Experiment: Status and Challenges

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Outline

1. General
2. Hadronic Vacuum Polarization (HVP)
3. How real is the accuracy?
4. Hadronic LbL
5. Conclusions

General

Major achievements coming from:

1. Energy Frontier:
   - LHC and Higgs discovery
   - (before that) Tevatron studied t quark physics and QCD
   - LEP and Standard Model success
2. Intensity/Precision Frontier:
   - E821 – a_μ; a_e and α
   - ϕ and B factories – R studies, CPV, exotic $c\bar{c}$ and $b\bar{b}$ states
   - Proton radius

Muon Anomalous Magnetic Moment

$$\vec{\mu} = g\frac{e}{2m}\vec{s}, \qquad a = (g-2)/2.$$

In Dirac theory for pointlike particles $g = 2$,
higher-order effects or new physics $\Rightarrow g \neq 2$

Any significant difference of a_μ^{exp} from a_μ^{th} indicates
New Physics beyond the Standard Model.

a_μ is much more sensitive to new physics effects than a_e:
the gain is usually $\sim (m_\mu/m_\mathrm{e})^2 \approx 4.3 \cdot 10^4$.

$$a_\mu^{\mathrm{th}} = a_\mu^{\mathrm{SM}} + a_\mu^{\mathrm{NP}}, \qquad a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}}.$$

Experimental Status of a_l

$$a_e = 1159652180.73(28) \times 10^{-12} \quad 0.24 \times 10^{-9}$$

D. Hanneke et al., PRL 100, 120801 (2008)
QED test or α determination

$$a_\mu = 116592080(63) \times 10^{-11} \quad 0.54 \times 10^{-6}$$

G.W. Bennett et al. (E821), PRD 73, 072003 (2006)
Sensitive test of the Standard Model

$$a_\tau = -0.018(17) \;\; \text{or} \;\; -0.052 < a_\tau < 0.013 \;\; 95\%\text{CL}$$

J. Abdallah et al. (DELPHI), EPJ C 35, 159 (2004)
Theory: $117721(5) \times 10^{-8}$, SE, M. Passera, MPL A 22, 159 (2007)

Update of the Experimental Value of a_μ

E821 at BNL (2006):

$$a_{\mu^+}^{\rm exp} = (11659204 \pm 6 \pm 5) \times 10^{-10}$$
$$a_{\mu^-}^{\rm exp} = (11659215 \pm 8 \pm 3) \times 10^{-10}$$

Their average assuming CPT and with account of correlations:

$$a_{\mu}^{\rm exp} = (11659208.9 \pm 5.3 \pm 3.3) \times 10^{-10}$$

These values take into account the newest CODATA value

for the μ/p magnetic ratio $\lambda = 3.183345137 \pm 85.$

The induced change in a_μ is $+0.92 \times 10^{-10}$.

P.J. Mohr, B.N. Taylor, and D.B. Newell, Rev. Mod. Phys. 80, 633 (2008)

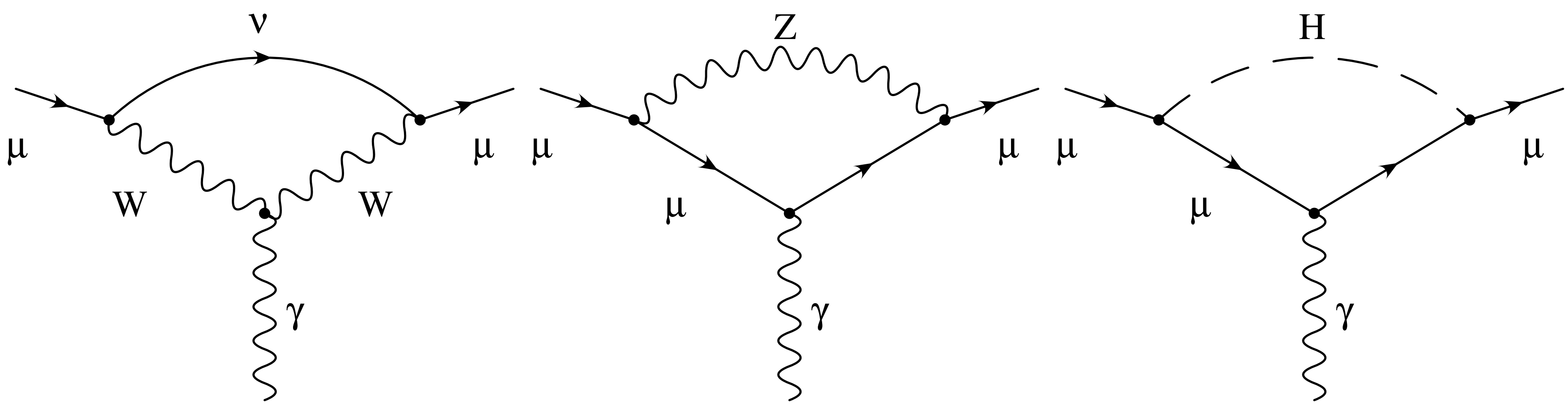
QED Contribution $a_\mu^{\rm QED}$

$a_\mu^{\rm QED} \cdot 10^{10} = \Sigma C_i (\frac{\alpha}{\pi})^i =$	11614097.3	(1-loop)	1 diagram
$+$	41321.8	(2-loop)	9
$+$	3014.2	(3-loop)	> 100
$+$	38.1	(4-loop)	> 1000
$+$	0.4	(5-loop)	> 20000

α^3 terms known analytically (S. Laporta, E. Remiddi, 1993),
α^4 terms – numerically (T. Kinoshita et al., 2003-2008),
L log α^5 (TK et al., 2005,2007; A.L. Kataev, 2006, K. Chetyrkin et al., 2008):
$a_\mu^{\rm QED} = (116584719.4 \pm 1.4) \cdot 10^{-11}$.

From the latest value of a_e (D. Hanneke et al., 2008; T. Kinoshita, 2012):
$\alpha^{-1} = 137.035999173(34)$, $a_\mu^{\rm QED} = (116584718.09 \pm 0.14 \pm 0.04) \cdot 10^{-11}$.
The errors are due to: a/ $\mathcal{O}(\alpha^5)$, b/ α

Electroweak contribution a_μ^{EW}



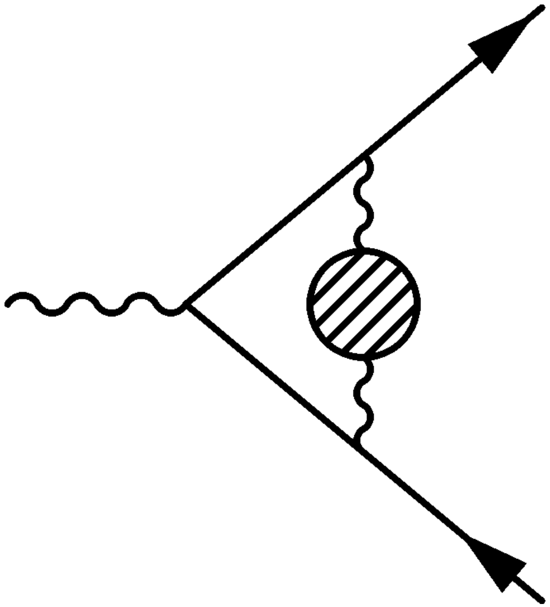
One-loop electroweak contributions

Authors	Year	a_μ^{EW}, 10^{-10}
$\ldots, \ldots, \ldots$	1972	19.5
A. Czarnecki et al.	1996	15.2 ± 0.4
A. Czarnecki et al.	2002	$15.4 \pm 0.1 \pm 0.2$

The errors are due to: a/ hadr. loops, b/ M_H, M_t, 3-loop effects.

Hadronic contribution $a_\mu^{\rm had}$

$$a_\mu^{\rm had} = a_\mu^{\rm had,LO} + a_\mu^{\rm had,HO} + a_\mu^{\rm had,LBL}$$

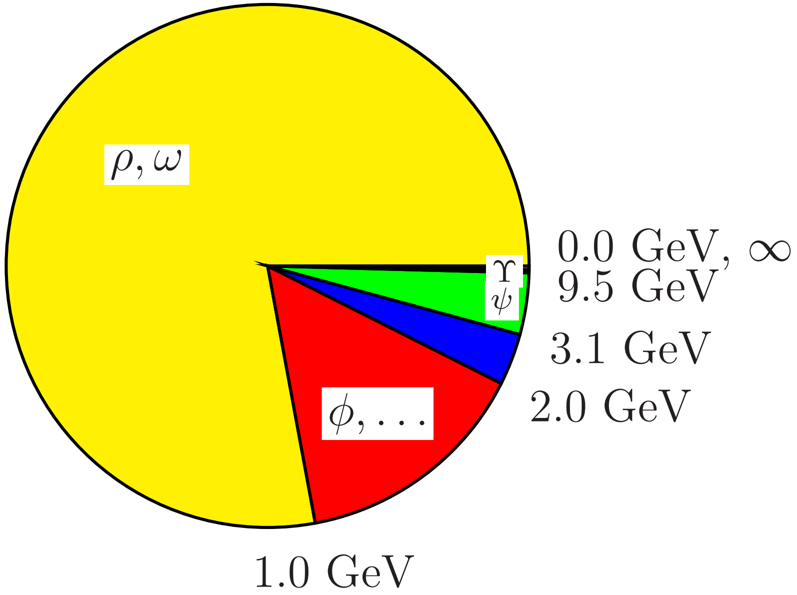


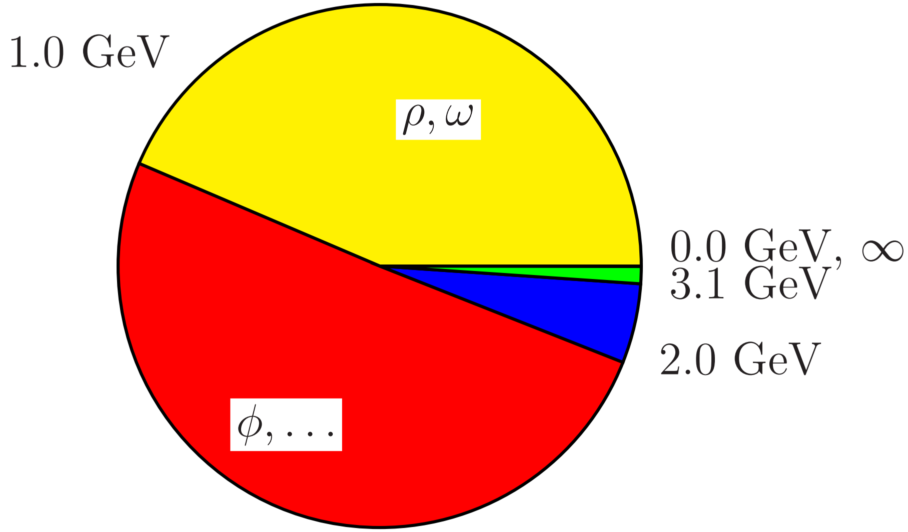
$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)\,\hat{K}(s)}{s^2}$, C. Bouchiat, L. Michel, Bouchiat, 1961; M. Gourdin, E. de Rafael, 1969

$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$,

$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$,
$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$.
$a_\mu^{\rm had,LO} \sim 700 \cdot 10^{-10}$ $\Rightarrow$ accuracy better than 1% needed

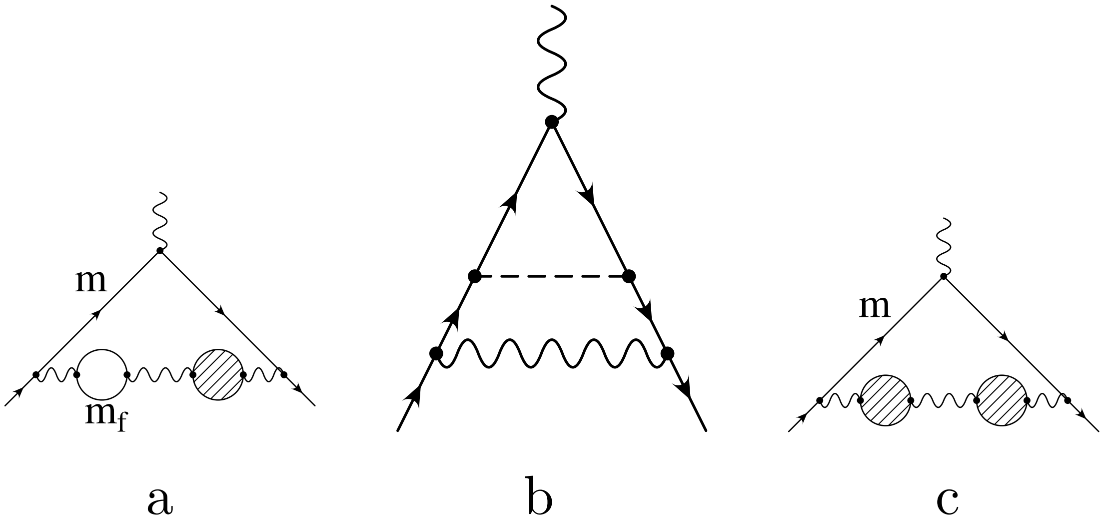
Contributions of Various Energy Ranges to $a_\mu^{\mathrm{had,LO}}$





More than 72% of $a_\mu^{\mathrm{had,LO}}$ come from $e^+e^- \to \pi^+\pi^-$ and more than 90% from the energy range below 2 GeV

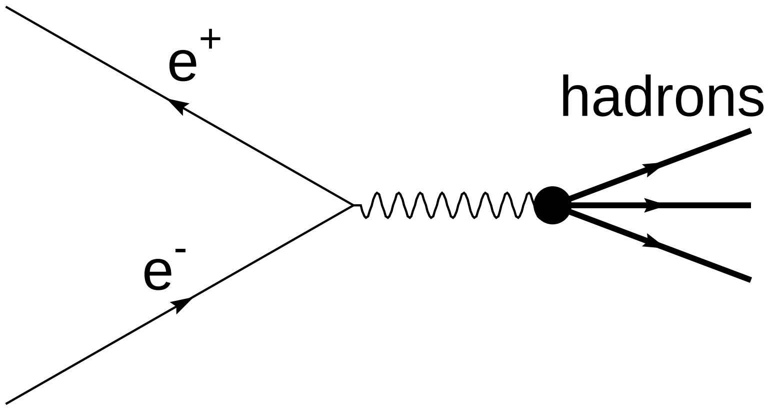
Higher Order Hadronic Contributions $a_\mu^{\rm had,HO}$



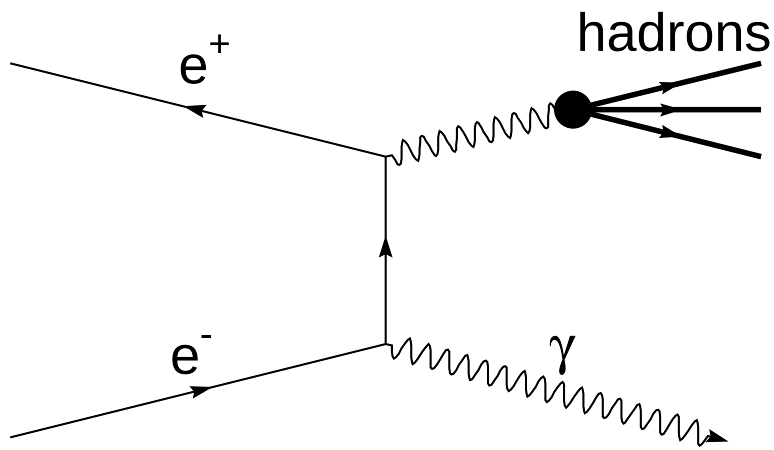
The contributions of all 3 graphs can be calculated in terms of the $\int R(s)G(s)ds/s^{2(3)}$, where $G(s)$ is a smooth function of s, so that the low energy range again dominates the integral. Several calculations agree. The recent value is (F. Jegerlehner and R. Szafron, 2011):

$$a_\mu^{\rm had,HO} = (-9.98 \pm 0.10) \cdot 10^{-10}.$$

Scan and ISR



Scan



ISR

Scan can provide larger data samples at fixed energy

ISR benefits from the same systematics and flat acceptance,

but may suffer from more complicated radiative effects,

a broad range of collision energies

Relation of Scan and ISR Center-of-mass Energy

If the nominal c.m. energy of the collider is $\sqrt{s}$ and initial electron or positron emit a photon with energy E_γ, the effective c.m. energy of the collision is

$$\sqrt{s'} = \sqrt{s - 2E_\gamma\sqrt{s}}$$

$\sqrt{s}$, GeV	$\sqrt{s'}$, GeV	E_γ, GeV
1.02 (m_ϕ)	0.770 (m_ρ)	0.22
10.58 ($m_{\Upsilon(4S)}$)	0.770 (m_ρ)	5.26
10.58 ($m_{\Upsilon(4S)}$)	3.1 ($m_{J/\psi}$)	4.84

How Is R Measured at Low Energy ($\sqrt{s} < 2$ GeV)?

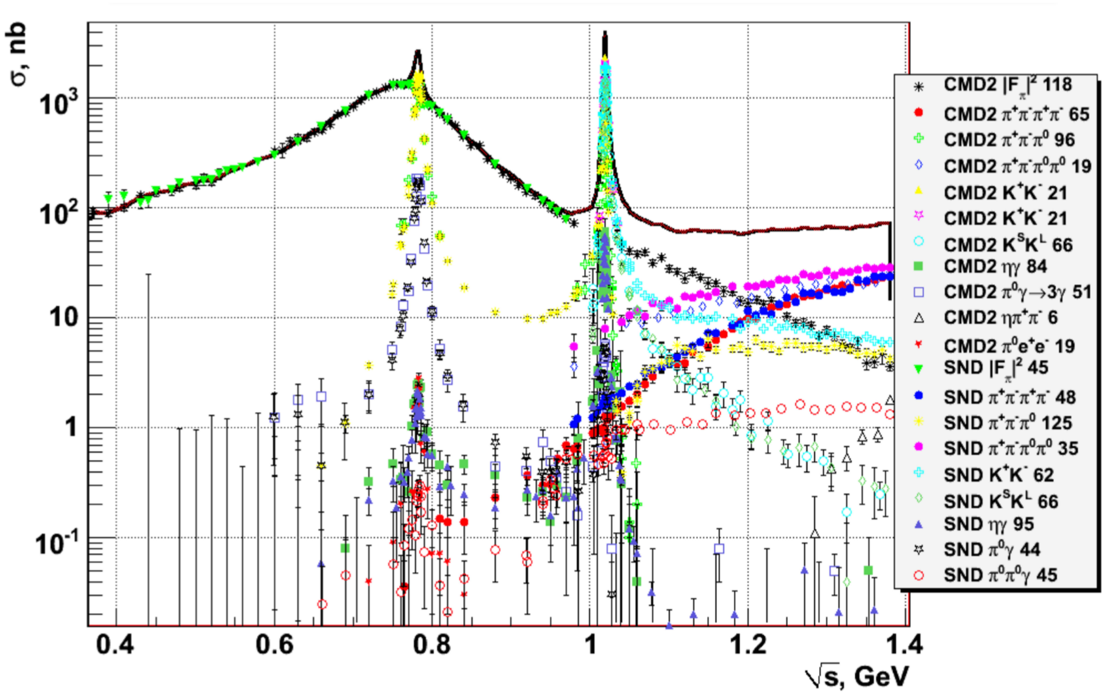
- The cross section rapidly changes with energy because one is far from asymptotics and there are many resonances
- There is no good theoretical model to find ϵ
- Exclusive approach: specific final states studied separately ($\pi^+\pi^-,\ K^+K^-,\ K_SK_L,\ ,n\pi,\ K\bar{K}m\pi,\ p\bar{p},\ n\bar{n},\ldots$)
- The cross sections measured summed
- Important not to miss some final states

R Measurement at Low Energies (< 5 GeV)

The main players in the field:

- Novosibirsk – scan (CMD-2/SND at VEPP-2M, $0.36 < \sqrt{s} < 1.4$ GeV, CMD-3/SND at VEPP-2000, $2m_\pi < \sqrt{s} < 2.0$ GeV)
- Frascati – ISR (KLOE/KLOE-2 at DAFNE, $2m_\pi < \sqrt{s} < 1.02$ GeV)
- Beijing – scan/ISR (BESII at $2.0 < \sqrt{s} < 5.0$ GeV, BESIII at $2m_\pi < \sqrt{s} < 4.6$ GeV)
- SLAC – ISR (BaBar at PEPII, $2m_\pi < \sqrt{s} < 5$ GeV)
- KEK – ISR (Belle at KEKB, $2m_\pi < \sqrt{s} < 5$ GeV, BelleII at SuperKEKB, $2m_\pi < \sqrt{s} < 5$ GeV)

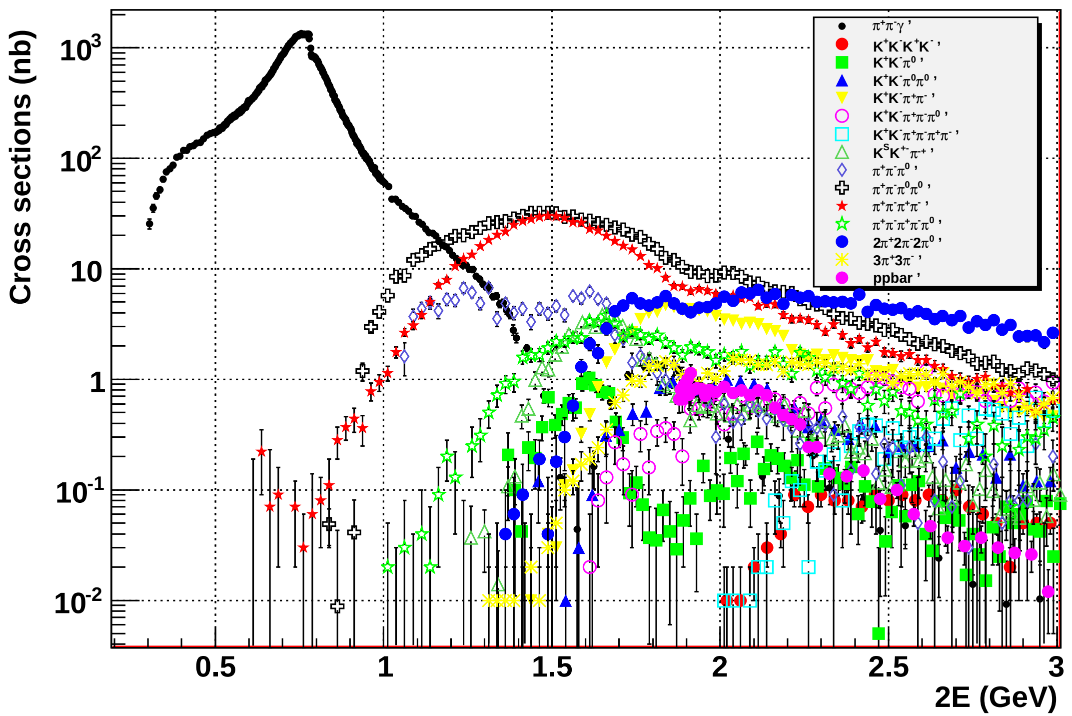
Current Status of R Below 2 GeV – Scan



Syst. errors: (0.6-1.0)% for $\pi^+\pi^-$, (5-15)% for multibody states

Cross sections vary by 4-5 orders!

Current Status of R Below 2 GeV – ISR



Syst. errors: 0.5% for $\pi^+\pi^-$, (2-15)% for multibody states

BaBar - all energies, Belle mainly in the charm region

Progress of Data-driven $a_\mu^{\text{had,LO}}$

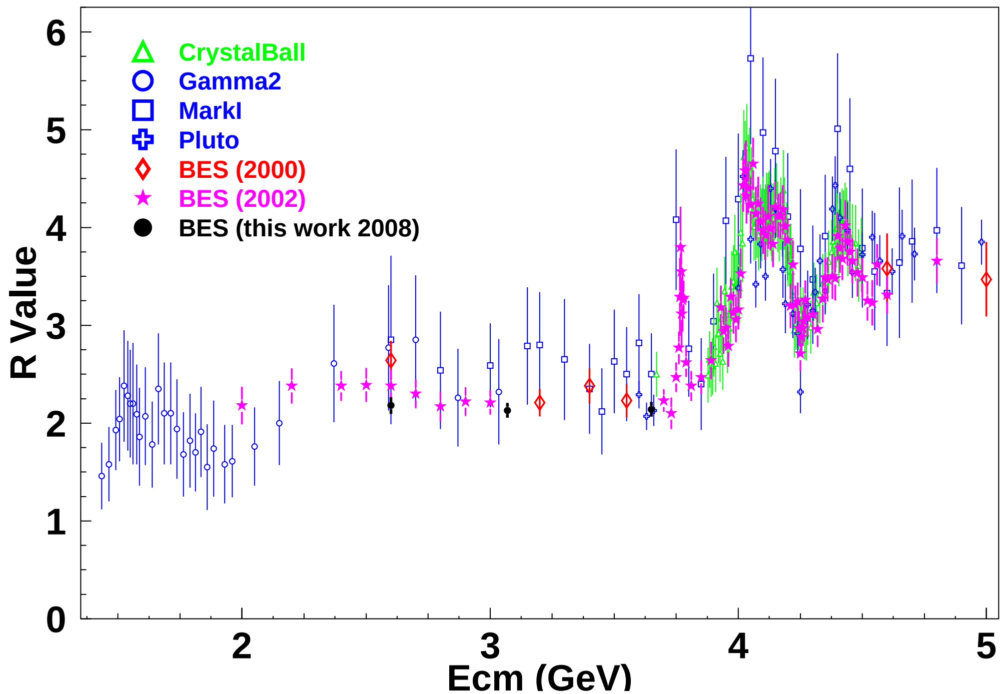
Author	Date	$a_\mu^{\text{had,LO}}$, 10^{-10}
V. Barger	1975	663 ± 85
SE, FJ	1994	702 ± 15
M. Davier, SE, ...	2003	696.3 ± 7.2
FJ, A. Nyffeler	2009	690.6 ± 5.3
M. Davier et al.	2011	692.3 ± 4.2

Impressive progress due to the new data

How Is R Measured at High Energy ($2 < \sqrt{s} < 5$ GeV)?

- Inclusive approach: all multihadronic events selected
- Background determined (τ decays, $\gamma\gamma$, QED)
- $\int \mathcal{L} dt$ found
- ϵ found from MC (LUND, PYTHIA, LUARLW)
- Radiative corrections applied: ISR (PHOKHARA), FSR (PHOTOS)

R Measurement Below 5 GeV

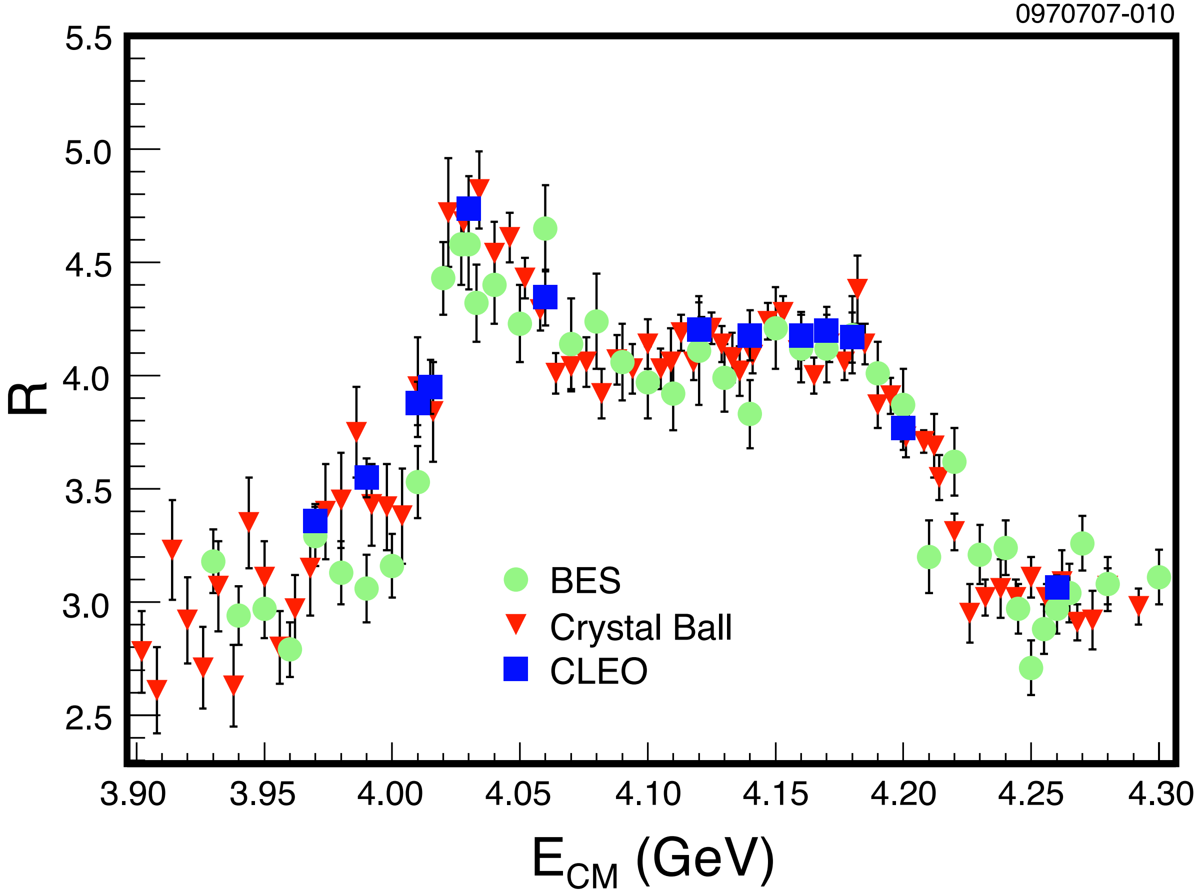


Dominated by BES: stat. errors (3-5)%, syst. errors (5-8)%

J.Z. Bai et al., Phys.Rev.Lett. 84 (2000) 594, Phys.Rev.Lett. 88 (2002) 101802;

M. Ablikim et al., Phys.Rev.Lett. 97 (2006) 262001, Phys.Lett. B677 (2009) 239

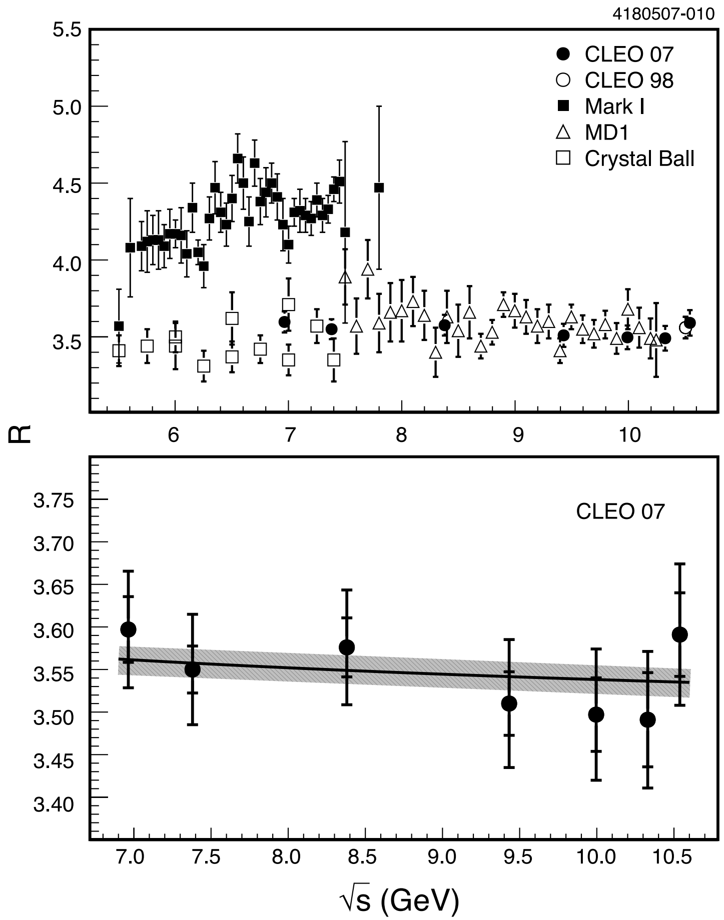
R Measurement by CLEO – I



CLEO-c: syst. errors (5.2-6.1)%

D. Cronin-Hennessy et al., Phys. Rev. D80 (2009) 072001

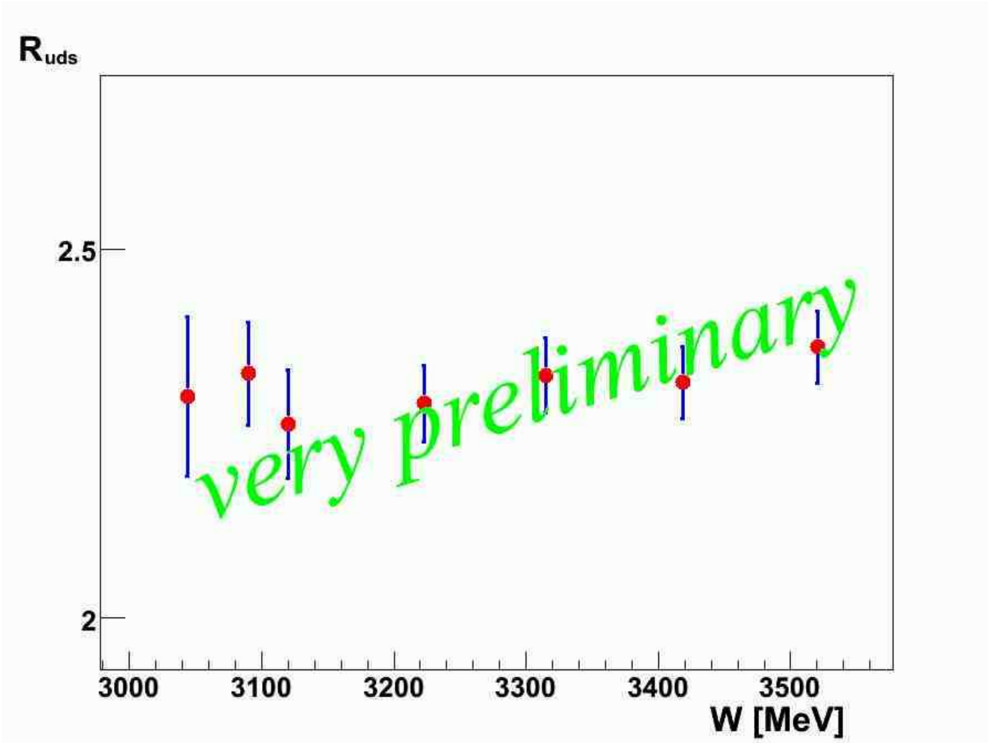
R Measurement by CLEO – II



CLEO3: syst. errors (1.7-2.3)%

D. Besson et al., Phys. Rev. D76 (2007) 072008

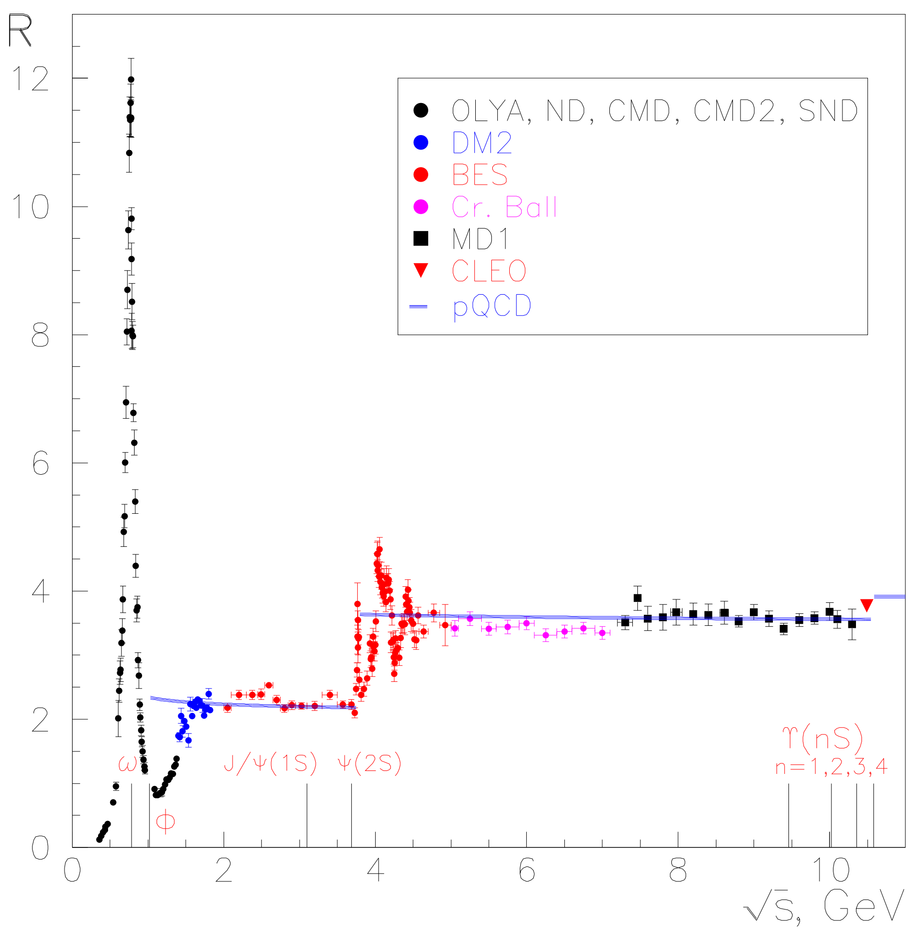
R Measurement at KEDR from 3.1 to 3.7 GeV



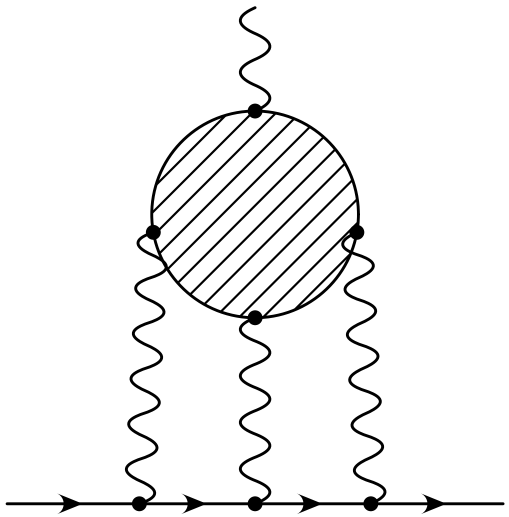
2k events per point, aimed at 4% systematics

With additional 2 pb^{-1} in 2014 the total $\Delta R/R \sim 3\%$ can be achieved

R Measurements below 10 GeV



Light-by-Light Scattering – I



Various approaches used:

- Vector Dominance and Chiral models
- Data on $\gamma\gamma^* \to \pi^0, \eta, \eta'$ (single-tag)
- Effective field theory
- Dyson-Schwinger equations

M. Knecht and A. Nyffeler, 2002: the correct sign!

Light-by-Light Scattering – II

Authors	Year	$a_\mu^{\rm lbl}$, 10^{-10}
J. Bijnens et al.	1996 (2002)	8.3 ± 3.2
M. Hayakawa and T. Kinoshita	1998 (2002)	9.0 ± 1.5
K. Melnikov and A. Vainshtein	2003	13.6 ± 2.5
M. Davier and W. Marciano	2004	12.0 ± 3.5
J. Prades, E. de Rafael, and A. Vainshtein	2009	10.5 ± 2.6
D. Greynat and E. de Rafael	2012	15.0 ± 0.3
T. Goecke, C.S. Fischer and R. Williams	2013	18.8 ± 9.0

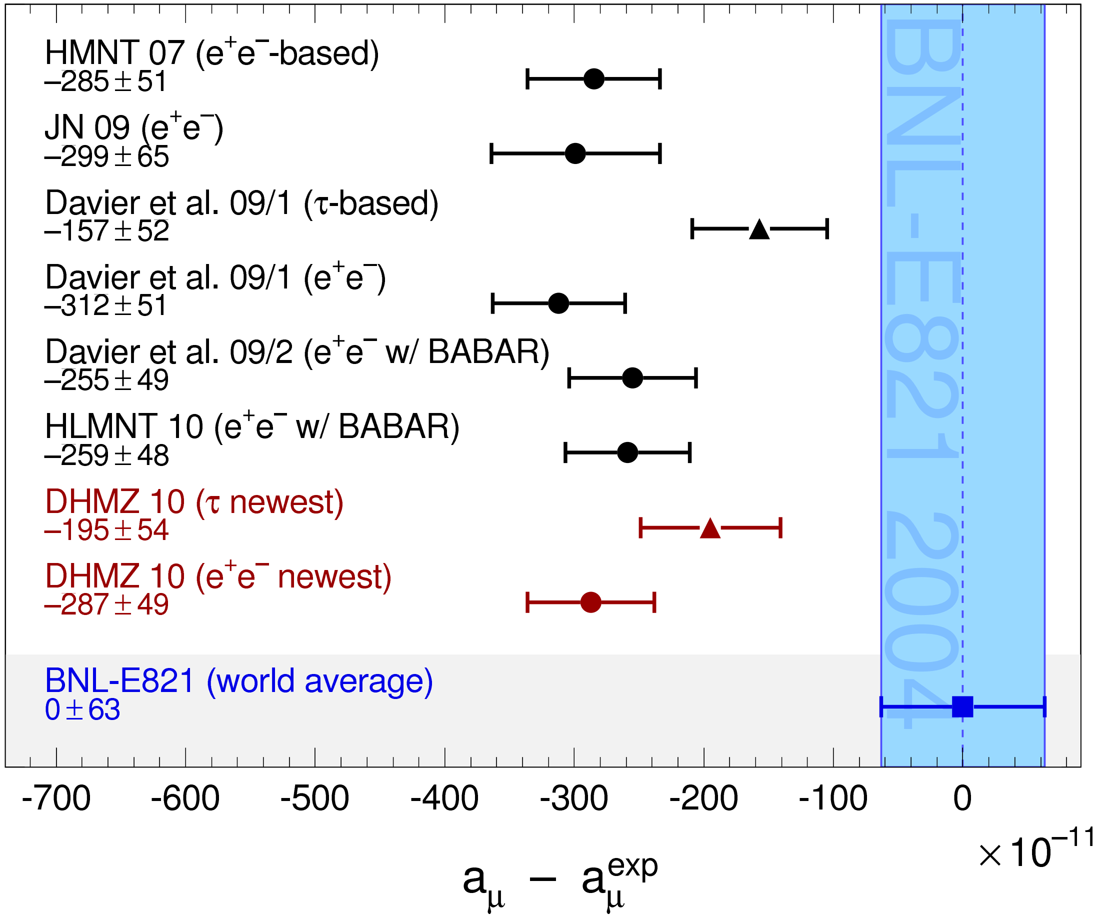
Experiment vs. Theory – I

$$a_\mu = (g_\mu - 2)/2,\ 10^{-10}$$

Experiment	$11659208.9 \pm 5.4 \pm 3.3$
QED	11658471.809 ± 0.015
EW	$15.4 \pm 0.1 \pm 0.2$
Had LO	692.3 ± 4.2
Had HO	-9.8 ± 0.1
Had LbL	10.5 ± 2.6
Theory	11659180.2 ± 4.9
Exp.-Th.	28.7 ± 8.0

Experiment is higher than theory by 3.6 standard deviations

Experiment vs. Theory – II



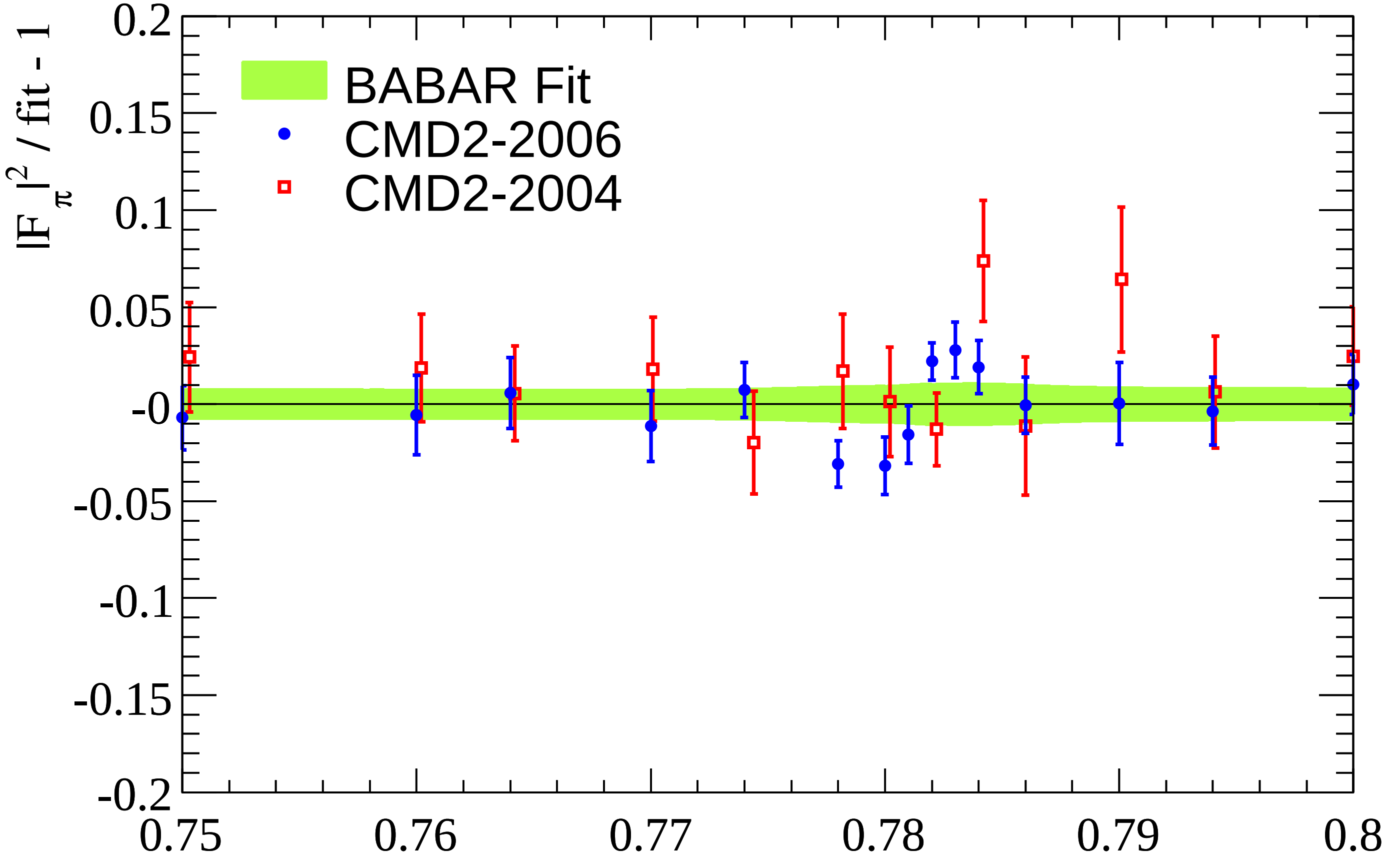
How Real is $a_\mu^{\rm had}$ Accuracy?

- Radiative corrections: ISR and HVP probably OK, FSR demands testing (charge asymmetry, $\pi^+\pi^-\gamma$)
- Scan vs. ISR method
- Missing states: neutrals, $\pi^+\pi^- n\pi^0$, $K\bar{K}n\pi$ - isospin
- Correlations
- Averaging
- Light-by-light term
- Double counting (LO and HO)

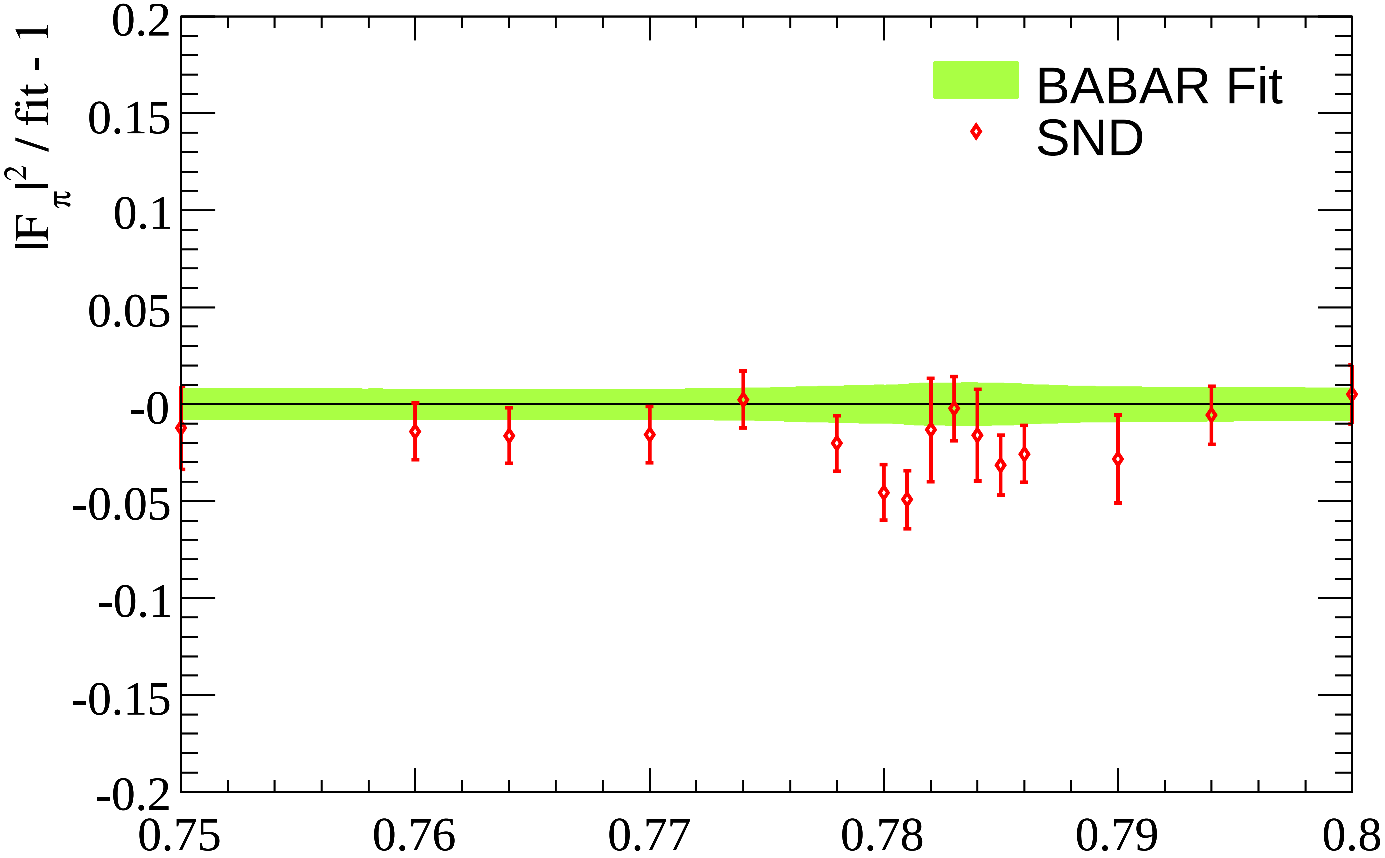
Contribution of Various Energy Ranges

$\sqrt{s}$, GeV	$\Delta a_\mu^{\mathrm{had,LO}}$
$\pi^+\pi^-$	507.80 ± 2.84
$\pi^+\pi^-\pi^0$	46.00 ± 1.73
K^+K^-	21.63 ± 0.73
$K_S^0 K_L^0$	12.96 ± 0.39
m/h < 1.8	45.50 ± 3.44
1.8-3.7	$33.45 \pm 0.28(2.00)$
> 3.7	17.16 ± 0.31
Total	692.3 ± 4.2

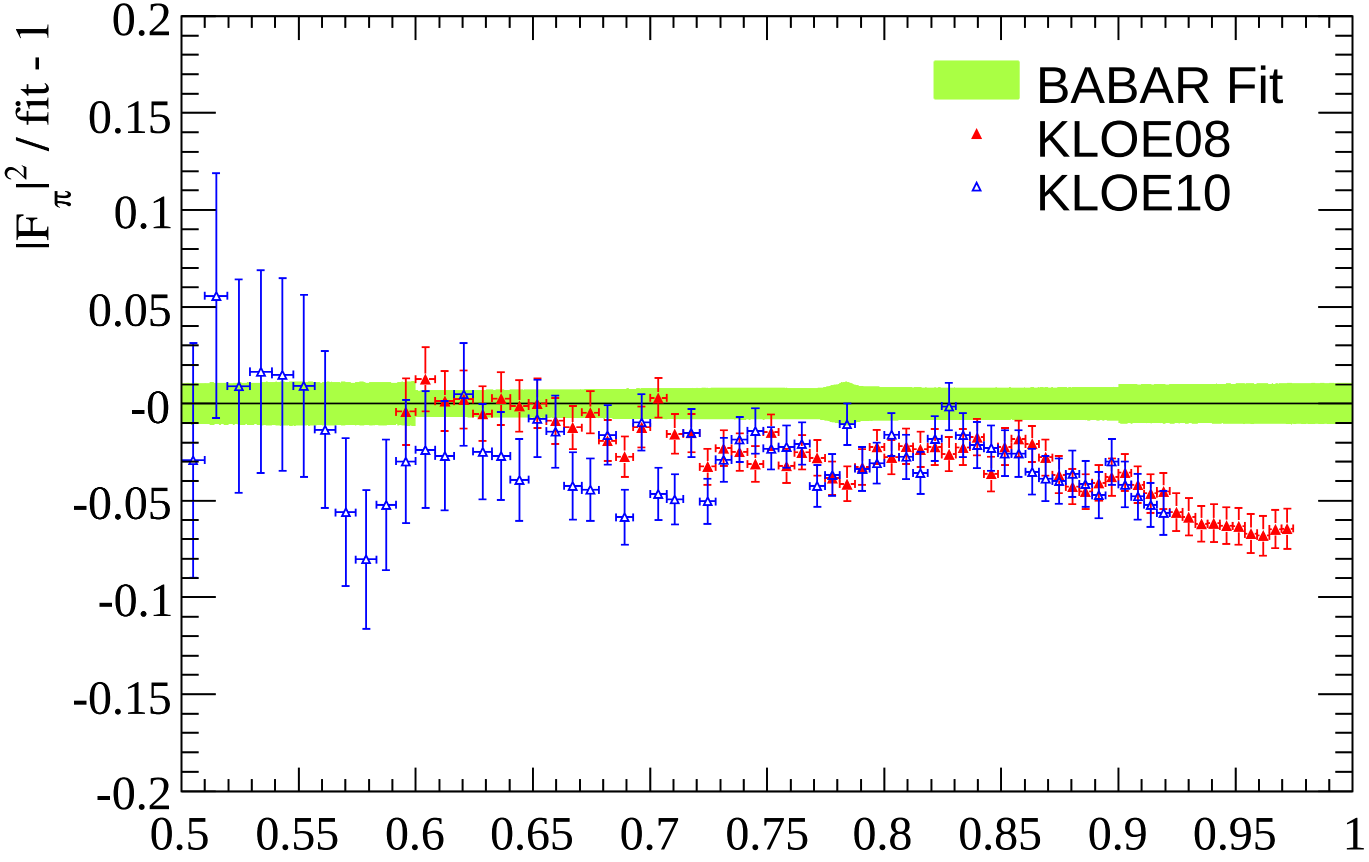
$e^+e^- \to \pi^+\pi^-$, BaBar vs. CMD-2



$e^+e^- \to \pi^+\pi^-$, BaBar vs. SND

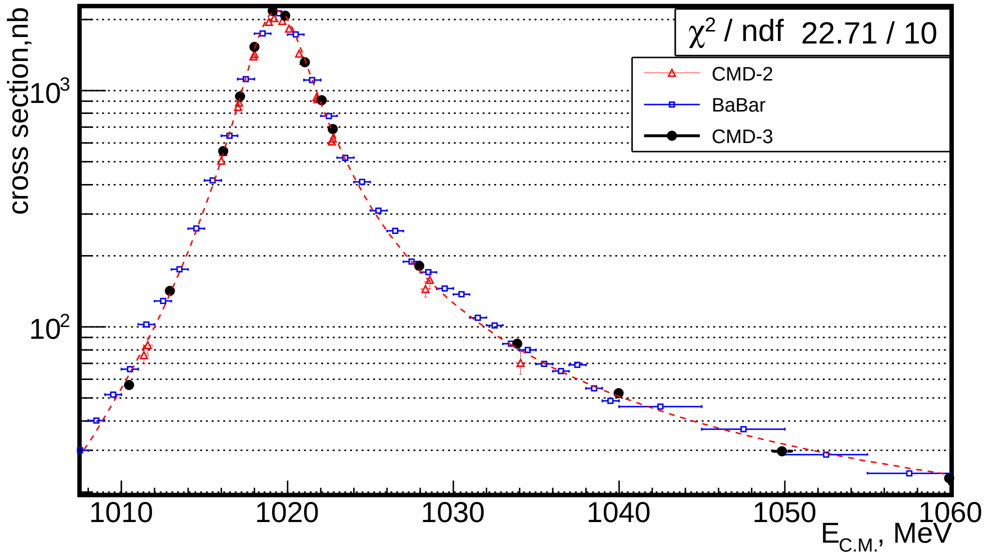


$e^+e^- \to \pi^+\pi^-$, BaBar vs. KLOE



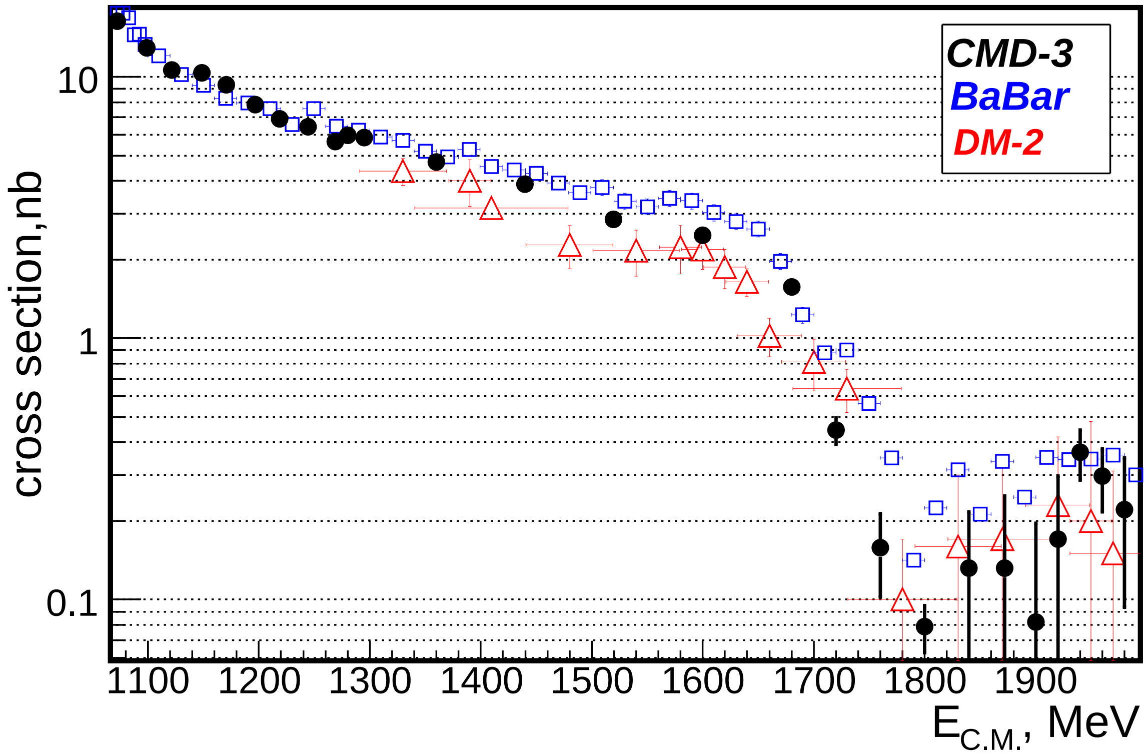
Do we have completely correct ISR theory?

$e^+e^- \to K^+K^-$ at CMD-3 – I



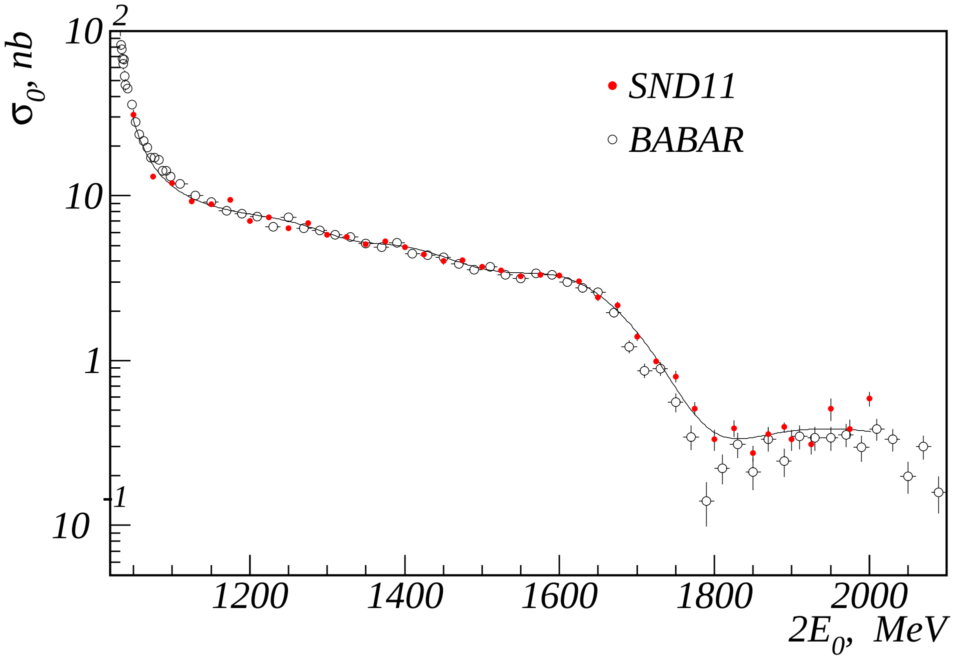
BaBar data higher than CMD-3, CMD-2 and CMD-3 agree

$e^+e^- \to K^+K^-$ at CMD-3 – II



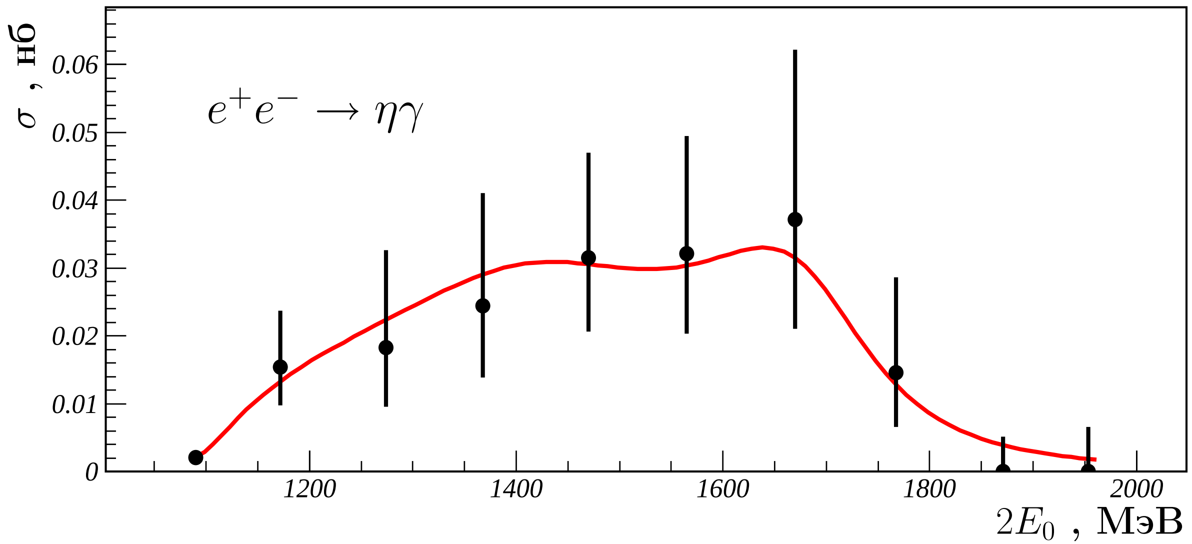
BaBar data higher than CMD-3

$e^+e^- \to K^+K^-$ at SND



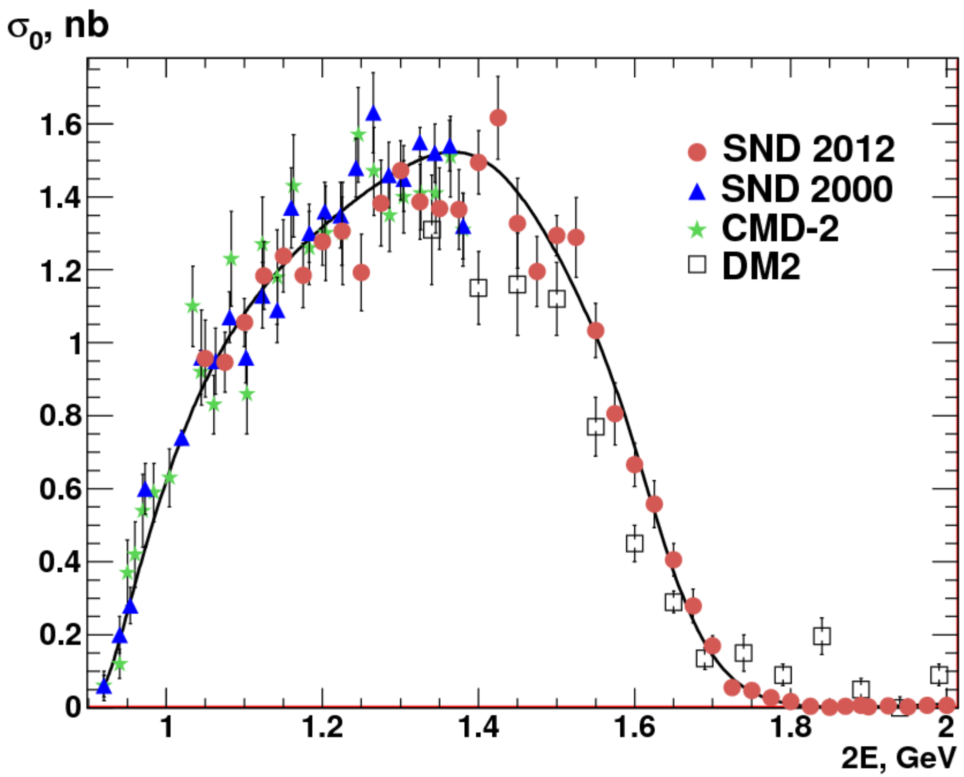
Very preliminary SND data agree with BaBar

$e^+e^- \to \eta\gamma$ at SND



The first measurement of radiative decays above 1.4 GeV, $\rho(1450)$ and $\phi(1680)$, the $\pi^0\gamma$ also looked for, 3γ suffers from QED background

$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ at SND



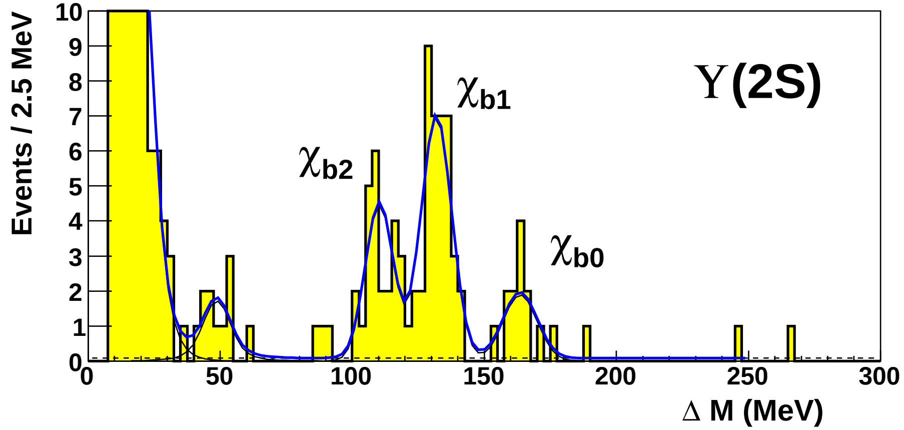
Phys. Rev. D 88 (2013) 054013

First observation above 1.4 GeV, $\pi^0\eta\gamma$, $\eta\eta\gamma$ needed

Missing States – Isospin Relations

- Correctly separate $I=0$ and $I=1$, e.g., $e^+e^- \to \pi^+\pi^-4\pi^0$ has $\omega(\phi)\eta$ with $I=0$
- $K\bar{K}\pi$ – $K^+K^-\pi^0$, $K_S^0K^\pm\pi^\mp$ seen, $K^0\bar{K}^0\pi^0$ – not yet
- Even more combinations with $K\bar{K}\pi\pi$, recent progress at BaBar

Importance of FSR Corrections – I



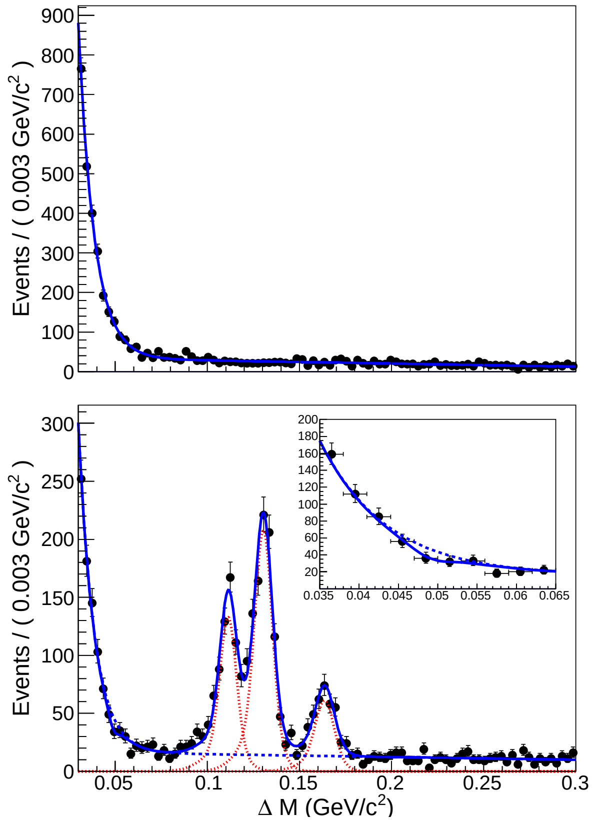
S. Dobbs et al., Phys. Rev. Lett. 109, 082001 (2012) used $9.3 \cdot 10^6$ $\Upsilon(2S)$ of CLEO data to study $\Upsilon(2S) \to \eta_b(2S)\gamma$

Importance of FSR Corrections – II

Group	Signal	$\Delta M_{\rm HF}$, MeV	M, MeV	Sign., σ
"CLEO"	$11.4^{+4.3}_{-3.5}$	$48.7 \pm 2.3 \pm 2.1$	$9974.6 \pm 2.3 \pm 2.1$	4.9
Belle	$(25.8 \pm 4.9) \cdot 10^3$	$24.3^{+4.0}_{-4.5}$	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	4.2

R. Mizuk et al., Phys. Rev. Lett. 109, 232002 (2012) (Belle) at the $\Upsilon(5S)$

Importance of FSR Corrections – III

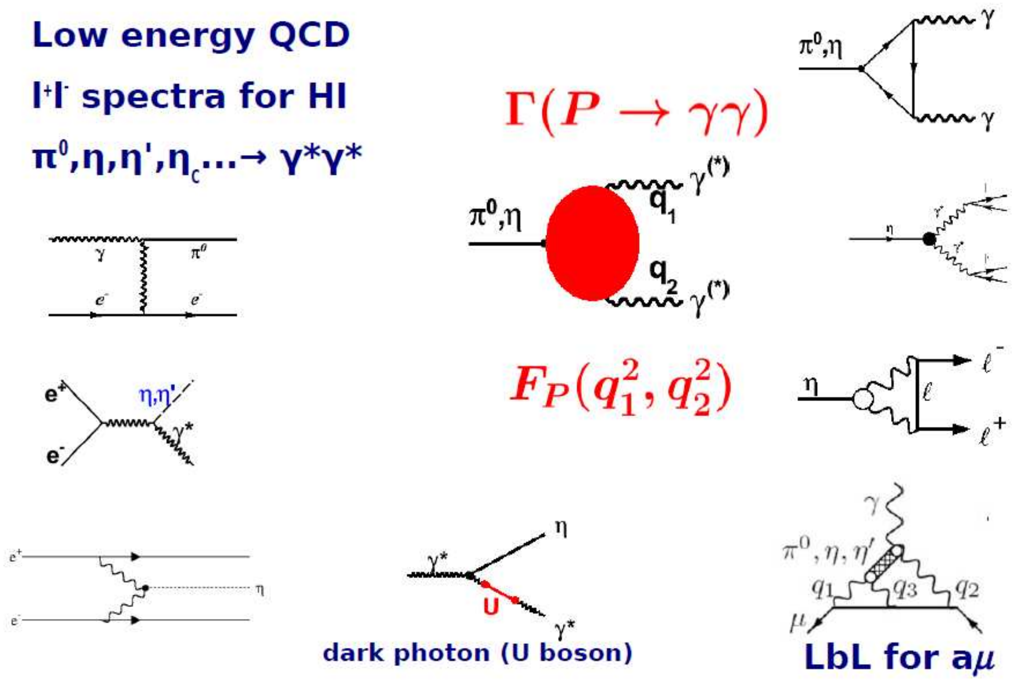


17 times larger statistics – no signal, UL for $\mathcal{B}$ 8 times smaller!

Conclusions on HVP

- VEPP-2000 is running smoothly with CMD-3 and SND
- New channels with many neutrals observed
- CMD-3 and SND at VEPP-2000 will provide high accuracy, comparable or better than ISR measurements, the tentative goals are 0.35%(0.5%) for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE, BaBar, Belle, BES3 and Belle2
- Above 2 GeV R measurements with 3-4% accuracy at BES3 and KEDR
- More precise measurements of Γ_{ee} for the narrow ψ and Υ at KEDR and Belle
- Various high-statistics experiments will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$

Transition Form Factors - I (General)



Transition Form Factors - II (General)

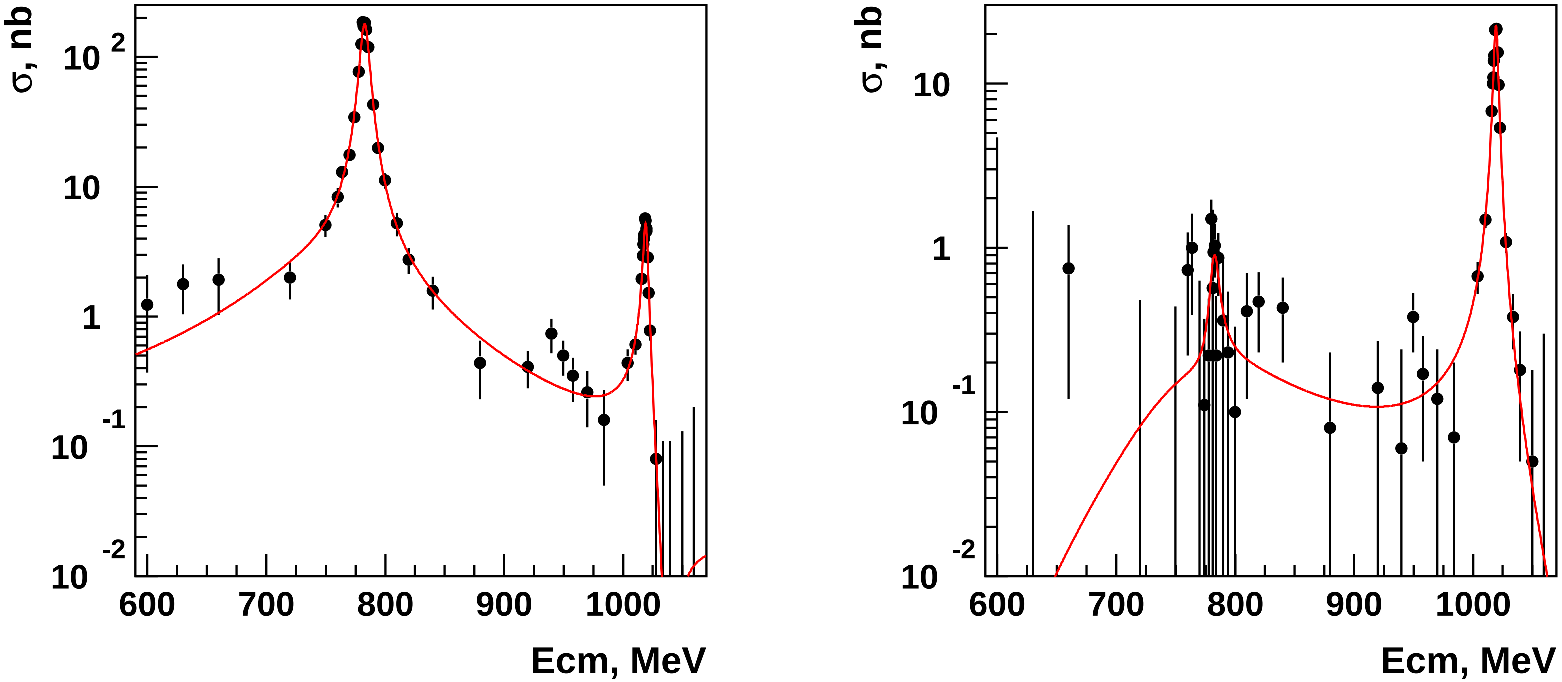
- We are interested in studying the $P\gamma\gamma$ vertex and
  the related TFF $\mathcal{F}_P(q_1^2, q_2^2)$, at any $q_{1(2)}^2$ and $P = \pi^0,\ \eta,\ \eta'$,
  the processes studied are $P \to \gamma^{(*)}\gamma^{(*)}$, $\gamma^* \to P\gamma^{(*)}$ and $\gamma^*\gamma^* \to P$

- In e^+e^- annihilation we study: $e^+e^- \to \gamma^* \to P\gamma,\ \ q_1^2 = s > 0$ and $q_2^2 = 0$;
  $e^+e^- \to \gamma^* \to P\gamma^* \to Pl^+l^-$, $l = e, \mu,\ \ q_1^2 = s > 0$, $4m_l^2 < q_2^2 < (\sqrt{s} - m_P)^2$;
  $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-P$ with $q_{1(2)}^2\ <\ 0$

- In VDM (vector dominance model) hadrons are produced via vector mesons,
  so any production of vectors $\gamma^* \to V \to P\gamma^{(*)}$ is relevant,
  e.g., $e^+e^- \to V \to P\gamma$ with $q_1^2 \sim m_V^2$ and $q_2^2 = 0$
  or $e^+e^- \to V \to Pl^+l^-$ with $q_1^2 \sim m_V^2$ and $4m_l^2\ <\ q_2^2\ <\ (m_V - m_P)^2$

- At the V factory radiative decays like $V \to P\gamma$ are a copious source
  of P decays, e.g., $P \to l^+l^-\gamma$ and $P \to l^+l^-l^+l^-$ can be studied

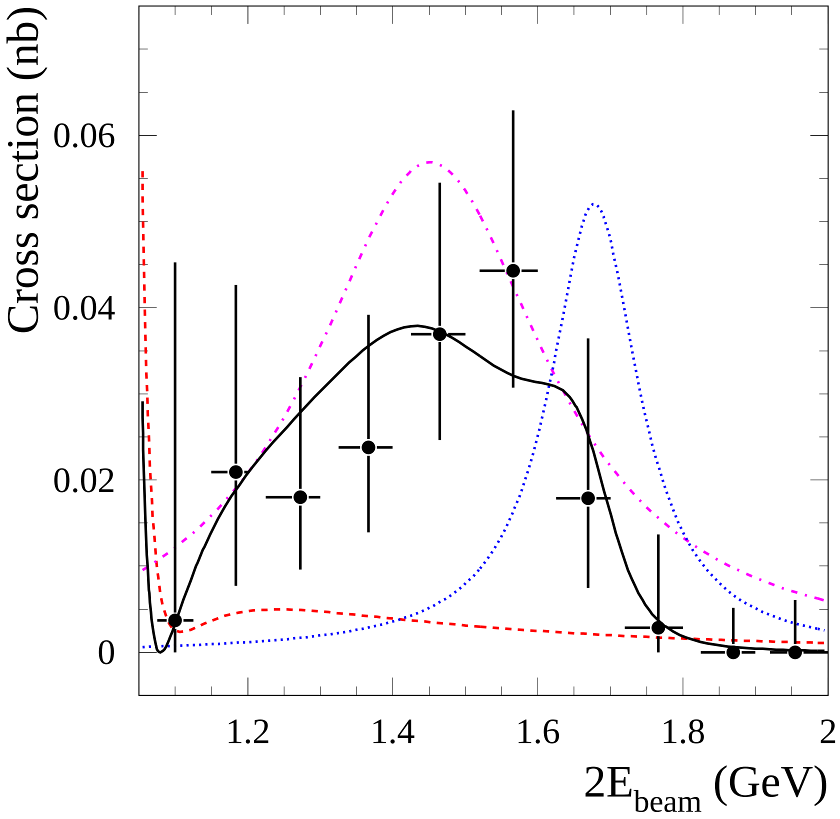
$e^+e^- \to \pi^0\gamma/\eta\gamma$ with CMD-2



R.R. Akhmetshin et al., Phys. Lett. B 605 (2005) 26

10 times larger statistics expected at VEPP-2000

$e^+e^- \to \eta\gamma$ with SND at VEPP-2000



The first measurement of radiative decays above 1.4 GeV, $\rho(1450)$, $\phi(1680)$

M.N. Achasov et al., arXiv:1312.7078

$e^+e^- \to \eta'\gamma$

Seen in ϕ decays only! A study of $\sigma(s)$ not simple. BaBar measured at $\Upsilon(4S)$

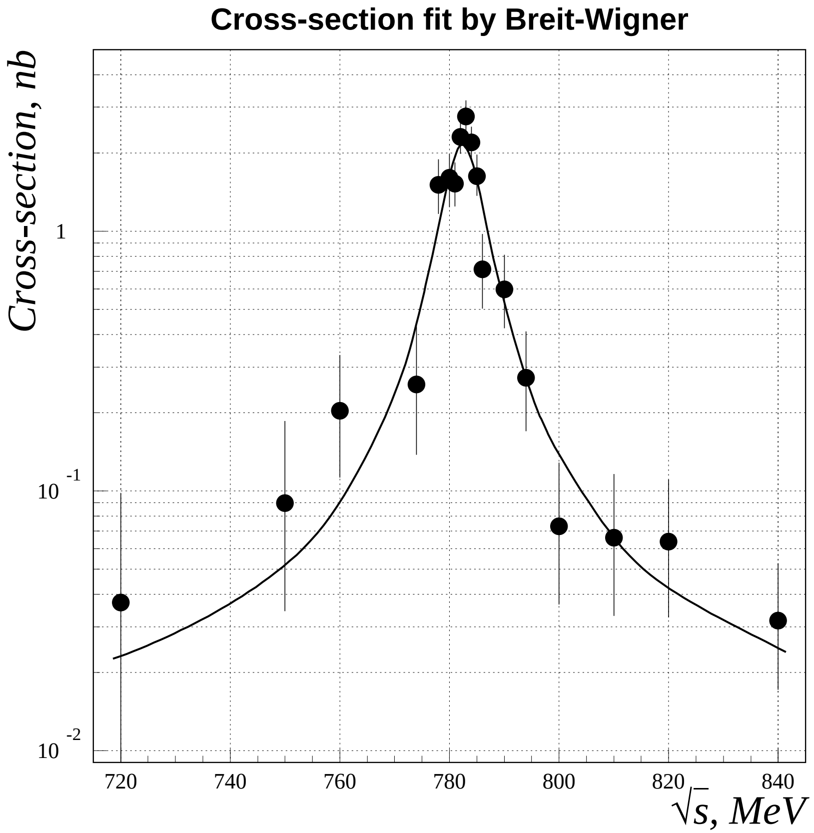
First observed by CMD-2 from 5.5M ϕ's with 6 events only

R.R. Akhmetshin et al., Phys. Lett. B 415 (1997) 445

Group	Date	$N_{\rm ev}$	$\mathcal{B}, 10^{-5}$
CMD-2	2000	30	6.4 ± 1.4
KLOE	2002	120	$6.10 \pm 0.61 \pm 0.43$
SND	2003	12	$6.7^{+2.8}_{-2.4} \pm 0.8$
KLOE	2007	3407	$6.25 \pm 0.28 \pm 0.11$
PDG	2012	–	6.25 ± 0.21

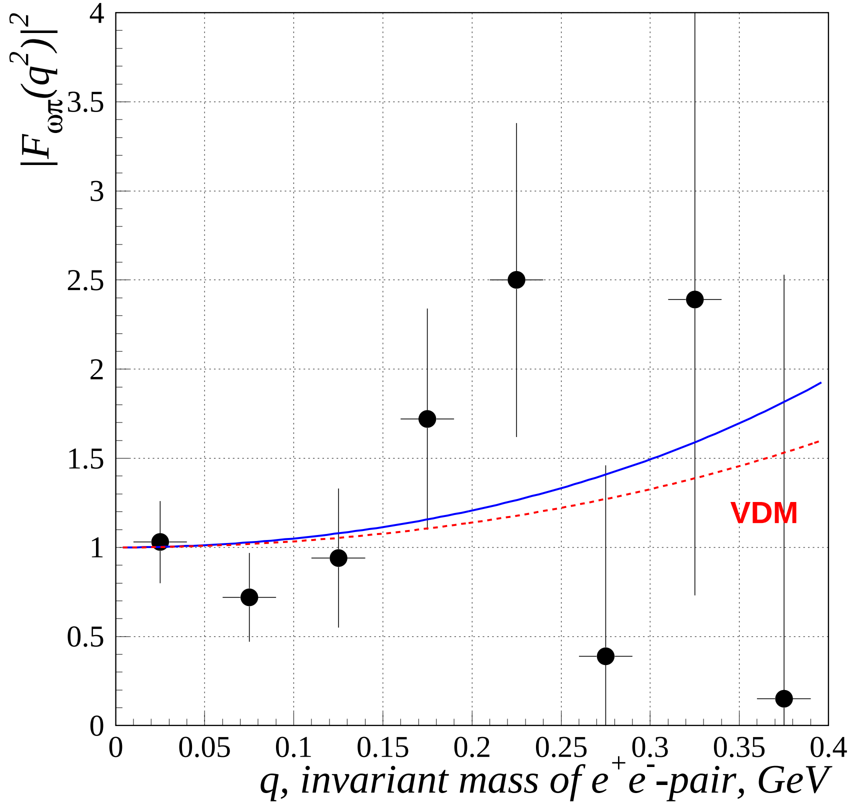
Conversion Decays of $\omega(\rho)$ Mesons – I

$e^+e^- \to \pi^0 e^+ e^-$ in the $\omega(\rho)$ energy range



R.R. Akhmetshin et al., Phys. Lett. B 613 (2005) 29

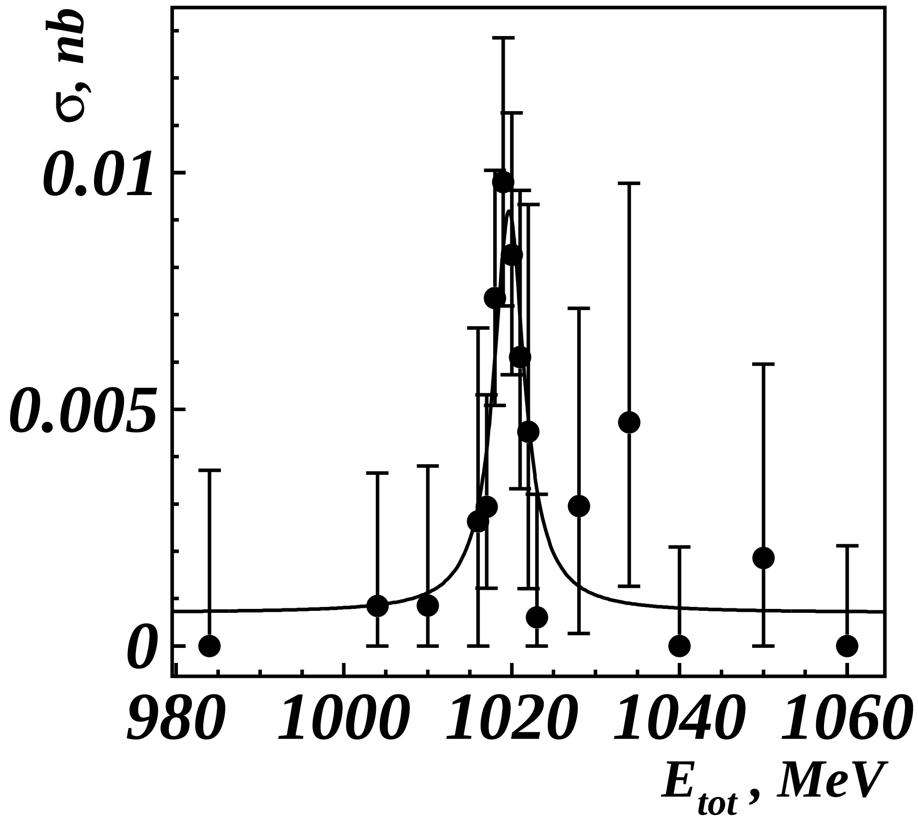
Conversion Decays of $\omega(\rho)$ Mesons – III



A fit gives a slope of 2.5 ± 3.1 GeV^{-2} compatible with $1/m_\rho^2 \sim 1.7$ GeV^{-2}

Conversion Decays of ϕ Mesons – I

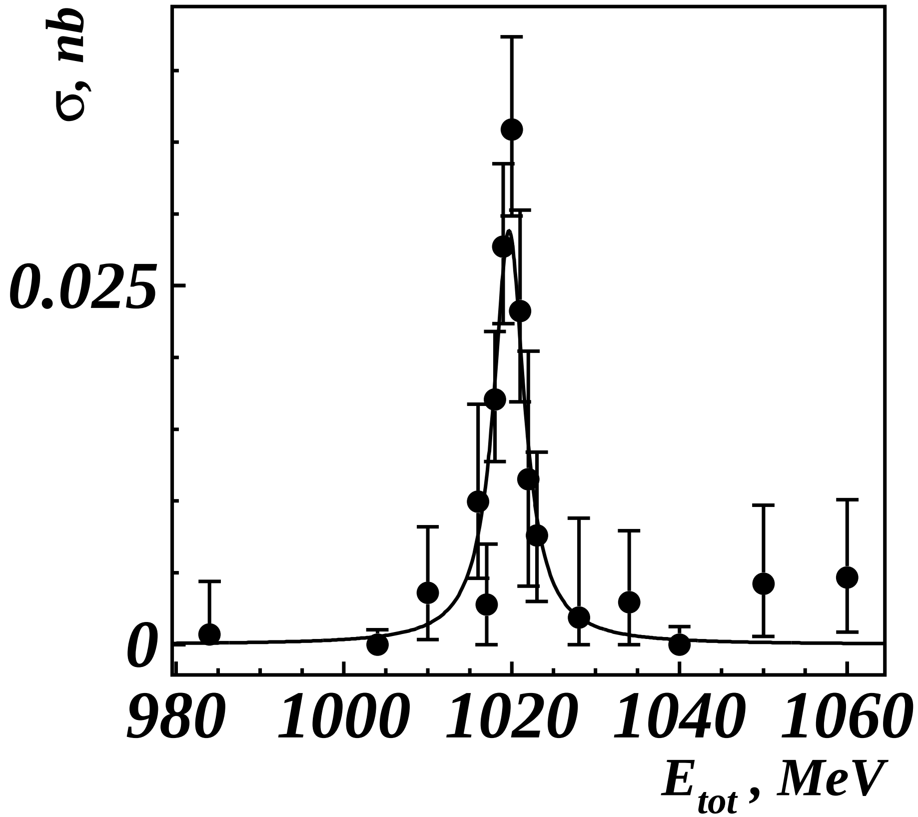
$e^+e^- \to \pi^0 e^+e^-$ in the ϕ energy range



R.R. Akhmetshin et al., Phys. Lett. B 503 (2001) 237

Conversion Decays of ϕ Mesons – II

$e^+e^- \to \eta e^+e^-$ in the ϕ energy range



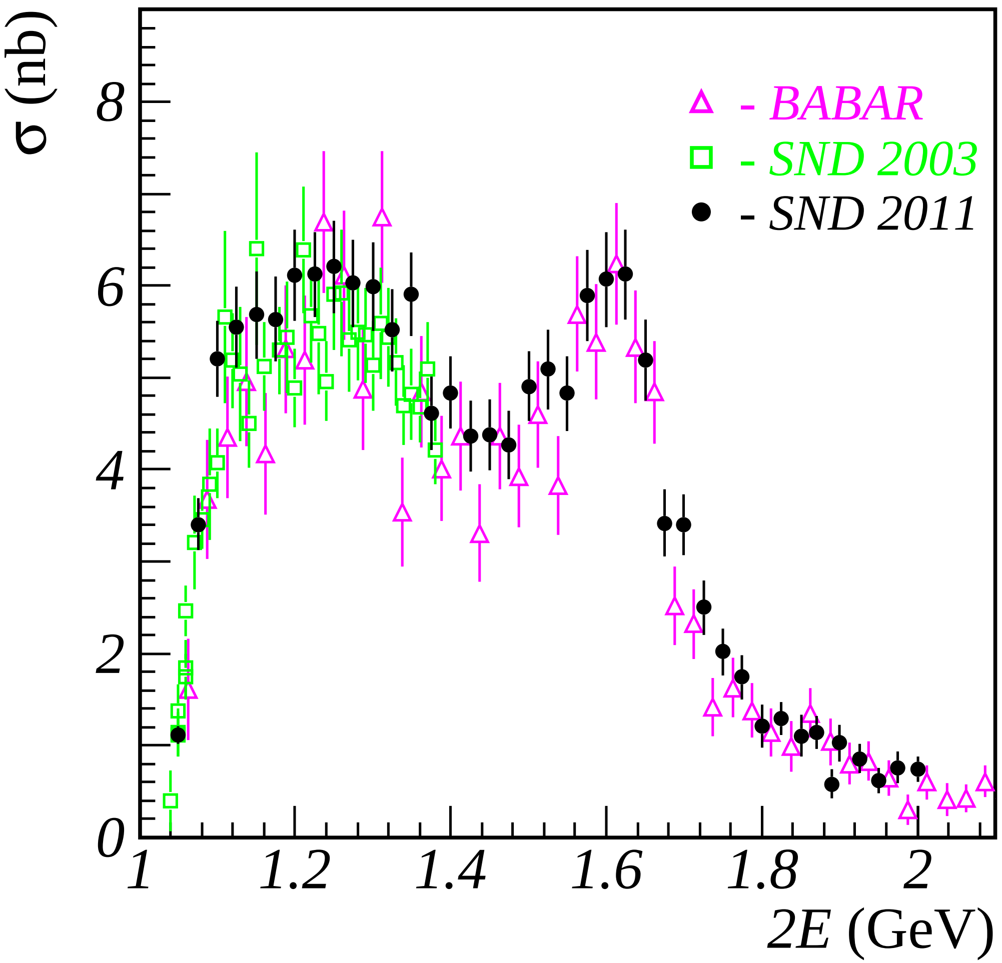
R.R. Akhmetshin et al., Phys. Lett. B 501 (2001) 191

Summary of ρ, ω, ϕ Conversion Decays

Decay	$l = e$		$l = \mu$	
	$\mathcal{B}_{\rm exp}$	$\mathcal{B}_{\rm th}$	$\mathcal{B}_{\rm exp}$	$\mathcal{B}_{\rm th}$
$\rho \to \pi^0 l^+ l^-$	$< 1.2 \cdot 10^{-5}$	$4.1 \cdot 10^{-6}$	–	$4.6 \cdot 10^{-7}$
$\rho \to \eta l^+ l^-$	$< 0.7 \cdot 10^{-5}$	$2.7 \cdot 10^{-6}$	–	$7.0 \cdot 10^{-11}$
$\omega \to \pi^0 l^+ l^-$	$(7.7 \pm 0.6) \cdot 10^{-4}$	$7.9 \cdot 10^{-4}$	$(1.3 \pm 0.4) \cdot 10^{-4}$	$9.2 \cdot 10^{-5}$
$\omega \to \eta l^+ l^-$	–	$6.0 \cdot 10^{-6}$	–	$1.8 \cdot 10^{-9}$
$\phi \to \pi^0 l^+ l^-$	$(1.12 \pm 0.28) \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$	–	$4.8 \cdot 10^{-6}$
$\phi \to \eta l^+ l^-$	$(1.15 \pm 0.10) \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$< 9.4 \cdot 10^{-6}$	$6.8 \cdot 10^{-6}$

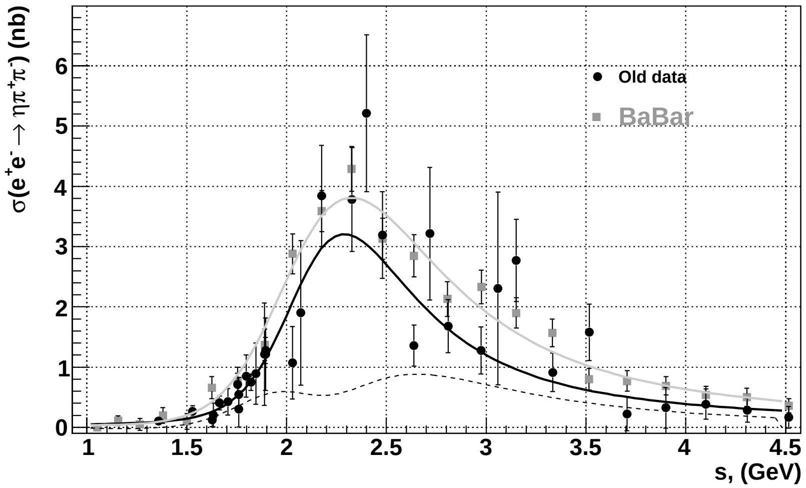
Decays with muons are much worse studied

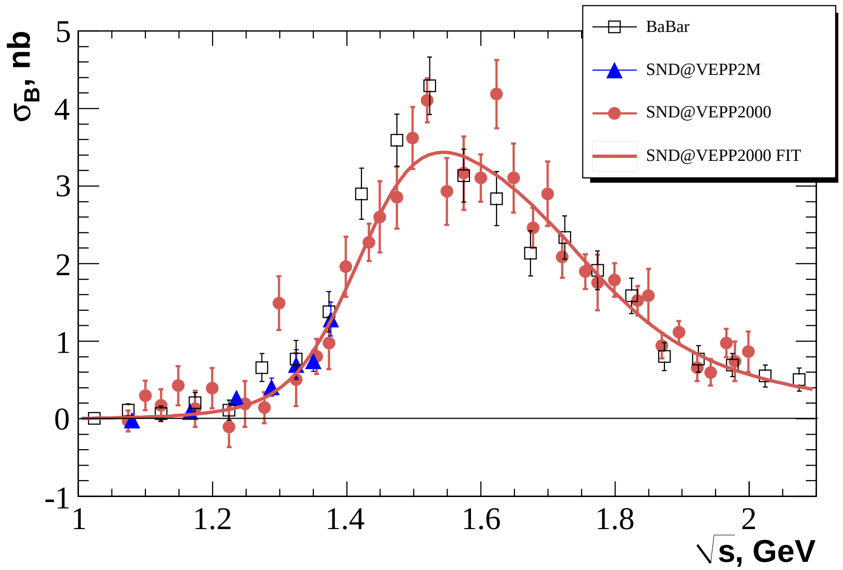
$e^+e^- \to \pi^+\pi^-\pi^0$ at SND



It's interesting to disentangle the $\rho\pi$ and direct 3π modes

$e^+e^- \to \eta\pi^+\pi^-$ at SND

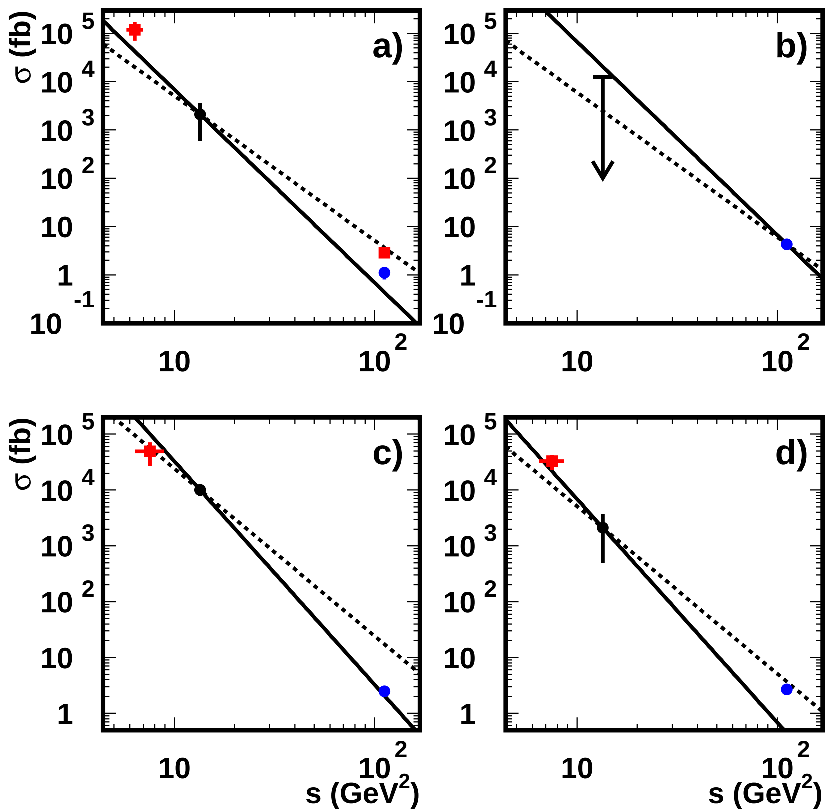




BaBar data higher than old data by $\sim 15\%$, not confirmed by new SND data?

Dominated by $e^+e^- \to \eta\rho$

$\gamma^* \to VP$



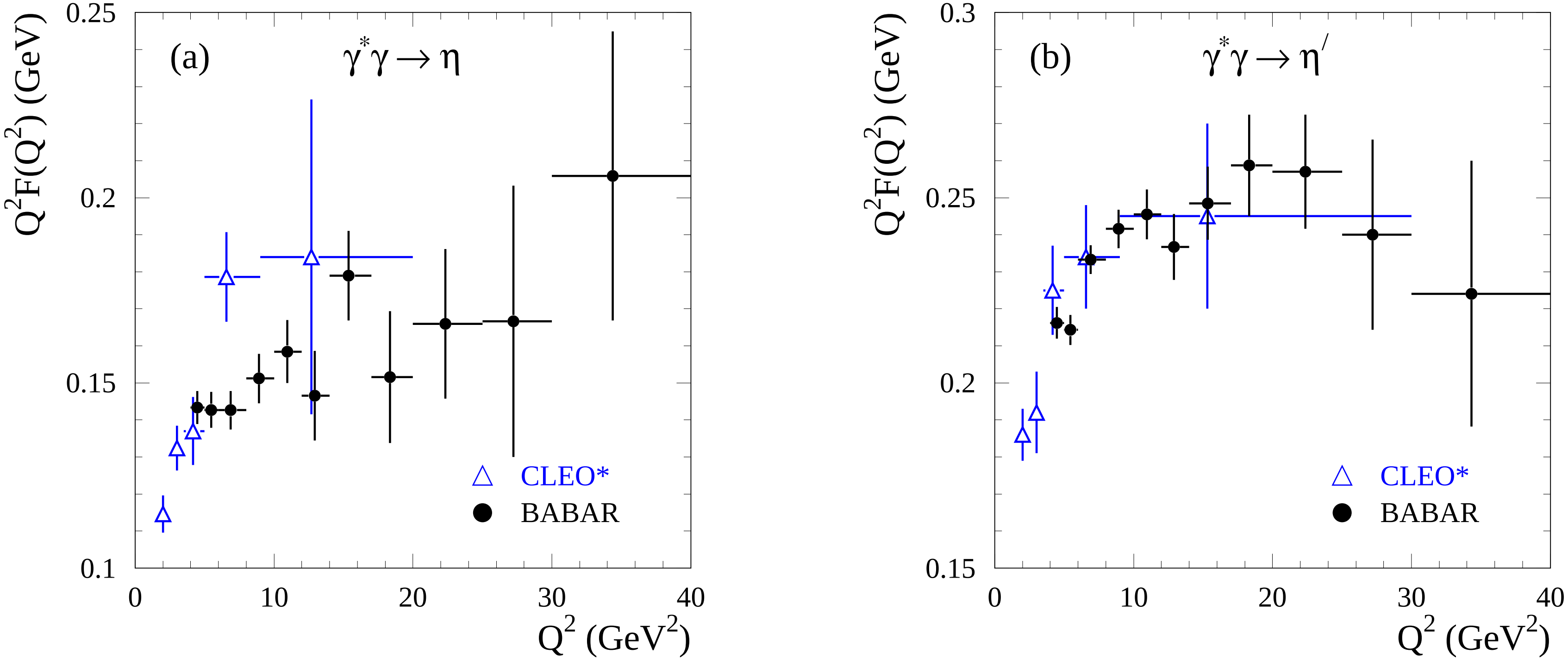
(a) $\phi\eta$, (b) $\phi\eta'$, (c) $\rho\eta$, (d) $\rho\eta'$

Solid – $1/s^4$, dashed – $1/s^3$

QCD Studies in $\gamma\gamma \to M_1 M_2$ at Belle

Final state	$\int L dt$, fb^{-1}	W, GeV	$\lvert\cos\theta^*\rvert$	Reference
$\pi^+\pi^-$,	87.7	2.4-4.1	< 0.6	H. Nakazawa et al.,
K^+K^-				PLB 615, 39 (2005)
$p\bar{p}$	89	2.025-4	< 0.6	C.C.Kuo et al.,
				PLB 621, 41 (2005)
$\pi^0\pi^0$	223	0.6-4.1	< 0.8	S.Uehara et al.,
				PRD 79, 052009 (2009)
$\eta\pi^0$	223	0.84-4.0	< 0.8	S.Uehara et al.,
				PRD 80, 032001 (2009)
$\eta\eta$	393	1.096-3.8	< 0.9	S.Uehara et al.,
			< 1.0	PRD 82, 114031 (2010)
$K^0_S K^0_S$	972	1.05-4.0	< 0.8	S.Uehara et al.,
				PTEP2013(2013)123C01

Transition Form Factors in $\gamma^*\gamma \to \eta,\ \eta'$

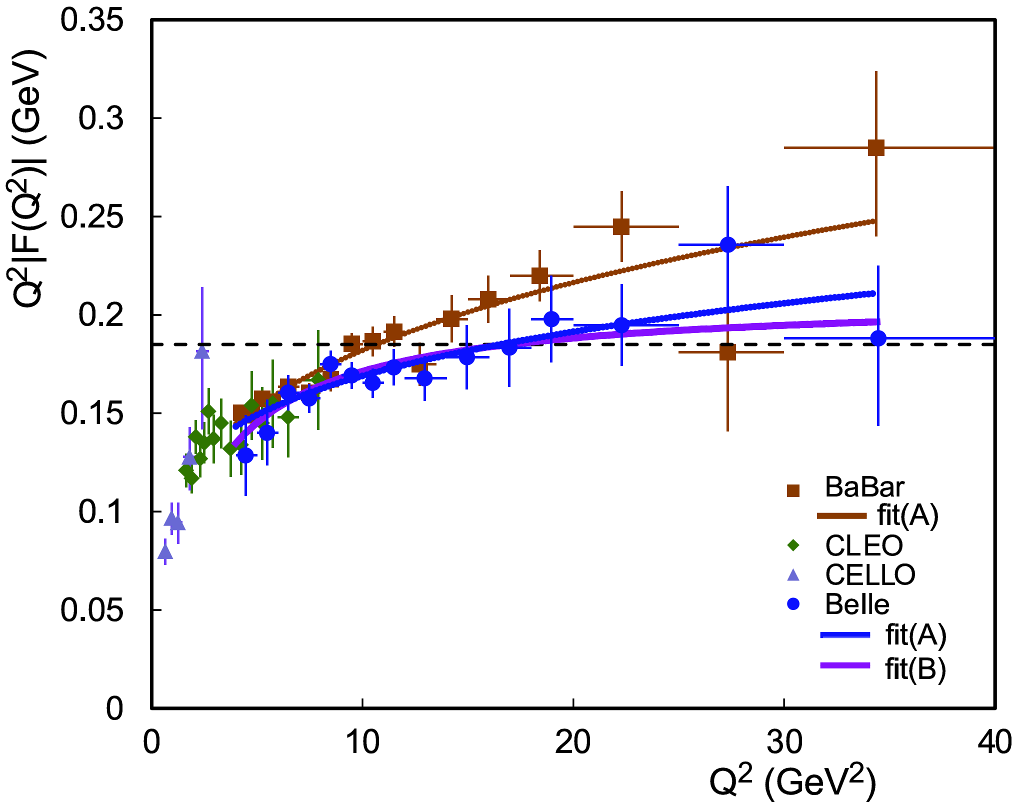


Single-tag measurements probe $\gamma\gamma^*$

P. del Amo Sanchez et al. (BaBar), Phys. Rev. D 84, 052011 (2011)

J. Gronberg et al. (CLEO), Phys. Rev. D 57, 33 (1998)

Transition Form Factors in $\gamma^*\gamma \to \pi^0$



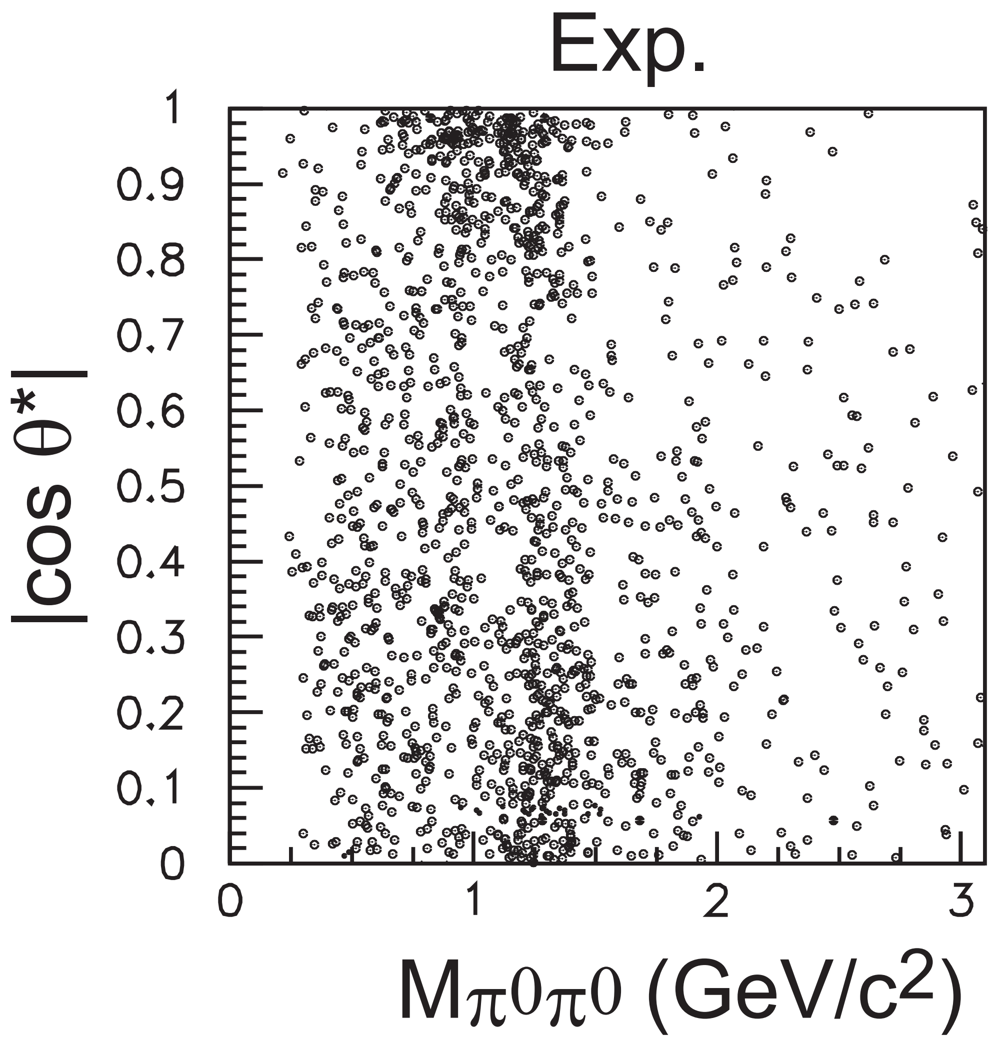
Belle data do not confirm fast rise observed at BaBar

S. Uehara et al., Phys. Rev. D 86 (2012) 092007

Single-tag $\gamma\gamma \to \pi^0\pi^0$ at Belle – I

- Background for single-tag $\gamma\gamma \to \pi^0$ (759 fb^{-1})
- A clear signal of $f_2(1270)$, possibly $f_0(980)$?
- A few thousand events, $3 < Q^2 < 30\text{GeV}^2$ and $0.5 < W < 2.5$ GeV
- Information on transition f/f for tensors, scalars;
  with other final states to axial vectors

Single-tag $\gamma\gamma \to \pi^0\pi^0$ at Belle – II



Conclusions

- e^+e^- colliders (DAFNE, VEPP-2000, BEPC-II and SuperKEKB) have a very high potential for studying $\gamma^{(*)}\gamma^{(*)}$ physics
- A lot of different possibilities: $e^+e^- \to P\gamma$, Pl^+l^-, $P\pi^+\pi^-$, $e^+e^- \to e^+e^-P$
- KLOE-2 with taggers – $\Gamma_{\gamma\gamma}$ for π^0, η, $\gamma\gamma \to \pi^0\pi^0$
- Taggers would be extremely helpful, but they are not absolutely necessary
- $\mathcal{F}_P(q_1^2, q_2^2)$ can be studied in various regions of q_i^2, hopefully leading to better modeling of HLbL for a_μ