Some Thoughts About Rare Kaon Decays

Ulrich Haisch
University of Oxford

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Theoretical Expectations

- Clearly an oxymoron, because every theorist expects different TeV-scale new physics
  - motivated by naturalness of electroweak scale
  - motivated by precision unification of couplings
  - not motivated, but why not
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- Experiments should try to falsify theories - especially true for indirect (as opposed to production) probes!
- Imagine to kill supersymmetry, extra dimensions & technicolor at once by signal defying expectations

Two Ways to Study New Physics

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Top-down approach:

- concrete model of new physics
- predict observables & correlations directly
- are smoking gun signals possible?

➡ discussed only sporadically

Two Ways to Study New Physics

Top-down approach:	Bottom-up approach:
concrete model of new physics	what data can be obtained?
predict observables & correlations directly	how is it parametrized efficiently?
are smoking gun signals possible?	what can be learned about model classes?

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➡ main theme of this talk

Bottom-Up Approach

- Fix minimal set of assumptions:
  - new physics enters at M_{NP} = O(1 TeV), allowing for systematic expansion in powers of $M_W/M_{NP} << 1$
  - standard model (SM) is weakly coupled to new sector (technical assumption could be relaxed)

Assumptions satisfied in many SM extensions

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

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  Assumptions satisfied in many SM extensions

- Use effective $SU(2)_L \times U(1)_Y$ invariant Lagrangian

$$\mathcal{L}_{\text{eff}} = \sum_i C_i Q_i$$

Similar to weak Hamiltonian with simple matching between two, but fewer operators per coefficient

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

Bottom-Up Approach Cont'd

- Effective framework takes care of assumptions, but no further prejudice

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Bottom-Up Approach Cont'd

- Effective framework takes care of assumptions, but no further prejudice

- In setup can now ask & answer important questions:
  - to what degree are $K \to \pi\nu\bar{\nu}$ channels linked to other kaon modes, such as $K_L \to \pi^0 l^+ l^-$, ΔM_K, ε_K & ε'/ε?
  - in particular, do these constraints rule out large effects in neutrino modes?
  - can one design models that break correlations & if so, does this lead to other observable signatures?
  - ...

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

Kaon Scoresheet

Operator		$K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 l^+ l^-$	$K_L \to l^+ l^-$	$K^+ \to l^+ \nu$	$P_T(K^+ \to \pi^0 \mu^+ \nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K	in MSSM?
$Q_{lq}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	✓
$Q_{lq}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\bar L_L \gamma^\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	—	—	✓
Q_{qe}	$(\bar D_L \gamma_\mu S_L)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	hs	✓	✓	—	—	small
Q_{ld}	$(\bar d_R \gamma_\mu s_R)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—	small
Q_{ed}	$(\bar d_R \gamma_\mu s_R)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	—	—	—	—	—	small
$Q_{lq}^\dagger$	$(\bar u_R S_L)(\bar l_R L_L)$	—	—	—	—	✓	✓	✓	—	—	tiny
$(Q_{lq}^t)^\dagger$	$(\bar u_R \sigma_{\mu\nu} S_L)(\bar l_R \sigma^{\mu\nu} L_L)$	—	—	—	—	—	?	?	—	—	tiny
Q_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	—	—	✓	✓	—	—	—	—	—	tiny
$Q_{qde}^\dagger$	$(\bar D_L s_R)(\bar l_R L_L)$	—	—	✓	✓	✓	✓	✓	—	—	large $\tan\beta$
$Q_{\phi q}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	✓
$Q_{\phi q}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\phi^\dagger D^\mu \sigma^i \phi)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$Q_{\phi d}$	$(\bar d_R \gamma_\mu s_R)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)	large $\tan\beta$ (non-MFV)

Observable

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

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6 operators, 6 observables

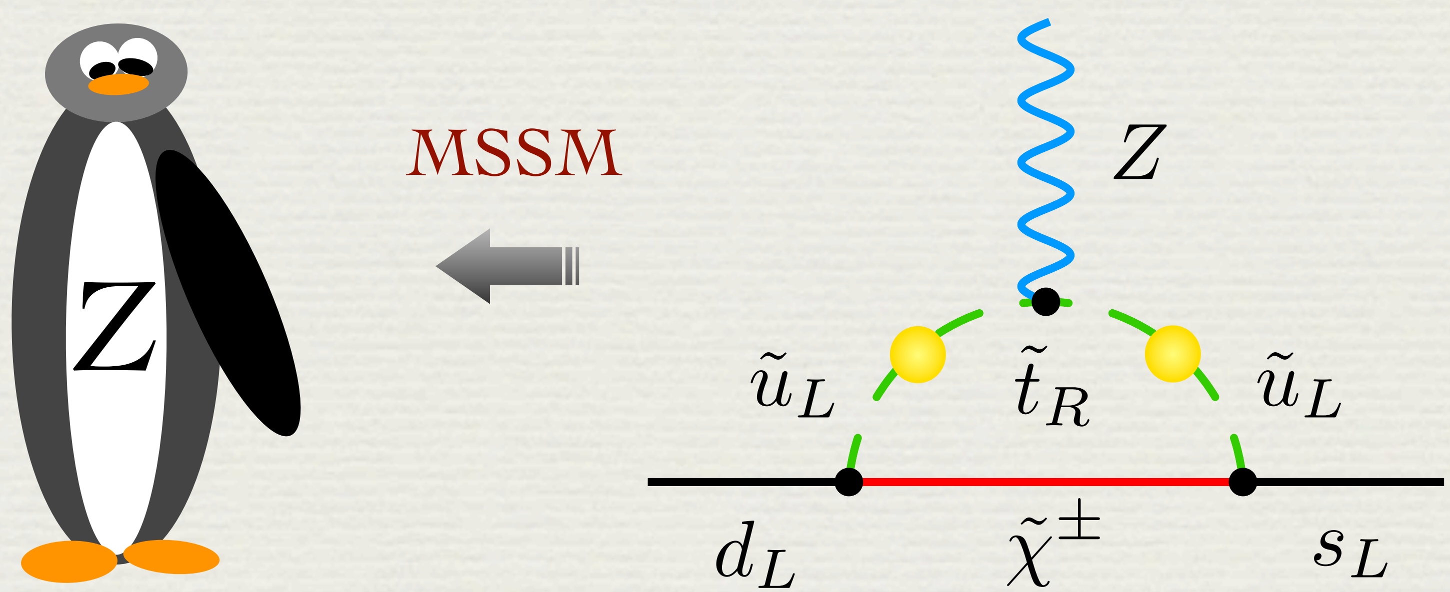
[see S. Jäger, talk at NA62 Physics Handbook Workshop]

Z-Penguin Operators

- Three operators involving Higgs field affect largest number of observables, so let's focus on them
- After electroweak symmetry breaking, one has

$$(\bar{D}_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi) \Longrightarrow \bar{d}_L \gamma_\mu s_L Z^\mu + \bar{u}_L \gamma_\mu c_L Z^\mu + \ldots$$

which is left-handed (LH) Z-penguin well-known from MSSM, Randall-Sundrum (RS) models, ...



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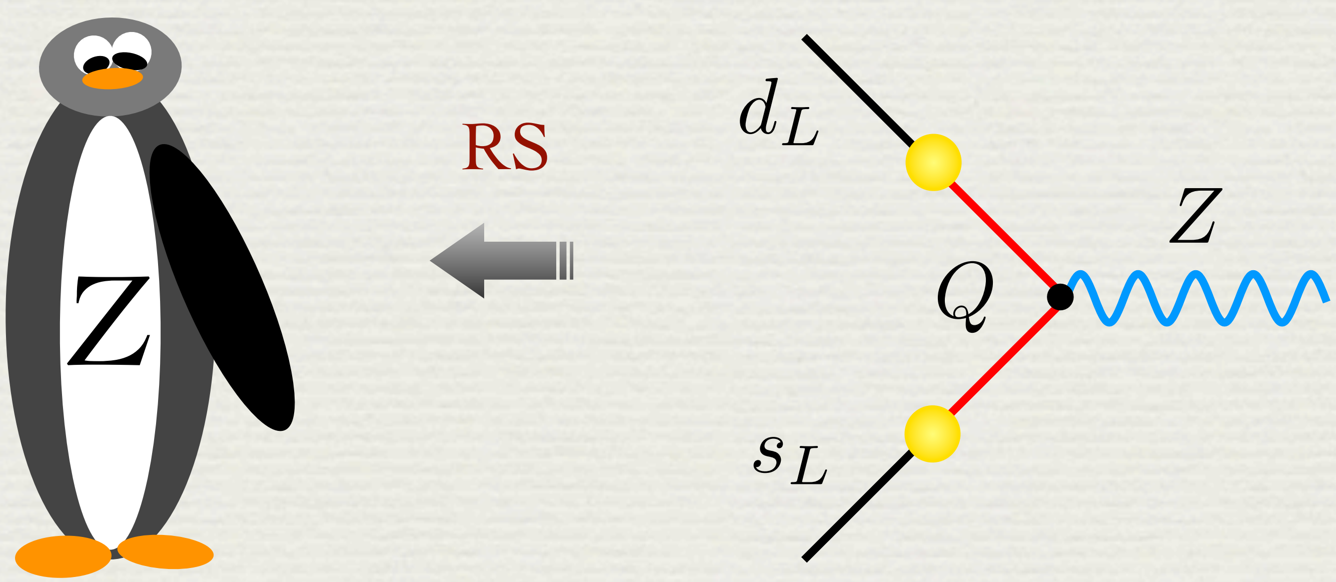

Z-Penguin Operators Cont'd

- Similarly, there is right-handed (RH) Z-penguin

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- Parametrize flavor-changing Z-boson vertices by

$$(V_{ts}^* V_{td}\, C_{\rm SM} + \boxed{C_{\rm NP}})\, \bar{d}_L \gamma_\mu s_L Z^\mu + \boxed{\widetilde{C}_{\rm NP}}\, \bar{d}_R \gamma_\mu s_R Z^\mu$$

where V_{ij} are Cabibbo-Kobayashi-Maskawa (CKM) elements & $C_{SM} \approx 0.8$ is value of Inami-Lim function characterizing LH Z-penguin in SM

Anatomy of Neutrino Modes

- After summation over neutrino flavors, branching ratios of $K \to \pi\nu\bar{\nu}$ channels can be written as

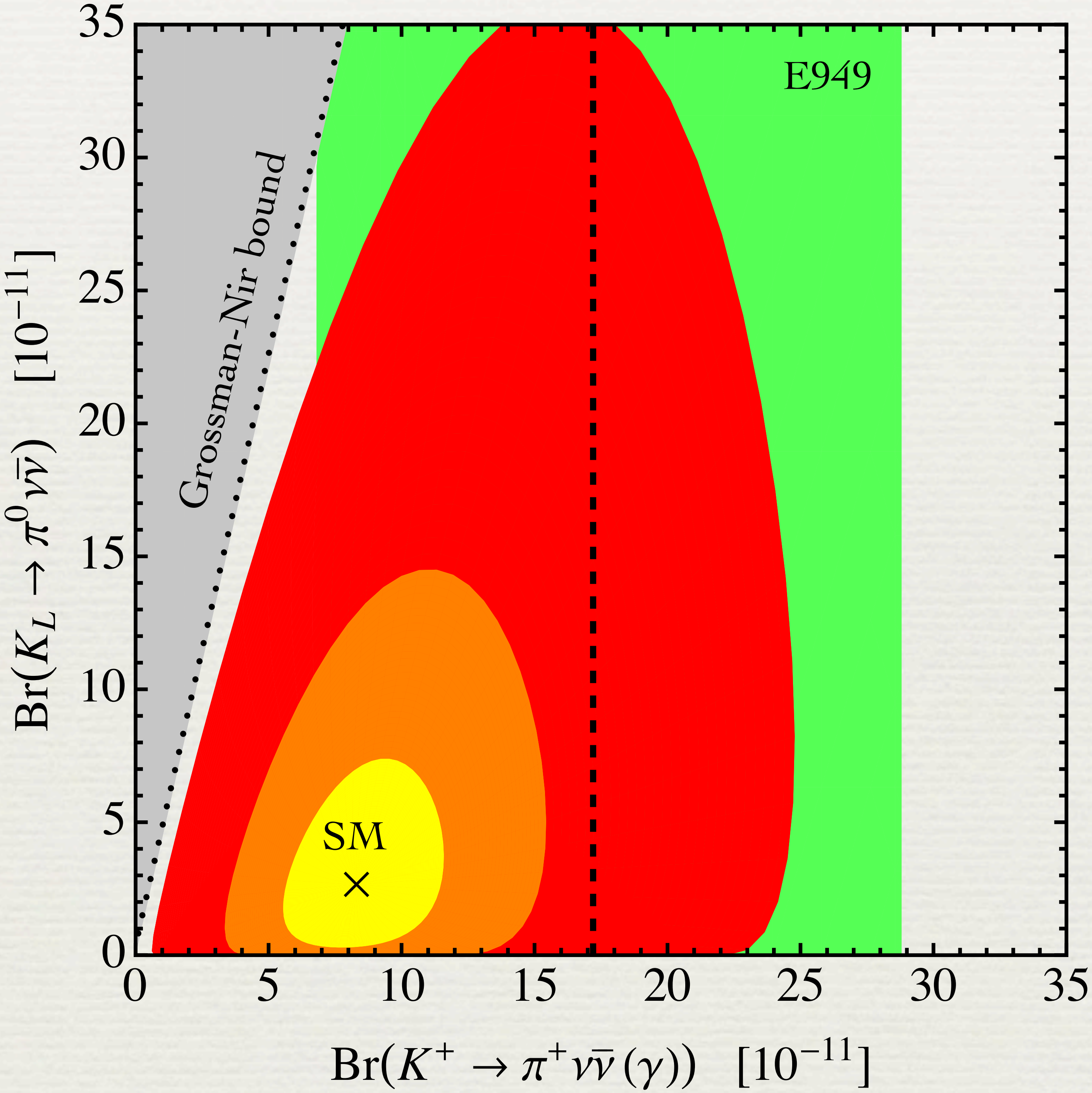
$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im}\, X)^2$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) \propto |X|^2$$

$$X = \frac{\lambda_t}{\lambda^5} X_t + \frac{\mathrm{Re}\lambda_c}{\lambda} P_{c,u} + \frac{1}{\lambda^5}\left(C_{\mathrm{NP}} + \widetilde{C}_{\mathrm{NP}}\right)$$

$$\lambda_i = V_{is}^* V_{id}\,, \quad \lambda \approx 0.23\,, \quad X_t \approx 1.5\,, \quad P_{c,u} \approx 0.4$$

Z-Penguins in Neutrino Modes



$|C_{\rm NP}| \leq 0.5|\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$

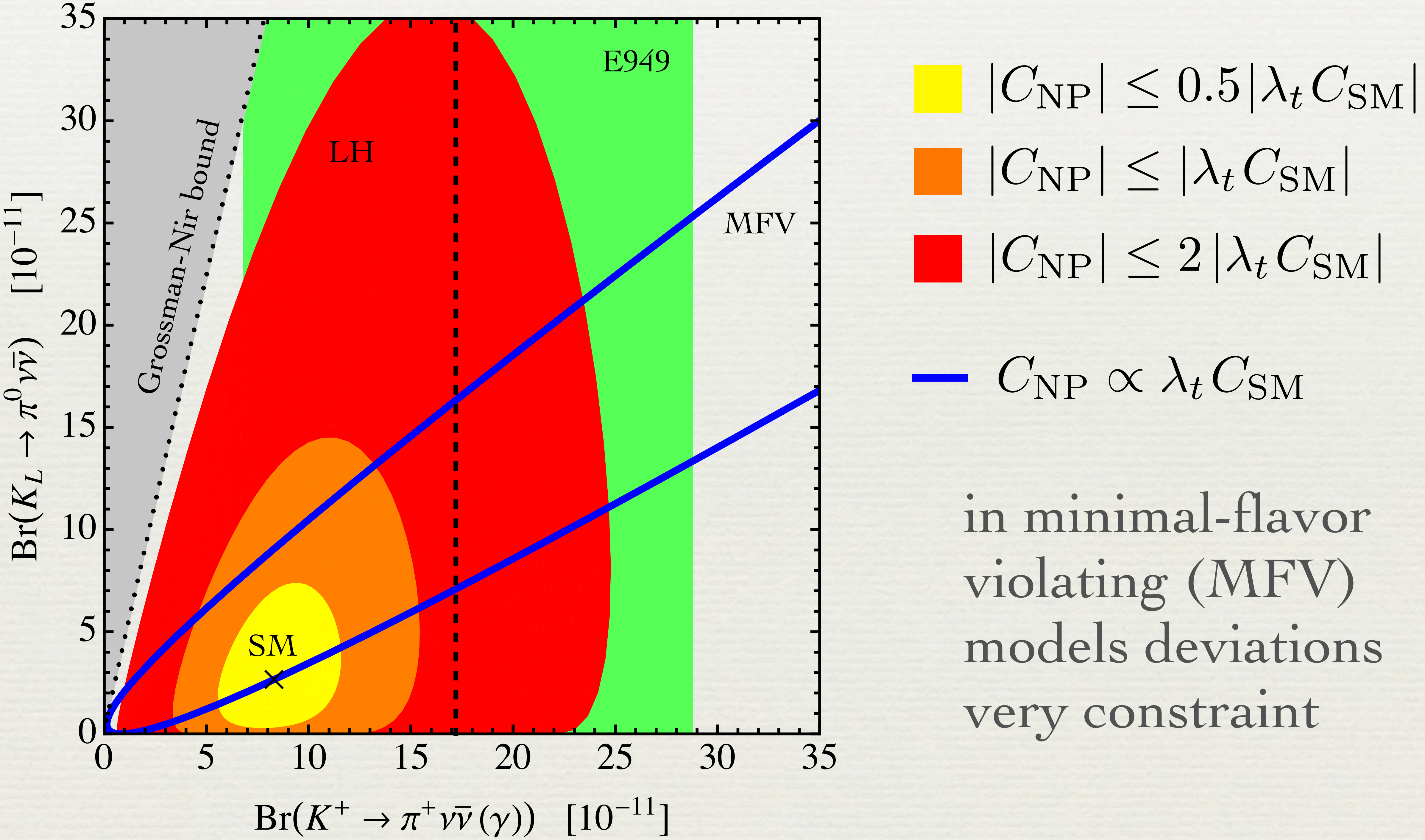
$|C_{\rm NP}| \leq 2\,|\lambda_t C_{\rm SM}|$

$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

same results obtained for RH Z-penguin

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

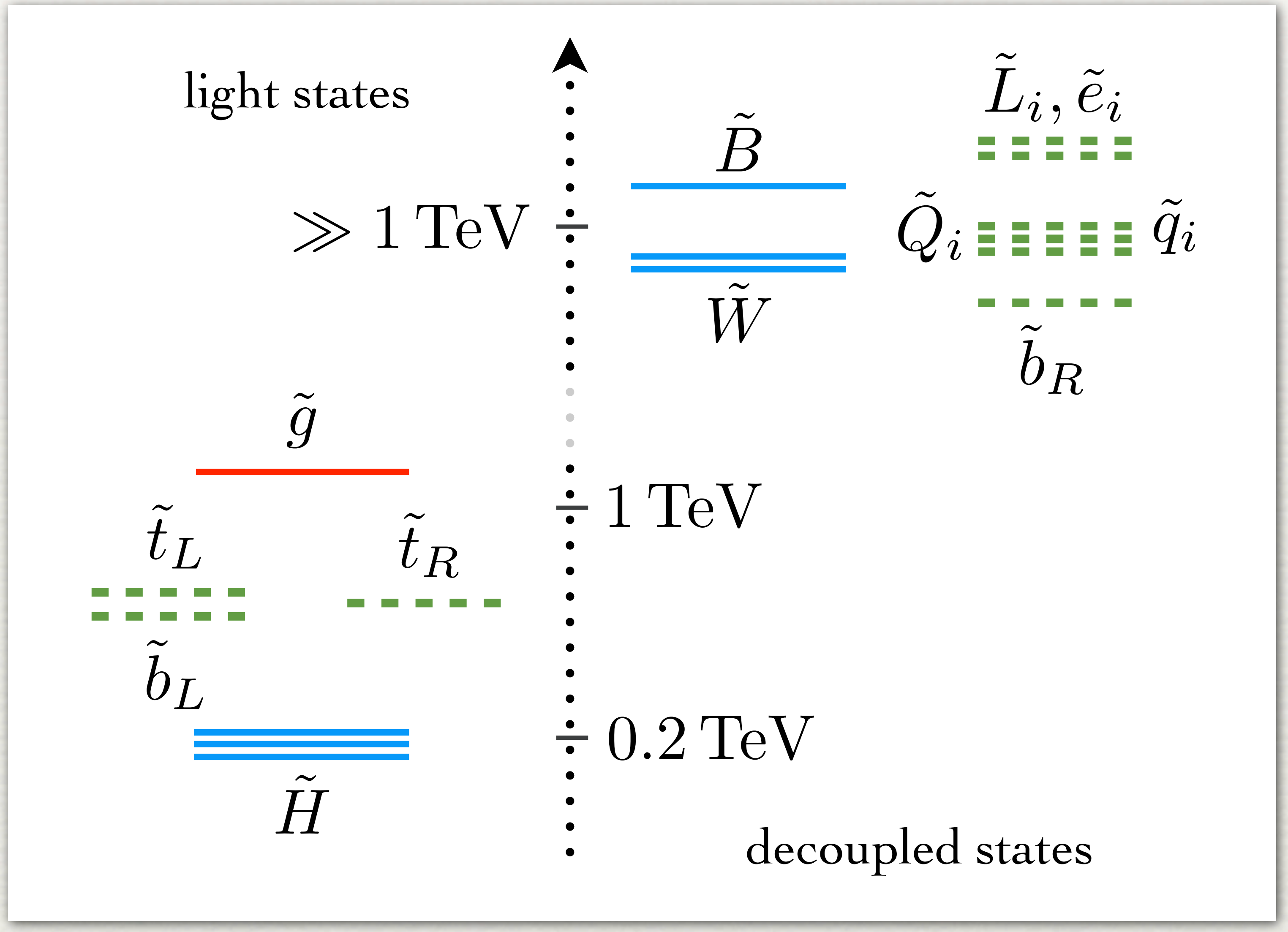
Z-Penguins in Neutrino Modes



in minimal-flavor violating (MFV) models deviations very constraint

[see S. Jäger, talk at NA62 Physics Handbook Workshop]

"Natural SUSY"

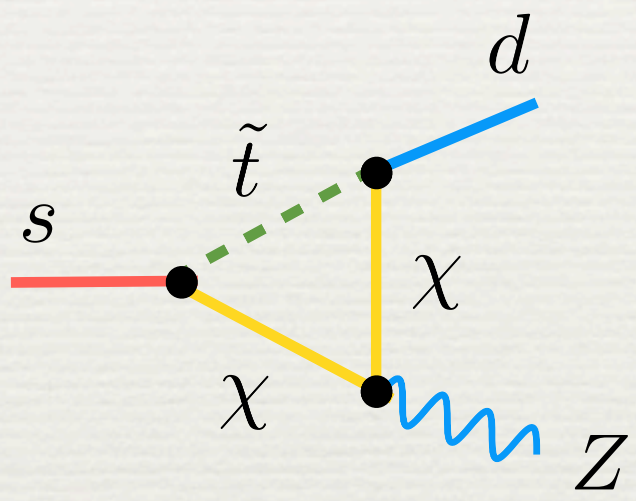


- To avoid destabilizing weak scale only higgsinos ($\tilde{H}$), stops ($\tilde{t}_L$, $\tilde{t}_R$), LH sbottom ($\tilde{b}_L$) & gluino ($\tilde{g}$) need to be TeVish

[see for example Brust et al. 1110.6670; Papucci, Ruderman & Weiler, 1110.6926]

"Natural SUSY"

- Light stops & charginos lead to specific pattern of deviations in flavor observables:

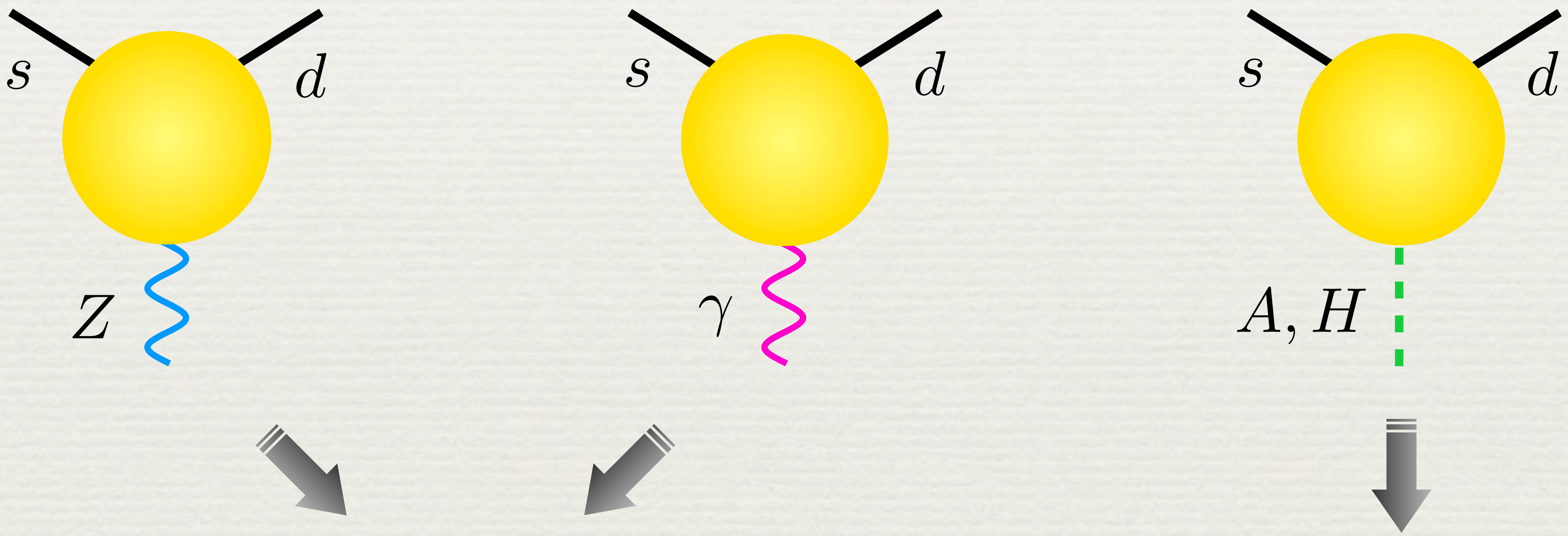


$$\frac{\Delta C}{C_{\rm SM}} \approx \frac{m_t^2 A_t^2}{12 s_\beta^2 m_{\tilde{t}_1}^4}$$

Due to hierarchy $|M_2| >> |\mu|$, stop-chargino effects in LH Z-penguin below 10% level. Predictions for rare kaon decays (as well as $B_s \to \mu^+\mu^-$ & $B \to K^*l^+l^-$) essentially unaltered in MFV MSSM

Anatomy of Leptonic Modes

- $K_L \to \pi^0 l^+ l^-$ modes receive contributions from (axial-) vector (A, V), (pseudo-)scalar (P, S), ... operators:



$$Q_V = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu l) \qquad Q_S = (\bar{d}s)(\bar{l}l)$$

$$Q_A = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu \gamma_5 l) \qquad Q_P = (\bar{d}s)(\bar{l}\gamma_5 l)$$

Anatomy of Leptonic Modes Cont'd

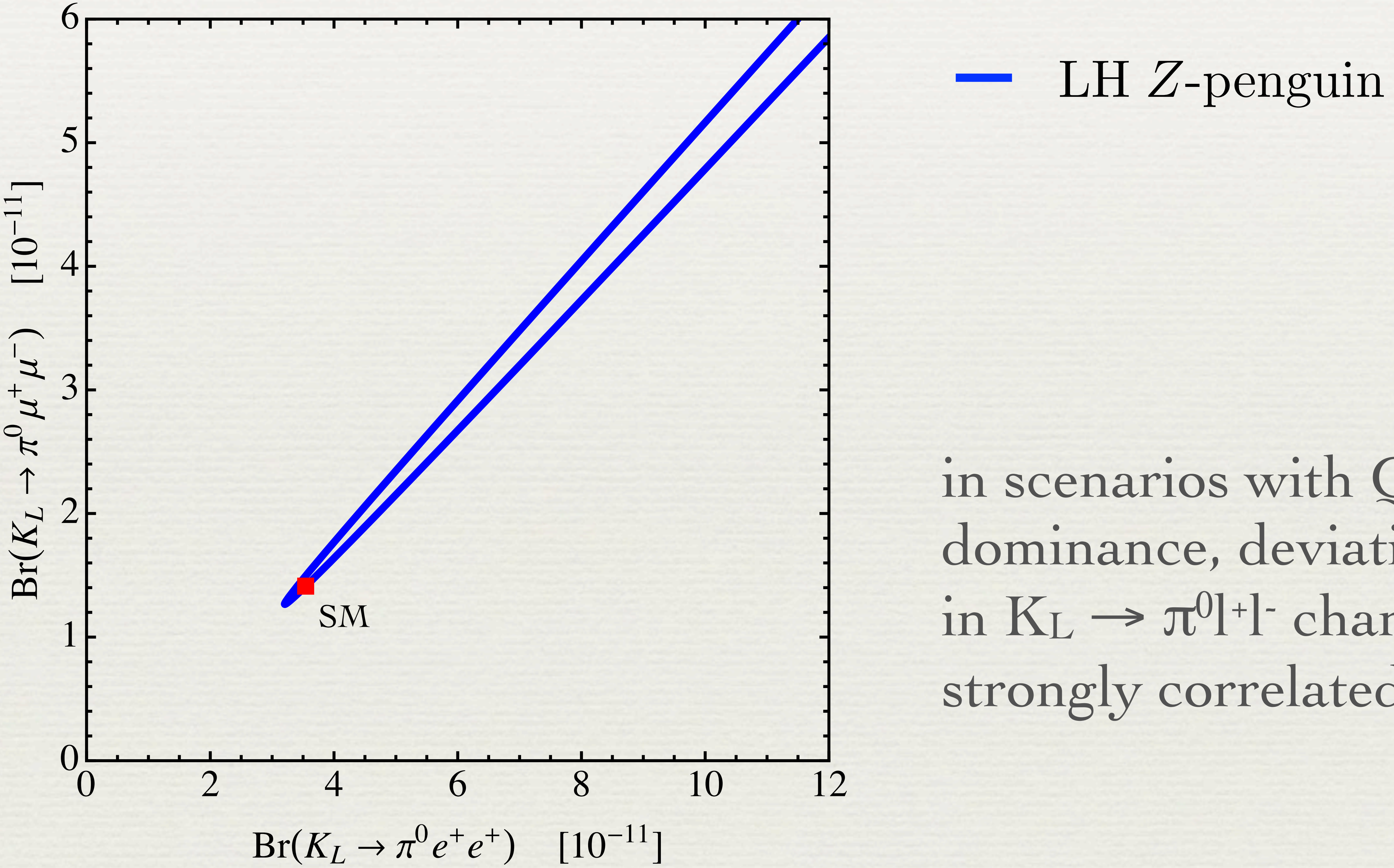
- In many explicit SM extensions such as RS scenarios, little Higgs models, scenarios with extra chiral/vector-like matter, ..., contribution from Q_A dominates over those of Q_V, Q_S & Q_P:

$$C_V \propto \left(\frac{1}{s_w^2} - 4\right)\left(C_{\rm NP} + \tilde{C}_{\rm NP}\right) \approx 0.4\left(C_{\rm NP} + \tilde{C}_{\rm NP}\right)$$

$$C_A \propto -\frac{1}{s_w^2}\left(C_{\rm NP} - \tilde{C}_{\rm NP}\right) \approx -4.4\left(C_{\rm NP} - \tilde{C}_{\rm NP}\right)$$

$$C_{S,P} \propto m_s m_l$$

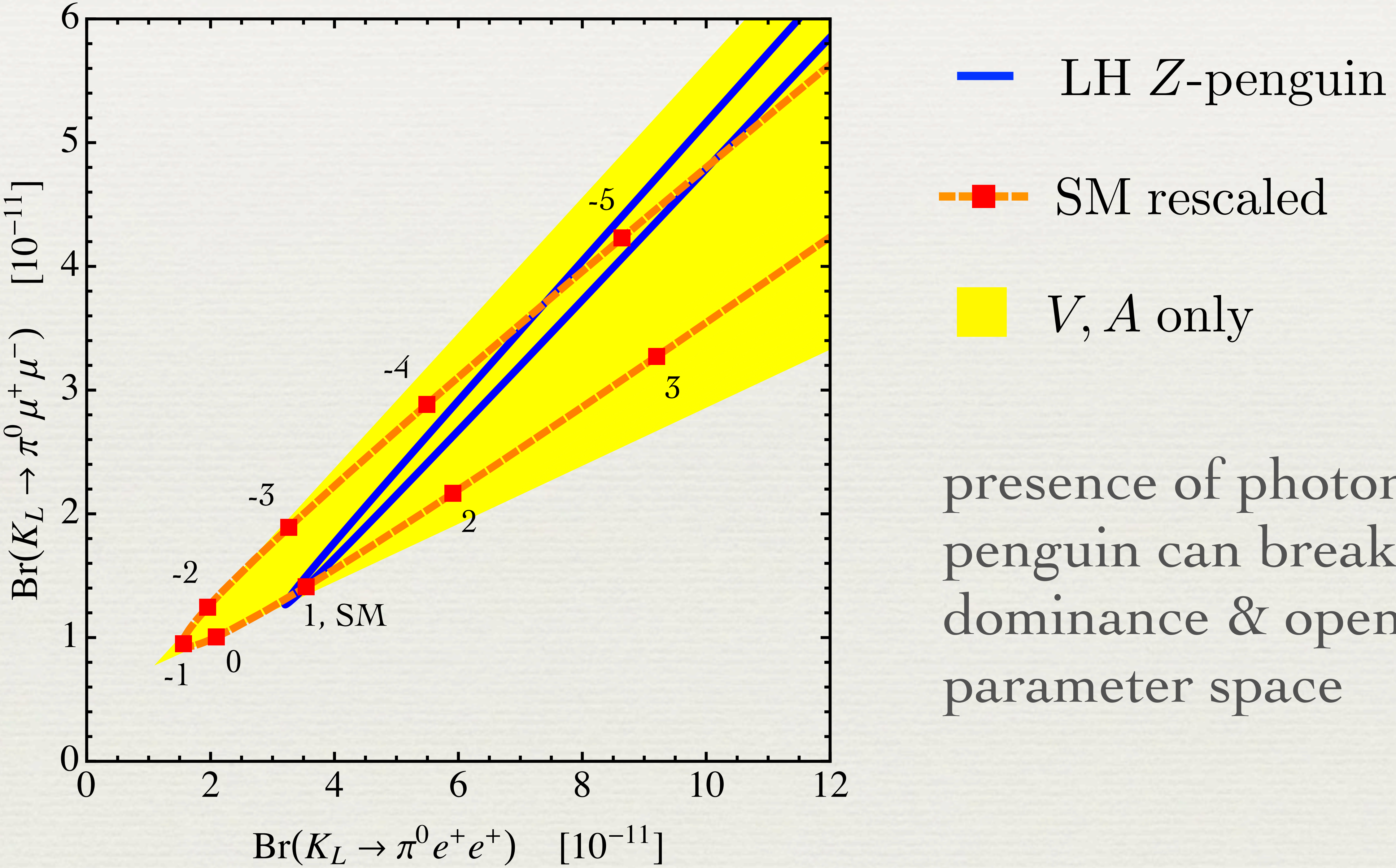
Correlations of Leptonic Modes



in scenarios with Q_A dominance, deviations in $K_L \to \pi^0 l^+ l^-$ channels strongly correlated

[see F. Mescia, C. Smith & S. Trine, hep-ph/0606081]

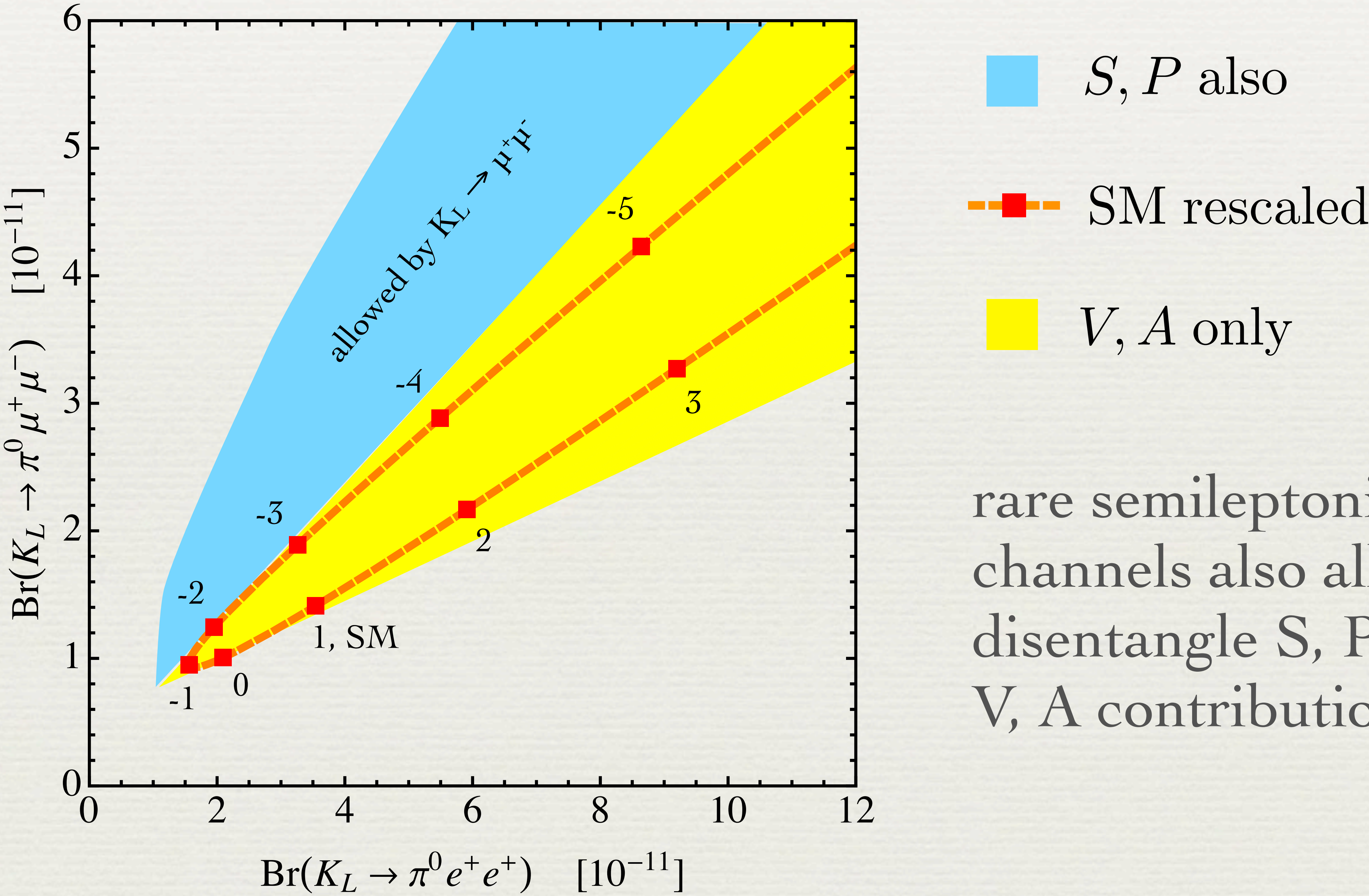
Correlations of Leptonic Modes



presence of photon penguin can break Q_A dominance & opens up parameter space

[see F. Mescia, C. Smith & S. Trine, hep-ph/0606081]

Correlations of Leptonic Modes



rare semileptonic kaon channels also allow to disentangle S, P from V, A contributions

[see F. Mescia, C. Smith & S. Trine, hep-ph/0606081]

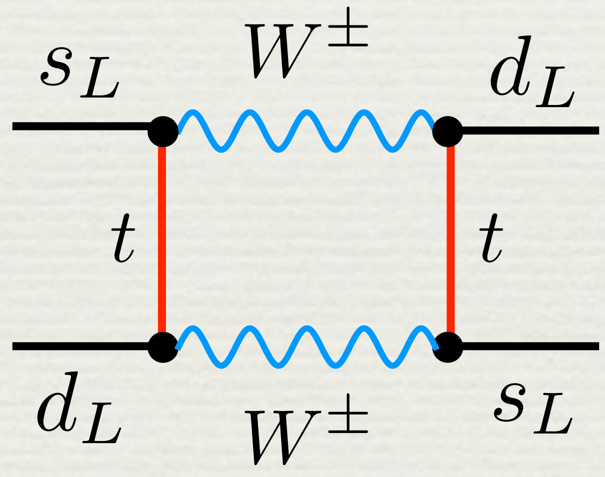
Anatomy of ε_K

- Most severe constraints on flavor structure in many non-MFV models due to CP violation in kaon sector:

$$\epsilon_K \underset{\sim}{\propto} \boxed{\mathrm{Im}}\left(C_{LL}^{sd} + \boxed{115}\, C_{LR}^{sd}\right)$$

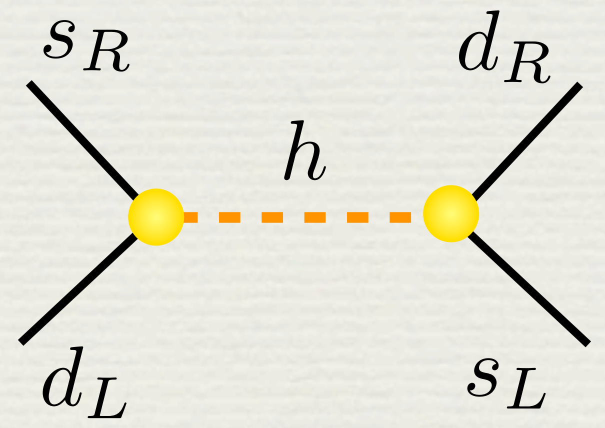
SM

$$Q_{LL}^{sd} = (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L) \Longleftarrow$$



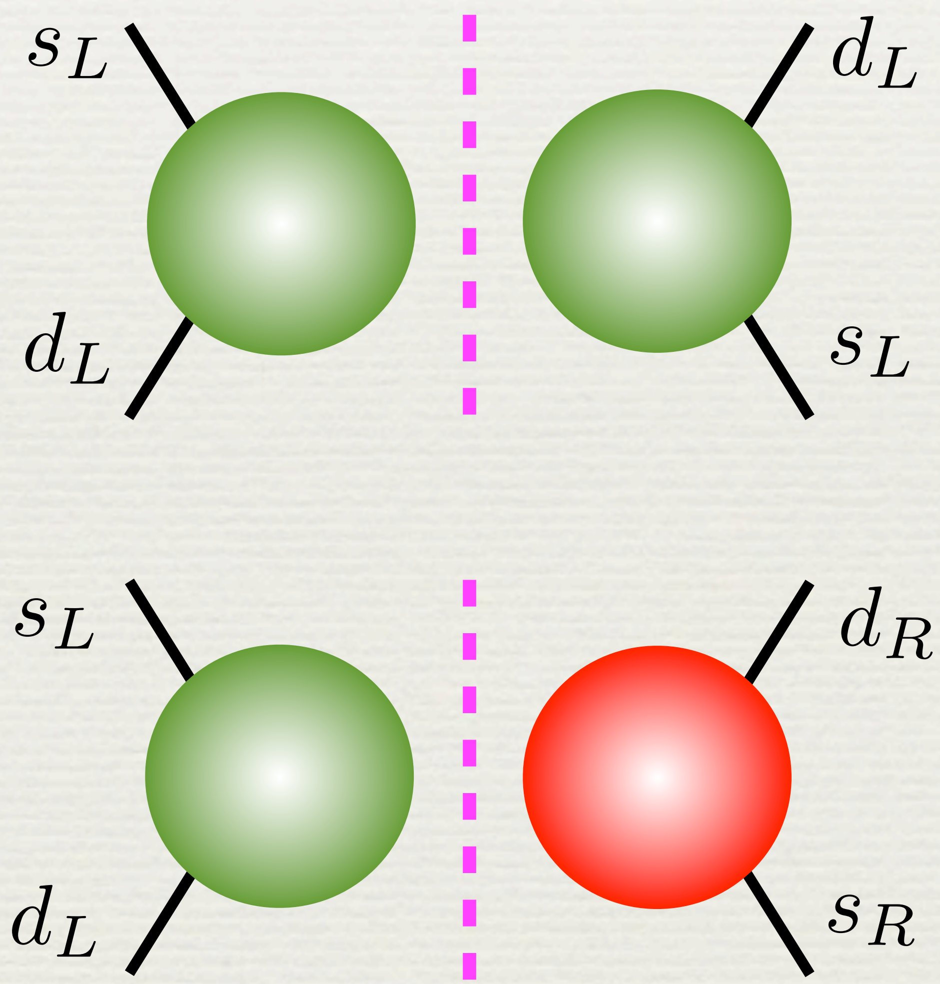
RS

$$Q_{LR}^{sd} = (\bar{s}_R d_L)(\bar{s}_L d_R) \Longleftarrow$$



ε_K & Rare K Decay Link

- SM extensions fall into two classes, those with pure LH structure & those with both LH & RH currents:



[see M. Blanke, arXiv:0904.2528 [hep-ph]]

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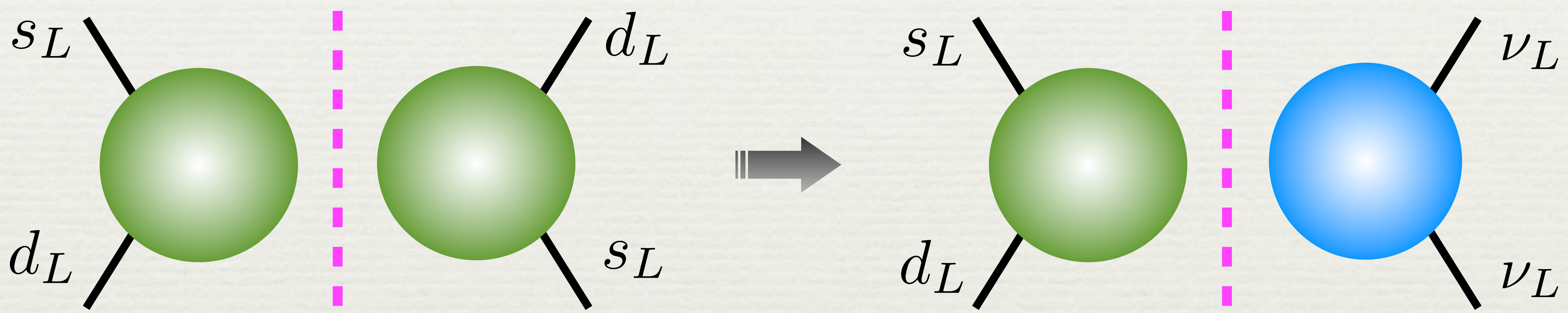
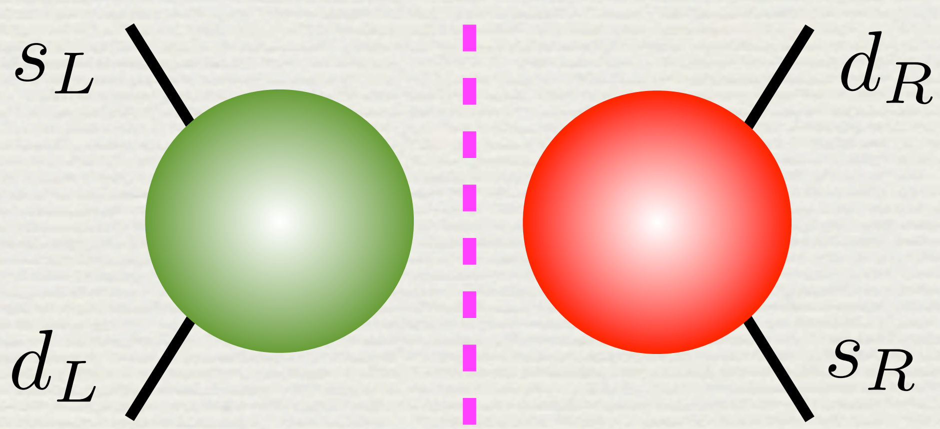
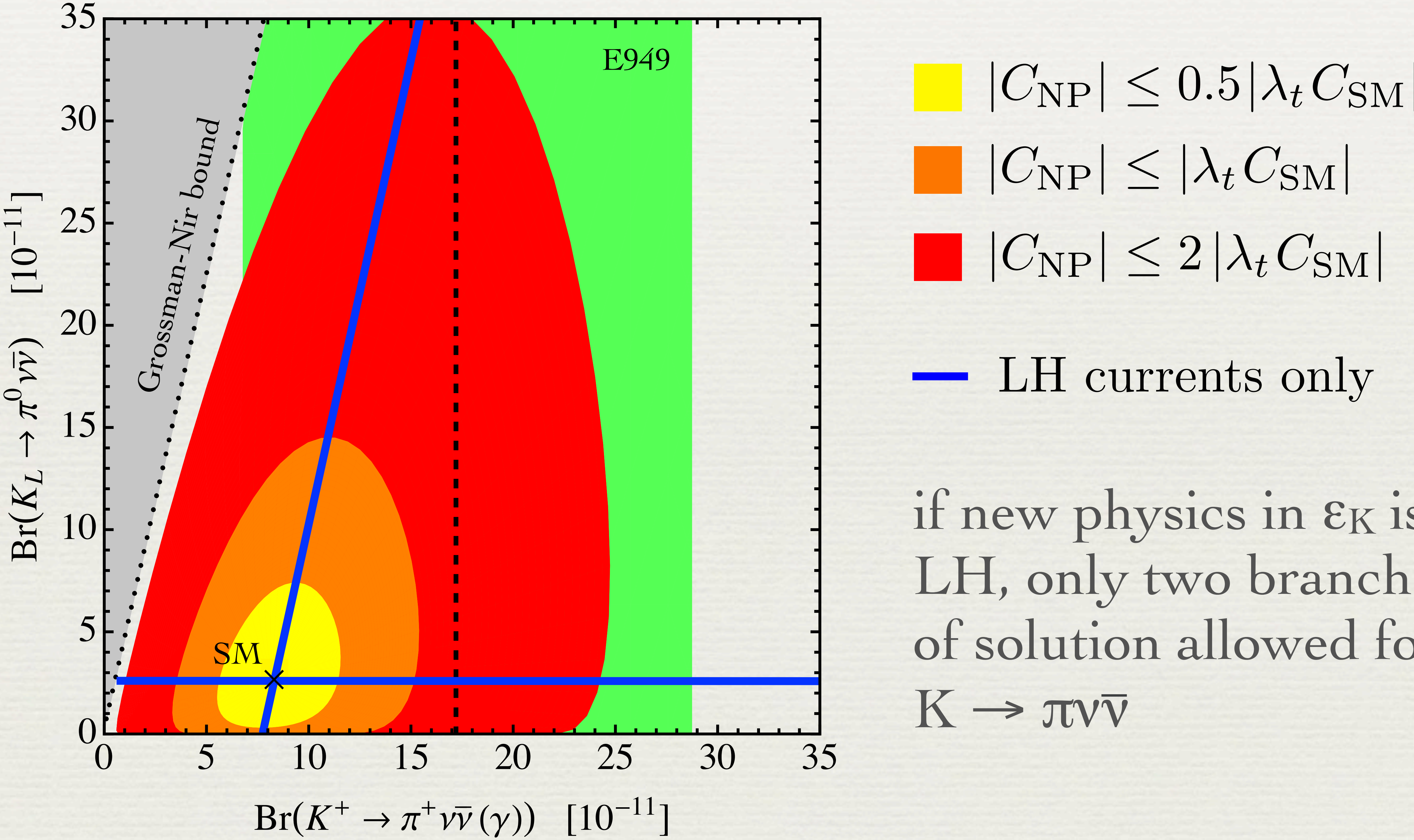




while in LH case, ε_K restricts phase in s $\rightarrow$ d transition, connection between ΔS = 2,1 lost, if RH interactions present

[see M. Blanke, arXiv:0904.2528 [hep-ph]]

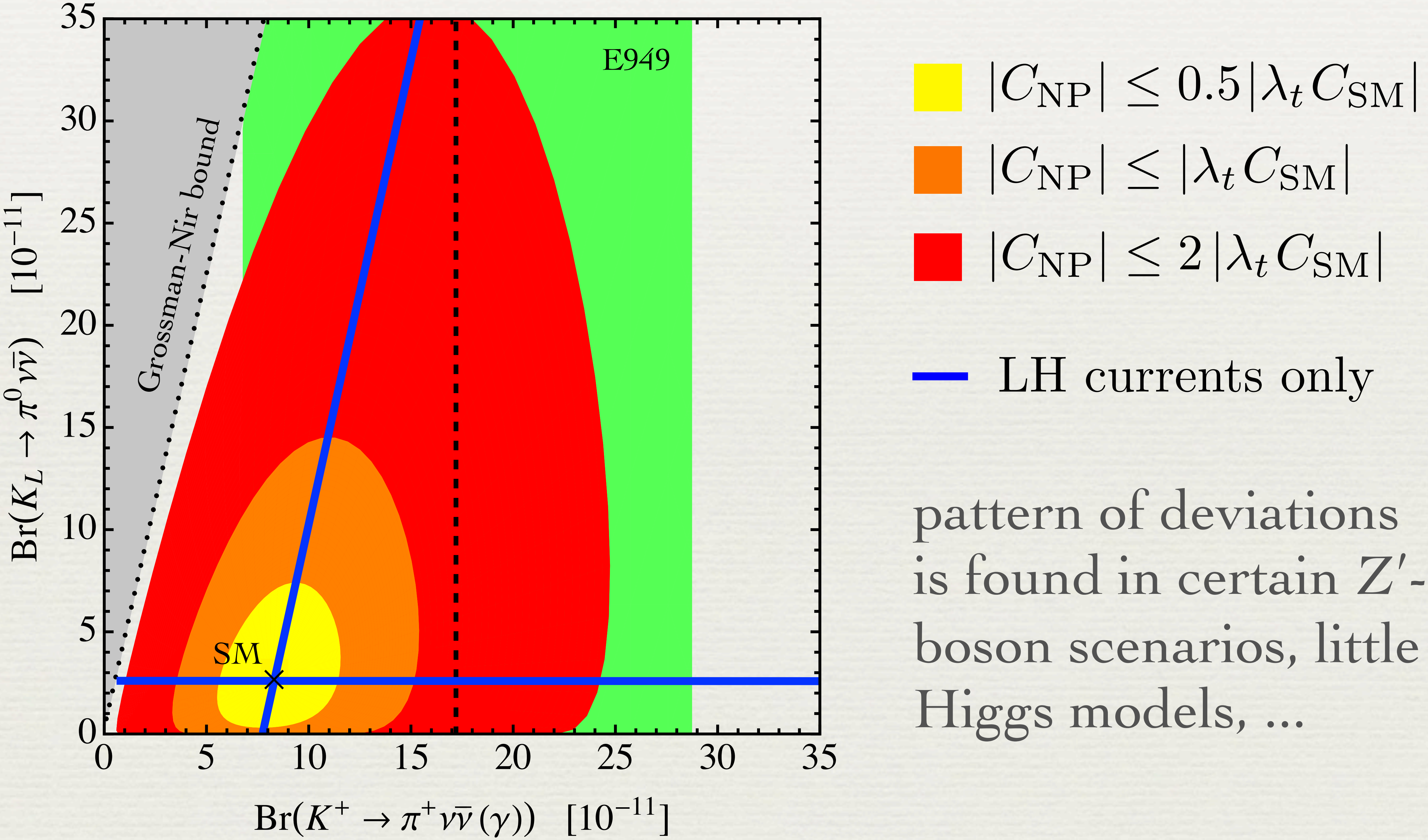
ε_K & Rare K Decay Link Cont'd



if new physics in ε_K is LH, only two branches of solution allowed for $K \to \pi\nu\bar{\nu}$

[see M. Blanke, arXiv:0904.2528 [hep-ph]]

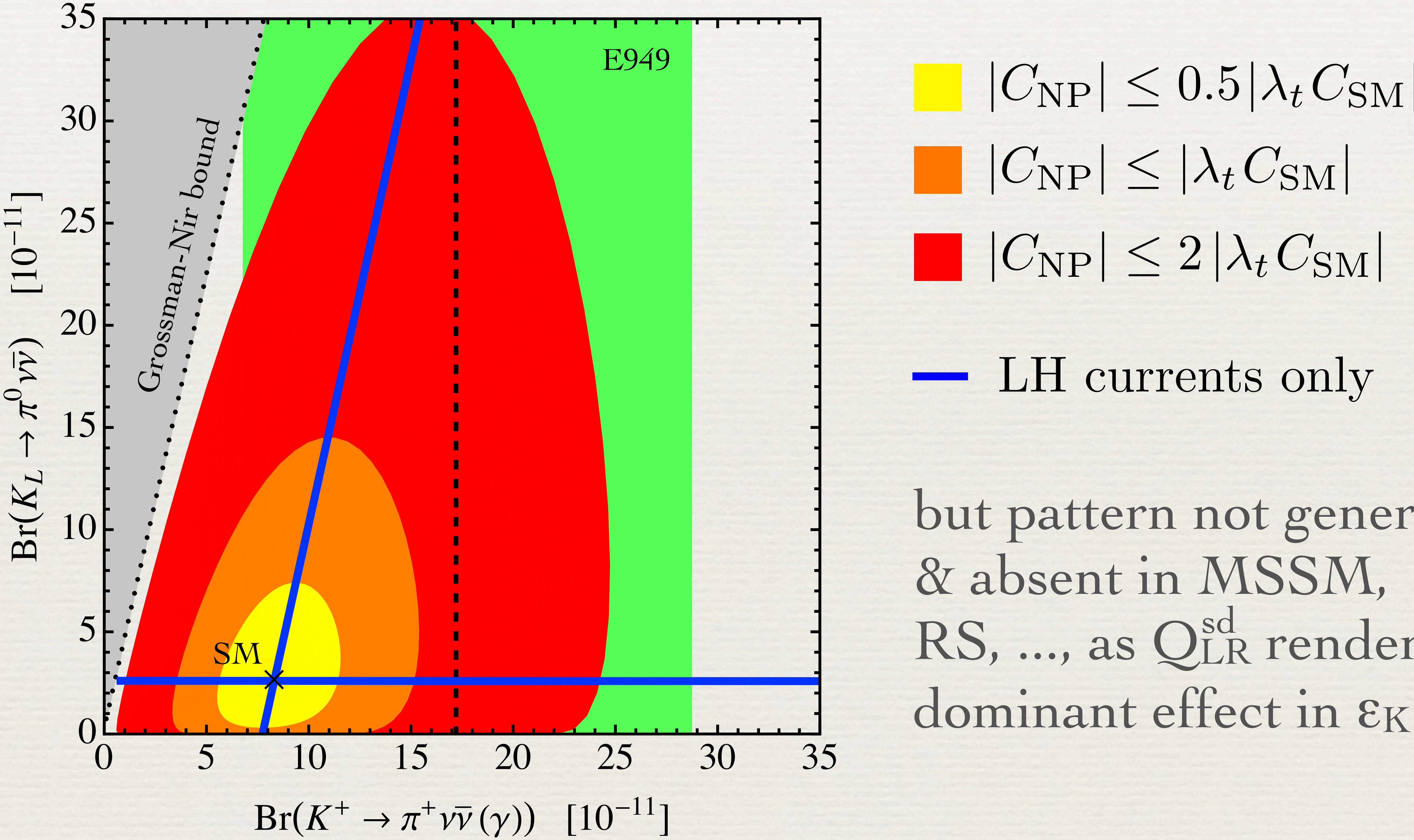
ε_K & Rare K Decay Link Cont'd



pattern of deviations is found in certain Z'-boson scenarios, little Higgs models, ...

[see M. Blanke, arXiv:0904.2528 [hep-ph]]

ε_K & Rare K Decay Link Cont'd



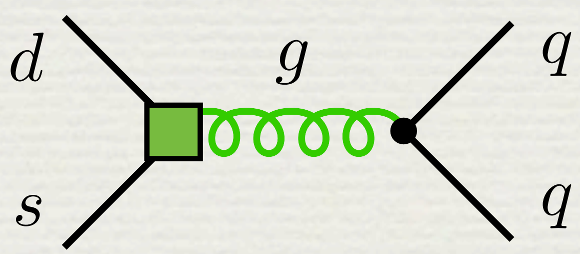
but pattern not generic & absent in MSSM, RS, ..., as Q_{LR}^{sd} renders dominant effect in ε_K

[see M. Blanke, arXiv:0904.2528 [hep-ph]]

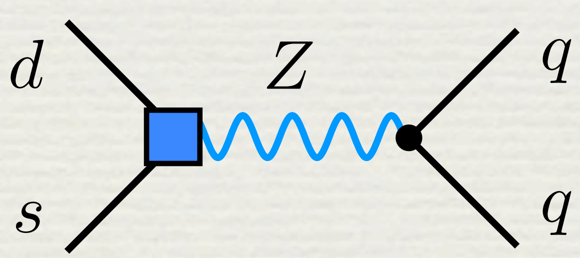
Anatomy of ε′/ε

- Prediction for ε′/ε very sensitive to interplay between QCD (Q_6) & electroweak (Q_8) penguin operators:

$$\frac{\epsilon'}{\epsilon} \propto -\mathrm{Im}\Big[\lambda_t\,(-1.4 + 13.8\,R_6 - 6.6\,R_8) + (1.5 + 0.1\,R_6 - 13.3\,R_8)\Big(C_{\rm NP} - \widetilde{C}_{\rm NP}\Big)\Big]$$



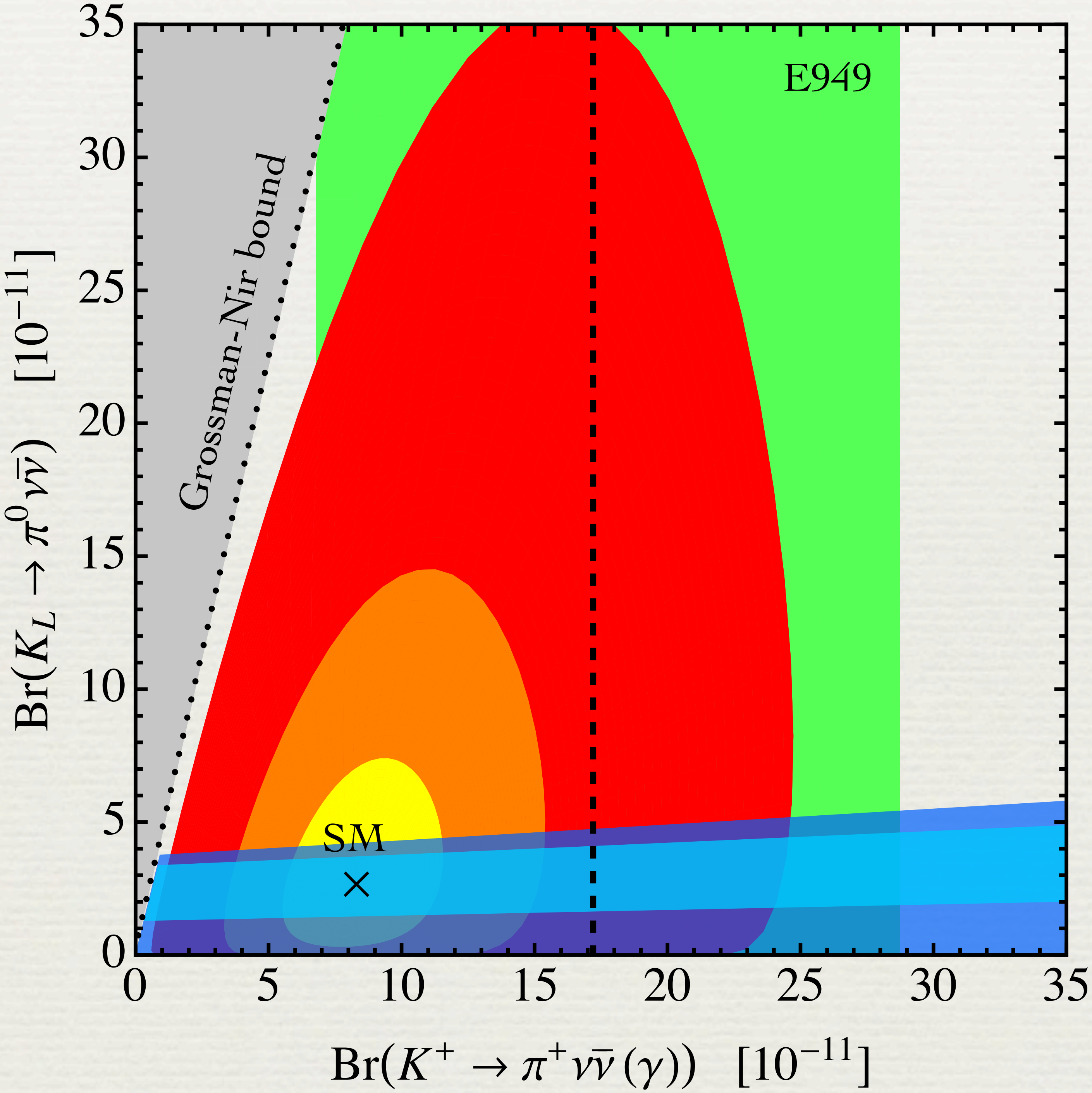
$$R_6 \propto \langle (\pi\pi)_{I=0} | Q_6 | K \rangle \underset{\sim}{\in} [0.8, 2.0]$$



$$R_8 \propto \langle (\pi\pi)_{I=2} | Q_8 | K \rangle \underset{\sim}{\in} [0.8, 1.2]$$

[see M. Bauer et al., arXiv:0912.1625 [hep-ph]]

ε′/ε Strikes Back



$|C_{\rm NP}| \leq 0.5\,|\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq 2\,|\lambda_t C_{\rm SM}|$

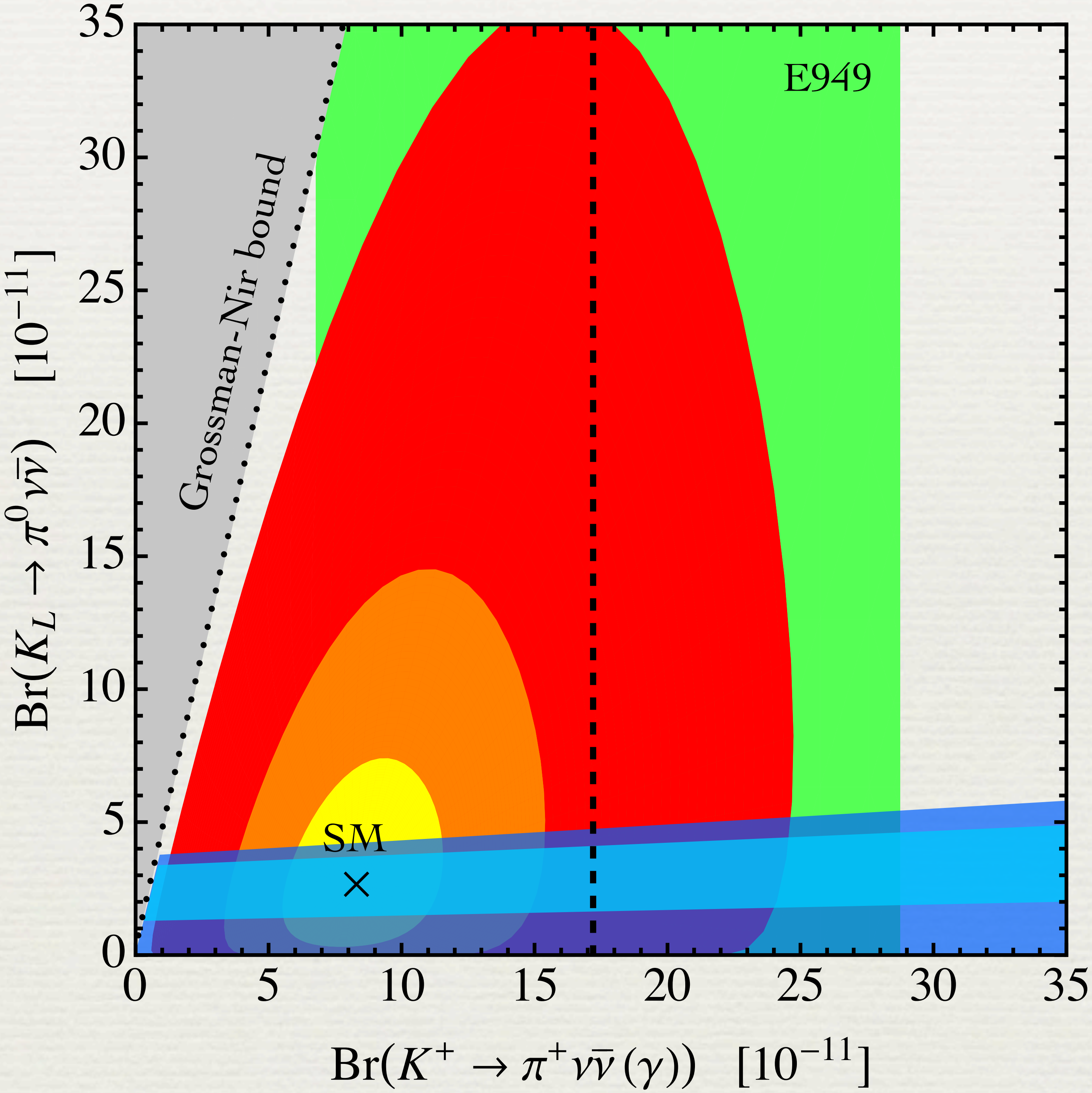
$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

$\epsilon'/\epsilon \in [0.5, 2]\,(\epsilon'/\epsilon)_{\rm SM}$

$\epsilon'/\epsilon \in [0.2, 5]\,(\epsilon'/\epsilon)_{\rm SM}$

[see S. Jäger, talk at NA62 Physics Handbook Workshop; M. Bauer et al., arXiv:0912.1625 [hep-ph]]

ε′/ε Strikes Back

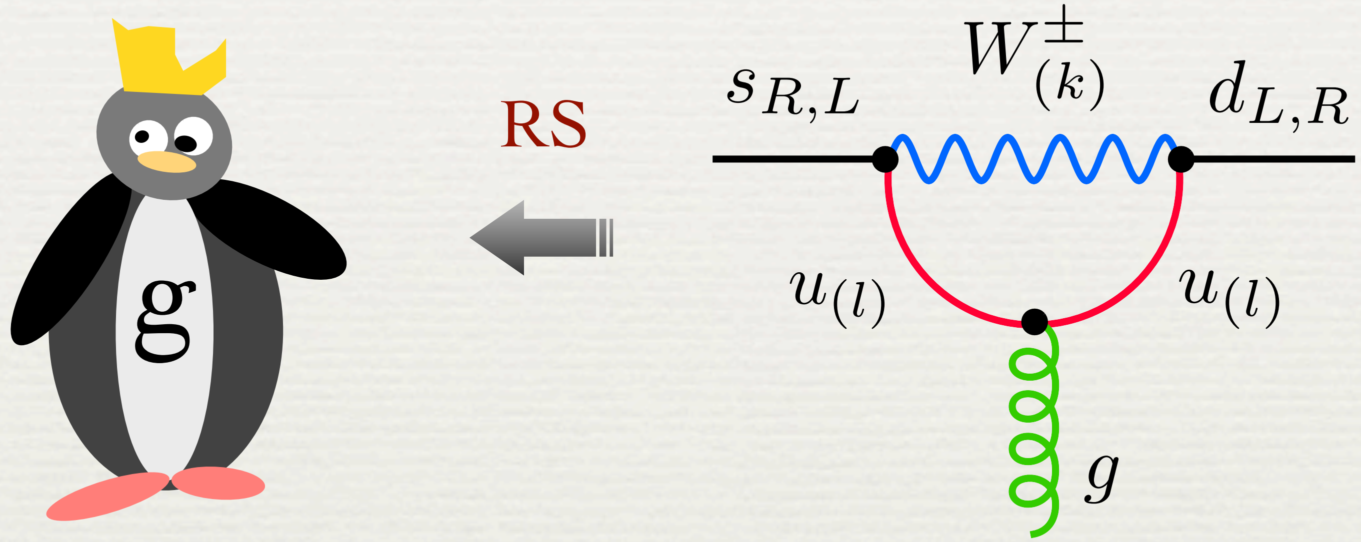


stringent correlation between CP-violating kaon observables present in MSSM, RS, compositeness, ...

ε′/ε "sleeping beauty" of flavor physics: when will lattice's kiss wake her?

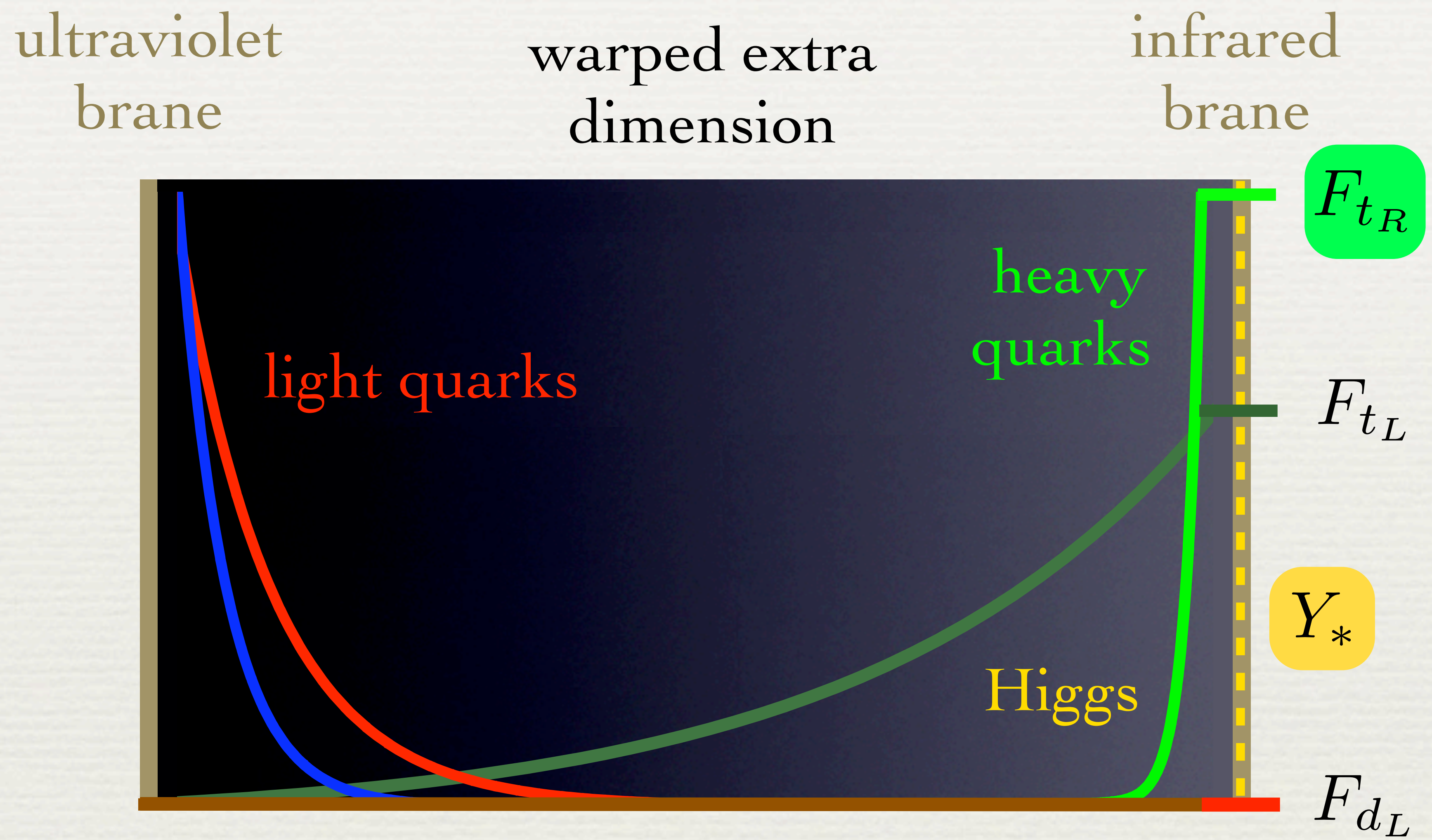
[see S. Jäger, talk at NA62 Physics Handbook Workshop; M. Bauer et al., arXiv:0912.1625 [hep-ph]]

Gluonic Penguins in ε′/ε



- Chromomagnetic penguin operators (Q_{8g}, $\tilde{Q}_{8g}$) can also give large correction to ε′/ε. But in general (meaning MSSM, RS, ...) there is no correlation with Z penguin. In fact, often possible to decouple effects

Gluonic Penguins in ε′/ε



$$\{C_{8g}, \widetilde{C}_{8g}\} \propto \left\{\lambda m_s, \frac{m_s}{\lambda}\right\} \frac{Y_*^2}{m_t}, \quad C \propto \frac{A^2\lambda^5}{Y_*^2 F_{t_R}^2}, \quad \widetilde{C} \propto \frac{m_d m_s F_{t_R}^2}{A^2\lambda^5 m_t^2}$$

[see M. Bauer et al., arXiv:0912.1625 [hep-ph]]

Conclusions & Outlook

- In view of "textbook measurements" of CP phase in B_s system, $B \to K^{*}\mu^{+}\mu^{-}$ & $B_s \to \mu^{+}\mu^{-}$ by LHCb, rare decays of kaons last place where indisputable signals of new physics could show up

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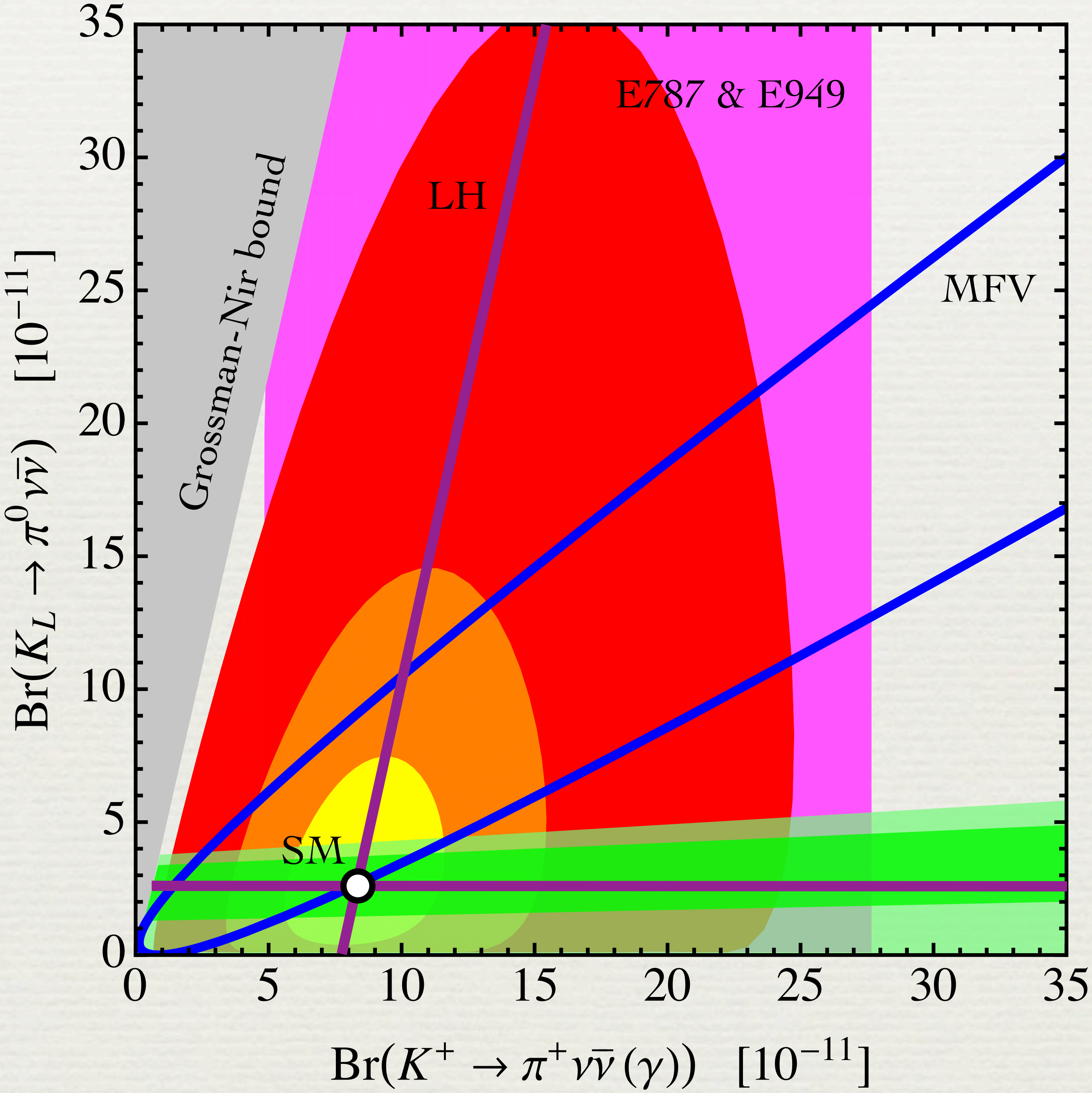
- Since kaon observables feature testable correlations, mandatory to measure as many rare kaon modes as possible. Only experiment can unravel flavor mystery!

Sources of Inspiration

- Talk by S. Jäger given at NA62 Physics Handbook Workshop, 10-12 December 2009 CERN
- F. Mescia, C. Smith & S. Trine, hep-ph/0606081
- M. Blanke, arXiv:0904.2528 [hep-ph]
- M. Bauer, S. Casagrande, U. Haisch & M. Neubert, arXiv:0912.1625 [hep-ph]
- ...

Neutrino Modes: Summary



Leptonic Modes: Summary