Tests and Possible Origin of Non-Standard Right-Handed Couplings of Quarks

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Two parts :

- **Theoretical framework** : Minimal not quite Decoupling EW Low - Energy Effective Theory (LEET)

Bottom up approach $\rightarrow$ hierarchy of possible effects beyond the SM

Johannes Hirn and J. Stern :

Eur. Phys. J. **C34** *(2004) 442; JHEP 0409 (2004) 058*

Phys. Rev. **D73** *(2006) 056001*

- Qualitative prediction of **couplings of RH quarks to W at NLO**
- New striking test of RHCs in $K_L(\mu 3)$ decays

  V. Bernard, M. Oertel, E. Passemar and J. Stern

  Phys. Letters **B638** *(2006) 480 ; + in preparation*
- Have the RHCs been seen by NA48 at CERN ?

  A. Lai et al (NA48) Phys. Letters **B647** *(2007) 341*

Couplings of right handed quarks to W :

i) Are they CONCEIVABLE ?

- Compatible with spontaneously broken $SU(2)_W \times U(1)_Y$ gauge symmetry.
- New way of probing EW symmetry breaking.

ii) Are they PLAUSIBLE ?

- Predicted at NLO of a general class of EW Effective Theories
- Predicted in a class of renormalizable models with extended Left-Right symmetric structure

iii) Are they COMPATIBLE with known experimental facts?

- Most of existing tests of $V-A$ structure of couplings to W concern LEPTONS
- Precise tests of $V-A$ couplings of QUARKS are difficult due to interference with QCD effects.

Framework :

ELECTROWEAK LOW ENERGY EFFECTIVE THEORY

Not quite decoupling LEET alternative - the bottom up approach

At $E > \Lambda_W$:

- New gauge particles beyond the SM

- New local symmetries $S_{nat} \supset S_{ew} = SU(2)_W \times U(1)_Y$

apriori unknown

At Low energy $E < \Lambda_W$

Heavy gauge particles decouple $\to$ leaving observed particles of the SM

BUT

The symmetry S_{nat} survives at low energies

S_{nat}/S_{ew} "non linearly realized"

- Does not show up in the low-energy spectrum (W , Z , γ , leptons , quarks)

- Constrains effective interaction vertices

- Objects carrying local charges $\in S_{nat}/S_{ew}$ do not propagate : They are scalar **SPURIONS**

LEET provides a classification of effects beyond the SM

Non standard interaction vertices are **ordered** according to their

- importance in the low-energy limit :

  $\mathcal{L}_{eff} = \sum_{d \geq 2} \mathcal{L}_d \qquad \mathcal{L}_d = \mathcal{O}([\frac{p}{\Lambda_W}]^d)$

  counting powers of momenta $(\Lambda_W \sim 3TeV)$

- symmetry properties under S_{nat}

  counting powers of spurions

The Symmetry S_{nat} can be deduced from known SM vertices

- $\mathcal{L}_2$ contains **unsupressed** $SU(2)_W \times U(1)_Y$ invariant vertices absent in the SM . Since they are not observed, they have to be suppressed by the symmetry S_{nat}.
- There is a unique minimal choice of $S_{nat} \supset SU(2)_W \times U(1)_Y$ which guarantees that the leading order $\mathcal{O}(p^2)$ of the low-energy expansion coincides with the Higgsless vertices of the SM.

Infrared power counting and order by order renormalization

concerns minimal low - energy effective theories containing

- 3 Goldstone bosons $\Sigma(x) \in SU(2)$ ... ID : $\boldsymbol{d = 0}$
- Canonically normalized (massive) gauge fields $G_\mu \ldots$ $\boldsymbol{d = 0}$,
  Gauge connections $\Gamma_\mu = gG_\mu \ldots$ $\boldsymbol{d = 1}$
- Chiral fermions $\Psi_{L/R} \ldots$ $\boldsymbol{d = 1/2}$

IR dimension of a vertex (operator) : $d = n_\partial + n_g + \frac{1}{2} n_\Psi$

In general : $d \neq D \ldots$ the mass or UV dimension.

d is more suitable than D to characterize the importance of an operator in the low - energy limit, regardless to the renormalizability.

Two complementary ways to represent $\mathcal{L}_{eff}$:

$\mathcal{L}_{eff} = \sum_{d \geq 2} \mathcal{L}_d \sim L_{SM} + \sum_{D>4} \Lambda^{4-D} \mathcal{O}_D.$

IR dimension of a connected Feynman graph with vertices $v = 1, 2 \ldots$ and L loops :

$d = 2 + 2L + \sum_v (d_v - 2)$, (Weinberg 1979 ...)

Systematic LE expansion renormalized order by order works if

• $d_v \geq 2$: Effective interaction becomes weak at low energies.

• All particles in the LEET are **naturally light compared to** Λ_W as a consequence of a symmetry : $m = \mathcal{O}(p^n), n \geq 1$.

Ex : Massive gauge boson $M_W \sim \frac{1}{2} g F_W$, $g = \mathcal{O}(p)$ (F_W a fixed scale $\sim 250 GeV$.

• Low - Energy expansion $\sim$ loop expansion :

$\Lambda_W \sim 4\pi F_W \sim 3TeV$

• Difficulty with non GB and non SUSY scalar particles .

$\mathcal{L}_d$ consists of **all possible terms** of IR dimension d that are allowed by the symmetries.

BOTTOM-UP RECONSTRUCTION OF THE HIDDEN SYMMETRY $\frac{S_{nat}}{S_{ew}}$ OF THE SM

If $S_{nat} = S_{ew} = SU(2)_L \times U(1)_Y$

$G_{L,R} \in SU(2)$, $[G_R, \tau_3] = 0$,

$\Sigma \to G_L \Sigma G_R^{-1}, \Psi_{L,R} \to G_{L,R} \exp(-i\frac{B-L}{2}\alpha)\Psi_{L,R}$

Unwanted Operators UOs : Non standard and unobserved $d = 2$ operators invariant under S_{nat}.

S_{nat} should be gradually enlarged until there are no more UOs left

First step : Custodial breaking UOs

Ex : $\mathcal{O}_T =< \tau_3 \Sigma^\dagger D_\mu \Sigma >^2$ spoils $\rho = 1$.

needed extension :

$S_{ew} \to S_{elem} = SU(2)_{G_L} \times SU(2)_{G_R} \times U(1)_{B-L} \subset S_{nat}$.

Many (custodial preserving) S_{elem} invariant UOs remain : **further extension of S_{nat} is needed.**

Custodial preserving UOs

$\mathcal{O}_S =< G_{L,\mu\nu} \Sigma G_R^{\mu\nu} \Sigma^\dagger >$ unsuppressed contribution to the parameter S.

$\mathcal{O}_L = \bar{\Psi}_L \gamma_\mu \Sigma D^\mu \Sigma^\dagger \Psi_L$ unsuppressed modification of fermion couplings.

$\mathcal{O}_{Yuk} = \bar{\Psi}_L \Sigma \Psi_R$ unsuppressed fermion masses $m \sim \Lambda_W$

Concerns Higgs sector : The Goldstone bosons Σ are the only LE manifestation of a new **spontaneously broken chiral symmetry**

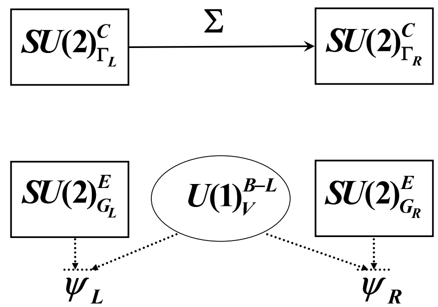
$S_{comp} = SU(2)_{\Gamma_L} \times SU(2)_{\Gamma_R} \quad \Sigma \to \Gamma_L \Sigma \Gamma_R^{-1}$

"Elementary" gauge bosons and fermions are neutral under S_{comp}

The minimal symmetry S_{nat} necessary and sufficient to kill all the UOs : $S_{nat} =$

$[SU(2)_{G_L} \times SU(2)_{G_R} \times U(1)_{B-L}]_{elem} \times [SU(2)_{\Gamma_L} \times SU(2)_{\Gamma_R}]_{comp}$

$[G_{L\mu}\ , \quad G_{R\mu}\ , \quad G_{B\mu}\ ;\ \Psi_{LR}] \quad \times [\Gamma_{L\mu}\ , \quad \Gamma_{R\mu}\ ;\ \ \Sigma]$



General $\mathcal{L}_2$ invariant under **linear action** of S_{nat}

$$\mathcal{L}_2 = \frac{F_W^2}{4} < D_\mu \Sigma^\dagger D^\mu \Sigma > -\frac{1}{2} < G_L^{\mu\nu} G_{L,\mu\nu} + G_R^{\mu\nu} G_{R,\mu\nu} >$$
$$-\frac{1}{4} G_B^{\mu\nu} G_{B,\mu\nu} + i\bar{\Psi}_L \gamma^\mu D_\mu \Psi_L + i\bar{\Psi}_R \gamma^\mu D_\mu \Psi_R$$

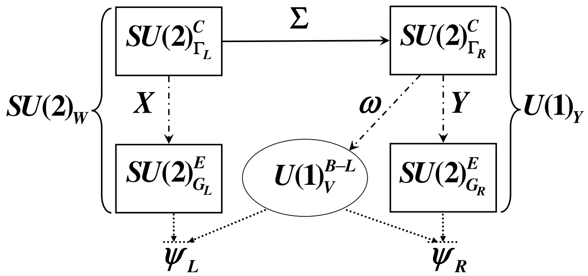
- Contains gauge fields **redundant at LE**
- Only "mass term" $\frac{F_W^2}{4} < (\Gamma_{L,\mu} - \Gamma_{R,\mu})^2 >$
- No link between elementary and composite sectors

Impose suitable S_{nat} **- invariant constraints** to reduce the linear symmetry back to S_{ew}

pairwise identification (up to a gauge) :

$\Gamma_{L/R,\mu} \sim g_{L/R} G_{L/R,\mu}, \Gamma_{R,\mu} \sim g_B B_\mu \frac{\tau_3}{2}$

Covariant constraints and Spurions



$$\Gamma_{L,\mu} = \mathcal{X} g_L G_{L,\mu} \mathcal{X}^{-1} + i\mathcal{X}\partial_\mu \mathcal{X}^{-1}$$
$$\Gamma_{R,\mu} = \mathcal{Y} g_R G_{R,\mu} \mathcal{Y}^{-1} + i\mathcal{Y}\partial_\mu \mathcal{Y}^{-1}$$

$\mathcal{X}$ and $\mathcal{Y}$ ... constant multiples of $SU(2)$ matrices $\Omega_{L/R}$

$\mathcal{X} = \xi\Omega_L \quad , \quad \mathcal{Y} = \eta\Omega_R$

Covariance under S_{nat} :

$\mathcal{X} \to \Gamma_L \mathcal{X} G_L^{-1} \quad , \quad \mathcal{Y} \to \Gamma_R \mathcal{Y} G_R^{-1}$

The covariant constraints are equivalent to $D_\mu \mathcal{X} = D_\mu \mathcal{Y} = 0$

non propagating spurions.

$U(1)_{B-L}$ embedded into $SU(2)$: $G_B = \exp(-i\alpha\tau_3)$

Last identification : $U(1)_{B-L}$ and right isospin $\rightarrow U(1)_Y$:

$\Gamma_{R,\mu} = \omega g_B G_{B,\mu} \frac{\tau_3}{2} \omega^{-1} + i\omega\partial_\mu \omega^{-1}$

covariance $\omega \rightarrow \Gamma_R \omega G_B^{-1}$

$\omega = \zeta \Omega_B \quad , \quad \Omega_B \in SU(2)$

- **Covariant projection on up and down components of RH doublets**

  $\Pi_u = \omega \frac{1+\tau_3}{2} \omega^{-1} \quad , \quad \Pi_d = \omega \frac{1-\tau_3}{2} \omega^{-1}$

  $\mathcal{Y}_{u,d} = \Pi_{u,d} \mathcal{Y} \rightarrow \Gamma_R \mathcal{Y}_{u,d} G_R^{-1}$

- **Lepton number violation is necessarily present**

  spurion $\mathcal{Z} = \omega \tau_+ \omega^\dagger \rightarrow \exp(i\alpha) \Gamma_R \mathcal{Z} \Gamma_R^{-1}$ carries two units of B-L.

Size of LNV violation $\mathcal{Z} \sim \zeta^2 \ll \xi, \eta$

Standard gauge : $\Omega_L = \Omega_R = \Omega_B = 1$ The constraints reduce to

- $\Gamma_{L,\mu} = g_L G_{L,\mu} \rightarrow SU(2)_W$

  $\Gamma^3_{R,\mu} = g_R G^3_{R,\mu} = g_B G_{B,\mu} \rightarrow U(1)_Y \quad , \quad \Gamma^{1,2}_{R,\mu} = g_R G^{1,2}_{R,\mu} = 0$

  $\frac{Y}{2} = T^3_R + \frac{B-L}{2}$
- **Spurions :** $\mathcal{X} = \xi \times 1$

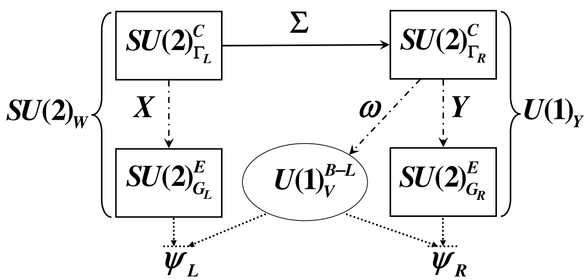
$$\mathcal{Y}_u = \eta\frac{1+\tau_3}{2} \qquad \mathcal{Y}_d = \eta\frac{1-\tau_3}{2}$$

$$\mathcal{Z} = \zeta^2\tau_+$$

  ξ , η , ζ three **naturally small** expansion parameters originating beyond the SM.

  constraints + standard gauge : $\mathcal{L}_2 \rightarrow L^{\star}_{SM}$
- W and Z standard masses and mixing
- Standard couplings to fermions (ν_R decouples)
- No physical scalars (3 GBs eaten by W and Z)
- Fermions massless
- Huge accidental flavour (family) symmetry

First manifestation of SPURIONS : FERMION MASSES



$$\bar{\Psi}_L \mathcal{X}^\dagger \Sigma \mathcal{Y}_{u,d} \Psi_R$$
$$m_{top}/\Lambda_W \sim \xi\eta = \mathcal{O}(p)$$

Higher powers of spurions : additional suppression factors

Majorana masses $\bar{\Psi}_R \mathcal{Y}^\dagger \mathcal{Z} \mathcal{Y} \Psi^C_R \sim \zeta^2\eta^2$

$$\bar{\Psi}_L \mathcal{X}^\dagger \Sigma \mathcal{Z} \Sigma^\dagger \mathcal{X} \Psi^C_L \sim \zeta^2\xi^2$$

Naturally suppressed by the factor $\zeta^2 \ll \xi\eta$, c.f. LNV processes.

Suppression of neutrino Dirac masses

Discrete symmetry : $\nu_R \to -\nu_R$, $l_R \to (1 - 2\Pi_u) l_R$

- At LO ν_R does not couple to any gauge field
- Allows for (small) Majorana mass
- Forbids Dirac masses of neutrino's
- **Forbids RH charged lepton currents** $\bar{e}_R \gamma \nu_R$

Beyond the Leading Order

- Construct **all** invariants from the S_{nat} gauge fields, GB's, fermion doublets **and from spurions**
- Order them according to $d^\star = d + \frac{1}{2} n_\xi + \frac{1}{2} n_\eta$
- Impose the constraints $D_\mu \mathcal{X} = D_\mu \mathcal{Y} = 0$ and go to the standard gauge.

<u>LO : $d^\star = 2$</u> ... $d = 2 \quad n_\xi = n_\eta = 0$ ... SM Higgsless vertices

$d = 1 \ , \ n_\xi = n_\eta = 1$ ... Fermion mass

<u>NLO : $d^\star = 3$</u> ... $\mathcal{O}(p^2 \xi^2) \quad \mathcal{O}(p^2 \eta^2)$

<u>NNLO : $d^\star = 4$</u> ... Start loops, oblique corrections, FCNC ...

Next to the Leading Order

Consists of two Non Standard Operators involving fermions

$\mathcal{O}_L = i\bar{\Psi}_L \gamma^\mu \mathcal{X}^\dagger \Sigma D_\mu \Sigma^\dagger \mathcal{X} \Psi_L$

$\mathcal{O}_{R,ab} = i\bar{\Psi}_R \gamma^\mu \mathcal{Y}_a^\dagger \Sigma^\dagger D_\mu \Sigma \mathcal{Y}_b \Psi_R$

$a, b = U$ or D

$\mathcal{O}_L = \mathcal{O}(p^2 \xi^2) \quad , \quad \mathcal{O}_{R,ab} = \mathcal{O}(p^2 \eta^2)$

- Non standard couplings of fermions to W and Z (suppressed by spurions)
- No contributions from loops (start at $d = 4$)
- Universal in family space : No breaking of LO accidental flavour symmetry at that order
- For **leptons** : $\mathcal{O}_{R,UD}$ and $\mathcal{O}_{R,DU}$ are absent due to the $\nu_R \to -\nu_R$ reflection symmetry.

NLO Couplings of fermions to W.

$$\mathcal{L}_{CC} = \frac{1}{\sqrt{2}} g(1-\xi^2\rho_L)(J_\mu^{\bar{U}D} + J_\mu^{\bar{N}L})W^\mu + h.c \qquad U = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}, N = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}, L = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

$$J_\mu^{\bar{U}D} = (1+\boxed{\delta})\overline{U_L} V_L \gamma_\mu D_L + \boxed{\varepsilon}\,\overline{U_R} V_R \gamma_\mu D_R$$

$$J_\mu^{\bar{N}L} = \overline{N_L} V_{MNS} \gamma_\mu L_L$$

- $\mathbf{V_L, V_R}$: 2 unitary matrices coming from the diagonalization of the U and D quark mass matrices.
- 3 parameters arising from spurions:

$$(1-\xi^2\rho_L) \qquad (1+\delta) \qquad \varepsilon$$

Effective vector and axial vector EW couplings.

- Experimentally, we have access to vector and axial currents.

$$J_\mu^{\bar{U}D} = \frac{1}{2}\left[\bar{U}\mathcal{V}_{eff}\gamma_\mu D + \bar{U}\mathcal{A}_{eff}\gamma_\mu\gamma_5 D\right]$$

$$\mathcal{V}_{eff}^{ij} = (1+\delta)\,\mathrm{V_L^{ij}} + \varepsilon\,\mathrm{V_R^{ij}} \;+ \mathrm{NNLO}$$ and $$\mathcal{A}_{eff}^{ij} = -(1+\delta)\,\mathrm{V_L^{ij}} + \varepsilon\,\mathrm{V_R^{ij}} \;+ \mathrm{NNLO}$$

$$\left|\mathcal{V}_{eff}^{ij}\right|^2 = \left|V_L^{ij}\right|^2\left\{1 + 2\delta + 2\varepsilon\,\mathrm{Re}\left(\frac{V_R^{ij}}{V_L^{ij}}\right)\right\} \qquad \left|A_{eff}^{ij}\right|^2 = \left|V_L^{ij}\right|^2\left\{1 + 2\cdot\delta - 2\varepsilon\cdot\mathrm{Re}\left(\frac{V_R^{ij}}{V_L^{ij}}\right)\right\}$$

- In the light quark sector, 4 independant parameters :

$$\mathcal{V}_{eff}^{ud} \equiv \cos\hat{\theta} \qquad \delta \qquad \varepsilon_{NS} = \varepsilon\cdot\mathrm{Re}\left(\frac{V_R^{ud}}{V_L^{ud}}\right) \qquad \varepsilon_S = \varepsilon\cdot\mathrm{Re}\left(\frac{V_R^{us}}{V_L^{us}}\right)$$

Order of magnitude of the parameters

- $\delta, \varepsilon \leq 1\%$ (top quark mass)

$$\varepsilon_{NS} = \varepsilon \, \mathrm{Re}\left(\frac{V_R^{ud}}{V_L^{ud}}\right) \qquad \varepsilon_S = \varepsilon \, \mathrm{Re}\left(\frac{V_R^{us}}{V_L^{us}}\right)$$

- V_L close to V_{CKM} $\Rightarrow$ experimental measurements $\begin{cases} |V_L^{ud}| \sim 0.97 \\ |V_L^{us}| \sim 0.23 \end{cases}$

- Unitarity of V_R $\Rightarrow$ $\begin{cases} |V_R^{ud}| \leq 1 \\ |V_R^{us}| \leq 1 \end{cases}$

$\Rightarrow$ $|\varepsilon_{NS}| \leq \varepsilon \sim 1\%$ et $|\varepsilon_S| \leq 4.5 \ \varepsilon$

- Possible enhancement of ε_S
- We are looking for effects of at most few percents.

Test of NLO effects

Experimental processes	Parameters extracted	Low Energy/QCD inputs
Nuclear β decays **$0^+ \rightarrow 0^+$**	$\left\lvert \mathcal{V}_{eff}^{ud} \right\rvert \equiv \cos\hat{\theta}$	**CVC + nuclear corrections** [Marciano & Sirlin '05]
Hadronic τ decays **R_V,R_A, R_S,** **Moments** ALEPH, OPAL	ε_{NS}, $\delta+\varepsilon_{NS}$	**OPE** [Braaten et al '92, Lediberder & Pich '92….] **$\alpha_S(m_\tau)$, m_q, condensates**
Γ_W LEP, TEVATRON	δ	**Perturbative QCD** $\alpha_S(m_W)$
DIS $\nu(\bar{\nu})$ on protons	δ	**Normalized pdf**
Kl3 decay rates	$\left\lvert \mathcal{V}_{eff}^{us} \right\rvert^2 = \sin^2\hat{\theta}\left(1+2\frac{\delta+\varepsilon_{NS}}{\sin^2\hat{\theta}}\right)\left(1+2\left(\varepsilon_S-\varepsilon_{NS}\right)\right)$	**$f_+(0)$**
$K^L{}_{\mu 3}$ decay	$\varepsilon_S - \varepsilon_{NS}$	**$K\pi$ scattering phases** [Buettiker, Descotes, Moussallam' 02] **and Δ_{CT}: χPT**

$K_{\mu 3}^{L}$ decays: Callan-Treiman Low Energy Theorem **(cf. Talk E.Passemar)**

$$C = f(\Delta_{K\pi}) = \frac{F_{K^+}}{F_\pi f_+^{K^0}(0)} + \Delta_{CT}$$

$$\Delta_{K\pi} = m_K^2 - m_\pi^2$$

$$\Delta_{CT}^{NLO} \sim -3.5.10^{-3}$$

[Gasser & Leutwyler]

- Experimental measurements :

→ $\left(\frac{F_K}{F_\pi}\left|\frac{\mathcal{A}_{eff}^{us}}{\mathcal{A}_{eff}^{ud}}\right|\right) = 0.27618(48)$ **[updated using recent KLOE measurement of $K_{\mu 2}$]**

→ $f_+^{K_0}(0)\left|\mathcal{V}_{eff}^{us}\right| = 0.21619(55)$ Average of most recent measurements of NA48, KTeV, KLOE.

→ $\left|\mathcal{V}^{ud}\right| = 0.97377(26)$ **[Towner & Hardy]** (0^+ → 0^+) updated by **[Marciano & Sirlin '05]**

$$C = f(\Delta_{K\pi}) = \underbrace{\frac{F_K \left|\mathcal{A}_{eff}^{us}\right|}{F_\pi \left|\mathcal{A}_{eff}^{ud}\right|} \frac{1}{f_+(0)\left|\mathcal{V}_{eff}^{us}\right|} \left|\mathcal{V}_{eff}^{ud}\right|}_{B_{exp}} \frac{\left|\mathcal{A}_{eff}^{ud}\right|}{\left|\mathcal{V}_{eff}^{ud}\right|} \frac{\left|\mathcal{V}_{eff}^{us}\right|}{\left|\mathcal{A}_{eff}^{us}\right|} + \Delta_{CT}$$

- Standard Model case : $\mathcal{V}_{eff} = -\mathcal{A}_{eff} = V_{CKM}$ $\Rightarrow$ $\frac{\left|\mathcal{A}_{eff}^{ud}\right|}{\left|\mathcal{V}_{eff}^{ud}\right|} \frac{\left|\mathcal{V}_{eff}^{us}\right|}{\left|\mathcal{A}_{eff}^{us}\right|} = 1$

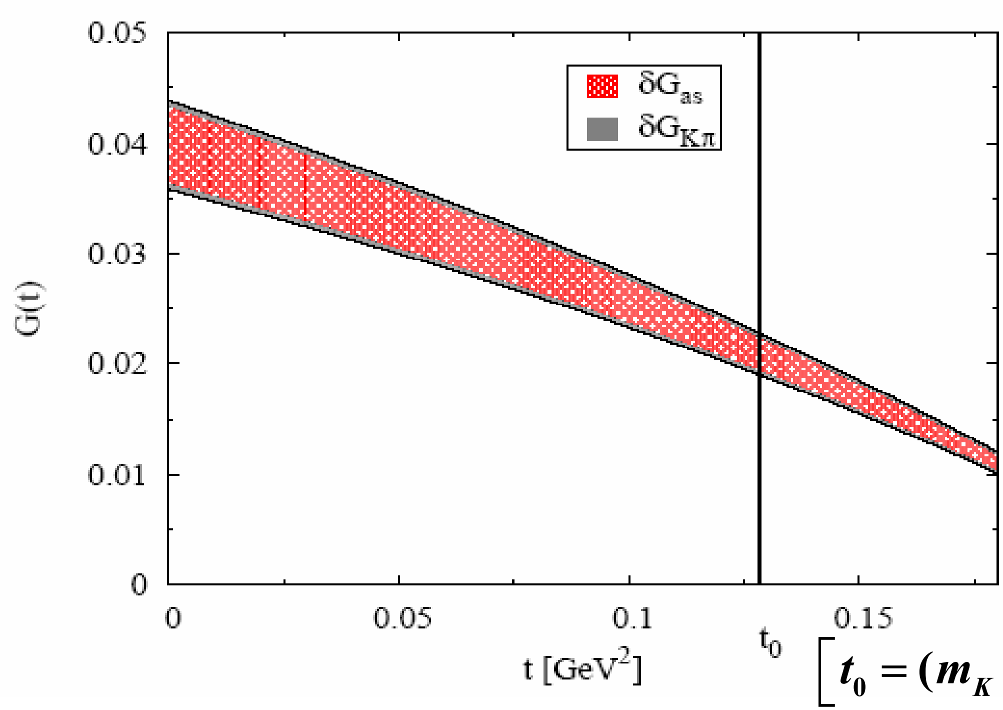
$\Rightarrow$ $$C_{SM} = 1.2440 \pm 0.0039 + \Delta_{CT}$$ $$\ln C_{SM} = 0.2183 \pm 0.0031 + \frac{\Delta_{CT}}{B_{exp}}$$

- LEET case : $\frac{\left|\mathcal{A}_{eff}^{ud}\right|}{\left|\mathcal{V}_{eff}^{ud}\right|} \frac{\left|\mathcal{V}_{eff}^{us}\right|}{\left|\mathcal{A}_{eff}^{us}\right|} = 1 + 2(\varepsilon_S - \varepsilon_{NS})$

$\Rightarrow$ $$\ln C = 0.2183 \pm \underbrace{0.0031}_{\text{Experimental uncertainties}} + \Delta\varepsilon$$ with $$\Delta\varepsilon = \underbrace{\tilde{\Delta}_{CT}}_{\left[\tilde{\Delta}_{CT} = \frac{\Delta_{CT}}{B_{exp}}\right]} + 2(\varepsilon_S - \varepsilon_{NS})$$

A dispersive representation of the $K\pi$ scalar form factor.

$$f(t) = \exp\left[\frac{t}{\Delta_{K\pi}} (\ln C - G(t))\right]$$ with $$G(t) = \frac{\Delta_{K\pi}(\Delta_{K\pi} - t)}{\pi} \int_{t_{\pi K}}^{\infty} \frac{ds}{s} \frac{\phi(s)}{(s - \Delta_{K\pi})(s - t)}$$



$$\left[t_0 = (m_K - m_\pi)^2\right]$$

G(t) with the uncertainties added in quadrature

$$G(0) = 0.0398 \pm 0.0040$$

G(t) does not exceed 20% of the expected value of lnC

lnC~0.20

- Similar representation for the vector form factor in terms of its slope.

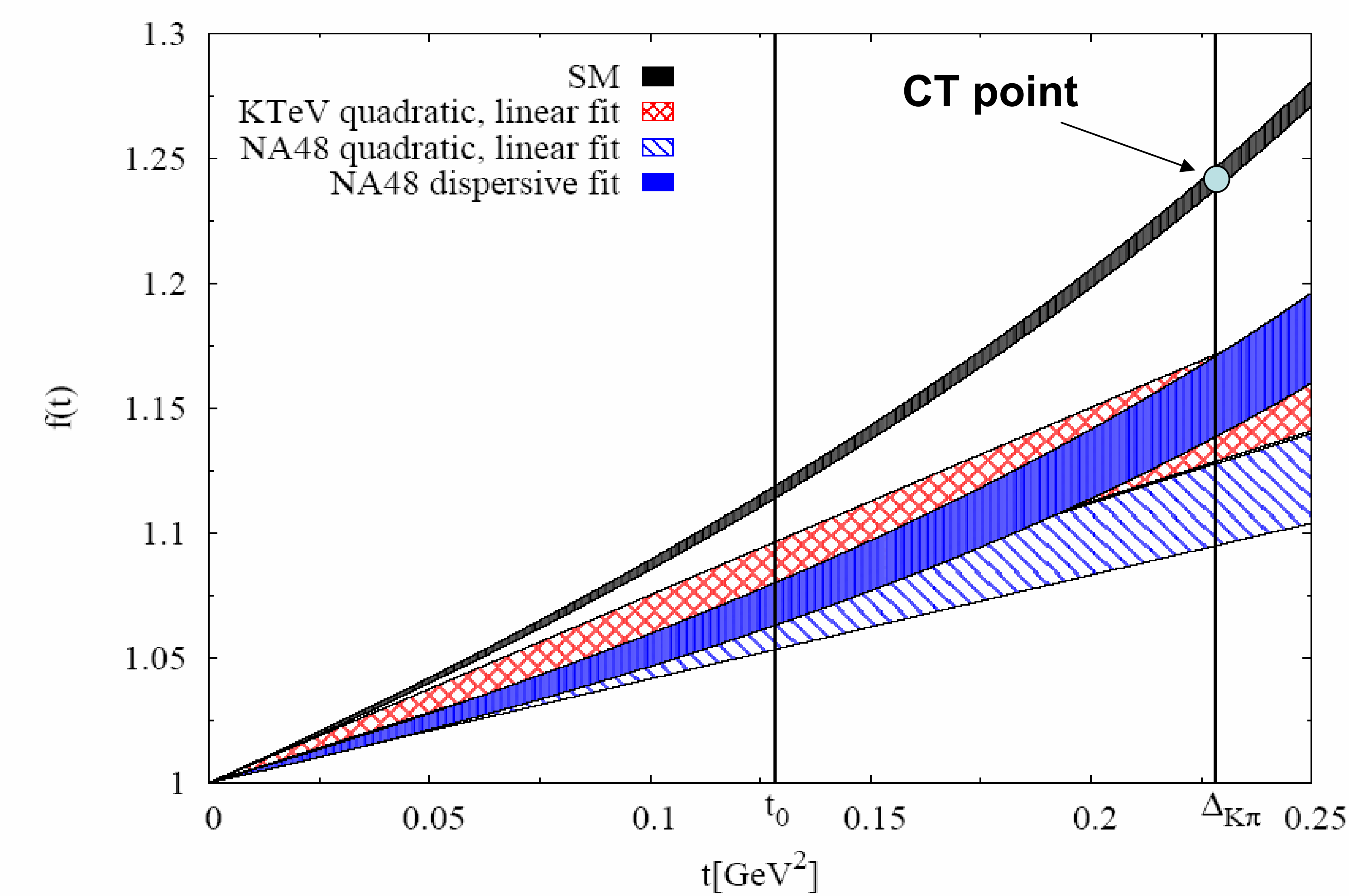
- Accurate dispersive parametrization of the $K_{\mu 3}$ Dalitz distribution $\left(E_{\mu}^{*}, E_{\pi}^{*}\right) \leftrightarrow$ 2 parameters $\Lambda_{+} = m_{\pi}^{2} \hat{f}_{+}'(0),\ \ln C.$

- NA48 : First dedicated high statistics (2.6 M of events) analysis of $K_{L\mu 3}$ Dalitz plot to directly extract lnC :

$$\begin{cases} \ln C_{\exp} = 0.1438 \pm 0.014 \\ \Lambda_{+} = 0.0233 \pm 0.0009 \end{cases} \quad \text{with} \quad \rho(\ln C, \Lambda_{+}) = -\,0.44$$

[NA48, Phys. Lett. B647:341, 2007]

- NB: Extracting the slope λ0 using the linear parametrization does not help us to determine lnC.



- With $\boxed{\Delta_{CT}^{NLO} = -3.5.10^{-3}}$ $\quad \ln C_{SM} = 0.2183 \pm 0.0031 + \dfrac{\Delta_{CT}}{B_{\exp}}$

NA48 Dalitz plot analysis : $\ln C_{\exp} = 0.1438 \pm 0.014$

$\Big\}$ 5 σ !

Interpretation in terms of RHCs :

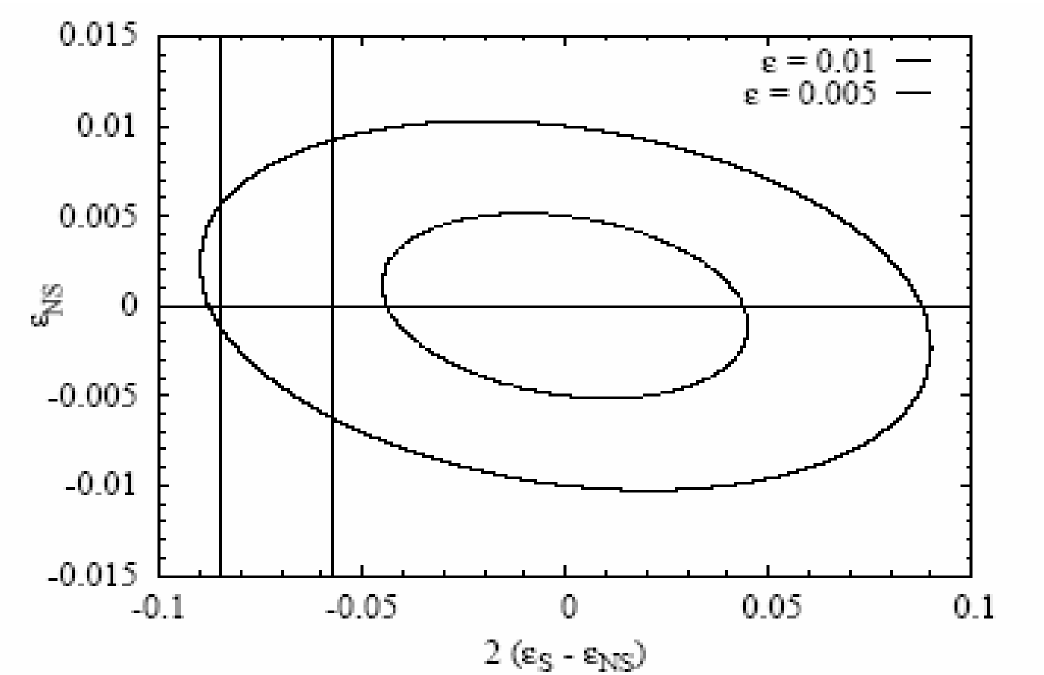
$$\ln C_{\exp} = \ln C_{SM} + \Delta\varepsilon$$

$$\Delta\varepsilon = \frac{\Delta_{CT}}{B_{\exp}} + 2(\varepsilon_S - \varepsilon_{NS}) \Rightarrow \Delta\varepsilon = -0.071 \pm 0.014\Big|_{NA48} \pm 0.002\Big|_{th} \pm 0.005\Big|_{exp}$$

- $\Delta\varepsilon = \dfrac{\Delta_{CT}}{B_{\exp}}$ requires $|\Delta_{CT}| \geq 20\ |\Delta_{CT}^{NLO}|$! with $\Delta_{CT}^{NLO} \sim -3.5.10^{-3}$
- If it is not the case :

  ε_S is enhanced !

  $|V_R^{ud}| < |V_R^{us}|$
- $|\varepsilon| \geq 0.0066$



Neutral current interactions.

$$\mathcal{L}_Z = \frac{e}{2\cos\theta_w \sin\theta_w}(1-\xi^2\rho_L)\Big[\bar{N}\gamma_\mu(g_V^N - g_A^N\gamma_5)N + \bar{L}\gamma_\mu(g_V^L - g_A^L\gamma_5)L$$
$$+\bar{U}\gamma_\mu(g_V^U - g_A^U\gamma_5)U + \bar{D}\gamma_\mu(g_V^D - g_A^D\gamma_5)D\Big]Z_\mu$$

Normalized factor
absorbed in G_F

- New couplings at NLO appearing in g^f_V and g^f_A :

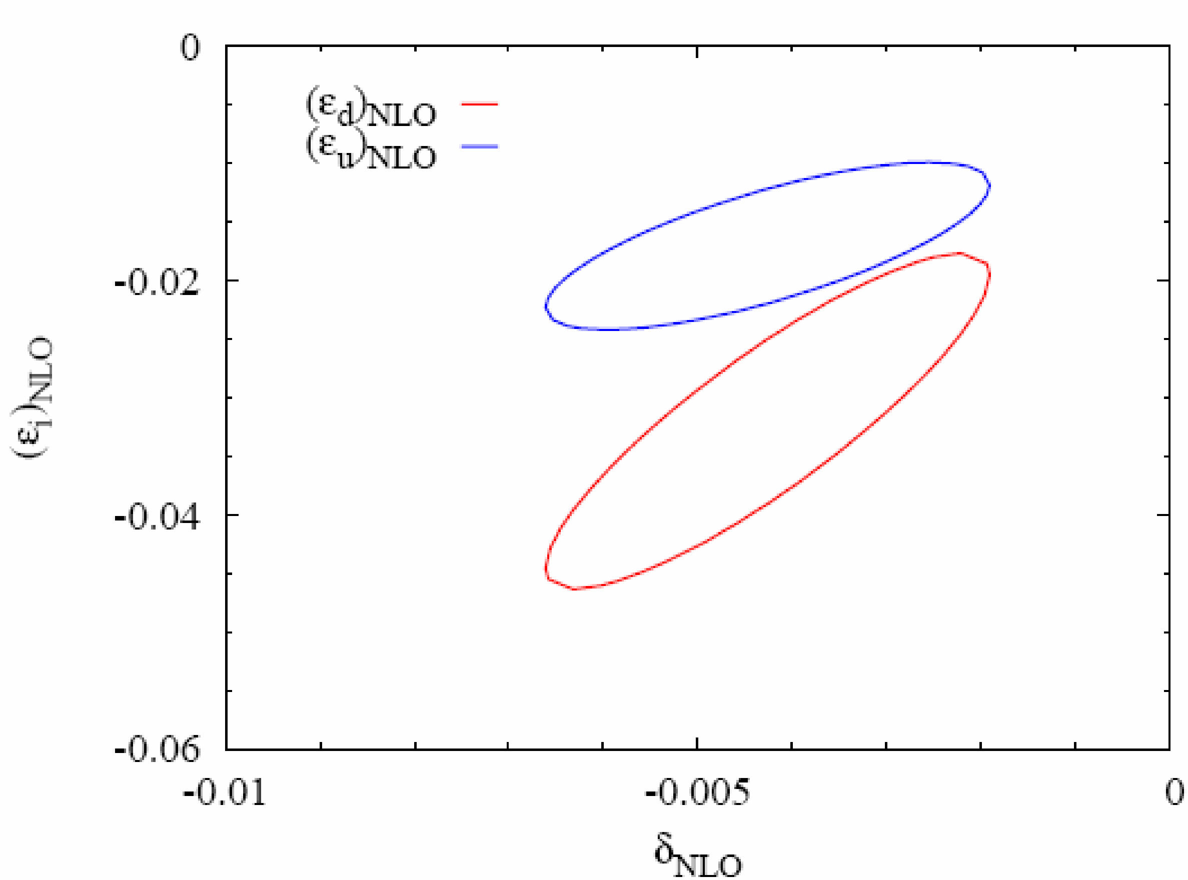
$$\begin{cases} g_V^N = \frac{1}{2} + \frac{\varepsilon^\nu}{2} \\ g_A^N = \frac{1}{2} - \frac{\varepsilon^\nu}{2} \end{cases} \qquad \begin{cases} g_V^L = -\frac{1}{2} + 2\tilde{s}^2 - \frac{\varepsilon^e}{2} \\ g_A^L = -\frac{1}{2} + \frac{\varepsilon^e}{2} \end{cases}$$

$$\begin{cases} g_V^U = \frac{1+\delta}{2} - \frac{4}{3}\tilde{s}^2 + \frac{\varepsilon^u}{2} \\ g_A^U = \frac{1+\delta}{2} - \frac{\varepsilon^u}{2} \end{cases} \qquad \begin{cases} g_V^D = -\frac{1+\delta}{2} + \frac{2}{3}\tilde{s}^2 - \frac{\varepsilon^d}{2} \\ g_A^D = -\frac{1+\delta}{2} + \frac{\varepsilon^d}{2} \end{cases}$$

Results

- Fit to first order in ε (NLO) ⇨ ε^{ν} not present in the fit
- δ =-0.004(2), $\tilde{s}^2$ = 0.2307(2), ε^{e}= -0.0024(5) ,

  ε^{u}= -0.02(1) , ε^{d}= -0.03(1) , χ^2/dof=8.5/8.



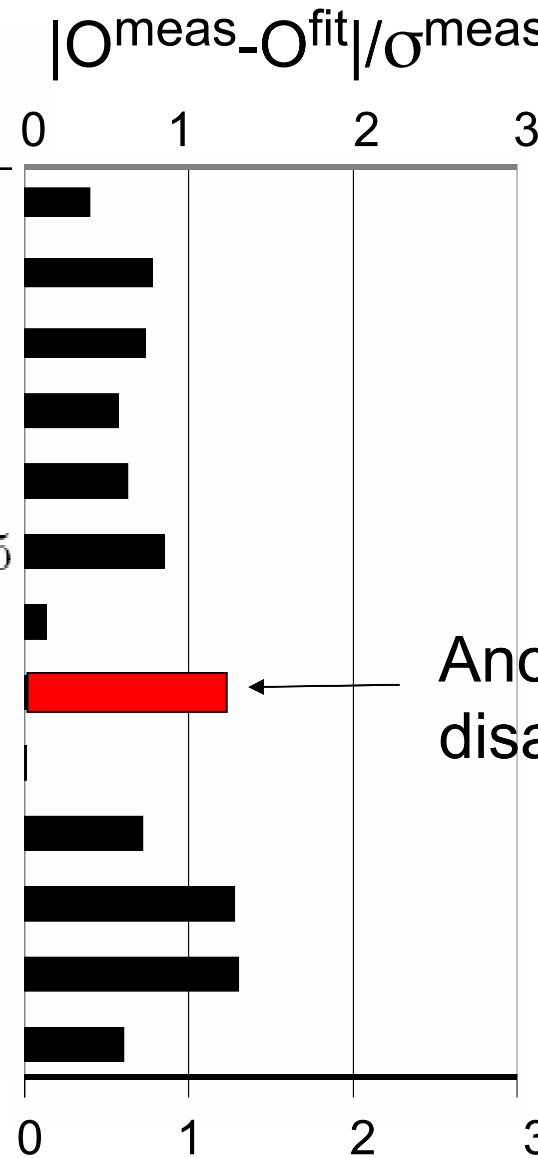
δ and ε^{e} very small ⇨ left-handed couplings not very affected at NLO.

Results in agreement with the order of magnitude

Uncertainties from experiments only !

Result of the NLO FIT

	Measurement	Fit
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	41.569
R_l	20.767 ± 0.025	20.785
$A^{0,l}_{fb}$	0.0171 ± 0.0010	0.0165
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1485
R_b	0.21629 ± 0.00066	0.21685
R_c	0.1721 ± 0.0030	0.1725
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1012
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0707
A_b	0.923 ± 0.020	0.910
A_c	0.670 ± 0.027	0.636
A_l(SLD)	0.1513 ± 0.0021	0.1485
$Br(W \to l)$	0.1084 ± 0.0009	0.1089



Anomaly A^b_{FB} disappears !

Values of low energy QCD observables extracted from semileptonic weak transitions

$$\mathcal{V}^{ud}_{eff} = 0.97377(26) \equiv \cos\hat{\theta} \quad (0^+ \to 0^+,\ CVC)$$

$$\Gamma\left[\pi^+ \to \mu^+\nu(\gamma)\right] \sim \left|F_\pi \mathcal{A}^{ud}_{eff}\right| \Rightarrow F_\pi = \widehat{F}_\pi\left(1 + 2\varepsilon_{NS}\right)$$

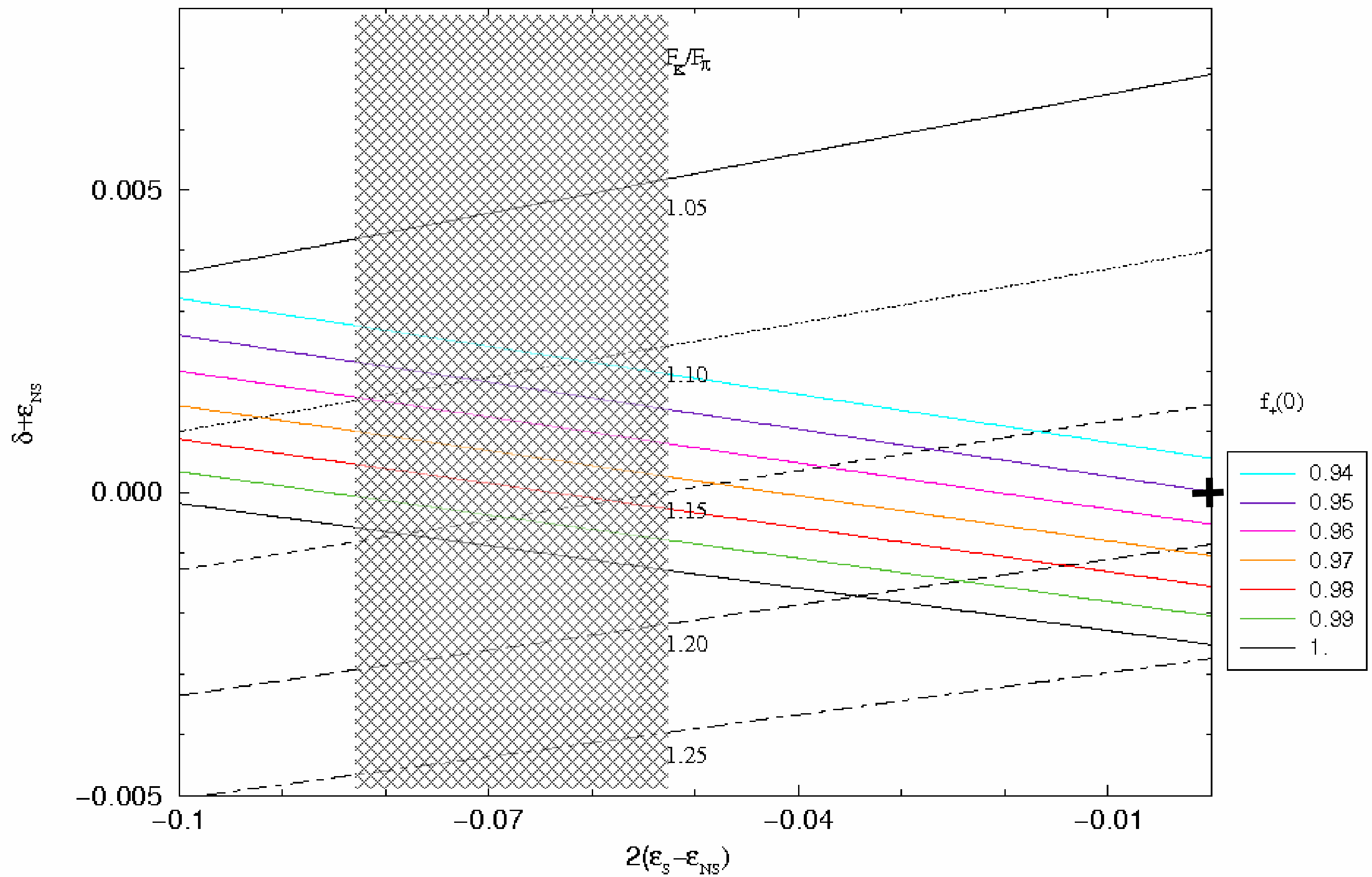
$$\widehat{F}_\pi = (92.4 \pm 0.2)\, MeV$$

$$Br\frac{\left[K^+ \to \mu^+\nu(\gamma)\right]}{\left[\pi^+ \to \mu^+\nu(\gamma)\right]} \sim \frac{\left|F_K \mathcal{A}^{us}_{eff}\right|^2}{\left|F_\pi \mathcal{A}^{ud}_{eff}\right|^2} \Rightarrow \left(\frac{F_K}{F_\pi}\right)^2 = \left(\frac{\widehat{F}_K}{\widehat{F}_\pi}\right)^2 \frac{1 + 2\left(\varepsilon_S - \varepsilon_{NS}\right)}{1 + \frac{2}{\sin^2\hat{\theta}}\left(\delta + \varepsilon_{NS}\right)}$$

$$\frac{\widehat{F}_K}{\widehat{F}_\pi} = 1.182 \pm 0.007$$

$$\Gamma\left[K^0 \to \pi^+ e^- \nu(\gamma)\right] \sim \left|f_+^{K^0}(0)\mathcal{V}^{us}_{eff}\right|^2 \Rightarrow \left[f_+^{K^0\pi^-}(0)\right]^2 = \left[\widehat{f}_+^{K^0\pi^-}(0)\right]^2 \frac{1 - 2\left(\varepsilon_S - \varepsilon_{NS}\right)}{1 + \frac{2}{\sin^2\hat{\theta}}\left(\delta + \varepsilon_{NS}\right)}$$

$$\widehat{f}_+^{K^0\pi^-}(0) = 0.951 \pm 0.005$$



$$\left|\mathcal{V}_{eff}^{ud}\right|^2+\left|\mathcal{V}_{eff}^{us}\right|^2 = 1+\underbrace{2(\varepsilon_S-\varepsilon_{NS})\sin^2\hat{\theta}}_{\text{NA48 : }-0.0035(7)}+2(\delta+\varepsilon_{NS})$$

NA48 : -0.0035(7)

SUMMARY AND COMMENTS

1. General class of electroweak LEET based on **infrared power counting and extended EW symmetries** predicts at NLO non standard universal couplings of right handed quarks to W and Z.
2. **In the CC sector**
   - Compare effective flavor mixing in the vector and axial vector currents. $\mathcal{V}_{eff} \neq -\mathcal{A}_{eff} \Rightarrow$ RHCs.
   - SM $\longrightarrow$ accurate prediction of $C = f(\Delta_{K\pi})$ based on QCD Callan-Treiman theorem.

     5σ discrepancy with the **direct measurement of C** through the NA48 $KL\mu3$ Dalitz plot analysis.
   - Either QCD/ChPT at NLO underestimates Δ_{CT} by a factor 20, or there exist couplings of RH quarks to W.
   - The observed size of the effect (7 percent) can be explained: Inverted hierarchy in the RH CKM mixing matrix.

3. **In the Neutral Current sector**: Very good NLO fit to precision Z - pole observables and atomic PV. A^b_{FB} puzzle solved without ad hoc modifications of universality.
4. **The NA48 analysis based on a realistic dispersive representation** should be applied to existing data from KTeV and KLOE. The slopes parameters extracted assuming a linear parametrization do not quite agree.
5. Hardly other sensitive NLO tests **inclusive hadronic τ decays**
6. **New NNLO tests** $K_0 - \bar{K}_0$, FCNC new CP violation effects but **new parameters,** $V_R^{ij} \ldots$

New contributions to $K_0 - \bar{K}_0$ suppressed by power counting :

Box diagramm with 0 RH vertex : $\mathcal{O}(p^4)$

1 RH vertex : $\mathcal{O}(p^5)$

7. Possible connection with (renormalizable) L-R symmetric models at $E \gg \Lambda_W \sim 3TeV$?

Additionnal slides

Low energy Experiments.

- Using the values of the parameters determined in the FIT $\Longrightarrow$ predictions at low energy.

- Atomic parity violation: test the couplings of electrons to the quarks inside the nucleus via neutral current.
  - Violating part amplitude: 2 contributions (A_e V_q) and (V_e A_q).
  - Limitate the uncertainties, take vector couplings for quarks (CVC).

$$\mathcal{L}_{NC}^{lq} = \frac{G_F}{\sqrt{2}} 4 g_A^e \bar{e} \gamma_\mu \gamma^5 e \left(g_V^u \bar{u} \gamma^\mu u + g_V^d \bar{d} \gamma^\mu d \right)$$

$$\Longrightarrow \quad Q_W = 4 g_A^e \left[Z \left(2 g_V^u + g_V^d \right) + N \left(g_V^u + 2 g_V^d \right) \right]$$

- Parity violation in Polarized Moller Scattering
  Measurement of the parity violating asymmetry (E-158)

$$\boxed{A_{PV} = \frac{\sigma_R(e_R) - \sigma_L(e_L)}{\sigma_R(e_R) + \sigma_L(e_L)}} = -\mathcal{A}\left(Q^2, y\right) Q_W^e$$

Kinematic factor

$$\left(y = Q^2 / s \right)$$

$$\boxed{Q_W^e = 4 g_A^e g_V^e}$$

- Results :

Observable	Measurement	NLO prediction
Q_W (^{133}Cs)	-72.62 ± 0.46	-70.72 ± 4.19
Q_W (^{205}Tl)	-116.40 ± 3.64	-111.95 ± 7.47
Q_W^p	Qweak ?	0.062 ± 0.022
Q_W^e	0.041± 0.005	0.074 ± 0.01

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3 σ !

- Good agreements except for weak charge of electron

⇨ $$Q_W^e = 1 - 4\tilde{s}^2(1-\varepsilon^e)$$

Accidental cancelation at NLO !

$$\left(4\tilde{s}^2(1-\varepsilon^e) \sim 1\right)$$

⇨ We have to go to NNLO !

Interdependence of Electroweak couplings and Low Energy QCD observables

- Example: Pion decay :

$$\Gamma\left[\pi^+ \to \mu^+ \nu(\gamma)\right] \to \mathcal{A}_{eff}^{ud} \langle 0 | \bar{u}\gamma_\mu\gamma_5 d | \pi \rangle \sim \left| F_\pi \boxed{\mathcal{A}_{eff}^{ud}} \right|$$

⇨ **We do not measure directly Fπ but a combination of Fπ and $\mathcal{A}_{eff}^{ud}$.**

$$F_\pi = \underbrace{F_\pi \left|\mathcal{A}_{eff}^{ud}\right|}_{\text{Exp.}} \underbrace{\left|\frac{1}{\mathcal{V}_{eff}^{ud}}\right|}_{(0^+ \to 0^+)} \underbrace{\left|\frac{\mathcal{V}_{eff}^{ud}}{\mathcal{A}_{eff}^{ud}}\right|}_{\boxed{1+2\varepsilon_{NS}}}$$

⇨ $$F_\pi = \widehat{F}_\pi \left(1 + 2\varepsilon_{NS}\right)$$

unknown in the PDG

F_π extracted in the SM ($\mathcal{V}_{eff}^{ud}$ = -$\mathcal{A}_{eff}^{ud}$ = V_{CKM}^{ud}) ⇨ $$\widehat{F}_\pi = (92.4 \pm 0.2)\, MeV$$