Low Energy $e^+e^- \to$ Hadrons and Status of $(g_\mu - 2)/2$

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Outline

1. Why is it important?
2. QED
3. Electroweak term
4. Progress with e^+e^- data
5. LO hadronic term
6. Future
7. Conclusions

Muon Anomalous Magnetic Moment

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

a_μ is measured with a $5 \cdot 10^{-7}$ relative accuracy:

G.W. Bennett et al., 2004, 2006 $\quad a_\mu = (11659208.0 \pm 6.3) \cdot 10^{-10}$.

$a_{\rm e}$ is measured with a $4.9 \cdot 10^{-10}$ accuracy, but a_μ is much more sensitive to new physics effects: the gain is usually $\sim (m_\mu/m_{\rm e})^2 \approx 4.3 \cdot 10^4$.

Any significant difference of $a_\mu^{\rm exp}$ from $a_\mu^{\rm th}$ indicates new physics beyond the Standard Model.

$$a_\mu^{\rm th} = a_\mu^{\rm SM} + a_\mu^{\rm non-SM}, \qquad a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}.$$

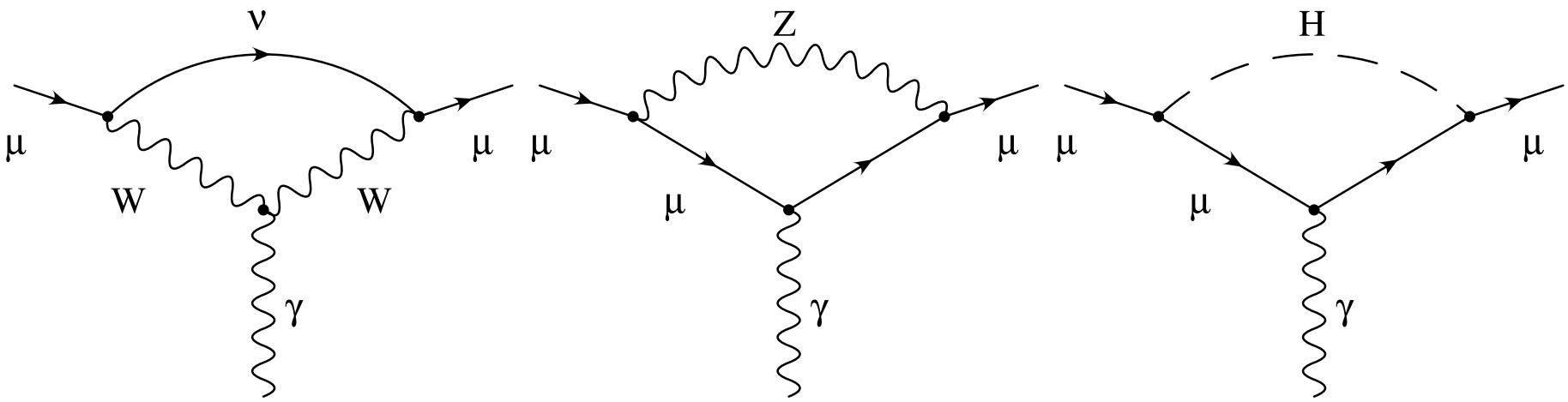
QED Contribution $a_\mu^{\rm QED}$

$$
\begin{aligned}
a_\mu^{\rm QED}\cdot 10^{10} = \Sigma C_i(\tfrac{\alpha}{\pi})^i = \quad & 11614097.3 \text{ (1-loop)} \\
+ \quad & 41321.8 \text{ (2-loop)} \\
+ \quad & 3014.2 \text{ (3-loop)} \\
+ \quad & 38.1 \text{ (4-loop)} \\
+ \quad & 0.4 \text{ (5-loop)}
\end{aligned}
$$

Terms up to α^3 are known analytically, a recent more accurate numerical calculation of the α^4 terms and the leading log α^5 terms gave (T. Kinoshita and M. Nio, 2005; A.L. Kataev, 2006):
$a_\mu^{\rm QED} = (116584719.4 \pm 1.4)\cdot 10^{-11}$.

From the latest value of a_e (G. Gabrielse et al., 2006; M. Passera, 2006):
$\alpha^{-1} = 137.035999710(96)$, $a_\mu^{\rm QED} = (116584718.09 \pm 0.14 \pm 0.08)\cdot 10^{-11}$.
The errors are due to: a/ $\mathcal{O}(\alpha^5)$, b/ α

Electroweak contribution $a_\mu^{\rm EW}$



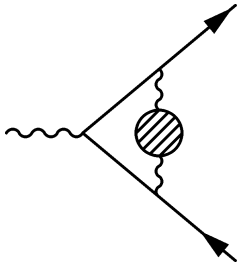
One-loop electroweak contributions

Authors	Year	$a_\mu^{\rm EW}$, 10^{-10}
..., ..., ...	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 $a_\mu^{\rm had}$

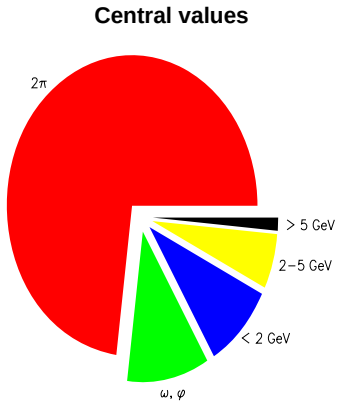
$$a_\mu^{\rm had} = a_\mu^{\rm had,LO} + a_\mu^{\rm had,HO} + a_\mu^{\rm had,LBL}$$

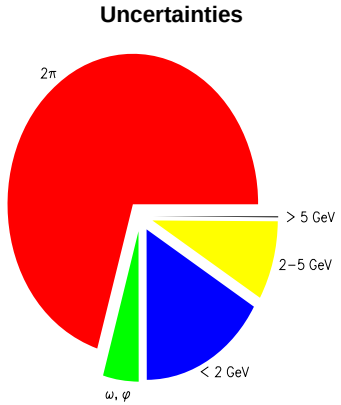


$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\,\hat{K}(s)}{s^2},$$

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

$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$, $1/s^2$ emphasizes the role of low energies, particularly important is the reaction $e^+e^- \to \pi^+\pi^-$ with a large cross section below 1 GeV.



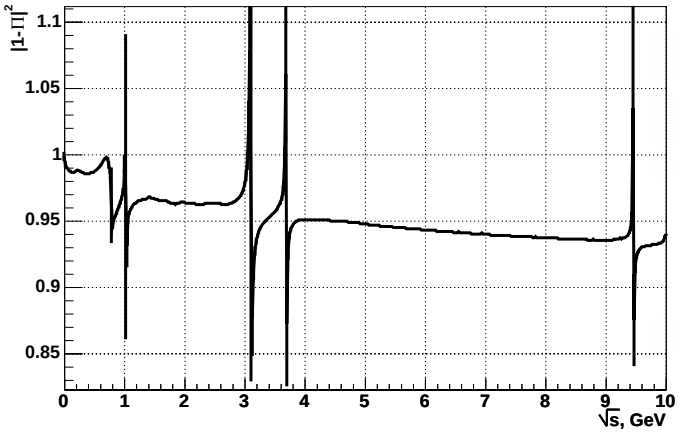


Measurement of R(s)

- $\sqrt{s} < 2$ GeV – exclusive modes $(\pi^+\pi^-, \pi^+\pi^-\pi^0, \ldots, K\bar{K}, \ldots)$
- Possibly missing (small σ, undetected) final states
- Above 2 GeV – total R (all multihadronic events)
- Initial state radiation (ISR), vacuum polarization (VP), final state radiation (FSR): M. Drees, K. Hikasa, 1990

$$\sigma_{\rm dr} = \frac{N}{\int Ldt\ \varepsilon\ (1+\delta_{\rm ISR})}$$

$$\sigma_{\rm bare} = \sigma_{\rm dr}|1-\Pi(s)|^2(1+\delta_{\rm FSR})$$



$|1-\Pi(s)|^2$

Radiative Return (ISR)

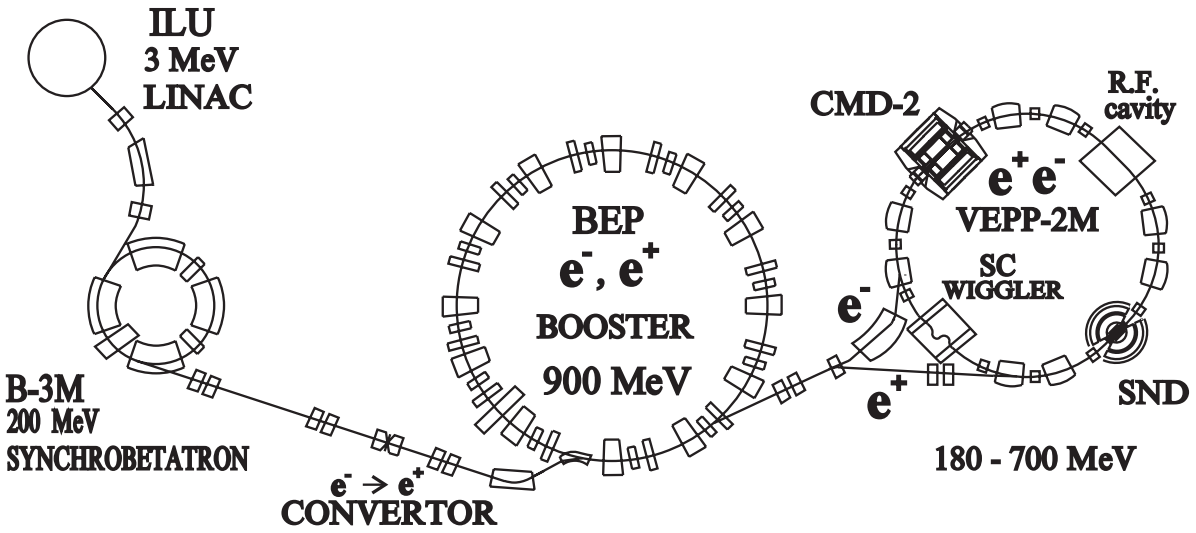
Scan: luminosity is collected at many separate c.m.energy points.

Radiative return: luminosity is collected at fixed c.m.energy. A photon with E_γ energy emitted by initial $e^\pm$ allows a study of hadron production at smaller energy: $2E' = 2E\sqrt{1 - E_\gamma/E}$. A smaller σ is compensated by a much higher $\mathcal{L}$.

KLOE – 11k/pb^{-1} vs. 360k/pb^{-1} with CMD-2, but 1.5M $\pi^+\pi^-$ events in total!
BaBar – $150 \cdot 10^3$ exclusive events between 1 and 3 GeV per 100 fb^{-1}.
Belle – starting.

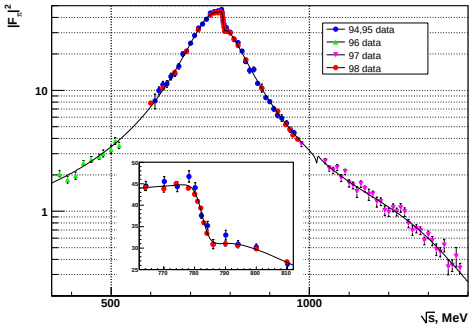
Recent developments include:
$e^+e^- \to \pi^+\pi^-$ at CMD-2 (scan from 370 MeV to 1380 MeV), SND (scan from 390 to 970 MeV) and KLOE (ISR from 590 to 970 MeV),
BaBar studies of $e^+e^- \to \pi^+\pi^-\pi^0$, $2\pi^+2\pi^-$, 6π (ISR below 2 GeV)

VEPP-2M Collider in Novosibirsk



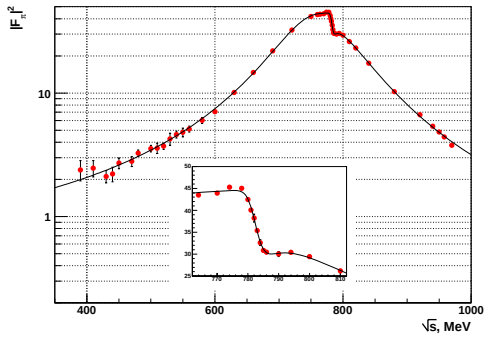
- Experiments: 1974 – 2000
- Energy range: $0.36 < \sqrt{s} < 1.40$ GeV
- Peak luminosity: $L_{\rm peak} = 3 \cdot 10^{30}$ cm^{-2} s^{-1}
- Integrated luminosity ≈ 70 pb^{-1} in Novosibirsk below 1.4 GeV compared to ≈ 6 pb^{-1} in Orsay and Frascati at $1.4 < \sqrt{s} < 3.0$ GeV!

$e^+e^- \to \pi^+\pi^-$ (CMD-2, SND and KLOE)



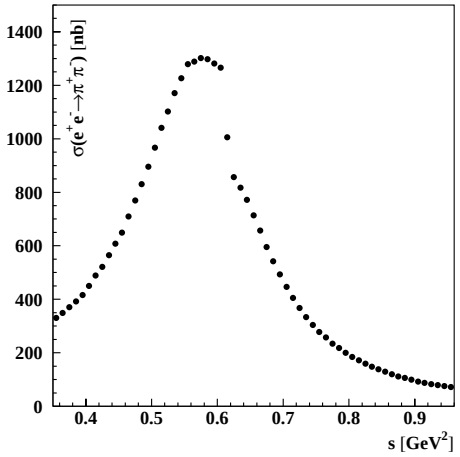
CMD-2: $\sim 9 \cdot 10^5$ ev.

2E, MeV	σ, %
370-520	0.7
600-970	0.6-0.8
1040-1380	1.3-4.2



SND: $\sim 8 \cdot 10^5$ ev.

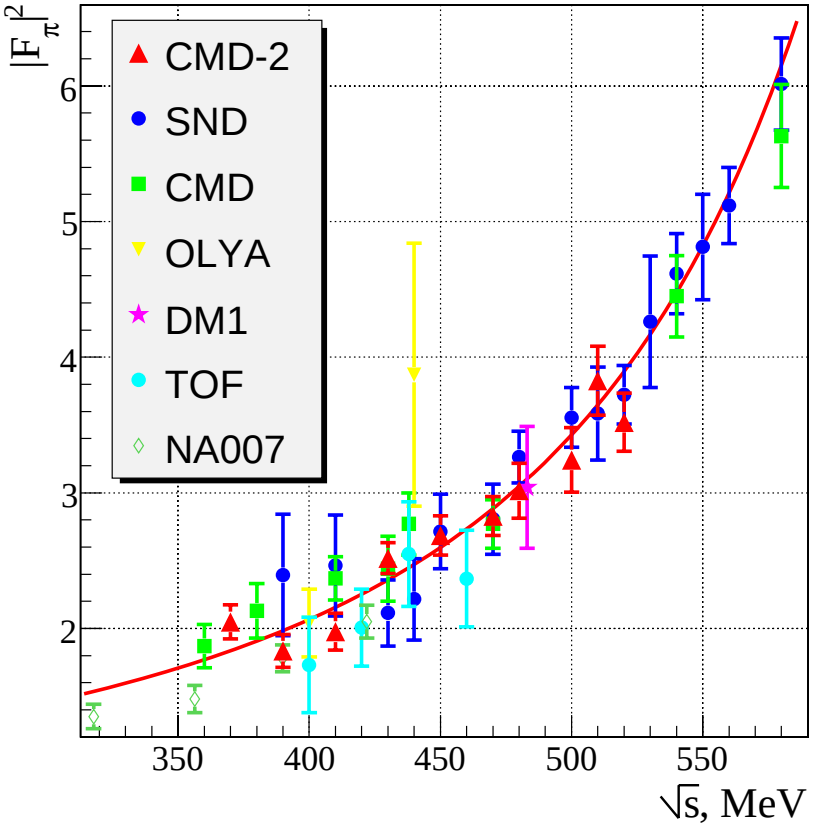
2E, MeV	σ, %
390-420	3.2
430-970	1.3



KLOE: $\sim 1.5 \cdot 10^6$ ev.

(590-970) MeV - 1.3%

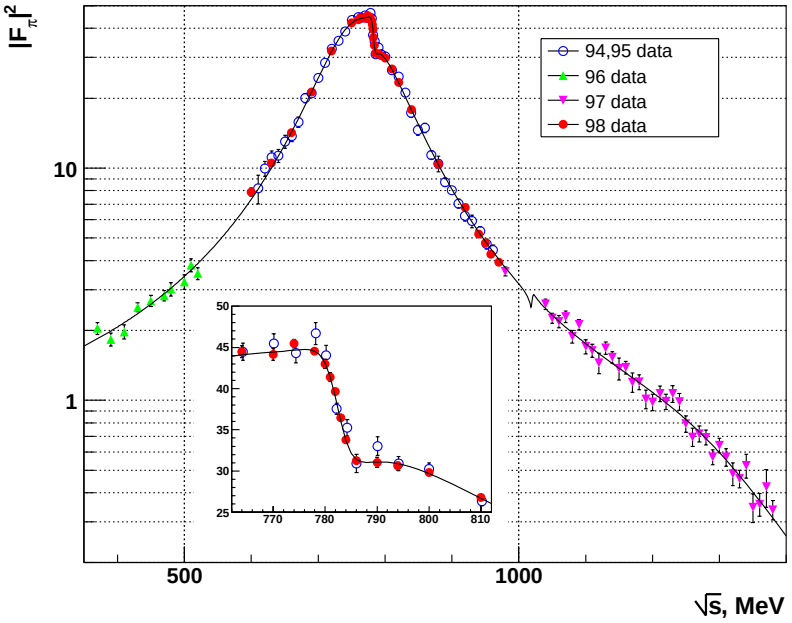
$e^+e^- \to \pi^+\pi^-$ from 390 to 520 MeV

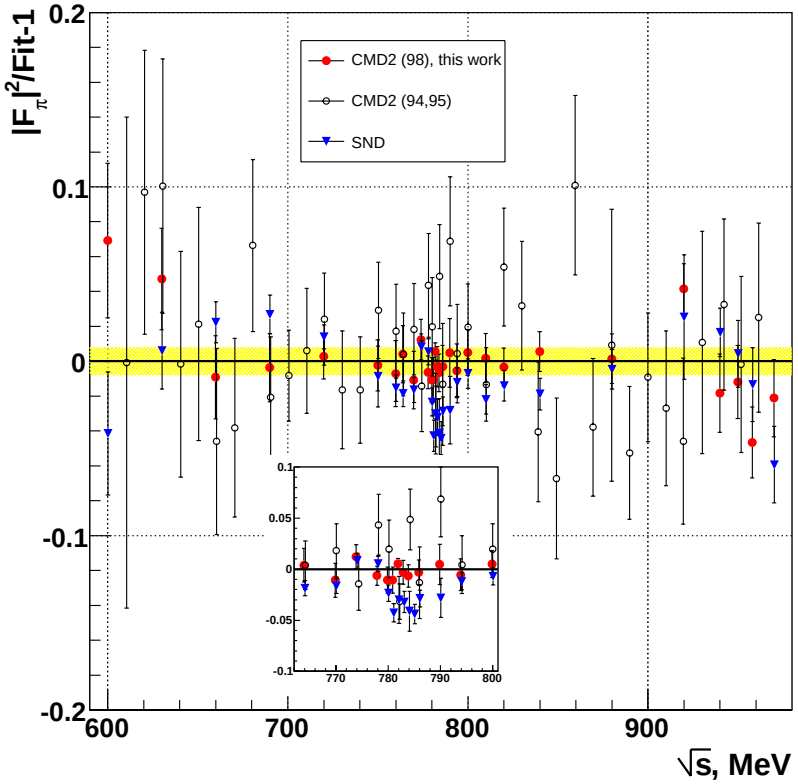


Group	$a_\mu^{\pi\pi,\mathrm{LO}}, 10^{-10}$
Old	$48.72 \pm 1.45 \pm 1.12$ (1.83)
CMD-2	$46.17 \pm 0.98 \pm 0.32$ (1.03)
SND	$47.80 \pm 1.73 \pm 0.69$ (1.86)
CMD-2/SND	$46.55 \pm 0.85 \pm 0.29$(0.90)
Average	$46.97 \pm 0.73 \pm 0.45$(0.86)

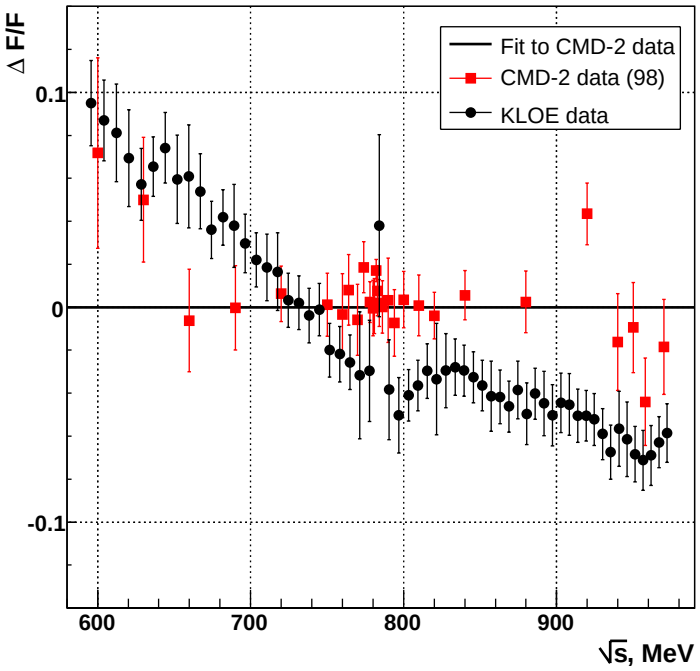
Two-fold improvement of $\Delta a_\mu^{\pi\pi,\mathrm{LO}}$ due to the CMD-2 and SND results

$e^+e^- \to \pi^+\pi^-$ near the ρ





$e^+e^- \to \pi^+\pi^-$ from 600 to 960 MeV

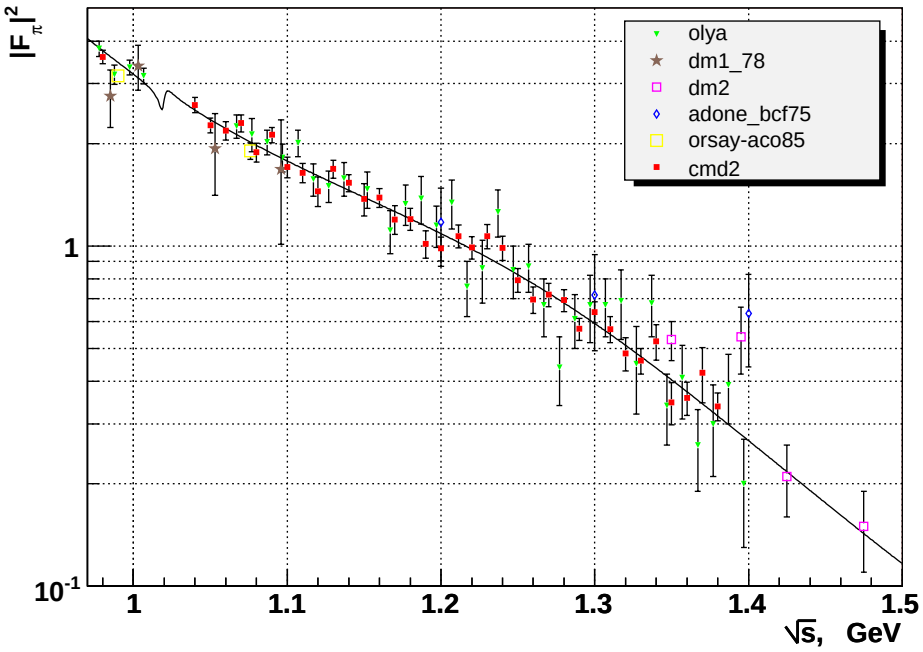


Group	$a_\mu^{\pi\pi,\mathrm{LO}}, 10^{-10}$
Old	$374.8 \pm 4.1 \pm 8.5$ (9.4)
CMD-2	$377.1 \pm 1.9 \pm 2.7$ (3.3)
SND	$376.8 \pm 1.3 \pm 4.7$ (4.8)
KLOE	$375.6 \pm 0.8 \pm 4.9$ (5.0)
Av. (w.KLOE)	$376.5 \pm 2.1 \pm 1.5$(2.5)
Av. (w/o KLOE)	$377.0 \pm 2.2 \pm 1.6$(2.7)

Local disagreement between KLOE and CMD-2/SND.

Should we use the KLOE result?

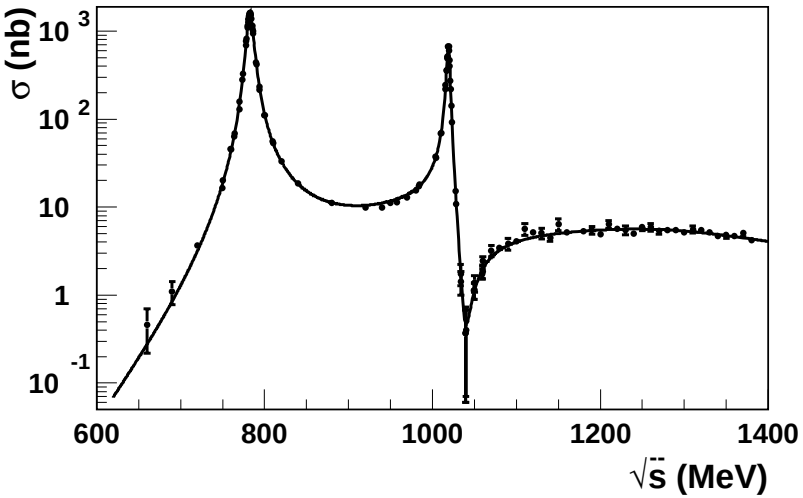
$a_\mu^{\pi\pi,\mathrm{LO}}$ from 1040 to 1380 MeV

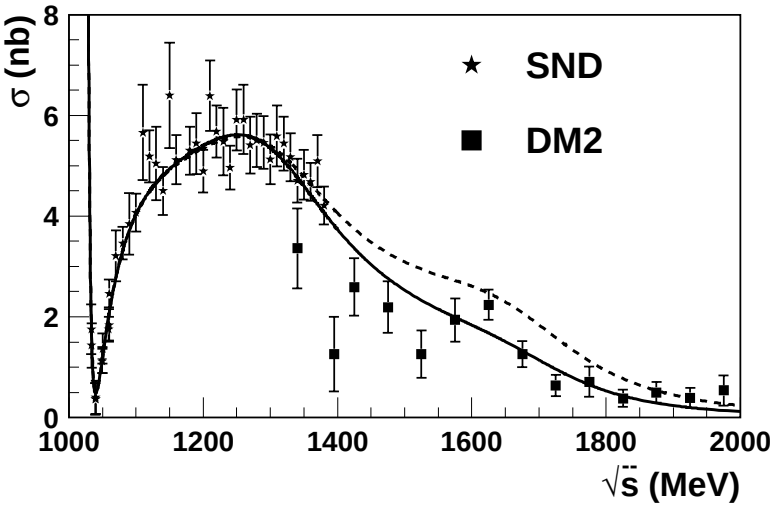


Group	$a_\mu, 10^{-10}$
OLYA	$7.49 \pm 0.18 \pm 0.83$ (0.85)
CMD-2	$7.01 \pm 0.10 \pm 0.16$ (0.19)
Average	$7.03 \pm 0.09 \pm 0.16$ (0.18)

Significant improvement due to the CMD-2 results

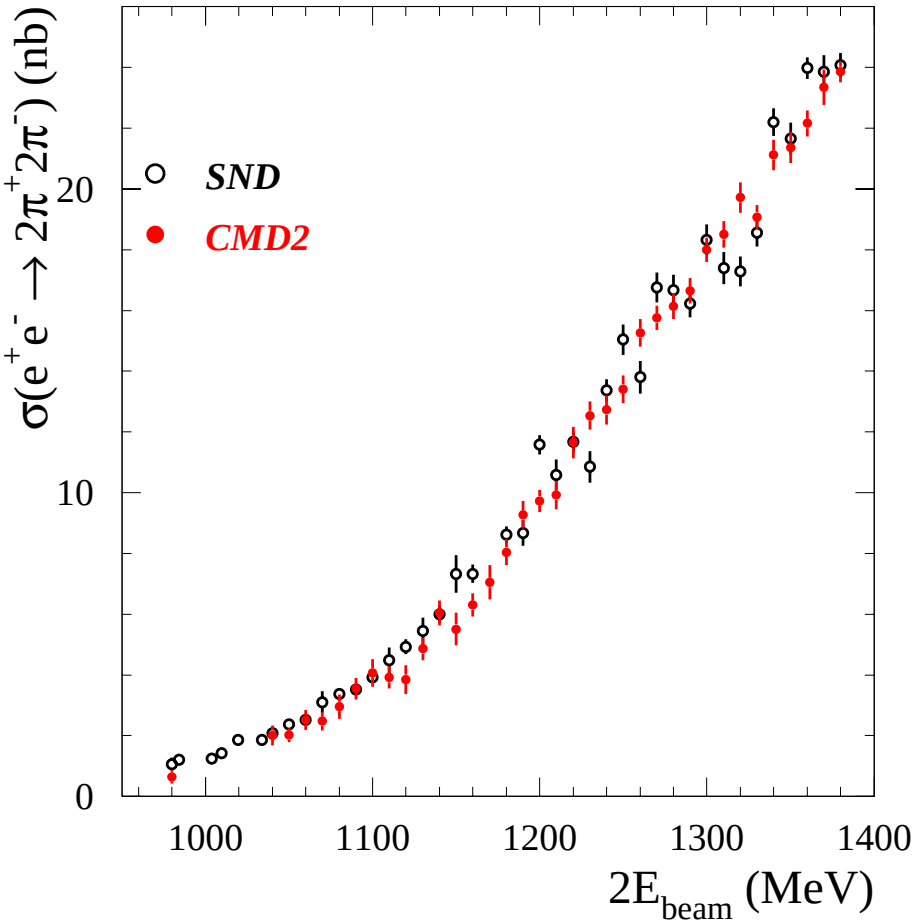
Study of $e^+e^- \to \pi^+\pi^-\pi^0$ at SND





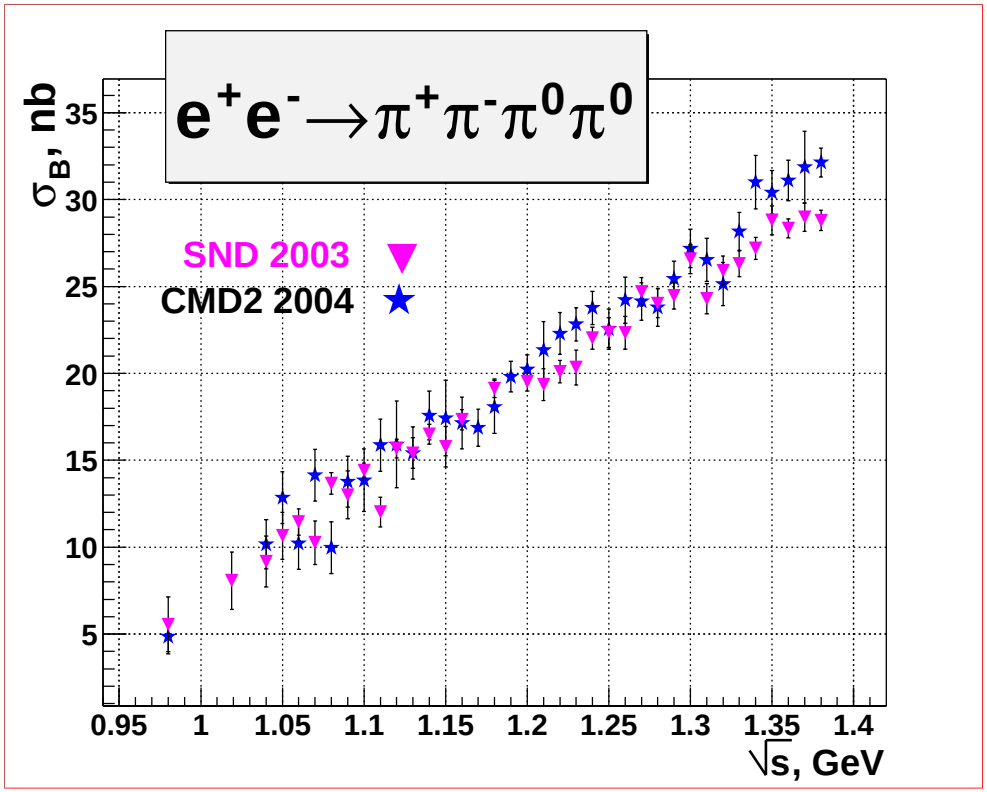
About $1.7 \cdot 10^6$ detected events. The systematic error is $\approx 5\%$. DM2 data are too low (by a factor of 1.6 or larger)!

Study of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$ with CMD-2 and SND



CMD-2: $38 \cdot 10^3$ ev., (5–7)% syst.

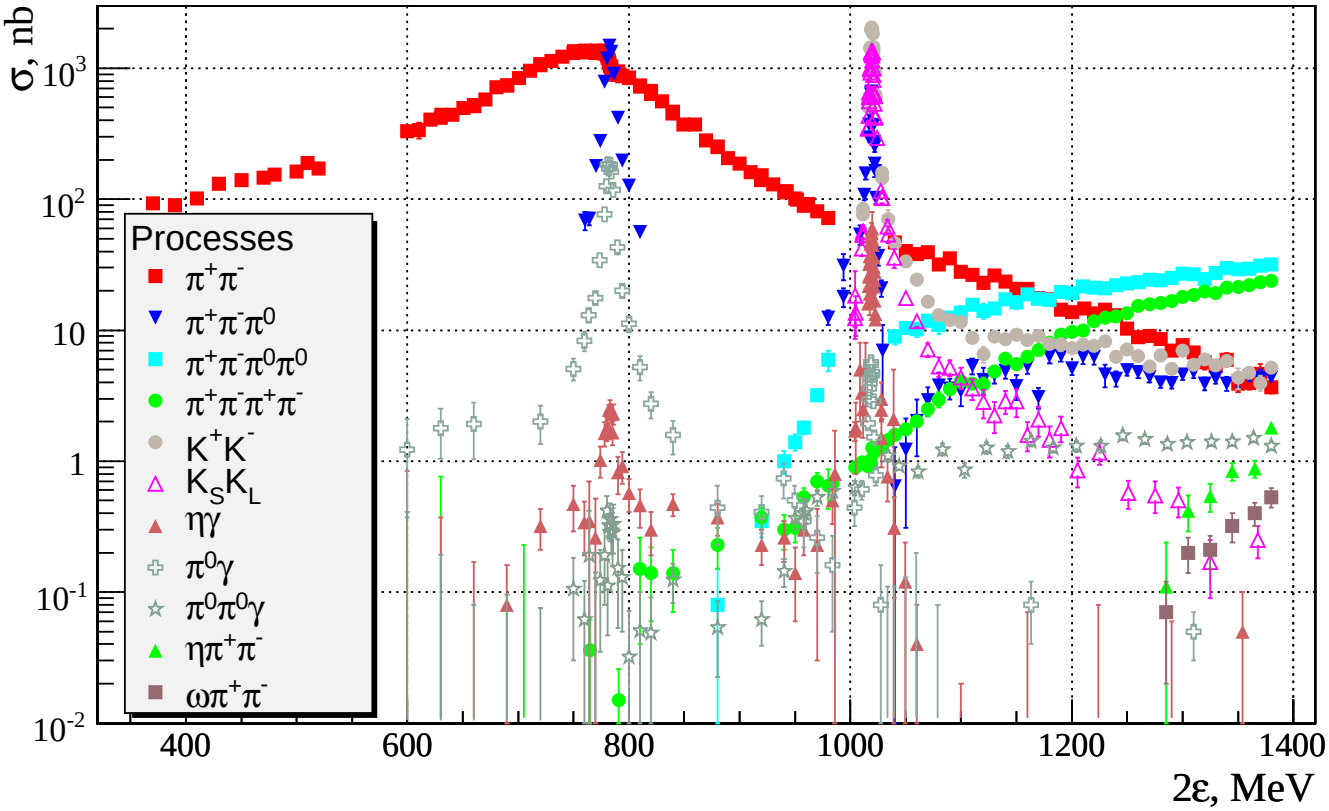
SND: $41 \cdot 10^3$ ev., 7% syst.



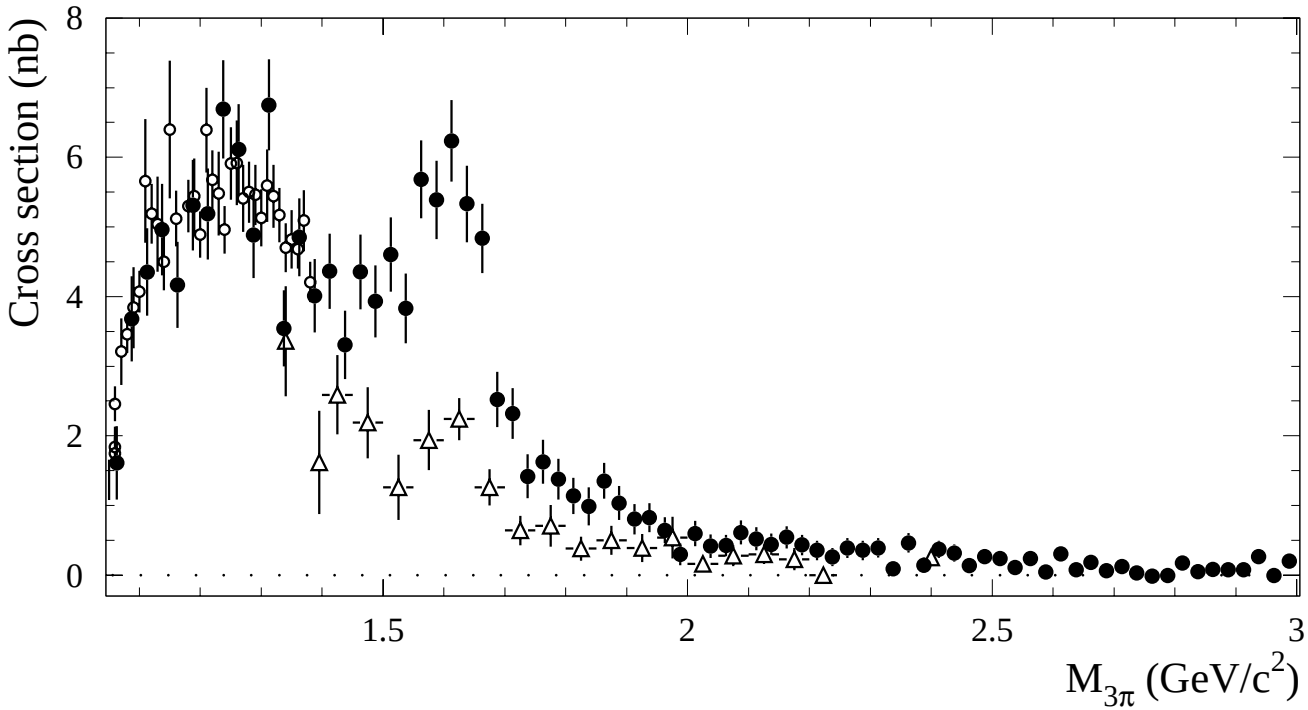
CMD-2: $10 \cdot 10^3$ ev.,, 6% syst.

SND: $54 \cdot 10^3$ ev., 8% syst.

Hadronic Cross Sections at CMD-2



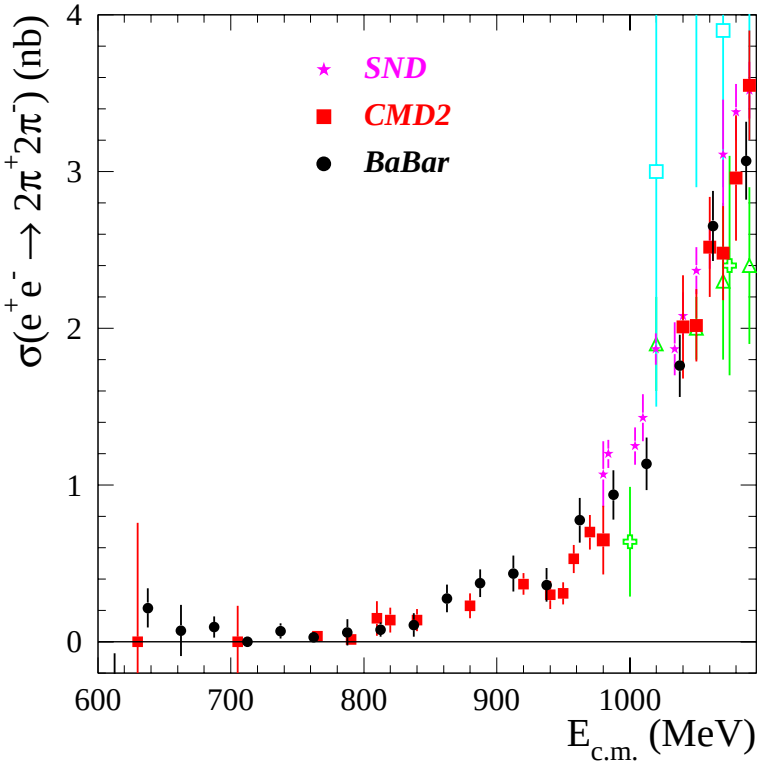
$e^+e^- \to \pi^+\pi^-\pi^0$ from BaBar

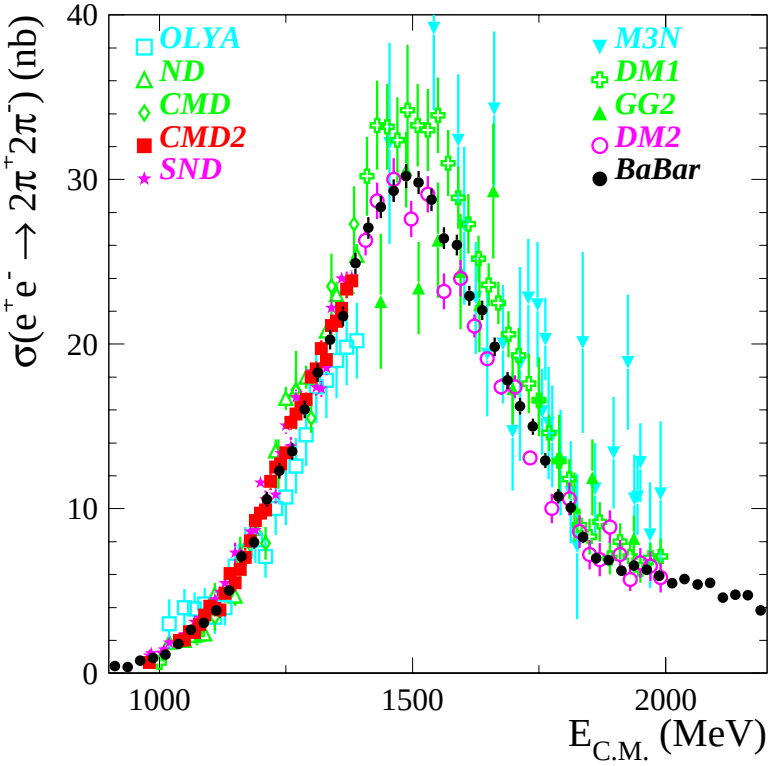


Good agreement with SND.

BaBar's points much higher than at DM2

$e^+e^- \to 2\pi^+2\pi^-$ from BaBar

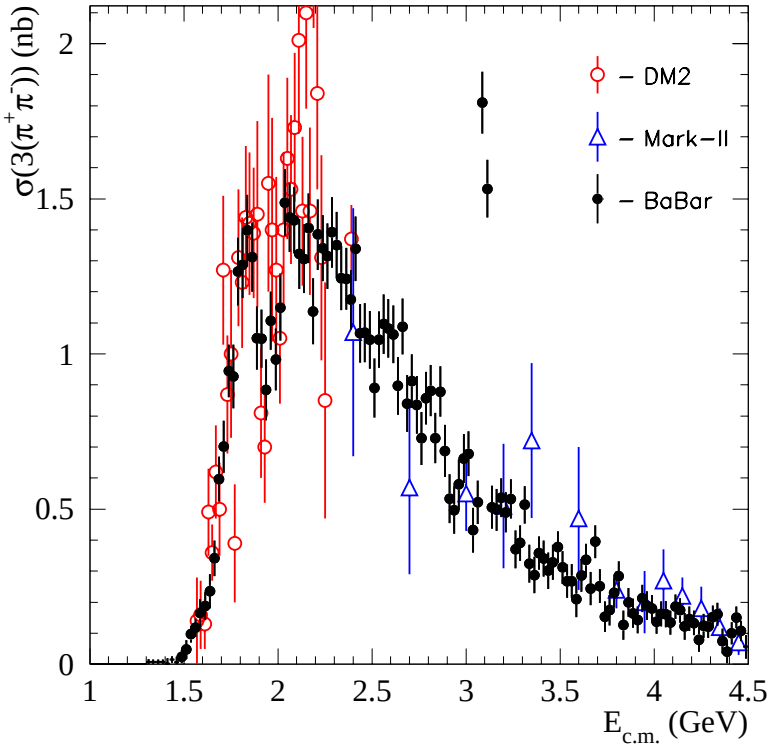


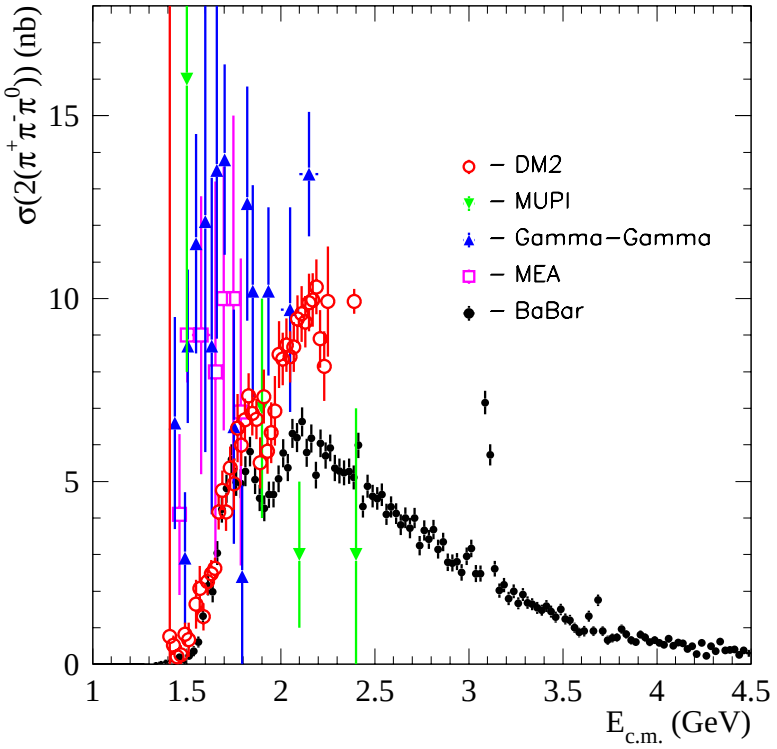


Good agreement with CMD-2/SND.

Error of continuum below 2 GeV improved.

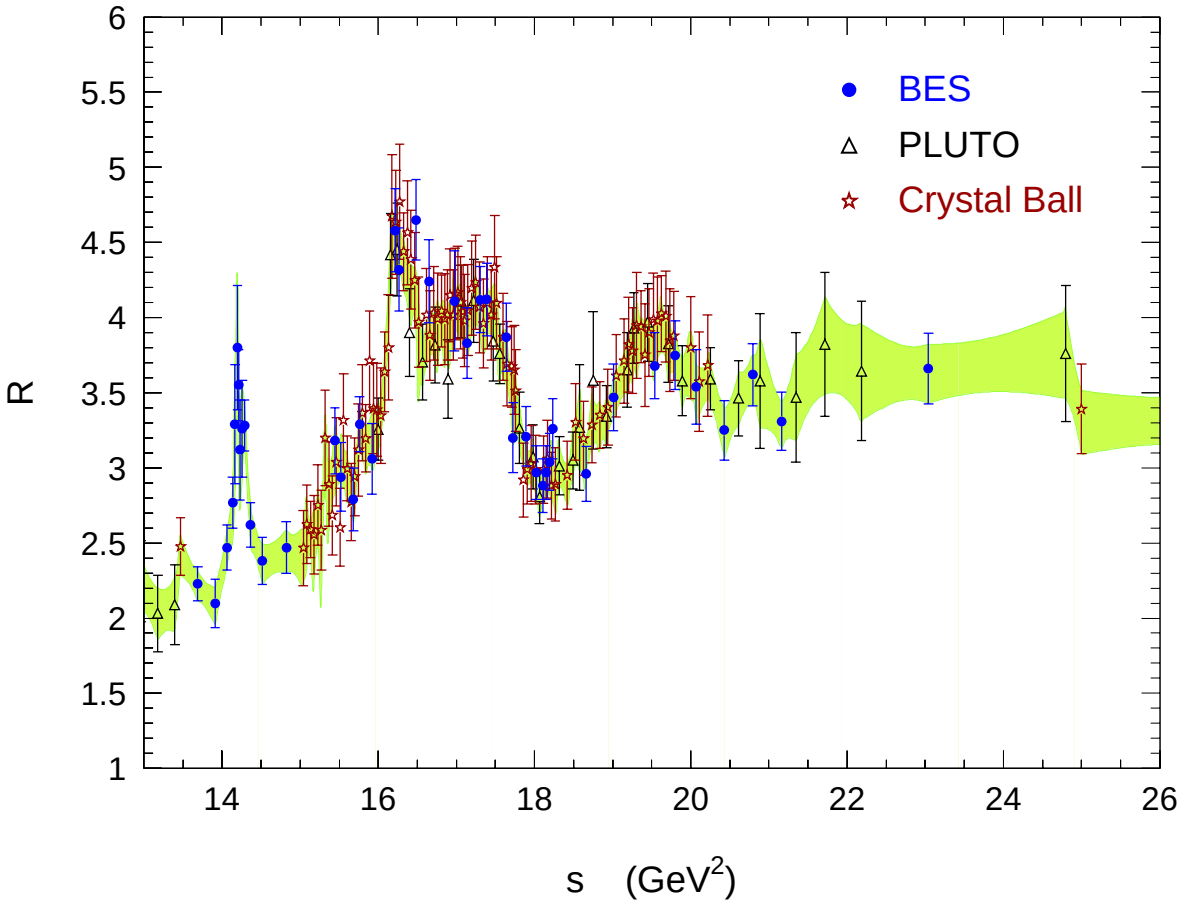
$e^+e^- \to 6\pi$ from BaBar





Significant improvement compared to the previous data!

R Measurements from 2 to 5 GeV



Preliminary R from CLEO in $c\bar{c}$ Region

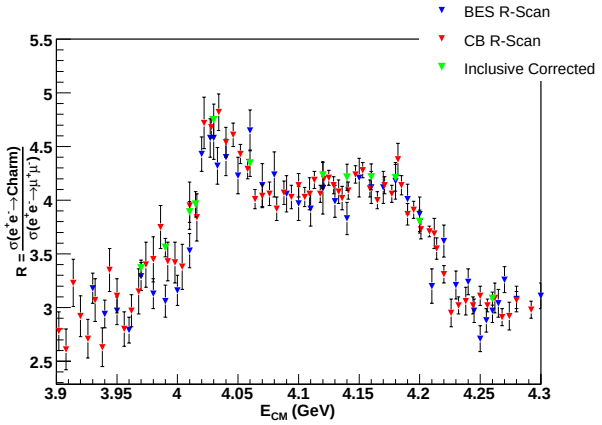
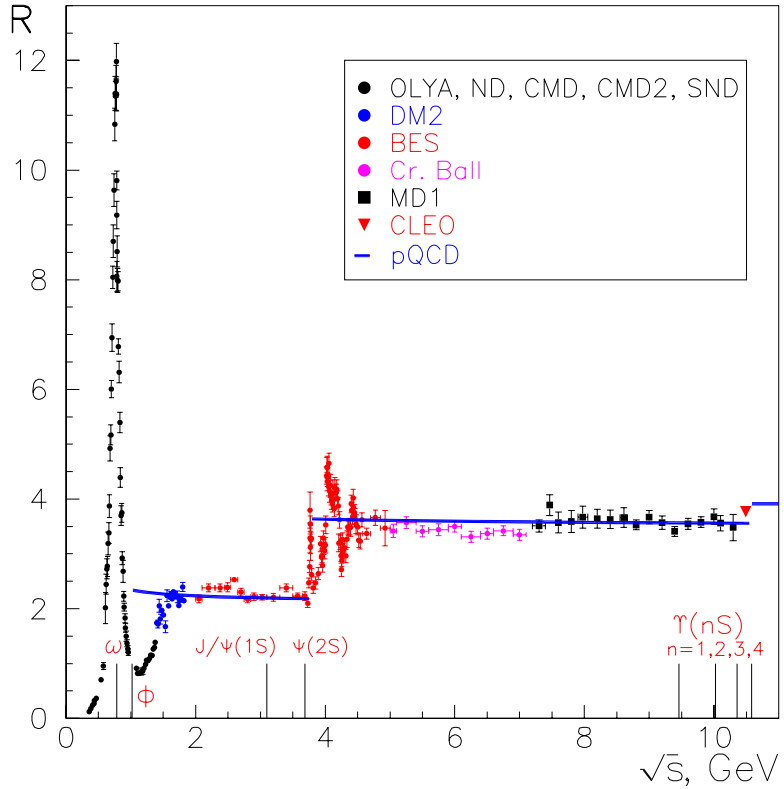


Figure 23: The radiatively corrected, using the KF interpolation method on the CB data, R measurement as obtained using the inclusive charm cross section. The error bars include the systematics as discussed in the text.

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R Measurements at $\sqrt{s} < 10$ GeV



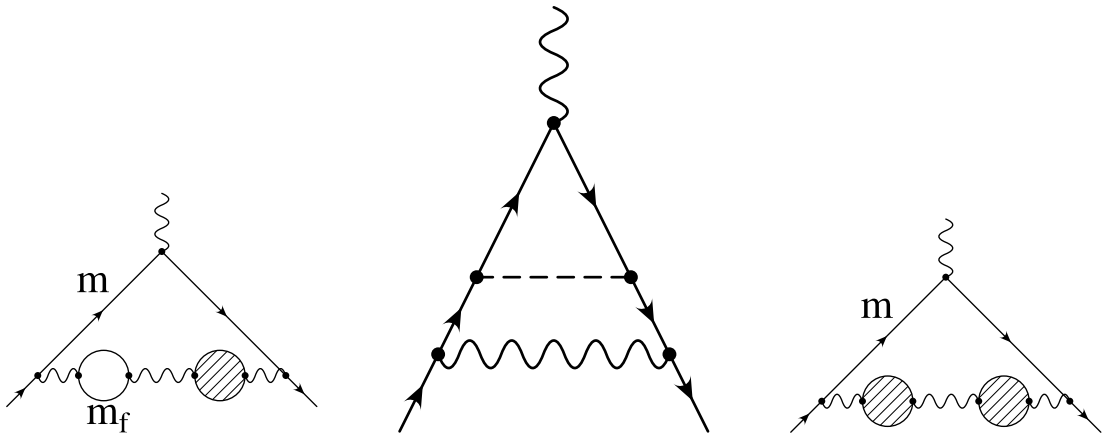
Excellent agreement with the pQCD predictions!

New e^+e^- Data Based Calculation of $a_\mu^{\rm had,LO}$

$\sqrt{s}$, GeV	$a_\mu^{\rm had,LO}, 10^{-10}$	$\delta a_\mu^{\rm had,LO}$, %
2π	$504.6 \pm 3.1 \pm 1.0$	73.0
ω	$38.0 \pm 1.0 \pm 0.3$	5.5
ϕ	$35.7 \pm 0.8 \pm 0.2$	5.2
$0.6 - 1.8$	$54.2 \pm 1.9 \pm 0.4$	7.8
$1.8 - 5.0$	$41.1 \pm 0.6 \pm 0.0$	6.0
$J/\psi, \psi'$	$7.4 \pm 0.4 \pm 0.0$	1.1
> 5.0	$9.9 \pm 0.2 \pm 0.0$	1.4
Total	$690.9 \pm 3.9_{\rm exp} \pm 1.9_{\rm rad} \pm 0.7_{\rm QCD}$	100.0

Higher accuracy of e^+e^- data: the $a_\mu^{\rm had,LO}$ error is 4.4 (0.63%) compared to 15.3 of EJ, 1995 and 7.2 of DEHZ, 2003!

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

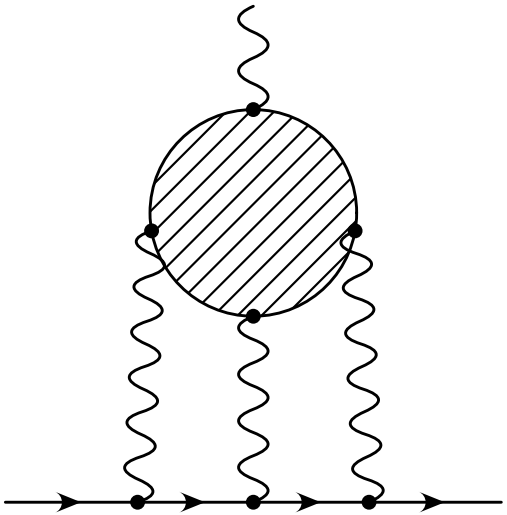


a b c

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 accepted value is (B. Krause, 1997; K. Hagiwara et al., 2003):

$$a_\mu^{\rm had,HO} = (-9.8 \pm 0.1) \cdot 10^{-10}.$$

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

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

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

Light-by-Light Scattering – II

- A. Pivovarov, 2001: $\sim 14.3 \cdot 10^{-10}$
  u, d, s with m_q, heavy quarks with standard masses
- J.F. de Trocóniz, F.J. Ynduráin, 2001: $(9.2 \pm 2.0) \cdot 10^{-10}$
  Constituent quarks + π^0
- A. Dorokhov, 2005: $(10.6 \pm 1.0) \cdot 10^{-10}$
  Instanton liquid model
- J. Erler, G. Toledo Sánchez,2006: $< 15.9 \cdot 10^{-10}$
  Parton model
- J. Bijnens and J. Prades, 2007: $(11 \pm 4) \cdot 10^{-10}$

Is there a way to consistently relate experimental data on $\gamma\gamma^* \to X^0$ with $J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{-+}, 2^{++}$ to the corresponding contributions to $a_\mu^{\rm had,LBL}$?

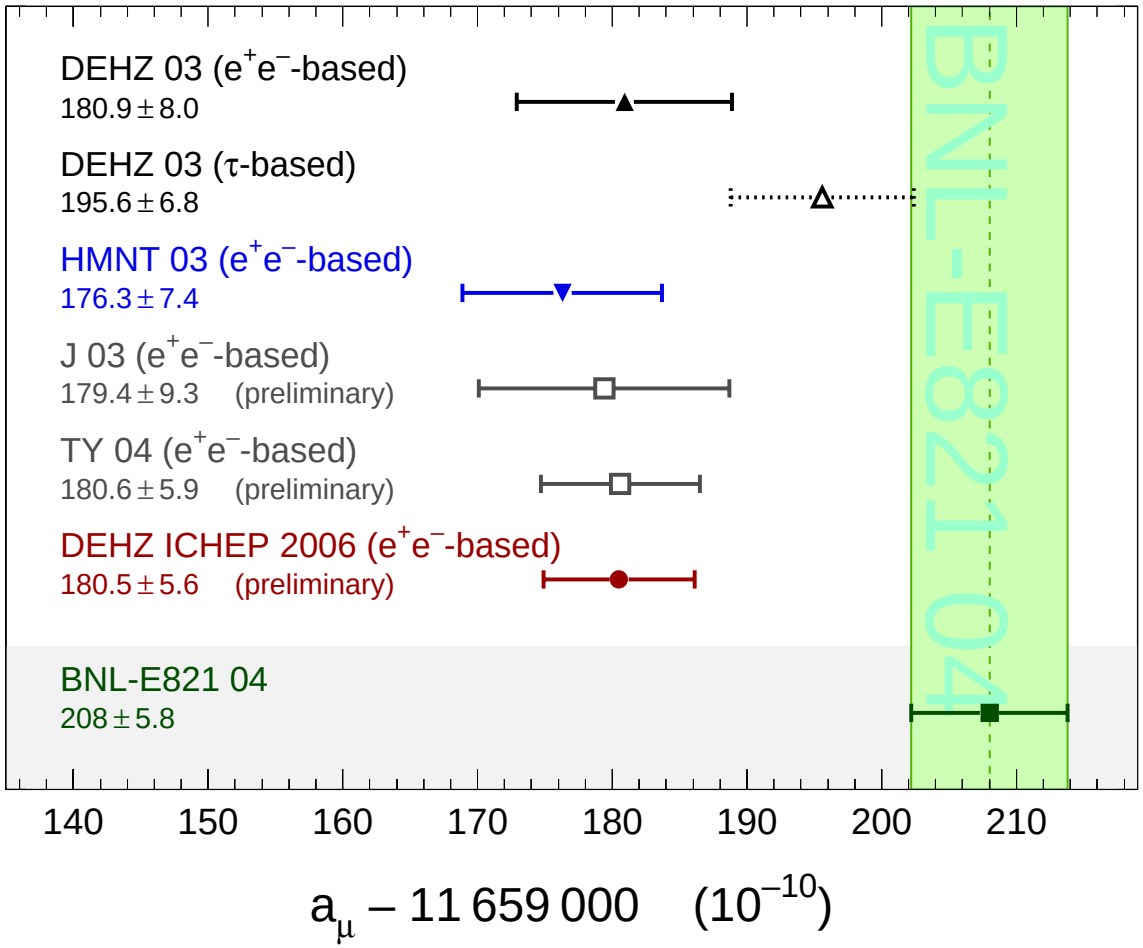
Theory vs Experiment – I

Contribution	$a_\mu, 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.8 ± 0.016
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.3 ± 5.6
Exp.–Theory	27.7 ± 8.4 (3.3σ)

The difference between experiment and theory is 3.3σ!

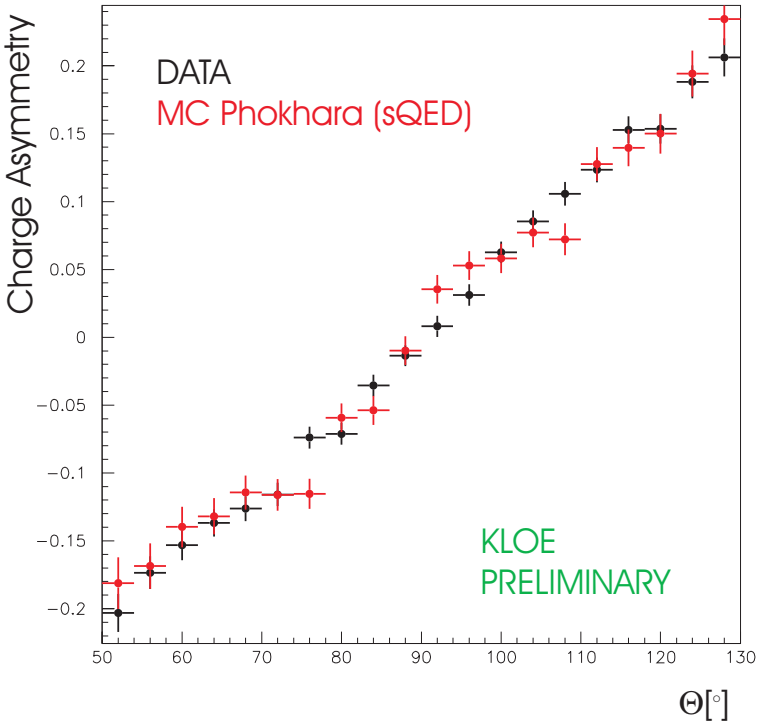
(K.Hagiwara et al., hep-ph/0611102 claim even 3.4σ)

Theory vs Experiment – II



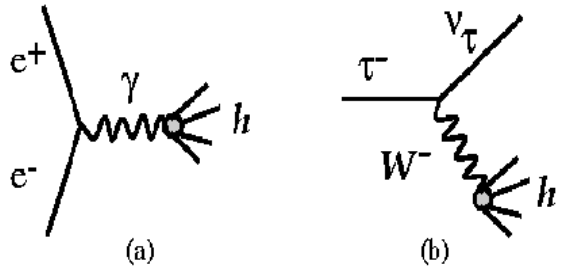
How Real Is $a_\mu^{\rm had}$ Accuracy?

- Missing states: neutrals;
  $\pi^+\pi^- n\pi^0, K\bar{K}n\pi$ - isospin
- Radiative corrections (FSR):
  Charge asymmetry at KLOE
  3k $e^+e^- \to \pi^+\pi^-\gamma$ evts at CMD-2
- Correlations
- Averaging
- Light-by-light term
- Double counting (LO and HO)



Charge asymmetry in $e^+e^- \to \pi^+\pi^-\gamma$
sQED is OK ($0.6 < M^2_{\pi\pi} < 0.7$ GeV^2)

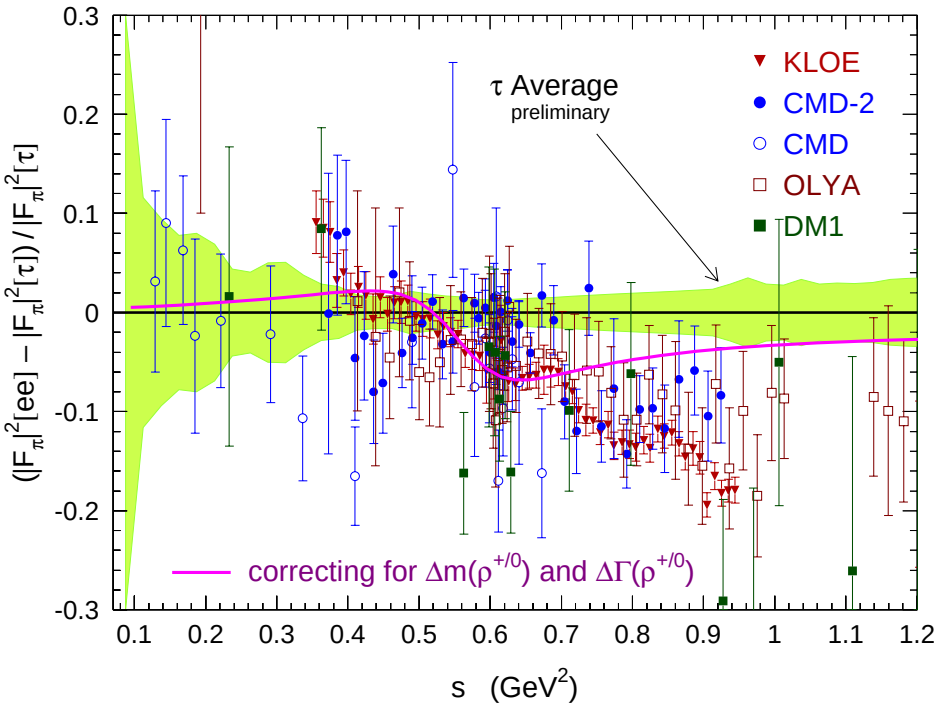
CVC. $e^+e^- \to X^0$ and $\tau^- \to \nu_\tau X^-$



Allowed $I^G J^P = 1^+1^-$:

$X^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-,$

$\eta\pi^-\pi^0, K^-K^0, (6\pi)^-, \ldots$



Large SU(2) breaking corrections from theory, V.Cirigliano et al., 2002

$M(\Gamma)_{\rho^0} \neq M(\Gamma)_{\rho^\pm}$ helps,

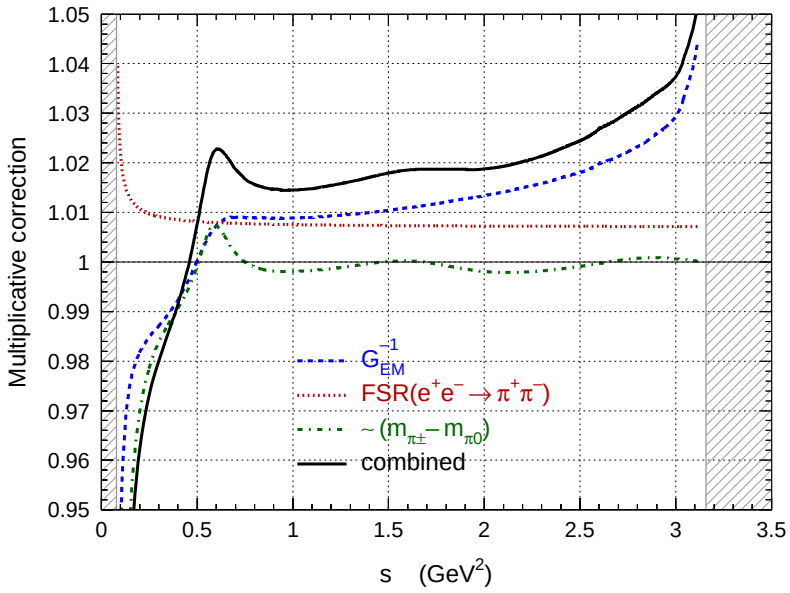
M.Davier, 2003; S.Ghozzi, F.Jegerlehner, 2004

Corrections to the τ Spectral Functions

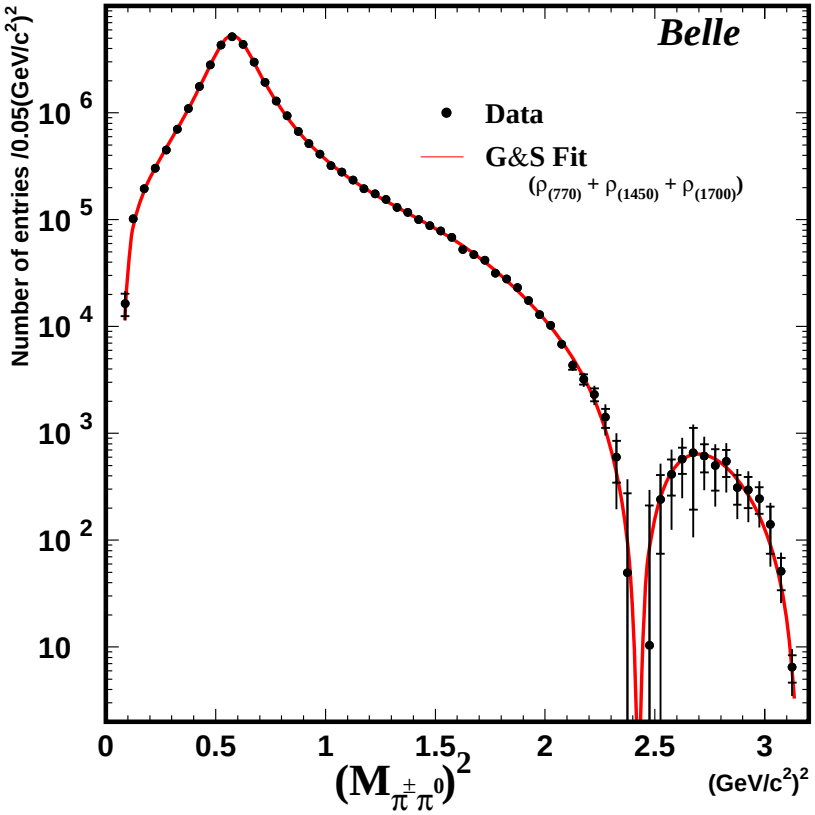
- $S_{EW} = 1.0233 \pm 0.0006$
- Real photons, loops
- FSR
- $m_{\pi^\pm} \neq m_{\pi^0}$
  (phase space, Γ_ρ)
- $m_{\rho^\pm} \neq m_{\rho^0}$
- $\rho - \omega$ interference
- Radiative decays
  $(\pi\pi\gamma, \pi(\eta)\gamma, l^+l^-)$
- $m_u \neq m_d$
  and 2 class currents

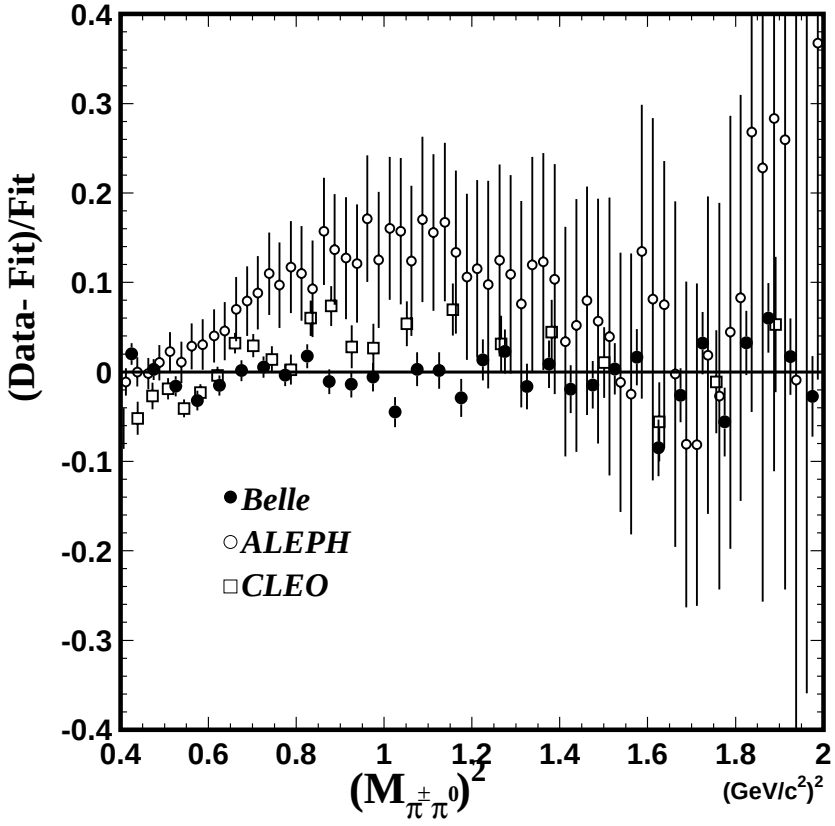
V. Cirigliano, G. Ecker, H. Neufeld, 2002

M. Davier, S. Eidelman, A. Höcker, Z. Zhang, 2002

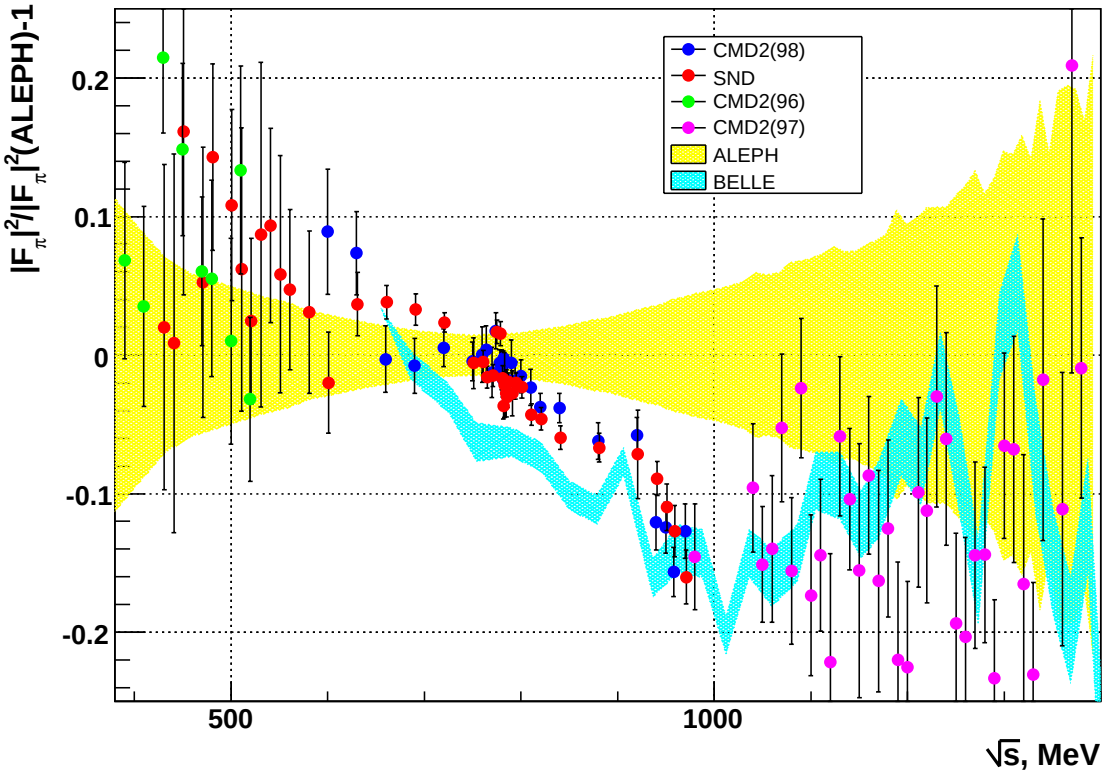


New data on $\tau^- \to \pi^-\pi^0\nu_\tau$ from Belle





2π Spectral Functions after Belle



Until CVC puzzle is solved, τ data are not used!

Why are e^+e^- and τ Spectral Functions Different?

- Problems with data: underestimated systematics, normalization, rad. corr.
- Problems with SU(2) breaking corrections; Is ChPT reliable? The uncertainty of corrections may be large (K.Maltman, 2005)
- Non (V-A) contribution to e/w interactions (M.Chizhov, 2003) inspired by problems in $\pi^+ \to e^+\nu_e\gamma$ (E.Frlez et al., 2003)
- Effect of charged Higgs propagator in τ decay
- $m_{\rho^\pm} > m_{\rho^0}$ by a few MeV (S.Ghozzi and F.Jegerlehner, 2003, M.Davier, 2003). Current experiments indicate equality within a few MeV.
- Pion F_V from unitarity and analyticity (A.Pich and J.Portoles, 2001)

Future of $a_\mu^{\rm had} - e^+e^-$

By 2008 more ISR analysis from KLOE, BaBar, Belle; better R below 4.3 GeV from CLEO-c: 4.4 $\to$ 2.8

Experiments are planned at the new machine VEPP-2000 (VEPP-2M upgrade) with 2 detectors (CMD-3 and SND) up to $\sqrt{s}$=2 GeV with $L_{\rm max} = 10^{32}$ cm^{-2}s^{-1}. First beams in 2007, first luminosity in 2008

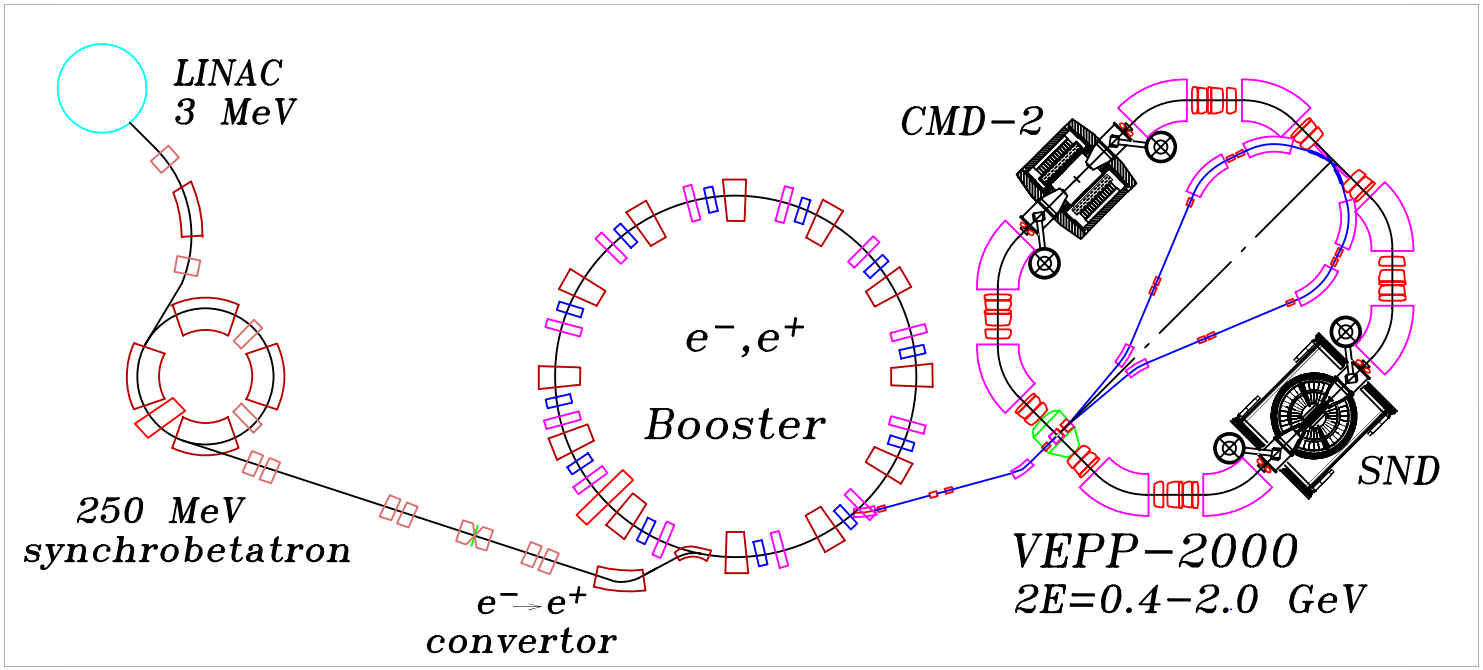
A similar machine (DAΦNE-II) is discussed in Frascati.

A $\tau - c$ factory in Beijing

By 2010: 2.8 $\to$ 2.2, the total error of 4.1 limited by the LBL term (3.5) and still higher than the expected 2.5 in E969.

VEPP-2000

Layout of the VEPP−2000 complex

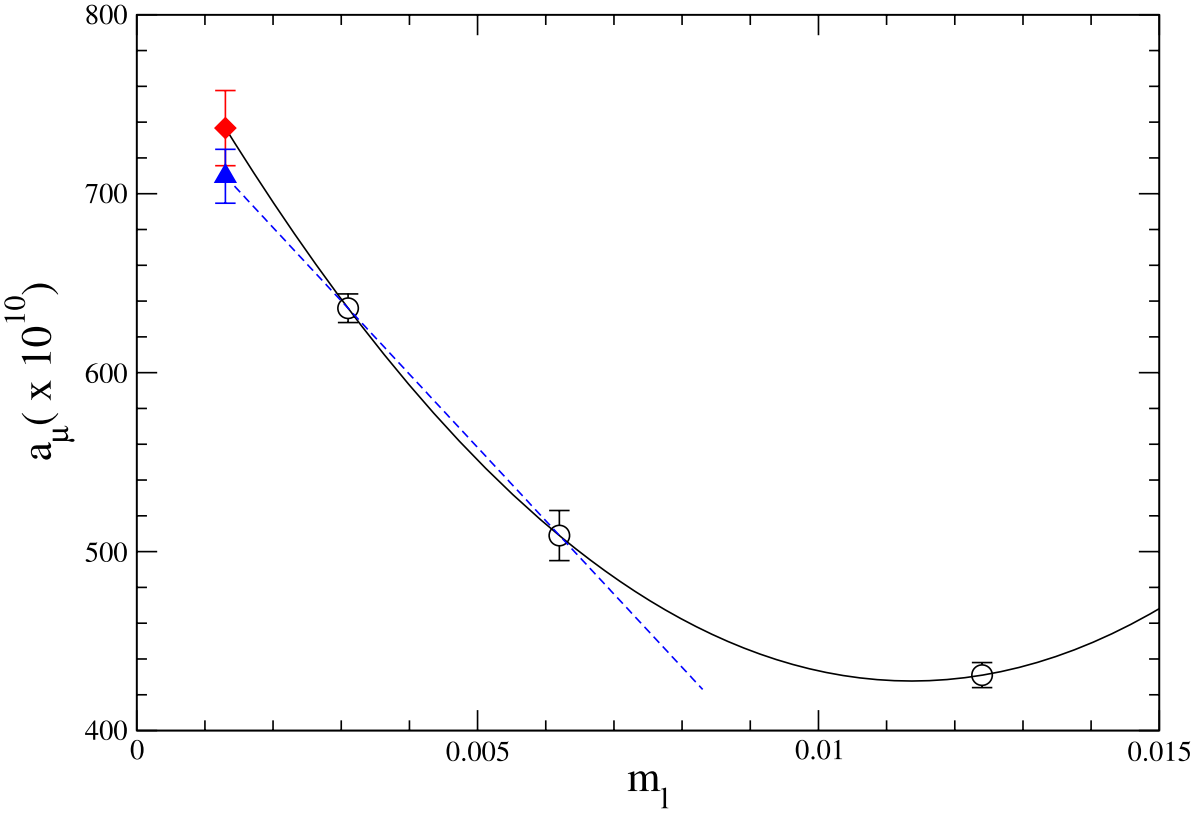


The design luminosity $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}, with $\int Ldt \approx 1 - 2$ fb^{-1} during 3–5 years $\Delta a_\mu^{\rm had}/a_\mu^{\rm had}$ can be improved by a factor of 2! Commissioning started.

Future of $(g_\mu - 2)/2$

1. Experiment
   - Today a_μ is known with a $5 \cdot 10^{-7}$ relative accuracy.
   - If funded, the E969 group can reach $2.5 \cdot 10^{-7}$ at BNL and $6 \cdot 10^{-8}$ – $1 \cdot 10^{-7}$ at J-PARC.
2. $a_\mu^{\rm had}$ calculation from 1st principles (QCD, Lattice).
   QCD instanton model (A. Dorokhov, 2003),
   Recently from the Lattice: $a_\mu^{\rm had} = (545 \pm 65) \cdot 10^{-10} \Rightarrow (667 \pm 20) \cdot 10^{-10}$
   (C. Aubin and T. Blum, 2005),
   attempts to estimate $a_\mu^{\rm lbl}$ (M. Hayakawa et al., 2005).

Lattice Predictions for $a_\mu^{\rm LO,had}$



Conclusions

- BNL success stimulated significant progress of experiment and related theory
- Improvement of e^+e^- data (CMD-2, SND, KLOE, BaBar and BES) significantly decreased an error of $a_\mu^{\rm had,LO}$ matching the experimental accuracy
- τ data could further improve the accuracy but a serious yet unexplained failure of CVC relations for e^+e^- and τ is observed
- Further improvement in $a_\mu^{\rm had,LO}$ by a factor of 2 will be possible after VEPP-2000, DAΦNE-II, CESRc and $(c-\tau)$ factory as well as with ISR at DAΦNE and B-factories
- More theory input needed
- $a_\mu^{\rm exp} - a_\mu^{\rm SM}$ differs from 0 by more than 3 $\sigma \Rightarrow$ A hint to New Physics?

Back-up Slides

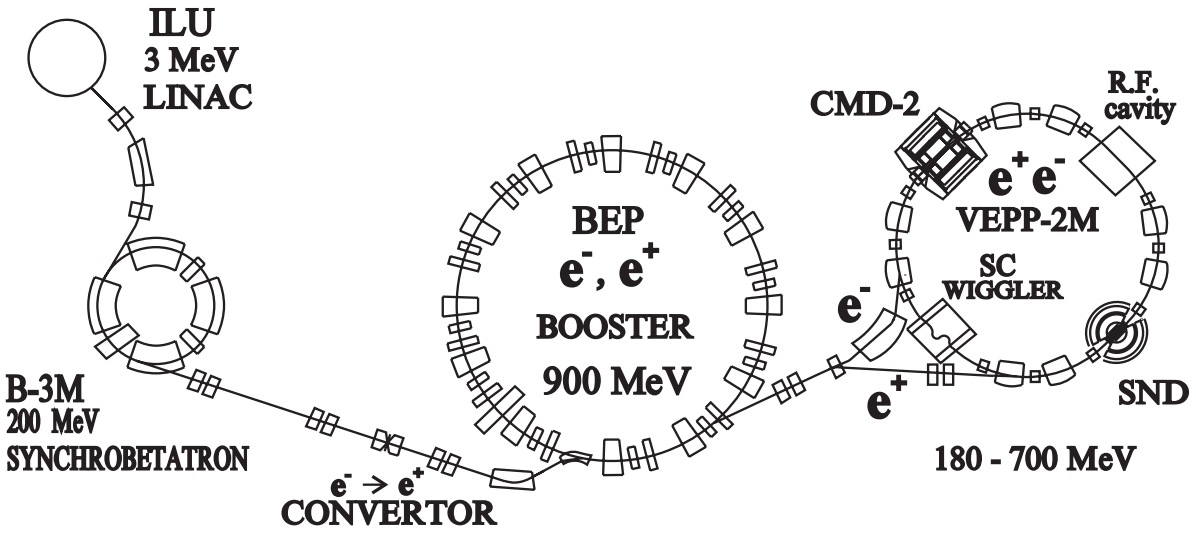
New Physics and a_μ

- Supersymmetry ($\tilde{m} \simeq 200$ GeV–1 TeV)
- Cold dark matter and neutralino
- Tachyons ($m^2 < 0$)
- Radiative m_μ generation (new scale $\Lambda \simeq 1 - 2$ TeV)
- Technicolor
- Leptoquarks
- New gauge bosons (Z$'$ etc.)
- Large extra dimensions ($M > 600$ GeV)
- Lepton flavor violation ($\mu \to e\gamma$, μ edm, $\tau \to \mu\gamma, \ldots$)
- $b \to s\gamma$
- Composite quarks and leptons

Calculations of $a_\mu^{\rm had,LO}$

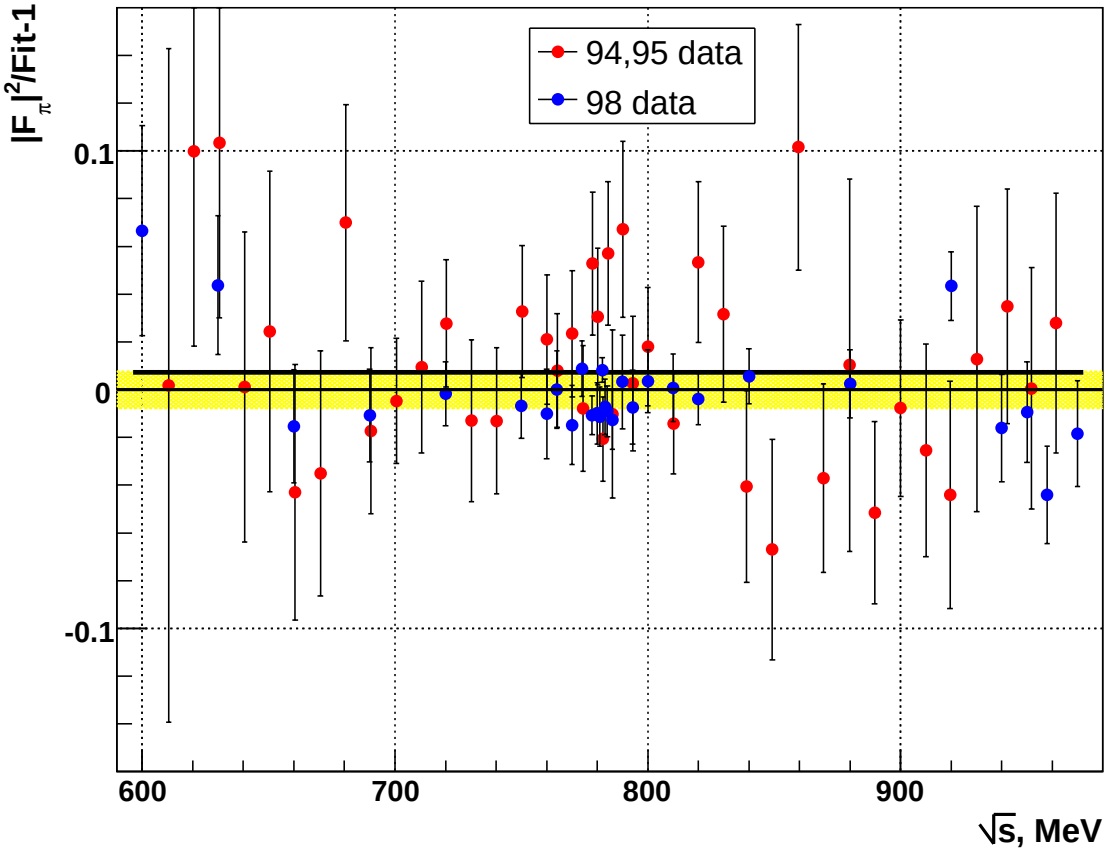
Authors	Year	$a_\mu^{\rm had,LO}$, 10^{-10}
C.Bouchiat, L.Michel	1961	$\simeq 648$
M.Gourdin, E. de Rafael	1969	650 ± 50
A.Bramon et al.	1972	680 ± 90
J.Calmet et al.	1977	702 ± 80
T.Kinoshita et al.	1985	707 ± 18
S.Eidelman, F.Jegerlehner	1995	702 ± 15
R.Alemany et al.	1998	701.1 ± 9.4
M.Davier, A.Höcker	1998	692.4 ± 6.2

VEPP-2M Collider in Novosibirsk

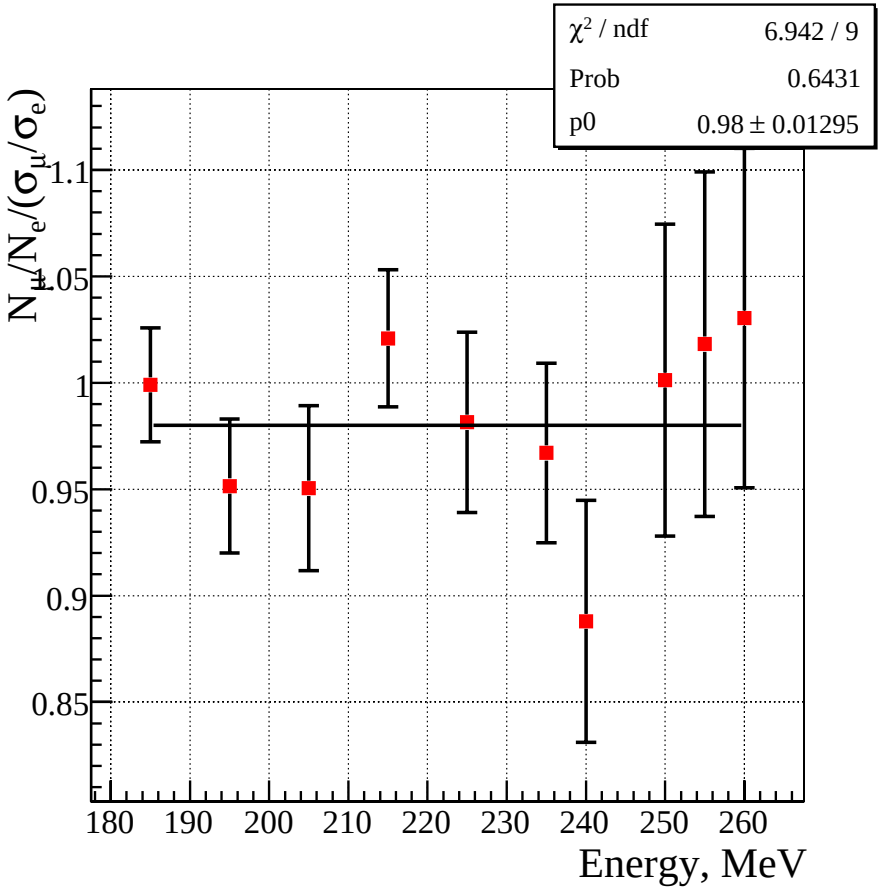


- Experiments: 1974 – 2000
- Energy range: $0.36 < \sqrt{s} < 1.40$ GeV
- Peak luminosity: $L_{\rm peak} = 3 \cdot 10^{30}$ cm^{-2} s^{-1}
- Integrated luminosity ≈ 70 pb^{-1} in Novosibirsk below 1.4 GeV compared to ≈ 6 pb^{-1} in Orsay and Frascati at $1.4 < \sqrt{s} < 3.0$ GeV!

Comparison of CMD-2 data on $e^+e^- \to \pi^+\pi^-$



Comparison of CMD-2 data on $e^+e^- \to \mu^+\mu^-,\ e^+e^-$

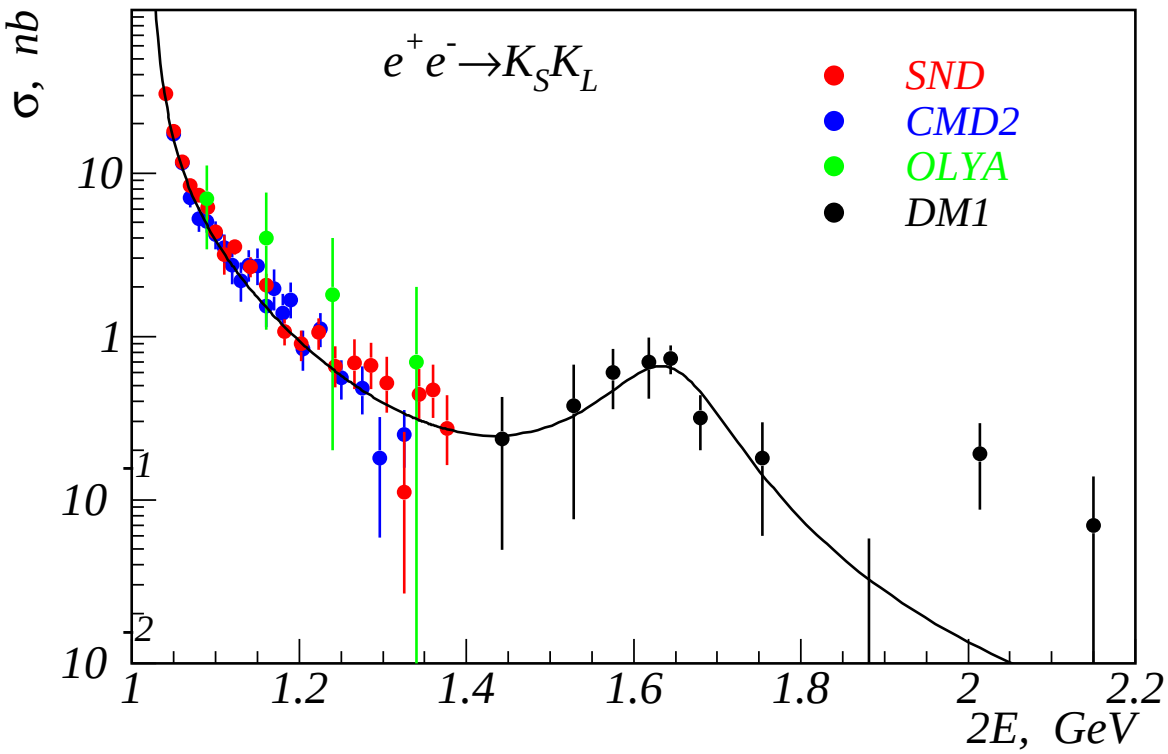


$$1 - R_{\mu e} = (2.0 \pm 1.3 \pm 0.7)\%$$

Budget of $e^+e^- \to \pi^+\pi^-$

Source $/\sqrt{s}$, GeV	0.37÷0.52	0.6÷0.96		1.04÷1.38
$N_{\pi\pi}, 10^3$ / Number of points	4/10	114/43	820/29	33/35
Stat. error/point, %	6.0	4.0	1.5	5.0 ÷ 13.0
Fiducial volume, %	0.2	0.2		0.2÷0.5
Detection efficiency, %	0.2	0.2	0.5	0.5÷2.0
Pion losses, %	0.2	0.2		0.2
Radiative corrections, %	0.3	0.4		0.5÷2.0
Background events, %	< 0.1	< 0.1		0.6÷1.6
Beam energy calibration, %	0.3	0.1	0.3	0.7÷1.1
Event separation, %	0.4	0.2		0.2÷1.5
Bremsstrahlung, %	0.2	0.2		0.05÷1.7
Total systematic error, %	0.7	0.6	0.8	1.2÷4.2

$$e^+e^- \to K_S^0 K_L^0$$

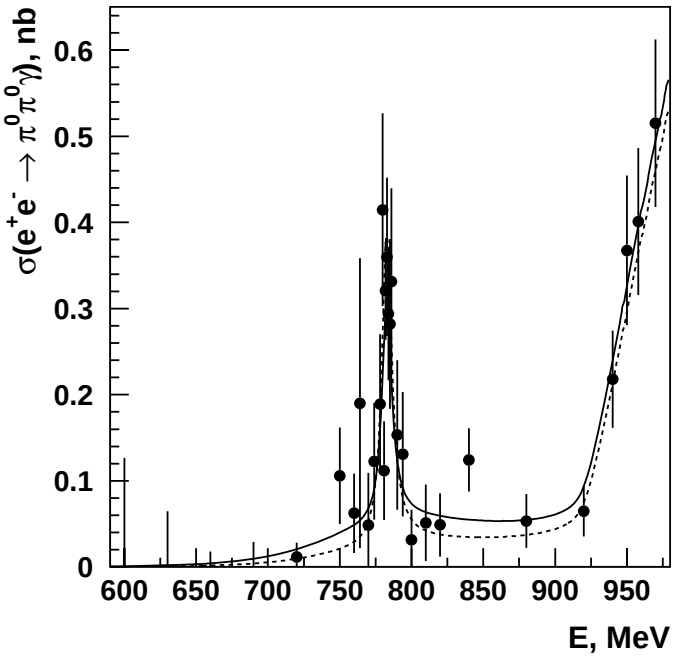


CMD-2: 950 events, syst. errors (5-10)%

SND: $\sim$ 2000 events, syst. errors (2.9-5.3)%

Study of Neutral Final States at VEPP-2M

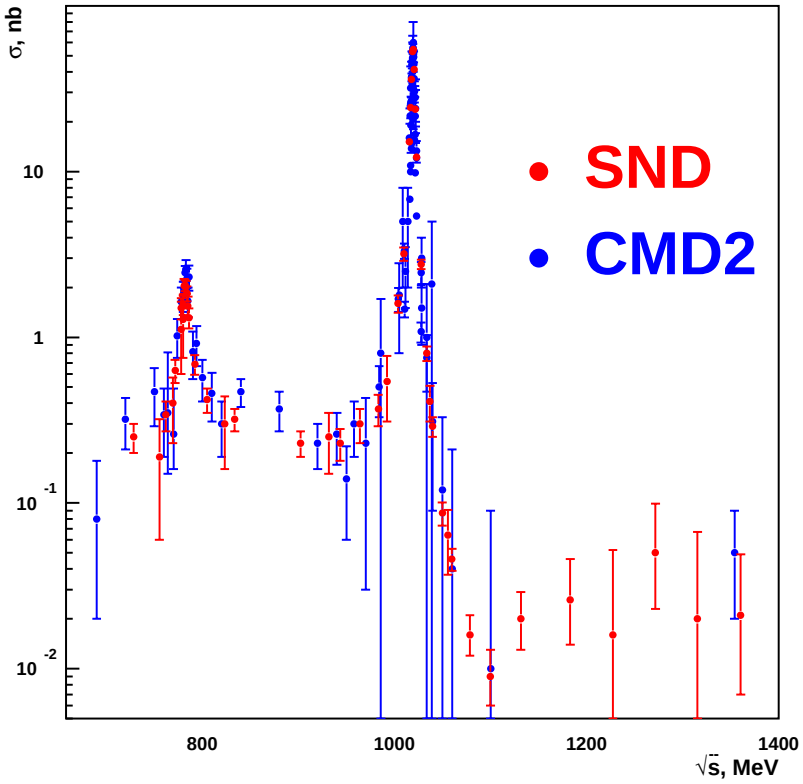
- $e^+e^- \to \pi^0\gamma$ (SND, CMD-2)
- $e^+e^- \to \eta\gamma$ (SND, CMD-2)
- $e^+e^- \to \pi^0\pi^0\gamma$ (SND, CMD-2)
- $e^+e^- \to \eta\pi^0\gamma$ (CMD-2)



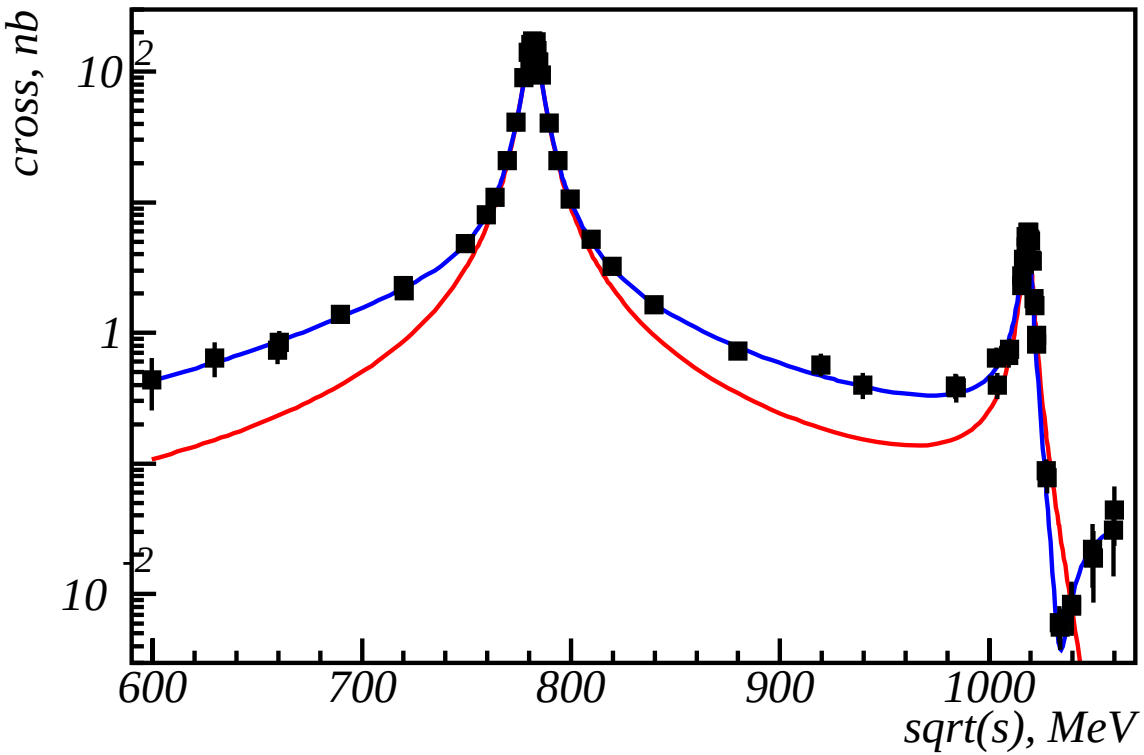
$\rho-, \omega-, \phi-$mesons dominate the cross sections.

From upper limits on nonresonant cross sections $a_\mu^{\rm rad,LO} < 0.7 \cdot 10^{-10}$.

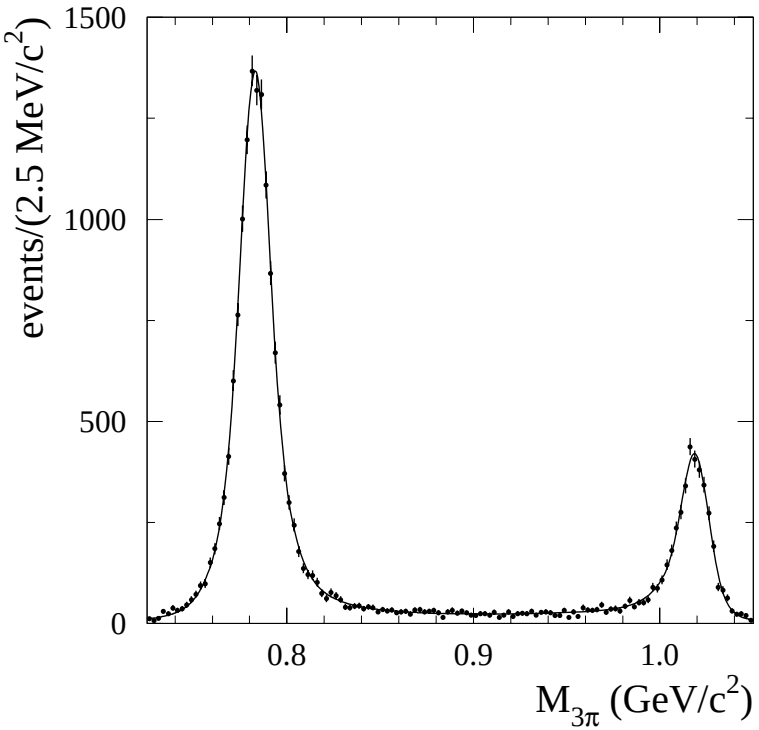
$e^+e^- \to \eta\gamma$ at VEPP-2M

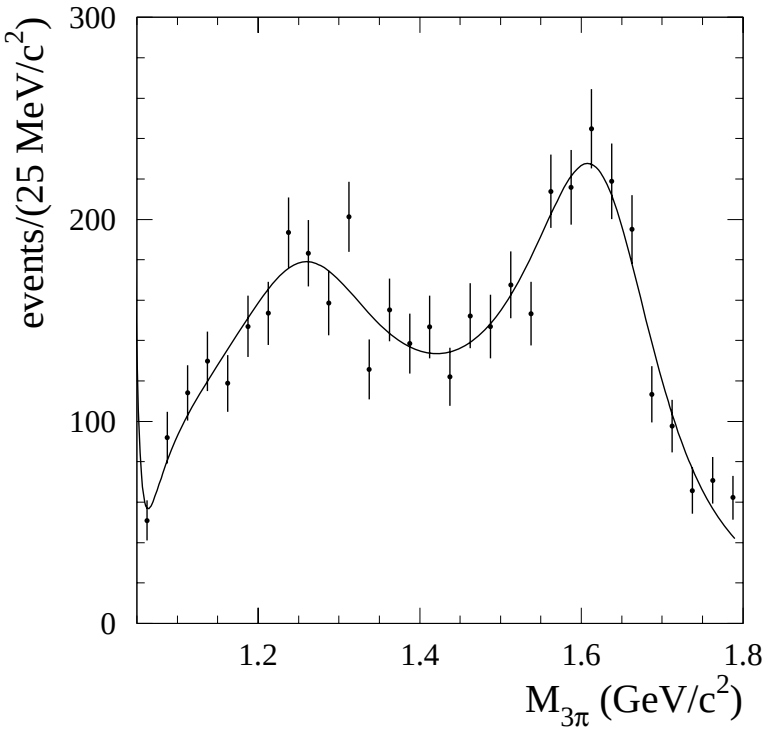


$e^+e^- \to \pi^0\gamma$ at VEPP-2M



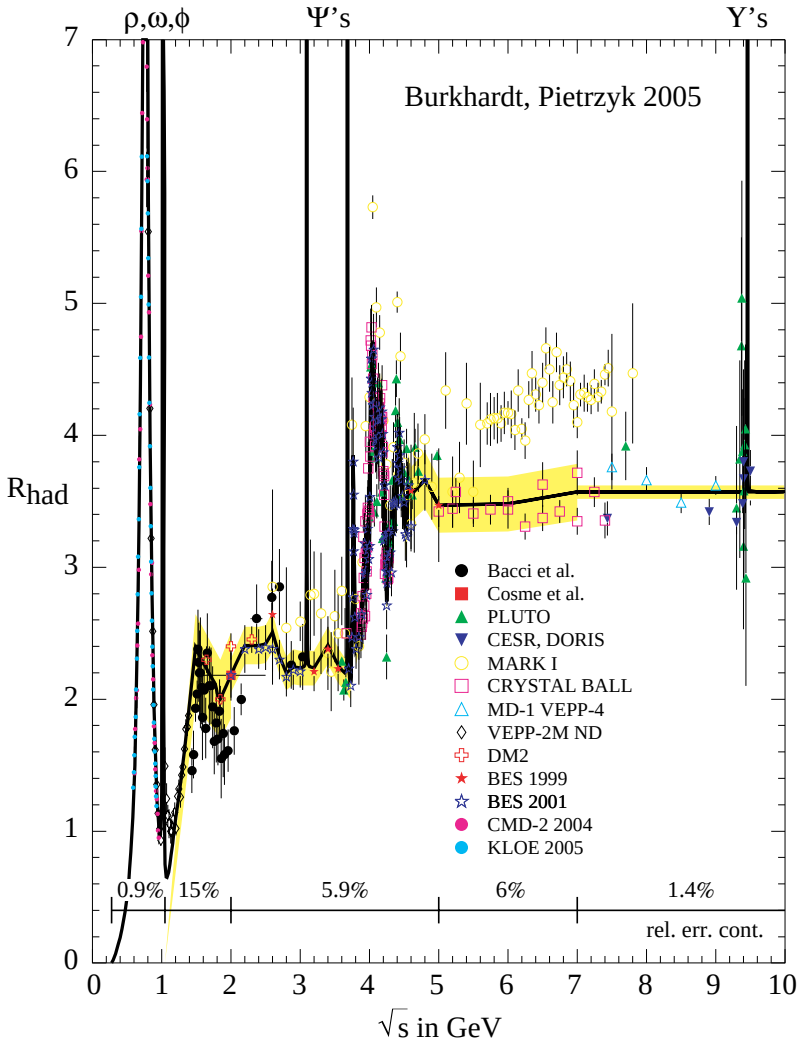
$e^+e^- \to \pi^+\pi^-\pi^0\gamma$ at BaBar





The final $\pi^+\pi^-\pi^0$ state is dominated by $\rho^+\pi^- + \rho^0\pi^0 + \rho^-\pi^+$

R below 10 GeV



Preliminary R from CLEO in $c\bar{c}$ Region

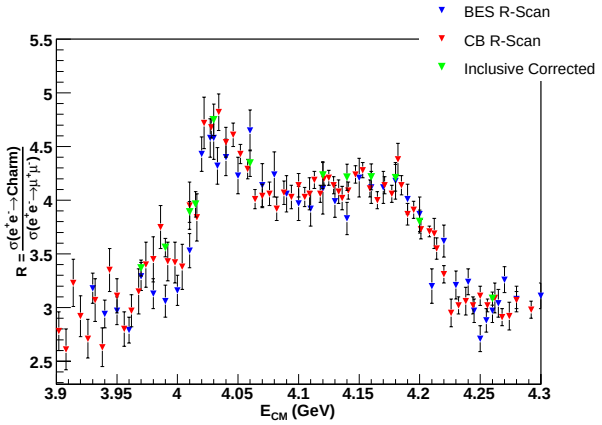
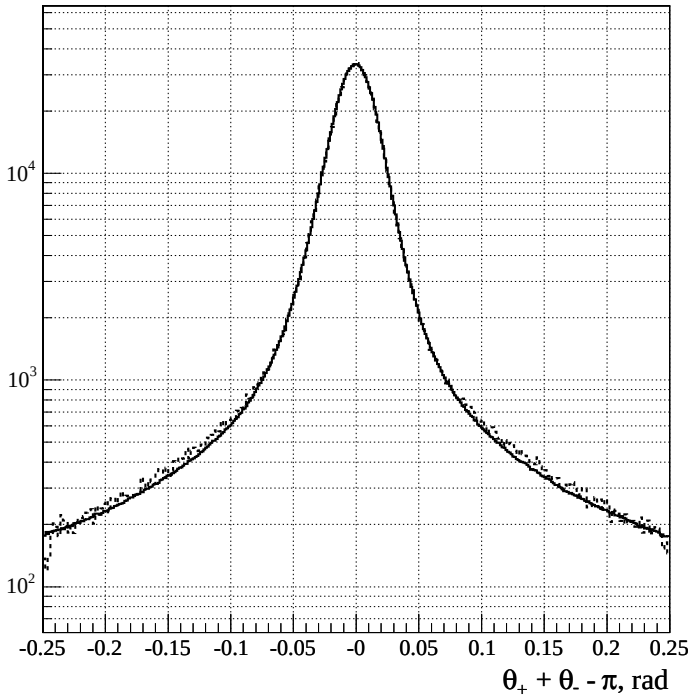
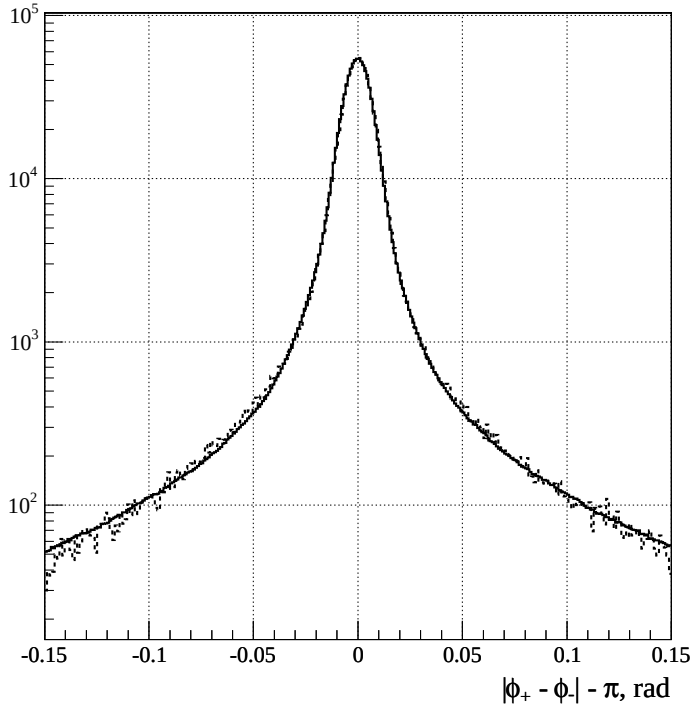


Figure 23: The radiatively corrected, using the KF interpolation method on the CB data, R measurement as obtained using the inclusive charm cross section. The error bars include the systematics as discussed in the text.

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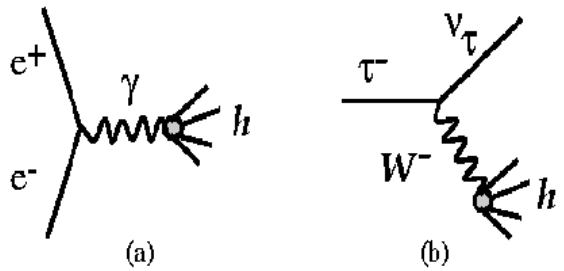
Radiative corrections





CMD-2 is using a MC generator based on A. Arbuzov et al., 1997; its accuracy $\sim 0.2\%$; agrees with BHWIDE and BABAYAGA within claimed accuracy.

CVC. $e^+e^- \to X^0$ and $\tau^- \to \nu_\tau X^-$



Allowed $I^G J^P = 1^+1^-$:
$X^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-,$
$\eta\pi^-\pi^0, K^-K^0, (6\pi)^-, \ldots$

$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ud}|^2 S_{EW}}{32\pi^2 m_\tau^3} f_{kin} v_1(q^2)$ with
$v_1(q^2) = \frac{q^2 \sigma^{I=1}_{e^+e^-}(q^2)}{4\pi\alpha^2}$.

CVC tests showed good agreement of the τ branchings predicted from e^+e^- with τ data (N. Kawamoto and A. Sanda, 1978, F. Gilman and D. Miller, 1978, S. Eidelman and V. Ivanchenko, 1991, 1997).

The very first application of τ data to $a_\mu^{had,LO}$ improved the accuracy by a factor of 1.5 (R. Alemany, M. Davier, A. Höcker, 1998)!

Branchings of $\tau^- \to X^- \nu_\tau$ Decay,%

Hadronic State X	Experiment, 2002	CVC Prediction	$\mathcal{B}_{\rm exp} - \mathcal{B}_{\rm CVC}$
$\pi^-\pi^0$	25.31 ± 0.18	24.76 ± 0.25	0.55 ± 0.31
$\pi^- 3\pi^0$	1.08 ± 0.10	1.07 ± 0.05	0.01 ± 0.11
$2\pi^-\pi^+\pi^0$	4.19 ± 0.23	3.84 ± 0.17	0.35 ± 0.29
$\omega\pi^-$	1.94 ± 0.07	1.82 ± 0.07	0.12 ± 0.10
Total	31.59 ± 0.31	30.28 ± 0.34	1.31 ± 0.46

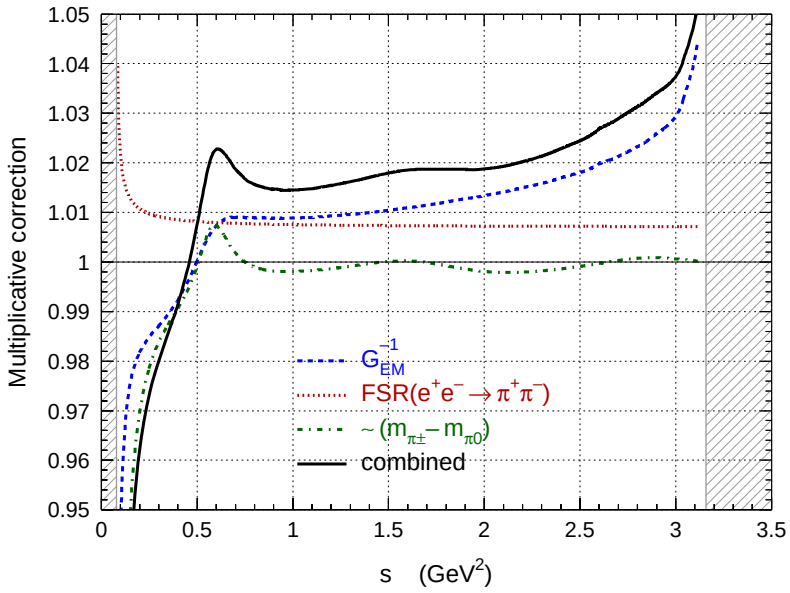
With more accurate data some deviations have been observed.

Corrections to the τ Spectral Functions

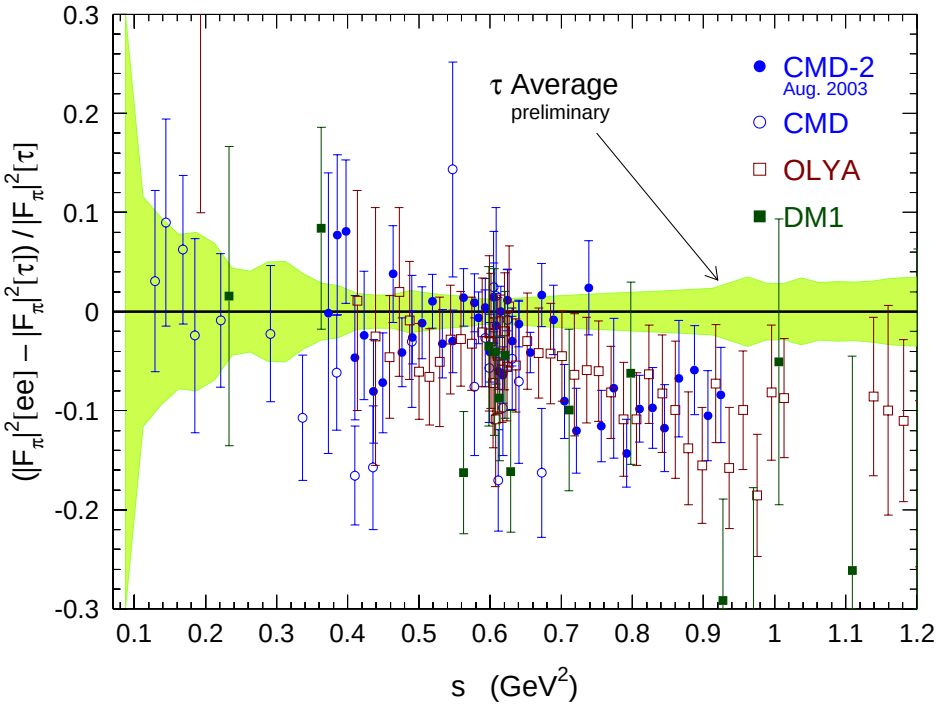
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- Real photons, loops
- FSR
- $m_{\pi^\pm} \neq m_{\pi^0}$
  (phase space, Γ_ρ)
- $m_{\rho^\pm} \neq m_{\rho^0}$
- $\rho - \omega$ interference
- Radiative decays
  $(\pi\pi\gamma, \pi(\eta)\gamma, l^+l^-)$
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  and 2 class currents

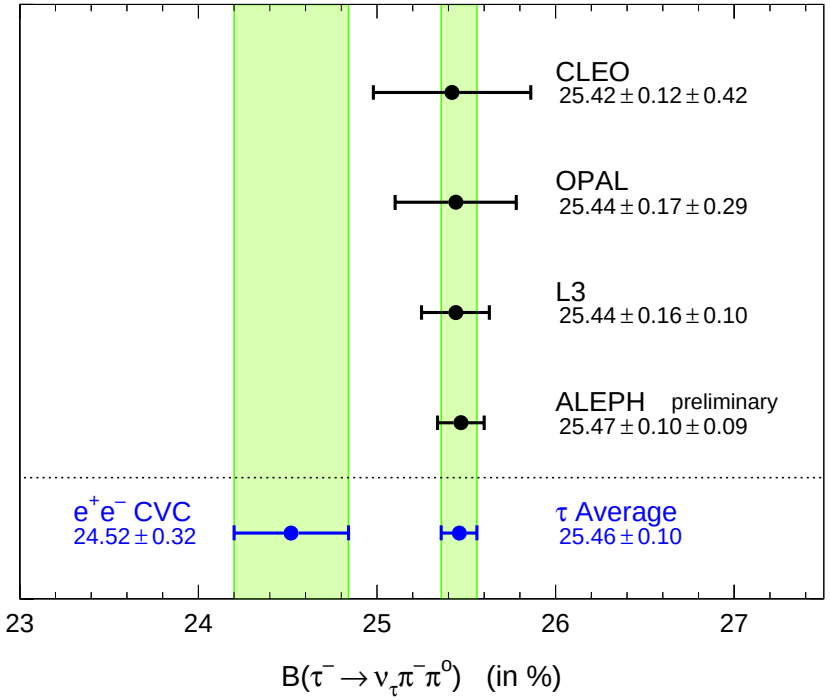
V. Cirigliano, G. Ecker, H. Neufeld, 2002

M. Davier, S. Eidelman, A. Höcker, Z. Zhang, 2002



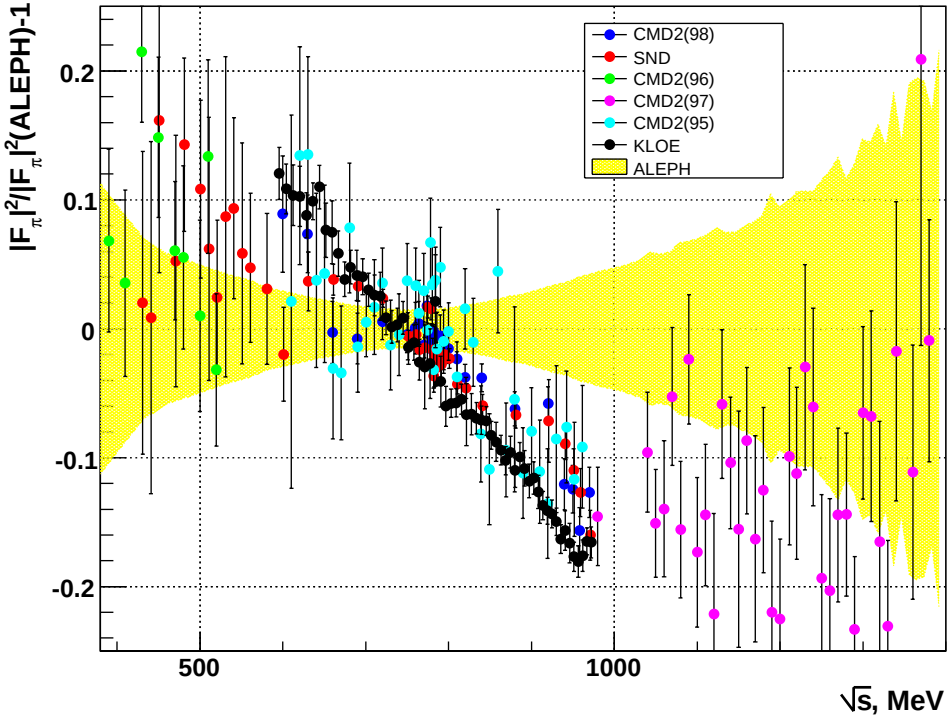
CVC in the 2π Channel. e^+e^- vs. τ





The branching from all groups is systematically higher than the CVC prediction:
$\mathcal{B}_\tau - \mathcal{B}_{ee} = (0.94 \pm 0.32)\%$!

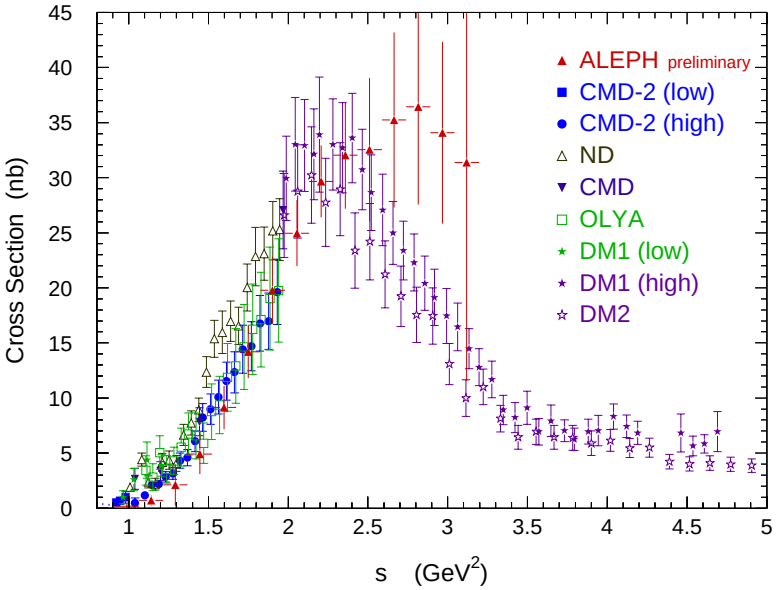
2π Spectral Functions in e^+e^- and τ after KLOE and SND



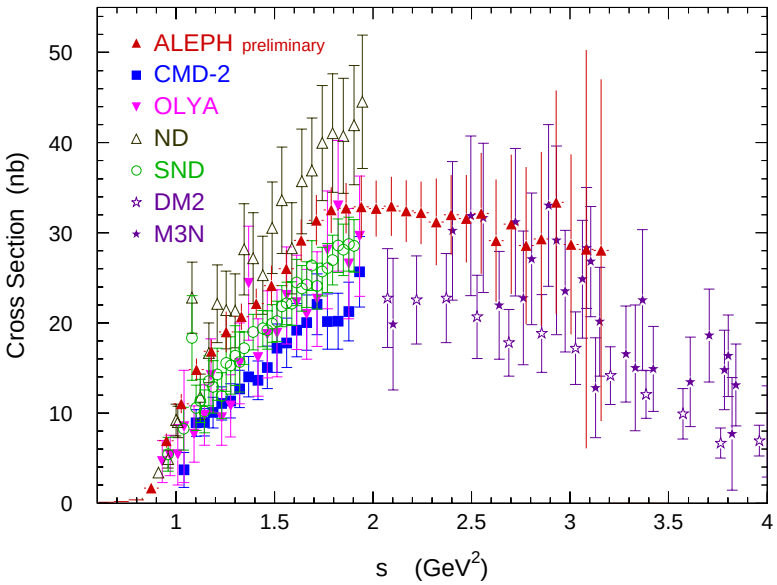
The puzzle remains unsolved $\Rightarrow$ τ data not used

CVC in the 4π Channel. e^+e^- vs. τ

$2\pi^+2\pi^-$



$\pi^+\pi^-2\pi^0$



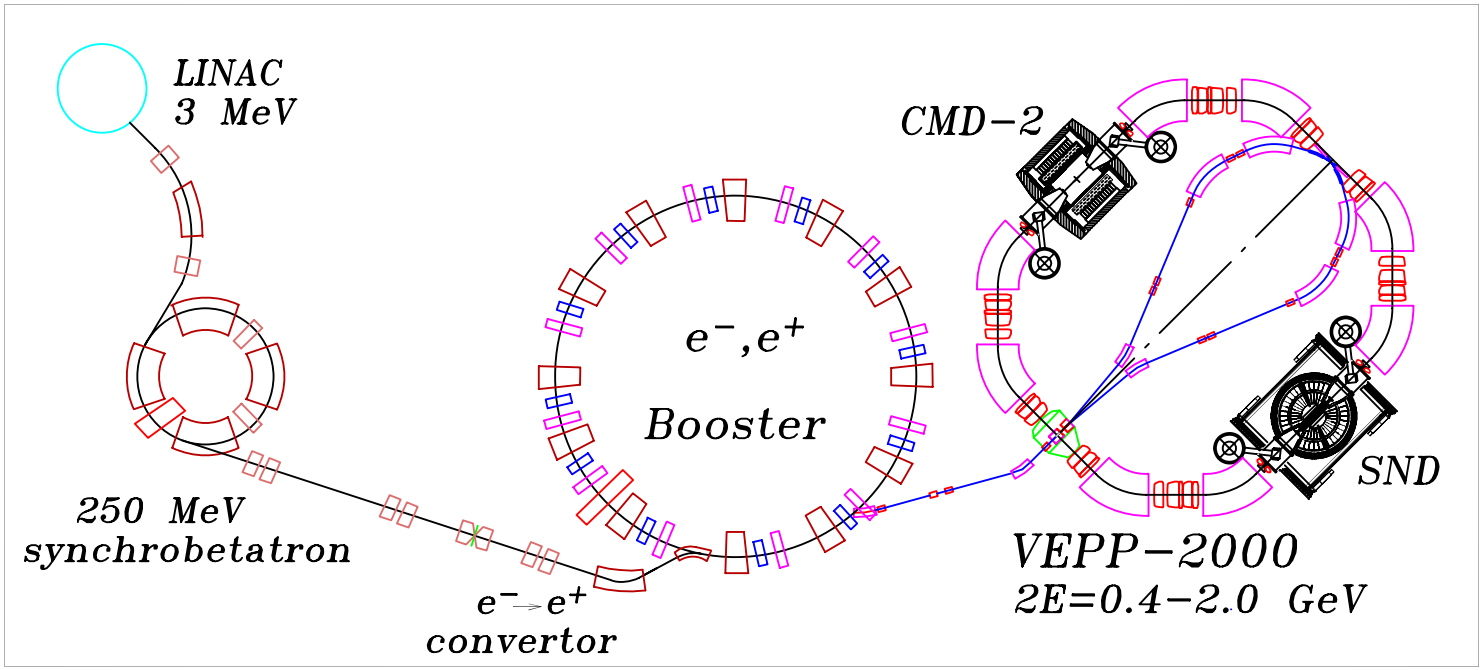
	$2\pi^+2\pi^-$	$\pi^+\pi^-2\pi^0$
$\mathcal{B}(\tau), \%$	1.01 ± 0.08	4.54 ± 0.13
$\mathcal{B}(\mathrm{CVC}), \%$	1.09 ± 0.08	3.63 ± 0.21
$\Delta\mathcal{B}, \%$	-0.08 ± 0.11	$+0.91 \pm 0.25$

Why are e^+e^- and τ Spectral Functions Different?

- Problems with data: underestimated systematics, normalization, rad. corr.
- Problems with SU(2) breaking corrections; Is ChPT reliable? The uncertainty of corrections may be large (K.Maltman, 2005)
- Non (V-A) contribution to e/w interactions (M.Chizhov, 2003) inspired by problems in $\pi^+ \to e^+\nu_e\gamma$ (E.Frlez et al., 2003)
- Effect of charged Higgs propagator in τ decay
- $m_{\rho^\pm} > m_{\rho^0}$ by a few MeV (S.Ghozzi and F.Jegerlehner, 2003, M.Davier, 2003). Current experiments indicate equality within a few MeV.

VEPP-2000

Layout of the VEPP−2000 complex



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