NEWS

NEw WindowS on the universe and technological advancements
from trilateral EU-US-Japan collaboration

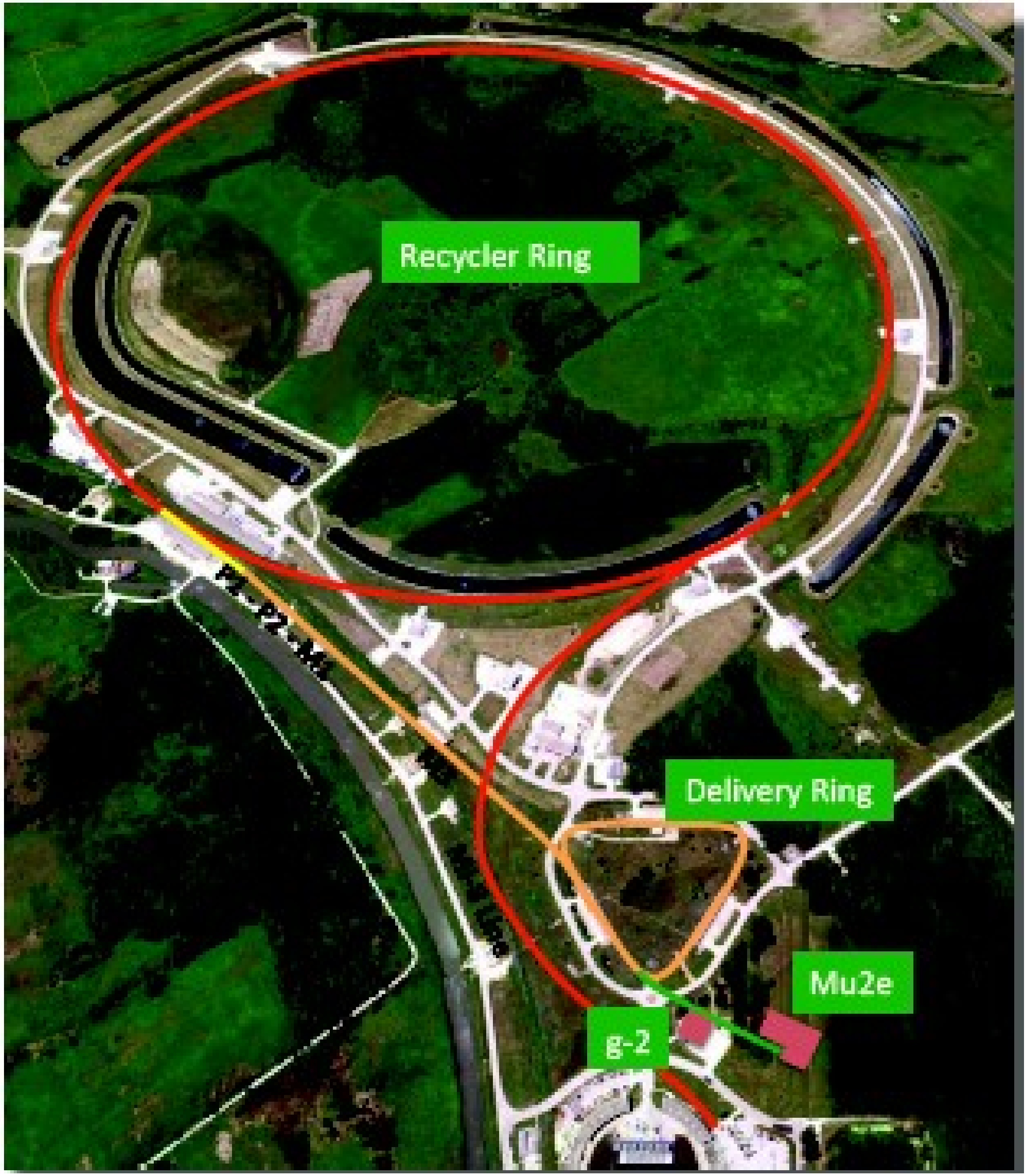
WP6: FNAL Muon Campus Experiments

Stefano Di Falco

MidTerm Review, Pisa, March 4-5, 2019

European Commission

Work Package objectives



The Muon campus at the Fermi National Accelerator Laboratory (aka FNAL or **Fermilab**) near Chicago (US) uses a 400 GeV proton beam to produce muons.

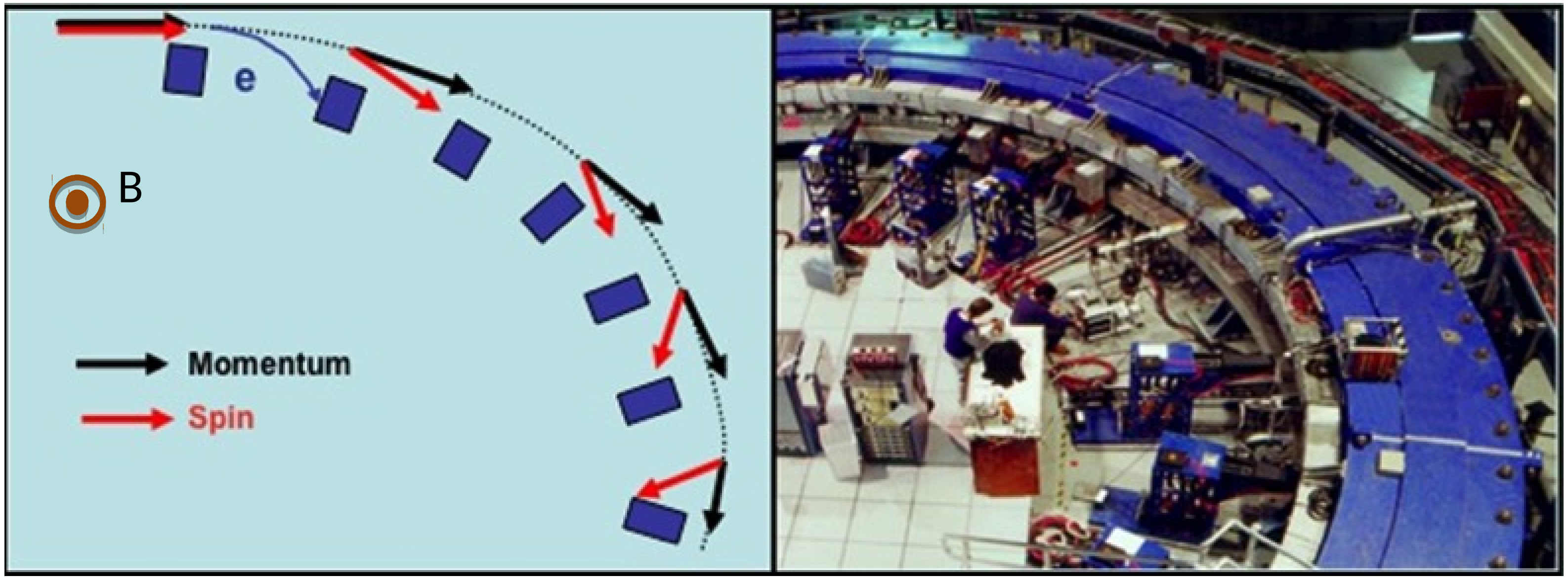
It hosts two experiments:
g-2, currently running, and **Mu2e**, that should start taking data in 2023, that aim to probe the limits of the Standard Model of Particle Interactions.

Task 6.1: g-2 calorimeters calibration

The g-2 experiment

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$

Muon magnetic moment

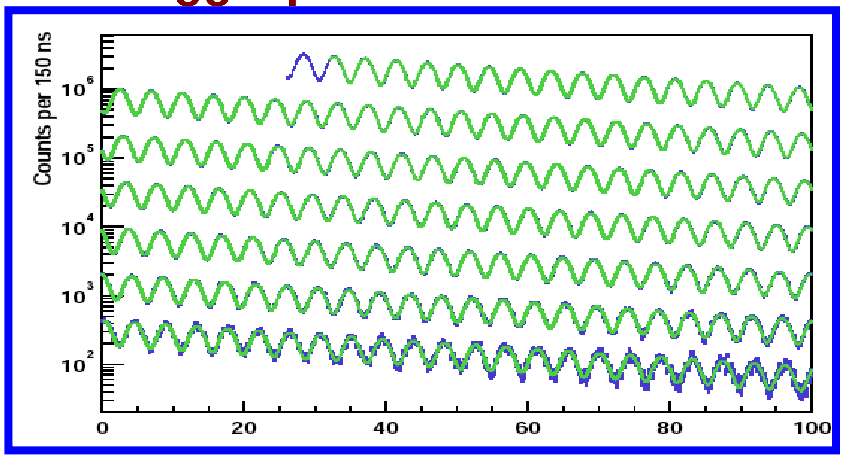


a_μ = **g-2 Muon anomaly**

currently 3.5σ dicrepancy between theory and experiment

$$\omega_a = \omega_S - \omega_c = \frac{eB}{m}a_\mu$$

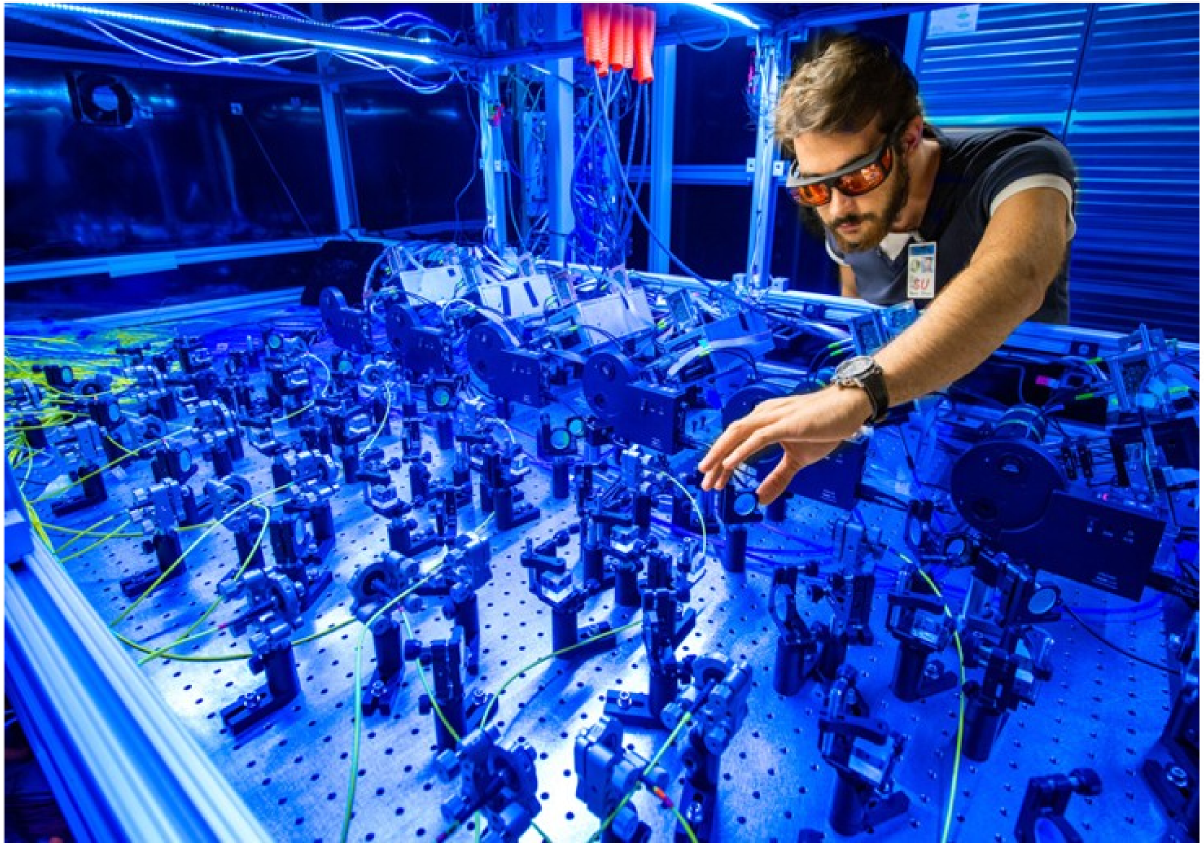
The Wiggle plot

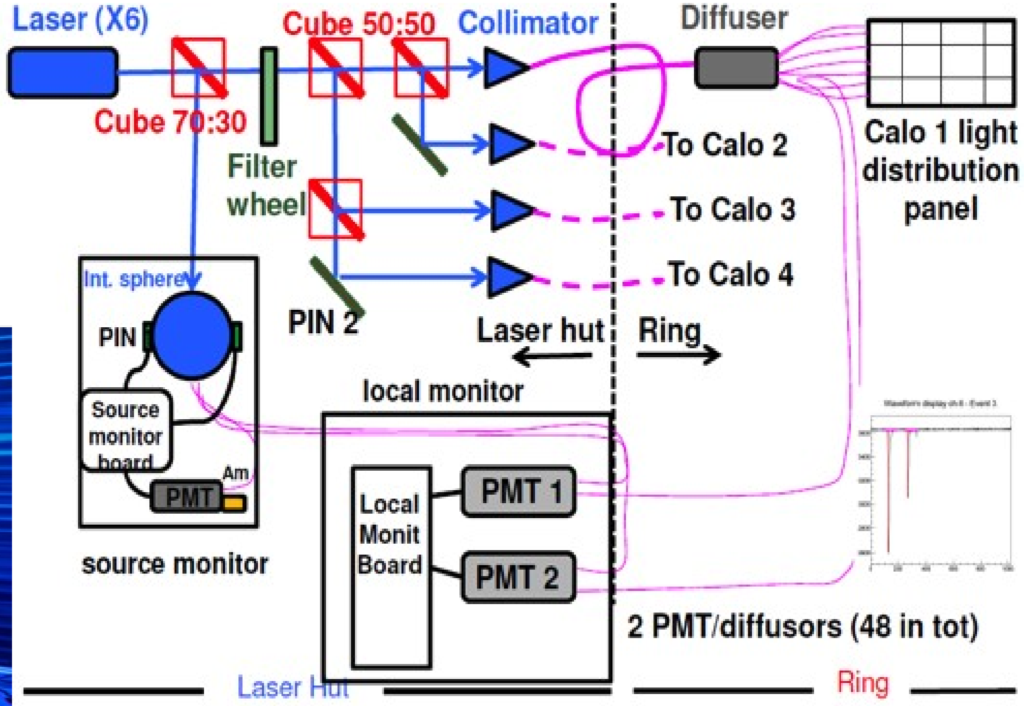


Number of muons decays detected by calorimeters

Task 6.1: g-2 calorimeters calibration

g-2 laser system





g-2 laser hut

6 lasers to calibrate 24 calorimeters and study the **gain variation** of each SiPM to reduce the corresponding **systematic error** on ω_a to **20 ppb!!**

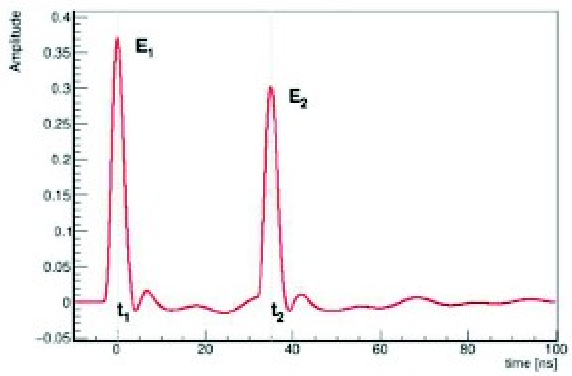
Laser signals are monitored locally and with a feedback fiber from each calorimeter

Task 6.1: g-2 calorimeters calibration

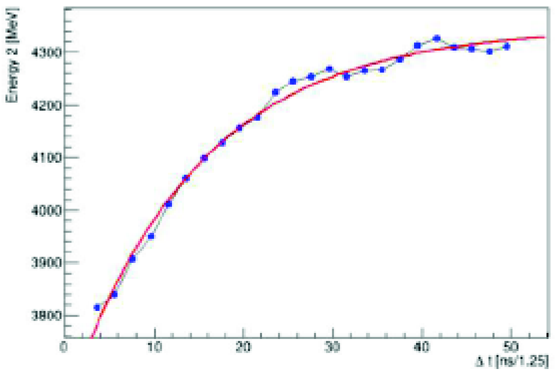
Gain corrections

Time scale	Method	Notes
> 10 sec	Out of Fill pulses	mostly temperature
< 700 μsec	In Fill pulses	mostly splash
~ 20 μsec	Long Term Double Pulse	check of In Fill Gain
~ 20 nsec	Short Term Double Pulse	SiPM recovery

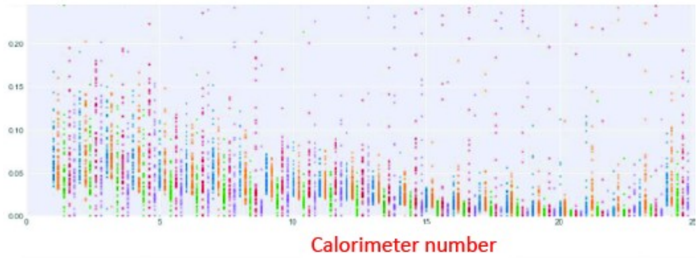
All this correction have been interfaced with the experiment software and are actively used to obtain high quality calibrated data



Double pulse tecnique

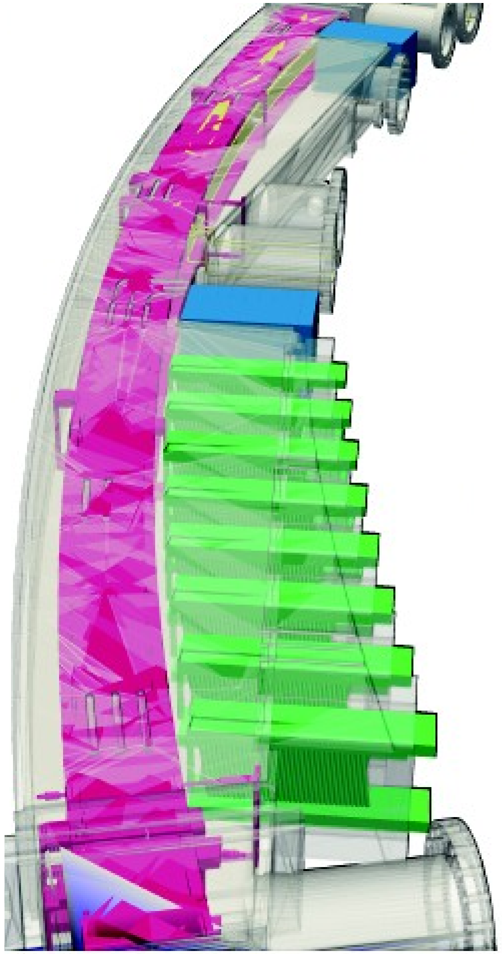


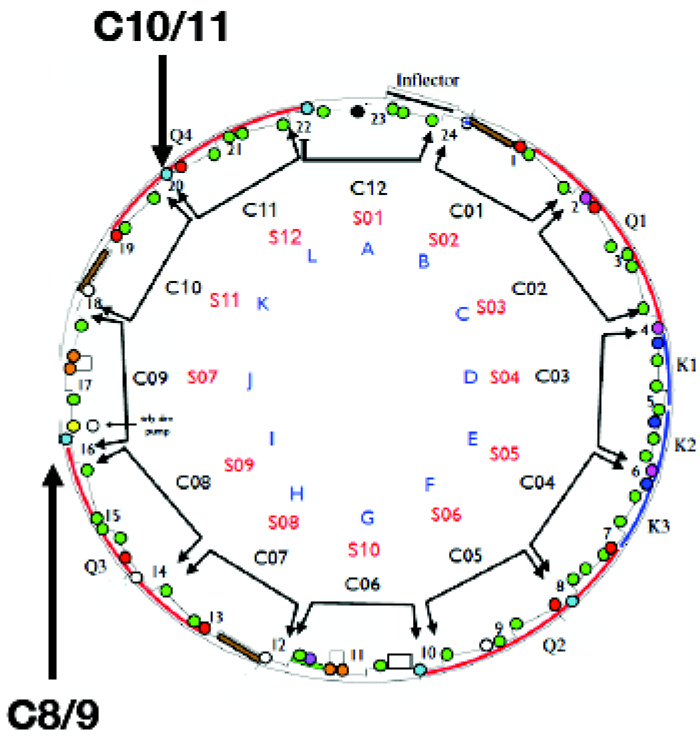
Example of short term Double pulse correction



Example of calibration parameters

Task 6.2: g-2 simulation

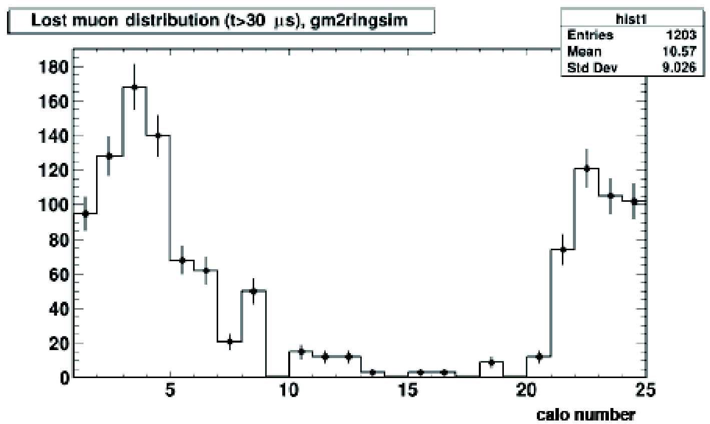




Our team has already achieved an important role in simulated data production and will be more and more involved in the next months

gm2ringsim package (based on Geant4) provides detailed descriptions of g-2 ring volumes and materials and of the magnetic fields (configurable with a set of parameters.

Simulation is important to understand features observed in the data



Example: muons lost because of beam interactions with collimators

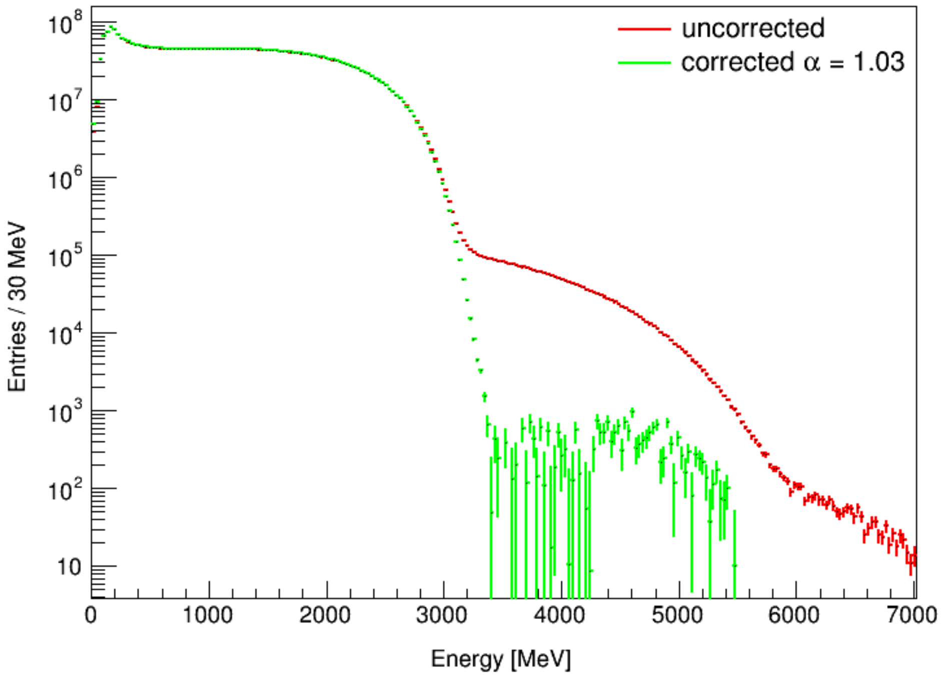
Task 6.3: g-2 ω_a blind analysis

Our group has participated, with an indepedent analysis, to a very important **analysis test** on a sample of 60 hours of data acquired in April 2018.

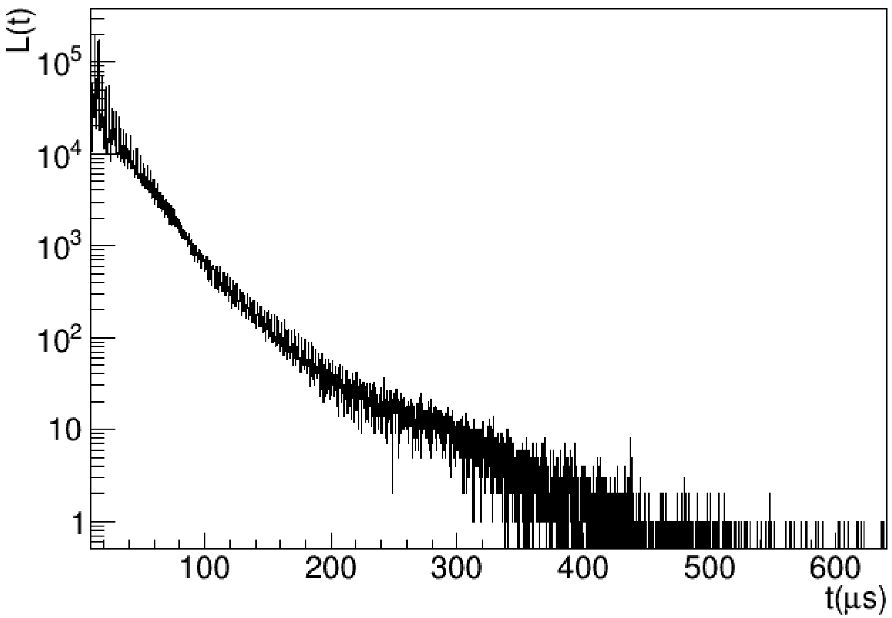
The analysis was differently blinded for every group. The **relative unblinding**, performed last week, has shown that our result is in **agreement** with the ones of the other groups, confirming the high quality of the job that has been much appreciated by our internal referees. All the analysis steps have been described in detail in **internal notes**.

The analysis contains the following steps:
- Good data quality runs selection
- Waveform fit, clustering and time alignment
- Laser gain corrections
- Pileup subtraction
- Fit including Beam Oscillations, Lost Muon subtraction
- Asymmetry-weighted fit (to enhance sensitivity)

Task 6.3: g-2 ω_a blind analysis

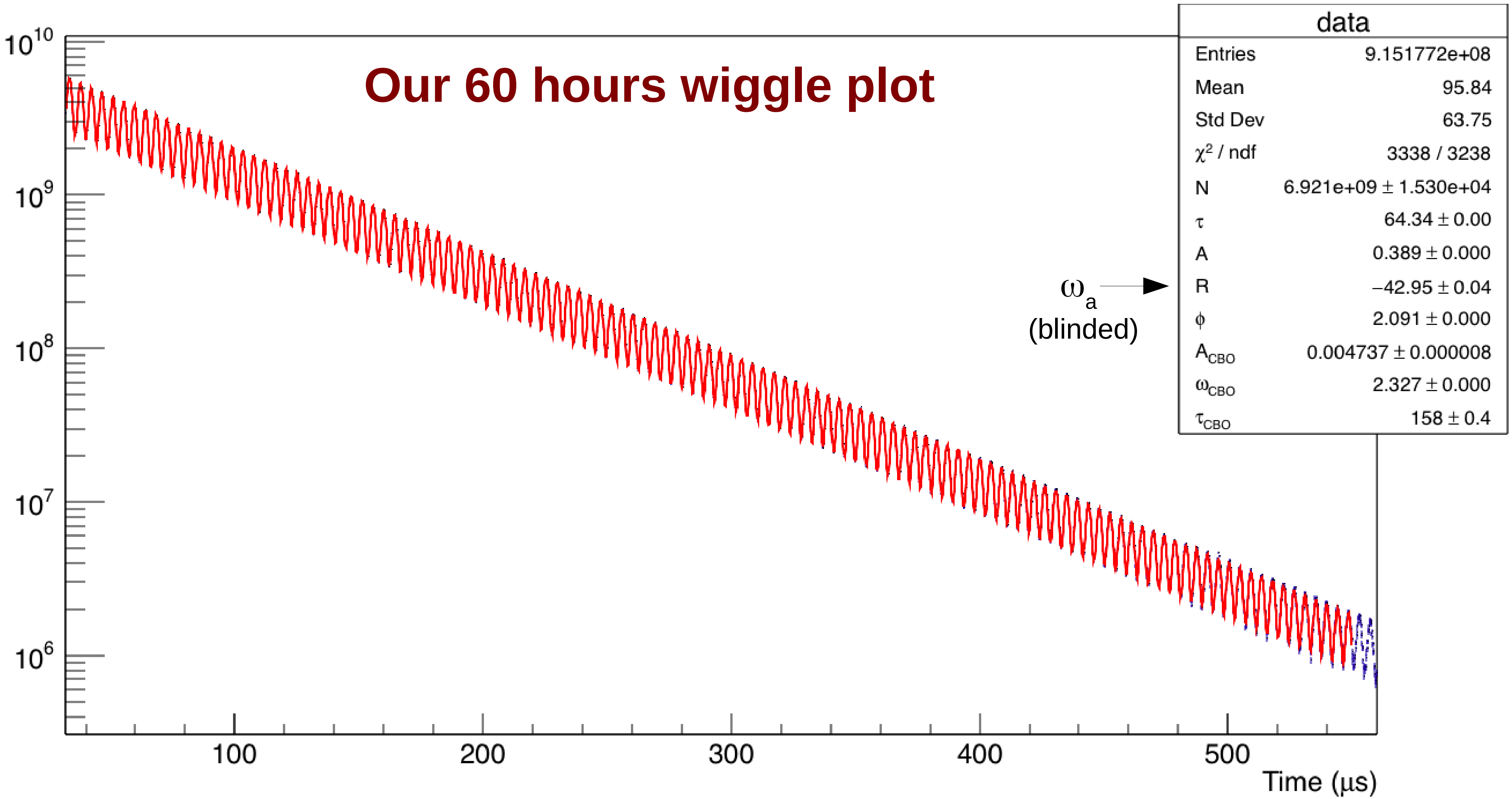


Pileup correction: separate energy deposits due to the overlap of different signals



Number of **lost muons** to be subtracted from the wiggle plot

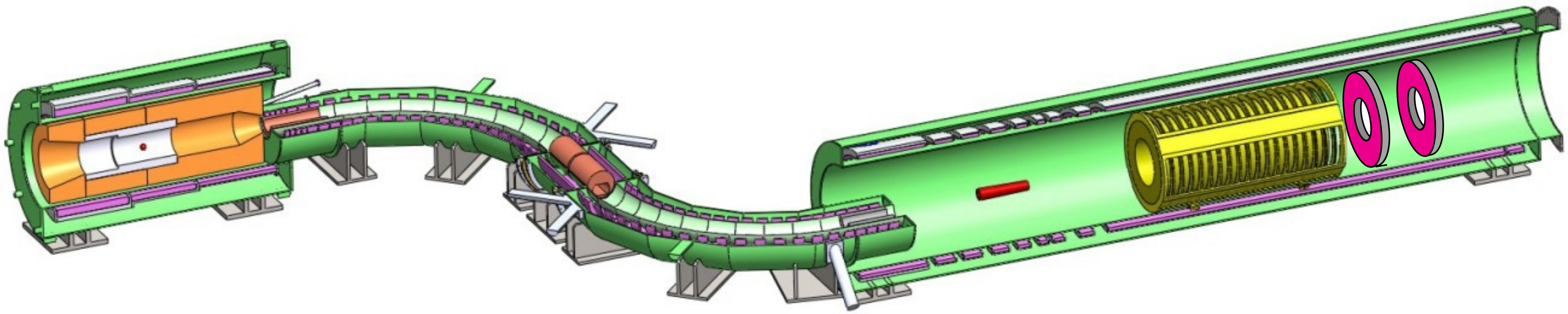
Task 6.3: g-2 ω_a blind analysis



The unblinding of the analyses of the full 2018 **g-2** dataset (**RUN 1**) will be done during the **Elba Physics week** that will be held between since **may 27** to **june 1, 2019**

Task 6.4: neutron shielding in Mu2e

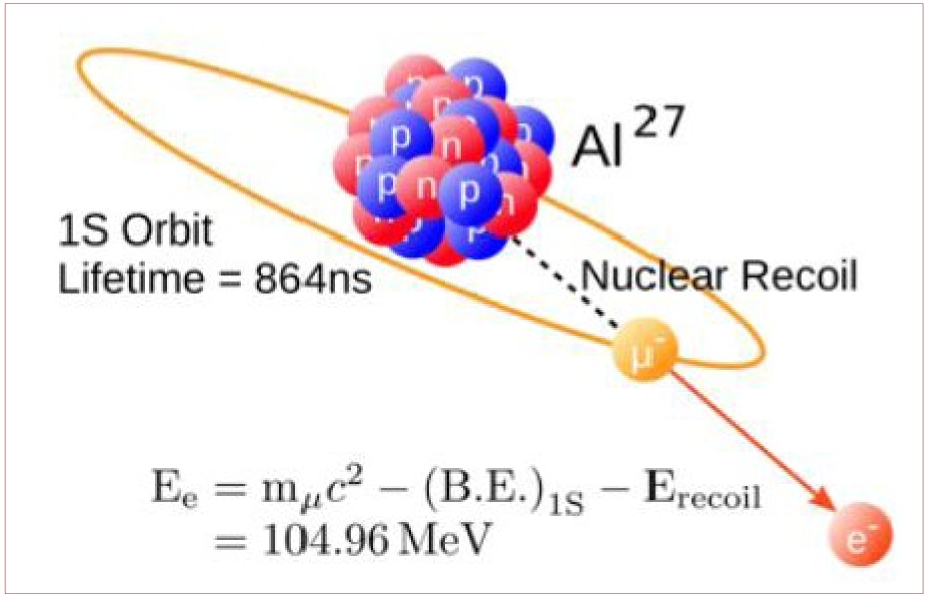
The Mu2e experiment



Search for a **muon conversion to electron** in the field of an Aluminum atom

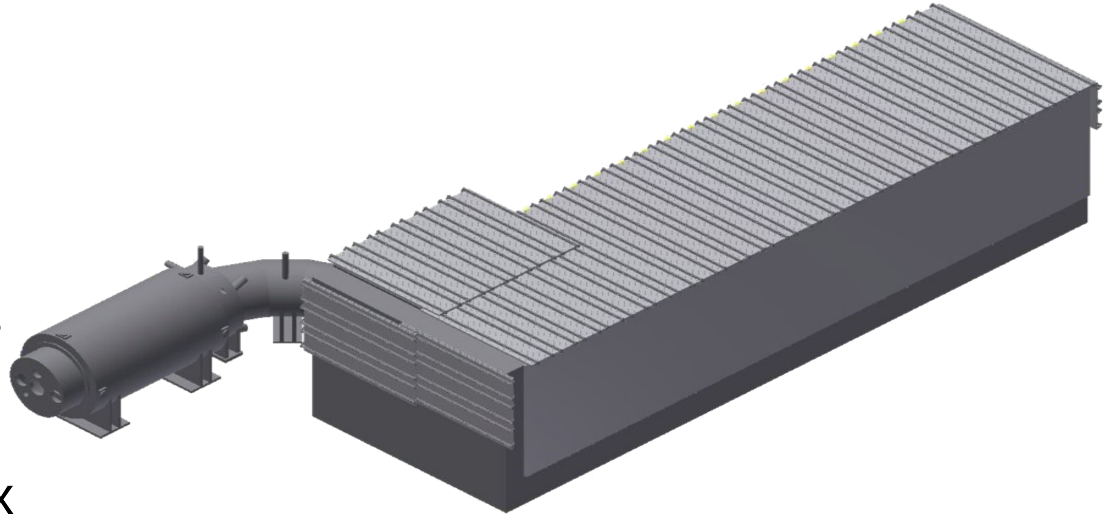
Aims to discover **Charged Lepton Flavour Violation** at a level not expected by the Standard Model of particle interactions

Will **improve** by a factor **10^4** the existing limit



Task 6.4: neutron shielding in Mu2e

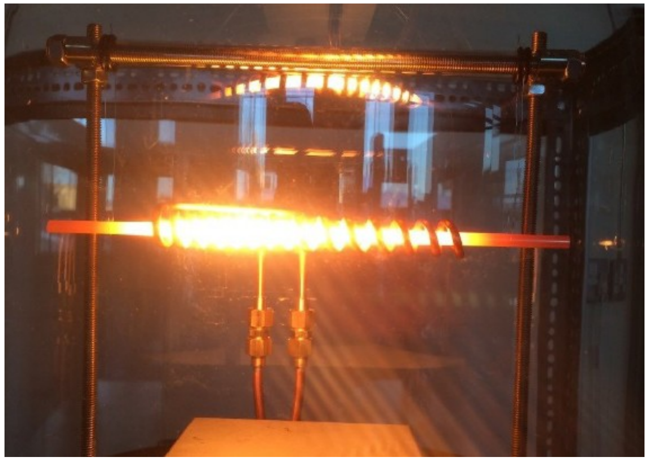
Mu2e cosmic ray veto



It's necessary to recognize cosmic muons emulating the conversion signal.

Can be blinded by the intense neutron flux coming from the **production target**

Requires to be efficiently **shielded**



Mu2e production target
(temperature test)

Shelding blocks

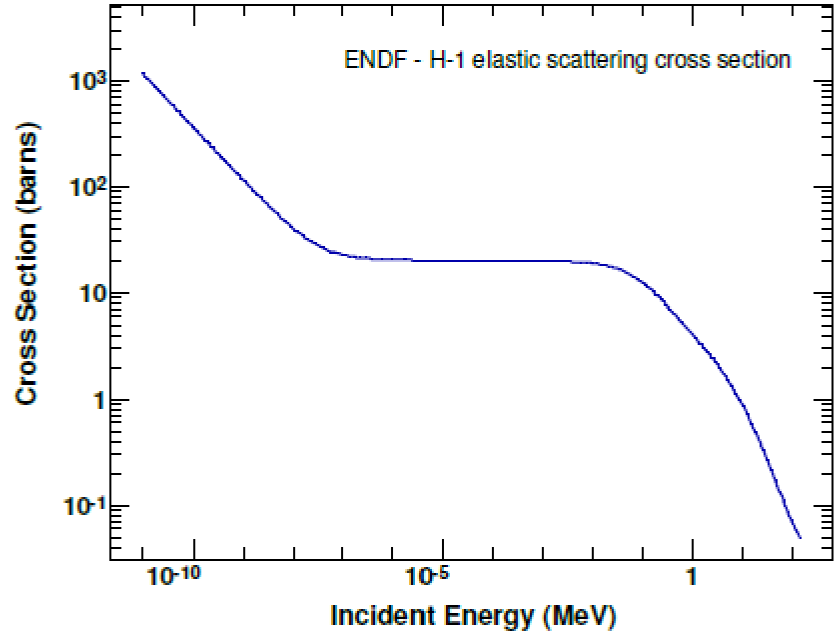
Task 6.4: neutron shielding in Mu2e

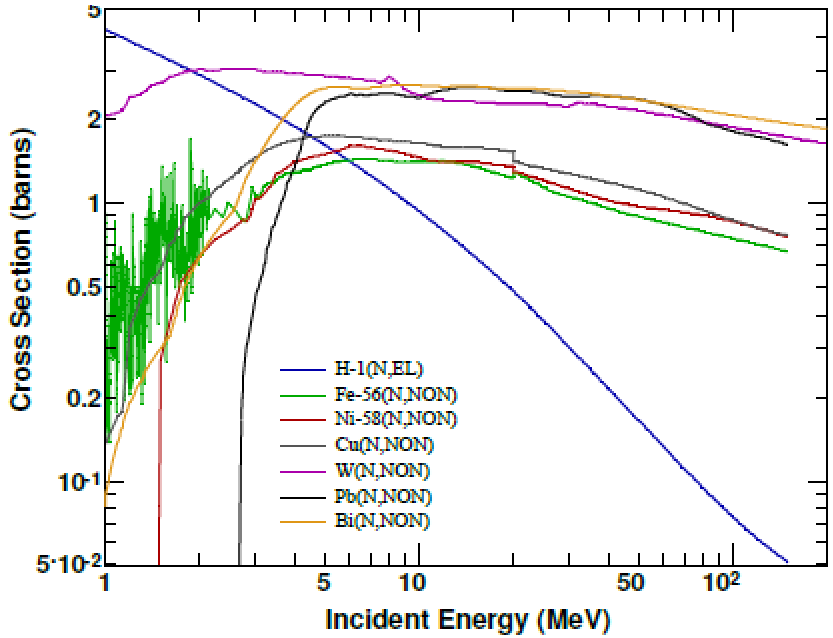
At high energy **neutron capture** is limited, thus a neutron shield has to:
- efficiently **degrade** the neutron **energy** low enough to be absorbed
- **stop** the **gammas** eventually produced by the absorption reactions

An efficient **neutron slowing down** is obtained through **elastic scatterings** with **low-mass** elements (e.g. hydrogen)

A suitable **photon shielding** is given by elements with **high density** and **high Z**

At energys >10 MeV, the non elastic cross section of Cu, Fe, Ni, W, Bi and Pb (providing also γ shielding) is larger than H elastic scattering cross section: **non elastic reactions** are more convenient



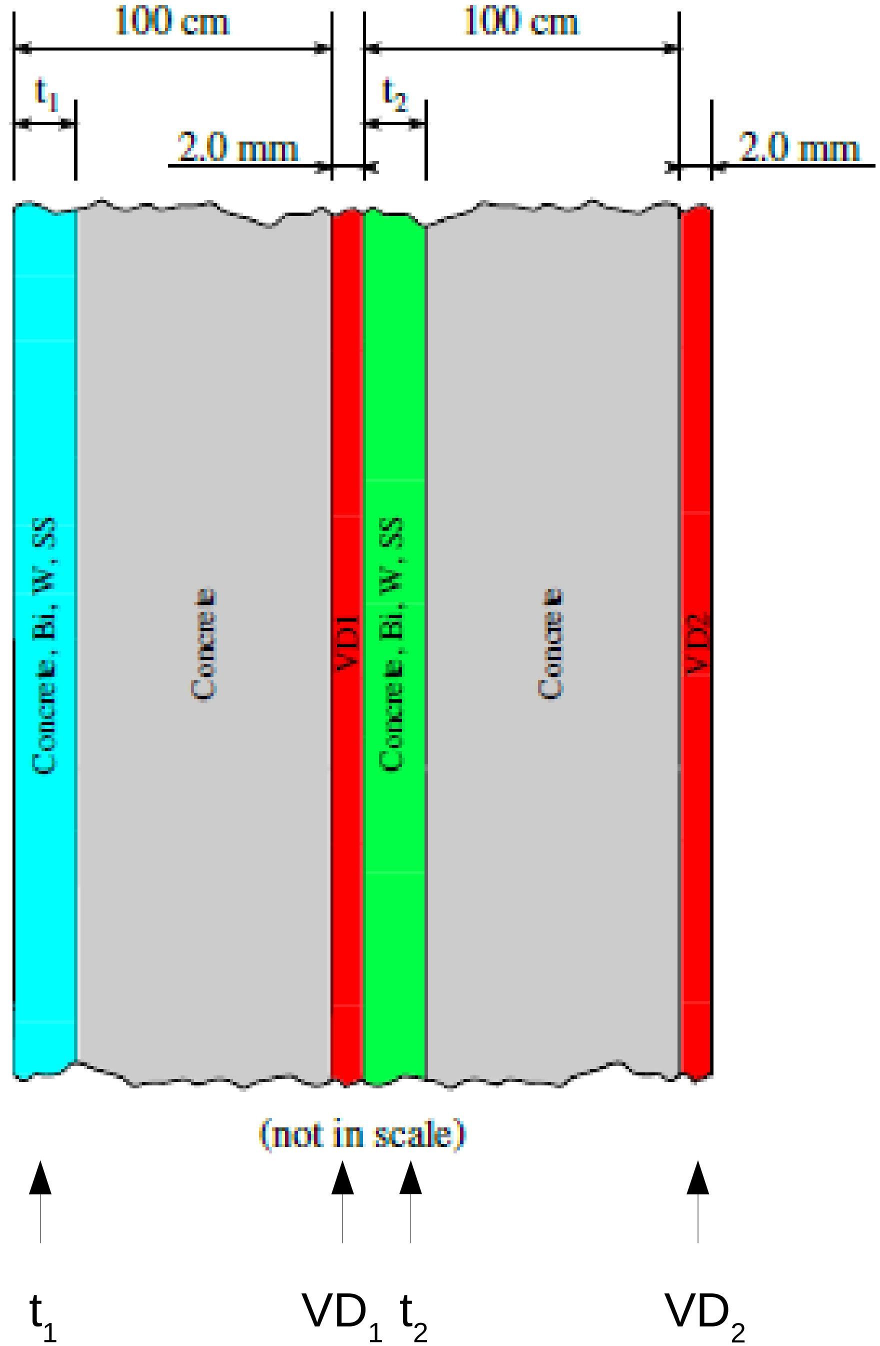


Task 6.4: neutron shielding in Mu2e

Simulations with **neutrons** of 10 or 100 MeV striking normally on a **two slab shield** have been performed. Neutrons and photons entering two virtual detectors (VD_1 and VD_2 in red), 2 mm thick, were counted.

To improve the performance, the front layers, t_1 (cyan) and t_2 (green), have been replaced by Bi, W or AISI-316 Stainless Steel (SS).

In some case, to efficiently remove the thermal neutrons a 0.32 cm thick sheet of Flex-Boron has been added after each slab in front of the virtual detector.



Task 6.4: neutron shielding in Mu2e

Material & thickness	t_1	t_2	Neutron energy: 100 MeV VD1 counts	VD2 counts
Regular concrete	0.0cm	0.0cm	4.493E-01 0.0%	2.326E-02 0.1%
			Δ	Δ
Borated concrete	0.0cm	0.0cm	-34.7%	-13.3%
Baryte concrete	0.0cm	0.0cm	-27.0%	-63.2%
Regular concrete	20.0cm, SS +FlexBoron	20.0cm, SS +FlexBoron	-54.3%	-84.3%
Borated concrete	20.0cm, SS	20.0cm, SS	-50.3%	-84.1%
Borated concrete	5cm W/15cm SS	5cm W/15cm SS	-47.2%	-88.9%
Baryte concrete	20.0cm, SS +FlexBoron	20.0cm, SS +FlexBoron	-67.1%	-92.8%
Baryte concrete	20.0cm, W +FlexBoron	20.0cm, W +FlexBoron	-80.3%	-98.6%

Tungsten (W) is very efficient to shield high energy neutrons.
However, it’s very **expensive** (a 93% W alloy is quoted ~110$/kg)
Stainless steel (AISI 316) is less efficient than W but much **cheaper**.

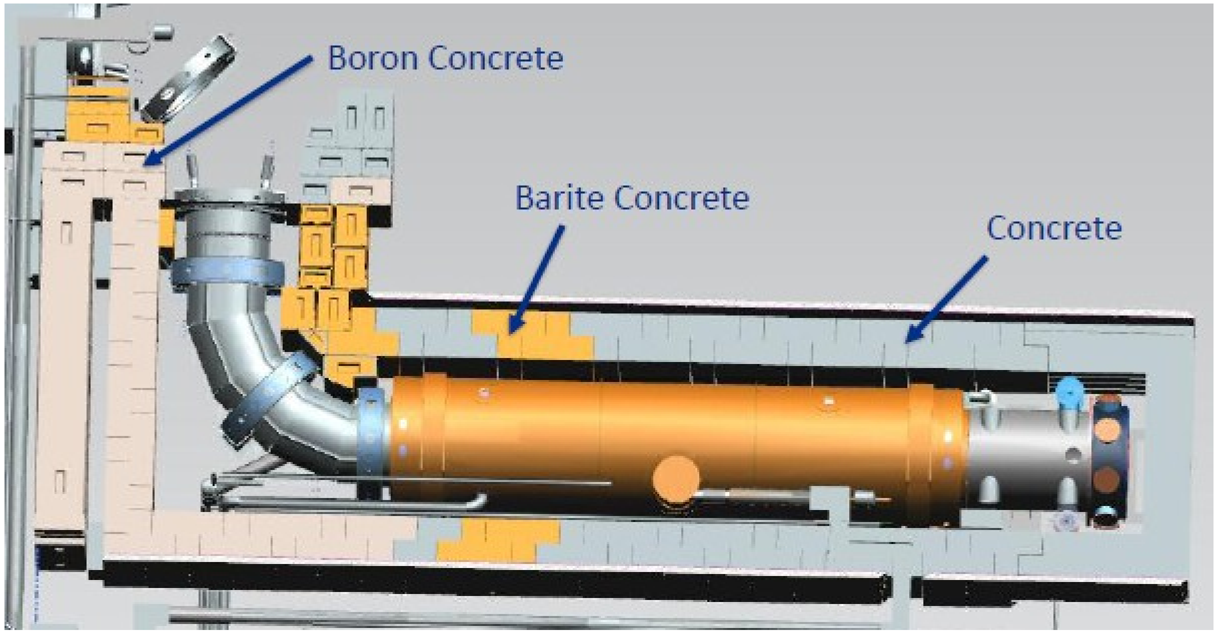
Task 6.4: neutron shielding in Mu2e

In case of **100 MeV** incident neutrons with respect to **regular concrete** the **transmission** is **reduced:**

- by a factor ~**25** replacing the first **20 cm** of each layer with **W**,

- by a factor ~**5** replacing the first **20 cm** of each layer with **SS**;
- by a factor ~**2** using **borated concrete** (1%$_w$ B_4C);
- by a factor **~3** using **baryte concrete**;
- by a factor **~12** using **baryte concrete** and **20 cm** of **SS**
- the use of **baryte concrete** reduces the transmission of neutrons by a

Using regular or baryte concrete (i.e. without boron) **borated rubber** (as FlexBoron®) can be used to absorb thermal neutrons.



Current Mu2e neutron shielding design

Task 6.5: Mu2e sensitivity

Mu2e aims to measure the ratio: $$R_{\mu e} = \frac{\Gamma(\mu^- + \mathrm{N} \to e^- + \mathrm{N})}{\Gamma(\mu^- + \mathrm{N} \to \text{all captures})}$$

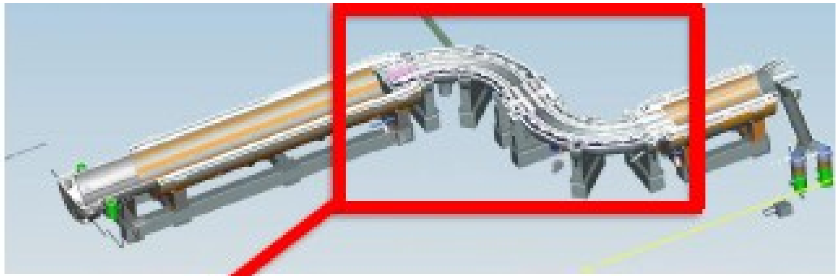
With a sensitivity of **$3 \cdot 10^{-17}$** (10^4 times better than best existing limit)

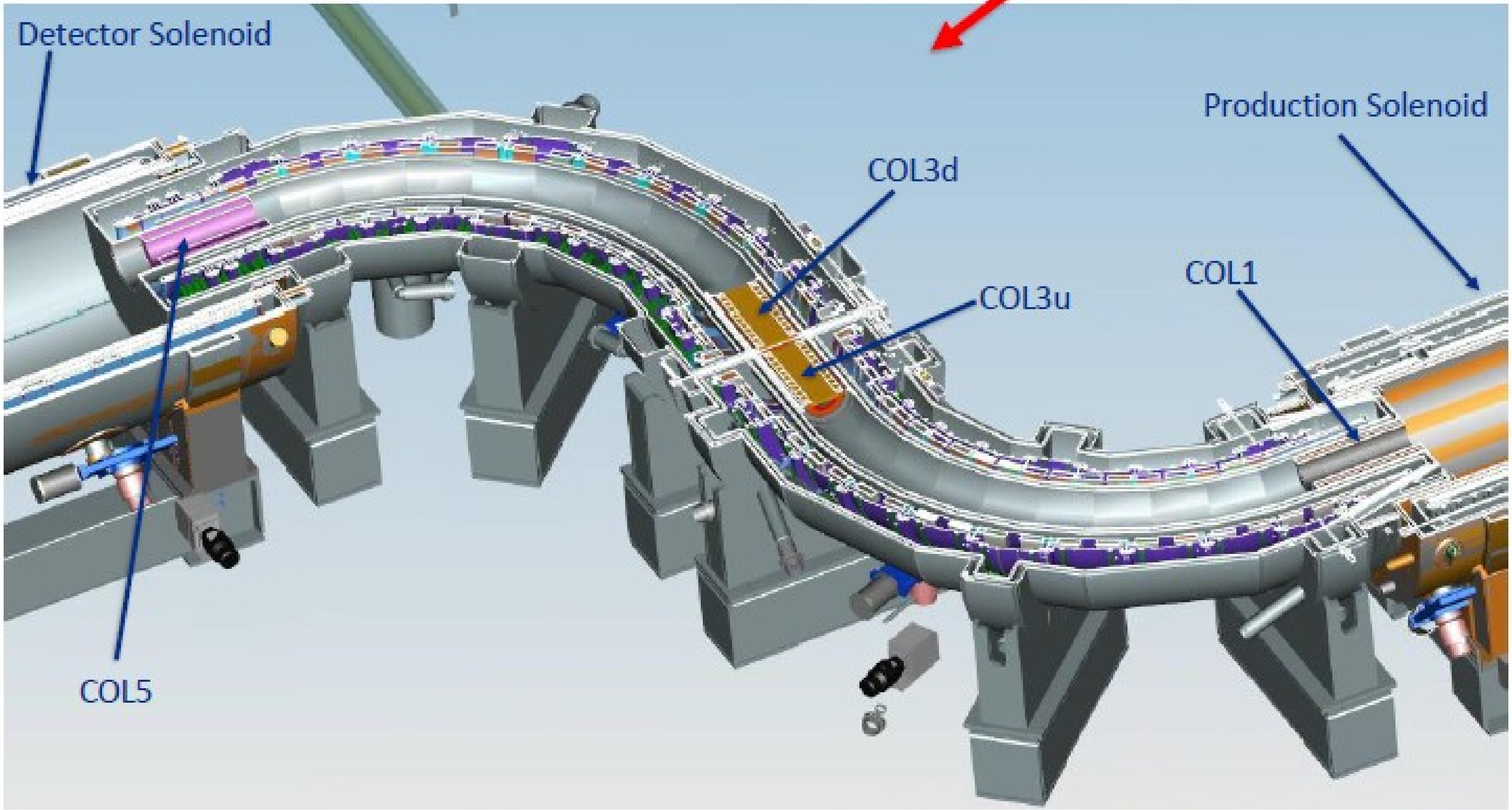
This sensitivity depends on signal detection efficiency and background subtraction.

Current activities in our group:
- Transfer solenoid optimization to improve signal acceptance and suppress antiproton background
- Trigger efficiency optimization
- Particle identification to suppress cosmic muons background (includes optimization of calorimeter and tracker time performances)
- Study of background produced by muons stopped out of the stopping target

Task 6.5: Mu2e sensitivity

Muon beam line collimators

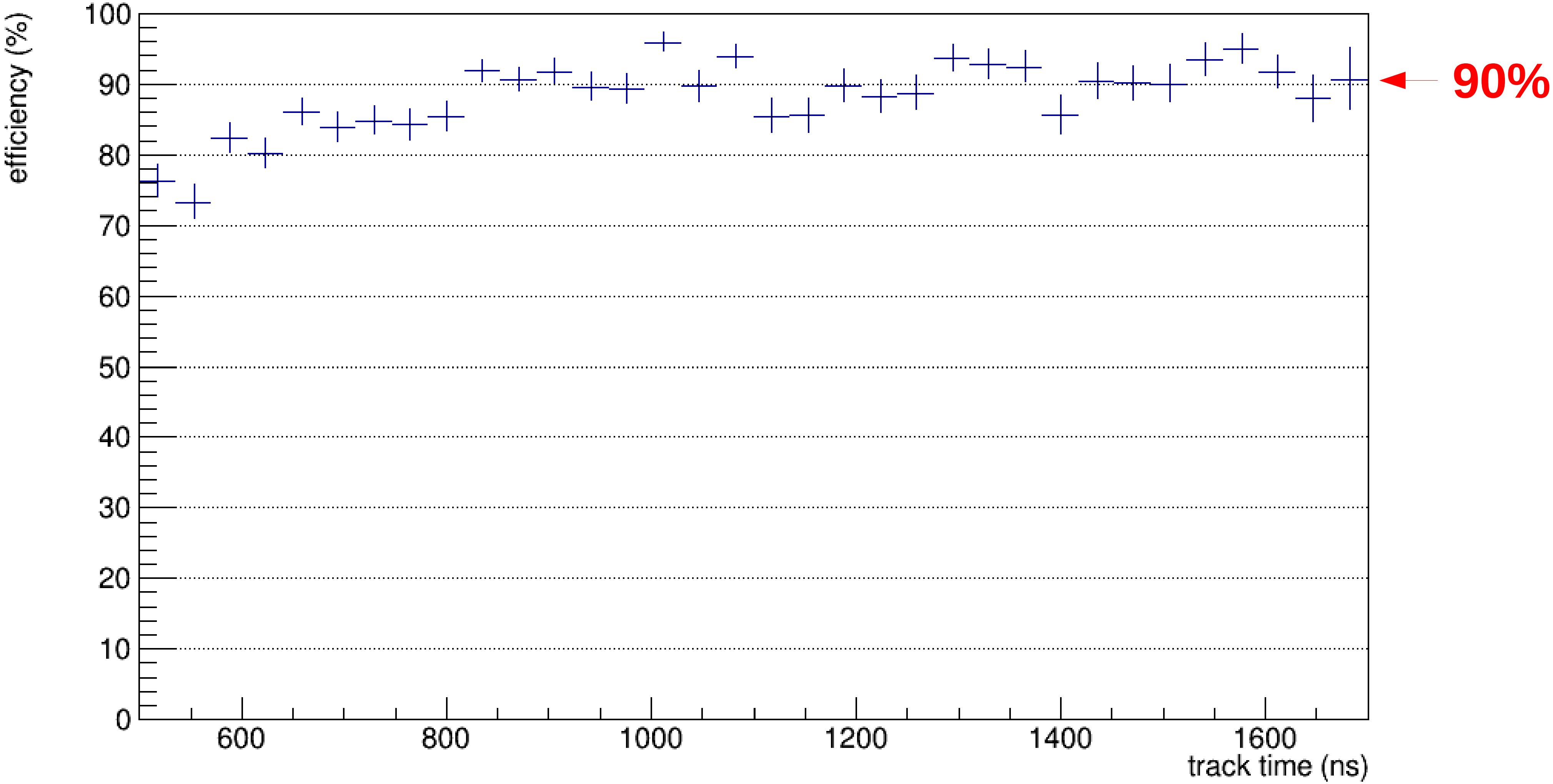




Task 6.5: Mu2e sensitivity

Trigger efficiency on signal

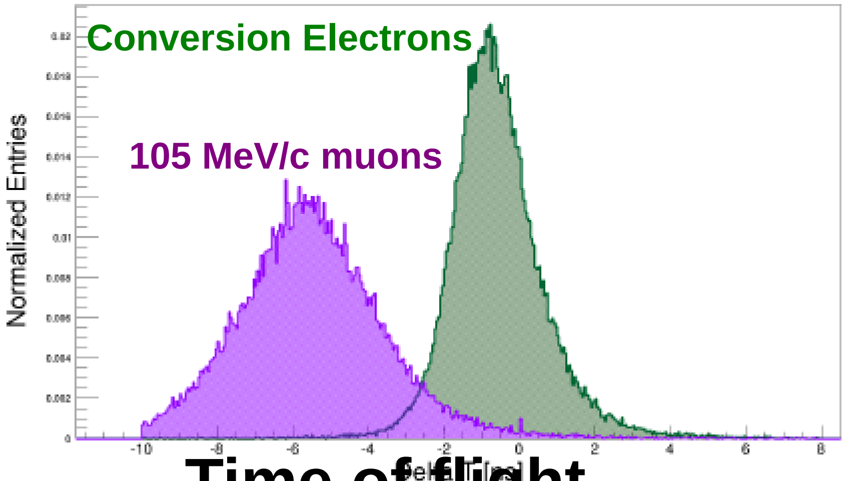
A multivariate analysis algorithm allows reach a **90%** efficiency on **signal** suppressing the **background** by a factor **200**



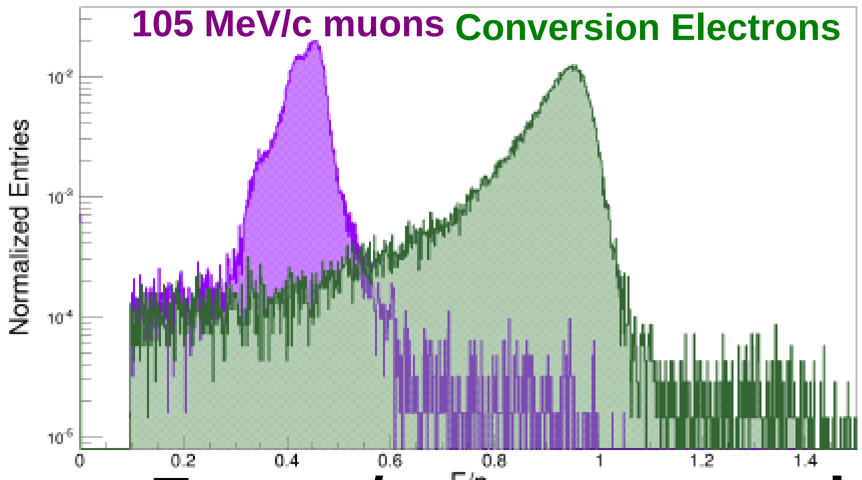
Task 6.5: Mu2e sensitivity

Particle identification

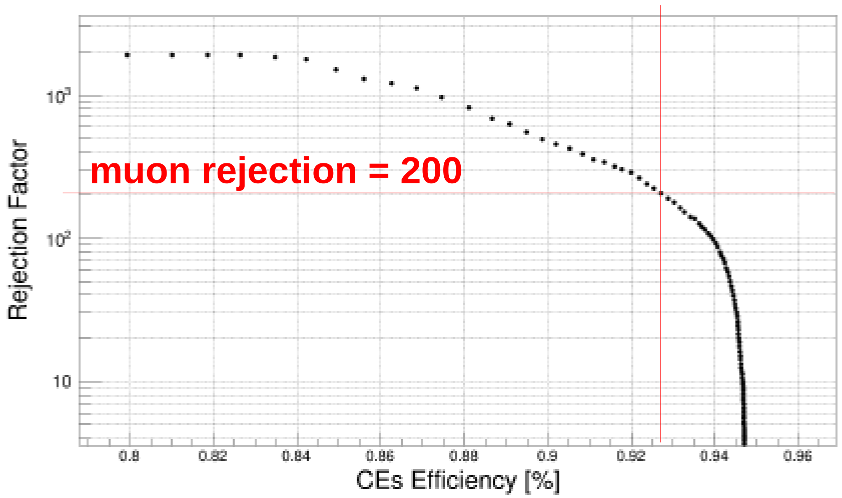
Electrons can be separated by muons by looking at their **time of flight** from the ttracker to the calorimeter and to their **energy deposit** in the calorimeter



Time of flight



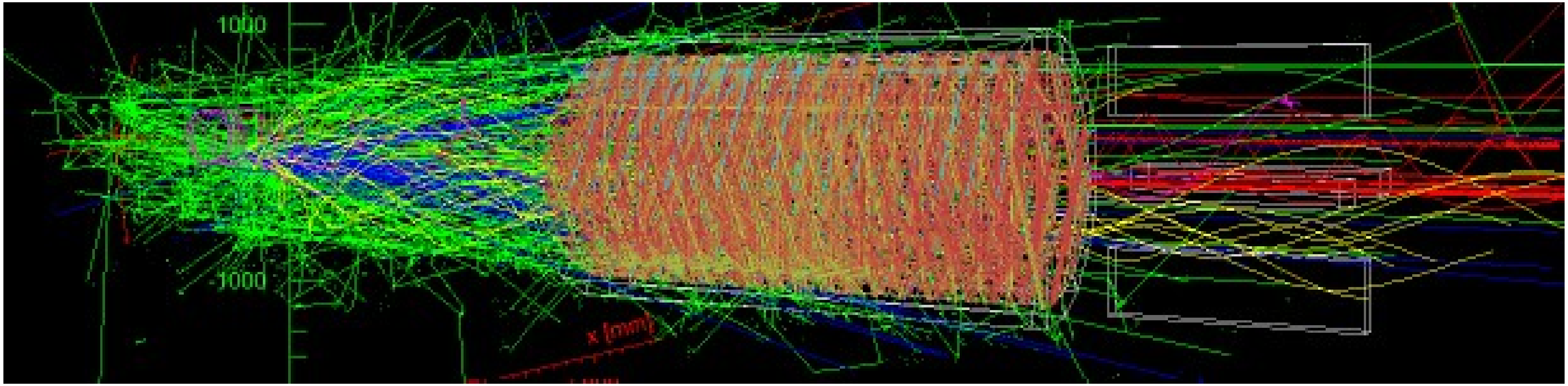
Energy/momentum ratio



A rejection factor 200 makes cosmic muon background negligible wrt cosmic induced electron background

Task 6.6: BaF_2 calorimeter simulation

The Mu2e-II experiment



Expected to start **2 years** after the end of Mu2e

Largely resuses **Mu2e** apparatus

Aims to improve by a **factor 10** Mu2e **sensitivity** exploiting higher beam intensity, lower proton energy beam (no antiprotons)

Requires **faster detectors** → BaF_2 calorimeter

Task 6.6: BaF_2 calorimeter simulation

BaF_2 properties

Specs/Crystal	$PbwO_4$	PbF_2	BaF_2	CsI	LYSO
Light Yield (pe/MeV)	10	2	100 (400)	100	2000
Wavelength (nm)	420	UV-Blue	220 (350)	315	420
Emission time (ns)	10	prompt	0.9 (600)	30	40
Rad-hardness LY loss @ 1 Mrad	80%	Not well known	50%	80%	50%
Density (g/cm³)	7.0	7.0	4.6	4.6	7.0
Radiation Length (cm)	0.9	0.9	1.8	2.0	0.9

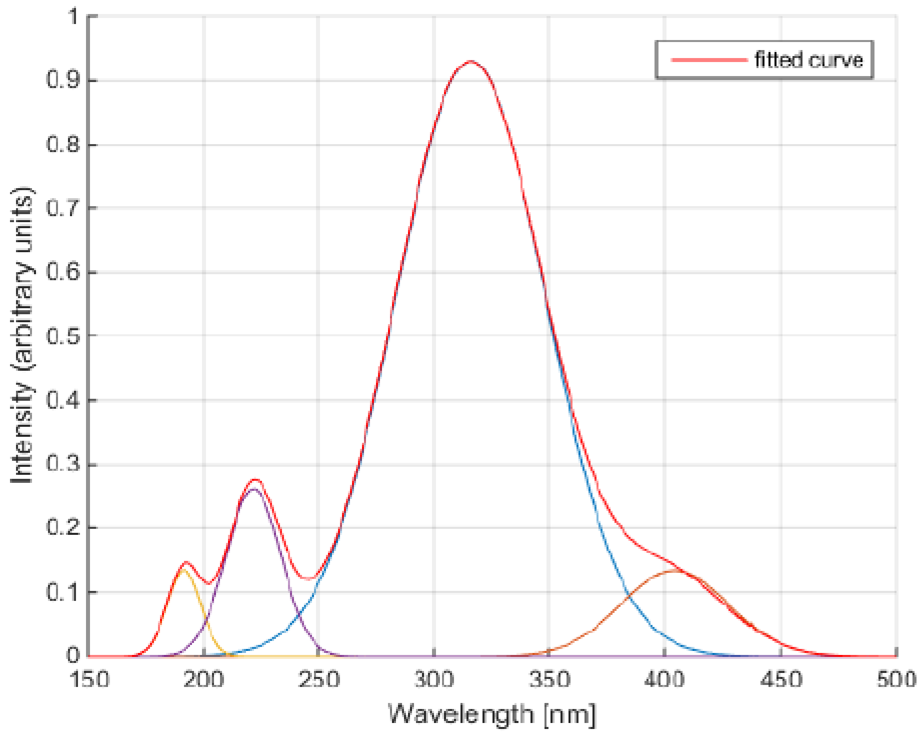
Barium fluoride is the fastest and has the same density of CsI:
no need to change mechanical infrastructure

Task 6.6: BaF_2 calorimeter simulation

BaF_2 emissions

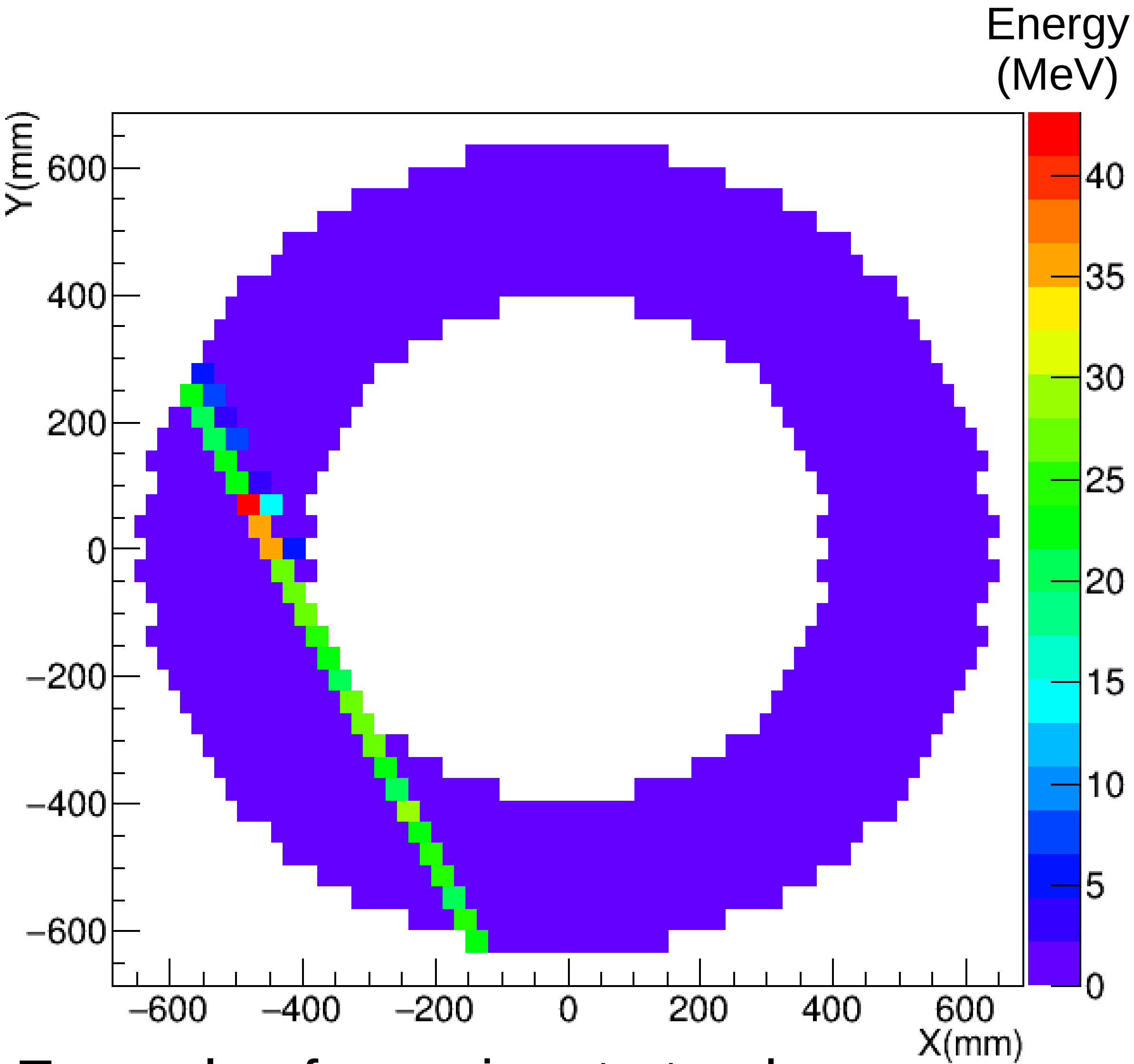
Fast emission: 195 and 220 nm

Slow emission: 320 and 400 nm



Slow emission can be suppressed:
- doping crystals with absorbers (like Y)
- using filters
- using ‘solar blind’ sensors

Task 6.6: BaF_2 calorimeter simulation

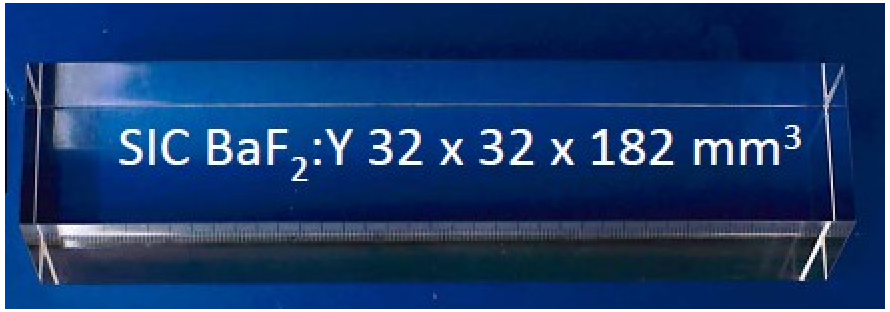


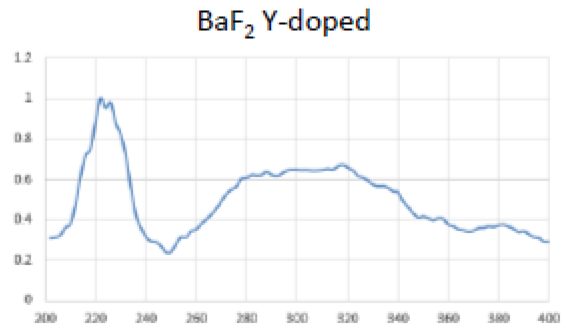
Example of cosmic rate track

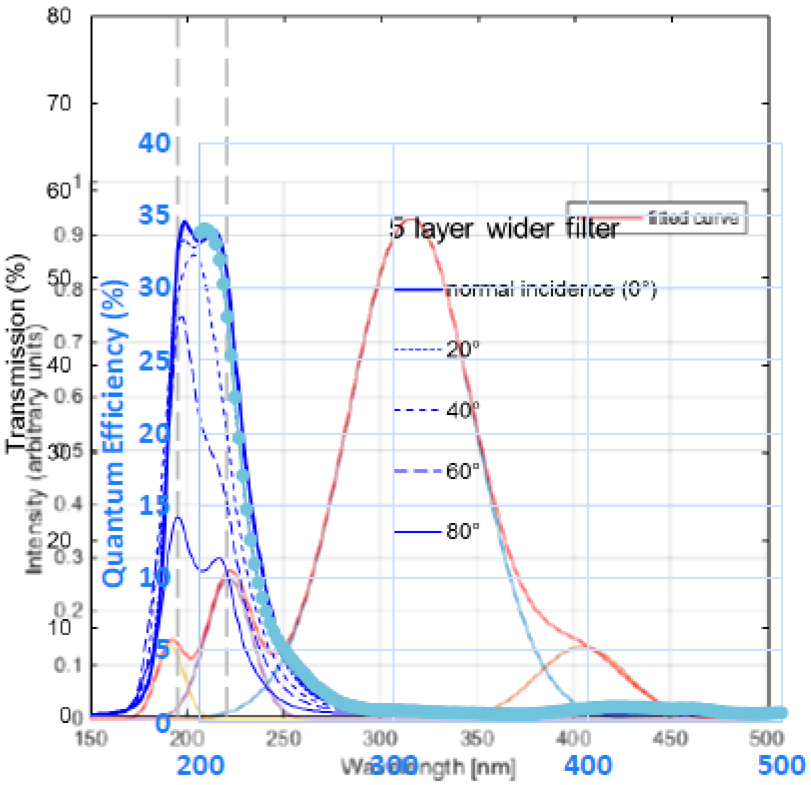
The Mu2e calorimeter simulation can be easily adapted to simulate a BaF_2 calorimeter using the same crystal dimensions

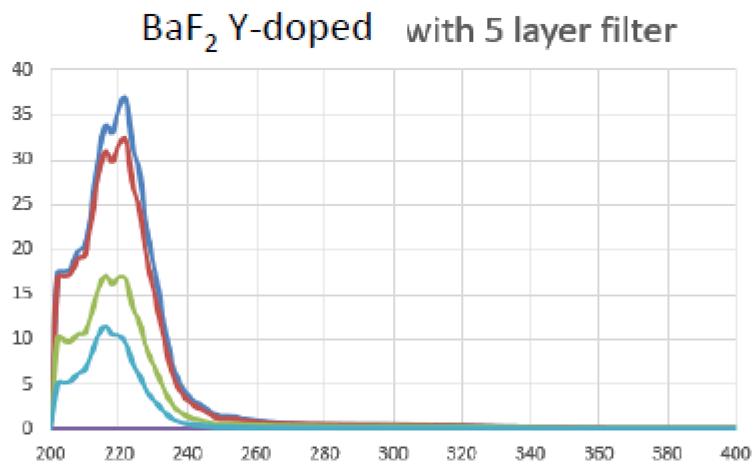
Crystal emission and readout sensor response can be easily implemented but at the moment are not known

Task 6.6: BaF_2 calorimeter design and test









BACKUP

Work Package objectives

O6.1: Develop analysis tools and computing infrastructure to participate in the Muon (g-2) experiment data analysis.

O6.2: Perform precision measurement of the anomalous muon magnetic moment with the full Muon (g-2) experiment collected data sample.

O6.3: Develop neutron transport simulation code and computing infrastructure for the Mu2e experiment.

O6.4: Develop GEANT4 simulation of the upgraded radiation-hard BaF_2 crystal calorimeter for the Mu2e-II experiment.

O6.5: Design the upgraded BaF_2 crystal calorimeter for the Mu2e-II experiment. Test of a BaF_2 crystal matrix on test beam.

Work Package tasks (I)

T6.1: Optimize the online and offline laser-based **calibration procedures** of the Muon (**g-2**) calorimeter (INFN, FNAL). The focus will be on the design of the rate of calibration pulses, rate and length of calibration runs, number of stored calibration parameters, all optimized in a **automated procedure** to give the exact quantities necessary to constrain the systematic errors on ω_a at the level of 0.02 ppm.

T6.2: Foster the integration of the Muon (**g-2**) **simulation** production with the workflow management infrastructure supported by the FNAL Scientific Computing Division (INFN, FNAL). Take leading role in the simulation of large scale samples of the order of 10^{11} muons from injection into the storage ring to fully reconstructed physics quantities for systematics estimate.

Work Package tasks (II)

T6.3: Perform the **blind analysis** to **measure** the muon spin precession frequency $\boldsymbol{\omega_a}$ in collaboration with the US groups (INFN, FNAL). Measure the muon spin precession frequency ω_a by recording the arrival times and energies of the decay positrons with energy above 1.8 GeV in the suite of 24 electromagnetic calorimeters. Take a leading role in the analysis for the ω_a measurement and perform a detailed study of the main expected systematics, including calorimeter gain changes and energy-scale stability, estimate of the fractions of muons that escape the storage ring before they decay, pileup, coherent betratron oscillations, and electric field corrections. Measure the muon anomalous magnetic moment from the measurement of ω_a, and of the magnetic field.

Work Package tasks (III)

T6.4: Develop FLUKA and MCNP6 simulation for **neutron transport** simulation in **Mu2e** (INFN, UNIPI, HZDR, FNAL). Compare FLUKA simulation, based on a multigroup approach, and MCNP6 simulation, based on a continuous-energy approach, to Mu2e codes to estimate backgrounds and improve Mu2e **detector shielding**. Integrate simulation code with the common Mu2e software infrastructure.

T6.5: Develop FNAL **computing infrastructure** (INFN, UNIPI, FNAL, Clever). Integrate Mu2e data processing framework within the common FNAL data handling infrastructure. Estimate **Mu2e sensitivity**.

Work Package tasks

T6.6: Develop GEANT4 **simulation** of the upgraded radiation-hard **BaF_2** crystal calorimeter for the **Mu2e-II experiment** (INFN, UNIPI, HZDR, FNAL). Optimize detector geometry and crystal size, estimate cluster time, energy and position resolution; estimate impact of upgraded calorimeter on Mu2e-II physics reach.

T6.7: Design upgraded radiation-hard BaF2 crystal calorimeter for the Mu2e-II (INFN, UNIPI, HZDR, FNAL, Prisma, Clever). This will imply developing and characterizing a **solar blind UV-extended SiPM,** characterize SiPM radiation hardness, design SiPM readout electronics. Measure performance of a BaF2 crystal matrix with complete readout on **test beam**.