WP-2: Overview

E. Diociaiuti, S. Mueller, F. Renga

aMuse General Meeting 09/17-19/2024

WP-2 Activities

The WP-2 objectives are related to the opportunities offered by the new higher intensity PIP-II beam promoting:

- the design of beamline components and detector for the Mu2e upgrade (Mu2e-II) with the start-up of an R&D and prototyping phase,
- feasibility study to adapt the Mu2e beam to a muon surface beam of world highest intensity to search for cLFV muon decays ($\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$) inside the Mu2e hall

Mu2e-II

Mu2e-II aims to improve the sensitivity ($R_{\mu e}$) to the neutrino-less conversion of a muon-to an-electron in the field of a nucleus by a further order of magnitude wrt Mu2e i.e. SES $\sim$ O (10^{-18}).

Mu2e-II will:

- be based at Fermilab and utilize 100kW proton beam from Proton Improvement Plan II (PIP-II);
- start a few years after the end of Mu2e run with an expected 3+1 years of physics running;
- salvage and refurbish as much of Mu2e infrastructure as possible;
- upgrade Mu2e components where required to handle higher beam intensity.

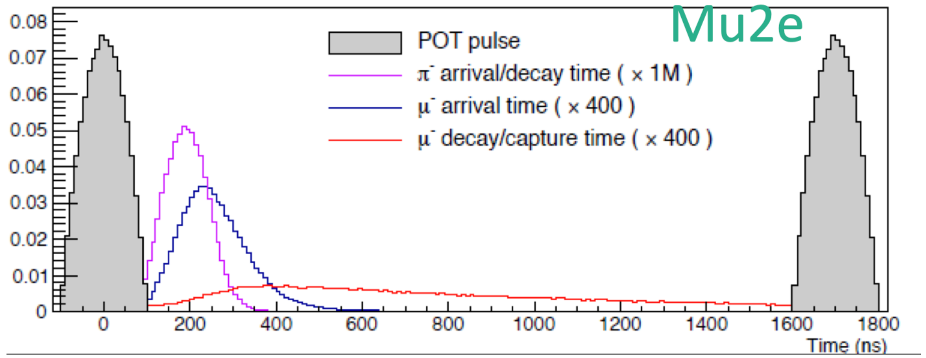
Mu2e-II beam improvements

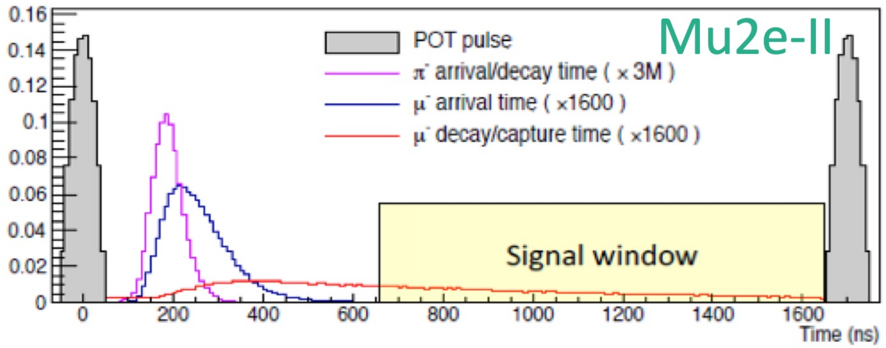
	Mu2e	Mu2e-II	Comments
source	Slow extracted form Delivery Ring	H- direct from PIP-II Linac	Mu2e will need to strip H- ions upstream of production target
Beam energy [MeV]	8000	800	Optimal beam energy 1-3 GeV
Total POT (3+1)y	4.7E+20	4.4E+22	Approximate, depends on μ-stop yield
Run duration (yr)	3	3	
Run time (s/yr)	2.0E+07	2.0E+07	
Experimental duty factor	25%	>90%	Important for keeping instantaneous rates under control
p pulse full width [ns]	250	<=100	
p pulse spacing [ns]	1695	~1700	Assumes an Al target, shorter spacing better for Ti or Au targets
extinction	1.0E-10	1.0E-11	Ration of (oot/it) protons
Average beam power [kW]	8	100	100 kW is approximate; will depend on production target design and transport, which will affect μ-stop yield

will affect μ-stop yield

Mu2e-II will have similar design of Mu2e:

- 3 Solenoids
- Anti-proton window removed
- Redesign detector for intense rate





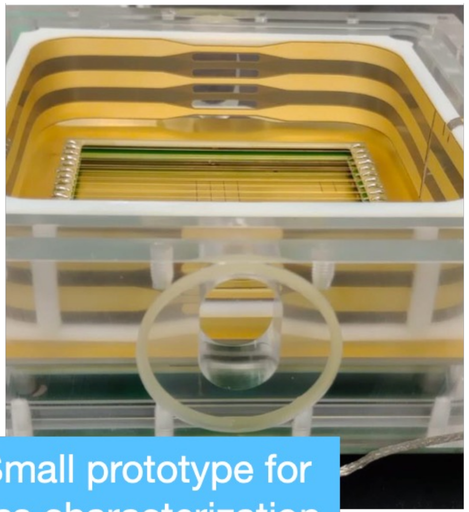
R&Ds for future tracker

- Two R&D lines:
  - gas mixtures for future trackers at high rates
  - radial TPC for e^+e^- tracking in an experiment with photon conversion

- Current activities:
  - characterization of MEG-like gas mixtures
  - investigation of a compact readout for a radial TPC

Gas Mixtures for future trackers

- The goal is to find a gas mixture for wire-based trackers with the capability of sustaining high rates (i.e. with a slow aging rate):
- Options under study:
  - He:isobutane + additives (like in MEG II)
  - hydrocarbon-free mixture (should be also eco-green)
- Tests with a small prototype are on going at LNF and will continue at Università Sapienza:
  - Characterization of the gas mixture (drift properties)
  - Aging and stability tests
- See E. Gabbrielli talk in the Young Scientist Forum

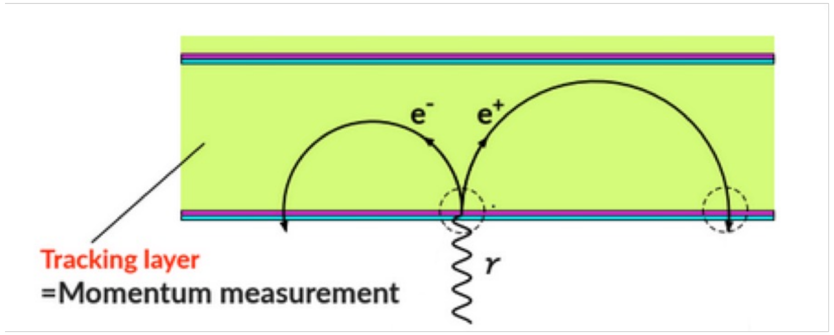


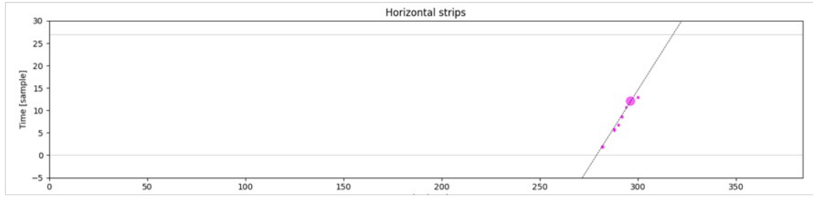
Small prototype for gas characterization

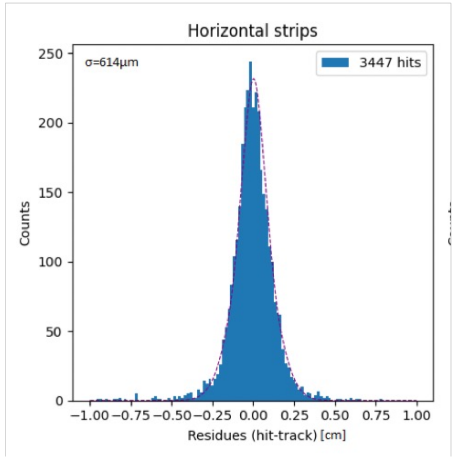
X-ray irradiation facility at INFN Roma

Compact readout for a radial TPC

- The next generation of experiments could reconstruct photons by converting them into e^+e^- and tracking the pair
  - optimal use of the increased beam intensity of future muon beam facilities
- We are investigating the possibility of using a cylindrical TPC with radial drift field as a pair tracker
  - geometrical constraints impose a compact readout
  - we are testing the performances of a TPC with a few cm drift and a strip readout (in contrast to the usual pad readout)







Mu2e-II calorimeter requirements

The Mu2e-II calorimeter should have the same energy ($< 10\%$) and time (< 500 ps) resolution as in Mu2e and

- Provide a standalone trigger, track seeding and PID
- *Provide independent (from STM) muon stop normalization*
- Be resistant to the strong radiation environment and cope with intensity (x 10 dose, x 3 occupancy/microbunch) :
  - 10^{12} - 10^{13} $n_{1\ MeV}/cm^2$ neutrons flux on photosensors → SiPMs leakage current increased, impossible to operated at their design temperature
  - $\sim$ 0.1 - 1 Mrad fluence on crystals →
    - LY reduced to a few photo-electrons (pe)/MeV with a signal width of O(100) ns
  - Assuming no change in the shielding the x3 occupancy will require a drastic reduction of the signal widths, which need to be kept below of O (30 ns).

Necessary to design an alternative calorimeter

Crystal Choice-1

BaF_2 crystals coupled with solar-blind UV-sensitive SiPMs:

- Capture rapid UV component (220 nm) of scintillation light
- Suppress slower component around 300 nm
- Increased resilience against Mu2e-II rates
- Requires ongoing development and commercialization of solid-state photosensors

LYSO crystals:

- Greater brightness, higher density, and enhanced radiation hardness compared to CsI
- Slower decay time (40 ns) than CsI
- Higher cost due to Lu_2O3 raw material and higher melting point

$PbWO_4$ crystals:

- Similar decay time to CsI
- Light yield less than 10% compared to CsI
- Radiation damage can recover at room temperature
- Continuous in situ light monitoring needed for calorimeter precision

PbF2 crystals:

- Extremely fast Cherenkov emission
- Very poor light yield

Crystal Choice-2

BaF_2 crystals coupled with solar-blind UV-sensitive SiPMs:

- Capture rapid UV component (220 nm) of scintillation light
- Suppress slower component around 300 nm
- Increased resilience against Mu2e-II rates
- Requires ongoing development and commercialization of solid-state photosensors

	CsI	LYSO	BaF_2	PbF_2	CRY18	GAGG	LaBr
Light Yield (γ /MeV)	1700	33200	13000, 1700	~20	30000	Up to 50000	63000
Wavelength [nm]	310	420	300,220	-	425	520	380
Decay time [ns]	26	40	600,0.9	-	45	90	16
Density [g/cm^3]	4.51	7.4	4.89	7.77	4.5	6.63	5.08
Radiation length [cm]	1.86	1.14	2.03	0.93	2.74	TBA	1.88

- Continuous in situ light monitoring needed for calorimeter precision

PbF2 crystals:

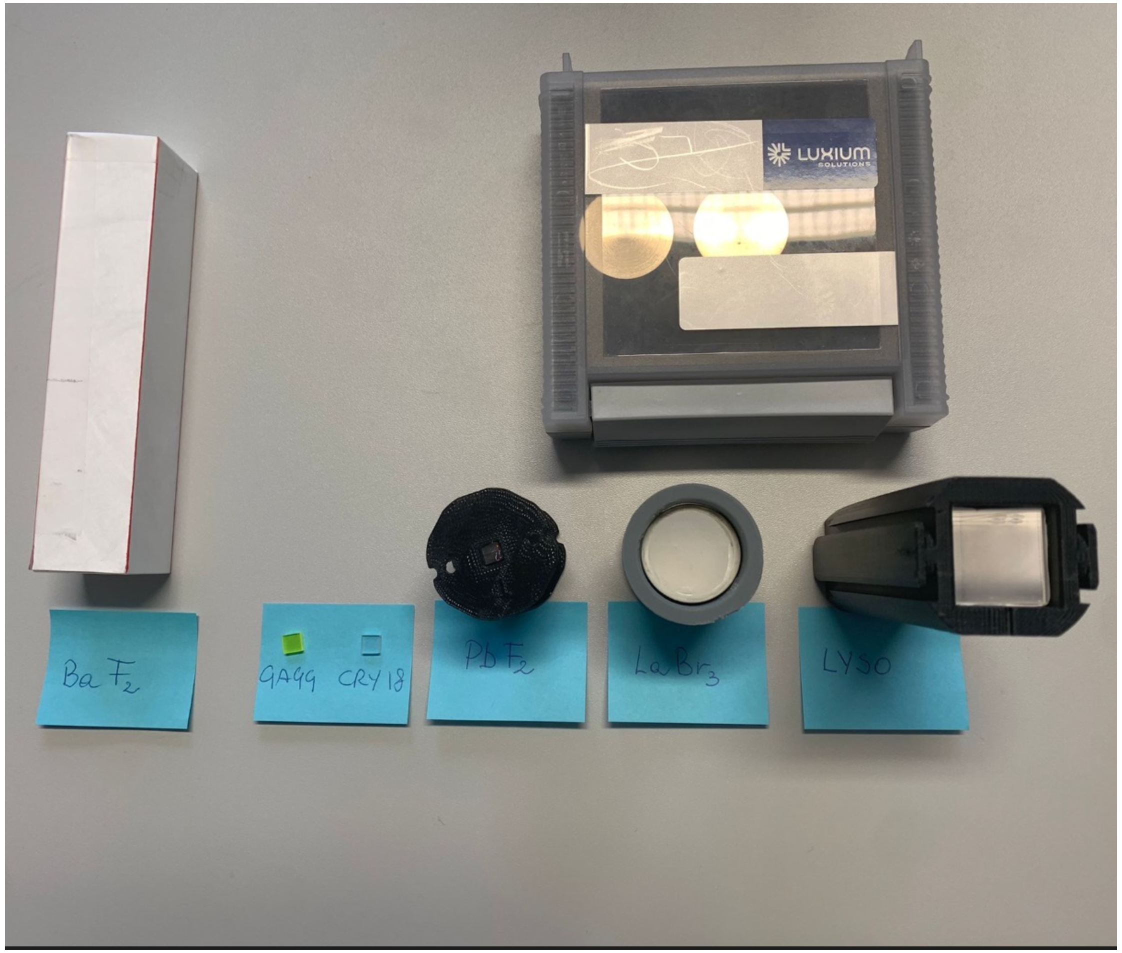
- Extremely fast Cherenkov emission
- Very poor light yield

Radiation resistance of different crystals

aMUSE

- Gamma irradiation performed at the end of October @ HZDR
- The required accumulated dose 5kGy (**10 kGy** Safety factor included)
- Waiting for accurate dosimetric measurements from CERN

	Sample dimensions
LaBr3	h=2.54cm crystal + 0.5cm light guide, housing 0.05cm Al, d=2.54cm
PbF2	0.5cm x 0.5cm x 4cm
CRY18	0.2cm x 0.2cm x 0.5cm
GAGG	0.2cm x 0.2cm x 0.5cm
LYSO	2cm x 2cm x 9.8cm
BaF2	3cm x 3cm x 14cm



LaBr - Preliminary Results (1)

		Measurement before shipment / before irradiation (with 3" HAMAMATSU R4017)			Measurement after irradiation (with 3" HAMAMATSU R4017)			Evolution of the performances		
		date	PHR @ 662keV (%)	HT (V)	date	PHR @ 662keV (%)	HT (V)	ΔPHR @ 662keV (%)	ΔHT (V)	ΔLO (%)
S/N#	Sample #1	16/10/2023	3,32	837	26/07/2024	4,58	968	-1,26	-131	-53%
	Sample #2	16/10/2023	4,21	945	26/07/2024	4,37	986	-0,16	-41	-20%
	Sample #3	16/10/2023	3,32	848	26/07/2024	3,45	892	-0,13	-44	-23%

LaBr - Preliminary Results (2)

- **Sample #1: Irradiated for a longer time wrt the other samples**
  - Noticeable yellow discoloration.
  - Significant optical coupling transmission loss.
  - Performance drift: 53% reduction in light output and high degradation of PHR@662keV.
- **Sample #2:**
  - Performance drift is acceptable, despite initially having the worst performance.
  - Light output loss: 20%.
  - PHR impact is minimal.
  - Optical coupling likely responsible for small drift, to be confirmed after disassembly.
- **Sample #3:**
  - Best initial performance (3.32 @ 662keV).
  - Acceptable performance drift.
  - Optical coupling may explain drift, to be confirmed after disassembly.
- **Next Steps:**
- Disassemble units to test individual components (crystal and light guide).

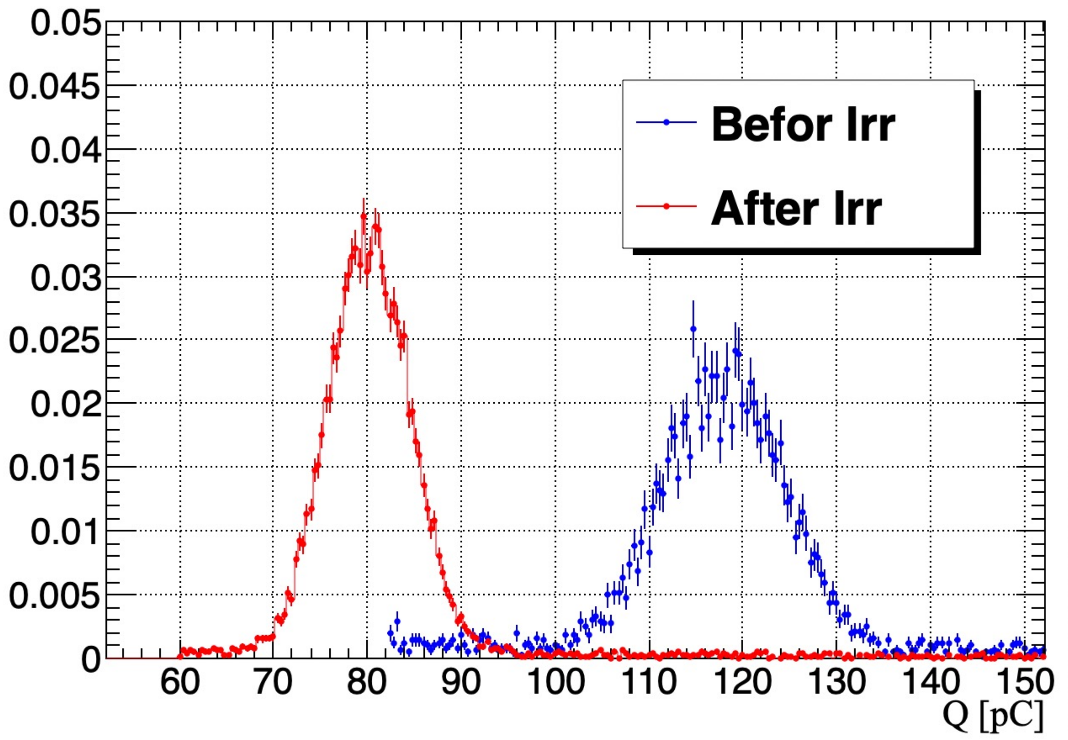
LYSO

- LYSO and BaF_2 tested with ^{22}Na source (0.511 MeV peak) before irradiation
- Crystal coupled with Hamamatsu PMT measured at both ends
- BaF_2 unfortunately broken immediately after the irradiation

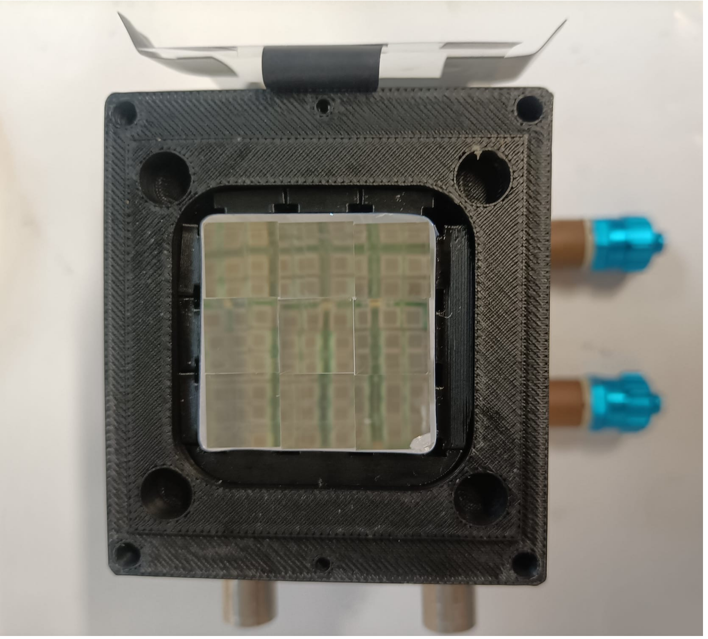
	NEAR		
	Before irradiation	After Irradiation	Delta LY
LY [Npe/MeV]	1487.35	947.82	0.36

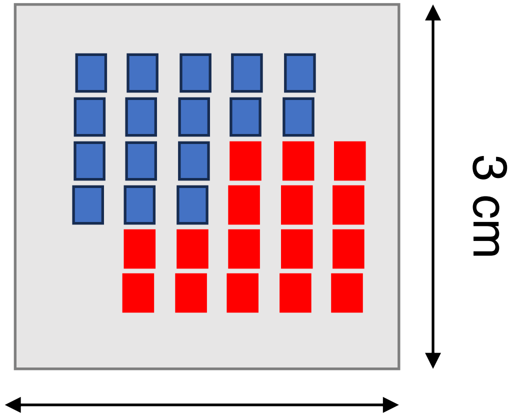
	FAR		
	Before irradiation	After Irradiation	Delta LY
LY [Npe/MeV]	1442.48	980.96	0.32

- "mean" integrated dose for LYSO is 26 kGy from simulation
- Not uniform along the crystal – i.e. One edge integrated up to 200 kGy



First tests of LYSO crystals with SiPM readout





Thanks to Crilin Group and Yuri

LYSO Crystals:

- Dimensions: 3x3x8 cm^3
- Wrapped with ESR (Enhanced Specular Reflector)
- No optical grease applied

Mu2e-II SIPMs:

- Configuration: Two new Mu2e SIPMs
- Each SIPM comprises 16 SiPMs (3x3 mm^2) with a 10 μm pixel size
- Equivalent to 4 SiPMs (6x6 mm^2) per channel
- Area SiPM/Cry → 16% per SiPM

Readout and Acquisition:

- Individual readout of each SiPM
- Acquired with Flash ADC CAEN V1742 at 2.5 Gs/s

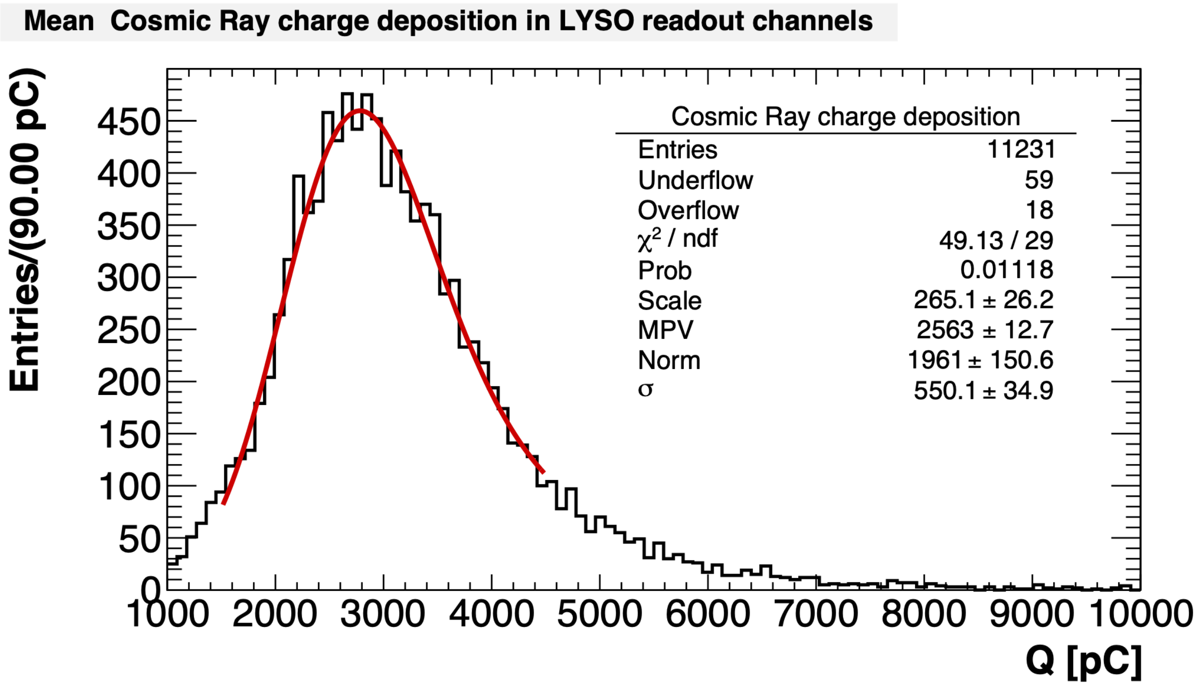
Future Studies:

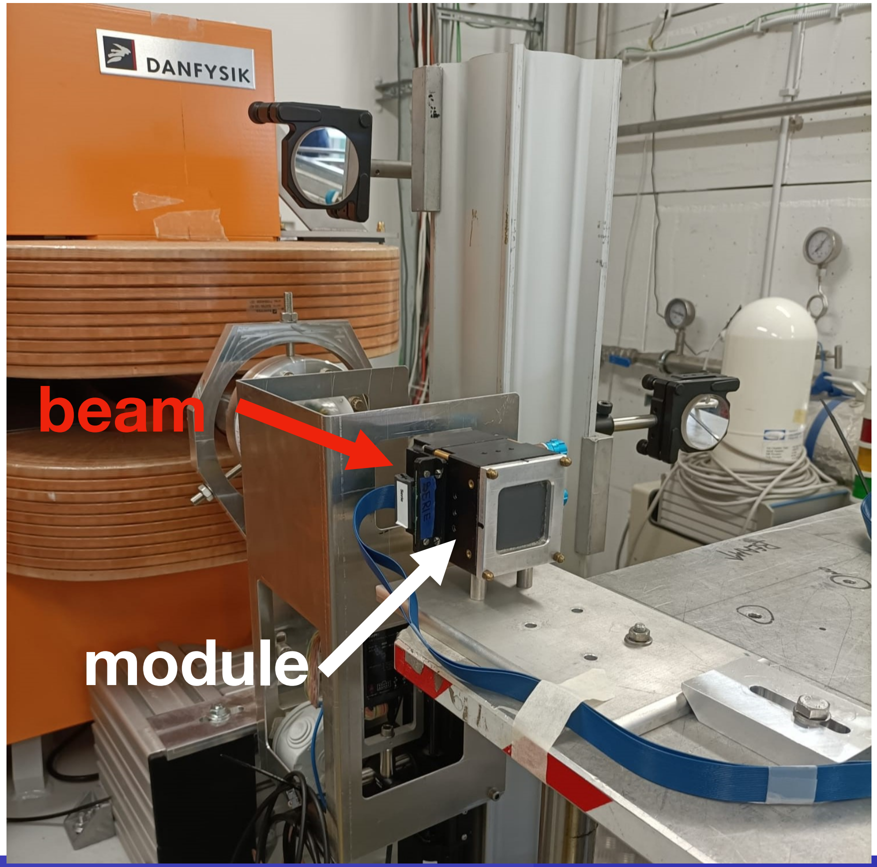
- Hamamatsu now offers 6x6 mm^2 SiPMs with a 10 μm pixel size
- **Future studies will utilize these new SiPMs directly**

- TB carried out at LNF BTF using e^- beam with multiplicity 1, **E = 100, 80, 60 MeV**
- Beam impacted on the center of the module

scale factor=0.0117 MeV/pC

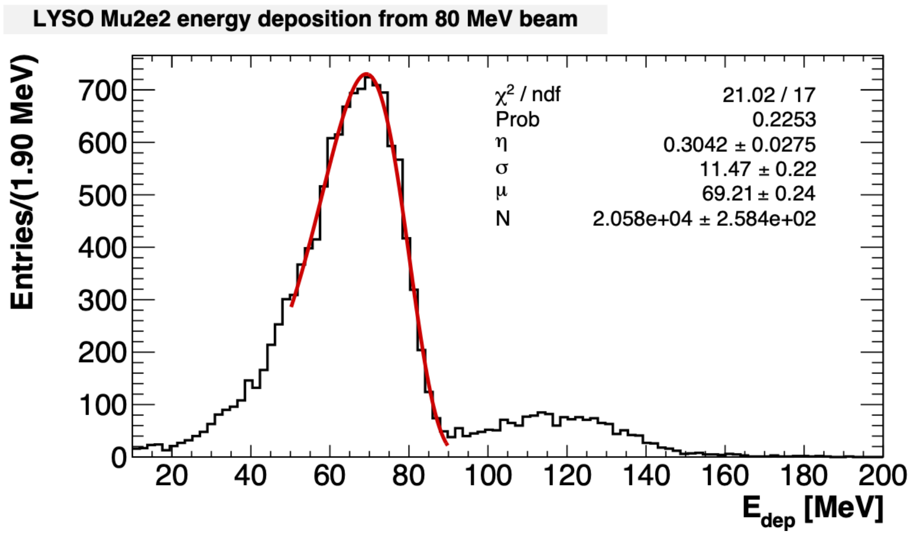
Npe/MeV ~ 300 p.e.



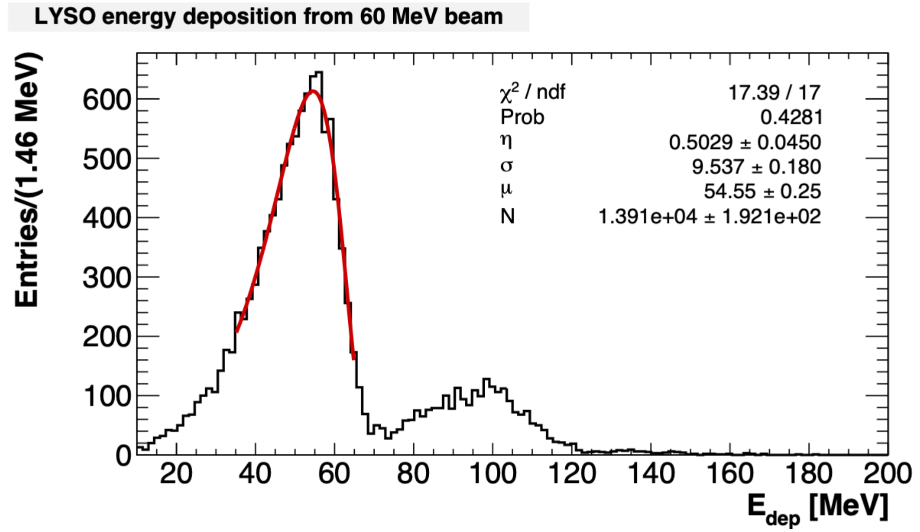


Energy response for electron beam

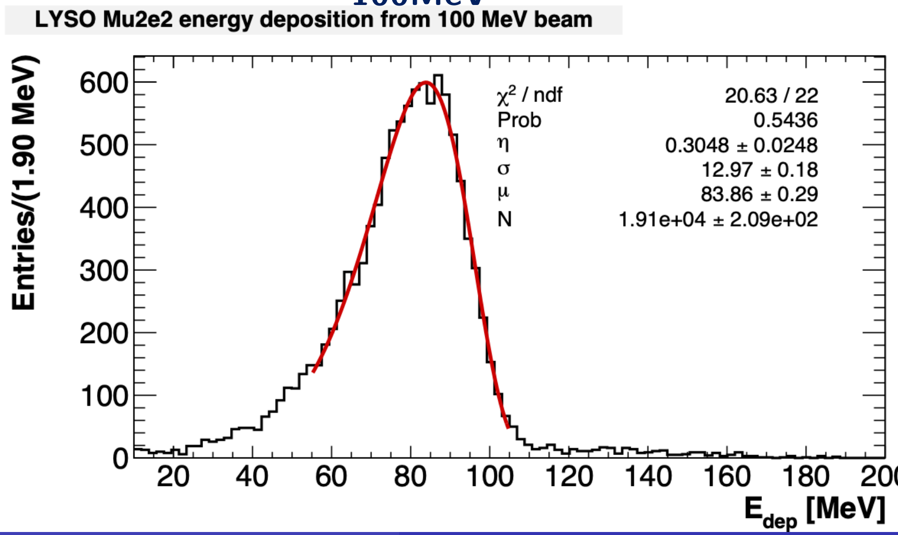
$\mathrm{Eres}_{80\mathrm{MeV}} = 16.5\%$



$\mathrm{Eres}_{60\mathrm{MeV}} = 17.4\%$



$\mathrm{Eres}_{100\mathrm{MeV}} = 15.4\%$

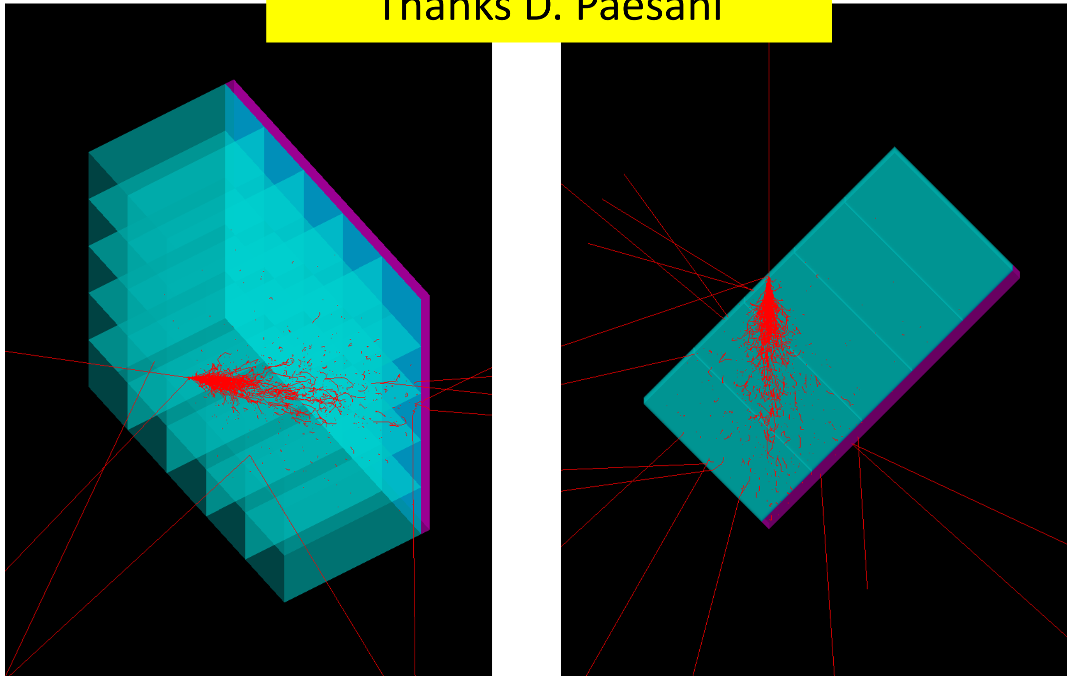


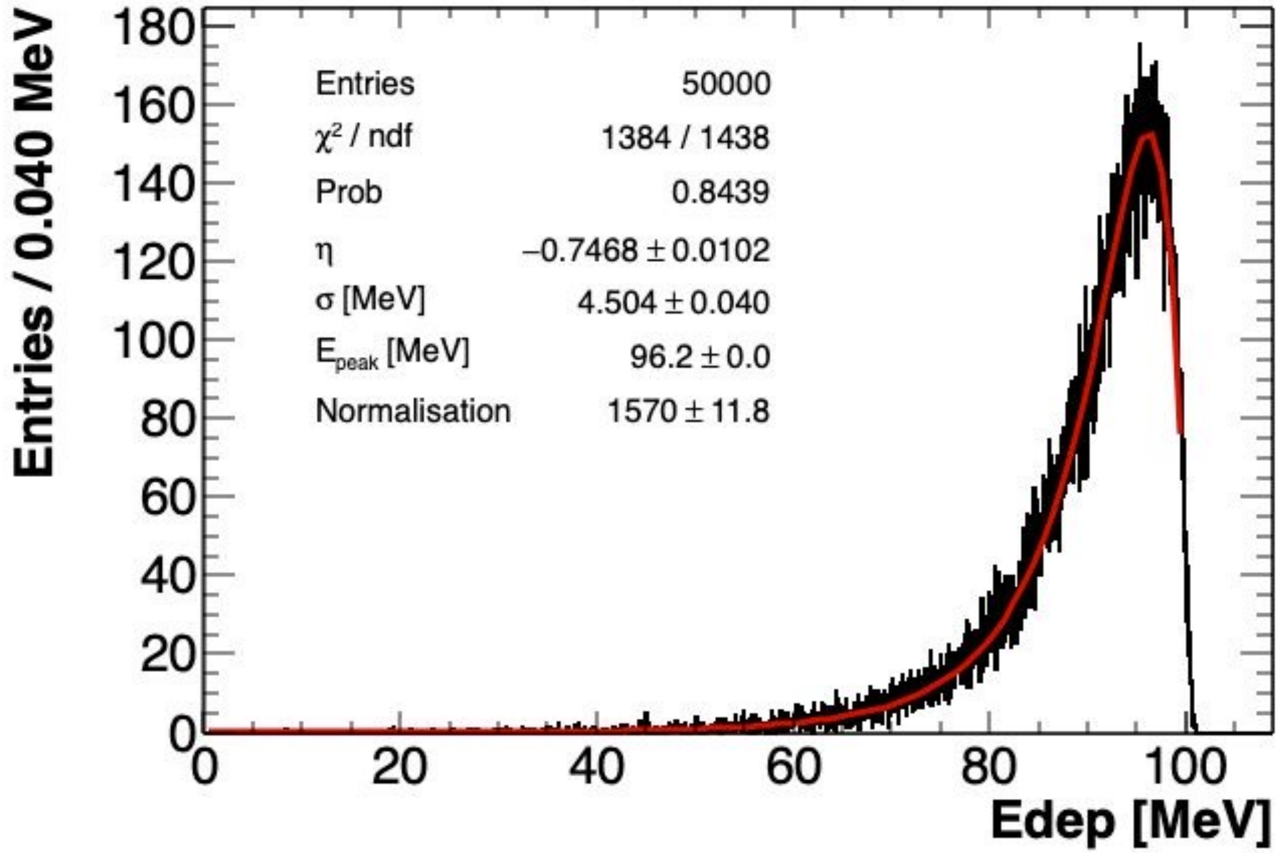
Simulation

- 25 Crystals with dimension 34x34x80 mm^3
- 300 p.e./MeV as measured
- 100 keV ENE with threshold apply @ 3σ
- 100 MeV e$^-$ at 45 degrees

4.6% @ 100 MeV

Thanks D. Paesani



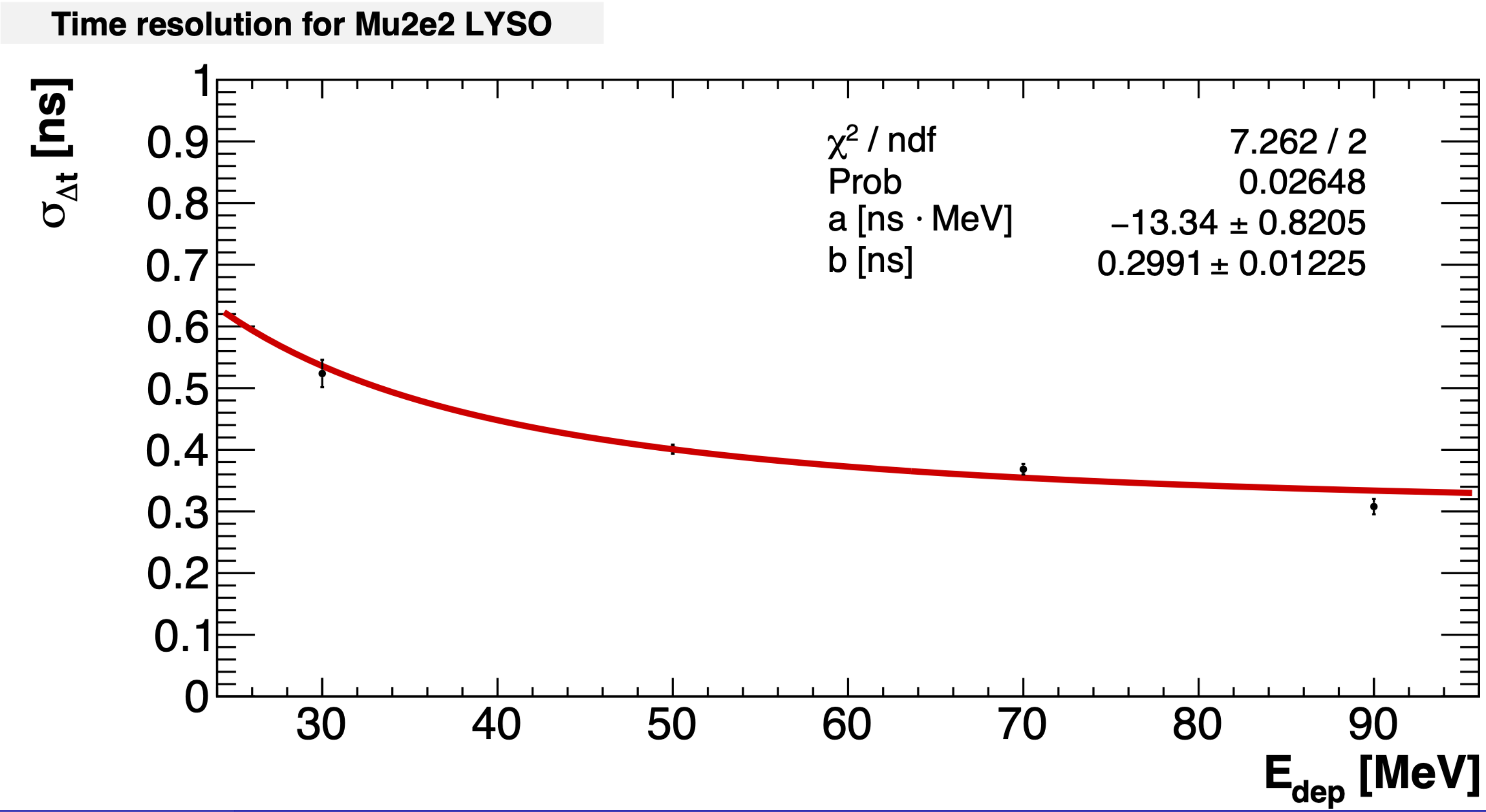


•**Waveform Summation:**

- Difficulty in summing waveforms corresponding to each SiPM

•**Upcoming Test:**

- Next test will be conducted directly in the Mu2e-like configuration
- Configuration: Parallel of two series per channel



Conclusions

The Mu2e-II project aims to improve the sensitivity to the neutrino-less conversion of a muon into an electron in the field of a nucleus by an order of magnitude compared to Mu2e. It will utilize a 100 kW proton beam from the Proton Improvement Plan II (PIP-II) and is expected to start a few years after the end of the Mu2e run, with a planned operational period of 3+1 years.
The main R&D activities include:

- **Gas Mixtures for Future Trackers**: Researching a gas mixture for wire-based trackers capable of sustaining high event rates.
- **Compact Readout for a Radial TPC**: Studying a cylindrical TPC with a radial drift field to track electron-positron pairs.
- **Mu2e-II Calorimeter Requirements**: Developing a calorimeter resistant to radiation and capable of handling high intensities, with energy and time resolution similar to Mu2e.

M2.1 is getting closer... still some work to do but we are on the good path