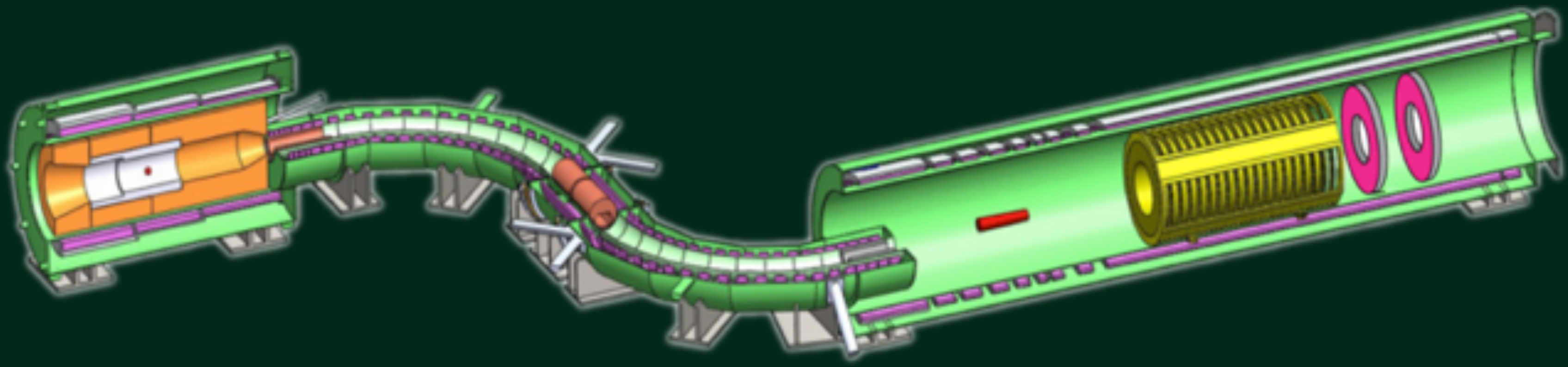
Design, R&D and status of the crystal calorimeter for the Mu2e experiment



Raffaella Donghia

Roma Tre University and LNF – INFN

May 12, 2016

XVII LNF Spring School "Bruno Touschek"

ROMA TRE UNIVERSITÀ DEGLI STUDI

Mu2e

INFN

Fermilab

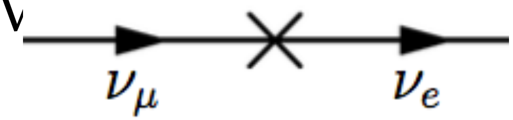
Outline

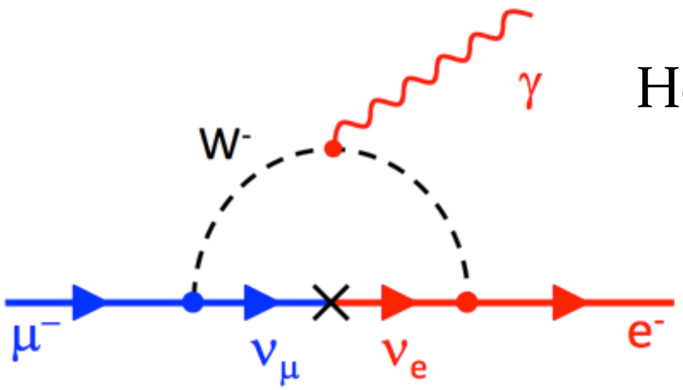
- CLFV
  - The muon sector
- The Mu2e apparatus
  - Detector Layout
- The crystal Calorimeter
  - Test results
- Conclusions

Charged Lepton Flavor Violation

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

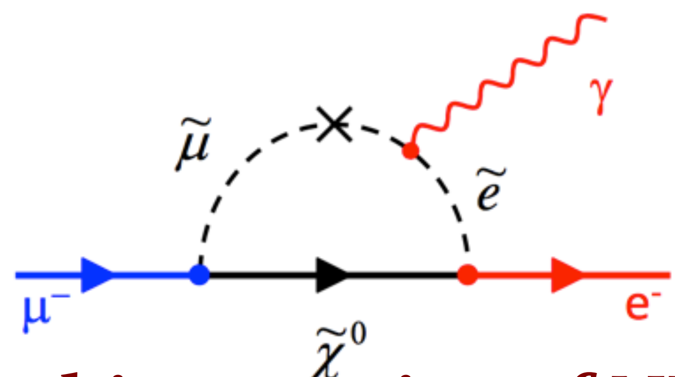
Even in the SM, neutral LFV implies CLFV through neutrino mixing





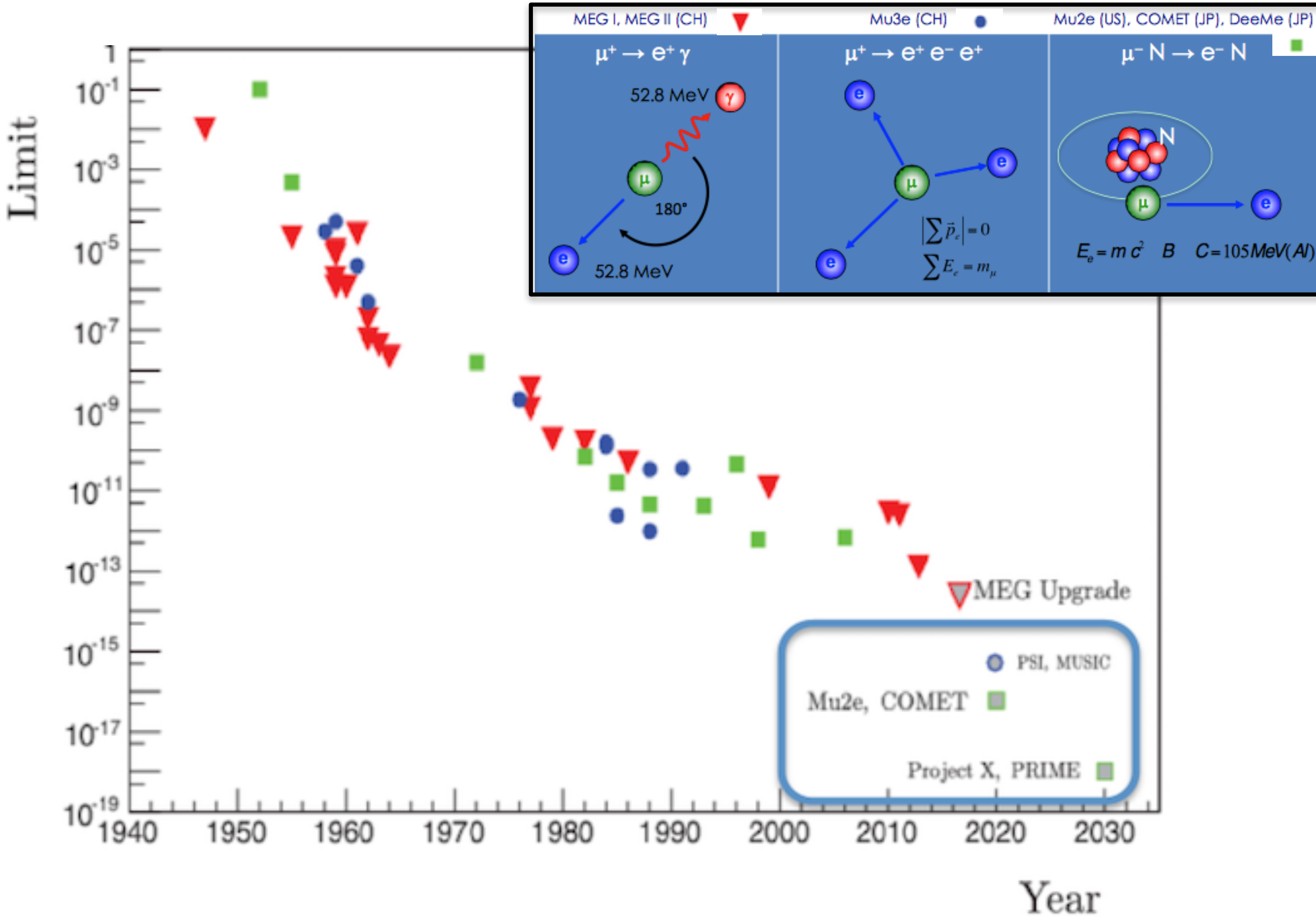
However, CLFV processes are strongly suppressed in the SM:
$BR(\mu \rightarrow e\,\gamma) < 10^{-54}$

New Physics can enhance CLFV rates to observable values



Observation of CLFV: unambiguous sign of NP

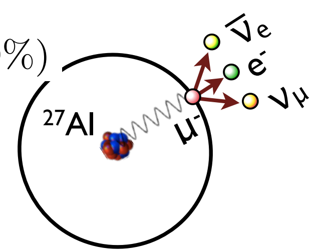
Muon-CLFV history



Mu2e in one page

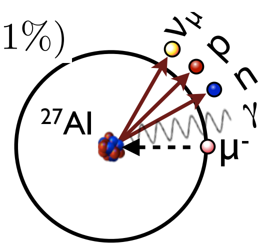
- Make muonic Al
  - Low momentum μ beam (< 100 MeV/c)
  - High intensity "pulsed" rate
- Watch it decay:

(BR=39%)

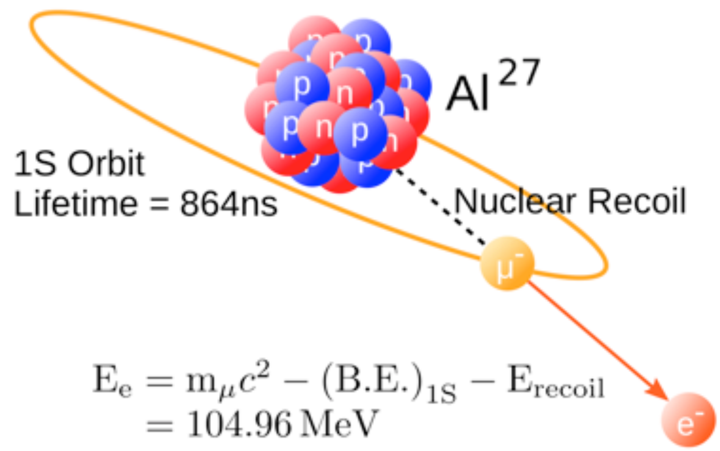


a) Decay in Orbit (DIO)

(BR=61%)

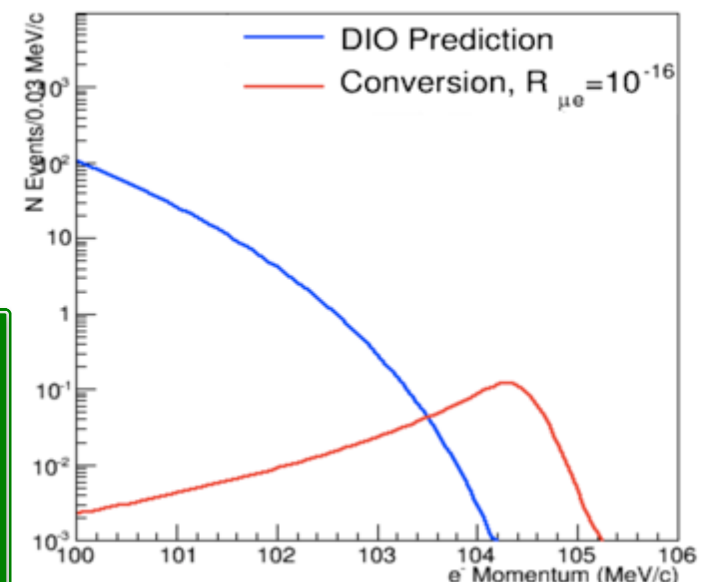


b) Muon Capture



c) Conversion Process

- Neutrinoless muon conversion
  - Monoenergetic electrons E_e ~ 105 MeV
  - At the endpoint of the DIO spectrum



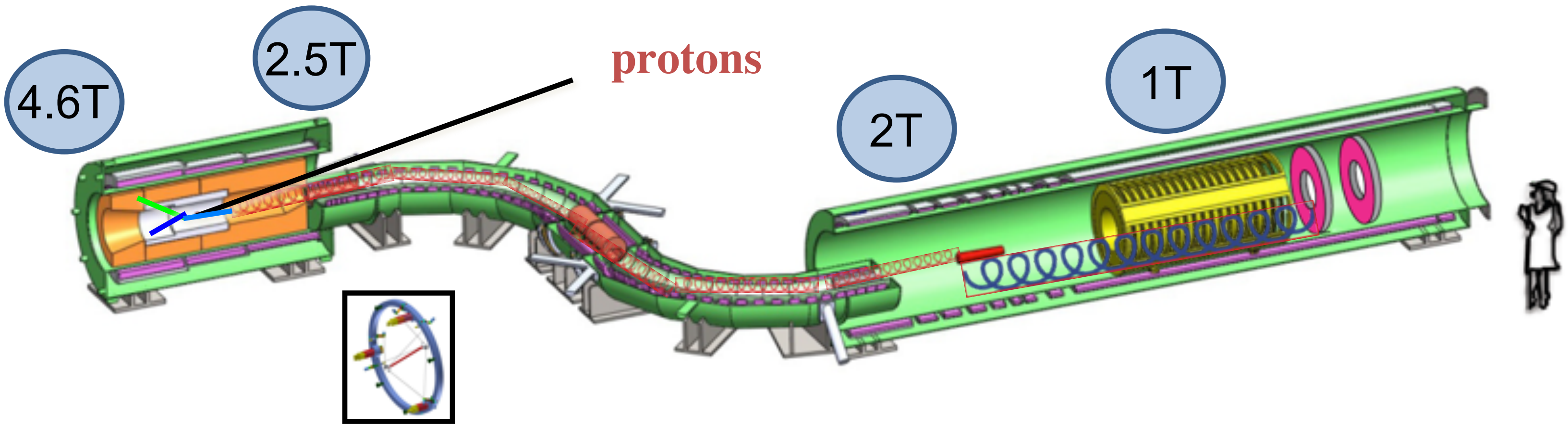
Design sensitivity for a 3 year run (@ 90% C.L.):

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \rightarrow e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N))} < 6 \times 10^{-17}$$

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



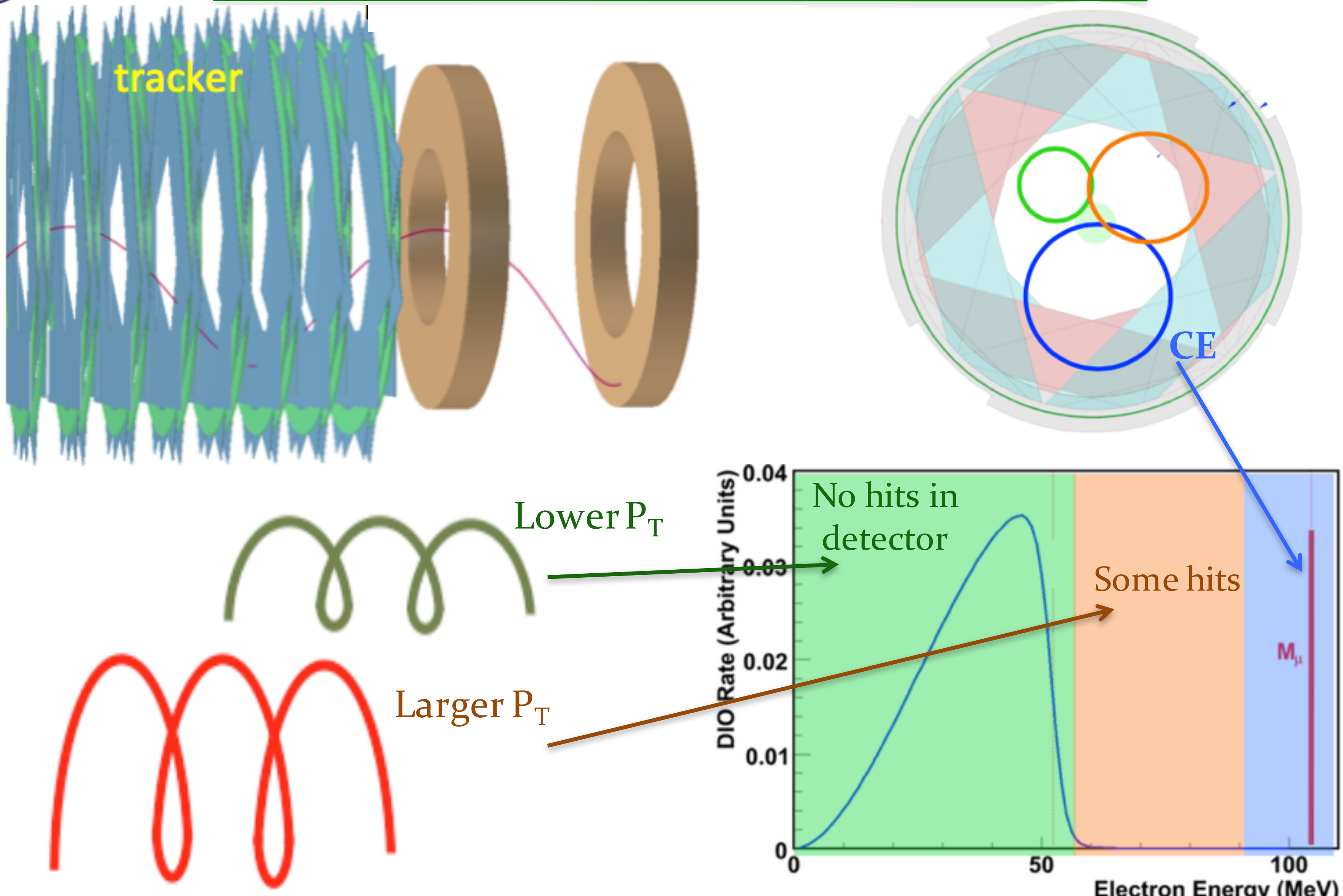
Transport Solenoid (TS)

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

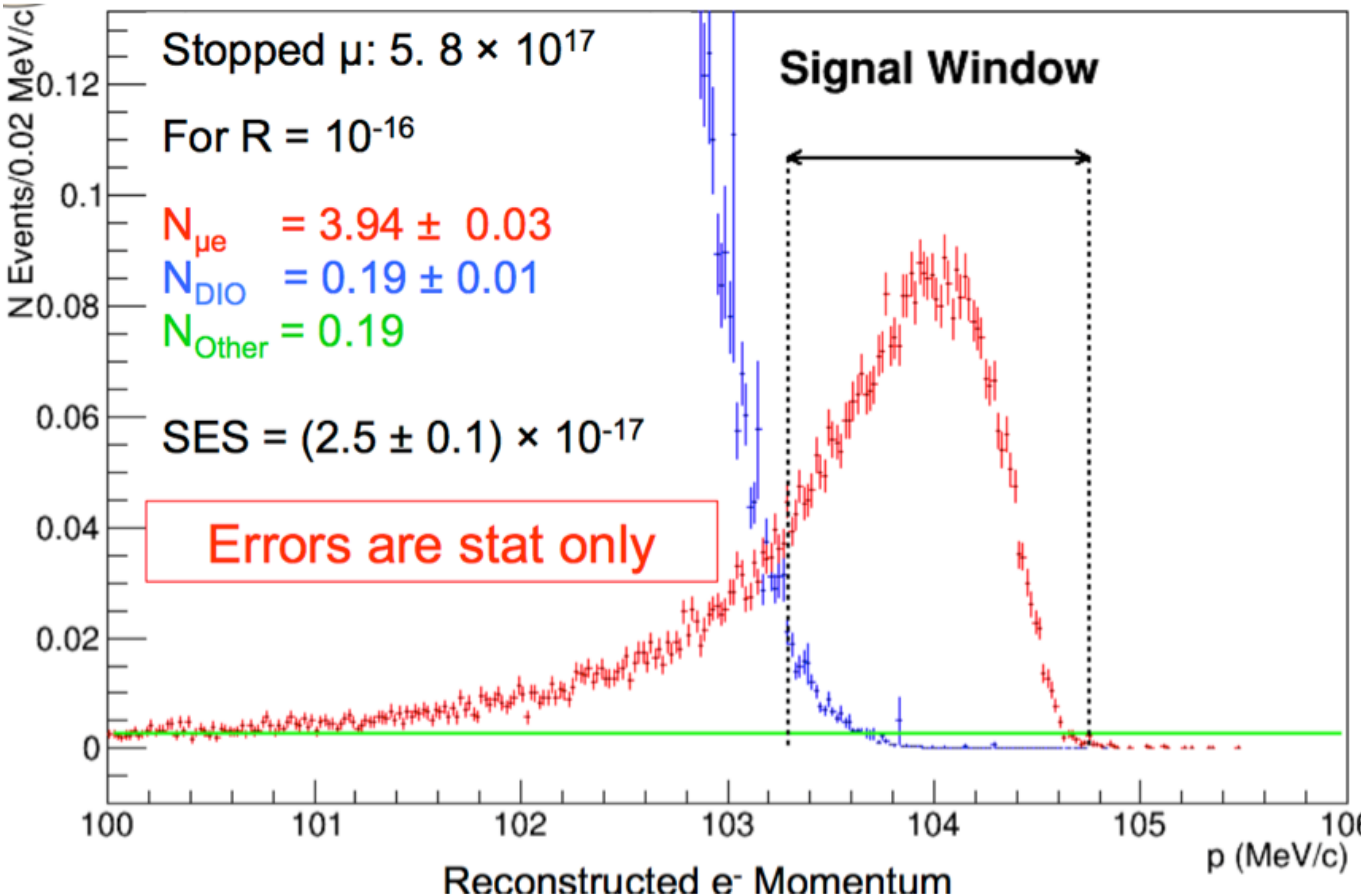
Detector Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker (with a resolution better than 120 keV @ 100 MeV) and energy in calorimeter
- CRV to veto Cosmic Rays event

How do you reach a SES of 2.5×10^{-17} ?



Simulated performances



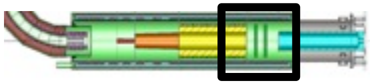
Calorimeter Requirements

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

- Large acceptance for CE
- Independent measurement of **energy / time / position**
- **PID capabilities**
- Independent trigger
- "seeds" to improve track finding efficiency at high occupancy

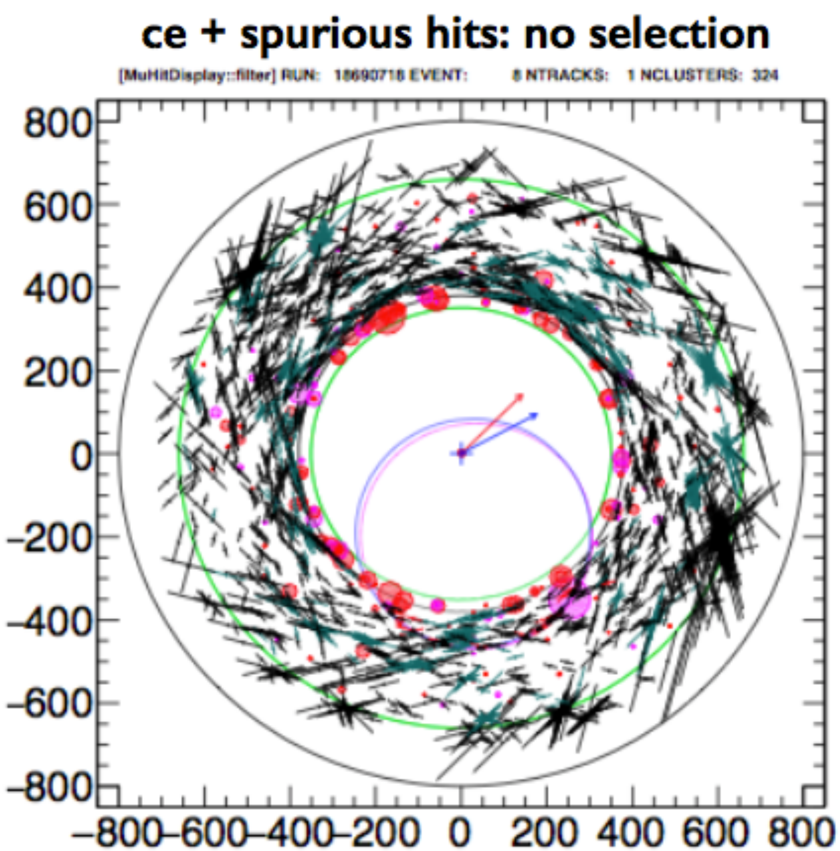
In order to do so the calorimeter should provide:

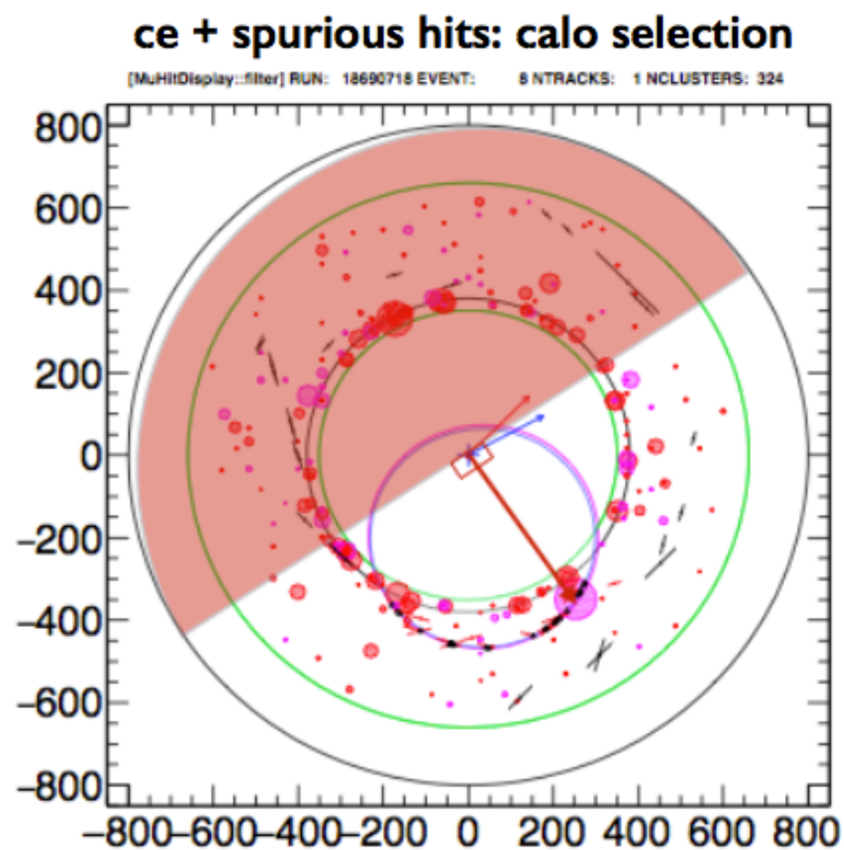
- **energy resolution σ_E/E of O(5 %)**
- **timing resolution $\sigma_{(t)} < 500$ ps**
- position resolution < 1 cm
- Crystals survive a radiation dose of 100krad and a neutron fluence of 10^{12}n/cm^2
- Photo-sensors survive a neutron fluence of 3×10^{11} n_1MeV/cm^2



Track seeding

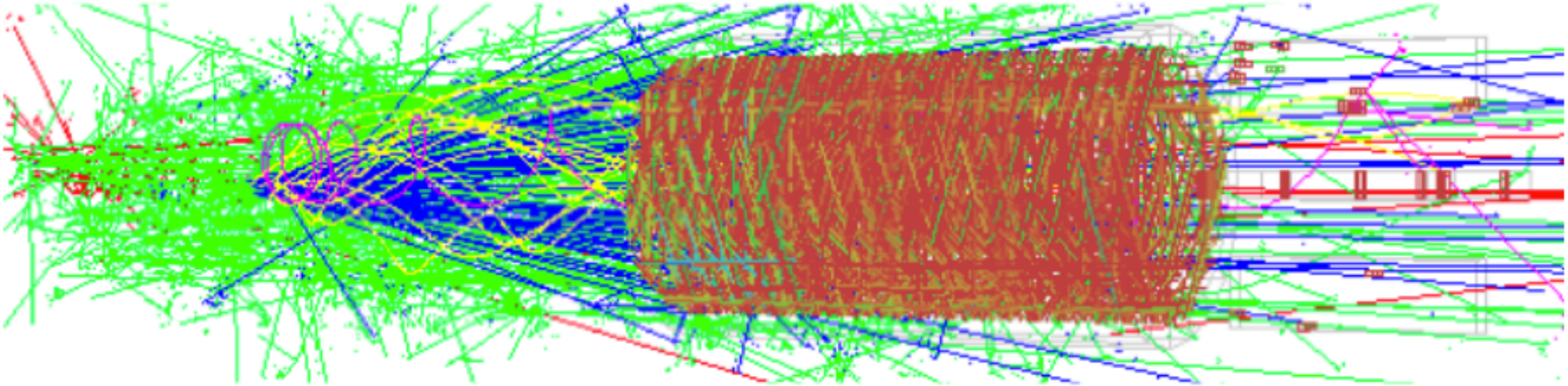
Speed and efficiency of tracker reconstruction is improved by selecting the calorimeter clusters and the tracker hits comparable with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters



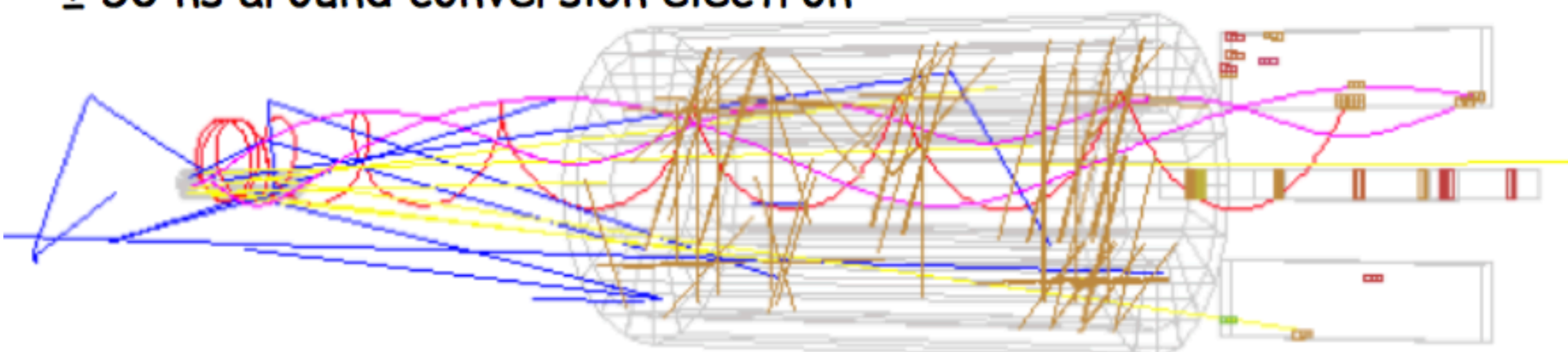


A single micro bunch event

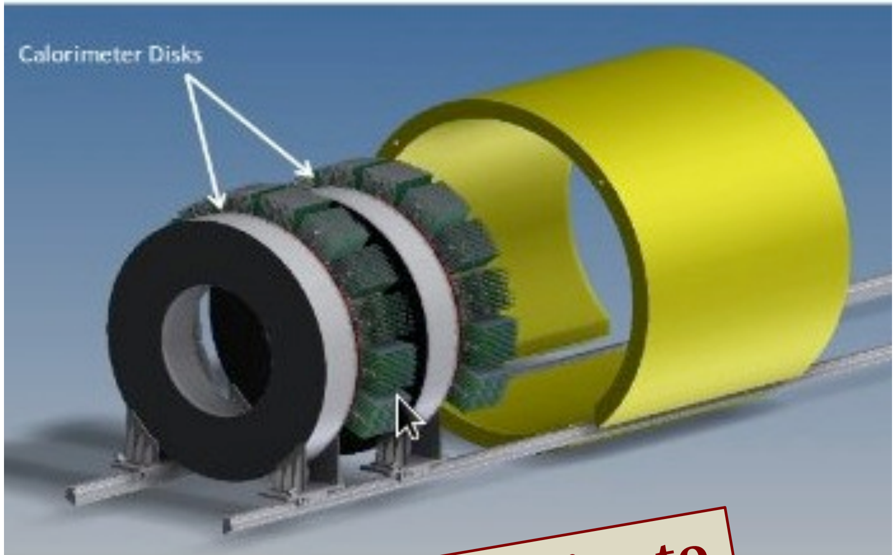
500 – 1695 ns window



± 50 ns around conversion electron

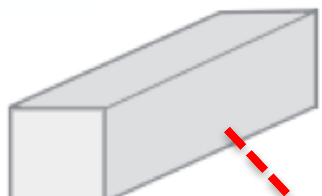


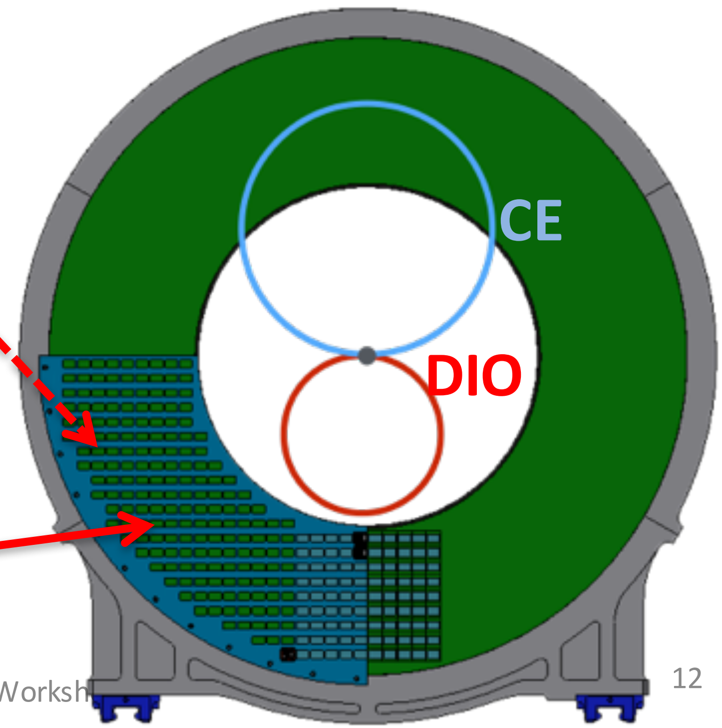
Calorimeter



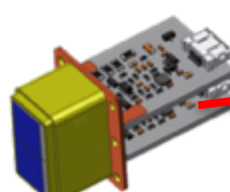
- 2 annular disks with 1400 square crystals (34 x 34 x 200) mm^3
- R_{IN} = 351 mm, R_{OUT} = 660 mm, Depth = 10 X_0 (200 mm)
- Distance 70 cm

Significant contribution to the calorimeter design from the INFN group



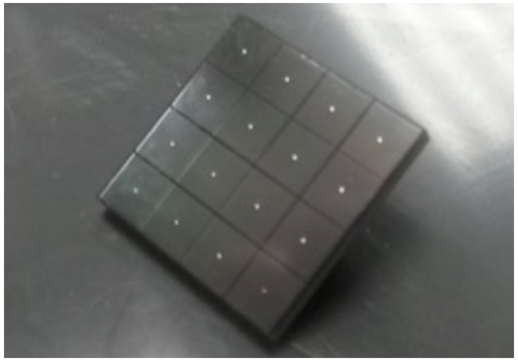


- 2 SiPMs/crystal (2800 total)
- Analog FEE and digital electronics located in near-by electronics crates



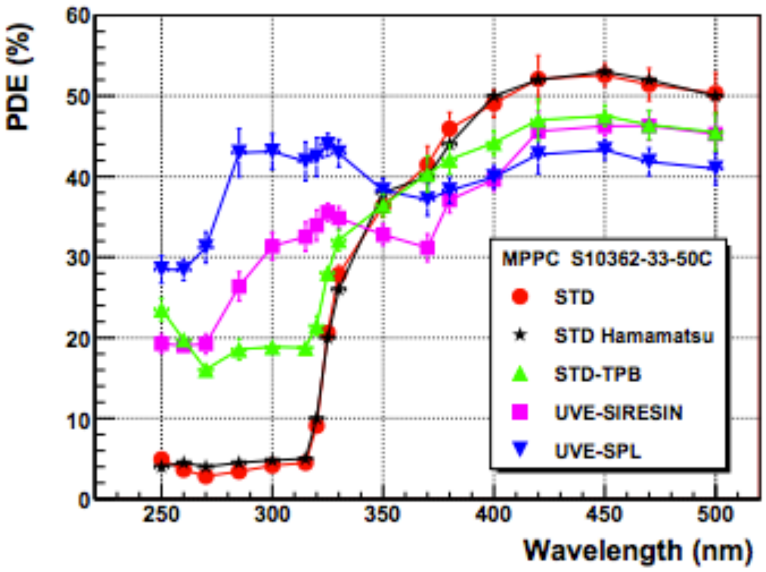
Crystals and Sensors choice

	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	**30**
Photosensor	APD	RMD APD	**SiPM**
Wavelength [nm]	402	220/300	**310**

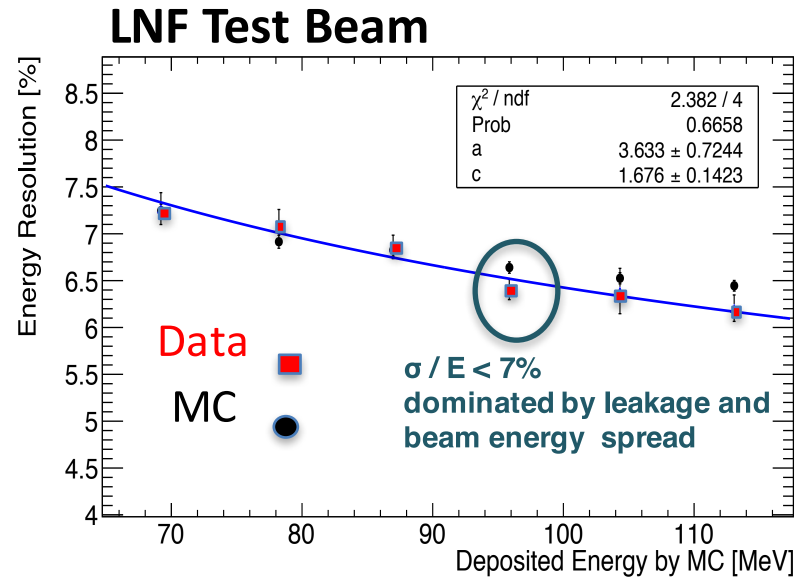


CsI(pure)

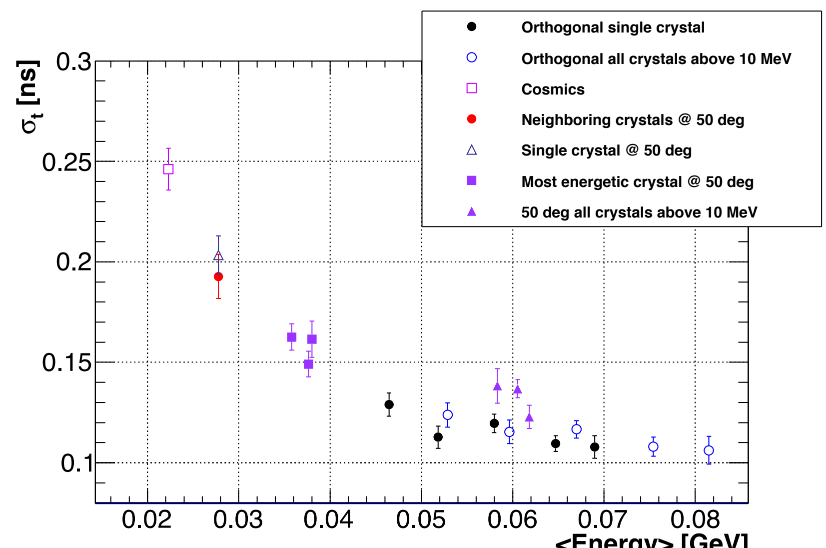
- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component.
- Emits @ 310 nm.
- Comparable LY of fast component of BaF_2.
- Lower cost (6-8 $/cc)



Meeting the requirements (1)



- Simulation performed as a function of LY and many other variables → **CsI+SIPM match requirements**
- Test beam with e^- @ BTF, LNF 80 to 130 MeV
  3x3 array of 30x30x200 mm^3 CsI + MPPC used
- Good energy (7%) and timing (110 ps) resolution



Exp tests → Matching EMC requirements

Meeting the requirements (2)

- **Crystals have been tested up to 100 krad and 10^{12} n/cm^2 with 14 MeV neutrons.**

→ No major issues/damages observed (LY drop 40% @ 100 krad)

→ Radiation hardness will be part of our QA test procedure

→ Effect of thermal neutrons on Radiation Induced Current being investigated

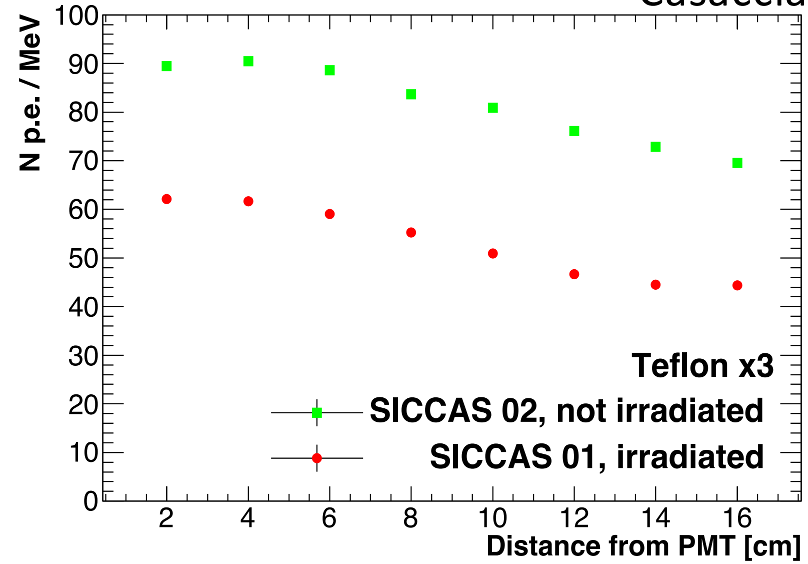
- **Photosensors have been tested up to 20 krad and 3 x 10^{11} n/cm^2.**

→ No problems with dose

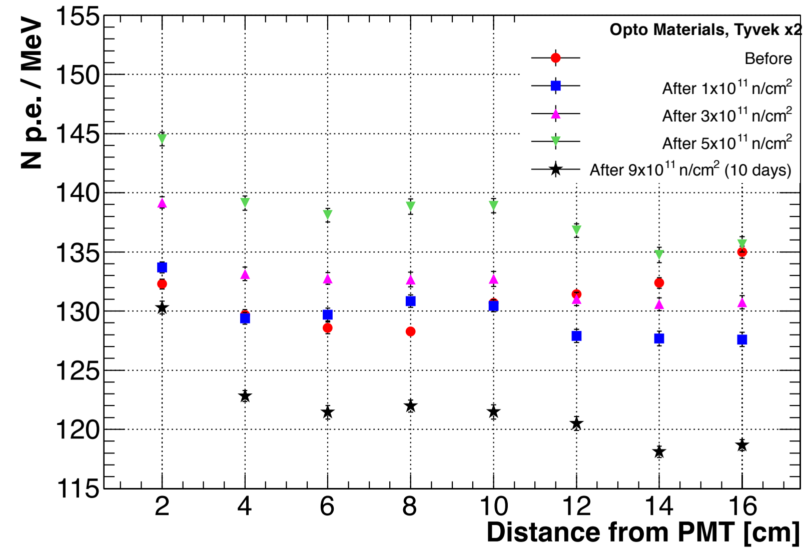
→ With neutrons, sensors are still working but leakage current increases to high values

→ Cooling photosensors to 0 C required.

Casaccia



FNG



Conclusions

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

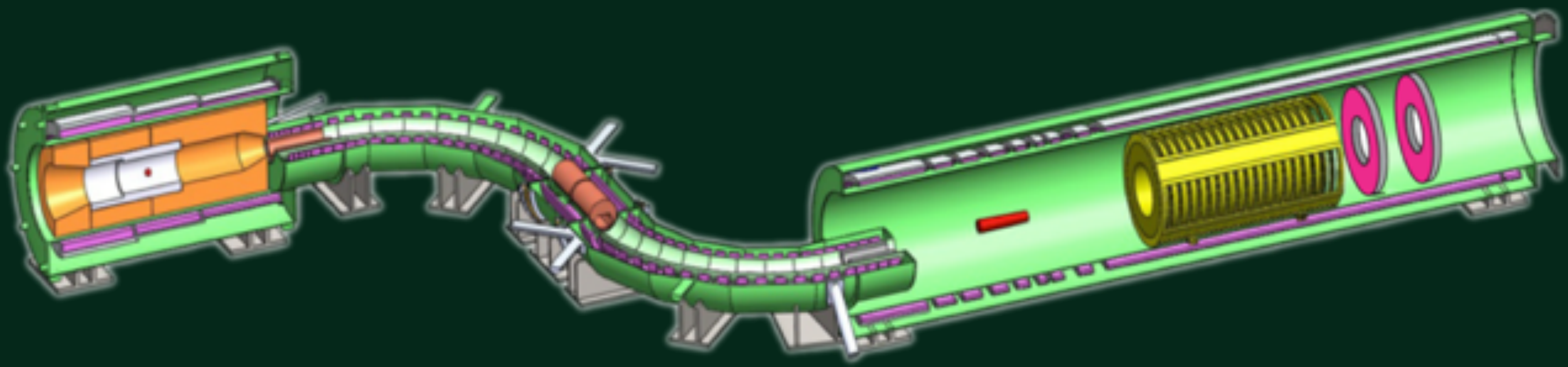
- **Mu2e will improve previous conversion experiment of 4 orders of magnitude and probe mass scales up to hundreds of TeV.**

- **< 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 in spring to freeze detector with CD3 in summer 2016
  → Construction period 2017-2019, followed by installation in 2019 - 2020

- **Mu2e-2 phase planned, increasing (x 10) intensity and sensitivity!**

Thank You!



Raffaella Donghia
Roma Tre University and LNF – INFN

XVII LNF Spring School "Bruno Touschek

ROMA TRE UNIVERSITÀ DEGLI STUDI
Mu2e
INFN
Fermilab

backup

Why muon conversion is unique?

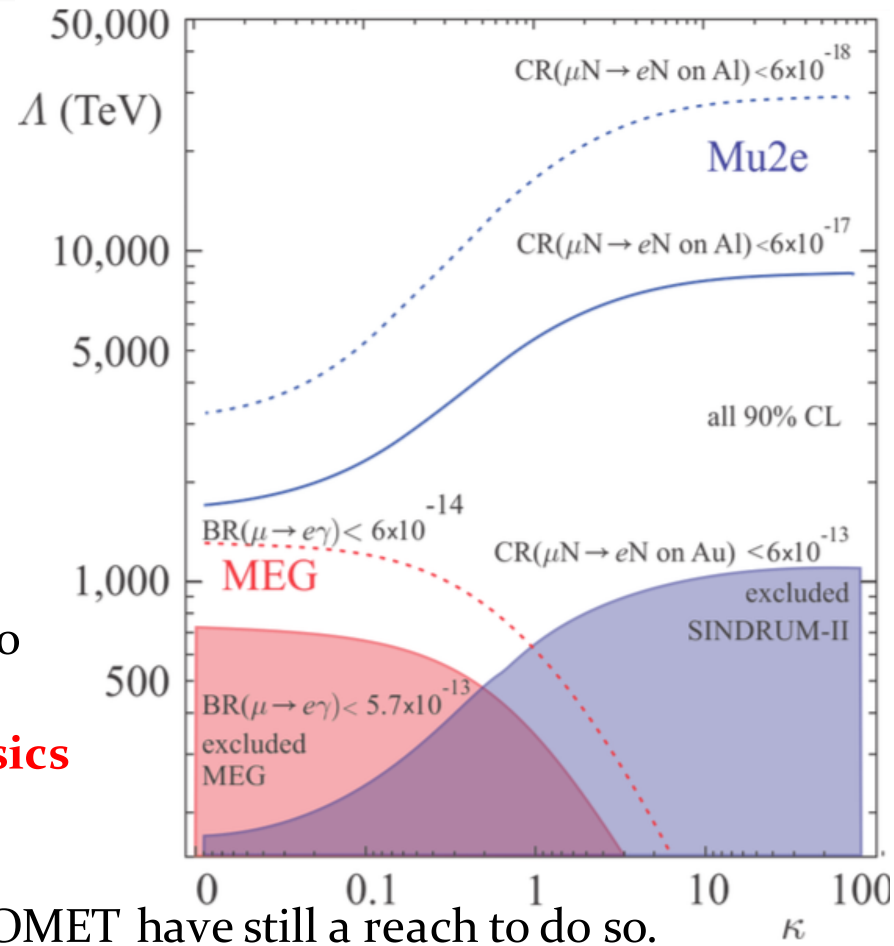
Muon conversion is a unique probe for BSM:

- **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/COMET do it with improved statistics.
  Ratio of the BR allows to pin-down physics model



  → If MEG does not observe a signal, MU2E/COMET have still a reach to do so.

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

Possible upgrade

Signal ?

Yes

Let's party!

Change the target to study the underlying NP

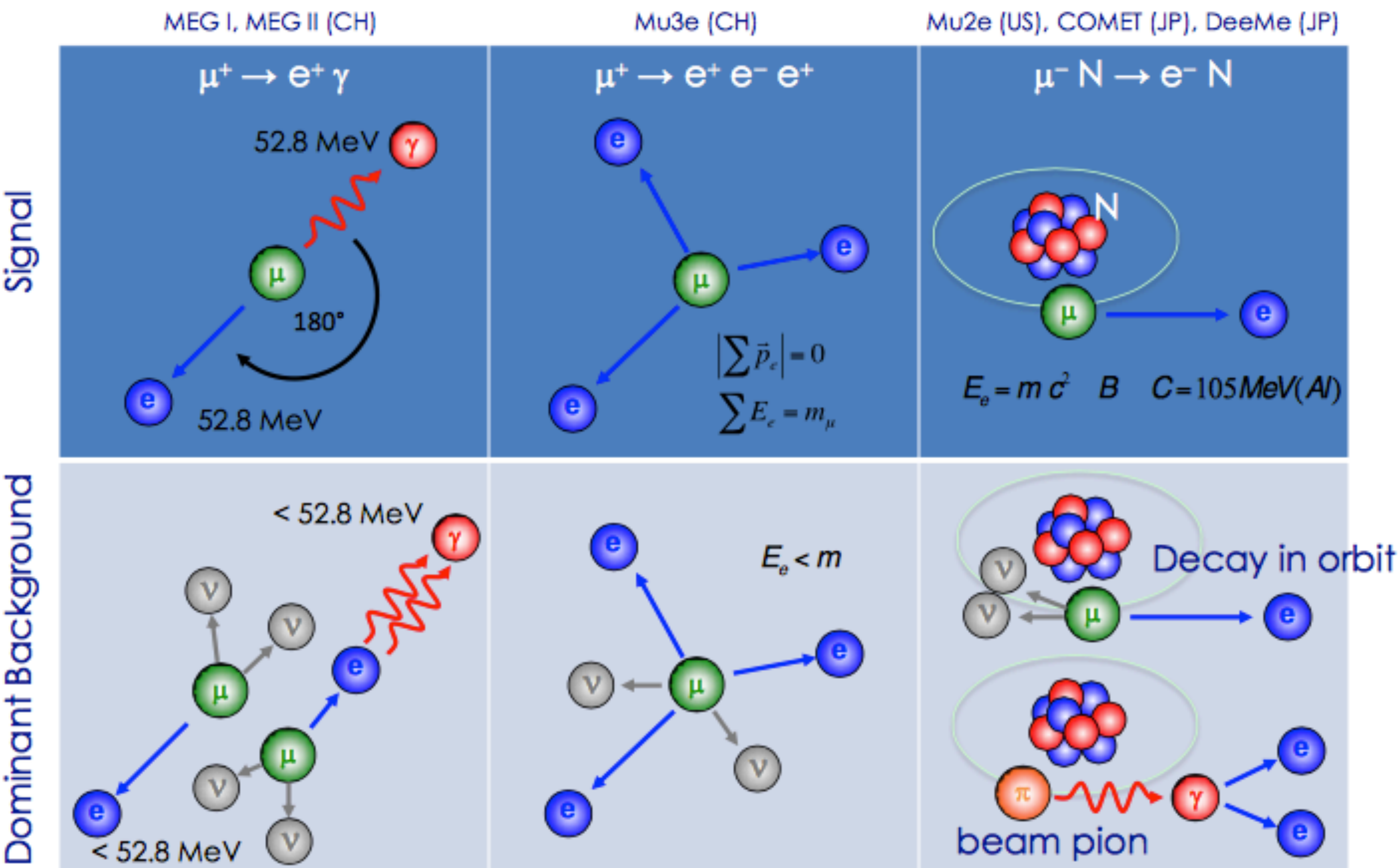
Redesign muon transport and detector

No

Higher rates, background must decrease to measure R at 10^{-18}

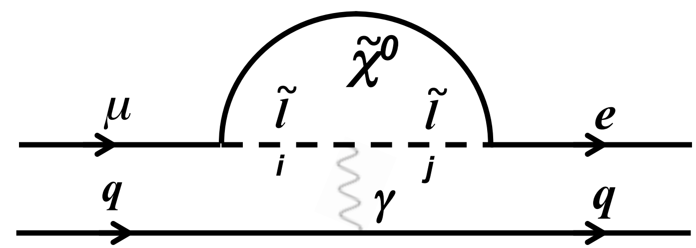
Redesign muon transport and detector

CLFV in the muon sector



Muon conversion

- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$
- μ-e is a CLFV process, similar but complementary to other CLFV processes as $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$
- It is a process strongly suppressed in the SM, but NP could enhance CLFV rates to observable values
  - **SO(10) SUSY** (L. Calibbi et al., hep-ph/0605139)



  - **Higgs triplet model** (M. Kakizaki et al., PLB 566)
  - **Littlest Higgs with T-parity** (M. Blanke et al., ActaPhys.Polon.B 41:657)
  - **Scalar Leptoquarks** (J.M. Arnold et al., Phys.Rev.D 88 035009)
  - **Left-Right symmetric model** (C.H.Lee et al., Phys.Rev.D 88, 093010)

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**
- …

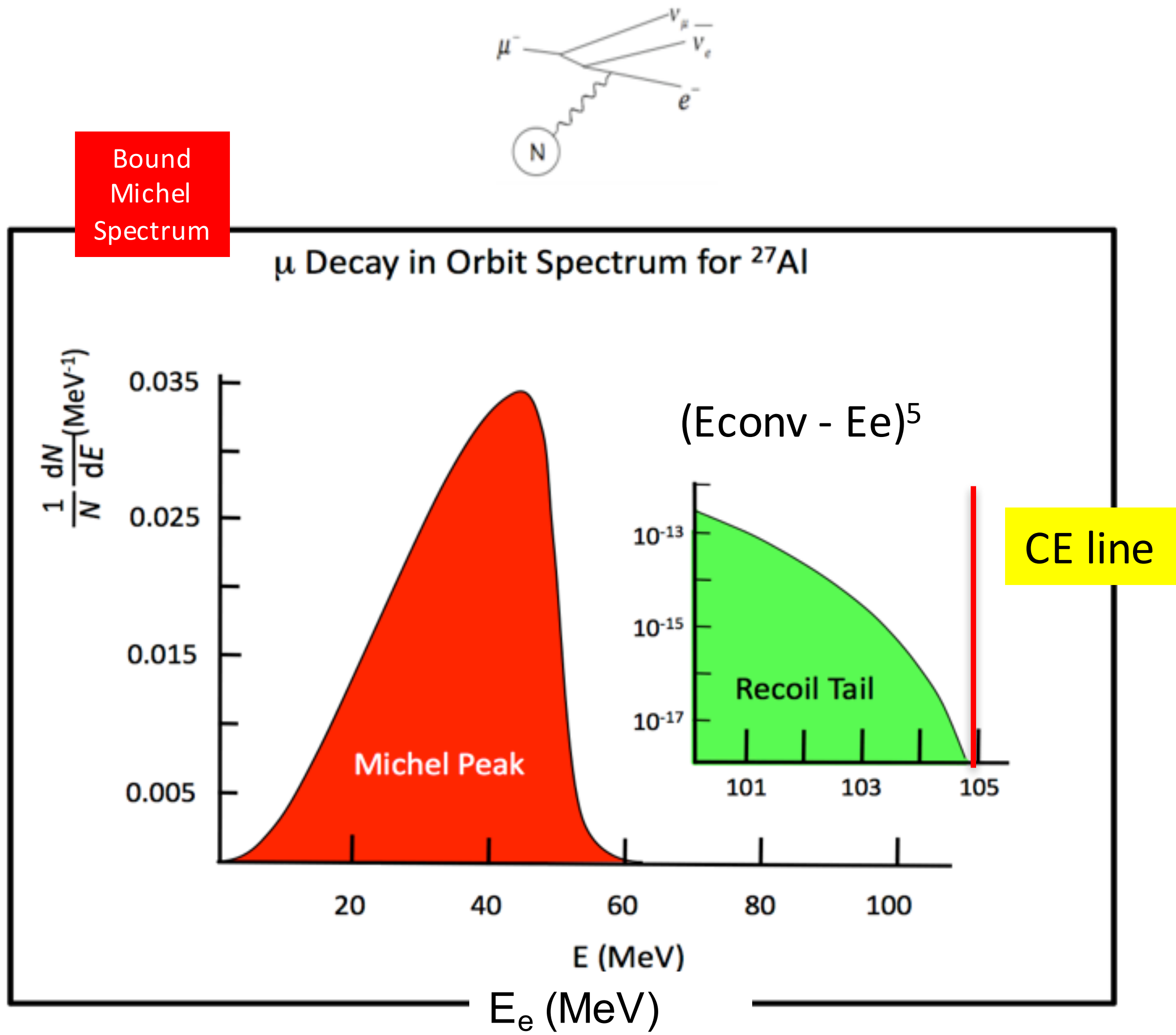
DIO background

- **The DIO background is the most difficult one.**

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

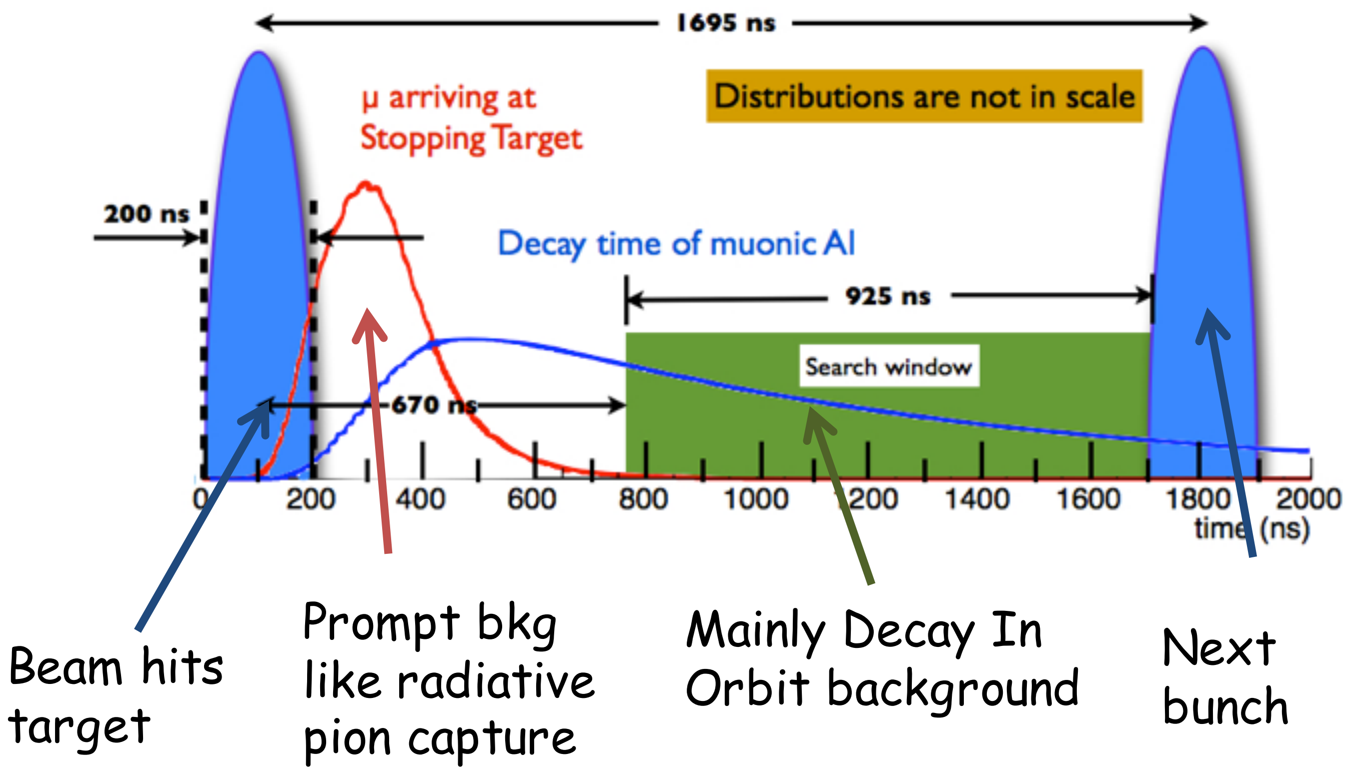
→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ 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

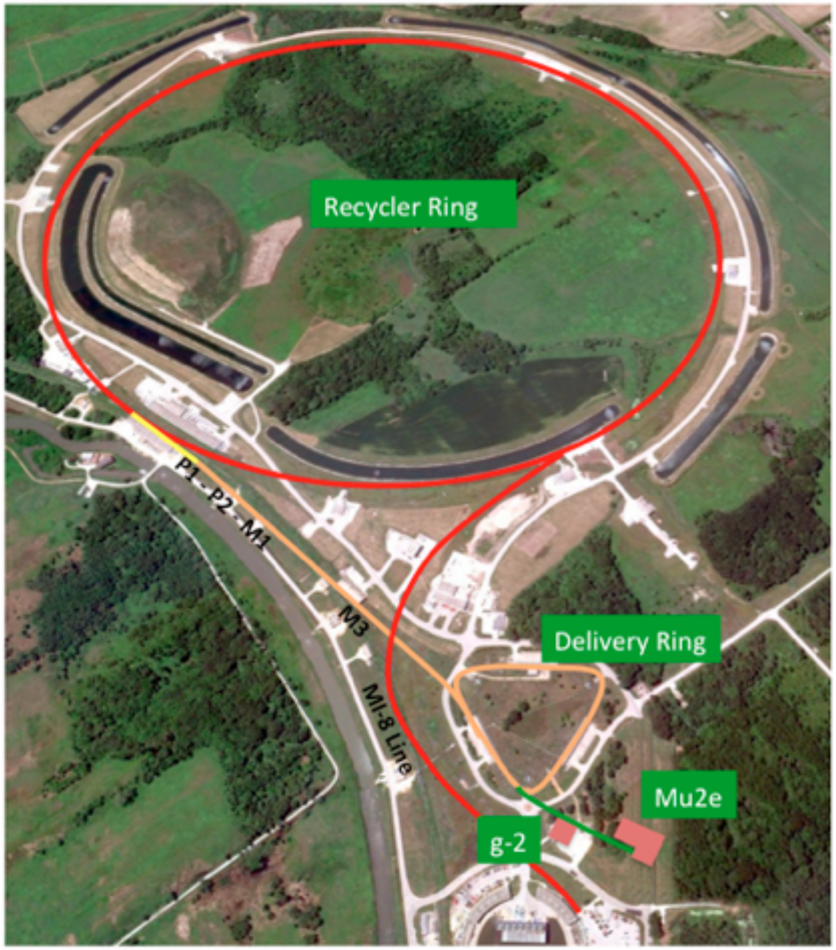


- **Use the fact that muonic atomic lifetime >> prompt background**
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab provides the beam we need !

- **OUT of time protons are also a problem.**
  To keep associated background low we need proton extinction of 10^{-10} :
  proton extinction (between pulses) → # protons out of beam/# protons in pulse

Accelerator Scheme & Proton extinction

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



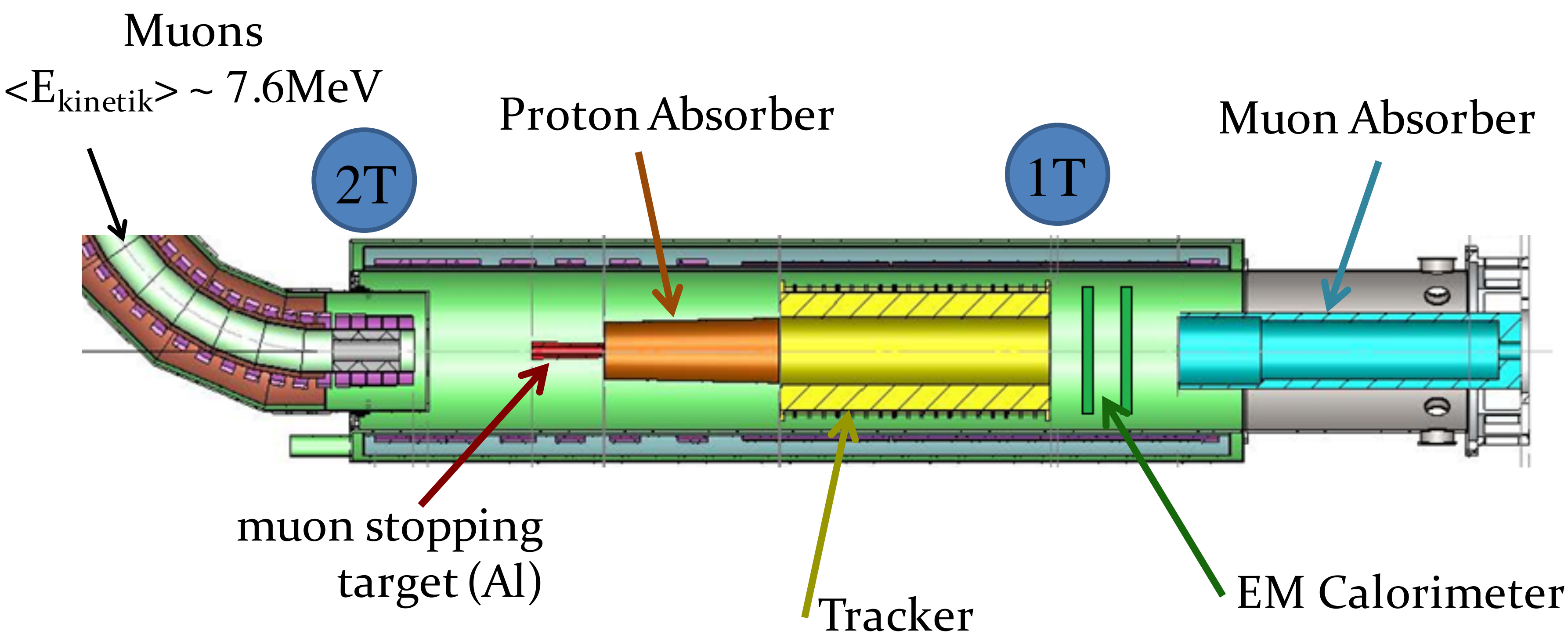
Proton Extinction

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

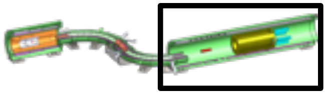
- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole

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

The Detector Solenoid



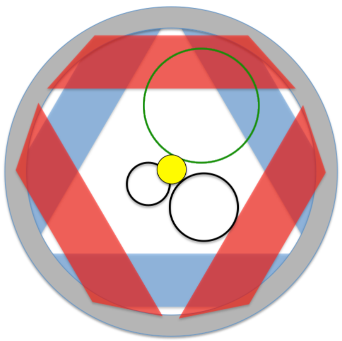
- Graded field “reflects” downstream a fraction of conversion electrons emitted upstream (isotropic process)
- For the sensitivity goal → ~ 6 x 10^{17} stopped muons for 3 years run → 10^{10} stopped muon/s (10 GHz)



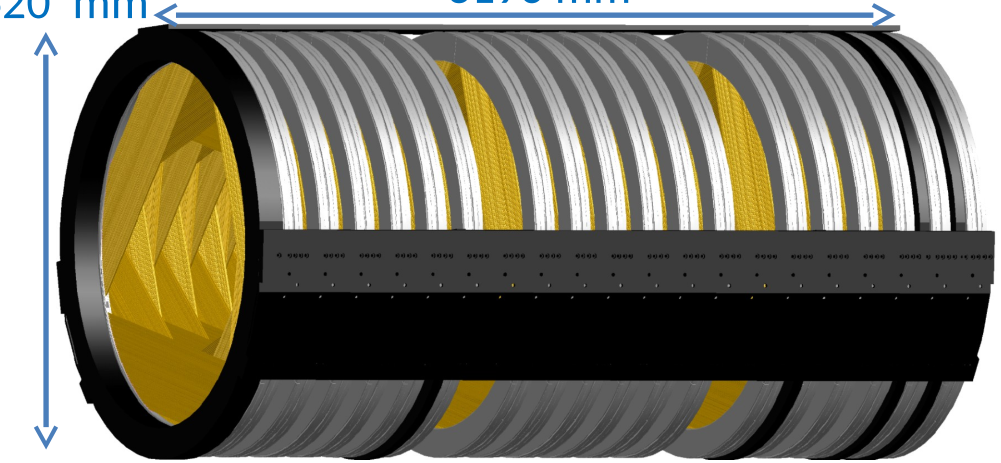
Tracker system

- Tracker is a low mass straw drift tubes design with tubes transverse to secondary beam
- 15 μm thick straw walls, 5 mm diameter, dual-ended readout, length 430 – 1120 mm.
- It must operate in vacuum
- ~ 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 background miss the tracker.

Tracker Plane



Planes rotated

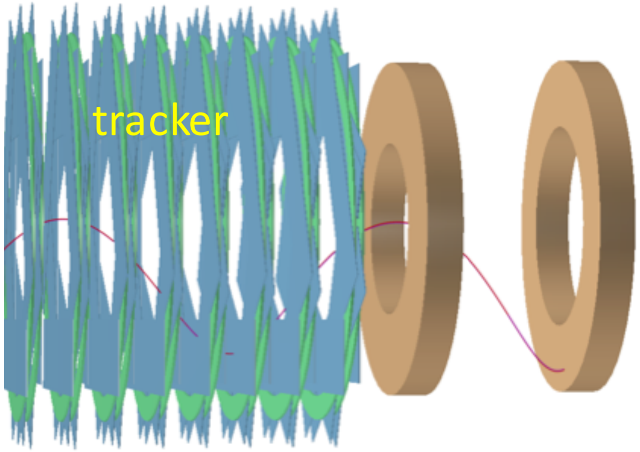


Calorimeter System (1)

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/cm²/year

Two disks separated by ½ wavelength (70 cm)

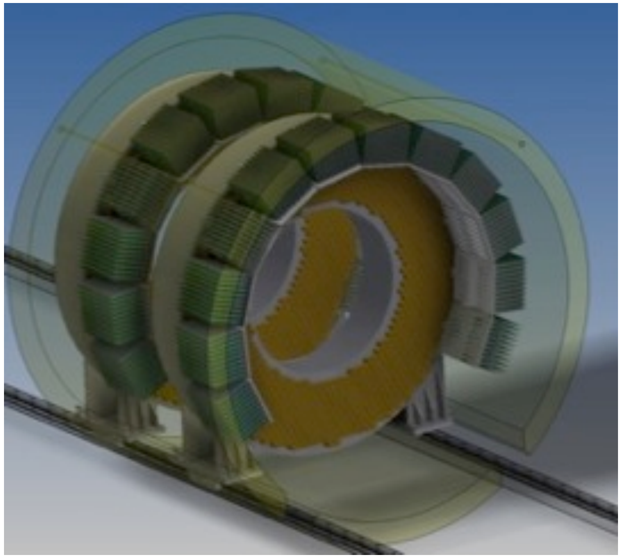


Calorimeter choice:

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



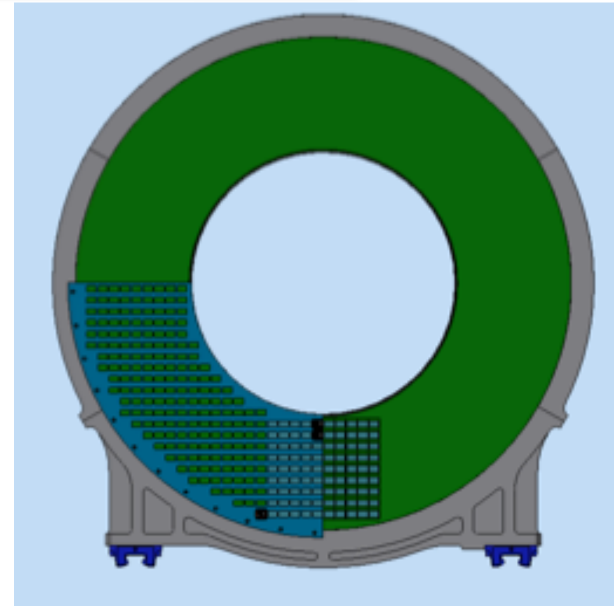
Disk geometry

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

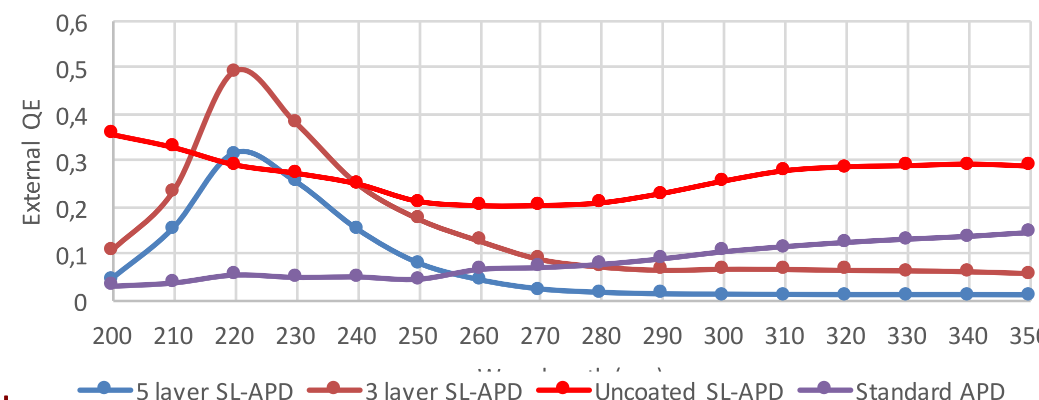
Calorimeter System (2)

The Calorimeter consists of two disks with 1650 BaF_2 square crystals (30x30x200) mm^3

- ❑ R_{IN} = 351 mm, R_{OUT} = 660 mm, Depth = 10 X_0 (200 mm)
- ❑ Each crystal readout by two SL APDs (9x9 mm^2)
- ❑ Analog FEE and digital electronics located on calo
- ❑ Radioactive source and laser systems provide absolute calibration and monitoring capability.



To reduce the slow BaF_2 component at higher wavelengths , a Caltech/JPL/RMD consortium formed to develop a RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** that incorporates also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for $\lambda > 300$ nm.

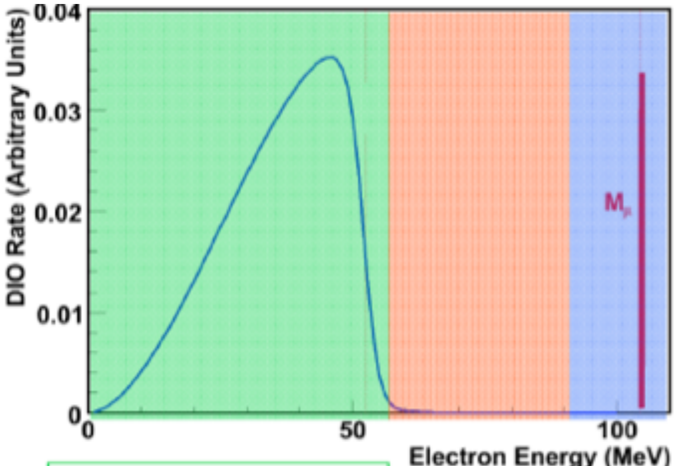


Prototypes with LYSO+APD, CsI+MPPC built
Next one with BaF_2 + SL APDs in progress

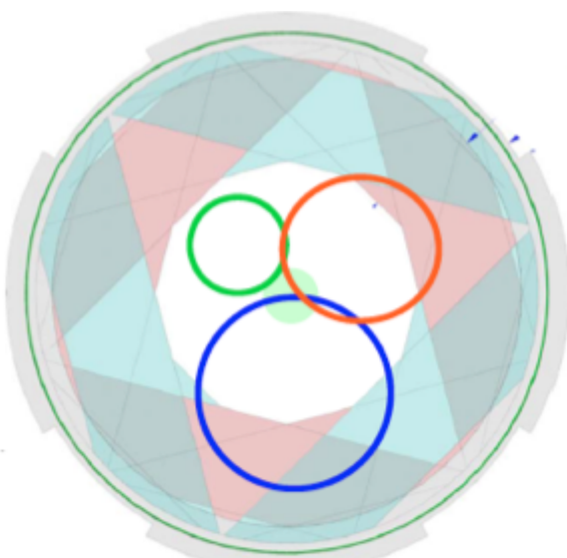
Good progresses on FEE and mechanics

Basic reconstruction scheme

Reconstructable tracks



no hits in tracker



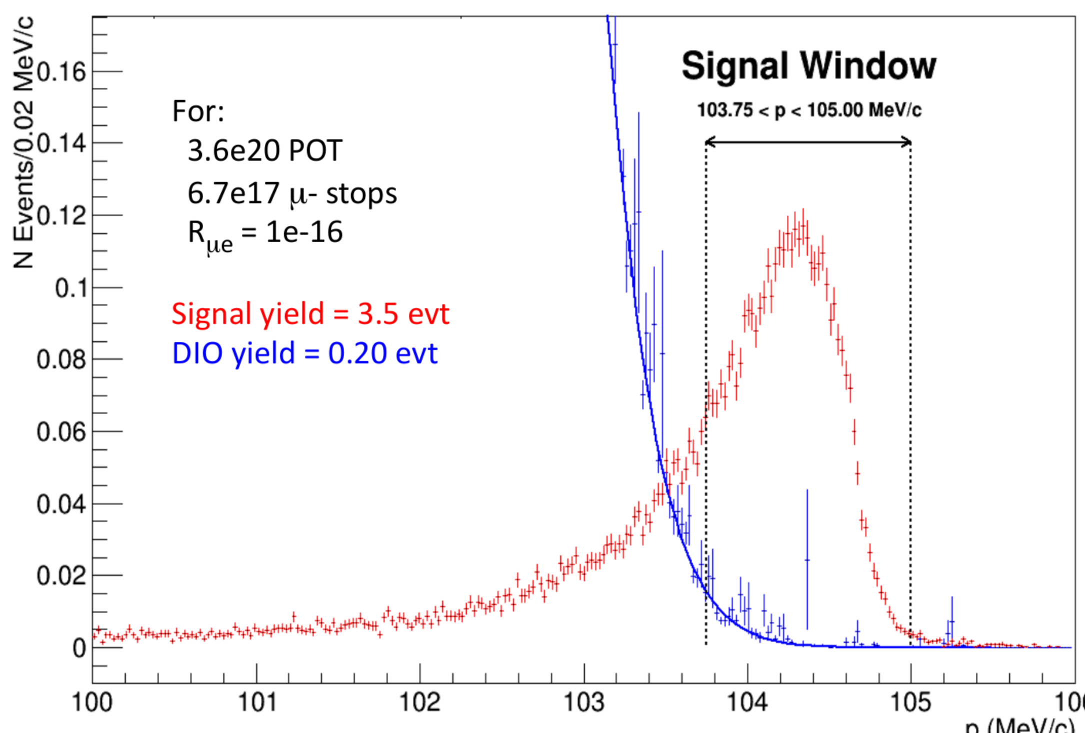
Tracking reconstruction based on
***BABAR* Kalman Filter algorithm**

No significant contribution of mis-reconstructed background

Momentum resolution for CE

core σ~120 keV

tail σ~175 keV (2.5%)



Mu2e Expected Background

(assuming ~ 10 GHz muon stops, $6x10^{17}$ stopped muons in $6x10^{7}$ 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)	$0.001 \pm <0.001$
	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 x 10^{-17} @ 90% C.L.

(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

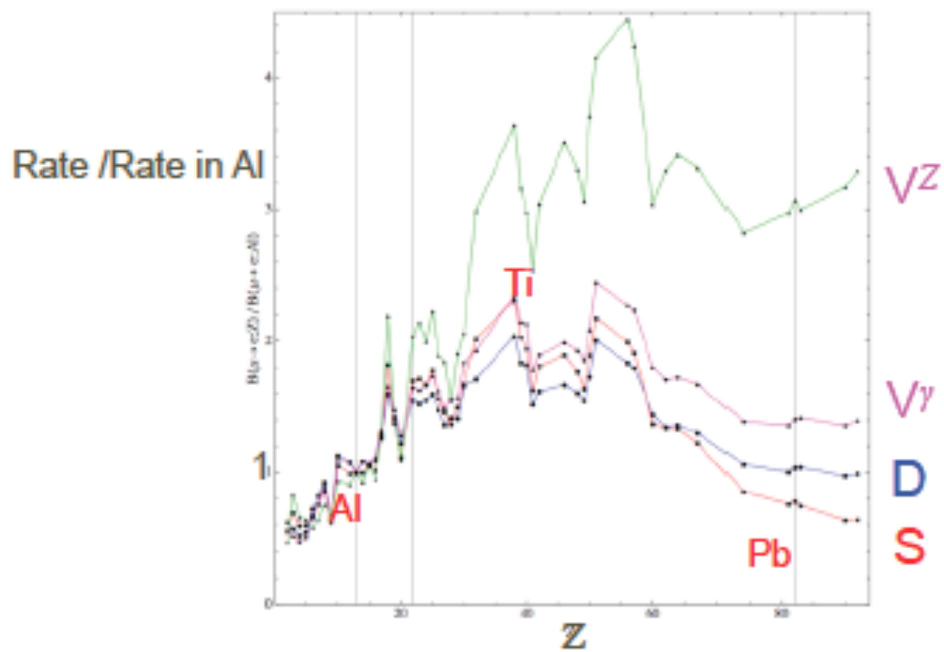


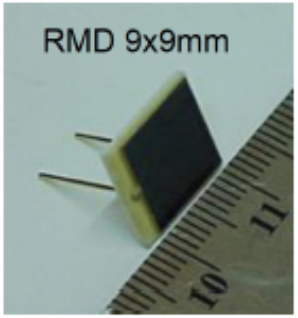
Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

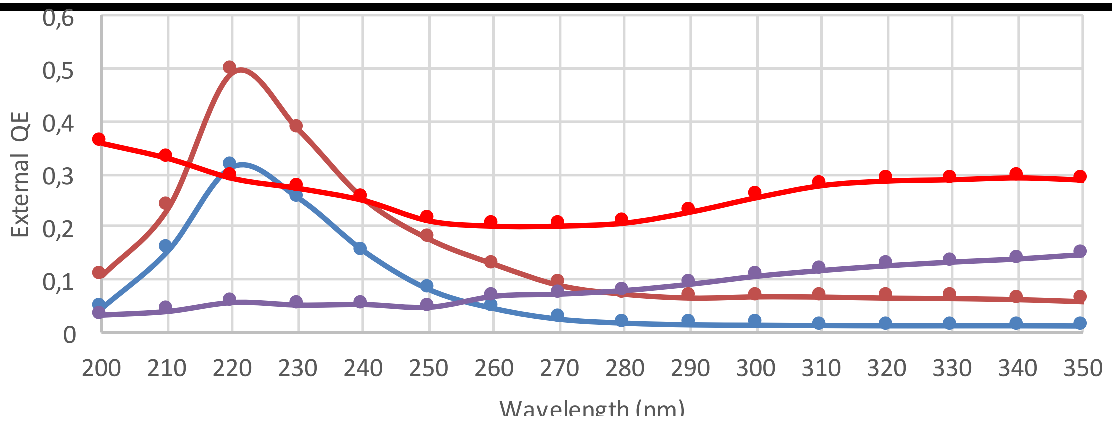
Photosensors Choice

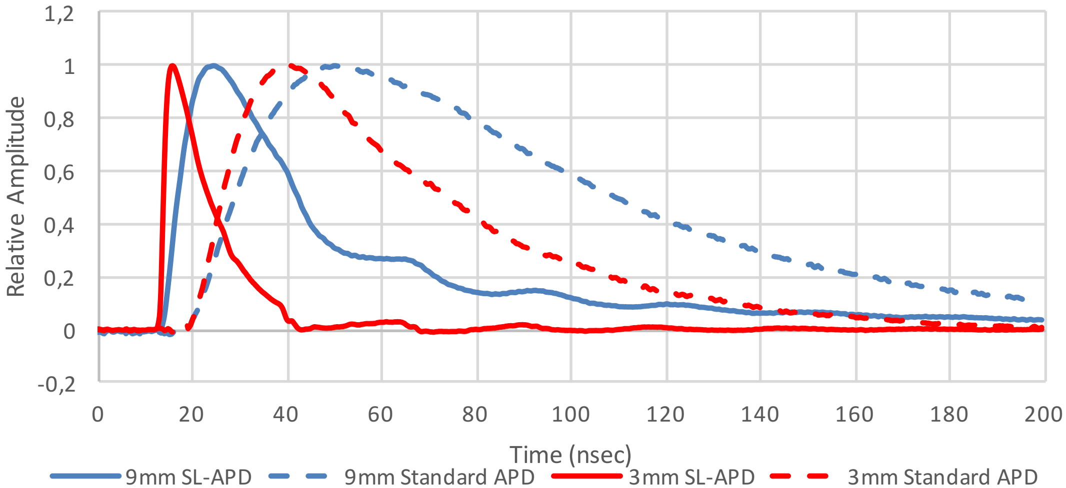
A Caltech/JPL/RMD consortium formed to develop a Large area RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** incorporating also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for wavelength > 300 nm.

- ✓ 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







CsI Crystals

	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)

Baseline for EDR

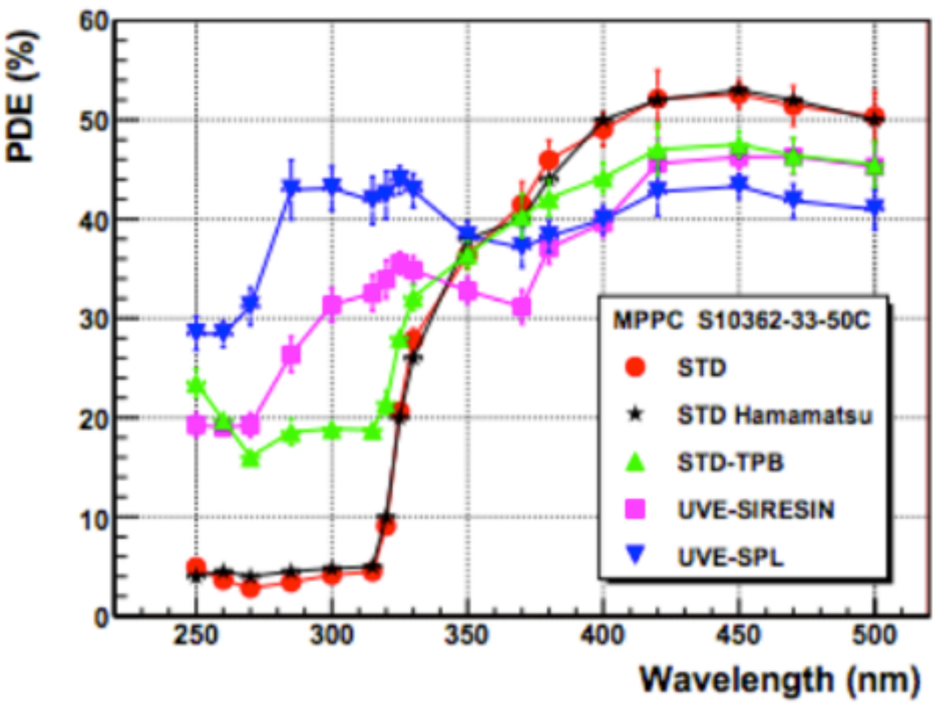
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

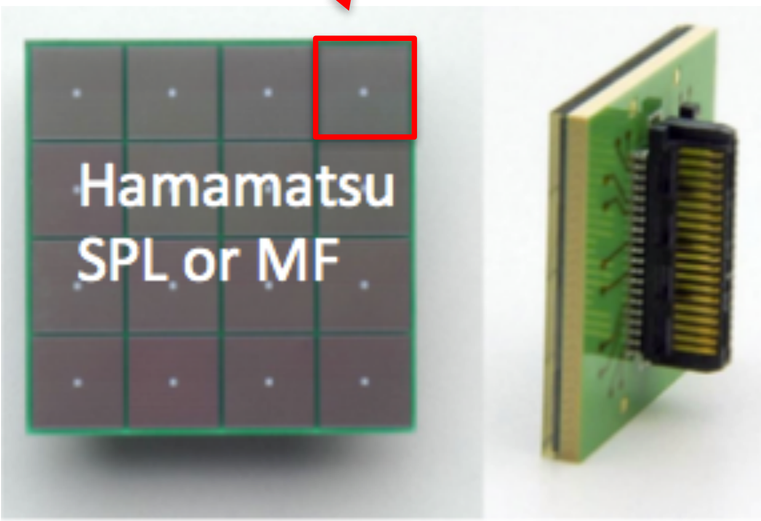
UV extended SiPM

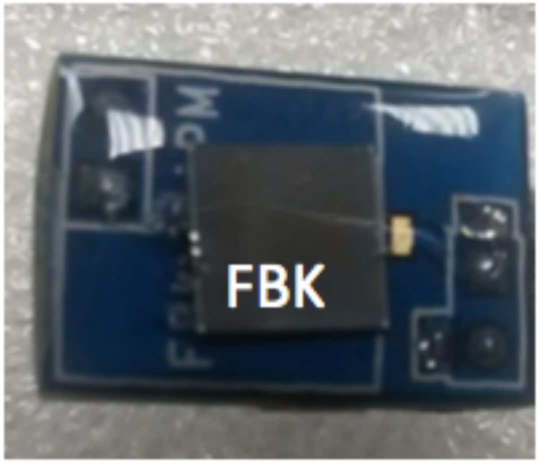
The basic SIPM element (pixel) is a combination of the Geiger-APD and quenching resistor

The PDE of UV-enhanced MPPC is higher than the standard one:

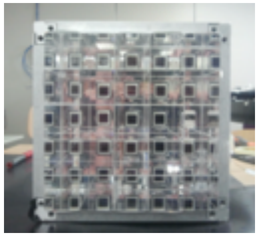
- **30-40% @ 310 nm** (CsI pure wavelength)
- with new silicon resin window
- Gain ~ 10^6

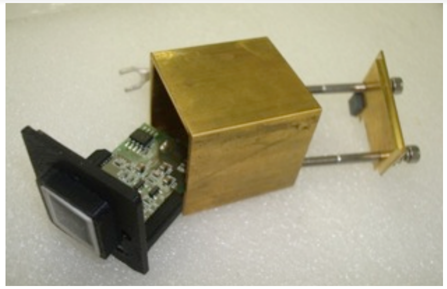


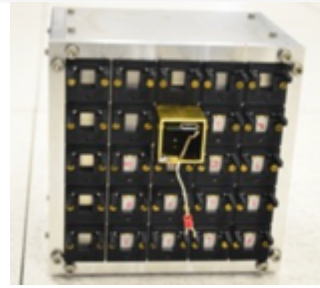


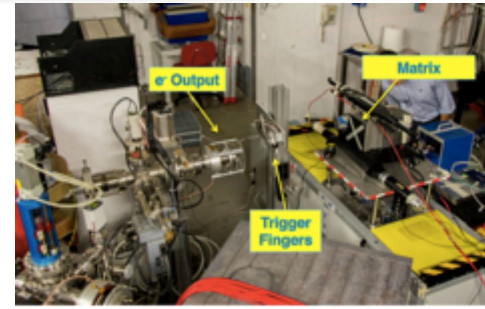


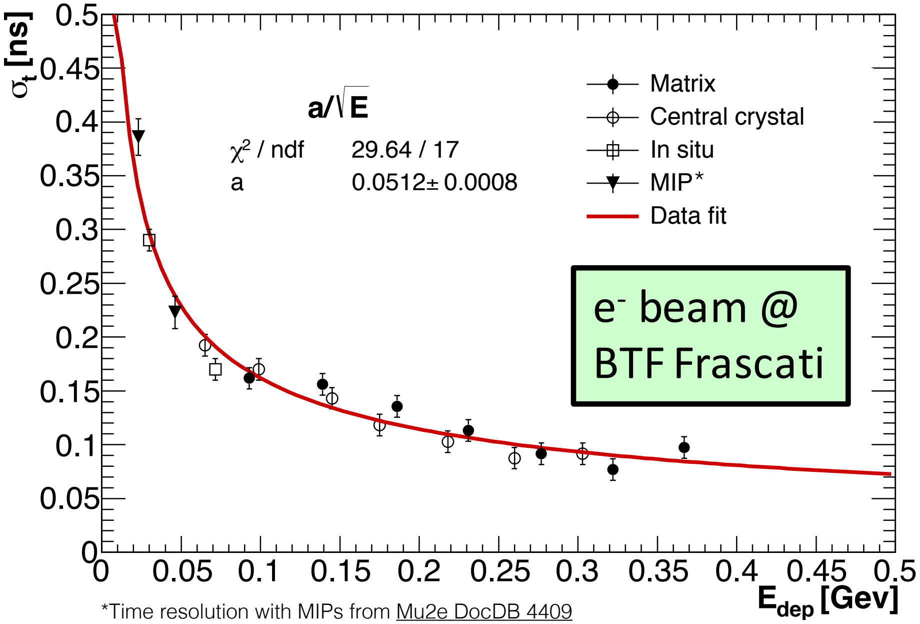
LYSO Legacy



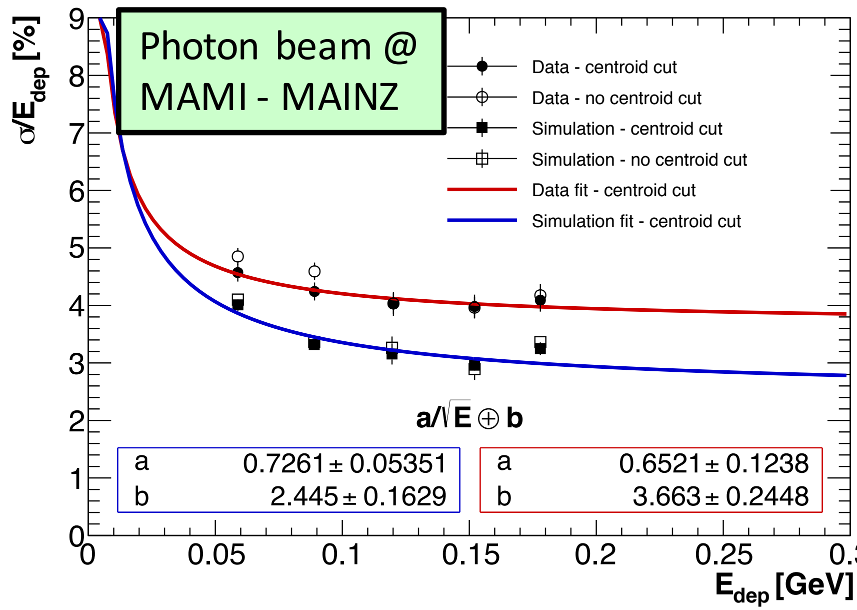








*Time resolution with MIPs from Mu2e DocDB 4409



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

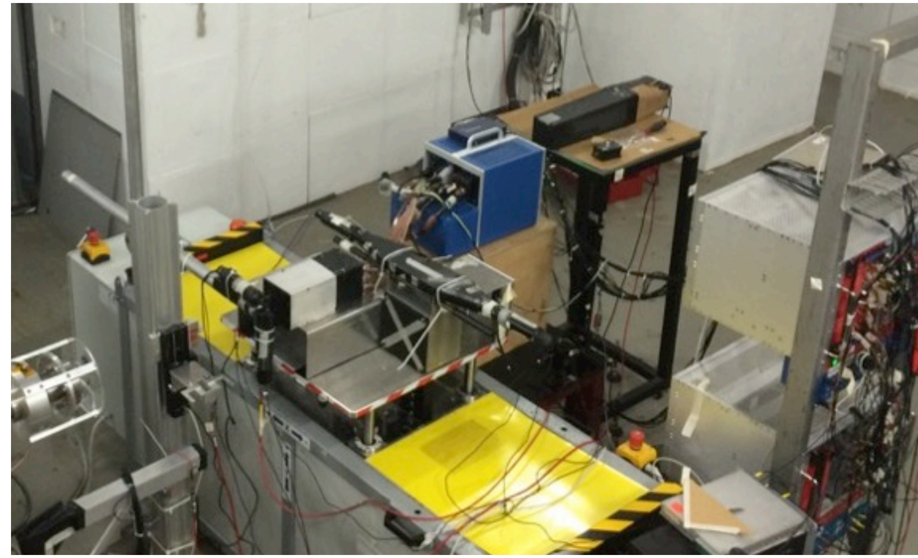
Energy resolution as a function of the energy deposition fitted with the function:

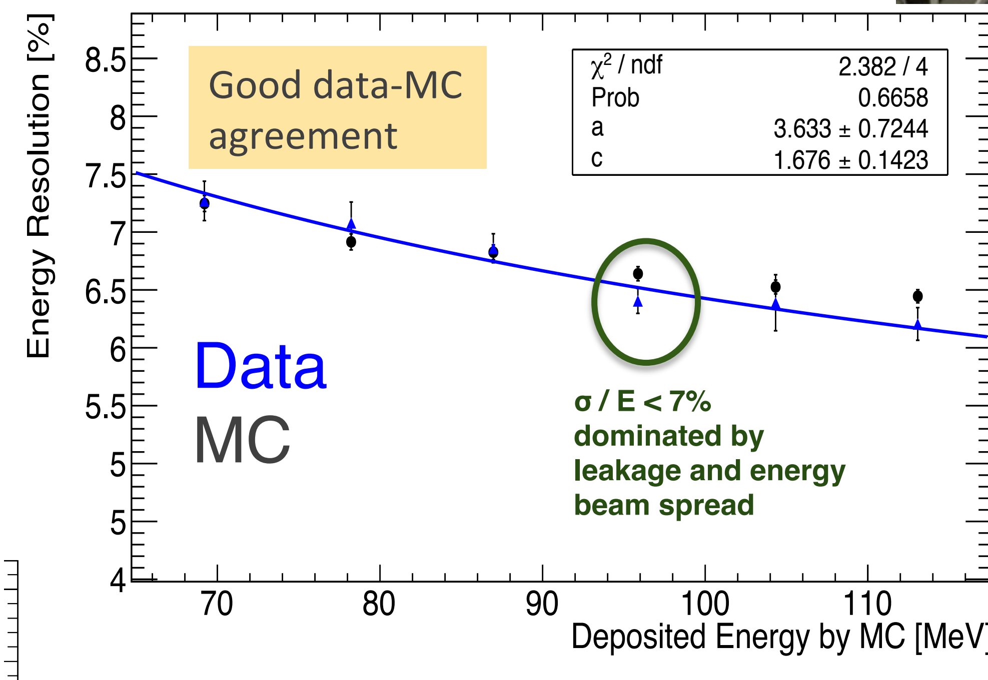
~ 4% @ 100 MeV

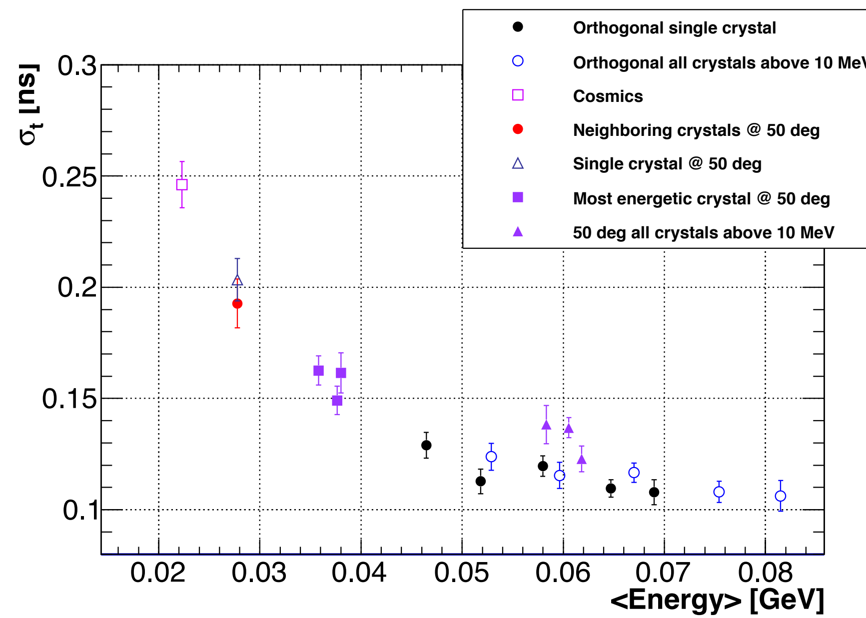
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

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

CsI+MPPC backup option

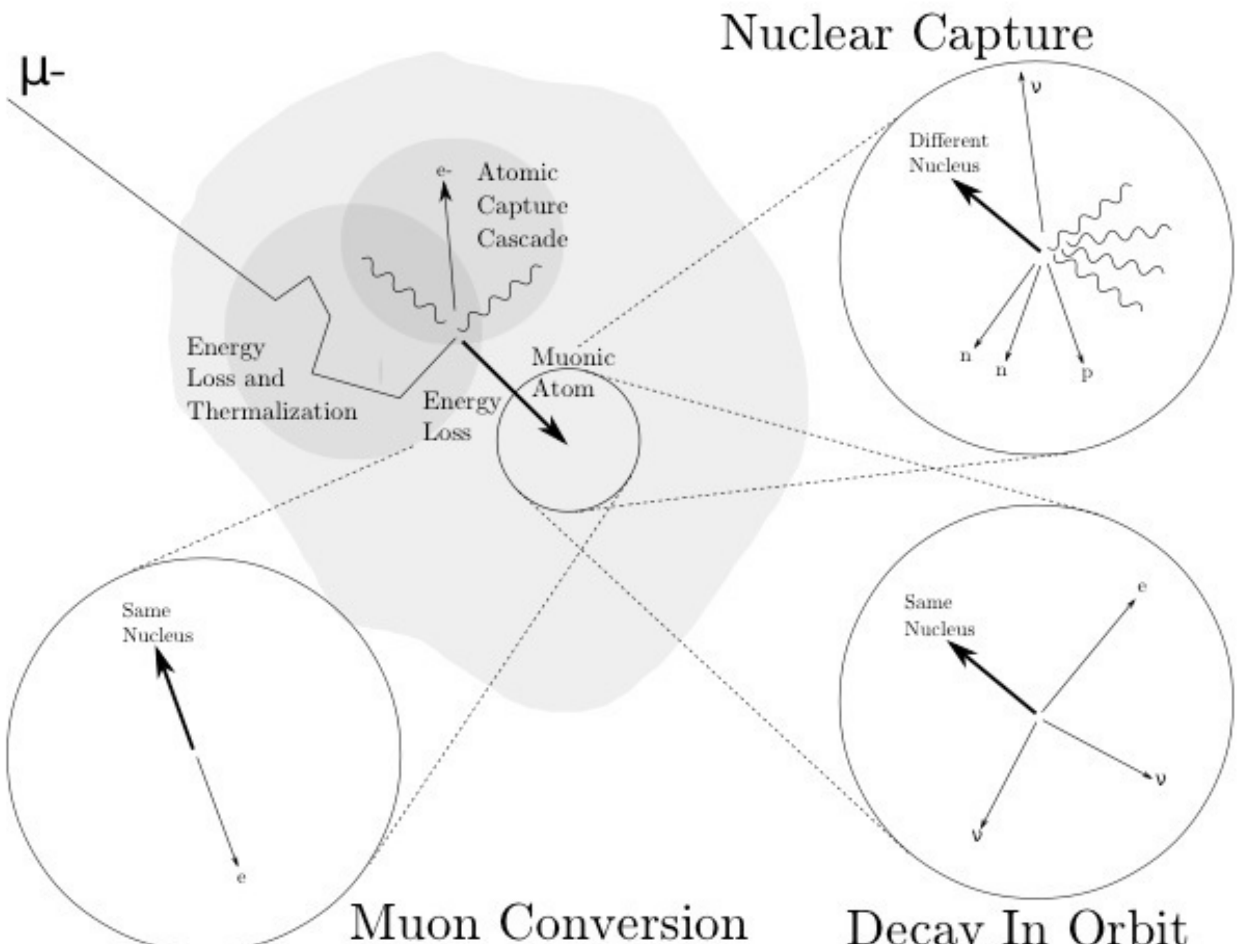






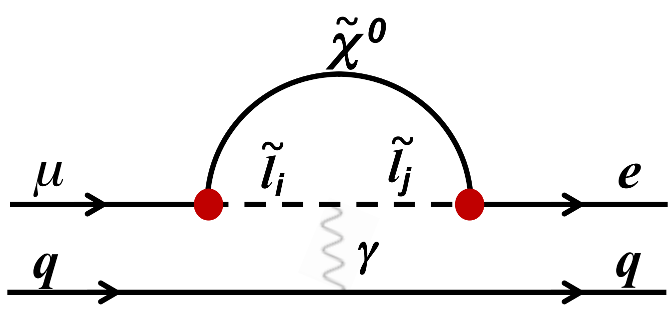
Muon Processes

The atomic, nuclear, and particle physics of μ^- drive the design of the experiment



Specific Example: SUSY

Probe SUSY through loops

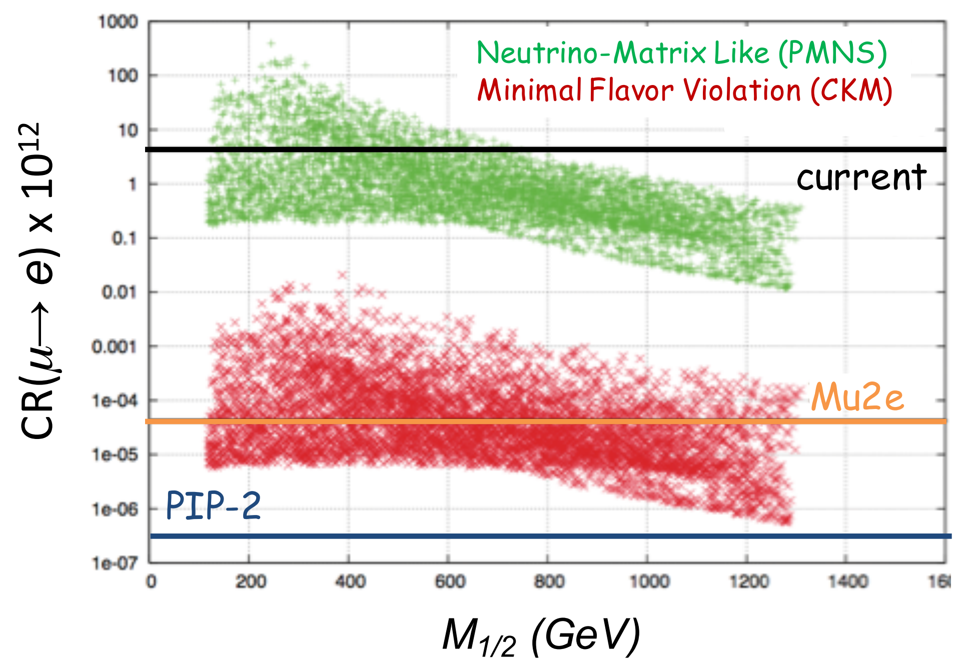


If SUSY seen at LHC → rate ~10^{-15}

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

SUSY GUT in an SO(10) framework

$\mu N \rightarrow eN$ ($\tan\beta = 10$)



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)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

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**

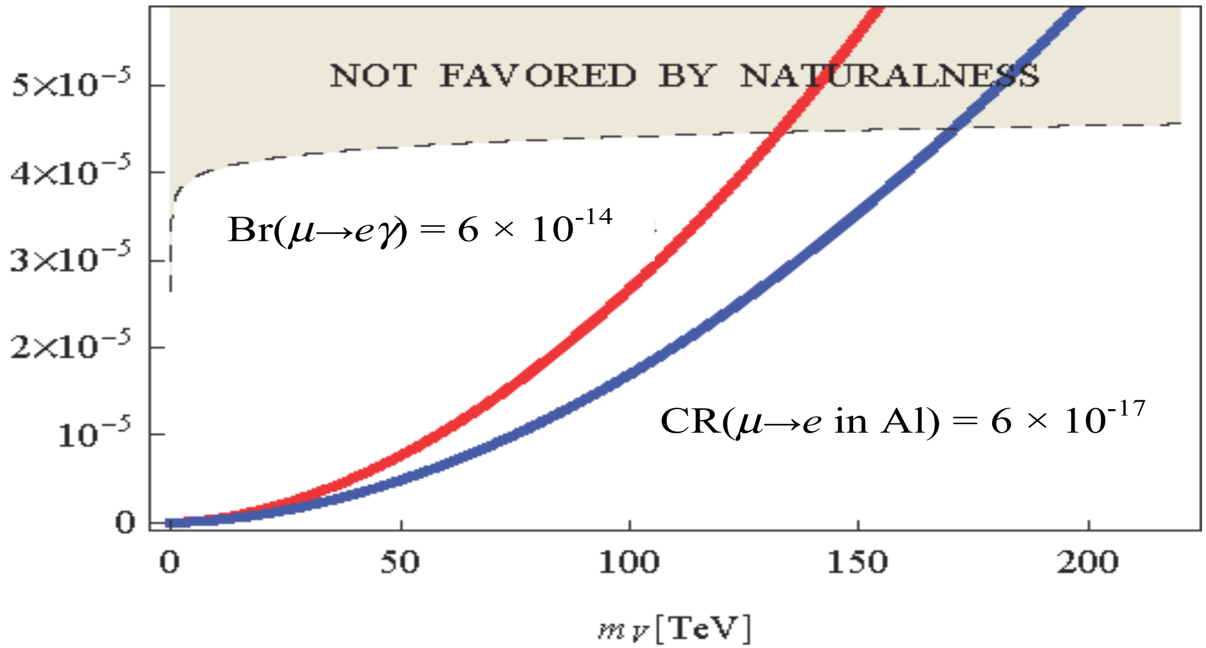
SUSY benchmark points vs LHC

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

- 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.

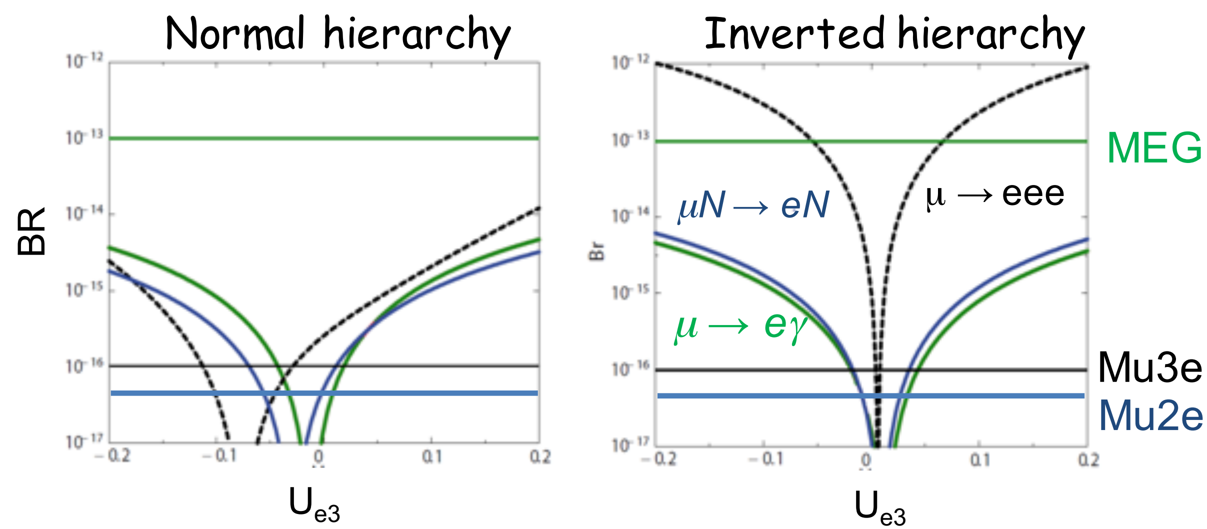
- Rosso: MEG-II
- Blu: Mu2e

Specific example: Higgs Triplet e LHT

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

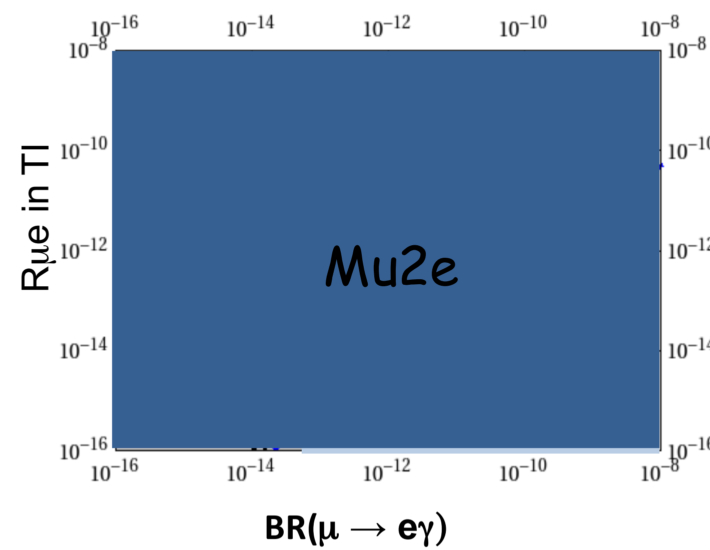
Higgs triplet model

Dependence on neutrino mass hierarchy and θ_{13}



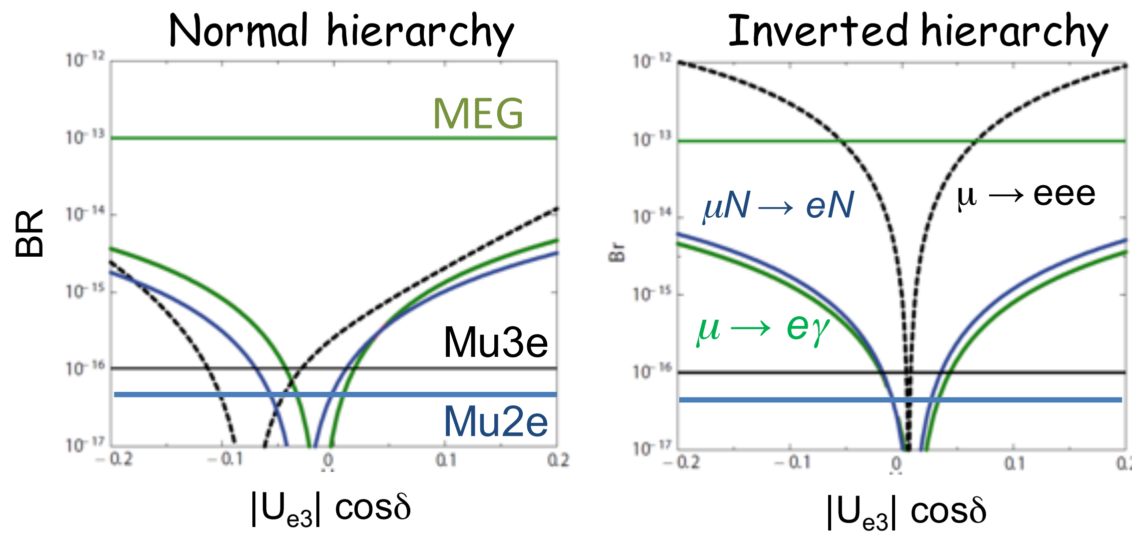
Littlest Higgs with T-parity

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

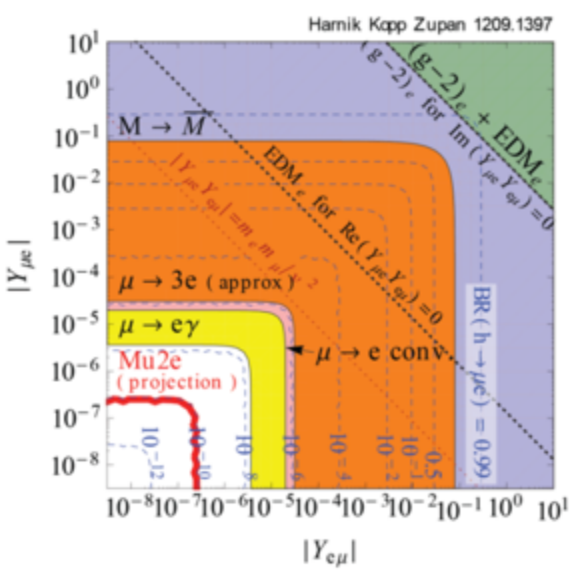


A few more models…

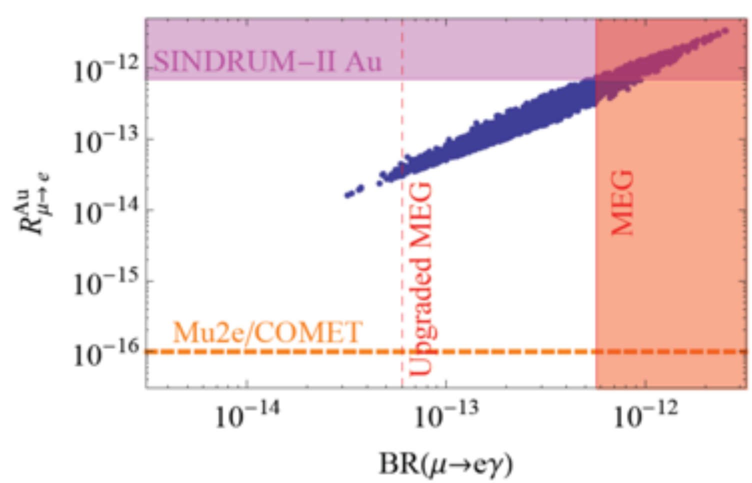
Higgs triplet model



Flavor violating Yukawa couplings



Left-right symmetric models



Stopping Target Monitor

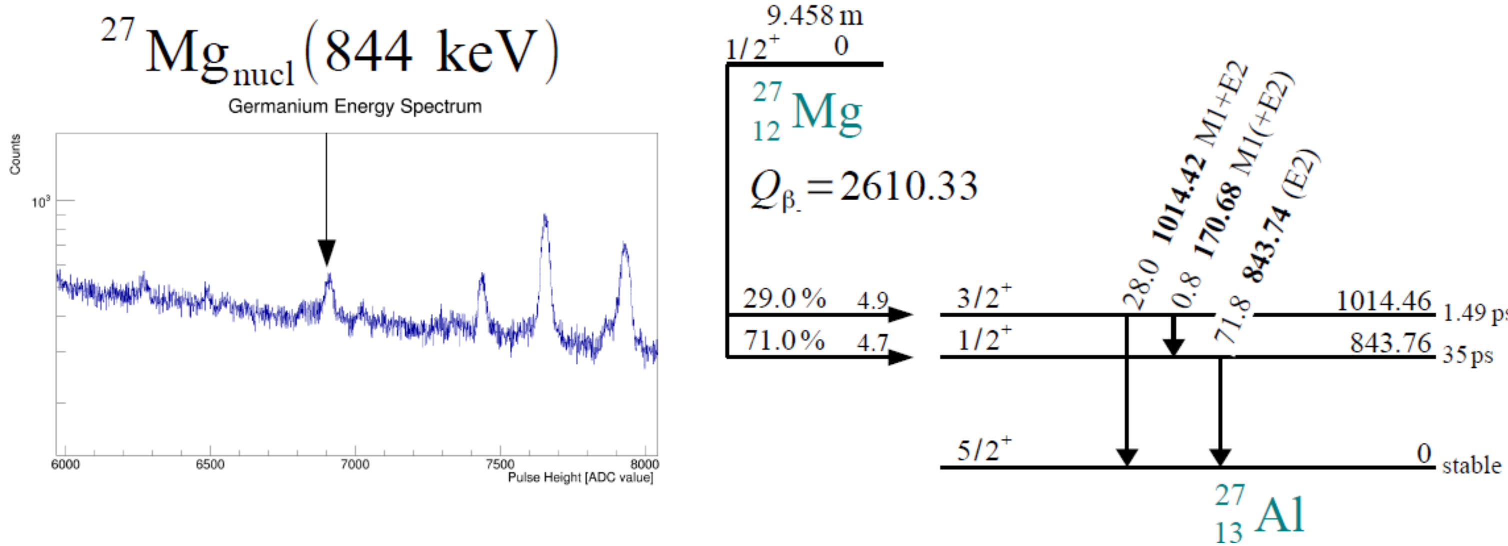


Figure 7.18. Preliminary singles germanium spectrum from the AlCap experiment at PSI. When muons stop in aluminum, they capture on the nucleus 60% of the time. A fraction of the captures produce ^{27}Mg in the ground state, which has a half-life of 9.5 minutes. In the decay, an 844 keV gamma is produced 72% of the time.

- Need a high precise gamma detector (HpGe)
- Energy of gamma ray is unique to the detector
- Detecting the delayed gamma rays eliminate problems related to beam flash
- Proton beam structure is 0.5 s on followed by 0.8 s idle. Gamma spectrum wil be acquired during idle time.
- Hpge should view the target far from the source and beyond DS

CE trajectory