Kaon rare decays in the warped extra dimensional model

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Fermilab,
June 19th 2012

Outline

1. Introduction on the warped extra dimensional model:

- Gauge hierarchy problem
- Flavor sector: connection between the flavor puzzle and new sources of flavor violation

2. Kaon Rare decays

- $K \longrightarrow \pi\nu\nu$
- $K_L \longrightarrow \pi ll$
- $K_L \longrightarrow \mu\mu$
- Correlations between these decays
- Correlations with other observables (ε' , $B_s \longrightarrow \mu\mu$)

3. Conclusions

Main references:

Blanke, Buras, Duling,Gemmler, S.G, JHEP 0903 (2009) 108

Bauer, Casagrande, Haisch, Neubert, JHEP 1009 (2010) 017

The Hierarchy Problem in a Warped Metric

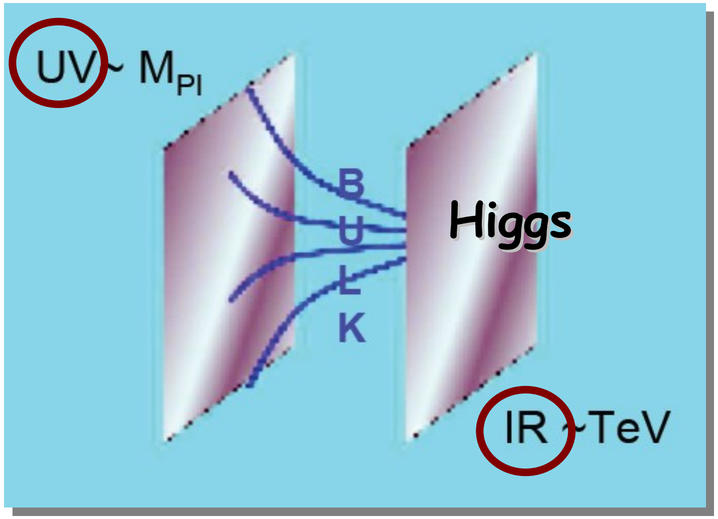
Randall, Sundrum, 1999

The gauge hierarchy problem

Huge hierarchy between the fundamental gravity scale M_{pl} & the EW scale Λ_{EWSB}

Even if $\frac{\Lambda_{EWSB}}{M_{pl}} \approx 10^{-16}$ is imposed at tree-level, loop corrections push $\Lambda_{EWSB} \sim M_{pl}$

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



Fundamental Planck scale on the **UV brane**: $\mathbf{M_{fund}}$

Energy scale in the bulk: $\mathbf{M_{fund} \times e^{-ky}}$

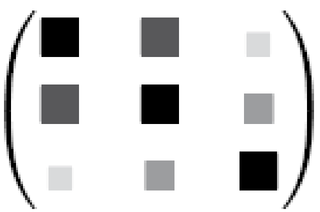
On the **IR brane** where the Higgs lives: $\mathbf{M_{fund} \times e^{-kL} \sim TeV}$

for kL~30

Geometrical solution of the gauge hierarchy problem

The Flavor Problem

Still a problem of Hierarchies

$V_{\mathrm{CKM}} =$ 

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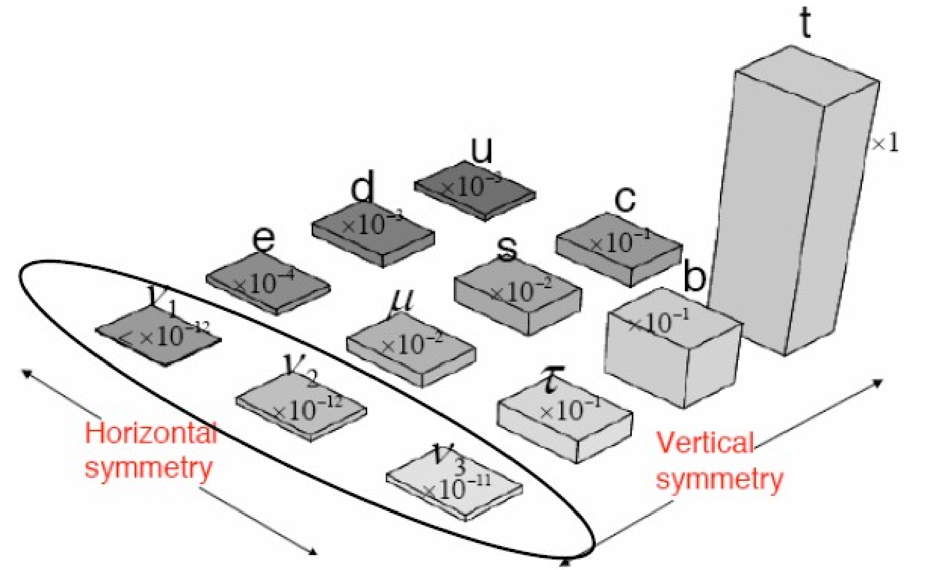


$$Y_D = \mathrm{diag}(m_d, m_s, m_b)/v$$

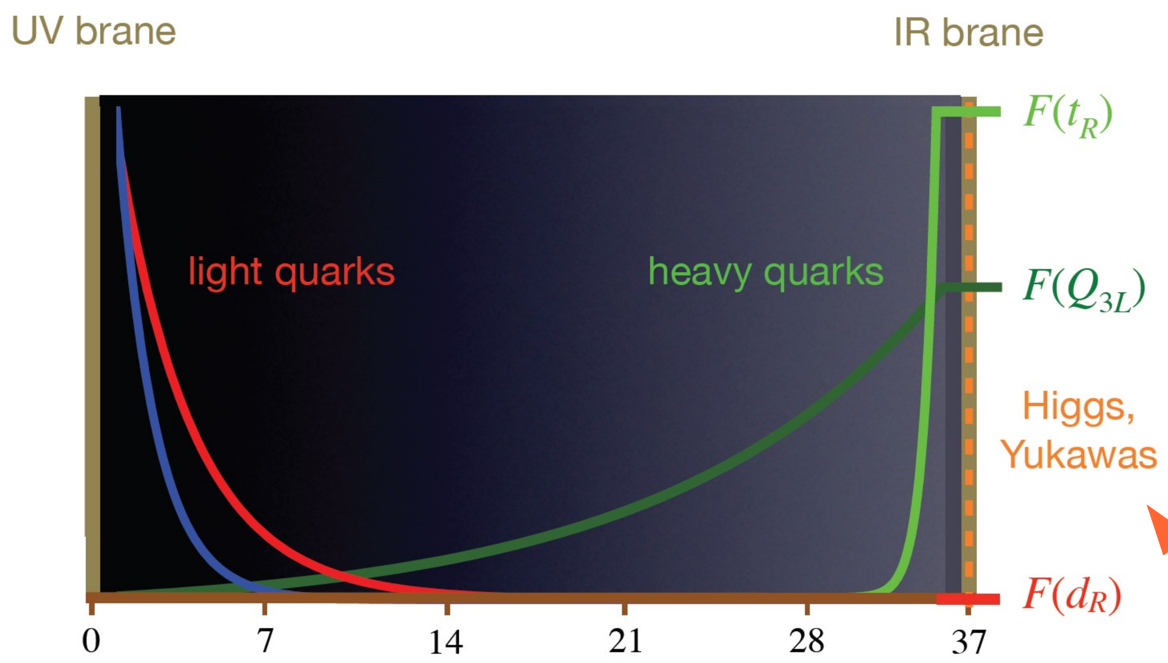
$$Y_U = V_{CKM}^{\dagger}(m_u, m_c, m_t)/v$$

Very hierarchical

Why?

The Flavor Problem

Fermions in the bulk ⟹ suggestive theory of flavor



Fermion zero mode shape function

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

bulk mass

4-D Yukawa couplings:

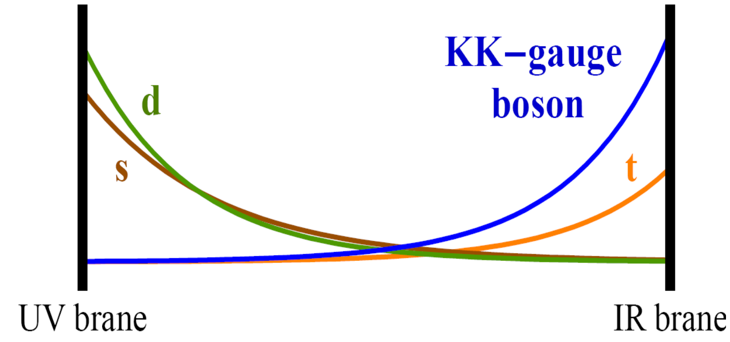
$$Y_{ij} \propto \int_0^L \frac{dy}{L^{3/2}} \lambda_{ij} h(y) f_L^{(0)}\left(y, c^i\right) f_R^{(0)}\left(y, c^j\right)$$

5-D Yukawa couplings **(complex)**

⟹ Slightly different c parameters of O(1) lead to large hierarchies in Y_{ij}, even for anarchical 5-D Yukawa couplings

New Sources of Flavor Violation

- KK tower of heavy gauge bosons
  ...that are all localized towards the IR brane

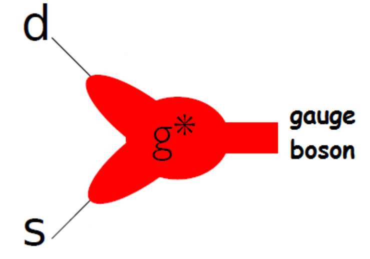


- Zero mode of the Z-boson
  ...that have in first approximation a flat shape function.
  Perturbations induced through the mixing with KK excitations/other gauge bosons

⇒ Their couplings to SM fermions are <u>non-universal</u>

...because couplings to SM fermions depend on their localization

$$\Delta_{L,R} \propto \int_0^L dy\, e^{ky} \left[f^{(0)}_{L,R}(y, c^i_\Psi) \right]^2 g(y)$$



Rotation to mass eigenstates:

non universalities → off-diagonal terms

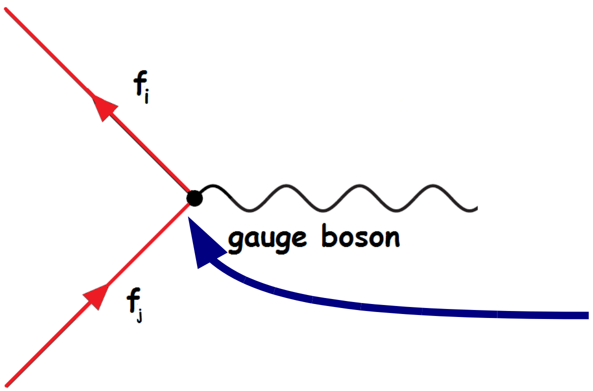
<u>Flavor Changing Neutral Currents at Tree Level</u>

$$\Delta^{mass}_{L,R} \sim U^\dagger_{L,R} \overbrace{\begin{pmatrix} \clubsuit & & \\ & \heartsuit & \\ & & \spadesuit \end{pmatrix}}^{\Delta_{L,R}} U_{L,R}$$

New sources of flavor and CP violation beyond CKM: **model is non-MFV**

RS-GIM Mechanism

Agashe, Perez, Soni, hep-ph/0406101



$$\Delta_{L,R} \propto \int_0^L dy\, e^{ky} \left[f^{(0)}_{L,R}(y, c^i_\Psi) \right]^2 g(y) = \begin{pmatrix} \clubsuit & & \\ & \heartsuit & \\ & & \spadesuit \end{pmatrix}$$

$$\Delta^{mass}_{L,R} \sim U^\dagger_{L,R} \begin{pmatrix} \clubsuit & & \\ & \heartsuit & \\ & & \spadesuit \end{pmatrix} U_{L,R}$$

Resulting FCNC couplings depend on same exponentially small overlap integrals $F(Q_L)$, $F(q_R)$ that generate fermion masses

Flavor off-diagonal couplings proportional to the mass splittings: $\Delta^{ij}_{L,R} \propto (m_i - m_j) U_{ij}$

$$m_d \sim m_s\,,\quad m_u \sim m_c \quad \Longrightarrow \quad \clubsuit \sim \heartsuit$$

Suppression of FCNCs which involve the first two generation quarks

Important for Kaon physics

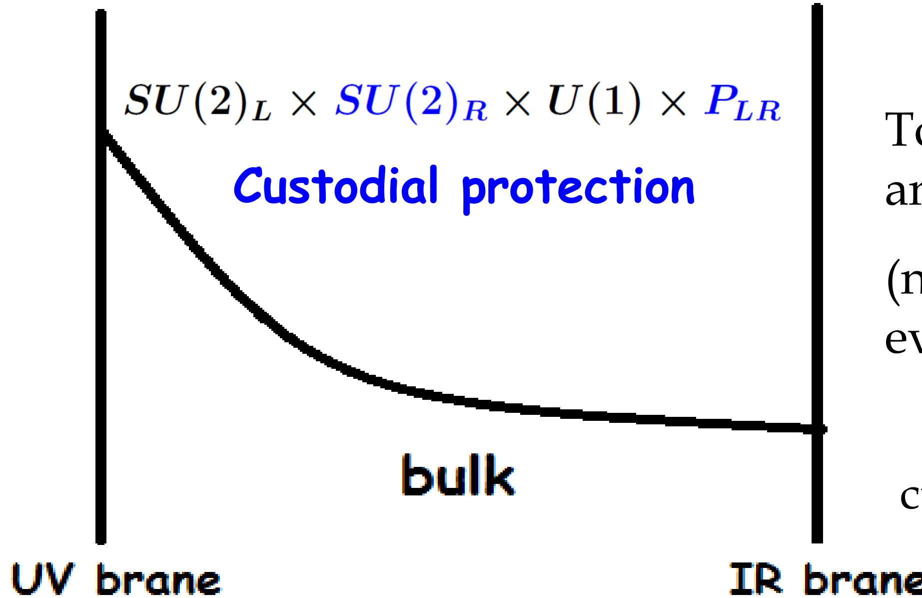
$m_t \gg m_{u,c} \Longrightarrow$ RS-GIM mechanism broken by the large top mass

The most part of the results presented are for

Agashe et al., 0605341
Csaki et al., 0308038

Scale of KK excitations:
$M_{KK} \approx 2.45 k e^{-kL}$

We fix:
M_{KK} = 2.5 TeV
↓
KK excitations directly accessible at the LHC



To protect T parameter and $Z\bar{b}_L b_L$ coupling

(not too large NP contribution even with low M_{KK} scale)

In the model without custodial protection, typically $M_{KK} \geq$ 10TeV

WED with Custodial Protection

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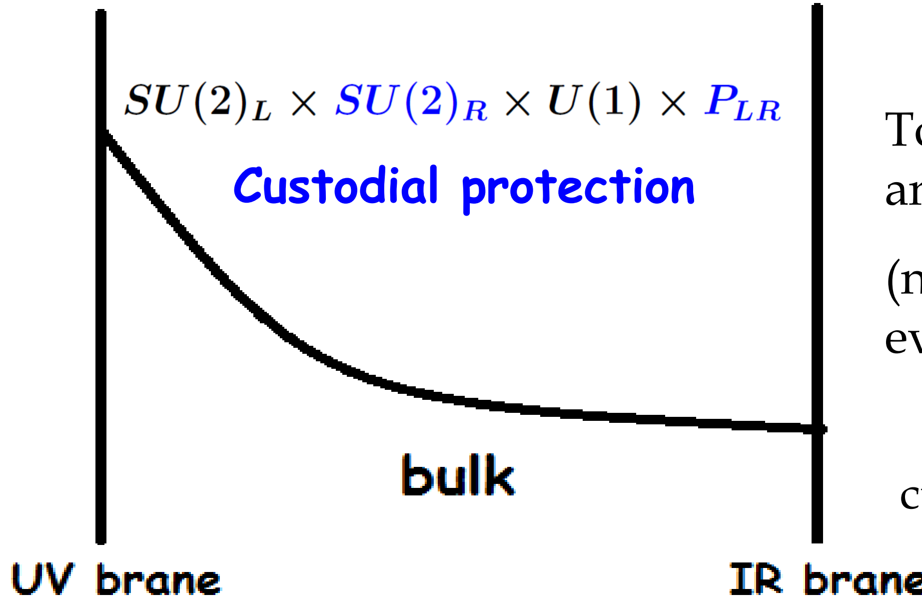
$SU(2)_L \times SU(2)_R \times U(1) \times P_{LR}$

Custodial protection



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Gauge bosons

$W^{\pm}_{\mu}$ $W^{\pm}_{H\mu}$ $\tilde{W}^{\pm}_{\mu}$

A_{μ} $A^{(1)}_{\mu}$

Z_{μ} $Z_{H\mu}$ Z'_{μ}

$G^{(0)}_{\mu}$ $G^{(1)}_{\mu}$

SM gauge bosons

Gauge bosons important for Kaon rare decays

Quarks

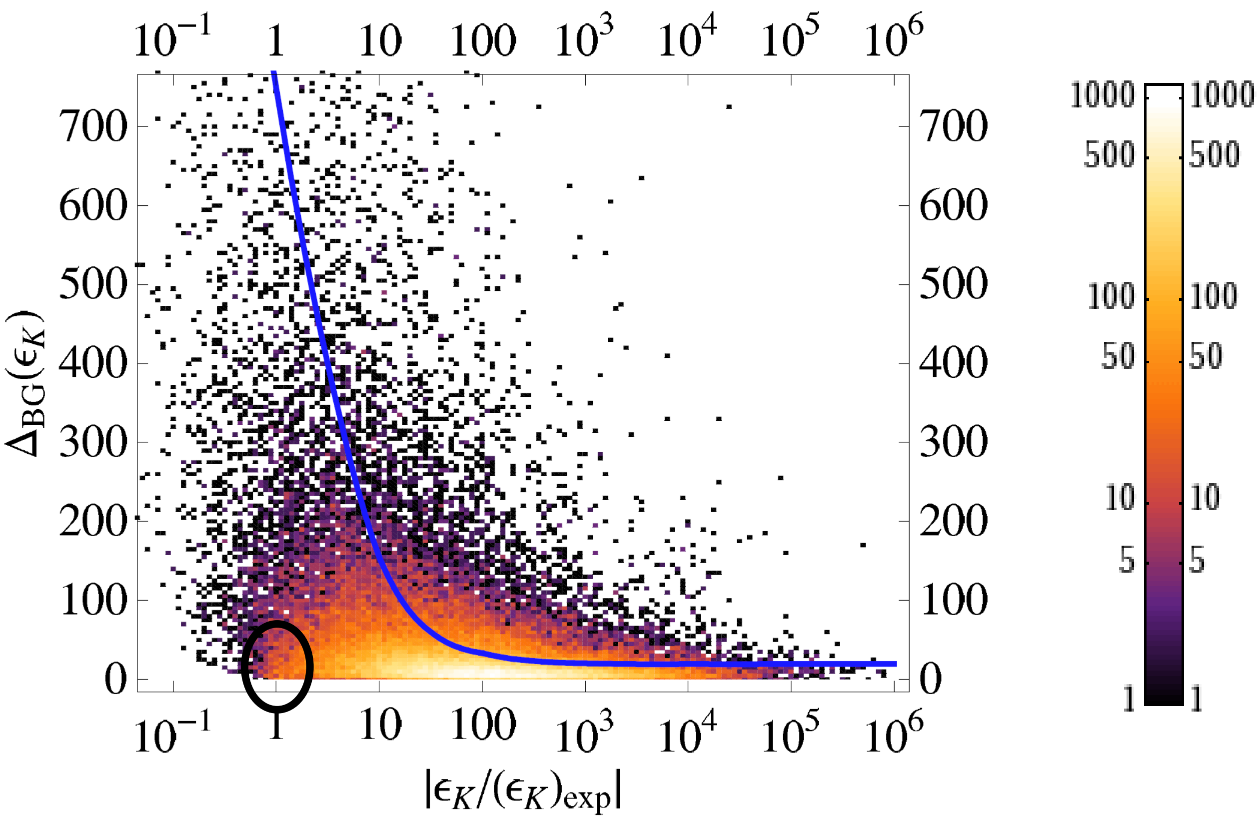
Left-handed down quarks (all three generations) are eigenstates of P_{LR}

⇓

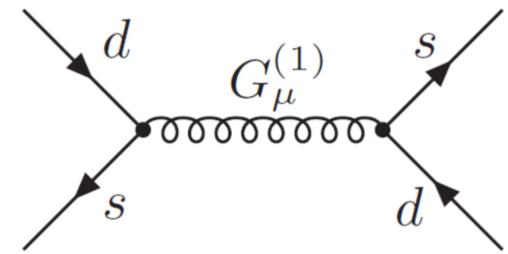
Small NP effects in $Z\bar{d}^i_L d^j_L$ couplings

ε_K: Still a Challenging Observable

Obtained for M_{KK} ~ 3TeV See also Csaki, Falkowski, Weiler, 2008



Blanke, Buras, Duling, SG, Weiler, 2009



$$Q_2^{LR} = (\bar{s}P_L d)(\bar{s}P_R d)$$

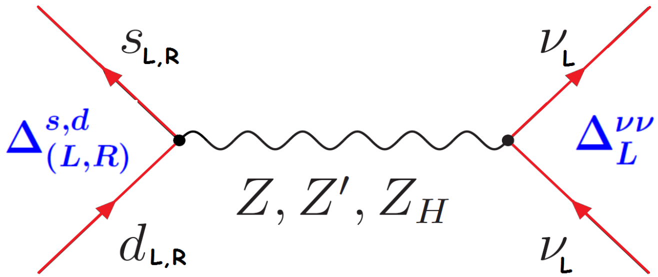
Very important contribution from the scalar operator
See Uli´s talk

Fitzpatrick, Perez, and Randall, 2007
Santiago, 2008

Some degree of fine tuning OR additional flavor symmetries would be required if we want to keep a relatively low NP scale (M_{KK}~ few TeV)

K→πνν: Theory

Cleanest window into
s ⟶ d transitions



SM operator

$$\mathcal{H}_{\rm eff} \propto \left[V_{ts}^* V_{td}(X(x_t) + X_{i,L}^{\rm NP}) + V_{cs}^* V_{cd} X_{\rm NNL}(x_c)\right] (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$$

$$+ \; V_{ts}^* V_{td}(X_{i,R}^{\rm NP})(\bar{s}_R \gamma_\mu d_R)(\bar{\nu}_L \gamma_\mu \nu_L)$$

$$X_{i,(L,R)}^{\rm NP} \propto \frac{\Delta_L^{\nu\nu} \Delta_{(L,R)}^{s,d}}{V_{ts}^* V_{td} M_{Z_i}^2}$$

Naively expected larger effects in Kaon rare decays than in B rare decays

$$|V_{ts}^* V_{td}| \sim 3 \cdot 10^{-4}$$
$$|V_{td}^* V_{tb}| \sim 9 \cdot 10^{-3}$$
$$|V_{ts}^* V_{tb}| \sim 4 \cdot 10^{-2}$$

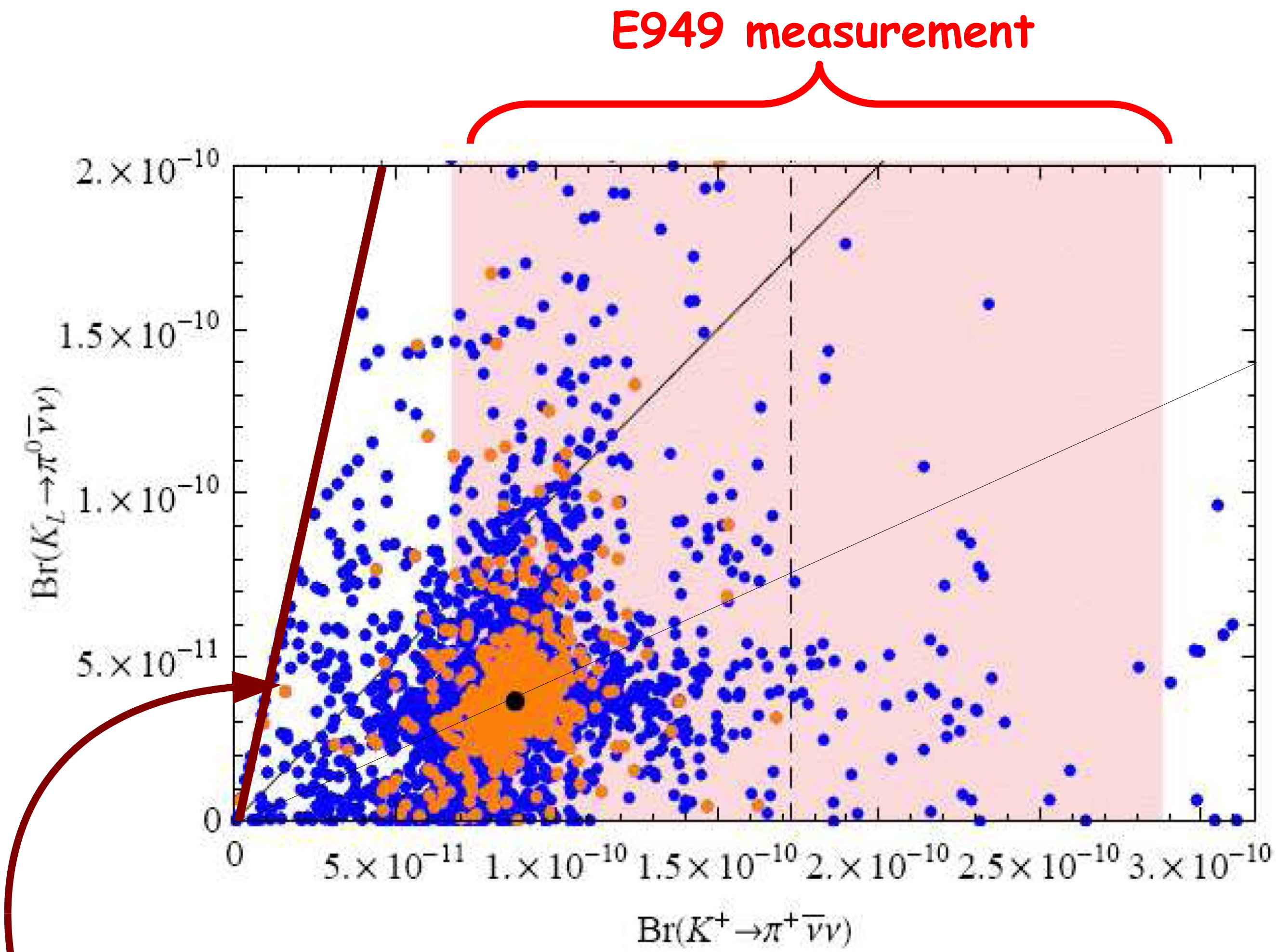
Since K and π are pseudoscalars: $\langle \pi | (\bar{s}\gamma_\mu \gamma_5 d) | K \rangle = 0$

- CP conserving process: $\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) \propto |V_{ts}^* V_{td} X|^2$
- CP violating process: $\mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) \propto \mathrm{Im}(V_{ts}^* V_{td} X)^2$

$$X \sim X(x_t) + X_{i,L}^{\rm NP} + X_{i,R}^{\rm NP} + \frac{V_{cs}^* V_{cd}}{V_{ts}^* V_{td}} X_{\rm NNL}(x_c)$$

K→πνν: Numerics

Blanke, Buras, Duling, Gemmler, S.G., 2009



The weak phase can take any value

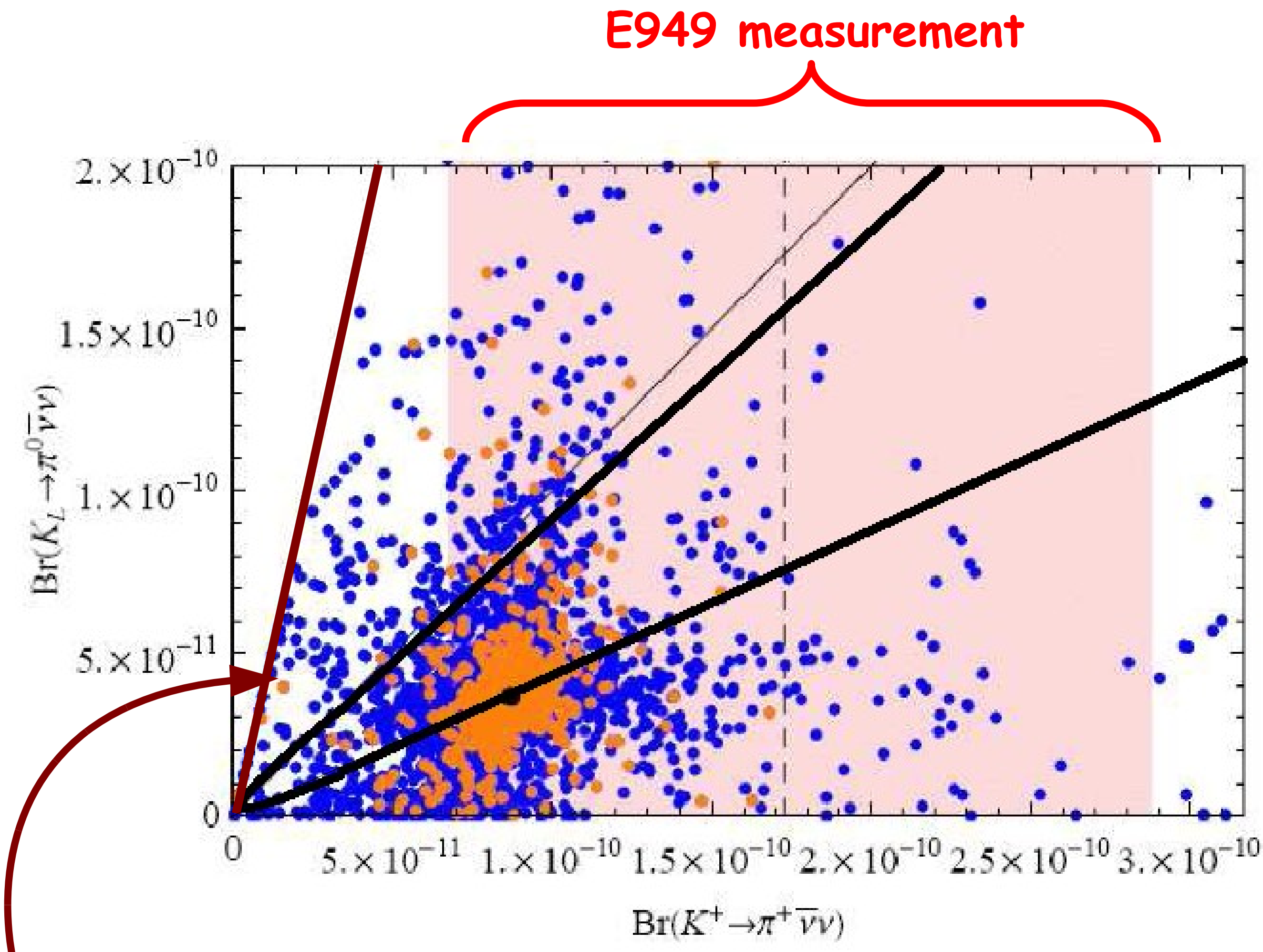
The two BRs are basically uncorrelated

Grossman-Nir bound: $\mathrm{BR}(K_L \to \pi^0\bar{\nu}\nu) < 4.3\,\mathrm{BR}(K^+ \to \pi^+\bar{\nu}\nu)$

Grossman, Nir, 1997

$K \to \pi\nu\nu$: Numerics

Blanke, Buras, Duling, Gemmler, S.G., 2009



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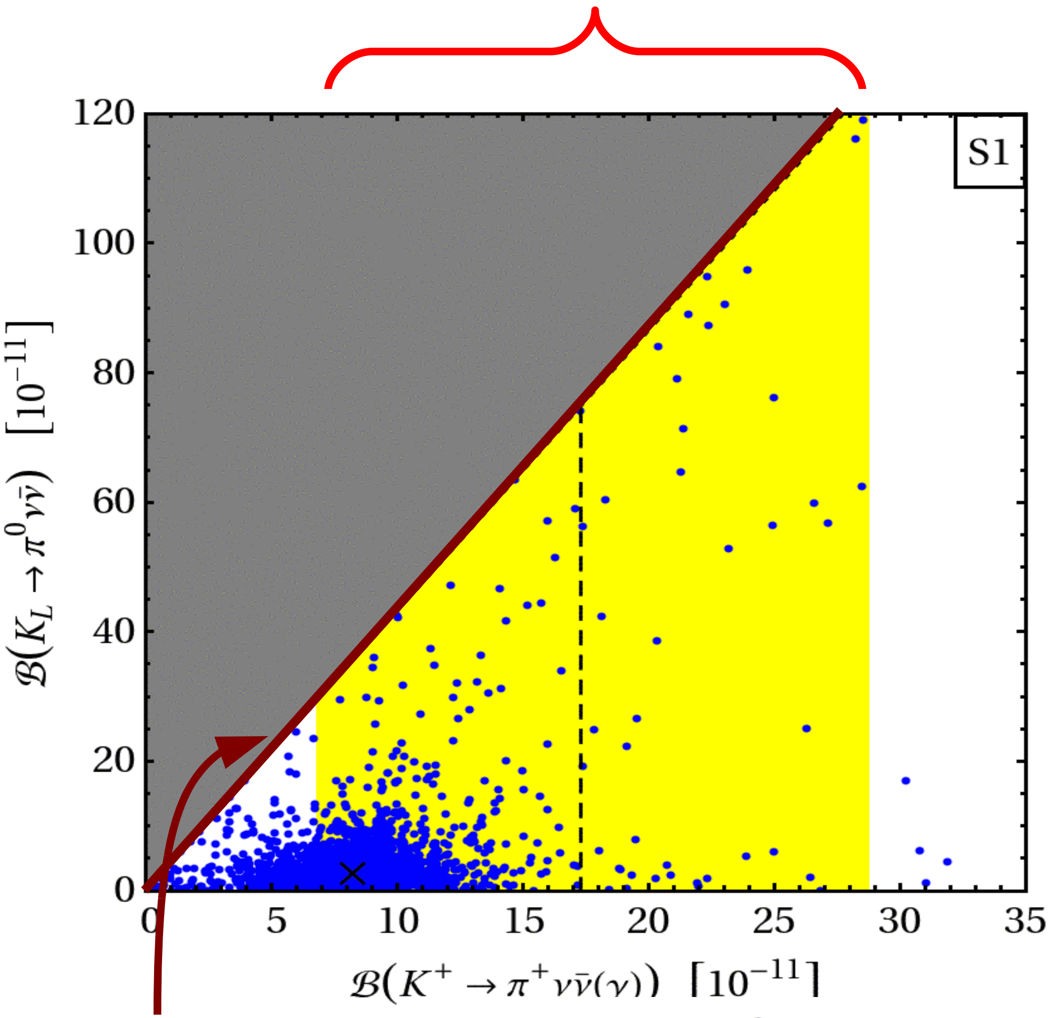
Grossman, Nir, 1997

Bauer, Casagrande, Haisch, Neubert, 2009

E949 measurement



Model without custodial protection $SU(2)_L \times U(1)$

Large effects possible also for larger M_{KK} scale (~(20-30)TeV)

Grossman-Nir bound: $\mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) < 4.3\, \mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu)$

Grossman, Nir, 1997

Constraint from $\varepsilon'/\varepsilon_K$

Constraints imposed in the plots of before:

- DF=2 observables (in particular ε_K);
- Quark masses and mixing angles (within 2 σ)

What about the constraint from $\varepsilon'/\varepsilon_K$?

Measures the direct CP violation in the decay $K \longrightarrow \pi\pi$

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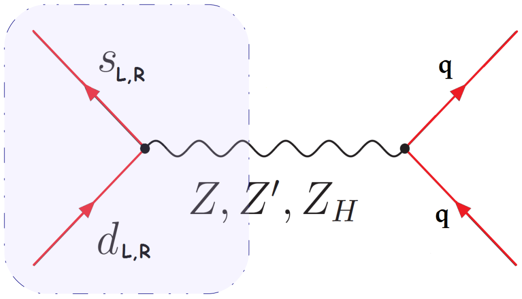
Study performed in the RS model without custodial protection

Bauer, Casagrande, Haisch, Neubert, 2009

See Uli´s talk

QCD and EW penguins, as well as chromomagnetic dipole operators, in principle affected by NP

Main NP contribution

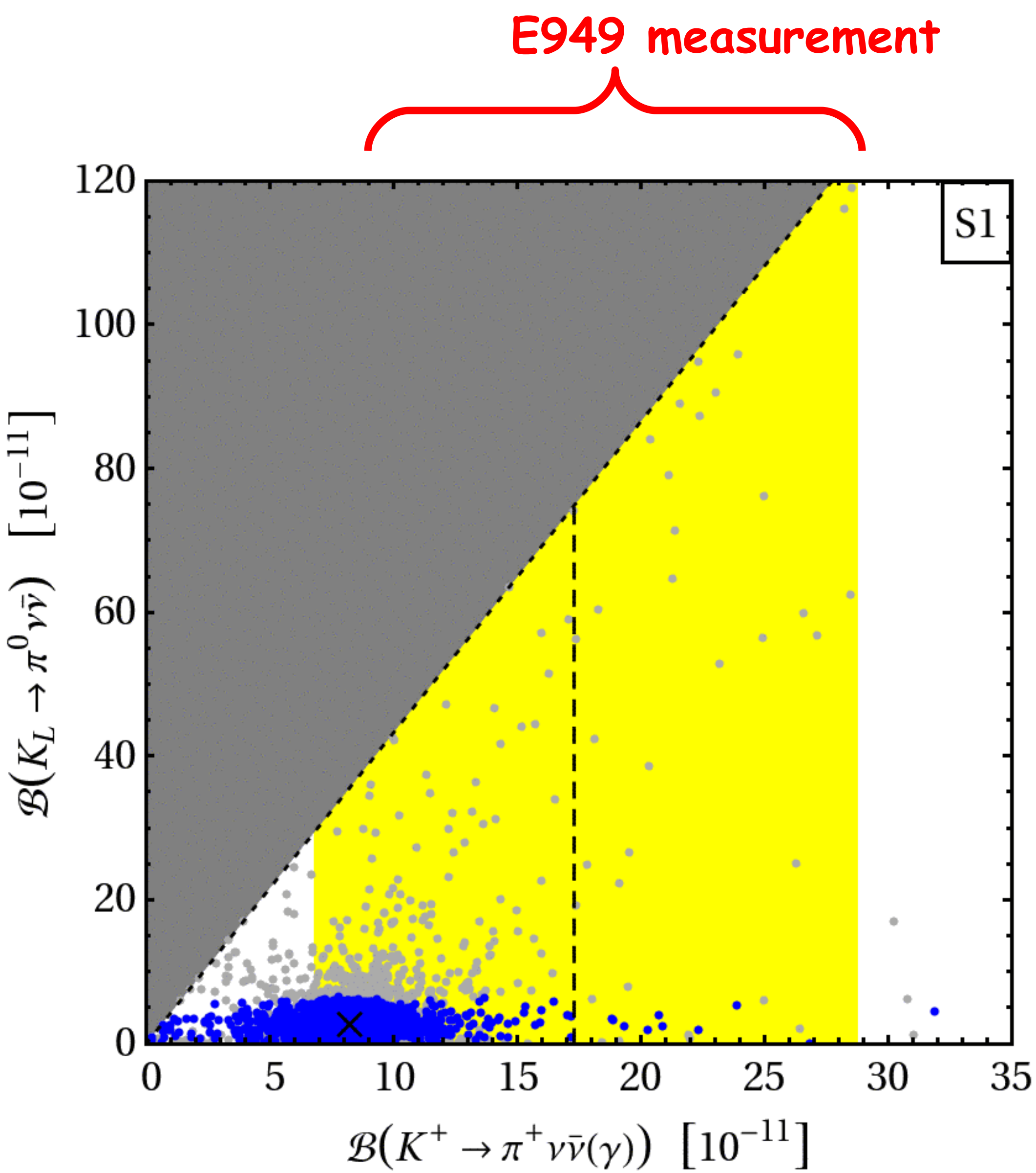


Correlation with the CP violating decay

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

Constraint from ε´/ε_K

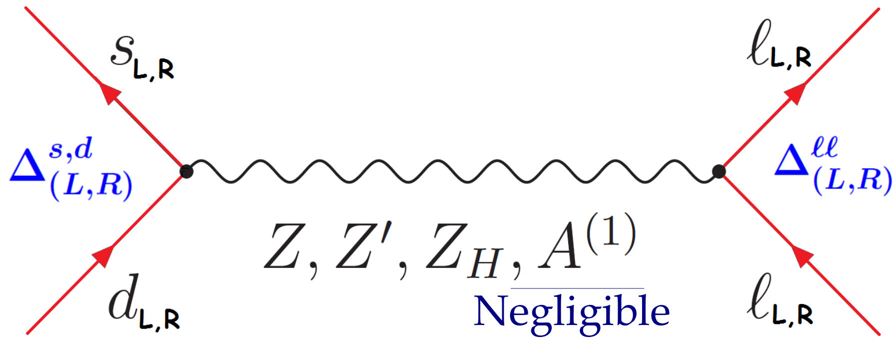
Bauer, Casagrande, Haisch, Neubert, 2009



Inverse correlation between ε´/ε_K and $K_L \to \pi^0 \bar{\nu}\nu$

Very large NP effects in $K_L \to \pi^0 \bar{\nu}\nu$ are disfavored

K→πl⁺l⁻: Theory



Negligible contribution

SM operators

$$\mathcal{H}_{\rm eff} \propto V_{ts}^* V_{td} \Big[Y_{i,R}^{\rm NP} (\bar{s}_R \gamma_\mu d_R)(\bar{\ell}_L \gamma_\mu \ell_L) + (Y(x_t) + Y_{i,L}^{\rm NP})(\bar{s}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma_\mu \ell_L)$$
$$+ Z_{i,R}^{\rm NP} (\bar{s}_R \gamma_\mu d_R)(\bar{\ell}_R \gamma_\mu \ell_R) + (Z(x_t) + Z_{i,L}^{\rm NP})(\bar{s}_L \gamma_\mu d_L)(\bar{\ell}_R \gamma_\mu \ell_R) \Big]$$

Since K and π are pseudoscalars: $\langle \pi | (\bar{s}\gamma_\mu \gamma_5 d) | K \rangle = 0$

CP violating process:

$$\mathrm{BR}(K_L \to \pi^0 \ell^+ \ell^-) \propto F(\mathrm{Im}(V_{ts}^* V_{td} Y_A), \mathrm{Im}(V_{ts}^* V_{td} Y_V))$$

$$\begin{cases} Y_A \sim Y(x_t) - Z(x_t) + Y_{i,L}^{\rm NP} - Z_{i,L}^{\rm NP} + Y_{i,R}^{\rm NP} - Z_{i,R}^{\rm NP} \\ Y_V \sim Y(x_t) + Z(x_t) + Y_{i,L}^{\rm NP} + Z_{i,L}^{\rm NP} + Y_{i,R}^{\rm NP} + Z_{i,R}^{\rm NP} \end{cases}$$

In principle also the scalar and pseudoscalar operators would contribute

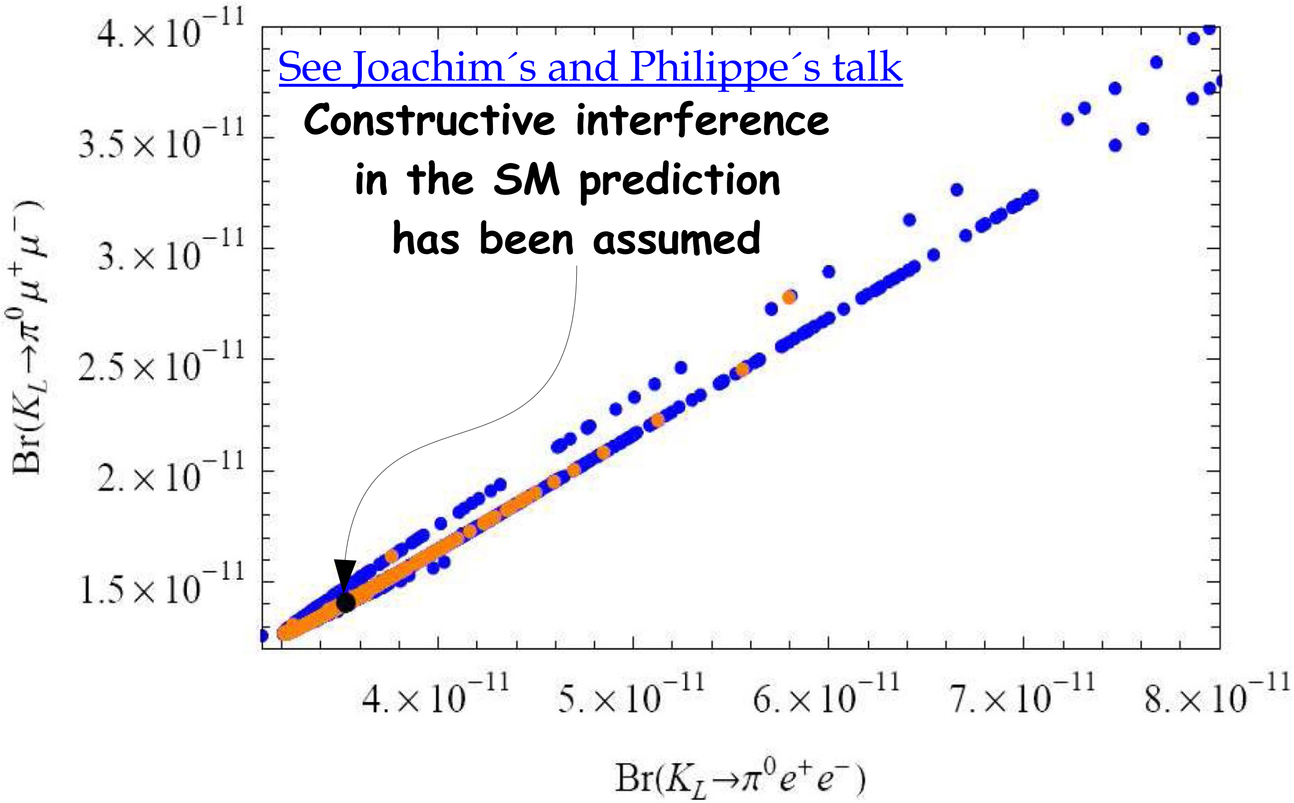
$$Q_S = (\bar{s}d)(\bar{\ell}\ell)$$
$$Q_P = (\bar{s}d)(\bar{\ell}\gamma_5 \ell)$$

Their contribution is however very suppressed

$K\to\pi l^+l^-$: Numerics

$$\mathrm{BR}(K_L \to \pi^0\mu^+\mu^-)_{\mathrm{SM}} = (1.4 \pm 0.3, 0.9 \pm 0.2)\cdot 10^{-12}$$
$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{SM}} = (3.5 \pm 0.9, 1.6 \pm 0.6)\cdot 10^{-12}$$

Blanke, Buras, Duling, Gemmler, S.G., 2009



Angle between the two branches is small since it is determined by $Y_V/Y_A \sim 1\text{-}4\mathrm{Sin}(\theta_W)^2 \sim 0.08$

(for theories with NP effects only in Z-penguins and negligible scalar and photon penguin contributions)

See Uli´s talk

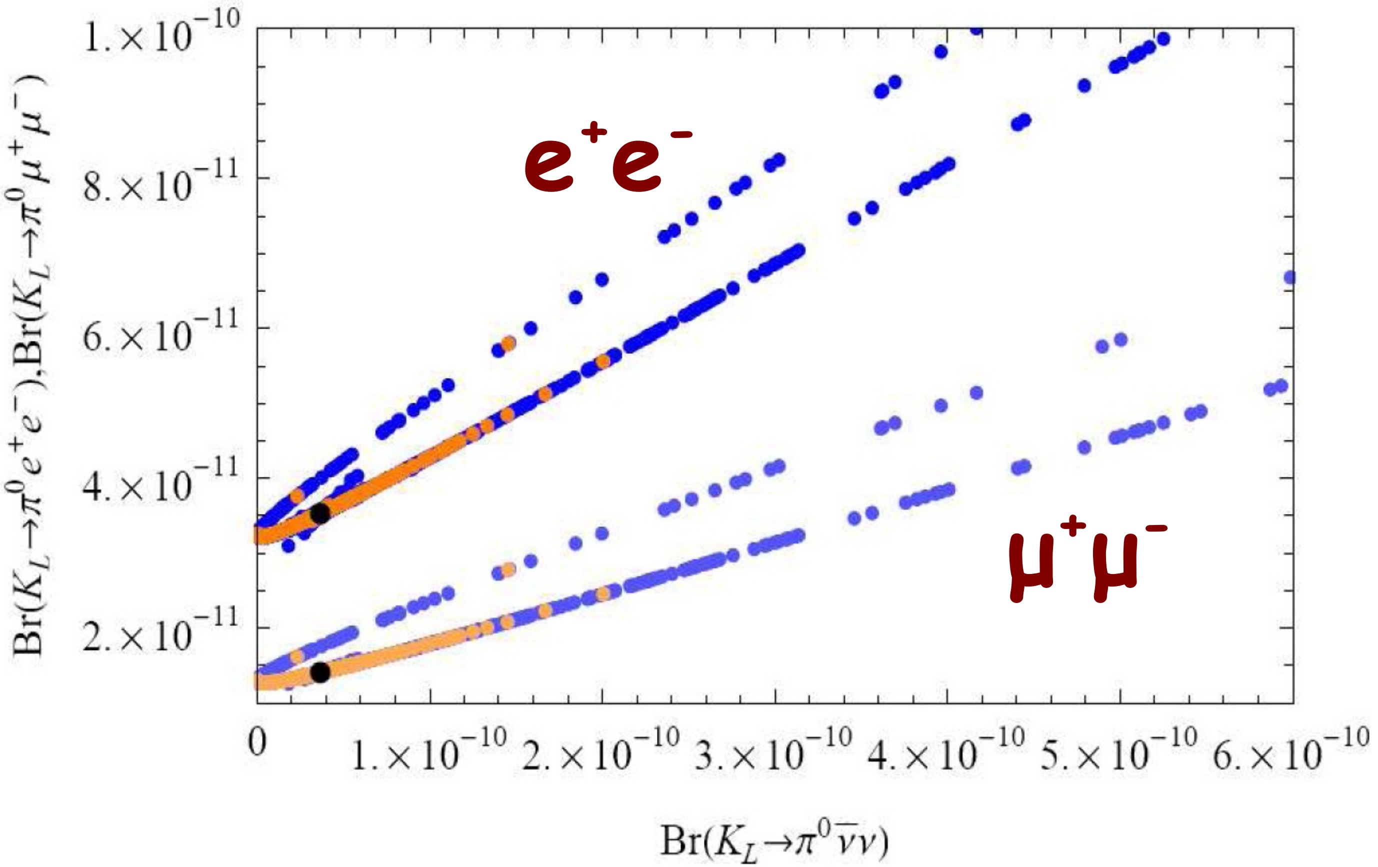
Similar results obtained in the non custodial model

Bauer, Casagrande, Haisch, Neubert, 2009

(even a larger enhancement is possible)

$K\to\pi l^+l^-$ & $K\to\pi\nu\nu$ Correlation

Blanke, Buras, Duling, Gemmler, S.G., 2009



Result of the interplay of the coupling of Z with leptons & neutrinos

Measurement of both decays is a good test of the operator structure of the model

Similar results obtained in the non custodial model

Bauer, Casagrande, Haisch, Neubert, 2009

(even a larger enhancement is possible)

K→μ⁺μ⁻: Theory

Same effective Hamiltonian as for the K ⟶ πll decay.

$$\mathcal{H}_{\rm eff} \propto V_{ts}^* V_{td} \Big[Y_{i,R}^{\rm NP} (\bar{s}_R \gamma_\mu d_R)(\bar{\ell}_L \gamma_\mu \ell_L) + (Y(x_t) + Y_{i,L}^{\rm NP})(\bar{s}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma_\mu \ell_L)$$
$$+ Z_{i,R}^{\rm NP} (\bar{s}_R \gamma_\mu d_R)(\bar{\ell}_R \gamma_\mu \ell_R) + (Z(x_t) + Z_{i,L}^{\rm NP})(\bar{s}_L \gamma_\mu d_L)(\bar{\ell}_R \gamma_\mu \ell_R) \Big]$$

However...

BR(K→ μ⁺μ⁻) is dominated by long distance contributions

Extraction of the short distance part from the data is subject to considerable uncertainties

$$\mathrm{BR}(K_L \to \mu^+\mu^-)_{\rm SD} < 2.5 \times 10^{-9}$$

Isidori, Unterdorfer, 2004

The scalar contribution is again negligible

Since $\langle 0|(\bar{s}\gamma_\mu d)|K_L\rangle = \langle 0|(\bar{\mu}\gamma_\mu \mu)|\mu^+\mu^-\rangle = 0$ only $(\bar{s}\gamma_\mu\gamma_5 d)(\bar{\mu}\gamma_\mu\gamma_5\mu)$ contributes

CP conserving process:

$$\mathrm{BR}(K_L \to \mu^+\mu^-) \propto F(\mathrm{Re}(V_{ts}^* V_{td} \tilde{Y}_A))$$

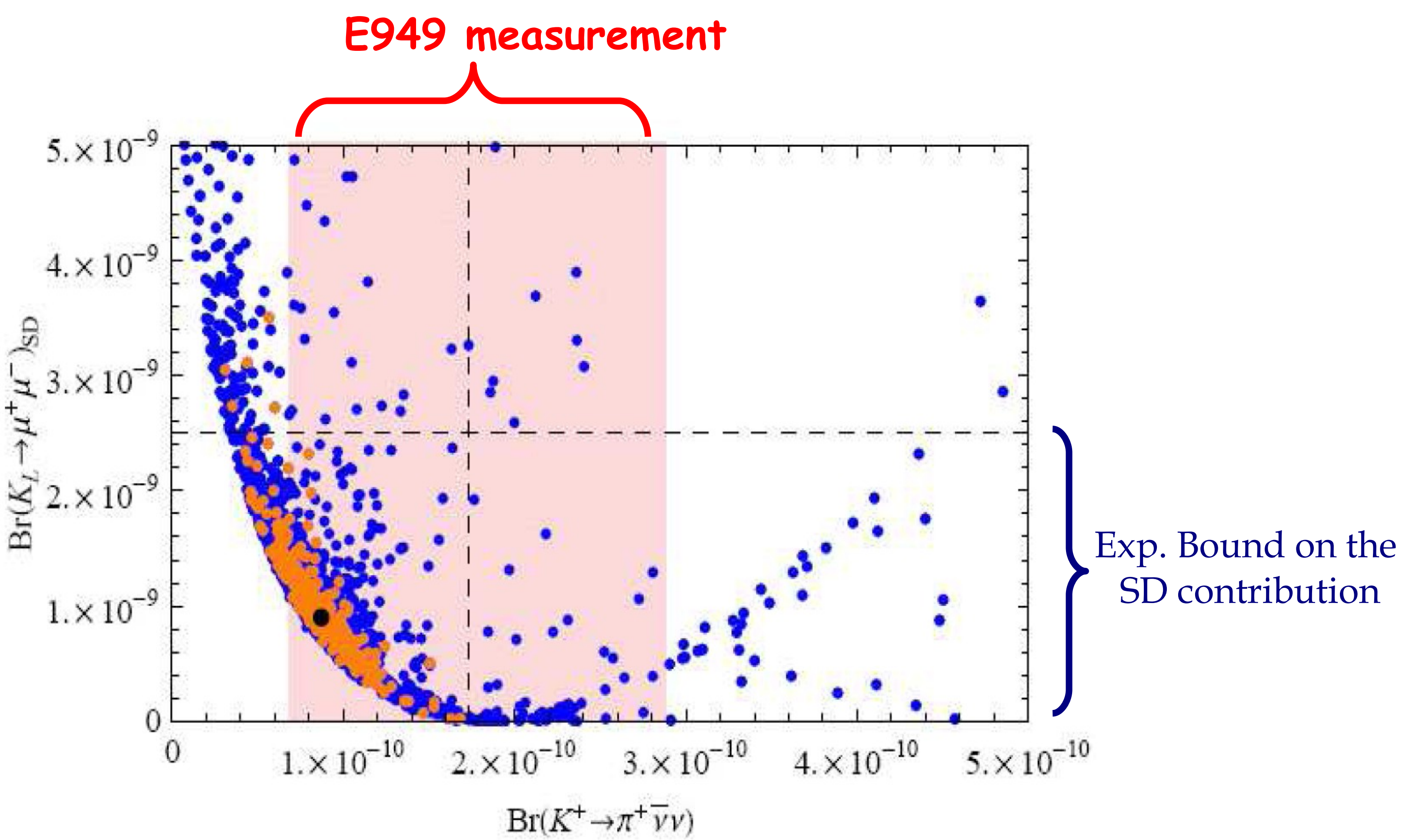
$$\tilde{Y}_A \sim Y(x_t) - Z(x_t) + Y_{i,L}^{\rm NP} - Z_{i,L}^{\rm NP} - Y_{i,R}^{\rm NP} + Z_{i,R}^{\rm NP}$$

Any correlation with the other CP conserving process?

$$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu)$$

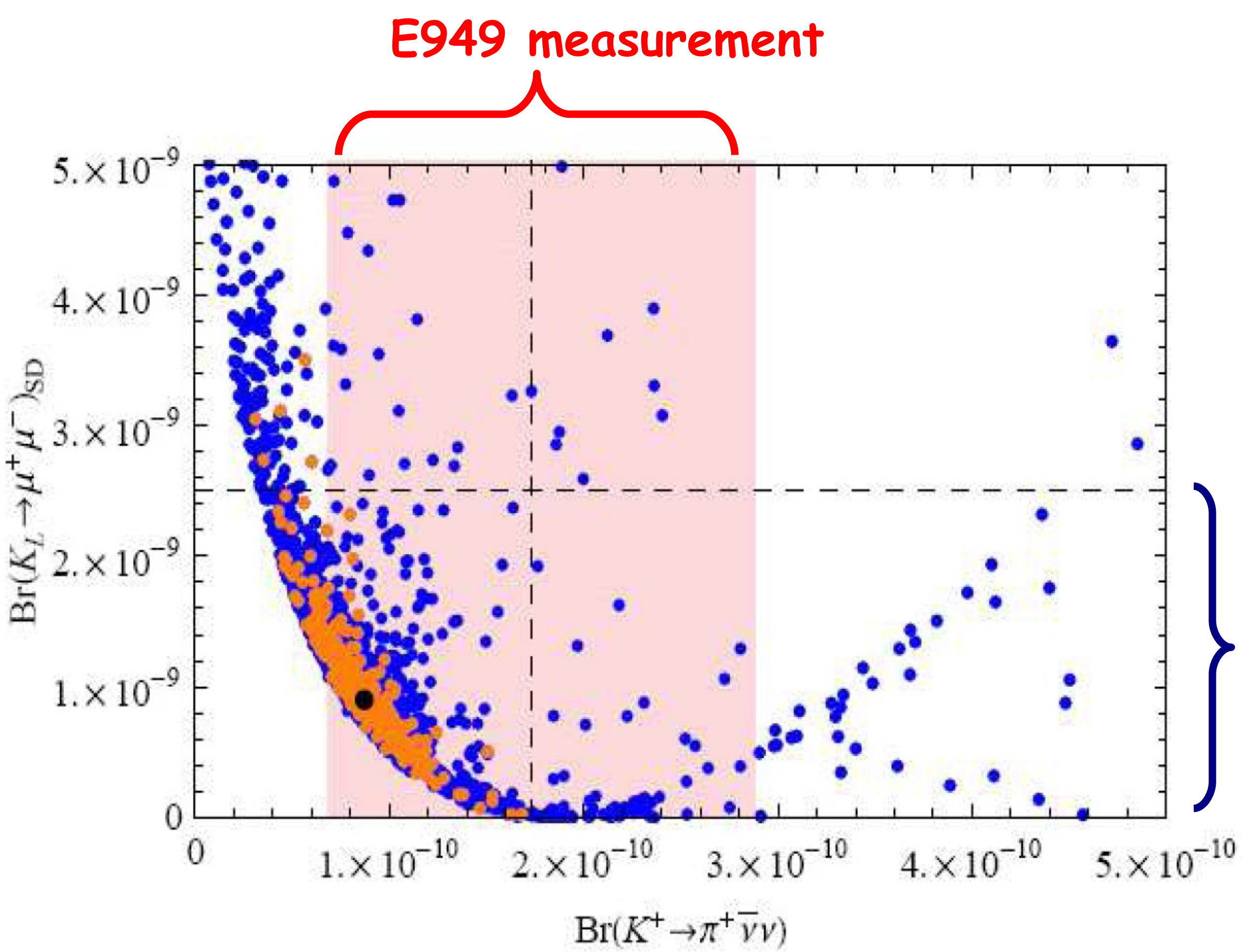
K→μ⁺μ⁻: Numerics

Blanke, Buras, Duling, Gemmler, S.G., 2009



$K \to \mu^+\mu^-$: Numerics

Blanke, Buras, Duling, Gemmler, S.G., 2009



$K^+ \to \pi^+ \bar{\nu}\nu$

measures the coupling $Z^\mu(\bar{s}\gamma_\mu d)$

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

measures the coupling $Z^\mu(\bar{s}\gamma_\mu\gamma_5 d)$

Main NP effects coming from

$$Z^\mu(\bar{s}_R\gamma_\mu d_R) \sim Z^\mu(\bar{s}\gamma_\mu(1+\gamma_5)d)$$

To compare with the SM Z-penguin

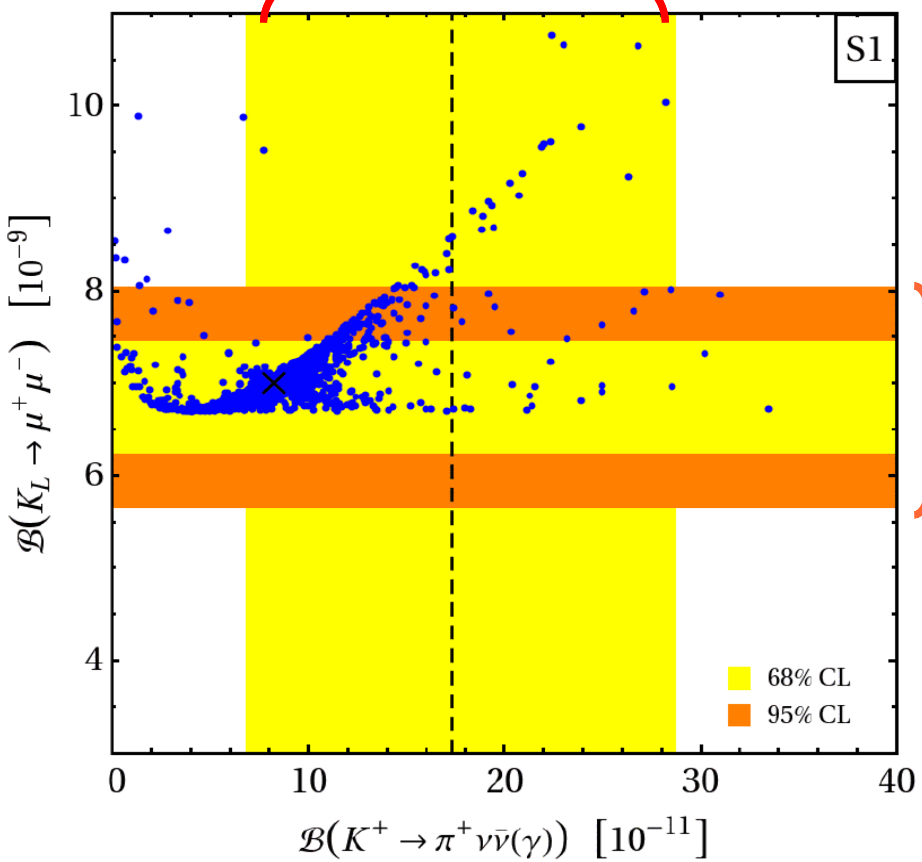
$$Z^\mu(\bar{s}_L\gamma_\mu d_L) \sim Z^\mu(\bar{s}\gamma_\mu(1-\gamma_5)d)$$

⇒ Inverse correlation

E949 measurement

Model without custodial protection

Bauer, Casagrande, Haisch, Neubert, 2009



Allowed range for the total $\mathrm{BR}(K_L \to \mu^+\mu^-)$

$K^+ \to \pi^+\bar{\nu}\nu$ measures the coupling $Z^\mu(\bar{s}\gamma_\mu d)$

$K_L \to \mu^+\mu^-$ measures the coupling $Z^\mu(\bar{s}\gamma_\mu\gamma_5 d)$

Main NP effect and SM Z-penguin

$$Z^\mu(\bar{s}_L\gamma_\mu d_L) \sim Z^\mu(\bar{s}\gamma_\mu(1-\gamma_5)d)$$

⇒ Positive correlation

K→μ⁺μ⁻: Numerics

Model without custodial protection

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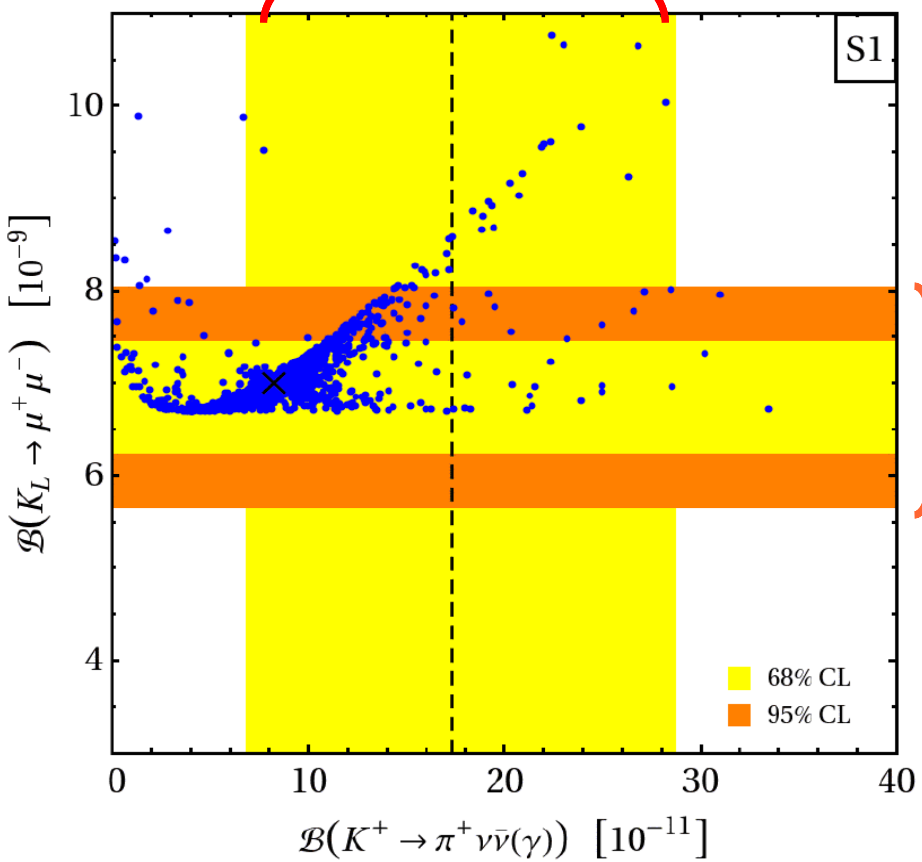
E949 measurement



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$K^+ \to \pi^+ \bar{\nu}\nu$

measures the coupling $Z^\mu(\bar{s}\gamma_\mu d)$

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

measures the coupling $Z^\mu(\bar{s}\gamma_\mu\gamma_5 d)$

Clear test of the handedness of NP flavor violating interactions

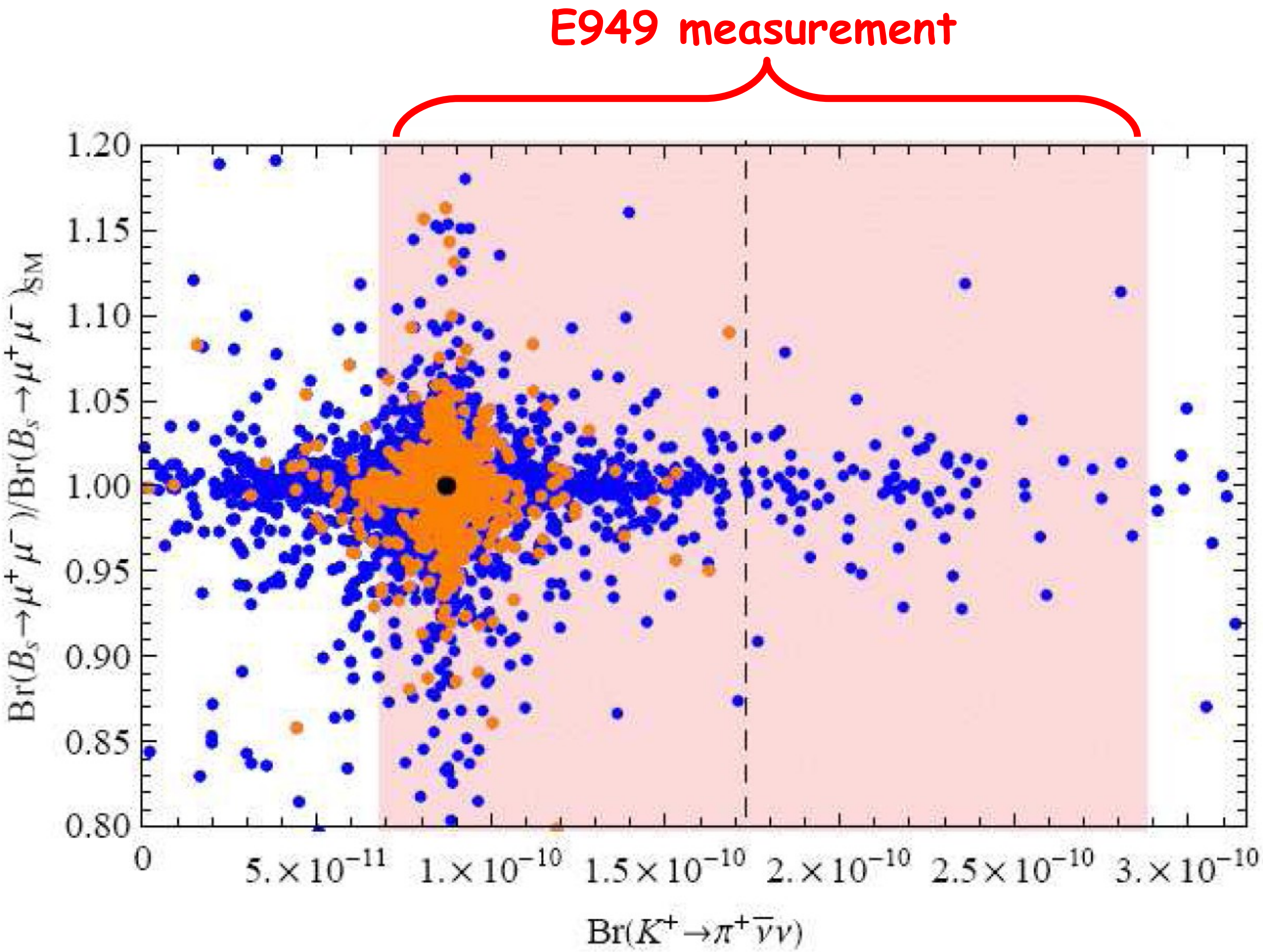
Main NP effect and SM Z-penguin

$$Z^\mu(\bar{s}_L\gamma_\mu d_L) \sim Z^\mu(\bar{s}\gamma_\mu(1-\gamma_5)d)$$

⇒ Positive correlation

Correlations between K and B Rare Decay?

Blanke, Buras, Duling, Gemmler, S.G., 2009



Rather smaller NP effects in $B_s \longrightarrow \mu\mu$

Simultaneous large effects in both observables is unlikely

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} \lesssim 1.5 \times \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$$

LHCb collaboration, 1203.4493

Conclusions

Warped extra dimensional models generically predict possible sizeable NP contributions in rare kaon decays (contrary to the prediction for B rare decays, that are more and more constrained by the present experiments)

The measurement of Kaon rare decays can unveil the flavor properties of this set of NP models

i.e. testing the correlations between the several kaon rare decays could offer a clear test of the type of NP arising in flavor transitions

Ex:

- **Which is the handedness of the NP flavor violating interactions?**

  $$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) \text{ vs. } \mathrm{BR}(K_L \to \mu^+\mu^-)$$

- **Are the scalar flavor violating interactions important?**

  $$\mathrm{BR}(K_L \to \pi^0 \bar{e} e) \text{ vs. } \mathrm{BR}(K_L \to \pi^0 \bar{\mu}\mu)$$

$K\to\pi l^+l^-$: Some more Theory

$$\mathrm{BR}(K_L \to \pi^0 \ell^+ \ell^-) \propto C^\ell_{\rm dir} \pm C^\ell_{\rm int}|a_S| + C^\ell_{\rm mix}|a_S|^2 + C^\ell_{\gamma\gamma} + C^\ell_S$$

Constructive/destructive interference

$$\begin{cases} C^\ell_{\rm dir} = G(\mathrm{Im}(V^*_{ts}V_{td}Y_A)^2, \mathrm{Im}(V^*_{ts}V_{td}Y_V)^2) \\ C^\ell_{\rm int} = \tilde{G}(\mathrm{Im}(V^*_{ts}V_{td}Y_V)) \end{cases}$$

Probably one should take the + sign
(more investigation needed)

Buchalla, D´Ambrosio, Isidori, 2003

Friot, Greynat, De Rafael, 2004

Comparing the Several NP Contributions

- FCNC couplings to left-handed quarks

$$\Delta_L^{ij}(Z_H) : \Delta_L^{ij}(Z') : \Delta_L^{ij}(Z) \sim \mathcal{O}(10^4) : \mathcal{O}(10^3) : 1$$

- FCNC couplings to right-handed quarks

$$\Delta_R^{ij}(Z_H) : \Delta_R^{ij}(Z') : \Delta_R^{ij}(Z) \sim \mathcal{O}(10^2) : \mathcal{O}(10^2) : 1$$

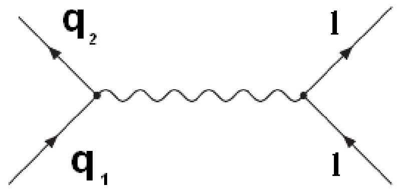
- Flavor conserving couplings with leptons

$$\Delta_{L,R}^{\nu\nu,\ell\ell}(Z_H) : \Delta_{L,R}^{\nu\nu,\ell\ell}(Z') : \Delta_{L,R}^{\nu\nu,\ell\ell}(Z) \sim \mathcal{O}(10^{-1}) : \mathcal{O}(10^{-1}) : 1$$

- Propagator of the gauge bosons

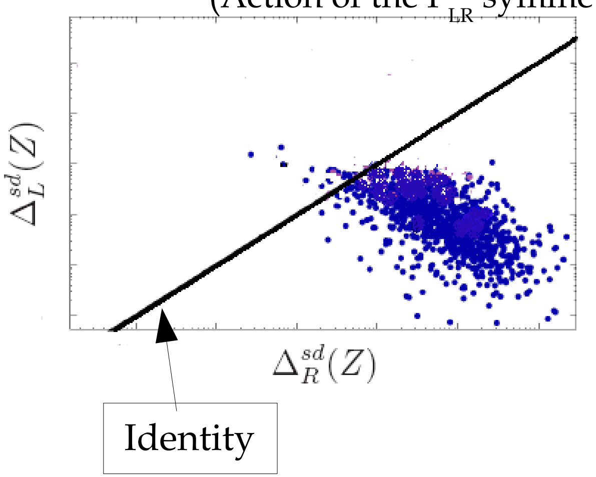
$$M_Z^2/M_{(Z_H,Z')}^2 \sim \mathcal{O}(10^{-3})$$

Z_H coupled with left-handed down-quarks
(≈ Z coupled with left-handed down-quarks)
&
Z coupled with right-handed down-quark
are dominant



Example:

(Action of the P_{LR} symmetry)



Z coupled with right-handed quark is the dominant contribution