Project X – Physics

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TOPICS TO BE DISCUSSED[a]

1. **NEUTRINO Oscillations;**

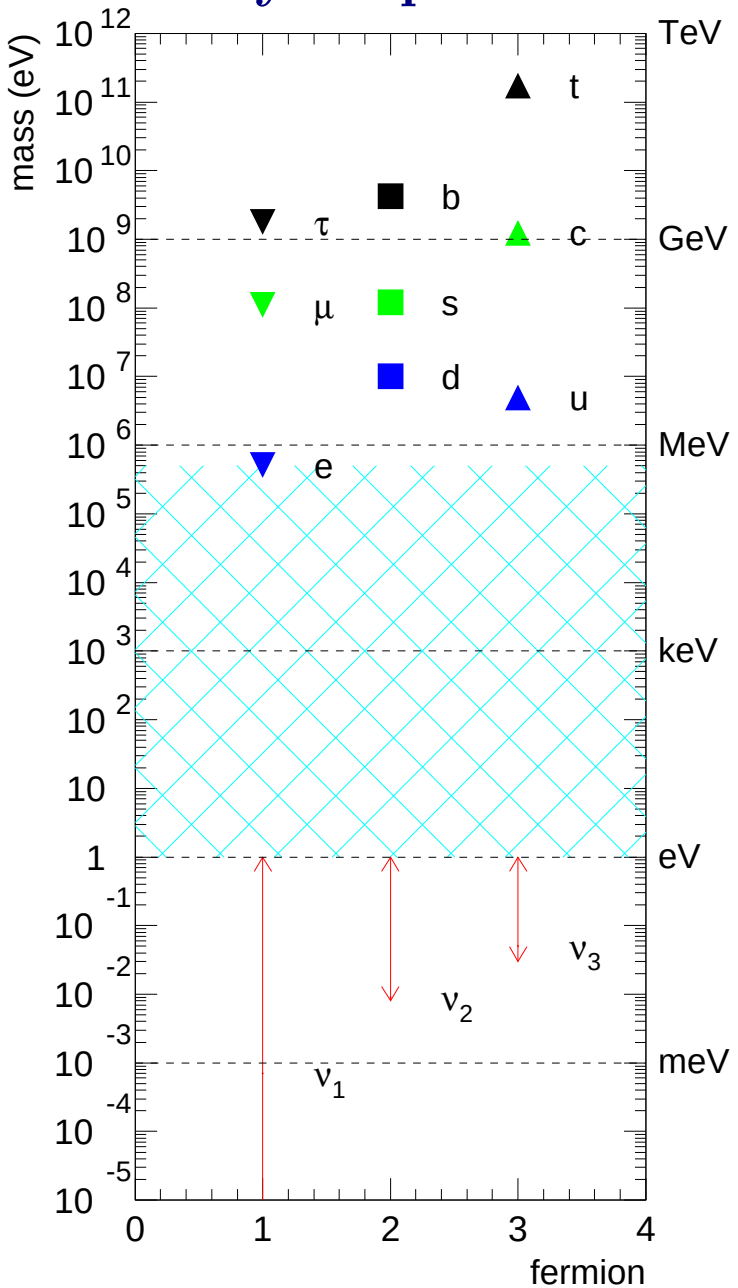
2. **MUON Properties and Rare Processes;**

3. **Very Rare KAON Decays.**

[a] Topics listed in anti-alphabetical order. List not meant to represent my or anyone's ranking or preference.

NEUTRINOS (neutrino oscillations)

Only Palpable Evidence of Physics Beyond the Standard Model:



NEUTRINOS HAVE MASS

Discovery → well-defined experimental questions:

– are neutrinos their own antiparticles?

– how light is the lightest neutrino?

– is the three neutrino + mixing paradigm complete?

Discovery → intriguing theoretical questions:

– neutrino masses ≪ charged fermion masses: why?

– how do neutrinos acquire mass? Too many choices!

– how do we learn more about this new physics?

Our story so far: we have uncovered an extended standard model parameter space!

Phenomenological Understanding of Neutrino Masses & Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

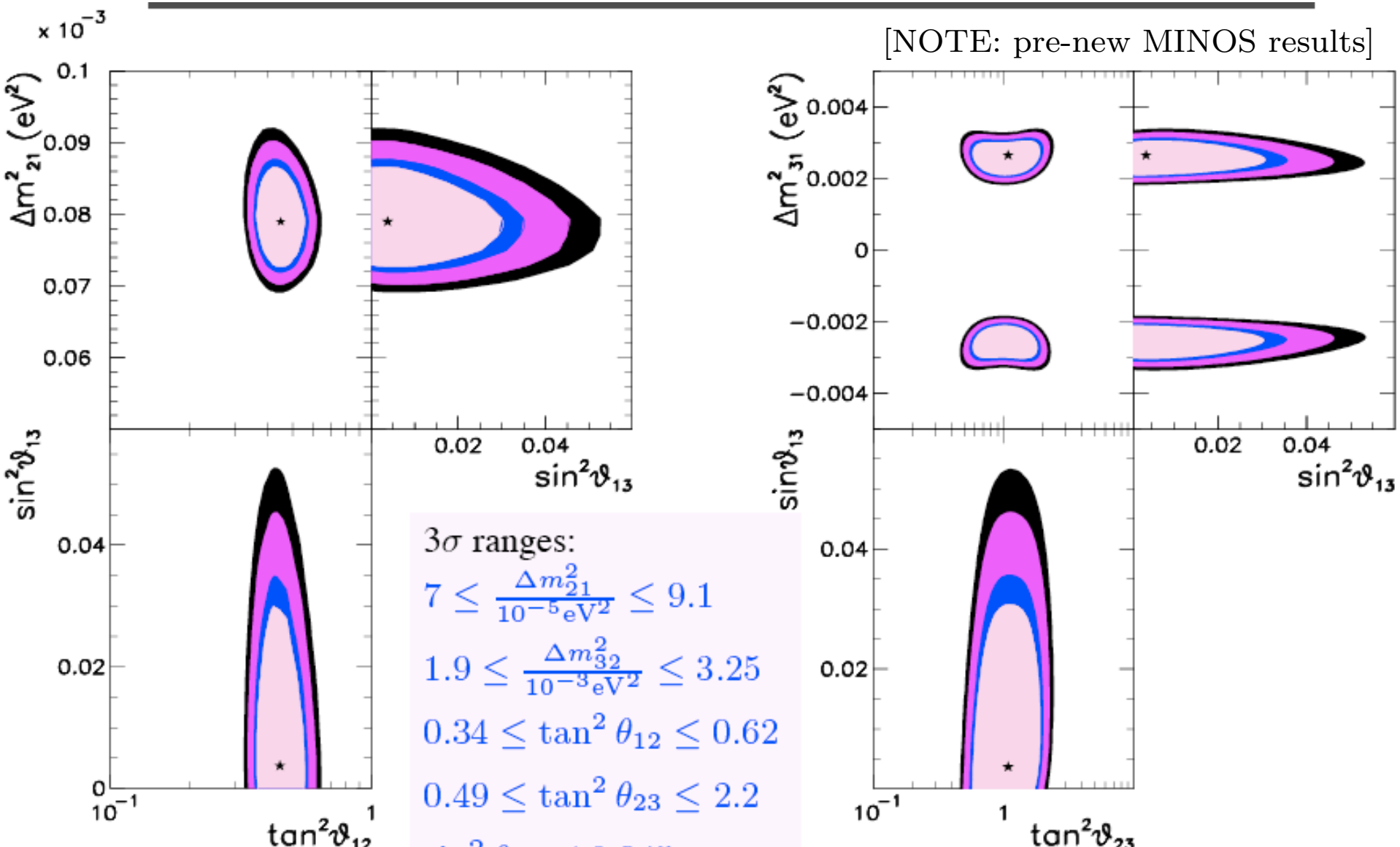
Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ — $\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ — $\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

3 Flavor Paradigm Fits All Data Very Well:

[NOTE: pre-new MINOS results]



3σ ranges:

$$7 \leq \frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2} \leq 9.1$$

$$1.9 \leq \frac{\Delta m^2_{32}}{10^{-3}\mathrm{eV}^2} \leq 3.25$$

$$0.34 \leq \tan^2\theta_{12} \leq 0.62$$

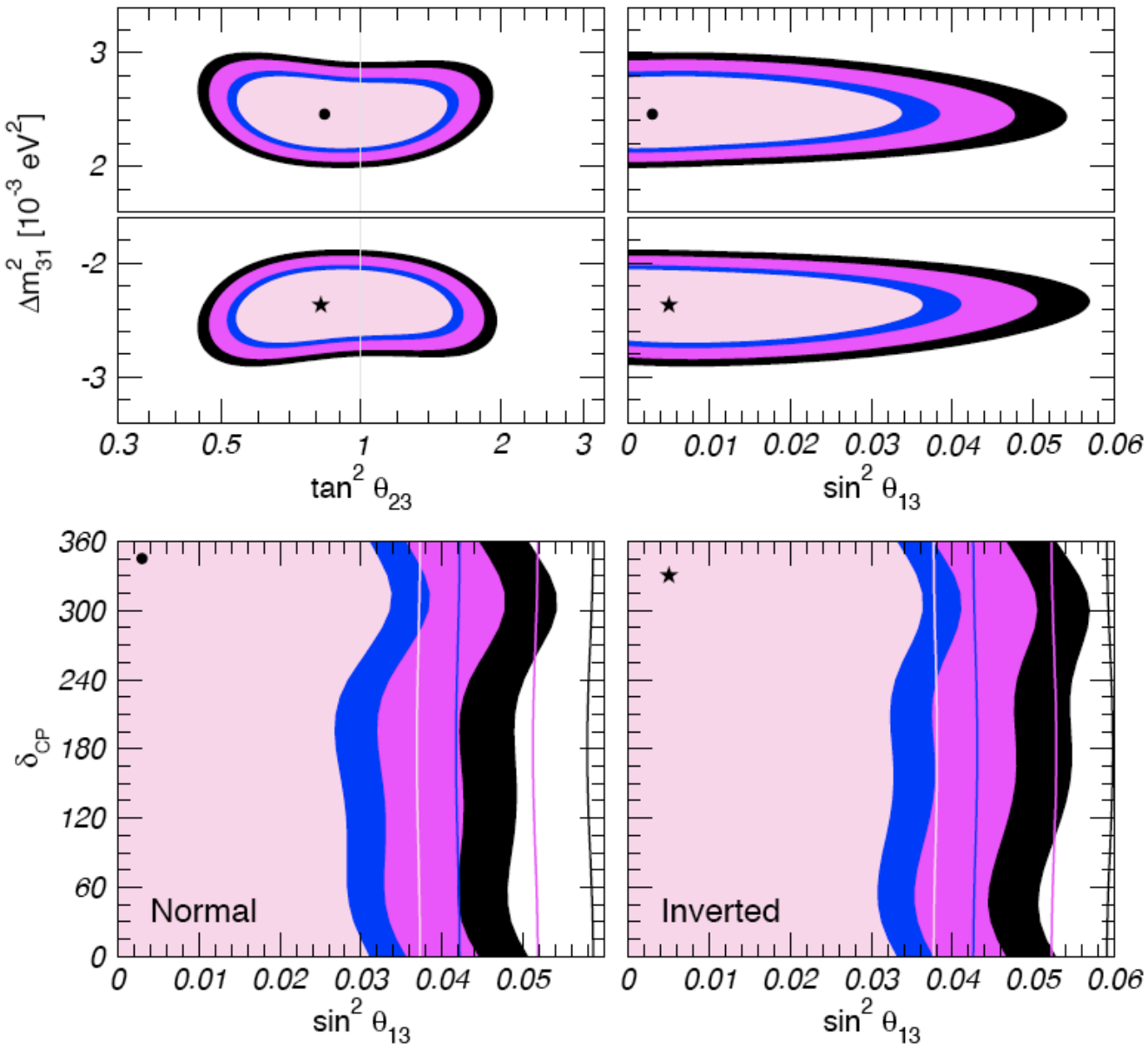
$$0.49 \leq \tan^2\theta_{23} \leq 2.2$$

$$\sin^2\theta_{13} \leq 0.045$$

$$-\pi \leq \delta \leq \pi$$

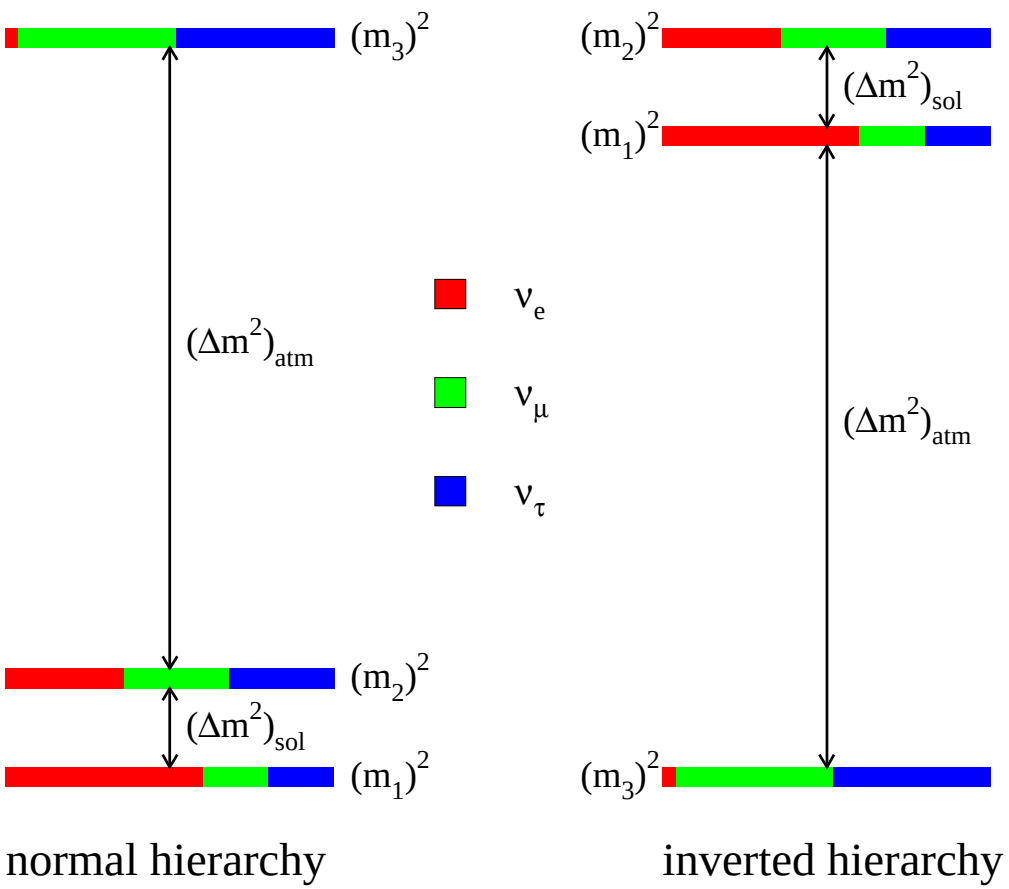
[from M.C. Gonzalez-Garcia]

(including new MINOS result – better Δm^2_{13} measurement)



[from Gonzalez-Garcia, Maltoni]

(Some of) What We Know We Don't Know: Missing Oscillation Parameters



- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with neutrino oscillation experiments.

Ultimate goal not just to measure parameters $\rightarrow$ test formalism (over-constrain parameters?)

The "Holy Graill" of Neutrino Oscillations – CP Violation

In the old Standard Model, there is only one[a] source of CP-invariance violation:

$\Rightarrow$ The complex phase in V_{CKM}, the quark mixing matrix.

Indeed, as far as we have been able to test, all CP-invariance violating phenomena agree with the CKM paradigm:

- ϵ_K;
- ϵ'_K;
- $\sin 2\beta$;
- etc.

Neutrino masses and lepton mixing provide strong reason to believe that other sources of CP-invariance violation exist.

[a] modulo the QCD θ-parameter, which will be "willed away" as usual.

- Physics Case for next-generation neutrino oscillation experiments VERY mature. (only fundamental particle cited in 'Quantum Universe' Questions!)
- In "worse-case" scenario, long-baseline oscillation experiments will measure fundamental physics parameters. θ_{13} as important to our understanding of nature as m_e or α or $m_{\rm Higgs}$.
- LEPTOGENESIS is the leading candidate explanation to the matter–antimatter asymmetry of the Universe. If we are ever to test it experimentally, long-baseline neutrino experiments will play a fundamental role.
- Connections to the LHC? to GUTs? to Dark Matter? to Dark Energy? We have only just begun to explore the new physics uncovered by neutrino oscillations. Only time will tell where it will lead us...

MUONS (magnetic moment, $\mu \to e$-conversion in nuclei)

Charged-Lepton Flavor Violation

With the discovery of neutrino masses and lepton mixing, we know that individual lepton numbers are not good quantum numbers.

So, what is the "Standard Model" rate? It depends on the physics responsible for non-zero neutrino masses. The massive neutrino contribution is known to be aburdly small. E.g.

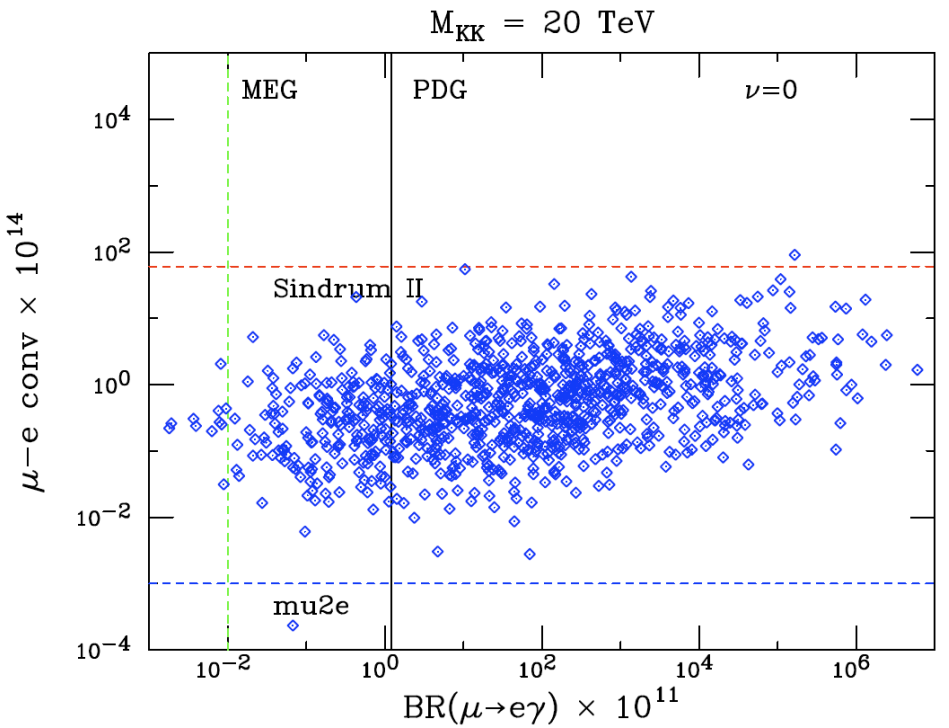
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54},$$

where $U_{\alpha i}$ are the elements of the leptonic mixing matrix, while Δm^2_{1i}, $i = 2, 3$ are the neutrino mass-squared differences. FCNC $\to$ GIM suppressed!

$\Rightarrow$ CLFV very, very clean probe of new physics!

$B(\mu \to e - \text{conv}) \equiv \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$, is the normalized rate.

- Interplay with LHC – complementary information regarding new physics at the TeV scale. We learn something about the TeV scale physics in the advent of positive and negative results from $\mu \to e$ searches at 10^{-17}.
- Interplay with other CLFV – non-trivial information to be obtained by combining $\mu \to e$-conversion and other CLFV processes ($\mu \to e\gamma$, $\mu \to eee$).
- Potentially strong connection to origin of neutrino masses. In case of SUSY, may provide invaluable information that may allow one to ultimately test leptogenesis! [Also fundamental for MFV]
- Can repeat the measurement with different targets. Non-trivial information on new physics in case of positive results.

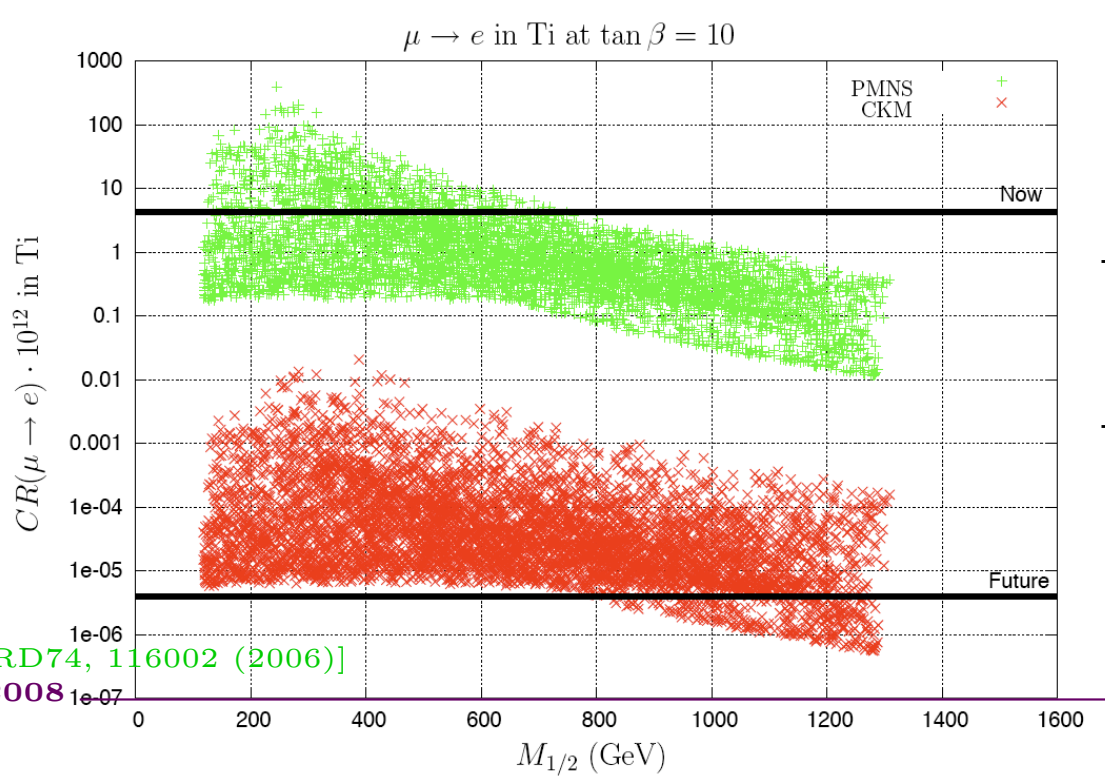


Randall-Sundrum Model

(fermions in the bulk)

- dependency on UV-completion(?)
- dependency on Yukawa couplings
- "complementarity" between $\mu \to e\gamma$, $\mu - e$ conv

[Agashe, Blechman, Petriello, hep-ph/0606021]



SUSY GUT

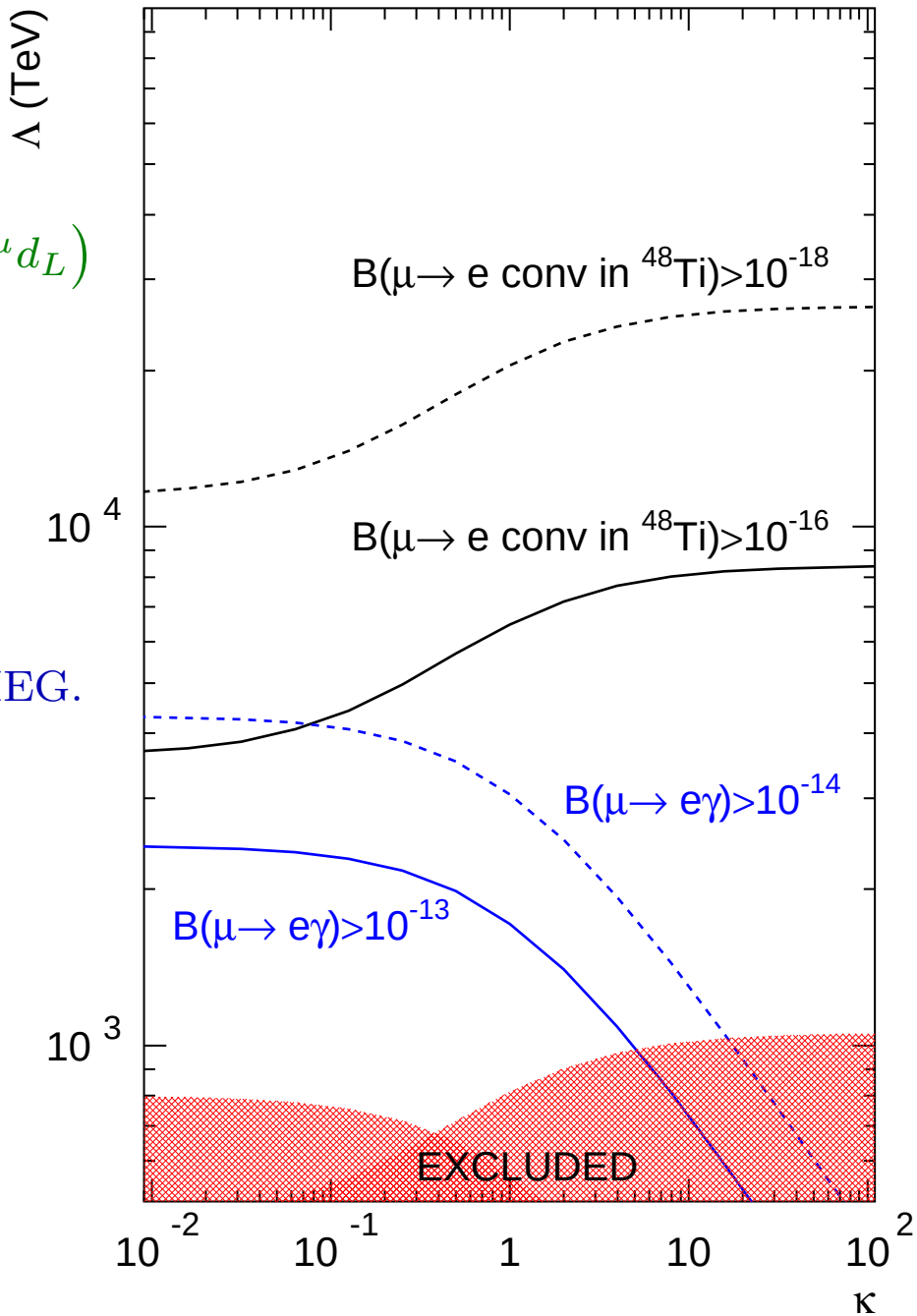
- dependency on choice for neutrino Yukawa couplings
- scan restricted to scenarios LHC discovers new states.

[Calibbi et al, PRD74, 116002 (2006)]

Model Independent Analysis

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

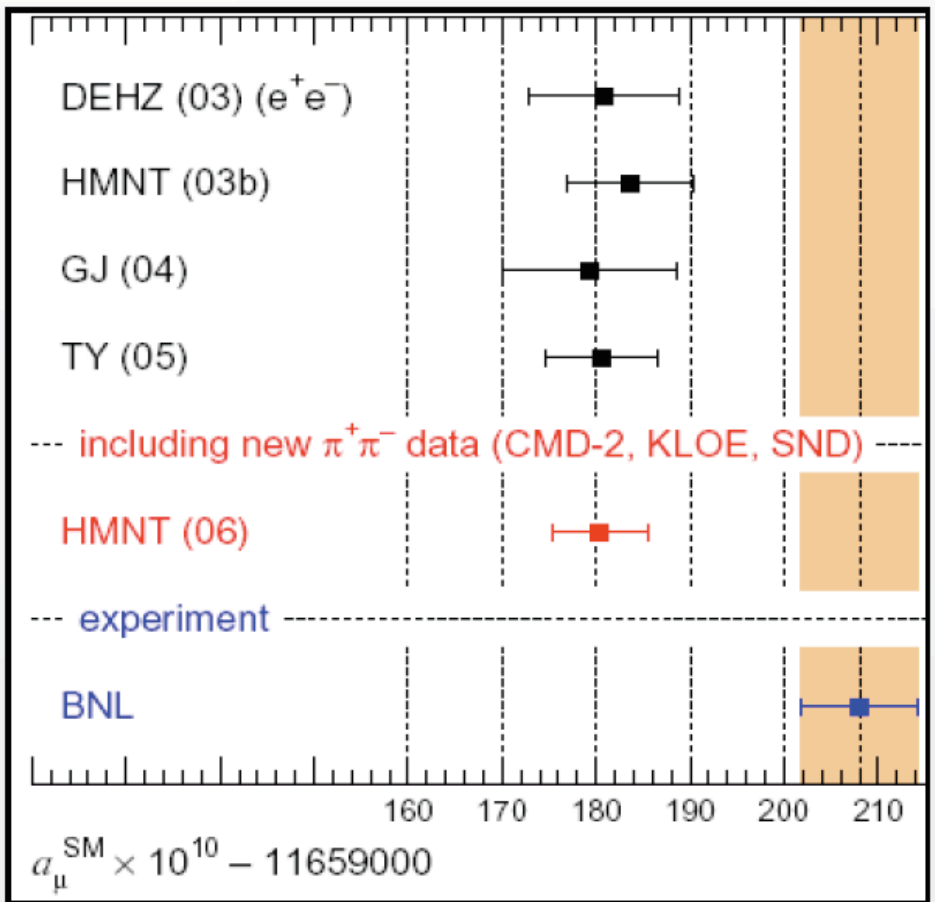
- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv "only" way forward after MEG.
- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.



Anomalous Magnetic Moment of the Muon, $(g-2)/2 \equiv a_\mu$

Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)

TIME



Compare

K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

Rep.Prog.Phys. 70, 795 (2007).

PLUS: Interplay with LHC – if there is new physics at the TeV scale, a_μ can differentiate among different models, provide precision measurement of model parameters.

Muon g-2, like other precision measurements, has powerful discriminating input

10^{-11} units

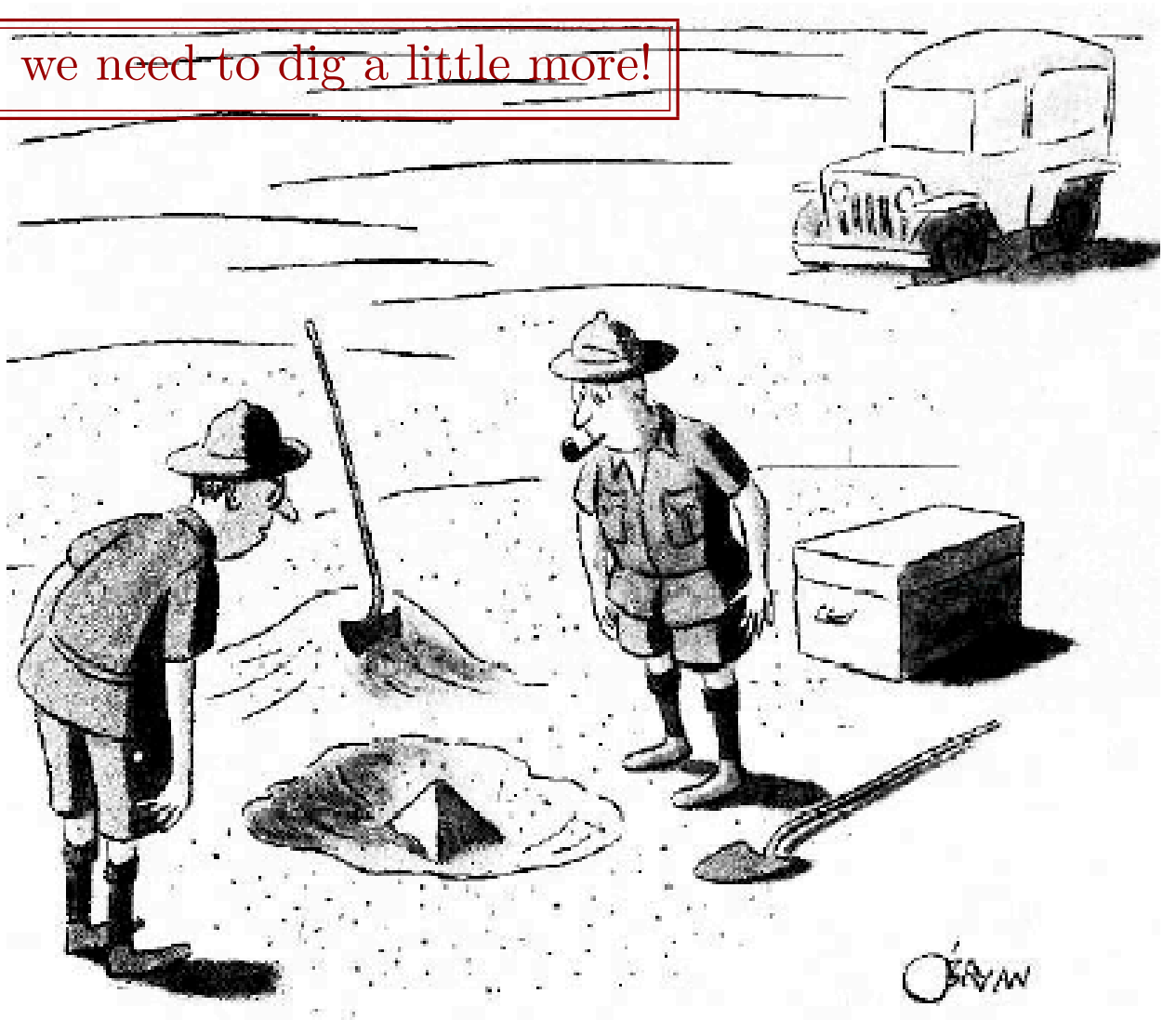
SPS Point	$a_\mu^{\mathrm{SUSY,1L}}$(improved)
SPS 1a	293
SPS 1b	318
SPS 2	16.5
SPS 3	135
SPS 4	490
SPS 5	86
SPS 6	169
SPS 7	237
SPS 8	173
SPS 9	-90

Compare to present Δa_μ =295

Compare uncertainty to $\delta\ \Delta a_\mu \sim \pm 35$

*Snowmass Points and Slopes:
http://www.ippp.dur.ac.uk/~georg/sps/sps.html

Δa_μ: we need to dig a little more!



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

KAONS $(K^{\pm} \to \pi^{\pm}\nu\bar{\nu},\ K_L \to \pi^0\nu\bar{\nu})$

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

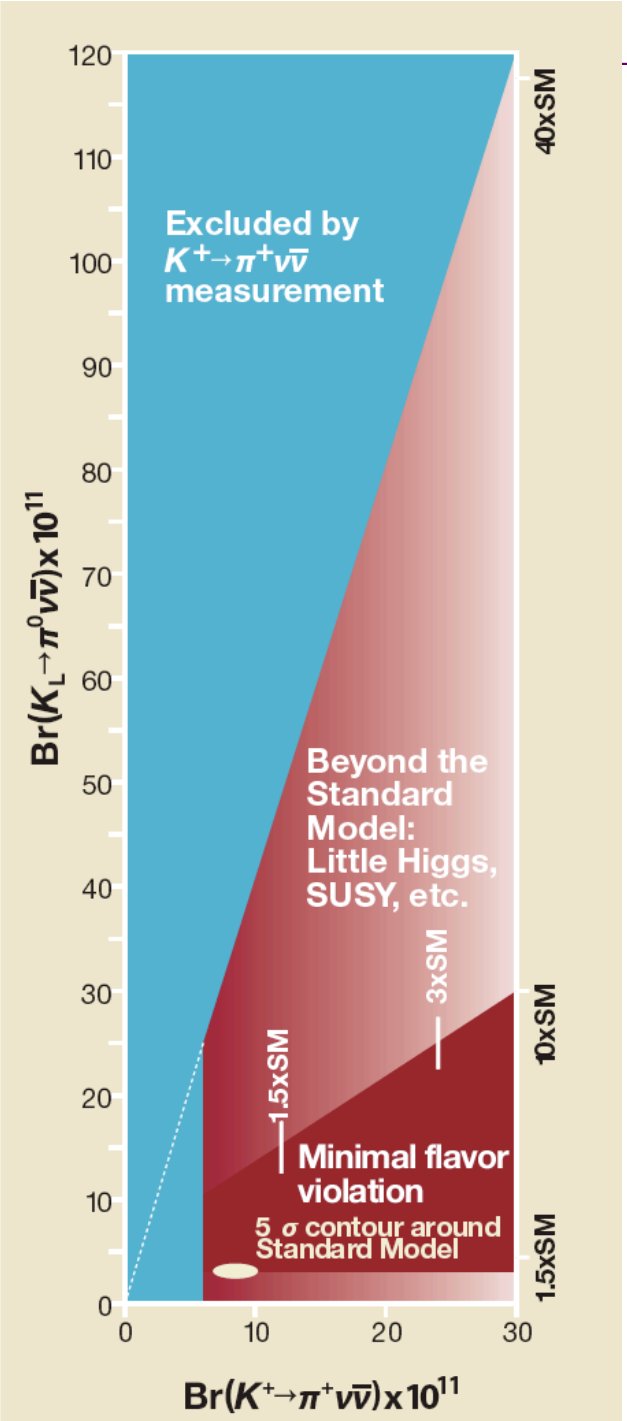
Both $K^{\pm}$ and K_L decays into $\pi\nu\bar{\nu}$ have a special place in the realm of rare hadron decays.

- SM expectations are really tiny – FCNC hence GIM suppressed, purely electroweak, 1-loop processes.
  $B(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (8.22 \pm 0.84) \times 10^{-11}$ [measured $\to$ $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$]
  $B(K_L \to \pi^0\nu\bar{\nu})_{SM} = (2.76 \pm 0.40) \times 10^{-11}$
- Unlike other meson decay process, long-distance QCD effects are small, under control – purely short-distance process $\to$ SM uncertainty small and under control. Largest sources of uncertainty elements of V_{CKM}, m_c. Ultimately,

$$\delta B_+ < 5\%$$
$$\delta B_0 < 5\%$$

(with a little help from B-factories and LHCb, and the lattice community)

$\Rightarrow$ Ideal Probe of New Physics at or above the TeV scale...



What About B-factory "Failed" Searches for New Physics?

SM is very successful in describing quark-flavor mixing!

$\Rightarrow$ New Physics is Really Heavy or

$\Rightarrow$ New Physics is Minimal Flavor Violating, i.e., all quark-flavor violating effects $\propto V_{CKM}, m_q$.

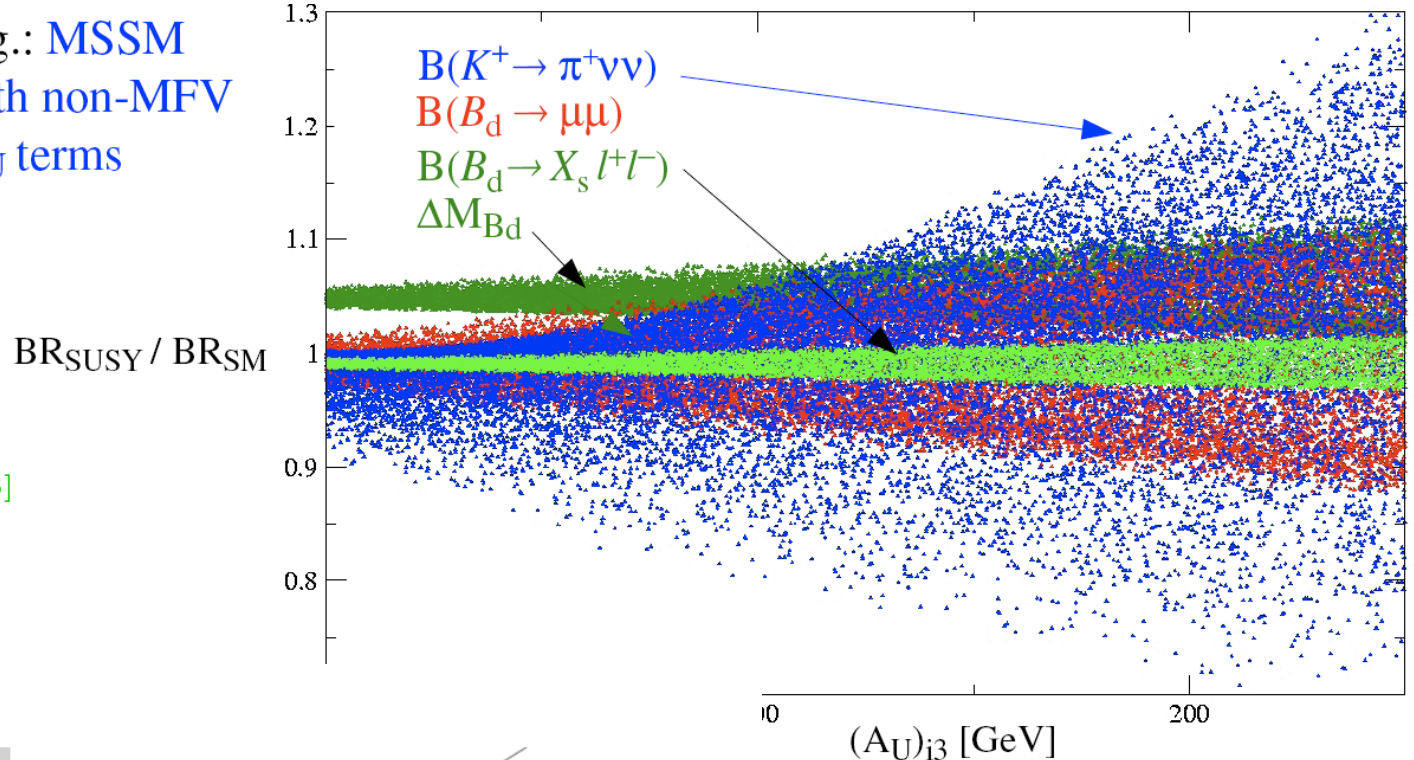
(with some exceptions [e.g., $B \to \mu\mu$])

Kaons to the rescue:

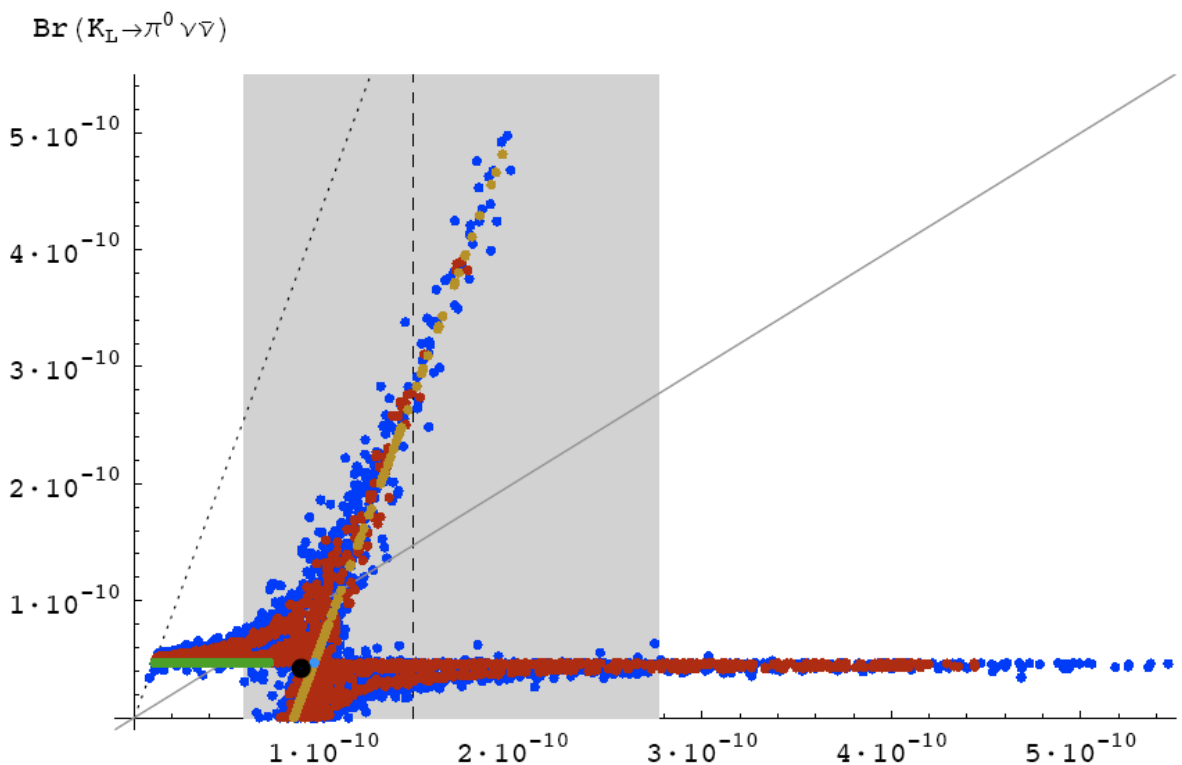
- Model Independent Sensitivity to $\Lambda \sim 10^4$ TeV and
- Non-MFV with TeV scale new physics still allowed.

$$L_{K\to\pi\nu\nu} \sim \frac{1}{\Lambda^2}\left(\bar{d}\gamma_\mu s\right)\left(\bar{\nu}\gamma^\mu \nu\right)$$

E.g.: MSSM with non-MFV A_U terms



[Isidori et al, JHEP 0608:064,2006]



Little Higgs Model

[Blanke et al, JHEP 0701:066,2007]

CONCLUSIONS

In order to successfully develop the physics that lies beyond the Standard Model, the exploration of the Intensity Frontier is of the utmost importance, at least comparable to the exploration of the High Energy Frontier.

- Natural first step to pursue Physics unlocked by neutrino oscillation data – next-generation neutrino oscillation experiments;
- Potential for strong interplay with physics responsible for neutrino masses;
- Flavor violating experiments complementary to LHC searches for new degrees of freedom. Unique information (disentangling degeneracies, details of SUSY breaking scheme, flavor structure of new physics, etc)!;
- If new physics is beyond LHC reach – Flavor violation provides only particle physics probe of whatever lies at short distances.
- Negative or SM-like results still valuable.

Energy Frontier × Intensity Frontier

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

Rare K decays

g-2

ν-oscillations ←

→ $0\nu\beta\beta$

β-decay (m_ν) ←

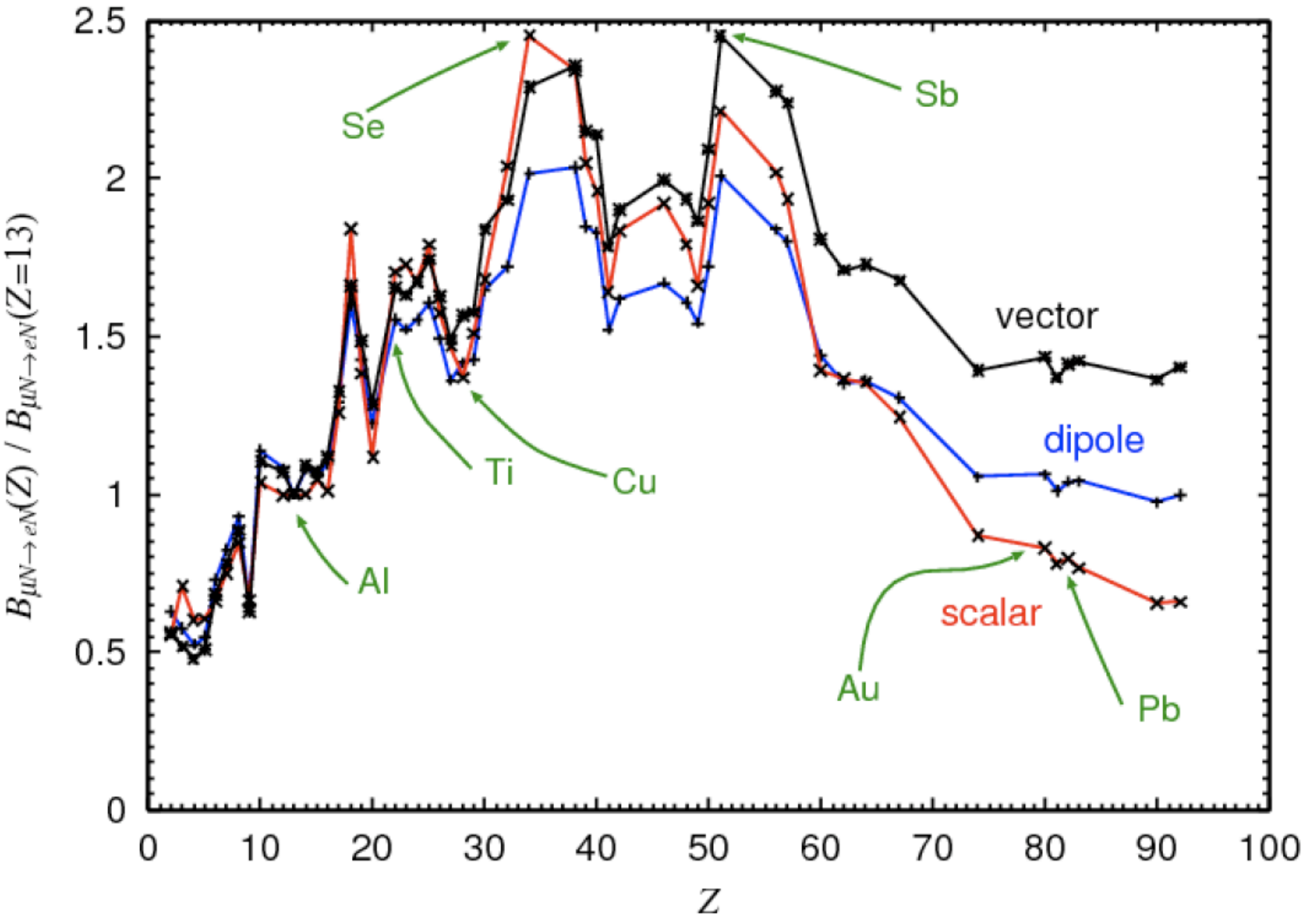
A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

[and maybe much more. . .]

[from G. Isidori, Lepton-Photon 2007]

BACK-UPs


2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Z
$B_{\mu N \to eN}(Z)$ / $B_{\mu N \to eN}(Z=13)$
Se
Sb
Ti
Cu
Al
Au
Pb
vector
dipole
scalar