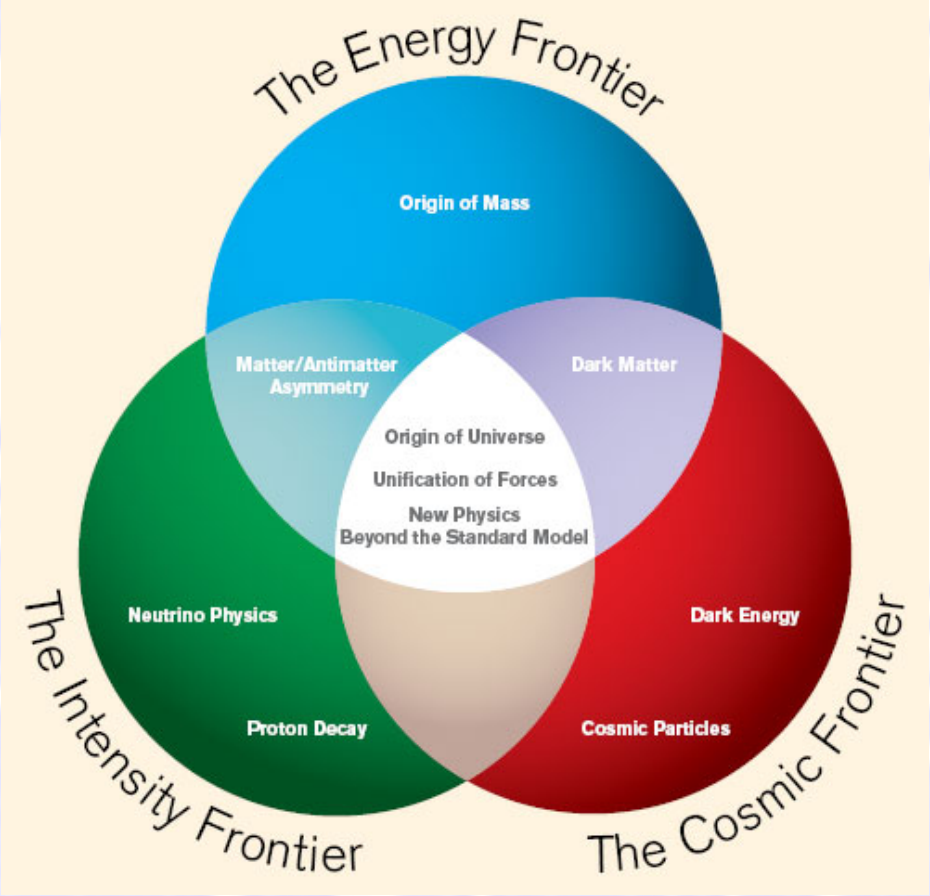
Fermilab Research Program Requirements of High Speed Readout Systems Relevant for Avalanche Geiger Mode Devices



Experimental Requirements

- Discussion of experimental requirements, rather than technical solutions. Example requirements:

- Operating in a high magnetic field (>1T)
- Operating in a high radiation environment (e.g. >10^{12} neutron exposure)
- Precision timing.
- Precision calorimetry
- Tagging efficiency
- Rate environment
- Threshold requirements
- Spectrum sensitivity

The Energy Frontier

Tevatron

LHC

Lepton Collider

(energy to be determined)

(technology, site to be determined)

March 2012
R. Tschirhart

Fermilab

CMS Hadron Calorimter Readout Requirements

- Requirement:

Low resolution calorimeter cells operating in high radiation field and a high magnetic field.

Advanced pre-conceptual design, draft specifications:

- area: ~5 mm2 (2.5 mm in dia)
- number of cells: ~22000
- cell recovery time: <8 ns
- operating voltage: < 100 V
- gain: (2-5)x10^5
- PDE(515nm): >15 %
- capacitance: <300 pF
- dark count: <5 MHz
- neutron dose: 5x10^{12}
- Temperature vs gain: not too important, < 5% per degree C

CMS Forward Proton TOF Readout Requirements

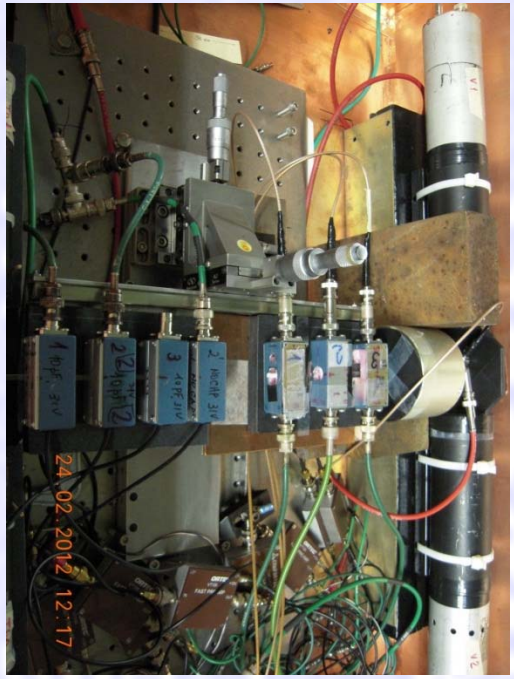
- Requirement:

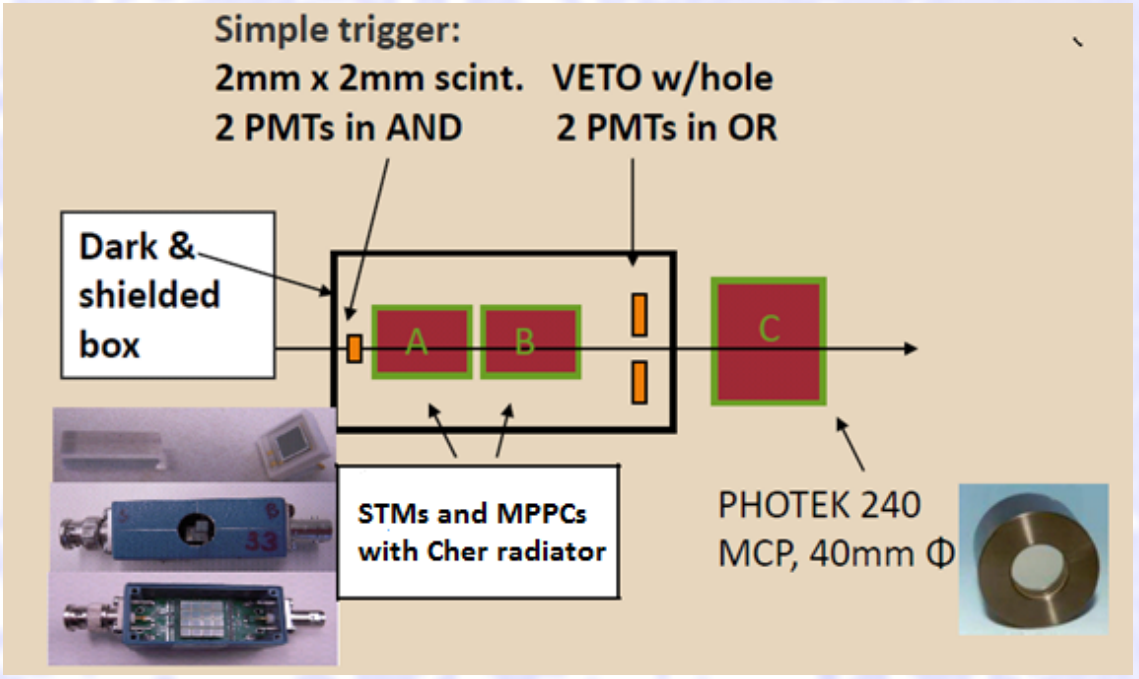
Provide breakthrough Time-of-Flight (10 psec) on elastic scattered protons at CMS in a high radiation environment and high magnetic field.

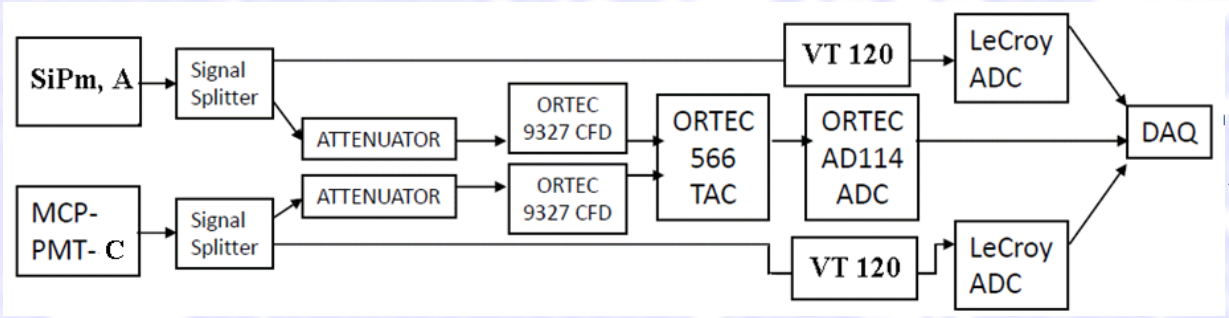
Some specifications:

T-979 Setup in Fermilab Test Beam Facility (FTBF)

Time interval between “start” (SiPm) and “stop” (SiPm or Photek 240) signals is measured value. Beam: 120 GeV protons. Light is generated in fused silica radiator for the SiPms and in the Photek 240 input window at normal particle incidence.



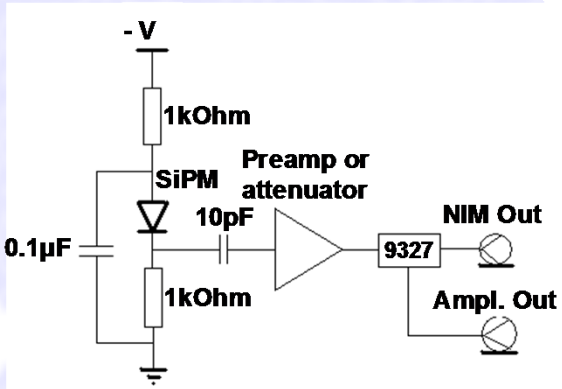




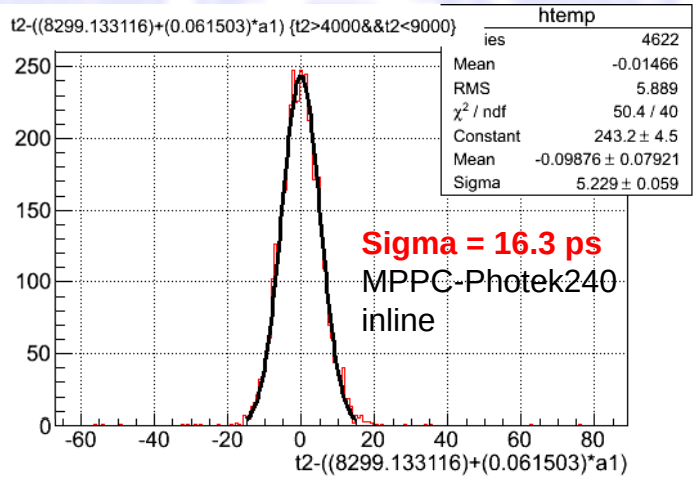
ORTEC readout:
CFD – constant fraction discriminator,
TAC – time amplitude converter,
ADC – analog to digital converter,
~16,000 channels, 3.1 ps/ch
“Electronic” time resolution (ETR) is 2 ps.

Courtesy A. Ronzhin

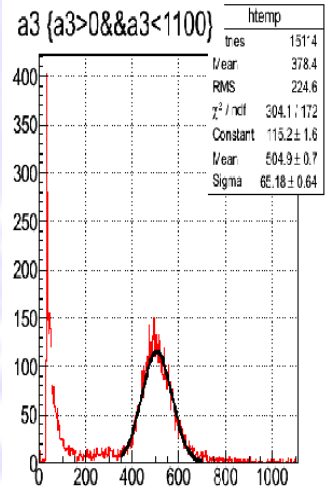
STM signal must be clipped to fit Ortec 9327 CFD (<5 ns, FWHM), previous best tb result – 14.5 ps, sigma



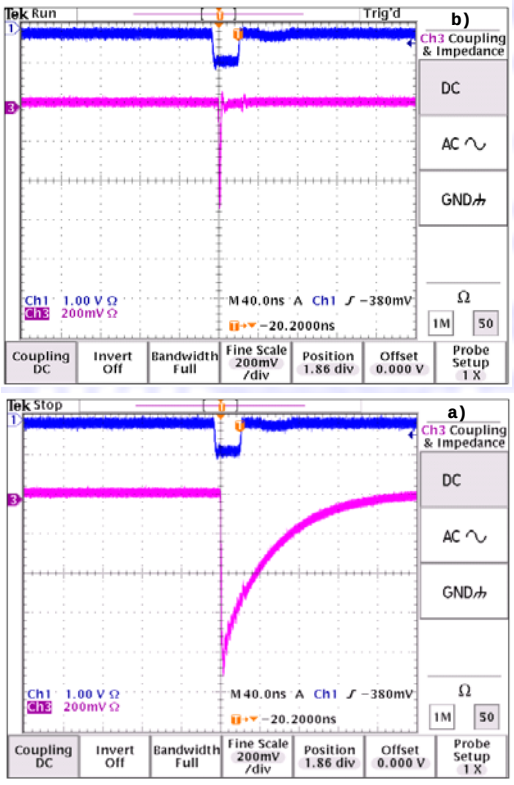
Schematic of STM biasing and readout



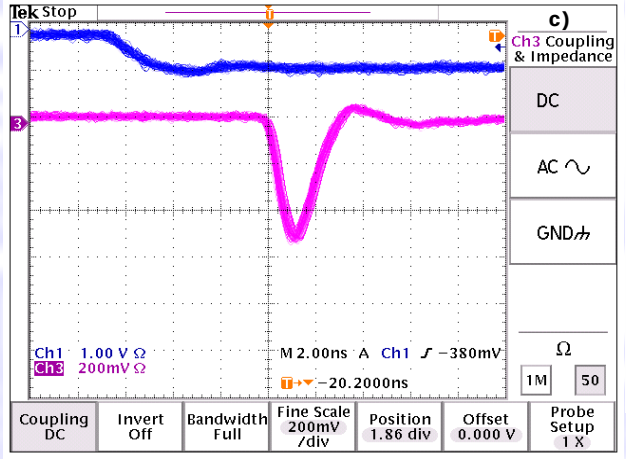
Timing difference spectrum for signals coming from MPPC (radiator is fused silica, 3x3x30 mm3) and Photek 240 (radiator is input window, 9.6 mm thick). 120 GeV protons. Normal incidence. The MPPC time resolution is 14.5 ps. Soft pulse height cuts and slewing correction applied. Both "start" and "stop" counters located next to each other.



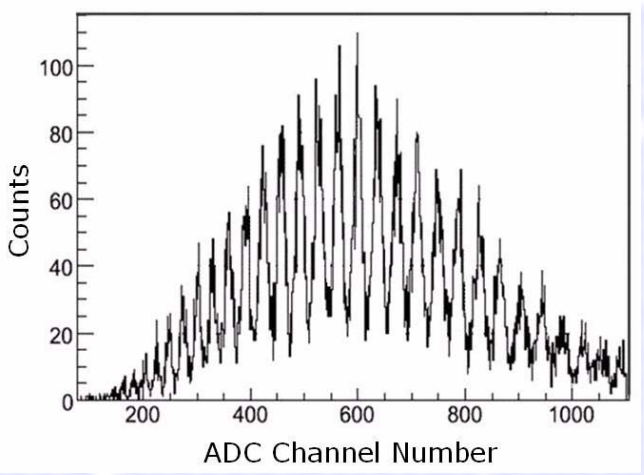
The MPPC pulse height spectrum, 120 GeV protons. Quartz radiator, 3x3x30 mm3 N of photoelectrons ~ 60 phes



STM signals with (top) and w/o (b) clipping capacitance, 40 ns scale



STM signal with clip cap, 2 ns scale



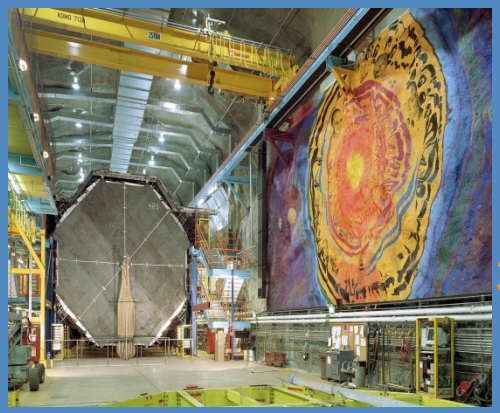
STM pulse height spectrum, mean number of photoelectrons = 17 phes. STM is 3.5x3.5mm2, 4900 pixels, 48x48um2 pixel size, 3.5V of OV.

Courtesy A. Ronzhin

Energy Frontier Requirements

	High Magnetic Field (> 1T)	High Rad Environ	Tagging efficiency	Precision Calorimetry	Precision timing	Pixel level data	Low Dark Rate	Low Thresholds (< 3 p.e.)	Low Wavelength Sensitivity (< 200 nm)
CMS HCAL	YES	YES $>10^5$ n	99%	NO	1000 psec	NO	NO	YES ()	NO
CMS TOF	NO	YES	99%	NO	**YES** 10 psec	NO	NO	YES ()	NO
Dual Readout Calorimetry	YES	YES	99.9%	YES	100 psec	YES	YES	YES	YES
Digital HCAL	YES	YES	99.9%	NO	100 psec	YES	YES	YES	NO
Digital SiPM tracking	YES	YES	99%	NO	100 psec	YES	YES	NO	N/A

Intensity Frontier Accelerators (now)



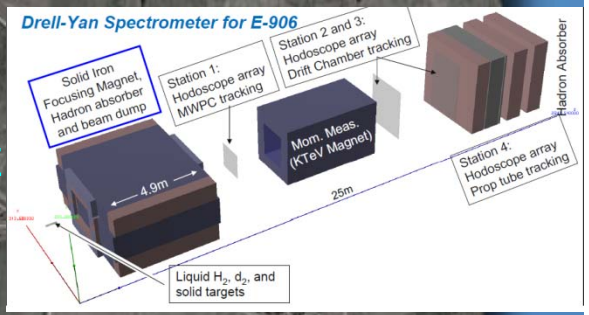
MINOS at 735 km

350 kW
@120 GeV

SCRF Test Facility
(Integrated program for Project X and ILC)

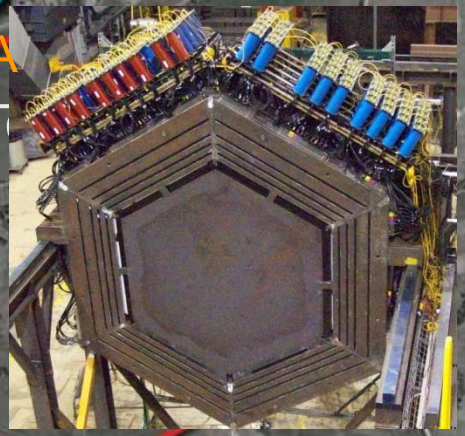
Testbeam

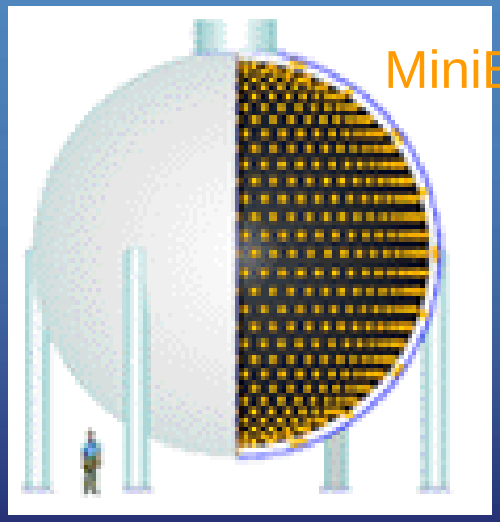
SeaQuest



MINERvA

T

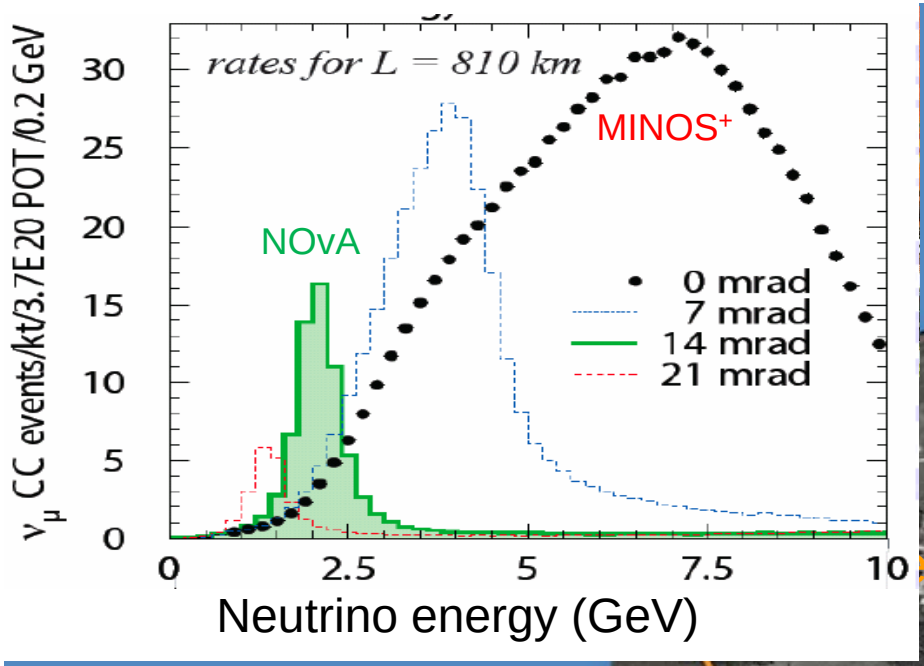




MiniBooNE

8 GeV

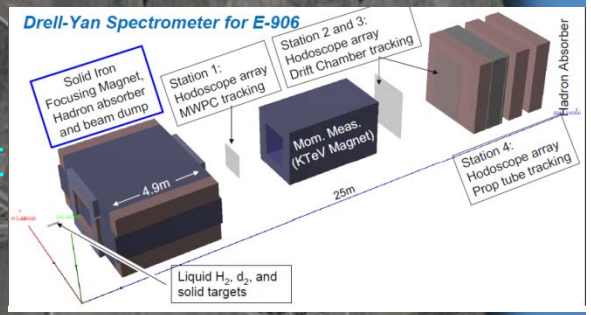
Intensity Frontier Accelerators from Spring 2013

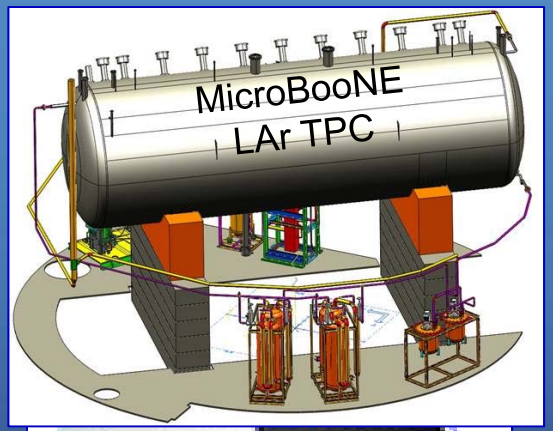


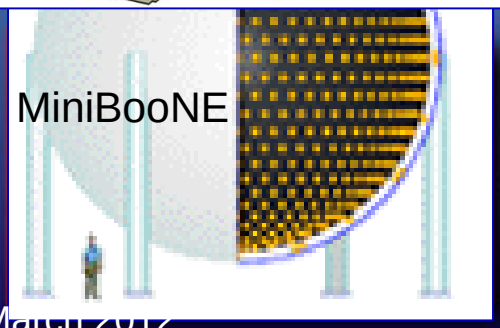
SCRF Test Facility with bright beams
(Project X, ILC, Accelerator Science)

Testbeam

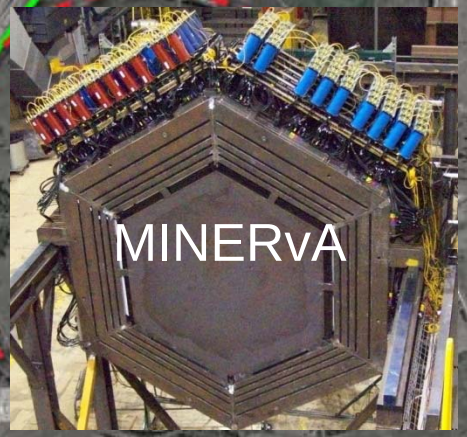
SeaQuest





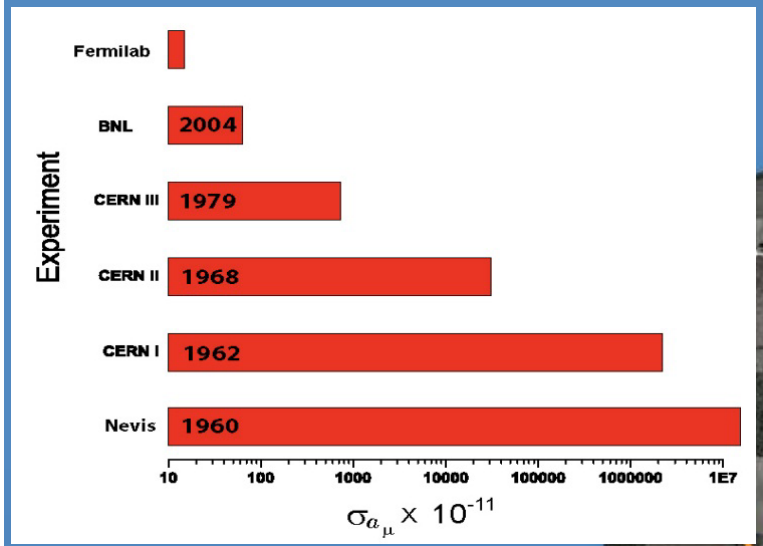


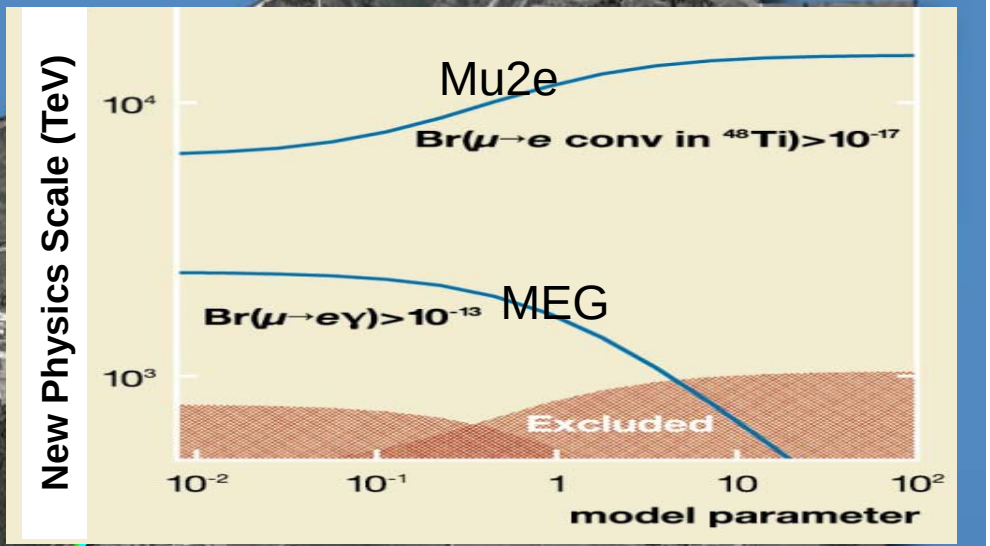
8 GeV



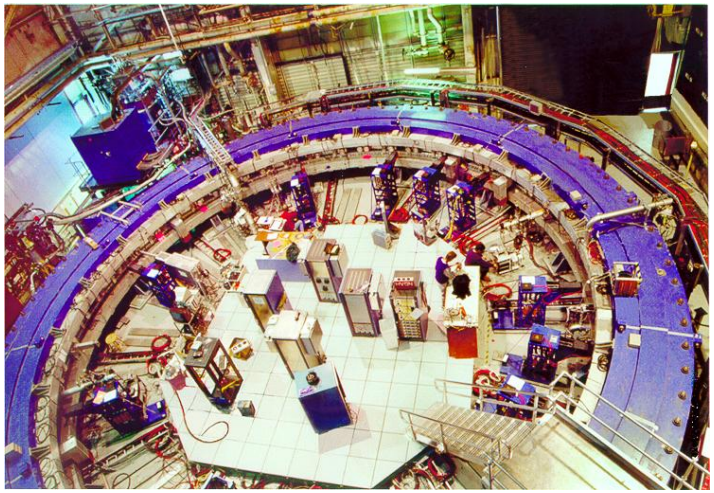
Muons g-2 (μ anomalous magnetic moment)
Mu2e (μ → e conversion)

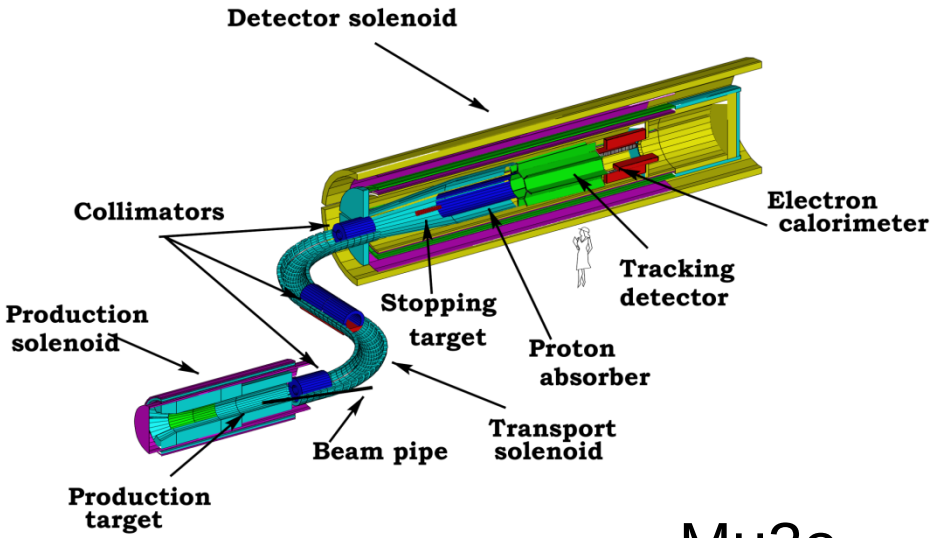
This decade





Muon g-2 (BNL → FNAL)





Mu2e

g-2 Electron tagger/calorimeter Readout Requirements

- **Requirement:**

Tag high energy electrons (> 1GeV) and *accurately* associate a time, while operating in a high rate environment through the use of high performance WFD techniques with optimzed pulse shaping.

Some specifications:

Rate per channel less than 500 kHz

- Gain stability versus time at 0.1% on millisec time scale
- Gain stability versus rate at 0.1% up to 500 kHz
- Must clearly resolve two pulses separated by 5 ns.

Ongoing g-2 Readout Studies

- Pulse profiles, etc from D. Hertzog expected.

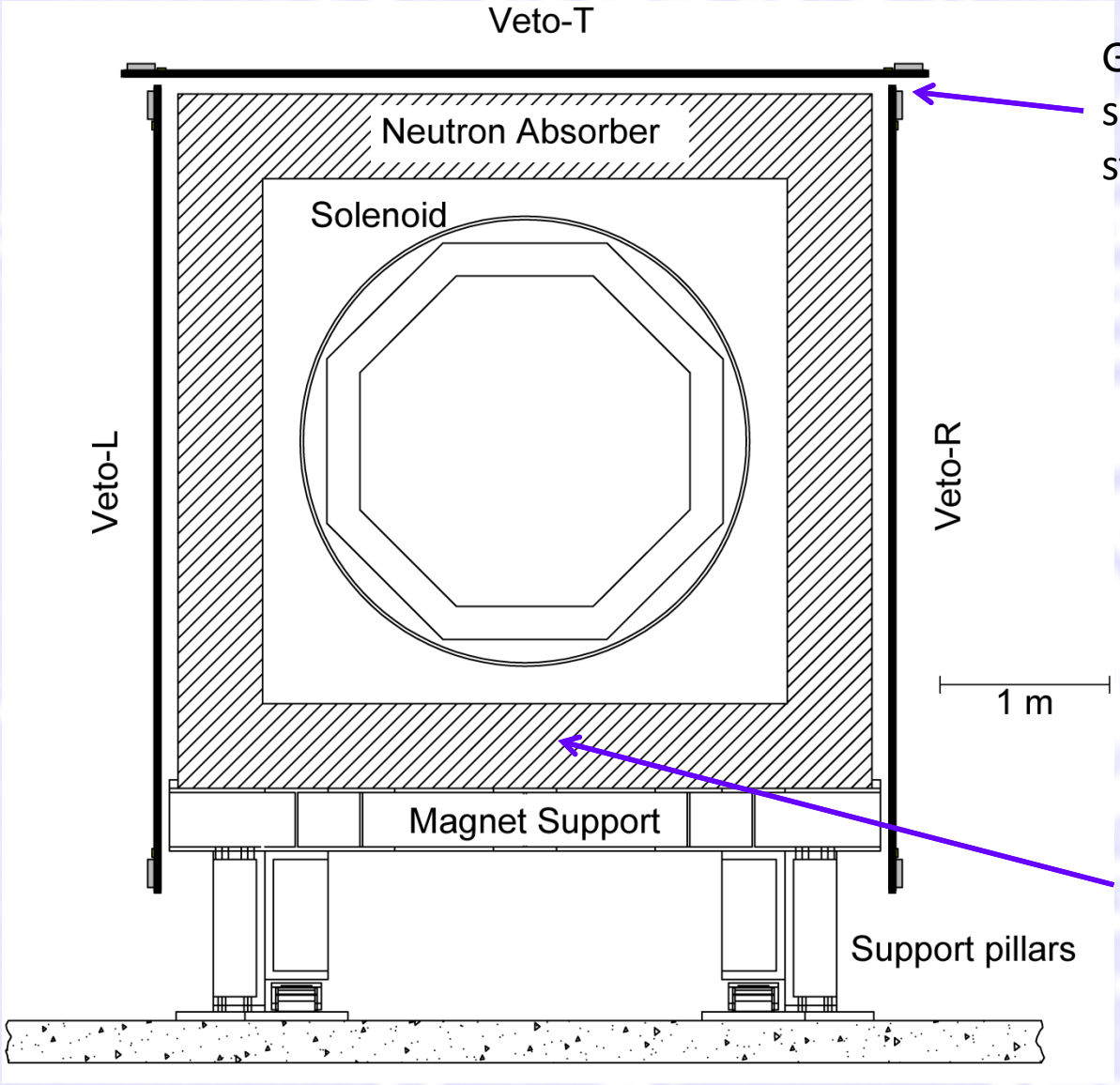
Mu2e Calorimeter & Cosmic Ray Veto Readout Requirements

- Requirements:

Calorimetry: Tag a 100 MeV/c electron in a high magnetic field in vacuum, modest radiation environment, energy resolution < 5 MeV.

Cosmic Veto: Veto shield to tag cosmic rays that can emulate/create a 100 MeV/c within the detector volume. Tag efficiency > 99.99%.

CRV Layout: Upstream End Elevation View



Gap for support structure

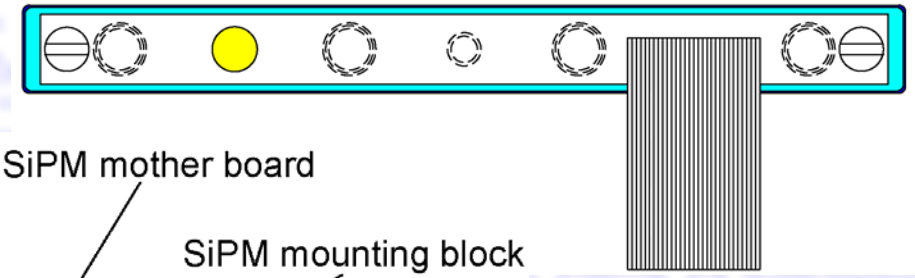
Bottom neutron absorber will be gone

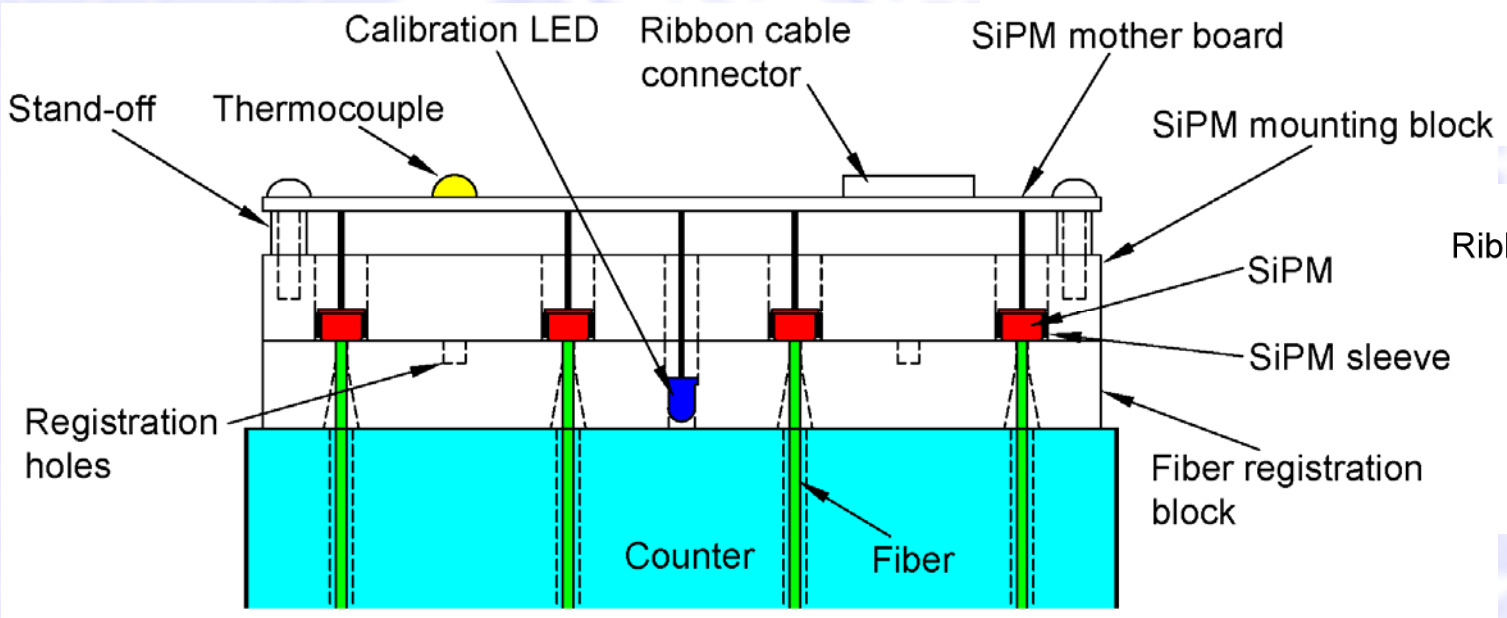
Mu2e Counter Design

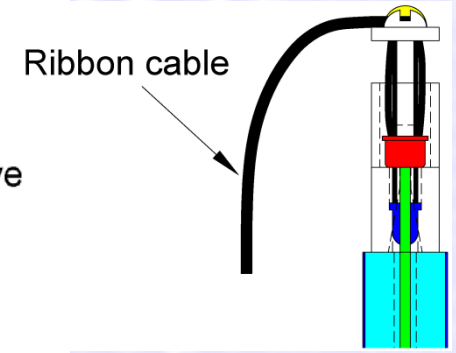
- Fiber registration block
  - glued to counter
  - conical sleeve forces fiber alignment
  - fiber potted and then entire block fly cut
  - hole for LED/fiber for calibration purposes
- SiPM mounting block
  - glued to fiber registration block
  - aligned to fiber registration block with holes
  - SiPMs mounted on sleeves
- SiPM mother board
  - screws into SiPM mounting block
  - SiPM leads used as springs
  - ribbon cable goes to front-end board

Note:
1. counters can be made (including fly cutting) and tested before being assembled into modules
2. if a SiPM fails the entire mother board is easily replaced
3. minimal dead space (~4 cm) at counter ends

Guarino, Dukes, Rubinov

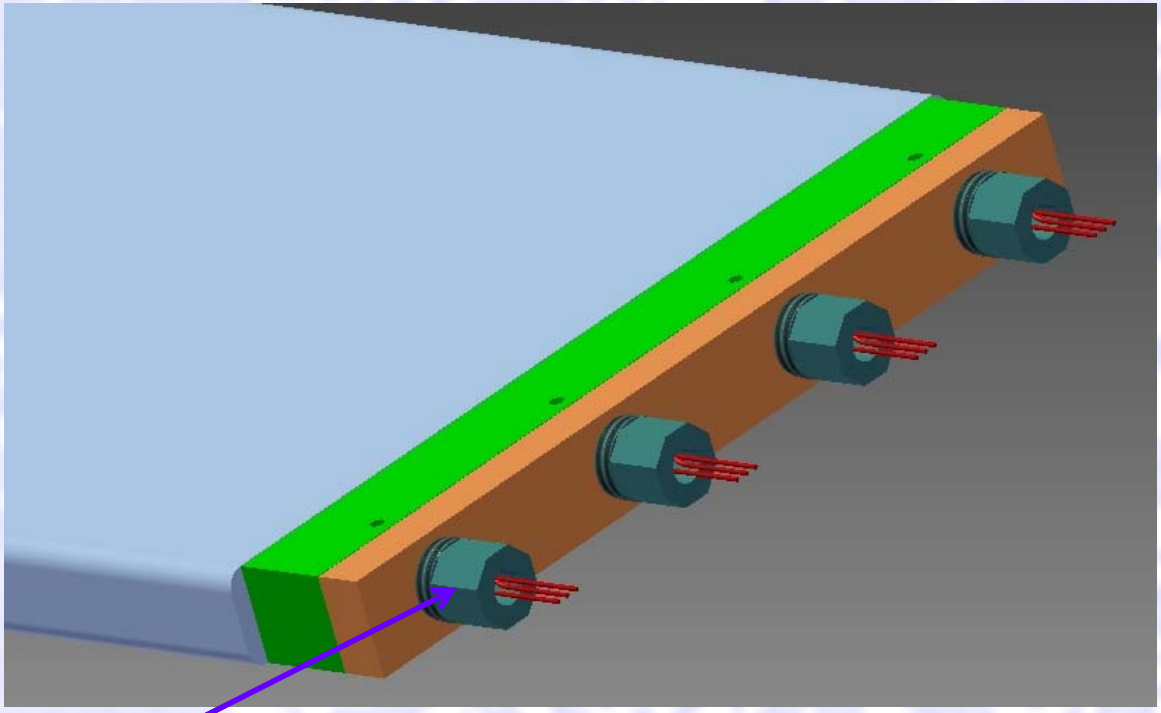






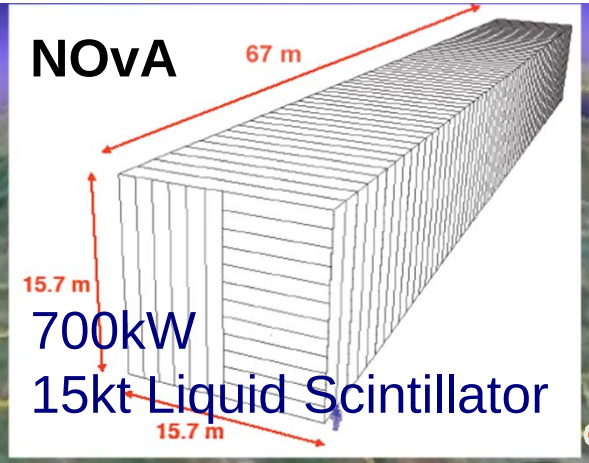
Mu2e Counter Design

CAD drawing by Vic Guarino (ANL)



SiPM sits in threaded fixture and screws into hole in fiber registration block

Long-Baseline Neutrino Program



700kW
15kt Liquid Scintillator

iron mine
at Soudan
MINOS (Far Det.)

810 km
735 km

LBNE
(Long Baseline Neutrino Experiment)
1300 km

~34 kton Liquid Ar TPC

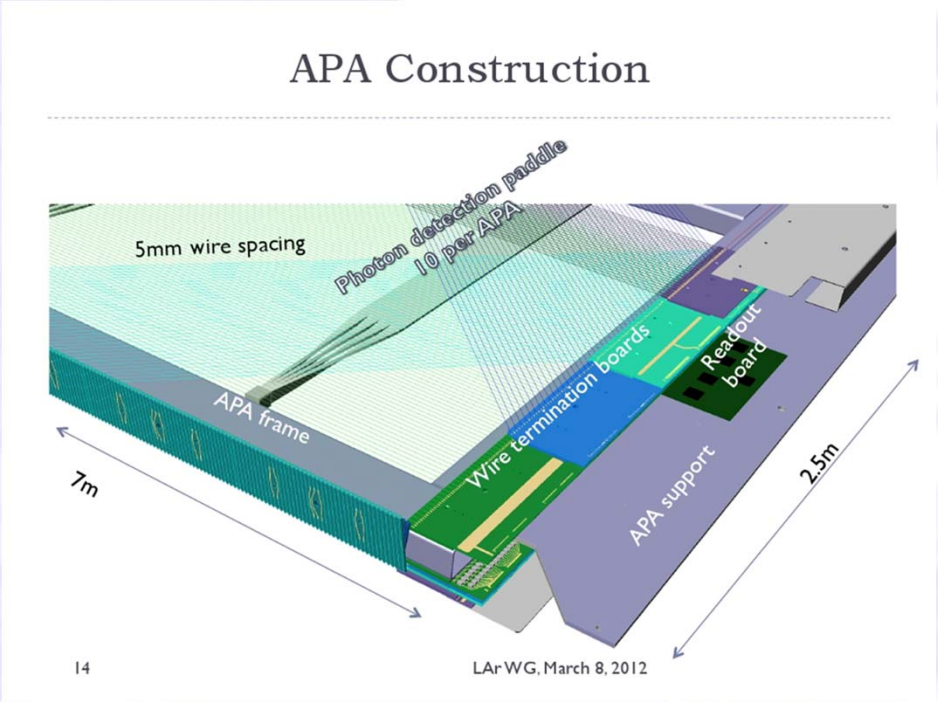
ICARUS
ArgoNeuT
MicroBooNE

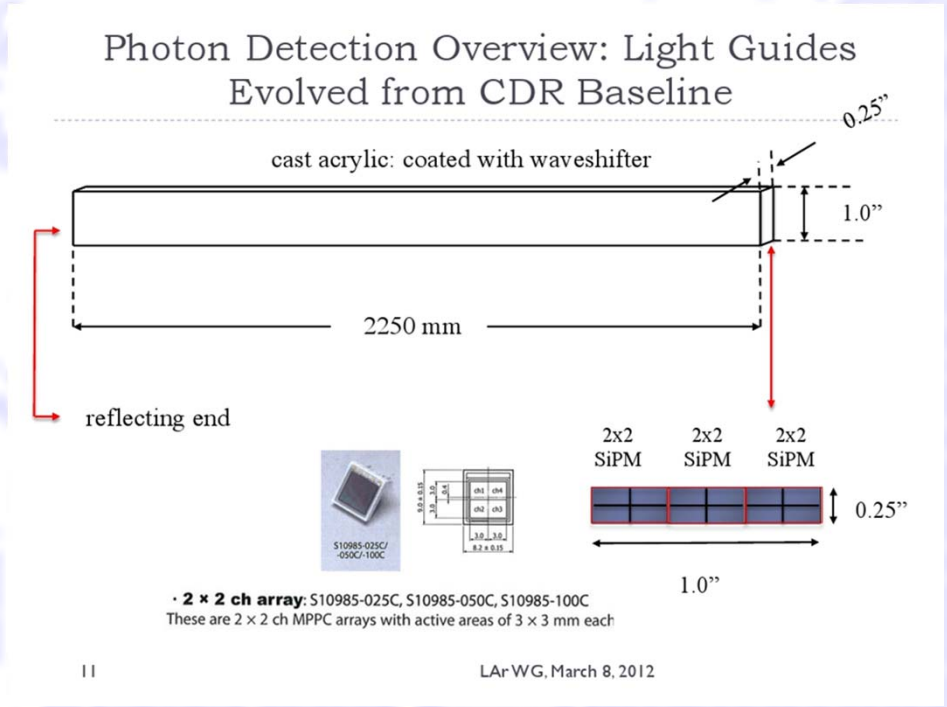
MiniBooNE
MINERvA
MicroBooNE

LBNE Liquid Argon Readout Requirements

- Detect the scintillation light of interactions induced by high energy (>500 MeV) neutrino beam interactions in a massive (34 kTon) Liquid Argon detector.

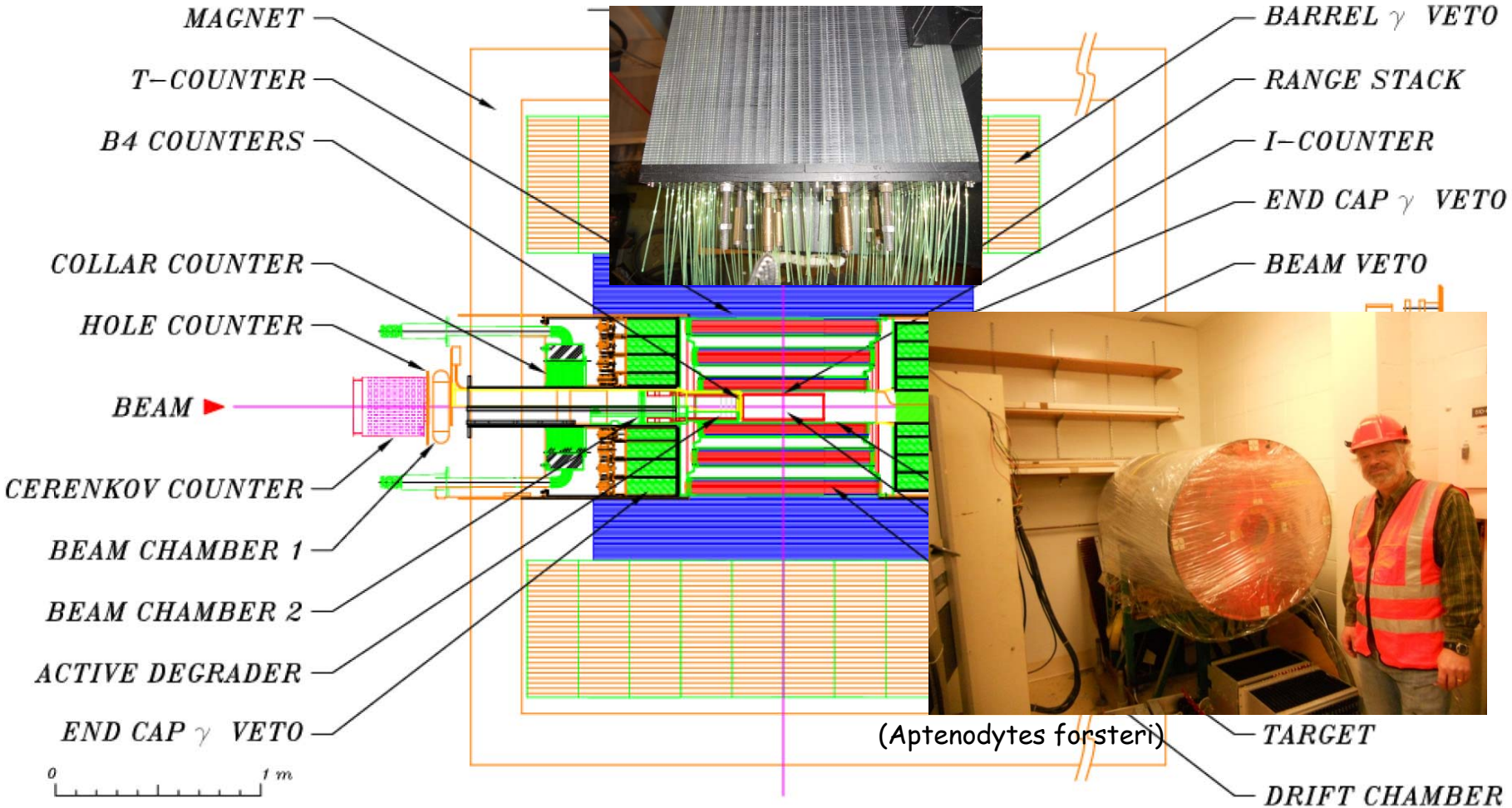
$Ar^* + Ar \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$ fast (< 10ns) 23% **(λ =128 nm !)**





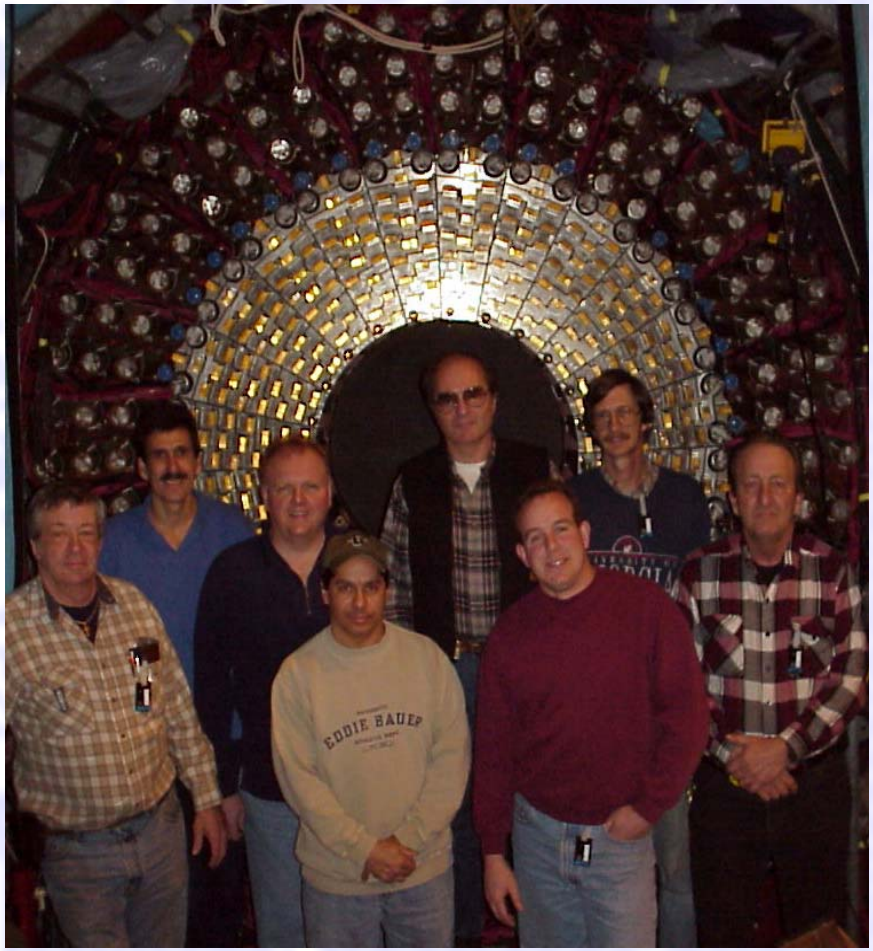
Courtesy C. Escobar

ORKA is a 4th Generation Detector
- x100 sensitivity -
x10 from kaon flux, x10 from detector



(Aptenodytes forsteri)

The Range Stack measures the π^+ decay chain, energy, range: Ripe for upgrade



ORKA Readout Requirements

Requirements:

- Tag the stopping and decay of a low energy charged kaon within a highly segmented fully active stopping target.

- Tag the stopping and decay of a low energy charged pion within a highly segmented fully active stopping target.

- Tag 20-200 MeV photons with very high efficiency (>99.99% per channel efficiency) .

Some Specifications:

In all cases the photon source will be organic scintillator with characteristics similar to BC-404. Photon veto can be readout with WLS (e.g. Y11). Stopping targets must be fully active, No WLS.

Project X: 5 MW Proton Accelerator

Construction later this decade, operating in 2020s

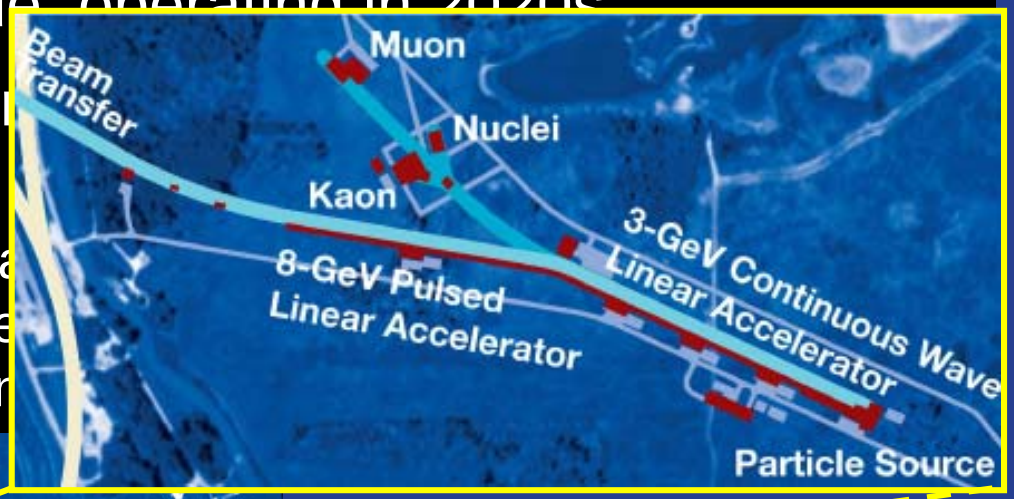
US National project with inter

MOUs for R&D

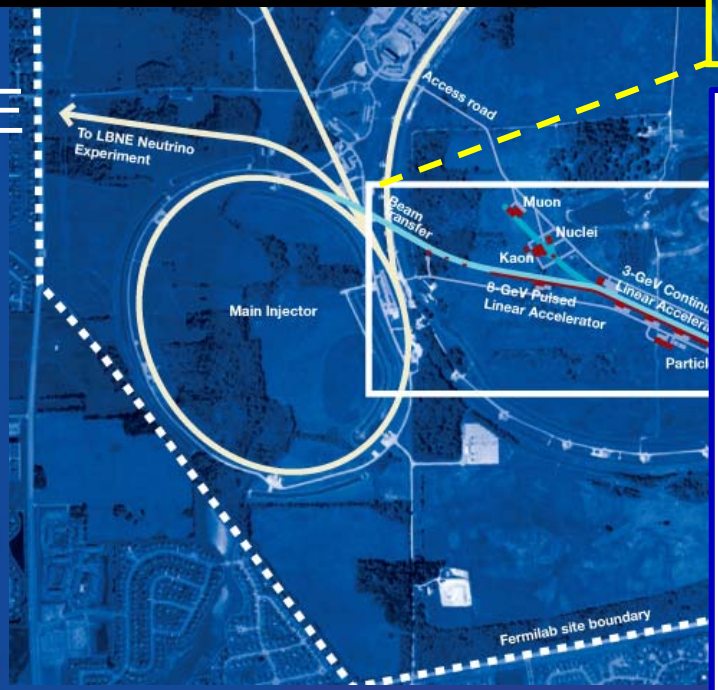
US: ANL, BNL, Cornell, Fermila

India: BARC/Mumbai, IUAC/De

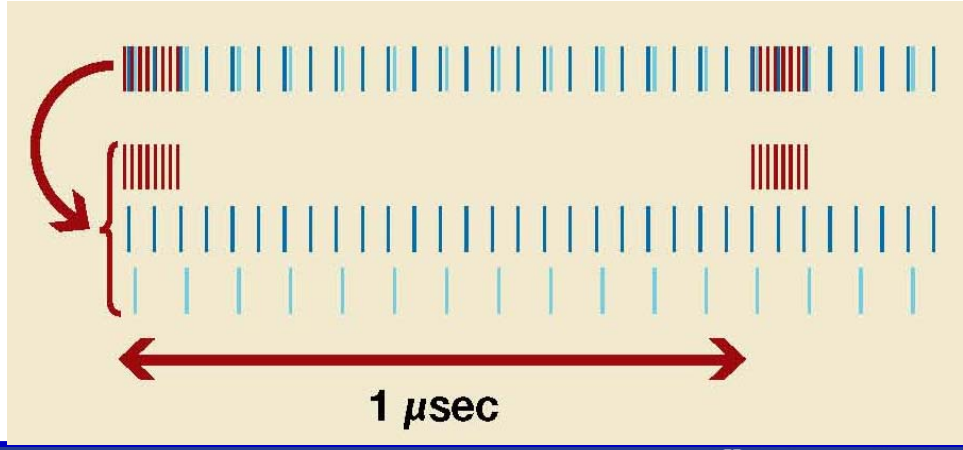
Additional collaboration with Chir



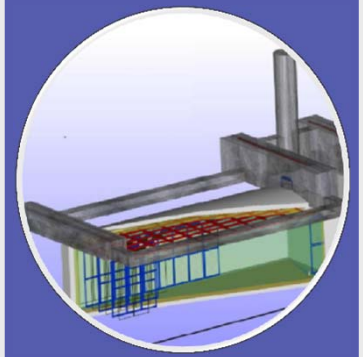
LBNE



Unique feature of *Project X*: flexible beam structure

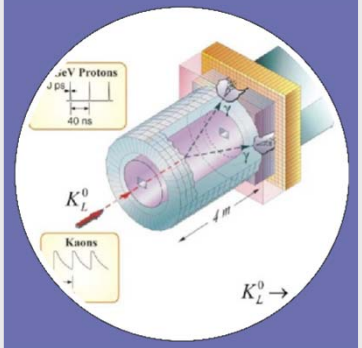


Project X: new experiments



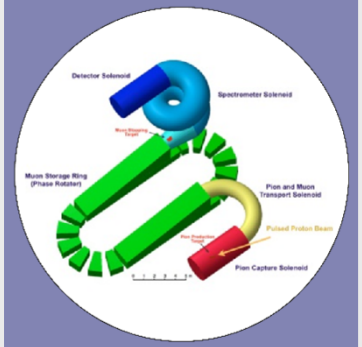
Neutrinos

- Matter-antimatter asymmetry
- Neutrino mass spectrum
- Neutrino-antineutrino differences
- Anomalous interactions
- Proton decay
- SuperNova bursts



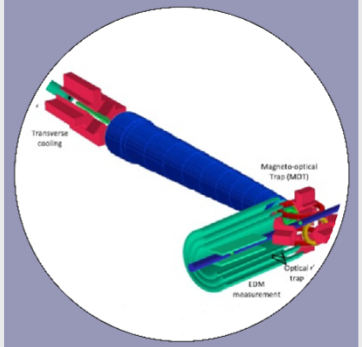
Kaons

- Physics beyond the Standard Model
- Elucidation of LHC discoveries
- Two to three orders of magnitude increase in sensitivity



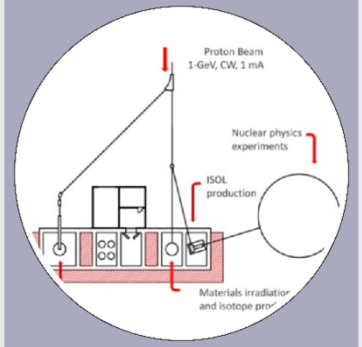
Muons

- Oscillation in charged leptons
- Physics beyond the Standard Model
- Elucidation of LHC physics
- Sensitive to energy/mass scales three orders of magnitude beyond LHC



Nuclei

- New generation of symmetry-test experiments
- Electric Dipole Moments
- Three or more orders of magnitude increase in Francium, Radium, Actinium isotopes



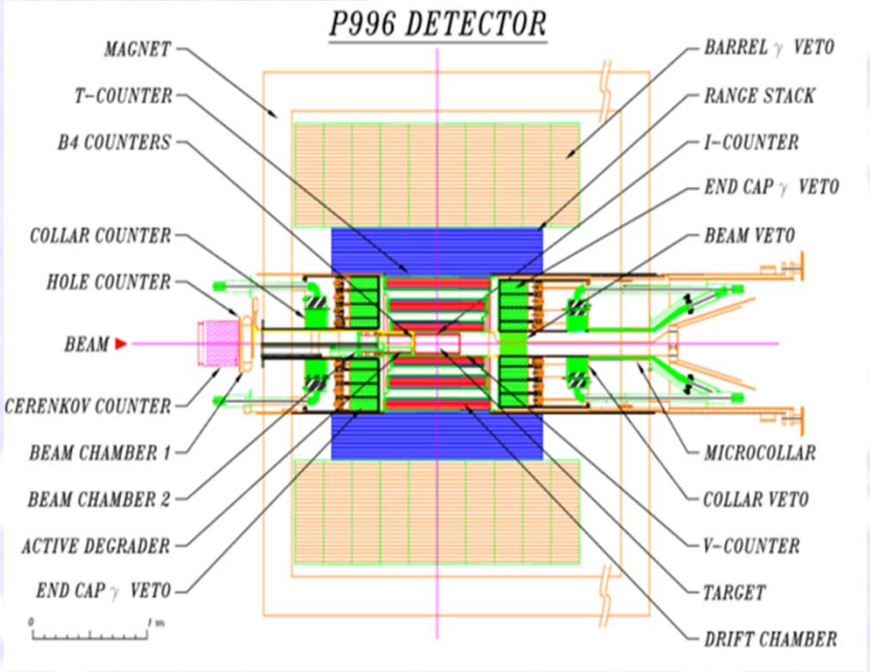
Energy Applications

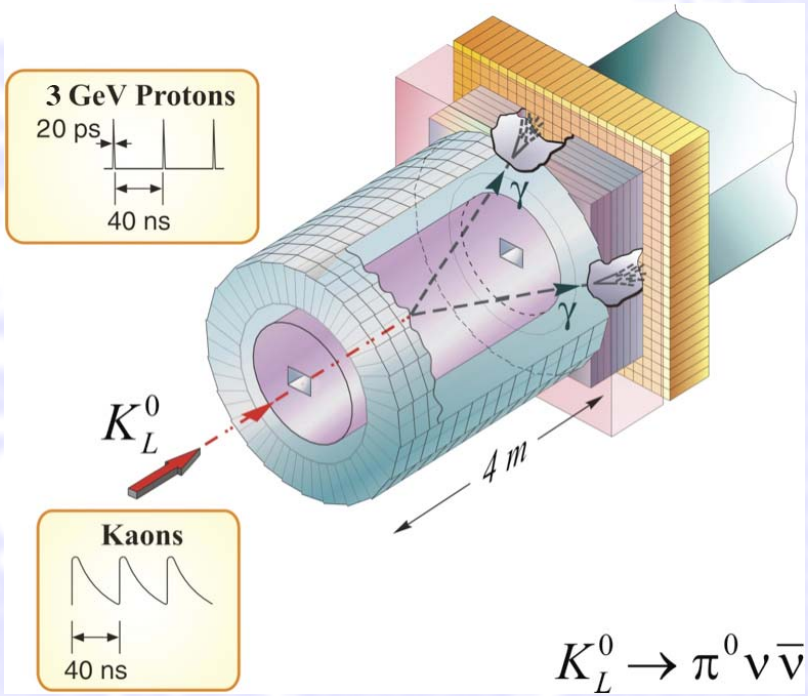
- Transmutation experiments with nuclear waste
- Spallation target configurations
- Materials test under high irradiation
- Neutron fluxes under various configurations relevant to ADS

Project X Day-1 program goals: Definitive Measurement of $K \to \pi\nu\bar{\nu}$

In the Project-X era the Fermilab ORKA experiment would precisely measure the rate and form-factor of $K^+ \to \pi\nu\bar{\nu}$.

The Project-X era presents an opportunity to measure the holy grail of kaon physics with precision: $K_L \to \pi\nu\bar{\nu}$.





Intensity Frontier Requirements

	High Magnetic Field (> 1T)	High Rad Environ	Tagging efficiency	Precision Calorimetry	Precision timing	Pixel level data	Low Dark Rate	Low Thresholds (< 3 p.e.)	Low Wavelength Sensitivity (<200 nm)
G-2	NO	NO	99%	Modest	200 psec	NO	NO	NO (>3 p.e)	NO
LBNE LAr	NO	NO	99%	NO	NO 1000 ps	NO	YES	NO ()	YES
Minvera-II	NO	NO	99%	NO	NO 1000 ps	NO	NO	NO ()	NO
Mu2e Calorimetry	YES	MID	99%	YES	NO 1000 ps	NO	NO	NO (>10 p.e)	NO
Mu2 Cosmic Veto	NO	YES	99.99%	NO	500 psec	?	YES	YES 2-3 p.e.	NO
ORKA photon veto	YES	NO	99.99%	NO	200 psec	?	YES	NO (>3 p.e.)	NO
ORKA stopping tgts	YES	MID	99%	Modest	200 psec	?	YES	NO (>3.p.e)	NO
Project X muons	YES	MID	99% - 99.99%	YES	100 psec	?	YES	NO 2-3 p.e.s, (>3 p.e.)	NO
Project X kaons	NO	MID	99.99%	YES	YES 20 psec	?	YES	NO (> 3 p.e.)	NO

Cosmic Frontier Requirements

	High Magnetic Field	High Rad Environ	Tagging efficiency	Precision Calorimetry	Precision timing (10 psec)	Pixel level data	Low Dark Rate	Low Thresholds (<3 p.e.)	Low Wavelength Sensitivity (<200 nm)
CTA	NO	NO	99%	NO	1000 psec	?	YES	YES	YES

Other Applications

	High Magnetic Field	High Rad Environ	Tagging efficiency	Precision Calorimetry	Precision timing (10 psec)	Pixel level data	Low Dark Rate	Low Thresholds (<3 p.e.)	Low Wavelength Sensitivity (<200 nm)
PET Imaging	Maybe	NO	99%	YES	YES 10 ps	NO	NO	NO	NO

Largely Common Issues & Dreams

- Photon collection fraction, adiabatic light transfer systems.
- System cost per channel.
- Fast timing and Wave-Form Digitization (WFD)
- Threshold & Temperture control & monitoring
- **Dreams:**

  Disable noisy pixels.
  Large area devices.

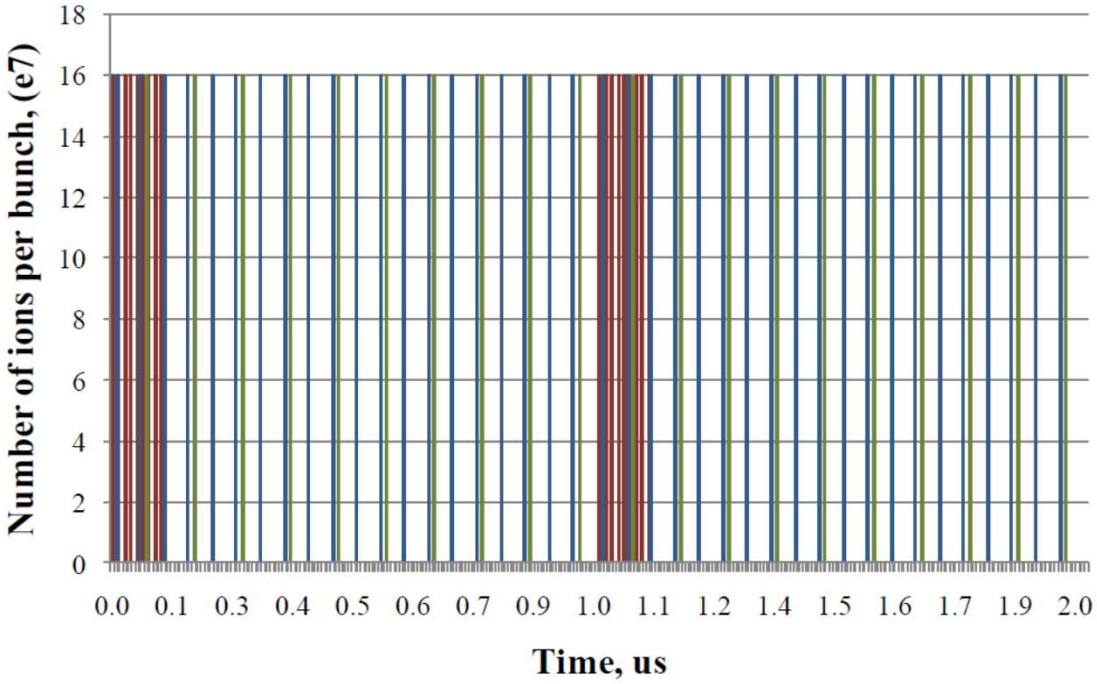
Spare Slides

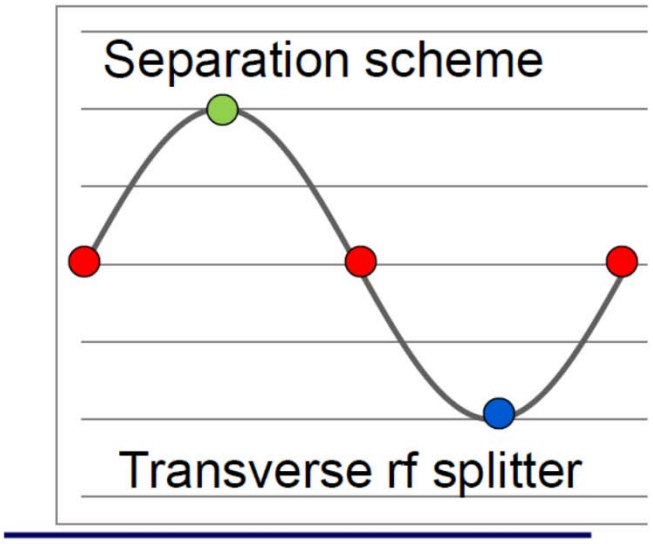
Chopping and splitting for 3-GeV experiments

1 μsec period at 3 GeV

Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz	700 kW
Kaon pulses (16e7) 20.3 MHz	1540 kW
Nuclear pulses (16e7) 10.15 MHz	770 kW

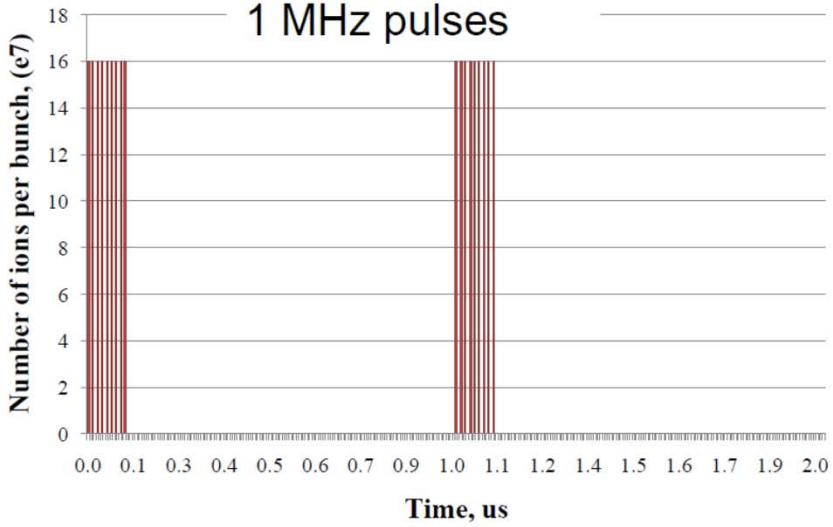
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ

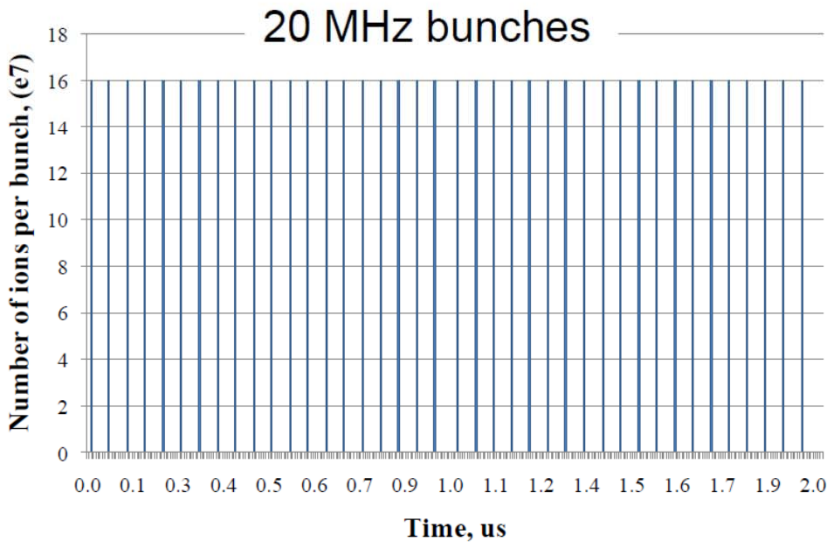


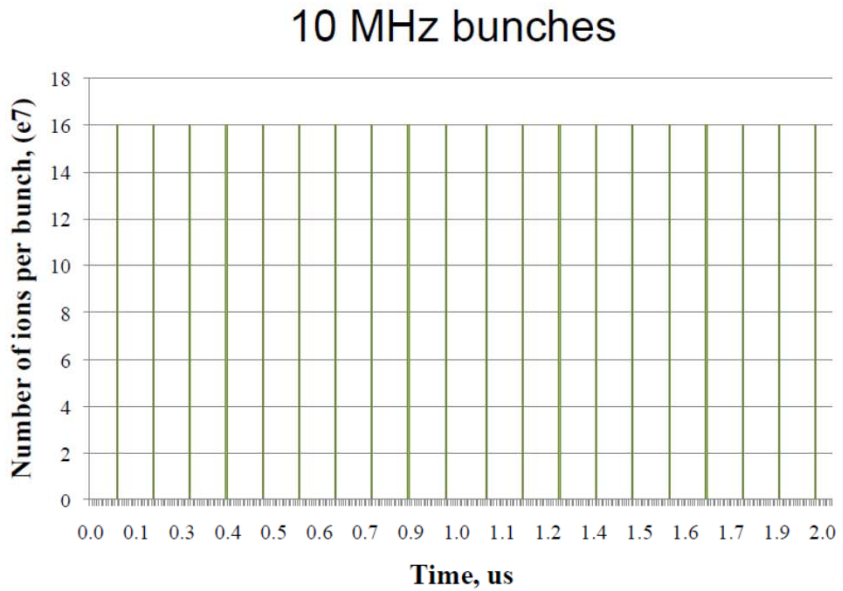


Courtesy of Nagaitsev

Beam after splitter







Courtesy of Nagaitsev

Fermilab Energy and Intensity Frontier Strategy

To build upon our existing strengths to establish a world-leading program at the Intensity Frontier, enabled by a world-class facility

NuMI (120 GeV): 350 kW **Booster (8GeV):** 35 kW

NuMI (120GeV): 700 kW **Booster (8GeV)**: 80 kW

Project-X: >2MW @ 120 GeV, 3MW @ 3 GeV, 150 kW @ 8 GeV

Neutrino Factory

…and use this program to provide a cornerstone for an Energy Frontier facility beyond LHC

LHC Tevatron

LHC Upgrades in luminosity and energy

Lepton Colliders

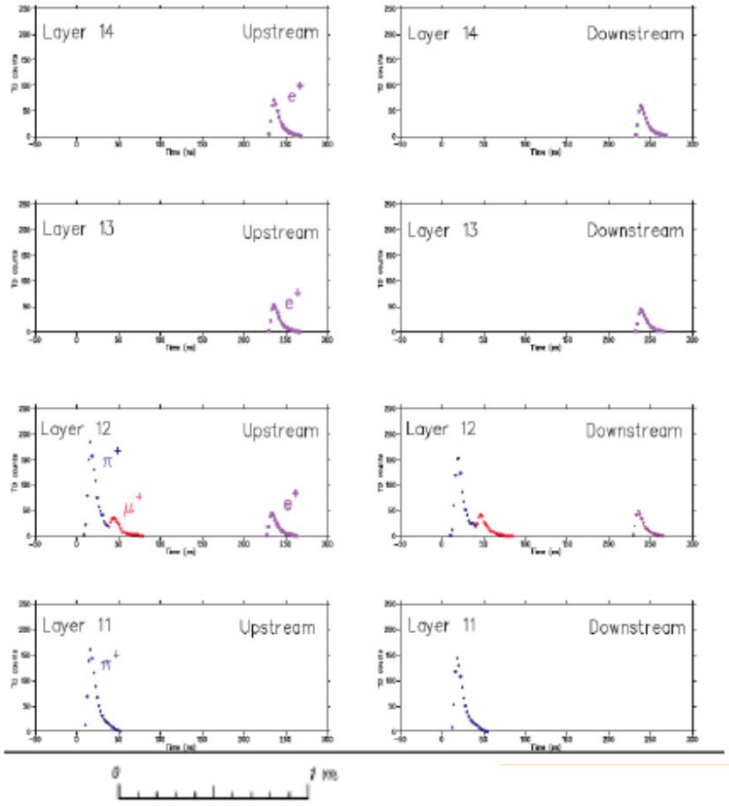
Technology Development and Fundamental Accelerator Science

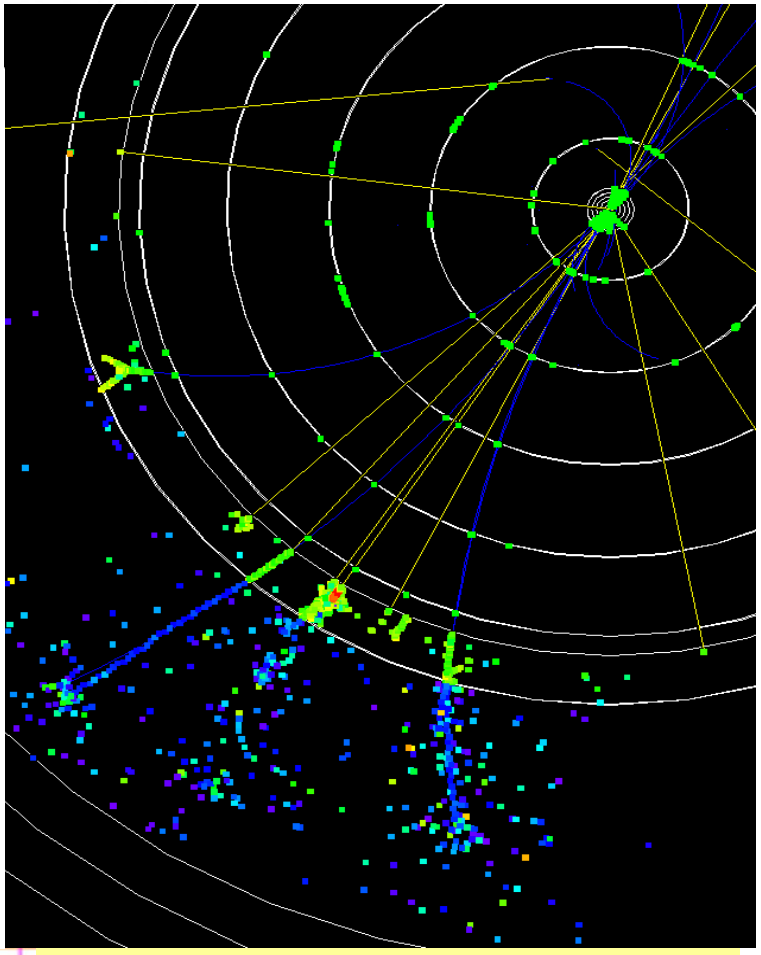
…while relying on a strong program of technology development and fundamental accelerator science.

ORKA Range Stack

Use existing (CDF or CLEO) solenoid

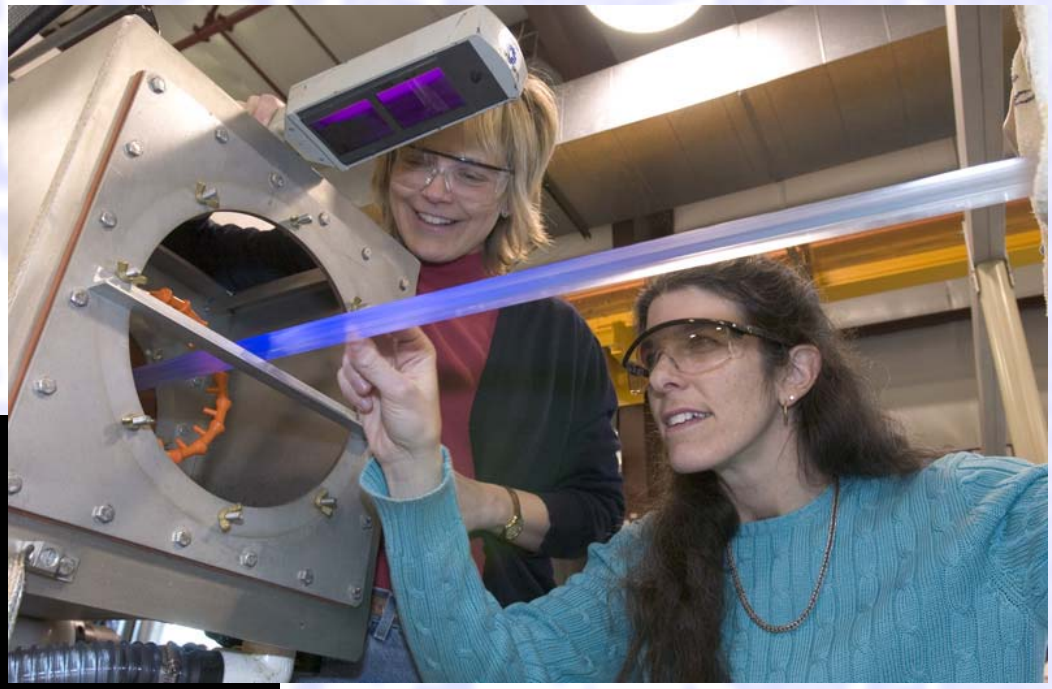
$\pi \longrightarrow \mu \longrightarrow e$ detection in E949

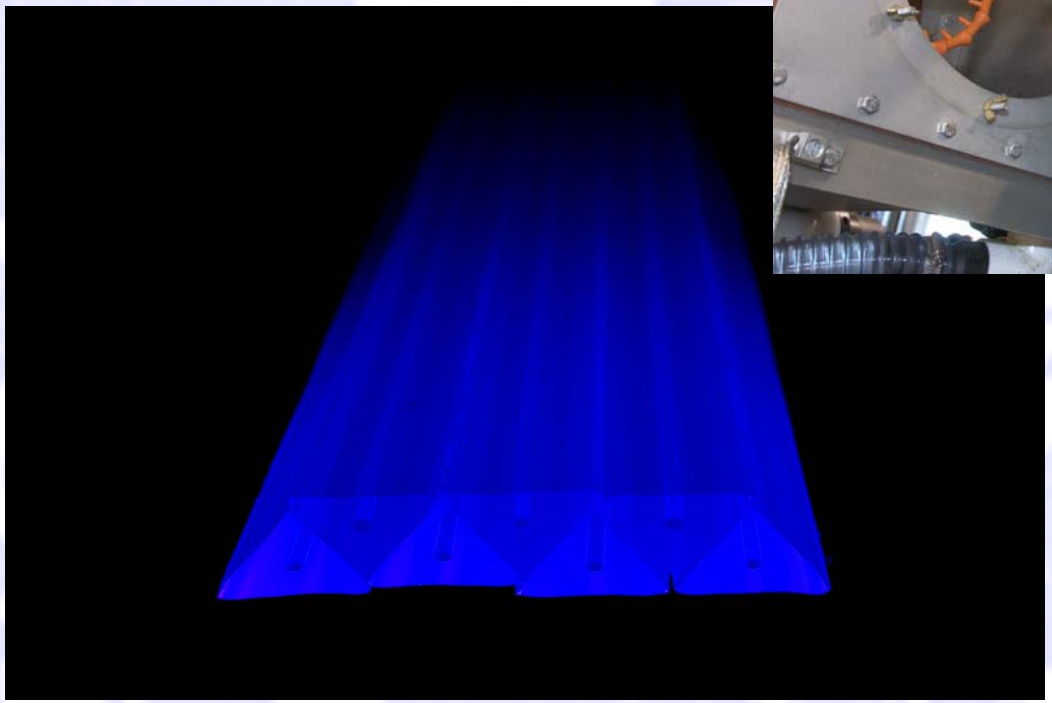




SiD fine grained calorimetery

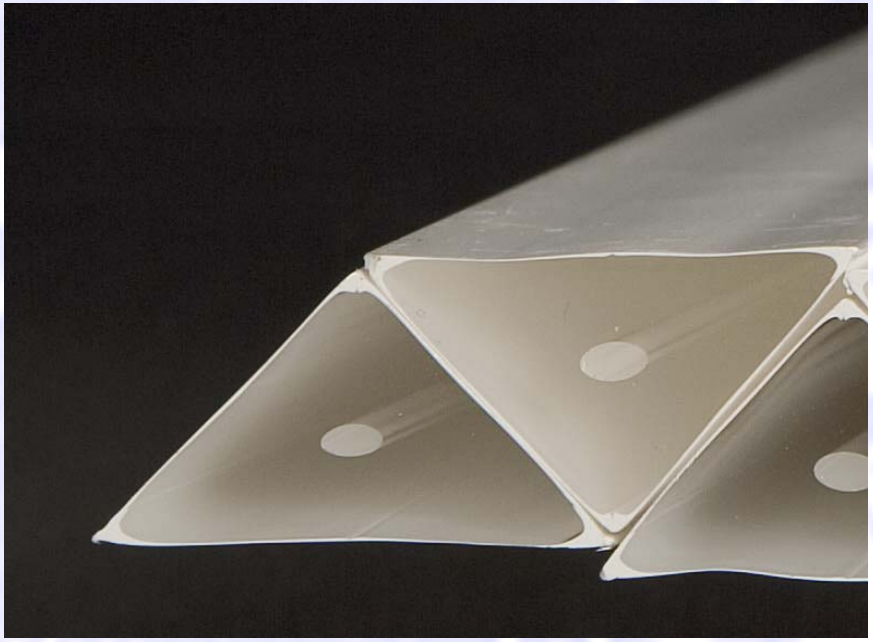
Extruded Scintillator technologies can lower costs…

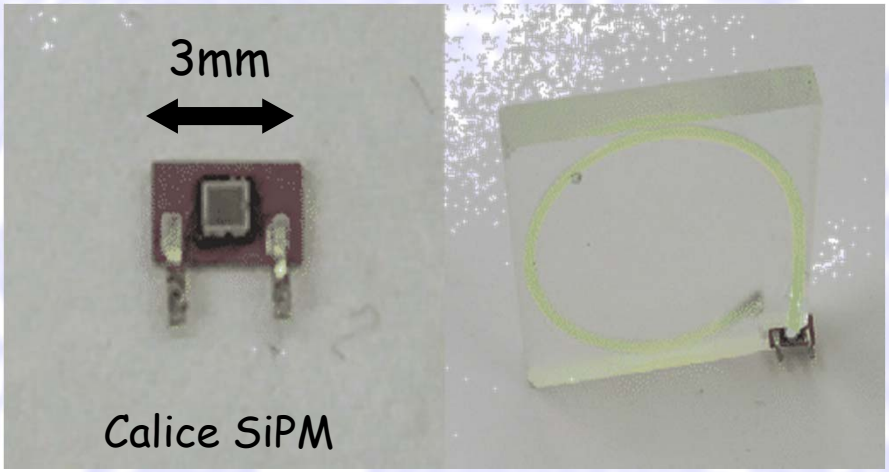


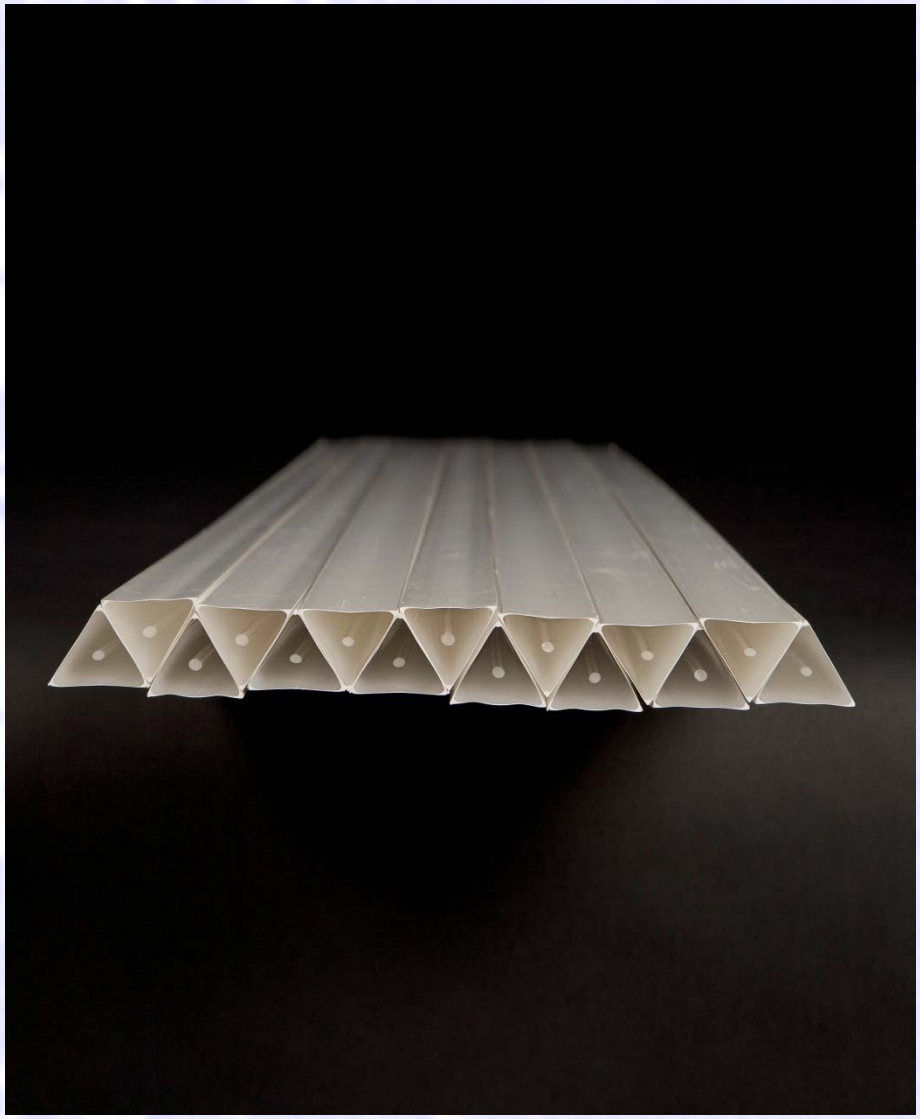


Minerva Scintillator

Development required for more precise extrusion and compact photon readout…







Active fiber target

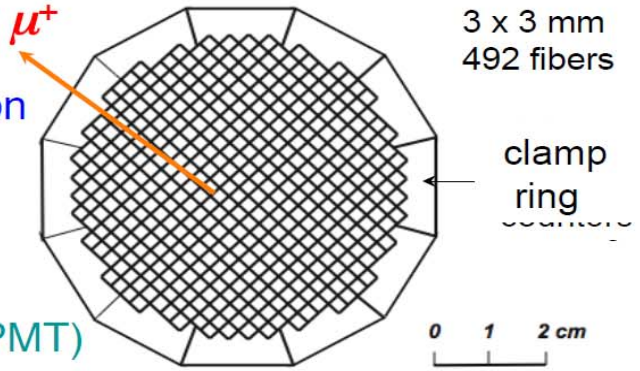
1. Finer segmentation for
   - Higher μ^+ tracking resolution
   - Higher K^+ stop point resolution
   - Better $K\pi 2$ background suppression

   (E246 : 256 fibers with 5 x5 mm^2)

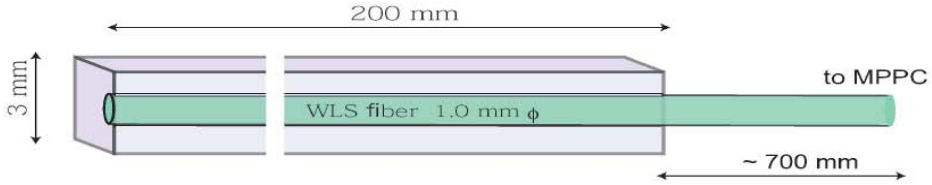
2. Compact and light system
   - By using MPPCs

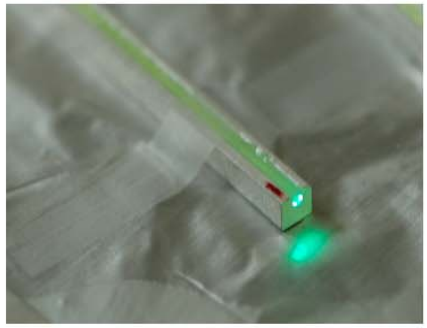
   (E246 : each fiber was read by a1/2" PMT)

Cross section



One element





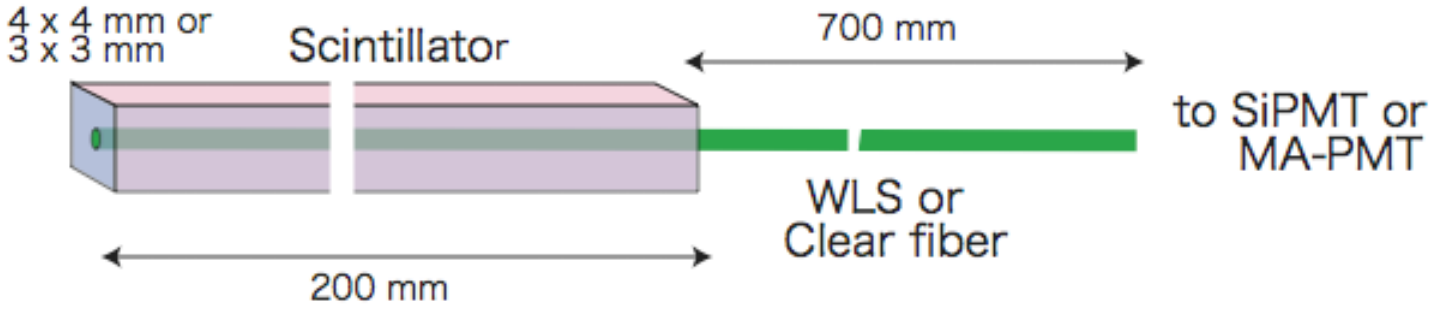
- MPPC direct readout test at KEK (2008)
- Radiation damage test of MPPC with 130 MeV/c π^+ (2008)

Detector preparation
(2) Active fiber target

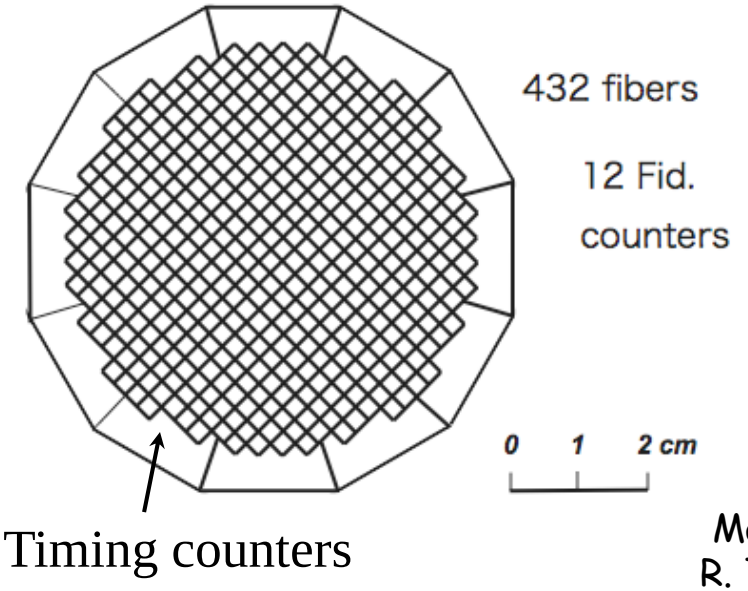
Current baseline design

c.f. E246 Ring counters
PSI FAST target

One element



Cross section



- Light guide :
  - Bicron 692 WLS or
  - Kuraray Y11 WLS or
  - Clear optical fiber
- Readout:
  - SiPMT (HPK MPPC) or
  - MA-PMT
- Beam test using 100 MeV/*c* pions at TRIUMF in this year

The BNL E787/E949 stopped kaon technique

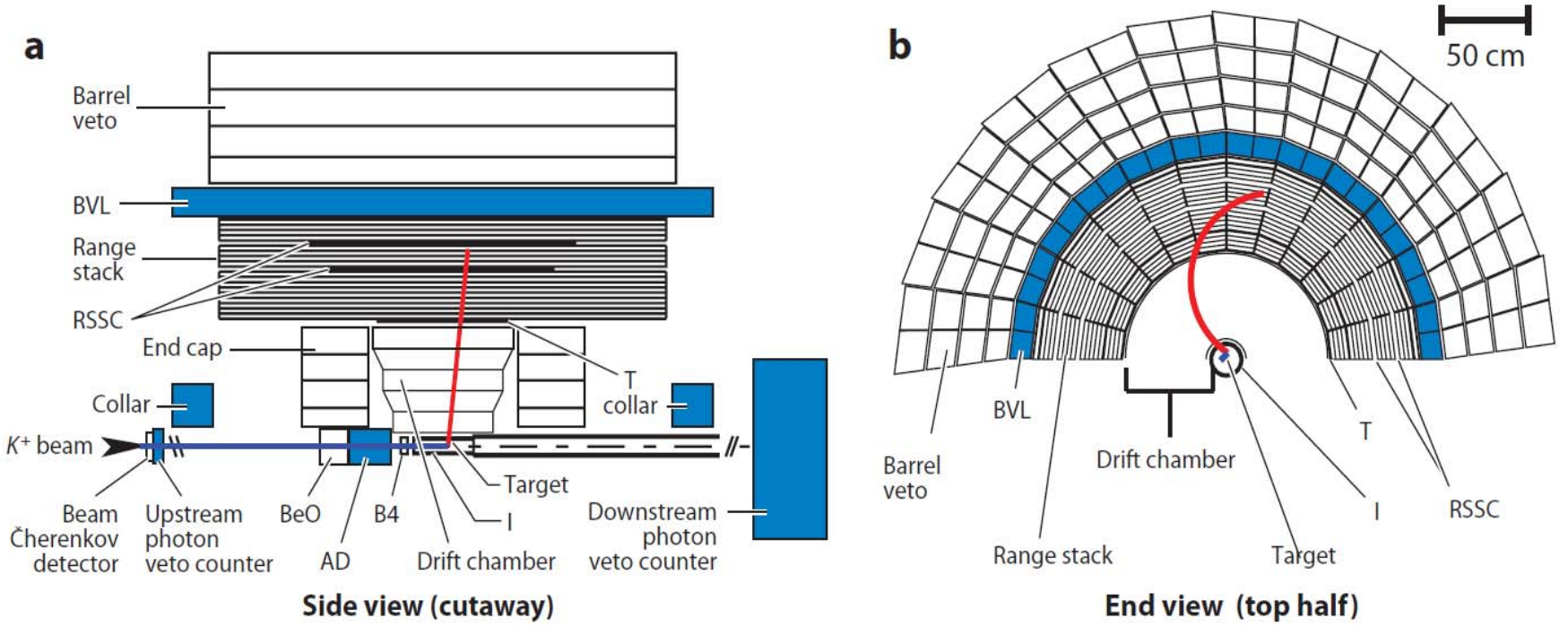


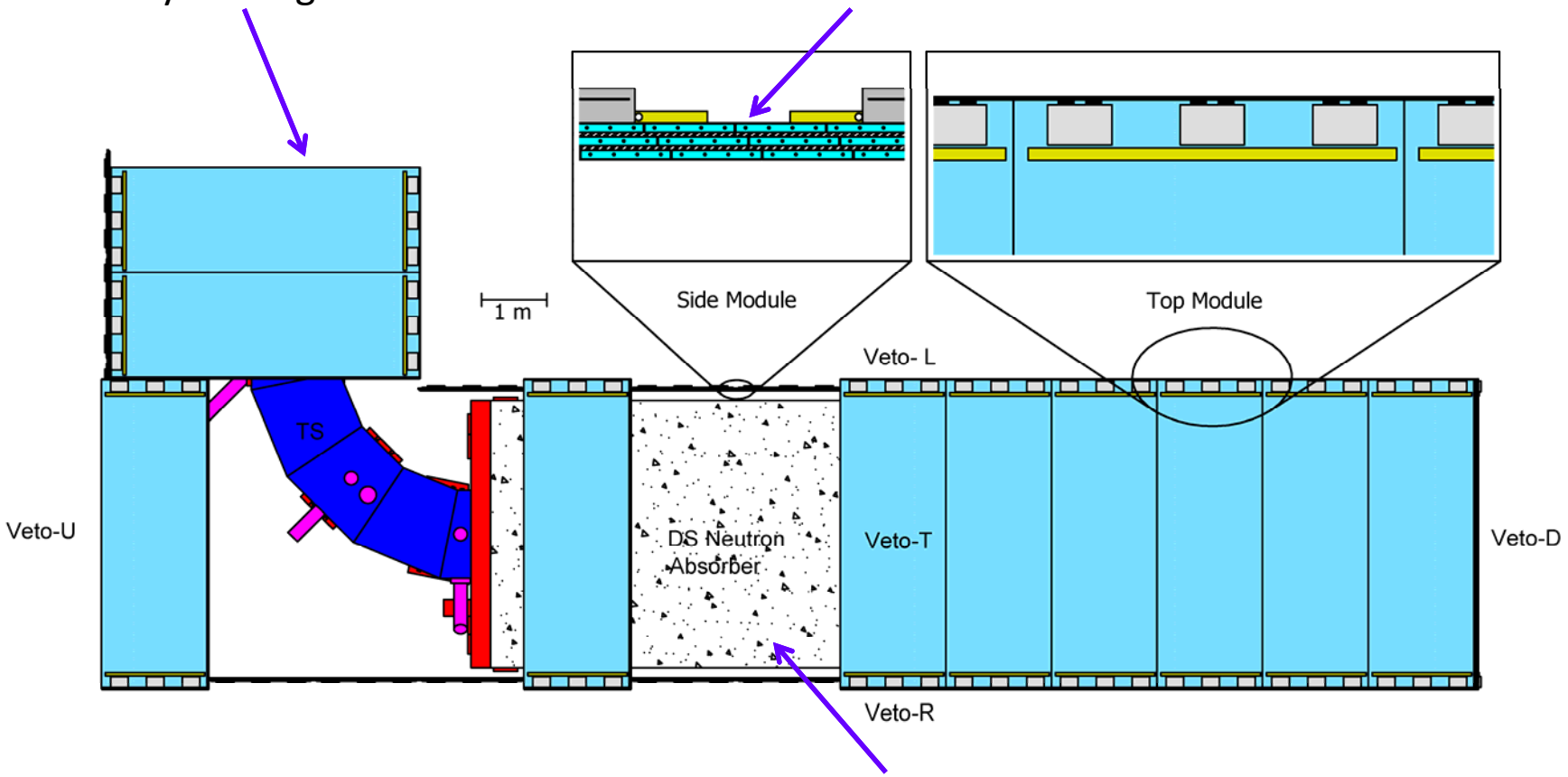
Figure 1

Elevation side view and end view schematic of the BNL E787 and E949 technique. (*a*) The 700-MeV/*c* K^+ beam enters from the left. (*b*) The stopped K^+ decays in the stopping target, and the subsequent decay π^+ track is momentum-analyzed by the tracker. The decay π^+ then stops in the range stack, where its range and energy are measured. The range stack STRAW chamber (RSSC) measures the position of the putative charged pion with the range stack. The barrel veto liner (BVL) is an upgrade of photon veto performance in E949 and E787. Abbreviations: AD, active degrader; DPV, UPV.

CRV Layout: Plan View

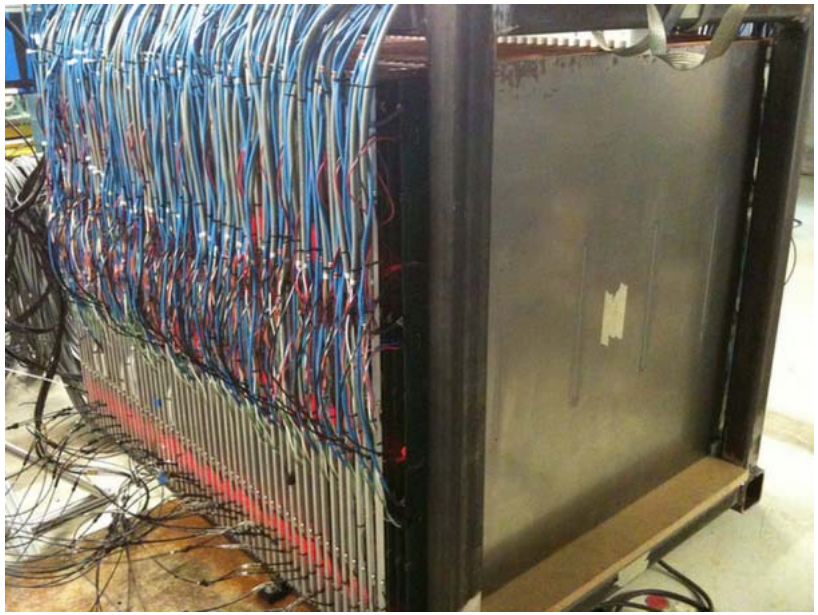
This area is complicated. Lots of shielding needed around the TS that has not yet designed.

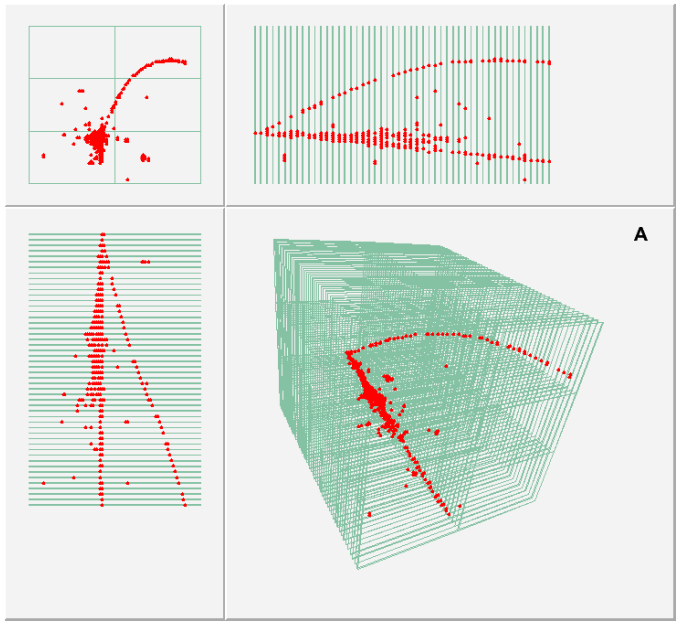
No cracks between modules.



Substituting 50 cm of Fe with 50 cm of concrete shield

Digital Hadron Calorimeter (ANL) at Fermilab Test Beam Facility





- This test device has more channels (400K) than CMS + ATLAS + LHCb calorimeters combined
- Fermilab designed the readout chip and trigger modules for this detector
- May pave the way for a pointing calorimeter for high intensity decay experiments

The Project-X Research Program

- ***Neutrino oscillation experiments***
- A high-power proton source with proton energies between 8 and 120 GeV would produce intense neutrino beams directed toward 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.

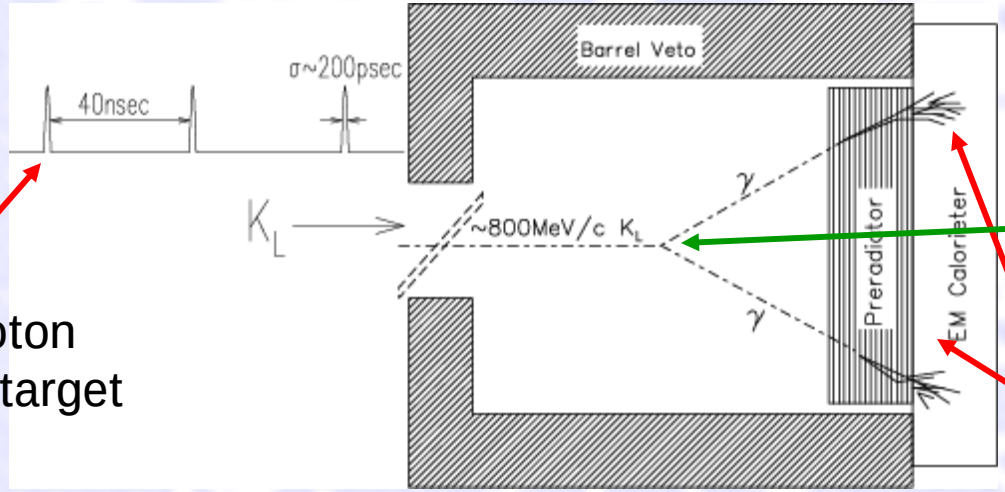
- ***Platform for evolution to a Neutrino Factory and Muon Collider***
- Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***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: Project X website

KOPIO inspired: Micro-bunch the beam, TOF determines K_L momentum.

Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.



Start when proton beam hits the target

End at the decay time and decay point reconstructed from the two photons.

Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 30ps is intrinsic.