The MECO Experiment

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Need More Collaborators!

What Will Observation of $\mu^- N \rightarrow e^- N$ Teach Us?

Discovery of $\mu^- N \rightarrow e^- N$ or a similar charged lepton flavor violating (LFV) process will be unambiguous evidence for physics beyond the Standard Model.

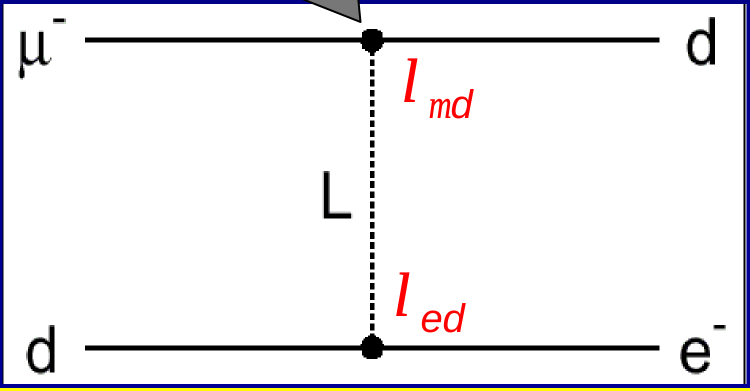
- For non-degenerate neutrino masses, ν oscillations can occur. Discovery of neutrino oscillations required changing the Standard Model to include massive ν.
- Charged LFV processes occur through intermediate states with ν mixing. Small ν mass differences and mixing angles ⇒ expected rate is well below what is experimentally accessible.

- Charged LFV processes occur in nearly all scenarios for physics beyond the SM, in many scenarios at a level that MECO or PSIMEG will detect.
- Effective mass reach of sensitive searches is enormous, well beyond that accessible with direct searches.

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')} = 10^{-16}$$

$$\Rightarrow \quad M_L = 3000\sqrt{\lambda_{\mu d}\,\lambda_{ed}}\ \mathrm{TeV}/c^2$$

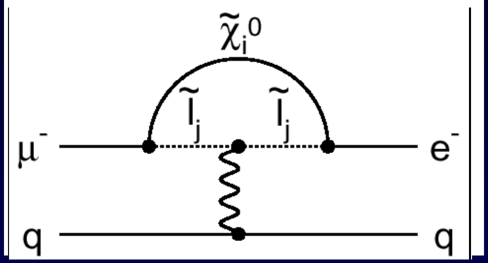
One example of new physics, with leptoquarks

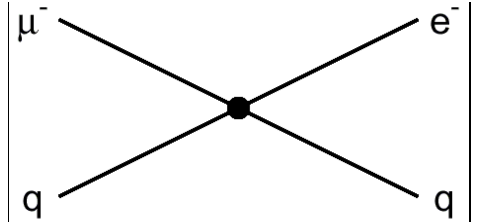


What might we expect?

Supersymmetry

Predictions at 10^{-15}



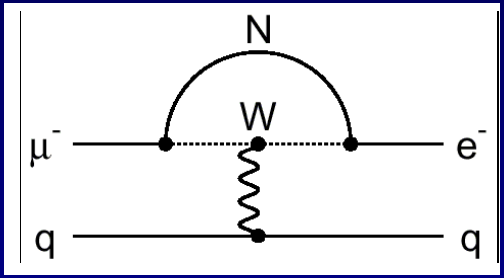


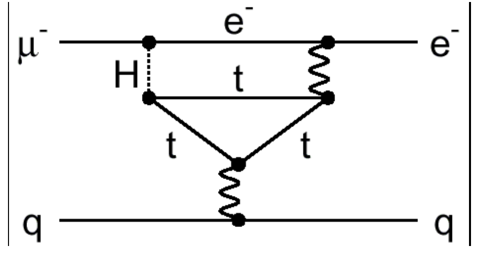
Compositeness

$?_C = 3000$ TeV

Heavy Neutrinos

$\left|U^*_{mN}U_{eN}\right|^2 = 8\times 10^{-13}$





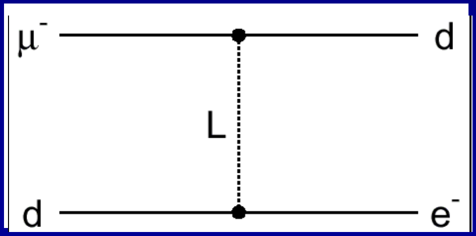
Second Higgs

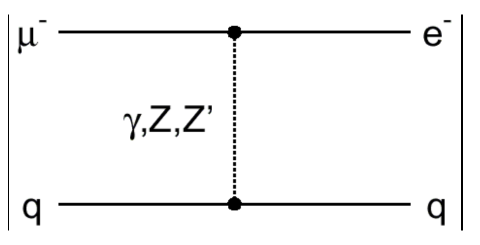
$g_{H_{me}} = 10^{-4} \times g_{H_{mm}}$

Leptoquarks

$M_L =$

$3000\sqrt{l_{md}\, l_{ed}}$ TeV/c^2





Heavy Z',
Anomalous Z
coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \to me) < 10^{-17}$

After W. Marciano

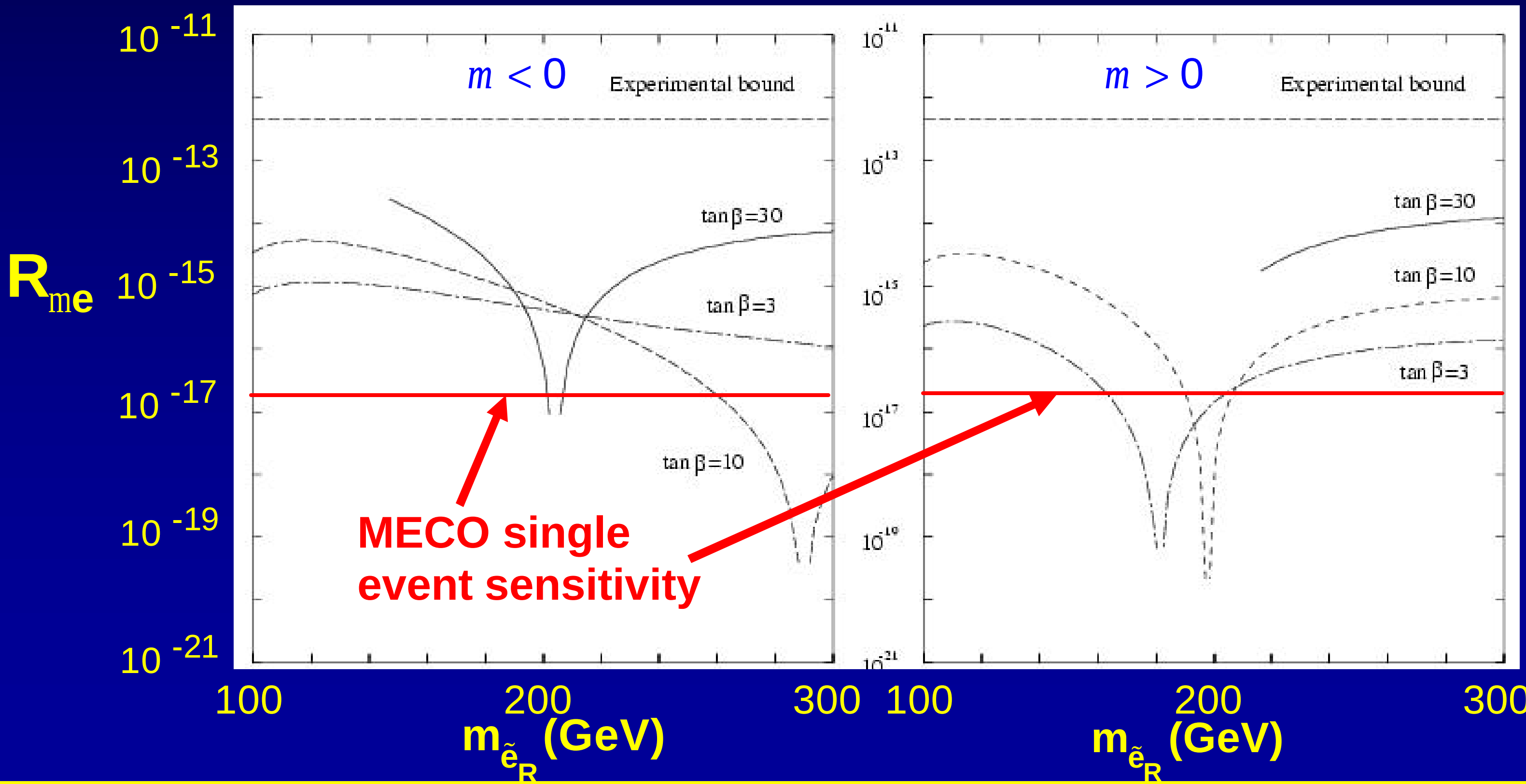
Supersymmetry Predictions for LFV Processes

- From Hall and Barbieri

  Large t quark Yukawa couplings imply observable levels of LFV in supersymmetric grand unified models

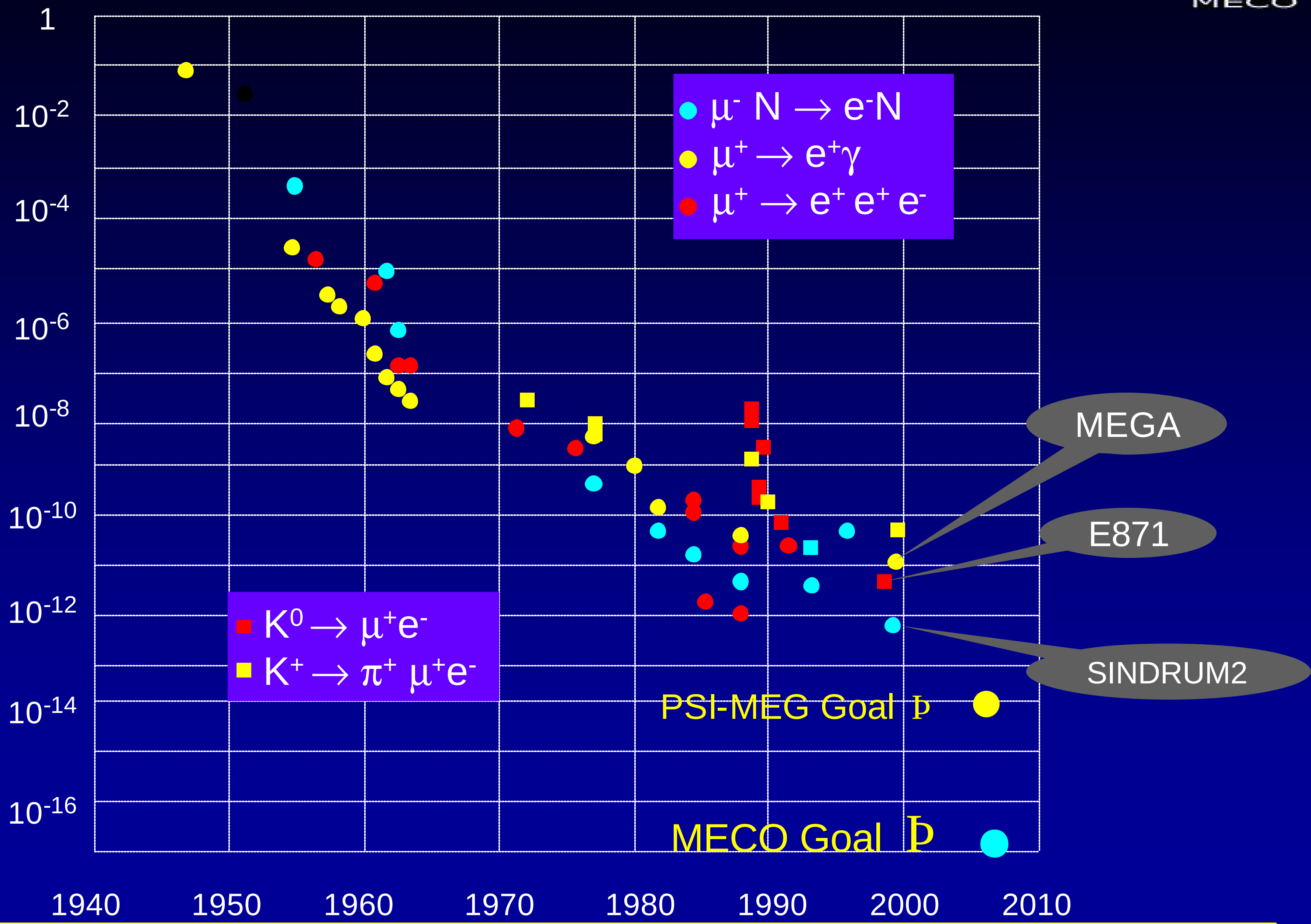
- Extent of lepton flavor violation in grand unified supersymmetry related to quark mixing
- Original ideas extended by Hisano, et al.

Process	Current Limit	SUSY level
$m^-N \rightarrow e^-N$	10^{-12}	10^{-15}
$m^+ \rightarrow e^+g$	10^{-11}	10^{-13}
$t \rightarrow mg$	10^{-6}	10^{-9}



MECO single event sensitivity

History of Lepton Flavor Violation Searches



MECO Experiment Method

- Muons stop in matter and form a muonic atom.
- They cascade down to the 1S state in less than 10^{-16} s.
- They coherently interact with a nucleus (leaving the nucleus in its ground state) and convert to an electron, without emitting neutrinos Þ μ^-? e^-
- Experimental signature is an electron with E_e=105.1 MeV emerging from stopping target, with no incoming particle near in time.

$$E_e = M_\mu - E_{NR} - E_B.$$

- More often, they are captured on the nucleus: $\mu^- N \rightarrow \nu_\mu N(Z\text{-}1)$ $[\mu^- p \rightarrow \nu_\mu n]$

or decay in the Coulomb bound orbit: $\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$

(τ_μ = 2.2 μs in vacuum, ~0.9 μs in Al)

- Rate is normalized to the kinematically similar weak capture process:

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N(Z\text{-}1))}$$

MECO goal is to detect $\mu^- N \rightarrow e^- N$ if $R_{\mu e}$ is at least 2 X 10^{-17} , with one event providing compelling evidence of a discovery.

Potential Sources of Background

Muon decay
in vacuum: $E_e < m_\mu c^2/2$

Muon decay in
bound orbit: $E_e < m_\mu c^2 - E_{NR} - E_B$

1. Muon Decay in Orbit –
   - $E_{max} = E_{conversion}$ when neutrinos have zero energy
   - $dN/dE_e \propto (E_{max} - E_e)^5$
   - Sets the scale for energy resolution required: ~200 keV
2. Radiative Muon Capture: $\mu^- N \rightarrow \nu_\mu N(Z\text{-}1)\, \gamma$
   - For Al, $E_g^{max} = 102.5$ MeV/c^2, $P(E_g > 100.5$ MeV/$c^2) = 4 \times 10^{-9}$
   - $P(g \rightarrow e^+e^-, E_e > 100.5$ MeV/$c^2) = 2.5 \times 10^{-5}$
   - Restricts choice of stopping targets: $M_{z\text{-}1} > M_z$
3. Radiative Pion Capture: $p^- N \rightarrow N(Z\text{-}1) g$
   - Branching fraction ~ 1.2% for $E_g > 105$ MeV/c^2
   - $P(g \rightarrow e^+e^-, 103.5 < E_e < 100.5$ MeV/$c^2) = 3.5 \times 10^{-5}$
   - Limits allowed pion contamination in beam during detection time

Other Potential Sources of Backgrounds

4. Muon decay in flight + e^- scattering in stopping target
5. Beam e^- scattering in stopping target
    - Limits allowed electron flux in beam
6. Antiproton induced e^-
    - Annihilation in stopping target or beamline
    - Requires thin absorber to stop antiprotons in transport line
7. Cosmic ray induced e^- – seen in earlier experiments
    - Primarily muon decay and interactions
    - Scales with running time, not beam luminosity
    - Requires the addition of active and passive shielding

Expected Signal and Background in MECO Experiment

Background Source	Events	Comments
μ decay in orbit	0.25	S/N = 4 for $R_{\mu e} = 2 \times 10^{-17}$
Tracking errors	< 0.006	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	No scattering in target
μ decay in flight	0.04	Scattering in target
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	10^{-4} CR veto inefficiency
Total Background	0.45	With 10^{-9} inter-bunch extinction

Background calculated for 10^7 s running time at intensity giving 5 signal event for $R_{\mu e} = 10^{-16}$.

Sources of background will be determined directly from data.

5 signal events with 0.5 background events in 10^7 s running if $R_{\mu e} = 10^{-16}$

Factors affecting the Signal Rate	Factor
Running time (s)	10^7
Proton flux (Hz) (50% duty factor, 740 kHz μpulse)	4×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in detection time window	0.49
Electron trigger efficiency	0.90
Geometrical acceptance, fitting and selection criteria efficiency	0.19
Detected events for $R_{\mu e} = 10^{-16}$	5.0

What Drives the Design of the MECO Experiment?

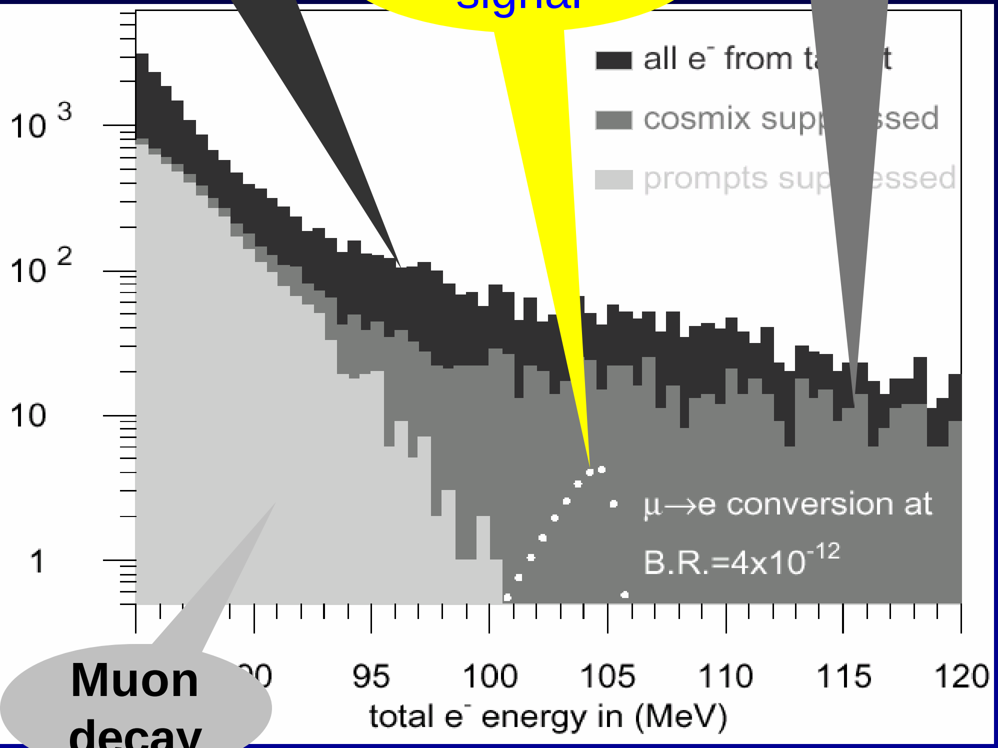
Considerations of potential sources of fake backgrounds specify much of the design of the beam and experimental apparatus.

Prompt background

Expected signal

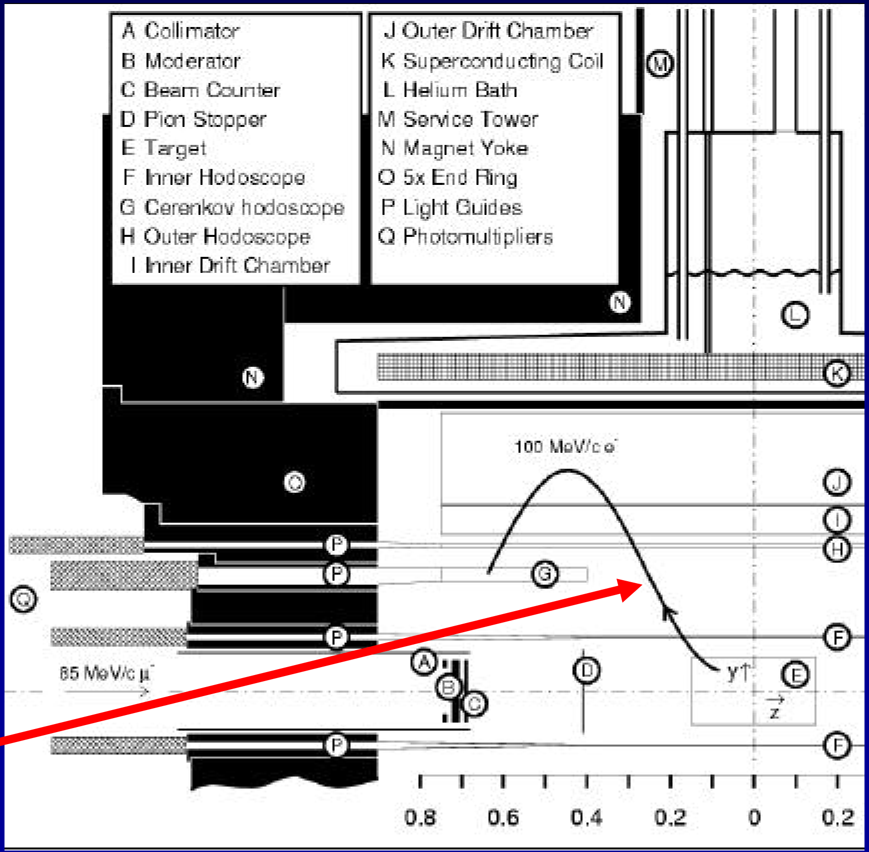
Cosmic ray background

Muon decay



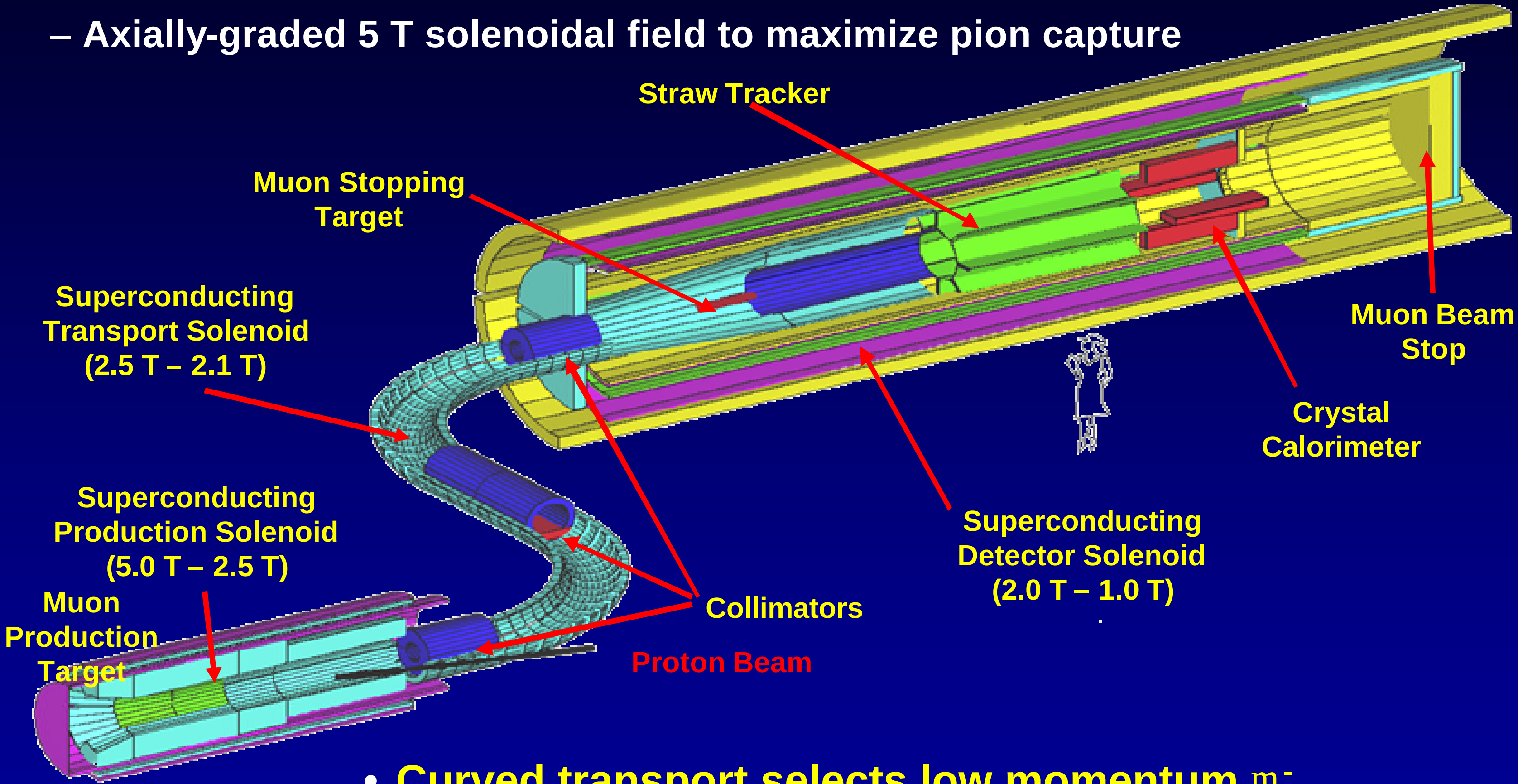
SINDRUM2 currently has the best limit on this process:

Experimental signature is 105 MeV e^- originating in a thin stopping target.



Features of the MECO Experiment

- **1000–fold increase in m beam intensity over existing facilities**
  - **High Z target for improved pion production**
  - **Axially-graded 5 T solenoidal field to maximize pion capture**



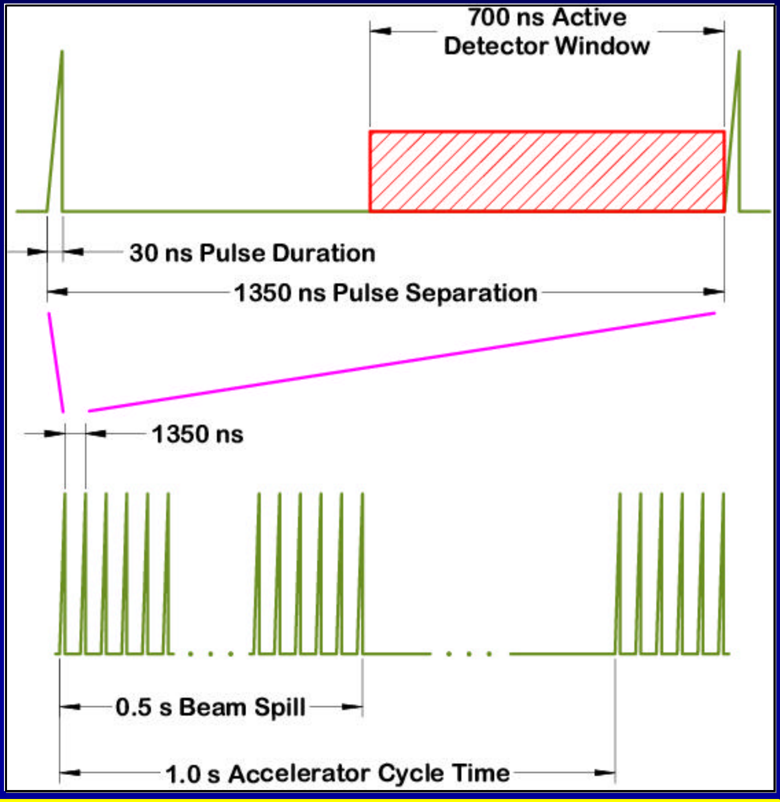
- **Curved transport selects low momentum m$^-$**
- **Muon stopping target in a 2 T axially-graded field to improve conversion e$^-$ acceptance**
- **High rate capability electron detectors in a constant 1 T field**

The MECO Pulsed Proton Beam

- Two of six RF buckets filled, giving 1.35 μsec separation between pulses for a 2.7 μsec rotation time. AGS cycle time is 1 sec.

- Extinction must be $>10^{-9}$; fast kicker in transport will divert beam from production solenoid; extinction can be monitored. In preliminary tests, extinctions of ~ 10^{-7} have been achieved.

- There's work to be done. 2 X 10^{13} protons/bucket is twice the present AGS bunch intensity.

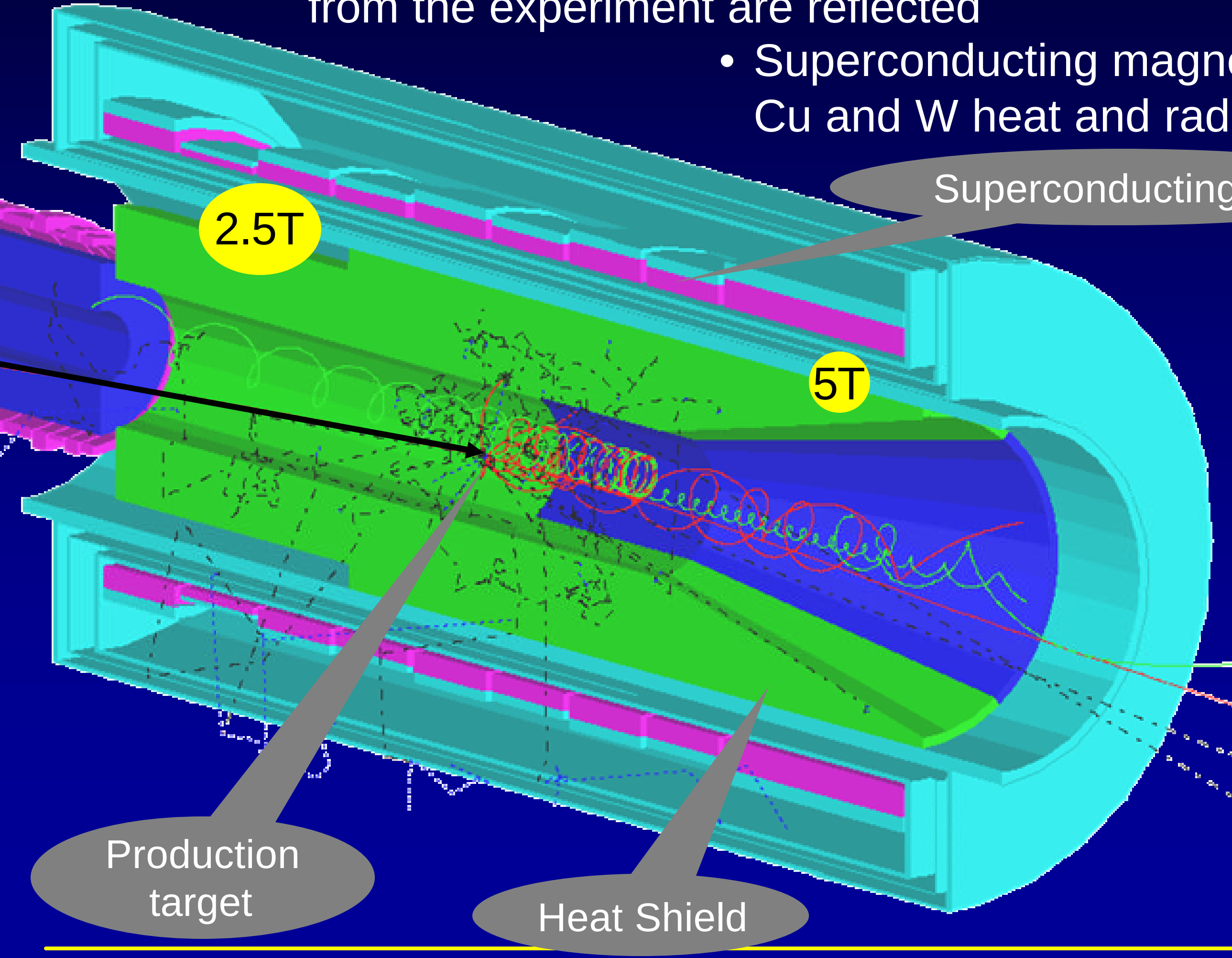


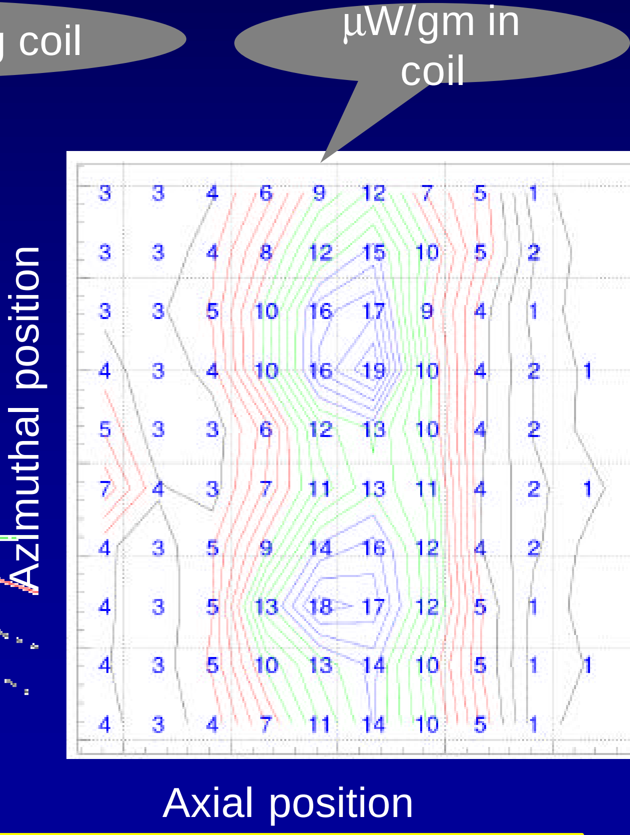
Muons Production and Capture in Graded Magnetic Field

Pions produced in a target located in an axially graded magnetic field:

- 50 kW beam incident on gold target
  - Charged particles are trapped in 5 – 2.5 T, axial magnetic field
  - Pions and muons moving away from the experiment are reflected
- Superconducting magnet is protected by Cu and W heat and radiation shield

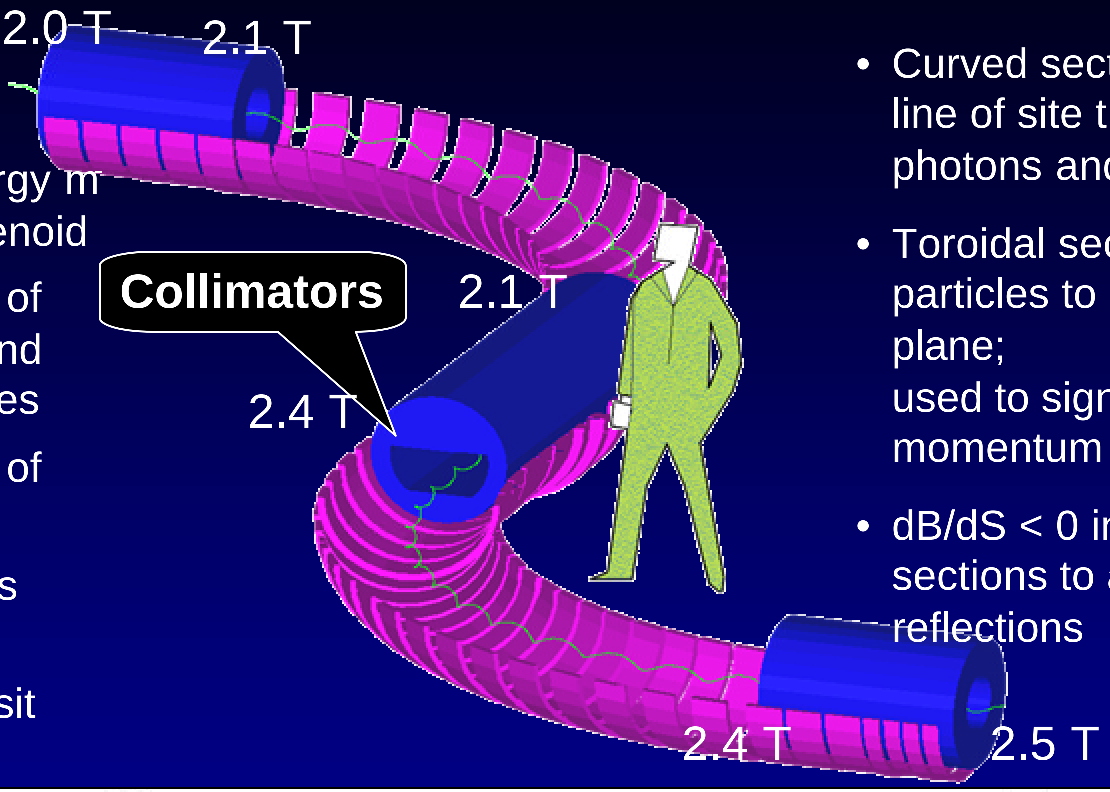
150 W load on cold mass
15 µW/g in superconductor
20 Mrad integrated dose





3	3	4	6	9	12	7	5	1	
3	3	4	8	12	15	10	5	2	
3	3	5	10	16	17	9	4	1	
4	3	4	10	16	19	10	4	2	1
5	3	3	6	12	13	10	4	2	
7	4	3	7	11	13	11	4	2	1
4	3	5	9	14	16	12	4	2	
4	3	5	13	18	17	12	5	1	
4	3	5	10	13	14	10	5	1	1
4	3	4	7	11	14	10	5	1	

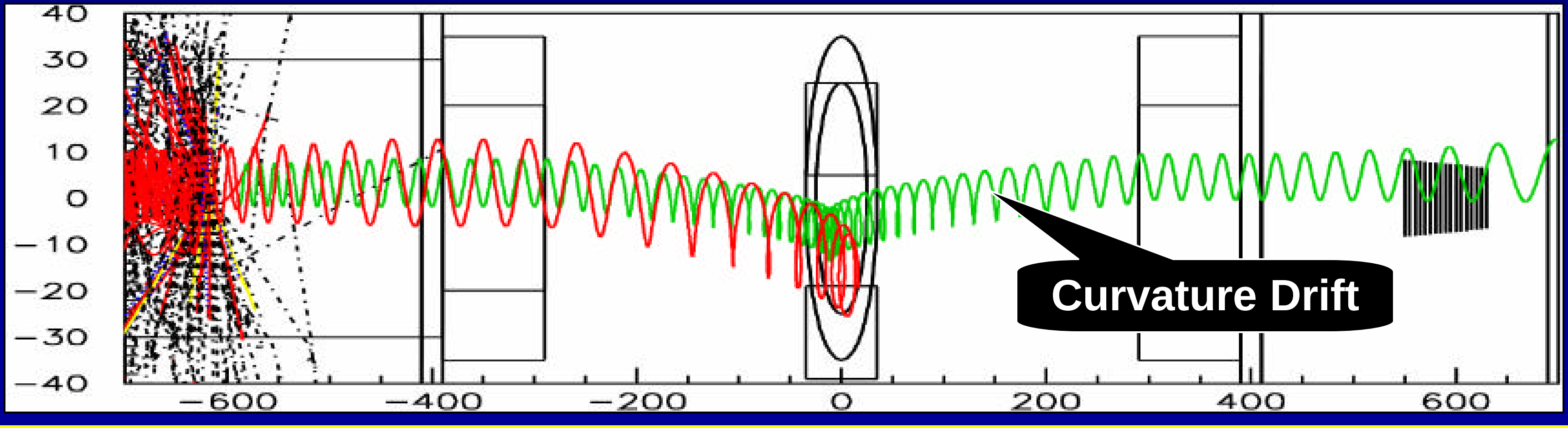
Transport Solenoid



Goals:

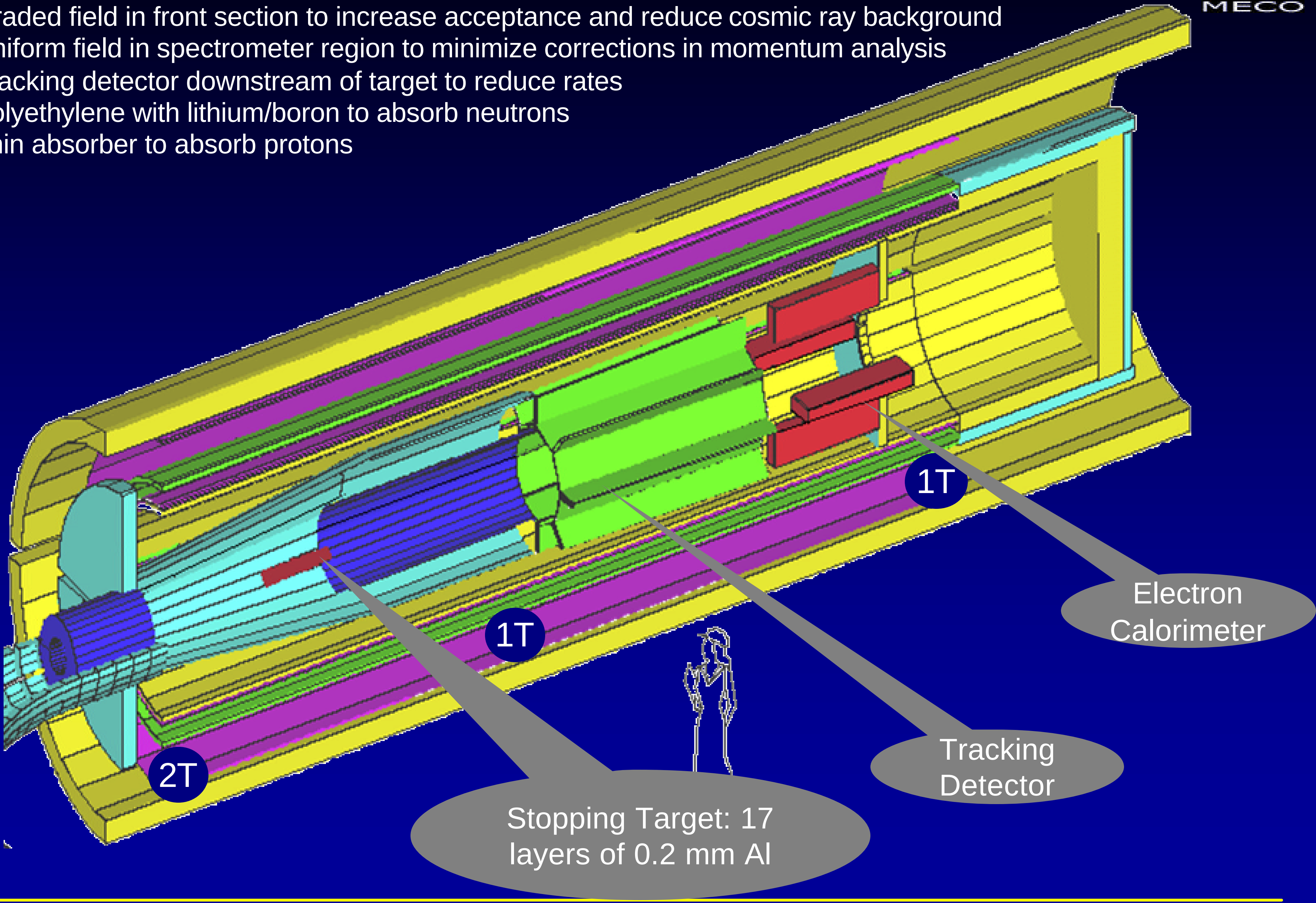
- Transport low energy m to the detector solenoid
- Minimize transport of positive particles and high energy particles
- Minimize transport of neutral particles
- Absorb anti-protons in a thin window
- Minimize long transit time trajectories

- Curved sections eliminate line of site transport of photons and neutrons.
- Toroidal sections causes particles to drift out of plane;
  used to sign and momentum select beam.
- dB/dS < 0 in the straight sections to avoid reflections



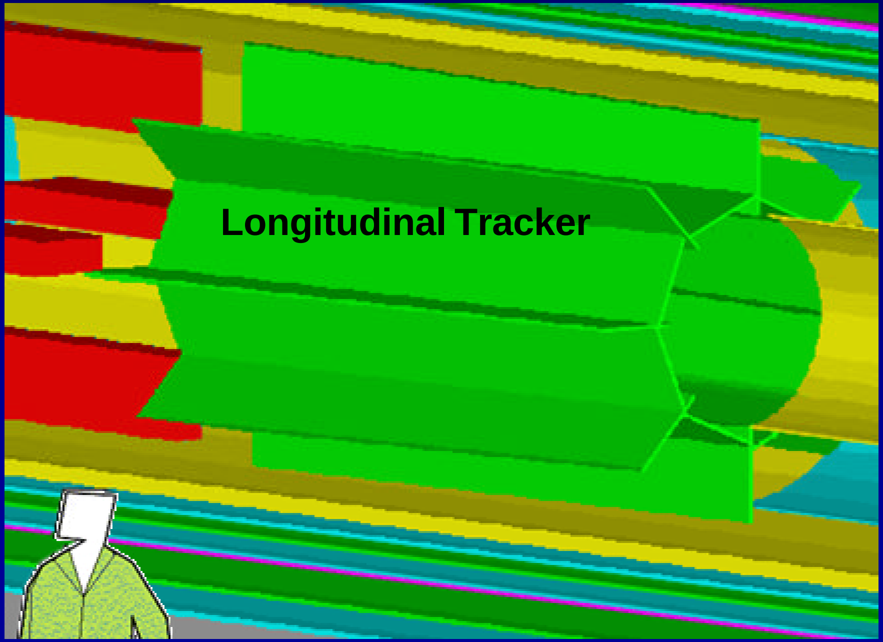
Stopping Target and Experiment in Detector Solenoid

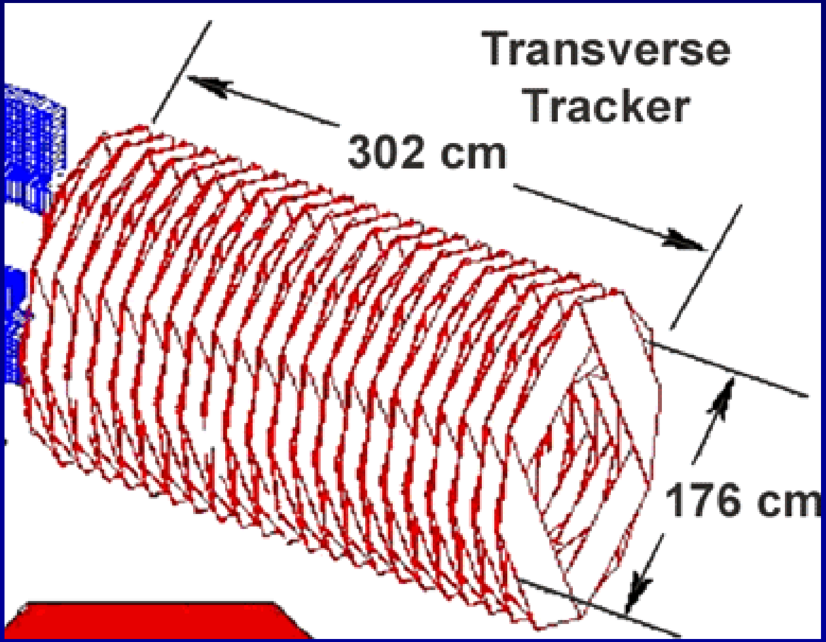
- Graded field in front section to increase acceptance and reduce cosmic ray background
- Uniform field in spectrometer region to minimize corrections in momentum analysis
- Tracking detector downstream of target to reduce rates
- Polyethylene with lithium/boron to absorb neutrons
- Thin absorber to absorb protons



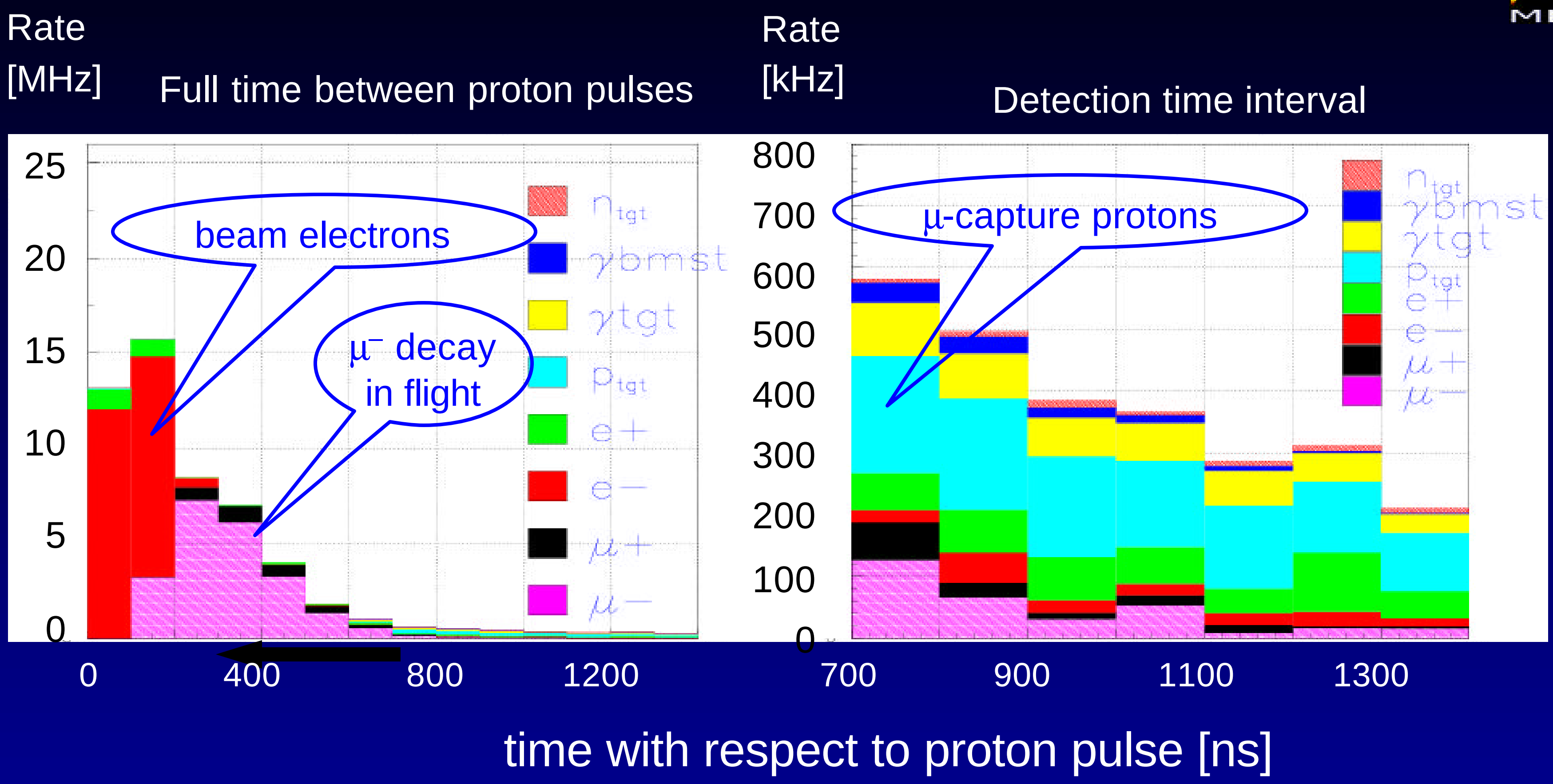
Tracking Detector

- Two tracker geometry options are being considered
  - Longitudinal geometry with ~3000 3m long straws oriented nearly coaxial with the DS and 19000 capacitively coupled cathode strips for axial coordinate measurement
  - Transverse geometry with ~13000 1.4 m straws, oriented transverse to the axis of the DS, readout at one or both ends
  - Both geometries appear to meet physics requirements





Tracking Detector Rates vs. Time

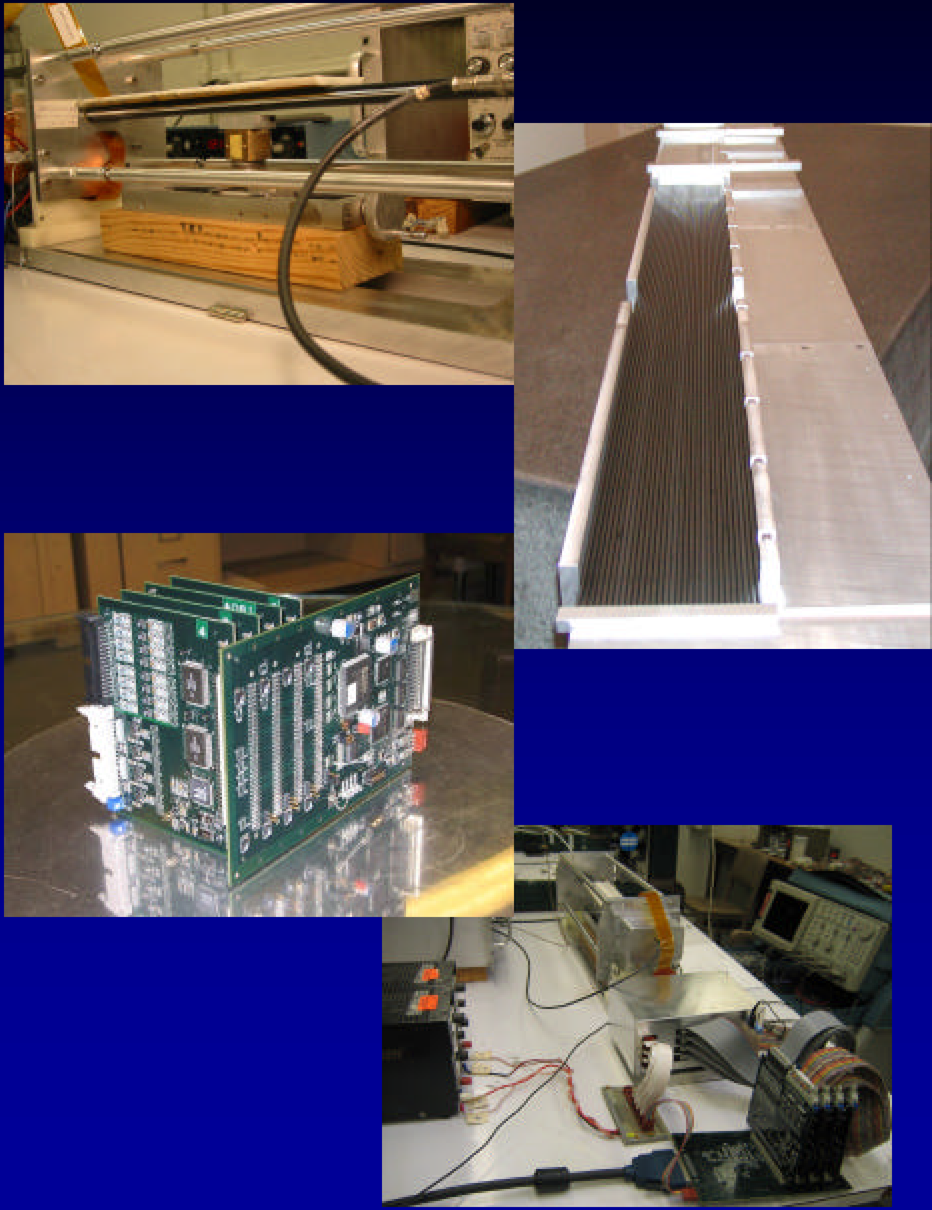

Full time between proton pulses

Detection time interval

- Very high rate from beam electrons at short times – potential problems with chamber operation
- Protons from μ capture are very heavily ionizing – potential problems with noise, crosstalk

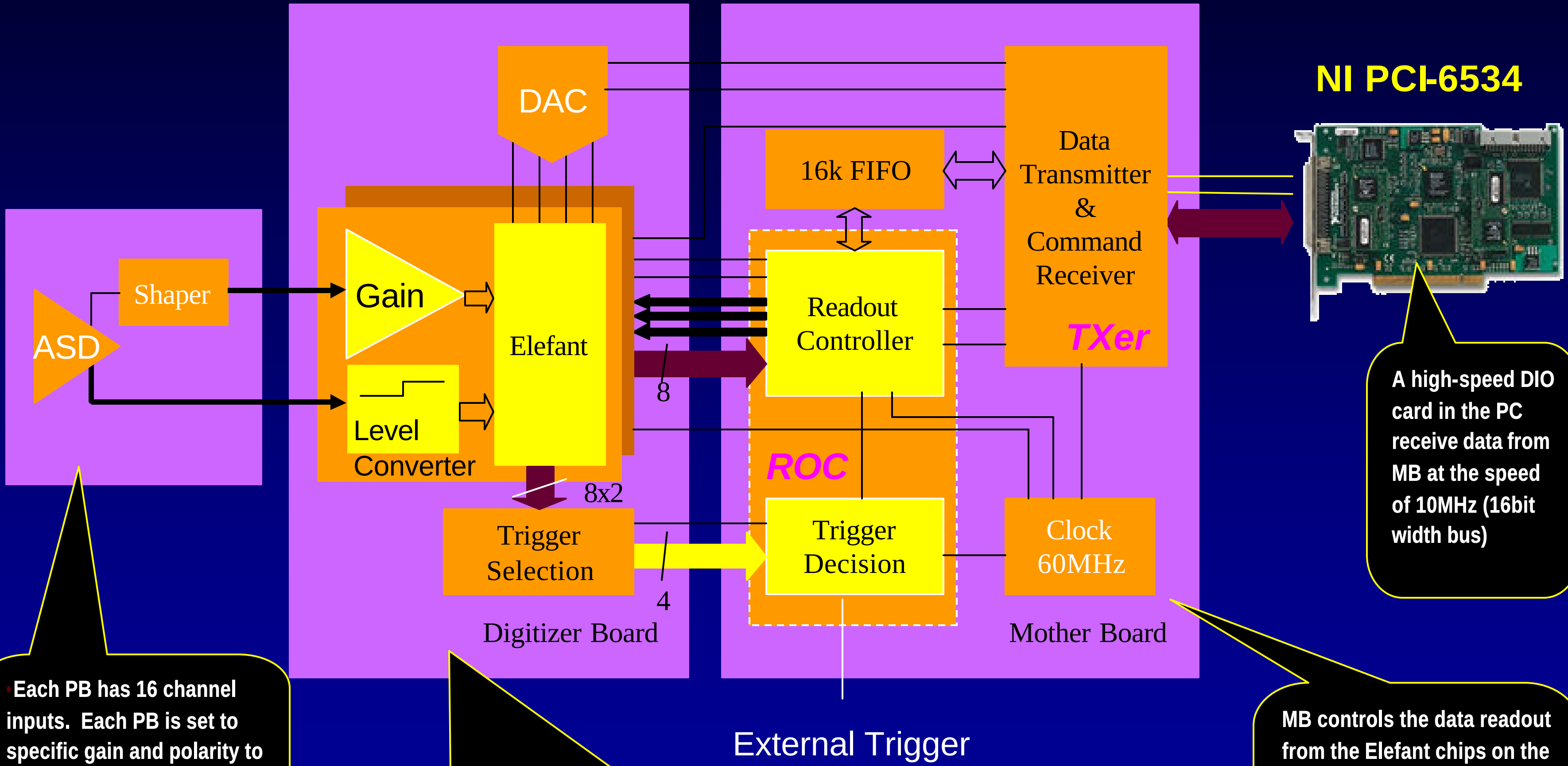
Tracker R&D (Houston)

- Short prototype detectors has been made, and are under testing now.
- Full-length longitudinal vane prototype remains a work in progress as mechanical stability and straw bonding issues are resolved.
- Electronics design and prototype work has progressed to testing prototype preamplifier, digitizer, and controller boards as a system using the current version of BaBar's Elefant chip with very promising results.
  - Work beginning on updating Elefant chip design to current technology
- The electronics work with either tracker designs



DAQ System Structure of Tracking Detector

- **The system includes four preamplifier boards (PB), four digitizer boards (DB), and one mother board (MB), and a PC.**



A high-speed DIO card in the PC receive data from MB at the speed of 10MHz (16bit width bus)

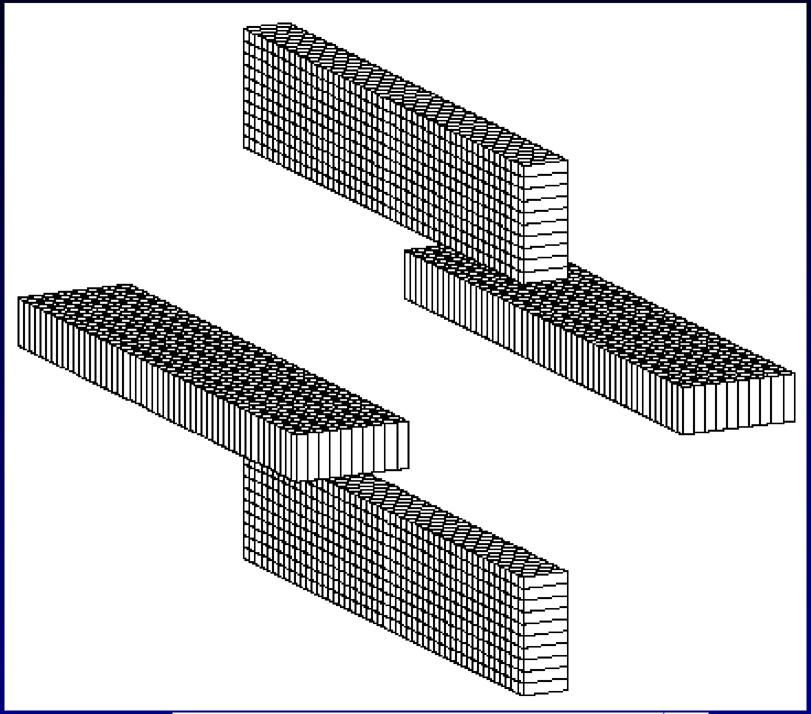
Each PB has 16 channel inputs. Each PB is set to specific gain and polarity to match the different signal inputs (anode or cathode).

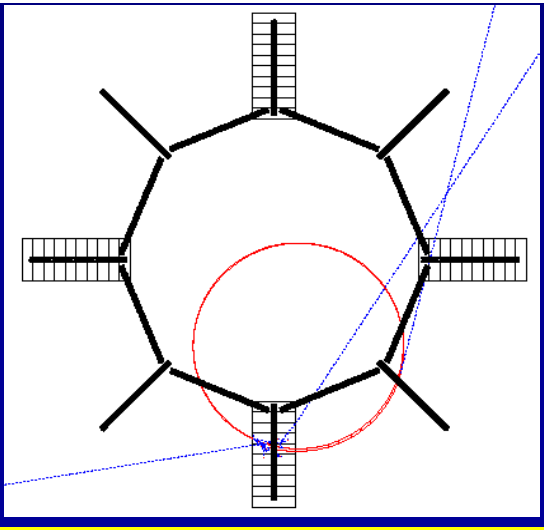
Each DB is connected to a PB. Two Elefant chips are located in a DB, each digitizing 8 channel inputs (analog and timing). To match the input requirements of the Elefant chips (polarity or amplitude), the analog and timing signal inputs from PB is processed in further before being digitized.

MB controls the data readout from the Elefant chips on the DB.

FPGA is used to control this readout sequence. A CPLD is used to send the data to a PC.

Electron Calorimeter



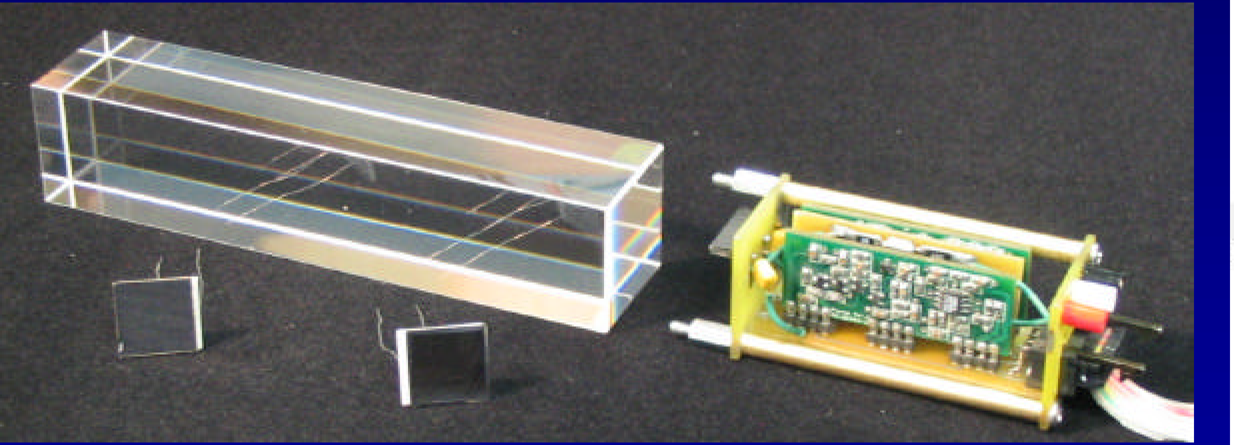


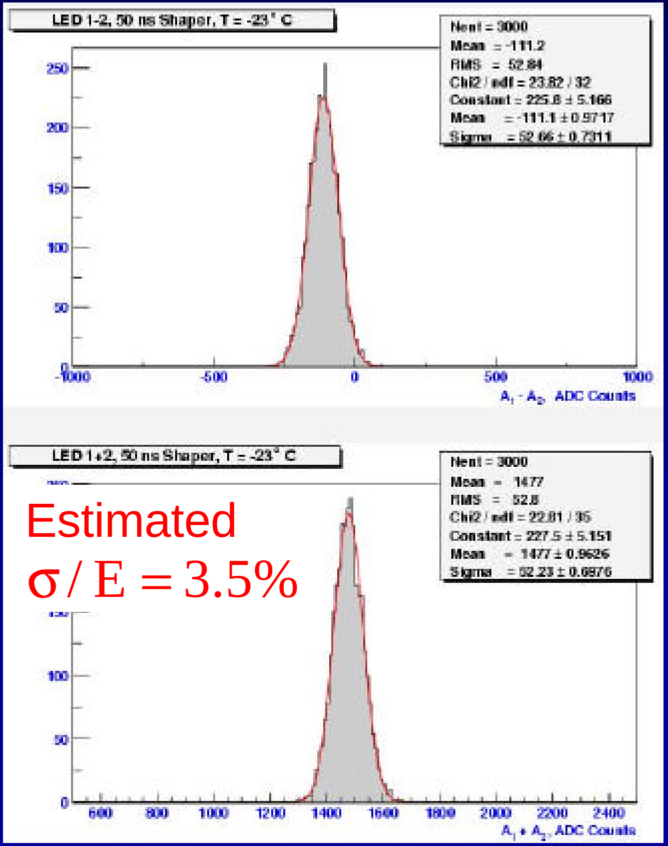
- Provides prompt signal proportional to electron energy for use in online event selection
- Provides position measurement to confirm electron trajectory
- Provides energy measurement to ~5% to confirm electron momentum measurement
- Consists of ~2000
  3 cm x 3 cm x 12 cm
  ($PbWO_4$ or BGO) crystals with APD readout

- Small arrays currently being studied for light yield, APD evaluation, electronics development

Calorimetric Electron Detector

- Indications are that $PbWO_4$ will meet MECO resolution requirements, demonstrating 20-30 photo e^-/MeV (as compared with CMS' 5 pe/MeV)
- We need to verify the system performance via beam tests of an 8´ 8 crystal array
- It appears that we can make use of fewer (larger) crystals allowing reductions in APD, and associated HV and readout channel counts (1152 crystals vs. 2000 originally)





Estimated
$\sigma / E = 3.5\%$

Current Status of MECO Approval, Funding, Schedule

Scientific approval status:

- Approved by BNL and by the NSF through level of the Director
- Approved (with KOPIO) by the NSB as an MREFC Project (RSVP)
- Endorsed by the recent HEPAP Subpanel on long-range planning

Technical review status:

- Positively reviewed by many NSF and Laboratory appointed panels
- Magnet system has been positively reviewed by external expert committees

Funding status:

- Currently operating on R&D funds of about $5M from the NSF plus some funds from U.S. and Japanese agencies supporting collaborating institutions
- Project start depends on U.S Congress – expected in FY05

Construction schedule

- Construction schedule driven by superconducting solenoids – estimate from the MIT Conceptual Design Study is 41 months from starting the engineering design until magnets are installed and tested

Running support will be provided by the NSF –
does not depend on DOE High Energy Physics support for the AGS

More information at http://meco.ps.uci.edu