Project X and the "Big Questions"

André de Gouvêa

Northwestern University

Project X Plenary Session

Community Summer Study, Minneapolis,

July 29–August 6, 2013

Introduction (Very Brief)

Project X is a proposed new facility, at Fermilab, dedicated for pursuing experimental particle physics research in the Intensity Frontier

- Project X is a superconducting proton linac. It increases the power available to Fermilab's existing Booster (8 GeV) and Main Injector (120 GeV) programs.
- Project X also provides further physics opportunities at 1 GeV and 3 GeV.

"The key to Project X is that it provides a platform for many experiments requiring high intensity. Not all of them are documented below, because, once the accelerator and experimental halls have been built, creative minds will generate new ideas that we cannot anticipate. Moreover, Project X can, in the farther future, lead to one or more of a neutrino factory, a muon collider ($\mu^+\mu^-$), or a very high-energy proton collider with energy well beyond that of the LHC."

[see remaining talks in this section for a lot more details!]

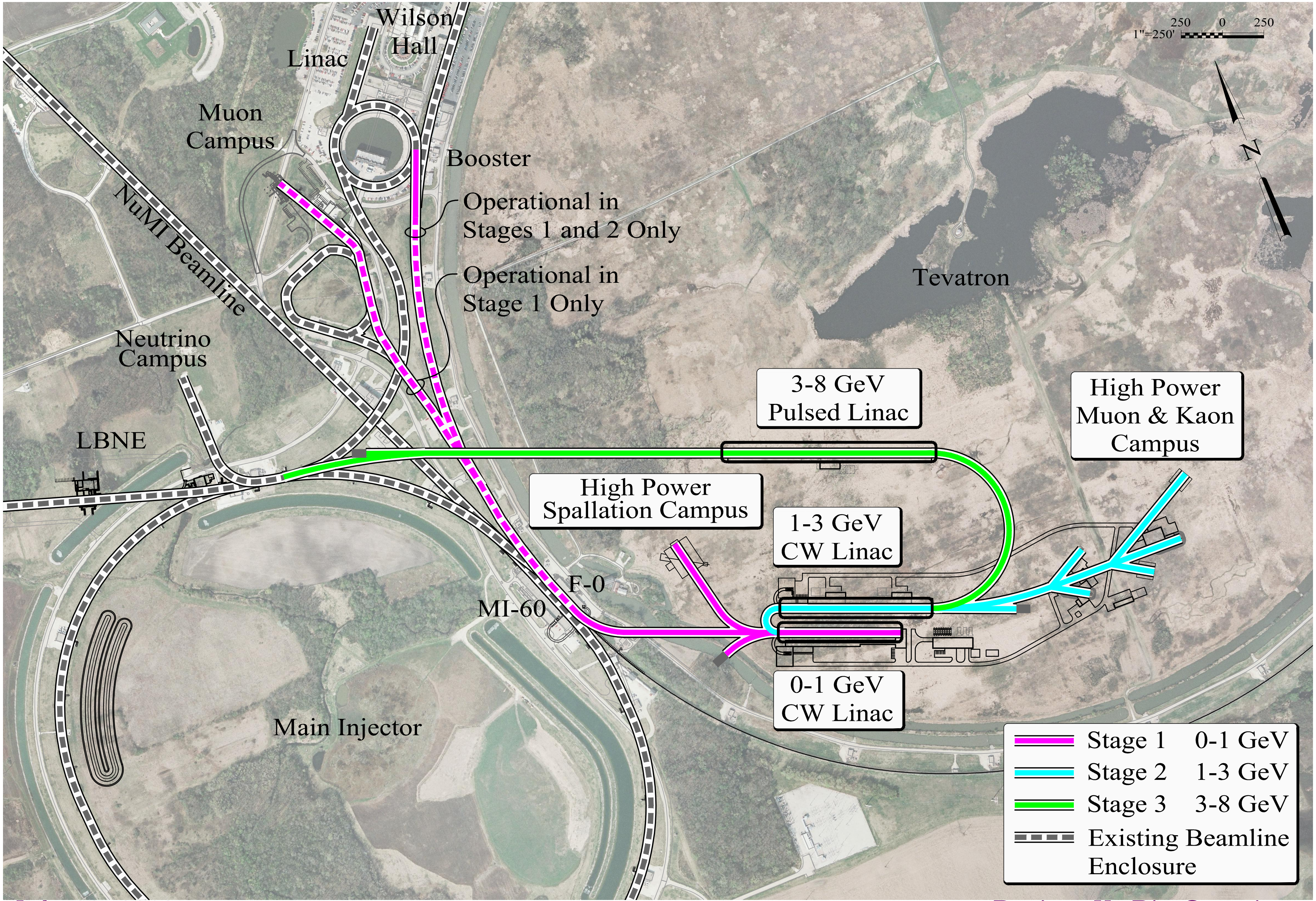

Wilson Hall
Linac
Muon Campus
Booster
Operational in Stages 1 and 2 Only
Operational in Stage 1 Only
NuMI Beamline
Neutrino Campus
Tevatron
LBNE
3-8 GeV Pulsed Linac
High Power Muon & Kaon Campus
High Power Spallation Campus
1-3 GeV CW Linac
F-0
MI-60
0-1 GeV CW Linac
Main Injector
N
250 0 250
1"=250'
Stage 1 0-1 GeV
Stage 2 1-3 GeV
Stage 3 3-8 GeV
Existing Beamline Enclosure

Table I-1: Physics opportunities for *Project X* by Stage. The accelerator Reference Design (RDR) is described in Part I of this book and comprises Stages 1, 2, and 3. In all Stages, *Project X* beam drives the Main Injector (MI)—in Stages 1 and 2 via the original 8-GeV Booster. During Stage 2, the Booster cycles at a higher rate, allowing the MI to operate over a wider energy range, 60–120 GeV (instead of 80–120 GeV). Examples of 8-GeV muon experiments include Mu2e and muon $g-2$; an example of a 1–3-GeV muon experiment is an extension of Mu2e with optimized time structure and no antiproton background. Muon spin rotation (μSR) and nuclear irradiation are broader impacts of *Project X* technology, discussed in Part III.

	Present	*Project X* Accelerator Reference Design			Beyond RDR
Program	NOνA operations	Stage 1	Stage 2	Stage 3	Stage 4
MI neutrino	470–700 kW[a,b]	515–1200 kW[a,b]	1200 kW	2450 kW	2450–4000 kW
8 GeV neutrino	15–65 kW[a,b]	0–130 kW[a]	0–130 kW[a]	0–172 kW[a]	3000 kW
8 GeV muon	20 kW	0–20 kW[a]	0–20 kW[a]	0–172 kW[a]	1000 kW
1–3 GeV muon	—	80 kW	1000 kW	1000 kW	1000 kW
Rare kaon decays	0–30 kW[b,c]	0–75 kW[b,d]	1100 kW	1870 kW	1870 kW
Atomic EDMs	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Cold neutrons	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
μSR facility	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Irradiation facility	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Number of programs	4	8	8	8	8
Total power	740 kW	2200 kW	4300 kW	6500 kW	12,000 kW

[a] Operating point in range depends on the MI proton beam energy for neutrino production.
[b] Operating point in range depends on the MI slow-spill duty factor for kaon and hadron-structure experiments.
[c] With less than 30% duty factor from Main Injector.
[d] With less than 45% duty factor from Main Injector.

[see talk by S. Holmes]

QUESTIONS FOR THE UNIVERSE

EINSTEIN'S DREAM OF UNIFIED FORCES

1

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

3

ARE THERE EXTRA DIMENSIONS OF SPACE?

4

DO ALL THE FORCES BECOME ONE?

THE PARTICLE WORLD

5

WHY ARE THERE SO MANY KINDS OF PARTICLES?

6

WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

7

WHAT ARE NEUTRINOS TELLING US?

THE BIRTH OF THE UNIVERSE

8

HOW DID THE UNIVERSE COME TO BE?

9

WHAT HAPPENED TO THE ANTIMATTER?

QUESTIONS FOR THE UNIVERSE

EINSTEIN'S DREAM OF UNIFIED FORCES

1

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

3

ARE THERE EXTRA DIMENSIONS OF SPACE?

4

DO ALL THE FORCES BECOME ONE?

THE PARTICLE WORLD

5

WHY ARE THERE SO MANY KINDS OF PARTICLES?

6

WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

7

WHAT ARE NEUTRINOS TELLING US?

THE BIRTH OF THE UNIVERSE

8

HOW DID THE UNIVERSE COME TO BE?

9

WHAT HAPPENED TO THE ANTIMATTER?

Curiosity List

- Is there any physics beyond the standard model? Everybody.
- What sets the EW scale? Is it natural?
- Is the world supersymmetric? EDMs g-2 LFV
- Is it the Higgs boson? EDMs LFV
- What is Dark Matter?
- Is there a dark sector? APEX g-2 Short Baseline
- What is Dark Energy?
- Can the CC be natural?
- Are we part of a Universe or a Multiverse?
- What sets the fermion masses? EDMs LFV QFV
- Why is there more matter than anti-matter? EDMs LBNE QFV
- Are neutrinos their own anti-particles? $0\nu\beta\beta$.
- Are there sterile Neutrinos? Short Baseline
- Do neutrino interact in a non standard way? LBNE/Nova Short Baseline
- What solves strong CP? EDMs
- Is there an axion? Is it Dark matter? time varying EDMs
- How many space-time dimensions do we live in? LFV QFV
- Do the forces unify? LBNE/proton decay
- ......

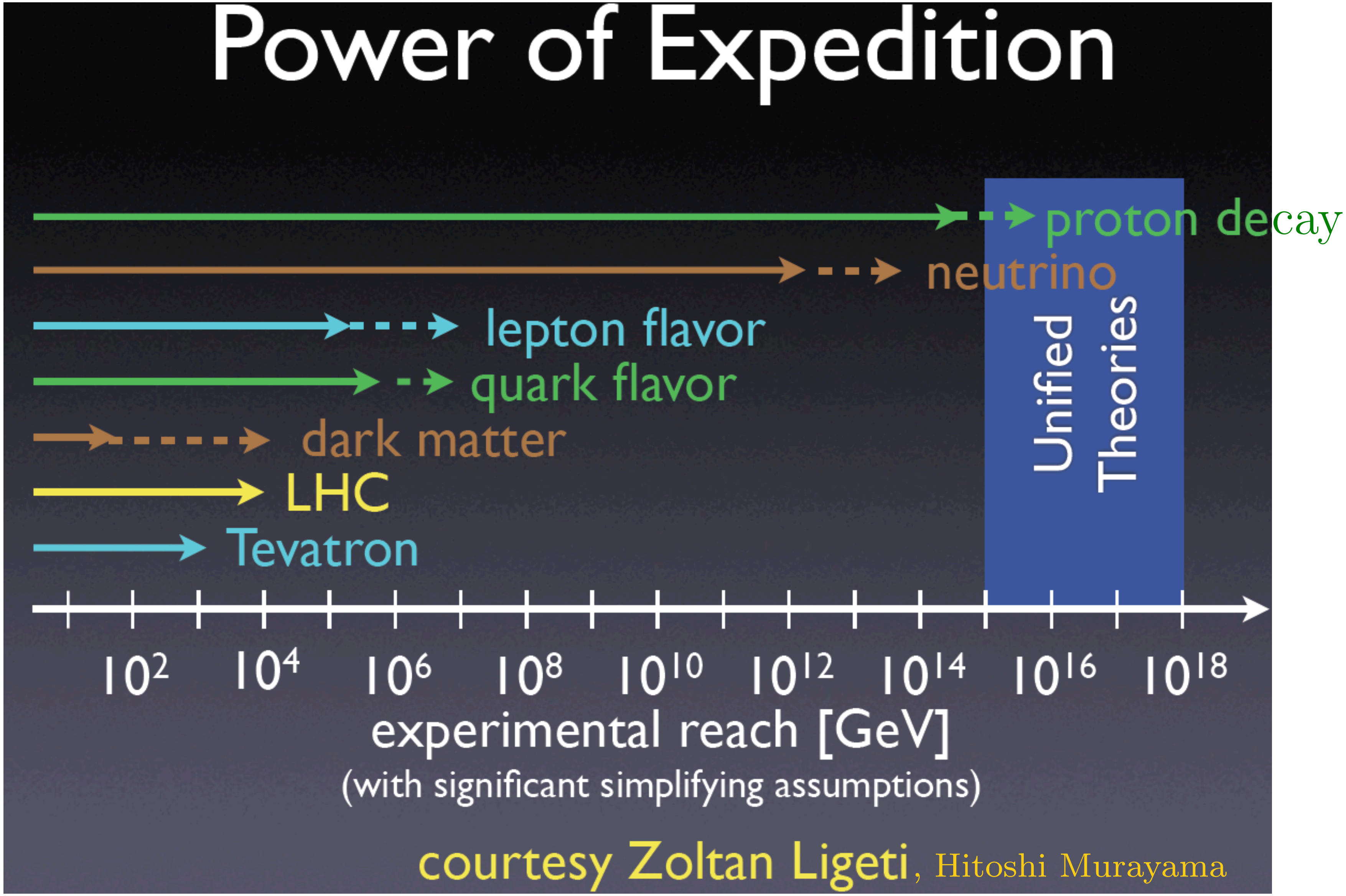
[R. Harnik, talk at IF Workshop, ANL]

Addressing the Big Questions: Capability to pursue MANY different, unique experiments, including

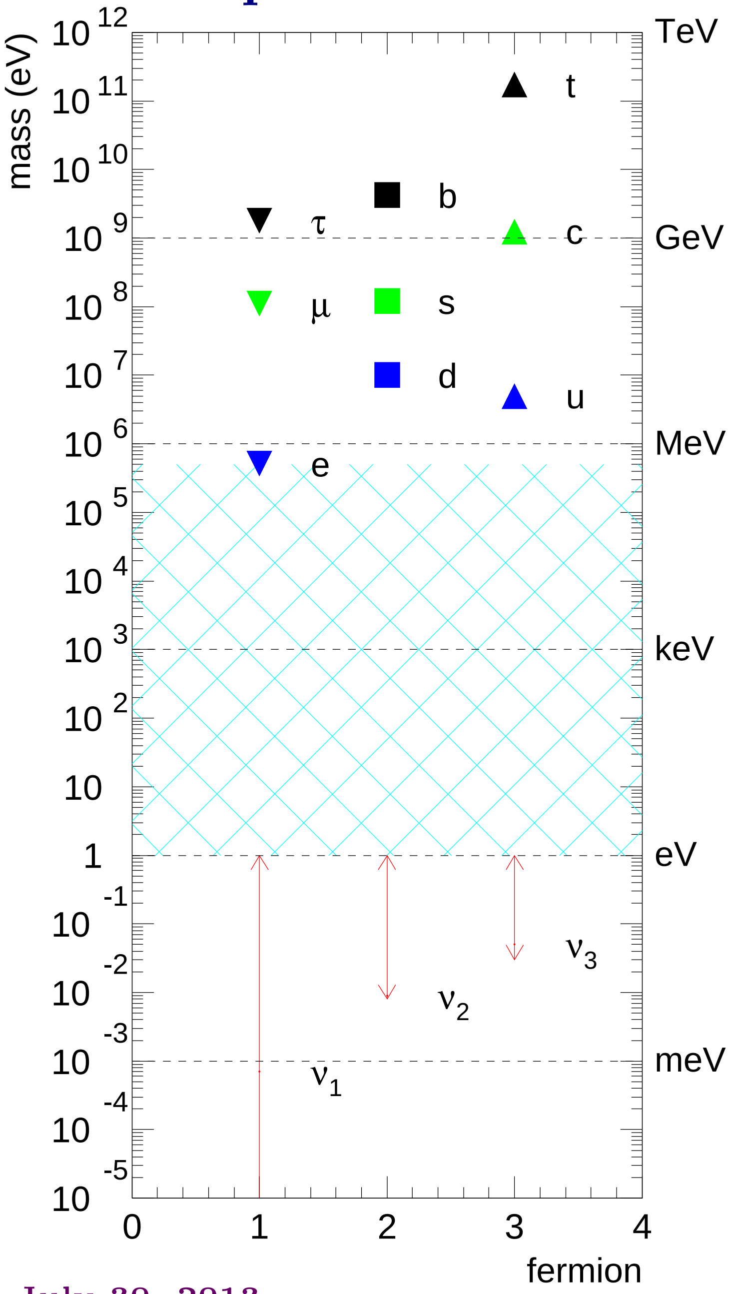
- Precision neutrino oscillation experiments (of different types).
- Muon experiments, ranging from rare muon processes to precision measurements.
- Searches for very rare kaon decays ($K \to \pi\nu\bar{\nu}$) with unprecedented statistics.
- New sources of CP-invariance violation (EDMs, including neutron and proton).
- Searches for new, very light and/or very weakly coupled new particles ("dark sector").
- searches for neutron–antineutron oscillations ($\Delta B = 2$ baryon number violation).
- Hadronic physics (scattering, structure, spectroscopy).

[see remaining talks in this section and many others in this meeting for a lot more details!]

Addressing the Big Questions: Unique Capability!



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?

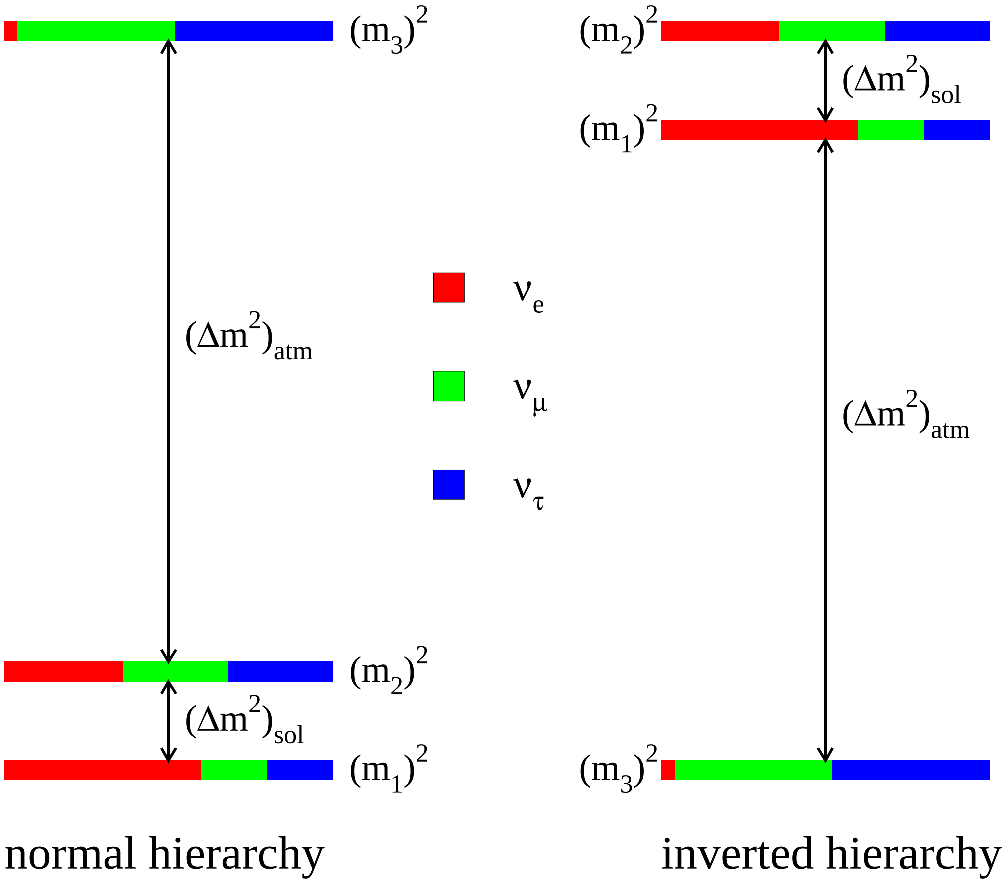
Discovery → intriguing theoretical questions:

– neutrino masses ≪ charged fermion masses: why?

– how do neutrinos acquire mass? Too many choices!

– how do we learn more about this new physics?

What We Know We Don't Know: Missing Oscillation Parameters

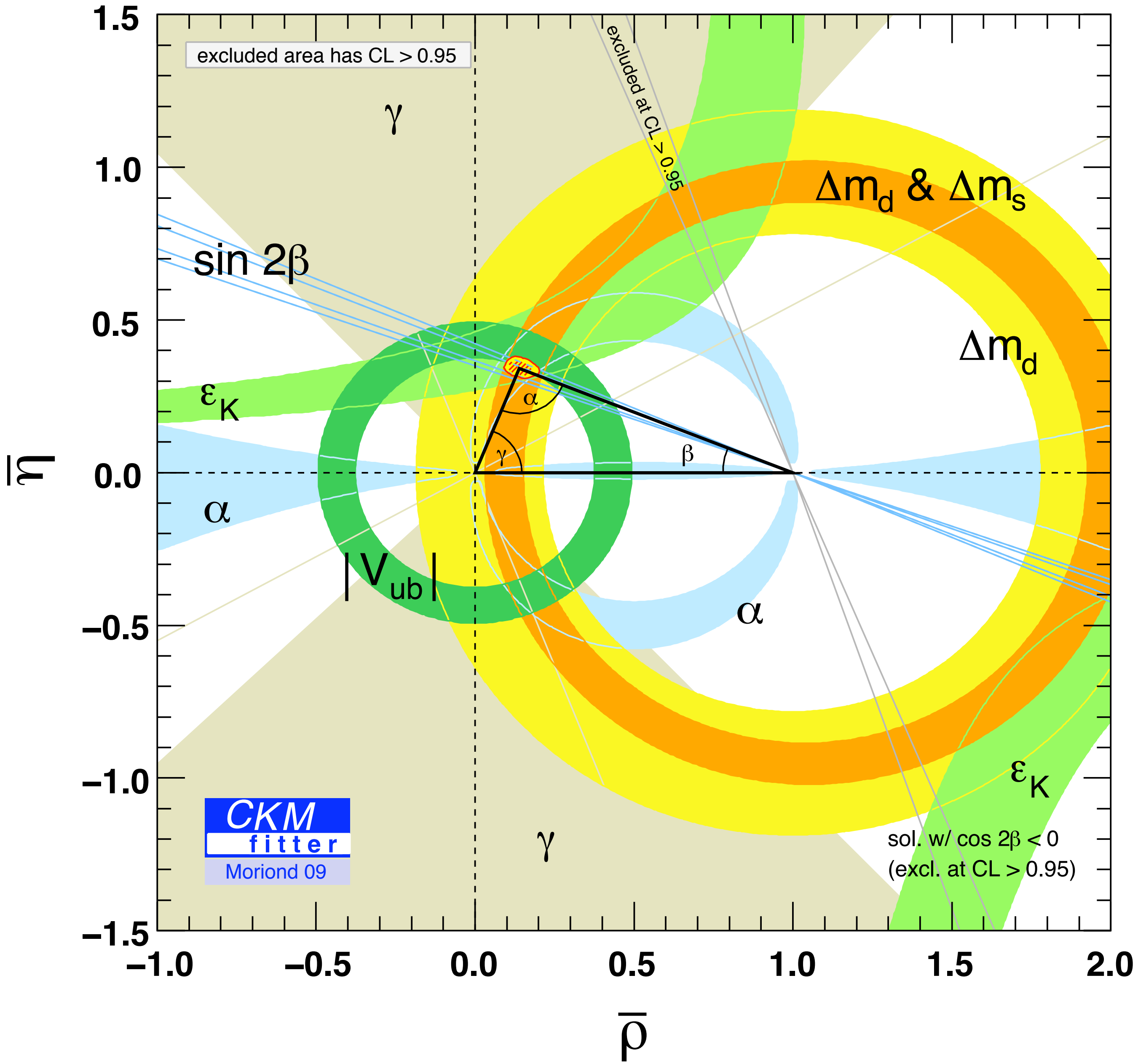


- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

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

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do this in the lepton sector!

Requirement to get serious: New facility!

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

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu 3}|^2$ (upper bound $\to$ hint) – MINOS, T2K.

We still have a ways to go!

CP-Violation in the Lepton Sector – Why Bother?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but t is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why? Cautionary tale: "Mixing angles are small"

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!

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

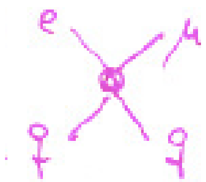
- Interplay with LHC – complementary information regarding new physics at the TeV scale. We learn something about the TeV scale physics in the advent of positive and negative results from $\mu \to e$ searches at 10^{-17}.
- Interplay with other CLFV – non-trivial information to be obtained by combining $\mu \to e$-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!
- Can repeat the measurement with different targets. Non-trivial information on new physics in case of positive results.

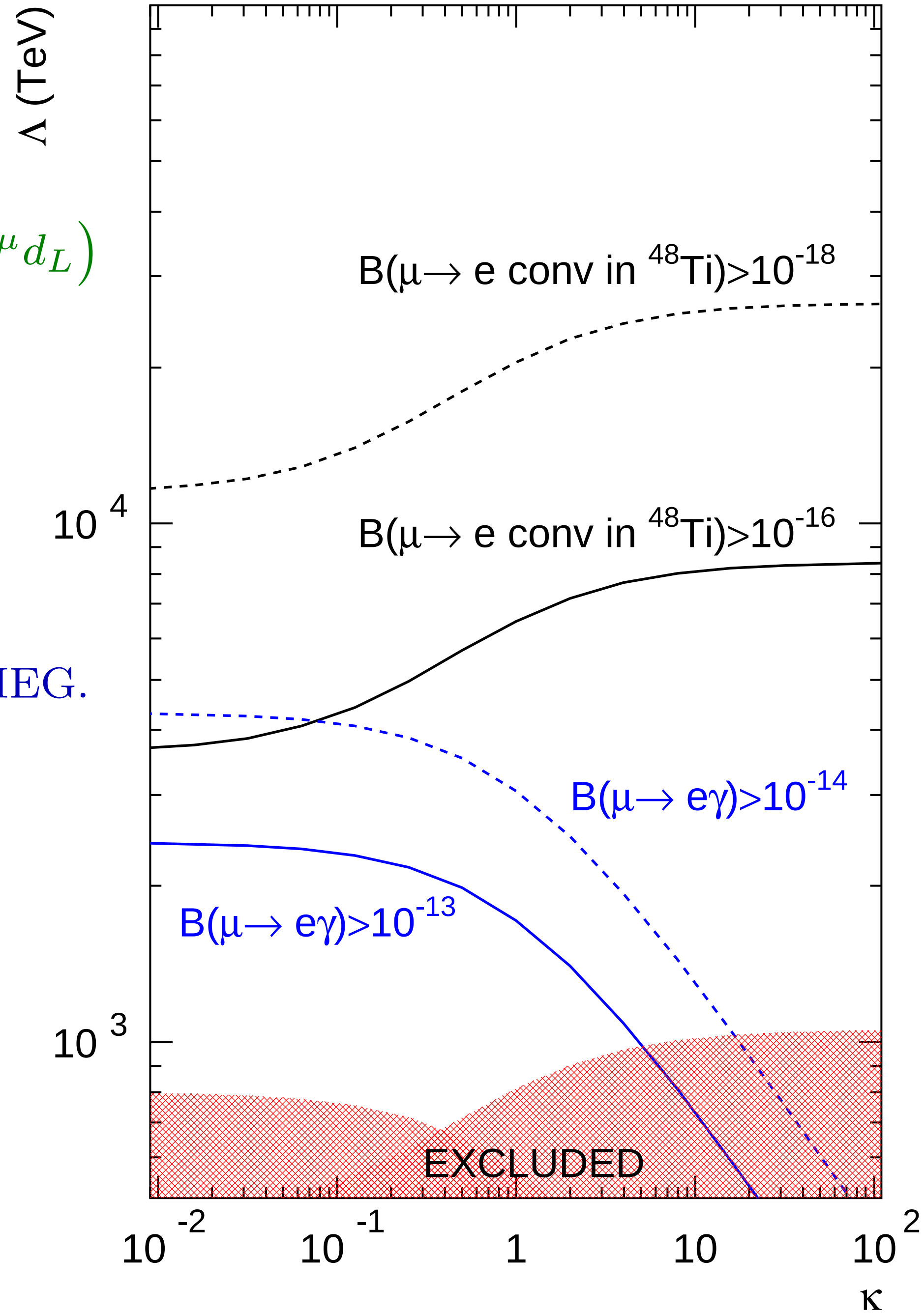
Model Independent Considerations

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} +$$

$$+\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

- $\mu \to e$-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: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.



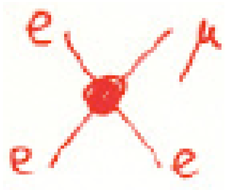


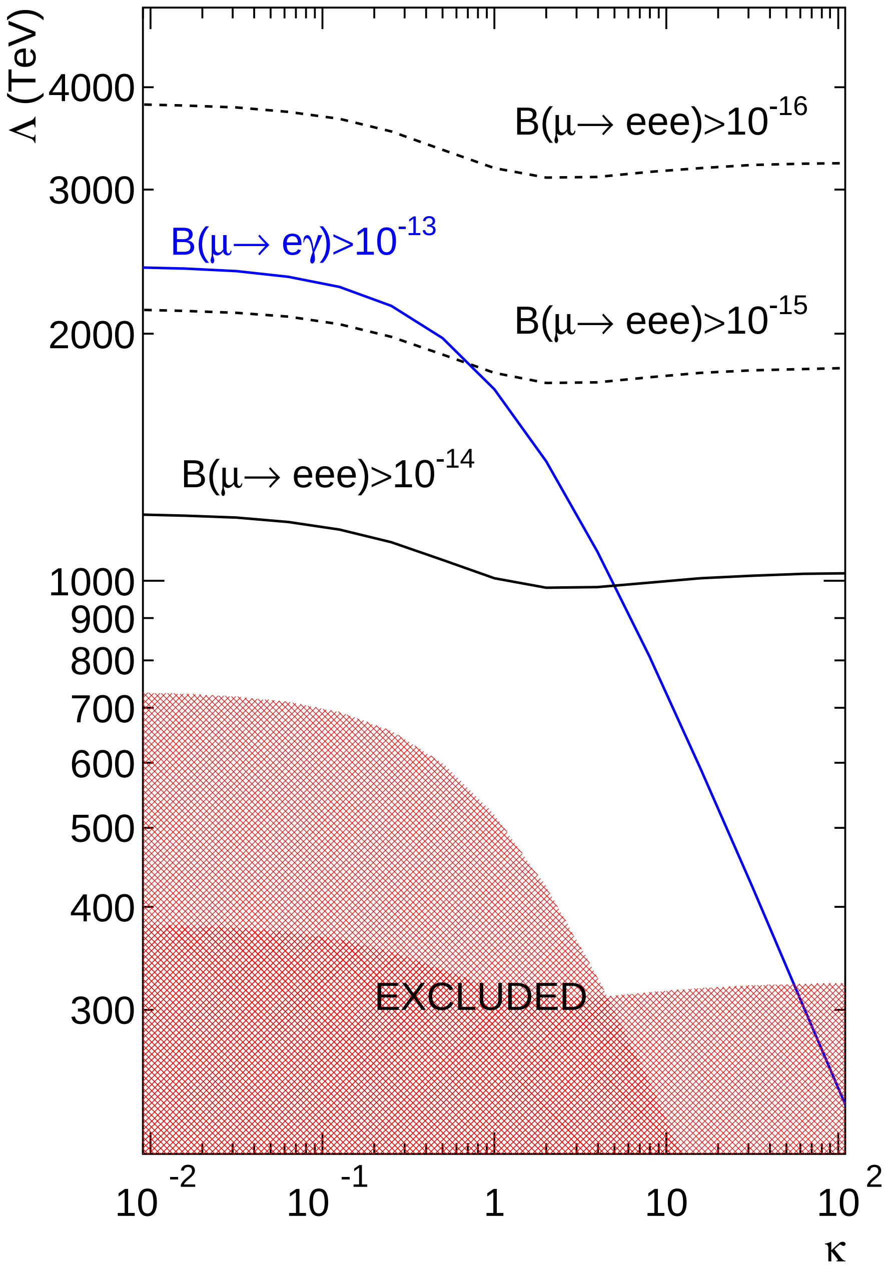
Other Example: $\mu \to e e^+ e^-$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + $$

$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

- $\mu \to eee$-conv at 10^{-16} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- $\mu \to eee$ another way forward after MEG?
- If the LHC does not discover new states $\mu \to eee$ among very few process that can access 1,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.





What does "Λ" mean?

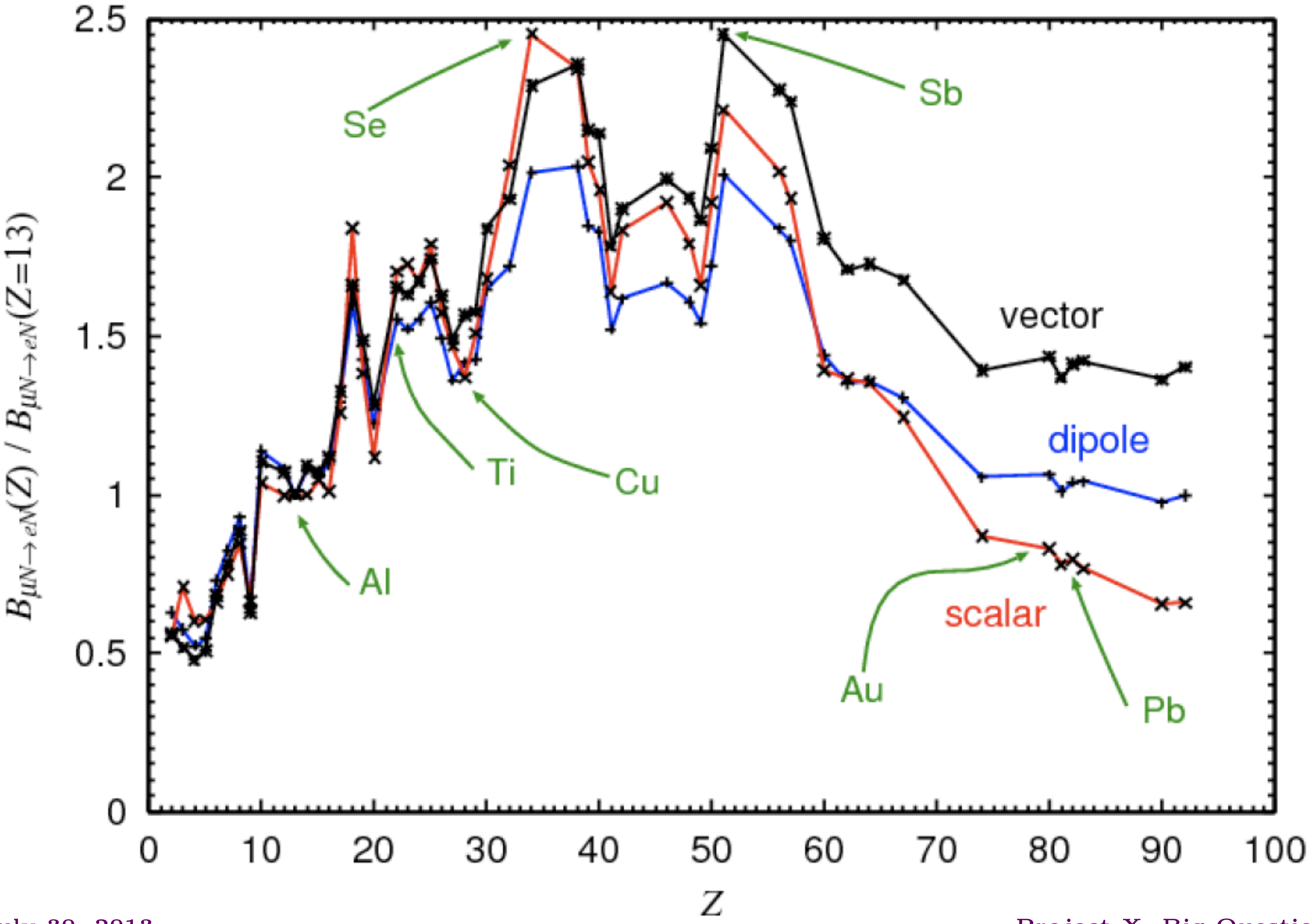
This is clearly model dependent! However, some general issues are easy to identify…

- $\mu \to e\gamma$ always occurs at the loop level, and is suppressed by E&M coupling e. Also chiral suppression (potential for "$\tan\beta$" enhancement).

$$\frac{1}{\Lambda^2} \sim \frac{e}{16\pi^2}\frac{\tan\beta}{M_{\rm new}^2}$$

- $\mu \to eee$ and $\mu \to e$-conversion in nuclei can happen at the tree-level

$$\frac{1}{\Lambda^2} \sim \frac{y_{\rm new}^2}{M_{\rm new}^2}$$


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
vector
dipole
scalar
Ti
Cu
Al
Au
Pb

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

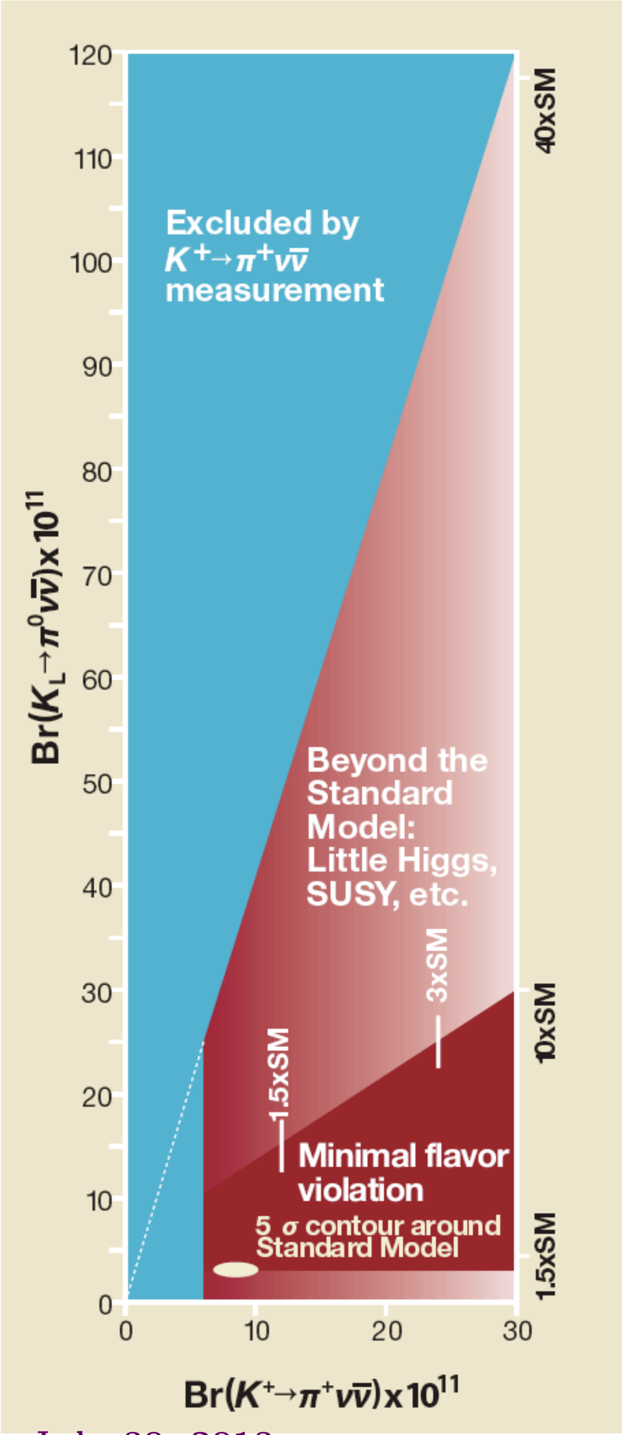
Both $K^{\pm}$ and K_L decays into $\pi\nu\bar{\nu}$ have a special place in the realm of rare hadron decays.

- SM expectations are really tiny – FCNC hence GIM suppressed, purely electroweak, 1-loop processes.
  $B(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (8.22\pm0.84)\times10^{-11}$ [measured $\to$ $(1.47^{+1.30}_{-0.89})\times10^{-10}$]
  $B(K_L \to \pi^0\nu\bar{\nu})_{SM} = (2.76 \pm 0.40) \times 10^{-11}$
- 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!

⇒ New Physics is Really Heavy or

⇒ 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.

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

QUESTIONS FOR THE UNIVERSE

EINSTEIN'S DREAM OF UNIFIED FORCES

1

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

3

ARE THERE EXTRA DIMENSIONS OF SPACE?

4

DO ALL THE FORCES BECOME ONE?

THE PARTICLE WORLD

5

WHY ARE THERE SO MANY KINDS OF PARTICLES?

6

WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

7

WHAT ARE NEUTRINOS TELLING US?

THE BIRTH OF THE UNIVERSE

8

HOW DID THE UNIVERSE COME TO BE?

9

WHAT HAPPENED TO THE ANTIMATTER?

Project X: 1, 3, 4, 5, 6, 7, 9

Example: 9. WHAT HAPPENED TO THE ANTIMATTER?

This issue could be resolved by Leptogenesis, which seems to be "everyone's" favorite solution. However, is it testable experimentally? The answers are (a) we don't know!, (b) it need not be, (c) we will need to gather a lot of information to find out. From lots of places...

- Neutrino experiments of all kinds. Is CP violated in the neutrino sector? Are neutrinos Majorana fermions? Are there sterile neutrinos? What are the neutrino masses?
- Charged Lepton Flavor Violation. Is there new physics close to the weak scale? Is it related to the physics responsible for neutrino masses?
- LHC and other collider experiments. Are there new particle? Are they 'flavorful'?
- Is baryon number violated? Is that energy scale related to the physics responsible for neutrino masses?
- etc.

CONCLUSIONS

We expect Intensity Frontier research to play a key role in exploring today's (and tomorrow's!) "Big Questions." Project X is an ambitious facility that allows state-of-the-art experiments with unique capability to teach us how to describe nature at the smallest possible distance scales.

- Natural first step to pursue the new physics unlocked by neutrino oscillation data – next-generation neutrino oscillation experiments;
- Potential for strong interplay with physics responsible for neutrino masses;
- Flavor and CP-invariance 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 and CP-invariance violation searches provide "only" particle physics probe of whatever lies at short distances.
- Negative or SM-like results still valuable.