Physics with *Project* X

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Opportunities for Polarized Physics at Fermilab

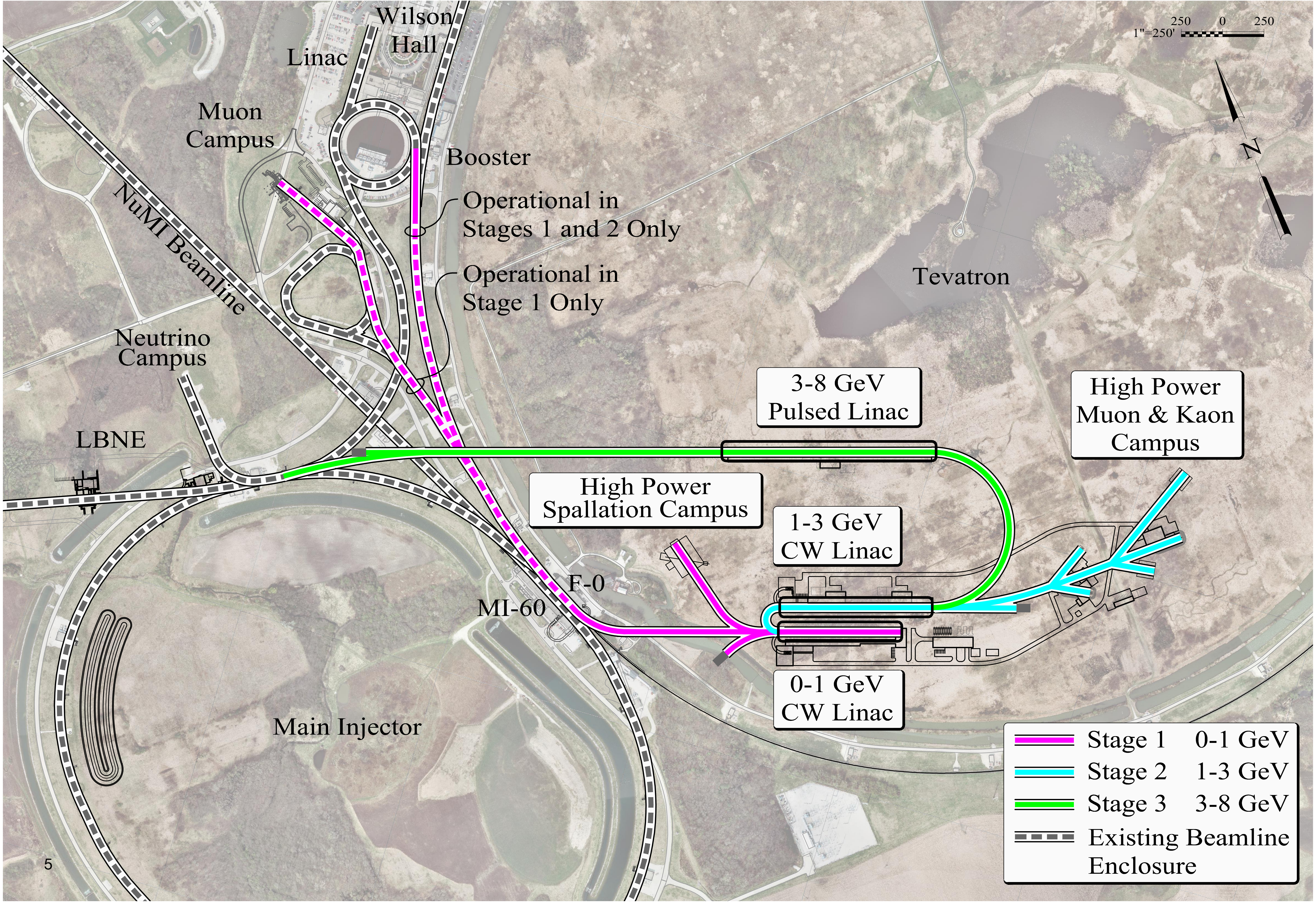
Project X Accelerator

Project X Accelerator

- An 8 GeV superconducting linac, to be built in stages.
- 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;
    - Stage 2: 3 GeV, 3 MW, cw linac;
    - Stage 3: 8 GeV (from 3 GeV) pulsed linac to replace aged booster.
- Eventually, Stage 4 could upgrade to 4 MW (MI), 3 MW (@ 8 GeV), and 12 MW (total).

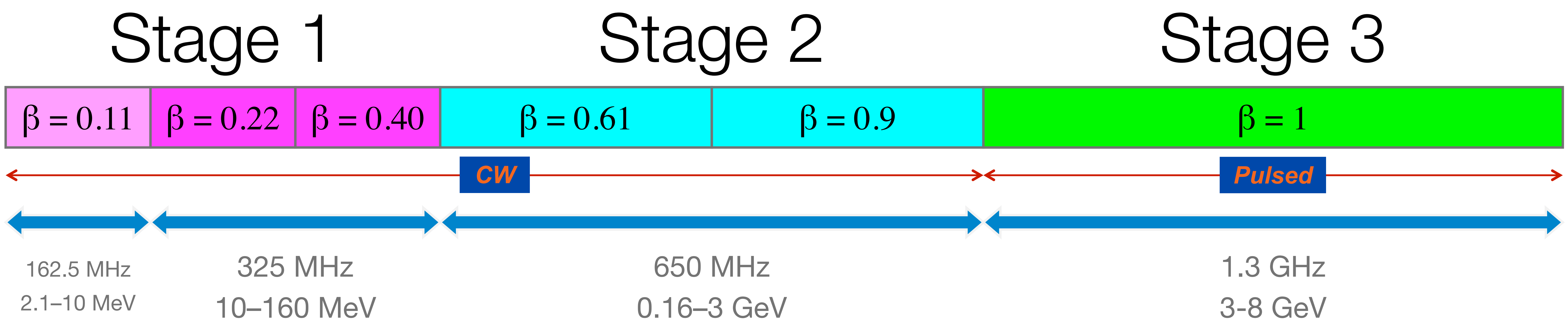
Experiments Exploring

- New forces in nature:
  - lepton flavor violation ($\mu \to e$);
  - 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 $d^4x\; dy$).

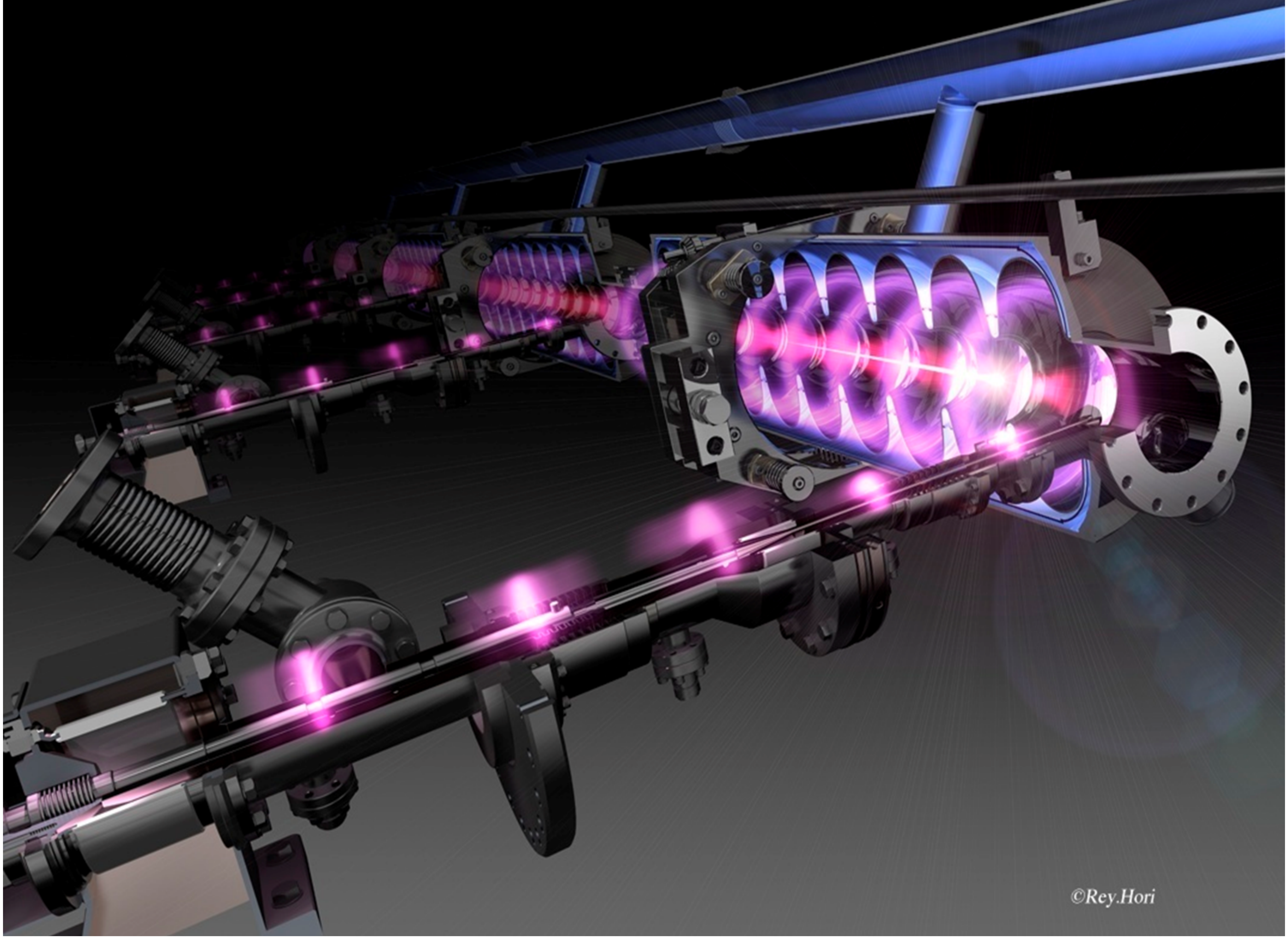

Wilson Hall
Linac
Muon Campus
Booster
Operational in Stages 1 and 2 Only
Operational in Stage 1 Only
NuMI Beamline
Neutrino Campus
LBNE
Tevatron
3-8 GeV Pulsed Linac
High Power Muon & Kaon Campus
High Power Spallation Campus
1-3 GeV CW Linac
F-0
MI-60
0-1 GeV CW Linac
Main Injector
250 0 250
1"=250'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

Project X Layout in Reference Design Report (RDR)

- Warm copper front end produces H^- and accelerates them to KE = 2.1 MeV.
- PX proper is superconducting niobium: ILC technology with modifications for $0.1 < \beta < 1$.



- Differently shaped RF cavities for each segment (slowest, slower, slow, fast, faster, fastest).
- CW stages accelerate H^-; pulsed linac accelerates naked protons.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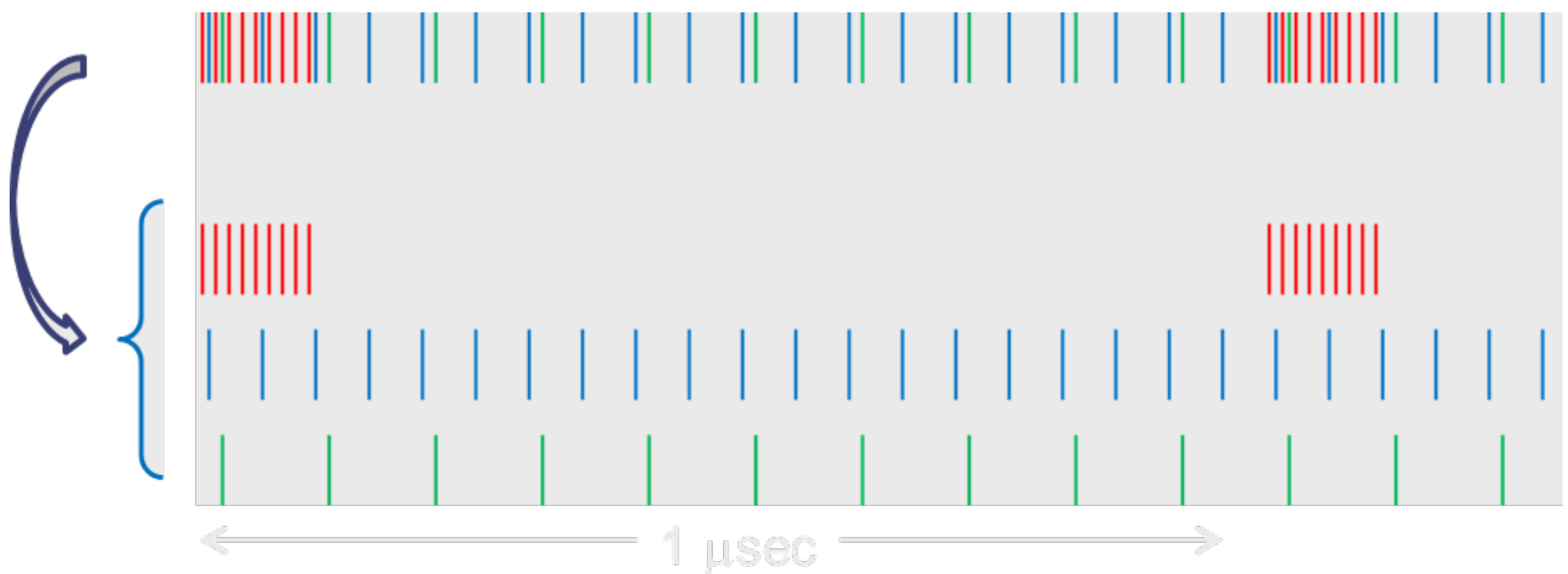
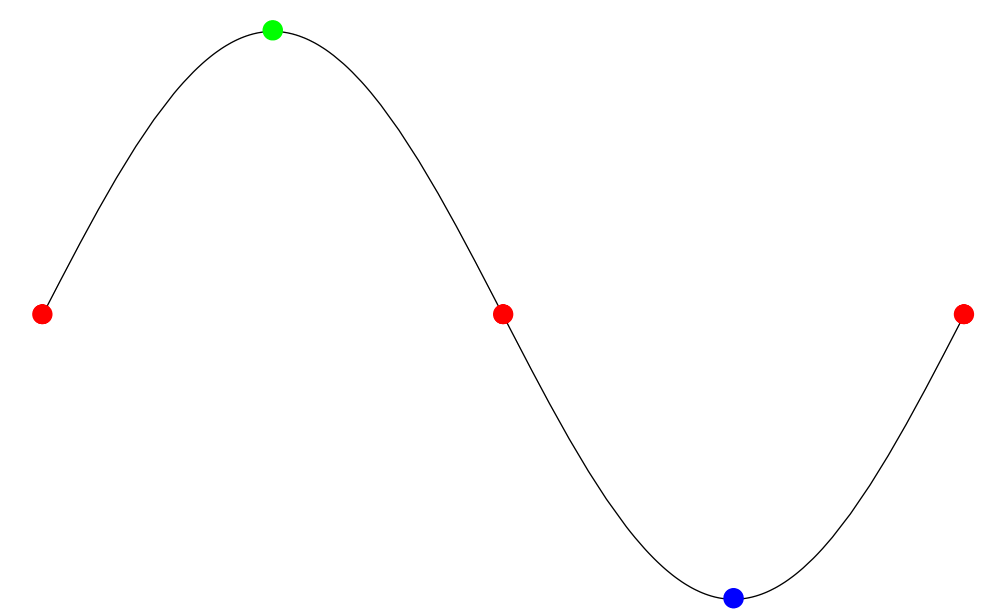
CW Enables Many Experiments

- Large 1 μs period at 1 and 3 GeV, with 80 ns substructure:
  - Muon pulses (12×10^7): 162.5 MHz, 80 ns, 700 kW;
  - Kaon pulses (12×10^7): 27 MHz, 320 ns, 1540 kW;
  - Nuclear pulses (12×10^7): 13.5 MHz, 640 ns, 770 kW;





transverse rf splitter

Example Power Staging Plan

Project X

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.

- orig. *U.S.* In *pl.*: the physical means or equipment required for doing something, or the service provide by this; freq. with modifying word, as ***educational facilities***, ***postal facilities***, ***[scientific] facilities***, etc.

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Stage 1

1 GeV, 1 MW, cw linac

- Increases beam power throughout the accelerator complex:
  - power to muon experiments (Mu2e, *g*–2) × 10;
  - power to 8-GeV-based neutrino experiments (MicroBooNE) × 3;
  - power to MI experiments (LBNE, SeaQuest,…) × 1.5.
- Enables a suite of new (for Fermilab) experiments:
  - electric-dipole measurements (*e.g.*, polarized protons);
  - ultracold neutrons, e.g., *n*-*ñ* oscillations.

Stage 2

3 GeV, 3 MW, cw linac

- Increases (again) beam power throughout the accelerator complex:
  - maintains MI power at 60 GeV, offering flexibility to neutrino experiments.
- Muon experiments— lepton flavor violation:
  - optimal for $\mu \to e$ conversion on many targets;
  - $\mu \to e\gamma$, $3e$, etc.
- Kaon experiments (× 10 over competing facilities);
  - *e.g.*, the SM-pristine and BSM-sensitive $K_L \to \pi^0 \nu\bar{\nu}$.

Stage 3

8 GeV, pulsed linac, with 2.4 MW & 170 kW at 60–120 MeV & 8 GeV

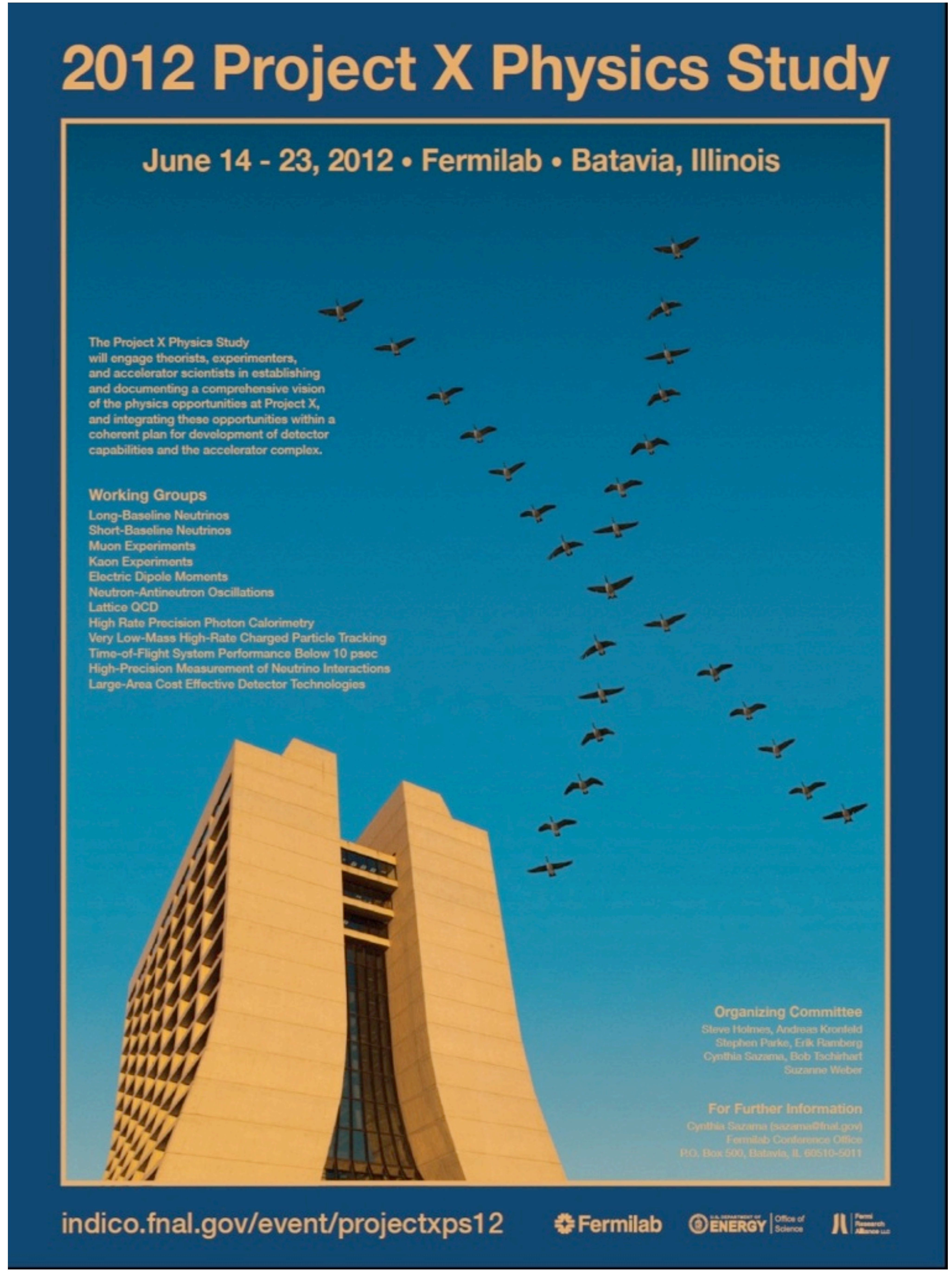
- Doubles power for Main Injector experiments:
    - 2.4 MW at 60 GeV & 120 GeV.
- Doubles power to 170 kW for 8 GeV-based experiments:
    - × 10 today's Booster.

Stage 4 (beyond RDR)

power upgrade to 4 MW & 3 MW at 60–120 MeV & 8 GeV

- Superbeams for neutrinos can be tuned to find first and second oscillation minimum.
- Another 4-5 MW still available for the 1 GeV & 3 GeV programs.
- Sets the stage for a muon storage ring, *i.e.*,
  - neutrino factory;
  - muon collider.
- Also the Fermilab accelerator complex would be a front end for a possible VLHC.

Project X Physics Study



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 measurements.
- Kaon experiments—Vincenzo Cirigliano, Kevin Pitts
  - Rare kaon decays. Experiments with kaon beams.
- Muon experiments—Graham Kribs, Bob Bernstein
  - Muon-to-electron conversion. Muon decay to electron+photon; to $3e$. Experiments with muon beams. Future opportunities for muon g–2.

- Electric dipole moments—Susan Gardner, Tim Chupp, Zheng-Tian Lu
    - Measurement of electric dipole moments of the neutron, proton, radioisotopes, ..., and related measurements.
- Neutron-antineutron oscillations—Chris Quigg, Albert Young
    - Extend reach of neutron-antineutron oscillation experiments.
- 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 $\mathscr{H}_{\mathrm{EW+BSM}}$ for mesons and baryons. Next-generation lattice-QCD calculations such as those needed for kaons, muon g – 2, mu capture, EDMs, *n*-*ñ*, neutrino scattering,…. Computer hardware and software requirements.

- Tracking—Jack Ritchie, Ron Lipton
    - Ultra-low-mass, charged-particle tracking technologies for very high rate environments.
- 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.
- 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.
- Large-area, cost-effective detectors—Yuri Kamyshkov, Mayly Sanchez
    - Large-area cost-effective detector technologies for nucleon decay and *n-ñ* oscillations.

Physics with *Project X*

(Stage 1 and beyond)

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.

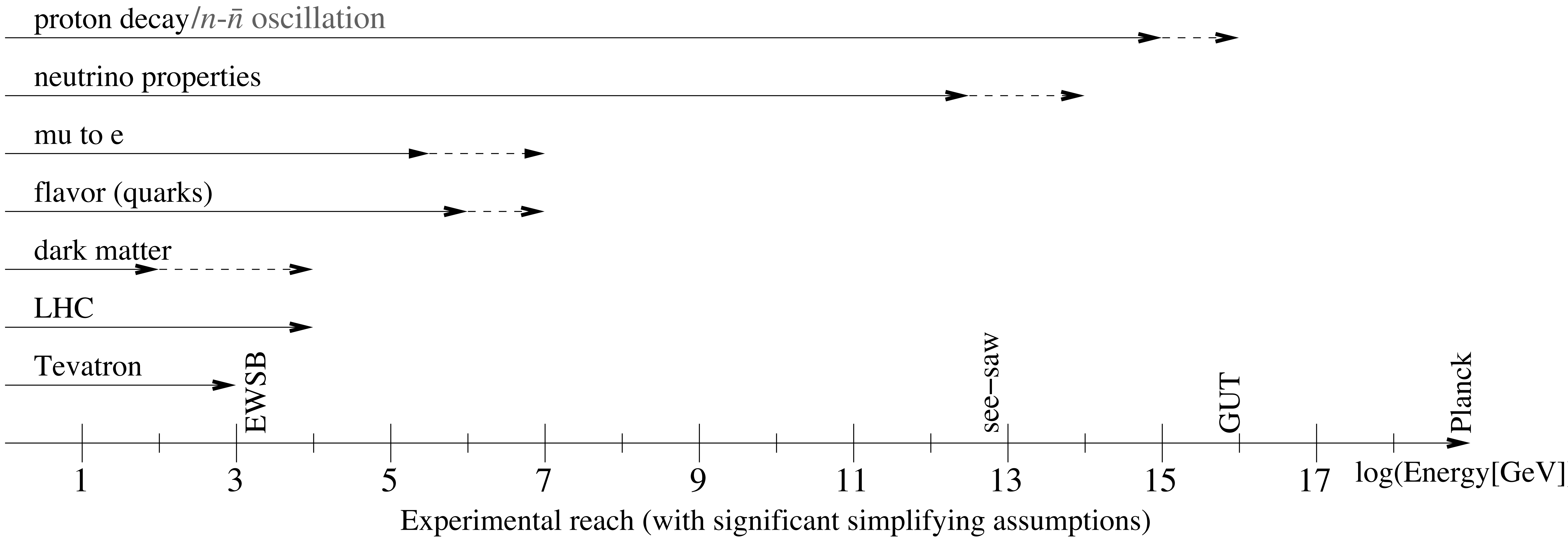
- Generically, a boring O(1) texture implies FCNC reach to *very* high energies. Conversely, (still unseen) physics at the TeV-scale would require a nontrivial texture to comply with flavor physics.

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.

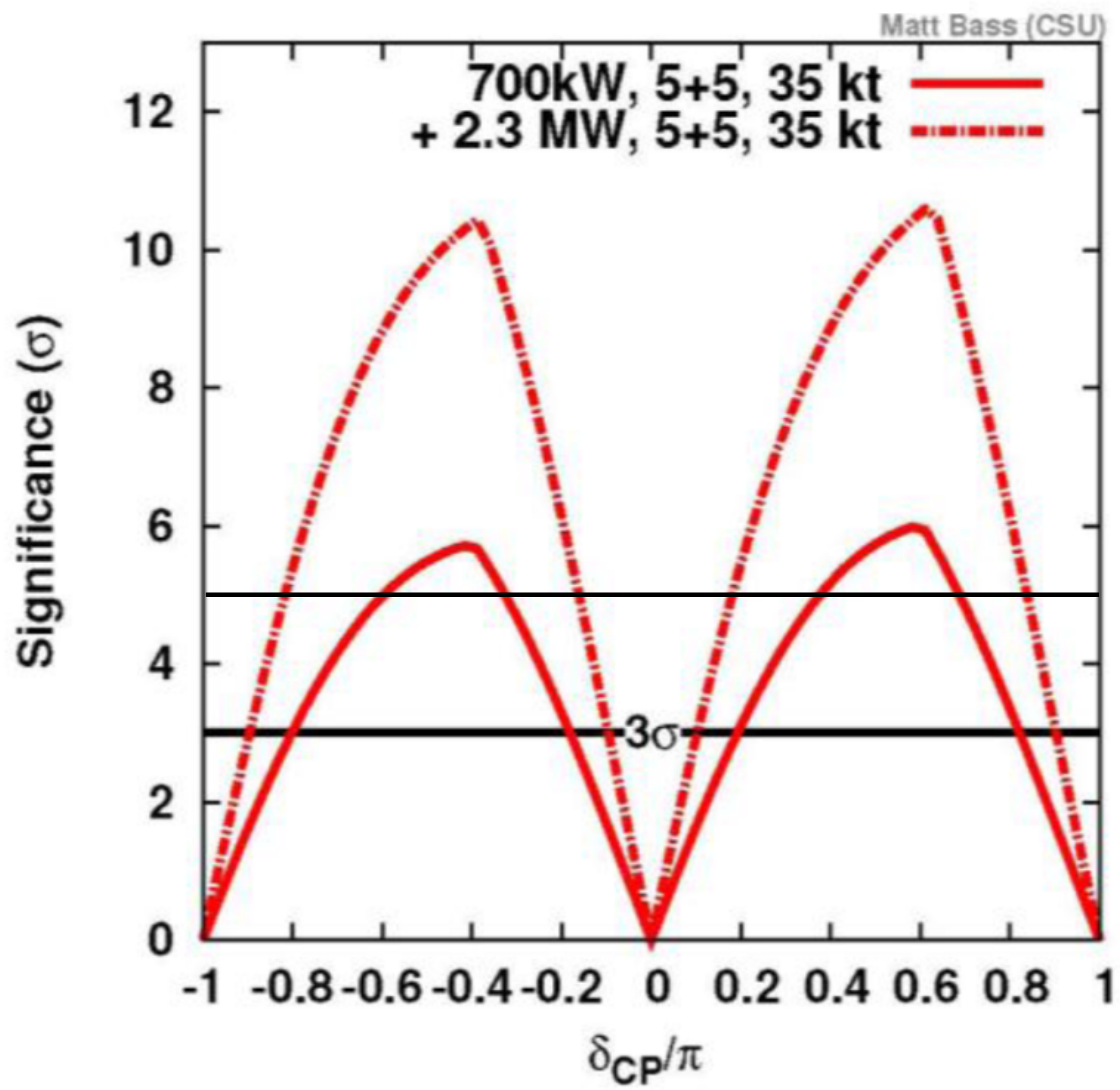
Minimal Flavor Violation (MFV)

- MFV hypothesizes that the only texture(s) that appear are CKM (PMNS):
  - motivated by experience with data;
  - can suppress baryon number violation [see *e.g.*, arXiv:0710.3129], obviating the need to impose R parity conservation (in susy) or similar *ad hoc* quantum numbers.
- Ruling out MFV is a discovery of a new texture, whose origin could be (non-exclusive)
  - a new force;
  - a new (*CP*-violating) property of matter;
  - a (set of) new dimension(s).

Neutrinos

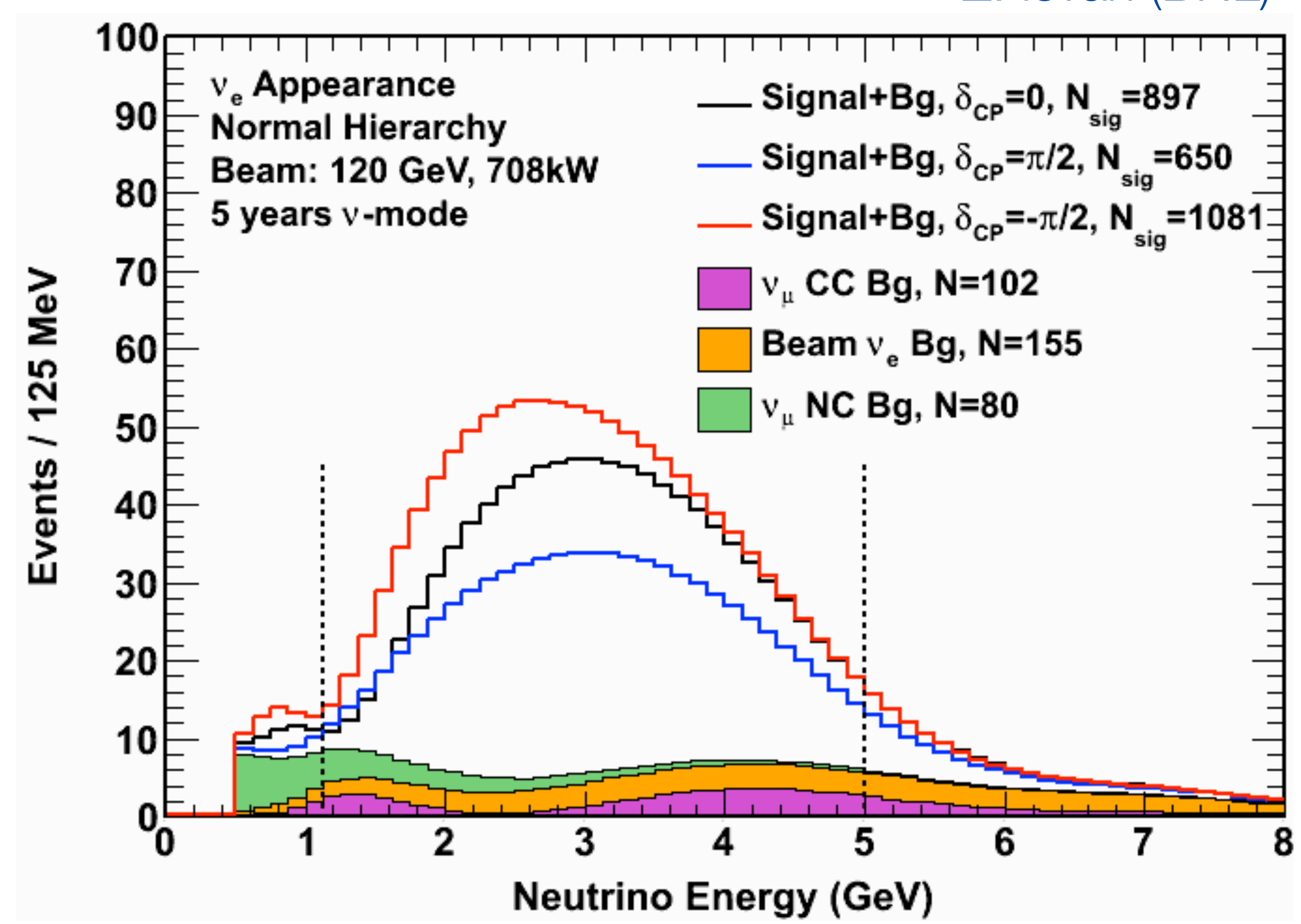
- Project X will dramatically increase LBNE's sensitivity to *CP* violation:

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 × 3; MI experiments × 1.5.

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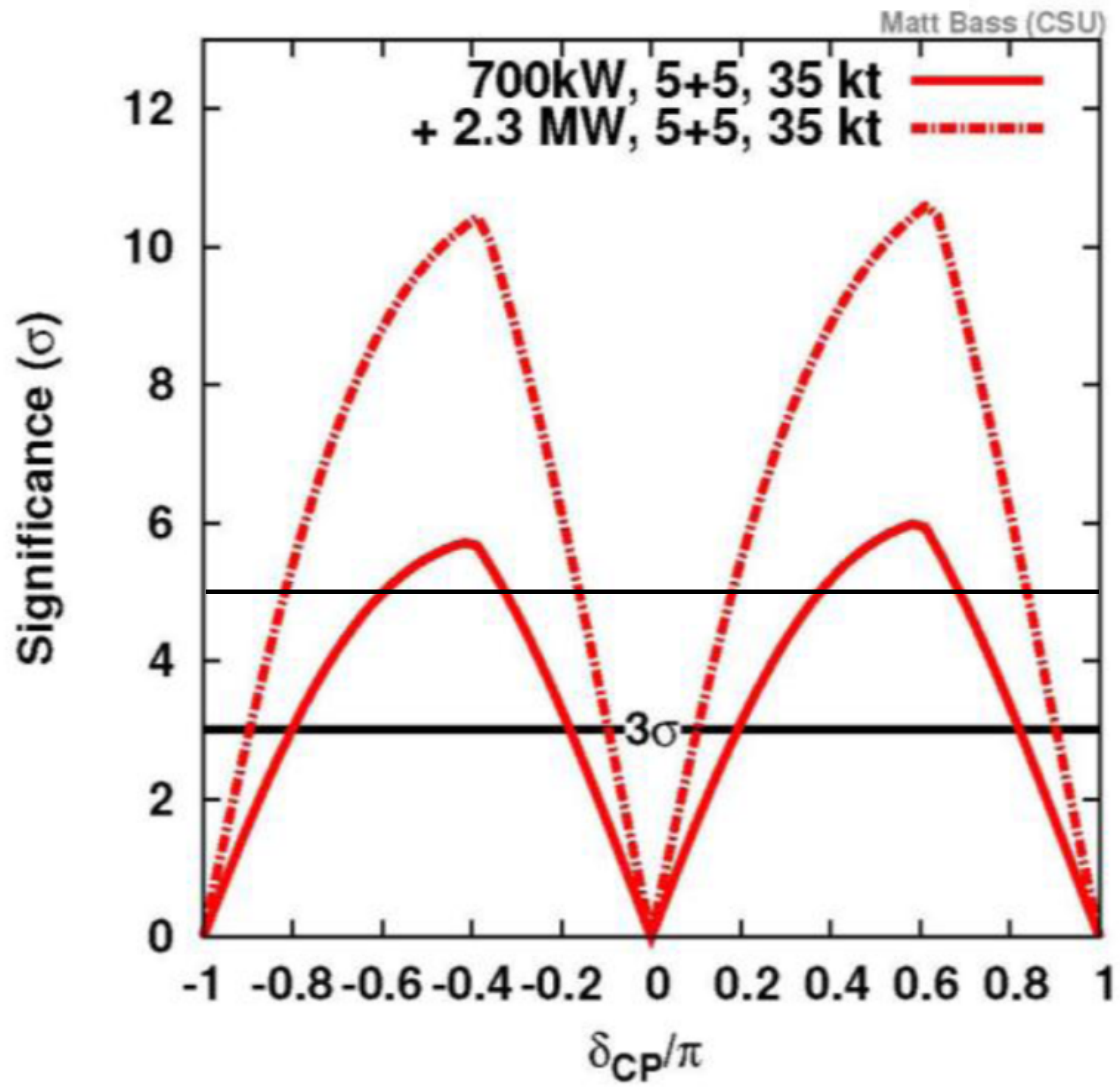

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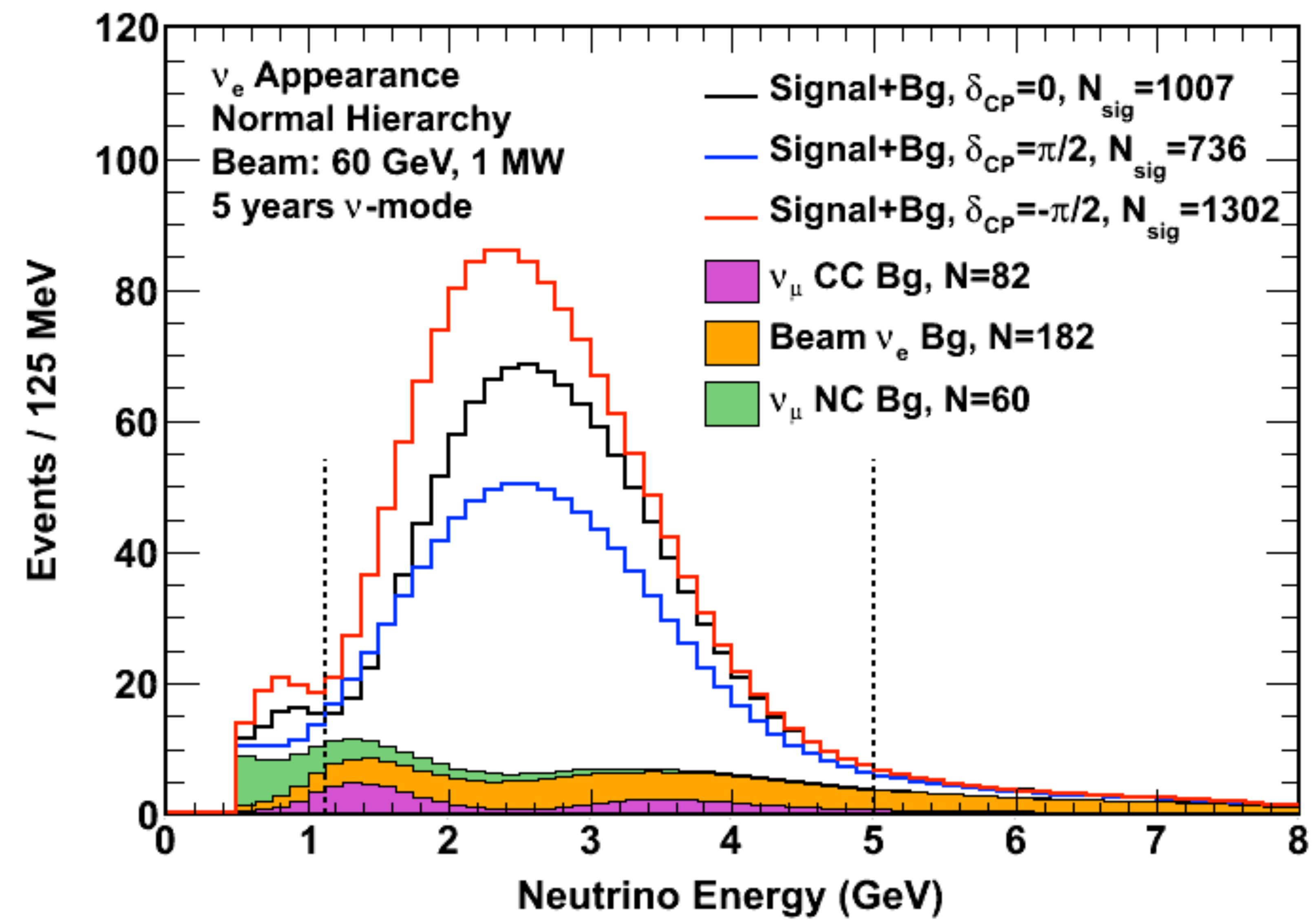

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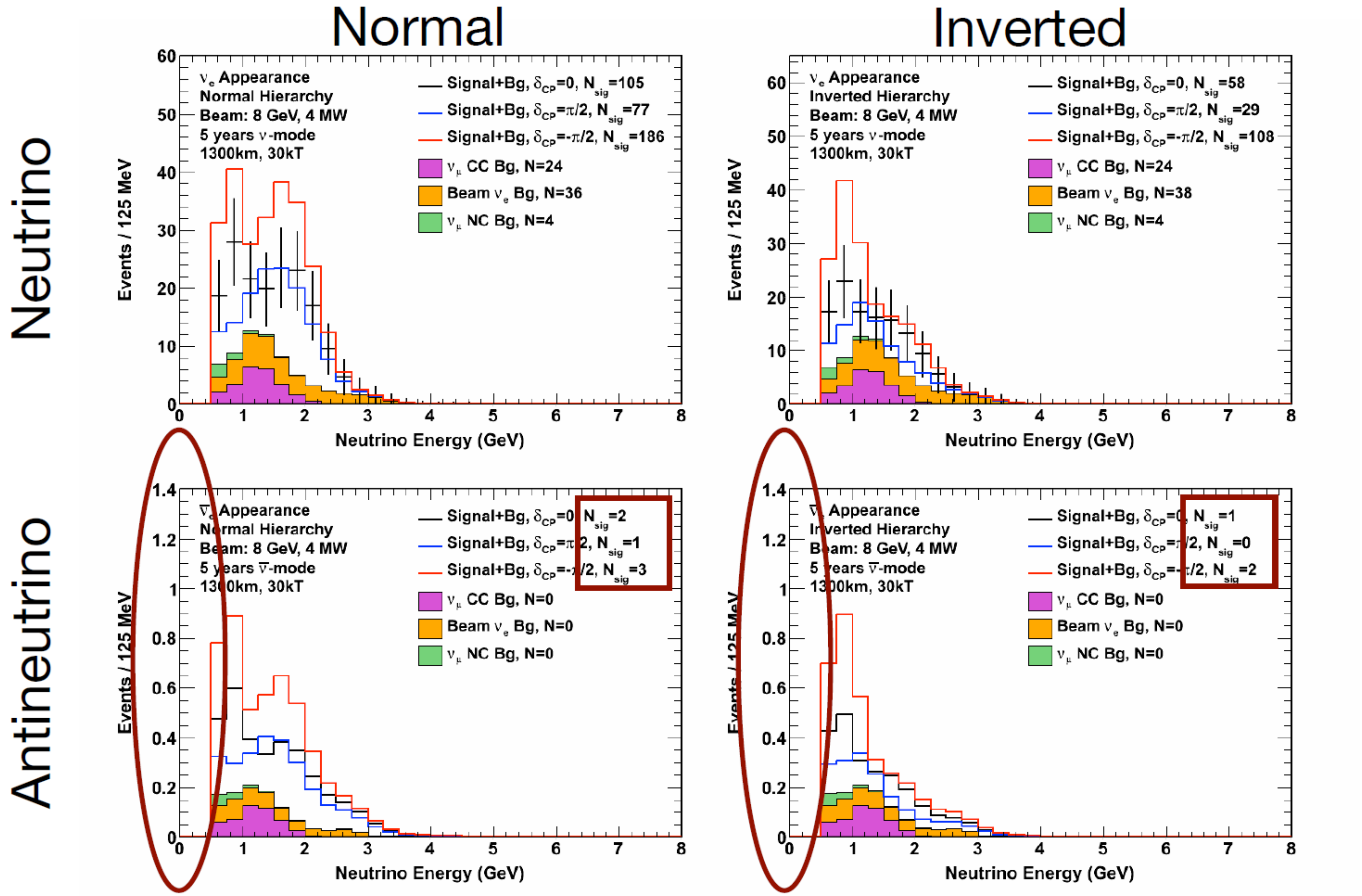
Matter vs CP effect with 8 GeV

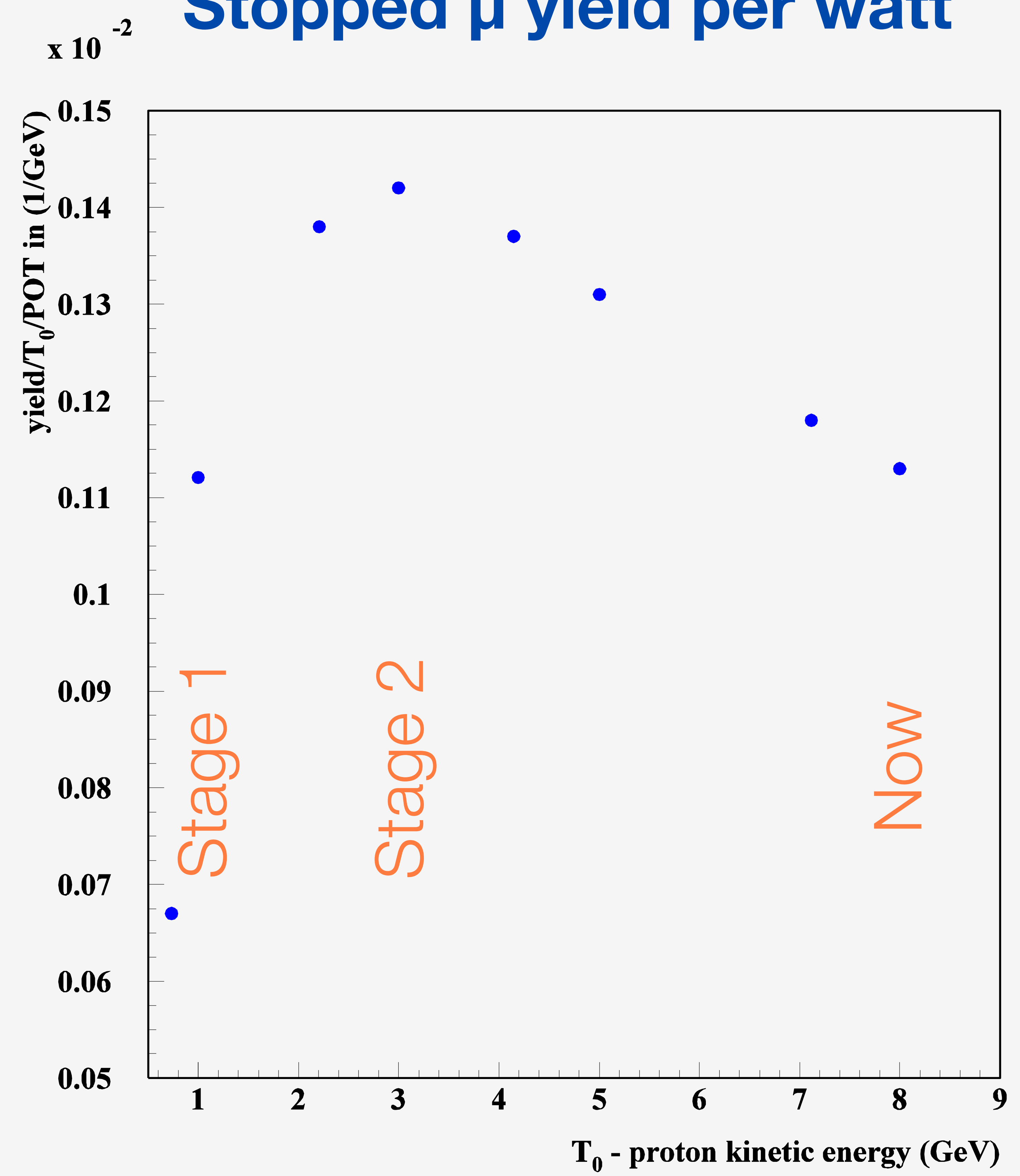


- Mass hierarchy and CP asymmetry non-degenerate - they're completely disentangled!

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

- Stage 1 increases power to Mu2e × 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].
- Larger nuclei capture muons quickly and, thus, tolerate shorter bunch spacing
    - a key design feature of Project X!
- Lower proton energy eliminates antiproton background.

Stopped μ yield per watt



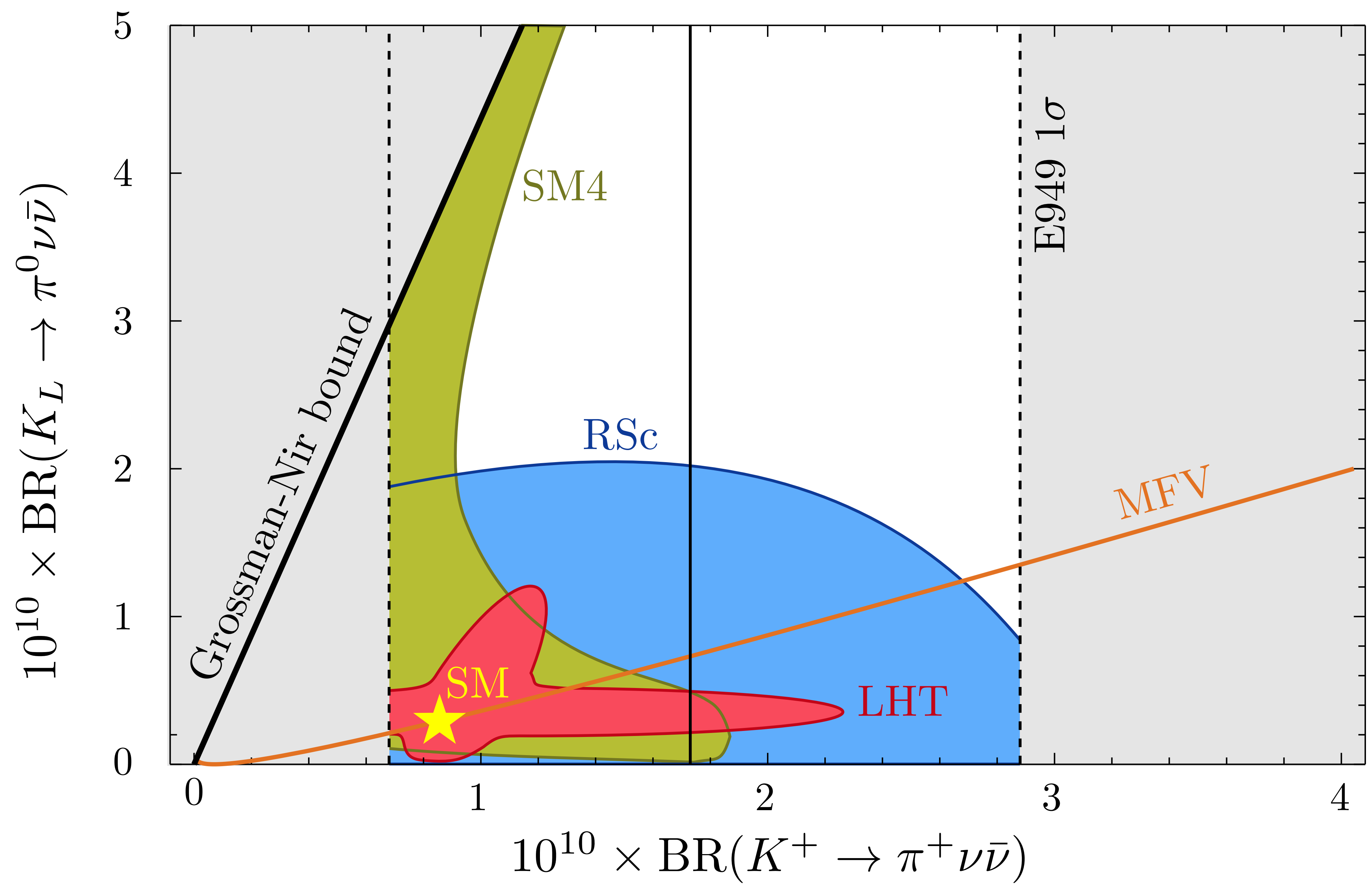
Negative muons at entrance to μ2e detector solenoid
S. Striganov *et al.*

Kaons

- ORKA should collect 100s events of $K^+ \to \pi^+ \nu\bar{\nu}$ before Project X; then 1000 with Stage 1.
- Stage 2 would enable a similar collection of $K_L \to \pi^0 \nu\bar{\nu}$ 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 $K_{L/S} \to \pi^0 \ell\ell$, $K_L \to \gamma\gamma$
  - LFV $K_L \to \mu e$
- Modes for a future K^+ experiment:
  - T violation in $K^+ \to \pi^0 \mu^+ \nu$
  - Nonuniversality in $\frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$

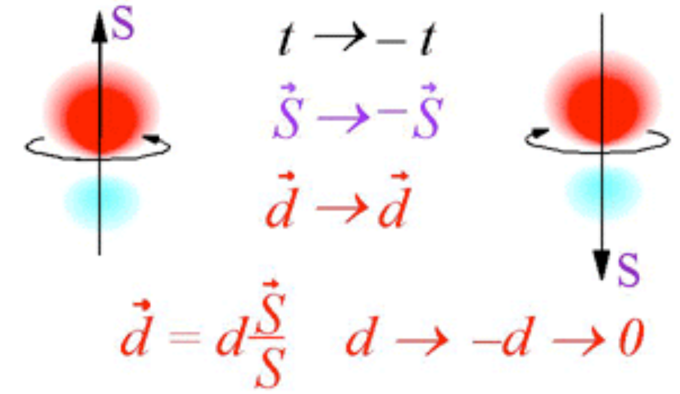
Sensitivity to New Physics

- 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 (⇐ quark & electron) EDMs.
- *CP*V from θ term in QCD, phase of CKM matrix, phase(s) of PMNS matrix, BSM/Higgs:
  - neutron: $-\sin\theta + \mathrm{GIM}\times\mathrm{loop}\times\sin\delta_{KM} + \mathrm{BSM} < 3\times10^{-26} \to 10^{-29}$ with Stage 1;
  - proton: $+\sin\theta + \mathrm{GIM}\times\mathrm{loop}\times\sin\delta_{KM} + \mathrm{BSM} < 7\times10^{-23} \to 10^{-29}$ 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 ($\sin\delta_{KM}$)	current limit	Stage 1 Project X
muon	$\sim 10^{-35}$ e cm	1.1×10^{-19} e cm	$\sim 10^{-23}$ e cm
neutron	$\sim 10^{-31}$ e cm	2.9×10^{-26} e cm	$\sim 10^{-29}$ e cm
proton	$\sim 10^{-31}$ e cm	6.5×10^{-23} e cm	$\sim 10^{-29}$ e cm
nuclei	$\sim 10^{-33}$ e cm (^{199}Hg)	3.1×10^{-29} e cm (^{199}Hg)	$\sim 10^{-29}$ e cm (^{225}Ra)
electron	$\sim 10^{-38}$ e cm	1.0×10^{-27} e cm	$\sim 10^{-30}$ 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

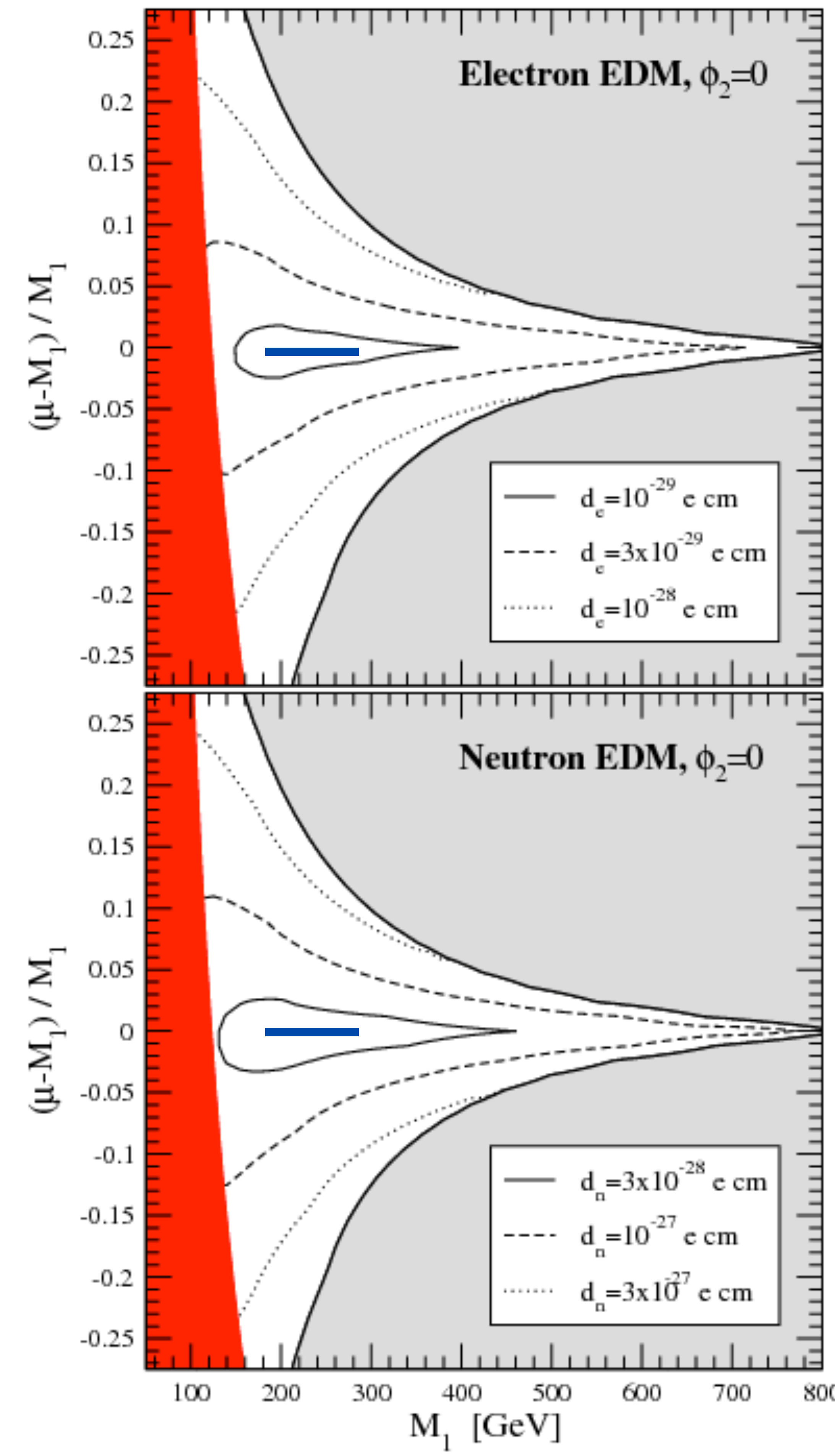
- EDMs are very sensitive to *CP* violation in the Higgs sector.

- 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*-*ñ* 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): $\tau_{n\bar{n}} > 2.4–3.4 \times 10^8$ s [arXiv:1109.4227].
- Expression of Interest to search for *n*-*ñ* 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

- Hadron structure—*cf*. SeaQuest experiment underway now:
  - unprecedented precision in DIS and DY will help disentangle EMC effect (nucleon structure in nuclei) and the allocation of spin in the nucleon (parton spin vs. OAM $\boldsymbol{L}$);
  - luminosity 15 times higher than nearest competitor (RHIC *spin*).
- Spectroscopy:
  - searches for glueballs and other exotics, especially with non–quark-model J^{PC};
  - experiment similar to LASS at SLAC, but with more intense incident beams.

Broader Impacts

- Muon spin rotation (μSR):
    - 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

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 ~ # 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

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- 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.