The High Intensity Horizon at Fermilab

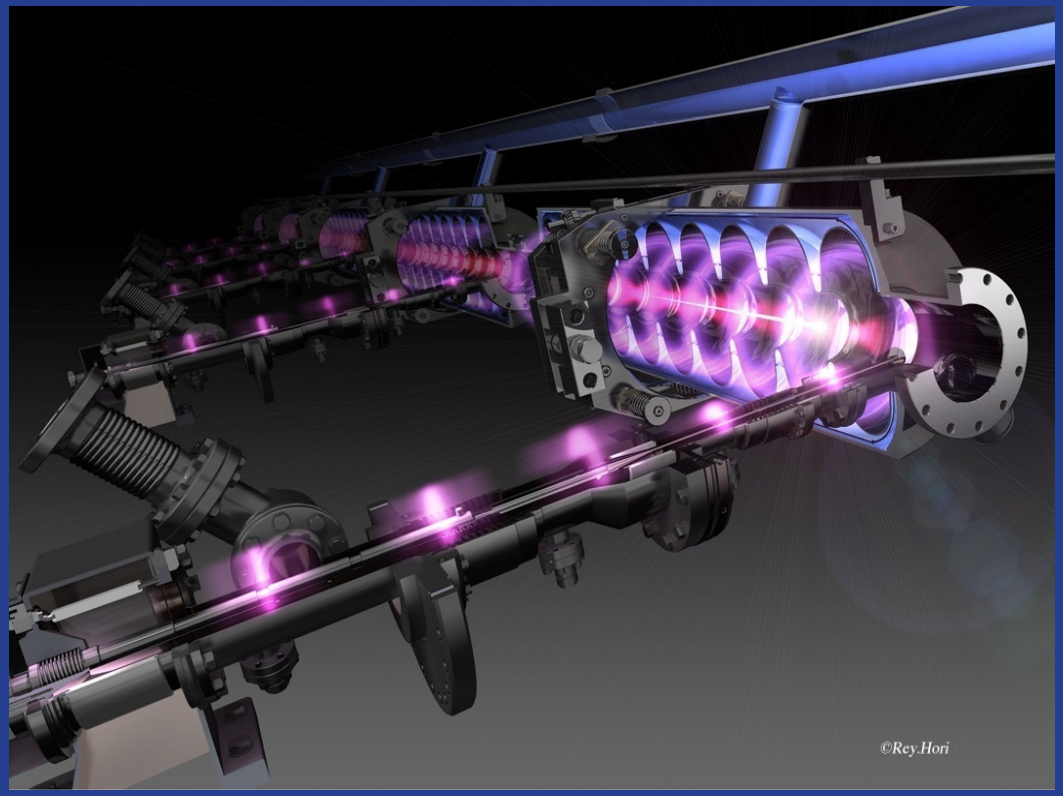
R. Tschirhart
Fermi National Accelerator Laboratory
IPAC 2012, New Orleans, USA.
May 23rd , 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

Project-X:

- Evolution of the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.



Project-X:

- Evolution of the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.

Project-Y: Origins…

- **The Origin of Mass:**

  How do massless chiral fermions become matter particles?
  (buzzword: "Higgs")

- **The Origin of Matter:**

  Why are there so many different kinds of matter particles with different properties?
  (buzzword: "Flavor")

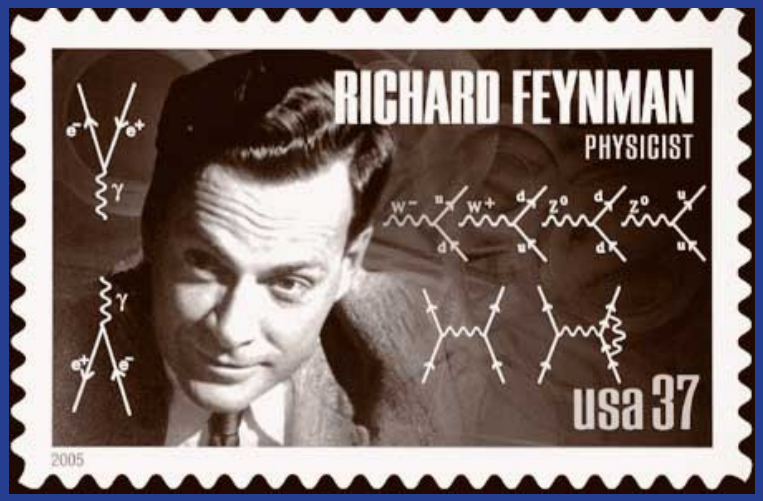
- **The Origin of the Universe:**

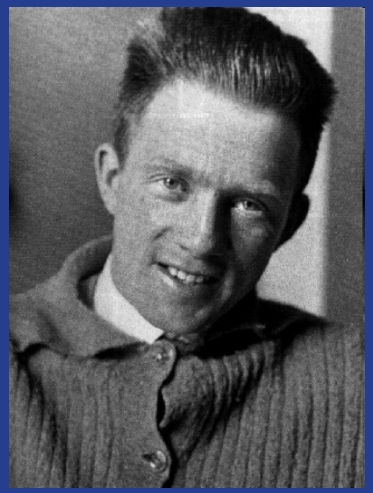
  Where did matter come from in the first place and why didn't it all annihilate with antimatter?
  (buzzwords: "Baryogenesis", "Leptogenesis")

-Joe Lykken

The Energy Frontier exploits Einstein's mass-energy relation, $E=mc^2$. The Intensity Frontier exploits Heisenberg's uncertainty principle, $\Delta E \Delta t \gtrsim \hbar/2$

Feymann's tools





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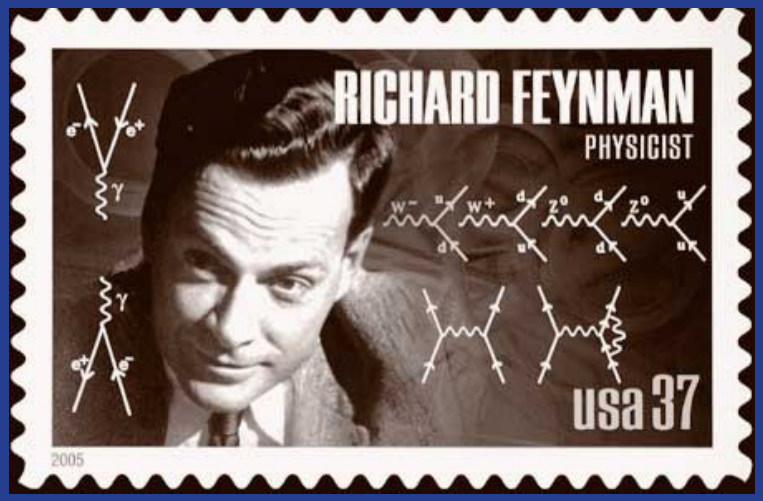

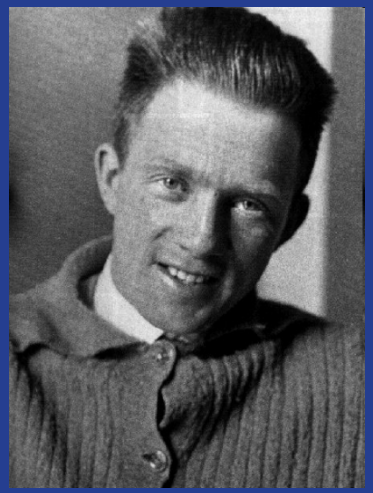

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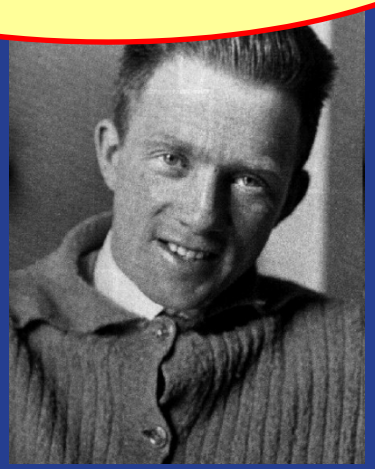

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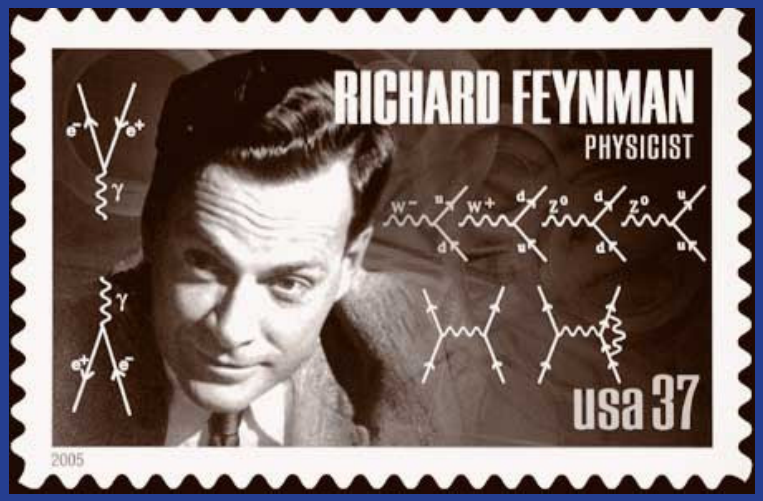

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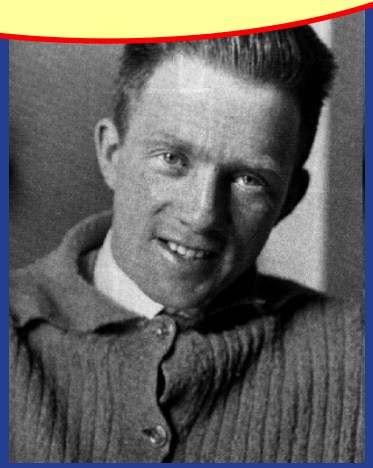

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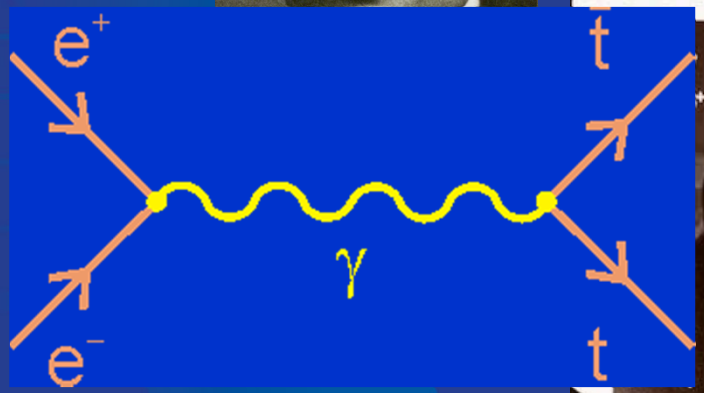

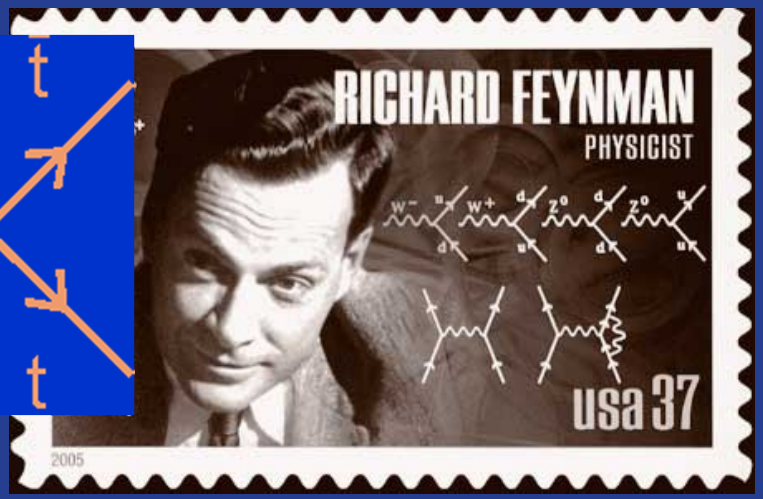

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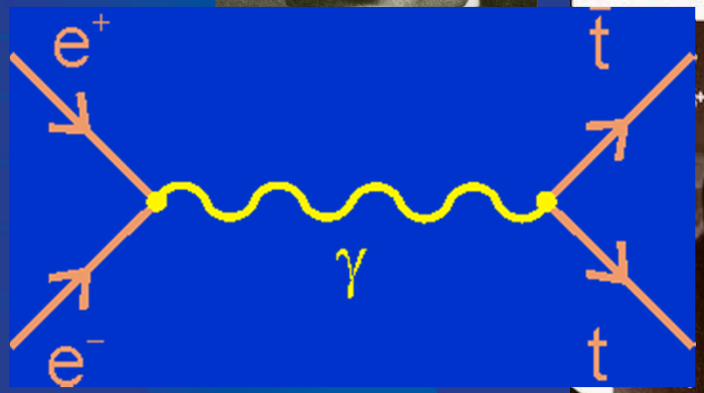

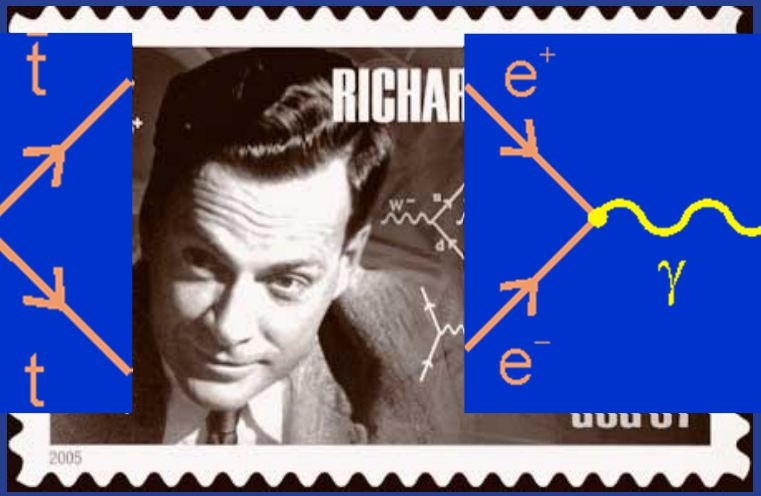

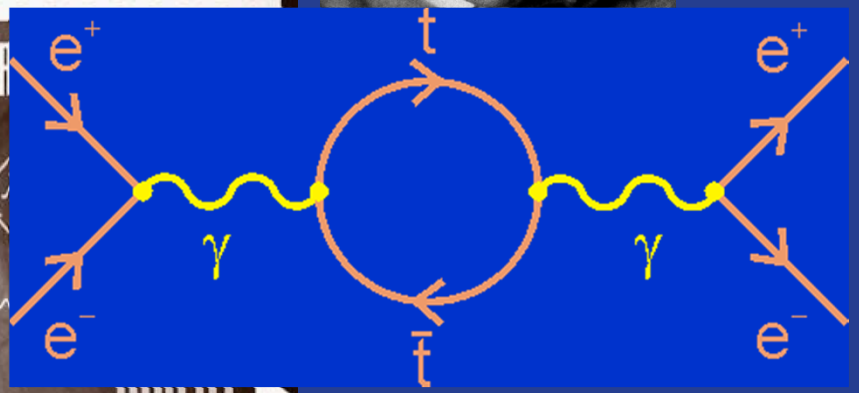

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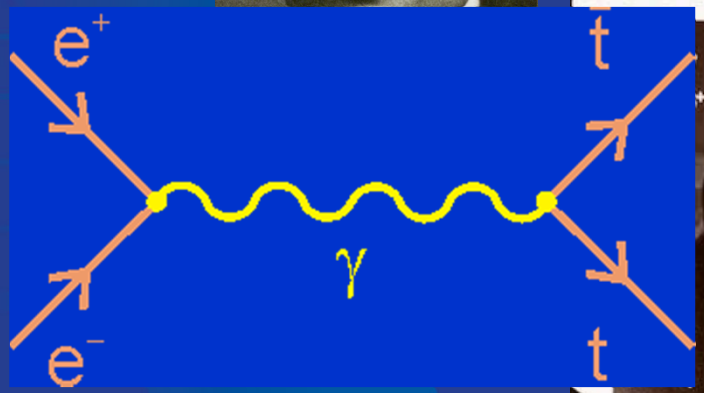

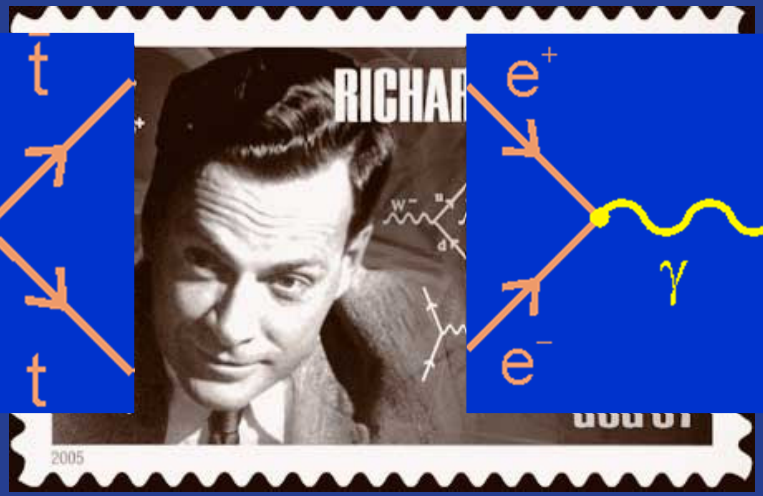

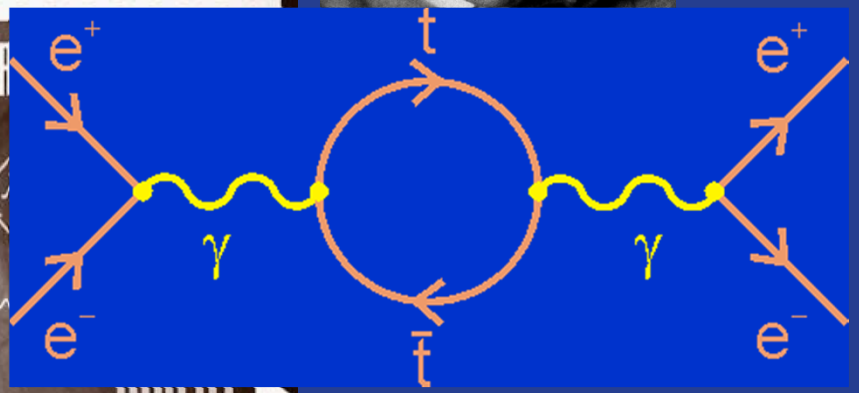

High energy crucial

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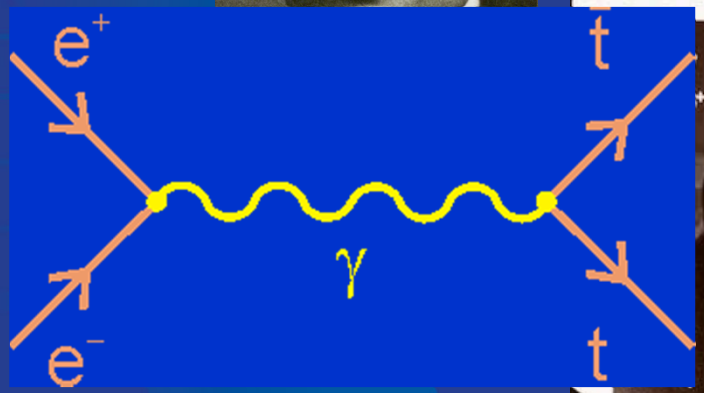
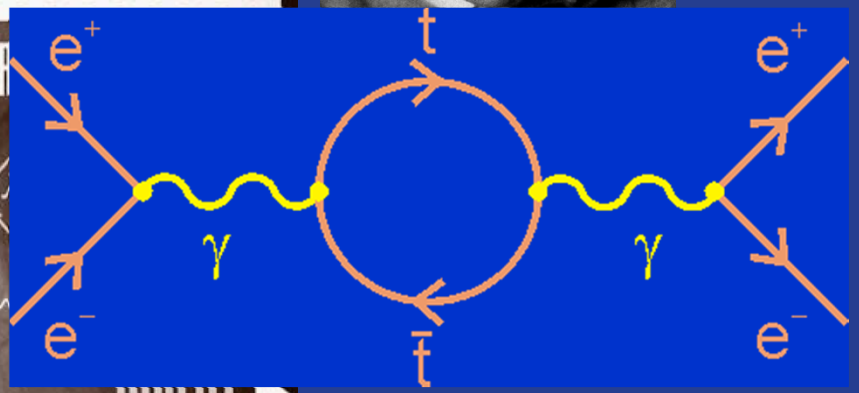




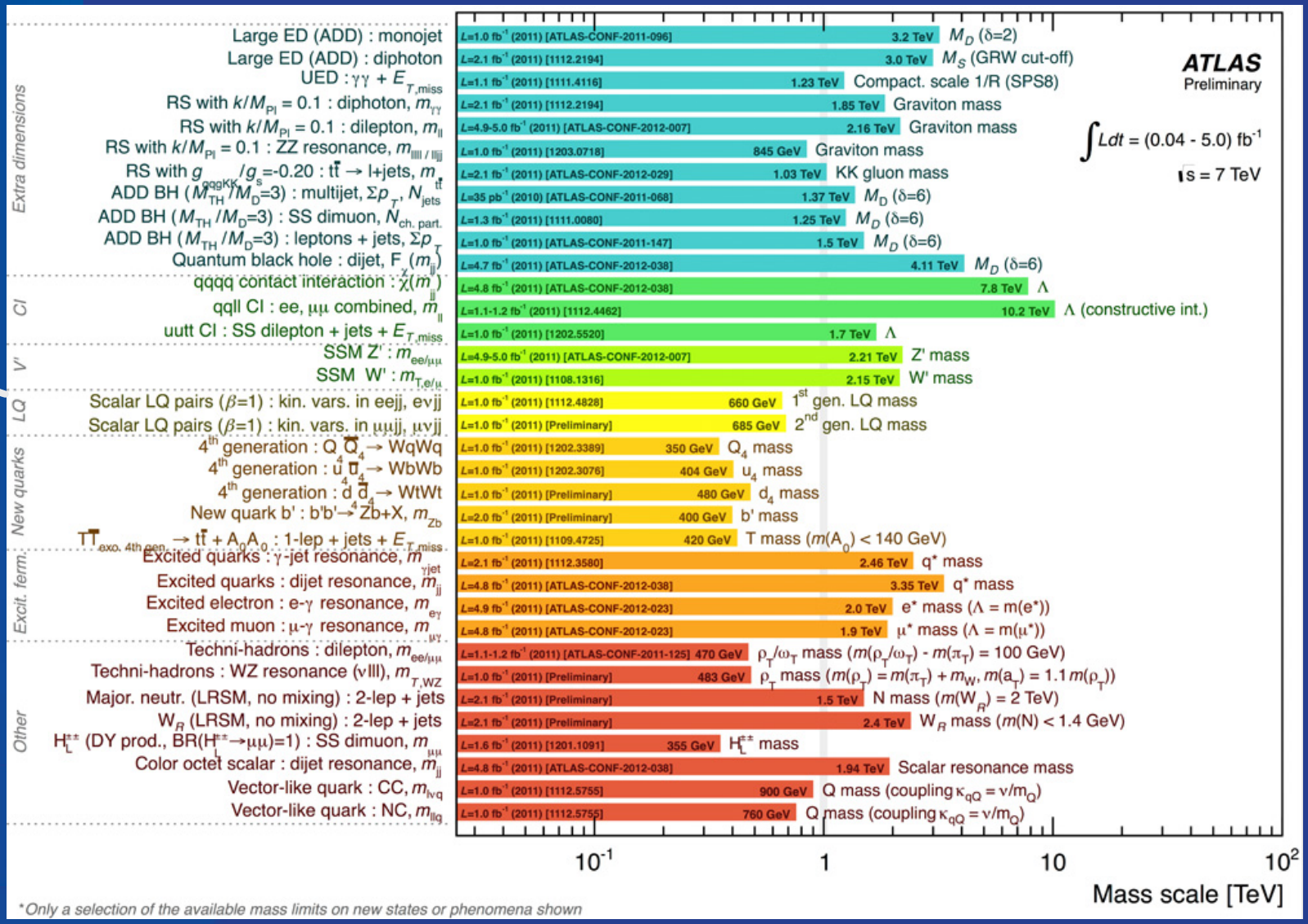
High energy crucial

High intensity crucial

Direct Challenges from the LHC to Models Beyond the Standard Model

Moriond 2012-EW

New Physics



Similar limits from CMS

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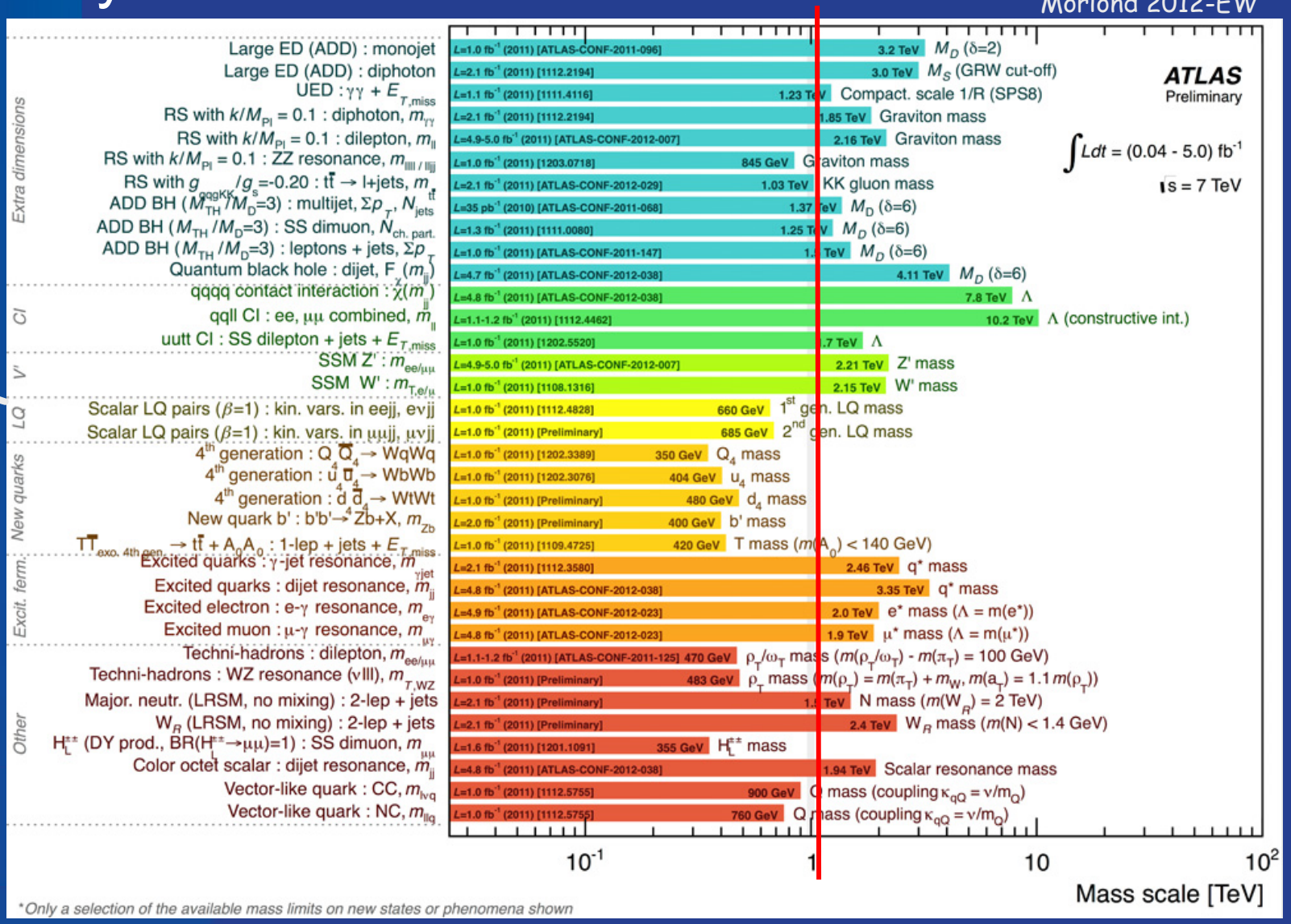


New Physics

Similar limits from CMS

In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

Project X Killer App? Not a *single* experiment! Beam Power & Flexibility is the Killer App.

Apologies to Jurassic Park and Hitoshi Murayama , ICFA October 2011

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 & neutron precision experiments***

These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), precision measurement of neutron properties 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.

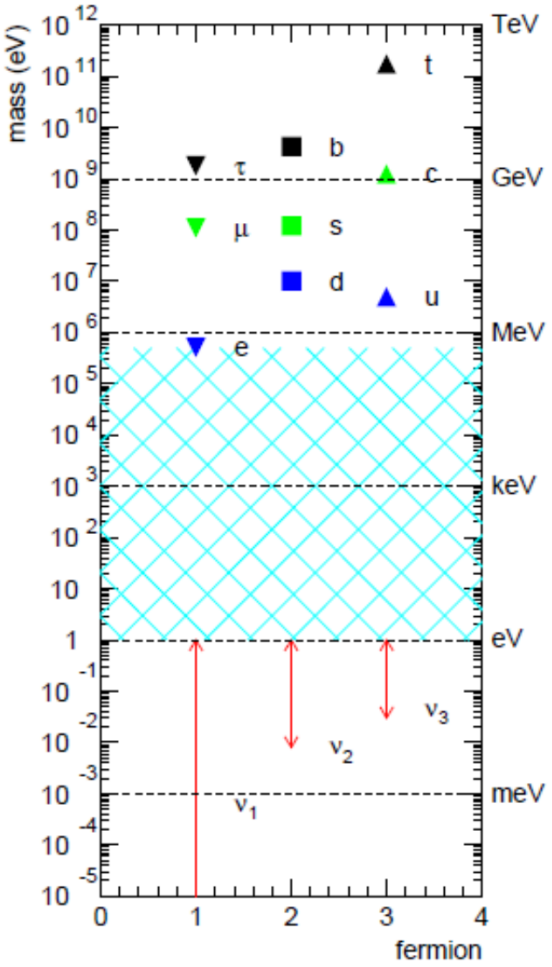
- ***Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

Detailed discussion on Project X website

What are Neutrinos Telling Us?

André de Gouvêa — Northwestern



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

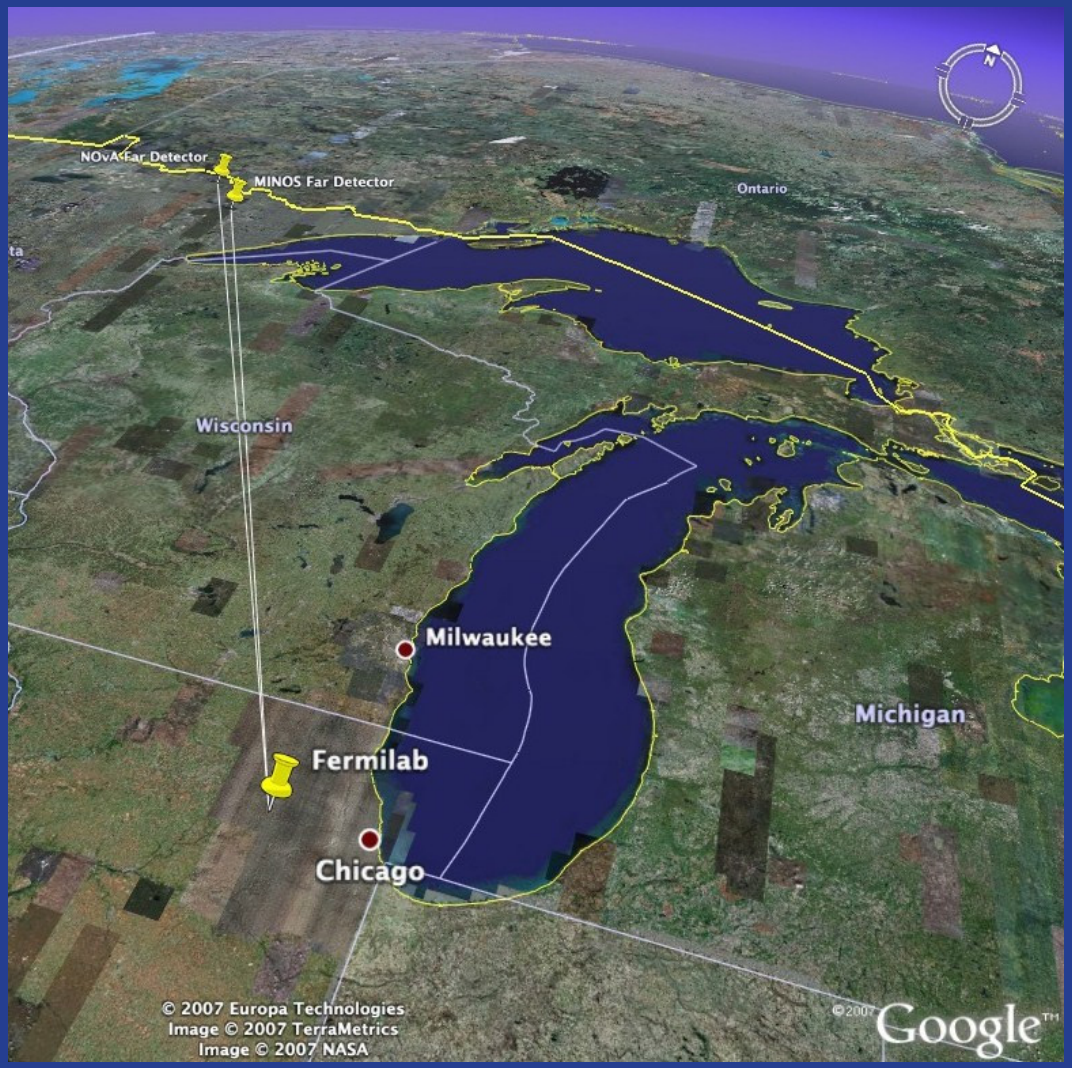
⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Andre de Gouvea

Long Baselines!



EDMs: New CPV?

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	10.5×10^{-28}	YbF	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame E	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}	10^{-28}

- *SM "background" well below new CPV expectations*
- *New expts: 10^2 to 10^3 more sensitive*

A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	Proton (ring)	BNL

+ TRIUMF

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IUMF

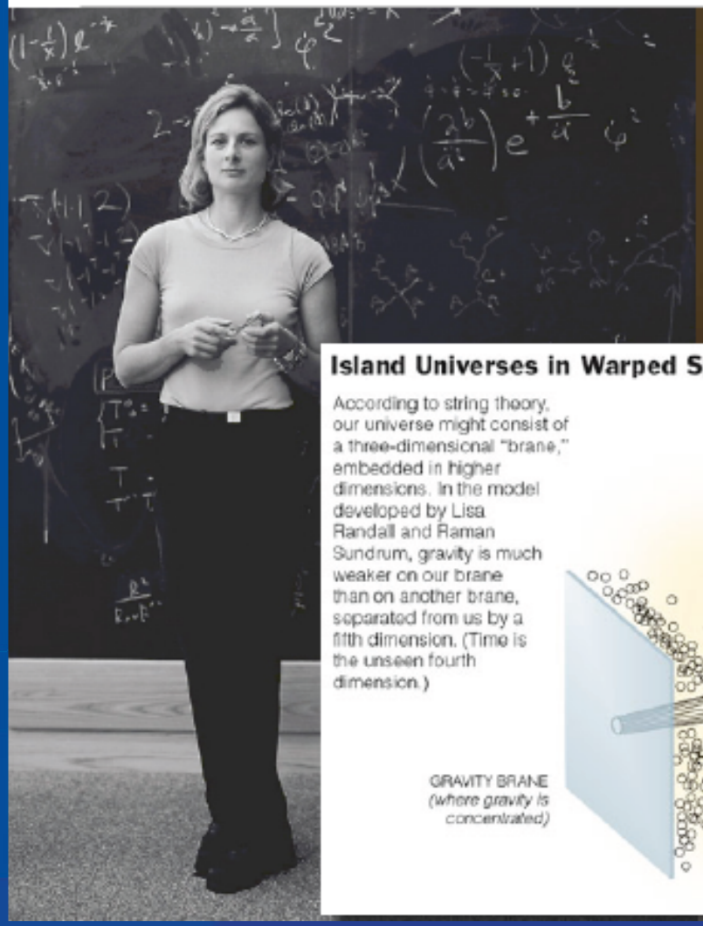
+ COSY (deuteron)

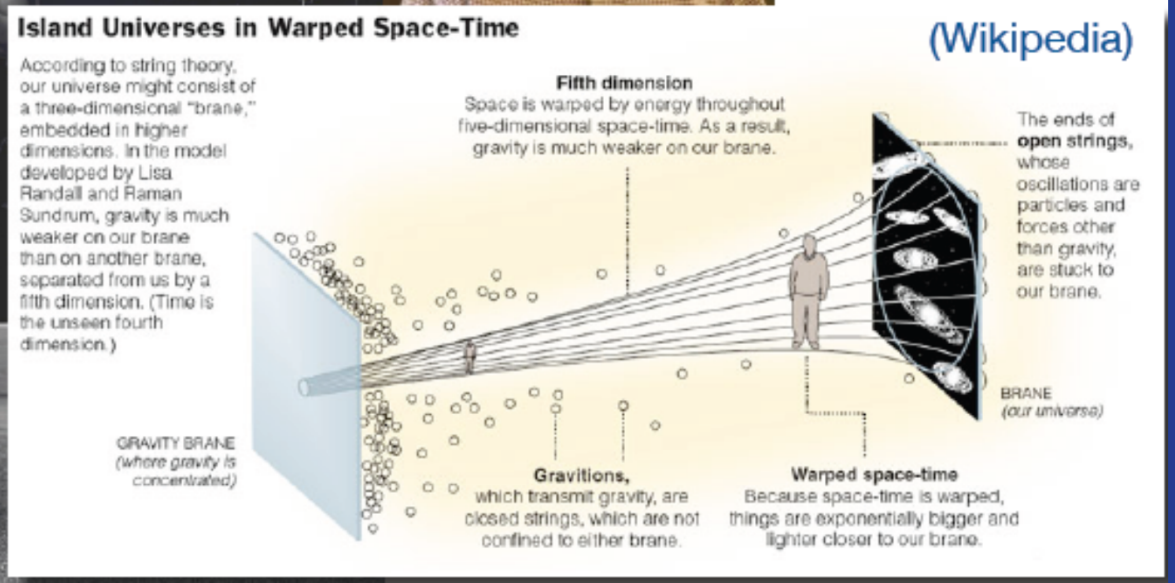
"n-EDM has killed more theories than any other single experiment"

-J.M. Pendlebury, Review of Particle Electric Dipole Moments

Rare processes sensitive to new physics…
e.g. Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea





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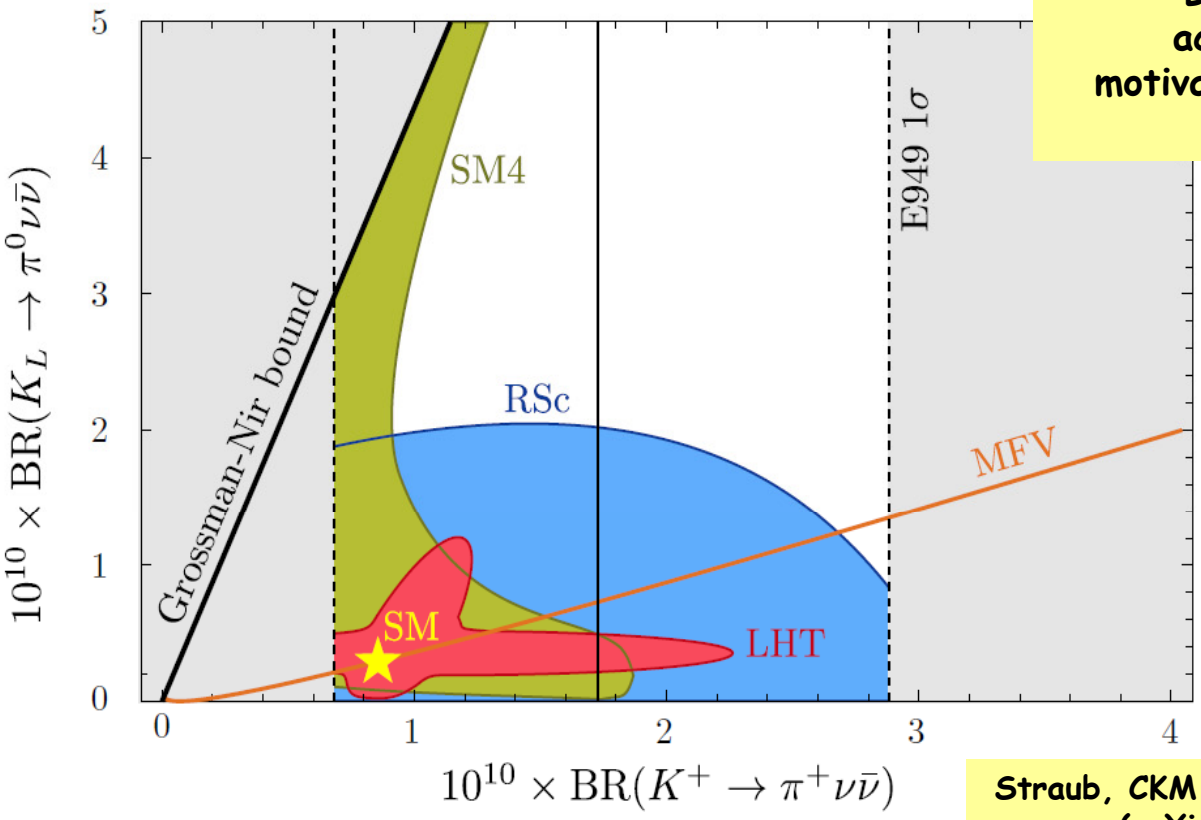


Buras et al. SM accuracy of <5%, motivates 1000-event experiments

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.

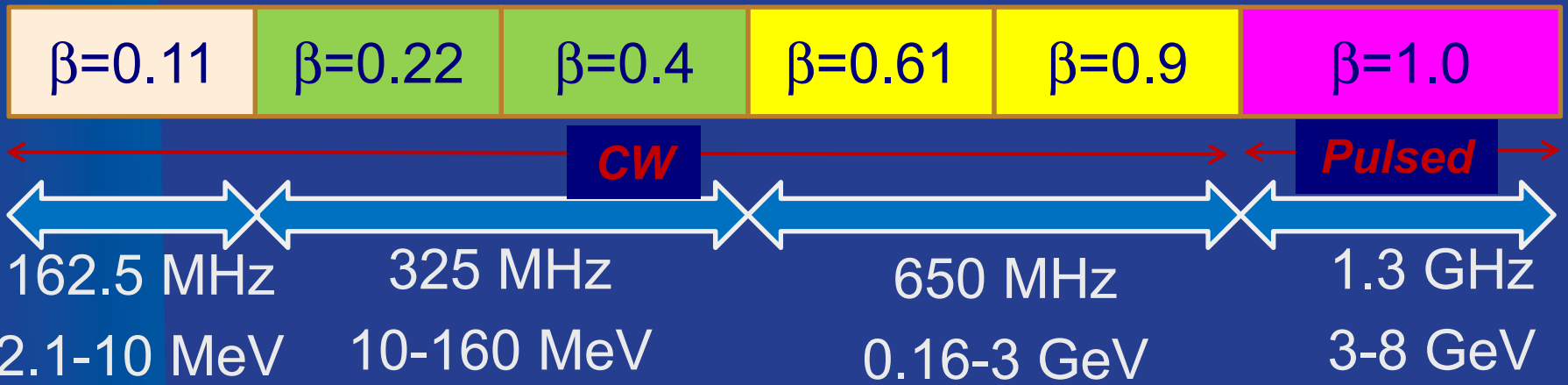
Project-X Accelerator
Functional Requirements*

CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	1.0-3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power @ 3 GeV	3000	kW
Beam Power to 3 GeV program	2870	kW
RCS/Pulsed Linac		
Particle Type	protons/H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	0.002/4.3	msec
Cycles to MI	6	
Particles per cycle to Recycler	2.6×10^{13}	
Beam Power to 8 GeV program	190	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.3	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2200	kW

simultaneous

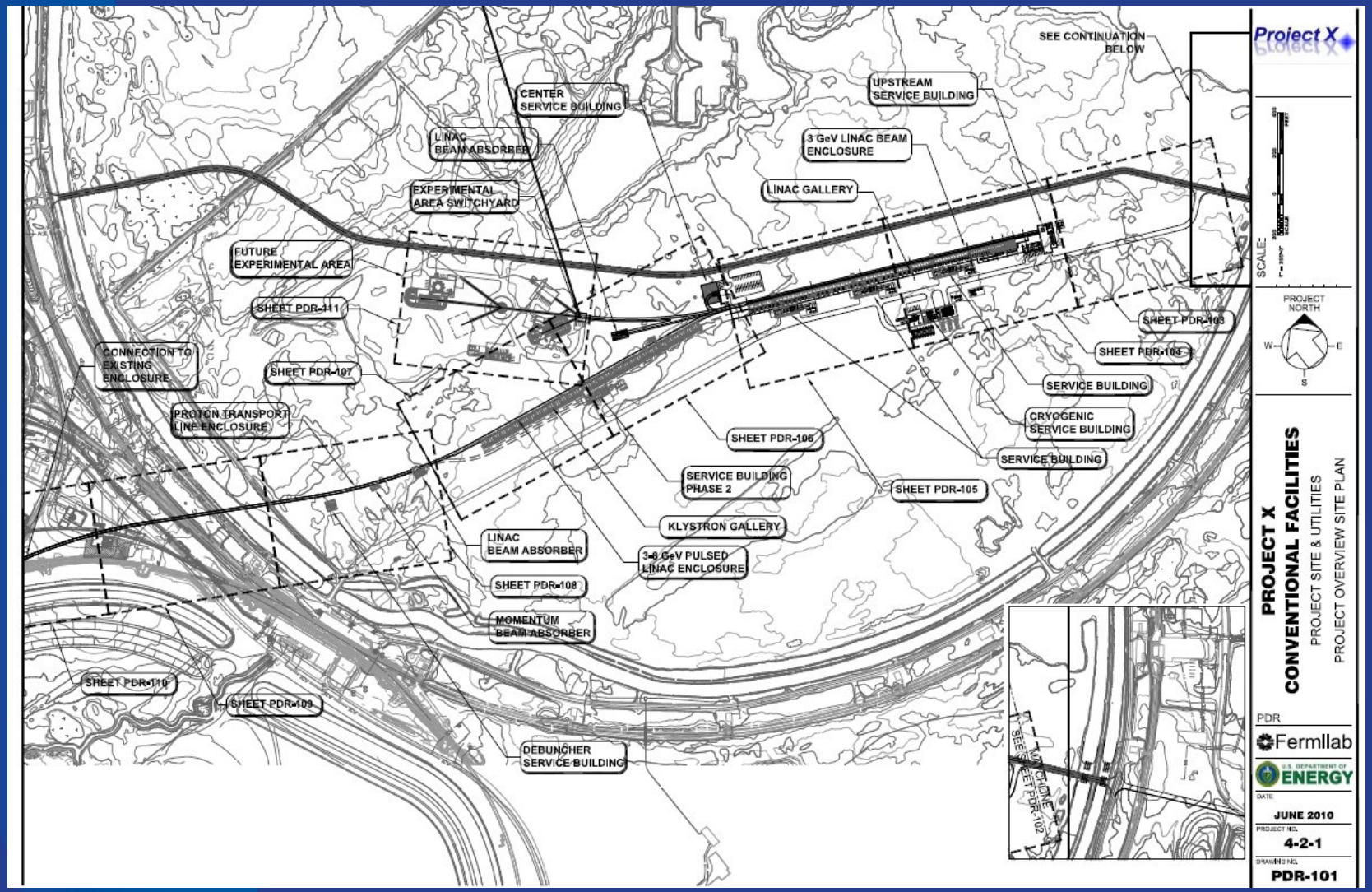
*http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=658

Project X SRF Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	9/6/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/18/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

Reference Design Siting



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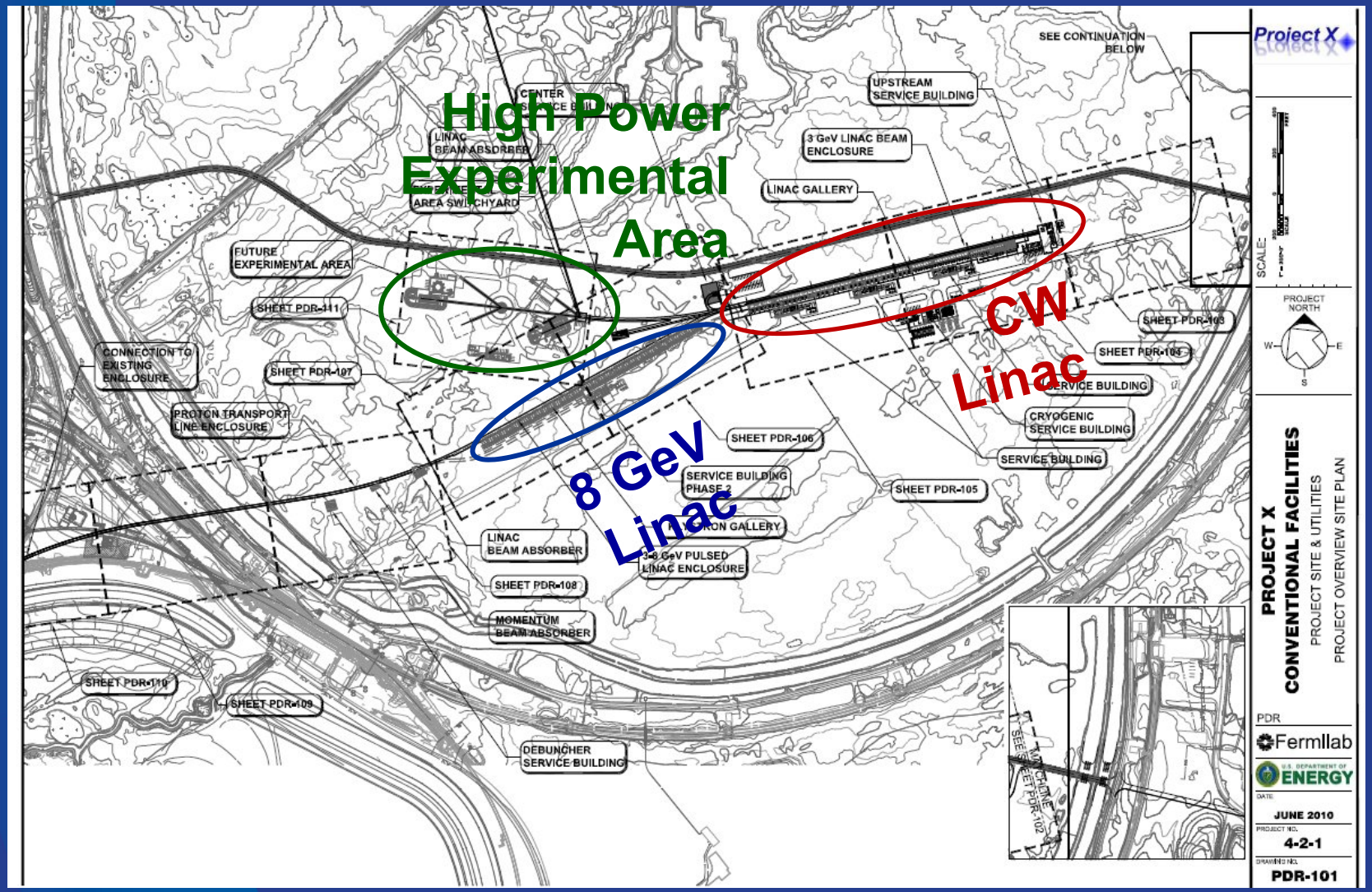
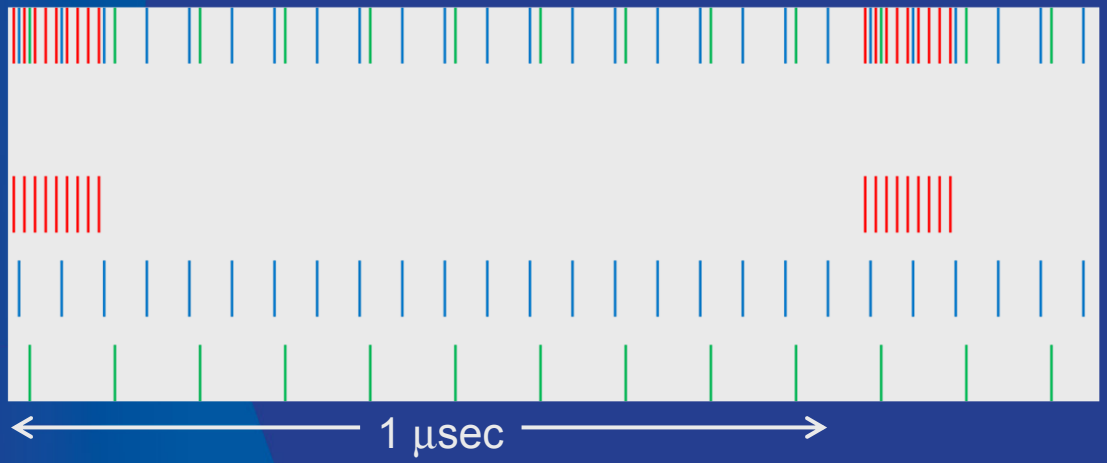


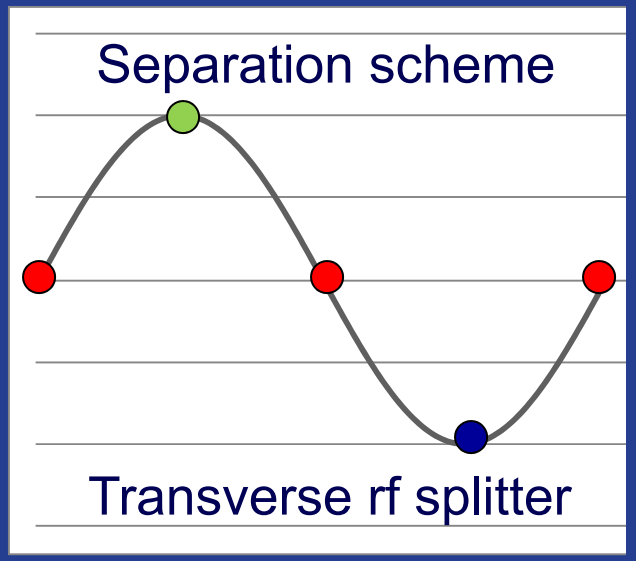
Operating Scenario for High Power Campus

1 μsec period at 3 GeV

Muon pulses (12e7) 162.5 MHz, 80 nsec	700 kW
Kaon pulses (12e7) 27 MHz	1540 kW
Nuclear pulses (12e7) 13.5 MHz	770 kW

Ion source and RFQ operate at 4.4 mA; 77% of bunches are chopped @ 2.1 MeV ⇒ maintain 1 mA over 1 μsec





A Partial Menu of World Class Science Enabled by Project-X

Neutrino Physics: **LBNE campaign is a candidate Day-1 program**

- **Mass Hierarchy**
- **CP violation**
- **Precision measurement of the θ_{23} (atmospheric mixing). Maximal??**
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Search for sterile neutrinos, CP & CPT violating effects in next generation $\nu_e, \bar{\nu}_e \rightarrow X$ experiments….x3 beam power @ 120 GeV, **x10-x20 power @ 8 GeV**.
- Next generation precision cross section measurements.

A Partial Menu of World Class Science Enabled by Project-X

Muon Physics: **Mu2e upgrade is a candidate Day-1 experiment**

- **Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.**
- Next generation $(g-2)_\mu$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \rightarrow 3e$
- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- A \rightarrow \mu^+ A'$; $\mu^- A \rightarrow e^+ A'$; $\mu^- e^-(A) \rightarrow e^- e^-(A)$
- Systematic study of radiative muon capture on nuclei.

A Partial Menu of World Class Science Enabled by Project-X

Kaon Physics: **ORKA is a candidate Day-1 experiment**

- **$K^+ \to \pi^+ \nu\bar{\nu}$: >1000 events, Precision rate and form factor.**
- $K_L \to \pi^0 \nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \to \pi^0 \mu^+ \nu$: Measurement of T-violating muon polarization.
- $K^+ \to (\pi,\mu)^+ \nu_x$: Search for anomalous heavy neutrinos.
- $K^0 \to \pi^0 e^+ e^-$: <10% measurement of CP violating amplitude.
- $K^0 \to \pi^0 \mu^+ \mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \to X$: Precision study of a pure K^0 interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \to$ LFV: Next generation Lepton Flavor Violation experiments

...and more

A Partial Menu of World Class Science Enabled by Project-X

Nuclear Enabled Particle Physics: Candidate Day-1

- **Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's. Production of Very-cold and Ultra-cold neutrons for EDM and n-nbar.**

Hadron and Baryon Physics:

- **Next generation QCD probes (e.g. evolution of Seaquest)**
- $pp \rightarrow \Sigma^+ \bar{K}^0 p^+$; $\Sigma^+ \rightarrow p^+ \mu^+ \mu^-$ (HyperCP anomaly, and other rare Σ^+ decays)
- $pp \rightarrow K^+ \Lambda^0 p^+$; Λ^0 ultra rare decays
- $\Lambda^0 \leftrightarrow \bar{\Lambda}^0$ oscillations (Project-X operates below anti-baryon threshold)

Power Staging for the Research Program

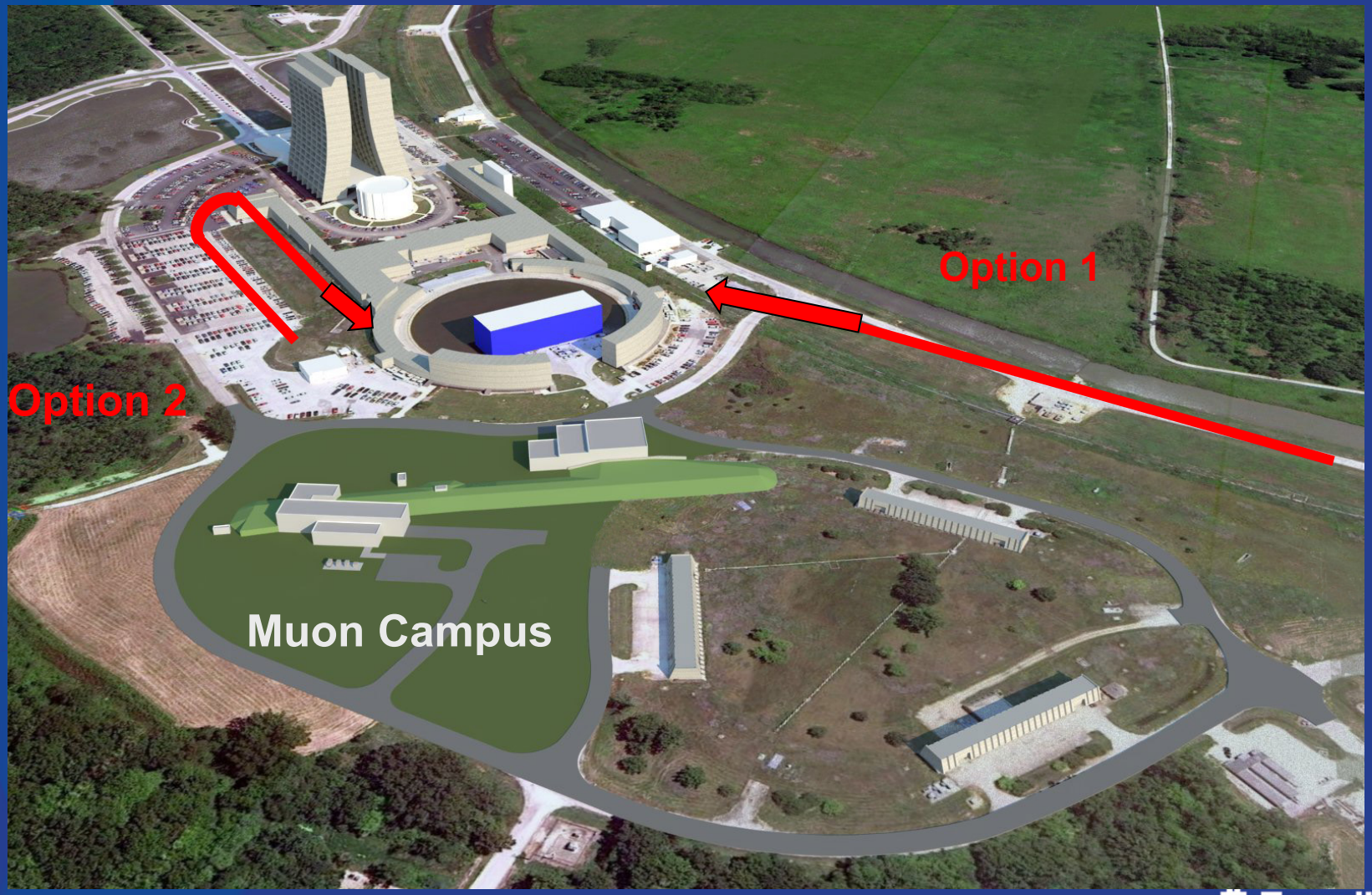
Project X Campaign

Program:	Onset of NOvA operation in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, EDM programs (MI>80 GeV)	Stage-2: Upgrade to 3 GeV CW Linac (MI>80 GeV)	Stage-3: Project X RDR (MI>60GeV)	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power:	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Stage-1: New 1-GeV CW Linac Driving the Existing Fermilab Booster



Science Enabled with Stage-1

- Promotes the Main Injector to a Mega-Watt class machine for neutrinos, and increases the potential beam power for possible slow-spill experiments (e.g. ORKA).
- Unshackles the $\mu \rightarrow e$ (Mu2e) experiment from the Booster complex: Potentially increases sensitivity of Mu2e by x10 - x100 with 1-GeV CW drive beam.
- World class ultra-cold neutron and ISOL programs optimized for particle physics: e.g. edms & neutron$\Leftrightarrow$anti-neutron oscillations.
- Increases the available integrated 8 GeV power for other experiments (e.g. short-baseline neutrinos) from the Booster complex by liberating Mu2e.

Broad World-leading Program in Neutrinos and Rare Processes

Science Enabled with Stage-2

- World leading kaon physics program: Megawatt power (x10 over competing facilities) can drive multiple experiments.
- World leading muon physics program: Mu2e descendant migrates to a higher power campus. Megawatt power for conversion experiments (x10 over competing facilities), opportunities for major next steps in other channels (e.g. $\mu \rightarrow 3e$).
- Removes pressure on sharing precious Main Injector beam power with a slow-spill program, corresponding boost in integrated beam power for Main Injector neutrinos.

Science Enabled with Stage-3 (RDR)

- Main Injector power upgrade to >2 Mega Watts, doubling power to long baseline Main Injector Neutrinos and Main Injector near-detector neutrino physics.
- 8 GeV beam power for experiments is increased by x10, which will support a new generation of short-baseline neutrino physics.

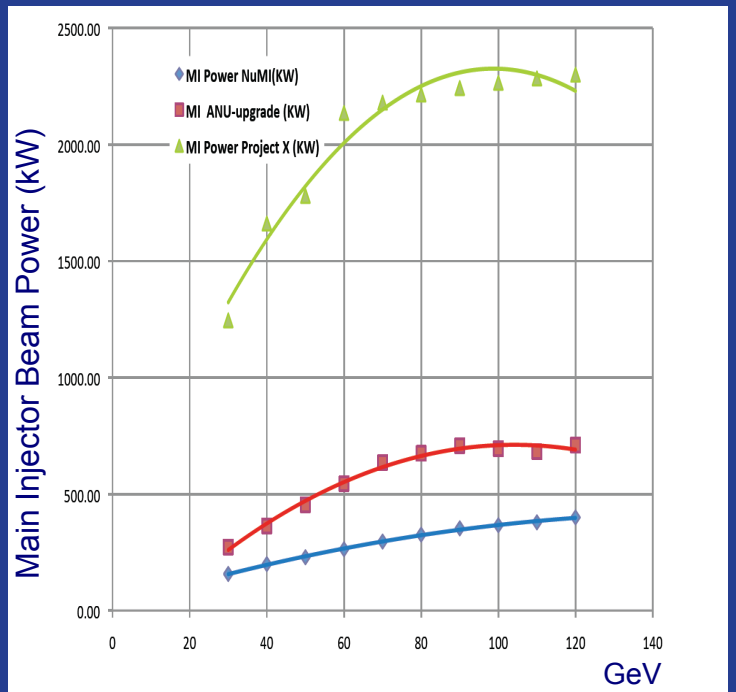


FIG. 4: Proton beam power as a function of proton energy from the Fermilab Main Injector. Shown are current capabilities labeled as NuMI. The recently funded upgrades (labeled as ANU) will increase the power to 550 kW at 60 GeV or 700 kW at 120 GeV. Project-X as currently conceived will allow beam power of 2 MW at 60 GeV and 2.3 MW at 120 GeV.

Figure courtesy of R. Zwaska

Science Enabled with Stage-4 (Beyond RDR)

- 4000kW @ 8 GeV and 4000kW at 60 GeV for the ultimate super beams.
- Double beam super-beam technique can tune illumination of the first and second maxima of long-baseline experiments of very massive next generation long-baseline detectors.
- Driver for an extremely powerful muon storage ring neutrino source, driving detectors based existing large magnetized neutrino detector technologies (MINOS), and possibly LAr in the future.

Science Enabled with Stage-4 (Beyond RDR)

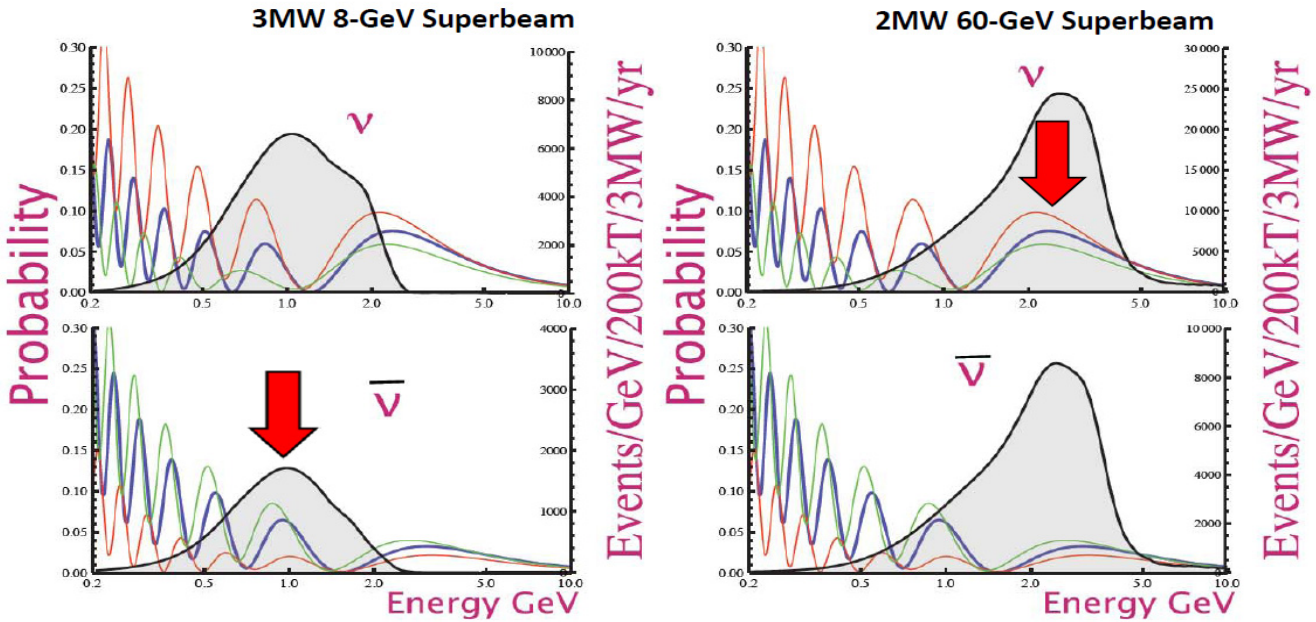
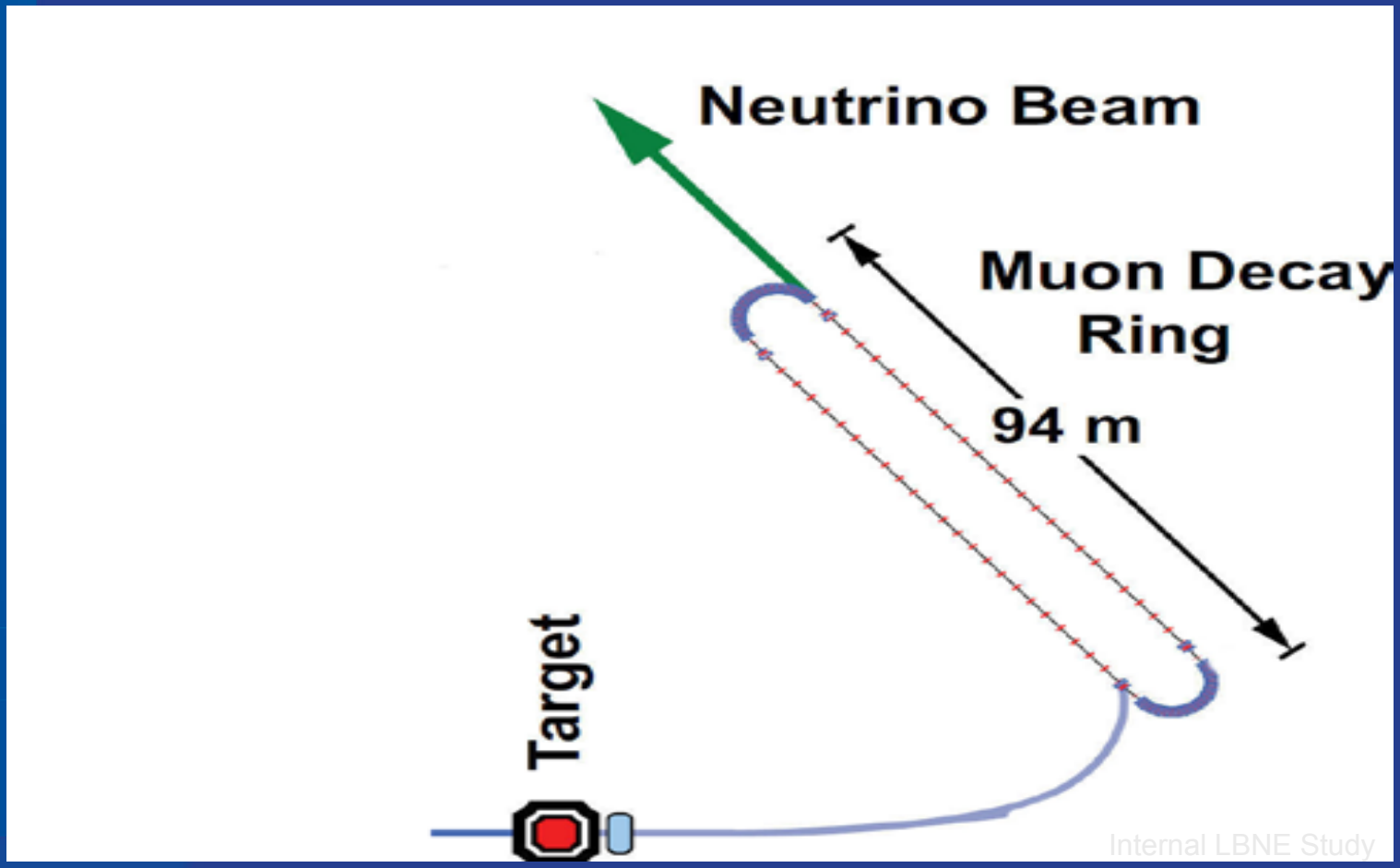


FIG. 5: Spectra of event rates as a function of energy for 8 GeV (left) and 60 GeV (right) proton beams from Fermilab. The spectra are superimposed on the expected oscillation probability for normal hierarchy. Spectra are for the total charged current cross-section for muon neutrino (top) and antineutrinos (bottom). The beam is from Fermilab to Homestake over a distance of 1300 km; the intensity for the 8 GeV beam is assumed to be 3 MW and for 60 GeV it is 2 MW. The detector size is 200 kTon fiducial mass.

Internal LBNE Study

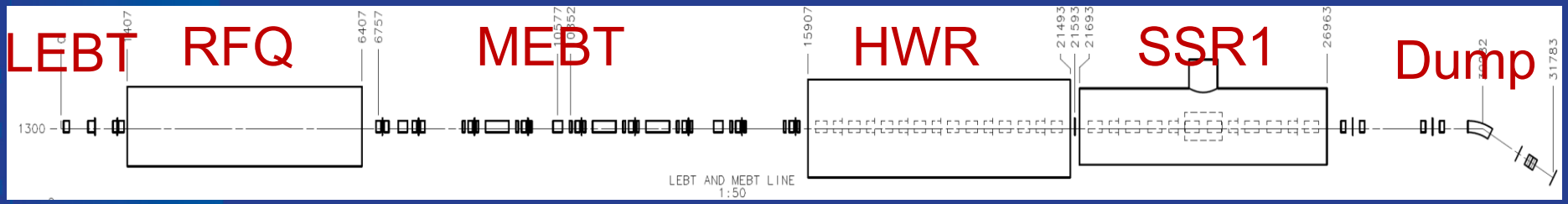
Science Enabled with Stage-4 (Beyond RDR)



Project X Injector Experiment PXIE

- PXIE is the centerpiece of the Project X R&D program
  - Integrated systems test for Project X front end components
    - Validate the concept for the Project X front end, thereby minimizing the primary technical risk element within the Reference Design.
    - Operate at full Project X design parameters
- Systems test goals
  - 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV
  - Achieve in 2016
- PXIE should utilize components constructed to PX specifications wherever possible
  - Opportunity to re-utilize selected pieces of PXIE in PX/Stage 1
- Collaboration between Fermilab, ANL, LBNL, SLAC, India

PXIE Program



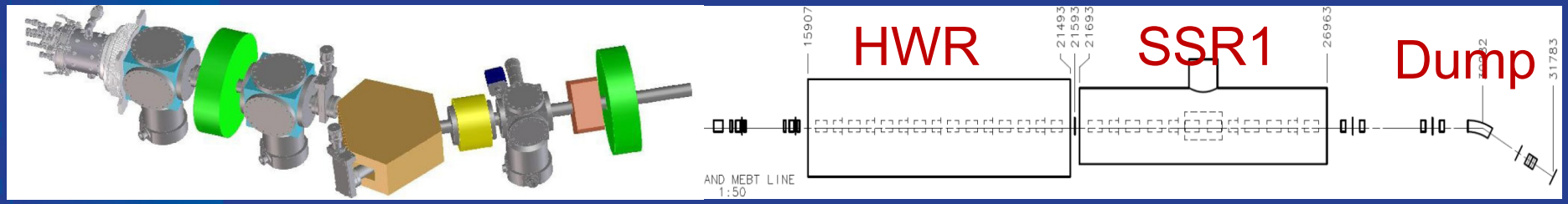
LBNL FNAL,SLAC ANL FNAL

32 m, 30 MeV

PXIE will address the address/measure the following:

- Ion source lifetime
- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Kicker extinction
- Effectiveness of MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam
- Emittance preservation and beam halo formation through the front end

PXIE Program



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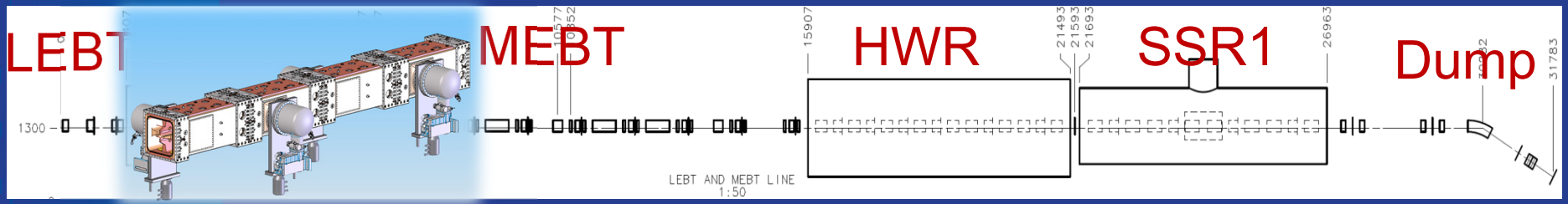

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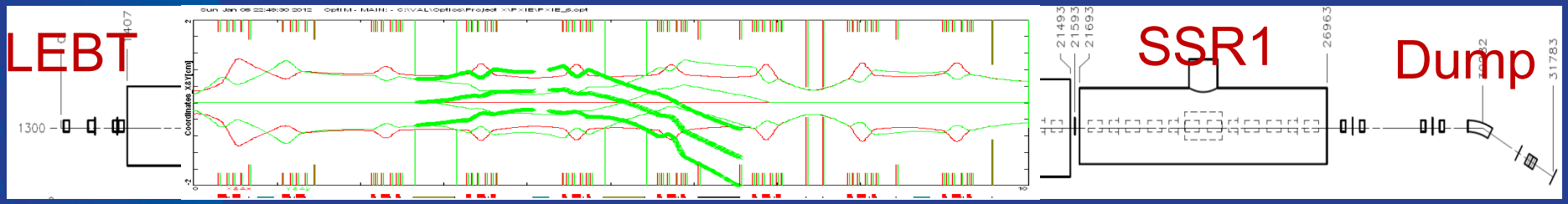

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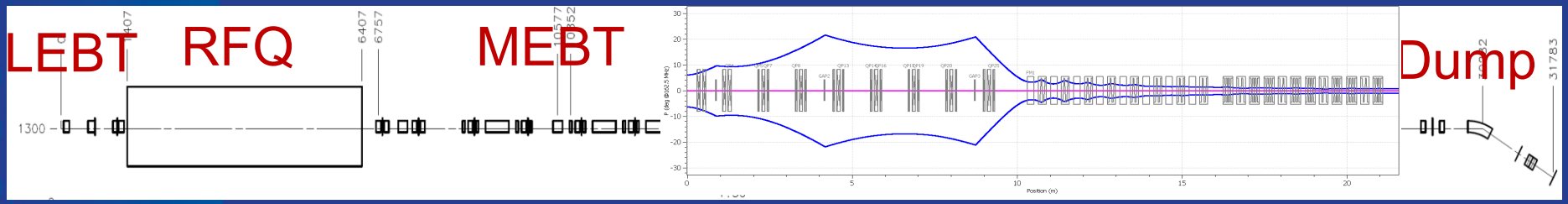
PXIE Program



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PXIE location

Other Invited Presentations on developing High Intensity Future Facilities at Fermilab

"Status and Plans for a Superconducting RF Test Facility at Fermilab"
(J. Liebfritz, MOOAC02)

"Accelerators for Intensity Frontier Research"
(P. Derwent, FRYBP01)

Project X Posters at IPAC-2012

- MOPPD041 Beam Loss Protection for a 2.3 Megawatt LBNE Proton Beam
- MOPPD043 Muon to Electron Conversion Experiments at Fermilab
- MOPPD068 Simulation Studies of the H- Beam Chopping in the LEBT of Project X
- MOPPR072 Fermilab PXIE Beam Diagnostics Development and Testing at the HINS Beam Facility
- TUPPC043 Design of Accumulator and Compressor Rings of the Neutrino Factory and Muon Collider Project-X Based Proton Driver
- WEPPC035 Design and Construction of a High-power RF Coupler for PXIE
- WEPPC039 Development of a Half-Wave Resonator for Project X
- WEPPC043 Transverse Kick Analysis of SSR1 due to Possible Geometrical Misalignments
- WEPPC044 Multipole Effects in the SSR2 Cavity of the Project X Front End
- WEPPC045 Optimization of the Geometric Beta for the SSR2 Cavities for Project X
- WEPPC046 Overview of Project X Superconducting RF Cavities and Cryo-modules
- WEPPC047 Effects of the RF Field Asymmetry in the SC Cavities of Project X
- WEPPC050 Main Couplers Design for Project X

Project X Posters at IPAC-2012

- THPPC086 A Conceptual Design of the Low Level RF Control System for Fermilab's Project X 3 to 8 GeV Pulsed Linac
- THPPP025 The Proton Improvement Plan at Fermilab
- THPPP054 A New Half-Wave Resonator Cryo-module Design for Project-X
- THPPP057 PXIE Optics and Layout
- THPPP058 PXIE: Project X Injector Experiment
- THPPP059 Development of the High Intensity Proton Accleelrator: Indian Institutions and Fermilab Collaboration.
- THPPP060 Studies of Collimation in the Project-X CW LIinac Front End.
- THPPP061 Adiabatic vs non-Adiabatic Acceleration in the Project-X CW Linac Front End
- THPPP063 Room Temperature Buncher for the Project X Front End
- THPPP064 Project X RFQ EM Design
- THPPP065 The FNAL Injector Upgrade Status
- THPPP090 Project X Functional Requirements Specification
- THPPP091 Status of the Project X CW Linac Lattice Design
- THPPP092 Progress of the Front-End System Development for Project X at LBNL.
- THPPP094 Simulation of the Fermilab Main Injector Including Space-Charge Effects, Non-Linear Multipoles, and Aperatures.
- THPPR012 Lorentz Force Compensation for Long Pulses in SRF cavities.
- THPPR041 Conceptual Design of the Shielding Layout and Beam Absorber at PXIE

Summary-
The High Intensity Horizon…

- Project-X is a staged evolution of the best assets of the Fermilab accelerator complex with the revolution in super-conducting RF technology.
- Each Stage of Project-X will raise many boats of the Intensity Frontier in particle physics, with a program scope of more than 20 world-leading particle physics experiments and an associated robust user community.
- The near term focused R&D for Project X is PXIE, and this effort in parallel with continuing critical SRF development could support a staged construction start for Project X as early as 2017.