Patterns of Flavour Violation in a RS Model with Custodial Protection

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Mixing, $\not{CP}$ in RS model [hep-ph/0809.1073]

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(50)

Rare K and B Decays in RS model [hep-ph/0812.3803]

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Electroweak and Flavour Structure [hep-ph/0903]


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Impact of KK Fermions on SM fermion couplings [hep-ph/0903]


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Strategy for the next 19 Minutes

1. Going beyond MFV
2. RS Framework
3. A RS-Model with Custodial Protection
4. Patterns of Flavour Violation in 3 Steps
5. Selected Numerical Results
6. Final Messages

1.

Going beyond MFV

Basic Structure of FCNC Amplitudes

Long Distance (Non-perturbative Lattice)

Flavour and CPV in SM and MFV enters only here

Short Distance Functions (Perturbation TH)

(real for MFV)

$$A(FCNC) = \sum_i B_i \eta_i^{QCD} V_i^{CKM} F_i(m_t, NP)$$

Renormalization Group (QCD) LD $\leftrightarrow$ SD

Only Loops if GIM works

NP can add new B_i´s absent in SM

(New Operators with new Dirac Structures)

NP can add new loops and trees with new flavour parameters and CPV phases

non-MFV

Possible Dirac Structures in $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$

SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1-\gamma_5)$$

LHT

Strong enhancements

Beyond SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1+\gamma_5)$$

$$\star \; (1-\gamma_5) \otimes (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1-\gamma_5)$$

$$\sigma_{\mu\nu} (1-\gamma_5) \otimes \sigma^{\mu\nu} (1-\gamma_5)$$

RS (first two structures)

SUSY (all four structures)

MSSM with large tanβ
General Supersymmetric Models
Models with complicated Higgs System; RS Models

NLO $\left[\eta^i_{QCD}\right]^{New}$: Ciuchini, Franco, Lubicz, Martinelli, Scimemi, Silvestrini

AJB, Misiak, Urban, Jäger

Enhancements of Q_{LR} versus Q_{LL} in $\Delta F=2$ Transitions

$$\mu \cong 3\text{TeV} \xrightarrow{RG} \begin{array}{l} \mu_B \approx 5\text{GeV} \\ \mu_K \approx 2\text{GeV} \end{array}$$

	Wilson Coefficient (RG Enhancement)	Hadronic Matrix Element (Chiral Enhancement)	Total
$K^0 - \overline{K}^0$	~ 7	20	140
$B^o_{d,s} - \overline{B}^0_{d,s}$	~ 4.3	1.5	6.5

Comparison of Beyond-MFV Scenarios

Scenario	New Flavour and CP Violation	New Operators	FCNC at Tree Level
LHT	★		
SUSY	★	★	
RS	★	★	★

(non-universitalities in gauge couplings implied by the manner CKM and mass hierarchies are explained)

General Structure of New Physics Contributions

SM :

$$\lambda_t^{(K)} = V_{ts}^* V_{td} \qquad \lambda_t^{(d)} = V_{tb}^* V_{td} \qquad \lambda_t^{(s)} = V_{tb}^* V_{ts}$$

Amplitudes :

$$\lambda_t^{(i)} X_{SM}(m_t)$$

$\nu\bar{\nu}$ in the final state

$$\lambda_t^{(i)} Y_{SM}(m_t)$$

$\mu^+\mu^-$ in the final state

Universality of short distance functions

$i = K, B_d, B_s$

LHT **RS** :

$$X_i = X_{MFV} + \frac{1}{\lambda_t^{(i)}} \xi_i \overline{X} \equiv |X_i| e^{i\theta_X^i}$$

real complex

$$Y_i = Y_{MFV} + \frac{1}{\lambda_t^{(i)}} \xi_i \overline{Y} \equiv |Y_i| e^{i\theta_Y^i}$$

Breakdown of Universality

New Flavour and ~~CP~~ in ξ_i

Non-MFV

Natural Expectations

$$X_i = X_{MFV} + \frac{1}{\lambda_t^{(i)}} \xi_i \overline{X} \equiv |X_i| e^{i\theta_X^i}$$

(similarly for Y_i) Non-MFV

$i = K, B_d, B_s$

$$\frac{1}{\lambda_t^{(K)}} \approx 2 \cdot 10^3$$

$$\frac{1}{\lambda_t^{(d)}} \approx 100$$

$$\frac{1}{\lambda_t^{(s)}} \approx 25$$

Natural size of NP contributions : **$K \gg B_d > B_s$**

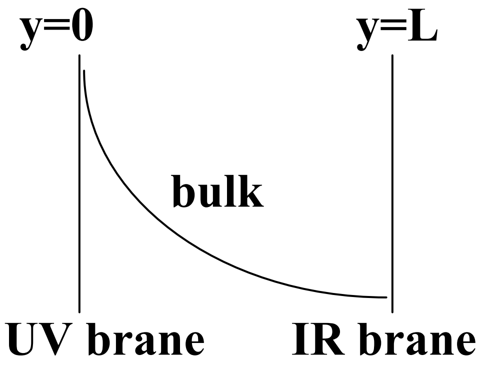
But can be modified for special structures of ξ_i

2.

Randall-Sundrum Framwork (Express Summary)

5D spacetime with warped metric:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu - dy^2 \qquad 0 \le y \le L$$



- **fermions and gauge bosons live in the bulk**
- **Higgs localised on IR brane**

(Chang, Okada et al.
Grossman, Neubert
Gherghetta, Pomarol)

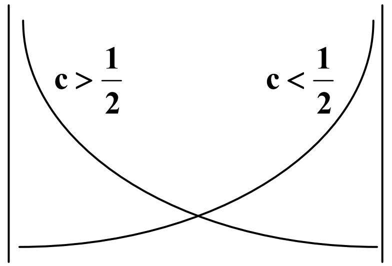
- **energy scales suppressed by warp factor e^{-ky}**
  natural solution to the gauge hierarchy problem.
- **Kaluza-Klein (KK) excitations of both SM fermions and gauge bosons live close to the IR brane.**

Fermion Localisation and Yukawa Couplings

SM fermion (zero mode) shape function depends strongly on bulk mass parameter characteristic for a given fermion:

$$f^{(0)}(y,c)\ \alpha\ \ e^{\left(\frac{1}{2}-c\right)y}$$

UV brane IR brane



Higgs

$c > \frac{1}{2}$: localisation near UV brane

$c < \frac{1}{2}$: localisation near IR brane

effective 4D Yukawa couplings:

$$\left(Y_{u,d}\right)_{ij} = \left(\lambda_{u,d}\right)_{ij} f_i^Q f_j^{u,d}$$

- $\lambda_{u,d} \sim 0(1)$ anarchic complex 3 x 3 matrices $\equiv Y_{5D}$
- hierachical structure of quark masses and CKM parameters can be naturally generated by exponential suppression of $f^{Q,u,d}$ at IR brane.

Bulk Profiles of SM Gauge Bosons

- **Gluons and Photon : flat** (protection by Gauge symmetry)
- **$W^{\pm}$, Z : flat before EWSB**

but

distorted near the IR brane after EWSB $0\left(\frac{v^2}{M_{KK}^2}\right)$

Equivalently : Mixing of KK gauge bosons with $W^{\pm}$, Z in the process of EWSB modifies the couplings of mass eigenstates $W^{\pm}$, Z

- **Recall :**

All KK gauge bosons live close to the IR brane

All KK fermions live close to the IR brane

First Implications for Phenomenology

1.

Gauge-Fermion Interactions: Overlaps of shape functions ⇒ **Non-universalities in Gauge Couplings** ← (in flavour)

of { KK-gauge bosons, $W^{\pm}$, Z }
to {SM fermions}

★

2.

Impact on Electroweak Precision Observables

$SU(2)_L \otimes U(1)_Y$

S parameter : $M_{KK} \geq$ (2-3) TeV
T parameter: $M_{KK} \gtrsim$ 10 TeV

Agashe, Delgado, May, Sundrum (2003)
Csaki, Grojean, Pilo, Terning (2003)

Also problems with $Z b_L \bar{b}_L$

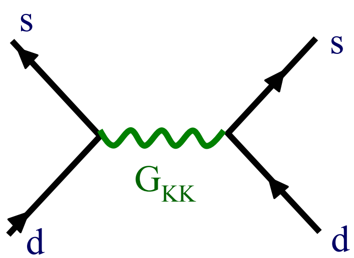
3. Tree Level FCNC mediated by KK gauge bosons and Z (breakdown of standard GIM mechanism)

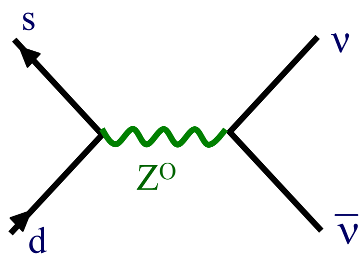
$$d \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\bar{d} D_L^{+} \begin{pmatrix} a & & \\ & b & \\ & & c \end{pmatrix} D_L \gamma_\mu Z^\mu d \neq \bar{d} \gamma_\mu Z^\mu d$$

(non-universality)

$$0\left(\frac{v^2}{M_{KK}^2}\right)$$





$$0\left(\frac{v^2}{M_{KK}^2}\right)$$

But RS-GIM helps in avoiding disaster.

Gherghetta, Pomarol
Huber, Shafi
Agashe, Soni, Perez

4.

Mixing of KK fermions with SM fermions and mixing of KK gauge bosons with SM gauge bosons

→ **Breakdown of Unitarity of the CKM matrix**

5.

Tree level exchanges of G_{KK} and Z → **Contributions of new operators. In particular Q_{LR} operators in addition to Q_{LL}, Q_{RR}**

6.

The presence of three 3 x 3 hermitian bulk matrices c^q, c^u, c^d in addition to usual Yukawa couplings → **New flavour and CP violating parameters:**
$3 * 6 = 18$ real
$3 * 3 = 9$ phases

Non-MFV

3.

A RS Model with Custodial Protection

$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X \otimes P_{LR}$

Gauge Group in the Bulk

$P_{LR} : SU(2)_L \leftrightarrow SU(2)_R$

P_{LR} symmetric fermion representations

What is protected in this Model?

(up to small symmetry breaking due to UV boundry conditions)

A. T-Parameter — Agashe, Delgado, May, Sundrum (0308036)
Csaki, Grojean, Pilo, Terning (0308038)

★

B. $Z\bar{b}_L b_L$ — Agashe, Contino, Rold, Pomarol (0605341)

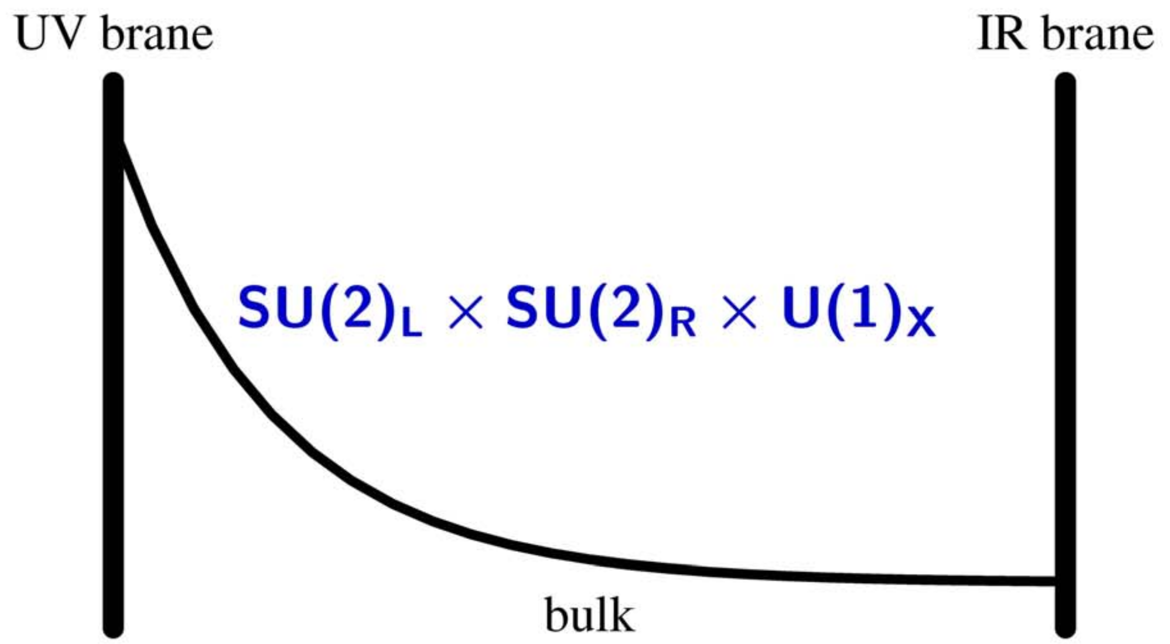
C. $Z\bar{d}^i_L d^j_L$ — Blanke, AJB, Duling, Gori, Weiler (0809.1073)
Blanke, AJB, Duling, Gemmler, Gori (0812.3803)

★

D. $Z\bar{u}^i_R u^j_R$ — AJB, Duling, Gori (0903xxx)

But: $Z\bar{d}^i_R d^j_R, \quad Z\bar{u}^i_L u^j_L, \quad W^+\bar{u}^i_L d^j_L$ **not protected**

A Realistic Model in the Reach of the LHC



$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
by boundary conditions

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
by Higgs VEV

$+$ $(L \leftrightarrow R)$-symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$

Particle Content of the Model

Albrecht, Blanke, AJB, Duling, Gemmler (0903xxx)

Gauge sector

$W^\pm$, Z^0, | $W_H^\pm$, $W'^\pm$, Z_H, Z' (KK)

A, G^a, | $A^{(\prime)}$, $G^{a(\prime)}$ (KK)

Quark sector (i=1,2,3)

$SU(2)_L \otimes SU(2)_R$

$$(2,2) = \begin{pmatrix} \chi^{u_i}(-+)_{5/3} & q^{u_i}(++)_{2/3} \\ \chi^{d_i}(-+)_{2/3} & q^{d_i}(++)_{1/3} \end{pmatrix}_L \qquad (1,1) = u_R^i(++)_{2/3}$$

$$(3,1) = \begin{pmatrix} \psi'^i(-+)_{5/3} \\ U'^i(-+)_{2/3} \\ D'^i(-+)_{-1/3} \end{pmatrix}_R \oplus \begin{pmatrix} \psi''^i(-+)_{5/3} \\ U''^i(-+)_{2/3} \\ D^i(++)_{-1/3} \end{pmatrix}_R = (1,3)$$

\+ states of opposite chirality

Q=5/3 Fermions!

(Feynman rules worked out for SM and n=1 KK modes)

Higgs and Mass Matrices

$$H = \begin{pmatrix} \pi^+ / \sqrt{2} & -\left(h^0 - i\pi^0\right)/2 \\ \left(h^0 + i\pi^0\right)/2 & \pi^- / \sqrt{2} \end{pmatrix}$$

For SM and n=1 KK modes with flavour i=1,2,3

$M(5/3) = 9 \text{ x } 9$ $M(2/3) = 18 \text{ x } 18$ $M(-1/3) = 12 \text{ x } 12$

a) Numerical Diagonalization (BB D GW)

b) Analytic Reduction to 3 x 3 by means of effective Lagrangians (integrating out of KK modes) (AJB, Duling, Gori)

4.

Patterns of Flavour Violation in 3 Steps

First look at $\Delta F = 2$: Burdman; Agashe, Perez, Soni

First more sophisticated analysis : Csaki, Falkowski, Weiler (0804.1954)

Application of model-independent results of Utfit group to RS-type models.

Hierarchy of fermion masses and weak mixings solely due to geometry Y_{5D} anarchic and 0(1)

KK-Gluon → Contribution to ε_k

$$M_{KK} \gtrsim 21\ \mathrm{TeV}$$

Step 1 : ($\Delta F = 2$ Processes)

(Blanke, AJB, Duling, Gori, Weiler (0809.1073))

A. Full RG analysis at the NLO level: (using AJB, Misiak, Urban; Jäger) (2000)

$$Q_1^{VLL} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_L d) \qquad Q_1^{LR} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_R d)$$

$$Q_1^{VRR} = (\bar{s}\gamma_\mu P_R d)(\bar{s}\gamma^\mu P_R d) \qquad Q_2^{LR} = (\bar{s}P_L d)(\bar{s}P_R d)$$

(For $K^0 - \bar{K}^0$, $B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ systems)

B. Inclusion of the contributions of all gauge bosons:
(G_{KK}, A_{KK}, Z, Z_H, Z') (Protection of Z and Z' pointed out)

$Z\bar{d}_d^i d_L^j$

$Z'\,\bar{d}_L^i d_L^j$

C. Phenomenology of ε_K, ΔM_K, ΔM_S, ΔM_d, $S_{\psi Ks}$, $S_{\psi\varphi}$, A_{SL}^q, $\Delta\Gamma_q$

D. Relation of RS flavour model to Froggatt-Nielsen (analytic formulae for masses and mixings)

E. Calculation of fine tuning (Barbieri + Giudice) of Yukawa couplings $\Delta_{BG}(\varepsilon_K)$ necessary to satisfy ε_K with $M_{KK} \sim$ 2-3 TeV

Main Results of Step 1

A. **Confirmation of CFW analysis for anarchic 5D Yukawa's.**

B. **Identifications of regions in parameter space with only modest fine-tuning of Y_{5D} which satisfy all $\Delta F = 2$ constraints, agree with quark masses and mixings and electroweak constraints for $M_{KK} \sim$ 2-3 TeV.**

C. **Pattern of NP contributions**

: ε_K, ΔM_K : dominated by Q_2^{LR} and G_{KK}

$\Delta M_d, \Delta M_s, S_{\psi K_s} S_{\psi\varphi}$: Competition between Q_1^{VLL} and Q_2^{LR} (Z_H and G_{KK} dominate)

D. **$S_{\psi\varphi}$ asymmetry can be by order of magnitude larger than $\left(S_{\psi\varphi}\right)_{SM}$.**

Step 2 : (Rare K and B Decays) ($\Delta F=1$)

(Blanke, AJB, Duling, Gemmler, Gori (0812.3803))

A. Calculation of $K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ K_L \to \pi^0 l^+ l^-,$

$K_L \to \mu^+\mu^-,\ B_{s,d} \to \mu^+\mu^-,\ B \to K\nu\bar{\nu},$

$B \to K^* \nu\bar{\nu},\ B \to X_{s,d}\nu\bar{\nu}$

For all allowed regions of parameters from Step 1 with $\Delta_{BG}(\varepsilon_K) \leq 20$

B. Dominance of tree level Z-exchanges but through its right-handed couplings.

C. Study of correlations between various $\Delta F=1$ branching ratios and of $(\Delta F=1) \leftrightarrow (\Delta F=2)$ correlations.

Main Results of Step 2

A. **Enhancements of** $Br(K_L \to \pi^0 \nu\bar{\nu})$ **by a factor 5**

$Br(K^+ \to \pi^+ \nu\bar{\nu})$ **by a factor 2**

$Br(K_L \to \pi^0 l^+ l^-)$ **by a factor 1.5**

} **possible (even simultaneously)**

B. **Large Enhancements of** $Br(K_L \to \mu^+\mu^-)$ **but not simultaneously with** $K^+ \to \pi^+ \nu\bar{\nu}$ **.**

C. **SM-like** $Br(B_{s,d} \to \mu^+\mu^-)$, $Br(B \to K\nu\bar{\nu})$, $Br(B \to K^* \nu\bar{\nu})$, $Br(B \to X_{s,d} \nu\bar{\nu})$ } **(10-20% effects)**

D. **Simultaneous large effects in** $S_{\psi\varphi}$ **and** $K \to \pi\nu\bar{\nu}$ **not possible.**

E. **Non-Universality of NP effects and consequently "golden relations" of MFV can be strongly broken.**

Step 3 : Impact of KK fermions (Effective Lagrangian approach)

(AJB, Duling, Gori (0903.xxx))

1. General formulae for corrections to SM fermion ↔ ($W^{\pm}$, Z, H) couplings from mixing with KK fermions.

2. Explicit demonstration that the custodial protection of $Zd_L^i \bar{d}_L^j$ and $Zu_R^i \bar{u}_R^j$ couplings remains valid in the presence of mixing with KK fermions (guaranteed by P_{LR} symmetric fermion representations)

3. Calculations of KK corrections to unprotected $Zd_R^i \bar{d}_R^j$ and $Zu_L^i \bar{u}_L^j$

4. Study of the violation of the unitarity of the CKM due to KK mixing

+ Comparison with brute force numerical diagonalization of 18 x 18 and 12 x 12 matices (for 3. and 4.)

5.

Selected Numerical Results

Fine Tuning in $\Delta F=2$ Processes (BBDGW)

$$\Delta_{BG}(Q) = \max_i \left| \frac{x_i}{Q} \frac{\partial Q}{\partial x_i} \right|$$

Barbieri + Giudice

$M_{KK} \approx 2.5\,\text{TeV}$

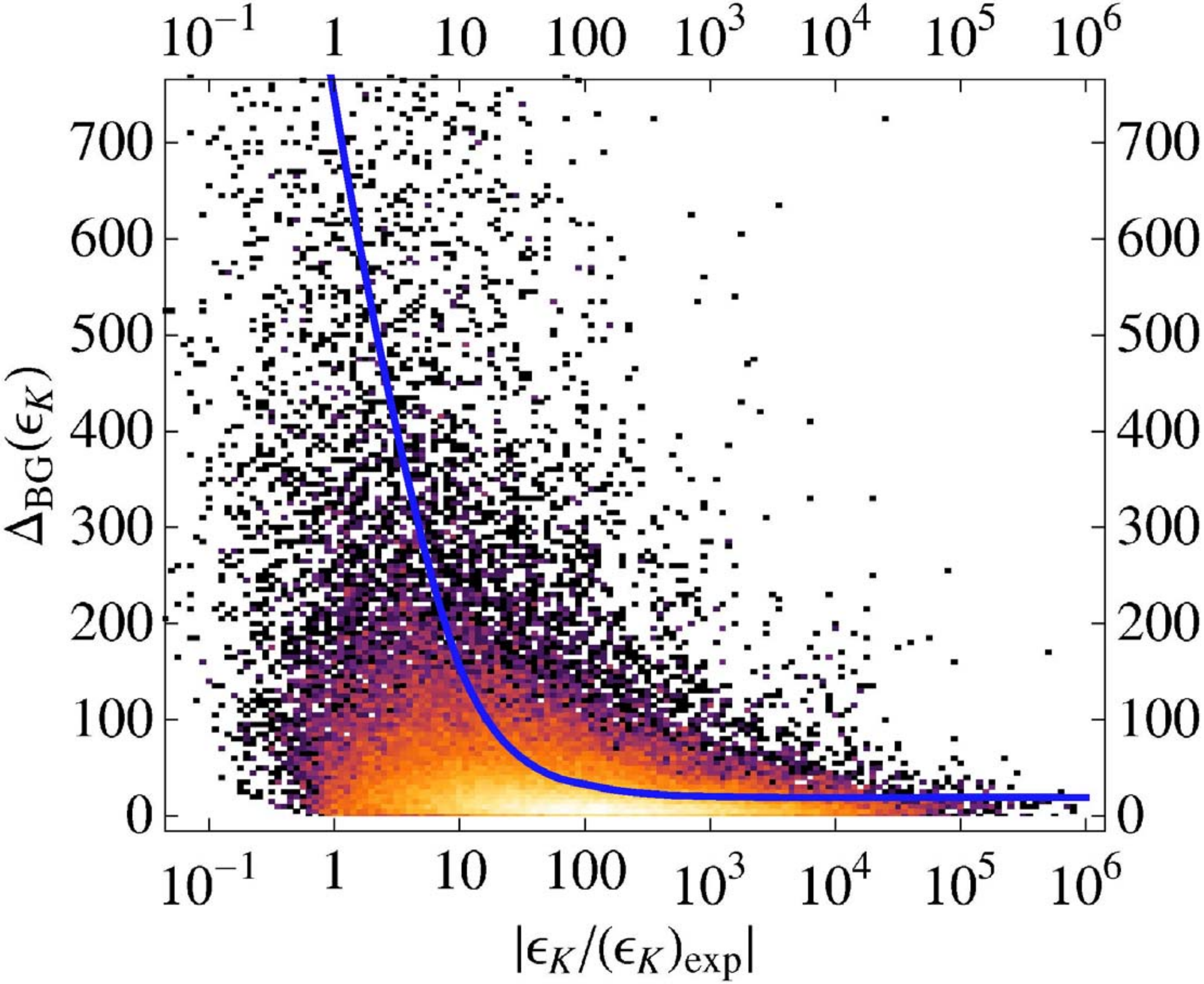
- Generically: $\varepsilon_K \cong 10^2 \varepsilon_K^{exp}$
- $\Delta_{BG}(\varepsilon_K)$ decreases with increasing ε_K
- Parameter sets with moderate $\Delta_{BG}(\varepsilon_K) \leq 20$ and $\varepsilon_K \approx \varepsilon_K^{exp}$ exist.

For ΔM_K and $\Delta B=2$ observables fine tuning much smaller.
Generically: $(\Delta_{BG} \lesssim 20)$ $(\Delta_{BG} \leq 5)$

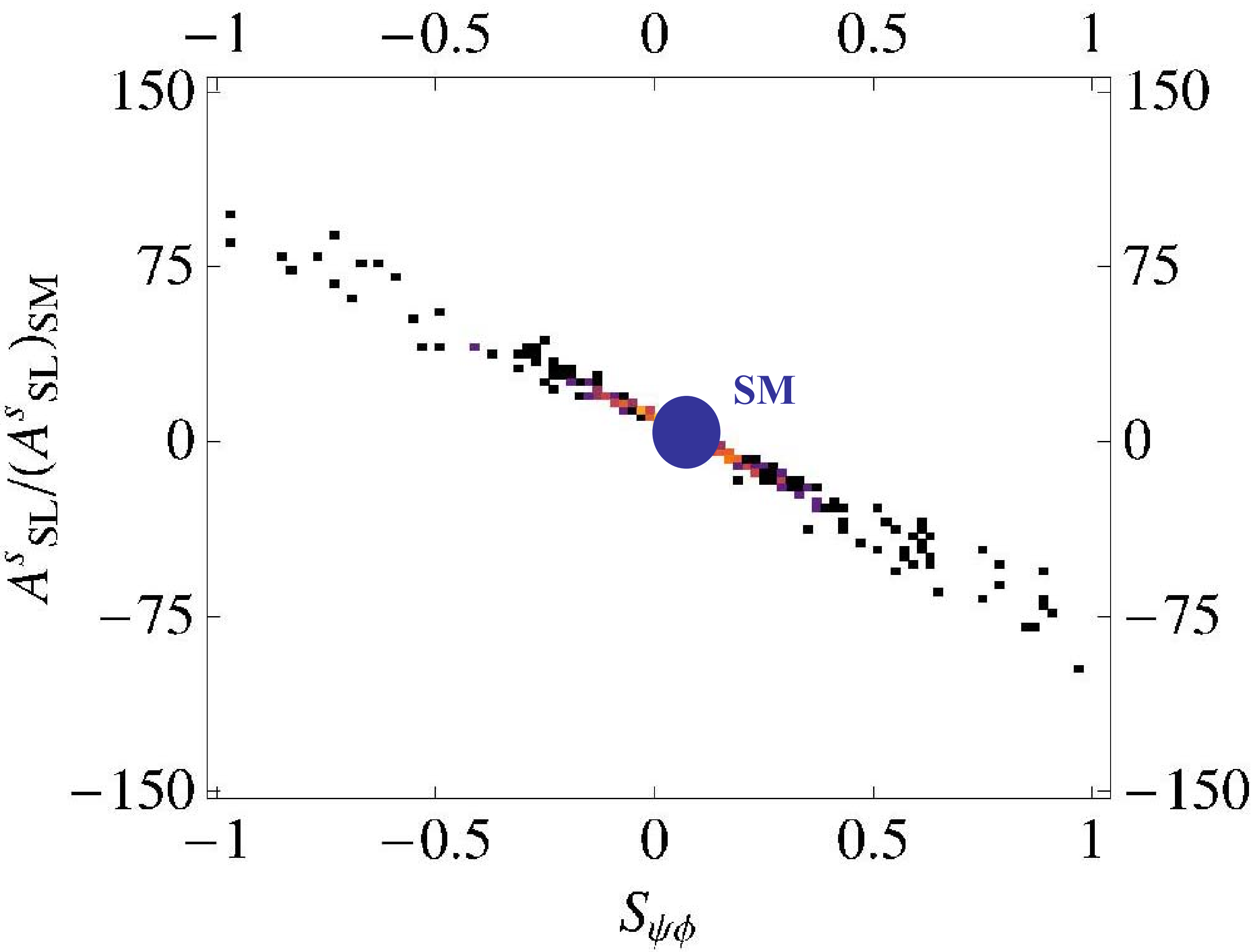
RS-GIM very effective

Fine Tuning in ε_K

Blanke
AJB
Duling
Gori
Weiler



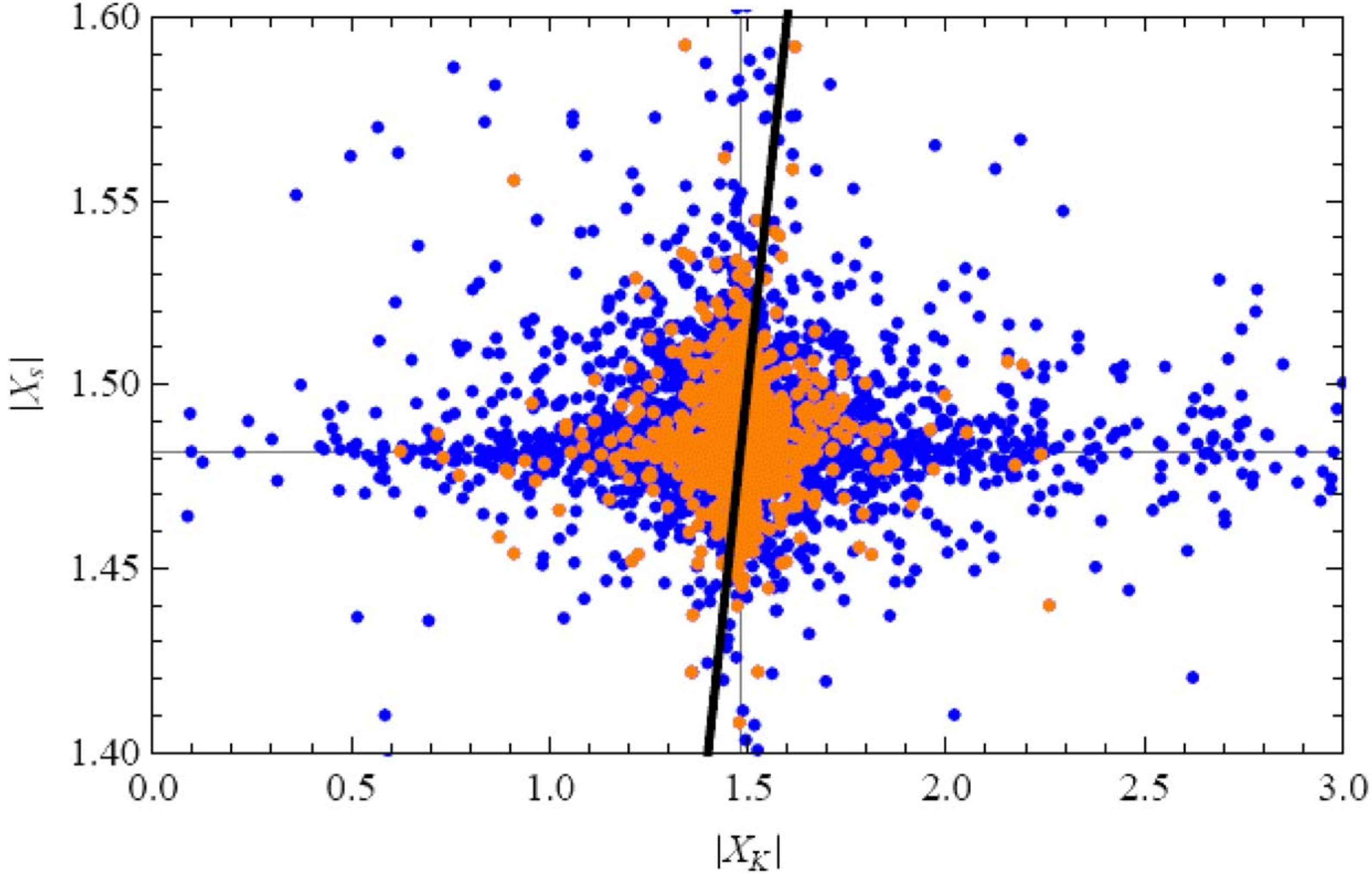
Correlation in Warped Extra Dimensions



M.Blanke, AJB, B.Duling, S.Gori, A.Weiler (2008)

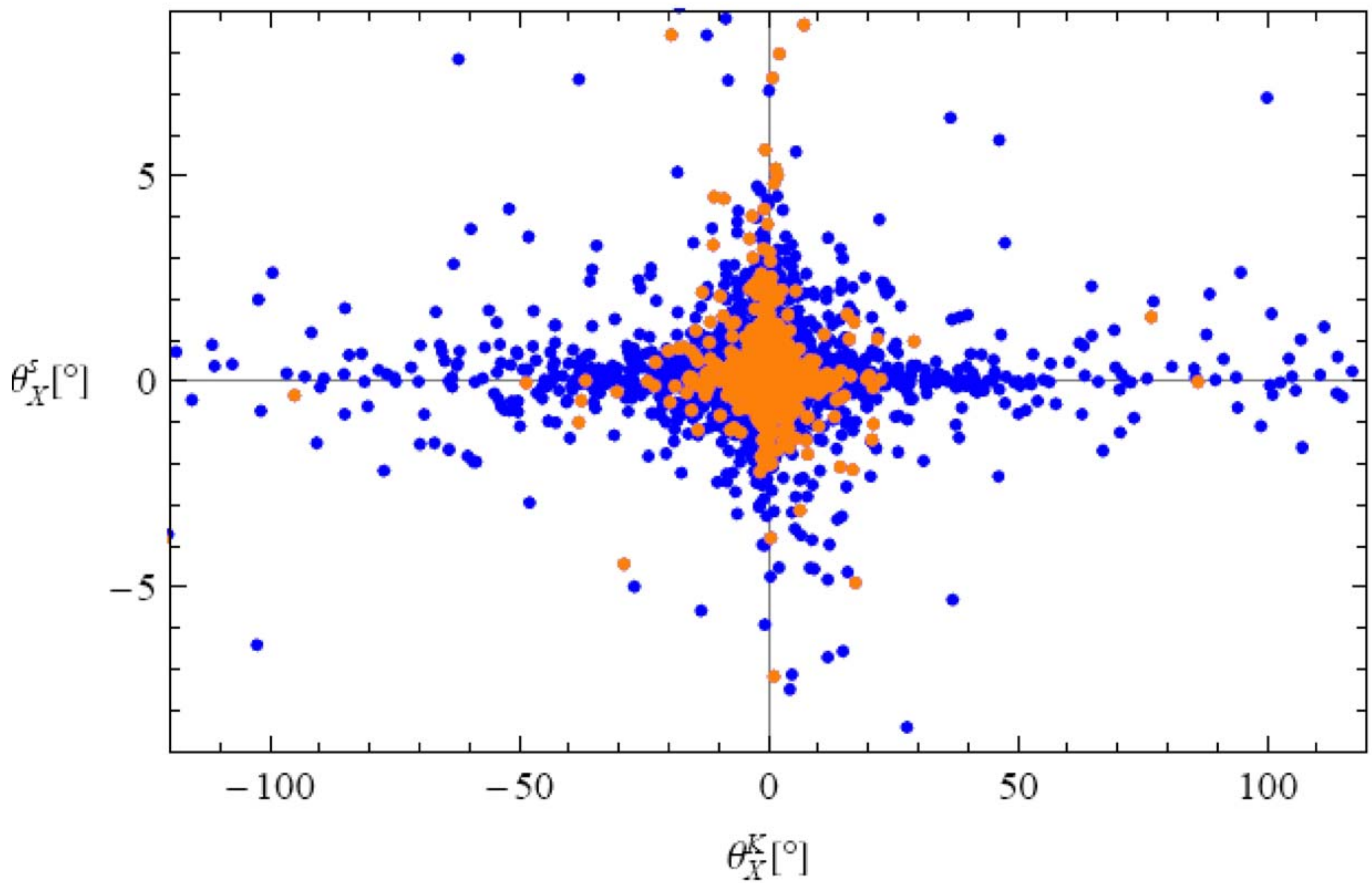
Breakdown of Universality in X

(NP effects much larger in K decays)



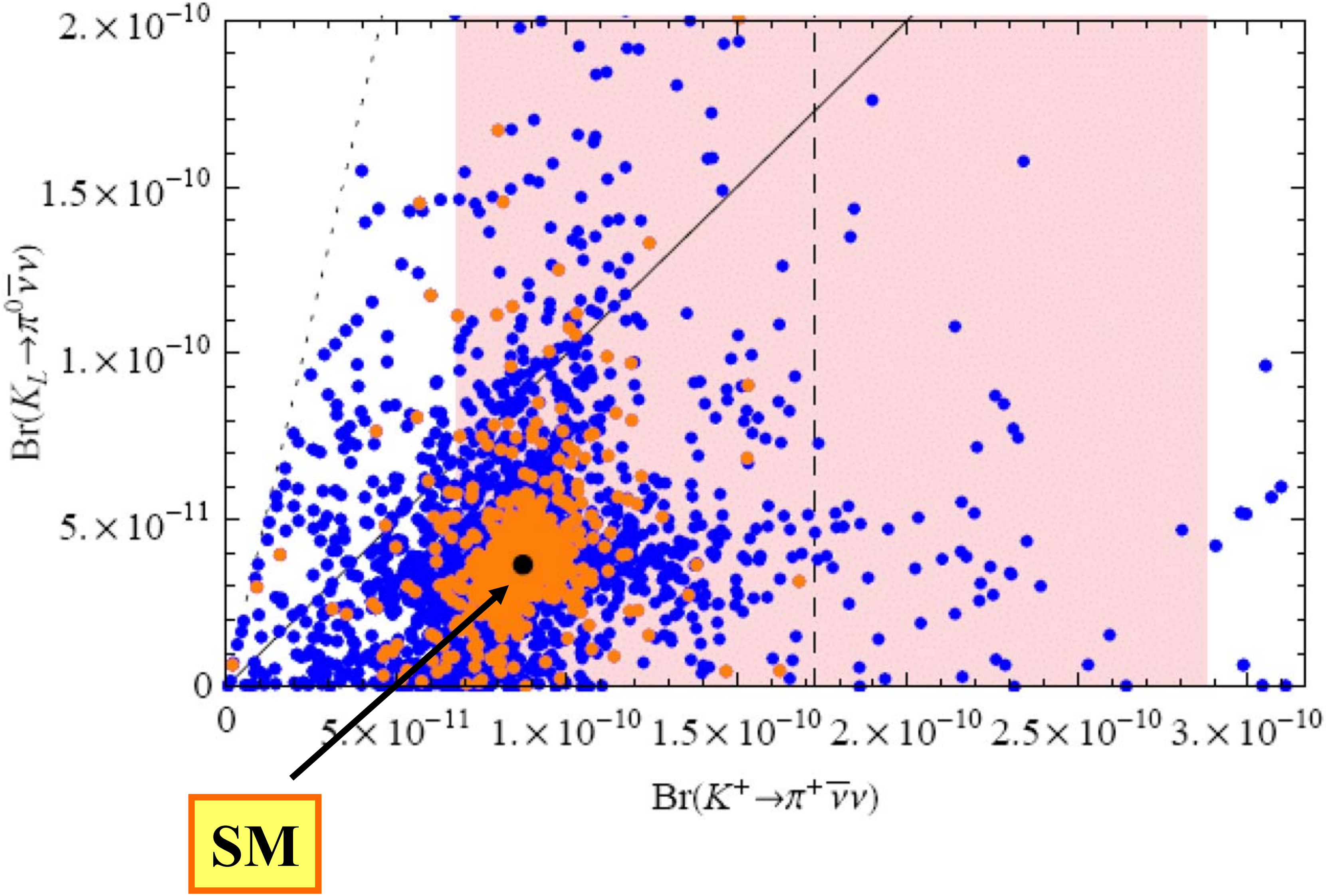
New CP-Violating Phases

(NP effects much larger in K decays)



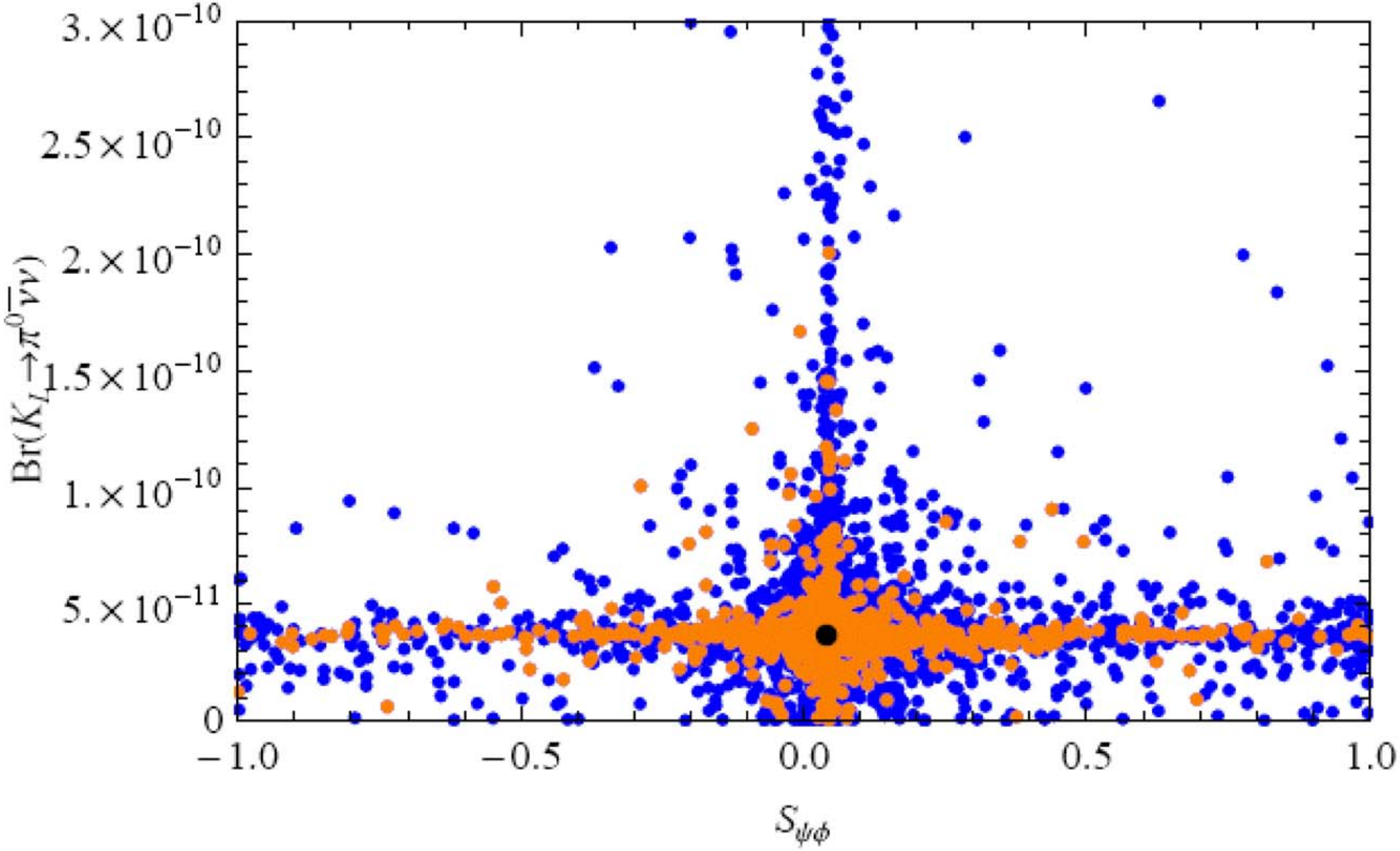
$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$

(Up to Factor 5 and 2 Enhancements)



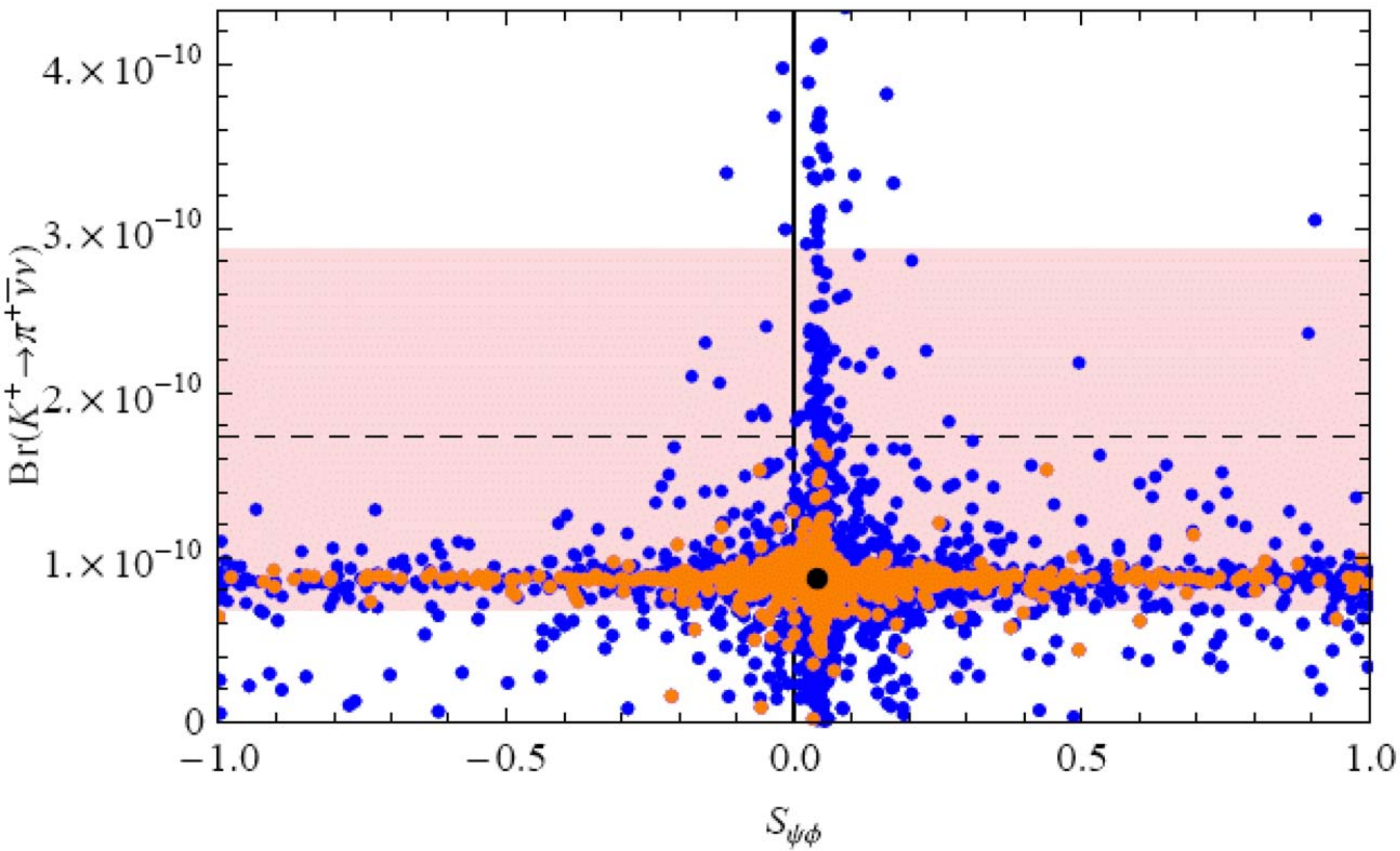
$K_L \to \pi^0 \nu\bar{\nu}$ vs. $S_{\psi\varphi}$

(Simultaneous Large Enhancements unlikely)

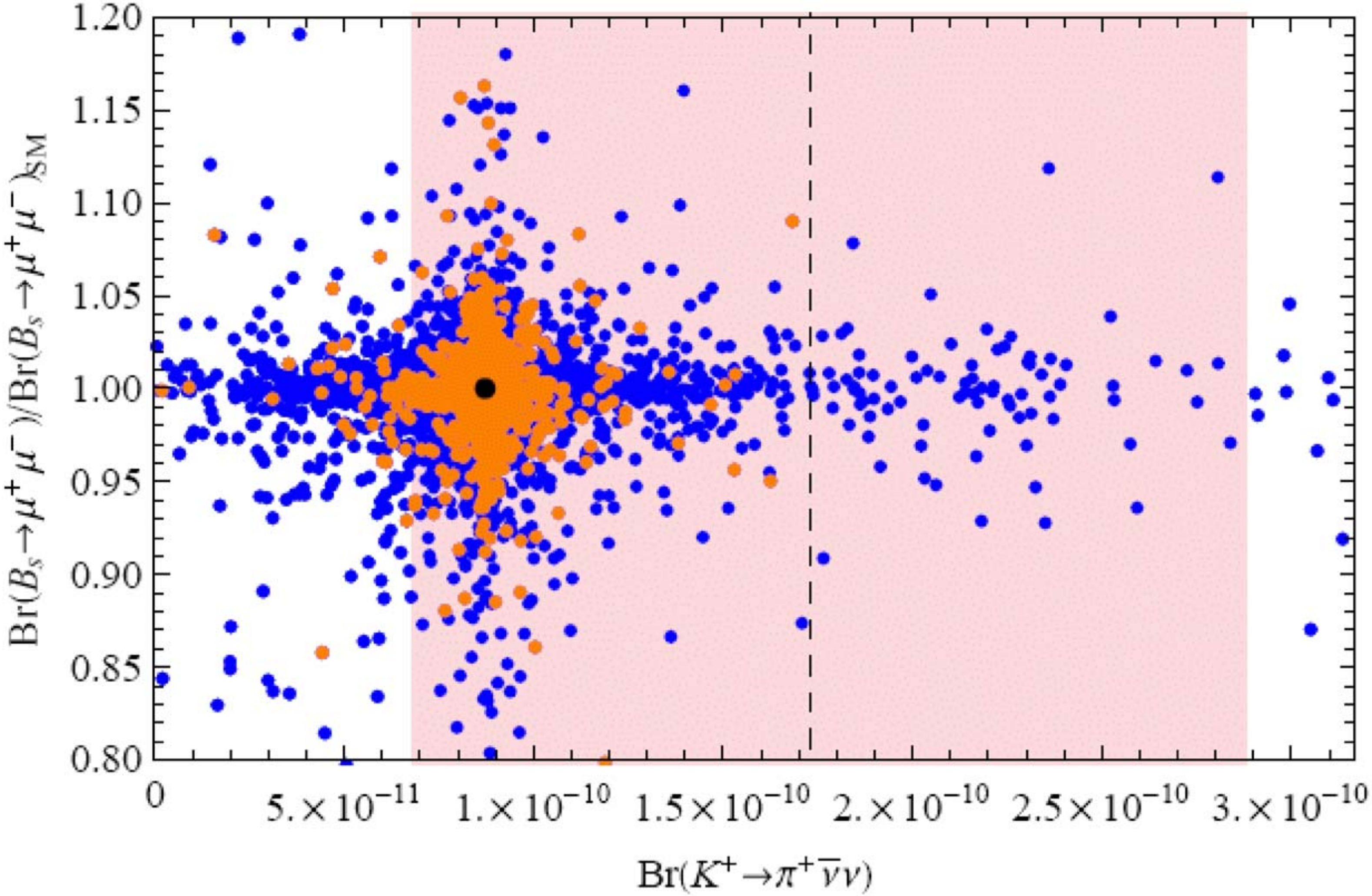


$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $S_{\psi\varphi}$

(Simultaneous Large Enhancements unlikely)

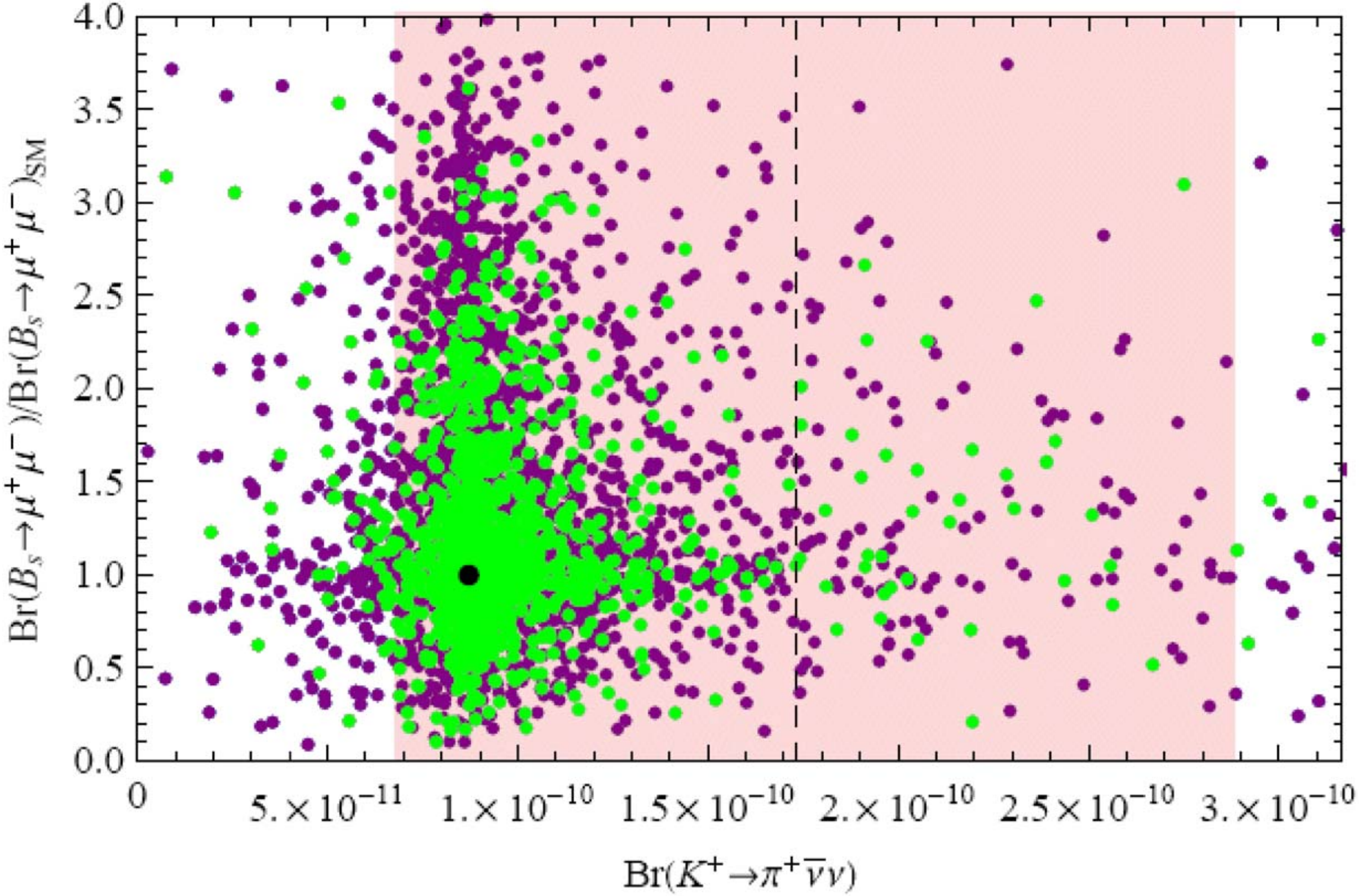


Very strong Protection for $B_s \to \mu^+\mu^-$

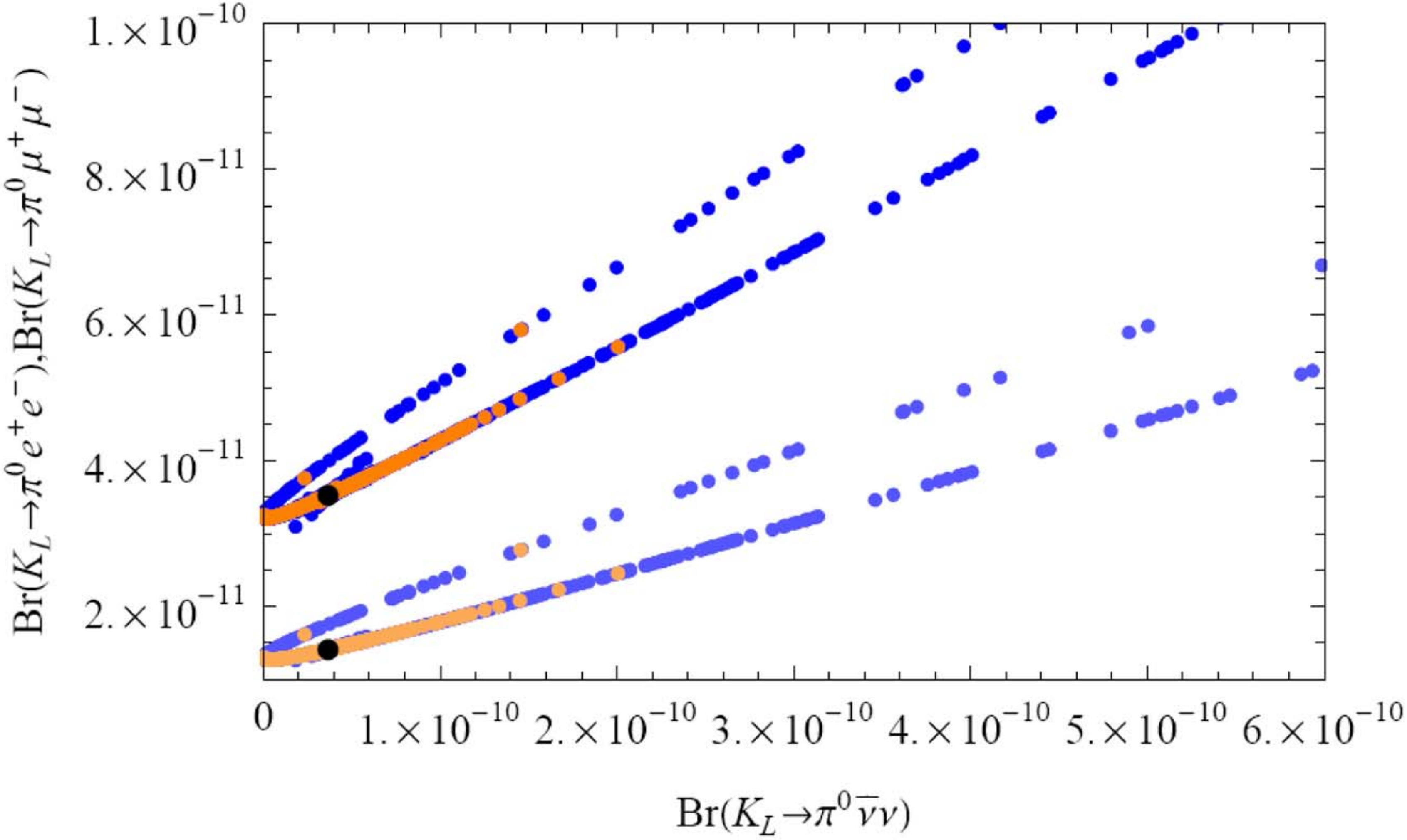


Removal of Protection

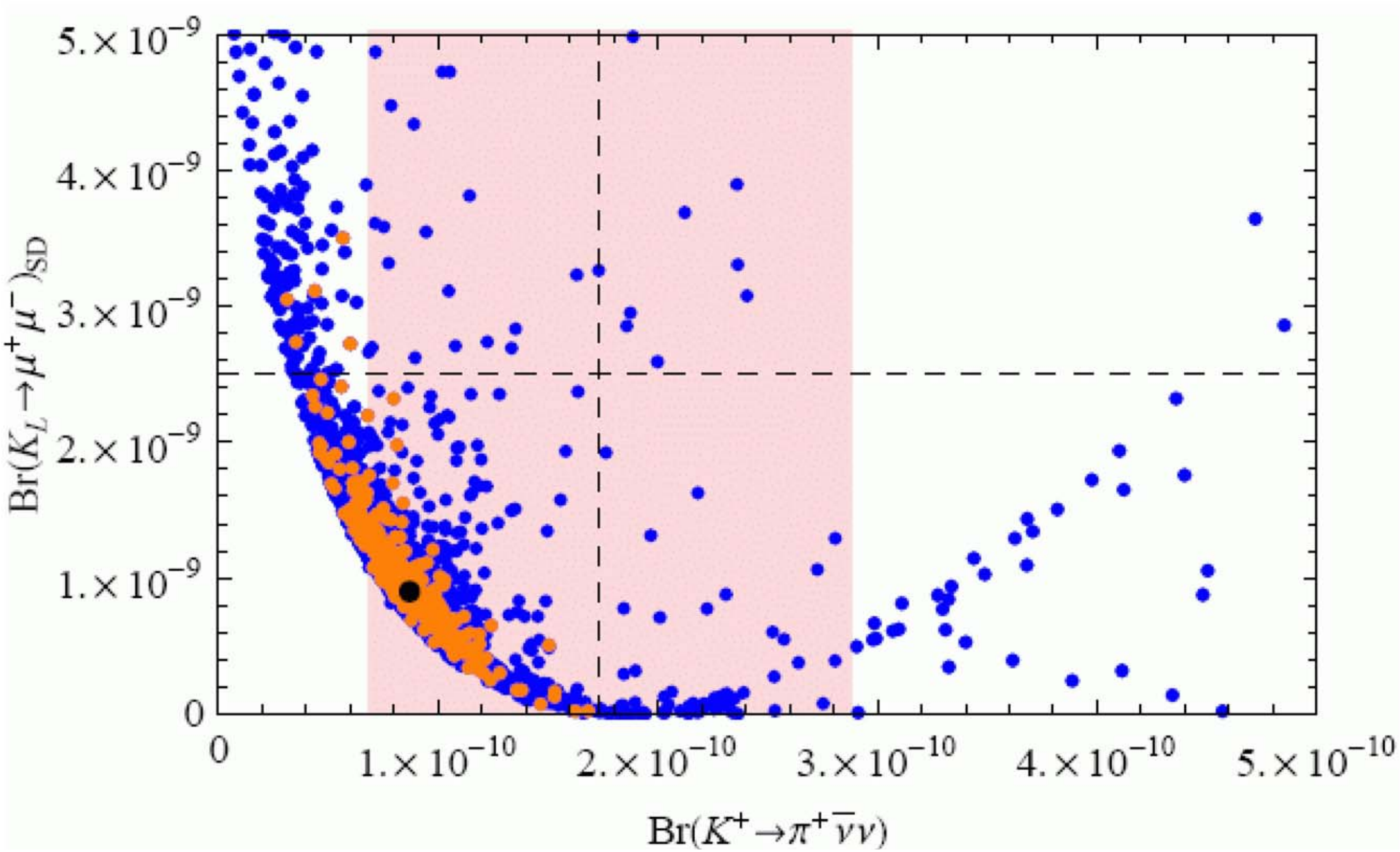
($Br\left(B_s \to \mu^+\mu^-\right)$ enhanced up to 10^{-8})



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



Correlation between $K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\nu\bar{\nu}$



Golden Relations of CMFV:

AJB (03)

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_{B_d}}{\hat{B}_{B_s}} \frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d} r$$

(CMFV)

r = 1

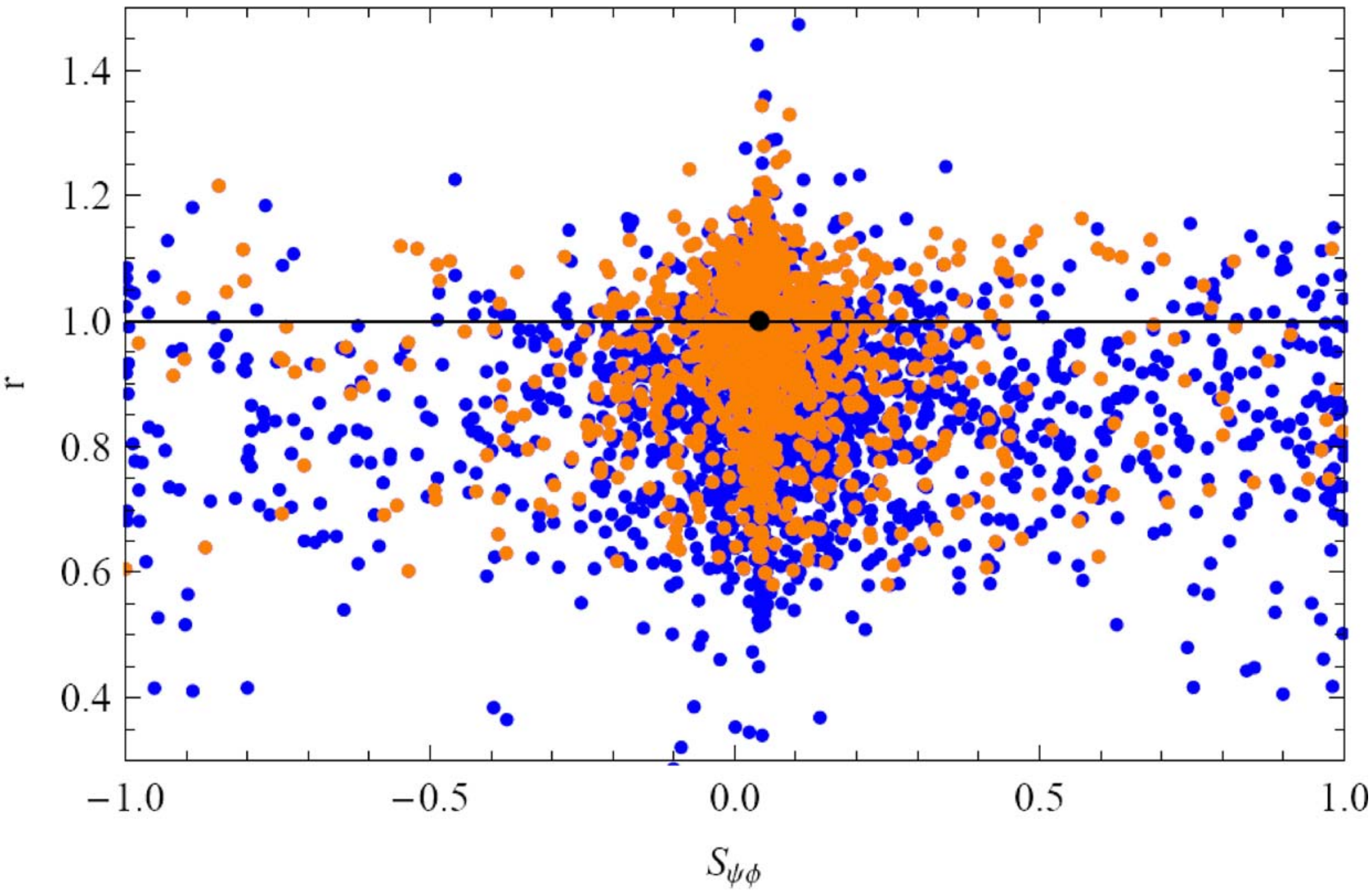
Buchalla
AJB (94)

$$(\sin 2\beta)_{B \to \psi K_S} = (\sin 2\beta)_{K \to \pi \nu \bar{\nu}}$$

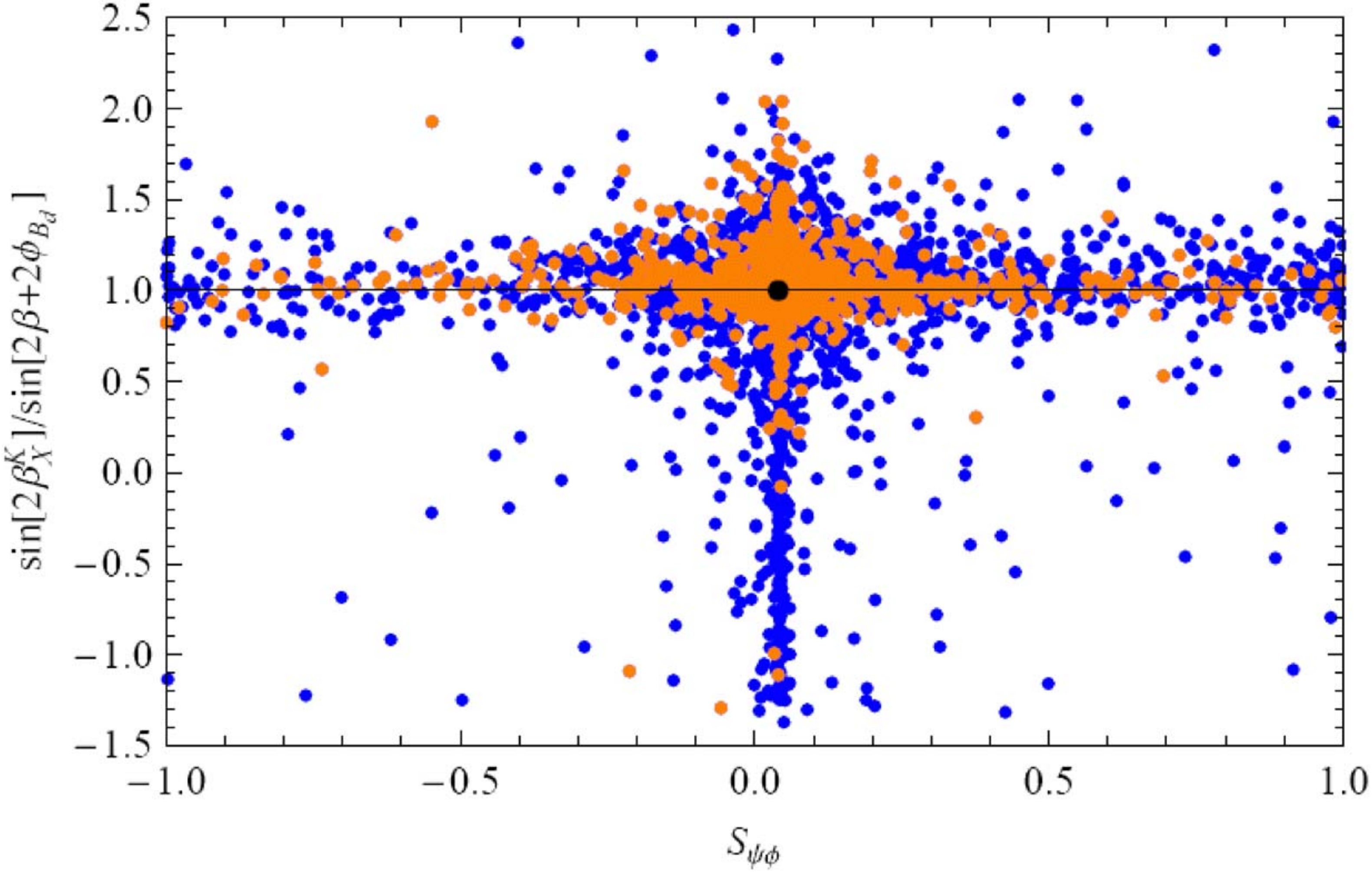
(MFV)

The violation of these model independent MFV (CMFV) relations would signal new flavour and CP-violating interactions (and/or new operators)

Violation of the Golden MFV Relation I



Violation of the Golden MFV Relation II



Clear Pattern of Flavour Violation

1. ε_K can be made consistent with data for $M_{KK} \cong 2-3\text{TeV}$ with only moderate tuning of Y_{5D}
2. $S_{\psi\varphi}$ can be much larger than $(S_{\psi\varphi})_{SM}$
3. $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ can be enhanced up to factors 5 and 2
4. Rare B-decays SM-like
5. Simultaneous enhancements of $S_{\psi\varphi}$ and $K \to \pi\nu\bar{\nu}$ very unlikely
6. Analysis of $B \to X_S\gamma$, $\mu \to e\gamma$, … in progress

Backup

Number of new Flavour Parameters

(Quark Sector) (physical)

	Real	~~CP~~ Phases	
SUSY	36	27	(R-parity)
LHT	7	3	some sensitivity to UV
RS	18	9	
SM	9	1	