KAONS IN AND BEYOND THE STANDARD MODEL

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with a high intensity proton source
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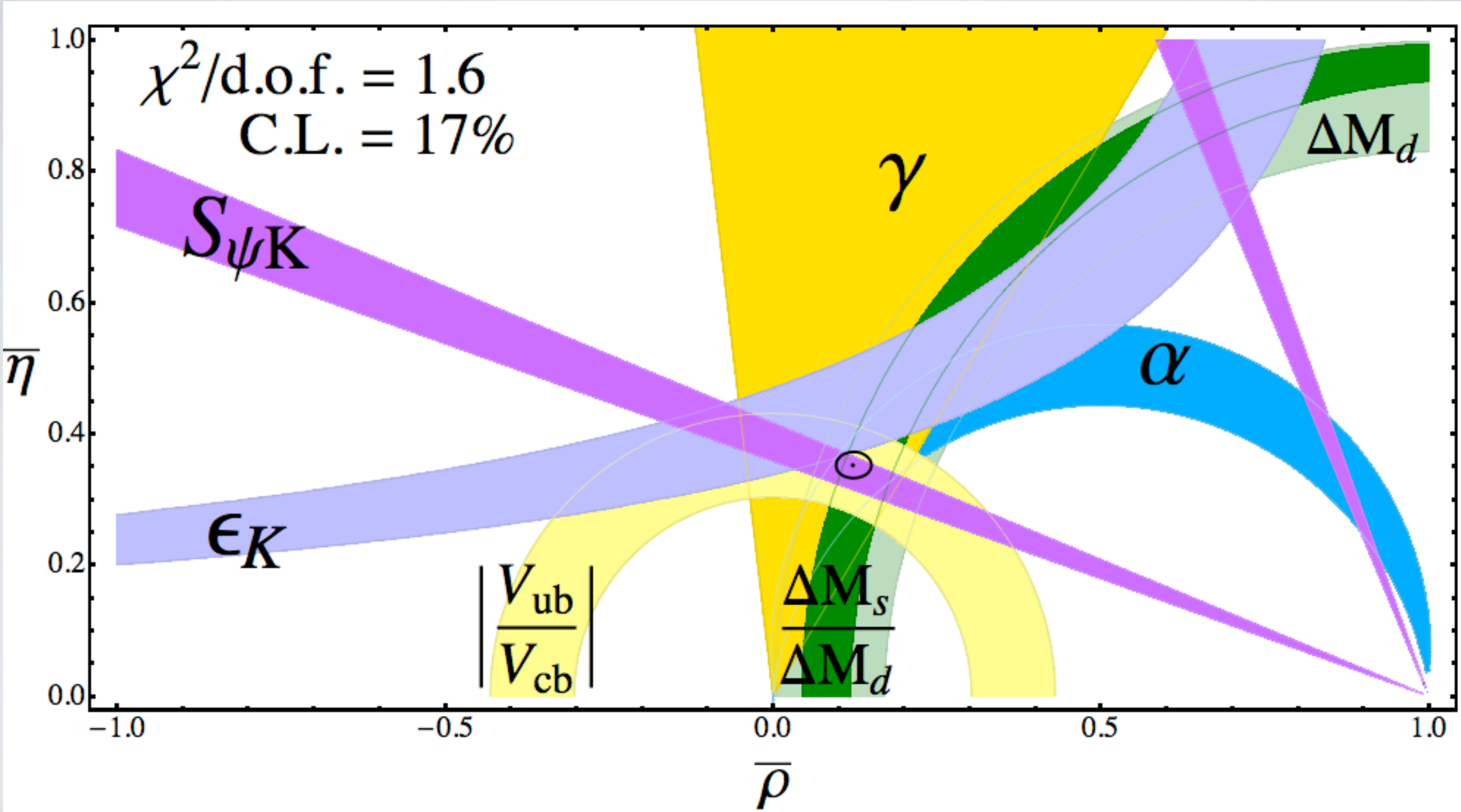
NEUTRAL KAON MIXING

- If you've come in from the energy frontier, you may be more familiar with neutral B_s mixing, where the mass difference is measured.
- In the kaon system, the mass difference is not so useful, owing to long-distance transitions like $K^0 \to \pi\pi \to \bar{K}^0$.
- Instead, the *CP*-violating quantity ε_K puts a useful constraint on the CKM matrix.

Laiho, Lunghi, Van de Water, arXiv:0910.2928



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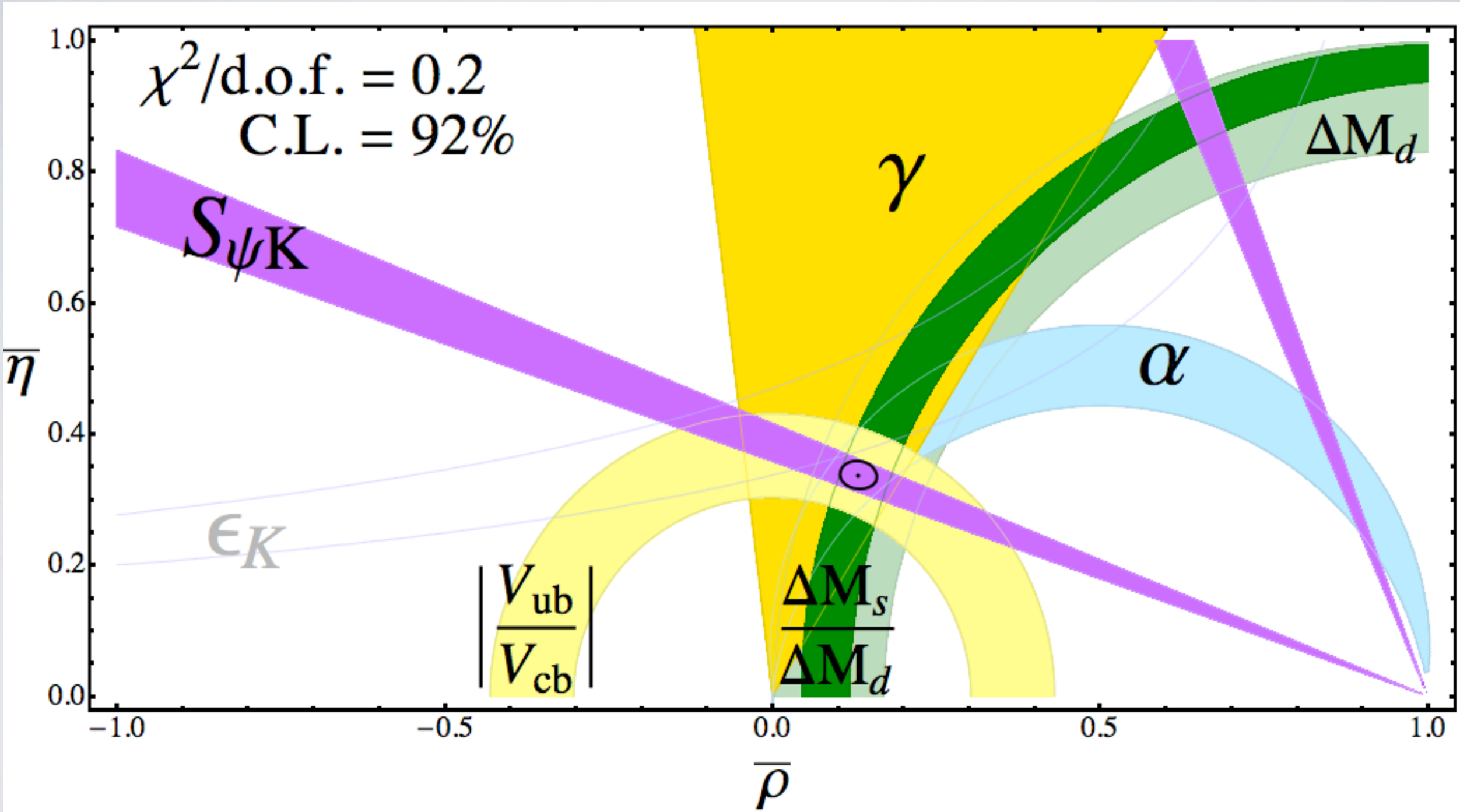
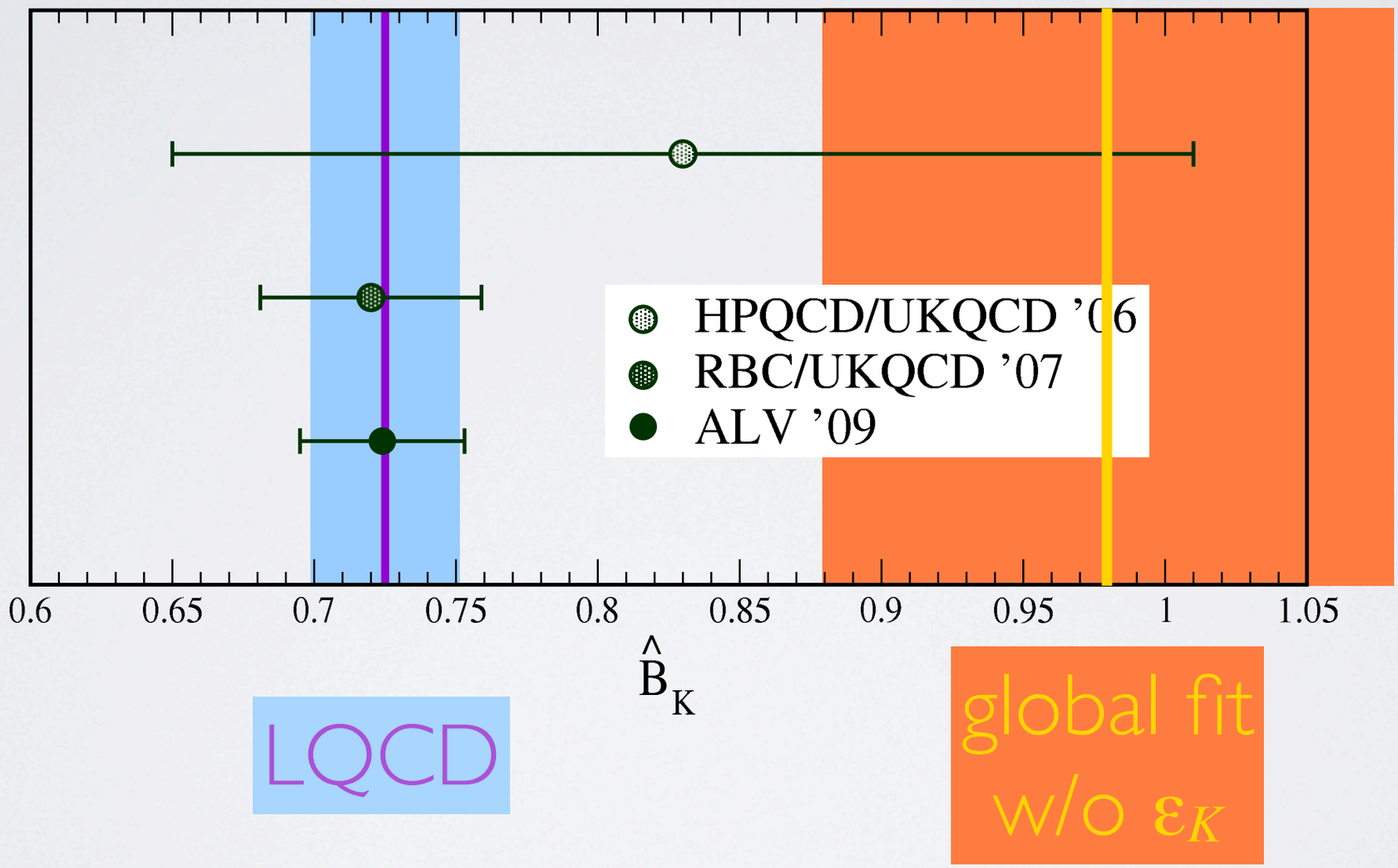


TENSION

[LUNGHI, SONI; BURAS, GUADANGOLI; LLV]



2.4σ tension

OUTLINE

- Prologue: Tension in ε_K
- Anatomy of (neutral and charge) $K \to \pi\nu\bar{\nu}$ in SM
  - and beyond
- Kaons' New Physics Problem & MFV
- Possibilities and Correlations
- Conclusions

STANDARD MODEL

$$B_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\tau_{K^+} M_{K^+}^5}{32\pi^3}(1+\Delta_{\rm EM})\left|f_+^{K^+\pi^+}(0)\right|^2 I_\nu^+ \left|\frac{G_F\,\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W} Y\right|^2$$

kinematics EM QCD weak

$$B_{\rm SM}(K_L \to \pi^0 \nu\bar{\nu}) = \frac{\tau_{K_L} M_{K_L}^5}{32\pi^3}\left|f_+^{K^0\pi^0}(0)\right|^2 I_\nu^0 \left|\frac{G_F\,\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W} {\rm Im}Y\right|^2$$

K_S has ${\rm Re}Y$

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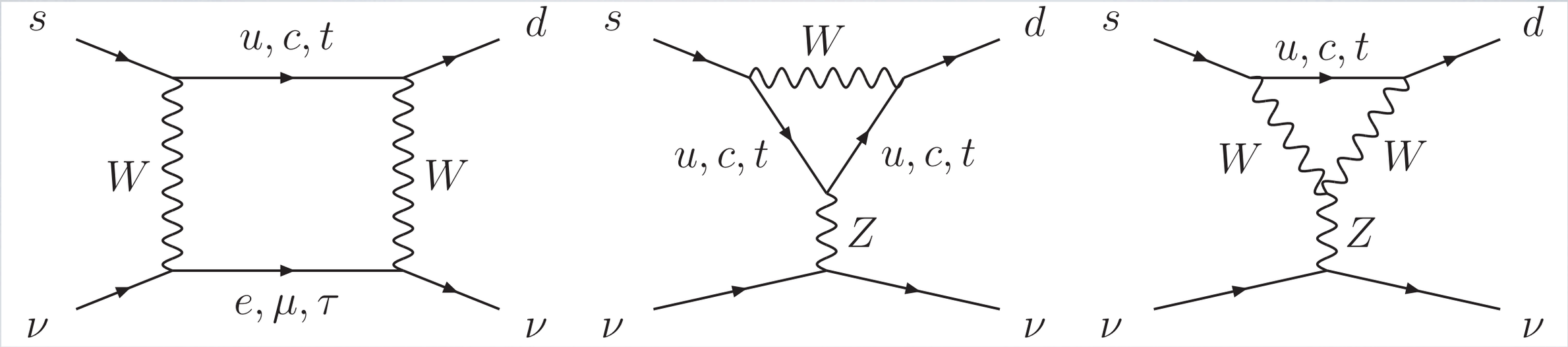
$$\frac{g^4}{16\pi^2 M_W^2}$$

K_S has $\mathrm{Re}Y$



- Induced in SM at one (and higher) loop(s):

$$
\begin{aligned}
Y &= V_{td}^* V_{ts} X(x_t) + V_{cd}^* V_{cs} X(x_c) + V_{ud}^* V_{us} X(x_u) \\
&= V_{td}^* V_{ts} X(x_t) + V_{cd}^* V_{cs} \left[X(x_c) + |V_{us}|^4 \delta P_{c,u} \right]
\end{aligned}
$$

where $X(x_q) = \frac{1}{3} \sum_l X(x_q, x_l)$, $x_q = m_q^2 / M_W^2$.

- GIM mechanism stems from CKM $V_{ud}^* V_{us} = -V_{td}^* V_{ts} - V_{cd}^* V_{cs}$.

- Last term is omnibus for higher dimension & long distance.

CKM & GIM & LOOP

- The top-quark loop is CKM suppressed:

$$V_{td}^* V_{ts} = 3.5 \times 10^{-4}$$

- So $V_{td}^* V_{ts} X(x_t) = 5 \times 10^{-4}$

- The charmed-quark loop is GIM suppressed:

$$X(x_c) \sim x_c \ln x_c$$

- So $V_{cd}^* V_{cs} X(x_c) = 2 \times 10^{-4}$

- Further suppressed by the loop: $g^4/16\pi^2$.

- Consequently sensitive to contributions of non-Standard partners, desired to solve the hierarchy problem.

- The top-quark loop has been calculated to NLO in pQCD [Buchalla, Buras].

- The charmed-quark loop yields large $\ln(x_c)$, now resummed to NNL [Buras, *et al.*].

- Even the NLO electroweak correction to the charmed-quark loop is available [Brod, Gorbahn].

- Current estimates:

$$B_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.51^{+0.57}_{-0.62} \pm 0.20 \pm 0.35 \pm 0.09) \times 10^{-11}$$
$$B_{\rm SM}(K_L \to \pi^0 \nu\bar{\nu}) = (2.54 \pm 0.34 \pm 0.14 \pm 0.16 \pm 0.08) \times 10^{-11}$$

where errors stem from CKM matrix, input parameters, truncation of perturbation theory, and K_{l3} normalization.

TACKLING CKM

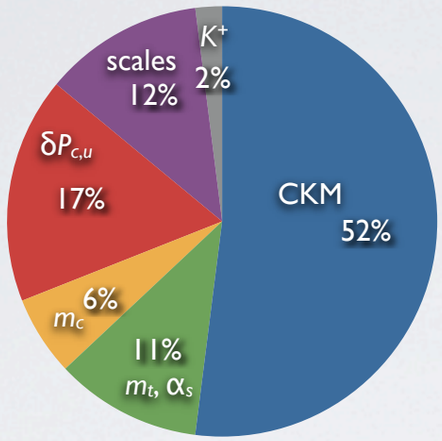
- The largest, but also the most reducible, error is from CKM.
- Need to improve determinations of $|V_{cb}|$, $|V_{ub}|$, & $|V_{td}/V_{ts}|$: lattice QCD is just starting and already competitive.
- Want to improve determination of CKM γ: LHC*b*.
- Lattice QCD can also reduce the uncertainty stemming from the model estimate of $\delta P_{c,u}$.
- Forecast that these will drop by ÷ 2.

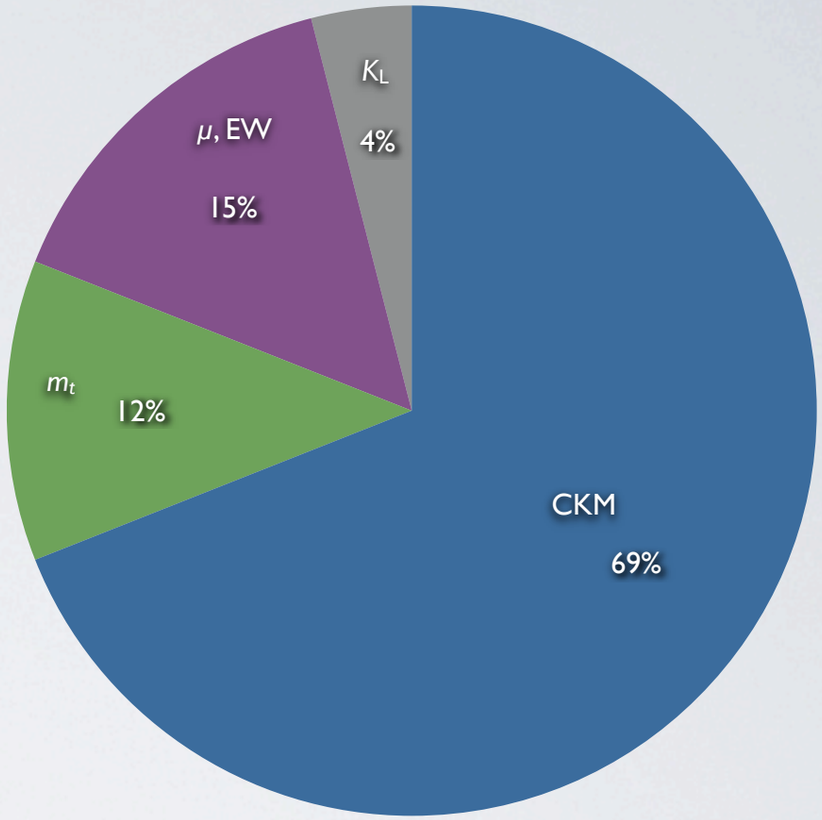
P996 proposal

charged

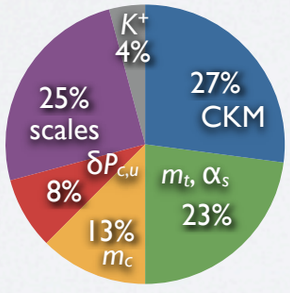
neutral

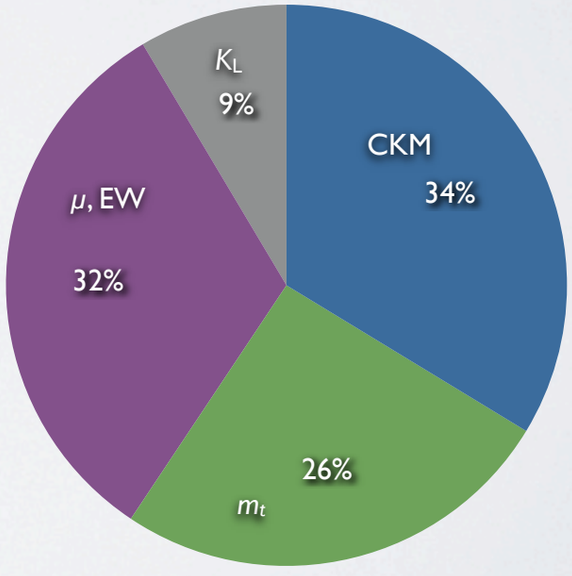
CKM 2009





CKM 2014





$(8.5 \pm 0.5)\times10^{-11}$

$(2.5 \pm 0.3)\times10^{-11}$

PATTERNS OF NEW PHYSICS

- In general, new particles modify the Wilson coefficients; some that vanish in SM could become non-zero.

- Here there is, essentially, one operator:

$$\left.\begin{array}{l}\bar{s}\gamma_\mu(1\mp\gamma_5)d\,\bar{\nu}_L\gamma^\mu\nu_L\\ \bar{s}\gamma_\mu(1\mp\gamma_5)d\,\bar{\nu}_R\gamma^\mu\nu_R\end{array}\right\}\Rightarrow\langle\pi|\bar{s}\gamma_\mu d|K\rangle\propto f_+(q^2)$$

- Take $|V_{us}||f_+(0)|$ from K_{l3}, with isospin corrections.

- Others would be suppressed by neutrino mass.

NON-STANDARD MODELS

$$B_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\tau_{K^+} M_{K^+}^5}{32\pi^3}(1+\Delta_{\rm EM})\left|f_+^{K^+\pi^+}(0)\right|^2 I_\nu^+ \left|\frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}Y\right|^2$$

$$B_{\rm SM}(K_L \to \pi^0 \nu\bar{\nu}) = \frac{\tau_{K_L} M_{K_L}^5}{32\pi^3}\left|f_+^{K^0\pi^0}(0)\right|^2 I_\nu^0 \left|\frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}{\rm Im}Y\right|^2$$

$$\frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}Y \to \frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}Y + C_{\rm new}X_{\rm new}$$

- If $C_{\rm new}X_{\rm new}$ is pure imaginary & overwhelms SM contribution, both modes are set by it and [Grossman, Nir]

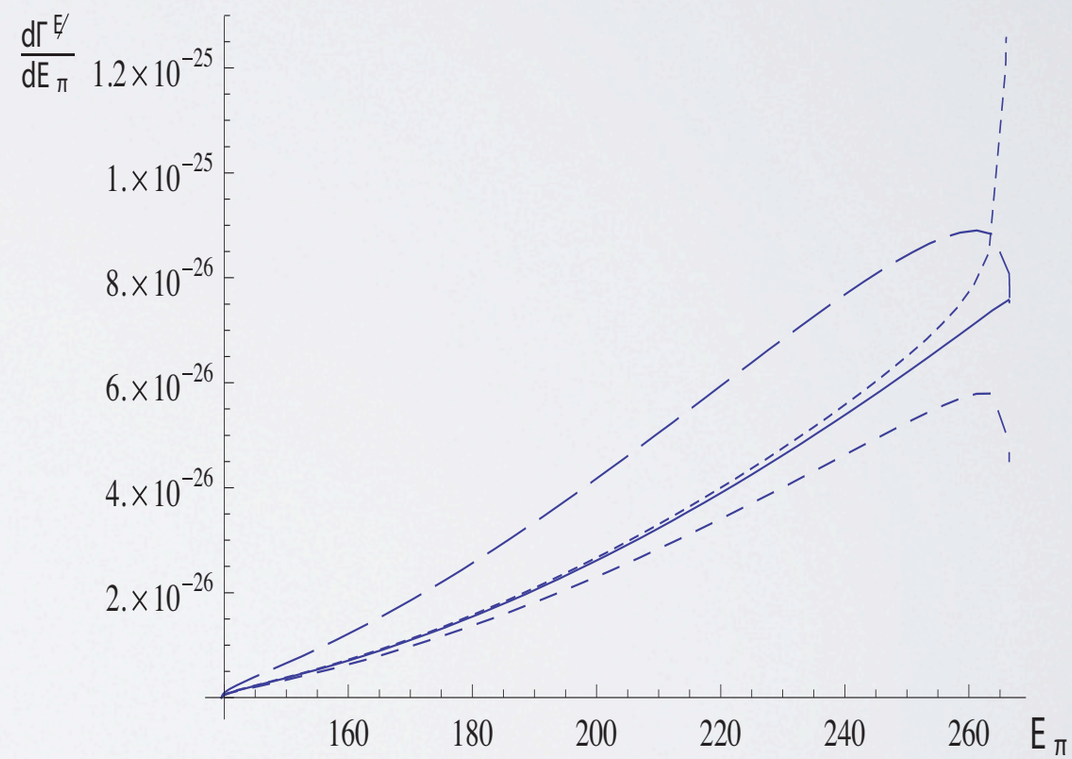
$$BR(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.4 BR(K^+ \to \pi^+ \nu\bar{\nu})$$

$K \to \pi \not{E}$

- The experimental signature is actually π^+ and missing energy.

- Some BSMs have measurable rates when $\not{E}$ is an axion, familon, ...

- Unparticle example:



- Wu, Zhang, 0712.3923

NEW PHYSICS FLAVOR PROBLEM

- Electroweak physics strongly suggests that new particles lurk at the TeV scale.
- Flavor-changing neutral currents, mediated by such particles, are observed to be unnaturally small:
  - are their flavor coupling special in some way?
  - are their masses unreasonable high?

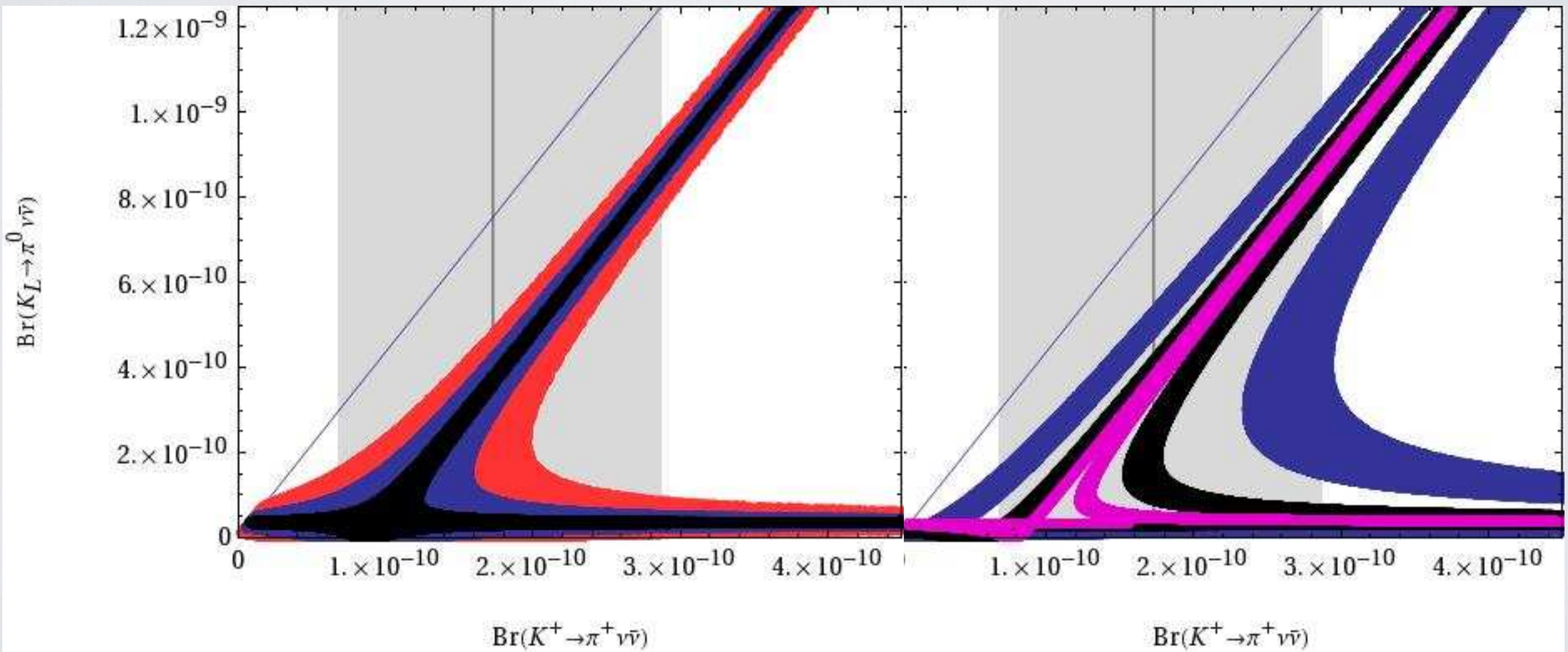
MFV

MÜNCHEN'S FUNNIEST VIDEOS

- Minimal flavor violation (MFV) has several definitions.
- Cleanest is based on $SU(3)^5$ symmetry of non-Yukawa sector:
  - promote Yukawa matrices to *spurions*: assign them artificial transformation properties, making all interactions invariant;
  - allow only invariant combos of the **Y**s to appear;
    - example: $m^2_{\tilde{Q}} = m^2_0 \left(a_1 1 + a_2 Y_u^\dagger Y_u + a_3 Y_d^\dagger Y_d \cdots \right)$
  - demand a_i to be $\mathrm{O}(1)$ (else "fine-tuning" or "non-MFV").

- Current body of knowledge tells us only that BSM flavor has non-generic structures.
- MFV is a framework to impose a structure that is "sure" to work and is necessary.
- We do not understand how the texture of the Yukawas arises, but we do know it does arise.
- So take this structure and no other.

- Correlations between the two rare K decays can arise:
  - via MFV constraints;
  - via other experimental constraints, like ε_K [Blanke]—

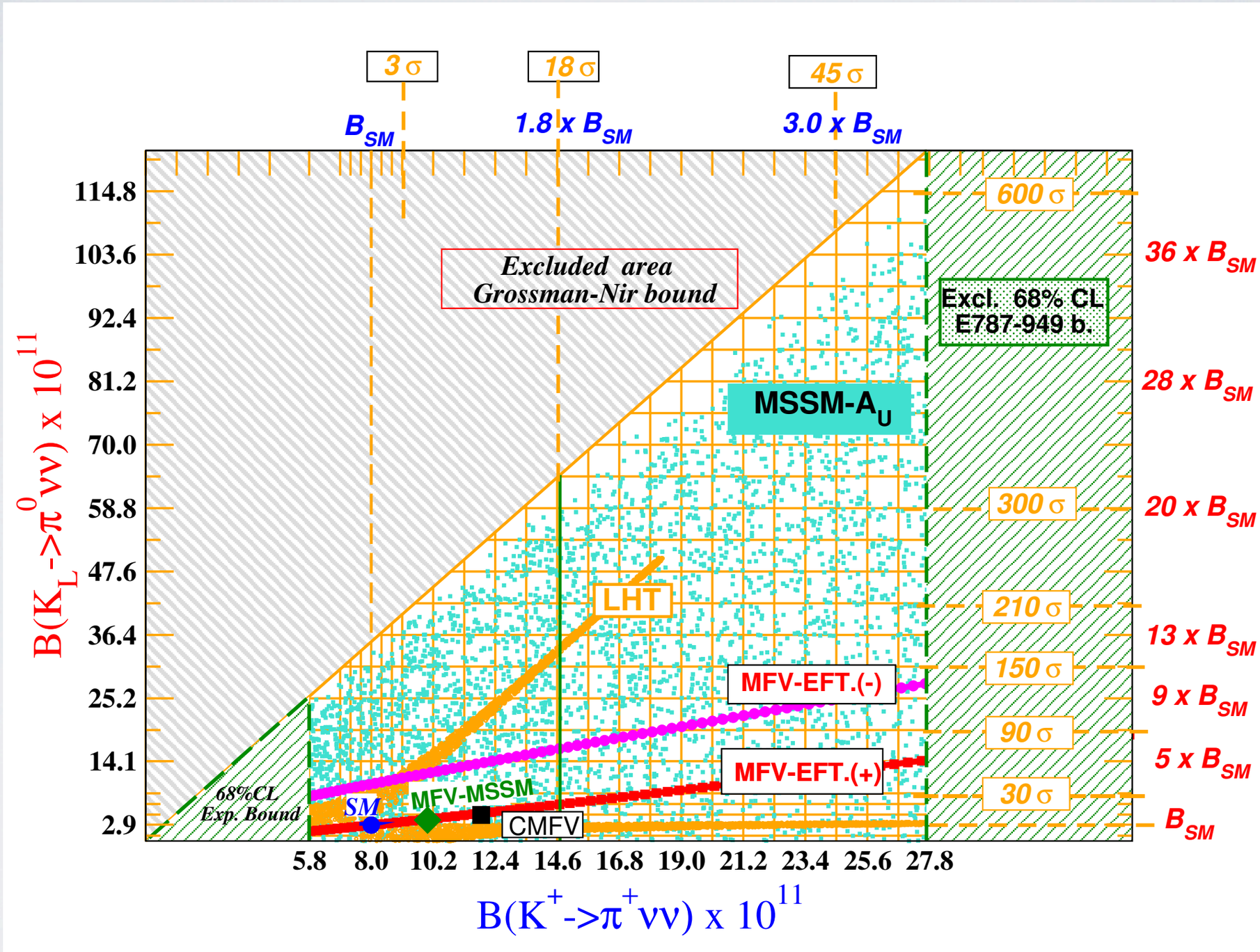


ε_K tension loosens

ε_K tension tightens

GENERAL BSM

- Nature could be more clever than model builders, so MFV is not a necessary outcome.
- Generic supersymmetric extensions, e.g. MSSM, are not MFV.
- Anything (consistent with Grossman-Nir) could happen.



Prepared by F. Mescia for G. Isidori [arXiv:0709.2438].

LHC-INSPIRED MODELS

- When signals of new particles emerge from LHC, *ad hoc* models will presumably appear.
- All of these can compute $C_{\rm new} X_{\rm new}$ and compare with flavor constraints.
- The rare kaon decays are special, because one won't have to deal with the QCD of extra operators ("clean").
- So measurement of both leaves little wiggle room.

SUMMARY

- Progress on the charmed-loop contribution has brought the error on the charged mode below the neutral mode.
- Largest uncertainty is parametric—from CKM—and should decrease of the next 5 or so years.
- With a comparably accurate measurement, a 30% deviation of the BR from the SM would be a 5σ indicator of new physics.
- In an arena where new physics could be O(1) or O(10)!