

Initial State Radiation results at *BABAR*: R-measurement via exclusive hadronic final states

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$(g - 2)_\mu$: Quo vadis?
Mainz
April 8, 2014



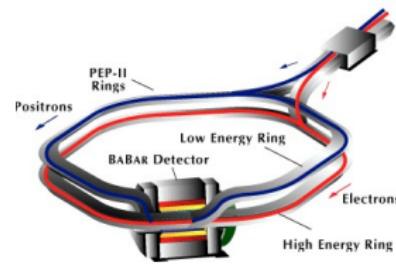
PEP-II and the *BABAR* detector at SLAC



main purpose: B -physics \rightarrow CP violation

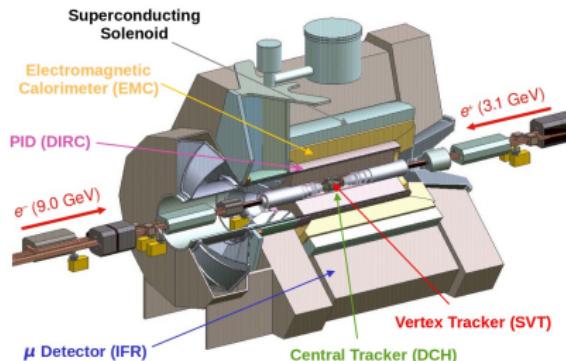
PEP-II

- asymmetric e^+e^- -colliders
- $\sqrt{s} = 10.58 \text{ GeV} \Rightarrow \Upsilon(4S)$
 \Rightarrow above $B\bar{B}$ -threshold



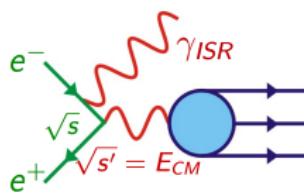
BABAR detector

- multi purpose detector
- data taking: 1999 – 2008:
- $\mathcal{L}_{int} = 531 \text{ fb}^{-1}$
 $\mathcal{L}_{int}(\Upsilon(4S)) = 454 \text{ fb}^{-1}$
 $\approx 4.7 \cdot 10^8 B\bar{B}$ pairs



BUT, there is more...

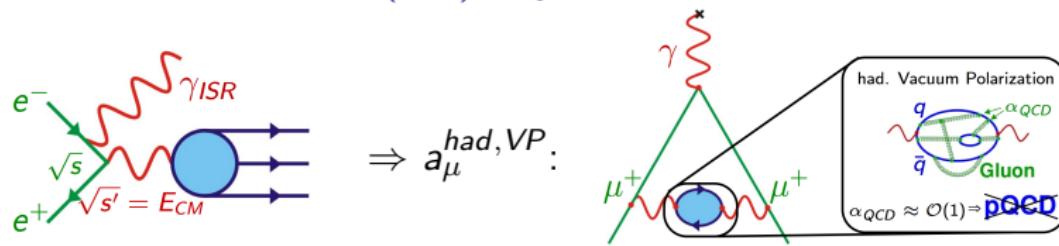
Initial State Radiation (ISR)-Physics



- **high energy** $\gamma_{ISR} \Rightarrow$ lower cms energy
- produce vectors: $J^{PC} = 1^{--}$
- measure σ_{had}

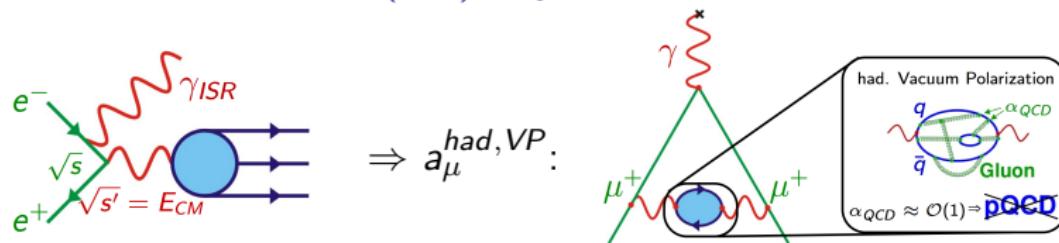
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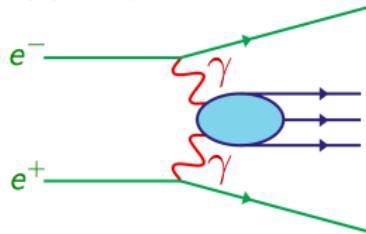


BUT, there is more...

Initial State Radiation (ISR)-Physics



$\gamma\gamma$ -Physics

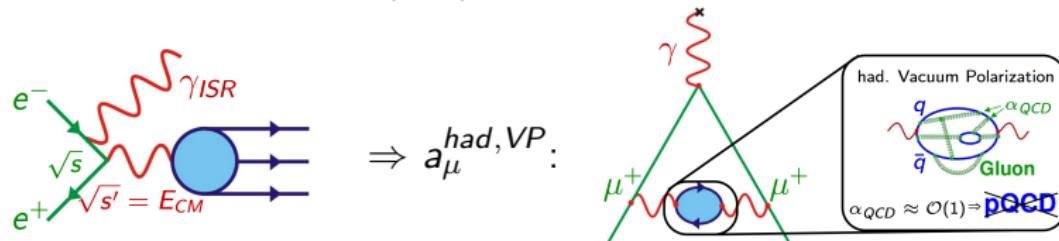


- produce $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$
- measure **meson photon transition FFs**

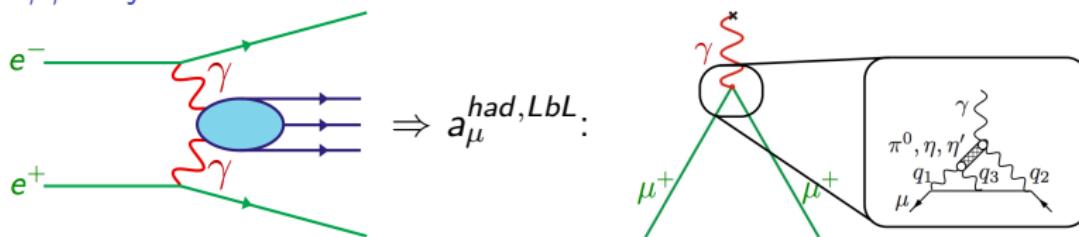
\Rightarrow low-energy hadron Physics (*u-d-s*-quarks) at *BABAR*

BUT, there is more...

Initial State Radiation (ISR)-Physics

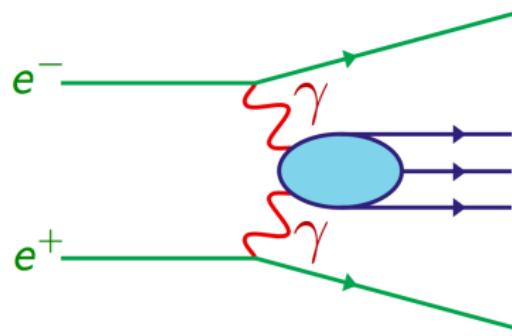


$\gamma\gamma$ -Physics

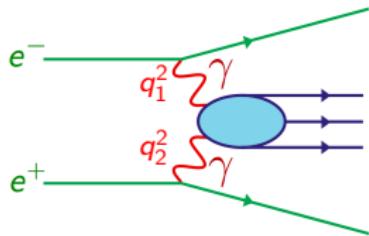


\Rightarrow low-energy hadron Physics (*u-d-s*-quarks) at *BABAR*

Meson photon transition form factors for $a_\mu^{had,LbL}$



Selection for meson-photon TFF at B -Factories

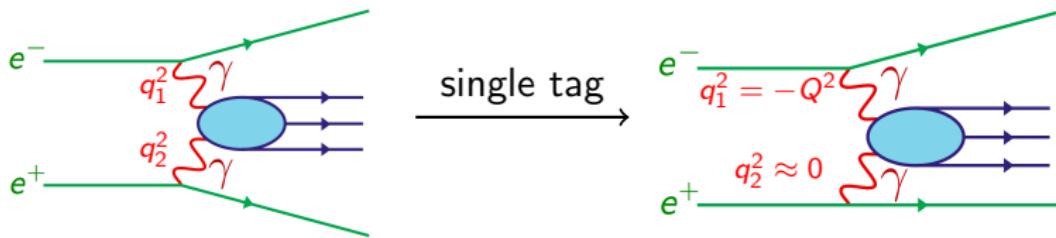


Amplitude for $\gamma\gamma^* \rightarrow P$ transition contains unknown function:
transition form factor (TFF): $F(q_1^2, q_2^2)$

$F(q_1^2, q_2^2)$ at B -factories in single tagged analyses:

- one e^\pm along beamline $\Rightarrow q_2^2 \approx 0$
- other e^\pm detected $\Rightarrow Q^2 = -q_1^2 > 4 \text{ GeV}^2$
- pseudoscalar (P) meson fully reconstructed
 \Rightarrow kinematic constraints to reject background

Selection for meson-photon TFF at B -Factories

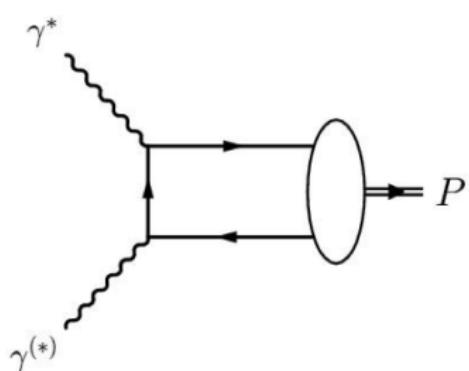


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Why is the form factor interesting?



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

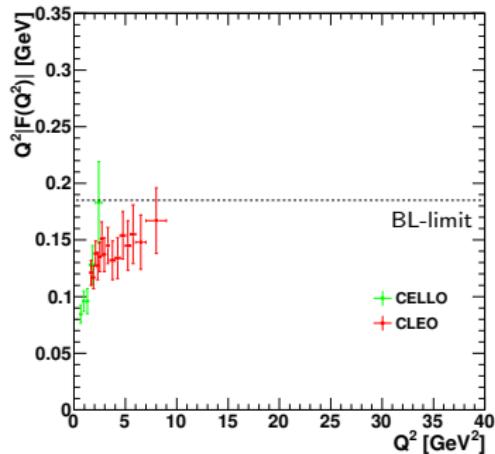
- ϕ : Meson distribution amplitude
- T : Hard scattering amplitude (pQCD)
- x : fraction of meson momentum carried by one of the quarks

Meson distribution amplitude ϕ

- important role in theoretical description of many QCD processes:
 $\gamma^* \rightarrow \pi^+ \pi^-$, $\gamma \gamma \rightarrow \pi \pi$, $B \rightarrow \pi l \nu, \dots$
- shape (x dependence) not known
- evolution with Q^2 predicted by QCD

\Rightarrow test ϕ shape models with $F(Q^2)$ data!

π^0 -photon transition form factor

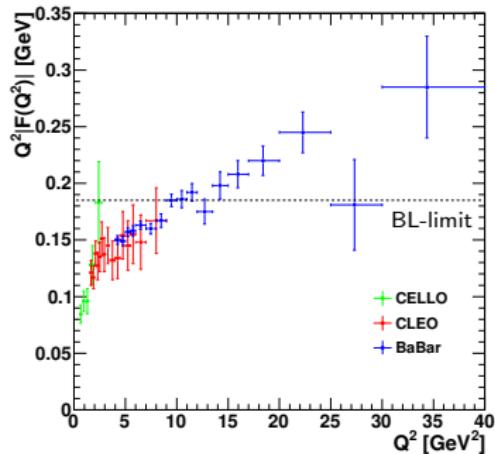


asymptotic limit from pQCD:

$$\lim_{Q^2 \rightarrow \infty} Q^2 F(Q^2) = \sqrt{2} f_\pi$$

[Brodsky, Lepage, Phys. Lett. B **87**, 359 (1979)]

π^0 -photon transition form factor



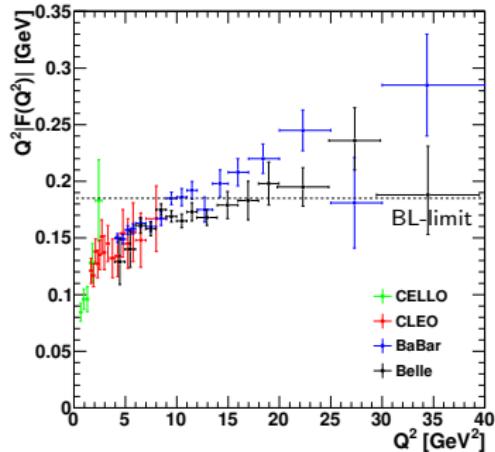
BABAR measurement:

- systematic uncertainty: 3-6%
- $4 \text{ GeV}^2 < Q^2 < 9 \text{ GeV}^2$: reasonable agreement with CLEO
- $Q^2 > 10 \text{ GeV}^2$:
pQCD: $\lim_{Q^2 \rightarrow \infty} Q^2 F(Q^2) = \sqrt{2} f_\pi$
 \Rightarrow asymptotic limit exceeded!

\Rightarrow triggered a lot of theoretical work

> 200 citations since 2009

π^0 -photon transition form factor



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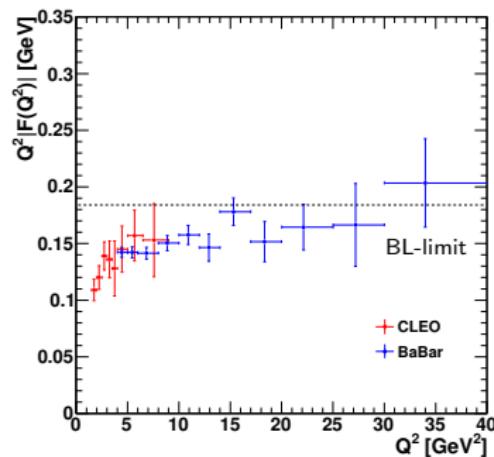
\Rightarrow triggered a lot of theoretical work and a new measurement at Belle:

- disagreement with *BABAR* at large Q^2
- BUT: also exceeds asymptotic limit
- slope in better agreement with pQCD

\Rightarrow need more data/experiments

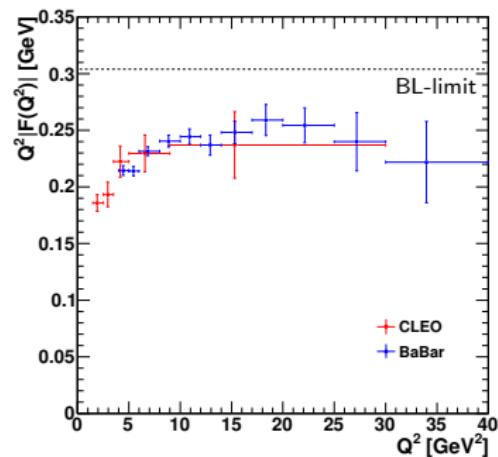
η/η' -photon transition form factors

$$\eta \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \rightarrow \gamma\gamma$$



systematic uncertainty: 2.9%
 η -FF approaches asymptotic limit

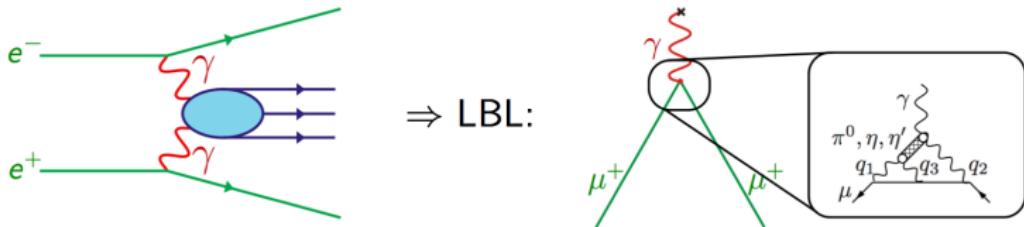
$$\eta' \rightarrow \pi^+ \pi^- \eta, \eta \rightarrow \gamma\gamma$$



systematic uncertainty: 3.5%
 η' -FF below asymptotic expectation

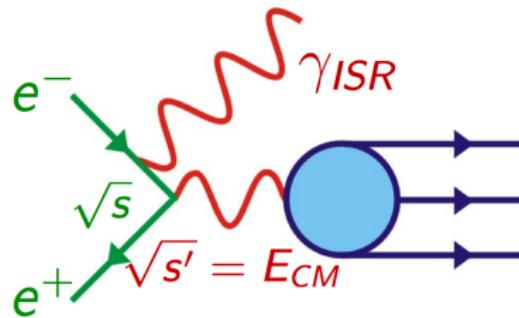
Status of $g_\mu - 2$: had. LbL

$$a_\mu^{\text{LBL}} = (10.5 \pm 2.6) \cdot 10^{-10}$$



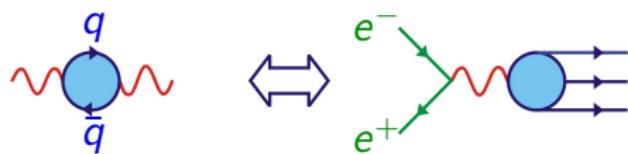
- evaluation not as straight forward as for VP:
⇒ models: relate measured $\pi^0/\eta/\eta'$ TFF to hadronic LbL term
- $Q^2 > 4 \text{ GeV}^2$: B -factories dominate the uncertainties:
 π^0 -puzzle should be solved ⇒ Belle-2
- most relevant input for a_μ^{LBL} : low Q^2 region
⇒ BESIII, CMD3, SND, MAMI, ...

Hadronic cross sections for $a_\mu^{had, VP}$



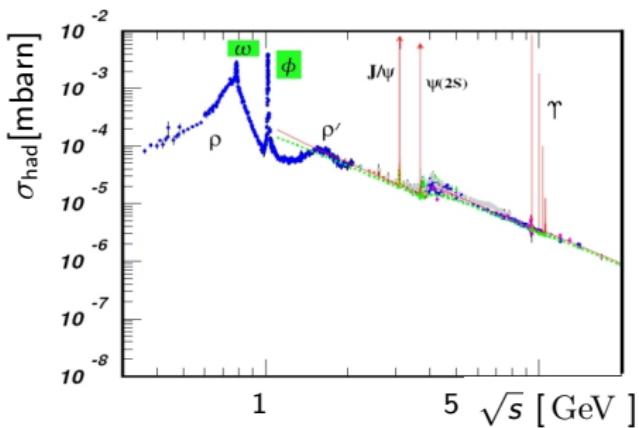
Experimental input for a_μ^{had}

Optical Theorem



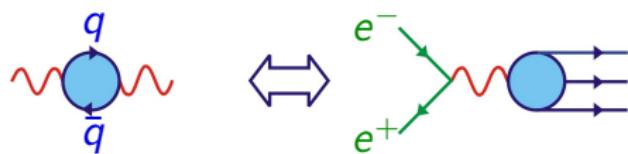
Energy scan

- CMD & SND@VEPP-2M & VEPP-2000, Novosibirsk
- BES-I & II, BEPC, Beijing



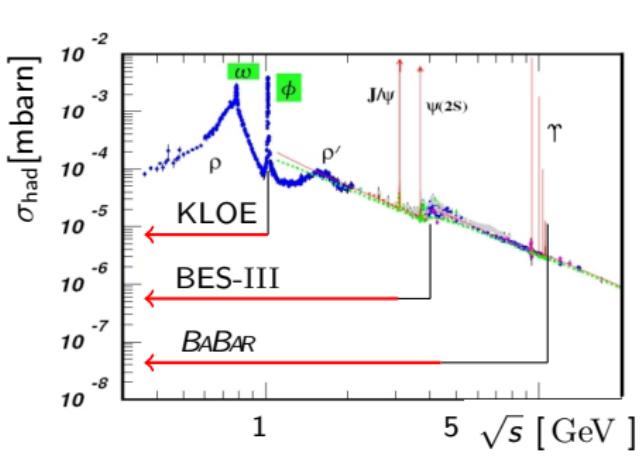
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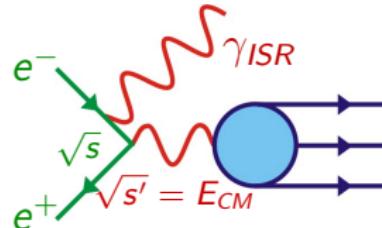


Energy scan

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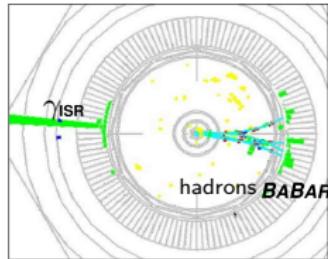
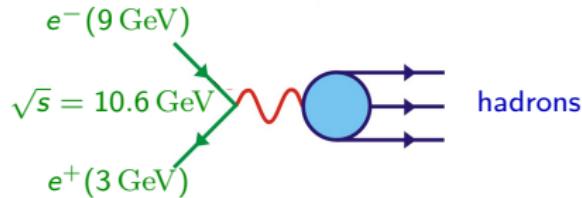


Initial State Radiation



- KLOE@DA ϕ NE in Frascati
- BABAR@PEP-II in Stanford
- BES-III@BEPC-II in Beijing

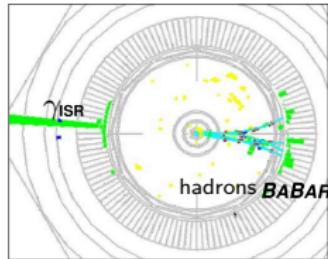
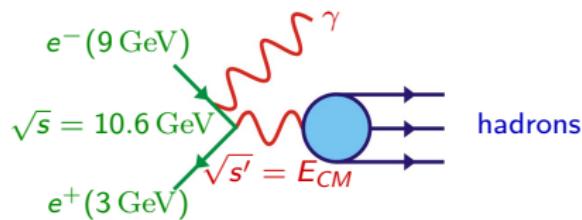
Initial State Radiation (ISR) events at *BABAR*



ISR selection

- Detected high energy photon: $E_\gamma > 3 \text{ GeV}$
→ defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
→ high acceptance
- Kinematic fit including γ_{ISR}
→ very good energy resolution (4 – 15 MeV)
- Continuous measurement from threshold to $\sim 4.5 \text{ GeV}$
→ provides common, consistent systematic uncertainties

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ISR analyses at *BABAR*

published

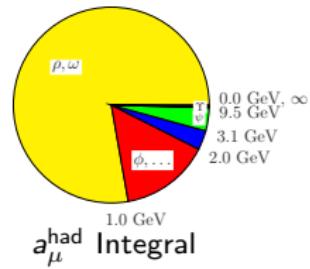
$e^+e^- \rightarrow \pi^+\pi^-$	PR D 86 (2012) 032013, PR L 103 (2009) 231801
$e^+e^- \rightarrow K^+K^-$	PR D 88, (2013) 032013
$e^+e^- \rightarrow \phi f_0(980)$	PR D 74 (2006) 091103, PR D 76 (2007) 012008
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$	PR D 70 (2004) 072004
$e^+e^- \rightarrow K^+K^-\eta, K^+K^-\pi^0, K_s^0 K^\pm \pi^\mp$	PR D 77 (2008) 092002, PR D 71 (2005) 052001
$e^+e^- \rightarrow 2(\pi^+\pi^-)$	PR D 85 (2012) 112009, PR D 76 (2007) 012008
$e^+e^- \rightarrow K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PR D 86 (2012) 012008, PR D 76 (2007) 012008
$e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PR D 76 (2007) 092005
$e^+e^- \rightarrow 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PR D 73 (2006) 052003
$e^+e^- \rightarrow p\bar{p}$ (small \sqrt{s})	PR D 87 (2013) 092005, PR D 73 (2006) 012005
$e^+e^- \rightarrow p\bar{p}$ (large \sqrt{s})	PR D 88 (2013) 072009
$e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Lambda\Sigma^0, \Sigma^0\bar{\Sigma}^0$	PR D 76 (2007) 092006
$e^+e^- \rightarrow c\bar{c} \rightarrow \dots$

ongoing analyses

$$e^+e^- \rightarrow K_s^0 K_L^0, K_s^0 K_L^0 \pi^+\pi^-, K_s^0 K_s^0 \pi^+\pi^-, K_s^0 K_s^0 K^+K^-, \pi^+\pi^-\pi^0\pi^0, K_s^0 K^\pm \pi^\mp \pi^0/\eta$$

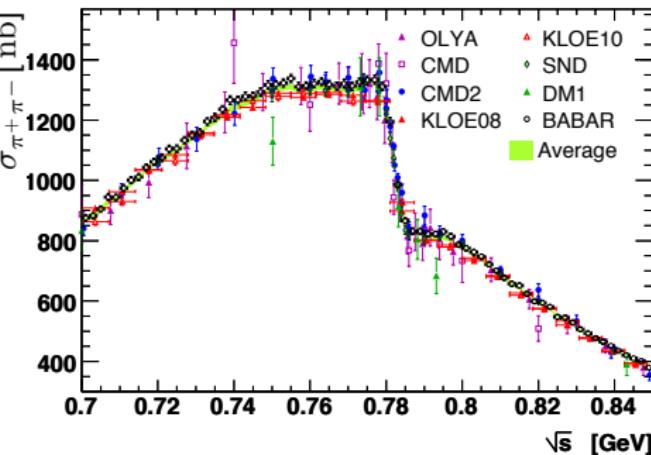
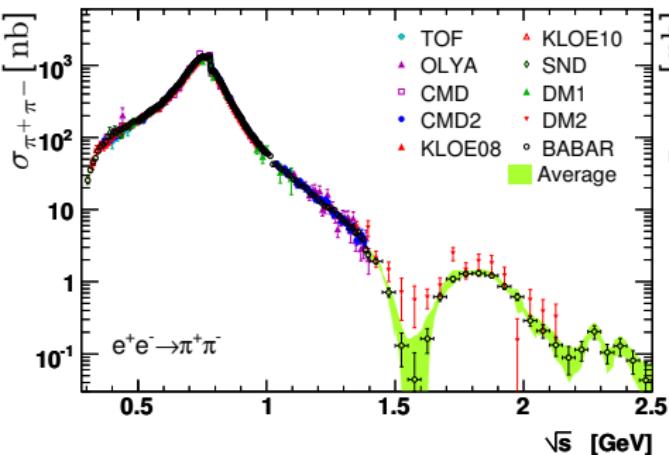
Contributions of exclusive final states to $g_\mu - 2$

Contributions of different energy regions to the dispersion integral



→ $E < 1 \text{ GeV}$ region dominates
→ $\pi^+ \pi^-$ channel needed!

$\pi^+\pi^-$ cross section

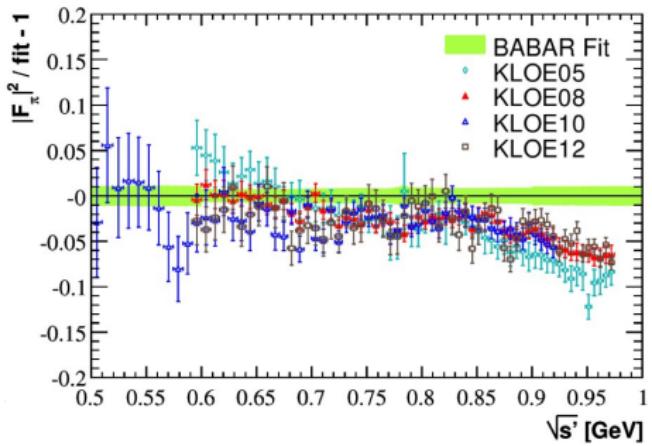


- ρ peak
- $\rho - \omega$ interference
- Dip at 1.6 GeV: excited ρ states
- Dip at 2.2 GeV
- Contribution to a_μ^{had} : 75%!

Systematic Uncertainties (ρ -region)

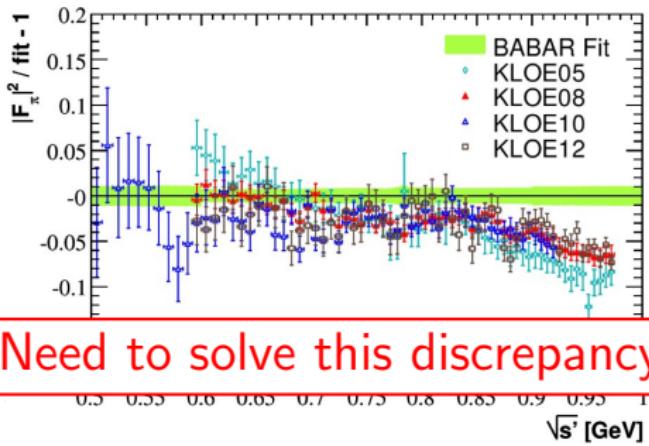
$BABAR$:	0.5%
CMD2:	0.8%
SND:	1.5%
KLOE:	0.8%

$\pi^+ \pi^-$ cross section



- KLOE and *BABAR* dominate the world average
- Uncertainty of both measurements smaller than 1%
- Systematic difference, especially above ρ peak
- Difference \rightarrow relatively large uncertainty for a_μ^{had}

$\pi^+ \pi^-$ cross section

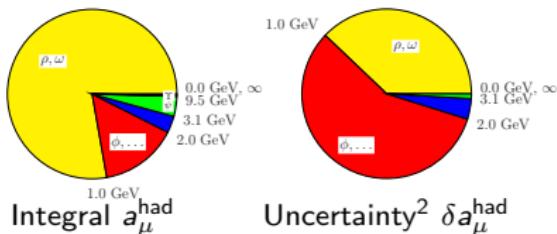


Need to solve this discrepancy!

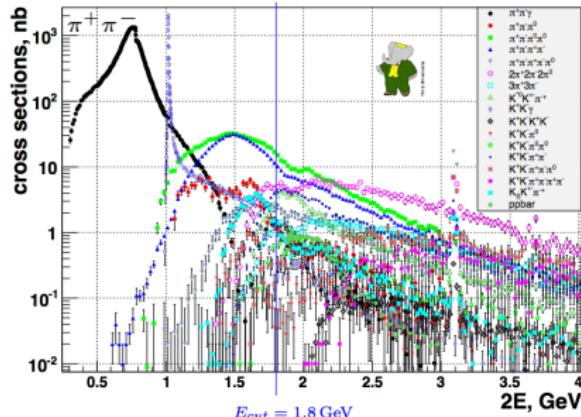
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Contributions of exclusive final states

Contributions of different energy regions to the dispersion integral



\Rightarrow Precise measurements
 $1 \text{ GeV} < E < 2 \text{ GeV}$ needed!

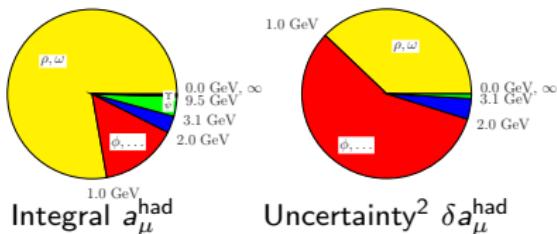


\Rightarrow Other channels important!

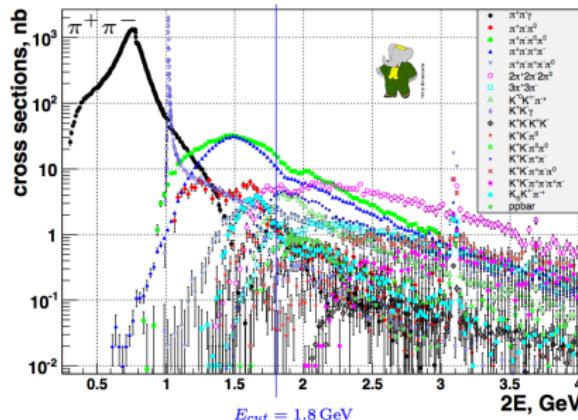
- K^+K^-
- $K_S^0 K_L^0$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^0$
- $\pi^+\pi^-\pi^0\pi^0$

Contributions of exclusive final states

Contributions of different energy regions to the dispersion integral



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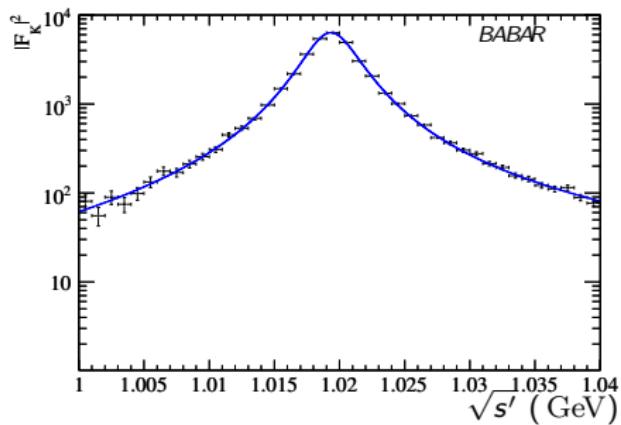
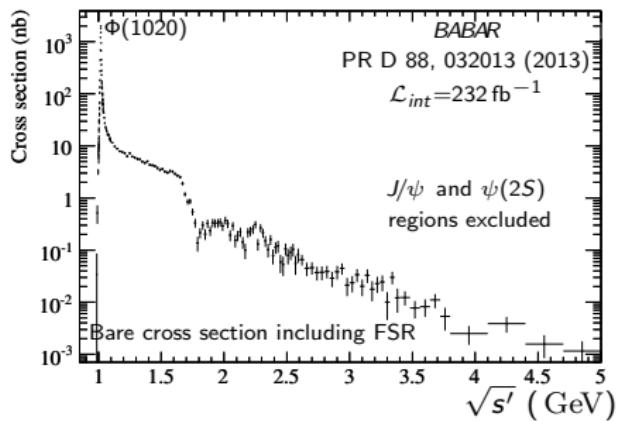
⇒ Other channels important!

- K^+K^-
- $K_s^0 K_L^0$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^0$
- $\pi^+\pi^-\pi^0\pi^0$

will be presented

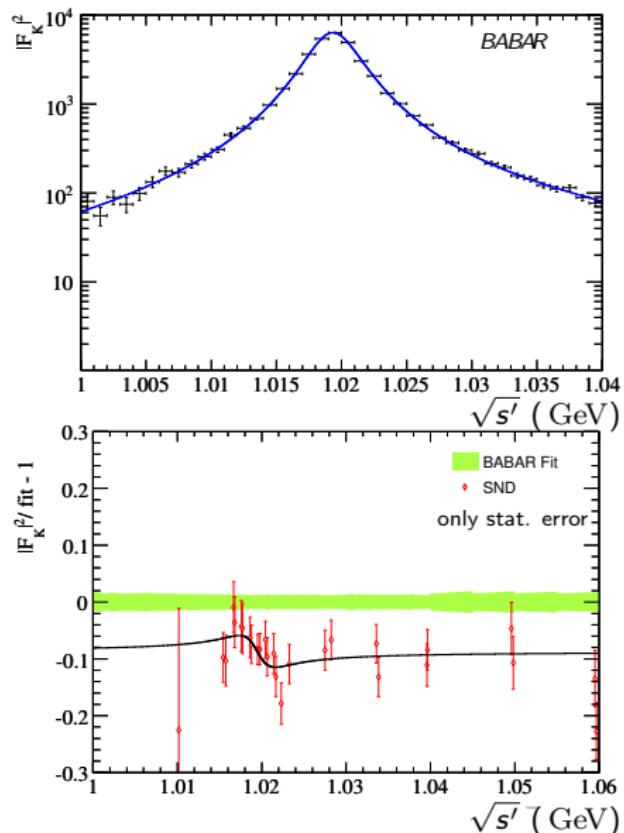
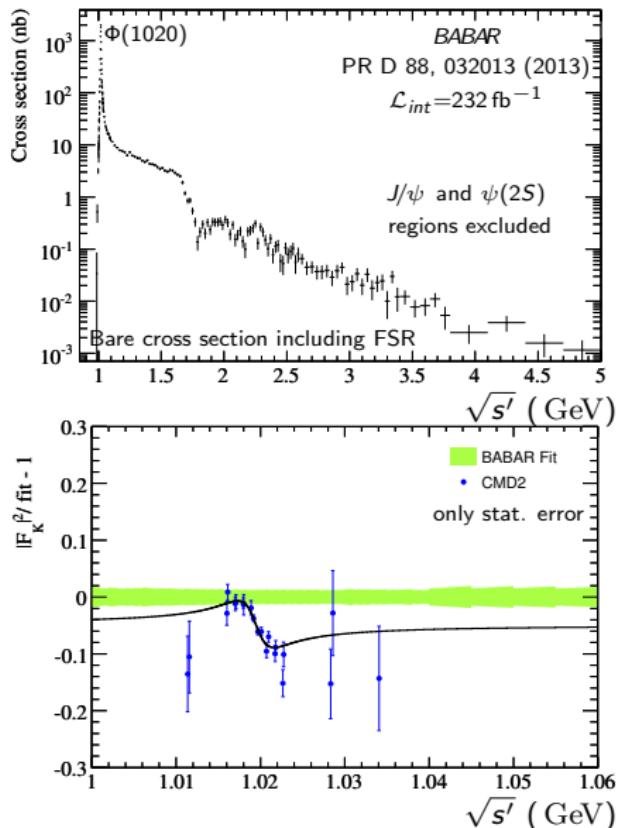
no recent results

Cross section $\sigma(e^+e^- \rightarrow K^+K^-)$

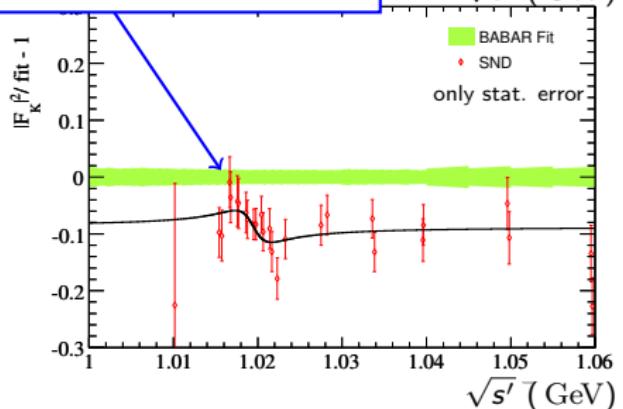
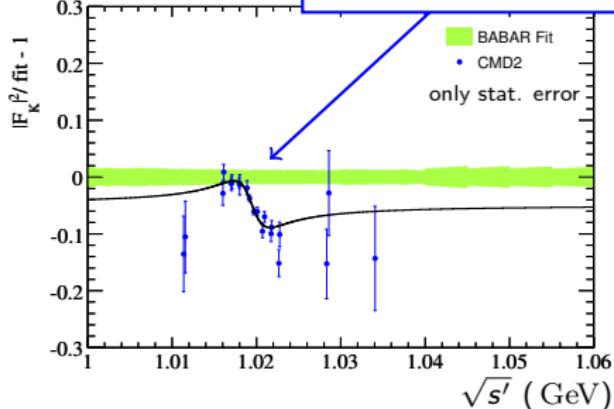
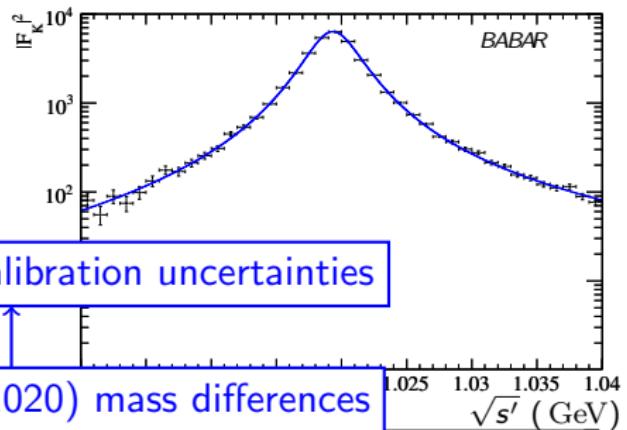
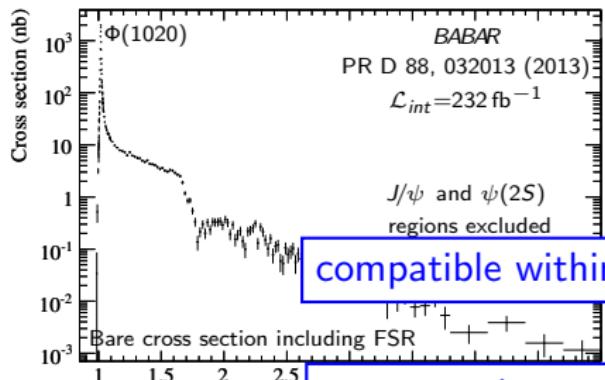


- uncertainty: 0.8% near ϕ peak!
- efficiency obtained from simulation [Kühn *et al.*, EPJC 18 (2001), 497]
→ data/MC corrections of utmost importance:
trigger, tracking, particle-ID
- ISR effective luminosity from $\mu\mu\gamma(\gamma)$ as in $\pi^+\pi^-$ study: KK/ $\mu\mu$ ratio

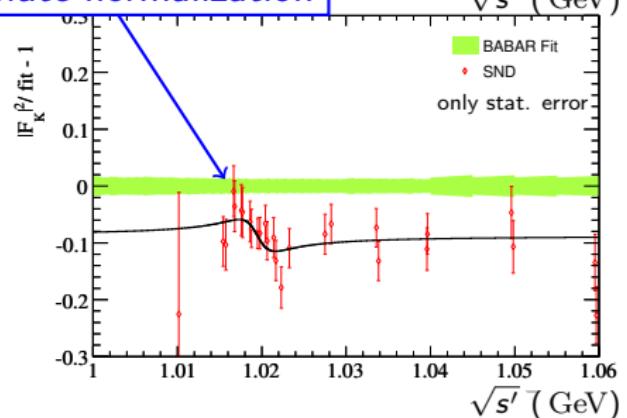
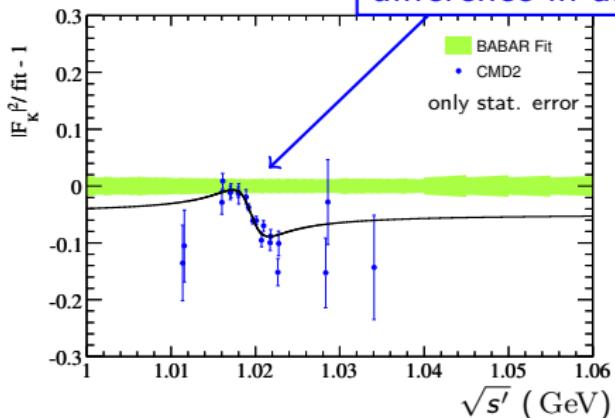
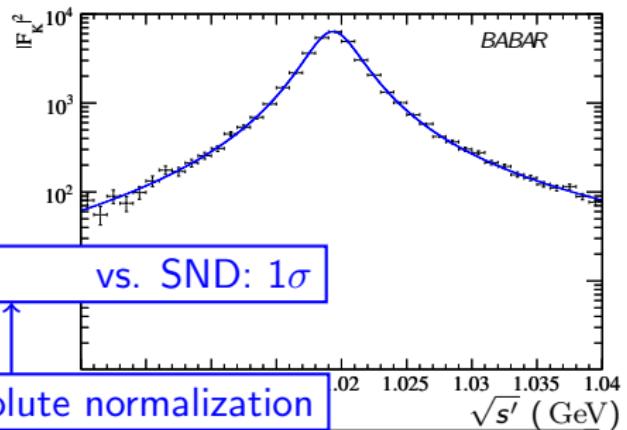
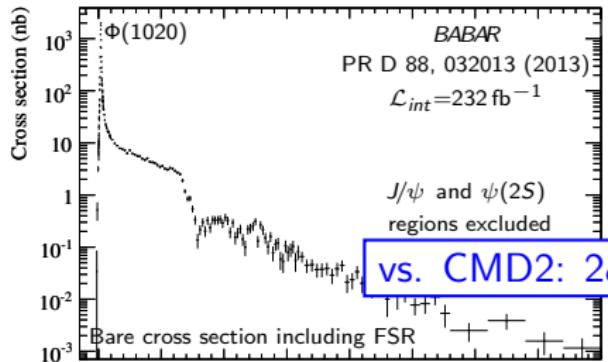
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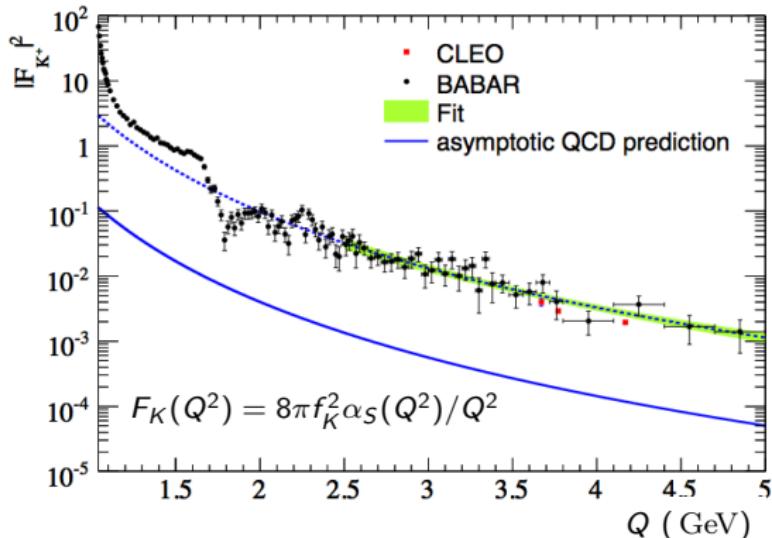
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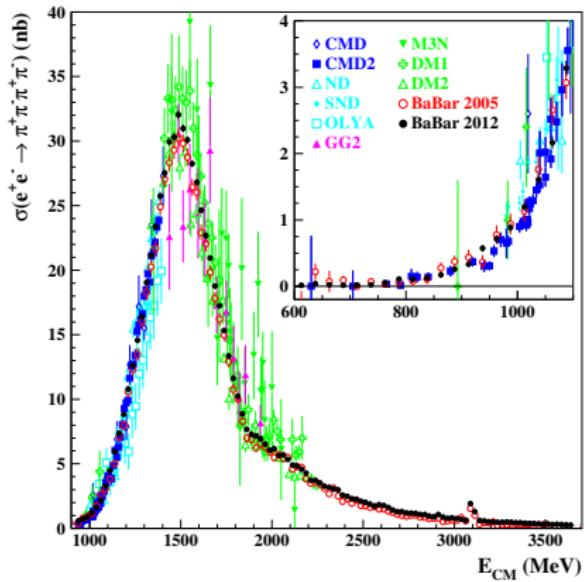


Charged kaon form factor at large Q^2

Predictions based on QCD in asymptotic regime (Chernyak, Brodsky-Lepage, Farrar-Jackson)

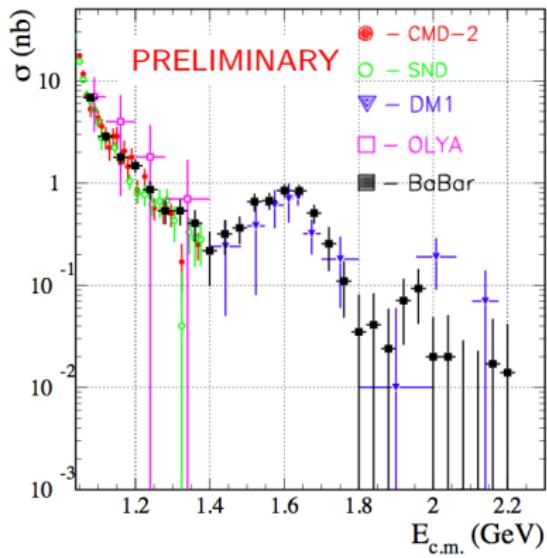
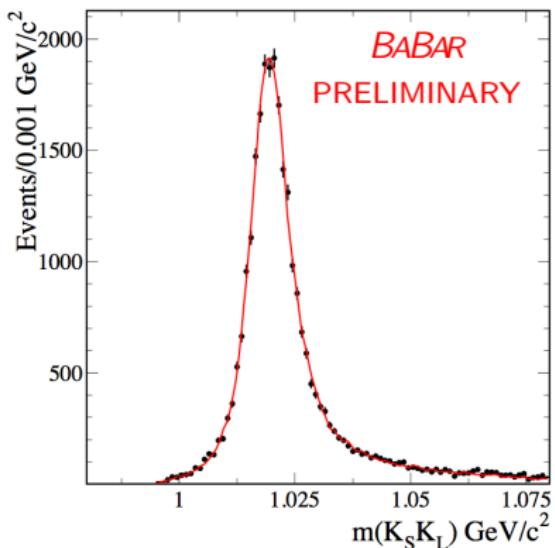
- Power law: $F_K \propto \alpha_S(Q^2)Q^{-n}$ with $n = 2$
→ in good agreement with the data (2.5-5 GeV $n = 2.10 \pm 0.23$)
- HOWEVER: data on $|F_K|^2$ factor ≈ 20 above prediction!
- No trend in data up to 25 GeV 2 for approaching the asympt. QCD prediction



Cross section $\sigma(e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-)$ 

- BABAR 12: 2.4% uncertainty in peak region
- various experiments agree

Cross section $\sigma(e^+e^- \rightarrow K_S^0 K_L^0)$



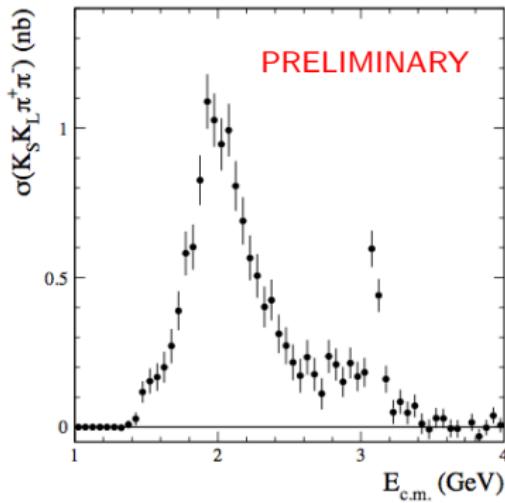
$$\Gamma_\phi^{ee} \mathcal{B}_{K_S^0 K_L^0} = 0.4200 \pm 0.0033 \pm 0.0122 \pm 0.0019$$

- within 1σ wrt CMD-2
- syst uncertainty: 2.9%
- dominated by trigger

systematic uncertainty:

- $\sim 10\%$ for $\sigma > 0.5 \text{ nb}$
- $\sim 30\%$ for $\sigma < 0.5 \text{ nb}$
- dominated by bkg-subtraction

Cross Section of $e^+ e^- \rightarrow K_S^0 K_L^0 \pi^+ \pi^-$



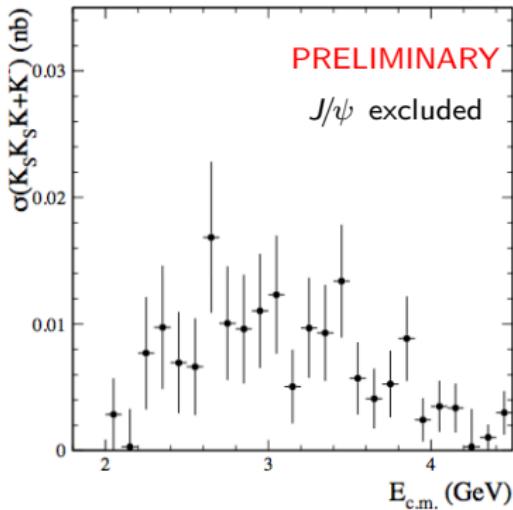
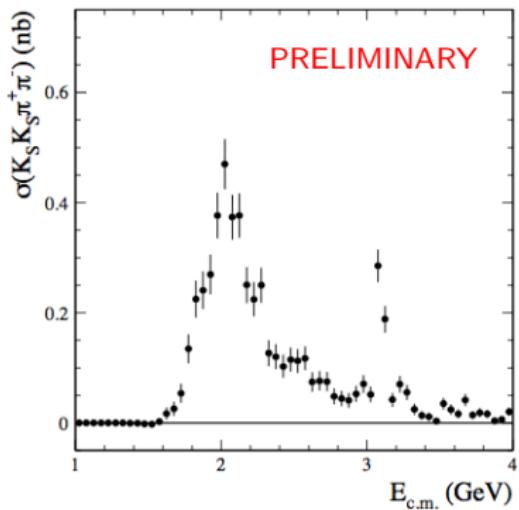
$$\mathcal{B}_{J/\psi \rightarrow K_S^0 K_L^0 \pi^+ \pi^-} = (3.7 \pm 0.6 \pm 0.4) \cdot 10^{-3}$$

1st measurement

Systematic uncertainty dominated by background-subtraction procedure:

- $\sim 10\%$ in peak region
- Increases to $\sim 30\%$ at 1.5 and 3 GeV
- $\sim 100\%$ above 3 GeV

Cross Section of $K_S^0 K_S^0 \pi^+\pi^-$ and $K_S^0 K_S^0 K^+K^-$



$$\mathcal{B}_{J/\psi \rightarrow K_S^0 K_S^0 \pi^+\pi^-} = (1.68 \pm 0.16 \pm 0.08) \cdot 10^{-3} \quad \mathcal{B}_{J/\psi \rightarrow K_S^0 K_S^0 K^+K^-} = (0.42 \pm 0.08 \pm 0.02) \cdot 10^{-3}$$

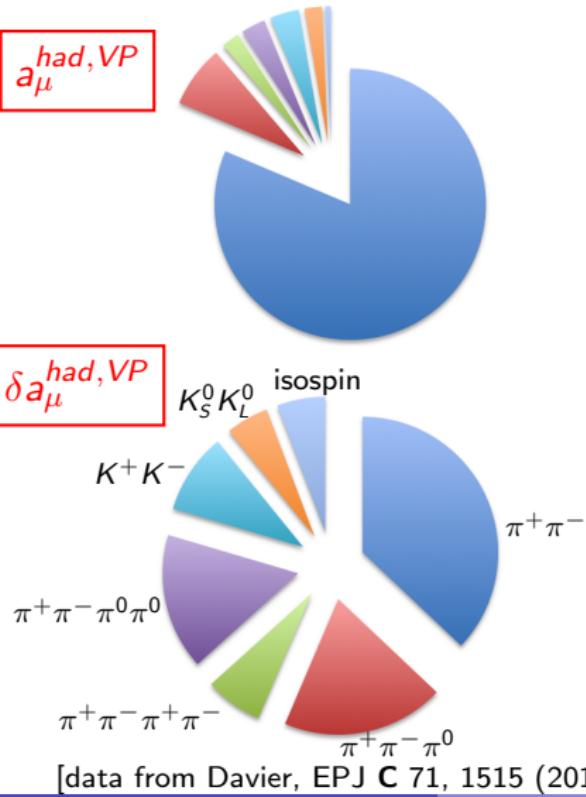
1st measurement

Systematic uncertainties:

- $\sim 5\%$ in peak region
- Increases to $\sim 20\%$ at 1.5/3 GeV
- $\sim 50 - 70\%$ above 3 GeV
- $\sim 5\%$
- stat. error dominates

Impact on $g_\mu - 2$: had. VP

$$a_\mu^{\text{VP,LO}} = (692.3 \pm 4.2) \cdot 10^{-10}$$



channels estimated with isospin rels

largest contributions: $K\bar{K}\pi$ and $K\bar{K}\pi\pi$

$$K_S^0 K_L^0$$

BABAR not evaluated, yet

$$K^+K^-$$

BABAR reduces $\delta a_\mu^{\text{had}}(K^+K^-)$ by factor 2.7

$$\pi^+\pi^-\pi^+\pi^-$$

BABAR reduces $\delta a_\mu^{\text{had}}(\pi^+\pi^-\pi^+\pi^-)$ by 40%

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

wait for *BABAR*, *BESIII*, and *CMD3* results

Summary & outlook

hadronic cross sections for $a_\mu^{had, VP}$

- still dominate the uncertainty of a_μ^{had} and thus a_μ^{theory}
- $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-, K^+K^-, K_S^0K_L^0$: well under control

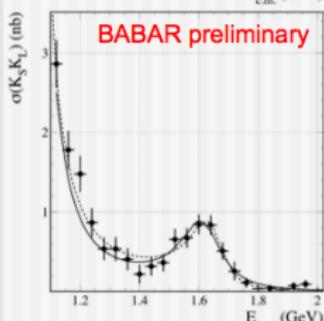
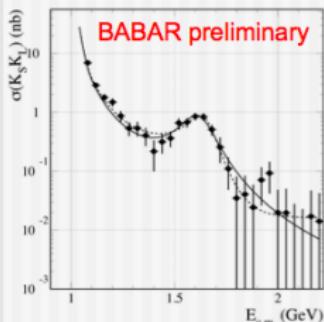
challenge between ISR and scan experiments continues

- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0 \Rightarrow BABAR, CMD3, BESIII$
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0, \pi^+\pi^- \Rightarrow CMD3, BESIII, (BABAR ???)$
⇒ validation is essential!

backup slides

$$\phi(1680) \rightarrow K_s^0 K_L^0$$

Is it $\phi(1680)$?



$$\sigma(s) = \frac{P(s)}{s^{5/2}} \left| \frac{A_{\phi(1020)}}{\sqrt{P(m_\phi)}} + \frac{A_X}{\sqrt{P(m_X)}} \cdot e^{i\varphi} + A_{bkg} \right|^2$$

$$P(s) = \left((s/2)^2 - m_{K^0}^2 \right)^{3/2}$$

$$A(s) = \frac{\Gamma(m^2) \cdot m^3 \sqrt{\sigma_0 \cdot m}}{s - m^2 + i\sqrt{s}\Gamma(s)}$$

$$\Gamma(s) = \Gamma \cdot \sum_f B_f \cdot \frac{P_f(s)}{P_f(m_f^2)}$$

$$A_{\phi(1020)} = A_\phi + A_\omega - A_\rho, \quad f = K^* K, \phi\eta, \phi\pi\pi, K_s K_L$$

$$\sigma_0 = 0.46 \pm 0.10 \pm 0.04 \text{ nb}$$

$$m = 1674 \pm 12 \pm 6 \text{ MeV/c}^2$$

$$\Gamma_0 = 165 \pm 38 \pm 70 \text{ MeV}$$

$$\varphi = 3.01 \pm 0.38 - \text{fixed to } \pi$$

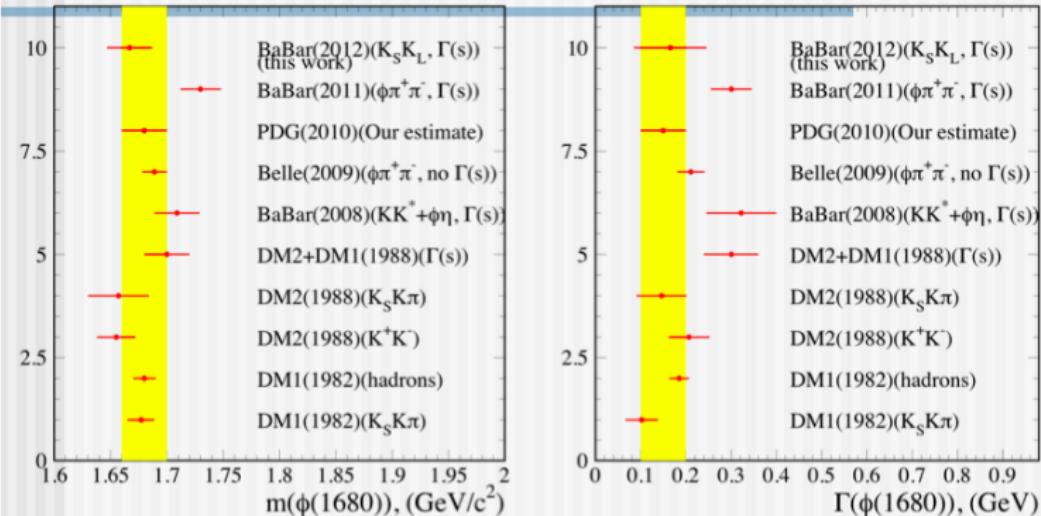
$$\sigma_{bkg} = 0.36 \pm 0.18 \text{ nb}$$

$$\Gamma_{ee} \cdot B_{KSKL} = 14.3 \pm 2.4 \pm 1.5 \pm 6.0 \text{ eV}$$

Simultaneous $K_s K_L$ and $K^+ K^-$ (and $\pi\pi$) fit is needed to separate $|l|=0,1$ states and $\omega(1420, 1650)$, $\rho(1450, 1700)$ contribution ..

$\phi(1680)$ observations in other channels

What we know about $\phi(1680)$

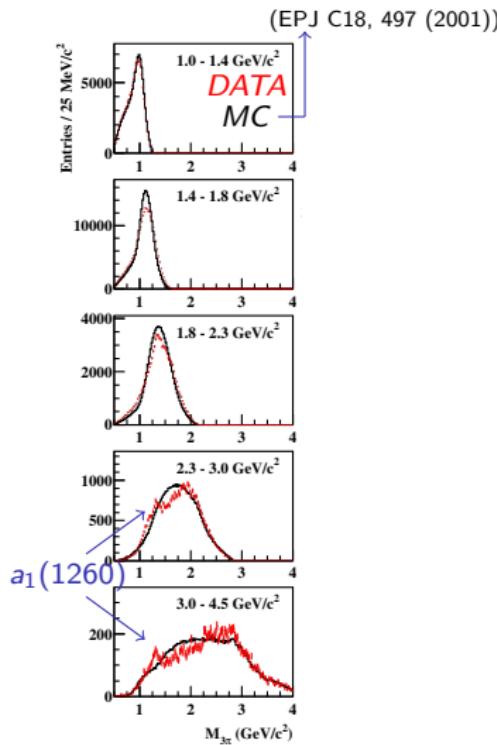


Energy dependence significantly increase width.

BaBar has measured $\phi(1680)$ parameters in major decay modes:

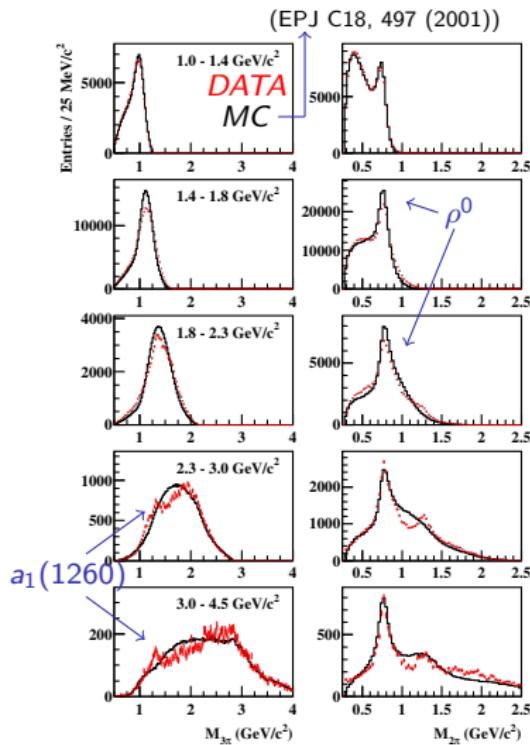
$\phi(1680) \rightarrow K_S K\pi, KK\pi^0 (K^*K), \phi\eta, \phi\pi\pi, K_S K_L$ (preliminary) - still no info in PDG

Internal structure in various E_{CM} energy slices



First column (4 entries/event):
 $a_1(1260)$

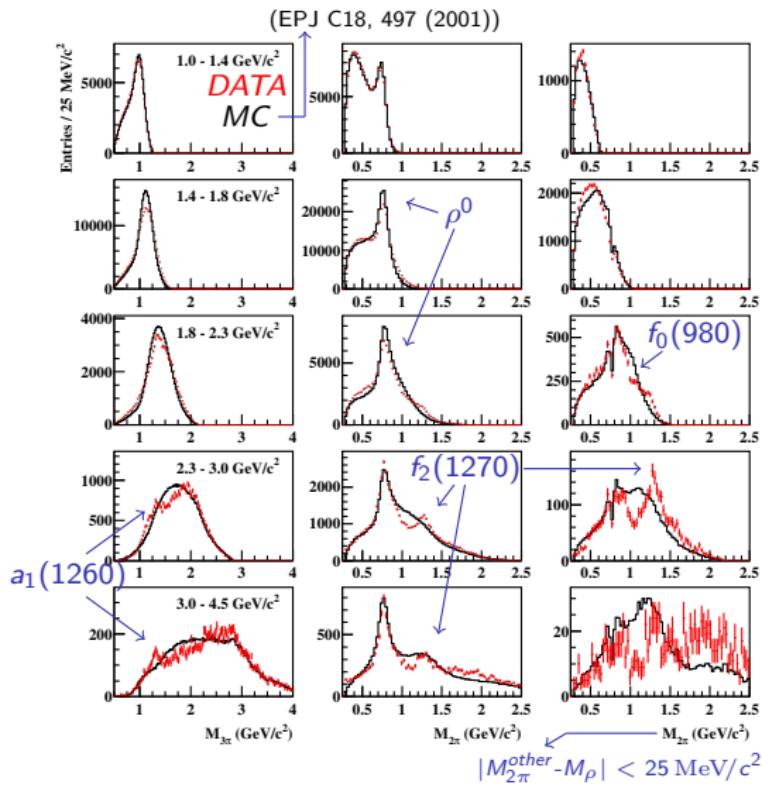
Internal structure in various E_{CM} energy slices



First column (4 entries/event):
 $a_1(1260)$

Second column (4 entries/event):
strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4 \text{ GeV}/c^2$:
1/4th of entries in ρ^0 peak
 $\rho^0\rho^0$ is forbidden
 $\rightarrow \rho^0$ in each event!

Internal structure in various E_{CM} energy slices



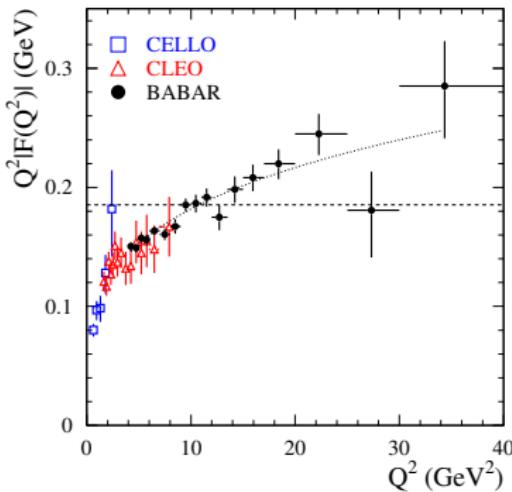
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1/4th of entries in ρ^0 peak
 $\rho^0 \rho^0$ is forbidden
 $\rightarrow \rho^0$ in each event!

Third column (1 entry/event):
 2π lie within ρ^0 mass
 \rightarrow other $\pi^+ \pi^-$'s mass plotted

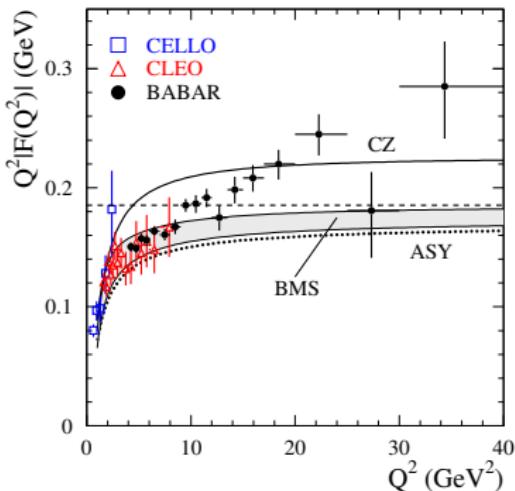
$f_2(1270)$, $a_1(1260)$, $f_0(980) \dots ?$
 \rightarrow Partial Wave Analysis needed

π^0 -photon transition form factors



- systematic uncertainty:
efficiency (trigger): 2.5%
bkg ($e^+e^- \rightarrow e^+e^-\pi^0\pi^0$): 0.3 – 6.0%
model uncertainty: 1.5%
- $4 \text{ GeV}^2 < Q^2 < 9 \text{ GeV}^2$: reasonable agreement with CLEO
- $Q^2 > 10 \text{ GeV}^2$:
pQCD: $\lim_{Q^2 \rightarrow \infty} Q^2 F(Q^2) = \sqrt{2} f_\pi$
 \Rightarrow asymptotic limit exceeded!

π^0 -photon transition form factors

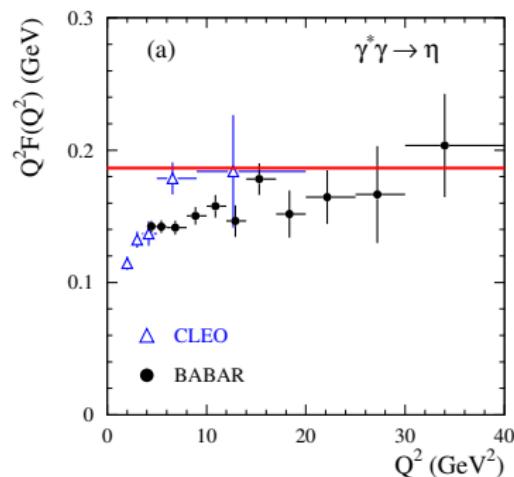


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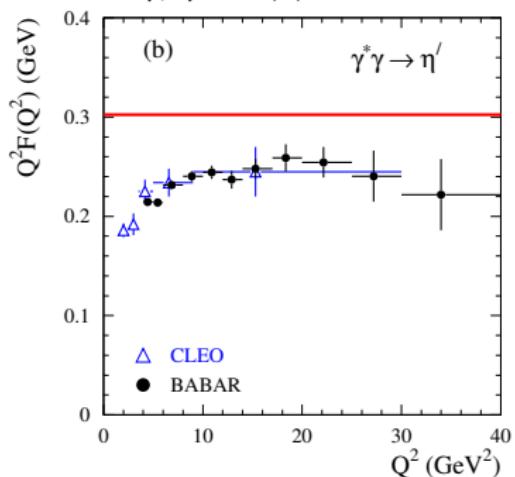
⇒ triggered a lot of theoretical work & a new measurement at Belle
 > 200 citations since 2009

η/η' -photon transition form factors

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



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

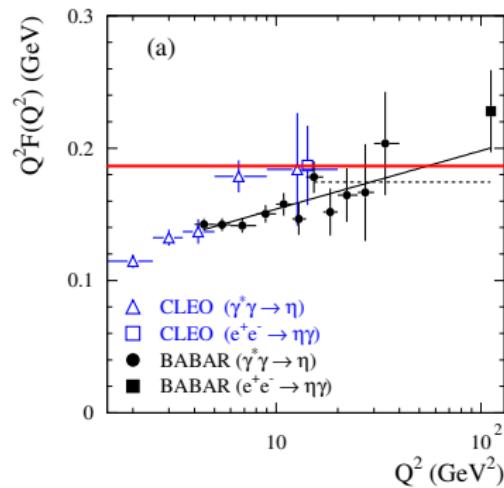


systematic uncertainty: 2.9%
dominated by model unc. & π^0 rec.

systematic uncertainty: 3.5%
dominated by model unc. & η rec.

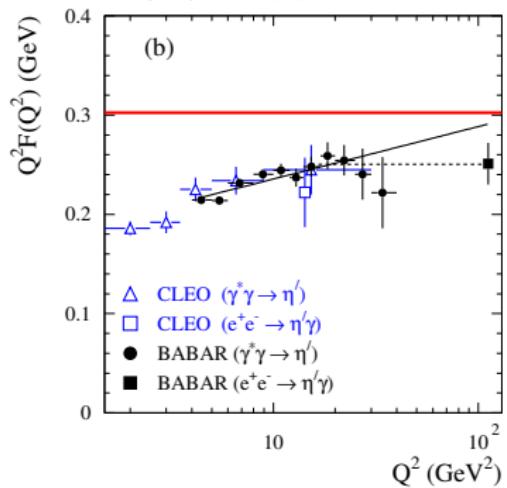
η/η' -photon transition form factors

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



systematic uncertainty: 2.9%
dominated by model unc. & π^0 rec.
 η -FF exceeds asymptotic limit

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



systematic uncertainty: 3.5%
dominated by model unc. & η rec.
 η' -FF below asymptotic expectation