(Particle) Physics with Extreme Beams*

André de Gouvêa

Northwestern University

43rd Annual Users' Meeting

Fermilab, June 2 and 3, 2010

---

*Extreme Beam "=" Accelerator-Based Particle Physics at the Intensity Frontier

Intensity Frontier and FNAL

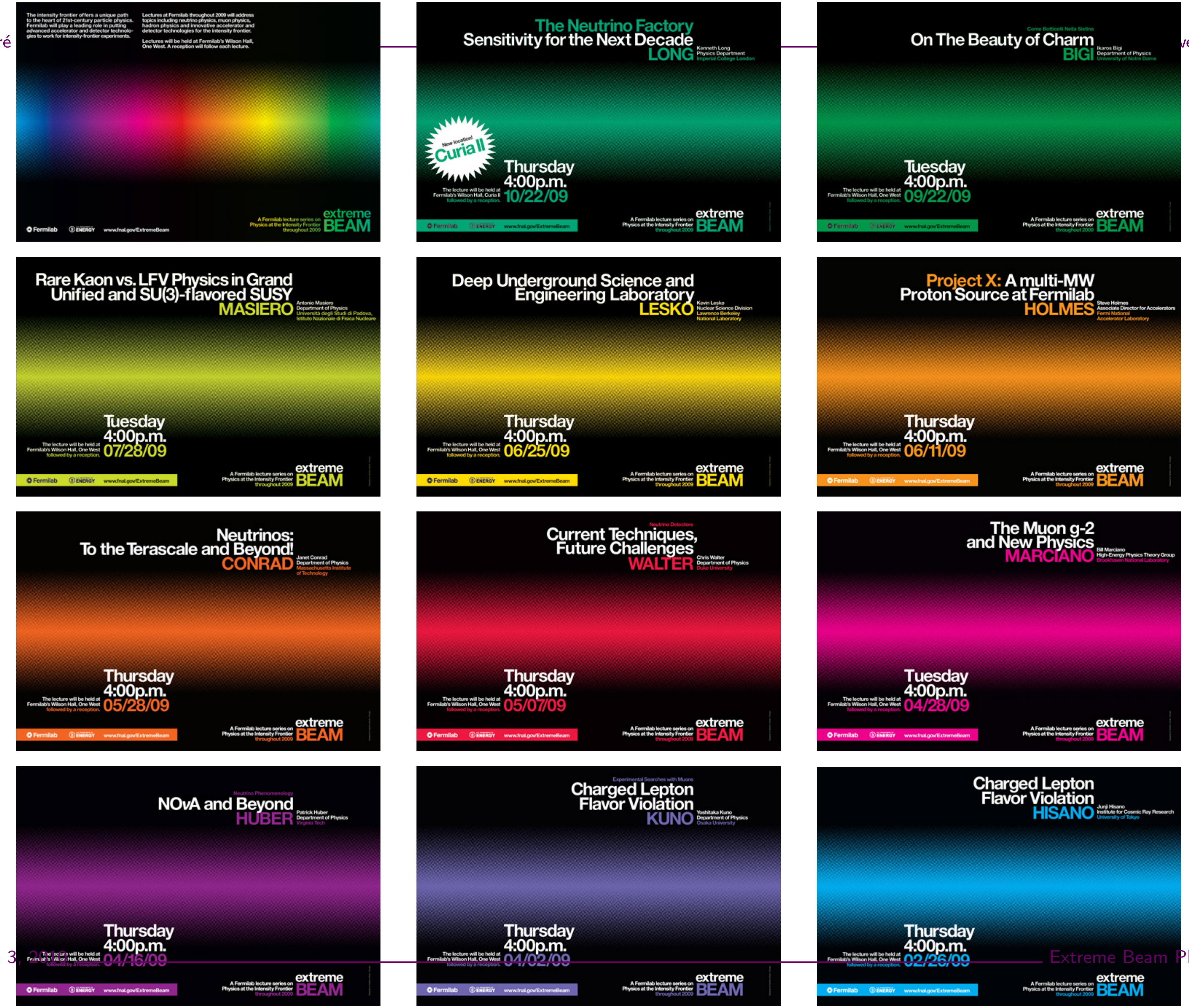
Accelerator Physics Experiments at the Intensity Frontier:

- Energy and type of beam dictated by the Physics (not "as high as possible");
- As many particles as possible;
- Ideal for very rare or "forbidden" processes, very rare probes, precision measurements, etc
- Examples: NuMI-MINOS, MiniBooNE, Belle, Babar, LEP-1.

As we heard yesterday and today, Fermilab's investment in the intensity frontier is growing.

Project X is envisioned as the main driver for a rich experimental program at the Intensity Frontier (and beyond). Over the past several years, we have been trying to understand "what is it good for?"

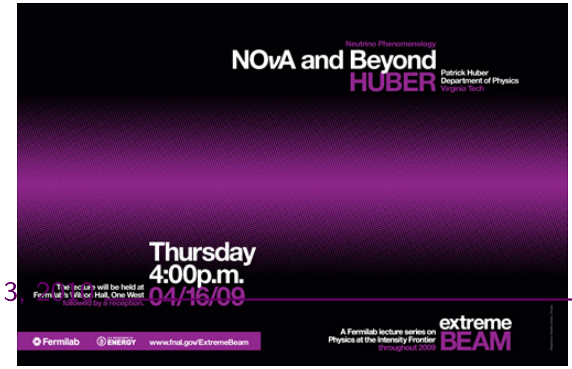
- Project X Website: http://projectx.fnal.gov
- Project X Physics Workshops. Latest one Nov 9-10, 2009 resulted in Project X Physics White Paper.
- Extreme Beam Lecture Series: Physics at the Intensity Frontier (Feb. to Oct. 2009). (AdG, Herman White)
- Second Extreme Beam Series – Conceptual Designs for Experiments: Coming Up September 2010.


The intensity frontier offers a unique path to the heart of 21st-century particle physics. Fermilab will play a leading role in putting advanced accelerator and detector technologies to work for intensity-frontier experiments.
Lectures at Fermilab throughout 2009 will address topics including neutrino physics, muon physics, hadron physics and innovative accelerator and detector technologies for the intensity frontier.
Lectures will be held at Fermilab's Wilson Hall, One West. A reception will follow each lecture.
A Fermilab lecture series on Physics at the Intensity Frontier throughout 2009
extreme BEAM
www.fnal.gov/ExtremeBeam
The Neutrino Factory
Sensitivity for the Next Decade
LONG
New location! Curia II
Thursday 4:00p.m. 10/22/09
On The Beauty of Charm
BIGI
Tuesday 4:00p.m. 09/22/09
Rare Kaon vs. LFV Physics in Grand Unified and SU(3)-flavored SUSY
MASIERO
Tuesday 4:00p.m. 07/28/09
Deep Underground Science and Engineering Laboratory
LESKO
Thursday 4:00p.m. 06/25/09
Project X: A multi-MW Proton Source at Fermilab
HOLMES
Thursday 4:00p.m. 06/11/09
Neutrinos: To the Terascale and Beyond!
CONRAD
Thursday 4:00p.m. 05/28/09
Current Techniques, Future Challenges
WALTER
Thursday 4:00p.m. 05/07/09
The Muon g-2 and New Physics
MARCIANO
Tuesday 4:00p.m. 04/28/09
NOvA and Beyond
HUBER
Thursday 4:00p.m. 04/16/09
Charged Lepton Flavor Violation
KUNO
Thursday 4:00p.m. 04/02/09
Charged Lepton Flavor Violation
HISANO
Thursday 4:00p.m. 02/26/09

Physics At the Intensity Frontier: An Incomplete List

- Precision Neutrino Scattering Physics: e.g. $\nu + e \rightarrow \nu + e$ or ν_τ properties;
- Neutrino Oscillation Experiments;
- Rare Muon Processes;
- Precision Measurement of Muon Properties: $(g-2)_\mu$, muon EDM;
- B-Physics;
- Charm Physics;
- Rare Kaon Processes: $K \rightarrow \pi\bar{\nu}\nu$;
- Nuclear Physics;
- ...

Neutrinos: What We Want and Why?



Phenomenological Understanding of Neutrino Masses & Mixing

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

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

- $m_1^2 < m_2^2$
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$

$\Delta m^2_{13} < 0$ – Inverted Mass Hierarchy

$\Delta m^2_{13} > 0$ – Normal Mass Hierarchy

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

(for a detailed discussion see AdG, Jenkins, arXiv:0804.3627)

Three Flavor Mixing Hypothesis Fits All Data Really Well.

$\Rightarrow$ Good Measurements of Oscillation Observables

parameter	Ref. [1] best fit$\pm 1\sigma$	Ref. [1] 3σ interval	Ref. [2] (MINOS updated) best fit$\pm 1\sigma$	Ref. [2] (MINOS updated) 3σ interval
Δm^2_{21} [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.05–8.34	$7.67^{+0.22}_{-0.21}$	7.07–8.34
Δm^2_{31} [10^{-3}eV^2]	$\pm 2.40^{+0.12}_{-0.11}$	$\pm$(2.07–2.75)	-2.39 ± 0.12 $+2.49 \pm 0.12$	$-$(2.02–2.79) $+$(2.13–2.88)
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67	$0.47^{+0.07}_{-0.06}$	0.33–0.64
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056	0.003 ± 0.015	≤ 0.049

Table 1: Determination of three–flavour neutrino oscillation parameters from 2008 global data [1, 2].

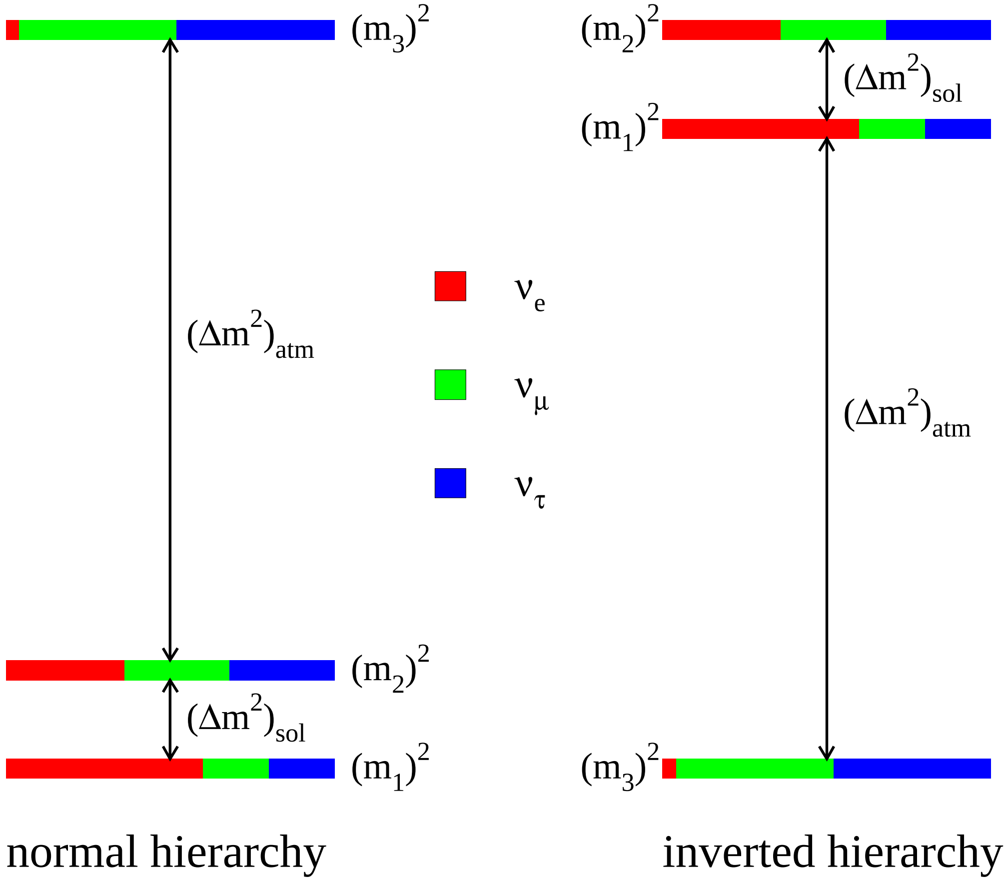
(1) Schwetz, Tortola and Valle, arXiv:0808.2016

(2) Gonzalez-Garcia and Maltoni, arXiv:0704.1800

(Maltoni and Schwetz, arXiv: 0812.3161)

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

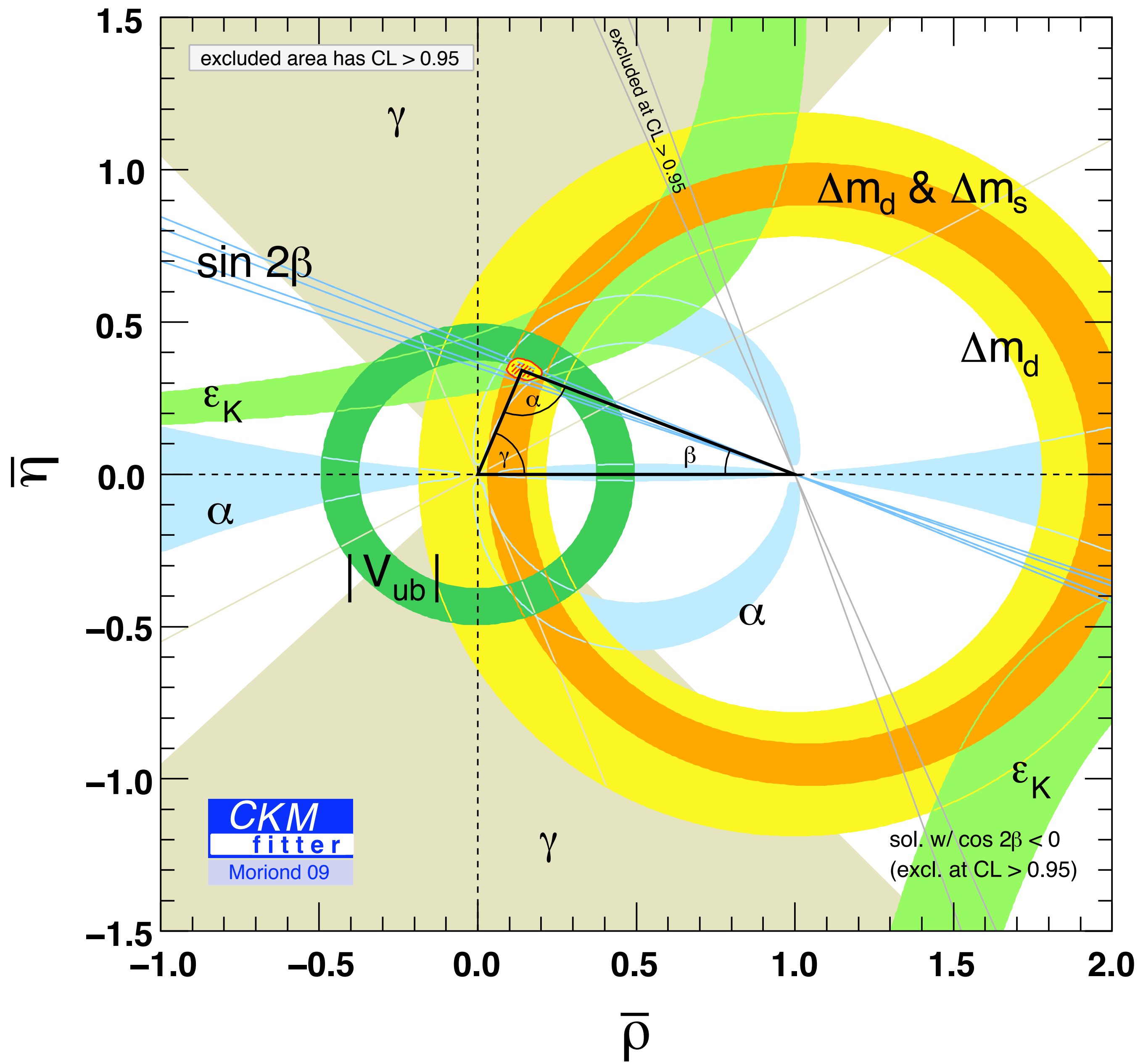
(Driving Force of Next-Generation Oscillation Program)



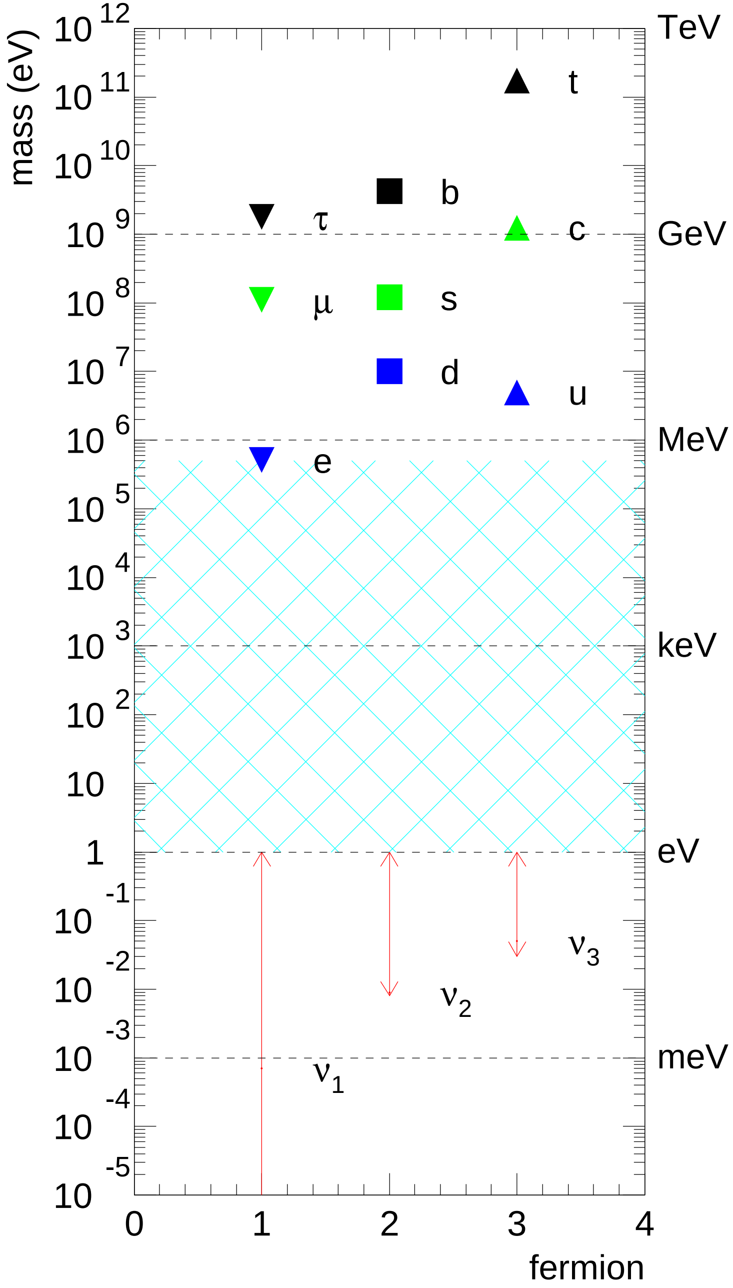
- What is the ν_e component of ν_3? $(\theta_{13} \neq 0?)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

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

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



We need to do this in the lepton sector!



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Who Cares About Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

---

* There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of "palpability" (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs *or* not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this "particle physics?").

What is the New Standard Model? (νSM)

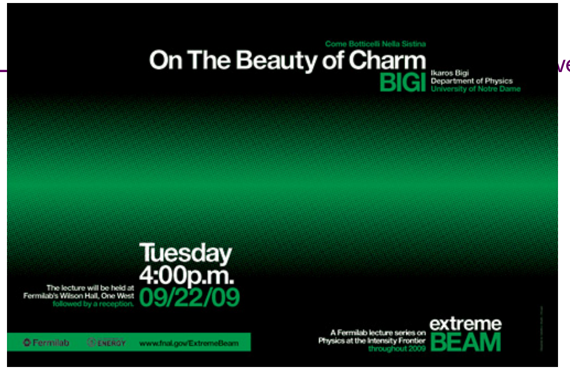
The short answer is – WE DON'T KNOW. Not enough available info!

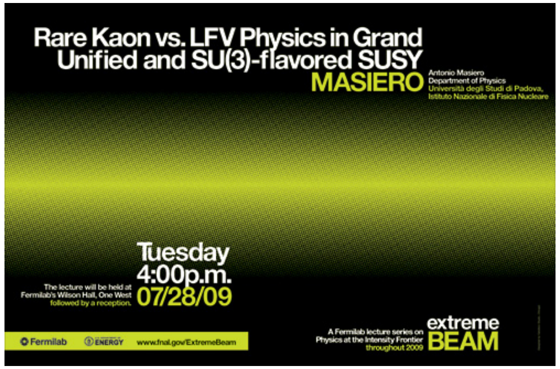
$\Updownarrow$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. (are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc)

We need more experimental input, and it looks like it may be coming in the near/intermediate future! Most of these lie within the Intensity Frontier. . .

Rare Processes: What We Want and Why?





KAONS

MUONS

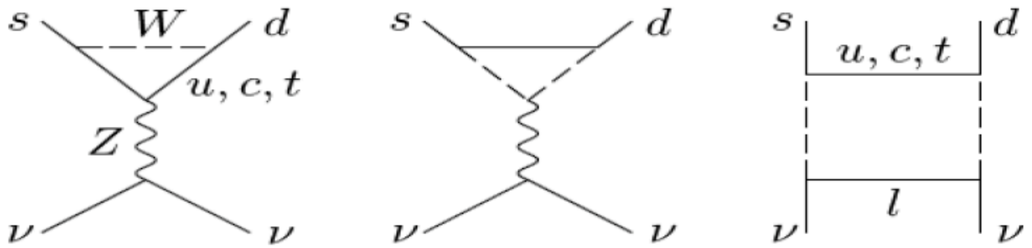
Searching for Rare Processes:

More specifically, $K^+ \to \pi^+ \bar{\nu}\nu$, $K_L \to \pi^0 \bar{\nu}\nu$, $\mu \to e$-conversion in nuclei

- These are processes where the physics beyond the SM (whatever it is) can stand out with respect to the SM contribution. Sometimes by a lot!
- Furthermore, the SM contribution, if not negligible has to be very well-known.
- Up-side: sensitive to potentially very heavy new physics.
- Up-side: sensitive to different aspects of new physics: flavor-nature, CP-properties, etc.
- Down-side: when the physics beyond the SM shows up, we won't recognize what it is.

$K \to \pi\nu\bar{\nu}$ in the SM

2nd order weak: proceeds very slowly!



Standard Model (*Buras*):

$\mathrm{Im}\,\lambda_t = \mathrm{Im} V^*_{ts} V_{td} = \eta A^2 \lambda^5$

$$B(K^0_L \to \pi^0 \nu\bar{\nu}) = 1.8x10^{-10} \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 2.5 \pm 0.40\,x10^{-11}$$

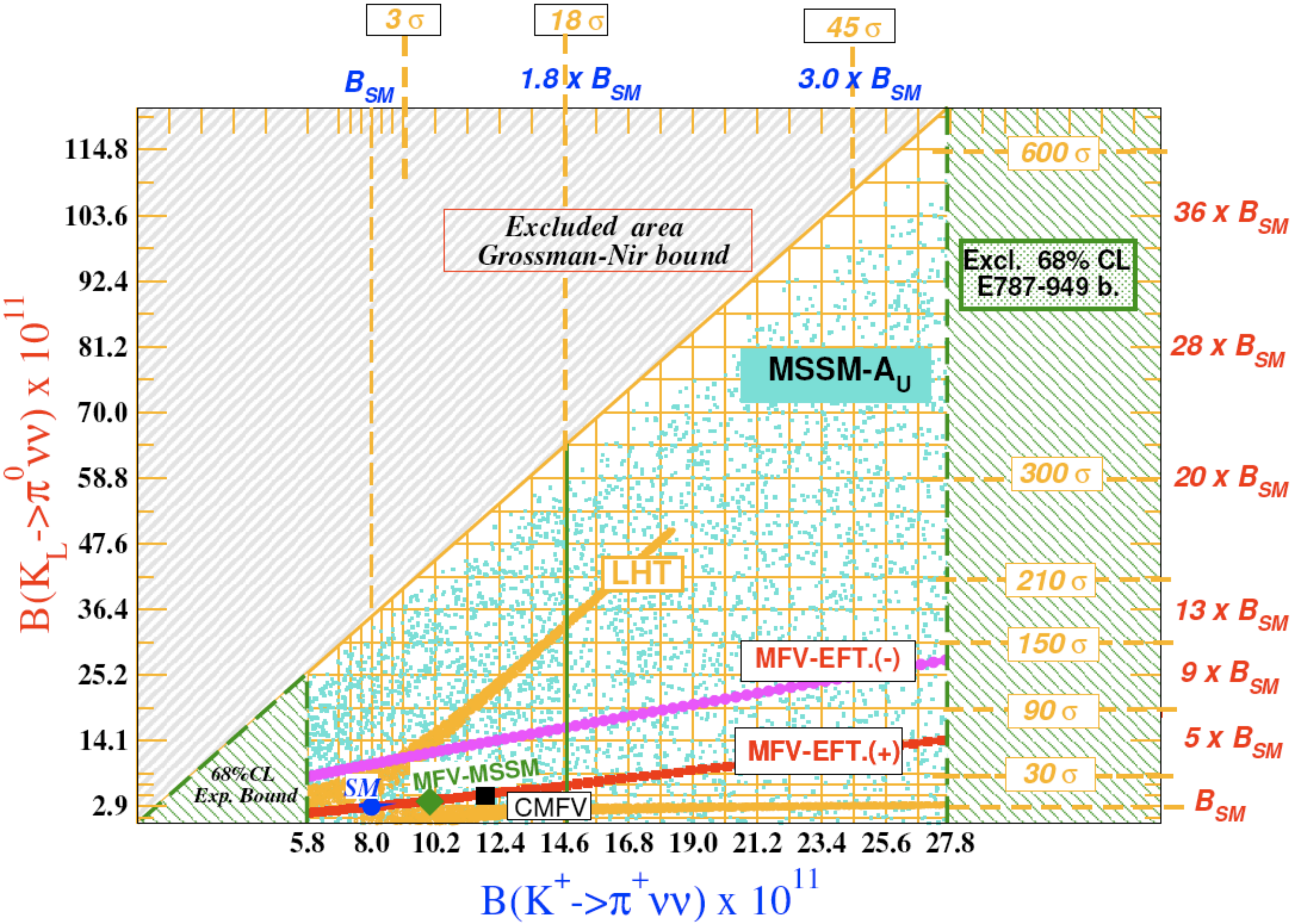
$(\pm 16\% \to \pm 12\%)$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1.0x10^{-10} A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 8.5 \pm 0.7\,x10^{-11}$$

$(\pm 8\% \to \pm 6\%)$

(From Talk by D. Bryman)

New Physics: Exchange $10^{-4}(M_W)^{-2}$ by $C_{\rm new}(M_{\rm new})^{-2}$



large data samples may teach us a lot . . . depending on where we are in (2017±?)

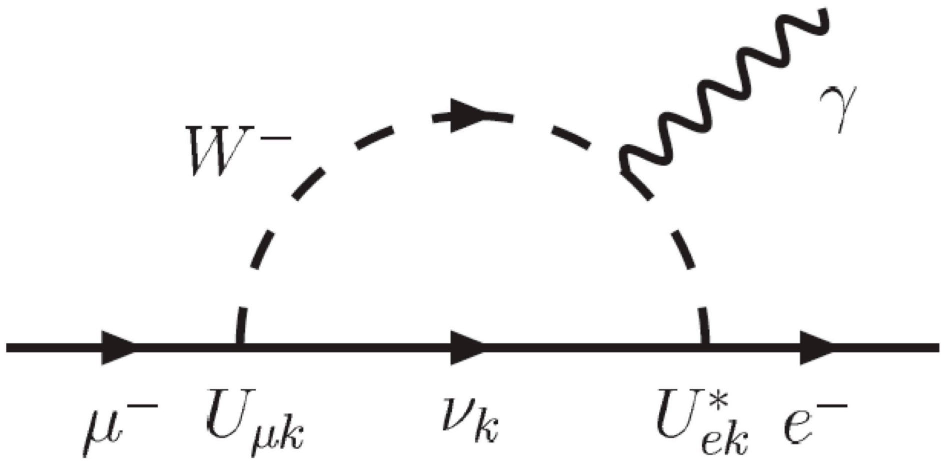
One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the GIM suppression is very efficient…

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

($U_{\alpha i}$ are the elements of the leptonic mixing matrix,

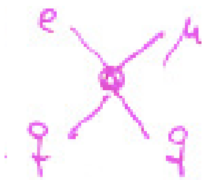
$\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2, 3$ are the neutrino mass-squared differences)

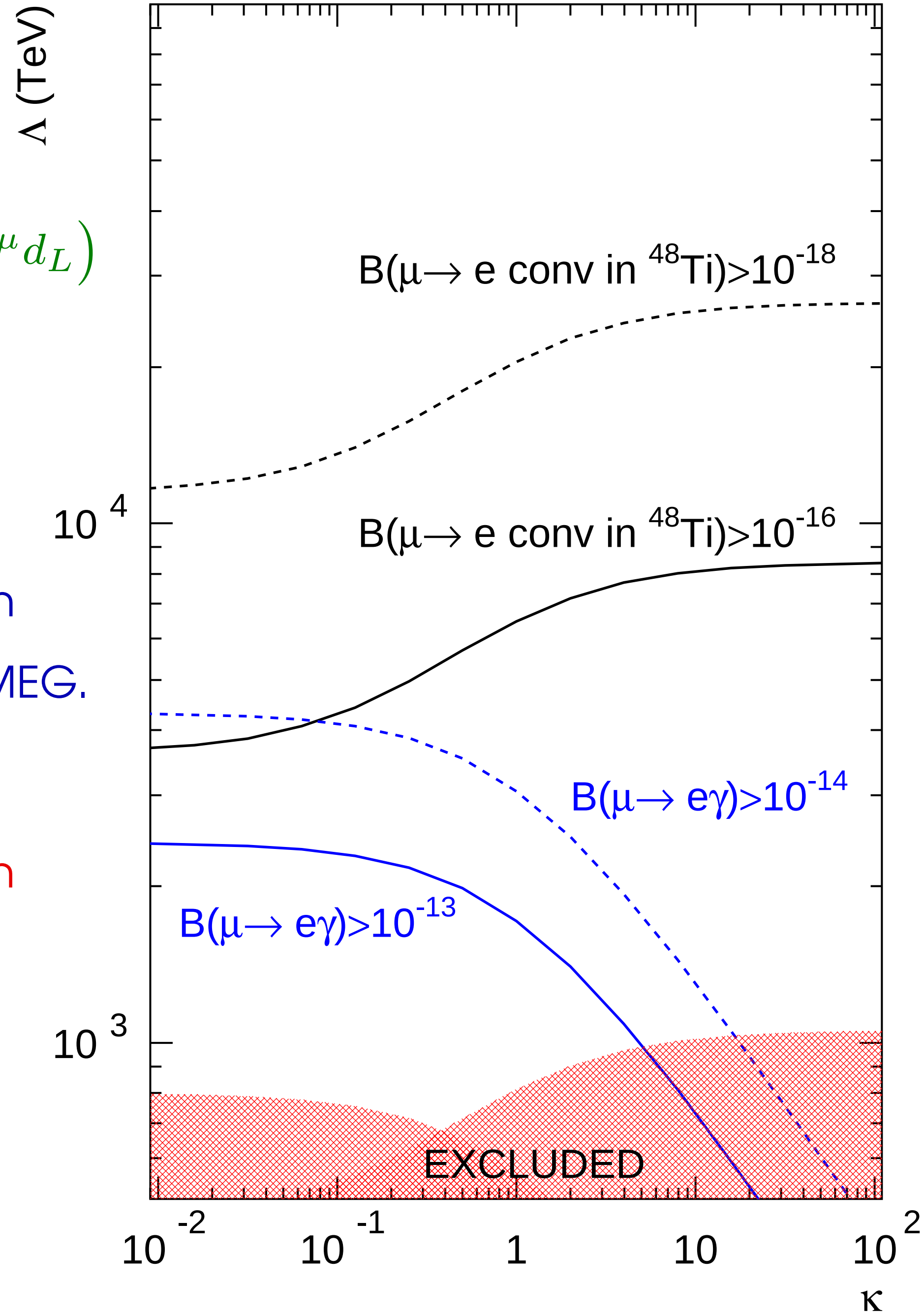


Model Independent Considerations

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

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





CONCLUSIONS

In order to figure out how nature works at the smallest distance scales, we will need a coordinated effort among the three identified Frontiers of Fundamental Science.

Here I concentrated on some of the activities I expect to see going on at Fermilab during this decade...

NEUTRINOS:

1. we have a very *successful parametrization of the neutrino sector*, and we have identified what we know we don't know → Well-defined experimental program.

2. Future neutrino program quite orthogonal to the Energy Frontier, even if we hope to learn about neutrino masses from the LHC. Neutrino experiments the "only" way to learn about lepton mixing, "only" place to look for light, new neutrinos, etc.

3. We know very little about the new physics uncovered by neutrino oscillations.
   - It could be renormalizable $\rightarrow$ "boring" Dirac neutrinos
   - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV $\rightarrow$ high energy seesaw. How can we ever convince ourselves that this is correct?
   - It could be due to very light new physics. Prediction: new light propagating degrees of freedom – sterile neutrinos
   - It could be due to new physics at the TeV scale $\rightarrow$ either weakly coupled, or via a more subtle lepton number breaking sector. Predictions: new flavor violating phenomena, collider signatures!
4. There is plenty of *room for surprises*, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).

RARE PROCESSES (flavor violation in the lepton and kaon sectors):

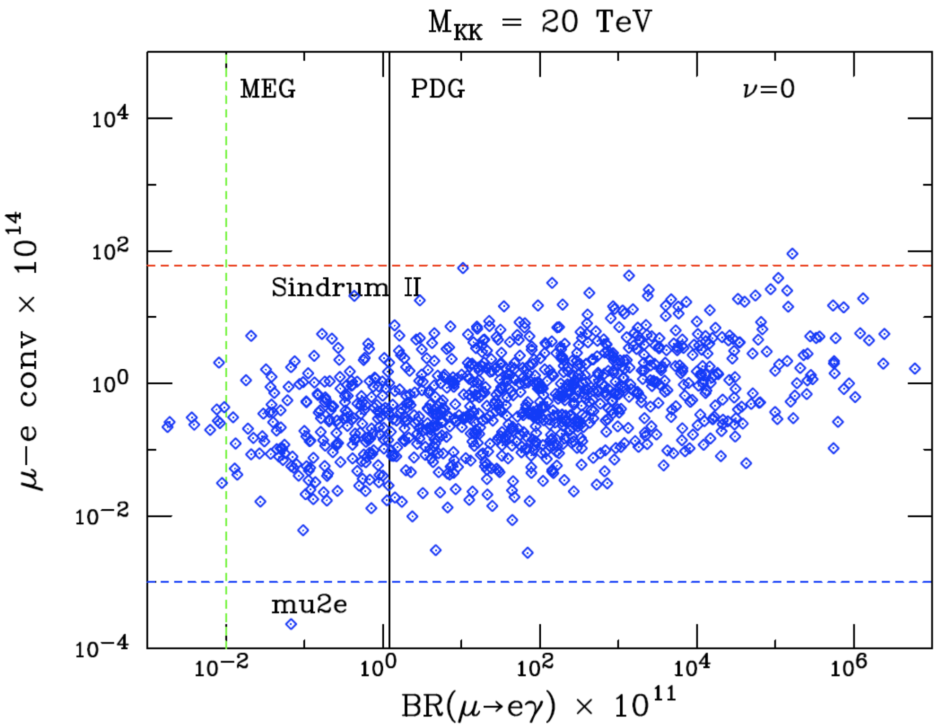
1. Rare Kaon processes may provide a window to new physics anywhere between the weak scale and 100 TeV. The SM contribution is very small and expected to be known very well.

2. We know that charged lepton flavor violation must occur. Naive expectations are really tiny in the νSM (neutrino masses too small).

3. If there is new physics at the electroweak scale, we "must" see new flavor violating phenomena (FV) "very soon". *'Why haven't we seen it yet?'*

4. Complementary to LHC and other searches for new physics. Guaranteed to learn something regardless of scenario:
   - New d.o.f. at LHC and positive signal for next-generation FV: best case scenario. Differentiate new scenarios for the new physics. Connections to neutrino masses?
   - New d.o.f. at LHC and negative signal for next-generation FV: New physics flavor blind. Why?
   - No new d.o.f. at LHC and positive signal for next-generation FV: New physics beyond the reach of LHC. Can we learn more? How?
   - No new d.o.f. at LHC and negative signal for next-generation FV: Next-next generation FV (possibly $\mu \to e$-conversion) among very few probes of new physics scales (along with neutrino oscillation experiments, astrophysics, cosmology, etc). How else do we learn more?

Backup Slides . . .

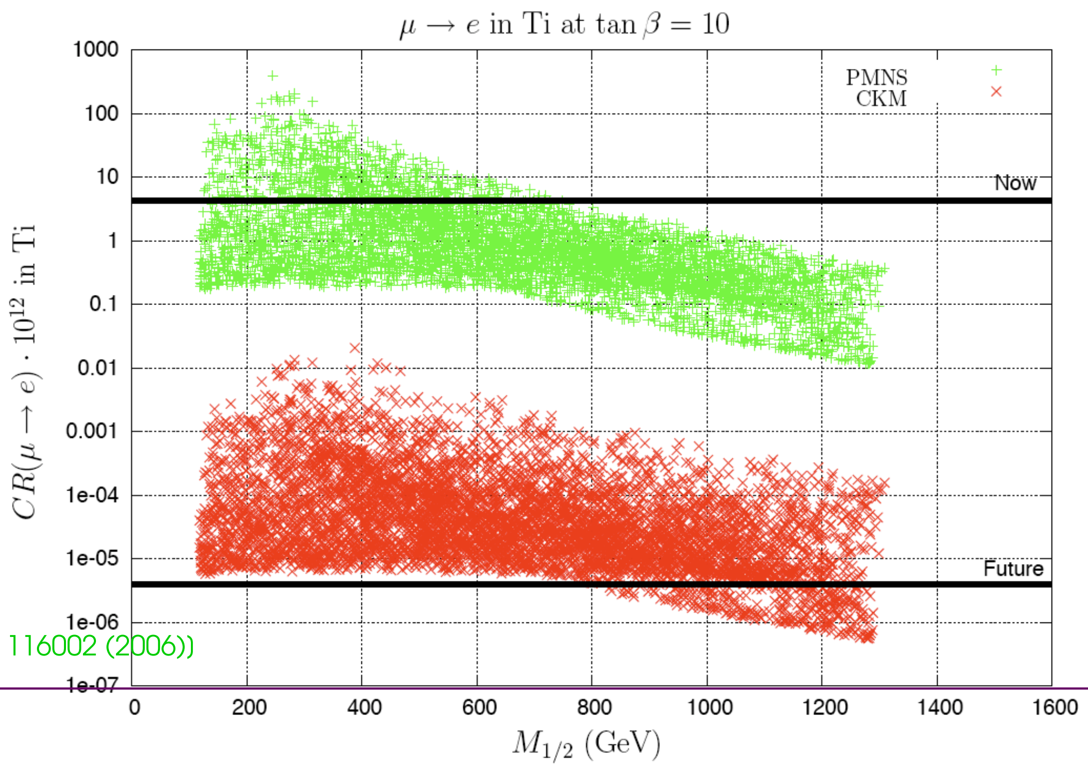


Randall-Sundrum Model

(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)



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

SUSY GUT

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

Why are Neutrino Masses Small? – Different Possibilities!

If $\mu \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{2\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

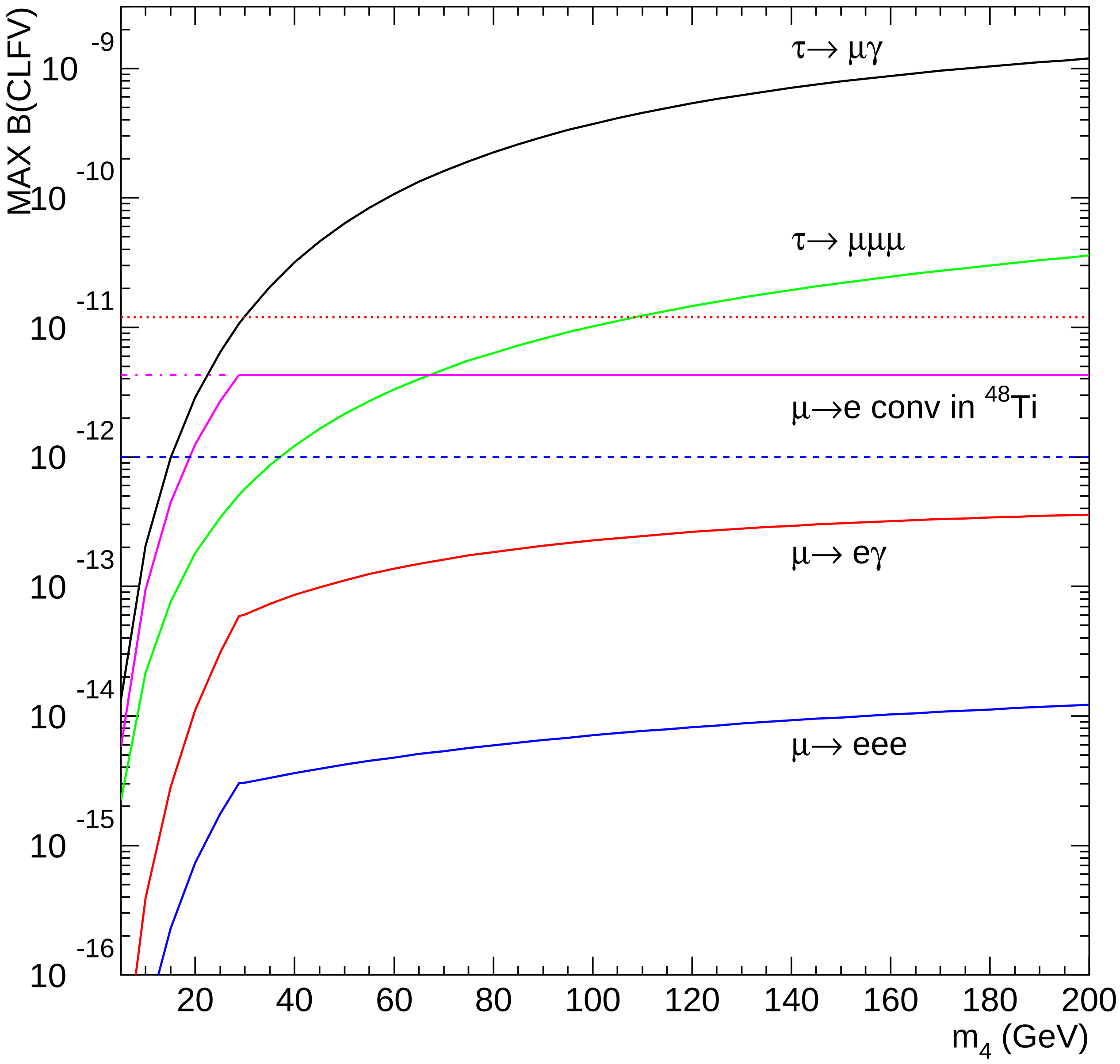
In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

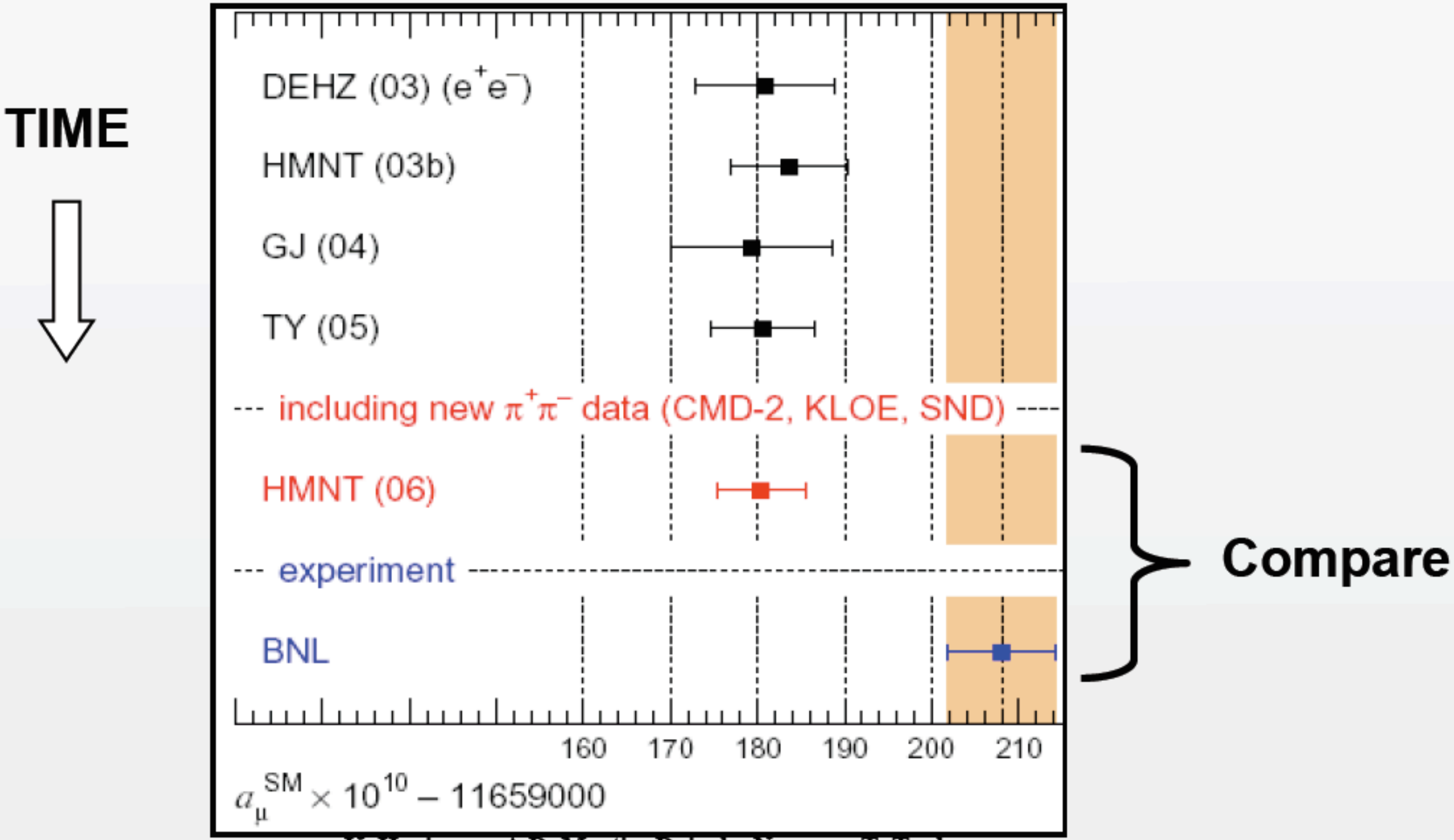
e.g.: SeeSaw Mechanism (minus "Theoretical Prejudice")



arXiv:0706.1732 (hep-ph)

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

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



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