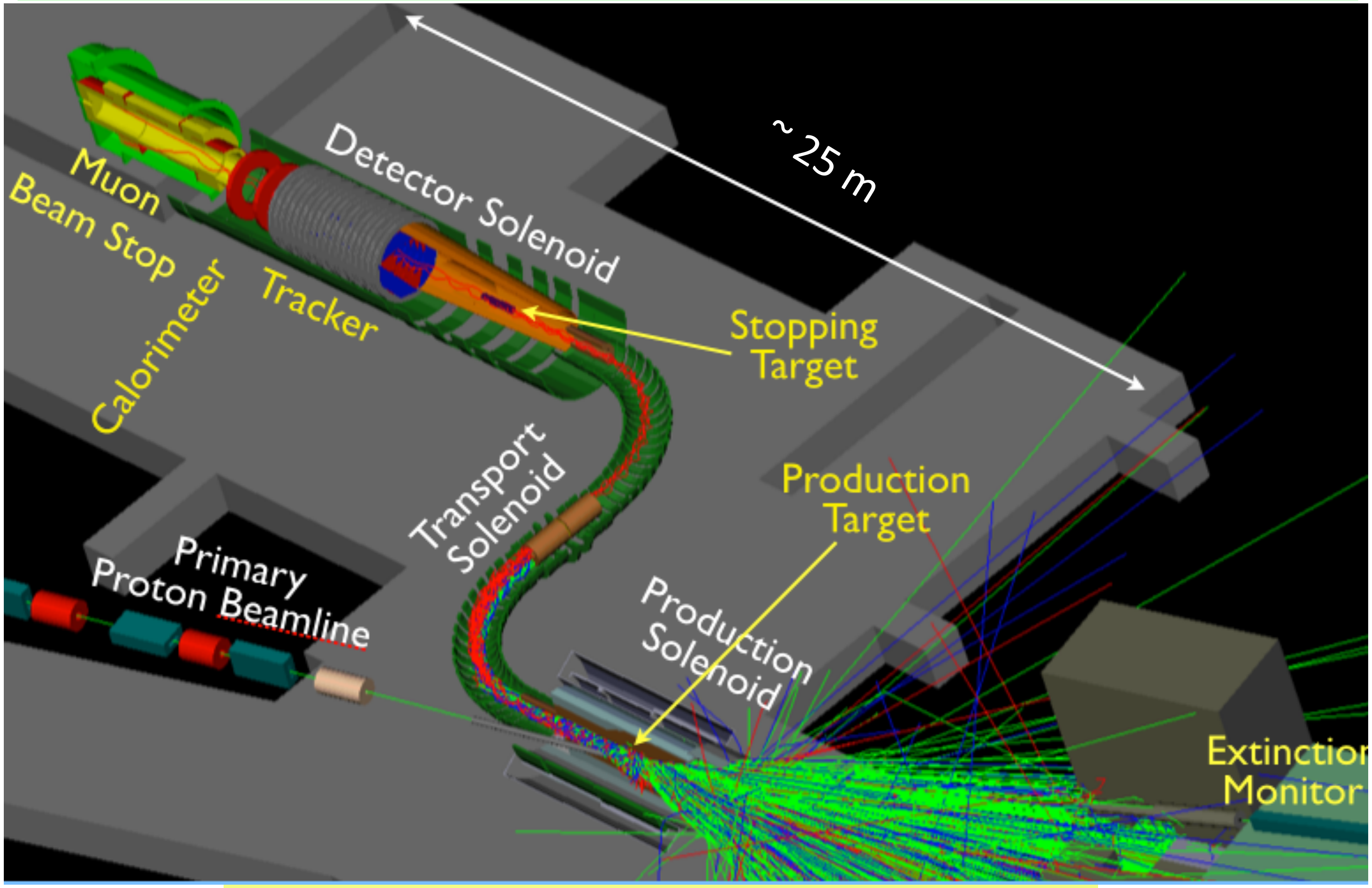
The Mu2e experiment



S. Miscetti
Laboratori Nazionali di Frascati
on behalf of the Mu2e Collaboration

University of Rome “La Sapienza”
8/6/2015

Outline

- The Physics
  - →CLFV processes
  - →BSM Reach: Mu2e vs MEG
- Description of Muonic Atom processes
- Experimental technique
- Accelerator Complex
- Detector Layout
- Status of Mu2e experiment
- INFN contribution
- Conclusions

Physics Program

CLFV processes

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

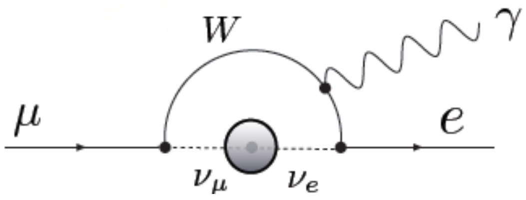
  similar but complementary to other CLFV processes as μ→ eγ and μ → 3e.

- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$

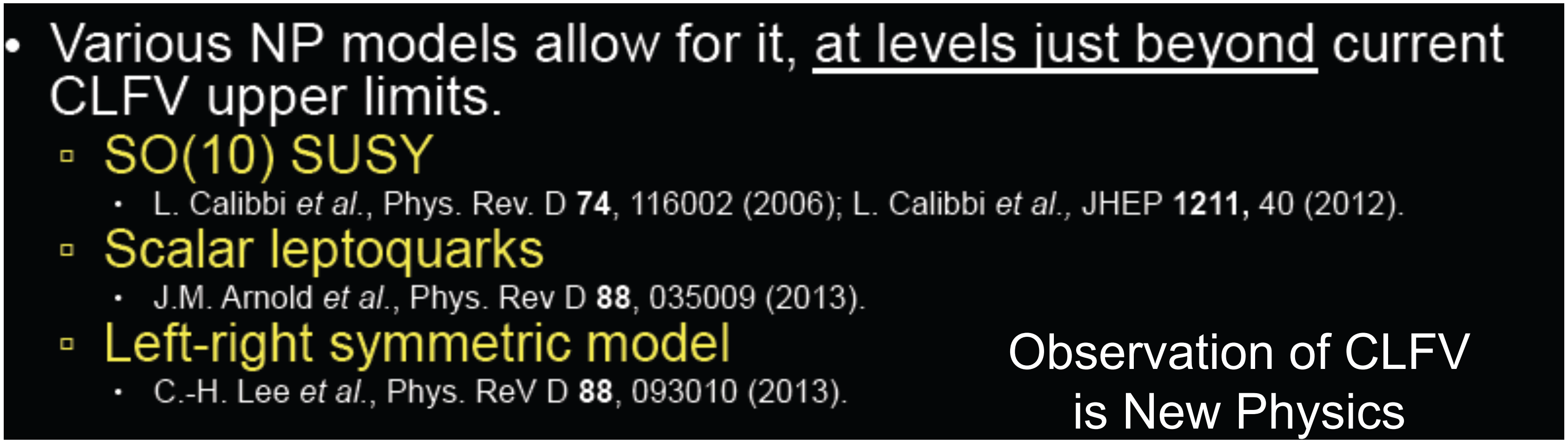
- CLFV processes are strongly suppressed in the Standard Model

  → In principle, not forbidden due to neutrino oscillations

  → In practice BR(μ → eγ) ~ 10^{-54} is negligible in the SM!



- New Physics could enhance CLFV rates to observable values

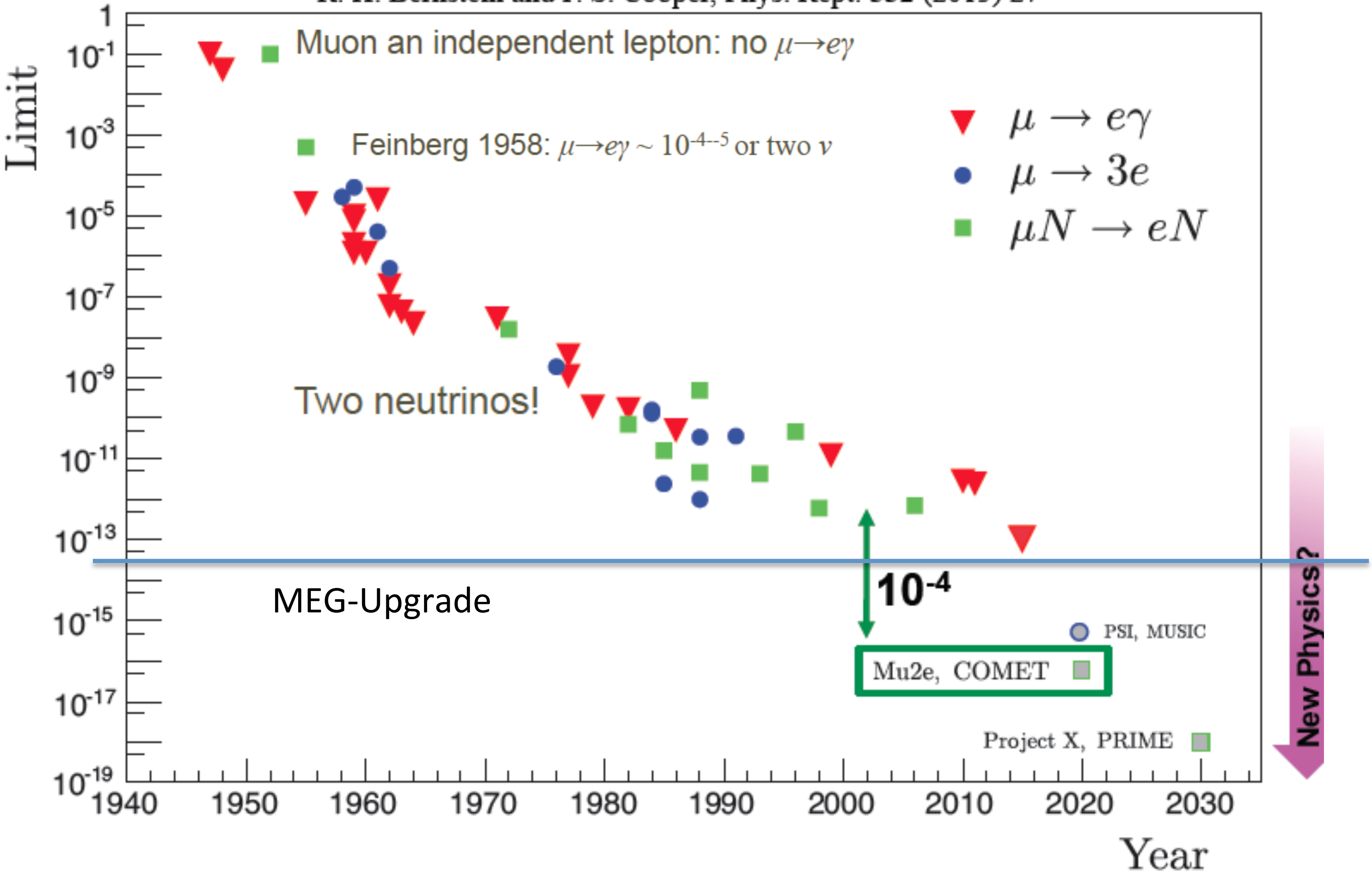


- Various NP models allow for it, at levels just beyond current CLFV upper limits.
  - SO(10) SUSY
    - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211,** 40 (2012).
  - Scalar leptoquarks
    - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
  - Left-right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

Observation of CLFV
is New Physics

CLFV history

R. H. Bernstein and P. S. Cooper, Phys. Rept. **532** (2013) 27

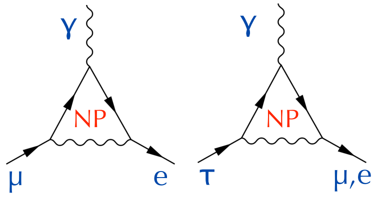


Mu2e vs MEG/MEG upgrade

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

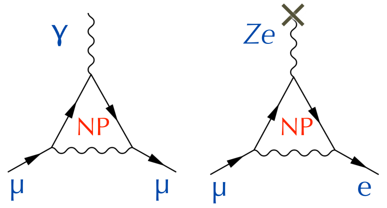
LOOP TERM

$\kappa \ll 1$



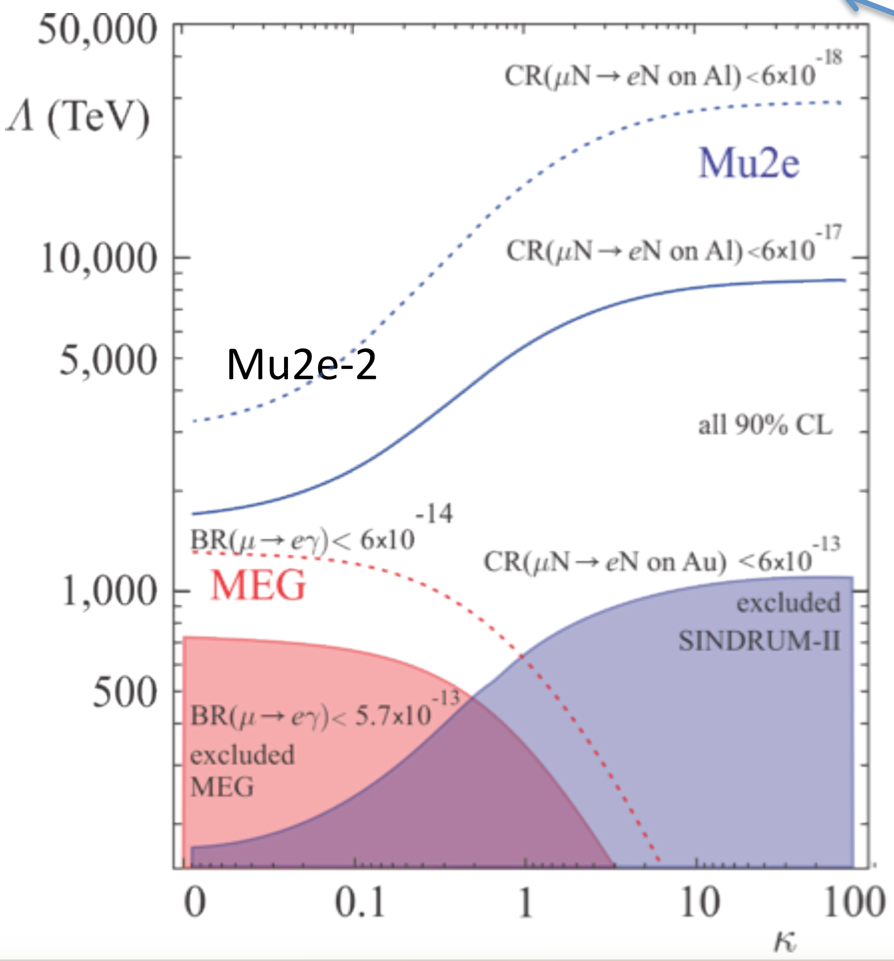
$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$



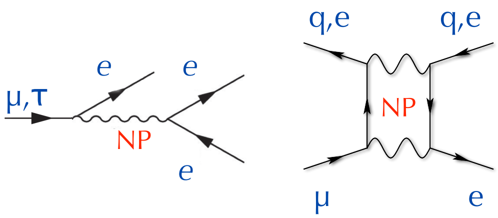
$(g-2)_\mu$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$

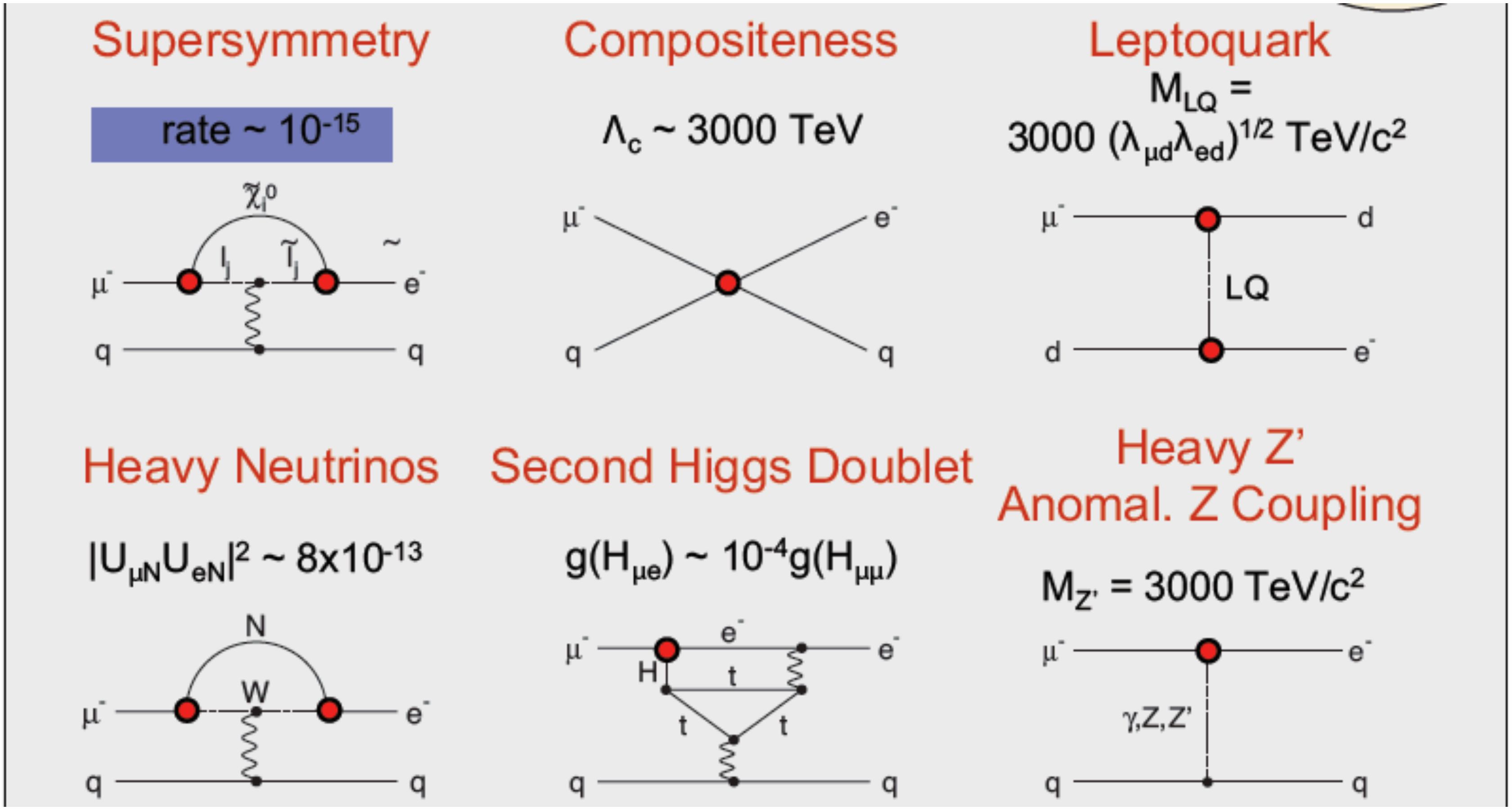


$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

Mu2e physics reach & goal



Supersymmetry

rate ~ 10^{-15}

Compositeness

$\Lambda_c \sim 3000$ TeV

Leptoquark

$M_{LQ} =$
$3000\,(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2

Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$

Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$

Heavy Z'
Anomal. Z Coupling

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

Sensitivity reach:

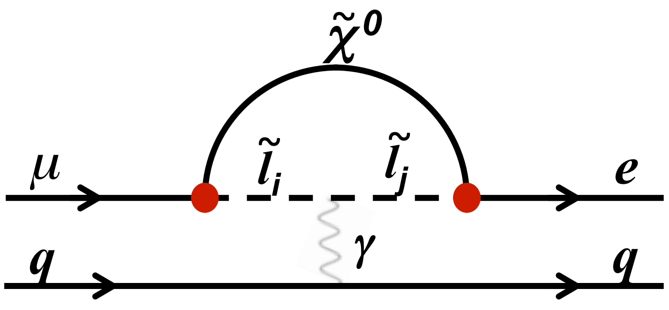
10^4 improvement with respect to previous muon to electron conversion experiment (Sindrum-II)

Test of Physics BSM:

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Specific Example: SUSY

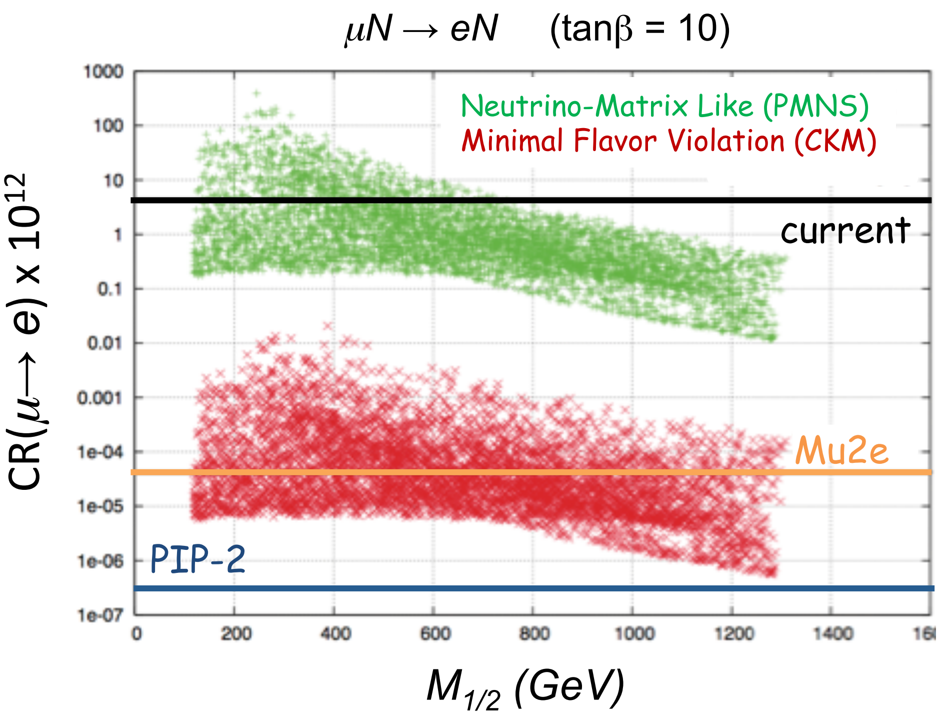
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies ~ 40-50 signal events with negligible background in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework

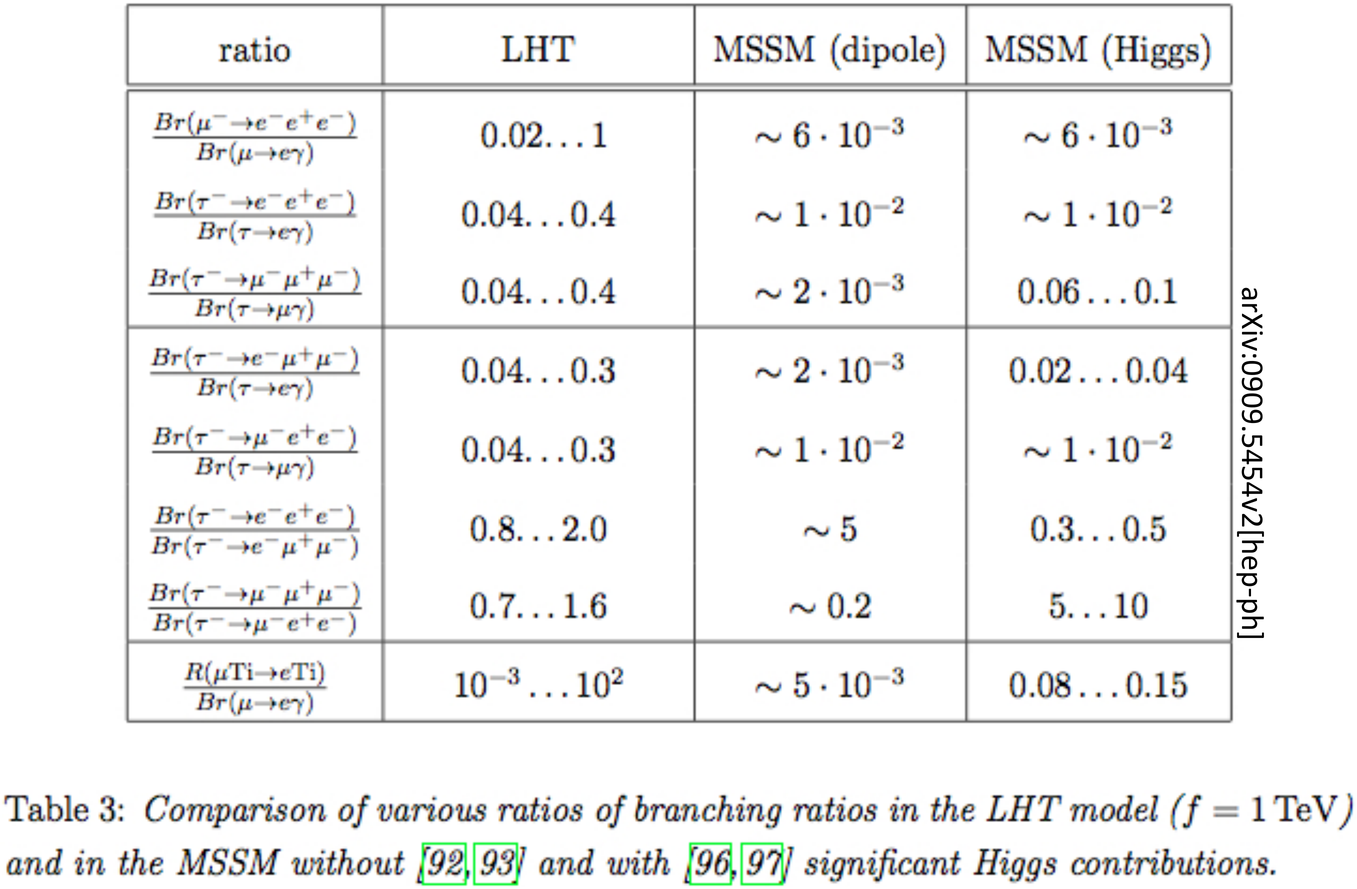


L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

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	$5 \ldots 10$
$\frac{R(\mu\text{Ti} \to e\text{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

arXiv:0909.5454v2[hep-ph]

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\text{TeV}$) 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**

Summary: why Mu2e is unique?

Muon to electron conversion is a unique probe for BSM:

◆ **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 the proton improvement plan (PIP-2) .. instead of Project-X

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

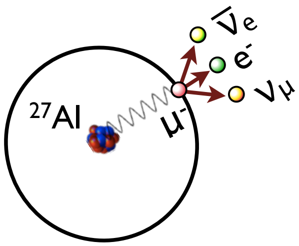
Primer of processes

Experimental Technique

- ☐ Low momentum μ beam (< 100 MeV/c)
- ☐ High intensity “pulsed” rate
- → 10^{10}/s muon stop on Al. target
- → 1.7 μsec micro-bunch
- ☐ Formation of muonic atoms that can make a:

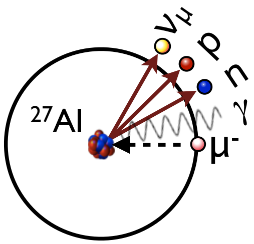
Decay in Orbit (DIO)

(BR=39%)



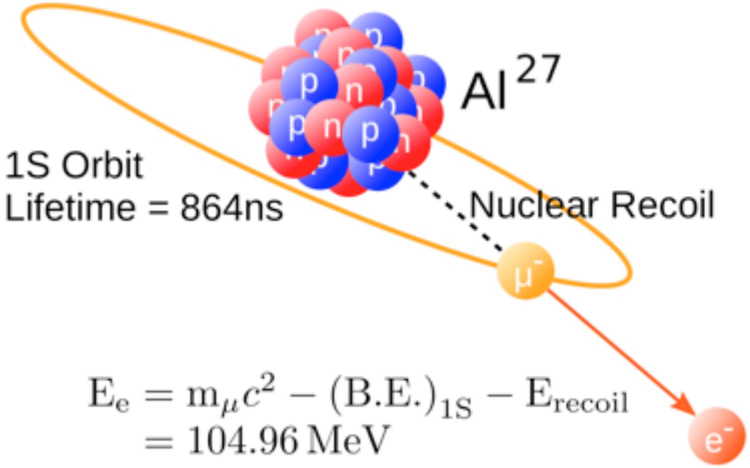
Muon Capture Process

(BR=61%)



The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass

Conversion Process

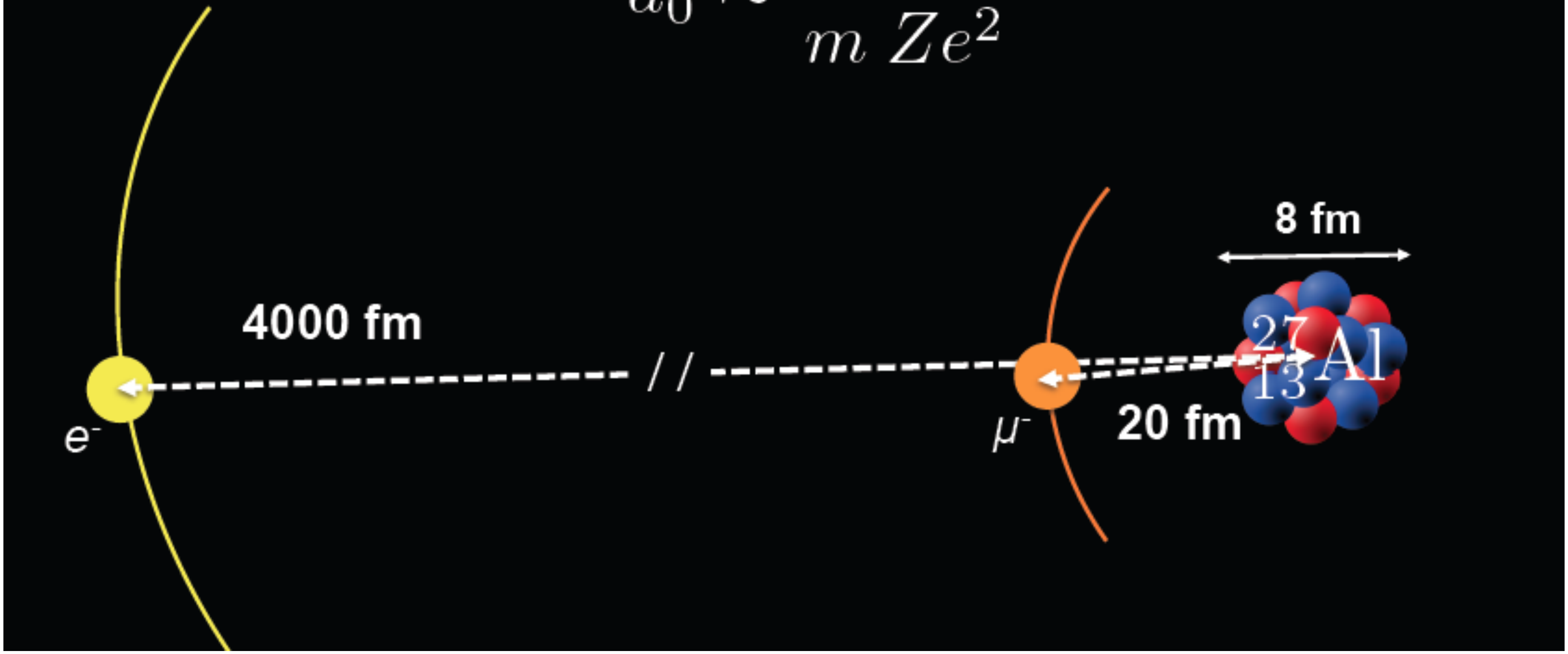


$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil}$$
$$= 104.96\,\mathrm{MeV}$$

The Muonic Atom

- Bound muon cascades quickly to 1*s* ground state (emits *X*-rays)
- Bohr radius of ground state:

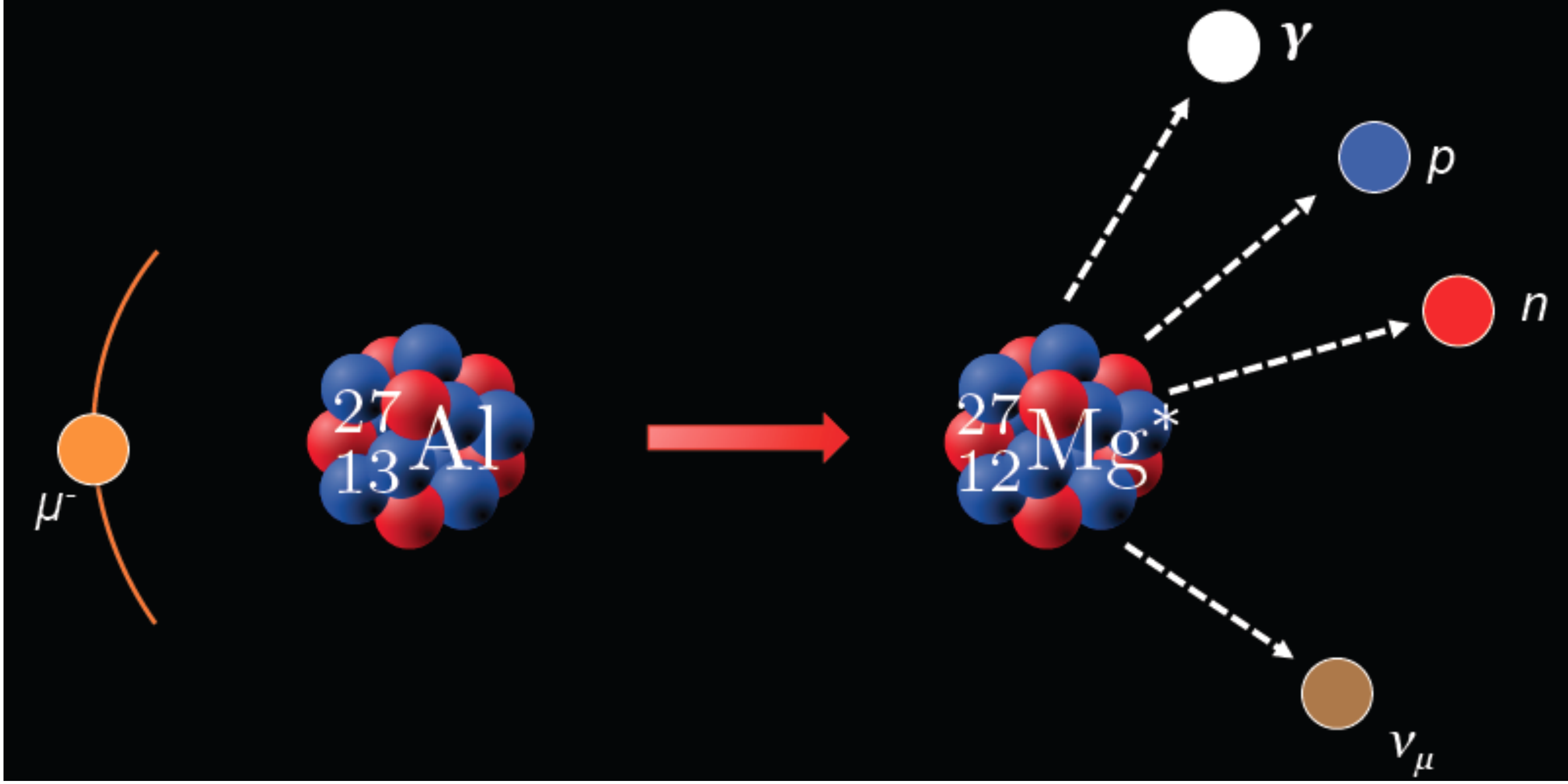
$$a_0 \sim \frac{1}{m}\frac{\hbar^2}{Ze^2}$$



Nuclear Capture processes

- Nuclear capture (61% of bound muons on Al)

$$\mu^- + N \to \nu_\mu + N'$$

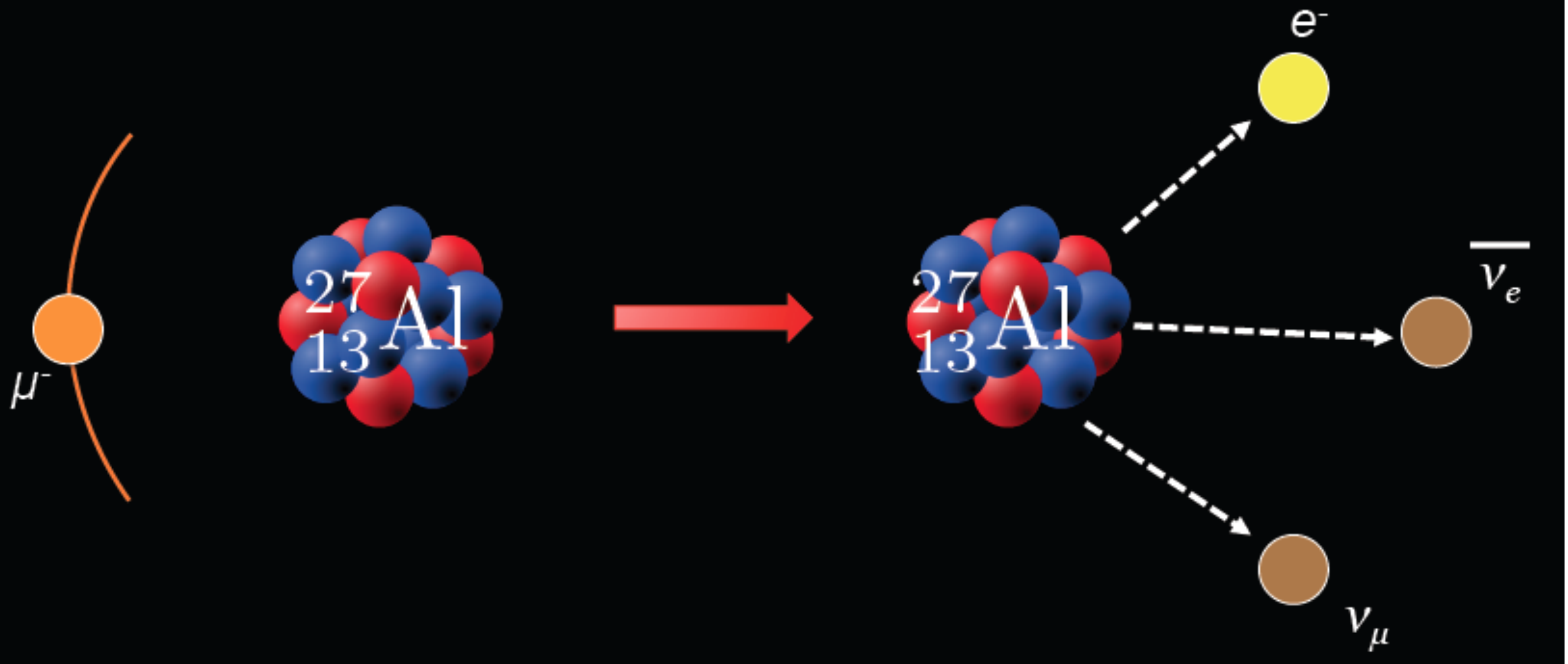


Decay In Orbit

- Decay-in-orbit (39% of bound muons on Al)

  Rest of talk: **DIO**

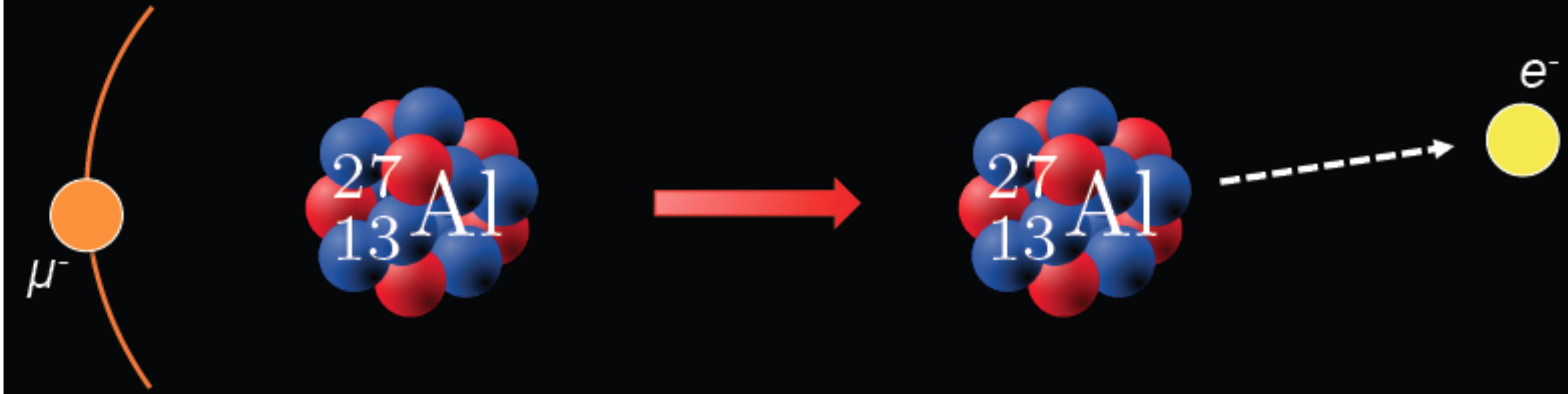
$$\mu^- + N \rightarrow e^- \overline{\nu}_e \nu_\mu + N$$



The signal: Conversion Electron

- Muon to electron conversion

$$\mu^- + N \to e^- + N$$



Experimental signature is a mono-energetic electron of energy

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

We know *exactly* where to look.

EXPERIMENTAL TECHNIQUE

List of Backgrounds to fight

- **Muon decay in orbit (DIO)**
- **Radiative pion capture (RPC)**

  $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N'$
- Antiprotons: produce pions when they annihilate in the target .. antiprotons are negative and they can be slow!
- Pion/muon decay in flight
- Electrons from beam
- **Cosmic rays**
- …

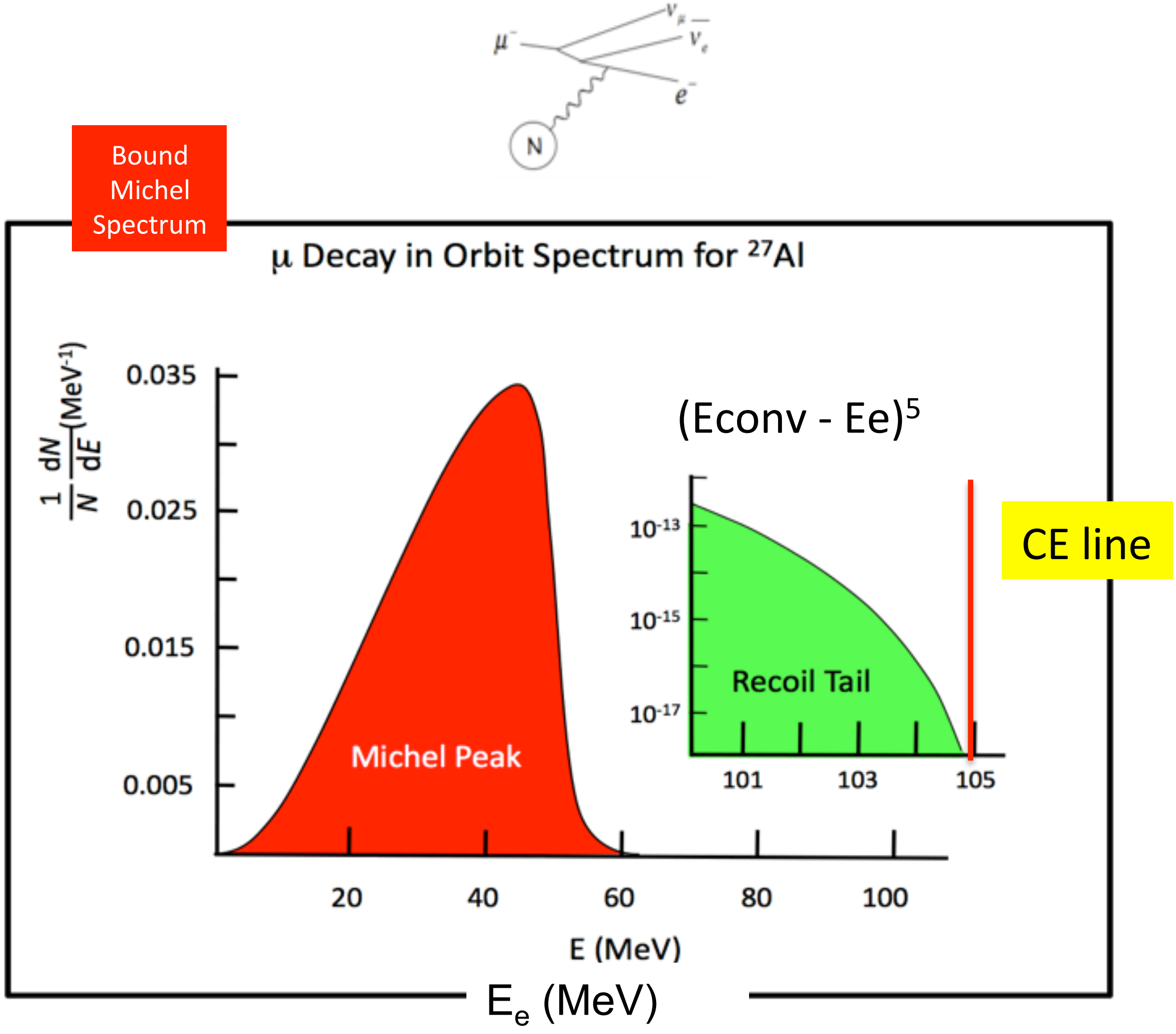
DIO background

☐ The DIO background is the most difficult one.

☐ Electron energy distribution from the decay of bound muons is a (modified) Michel spectrum:

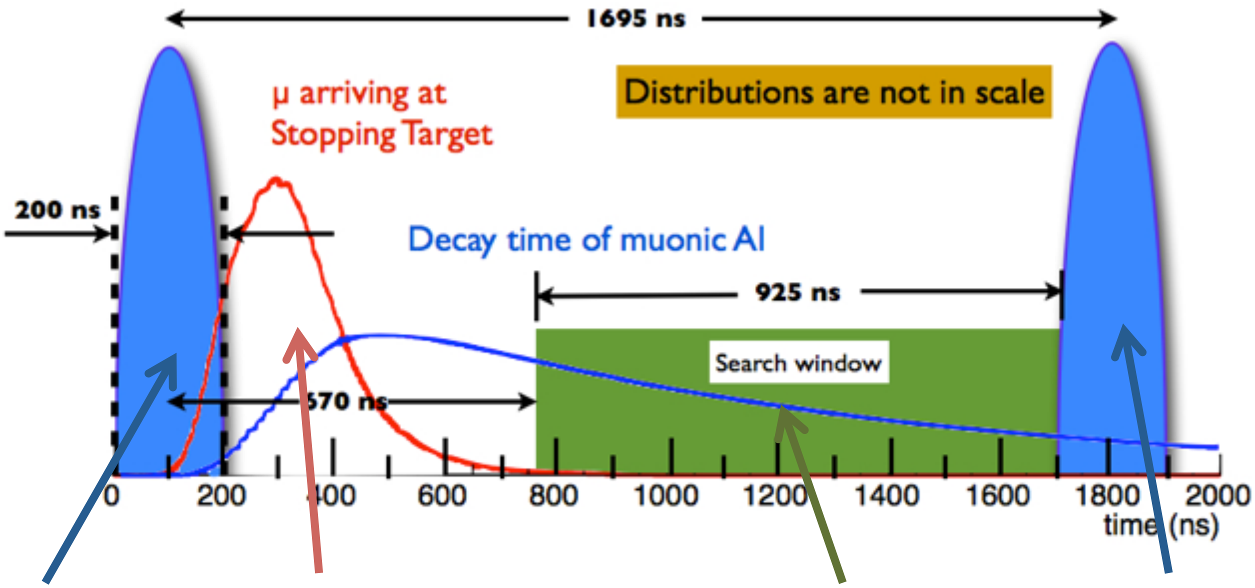
→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ To separate DIO endpoint from CE line we need a high Resolution Spectrometer



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

Beam structure → prompt background



Beam hits target

Prompt bkg like radiative pion capture

Mainly Decay In Orbit background

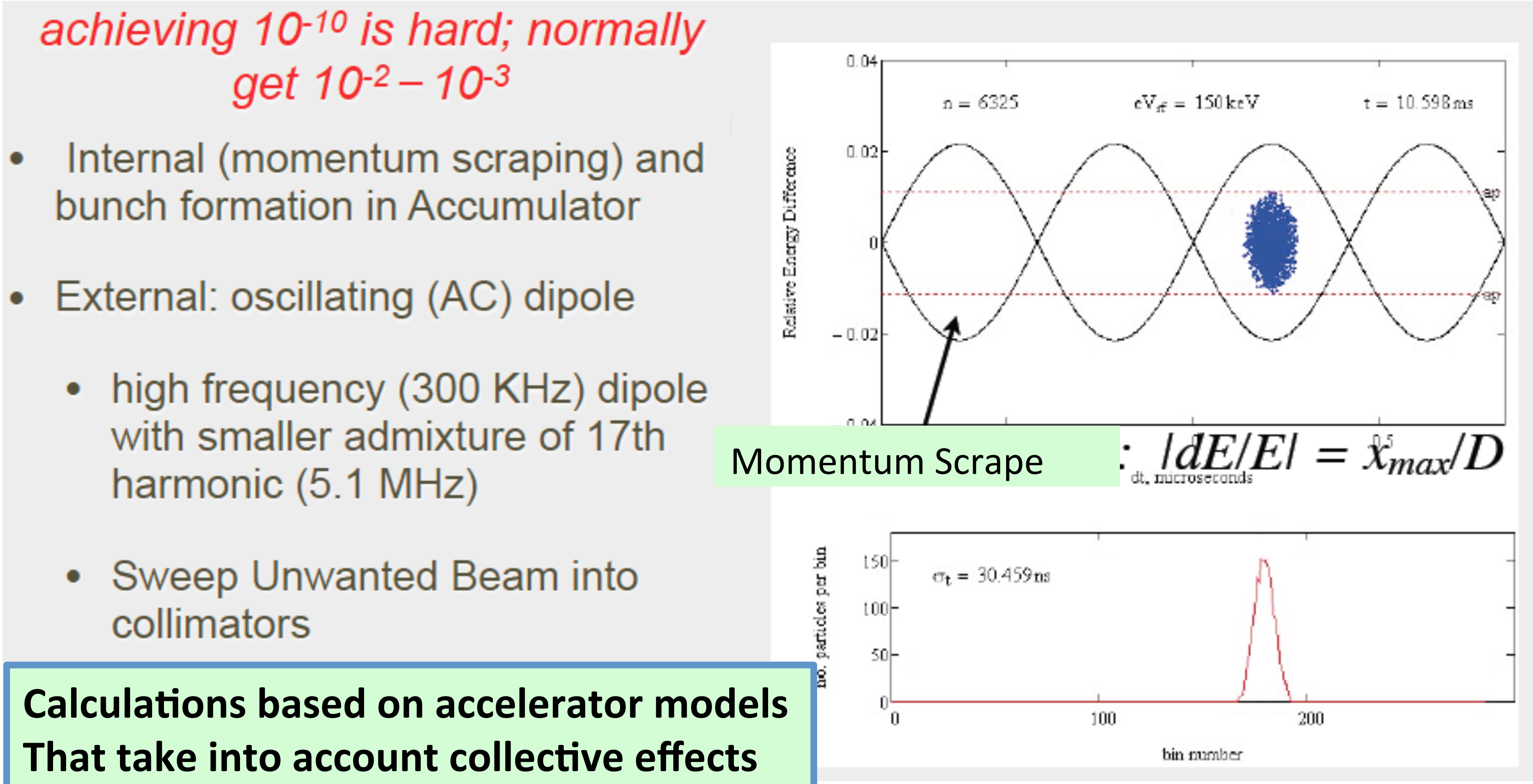
Next bunch

The trick is … muonic atomic lifetime >> prompt background

Need a pulsed beam to wait for prompt background to reach acceptable levels!
Fermilab provides the beam we need !

Out of Time proton → Extinction Method

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

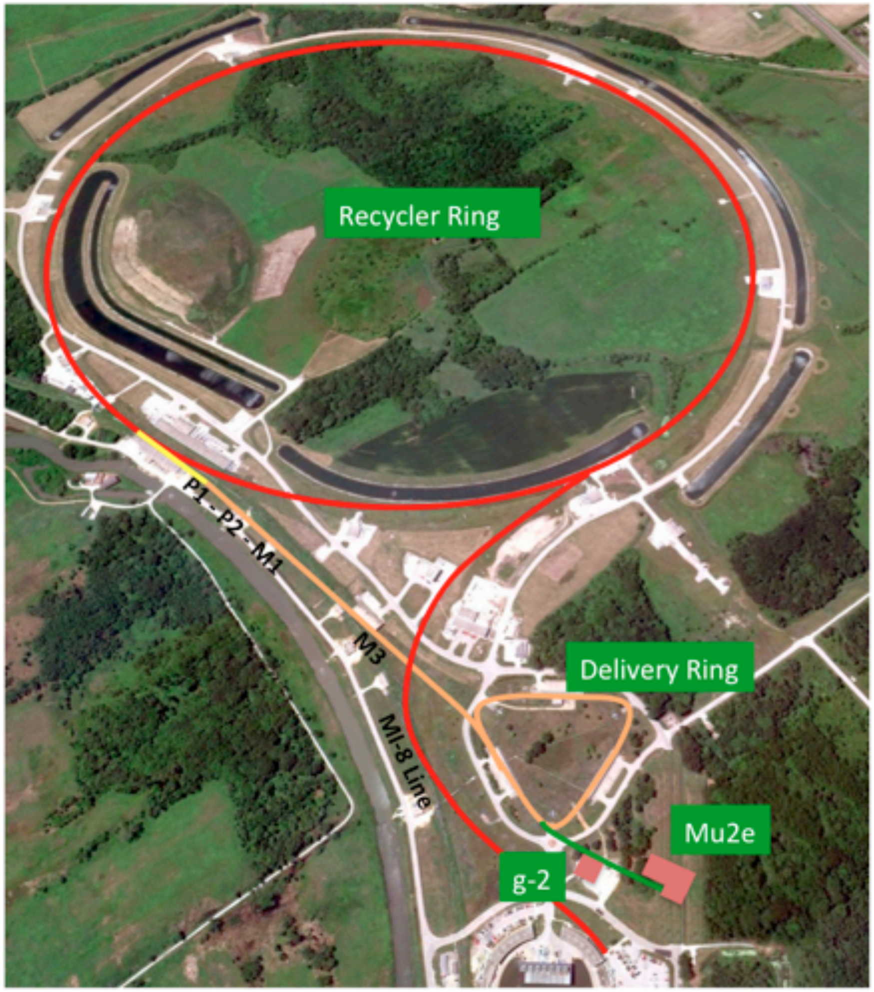
Momentum Scrape

: $|dE/E| = x_{max}/D$

Calculations based on accelerator models
That take into account collective effects
Shows that this combination gets ~ 10^{-12}

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 ~3x10^7 protons each, separated by 1.7 µs (debuncher ring period)**



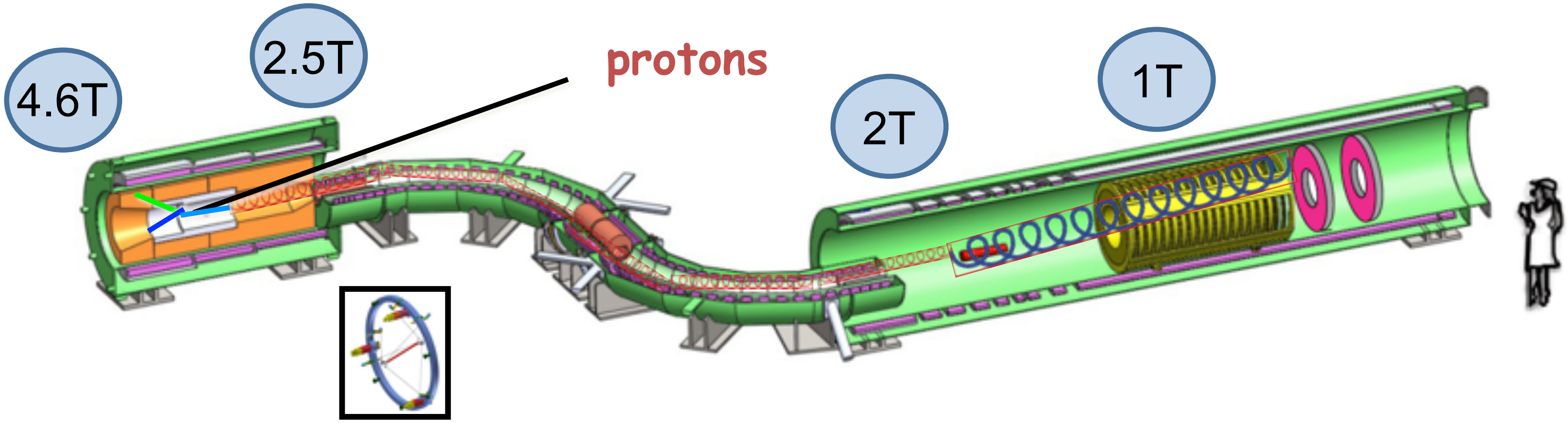
Muon campus: g-2 and Mu2e

Experiment Layout

Muon Beam-line

Production Target / Solenoid (PS)

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



→ Heat and radiation shielding
→ Tungsten target.

Target, Detector and Solenoid (DS)

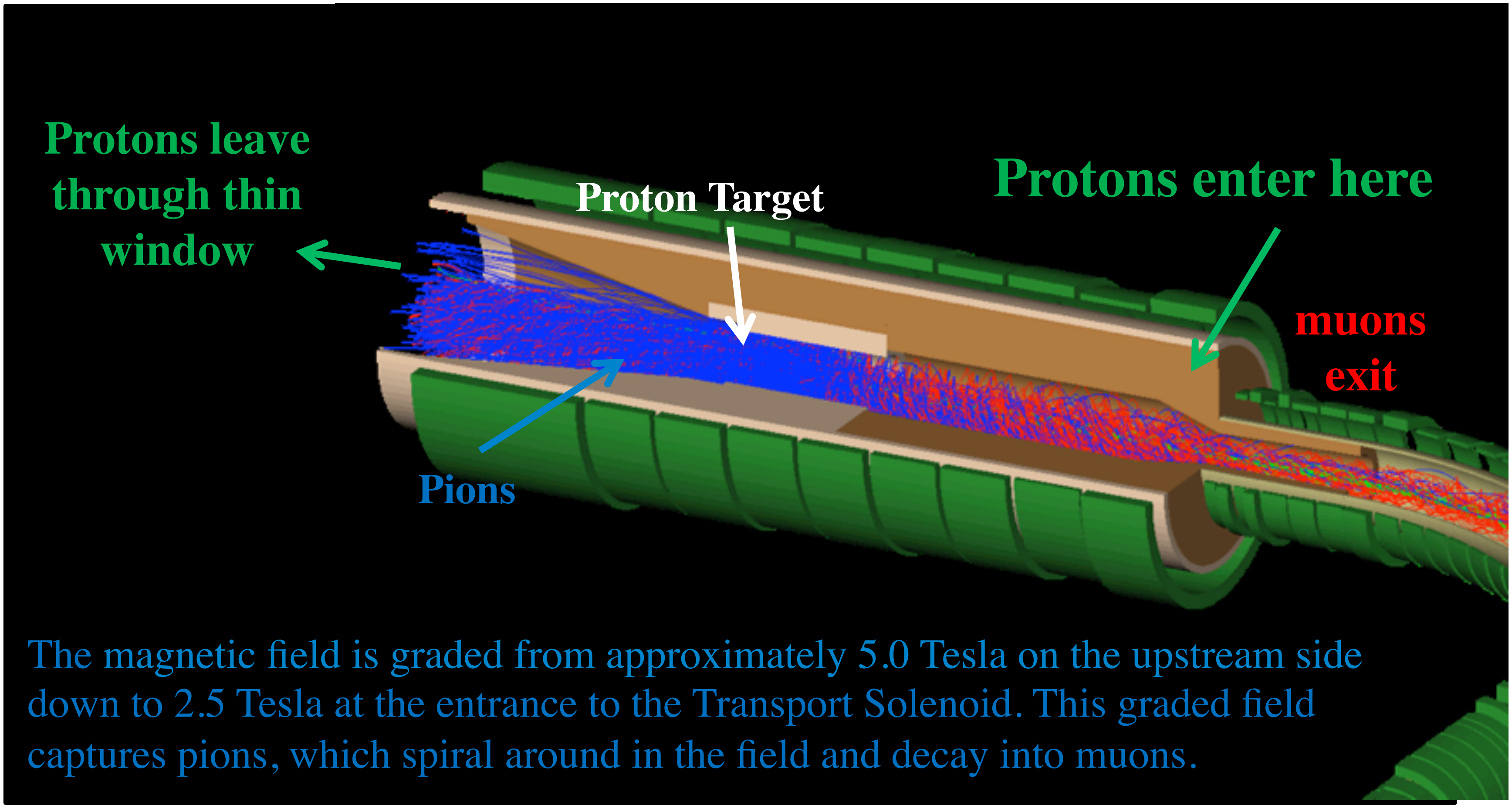
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Transport Solenoid (TS)

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

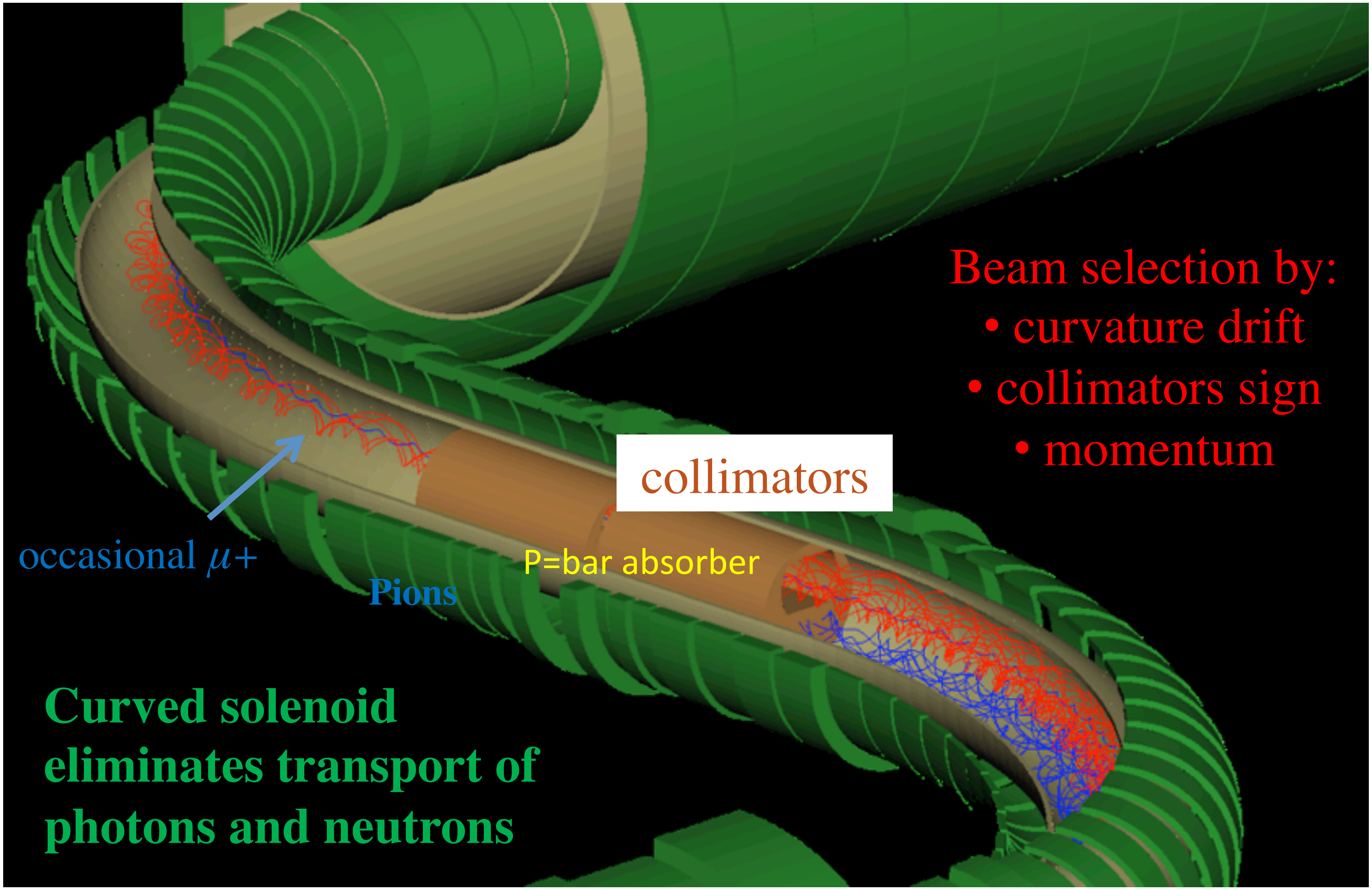
Production Solenoid

Protons enter opposite to outgoing muons:
This is a central idea to remove prompt background



The magnetic field is graded from approximately 5.0 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

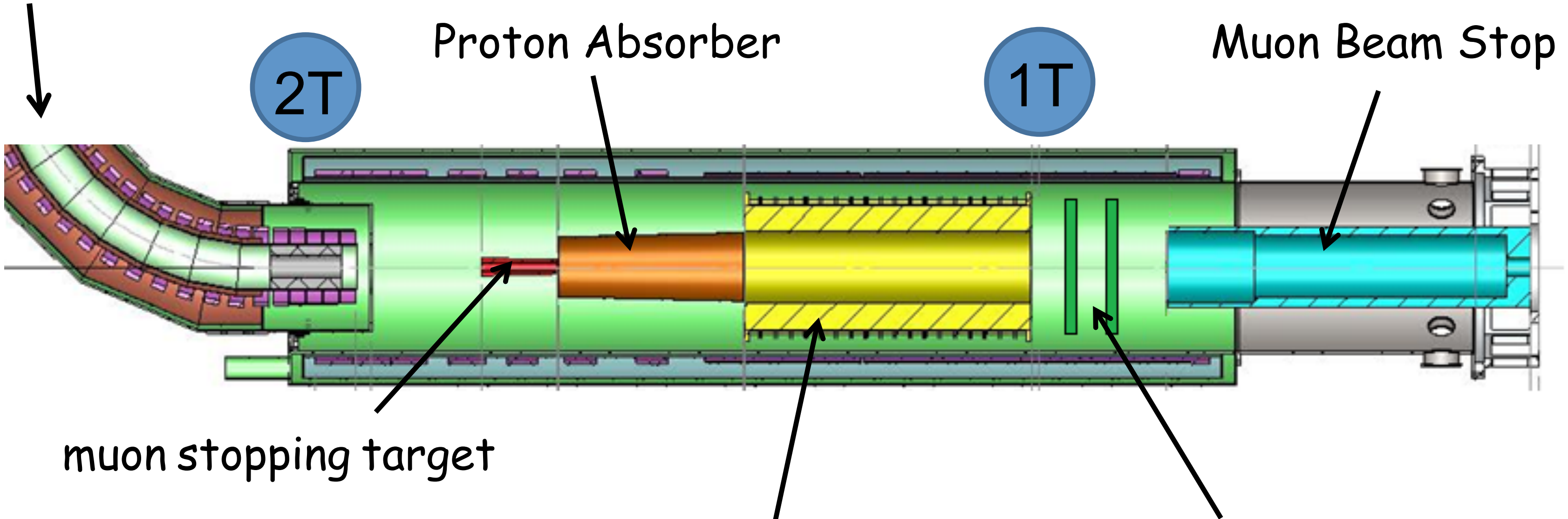


Beam selection by:
- curvature drift
- collimators sign
- momentum

Curved solenoid eliminates transport of photons and neutrons

Detector Solenoid

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



17 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

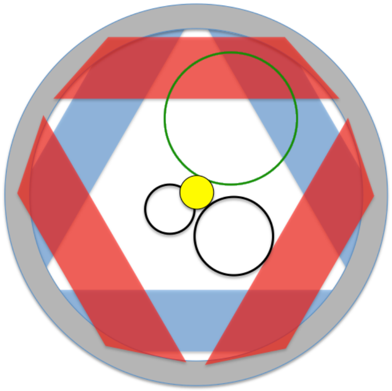
Tracker system

- Tracker is made of arrays of straw drift tubes (red/blue stripes in tracker stations)

- ~ 20000 tubes arranged in planes on stations,
- the tracker has 18 stations.

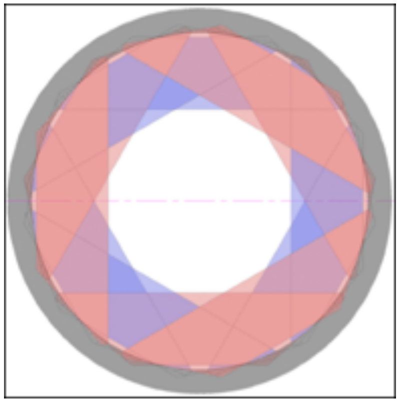
- Tracking at high radius ensures operability (beam flash produces a lot of low momentum particles, large DIO background. Most of this background miss the tracker.)

Tracker Plane



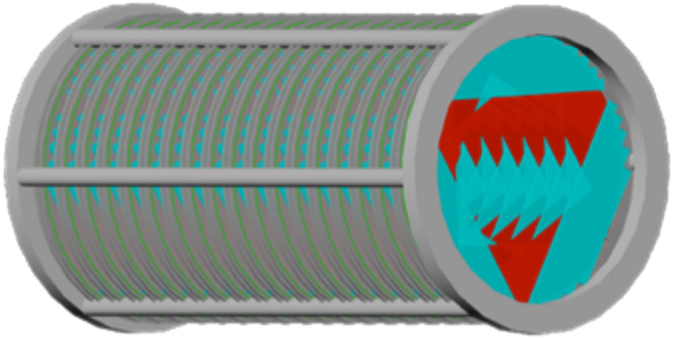
→

Planes rotated



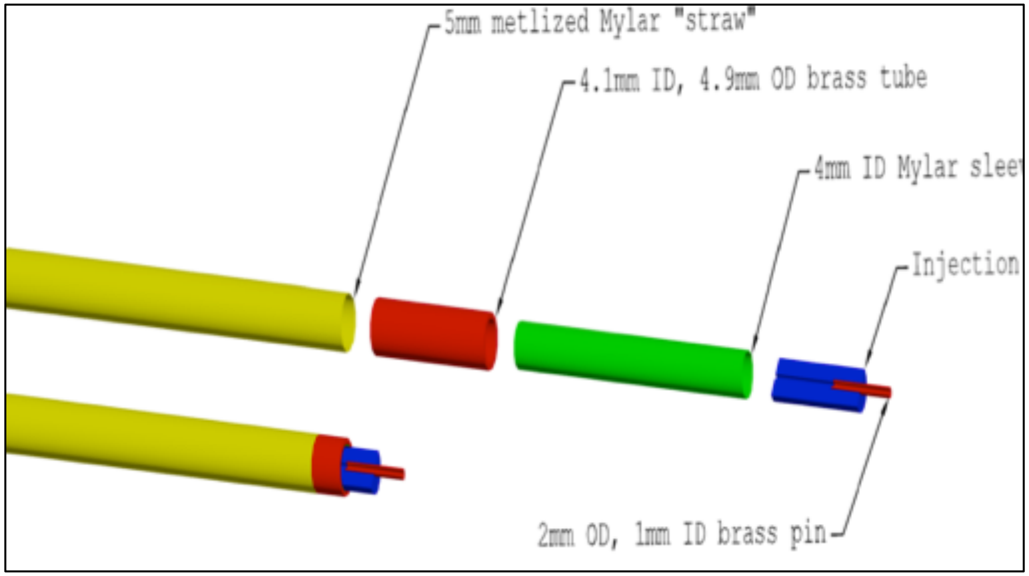
→

Tracker



Straw Characteristics

Straw tube



Characteristics:

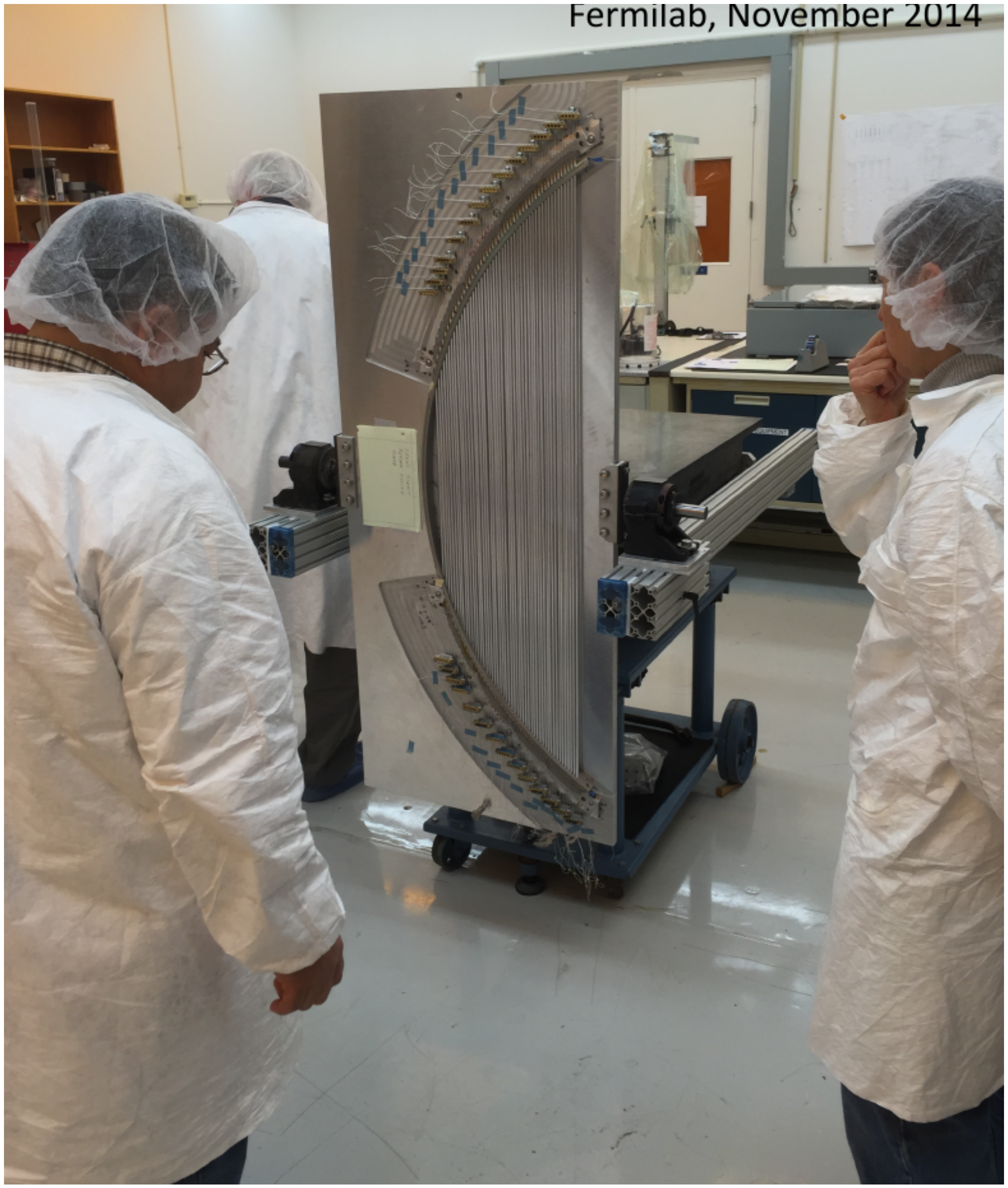
- 5mm diameter and 334-1174 mm length
- 25 μm W sense wire (gold plated) at the center
- 15 microns Mylar wall
- Must operate in vacuum

Straw tubes

- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm) never done before**

Tracker: first panel prototype

Electrical and
vacuum test
in progress



Fermilab, November 2014

Calorimeter System

Calorimeter requirements:

→ Particle Identification to distinguish e/mu

→ Seed for track pattern recognition

→ Tracking independent trigger

→ Work in 1 T field and 10^{-4} Torr vacuum

→ RadHard up to 30 krad, 10^{12} n/cm^2/year

Calorimeter choice:

High granularity crystal based calorimeter with:

→ σ/E of O(5%) and Time resolution < 500 ps

→ Position resolution of O(1 cm)

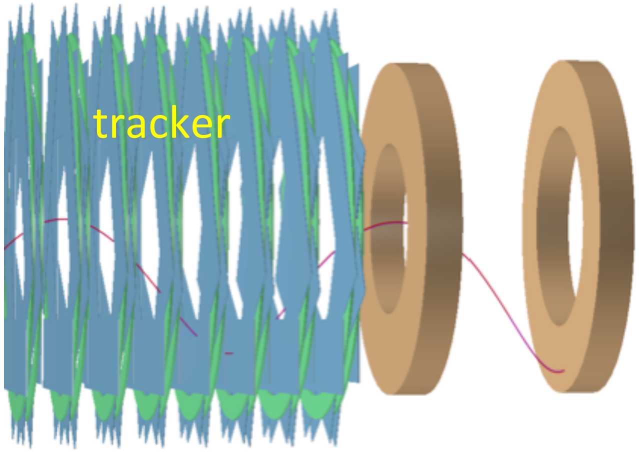
→ almost full acceptance

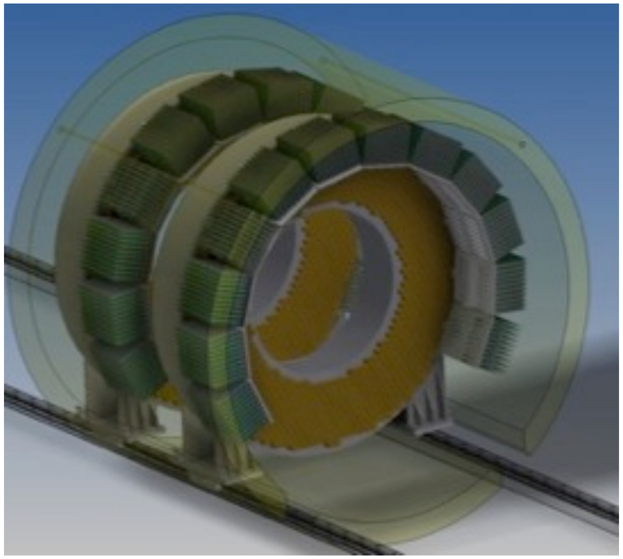
for CE signal @ 100 MeV

Disk geometry

- Square crystals
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$

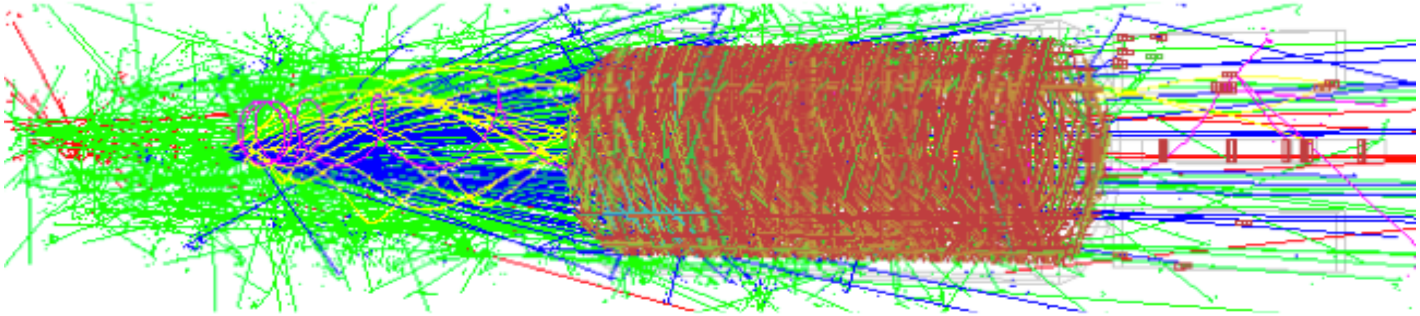
Two disks separated by ½ wavelength (70 cm)



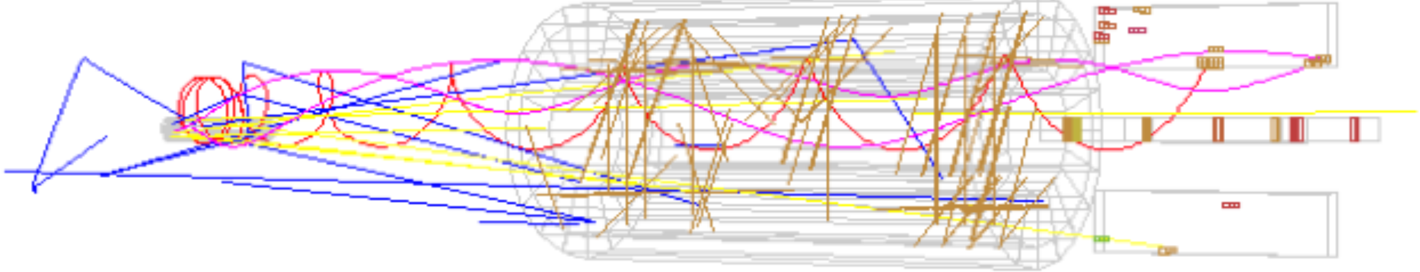


A typical Mu2e event: Calo track seeding

500 – 1695 ns window



± 50 ns around conversion electron

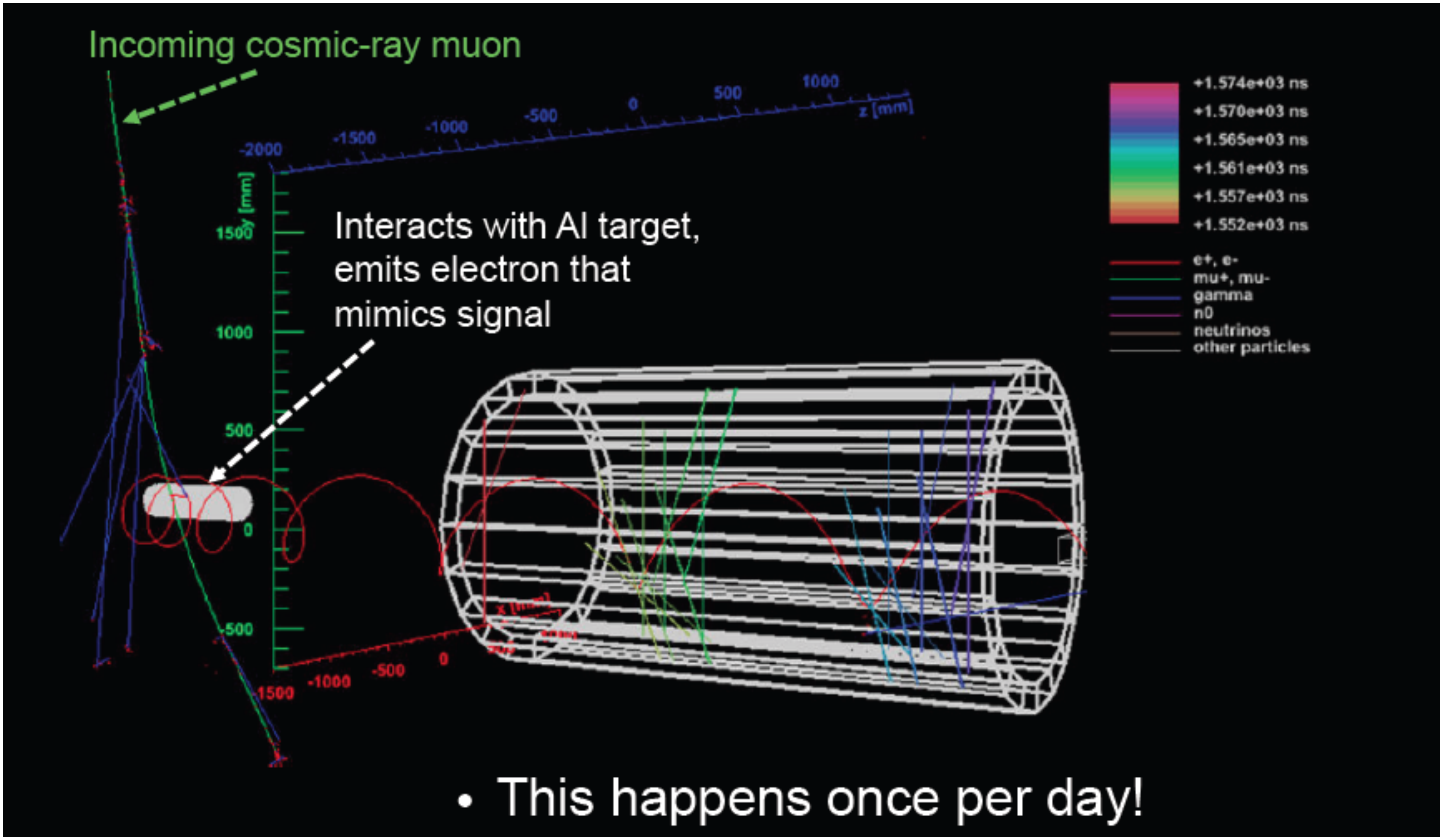


☐ Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → simplification of pattern recognition

☐ Add search of an Helix passing through cluster and selected hits + use calorimeter time to calculate tracking Hit drift times.

→ Reduce the wrong drift sign assignments i.e. **smaller positive momentum tail**

Cosmic Rays are a problem



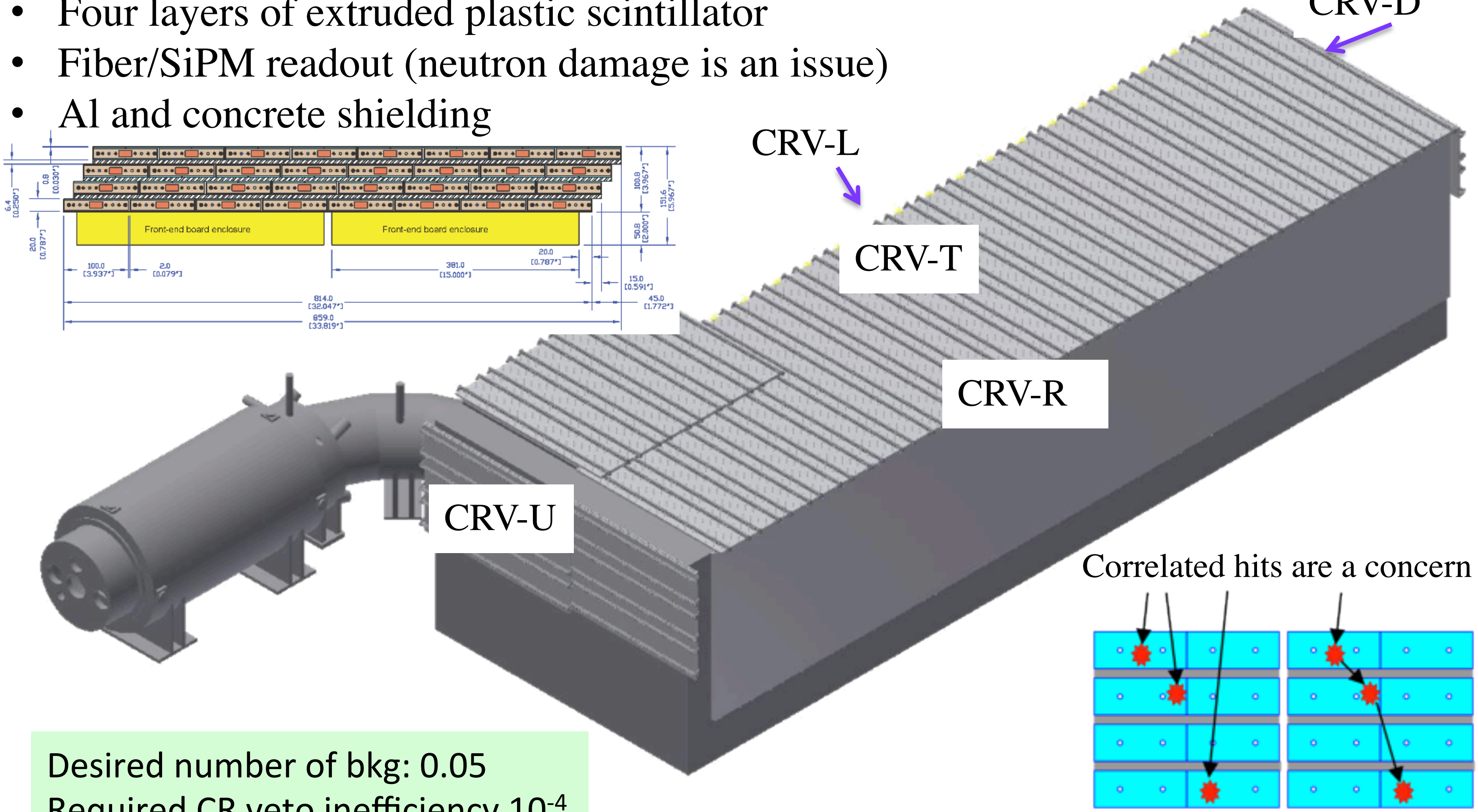
Incoming cosmic-ray muon

Interacts with Al target, emits electron that mimics signal

- This happens once per day!

Cosmic Ray Veto

- Four layers of extruded plastic scintillator
- Fiber/SiPM readout (neutron damage is an issue)
- Al and concrete shielding

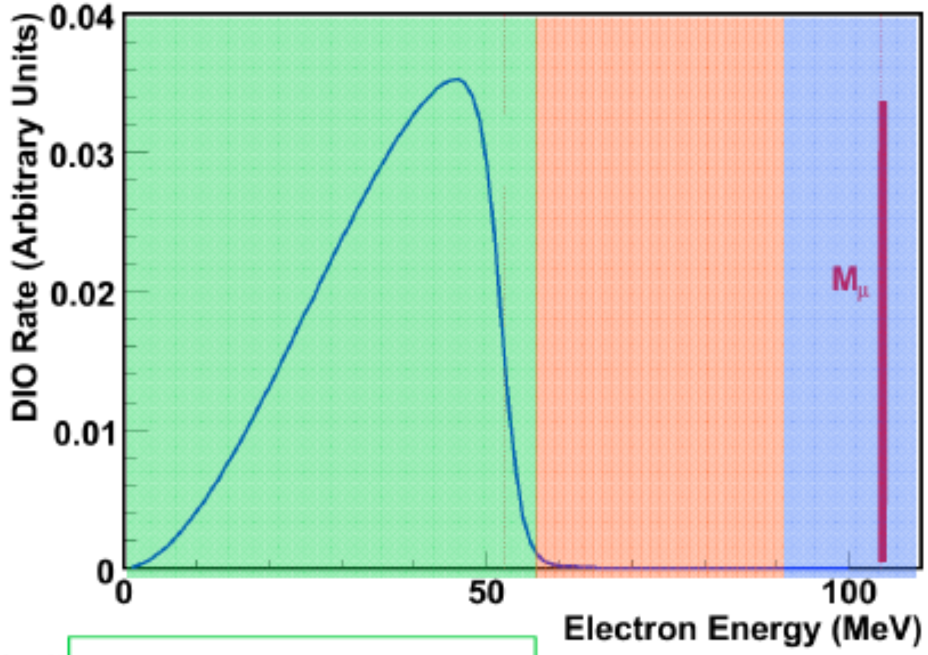


Correlated hits are a concern

Desired number of bkg: 0.05
Required CR veto inefficiency 10^{-4}

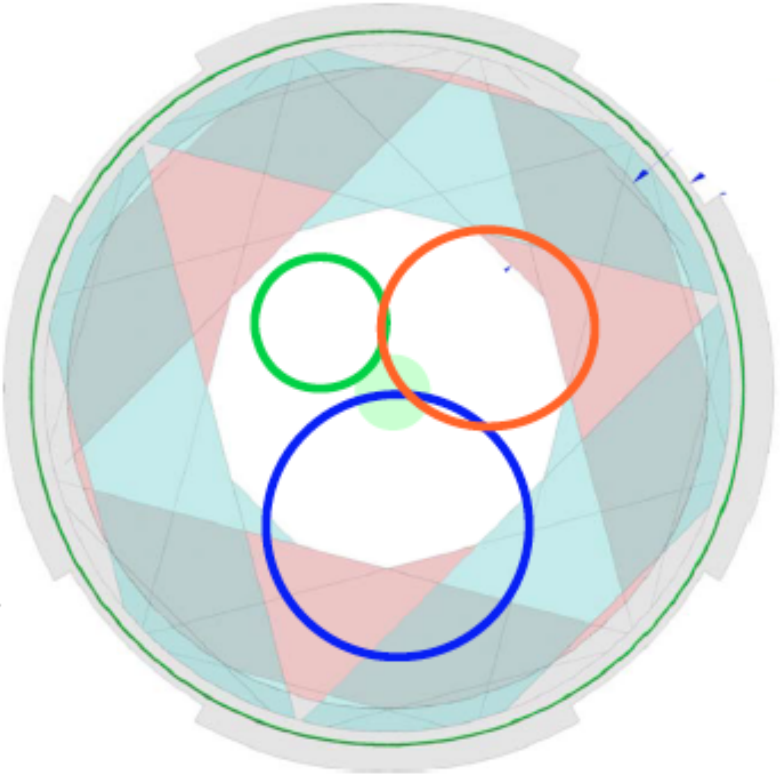
Basic reconstruction scheme

reconstructable tracks



no hits in tracker

some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

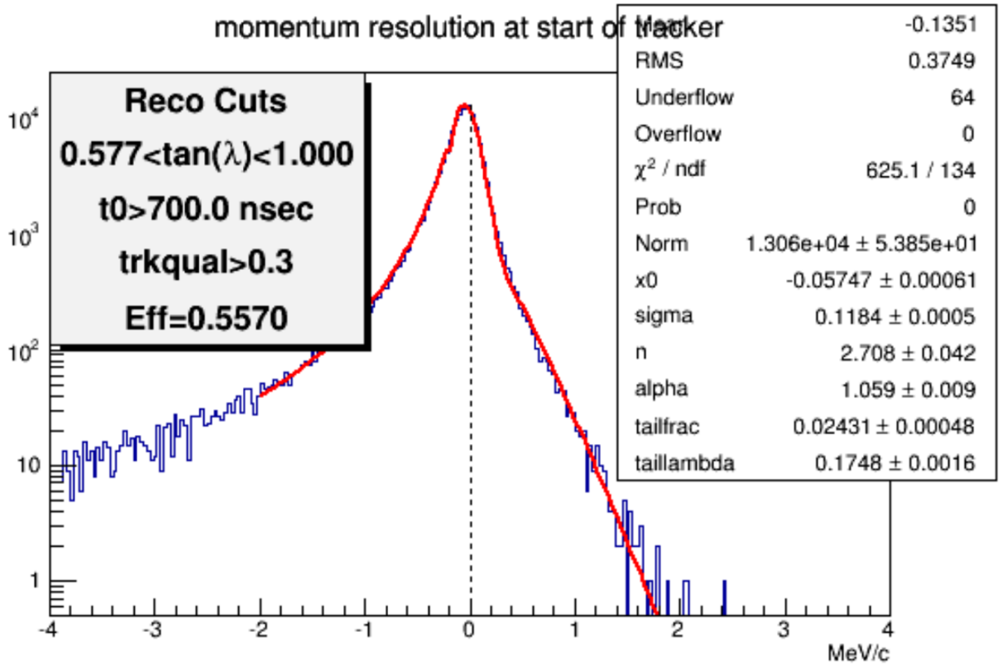
Simulation results on tracker

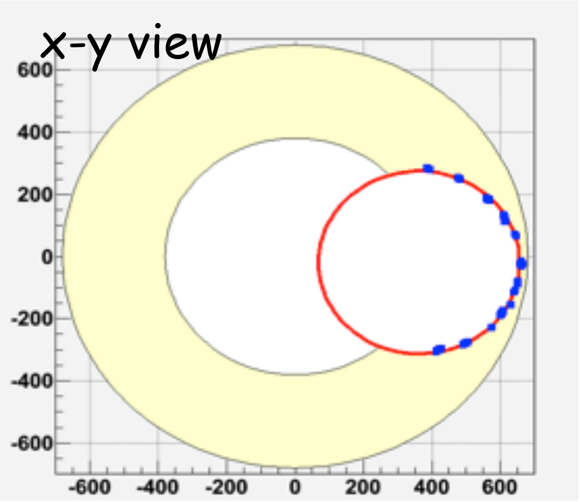
Pattern Recognition based on
***BABAR* Kalman Filter algorithm**

No significant contribution of
mis-reconstructed background

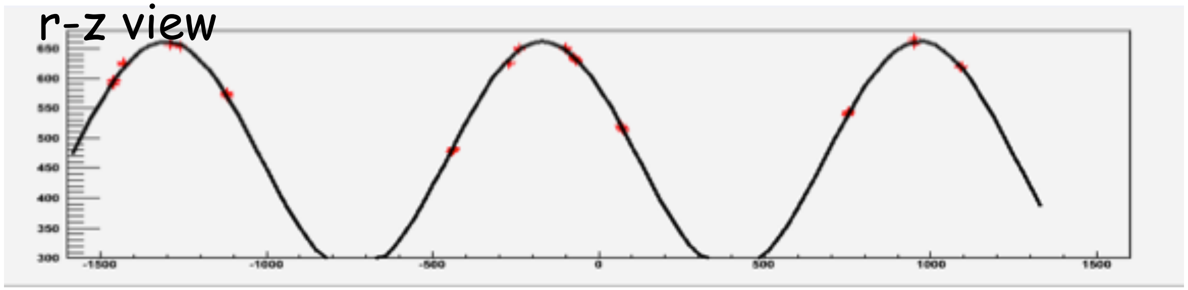
Momentum resolution

core σ~120 keV
tail σ~175 keV (2.5%)

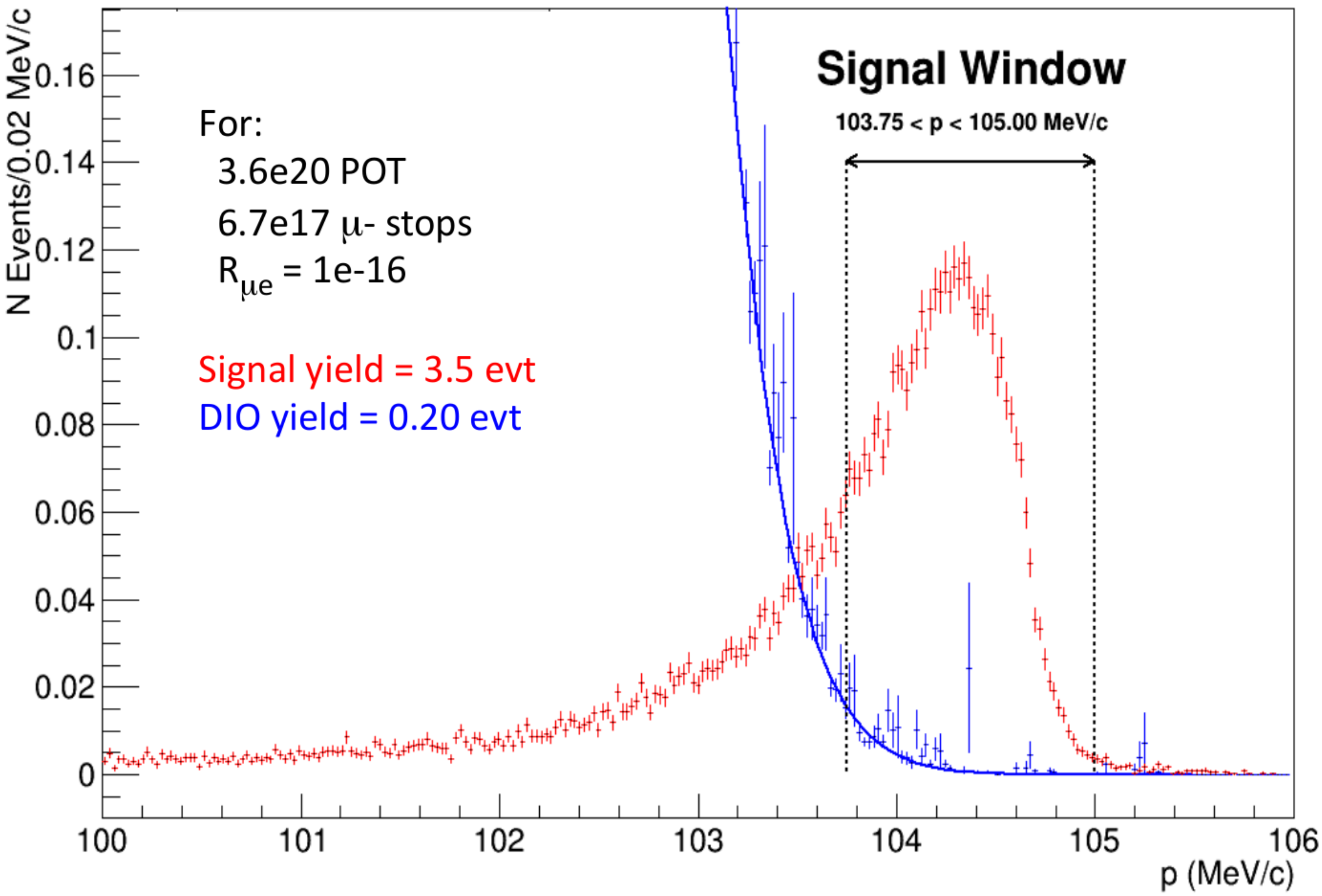




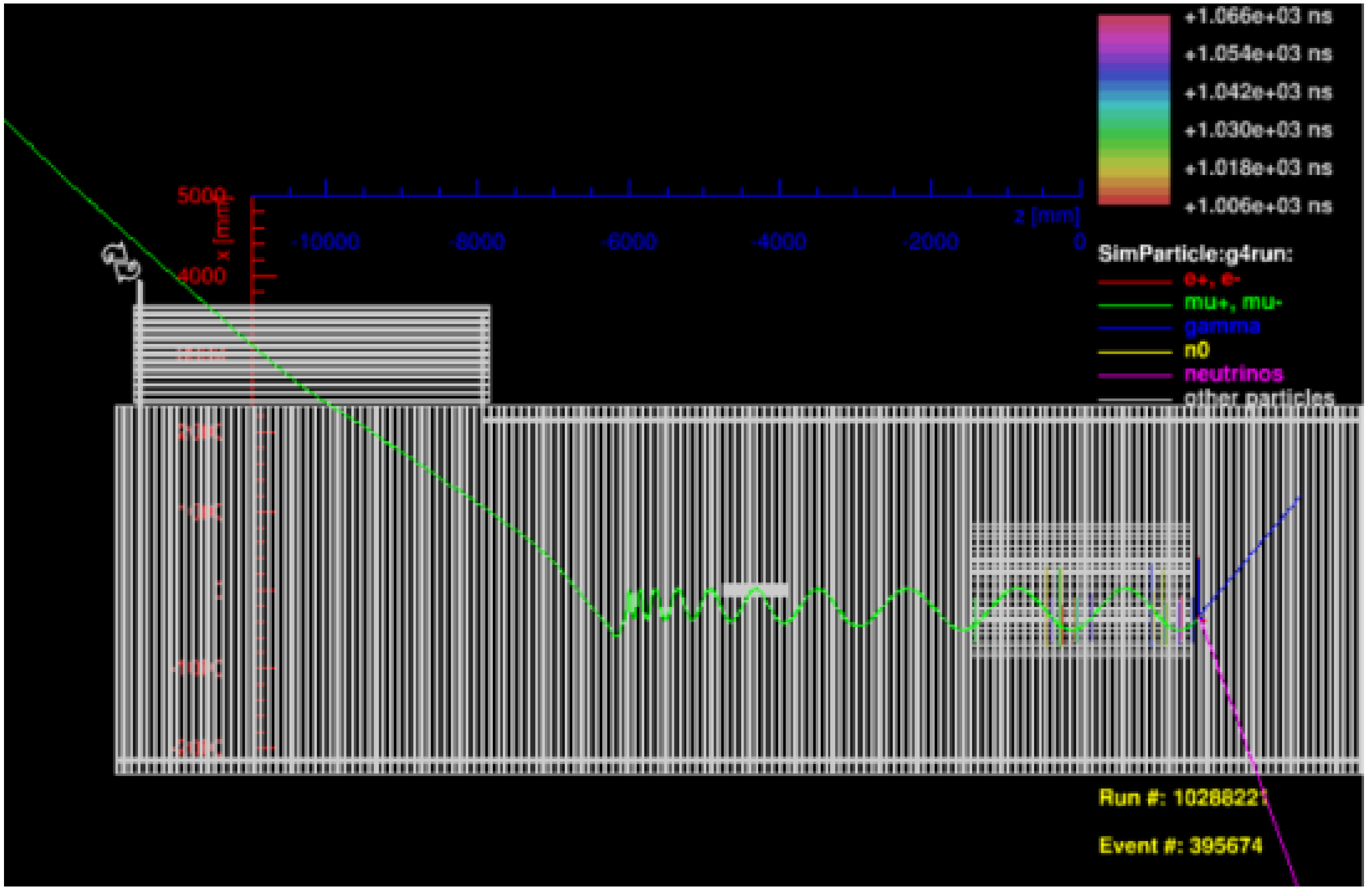
Fit: Crystal Ball + exponential



DIO/CE final count with simulation



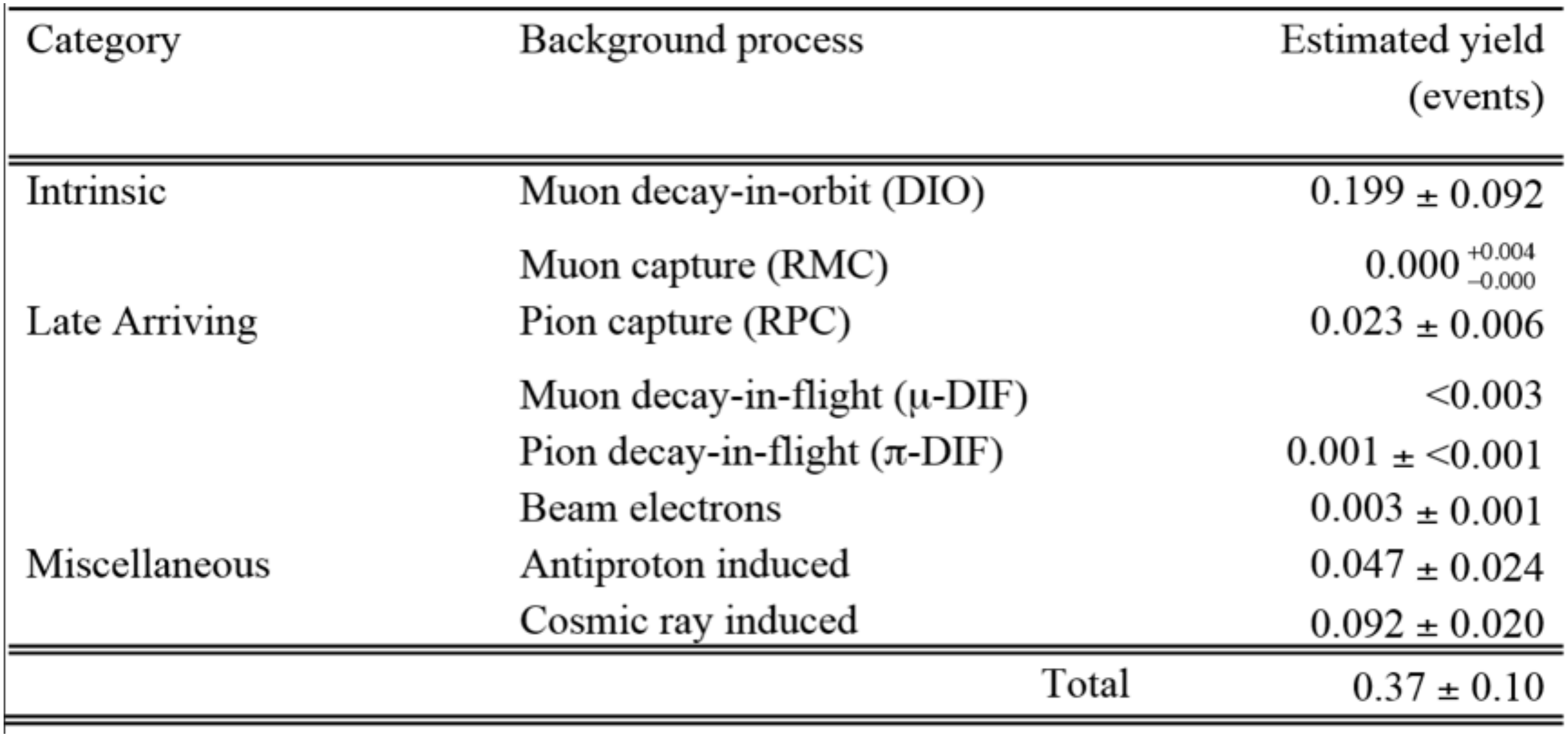
“fake” CE from CR events



- ❑ A long MC production used to optimize the CRV geometry by generating the same amount of cosmics that will cross the detector in MU2E running period.
- ❑ **few events evaded the CRV**, passing closely enough to the target, were tracked by the tracker and passed all reconstruction tracking criteria. They were all μ^- → **rejected due to the combination of Calorimeter and tracking information : timing and *E*/*p***

Mu2e Expected Background

(assuming ~ 10 GHz muon stops, 6×10^{17} stopped muons in 6×10^{7} s of beam time)



Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6×10^{-17} @ 90% C.L.

Mu2e Status and plans

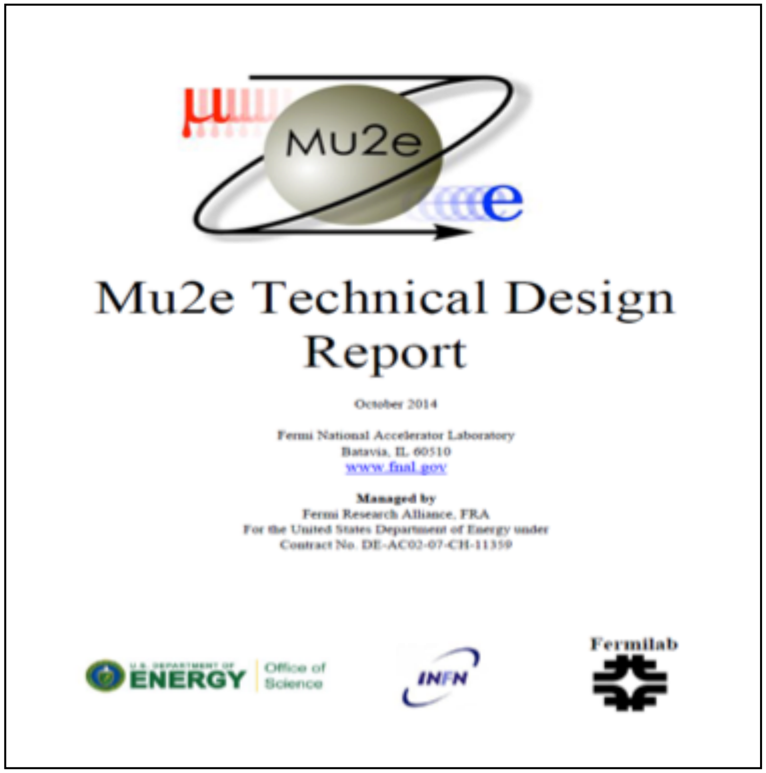
Mu2e Collaboration

Mu2e Collaboration 2013

- ~185 Collaborators, 32 Institutions, 3 +2 Countries
- Still growing. Discussion with several USA university groups.
- **2 UK groups joining: UCL(M.Lancaster), Liverpool(T.Bowcock)**
- **HZDR Dresda joining (A.Ferrari)**

Dresda groups joined @ April CM, UK in 2016

Mu2e TDR

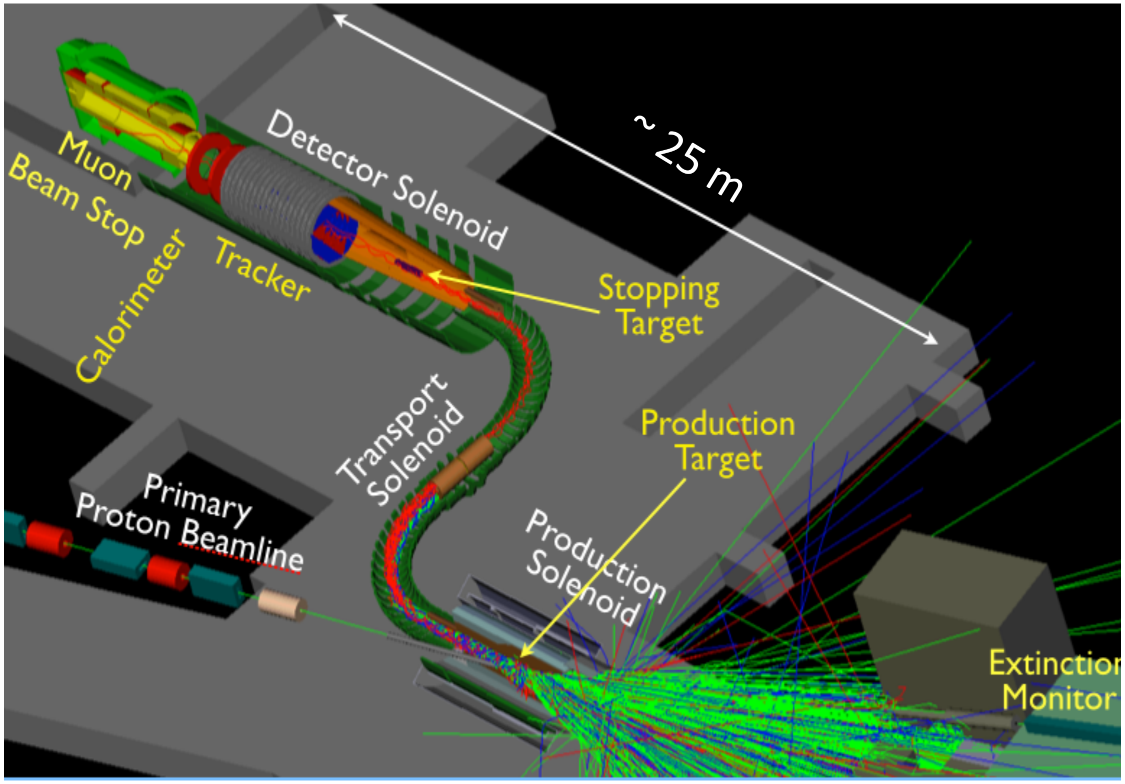


Mu2e Technical Design Report

October 2014

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359



http://mu2e.fnal.gov/

TDR available at http://arxiv.org/abs/1501.05241

Mu2e Schedule and plans

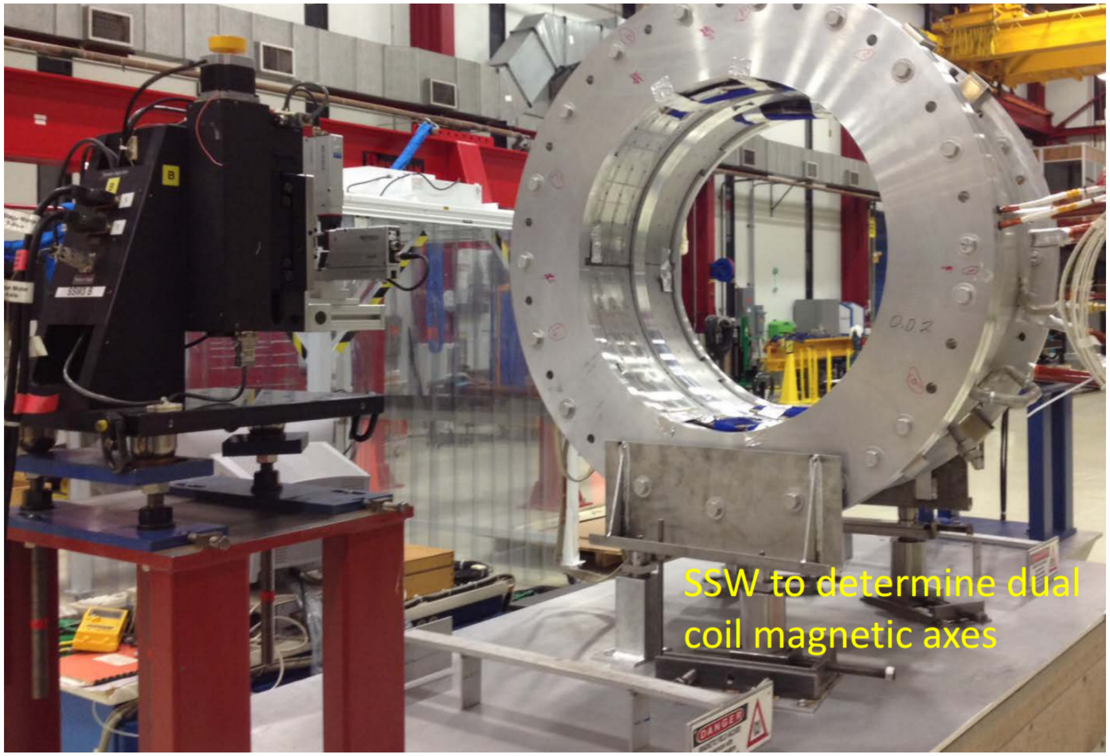
- CD2 for detectors (baseline/TDR) obtained on the 5th of March 2015
- CD3b for Civil Construction and start for TS Bid obtained on same date.

- **Final signatures from DOE done:**
  - → Procurement of Superconducting cables in progress
  - → Bid for DS/PS assigned to General Atomics
  - → Bid for TS completed. Expected output on May 2015
  - → Civil Construction started**: Ground Breaking Cerimony Apr. 18**.

- CD3 for detectors planned for spring 2016

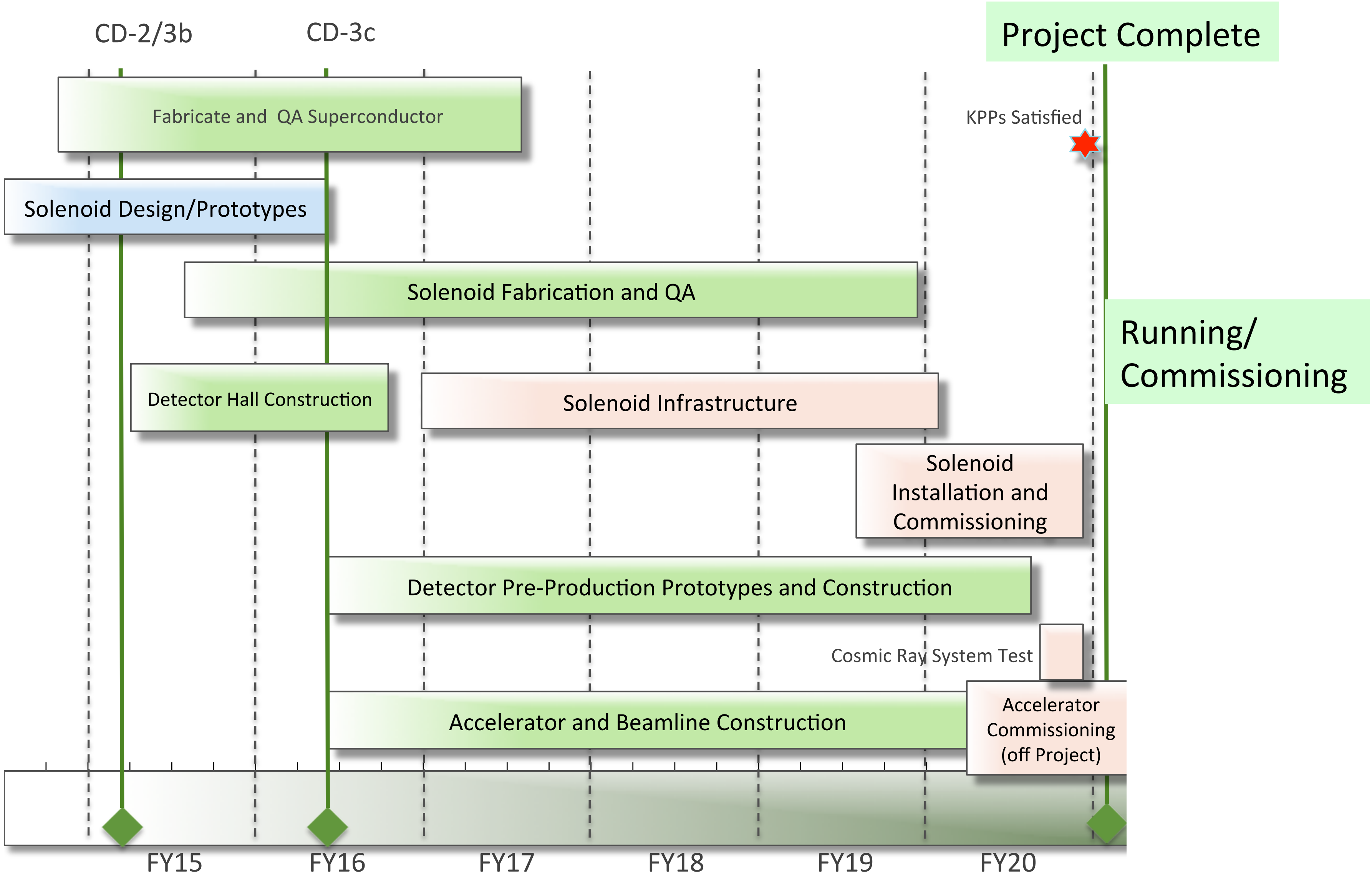
- **Overall DOE budget secured, 274 M$**.

Status of Magnetic System



- ☐ **The Super Conducting magnets are the heart of MU2E Apparatus**
- ☐ PS and DS bid is over. **They will be built by General Atomics, USA**
- ☐ TS prototype manufactured by ASG Superconductors, Genova
- ☐ **TS proto @ FNAL since December 2014, under test now**
- ☐ **TS BID in progress → expect to know the final choice in 1 month**

Mu2e project schedule



CD-2/3b

CD-3c

Project Complete

Fabricate and QA Superconductor

KPPs Satisfied

Solenoid Design/Prototypes

Solenoid Fabrication and QA

Running/ Commissioning

Detector Hall Construction

Solenoid Infrastructure

Solenoid Installation and Commissioning

Detector Pre-Production Prototypes and Construction

Cosmic Ray System Test

Accelerator and Beamline Construction

Accelerator Commissioning (off Project)

FY15 FY16 FY17 FY18 FY19 FY20

(WhatNext?) Mu2e → Mu2e-2

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)
→ 2 MW at regime at LNBF
→ **x 10 at Mu2e**

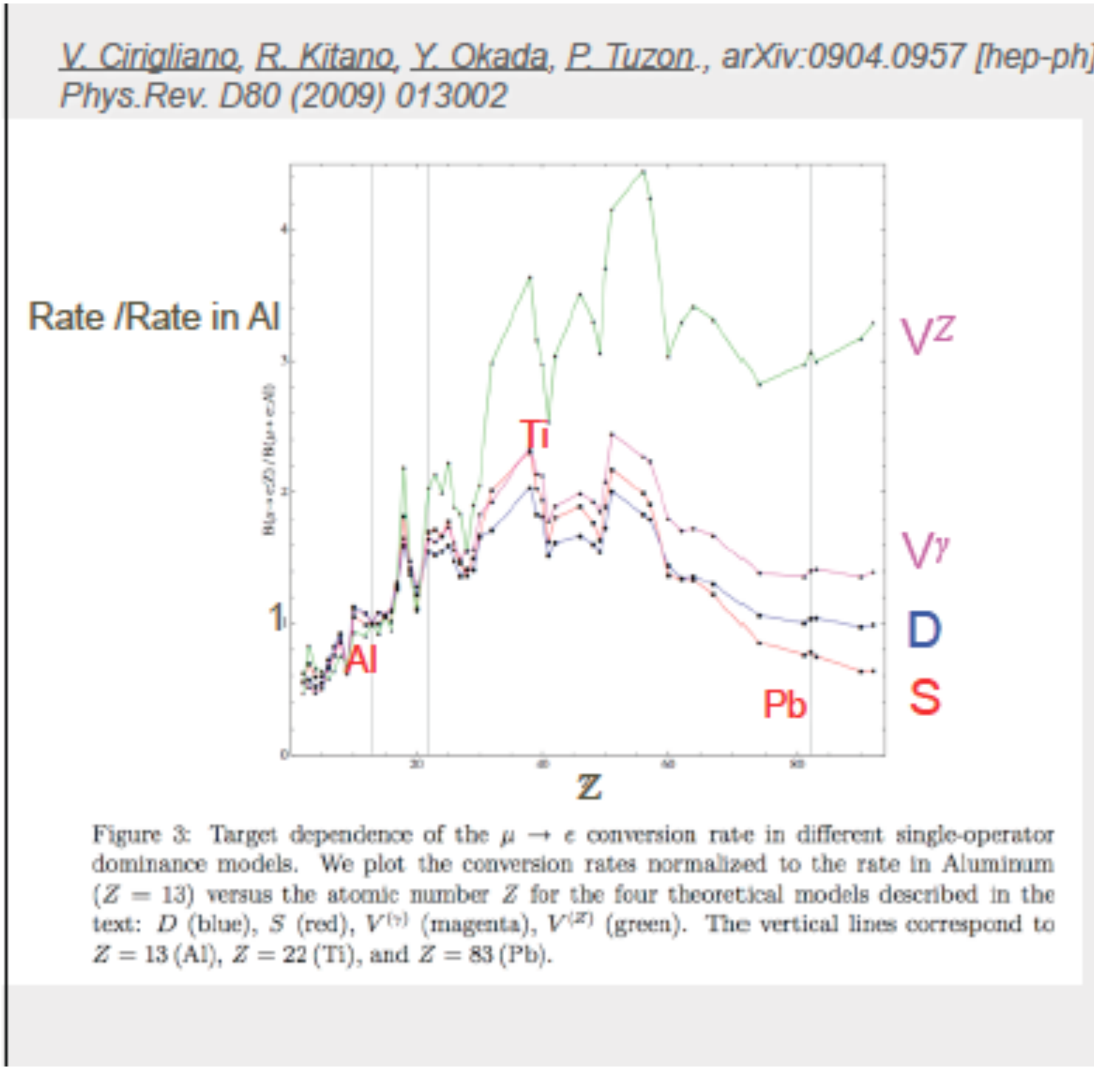
Projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232
CLVF-snowmass →Arxiv.1311.5278
Mu2e-2 → Arxiv.1307.1168v2.pdf

2) **Depending on the beam Structure available:**
→ study Z dependence if signal is observed

3) If no signal is observed

Use x 10 events in Mu2e-2

Minor modifications of the detector → **BR < 6 x 10^{-18}**



V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph]
Phys.Rev. D80 (2009) 013002

Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

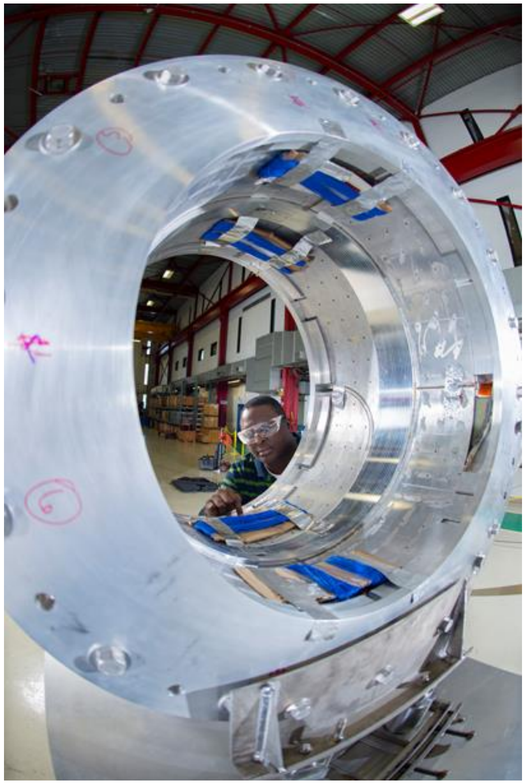
Mu2e and INFN

Mu2e & INFN

Strong involvement of INFN group in two items:

(1) Calorimeter system: project leadership, design & construction of proto, FEE and mechanics, Laser system.

(2) Construction of prototypes for the TS magnet done by INFN Genova (via ASG superconducting). Test of Superconducting cables.



INFN group size extrapolated to 2017

→ 30 people, O(20 FTE)

INFN financial contribution so far:

- ☐ 500 kEuro for construction of TS proto
- ☐ 400 kEuro R&D calorimeter and I-tracker

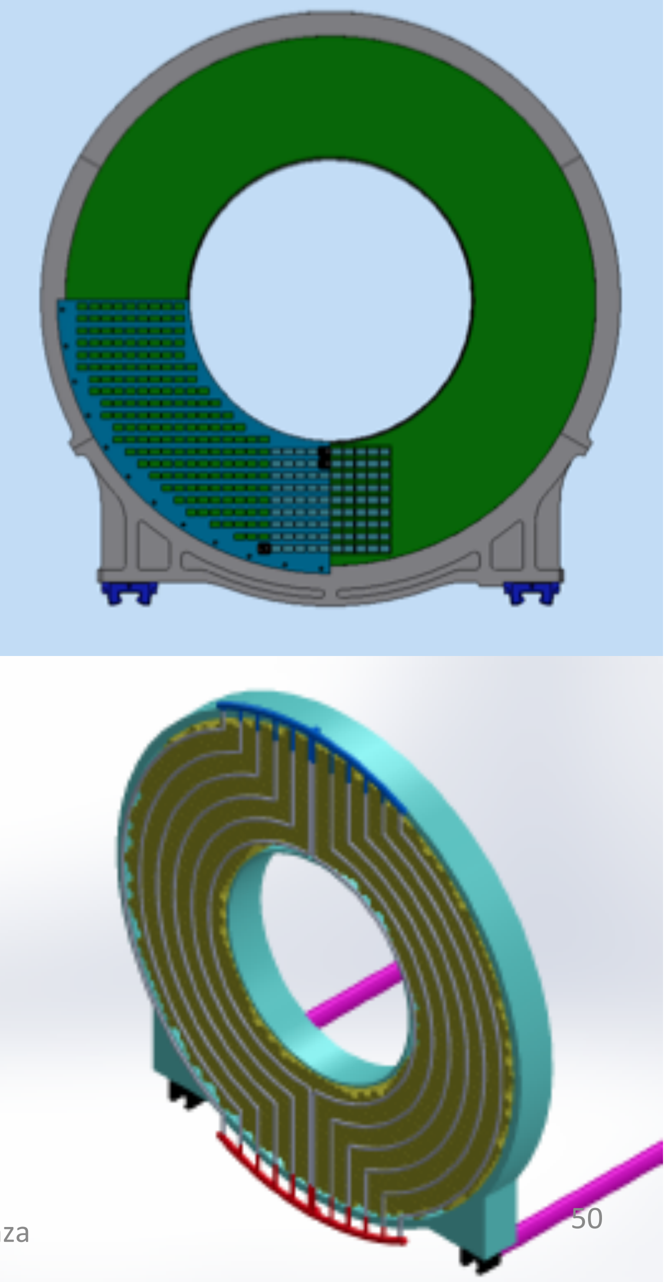
Expected Core contribution O(3 MEuro)

Next steps → INFN CTS

Calorimeter Layout

The Calorimeter consists of two disks with 1650 square crystals (30x30x200) mm^3

- ☐ R_{IN} = 351 mm, R_{OUT} = 660 mm
  Depth = 10 X_0 (200 mm)
- ☐ Each crystal readout by two APDs (9x9 mm^2) (3300 total) for redundancy and NCE x-check
- ☐ Analog FEE and digital electronics located in near-by electronics crates
- ☐ Radioactive source and laser systems provide absolute calibration as well as fast and reliable monitoring capability.



Crystal Choice

	~~LYSO~~	BaF$_2$	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF$_2$)

BASELINE-TDR

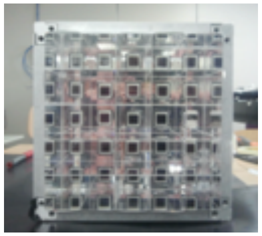
- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be “solar”-blind
- Medium cost 10$/cc

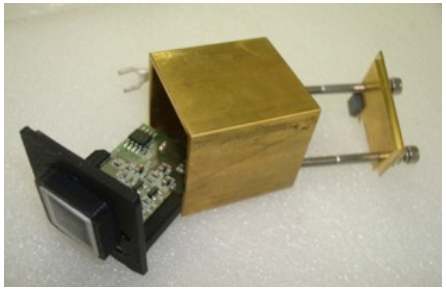
CsI(pure)

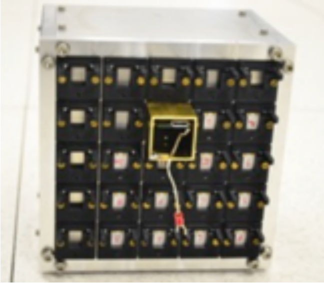
TDR Alternative

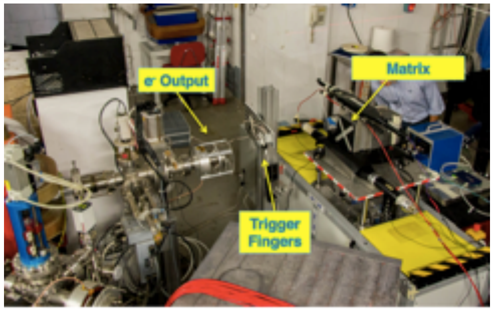
- Not too radiation hard
- Slightly hygroscopic
- 20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF$_2$.
- Cheap (6-8 $/cc)

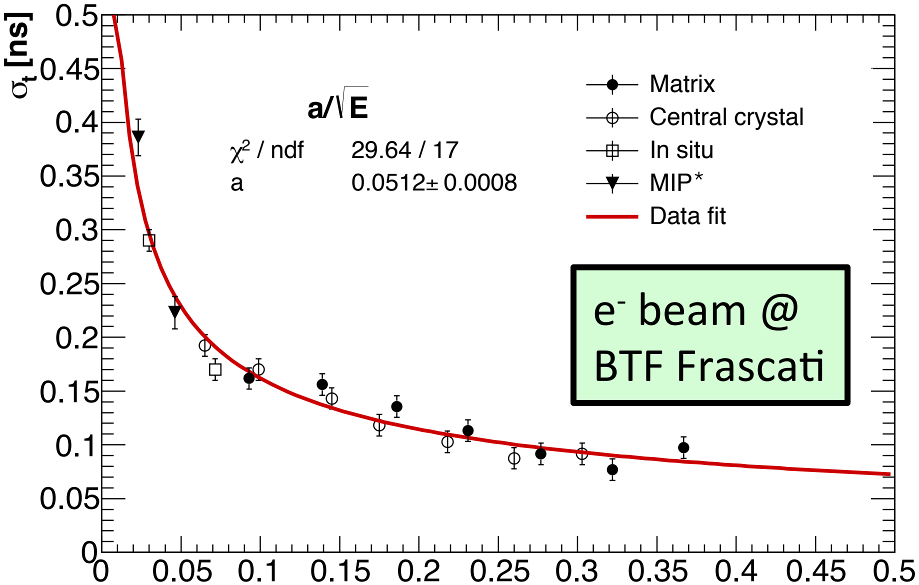
LYSO Legacy



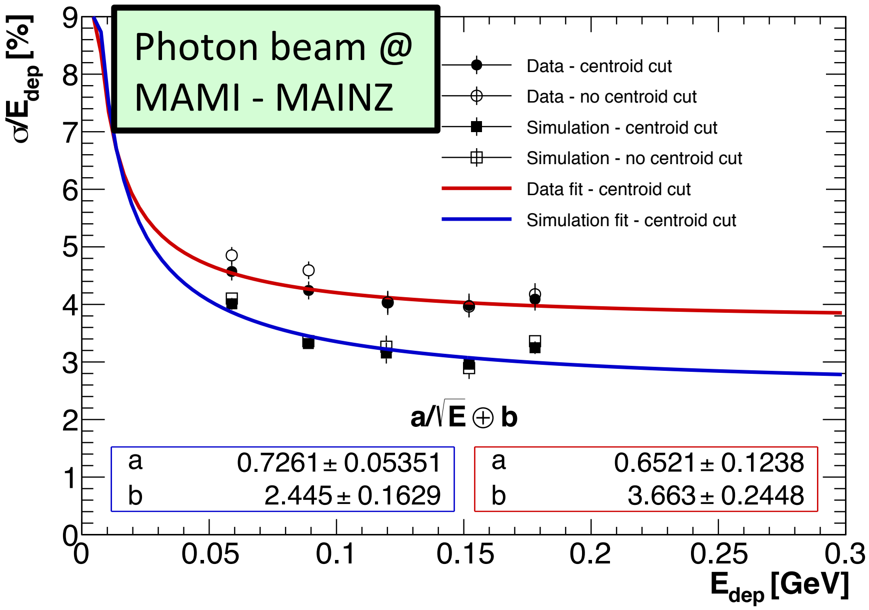








*Time resolution with MIPs from Mu2e DocDB 4409



Energy resolution as a function of the energy deposition fitted with the function:

~ 4% @ 100 MeV

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

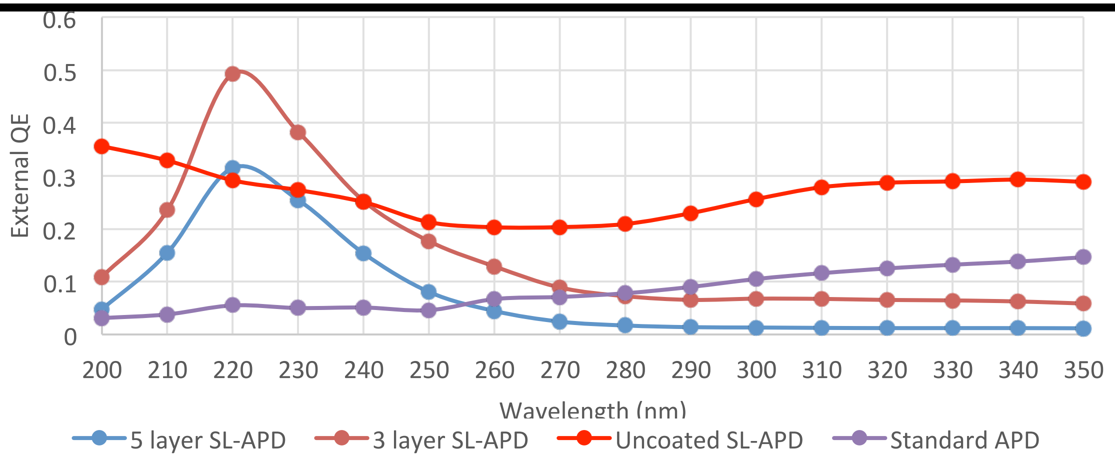
Noise term *b* considered negligible (~0.1% in quadrature).

σ_T = 51 ps/sqrt(E/GeV)
compare with KLOE
~ 55 ps/sqrt(E/GeV)

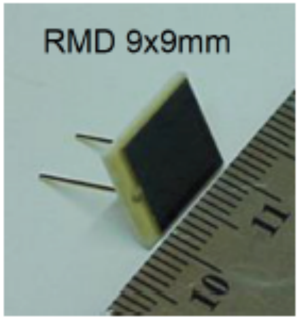
Photosensors Choice

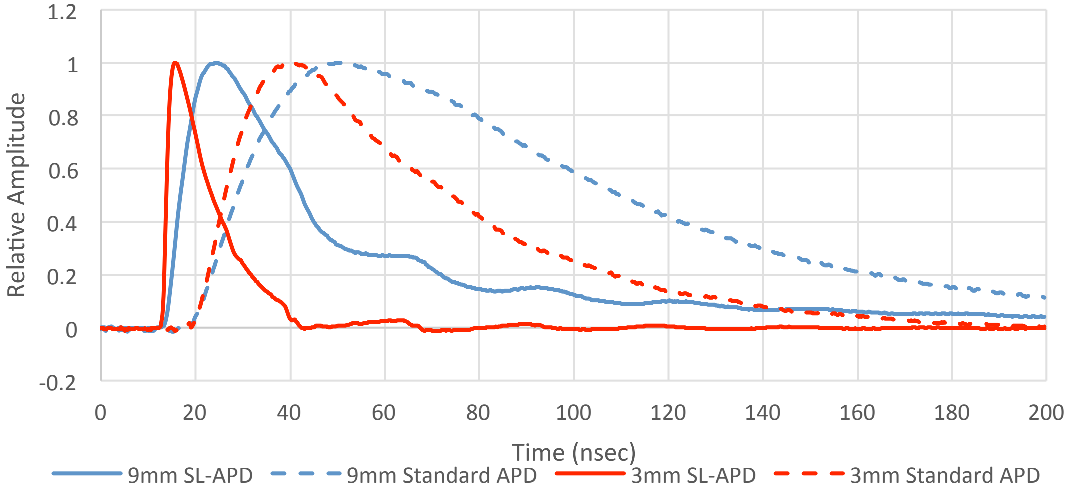
A Caltech/JPL/RMD consortium formed to develop a Large area RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** incorporating also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for wavelength > 300 nm.

- ✓ 60% QE @ 220 nm
- ✓ ~ 0.1 % QE @ 300 nm
- ✓ capacitance ~ 60 pF (1/5 of Ham S8664)
- ✓ HV ~ 1800 V
- ✓ Operation Gain ~ 500
- ✓ Decay time ~ 25 ns.



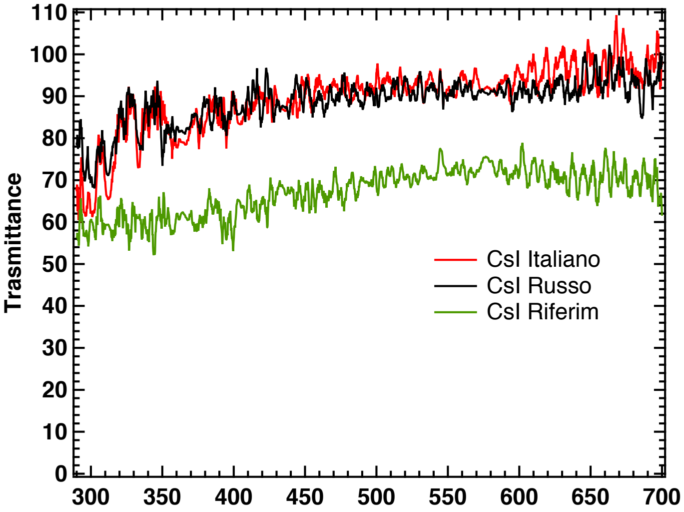
deltadoped APD from RMD

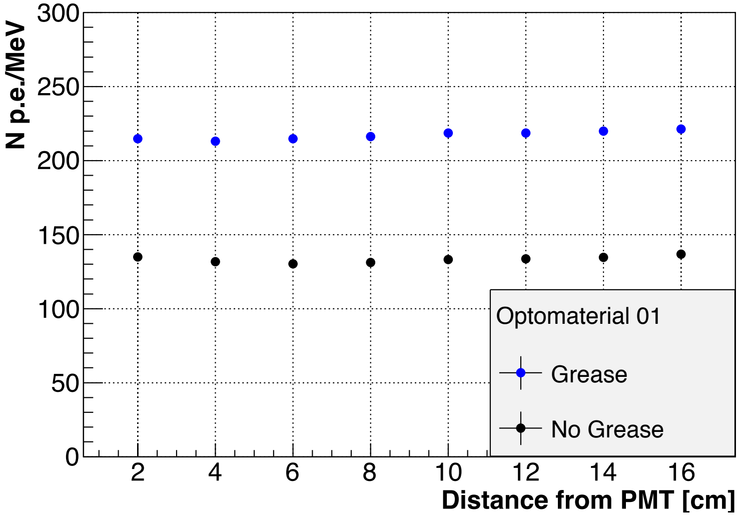


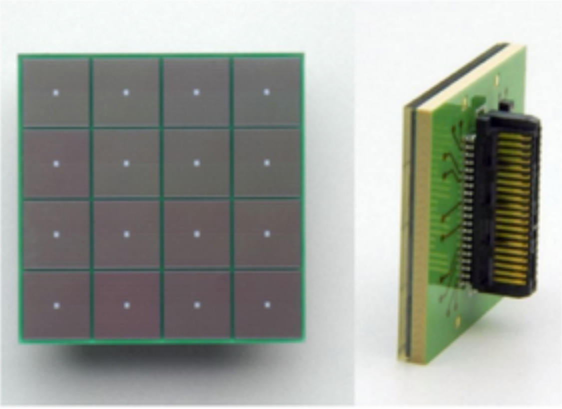


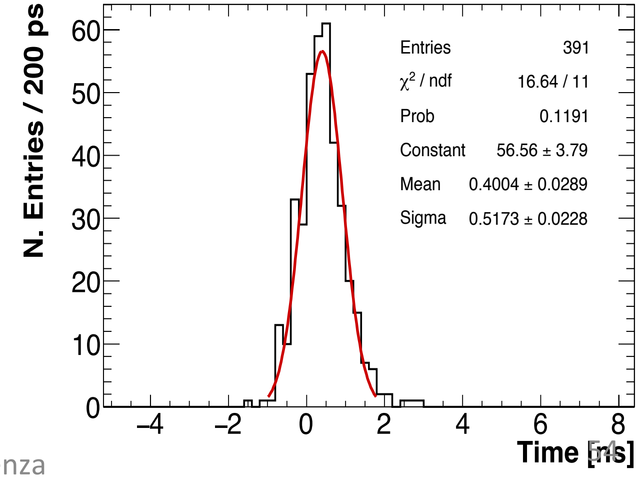
R&D on CsI(pure) crystals

- 4+7 crystals from Kharkov (ISMA) + 2 from Optomaterial (Italy) received in April.
- **Improved transmittance and uniformity** w.r.t. first SICCAS (China) production
- Measurement of time resolution done (from 1 to 5 ns WF sampling) → 420 ps/MIP (22 MeV)
- **10 MPPC new generation TSV received.**

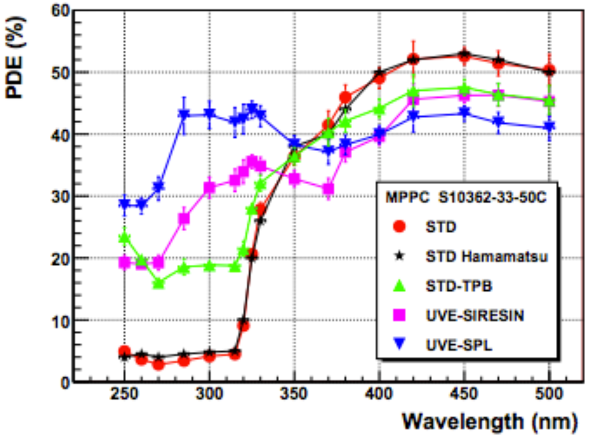




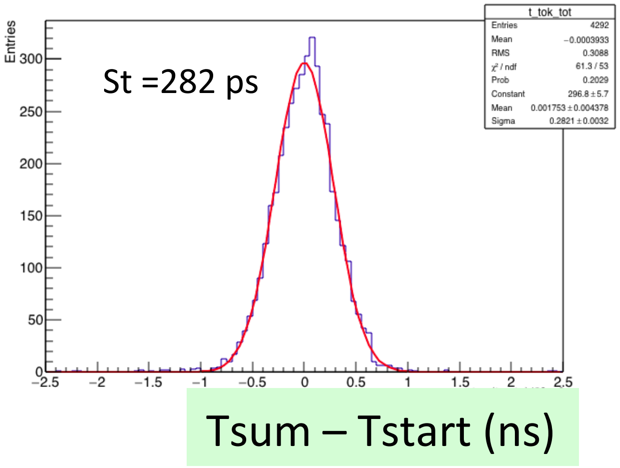




Final R&D steps and TCR



- **Test beam done @ BTF with 3x3 CsI matrix and 9 new UV extended TSV Hamamatsu MPPC**
  - **→ 7% energy resolution**
  - **→ 260 ps resolution obtained at 50 ° incidence angle.**
- Concluding the radiation hardness program for CsI crystals and MPPC with neutrons at FNG.
- **Radiation hardness with TID OK (-20/30% at 90 krad)**
- Technology Choice Review set for end of July.
  - **→ BaF$_2$ vs CsI to freeze the engineering design**



Conclusions

- **The Mu2e experiment is a CLVF first-class experiment looking for physics BSM with high complementarity to other programs while increasing reach and diversification in models testing.**

- **MU2E will improve previous conversion experiment of 4 orders of magnitude and probe mass scales up to hundreds of TeV.**

- **< 10 years Timeline for completion of first phase.**

- **Mu2e has completed the CD-2 and CD3 for the long lead items**

  → Construction of the solenoids will start next year.

  → Detector Review at end of 2015 to freeze detector with CD3 in 2016

  → **INFN mainly involved on calorimeter construction and follow up of TS construction.**

  → **INFN CTS review will be done during this year**

  → Construction period 2016-2018 followed by installation in 2019

- **A longer term plan is being discussed.**
- **a Mu2e-2 phase being planned for a (x 10) increase in intensity and sensitivity!**

Additional Material

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.

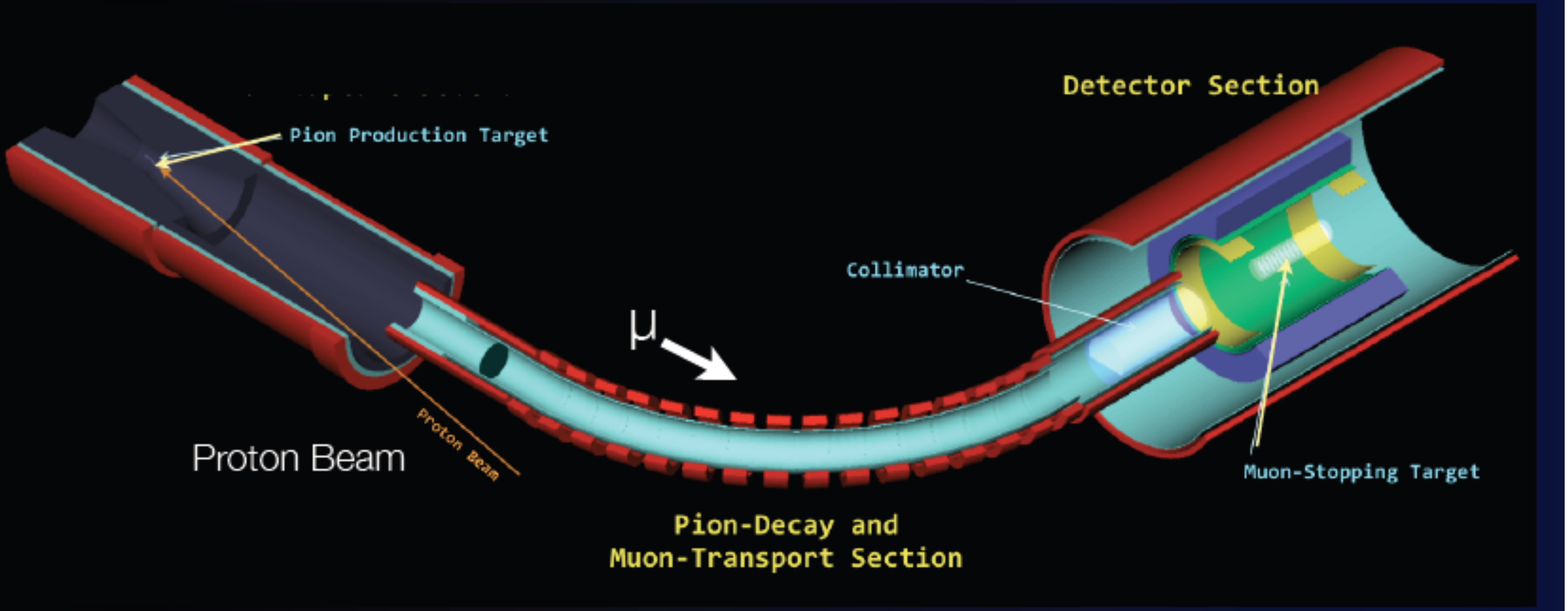
❑ It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)
- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam -> higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry "cost" in operation

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 :

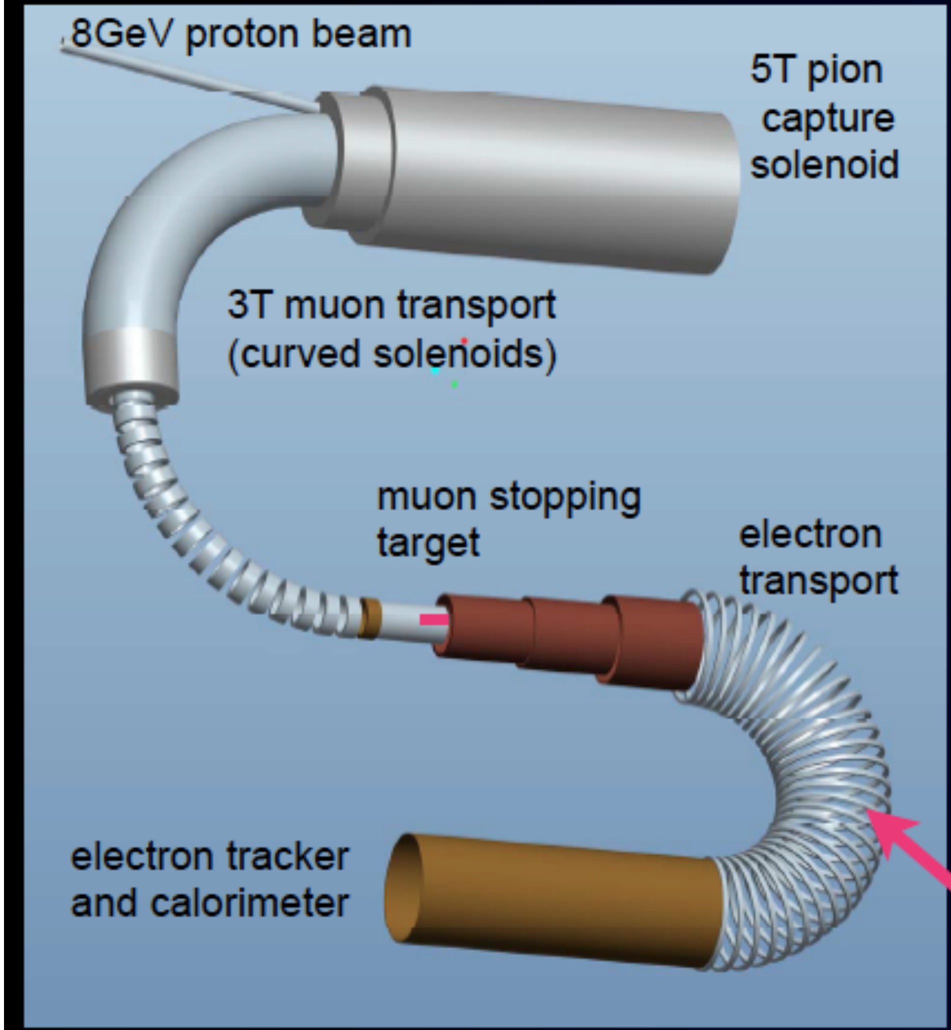
(1~3)x10^{9} muon/sec with 3kW beam produced. The world highest intensity.

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

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$

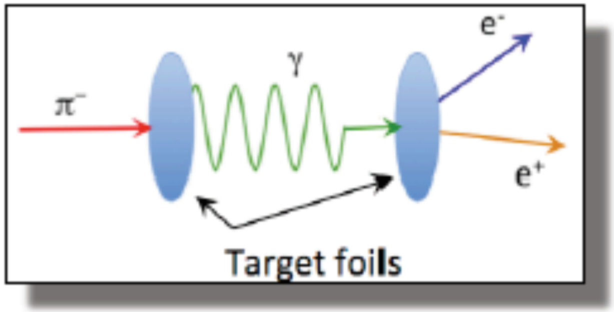
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- 2×10^7 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.

Mu2e-2

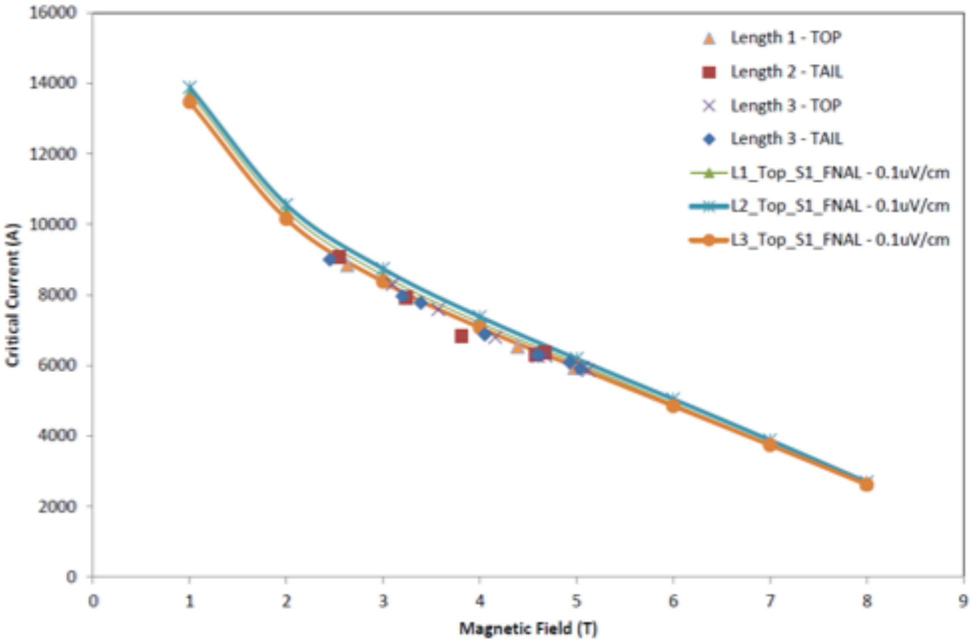
- Mu2e can simultaneously see electrons and positrons from the stopping target
  - Access to additional physics mode: $\mu^- N(Z,A) \rightarrow e^+ N(Z-2,A)$
    - ($\Delta L=2$ transition – charged analog of neutrinoless double beta decay)
  - High energy positrons are an additional handle on radiative backgrounds with converted photons

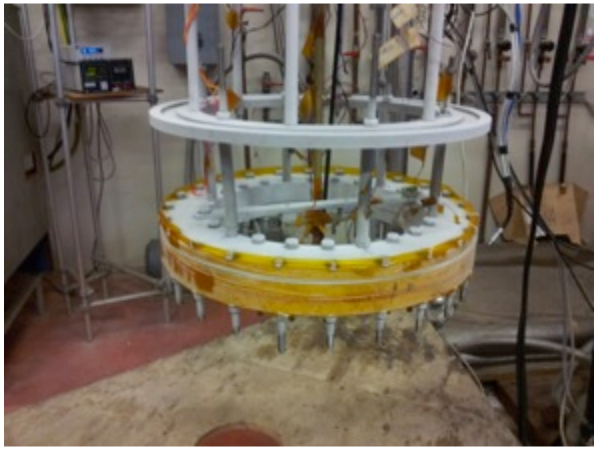


- Mu2e is the fastest, cheapest path to broad discovery sensitivity in CLFV sector.

Critical Current Measurements

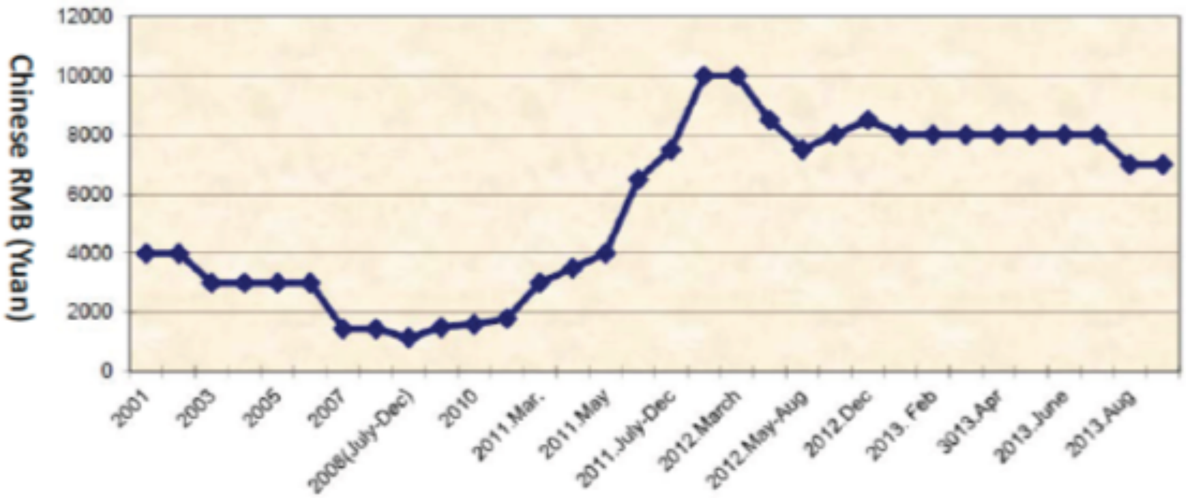
- FNAL awarded a contract to Hitachi for three lengths of TS conductor (1000 m)
- INFN Genova received six samples (head and tail of production)
- Critical currents of five sample were measured. Except a case (bad soft soldering of the sample) four runs went well.
- Measured critical currents compare very well with the ones performed at Fermilab on extracted strands
- **After these results Fermilab is asking INFN Genova to test all 60 cables involved in Mu2e solenoids.**





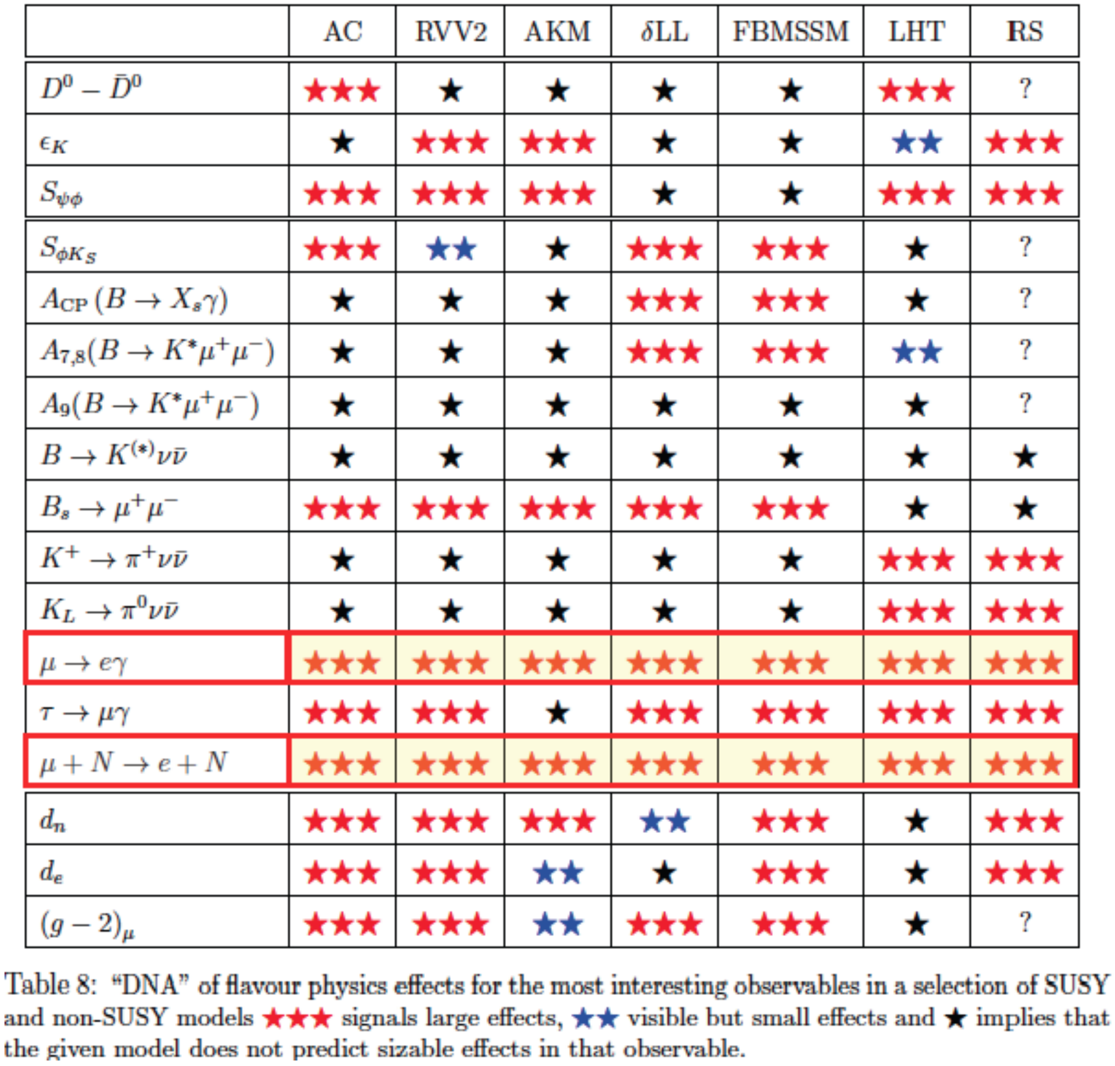
INFN Calo R&D (2013-2014)

- Simulation/reconstruction of clusters + calorimeter based seed for tracking
- Design and construction of 2 LYSO + APD calorimeter prototypes
- Control stations for characterization of crystals and photosensors
- Design/construction/operation of 50 FEE amplifiers/Voltage regulator + 5 ARM based controller (SEA LNF) + 5 WF prototype (Illinois/Pisa)
- 1 Laser prototype (green light + distribution system)
- Completion of mechanical drawings for CD-2
- 2 NIMs in writing, 6 contributions to Detector conferences this year
- **Change on technology and R&D due to sudden LYSO cost increase (x 3) in 2012-2013.**



Are CLFV processes relevant ?

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

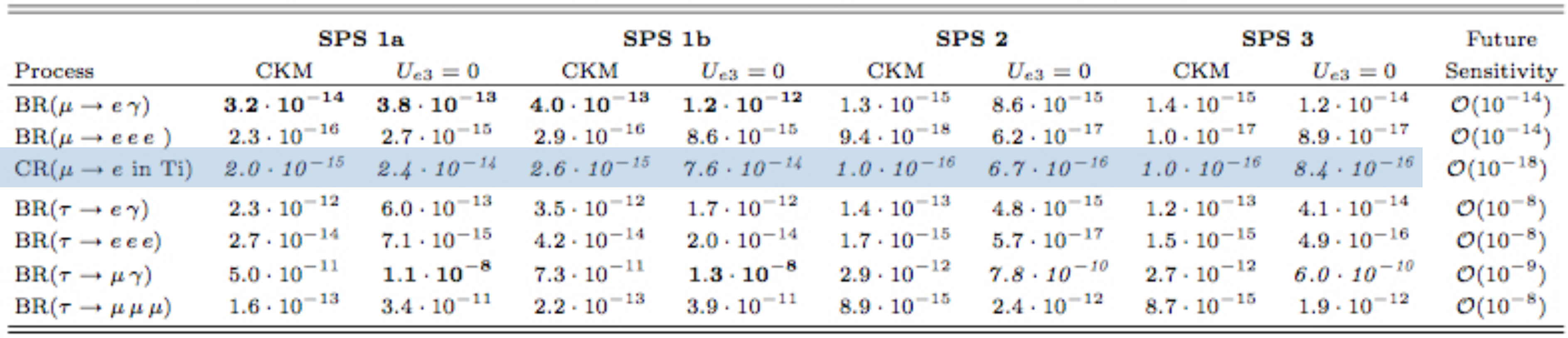


	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★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

SUSY benchmark points vs LHC

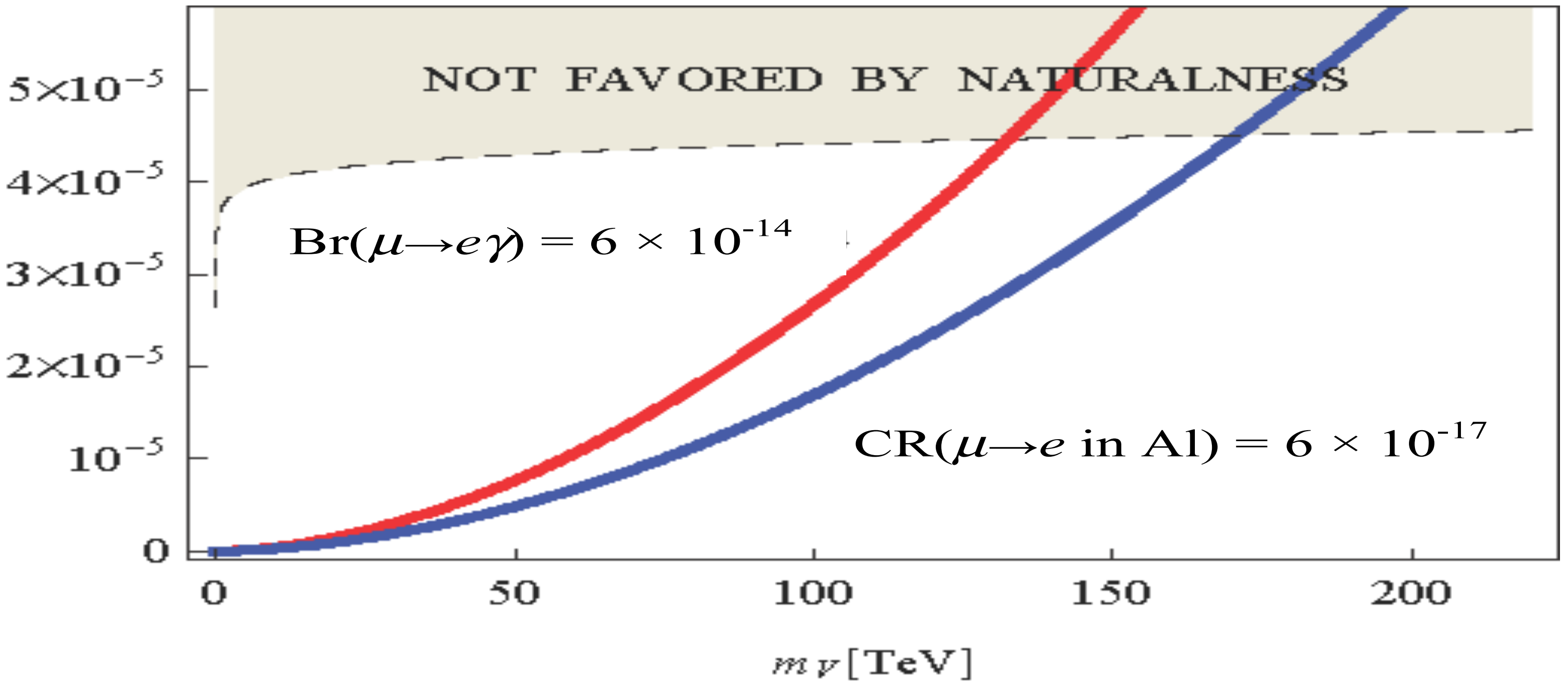
TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME,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

Specific example: Leptoquarks



Leptoquarks

Presenza di leptoquarks alla scala del TeV potreb indurre processi CLFV con una costante di accoppiamento λ.

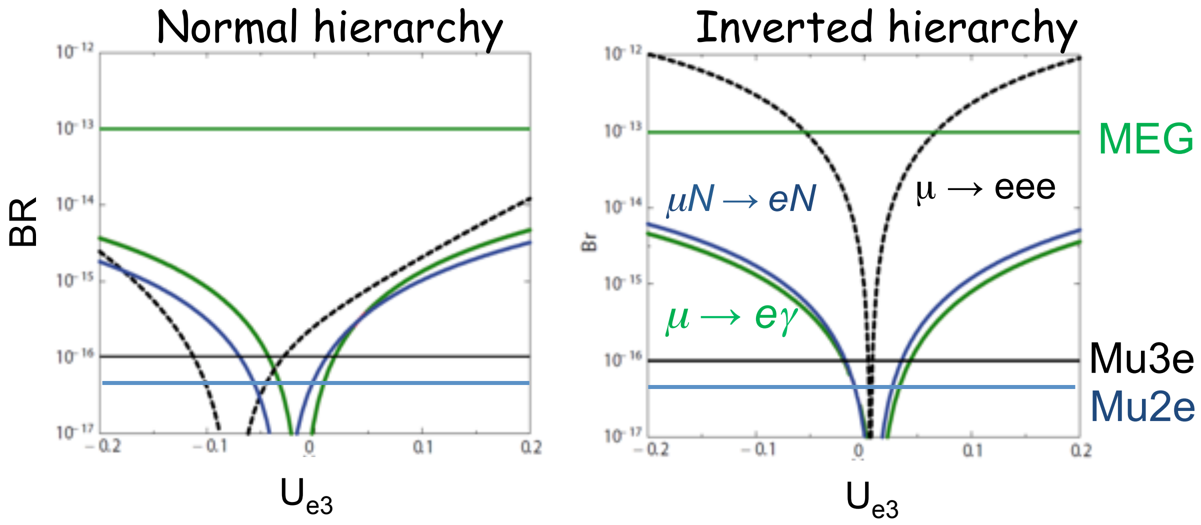
- Rosso: MEG-II
- Blu: Mu2e

Specific example: Higgs Triplet e LHT

M. Kakizaki et al., PLB566 (2003) 210

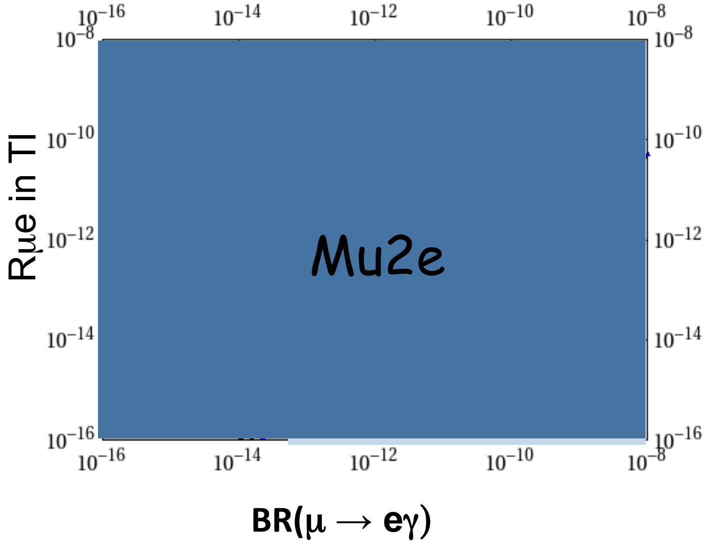
Higgs triplet model

Dependence on
neutrino mass
hierarchy and θ_{13}



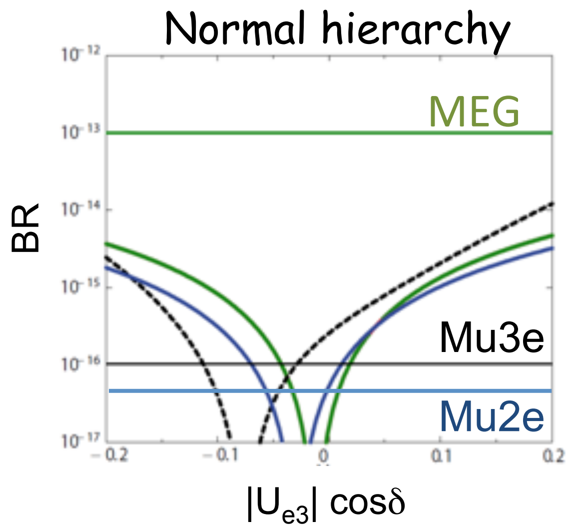
Littlest Higgs with T-parity

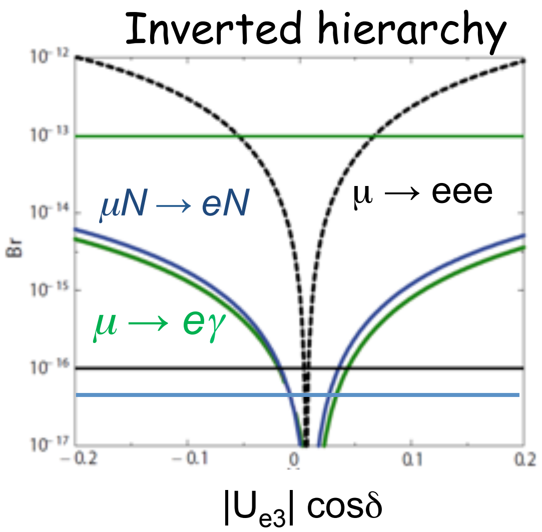
M. Blanke et al., Acta Phys.Polon.B41:657,2010



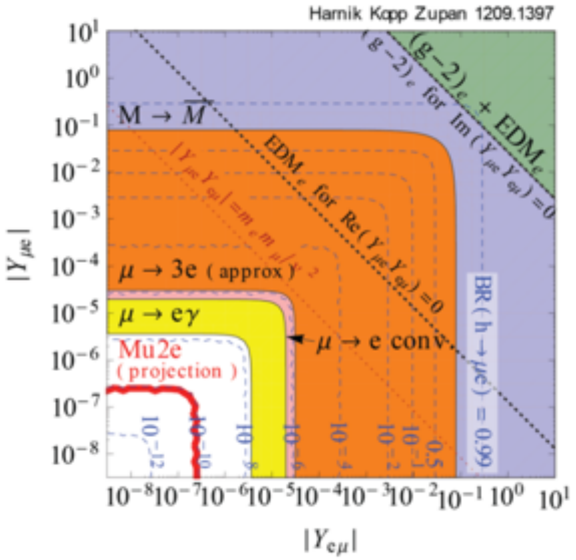
A few more models…

Higgs triplet model

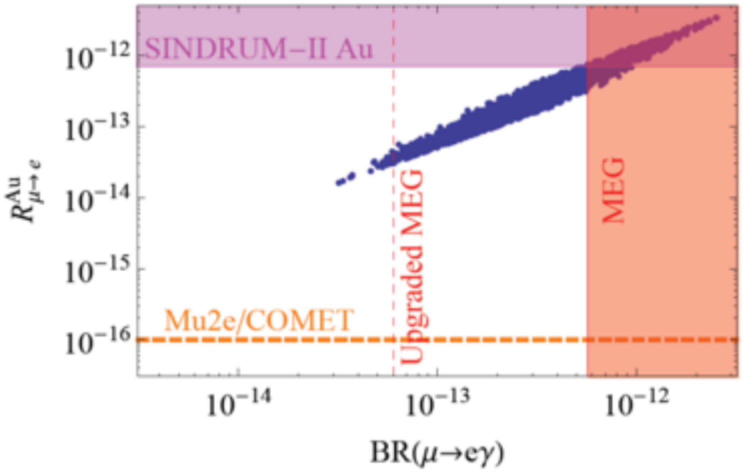




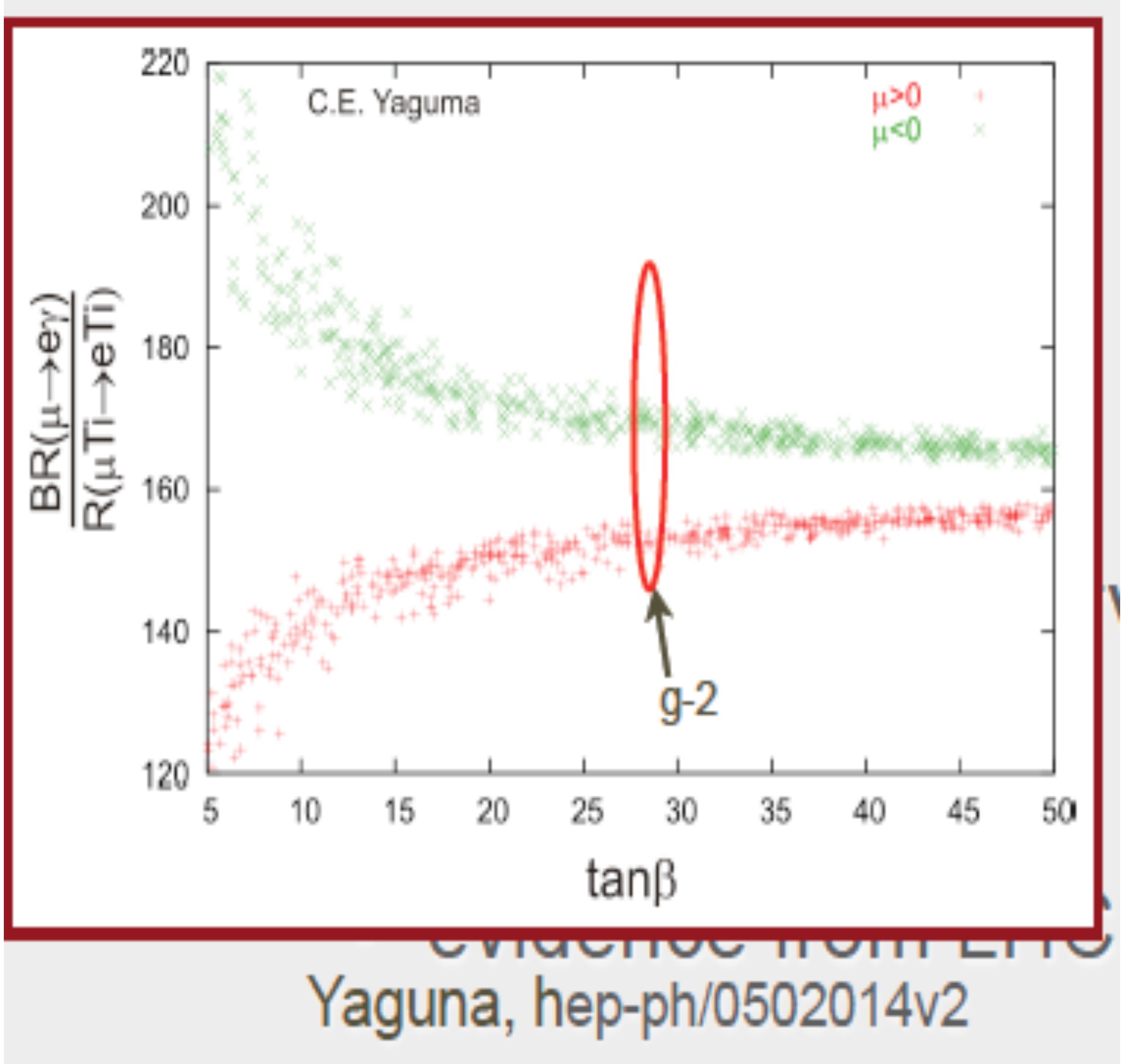
Flavor violating Yukawa couplings



Left-right symmetric models

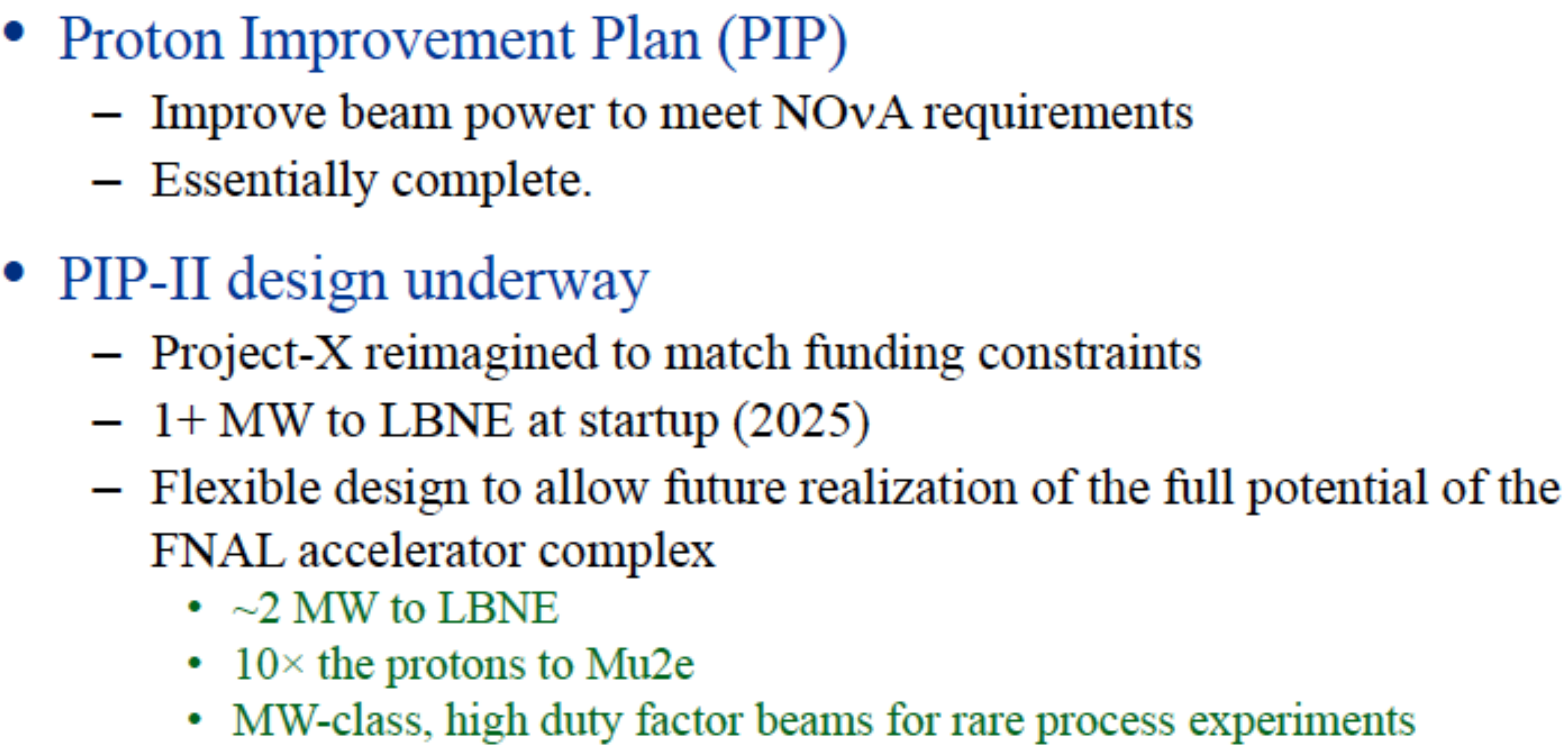


MSSM- mSugra



Yaguna, hep-ph/0502014v2

Next Generation Proton Source

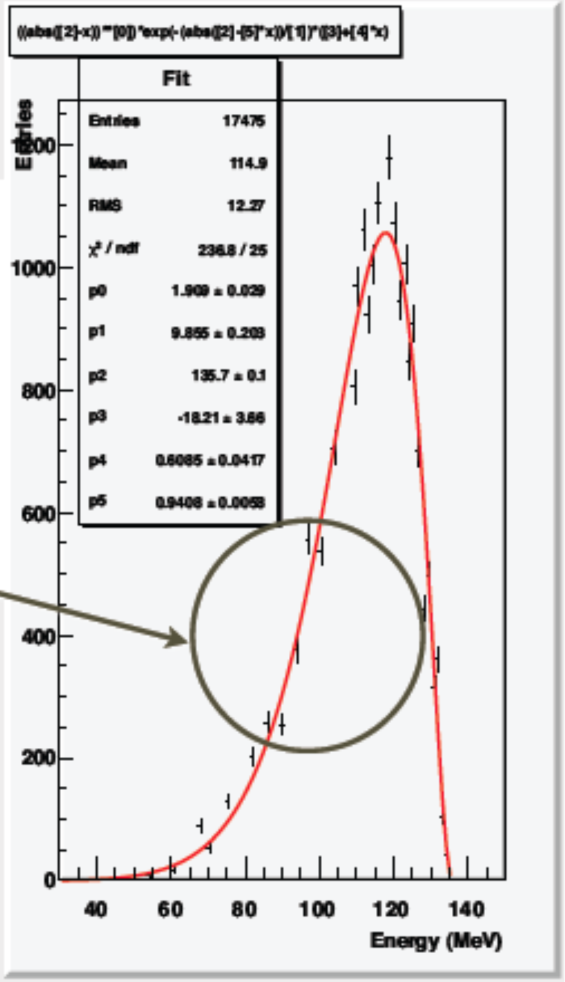


- Proton Improvement Plan (PIP)
  - Improve beam power to meet NOνA requirements
  - Essentially complete.
- PIP-II design underway
  - Project-X reimagined to match funding constraints
  - 1+ MW to LBNE at startup (2025)
  - Flexible design to allow future realization of the full potential of the FNAL accelerator complex
    - ~2 MW to LBNE
    - 10× the protons to Mu2e
    - MW-class, high duty factor beams for rare process experiments

Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars

- **Radiative pion capture**, π-+A(N,Z) →γ +X.
  - γ up to m_{π}, peak at 110 MeV; $\gamma \rightarrow$ e+e- ; if one electron ~ 100 MeV in the target, looks like signal: ***limitation in best existing experiment, SINDRUM II?***



energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

also included internal conversion, $\pi^- N \rightarrow e^+ e^- X$

SINDRUM-II Results

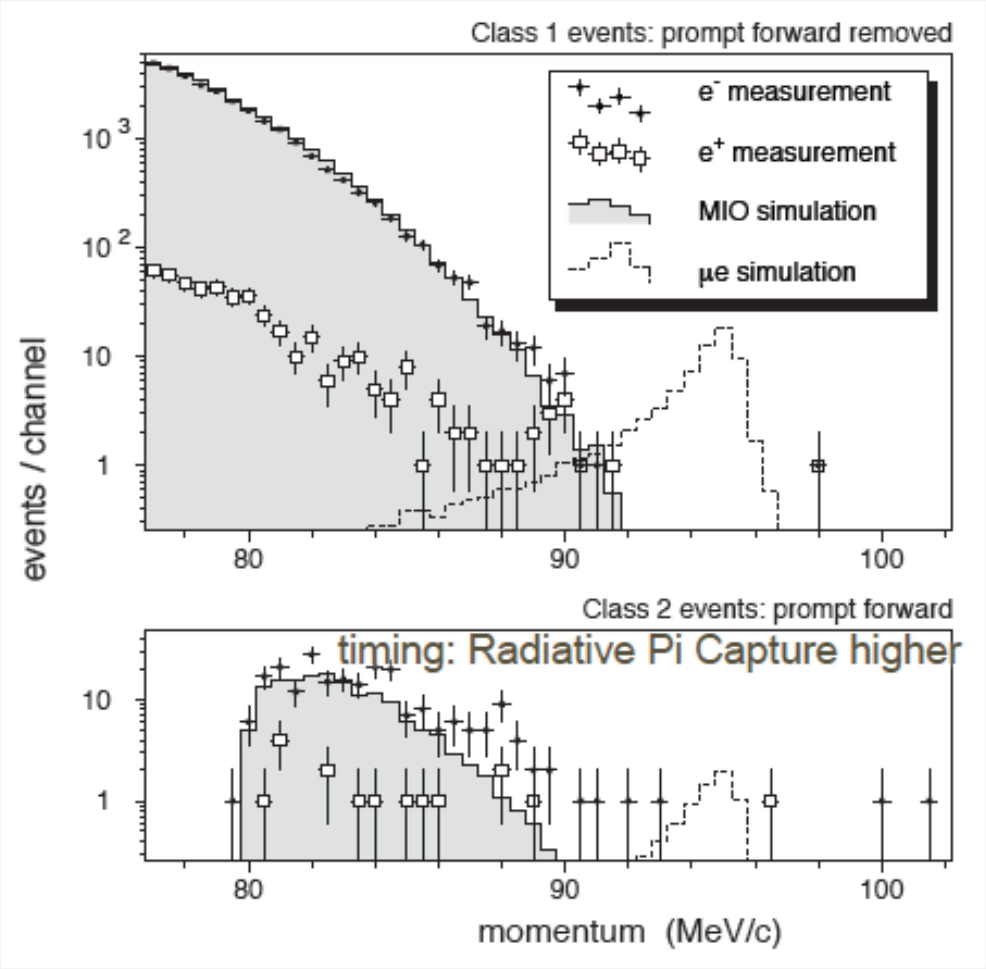
- Final Results on Au:

$$B_{\mu e}^{\mathrm{Au}} \quad < \quad 7 \times 10^{-13} \text{ @ } 90\% \text{ CL}$$

51 MHz (20 nsec) repetition rate, width of pulse ~0.3 nsec

little time separation between
signal and prompt background

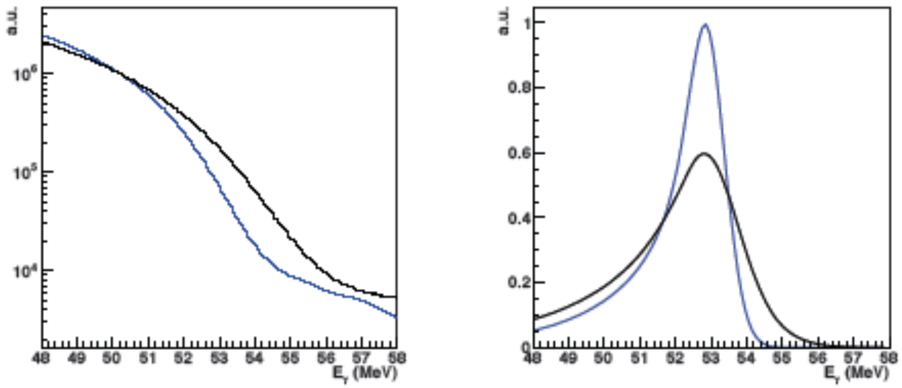
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)



timing: Radiative Pi Capture higher

MEG^{UP} sensitivity

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

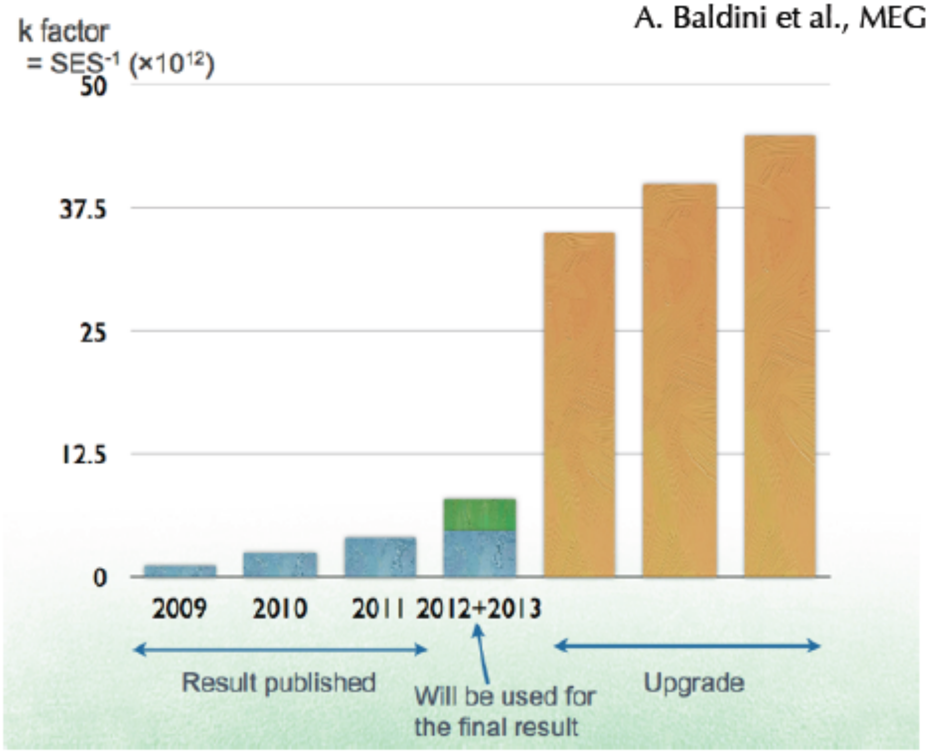


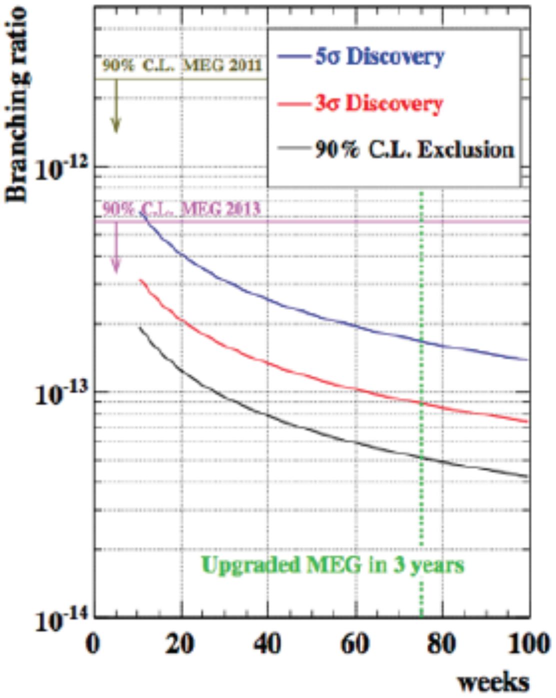
$$5.7 \times 10^{-13}$$

MEG^{UP} sensitivity

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

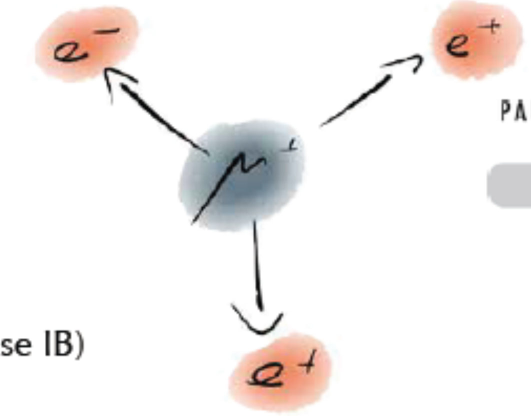
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |



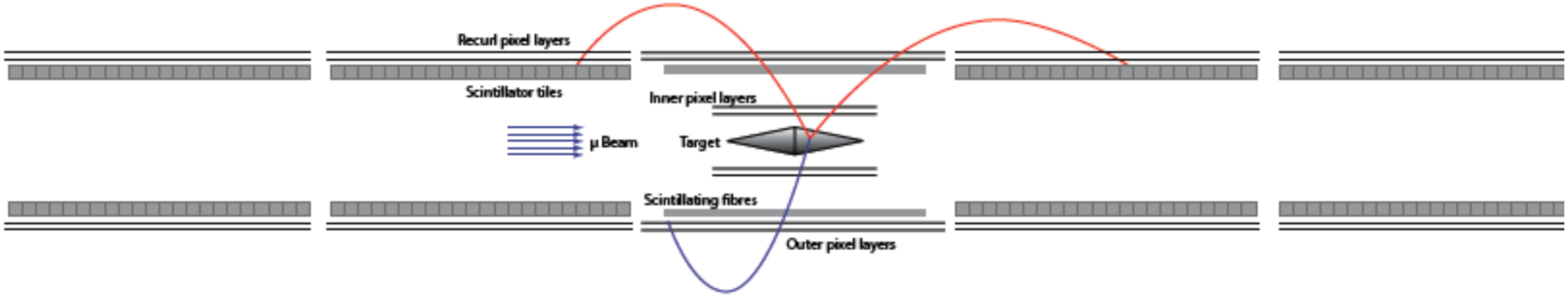


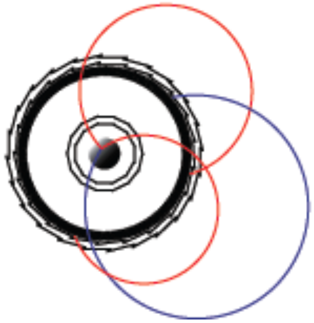
Mu3e at PSI

- Search for μ→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
PSI





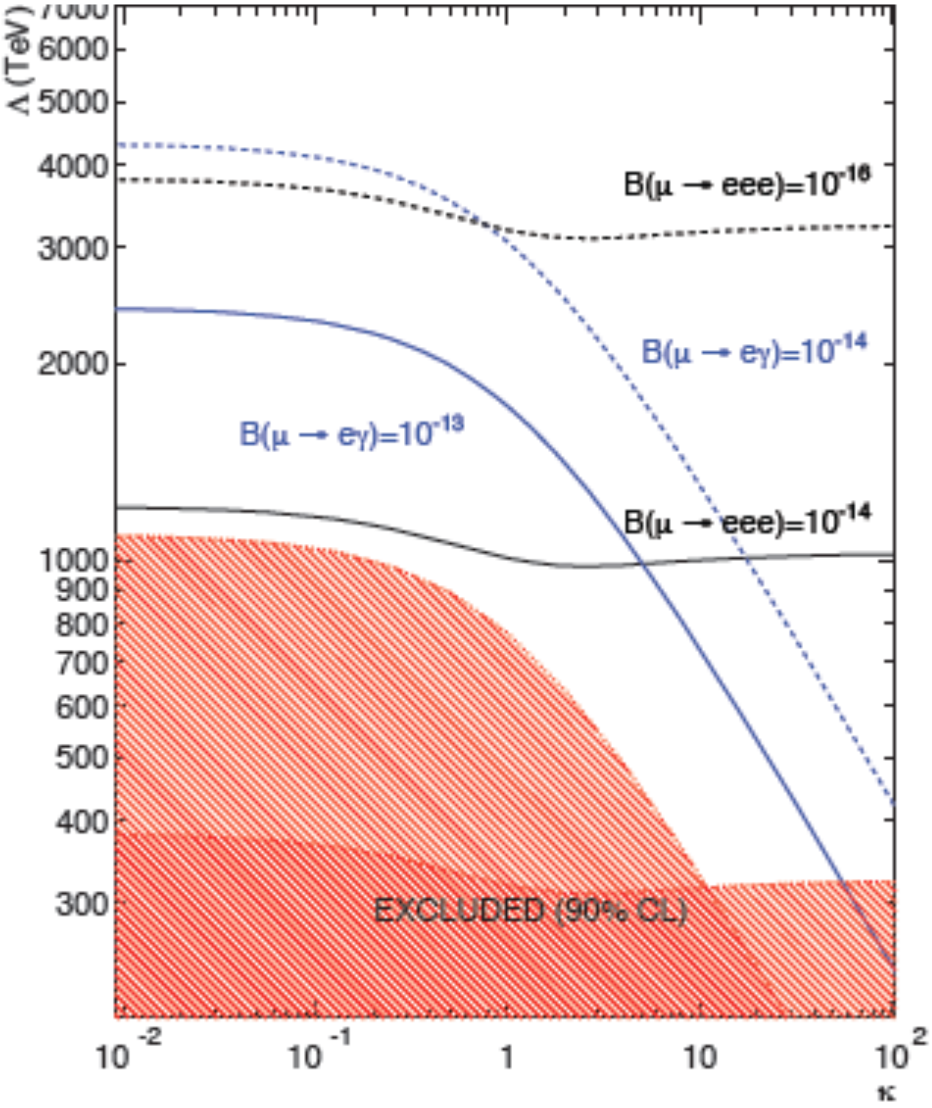
vw.psi.ch/mu3e

MEG vs Mu3e

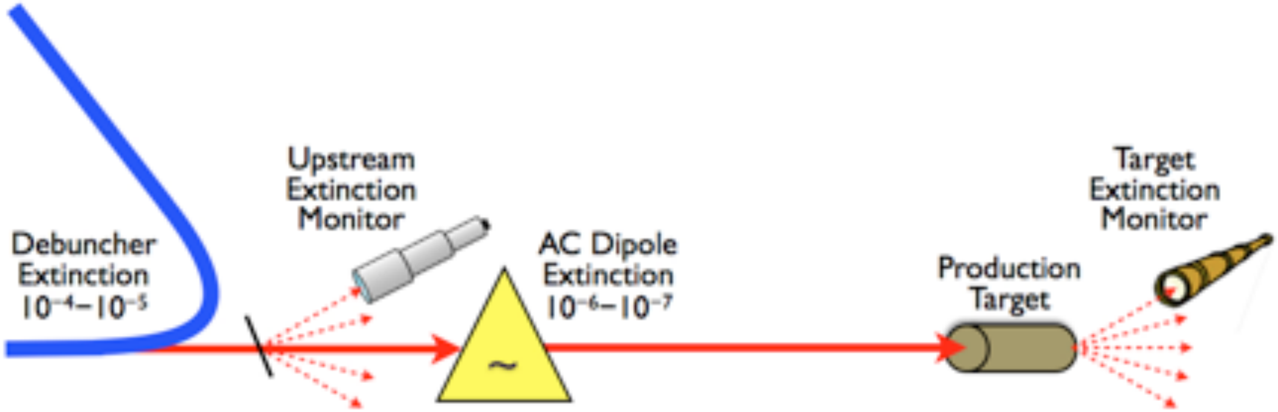
- Mu3e decays test also values of K larger than MEG but with different (reduced) sensitivity al large K with respect to Mu2e

- Phase 1 Mu3e at PSI aims to 10^{-15} (approved)

- Next phase aims to 10^{-16}
  .. Not yet clear



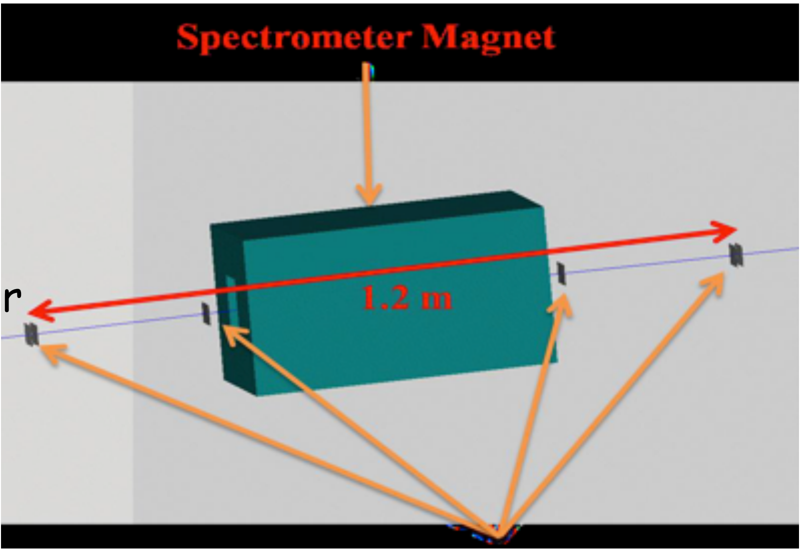
Extinction Monitor



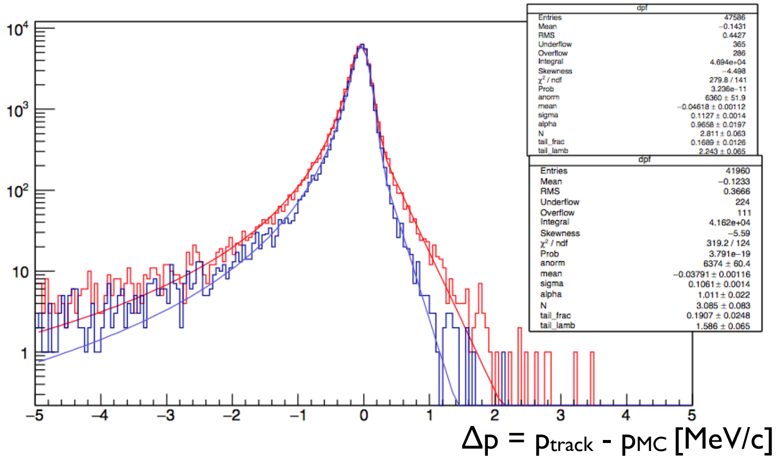
- Thin foils in the debuncher → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback – timescale of hours)

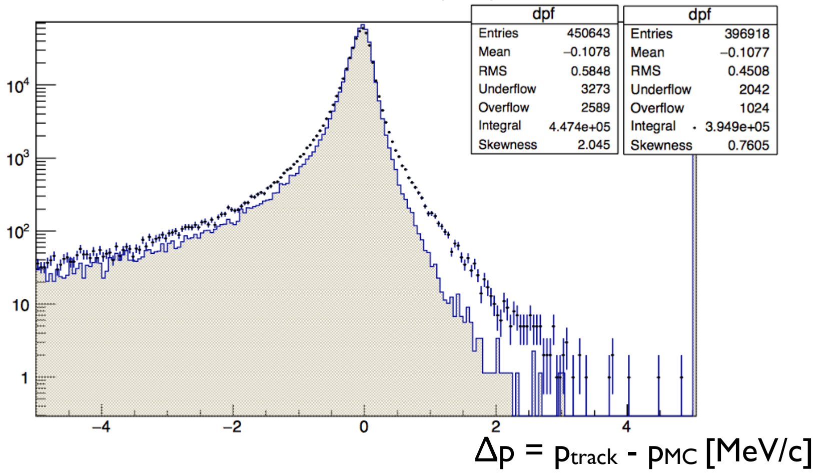
Spectrometer based on ATLAS pixel detector

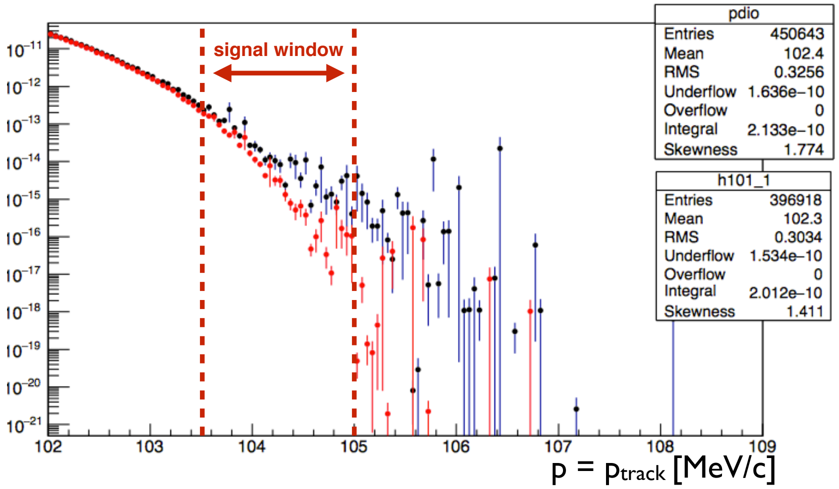
Reach a 10^{-10} extinction sensitivity in an hour or so

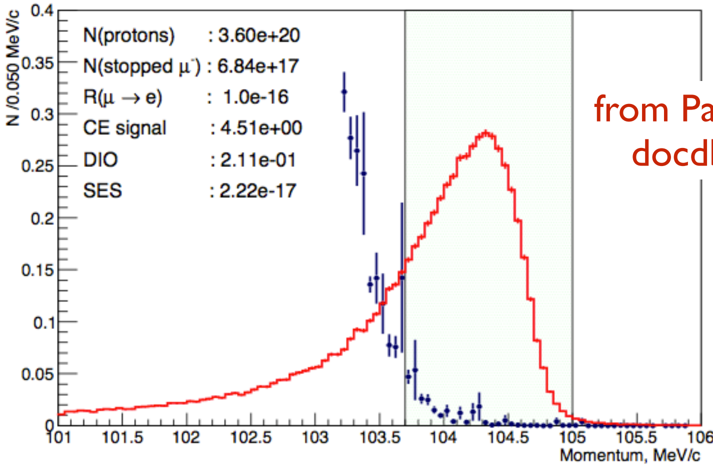


Tracking vs CaloTrack









from Pasha's talk
docdb-5386

- Reduction of DIO background in signal window (x 3)
- Sensitivity improves of 19% w.r.t. TDR, 10% w.r.t to last study
- SES = 2.2 x 10^{-17} w.r.t. Mu2e benchmark of 2.5 x 10^{-17}