International Conference ``Heavy Quarks and Leptons´´
16-20 October 2006, Munich

B and K Physics in the Littlest Higgs Model with T-Parity (LHT)

1. <u>Introduction to Little Higgs Models</u>

2. <u>Flavour Analysis in LHT</u>:

- Mixing, ~~CP~~, B -> $X_s\ \gamma$
  [Blanke,Buras,Poschenrieder,CT,Uhlig,Weiler]
- B and K rare decays
  [Blanke,Buras,Poschenrieder,Recksiegel,CT,Uhlig,Weiler]

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Success and Limits of the SM

``The SM works very well but important open issues are left´´

The SM is in excellent agreement with experiments both in electroweak (ew) and flavour physics

BUT

It cannot explain:

- **matter-antimater asymmetry**
- **dark matter**
- **quantum gravity**
- **…**

AND

The ew symmetry breaking remains poorly understood

The Little Hierarchy Problem

``New Physics (NP) at 1 TeV is expected but its effects are not observed´´

From the instability of the (fundamental scalar) Higgs mass:

$\delta m_H^2 \propto \Lambda^2$, $m_H = O(v) \approx 10^2\,\mathrm{GeV}$ ⇨ $\Lambda \approx 1\,\mathrm{TeV}$ is the natural value for the NP scale

WHILE

Parameterizing NP by higher-dimensional operators suppressed by Λ:

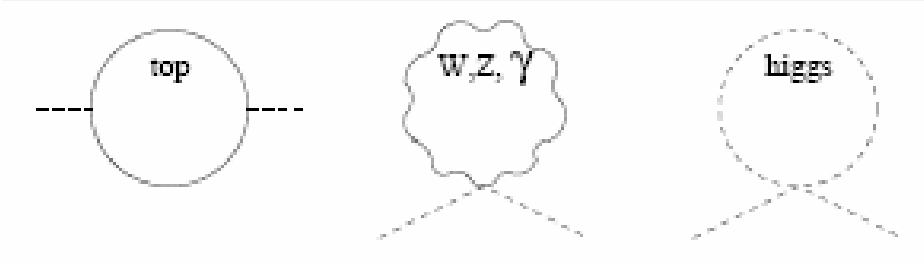
$(h^\dagger D_\mu h)^2/\Lambda^2$, $(D^2 h^\dagger D^2 h)/\Lambda^2$,…

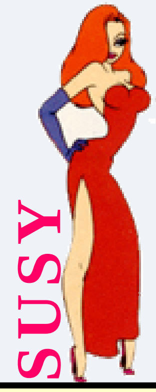
Ew precision tests yield $\Lambda \geq 5\text{-}10\,\mathrm{TeV}$

Is it possible to stabilize the Higgs mass without violating the above bound?

SUSY vs Little Higgs

Problematic quadratic divergences in m_H^2





	SUSY	Little Higgs
Quadratic divergences canceled by:	(different statistics) super-partners	(same statistics) heavy partners
Coupling relationships due to:	boson-fermion symmetry	global symmetry

- SUSY has a lot of virtues (required at M_{Pl},computable up to M_{Pl},helps GUT) but also …a lot of parameters (~120 in MSSM)
- Lack of SUSY signals at LEP constrains the MSSM parameters to be ~fine-tuned

- Little Higgs models are low-energy effective theories computable up to Λ~10 TeV
- Little Higgs can have less parameters (~20 in LH with T-parity)
- T-parity makes LH well compatible with ew precision tests, without fine-tuning

The General Mechanism of Little Higgs Models

The "little Higgs" is a pseudo-Nambu-Goldstone boson of a spontaneously broken symmetry. This symmetry is also explicitly broken but only "collectively", i.e. the symmetry is broken when two or more couplings in the Lagrangian are non-vanishing. Setting any one of these couplings to zero restores the symmetry and therefore the masslessness of the "little Higgs".

[N. Arkani-Hamed, A.G. Cohen, H. Georgi (2001)]

1. The **light Higgs** is interpreted as a **Goldstone boson** of a spontaneously broken global symmetry **(G)**

2. **Gauge and Yukawa couplings** of the Higgs are introduced by **gauging a subgroup of G**

3. These terms would yield ``dangerous´´ **quadratic corrections**: they are **avoided** through **Collective Symmetry Breaking**

- The Higgs dynamics is described (similarly to ChPT) by a **non-linear sigma model up to Λ ~10TeV**
- The **UV completion** is **unknown** (another LH?,SUSY?,ED?)

The most economical in matter content: Littlest Higgs (LH)

[N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson (2002)]

Global Spontaneous SB: $SU(5) \xrightarrow[f \approx O(1\,TeV)]{} SO(5)$

Gauging: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \xrightarrow{f} SU(2)_L \otimes U(1)_Y$

(g_1) (g'_1) (g_2) (g'_2)

Collective SB: $\delta m_H^2 \propto g_1^{(\prime)2} g_2^{(\prime)2}$

Collective SB at work:

- If $g_1, g_1' = 0$ there is a larger symmetry $SU(3)_1 \otimes [SU(2) \otimes SU(1)]_2$ which prevents the Higgs from getting a mass
- the same mechanism, when $g_1, g_1', g_2, g_2' \neq 0$, forbids quadratic divergences at one-loop

To cancel the top quadratic divergence, the collective SB has to be implemented in the top sector, by introducing a heavy weak-singlet **T**

New Particles in the LH model (without T-parity)

Gauge Bosons: $W^{\pm}_H$, Z^0_H, A^0_H
Fermions: T
Scalars: Φ(triplet)

(with O(f) masses)

$\Lambda = (4\pi\, f)$

Tree-level heavy gauge boson contributions and the triplet Φ vev make ew precision tests higly constraining
[Han, Logan, McElrath, Wang]
[Csaki, Hubisz, Kribs, Meade, Terning]

⇒ $f \geq 2\text{-}3$ TeV

The little hierarchy problem we wanted to solve is back!

The solution comes from a discrete symmetry under which SM particles are even and new particles are odd.
(similarly to R-parity in SUSY)
It forbids the unwanted contributions above.

T-Parity

[H.C. Cheng, I. Low (2003)]

smaller f allowed by ew tests
[Hubisz,Meade,Noble,Perelstein]

⇒ $f \geq 500$ GeV

The little hierarchy problem is solved!

Symmetry under $[SU(2)\otimes U(1)]_1 \longleftrightarrow [SU(2)\otimes U(1)]_2$

⇔ $g_1 = g_2$ $g'_1 = g'_2$

- New fermions, called **mirror fermions**, are required
- There is a **candidate for dark matter**: the heavy photon A_H
- **LHT signals** at LHC **risk** to be **similar to SUSY with R-parity**

(promising signature: $l^\pm l^\pm \not{E}_T$ jets, many events free of $t\bar{t}$ background)

$p\,p \to u_H\, u_H \to W^+_H\, d\, W^+_H\, d \to W^+\, W^+\, A_H\, A_H\, d\, d \to l^+\, l^+ \not{E}_T$ jets

[Belyaev,Chen,Tobe,Yuan]

T-even Sector:

SM Particles + T_+

T-odd Sector:

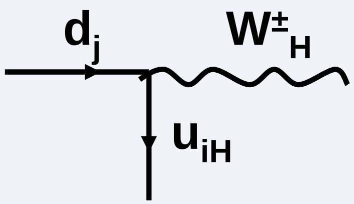
Gauge Bosons: $W^\pm_H$, Z^0_H, A^0_H
Fermions: T_-, **Mirror Fermions** (q_H)
Scalars: Φ

with **NEW** flavour interactions

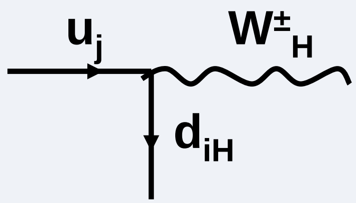
LHT goes beyond Minimal Flavour Violation (MFV)

(without introducing new operators and non-perturbative uncertainties)

``visible effects in flavour physics are possible´´



$\sim\ (V_{Hd})_{ij}\ \gamma_\mu\ (1-\gamma_5)$



$\sim\ (V_{Hu})_{ij}\ \gamma_\mu\ (1-\gamma_5)$

$V^\dagger_{Hu}\ V_{Hd} = V_{CKM}$

[Low], [Hubisz,Lee,Paz]

$$V_{Hd} = \begin{pmatrix} c^d_{12}c^d_{13} & s^d_{12}c^d_{13}e^{-i\delta^d_{12}} & s^d_{13}e^{-i\delta^d_{13}} \\ -s^d_{12}c^d_{23}e^{i\delta^d_{12}} - c^d_{12}s^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{23})} & c^d_{12}c^d_{23} - s^d_{12}s^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{12}-\delta^d_{23})} & s^d_{23}c^d_{13}e^{-i\delta^d_{23}} \\ s^d_{12}s^d_{23}e^{i(\delta^d_{12}+\delta^d_{23})} - c^d_{12}c^d_{23}s^d_{13}e^{i\delta^d_{13}} & -c^d_{12}s^d_{23}e^{i\delta^d_{23}} - s^d_{12}c^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{12})} & c^d_{23}c^d_{13} \end{pmatrix}$$

V_{Hd} parameterization similar to CKM, but with 2 additional phases (the phases of SM quarks are no more free to be rotated)

[Blanke,Buras,Poschenrieder,Recksiegel,CT,Uhlig,Weiler]

LHT Flavour Analysis

Blanke,Buras,Poschenrieder,CT,Uhlig,Weiler,[hep-ph/0605214]

Mixing, ~~CP~~, $B \to X_s \gamma$

Blanke,Buras,Poschenrieder,Recksiegel,CT,Uhlig,Weiler,[coming soon]

B and K rare decays

Mixing, $\not{CP}$, B $\to X_s\,\gamma$
``The Strategy´´

- Impose constraints on: ΔM_K, ε_K, $\Delta M_{d,s}$, $\Delta\Gamma^{d,s}$, $S_{\psi K_S}$, $B \to X_s\,\gamma$
- Explore LHT effects in: $A^{d,s}_{SL}$, $S_{\psi\Phi}$
- Special attention to: $S_{\psi K_S}$, ΔM_s

BaBar+Belle

$$\sin(2\beta)_{\psi K_S} = 0.675 \pm 0.026$$

tree-level decays only, free from NP

$$\sin(2\beta)_{UTA} = 0.794 \pm 0.045$$

2.3 σ difference!
Is it the effect of a NP phase in
$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{Bd})???$$

recent CDF measurement

$$\Delta M_s = (17.77 \pm 0.10 \pm 0.07)/\text{ps}$$

The UTA predicts a slightly larger value:

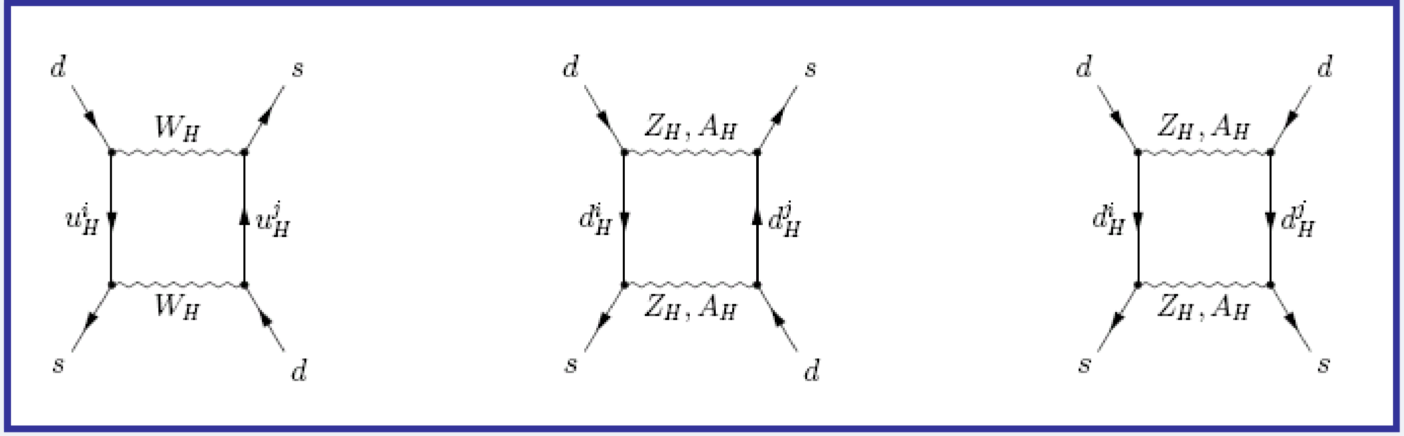
$(18.4 \pm 2.4)/\text{ps}$ [UTfit]

$(21.7^{+5.9}_{-4.2})/\text{ps}$ [CKMfitter]

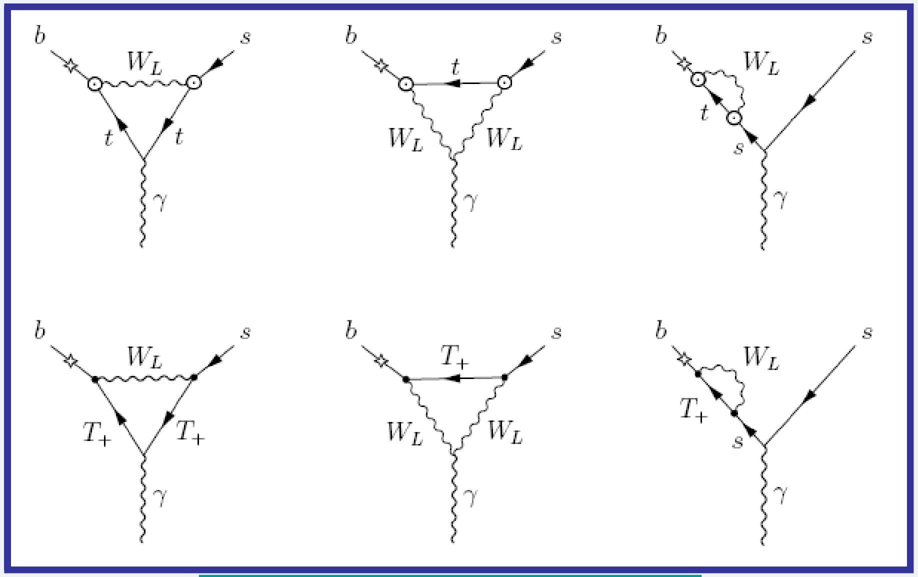
Can the LHT prediction approach the CDF measurement???

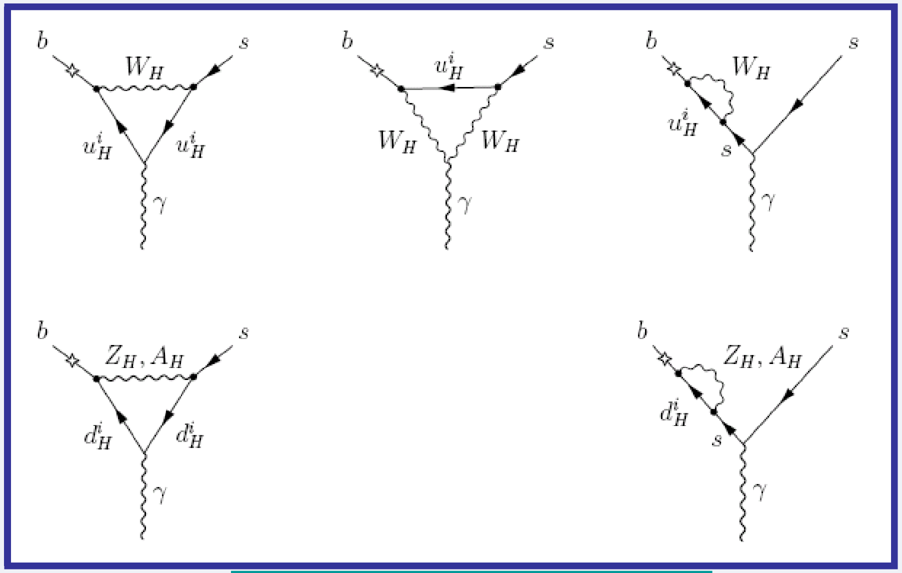
A quick look at the Feynman Diagrams

Particle-Antiparticle Mixing



$B \rightarrow X_s \gamma$





T-even contribution

T-odd contribution

Scenarios

Parameters:

- f
- x_L (top-sector)

} allowed ranges from ew precision tests

Mirror fermion masses: m_{H1}, m_{H2}, m_{H3}

V_{Hd} parameters: $\theta^d_{12}, \theta^d_{13}, \theta^d_{23}, \delta^d_{12}, \delta^d_{13}, \delta^d_{23}$

- The ΔM_K and ε_K constraints require almost degenerate $m_{H1} \approx m_{H2} \approx 500$ GeV
- Large effects in B physics are possible with a peculiar V_{Hd} hierarchy

V_{CKM}

$$\begin{pmatrix} c_{12} & s_{12} & s_{13}e^{-i\gamma} \\ -s_{12} & c_{12} & s_{23} \\ s_{12}s_{23} - s_{13}e^{i\gamma} & -s_{23} & 1 \end{pmatrix}$$

$$s_{13} << s_{23} << s_{12}$$

$(4\cdot10^{-3})$ $(4\cdot10^{-2})$ (0.2)

V_{Hd} $\delta^d_{12} = \delta^d_{23} = 0$ (minor impact)

$$\begin{pmatrix} \hat{c}_{12} & \hat{s}_{12} & \hat{s}_{13}e^{-i\hat{\delta}} \\ -\hat{s}_{12} & \hat{c}_{12} & \hat{s}_{23} \\ -\hat{c}_{12}\hat{s}_{13}e^{i\hat{\delta}} & -\hat{s}_{12}\hat{s}_{13}e^{i\hat{\delta}} & 1 \end{pmatrix}$$

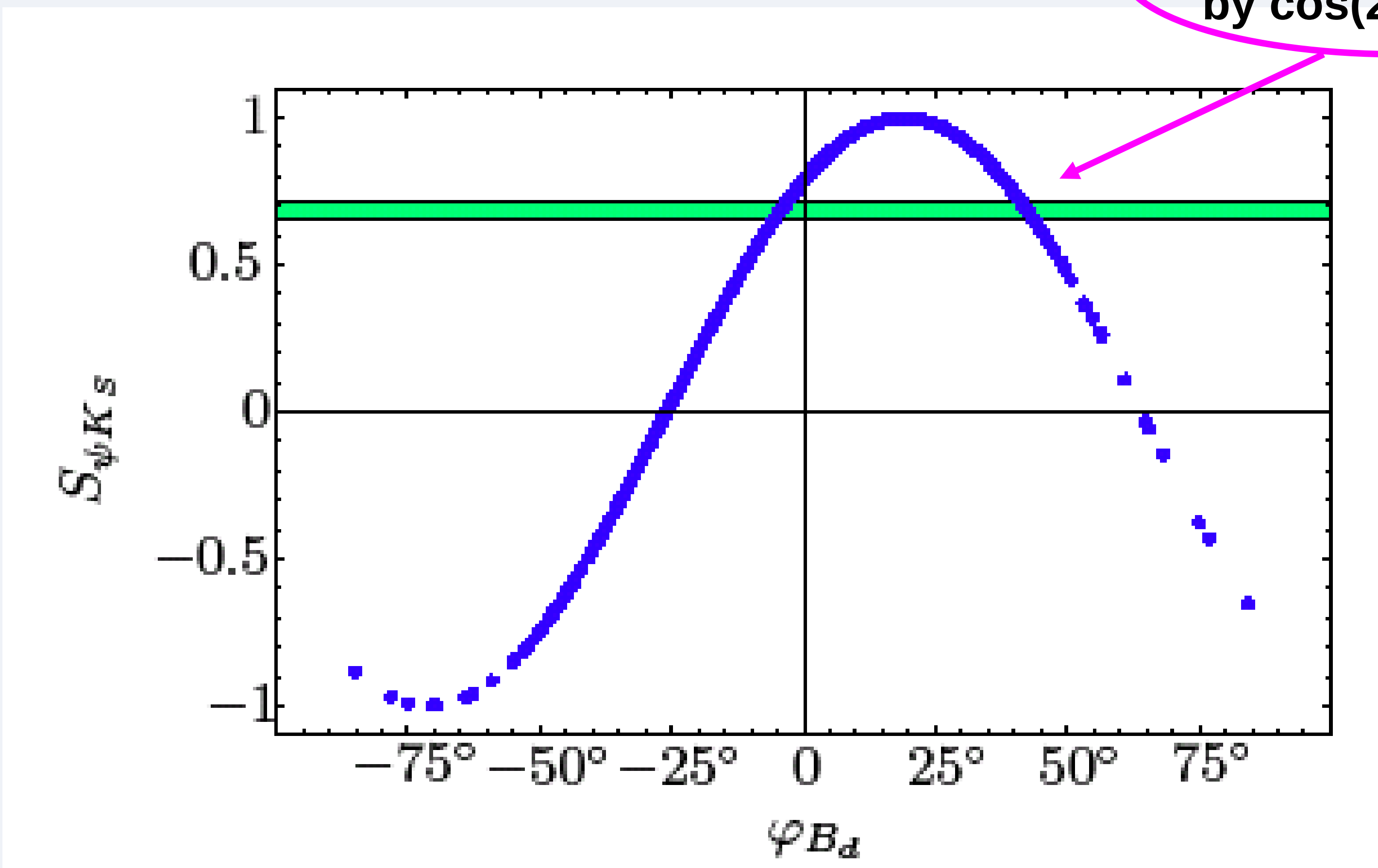
$$\hat{s}_{23} << \hat{s}_{13} < \hat{s}_{12}$$

$(4\cdot10^{-4})$ $(8\cdot10^{-2})$ (0.90)

The sin2β difference can be explained in terms of a new phase

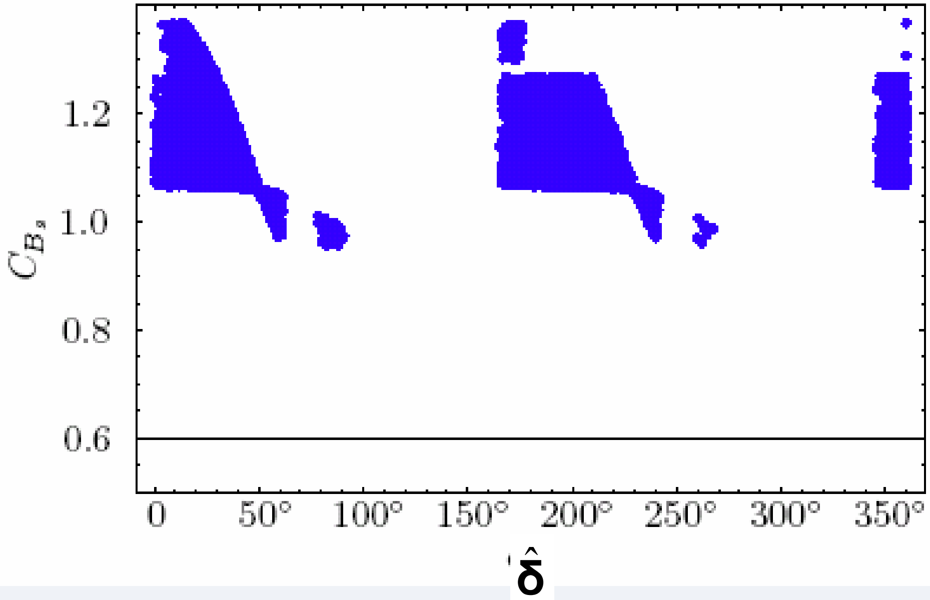
$\varphi_{Bd} \approx -5°, +43°$

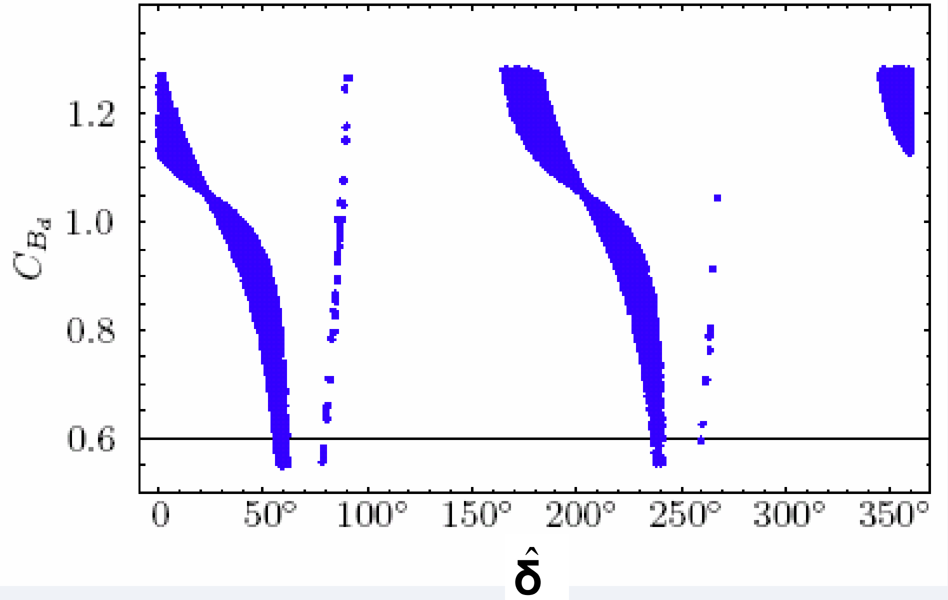
strongly disfavored by $\cos(2\beta+2\varphi_{Bd})^{exp}$



ΔM_s

$$C_{Bq} = \frac{(\Delta M_q)_{LHT}}{(\Delta M_q)_{SM}}$$





$C_{Bs} \geq 0.93$

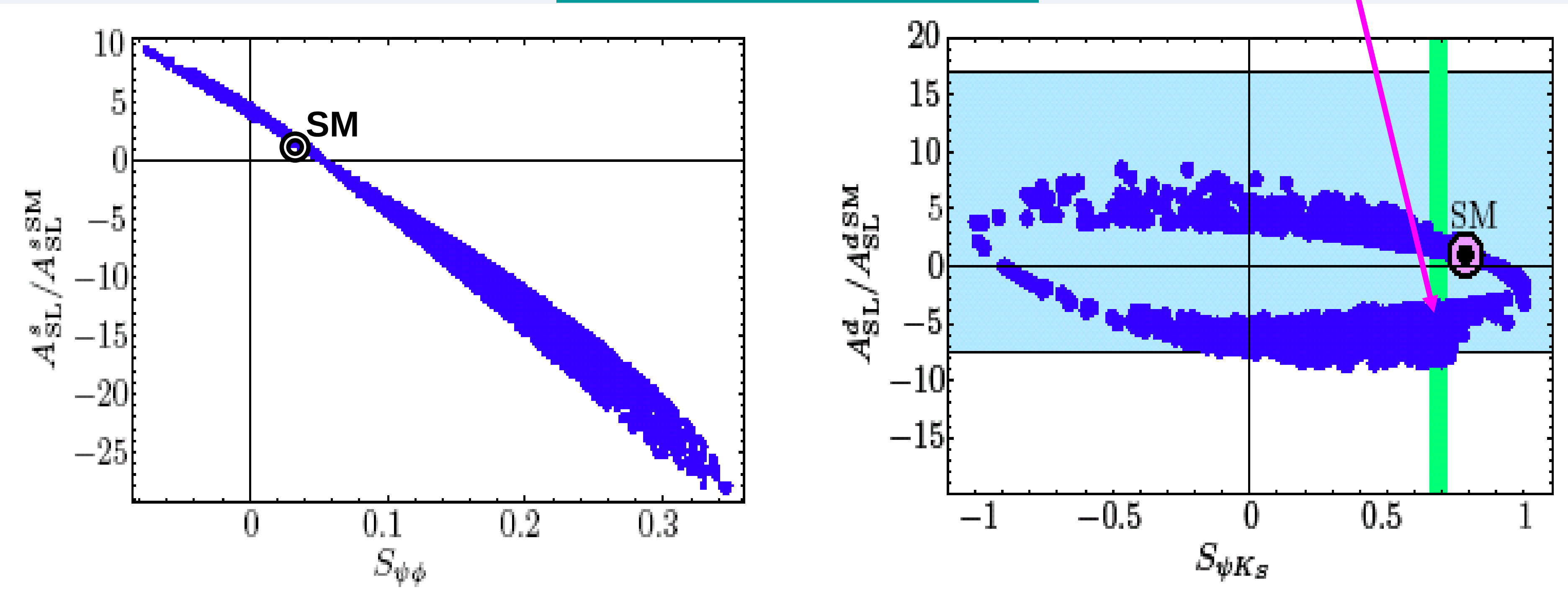
$(\Delta M_s)_{LHT} < (\Delta M_s)_{SM}$
is possible,
approaching the CDF measurement

Semileptonic and t-dependent CP-asymmetries

$$A^{q}_{SL} = \frac{\Gamma(\bar{B}^0_s \to l^+ X) - \Gamma(B^0_s \to l^- X)}{\Gamma(\bar{B}^0_s \to l^+ X) + \Gamma(B^0_s \to l^- X)}$$

$$S_{\psi K_s} = \sin(2\beta + 2\varphi_{B_d}),$$
$$S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{B_s})$$

φ_{Bd} =+43° disfavored also by $(A^d_{SL})_{exp}$



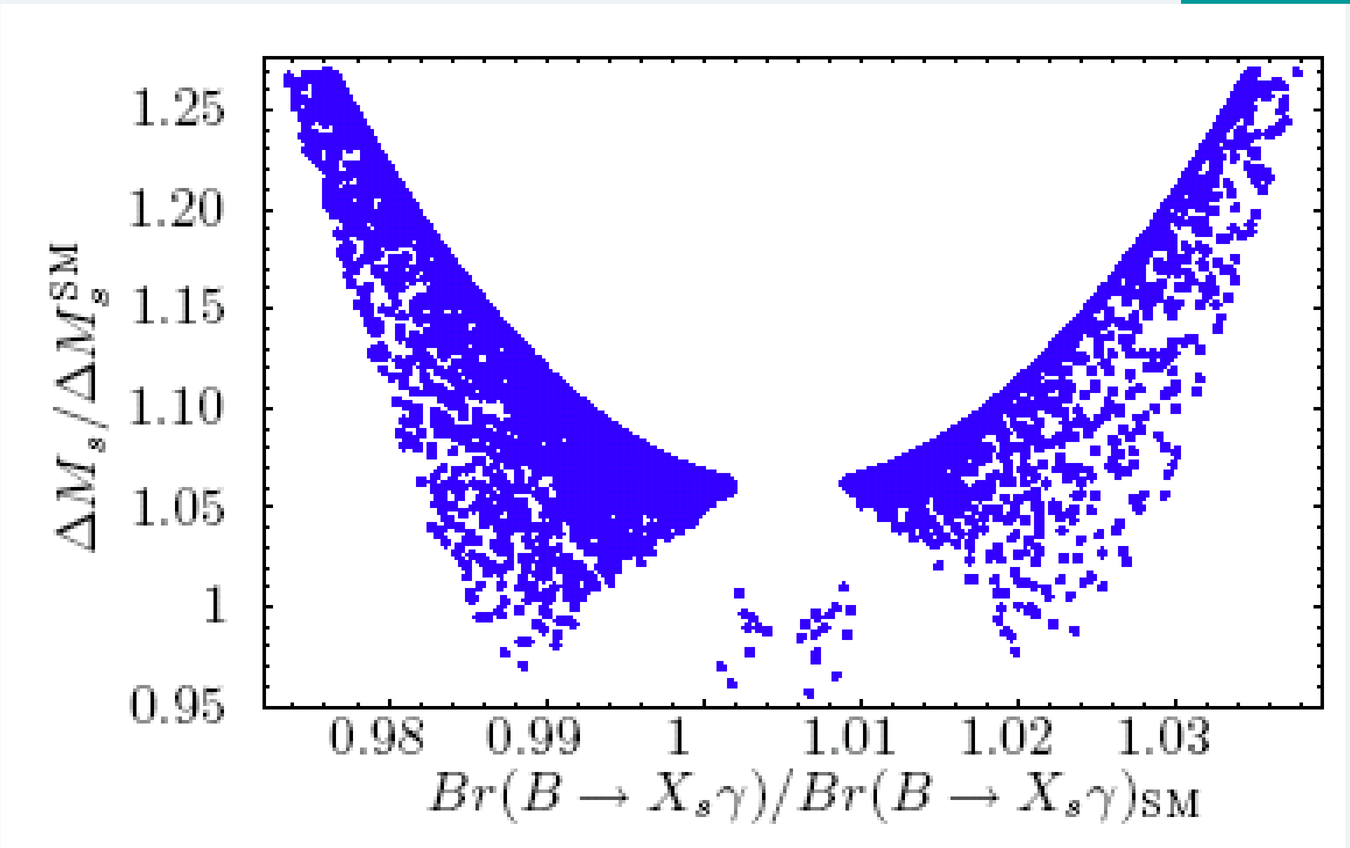
- A^s_{SL} enhanced by 10-20, A^d_{SL} by ~3
- $S_{\psi\Phi}$ can be as high as +0.3

Br(B->X_s γ)

At most ±4% effects in the LHT Model

Good agreement with data

Small effects also in A_{CP}(B->X_s γ)



B and K rare decays
``The Strategy´´

- **Impose constraints on:** ΔM_K, ε_K, $\Delta M_{d,s}$, $\Delta\Gamma^{d,s}$, $S_{\psi K_S}$, $B\to X_s\gamma$ and $B\to X_s l^+ l^-$
- **Explore LHT effects in:** $B_{s,d}\to\mu^+\mu^-$, $B\to X_{s,d}\nu\bar{\nu}$, $K^+\to\pi^+\nu\bar{\nu}$, $K_L\to\pi^0\nu\bar{\nu}$, $K_L\to\pi^0 l^+ l^-$, $B\to\pi K$

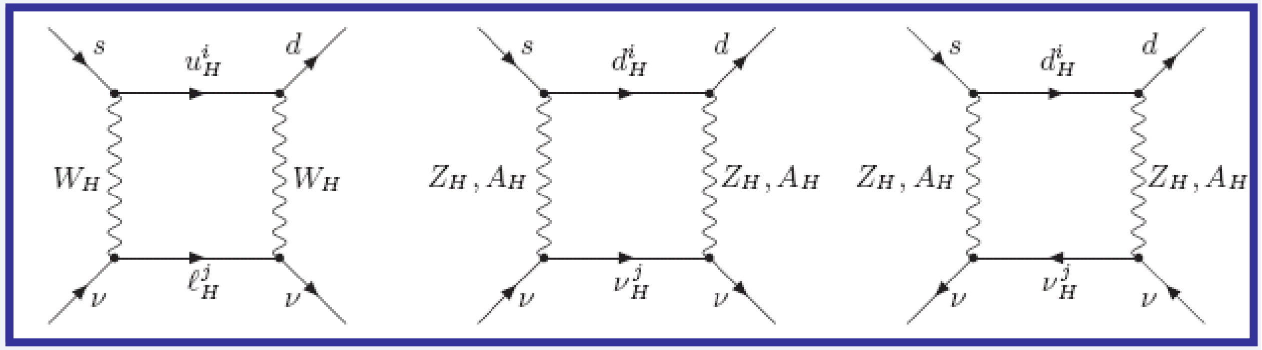
	Exp.	SM	One-loop Functions
$B_d\to\mu^+\mu^-$	$<3\cdot10^{-8}$ [CDF]	$1.0(1)\cdot10^{-10}$ [Buras]	Y_d
$B_s\to\mu^+\mu^-$	$<1\cdot10^{-7}$ [CDF]	$3.4(3)\cdot10^{-9}$ [Buras]	Y_s
$K_L\to\pi^0\nu\bar{\nu}$	$<2.1\cdot10^{-7}$ [E391a]	$2.9(4)\cdot10^{-11}$ [Buras,Gorbahn,Haisch,Nierste]	X_K
$K^+\to\pi^+\nu\bar{\nu}$	$1.5(11)\cdot10^{-10}$ [E787,E949]	$8.0(11)\cdot10^{-11}$ [Buras,Gorbahn,Haisch,Nierste]	X_K
$K_L\to\pi^0 e^+e^-$	$<2.8\cdot10^{-10}$ [KTeV]	$3.5(10)\cdot10^{-11}$ [Buchalla,D'Ambrosio,Isidori] [Isidori,Smith,Unterdorfer] [Mescia,Smith,Trine]	Y_K, Z_K
$K_L\to\pi^0\mu^+\mu^-$	$<3.8\cdot10^{-10}$ [KTeV]	$1.4(3)\cdot10^{-11}$ [Buchalla,D'Ambrosio,Isidori] [Isidori,Smith,Unterdorfer] [Mescia,Smith,Trine]	Y_K, Z_K

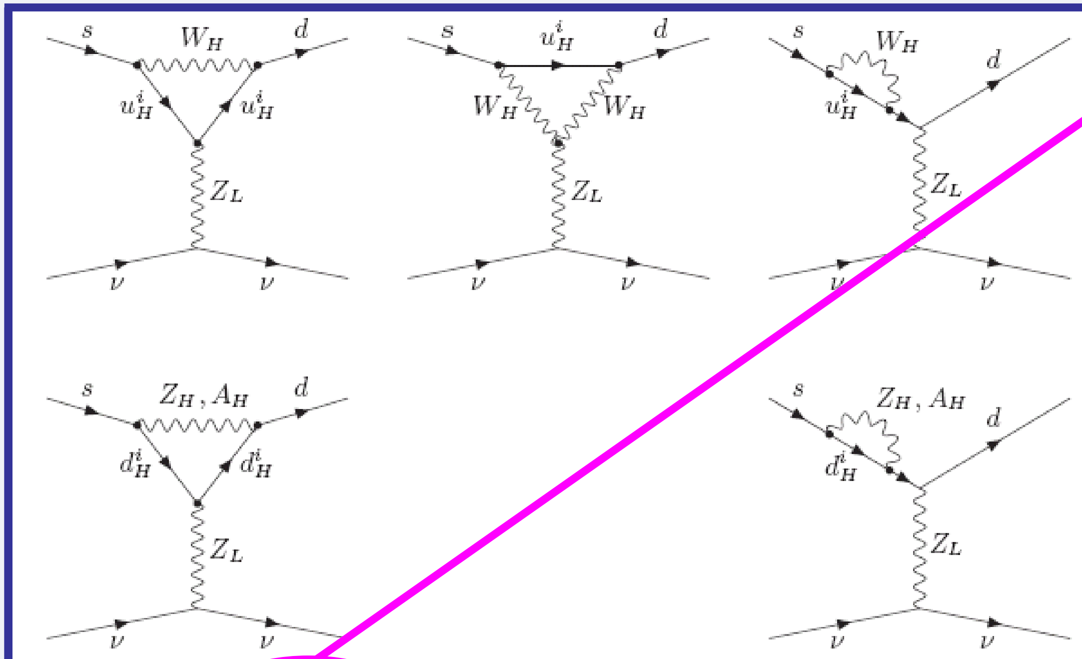
In the SM and MFV X,Y,Z are: real and universal ($X_d=X_s=X_K$) (dominant top-contribution)

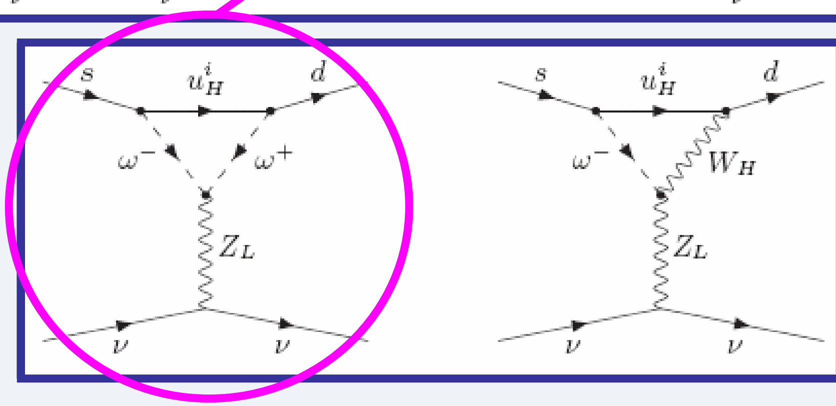
In LHT X_i,Y_i,Z_i can be: complex and non-universal ($X_d\neq X_s\neq X_K$) (V_{Hd} + mirror fermions)

Thanks to A. Weiler for having discussed the status of the art!

A quick look at the [Feynman Diagrams]







(gauge-independent)
divergences remain!!!

They reflect a sensitivity of the non-linear sigma model to the UV completion
(behavior known in ChPT and previously found in LH without T-parity
[Buras,Poschenrieder.Uhlig,Bardeen])

Assuming no complicate flavour interactions in the UV-completion we can estimate:

$$\frac{1}{\varepsilon} + \log\frac{\mu^2}{M_{W_H}^2} \rightarrow \log\frac{\Lambda^2}{M_{W_H}^2}$$

[dim.reg. $\rightarrow$ cut-off reg.]

Scenarios

The same as in the previous analysis:
large effects in B systems
(green points)

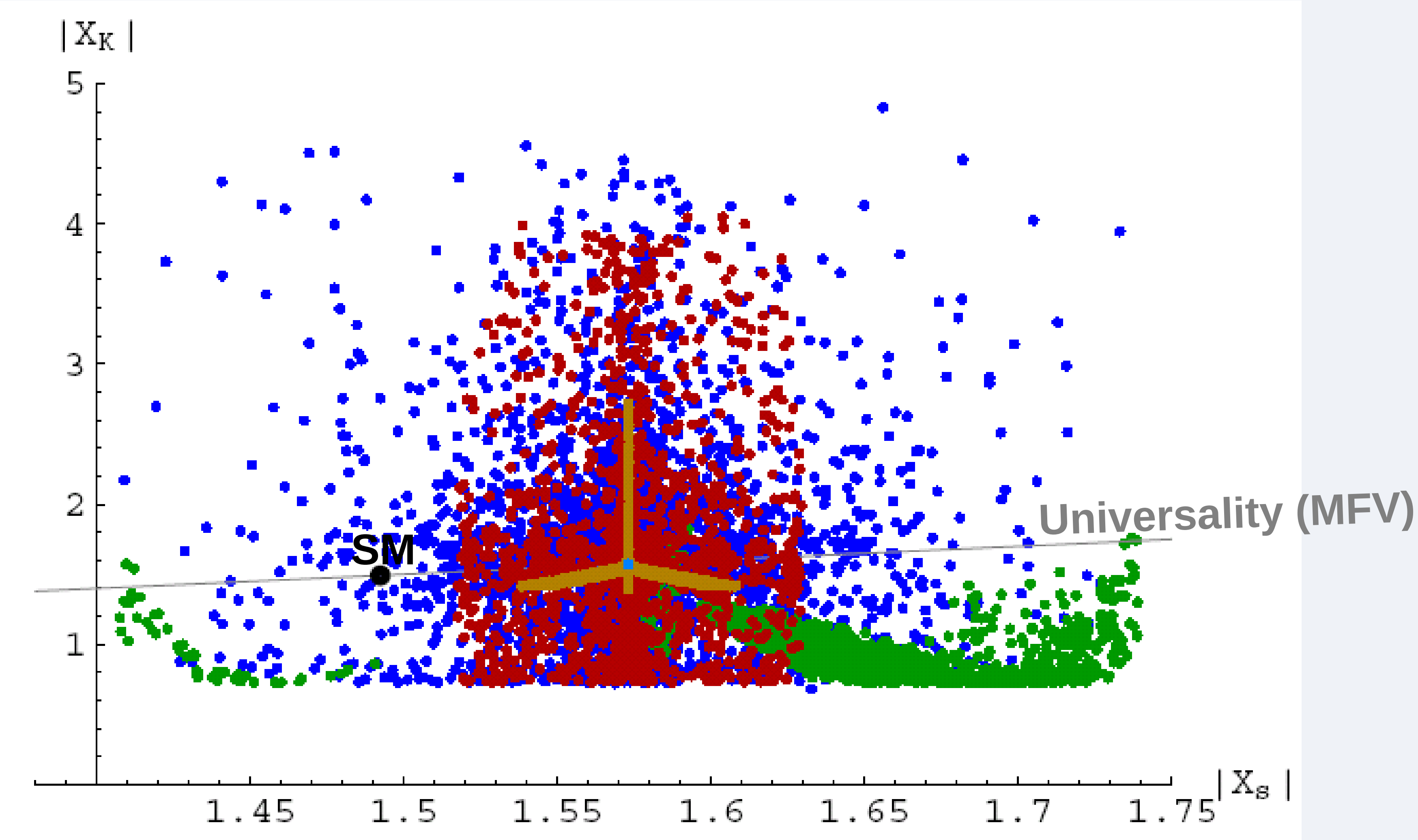
A new scenario:
($m_{H1} \approx m_{H2} \approx 500$ GeV, and a peculiar V_{Hd} hierarchy)
large effects in K rare decays (but not in ΔM_K and ε_K)
(brown points)

$$V_{Hd} = \begin{pmatrix} \frac{c^d_{13}}{\sqrt{2}} & \frac{c^d_{13}}{\sqrt{2}} & s^d_{13} e^{-i\delta^d_{13}} \\ -\frac{1}{\sqrt{2}\sqrt{1+{s^d_{13}}^2}}\left(1 + {s^d_{13}}^2 e^{i\delta^d_{13}}\right) & \frac{1}{\sqrt{2}\sqrt{1+{s^d_{13}}^2}}\left(1 - {s^d_{13}}^2 e^{i\delta^d_{13}}\right) & \frac{s^d_{13} c^d_{13}}{\sqrt{1+{s^d_{13}}^2}} \\ \frac{s^d_{13}}{\sqrt{2}\sqrt{1+{s^d_{13}}^2}}\left(1 - e^{i\delta^d_{13}}\right) & -\frac{s^d_{13}}{\sqrt{2}\sqrt{1+{s^d_{13}}^2}}\left(1 + e^{i\delta^d_{13}}\right) & \frac{c^d_{13}}{\sqrt{1+{s^d_{13}}^2}} \end{pmatrix}$$

A general scan over parameters:
large effects in both B and K systems
(blue points)

A scan on V_{Hd}
with fixed mass spectrum
(red points)

Universality Breakdown in X,Y,Z



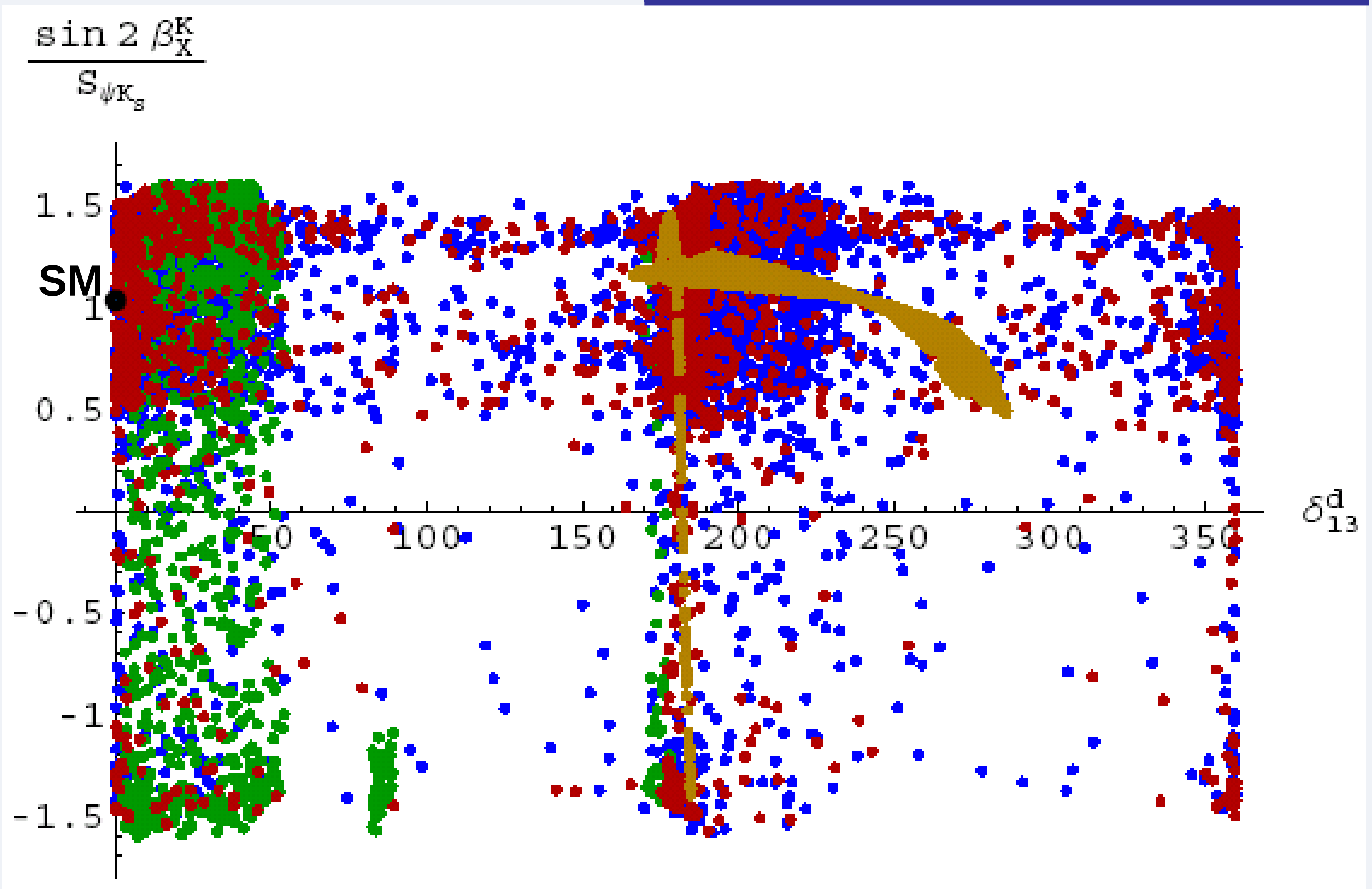
~20% NP effects in **B systems**

~300% NP effects in **K system**

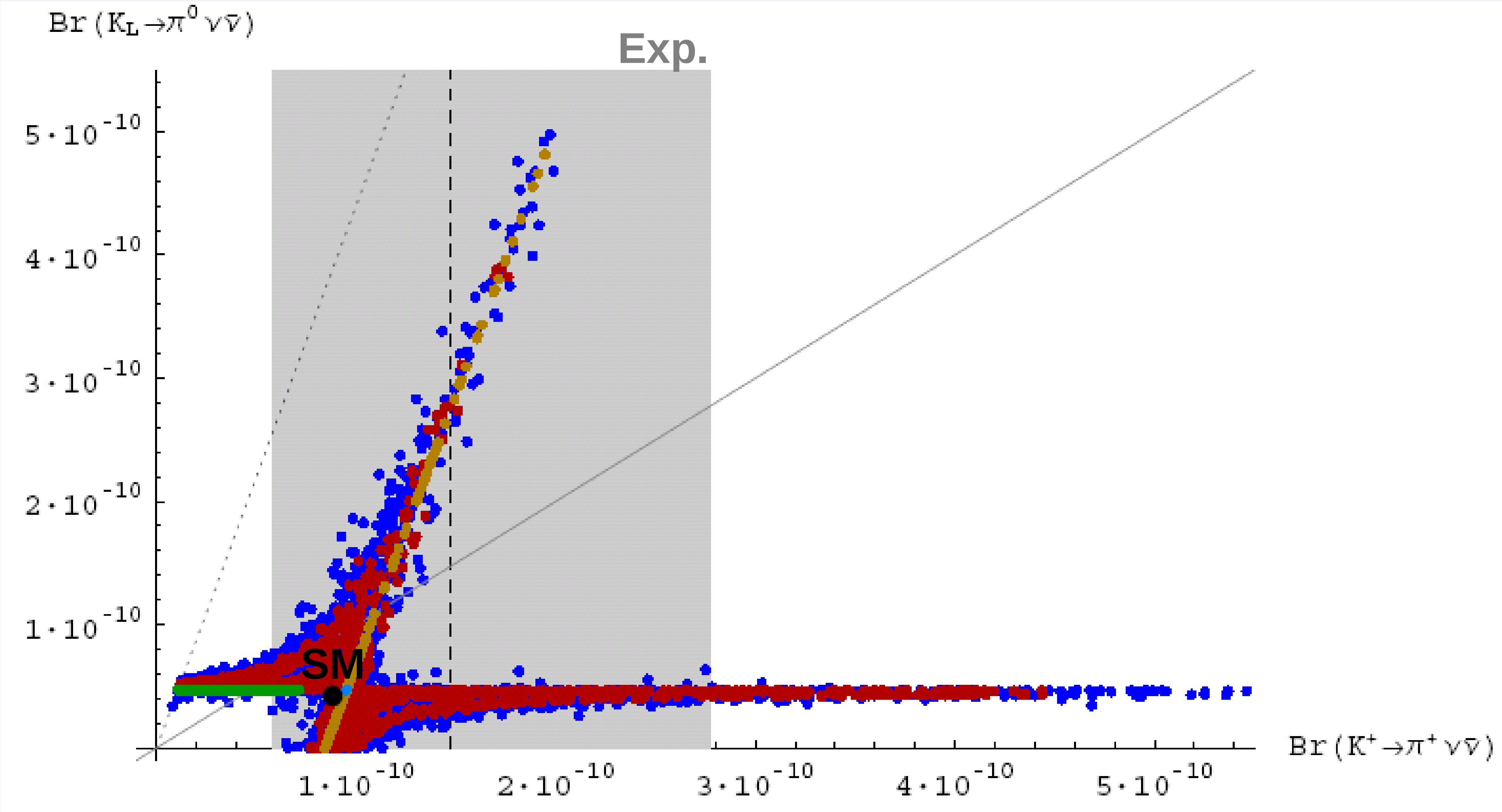
where the SM contribution is tiny: proportional to $\lambda_t^{(K)} \approx 4 \cdot 10^{-4}$

An evident Consequence of Universality Breakdown

The MFV identity between β from $B \to J_\psi K_S$ and $K_L \to \pi^0 \nu \bar{\nu}$ can be strongly violated



K-system: $K_L \to \pi^0 \nu\bar{\nu}$ vs $K^+ \to \pi^+ \nu\bar{\nu}$

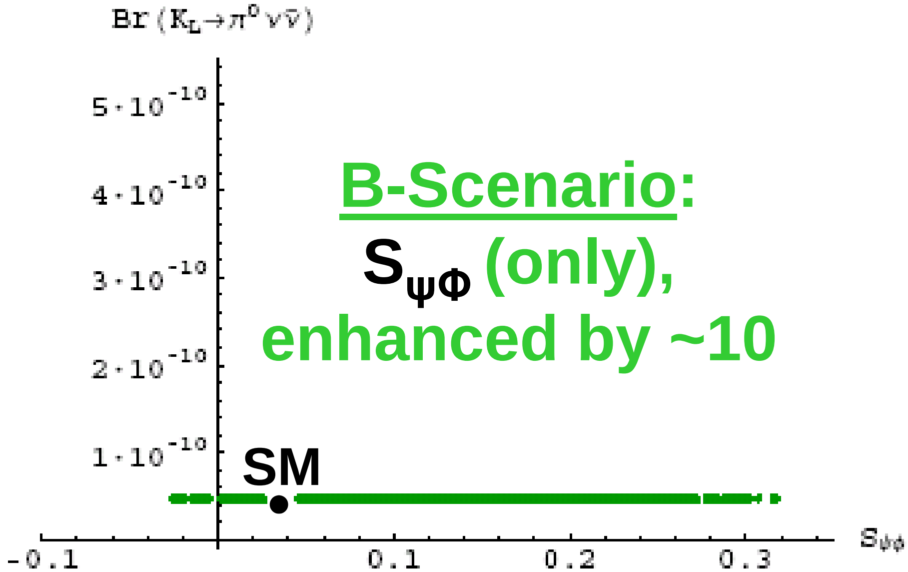


Two distinguished branches appear!

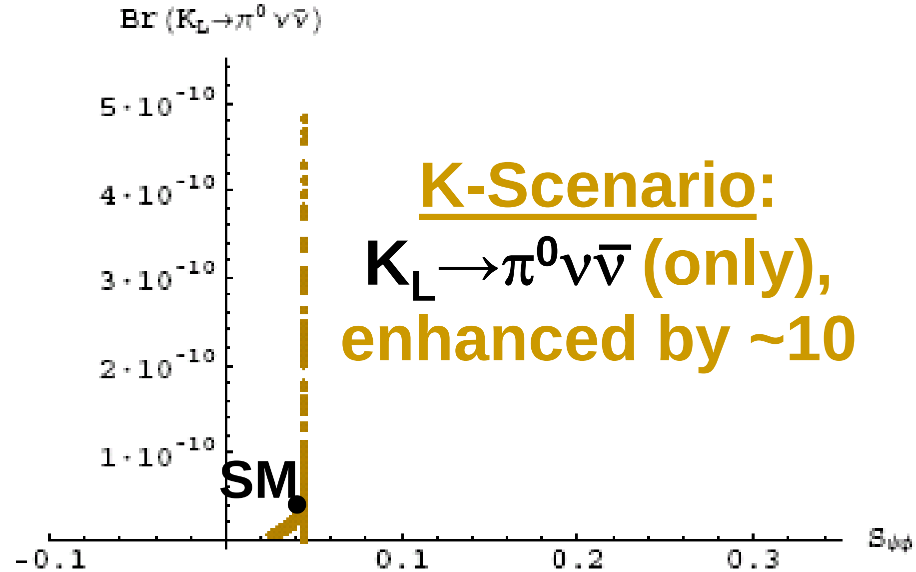
~10 times enhancement in $K_L \to \pi^0 \nu\bar{\nu}$

~5 times enhancement in $K^+ \to \pi^+ \nu\bar{\nu}$

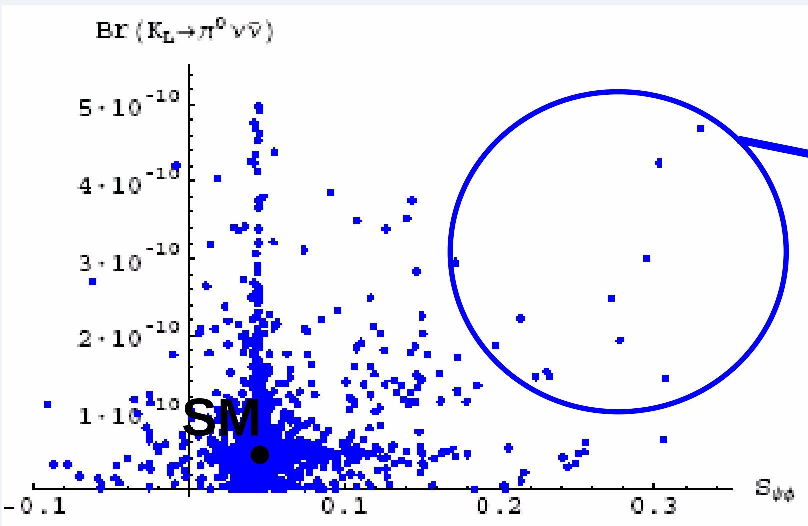
K-system vs B_s-system: $K_L \to \pi^0 \nu\bar{\nu}$ vs $S_{\psi\Phi}$



B-Scenario:
$S_{\psi\Phi}$ (only),
enhanced by ~10

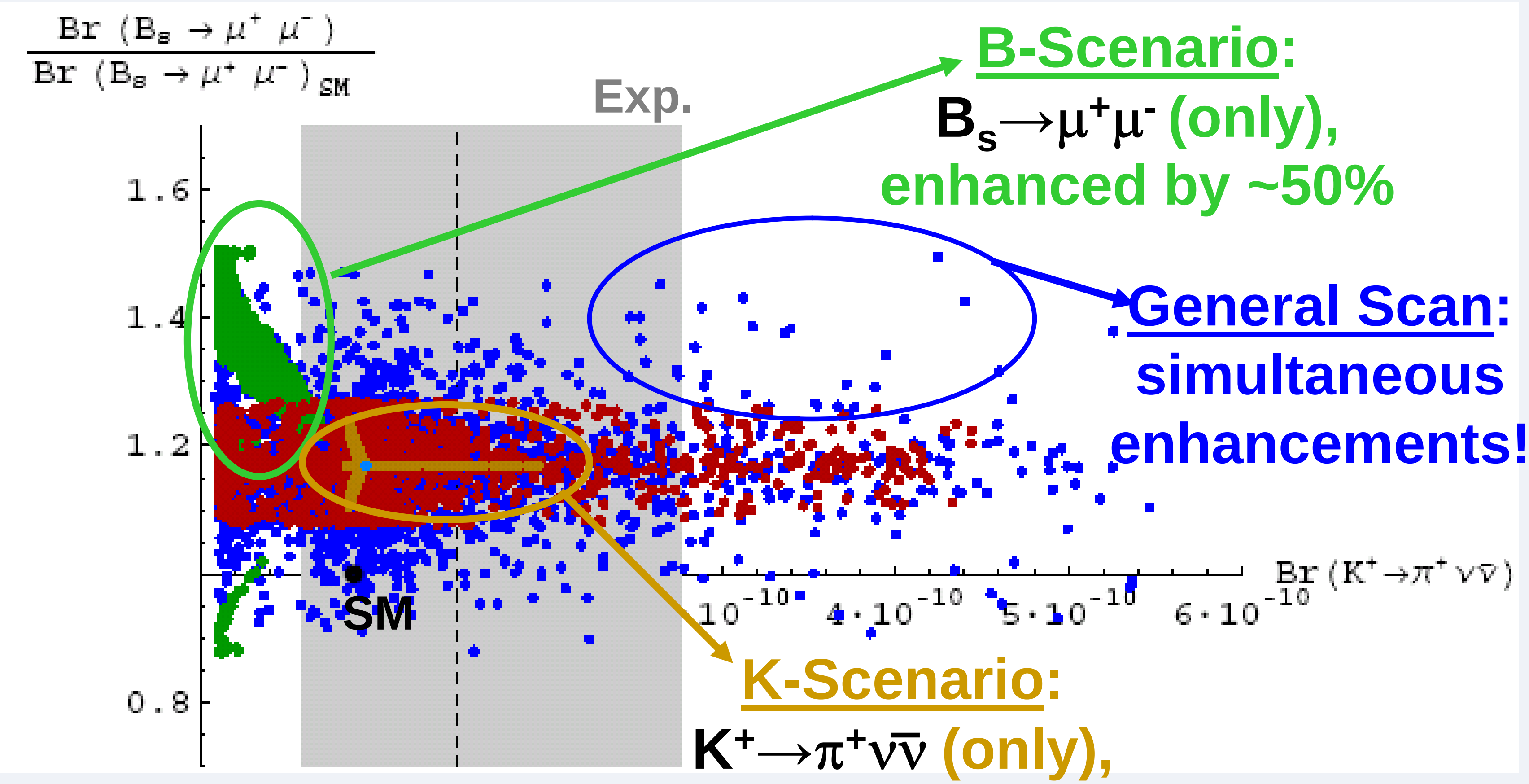


K-Scenario:
$K_L \to \pi^0 \nu\bar{\nu}$ (only),
enhanced by ~10



General Scan: simultaneous enhancements!
(with some fine-tuning between masses and V_{Hd})

B_s-system vs K-system: $B_s \to \mu^+\mu^-$ vs $K^+ \to \pi^+\nu\bar{\nu}$

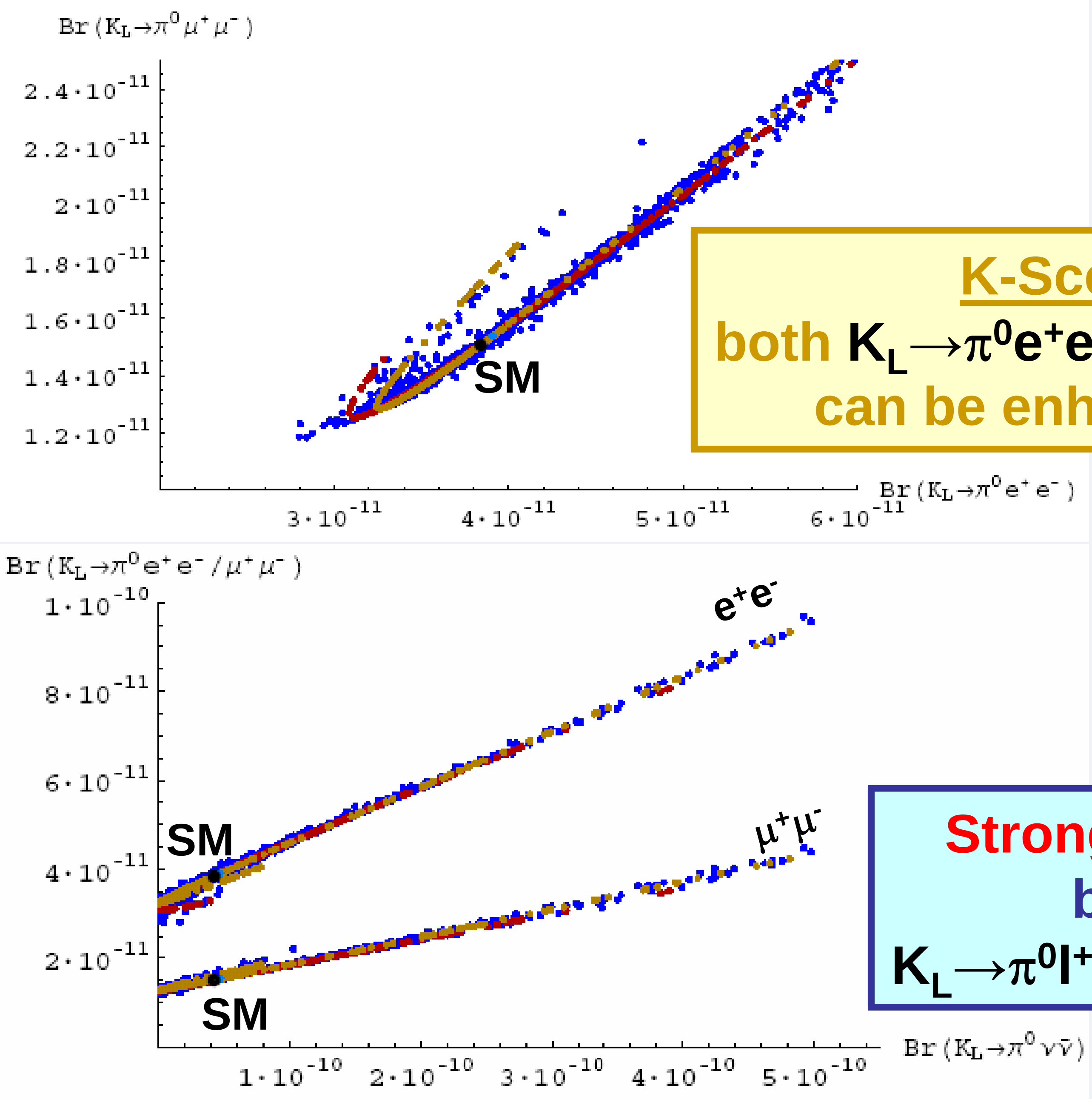


B-Scenario:
$B_s \to \mu^+\mu^-$ (only), enhanced by ~50%

General Scan:
simultaneous enhancements!

K-Scenario:
$K^+ \to \pi^+\nu\bar{\nu}$ (only), enhanced by ~5

K-system: $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$



K-Scenario:
both $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ can be enhanced by ~2

Strong correlation between $K_L \to \pi^0 l^+ l^-$ and $K_L \to \pi^0 \nu \bar{\nu}$

Conclusions

The Littlest Higgs Model with T-Parity:

- Is perturbatively computable up to Λ ~10 TeV
- Has a rather small number of new parameters (~ 20)
- Is in good agreement with electroweak precision tests (f > 500GeV)

In B and K Physics, evident departures from the SM are possible.
Mainly in:

- A^s_{SL}, $S_{\psi\Phi}$, $K_L\to\pi^0\nu\bar{\nu}$ (enhanced by ~10)
- $K^+\to\pi^+\nu\bar{\nu}$ (enhanced by ~ 5), $K_L\to\pi^0 l^+l^-$ (enhanced by ~ 2)
- $B_{s,d}\to\mu^+\mu^-$ (enhanced by ~ 50%), $B\to X_{s,d}\nu\bar{\nu}$ (enhanced by ~ 35%)

MFV relations can be sizably violated

Only small effects are allowed in $B\to X_{s,d}\gamma$, $B\to X_{s,d}l^+l^-$, $B\to\pi K$