Flavour Physics Effects of a 4th Generation

Stefan Recksiegel TUM Capri, 7th July 2010

Why (not) four generations ?

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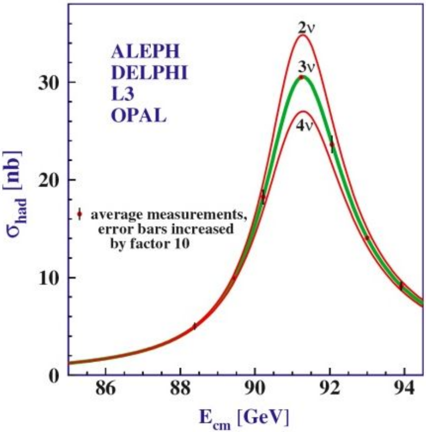
There are only three light neutrinos:



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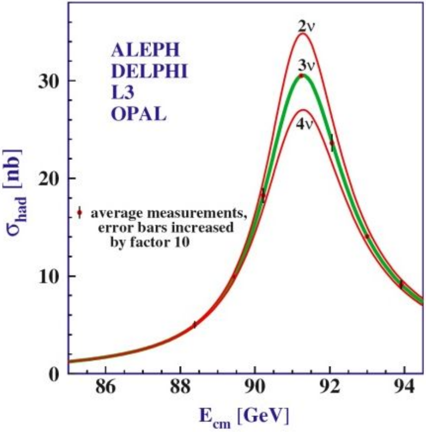

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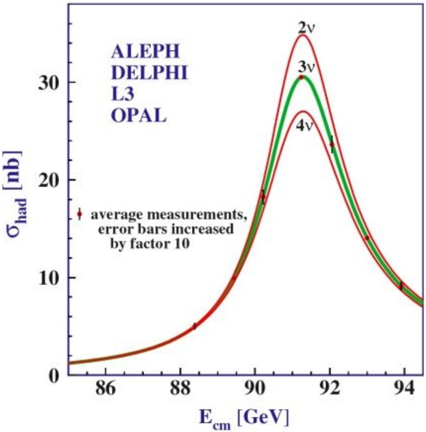

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Non-decoupling radiative corrections to

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T parameter and $Zb\bar{b}$ vertex corrections are modified.

Upper bound on s_{34} as a function of $m_{t'}$:

$$|\sin\theta_{34}| \leq \frac{M_W}{m_{t'}}$$

(Chanowitz '09)

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- The most **obvious extension** to the SM
- Avoid necessity for **light Higgs**
  See above: Modification of EWPO, "blue band plot" changes
- SU(5) **gauge coupling unification** possible without SUSY
- **Electroweak baryogenesis** might be viable
- Relieve tension in **SM3 fits**
- ...
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  (A. Lenz: "The **most boring** *extension to the SM")*
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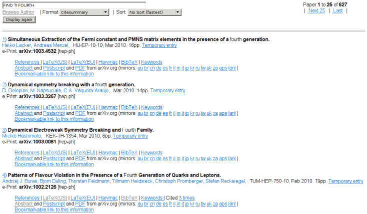
SM4: The SM with a 4th Generation

The SM with a 4th Generation

The **4th Generation** has been **well studied**, e.g. “`find ti fourth`”: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1) **Simultaneous Extraction of the Fermi constant and PMNS matrix elements in the presence of a** fourth **generation.**
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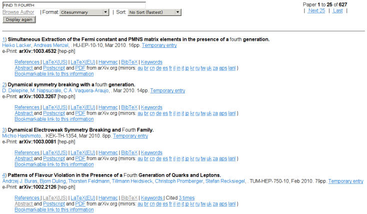

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The CKM Matrix for 4 generations

Five additional parameters: θ_{14}, θ_{24}, θ_{34}, δ_{14} and δ_{24}. (+masses, +leptons)

$V_{\mathrm{CKM}4}$ can be written as the product of a **new matrix** and $V_{\mathrm{CKM}3}$:

($c_{14} = \cos\theta_{14}, \ldots$)

$$V_{\mathrm{CKM}4} = \begin{pmatrix} c_{14} & 0 & 0 & e^{-i\delta_{14}} s_{14} \\ -e^{i(\delta_{14}-\delta_{24})} s_{14} s_{24} & c_{24} & 0 & e^{-i\delta_{24}} c_{14} s_{24} \\ -e^{i\delta_{14}} c_{24} s_{14} s_{34} & -e^{i\delta_{24}} s_{24} s_{34} & c_{34} & c_{14} c_{24} s_{34} \\ -e^{i\delta_{14}} c_{24} c_{34} s_{14} & -e^{i\delta_{24}} c_{34} s_{24} & -s_{34} & c_{14} c_{24} c_{34} \end{pmatrix}$$

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New mixing, new phases $\Rightarrow$ SM4 goes **beyond MFV** !

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Minimal Flavour Violation $\leftrightarrow$ Non-MFV

(Buras et al. 01, D'Ambrosio et al. 02)

Models are **MFV** if there are **no new sources** of Flavour Violation (i.e. only SM-Yukawa).

Examples of **MFV**:

- **Universal extra dimensions** (UED) (**A**ppelquist, **C**heng, **D**obrescu)
- **SUSY** with universal soft-scalar masses and trilinear soft terms proportional to Yukawa couplings (squark, quark masses aligned)
- **Little Higgs** without T-parity (no *mirror quarks*)

Examples of **non-MFV**:

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The theoretical framework

SM4 goes beyond MFV, but **operator structure** of the SM3 effective Hamiltonian remains intact (c.f. LHT, but unlike SUSY).

$\Rightarrow$ Introduce generalised complex **master functions**

$$S_i,\ X_i,\ Y_i,\ Z_i,\ D_i',\ E_i',\ E_i\,(i = K, d, s)$$

Observables can be written in terms of these functions, e.g. **$\mathbf{B\bar{B}}$ mixing**:

$$M_{12}^q = \frac{G_F^2}{12\pi^2} F_{B_q}^2 \hat{B}_{B_q} m_{B_q} M_W^2 \lambda_t^{(q)*\,2} \eta_B\, {S_q}^*$$

Just like **SM3**, but $S_0 \to S_q$.

Master Functions

The new **master functions** are composed of the old functions, e.g.

$$S_q = S_0(x_t) + \left(\frac{\lambda_{t'}^{(q)}}{\lambda_t^{(q)}}\right)^2 S_0(x_{t'}) + 2\frac{\lambda_{t'}^{(q)}}{\lambda_t^{(q)}} S_0(x_t, x_{t'}) \,,$$

and **CKM(4)** factors,

$$\lambda_i^{(K)} = V_{is}^* V_{id} \,, \quad \lambda_i^{(d)} = V_{ib}^* V_{id} \,, \quad \lambda_i^{(s)} = V_{ib}^* V_{is} \,.$$

Similar to the SM(3) case, **unitarity**, e.g.:

$$\lambda_u^{(K)} + \lambda_c^{(K)} + \lambda_t^{(K)} + \lambda_{t'}^{(K)} = 0 \,.$$

Flavour Physics Constraints

Flavour Physics Observables

We require the **observables**

$$\varepsilon_K\,,\quad \Delta M_K\,,\quad \Delta M_q\,,\quad \Delta M_d/\Delta M_s\,,\quad S_{\psi K_s}$$

to lie inside their **experimental 1σ ranges**.

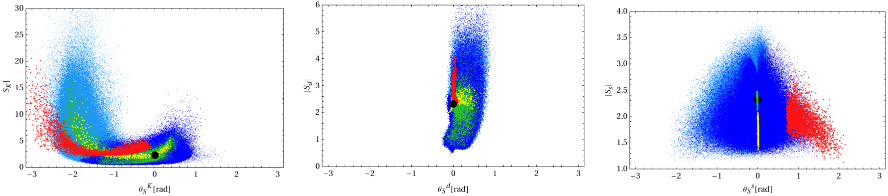
For ΔM_K we employ a larger range due to the large **hadronic uncertainty**, the SM3 **short distance contribution** is only 70% of the measured value.

Also, we impose (looser) **constraints** on $\mathrm{Br}(B \to X_s \ell^+ \ell^-)$, $\mathrm{Br}(B \to X_s \gamma)$, $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$ and $B_{s,d} \to \mu^+ \mu^-$.

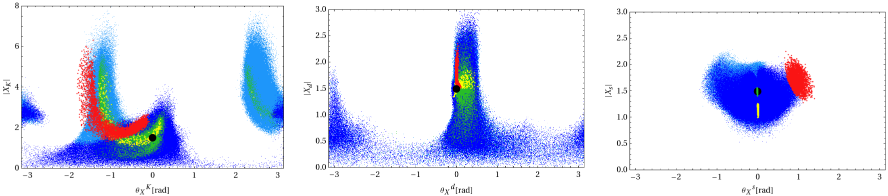
We generate a **large number of random points** in parameter space and keep only those that satisfy all **tree level CKM constraints** and those listed above.

Numerical results

Violation of Universality



$\Uparrow$ ArgS_i against $|S_i|$ $\Uparrow$ $\quad i = K, d, s \quad$ $\Downarrow$ ArgX_i against $|X_i|$ $\Downarrow$



In **SM3** (•), the functions are real and independent of the meson system !

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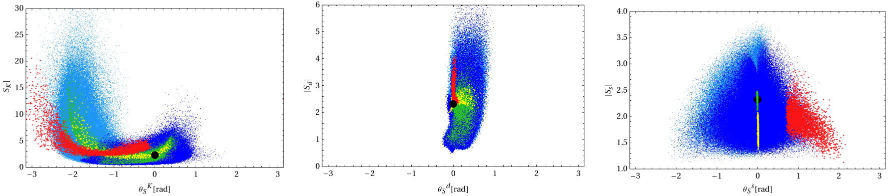

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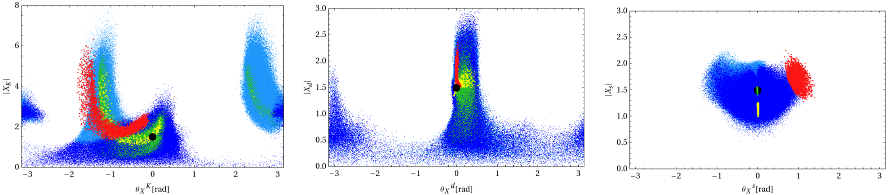
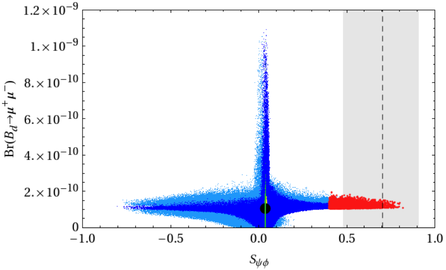
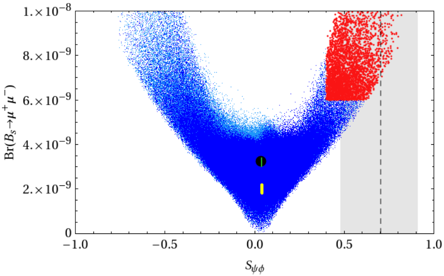


Effects **largest in K system** because $\lambda_{t'}^{(q)}/\lambda_t^{(q)}$ and $\lambda_t^{(K)} \ll \lambda_t^{(d)} < \lambda_t^{(s)}$

Colour coding

	Scenario1	Scenario2	Scenario3
$S_{\psi\phi}$	0.04 ± 0.01	0.04 ± 0.01	≥ 0.4
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	$(2 \pm 0.2) \cdot 10^{-9}$	$(3.2 \pm 0.2) \cdot 10^{-9}$	$\geq 6 \cdot 10^{-9}$





$\mathrm{Br}(B_d \to \mu^+\mu^-)$ and $\mathrm{Br}(B_s \to \mu^+\mu^-)$ as a function of $S_{\psi\phi}$

Exp. bounds: $\mathrm{Br}(B_s \to \mu^+\mu^-) \leq 3.3\ (5.3) \cdot 10^{-8}$, $\mathrm{Br}(B_d \to \mu^+\mu^-) \leq 1 \cdot 10^{-8}$.

$\mathrm{Br}(B_s \to \mu^+\mu^-)$ is **correlated with $\mathbf{S}_{\psi\phi}$** , $\mathrm{Br}(B_d \to \mu^+\mu^-)$ is not !

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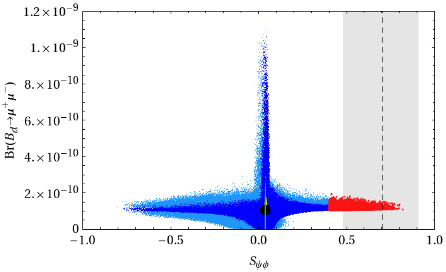

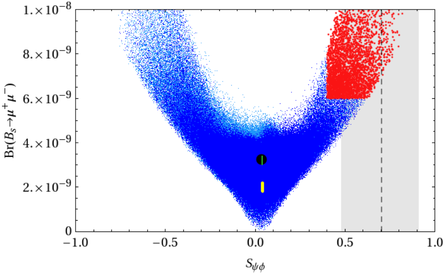

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$\mathbf{S_{\psi\phi}}$ can go up to the **current measured value**!

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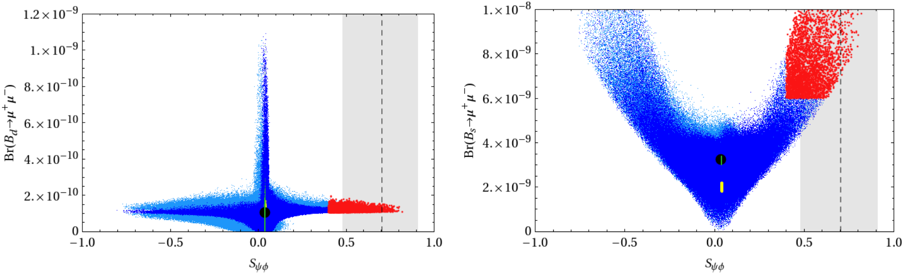

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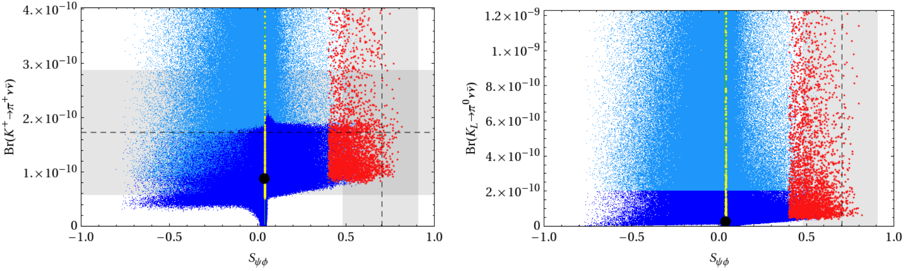
$\mathbf{Br(B_{s/d} \to \mu^+\mu^-)}$ can be **significantly enhanced**! (→LHCb)

Colour coding II

Dark blue/light blue indicates size of $\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu})$.



$\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$ and $\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu})$ as functions of $S_{\psi\phi}$

$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu})$ can be **significantly enhanced** !

Interesting decay channel because **theoretically very clean** measure of $\not{CP}$.

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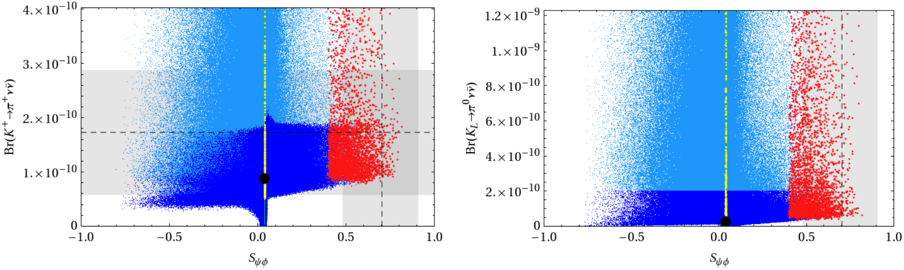

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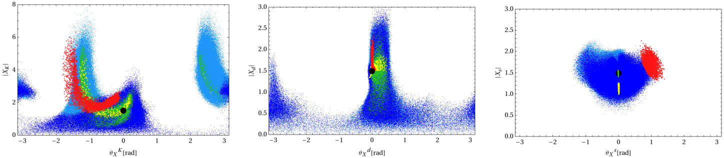
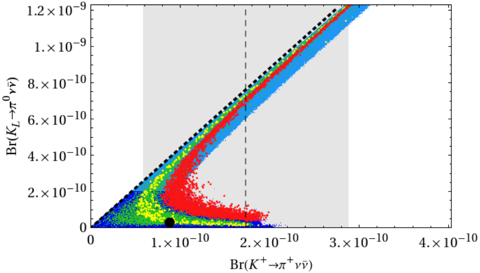
$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

Reminder: Scenarios restrict B_s , but **large effects** in K system possible !





$\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})$ against $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$

$\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})$ can be **large**, close to the Grossman-Nir-bound !

Interesting: Large $K^+ \to \pi^+\nu\bar{\nu}$ only for large $K_L \to \pi^0\nu\bar{\nu}$.

$\Rightarrow$ Structure of BRs, **correlation** with $K_L \to \mu^+\mu^-$

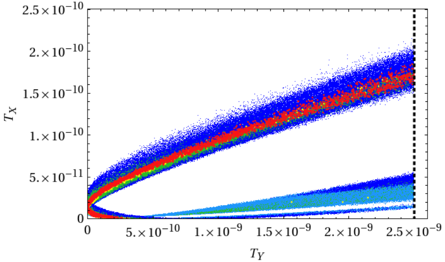
$K_L \to \mu^+\mu^-$

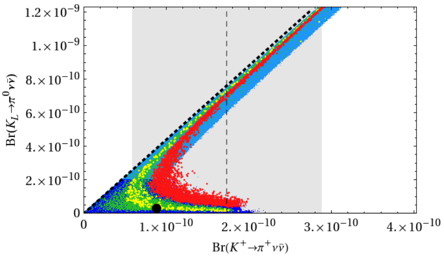
Limit $\mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}} \leq 2.5 \cdot 10^{-9}$ is **saturated** in SM4. (SM3: ~ 0.8)

Define $T_Y \equiv \mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}}$, $T_X \equiv \kappa_+ \left(\frac{Re\lambda_c^{(K)}}{V_{us}} P_c^l(X) + \frac{Re(\lambda_t^{(K)} X_K^l)}{V_{us}^5} \right)^2$, then

$$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{\kappa_+}{\kappa_L} \mathrm{Br}(K_L \to \pi^0\nu\bar{\nu}) + T_X$$

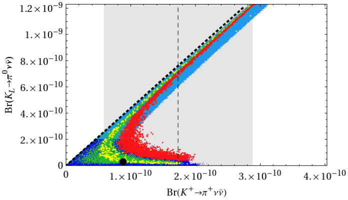
Correlation between T_X and T_Y $\Rightarrow$ Observed behaviour for K_L, K^+



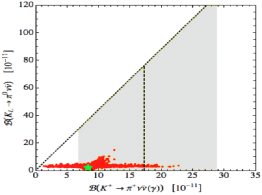


Comparison with other NP models

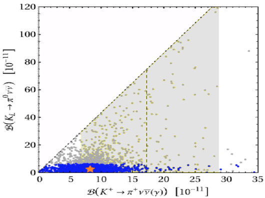
How can we distinguish between **different models of New Physics** ?



4G



LHT



RS

Littlest Higgs with T parity and **Randall-Sundrum** produce similar signatures for $K_L/K^+ \to \pi\nu\bar{\nu}$, **4G** is different !

(Thanks to U. Haisch for RS plot)

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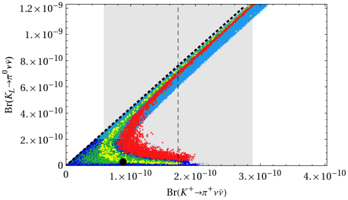

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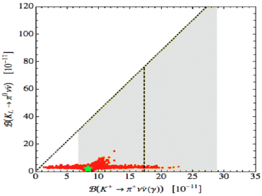

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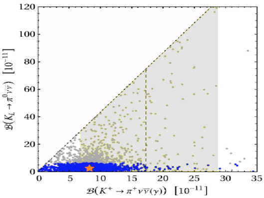

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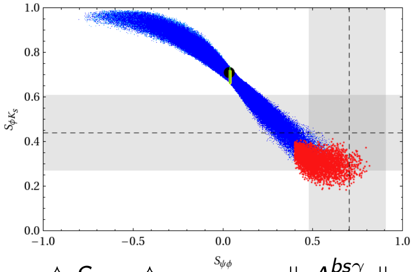
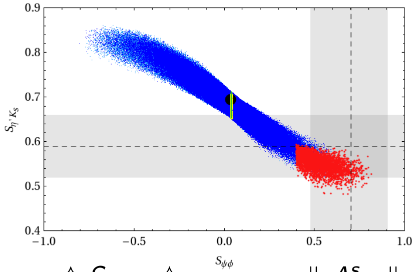
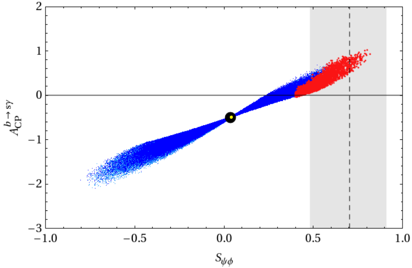
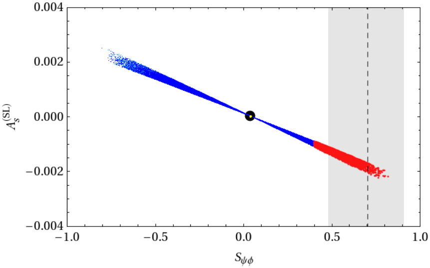
CP asymmetries as a function of $S_{\psi\phi}$





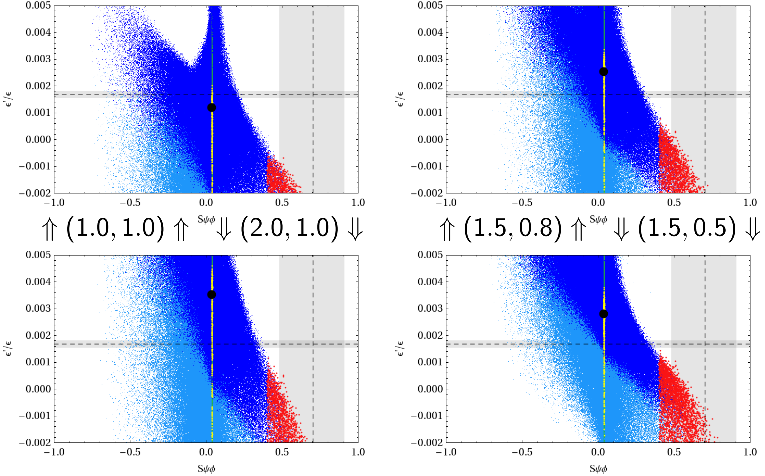
$\Uparrow S_{\phi K_S} \Uparrow$ $\Downarrow A_{\rm CP}^{bs\gamma} \Downarrow$ $\Uparrow S_{\eta' K_S} \Uparrow$ $\Downarrow A_{SL}^{s} \Downarrow$





Direct $\not{CP}$ in the Kaon system: ε'/ε

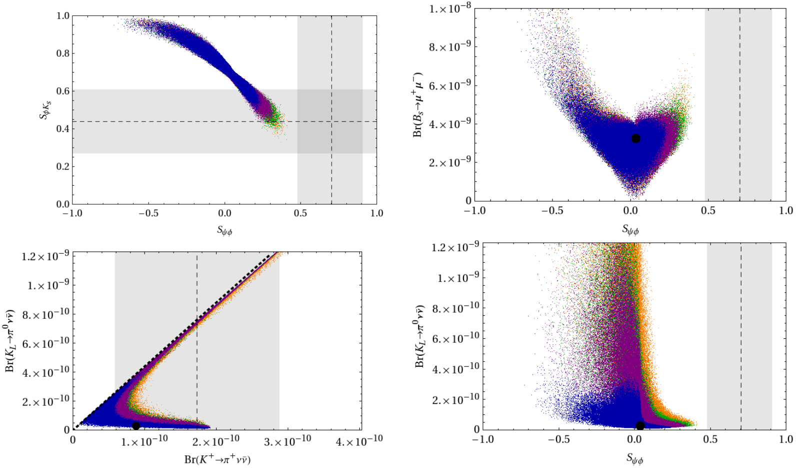
ε'/ε depends strong on two **hadronic parameters**: R_6 and R_8



All values of the hadr. param. are **consistent** with experiment in SM4. . .

Direct $\not{CP}$ in the Kaon system: ε'/ε

... but ε'/ε can still give constraints, e.g. on $S_{\psi\phi}$: Impose ε'/ε bound!



(The colours correspond to different values for R_6 and R_8 on prev. slide)

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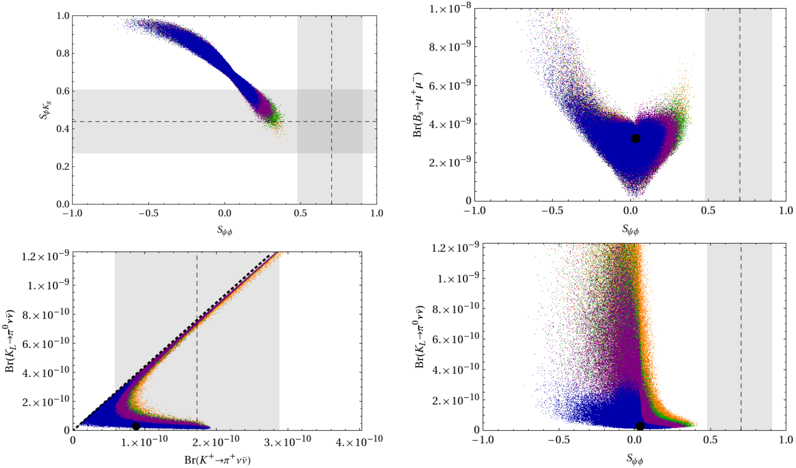


If we take ε'/ε seriously, very large values for $S_{\psi\phi}$ are excluded !

Scaling Scenarios

Scaling Scenarios

The **Wolfenstein expansion**

$$\lambda \equiv s_{12}\,, \quad s_{23} \equiv A\lambda^2\,, \quad s_{13} e^{i\delta_{13}} \equiv A\lambda^3(\rho + i\eta) \equiv A\lambda^3\, z_\rho$$

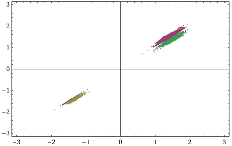
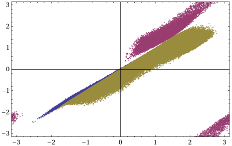
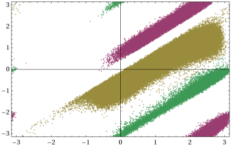
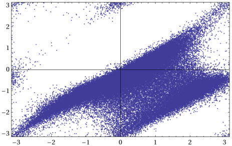
can be **generalised to 4G**:

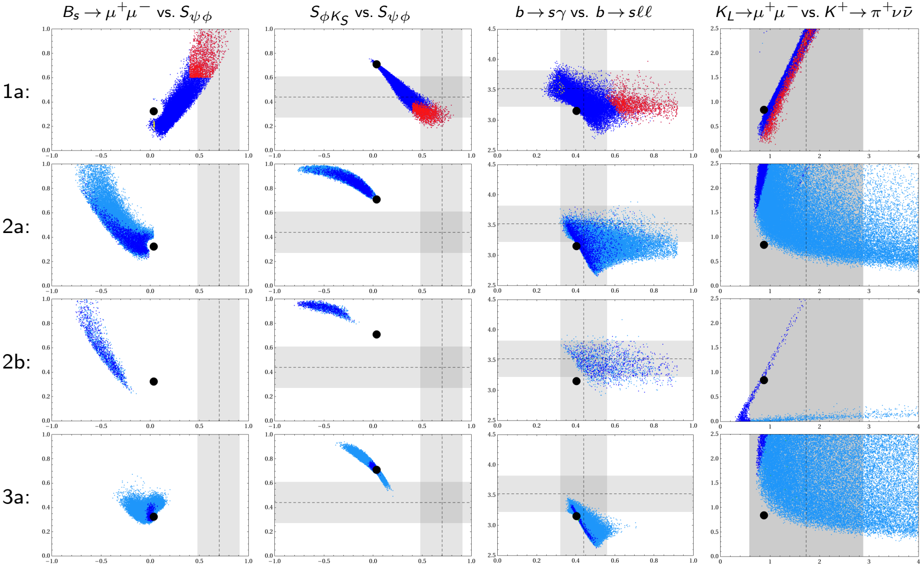
$$s_{14} e^{i\delta_{14}} = \lambda^{n_1} z_\tau\,, \quad s_{24} e^{i\delta_{24}} = \lambda^{n_2} z_\sigma\,, \quad s_{34} = \lambda^{n_3} B$$

$A, B, z_i \sim \mathcal{O}(1)$

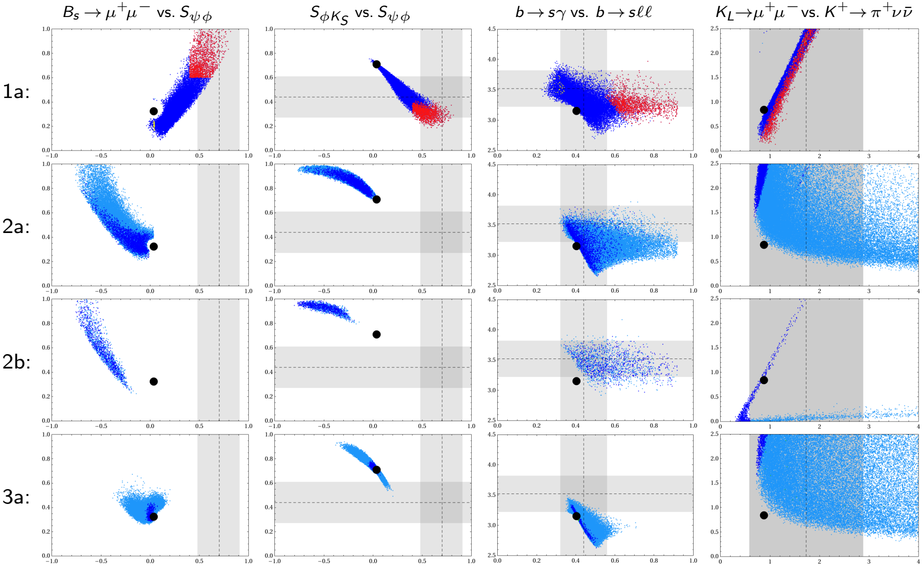
Scaling scenarios are defined by (n_1, n_2, n_3).

We can **classify the valid parameter points** according to these scenarios.

(n_1, n_2, n_3)	Correlation δ_{24} vs. δ_{14}	Assignment
$(2,1,1)$ $(2,2,1)$		$\rightarrow$ class 1a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}$, $\delta_{24} < 0$. class 1b: $\delta_{14} - \frac{\pi}{8} < \delta_{24} < \delta_{14}$, $\delta_{24} < 0$. class 2a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}$, $\delta_{24} > 0$. class 2b: $\delta_{14} - \frac{\pi}{8} < \delta_{24} < \delta_{14}$, $\delta_{24} > 0$.
$(3,2,1)$		$\rightarrow$ class 1a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}$, $\delta_{24} < 0$. class 2a/3a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{3\pi}{8}$, $\delta_{24} > 0$. class 3b: $\delta_{14} - \frac{3\pi}{8} < \delta_{24} < \delta_{14}$.
$(3,3,1)$ $(3,3,2)$		$\rightarrow$ class 3a: $\delta_{14} + \frac{\pi}{8} < \delta_{24} < \delta_{14} + \frac{\pi}{2}$. class 3b: $\delta_{14} - \frac{3\pi}{4} < \delta_{24} < \delta_{14}$. class 4: $\delta_{14} - \frac{9\pi}{8} < \delta_{24} < \delta_{14} - \frac{3\pi}{4}$.
$(4,3,1)$ $(4,3,2)$		$\rightarrow$ class 5: $\delta_{14} - \frac{3\pi}{2} < \delta_{24} < \delta_{14} + \frac{\pi}{4}$



→ We can **determine the scaling scenario** (and thereby the 4G parameters) from correlations.



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Dimensional Analysis

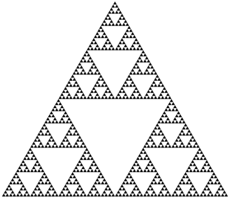
Fractal Dimensions

Haussdorff dimension

A geometric shape has *Haussdorff dimension d* if the relationship between is mass m and length L is

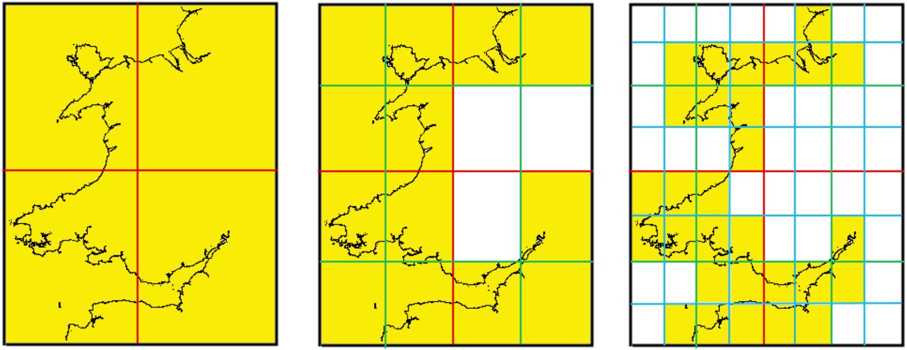
$$m \propto L^d$$

This coincides with the “normal life” understanding of dimensionality for integer d. For Fractals, d is not an integer.



E.g. *Sierpínski triangle*: mass triples when size doubles $\rightarrow d = log(3)/log(2) \approx 1.585$

The Box Counting algorithm



1/1 4/4 13/16 28/64

For **solid** objects, the fill ratio will approach a constant, for a **line**, it will approach $1/n$ ($n \times n$ boxes). For a fractal, . . .

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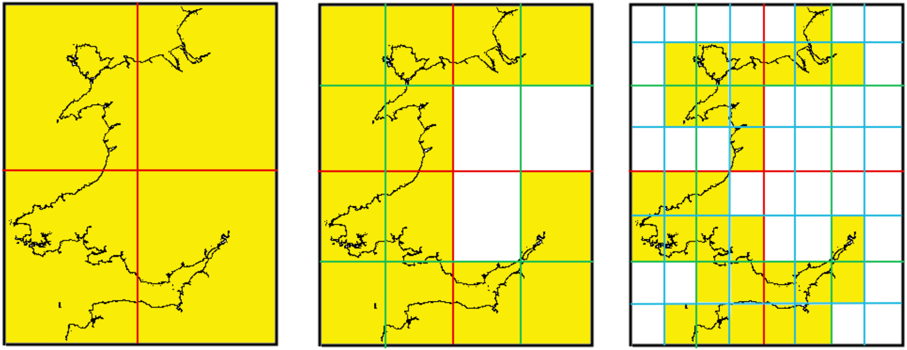

1/1 4/4 13/16 28/64

For **solid** objects, the fill ratio will approach a constant,
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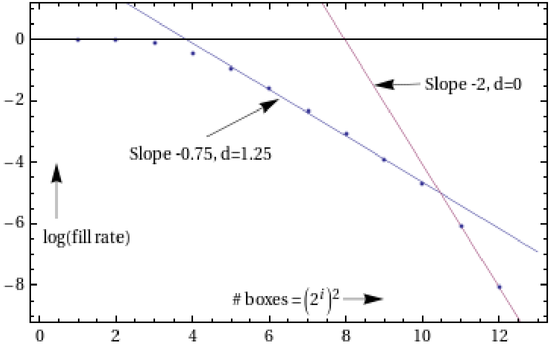
We can make a logarithmic plot of the fill ratio:

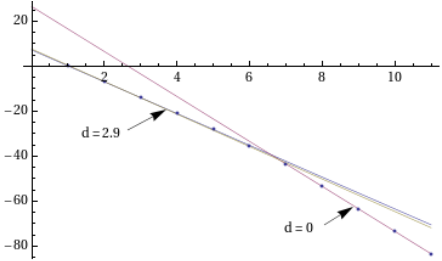


The dimension of the **British coastline** is **1.25**

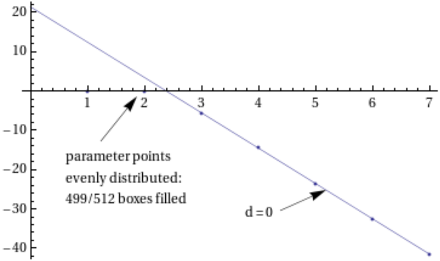
(Benoît Mandelbrot, 1967)

The effective dimension of the parameter space of SM4

The parameter space in **SM4** ...



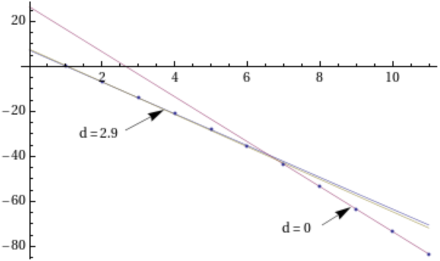
... and in **LHT**

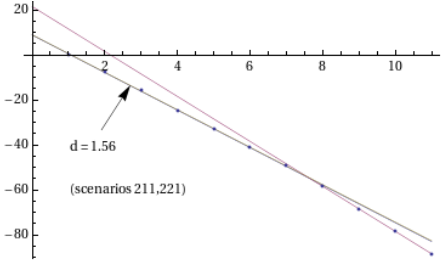


In **SM4**, the valid points in parameter space lie on a complicated structure in 10-dim. space with an **effective dimension** of ~ 3.
In **LHT**, the valid points are **distributed evenly** over the parameter space, the exp. constraints are fulfilled by **tuning** the mixing parameters and the mirror fermion masses.

Dimension of parameter space of sub-Scenarios

The parameter space in **full SM4** ... | ... and in **Scenarios 211+221**





If we restrict ourselves to certain **Scenarios** (i.e. scaling of the mixing parameters), the **effective dimension** of the parameters space **decreases**.

Effective **measure of distribution** of data points, correlations, tuning.

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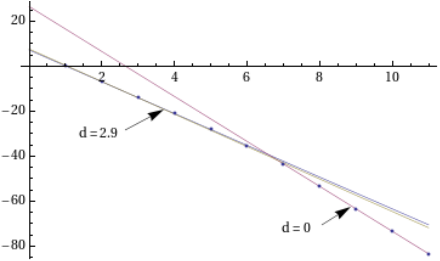

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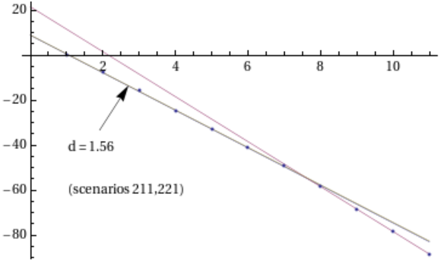

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Conclusions and Outlook

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  Contrary to popular belief, not excluded by LEP, EWPO, ...
- Spectacular effects in **Flavour Physics** observables are possible
  LHC(b): $S_{\psi\phi}$, $B_s \to \mu^+\mu^-$ (physics started Mar30th)
- Tension between **experimental results** and SM3 can be relieved

  (Explanation of the $S_{\psi\phi}$ **anomaly** involves a significant **enhancement** of Br($B_s \to \mu^+\mu^-$)!)
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- The **signature** of SM4 is different from **other NP models**
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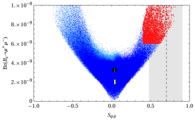

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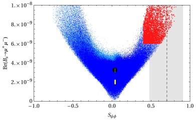

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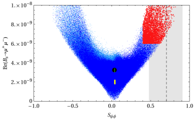

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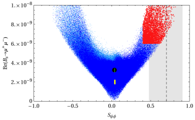
Conclusions and Outlook

- The **SM4** is a **viable** and **interesting** extension of the **SM(3)**
  Contrary to popular belief, not excluded by LEP, EWPO, ...
- Spectacular effects in **Flavour Physics** observables are possible
  LHC(b): $S_{\psi\phi}$, $B_s \to \mu^+\mu^-$ (physics started Mar30th)
- Tension between **experimental results** and SM3 can be relieved

  (Explanation of the $S_{\psi\phi}$ **anomaly** involves a significant **enhancement** of $\mathrm{Br}(B_s \to \mu^+\mu^-)$!)



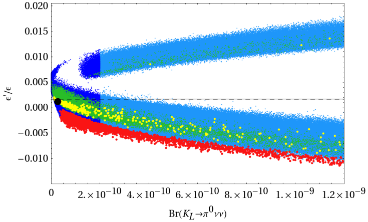
- ε'/ε seems to exclude very large values for $S_{\psi\phi}$
- The **signature** of SM4 is different from **other NP models**
- Once 4G **has been found**, study parameters from **correlations** of observables.

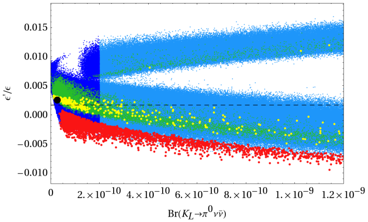
Thank you!

Backup Slides

Correlation between ε'/ε and $K_L \to \pi^0\nu\bar{\nu}$

ε'/ε does **not** really restrict $K_L \to \pi^0\nu\bar{\nu}$:





$\Uparrow$ (1.0, 1.0) $\Uparrow$ $\Downarrow$ (2.0, 1.0) $\Downarrow$ $\Uparrow$ (1.5, 0.8) $\Uparrow$ $\Downarrow$ (1.5, 0.5) $\Downarrow$