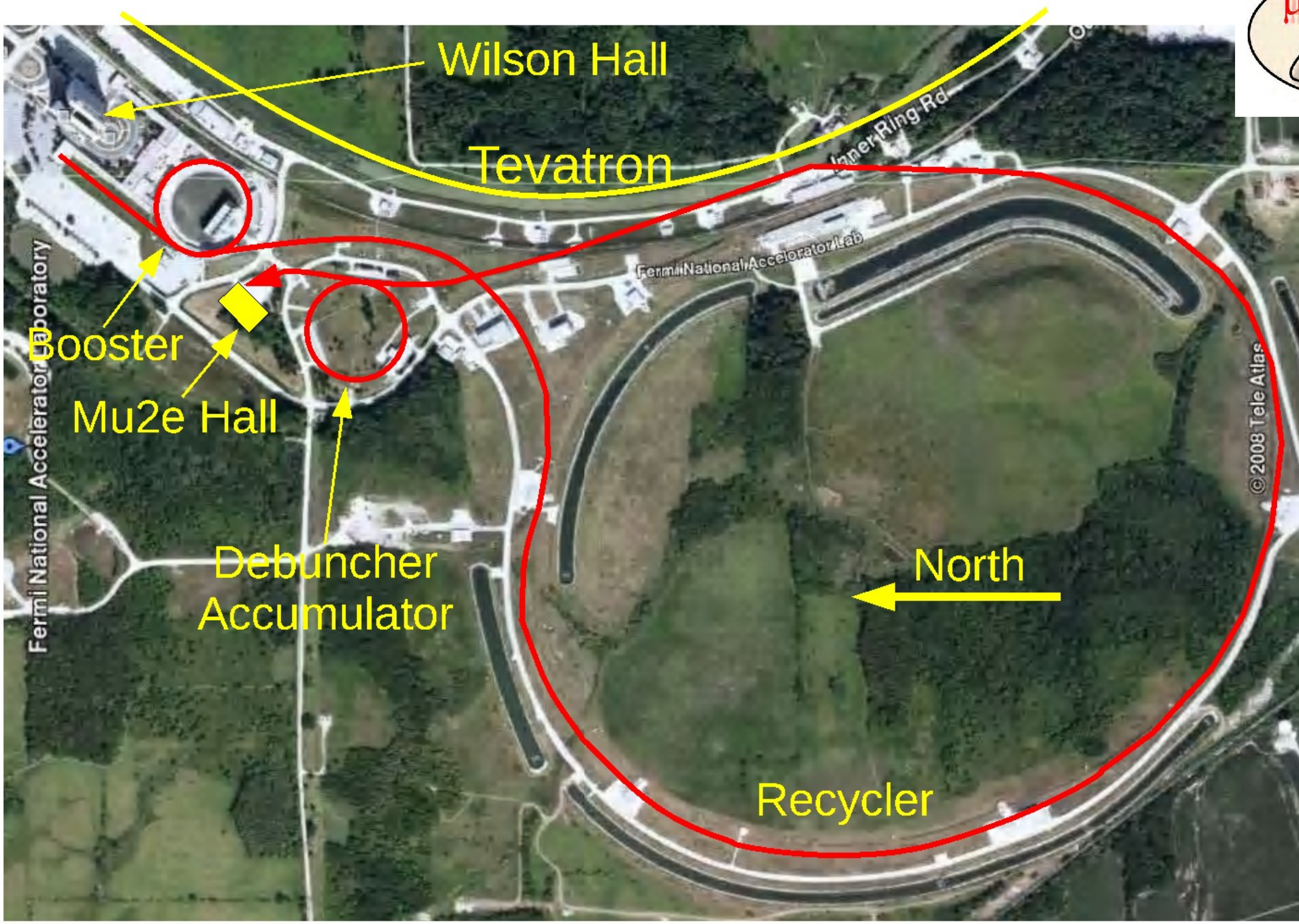
P-Mu2e

R. Carosi + Mu2e Pisa, 20 giugno 2011

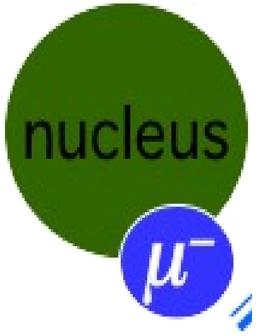
- Consuntivo
  - Breve descrizione dell' esperimento
  - Stato dell' esperimento
  - Attività svolta nel 2011
- Attività per il 2012
- Richieste finanziarie
- Manpower 2012
- Richieste INFN per servizi locali e spazi

Mu2e Site


Wilson Hall
Tevatron
Inner Ring Rd
Fermi National Accelerator Lab
Booster
Mu2e Hall
Fermi National Accelerator Laboratory
Debuncher
Accumulator
North
Recycler
©2008 Tele Atlas

Mu2e principles

- Make muonic Al.
- Watch it decay:
  - Muon decay in orbit: ≈40%
    - Continuous E_e spectrum.
  - Muon capture on nucleus: ≈60%
    - Nuclear breakup: 2n, 2γ, 0.1 p
  - Signal:
    - Mono-energetic E_e ≈ 105 MeV
    - At endpoint of continuous spectrum.
- Measure E_e spectrum.
  - Is there a bump at the endpoint?

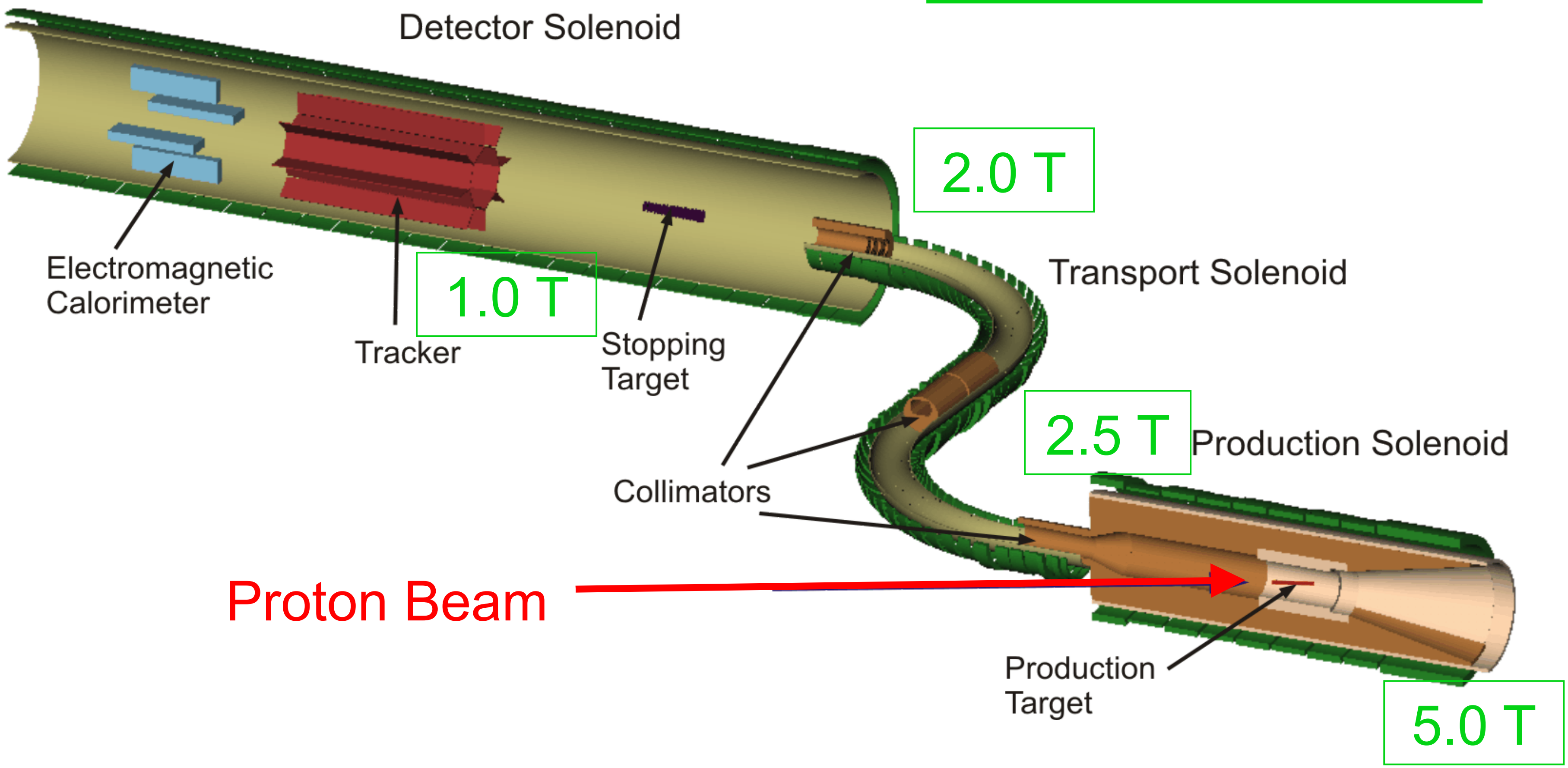


For Al:
Bohr radius ≈ 20 fm
Nuclear radius ≈ 4 fm
Lifetime: 864 ns

A Back-scattered Muon Beam

Tracker + ECAL: Uniform 1.0 T

Graded Solenoids:
Magnetic Mirror



Sensitivity of Mu2e

Two years running

$R_{\mu e}$ < 6 x 10^{-17} 90% CL

For $R_{\mu e} = 10^{-15}$

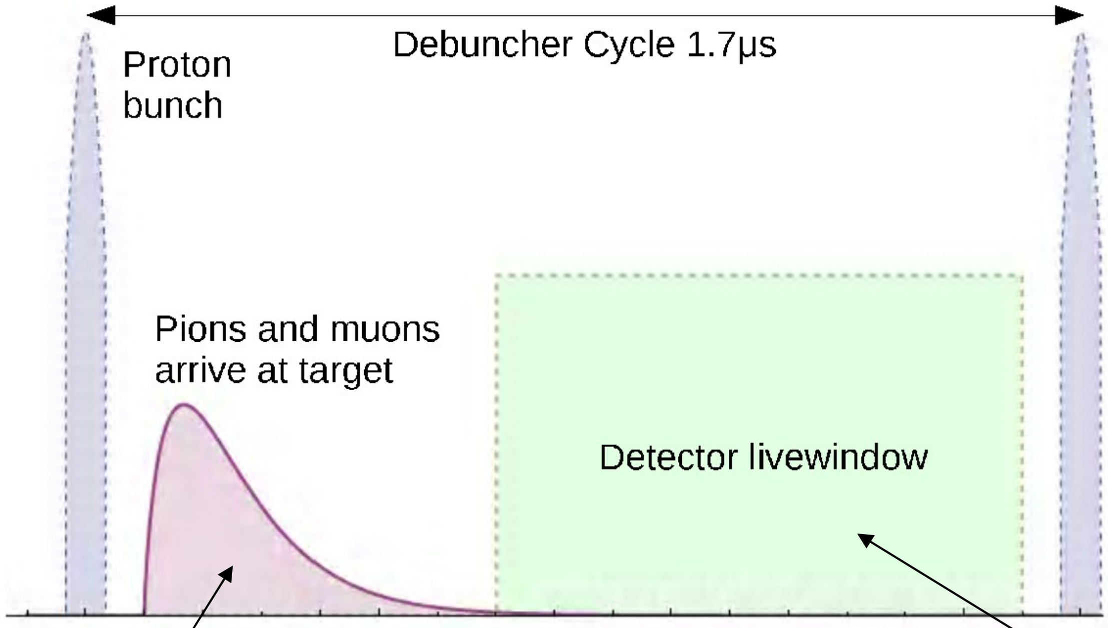
~40 events / 0.4 bkg (LHC SUSY?)

For $R_{\mu e} = 10^{-16}$

~4 events / 0.4 bkg

The two most dangerous backgrounds have very different timing properties at FNAL.

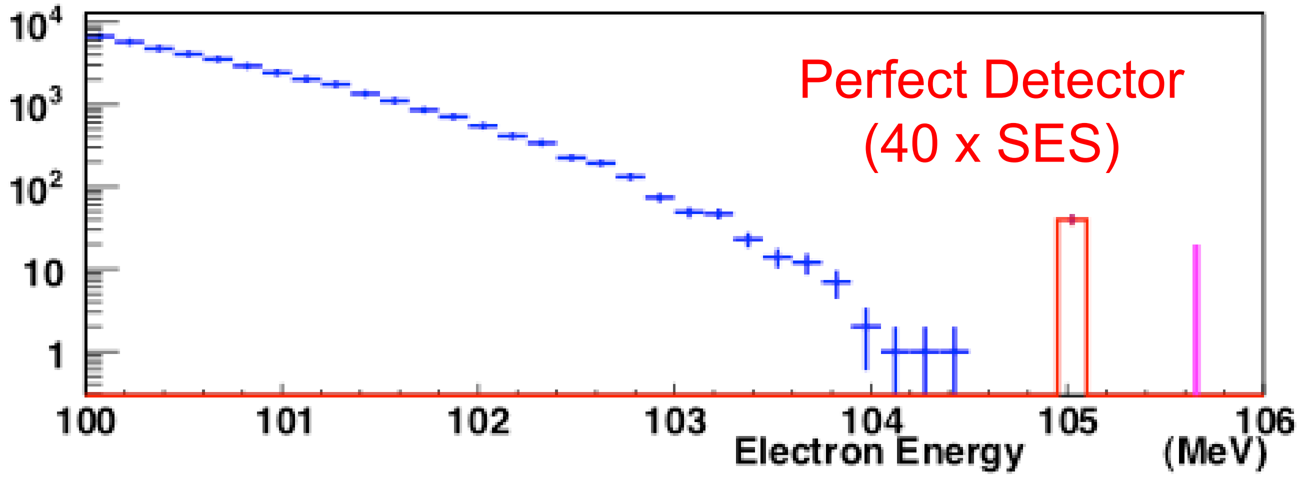
The FNAL accelerator complex produces proton beams with a pulsed structure.



Prompt: Radiative Pion Capture with pair production

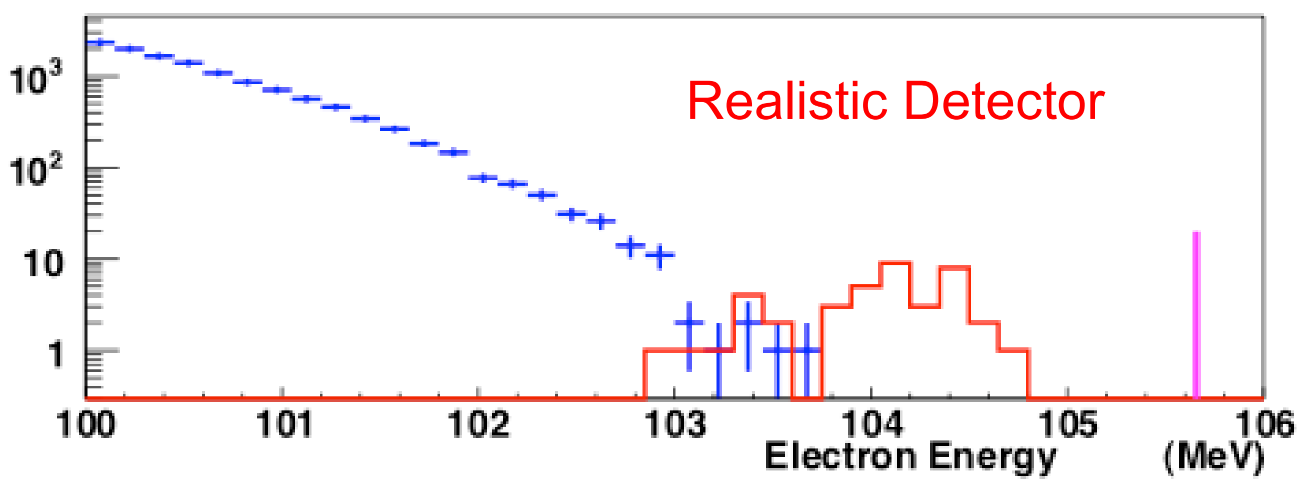
Delayed: Muon Decay-in-Orbit

Muon Decay-In-Orbit

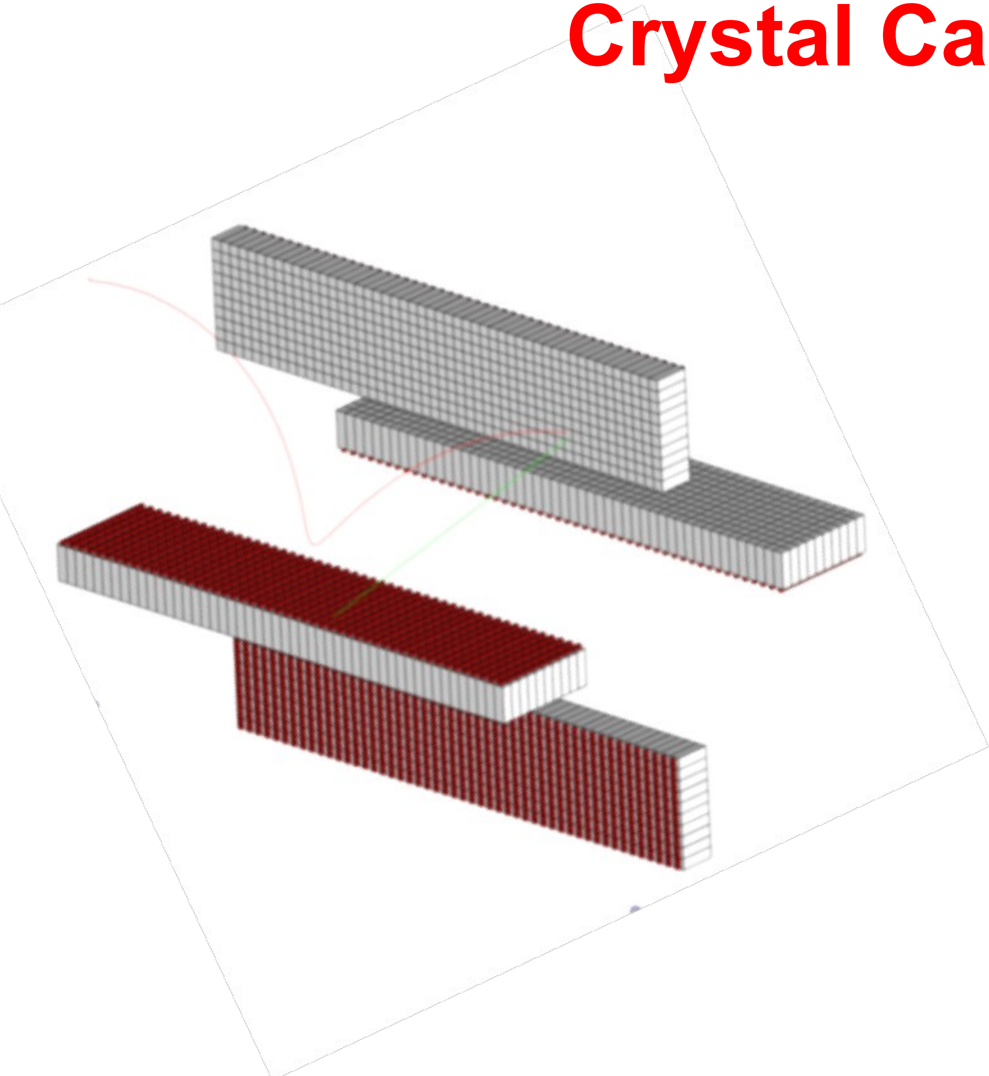


2 years running

DIO with E>100 MeV
~3×10^{-13} of total



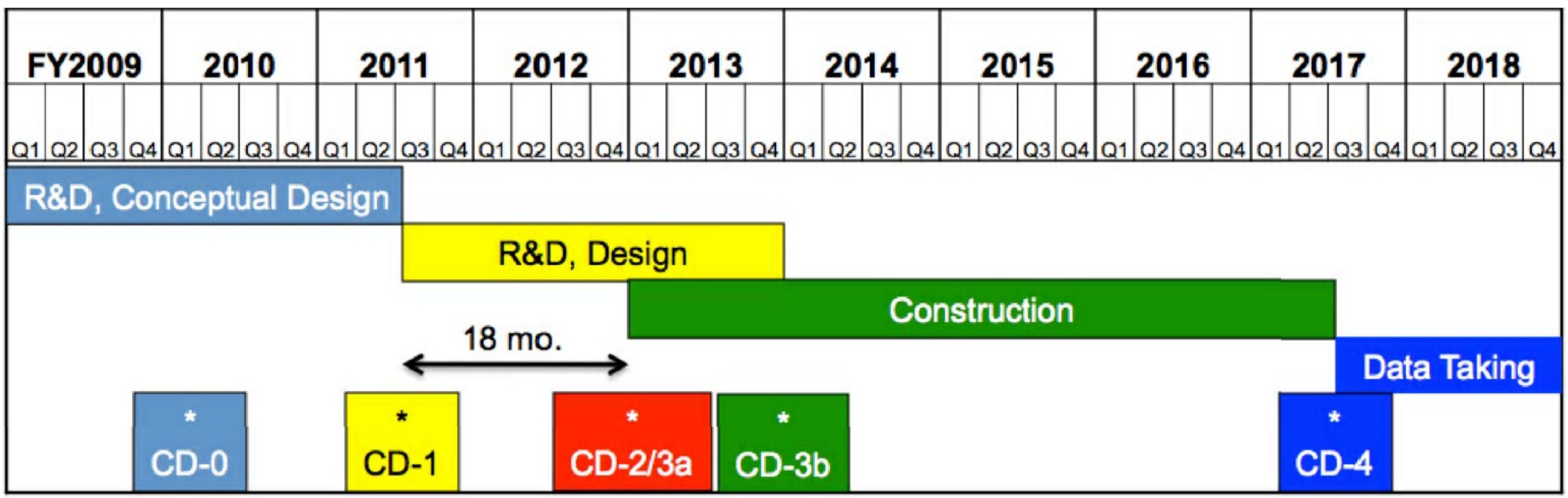
Crystal Calorimeter



- ~2000 $PbWO_4$ crystals.
  - 3.5×3.5×12 cm
  - Short scint. Time (τ ~ 10ns)
  - Low light yield. Requires cooling
- $\sigma(E)/E \approx$ 5 MeV
- Main job is to trigger on interesting tracks.
- Spatial match of extrapolated track will help reject badly mis-reconstructed tracks.
- Most tracks from DIO curl inside.
- Pisa and LNF groups evaluating LXe, LSO, LYSO which might provide good enough $\sigma(E/p)$ to be interesting.

The schedule is technically driven

- We have received both Stage 1 approval and CD-0.
- Magnet design and construction remain the schedule drivers.



CD-1 Independent Design Review

(May 2011)

Findings, Comments, Recommendations

- More formal R&D plans
- Documents cleanup
- Simulation
  - Proof that we can do pattern recognition in the tracker
  - Justification for the calorimenter and minimum requirements
  - More numbers for rates for the DAQ
- CD-1 in September?

Attività svolta

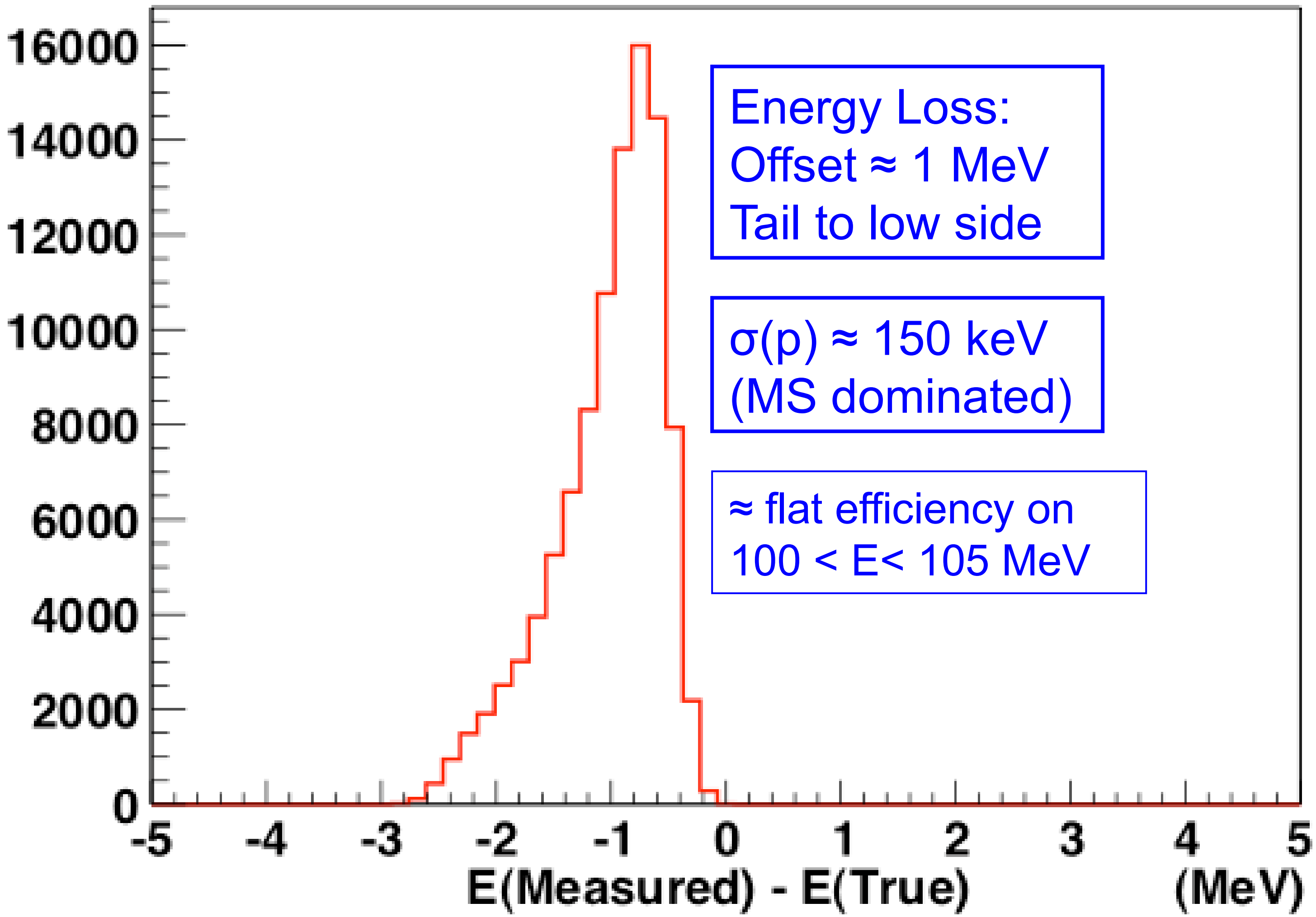
- *Partecipazione alla stesura del CDR*
- Calorimetro e.m. (simulazione, prestazioni)
- Test di cristalli
- Radiation damage ("Stimulated recovery")
- Calibrazione
- Elettronica di lettura
- Test beam (Mainz)
- Alternative al calorimetro a cristalli (2009/10):
  - Studio di cal. a Xenon liquido, scintillazione + ionizzazione (Meg)

Calorimeter (Pisa+Frascati)

- Simulation studies:
  - Optimal geometry: 4 vanes
  - Crystal length: < 14 cm
  - Signal acceptance: ~75%
  - Cal. In mu2e framework to cross check results
  - Impact of edges, supports, structure,..., to be estimated

- PWO-2: cooling
  - L.Y. @ -25 C improves by 4x
  - 3 ppm response stability
  - Slow decrease of light response with irrad. Time
- LYSO vs PWO-2
  - Excellent L.Y., better stability with T, more rad. Resistant
  - More expensive (x3?), slower (~40ns vs ~10ns), smaller density.
- L.A. APD's
- 2 vs 1 APD/crystal
  - Increases Npe, reduces noise; increases #channels.

Detector Response



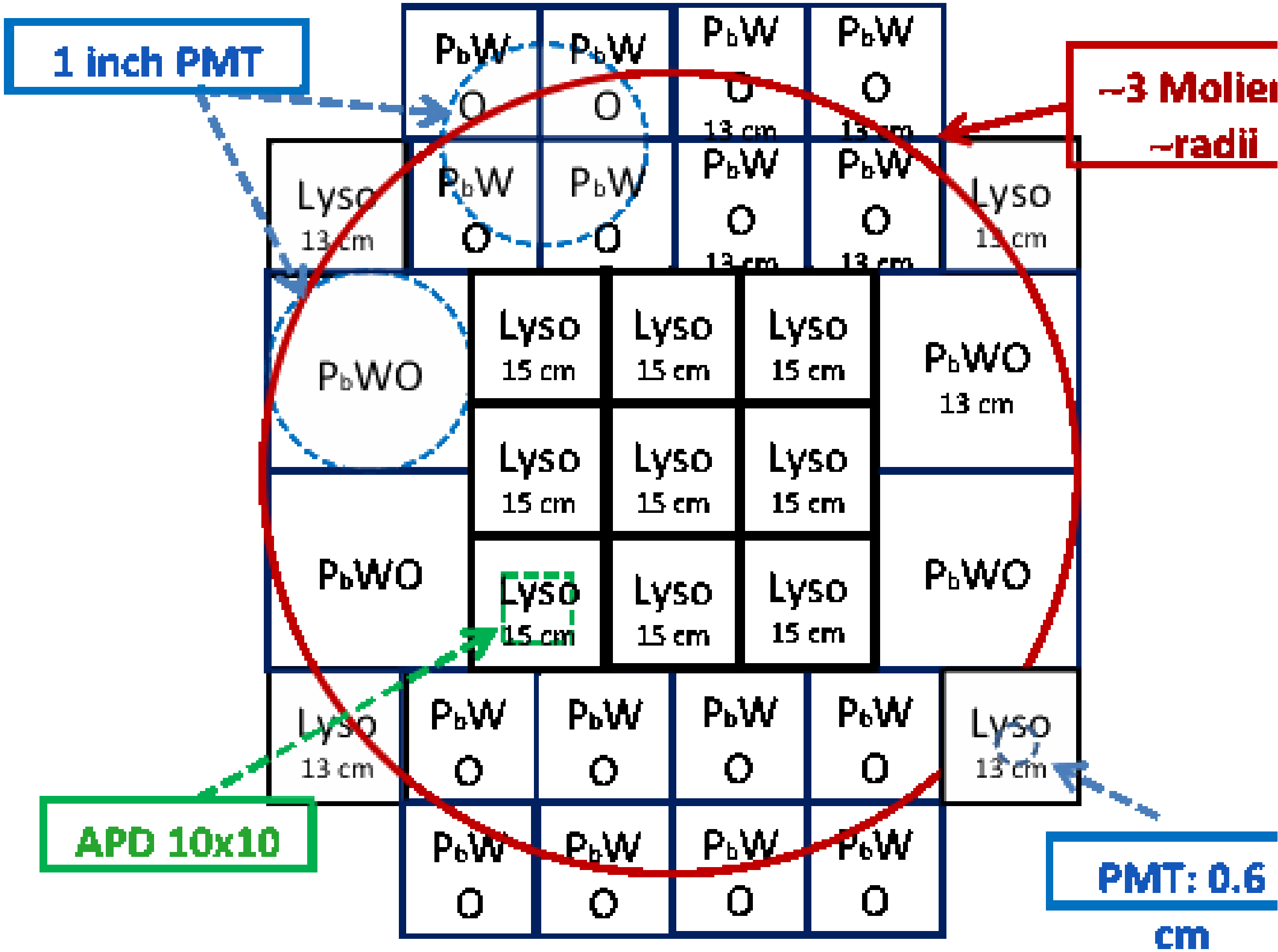
Electronics

- Assumption: 528x4=2112 crystals, 4224 APD's
- Option *A*:
  - FEE Preamps inside
  - WF digitizer inside
  - HV cables from outside
  - Optical fibers for calibration
  - Cooling line
- Option *B*: same as *A* but HV distributor inside

Calorimeter Prototype: Mainz Test Beam

Many improvements:

- Outer matrix enlarged and optically separated
- Inner matrix longitudinal dimension of 15 cm with new SICCAS crystals
  20x20x150 mm³ --> 10x10 mm² APD
- Coverage of ~3 Rm
- 13 cm LYSO on corners not inserted

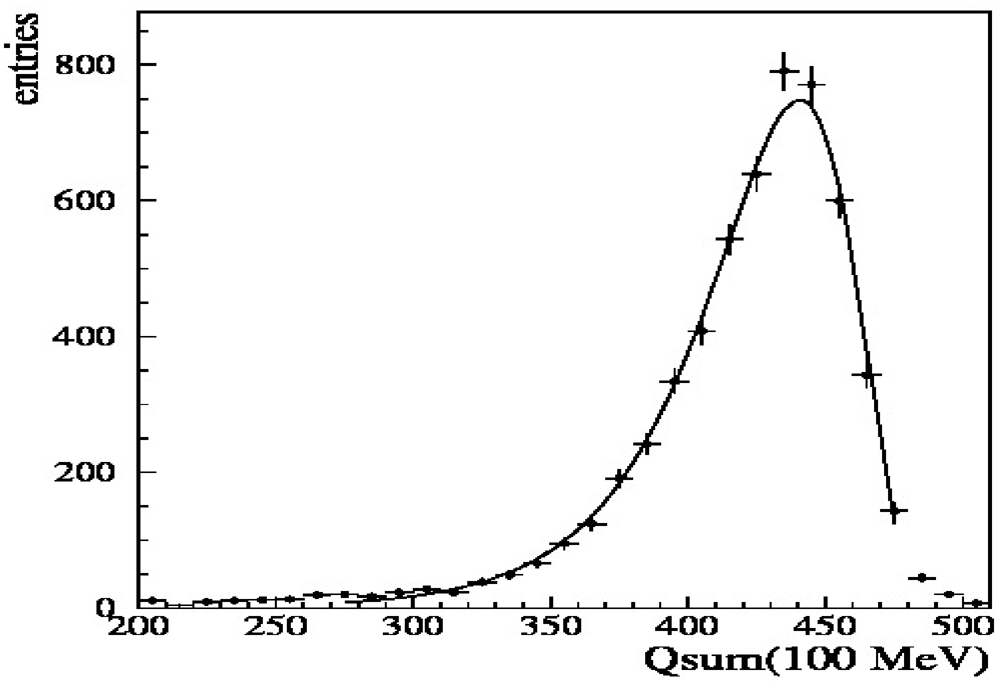


LYSO and APD's OK in Sep 2010

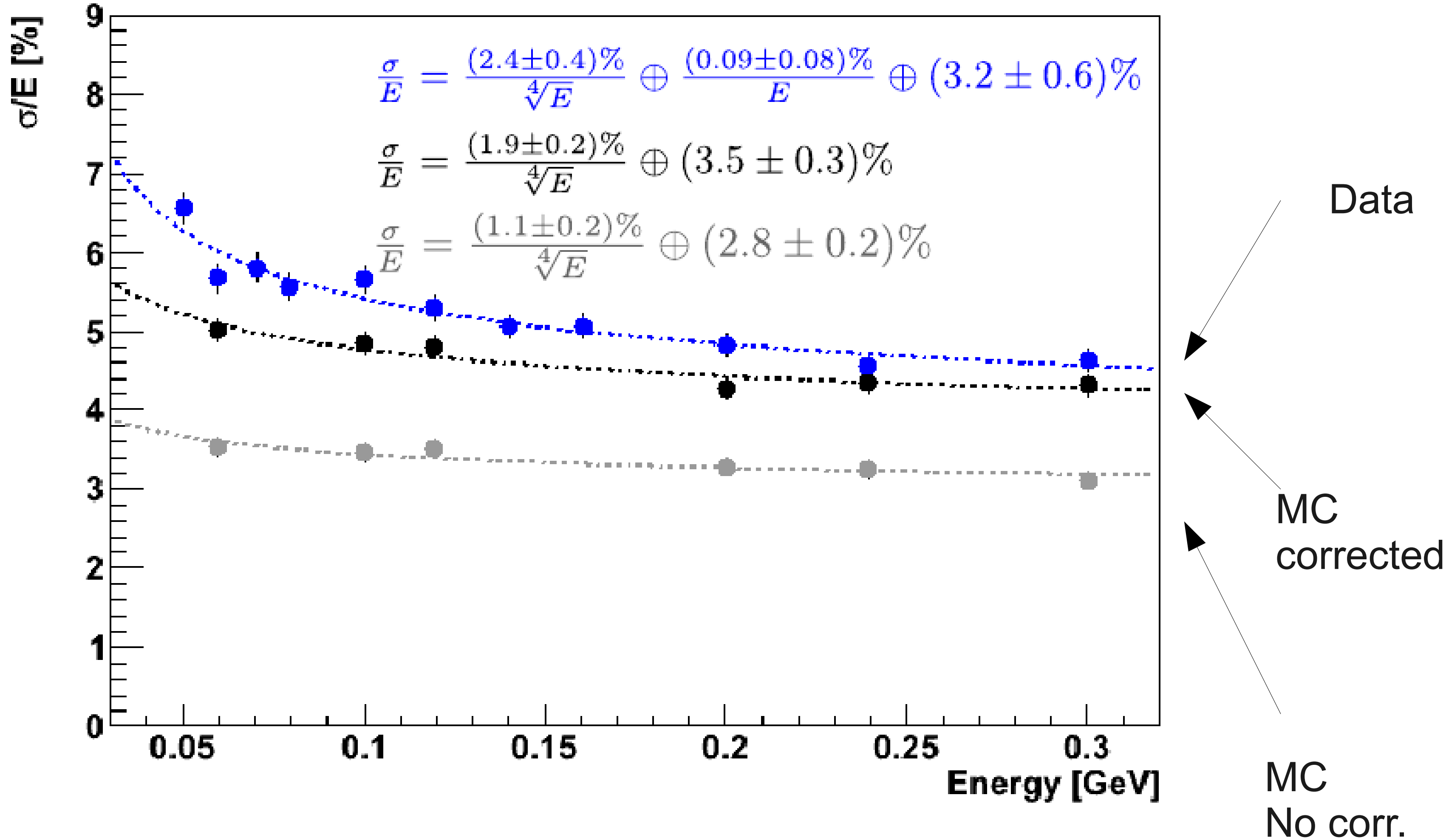
QA @ LNF: LRU< 10%, LY~400 pe/MeV, Mech.Tolerance OK

Cordelli/Happacher/Sarra/Saputi (LNF)

100 Mev
No calib.



Preliminary energy distribution. Resolution 5-6%. Electronic noise ~400-600 keV (sum over 17 cells).



σ/E [%]
Energy [GeV]
σ/E = (2.4±0.4)%/∜E ⊕ (0.09±0.08)%/E ⊕ (3.2 ± 0.6)%
σ/E = (1.9±0.2)%/∜E ⊕ (3.5 ± 0.3)%
σ/E = (1.1±0.2)%/∜E ⊕ (2.8 ± 0.2)%
Data
MC
corrected
MC
No corr.

Attività previste per il 2012

- Studi sul calorimetro:
  - Test cristalli (LYSO,...)
  - Prestazioni e limiti
  - Segnale/fondo
  - Mu – rejection (diff. dalla targh.)
  - Risoluzione vs ΔE
- Trigger
  - Elettronica
  - Simulazione
- Meccanica
  - Inserimento di Pisa nelle attività

Trigger / DAQ

- Baseline: **streaming**
  - Rate ~ 87 GB/s (mostly from tracker)
    - ~83 from tracker
    - ~3 from calorimeter
  - 2.5 GB/s optical data links
  - Dedicated event building network
  - Rate to write to disk: ~5kHz
  - Flexible, but expensive
- Alternative: **trigger**
  - Rate ~ few GB/s
  - Electronics
  - Calorimeter based (?)

Trigger / DAQ

- Advanced trigger
  - Energy thresholds
    - Thresholds values? Simulation
    - e.g. 70 Mev (1% cal. Resol.), 90 MeV (2% res.)
  - Use of shower development
  - Use info from tracker
  - Shower position and direction
- Development of FPGA with digital sums of calorimeter modules, test trigger performances in resolution and speed
- Determine most functional WF w.r.t. Shaping to get good energy resolution, reasonable timing, pileup rejection

Mechanics

- Realize a proto-cell or proto-module
- Final choice of wrapping material
- Realize proto-holder for photosensor or study the gluing of APD.
- Test all of the above on vacuum.
- Realize proto-system for APD temperature stabilization.
- Realize proto-vane smaller size.

Calorimeter Integration in DS: 3D view

First feasibility study of the calorimeter support structure carried out from our Mech. Engineer while respecting integration requirements.

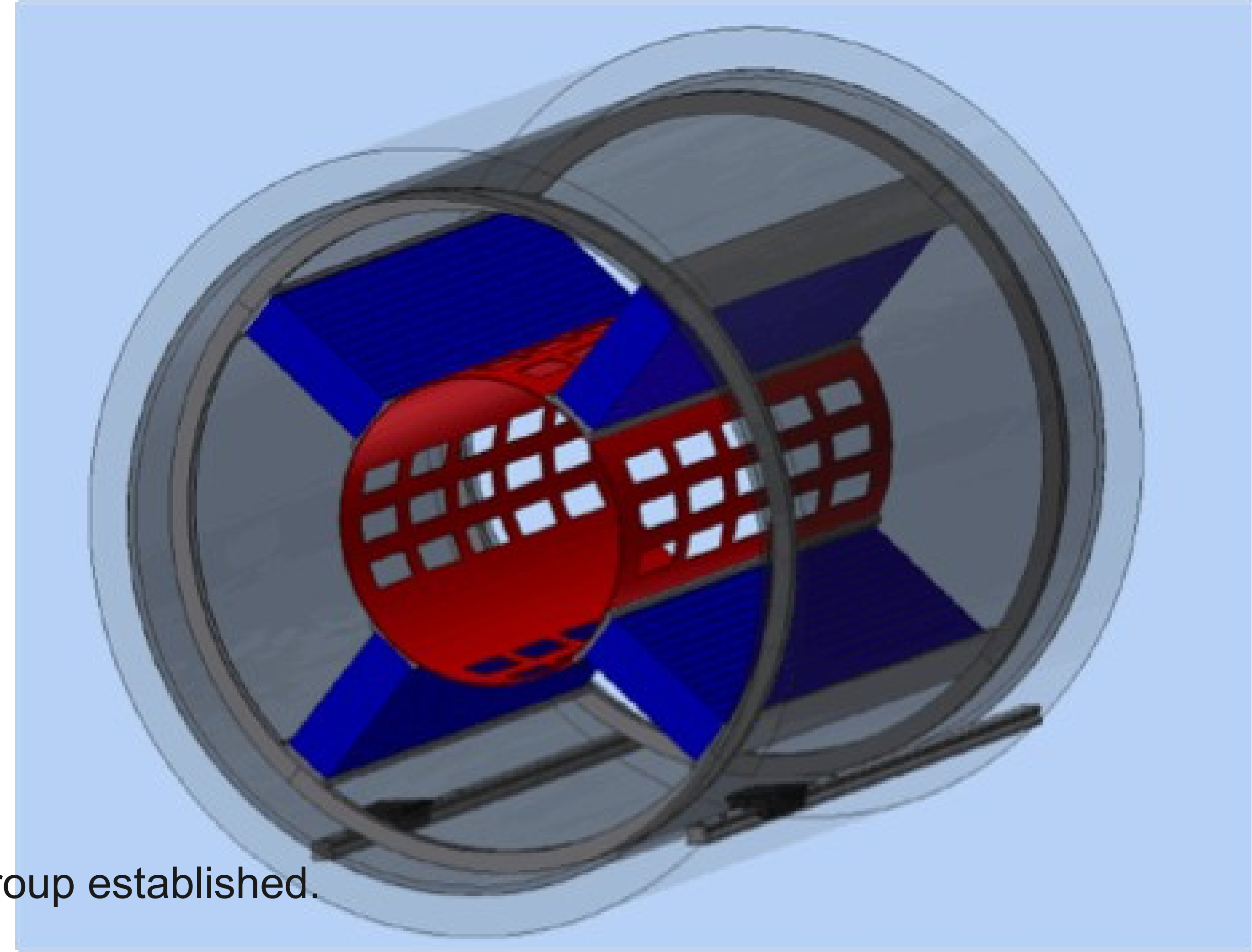
(1) C.Fiber structure for each vane.

(2) External rings in stainless steel (5 cm wide)

(3) Inner C.Fiber ring, of 5 mm thickness (< 1.7% X0).

(4) Work is in progress to reduce (3) to 2 mm thick.

(5) “Finite elements study” in progress for this and the “standard” 90 degree option.

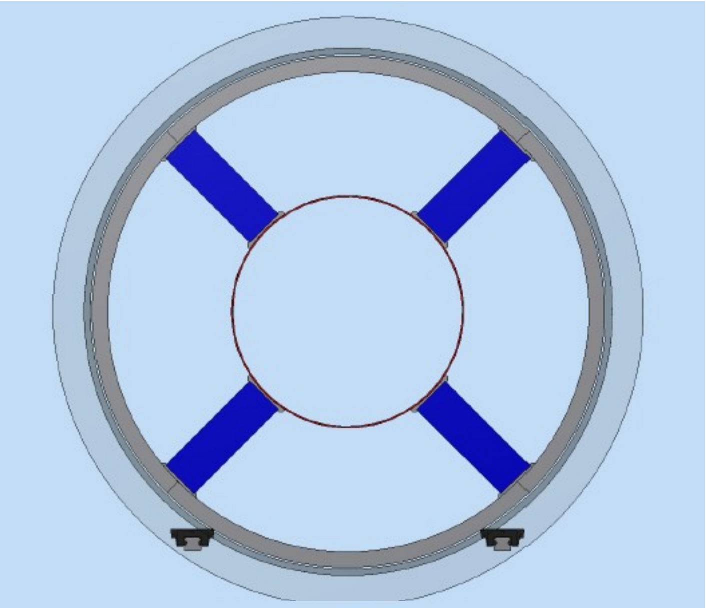


(6) Relation with DS integration group established.

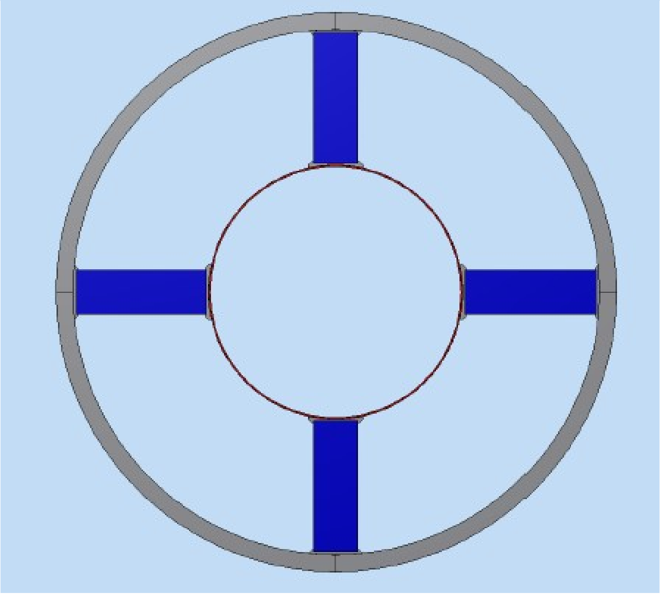
A.Saputi (LNF)

Calorimeter support: Front/Side views

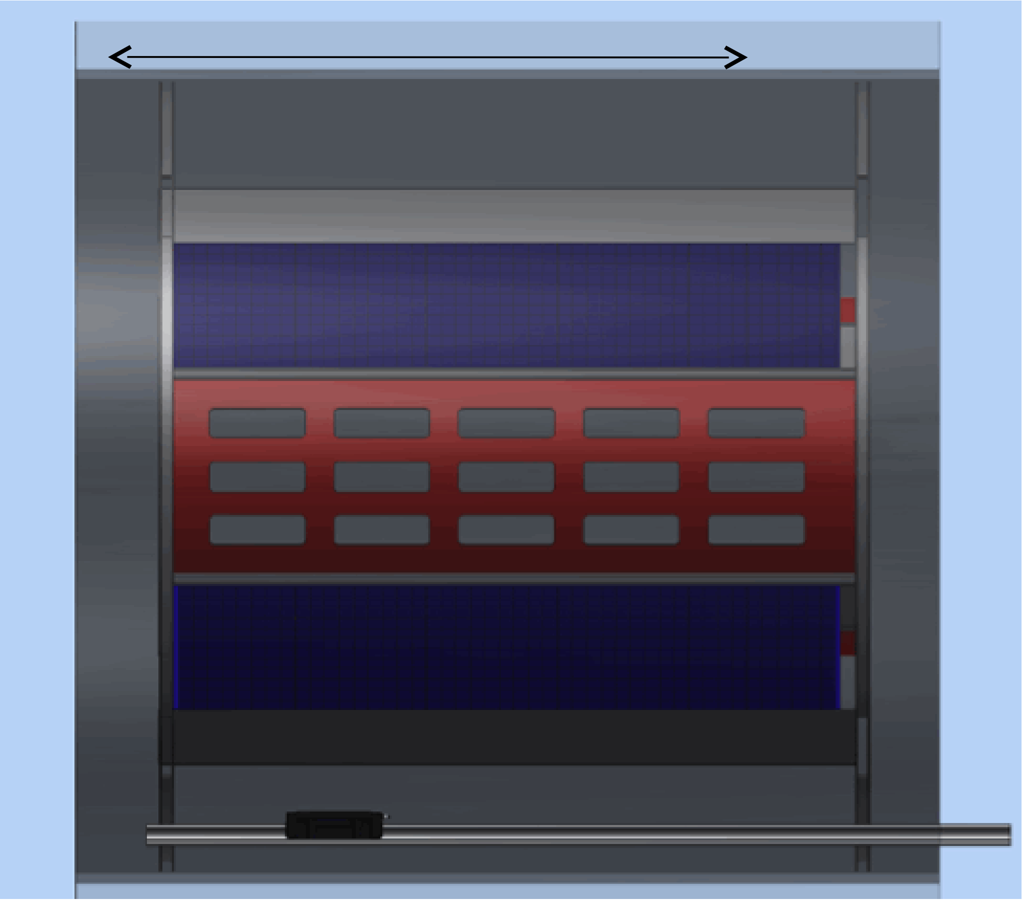
45 Degree Option (A)



90 Degree Option (B)



Overall Length: 1450 mm
Mech. Support included



Both front options valid from mechanical point of view. Option B) favored by a more symmetrical illumination of cosmic rays over the calorimeter surfaces.

Richieste finanziarie

- Missioni interne
  - 2011: 1k (chiesti 2k)
  - 2012: 2k
- Missioni estere
  - 2011: 4k+16k sj (chiesti 14k)
  - 2012: 15k
- Materiale di consumo
  - 2011: 10k+5k sj (chiesti 15k)
  - 2012: 25k
- Materiale inventariabile
- Costruzione apparati

Manpower 2012

- Carosi 60%
- Cervelli 40% (RN)
- Ristori 20% → 30-40% ?
- Vannini 40%
- Ric.AMS 20-30%
- Spinella 20% → 40% ?
- Moggi 10%
- Pilo, Gallucci
- ***3 laureandi spec.*** (2 summer students)

Richieste INFN

- Elettronica
  - Laboratorio
  - XX% tecnologo
- Calcolo
  - Fermilab ILCSIM
  - Desktop
  - Pagina web
- Meccanica
  - Non ancora chiaro

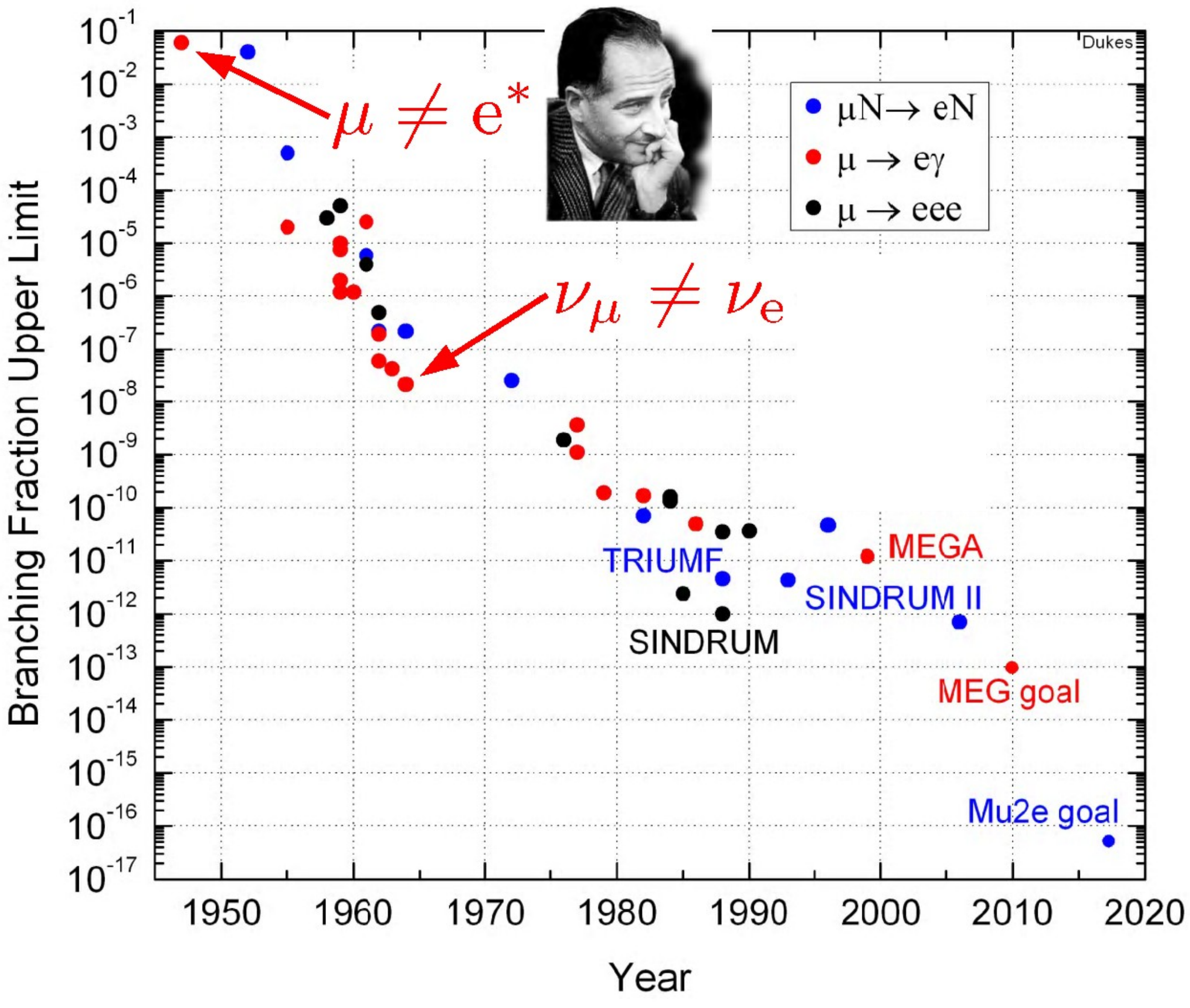
Backup slides

DOE Order 413.3A

- CD-0: Approve Mission Need
  - A determination is made that there is a scientific case to pursue the project. Some of the possible alternative means of delivering the science are presented as well as a coarse estimate of the cost.
- CD-1: Approve Alternative Selection and Cost Range
  - One of the alternatives proposed in the CD-0 is selected and a credible cost range is established.
- Critical Decision 2: Approve Performance Baseline
  - The technical scope of work, the cost estimate, and the construction schedule is sufficiently well known that the project can be completed on time and within budget.
- Critical Decision 3: Approve Start of Construction
  - Engineering and design are sufficiently complete that construction, procurement, and/or fabrication can begin.
- Critical Decision 4: Approve Start of Operations
  - The project is ready to be turned over to the organization that will operate and maintain it. The criteria for this stage are defined in the Performance Baseline.

http://www.er.doe.gov/hep/project_status/index.shtml

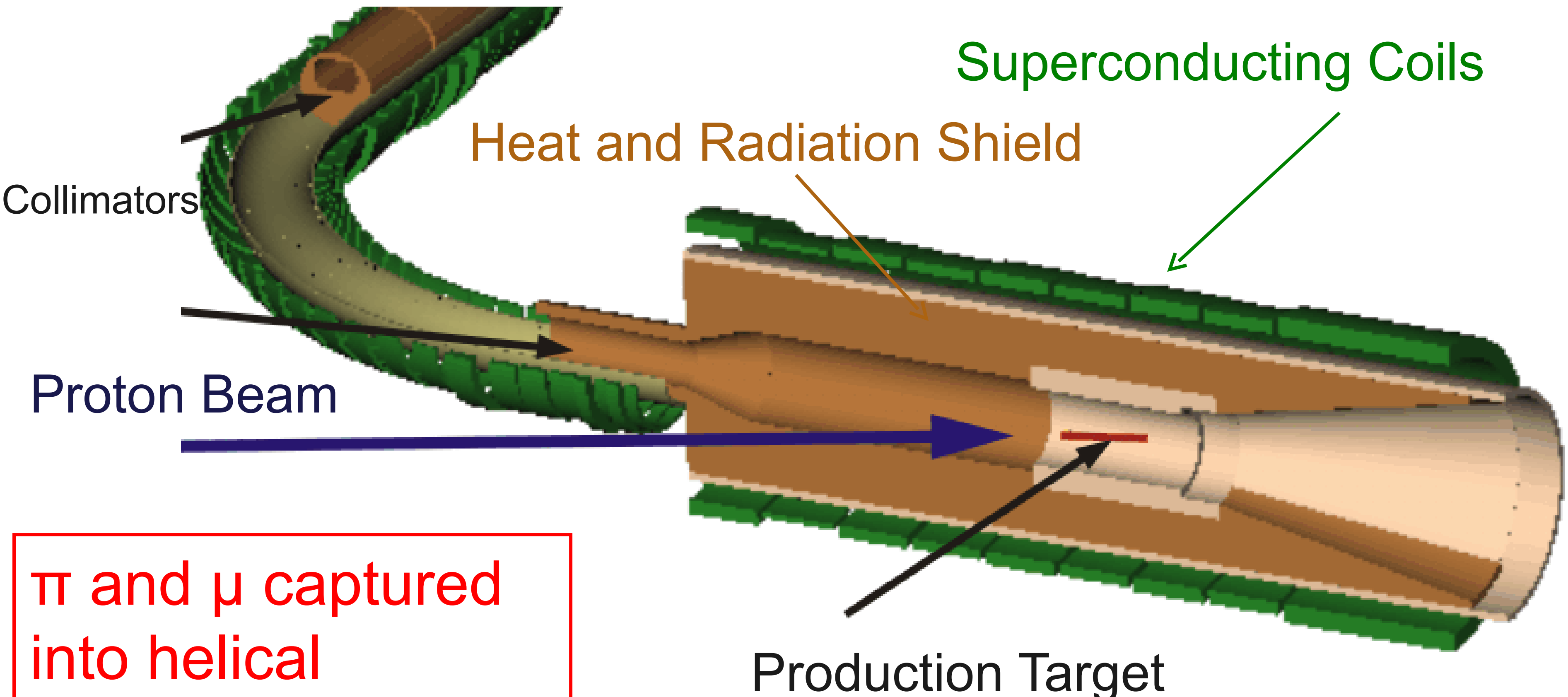
The mystery of lepton flavour



Why Do Mu2e?

- Access physics beyond the Standard Model (SM).
  - Precision measurements and searches for ultra-rare processes complement direct searches at the highest available energies.
- Negligible standard model backgrounds.
  - Wide discovery window.
  - Any non-zero observation is evidence for physics beyond SM.
- Violates conservation of lepton family number.
  - Already observed in neutrino sector.
  - Addresses the puzzle of generations.
  - Strength (or absence) of particular CLFV signals can help remove ambiguities from new physics signals seen elsewhere.

Production Solenoid

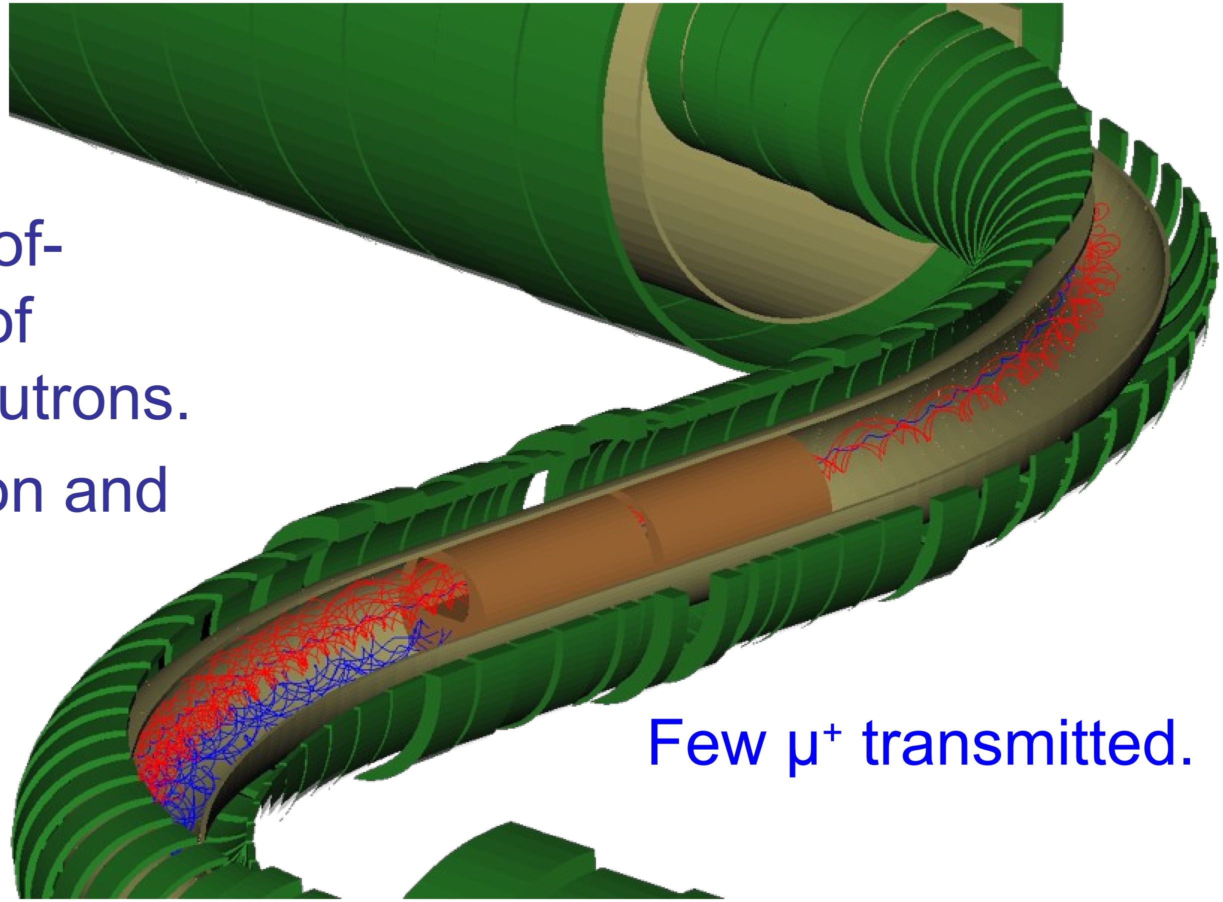


π and μ captured into helical trajectories

The off-axis 8GeV proton beam delivers $3x10^7$ protons per pulse, every 1.7 μs

Transport Solenoid

- Curved solenoid:
  - Eliminates line-of-sight transport of photons and neutrons.
  - Negative/position and particles shift up/down.
- Collimators sign and momentum select the beam.

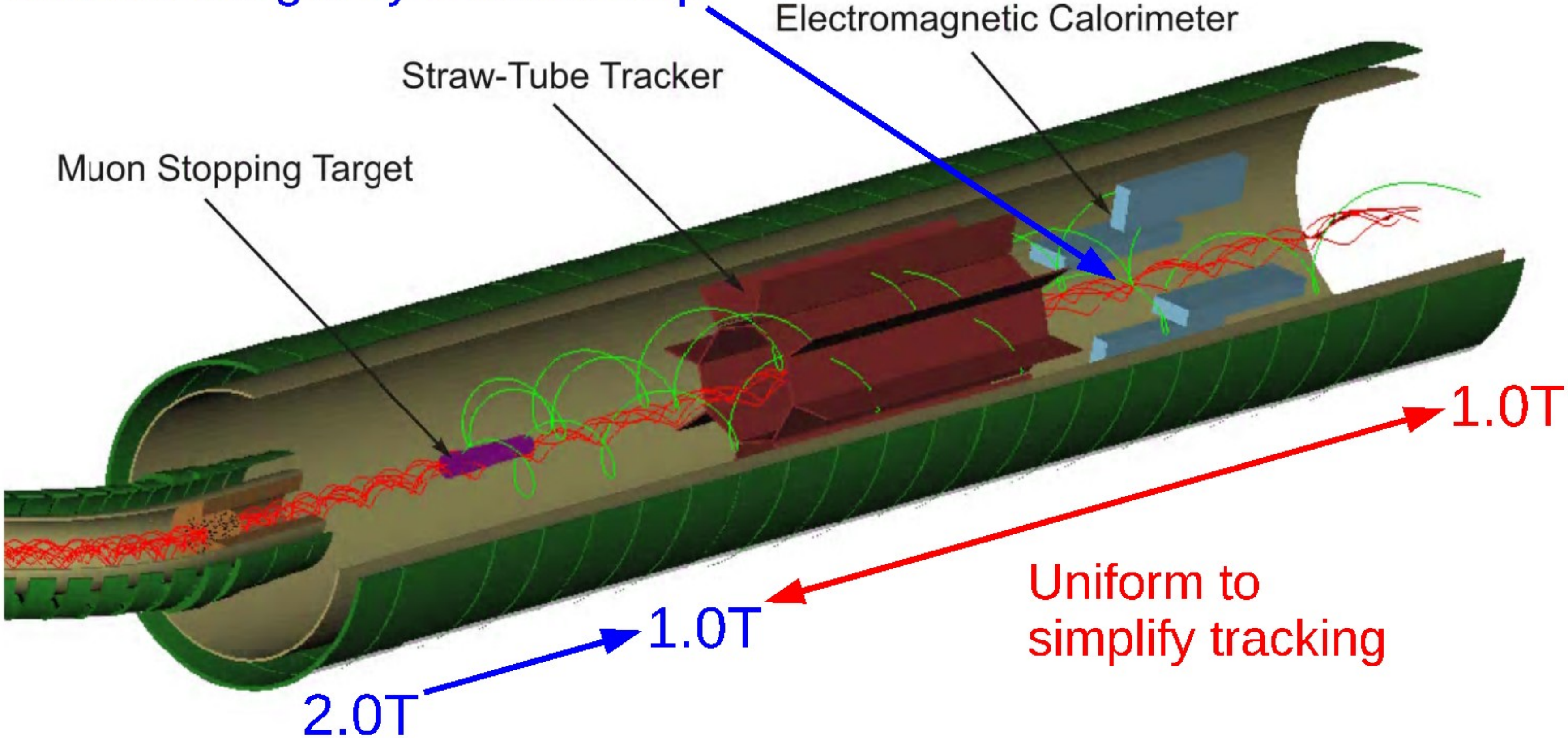


Few μ⁺ transmitted.

13.1 m along axis × ~*0.25 m* radius

The detector solenoid and stopping target

The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.

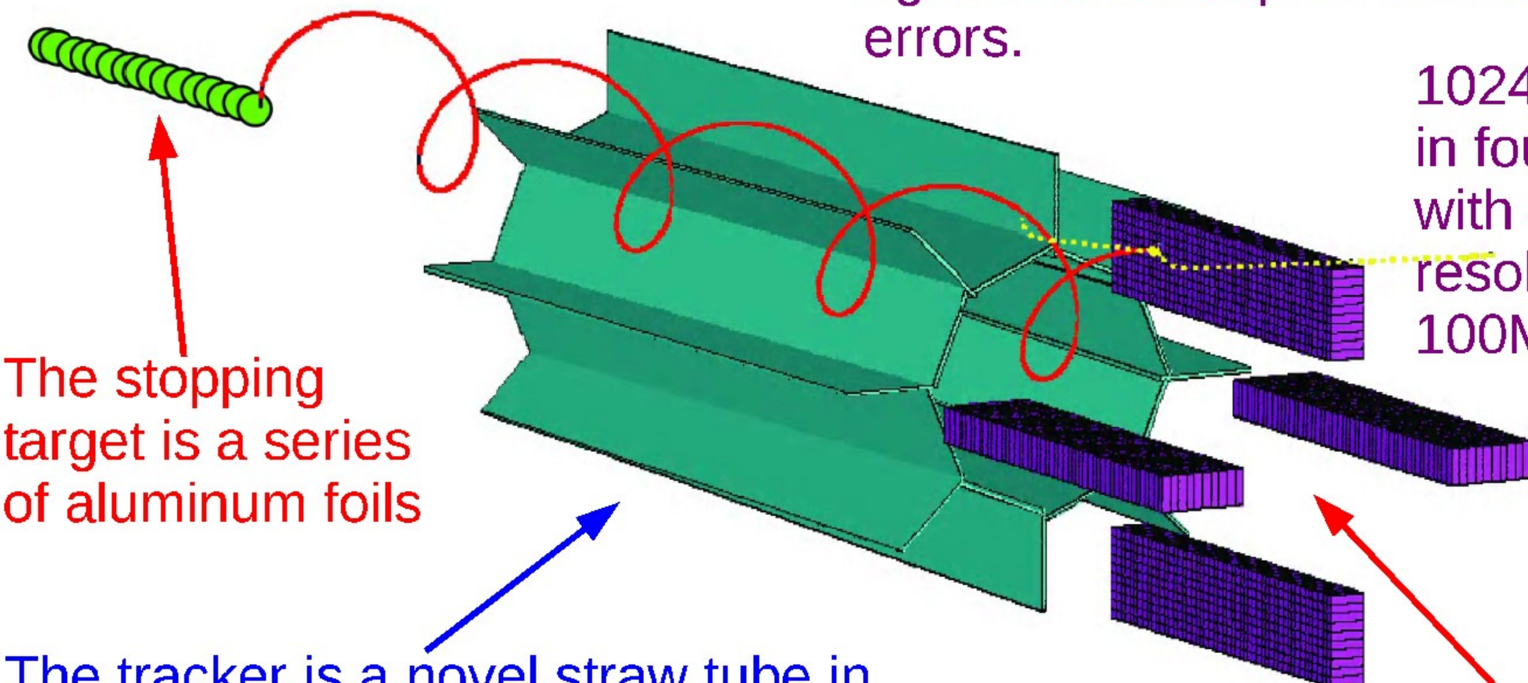


Graded to reflect electrons toward the tracker

The target and detectors

The crystal calorimeter provides direct measures of track position, time, and energy to help protect against catastrophic reconstruction errors.

A conversion electron track



1024 crystals in four vanes with 4MeV resolution at 100MeV

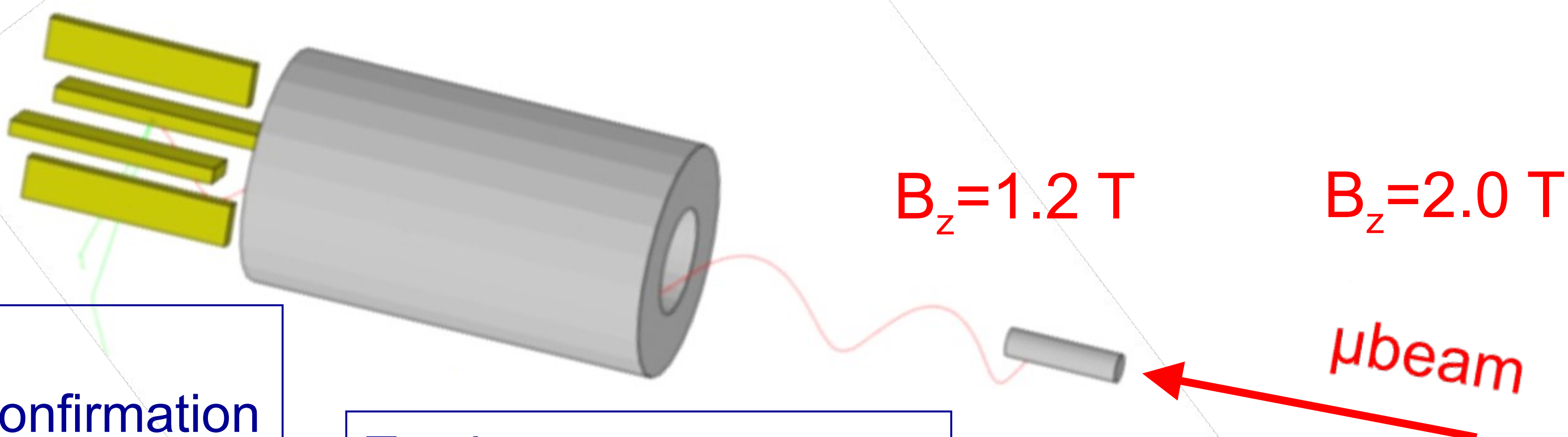
The stopping target is a series of aluminum foils

The tracker is a novel straw tube in vacuum design. A number of baseline designs are under consideration; all would have or order 20000 readout channels.

The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.

Detector Solenoid and Detector

B_z=1.0 T uniform field in Tracker + ECal



ECAL:
Trigger + confirmation of a real track.

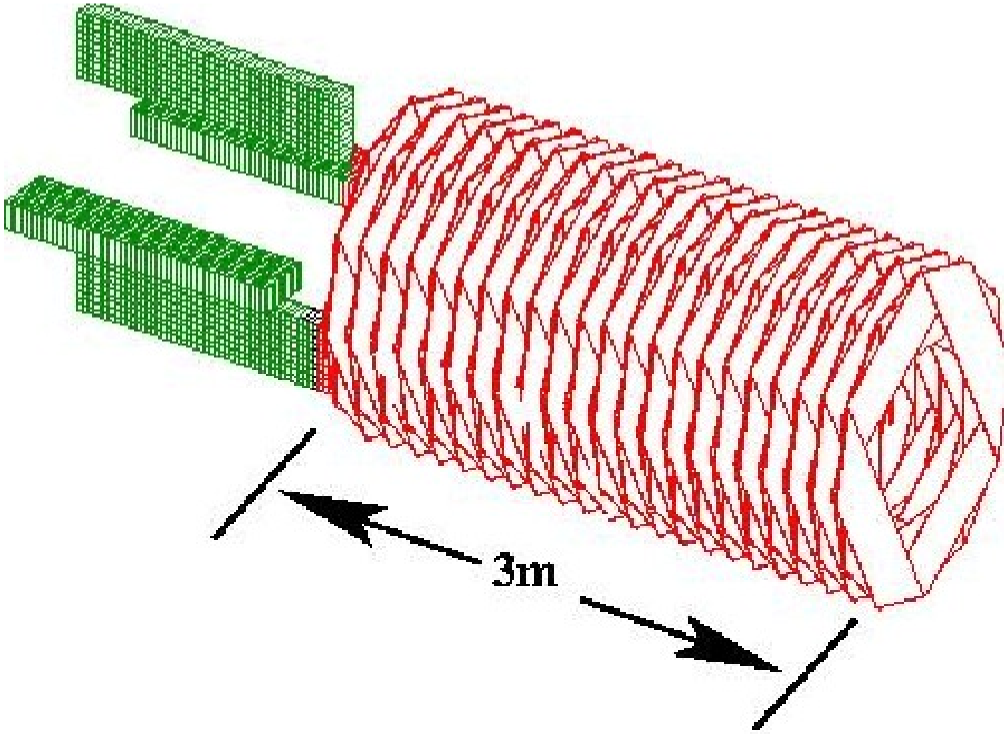
Tracker:
Precision momentum measurement

Stopping target:
in graded field

Require:
σ(p) ≈ 150 keV at p=105 MeV

Useful tracks make 2 to3 turns inside the tracker.

T-Tracker (T=Transverse)



- Straw planes in vacuum.
- Basic unit: plane
  - 3 panels each side
  - 2 layers per panel
  - 50 straws per layer
- Station
  - 2 planes close packed
  - 30 degree rotation
- Tracker
  - 18 Stations
- Most DIO electrons pass through central hole.

I-Tracker (I=Italian)

- Proposed by group from INFN Lecce.
- KLOE style cluster counting drift chamber.
  - Axial and stereo layers.
  - Central region empty (as with L and T).
- Advantage:
  - Robust pattern rec.; many measurements per track.
- Issues:
  - Material budget in upstream endplate.
  - Rates.

Calorimeter Requirements

The calorimeter requirements are described in Mu2e-doc-864.

- The calorimeter will be used to confirm that a reconstructed track is well-measured and was not created by a spurious combination of hits in the tracker.

1. extrapolate reconstructed tracks to the calorimeter and compare with actual energy deposit → $\sigma(x)$ O(cm).
2. compare the energy deposited in the calorimeter to the reconstructed track momentum → $\sigma(E)$ O(< 5 %)
3. check the time of the energy deposit in the calorimeter to a time determined from the tracker -> $\sigma(t)$ O(< ns).
4. provide particle identification to separate, for example, electrons from muons.

1. Provide a trigger that can be used for event selection
2. Keep functionality in a 160 Gy/year radiation environment

+ *independent measurement of p (E) with ~same resolution as the tracker*

Other Detector Systems

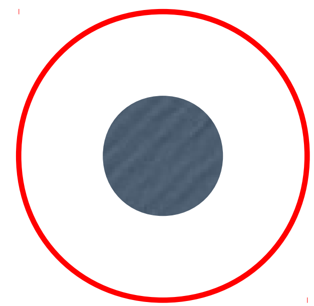
- Active Cosmic Ray Veto
  - Requirement: 99.99% efficiency to veto cosmic rays.
  - 3 Layers of 1 cm thick scintillator;
    - MINOS Style WLS fiber readout.
  - Option: RPC if n flux gives high dead time.
- Muon Capture Monitor
  – One way to get at the denominator in $R_{\mu e}$.
  - Measure X-ray lines from muon capture on Al.
  - Ge detector located downstream of main beam dump.
  - Views target foils via tiny bore holes.

Overview Of Processes

μ^- stops in thin Al foil

the Bohr radius is ~ 10 fm,
so the μ^- sees the nucleus

μ^- in 1s state



Al Nucleus
~4 fm

total disappearance rate =0.864 μ sec

60% captured

1.4 μ sec

1. μ^- emits ν
2. Al turns into Mg

NORMALIZATION

40% decay-in-orbit

2.2 μ sec

decays by normal process but can recoil off nucleus

BACKGROUND

Why Normalize to Capture?

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

Al turns into Mg

- Nuclear wavefunctions "cancel," calculation simpler

- As muon cascades to 1s, X-rays give stop rate

- and Al →Mg yields a 2.6 MeV β followed by γ that can be used to measure capture rate

1. μ^- emits ν
2. Al turns into Mg

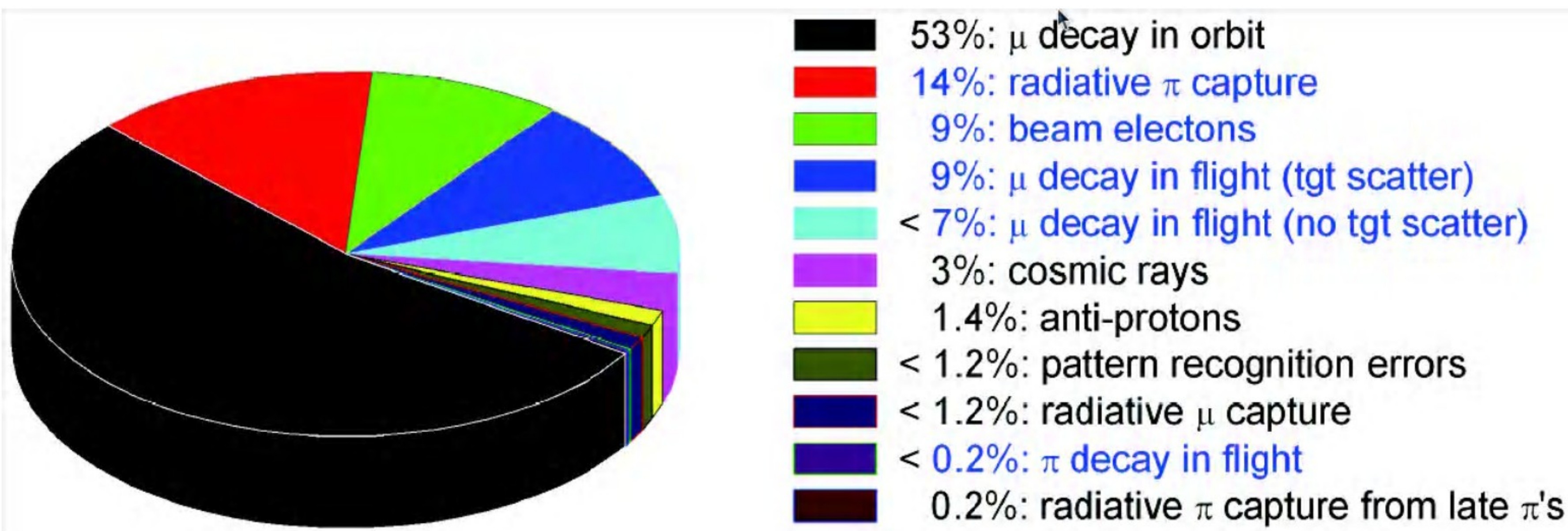
NORMALIZATION

With this design, the background rates are indeed very small!

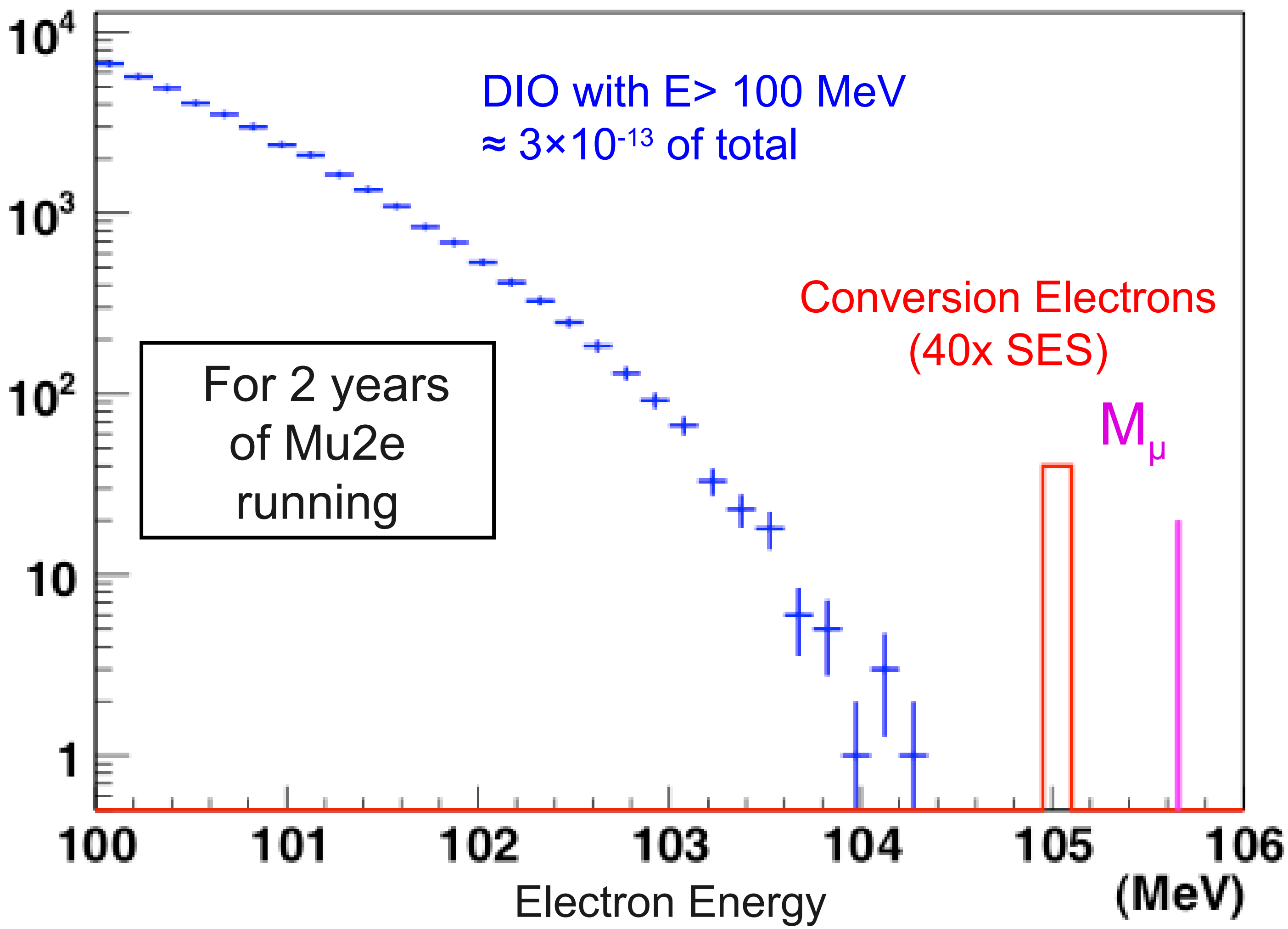
In two years of running, we expect fewer than one background event in the signal region.

If $R_{\mu e} = 10^{-15}$, we will see 40 signal events

Background	Events per 2×10^{7}s
μ DIO	0.225
Radiative π capture	0.072
μ DIF	0.072
Scattered beam e	0.035
Total	**0.41**

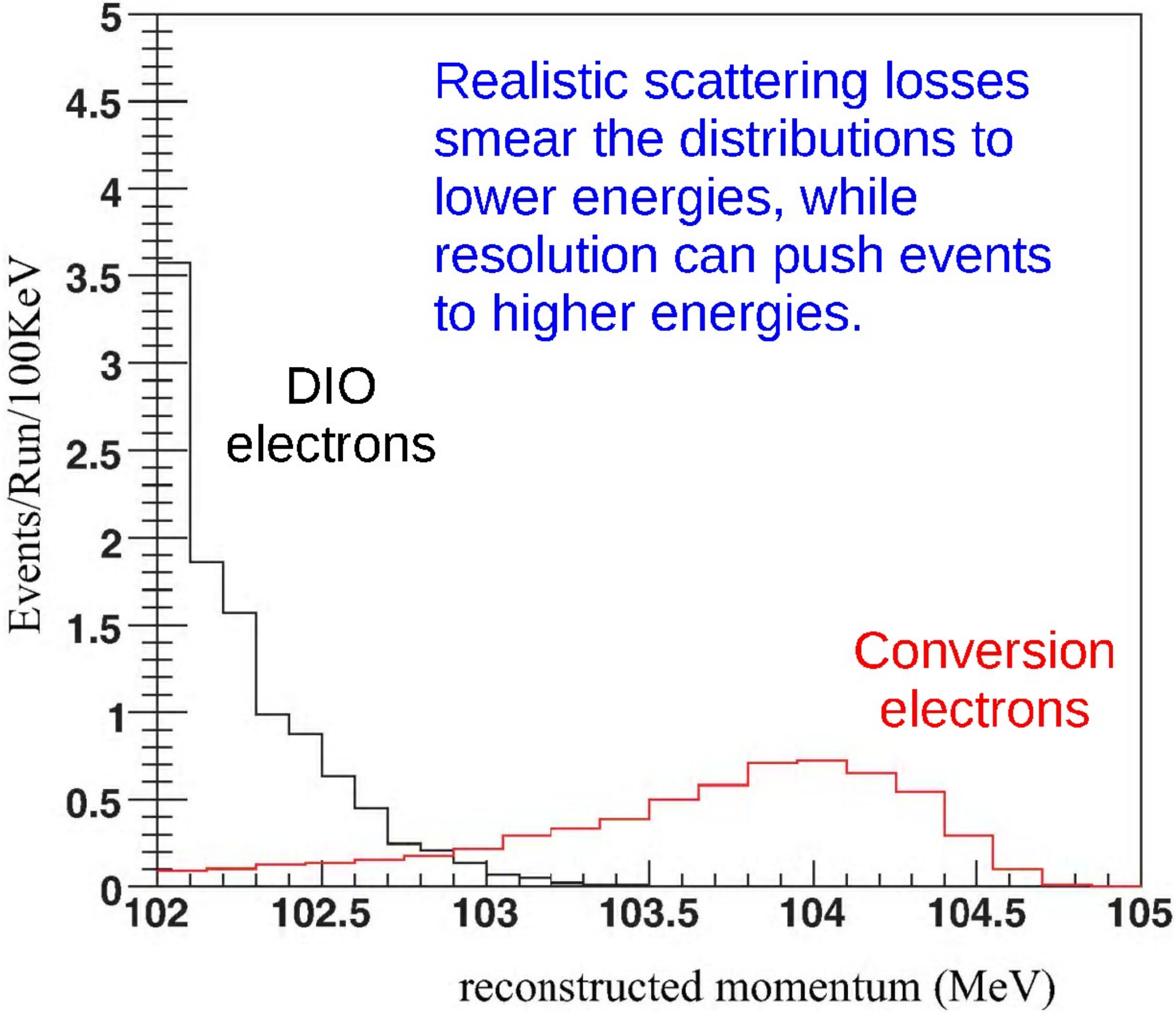


EndPoint in a Perfect Detector

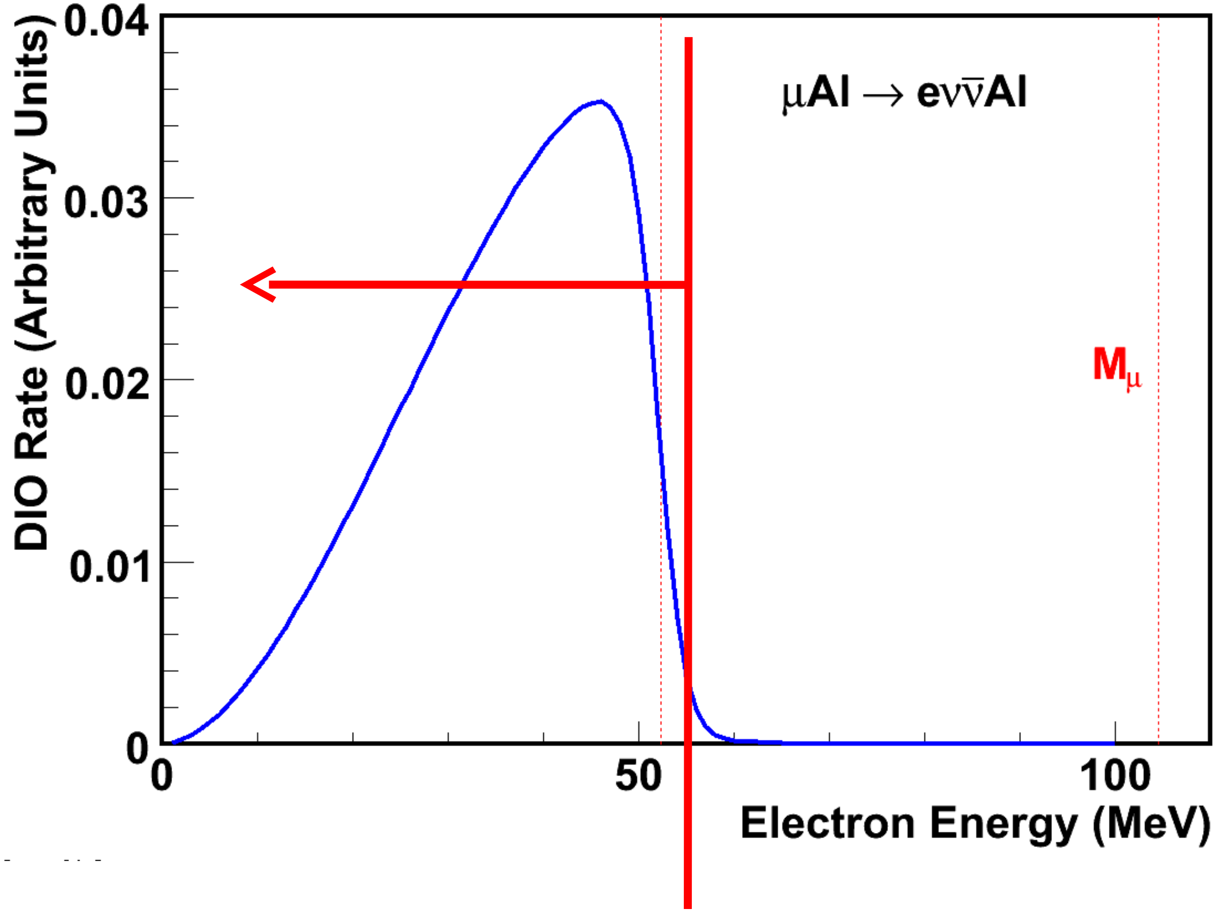


SES = Single Event Sensitivity.

An experimental reality check



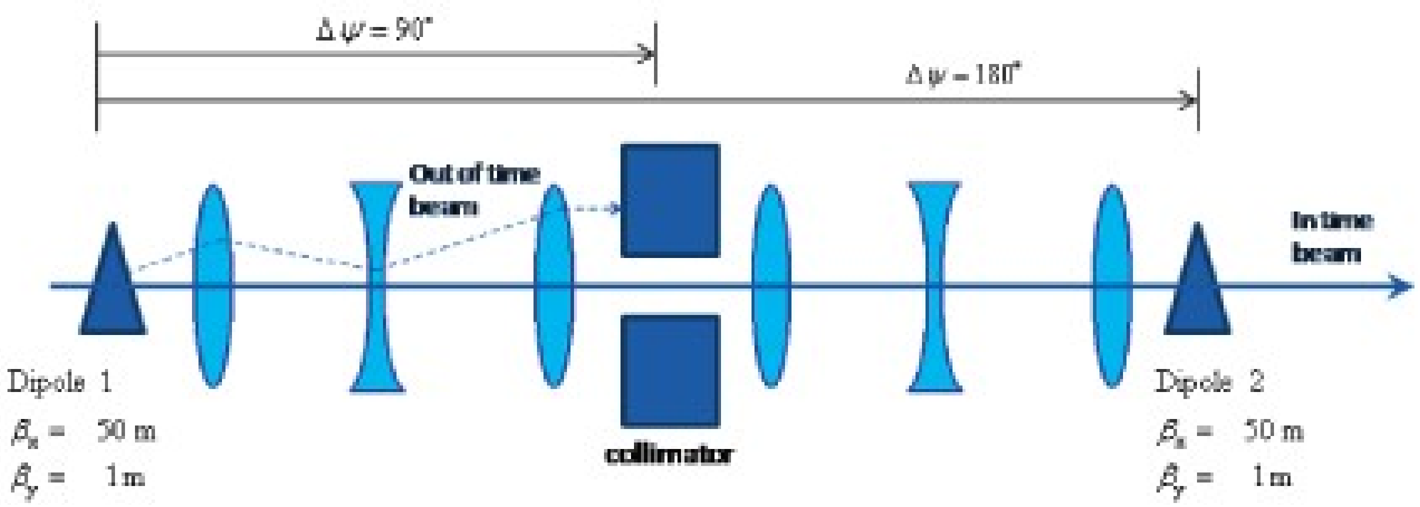
How do you measure 2.3×10^{-17} ?



Make a detector that is blind to most of the DIO spectrum.
Curl them up in a 1 T magnetic field.

Required Extinction 10^{-10}

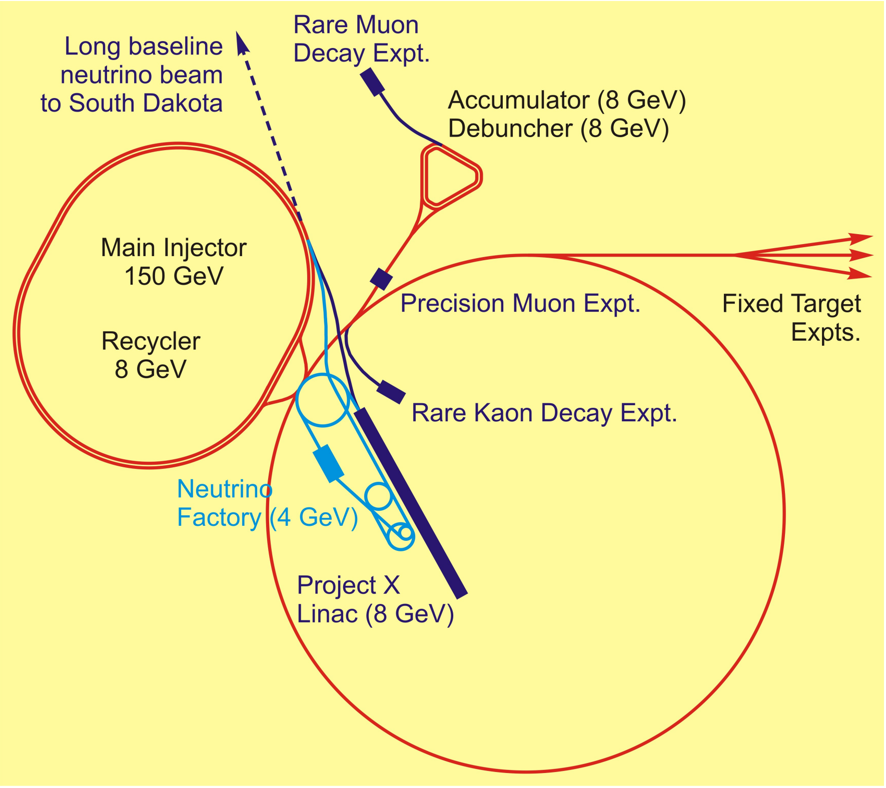
- Internal: 10^{-7} already demonstrated at AGS.
  - Without using all of the tricks.
  - Normal FNAL: 10^{-2} to 10^{-3}; but better has not yet been needed.
- External: in transfer-line between ring and production target.
  - Fast cycling dipole kickers and collimators.
- Monitoring techniques under study.



Mu2e In the Project X Era

- Project X: high intensity proton source to replace existing Booster.
  - Booster: 20 kW beam power at 8 GeV.
  - Project X: 200 kW at 8 GeV (with upgrade path to 2000 kW).
    - With corresponding upgrades at 120 GeV.

- If we have a signal:
  - Study Z dependence by changing stopping target.
  - Helps disentangle the underlying physics.
- If we have no signal:
  - Up to to 100 × Mu2e physics reach, $R_{\mu e} < 10^{-18}$.
  - First factor of ≈10 can use the same detector.



Parameter		CeF_3	LSO/LYSO:Ce	BGO	PWO	PWO-II
ρ	g/cm^3	6.16	7.40	7.13	8.28	
X_0	cm	1.77	1.14	1.12	0.89	
R_M	cm	2.60	2.30	2.30	2.00	
τ_{decay}	ns	30	40	300	6.5	
λ_{max}	nm	330	420	480	420	
n at λ_{max}		1.63	1.82	2.15	2.24/2.17	
relative LY	% (LY NaI)	5	75	9	0.3 at RT 0.8 at -25°C	0.6 at RT 2.5 at -25°C
hygroscopic		no	no	no	no	
dLY/dT	%/°C	0.1	0	-1.6	- 2.7 at RT	-3.0 at RT
dE/dx (MIP)	MeV/cm	6.2	9.6	9.0	10.2	

SICCAS CRYSTALS

Size	pcs	LYSO	PWO
24*130	30	4500	1000
30*130	30	9000	1800
37*130	30	15000	3100
24*130	250	4000	900
30*130	250	8000	1600
37*130	250	13000	2800
24*130	4000	3500	800
30*130	2400	5200	1300
37*130	1800	8000	2300

Prize List in USD/PC

External Connections

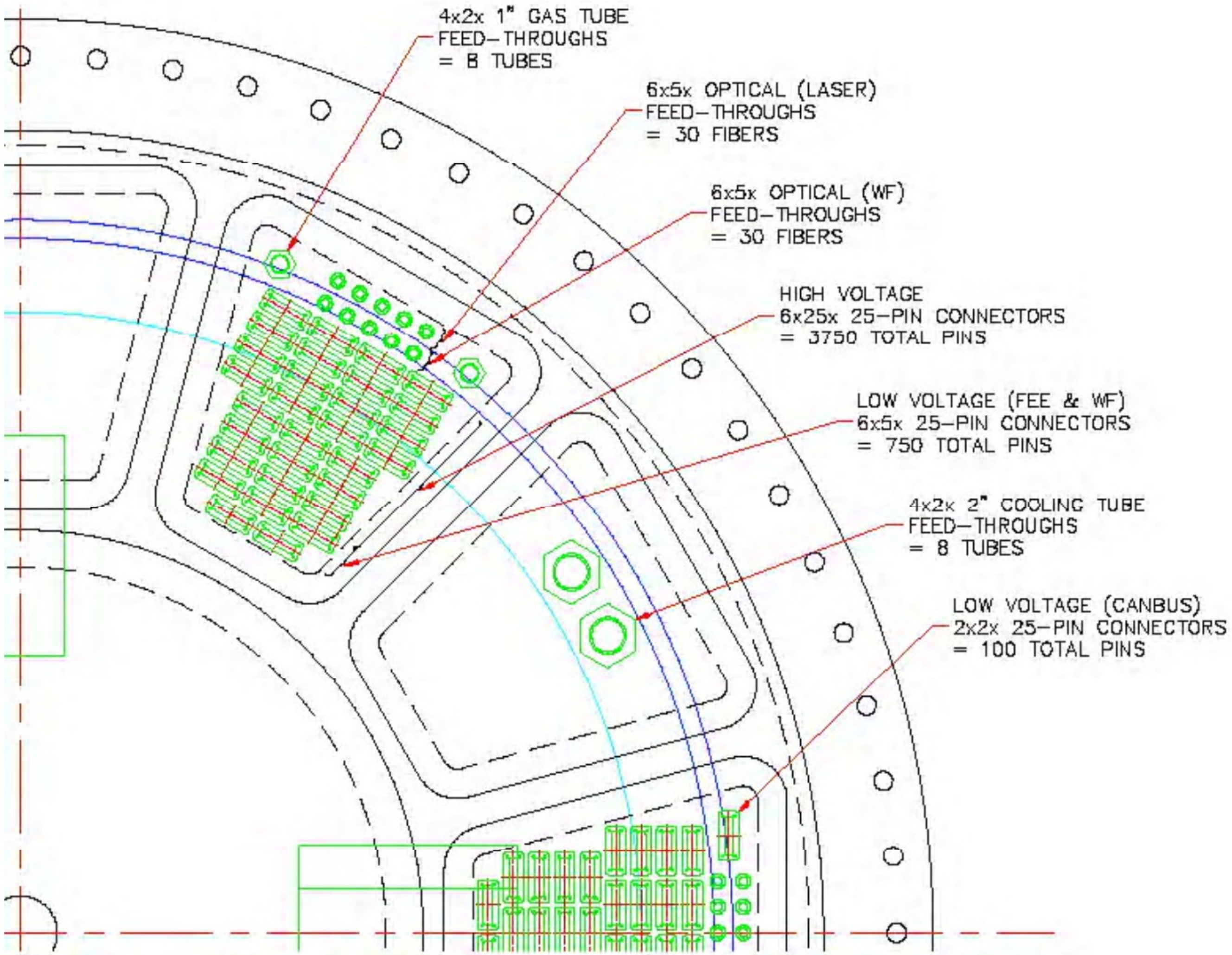
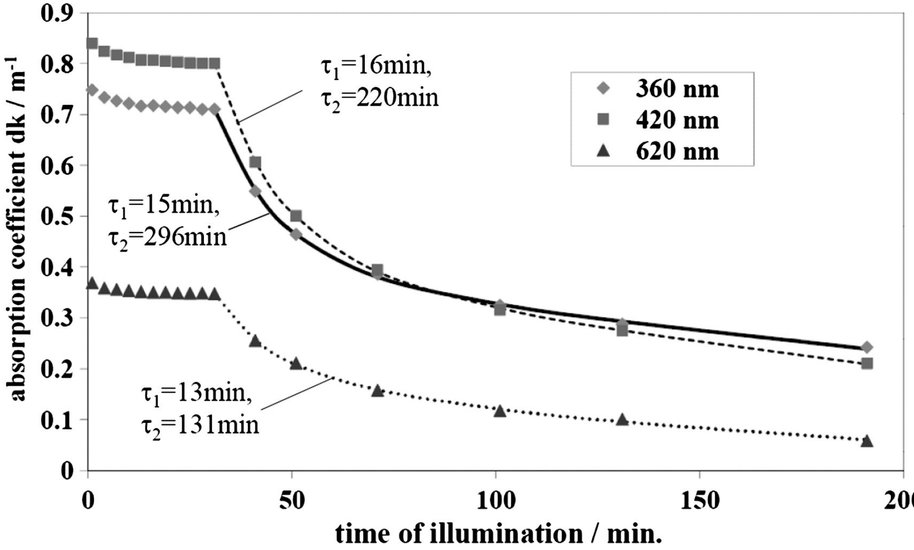


Fig. 11 – Calorimeter Feed-Throughs

- The Calorimeter will require ~ 580 FEE and 288 WF low voltage signal pins.
- The Calorimeter will require approximately 4370 high voltage pins.

Recovery after radiation damage

- 160 Gy/year (=16krad/year) → ~2 rad/hr
- Slow decrease of light response ~30%/2 months of continuous running (PWO-2)
- Recovery w/o beam very slow at -25 C
- **Stimulated recovery**: NIM A623(2010) 1082
- Spontaneous relaxation
  - Thermodynamical process
  - accelerated by injection of energy (heating, ionization or excitation)
- Excitation in the infrared or visible (LED**)**
- Example: PANDA calorimeter



Calibration

- All modules will be calibrated with Cosmic Rays, e-beam and cross calibrated with UV light
- In the DS, we will use a calibration system:
  - For charge, by pulsing FEE
  - For APD gain, by sending blue light from the front face (this increases by a factor 2 the input fibers for each crystal and the big UV fibers
  - For scintillation stability by sending UV light from the front face
  - Continuous calibration with CR
  - Energy scale control at low momentum using electrons from DIO with calorimeter vs tracker measurement
  - With a source we can think of enhancing APD gain and check the energy scale at 1 MeV level

Trigger considerations

- We expect around 80-90 GB/sec from DAQ in streaming mode.
- If we assume 10**7 s/year we need

10**9 GB → 1 milion TB, 1000 pB, 1 AB

i.e. to store on disk w/o selection → 100 Tier1.

Even with a good Moore Law of a factor 2 improvement/year we cannot gain more than a factor 10 In 4 years. Let'us assume that we should reduce the writing on disk at least of a factor 100 , i.e. 10 PB, i.e. as Tier1 now.

The rate to write on disk will be of 5 kHz.

What is the threshold needed on DIO to get such reduction?

The chosen threshold should also be O(100%) efficient on Signal.

e.g. 90 MeV for 1% resolution

70 MeV for 2% resolution

We need to do this in a clean way assuming also :

- Full simulation and edge effects
- a reconstruction digital pattern to be used on FPGA.

Mu2e Italia

- Pisa (Calorimetro con Frascati, Trigger)
  - Carosi 50%
  - Cervelli 40%
  - Ristori 20%
  - Vannini 40%
  - Spinella, Basti
- Frascati (Calorimetro)
  - Miscetti, Happacher, Cordelli, Giovannella
- Lecce (Tracker)
  - Grancagnolo et al.
- Udine (Veto)
  - Pauletta, Cauz