Search for new physics in experiments with the Fermilab high-intensity muon beams

The report and the proposal to extend

Проект: Поиск новой физики в экспериментах на интенсивных пучках мюонов Фермилаб

Artikov A.M., Atanov N.V., Atanova O.S., Azaryan N.S., Baranov V.A, Baranov V.Yu., Batusov V.Yu., Budagov J.A., Chokheli D., Davydov Yu.I., Demin D.L., Duginov V.N., Galoyan A., Glagolev V.V., Gritsaj K.I., Ivanov V.V., Kazakov D.I., Kharzheev Yu.N., Khomutov N.V., Kozlov G.A., Kolomoets V.I., Kolomoets S.M., Kulchitsky Y.A., Kravchuk N.P., Krylov V.A., Kuchinsky N.A., Lyablin M.V., Mamedov T.N., Movchan S.A., Romanov V.M., Rudenko A.I., Sazonova A.V., Shalyugin A.N., Simonenko A.V., Studenov S.N., Suslov I.A., Tarasov O.V., Tereschenko V.V., Tereschenko S.V., Titkova I.V., Usubov Z.U., Uzhinsky V.V., Vasilyev I., Volnykh V.P.

Joint Institute for Nuclear Research, Dubna, Russia

Djilkibaev R.M., Matushko V.L.

Institute for Nuclear Research, Moscow, Russia

Baturitsky M.A., Chehovsky V.A., I.F. Emeliantchik

BGU national scientific-educational center of particle and high energy physics, Minsk, Belarus

Korjik M.V., Lobko A.,S., Misevich O.V., Fedorov A.A.

BGU Institute of Nuclear Problems, Minsk, Belarus

Boyarintsev A.Yu., Gektin A.V., Grinev B.V., Sidletskiy O.Ts.

Institute for Scintillation Materials NAS of Ukraine, Kharkov, Ukraine

Dubnicka S., Bartos E., Adamuscin C., Liptaj A.

Institute of Physics Slovak Academy of Sciences, Bratislava, Slovak republic

Dubnickova A.Z.

Comenius University, FMFI , Bratislava, Slovak Republic

Chizhov M.V.

The St. Clement of Ohrid University of Sofia, Bulgaria

Muon g-2

Muon magnetic dipole momentum precise measurement

$$\vec{\mu}_{\mu} = \frac{gQe}{2m_{\mu}}\vec{S}$$

$$g = 2(1 + a)$$

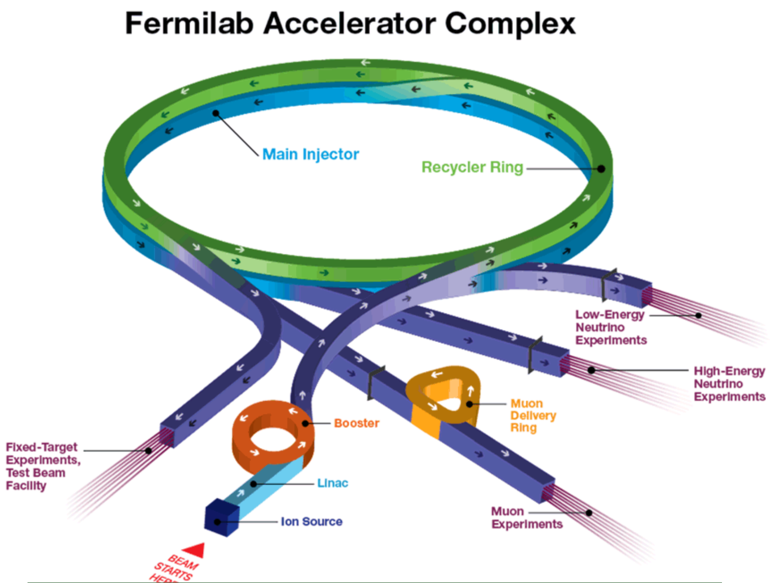
Mu2e

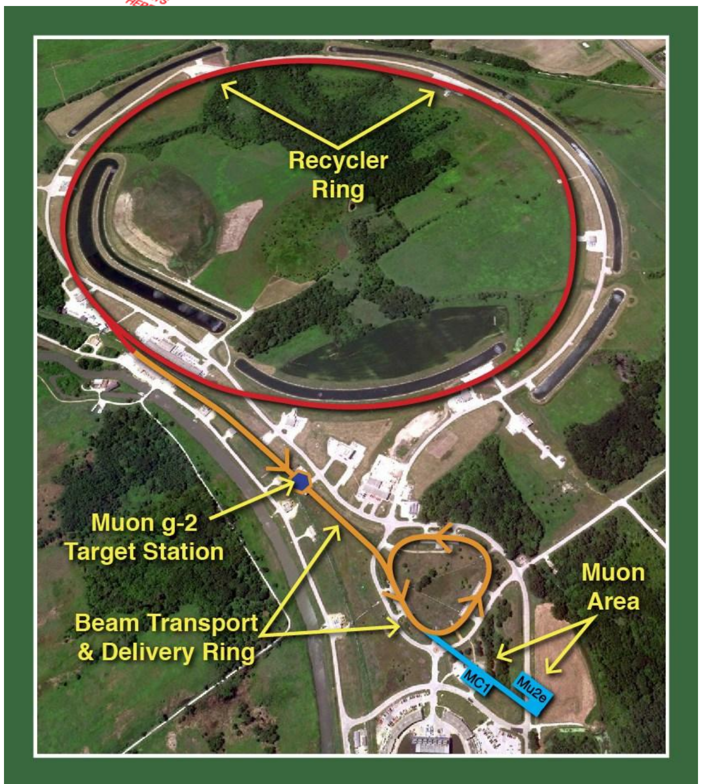
Search for neutrinoless conversion of a muon into an electron in the field of a nucleus

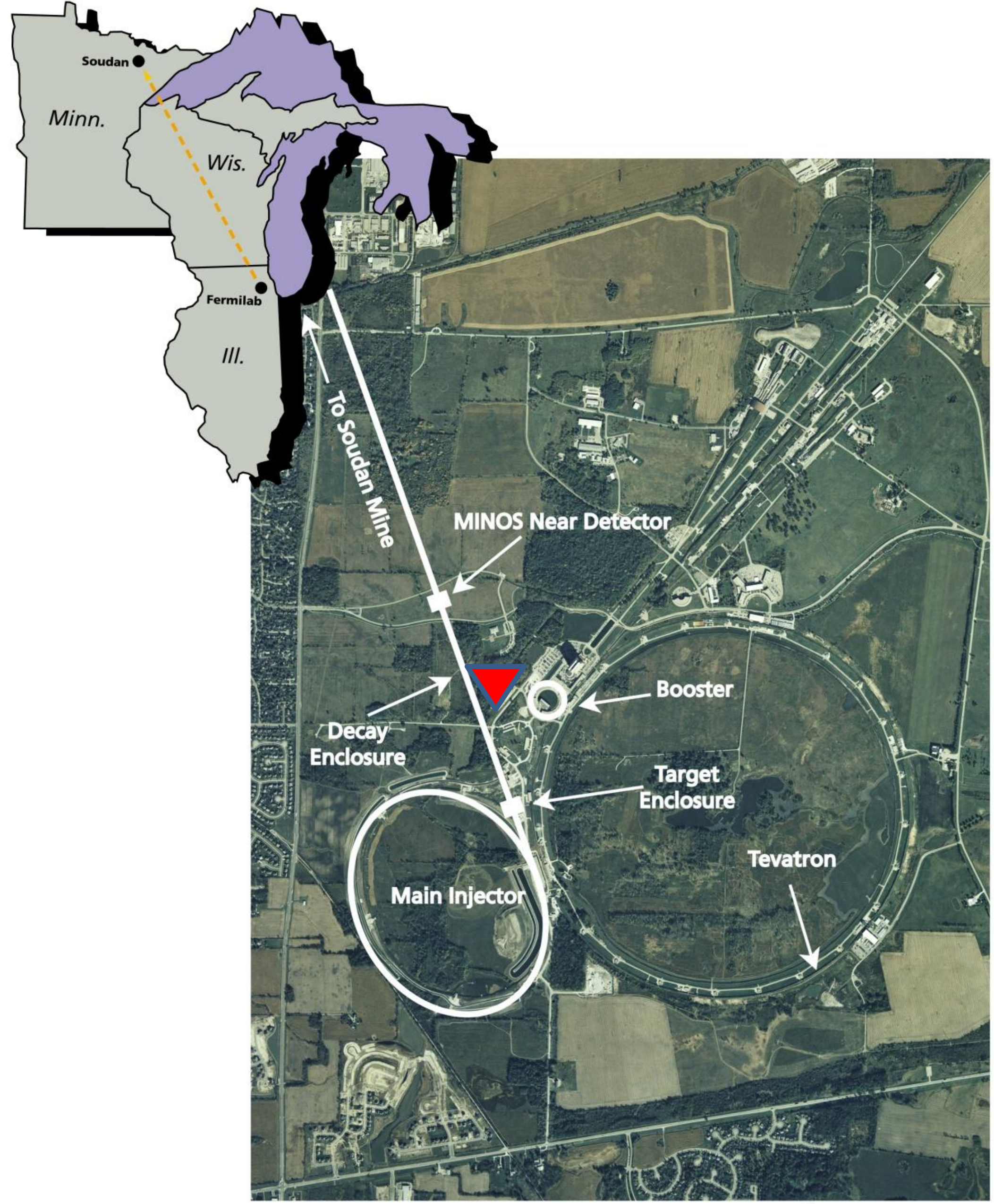
$$\mu^{-}N \rightarrow e^{-}N$$

Charged Lepton Flavor Violation


JINR
Mu2e
NOVA
Happy 50th Anniversary from JINR
Fermilab
Muon g-2
DUNE







FERMILAB #98-1321D

Muon g-2

E989 Collaboration: 35 Institutes; 185 Members

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Kentucky
- Michigan
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab
- **Consultant collaborators**
  - Muons, Inc.

Italy
- Frascati,
- Pisa,
- Roma 2,
- Udine*

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Japan:
- Osaka

Russia:
- Dubna
- PNPI
- Novosibirsk

England

University College London
Cockcroft Institute
Liverpool
Oxford
Rutherford
Queen Mary

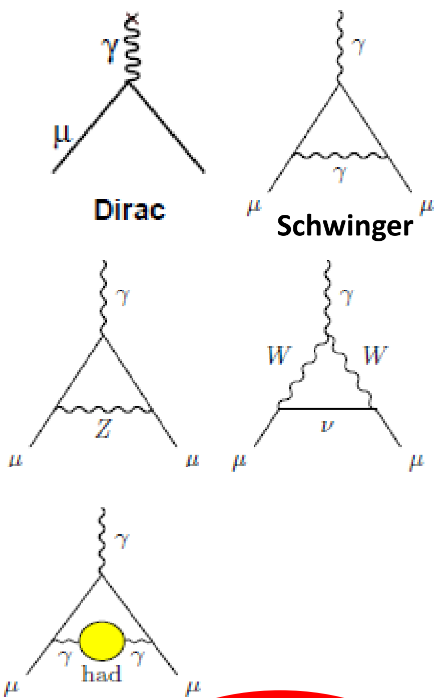
Virtual Ring at FNAL

D.W. Hertzog, Co-Spokesperson
B.L. Roberts, Co-Spokesperson
C. Polly, Project Manager

muon g-2: SM prediction and New Physics

g-2: $\vec{\mu} = g\frac{e}{2m}\vec{s}$ Dirac: $g = 2$ Schwinger (1948): $a \equiv (g-2)/2 = \alpha/(2\pi)$

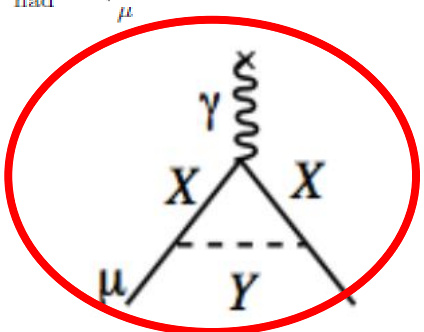
$$a_\mu = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm hadronic} + a_\mu^{\rm NP?}$$



Several groups have produced hadronic compilations over the years.

Here: Hagiwara+Liao+Martin+Nomura+T

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	−9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**



(Numbers taken from HLMNT11, arXiv:1105.3149)

Muon g-2 Experiment Goal

Goal:

$$\vec{\mu}_\mu = \frac{gQe}{2m_\mu}\vec{S}$$

Measurement of the value of muon anomalous magnetic moment, a_μ, to an uncertainty of 16×10[-11] (0.14 ppm) where, $a_\mu = \frac{g_\mu - 2}{2}$

Present Situation:

$$a_\mu^{SM} = 116591834(49) \times 10^{-11} \; (0.42 \text{ ppm})$$

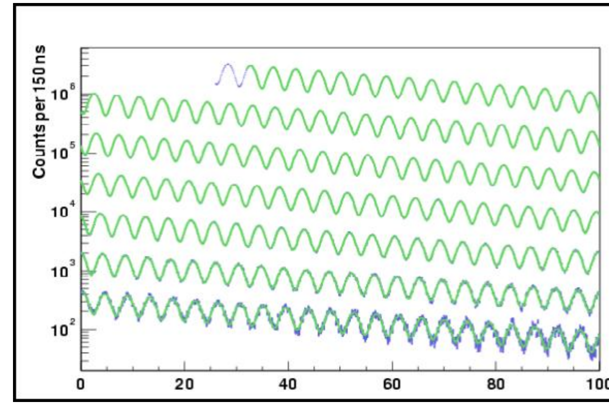
$$a_\mu^{exp} = 116592089(63) \times 10^{-11} \; (0.54 \text{ ppm})$$

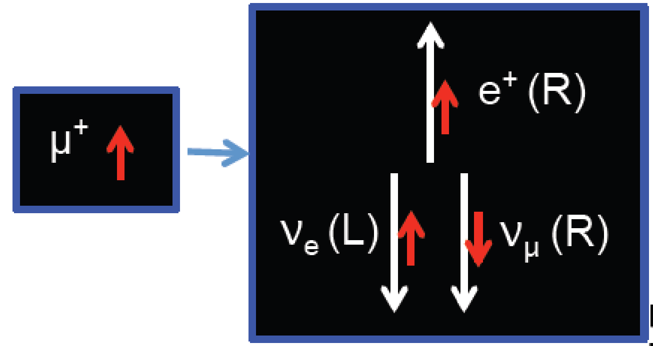
$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{SM} = (255 \pm 80) \times 10^{-11}$$

Physics beyond the standard model

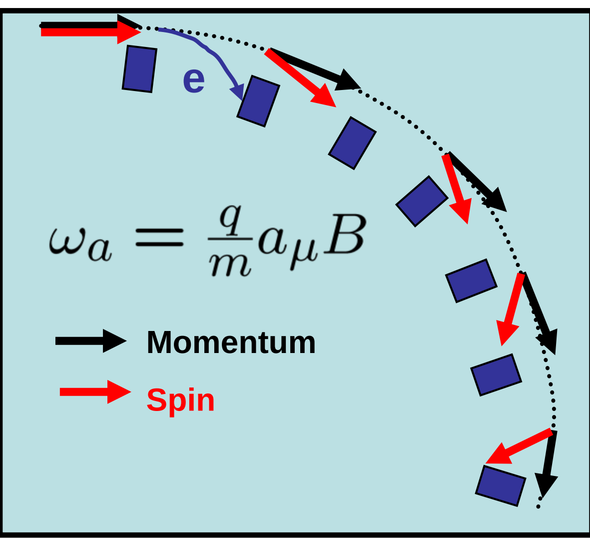
g-2 Experimental Technique

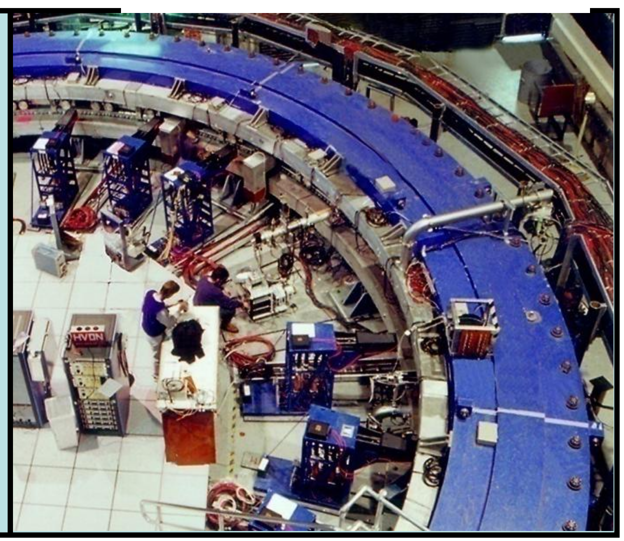
- Capture 3.094 GeV/c muons in a uniform magnetic field
- Measure the precession frequency of the muon spin
- The precession frequency, under special circumstances, is proportional to a_μ





muon storage ring

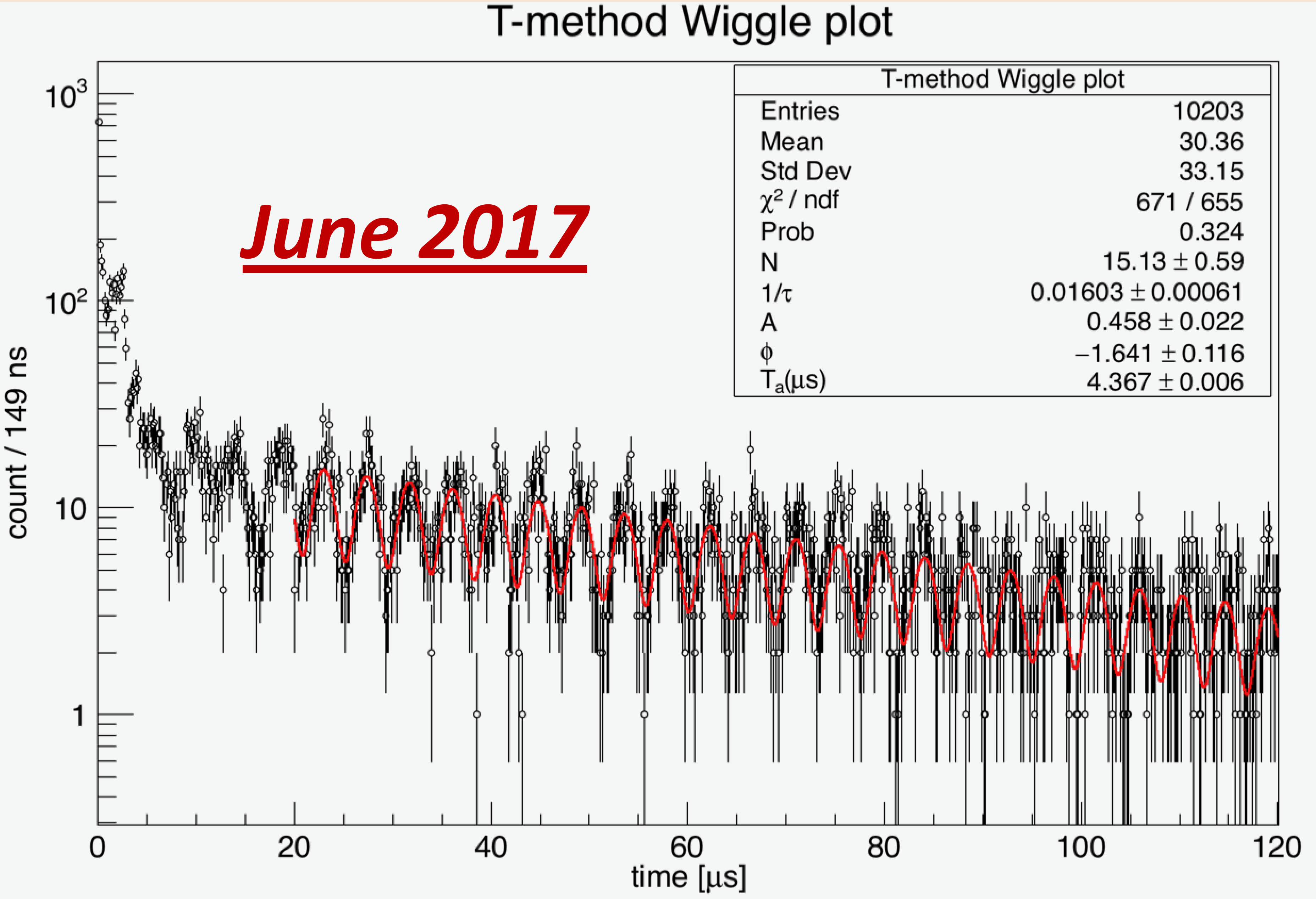




Highest energy positrons occur when muon spin and momentum are aligned (decay is boosted)

Positron direction follows muon spin

First "wiggle plot" from the muon g-2 experiment



How to achieve a fourfold improvement ?

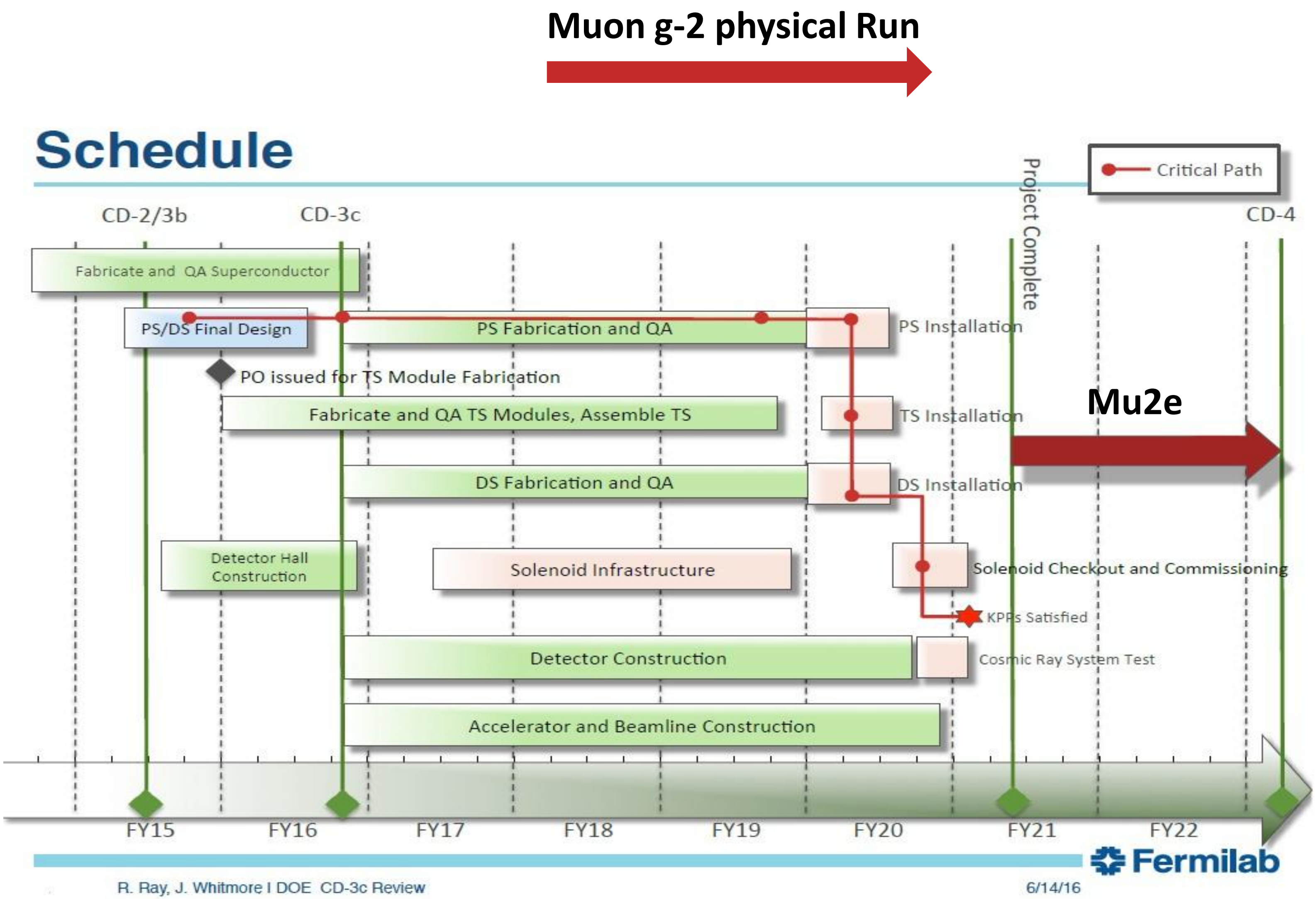
New Experimental Goal: 63 → 16 x 10^{-11}

- Statistics: 0.46 → 0.10 ppm
- Systematics on Precession: 0.21 → 0.07 ppm
- Systematics on Field: 0.17 → 0.07 ppm

21 x BNL

- Need counts
  - Note: E821 was already "rate limited"
    - Cleaner beam
    - Inject more often
    - Run longer
- Reduce systematics
  - Note: Many scale with counts; others were "good enough"
    - Modern detectors / electronics / DAQ critical
    - Improved field intrinsic uniformity
    - Better environment (building)
    - Improved injection

schedule


Muon g-2 physical Run
Schedule
Critical Path
CD-2/3b
CD-3c
CD-4
Project Complete
Fabricate and QA Superconductor
PS/DS Final Design
PS Fabrication and QA
PS Installation
PO issued for TS Module Fabrication
Fabricate and QA TS Modules, Assemble TS
TS Installation
Mu2e
DS Fabrication and QA
DS Installation
Detector Hall Construction
Solenoid Infrastructure
Solenoid Checkout and Commissioning
KPPs Satisfied
Detector Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
Fermilab
R. Ray, J. Whitmore I DOE CD-3c Review
6/14/16

JINR contribution

plan

Muon g-2 experiment

Done

Online data quality monitoring (DQM) software for the calorimeter prototype using the ROME (Root based Object oriented Midas (Multi Instance Data Acquisition System) Extension) framework has been developed and successfully used during test run at SLAC in April 2016.

Prototype of the straw tracker with 1 mm longitudinal space resolution was created and tested successfully.

In progress

A development of an online event display program based on PARAVIEW data analysis and visualization software is in progress. The real time data from the detector will be transferred to a special server where the MIDAS data are converted on-the-fly to the ART format.(2018-2019)

MIDAS online alarm system development and support. Integration of all required alarms from different experiment subsystems into the central MIDAS DAQ. Testing and debugging of the new alarm system during engineering runs before data taking. Support of the alarm system during beam runs. (2018-2020)

New

MIDAS ODB support and interfacing
Development of new custom JavaScript web pages for the MIDAS ODB control. Special applications scripts for checking ODB integrity and correcting possible errors. (2018-2020)

Participation in the test and data taking runs
Participation in final integration and testing of the full DAQ system .Expert support of the MIDAS software during physical runs 2018-2020.

Analysis of the physical data (2018 ->)

The Mu2e Collaboration

Over 200 scientists from 37 institutions

The Mu2e Collaboration, Feb 2017

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

Mu2e Muon-to Electron Conversion

Mu2e will measure the ratio of the coherent neutrinoless muon-to-electron conversion rate to muon capture rate

muon converts to electron in the field of a nucleus

$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

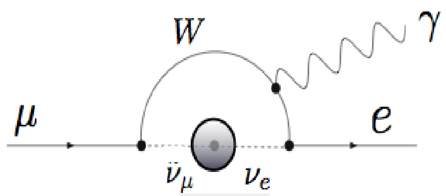
$\mu^- A \rightarrow e^- A$	$R_{\mu e}^{Au} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

SINDRUM II collaboration, PSI, 2006, Eur.Phys.J. C47 (2006) 337-346

- manifest Beyond-Standard-Model physics
- SES of 2.3×10^{-17}, 0.4 evt bkg; 6×10^{-17} at 90% CL
- Standard Model Background of 10^{-54}

Mu2e : SM prediction and New Physics

The BR of CLFV processes in the Standard Model



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

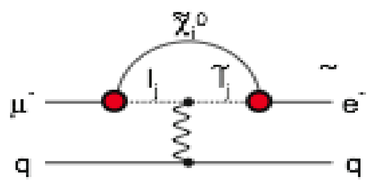
Mu2e sensitivity is $6*10^{-17}$

NP

Sensitive to mass scales up to O(10,000 TeV)

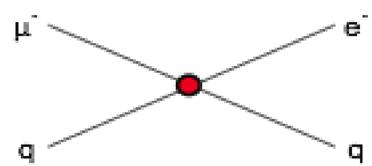
Supersymmetry

rate ~ 10^{-15}



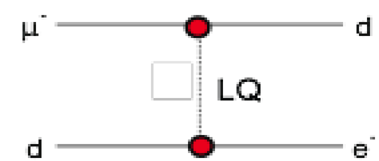
Compositeness

Λ_c ~ 3000 TeV



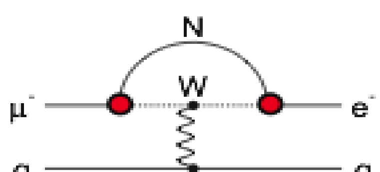
Leptoquark

M_{LQ} = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c²



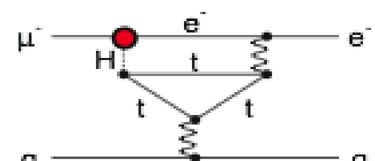
Heavy Neutrinos

$|U_{\mu N} U_{eN}|^2$ ~ 8x10^{-13}



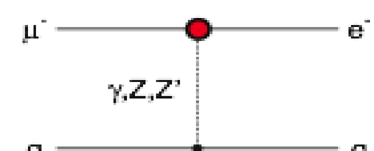
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c²



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

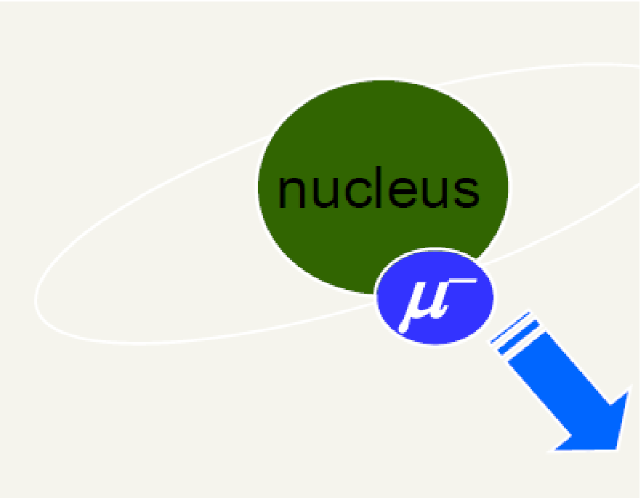
Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J.C57:13-182,2008

The great-grandparents of the Mu2e (MELC, 1992; MECO, 1997) are INR scientists V.M. Lobashev and R.M. Djilkibaev

Владимир Михайлович Лобашёв
(29.07.1934–03.08.2011)

The Measurement Method

- Stop negative muons in an aluminum target
- The stopped muons form muonic atoms
  - 207x smaller radius than inner e^- in Al–>
  - well inside electron orbits →
    muon forms a hydrogen-like atom, unaffected by e's
  - hydrogenic 1S : Bohr radius ~20 fm, BE~500 keV
  - Nuclear radius ~ 4 fm →
    muon and nuclear wavefunctions overlap significantly

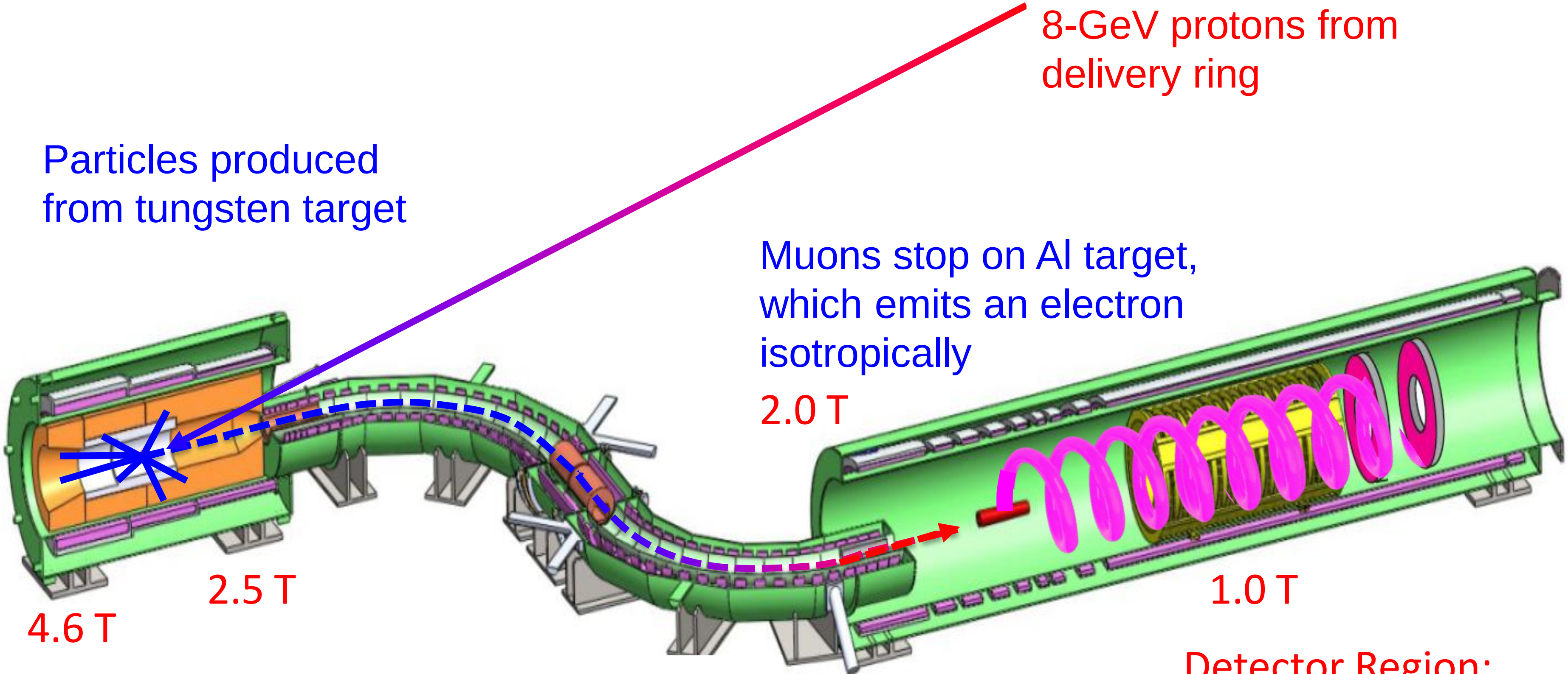


- Three main things can happen (numbers for case of Al):
  - Muon decays (40%): $\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$
  - Muon captures on the nucleus (60%): $\mu^- + {}^{27}_{13}Al \rightarrow X + \nu_\mu (capture)$

  (capture is roughly sum of reactions with protons in nucleus: $\mu^- + p \rightarrow \nu_\mu + n$)
  - Muon to electron conversion: $\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^-$
- Muon lifetime in 1S orbit of aluminum ~864 ns

  (40% decay, 60% nuclear capture), compared to 2.2 μsec in vacuum
- Look for 105 MeV conversion electron signal $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$ E_e=104.96 MeV

Baseline Mu2e Apparatus



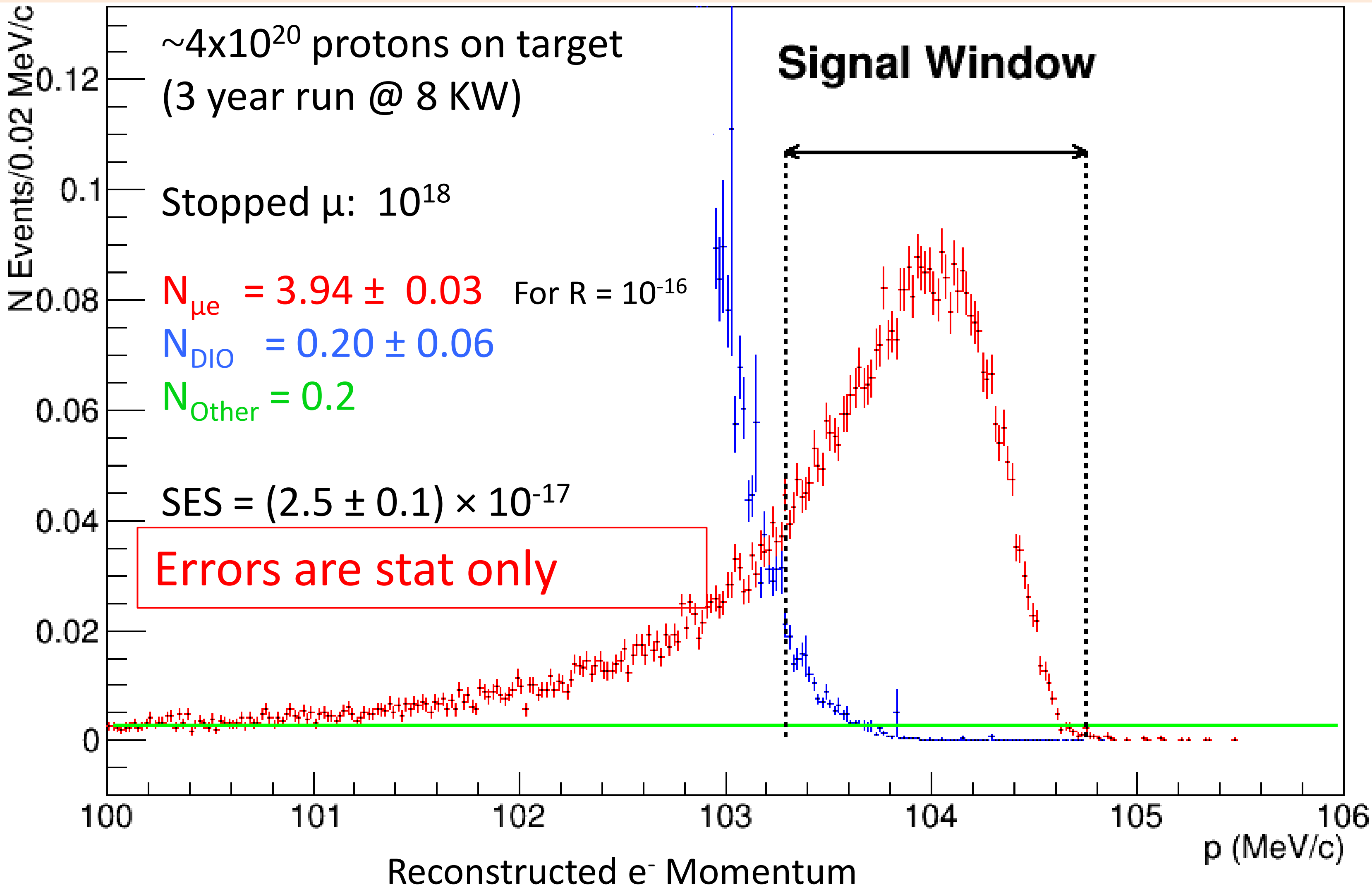
Graded B for most of length

Detector Region:
Uniform Field 1T

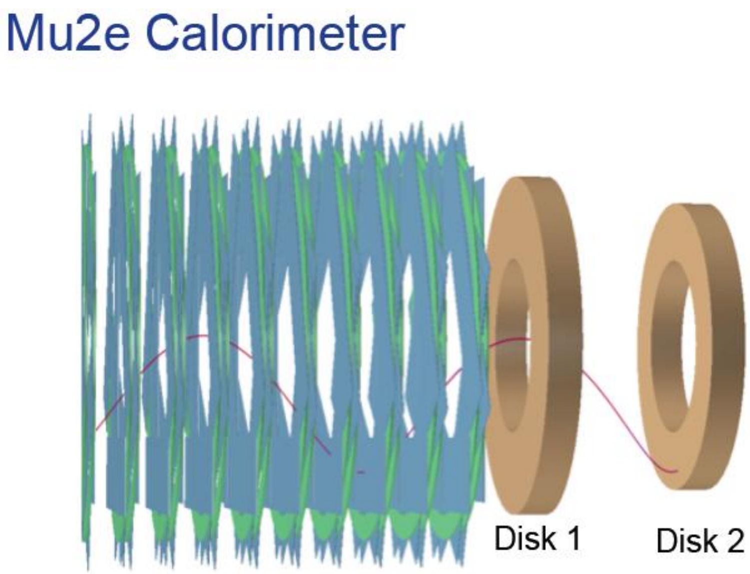
S-shaped solenoid:
- transports particles to detector area, and
- allows remaining pions to decay to muons
- collimator selects negatively-charged particles

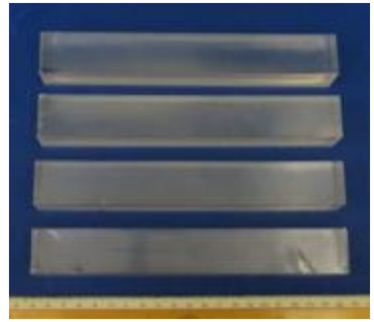
Tracker/calorimeter detect electron signature

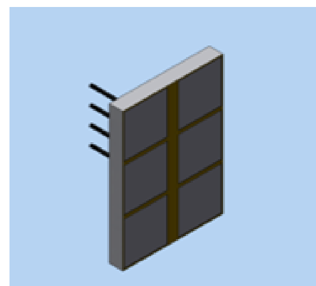
Signal Sensitivity for 3 Year Run

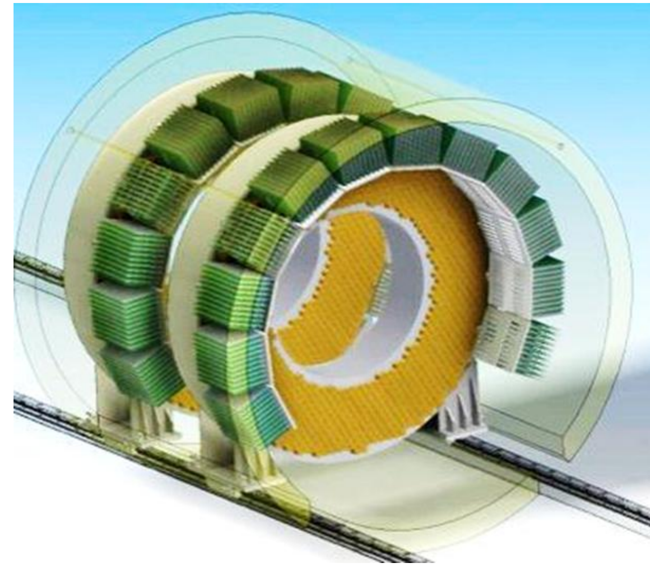


Mu2e Calorimeter









The calorimeter should be able to operate in an environment where a dose up to 100 krad and a neutron fluency of 10^{12} n/cm^2 are expected. It must also works in a 1 T magnetic field and 10^{-4} Torr vacuum.

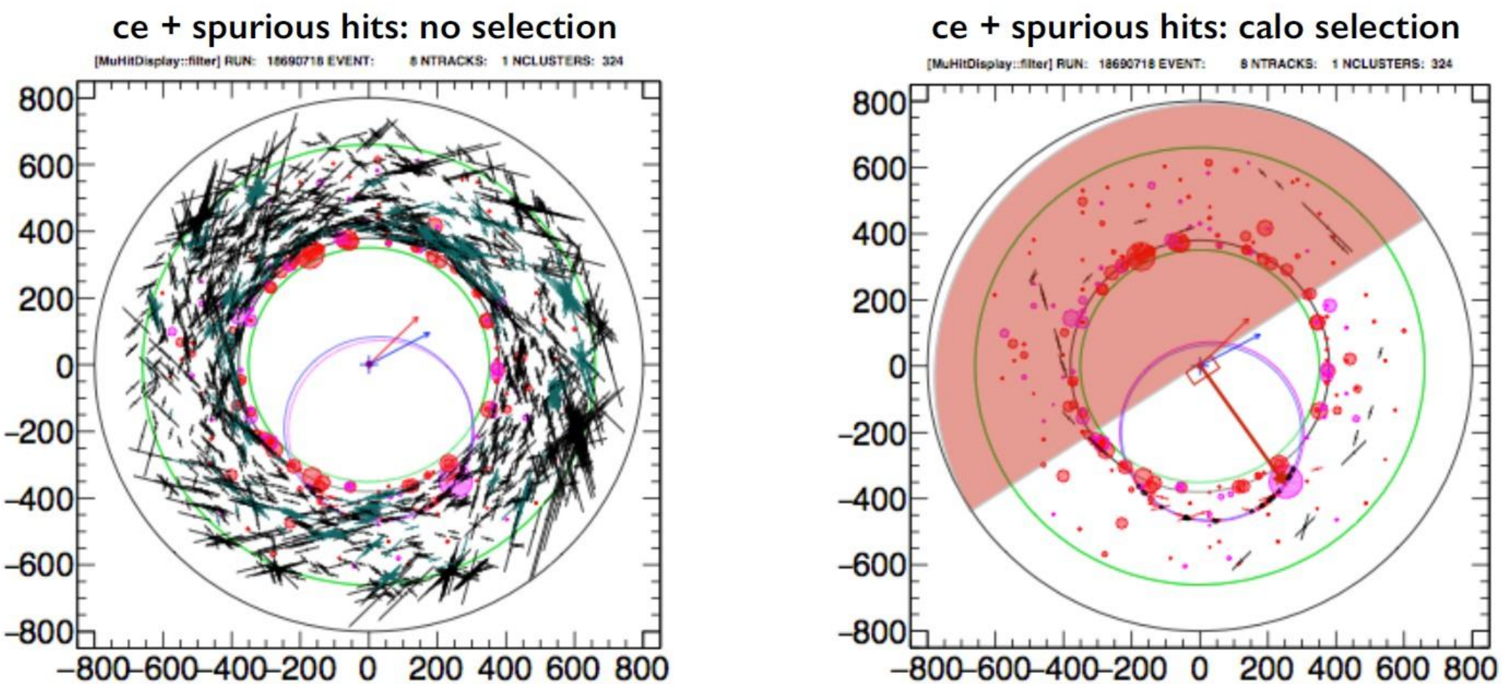
Each disk has an internal (external) radius of 374 mm (660 mm) and is filled with ~700 34×34×200 mm^3 CsI crystals.

Each crystal is readout by two large area UV extended SiPM's (14x20 mm^2)

The requirements :

- Provide energy resolution σ_E/E of O(5 %)
- Provide timing resolution σ(t) < 500 ps
- Provide position resolution < 1 cm
- Provide almost full acceptance **for Conversion Electron @ 100 MeV**
- Redundancy in FEE and photo-sensors

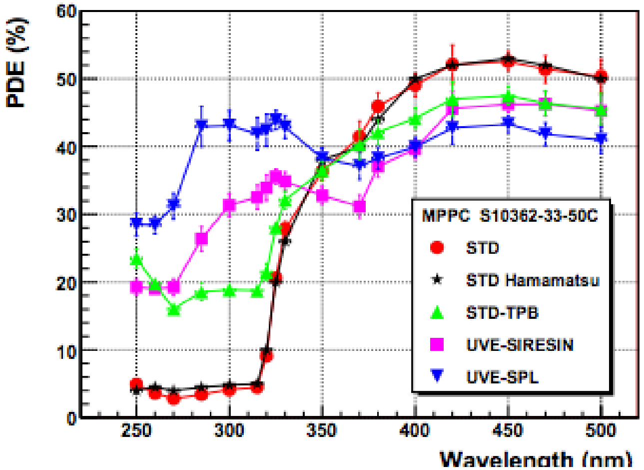
Mu2e Pattern Recognition



Example of a full simulated conversion electron (CE) event in overlap with all hits from the environmental background: (left) without any requirement on the calorimeter system and (right) with a calorimeter based selection. Black points are hits from the tracker. Red points are from calorimeter clusters. By requiring the track hits to be in time with the most energetic cluster of the event, in a time window of 50 ns, the quantity of background hits is strongly reduced

Crystals choice

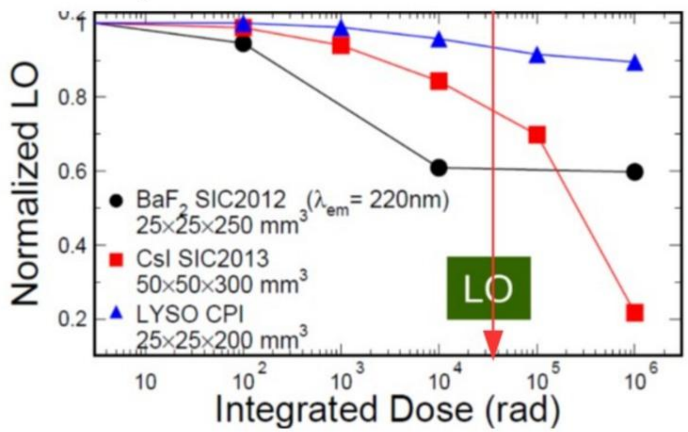
	LYSO	BaF_2	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310



Undoped CsI

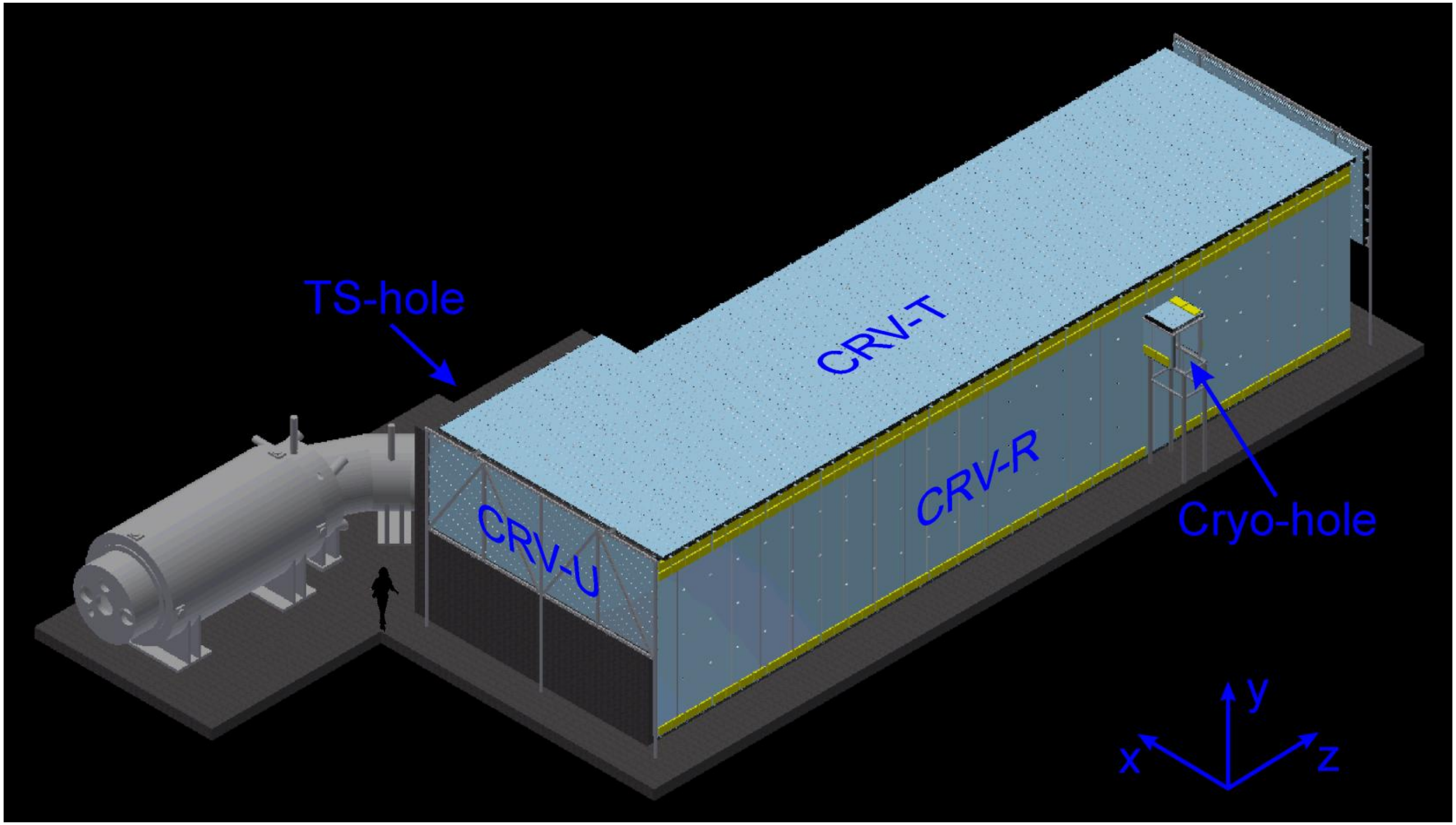
- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component.
- Emits @ 310 nm.
- Comparable LY of fast component of BaF_2.
- Lower cost (6-8 $/cc)
- **Well know crystal.**

Crystal radiation hardness



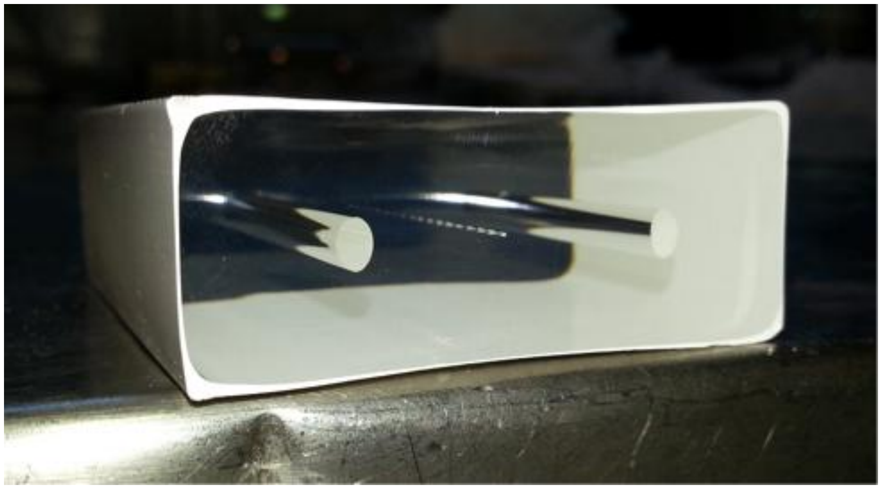
- under irradiation, BaF_2 and CsI crystals behave very differently
- BaF_2-based option has an advantage for doses above 1 Mrad
- the expected calorimeter dose in 3 years of Mu2e running < 50 Krad
  - this favors the CsI-based option

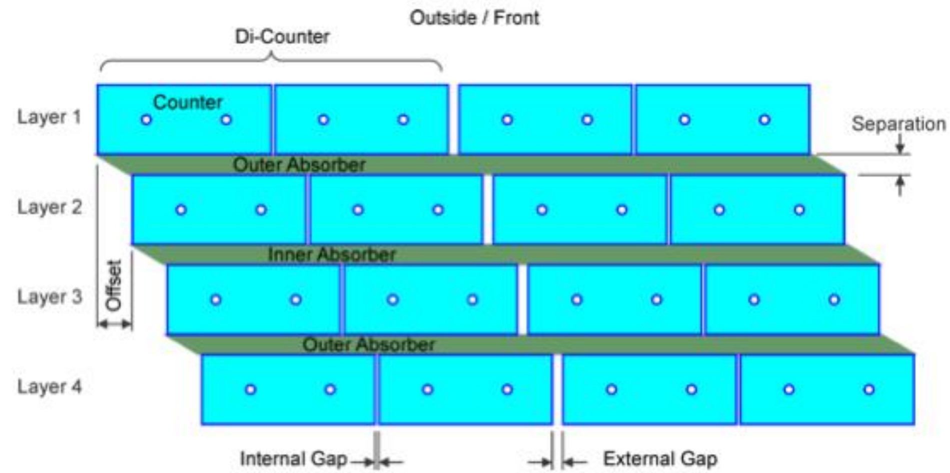
Mu2e Cosmic-Ray Veto



- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto





- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x (450 – 660) cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

JINR contribution (summary)

plan

Mu2e experiment (calorimeter)

Done

E.m. calorimeter simulation
Lyso, CsI crystals and matrix simulation: time, energy resolution, longit. uniformity

prototype Lyso crystal matrix (3x3) tests at electron beams and data analysis

prototype CsI crystal matrix (3x3) tests (with PMT) at Yerevan electron accelerator (15-35 MeV) and data analysis

prototype CsI crystal matrix (3x3) tests (with SiPM) at Frascati electron accelerator (70-105 MeV) and data analysis

Radioactive sources test of CsI crystals at DLNP lab. Longitudinal response uniformity and ratio fast to total scintillation component

In progress

E.m. calorimeter simulation
Calorimeter in situ calibration methods (2018-2020)

Preparation to the crystal tests at JINR electron accelerator LINAC-800. Testing the accelerator in the low intensity operation and background conditions. (2018-2020)

RnD with BaF_2 crystals and solar blind photodetectors. (2018-2020)

New

CsI crystals QA tests at Yerevan electron accelerator (15-40 MeV e^- beam) and data analysis (2018-2020)

CsI crystals QA tests at Frascati electron accelerator (70-120 MeV) (2018-2020)

CsI crystals QA tests at DLNP lab on radioactive sources and cosmic muons (2018-2020)

Participation in the calorimeter assemble and commissioning (2020)

JINR contribution

E.m. calorimeter simulation

We are developing the new calibration method for the calorimeter in Mu2e experiment using electrons from muon decays-in-orbit (DIO). To provide uniform coverage and high statistics, the magnetic field will be reduced from 1 T to 0.5 T.

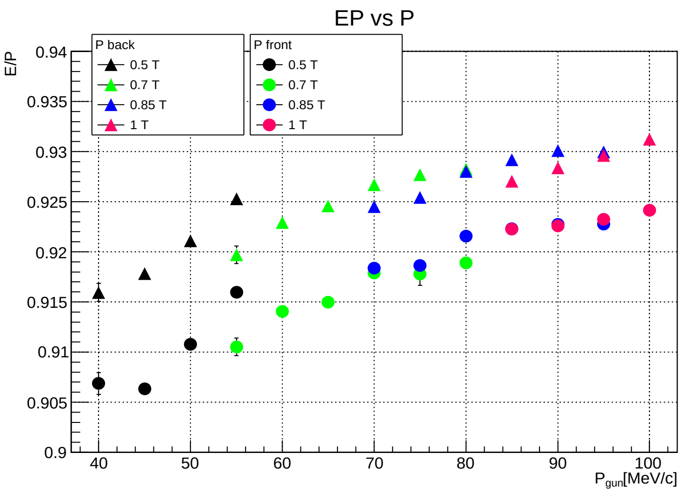


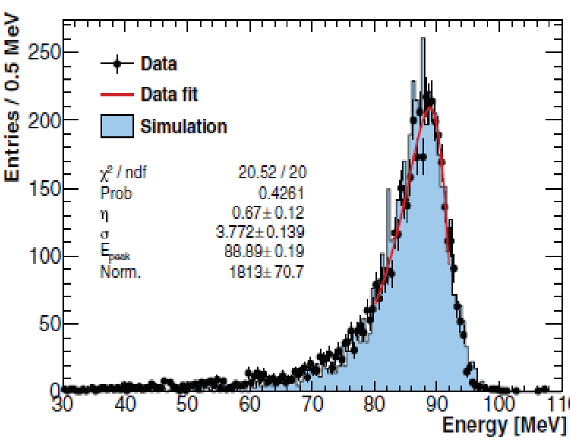
Fig.shows the most probable values of *E/P* distributions *vs* the initial electron momentum P_{gun} in different magnetic fields. The points for cases when *P* is measured in the front and back of the tracker are presented on the plot. Estimating <*E/P*> variations from the plot one can conclude that the calibration with accuracy of ~1.5% is possible. The accuracy can be increased after understanding of behavior of <*E/P*> vs the magnetic field and momentum.

We have investigated scintillation light distribution in BaF_2 and pure CsI crystals with dimensions 3x3x20 cm^3 using the Geant4 toolkit. The diffuse wrapping material is selected as coating for the crystals.

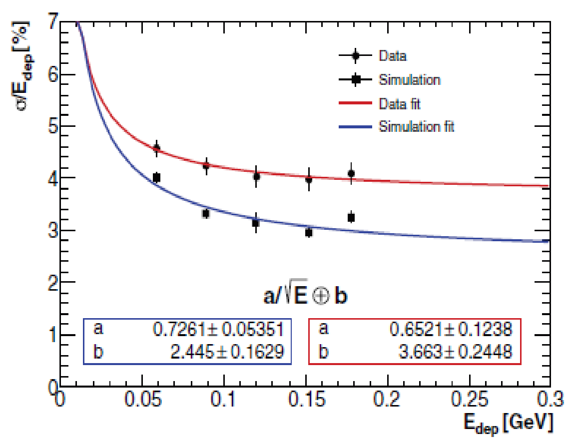
JINR contribution

Test of LYSO crystal matrix at MAMI and Frascati accelerators

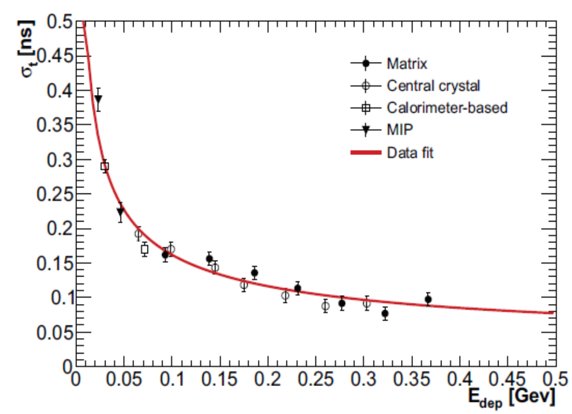
JINR colleagues strongly participated in the LYSO matrix tests. A LYSO matrix prototype was built in March 2014 with an overall transverse dimension corresponding to a ~ 3.6 Moli`ere Radius (*RM*) and a longitudinal dimension corresponding to ~ 11.2 radiation lengths (*X*0). The prototype consisted of 25 LYSO crystals ($30 \times 30 \times 130$ mm^3) . Each crystal was wrapped with a 60 μm thick layer of super-reflective ESR-3M and read out by a Hamamatsu S8664-1010 APD. The APDs were optically connected to the crystals by means of Saint-Gobain BC-630 optical grease.



Energy distribution for 92.5 MeV photons



energy resolution as a function of the deposited energy



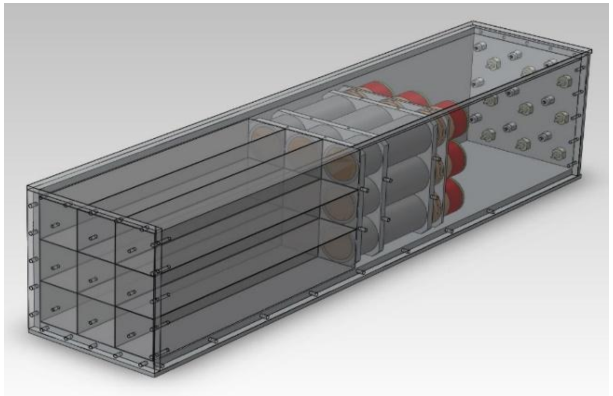
Time resolution as a function of the energy deposited in the matrix

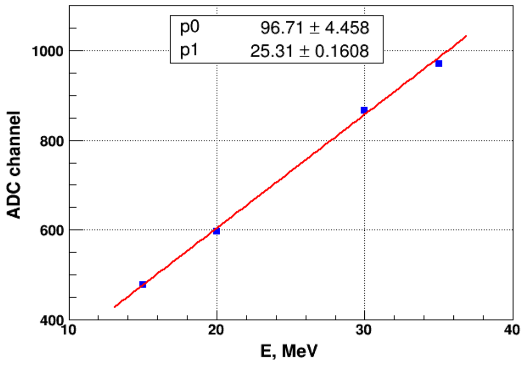
JINR contribution

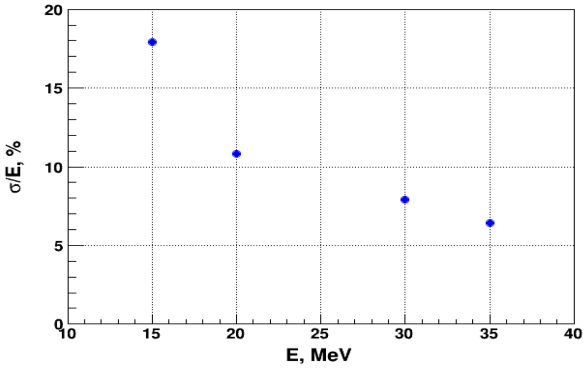
Test of CsI crystal matrix at Frascati electron accelerator (time resolution 200 ps)

Test of CsI crystal matrix at Yerevan electron accelerator

DLNP and Erevan Physics Institute (A.Alikhanyan National Laboratory) groups established a cooperation in 2015 to carry out beam tests of the e.m. calorimeter prototype on the Erevan Linac LUE-75. Calorimeter beam test requires single electron events, i.e. it is required to suppress the beam intensity by 10-11 orders of magnitude. Accelerator staff successfully got a steady LUE-75 operation mode with extremely low beam intensity (10-20 electrons/s) . Several Runs DLNP physics performed at LUE-75 with CsI crystal matrix.







Tested 3x3 matrix of pure CsI crystals 30x30x200 mm^3 each with PMT readout

Matrix demonstrates good linearity of energy response

Energy resolution is about $\sigma_E/E \approx 6.4\%$ at 35 MeV

JINR contribution

JINR electron linear accelerator

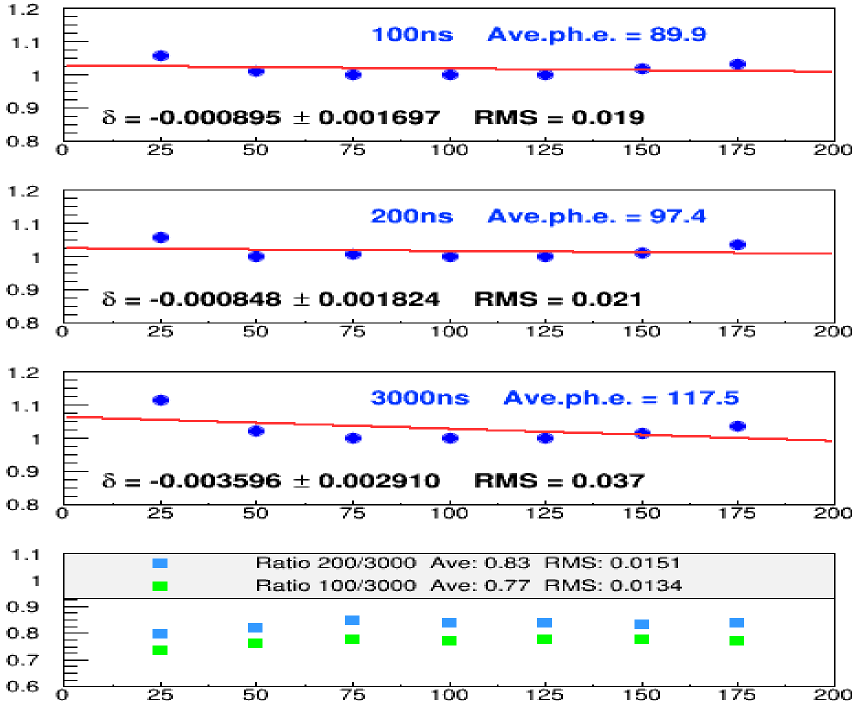
DLNP in cooperation University Centre are interested in the soonest start of the linear electron accelerator (LINAC-800) in the building No. 118 sites LNP and its further use. In this regard, aiming to create an experimental base for carrying out scientific-methodical works using a beam of electrons in the energy range 5-240 MeV accelerator stand.

We investigating the possibility to obtain of a low-intensity (1…3 electron) beam of elections at the linear accelerator LINAC-800. Low-intensity beam of electrons with 1…3 electrons on each spill will allow us to study the characteristics of CsI and other type crystals.

JINR contribution

Radioactive Sources test

A study of scintillation properties of undoped CsI crystals. Undoped CsI sample 30x30x200 mm^3 from Institute for Scintillation Materials (Kharkiv, Ukraine) was tested at DLNP lab. Tested undoped CsI crystal shows a good light yield ~100 p. e./MeV (gate 200ns). Longitudinal response uniformity not worse 7% at 100-200 ns gates. Measured ratio of fast/total scintillation components is 0.83.

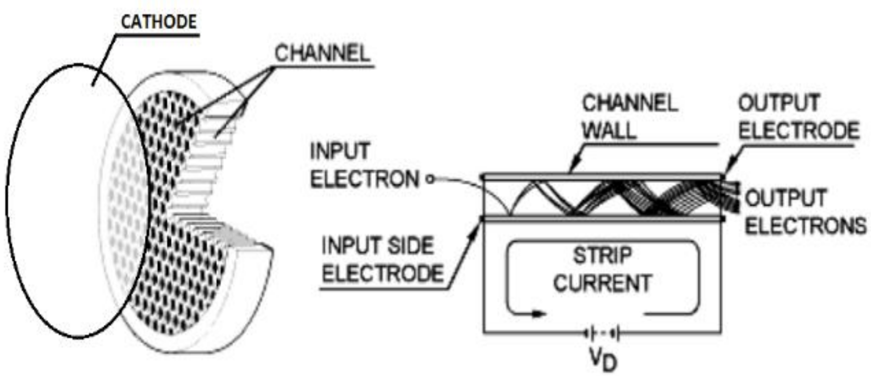


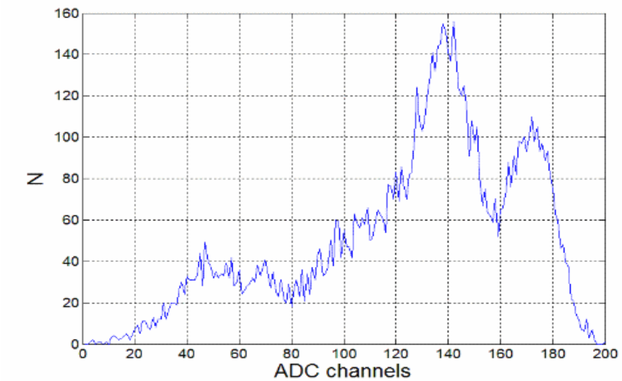
Longitudinal response uniformity and ratio fast to total scintillation component

JINR contribution

RnD with BaF2 crystals and solar blind photodetectors.

In the second stage of the Mu2e with two order high luminosity suppose to reassemble calorimeter on BaF2 crystals which have propriate radiation hardness. We ordered and obtaind 2 BaF2 crystals from Incrom (Saint-Pitersburg). They were tested at Dubna and Frasctai and showed acceptable quality.





There are no commercially available UV photodetectors able to work in magnetic field 1 T. We carried out research on photodetectors for BaF2 crystals. Developing a photodetector sensitive to the fast component of the spectrum of the crystal in the range up to 260 nm and insensitive to the slow component peaking at 310 nm. As UV photodetectors, suitable for isolation only fast emission components of BaF_2 crystals, applied photocathode with upper p-emitter layer AlGaN:Mg. AlGaN photocathode with a mass fraction of Al x=0.3 was combined into one device with a microchannel plate. Our testing with Co^{60} shows FWHM~10% .

JINR contribution (summary)

plan

Mu2e experiment (CRV)

Done

Simulation of the CRV counters characteristics under different test conditions and optical resin filling

Increasing the light yield from scintillation strips . The method of parallel filling of several fiber channels is developed. The measured light yield of the strip filled with optical resin SKTN-MED(E) in average is 1.5-1,8 times higher than that of the "dry" strip

Test beam of the CRV counter prototypes. Participation in the tests at 120 GeV proton beam and data analysis

Technology of the CRV 4-layers module assembly is developed and pilot module is produced

In progress

Simulation of the CRV efficiency in the experimental setup (2018-2019)

Radiation hardness tests of the scintillator strips and filler samples at the JINR IBR-2 facility are performing (2018)

New

Test beams of the SKTN filled counters (2018)

Design and creation of the stand for QA testing of the produced CRV 4-layers modules up to 6.6 m length (2018)

Control on the CRV modules production and QA tests of the manufactures CRV modules (2018-2020)

Participation in the CRV system assemble and commissioning (2020)

Participation in the data analysis (2021 ->)

JINR contribution

Increasing the light yield from scintillation strips (CRV system)

In order to veto incoming muons with an inefficiency of 1 x 10^{-4}, single layer inefficiencies must be no more than 0.4%. Test-beam results with new SiPMs from Hamamatsu give safety factor of 1.5 at run start. Taking into account aging of the counters, radiation damage; the extra long counters (6.6 m) with one end read out are in the crucial situation.

<u>One of efficient methods of increasing light collection from a plastic scintillator by WLS fiber is filling a space between them with optical glue or some other filler with refractive index of wich close to that of the scintillator</u>. In case of using high viscosity optical transparent filler the special technique we developed for injecting it into the strip hole.

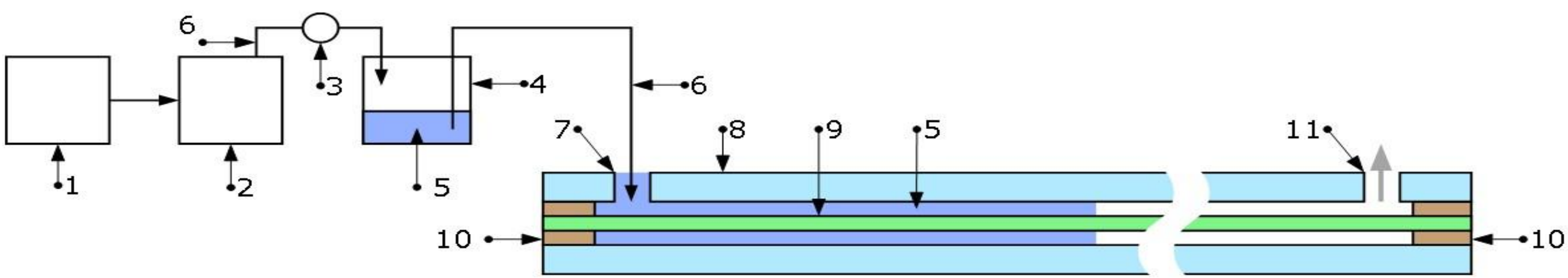
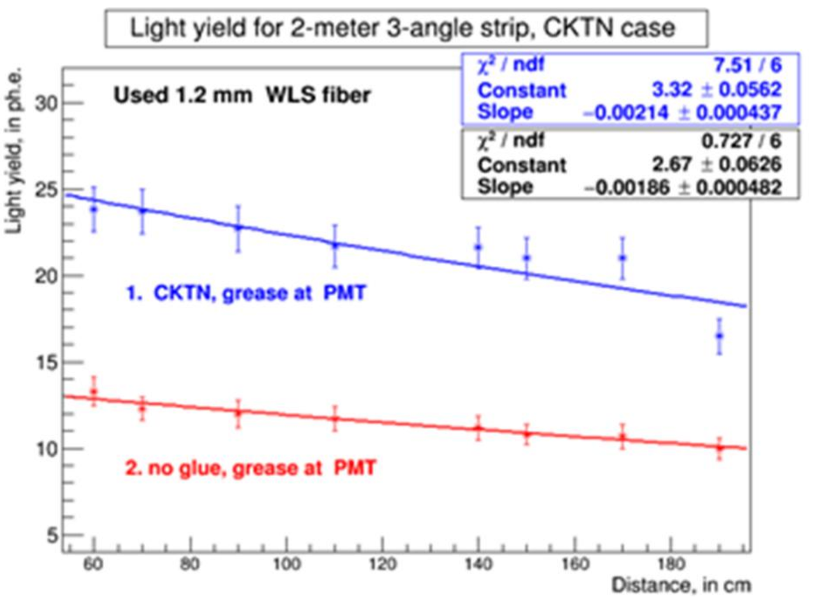


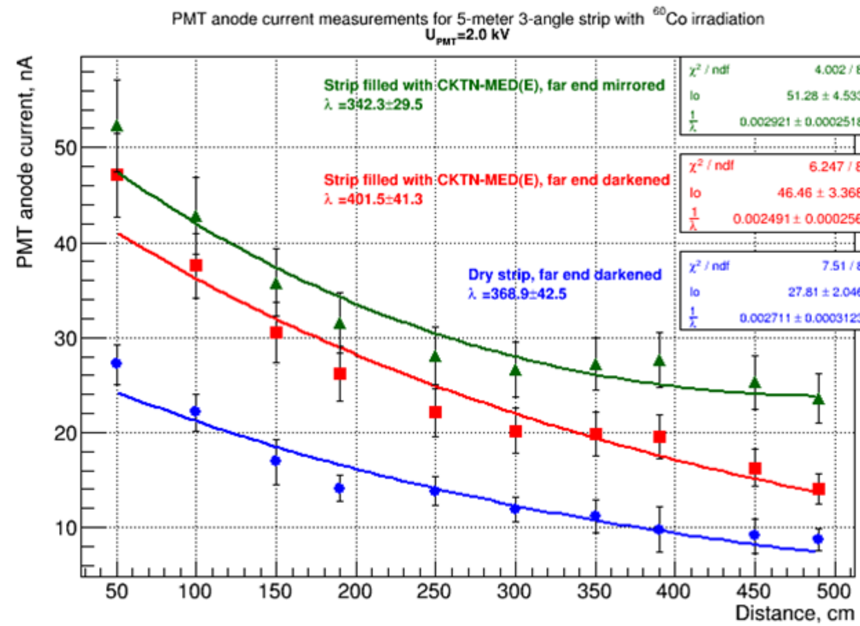
Figure. Setup to pump the high viscosity filler into the co-extruded hole of the scintillation strip (not in scale): (1) dry type compressor; (2) SL101N digital Liquid Dispenser; (3) manometer; (4) special vessel with filler; (5) filler; (6) polyvinylchloride tube; (7) inlet for filling; (8) strip; (9) WLS fiber; (10) sealing; (11) exhaust outlet for extracting air.

JINR contribution

Increasing the light yield from scintillation strips   (CRV system)



Light yield collection for the strip filled by CKTN-MED(E) with 1.2 mm WLS fiber.
Cosmic muons trigger



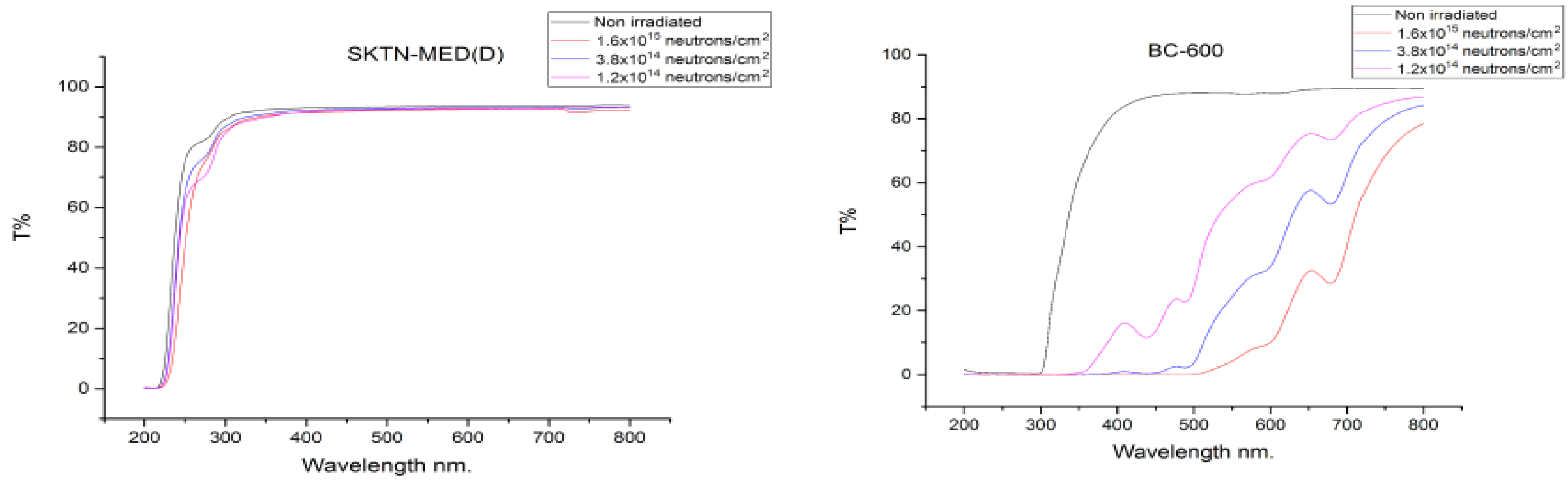
PMT anode current measurement with ^{60}Co irradiation

<u>The light yield of the strip filled with optical resin SKTN-MED(E) in average is 1.5-1.8 times higher than that of the “dry” strip</u>

JINR contribution

Radiation hardness tests of the scintillator strips and filler samples

We have carried out the investigations on radiation hardness of scintillation strips and SKTN-MED(D) and Bicron-600 (for comparision) in the neutrons flux (E>1MeV) from fast neutron reactor IBR-2 of JINR. Fillers and strips with length 15 cm with WLS fiber in the its hole with/without filler were irradiated on neutron integral flux up to $1.6x10^{15}$neutrons/cm^2.



Transmission spectra of glue SKTN-MED(D) (a), BC-600 (b) measured on neutron integral flux ($1.6x10^{15}$, $3.8x10^{14}$, $1.2x10^{14}$) neutrons/cm^2

JINR contribution

Technology of the CRV 4-layers module assembly

In the 2015,2016 a group of JINR colleagues was sent to the University of Virginia, USA to establish a mass-production process of scintillation modules CRV. They successfully develop a procedure of module assemble and created two pilot CRV modules with a length of 90 cm and prepared scintillation strip components for 4.5 meter length module.

Agreements

- Memorandum of Understanding JINR-FNAL
  - Mu2e, muon (g-2)
  - 2013-2018
- Implementation Agreement JINR-FNAL
  - Mu2e
  - 2013-2016
- NON-PROPRIETARY USER'S AGREEMENT BETWEEN JOINT INSTITUTE OF NUCLEAR RESEARCH, DUBNA, AND FERMI RESEARCH ALLIANCE, LLC DATED August 18, 2015
- Statement of work For participation in the Mu2e Experiment at Fermilab, February 2017

Our publications connected to this Project

1. J. Budagov et al., "The calorimeter project for the Mu2e experiment", Nucl. Instr.&Meth. A718(2013) 56-59.
2. O. Sidletskiy et al., "Evaluation of LGSO:Ce scintillator for high energy physics experiments", Nucl. Instr.&Meth. A735(2014) 620-623.
3. K. Afanaciev et al., "Response of LYSO:Ce scintillation crystals to low Energy gamma-rays", Part. Nucl. Lett. (2015), Vol. 12 (193), p.476
4. Z. Usubov, "Electromagnetic calorimeter simulation for future μ→e conversion experiments", arXiv:1212.4322 (2012).
5. Z. Usubov, "Light output simulation of LYSO single crystal", arXiv:1305.3010 (2013).
6. N. Atanov et al., "Measurement of time resolution of the Mu2e LYSO calorimeter prototype", Nucl. Inst. Meth. A 812 (2016), 104.
7. N. Atanov et al., "Design and status of the Mu2e electromagnetic Calorimeter", Nucl. Inst. Meth. A 824 (2016), 695.
8. Z.Usubov, "Scintillation light simulation in big-sized BaF_2 and pure CsI crystals" http://arxiv.org/abs/1604.00827
9. N.Atanov et al., "Characterization of a prototype for the electromagnetic calorimeter of the Mu2e experiment" IL NUOVO CIMENTO 39 C (2016) 267
10. N. Atanov et al, "Energy and time resolution of a LYSO matrix prototype for the Mu2e experiment" NIM A824, 11 July 2016, Page 684
11. N. Atanovet al, "Characterization of a 5 × 5 LYSO Matrix Calorimeter Prototype" IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016, p.596
12. M.Angelucci et al., "Longitudinal uniformity, time performances and irradiation test of pure CsI crystals" Nucl.Instrum.Meth. A824 (2016) 678
13. A. Artikov et al. "Optimization of light yield by injecting an optical filler into the co-extruded hole of the plastic scintillation bar." JINST 11 (2016), T05003.
14. A. Simonenko et al., " The increase of the light collection from scintillation strip with hole for WLS fiber using various types of fillers" , submitted to Part. Nucl. Lett. (2016), in Russian, arXiv:1604.02286.

Conference reports

1. **Baranov V.Y., JINR, “Research of properties undoped crystals CsI” Fifth International Conference ISMART 2016 “Engineering of Scintillation Materials and Radiation Technologies” , 26 - 30 September 2016**

2. **Atanov N.V., Ivanov S.V., Jmeric V.N., Nechaev D.V., Tereshchenko V.V. “Solar-blind photodetectors with AlGaN photocathodes for light registration in UVC range” conference NTIHEP-2016, Montenegro, Budva**

3. **Kharzheev Yu.N., “New trends in using Scintillation counters in modern high energy experiments” THE 6th INTERNATIONAL CONFERENCE ON CONTEMPORARY PHYSICS, June 7-10, 2016, Ulaanbaatar Mongolia**

4. **Vasilyev I.I., JINR, « The light yield of a long scintillation strip with WLS fiber embedded into the co-extruded hole » Fifth International Conference ISMART 2016 “Engineering of Scintillation Materials and Radiation Technologies” , 26 - 30 September 2016**

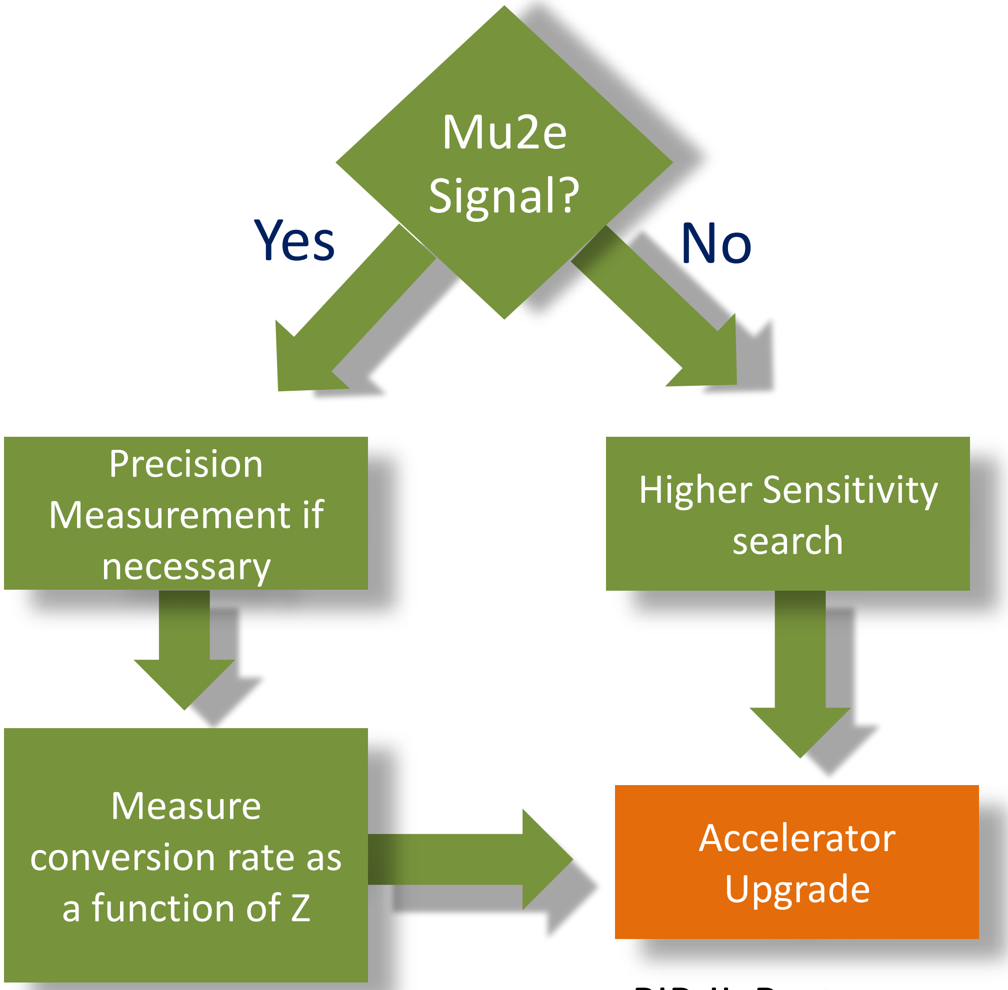
5. **A.Simonenko et al, «INCREASING THE LIGHT YIELD FOR SCINTILLATION STRIPS WITH WLS FIBER EMBEDDED INTO THE CO-EXTRUDED HOLE» New Trends in High Energy Physics, 2016, Montenegro, Budva**

6. **Kharzheev Yu.N., “Scintillation Detectors in modern High Energy Physics Experiments and Prospect of their use in Future Experiments”, International Conference on Astrophysics and Particle Physics, December 8-10, 2016, Dallas, USA**

7. **N. V. Khomutov, “Using the cathode surface of straw tube for measuring the track coordinate along the wire and increasing rate capability”, New Trends in High-Energy Physics. Budva, Becici, Montenegro, 02 October - 08 October, 2016.**

8. **N. P. Kravchuk, “Tracker prototype on a base of cathode straw”, Fifth International Conference ISMART 2016 “Engineering of Scintillation Materials and Radiation Technologies”, September 26-30, 2016, Minsk, Belarus.**

What next?



PIP-II Proton improvement plan

- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator

FTE

#	Name	Lab	Task	FTE(%)
1	Artikov A.M.	DLNP	CRV, calorimeter	80
2	Atanov N.V.	DLNP	calorimeter, CRV	80
3	Atanova O.S.	DLNP	calorimeter	30
4	Baranov V.A.	DLNP	Muon g-2	50
5	Baranov V.Yu.	DLNP	calorimeter, CRV	80
6	Budagov J.A	DLNP	calorimeter, CRV	50
7	Chokheli D.	DLNP	calorimeter, CRV	100
8	Davydov Yu.I.	DLNP	calorimeter, CRV	80
9	Demin D.L.	DLNP	calorimeter	20
10	Duginov V.N	DLNP	calorimeter	30
	Duginov V.N	DLNP	Muon g-2	20
11	Glagolev V.V.	DLNP	calorimeter, CRV	70
12	Gritsaj K.I.	DLNP	Muon g-2	20
13	Kharzheev Yu.N.	DLNP	CRV, calorimeter	100
14	Khomutov N.V.	DLNP	Muon g-2	80
15	Kolomoets V.I.	DLNP	CRV, calorimeter	100
16	Kolomoets S.M.	DLNP	CRV, calorimeter	30
17	Kravchuk N.P.	DLNP	Muon g-2	30
	Kravchuk N.P.	DLNP	Mu2e	20
18	Krylov V.A.	LRB	Muon g-2	50
19	Kuchinsky N.A.	DLNP	Muon g-2	70
20	Mamedov T.N.	DLNP	Muon g-2	30
21	Sazonova A.V.	DLNP	CRV	30
22	Shalyugin A.N.	DLNP	CRV, calorimeter	80
23	Simonenko A.V.	DLNP	CRV, calorimeter	80
24	Suslov I.A.	DLNP	Calorimeter simul.	70
25	Tereschenko V.V.	DLNP	CRV, calorimeter	50
26	Tereschenko S.V.	DLNP	CRV, calorimeter	50
27	Titkova I.V.	DLNP	CRV, calorimeter	10
28	Usubov Z.	DLNP	CRV, calorimeter sim.	100
29	Vasilyev I.I.	DLNP	CRV, calorimeter	80
30	Volnykh V.P.	DLNP	Muon g-2	50
			Mu2e	1420
			Muon g-2	400

plan of expenses for materials and travel

#	Activity	support	Resources (k$)		
			2018	2019	2020
	Muon g-2				
1	DAQ computers	Apple Mac Pro, servers	5	5	5
2	Hardware for DAQ development	Micro TCA crate and units	20	20	20
3	DAQ start up, maintenance, data taking shifts (phys. Runs from 2018)	scientific trips	25	25	25
	Mu2e				
1	Calorimeter in-kind contribution	200 CsI crystals ($34x34x200\ mm^3$)	100	100	100
2	Upgrade DLNP rad sources and cosmic muons test stands	NIM logic units, VME flash ADC, power supplies, coordinate table, SiPM's , preamplifiers, scopes	40	30	20
3	Development of the JINR Linac-800 crystal test stand	coordinate table, power supplies for trigger counters, NIM and VME units	20	10	
4	Crystals beam and QA tests at Frascati, Fermilab and Yerevan, front end electronic development and calorimeter construction, tests, simulation	scientific trips to Frascati, Fermilab, Yerevan	28	28	26
5	R&D on BaF2 photodetectors	AlxGa(1-x)N photocathodes and avalanche photodiode, BaF2 crystal samples	10	10	20
6	Tests of the CRV counters at Fermilab beam	scientific trips to Fermilab	12	12	14
7	Development of the CRV modules assemble procedure and creation of the QA stand for tests of the produced modules	scientific trips to Virginia University	20	20	20
8	Computers and accessories		5	5	5

Form 26

Equipment and systems of the installation, resources, funding sources			Required resources (k$).	Proposed funding and sources distribution schedule 2018	2019	2020
Basic equipment and systems :						
Stand equipment and R@D						
- stand equipment (crates, FADC, VME,NIM modules, scope, etc.)			90	50	30	10
- detectors (SiPM, solar blind ph.d.)			45	15	15	15
- crate, microTCA modules (g-2)			60	20	20	20
- computers and accessories			30	10	10	10
Materials :						
- sc. crystals CsI pure			300	100	100	100
- sc. Crystals BaF_2			20	5	5	10
Required resources	man-hour	JINR LINAC-800	550 h	200 h	200 h	150 h
		Designer group	300 MH	100 MH	100 MH	100 MH
		JINR workshop	300 MH	100 MH	100 MH	100 MH
	k$	Participation at the setup tests and creation	255	85	85	85
Sources of funding :						
budget:						
Expenses from budget including foreign currency			695	250	230	215
additional:						
contribution of collaborators, grants			75	25	25	25
grant of Belarus			30	10	10	10

Form 29 PROJECT direct expenses:

#	Item	full cost	2018	2019	2020
1	Computer communication	-	-	-	-
2	Design works	300 MH	100 MH	100 MH	100 MH
3	Workshop	300 MH	100 MH	100 MH	100 MH
4	Materials	320 K$	105 k$	105 K$	110 K$
5	Equipment	195 K$	85 k$	65 K$	45 K$
6	Travel Expenses	180 K$	60 K$	60 K$	60 K$
	Total:	695 K$	250 K$	230 K$	215 K$

Summary

Precise muon experiments :

- Improve sensitivity by a factor of 10^4 (Mu2e)
- Provide *discovery capability* over wide range of New Physics models
- Are complementary to LHC, heavy-flavor, and neutrino experiments

Backup slides

Problems of the Standard Model

Dark Matter: There is a particle that exists and is floating around making up 80% of the mass of our Universe and galaxy.

Baryon Asymmetry: We don't understand why there is more matter than anti-matter in the Universe. We know that the Standard Model inside Inflationary Big Bang Cosmology doesn't produce anywhere near enough of an excess.

Strong CP problem According to quantum chromodynamics there could be a violation of CP symmetry in the strong interactions. However, there is no experimentally known violation of the CP-symmetry in strong interactions.

Inflation: There needs to be an inflationary field that reheats the Standard Model.

Origin of Masses: The problem is complicated because mass is strongly connected to gravitational interaction, and no theory of gravitational interaction reconciles with the SM.

Neutrino oscillation : observation of the phenomenon implies that the neutrino has a non-zero mass, which was not included as part of the original SM.

47

BNL, FNAL, and J-PARC

- complimentary

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.11 ppm

Sensitivity to High Mass Scales

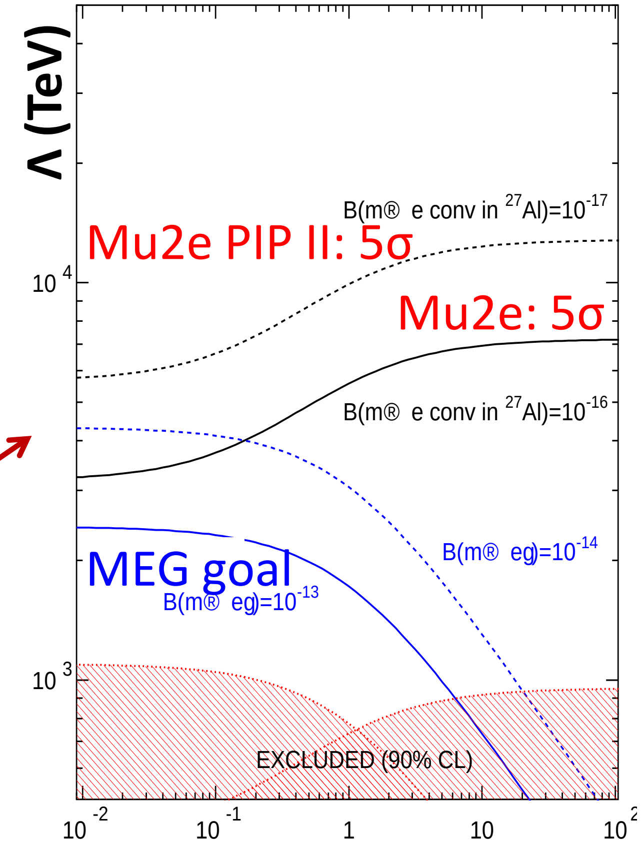
High energy experiments

Table 16: The 95% C.L. lower limits that can be obtained in ATLAS on the compositeness scale Λ by using di-jet angular distributions and for various energy/luminosity scenarios.

Scenario	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 300 fb^{-1}	28 TeV 3000 fb^{-1}
Λ(TeV)	40	60	60	85

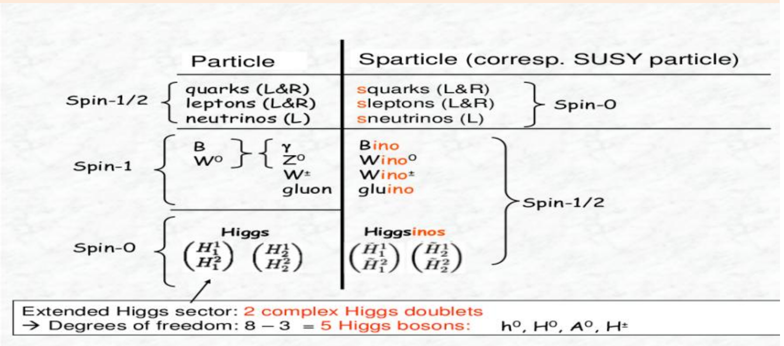
Of course, the high-energy frontier is not the only option to look for BSM physics. Rather than manifesting itself through new particles as external states, BSM can modify processes with only SM external particles through virtual effects.

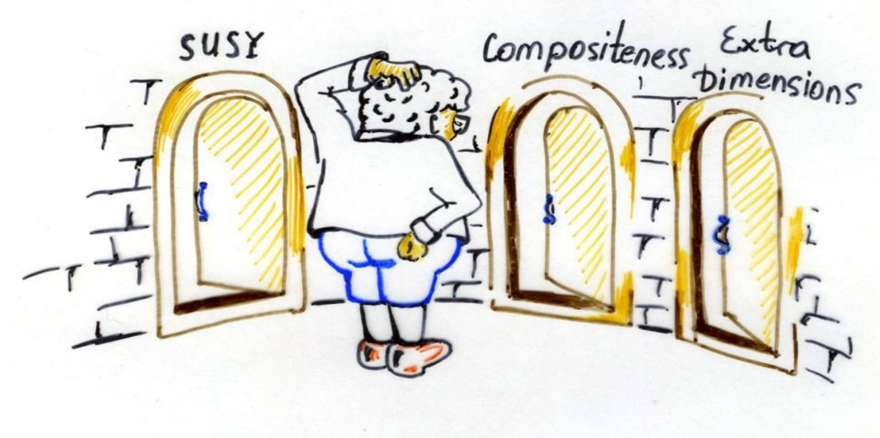
Precision muon experiments



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

BSM models





1. **Supersymmetry.** It is one of the best motivated extension of the SM. The theory proposes a new symmetry between bosons (integer spin) and fermions (half integer spin).

2. **Grand Unified Theories.** Attempt at unifying the electroweak and strong interactions at high energy. They are based on larger symmetry groups, like SU(5), SO(10), E6. The full symmetry is restored at very high energies. Typical scales of 10^{16} GeV emerge from the different running (meeting point) of the strong, weak and electromagnetic couplings.

3. **Additional spatial dimension(s).** An option to attack the hierarchy problem, i.e. the huge difference in scale between the gravitational interaction ($M_{Pl}=1.2\times10^{19}$ GeV) and the other fundamental interactions ($M_{ewk}\approx100$ GeV), relies on modifying the space-time structure of our universe.

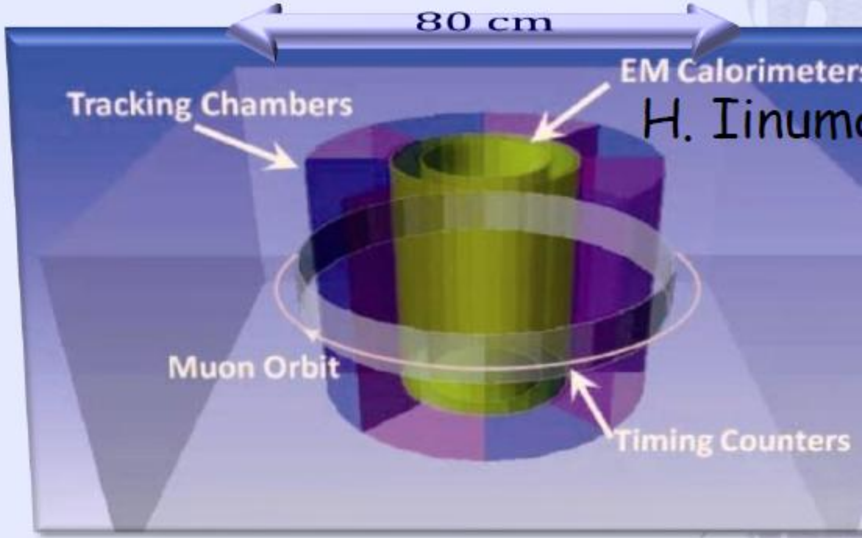
4. **Dynamical symmetry breaking. (technicolor, compositeness, Little Higgs…)** Another class of theories introduce a new strong interaction that breaks the gauge symmetry of the SM. The scalar particles are bound states of fermions charged under the strong interaction, similar to pions in QCD.

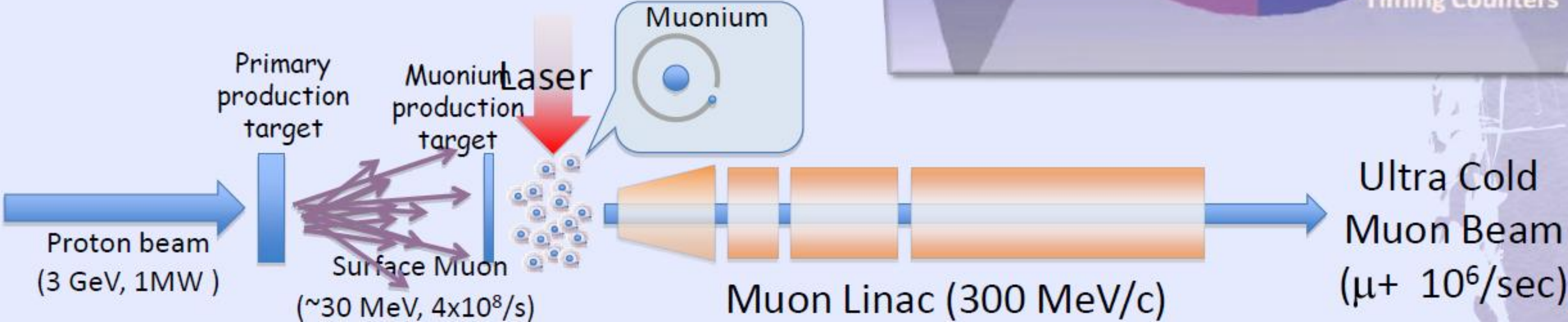
Search for flavor violation in processes with charged leptons

Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}_{\mu e}^{\mathrm{Au}} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

New Generation of Muon g-2@J-PARC

- New generation of muon g-2 experiment is being explored at J-PARC
  - To establish the deviation by improving the statistics and systematics
  - To further explore new physics
- With completely new technique
  - Off magic momentum with ultra-cold muon beam at 300 MeV/c
  - Stored in ultra-precision B field without E-field so that the β x E term drops





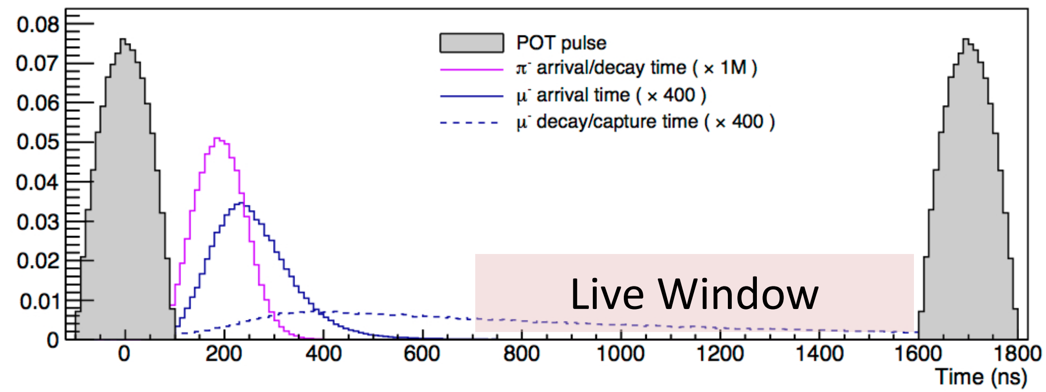
Backgrounds

- Stopped Muon induced
  - Muon decay in orbit (DIO)
- Out of time protons or long transit-time secondaries
  - Radiative pion capture; Muon decay in flight
  - Pion decay in flight; Beam electrons
  - Anti-protons
- Secondaries from cosmic rays

- Mitigation:
  - Excellent momentum resolution
  - Excellent extinction plus delayed measurement window
  - Thin window at center of TS absorbs anti-protons
  - Shielding and veto

Prompt Background Suppression

- Prompt background
  - Happens around the time, when the beam arrives at the target.
  - Sources
    - beam electrons,
    - muon decay in flight,
    - pion decay in flight,
    - radiative pion capture
  - May creaste electrons with energies in the signal region



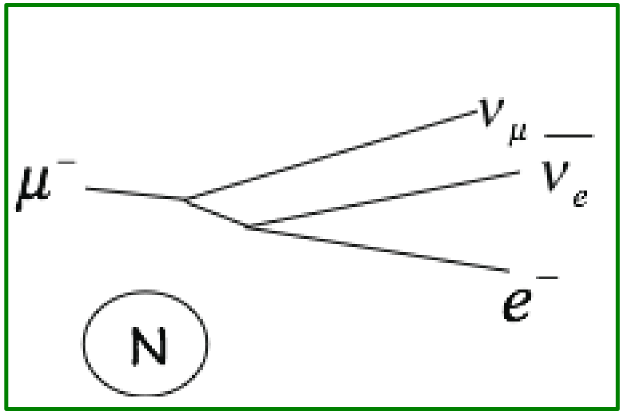
- Prompt background can be suppressed by not taking data during the first 670 ns after the peak of the proton pulse.

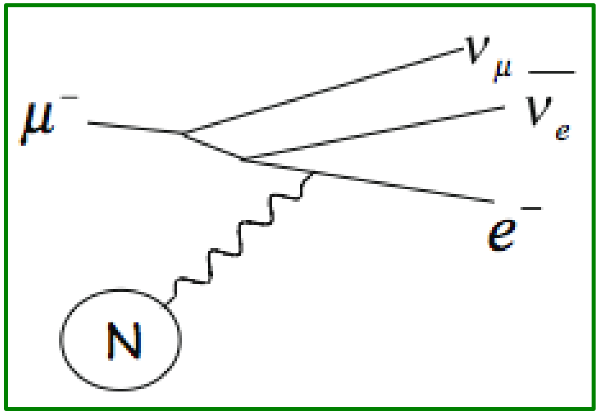
The lifetime of a muon in an Al orbit is 864 ns

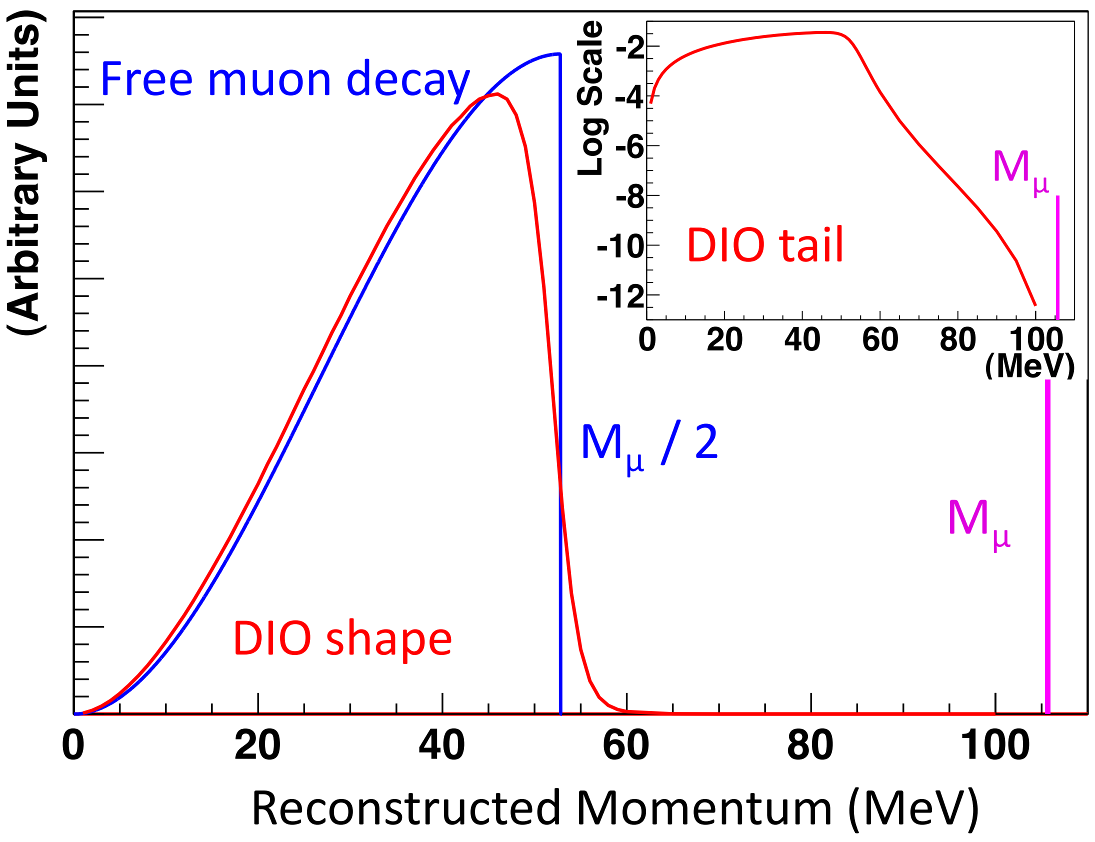
- However, this prompt background cannot be eliminated entirely, since some of the protons arrive "out of time".
  - A ratio of 10^{-10} is required for the beam between pulses vs. the beam contained in a pulse.

Decay–in-Orbit: Dominant Background

DIO: Decay in orbit







Backgrounds for 3 Year Run

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	0.000
Late Arriving*	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (m-DIF)	<0.003
	Pion decay-in-flight (p-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.082 ± 0.018
	Total	0.36 ± 0.10

All values preliminary

- * scales with extinction: values in table assume extinction = 10^{-10}

Straw Tracker

18 stations over 3.2 meters, Rout = 70 cm ; station consists of two planes; 6 panels in the plane

- a panel: 2x48 straws
- D=5 mm, L= 33-117cm
- Walls: 12μm mylar + 3μm epoxy + 200 Å Au + 500 Å Al
- sense wires: 25μm W Au-plated
- gas: 80/20 Ar/CO2 at $\sim$ 1500 V
- support, electronics - outer part

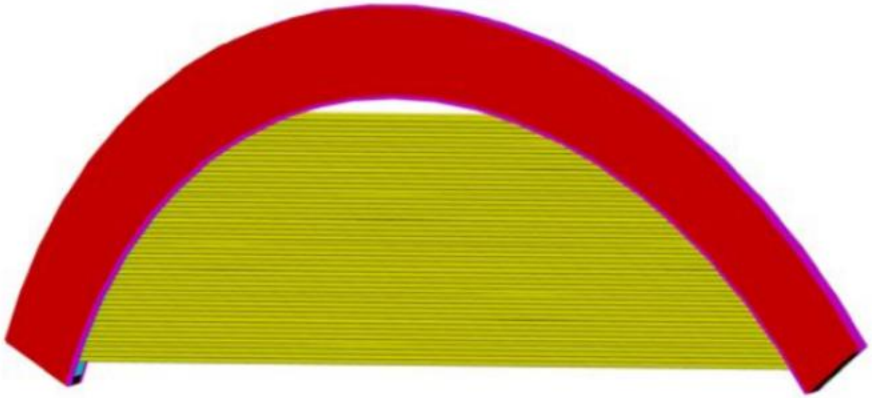
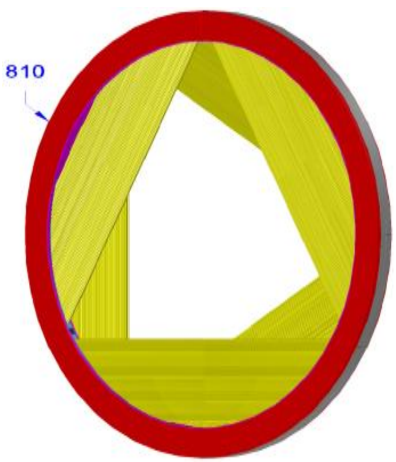
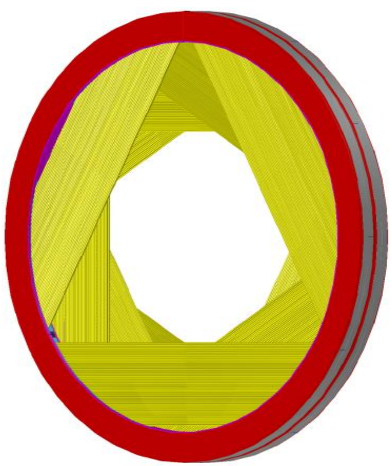


Figure 8.6. Completed panel, with covers shown in red. Screws to attach covers not shown.



plane



station

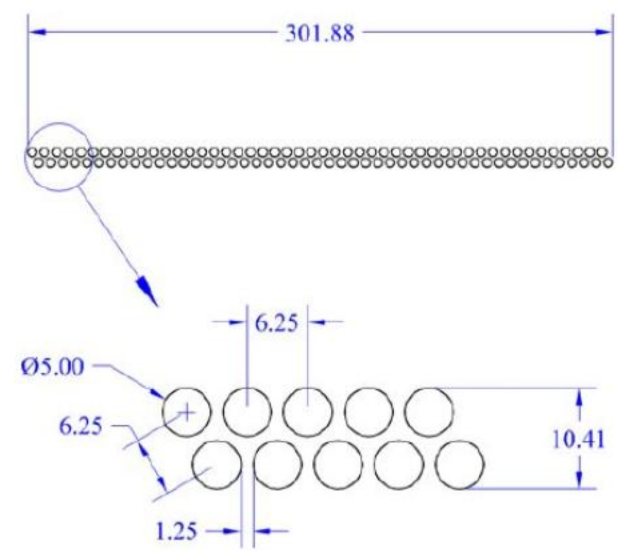
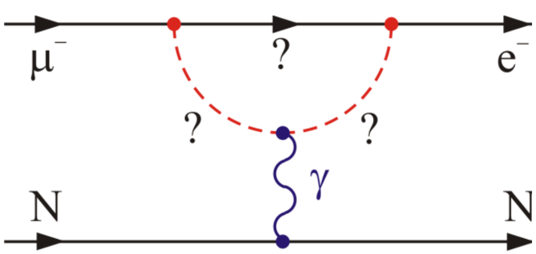


Figure 8.7. Edge view of a panel showing the arrangement of straws within a panel. Dimensions are in millimeters.

Precision muon experiments :
Sensitivity to High Mass Scales

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

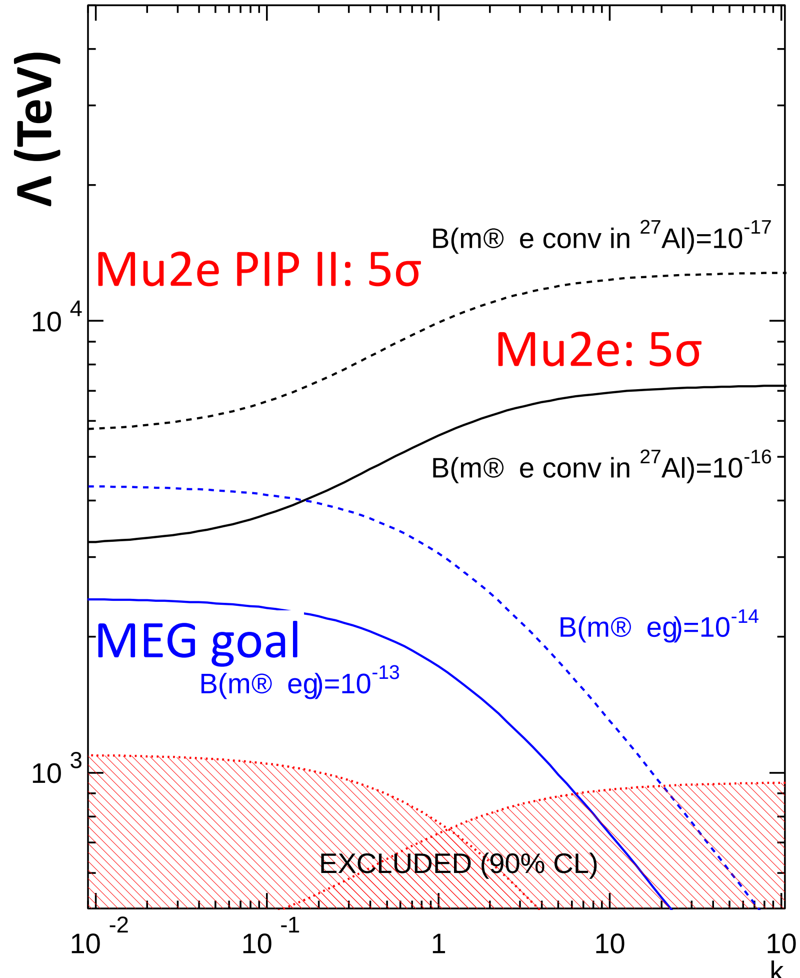
Loops dominate for κ << 1



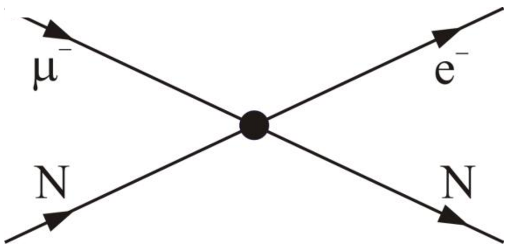
μ→eγ

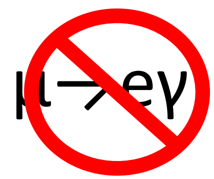
μN→eN

μ→eee



Contact terms dominate for κ >> 1





μN→eN

μ→eee

JINR contribution

Test of CsI crystal matrix at Frascati electron accelerator

JINR colleagues participated in the beam test of CsI matrix which was done during April 2015 at the Beam Test Facility in Frascati (Italy) . Time and energy measurements have been performed using a low energy electron beam, in the energy range [70,120] MeV.

The calorimeter prototype consisted of nine 3 x 3 x 20 cm^3 undoped CsI crystals wrapped into 150 μm of Tyvek®, and arranged into a 3x3 matrix. Out of the nine crystals, two were produced by Filar OptoMaterials, while the remaining 7 came from ISMA (Kharkov).

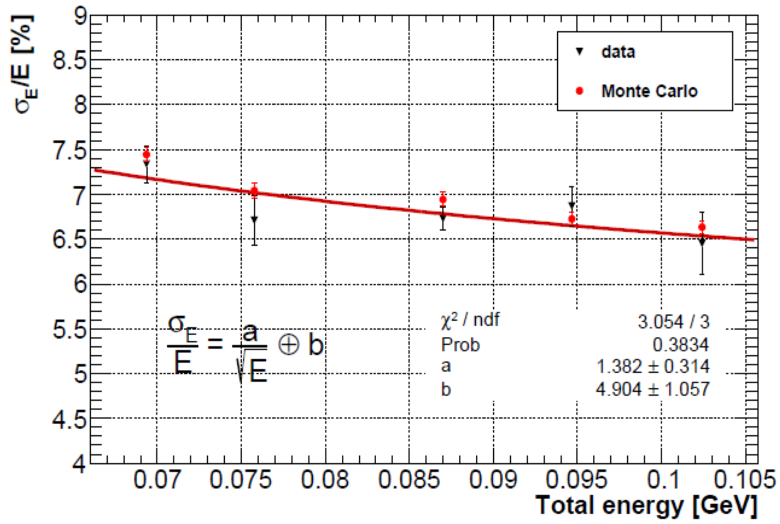
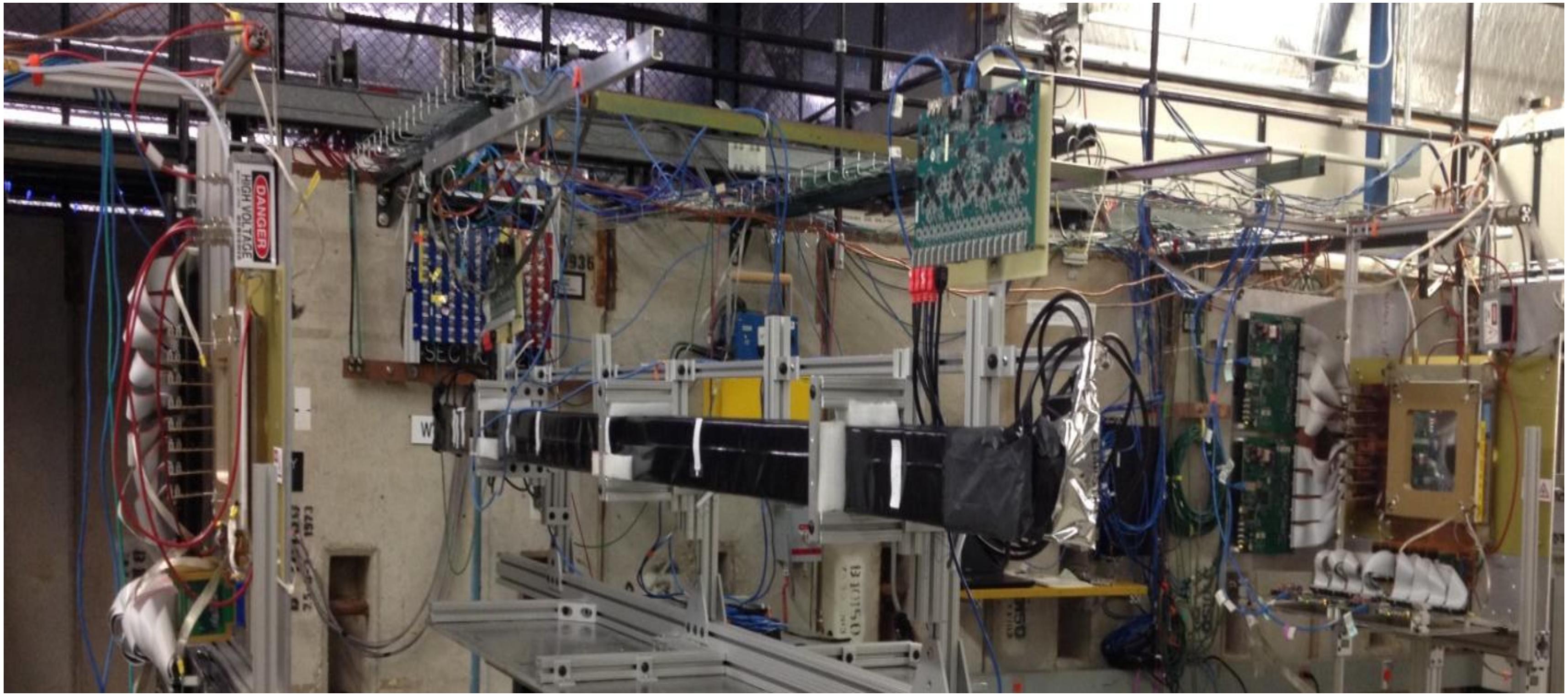


Figure : Energy resolution obtained from the data (black) compared with the Monte Carlo (red).

The time resolution for 100 MeV electrons is бt ~ 200 ps.

JINR contribution

Test beam of the CRV counter prototypes



Tests of the CRV counter prototypes were performed at Fermilab 120 GeV proton beam.

According to the performed tests for the CRV modules were choosen :

- 2 mm X 2 mm SiPM Hamamatsu (small cross-current, low-noise);
- 1.4 mm fiber;

The paper is under preparation.

JINR plans (according to Statement of work for participation in the Mu2e Experiment at Fermilab)

VII.2.1 QA for crystals:
The JINR will test the crystals supplied by JINR as specified by the L2 manager of the calorimeter sub-system. This may involve using an electron accelerator beam from JINR or INFN, and/or radioactive sources, and/or cosmic rays collected via a test stand setup as will be determined by the preparation of experiment. JINR will determine the optical parameters of the crystals as well.
VII.2.2 Calorimeter FEE
JINR will be available to participate in the design and testing of the calorimeter Front-end Electronics (FEE) boards and waveform digitizers.
VII.2.3 Calorimeter commissioning
This activity, scheduled in 2020, will be described in a future addendum to this SOW.
VII.2.4 CRV module production
JINR will contribute to the development of a method for mass production of the CRV modules.
VII.2.5 Radiation tests of optical silicone
JINR will perform radiation hardness tests of the optical silicon and prototypes of CRV counters at the JINR neutron reactor.

JINR plans (according to Statement of work for participation in the Mu2e Experiment at Fermilab)

VII.2.6 Quality Assurance test stand for CRV modules
JINR will create the test stand for the Quality Assurance (QA) testing of assembled CRV modules.
VII.2.7 Filling fiber holes in long CRV modules
If the Mu2e project chooses to pursue the option of using optical silicone to increase light yield, JINR will fill the fiber holes of the 9 CRV extra-long (6.6.m) modules.
VII.2.8 CRV test beams
JINR will participate in test beams for CRV prototypes and modules.
VII.2.9 CRV commissioning
This activity, scheduled in 2020, will be described in a future addendum to this SOW.
VII.2.10 Simulations
JINR will participate in the Mu2e calorimeter and CRV simulation focusing on the developed of a calibration method for the calorimeter using electrons from muon decays-in-orbit.
VII.2.11 Photosensor R&D
JINR will participate in the R&D with solar blind Aluminium gallium nitride (AlGaN) photodetectors for BaF2 crystal calorimeter for Mu2e-II.