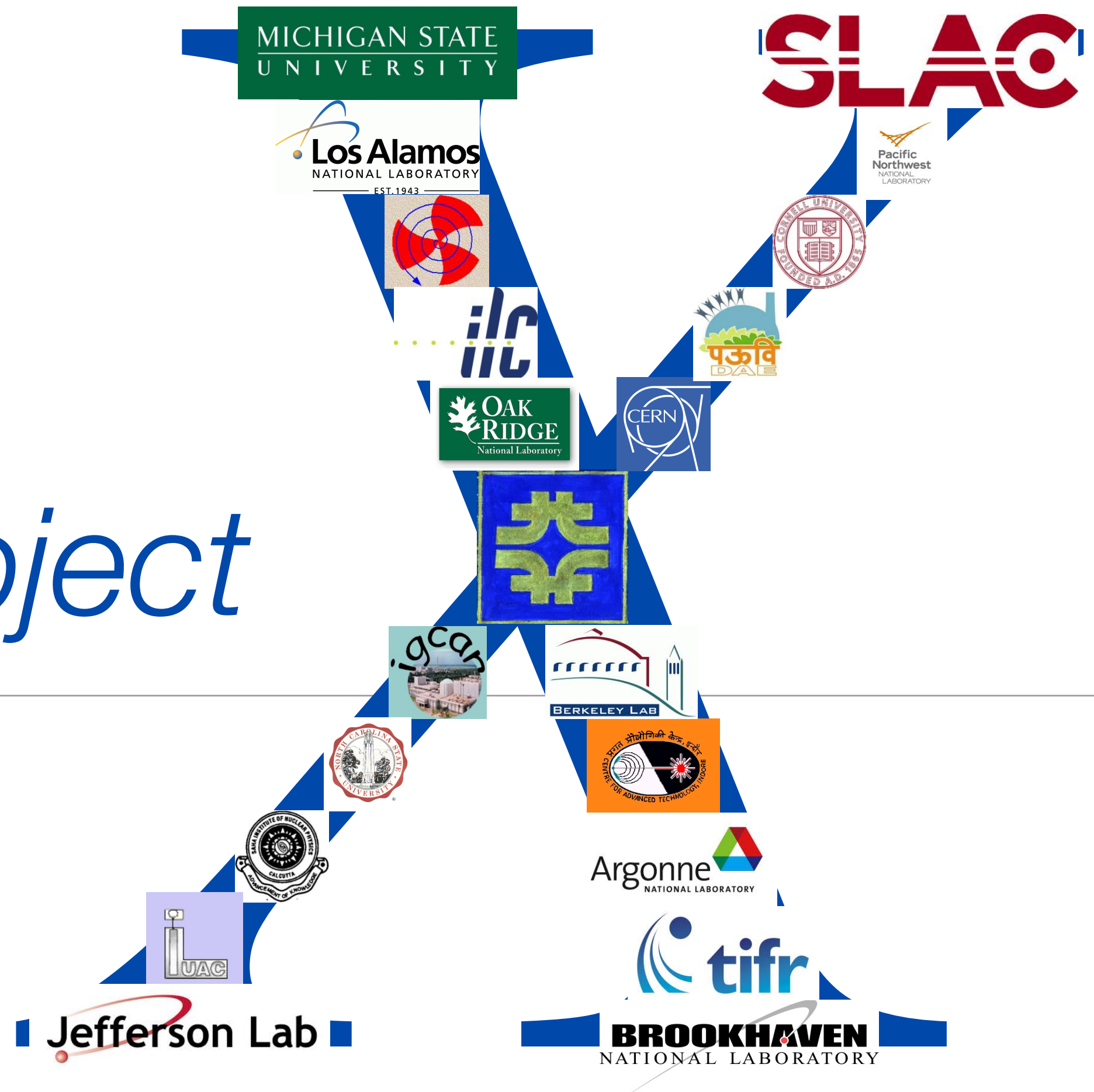


Physics with *Project*

Andreas S. Kronfeld 
February 13, 2013
HEPAP Subpanel on Facilities



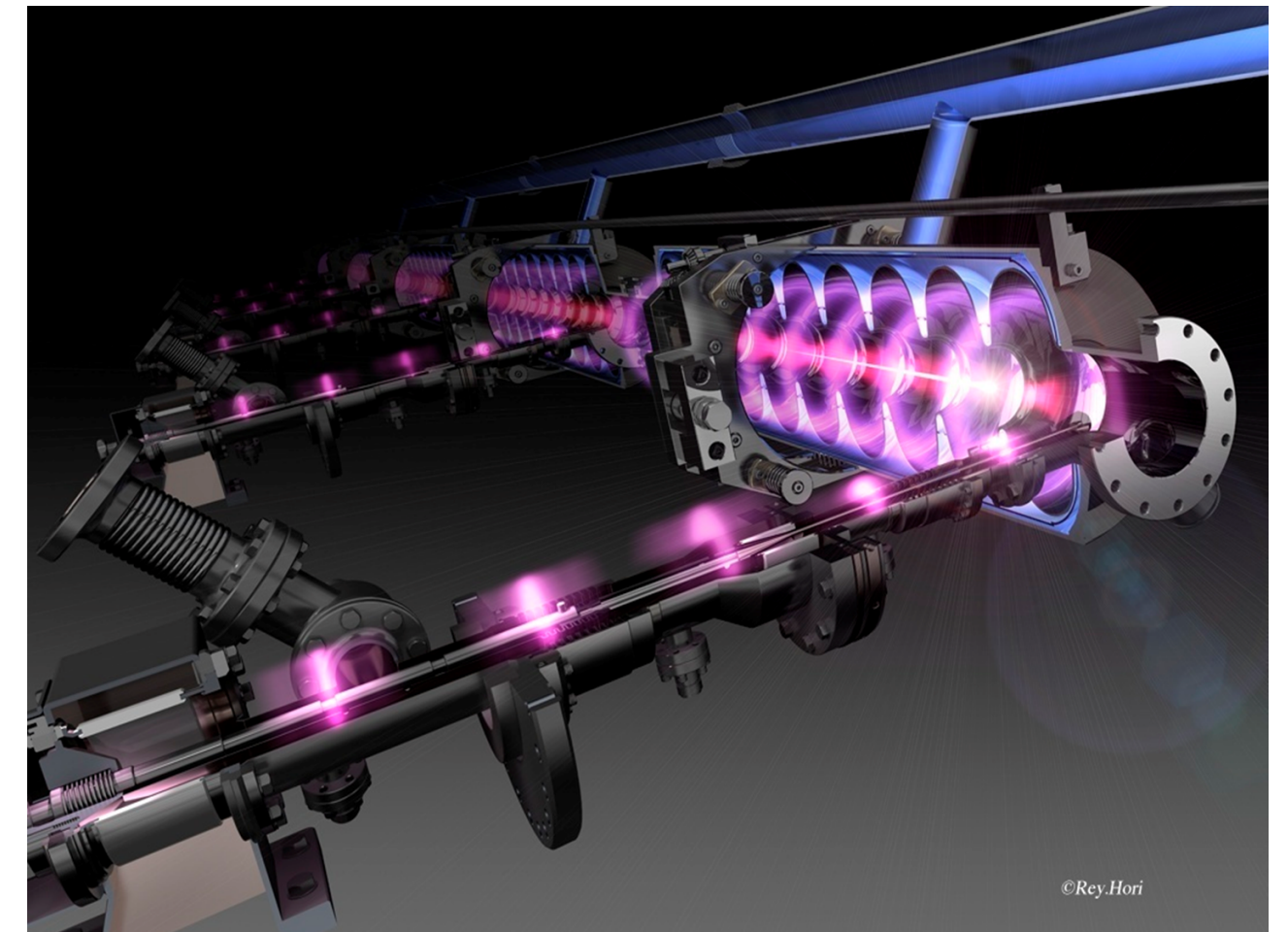
Project X Accelerator

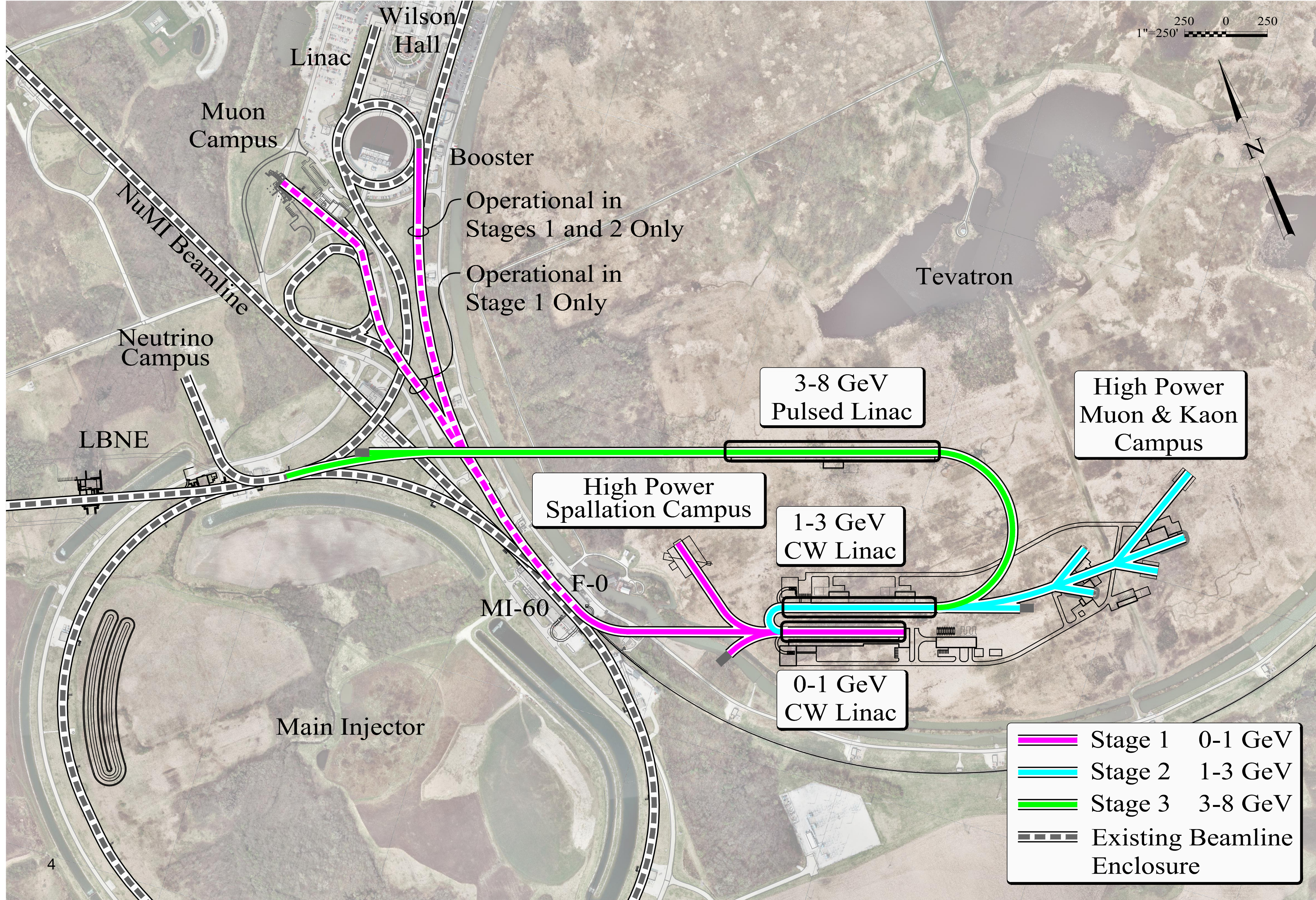
- An 8 GeV superconducting linac, to be built in stages, that dramatically increases the beam power available for a broad program of experiments.
- Each stage is affordable, improves ongoing programs, and enables new experiments:
 - **Stage 1:** 1 GeV, **1 MW, continuous wave (cw)** linac; physics opportunities on next slide.
 - **Stage 2:** 3 GeV, **3 MW, cw** linac that is optimal for $\mu \rightarrow e$ conversion on many targets; enables rare kaon decay exp'ts, e.g., the SM-pristine and BSM-sensitive $K_L \rightarrow \pi^0 \nu \bar{\nu}$.
 - **Stage 3:** 8 GeV (from 3 GeV) **pulsed linac** to replace aged booster and provide **2.4 MW** for Main Injector experiments (at 60 & 120 GeV) as well as **170 kW** to 8 GeV-based expts.
- Eventually, **Stage 4** could upgrade to **4 MW** (MI), **3 MW** (@ 8 GeV), and **12 MW** (total), setting the stage for a neutrino factory or muon collider.

Stage 1

1 GeV, 1 MW, cw linac

- Increases beam power throughout the accelerator complex:
 - power to muon experiments (Mu2e, $g-2$) $\times 10$;
 - power to 8-GeV-based neutrino experiments (MicroBooNE) $\times 3$;
 - power to MI experiments (LBNE, SeaQuest,...) $\times 1.5$.
- Enables a suite of new (for Fermilab) experiments:
 - electric-dipole measurements;
 - ultracold neutrons, e.g., $n-\bar{n}$ oscillations.





Example Power Staging Plan



Program \ Stage	Present complex w/ Proton Improvement Plan	Stage 1 1 GeV CW Linac	Stage 2 3 GeV CW Linac	Stage 3 Project X RDR	Stage 4 (beyond RDR)
Main Injector neutrino	470–700 kW**	515–1200 kW**	1200 kW	2450 kW	2450–4000 kW
8 GeV neutrino	15 kW + 0–50 kW**	0–42 kW* + 0–90 kW**	0–84 kW*	0–172 kW*	3000 kW
8 GeV muon	20 kW	0–20 kW*	0–20 kW*	0–172 kW*	1000 kW
1–3 GeV muon	none	80 kW	1000 kW	1000 kW	1000 kW
Kaon program	0–30 kW**	0–75 kW**	1100 kW	1870 kW	1870 kW
Nuclear EDMs	none	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Ultracold neutrons	none	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Nuclear technology	none	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Muon spin rotation	none	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Number of programs	4	9	9	9	9
Total maximum power	735 kW	2222 kW	4284 kW	6492 kW	11870 kW

* Operating point depends on Main Injector energy for neutrinos.

** Operating point depends on Main Injector slow-spill duty factor.

facility, facilities, *n.*

[Oxford English Dictionary]

- Opportunity, esp. of an unlimited kind, to do something.
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Experiments Exploring

- New forces in nature:
 - lepton flavor violation ($\mu \rightarrow e$);
 - baryon number violation ($n - \tilde{n}$);
 - non-Standard flavor-changing neutral currents (kaons).
- New properties of matter:
 - sources of CP violation in neutrinos, charged leptons, and quarks.
- New dimensions:
 - constraints on supersymmetric amplitudes from EDMs (superspace $d^4x d\theta d\bar{\theta}$);
 - constraints on warped dimensions from rare kaon decays (Randall-Sundrum $d^4x dy$).

The Pattern of FCNC

- Neutral flavor-changing rates take the form:

$$\Gamma = \frac{\text{couplings}}{\text{high-energy scales}} \times \text{texture} < \text{expt sensitivity}$$

where texture refers to quark masses, mixing angles, loop suppression.

- In the SM, the first factor is v^{-2} , and the texture brings in the Yukawa matrices, *i.e.*, quark or lepton masses, CKM or PMNS, and GIM.
- We do not understand where these textures come from, and no solid principle says that BSM physics should retain the SM's textures.
- Generically, a boring O(1) texture implies FCNC reach to *very* high energies. Conversely, (still unseen) physics at the TeV-scale would require a nontrivial texture to comply with flavor physics.

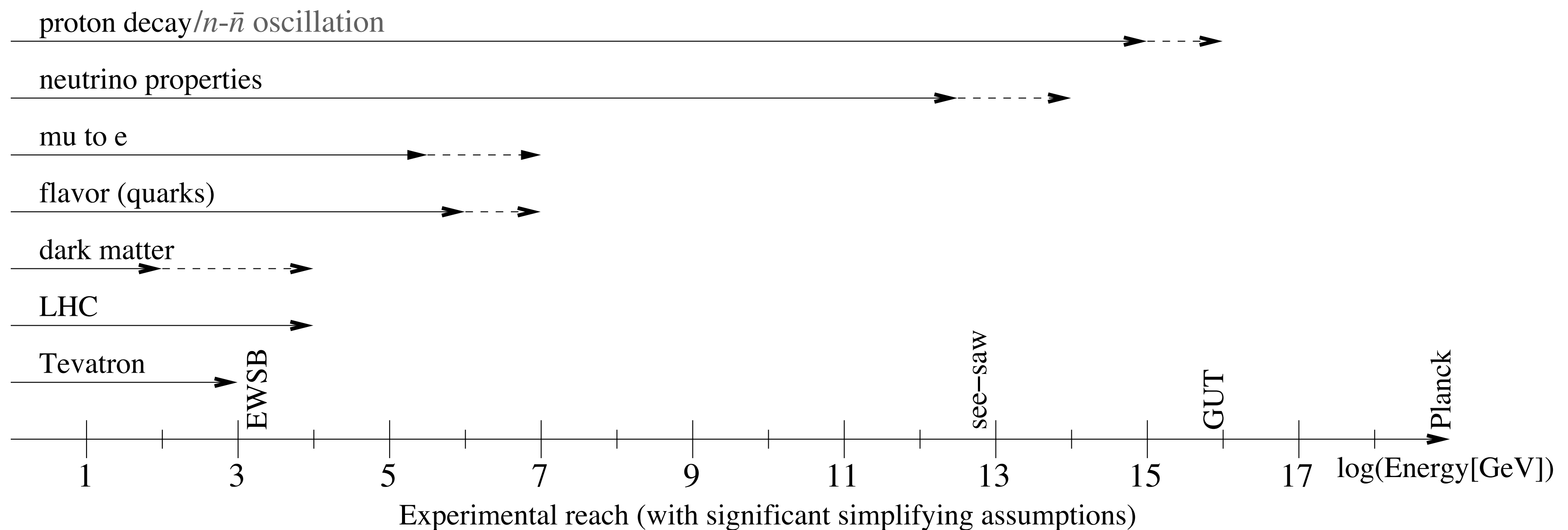
CKM



PMNS

Which path does Nature take?

- Suppose texture is boring (the *Zoltan* plot, taken from the *Grossman* talk):



- Alternatively, if LHC reveals rich TeV-scale physics, the BSM texture must be complicated; intensity-frontier experiments aid LHC measurements of BRs to complete the dossier.

Minimal Flavor Violation (MFV)

- MFV hypothesizes that the only texture(s) that appear are CKM (PMNS):
 - motivated by experience with data;
 - can suppress baryon number violation; thus, a possible alternative in susy to R parity conservation [see e.g., [arXiv:0710.3129](#)].
- Ruling out MFV (in a rich BSM context) is a discovery of a new texture.

Project X Physics Study

14–23 June 2012

Working Groups in the Project X Physics Study

- **Neutrino experiments**—Patrick Huber, André de Gouvêa , Koichiro Nishikawa, Geoff Mills, Steve Geer
 - Long- and short-baseline neutrino oscillation experiments. Non-oscillation neutrino experiments. Neutrino cross section measurement. [Summary paper](#)
- **Kaon experiments**—Vincenzo Cirigliano, Kevin Pitts
 - Rare kaon decays. Experiments with kaon beams. [Summary paper](#)
- **Muon experiments**—Graham Kribs, Bob Bernstein
 - Muon-to-electron conversion. Muon decay to electron+photon. Experiments with muon beams. [Summary paper](#)

- **Electric dipole moments**—Susan Gardner, Tim Chupp, Zheng-Tian Lu
 - Measurement of electric dipole moments of the neutron, proton, radioisotopes, ..., and related measurements. [Summary paper](#)
- **Neutron-antineutron oscillations**—Chris Quigg, Albert Young
 - Reach of neutron-antineutron oscillation experiments. [Summary paper](#)
- **Hadronic physics**—Stephen Godfrey, Paul Reimer
 - Hadron structure, including pdfs & quark content of the nucleon. Fundamental physics measurements with hadronic beams. Hadron spectroscopy.
- **Lattice QCD**—Ruth Van de Water, Thomas Blum
 - Hadronic matrix elements of $\mathcal{H}_{\text{EW+BSM}}$ for mesons and baryons. Next-generation lattice-QCD calculations such as those needed for muon $g - 2$. Computer hardware and software requirements. [Summary paper](#)

- **Tracking**—Jack Ritchie, Ron Lipton
 - Ultra-low-mass, charged-particle tracking technologies for very high rate environments. [Summary paper](#)
- **Electromagnetic calorimetry**—David Hitlin, Milind Diwan
 - "Perfect" high-energy photon detector: next-generation performance in energy, position, direction and timing measurements in a high-rate environment. [Summary paper](#)
- **Time of flight**—Bob Wagner, Mike Albrow
 - Develop field-work proposals supporting R&D for next-generation time-of-flight systems with performance better than 10 ps.
- **Neutrino detectors**—Jonghee Yoo, Kevin McFarland, Rex Tayloe
 - High-resolution measurement techniques for neutrino and exotica interactions near a high-power target. [Summary paper](#)
- **Large-area, cost-effective detectors**—Yuri Kamyshev, Mayly Sanchez
 - Large-area cost-effective detector technologies for nucleon decay and $n-\bar{n}$ oscillations.

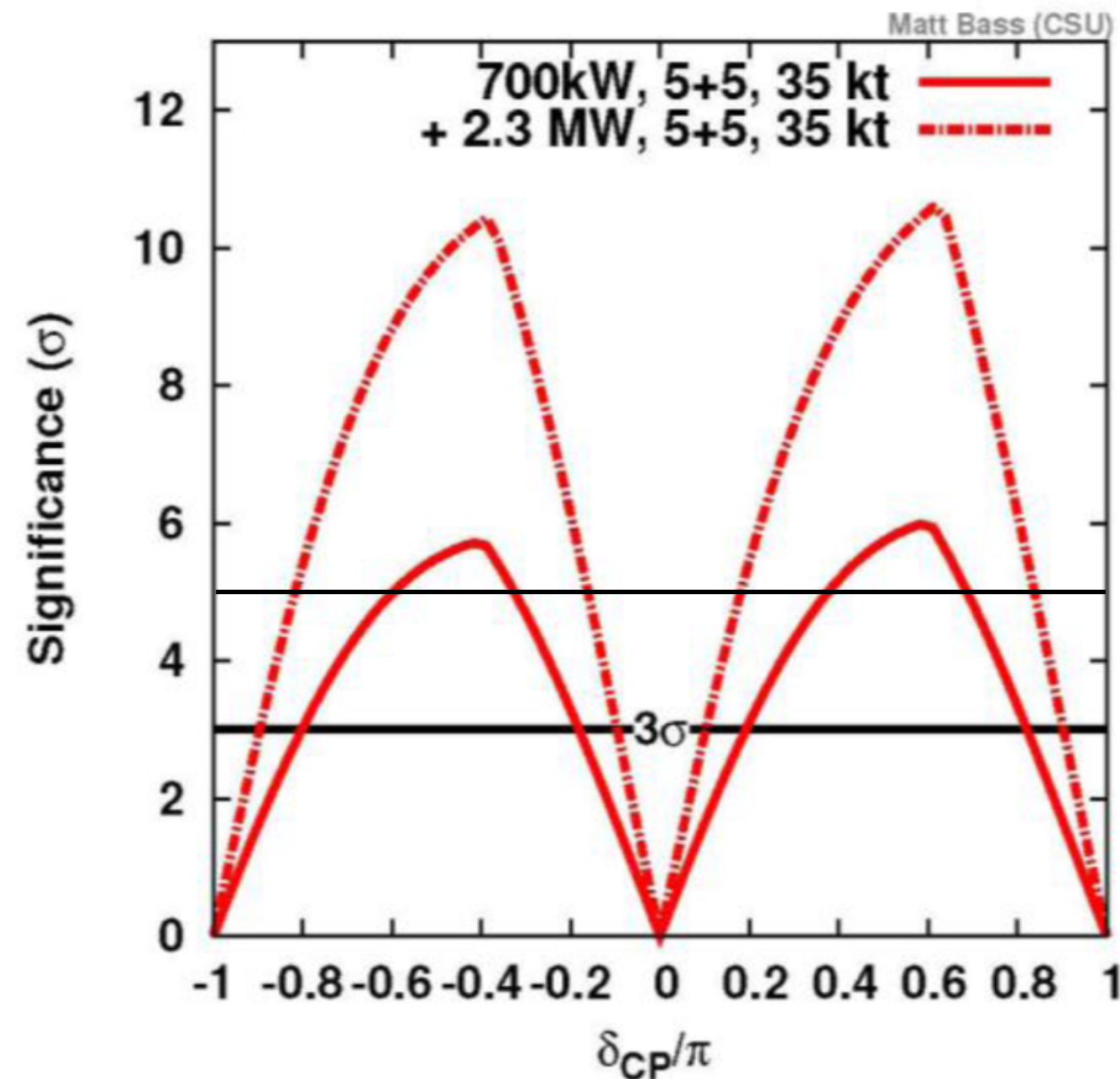
Physics with *Project X*

(Stage 1 and beyond)

Neutrinos

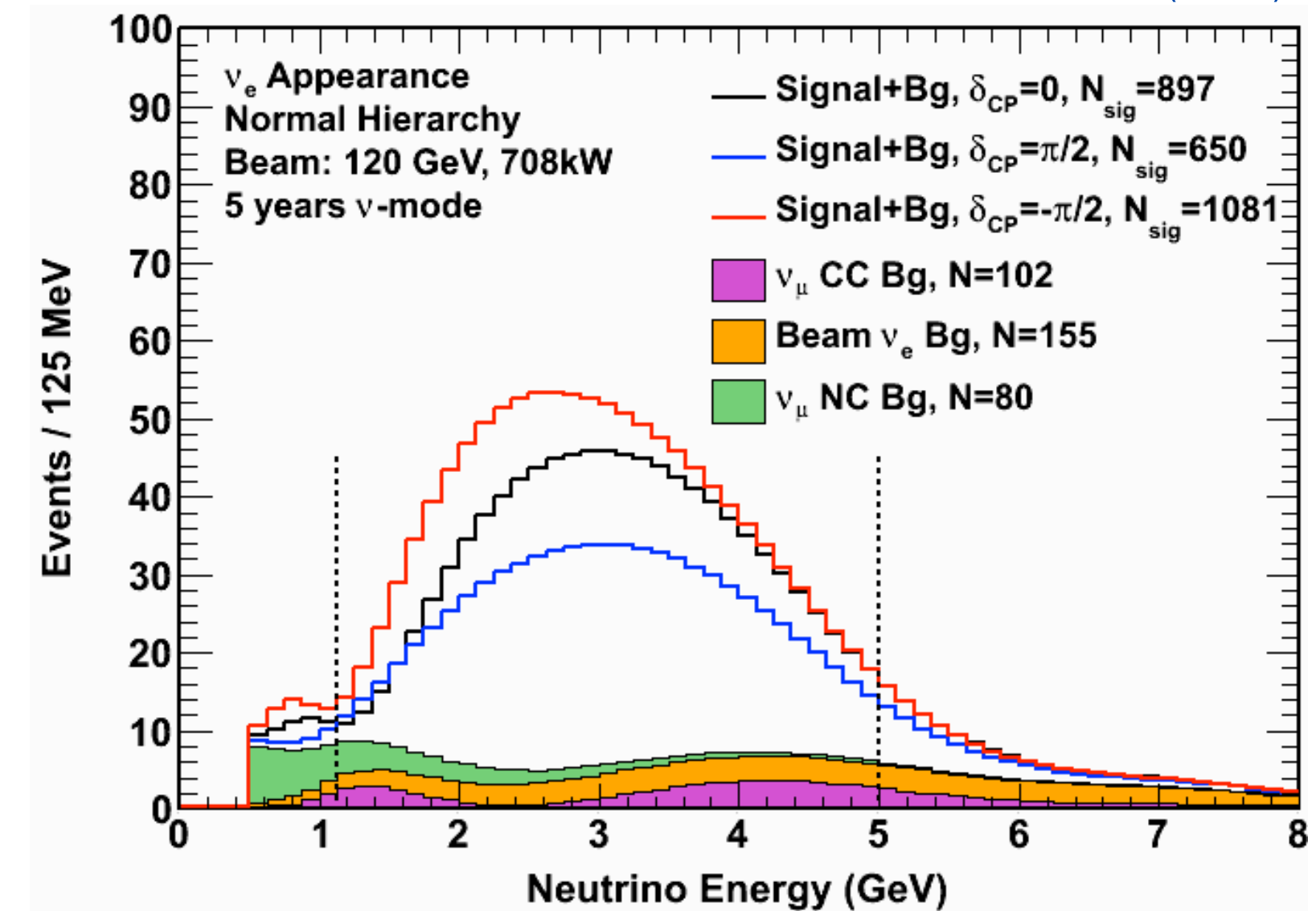
- **Project X** will dramatically increase LBNE's sensitivity to CP violation:

normal hierarchy



- With PX **Stage 2**, LBNE will profit from flexible energy choice of neutrino beam:

Z. Isvan (BNL)

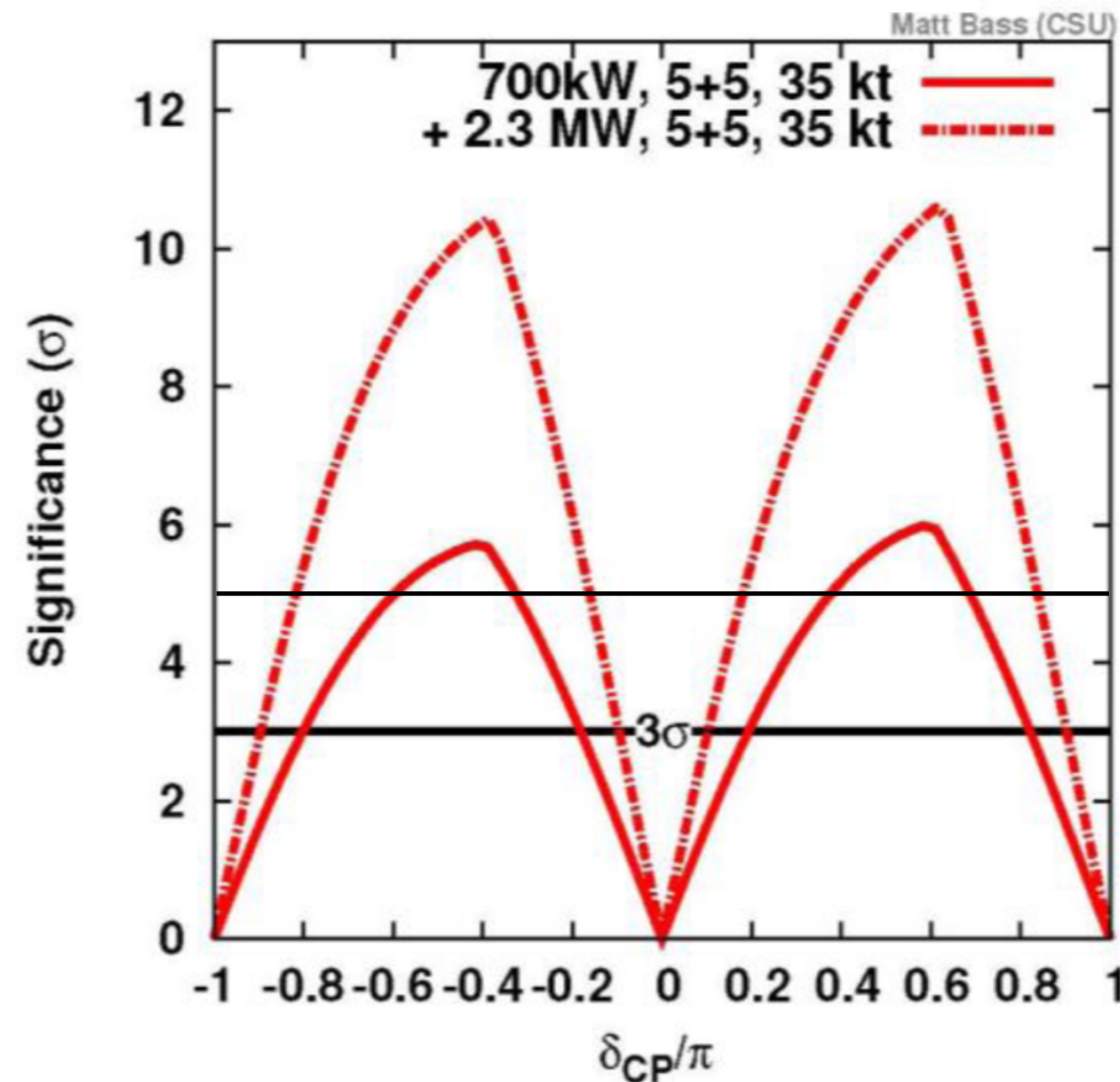


- PX **Stage 1** increases the power for Booster experiments $\times 3$; MI experiments $\times 1.5$.

Neutrinos

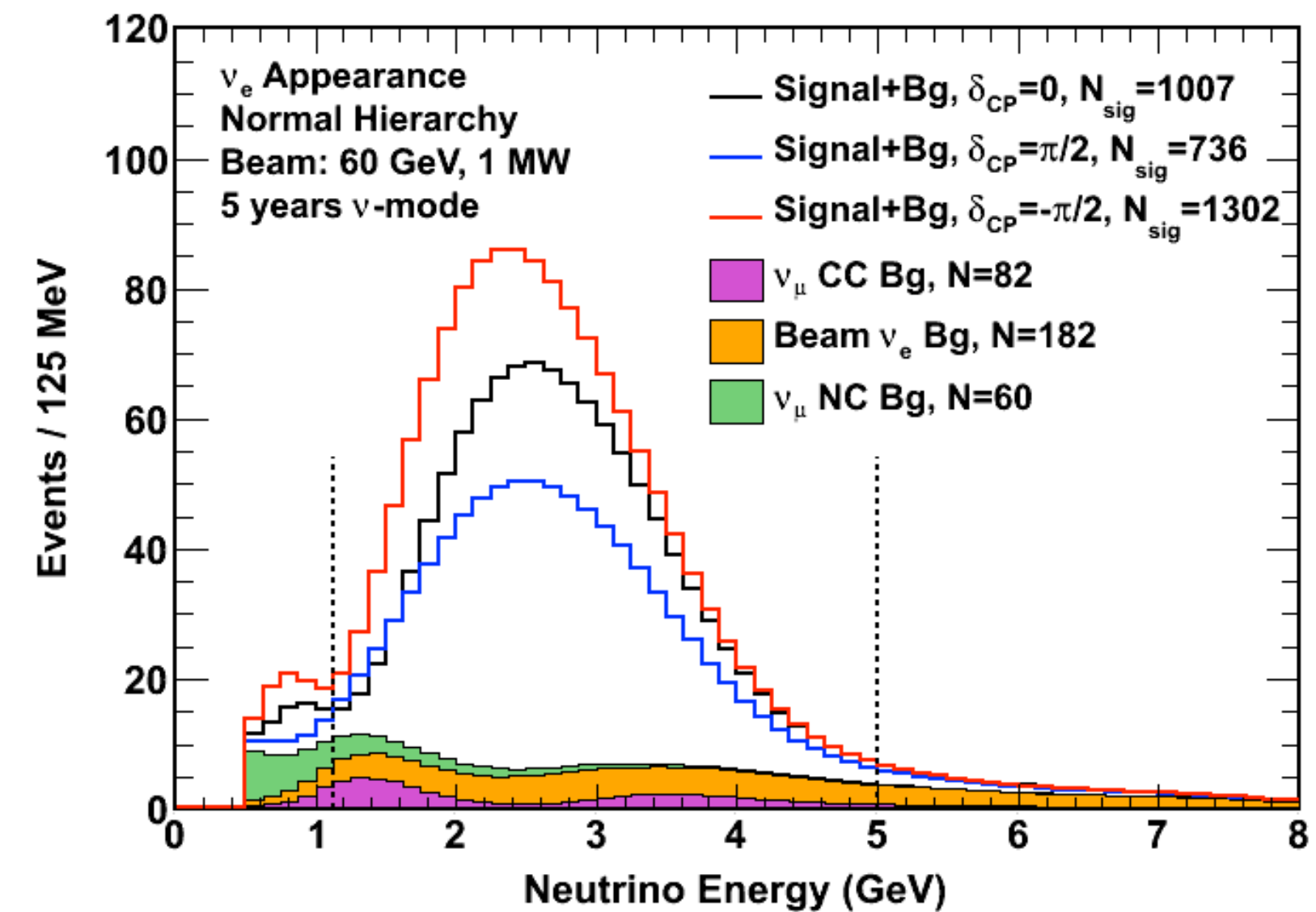
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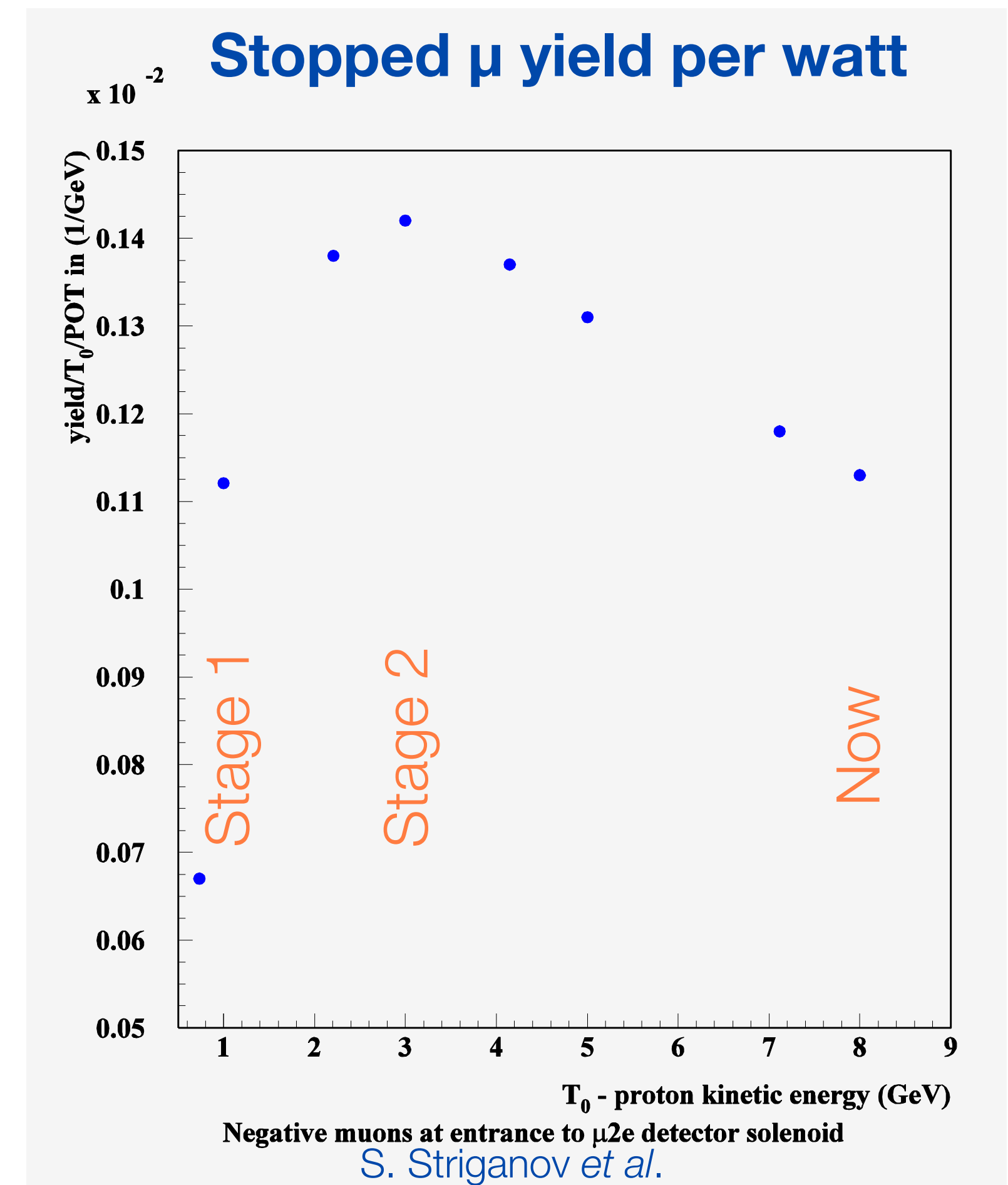
Z. Isvan (BNL)



- PX **Stage 1** increases the power for Booster experiments $\times 3$; MI experiments $\times 1.5$.

Muons: optimum beam energy for $\mu \rightarrow e$, etc.

- Stage 1 increases power to $\mu 2e \times 10$.
- The 3-GeV energy of Stage 2 is chosen to optimize muon production.
- Improved yield, combined with intensity, enables runs on many target nuclei:
 - different sensitivity [[hep-ph/0203110](https://arxiv.org/abs/hep-ph/0203110)].
- Larger nuclei capture muons quickly and, thus, tolerate shorter bunch spacing
 - a key design feature of Project X!
- Lower proton energy eliminates antiproton background.

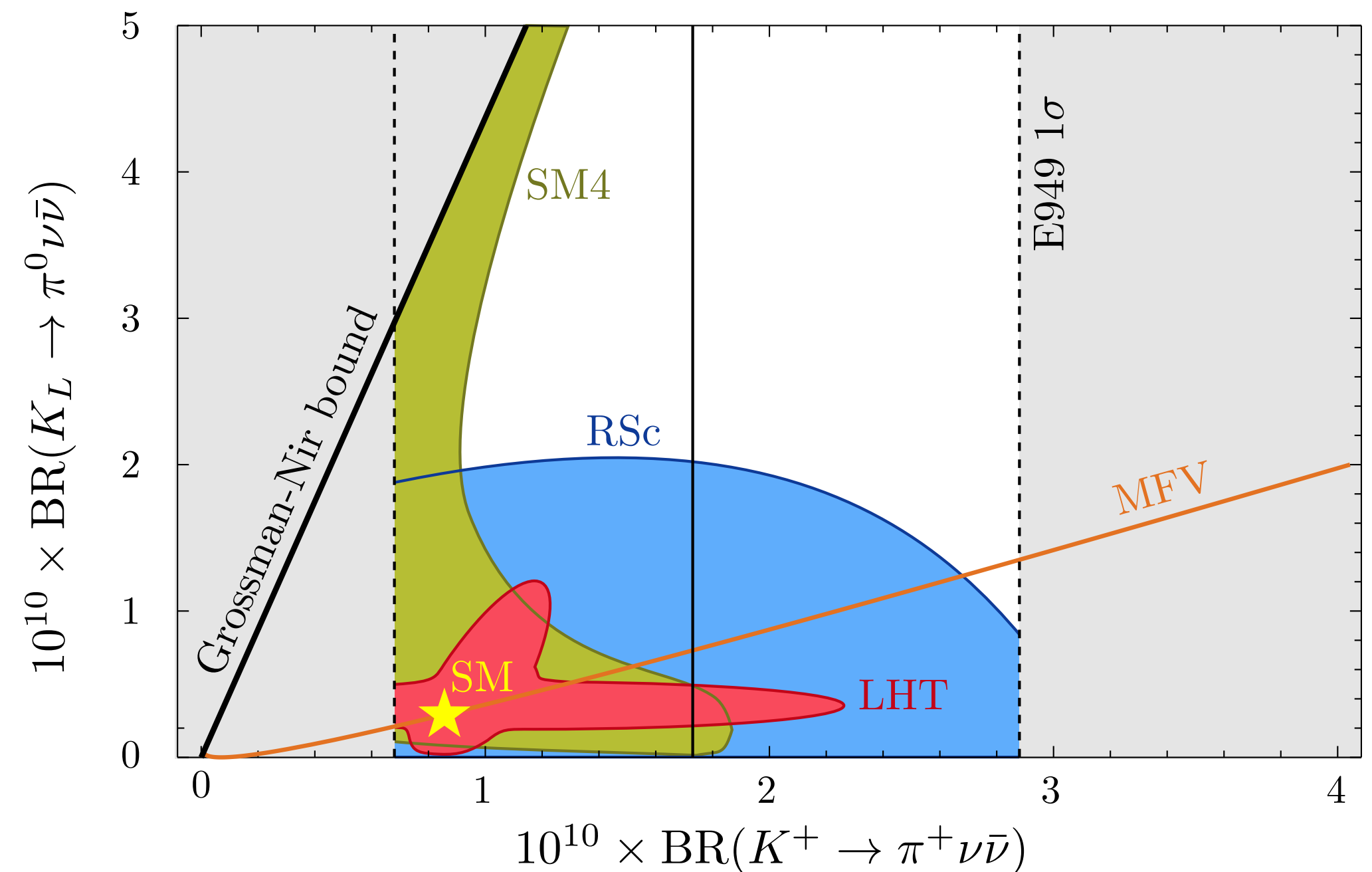


Kaons

- ORKA should collect 1000 events of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ before Project X is built.
- **Stage 2** would enable a similar collection of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events:
 - “this experiment was made for Project X” —Laurie Littenberg;
 - “Project X was made for this experiment” —theorists.
- Other modes in a K_L experiment:
 - FCNCs $K_{L/S} \rightarrow \pi^0 \ell \ell, K_L \rightarrow \gamma \gamma$
 - LFV $K_L \rightarrow \mu e$
- Modes for a future K^+ experiment:
 - T violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$
 - Nonuniversality in $\frac{\Gamma(K^+ \rightarrow e^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)}$

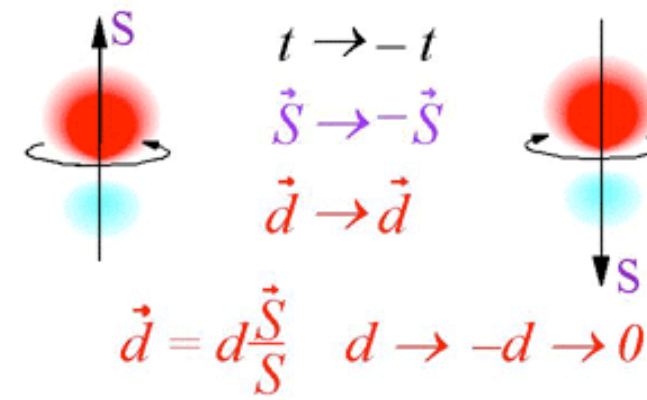
Sensitivity to New Physics

- Rare kaon decays exhibit correlations with each other and with B decays.
- ORKA (K^+ with MI) is ready to start this decade, aiming for 1000 events.
- A 1000-event K_L experiment would be part of the **Stage 2** program.
- Either could make a discovery (😊).
- Together, the measurements would kill models (😞) and/or diagnose the flavor structure of new LHC particles (😊).



[D. Straub \[arXiv:1012.3893\]](#)

Electric Dipole Moments



exciting prospect for [Stage 1](#)

- The electric dipole moment couples spin to electric fields:
 - T odd, so, in a CPT -invariant world, a signal of new CP violation (as needed for baryons).
- [Project X](#) will enable experiments on muon, proton, neutron, and nuclear isotopes ($\Leftarrow$ quark & electron) EDMs.
- CPV from θ term in QCD, phase of CKM matrix, phase(s) of PMNS matrix, BSM/Higgs:
 - neutron: $-\sin \theta + \text{GIM} \times \text{loop} \times \sin \delta_{KM} + \text{BSM} < 3 \times 10^{-26} \rightarrow 10^{-29}$ with [Stage 1](#);
 - proton: $+\sin \theta + \text{GIM} \times \text{loop} \times \sin \delta_{KM} + \text{BSM} < 7 \times 10^{-23} \rightarrow 10^{-29}$ with [Stage 1](#).
- Expression of Interest for a proton EDM experiment in an electrostatic storage ring.

Stage 1 EDM Sensitivities

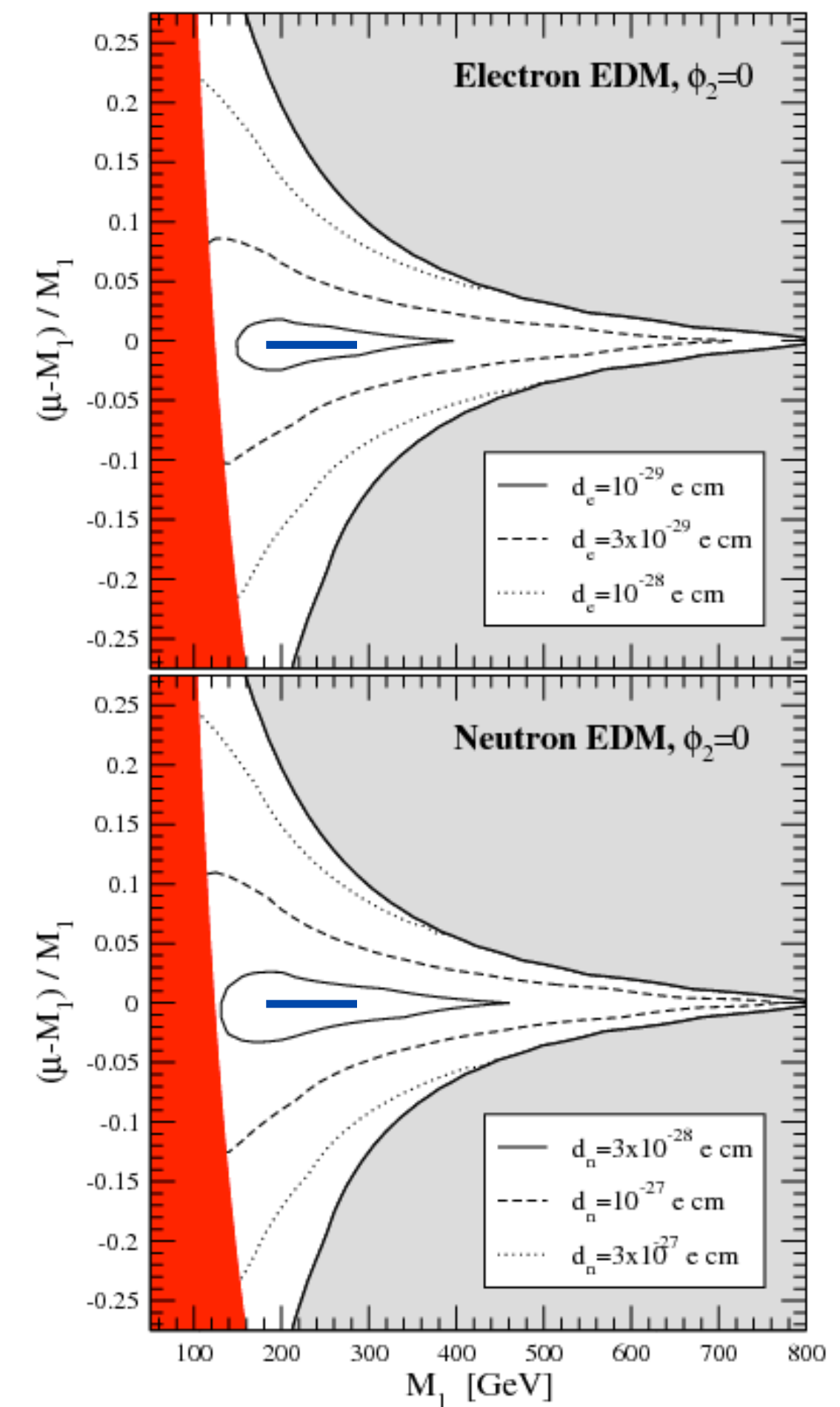
- SM predictions and current and expected limits on selected examples of EDMs.

EDMs	SM ($\sin \delta_{\text{KM}}$)	current limit	Stage 1 Project X
muon	$\sim 10^{-35} \text{ e cm}$	$1.1 \times 10^{-19} \text{ e cm}$	$\sim 10^{-23} \text{ e cm}$
neutron	$\sim 10^{-31} \text{ e cm}$	$2.9 \times 10^{-26} \text{ e cm}$	$\sim 10^{-29} \text{ e cm}$
proton	$\sim 10^{-31} \text{ e cm}$	$6.5 \times 10^{-23} \text{ e cm}$	$\sim 10^{-29} \text{ e cm}$
nuclei	$\sim 10^{-33} \text{ e cm } (^{199}\text{Hg})$	$3.1 \times 10^{-29} \text{ e cm } (^{199}\text{Hg})$	$\sim 10^{-29} \text{ e cm } (^{225}\text{Ra})$
electron	$\sim 10^{-38} \text{ e cm}$	$1.0 \times 10^{-27} \text{ e cm}$	$\sim 10^{-30} \text{ e cm}$

- Probe 3–6 orders of magnitude: opportunities for transformative discoveries.
- More info: [Project X Forum on Spallation Sources for Particle Physics](#).

Complementarity with Colliders

- EDMs are very sensitive to CP violation in the Higgs sector.
- The parameter space of the MSSM that explains the baryon asymmetry yields electron and neutron EDMs that exceed certain values (figure).
- Project X limits (10^{-30} for e ; 10^{-29} for n) would shrink the allowed region almost to nil.
- References: [hep-ph/0606298](#), [arXiv:0910.4589 \[hep-ph\]](#), [arXiv:1003.2447 \[hep-ph\]](#), [arXiv:1206.2942 \[hep-ph\]](#).
- In figures: bino mass M_1 ; Higgs-higgsino parameter μ ; **LEP susy exclusion**; not enough baryons.



V. Cirigliano et al. [arXiv:0910.4589]

Neutron-antineutron Oscillations

exciting prospect for [Stage 1](#)

- Complement to proton decay in the search for baryon-number violation.
- Can construct models with n - $\bar{n}$ oscillations but stable proton [[arXiv:1212.4556 \[hep-ph\]](#)].
- Previous limit with free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^8$ s [[Z. Phys. C **63**, 409 \(1994\)](#)].
- Previous limit with bound neutrons in ^{16}O (SuperK): $\tau_{n\bar{n}} > 2.4\text{--}3.4 \times 10^8$ s [[arXiv:1109.4227](#)].
- Expression of Interest to search for n - $\bar{n}$ oscillations at [Stage 1](#), aiming to exceed SuperK (by far) in horizontal first phase (vertical second phase): $\tau_{n\bar{n}} > 10^{10}$ s (3×10^{11} s).
- Improvements from [PX Stage 1](#) with supermirrors, vertical layout, and 4π reflective target.

Hadronic Physics

(reaching beyond particle physics)

- **Hadron structure**—*cf.* SeaQuest experiment underway now—[[Reimer talk](#)]:
 - unprecedented precision in DIS and DY will help disentangle EMC effect (nucleon structure in nuclei) and the distribution of spin in the nucleon;
 - luminosity 15 times higher than nearest competitor (RHIC *spin*).
- **Spectroscopy** [[Godfrey talk](#)]:
 - searches for glueballs and other exotics;
 - similar to COMPASS at CERN, but with more intense incident beams.

Broader Impacts

- Muon spin rotation (μ SR):
 - An established tool (complementary to light and neutron sources) to study the magnetic structure of materials important to understanding superconducting materials, emerging nanoscale and mesoscale disciplines, and the associated design of advanced materials.
- 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.
 - The spallation target (neutron source) optimized for particle physics can also serve as an irradiation resource for the study of materials important for energy applications.

Summary

- Many experiments, each illuminating a different facet of fundamental physics;
 - compare with ATLAS/CMS, which are Higgs experiments, BSM experiments, quark-flavor experiments, EW experiments, QCD experiments, even heavy-ion experiments;
 - # intensity-frontier collaboration $\sim$ # energy-frontier physics group.
- At the intensity frontier, the key is a powerful, flexible accelerator that can drive many simultaneous experiments: *Project X*.

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Acknowledgments

- Project X Physics Study conveners: Patrick Huber, André de Gouvêa, Koichiro Nishikawa, Geoffrey Mills, Steve Geer; Vincenzo Cirigliano, Kevin Pitts; Graham Kribs, Bob Bernstein; Susan Gardner, Tim Chupp, Zheng-Tian Lu; Chris Quigg, Albert Young; Stephen Godfrey, Paul Reimer; Ruth Van de Water, Tom Blum; Jack Ritchie, Ron Lipton; David Hitlin, Milind Diwan; Bob Wagner, Mike Albrow; Jonghee Yoo, Kevin McFarland, Rex Tayloe; Yuri Kamyshev, Mayly Sanchez.
- Project X Stage 1 summary document: Wolfgang Altmannshofer, Marcela Carena, Patrick Fox, Stuart Henderson, Stephen Holmes, Young-Kee Kim, Joachim Kopp, Joseph Lykken, Chris Quigg, and Robert Tschirhart.