Searching for new physics with a non decoupling effective theory

Theory group LTP, PSI
March 6th, 2008

Emilie Passemar, ITP, Bern
passemar@itp.unibe.ch

Collaborators: V. Bernard (LPT-Strasbourg)
M. Oertel (LUTH Meudon)
J. Stern (IPN Orsay)

Paper: Phys. Lett. B638:480, 2006 (hep-ph/0603202).
JHEP 0801:15, 2008 (Arxiv: 0707.4194 [hep-ph]).

Outline

1. The Low Energy Effective Theory beyond the Standard Model.

2. How to probe the electroweak couplings of quarks ?

3. $K_{\mu 3}^{L}$ decay : a stringent test of right-handed quark currents.

4. Tests of the electroweak couplings to Z boson.

5. Conclusion and outlook.

1. The Low Energy Effective Theory beyond the Standard Model

1.1 The Standard Model

- Theory of strong and electroweak interactions.
- The elementary particles:
  - The quarks
  - The leptons

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} b_L \\ t_L \end{pmatrix}$$

$$u_R, d_R, c_R, s_R, b_R, t_R$$

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \rightarrow \chi_L$$

$$e_R, \mu_R, \tau_R \rightarrow \chi_R$$

  - The gauge bosons or Yang-Mills fields: $W^{\pm}, Z^0, A$
- Gauge group: $SU(2)_W \otimes U(1)_Y$
- Mass generation: Higgs Mecanism. A scalar particle remains in the spectrum H
- Theory renormalizable.

- A decade of experimental success:
  - Prediction of the quark top before its discovery.
  - CP violation measured in the B and K decays (CKM matrix).

- But hints of new physics (SM: theory valid up to a certain energy scale):
  - Not enough CP violation to explain the matter/antimatter asymmetry.
  - Neutrino oscillations: $m_\nu \neq 0$
  - m_ν very small compared to the other lepton masses, new scale ?
  - Mass origin ? (Standard Higgs or other ?)
  - Dark matter, dark energy.

- Extensions/Alternatives:
  - Supersymmetry, extra dimensions.
  - Higgsless theories (naturality, non observed particle…).

1.2 Effective approach (framework) beyond the Standard Model

- The Standard Model, effective theory: Theory valid up to an energy scale Λ:
  - all observed particles
  - gauge group $SU(2)_W \otimes U(1)_Y$
  - renormalizability

  } **Standard Model**

- At higher energy (Λ>~1TeV), : New symmetries and particles.
  - heavy states (M > Λ) beyond the Standard Model.
  - Larger symmetry group beyond the SM one : $S \supset SU(2)_W \otimes U(1)_Y$

Usual decoupling scenario

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{D>4} \frac{1}{\Lambda^{D-4}} \mathcal{O}_D$$

with D: mass dimension.

SM degrees of freedom

New physics

- If Λ large enough, the new symmetries and particles are irrelevant at low energy $E \ll \Lambda$.
- At NLO, 80 independent invariant operators of D=6 dimension.
- Research of New Physics quasi impossible !

Construction of an effective theory a la ChPT.

- Build **all** the operators invariant under $SU(2)_W \otimes U(1)_Y$.

- Theory non renormalizable in the usual sense.

- Expansion in external momenta, coupling constants…

$$\mathcal{L}_{eff} = \sum_{d \geq 2} \mathcal{L}_d \quad , \quad d = n_p + n_g + \frac{n_\chi}{2}$$

- Validity : $\mathbf{p} << \Lambda \sim 3\ \mathrm{TeV}$.

- Renormalizable and unitarized order by order in the expansion.

Difficulties of an electroweak effective theory based on $SU(2)_W \otimes U(1)_Y$ symmetry

- At Leading Order operators $SU(2)_W \otimes U(1)_Y$ invariant .
  ⇨ Unwanted operators.

- Example: right-handed currents.
  → **Left-handed sector :**

$$i\overline{\chi_L^i}\gamma^\mu\left(\Sigma D_\mu \Sigma^\dagger\right)\chi_L^j = \mathcal{O}\left(p^2\right)$$

  → **Right-handed sector :**

$$i\overline{\chi_R^i}\gamma^\mu\left(\Sigma^\dagger D_\mu \Sigma\right)\chi_R^j = \mathcal{O}\left(p^2\right)$$

$\Sigma \equiv e^{i\vec{\pi}.\vec{\tau}/f_W}$: Goldstone bosons, χ_L, χ_R : fermions

- Suppressed in the SM case : operators of dimension D=6.

$$\frac{1}{\Lambda^2}\overline{\chi_L^i}\gamma^\mu\Phi\left(D_\mu\Phi^\dagger\right)\chi_L^j$$

$$\frac{1}{\Lambda^2}\overline{\chi_R^i}\gamma^\mu\Phi^\dagger\left(D_\mu\Phi\right)\chi_R^j$$

Couplings experimentally excluded at Leading Order !

- Difficulty: Leading Order ($\mathcal{O}\left(p^2\right)$) operators non present in the SM and experimentally excluded.

- Solution: enlarge the symmety $S_{nat} \supset SU(2)_W \otimes U(1)_Y$ which becomes non-linearly realised:
  - not manifest in the low energy spectrum (the gauge fields associated to this symmetry do not all appear in the spectrum).
  - but constrains the effective interaction (cf. Custodial Symmetry).

⇨ The minimal low-energy effective theory (LEET), a not quite decoupling theory:

- Heavy states present at $E > \Lambda$ still decouple at low energy.
- BUT higher (local) symmetry $S_{nat} \supset SU(2)_W \otimes U(1)_Y$ survives at low energy and becomes non linearly realised.

1.3 Minimal Higgs-less LEET
[J.Hirn & J.Stern, Phys.Rev.D73 '06]

- What is S_{nat}?

⇨ S_{nat} **can be inferred from** $\mathcal{L}_{SM}$ asking :
  - At $\mathcal{O}(p^2)$, S_{nat} selects all the (Higgs-less) vertices of the SM and nothing else.
  - Minimality.

⇨ $$S_{nat} = \left[SU(2)\otimes SU(2)\right]^2 \otimes U(1)_{B-L} \otimes Z_{2\nu_R}$$

- $Z_{2\nu_R}$: $\nu_R \to -\nu_R$: forbids Dirac neutrino masses and charged leptonic right-handed currents.

More concretely,

- At leading order, one unwanted operator: $\left[Tr\left(\tau_3\Sigma^\dagger D_\mu\Sigma\right)\right]^2 = \mathcal{O}\left(p^2\right)$
  operator that can potentially induce a large modification of the SM gauge boson mixing: contribution to the « oblique parameter T ».

- Operator invariant under $SU(2)_W \otimes U(1)_Y$

$$\Sigma(x) \rightarrow G_L(\mathrm{x})\,\Sigma(x)\,G_R^{-1}(x),\quad G_L \in SU(2)_W,\quad G_R \in U(1)_Y.$$

with $G_R(x)\tau_3 G_R^{-1}(x) = \tau_3$

- Enlarge the symmetry: $SU(2)_W \otimes U(1)_Y \rightarrow S_{elem} = SU(2)_{G_L} \otimes SU(2)_{G_R} \otimes U(1)_{G_B}^{B-L}$

⟹ $\left[Tr\left(\tau_3\Sigma^\dagger D_\mu\Sigma\right)\right]^2$ no more invariant under S_{elem}.

$$G_R(x)\tau_3 G_R^{-1}(x) \neq \tau_3$$

Reduction of S_{nat} $S_{nat} \to SU(2)_W \otimes U(1)_Y$: via the spurions.

$$SU(2)_{G_L} \times SU(2)_{\Gamma_L} \times SU(2)_{G_R} \times SU(2)_{\Gamma_R} \times U(1)_{G_B}^{B-L}$$

$X \to G_L X \Gamma_L^{-1}$ $\quad X \quad$ $Y_{u,d} \to G_R Y_{u,d} \Gamma_R^{-1}$ $\quad Y = Y_u + Y_d$

$$SU(2)_W \quad \times \quad SU(2)_{\Gamma_R} \times U(1)_{B-L}$$

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

$Z \to e^{i\alpha}\, \Gamma_R Z \Gamma_R^{-1}$ $\quad Z$

$$SU(2)_W \quad \times \quad U(1)_Y$$

- $S_{nat} / SU(2)_W \otimes U(1)_Y \equiv \left[SU(2)\right]^3$ populated by spurions
- X, Y, Z are called spurions ($D_\mu\left(spurions\right) = 0$).
- It exists a gauge where the spurions become constants κ: ⇨ 3 parameters which describe the hierarchical breaking of S_{nat} (~ quark masses in ChPT).

Power counting scheme or how searching for physics beyond the SM

- Terms explicitly involving spurions ⇨ fermion masses and genuine effects beyond the SM.
- The operators are ordered in power of momenta and of explicit symmetry breaking parameters (spurions: κ) :

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}\left(p^2\kappa^0\right) + \mathcal{L}\left(p^1\kappa^2\right)}_{\textbf{LO}:\ \mathcal{O}\left(p^2\right)} + \underbrace{\mathcal{L}\left(p^2\kappa^2\right)}_{\textbf{NLO}:\ \mathcal{O}\left(p^3\right)} + \underbrace{\mathcal{L}\left(p^4\right)}_{\textbf{NNLO}:\ \mathcal{O}\left(p^4\right)} + \ldots.$$

Loops, oblique corrections

- Counting rule: $\frac{m_t}{\Lambda} = \kappa^2 = \mathcal{O}(p)$

1.4 First effets beyond the SM

- At Leading Order (LO), $\mathcal{O}\left(p^2\right)$: we recover the Standard Model at tree level without a Higgs.

- At Next to Leading Order (NLO) $\mathcal{O}\left(p^2\kappa^2\right)$ new physics (contains spurions) arising before loops, oblique corrections….. only 2 operators :

→ **Left-handed sector :**

$$i\overline{\chi_L^i}\gamma^\mu\left(\Sigma D_\mu \Sigma^\dagger\right)\chi_L^j = \mathcal{O}\left(p^2\right)$$

→ **Right-handed sector :**

$$i\overline{\chi_R^i}\gamma^\mu\left(\Sigma^\dagger D_\mu \Sigma\right)\chi_R^j = \mathcal{O}\left(p^2\right)$$

$\Sigma \equiv e^{i\vec{\pi}.\vec{\tau}/f_W}$: Goldstone bosons, χ_L, χ_R : fermions

Operators invariant under $SU(2)_W \otimes U(1)_Y$ but not invariant under S_{nat}

To make them invariant under S_{nat}, we insert spurions: ⇨

spurions

$$i\overline{\chi_L^i}\gamma^\mu \mathcal{X}^\dagger\left(\Sigma D_\mu \Sigma^\dagger\right)\mathcal{X}\,\chi_L^j = \mathcal{O}\left(p^2\kappa^2\right)$$

spurions

$$i\overline{\chi_R^i}\gamma^\mu \mathcal{Y}_a^\dagger\left(\Sigma^\dagger D_\mu \Sigma\right)\mathcal{Y}_b\,\chi_R^j = \mathcal{O}\left(p^2\kappa^2\right)$$

1.4 First effets beyond the SM

- At leading order (LO) $\mathcal{O}\left(p^2\right)$, we recover the Standard Model at tree level without a Higgs.

- At Next to the Leading Order (NLO) $\mathcal{O}\left(p^2\kappa^2\right)$ before the loops only 2 operators instead of the 80 that appear in the decoupling scenario !
  ⇨ new couplings of fermions to W and Z.

$$\mathcal{L}_{\mathcal{NLO}} \equiv \mathcal{L}_{\mathcal{CC}} + \mathcal{L}_{NC}$$

⇓ W couplings ⇓ Z couplings

- Counting rule: NLO, potentially the most important effects of physics beyond the SM.

1.5 Conclusion

- New approach to go beyond the Standard Model : the minimal low-energy effective theory.
- Larger symmetry non linearly realised.
- Power counting scheme ⇨ classifies and hierarchizes the effects beyond the Standard Model.
- First predicted effects ⇨ modification and new electroweak couplings of fermions (quarks and leptons).

Couplings of the fermions to W : charged currents

$$\mathcal{L}_{cc} = \frac{1}{\sqrt{2}} g(1-\xi^2\rho_L)(J_\mu^{\bar{U}D} + J_\mu^{\bar{N}L})W^\mu + h.c,$$

$$\mathrm{U} = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \mathrm{D} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \mathrm{N} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}, \mathrm{L} = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

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

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

- **V_L, V_R** : 2 unitary flavor mixing matrixes from the diagonalisation of the mass matrix of U and D quarks.
- 3 parameters which involve spurions arise :

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

Charged Currents parameters at NLO

$(1-\xi^2\rho_L)$ Common factor absorbed in the G_F definition.

$(1+\delta)$ Normalisation of the left-handed quarks with respect to the leptons.

ε Strength of right-handed quark currents.

Experimental probe

- Experimentally, we measure axial and vectorial currents.
- We write the charged current in term of axial and vectorial currents:

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

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

- V_L and V_R unitary but not $\mathcal{V}_{eff}$ and $\mathcal{A}_{eff}$!
- At LO (SM) : $\delta=\varepsilon=0$, $\mathcal{V}_{eff} = -\mathcal{A}_{eff} = V_{CKM}$ (V-A interaction).
- At NLO: $\mathcal{V}_{eff} \neq -\mathcal{A}_{eff}$ charged right-handed currents appear.

Experimental probe

- Experimentally, we measure axial and vectorial currents.
- We write the charged current in term of axial and vectorial currents:

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

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

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

- In the light quark sector, 3 quantities to determine:

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

Order of magnitude of the parameters

- $\delta, \varepsilon \leq 1\%$ (quark top 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} ⇒ experimental measurements $\begin{cases} |V_L^{ud}| \sim 0.97 \\ |V_L^{us}| \sim 0.23 \end{cases}$
- V_R unitary ⇒ $\begin{cases} |V_R^{ud}| \leq 1 \\ |V_R^{us}| \leq 1 \end{cases}$

⇒ $|\varepsilon_{NS}| \leq \varepsilon \sim 1\%$ and $|\varepsilon_S| \leq 4.5 \; \varepsilon$

- Possible enhancement of ε_S
- Expected effects of at most several percents.

2. How to probe the electroweak couplings of quarks ?

2.1 Introduction

- Experiments of parity violation 50 years ago ⇨ adoption of the assumption that the weak interaction is V-A like.

- Have we probed that the weak interaction is V-A ?

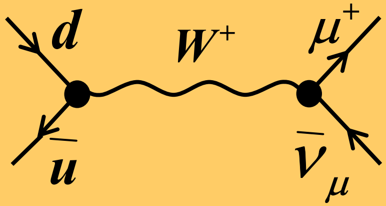
- Several tests for the leptons (Muon, Tau polarisation measurements…)

- And for the quarks ? ⇨ Couplings difficult to test: we can not access directly to quarks because of the confinement !

- Experimentally, the measurements of the electroweak couplings $\left(\mathcal{V}_{eff}\ ,\ \mathcal{A}_{eff}\right)$ depend on the knowledge of the QCD observables and vice versa !

2.2 Dependence of the electroweak couplings and the low-energy QCD observables

- Example: Decay of the pion:



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

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

- In the case of the electroweak couplings of the SM : $\left(\mathcal{V}_{eff} = -\mathcal{A}_{eff} = V_{CKM}\right)$

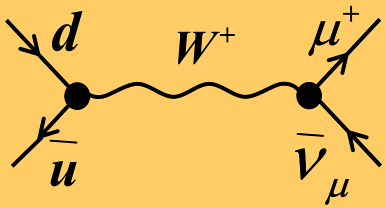
$\mathcal{A}_{eff}^{ud} \to V_{CKM}^{ud}$ very precisely measured from (0+ → 0+) superallowed β decays: $\mathcal{V}_{eff}^{ud} = 0.97418(26)$ **[Towner and Hardy'07].**

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

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

2.2 Dependence of the electroweak couplings and the low-energy QCD observables

- Example: Decay of the pion:



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

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

- To be more precise

$$F_\pi = F_\pi \left|\mathcal{A}_{eff}^{ud}\right| \left|\frac{1}{\mathcal{V}_{eff}^{ud}}\right| \left|\frac{\mathcal{V}_{eff}^{ud}}{\mathcal{A}_{eff}^{ud}}\right|$$

Exp. $(0^+ \to 0^+)$ $1 + 2\varepsilon_{NS}$

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

unknown ($\hat{F}_\pi$) — in the PDG (F_π)

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

2.2 Dependence of the electroweak couplings and the low-energy QCD observables

- But also β-decay of the neutron :

$$\langle p | \mathcal{V}_{eff}^{ud} \bar{u}\gamma_\mu d + \mathcal{A}_{eff}^{ud} \bar{u}\gamma_\mu\gamma_5 d | n \rangle \sim \left|\mathcal{V}_{eff}^{ud}\right| \left(g_V(q^2)\gamma_\mu - i\frac{g_M(q^2)}{m_n}\sigma_{\mu\nu}q^\nu \right)$$
$$+ \left|\mathcal{A}_{eff}^{ud}\right| \left(g_A(q^2)\gamma_\mu\gamma_5 + \frac{g_S(q^2)}{m_n}\gamma_5 q_\mu \right)$$

- Measurement of the neutron life time and polarisation do not allow us any more to extract g_A !

The knowledge of the QCD parameters would allow to determine the electroweak couplings and vice versa !

2.3 How to probe these couplings ?

- Among all the experimental processes involving charged currents, we are looking for those whose QCD parameters (form factors, α_S , m_q ...) are under control or enough small.

- We are looking for effects to first order in δ et ε.

⇨ Not a lot of processes…

2.4 Test of NLO effects

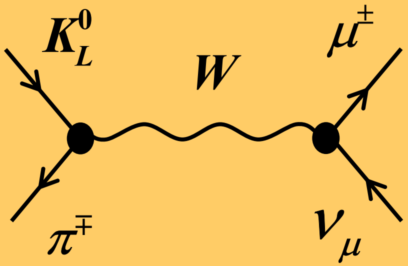
Experimental processes	Parameters extracted	Low Energy/QCD inputs
Nuclear β decays **$0^+ \to 0^+$**	$\left\|\mathcal{V}^{ud}_{eff}\right\|$	**CVC + nuclear corrections** [Towner & Hardy '07]
Hadronic τ decays **R_V, R_A, R_S, Moments** ALEPH, OPAL	ε_{NS}, $\delta+\varepsilon_{NS}$	**OPE** [Braaten et al '92, Lediberder & Pich '92….] **$\alpha_S(m_\tau)$, m_q, condensates**
Γ_W LEP, TEVATRON	δ	**Perturbative QCD** $\alpha_S(m_W)$
DIS $\nu(\overline{\nu})$ on protons	δ	**Normalized pdf**
$K^L_{\mu 3}$ decay KTeV, NA48, KLOE	$\varepsilon_S - \varepsilon_{NS}$	**$K\pi$ scattering phases** [Buettiker, Descotes, Moussallam' 02] **and Δ_{CT}: χPT**

2.4 Test of NLO effects

Experimental processes	Parameters extracted	Low Energy/QCD inputs
Nuclear β decays **$0^+ \to 0^+$**	$\left\lvert V^{ud}_{eff} \right\rvert$	**CVC + nuclear corrections** [Towner & Hardy '07]
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 $\nu(\overline{\nu})$ on protons	δ	**Normalized pdf**
$K^L_{\mu 3}$ decay KTeV, NA48, KLOE	$\varepsilon_S - \varepsilon_{NS}$	**$K\pi$ scattering phases** [Buettiker, Descotes, Moussallam' 02] **and Δ_{CT}: χPT**

3. $K_{\mu 3}^{L}$ decay : a stringent test of right-handed quark currents.

3.1 Introduction



- $K_L^0 \to \pi^\mp \mu^\pm \nu_\mu$

  Hadronic part :

  $$\left\langle \pi^-(p_\pi) \right| \bar{s}\gamma_\mu u \left| K^0(p_K) \right\rangle = f_+(t)(p_K + p_\pi)_\mu + f_-(t)(p_K - p_\pi)_\mu$$

  → $f_+(t)$, $f_-(t)$: facteurs de forme

  → $t = q^2 = (p_\mu + p_{\nu_\mu})^2 = (p_K - p_\pi)^2$

- We consider the scalar form factor : $f_s(t) = f_+(t) + \dfrac{t}{m_K^2 - m_\pi^2} f_-(t)$

  → Normalisation : $\bar{f}_0(t) = \dfrac{f_s(t)}{f_+(0)}, \; f_0(0) = 1$

3.2 Theoretical knowledge: the Callan-Treiman relation

- Callan-Treiman Theorem: SU(2) x SU(2) theorem

$$C = \overline{f_0}(\Delta_{K\pi}) = \frac{F_K}{F_\pi f_+^{K^0}(0)} + \Delta_{CT}$$

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

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

[Gasser & Leutwyler]

- Corrections of order m_u, m_d
  → No chiral logarithms : $\Delta_{CT} \sim \mathcal{O}\left(m_{u,d} / 4\pi F_\pi\right)$

  → K^0 decay : no small denominators due to π^0 - η mixing ($\mathcal{O}\left(\left(m_d - m_u\right)/m_s\right)$) .

$$C = \bar{f}_0(\Delta_{K\pi}) = \underbrace{\frac{F_K \left|\mathcal{A}^{us}_{eff}\right|}{F_\pi \left|\mathcal{A}^{ud}_{eff}\right|} \frac{1}{f_+(0)\left|\mathcal{V}^{us}_{eff}\right|} \left|\mathcal{V}^{ud}_{eff}\right|}_{B_{exp}} \frac{\left|\mathcal{A}^{ud}_{eff}\right|}{\left|\mathcal{V}^{ud}_{eff}\right|} \frac{\left|\mathcal{V}^{us}_{eff}\right|}{\left|\mathcal{A}^{us}_{eff}\right|} + \Delta_{CT}$$

- B_{exp} is known from experiment using the measured Br: $Br(K_{l2}/\pi_{l2})$, $\Gamma(K_{e3})$ and $\left|\mathcal{V}_{ud}\right|$.

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

⇨ $C_{SM} = 1.2439 \pm 0.0042 + \Delta_{CT}$ $\qquad \ln C_{SM} = 0.2183 \pm 0.0034 + \frac{\Delta_{CT}}{B_{exp}}$

- Relation which tests the Standard Model very accurately.
  If physics beyond the SM: ~1% difference between C and B_{exp}. Uncertainties from Δ_{CT} and B_{exp} on the permile level ⇨ opportunity to see a possible effect.

$$C = \overline{f}_0(\Delta_{K\pi}) = \underbrace{\frac{F_K \left|\mathcal{A}^{us}_{eff}\right|}{F_\pi \left|\mathcal{A}^{ud}_{eff}\right|} \frac{1}{f_+(0)\left|\mathcal{V}^{us}_{eff}\right|} \left|\mathcal{V}^{ud}_{eff}\right|}_{B_{exp}} \frac{\left|\mathcal{A}^{ud}_{eff}\right|}{\left|\mathcal{V}^{ud}_{eff}\right|} \frac{\left|\mathcal{V}^{us}_{eff}\right|}{\left|\mathcal{A}^{us}_{eff}\right|} + \Delta_{CT}$$

- B_{exp} is known from experiment using the measured Br: $Br(K_{l2}/\pi_{l2})$, $\Gamma(K_{e3})$ and $\left|\mathcal{V}_{ud}\right|$.
- Standard Model case : $\mathcal{V}_{eff} = -\mathcal{A}_{eff} = V_{CKM}$ $\Rightarrow$ $\frac{\left|\mathcal{A}^{ud}_{eff}\right|}{\left|\mathcal{V}^{ud}_{eff}\right|} \frac{\left|\mathcal{V}^{us}_{eff}\right|}{\left|\mathcal{A}^{us}_{eff}\right|} = 1$

$\Rightarrow$ $C_{SM} = 1.2439 \pm 0.0042 + \Delta_{CT}$ $\quad \ln C_{SM} = 0.2183 \pm 0.0034 + \frac{\Delta_{CT}}{B_{exp}}$

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

$\Rightarrow$ $\ln C = 0.2183 \pm \underbrace{0.0034}_{\text{experimental uncertainties}} + \Delta\varepsilon$ with $\Delta\varepsilon = \underbrace{\tilde{\Delta}_{CT}}_{} + 2(\varepsilon_S - \varepsilon_{NS})$

$$\left[\tilde{\Delta}_{CT} = \frac{\Delta_{CT}}{B_{exp}}\right]$$

$$\Rightarrow \quad \ln C = \underbrace{0.2183 \pm 0.0034}_{\text{experimental uncertainties}} + \Delta\varepsilon \quad \text{with} \quad \Delta\varepsilon = \underbrace{\tilde{\Delta}_{CT}}_{\left[\tilde{\Delta}_{CT} = \frac{\Delta_{CT}}{B_{\exp}}\right]} + 2(\varepsilon_S - \varepsilon_{NS})$$

- $\Delta_{CT} \sim 10^{-3}$: to extract a quantitative information on right-handed currents (RHCs), lnC has to be measured with an accuracy of 10%.

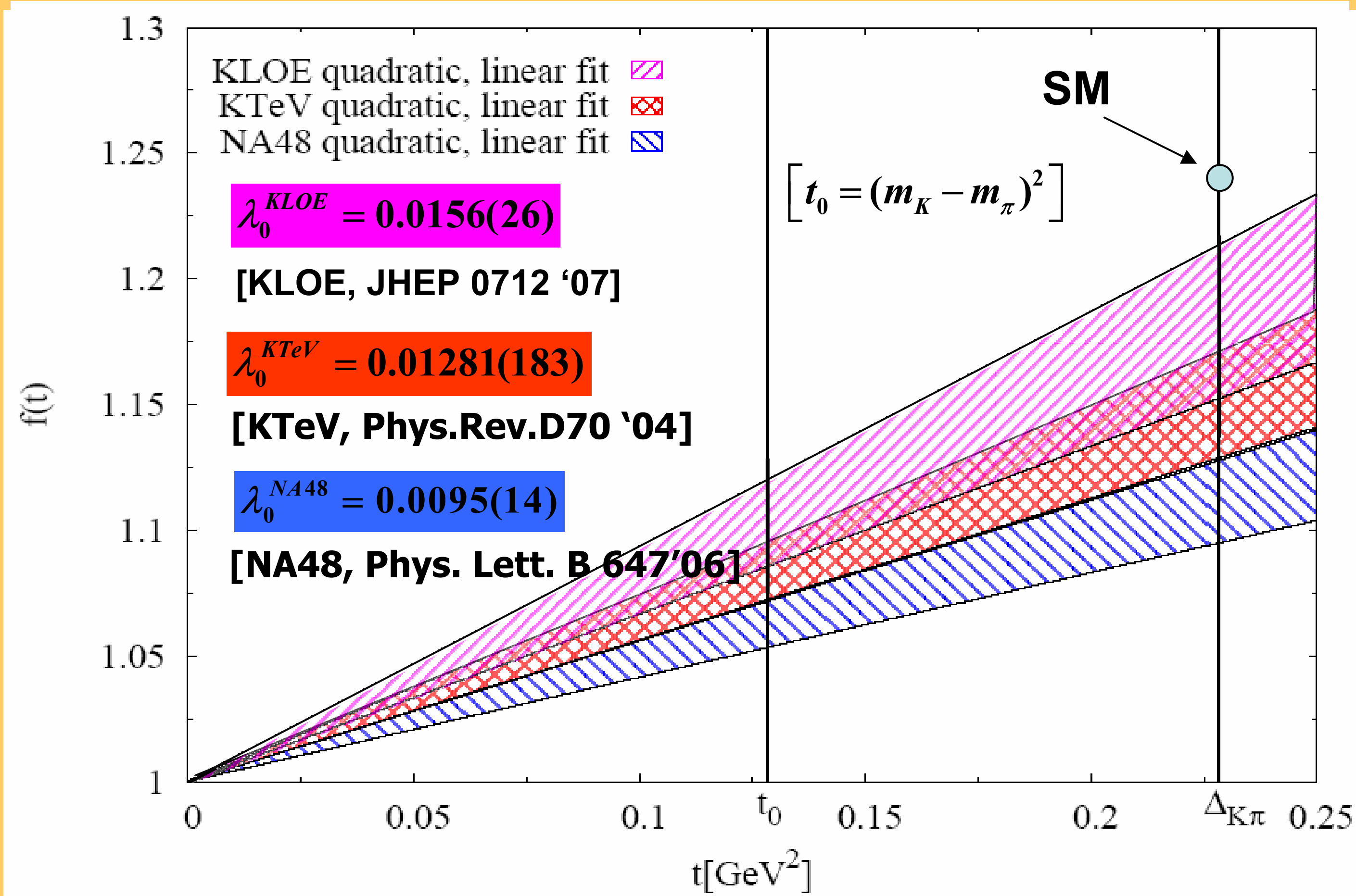
How to measure lnC ?

3.3 Experimental measurements

- Data available from KTeV, NA48 and KLOE.
- Necessity to parametrize the 2 form factors $\bar{f}_+$ and $\bar{f}_0$ to fit the measured distributions.
- Usually, use of linear parameterization or pole parameterization :

$$f_{lin}(t,\lambda) = 1 + \lambda \frac{t}{m_\pi^2}$$

$$f_{pol}(t, m_s) = \frac{m_s^2}{m_s^2 - t}$$



- Extrapolation with a linear parametrization: impossible to test the SM at the CT point with enough accuracy.
- A curvature exists and we can not neglect it !

How to improve the parametrization to measure $C=f(\Delta_{K\pi})$?

3.4 Dispersive parametrization for the scalar FF.

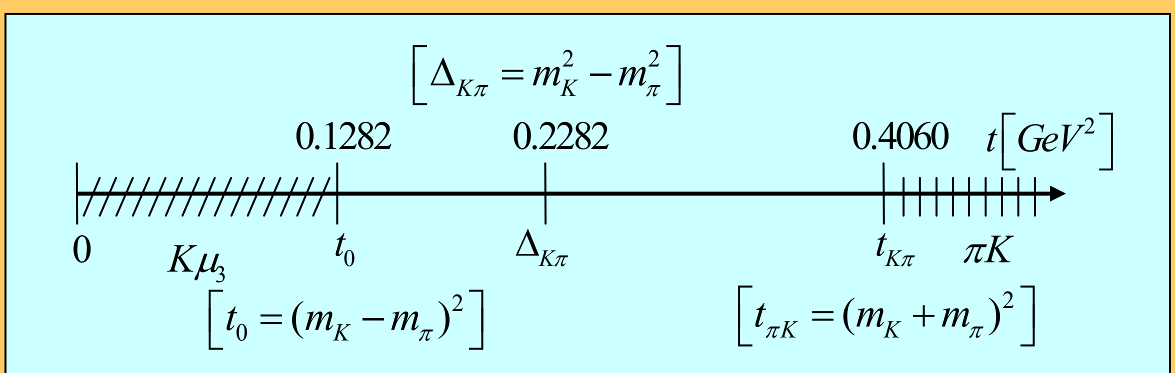
- Problem : How to construct a very precise representation of $\bar{f}_0(t)$ between 0 and $\Delta_{K\pi}$?
- Knowledge :
  - → $\bar{f}_0(0) = 1$
  - → $\bar{f}_0(\Delta_{K\pi}) = C$, Callan-Treiman point
  - → $K\pi$ scattering phase
  - → Asymptotic behaviour of the form factor : $\bar{f}_0(s) \underset{s\to -\infty}{=} \mathcal{O}(1/s)$
- A dispersion relation with two substractions at 0 and $\Delta_{K\pi}$ for $\ln(\bar{f}_0(t))$:

$$\bar{f}_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}\left(\ln C - G(t)\right)\right]$$

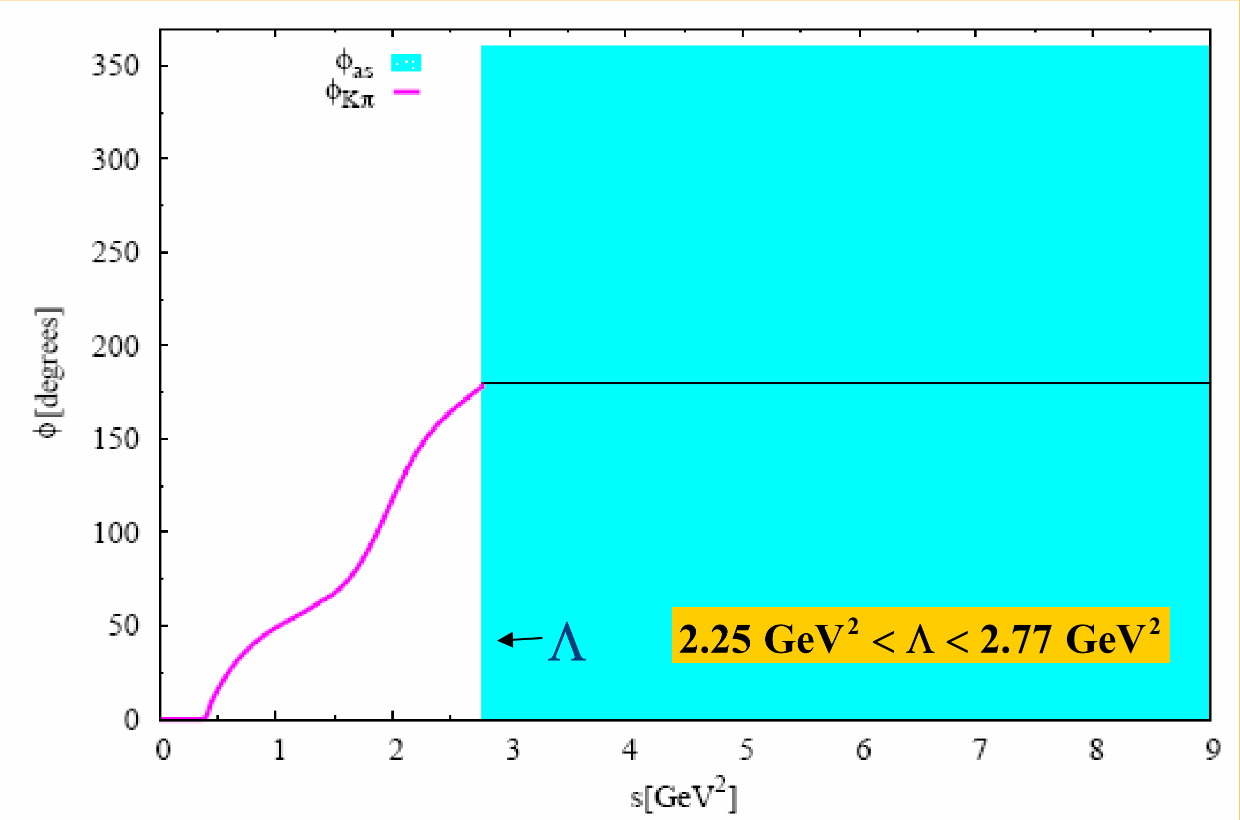
with

$$G(t) = \frac{\Delta_{K\pi}(\Delta_{K\pi} - t)}{\pi}\int_{t_{\pi K}}^{\infty}\frac{ds}{s}\frac{\phi(s)}{(s-\Delta_{K\pi})(s-t)}$$

→ $\phi(t)$ phase of form factor : $\bar{f}_0(t) = \left|\bar{f}_0(t)\right| e^{i\phi(t)}$



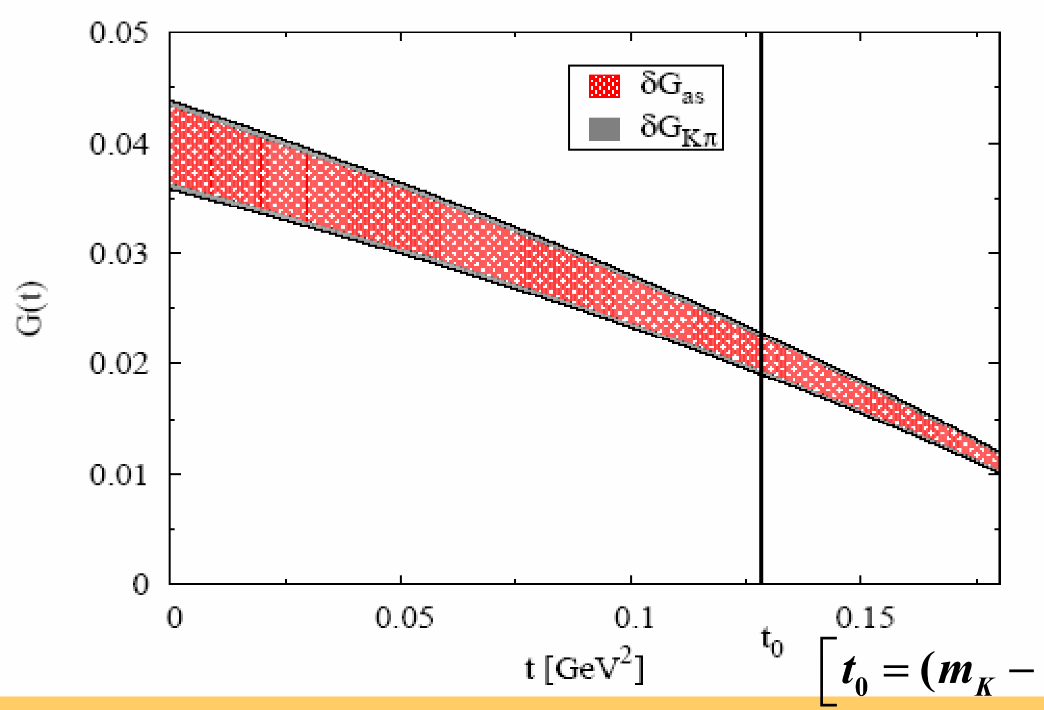
- Phase used



- Elastic up to ~1.5 GeV ⇨

$$t < \Lambda : \; \phi(t) = \phi_{K\pi}(t) = \delta^{s,\frac{1}{2}}_{\pi,K}(t) \pm \Delta\delta^{s,\frac{1}{2}}_{\pi,K}(t)$$

$$t > \Lambda : \; \phi(t) = \phi_{as}(t) = \pi \pm \pi$$



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

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

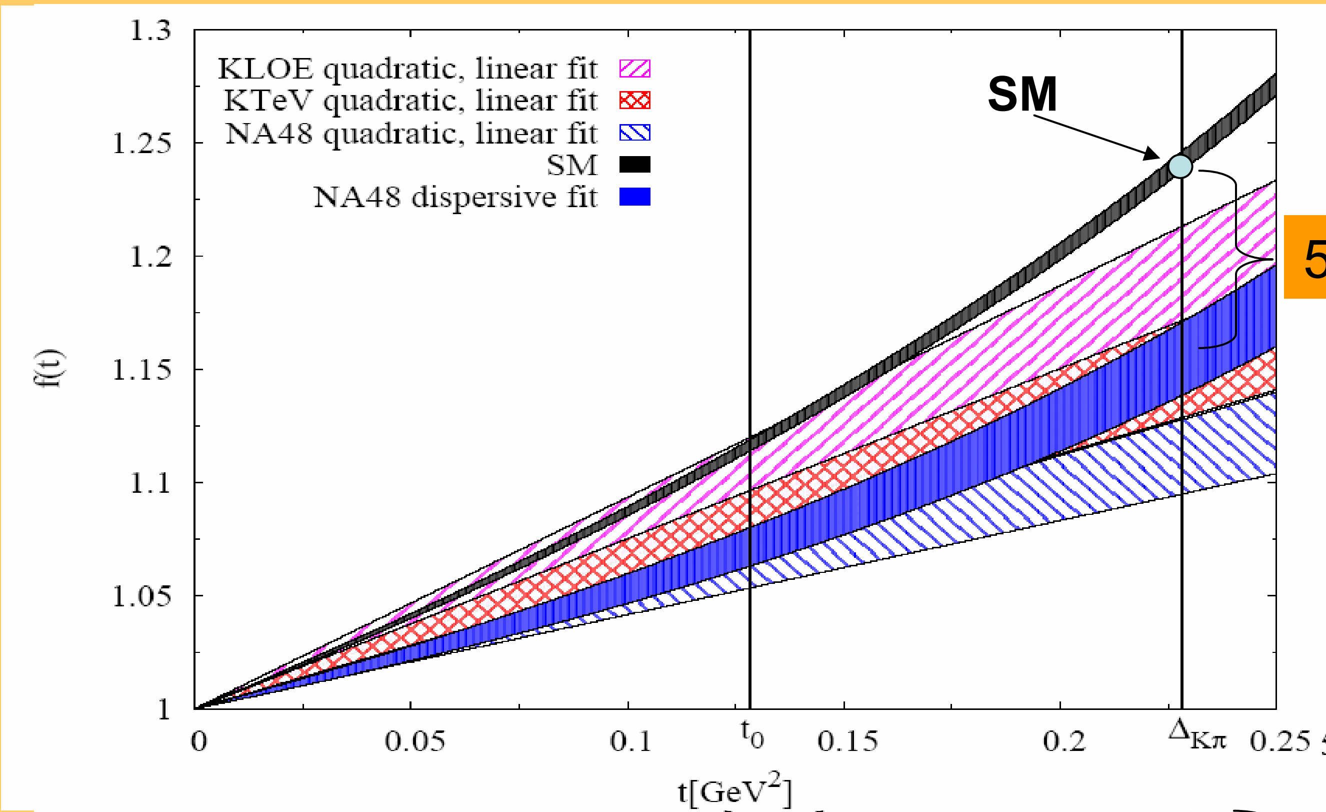
lnC~0.20

- Apart from the parameter (lnC) to be determined by a fit, very precise parametrization of the form factor in the physical region.

3.5 First measurement: a discrepancy with the SM ?

- Use of the dispersive parametrization to fit the measured distribution and to extract lnC : $f(t) = \exp\left[\frac{t}{\Delta_{K\pi}}(\ln C - G(t))\right]$ $\Rightarrow$ $\ln C_{NA48} = 0.1438 \pm 0.014$

[NA48 Phys. Letter B 647 '06]



5 σ !

- With $\Delta_{CT}^{NLO} = -3.5.10^{-3}$

$$\ln C_{SM} = 0.2183 \pm 0.0034 + \frac{\Delta_{CT}}{B_{\exp}}$$

$$\ln C_{NA48} = 0.1438 \pm 0.014$$

5 σ !

Experimental result for $\Delta\varepsilon$

- $$\Delta\varepsilon = \frac{\Delta_{CT}}{B_{\exp}} + 2(\varepsilon_S - \varepsilon_{NS}) \quad \Longrightarrow \quad \Delta\varepsilon = -0.074 \pm 0.015$$

  Possibility to disentangle Δ_{CT} from the RHCs by a matching with the ChPT two loop representation for the form factors [Bernard & E.P'07].

- $\Delta\varepsilon = \frac{\Delta_{CT}}{B_{\exp}}$ asks for $|\Delta_{CT}| \geq 20\ |\Delta_{CT}^{NLO}|$! with $\Delta_{CT}^{NLO} \sim -3.5.10^{-3}$

- If it is not the case the measurement gives us an information on the right-handed mixing matrix : ε_S is enhanced and inverse hierarchy in the right-handed sector !

3.6 But other « contradictory » measurements

- Only combined Ke3 + Kμ3 result for KLOE (to reduce the uncertainties) :

$$\ln C_{KLOE} = 0.207 \pm 0.023$$

large uncertainty

- Preliminary results for KTeV :
  - Kμ3 alone : $\ln C_{KTeV} = 0.195 \pm 0.014$
  - Combined Ke3 + Kμ3 : $\ln C_{KTeV} = 0.191 \pm 0.012$

- Consistent results at 1-1.5σ from the SM, confirming the same direction but in disagreement with the NA48 result !

- K^+ analysis in progress to solve this experimental puzzle.

3.7 Conclusion

- Stringent test of the V+A coupling in $K_{\mu 3}^{L}$ decays.
- Experimental situation not completly clear: from 1σ to 5σ away from the SM depending on the experiment. ⇨ Mesurement of the direct coupling of right-handed quarks to W boson: $\mathbf{2(\varepsilon_S - \varepsilon_{NS})}$
- Tendancy of an enhancement of ε_S , inverted hierarchy of V_R .
- No other experiments where ε_S is involved.

4. Tests of the electroweak couplings to the Z boson.

4.1 Neutral current interactions.

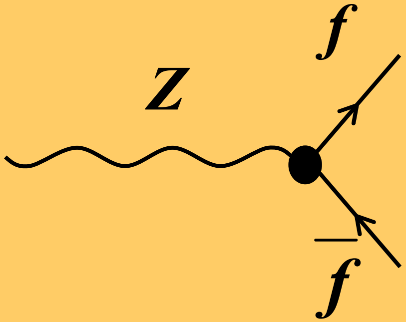
$$\mathcal{L}_Z = \frac{e}{2\cos\theta_w \sin\theta_w}(1-\xi^2\rho_L)\Big[\bar{N}\gamma_\mu(g_V^N - g_A^N\gamma_5)N + \bar{L}\gamma_\mu(g_V^L - g_A^L\gamma_5)L$$
$$+ \bar{U}\gamma_\mu(g_V^U - g_A^U\gamma_5)U + \bar{D}\gamma_\mu(g_V^D - g_A^D\gamma_5)D\Big]Z_\mu$$

Normalized factor absorbed in G_F

- $\dfrac{G_F}{\sqrt{2}} = \dfrac{g^2}{8m_w^2}(1-\xi^2\rho_L)^2$

$$N=\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix},\ L=\begin{pmatrix}e\\ \mu\\ \tau\end{pmatrix},\ U=\begin{pmatrix}u\\ c\\ t\end{pmatrix},\ D=\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$

- $g = \dfrac{e}{\sin\theta_w}$



- $\sin\theta_w^2 = 1 - \dfrac{m_w^2}{m_Z^2}$

4.1 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 :

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

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

- At NLO 6 parameters:
  - modification of the left couplings: δ
  - modification of the right couplings :
    - For the neutrinos and electrons : ε^{ν}, ε^{e}
    - For the quarks: ε^{u}, ε^{d}
  - Normalisation factor: $1-\xi^2\rho_L \Longrightarrow \tilde{s}^2 = \dfrac{s^2}{1-\xi^2\rho_L}$
- Expectation: percent level.
- Universality of the couplings is assumed.

4.2 FIT to Z pole observables

- How to constrain these parameters ?
  ⇨ Data from LEP and SLD.

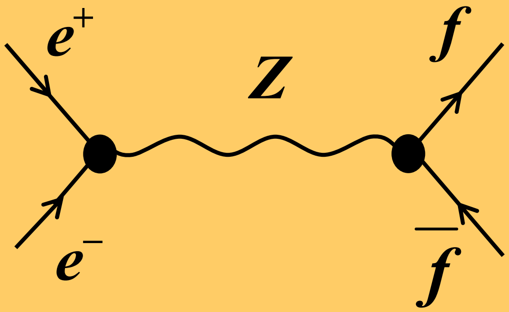
- Definition of « pseudo-observables » : Γ_Z, Γ_{had}, Γ_{ff}, σ_f, A_{FB}, A_f…

- Take the less correlated and the independant one for a FIT of the couplings: Γ_Z, σ_{had}, R_e, R_b, $\mathbf{A}_{\mathbf{FB}}^{e,b,c}$

$$\Gamma_f = N_c^f \frac{G_F}{6\sqrt{2}\pi} m_Z^3 \left[\left(g_V^f\right)^2 R_V^f + \left(g_A^f\right)^2 R_A^f \right]$$

Corrections QCD+QED

Observables of the FIT :



- Total decay width of Z : $\Gamma_Z = \sum_f \Gamma_f$
- Hadronic pole cross section : $\sigma_{had} = \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$
- Ratio R_b : $R_b = \frac{\Gamma_b}{\Gamma_{had}}$ $(3R_b+2R_c=1)$
- Ratio R_l : $R_l = \frac{\Gamma_{had}}{\Gamma_l}$
- The forward backward asymmetries: $A_{FB}^f = \frac{n_F(\theta_f < 90^\circ) - n_B(\theta_f > 90^\circ)}{n_F(\theta_f < 90^\circ) + n_B(\theta_f > 90^\circ)}$

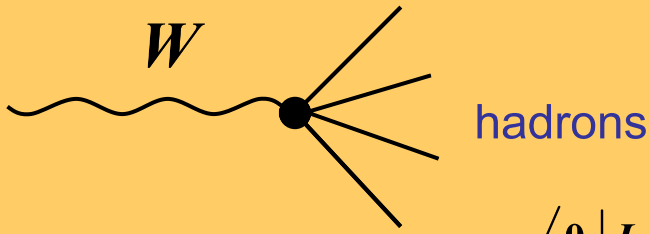
$$A_{FB}^f = 3 \frac{g_V^e g_A^e}{\left[(g_V^e)^2 + (g_A^e)^2\right]} \frac{g_V^f g_A^f}{\left[(g_V^f)^2 + (g_A^f)^2\right]}$$

for f=e,b,c

$1/2\ A_e$ $\quad$ $1/2\ A_f$

W leptonic Branching Ratios

- Interface charged/neutral currents: ⇨ δ



$$\Gamma(W^\pm \to h^\pm) \propto \langle 0 | J^\mu | h \rangle \langle h | J^{\nu\dagger} | 0 \rangle$$

$$\langle 0 | J^\mu | h \rangle = \left\langle 0 \left| \sum_{ij} (1+\delta) V_L^{ij} \overline{u_L^i} \gamma_\mu d_L^j + \varepsilon V_R^{ij} \overline{u_R^i} \gamma_\mu d_R^j \right| h \right\rangle$$

$$\Gamma(W^\pm \to h^\pm) = (1+2\delta) \cdot \Gamma_{SM}(W^\pm \to h^\pm)$$

- Theoretical calculation: pertubative QCD

$$\Gamma_{Wtot} = \frac{G_F M_W^3}{6\sqrt{2}\pi} \left[3 + 6 \cdot (1+2\delta) \cdot \left[1 + \frac{\alpha_S(M_W)}{\pi} + 1.409 \left(\frac{\alpha_s(M_W)}{\pi} \right)^2 - 12.77 \left(\frac{\alpha_s(M_W)}{\pi} \right)^3 \right] \right]$$

- Take the leptonic branching ratio:

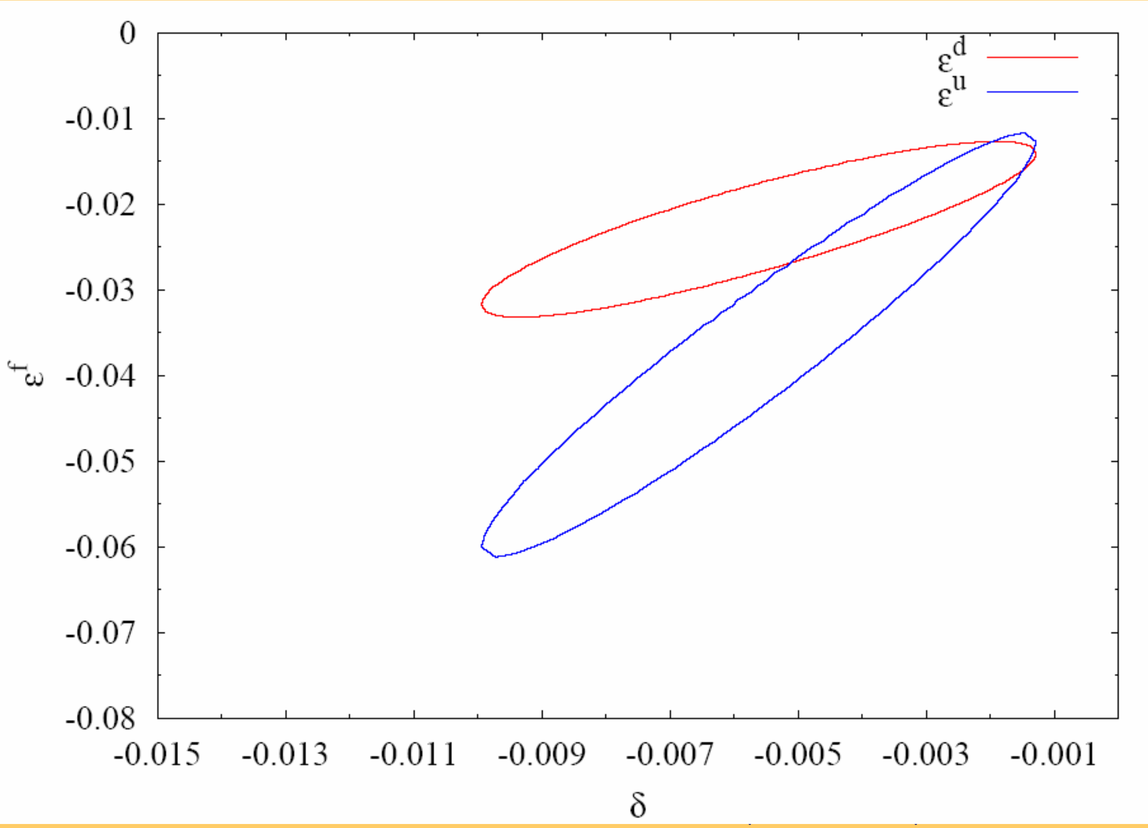
$$\mathrm{Br}(\mathrm{W} \to l\nu) = \frac{\Gamma_{W \to l\nu}}{\Gamma_{Wtot}}$$

⇨ very accurate measurement from LEP : $\mathrm{Br}(\mathrm{W} \to l\nu) = 0.1084(9)$.
Very sensitive to δ.

Results

- Fit to first order in ε (NLO) ⇨ ε^{ν} not present in the fit
- $\alpha_S(M_z)$=0.1190 fixed, impossible to determine simultaneously with the EW parameters.
- δ=-0.0054(44), $\tilde{s}^2$ = 0.2308(4), ε^e= -0.0024(5) ,

  ε^u= -0.0223(104) , ε^d= -0.0355(257) , χ^2/dof=3.09/3.



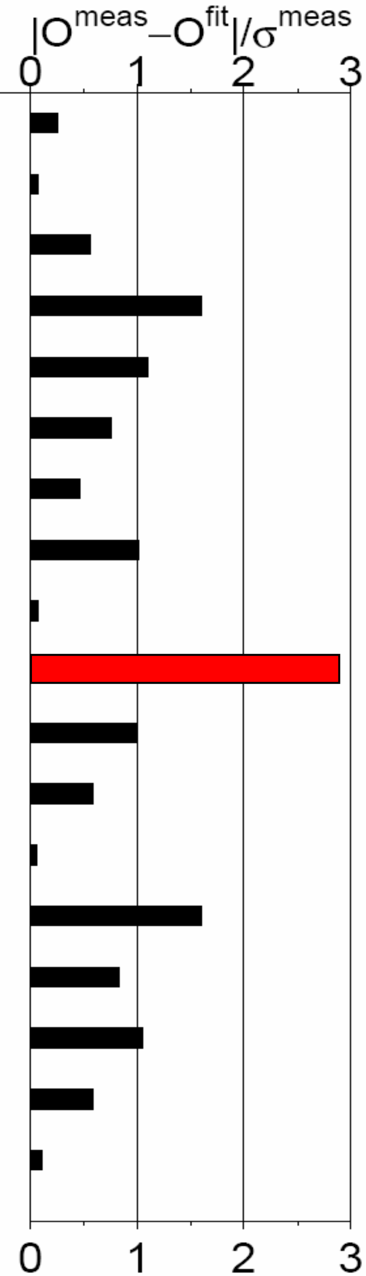
δ and ε^e very small ⇨ left-handed couplings not very affected at NLO.

Results in agreement with the order of magnitude

Uncertainties from experiments only !

Results FIT SM (LEP'06)

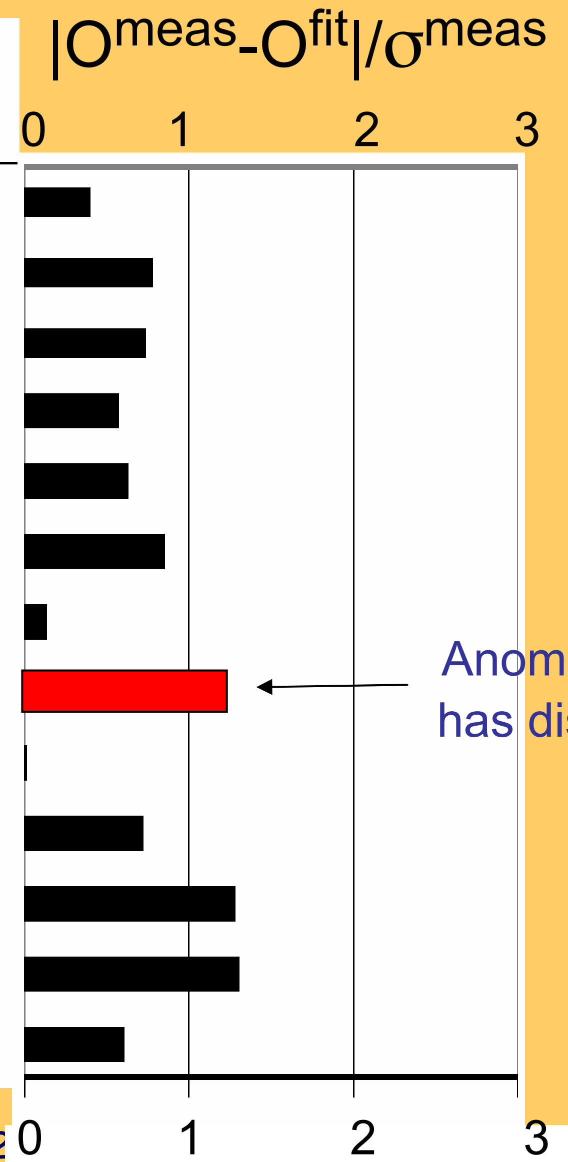
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



← Anomaly A^b_{FB} !

From the NLO fit

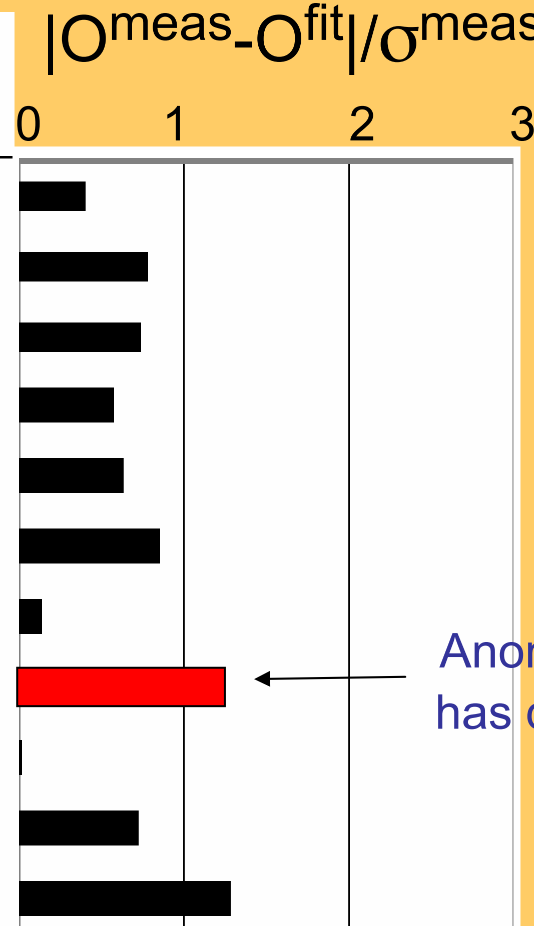
	Measurement	Fit
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	41.569
R_l	20.767 ± 0.025	20.785
$A^{0,l}_{\rm fb}$	0.01714 ± 0.00095	0.01653
$A_l(P_\tau)$	0.1465 ± 0.0032	0.01486
R_b	0.21629 ± 0.00066	0.21685
R_c	0.1721 ± 0.0030	0.1725
$A^{0,b}_{\rm fb}$	0.0992 ± 0.0016	0.1011
$A^{0,c}_{\rm fb}$	0.0707 ± 0.0035	0.0707
A_b	0.923 ± 0.020	0.909
A_c	0.670 ± 0.027	0.635
A_l(SLD)	0.1513 ± 0.0021	0.01486
$Br(W \to l)$	0.1084 ± 0.0009	0.1089



Anomaly A^b_{FB} has disappeared !

From the NLO fit

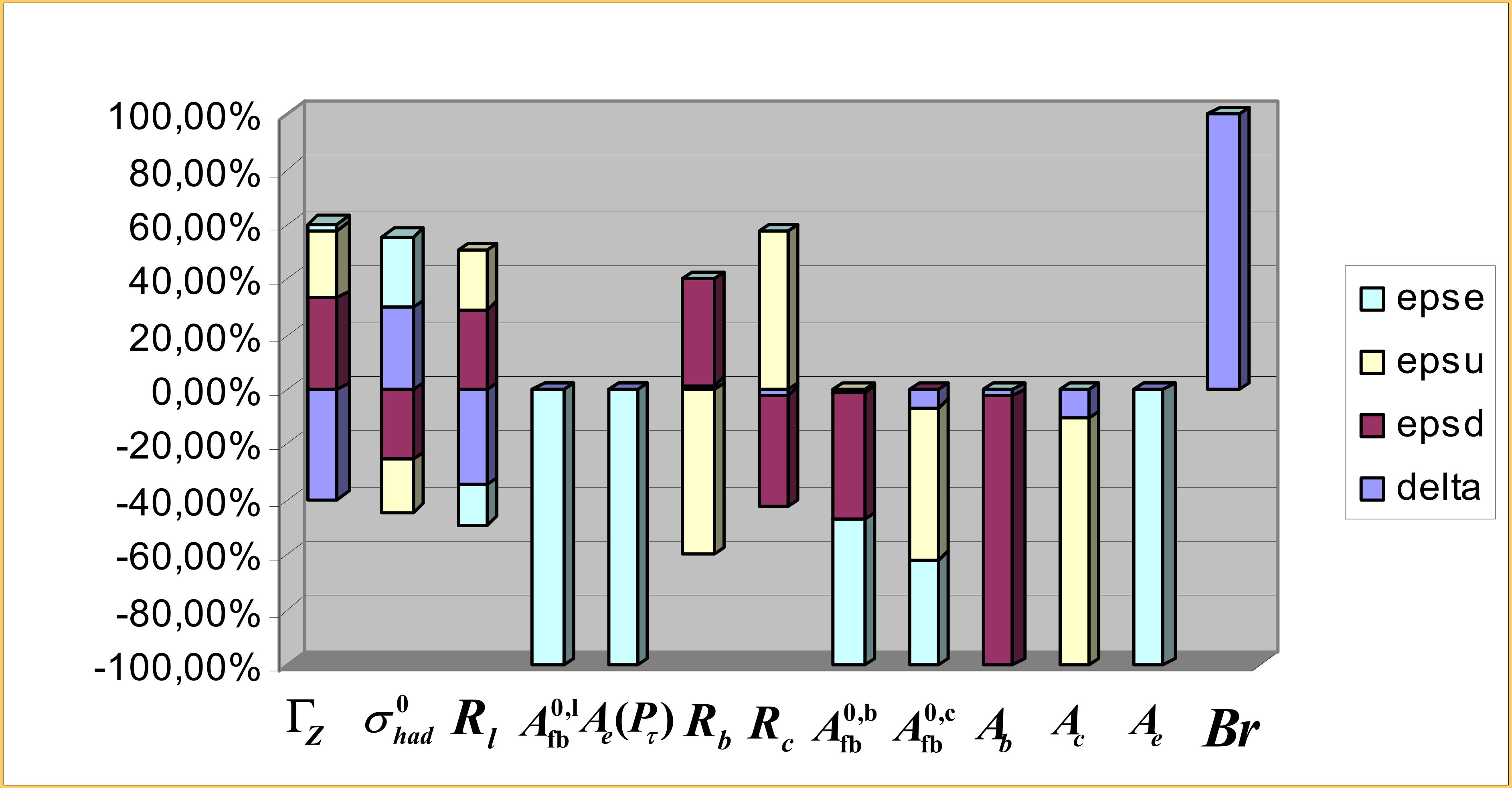
	Measurement	Fit
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943
σ^0_{had} [nb]	41.540 ± 0.037	41.569
R_l	20.767 ± 0.025	20.785
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01653
$A_l(P_\tau)$	0.1465 ± 0.0032	0.01486
R_b	0.21629 ± 0.00066	0.21685
R_c	0.1721 ± 0.0030	0.1725
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1011
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0707
A_b	0.923 ± 0.020	0.909
A_c	0.670 ± 0.027	0.635



Anomaly A^b_{FB} has disappeared !

- Remarquable agreement at NLO (less than 1 σ) , the anomaly A_{FB} for b quarks disappears without breaking the universality.
- Parameters susceptible to be modified at NNLO (only loop corrections + counter terms meaningful within the LEET) but hardly imaginable that the nice agreement with data will be spoiled.

Contributions of the different parameters to observables



4.3 Low energy Experiments

- Using the values of the parameters determined in the FIT
  ⇨ 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).

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

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

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

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

Kinematic factor

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

$$Q_W^e = 4 g_A^e g_V^e$$

- Results :

Observable	Measurement	NLO prediction
$Q_W\,(^{133}Cs)$	-72.62 ± 0.46	-70.73 ± 4.44
$Q_W\,(^{205}Tl)$	-116.40 ± 3.64	-111.95 ± 7.47
Q_W^p	Qweak ?	0.060 ± 0.017
Q_W^e	0.041± 0.005	0.074 ± 0.02

Observable	Measurement	NLO prediction
$Q_W(^{133}Cs)$	-72.62 ± 0.46	-70.73 ± 4.44
$Q_W(^{205}Tl)$	-116.40 ± 3.64	-111.95 ± 7.47
Q_W^p	Qweak ?	0.060 ± 0.017
Q_W^e	0.041± 0.005	0.074 ± 0.02

5 σ !

- Good agreements except for weak charge of electron

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

Accidental cancelation at NLO !

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

- We have to go to NNLO !

4.4 Conclusion

- Experimental tests to the Z pole successful !
- B quark asymmetry A_{FB} anomaly solved.
- Agreement with the low-energy experiments.

5. Conclusions and prospects

5.1 Conclusions

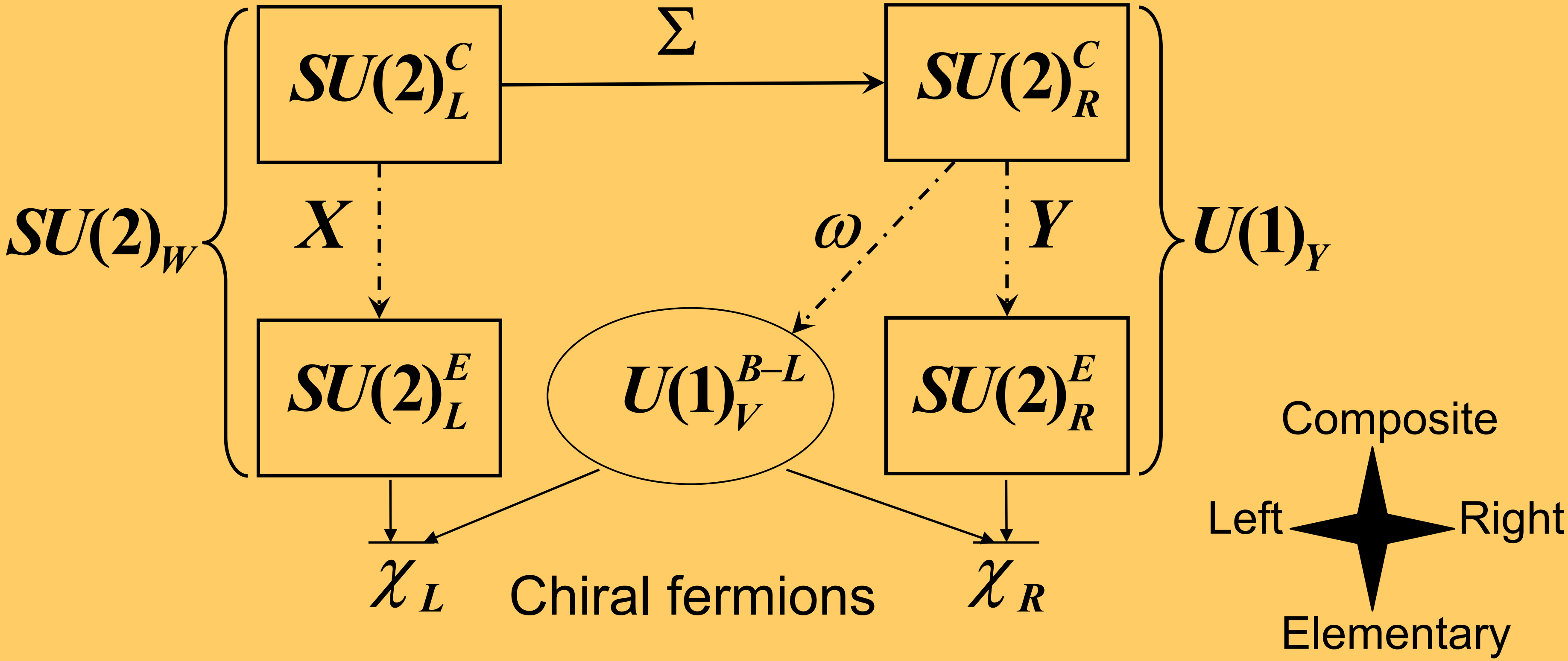
- Minimal low-energy effective theory ⇒ tool to look for physics beyond the Standard Model.
- Prediction of NLO non standard couplings of fermions to W and Z bosons.
- The most dramatic effect: right-handed quark coupling to W ⇒ ε.
- Quasi non-existent tests of the V-A couplings of quarks because of the confinement ⇒ use of precise hadronic physics, ChPT, short distances.
- $K^{L}_{\mu 3}$ decay : ideal decay ⇒ experimental puzzle: the 5 discrepancy found by NA48 not confirmed. Measurement of RHCs
- Precision tests to the Z pole successful !

5.2 Prospects

- NLO : heavy quark sector.
- NNLO, loop effects : Flavour Changing Neutral Currents, CP violation, Dipolaire Electric Moments

⇒ V_R matrix completely unknown to constrain !

Additional slides



- GB Σ : link $L \longleftrightarrow R$
- Spurions X, Y, ω : link $C \longleftrightarrow E$
- Covariant constraints reducing the symmetry and the physical dof to

$$SU(2) \otimes U(1)_Y \Leftrightarrow \boxed{D_\mu X = D_\mu Y = D_\mu \omega = 0}$$

- $X \sim \xi \quad Y \sim \eta \quad \omega \sim \varsigma$ small expansion parameters :

$$\xi . \eta = \frac{m_{top}}{\Lambda_W} = O(p), \;\; \varsigma \ll \xi, \eta ... LNV$$

3.2 Theoretical knowledge: the Callan-Treiman relation

- Callan-Treiman Theorem: SU(2) x SU(2) theorem

$$C = \overline{f_0}(\Delta_{K\pi}) = \frac{F_K}{F_\pi f_+^{K^0}(0)} + \Delta_{CT}$$

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

- Corrections of order m_u, m_d
  - → No chiral logarithms : $\Delta_{CT} \sim \mathcal{O}\left(m_{u,d} / 4\pi F_\pi\right)$
  - → Isospin limit $m_d = m_u$: $\Delta_{CT}^{NLO} \sim -3.5.10^{-3}$ **[Gasser & Leutwyler]**
  - → K^0 decay : no small denominators due to π^0 - η mixing $(\mathcal{O}((m_d - m_u)/m_s))$.
  - → K^+ decay case : enhancement by π^0 - η mixing in the final state

    ⇒ $\Delta_{CT}^{K^+} \sim few\ 10^{-2}$ (K^0 ideal decay)

- Estimations of the higher order terms: corrections in $\mathcal{O}(m_{u,d})$ and $\mathcal{O}(m_s)$

  ⇒ $\Delta_{CT} = (-3.5 \pm 8).10^{-3}$

3.3 Experimental measurements

- Data available from KTeV, NA48 and KLOE.

- **In fix target experiments** (KTeV, NA48), it is impossible to measure directly the t-distribution (Initial energy of K_L unknown) : for each event, 2 possible values of t.

  ⇨ Trick: → For NA48, choice of the most probable t value and bias accounted in the detector acceptance.

  → For KTeV: use of tranverse t.

- For KLOE: K_L produced at rest, the t-distribution is known but difficulty to separate the muons from the pions at low energy: use the neutrino distribution.

- Necessity to parametrize the 2 form factors $\bar{f}_+$ and $\bar{f}_0$ to fit the measured distributions.

- Usually, use of linear parameterization or pole parameterization :

$$f_{lin}(t,\lambda) = 1 + \lambda \frac{t}{m_\pi^2} \qquad f_{pol}(t, m_s) = \frac{m_s^2}{m_s^2 - t}$$