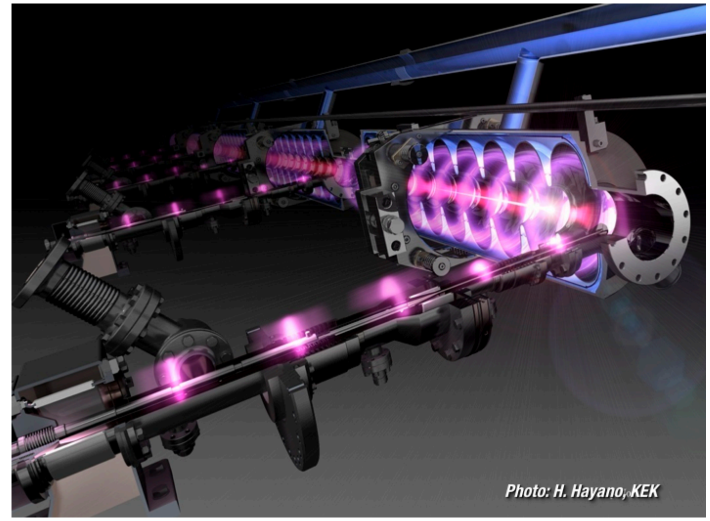

Muons and Kaons at the Intensity Frontier: How Project X Enables a World Leading Program

Argonne Intensity Frontier Workshop
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Fermilab

Life on the Intensity Frontier

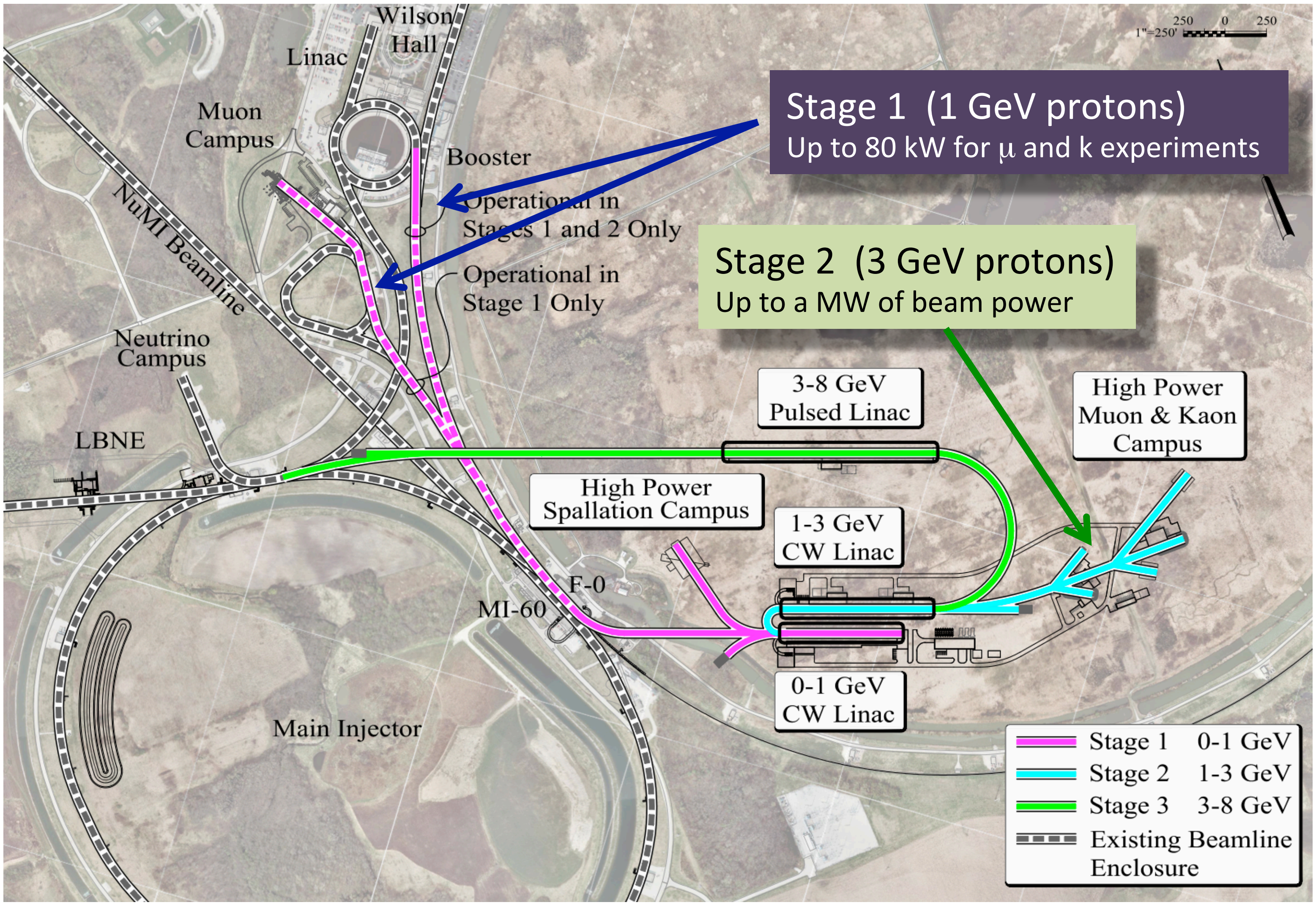
- Intensity Frontier physics is a campaign that often requires multiple steps
- Initial steps generate improved limits
  - Improvements are the result of better detectors, better beams and accumulated experience
- A subsequent step may lead to an observation of a few events
- Next step is a more precise measurement
- Eventually the discovery becomes a calibration for somebody else.
- "Yesterday's sensation is today's calibration and tomorrow's background"

Old saying/multiple attributions

Project X

- Project X is a unique opportunity to enable not just one physics campaign, but multiple communities of physicists.
  - Project X will provide, by a large margin, the best neutrino, kaon and muon beams.
  - The beam power and flexibility of Project X will make it possible to push the limits of sensitivity across a broad array of physics measurements.
- Project X will define the Intensity Frontier for a generation of physicists.
- In this presentation I will focus on kaons and muons, leaving neutrinos and EDMs to others.

Project X



Stage 1 (1 GeV protons)
Up to 80 kW for μ and k experiments

Stage 2 (3 GeV protons)
Up to a MW of beam power

Kaons @ Project X

- Kaons are a unique and prodigious laboratory that have contributed key pieces to the Standard Model.
- Kaons may still have more to teach us.
  - New CP and T violation
  - Universality
  - LFV
  - Searches for scalar and pseudoscalar interactions, exotics, ..
- Existing limits in kaon physics is impressive
- New and powerful tools are required to make continued progress.
  - Project X offers an unprecedented opportunity to find new physics with rare kaon decays.

Kaons at the Sensitivity Frontier Parts per Trillion

CERN NA62	100×10^{-12} measurement sensitivity of $K^+ \to e^+\nu$
Fermilab KTeV	20×10^{-12} measurement sensitivity of $K_L \to ee\mu\mu$
Fermilab KTeV	20×10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
BNL E949	20×10^{-12} measurement sensitivity for $K^+ \to \pi^+\nu\bar{\nu}$
BNL E871	1×10^{-12} measurement sensitivity for $K_L \to e^+e^-$
BNL E871	1×10^{-12} search sensitivity for $K_L \to \mu e$

Next goal: 1000-event $\pi\nu\bar{\nu}$ experiments - 10^{-14} sensitivity

World Class Kaon Physics Enabled by Project X

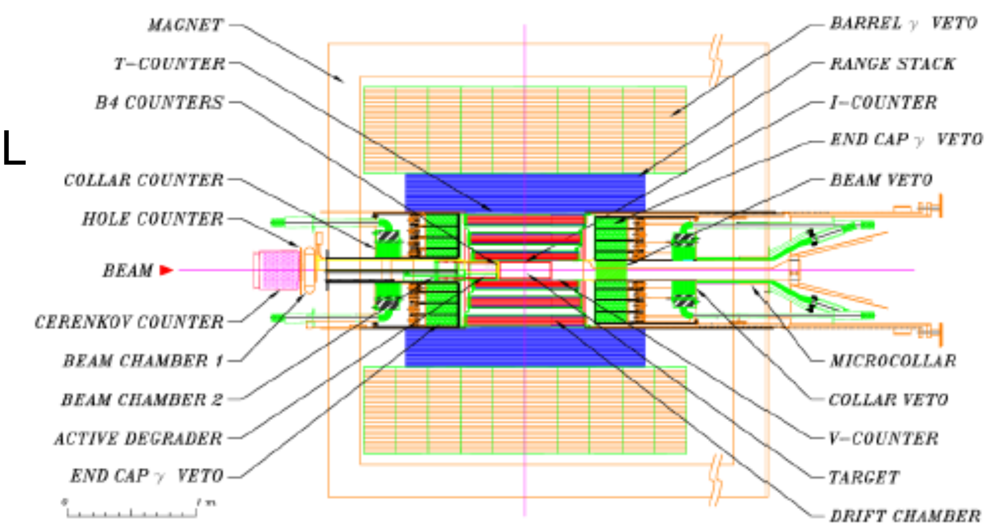
Day-1 Experiment using Stage 1 of PX

$K^+ \to \pi^+ \nu\bar{\nu}$	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 K0 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

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ @ Project X

- ORKA is a 4th generation experiment standing on the shoulders of the BNL program that observed a handful of events.
- Approved proposal (Stage 1) to run prior to Project X, but requires ~30% reduction in beam to NOvA in the out years.
- Stage 1 of Project X provides more protons (still uses ~30% of MI protons) and enables a broad menu of charged kaon physics.
  - Reuses CDF Detector Hall, infrastructure and magnet.
  - 100 times the sensitivity of BNL E949, reduced backgrounds
  - ×10 from beam power
  - ×10 from detector improvements



ORKA Research Opportunities

Broad, best in world program of charged kaon physics

$K^+ \to \pi^+ + \text{missing energy}$

- $K^+ \to \pi^+ \upsilon\bar{\upsilon}$
- $K^+ \to \pi^+ \upsilon\bar{\upsilon}\gamma$
- $K^+ \to \pi^+ X$
- $K^+ \to \pi^+ \tilde{x}_0 \tilde{x}_0$

$K^+ \to \pi^+ \pi^0 + \text{missing energy}$

- $K^+ \to \pi^+ \pi^0 \upsilon\bar{\upsilon}$
- $K^+ \to \pi^+ \pi^0 X$

$K^+ \to \mu^+ + \text{missing energy}$

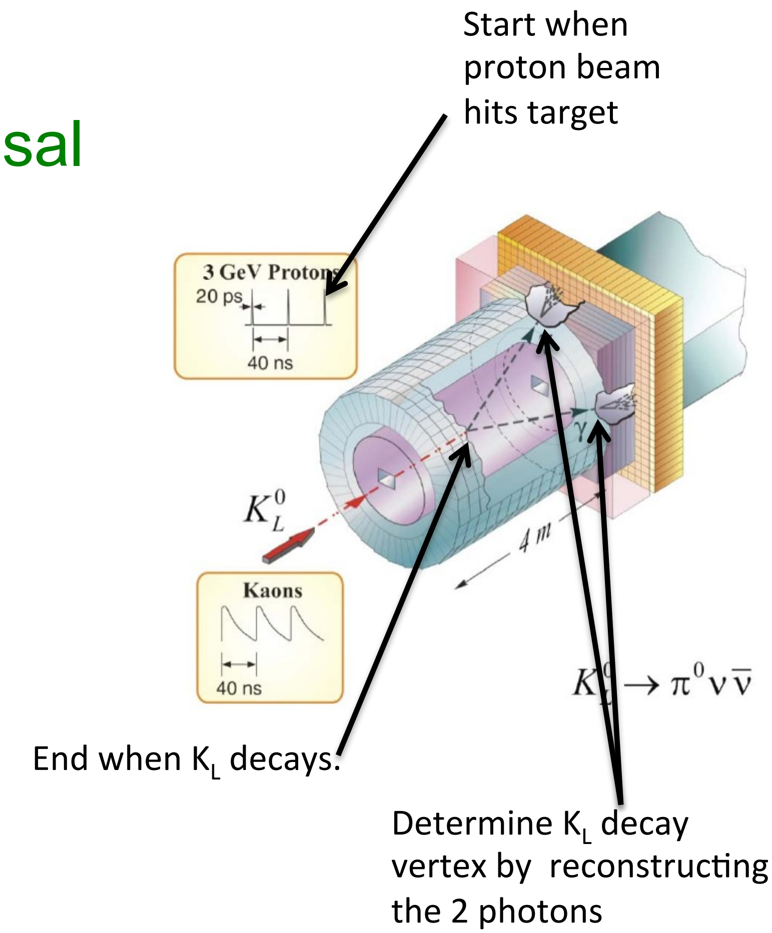
- $K^+ \to \mu^+ \nu_{heavy}$
- $K^+ \to \mu^+ \nu M (M = Majoran)$
- $K^+ \to \pi^+ \upsilon\bar{\upsilon}\nu$

- $K^+ \to \pi^+ \gamma$
- $K^+ \to \pi^+ \gamma\gamma$
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+ e^+ e^-$
- K^+ lifetime
- $\mathrm{B}(K^+ \to \pi^+ \pi^0) / B(K^+ \to \mu^+ \nu)$
- $K^+ \to \pi^+ \pi^0 e^+ e^-$
- $K^+ \to \pi^- \mu^+ \mu^- \ (LFV)$
- $\pi^0 \to nothing$
- $\pi^0 \to \gamma e^+ e^-$
- $\pi^0 \to \gamma X$

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ Project X

Stage 2 of Project X enables an improved version of the KOPIO proposal

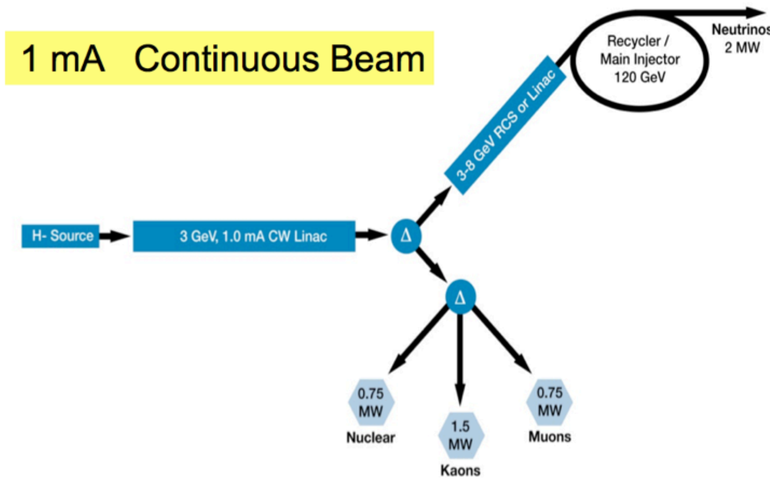
- Nothing in, nothing out
- Standard Model BR ~ 3×10^{-11}
  - Need ~10^{15} K_L to observe 1000 at 1% efficiency
- Use TOF to work in K_L c.m. system
  - Reconstruct $\pi^0 \rightarrow \gamma\gamma$ with a pointing calorimeter
- $K_L \rightarrow \pi^0\pi^0$ is primary background
  - 4π photon and charged particle veto
  - Veto inefficiency must be < 10^{-4}



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ Project X

Advantages provided by Project X

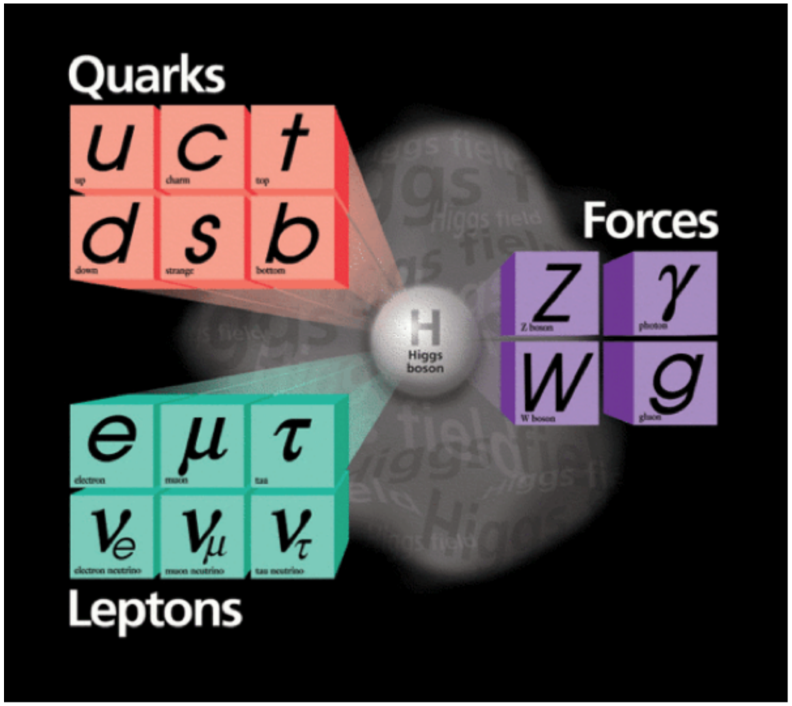
- 20 ps wide proton bunches allows accurate determination of K_L production time
- >>10^{-3} extinction suppresses inter-bunch background
- High beam power permits use of pencil beam
  - Significant improvement from KOPIO
  - Simpler beam line
  - More hermetic detector
  - Symmetric beam, detector maximizes acceptance
  - 2-D Beam kinematic constraint increases S/B



	Beam Energy	Target (Λ_I)	K_L/second (into 500 μsr)	K_L/n Ratio (En > 10 MeV)
BNL AGS	24 GeV	1.1 Platinum	60×10^6	~1:1000
Project X	3.0 GeV	1.0 Carbon	450×10^6	~1:2700

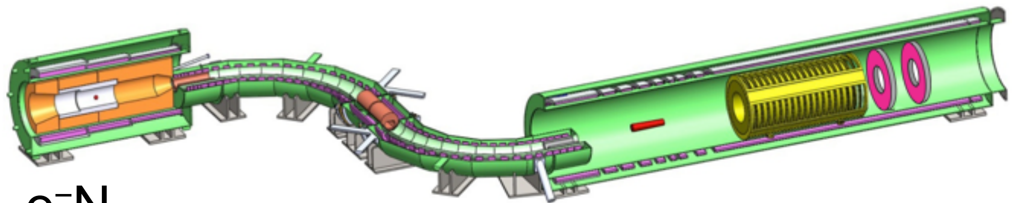
Muons and the Intensity Frontier

- Muons provide broad discovery potential, excellent reach and access to highest mass scales.
  - Easily made in large numbers
  - No confinement considerations
  - Relatively long life time 2.2 μs
  - Relatively heavy $(m_\mu/m_e)^2 = 40000$
- Fermilab program includes 2 muon experiments this decade using Booster beam and a full menu of interesting future possibilities enabled by Project X.

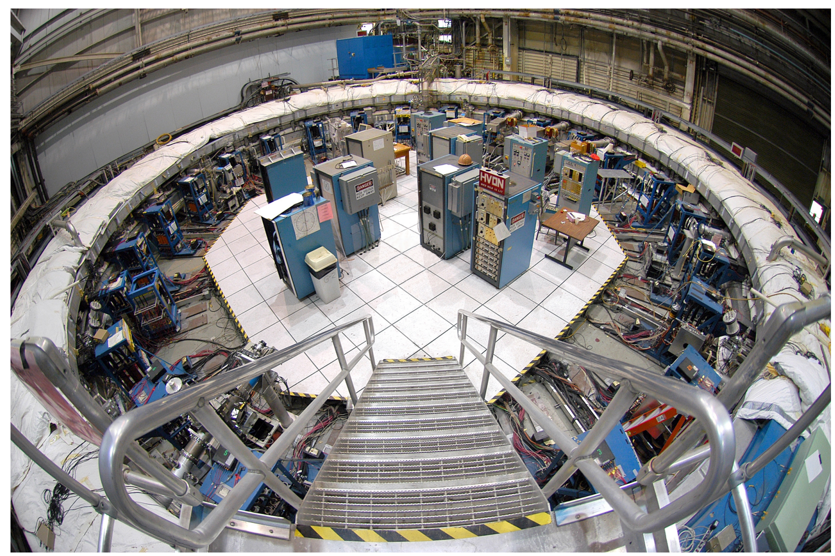


Muon Physics in the Booster Era

- Mu2e
  - x10,000 improvement over Sindrum II for $\mu^- N \rightarrow e^- N$
  - Extraordinary physics sensitivity and mass reach
  - Begins data taking in 2019



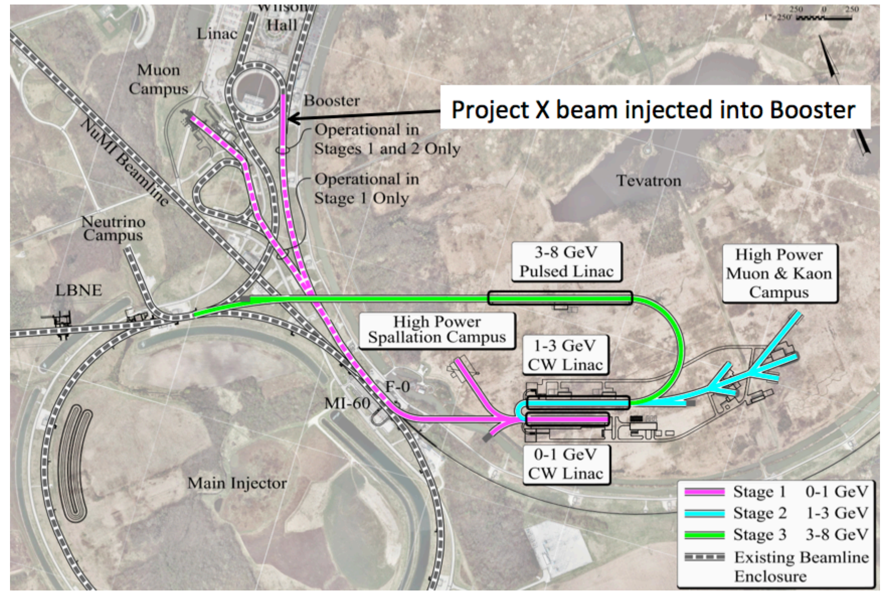
- g-2
  - Current result is statistics limited
    - 3.6 σ difference from S.M.
  - Statistics and systematics can be improved using FNAL Booster
    - If the current discrepancy persists $\Rightarrow$ 5.6 σ discovery
    - Begins data taking in 2016-17



g-2 @ Project X

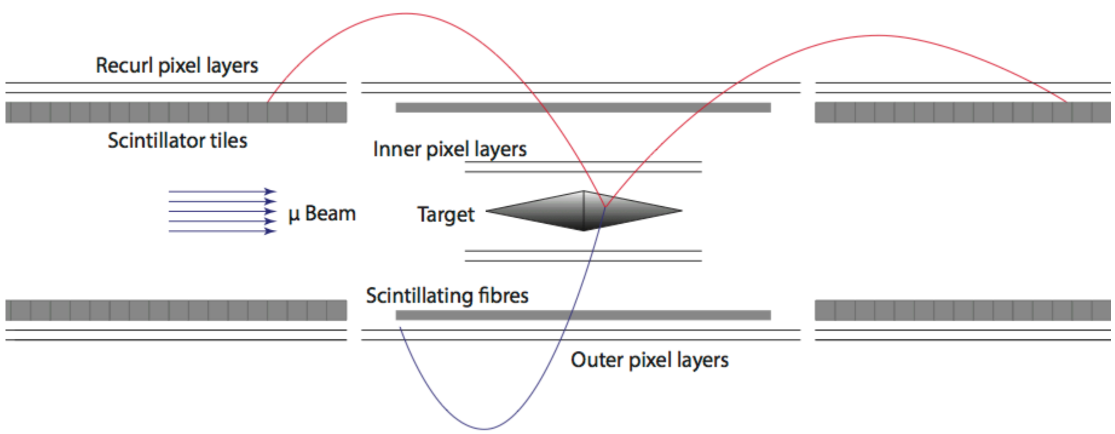
Why run g-2 at Project X?

- Improvement in theory or motivation from LHC
- Repeat measurement with μ^-
  - π^- down by x 2.5 relative to π^+ with 8 GeV protons
  - Systematic check (reverse B field)
  - Reduce overall error by another 20%



$\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

- MEG upgrade at PSI aims for $B(\mu \rightarrow e\gamma) \sim 6 \times 10^{-14}$ (SES)
- Mu3e proposal approved at PSI
  - Phase I uses MEG beamline to provide ~ 10^8 μ^+/s to get to 10^{-15}
  - Phase II assumes construction of new high intensity beam at PSI spallation neutron source to reach 10^{-16}



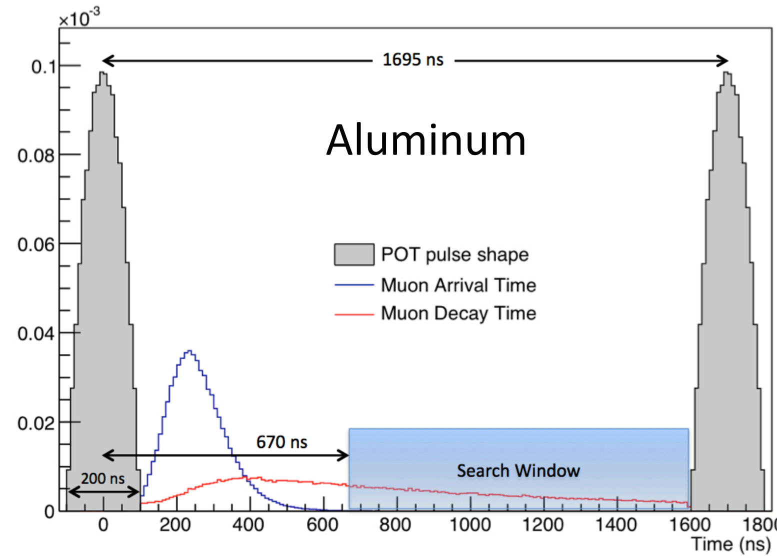
- Project X can provide the necessary beam to push these measurements beyond PSI sensitivities, but…

$\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

- Combinatorial background limits sensitivity
- For $\mu \rightarrow e\gamma$ combinatorial background increases quadratically with muon stopping rate while sensitivity increases linearly
- Similar limitations for $\mu \rightarrow 3e$
- Project X can provide the beam. The real questions are on the experimental side.
- New ideas and techniques required to make additional progress on these modes. Heard some good ideas yesterday from Winter, Cheng, Echenard and Brown
  - Improved timing and mass resolution required
  - Active target can help reduce accidentals
  - Distributed target?
- More work is required to understand if experiments at Project X make sense for these modes.

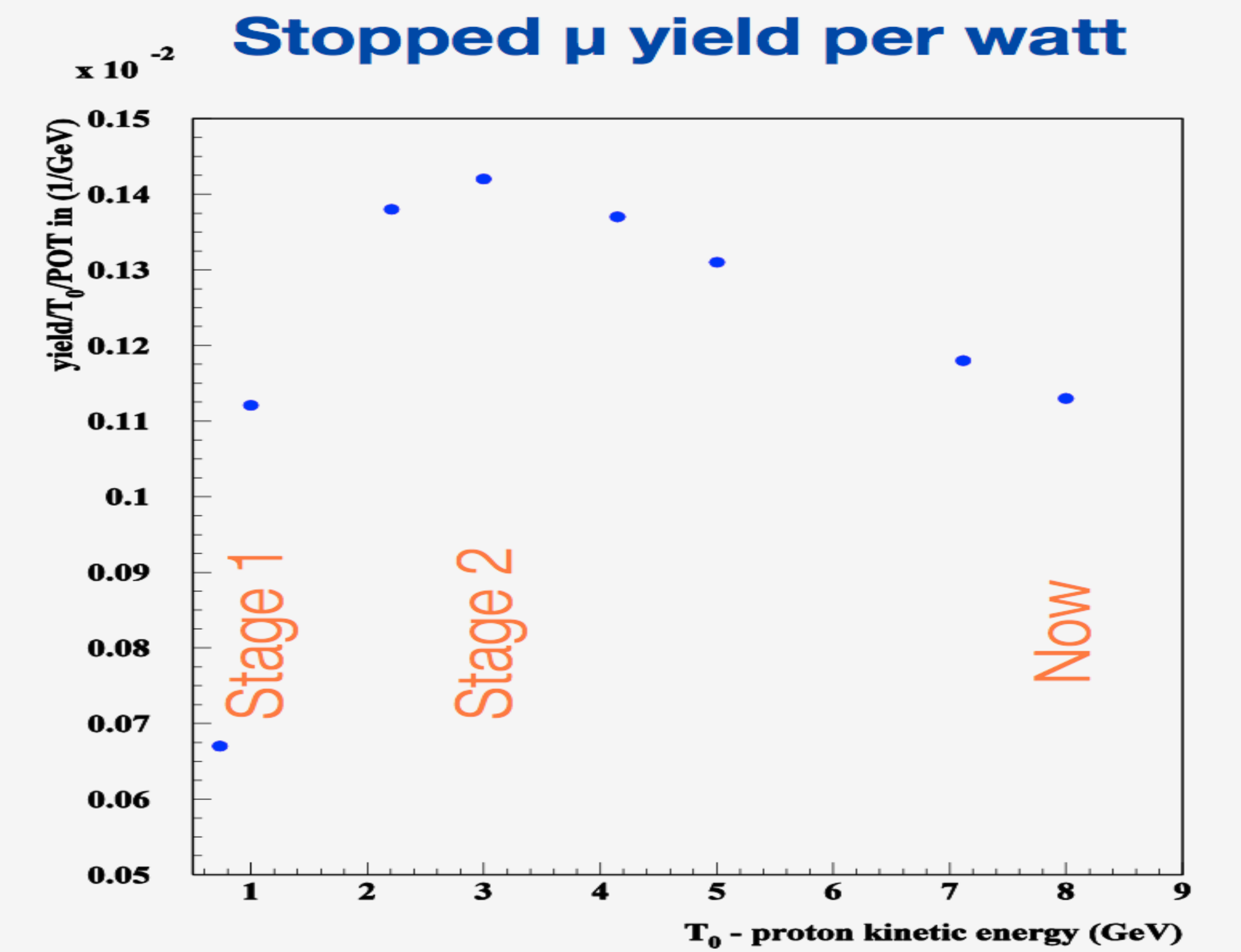
Mu2e X

- Mu2e uses 8 GeV protons from Booster
  - 200 ns wide pulses
  - 1695 ns pulse spacing
  - ~10^{10} Hz of stopped μ^-
  - Delayed search window
- First stage of Project X could provide up to x10 more beam power.
  - 1 GeV protons – no pbar background
  - Narrower proton pulses (50 - 100 ns)
  - Flexible beam structure



- Second stage of Project X could provide x100 more beam power at new high intensity Muon/Kaon Campus
  - 3 GeV protons optimize muon production
  - Need new ideas to accommodate beam power, high rates, eliminate pions
    - FFAG Ring? Helical cooling channel?

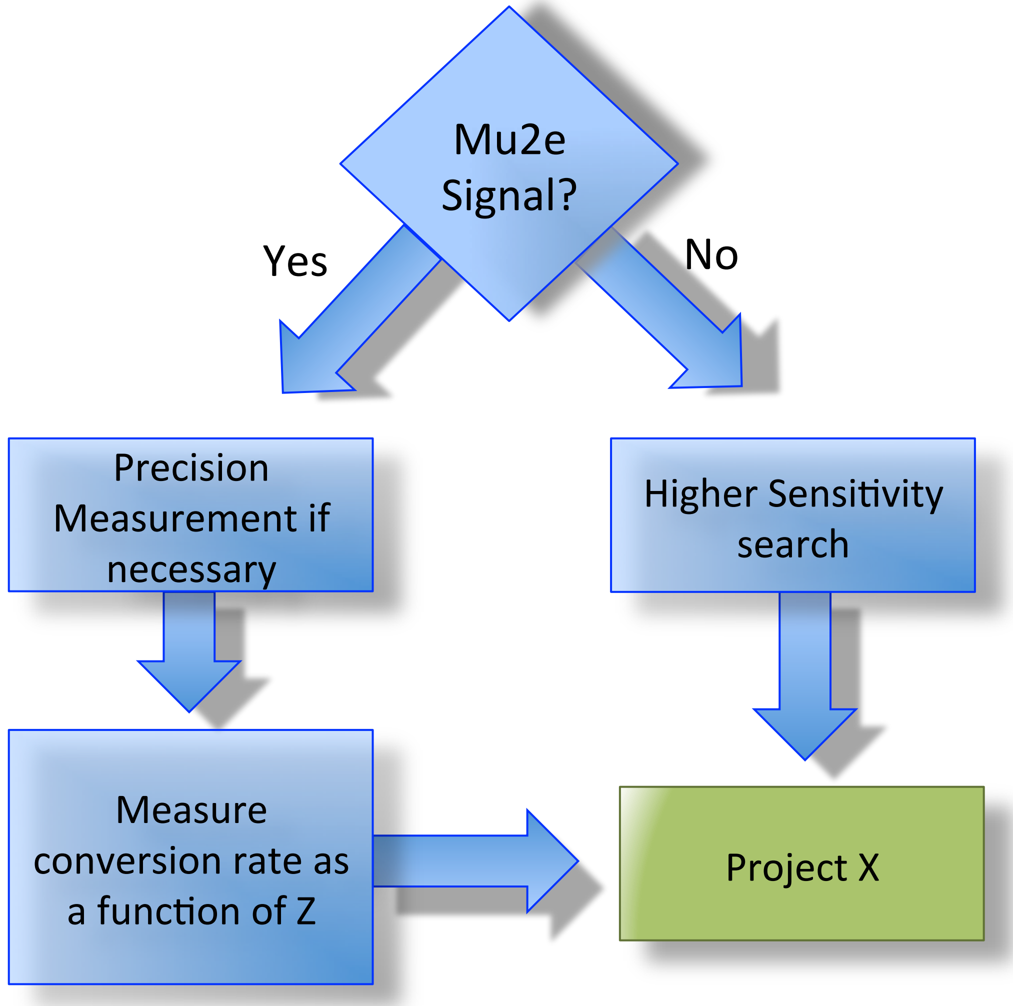
Project X Beam Energy



Negative muons at entrance to μ2e detector solenoid

S. Striganov *et al.*

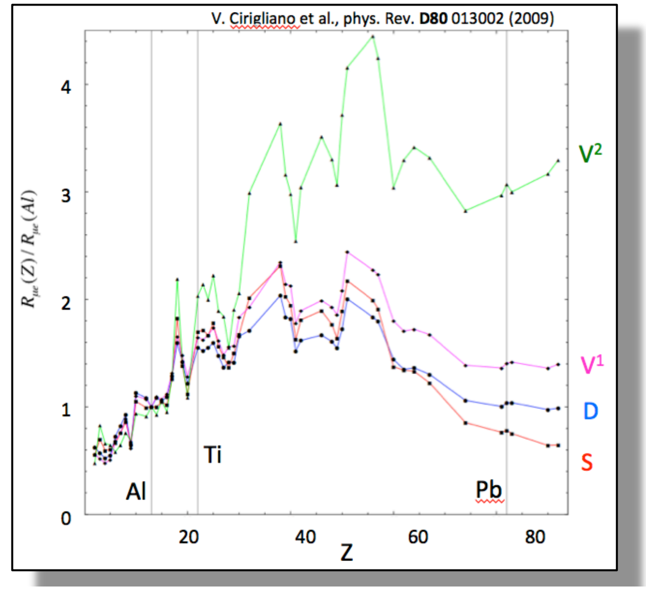
First Phase of Mu2e

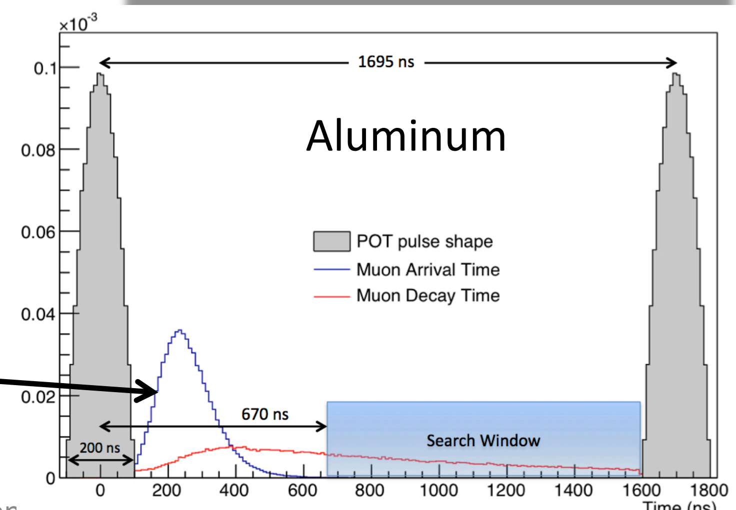


Mu2e Sees a Signal

- If Mu2e sees a signal in its initial run, next step is to map out conversion rate for various target nuclei where model dependent effects vary by a factor of 3.
- However, muon lifetime varies with Z
  - Big impact on execution of measurement

Nucleus (Z)	Muon Lifetime (ns)
Al(13)	864
Ti(22)	329
Au(79)	73



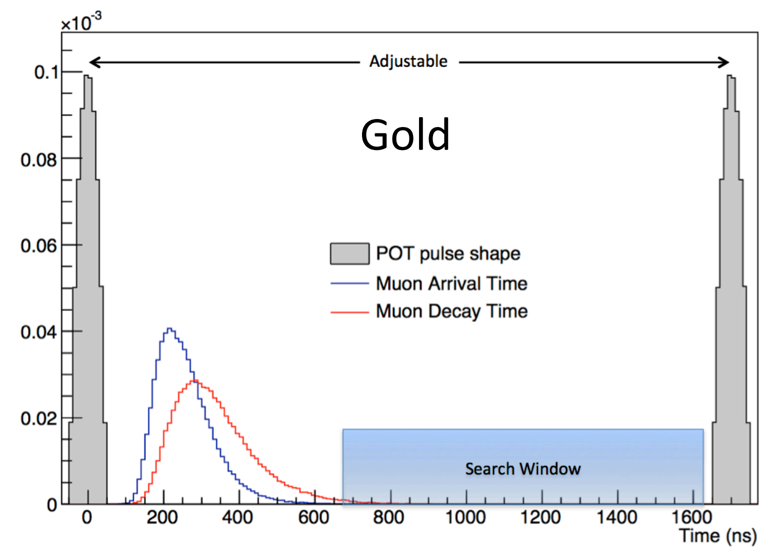


Arrival time of μ/π at stopping target
Increase in muon decays and RPC as one looks earlier in time

Mu2e Sees a Signal

Stage 1 of Project X makes these measurements possible with the existing solenoid system.

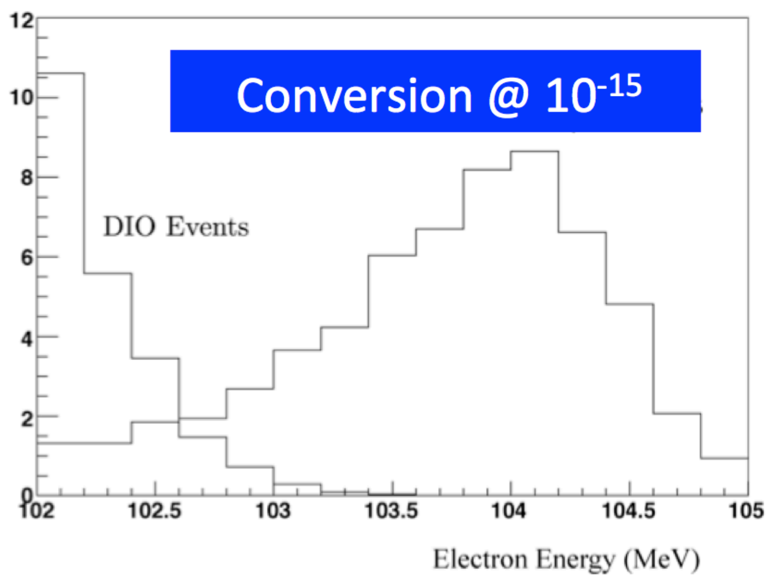
- Narrower proton beam pulse, intrinsic extinction and beam power enables use of stopping targets with shorter muon lifetimes
  - Limit to how early we can search due to muon decay in-flight and RPC background, assuming same background level required.
  - Rely on beam power to wait more muon lifetimes
    - Instantaneous rates decrease with time – reduces backgrounds
  - Flexible time structure allows us to wait longer than 1695 ns if desirable
    - Optimization different for different target nuclei.



Mu2e Does Not See a Signal

Stage I of Project X makes it possible to push the sensitivity another order of magnitude.

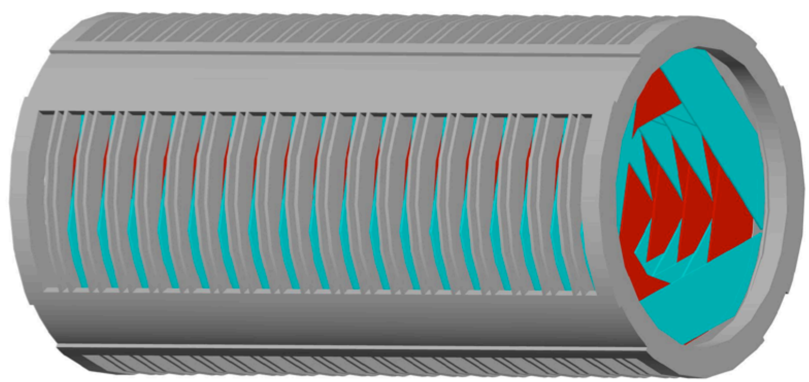
- Reductions in background also required. (See Doug Glenzinski's talk)
  - Narrow proton beam pulse and intrinsic extinction provided by Project X reduces prompt backgrounds.
  - No pbar background with 1 GeV protons.
- Improved momentum resolution required to reduce DIO background.



Mu2e Does Not See a Signal

Momentum resolution depends on

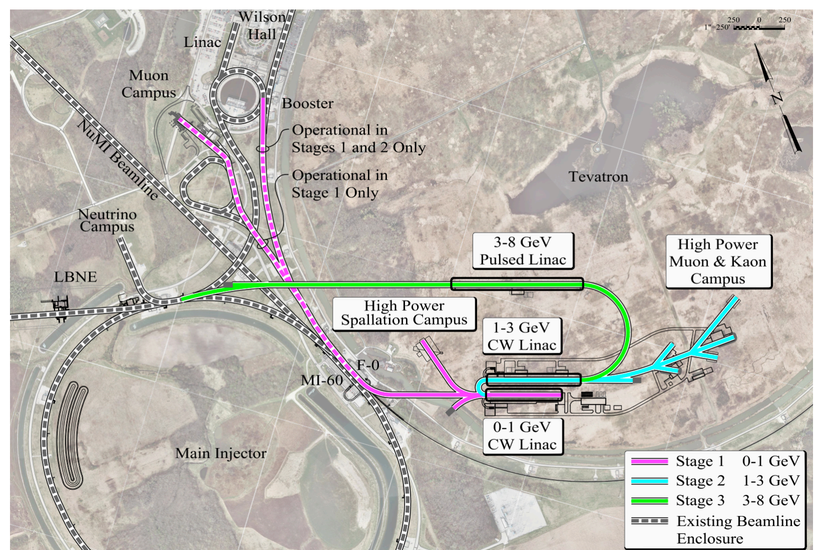
- Target straggling
  - Can possibly be improved with smarter geometry
- Material between stopping target and tracker
  - Some material is likely required to absorb protons. Mu2e has not fully studied this yet.
- Multiple scattering in tracker
  - Thinner Mylar?
  - Different technology?
  - R&D required



Project X Staging Plan

	Present complex with PIP*	Stage 1 Project X 1 GeV CW Linac	Stage 2 Project X 3 GeV CW Linac
8 GeV Muon	20 kW	0 – 20 kW	0 – 20 kW
1 GeV Muon	None	80 kW	none
3 GeV Muon	None	None	1000 kW
Kaon Program	0 – 30 kW	0 – 75 kW	1100 kW

* PIP = Proton Improvement Plan



Example of an Experimental Program

	Present complex with PIP*	Stage 1 Project X 1 GeV CW Linac	Stage 2 Project X 3 Gev CW Linac
Mu2e	X	X	X
g-2	X	X (1 GeV into Booster)	
$\mu \rightarrow e\gamma$			X
$\mu \rightarrow 3e$			X
K^+ measurements	X	X	X
K_L measurements			X
EDM		X	X

* PIP = Proton Improvement Plan

Summary

- Project X is an ideal platform for the next generation of kaon and muon experiments
  - Beam power and flexible beam parameters enable a broad program that addresses the unique requirements of each measurement.
  - Deliver substantial beam power simultaneously to multiple programs
  - Each stage of Project X is affordable and produces world class science
  - Staging of Project X matches well with the steps that can be made on the experimental side.
- When we build it, the world will come
  - At least the part of the world that is interested in neutrino, kaon and muon physics.