The Muon to Electron (MU2E) conversion experiment at the FERMILAB Muon Campus

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Lecture overview

- The CLFV processes
- The mu-to-e conversion process
- Physics Reach of Mu2e
- Mu2e experimental technique
- Status of the Mu2e experiment
- Summer School @ FNAL

Direct and indirect searches

We have not yet seen any unambiguous signal of physics beyond the SM.

Are we searching at the right places?
Are we looking at high enough energies?

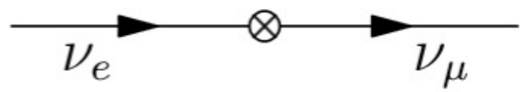
We do not have the answer to these questions. So, we should keep trying hard. Two methods are followed in HEP:

1. Direct searches at colliders (LHC), compelling but probe only relatively low mass scales, up to a few TeV
2. Indirect searches, probing masses far greater than those accessible at colliders, but requiring high precision measurements (e.g. $B_{s,d} \rightarrow \mu^+\mu^-$, Higgs couplings,…)

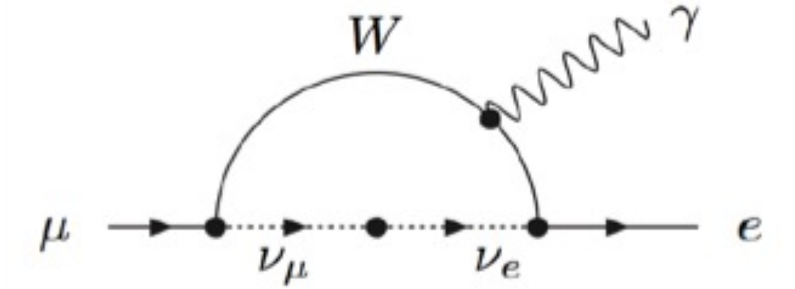
Among indirect searches, **charged lepton flavor violating** processes are particularly well suited to search for New Physics and study its structure.

Charged Lepton Flavour Violation

Neutral lepton flavor violation (i.e. neutrino mixing) implies charged lepton flavor violation (CLFV) through neutrino mixing.



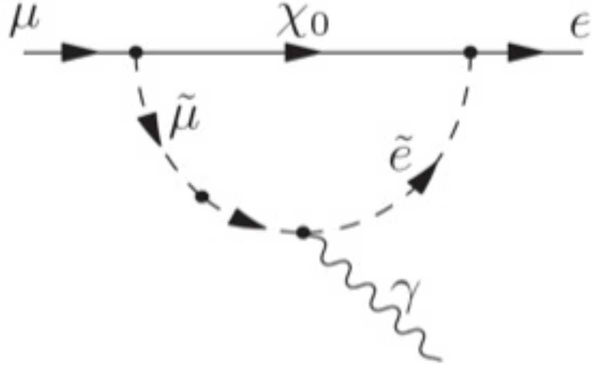
However, CLFV processes are strongly suppressed in the Standard Model.



BR($\mu \rightarrow e\,\gamma$) < 10^{-54} in the SM i.e. negligible.

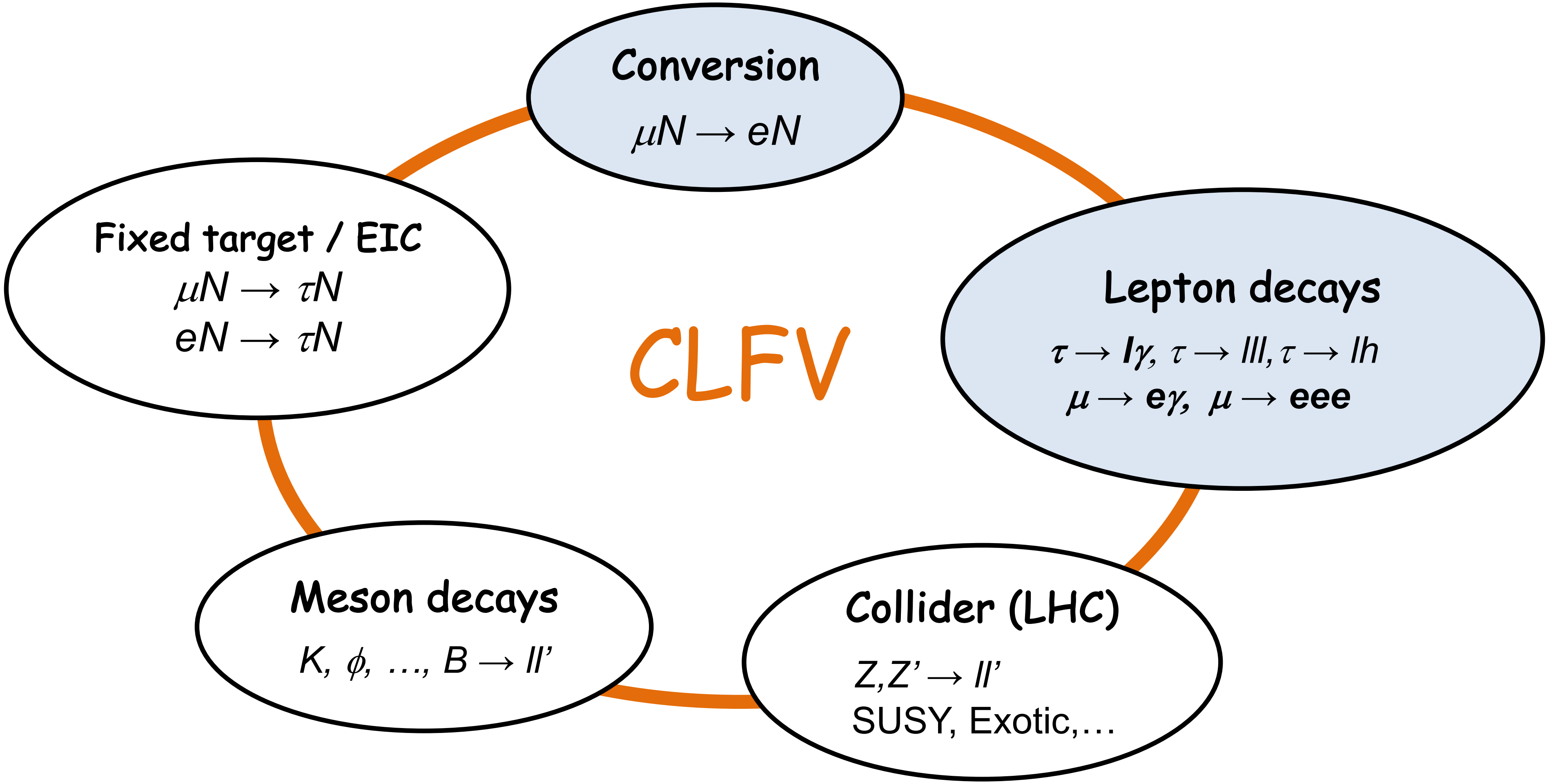
$$\mathrm{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}$$

New Physics can enhance CLFV rates to observable values.



Observation of CLFV is an unambiguous sign of New Physics

The big CLFV loop



Lepton decays or conversions have a primary role in the CLFV processes …

LFU with $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$ LHCb-PAPER-2021-004

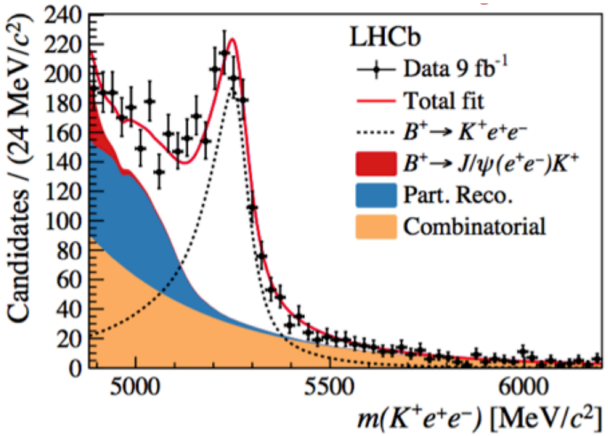
- Standard Model predicts identical electroweak couplings of e, μ
- Hints from LHCb in recent years of deviations from SM in $b \rightarrow sl^+l^-$ ratios, as well as in angular distributions and branching fractions

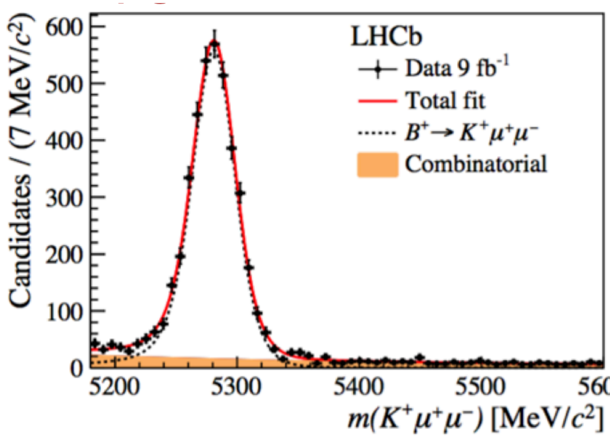
$$R_H \equiv \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2}dq^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2}dq^2}$$

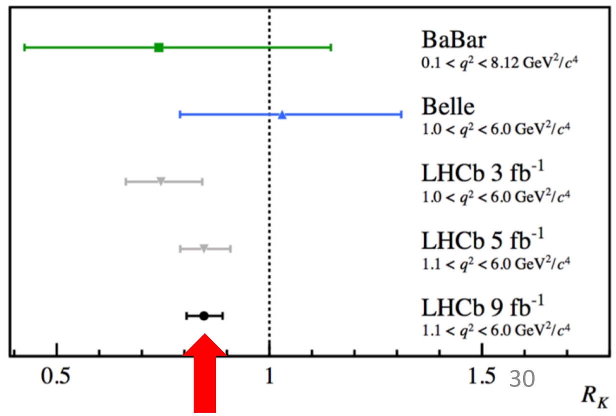
- Novel measurement of R_K with full dataset

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$ 3.1σ from SM

- Additional measurements with existing data set will provide further information, then data from LHCb Upgrade







Muon Campus @ FNAL: new physics hints @ g-2

CLFV processes on muon sector

- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)

  similar but complementary to other CLFV processes as $\mu \to e\gamma$ and $\mu \to 3e$.

- $\mu \to e\gamma$ is a CLFV decay searched @ PSI by the MEG (and now MEG-upgrade) experiment. **It is leading the research in this field.**

- Also $\mu \to 3e$ is an experiment proposed @ PSI. It will be carried out

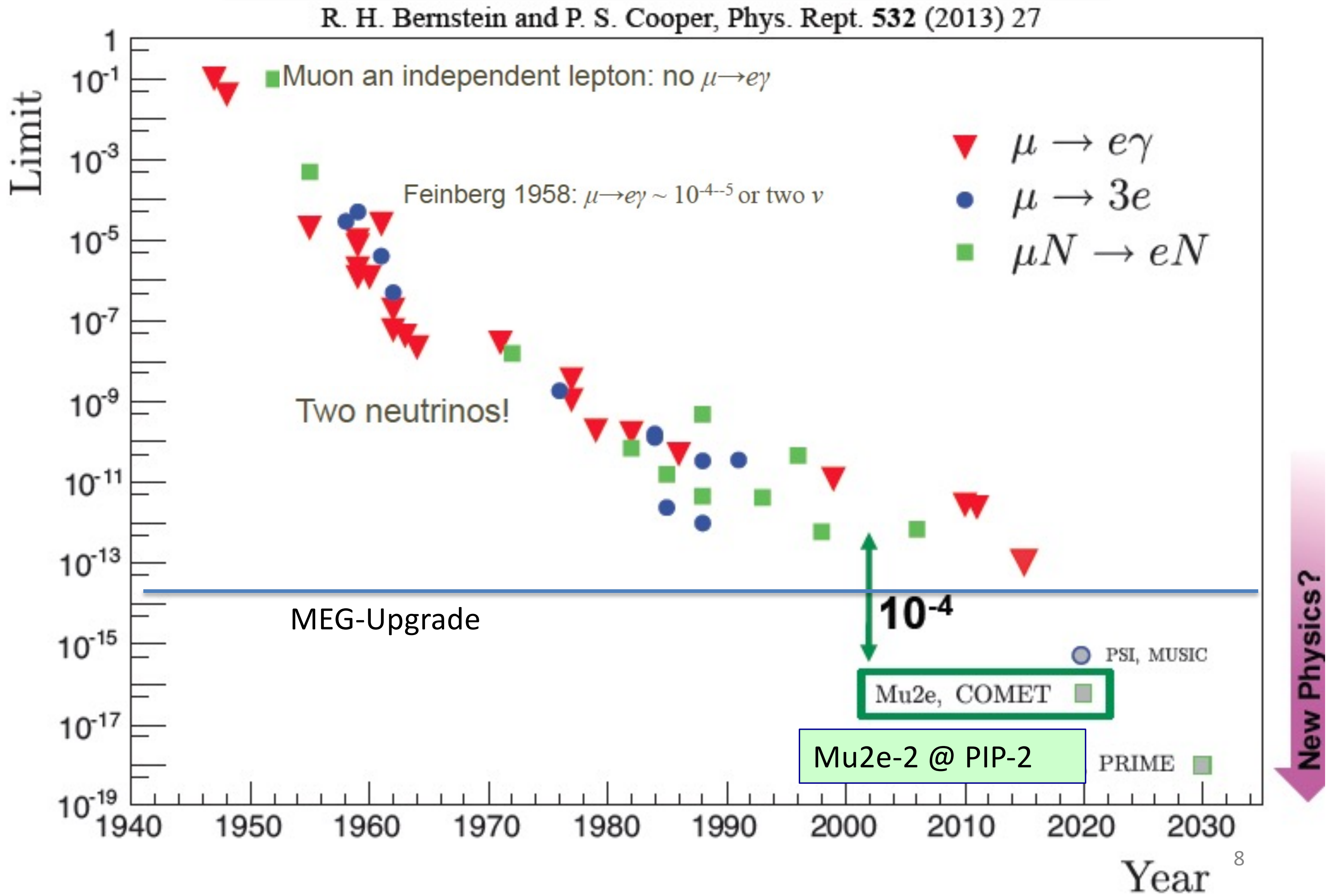
  in two phases for different reach in sensitivity (10^{-15}, 10^{-16})

- The Mu2e experiment @ FNAL (and COMET in Japan) searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \to e^- Al$

- Various NP models allow for it, <u>at levels just beyond</u> current CLFV upper limits.
  - SO(10) SUSY
    - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211**, 40 (2012).
  - Scalar leptoquarks
    - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
  - Left-right symmetric model
    - C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

Observation of CLFV is New Physics

CLFV history

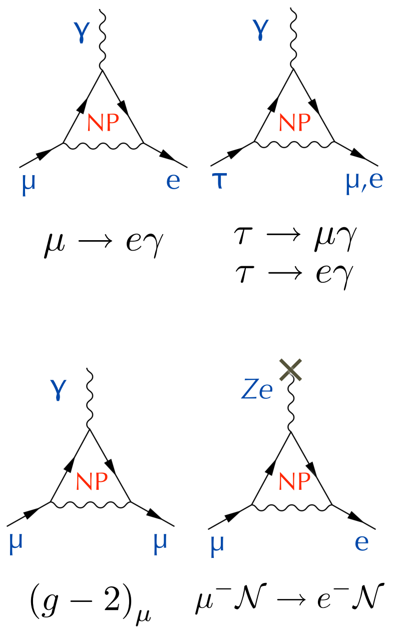


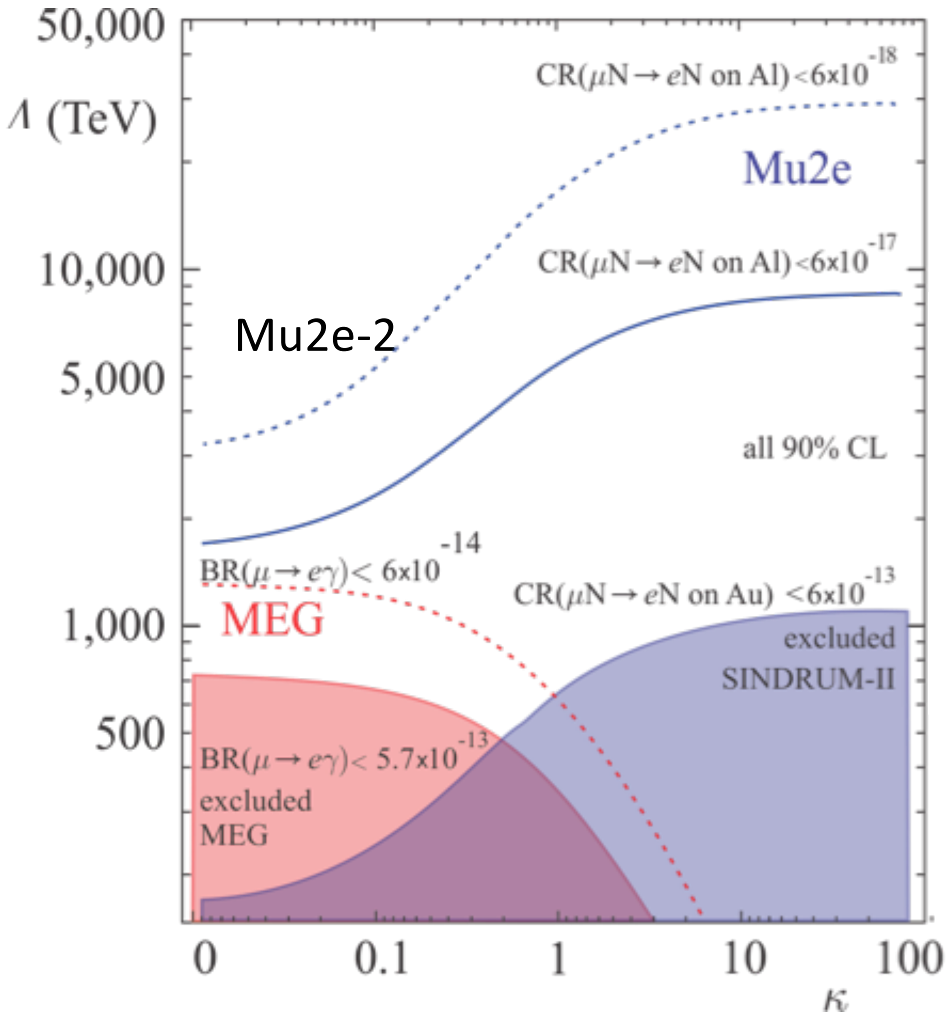
Mu2e vs MEG/MEG upgrade

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

LOOP TERM

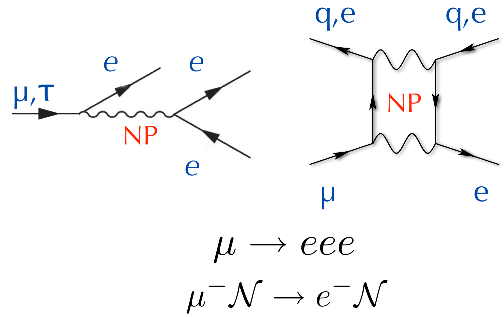
$\kappa \ll 1$





CONTACT TERM

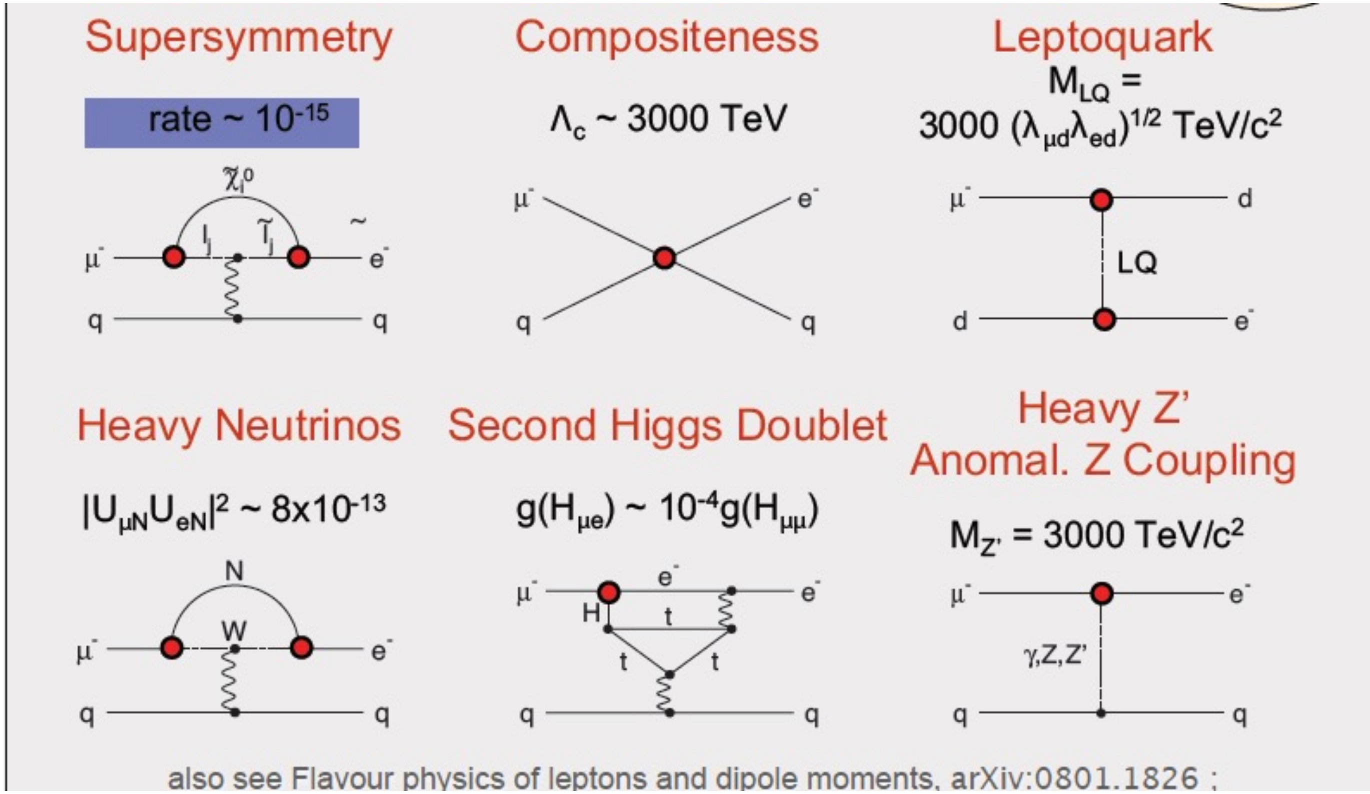
$\kappa \gg 1$



Mu2e physics reach & goal

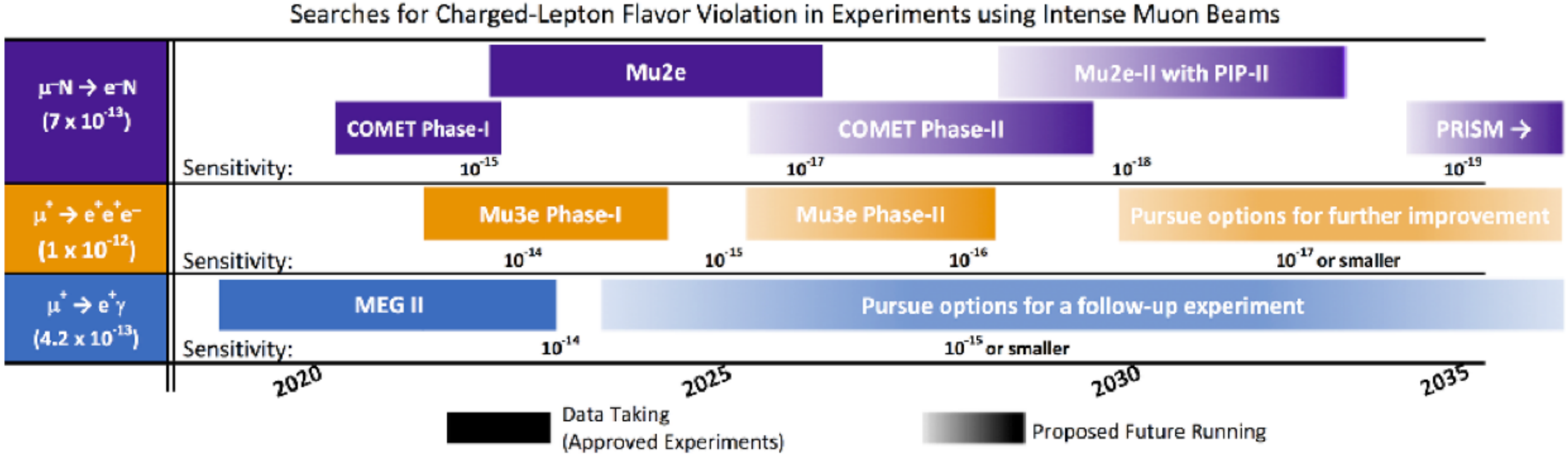
Sensitivity reach:
10^4 improvement with respect to previous μ to electron conversion experiment (Sindrum-II) by means of 4 handles:

- → Rate (Intensity)
- → Out of Time extinction
- → Delayed gate
- → Precise Resolution



$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%\mathrm{CL})$$

Summary: CLFV search on Muon Sector



Mu2e has a broad discovery sensitivity across all models:

→ Sensitivity to the same physics of MEG but with better mass reach

→ Sensitivity to physics that MEG is not

→ If MEG observes a signal, MU2E does it with improved statistics.
Ratio of the BR allows to pin-down physics model

→ If MEG does not observe a signal, MU2E has still a reach to do so.
In a long run, it can also improve further with PIP-2 at FNAL

◆ **Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator**

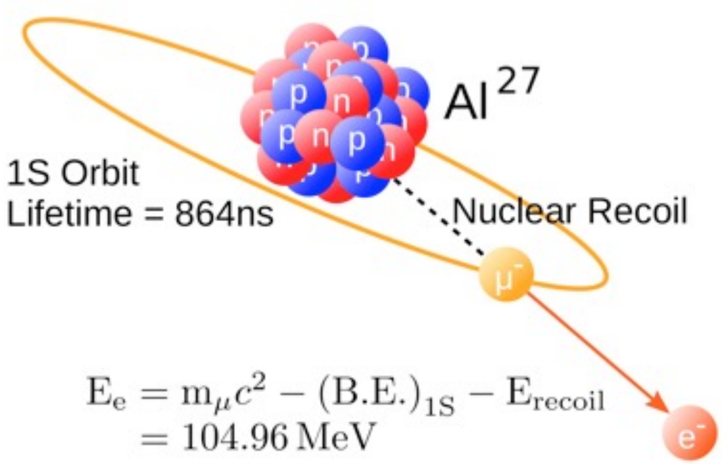
The Conversion Process and the experimental technique

Experimental Technique (1)

Experimental concept to search for muon-to-electron conversion

- Produce muons via protons hitting a fixed target:
  p + nucleus $\rightarrow \pi^- \rightarrow \mu^- \nu_\mu$
- Collect and stop low momentum muons in atoms
  Aluminum target for Mu2e
- Muons cascade to K shell (~ps) firing off X rays (348 keV), 20 fm orbit radius, measure X rays spectrum to estimate the number of captures
- Wait for muon to convert into electron
  for Al, t_m^{Al} = 864 ns
- Signal is a mono-energetic electron

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\mathrm{recoil}} \\ &= 104.973\ \mathrm{MeV} \quad (\mathrm{for\ Al}) \end{aligned}$$



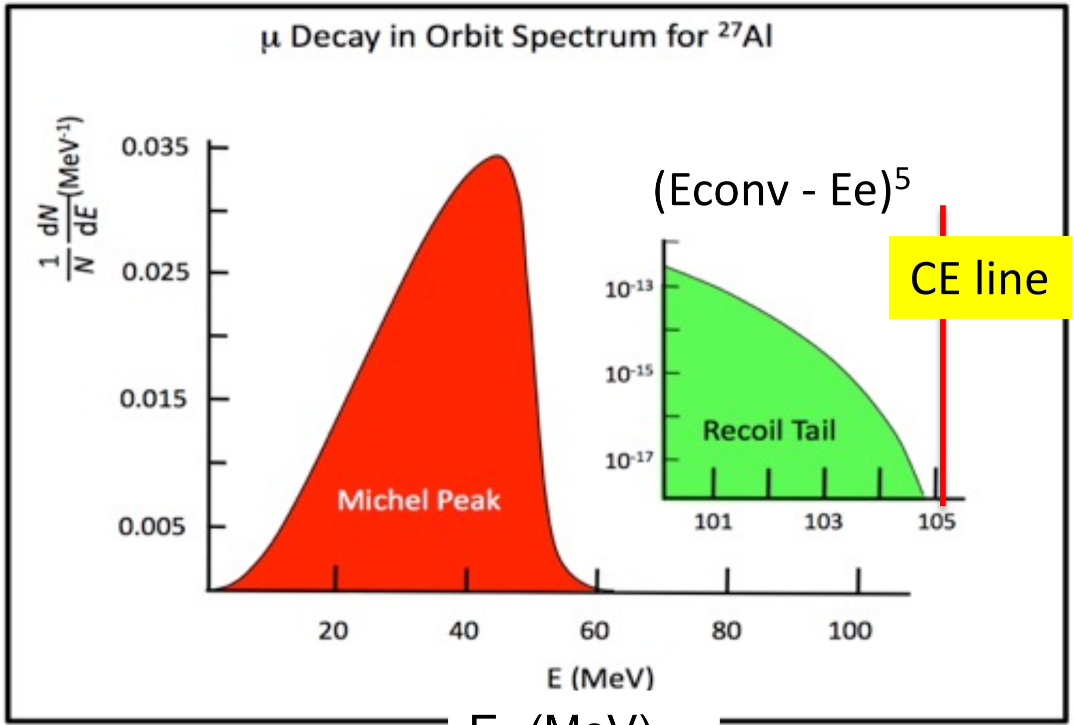
Experimental Technique (2)

Nuclear capture (~61% for Al)

$$\mu N \rightarrow \nu_\mu N'^*$$

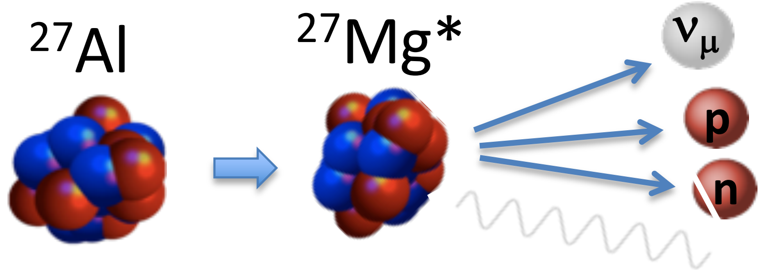
Muon decay in orbit (~39% for Al)

$$\mu \rightarrow e\, \nu_\mu\, \nu_e$$

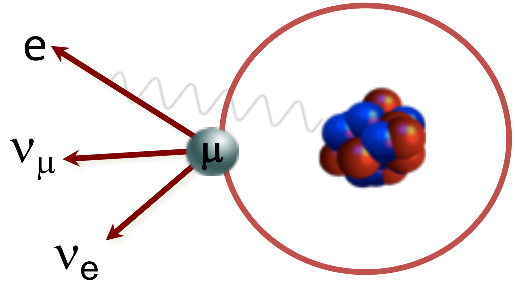


E_e (MeV)

Czarnecki et al., Phys. Rev. D 84, 013006 (2011)
arXiv:1106.4756v2



Decay products could produce electrons and pile-up with the signal. Neutrons provide a source of irradiation on Detectors



The Michel spectrum is distorted by the presence of the nucleus and the electron can be at the conversion energy if the neutrinos are at rest

To separate DIO from CE-line, we need a high resolution spectrometer

Other backgrounds

Prompt background

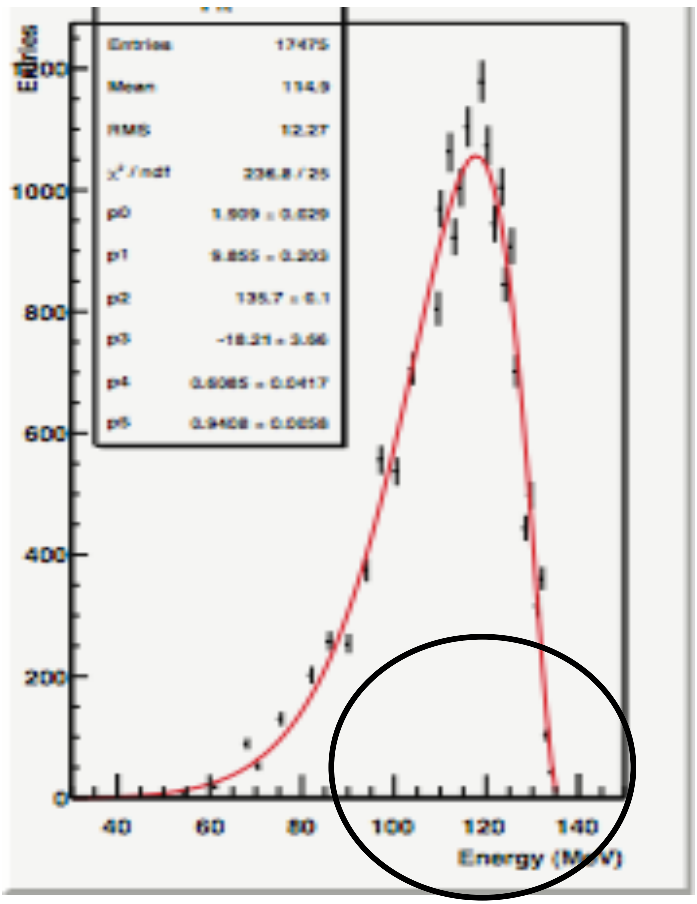
Particles produced in addition to the muons by primary protons which interact almost immediately when they hit the stopping target: pions, neutrons, antiprotons.

- Radiative pion capture (RPC)
  $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$
  $\pi^- N \rightarrow e^+e^- N'$
- Pion/muon decays in flight

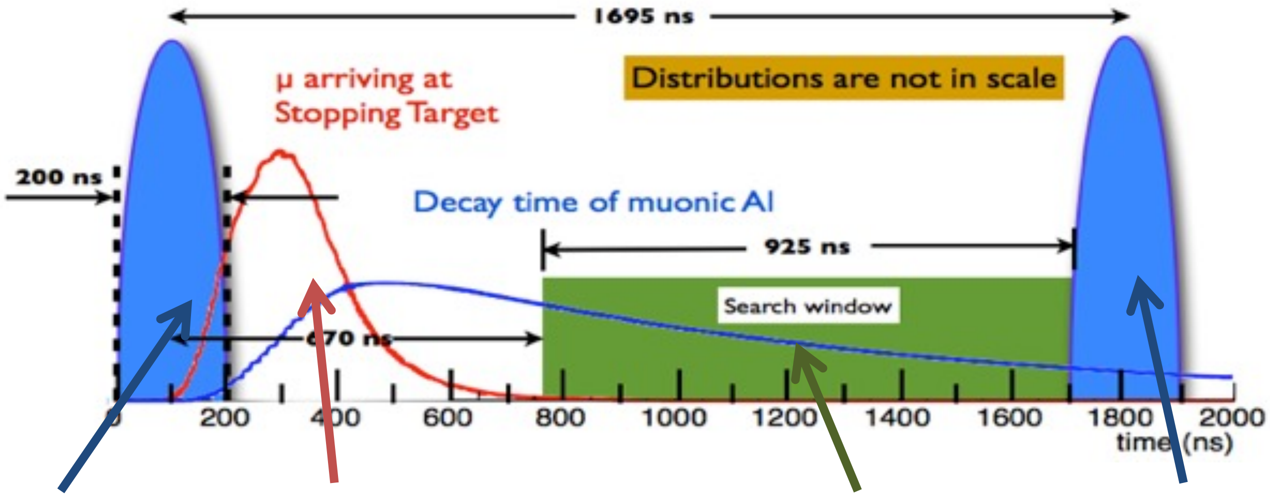
Other background

- Antiprotons producing pions when annihilating in the target
- Cosmic rays induced background mimicking CE

Photon energy spectrum from radiative pion capture in Mg



Beam structure → prompt background



Beam hits target

Prompt bkg like radiative pion capture

Mainly Decay In Orbit background

Next bunch

Need a pulsed beam to wait for prompt background to reach acceptable levels!

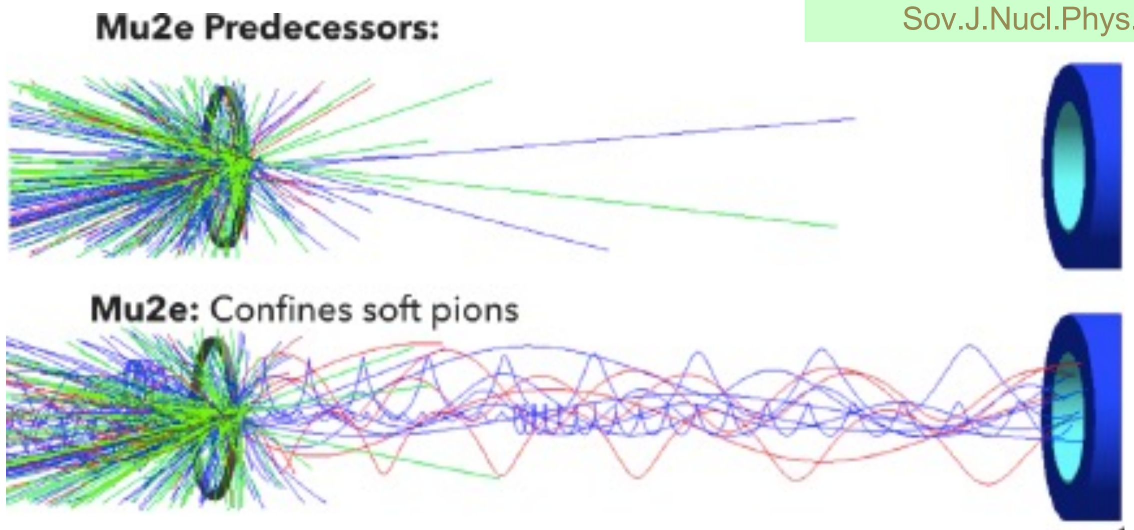
- ❑ RPC = Radiative Pion Capture ($\pi^- N \rightarrow \gamma N$), e^- in the beam,
- ❑ decay in flight of muons/pions

FNAL accelerator provides the right beam

Summary: the keys to Mu2e Success

- **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons ($< 10^{-10}$)
  - 3×10^7 proton/pulse.
- **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields
- **Excellent detector for 100 MeV electrons**
  - → Excellent momentum resolution (< 200 keV core)
  - → Calorimeter for PID, triggering and track seeding
  - → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  - → Thin anti-proton annihilation window(s)

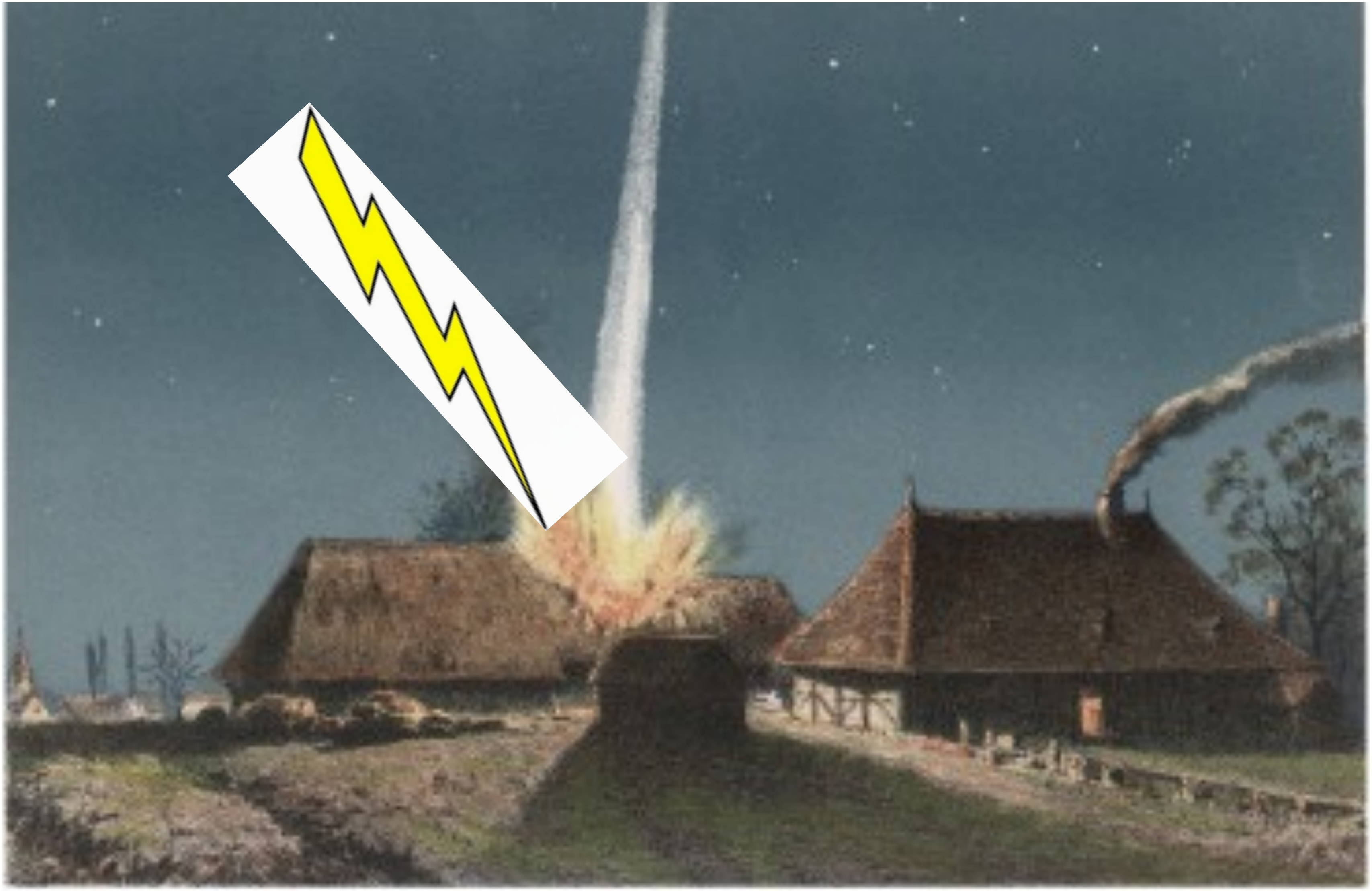
Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)



This is a very “low” probability search …

Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flpping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

A low probability as this!



Mu2e sensitivity and rates

- **Design goal: single-event-sensitivity of 3 x 10^{-17}**
  - Requires about **10^{18} stopped muons**
    (as many muons as the Heart sand grains)
  - Requires about **10^{20} protons on target**
  - Requires extremely high suppression of backgrounds

- **Expected limit: $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL**
  - **Factor 10^4 improvement**

- **Discovery sensitivity: $R_{\mu e} > 2 \times 10^{-16}$**
  - Covers broad range of new physics theories

The Mu2e experiment

Mu2e Collaboration

>220 scientists from 38 institutions

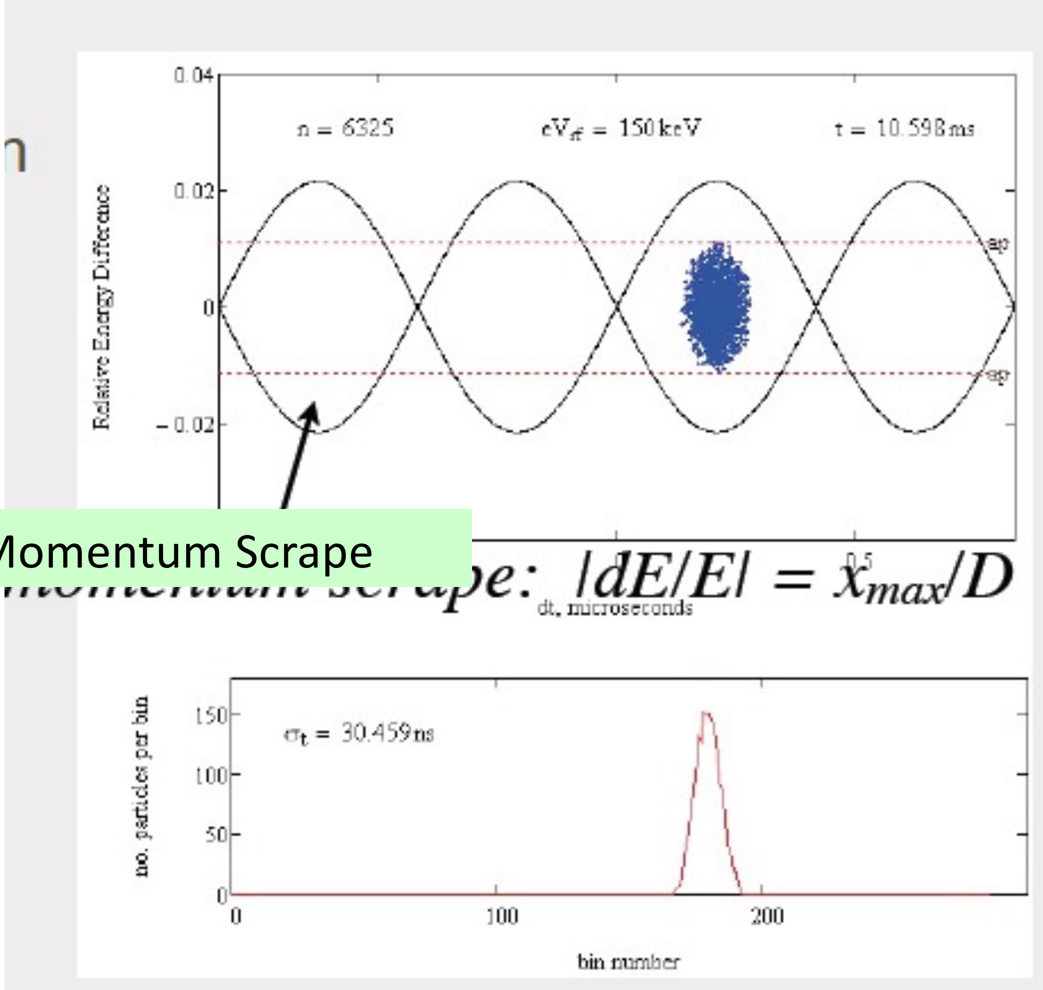
Argonne National Laboratory, Boston University, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, **Laboratori Nazionale di Frascati,** University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Michigan, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University

Out of Time proton → Extinction Method

- **FNAL accelerator produces bunches of 3×10^{7} protons each separated by 1.7 us (delivery ring period)**
- **Proton extinction between pulses → # protons out of beam/# protons in pulse**

achieving 10^{-10} is hard; normally get $10^{-2} – 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
- **Calculations based on accelerator models that take into account collective effects shows that this combination gets ~ 10^{-12}**



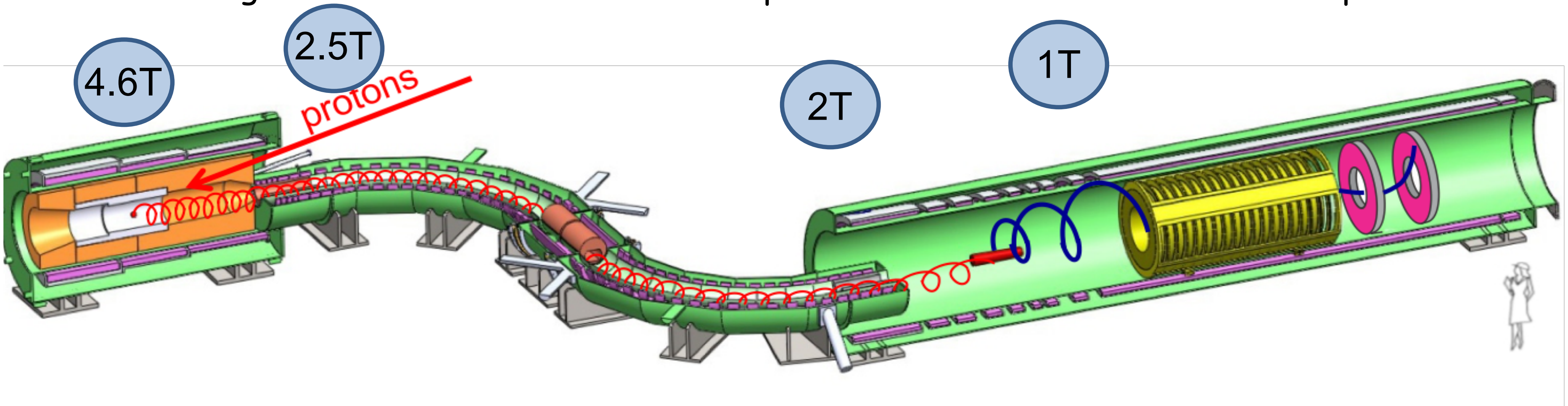
Muon campus & Mu2e Hall status

- Detector Hall Building
  - Broke Ground (April 2015)
  - Building Acceptance (March 2017)
- Infrastructure installation (still on going)
  - LCW pipes, Bus bar, Cable Trays
  - Interlocks, Networking, DAQ infrastructure
  - Cryo Distribution box …

Muon Beam-line

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pi's/mu's and reflects slow forward pi's/mu's



Transport Solenoid (TS)

Selects low momentum, negative muons
Antiproton absorber in the mid-section

For the sensitivity goal →
~ 6 x 10^{17} stopped muons
with 3 year run , 6 x 10^{7} sec →
10^{10} stopped muon/sec

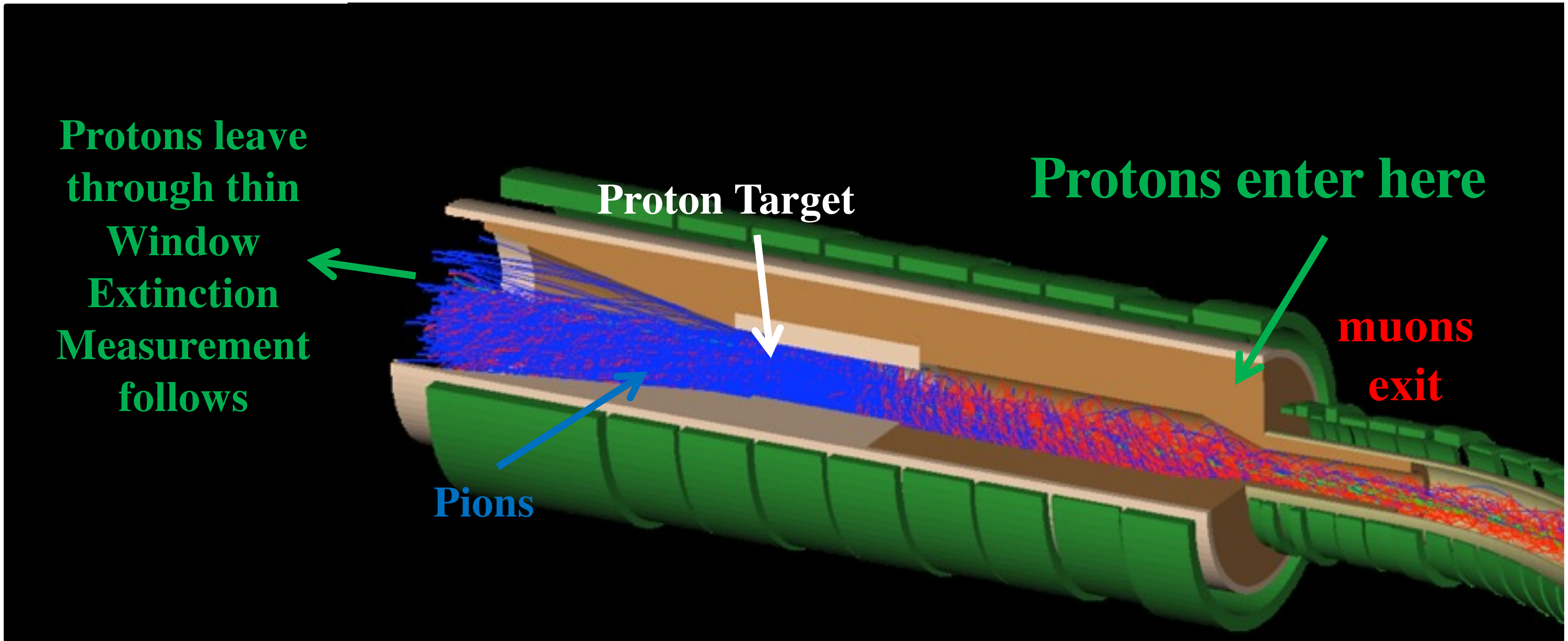
Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream (isotropic process)

Production Solenoid

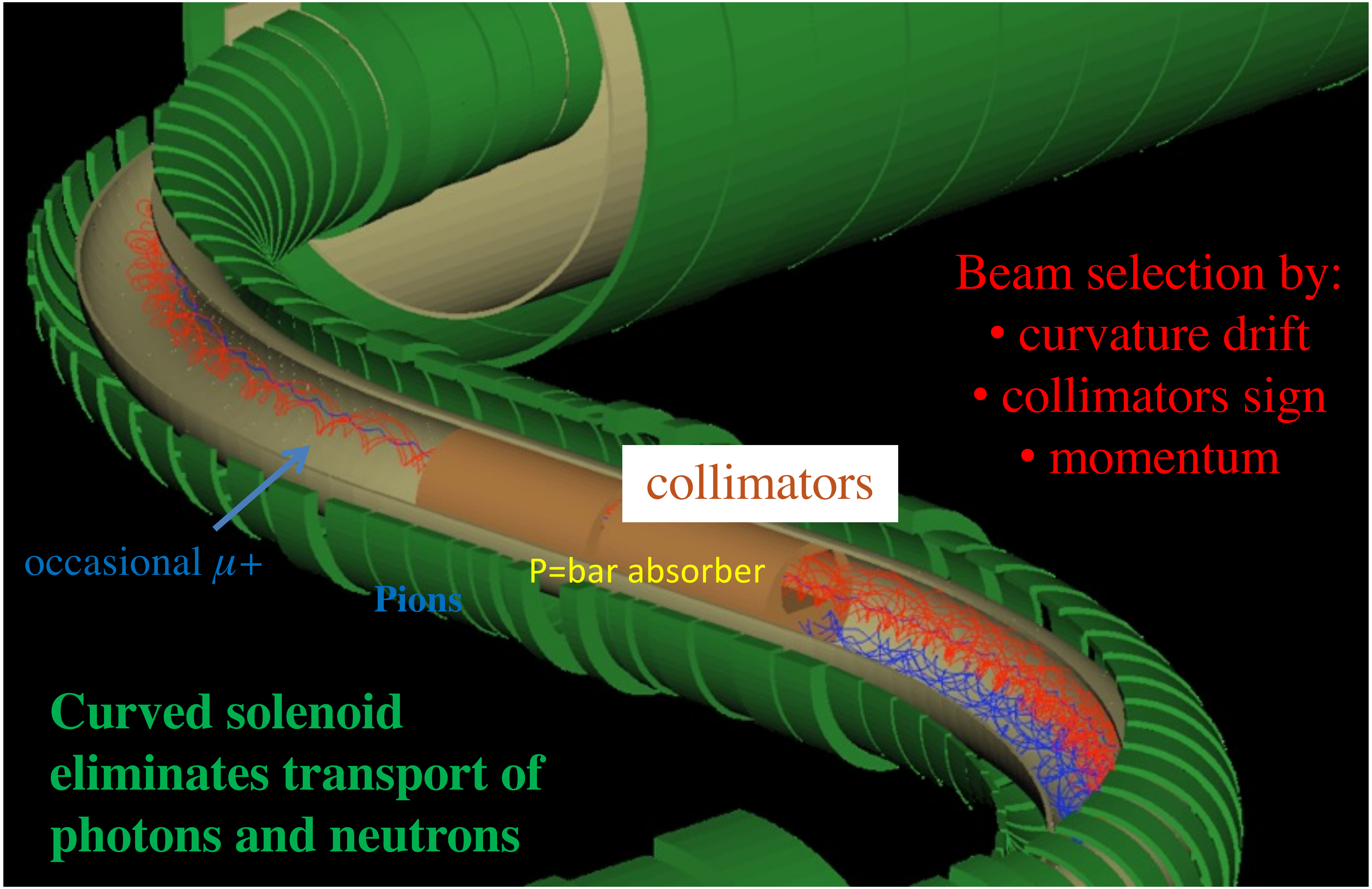
Protons enter opposite to outgoing muons:

This is a central idea to remove prompt background



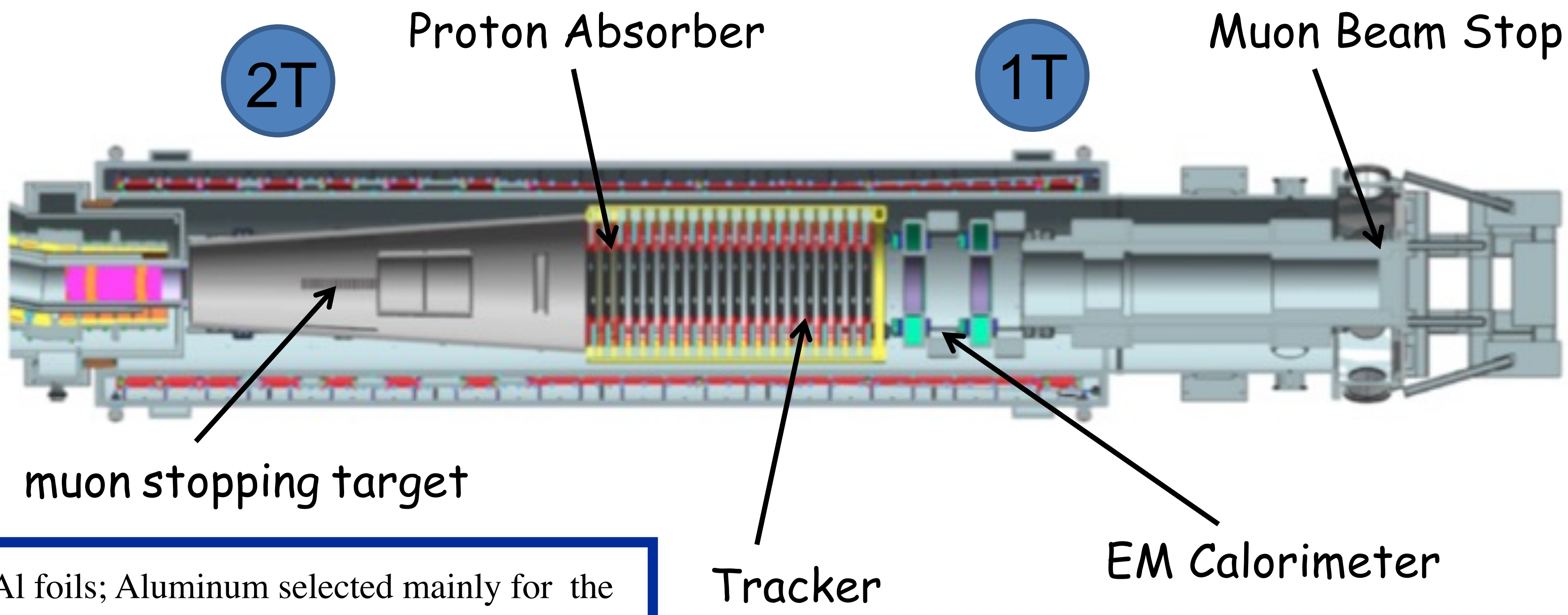
The magnetic field is graded from 4.6 Tesla on the upstream side down to 2.5 Tesla at the entrance to the Transport Solenoid. This graded field captures pions, which spiral around in the field and decay into muons.

Transport Solenoid



Detector Solenoid

Graded field "reflects" downstream a fraction of conversion electrons emitted upstream

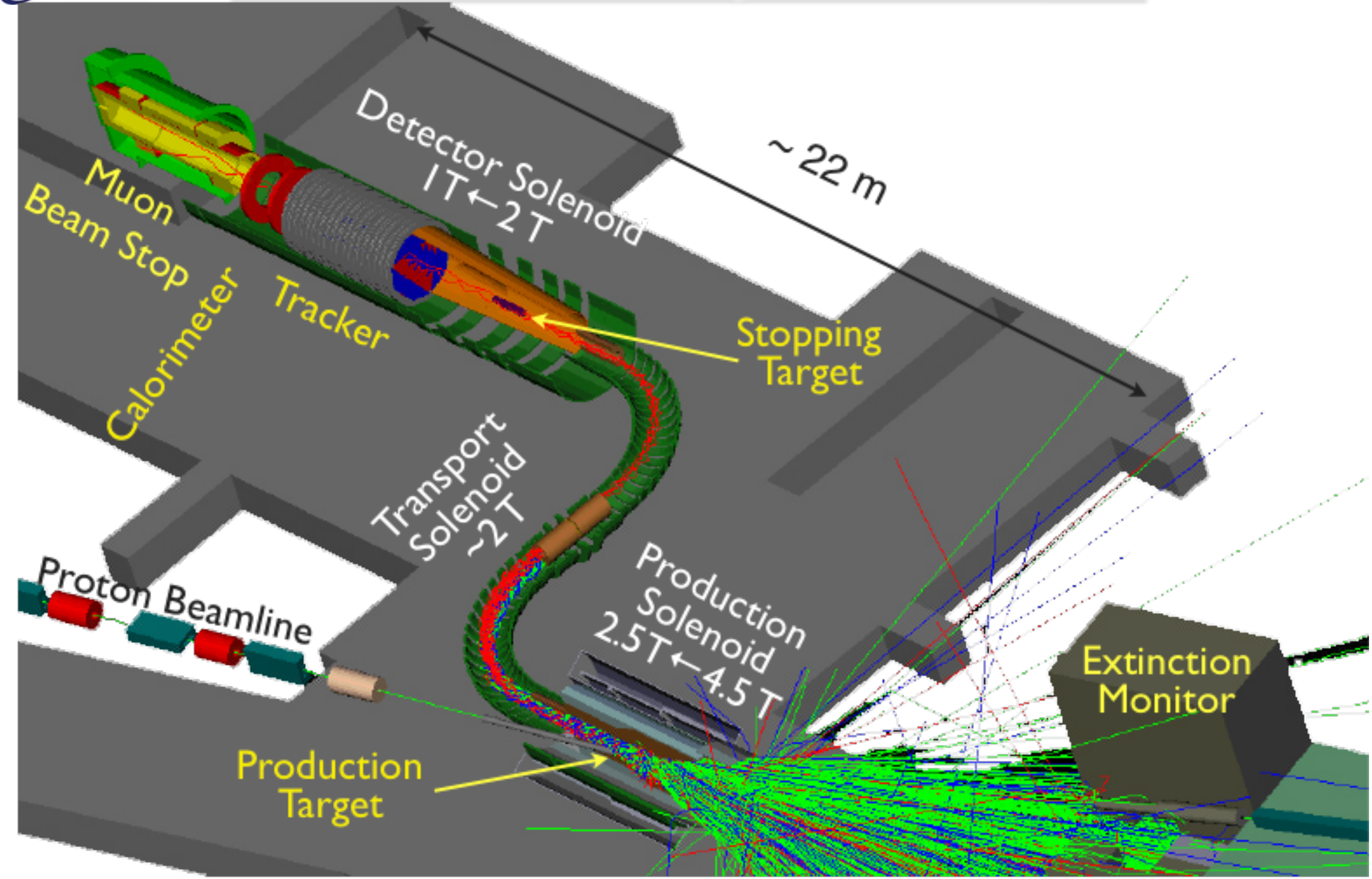


34 Al foils; Aluminum selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the prompt separation in the Mu2e beam structure.

For the sensitivity goal → ~ 6 x 10^{17} stopped muons

For 3 year run , 6 x 10^7 sec → 10^{10} stopped muon/sec (10 GHz)

Beam's Eye View



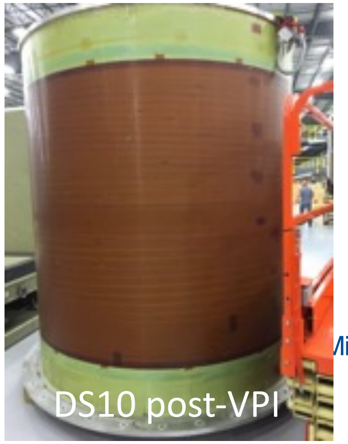
Cryogenics and Transport Solenoid

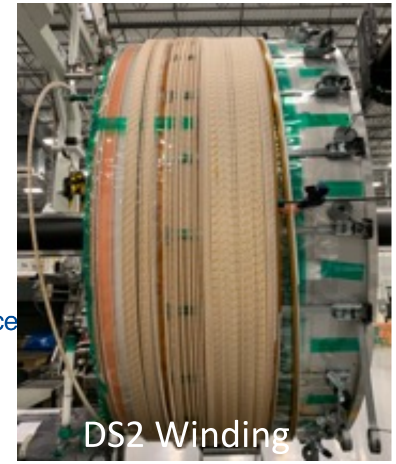
Production and Detector Solenoids

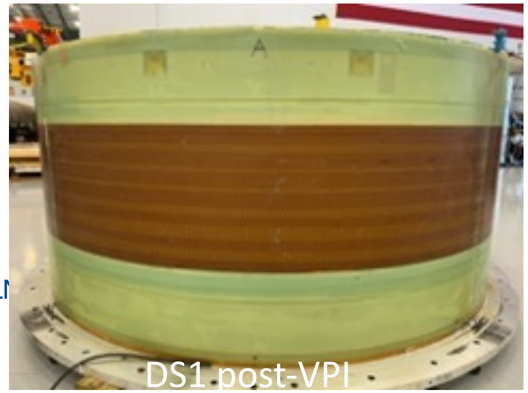

PS2 winding


PS3 Shell Insertion


PS1 Layer 2 Compression

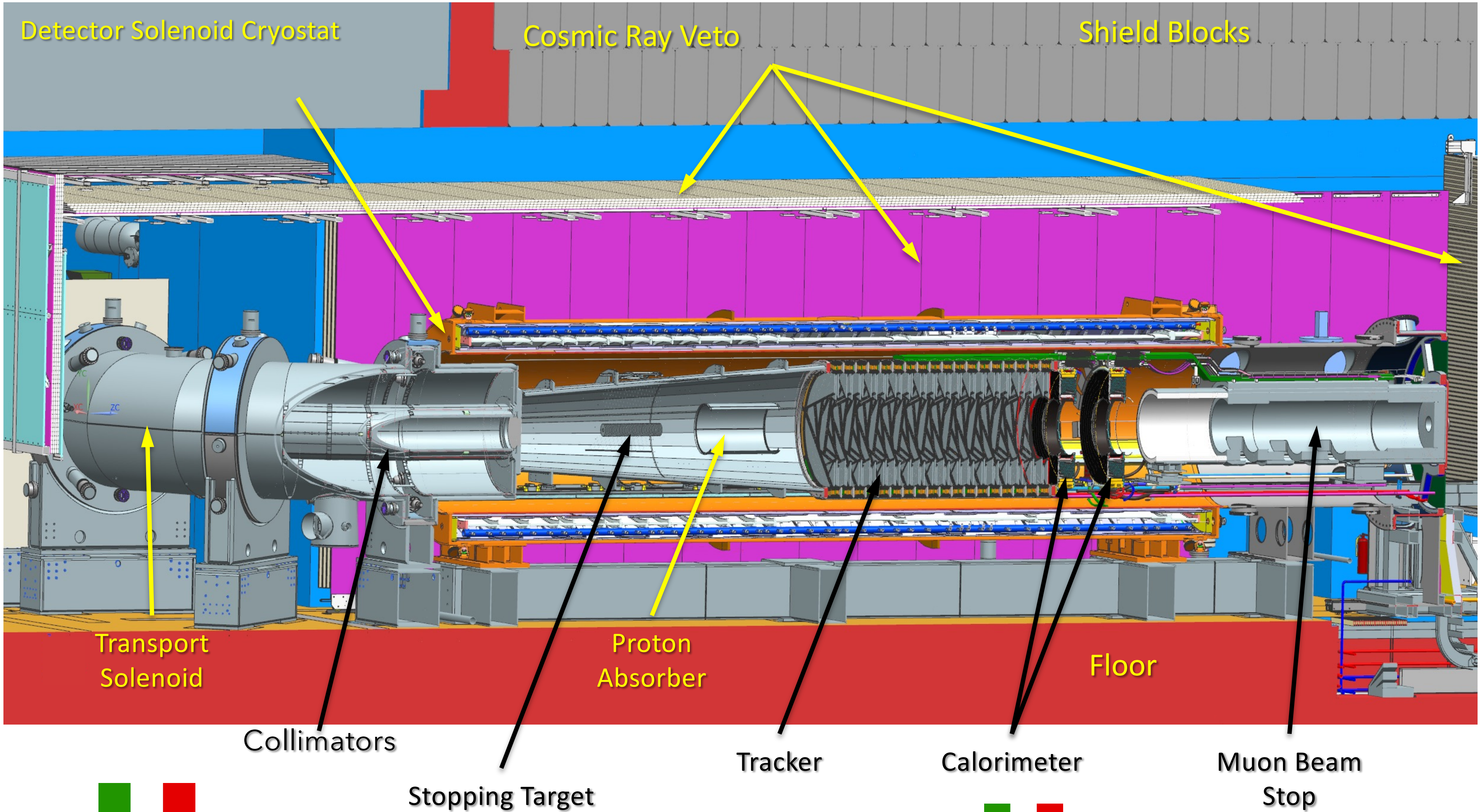

DS10 post-VPI


DS2 Winding


DS1 post-VPI


DS and PS cryostats

Detector Solenoid Layout



Still 2-3 years to go for commissioning and then data taking with beam …

Tracking Design considerations

- High reconstruction efficiency for Conversion Electron (CE)
- High momentum resolution @ 100 MeV

In order to do so:

→ Minimize multiple scattering (small material budget)
→ High efficiency on single point
→ Good single point space resolution
→ Require many points/track (> 20)

Larger p_T

- Axial B(field) = 10 kG = 1 T (uniform)
- Higher P_T = 100 MeV
- ρ_{max} (m)= P_T/(0.3 B) = 0.1 (GeV)/0.3x1 (T) → 0. 33 m = 33 cm

Lower p_T

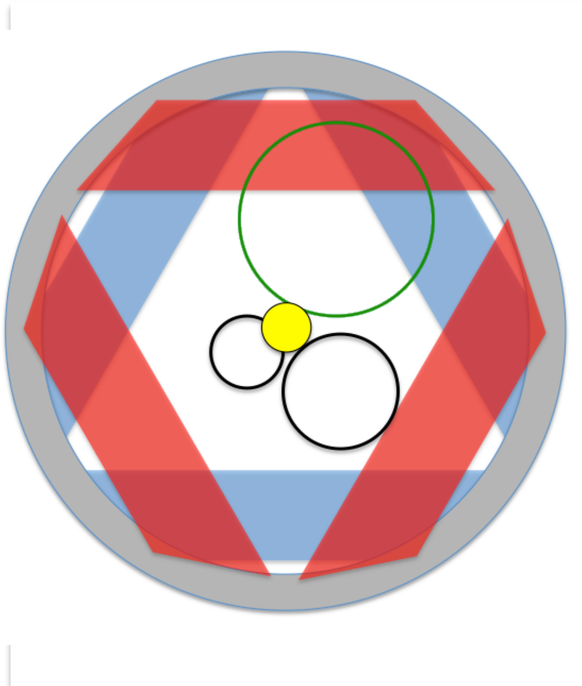
$$\boxed{\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\,\frac{\sigma_y p_\perp}{(0.3BL^2)}\ \textbf{(m, GeV/c, T)}}$$

σ(p)/p = 200 keV

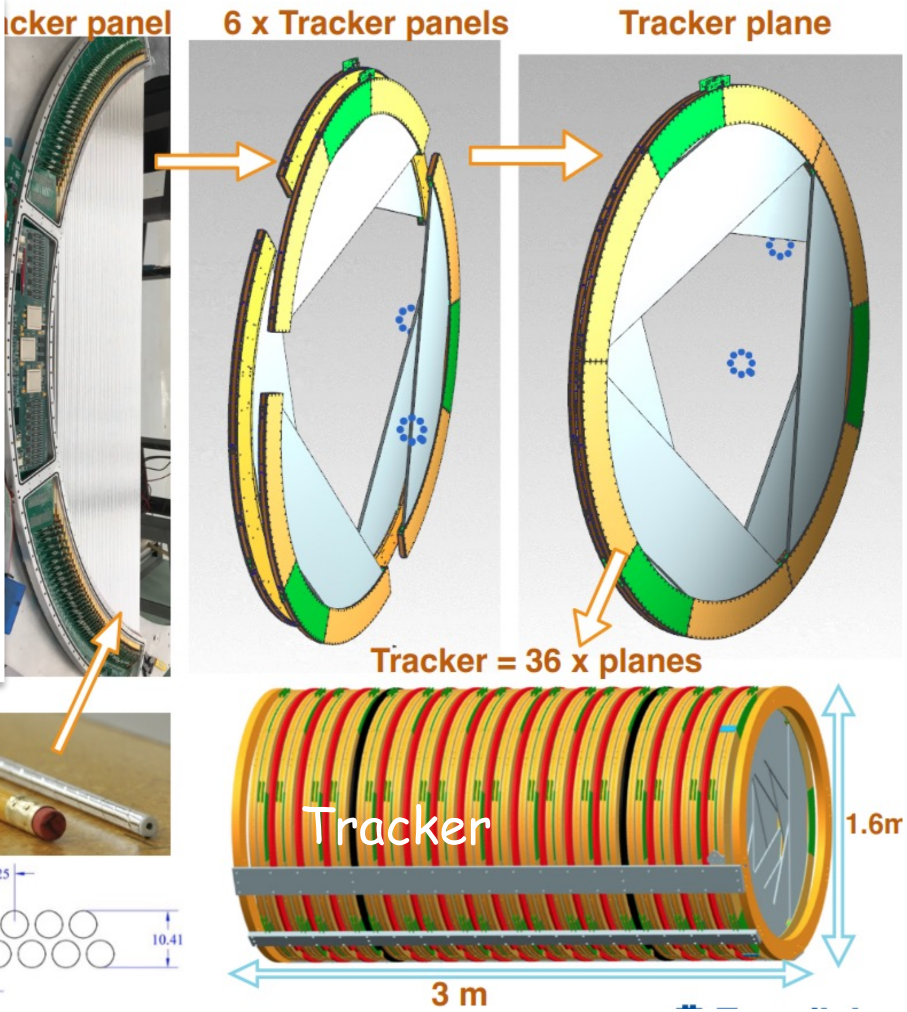
Tracker Design: Thin Straw Tubes

- Tracker made of arrays of straw drift tubes
- ~ 20000 tubes arranged in planes on stations, for a total of 18 stations.

Tracking at high radius ensures operability (beam produces a lot of low momentum particles and a large DIO background.

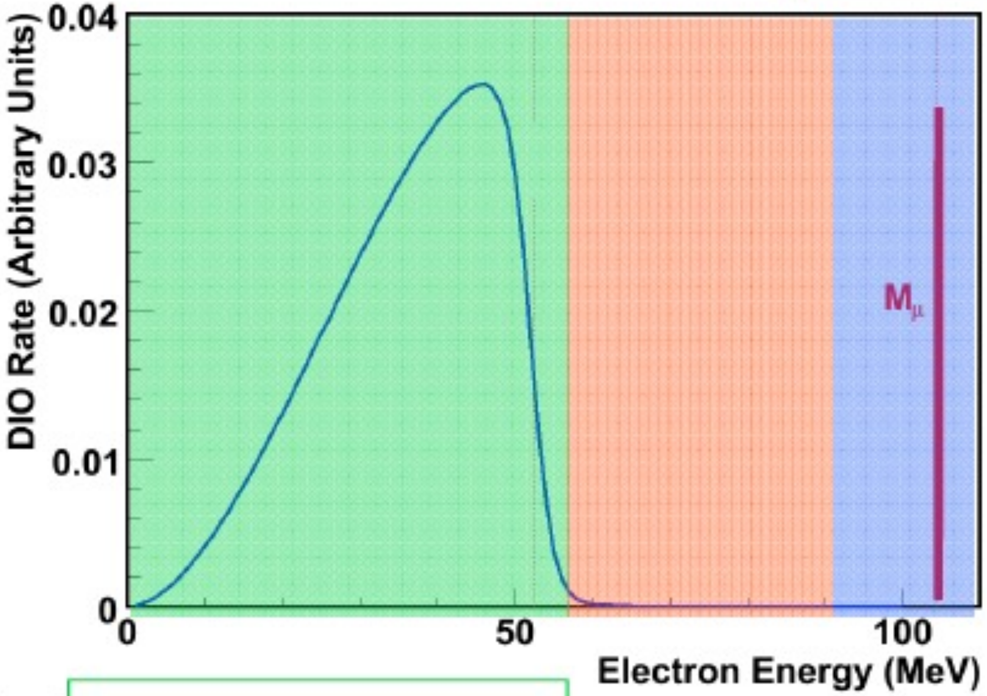


Most of this background just miss the tracker



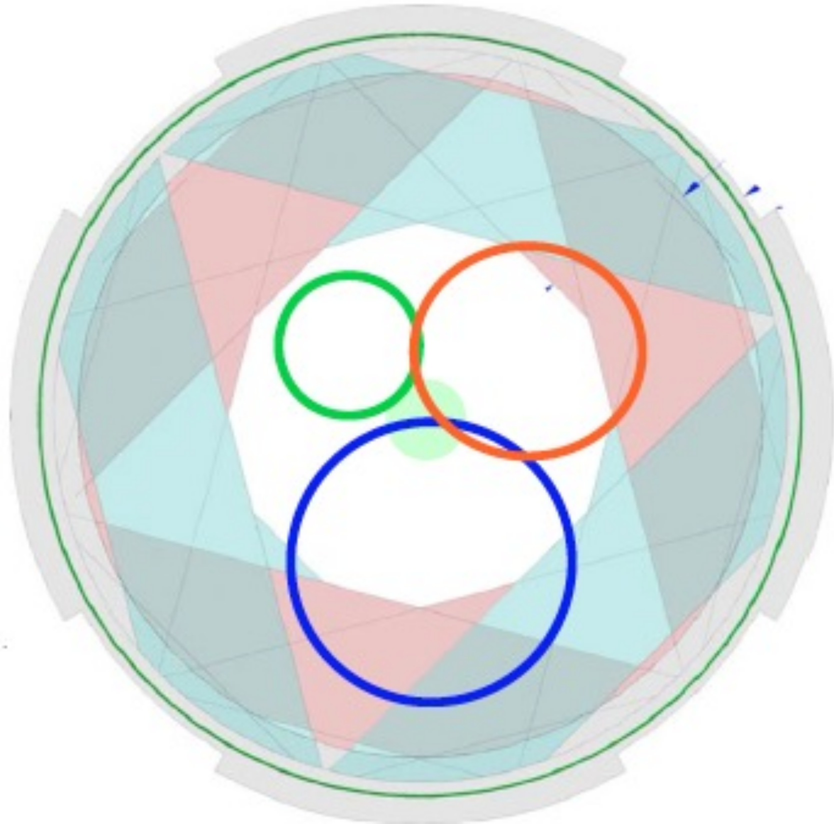
Tracking Pattern idea

reconstructable tracks



no hits in tracker

some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

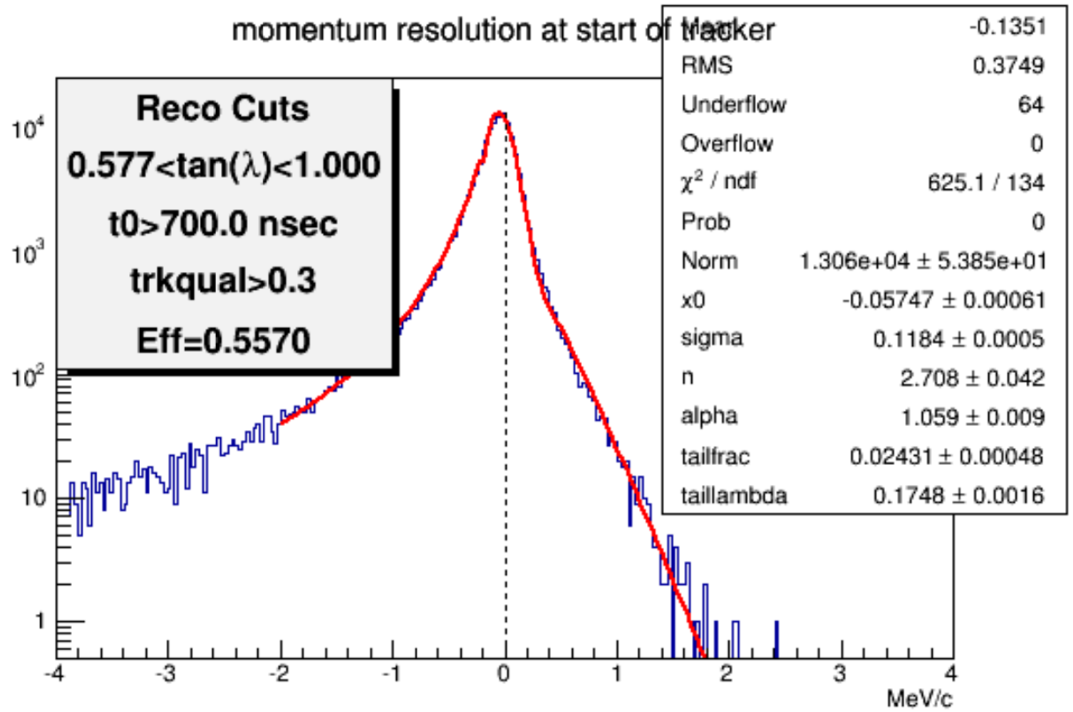
Tracking Performance

Pattern Recognition based on
***BABAR* Kalman Filter algorithm**

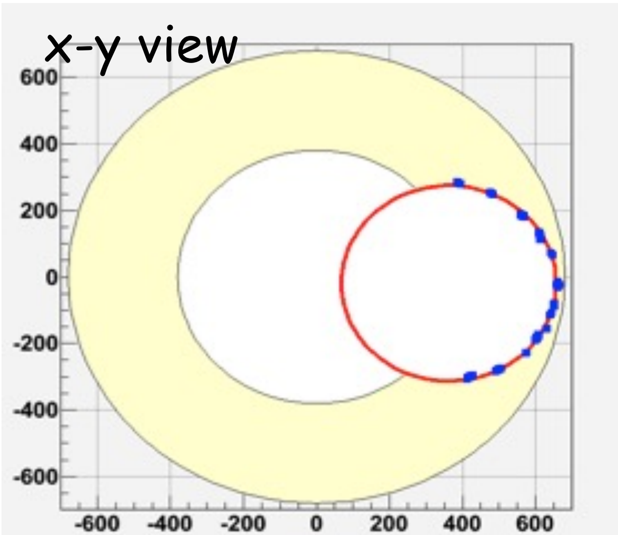
No significant contribution of mis-reconstructed background

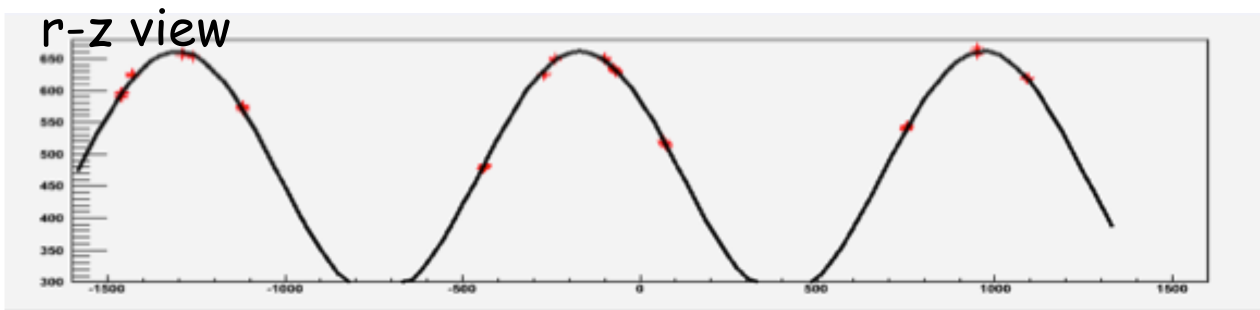
Momentum resolution

core σ~120 keV
tail σ~175 keV (2.5%)



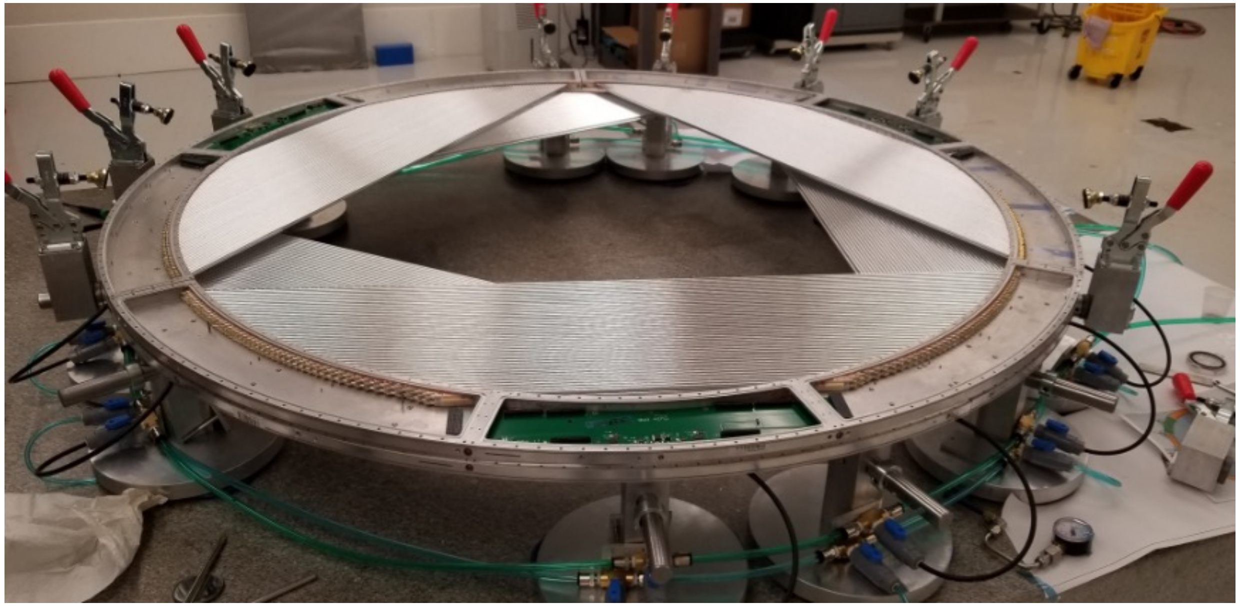
Fit: Crystal Ball + exponential

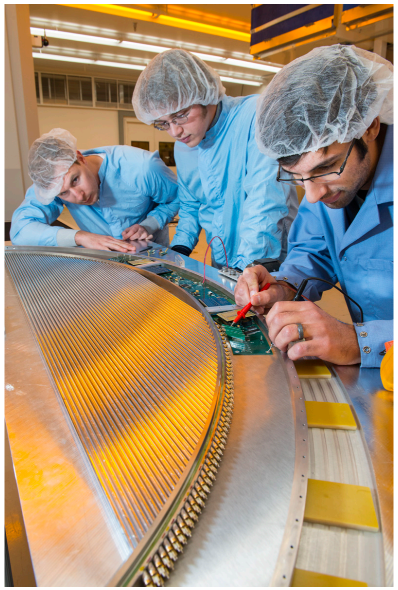




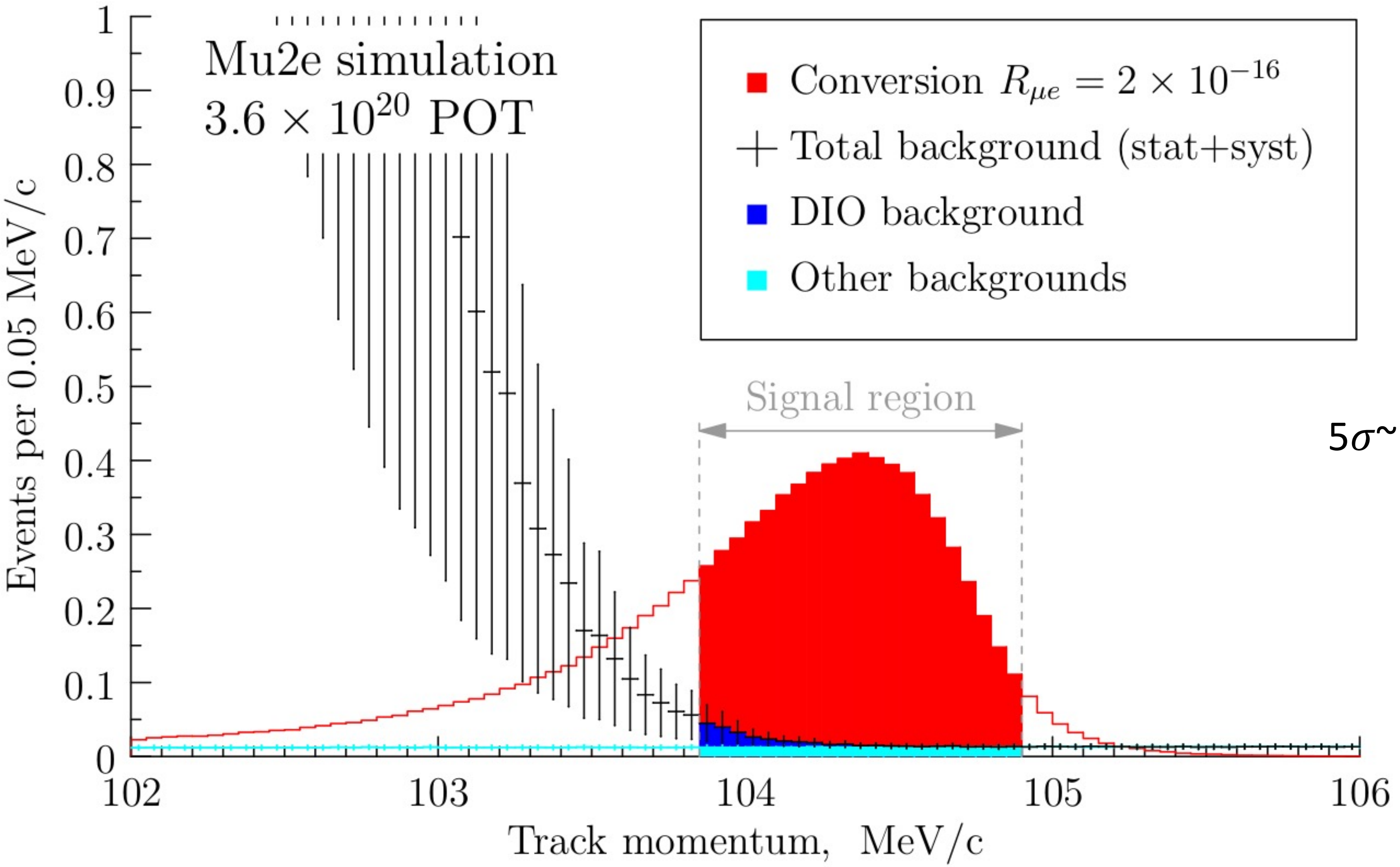
Tracking Construction Status

- Panels are produced at U. Minnesota
  - All straw manufactured
  - **>50% of the panels processed**
- Work ongoing to prepare a vertical slice test on a full plane





Full simulation for signal extraction



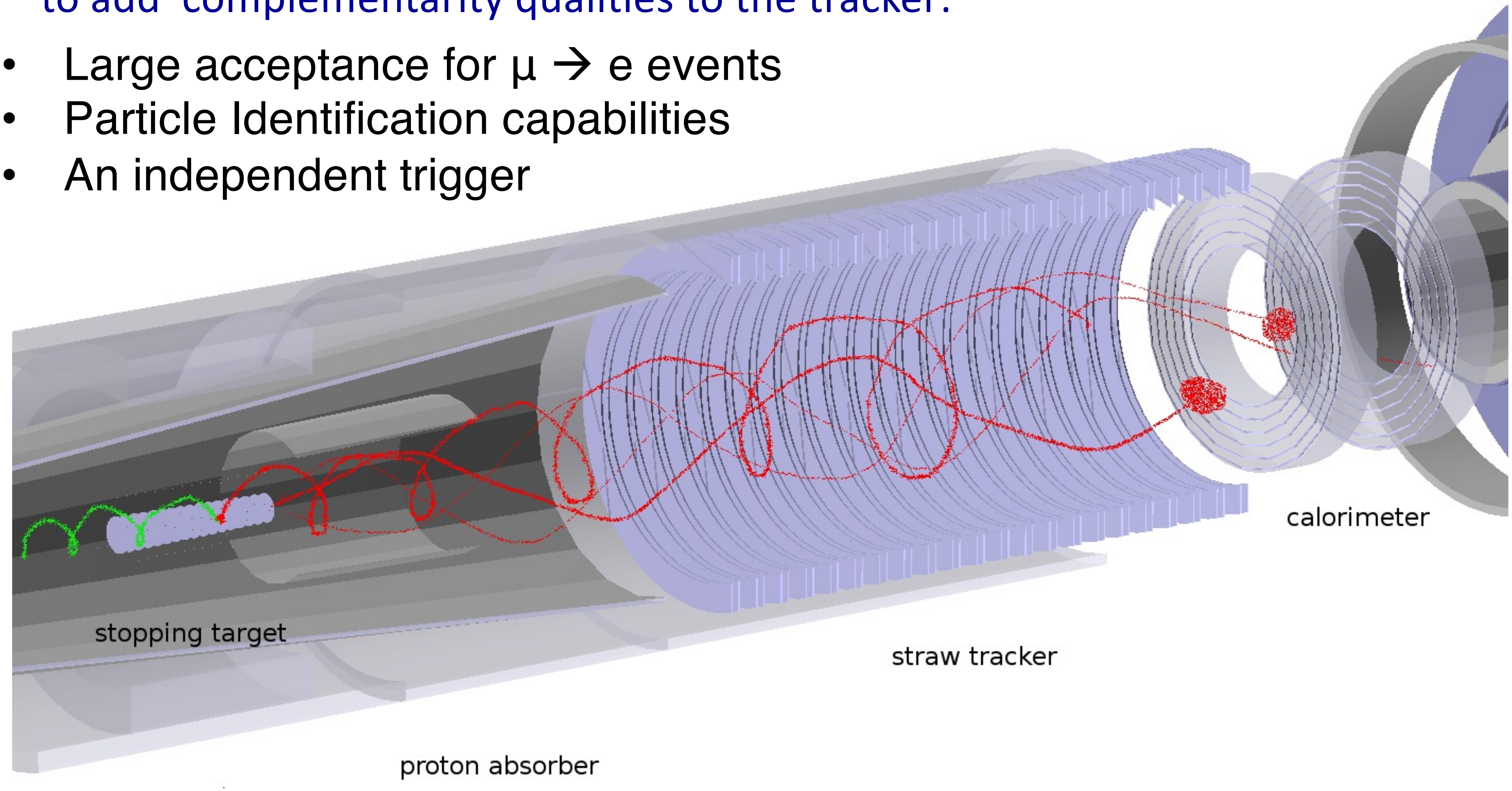
$5\sigma \sim 10^{-16}$

typical SUSY at 10^{-15}: 40 events vs 0.4 backgrounds

Calorimeter Requirements

In order to add redundancy to this "super-rare" search, the calorimeter has to add complementarity qualities to the tracker:

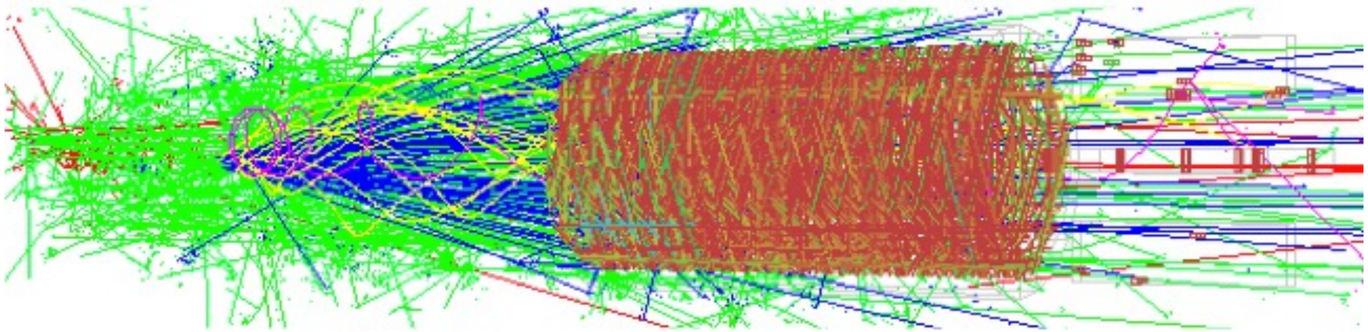
- Large acceptance for μ → e events
- Particle Identification capabilities
- An independent trigger



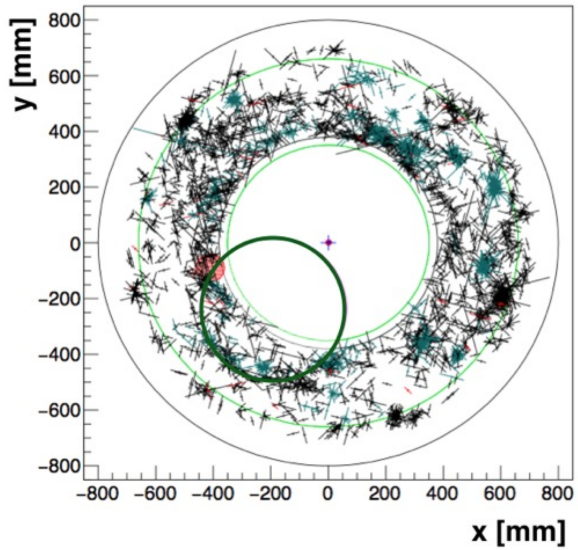
- "seeds" to improve track finding efficiency at high occupancy
- Resistant to radiation dose and working in vacuum @ 10^{-4} Torr

Tracking seeding – basic idea

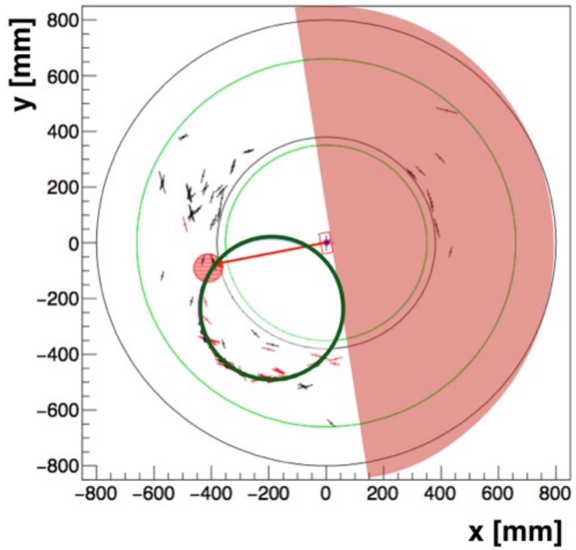
500 – 1695 ns window



no selection



calorimeter selection



The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters →

simplification of the pattern recognition

Summary of Calorimeter Requirements

- Provide high e^- reconstruction efficiency for μ rejection of 200
- Provide online trigger capability (HLT)
- Provide cluster-based seeding for track finding

YOU WILL have a dedicated Talk on Calorimetry and on the Long trail to arrive to the final Technical choice .. IT TOOK MANY YEARS

In order to do so the calorimeter should:

→ Provide energy resolution σ_E/E of O(10 %)
→ Provide timing resolution σ(t) < 500 ps
→ Provide position resolution < 1 cm

✓ Work in 1 T field and 10^{-4} Torr
✓ Radhard up to 100 krad, 10^{12} n/cm^2/year
✓ Operate reliably for 1 year w.o. interruptions

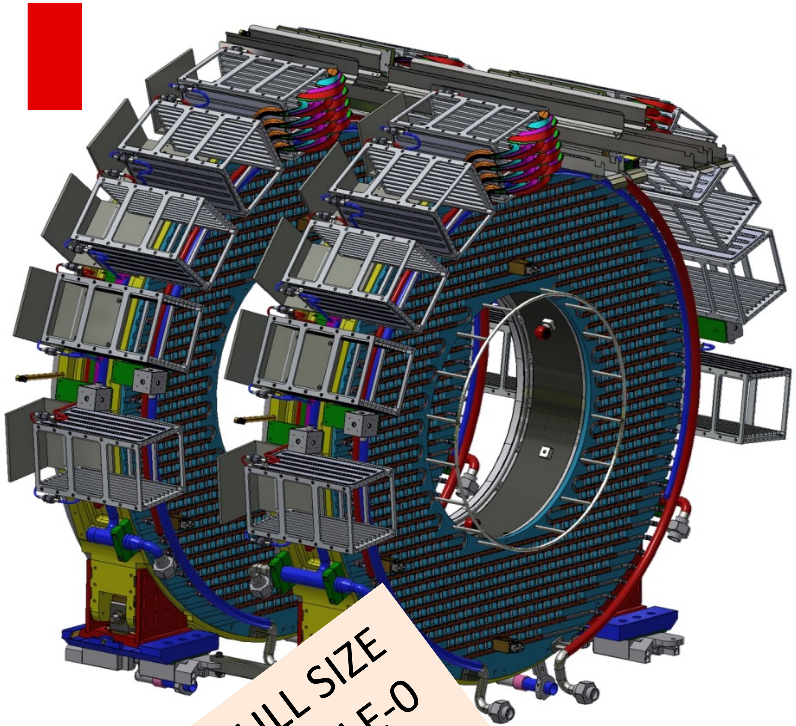
Worser than Space Satellites Requirements

Calorimeter Design

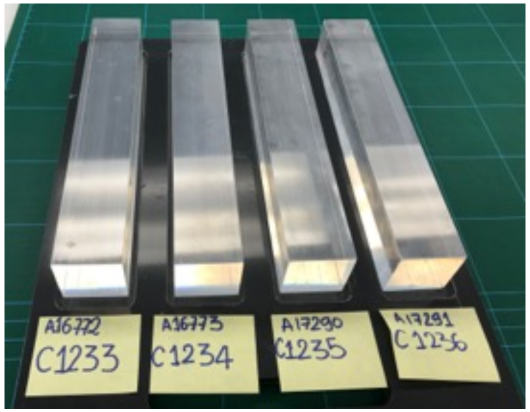
- 2 annular disks filled with 674 pure **CsI crystals** ($34x34x200\ mm^3$) each;

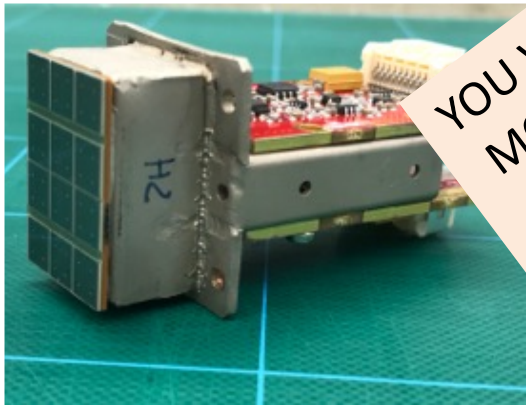
- Each crystal readout by 2 custom array of **UV-extended SiPMs**
- R_{IN} =35.1 cm R_{OUT} = 66 cm
- Depth = 10 X0 (200 mm),

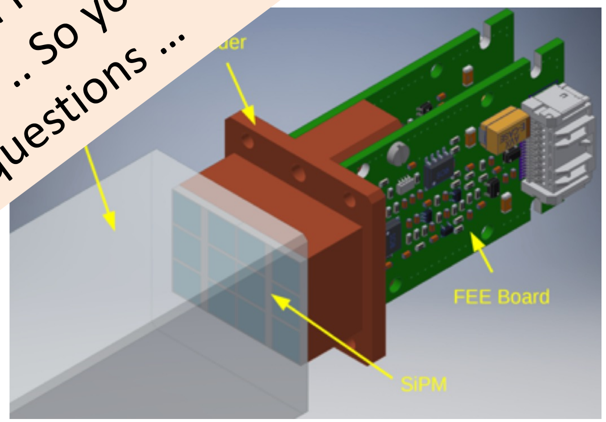
  Disk separation ~ 75 cm
- 1FEE/SiPM, Digital readout on crates (5ns/sampling)
- Radioactive source and laser system provide absolute calibration and monitoring capability



YOU WILL SEE A FULL SIZE MOCKUP and MODULE-0 Tomorrow .. So you can Ask questions …



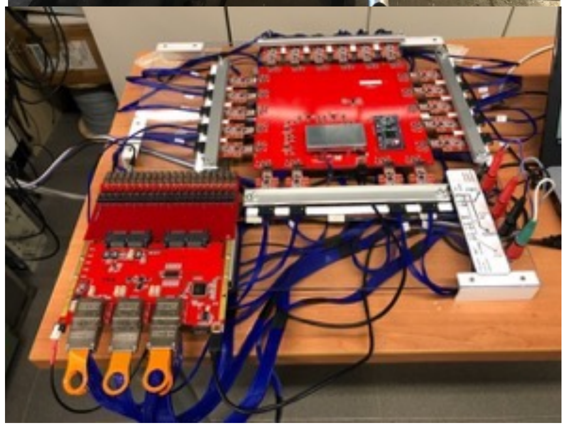




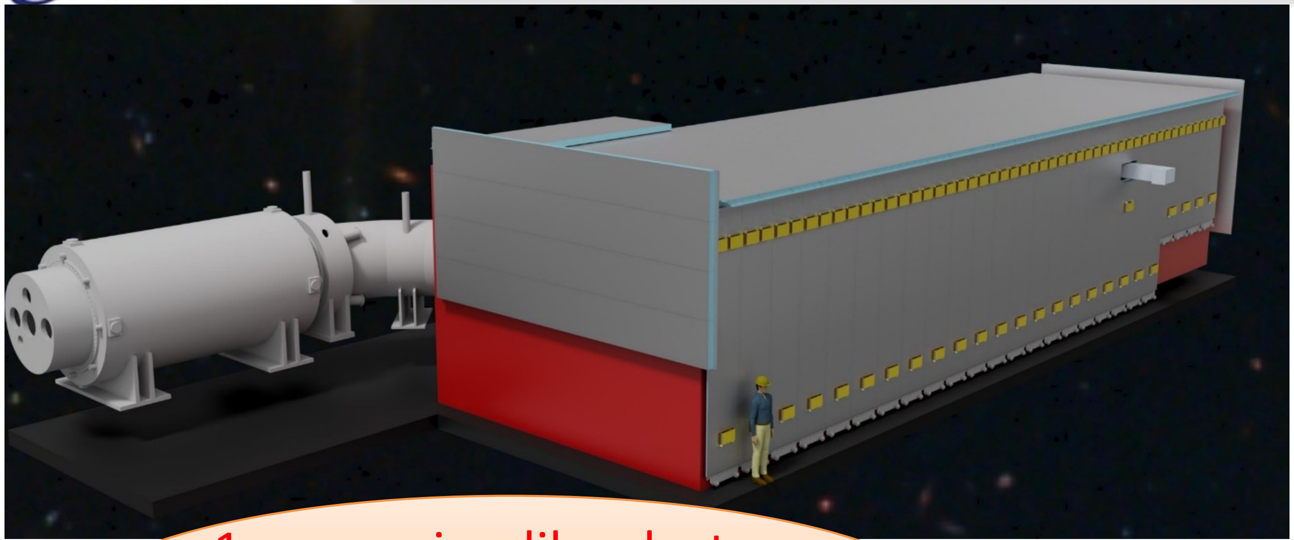
Calorimeter Construction status

- Test beam on a large size prototype in 2017
- Production of 4000 SiPMs , 1450 crystals completed!
- 2500 out of 3500 FEE boards already produced
- SiPM glueing procedure @ LNF (30% done)
- Al outer disks, FEE and source plates produced
- CF parts and crates under construction
- Digital electronics prototype OK ready to start
- VST done

YOU WILL SEE A FULL SIZE MOCKUP and MODULE-0 Tomorrow .. So you can Ask questions …



Cosmic Ray Veto (CRV) system



1 conversion-like electron per day is produced by cosmic-ray muons

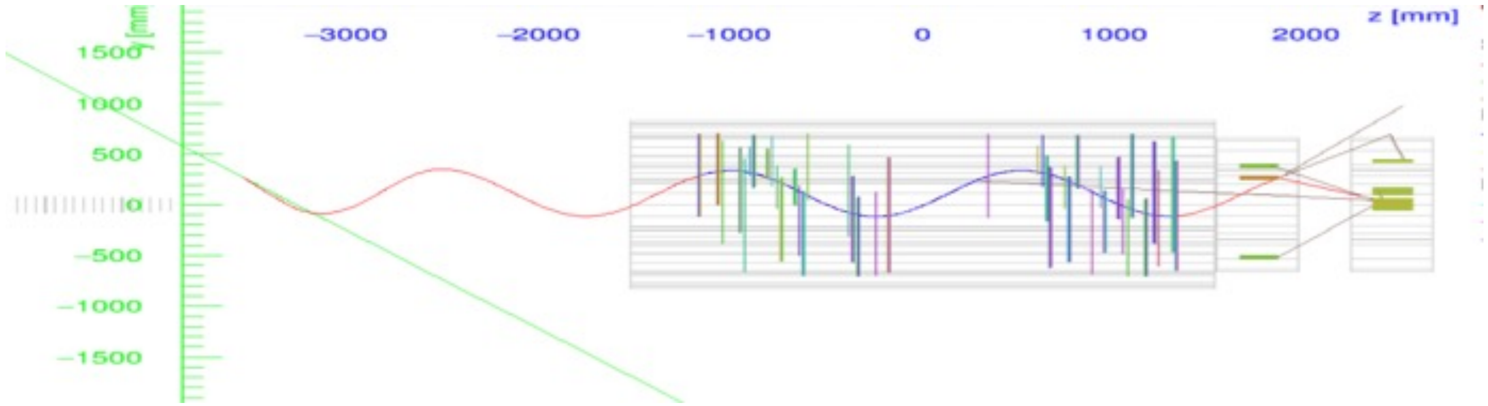
Details:

- Area: 335 m^2
- 83 modules; 10 types
- 5,344 counters
- 10,688 fibers
- 19,392 SiPMs
- 4,848 Counter motherboards
- 339 Front-end Boards
- 17 Readout Controllers

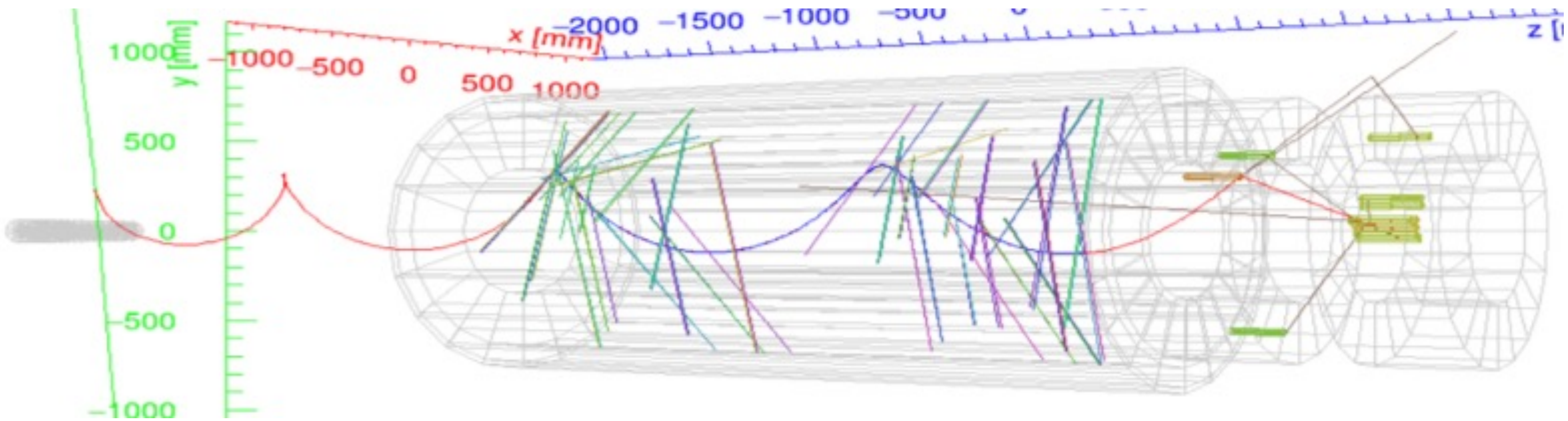
- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high background rates, access to electronics, and constrained space.
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- A track stub in 3/4 layers, localized in time+space produces an Offline-veto

Cosmic Ray “Fake” Candidates

The Cosmic Ray Veto (CRV)

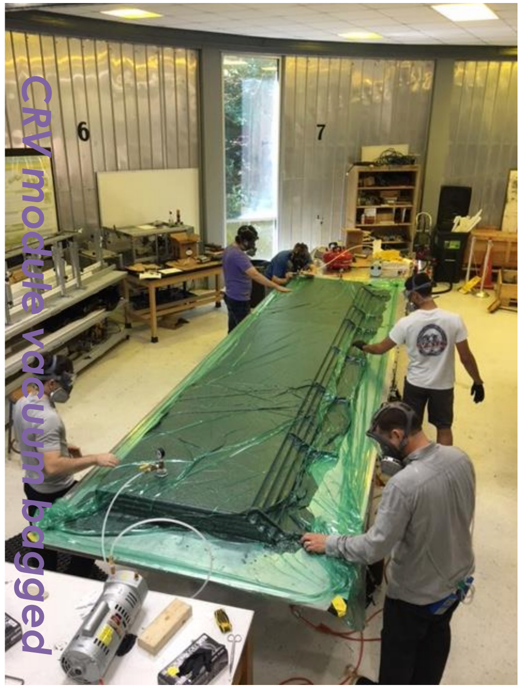


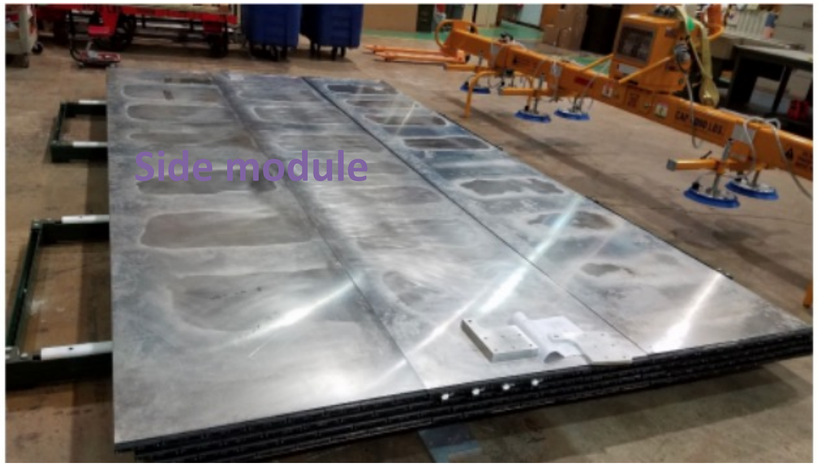
- **Cosmic ray muons and interaction products can fake conversion electrons at a rate of ~1 per day**



CRV Construction status

- Prototype tested in Fermilab test beam:
  - LY meets specifications
- SiPMs,FEE produced
- more than half di-counters produced
- more than 30% of modules completed and tested





Summary of INFN contributions to Mu2e

➔ More than 30 active members from INFN LNF, Pisa, Trieste, Genova and Lecce + associated Universities

➔ Large design, prototyping and construction contribution for the **Transport Solenoid**

➔ **Calorimeter system**, project leadership and a lot of sub-detector responsibilities mosty shared btw LNF and Pisa

➔ **TDAQ and Slow Control** development

➔ Leadership also on **Simulation working group**

➔ Members on Executive Boards, Pubblication and Speaker boards

➔ Social media management leadership

+

A lot of summer students, engineers + Laurea and PhD thesys

+

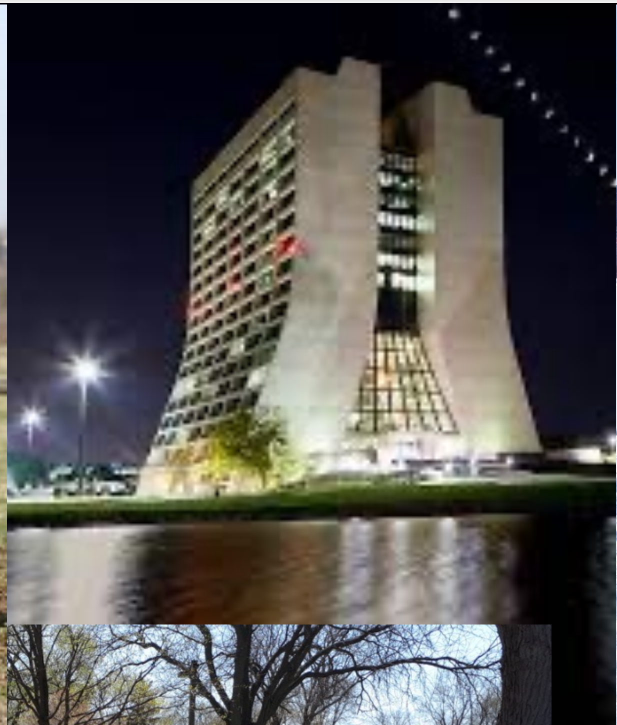
That's why we want to keep this school alive

FNAL Summer School →This workshop

Latest round of Summer Students’
Deployed Troup @FERMILAB
in 2019 → Visiting CleanRooms

Travelling Ban in 2020,2021
This year we made this workshop
→next year let’s hope to be back
@ FNAL

Winter/Summer life @ (ChicagoLand)



Conclusions

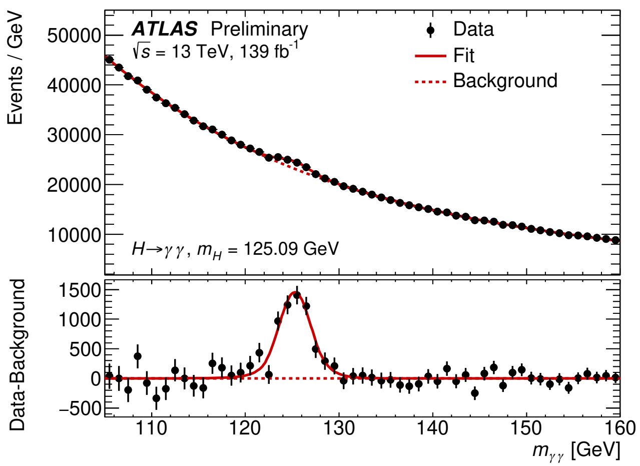
- ✓ The muon conversion experiments (CLFV in general) are excellent tools to look for new physics (BSM).
- ✓ They belong to the Intensity Frontier searches and are complementary to searches @ high-energy colliders while exploring a mass scale not directly accessible.
- ✓ The construction of the Mu2e experiment is under way and the commissioning and data taking phase is approaching. *Small size experiment where is easier to put hands in all aspects and seriously contribute*
- ✓ Mu2e offers a lot of opportunities for brilliant students to participate to a state of the art, world class, experiment in USA.

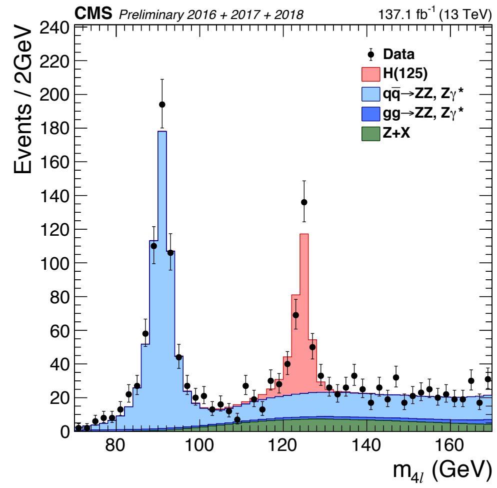
Contact me if you need it @ Stefano.Miscetti@lnf.infn.it

ADDITIONAL MATERIAL

Introduction: SM

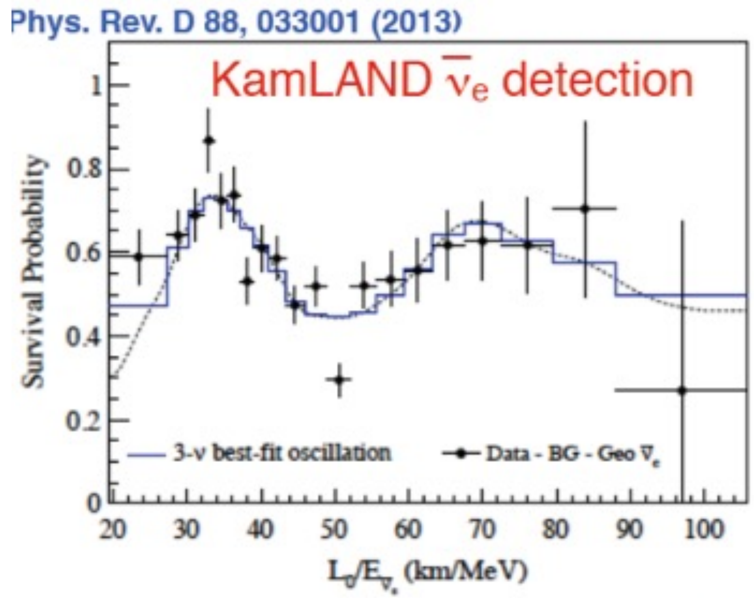
The Standard Model (SM) represents our better =understanding of particles and forces (besides gravity) and it is very successful at describing a wide range of observations, but it does not explain yet:





- number of generations
- Pattern of masses
- dark matter / dark energy
- prevalence of matter over antimatter
- …

And it doesn't account for neutrino mixing, which requires massive neutrinos (and which implies lepton number violation).



There should be physics beyond the SM!

Are CLFV processes relevant ?

W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`

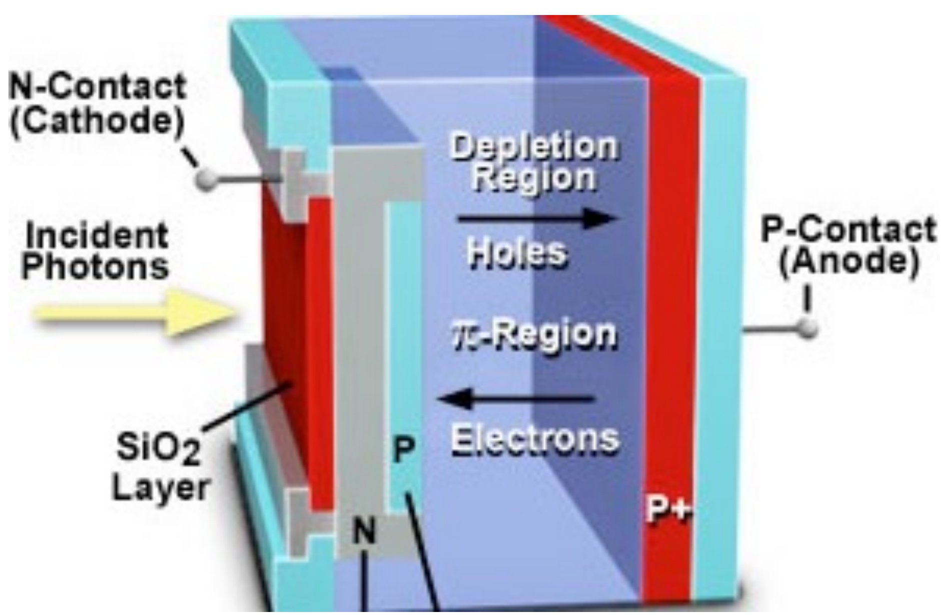
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

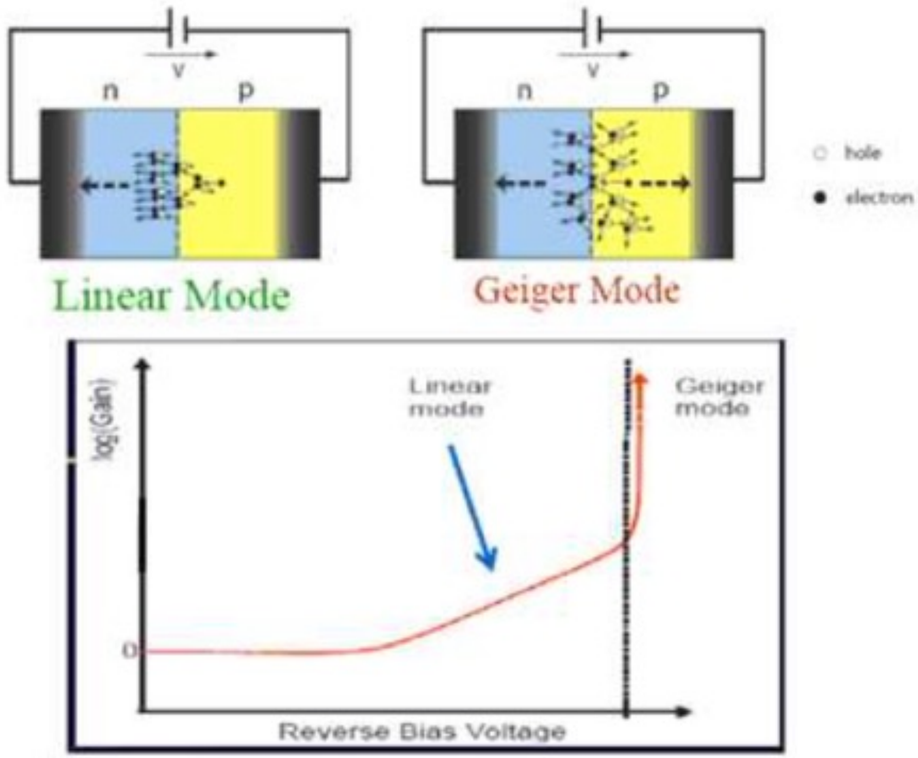
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Silicon Photosensors

- A silicon photo-sensor is "in practice" a reverse Silicon N-P junction with a photo sensitive layer where "photo"electrons are extracted.
- The reverse bias helps to create a large depleted region and reduce to negligible values the "dark current", Id, i.e. the current seen without any signal in input
- **3 work regimes:**

→ **Photodiode (G=1)** all e- produced in the photosensitive layer are collected at the anode.
→ **APD (G=50-2000)** , or Avalanche Photodiode, working in proportional regime and
→ **Geiger APD (G=10^5-10^6)** working in Geiger mode



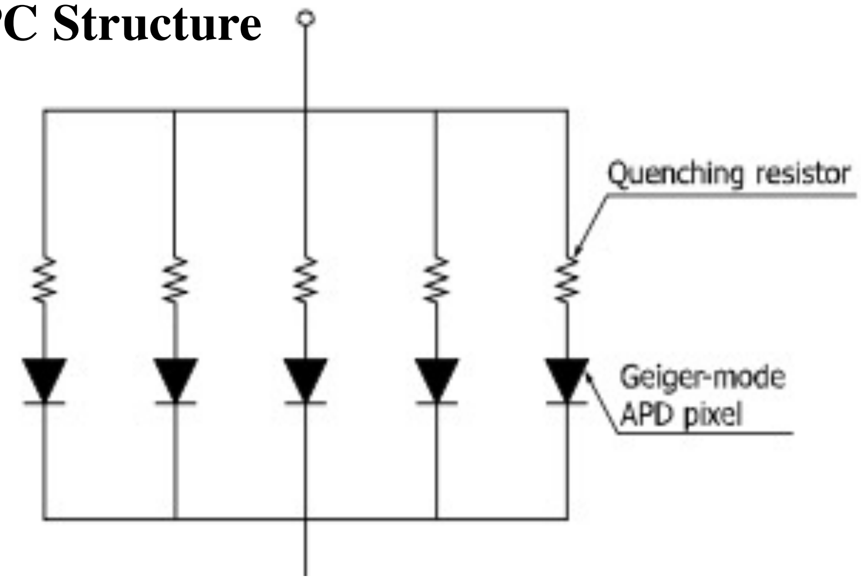


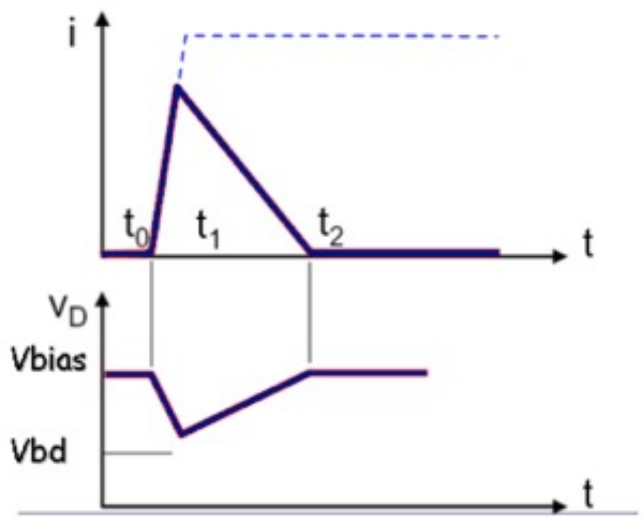
Silicon PMT (1)

- The MPPC (multi-pixel photon counter) is one of the devices called silicon photomultipliers (SiPM) or Geiger APD. It is a photon-counting device **that uses multiple APD pixels operating in Geiger mode;**

- The Geiger mode allows obtaining a **large output by the discharge even when detecting a single photon**. Once the Geiger discharge begins, it continues as long as the electric field is maintained.
- One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with each APD pixel. This quickly stops the multiplication in the APD since a voltage drop occurs when the output current flows.

MPPC Structure





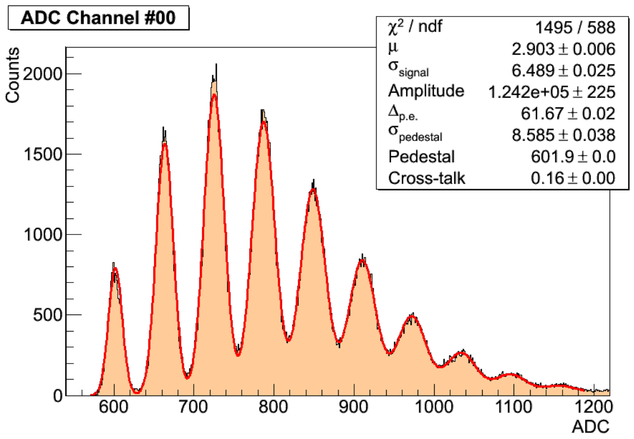
Silicon PMT (2)

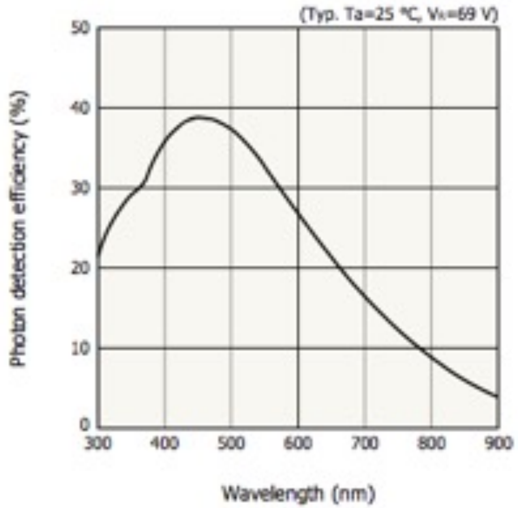
The basic SIPM element (pixel) is a combination of the Geiger-APD and quenching resistor

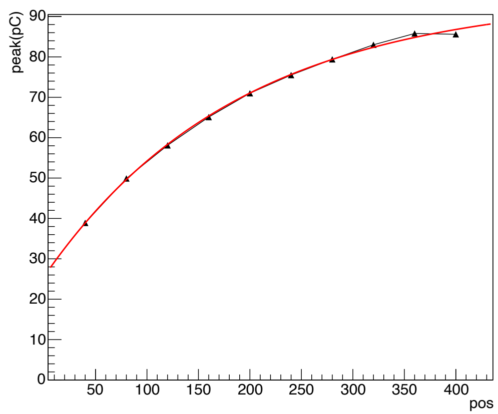
→ a large number of these pixels are electrically connected and arranged in two dimensions;

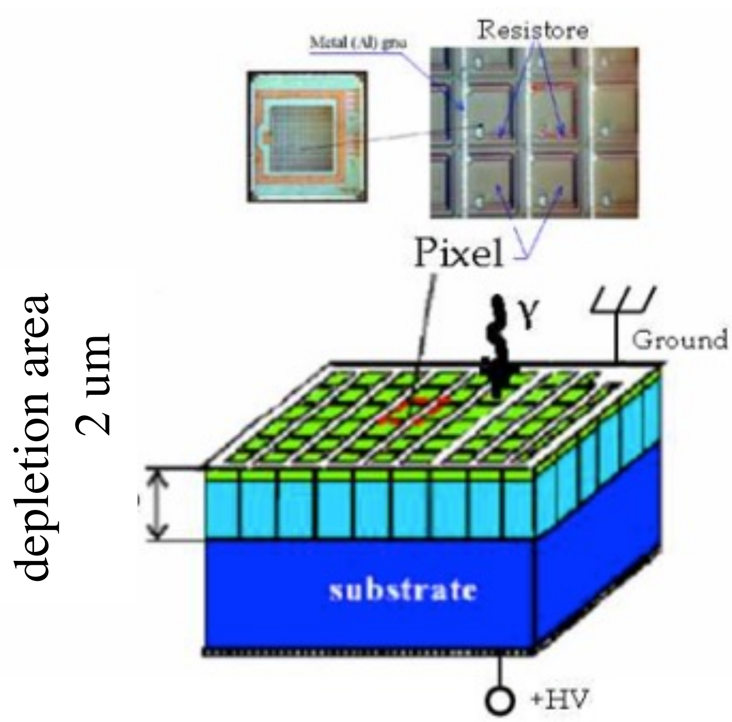
→ Each pixel generates a pulse of the same amplitude when it detects a photon .

→ The output signal from multiple pixels is the superimposition of single pixel pulses.









- ➢ Single photon counting
- ➢ Photon Detection Efficiency
- ➢ “Intrinsic” not-linearity on the response.

COMET vs Mu2e

- ❑ Similar capabilities as physics reach

- ❑ COMET designed to operate at 56 kW, Mu2e 8 kW
  → COMET will use all JPARC beam
  → Mu2e runs simultaneously with neutrino beam

- ❑ Final bend after COMET stopping target efficiently transmits conversion e- and provides rate suppression in detector.

- ❑ It does not transmit positrons (no $\mu^- N \to e^+ N$)

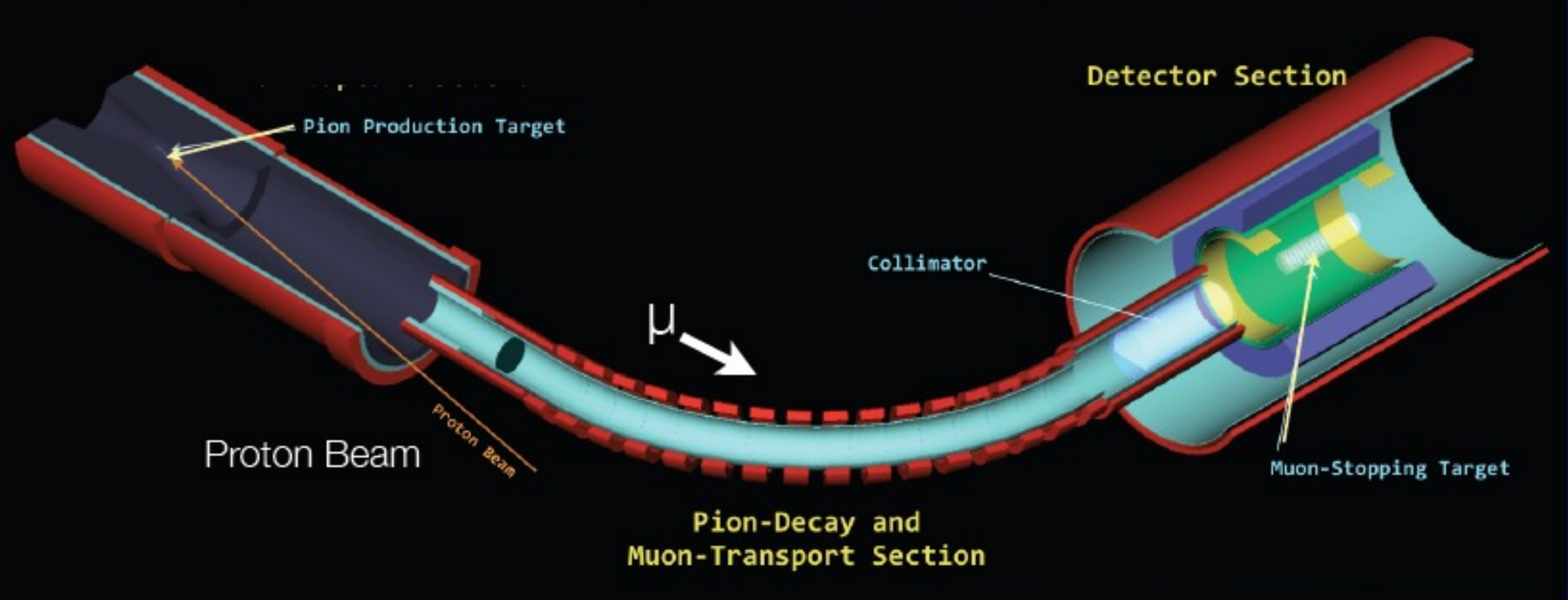
- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam -> higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry "cost" in operation

Phase-1 could be useful if successful to study background rate
→ Path to Phase-2 is still difficult.

physics case coupled with the explicit scope of the experiment

COMET Phase-I Experimental Layout

Osaka University



COMET muon beam-line :

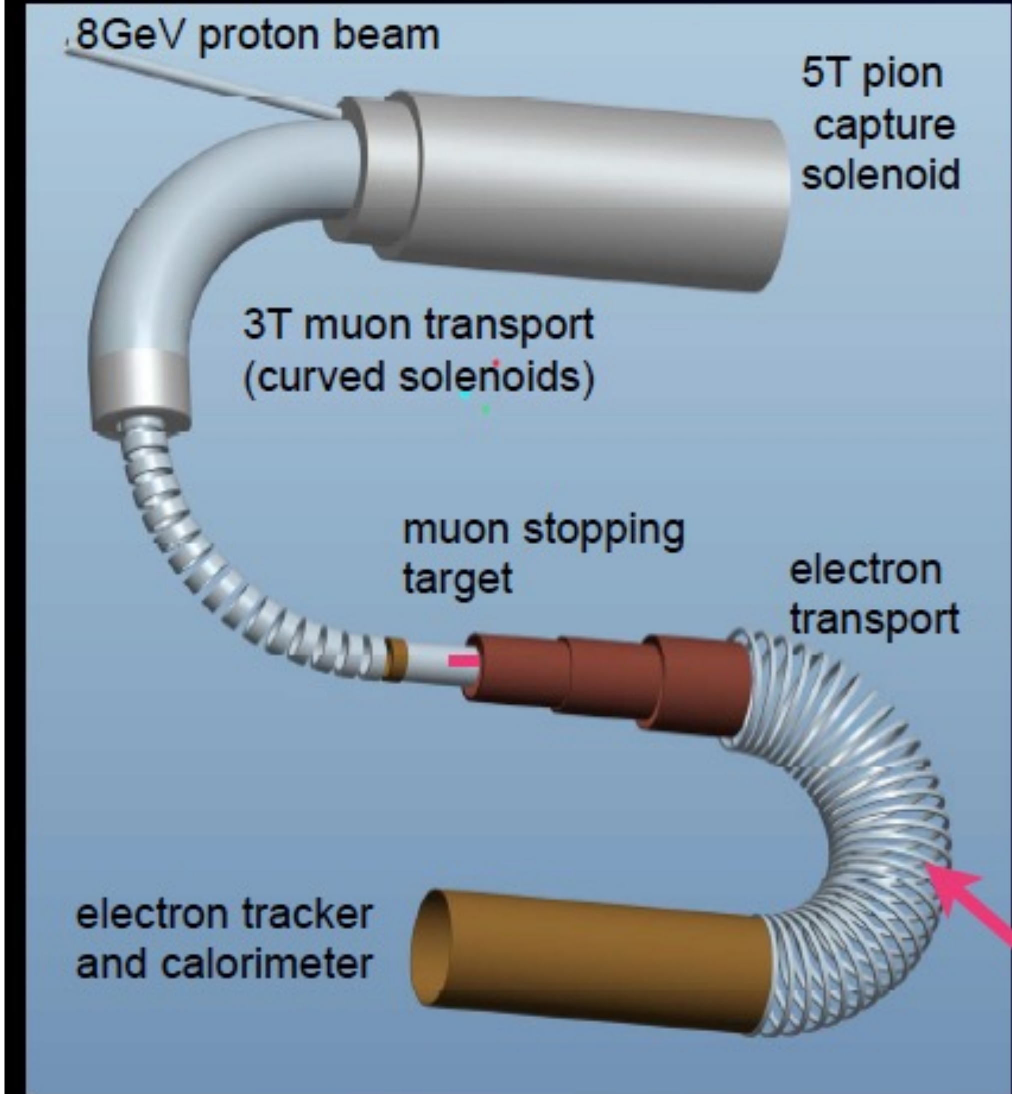
$(1\sim3)\times10^9$ muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector :

Cylindrical drift chamber (CDC) for μ-e conversion is used. Straw chamber and ECAL are for beam studies.

Q:physics case coupled with the explicit scope of the experiment

What is COMET (E21) at J-PARC



Experimental Goal of COMET

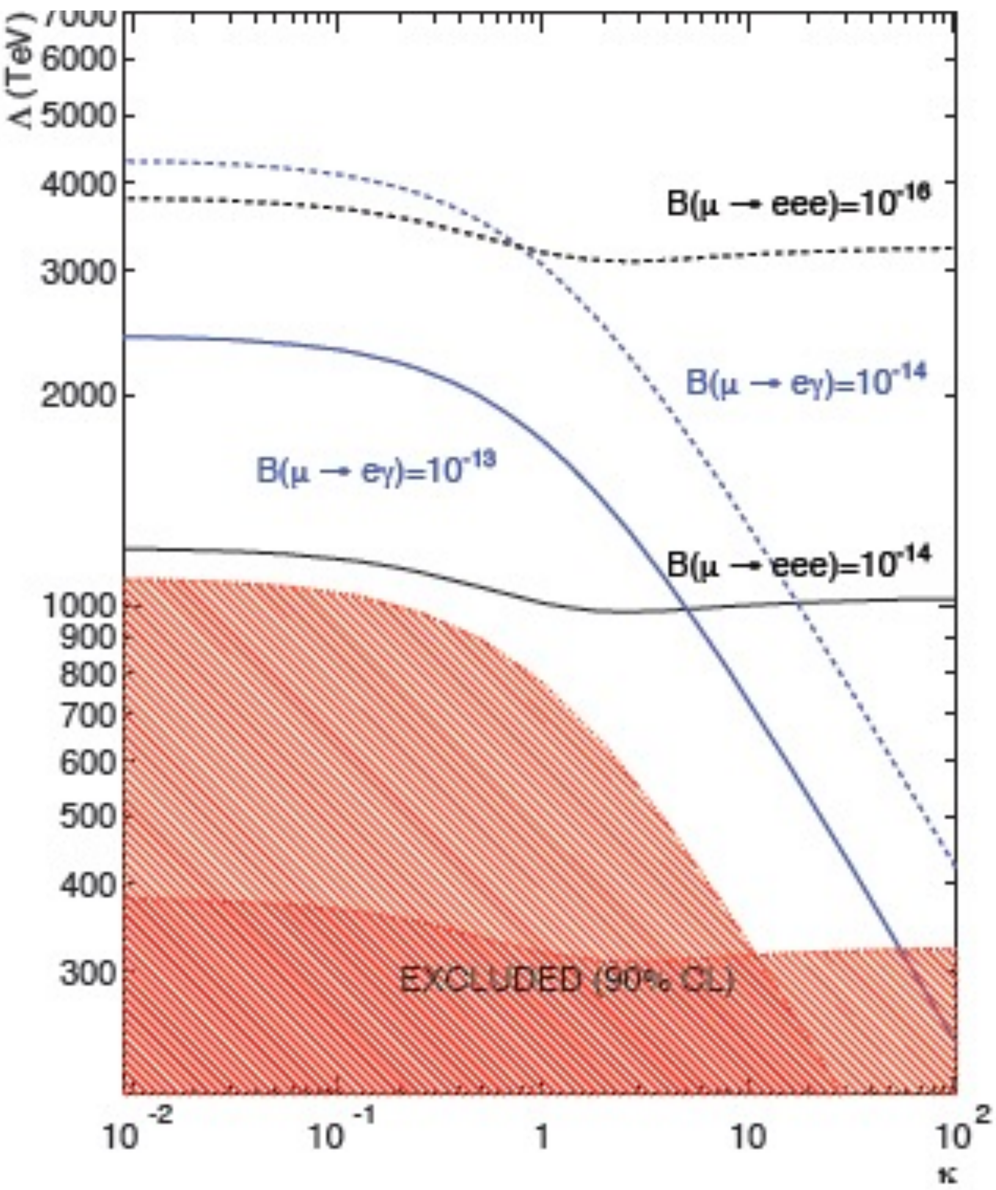
$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- $2\text{x}10^7$ running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

MEG vs Mu3e

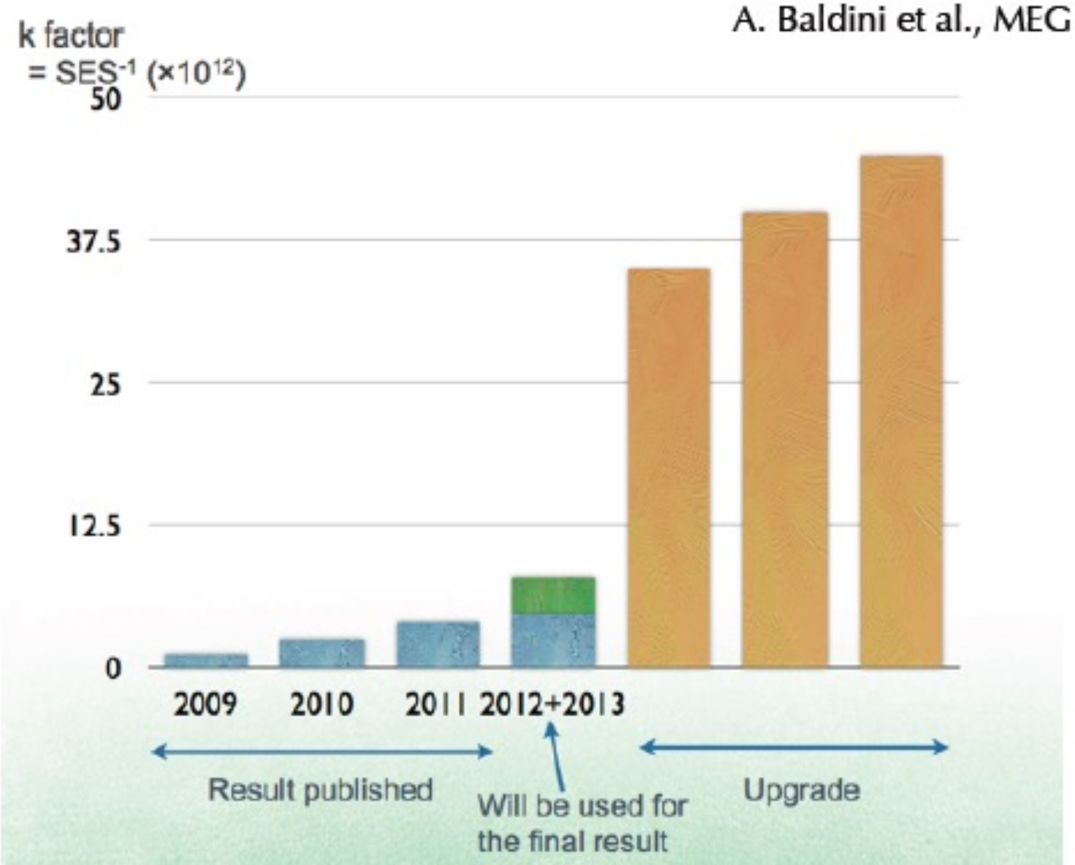
- Mu3e decays test also K values larger than MEG but with different (reduced) sensitivity al large k with respect to Mu2e
- Phase 1 Mu3e @ PSI aims to 10^{-15} (approved)
- Next phase aims to 10^{-16}
  → Not yet approved

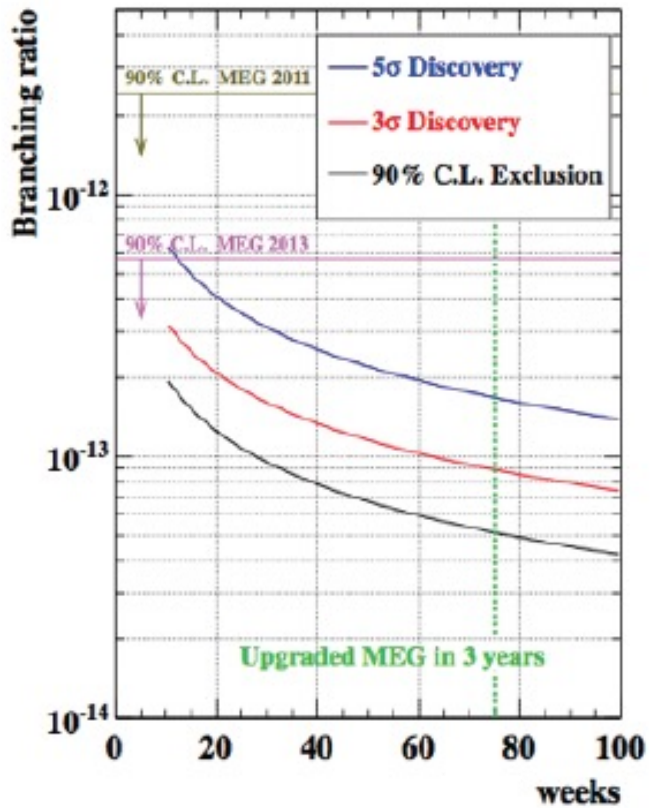


MEG^{UP} sensitivity

- Ultimate sensitivity at the few x 10^{-14} level
- Engineering run 2015
- Data taking 2016-2018

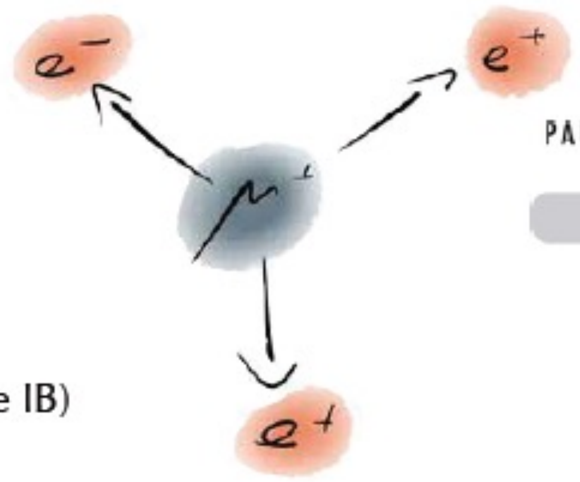
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |



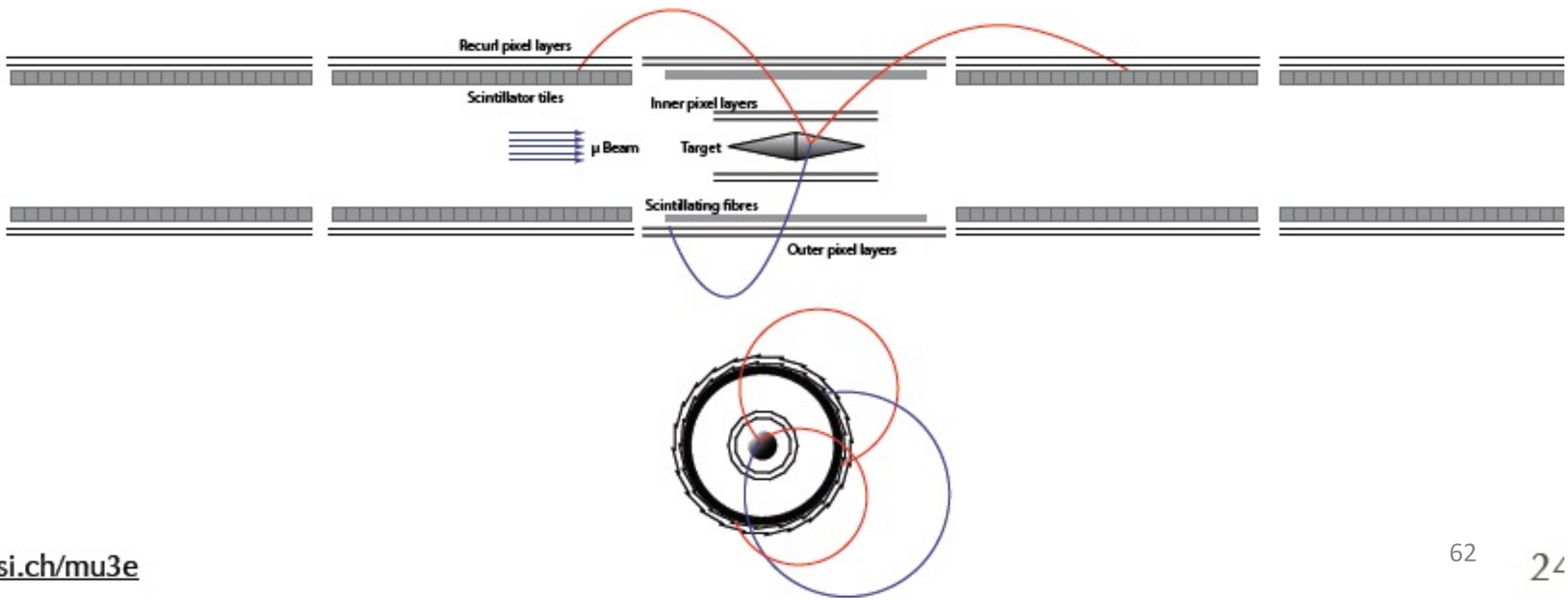


Mu3e at PSI

- Search for $\mu \rightarrow e\,e\,e$
  - 10^{-15} sensitivity in phase IA / IB
  - 10^{-16} sensitivity in phase II
- Project approved in January 2013
  - Double cone target
  - HV-MAPS ultra thin silicon detectors
  - Scintillating fibers timing counter (from phase IB)



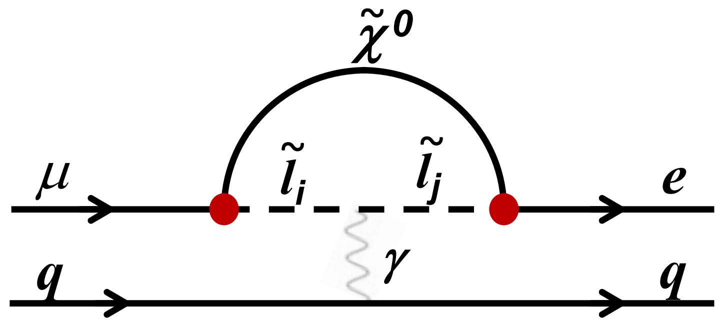
PAUL SCHERRER INSTITUT



ww.psi.ch/mu3e

Specific Example: SUSY

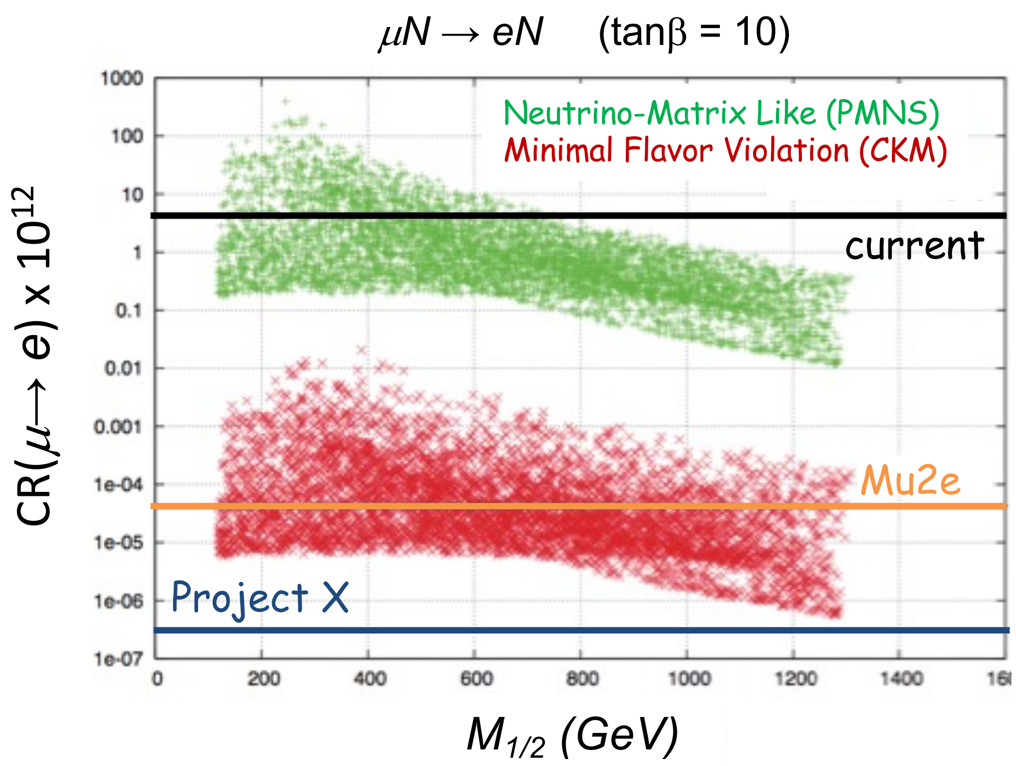
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework



L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

SUSY benchmark points vs LHC

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
$\mathrm{BR}(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SUSY benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

Other CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

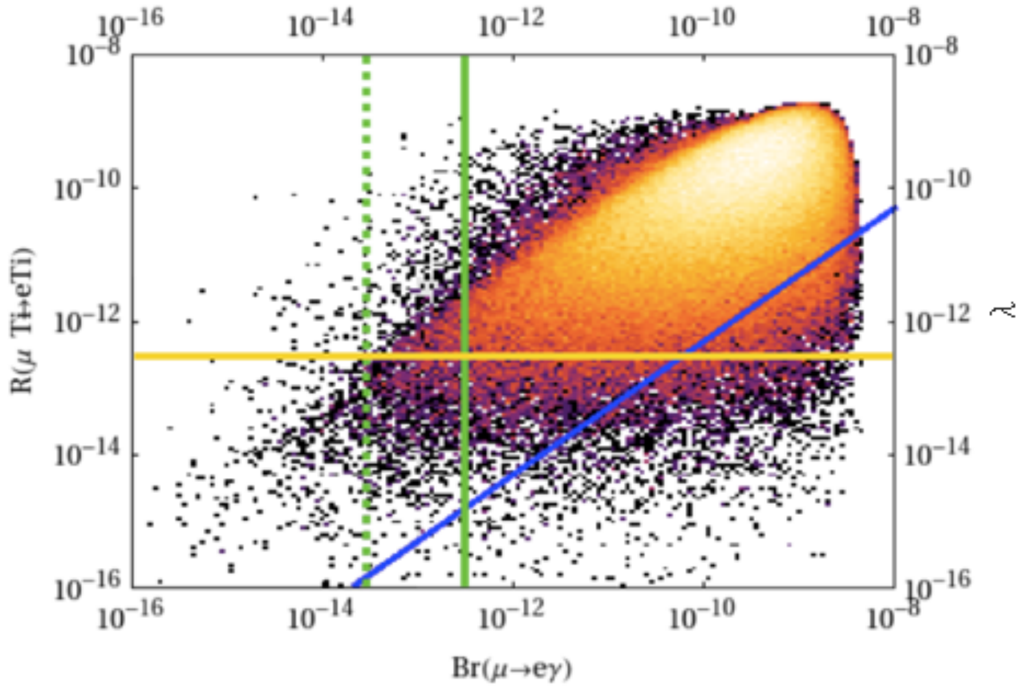
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\cdot 10^{-3}$	$\sim 6\cdot 10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.02\ldots 0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots 2.0$	~ 5	$0.3\ldots 0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots 1.6$	~ 0.2	$5\ldots 10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$0.08\ldots 0.15$

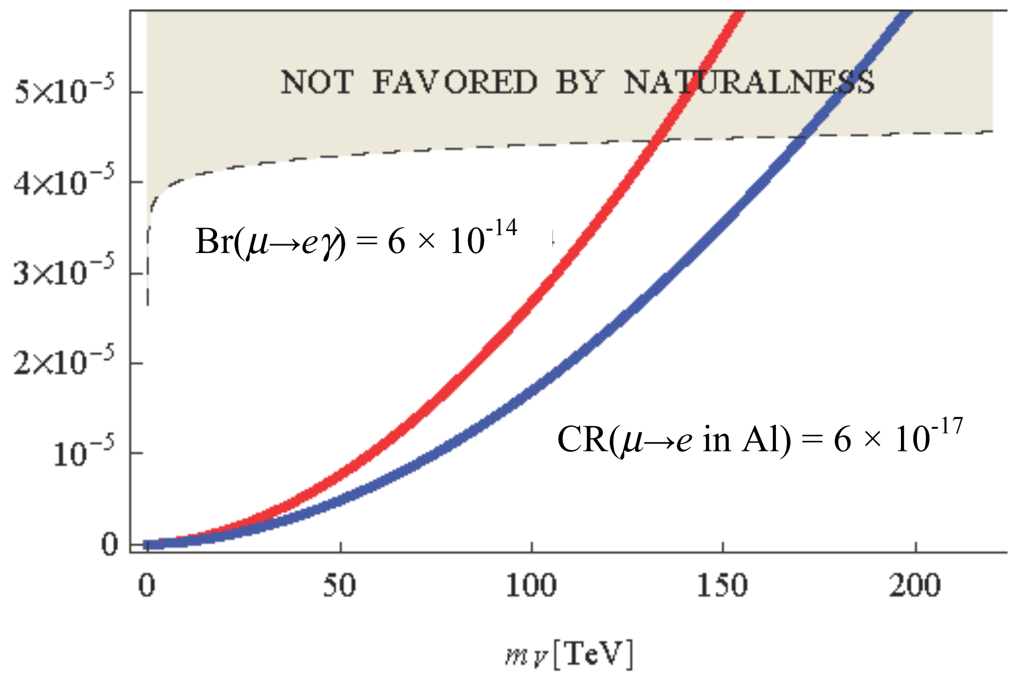
arXiv:0909.5454v2[hep-ph]

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

- **Relative rates are model dependent**
- **Measure ratios to pin-down theory details**

MU2E vs MEG-upgrade





Littlest Higgs model with T-parity

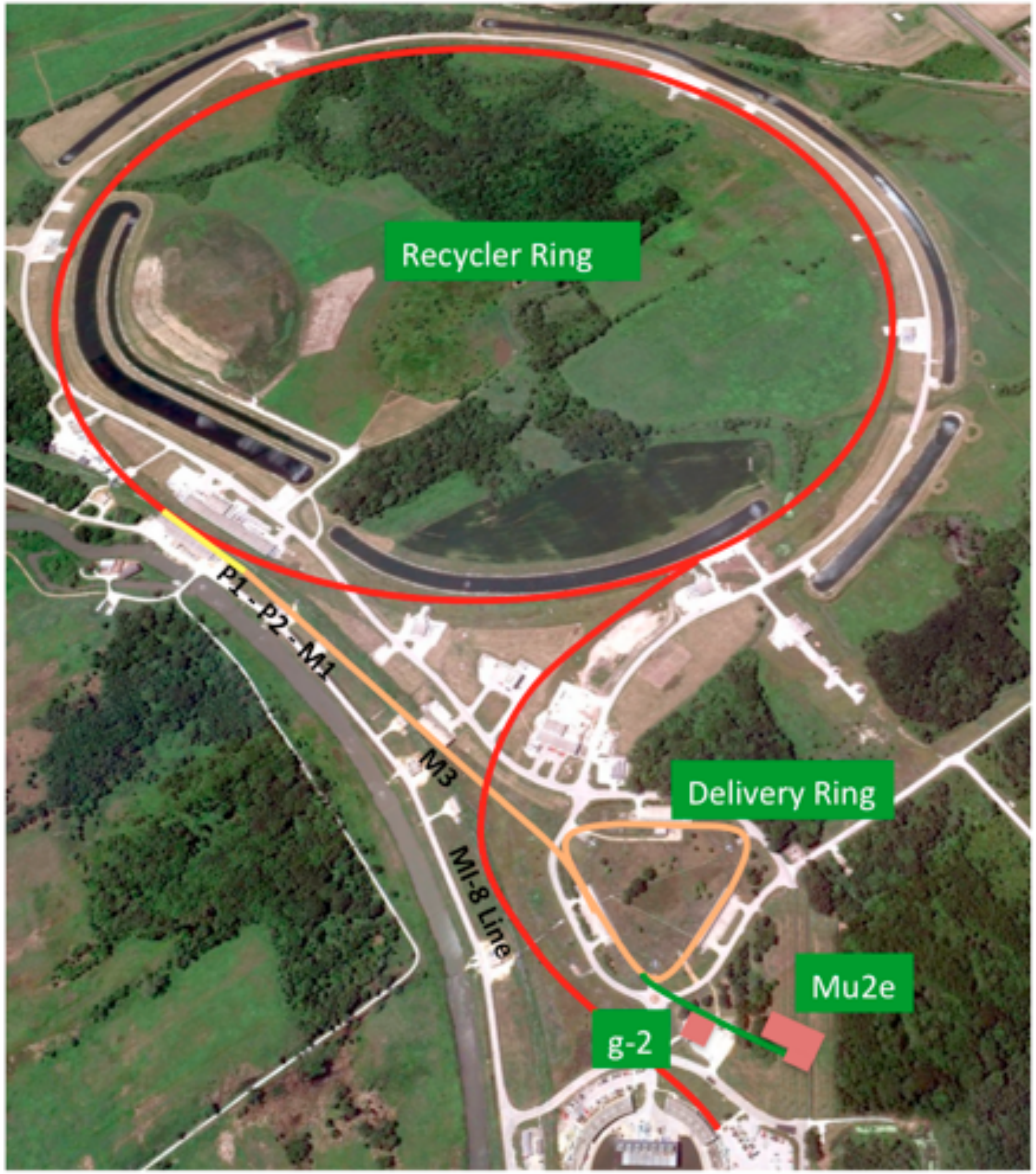
- Yellow line, limit by SINDRUM-II
- Grenn lines, MEG and MEG-upgrade
- Mu2e covers all parameter space

Leptoquarks

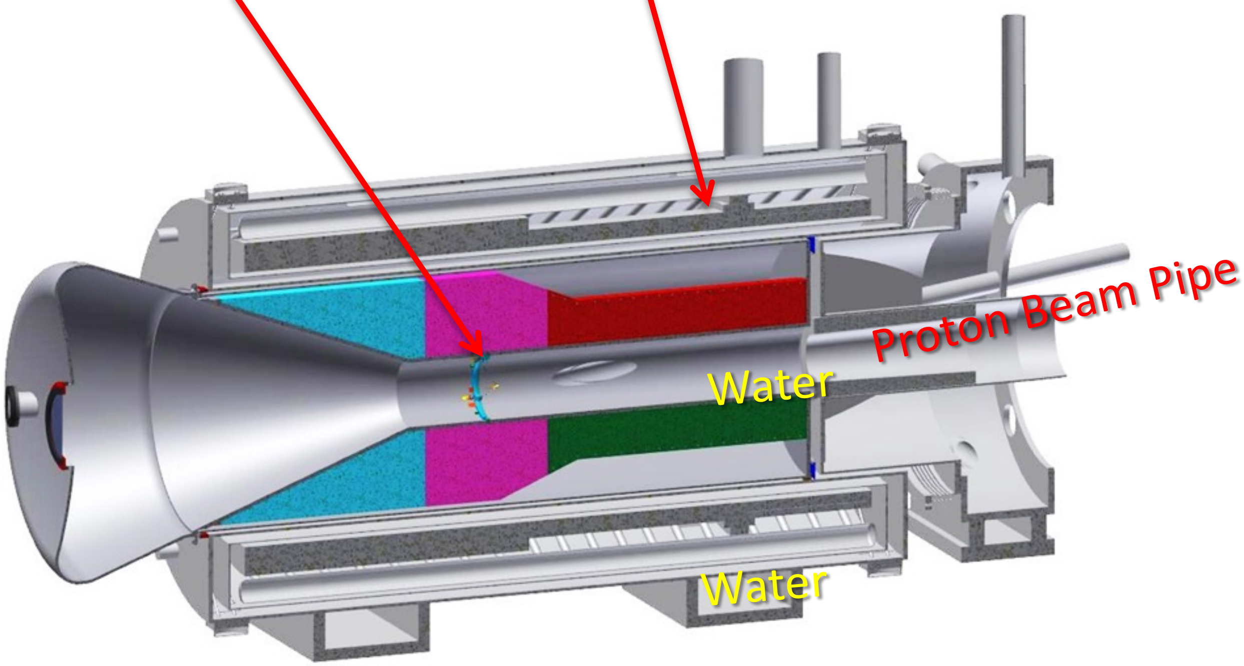
- Red line → MEG-upgrade
- Blue line → MU2E

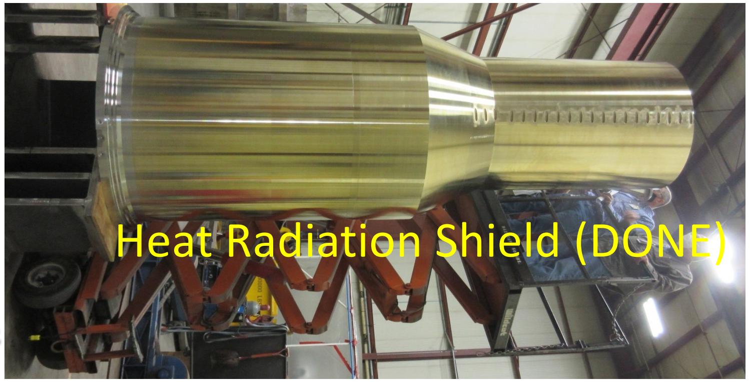
Accelerator Scheme

- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is re-bunched into 4 bunches
- These are extracted one at a time to the Debuncher/Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- **Produces bunches of ~$3\text{x}10^7$ protons each, separated by 1.7 μs (debuncher ring period)**



PS details





- “Bunch/Pulse” of protons delivered every 1695 ns
- Protons on production target produce a spray of particles
  - Highest energy escape to beam dump.
  - Low energy reflected by magnetic field gradient, swept downstream

Stopping Target

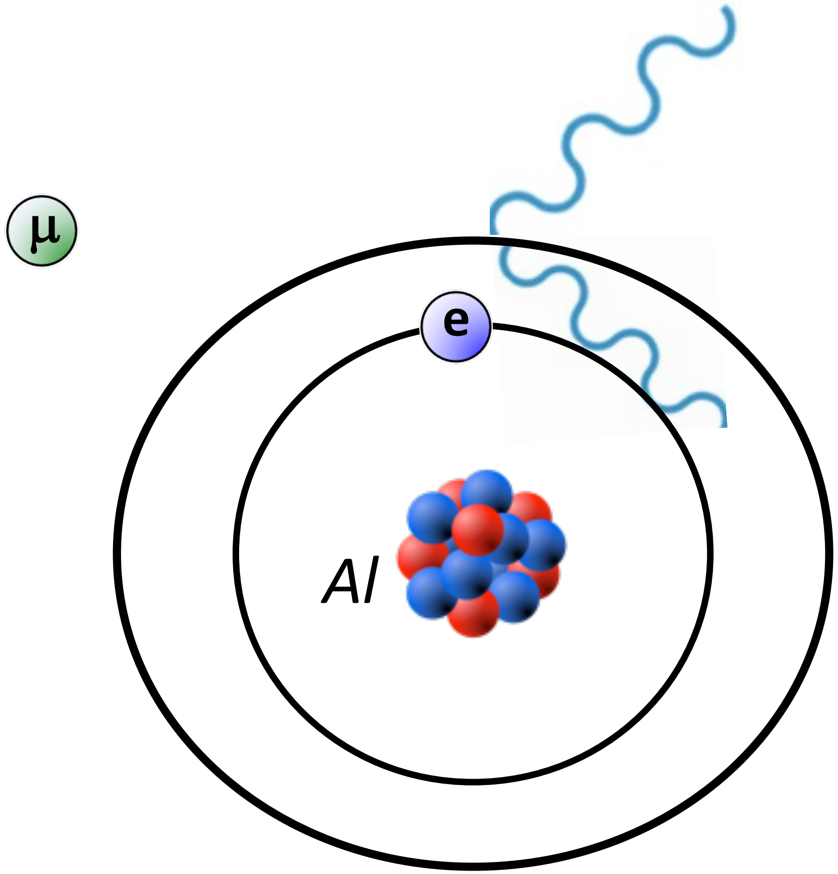
Stopping Target:

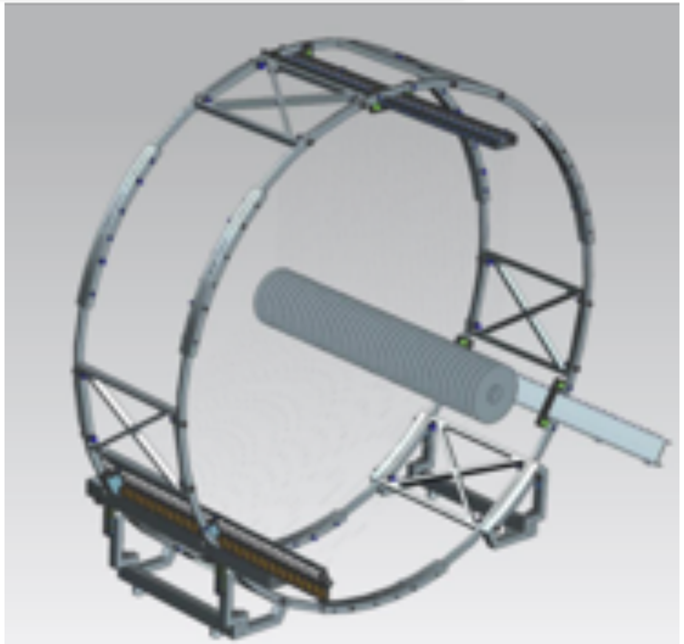
34 Thin (200 micron thick) Al foils

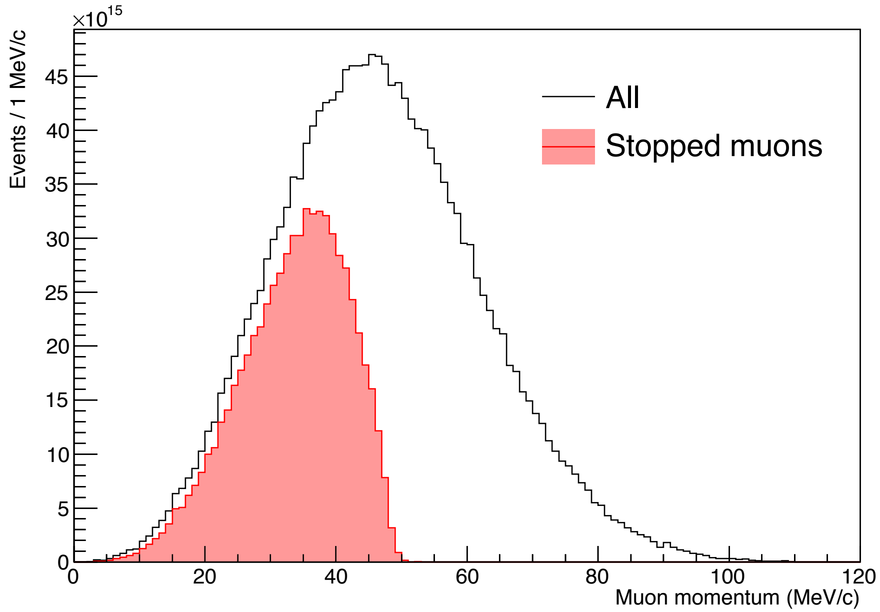
few cm spacing

From 10 cm to 6 cm radius

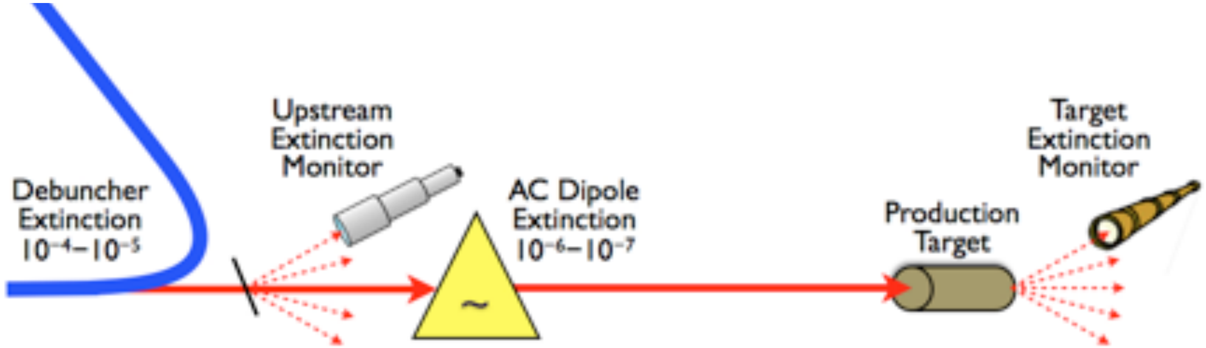
This is where this happens







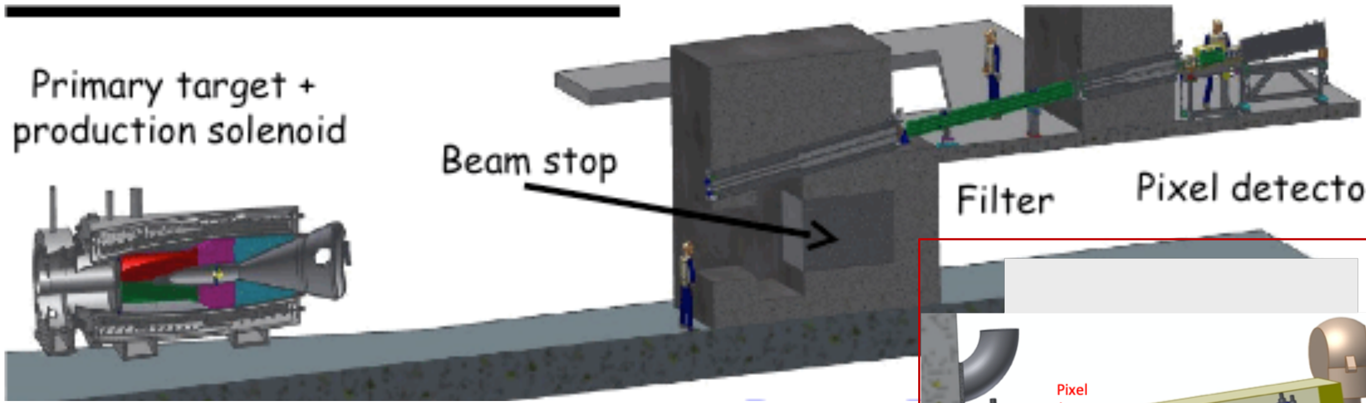
Extinction monitor

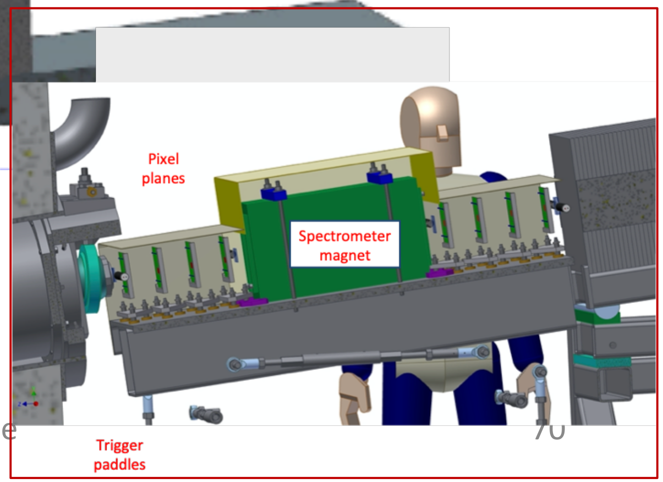


- Thin foils in the debuncher → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback – timescale of hours)

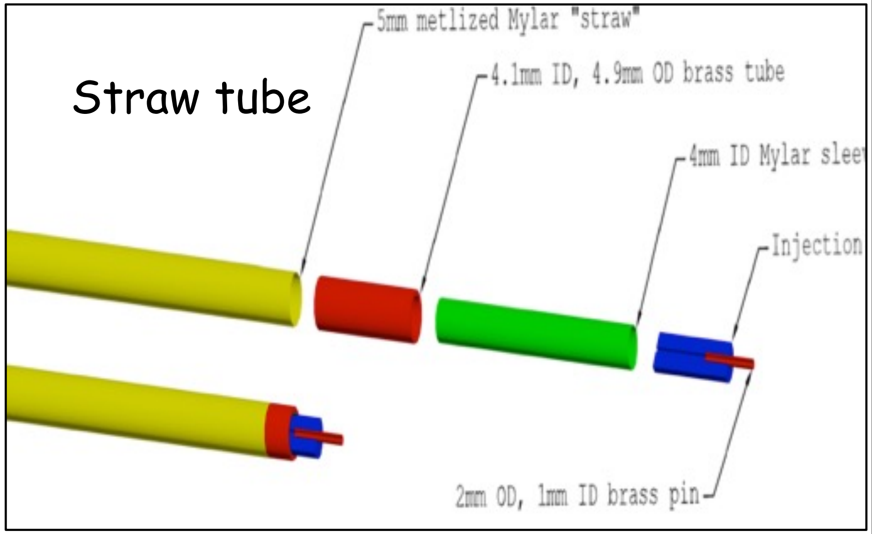
Spectrometer based on ATLAS pixel detector

Reach a 10^{-10} extinction sensitivity in an hour or so



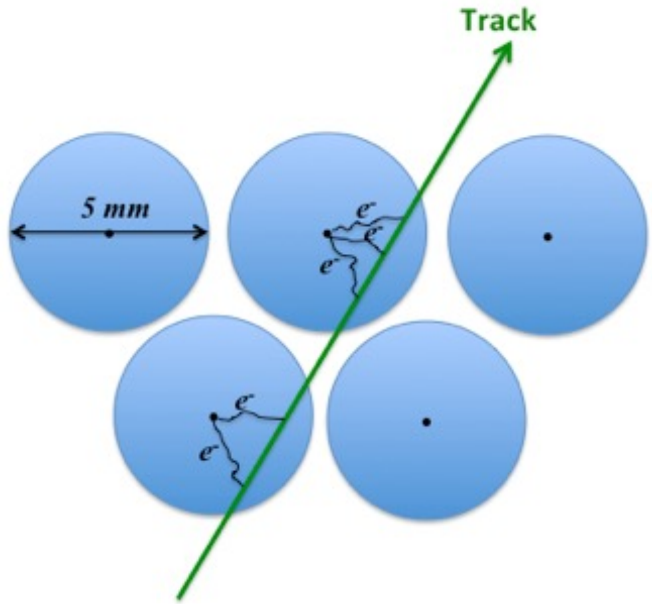


Tracker Design: Thin Straw Tubes - 2



Straw Diameter	5 mm
Straw Length	430 – 1200 mm, 910 mm average
Straw Wall	15 μm Mylar (2×6.25μm plus adhesive)
Straw Metallization	500Å aluminum, inner and outer surface 200Å gold overlaid on inner surface
Gas Volume (straws only)	$4\cdot10^8$ mm³ (0.4 m³)
Sense wire	25 μm gold-plated tungsten
Drift Gas	$Ar:CO_2$, 80:20
Gas gain	$3\text{-}5\cdot10^4$ (exact value to be set later)
Detector Length	3196 mm (3051 mm active)
Detector Diameter	1620 mm (1400 mm active)

- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm)**



“back on the envelope” resolution

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\,\frac{\sigma_y p_\perp}{(0.3BL^2)}\ \textbf{(m, GeV/c, T)}$$

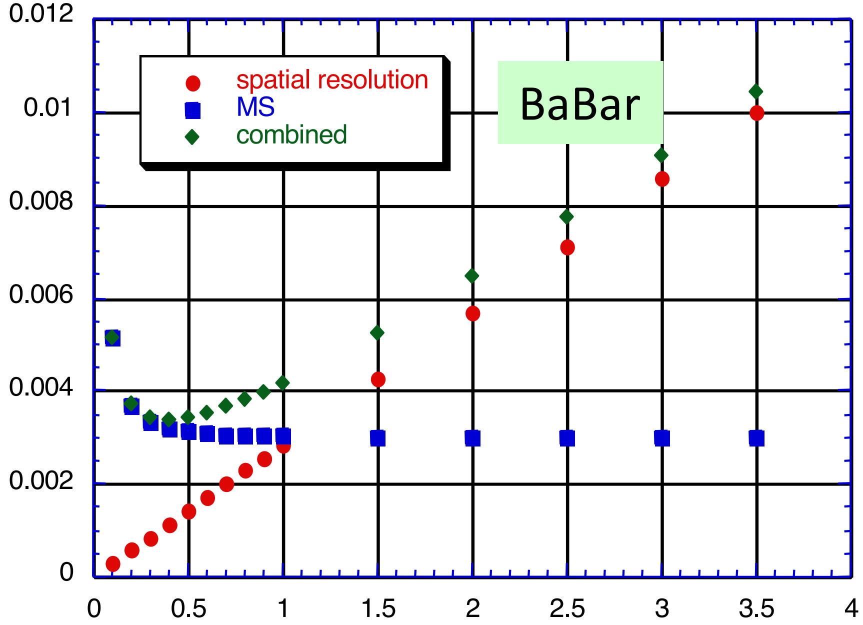
(P_T example = 100 MeV = 0.1 GeV)

1) SPATIAL RESOLUTION CONTRIBUTION

- **N(hits) per track = 40, B(Field) = 1 T, L = 0.3 x 2π = 2 m, Sy = 200 μm**
- SQRT(720/44) xσ (point) x 0.1 / (0.3 x 1 x 4)

→ 4 x σ(point) x 0.1 x 0.8 = 0.3 x Sy (m) ~ 60 x 10^{-6} = 0.6 x 10^{-4} = 0.06 permil
→ @ 100 MeV → 0.06 x 100 keV = 6 keV

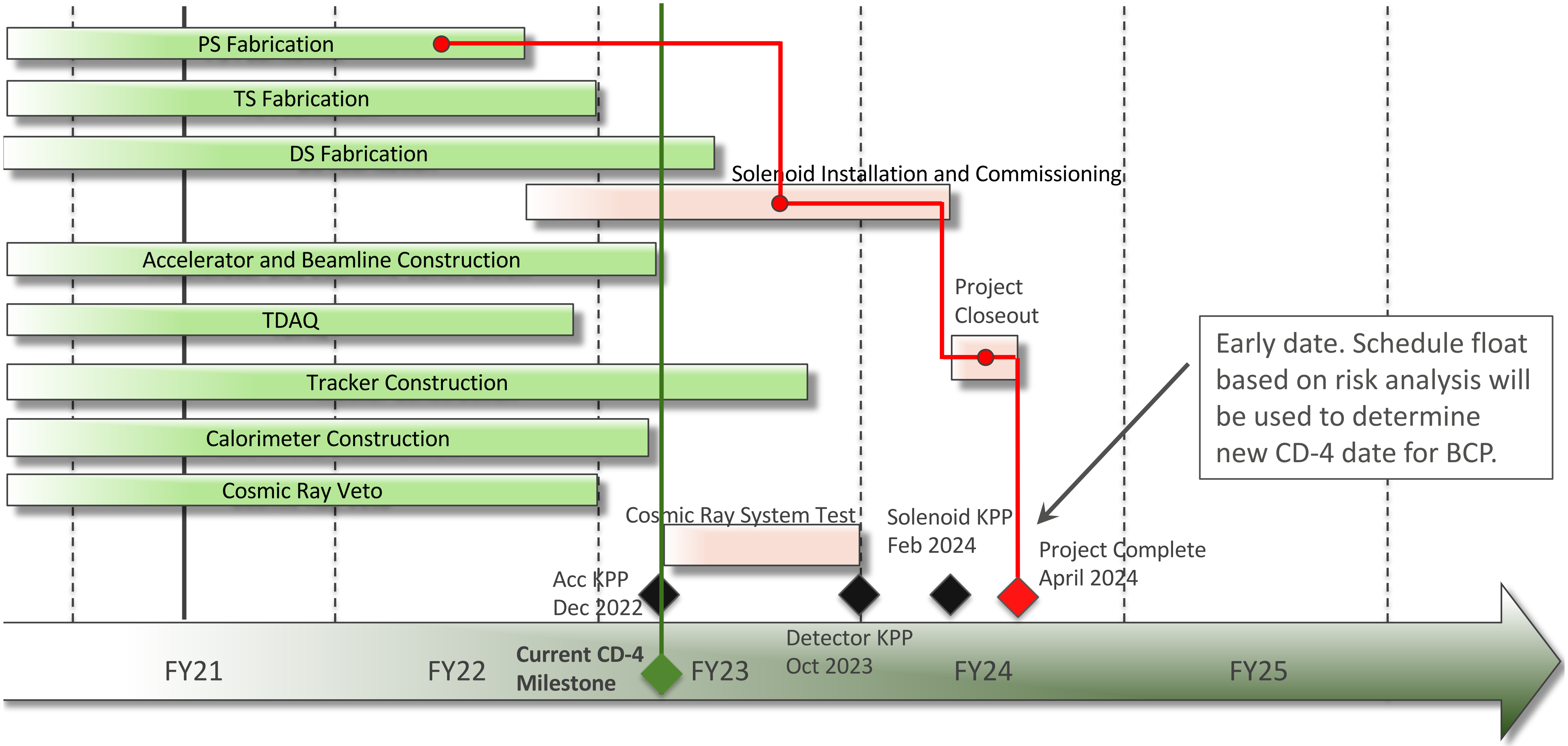
momentum resolution at 90^0



2) MULTIPLE SCATTERING CONTRIBUTION

- Sy (m.s.) = L sin0 x Theta_rms =
- Theta_rms =13 MeV/P(MeV) x SQRT(L(X0))
  → @ 100 MeV and 0.5% X0
  → Theta_rms = 0.13 x SQRT(0.5$10^{-2}$)
  → 0.13 x 0.07 = 0.09
- **Sy (m.s.) = 0.9 cm**
  30 times larger than space resolution
- **σ(p)/p = 0.06 x 30 permil = 0.002**

Mu2e Schedule revised (Covid +GA)



Early date. Schedule float based on risk analysis will be used to determine new CD-4 date for BCP.

Still 2-3 years to go for commissioning and then data taking with beam …