$\rho - \gamma$ mixing and e^+e^- vs. τ spectral functions

Robert Szafron
University of Silesia, Katowice

Work in collaboration with *Fred Jegerlehner*

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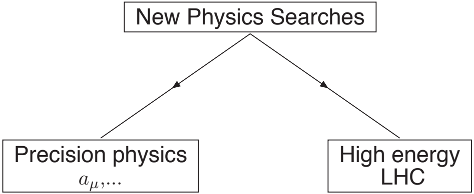
Outline

- Motivation
- The τ vs. e^+e^- problem
- A minimal model: VMD + sQED
- $F_\pi(s)$ with $\rho - \gamma$ mixing at one-loop
- Applications: a_μ and $B_{\pi\pi^0}^{\mathrm{CVC}} = \Gamma(\tau \to \nu_\tau \pi\pi^0)/\Gamma_\tau$
- Summary and Outlook

Motivation

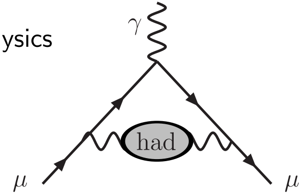


Good news:

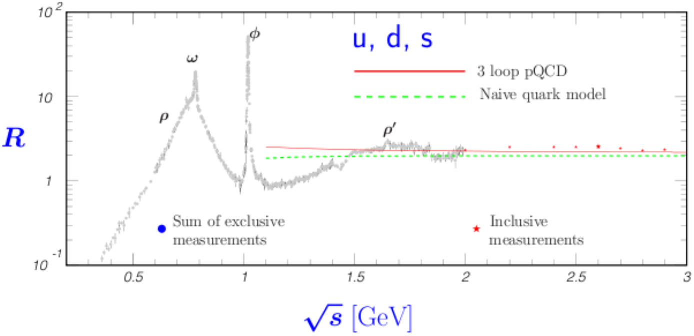
- a_μ is sensitive to a New Physics ($\delta a_l \sim \frac{m_l^2}{\Lambda^2}$)
- $\frac{\delta a_\mu}{\delta a_e} \backsim \frac{m_\mu^2}{m_e^2} \backsim 42725$
- Despite worse precision of a_μ it is still about 50 times more sensitive to New Physics

Bad news:

- a_μ is sensitive to hadronic contributions



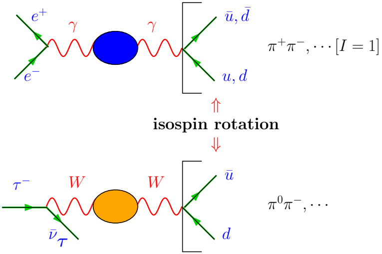
$$R(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$



PDG (2010)

The τ vs. e^+e^- problem

A good idea: improve e^+e^-–data by isospin rotated/corrected τ–data + CVC



ALEPH–Coll., (OPAL, CLEO), Alemany, Davier, Höcker 1996,
Belle–Coll. Fujikawa, Hayashii, Eidelman 2008

We relate the τ and e^+e^- data:

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

where X^- and X^0 are hadronic states related by isospin rotation. The e^+e^- cross–section is then given by

$$\sigma^{I=1}_{e^+e^- \to X^0} = \frac{4\pi\alpha^2}{s} \frac{\beta_0^3(s)}{\beta_-^3(s)} v_{1,X^-} \quad , \quad \sqrt{s} \le M_\tau$$

in terms of the τ spectral function v_1.
Mainly improves the knowledge of the $\pi^+\pi^-$ channel (ρ–resonance contribution) which is dominating in a_μ^{had} (72%)

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

Isospin violation

Quark mass difference $m_u \neq m_d$ $\Leftrightarrow$ isospin violation
e^+e^- – data*= data corrected for isospin violations:

A well known effect: in e^+e^- channel $\rho - \omega$ mixing.

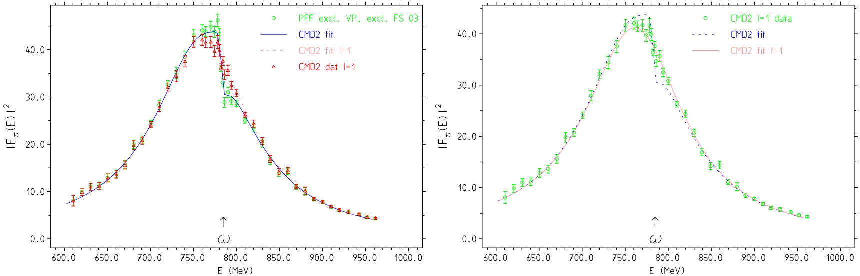
$\Rightarrow$

I=0 component; to be subtracted for comparison with τ data

$$|F(s)|^2 = (|F(s)|^2 - data) / \left| \left(1 + \frac{\epsilon s}{(s_\omega - s)} \right) \right|^2$$

with $s_\omega = (M_\omega - \frac{i}{2}\Gamma_\omega)^2$

ϵ determined by fit to the data: $\epsilon = 0.00172$

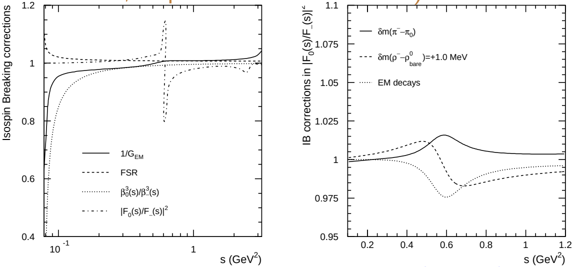


CMD-2 data for $|F_\pi|^2$ in $\rho - \omega$ region together with Gounaris-Sakurai fit. Left before subtraction right after subtraction of the ω.

I=0 component to be added to τ data for calculating $a_\mu^{\rm had}$!

Other isospin-breaking corrections

(Cirigliano et al. 2002, López Castro el al. 2007)



Left: Isospin-breaking corrections $G_{\rm EM}$, FSR, $\beta_0^3(s)/\beta_-^3(s)$ and $|F_0(s)/F_-(s)|^2$.

Right: Isospin-breaking corrections in $I=1$ part of ratio $|F_0(s)/F_-(s)|^2$:

– π mass splitting $\delta m_\pi = m_{\pi^\pm} - m_{\pi^0}$,

– ρ mass splitting $\delta m_\rho = m_{\rho^\pm} - m_{\rho^0_{\rm bare}}$, and

– ρ width splitting $\delta\Gamma_\rho = \Gamma_{\rho^\pm} - \Gamma_{\rho^0}$.

Possible origin of problems:

- Radiative corrections involving hadrons?
- IB in parameter shifts: $m_{\rho^+} - m_{\rho^0}$, $\Gamma_{\rho^+} - \Gamma_{\rho^0}$?

Key problem: Gounaris-Sakurai type parametrizations which are commonly used $\Rightarrow$
e^+e^- vs. τ fit with same formula which differ in parameters only: NC vs. CC process δM_ρ, $\delta\Gamma_\rho$, mixing coefficients etc.
Other possible source: do we really understand quantum interference?

- e^+e^-: $|F_\pi^{(e)}(s)|^2 = |F_\pi^{(e)}(s)[I=1] + F_\pi^{(e)}(s)[I=0]|^2$ what we need and measure
- τ: $|F_\pi^{(\tau)}(s)[I=1]|^2$ measured in τ-decay
- $ee+\tau$: $|F_\pi^{(e)}(s)|^2 \simeq |F_\pi^{(e,\tau)}(s)[I=1]|^2 + |F_\pi^{(e)}(s)[I=0]|^2$??? usual approximation

Need **theory** $\rightarrow$ specific model for the complex amplitudes

A minimal model: VMD + sQED

Effective Lagrangian $\mathcal{L} = \mathcal{L}_{\gamma\rho} + \mathcal{L}_\pi$

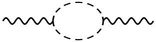
$$\mathcal{L}_\pi = D_\mu \pi^+ D^{+\mu} \pi^- - m_\pi^2 \pi^+ \pi^-; \quad D_\mu = \partial_\mu - i\, e\, A_\mu - i\, g_{\rho\pi\pi}\, \rho_\mu$$

$$\mathcal{L}_{\gamma\rho} = -\frac{1}{4}\, F_{\mu\nu}\, F^{\mu\nu} - \frac{1}{4}\, \rho_{\mu\nu}\, \rho^{\mu\nu} + \frac{M_\rho^2}{2}\, \rho_\mu\, \rho^\mu + \frac{e}{2\, g_\rho}\, \rho_{\mu\nu}\, F^{\mu\nu}$$

The Feynman rules in momentum space are:

$$\begin{array}{lcl c lcl}
A^\mu \pi\pi & \hat{=} & -i\, e\, (p + p')^\mu & , & \rho^\mu \pi\pi & \hat{=} & -i\, g_{\rho\pi\pi}\, (p + p')^\mu \\
A^\mu A^\nu \pi\pi & \hat{=} & 2\, i\, e^2\, g^{\mu\nu} & , & \rho^\mu \rho^\nu \pi\pi & \hat{=} & 2\, i\, g_{\rho\pi\pi}^2\, g^{\mu\nu} \\
A^\mu \rho^\nu \pi\pi & \hat{=} & 2\, i\, e\, g_{\rho\pi\pi}\, g^{\mu\nu} & , & A^\mu \rho^\nu & \hat{=} & -i\, e / g_\rho\, (p^2\, g^{\mu\nu} - p^\mu p^\nu).
\end{array}$$

Self-energies: pion loops to $\gamma - \rho$ vacuum polarizations

$-\mathrm{i}\,\Pi_{\gamma\gamma}^{\mu\nu\,(\pi)}(q) =$  $+$  .

bare $\gamma - \rho$ transverse self-energy functions

$$\Pi_{\gamma\gamma} = \frac{e^2}{48\pi^2}\, f(q^2), \quad \Pi_{\gamma\rho} = \frac{e g_{\rho\pi\pi}}{48\pi^2}\, f(q^2) \quad \text{and} \quad \Pi_{\rho\rho} = \frac{g_{\rho\pi\pi}^2}{48\pi^2}\, f(q^2),$$

where

$$f(q^2) \equiv q^2\, h(q^2) = \left(B_0(m_\pi, m_\pi; q^2)\,(q^2 - 4\, m_\pi^2) - 4\, A_0(m_\pi) - 4\, m_\pi^2 + \frac{2}{3} q^2 \right).$$

Explicitly, in the $\overline{\mathrm{MS}}$ scheme (μ the $\overline{\mathrm{MS}}$ renormalization scale)

$$h(q^2) \equiv f(q^2)/q^2 \quad = \quad 2/3 + 2\,(1-y) - 2\,(1-y)^2\, G(y) + \ln \frac{\mu^2}{m_\pi^2},$$

where $y = 4m_\pi^2/s$ and $G(y) = \frac{1}{2\beta_\pi}\,(\ln \frac{1+\beta_\pi}{1-\beta_\pi} - i\,\pi)$, for $q^2 > 4\,m_\pi^2$.
Mass eigenstates, diagonalization: renormalization conditions are such that the matrix is diagonal and of residue unity at the photon pole $q^2 = 0$ and at the ρ resonance $s = M_\rho^2$, [$\Pi_{..}(0) = 0\,, \Pi'_{\gamma\gamma}(q^2) = \Pi_{\gamma\gamma}(q^2)/q^2$]

$$\Pi^{\rm ren}_{\gamma\gamma}(q^2) \quad = \quad \Pi_{\gamma\gamma}(q^2) - q^2\, \Pi'_{\gamma\gamma}(0) \doteq q^2\, \Pi'^{\rm ren}_{\gamma\gamma}(q^2)$$

$$\Pi^{\rm ren}_{\gamma\rho}(q^2) \quad = \quad \Pi_{\gamma\rho}(q^2) - \frac{q^2}{M_\rho^2}\,{\rm Re}\,\Pi_{\gamma\rho}(M_\rho^2)$$

$$\Pi^{\rm ren}_{\rho\rho}(q^2) \quad = \quad \Pi_{\rho\rho}(q^2) - {\rm Re}\,\Pi_{\rho\rho}(M_\rho^2) - (q^2 - M_\rho^2)\,{\rm Re}\,\frac{d\Pi_{\rho\rho}}{ds}(M_\rho^2)$$

Propagators = inverse of symmetric 2×2 self-energy matrix

$$\hat{D}^{-1} = \begin{pmatrix} q^2 + \Pi_{\gamma\gamma}(q^2) & \Pi_{\gamma\rho}(q^2) \\ \Pi_{\gamma\rho}(q^2) & q^2 - M_\rho^2 + \Pi_{\rho\rho}(q^2) \end{pmatrix}$$

inverted $\Rightarrow$

$$D_{\gamma\gamma} = \frac{1}{q^2 + \Pi_{\gamma\gamma}(q^2) - \frac{\Pi^2_{\gamma\rho}(q^2)}{q^2 - M_\rho^2 + \Pi_{\rho\rho}(q^2)}}$$

$$D_{\gamma\rho} = \frac{-\Pi_{\gamma\rho}(q^2)}{(q^2 + \Pi_{\gamma\gamma}(q^2))(q^2 - M_\rho^2 + \Pi_{\rho\rho}(q^2)) - \Pi^2_{\gamma\rho}(q^2)}$$

$$D_{\rho\rho} = \frac{1}{q^2 - M_\rho^2 + \Pi_{\rho\rho}(q^2) - \frac{\Pi^2_{\gamma\rho}(q^2)}{q^2 + \Pi_{\gamma\gamma}(q^2)}} .$$

To diagnolize the mixed propagator we perform

i) Infinitesimal (perturbative) rotation

$$\begin{pmatrix} A_b \\ \rho_b \end{pmatrix} = \begin{pmatrix} 1 & -\Delta_0 \\ \Delta_0 & 1 \end{pmatrix} \begin{pmatrix} A' \\ \rho' \end{pmatrix} \quad (1)$$

diagonalizing the mass matrix at one-loop.

ii) Upper diagonal matrix wave function renormalization

$$\begin{pmatrix} A' \\ \rho' \end{pmatrix} = \begin{pmatrix} \sqrt{Z_\gamma} & -\Delta_\rho \\ 0 & \sqrt{Z_\rho} \end{pmatrix} \begin{pmatrix} A_r \\ \rho_r \end{pmatrix}$$

which allows to normalize the residues to one for the γ- and ρ-propagator.

Such that:

$$\begin{aligned} A_b &= \sqrt{Z_\gamma} A_r - (\Delta_\rho + \Delta_0)\, \rho_r \\ \rho_b &= \sqrt{Z_\rho} \rho_r + \Delta_0\, A_r\ . \end{aligned}$$

Diagonalization $\Rightarrow$ physical ρ acquires a direct coupling to the electron

$$\mathcal{L}_{\mathrm{QED}} = \bar{\psi}_e \gamma^{\mu} (\partial_{\mu} - i\, e_b\, A_{b\mu})\, \psi_e$$
$$\Downarrow$$
$$\mathcal{L}_{\mathrm{QED}} = \bar{\psi}_e \gamma^{\mu} (\partial_{\mu} - i\, e\, A_{\mu} + i\, g_{\rho ee} \rho_{\mu})\, \psi_e$$

with $g_{\rho ee} = e\,(\Delta_{\rho} + \Delta_0)$, where in our case $\Delta_0 = 0$.

Resonance parameters $\Leftrightarrow$ location s_P of the pole of the propagator

$$s_P - m^2_{\rho^0} + \Pi_{\rho^0\rho^0}(s_P) - \frac{\Pi^2_{\gamma\rho^0}(s_P)}{s_P - \Pi_{\gamma\gamma}(s_P)} = 0,$$

with $s_P = \tilde{M}^2_{\rho^0}$ complex.

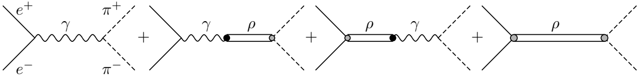
$$\tilde{M}^2_{\rho} \equiv \left(q^2\right)_{\mathrm{pole}} = M^2_{\rho} - i\, M_{\rho}\, \Gamma_{\rho}$$

$F_\pi(s)$ with $\rho - \gamma$ mixing at one-loop

The $e^+e^- \to \pi^+\pi^-$ matrix element in sQED is given by

$$\mathcal{M} = -i\, e^2\, \bar{v}\gamma^\mu u\, (p_1 - p_2)_\mu\, F_\pi(q^2)$$

with $F_\pi(q^2) = 1$. In our extended VMD model we have the four terms



Diagrams contributing to the process $e^+e^- \to \pi^+\pi^-$.

$$F_\pi(s) \propto e^2\, D_{\gamma\gamma} + e g_{\rho\pi\pi}\, D_{\gamma\rho} - g_{\rho ee}\, e D_{\rho\gamma} - g_{\rho ee} g_{\rho\pi\pi}\, D_{\rho\rho}\,,$$

Properly normalized (VP subtraction: $e^2(s) \to e^2$):

$$F_\pi(s) = \left[e^2\, D_{\gamma\gamma} + e\,(g_{\rho\pi\pi} - g_{\rho ee})\, D_{\gamma\rho} - g_{\rho ee} g_{\rho\pi\pi}\, D_{\rho\rho}\right] / \left[e^2\, D_{\gamma\gamma}\right]$$

Typical couplings

$g_{\rho\pi\pi\,\mathrm{bare}} = 5.8935$, $g_{\rho\pi\pi\,\mathrm{ren}} = 6.1559$, $g_{\rho ee} = 0.018149$, $x = g_{\rho\pi\pi}/g_\rho = 1.15128$.

We note that the precise s-dependence of the effective ρ-width is obtained by evaluating the imaginary part of the ρ self-energy:

$$\mathrm{Im}\,\Pi_{\rho\rho} = \frac{g^2_{\rho\pi\pi}}{48\,\pi}\,\beta_\pi^3\, s \equiv M_\rho\, \Gamma_\rho(s),$$

we obtain

$$g_{\rho\pi\pi} = \sqrt{48\,\pi\,\Gamma_\rho/(\beta_\rho^3\, M_\rho)}.$$

In our model, in the given approximation, the on ρ-mass-shell form factor reads

$$F_\pi(M_\rho^2) = 1 - i\,\frac{g_{\rho ee}\,g_{\rho\pi\pi}}{e^2}\,\frac{M_\rho}{\Gamma_\rho}, \quad |F_\pi(M_\rho^2)|^2 = 1 + \frac{36}{\alpha^2}\,\frac{\Gamma_{ee}}{\beta_\rho^3\,\Gamma_\rho},$$

$$\Gamma_{\rho ee} = \frac{1}{3}\,\frac{g_{\rho ee}^2}{4\pi}\,M_\rho, \quad g_{\rho ee} = \sqrt{12\pi\,\Gamma_{\rho ee}/M_\rho}.$$

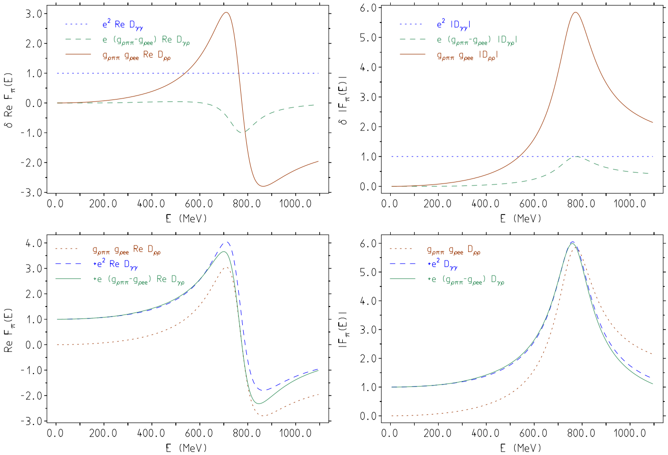
While in Gounaris-Sakurai (GS) formula

$$F_\pi^{\mathrm{GS}}(s) = \frac{-M_\rho^2 + \Pi_{\rho\rho}^{\mathrm{ren}}(0)}{s - M_\rho^2 + \Pi_{\rho\rho}^{\mathrm{ren}}(s)}, \quad \Gamma_{\rho ee}^{\mathrm{GS}} = \frac{2\alpha^2\,\beta_\rho^3 M_\rho^2}{9\,\Gamma_\rho}\,\left(1 + d\,\Gamma_\rho/M_\rho\right)^2.$$

GS does not involve $g_{\rho ee}$ resp. $\Gamma_{\rho ee}$ in a direct way, as normalization is fixed by applying an overall factor $1 + d\,\Gamma_\rho/M_\rho \equiv 1 - \Pi_{\rho\rho}^{\mathrm{ren}}(0)/M_\rho^2 \simeq 1.089$ to enforce $F_\pi(0) = 1$ (in our approach "automatic" by gauge invariance).

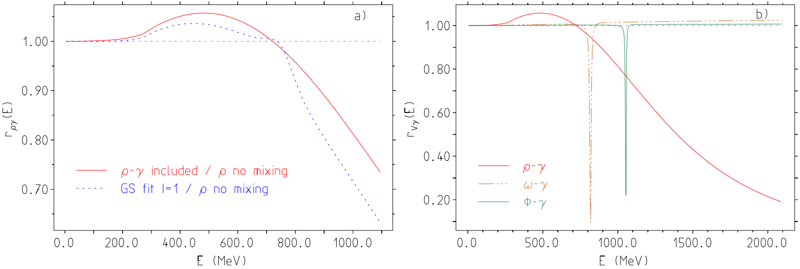
The interference of terms in $F_\pi^{(e)}$

Real parts and moduli of the 3 individual and added terms normalized to the sQED term are displayed:



Detailed comparison, in terms of the ratio

$$r_{\rho\gamma}(s) \equiv \frac{|F_\pi(s)|^2}{|F_\pi(s)|^2_{D_{\gamma\rho}=0}}$$



a) Ratio of $|F_\pi(E)|^2$ with mixing vs. no mixing. Same ratio for GS fit with PDG parameters. b) The same mechanism scaled up by the branching fraction $\Gamma_V/\Gamma(V \to \pi\pi)$ for $V = \omega$ and ϕ. In the $\pi\pi$ channel the effects for resonances $V \neq \rho$ are tiny if not very close to resonance.

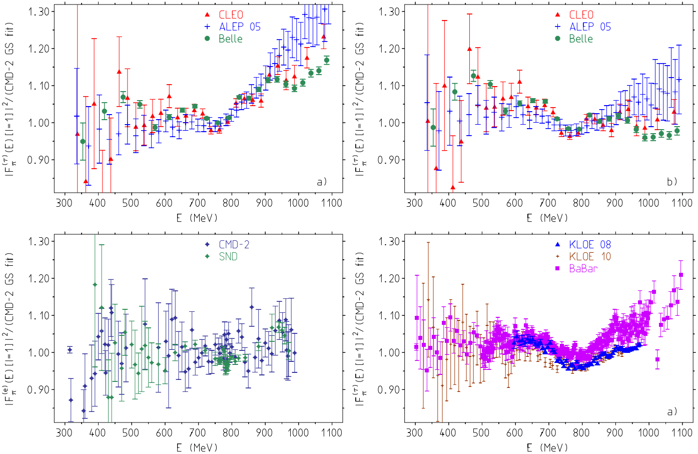
If mixing not included in $F_0(s)$ $\Rightarrow$ total correction formula on spectral functions

$$v_0(s) = r_{\rho\gamma}(s)\, R_{\mathrm{IB}}(s)\, v_-(s)$$

$$R_{\mathrm{IB}}(s) = \frac{1}{G_{\mathrm{EM}}(s)} \frac{\beta_0^3(s)}{\beta_-^3(s)} \left| \frac{F_0(s)}{F_-(s)} \right|^2$$

- $G_{\mathrm{EM}}(s)$ electromagnetic radiative corrections
- $\beta_0^3(s)/\beta_-^3(s)$ phase space modification by $m_{\pi^0} \neq m_{\pi^\pm}$
- $|F_0(s)/F_-(s)|^2$ incl. shifts in masses, widths etc

Final state radiation correction FSR(s) and vacuum polarization effects $(\alpha/\alpha(s))^2$ and I=0 component $(\rho - \omega)$ we have been subtracted from all e^+e^--data.



$|F_\pi(E)|^2$ in units of e^+e^- I=1 (CMD-2 GS fit): a) τ data uncorrected for $\rho-\gamma$ mixing, and b) after correcting for mixing. Lower panel: e^+e^- energy scan data [left] and e^+e^- radiative return data [right]

Applications: a_μ and $B^{\mathrm{CVC}}_{\pi\pi^0} = \Gamma(\tau \to \nu_\tau \pi\pi^0)/\Gamma_\tau$

How does the new correction affect the evaluation of the hadronic contribution to a_μ? To the lowest order in terms of e^+e^--data, represented by $R(s)$, we have

$$a_\mu^{\mathrm{had,LO}}(\pi\pi) = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds\, R^{(0)}_{\pi\pi}(s) \frac{K(s)}{s},$$

with the well-known kernel $K(s)$ and

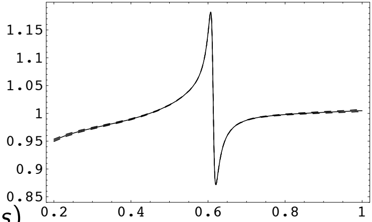
$$R^{(0)}_{\pi\pi}(s) = (3s\sigma_{\pi\pi})/4\pi\alpha^2(s) = 3v_0(s).$$

Note that the $\rho - \gamma$ interference is included in the measured e^+e^--data, and so is its contribution to a_μ^{had}. In fact a_μ^{had} is intrinsic an e^+e^--based "observable" (neutral current channel).

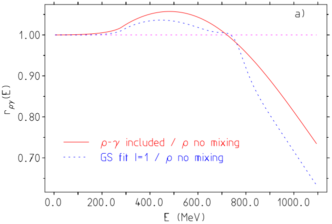
How to utilize τ data: subtract CVC violating corrections

- traditionally $v_-(s) \to v_0(s) = R_{\rm IB}(s)\, v_-(s)$
- our correction $v_-(s) \to v_0(s) = r_{\rho\gamma}(s)\, R_{\rm IB}(s)\, v_-(s)$

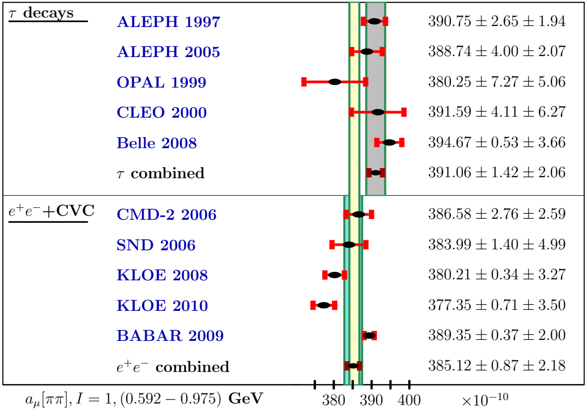
Result for the I=1 part of $a_\mu^{\rm had}[\pi\pi]$: $\delta a_\mu^{\rm had}[\rho\gamma] \simeq (-5.1 \pm 0.5) \times 10^{-10}$



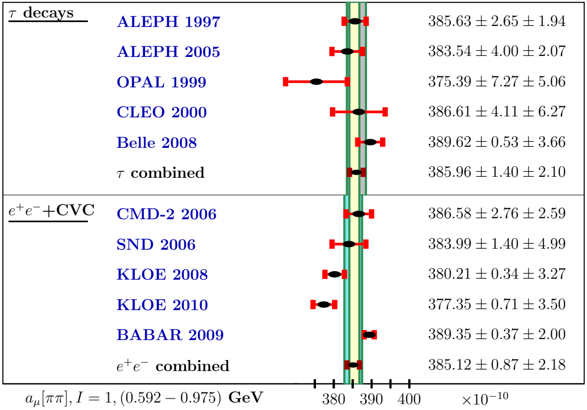
$R_{IB}(s)$



(Cirigliano et al. 2002)



I=1 part of $a_\mu^{\mathrm{had}}[\pi\pi]$

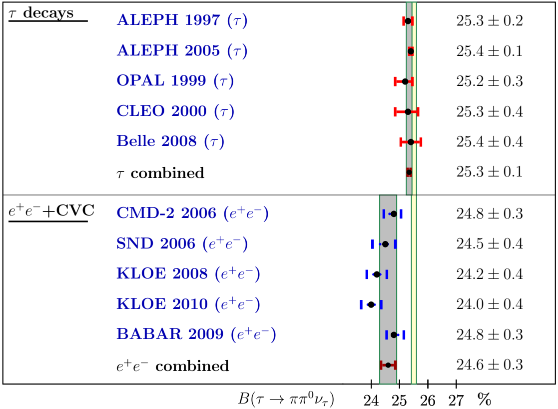


I=1 part of $a_\mu^{\rm had}[\pi\pi]$

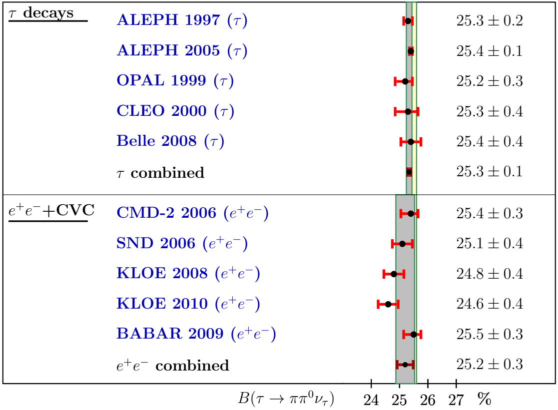
The $\tau \to \pi^0 \pi \nu_\tau$ branching fraction $B_{\pi\pi^0} = \Gamma(\tau \to \nu_\tau \pi\pi^0)/\Gamma_\tau$ is another important quantity which can be directly measured. This "τ-observable" can be evaluated in terms of the I=1 part of the $e^+e^- \to \pi^+\pi^-$ cross section, after taking into account the IB correction $v_0(s) \to v_-(s) = v_0(s)/R_{\mathrm{IB}}(s)/r_{\rho\gamma}(s)$,

$$B_{\pi\pi^0}^{\mathrm{CVC}} = \frac{2S_{\mathrm{EW}} B_e |V_{ud}|^2}{m_\tau^2} \int_{4m_\pi^2}^{m_\tau^2} ds\, R^{(0)}_{\pi^+\pi^-}(s) \left(1 - \frac{2}{m_\tau^2}\right)^2 \left(1 + \frac{2s}{m_\tau^2}\right) \frac{1}{r_{\rho\gamma}(s)\, R_{\mathrm{IB}}(s)}.$$

where here we also have to "undo" the $\rho - \gamma$ mixing which is absent in the charged isovector channel. The shift is $\delta B_{\pi\pi^0}^{\mathrm{CVC}}[\rho\gamma] = +0.62 \pm 0.06\ \%$



Branching fractions $B(\tau \to \pi\pi^0\nu_\tau)$



Branching fractions $B(\tau \to \pi\pi^0\nu_\tau)$

Summary and Conclusions

VMD+sQED EFT:

- pion-loop effects in $\rho - \gamma$ mixing is important contribution (interferences)
- proper ρ propagator self-energy effects ($\rho \to \pi\pi$)

Note: so far PDG parameters masses, widths, branching fractions etc. of resonances like ρ^0 all extracted from data assuming GS like form factors (model dependent!)
Pattern:

- moderate positive interference (up to $+5\%$) below ρ, substantial negative interference (-10% and more) above the ρ (must vanish at $s = 0$ and $s = M_\rho^2$)

- remarkable agreement with pattern of e^+e^- vs τ discrepancy
- shift of the τ data to lie perfectly within the ballpark of the e^+e^- data

Effective field theory is the basic tool!

- $\rho - \gamma$ correction function $r_{\rho\gamma}(s)$ entirely fixed from neutral channel
- τ data provide independent information

What does it mean for the muon $g-2$?

- it looks we have fairly reliable model to include τ data to improve $a_\mu^{\rm had}$
- there is no τ vs. e^+e^- alternative of $a_\mu^{\rm had}$

For the lowest order hadronic vacuum polarization (VP) contribution to a_μ we find $a_\mu^{\rm had,LO}[e,\tau] = 690.96(1.06)(4.63) \times 10^{-10} \quad (e+\tau)$

$$a_\mu^{\rm the} = 116591797(60) \times 10^{-11} \; a_\mu^{\rm exp} = 116592080(54)(33) \times 10^{-11}$$
$$a_\mu^{\rm exp} - a_\mu^{\rm the} = (283 \pm 87) \times 10^{-11}$$

$3.3\,\sigma$

- Note: ratio $F_0(s)/F_-(s)$ could be measured within lattice QCD, without reference to sQED or other hadronic models.
- Including $\omega, \phi, \rho', \rho'', \cdots$ requires to go to appropriate Resonance Lagrangian extension (e.g HLS model (Benayoun et al.))

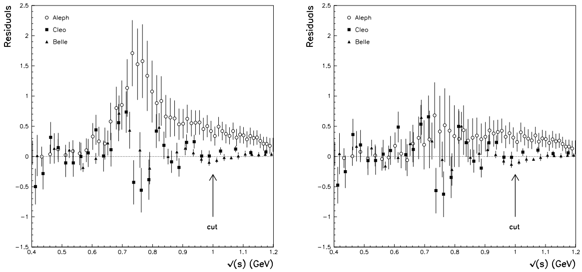
Outlook

- The New Muon g-2 Experiment at Fermilab (2015)
- The goal of the E-989 muon g-2 experiment is to measure the muon anomalous magnetic moment to 0.14 ppm
- Improvement needed on theory side - HVP and HLbL
- a_μ can be used to put constrains on New Physics parameters which are not directly accessible by LHC

Backup slides

The HLS model calculation of $F_\pi(e)$ and $F_\pi(\tau)$

Benayoun et al 09
includes $\rho - \gamma$ mixing as well. The Figure shows τ data vs. residual distribution in the fit of τ data: Left: BELLE+CLEO, Right: ALEPH+BELLE+CLEO (from Benayoun et al 09))



The model yields good simultaneous fits e^+e^-- and τ-data.

Our results in Tables

Isovector (I=1) contribution to $a_\mu^{\rm had} \times 10^{10}$ from the range [0.592 - 0.975] GeV from selected experiments. First entry: results from τ-data after standard breaking (IB) corrections. Second entry: results from τ-data after applying in addition the $\rho - \gamma$ mixing corrections $r_{\rho\gamma}(s)$, with fitted values for M_ρ, Γ_ρ and $\Gamma_{\rho ee}$ [$M_\rho = 775.65\ MeV, \Gamma_\rho = 149.99\ MeV, \mathcal{B}[(\rho \to ee)/(\rho \to \pi\pi)] = 4.10 \times 10^{-5}$]. For the $\rho - \omega$ mixing we subtracted 2.67×10^{-10}. Errors are statistical, systematic, isospin breaking and $\rho - \gamma$ mixing, assuming a 10% uncertainty for the latter. Final state radiation is not included.

Data	standard IB corrections	incl. $\rho - \gamma$ mixing
ALEPH 1997	390.75(2.69)(1.97)(1.45)	385.63(2.65)(1.94)(1.43)(0.50)
ALEPH 2005	388.74(4.05)(2.10)(1.45)	383.54(4.00)(2.07)(1.43)(0.50)
OPAL 1999	380.25(7.36)(5.13)(1.45)	375.39(7.27)(5.06)(1.43)(0.50)
CLEO 2000	391.59(4.16)(6.81)(1.45)	386.61(4.11)(6.72)(1.43)(0.50)
BELLE 2008	394.67(0.53)(3.66)(1.45)	389.62(0.53)(3.66)(1.43)(0.50)
average	391.06(1.42)(1.47)(1.45)	385.96(1.40)(1.45)(1.43)(0.50)
CMD-2 2006		386.34(2.26)(2.65)
SND 2006		383.99(1.40)(4.99)
KLOE 2008		380.24(0.34)(3.27)
KLOE 2010		377.35(0.71)(3.50)
BABAR 2009		389.35(0.37)(2.00)
average		385.12(0.87)(2.18)
all e^+e^- data		385.21(0.18)(1.54)
$e^+e^- + \tau$		385.42 (0.53)(1.21)

Calculated branching fractions in % from selected experiments. Experimental data completed down to threshold and up to m_τ by corresponding world averages where necessary. The experimental world average of direct branching fractions is $B_{\pi\pi^0}^{\rm CVC} = 25.51 \pm 0.09$ % .

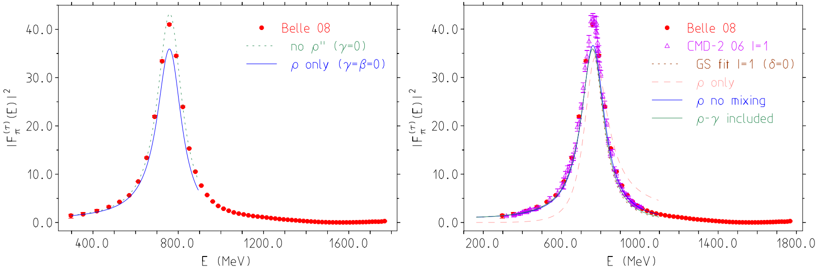
τ data	$B_{\pi\pi^0}$[%]	e^+e^- data	$B_{\pi\pi^0}^{\rm CVC}$[%]
ALEPH 97	$25.27 \pm 0.17 \pm 0.13$	CMD-2 06	$25.40 \pm 0.21 \pm 0.28$
ALEPH 05	$25.40 \pm 0.10 \pm 0.09$	SND 06	$25.09 \pm 0.30 \pm 0.28$
OPAL 99	$25.17 \pm 0.17 \pm 0.29$	KLOE 08	$24.82 \pm 0.29 \pm 0.28$
CLEO 00	$25.28 \pm 0.12 \pm 0.42$	KLOE 10	$24.65 \pm 0.29 \pm 0.28$
Belle 08	$25.40 \pm 0.01 \pm 0.39$	BaBar 09	$25.45 \pm 0.18 \pm 0.28$
combined	$25.34 \pm 0.06 \pm 0.08$	combined	$25.20 \pm 0.17 \pm 0.28$

For the direct τ branching fractions the first error is statistical the second systematic. For e^+e^-+CVC the first error is experimental the second error includes uncertainties of the IB correction $+0.06$ from the new mixing effect. Remaining problems seem to be experimental.

$\rho - \omega$ mixing

see our paper e-Print: arXiv:1101.2872 for an first attempt in the field theory approach. A complete treatment requires an extension of the model to include the $\omega \to \pi\pi\pi^0$ and $\omega \to \pi^0\gamma$ channel. (see from Benayoun et al 09)

Relation to data

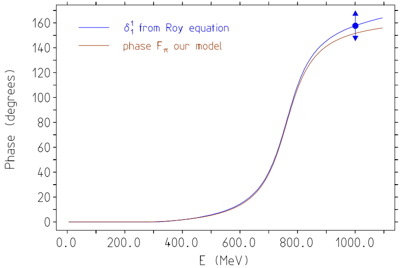


Left: GS fits of the Belle data and the effects of including higher states ρ' and ρ'' at fixed M_ρ and Γ_ρ. Right: Effect of $\gamma - \rho$ mixing in our simple EFT model

Parameters: $M_\rho = 775.5\ MeV$, $\Gamma_\rho = 143.85\ MeV$, $\mathcal{B}[(\rho \to ee)/(\rho \to \pi\pi)] = 4.67 \times 10^{-5}$, $e = 0.302822$, $g_{\rho\pi\pi} = 5.92$, $g_{\rho ee} = 0.01826$.

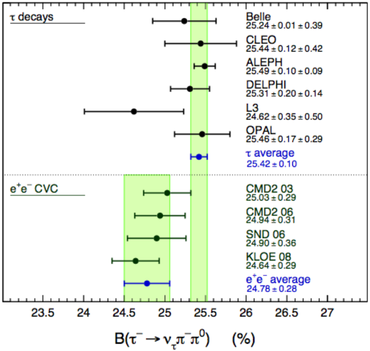
Comparison of $\pi\pi$ rescattring with Colangelo-Leutwyler's from first principles approach

One of the key ingredients in this approach is the strong interaction phase shift $\delta_1^1(s)$ of $\pi\pi$ (re)scattering in the final state. We compare the phase of $F_\pi(s)$ in our model with the one obtained by solving the Roy equation with $\pi\pi$-scattering data as input. We notice that the agreement is surprisingly good up to about 1 GeV. It is not difficult to replace our phase by the more precise exact one.

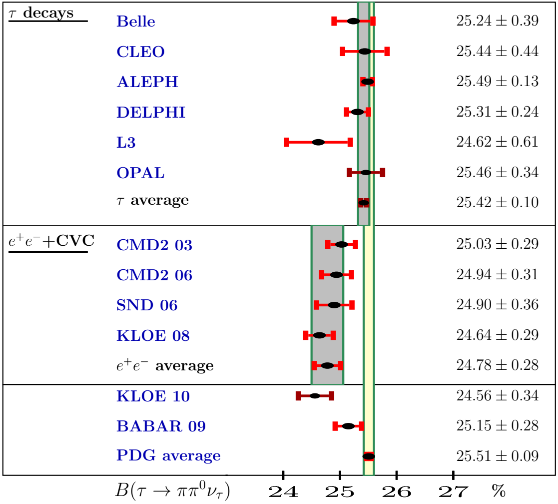


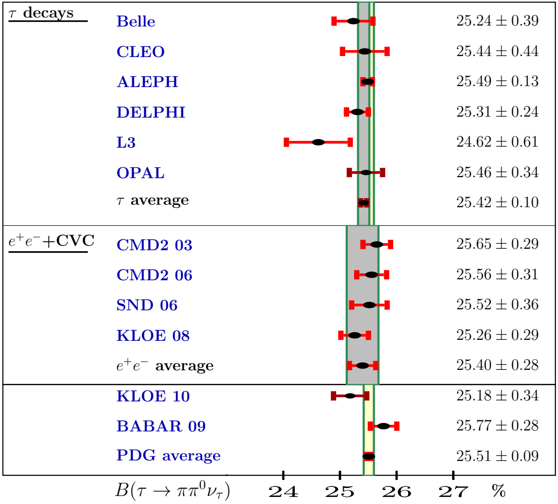
$B_{\pi\pi^0}^{\rm CVC}$: Most recent results of Davier et al

Pre BaBar:	25.42 ± 0.10 %			for τ
	24.78 ± 0.28 %	$\overset{+\rho\gamma}{\Rightarrow}$	$25.40 \pm 0.28 \pm 0.06$ %	for e^+e^- + CVC
New BaBar:	25.15 ± 0.28 %	$\overset{+\rho\gamma}{\Rightarrow}$	$25.77 \pm 0.28 \pm 0.06$ %	for e^+e^- + CVC



shift $\delta B_{\pi\pi^0}^{\rm CVC}[\rho\gamma] = +0.62 \pm 0.06$ %


τ decays
Belle 25.24 ± 0.39
CLEO 25.44 ± 0.44
ALEPH 25.49 ± 0.13
DELPHI 25.31 ± 0.24
L3 24.62 ± 0.61
OPAL 25.46 ± 0.34
τ average 25.42 ± 0.10
e+e− +CVC
CMD2 03 25.03 ± 0.29
CMD2 06 24.94 ± 0.31
SND 06 24.90 ± 0.36
KLOE 08 24.64 ± 0.29
e+e− average 24.78 ± 0.28
KLOE 10 24.56 ± 0.34
BABAR 09 25.15 ± 0.28
PDG average 25.51 ± 0.09
B(τ → ππ0ντ) 24 25 26 27 %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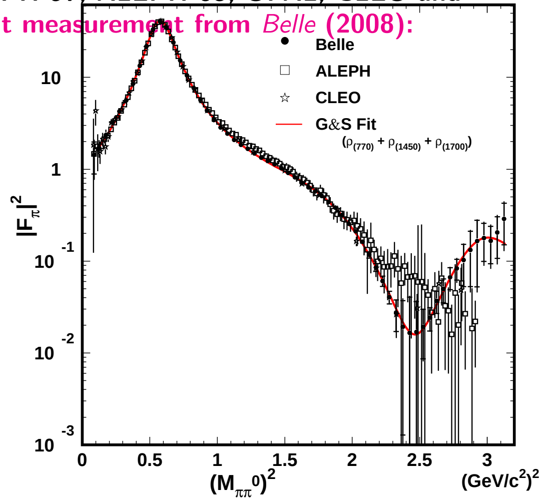
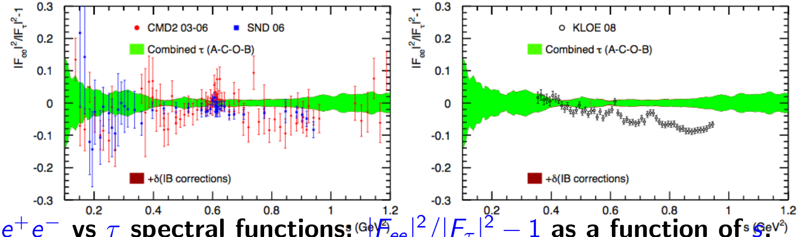
τ average 25.42 ± 0.10
e+e− +CVC
CMD2 03 25.65 ± 0.29
CMD2 06 25.56 ± 0.31
SND 06 25.52 ± 0.36
KLOE 08 25.26 ± 0.29
e+e− average 25.40 ± 0.28
KLOE 10 25.18 ± 0.34
BABAR 09 25.77 ± 0.28
PDG average 25.51 ± 0.09
B(τ → ππ0ντ)
24
25
26
27
%

Data: ALEPH 97, ALEPH 05, OPAL, CLEO and most recent measurement from *Belle* (2008):



New isospin corrections applied shift in mass and width [as advocated by S. Ghozzi and F. Jegerlehner in 2003!!!] plus changes [López Castro, Toledo Sánchez et al 2007] below the ρ. New BaBar radiative return $\pi\pi$ spectrum in much better agreement, in particular with *Belle* τ spectrum!



e^+e^- vs τ spectral functions: $|F_{ee}|^2/|F_\tau|^2 - 1$ as a function of s. Isospin-breaking (IB) corrections are applied to τ data with its uncertainties included in the error band.