Flavour Opportunities at the Intensity Frontier

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- Introduction
- Present status of flavour physics
- Future perspectives and goals
- Conclusions

INTRODUCTION

The Standard Model works beautifully up to a few hundred GeV's, but it must be an effective theory valid up to a scale $\Lambda \leq M_{planck}$:

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

EW scale

Has accidental symmetries

Violates accidental symmetries

INTRODUCTION - II

Two accidental symmetries of the SM are crucial for our discussion:

1) Absence of tree-level flavour changing neutral currents, GIM suppression of FCNC @ the loop level

2) No CP violation @ tree level

⇒ Flavour physics extremely sensitive to NP!!

EXPRESS REVIEW OF THE SM

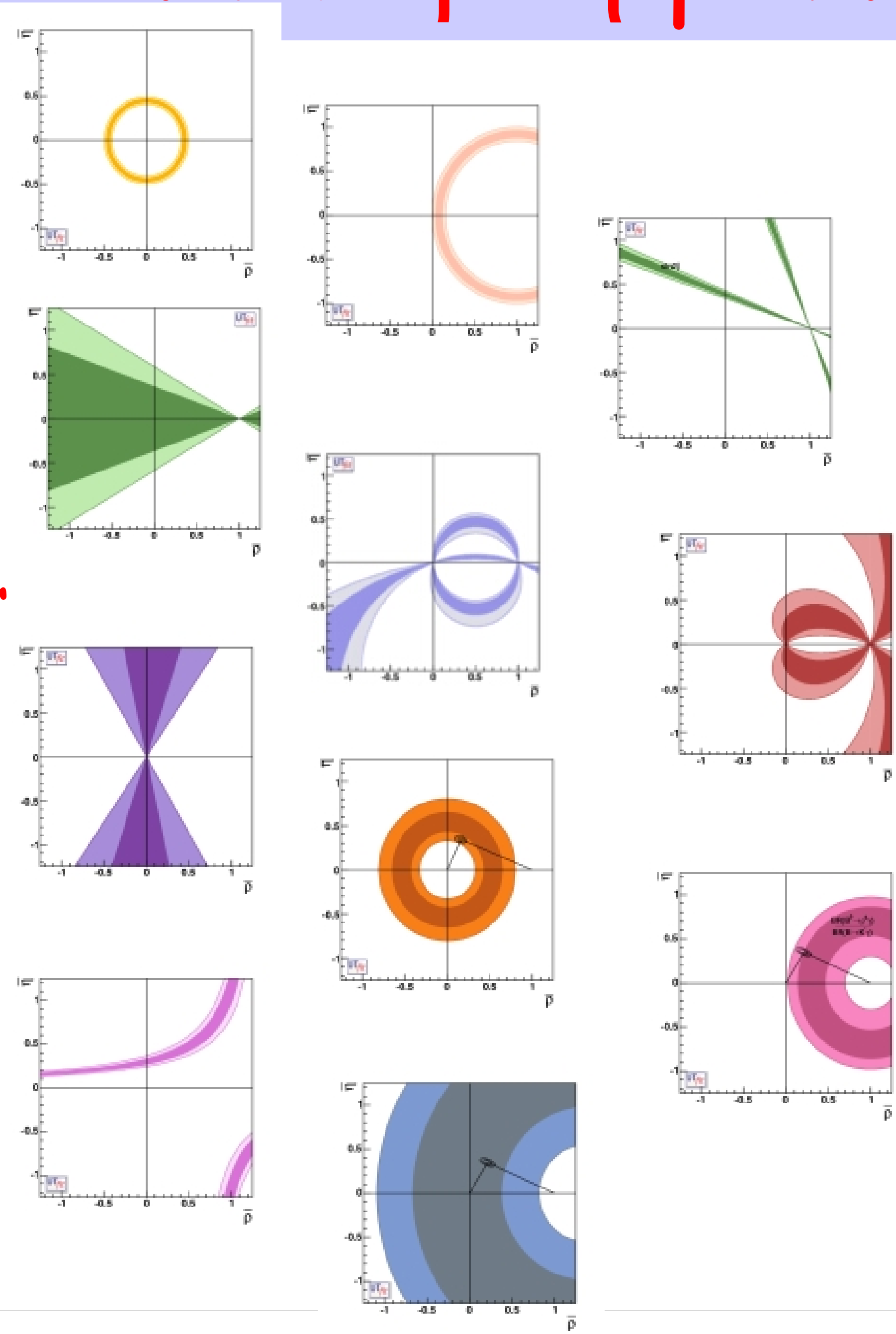
- All flavour violation from charged current coupling: CKM matrix V

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Top quark exchange dominates FCNC loops: third row (V_{tq}) determines FCNC's $\leftrightarrow \bar{\rho}, \bar{\eta}$

Flavour summarized on the ρ–η plane

BR(b→ulν), BR(B→πlν)	CC
Δm_q (B_q-$\bar{B}_q$ mass diff.)	NC
$A_{CP}(b\to c\bar{c}s)$ (J/ψ K, ...)	CC
$A_{CP}(b\to s\bar{s}s,\ d\bar{d}s)$ (φ K, πK, ...)	NC
$A_{CP}(b\to d\bar{d}d,\ u\bar{u}d)$ (ππ, ρρ, ...)	CC/NC
$BR(b\to c\bar{u}d,\ c\bar{u}s)$ (DK, ...)	CC
BR(B→τν)	CC
BR(B→ργ)/BR(B→K*γ)	NC
ε_K	NC
$K^+\to\pi^+\nu\nu$	NC



Present status: UTA & NP in ΔF=2

Consider ratios of (SM+NP)/SM ΔF=2 amplitudes

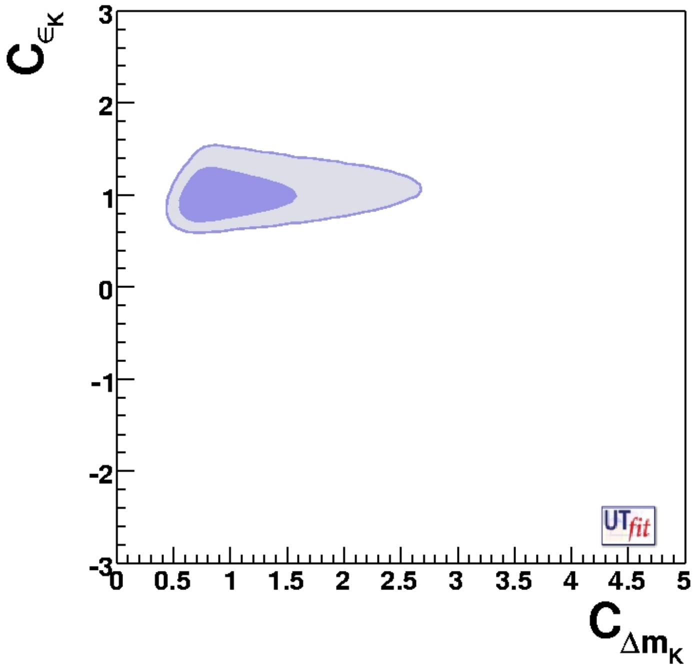
$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \bar{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \bar{B}_q \rangle} = \frac{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}} + A_q^{\rm NP} e^{2i(\phi_q^{\rm SM}+\phi_q^{\rm NP})}}{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}}}$$

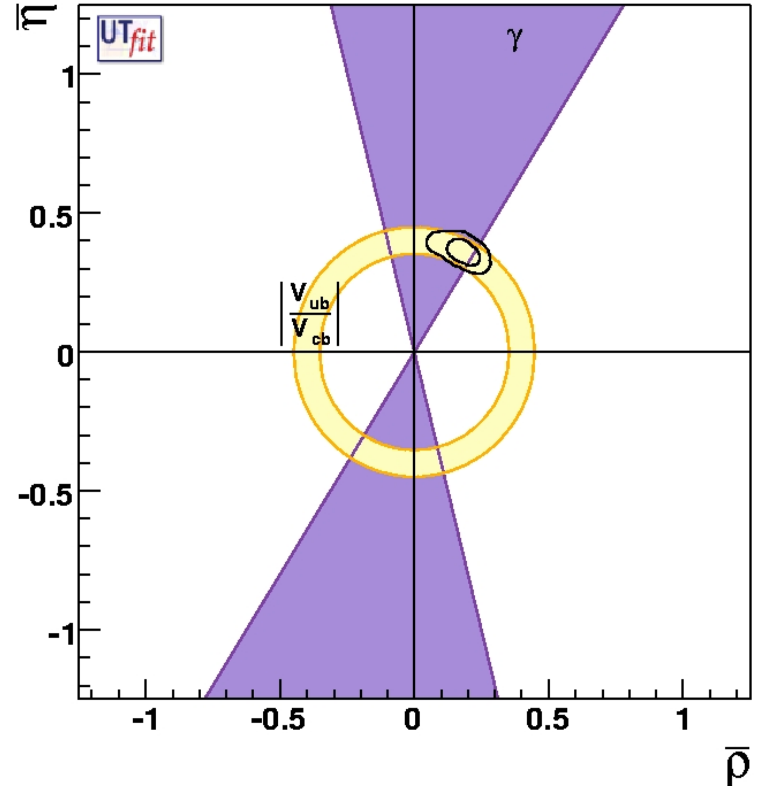
$$C_{\epsilon_K} = \frac{{\rm Im}[\langle K^0 | H_{\rm eff}^{\rm full} | \bar{K}^0 \rangle]}{{\rm Im}[\langle K^0 | H_{\rm eff}^{\rm SM} | \bar{K}^0 \rangle]}, \qquad C_{\Delta m_K} = \frac{{\rm Re}[\langle K^0 | H_{\rm eff}^{\rm full} | \bar{K}^0 \rangle]}{{\rm Re}[\langle K^0 | H_{\rm eff}^{\rm SM}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

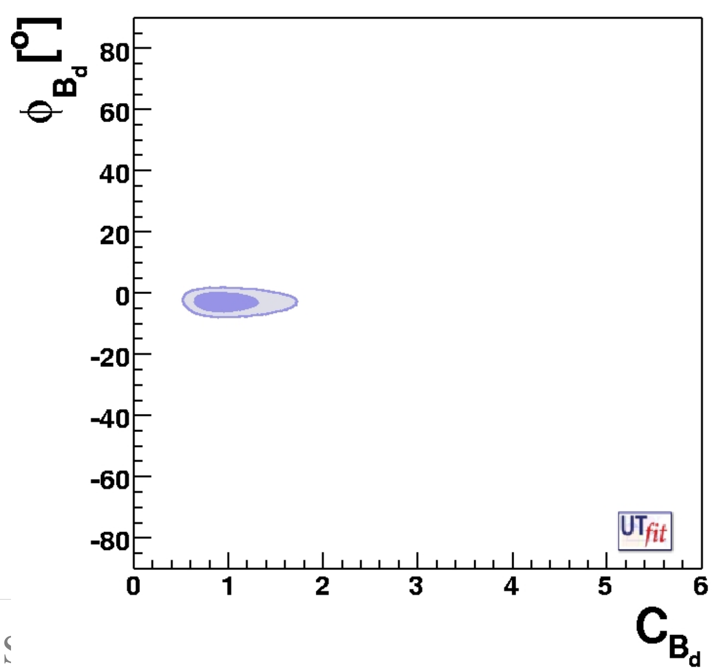
Determine ρ, η, C's and ϕ's using generalized UT analysis

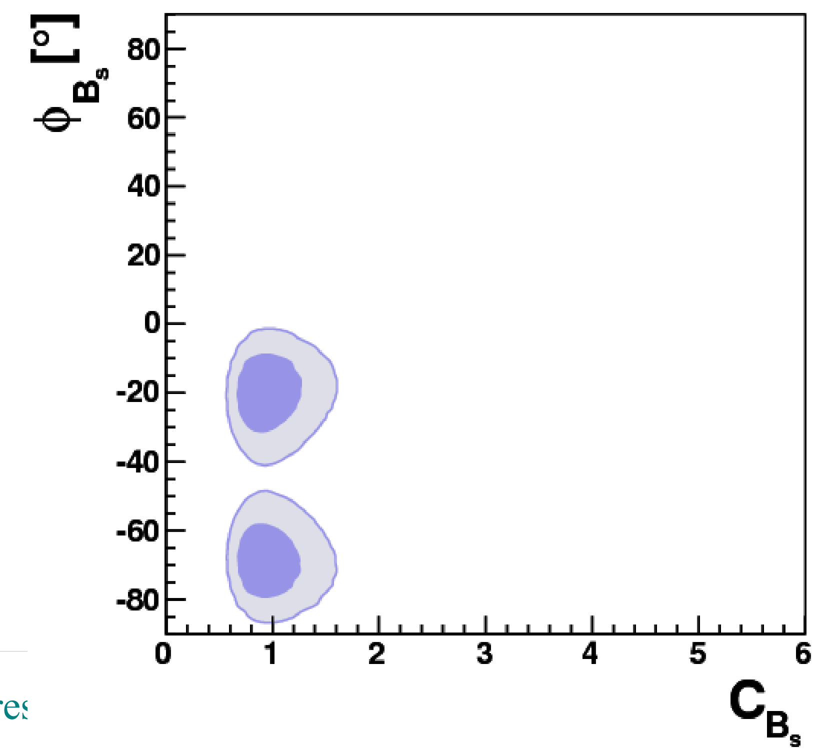
Derive bounds on NP scale and/or couplings

Our present knowledge:





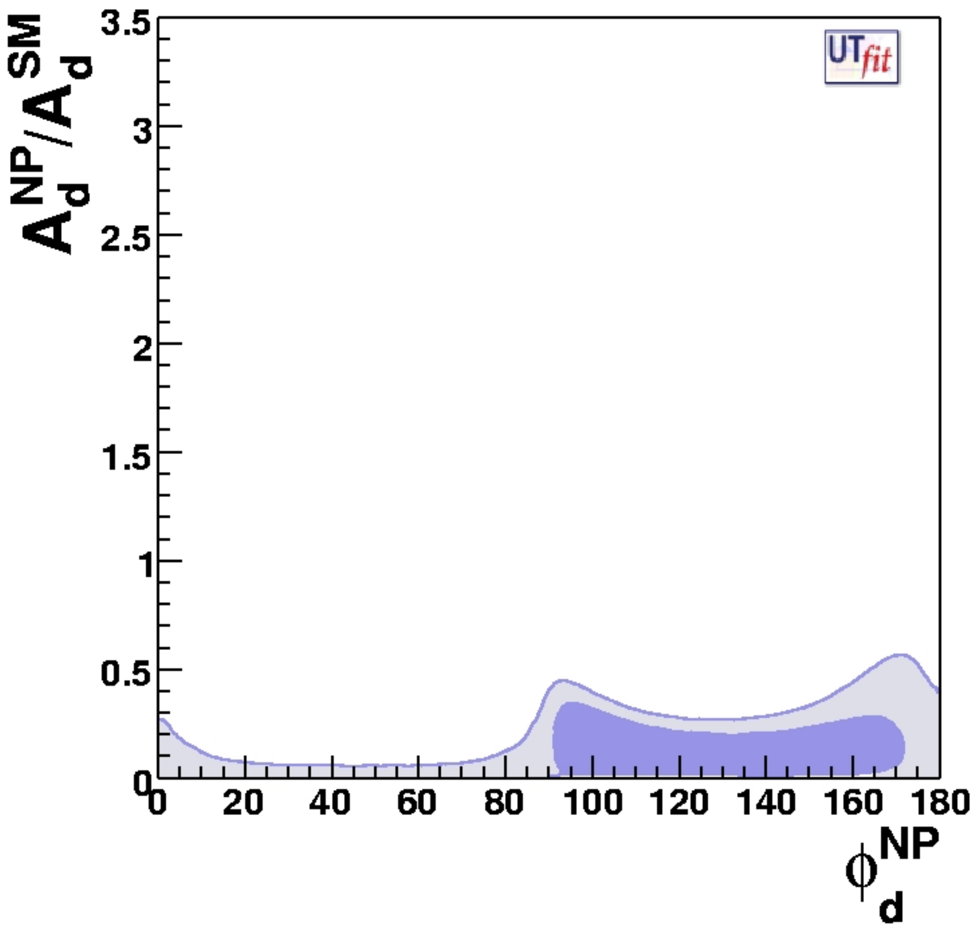


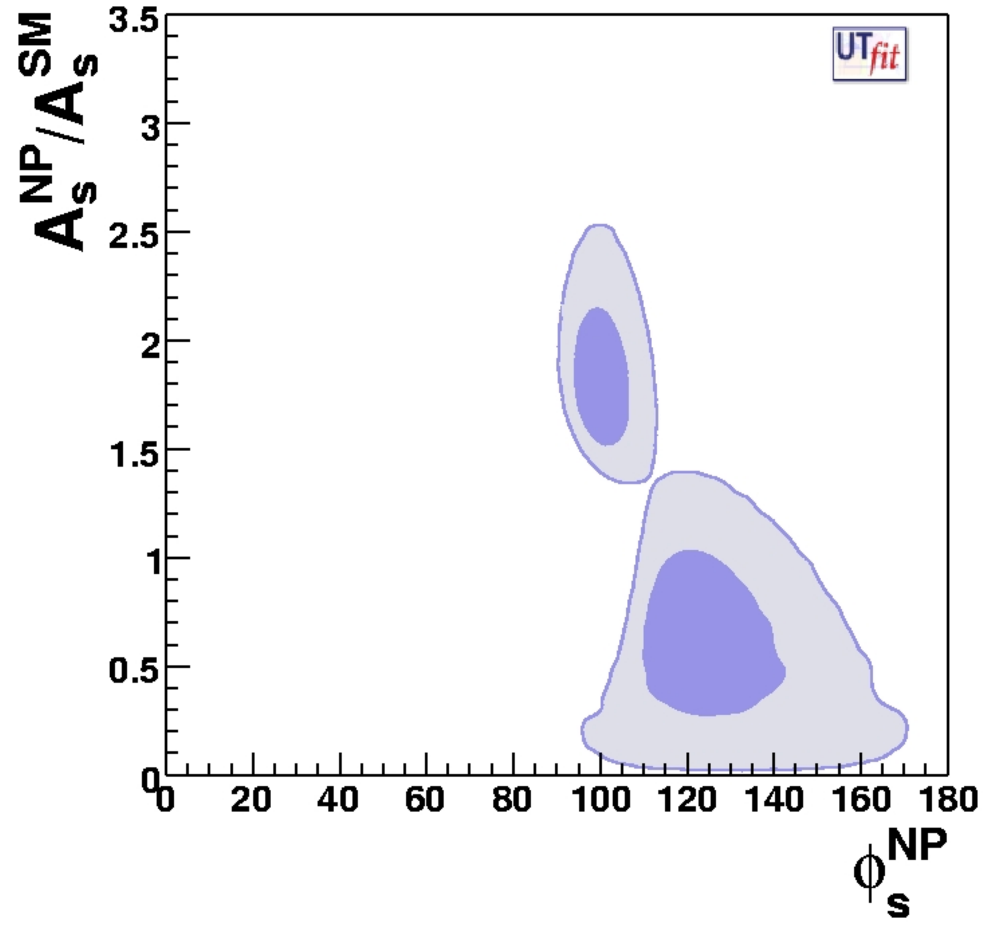


SUMMARY OF CONSTRAINTS

Parameter	Output	Parameter	Output
$C_{\Delta m_K}$	0.96 ± 0.34	C_{ε_K}	0.99 ± 0.16
C_{B_d}	0.96 ± 0.23	ϕ_{B_d}	$(-2.9 \pm 1.9)^\circ$
C_{B_s}	0.94 ± 0.19	ϕ_{B_s}	$(-19 \pm 8)^\circ \cup (-69 \pm 7)^\circ$
$\bar{\eta}$	0.360 ± 0.031	$\bar{\rho}$	0.177 ± 0.044
$\bar{\eta}_{SM}$	0.342 ± 0.014	$\bar{\rho}_{SM}$	0.155 ± 0.022

No deviation seen in K and B_d mixing, ample room for NP in phase of B_s mixing (might become solid evidence)





Ratio of NP/SM contributions is $<$ 40% @ 95% prob. in B_d mixing, and ~60% in B_s mixing (but compatible with zero at 2σ).

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:

$A_{NP}/A_{SM} \sim C/C_{SM}$

$$C_i(\Lambda) = K_i F_i \frac{L}{\Lambda^2}$$

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

BOUNDS ON THE NP SCALE

Scenario	strong/tree	α_s loop	α_W loop
MFV (small $\tan\beta$)	5.5	0.5	0.2
MFV (large $\tan\beta$)	5.1	0.5	0.2
M_H in MFV at large $\tan\beta$	$5\sqrt{(a_0+a_1)(a_0+a_2)}\left(\frac{\tan\beta}{50}\right)$		
NMFV	62	6.2	2
General	24000	2400	800

To be relevant for the hierarchy problem, NP must have a highly nontrivial flavour structure!!

Two broad flavour scenarios

1) Minimal Flavour Violation (i.e. no new source of flavour violation beyond Yukawa couplings) effectively holds at least at the level seen in K and B_d mixing, i.e. < 40%.

2) New sources of Flavour & CPV are at work in transitions between 2nd and 3rd families, but strongly suppressed elsewhere. Nonabelian flavour symmetries? Guts + ν?

Tevatron and LHCb will tell us soon!

What we are aiming at

- Being able to determine the flavour structure of whatever NP seen at the LHC
- Being able to derive info on the full spectrum of NP if LHC only sees part of it
- Being able to cover indirectly the region of NP masses just above the LHC reach, pushing the indirect bound on Λ as high as possible

How do we get there - I

- A few % error on CKM parameters in the generalized UTA;
- Determining NP contributions to $\Delta F=2$ and $\Delta F=1$ transitions in all sectors (K, B_d, B_s, D) at the few percent level;
- Improving Lepton Flavour Violation and Lepton Universality bounds by more than one order of magnitude

How do we get there - II

- CKM parameters in the presence of loop-mediated NP: $V_{cb,ub}^{incl,excl}$, $\gamma(B\to DK)$
- NP contributions to $\Delta F=2$ amplitudes: $\beta(b\to ccs)$, $\beta_s(b\to ccs)$, $D^0\to KK, K\pi, K\pi\pi$, $A_{SL}^{d,s}$, $(\Delta\Gamma/\Gamma)_{d,s}$

How do we get there - III

- NP contributions to $\Delta F=1$ amplitudes:
  - $b \to s$: $\beta(B \to K_S\phi, K_SK_SK_S, \ldots)$, $B_s \to K^{*0}K^{*0}$ (penguins), $B \to K^{(*)}\pi$ (penguins & ewp), $B \to X_s\nu\nu$ (ewp), $B \to X_s\gamma$ (BR&ACP) (photon peng), $B \to X_s ll$ (BR&AFB) (photon & ewp), $\beta(B \to K_s\pi^0\gamma)$ (RH ops), $B_s \to \mu\mu$ (scalar peng)
  - $b \to d$: $\alpha(B \to \pi\pi, \rho\pi, \rho\rho)$ (ewp), $B \to X_d\nu\nu$ (ewp), $B \to X_d\gamma$ (BR&ACP) (photon peng), $B \to X_d ll$ (BR&AFB) (photon & ewp), $S(B \to \rho^0\gamma)$ (RH ops), $B_d \to \mu\mu$ (scalar peng)
  - $s \to d$: $K_L \to \pi^0\nu\nu$, $K^+ \to \pi^+\nu\nu$ (ewp), $K_L \to \pi^0 ll$ (photon & ewp)

How do we get there - IV

- LFV: $\tau\to\mu\gamma$, $\tau\to e\gamma$, $\mu\to e\gamma$ (photon peng), $\tau\to\mu ll$, $\tau\to ell$, $\mu\to eee$, $\mu\leftrightarrow e$ (photon, ewp & boxes), $\tau\to\mu\eta$, $\tau\to e\eta$ (photon, ewp, boxes & Higgs)
- Lepton Universality: $K\to e\nu/K\to\mu\nu$, $B\to\tau\nu/B\to\mu\nu$ (Higgs)
- Charged current scalar interactions: $B\to\tau\nu$ (Higgs)

Experimental...

B physics @$\Upsilon(4S)$

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ ($J/\psi\,K^0$)	0.018	0.005 (†)
$\cos(2\beta)$ ($J/\psi\,K^{*0}$)	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\,\pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
γ ($B\to DK$, $D\to CP$ eigenstates)	$\sim 15^\circ$	2.5°
γ ($B\to DK$, $D\to$ suppressed states)	$\sim 12^\circ$	2.0°
γ ($B\to DK$, $D\to$ multibody states)	$\sim 9^\circ$	1.5°
γ ($B\to DK$, combined)	$\sim 6^\circ$	1–2°
α ($B\to\pi\pi$)	$\sim 16^\circ$	3°
α ($B\to\rho\rho$)	$\sim 7^\circ$	1–2° (∗)
α ($B\to\rho\pi$)	$\sim 12^\circ$	2°
α (combined)	$\sim 6^\circ$	1–2° (∗)
$2\beta+\gamma$ ($D^{(*)\pm}\pi^\mp$, $D^\pm K^0_S\pi^\mp$)	20°	5°
$\lvert V_{cb}\rvert$ (exclusive)	4% (∗)	1.0% (∗)
$\lvert V_{cb}\rvert$ (inclusive)	1% (∗)	0.5% (∗)
$\lvert V_{ub}\rvert$ (exclusive)	8% (∗)	3.0% (∗)
$\lvert V_{ub}\rvert$ (inclusive)	8% (∗)	2.0% (∗)
$BR(B\to\tau\nu)$	20%	4% (†)
$BR(B\to\mu\nu)$	visible	5%
$BR(B\to D\tau\nu)$	10%	2%
$BR(B\to\rho\gamma)$	15%	3% (†)
$BR(B\to\omega\gamma)$	30%	5%
$A_{CP}(B\to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B\to\rho\gamma)$	~ 0.20	0.05
$A_{CP}(b\to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b\to(s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S\pi^0\gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B\to K^*\ell\ell)$	7%	1%
$A^{FB}(B\to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B\to X_s\ell\ell)s_0$	35%	5%
$BR(B\to K\nu\overline{\nu})$	visible	20%
$BR(B\to\pi\nu\bar{\nu})$	–	possible

Charm physics

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0\to K^+K^-$	y_{CP}	2–3×10^{-3}	5×10^{-4}
$D^0\to K^+\pi^-$	y'_D	2–3×10^{-3}	7×10^{-4}
	x'^2_D	1–2×10^{-4}	3×10^{-5}
$D^0\to K^0_S\pi^+\pi^-$	y_D	2–3×10^{-3}	5×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}
Average	y_D	1–2×10^{-3}	3×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}

Mode	Sensitivity
$D^0\to e^+e^-$, $D^0\to\mu^+\mu^-$	1×10^{-8}
$D^0\to\pi^0e^+e^-$, $D^0\to\pi^0\mu^+\mu^-$	2×10^{-8}
$D^0\to\eta e^+e^-$, $D^0\to\eta\mu^+\mu^-$	3×10^{-8}
$D^0\to K^0_S e^+e^-$, $D^0\to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+\to\pi^+e^+e^-$, $D^+\to\pi^+\mu^+\mu^-$	1×10^{-8}
$D^0\to e^\pm\mu^\mp$	1×10^{-8}
$D^+\to\pi^+e^\pm\mu^\mp$	1×10^{-8}
$D^0\to\pi^0e^\pm\mu^\mp$	2×10^{-8}
$D^0\to\eta e^\pm\mu^\mp$	3×10^{-8}
$D^0\to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+\to\pi^-e^+e^+$, $D^+\to K^-e^+e^+$	1×10^{-8}
$D^+\to\pi^-\mu^+\mu^+$, $D^+\to K^-\mu^+\mu^+$	1×10^{-8}
$D^+\to\pi^-e^\pm\mu^\mp$, $D^+\to K^-e^\pm\mu^\mp$	1×10^{-8}

τ physics

Process	Sensitivity
$\mathcal{B}(\tau\to\mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau\to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau\to\mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau\to eee)$	2×10^{-10}
$\mathcal{B}(\tau\to\mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau\to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau\to\ell K^0_S)$	2×10^{-10}

+ τ FC physics (CPV, ...)

μ physics

$\mu\to e\gamma$ @ 10^{-13}

$\mu\to e$ conv. @ 10^{-18}

K physics

$K\to e\nu/K\to\mu\nu$ @ 0.1%

$K\to\pi\nu\nu$ @ 10^{-12}

B_s physics

$B_s\to\mu^+\mu^-$ @ 10^{-9}

$\sin2\beta_s(J/\Psi\phi)$ @ 1°

$S(B_s\to\phi\phi)$ @ 2°

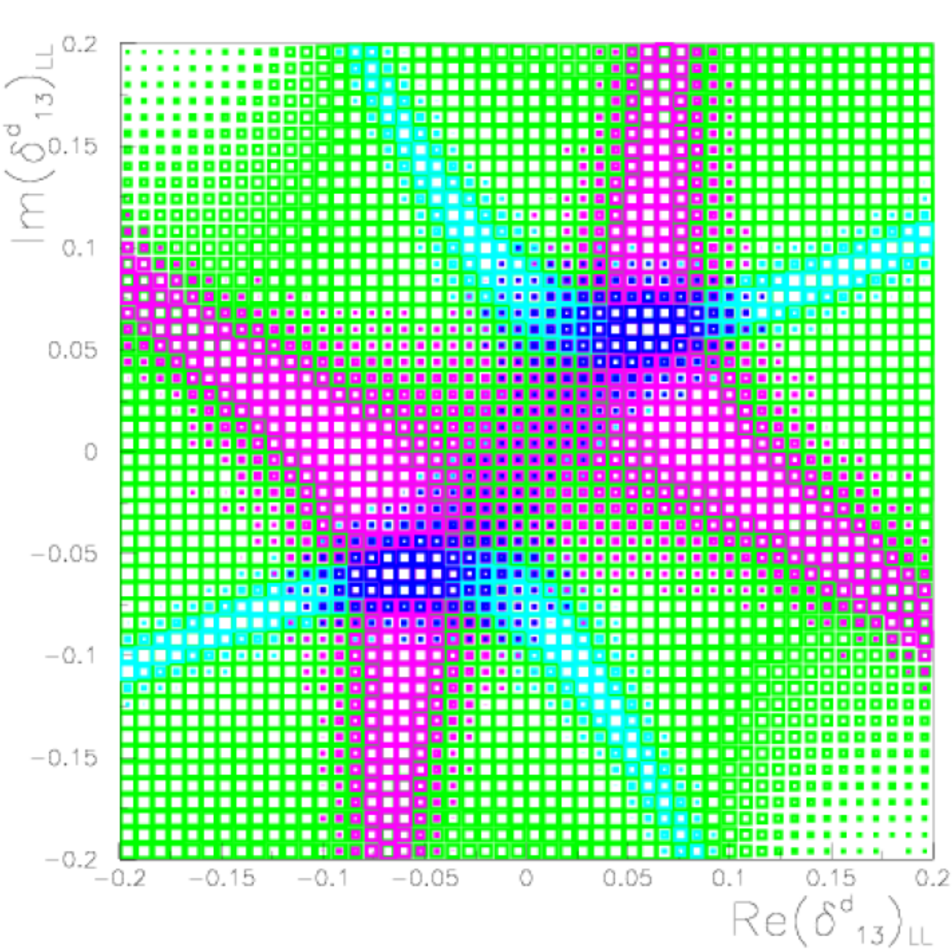
...and theoretical efforts needed!

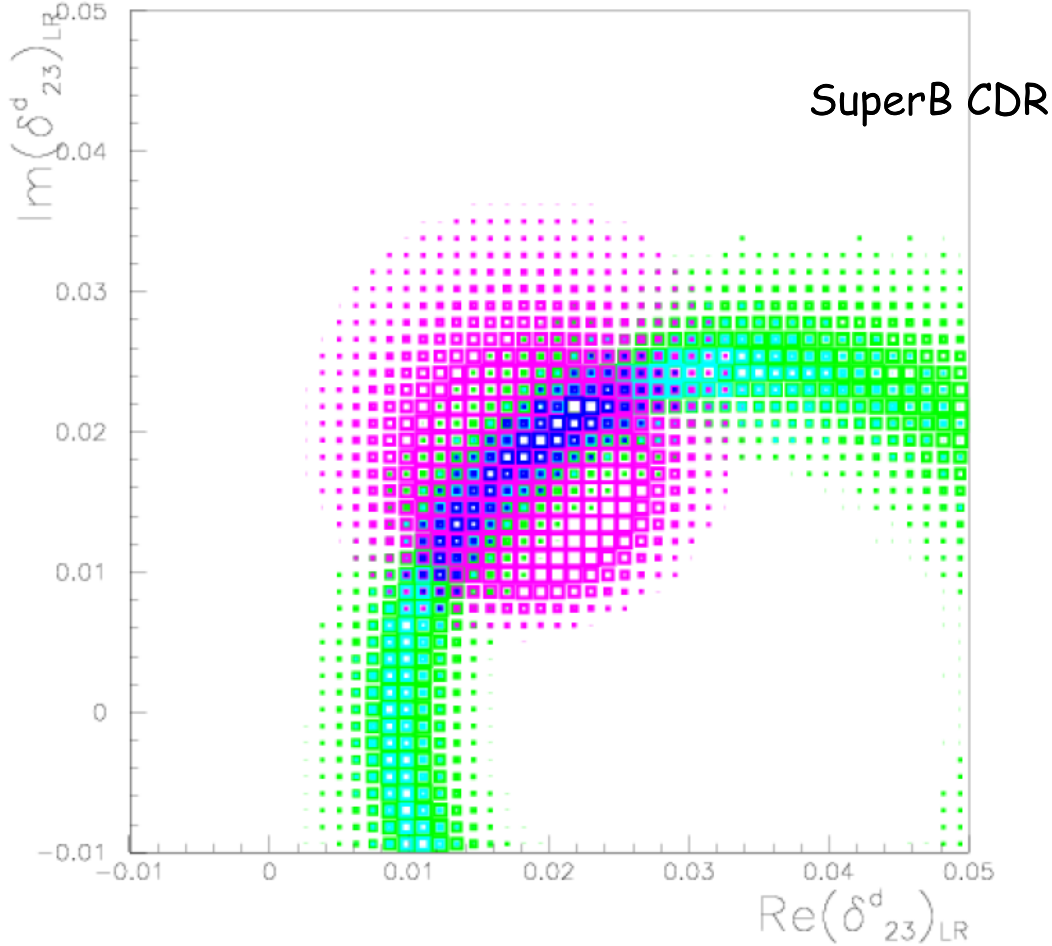
no theory improvements needed	$\beta(J/\psi\ K)$, $\gamma(DK)$, α, lepton FV & UV, CPV in $B \to X\gamma$, D and τ decays, zero of FB asymmetry $B \to X_s l^+ l^-$	SM already known with the required accuracy
improved lattice QCD	meson mixing , $B \to D(*) l\nu$, $B \to \pi(\rho) l\nu$, $B \to K^*\gamma$, $B \to \rho\gamma$, $B \to l\nu$, $B_s \to \mu\mu$	target error: ~1-2% Feasible (see SuperB CDR)
improved OPE+HQE	$B \to X_{u,c} l\nu$	target error: ~2-3% Feasible getting exp. rid of annihilation & shape function (see arXiv:0810.1312)
improved QCDF or SCET or flavour symmetries or data driven methods	S's from TD A_{CP} in b -> s transitions	target error: ~2-3% need either breakthrough in computing power corrections or data-driven approaches (Dalitz analyses particularly favourable)

Reconstructing L_{SUSY}

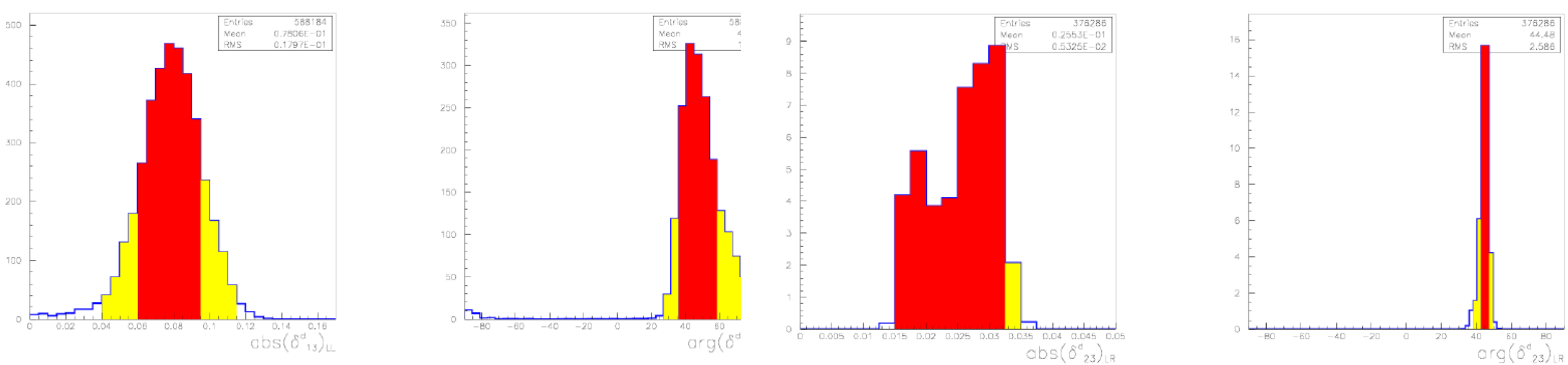
$$m^2_{\tilde{d}} = \begin{pmatrix} (m^2_{11})_{LL} & (\Delta^d_{12})_{LL} & (\Delta^d_{13})_{LL} & (\Delta^d_{11})_{LR} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LR} \\ (\Delta^d_{12})^*_{LL} & (m^2_{22})_{LL} & (\Delta^d_{23})_{LL} & (\Delta^d_{21})_{LR} & (\Delta^d_{22})_{LR} & (\Delta^d_{23})_{LR} \\ (\Delta^d_{13})^*_{LL} & (\Delta^d_{23})^*_{LL} & (m^2_{33})_{LL} & (\Delta^d_{31})_{LR} & (\Delta^d_{32})_{LR} & (\Delta^d_{33})_{LR} \\ (\Delta^d_{11})^*_{LR} & (\Delta^d_{21})^*_{LR} & (\Delta^d_{31})^*_{LR} & (m^2_{11})_{RR} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RR} \\ (\Delta^d_{12})^*_{LR} & (\Delta^d_{22})^*_{LR} & (\Delta^d_{32})^*_{LR} & (\Delta^d_{12})^*_{RR} & (m^2_{22})_{RR} & (\Delta^d_{23})_{RR} \\ (\Delta^d_{13})^*_{LR} & (\Delta^d_{23})^*_{LR} & (\Delta^d_{33})^*_{LR} & (\Delta^d_{13})^*_{RR} & (\Delta^d_{23})^*_{RR} & (m^2_{33})_{RR} \end{pmatrix}$$

(Some of the) Diagonal sfermion masses will be measured @ LHC; off-diagonal terms to be determined from flavour (relevant parameters: $(\delta^d_{ij})_{AB} = (\Delta^d_{ij})_{AB}/(m_{ii})_{AA}(m_{jj})_{BB}$)





Reconstructing $(\delta^d_{13})_{LL}=0.085\ e^{i\pi/4}$ and $(\delta^d_{23})_{LR}=0.028\ e^{i\pi/4}$ for m_{SUSY}=1TeV



- For a full reconstruction of the hadronic part of the SUSY Lagrangian, need % knowledge of meson mixings (including D) and FCNC decays
- Agreement with the SM as useful as disagreement
- If deviation from SM in B_s confirmed, effort in measuring $b \to s$ decays mandatory
- Notice that a large $\tilde{b} \leftrightarrow \tilde{s}$ mixing could invalidate standard LHC strategies to search for SUSY

Flavour @ LHC Workshop, arXiv:0801.1800

CONCLUSIONS: PRESENT

- Present status: control CKM + NP $\Delta F=2$ at the 20-30% level, except for B_s mixing where O(1) NP is favoured
- Bounds on NP scale tell us that NP can be within the LHC reach only if
  - it is MFV-like within at most 40% or
  - it contributes O(1) to $b \leftrightarrow s$ and <40% elsewhere

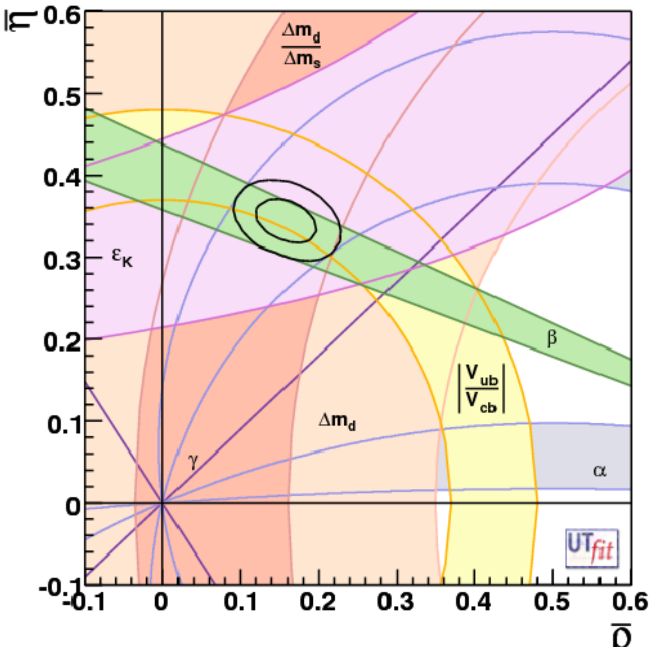
CONCLUSIONS: FUTURE

- Control CKM + NP in $\Delta F=1,2$ at the % level; push down searches for LFV by two orders of magnitude or lower; improve tests of LU
- Ensure determination of flavour structure of whatever NP seen at the LHC
- Ensure sensitivity to moderately fine-tuned NP above the LHC reach
- Requires covering the full spectrum of $B_{(s)}$, D, K and LFV observables

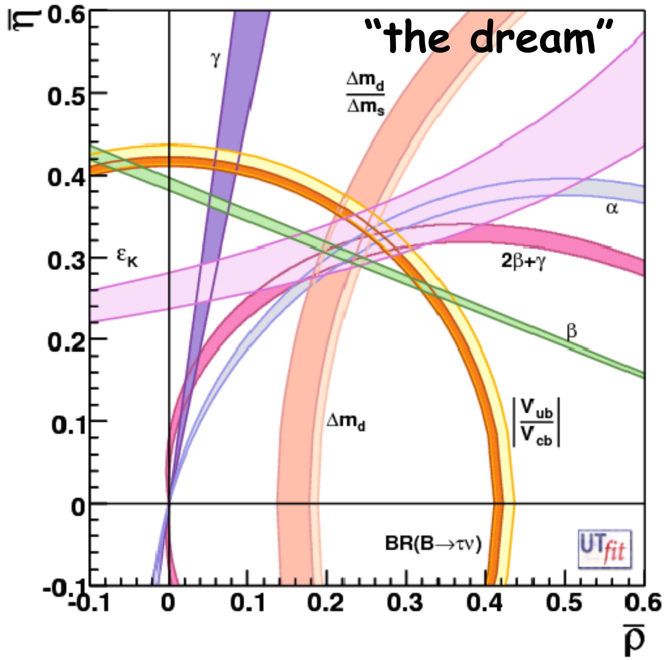
BACKUP SLIDES

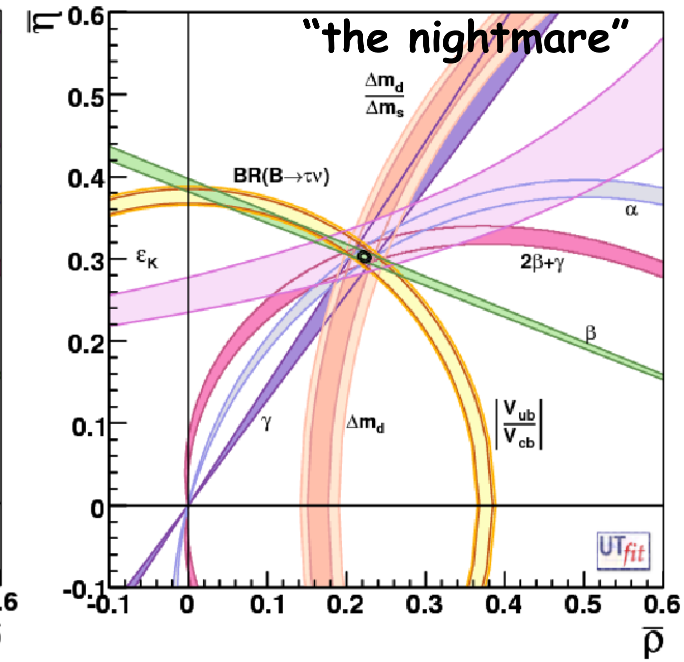
The basic step: CKM matrix at the %

Today



With a SuperB in 2015





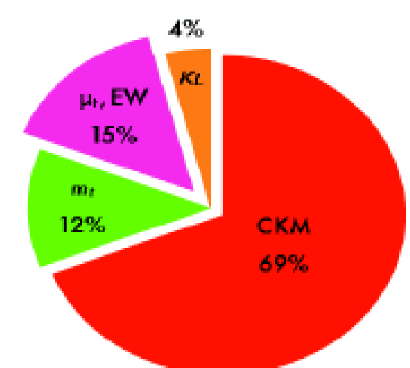
Generalized UT fits:
CKM at % in the presence of NP!

	today	SuperB
$\bar\rho$	0.177±0.044	±0.005
$\bar\eta$	0.360±0.031	±0.005

Will detect deviations from the SM at the level of 3% in C_{Bd} and of 0.5° in ϕ_{Bd}

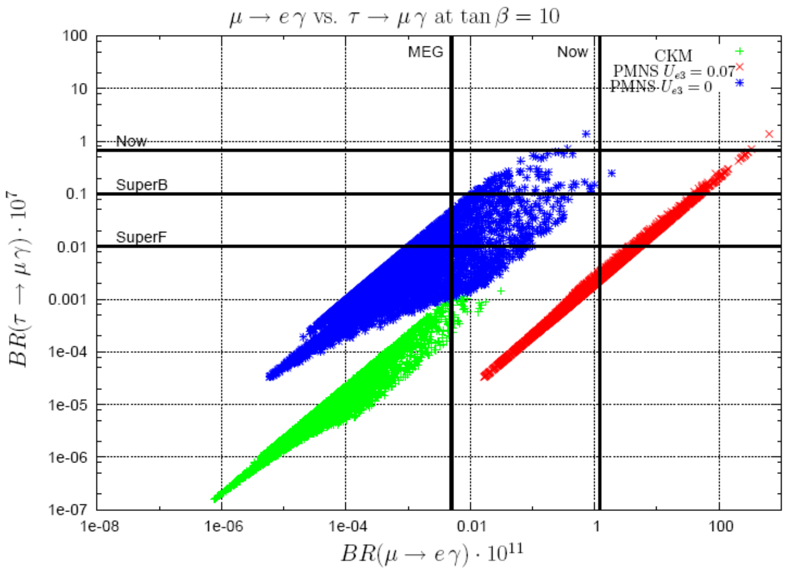
$K_L \to \pi^0 \nu \bar\nu$

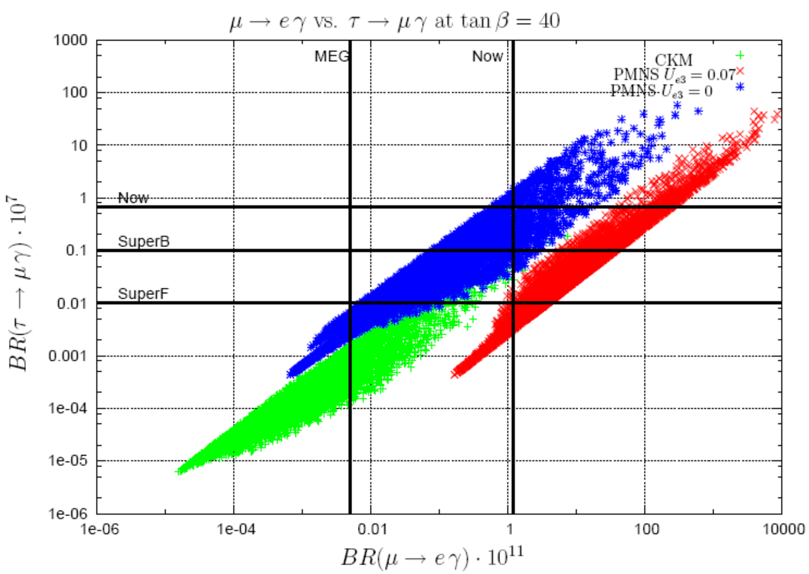
error budget

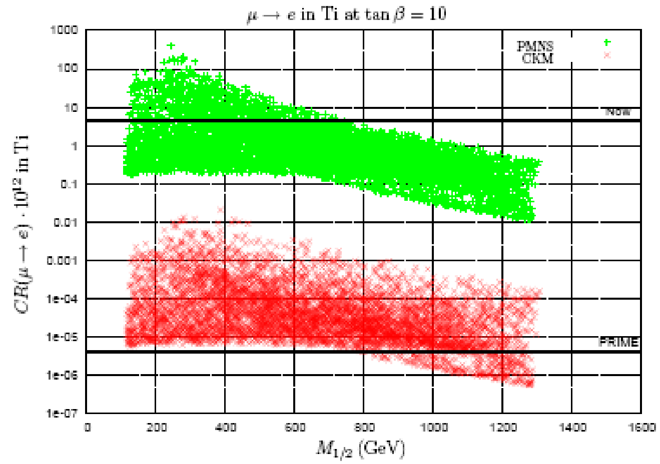


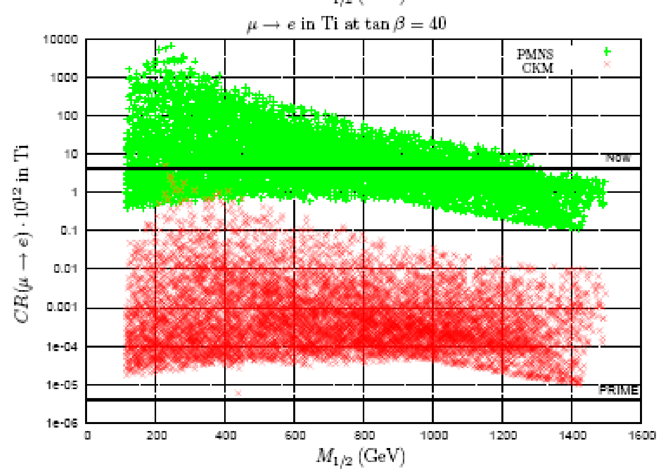
U. Haisch, Kaon '07

LFV in an SO(10) SUSY-GUT









Calibbi et al. 06

$l_i \to l_j ll$ and $l_i \to l_j P$ useful to constrain Higgs and box contributions