Intensity Frontier Physics with a Mega-Watt Proton Source

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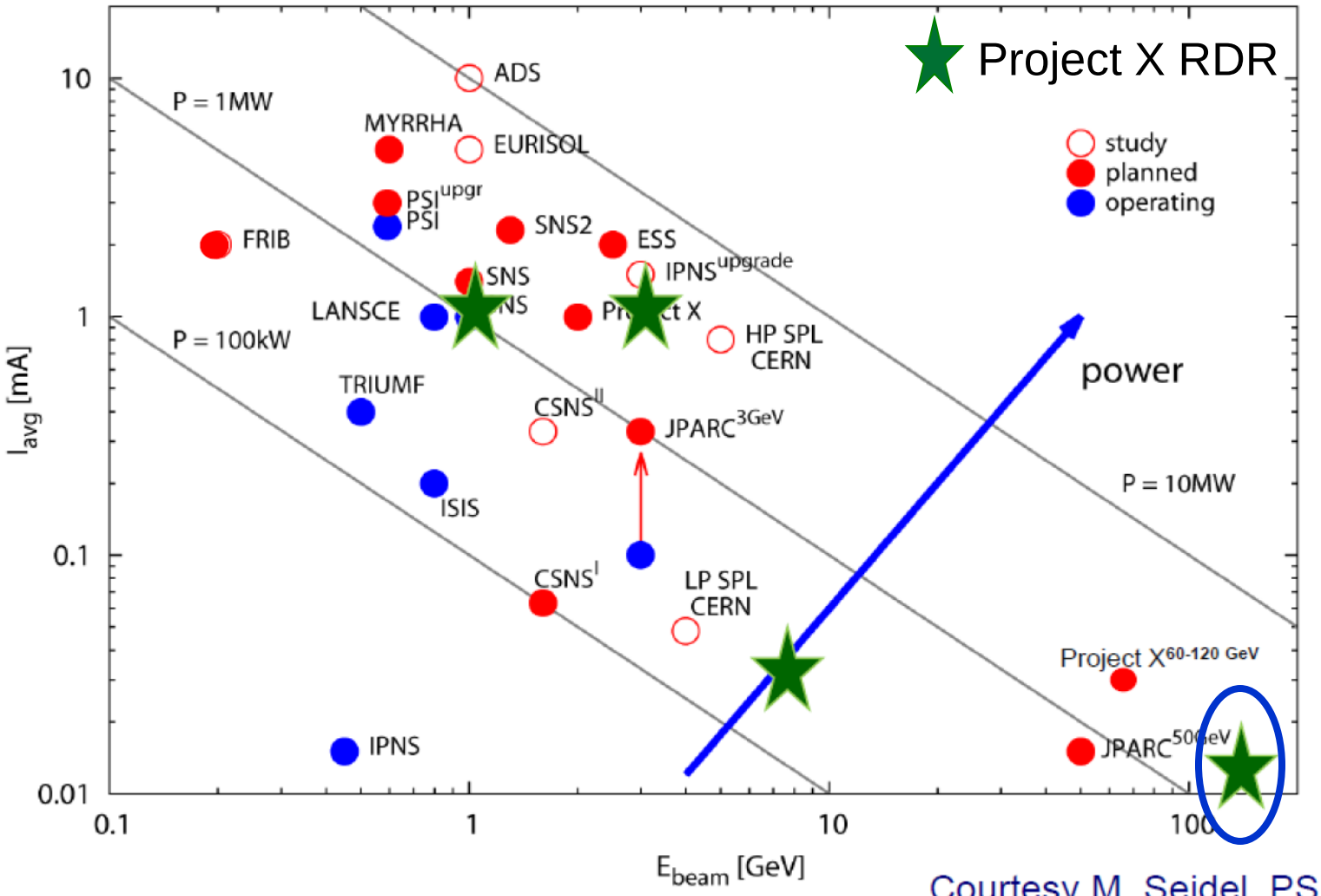
Project-X: A Mega-Watt Proton Source

- Proposal to evolve the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.

Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…



Courtesy M. Seidel, PSI

The Project-X Research Program

- ***Neutrino experiments***

A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating near detectors on the Fermilab site and massive detectors at distant underground laboratories.

- ***Kaon, muon, nuclei & nucleon precision experiments***

These could include world leading experiments searching for lepton flavor violation in muons, atomic, muon, nuclear and nucleon electron dipole moments (edms), precision measurement of neutron properties (e.g. n,nbar oscillations) and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Material Science and Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstrations which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems. Possible applications of muon Spin Resonance techniques (muSR). as a sensitive probes of the magnetic structure of materials .

Detailed discussion in 'The Book' Project X website

The Project-X Research Program…Redux

- ***New Forces***

  Lepton Flavor Violation (e.g. $\mu \rightarrow e$)

  Baryon Number Violation ($n \rightarrow \bar{n}$ oscillations)

  Non-standard flavor changing neutral currents

- ***New properties of matter***

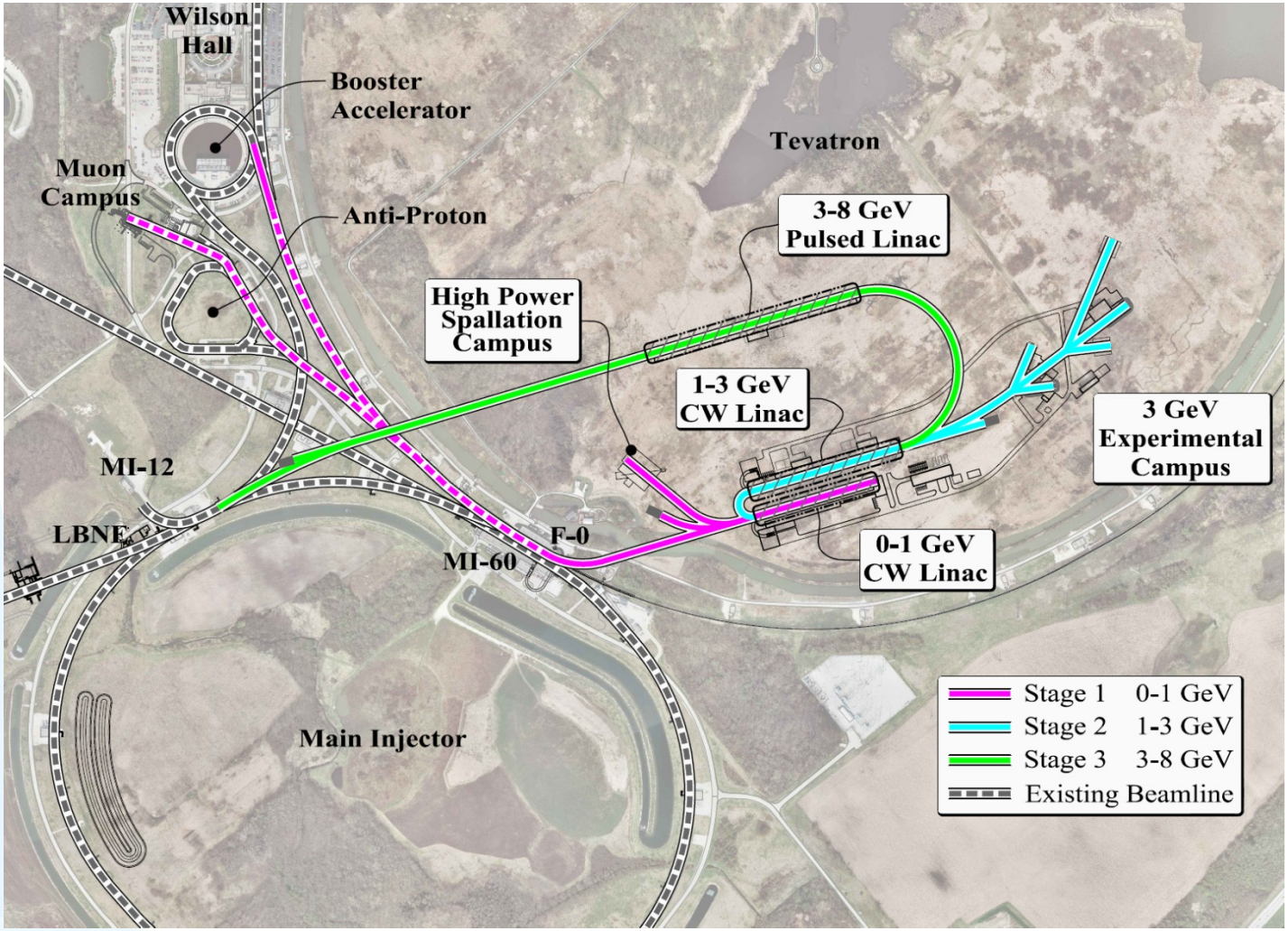
  CP violation in neutrinos, charged leptons, quarks

- ***New dimensions***

  e.g. super-symmetric amplitudes via EDMs

  Warped dimensions via kaon decays

Project X Strategy:
Simultaneous Operation of Program Elements.



Project X Research Program in the March 2013 Facilities Analysis

- "Project X experiments that compose the research program range from important to absolutely central, but scientifically the Project X research program as a whole is classified as absolutely central. Being in the planning phase, the construction readiness of the Project X research program is classified as mission and technical requirements not yet fully defined, although some experiments are beyond this phase."

Project X Book prepared for Snowmass:

- The "Project X Book", is a 3 part book describing the Accelerator Reference Design, Physics Opportunities, and Broader Research Impacts.

Part 1: Accelerator Reference Design:
http://arxiv.org/abs/1306.5022

Part 2: Physics Opportunities:
http://arxiv.org/abs/1306.5009

Part 3: Broader Impacts:
http://arxiv.org/abs/1306.5024

More than 300 contributors from the community, major contributions from Fermilab staff.

Neutrino Physics

- Strong call from the community in the Snowmass process for accelerator driven neutrino experiments.
- Project X drives more than (detector-Mass x Power). Power at lower Main Injector beam energy improves the performance of the (detector-Mass x Power) metric.
- Big boost (x3 – x10) for short-baseline experiments.
- Exploration of integrating the early stages of the Muon Accelerator Program (MAP) with Project X and LBNE.

There is no substantive competition to Project X

Rare Processes, Muons

- Project X proton drive energies (1-3 GeV T_p) are optimal for muon-to-electron conversion experiments.

- Project X beam timing is optimal for all rare muon decay experiments, muon-to-electron conversion in particular.

There is no substantive competition to Project X

Rare Processes, Kaons

- The community has embraced and is fully supportive of 1000-event $K \to \pi\nu\bar{\nu}$ experiments

- $K \to \pi\nu\bar{\nu}$ experiment concepts for Project X are the only plausible schemes to reach 1000 events

- Broad program of many other processes

There is no substantive competition to Project X

Rare Processes, EDMs

- The High Energy Physics theory community has embraced EDM research as very important research for the field
- Project X can super-charge existing EDM experiments (e.g. ^{225}Ra, ^{223}Rn)
- Project X can drive new concepts such as the proton EDM storage ring

There is no substantive competition to Project X

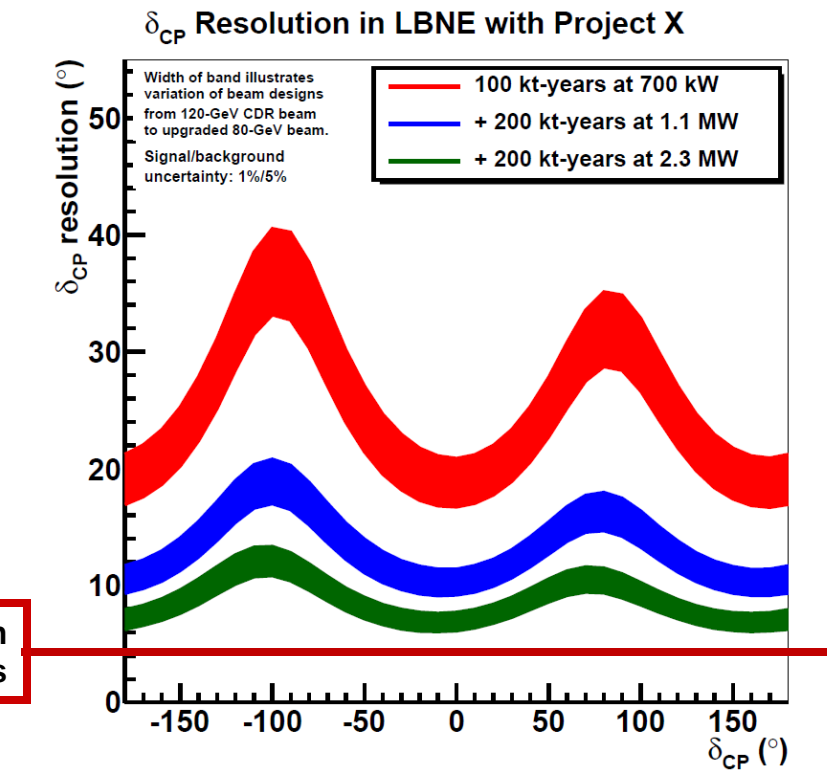
Rare Processes, Neutrons

- A neutron–antineutron oscillation experiment driven by a high power neutron spallation target can reach far beyond where massive underground detectors can ever reach for $\Delta B=2$ BSM processes.

- Neutron-edm: Project X can drive the “winning” technology of the current world-wide portfolio. The HEP experience of effective large collaborations could substantially benefit a next generation attack based in the Americas.

New properties of matter: CP & T violation research

Neutrinos: > x3 increase in the Long Baseline Neutrino Experiment (LBNE) neutrino statistics.



Electric **D**ipole **M**oments:

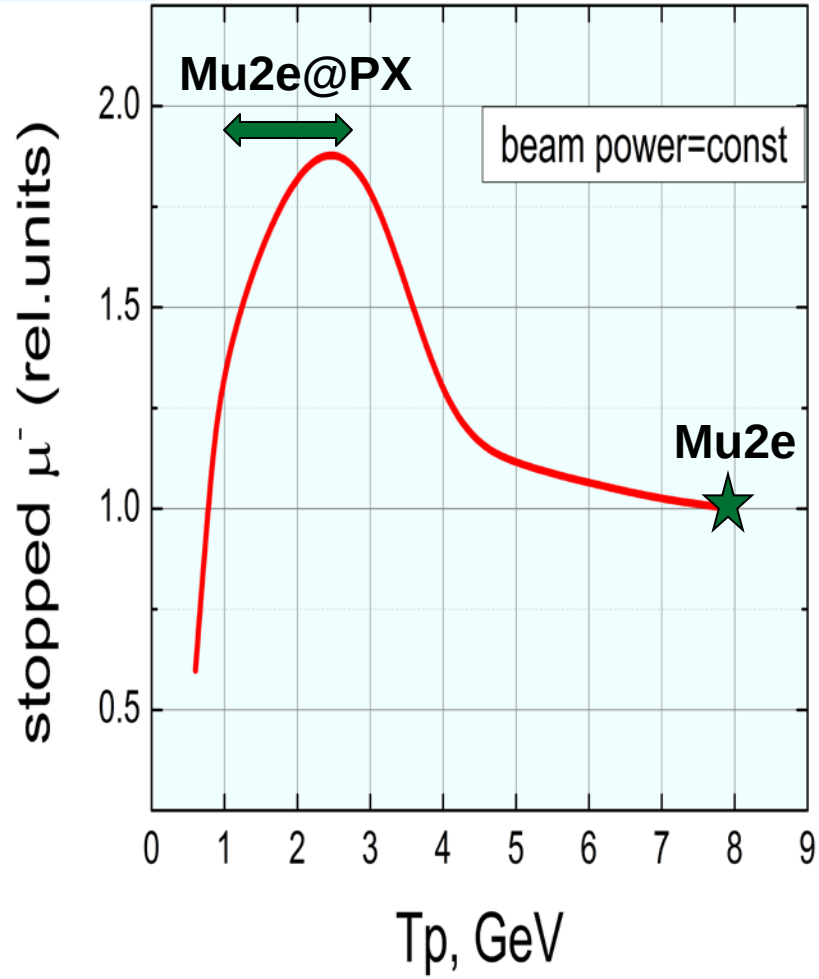
- Proton-EDM, x10^6 reach, *advanced concepts exist*
- Muon-EDM, x10^4 reach, *concepts exist*
- Neutron & Atomic EDMs x10^2 – x10^4 reach, *explorations now*

Table 2: SM predictions and current and expected limits on selected examples of EDMs.

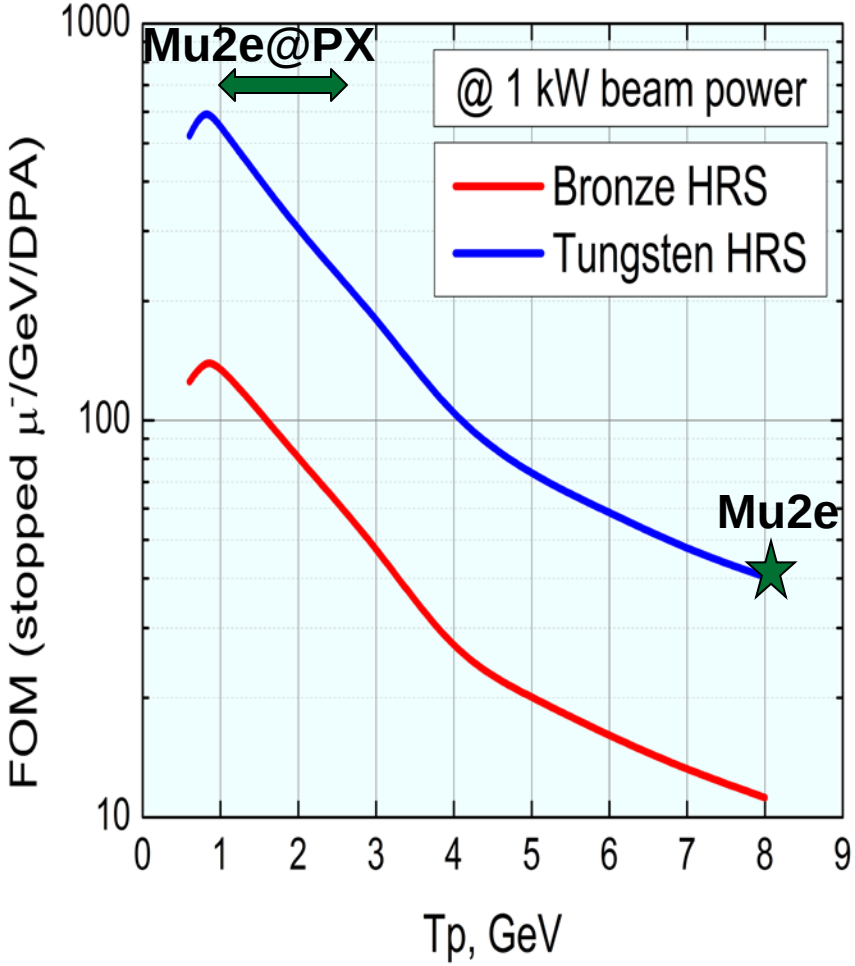
EDMs	SM	current limit	Project X
electron	$\sim 10^{-38}\,e$ cm	$1.0 \times 10^{-27}\,e$ cm	$\sim 10^{-30}\,e$ cm
muon	$\sim 10^{-35}\,e$ cm	$1.1 \times 10^{-19}\,e$ cm	$\sim 10^{-23}\,e$ cm
neutron	$\sim 10^{-31}\,e$ cm	$2.9 \times 10^{-26}\,e$ cm	$\sim 10^{-29}\,e$ cm
proton	$\sim 10^{-31}\,e$ cm	$6.5 \times 10^{-23}\,e$ cm	$\sim 10^{-29}\,e$ cm
nuclei	$\sim 10^{-33}\,e$ cm (^{199}Hg)	$3.1 \times 10^{-29}\,e$ cm (^{199}Hg)	$\sim 10^{-29}\,e$ cm (^{225}Ra)

Project-X capability, described in *The Book*

New Forces: Evolution of Mu2e



V. Pronskikh et al, http://arxiv.org/abs/1306.5009



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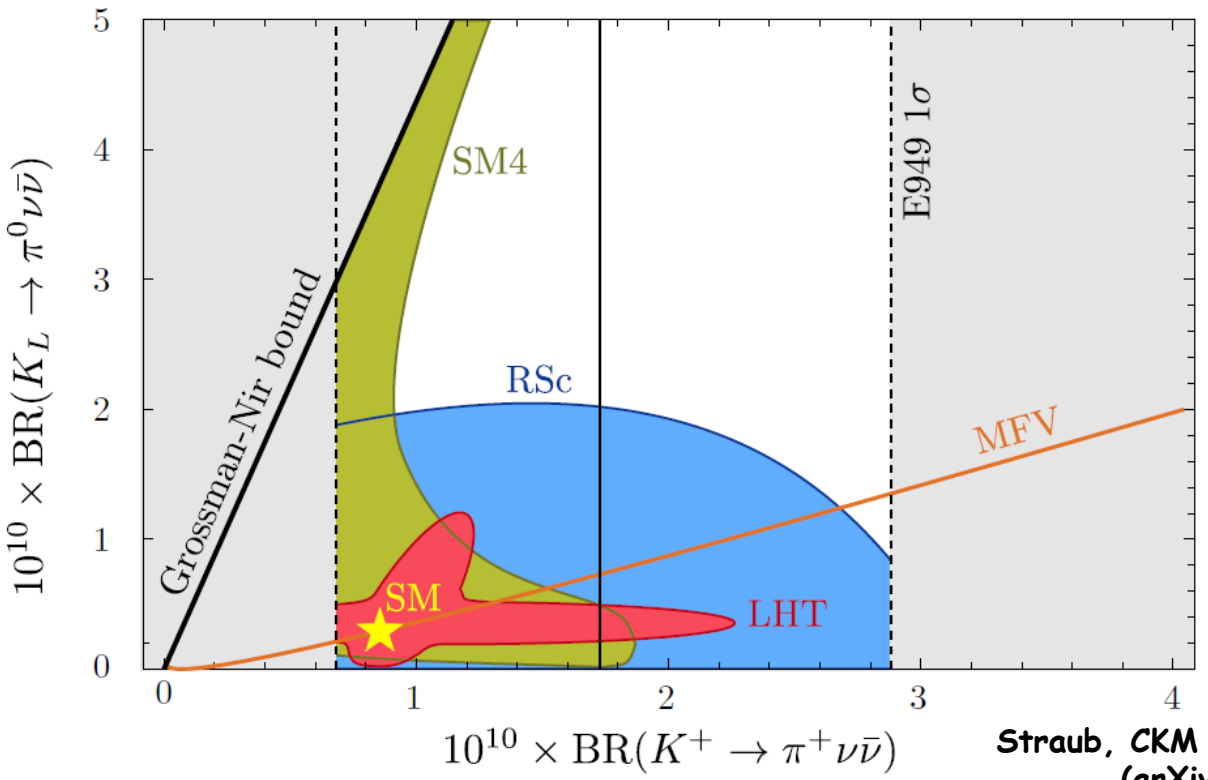
New dimensions:
Warped Extra Dimensions as a Theory of Flavor??



Buras et al. SM accuracy of <5%, motivates 1000-event experiments

Straub, CKM 2010 workshop (arXiv:1012.3893v2)

Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

Kaon Physics Reach of Project X

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	~10% at NA62 ~5% at ORKA ~2% at *Project X*
$\mathcal{B}(K_L^0 \to \pi^0 \nu\overline{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO ~5% at *Project X*
$\mathcal{B}(K_L^0 \to \pi^0 e^+ e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	~10% at *Project X*
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+ \mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	~10% at *Project X*
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at *Project X*
$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$	$2.477(1) \times 10^{-5}$	$2.488(10) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at *Project X*
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at *Project X*

Table 1-2. *A summary of the reach of current and proposed experiments for some key rare kaon decay measurements, in comparison to standard model theory and the current best experimental results. In the SM predictions for the $K \to \pi\nu\overline{\nu}$ and $K \to \pi\ell^+\ell^-$ the first error is parametric, the second denotes the intrinsic theoretical uncertainty.*

"Snowmass" (CSS2013) Quark Flavor Physics Summary

Results from Snowmass,
From the full executive summary:

- *"Execute a program with the U.S. as host that provides precision tests of the neutrino sector with an underground detector; search for new physics in quark and lepton decays in conjunction with precision measurements of electric dipole moment and anomalous magnetic moments".*

- **Neutrinos:** "Future multi-megawatt beams aimed at LBNE, such as those from Project X at Fermilab, would enable studies of CP violation in neutrino oscillations with conclusive accuracy."

- **Electric Dipole Moments:** "Project X could provide the means to make incisive EDM measurements of unprecedented precision."

- **Quark Flavor Physics:** "Each [experiment] probes a different aspect of new physics in a unique way. Project X will complement and extend results of these experiments."

Results from Snowmass, From the Intensity Frontier Summary:

- **Neutrinos:** "The U.S., with the Long-Baseline Neutrino Experiment (LBNE) and a future multi-megawatt beam from Project X at Fermilab, is uniquely positioned to lead an international campaign to measure CP violation and push the limits of the three-flavor paradigm."

- **Charged Leptons:** "The physics potential of the charged lepton experimental program is significant with discovery opportunities in experiments being conducted this decade and in even more sensitive experiments possible with future facilities such as Project X at Fermilab."

- **Quark Flavor Physics:** "Kaon decays to unprecedented precision and would retain the U.S. capability to perform quark flavor experiments. Longer term, Project X at Fermilab could become the dominant facility in the world for rare Kaon decays."

- **Neutron-antineutron oscillations:** **"**A new experiment at Project X at Fermilab uses free neutrons from a 1 MW spallation target and could improve existing constraints by 4 orders of magnitude."

Conclusions

- Next Steps: Documentation complete, closeout of the Physics Study in progress.
- Intensity Frontier science requires a broad experimental program. Breadth is not a luxury.
- The Project X Physics Study is an important resource for developing breadth of the future intensity frontier research program based on a Mega-Watt proton source.