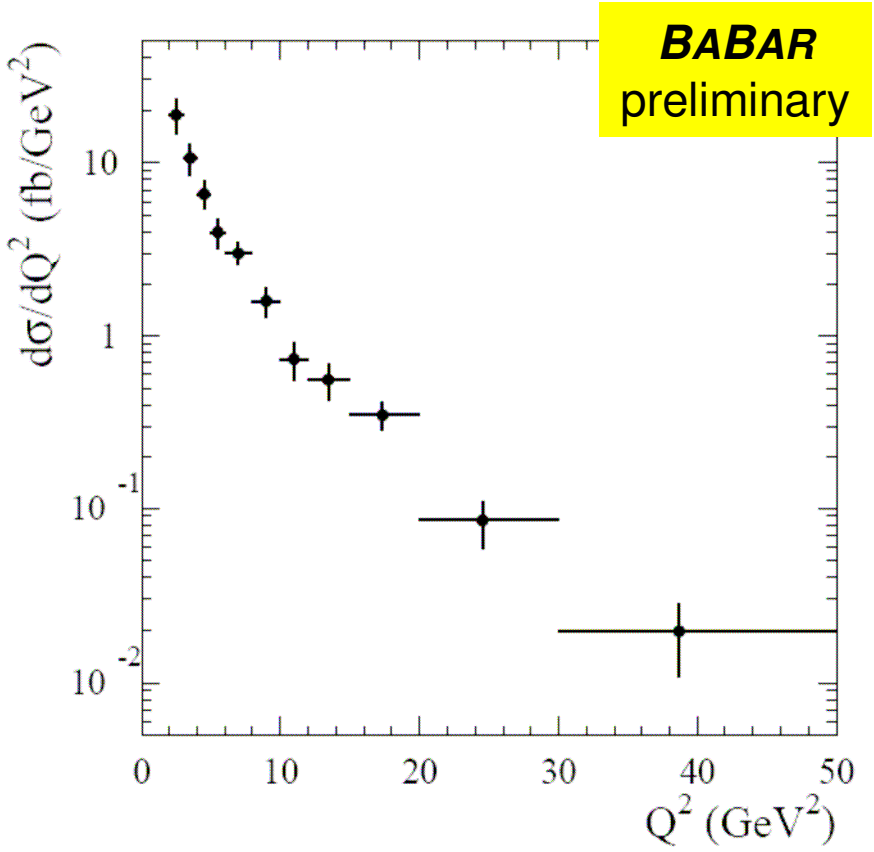
$Q^2 < 10$ GeV²: ~ 1%

$Q^2 \approx 30$ GeV²: ~ 5%



Main backround

$e^+e^- \rightarrow e^+e^-\eta_c$ cross section



Q^2 independent syst. error: 6.7%

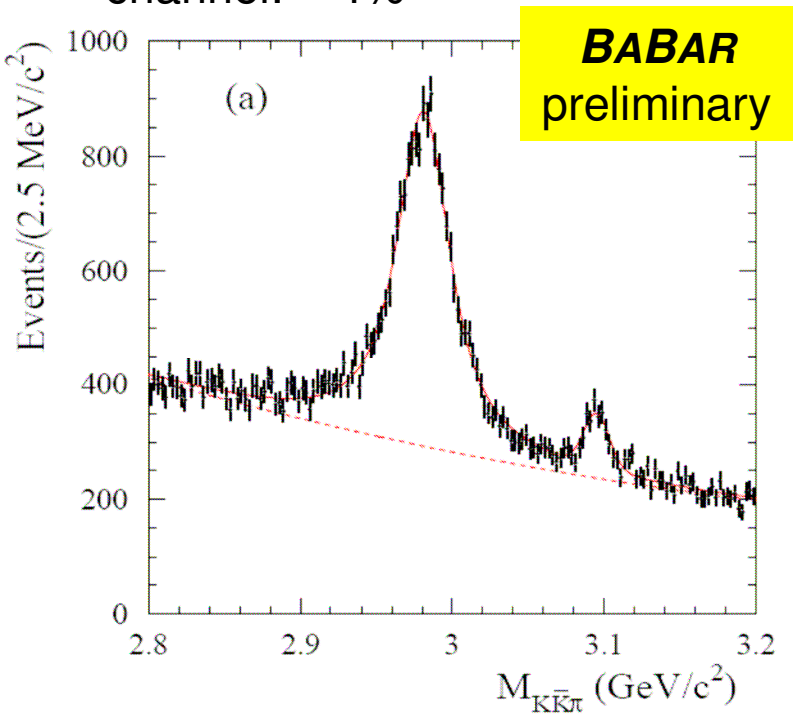
$e^+e^- \to e^+e^-\eta_c$ $F(Q^2 = 0)$

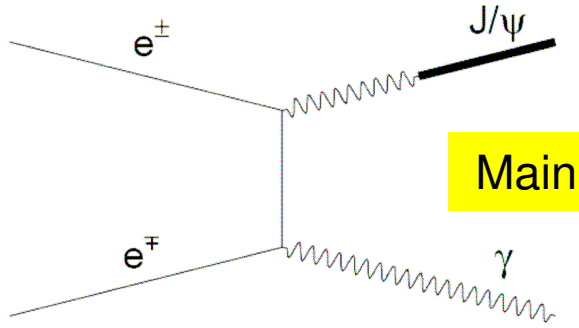
Measured with No Tag Method:

Both e^+ and e^- are not detected and quasi-real ($Q^2 \approx 0$)

Main background:

- Two-Photon
- ISR
- Peaking background from ISR-J/ψ-channel: ~ 4%





Main backround

$N = 13890 \pm 320 \pm 670$

$m = 2982.2 \pm 0.4 \pm 1.5$ MeV/c^2

PDG: 2980.3 ± 1.2 MeV/c^2

$\Gamma = 31.7 \pm 1.2 \pm 0.8$ MeV/c^2

PDG: 26.7 ± 3.0 MeV/c^2

$\sigma = 0.911 \pm 0.021 \pm 0.074$ pb

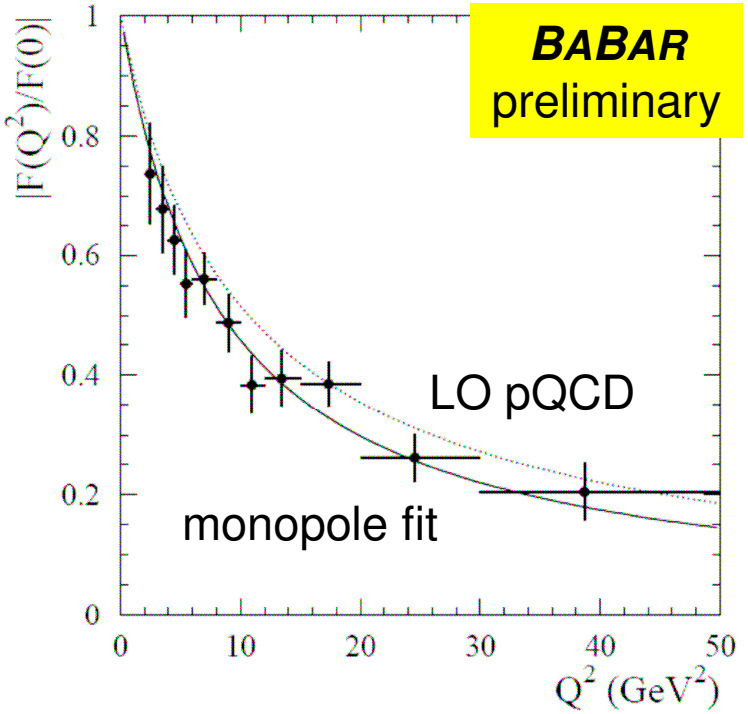
$\Gamma(\eta_c \to \gamma\gamma)\, B(\eta_c \to KK\pi) =$

$0.379 \pm 0.009 \pm 0.031$ keV

PDG: 0.44 ± 0.04 keV

CLEO: $0.407 \pm 0.022 \pm 0.028$ keV

The η_C Transition Form Factor



Monopole Fit:

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

$\rightarrow$ $\Lambda = 8.5 \pm 0.6 \pm 0.7\ \mathrm{GeV}^2$

- No contradiction to Vector Dominance Model ($\Lambda = m^2_{J/\psi} = 9.6\ \mathrm{GeV}^2$)
- Data below LO pQCD

Q^2 independent syst. err.: 4.3%

Conclusion

- BaBar is providing a huge disversity of results beside B-physics

- ISR physics
  - Very important for the theoretical predictions of $(g_\mu - 2)$
  - Impact of the running fine structure constant $\alpha_{QED}(M_Z)$ and the Higgs mass
  - Measurements over the entire range from threshold up to 5 GeV/c^2
  - Many measurement done for the first time with high accuracy

- Two-Photon physics
  - Shows deviation from the expected behaviour for Q^2 >10 GeV^2 (π^0)
    $\rightarrow$ Confirmation needed !!
  - VDM suitable for the description of the η_c transition form factor
  - Have impact on the understanding of pQCD and Light-by-Light-Scattering
  - Measured for the first time for Q^2 > 10 GeV^2

Outlook

- ISR physics

  Finished soon:
  - 2π analysis (expected for fall, syst. error < 1%)
  - $2\pi 2\pi^0$ analysis with whole dataset (syst. error 5%)

  Expected Updates:
  - 4π channel with the whole dataset (syst. error 3%)
  - Other 4 meson channels in review

  Further Projects:
  - Channels with >4 mesons become important
  - Inclusive measurement of the hadronic cross section
  - Partial wave analysis for the 4π channels

- Two-Photon physics
  - $2\pi^0$ analysis in progress
  - Other final states will be explored