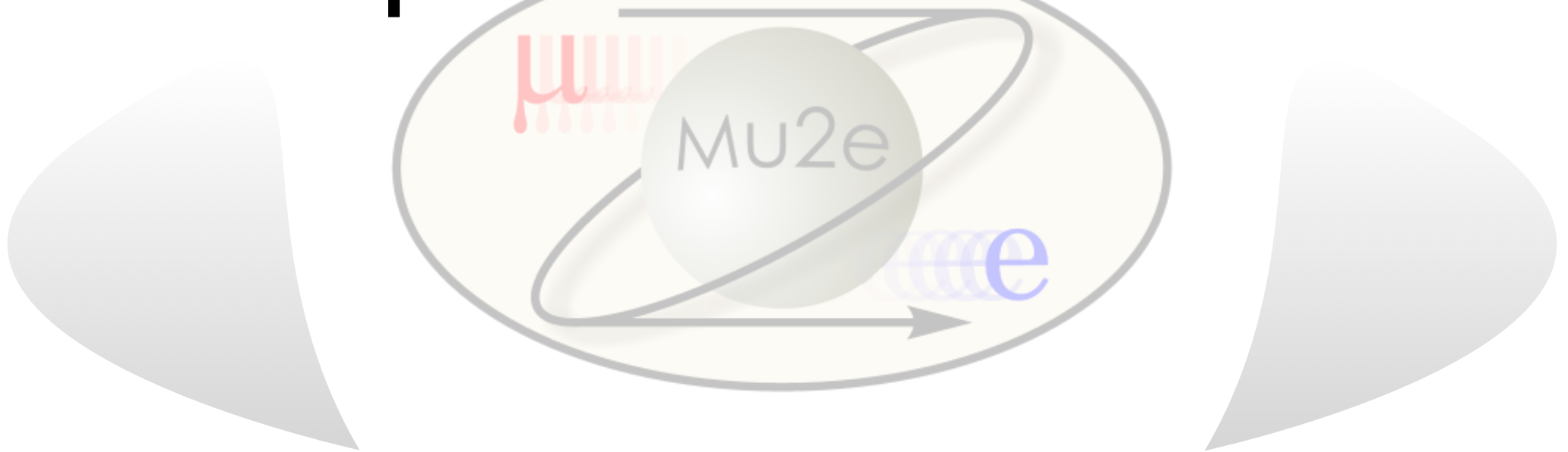


Mu2e: coherent $\mu \rightarrow e$ conversion experiment at Fermilab



Gianantonio Pezzullo
INFN of Pisa

on behalf of the Mu2e collaboration

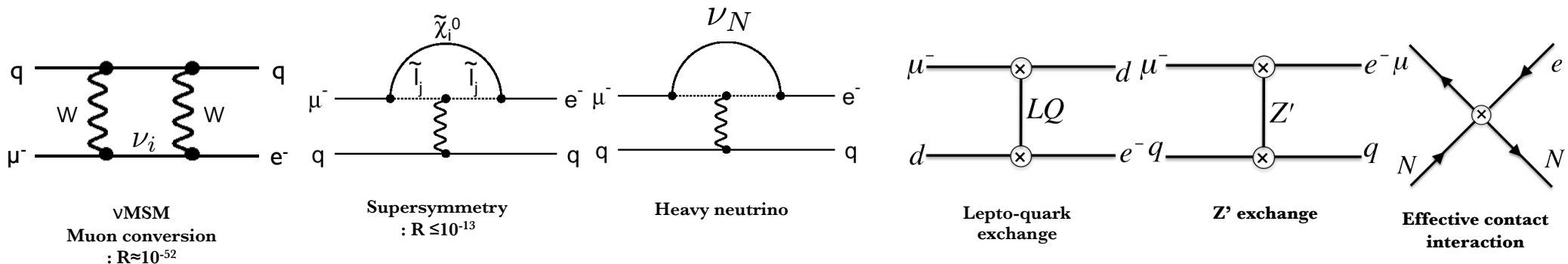


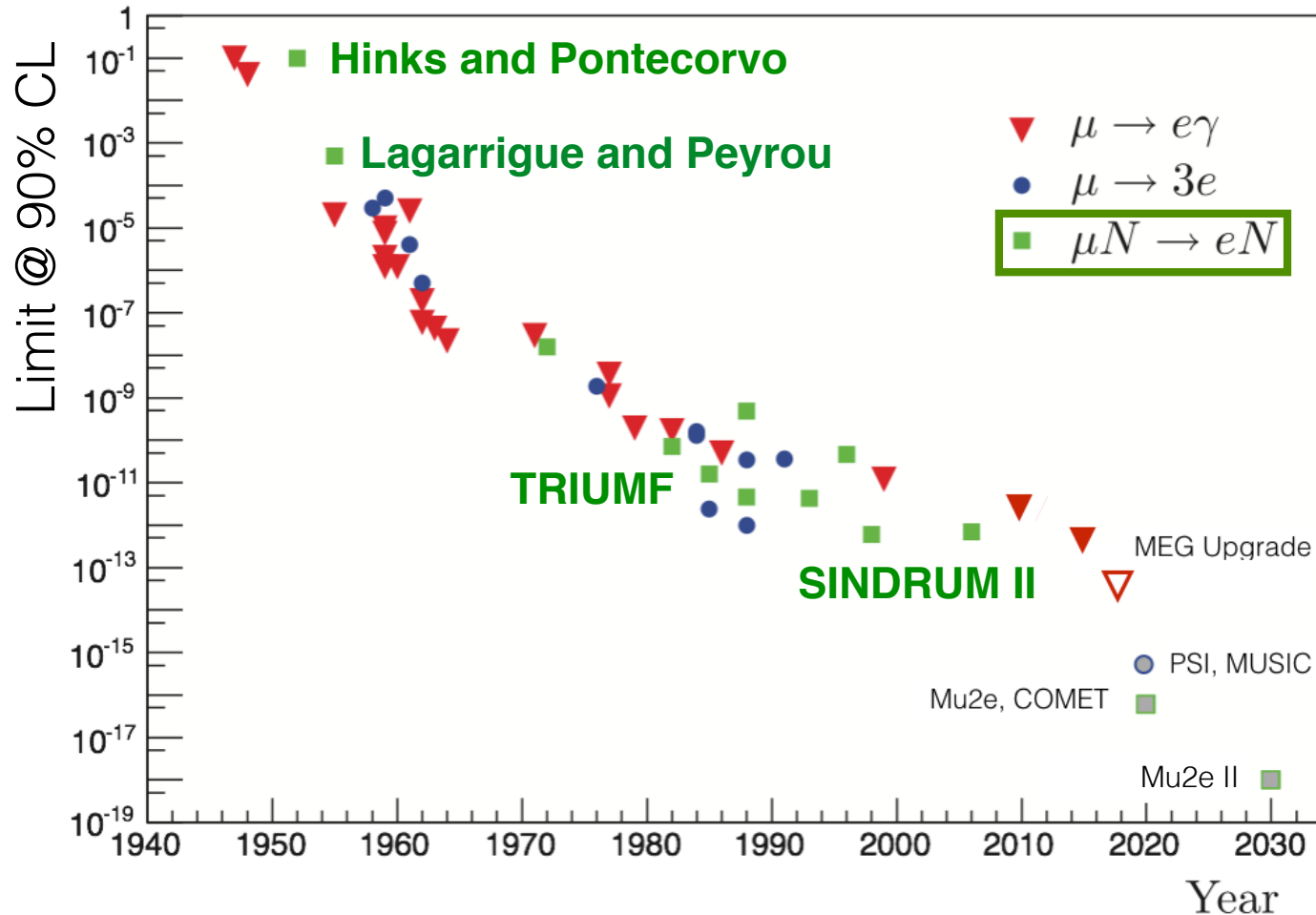
Argonne National Laboratory, Boston University, Brookhaven National Laboratory
 University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York,
 Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator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

- μ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.973 \text{ MeV}$$

- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy (0.48 MeV)} \\ C(A) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$
- μ conversion in the SM is introduced by the **neutrino masses and mixing** at a negligible level $\sim 10^{-52}$
- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop...)





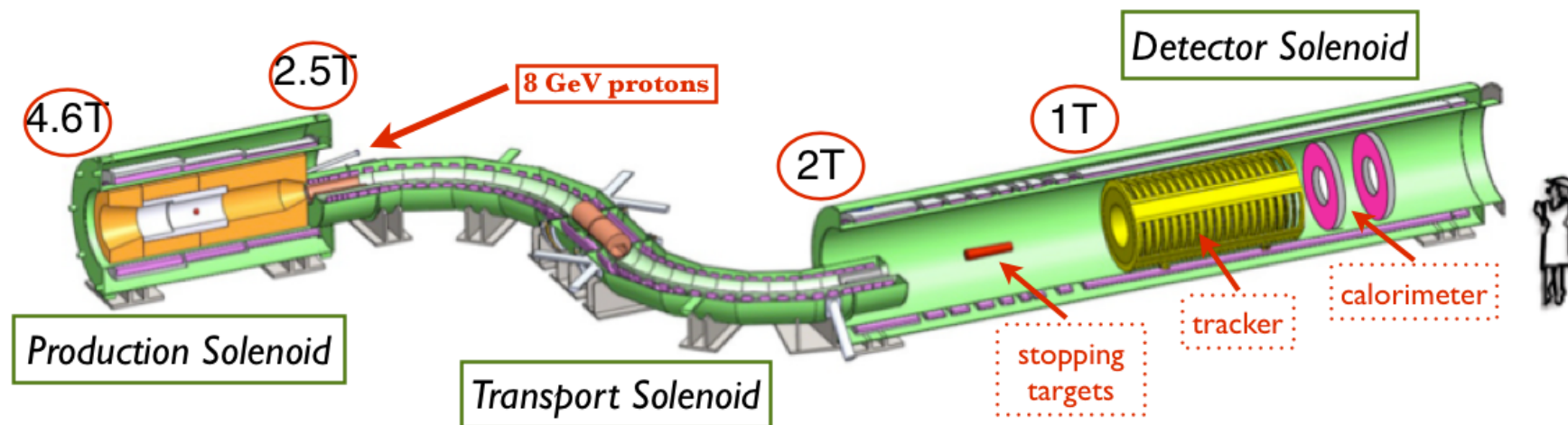
- Mu2e will improve by a factor 10^4 the present best limit!

- **Production Solenoid:**

- ➔ Proton beam strikes target, producing mostly pions
- ➔ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

- **Detector Solenoid:**

- ➔ Capture muons on Al target
- ➔ Measure momentum in tracker and energy in calorimeter
- ➔ Graded field “reflects” downstream conversion electrons emitted upstream



- **Transport Solenoid:**

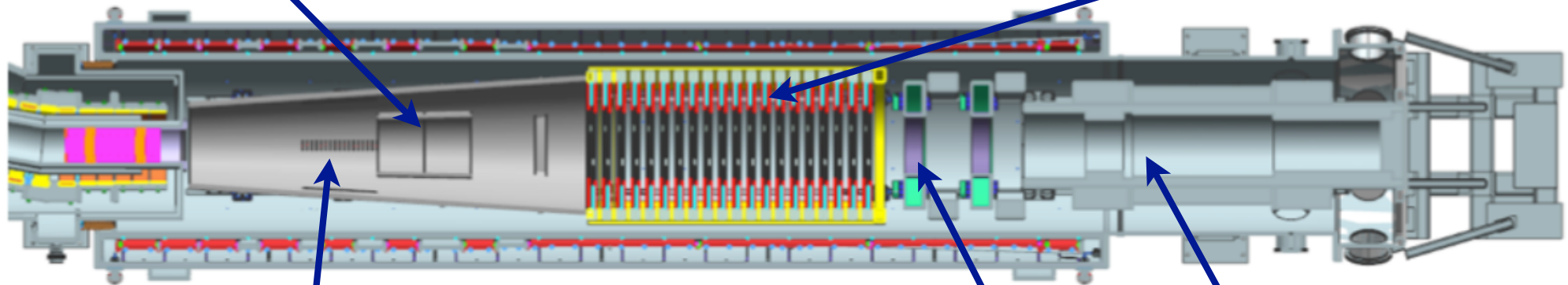
- ➔ Select low momentum, negative muons
- ➔ Antiproton absorber in the mid-section

- **Proton absorber:**

- ❖ made of high-density polyethylene
- ❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- **Tracker:**

- ❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
- ❖ Expected momentum resolution $< 200 \text{ keV}/c$



- **Targets:**

- ❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

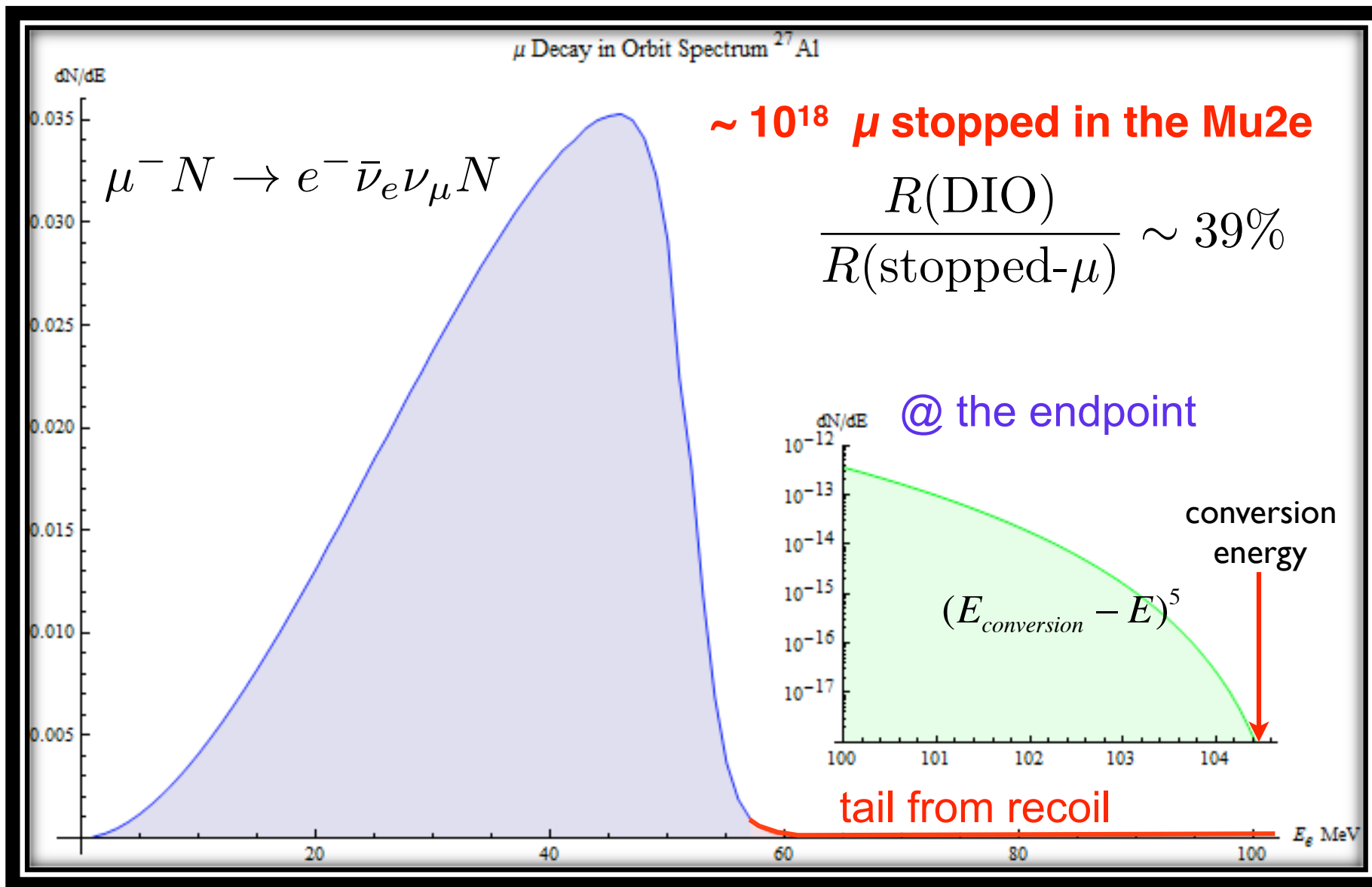
- **Calorimeter:**

- ❖ 2 disks composed of undoped CsI crystals

- **Muon beam stop:**

- ❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

- μ decay-in-orbit
- Cosmic-induced background
- Antiproton-induced background
- Radiative π capture

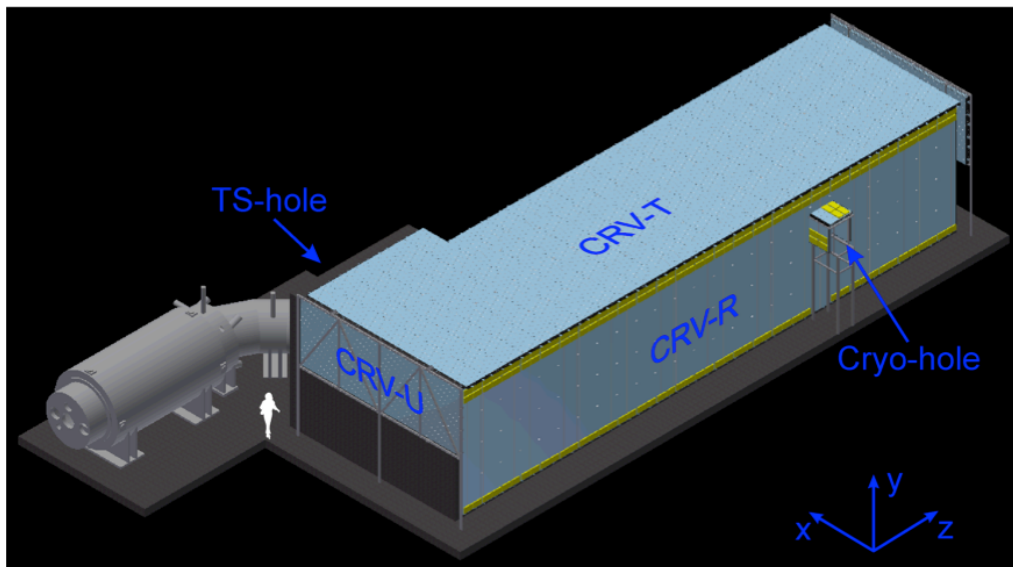
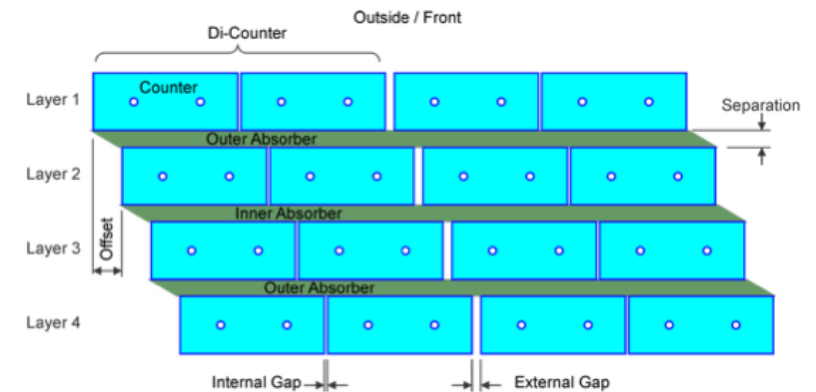


Czarnecki et al., arXiv:1106.4756v2 [hep-ph] Phys. Rev. D 84, 013006 (2011)

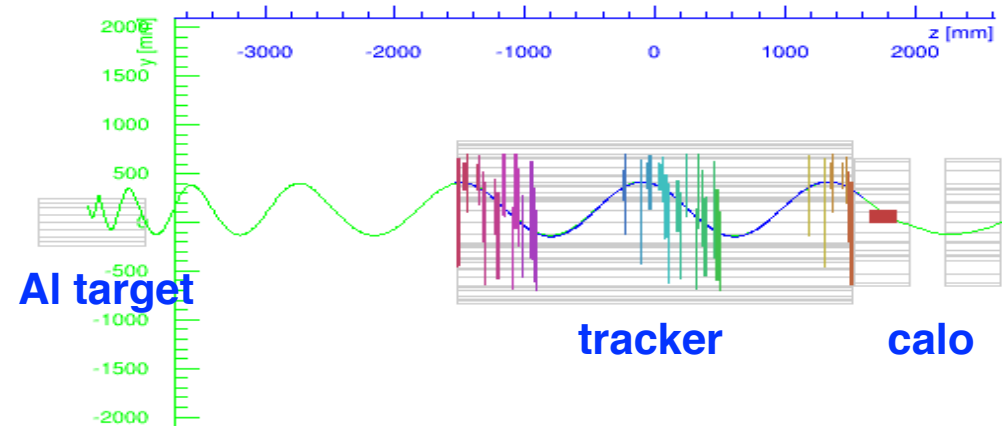
- μ decay-in-orbit:
 - ✓ low-mass tracker with high performance
- Cosmic-induced background
- Antiproton-induced background
- Radiative π capture

- μ decay-in-orbit:
 - ✓ low-mass tracker with high performance
- **Cosmic-induced background:**
 - ✓ **cosmic ray veto and PID**
- Antiproton-induced background
- Radiative π capture

- Veto system covers entire DS and half TS
- 4 layers of scintillator
 - ❖ each bar is $5 \times 2 \times \sim 450 \text{ cm}^3$
 - ❖ 2 WLS fibers/bar
 - ❖ read out at both ends with SiPM
- inefficiency $< 10^{-4}$



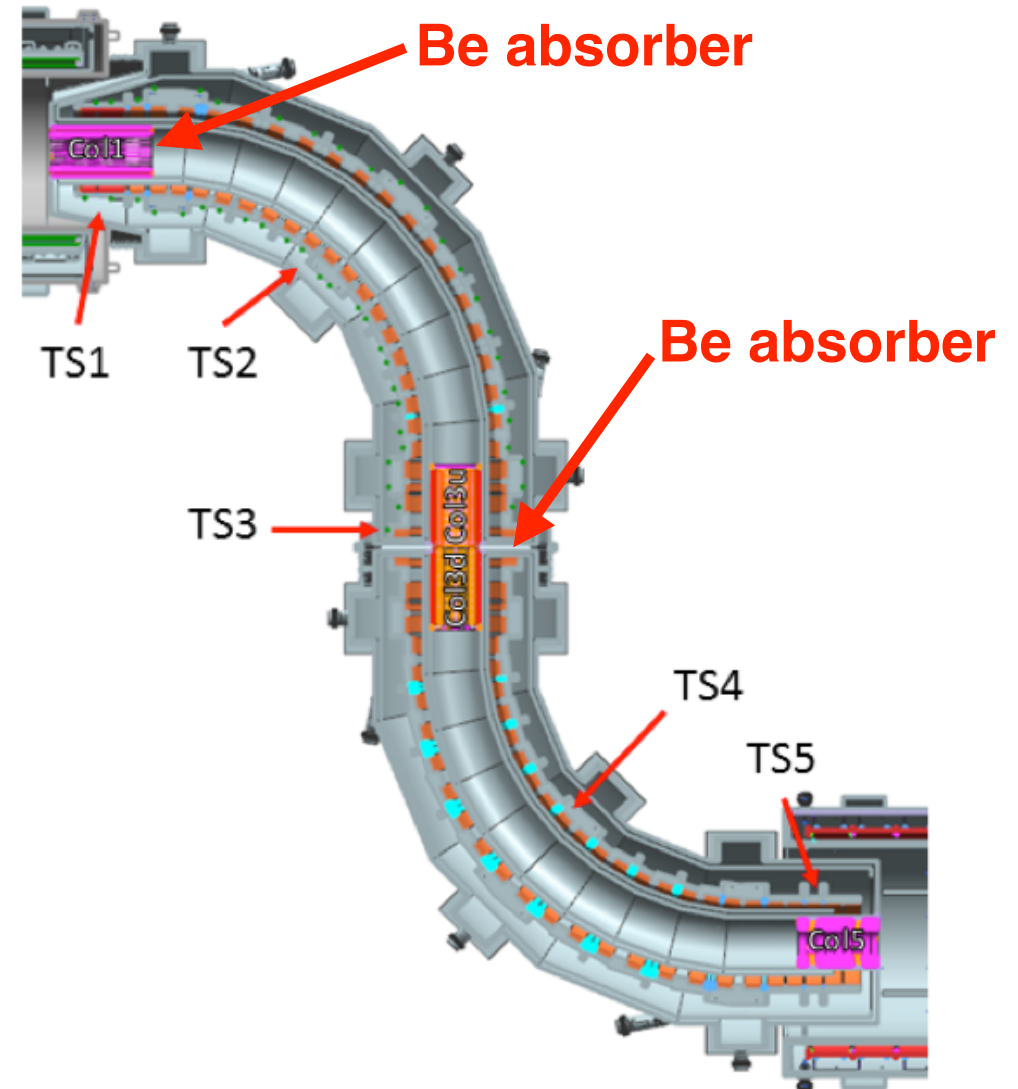
μ mimicking the signal



- μ decay-in-orbit:
 - ✓ low-mass tracker with high performance
- Cosmic-induced background:
 - ✓ cosmic ray veto and PID
- **Antiproton-induced background**
 - ✓ **beam line and PID**
- Radiative π capture

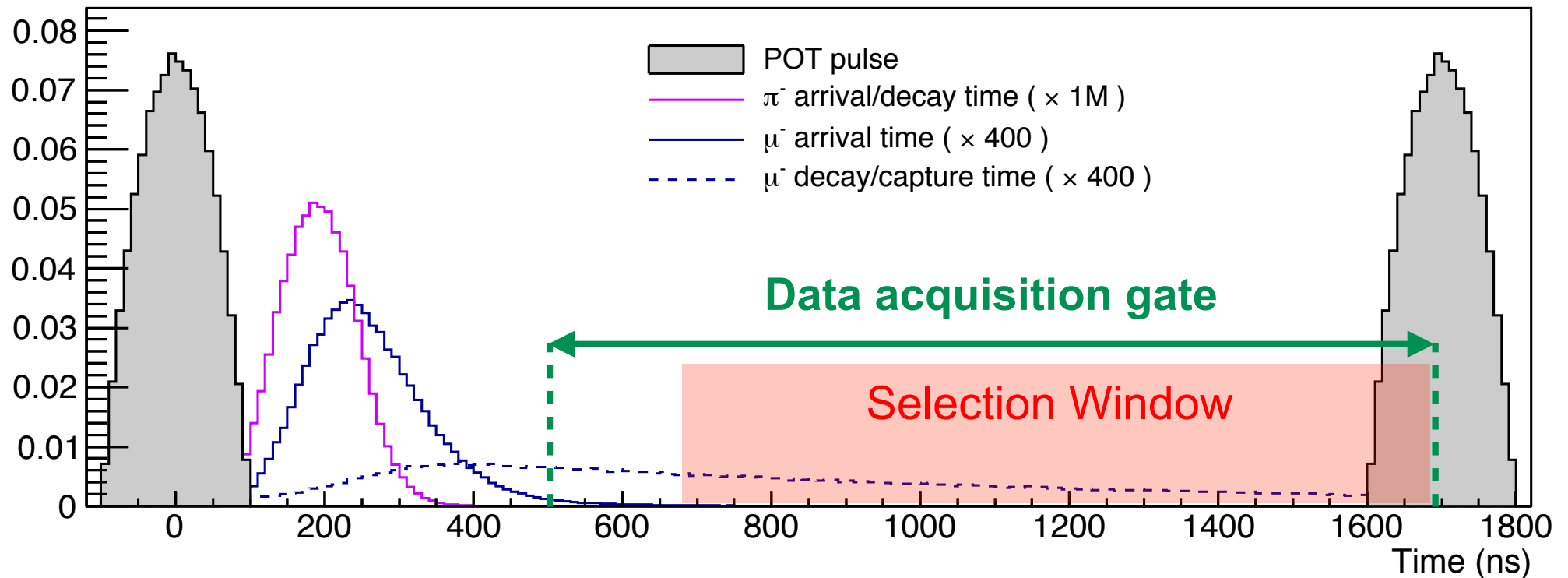
Transport solenoid - top view

- \bar{p} reaching the Detector Solenoid can annihilate in the Al stopping target
 - ❖ $\sim 2\text{GeV}$ of shower created
- **2 Be absorbers** in the Transport Solenoid (TS) are used to limit the \bar{p} flux:
 - ❖ at the **entrance** of the TS
 - ❖ in the **middle** of the TS



- μ decay-in-orbit:
 - ✓ low-mass tracker with high performance
- Cosmic-induced background:
 - ✓ cosmic ray veto and PID
- Antiproton-induced background
 - ✓ beam line and PID
- **Radiative π capture: $\pi^- + N \rightarrow \gamma + N'$**
 - ✓ **pulsed beam and extinction of out-of-time protons**

- Beam period : $1.7 \mu\text{s} \sim 2 \times \tau_{\mu}^{Al}$
- Beam intensity: 3.15×10^7 p/bunch
- duty cycle : $\sim 30\%$
- out-of-time protons / in-time protons $< 10^{-10}$

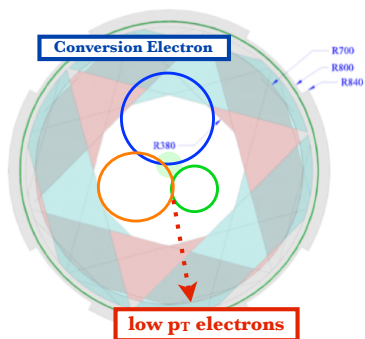


- 18 stations with straws transverse to the beam
- Straw technology employed:
 - ✓ 5 mm diameter, 15 μm Mylar walls
 - ✓ 25 μm Au-plated W sense wire
 - ✓ 80/20 Ar/CO₂ with HV \sim 1500 V
- Inner 38 cm un-instrumented:
 - ✓ blind to beam flash
 - ✓ blind to low pT charged particles coming from the Al target

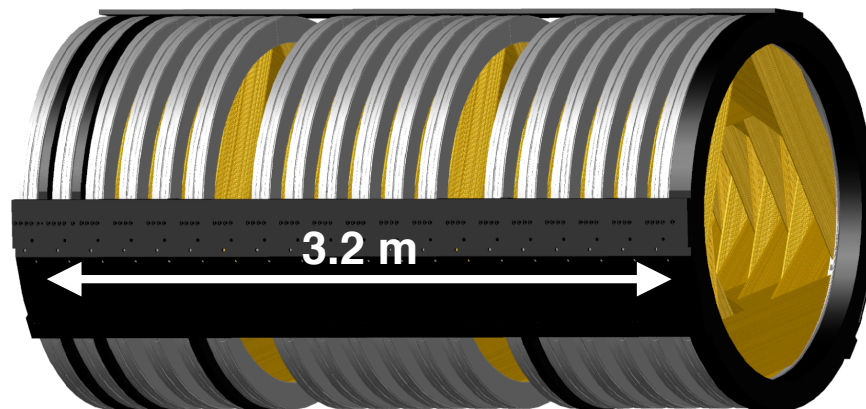
straw tube



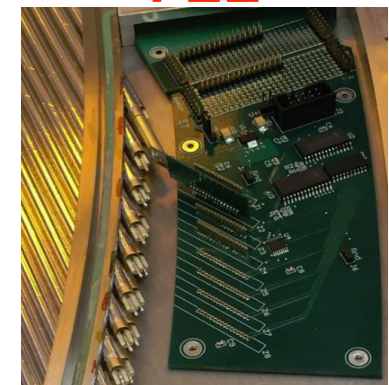
station



x18

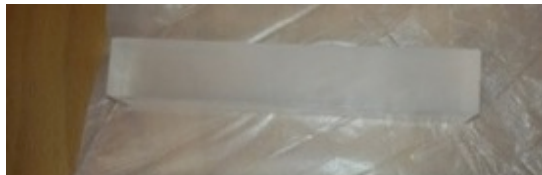


FEE

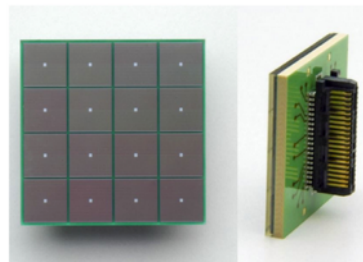


- 2 disks; each disk contains 860 undoped CsI crystals $20 \times 3.4 \times 3.4 \text{ cm}^3$
- Readout by large area MPPC + waveform digitizer boards @ 200 MHz
- Allows to measure: E/p and TOF to provide **Particle identification**
- Improve track search via a calorimeter-seed pattern recognition
- Time resolution $\sigma_t < 200 \text{ ps}$ @ 100 MeV measured @ BTF in Frascati

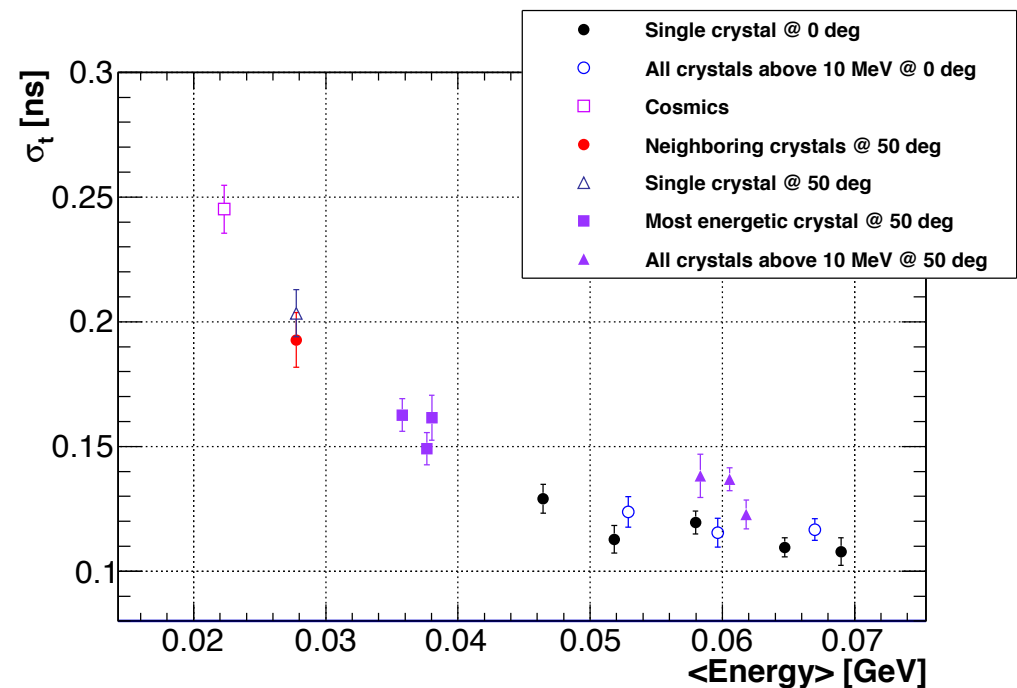
undoped CsI



MPPC



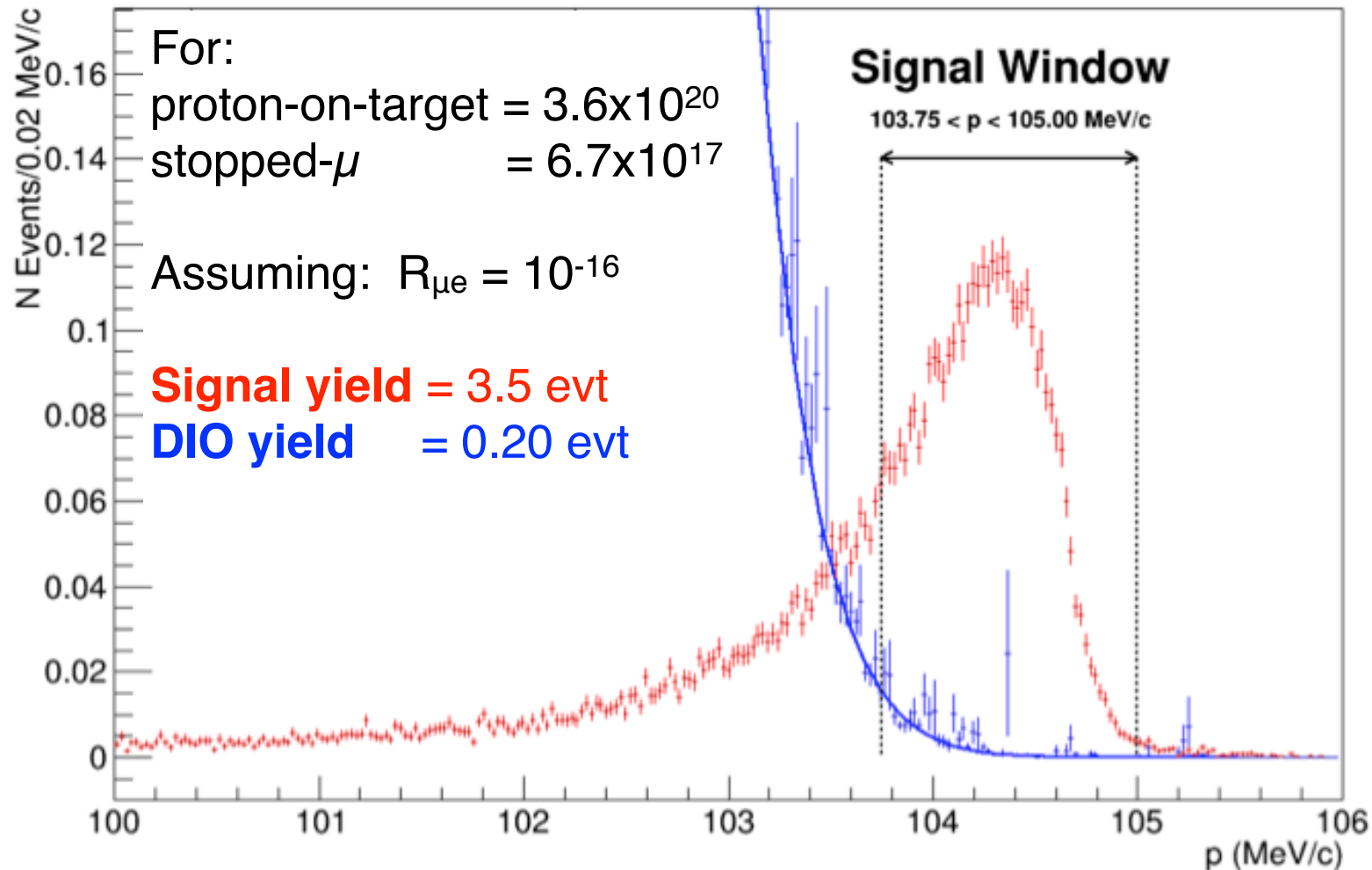
Beam test @ BTF in Frascati



Calorimeter prototype

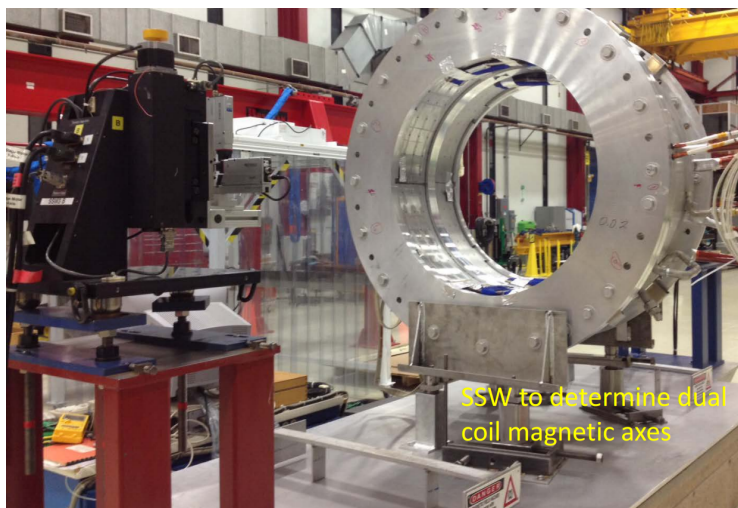


Reconstructed e^- Momentum

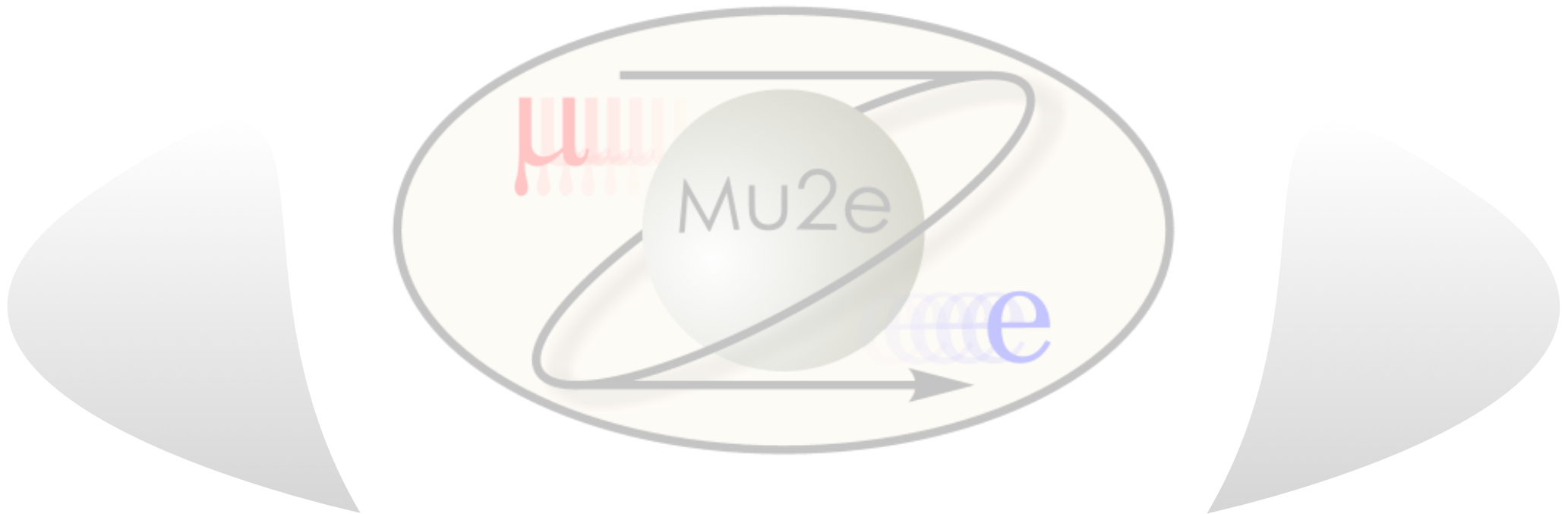


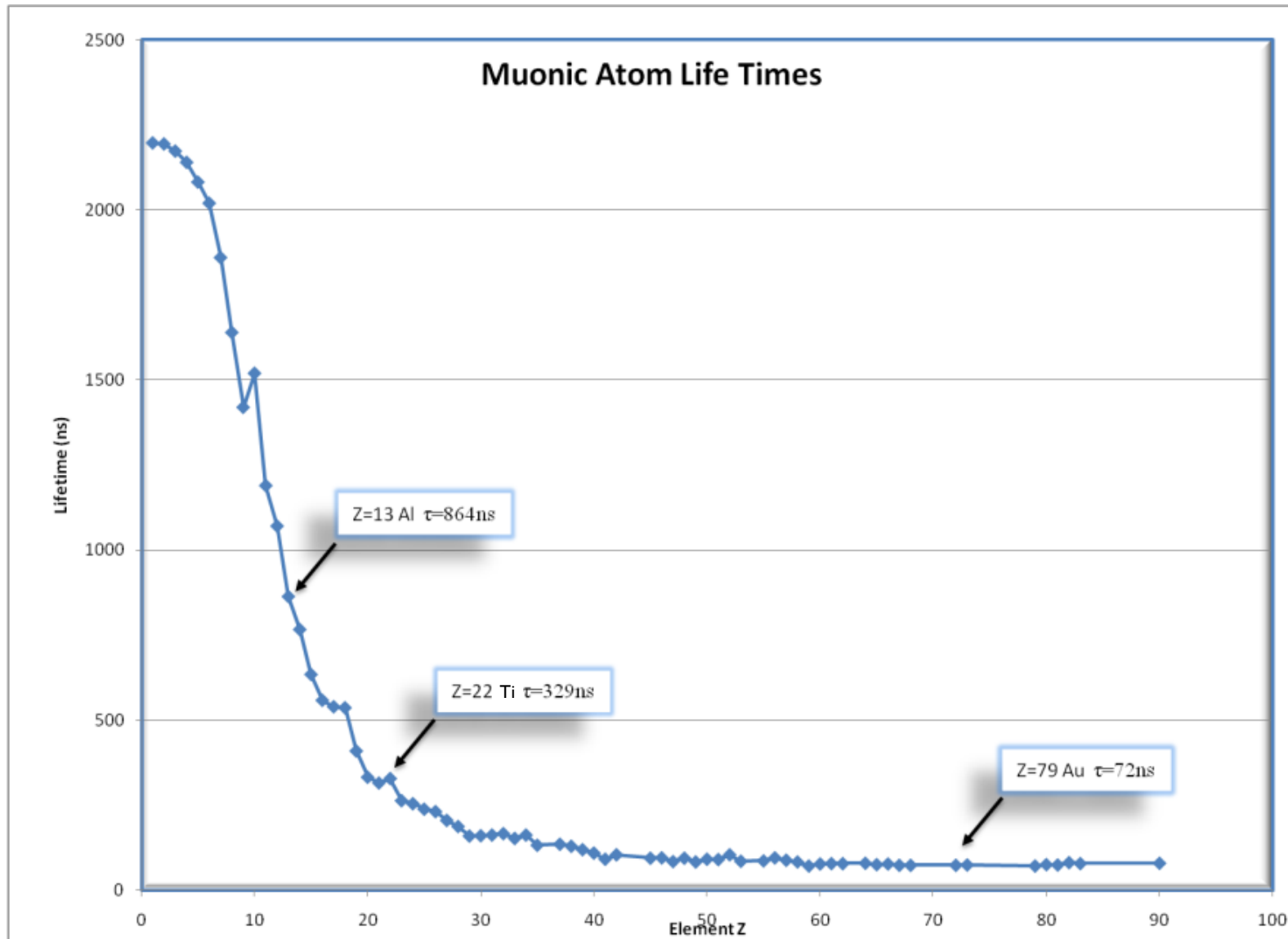
- Single-event-sensitivity = 2.9×10^{-17}
- Total background < 0.5 events

- Mu2e is an experiment to search for CLFV in μ coherent conversion
 - ✓ aims 4 orders of magnitude improvement
 - ✓ expected SES = 2.9×10^{-17}
 - ✓ any signal would be an un-ambiguous proof of physics BSM
- R&D phase mostly completed
- Civil construction and magnets procurement already started
- Data taking starts on 2021

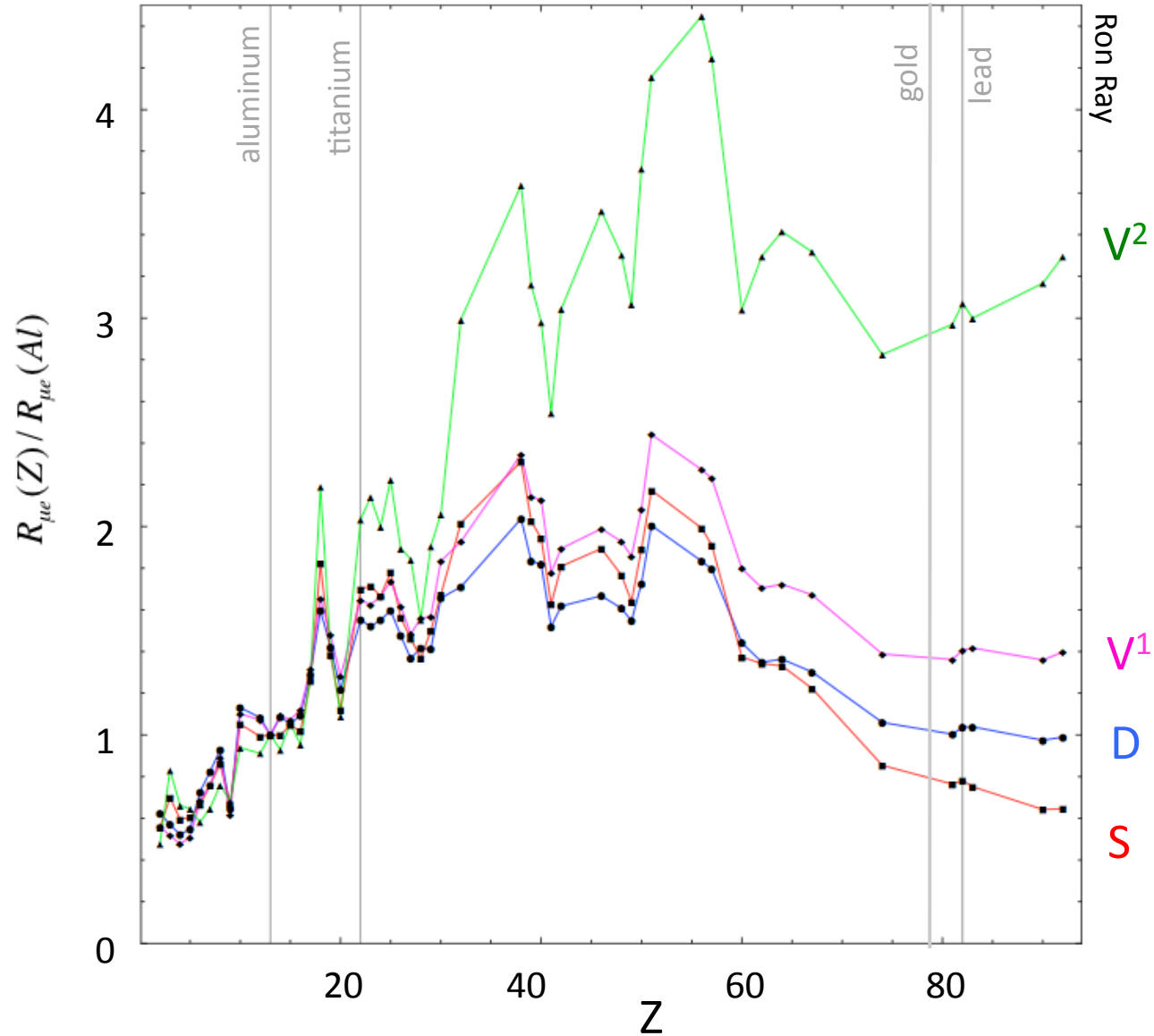


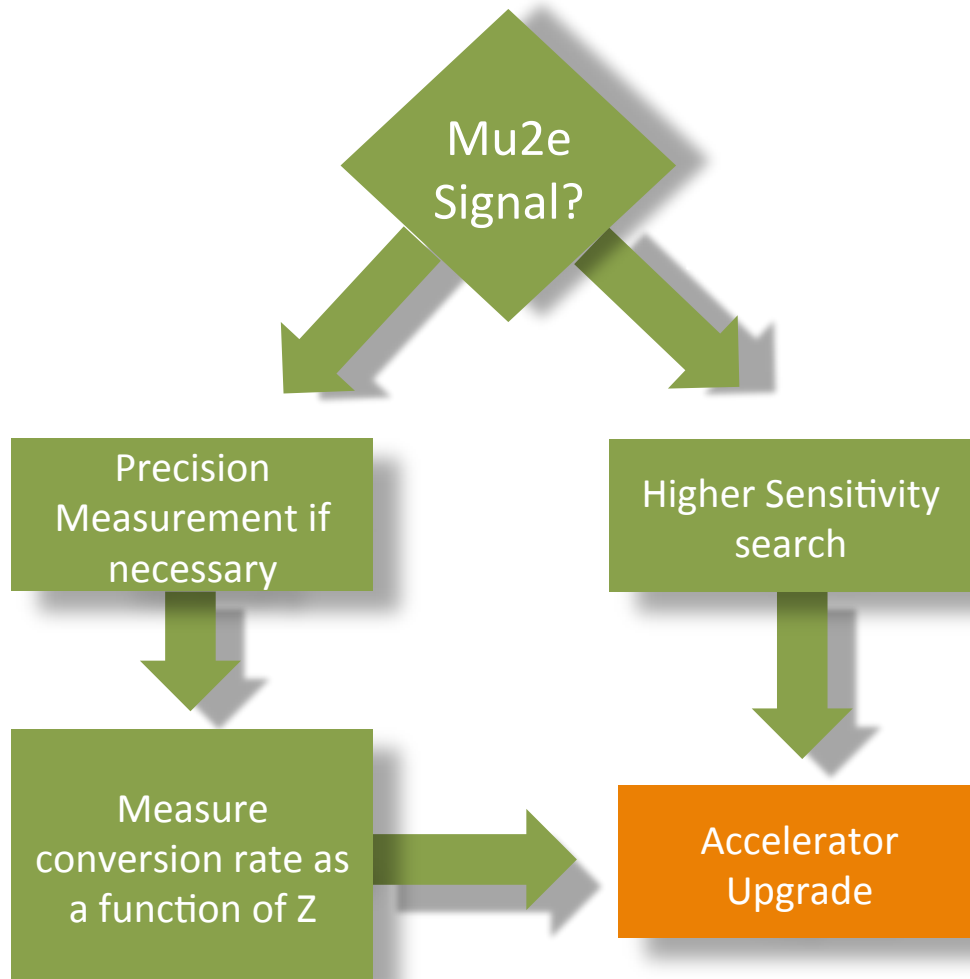
backup slides





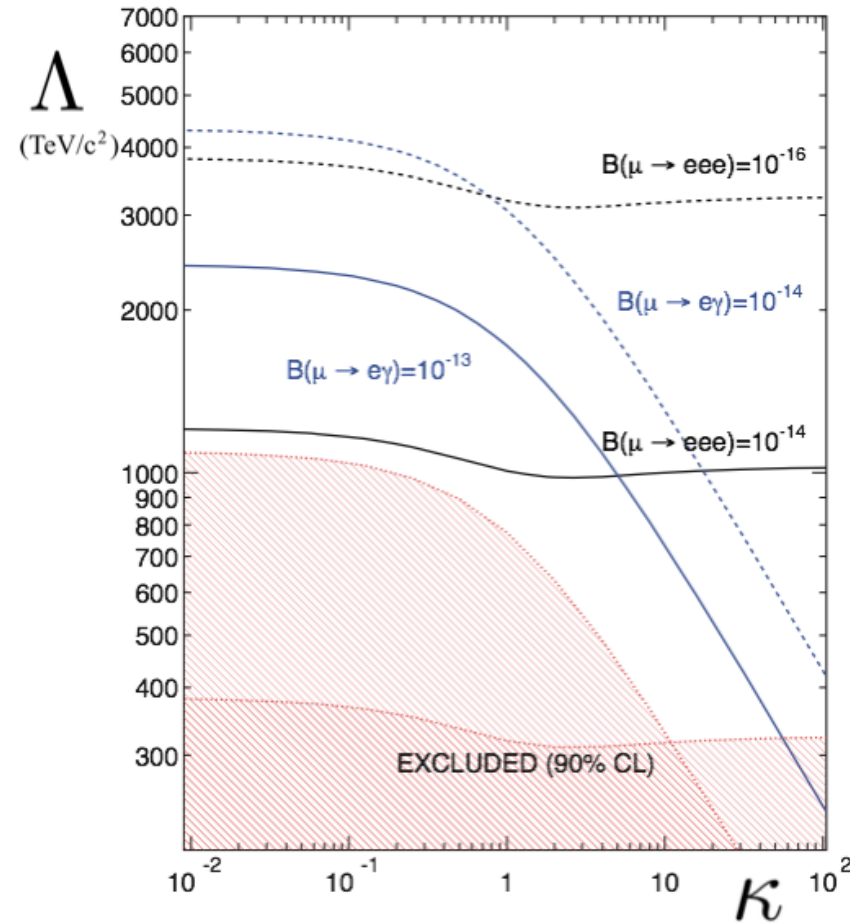
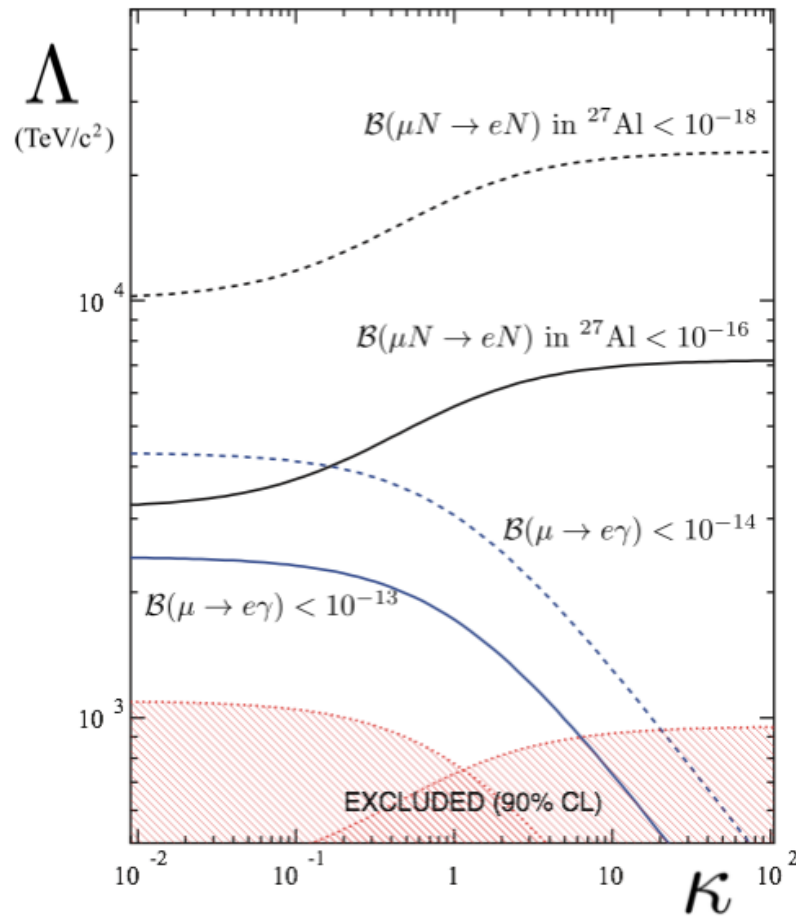
V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)





- A next-generation Mu2e experiment makes sense in all scenarios:
 - ✓ Push sensitivity or
 - ✓ Study underlying new physics
 - ✓ Will need more protons upgrade accelerator
 - ✓ **Snowmass white paper**, arXiv:1307.1116

MUSE Model independent Lagrangian



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

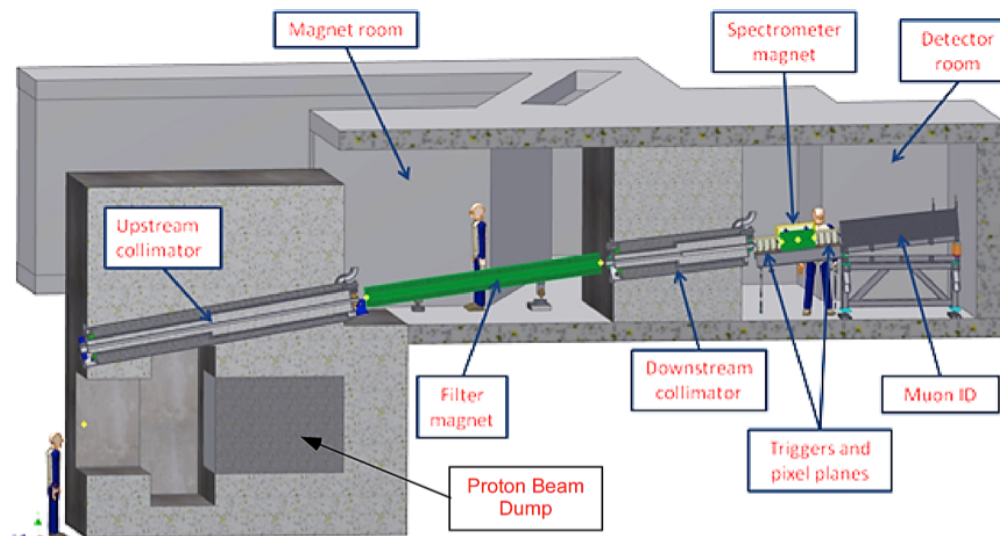
“dipole term”

“contact term”

Process	Upper limit
$\mu^+ \rightarrow e^+ \gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \rightarrow e^+ e^- e^+$	$< 1.0 \times 10^{-12}$
$\mu^- \text{Ti} \rightarrow e^- \text{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^- \text{Au} \rightarrow e^- \text{Au}$	$< 7 \times 10^{-13}$
$\mu^+ e^- \rightarrow \mu^- e^+$	$< 3.0 \times 10^{-13}$
$\tau \rightarrow e \gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \rightarrow \mu \gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \rightarrow e^- e^+ e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \rightarrow e^- \mu^+ \mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \rightarrow \mu^- e^+ e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \rightarrow e^+ \mu^- \mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \rightarrow \mu^+ e^- e^-$	$< 1.5 \times 10^{-8}$

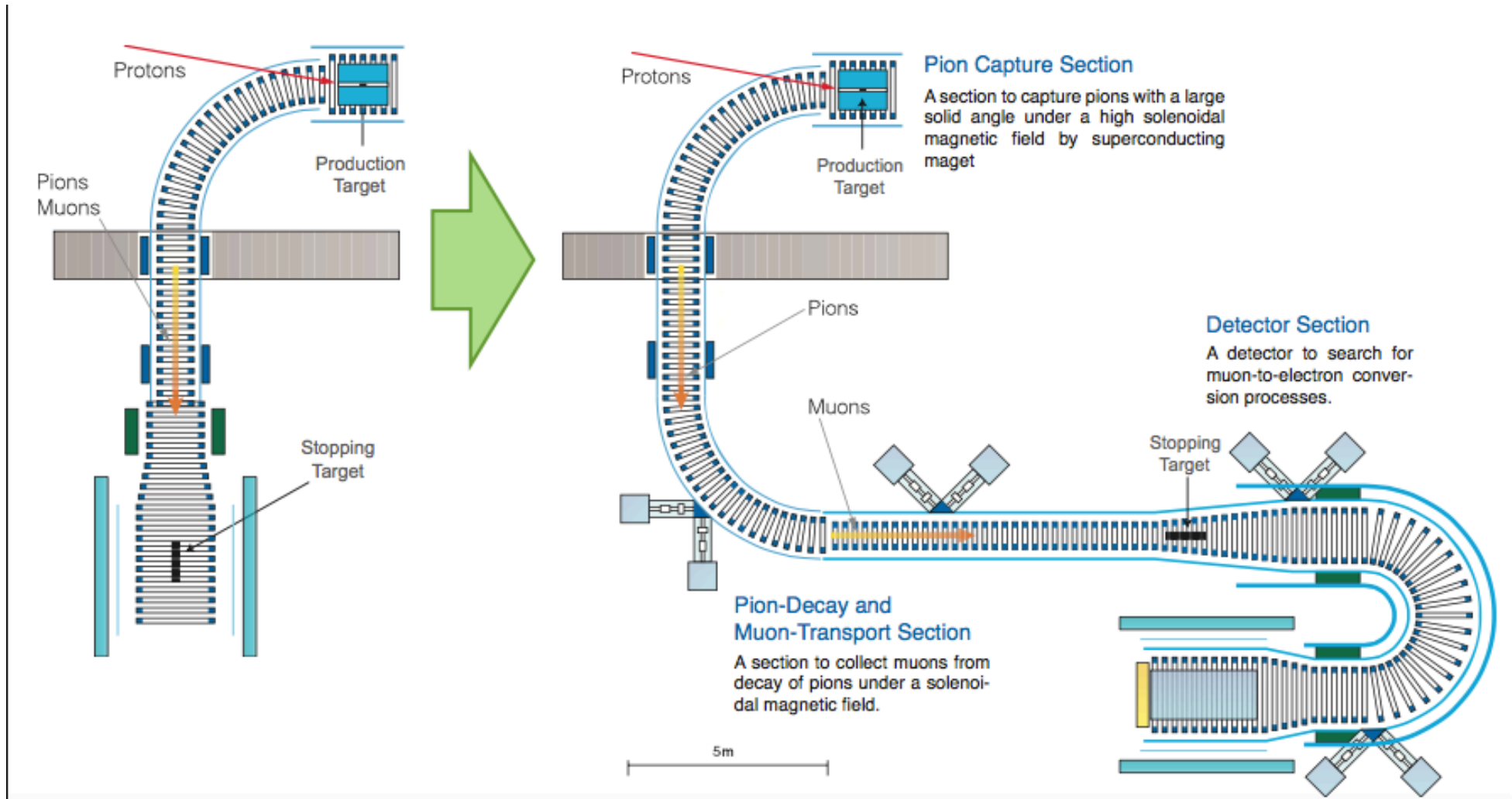
Process	Upper limit
$\pi^0 \rightarrow \mu e$	$< 8.6 \times 10^{-9}$
$K_L^0 \rightarrow \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \rightarrow \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$
$K_L^0 \rightarrow \pi^0 \mu^+ e^-$	$< 4.4 \times 10^{-10}$
$Z^0 \rightarrow \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \rightarrow \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \rightarrow \tau \mu$	$< 1.2 \times 10^{-6}$

- The RF structure of the Recycler provides some “intrinsic” extinction:
 - ✓ **Intrinsic extinction $\sim 10^{-5}$**
- A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
 - ✓ **AC dipole extinction $\sim 10^{-6} - 10^{-7}$**
- Together they provide a total extinction:
 - ✓ **Total extinction $\sim 10^{-11} - 10^{-12}$**
- Extinction measured using a detector system: Si-pixel + sampling EMC

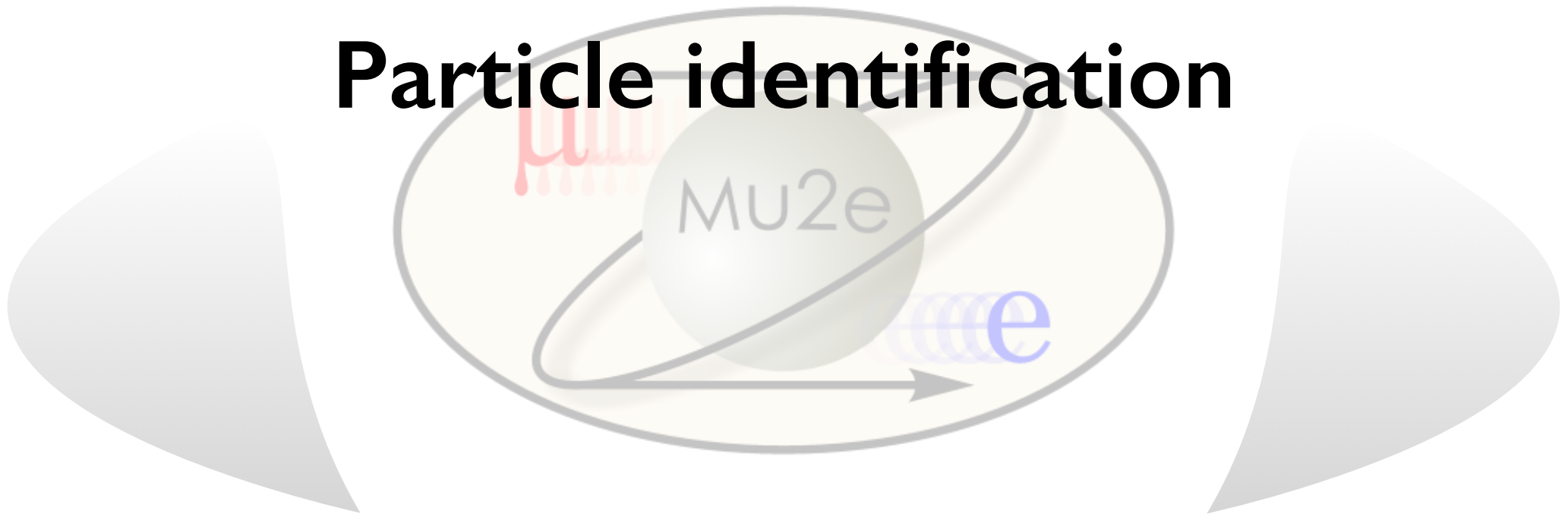


phase I

phase II



Particle identification



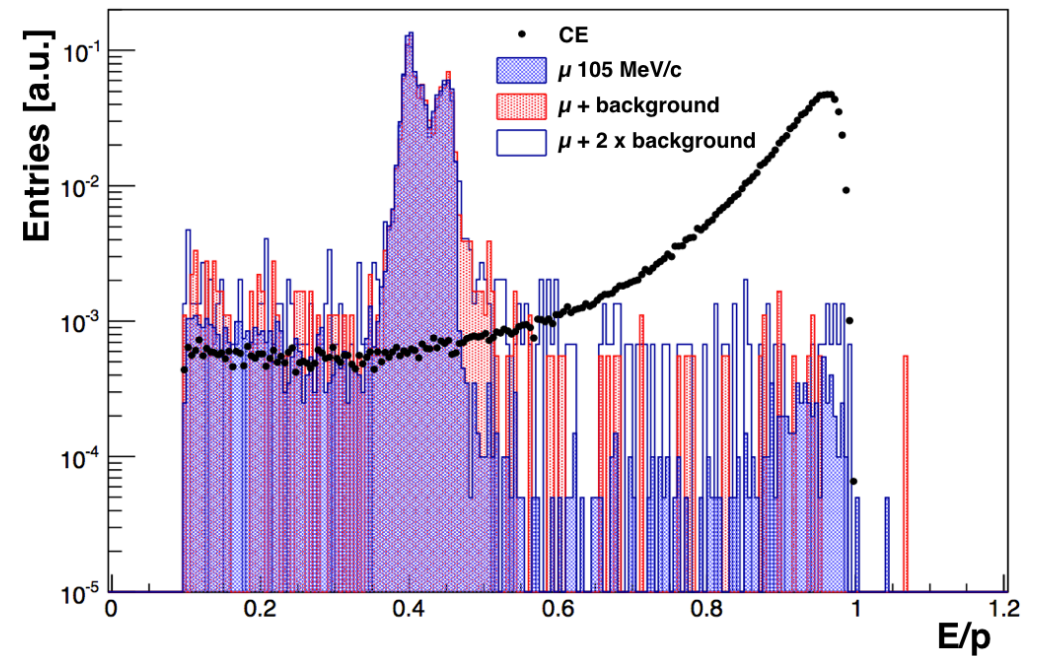
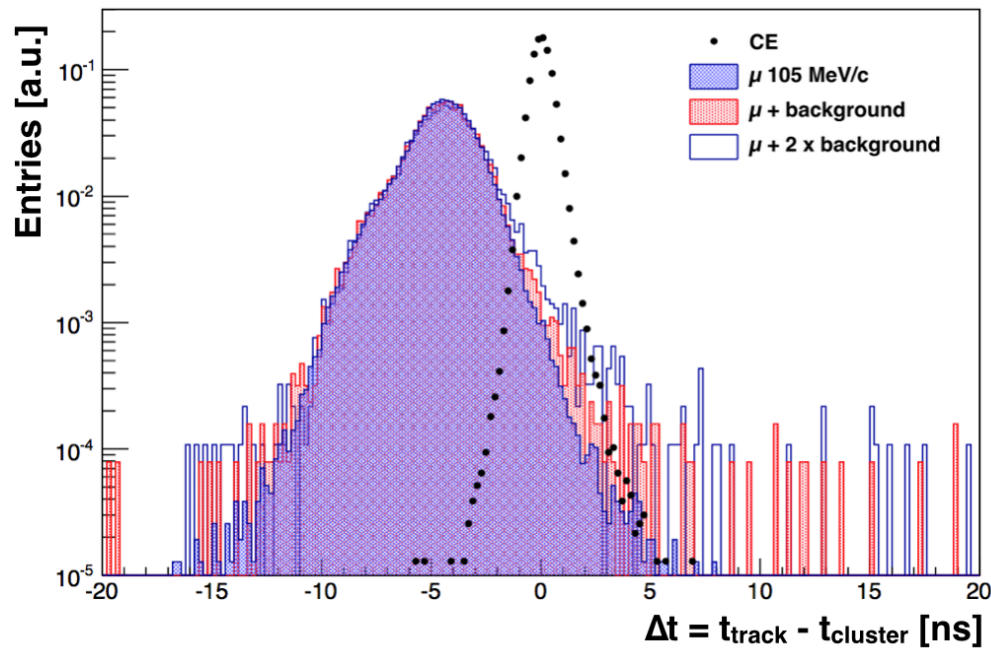
- **Cosmic ray and antiproton** induced background can be divided into 2 main categories:
 1. e^- generated via interactions producing a track mimicking the CE
 2. non-electron particles (μ and π) that are reconstructed as an “electron-like” track mimicking the CE
- (1) represents the irreducible background, while (2) can be suppressed using a PID method

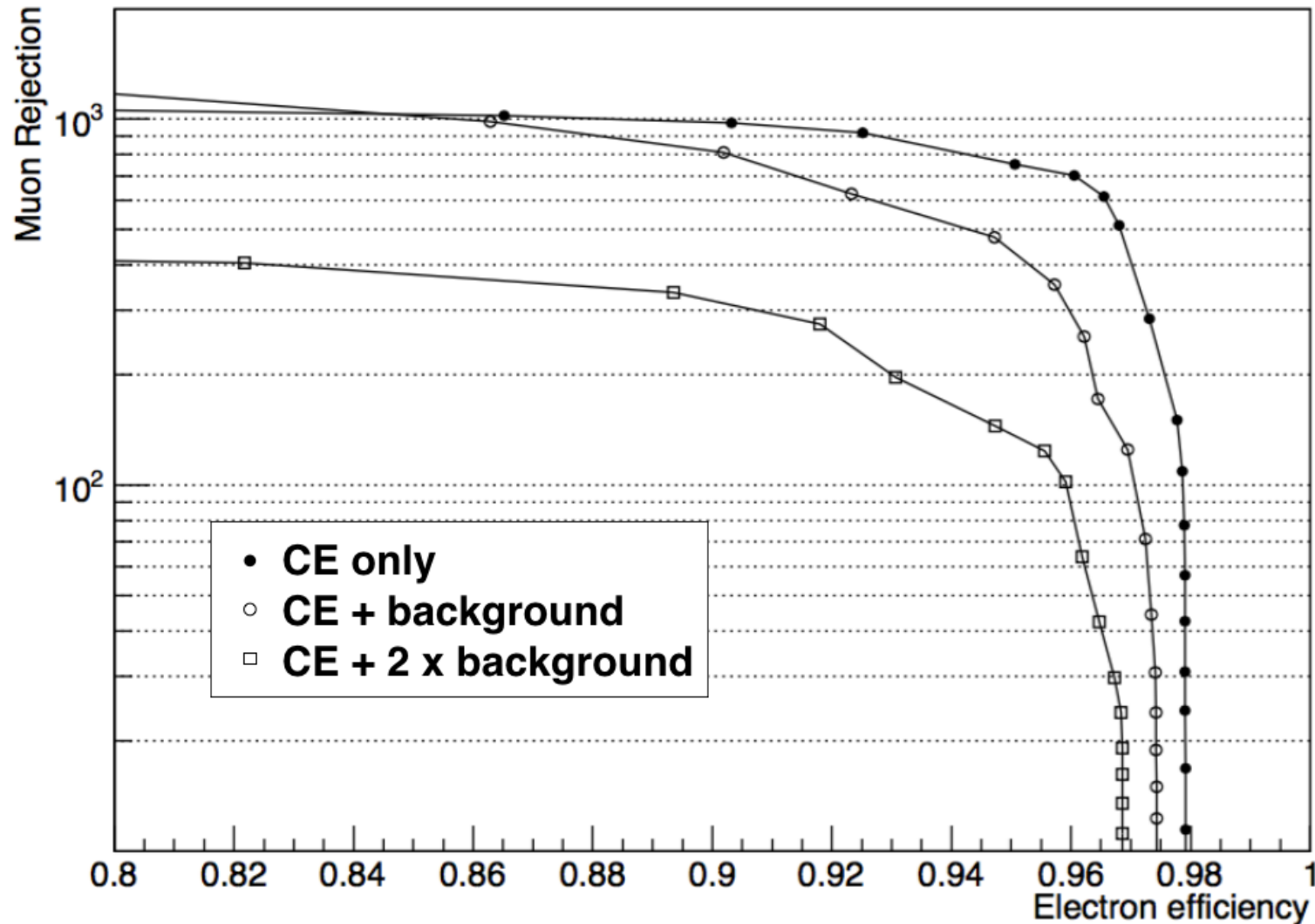
Mu2e PID method:

- Information from reconstructed tracks and calorimeter clusters are combined for identifying group (2)
- Stringent requirement from Cosmic: **μ -rejection factor ≥ 200**

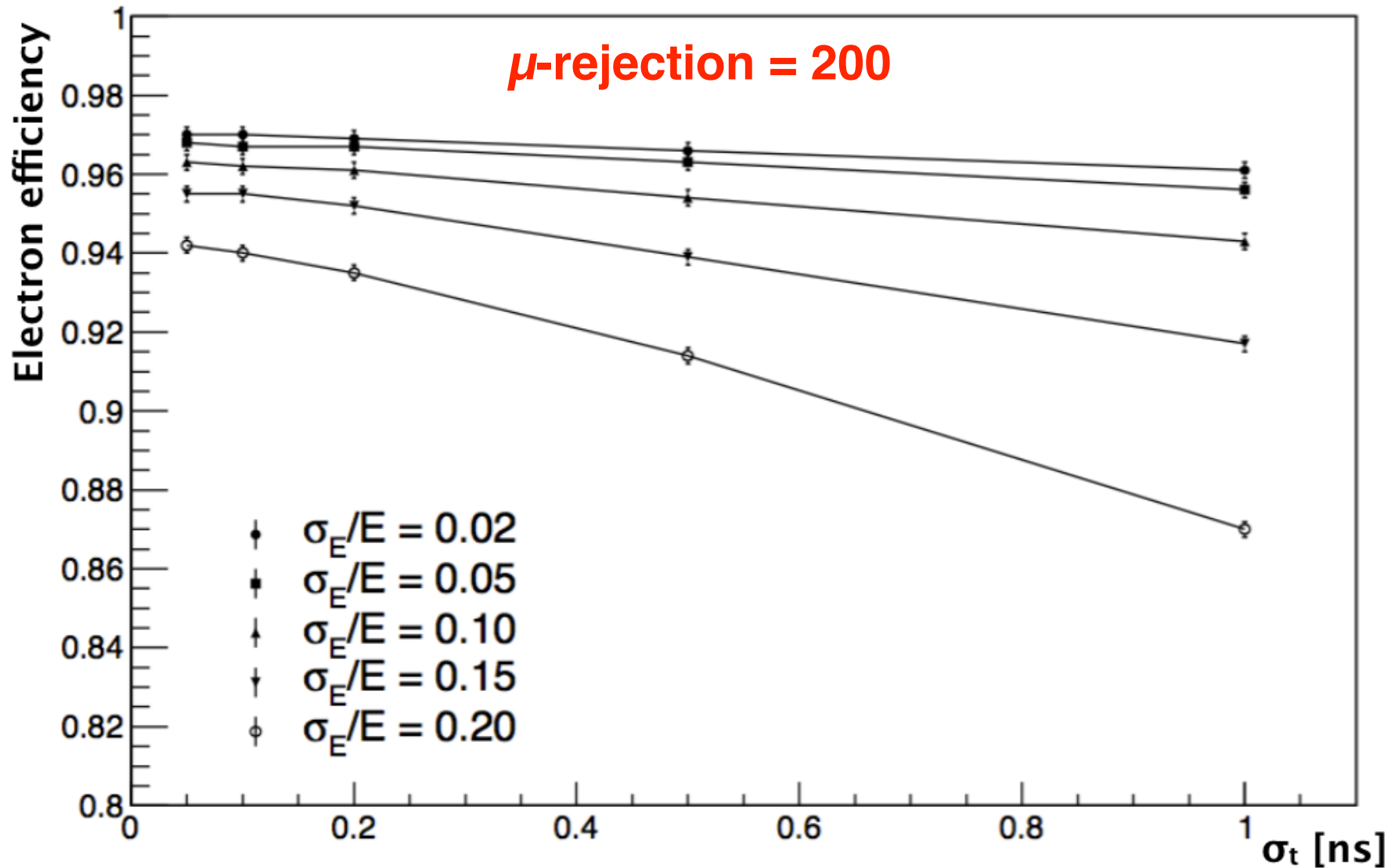
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have $\beta \sim 0.7$ and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{\text{track}} - t_{\text{cluster}}$ and E/p :

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$



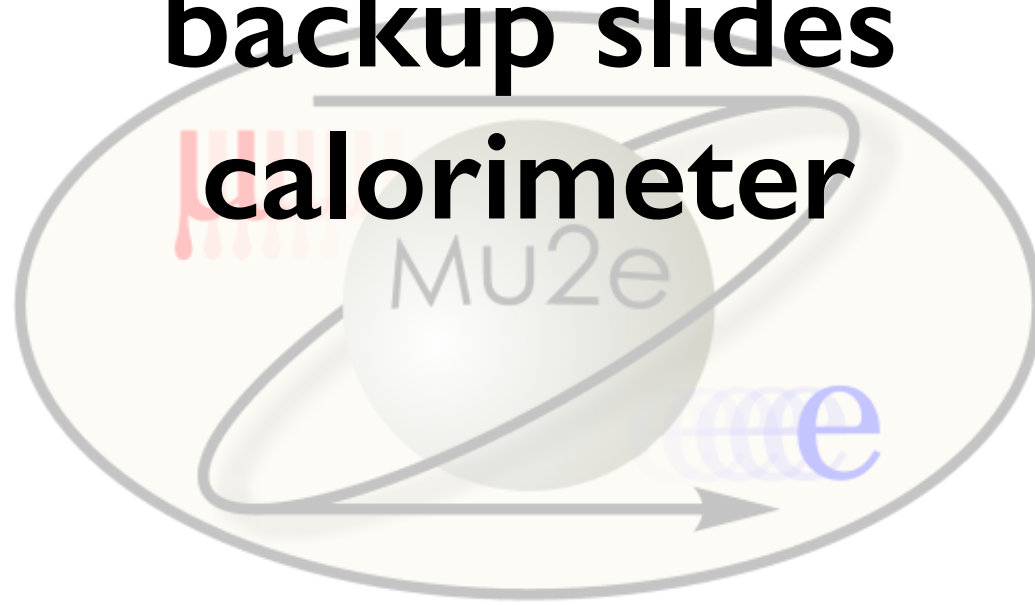


- A muon-rejection of 200 corresponds to a cut at $\ln L_{e/\mu} > 1.5$ and an e^- efficiency of $\sim 96\%$

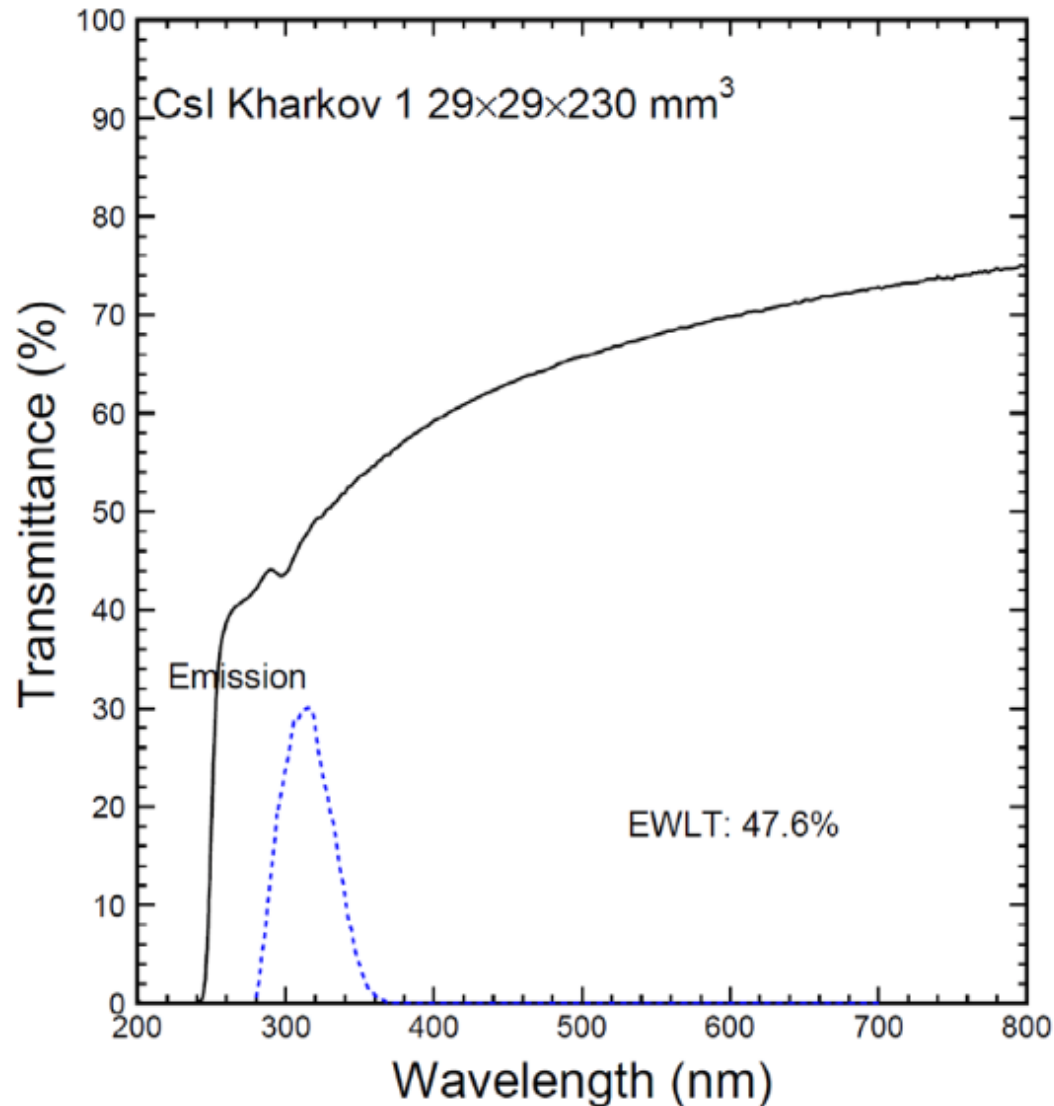


- In the range $\sigma_E/E < 0.1$ and $\sigma_t < 0.5$ ns the e^- efficiency is within 2%

backup slides calorimeter

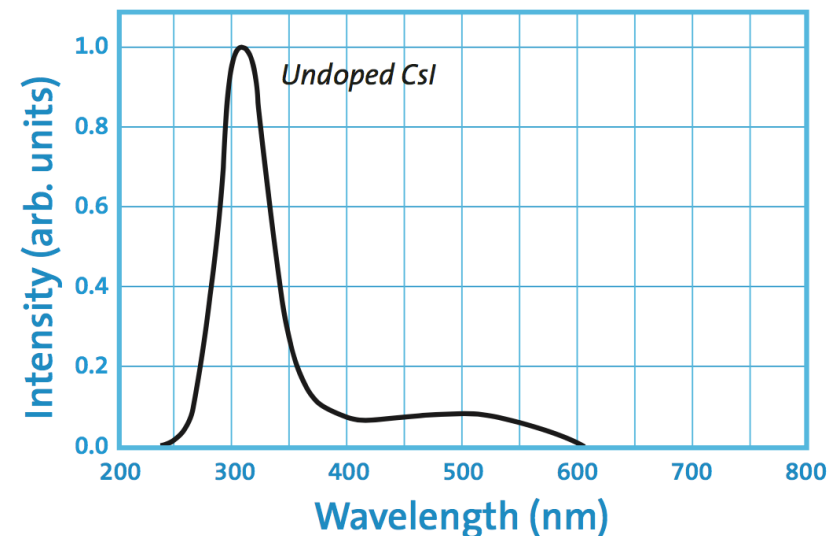


Crystal	BaF ₂	LYSO	CsI
Density [g/cm ³]	4.89	7.28	4.51
Radiation length [cm] X ₀	2.03	1.14	1.86
Molière radius [cm] R _m	3.10	2.07	3.57
Interaction length [cm]	30.7	20.9	39.3
dE/dx [MeV/cm]	6.5	10.0	5.56
Refractive Index at λ _{max}	1.50	1.82	1.95
Peak luminescence [nm]	220, 300	402	310
Decay time τ [ns]	0.9, 650	40	16
Light yield (compared to NaI(Tl)) [%]	4.1, 3.6	85	3.6
Light yield variation with temperature [%/°C]	0.1, -1.9	-0.2	-1.4
Hygroscopicity	Slight	None	Slight

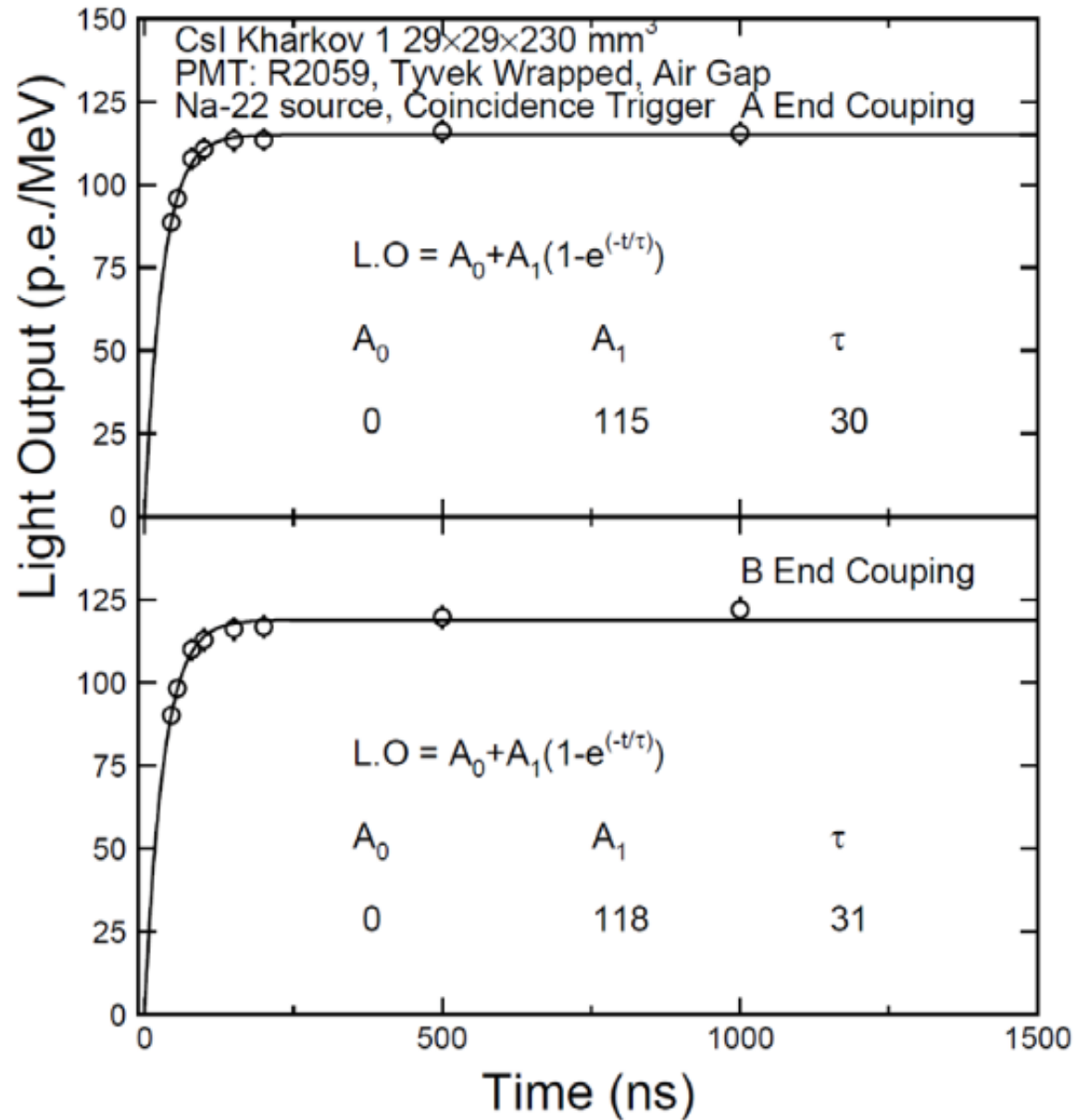


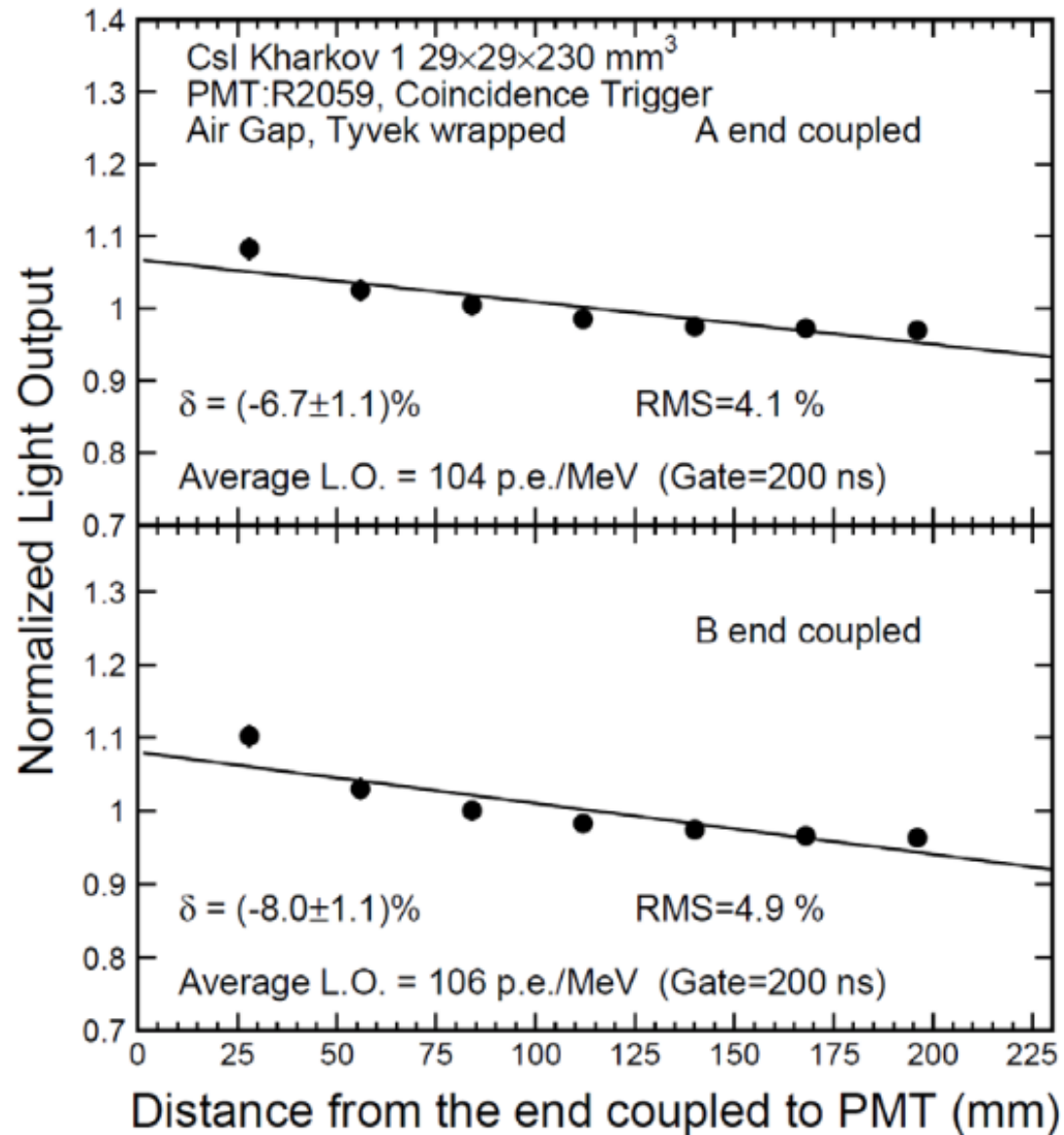
$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

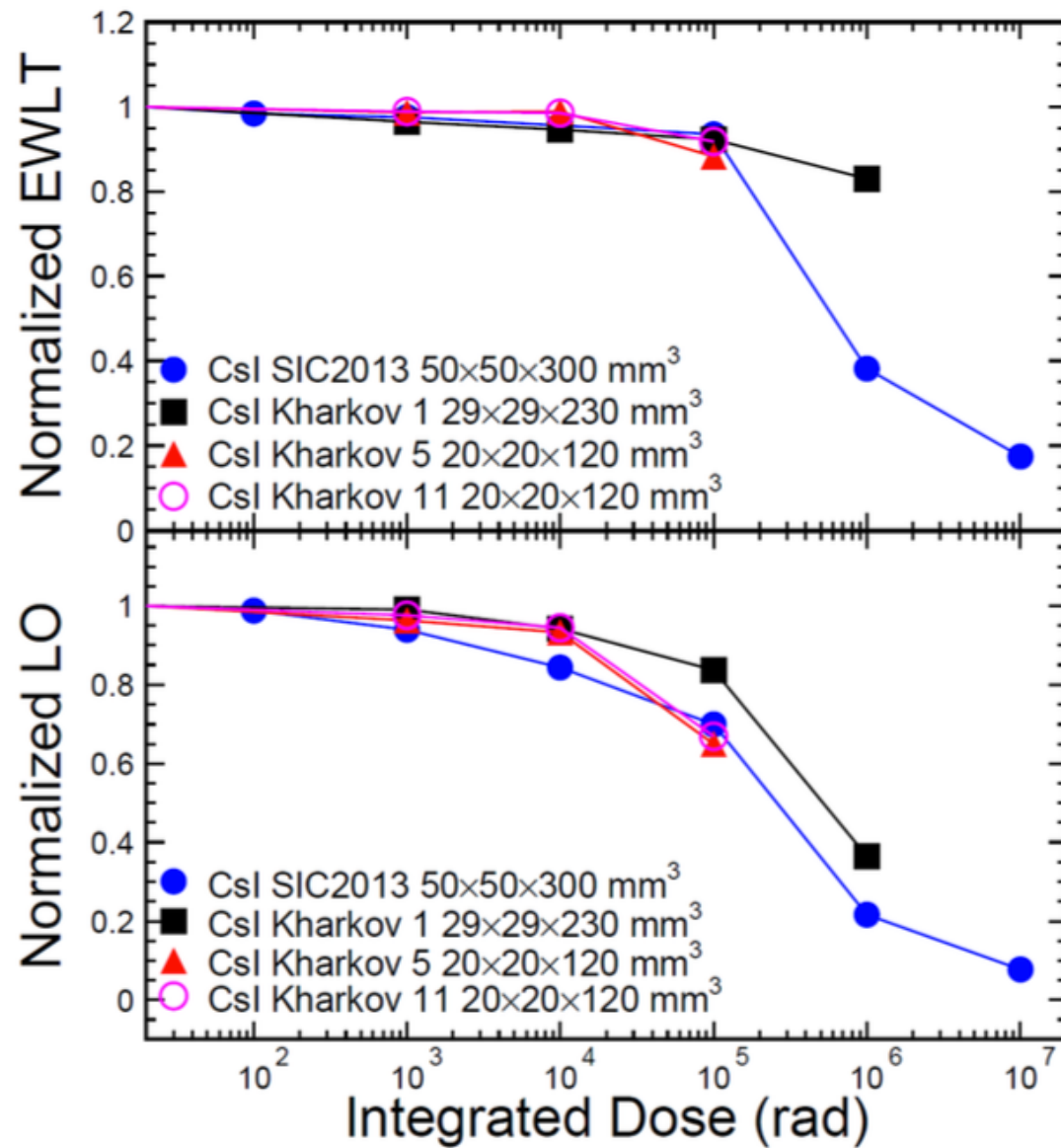
- where $LT(\lambda)$ is the light transmittance and $Em(\lambda)$ is the emission spectrum

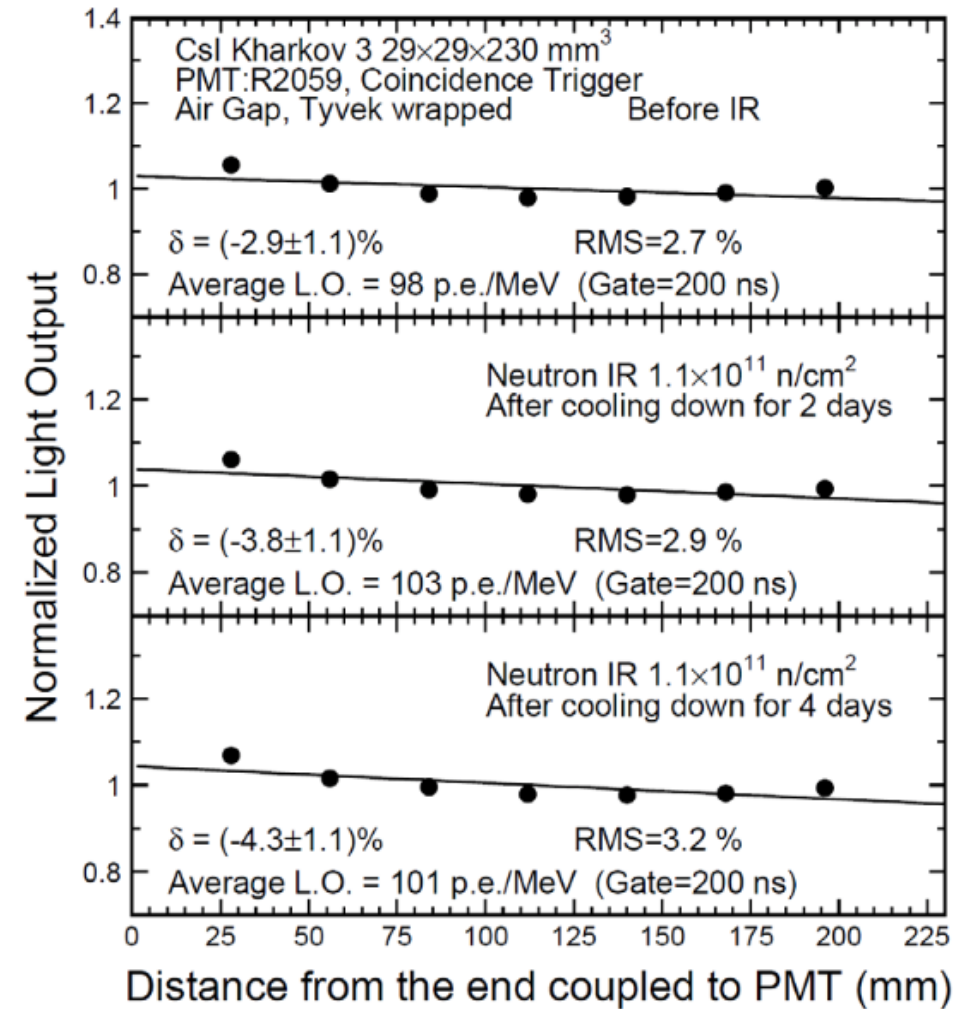
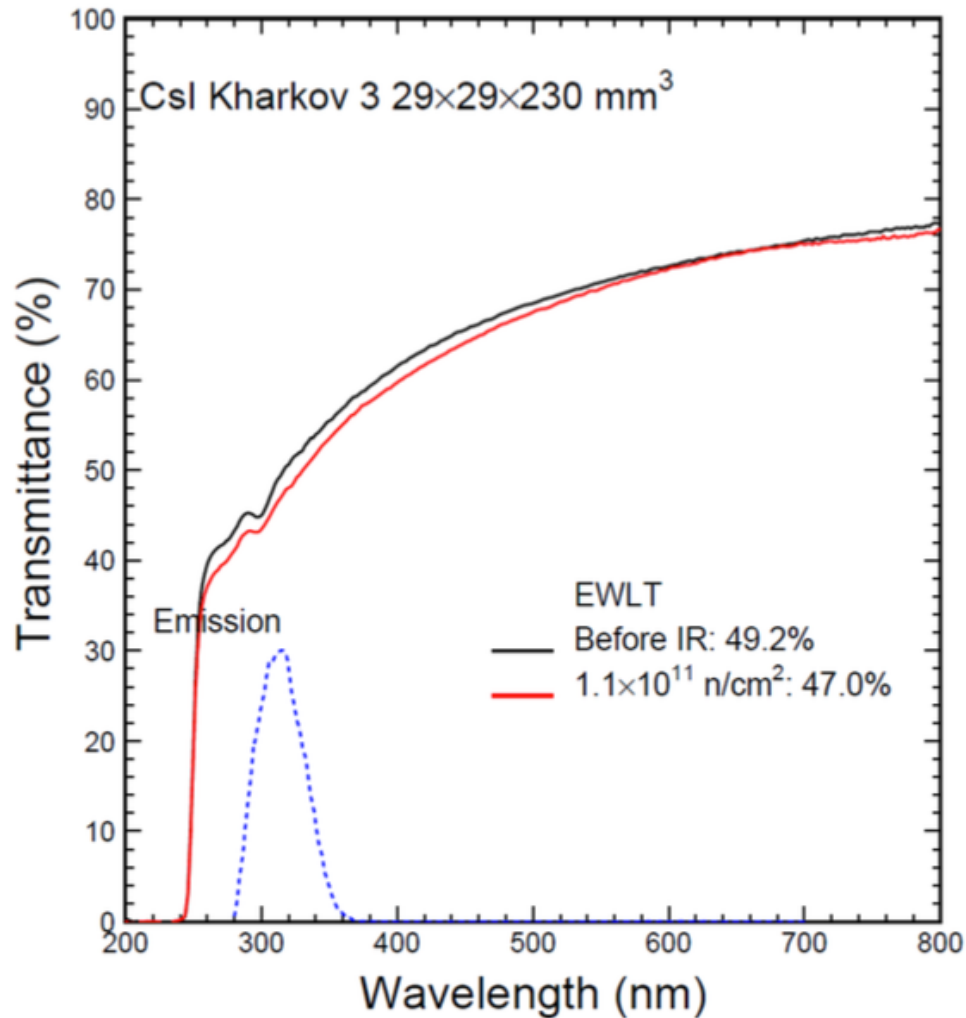


CsI Light Output



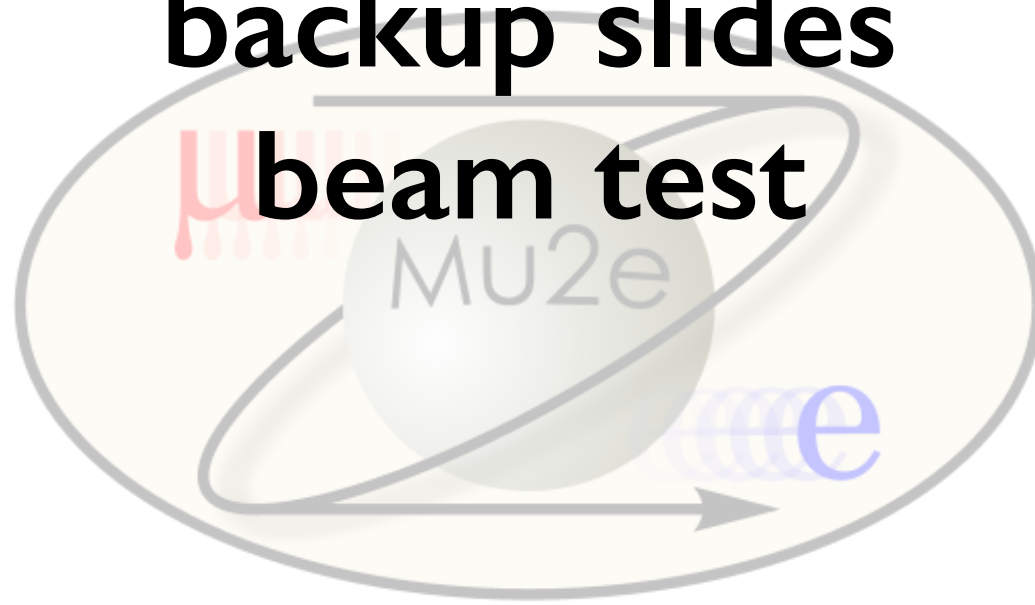


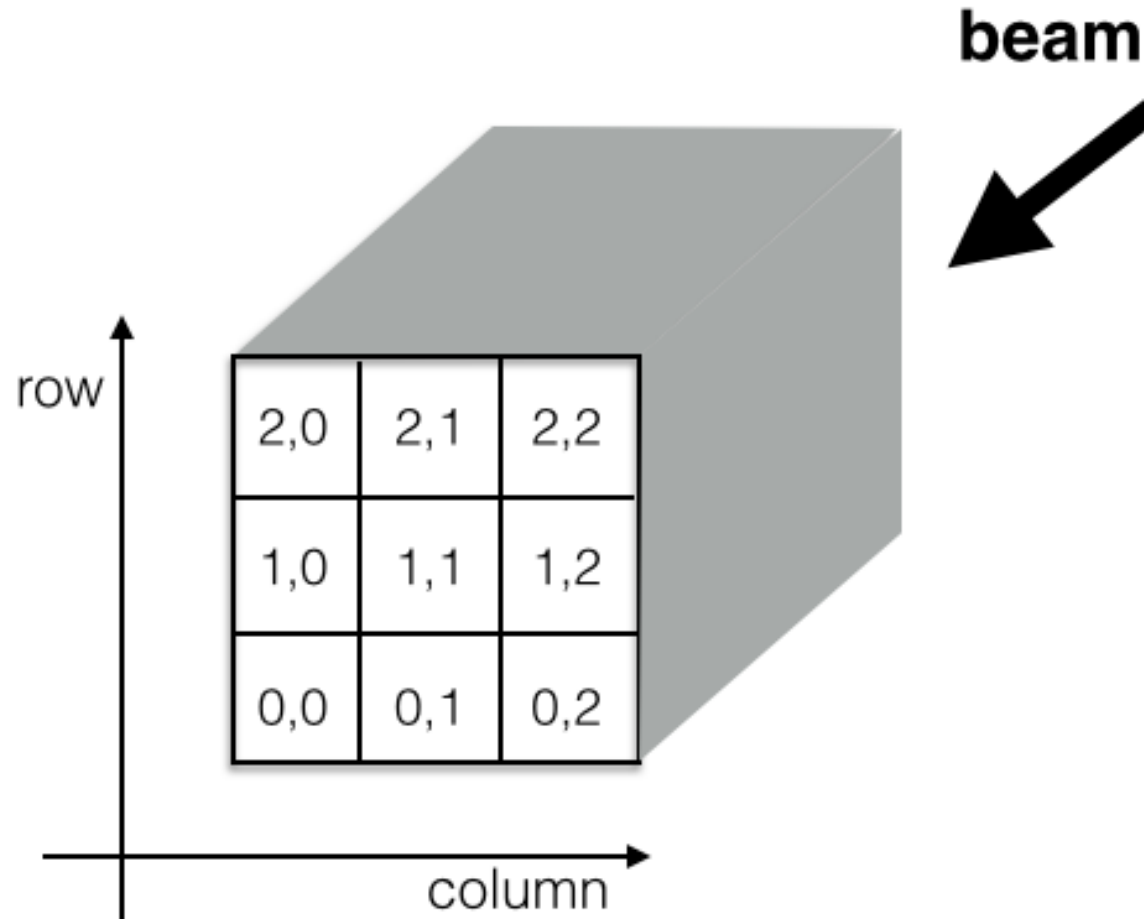




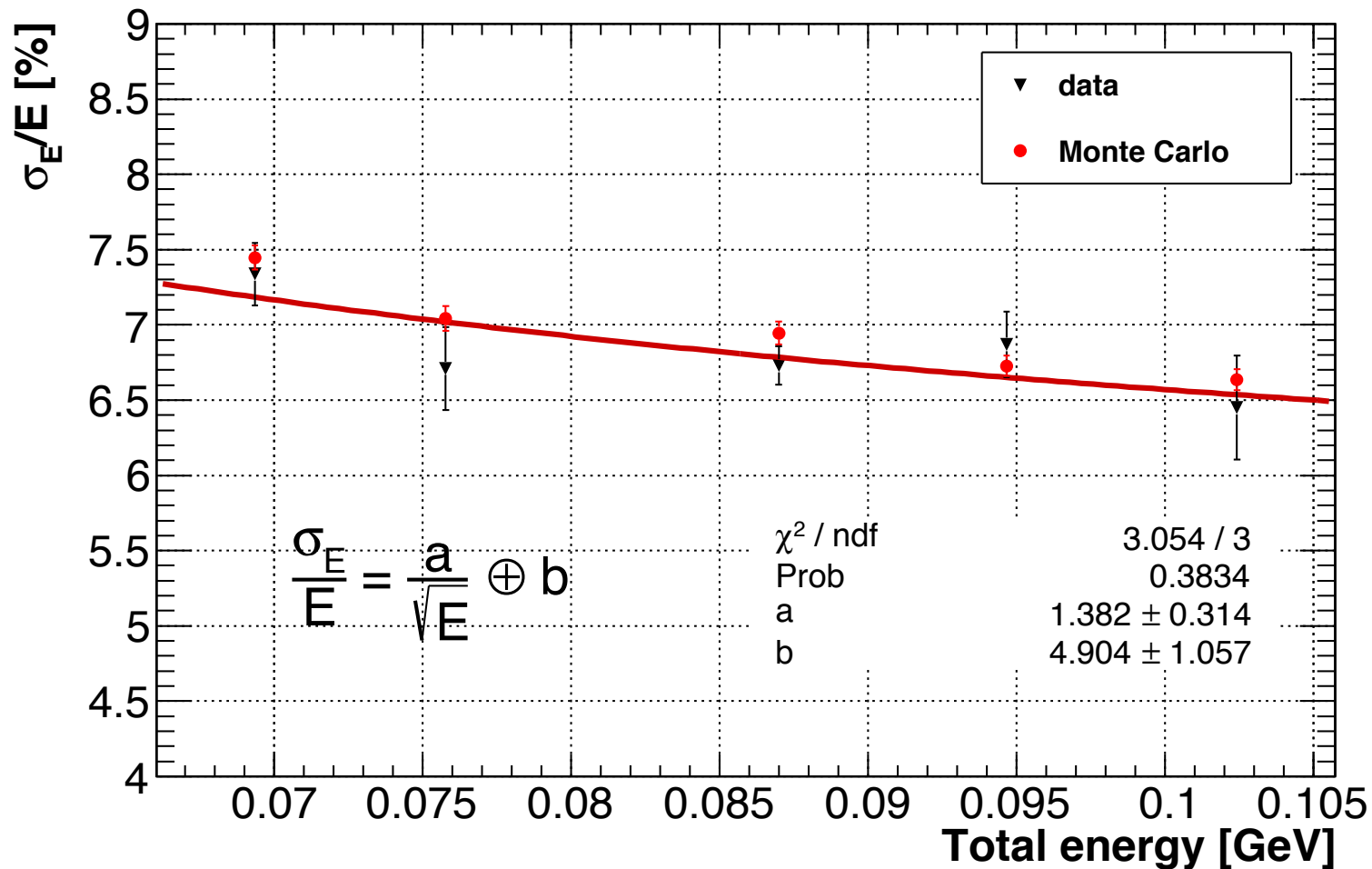
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μ beam test



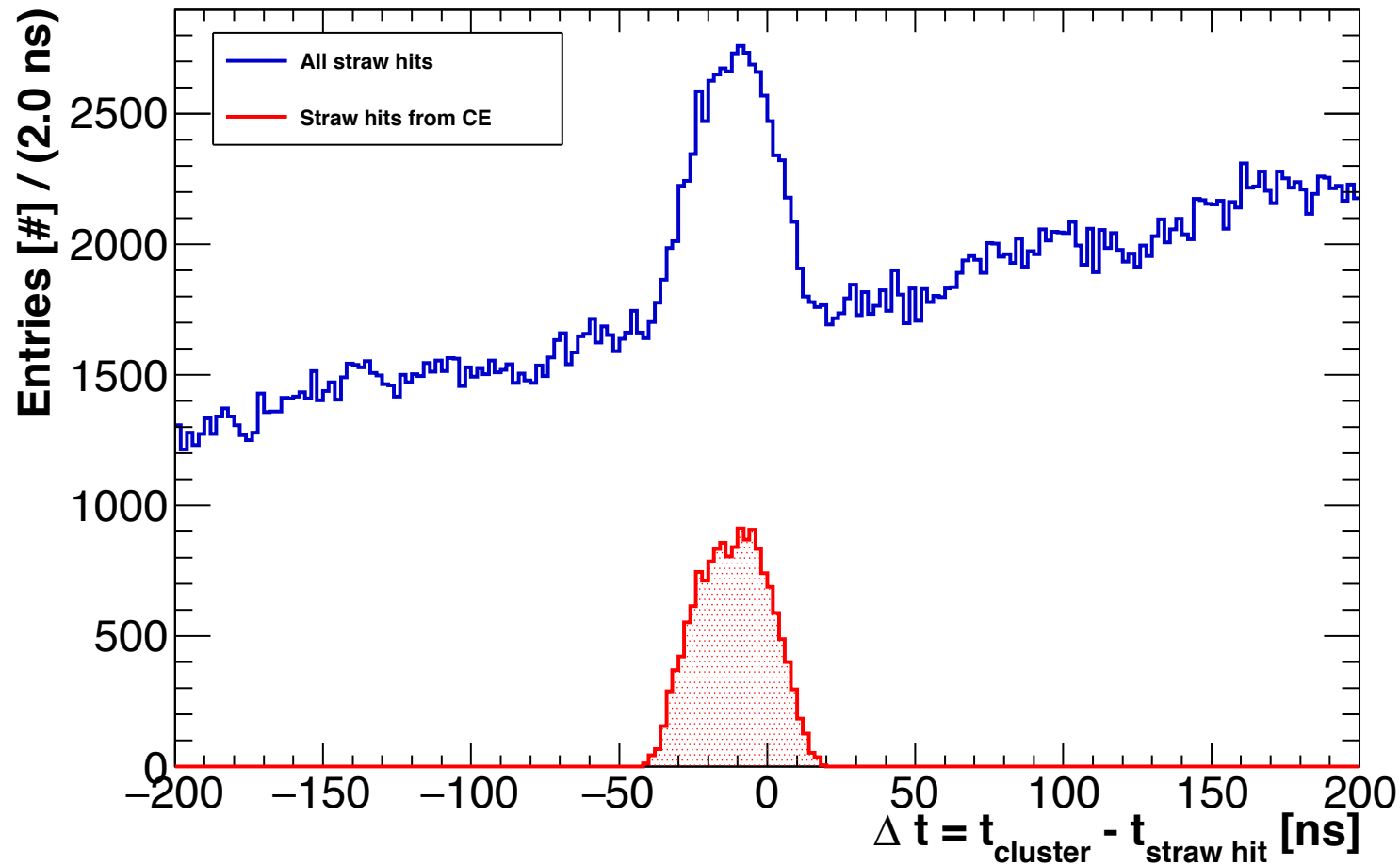


- Prototype dimensions: $1.3 R_{\text{Moliere}}^2 \times 10 X_0$
- Still comparison between data and Monte Carlo useful



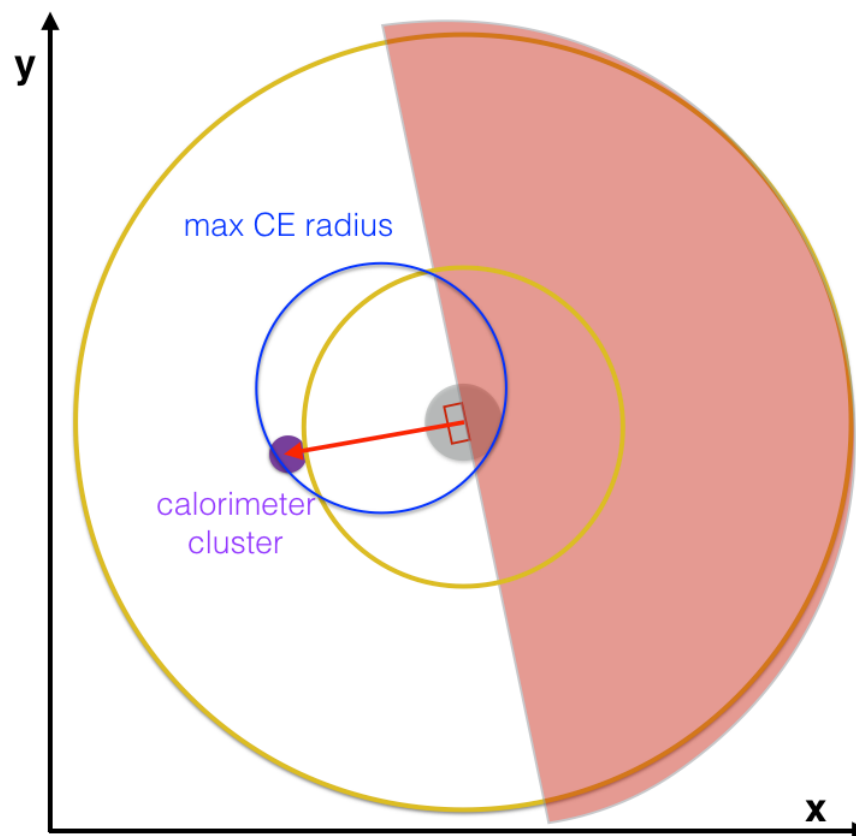
backup slides track reconstruction





- Average tof from middle of the tracker to the calorimeter ~ 8 ns
- Mean drift time ~ 20 ns
- Difference of these two numbers is consistent with the peak position

MUSE Cluster position selection



- Graded magnetic field between the stopping target and the tracker limits the CE pT
- Cluster position identifies the semi-plane where the CE track relies

MUSE Mu2e track reconstruction



The Mu2e track reconstruction has several specific features:

- a CE makes 2-3 full turns in the tracker
- **time dependence** of the track-hit position:

$$r_{\text{drift}} = v_{\text{drift}} \cdot (t_{\text{measured}} - T_0 - t_{\text{flight}})$$

The **track reconstruction** is factorized into 2 main steps:

1. **Track finding**: provides a set of straw hits consistent with a track candidate
2. **Kalman based fitter**: performs the final reconstruction

The **track finding** uses two algorithms:

- A. **Standalone**: relies only on the tracker information
- B. **Calorimeter-seeded**: seeds the track search using the reco cluster