Particle Physics and the Intensity Frontier

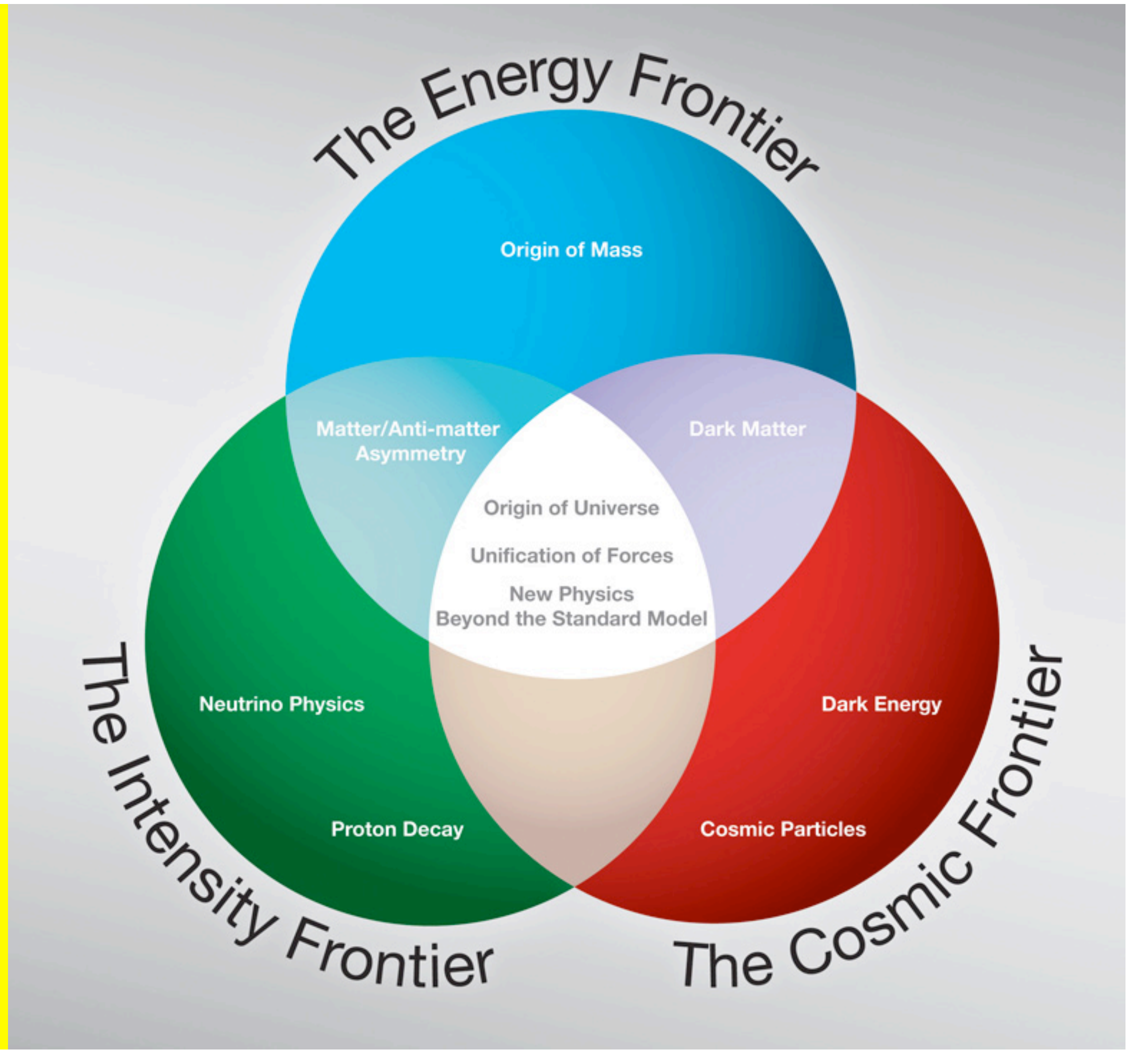
Joseph Lykken
Fermilab

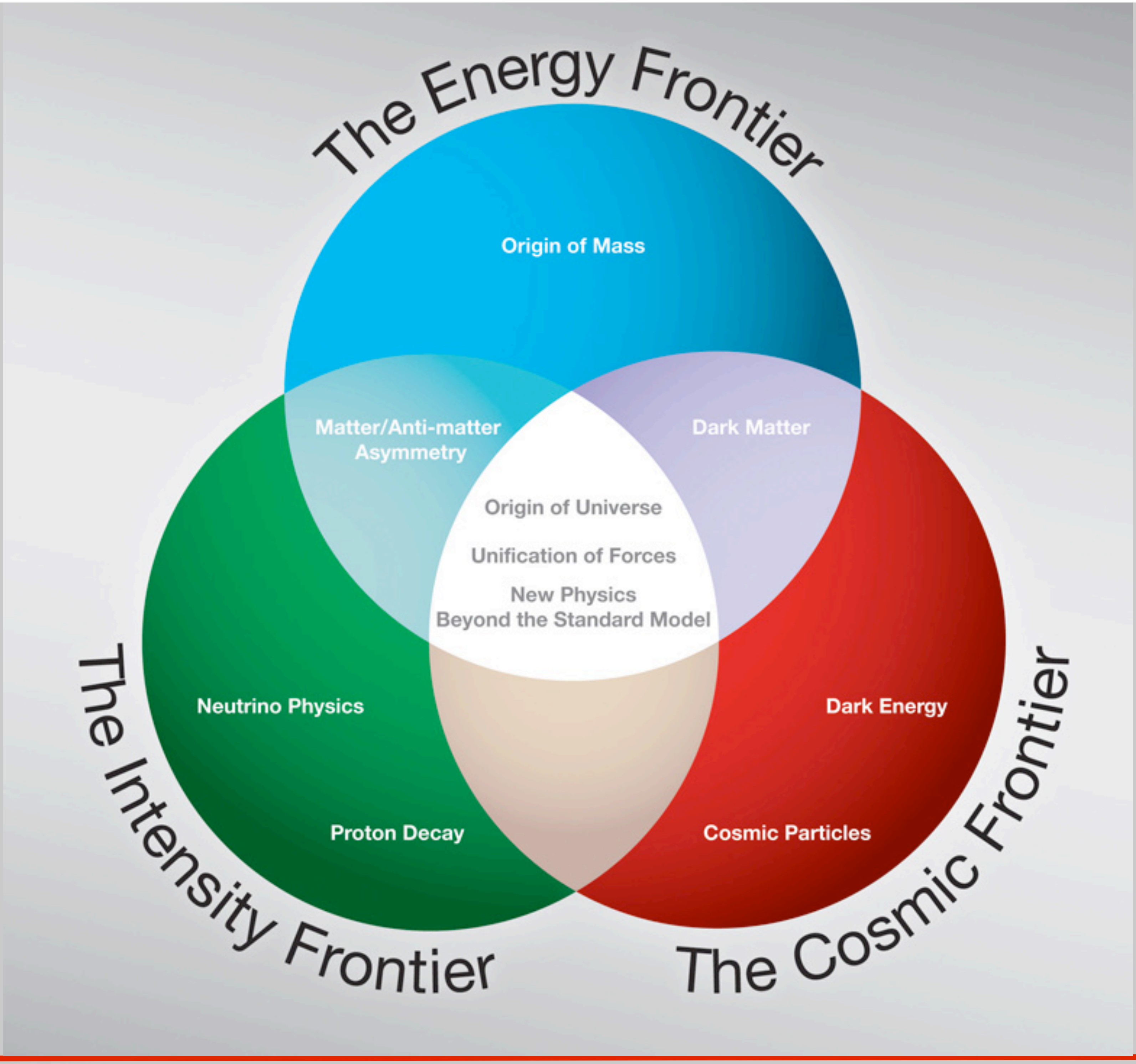
Outline

- The Intensity Strategy
- Three Frontiers Scorecard
- Neutrinos
- Muons
- Kaons

History of Popular Graphics at the DOE

Then | **Now**




The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

The Intensity Strategy

Question: Why haven't we already observed all phenomena of relevance to fundamental physics?

1. **The phenomena involve objects that are hard to make in the laboratory (e.g. black holes, heavy gluinos, ...)**
2. **The phenomena involve interactions that are fundamentally weak and thus rare**
3. **The phenomena involve interactions that are very short range and thus rare**

In case #1, proceed to Energy or Cosmic Frontiers

In cases #2 and #3, we can use high intensities to observe rare phenomena

Advancing the Frontiers: 1995 -2010

	Huge Surprising Discoveries	Evidence of New Fundamental Phenomena	First Observations or Strong Limits
Intensity	Neutrinos have mass! Lepton flavor not conserved!	g-2 anomaly (superpartners?) direct CP violation in kaons B -> tau nu anomaly + other B puzzles	Too numerous to enumerate here (hundreds)
Energy	Heavy top quark!	DZero muon asymmetry (new CP violation and quark flavor violation?)	Too numerous to enumerate here (hundreds)
Cosmic	Dark matter is nonbaryonic and mostly cold! Dark energy!?	Universe is flat (inflation?) Primordial density fluctuations (inflation?)	Too numerous to enumerate here (dozens)

Advancing the Frontiers: 2010 -2025

	Huge Surprising Discoveries	Evidence of New Fundamental Phenomena	First Observations or Strong Limits
Intensity	Neutrinos violate CP! Charged leptons mix! Neutrinos see a new force! etc!	Leptogenesis! Grand Unification! The origin of matter!	Too numerous to enumerate here (hundreds)
Energy	Nonstandard or No Higgs! Dark matter particles produced! New forces! New dimensions, etc!	Dark/hidden sectors! Grand Unification! The origin of matter!	Too numerous to enumerate here (hundreds)
Cosmic	Dark matter particles observed! Dark energy is dynamical! Footprints of inflation! etc!	The origin of the universe! The fate of the universe!	Too numerous to enumerate here (hundreds)

Origins

- **The Origin of Mass:**
  - **How do massless chiral fermions become matter particles? (buzzword = “Higgs”)**
- **The Origin of Matter:**
  - **Why are there so many different kinds of matter particles with different properties? (buzzword = “Flavor”)**
- **The Origin of the Universe:**
  - **Where did matter come from in the first place, and why didn’t it all annihilate with antimatter? (buzzwords = “Leptogenesis”, “Baryogenesis”)**

1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics)

= Theory of atomic structure

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (???????)

= Theory explaining both unity and origins of matter

1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics)

= Theory of atomic structure

makes scientists happy

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (???????)

= Theory explaining both unity and origins of matter

1925:

Chemistry and spectroscopy + fundamentally new idea (quantum mechanics)

= Theory of atomic structure

$10 trillion game-changer!

?

2025?

Neutrino, charged lepton, quark, (+?) properties + fundamentally new idea (???????)

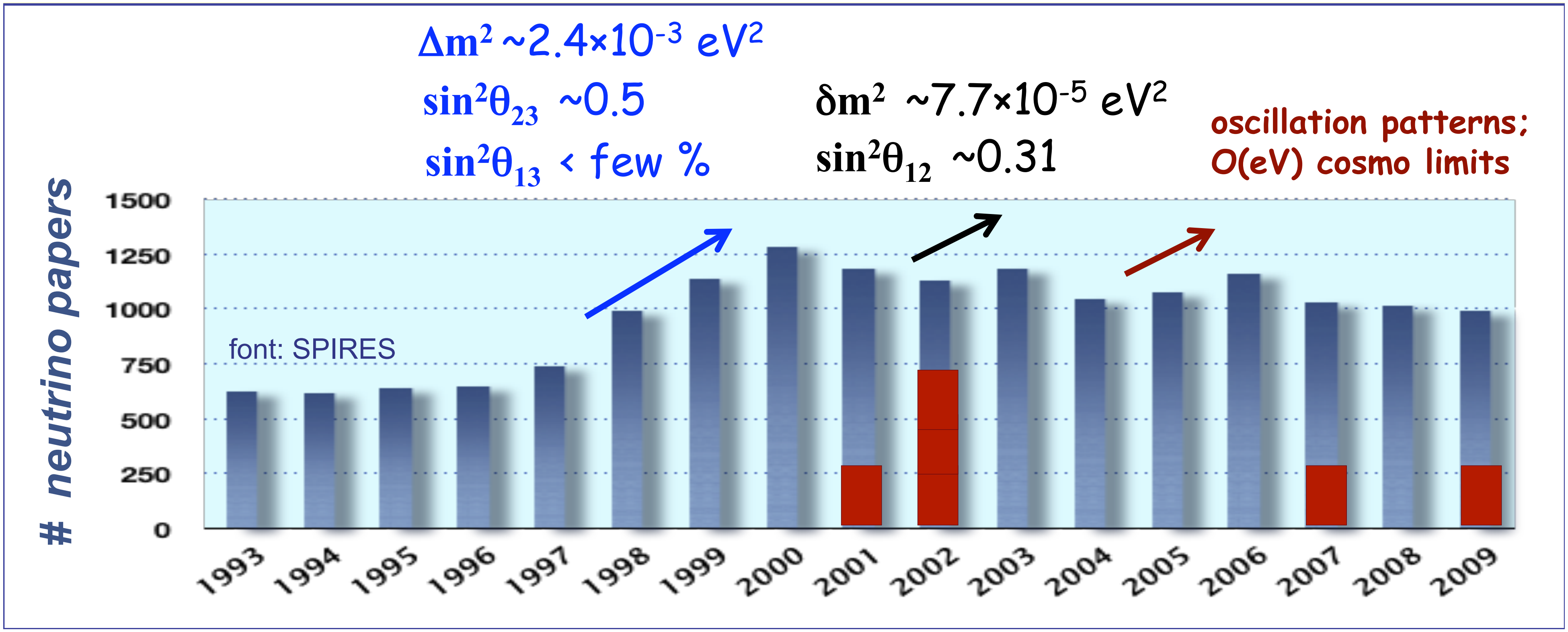
= Theory explaining both unity and origins of matter

Project X Intensity Frontier Physics Portfolio

- **Neutrinos**
  - **Long baseline neutrino oscillations**
  - **Shorter (or no) baseline neutrino experiments**
- **Muons**
  - **Muon to electron conversion**
  - **anomalous g-2 of muon**
  - **Electric dipole moments**
- **Kaons**
  - **Rare charged kaon decays**
  - **Rare neutral kaon decays**
- **+ more to come**

Intensity Frontier: Neutrinos

Neutrinos are interesting



red bars = neutrino papers by J.L. (times 250)

E. Lisi, talk at ICHEP 2010

Neutrinos are Messengers of New Physics

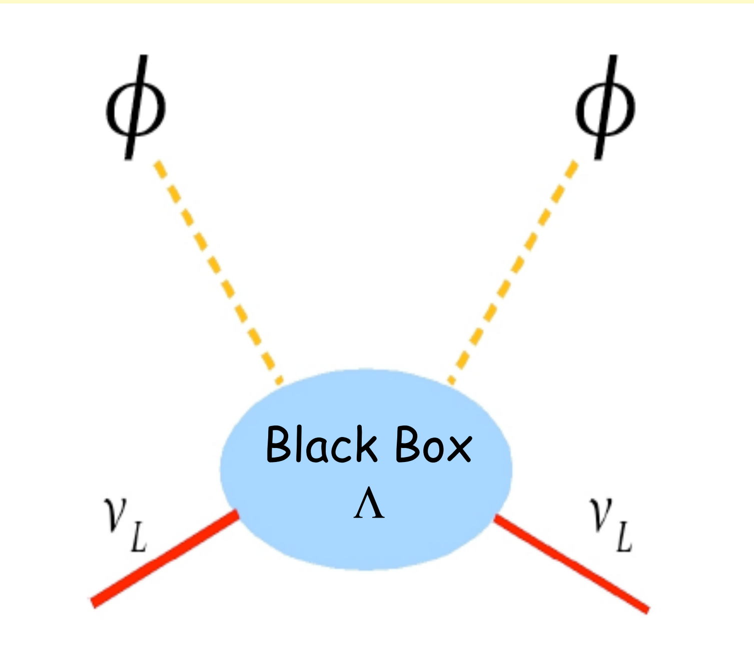
Neutrinos, unlike quarks:

- Have tiny masses
- May have "inverted" mass splittings
- Have large mixings
- Might be mixed with additional light fermions ("steriles")
- Might be their own antiparticles ("Majorana")
    - thus violating L and B - L
    - and having extra CP phases
    - and having superheavy partners

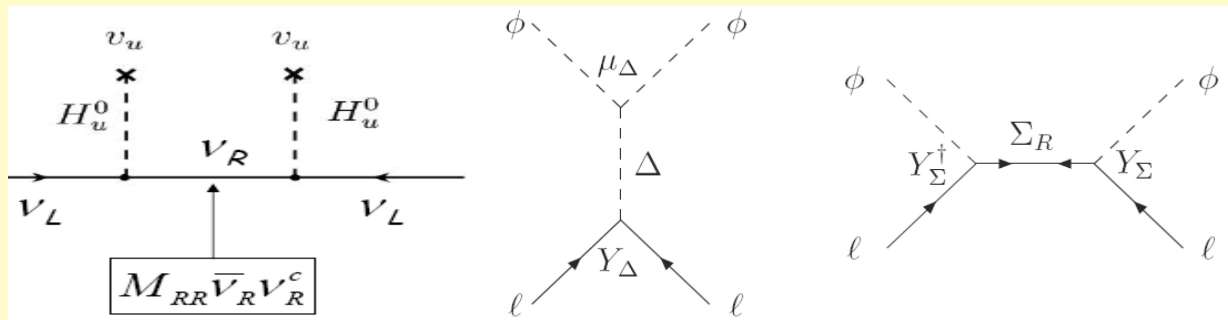
Furthermore:

- They oscillate flavors over macroscopic distances
- This oscillation phase is sensitive to the medium (matter effects)
- They are part of the dark matter and may be related to dark energy
- They may experience new interactions or exotic effects

How do neutrinos talk to the Higgs?



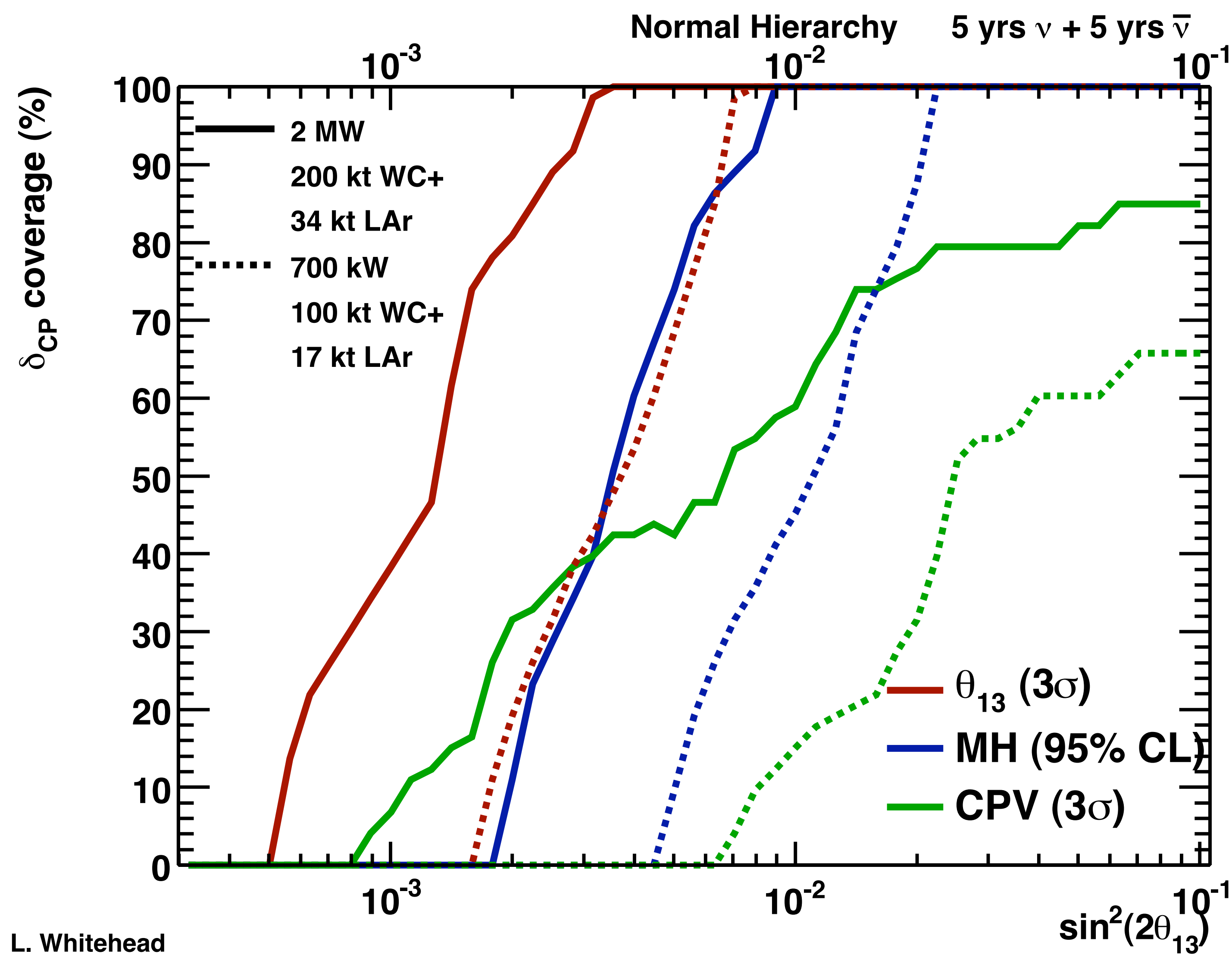
Type I, fermion singlet N, charge 0	Type II, scalar triplet Δ, charge 0, 1, 2	Type III, fermion triplet Σ, charge 0, 1



+ variants (inverse, +SUSY, +LR, +radiative,...)

- Either neutrinos couple to the Higgs via superheavy partners, or via new TeV particles accessible at the LHC
- Need to nail down the neutrino masses, mixings, and possible CP phases
- Even more so if neutrinos have one or more sterile components

Project X Long Baseline Neutrinos

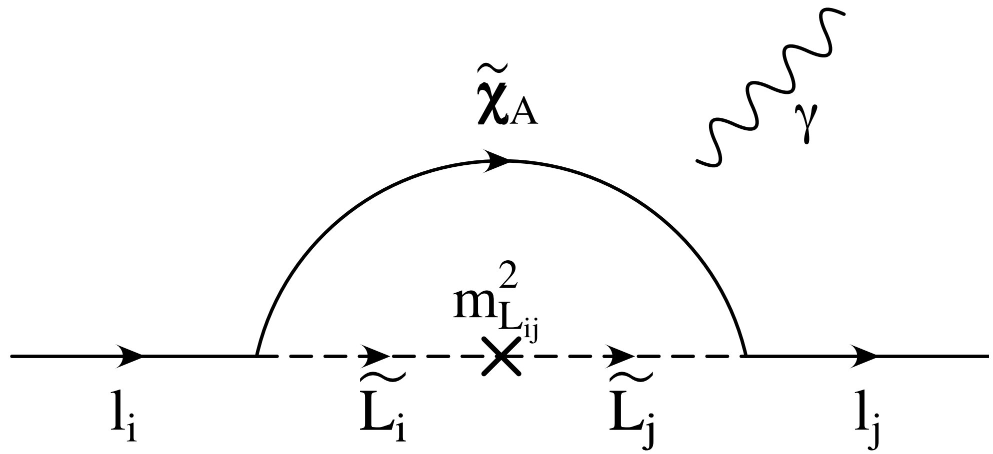


Intensity Frontier: Muons

- Muons
    - Muon to electron conversion
        - Not yet observed, requires new physics
    - anomalous g-2 of muon
        - BNL experiment saw >3 sigma effect, requires new physics
    - Electric dipole moments of muon, electron, neutron, nuclei
        - Not yet observed, requires new physics

These could all come from the *same* new physics, involving both neutrinos new LHC-accessible particles

A scenario for new physics with muons



Some new heavy particles (e.g. sleptons and gauginos in supersymmetry) have quantum effects on leptons, e.g. the muon

- **The lepton flavor conserving, CP conserving part of this contributes to muon g-2**
- **The lepton flavor conserving, CP violating part creates an EDM**
- **The lepton flavor violating part induces mu to e conversion. Note that a heavy Majorana neutrino sector will induce this automatically**

W. Altmannshofer, A. Buras, S. Gori, P. Paradisi, D. Straub, arXiv:0909.1333

A scenario for new physics with muons

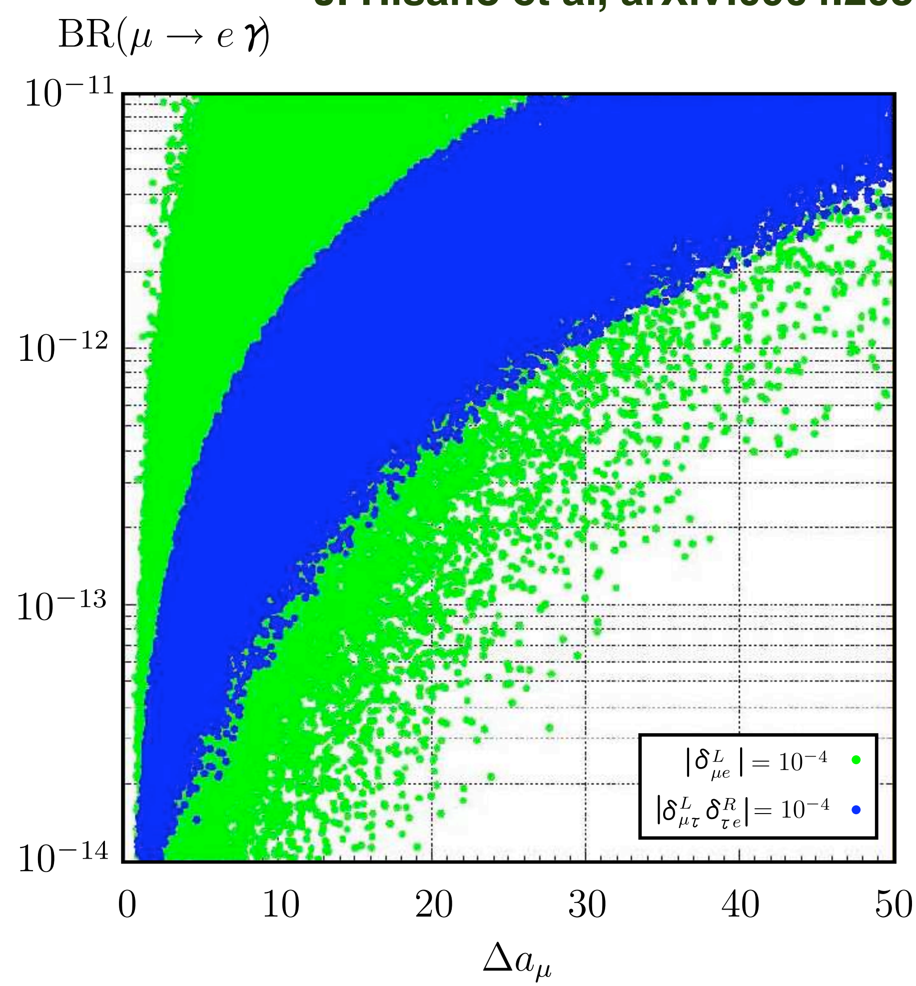
In this picture a g-2 anomaly implies heavy lepton partners at the LHC, AND very likely signals for MEG and mu2e, AND possibly detectable EDMs

$$\frac{a_\mu^{\rm MSSM}}{1\times 10^{-9}} \approx 1.5 \left(\frac{\tan\beta}{10}\right)\left(\frac{300\ {\rm GeV}}{m_{\tilde\ell}}\right)^2 {\rm sgn}\,\mu$$

$$\frac{d_e}{d_\mu} = \frac{\Sigma_{k=2,3}{\rm Im}((\delta_e^{RR})_{1k}(\delta_\ell^{LL})_{k1})}{{\rm Im}((\delta_e^{RR})_{23}(\delta_\ell^{LL})_{32})}$$

$${\rm BR}(\mu\to e\gamma) \approx 2\times 10^{-12}\left[\frac{\Delta a_\mu^{\rm SUSY}}{3\times 10^{-9}}\right]^2 \left|\frac{(\delta_\ell^{LL})_{21}}{10^{-4}}\right|^2,$$

J. Hisano et al, arXiv:0904.2080



Probing physics at 3,000 TeV?

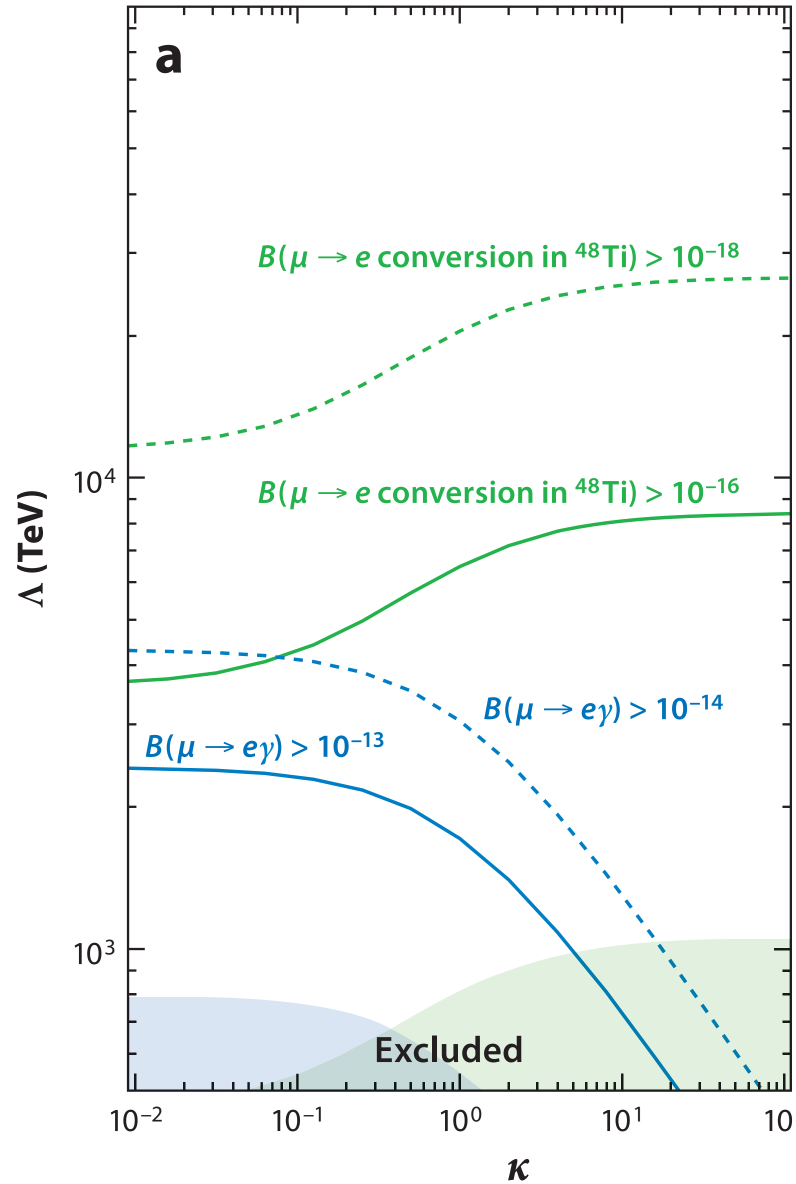
A model-independent analysis of mu to e:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{e}\gamma^\mu e).$$

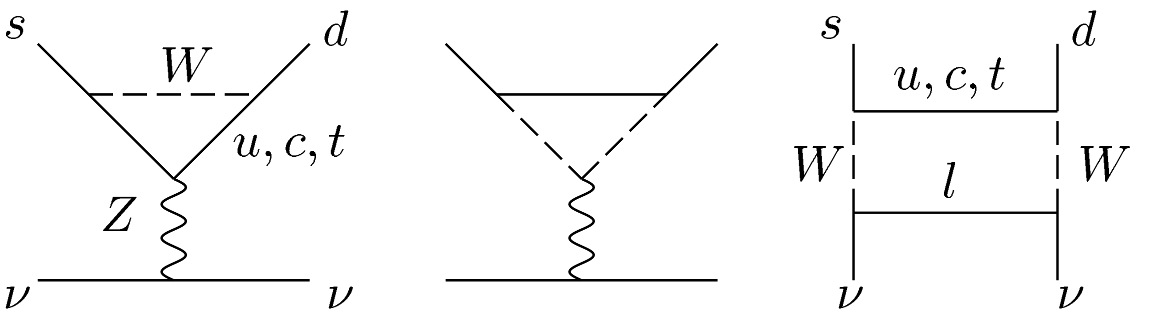
Our previous scenario amounts to an interpretation of Λ

$$\frac{1}{\Lambda^2} \sim \frac{g^2 e}{16\pi^2 M_{\text{SUSY}}^2}\theta_{e\mu},$$

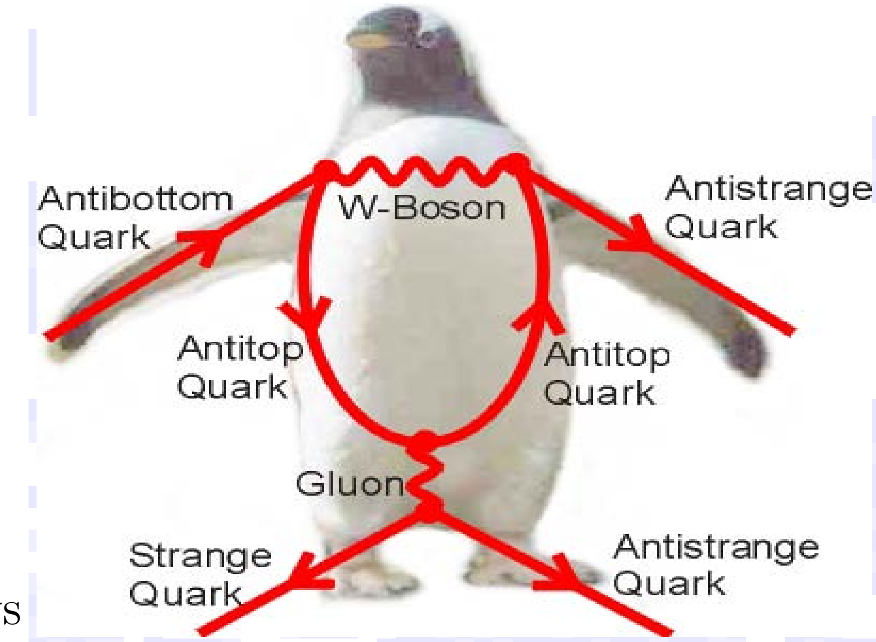
But Λ could directly correspond to a new 3,000 TeV energy scale, e.g. the scale of lepton compositeness



Intensity Frontier: Kaons



Leading Feynman diagrams relevant to $K \to \pi \nu \bar{\nu}$ decays



Standard Model decay rates are small, easily affected by interference with new physics

Uncertainty in predictions is already small and will shrink more over time

$$B_{\rm SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.51 \pm 0.72) \times 10^{-11}$$

$$B_{\rm SM}(K_L \to \pi^0 \nu \bar{\nu}) = (2.54 \pm 0.48) \times 10^{-11},$$

Effects of new physics, a conservative example: Minimal Flavor Violating Supersymmetry

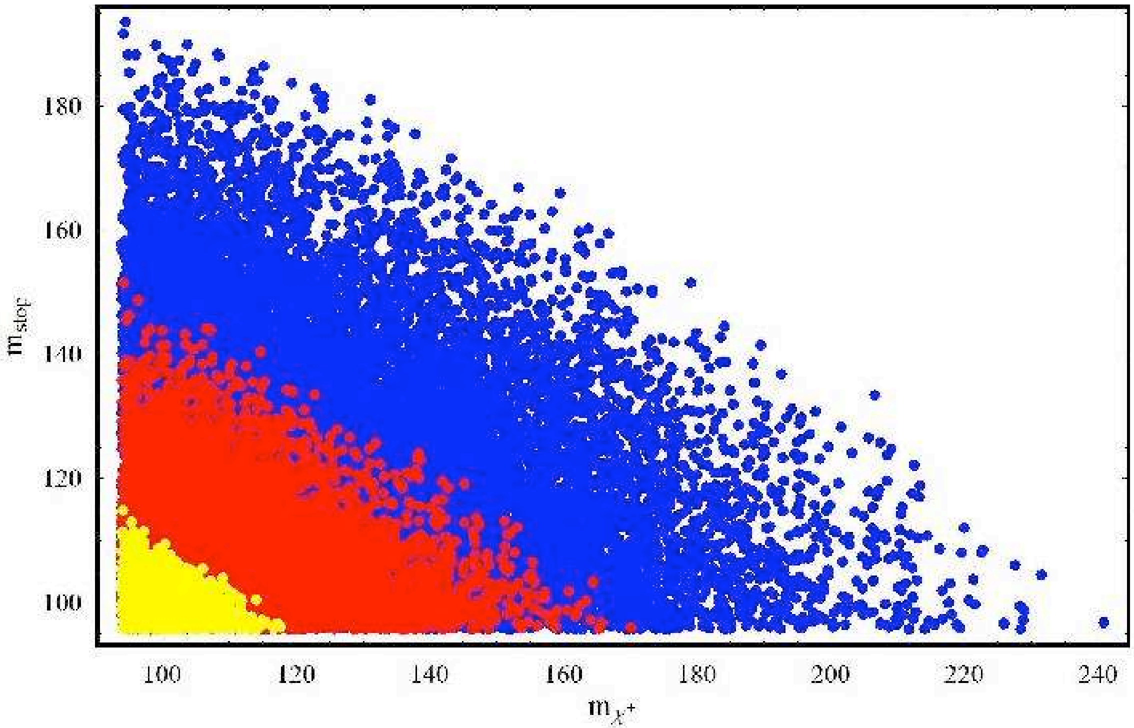
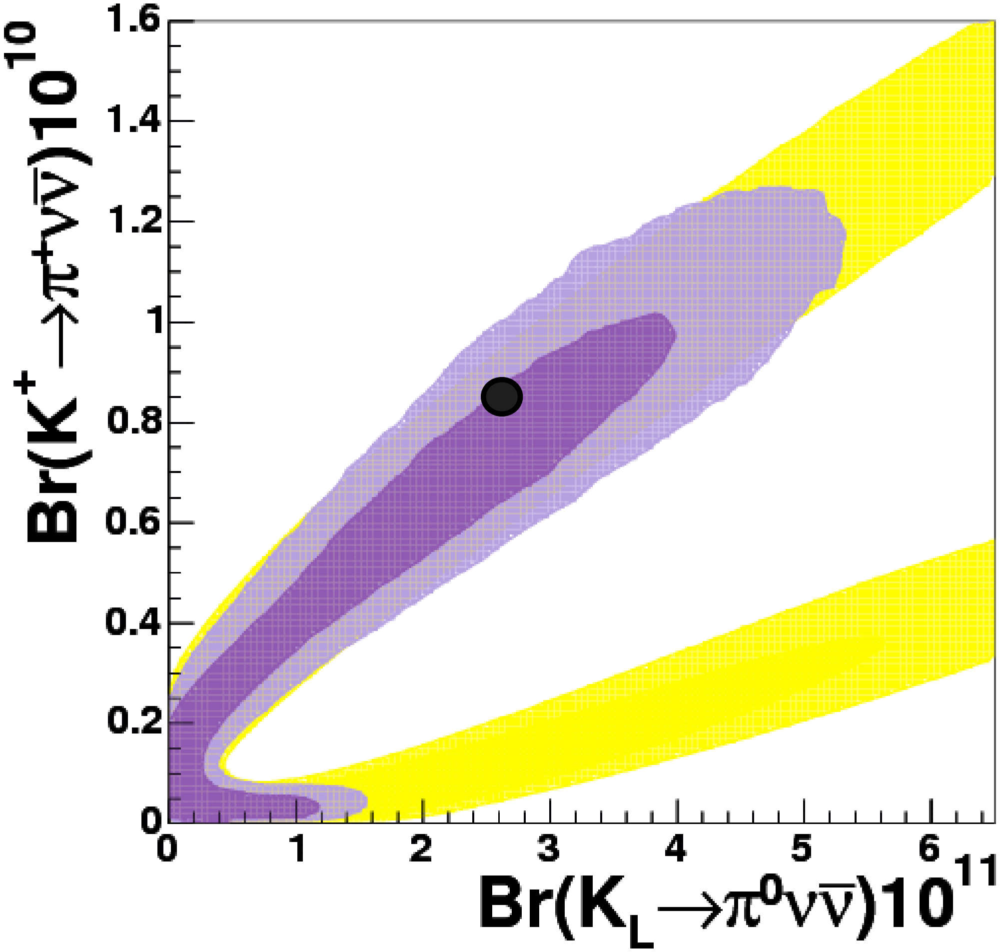


Figure 1: Regions in the $m_{\tilde{t}} - m_{\tilde{\chi}}$ plane (lightest stop and chargino masses) allowing enhancements of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ of more than 11% (yellow/light gray), 8.5% (red/medium gray) and 6% (blue/dark gray) in the MFV scenario, for $\tan\beta = 2$ and $M_{H^+} > 1$ TeV [the corresponding enhancements for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ are 15%, 12.5% and 10%, respectively, see Eq. (21)].

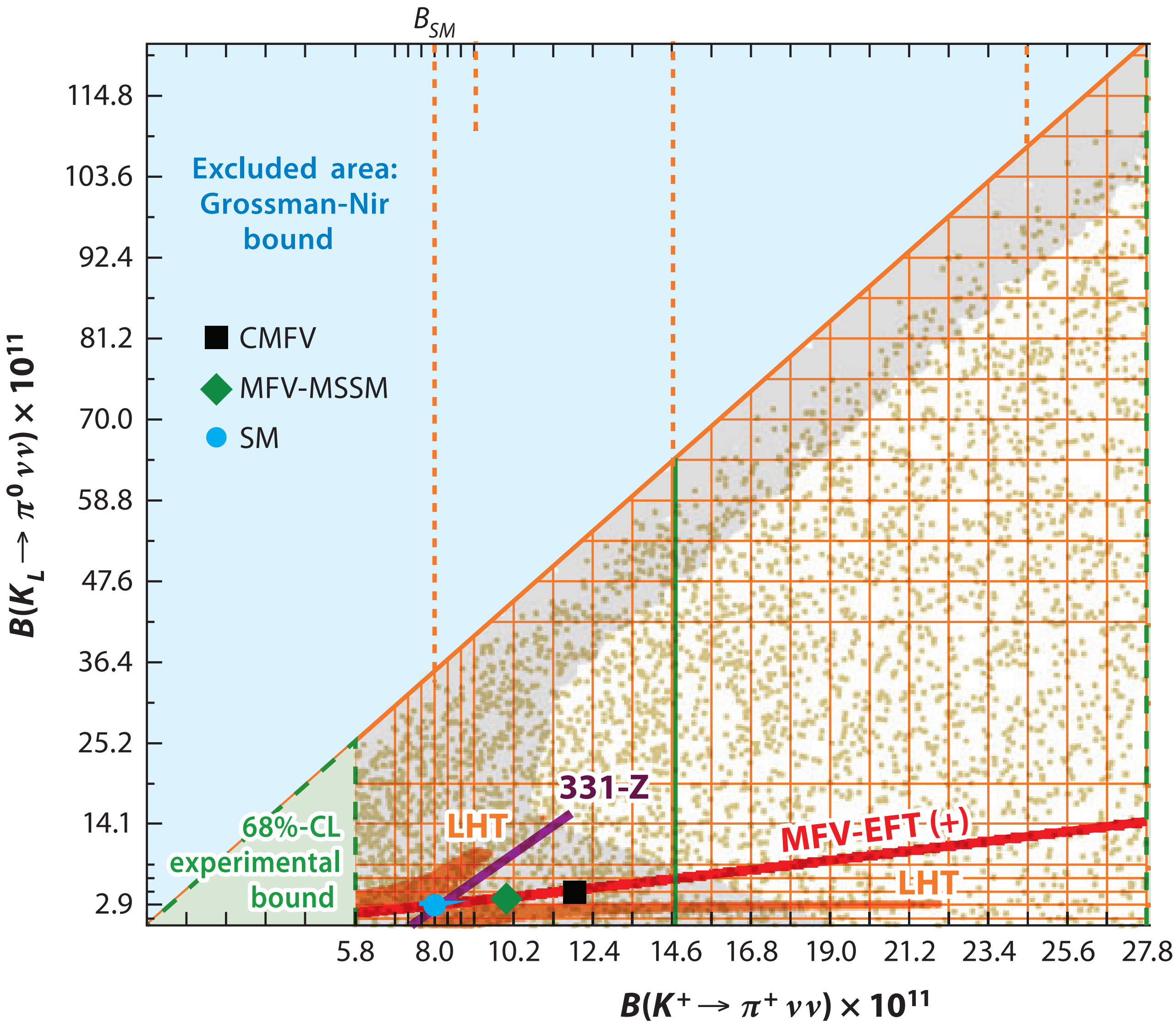
G. Isidori et al, hep-ph/0604074

Effects of new physics, a conservative example: Minimal Flavor Violating Supersymmetry



Correlations provide a strong test of the hypothesis of Minimal Flavor Violation

C. Bobeth, M. Bona, A. Buras, T. Ewerth, M. Pierini, L. Silvestrini, A. Weiler hep-ph/0505110



A. de Gouvea and N. Saoulidou, Ann. Rev. Nucl. Part. Sci. 2010.60:513

The Really Big Proton Gun


"All the News That's Fit to Print"
The New York Times
Late Edition
Particles Collide, and Champagne Glasses Clink

Project X uniquely enables a broad discovery program where many wonderful things may happen

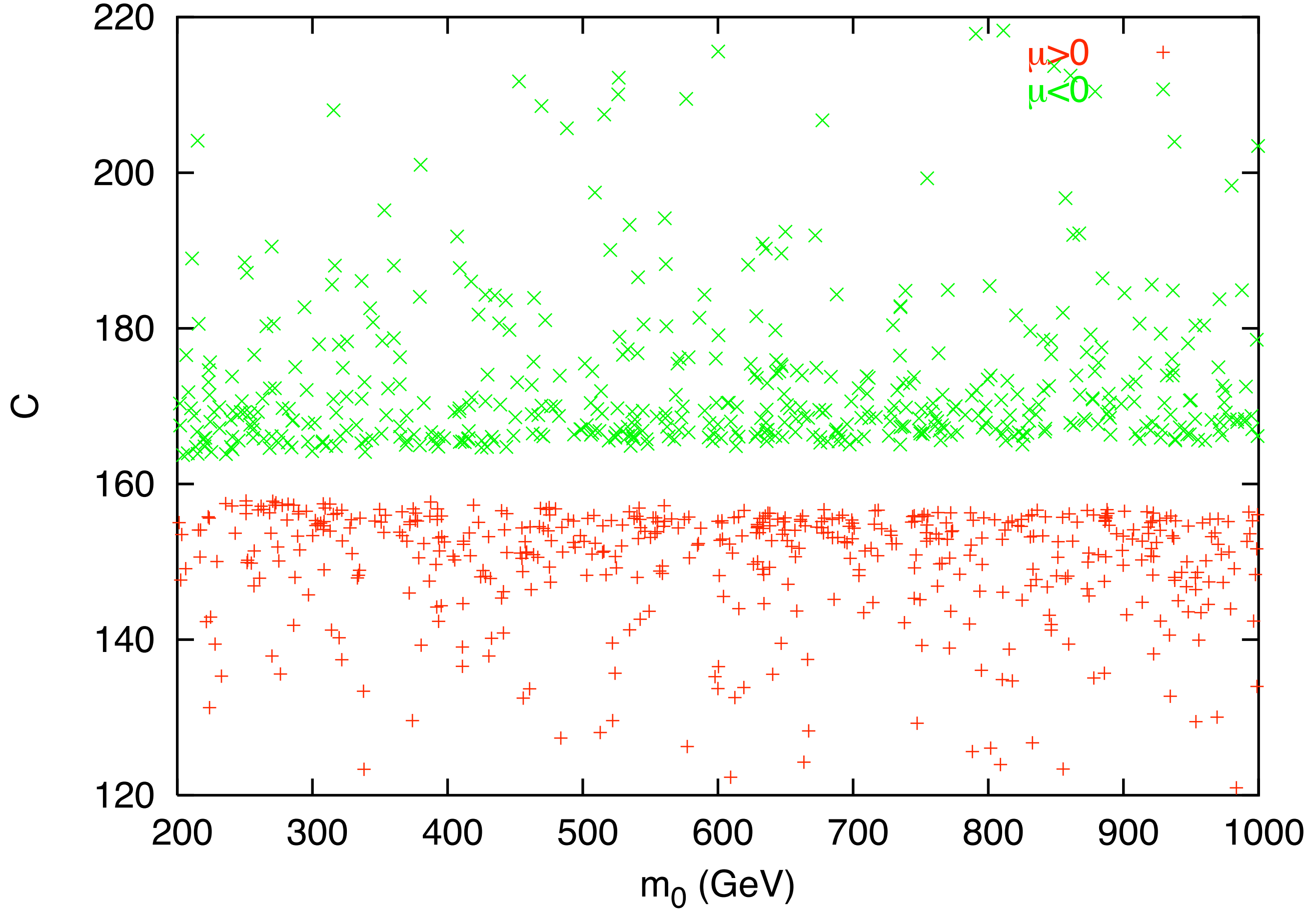
If history is any guide, this will include one or more big surprises

Project X discoveries combined with advances from the Energy and Cosmic Frontiers will illuminate the unified origins of everything, and more.

Backup Slides

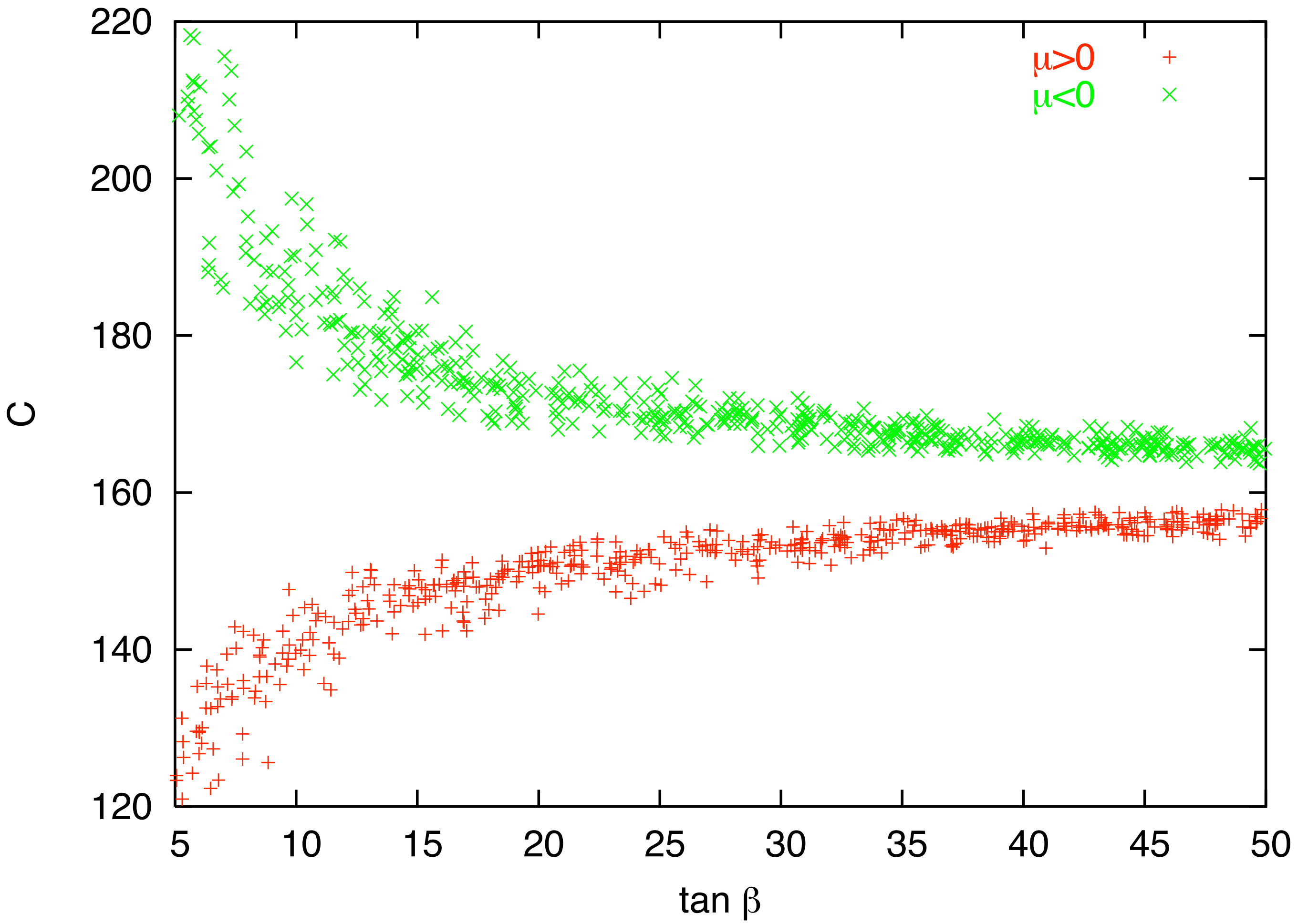
➡ Thus suppose we can measure (with pretty good precision) the ratio

$$\frac{BR(\mu \to e\gamma)}{R(\mu\, Ti \to e\, Ti)} \equiv C$$



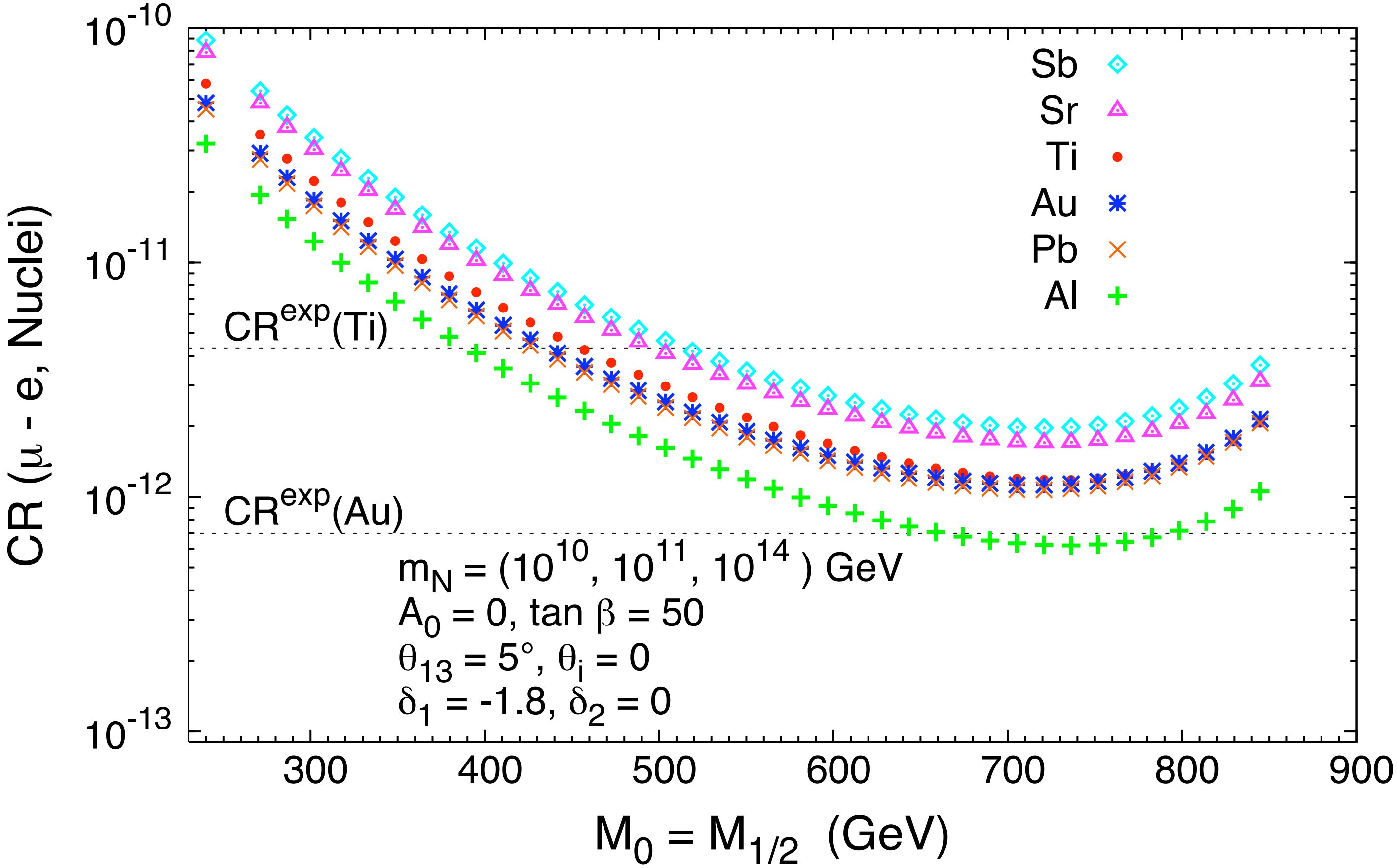
C. Yaguna, hep-ph/0502014

scan over mSUGRA models
note C is always between ~ 120 and 220



C. Yaguna, hep-ph/0502014

sensitivity to both $\tan\beta$ and the sign of μ



E. Arganda, M-J Herrero, A. Teixeira, arXiv:0707.2955

using other nuclei gives added handles

Process	Present Bounds	Expected Future Bounds	Future Experiments
$\mathrm{BR}(\mu \to e\,\gamma)$	1.2×10^{-11}	$\mathcal{O}(10^{-13} - 10^{-14})$	MEG, PSI
$\mathrm{BR}(\mu \to e\,e\,e)$	1.1×10^{-12}	$\mathcal{O}(10^{-13} - 10^{-14})$	?
$\mathrm{BR}(\mu \to e$ in Nuclei (Ti)$)$	1.1×10^{-12}	$\mathcal{O}(10^{-18})$	J-PARC
$\mathrm{BR}(\tau \to e\,\gamma)$	1.1×10^{-7}	$\mathcal{O}(10^{-8})$	SuperB
$\mathrm{BR}(\tau \to e\,e\,e)$	2.7×10^{-7}	$\mathcal{O}(10^{-8})$	SuperB
$\mathrm{BR}(\tau \to e\,\mu\,\mu)$	$2. \times 10^{-7}$	$\mathcal{O}(10^{-8})$	SuperB
$\mathrm{BR}(\tau \to \mu\,\gamma)$	6.8×10^{-8}	$\mathcal{O}(10^{-8})$	SuperB
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	2×10^{-7}	$\mathcal{O}(10^{-8})$	LHCb
$\mathrm{BR}(\tau \to \mu\,e\,e)$	2.4×10^{-7}	$\mathcal{O}(10^{-8})$	SuperB

Table 5: Present [81] and upcoming experimental limits on various leptonic processes at 90% C.L.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

observable	SM prediction	exp. current	exp. future
$S_{\psi\phi}$	$\simeq 0.036$ [81]	$0.81^{+0.12}_{-0.32}$ [1]	$\simeq 0.02$ [193]
$S_{\phi K_S}$	$\sin 2\beta + 0.02 \pm 0.01$ [2]	0.44 ± 0.17 [1]	$(2-3)\%$ [194]
$S_{\eta' K_S}$	$\sin 2\beta + 0.01 \pm 0.01$ [2]	0.59 ± 0.07 [1]	$(1-2)\%$ [194]
$A_{\rm CP}(b \to s\gamma)$	$\left(-0.44^{+0.14}_{-0.24}\right)\%$ [195]	$(-0.4 \pm 3.6)\%$ [1]	$(0.4-0.5)\%$ [194]
$\langle A_7 \rangle$	$(3.4^{+0.4}_{-0.5})10^{-3}$ [140]		
$\langle A_8 \rangle$	$(-2.6^{+0.4}_{-0.3})10^{-3}$ [140]		
$\langle A_9 \rangle$	$(0.1^{+0.1}_{-0.1})10^{-3}$ [140]		
$\lvert d_e \rvert$ (e cm)	$\simeq 10^{-38}$ [196]	$< 1.6 \times 10^{-27}$ [197]	$\simeq 10^{-31}$ [196]
$\lvert d_n \rvert$ (e cm)	$\simeq 10^{-32}$ [196]	$< 2.9 \times 10^{-26}$ [198]	$\simeq 10^{-28}$ [196]
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.60 \pm 0.37)10^{-9}$	$< 5.8 \times 10^{-8}$ [146]	$\simeq 10^{-9}$ [199]
$\mathrm{BR}(B_d \to \mu^+\mu^-)$	$(1.08 \pm 0.11)10^{-10}$	$< 1.8 \times 10^{-8}$ [146]	
$\mathrm{BR}(B \to X_s\gamma)$	$(3.15 \pm 0.23)10^{-4}$ [200]	$(3.52 \pm 0.25)10^{-4}$ [1]	
$\mathrm{BR}(B \to X_s\ell^+\ell^-)$	$(1.59 \pm 0.11)10^{-6}$ [201]	$(1.59 \pm 0.49)10^{-6}$ [202, 203]	
$\mathrm{BR}(B \to \tau\nu)$	$(1.10 \pm 0.29)10^{-4}$	$(1.73 \pm 0.35)10^{-4}$ [112]	