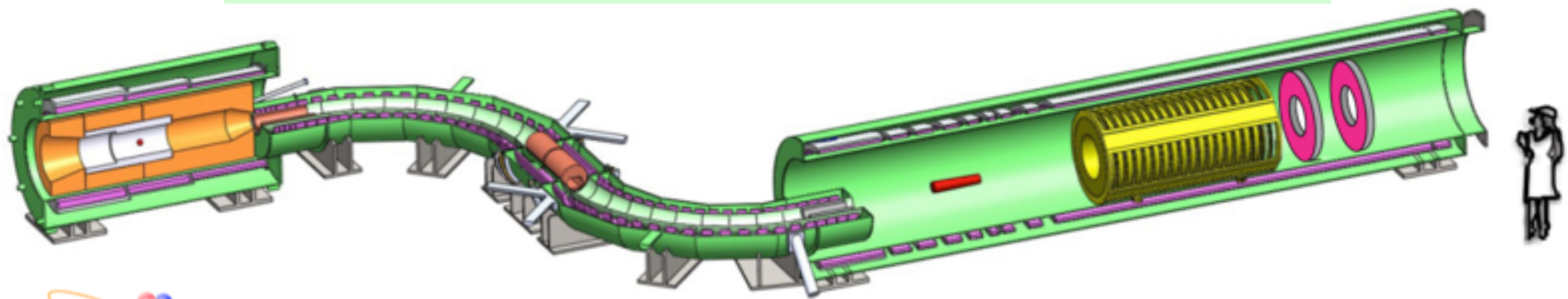
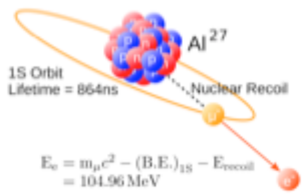
The Mu2e experiment @ FNAL





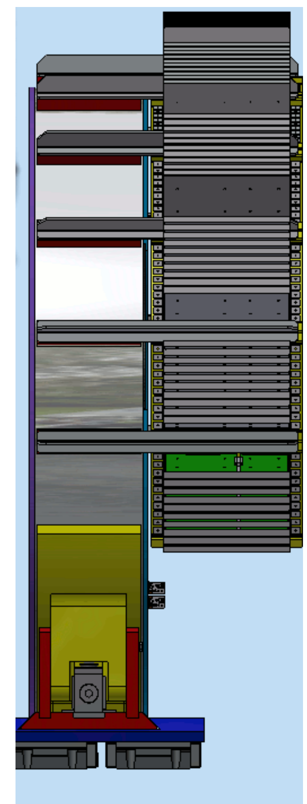
S. Miscetti, LNF INFN

On behalf of the Mu2e INFN group

LNF group (M.Angelucci, M.Cestelli Guidi, P.Ciambrone, F.Colao, M.Cordelli, G.Corradi, E.Dane`,R.Donghia, F.Fontana, S.Giovannella, F.Happacher, M.Martini, S.Miscetti, E.Pace, G.Pileggi, B.Ponzio, A.Saputi, I.Sarra, R.Soleti)

LNF Scientific Committee

18/5/2015



Talk Layout

- The Physics
  - →CLFV processes
  - →BSM Reach: Mu2e vs MEG
- Experimental technique
- Detector Layout
- Status of experiment
- INFN contribution
- MU2E Calorimeter
- Conclusions

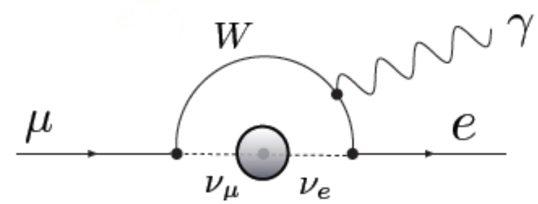
CLFV processes

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

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



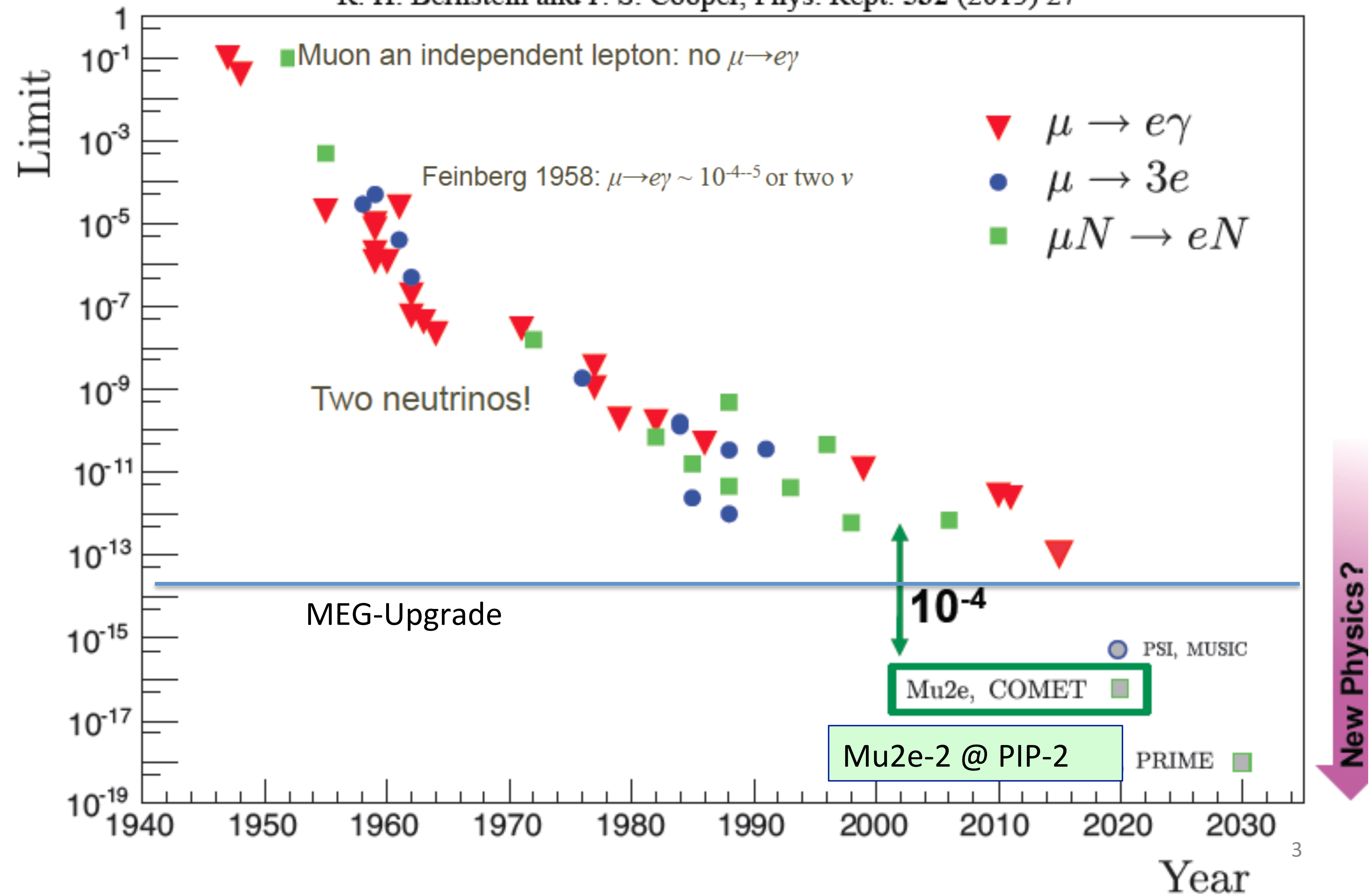
- New Physics could enhance CLFV rates to observable values

- Various NP models allow for it, <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

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

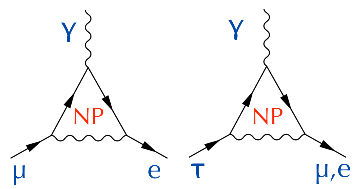


Mu2e vs MEG/MEG upgrade

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

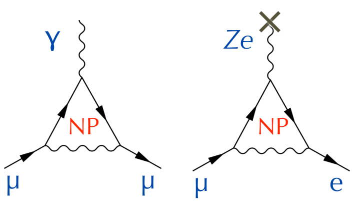
LOOP TERM

$\kappa \ll 1$

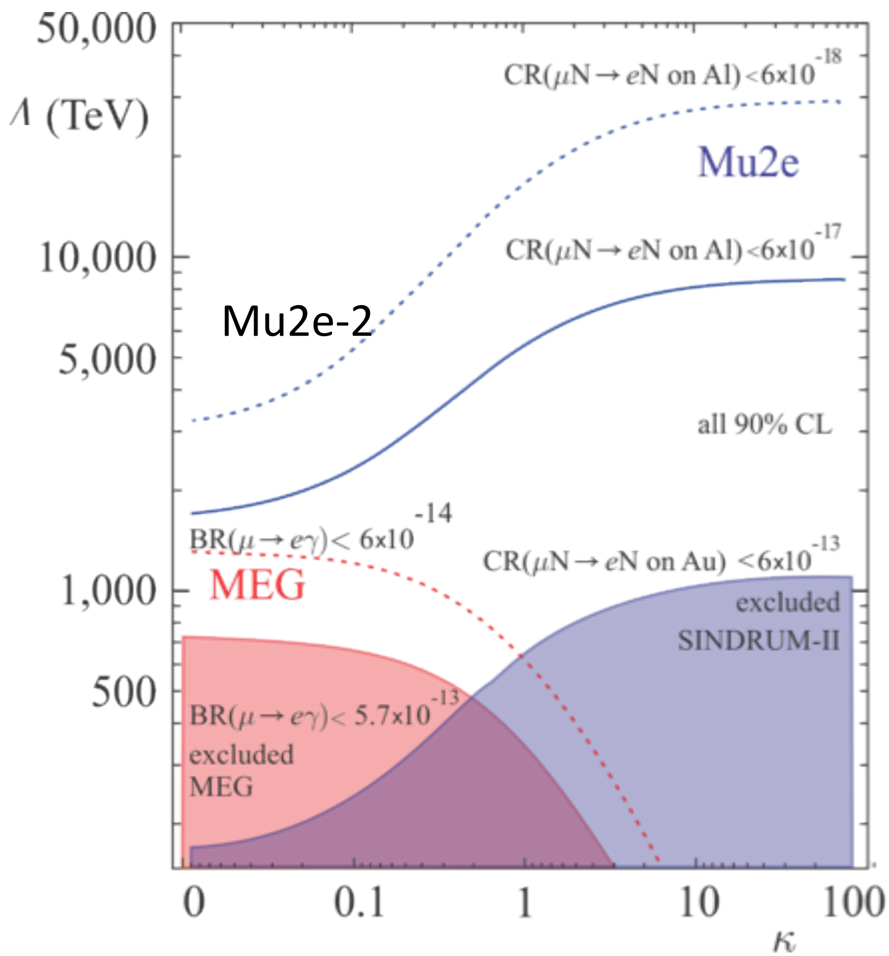


$\mu \to e\gamma$

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

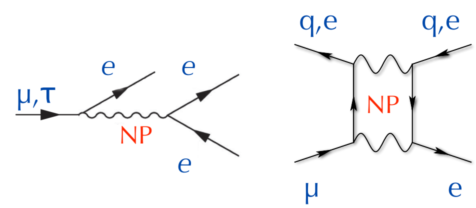


$(g-2)_\mu$ $\mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$



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

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

Summary: why Mu2e is unique?

Muon to electron conversion is a unique probe for BSM:

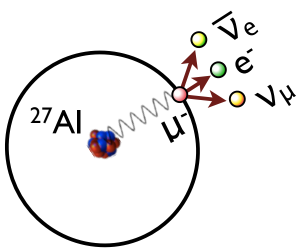
- **Broad discovery sensitivity across all models:**
  - → Sensitivity to the same physics of MEG but with better mass reach
  - → Sensitivity to physics that MEG is not
  - → If MEG observes a signal, MU2E does it with improved statistics.
    Ratio of the BR allows to pin-down physics model
  - → If 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**

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:

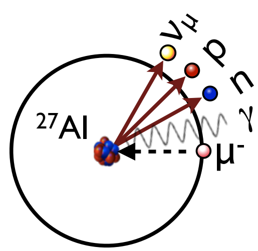
Decay in Orbit (DIO)

(BR=39%)

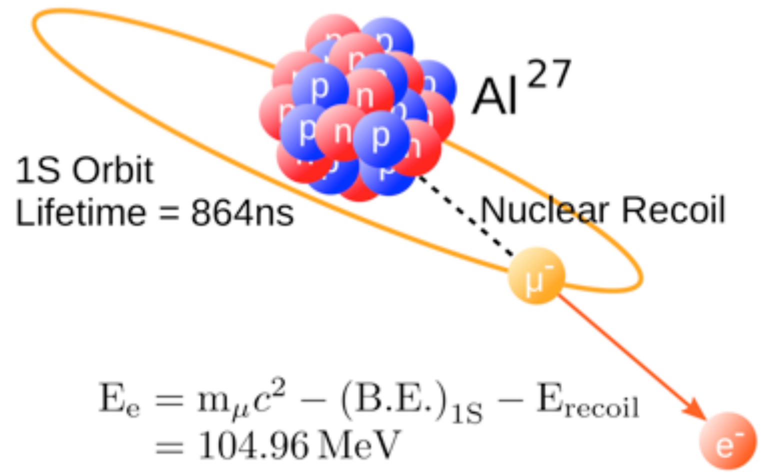


Muon Capture Process

(BR=61%)



Conversion Process



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

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

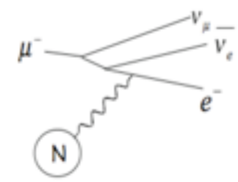
DIO (decay in orbit) background

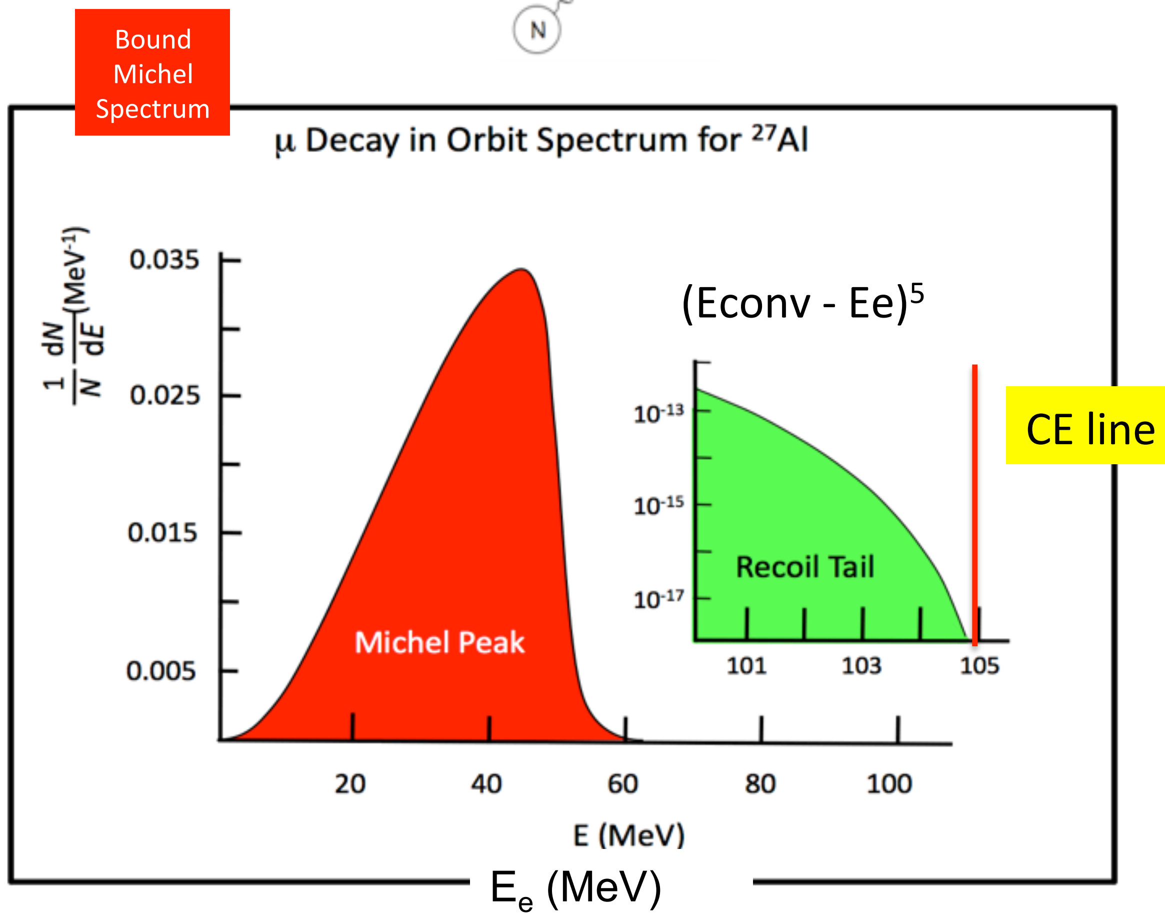
- ❑ The DIO background is the most difficult one.

- ❑ 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

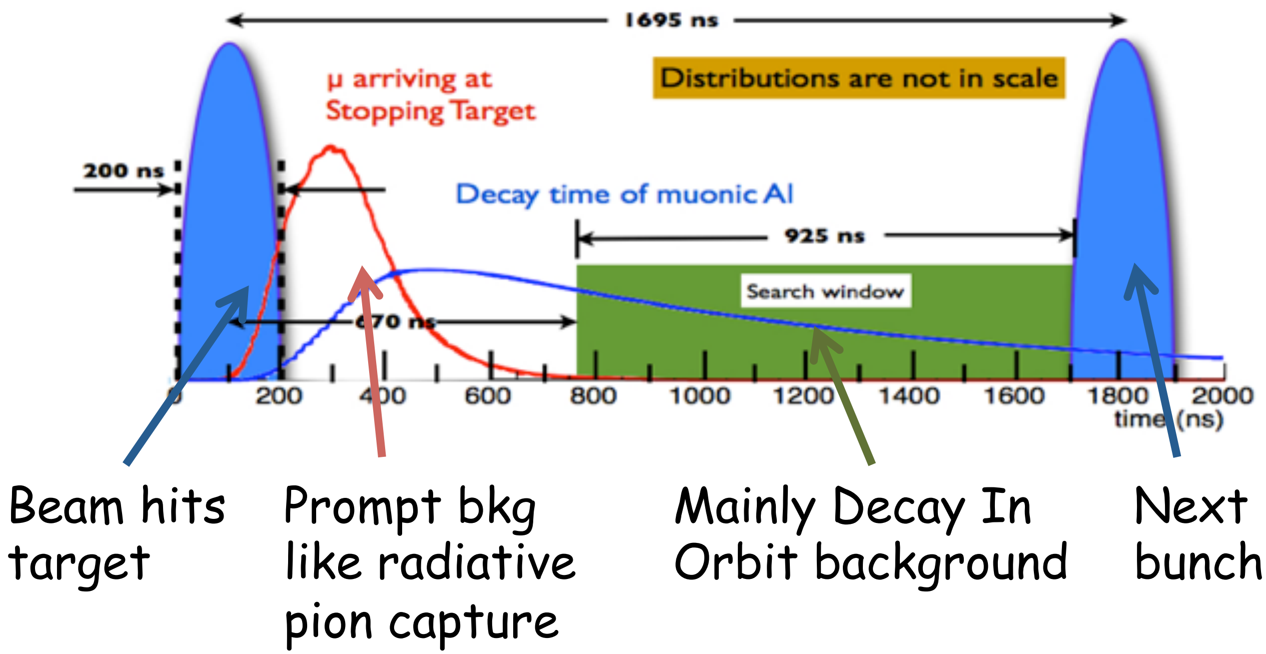
→ To separate DIO endpoint from CE line we need a high Resolution Spectrometer





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

Beam structure → prompt background



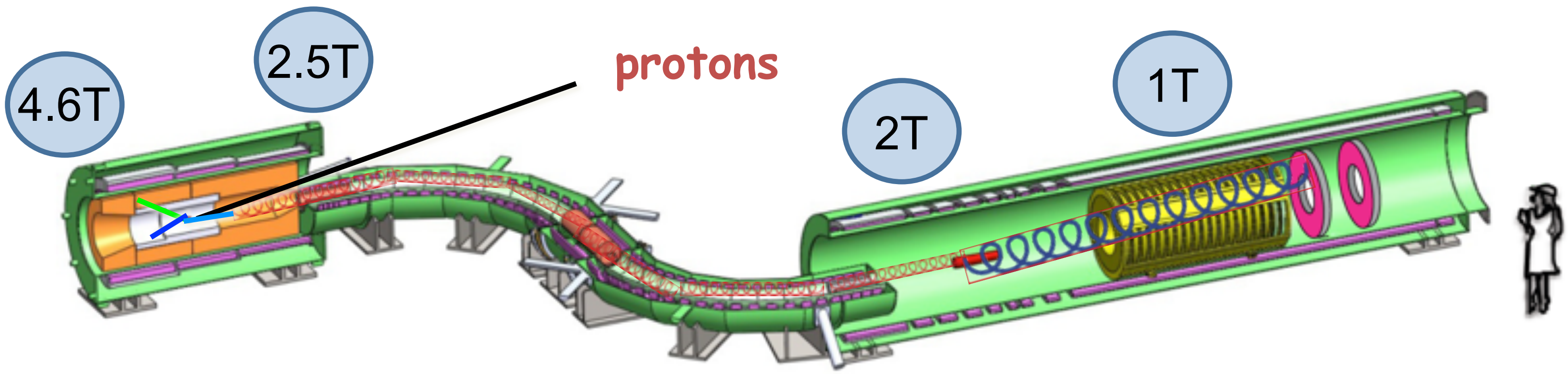
Need a pulsed beam to wait for prompt background to reach acceptable levels!

- 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:**
  → Booster proton batches are sent to the Recycler to be grouped in 4 bunches
  → They are sent to the Delivery Ring that extract < 200 ns μ-bunches each 1.7 μsec
  → From Delivery ring they are then sent to target → POT = 3×10^7 / μ-bunch
  → Extraction scheme : 1/3 for Mu2e, 2/3 for NOVA

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

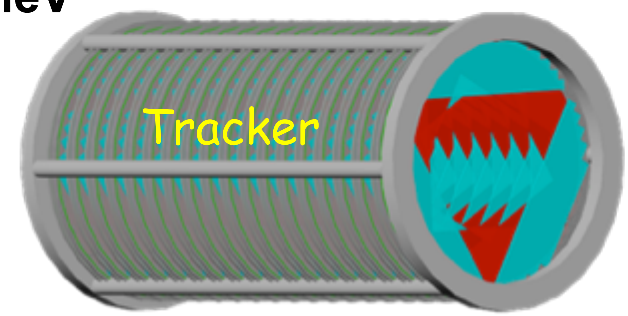
Target, Detector and Solenoid (DS)

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

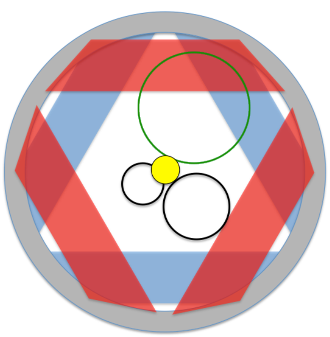
For the sensitivity goal → ~ 6 x 10^{17} stopped muons with 3 year run , 6 x 10^7 sec → 10^{10} stopped muon/sec

Tracker system

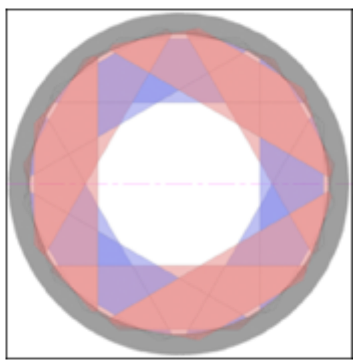
- Tracker is made of arrays of straw drift tubes (red/blue stripes in tracker stations)
- ~ 20000 tubes arranged in planes on stations,
- The tracker has 18 stations.
- Tracking at high radius ensures operability (beam flash produces a lot of low momentum particles, large DIO background). Most of it miss the tracker.
- **Core momentum resolution 120 keV/c @ 100 MeV**

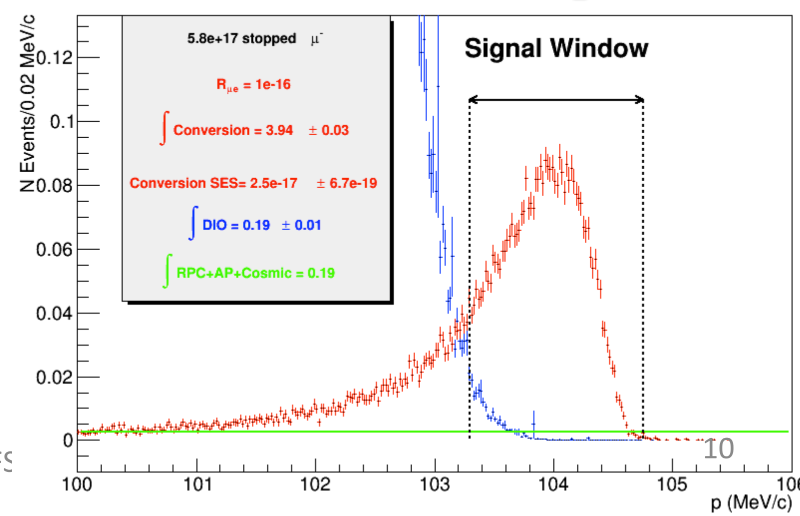


Tracker station



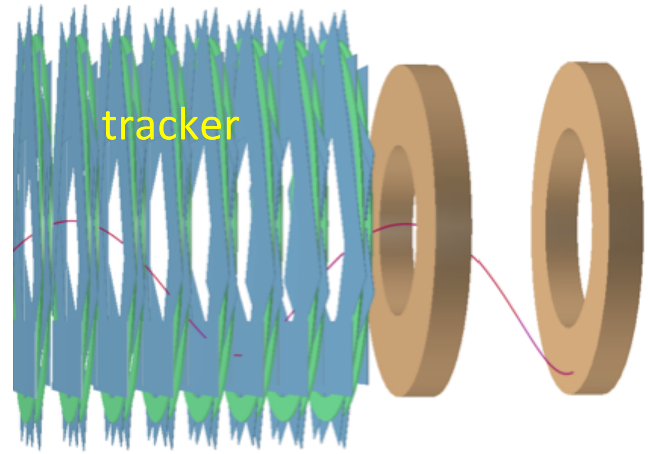
Stations are rotated





Calorimeter System

Two disks separated by ½ wavelength (70 cm)

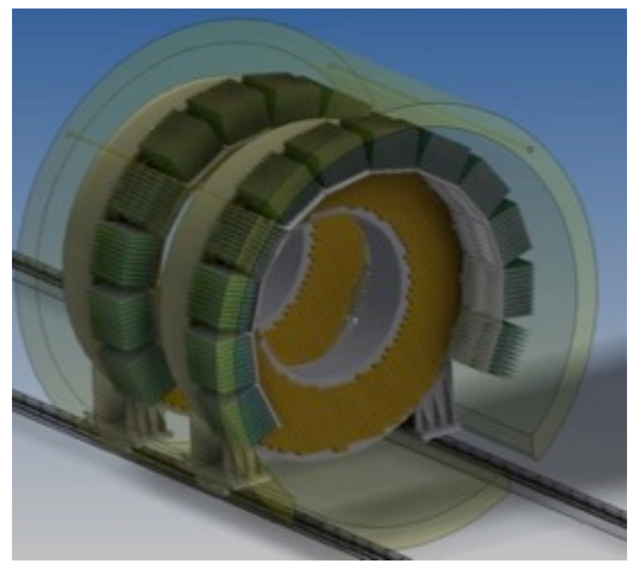


Calorimeter requirements:

→ Particle Identification to distinguish e/muons
→ Seed for tracking pattern recognition
→ Tracking independent trigger
→ Work in 1 T field and 10^{-4} Torr vacuum
→ RadHard up to 100 krad, 10^{12} n/cm^2/year

Calorimeter choice:

Crystal based calorimeter with σ/E of O(5%) ,
Time resolution < 500 ps @, high granularity
→ almost full acceptance for CE signal @ 100 MeV

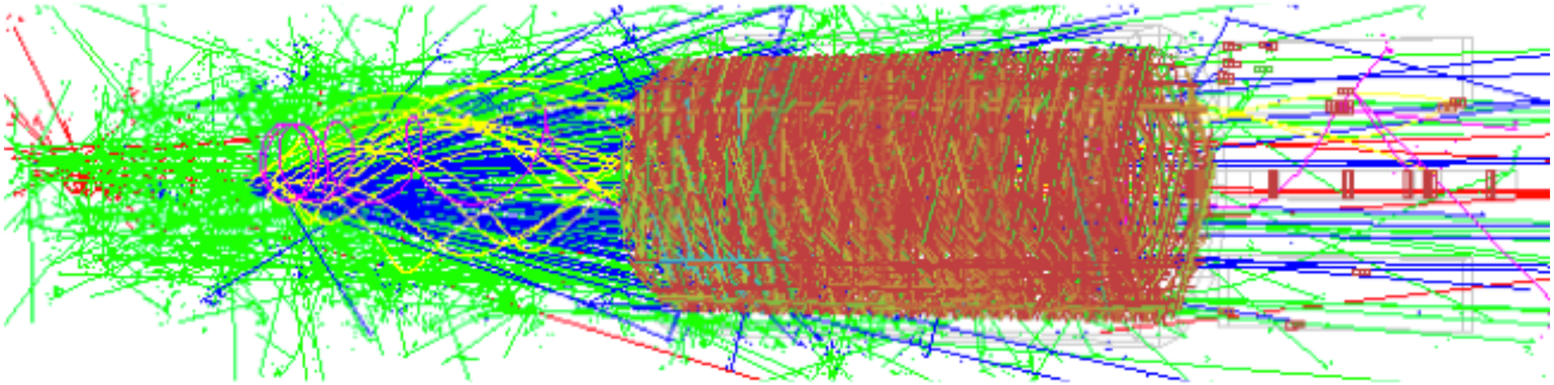


Disk geometry

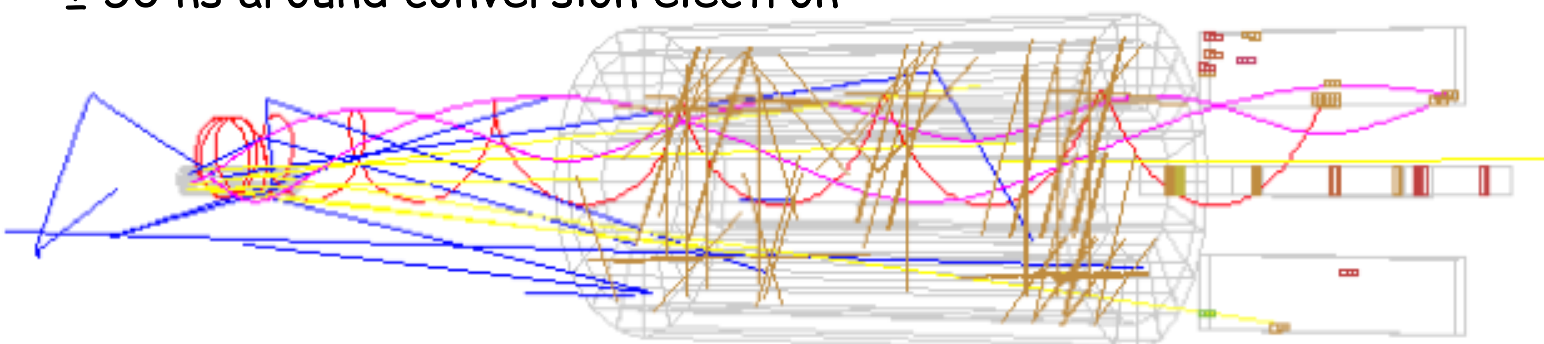
- Hexagonal or square crystals
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$

A typical Mu2e micro-bunch event

500 – 1695 ns window



± 50 ns around conversion electron



Quite challenging to find the conversion electron, good tracker performance and pattern recognition algorithm critical Joint Calorimeter-Tracker reconstruction helps

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 Experiment Status

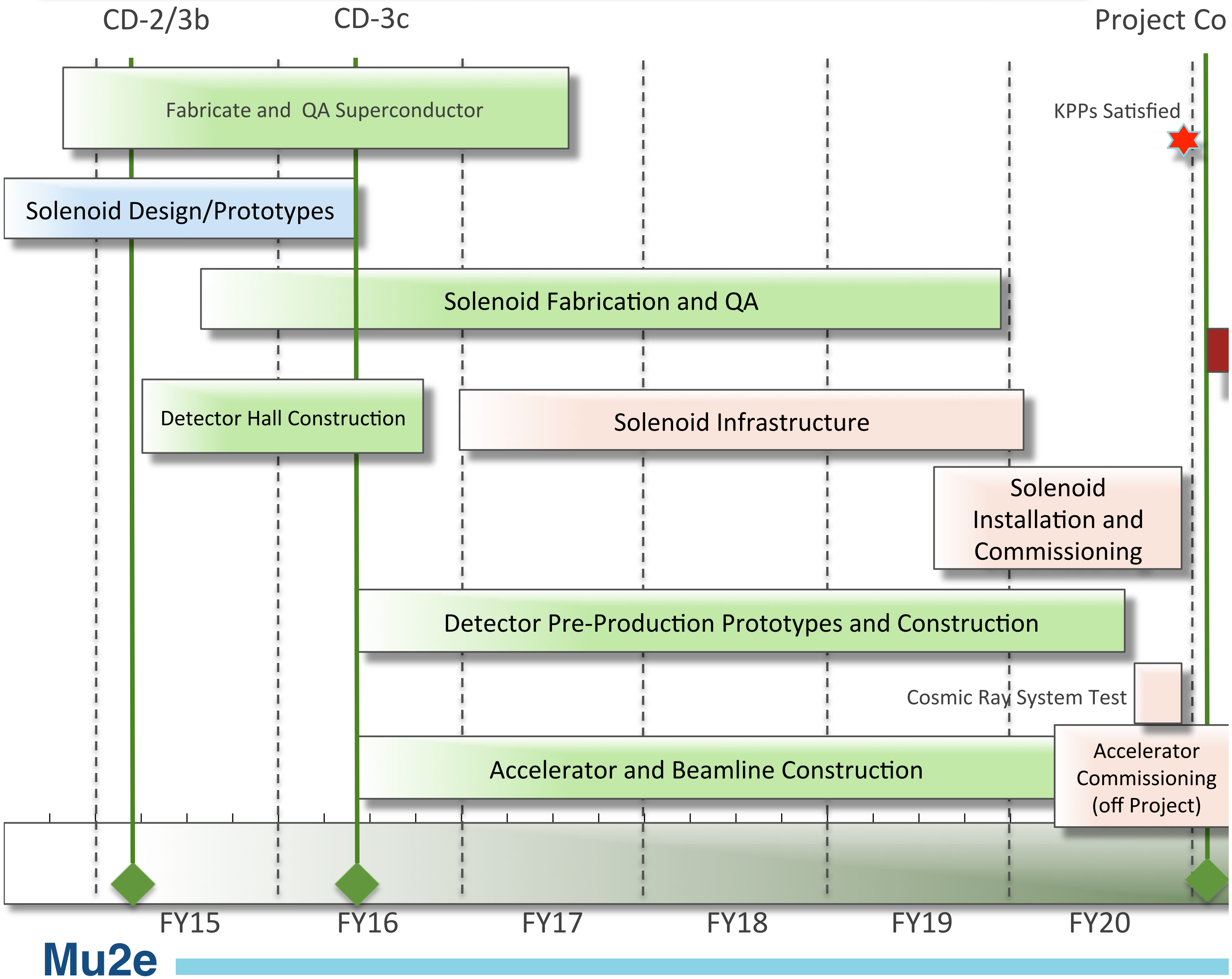
- CD2 for detectors (baseline/TDR) obtained on the 5th of March 2015
- CD3b for Civil Construction and start for TS Bid obtained on same date.

- **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 March 2016

- **Overall DOE budget secured, 280 M$**.

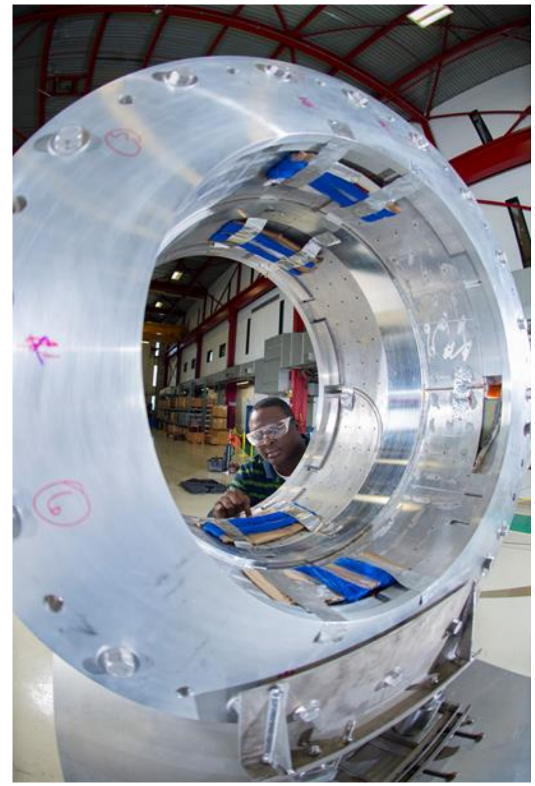
Mu2e schedule



Mu2e & INFN

Strong involvement of INFN group in two items:

(1) Calorimeter system: project leadership (S.Miscetti), design & construction of proto, FEE and mechanics, Laser system.
(2) Construction of prototypes for the TS magnet, DONE by P.Fabbricatore and INFN Genova (via ASG)



INFN group size extrapolated to 2017

→ 30 people, O(20 FTE)
→ LNF composition (5+2 Researcher, 3 Engineers, 3 techs, 1 post doc, 2 students)

INFN financial contribution so far:

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

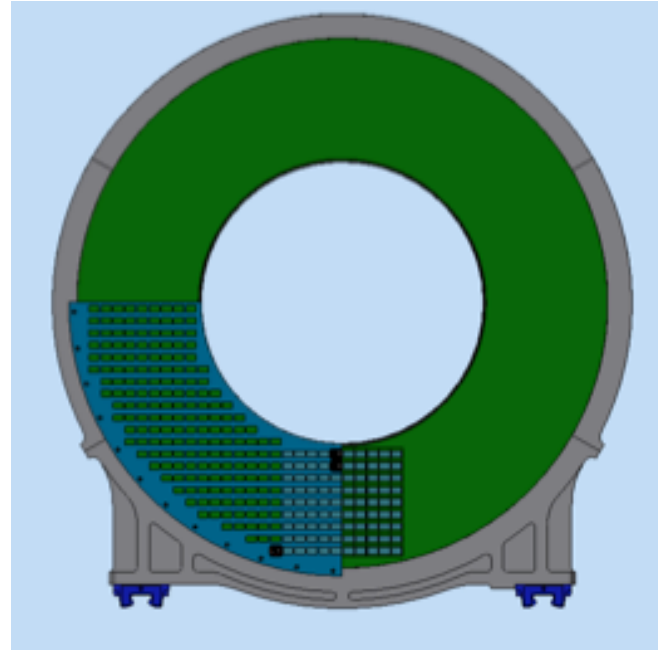
Expected Core contribution O(3 MEuro)

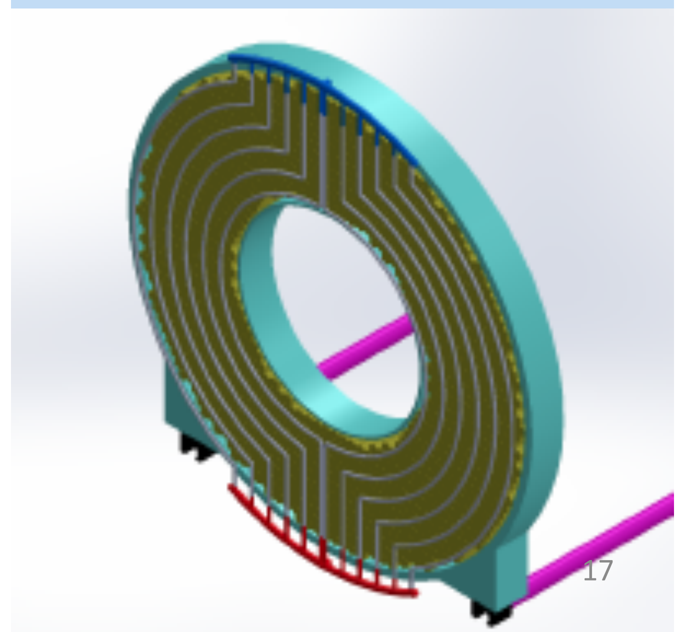
Next steps → CSN1 review in June then INFN CTS

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

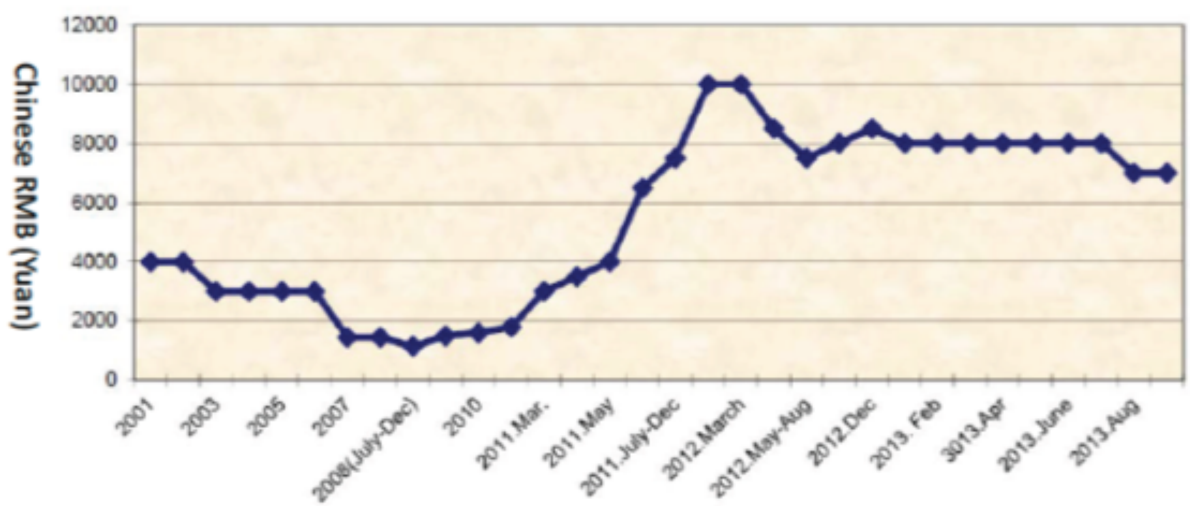
CsI(pure)

TDR Alternative

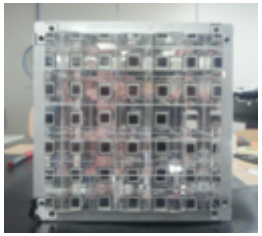
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

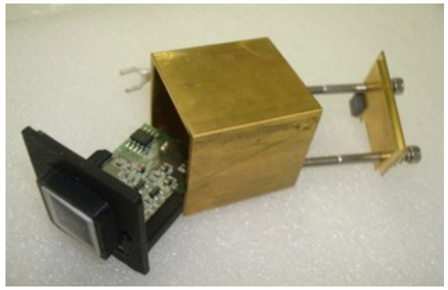
INFN Calo R&D (2013-2014)

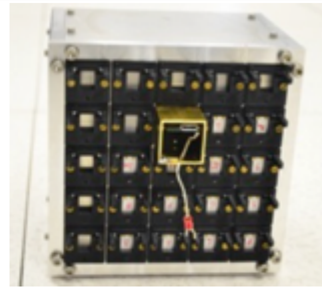
- Simulation/reconstruction of clusters + calorimeter based seed for tracking
- Design and construction of 2 LYSO + APD calorimeter prototypes
- Control stations for characterization of crystals and photosensors
- Design/construction/operation of 50 FEE amplifiers/Voltage regulator + 5 ARM based controller (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.**

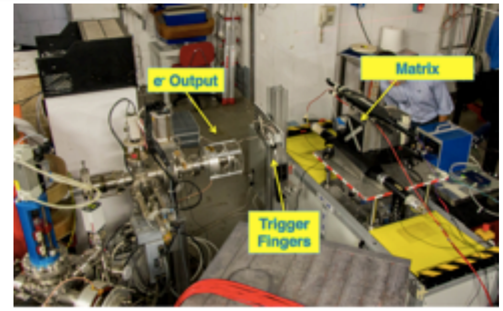


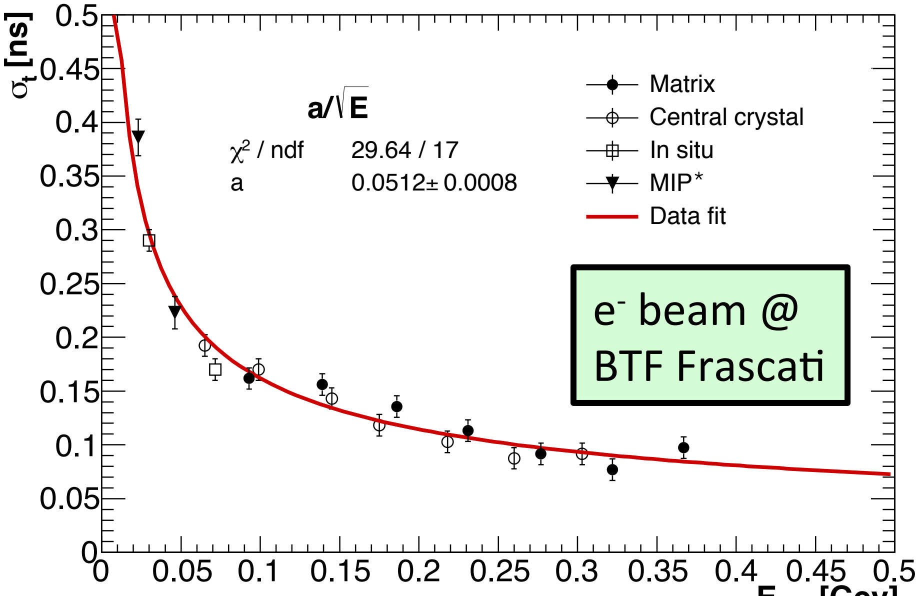
LYSO Legacy



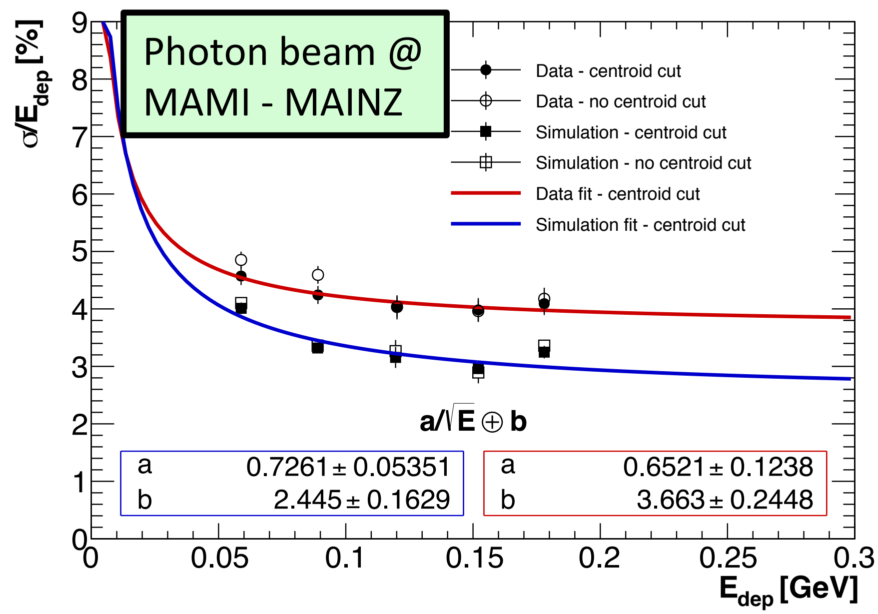








*Time resolution with MIPs from Mu2e DocDB 4409



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

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

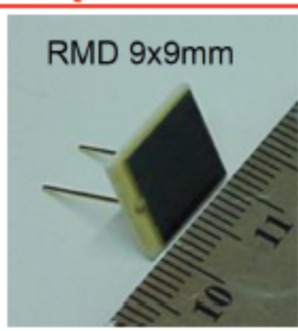
Noise term *b* considered negligible (~0.1% in quadrature).

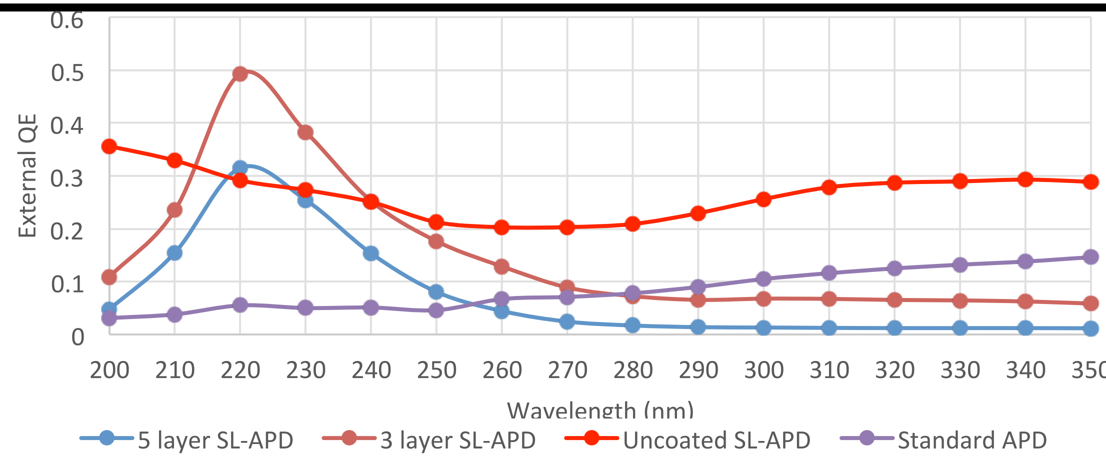
Photosensors Choice

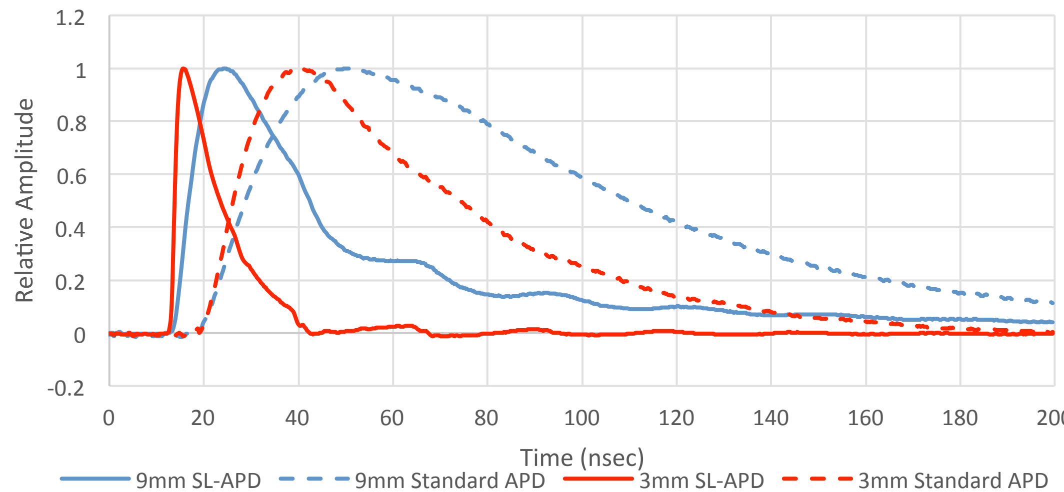
A Caltech/JPL/RMD consortium formed to develop a Large area RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** incorporating also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for wavelength > 300 nm.

- ✓ 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

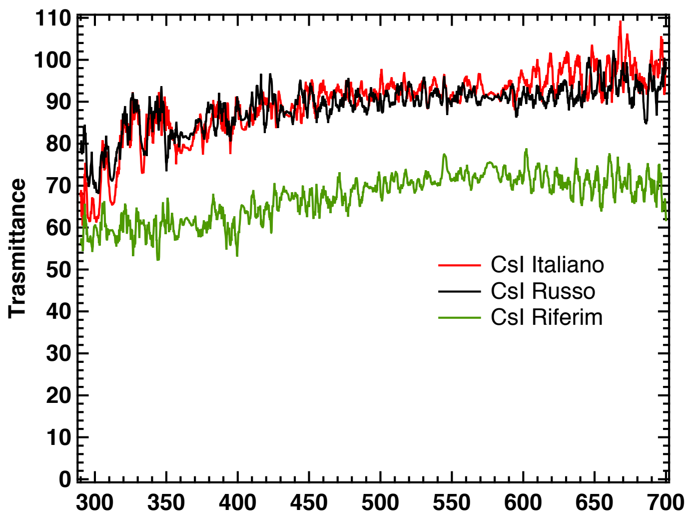


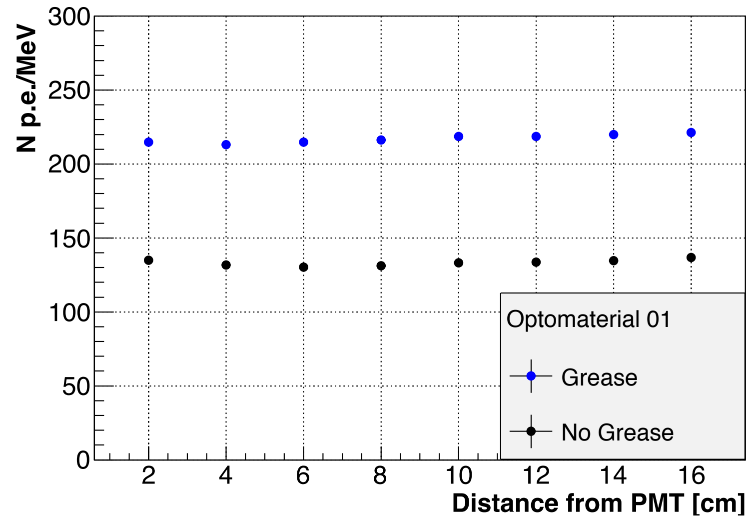


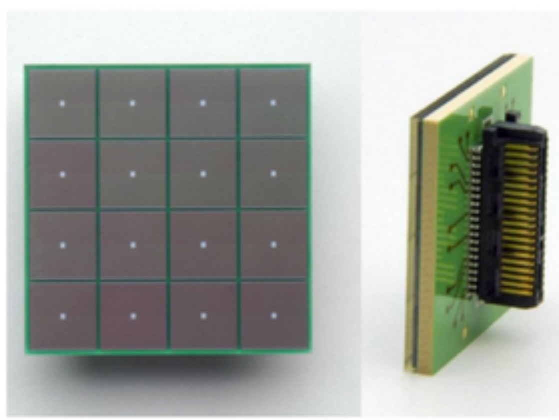


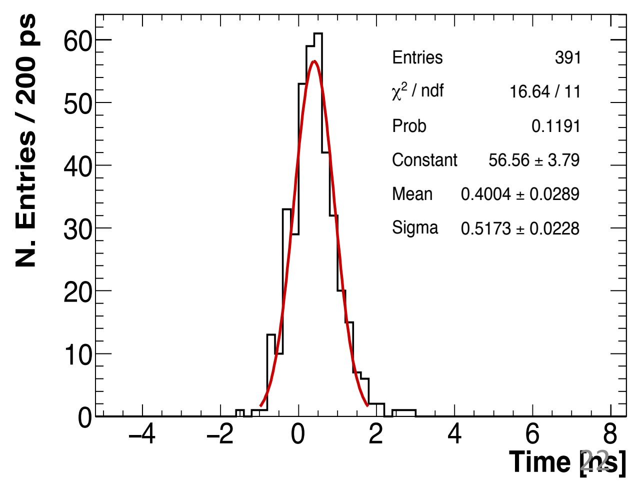
R&D on CsI(pure) crystals

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

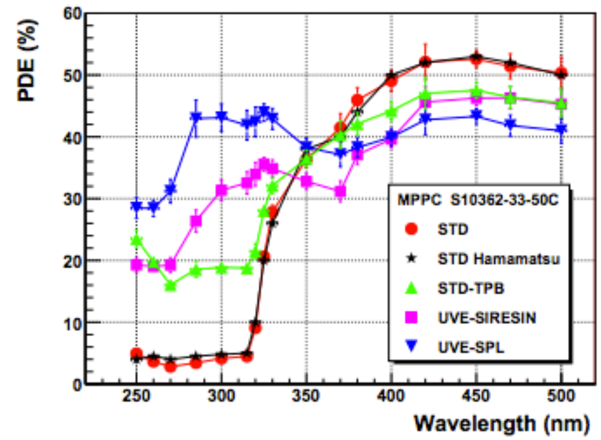




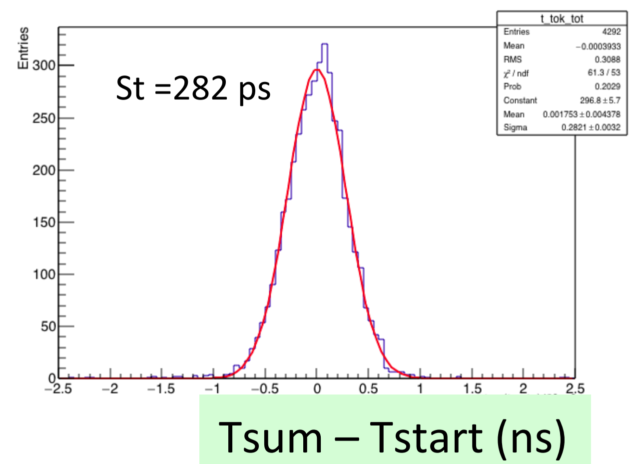




Final R&D steps and TCR



- **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.**
- Next steps (this week) conclude 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 (External) 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.**

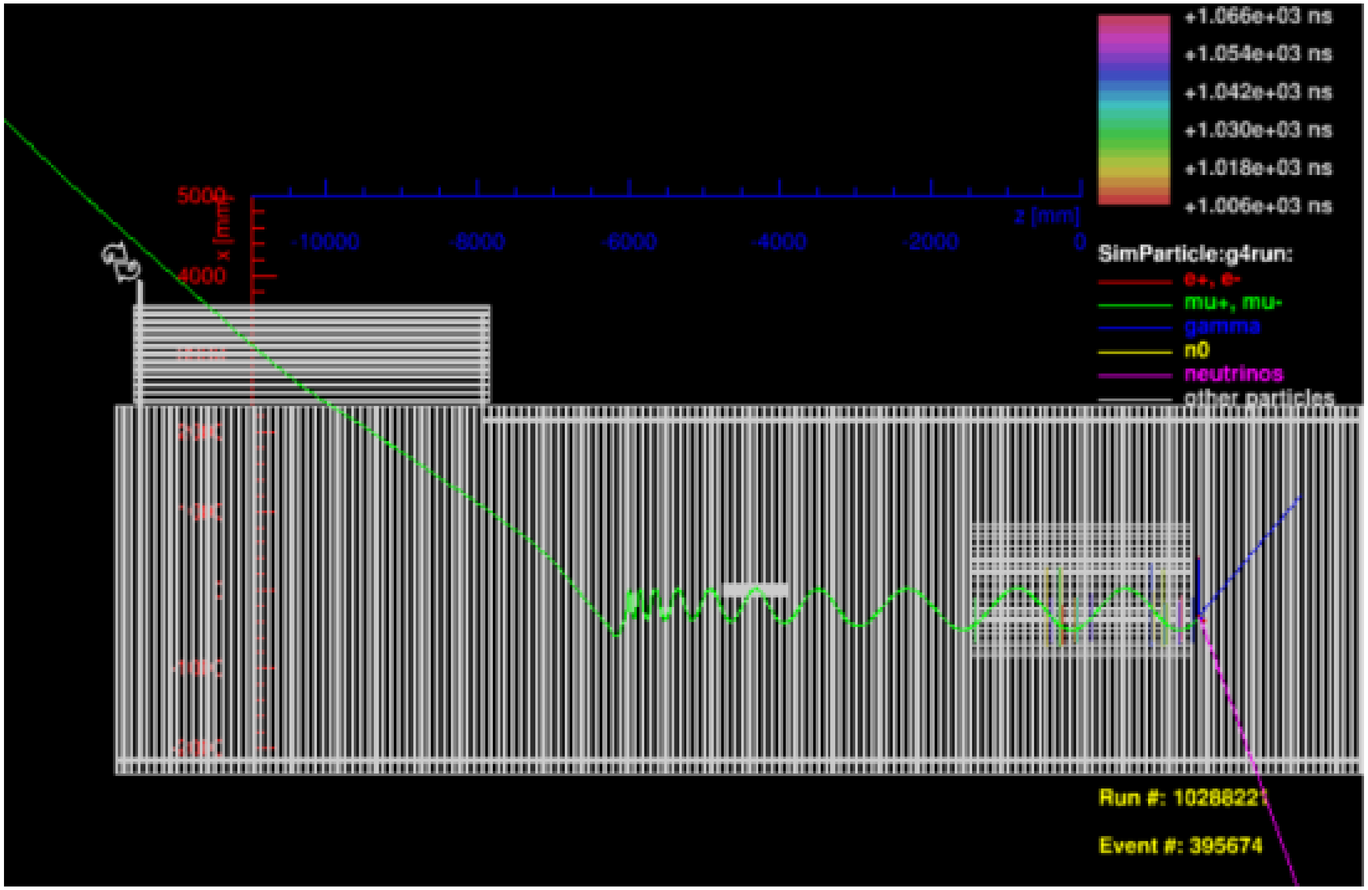
- **< 10 years Timeline for completion of first phase.**

- **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!**

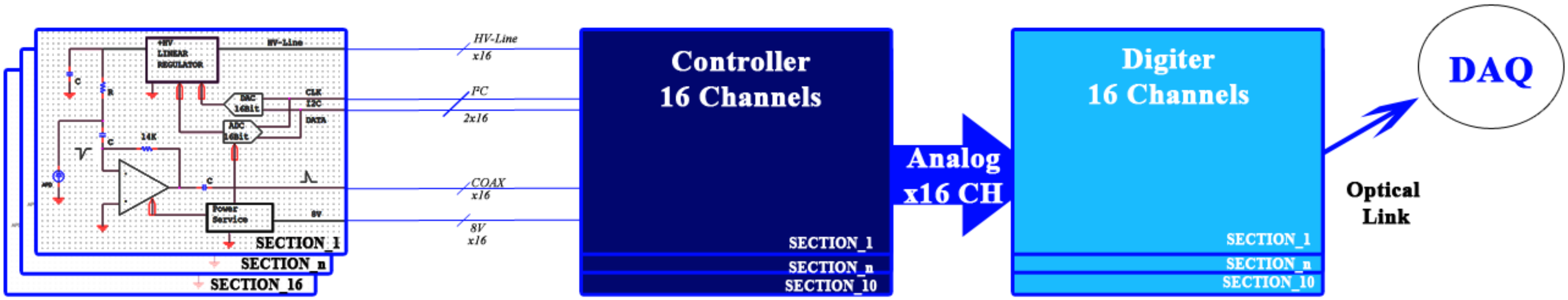
Additional Material

“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 its running period.
- **11 events evaded the CRV**, passed closely enough to the target, were tracked by the tracker and passed all reconstruction tracking criteria. They were all μ^- → **rejected thanks to the combination of Calorimeter and tracking information : timing and *E*/*p***

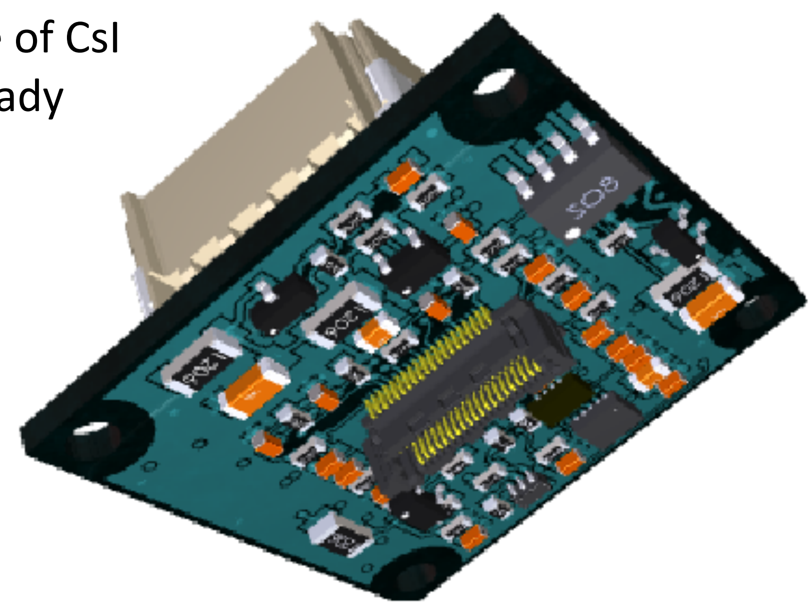
Electronics



FEE electronics being adapted from Hamamatsu APD, already developed, to SL Solar Blind APD:
Bias Voltage: 500 V to 1800 V
Cd = from 240 to 60 pF
Gain = 300

- First drawing exists
- **Prototype of discrete amplifier in progress** → to be tested on receiving of the first working version of 9 mm^2 SL APD

FEE for INFN alternative of CsI +MPPC ready



Digital Electronics

WF digitizer protos under test @ Illinois

New version from INFN:

→ Format: From 8 to 16/24 channels

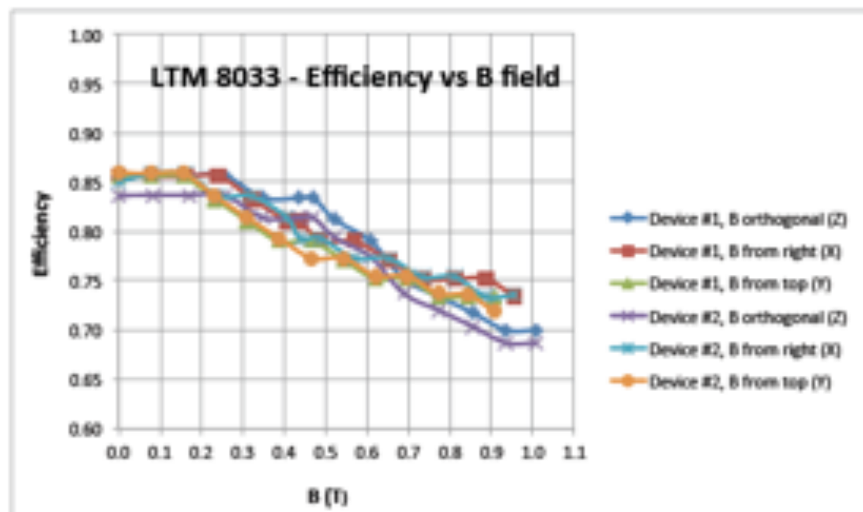
→ FPGA: Xilinx to Smart Fusion2 M2S150T SEU immune.

→ ADC: new version under study **Analog Devices: AD9230**

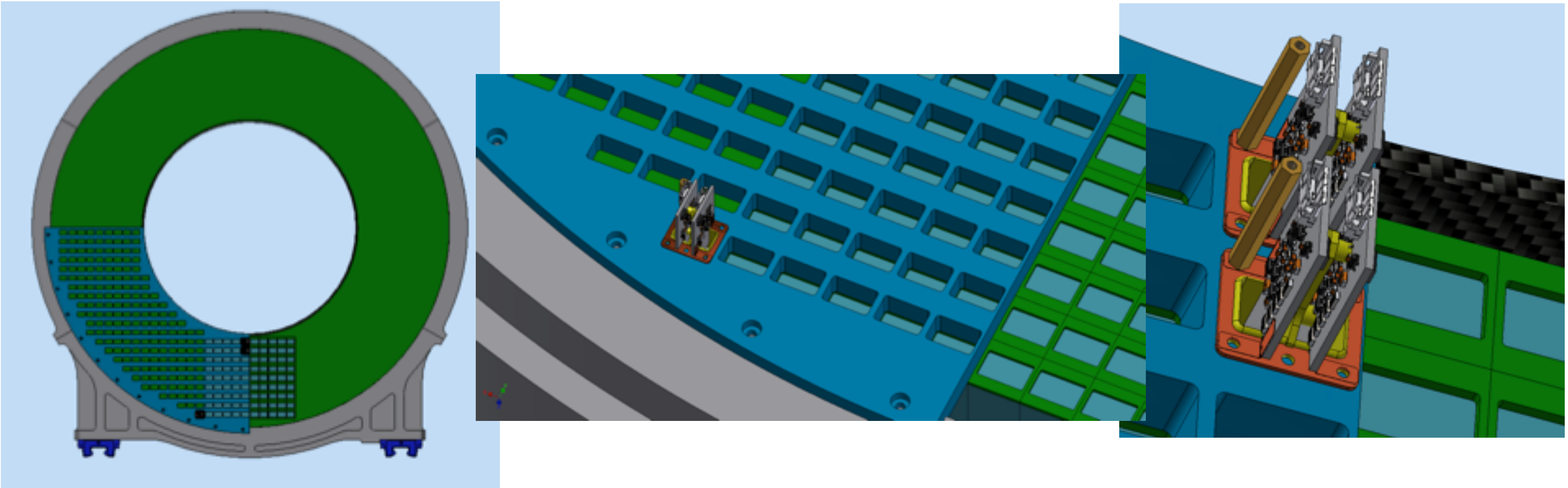
→ **DC-DC converter: LTM8033**
This is great achievement if OK after irradiation test. Indeed only 28 V lines needs to penetrate in Vacuum enclosure.

→ Board dimensions 6U VME (23x16 cm^2)

→ Cooling being integrated in mechanical drawings…



Mechanics



- Full FEA done for the hexagonal crystal case. Drawing have been adjusted and repeated for the calculation with square crystals.
- Towards an executable drawing done with the option of a Back Plate. Calculation of FEE cooling   being repeated in this final version.
- Integration and interfaces with muon beam line being carried out (Load and cabling)

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

(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}**

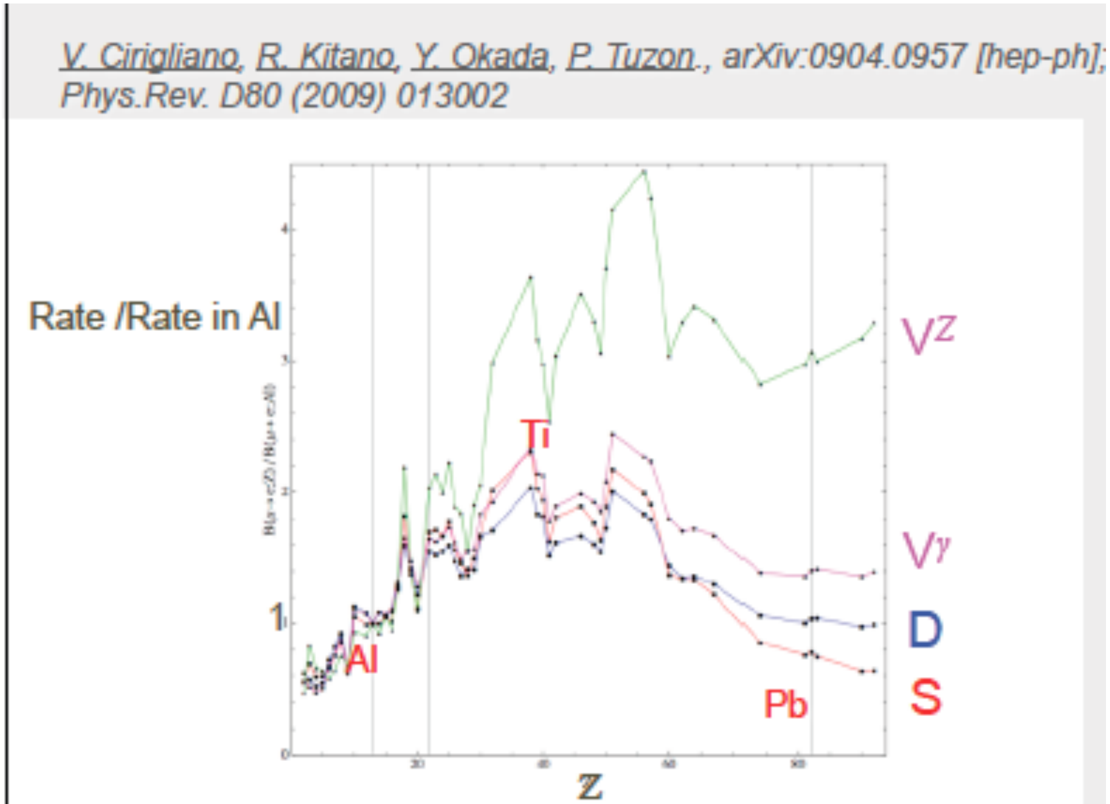
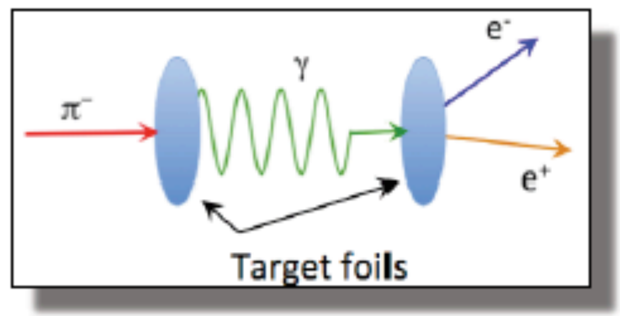


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

Mu2e - ΔL=2 transition

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

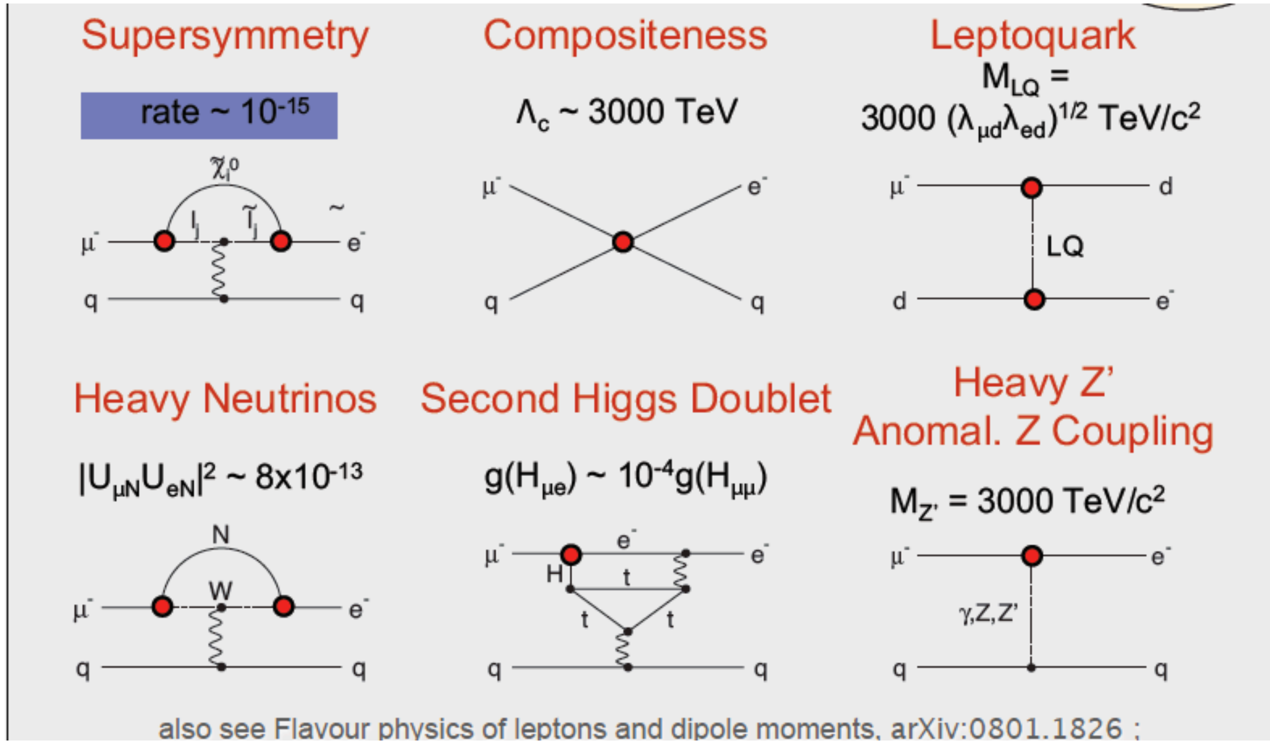


- Mu2e is the fastest, cheapest path to broad discovery sensitivity in CLFV sector.

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



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

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**

Are CLFV processes relevant ?

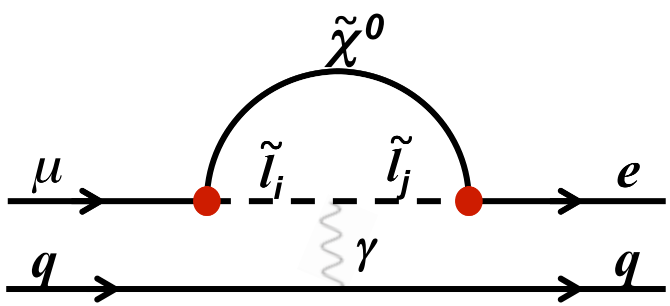
W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`

	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.

Specific Example: SUSY

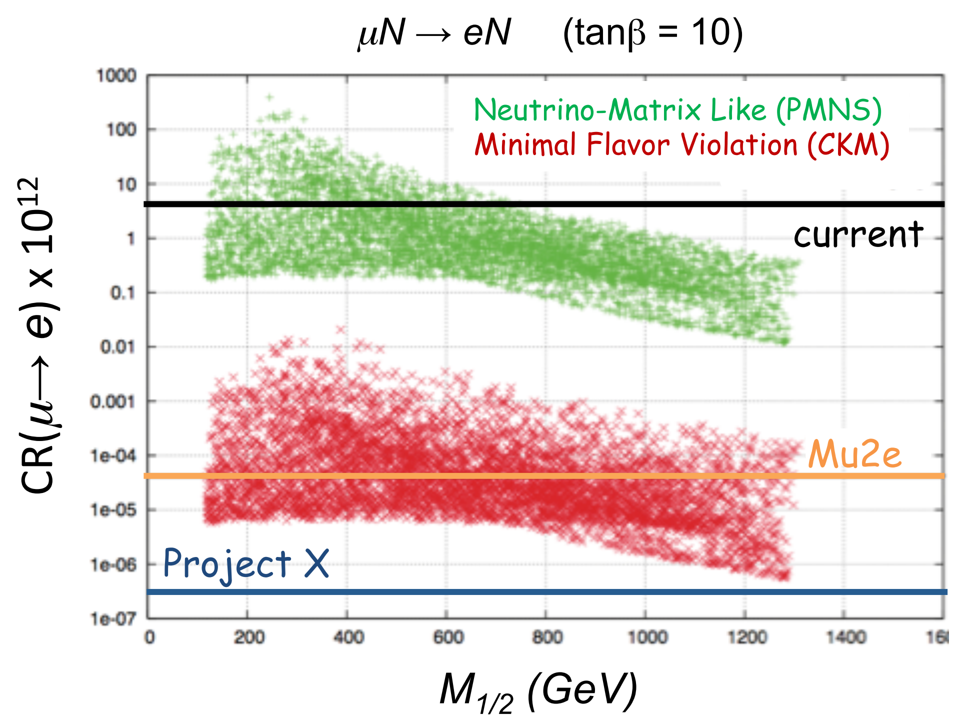
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies dozens of signal events with negligible background in Mu2e for many SUSY models.

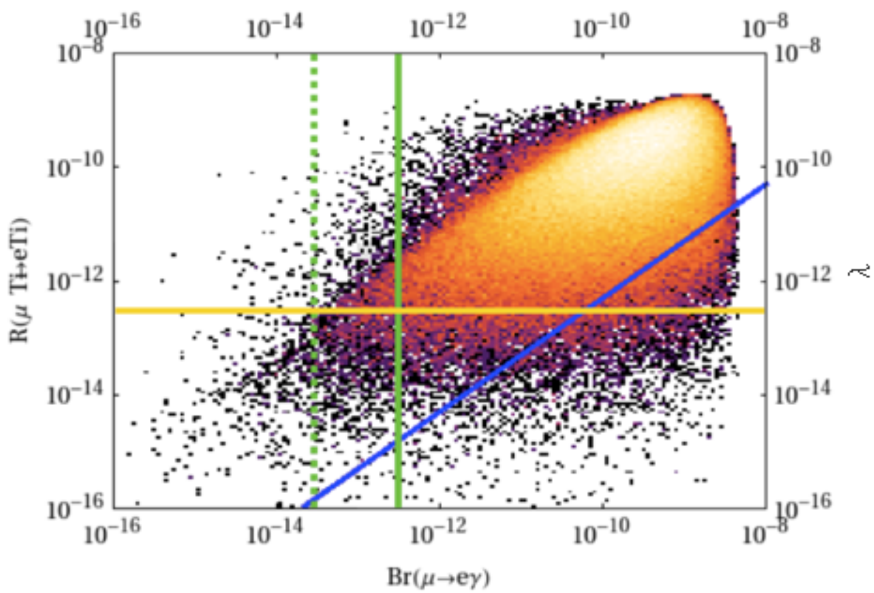
SUSY GUT in an SO(10) framework

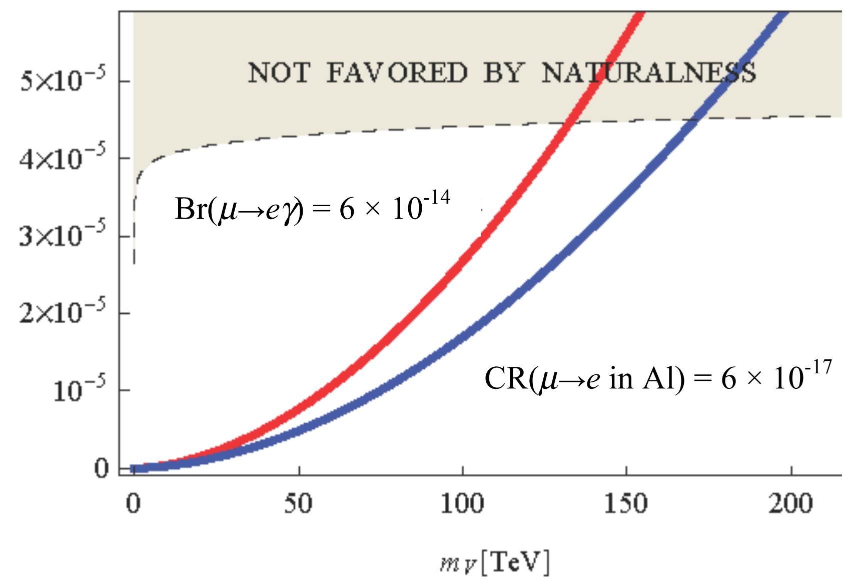


L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

MEG vs MU2E





Littlest Higgs model with T-parity

Modello in cui il bosone di Higgs è un bosone di Goldstone sotto diverse simmetrie.

Solo se tutte le simmetrie vengono rotte, il bosone di Higgs acquista masse

- Giallo: SINDRUM II
- Verde: MEG e MEG-II

Mu2e copre tutto lo scan dei parametri.

Leptoquarks

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

- Rosso: MEG-II
- Blu: Mu2e

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.

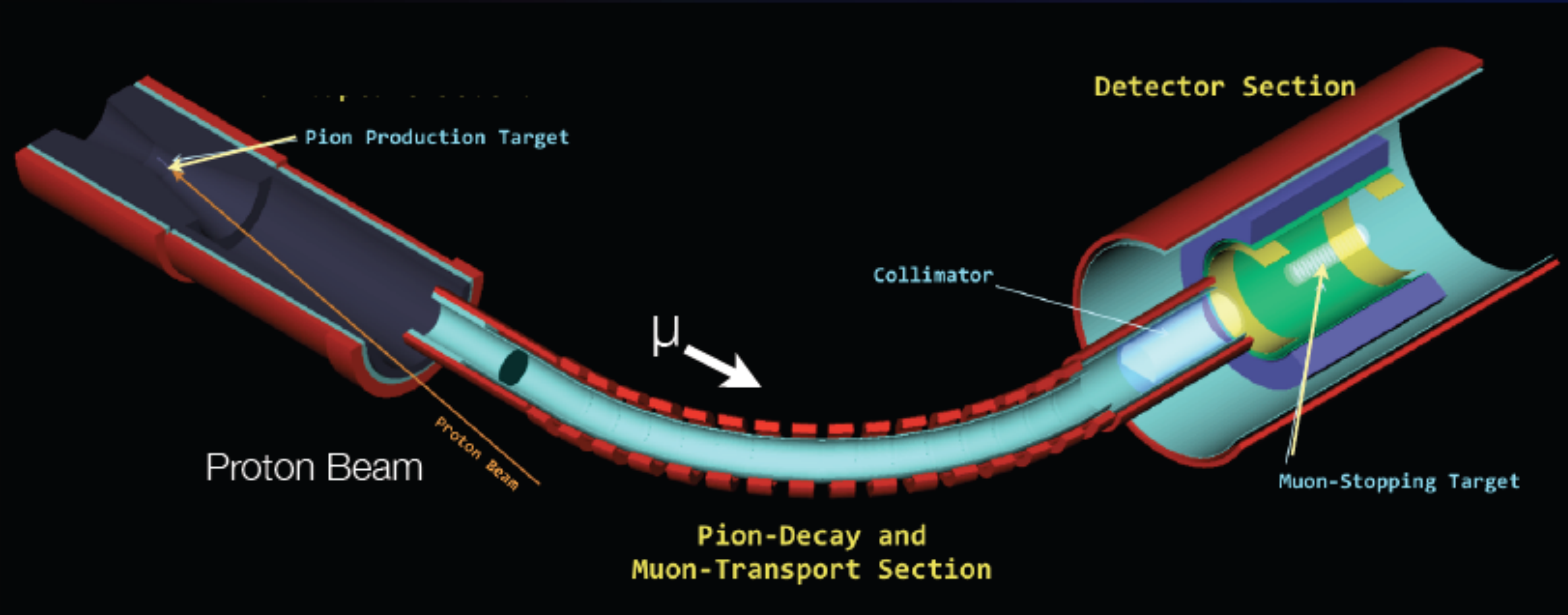
- It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)
- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam -> higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry "cost" in operation

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 :

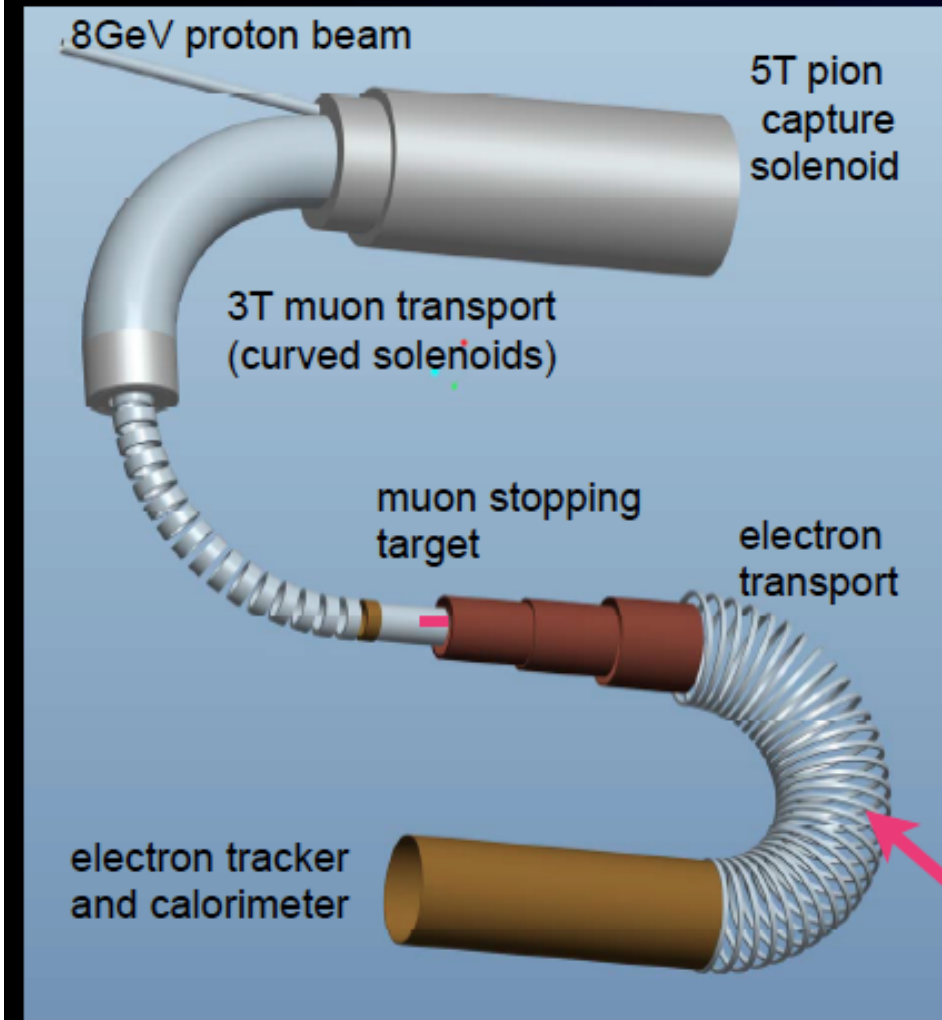
(1~3)x10⁹ muon/sec with 3kW beam produced. The world highest intensity.

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

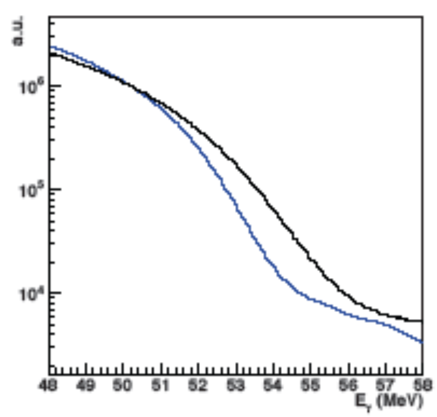
$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

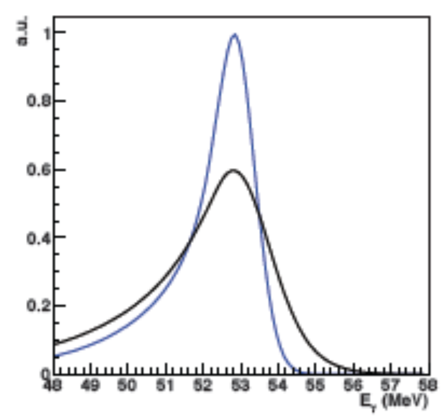
- 10^{11} muon stops/sec for 56 kW proton beam power.
- $2\text{x}10^7$ running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

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

MEG^{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



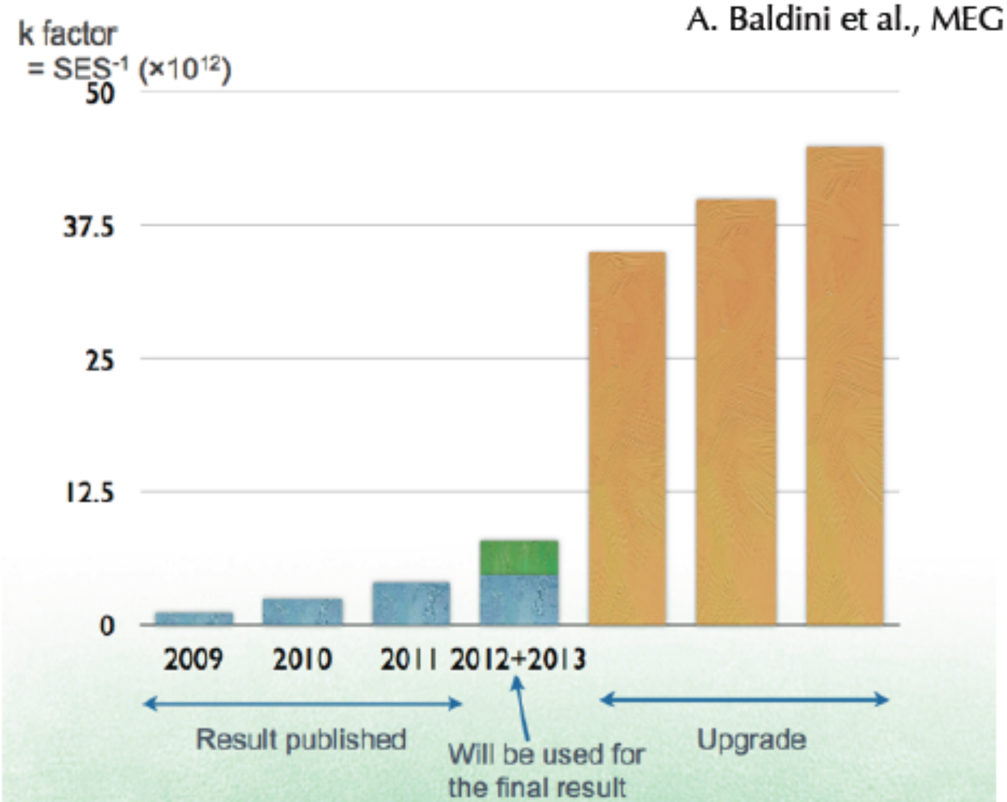


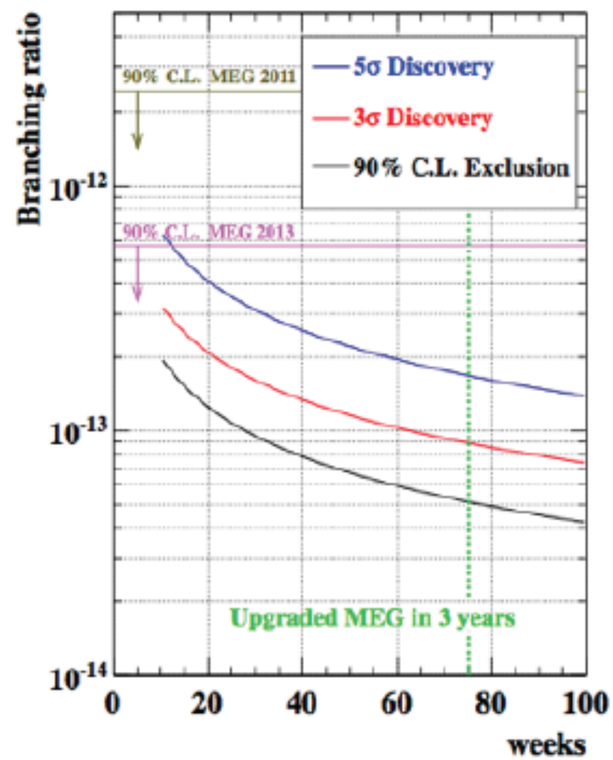
$$5.7 \times 10^{-13}$$

MEG^{UP} sensitivity

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

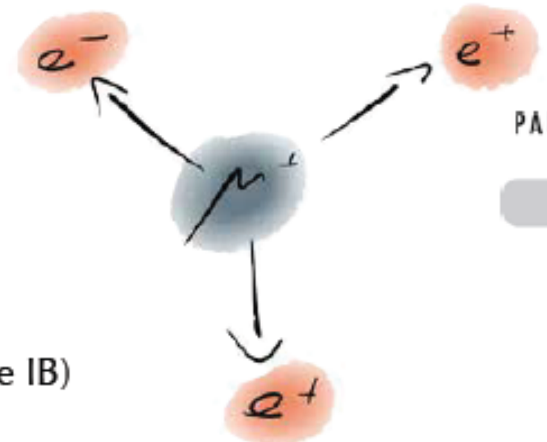
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |





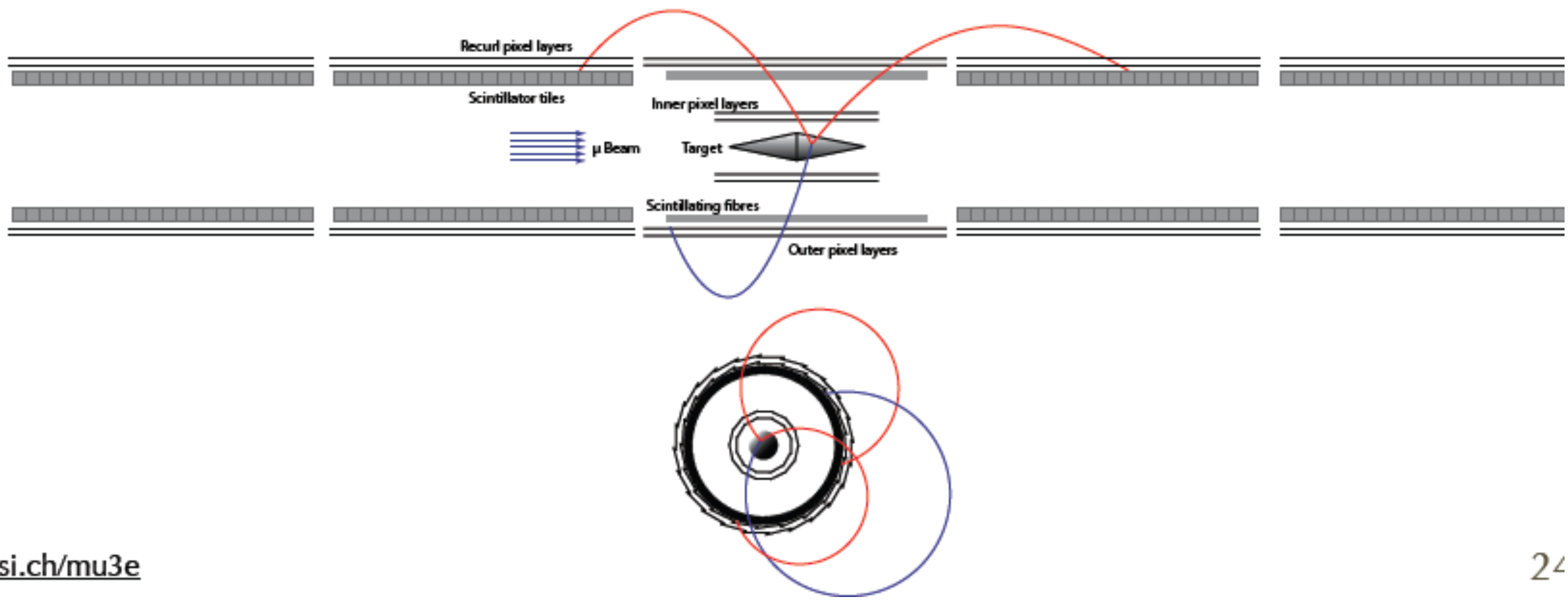
Mu3e at PSI

- Search for $\mu \rightarrow e\,e\,e$
  - 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)



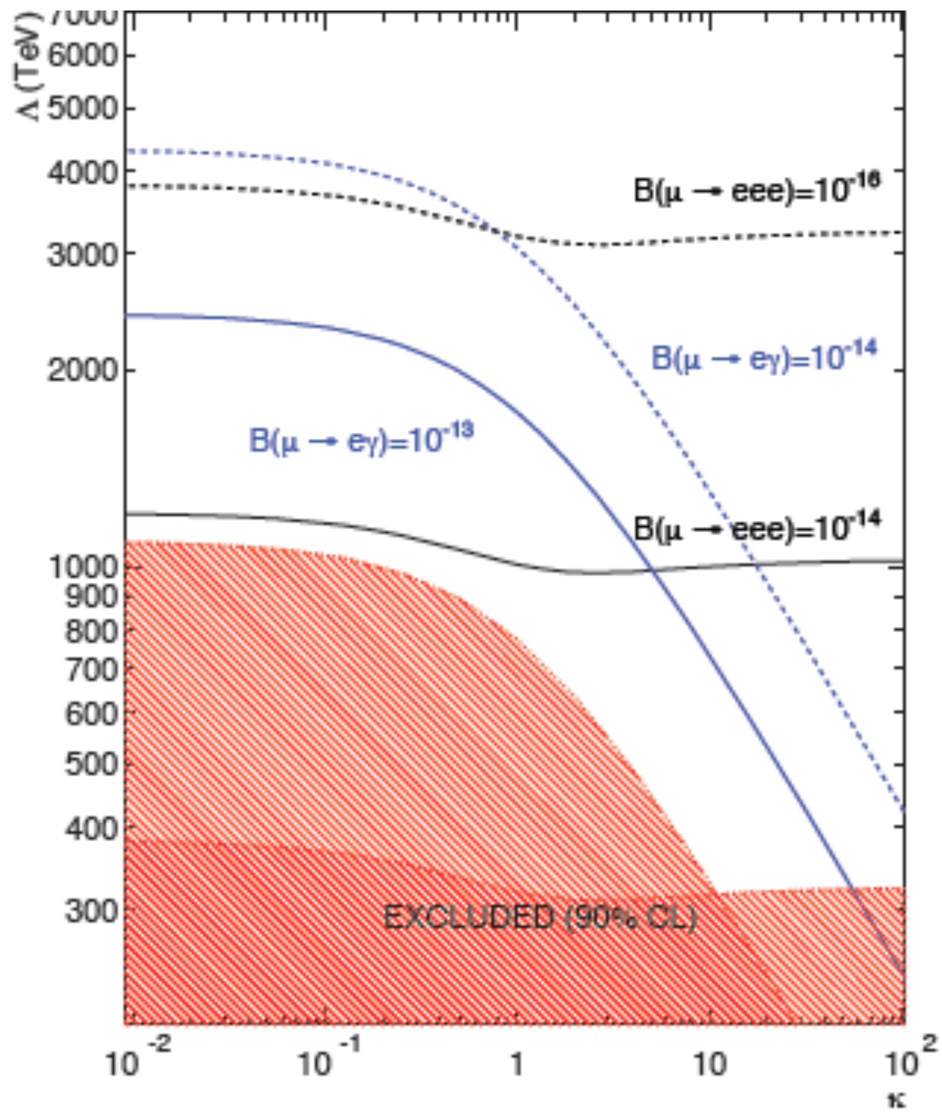
PAUL SCHERRER INSTITUT

PSI



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

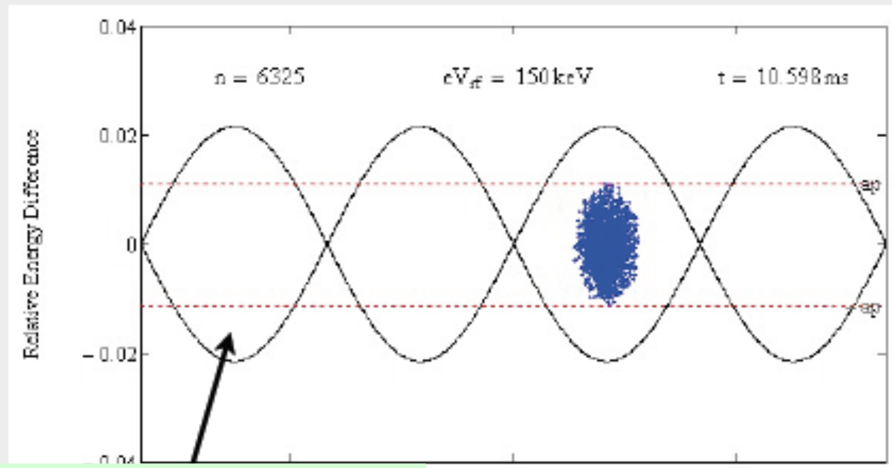


Out of Time proton → Extinction Method

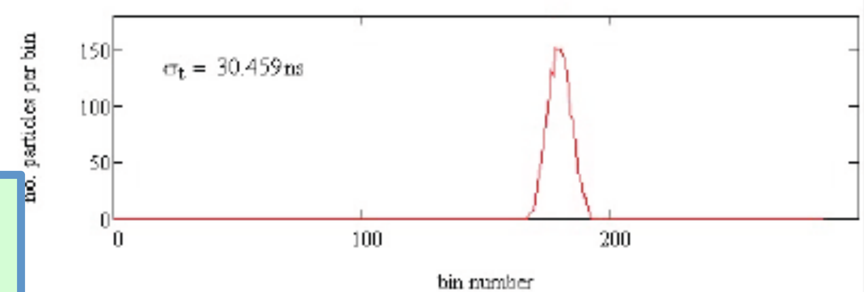
Proton extinction between pulses → # protons out of beam/# protons in pulse

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}

Mu2e Expected Background

(assuming ~ 20 GHz muon beam, 6x E17 stopped muons in 6x E7 s of beam time)

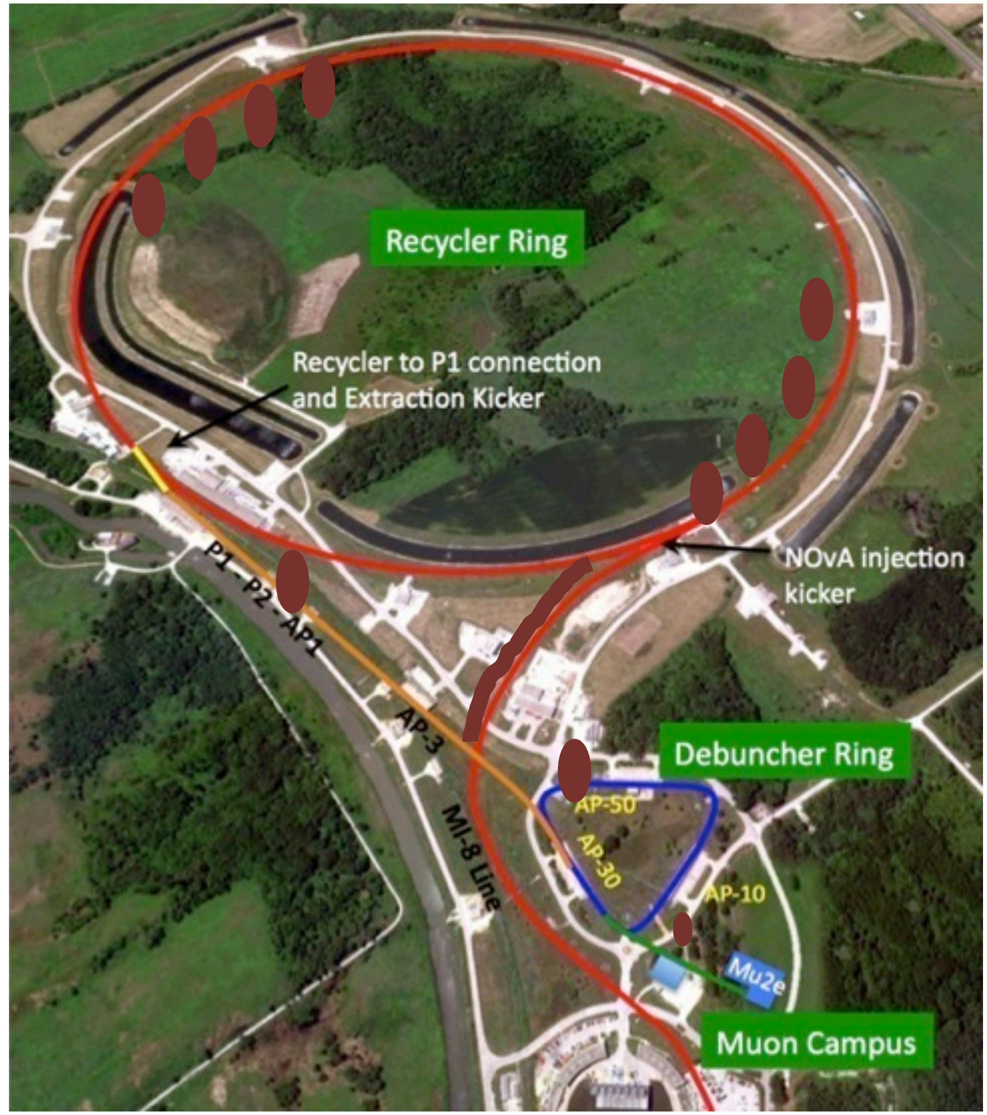
Category	Source	Events		
Intrinsic	μ decay in orbit	0.20	$\pm$	0.06
Late-arriving	Radiative π capture	0.04	$\pm$	0.02
	Beam electrons	0.001	$\pm$	0.001
	μ decay in flight	0.010	$\pm$	0.005
	π decay in flight	0.003	$\pm$	0.002
Miscellaneous	Antiproton capture	0.10	$\pm$	0.06
	Cosmic ray	0.050	$\pm$	0.013
Total Background		0.4	$\pm$	0.1

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6 x 10^{-17} @ 90% C.L.

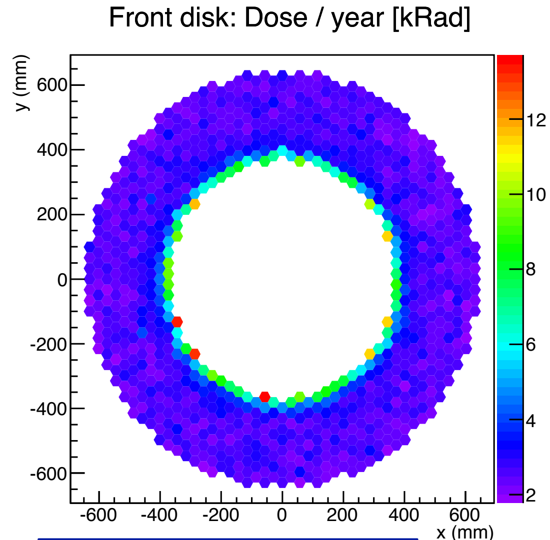
Accelerator Scheme

- Booster: batch of 4×10^{12} protons every $1/15^{th}$ 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 ~3×10^{7} protons each, separated by 1.7 μs (debuncher ring period)**

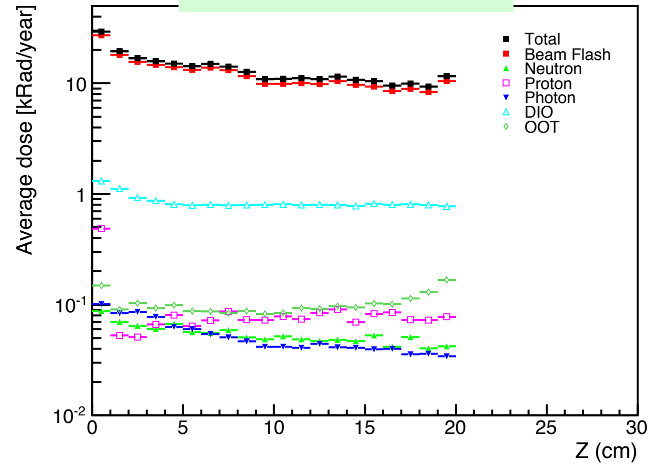


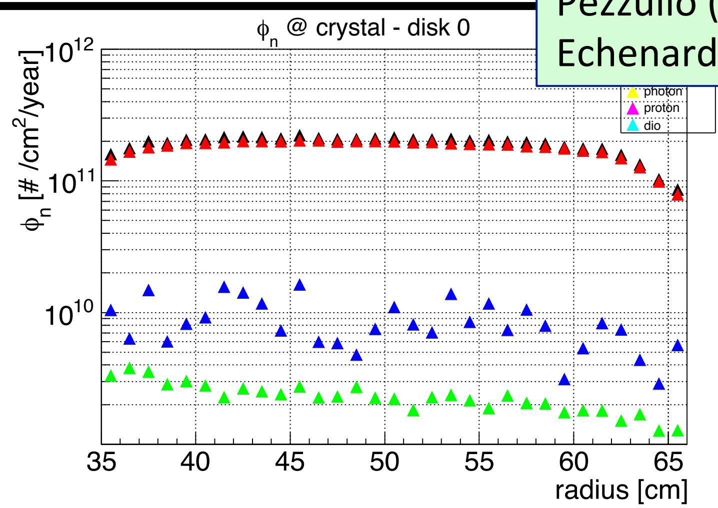
Radiation hardness (simulation)

- Radiation dose driven by Beam flash (300 ns from interaction on target). **Dose from Muon capture x 10 smaller**
- Strongly limited to inner radius (up to 400 mm)
- **Highest dose/year ~ 10 krad**
- **Highest n flux/year on crys. ~ $2x10^{11}$ n/cm²**
- **Highest dose/year on APD ~ $6x10^{10}$ n_1Meveq/cm²**

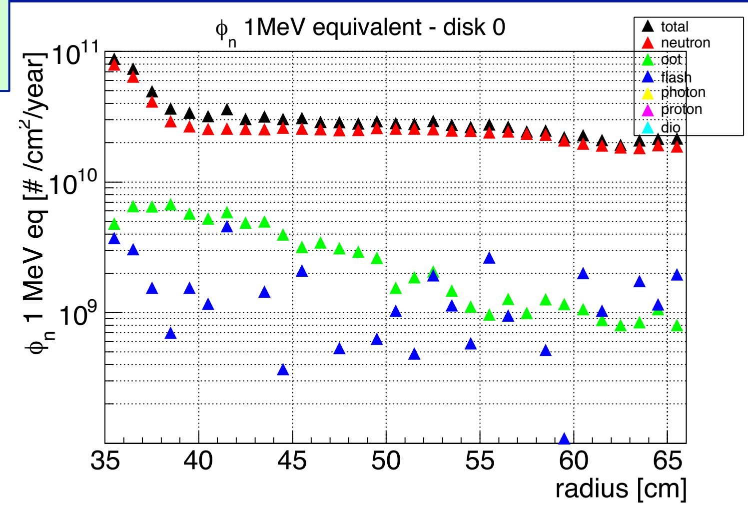


Radius = 36 cm





Pezzullo (Pisa), Echenard (Caltech)



Rad-Hard test: qualify crystals up to 100 krad , 10^{12} n/cm²
Qualify photo-sensors up to 10^{11} --- $3x10^{11}$ n_1MeV/cm²