e^+e^- PRECISION PHYSICS: FROM LEP TO SUPER-B

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- LEP, EW symmetry breaking, higher dimensional operators and the scale of NP
- B-factories, flavour symmetry breaking, higher dimensional operators and the scale of NP
- The super-B high-energy frontier

Thanks to M. Pierini

PART I: LEP

- Electroweak symmetry breaking by the Higgs mechanism: three fundamental parameters (g, g', v) determine all masses and couplings in EW sector (M_W, M_Z, G_F, g_V^i, g_A^i,...)
- Tree-level relations (ex. ρ=1) between masses and couplings receive finite and calculable loop corrections in the SM

PART I: LEP

- If there is NP at the scale Λ, it will generate new operators of dimension D with coefficients proportional to $\Lambda^{(4-D)}$:

$$\mathcal{L}(M_W) = \Lambda^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{1}{\Lambda}\mathcal{L}^5 + \frac{1}{\Lambda^2}\mathcal{L}^6 + \dots$$

- Operators with D>4 contribute to EW processes and modify the relations and predictions of the SM

Dimension 6 operators	Effects on precision observables		
$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	$\delta e_3 = 2/\tan\theta_{\rm W}$		
$\mathcal{O}_H = \lvert H^\dagger D_\mu H \rvert^2$	$\delta e_1 = -1$		
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	$\delta G_{\rm VB} = 2$		
$\mathcal{O}'_{HL} = i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	$\delta g_{Ve} = \delta g_{Ae} = -1$	$\delta g_{V\nu} = \delta g_{A\nu} = +1,$	$\delta G_{\rm VB} = 4$
$\mathcal{O}'_{HQ} = i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	$\delta g_{Vd} = \delta g_{Ad} = -1$	$\delta g_{Vu} = \delta g_{Au} = +1$	
$\mathcal{O}_{HL} = i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	$\delta g_{Ve} = \delta g_{Ae} = -1$	$\delta g_{V\nu} = \delta g_{A\nu} = -1$	
$\mathcal{O}_{HQ} = i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	$\delta g_{Vd} = \delta g_{Ad} = -1$	$\delta g_{Vu} = \delta g_{Au} = -1$	
$\mathcal{O}_{HE} = i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	$\delta g_{Ve} = -\delta g_{Ae} = -1$		
$\mathcal{O}_{HU} = i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	$\delta g_{Vu} = -\delta g_{Au} = -1$		
$\mathcal{O}_{HD} = i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	$\delta g_{Vd} = -\delta g_{Ad} = -1$		

Barbieri & Strumia, PLB 99

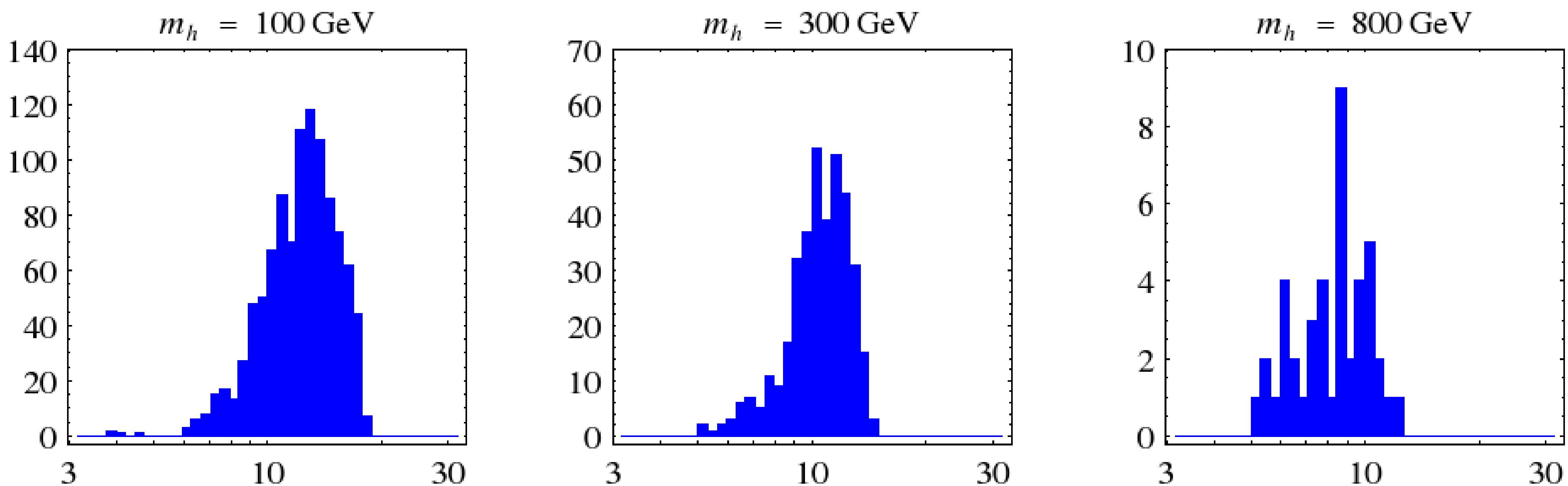


Figure 2: *Distribution of the limits on* $\Lambda/$ TeV *at* 95% C.L. *for the set of 1024 "theories" defined in the text.*

PART II: B-FACTORIES

- Flavour symmetry breaking by Yukawa couplings: four fundamental parameters (λ, A, ρ, η) determine all FCNC and CP violating processes
- FCNC and CPV are absent at the tree level and receive finite and calculable loop corrections in the SM (GIM mechanism)
- Operators with D>4 contribute to EW processes and modify the relations and predictions of the SM

PART II: B-FACTORIES

- Strategy for $\Delta F=2$ processes:

1. Determine allowed ranges for NP contributions from generalized UTA
2. Determine allowed ranges for coefficients of higher-dimensional operators
3. Compute lower bound on NP scale

STEP 1.

- Consider ratios of (SM+NP)/SM amplitudes

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q|H_{\rm eff}^{\rm full}|\bar{B}_q\rangle}{\langle B_q|H_{\rm eff}^{\rm SM}|\bar{B}_q\rangle} = \frac{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}} + A_q^{\rm NP} e^{2i(\phi_q^{\rm SM}+\phi_q^{\rm NP})}}{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}}}$$

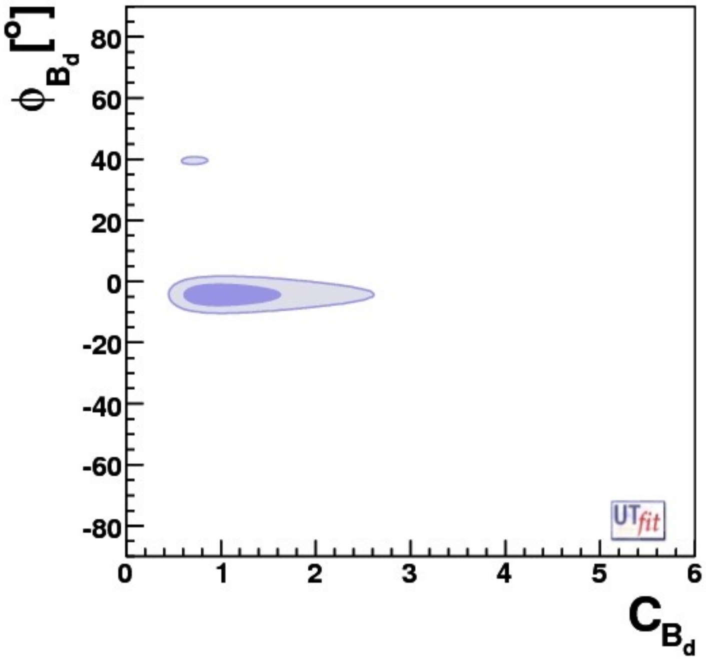
$$C_{\epsilon_K} = \frac{{\rm Im}[\langle K^0|H_{\rm eff}^{\rm full}|\bar{K}^0\rangle]}{{\rm Im}[\langle K^0|H_{\rm eff}^{\rm SM}|\bar{K}^0\rangle]}, \qquad C_{\Delta m_K} = \frac{{\rm Re}[\langle K^0|H_{\rm eff}^{\rm full}|\bar{K}^0\rangle]}{{\rm Re}[\langle K^0|H_{\rm eff}^{\rm SM}|\bar{K}^0\rangle]}$$

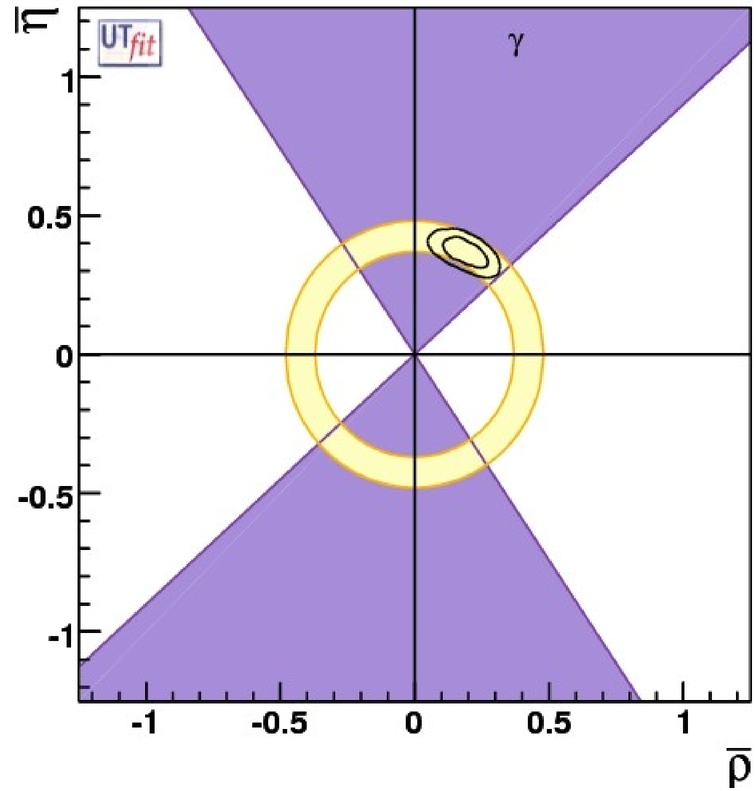
- Determine C's and ϕ's using generalized UT analysis

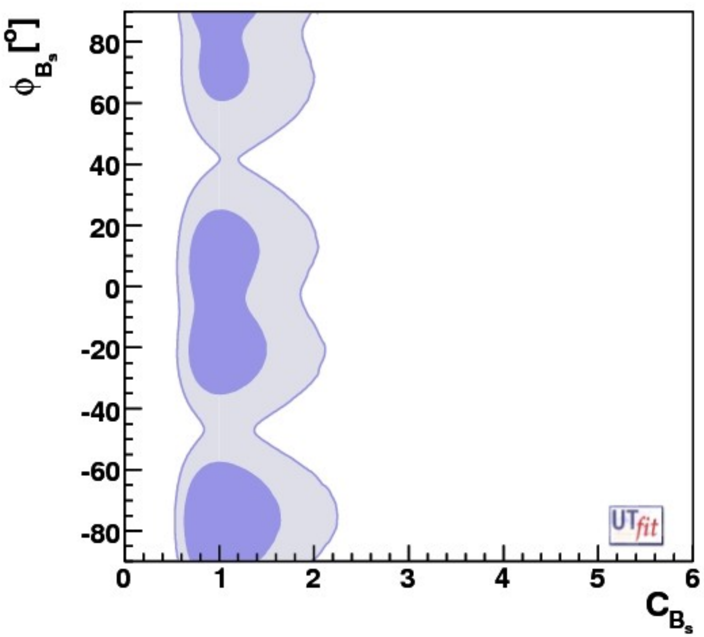
NP parameters & exp constraints

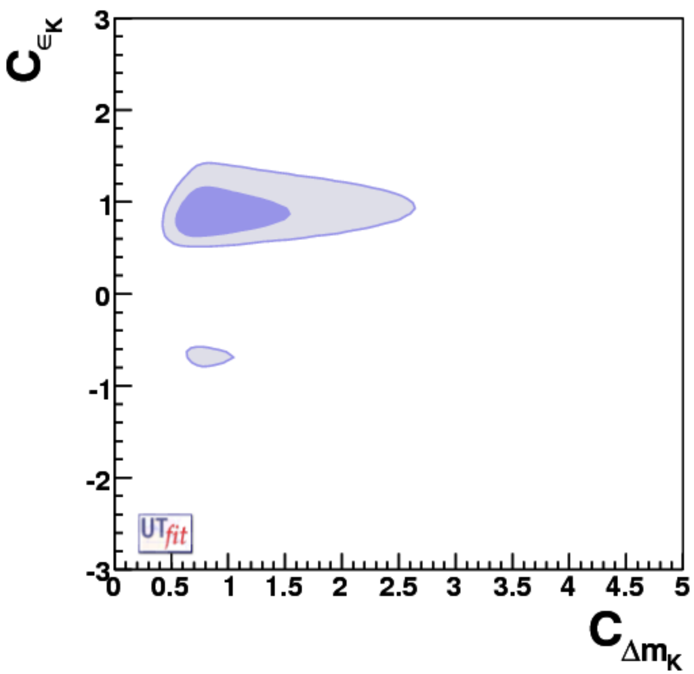
- Angle measurements determine ρ, η and ϕ_d up to an ambiguity of 180°
- Δm_d, Δm_s, ε & Δm_K fix C_{Bd}, C_{Bs}, C_ε and $C_{\Delta MK}$
- $\Delta\Gamma_s/\Gamma_s$ and $B_s \to J/\psi\phi$ constrain ϕ_s
- A_{SL} and A_{CH} suppress the "wrong" solution in the $\rho - \eta$ plane and constrain ϕ_s
- $\Delta\Gamma_d/\Gamma_d$ improves the constraint on ϕ_d

- Using all constraints:









SUMMARY OF CONSTRAINTS

Parameter	Output	Parameter	Output
C_{B_d}	1.04 ± 0.34	$\phi_{B_d}[^\circ]$	-4.4 ± 2.1
C_{B_s}	1.04 ± 0.29	C_{ϵ_K}	0.87 ± 0.14
$\phi_{B_s}[^\circ]$	$-77 \pm 16 \cup -20 \pm 11 \cup 9 \pm 10$		
$\overline{\rho}$	0.169 ± 0.051	$\overline{\eta}$	0.391 ± 0.035
$\alpha[^\circ]$	88 ± 7	$\beta[^\circ]$	25.1 ± 1.9
$\gamma[^\circ]$	67 ± 7	$\mathrm{Im}\lambda_t[10^{-5}]$	15.6 ± 1.3

THE SCALE OF NP

- The constraints we obtained can be used to put lower bounds on the scale of NP models with a given flavour structure:

$$\langle \bar{B}_q | \mathcal{H}_{\rm eff} | B_q \rangle \sim C_i(\Lambda) = K_i F_i \frac{L}{\Lambda^2}$$

- K_i numeric coefficient of O(1), F_i flavour structure, L loop coefficient, Λ NP scale

- Determine coefficients of dimension-6 operators:

$$\mathcal{H}_{\text{eff}}^{K-\bar{K}} = \sum_{i=1}^{5} C_i\, Q_i^{sd} + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i^{sd}$$

$$\mathcal{H}_{\text{eff}}^{D-\bar{D}} = \sum_{i=1}^{5} C_i\, Q_i^{cu} + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i^{cu}$$

$$\mathcal{H}_{\text{eff}}^{B_q-\bar{B}_q} = \sum_{i=1}^{5} C_i\, Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i^{bq}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \,, \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \,, \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \,, \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \,, \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \,,
\end{aligned}$$

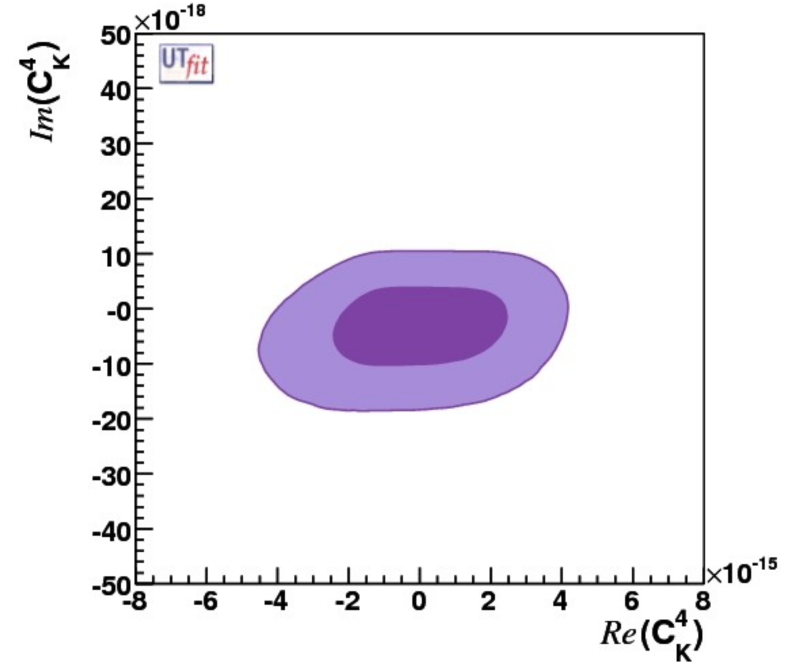
- In the SM, only Q_1 is present. $Q_{2\text{-}5}$ are RG- and chirality-enhanced

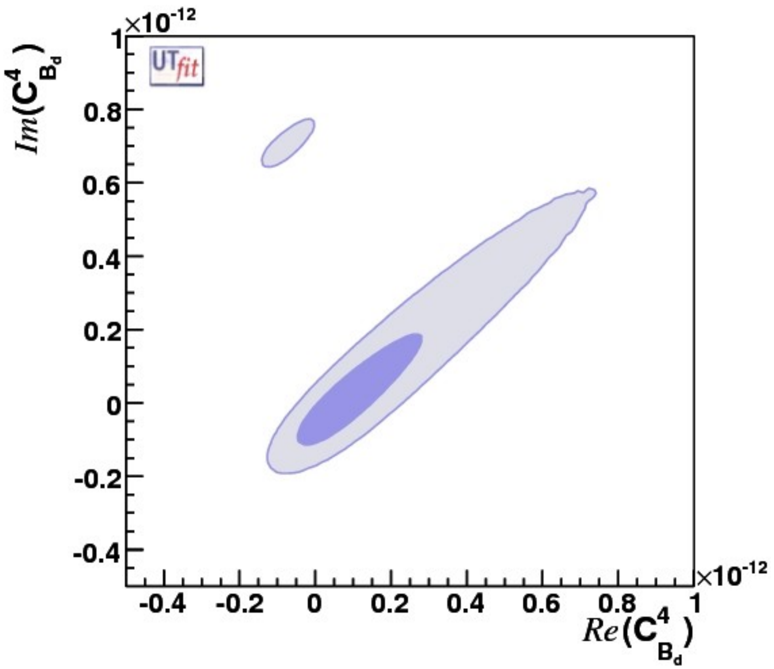
$\mathrm{Im}\, C_K^4 < 10^{-17}\ \mathrm{GeV}^{-2}$

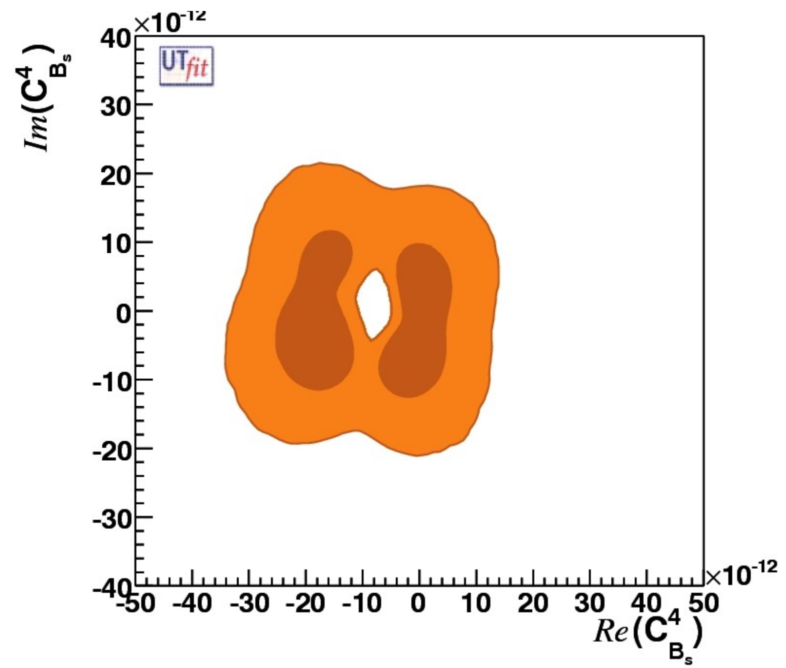
$\mathrm{Re}\, C_K^4 < 4\ 10^{-15}\ \mathrm{GeV}^{-2}$

$|C_{Bd}^4| < 3.0\ 10^{-13}\ \mathrm{GeV}^{-2}$

$|C_{Bs}^4| < 6.8\ 10^{-11}\ \mathrm{GeV}^{-2}$







the NP scale Λ can be defined as

$$\Lambda = \sqrt{\frac{F_i L_i}{C_i(\Lambda)}}$$

tree-level: $L=1$

loop-mediated: $L=\alpha_{NP}^2$

(ex: SM $L=\alpha_W^2$, SUSY $\alpha_{W,s}^2$)

MFV: $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$ and $F_{i\neq 1} = 0$

generic flavour structure	next-to-MFV
- $|F| \sim 1$	- $|F| \sim F_{SM}$
- arbitrary phases	- arbitrary phases

Generic Flavour Violation

UTfit collaboration, in preparation

PRELIMINARY

From ε_K:

$\Lambda > 3.2\ 10^5$ TeV (tree-level), $\Lambda > 10^4$ TeV (weak loop)

From Δm_K:

$\Lambda > 16000$ TeV (tree-level), $\Lambda > 520$ TeV (weak loop)

From B_d mixing:

$\Lambda > 1800$ TeV (tree-level), $\Lambda > 60$ TeV (weak loop)

From B_s mixing:

$\Lambda > 220$ TeV (tree-level), $\Lambda > 7$ TeV (weak loop)

Pre B-factory & TeVatron: O(1) possible in K and B_d, no bound on B_s

Now: only O(10%) possible in all sectors

Next-to-Minimal Flavour Violation

$|F| \sim F_{SM} \sim (V_{tq} V_{tb}^*)^2$, arbitrary phases **PRELIMINARY**

From ε_K:

$\Lambda > 100$ TeV (tree-level), $\Lambda > 3$ TeV (weak loop)

From Δm_K:

$\Lambda > 5$ TeV (tree-level), $\Lambda > 150$ GeV (weak loop)

From B_d mixing:

$\Lambda > 12$ TeV (tree-level), $\Lambda > 390$ GeV (weak loop)

From B_s mixing:

$\Lambda > 7$ TeV (tree-level), $\Lambda > 220$ GeV (weak loop)

Clearly beyond the reach of the LHC for tree-level (warped extra-dim, etc.). Even weakly interacting loop-mediated on the border!!!

Minimal Flavour Violation

A worst-case scenario: NP with no new source of flavour and CP violation. Everything ruled by the CKM matrix.

For small tan β:

$\Lambda > 5.5$ TeV (tree-level)

$\Lambda > 185$ GeV (weak loop)

For large tan β:

$\Lambda > 5.1$ TeV (tree-level)

$\Lambda > 170$ GeV (weak loop)

Still well within the reach of LHC if weak loop...

PART III: SUPER-B

- Uncertainties of the $\Delta F=2$ analysis:
  - Hadronic uncertainties: Lattice QCD matrix elements

    expect errors to be reduced by one order of magnitude
  - Parametric uncertainties: error in the determination of CKM parameters in the presence of NP

    expect errors to be reduced by one order of magnitude
  - Experimental uncertainties: determination of UT angles α and γ, semileptonic asymmetries for B_d and B_s, CP violation and width differences in B_s

    expect to gather all missing experimental info at LHC and Super-B

PART III: SUPER-B

Based on the CDR results, expect to increase the NP scale by a factor 3-5:

- Generic flavour violation: $\Lambda>10^6$ TeV (tree), $\Lambda>3\ 10^4$ TeV (loop)
- Next-to-minimal flavour violation: $\Lambda>300$ TeV (tree), $\Lambda>10$ TeV (loop)
- Minimal flavour violation: $\Lambda>17$ TeV (tree), $\Lambda>570$ GeV (loop)

CONCLUSIONS - I

- LEP studies of EWSB put constraints on the NP scale: $\Lambda > 10$ TeV (tree, generic), $\Lambda > 300$ GeV (EW loop, generic)
- B-factories & TeVatron studies of FCNC & CPV: from O(1) to O(10%) NP effects in all sectors (except ϕ_s). Implications for NP: $\Lambda > 3\ 10^5$ TeV (tree, generic), $\Lambda > 10^4$ TeV (EW loop, generic), $\Lambda > 100$ TeV (tree, NMFV), $\Lambda > 3$ TeV (EW loop, NMFV), $\Lambda > 5$ TeV (tree, MFV), $\Lambda > 180$ GeV (EW loop, MFV)

CONCLUSIONS - II

- For NP to be visible at LHC, it must be weakly interacting, loop mediated, and have better flavour properties than NMFV
- A Super-B factory will allow us to raise the NP scale sensitivity of a factor > 3
- It will detect indirect signals of (almost) any NP visible at the LHC
- It will give the most stringent bounds on strongly interacting and/or non-MFV NP