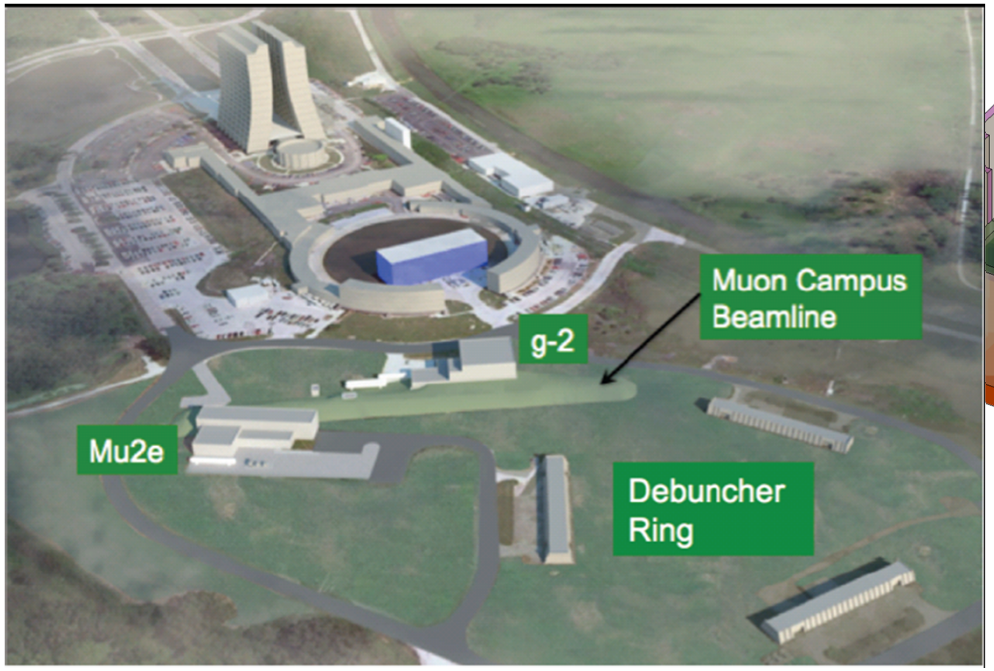
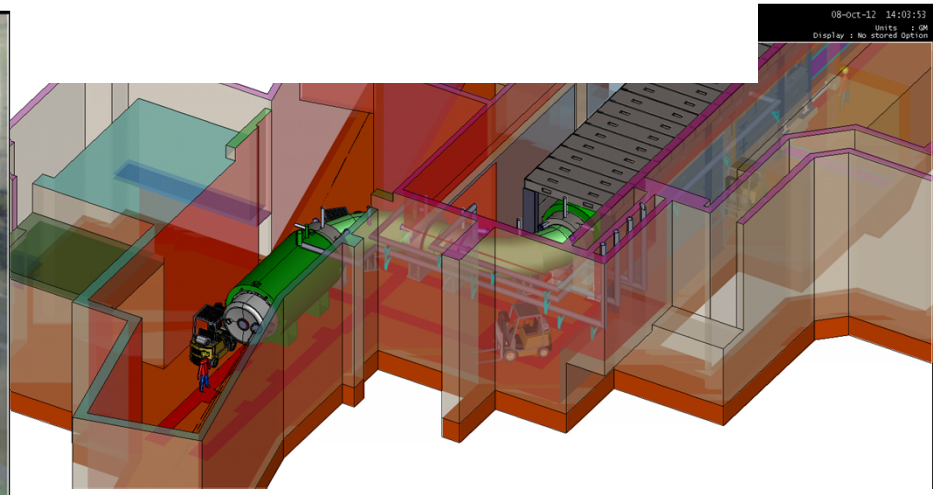
# Status of the Mu2e Experiment



Jim Miller, Boston University

October 2012 Fermilab PAC Meeting

# Outline

I. Brief Introduction:
   Mu2e Goal, Experimental Principles
II. Status and Progress of Rate and
   Backgrounds Studies
III. Closing Remarks

# Introduction

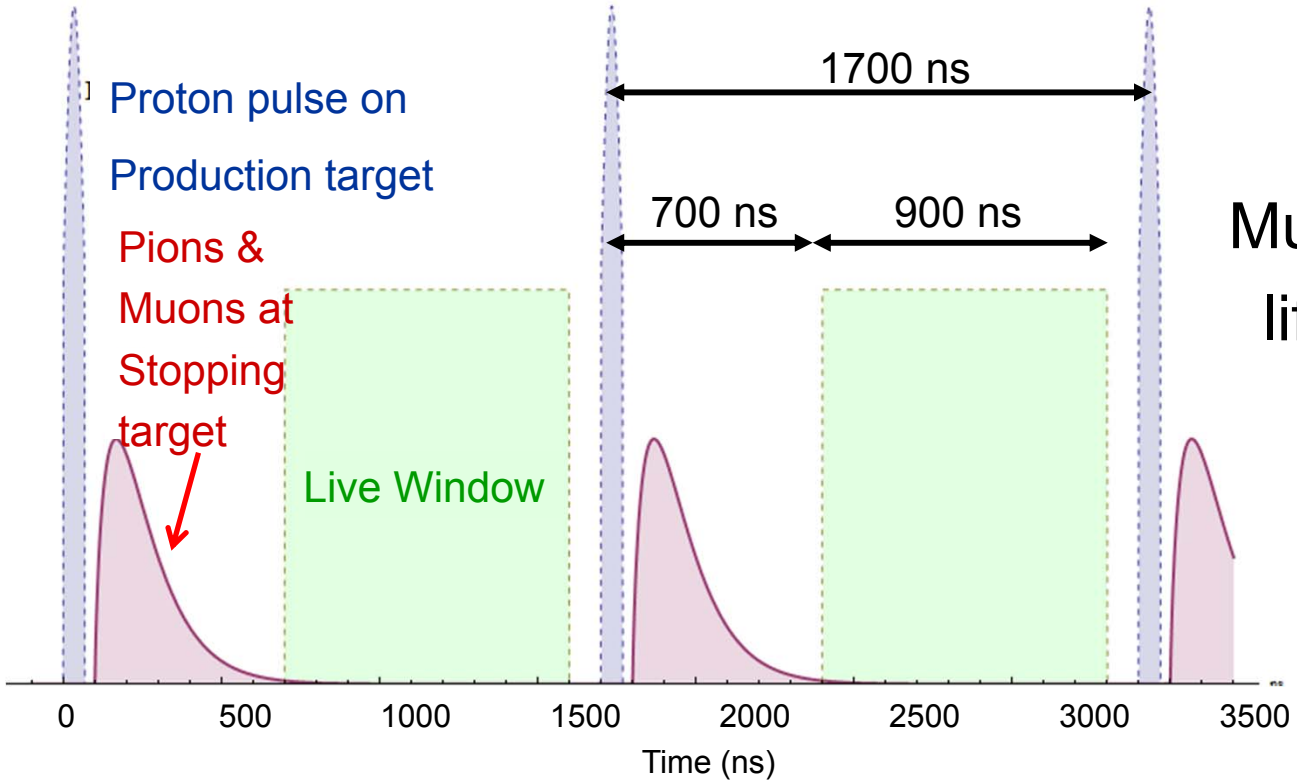
- Mu2e experiment: Muon to electron conversion- a search for Charged Lepton Flavor Violation (CLFV) via of $\mu^- N \rightarrow e^- N$

- Target sensitivity has great discovery potential
  - Goal: Single-event-sensitivity of $2 \times 10^{-17}$, background < 0.5 event
  - Factor of $10^4$ improvement over world's previous best measurements of $\mu \rightarrow e$ conversion at PSI
    - W.Bertl et al. (Sindrum II), Eur Phys J C47 (2006) 337
    - C. Dohmen et al. (Sindrum II), Phys Lett B317 (1993) 631
    - Super Symmetry, Little Higgs, Leptoquarks, Extended Technicolor, Extra Dimensions, Z'
- Complementary sensitivity to other physics programs
  - $\mu$ decays (e.g. $\mu \rightarrow e\gamma$) , LHC, $\nu$ mixing, B-factory

# Mu2e Experimental Approach

- Measure rate of conversion of a muon to an electron in the near-field of a nucleus
  - Stop high intensity of low energy muons in aluminum
  - Muon is bound in atomic orbit, lifetime 864 ns
  - Search for 105 MeV electron from $\mu^- +^{27}_{13} Al \rightarrow e^- +^{27}_{13} Al$
    - Nucleus is needed to conserve momentum and energy
    - Coherent process, nucleus is unchanged
    - Compared to $\mu^+ \rightarrow e^+ + \gamma$ , is that there can be exchange of heavy new particles with quarks
- Need ~$10^{18}$ stopped muons to get to $2 \times 10^{-17}$ SES
  - Requires a new, more powerful source of muons
    - Fermilab is well-suited to provide this beam

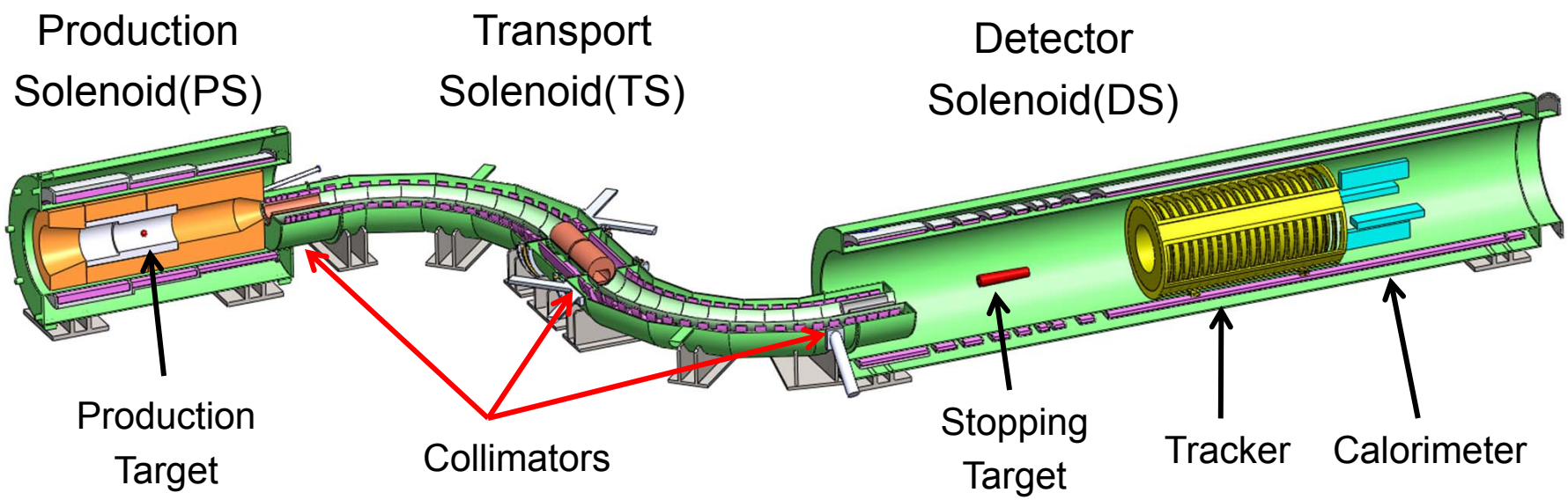
# Mu2e Beam Time Structure




Muonic aluminum lifetime=864 ns

- Pions (which cause background via Radiative Pion Capture- RPC) disappear in a few hundred ns; only after that do we begin search for conversion electrons
- Extinction: out-of time proton intensity must be $<10^{-10}$ times in-time intensity
- Cyclotron period of Debuncher Ring (Renamed Delivery Ring) is good match to the muonic aluminum lifetime of 864 ns.

# Mu2e Apparatus




(not shown: Cosmic Ray Veto, Proton Dump, Muon Dump, Proton/Neutron absorbers, Extinction Monitor, Stopping Monitor)

- Mu2e experiment consists of 3 solenoid systems

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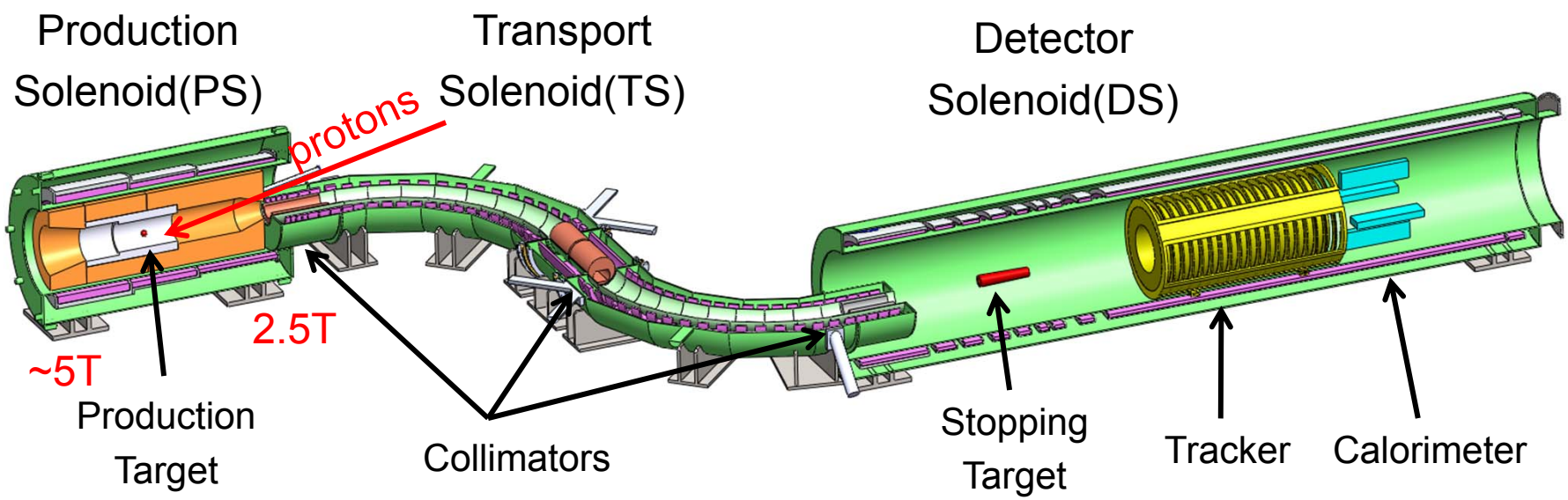


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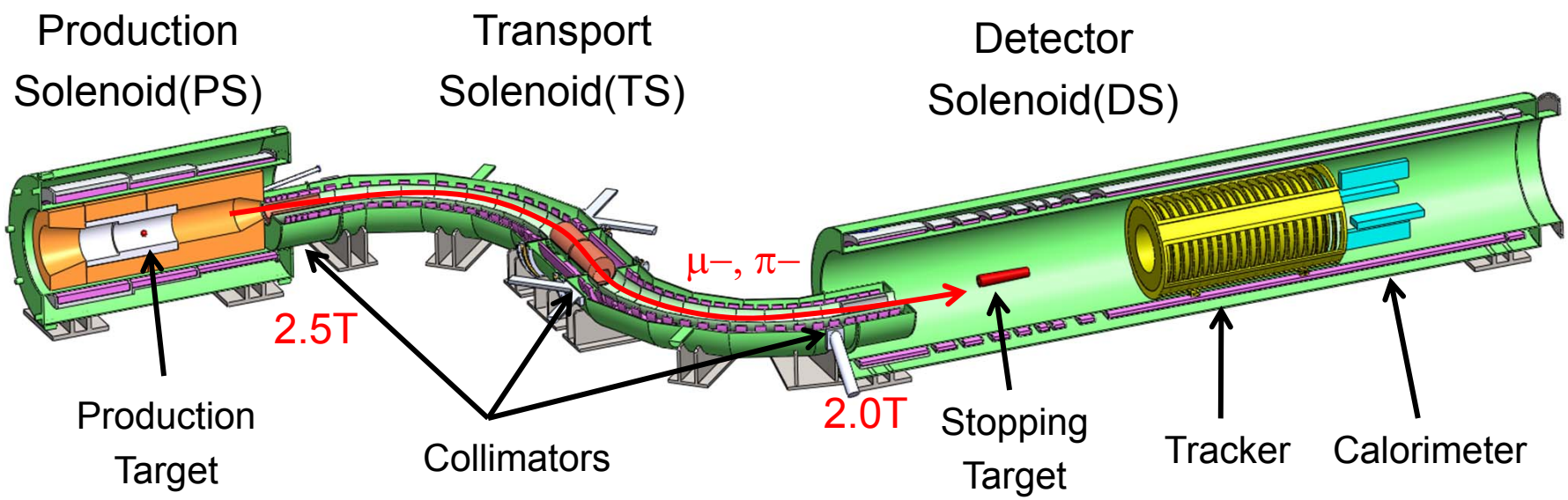


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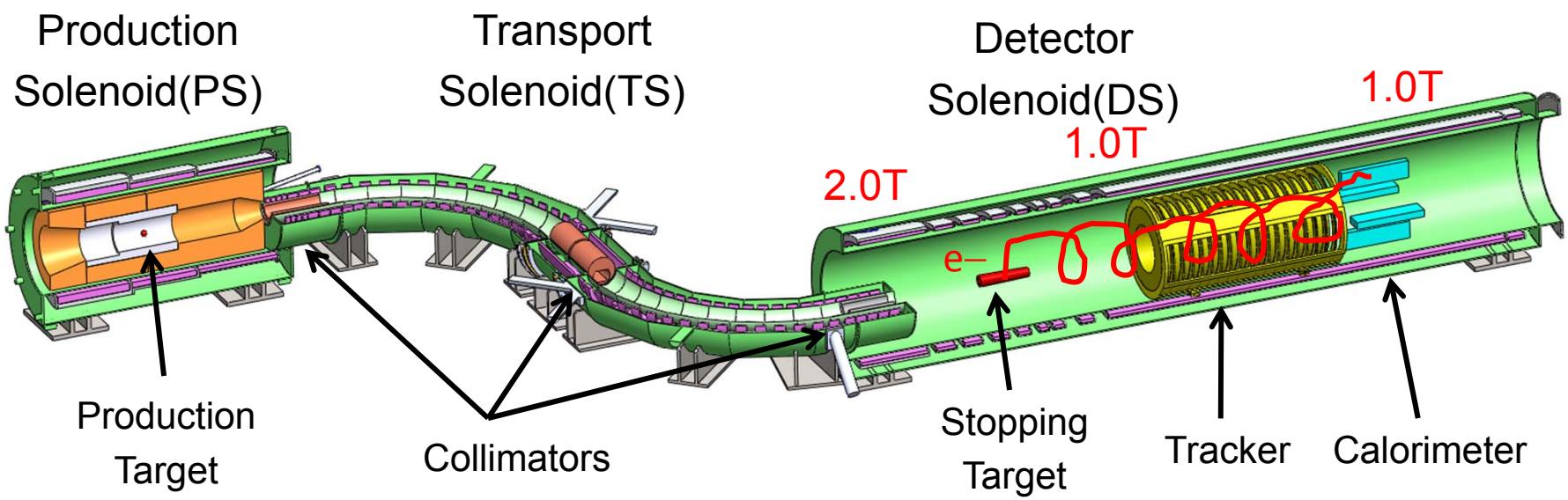


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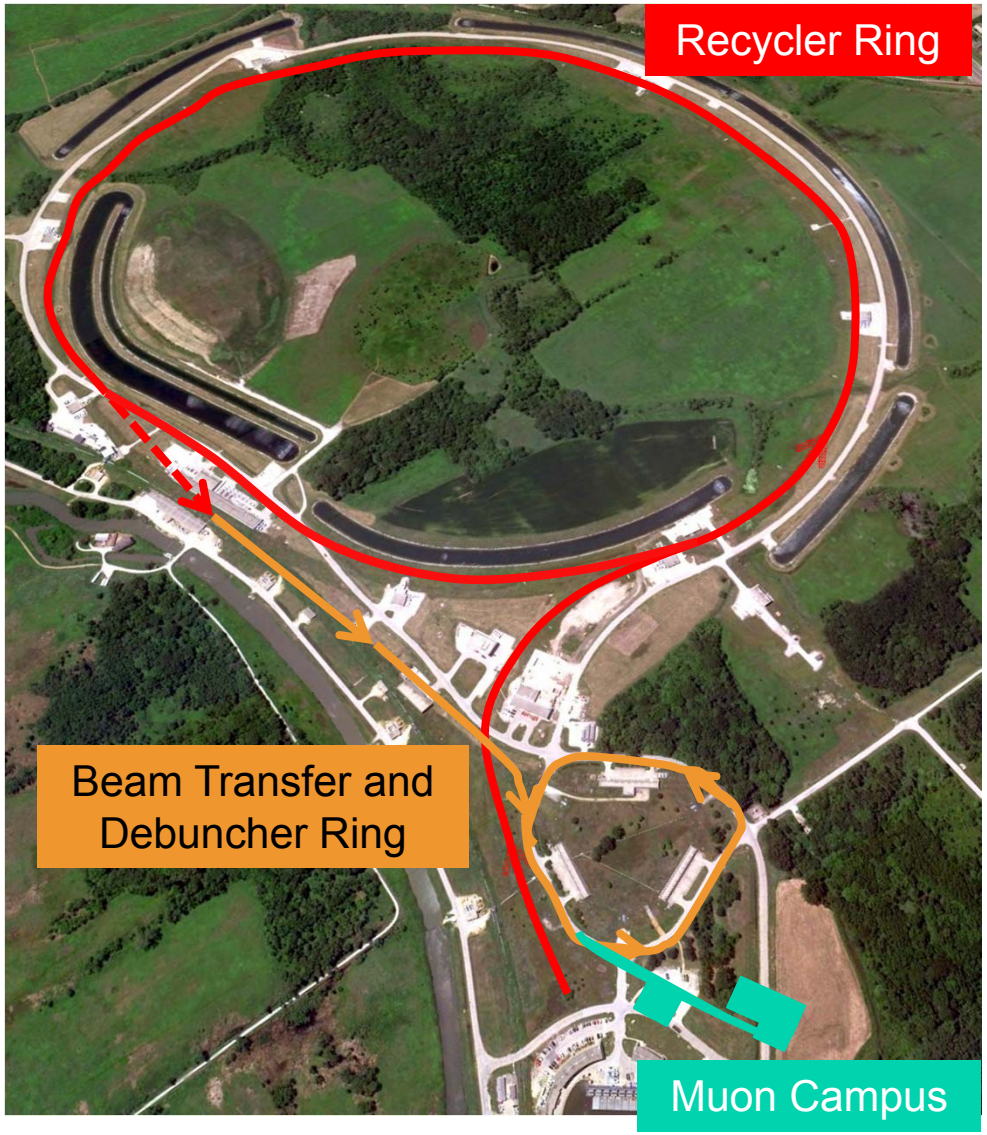
- Mu2e experiment consists of 3 superconducting solenoid systems

# Proton Beam Delivery




Many elements in common with g-2

→ Recycler Upgrade AIP

- RF capability
- Connection to former pbar complex

→ Debuncher/Delivery Ring AIP

- Beam transport to and injection into Debuncher
- Proton abort system
- Removal of TeV equipment

→ Muon Campus

- MC-1 Building (GPP)
- MC Cryo Plant (AIP)
- MC Beamline Enclosure (GPP)
- MC Site Preparation (GPP)

# Mu2e CD and Review Status

- Received CD-0 in November 2009
- Mu2e CDR completed March 2012
- Had a successful CD-1 review and received CD-1 in July, 2012
  - As a result PED funds for FY12 and FY13
- Aiming for next CD milestones over next 18 months
  - CD-2 in 18 months.
  - CD-3a production of superconductor

# PAC Report

"Concerning Mu2e, in its December 2011 report the PAC wrote:

'The Committee encourages the experiment to continue to quantify the risks associated with uncertainties in sensitivity and background projections, making measurements where possible, and to put mitigation plans into place as early as possible to avoid erosion of discovery capability. The Committee also recommends that the Laboratory pay particular attention to ensure that the project is ready for effective reviews.'

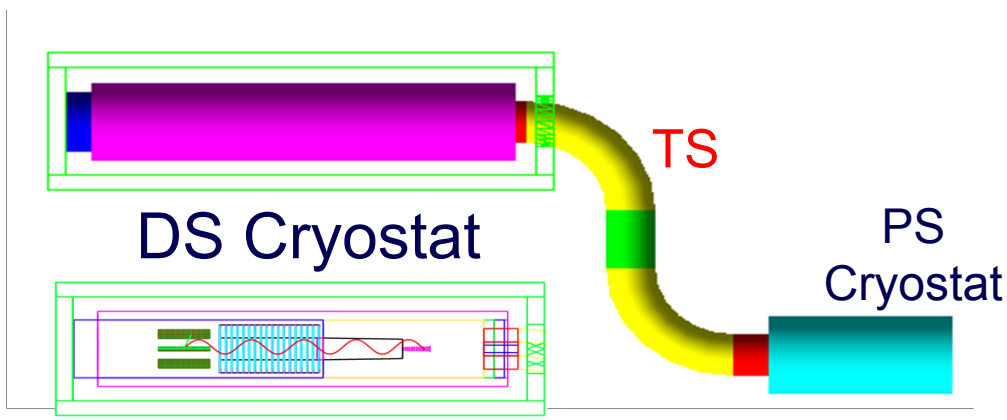
The PAC was told that the recent Lehman review of Mu2e was successful, which reflects very well on the Collaboration and the Laboratory. As this is a challenging experiment, the PAC recommends continued careful attention by the Laboratory to Mu2e and requests updates on the progress at future meetings."

# Our Response

- Established uncertainties on backgrounds in CDR and progress continues to set uncertainties on all quantities that affect sensitivity
- Established prioritized list of simulations
  - poll of L2 managers, simulations group, discussion s w/rest of collaboration
- Redouble our emphasis on simulations that drive the design
- Identify personnel and recruit as necessary

# Progress in Background, Signal Simulation Tools

- Baseline: Mu2e Offline.
  - architecture inherited from CMS and shared among all Intensity Frontier experiments ("art")
  - Full power of G4
  - Advanced prototype hit level tracker simulation that includes the full beam line and detector details
  - Detailed experiment model and implemented; detailed particle history is available
  - Includes all background processes, possibility to overlay
  - Under continual refinement



- Mu2e Offline (Cont'd)
  - To expand simulation participation: Week long school was held in August 2012 to train collaborators in its use. (R. Kutschke, D. Brown).
  - Possible model for other Intensity Frontier projects
- Successfully launched several new people to use Mu2e Offline:
  - Emma Barnes (BU), Antonio de Maria (Pisa), Martin Frank (UVa), Glen Warren(PNNL), Ricco Bonicalzi(PNNL).
  - Others with some previous experience are now much more capable: Ehrlich(UVa), Frank(UVa), Echenard(Caltech), Onorato(INFN), Hodge(NIU)
- Training materials being developed to continue process

# More Background and Signal Simulation Tools

- Parallel avenues of simulations, many people involved
  - G4beamline (Muons, Inc.), a wrapper based on GEANT4 but with simplified geometry implementation
    - Best adapted to straightforward tests of geometries of collimator, targets, etc., first estimates of rates, checks of other calculations.
  - MARS
    - Substantial participation of MARS group in Mu2e simulations
    - Emphasis on particle production, transport , shielding issues (e.g. PS shield, neutron shielding)
    - Updated pion production cross sections updated using recent HARP data
    - Created model antiproton production (not available in GEANT4 physics packages)

# MARS Production cross sections: pions, antiprotons

- Uncertainty in muon stopping rate in the Al stopping target
  - Has varied by ~20% as production cross sections and beamline modeling evolved
    - Latest version of QGSP_BERT G4 physics list gives good agreement with MARS cross sections for stopping rate
    - 0.0016(.0004) stopped muons per incident 8 GeV proton
- Antiproton background
  - 8 GeV protons produce pbars (at very low rate)
  - Pbar stop in stopping target, release 1.8 GeV, possibly 105 MeV electrons
  - Simulations completed in March: background 0.1(0.05) events

# Summary of Background Estimates(CDR)

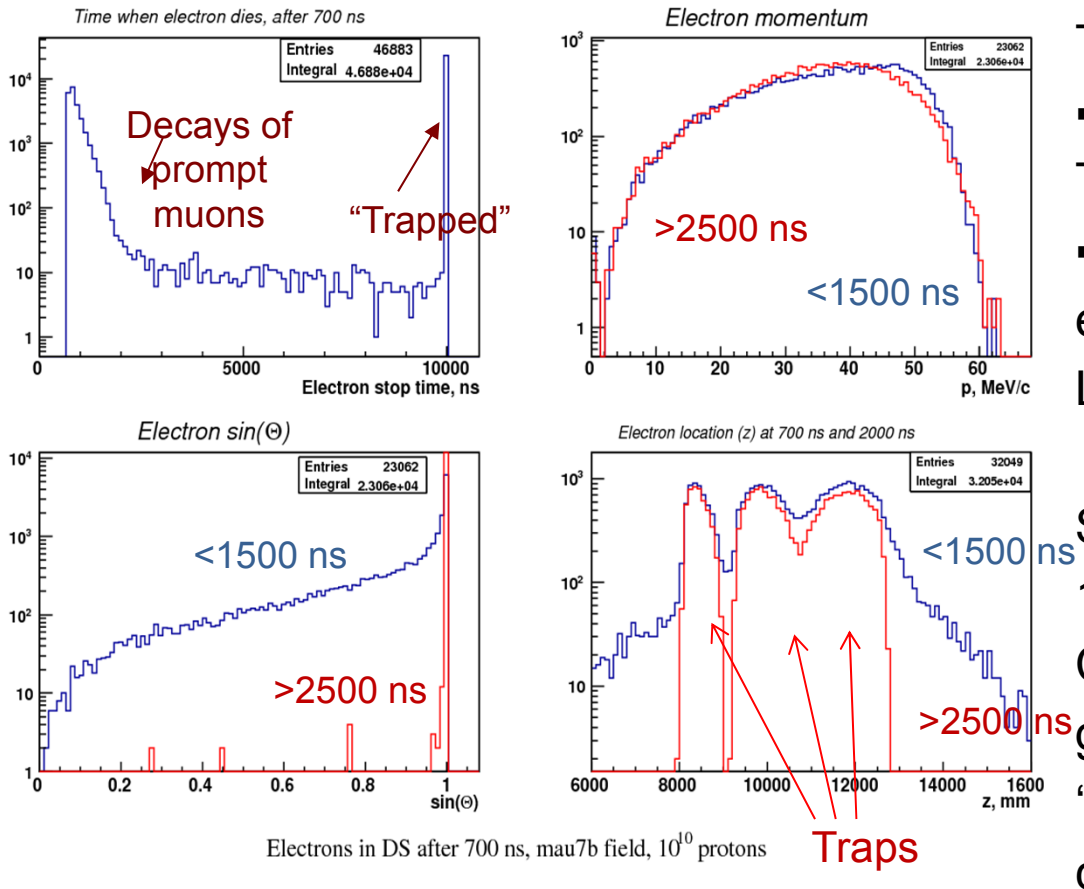
| Background | Background Estimate | Error Estimate | Reference | Justification |
|---|---|---|---|---|
| Muon decay-in-orbit | 0.22 | ± 0.06 | 2085 | Acceptance and energy loss modeling, spectrum calculation; reconstruction algorithm |
| Cosmic Rays | 0.05 | ± 0.013 | CDR | Statistics of sample |
| Radiative Pion Capture | 0.03 | ± 0.007 | 2085 | Acceptance and energy loss modeling |
| Pion decay In-Flight | 0.003 | ± 0.0015 | 2085 | Cross-section, acceptance and modeling |
| Muon decay In-Flight | 0.01 | ± 0.003 | 2085 | Cross-section, acceptance and modeling |
| Antiproton Induced | 0.10 | ± 0.05 | 2121 | Cross-section, acceptance and modeling |
| Beam electrons | 0.0006 | ± 0.0003 | 2085 | Cross-section and acceptance (this is an upper limit) |
| Radiative muon capture | $< 2 \times 10^{-6}$ | – | 1230 | Calculation |
| **Total** | **0.41** | **± 0.08** | 2085 | Add in quadrature |

(assuming 6E17 stopped muons in 2E7 s of live time)

# Priority List of Simulation Items

- Top priority (timescale < 6 months)
  - Simulations required to finalize solenoid designs (time scale < 3 months)
  - Simulations required to understand neutrons
    - Impacts hit rates in Cosmic Ray Veto, Tracker, Calorimeter
    - Impacts shielding, tunnel sizes, muon beam stop and collimator
  - Simulations required to make choices between the two tracker options
  - Simulations required to quantify cosmic ray background
  - Simulations needed to make choice between two extinction monitor options
- High Priority (9-12 months)
  - Energy calibration of tracker
  - Calorimeter vane vs disk configuration
  - Stopping target monitor signal and backgrounds

# Simulation Affecting Solenoid Design: Stored Particles in Tracker Region




Electrons in DS after 700 ns, mau7b field, $10^{10}$ protons

Two issues

- High momentum muons trapped

They decay to 105 MeV electrons

- Low momentum muon or electrons trapped

Leads to unnecessary hits in tracker

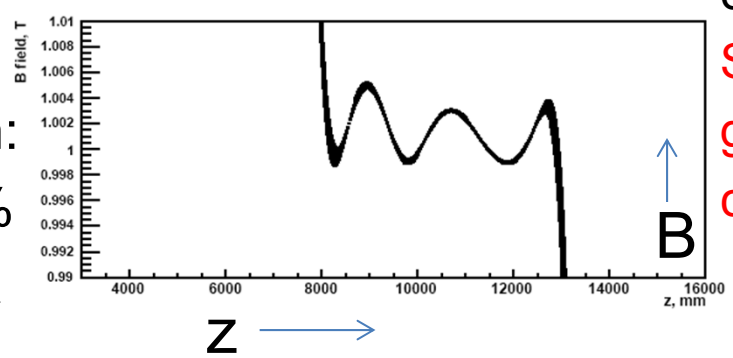
Study just completed

105 MeV background not a problem

Considering small negative gradient to fill in dips- pushes out 'Lingering' particles (low energy but causing repeated hits in tracker)

Study finished→Insert negative gradient, 2% over 5 m, in tracker calorimeter region

'Uniform' field in tracker region: variation +-0.5% w/ local minima



# Neutron Background

- Neutrons are copiously produced
  - muon captures $\mu^- + {}^A_Z X \rightarrow \nu_\mu + {}^A_Z X' + an + bp + c\gamma$, a~1.2, b~0.1, c~2
    - Transport solenoid collimators, stopping target, muon beam stop
  - From the production target
- Neutron induced hits affect detector performance: efficiency and/or resolution. Primarily low energy hits.
  - Cosmic Ray Veto
  - Tracker
  - Calorimeter
  - Stopping target monitor
  - Extinction monitor

# Neutron Task Force Formed

# 1st Study- Detailed Look at Tracker & Calorimeter Response to Neutrons from Stopping Target

## Neutron absorber configurations

-Tested different neutron absorbers available in the geometry

- -Simple plastic (Polyethylene092)
- -Polyethylene with Borum050 ( 5% of Borum )
- -Polyethylene with Borum300 ( 30% of Borum )
- -Polyethylene with Lithium ( 7.5% of Lithium )
- -No neutron absorber at all

- -No time folding in particle generation
- -QSGP_BERT_HP physics list
- -0.01 min Range Cut



Giovanni Onorato

# 2nd Study- MARS

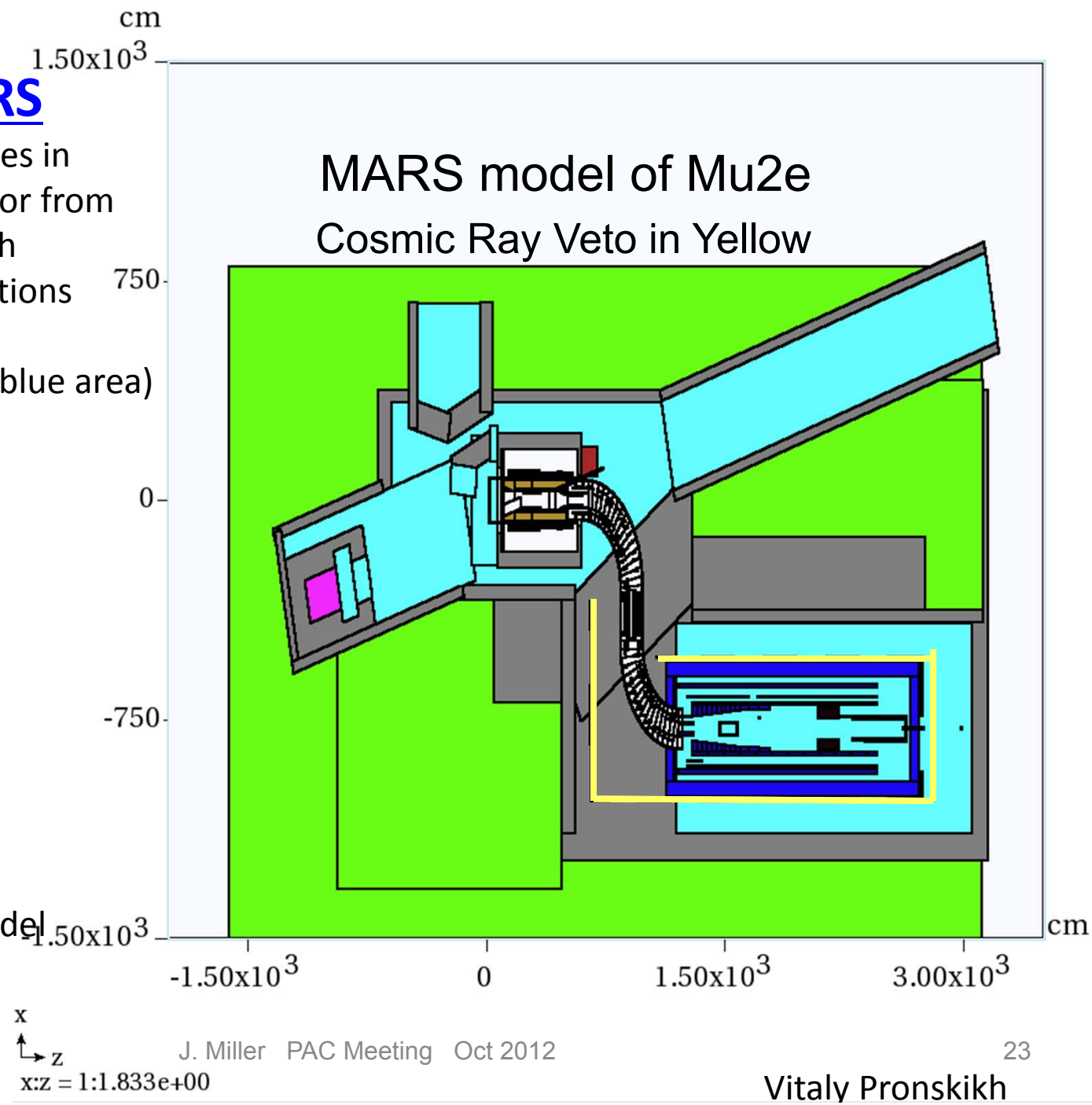
Study of neutron hit rates in Cosmic Ray Veto detector from all Neutron Sources with two shielding configurations

- Heavy Concrete (dark blue area)
- Concrete (gray)
- Li doped poly internal DS absorber

AND

- Iron Shield (dark blue)
- Concrete (gray)
- B doped Poly internal DS absorber

(Extension of MARS model used to study Heat and Radiation Shield in Production Solenoid)




Vitaly Pronskikh

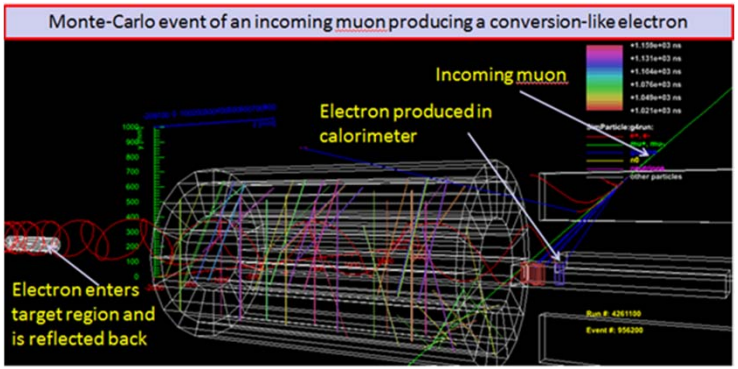
# Now In progress by Neutron Task Force*

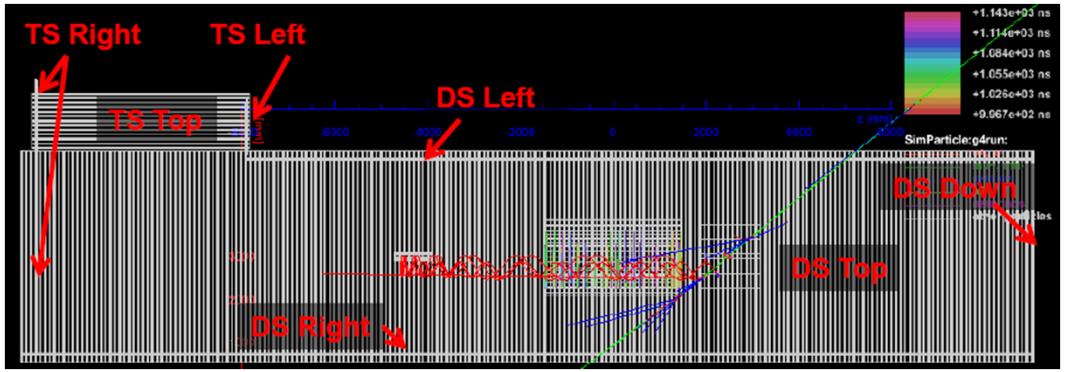
- Update both MARS and GEANT4 based simulations with higher fidelity geometry- nearly finished
- Compare MARS and GEANT4- early comparisons look reasonable
- Include the rates from each source: Production and stopping targets, collimators, muon beam stop,...
- Make shielding or design modifications to meet detector background/rate specifications
- Work started in July, final report due end of year
- Lost one key contributor (Onorato, returned to Italy), could use one more person now, additional MARS person arriving in January

*Rick Coleman, Dave Hedin, Martin Frank, Vladimir Khalatian, Vitaly Pronskikh

# Simulation Activities: Cosmic-Ray Monte Carlo

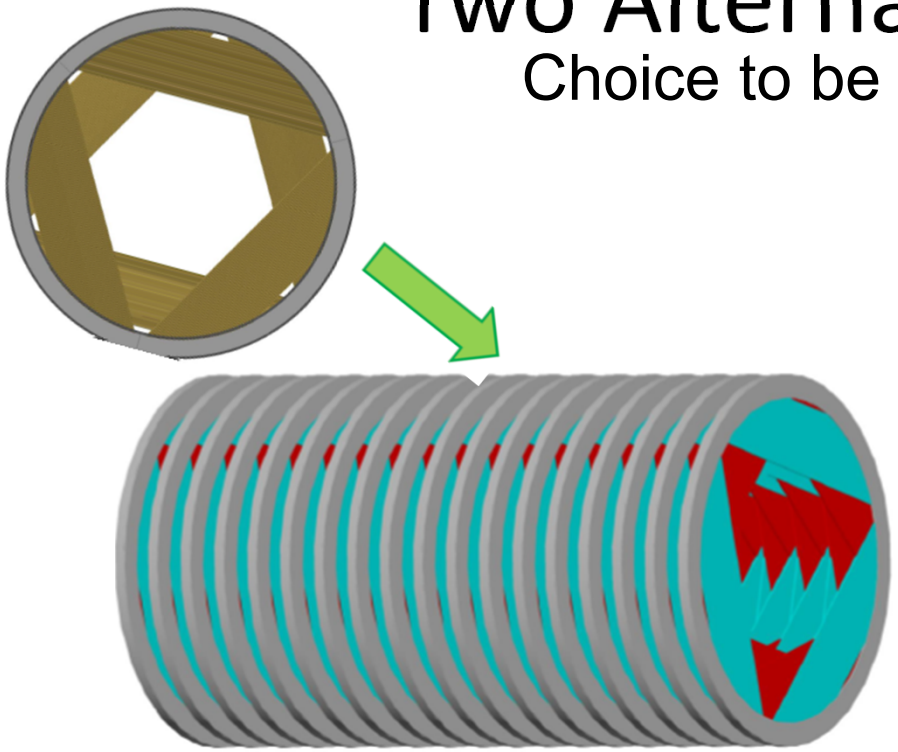
- Mu2e Offline: full GEANT4 simulation of the building, detectors, solenoids, neutron absorbers, etc. All requisite physics processes are included. Track finding included.
- 3 Layers surrounding all but bottom around DS, require 2/3 planes for veto. Results:
  1. Conversion-like electron background from cosmic-ray muons:
     $\Rightarrow$ 468 $\pm$ 62 background events over entire run without any CRV
  2. Required efficiency of cosmic-ray veto counters (require at least 2 of 3 planes fire)
     $\Rightarrow$ < 1.1 x $10^{-4}$ produces requirement of 1/20$^{th}$ event over entire run @ 90%CL
  3. Required coverage of cosmic-ray veto:
     $\Rightarrow$ Unavoidable holes in coverage are being studied using "beams" of cosmic-ray muons. We have yet to find any background events that have not produced hits in at least 2/3 cosmic ray counters.
- Goals for CD-2:
  - Explore required coverage in upstream area where neutron background is large
  - Test prototypes for light production/efficiency, sensitivity to neutrons



# Two Alternative Tracker Designs

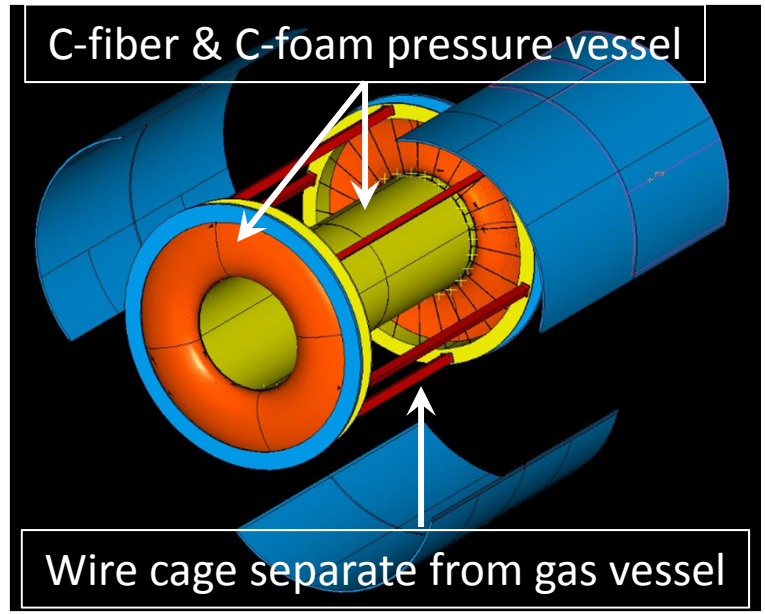
## Choice to be made by end of year



3m

T-Tracker (straws)- baseline

- Broken straws localized
- Broken wires more easily repaired
- Received emphasis of study as CD-1 baseline



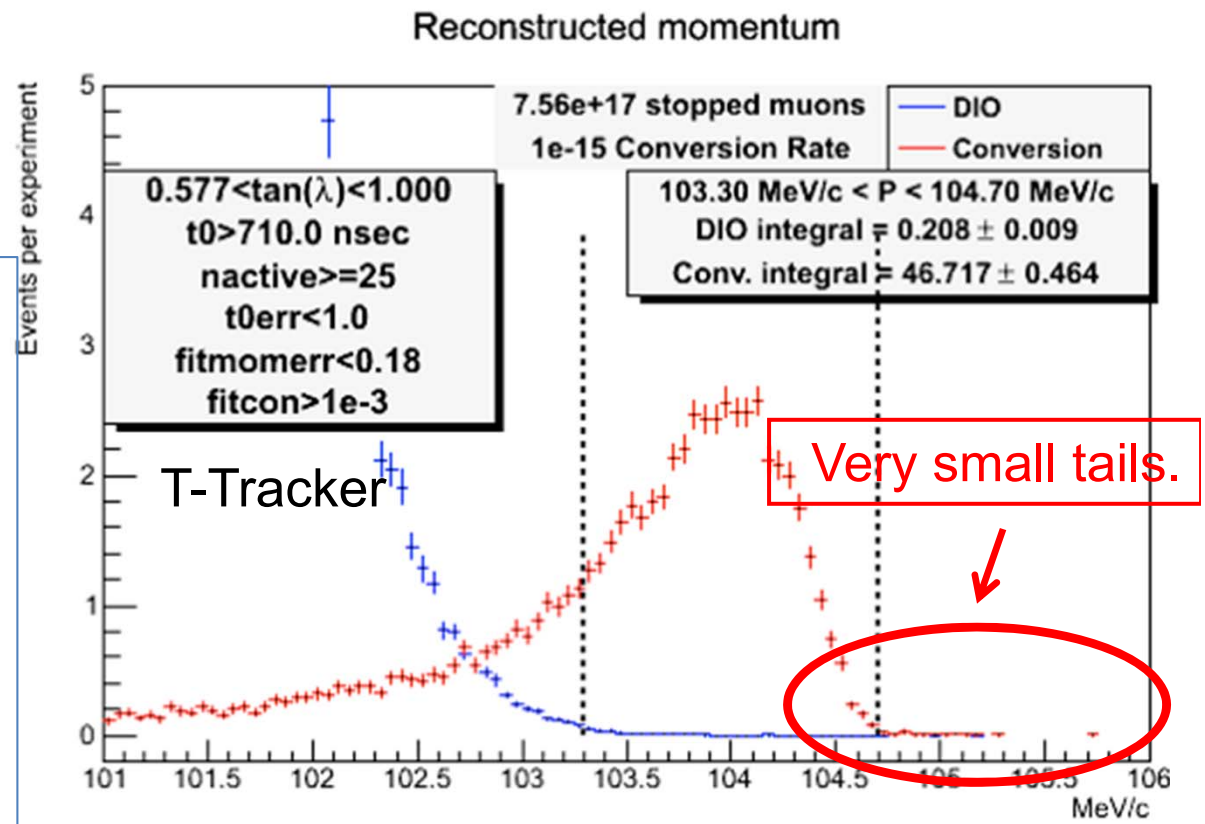

- I-Tracker (stereo drift chamber, wires ~parallel to solenoid axis)
  - More hits per track
  - Potentially larger acceptance
  - Detailed simulation studies (catching up to T-Tracker)and mechanical design in progress

# Simulation of Signal + Background (T-Tracker)

- In Mu2e Offline package: Multiple-step track pattern recognition, Kalman filter track fitter
- Includes cocktail of all background hits
- High E Tail of electrons from muon decay in orbit(DIO), recent ~15% theory calculation
- Conversion electron peak assuming conversion electron BR $=10^{-15}$ in the figure.
- Energy straggling in materials (e.g. target), tracker resolution are included
- Signal efficiency improved by x2 since CDR (improved handling of L/R ambiguity, smarter removal of delta rays, more improvements coming)

For: $7.56 \times 10^{17}$ POT
Assuming $R\mu e = 10^{-15}$
In signal window:
47 CE , 0.21 DIO

**>Double the noise hit rates:**
20% efficiency loss
no change in σ(momentum)
**>Double $\sigma_t$ in time division**
10% efficiency loss
**>15 μm→25 μm straw walls**
10% loss in E resolution
40% loss in efficiency
>Some losses perhaps recoverable by tuning reconstruction

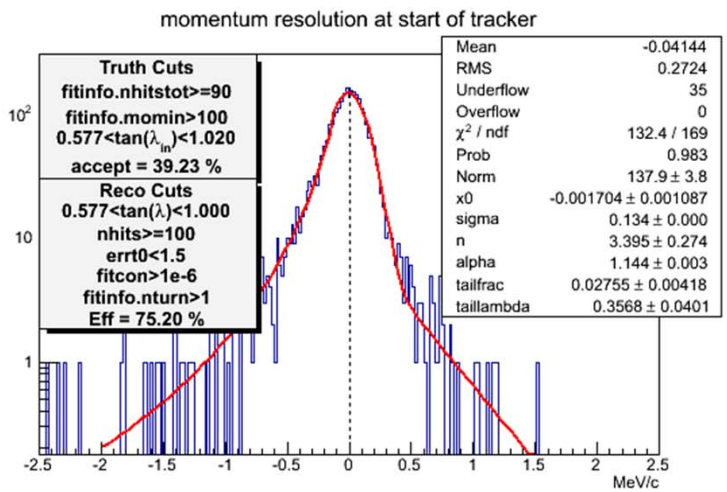


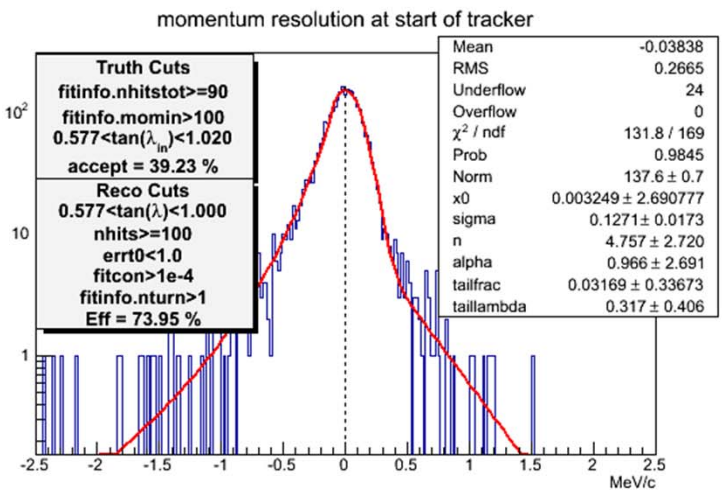
# Recent Results from I-Tracker

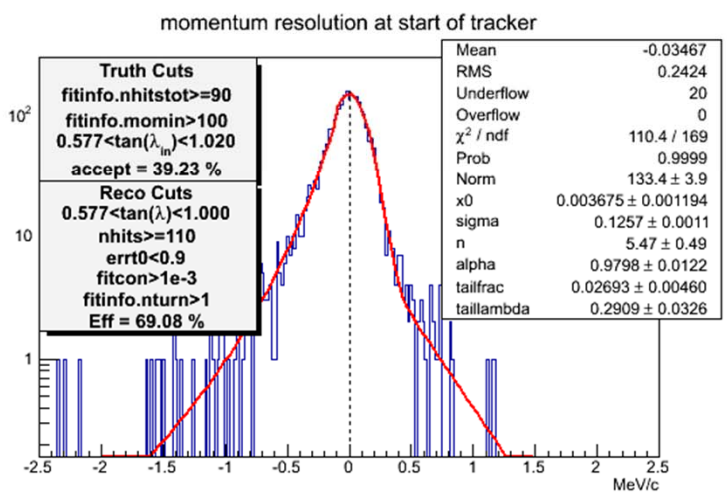
Resolution on Conversion Electron from tracking only,

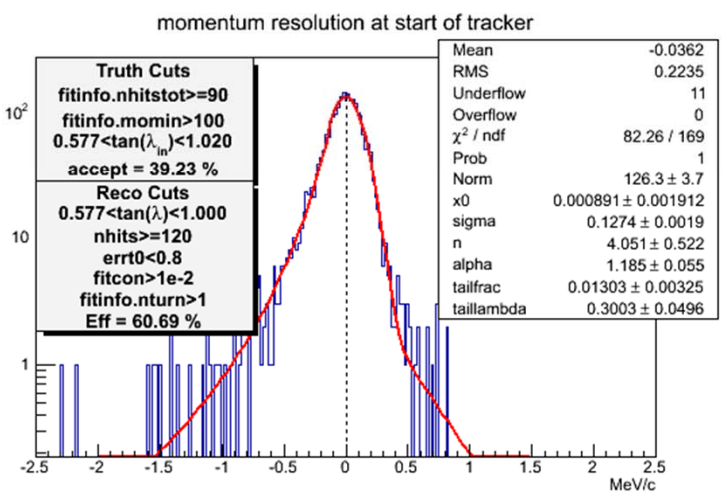
no energy straggling in target, etc.

Simulations behind because T-Tracker was CD-1 baseline, but catching up



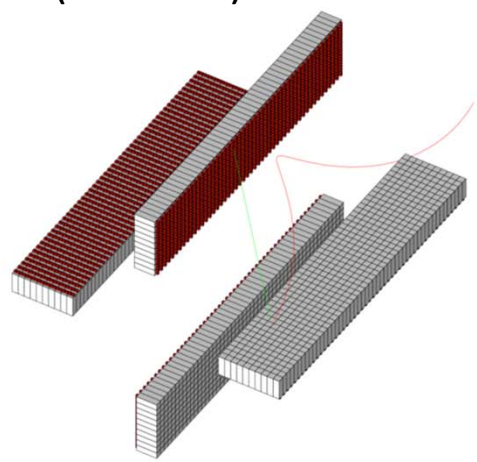



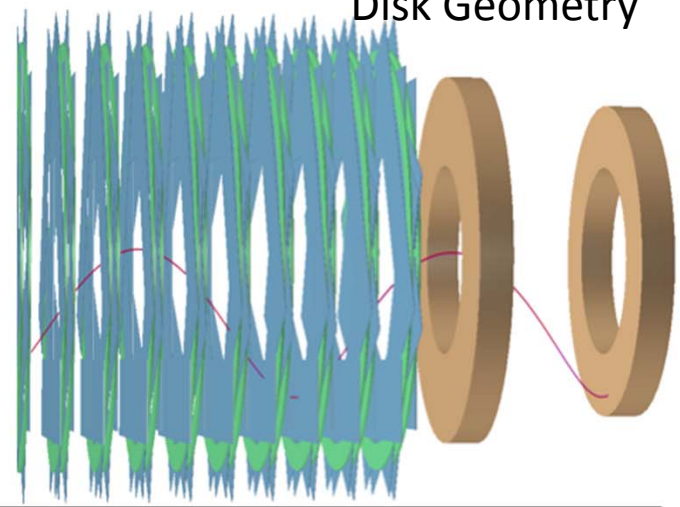
# Electromagnetic Calorimeter: Vanes vs Disks

- **Chosen material: LYSO**
- **Disks are now implemented in the Mu2e Offline**
  - **Clustering studies in progress**
- Comparison of reconstruction will be based on conversion events with full background overlays

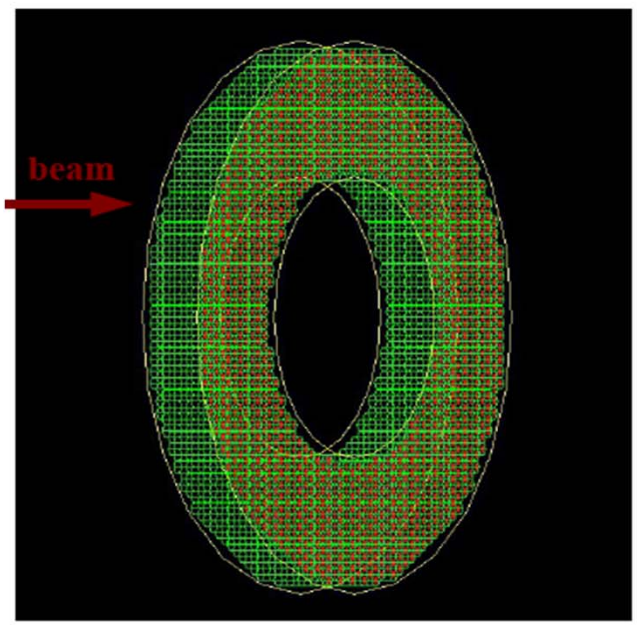
Vane-geometry (baseline)

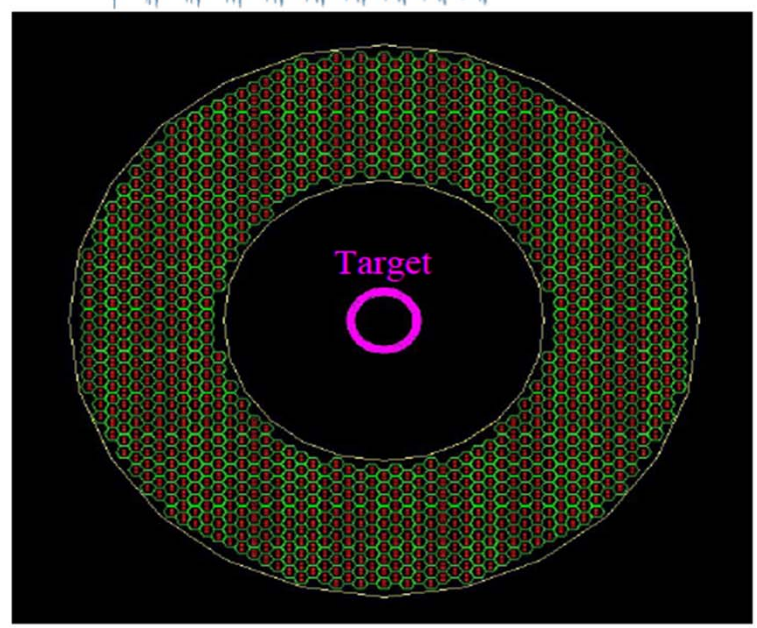


Disk Geometry



**Details of simulated Disk geometry**



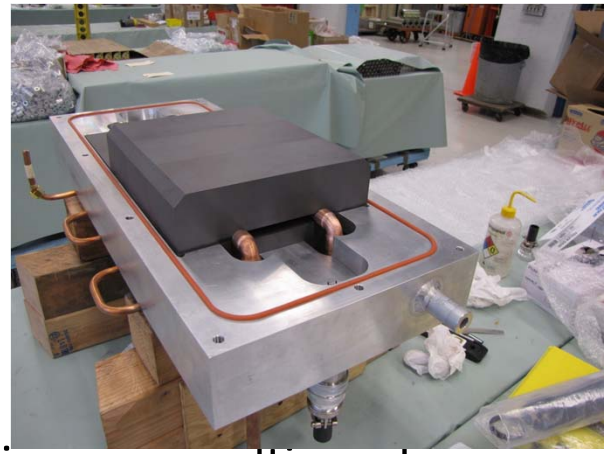



# Calorimeter Simulation Status & Plan

- Full suite of simulations done or in progress
  - A full simulation of the vanes and disks in the Mu2e framework, with background hits
  - Cluster optimization
  - EMC based trigger scheme, incorporation of t, E, position into tracker recon
  - mu/e PID.
  - Prototype beam tests on 3x3 LYSO array conducted earlier.
  - Signal Shape and pileup studies in progress
- Plan: **Complete the comparison between Disks and Vanes for the reconstruction of electrons with pileup in the full background environment.**
- Testing of APD, SiPM photomultipliers
- INFN is process of purchasing 5x5 array of LYSO to test at Mainz or LNF

# Beam Extinction

- Goal (protons out of time)/(protons in time)=$10^{-10}$
- Achieved in two steps
  - $10^{-5}$ in-ring extinction (as extracted from the delivery ring)
    - New scientist from Fermilab (Shulamet Moed Shur) recently began simulation work on evolution of out of time beam, determine mitigation
      - Space charge, intra-beam scattering, beam scattering from gas or extraction septum
  - $10^{-7}$ extinction from AC Dipoles in beamline leading to production target
    - Simulations on optimization of collimation continue
      - initial simulation results indicate $10^{-7}$ or better
    - Prototype tests continue for AC dipole, including new multi-mode powering scheme, which may reduce heat load on magnets.



- Extraction needs to be tested well in advance of beam for Mu2e, perfecting extraction expected to take time

# Extinction Monitoring

- Two mature extinction monitor detector conceptual designs. Committee is being convened in preparation for a down selection in November

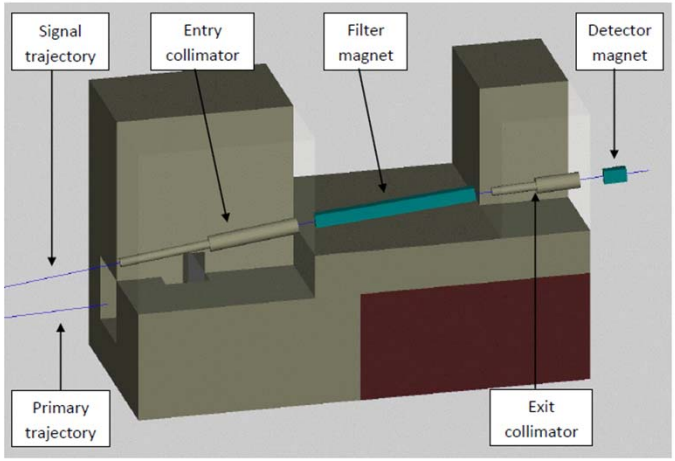



*Figure 1: Extinction monitor filter components as modeled in G4beamline.*

- Each option uses a telescope of detectors to measure the rate of protons on the production target in-time and out-of time , by sampling a tiny portion of secondaries.

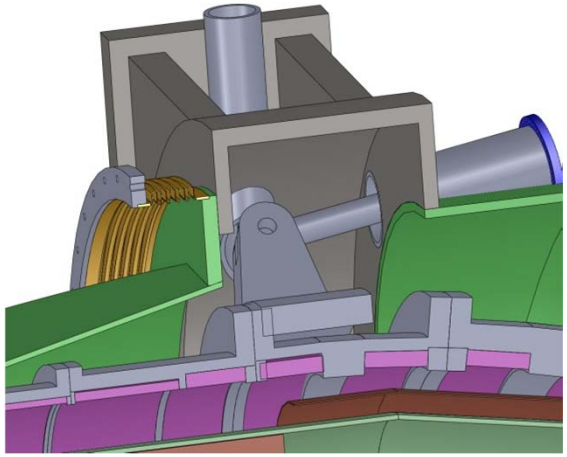
# Stopping Target Studies: Test Beam

- Plan: Stop muons in sample targets at a low energy muon facility (TRIUMF, PSI), Collaboration between Mu2e and COMET
- Goal: Measure proton, neutron fluxes from muon nuclear captures on candidate stopping target materials (Al, Si, Ti).
- Test the proposed monitoring of stopping target method using a Ge detector to measure muonic xrays
- Beam anticipated over next year.
  - Three weeks beam time allocated at TRIUMF
    - Scheduled Nov 2012 run delayed: problems with vacuum seal in TRIUMF beam line
  - Also exploring beam time at PSI

# Solenoids

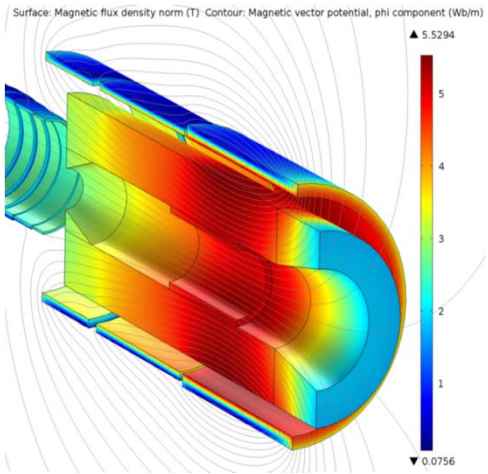
## Major Accomplishment in 2012: Completed Conceptual Design

- **Magnetic, quench/thermal, structural analysis**
  - Effects of cool down, quench, beam induced radiation
  - PS is particularly challenging
- **Detailed solid model for intra-solenoid and solenoid-experiment interfaces**

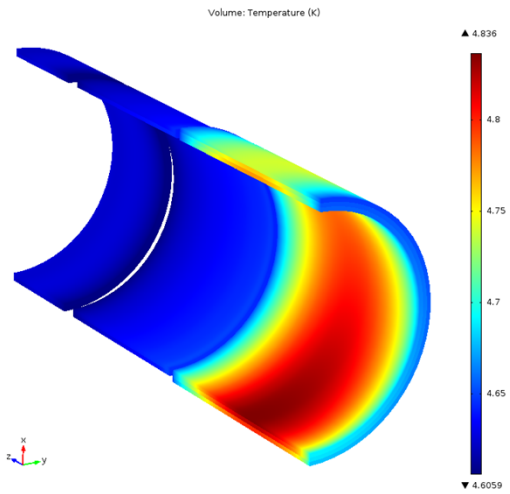


Solid model of cryostat supports with TS/DS interface

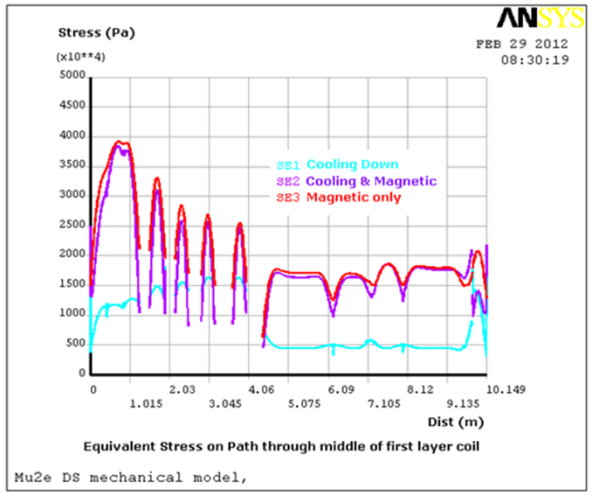
**Examples:**




Magnetic model of PS including heat/radiation shield




Thermal analysis of PS coils from beam-induced heating




Stress analysis of DS coils from cool down and excitation

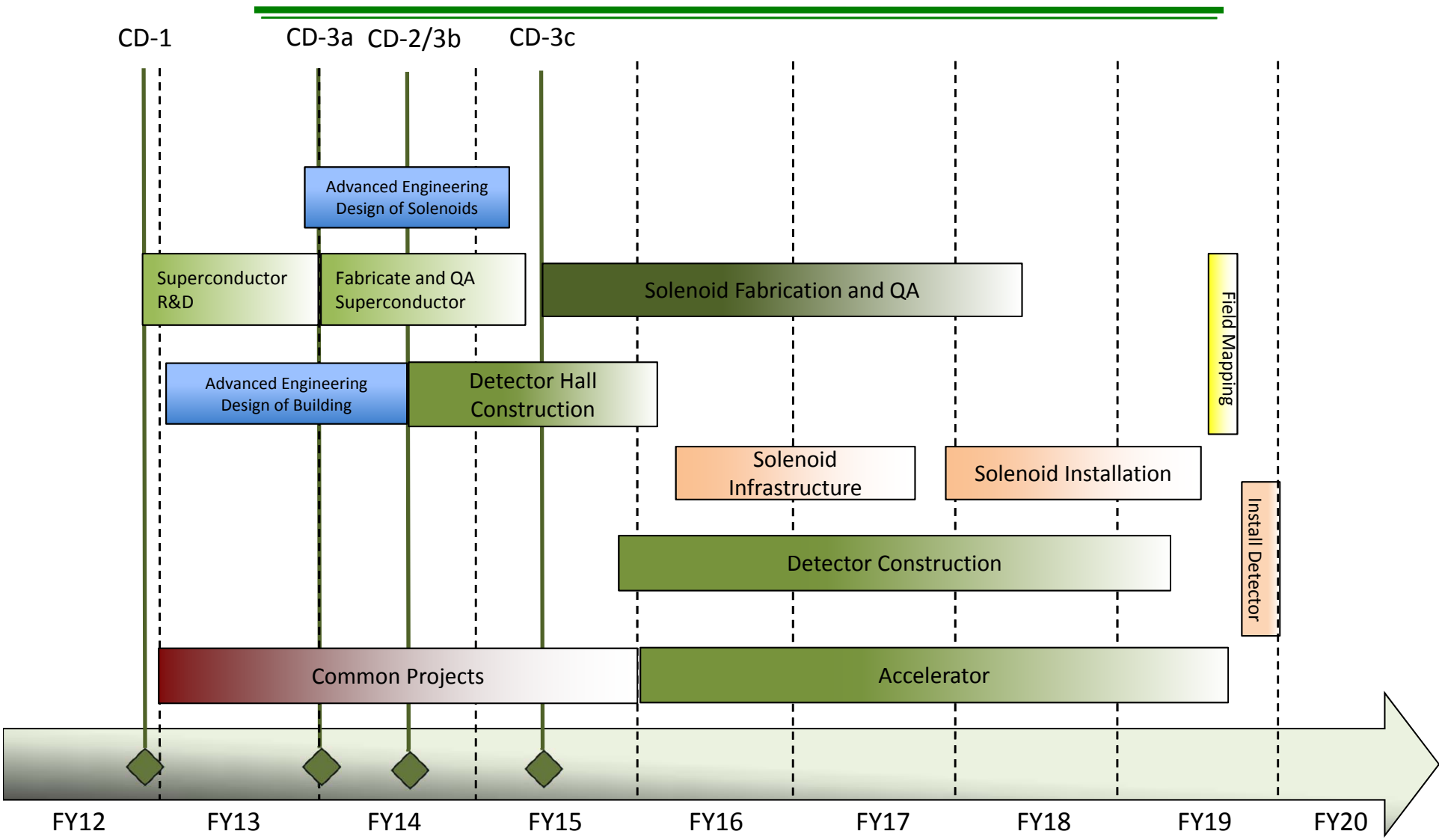
# Solenoids: Moving towards CD2

**The solenoid system is on the critical path....**

**Primary goal in next year is to**

- Complete Preliminary Design of major sub systems including detailed interface drawings and specifications
- Prove 4 kinds of superconducting cable can be made for PS/TS/DS
    - RFP's ready to go
- Start procuring long lead item Conductor
- Prototype conductor for PS/DS/TS
    - 4 types of aluminum stabilized cable needed
    - ~200 meters of PS/DS cable type
    - Enough TS cable to wind prototype unit (3 km)
    - Test windings in house PS and DS
- SC Cable Joint Testing
- Tevatron HTS power lead testing
- Test facility upgrades to test model PS and TS solenoids

# Draft Schedule



# Summary Mu2e Progress

- CD-1 approval received in July, review went well
- Solid simulation progress
  - We have greatly advanced the available tools in several software platforms, each with own strengths, powerful cross-checks
  - Advanced prototype pattern recognition and track fitting producing clean signal with good efficiency for TTracker; I-Tracker catching up quickly
  - Substantial manpower committed to continual improvement
  - Large on-going effort to finish neutron background and other estimates
  - Could always use a few more in the simulations teams
- All systems on track for preliminary designs for CD-2/CD-3a over next 18 months.
- Extensive sharing of facilities with g-2, with associated cost savings.
- Mu2e has compelling discovery potential
  - In (3+1) years of running, SES $2 \times 10^{-17}$
  - $10^4$ improvement over previous measurements

# END

# Extra Slides

# Mu2e Collaboration

25 Institutions
~ 140 Collaborators

Boston University
Brookhaven National Laboratory
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
Lewis University
Los Alamos National Laboratory
Muons Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of California, Berkeley
Lawrence Berkeley National Laboratory
University of Houston
University of California, Irvine
University of Illinois
University of Massachusetts, Amherst
University of Virginia
University of Washington

Instituto Nazionale di Fisica Nucleare, Lecce
Instituto Nazionale di Fisica Nucleare, Pisa
Laboratori Nazionali di Frascati
Universita di Udine

Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

# Accelerator L2 R&D and Preliminary Design status

- Transport, Delivery Ring:
  - The technical scope is well defined
  - Issues to resolve before the technical design:
    - Beam delivery scenarios to accommodate both Mu2e and G-2:
      - Extremely tight space in straight Section 30, where all injection and extraction for both experiments is taking place
      - Solutions exist; the goal is minimize transition between the two experiments
    - Instrumentation:
      - Delivery ring tune measurement require significant engineering effort for fast tune tracking with high precision. The instrumentation specialist has been assigned to design the diagnostics. Preliminary tests with beam have been made.
    - Controls:
      - Need to work out details of scheduling work common for Mu2e and G-2. This includes coordination with FESS of the communication lines re-routing between service and detector buildings.
    - As much as possible, all the Accelerator modifications that are common for both Mu2e and G-2 are done off projects, in AIP and GPP packages, and this is high priority now to accommodate G-2 schedule

# Accelerator L2 R&D and Preliminary Design status

- Radiation safety improvements
  - Good progress with TLM detector R&D
    - Improved design
    - Plan to install TLMs in the NTF this month
- Resonant Extraction of beam from Delivery Ring to Mu2e production target
  - Good progress in simulations
  - Parameter optimization is on the way- need to complete by CD-2
  - Engineering design for ESS (electrostatic septum) has started
- Delivery Ring RF
  - RF Modules same as Recycler Ring.
  - Engineering support for RF to begin Nov or Dec 2012
- External Beam Line
  - Final focus adjustment made to accommodate the TS protection collimator
  - Now concentrating on the design of beam line split with g-2
  - Need to finalize the detector building coordinates this month for the civil construction

# Accelerator L2 R&D and Preliminary Design status

- Target Station
  - Lead engineer for the Target general is assigned
  - Decision is made that FNAL takes over the design and implementation of the Remote handling, lead engineer is assigned. Early designs eliminate the need for expensive hot cell and manipulator arms, but this is at a very early stage.
  - RAL(Rutherford) will concentrate on the target design. Plan has been revised for the R&D prior to CD-2. A new proposal from RAL is being written now for tests and calculations for the next 1 year. A full-scale prototype would follow after this one year.
  - HRS MARS simulations show that the 2$^{nd}$ scallop for the extinction monitor is acceptable. Optimization of the 1$^{st}$ scallop is under way.
  - New simulations indicate that we may be able to reduce the mass of the HRS by 20-30% by eliminating shielding upstream of the TS. If this holds up, we will need significant engineering changes to the mechanical design, but it can save considerably on the $3M cost of HRS.
  - Beam dump: modifications of the fins made to reduce the air activation.
  - Radiation map of the area is being developed, need to be completed before CD-2

# Institutions- T-Tracker

- Duke, York, Rice
  - Straw leak and creep tests
- Duke
  - Straw termination
  - Straw alignment
- York
  - Detector alignment
- Rice, Houston, Fermilab
  - Panel assembly
- Fermilab
  - Gas seal
- LBNL/Berkeley
  - Digitizers
  - Irradiation tests
- Houston
  - Readout Controller
- Fermilab
  - Preamps

Underlined: *in progress or starting within the next few months*

# Neutron Background Simulations

- Neutrons task force established over the summer to tackle these simulations
  - Neutron task force to understand neutron backgrounds in detail in all regions and detectors-currently updating geometry to CDR, then investigate other shielding options, final report due in 3 months
- 1st Study – Background hits in the tracker and calorimeter from muon nuclear capture in the stopping target

$$\mu^- + {}^{27}_{13}Al \rightarrow {}^{A}_{Z}X + an + bp + c\gamma,\ \text{a}\sim1.2,\ \text{b}\sim0.1,\ \text{c}\sim2$$

- 2nd Study – Simulate all sources of neutron background (production and stopping targets, muon beam collimators, muon beam stop, etc.)
- Tools: MARS, G4beamline, Mu2e offline, all will be compared. Check cross-sections and simulations by comparing simple geometries with MCNP.

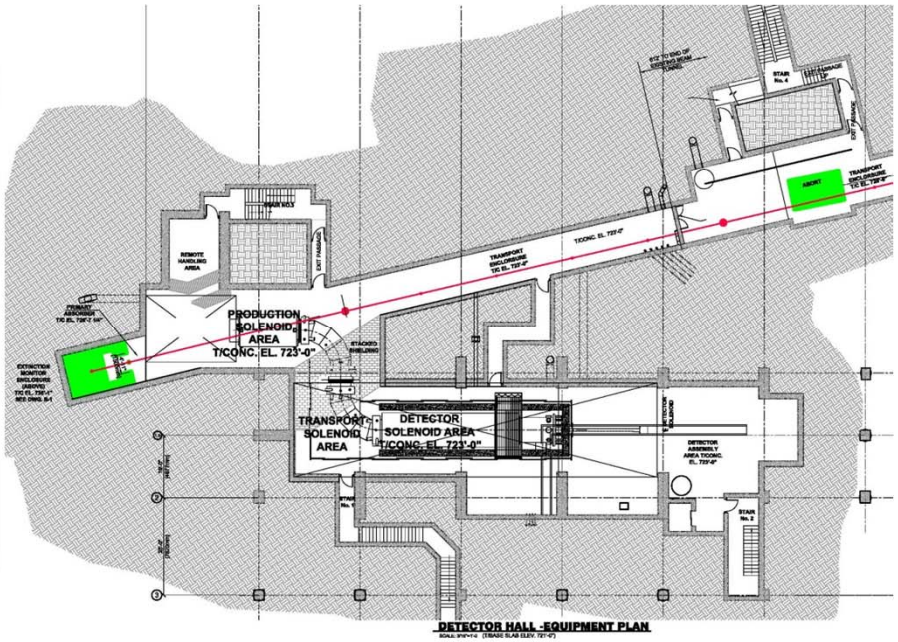
# Summary of Changes

D. Glenzinski
PAC, Dec. 2011

| L2 System | New Base Cost + Contingency ($) | Changes Made |
|---|---|---|
| Project Management | 16M | Leaner |
| Accelerator | 38M | Accumulator eliminated, tungsten replaced, AIP |
| Civil Construction | 24M | Footprint reduced, AP shielding eliminated, GPP |
| Solenoids | 106M | Iron yoke eliminated, coil designs simplified, reduce PS field, GPP |
| Muon Channel | 10M | Internal neutron shielding eliminated |
| Tracker | 8M | No change |
| Calorimeter | 0M | Supported off project (e.g. INFN) |
| Cosmic Veto | 5M | No change |
| DAQ | 6M | Use some physicist labor, reduce hardware |
| **Total** | **213M** | |

Strategy: Simplify proton beam, trade Rate for Run Time (3x lower average beam), do not sacrifice sensitivity

# Progress: Building




Mu2e on Muon Campus

Design: Plan View

- Selection process for A&E firm under way, RFP in draft form
- Anticipated to follow DOE CD-1 recommendations
  - reduce duration of preliminary design completion to start of final design (team continuity)
  - accelerate the start of civil construction: advantageous construction market conditions.
- Plan early start of Detector Hall after CD-3b/CD-2 approval, possibly with construction contracts already in hand

# DAQ Status and Plans

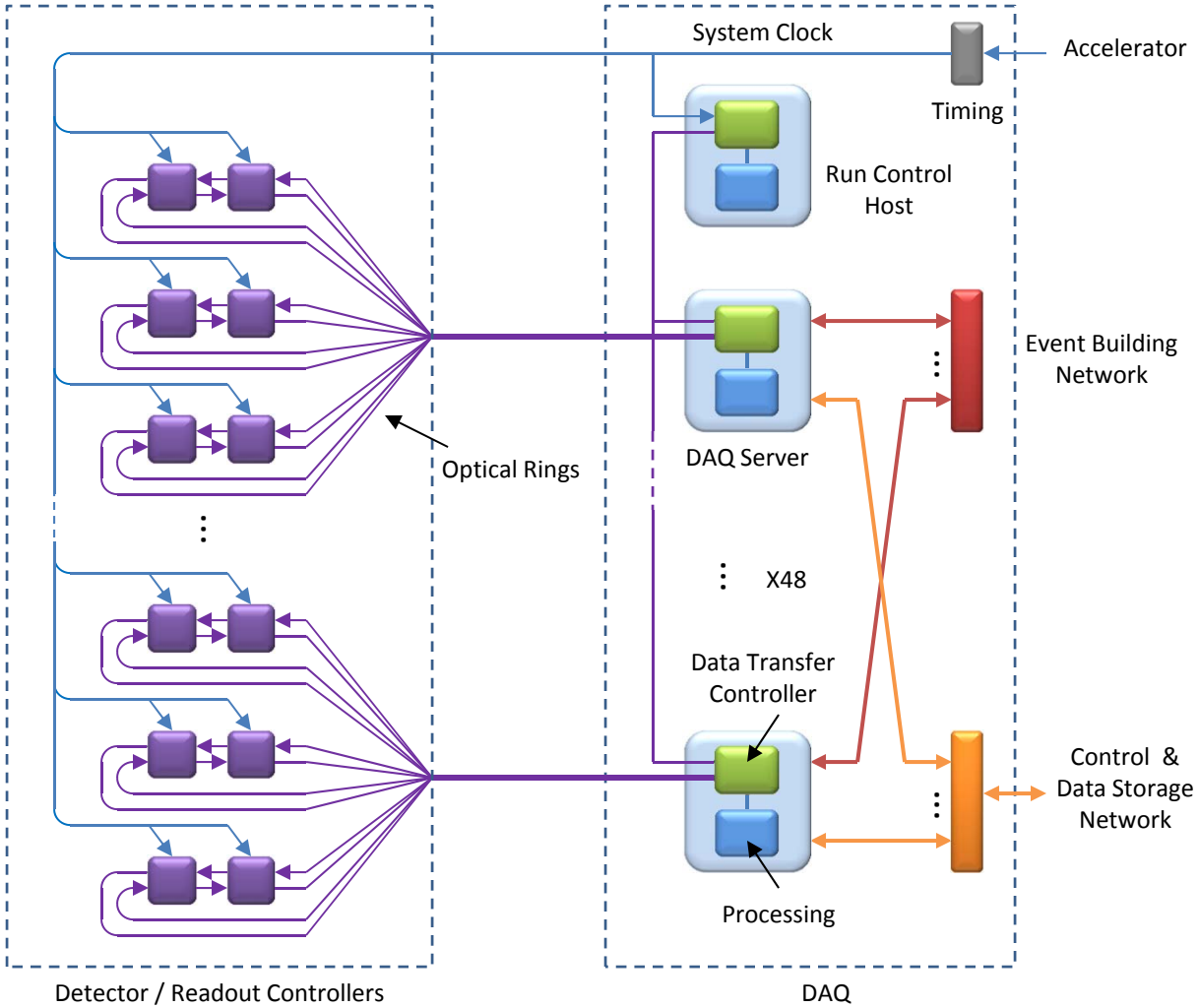
The Mu2e DAQ collects and filters data from 300 detector sources, at a combined rate of approximately 30 GBytes/sec.

The DAQ hardware is based almost entirely on commercial, off-the-shelf components. Most of the design effort is in software and firmware.

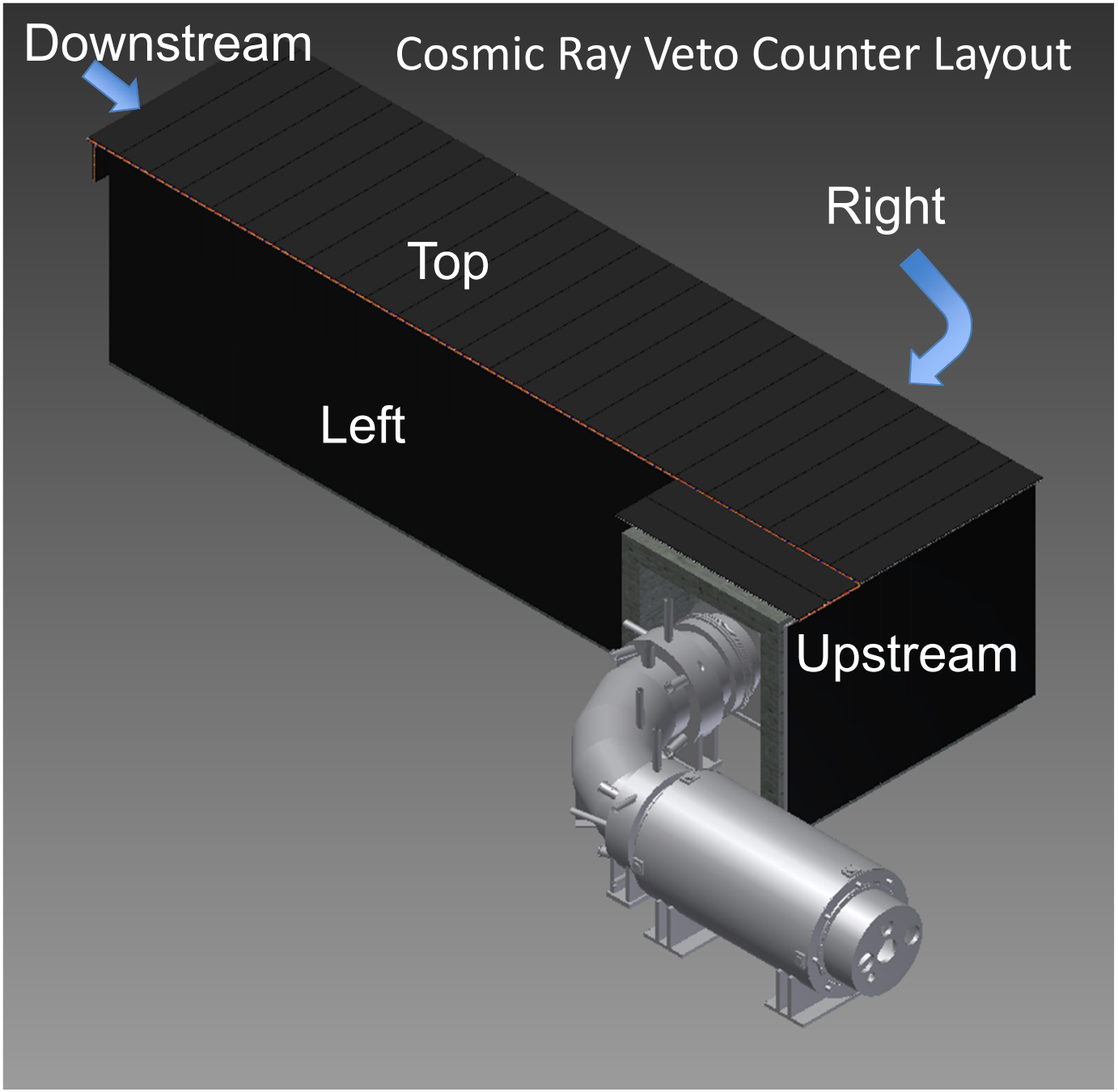
A complete conceptual design, cost and schedule estimate was developed for CD-1. We are now generating detailed system specifications.

FY13 plans include

1) setup of a small development system
2) online processing & filter benchmarks
3) FPGA firmware for basic data collection and system synchronization
4) preliminary online software for readout and filtering
5) standard readout controller interface and protocol definitions
6) initial slow control framework


System Clock
Accelerator
Timing
Run Control
Host
Event Building
Network
DAQ Server
Optical Rings
X48
Data Transfer
Controller
Control &
Data Storage
Network
Processing
Detector / Readout Controllers
DAQ

Mu2e DAQ


Downstream
Cosmic Ray Veto Counter Layout
Right
Top
Left
Upstream

# Solenoid R&D Plan for the Next 12 Months

- Prototype conductor for PS/DS/TS
  - 4 types of  aluminum stabilized cable needed
  - ~200 meters of PS/DS cable type
  - Enough TS cable to wind prototype unit (3 km)
  - Test windings in house PS and DS
- SC Cable Joint Testing
- Tevatron HTS power lead testing
- Transport Solenoid (TS) prototype
- Test facility upgrades to test model PS and TS solenoids

| Description | Project | Comment |
|---|---|---|
| Recycler RF upgrade | RR AIP | |
| Recycler extraction/P1 stub line | RR AIP | |
| P1,P2 and M1 aperture upgrade | DR AIP | M1 final focus quadrupoles are g-2 |
| Reconfigure AP-2 and AP-3 | g-2 | New lines are called M2 and M3 |
| Final focus to AP-0 Target Station | g-2 | |
| AP-0 Target Station upgrades | g-2 | |
| Beam transport instrumentation | DR AIP | |
| Beam transport controls | Mu2e | |
| Beam transport infrastructure | DR AIP | |
| Delivery Ring injection | DR AIP | |
| D30 straight section preparation | DR AIP | |
| Delivery Ring modification | DR AIP | |
| D.R. abort/proton removal | DR AIP | |
| Delivery Ring RF system | Mu2e | |
| Delivery Ring controls | Mu2e | |
| Delivery Ring instrumentation | DR AIP | DCCT and Tune measure are Mu2e |
| Resonant extraction from D.R. | Mu2e | |
| Fast extraction from D.R. | g-2 | |
| Delivery Ring infrastructure | DR AIP | |
| Extraction line to split | g-2 | Upstream M4 line |
| Extraction line from split to Mu2e | Mu2e | Downstream M4, including extinction |
| Extraction line from split to g-2 | g-2 | Beamline to MC-1 building |

# Current Cosmic Ray Veto Hardware

Design:

•Complete preliminary engineering design of counters, modules, and mounts, as well as counter and module fabrication jigs

•Complete design of front-end boards and readout controllers

•Complete engineering design of CSC alternative

Fabrication:

•Fabricate cosmic-ray test stand

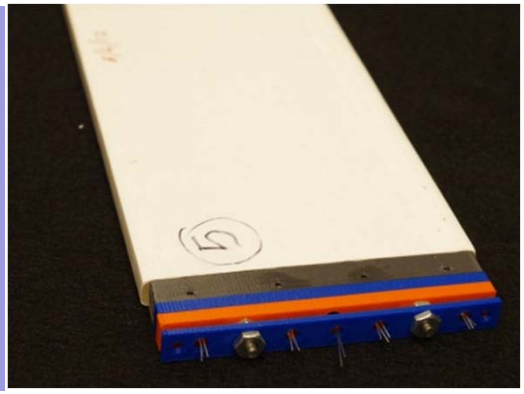
•Produce a preliminary design module mockup

•Fabricate and test prototype counters

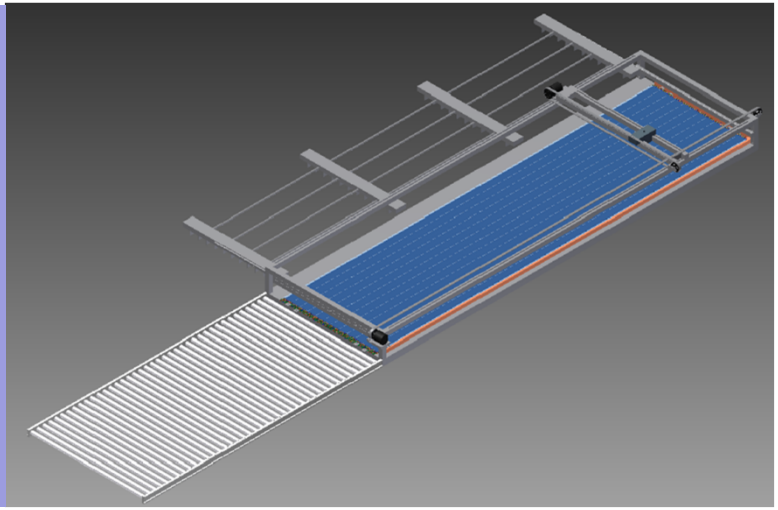
- Measure photoelectron yield → counter efficiency
- Measure neutron efficiency

•Fabricate and test prototype front-end boards

Prototype Counter



Module Assembly Jig



# Tracker Reconstruction Plans

- Refinements planned soon or in progress
  - Include calorimeter information: t0, position, E
  - Track back to target foils
  - Improve algorithms to ID background low energy electrons (Compton, photoeffect, pair production, deltas...)
  - General improvements in pattern recognition
    - selectivity against e+, muons, protons
  - Detailed studies of reconstruction efficiency and resolution vs background, hit wire resolution, time division resolution
  - Calibration requirements
  - One additional person being recruited for this

# Mu2e Tracker Schedules

T-Tracker

- Sample straws tested for leakage, creep
- First "panel" prototype (100 straws) in progress, new composite support
  - Intended for mechanical tests only
- Drawings in progress for new panel design
- Expect to order parts early next year
- Preamps:
  - Tests in progress
  - Calibration, HV disconnect not yet included
- Digitizers:
  - 4-channel prototype ASIC received
  - Tests in progress
- Issues also being studied/developed
  - Straw gas leakage/seals, creep, termination, readout controller
- Duke, FNAL, Houston, LBNL/Berkeley, Rice, York

I-Tracker

- Working prototype under completion 20 layers x 10 cells to be tested with cosmic rays during spring 2013
- Full length prototype, few layers x 16 cells, to be completed within 2013 (synergy with MEG upgrade)
- Characterization of the chosen materials: C-fiber, C-foam and structural and buckling tests
- Characterization of helium gas mixtures at pressures below 1 bar
- Electronics:
  - preamp prototypes under test
- INFN Lecce, G. Marconi U. Rome, Salento U.

# Mu2e and (g-2) Synthesis

Extraction kicker required by Mu2e and g-2.

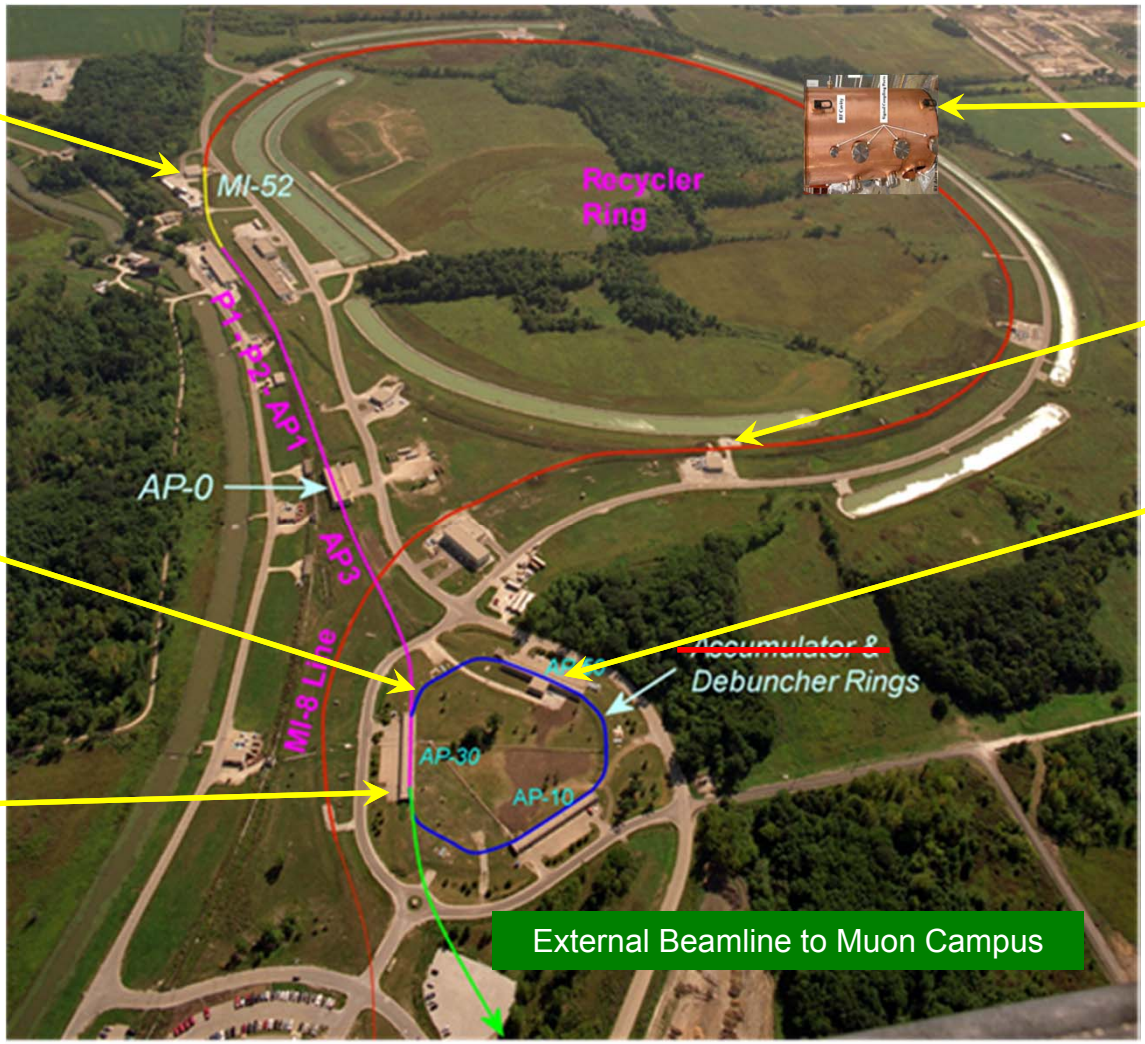
New 2.5 MHz RF system using recycled MI RF. Required by Mu2e and g-2.

Recycler Injection Kicker – Provided by NOvA

Abort Kicker – Required for Mu2e. Power supply shared with g-2 Extraction Kicker.

New Debuncher Injection Kicker

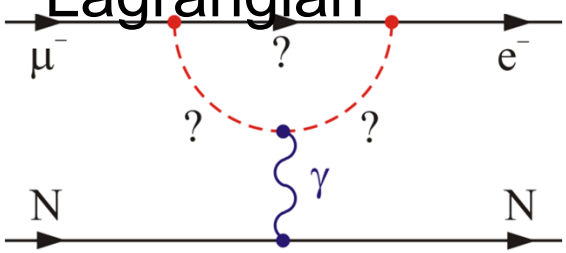
Mu2e resonant extraction System/ g-2 Extraction Kicker



# cLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

Model independent effective cLFV Lagrangian

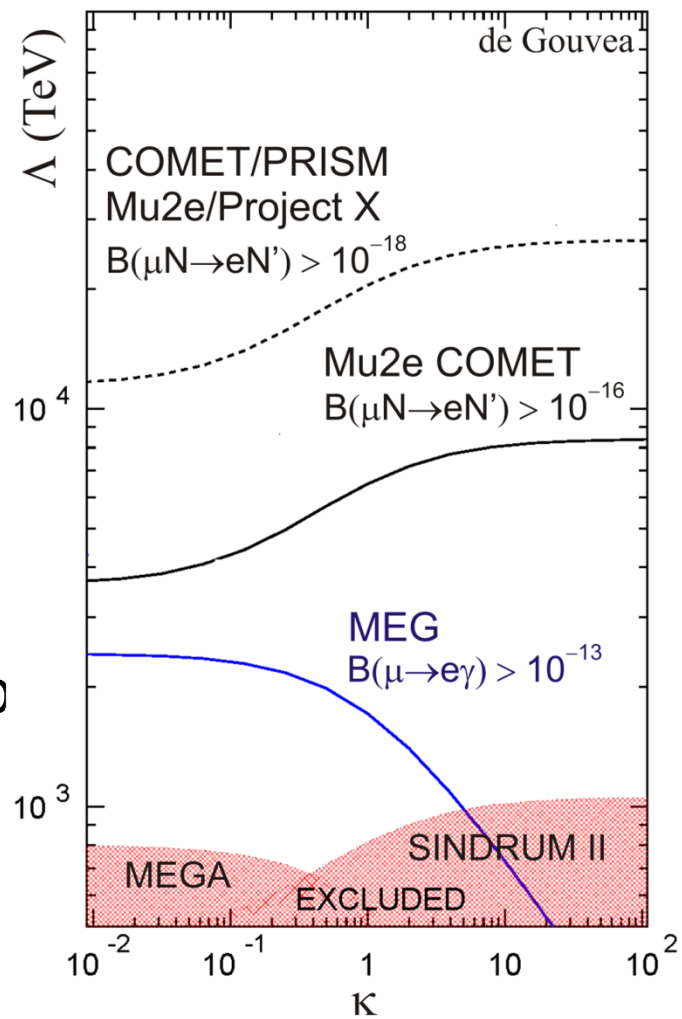
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$

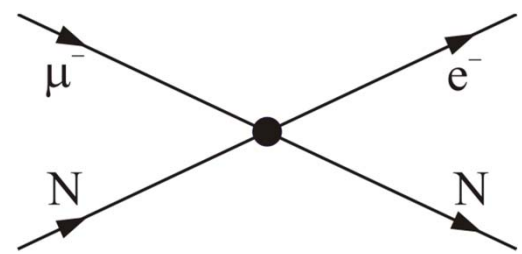



$\kappa$<<1

magnetic moment typ operator

$\mu \rightarrow e\gamma$ rate ~300X $\mu N \rightarrow eN$ rate



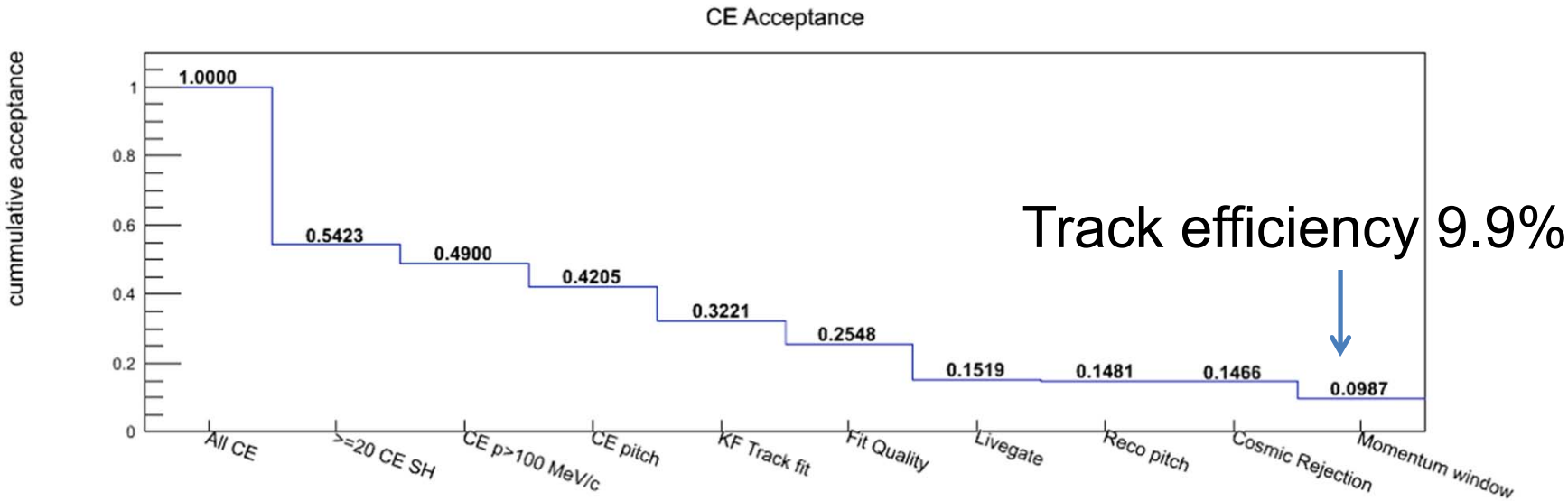

$\kappa$>>1

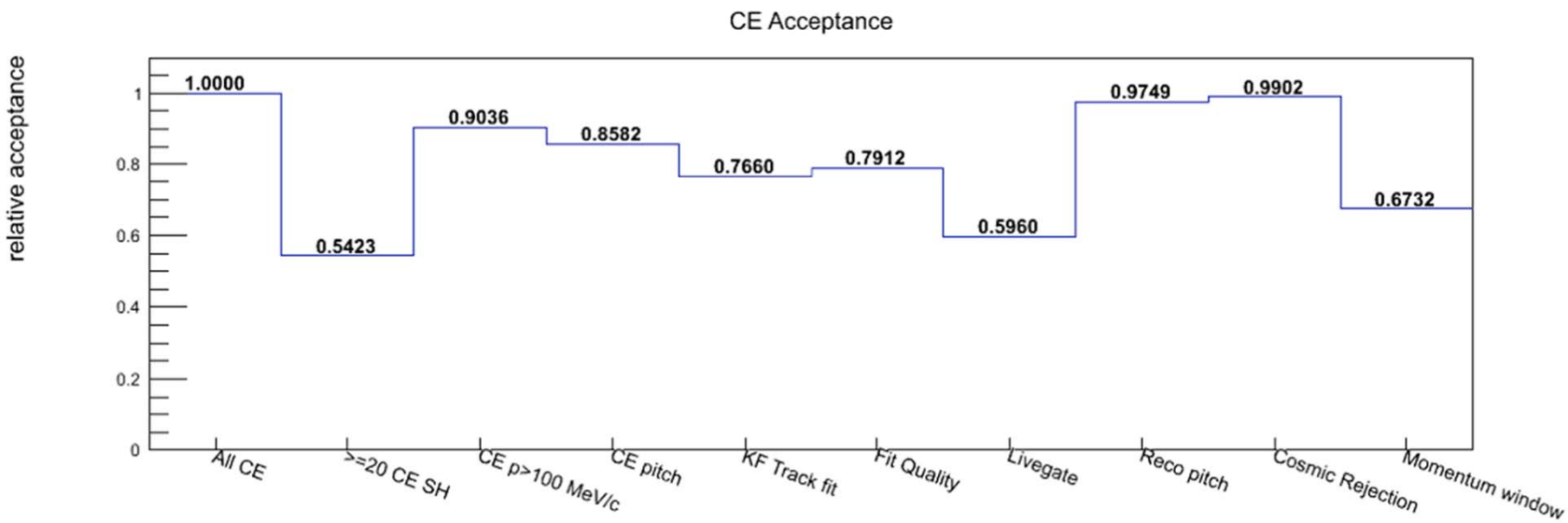
Contact interaction

$\mu N \rightarrow eN$ rate many orders of magnitude greater than $\mu \rightarrow e\gamma$ rate

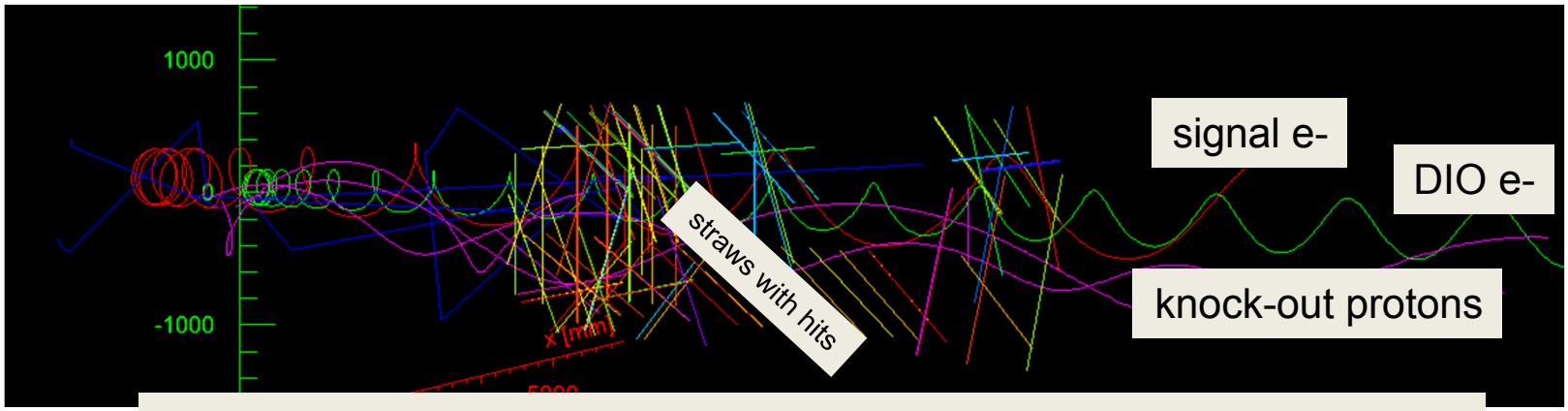
# Track Reconstruction Efficiency

Improved by x2 since CDR: improved delta ray rejection and L/R ambiguity



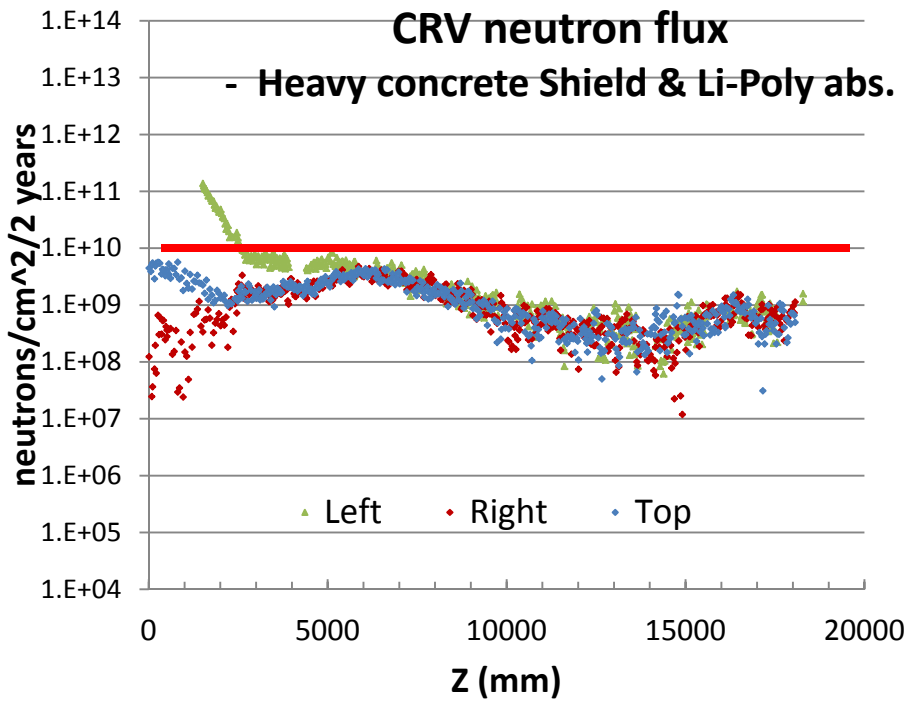



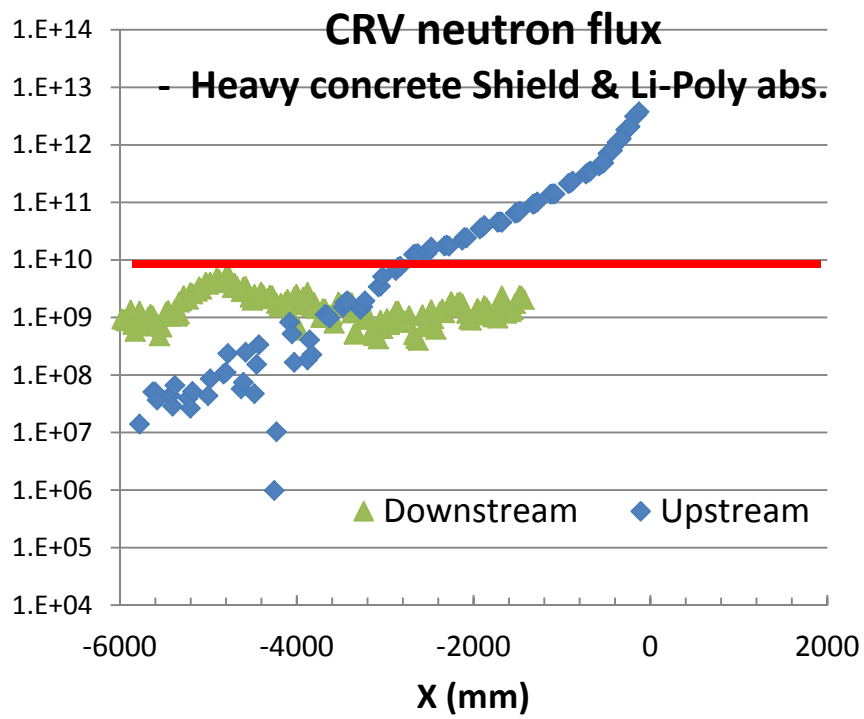
# Pattern Recognition




(particles with hits within +/-50 ns of signal electron $t_{mean}$)

- Signal tracks deposit their hits over 100 ns
  - We use timing information to eliminate most hits and simplify pattern recognition


CRV neutron flux
- Heavy concrete Shield & Li-Poly abs.
neutrons/cm^2/2 years
1.E+14
1.E+13
1.E+12
1.E+11
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
0
5000
10000
15000
20000
Z (mm)
Left
Right
Top


CRV neutron flux
- Heavy concrete Shield & Li-Poly abs.
1.E+14
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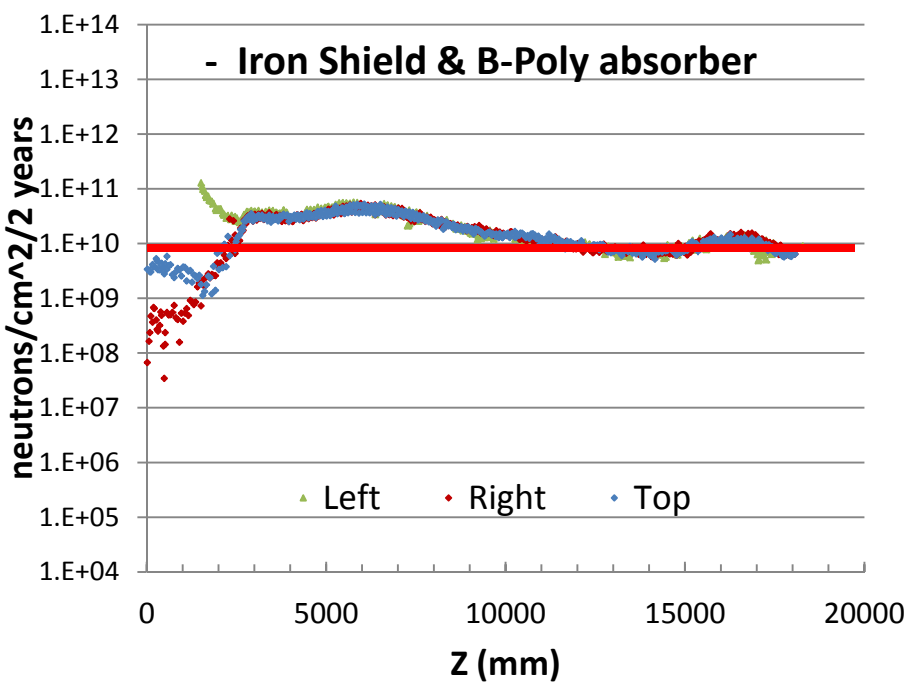
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
-6000
-4000
-2000
0
2000
X (mm)
Downstream
Upstream


- Iron Shield & B-Poly absorber
neutrons/cm^2/2 years
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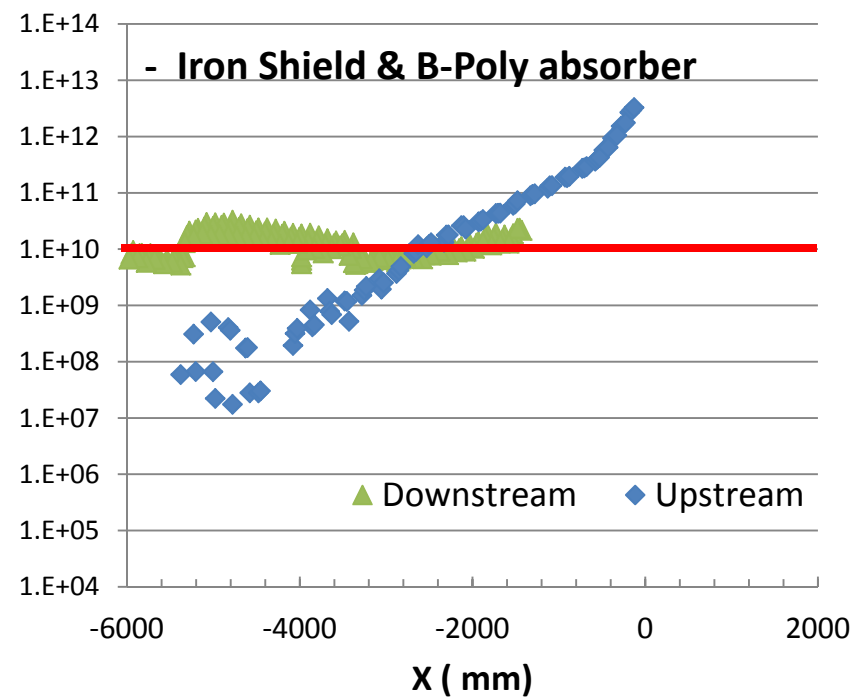
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
0
5000
10000
15000
20000
Z (mm)
Left
Right
Top


- Iron Shield & B-Poly absorber
1.E+14
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1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
-6000
-4000
-2000
0
2000
X ( mm)
Downstream
Upstream