Status of the muon g-2

and the

theoretical uncertainty of the hadronic contributions

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Outline of Talk:

① **Lepton magnetic moments: basics**

② **The Anomalous Magnetic Moment of the Muon**

③ **Standard Model Prediction for a_μ**

④ **Evaluation of $a_\mu^{\rm had}$**

⑤ **e^+e^-–Cross Sections via τ–Decay Spectral Functions**

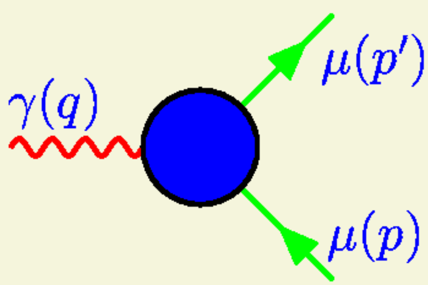
⑥ **Outlook**

Abstract: The muon anomalous magnetic moment is one of the most precisely measured quantities in particle physics. New high precision measurements at Brookhaven indicate a 2.6 sigma deviation from the electroweak Standard Model and thus might signal a contribution from yet unknown new physics. I review the status of the theoretical predictions and in particular discuss the role of hadronic vacuum polarization effects and the light--by--light scattering contribution.

① Lepton magnetic moments: basics

$$\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\,\vec{s}\;;\quad g_\mu = 2\,(1+a_\mu)$$

Dirac: $g_\mu = 2$, a_μ **muon anomaly**



$$= (-ie)\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_2(q^2)\right]u(p)$$

$$F_1(0) = 1\;;\quad F_2(0) = a_\mu$$

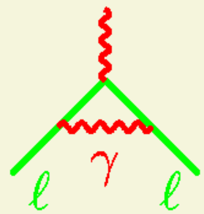
a_μ responsible for the Larmor precession

directly proportional at magic energy $\sim$ 3.1 GeV

CERN, BNL g-2 experiments

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]_{\text{at "magic }\gamma\text{"}}^{E\sim 3.1\,\mathrm{GeV}} \simeq \frac{e}{m}\left[a_\mu \vec{B}\right]$$

a_ℓ: dimensionless (just a number), must vanish at tree level in any renormalizable theory $\rightarrow$ finite prediction , testing helicity flip, most precisely measured electroweak observables. Lowest order QED/SM prediction: a_ℓ universal



$$a_e = a_\mu = a_\tau = \frac{\alpha}{2\pi}$$ Schwinger 48

a_e: Presently most precise determination of $\alpha = e^2/4\pi$

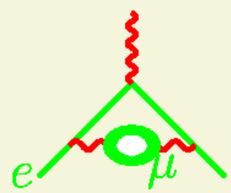
a_μ: Enhanced sensitivity to New Physics, severe constraints to physics beyond the SM

$$a_\ell \sim \left(\frac{m_\ell}{m_{\rm NP}}\right)^2 \Rightarrow \left(\frac{m_\mu}{m_e}\right)^2$$

$a_\mu \sim$ 40000 times more sensitive than a_e

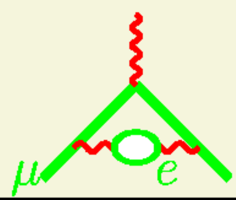
Even so a_μ is 143$\times$ less precise than a_e its still 280$\times$ more sensitive to NP

Mass effects: — HEAVY internal masses decouples



$$= \left[\frac{1}{45}\left(\frac{m_e}{m_\mu}\right)^2 + O\left(\frac{m_e^4}{m_\mu^4}\ln\frac{m_\mu}{m_e}\right)\right]\left(\frac{\alpha}{\pi}\right)^2$$

— LIGHT internal masses give rise to log's of mass ratios



$$= \left[\frac{1}{3}\ln\frac{m_\mu}{m_e} - \frac{25}{36} + O\left(\frac{m_e}{m_\mu}\right)\right]\left(\frac{\alpha}{\pi}\right)^2$$

Universal contributions

- 2-loop diagrams [7] with common fermion lines

$$a_\ell^{(4)} = \left[\frac{197}{144} + \frac{\pi^2}{12} - \frac{\pi^2}{2}\ln 2 + \frac{3}{4}\zeta(3)\right] \left(\frac{\alpha}{\pi}\right)^2$$

Peterman 57, Sommerfield 57

- 3-loop diagrams [72] with common fermion lines

$$a_\ell^{(6)} = \left[\frac{28259}{5184} + \frac{17101}{810}\pi^2 - \frac{298}{9}\pi^2\ln 2 + \frac{139}{18}\zeta(3) + \frac{100}{3}\left\{{\rm Li}_4(\frac{1}{2}) + \frac{1}{24}\ln^4 2 - \frac{1}{24}\pi^2\ln^2 2\right\} - \frac{239}{2160}\pi^4 + \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5)\right] \left(\frac{\alpha}{\pi}\right)^3$$

Laporta & Remiddi 96

- 4-loop diagrams [891] with common fermion lines numerically

Kinoshita 99, Kinoshita & Nio 02

$$a_\ell^{\rm universal} = 0.5\left(\frac{\alpha}{\pi}\right) - 0.3284789655\ldots\left(\frac{\alpha}{\pi}\right)^2 + 1.18124145\ldots\left(\frac{\alpha}{\pi}\right)^3 - \boxed{1.7502(384)}\left(\frac{\alpha}{\pi}\right)^4$$

Kinoshita & Nio 02 coefficient of $\left(\frac{\alpha}{\pi}\right)^4$ changed by -0.24

Corrections due to internal μ- and τ-loops

$$a_e = a_e^{\rm uni} + a_e(\mu) + a_e(\tau)$$

$$a_e(\mu) = \underbrace{5.197 \times 10^{-7}}_{\mu\ \ {\rm VP}} \left(\frac{\alpha}{\pi}\right)^2 + (\underbrace{-2.1768 \times 10^{-5}}_{\mu\ \ {\rm ho\ VP}} + \underbrace{1.4394 \times 10^{-5}}_{\mu\ \ {\rm LBL}}) \times \left(\frac{\alpha}{\pi}\right)^3$$

$$a_e(\tau) = \underbrace{1.838 \times 10^{-9}}_{\tau\ \ {\rm VP}} \left(\frac{\alpha}{\pi}\right)^2$$

Hadronic corrections: $a_e^{\rm had} = 1.67(3) \times 10^{-12}$

Weak corrections: $a_e^{\rm wcak} = 0.03 \times 10^{-12}$

$\Rightarrow a_e$ is excellent observable for extracting $\alpha_{\rm QED}$!

Most precise $\alpha_{\rm em}$ from $a_e \equiv (g_e-2)/2$

Compare extraordinary precise measurements of electron anomalous magnetic moment

$$a_e \equiv (g_e-2)/2$$

$$a_{e^-}^{\rm exp} = 0.001\,159\,652\,188\,4(43), \quad a_{e^+}^{\rm exp} = 0.001\,159\,652\,187\,9(43)$$

Dehmelt et al. 1987

with the prediction

$$a_e^{\rm SM} = \frac{\alpha}{2\pi} - 0.328\,478\,444\,00\left(\frac{\alpha}{\pi}\right)^2 + 1.181\,234\,017\left(\frac{\alpha}{\pi}\right)^3 - 1.7502(384)\left(\frac{\alpha}{\pi}\right)^4 \; {}^* + 1.66(3)\times 10^{-12}$$ **(hadronic & electroweak loops)**

$$\Downarrow$$

currently provides the best determination of the fine structure constant

$$\alpha^{-1}(a_e) = 137.035\,998\,75(52)$$ **(3.8 ppb)**

* **Kinoshita, Nio 2003** $[-0.24]\times\left(\frac{\alpha}{\pi}\right)^4$ **update announced**

② The Anomalous Magnetic Moment of the Muon

a_μ most precise test of quantum field theory model (QED/SM)

Experimental results: from muon storage rings

history CERN 1977:

ave μ^+ **and** μ^-**:** $a_\mu^{\rm exp} = 11\,659\,\underline{230}(84) \times 10^{-10}$ **(CERN 1977)**

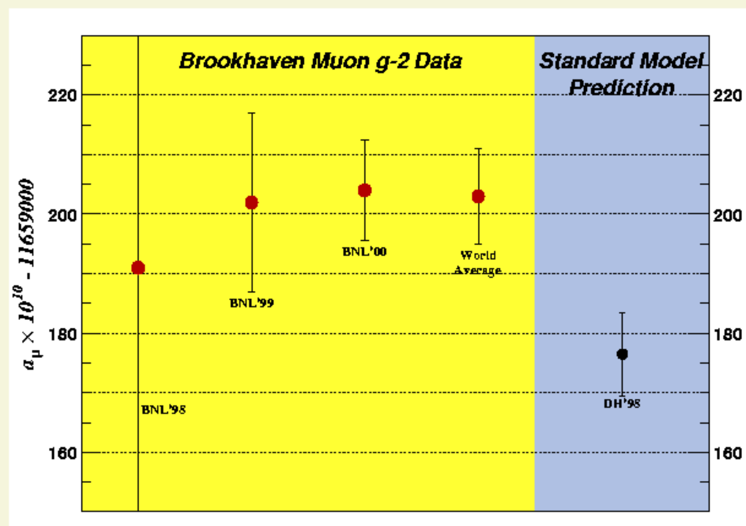
from ongoing experiment E821 at BNL 1998, $\cdots$**:**

BNL 2002 with μ^+**:** $a_{\mu^+} = 11\,659\,\underline{203}(8) \times 10^{-10}$ **(BNL'02+$\cdots$)**

BNL 2003 with μ^-**:** $a_{\mu^-} = 11\,659\,\underline{214}(8)(3) \times 10^{-10}$ **(BNL'04)**

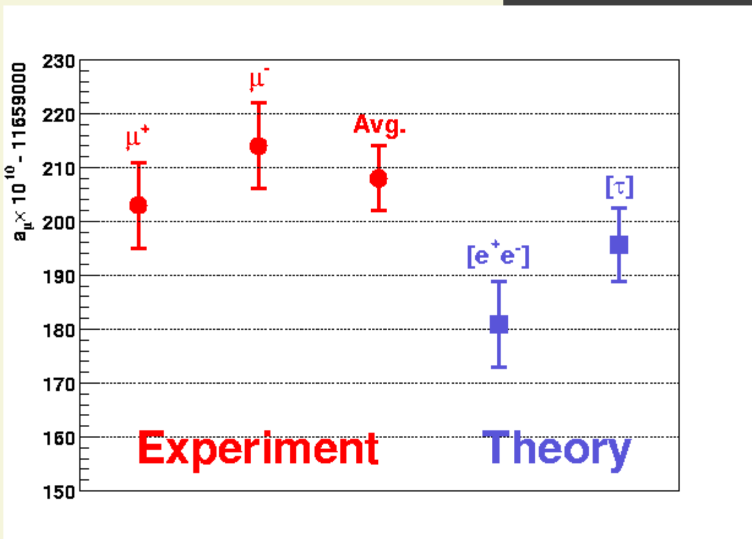
Averaged (CPT assumed):

$a_\mu(\rm exp) = 11\,659\,\underline{208}(6) \times 10^{-10}$ **(0.5 ppm)**



$(g-2)_\mu$ **and** $a_\mu^{\rm had}$

Experiment vs. Theory Summary 2004



$2.7\,\sigma\,(e^+e^-)$ [$1.4\,\sigma\,(\tau)$]

BNL - E821

Muon (g-2) Collaboration

hep-ex/0401008

	experiment	0.5ppm	=	6×10^{-10}	[5×10^{-10} stat, 4×10^{-10} syst]
Uncertainties:	theory	0.7ppm	=	8×10^{-10}	(e^+e^-) [0.6ppm = 7×10^{-10} (τ)]
	BNL design	0.35ppm	=	4×10^{-10}	

New physics sensitivity: (example) $\Delta a_\mu^{\rm SUSY}/a_\mu \simeq 1.25{\rm ppm} \left(\frac{100{\rm GeV}}{\tilde{m}}\right)^2 \tan\beta$

2-loops may amount $\sim 1.0\,\sigma$

for allowed parameter space

$\tilde{m}$ lightest SUSY particle

Heinemeyer, Stöckinger, Weiglein

hep-ph/0312264

$\tan\beta = \frac{v_1}{v_2}, v_i = < H_i >\ ;\ \ i = 1,2$

SUSY requires two Higgs fields

see Sven Heinemeiers talk

③ Standard Model Prediction for a_μ

❶ QED Contribution

The QED contribution to a_μ has been computed (or estimated) through **5 loops**

$$a_\mu^{\rm QED} = \frac{\alpha}{2\pi} + 0.765\,857\,376(27)\left(\frac{\alpha}{\pi}\right)^2 + 24.050\,508\,98(44)\left(\frac{\alpha}{\pi}\right)^3 + 126.07(41)\left(\frac{\alpha}{\pi}\right)^4 + 930(170)\left(\frac{\alpha}{\pi}\right)^5 .$$

Growing coefficients in the α/π expansion reflect the presence of large $\ln \frac{m_\mu}{m_e} \simeq 5.3$ terms coming from electron loops. Employing the value of α from a_e leads to

$$a_\mu^{\rm QED} = 116\,584\,705.7(2.9) \times 10^{-11} \text{ (old)}$$

The current uncertainty is well below the $\pm 40 \times 10^{-11}$ ultimate experimental error anticipated from E821 and should, therefore, play no essential role in the confrontation between theory and experiment.

Not quite: Corrections due to internal e- and τ-loops updated

$$a_\mu = a_e^{\rm uni} + a_\mu(m_\mu/m_e) + a_\mu(m_\mu/m_\tau) + a_\mu(m_\mu/m_e, m_\mu/m_\tau)$$

$$\begin{aligned} a_\mu(m_\mu/m_e) &= 1.094\,258\,282\,8\,(98)\left(\frac{\alpha}{\pi}\right)^2 + 22.868\,379\,36\,(23)\left(\frac{\alpha}{\pi}\right)^3 \\ &+ \boxed{132.682\,3\,(72)}\left(\frac{\alpha}{\pi}\right)^4 \\ a_\mu(m_\mu/m_\tau) &= 7.8059\,(25)\times 10^{-5}\left(\frac{\alpha}{\pi}\right)^2 + 36.054\,(21)\times 10^{-5}\left(\frac{\alpha}{\pi}\right)^3 \\ &+ \boxed{127.50\,(41)}\left(\frac{\alpha}{\pi}\right)^4 \\ a_\mu(m_\mu/m_e, m_\mu/m_\tau) &= 52.763\,(17)\times 10^{-5}\left(\frac{\alpha}{\pi}\right)^3 \\ &+ \boxed{0.037\,594\,(83)}\left(\frac{\alpha}{\pi}\right)^4 \end{aligned}$$

with $\alpha^{-1}(\mathrm{a.i.}) = 137.036\,000\,3\;(10)$ [7.4 ppb]

$$a_\mu^{\rm QED} = 116\,584\,719.35\;\underbrace{(0.03)}_{\alpha^4}\underbrace{(1.15)}_{\alpha^5}\underbrace{(0.85)}_{\alpha_{\rm inp}}\times 10^{-11}$$

shift by $\boxed{+13.7\times 10^{-11}}$

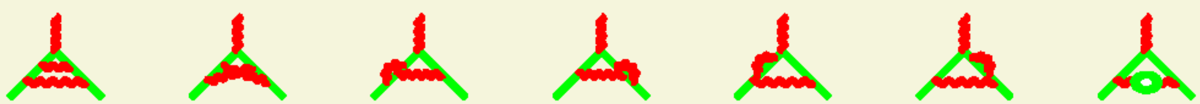
Kinoshita, Nio 04

$(g-2)_\mu$ and $a_\mu^{\rm had}$

# of loops	$a_\mu^{\rm QED} \times 10^{11}$
1	116140972.87 (0.44)
2	413217.60 (0.02)
3	30141.90 (0.00)
4	367.01 (1.19)
5	6.29 (1.15)
tot	116584705.66 (2.80)

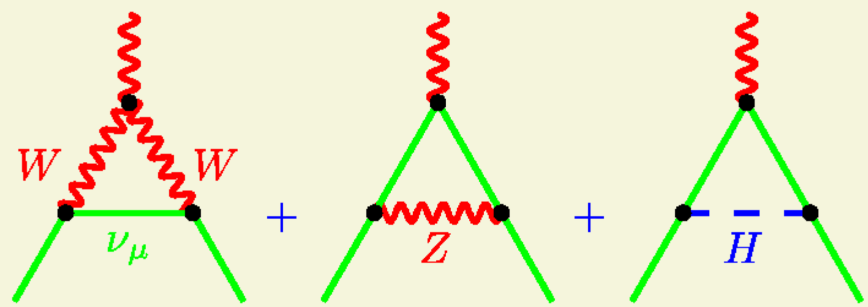
1. 1 diagram — Schwinger 1948

2. 7 diagrams — Peterman 1957, Sommerfield 1957



3. 72 diagrams — Lautrup, Peterman, de Rafael 1974, Laporta, Remiddi 1996
4. about 1000 diagrams — Kinoshita 1999, Kinoshita, Nio 2004
5. RG estimate — Czarnecki, Marciano 00

❷ Weak Contributions

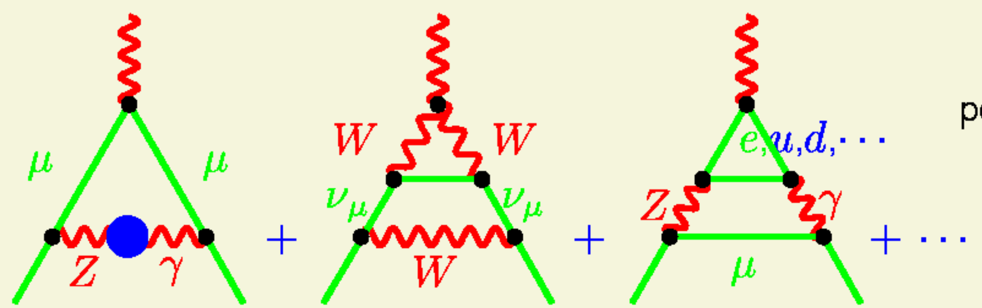


$$a_\mu^{\mathrm{wcak}(1)} = (195 \pm 0) \times 10^{-11}$$

Brodsky, Sullivan 67, ...,

Bardeen, Gastmans, Lautrup 72

Higgs contribution tiny!



$$a_\mu^{\mathrm{wcak}(2)} = -(44 \pm 4) \times 10^{-11}$$

Kukhto et al 92

potentially large terms $\sim G_F m_\mu^2 \frac{\alpha}{\pi} \ln \frac{M_Z}{m_\mu}$

Peris, Perrottet, de Rafael 95

quark-lepton (triangle anomaly) partial

Czarnecki, Krause, Marciano 96 full result

Most recent evaluations: improved hadronic part (beyond QPM)

$a_\mu^{\mathrm{wcak}} = (152 \pm 1[\mathrm{had}] \pm ?) \times 10^{-11}$ **(Knecht, Peris, Perrottet, de Rafael 02)**

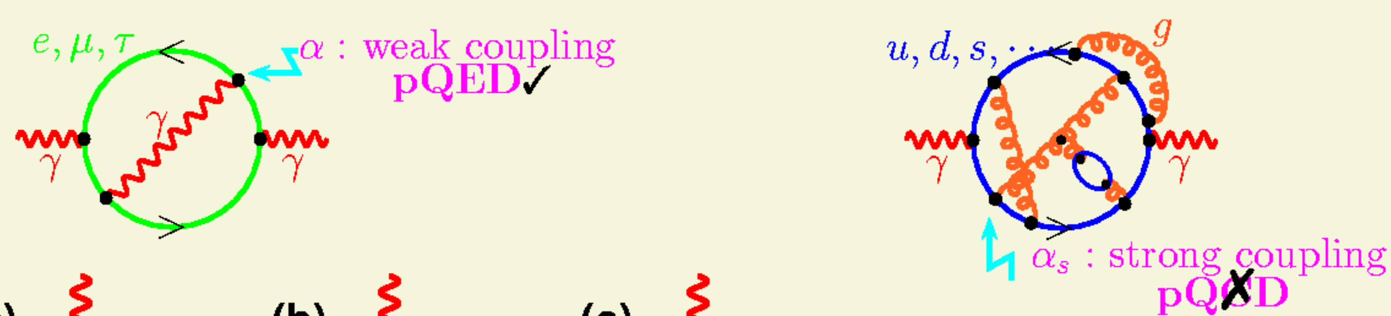
$a_\mu^{\mathrm{wcak}} = (154 \pm 1[\mathrm{had}] \pm 2[\mathrm{m_H}, \mathrm{m_t}, 3-\mathrm{loop}]) \times 10^{-11}$ **(Czarnecki, Marciano, Vainshtein 02)**

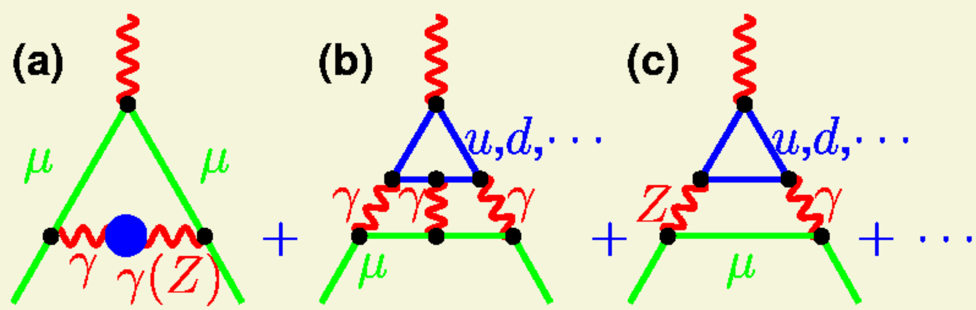
❸ Hadronic Contributions

General problem in electroweak precision physics:

contributions from hadrons (quark loops) at low energy scales

Leptons **Quarks**





(a) Hadronic vacuum polarization $O(\alpha^2), O(\alpha^3)$

(b) Hadronic light-by-light scattering $O(\alpha^3)$

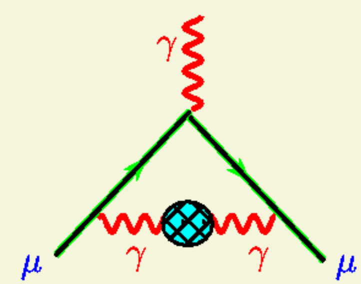
(c) Hadronic effects in 2-loop EWRC $O(\alpha G_F m_\mu^2)$

Light quark loops $\to$ Hadronic "blob"

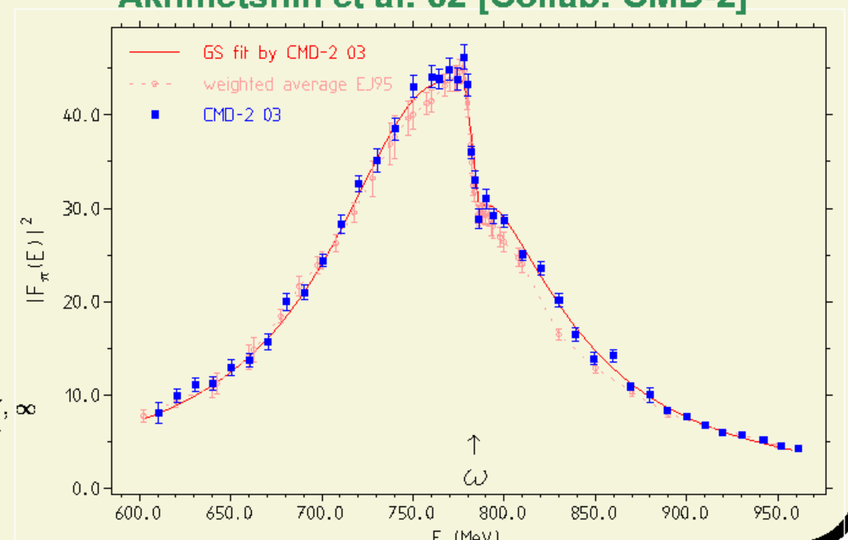
④ Evaluation of $a_\mu^{\rm had}$

Leading non-perturbative hadronic contributions $a_\mu^{\rm had}$ can be obtained in terms of $R_\gamma(s) \equiv \sigma^{(0)}(e^+e^- \to \gamma^* \to {\rm hadrons})/\frac{4\pi\alpha^2}{3s}$ data via dispersion integral:

$$a_\mu^{\rm had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left(\int\limits_{4m_\pi^2}^{E^2_{\rm cut}} ds \frac{R_\gamma^{\rm data}(s)\ \hat{K}(s)}{s^2} + \int\limits_{E^2_{\rm cut}}^{\infty} ds \frac{R_\gamma^{\rm pQCD}(s)\ \hat{K}(s)}{s^2} \right)$$



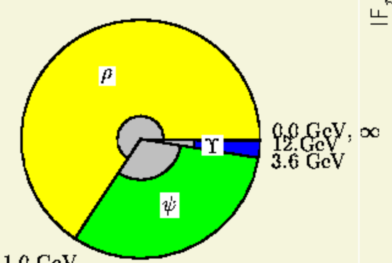
Data:
Akhmetshin et al. 02 [Collab. CMD-2]



- **Experimental error implies theoretical uncertainty!**
- **Low energy contributions enhanced: $\sim 67\%$ of error on $a_\mu^{\rm had}$ comes from region $4m_\pi^2 < m_{\pi\pi}^2 < M_\Phi^2$**

$$a_\mu^{\rm had(1)} = (694.8 \pm 8.6)\ 10^{-10}$$

e^+e^-–data based



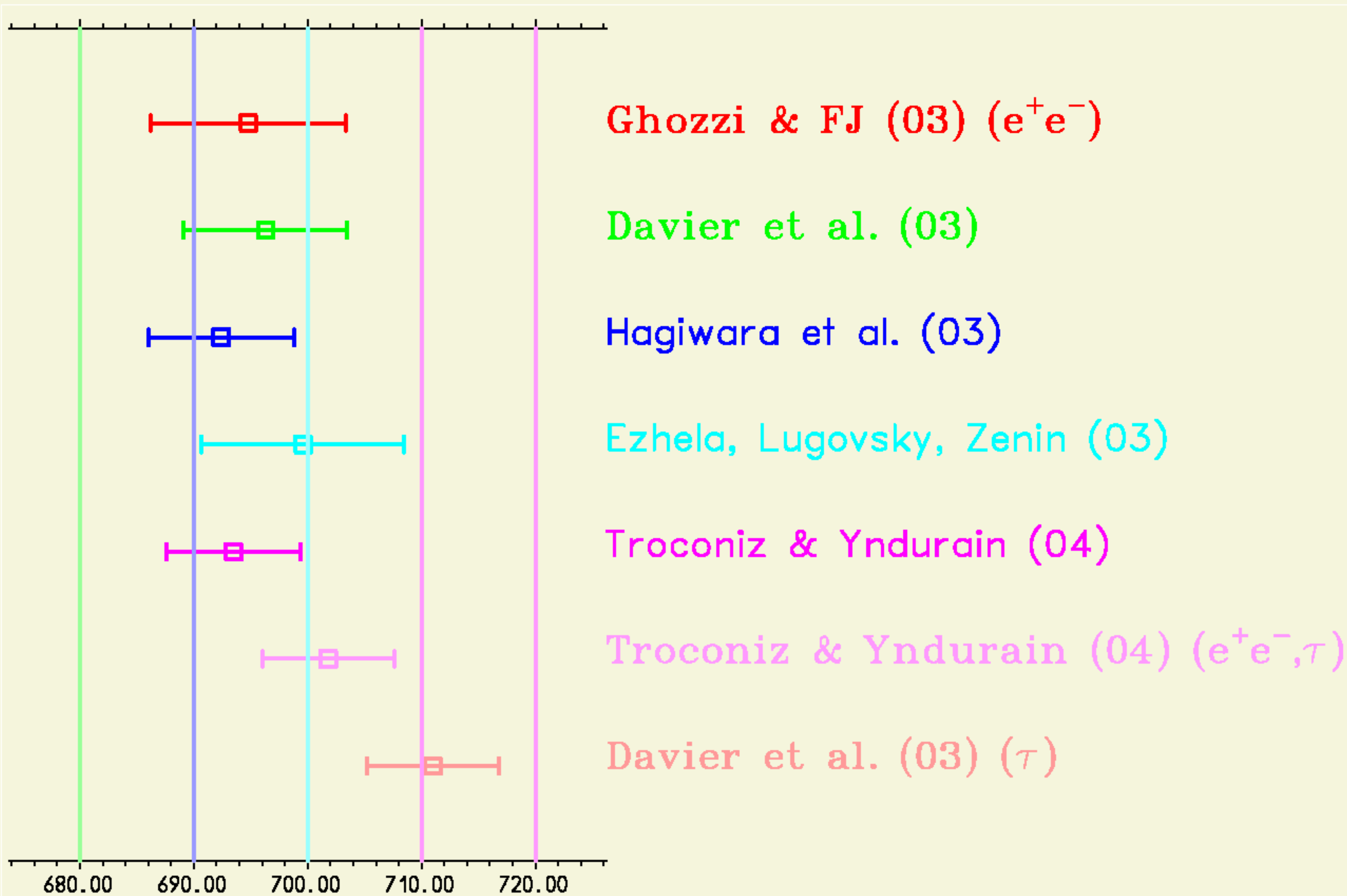
Recent evaluations of $a_\mu^{\rm had}$

Only results based on most recent data CMD-2 03,BES II 01 shown

data	$a_\mu^{\rm had(1)} \times 10^{10}$	Ref.	hep-ph
e^+e^-	$694.8[8.6]$	FJ,GJ 03	0310181
e^+e^-	$696.3[7.2](6.2)_{\rm exp}(3.6)_{\rm rad}$	DEHZ 03	0308213
e^+e^-	$692.4[6.4](5.9)_{\rm exp}(2.4)_{\rm rad}$	HMNT 03	0312250
e^+e^-	$699.6[8.9](8.5)_{\rm exp}(1.9)_{\rm rad}(2.0)_{\rm proc}$	ELZ 03	0312114
τ	$711.0[5.8](5.0)_{\rm exp}(0.8)_{\rm rad}(2.8)_{SU(2)}$	DEHZ 03	0308213
e^+e^-	$693.5[5.9](5.0)_{\rm exp}(1.0)_{\rm rad}(3.0)_{\ell\times\ell}$	TY 04	0402285
$e^+e^- + \tau$	$701.8[5.8](4.9)_{\rm exp}(1.0)_{\rm rad}(3.0)_{\ell\times\ell}$	TY 04	0402285

Differences in errors mainly by utilizing more or less theory: pQCD, SR, low energy QCD methods

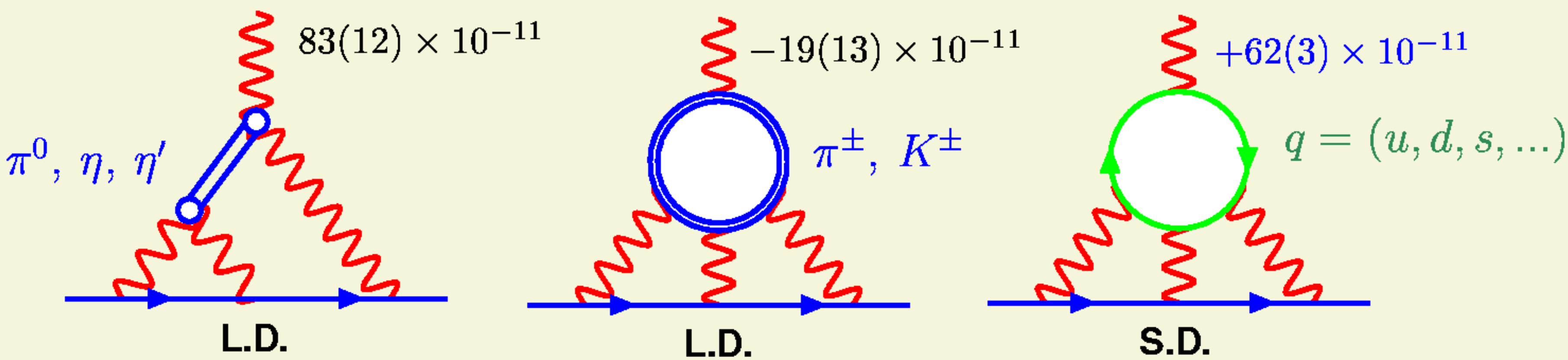
$(g-2)_\mu$ and $a_\mu^{\rm had}$



$(g-2)_\mu$ and $a_\mu^{\rm had}$

- **Higher order hadronic contributions** $a_\mu^{\rm had(2)} = -(100 \pm 6) \times 10^{-11}$ **(Krause 96)**
  $a_\mu^{\rm had(2)} = -(\,98 \pm 1) \times 10^{-11}$ **(Hagiwara et al. 03)**

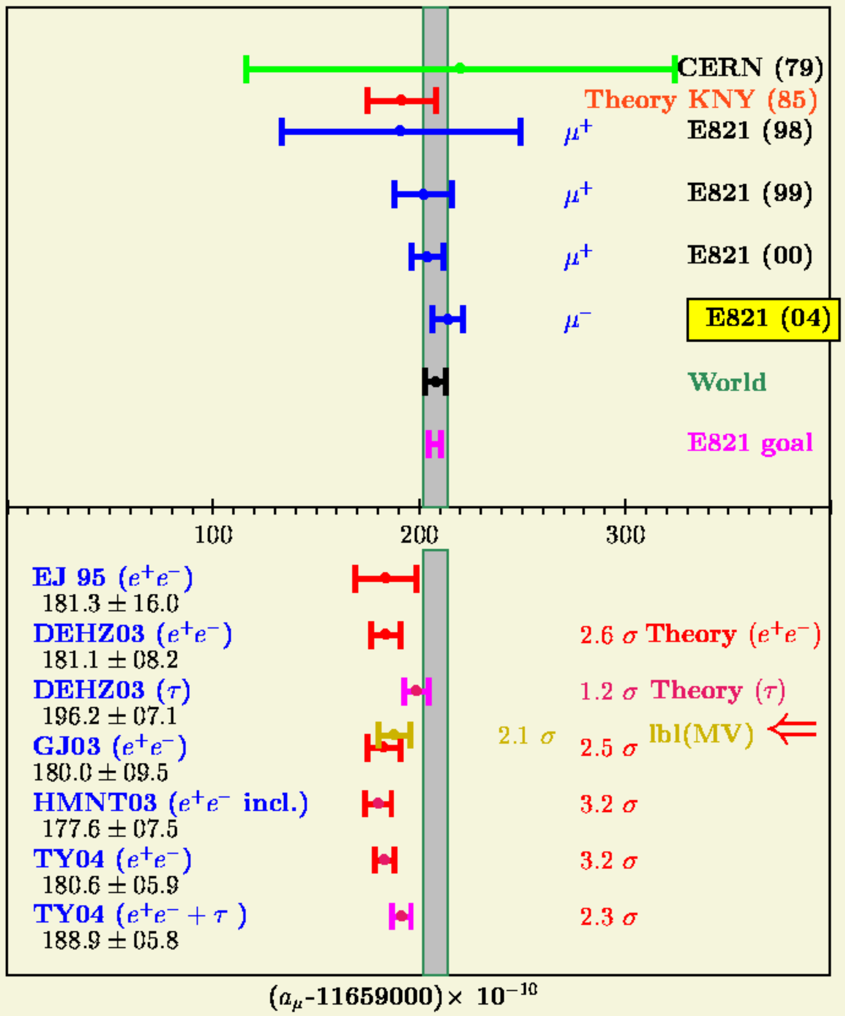
- **Hadronic light–by–light scattering** $a_\mu^{\rm lbl} = (\,80 \pm 40)\ \times 10^{-11}$ **(Nyffeler 02)**
  $a_\mu^{\rm lbl} = (136 \pm 25)\ \times 10^{-11}$ **(Melnikov & Vainshtein 03)** **shift by** $+56 \times 10^{-11}$



Low energy effective theory: e.g. ENJL

see Kirill Melnikov's talk

a_μ Summary: experiment vs. theory

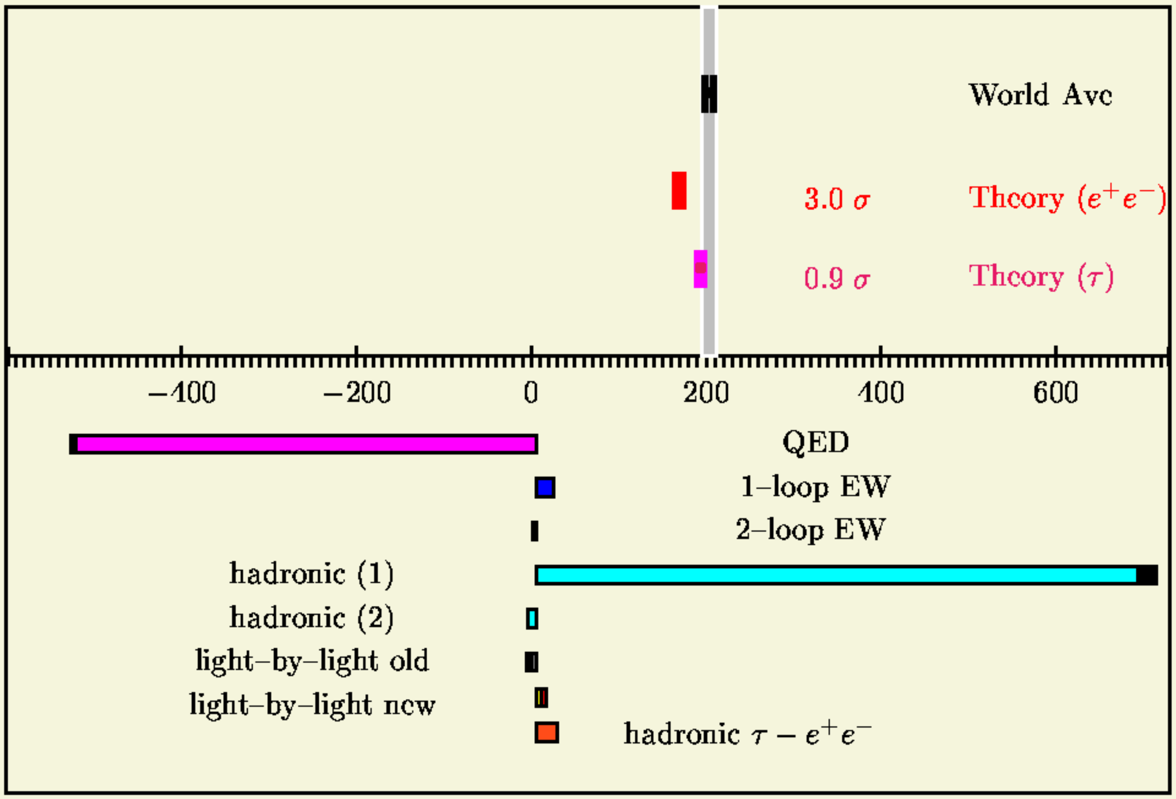


Given theory results only differ by $a_\mu^{\rm had(1)}$!

$(g-2)_\mu$ and $a_\mu^{\rm had}$

a_μ: type and size of contributions

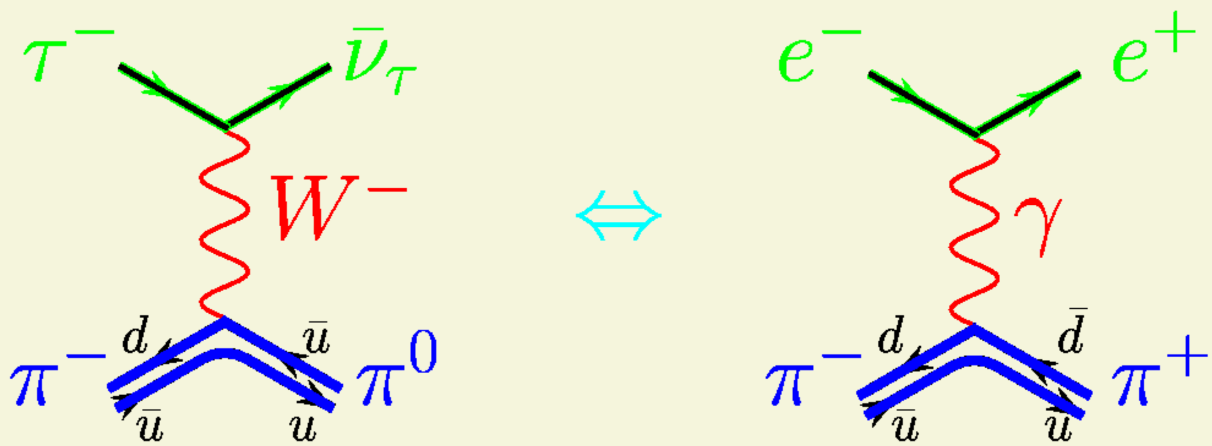
$$a_\mu = a_\mu^{\rm QED} + a_\mu^{\rm had(1)} + a_\mu^{\rm had(2)} + a_\mu^{\rm weak(1)} + a_\mu^{\rm weak(2)} + a_\mu^{\rm lbl} \; (+a_\mu^{\rm new\ physics})$$



All kind of physics meets !

⑤ e^+e^-–cross sections via τ–decay spectral functions

The iso-vector part of $\sigma(e^+e^- \to \mathrm{hadrons})$ may be calculated by a iso-spin rotation from τ–decay spectra (to the extend that CVC is valid)



$\tau^- \to X^- \nu_\tau \qquad \leftrightarrow \qquad e^+ e \to X^0$

X^- and X^0 are hadronic states related by iso-spin rotation.

The e^+e^- cross–section is then given by

$$\sigma^{I=1}_{e^+e^- \to X^0} = \frac{4\pi\alpha^2}{s} v_{1,X^-} \quad , \quad \sqrt{s} \leq M_\tau$$

in terms of the τ spectral function v_1.

$(g-2)_\mu$ and $a_\mu^{\rm had}$

- Additional "e^+e^-" data: τ–data + CVC ALEPH, OPAL, CLEO (ADH96, DEHZ02)
- mainly improves the knowledge of the $\pi^+\pi^-$ channel (ρ–resonance contribution)
- which is dominating in $a_\mu^{\rm had}$ (72%)

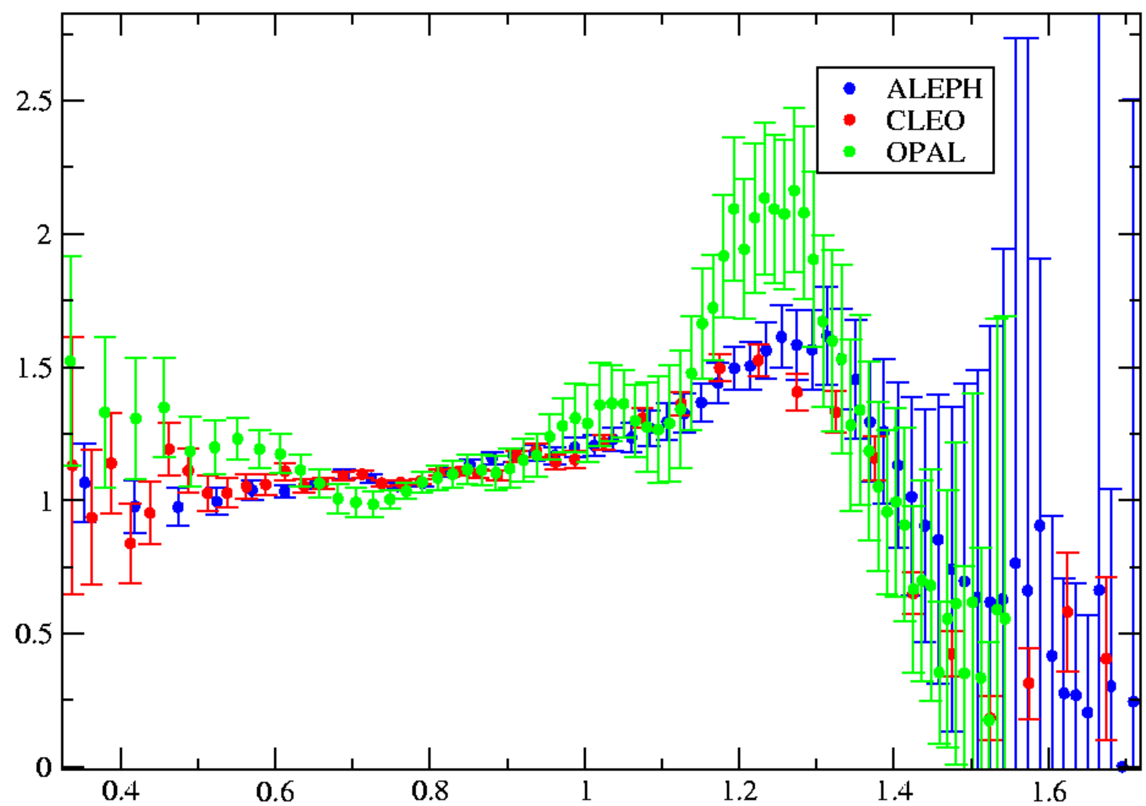
$I=1 \sim 75\%\,;\; I=0 \sim 25\% \Longrightarrow \tau$–data cannot replace e^+e^-–data

Alemany, Davier, Höcker 95:

$$\begin{array}{lcccc} \delta a_\mu & : & 15.6\times 10^{-10} & \to & 10.2\times 10^{-10} \\ \delta\Delta\alpha & : & 0.00067 & \to & 0.00065 \end{array}$$

All kind of isospin breaking effects have to be taken into account !!!

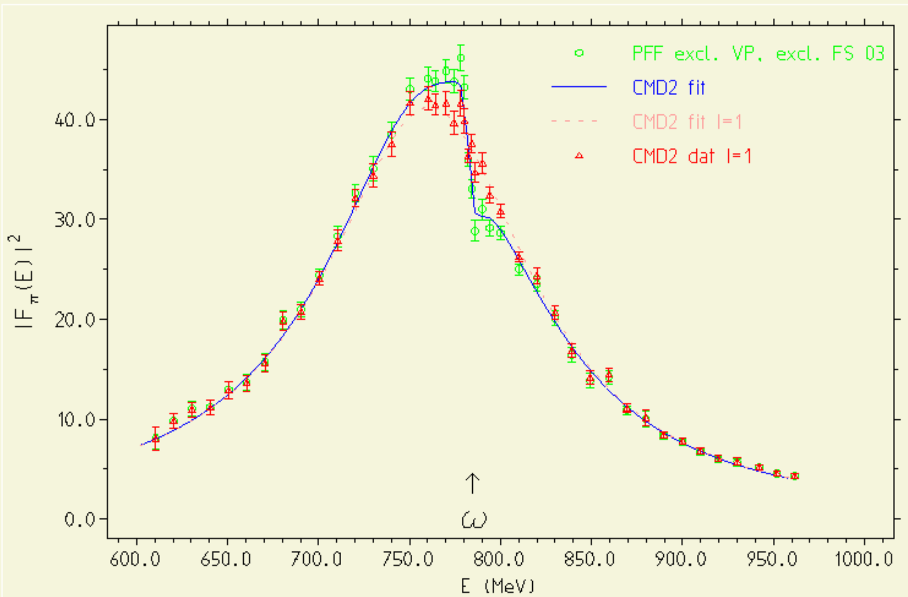
- **Comparison of τ–data:**

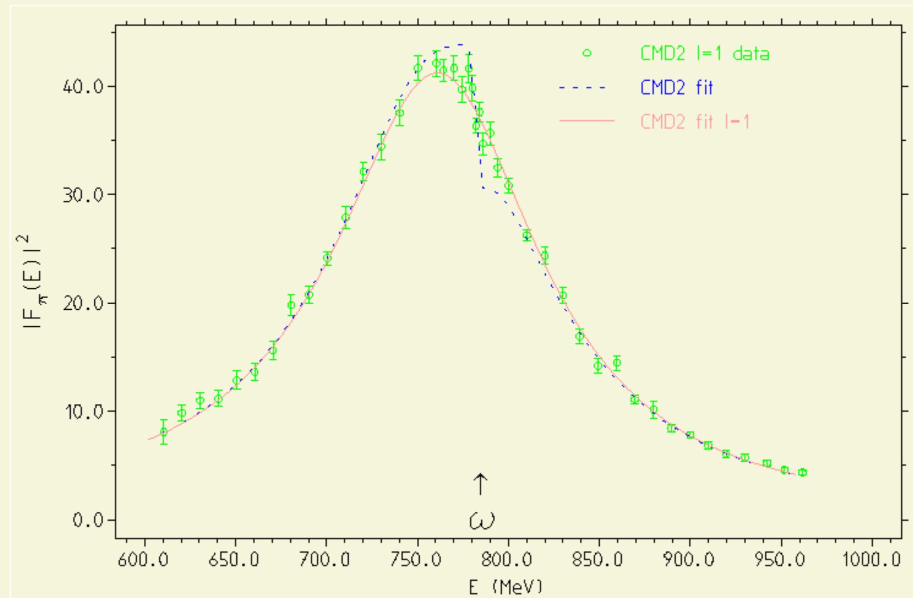


τ–data may be not so easy; DELPHI, L3 could not measure τ spectral–functions; ALEPH vs. OPAL no good agreement.

Comparing e^+e^- and τ data: use Gounaris-Sakurai for parametrization

1) no VP, no FSR, undo $\rho-\omega$-mixing





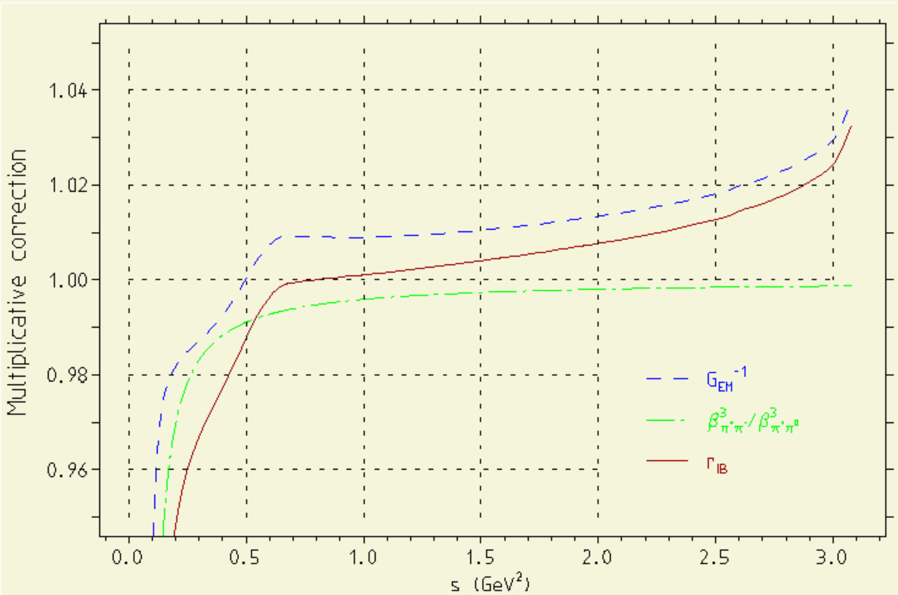
Fit for m_{ρ^0} and Γ_{ρ^0} at fixed background:

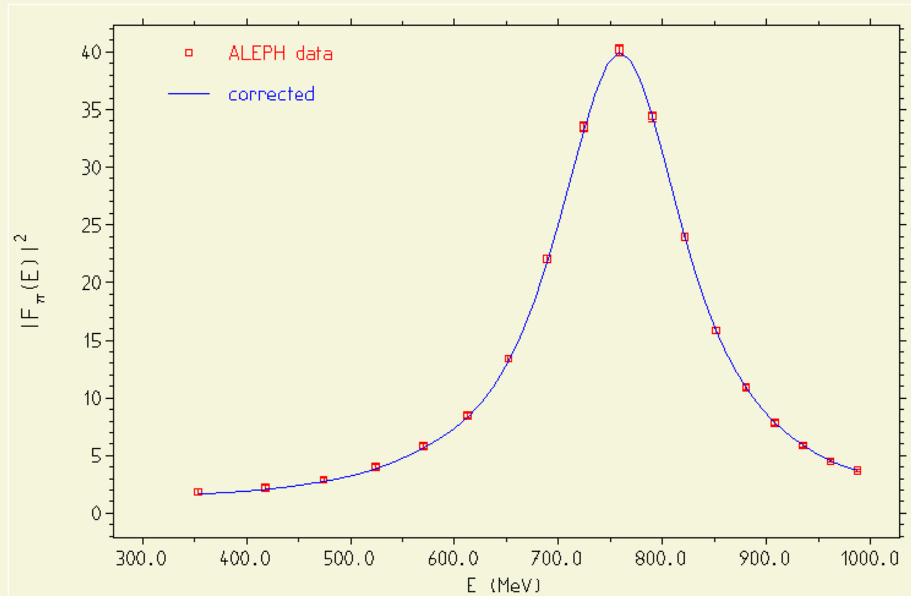
$$m_{\rho^0} = 772.5 \pm 0.6 \;\;,\;\; \Gamma_{\rho^0} = 148.1 \pm 1.0$$

(in agreement with M. Davier's fit)

CMD-2 data for $|F_\pi|^2$ in $\rho-\omega$ region together with Gounaris-Sakurai fit. Left before subtraction right after subtraction of the ω.

2) Iso-spin corrections applied to the τ data: left the corrections (CEN 02), with





$$r_{\rm IB}(s) = \frac{1}{G_{\rm EM}(s)}\,\frac{\beta^3_{\pi^-\pi^+}}{\beta^3_{\pi^-\pi^0}}\,\frac{S_{\rm EW(old)}}{S_{\rm EW(new)}}$$

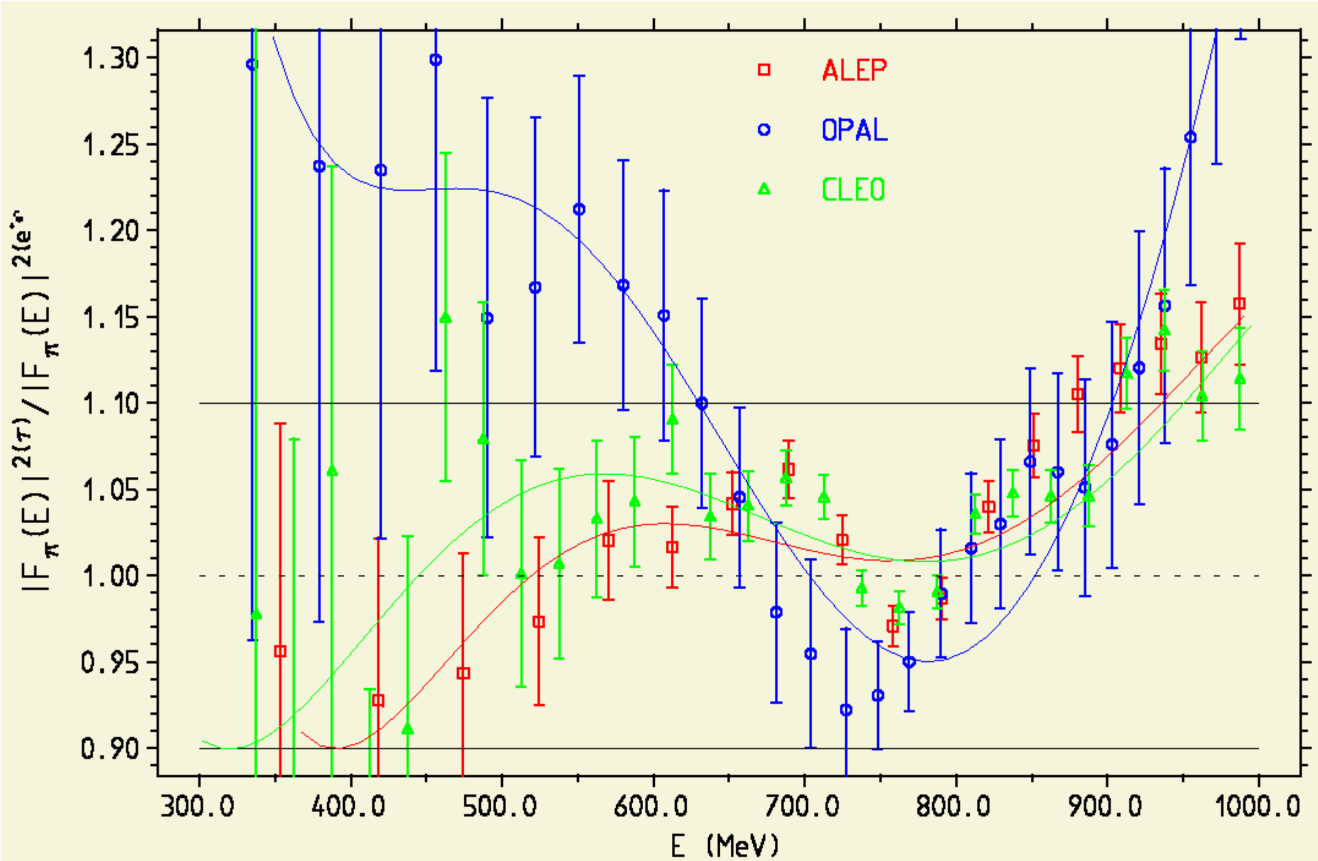
and right the effect on the ALEPH data.

Fit ALEPH data for m_{ρ^-} and Γ_{ρ^-} at fixed background:

$$m_{\rho^-} = 776.0 \pm 0.7 \;\;,\;\; \Gamma_{\rho^-} = 150.6 \pm 1.3$$

(M. Davier's fit, covariance matrix!)

The ratio: S. Ghozzi, FJ, hep-ph/0308117



Can fit ratio to 1 ± 0.001 by letting float m_ρ and Γ_ρ in th GS-formula in numerator $\Rightarrow$ yields back

$$m_{\rho^0} \quad \text{and} \quad \Gamma_{\rho^0}$$

not completely trivial as it works over the range shown.

$(g-2)_\mu$ and $a_\mu^{\rm had}$

- Two sets of reasonably consistent data: τ–data ALEPH, CLEO vs. CMD-2, KLOE
- What effect is able to to give 10% in a resonance tail? Answer: a shift of the energy by about 1%. Could be a problem of energy calibration, but this is very unlikely. Rather the physical resonance parameters have no reason to be identical!
- In spite of possible experimental problems, there is no reason to expect the neutral channel parameters to be the same as the charged current ones. Example, pions: $m_{\pi^\pm} - m_{\pi^0} = 4.5935 \pm 0.0005$ MeV. Why should this be very different for the ρ a similar (same quark content) bound state?
- Usual argument $\Delta m_\rho^2 = \Delta m_\pi^2$ from a sum rule yields $m_{\rho^-} - m_{\rho^0} = \frac{1}{2}\frac{\Delta m_\pi^2}{m_{\rho^0}} \sim 0.02$MeV !.
- This is based on an assumption which easily could be wrong!
- Our conclusion: the observed discrepancy is a so far unaccounted iso-spin breaking effect, which the τ-data have to be corrected for!
- Relevant for calculating $a_\mu^{\rm had}$ are the e^+e^-–data in first place.
- How to include the τ–data? Should know Δm_ρ and $\Delta\Gamma_\rho$ from elsewhere. Other

parameters like $m_{\rho'}$ and $\Gamma_{\rho'}$ are affected as well, but his is a higher order effect.

- In spite that the peak is shifted downwards and the s^{-2} weight in the integral which yields $a_\mu^{\rm had}$ the latter does not go up, it rather goes down, because the width also substantially goes down and over-compensates the effect of the mass shift.
- If you don't like the idea: notice that the $\frac{\partial a_\mu^{\rm had}}{\partial m_\rho [\Gamma_\rho]}$ is very large so that this quantity is very sensitive to the parameters.

My conclusion:

we are back to <u>one</u> prediction for a_μ

at 2σ from the experimental value!

⑥ Outlook

Summary:

- the new a_{μ^-} measurements is in very good agreement with the a_{μ^+} value in accordance with CPT and the combined result with an error of 60×10^{-11} not so far from the original goal of 40×10^{-11}.
- the increasing precision required and triggerd a lot of new efforts to understand and/or settle the observed “discrepancy”
- still a big challenge on both the experimantal side (e^+e^- cross sections) and on the theory side (also Lattice QCD could become an important tool (Blum 03, Schierholz et al. 03).
- with unprecedented precision of the g-2 of the Muon experiment new obstacles showed up in many places which require more efforts on the theory side.
- remember situation similar to the one with CERN experiment 25 years ago (error in theory, leptonic lbl)

$(g-2)_\mu$ and $a_\mu^{\rm had}$

- e^+e^--databased data seem to be related more directly to what we need in the evaluation of $a_\mu^{\rm had}$
- τ-data require more reliable estimates of isospin breaking effects
- a conservative estimate is

$$\left|a_\mu^{\rm exp} - a_\mu^{\rm SM}\right| = (28 \pm 11) \times 10^{-10}$$

Still an exciting situation, some room for new physics, serious challenges for theory and experiment

- Need better e^+e^--data: KLOE is now finalizing their measurement by the radiative return method
  similar results expected from the B–factories
  ongoing upgrades: Novosibirsk, Beijing
- τ–charm factory
  able to perform an energy scan between 2 and 3.6 GeV
  would satisfy requirements of future precision experiments g-2, GigaZ,...

- Last but not least: need further progress in theory
  - ✗ more careful study of isospin breaking in τ–data vs. e^+e^-–data
  - ✗ constraints to $F_\pi(s)$ from χPT, unitarity and analyticity below the ρ
  - ✗ still a theoretical challenge:
    the hadronic light–by–light scattering contribution !
  - ✗ Concerning τ–data vs. e^+e^-–data discrepancy: need more careful check of radiative corrections which have been applied !
  - ✗ Further progress in radiative corrections calculations needed for the processes involved in R–measurements
  - ✗ Further progress in determination of QCD parameters crucial for improving PQCD part

Big experimental challenge: attempt cross-section measurements at 1% level up to $J/\psi[\Upsilon]$!!! crucial for $\alpha_{\rm QED}(M_Z)$ at GigaZ.