The Mu2e experiment at Fermilab

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on behalf of the Mu2e collaboration

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

MUSE What is μ→e conversion

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

$$\mathrm{E}_e = \mathrm{m}_\mu \ \mathrm{c}^2 \text{ - } \mathrm{B}_\mu(\mathrm{Z}) \text{ - } \mathrm{C(A)} = 104.973 \ \mathrm{MeV}$$

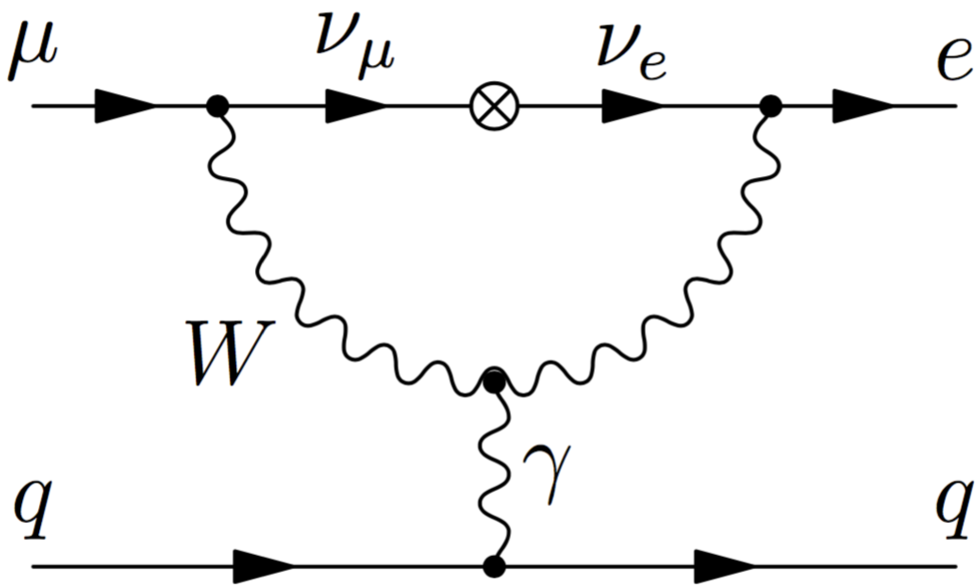
- for Aluminum: $\begin{cases} \mathrm{B}_\mu(\mathrm{Z}) \text{ is the muon binding energy (0.48 MeV)} \\ \mathrm{C(A)} \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

- Signal normalization:

$$\mathrm{R}_{\mu \mathrm{e}} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

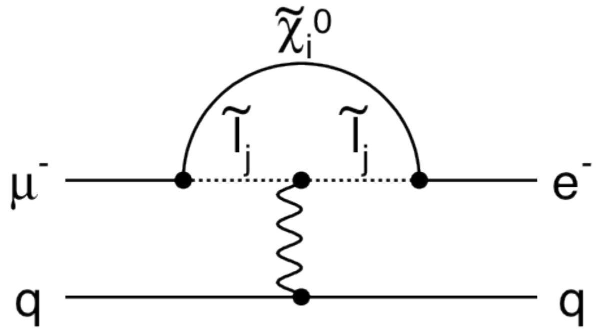
CLFV in the SM

- **CLFV** process forbidden in the **SM**
- μ conversion in the SM is introduced by the **neutrino masses and mixing** at a negligible level ~ 10^{-52}

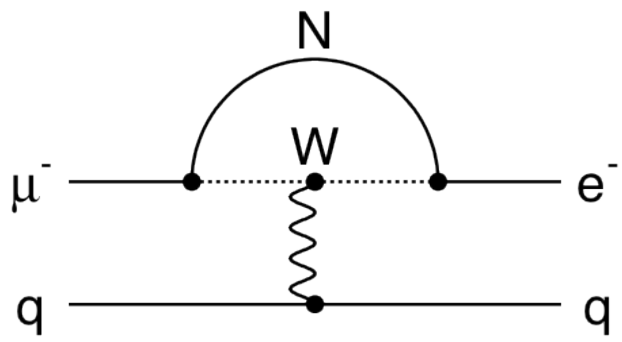


- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)

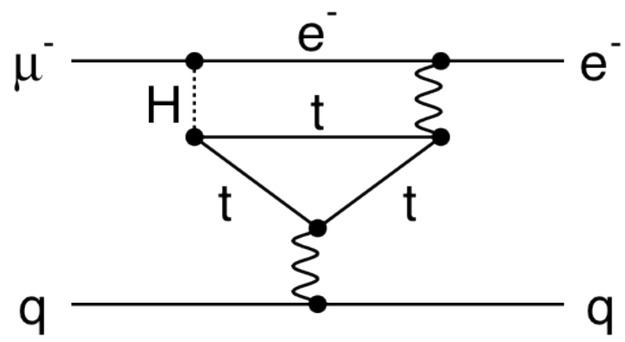
NP contributions to $\mu \to e$



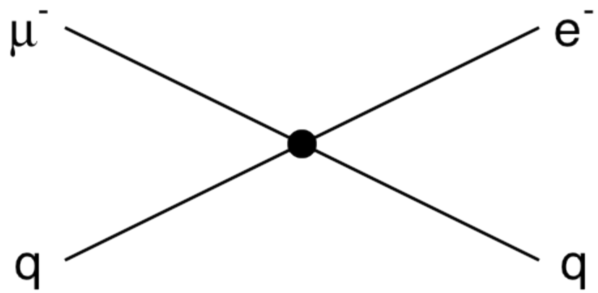
SUSY



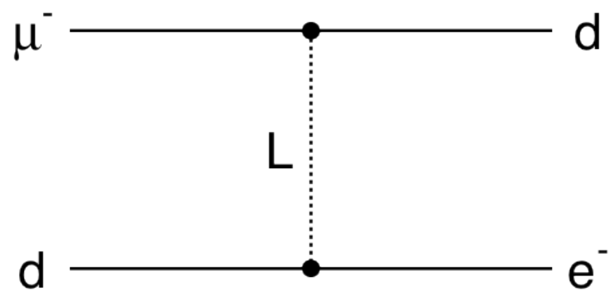
Heavy neutrino



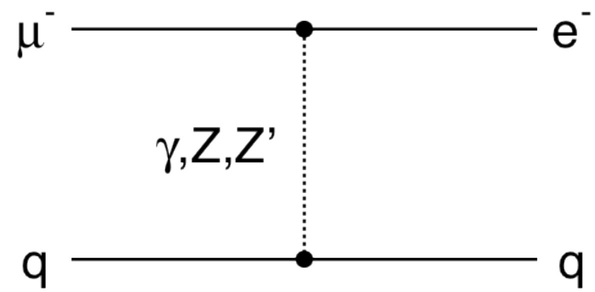
Two Higgs doublets



Compositeness



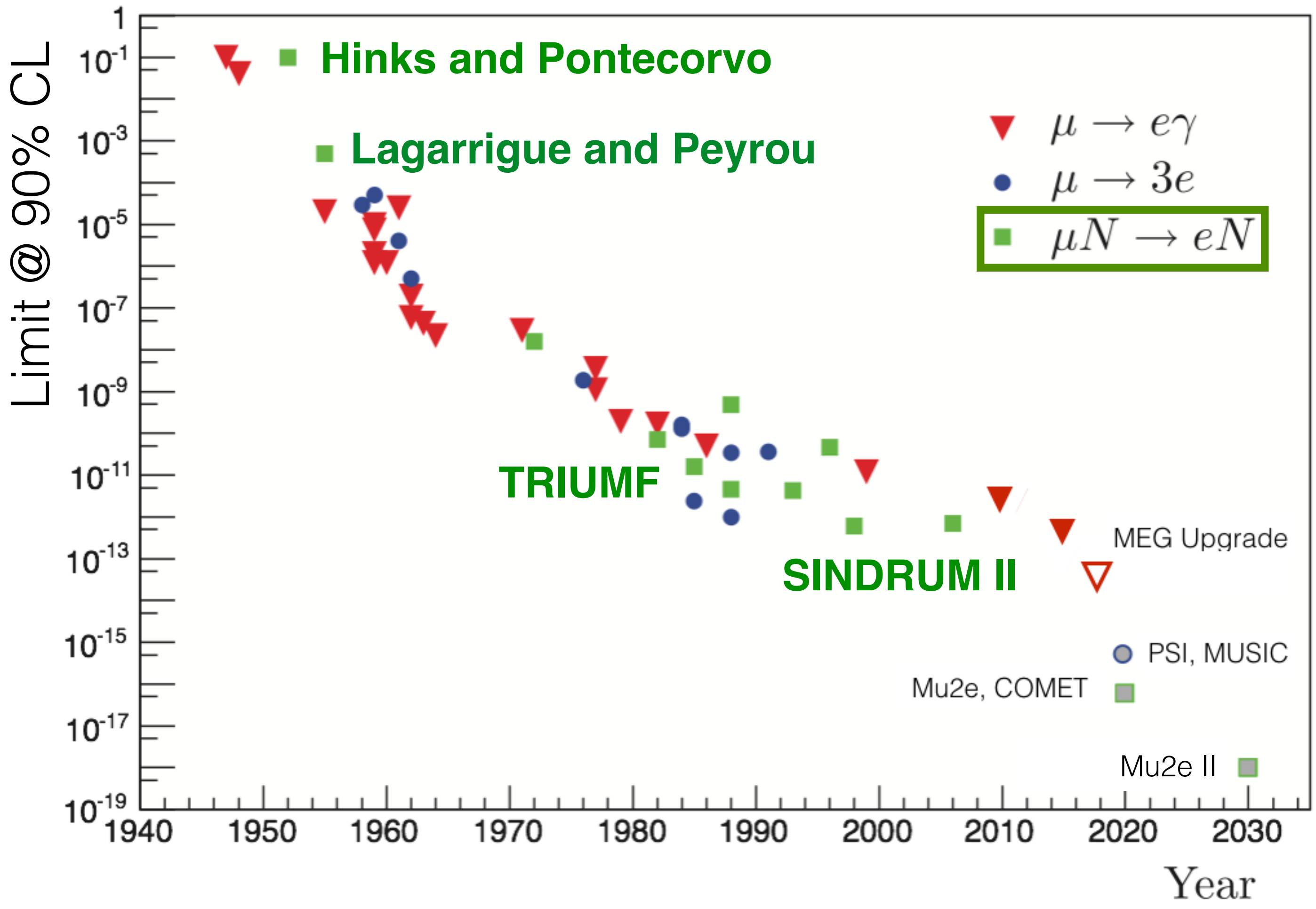
Leptoquarks



Z'/anomalous couplings

- Any signal observation would be an unambiguous sign of **NP**

Historical perspective

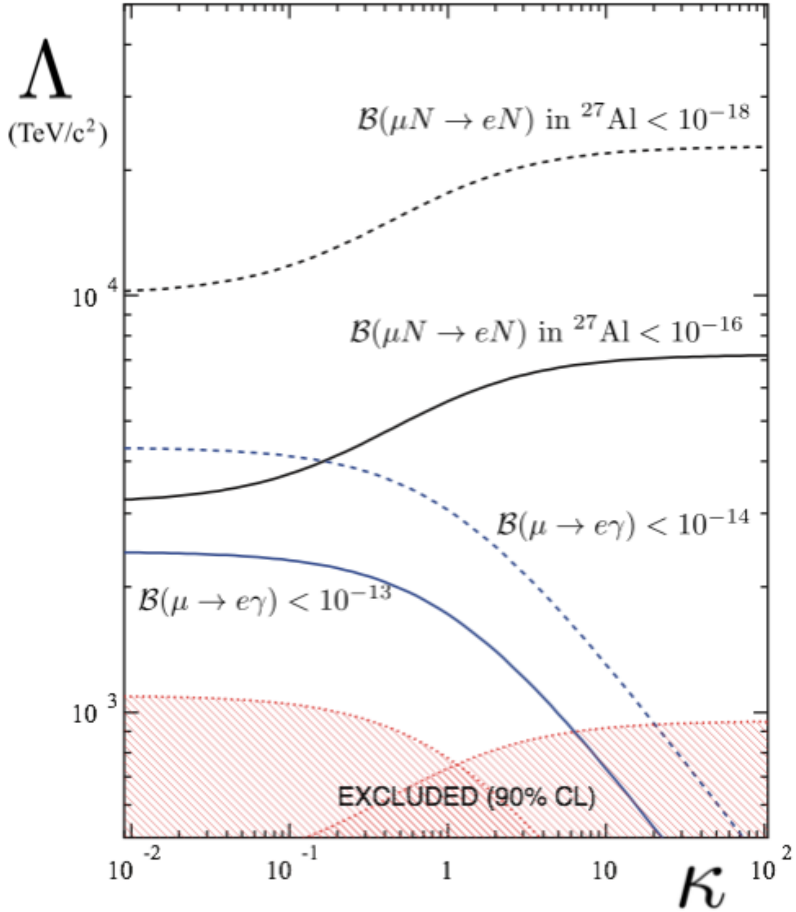


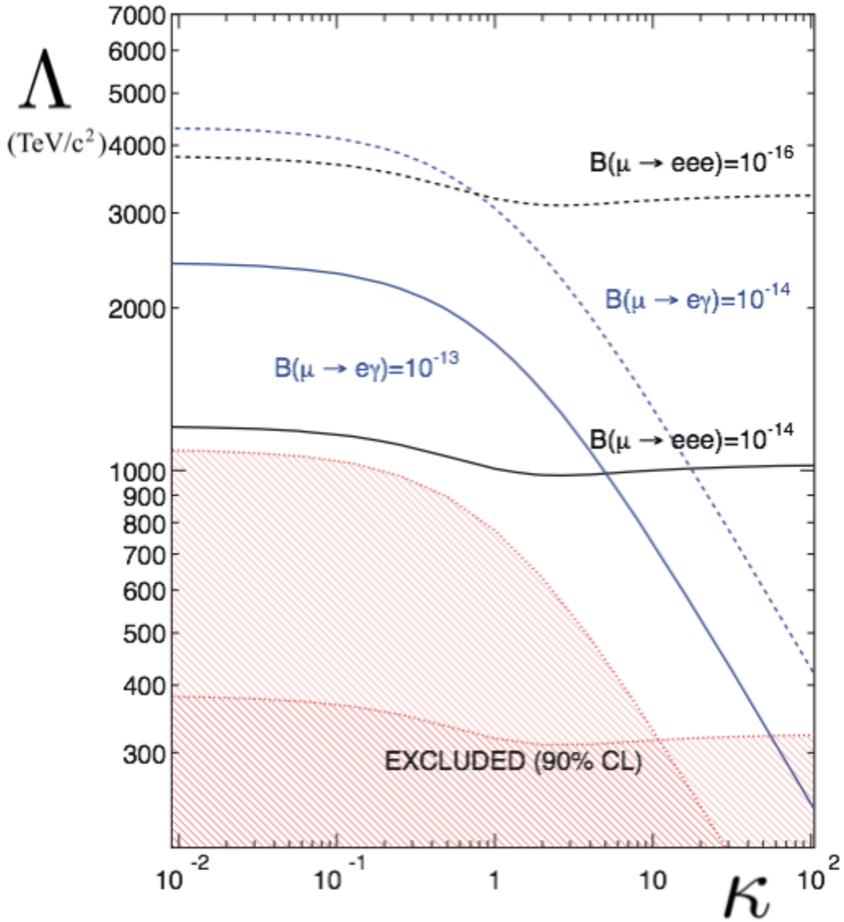
- Best limit: $R_{\mu e} < 7 \times 10^{-13}$ by SINDRUM II at PSI [*Eur.Phys.J C47(2006)*]
- Mu2e will improve by a factor 10^4

MUSE Model independent Lagrangian

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

"dipole term" **"contact term"**





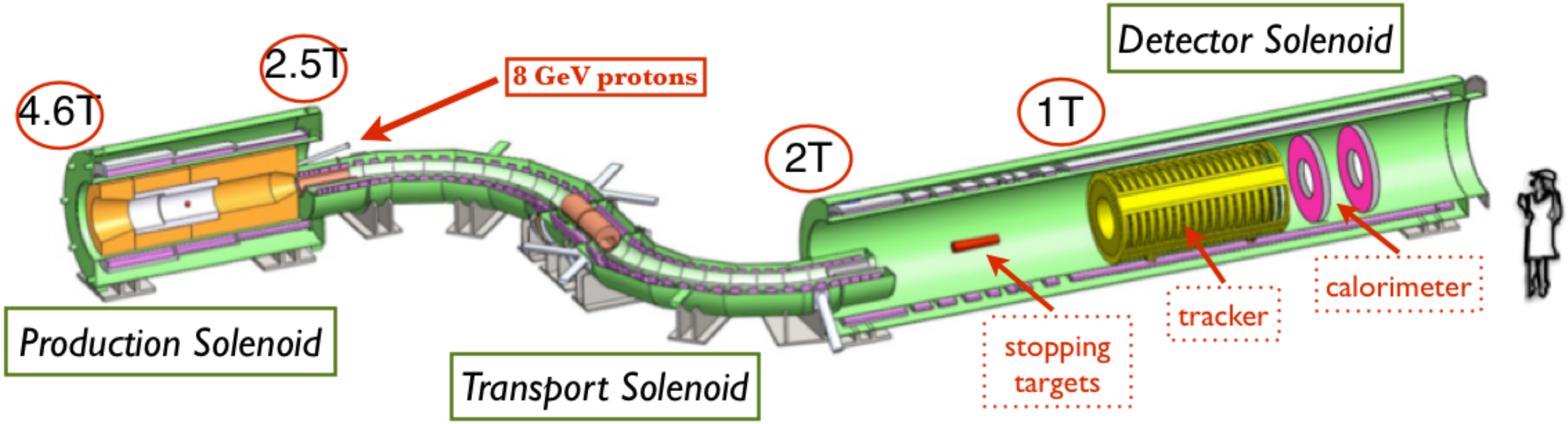
Experimental setup

- ***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

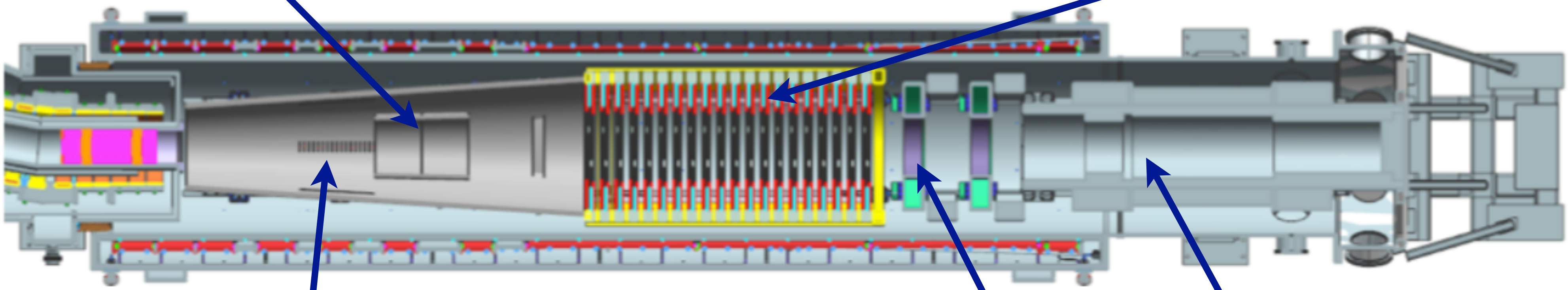
Mu2e Detector

- *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 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

Muonic atoms

- Stopped μ⁻ is captured in atomic orbits
  ➡ quickly (~fs) cascades into 1S state
- Bohr radius ~20 fm (for Al)
  ➡ significant overlap between the μ⁻ and nucleus wave-functions
- For a μ⁻ in orbit three processes may happen:
  ➡ **decay (39%):** $\mu^- N \to e^- \bar{\nu}_e \nu_\mu N$, **background**
  ➡ **capture (61%):** $\mu^- + N \to \nu_\mu + N'$, **normalization**
  ➡ **conversion (<10^{-13}):** $\mu^- + N \to e^- + N$, **signal**

Mu2e Detector

- **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
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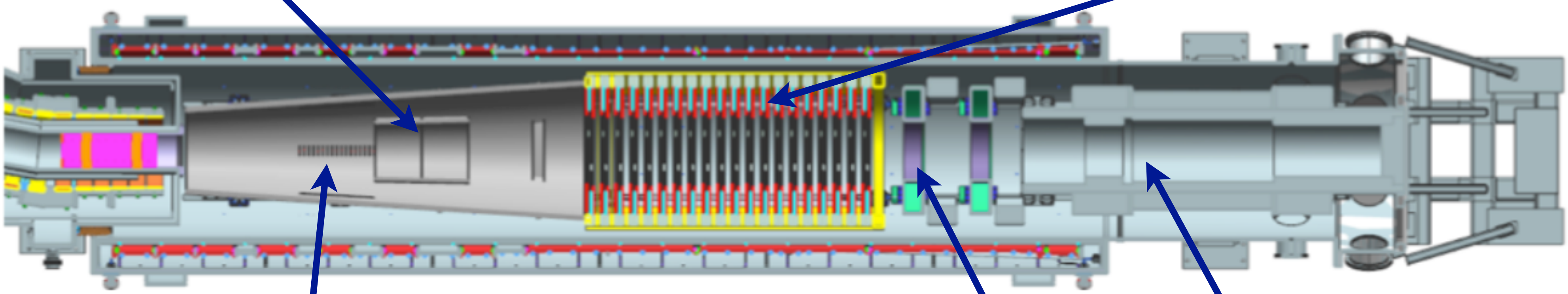

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- **Calorimeter:**
  - ❖ 2 disks composed of undoped CsI crystals

- **Muon beam stop:**
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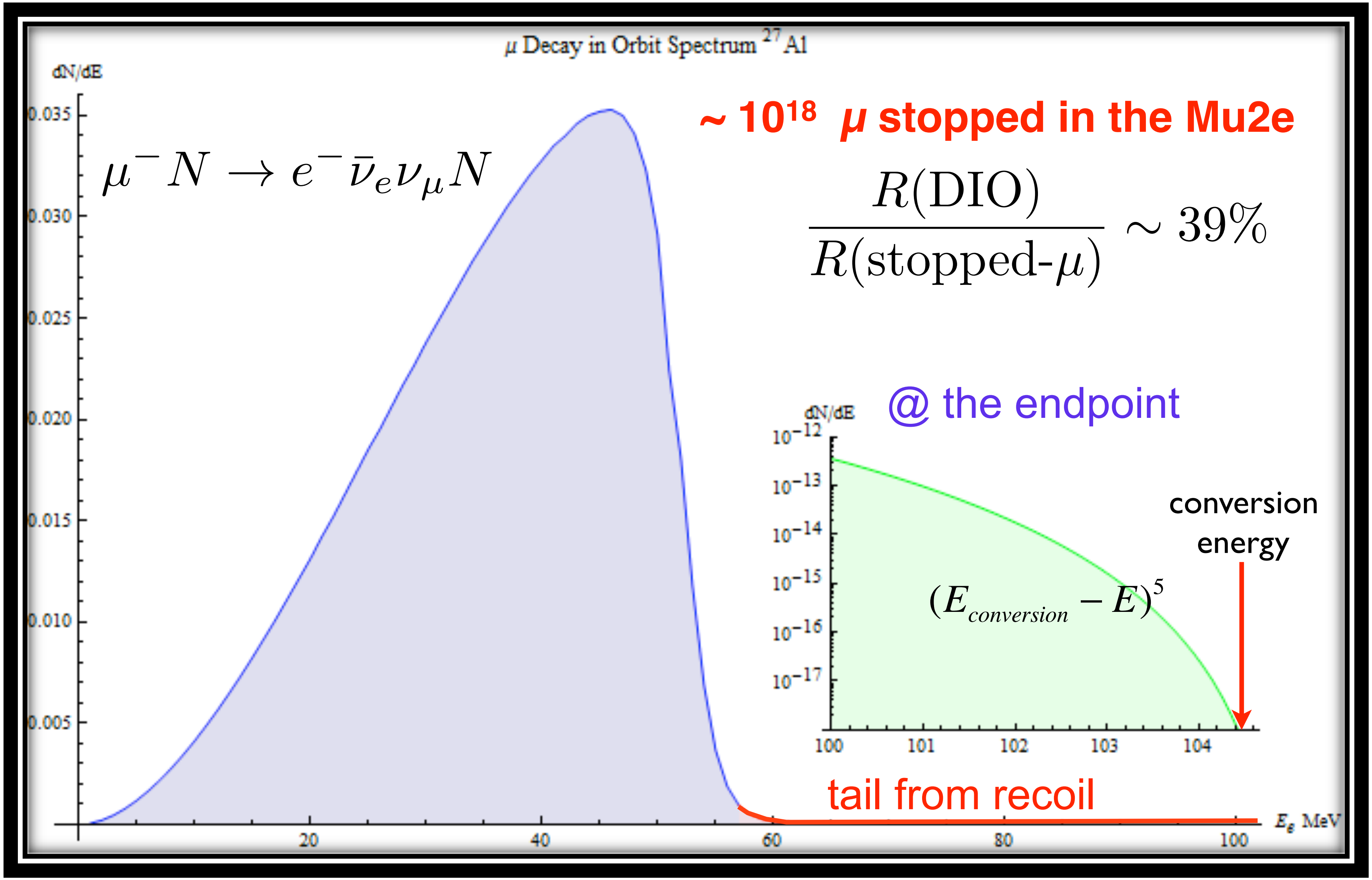
Physics background

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

μ decay-in-orbit (DIO)



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

Physics background

- **μ decay-in-orbit:**

  ✓ **low-mass tracker with high performance**

- Cosmic-induced background

- Antiproton-induced background

- Radiative π capture

MUSE

Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- **Cosmic-induced background:**

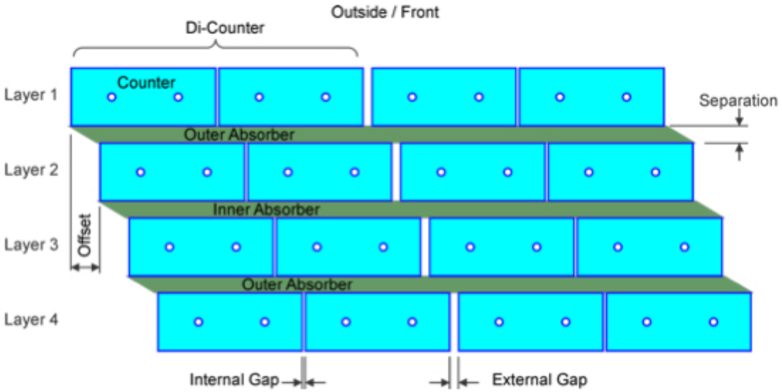
  ✓ **cosmic ray veto and PID**

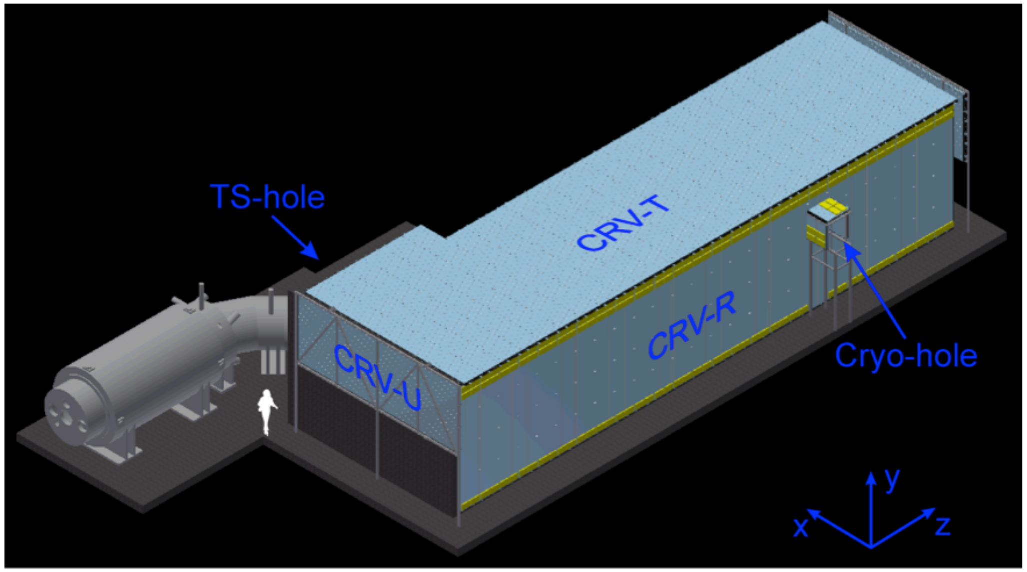
- Antiproton-induced background

- Radiative π capture

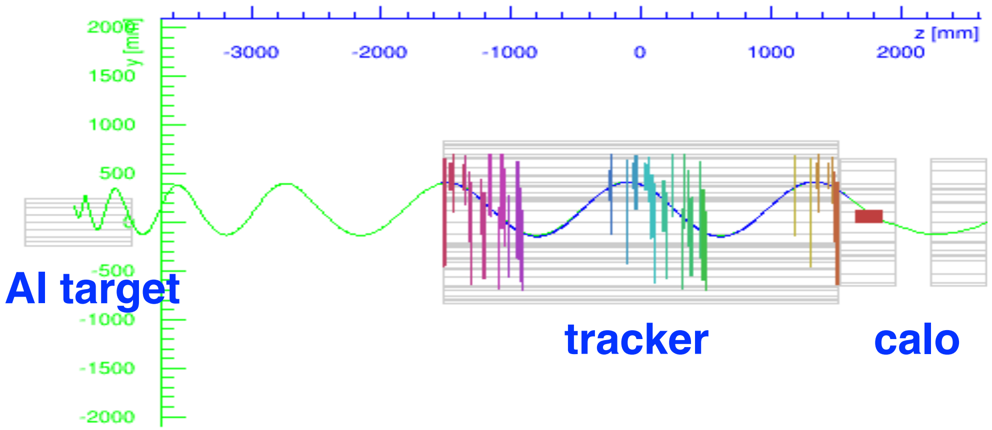
Cosmic Ray Veto

- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - ❖ each bar is 5x2x~450 cm^3
  - ❖ 2 WLS fibers/bar
  - ❖ read out with SiPM
- inefficiency < 10^{-4}





μ mimicking the signal



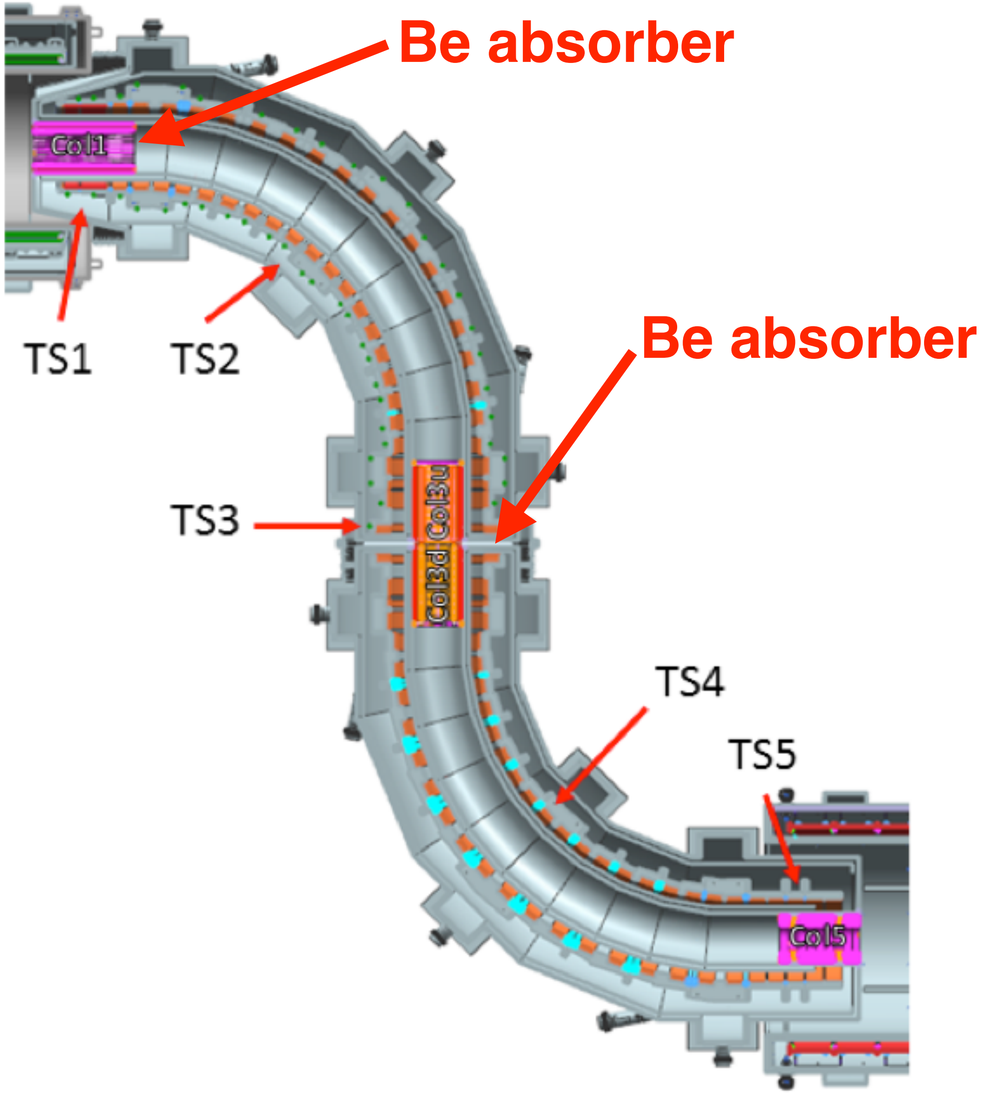
Physics background

- 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

Antiproton absorber

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

Transport solenoid - top view



Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- Cosmic-induced background:

  ✓ cosmic ray veto and PID

- Antiproton-induced background

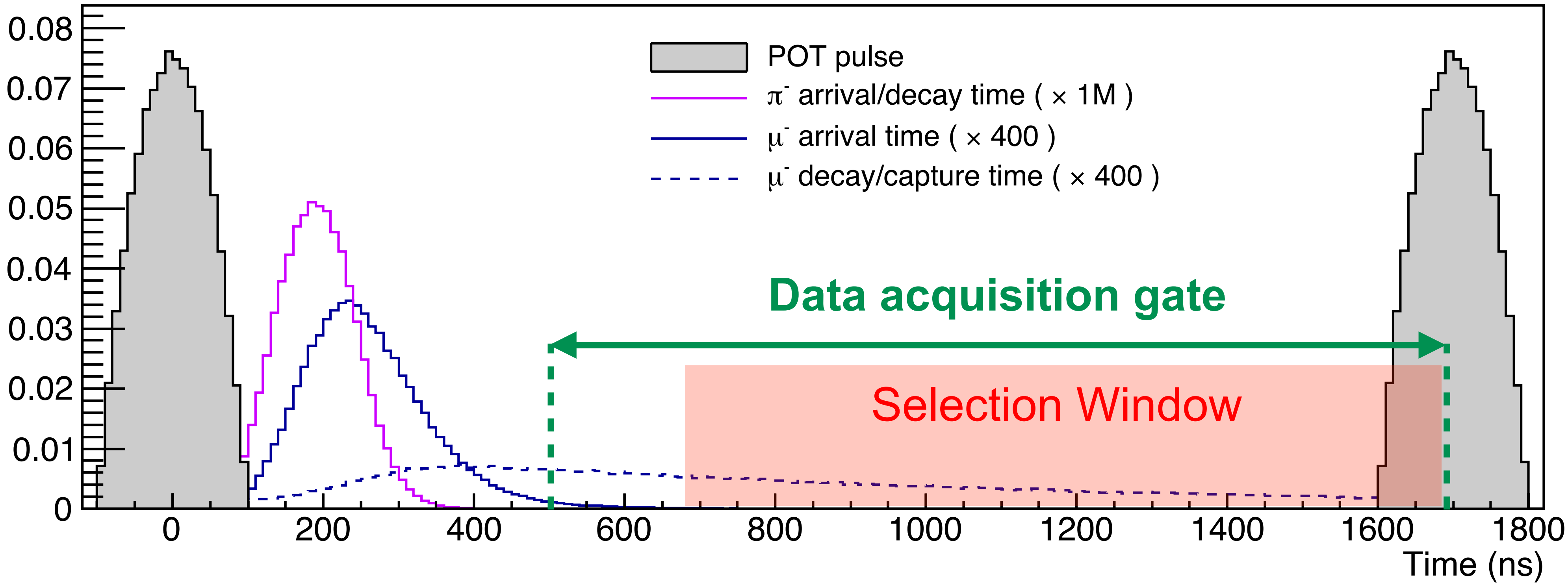
  ✓ beam line and PID

- **Radiative π capture: $\pi^- + N \rightarrow \gamma + N'$**

  ✓ pulsed beam and extinction of out-of-time protons

Pulsed beam

- Beam period : 1.7 μs ~ 2 x τ_{μ}^{Al}
- Beam intensity: 3.15 x 10^7 p/bunch
- duty cycle : ~ 30%
- out-of-time protons / in-time protons < 10^{-10}

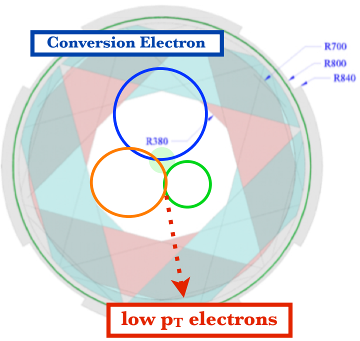


Tracker

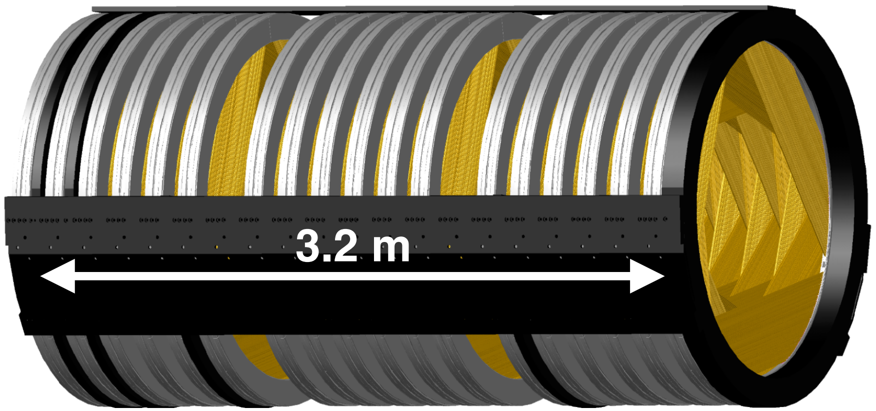
- 18 stations with straws transverse to the beam
- Straw technology employed:
  - ✓ 5 mm diameter, 15 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to low pT charged particles coming from the Al target
- Expected $\sigma_p < 200$ keV/c

straw tube

station



x18



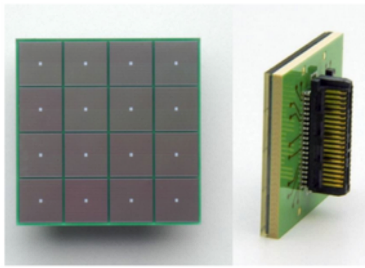
FEE

Calorimeter

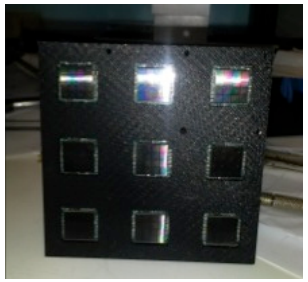
- 2 disks; each disk contains 860 undoped CsI crystals 20 x 3.4 x 3.4 cm^3
- Readout by large area MPPC + waveform digitizer boards @ 200 MHz
- Allows to measure: E/p and TOF to provide **Particle identification**
- Improve track search via a calorimeter-seed pattern recognition
- Time resolution σ_t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

undoped CsI

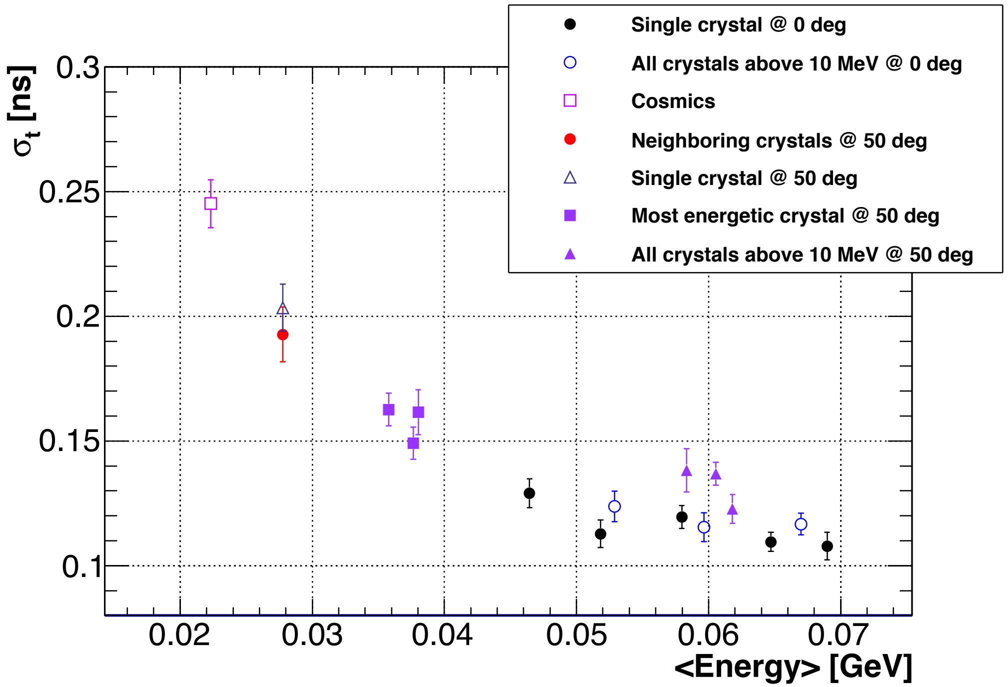
MPPC



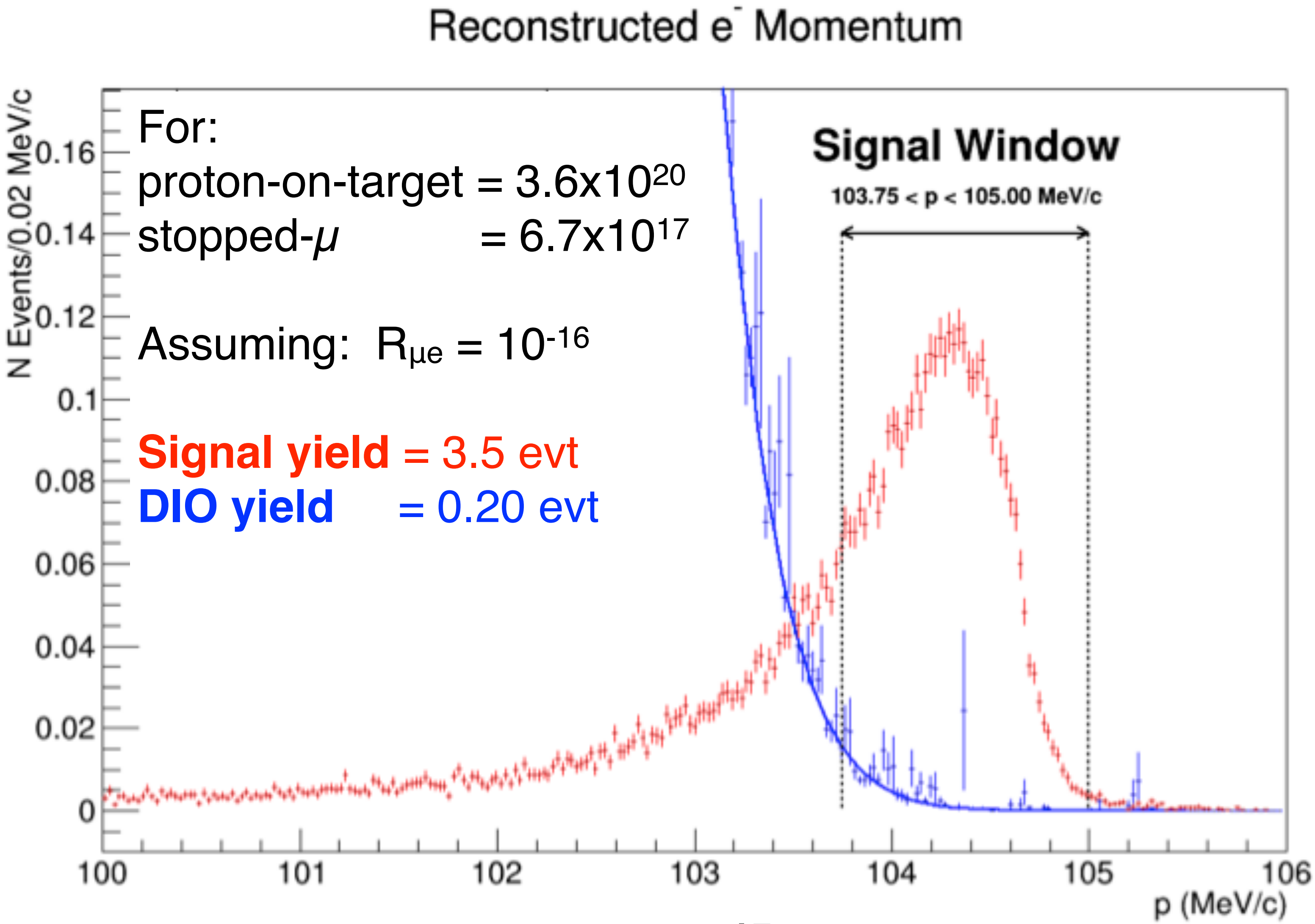
Calorimeter prototype



Beam test @ BTF in Frascati



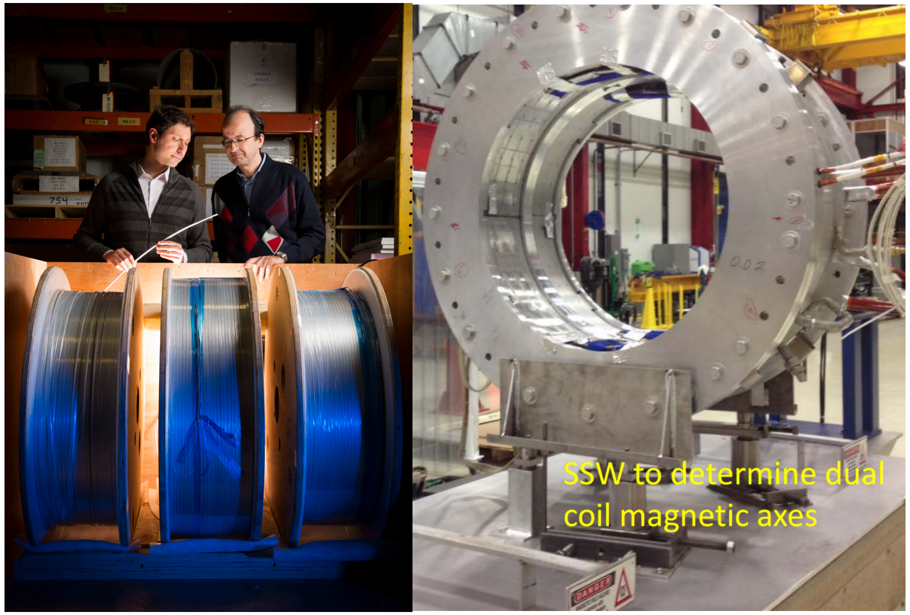
Mu2e signal sensitivity



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

Conclusions

- Mu2e is an experiment to search for CLFV in μ coherent conversion
  - ✓ aims 4 orders of magnitude improvement
  - ✓ unprecedented sensitivity to NP with mass scale up to ~ 10^4 TeV
- Civil construction and magnets procurement already started
- R&D mature with data taking scheduled on 2021
- More info: http://mu2e.fnal.gov

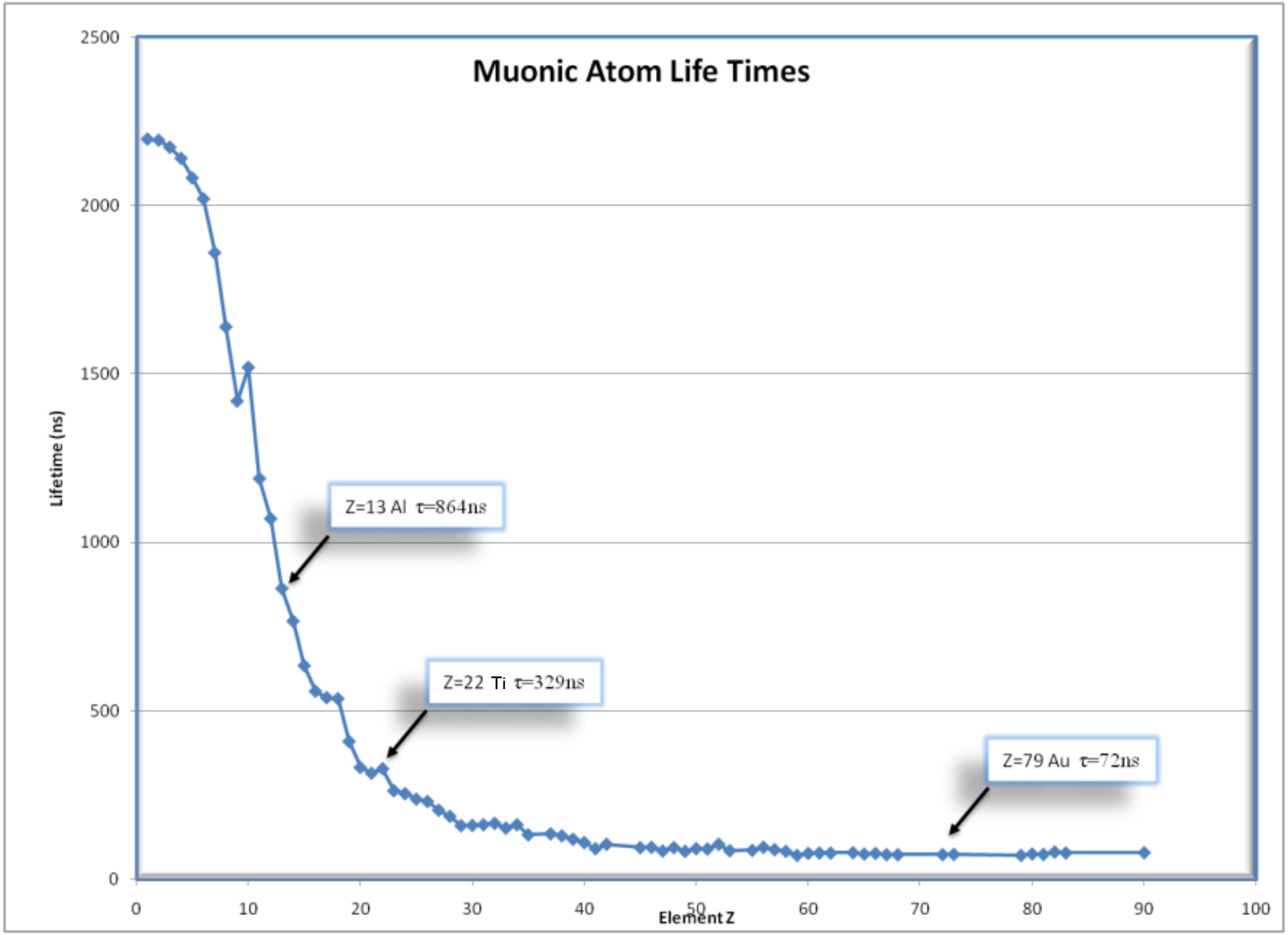


Backup slides

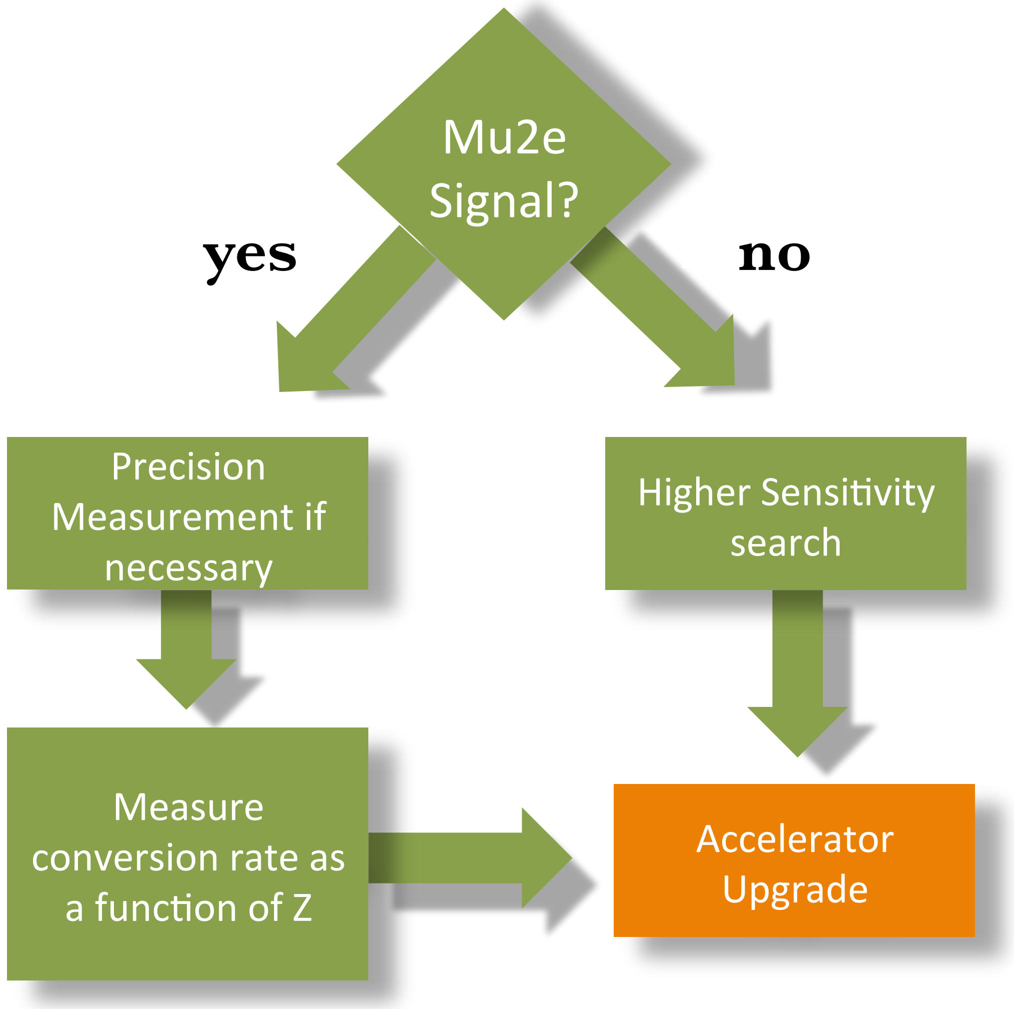
MUSE

Muonic atom life times

INFN



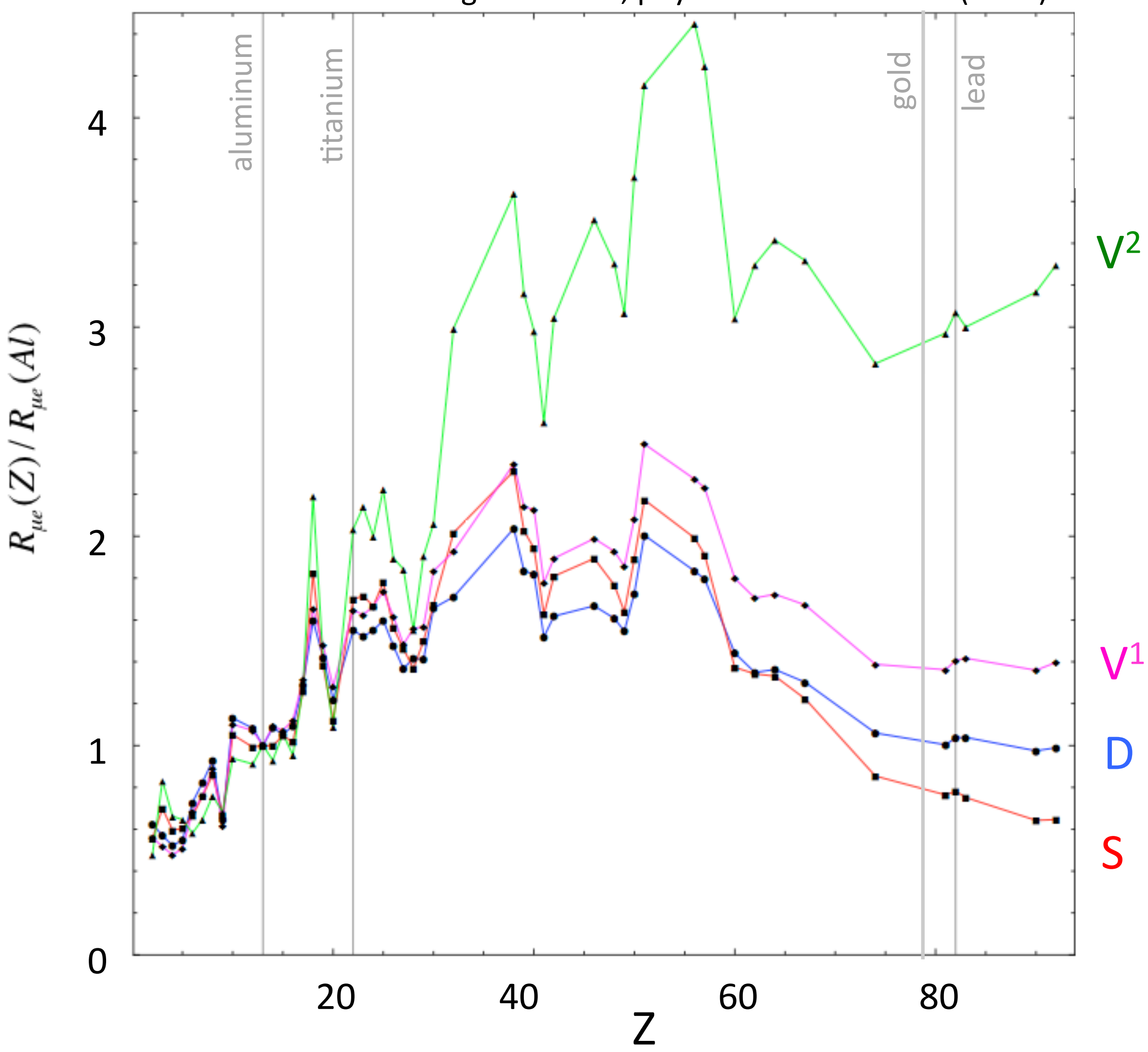
Mu2e signal?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
- **Proton driver upgrade**
  - https://pip2.fnal.gov
- **Snowmass report:**
  - ✓ arXiv:1311.5278

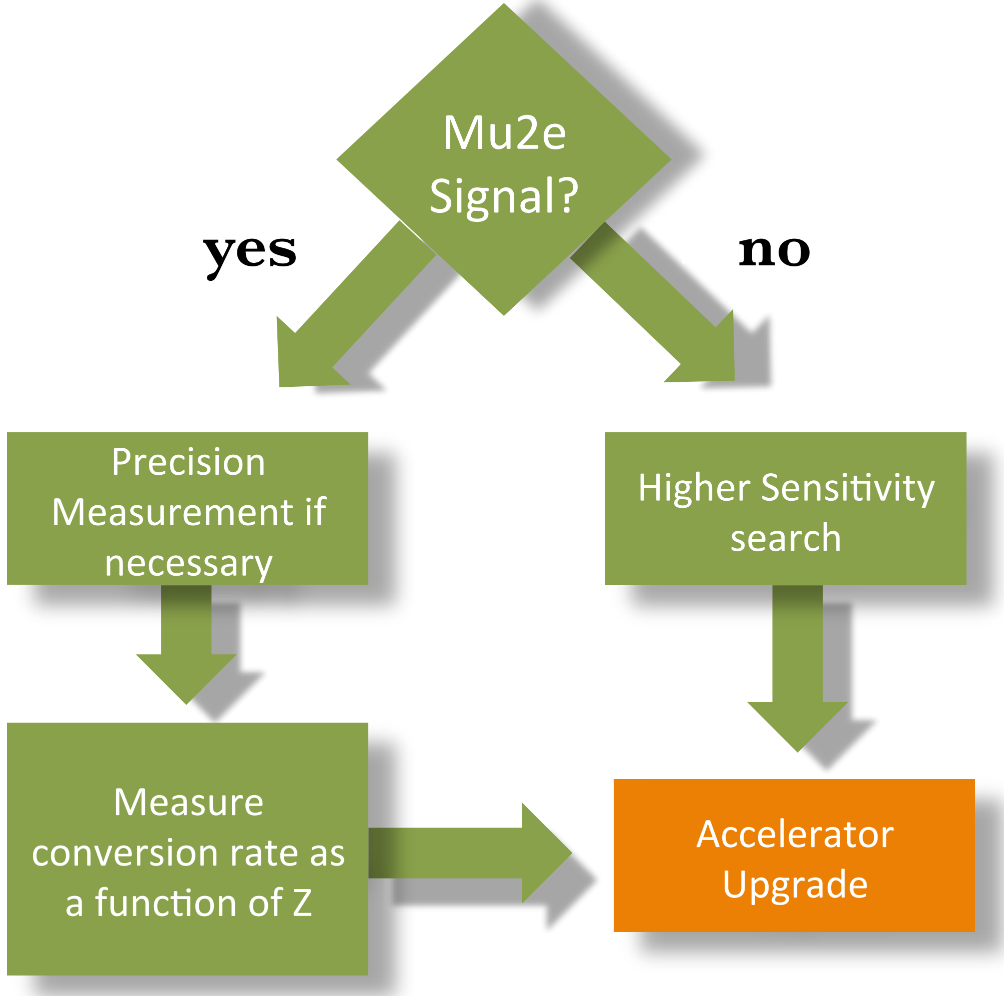
$R_{\mu e}$ rate vs Z

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



- Can use ratio of rates to determine dominant operator contribution

Mu2e signal?



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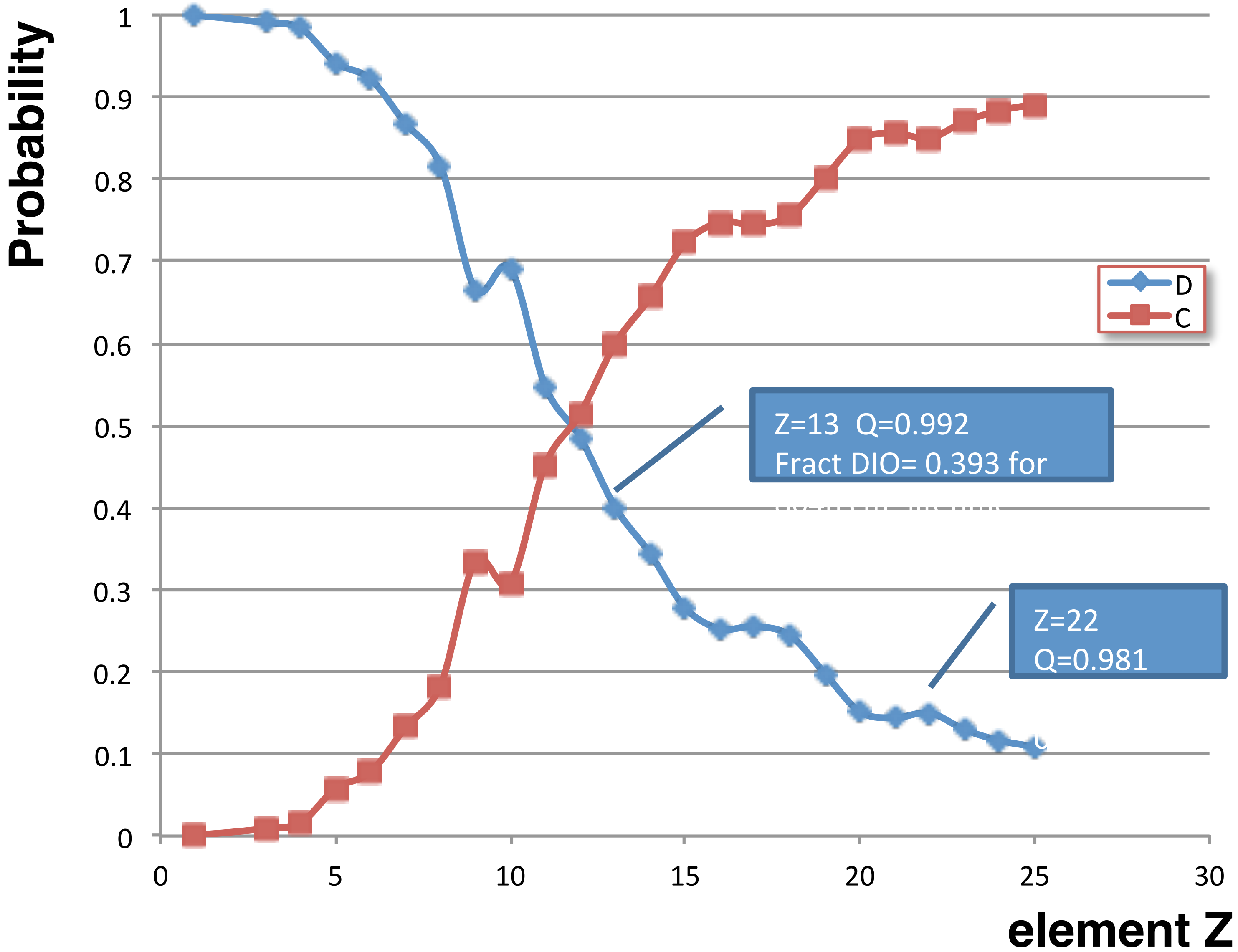
MUSE Decay/Capture rate vs Z



CLFV limits I

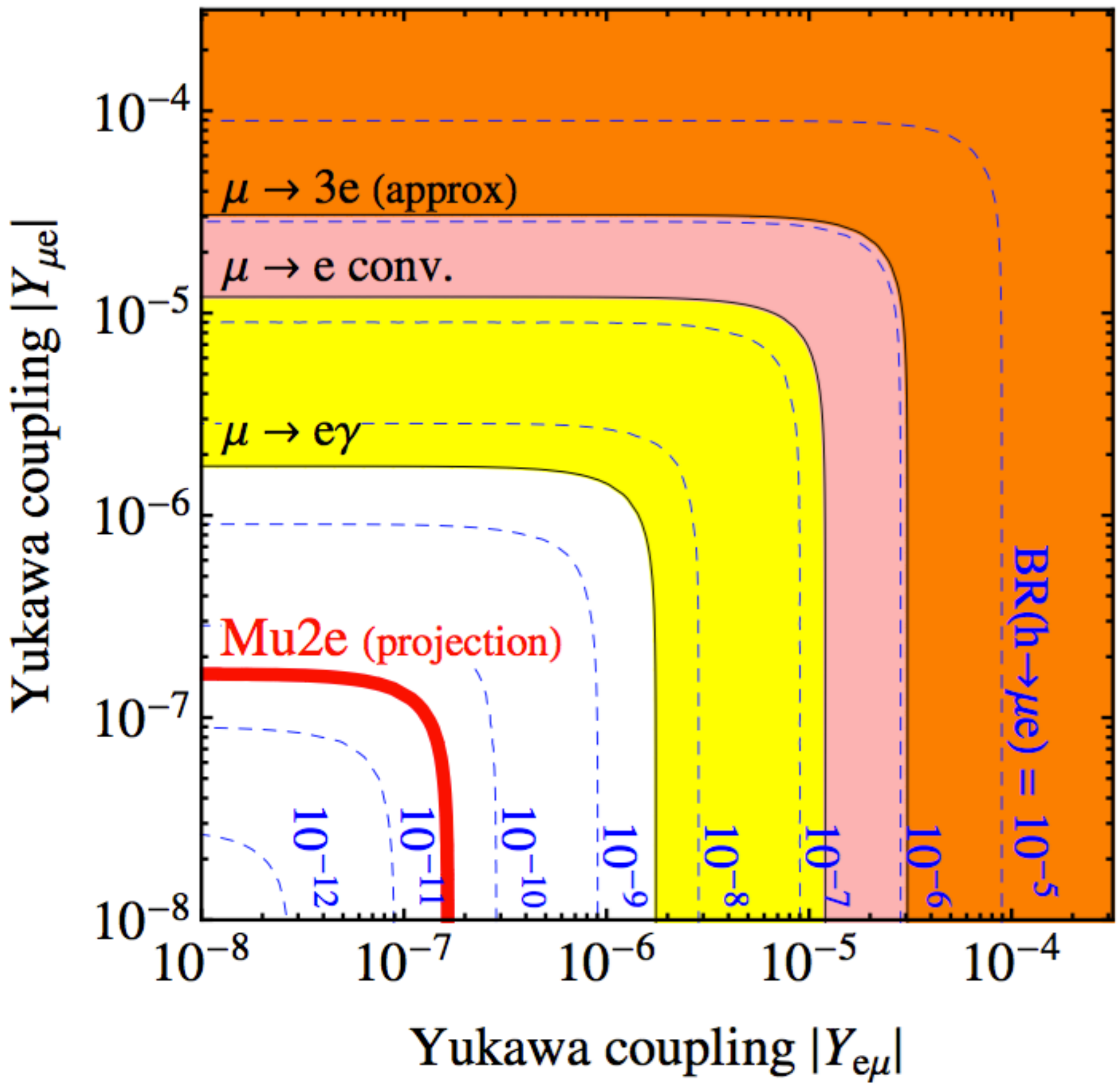
Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 3.0 \times 10^{-13}$
$\tau \to e\gamma$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

CLFV limits 2

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

Higgs couplings to μe

based on Harnik, Kopp, Zupan, arXiv:1209.1397

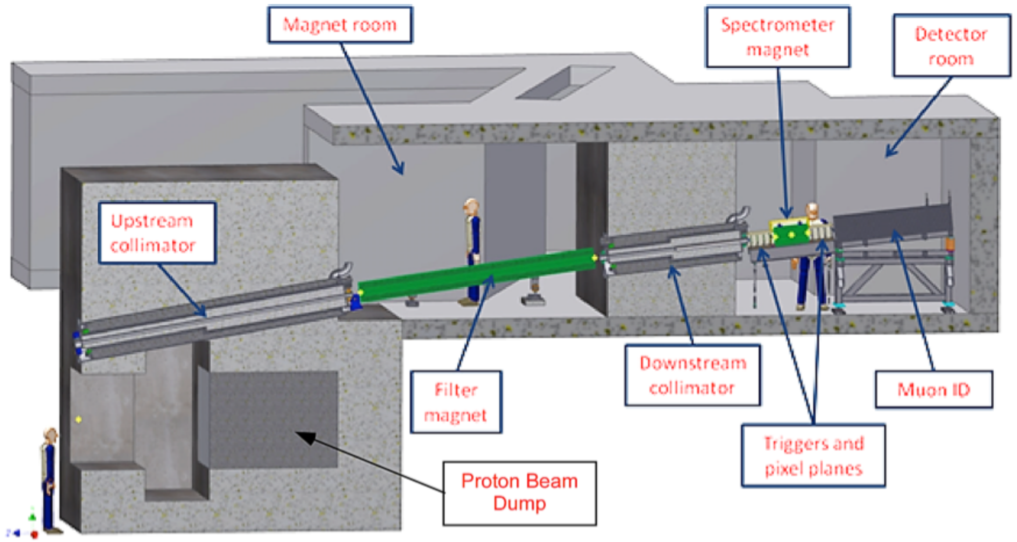


- Mu2e explores BR down to 10^{-11}
- Outside the LHC reach

Out-of-time protons

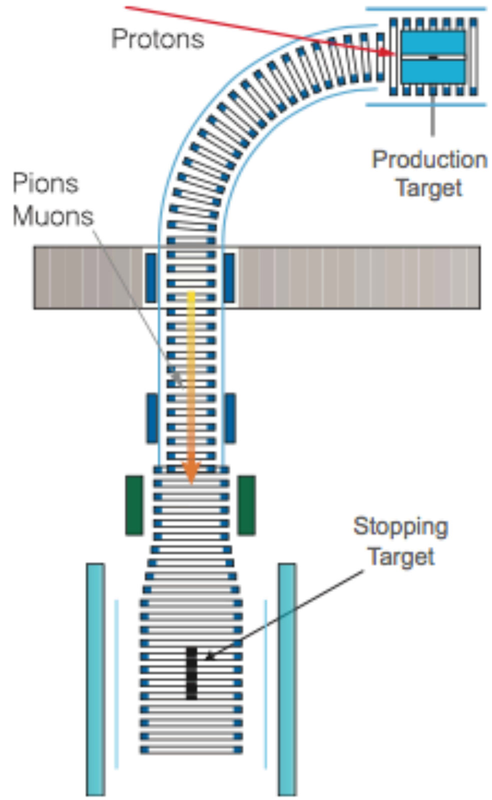
- The RF structure of the Recycler provides some "intrinsic" extinction:
  - ✓ **Intrinsic extinction ~10^{-5}**
- A custom-made AC dipole placed just upstream of the production solenoid provides additional extinction:
  - ✓ **AC dipole extinction ~ 10^{-6} - 10^{-7}**
- Together they provide a total extinction:
  - ✓ **Total extinction ~ 10^{-11} - 10^{-12}**

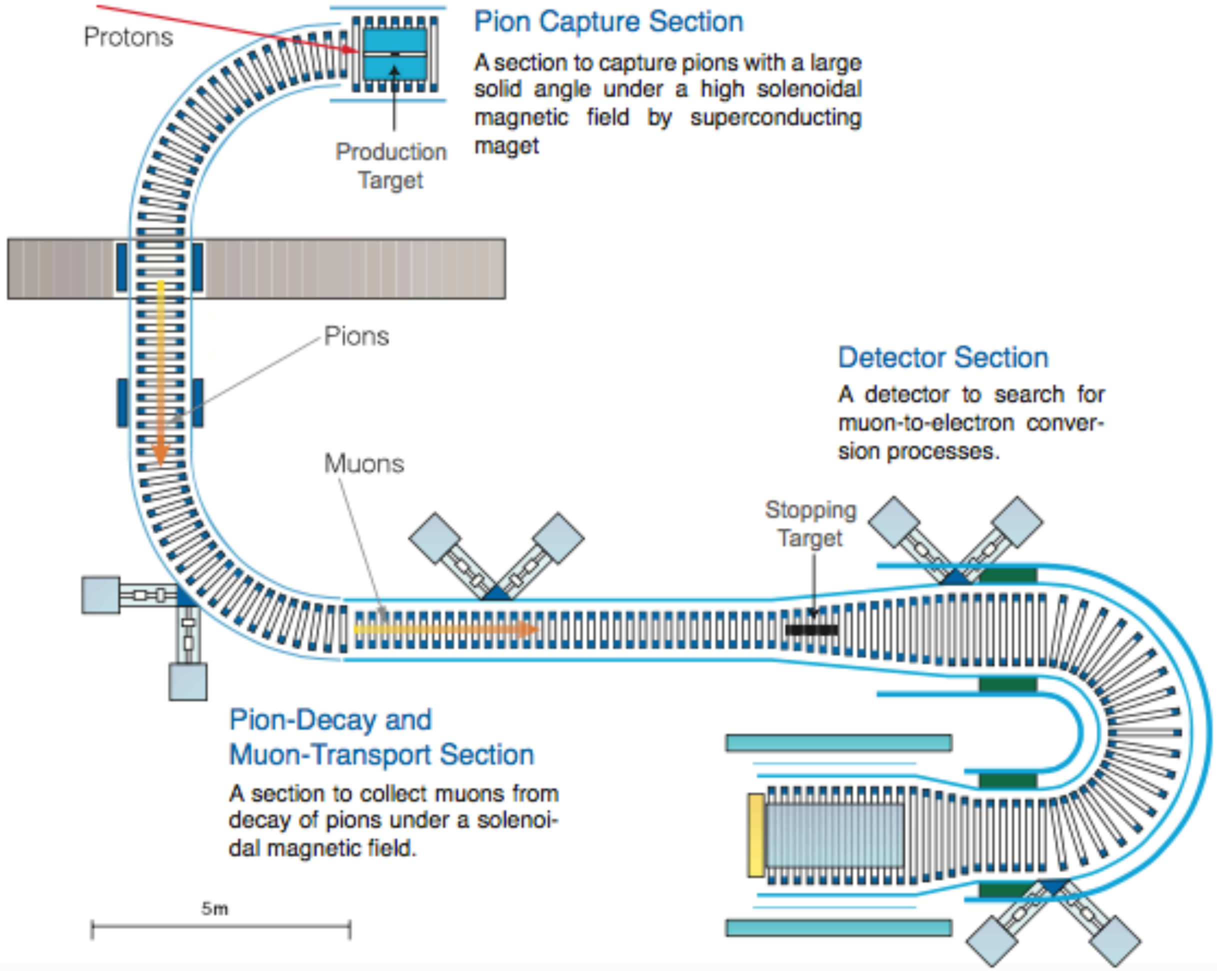
- Extinction measured using a detector system: Si-pixel + sampling EMC



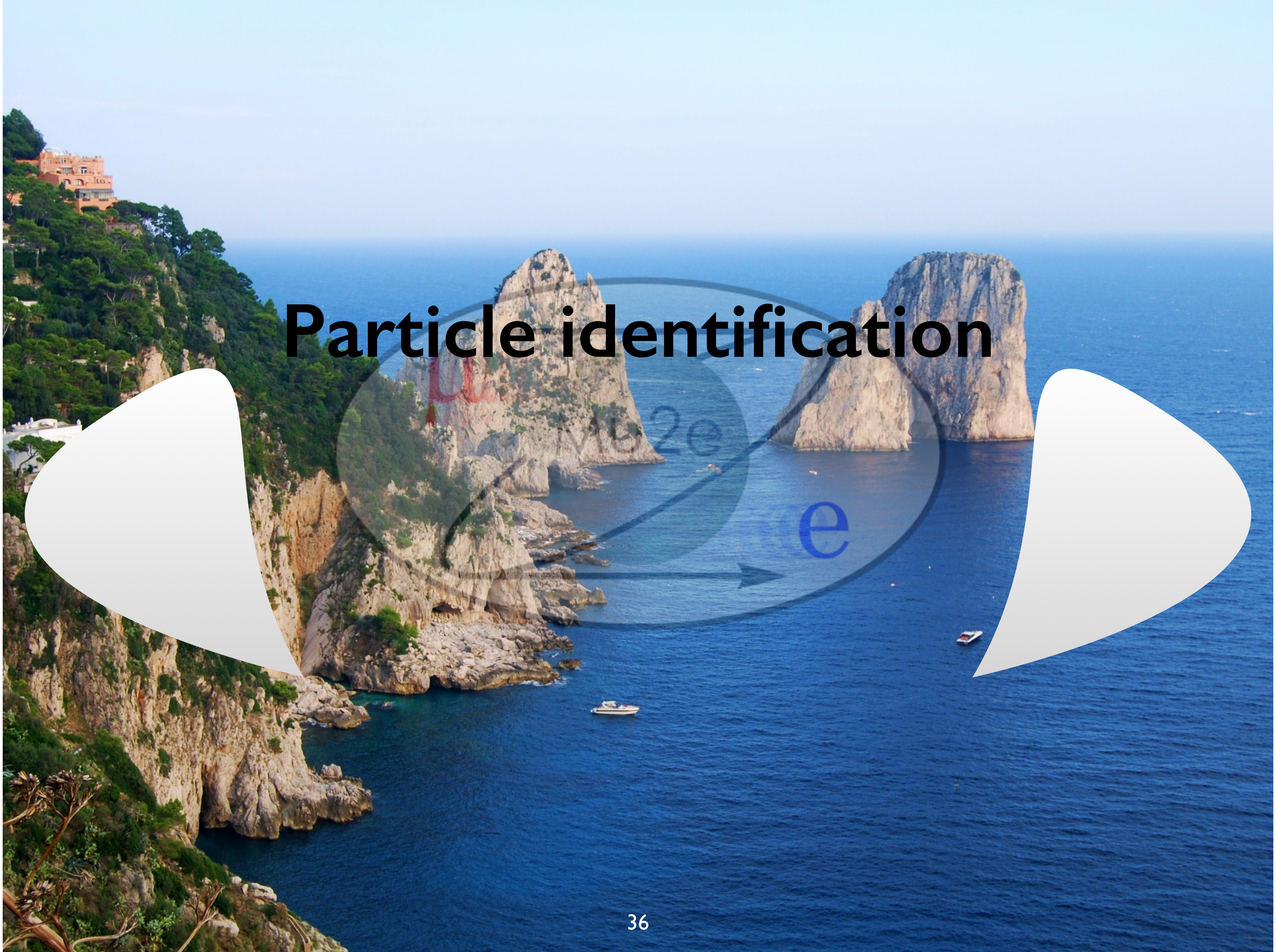
COMET experiment

phase I **phase II**





Particle identification



Why Particle Identification is needed

- **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

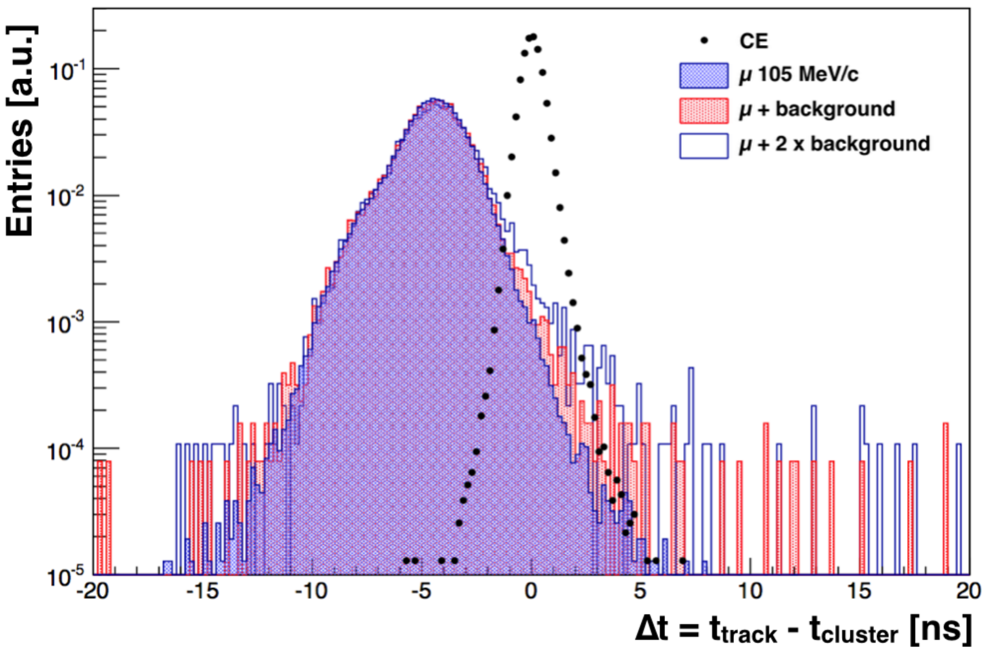
Mu2e PID method:

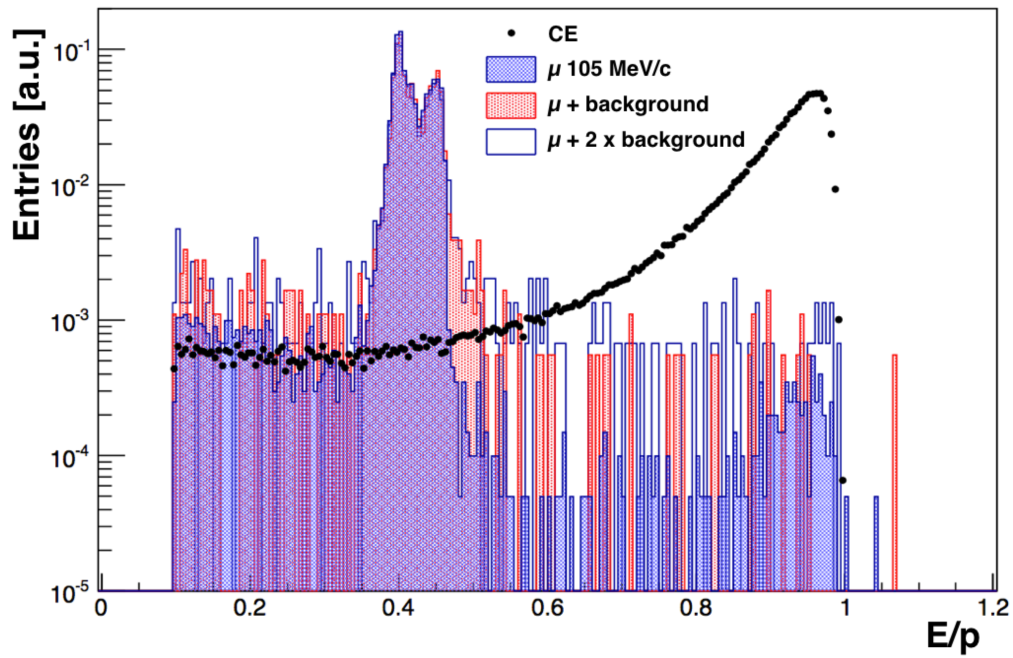
- Information from reconstructed tracks and calorimeter clusters are combined for identifying group (2)
- Stringent requirement from Cosmic: **μ-rejection factor ≥ 200**

Cosmic μ rejection

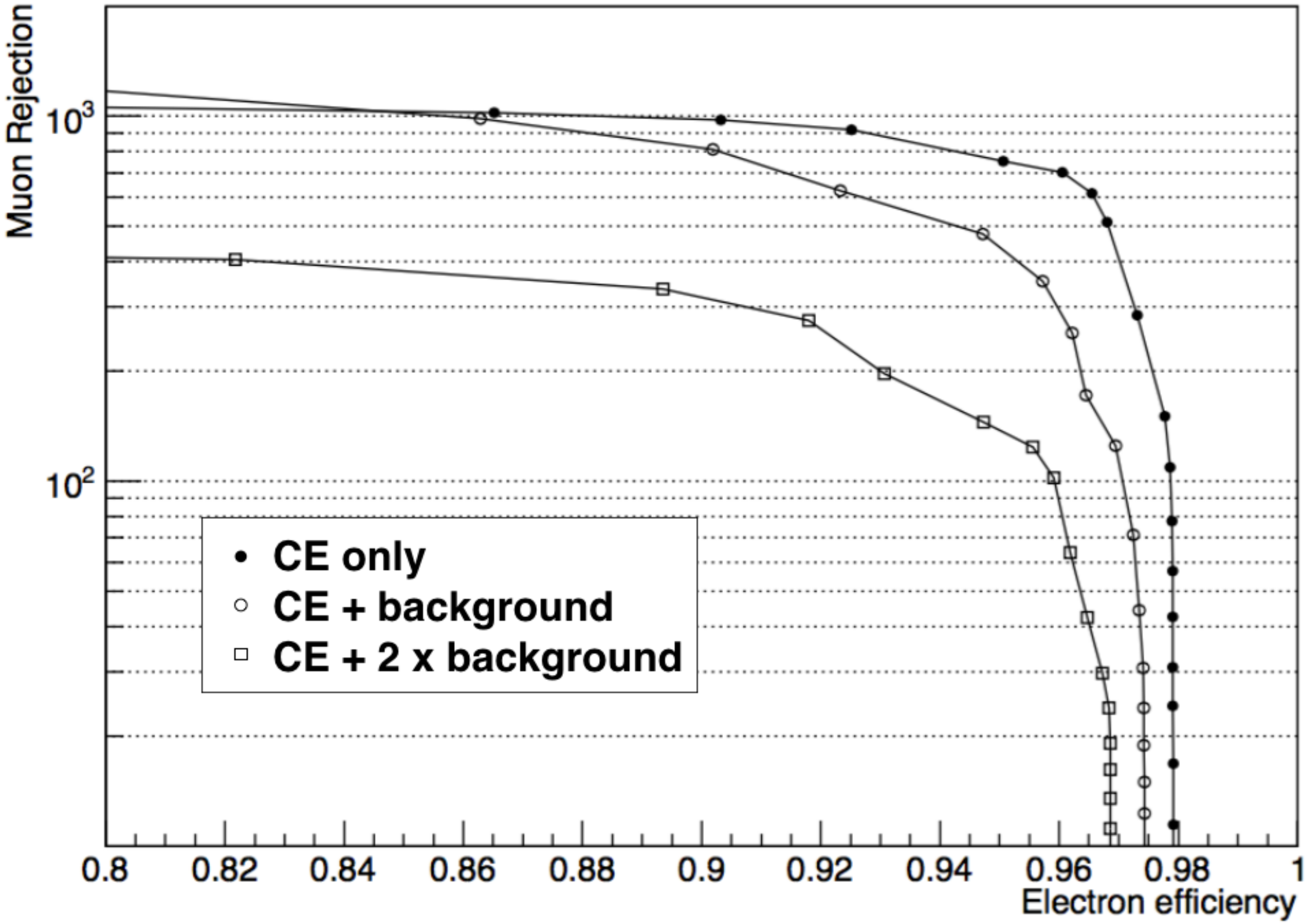
- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{track} - t_{cluster}$ and E/p:

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



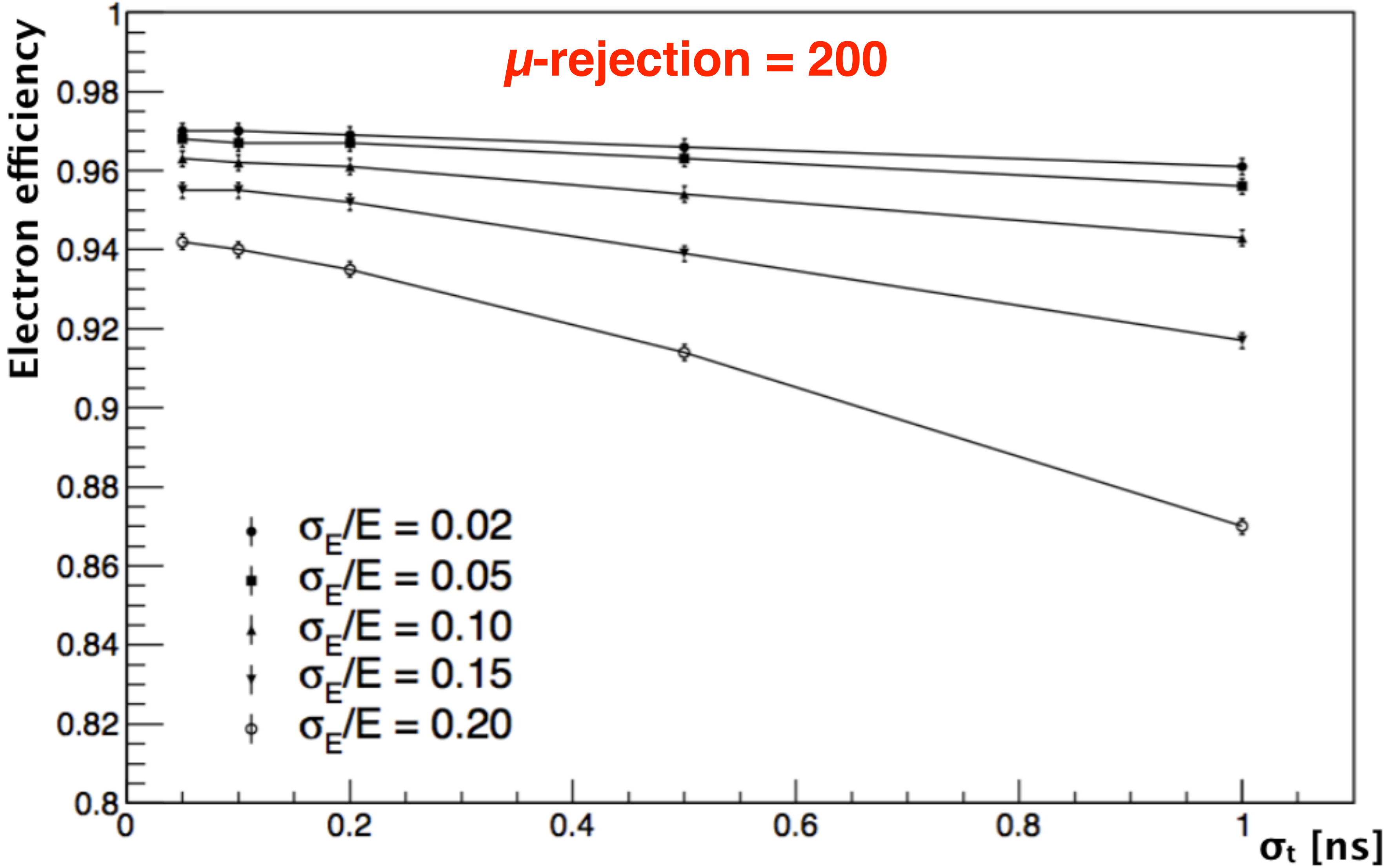


PID performance



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

PID yield vs performance



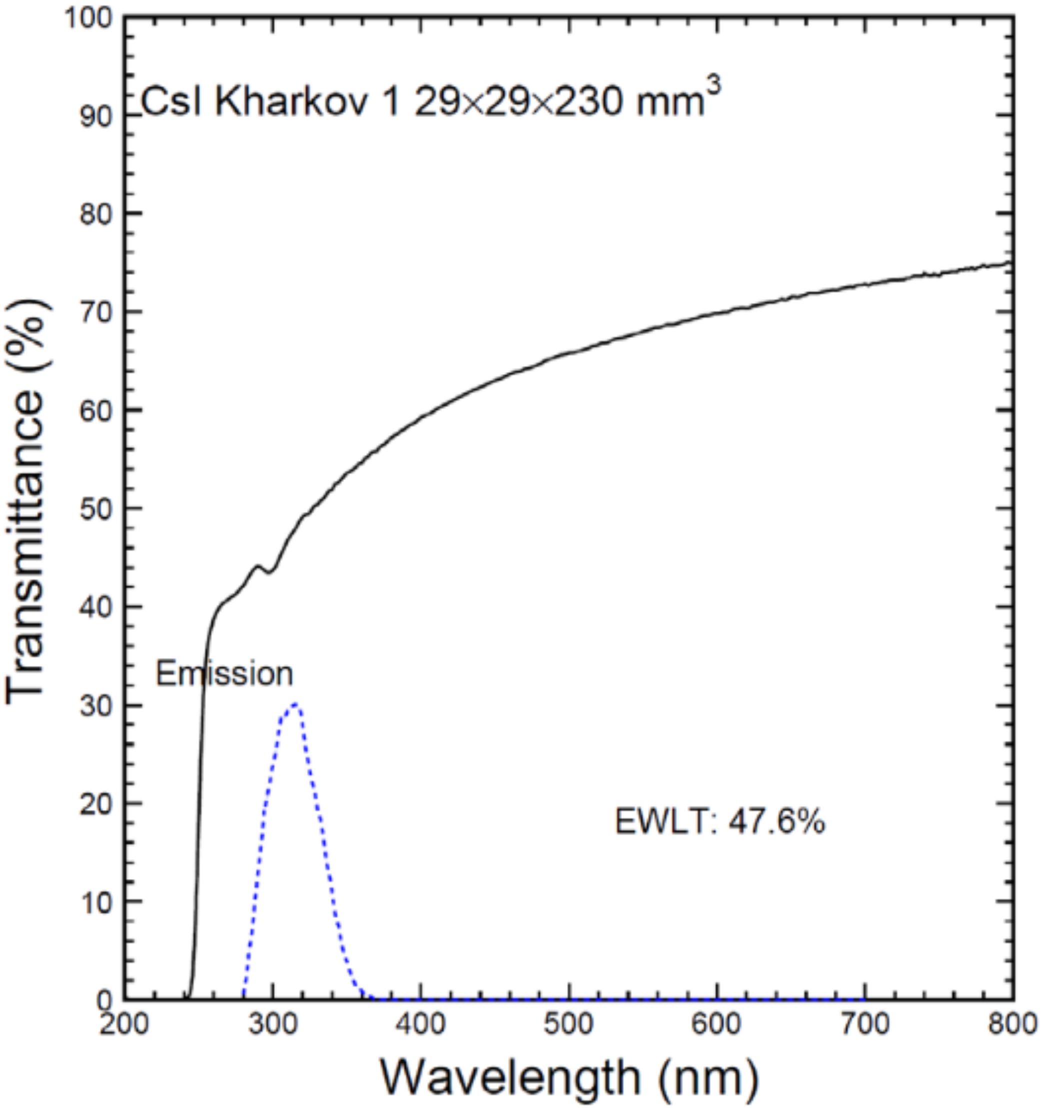
- In the range $\sigma_E/E<0.1$ and $\sigma_t<0.5$ ns the e^- efficiency is within 2%

backup slides
calorimeter

Crystals properties

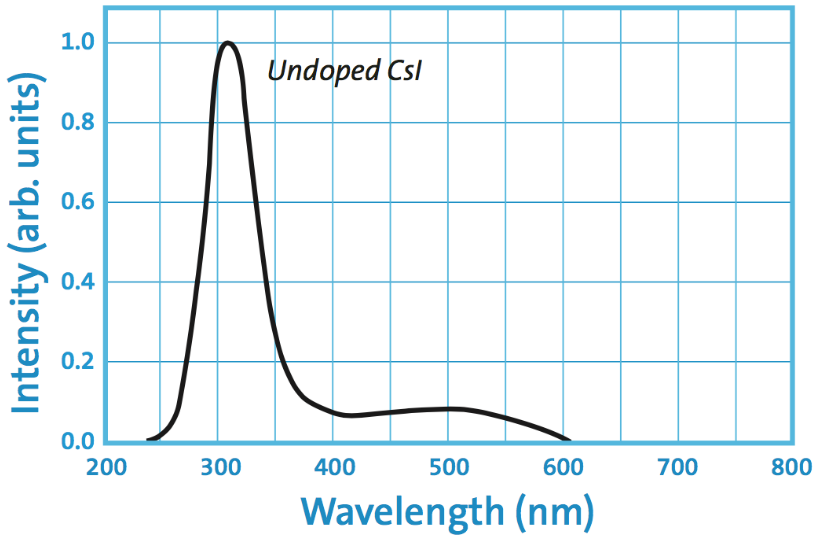
Crystal	BaF_2	LYSO	CsI
Density [g/cm^3]	4.89	7.28	4.51
Radiation length [cm] X_0	2.03	1.14	1.86
Molière radius [cm] R_m	3.10	2.07	3.57
Interaction length [cm]	30.7	20.9	39.3
dE/dx [MeV/cm]	6.5	10.0	5.56
Refractive Index at λ_{max}	1.50	1.82	1.95
Peak luminescence [nm]	220, 300	402	310
Decay time τ [ns]	0.9, 650	40	16
Light yield (compared to NaI(TI)) [%]	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

CsI properties

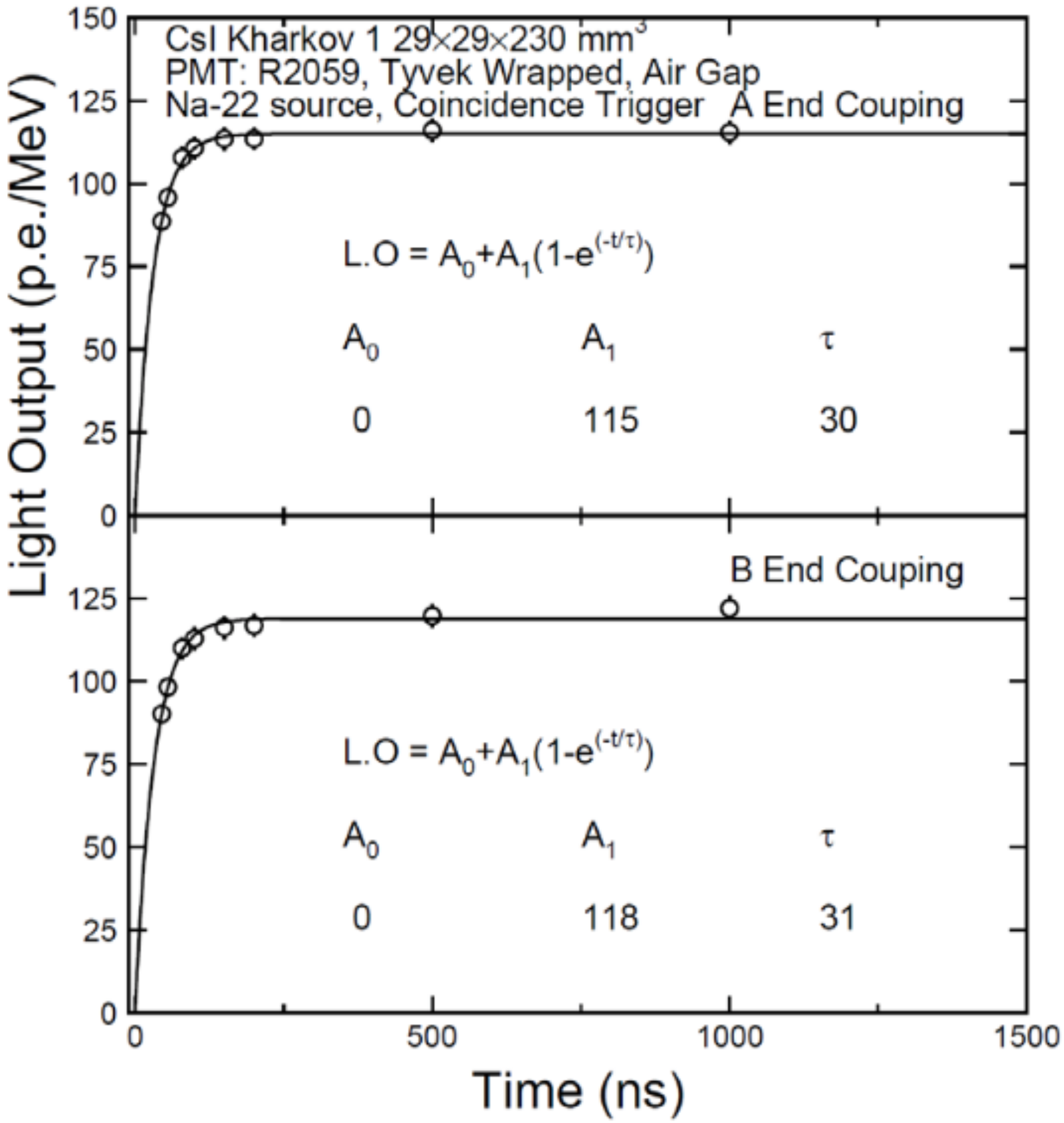


$$\mathrm{EWLT} = \frac{\int \mathrm{LT}(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

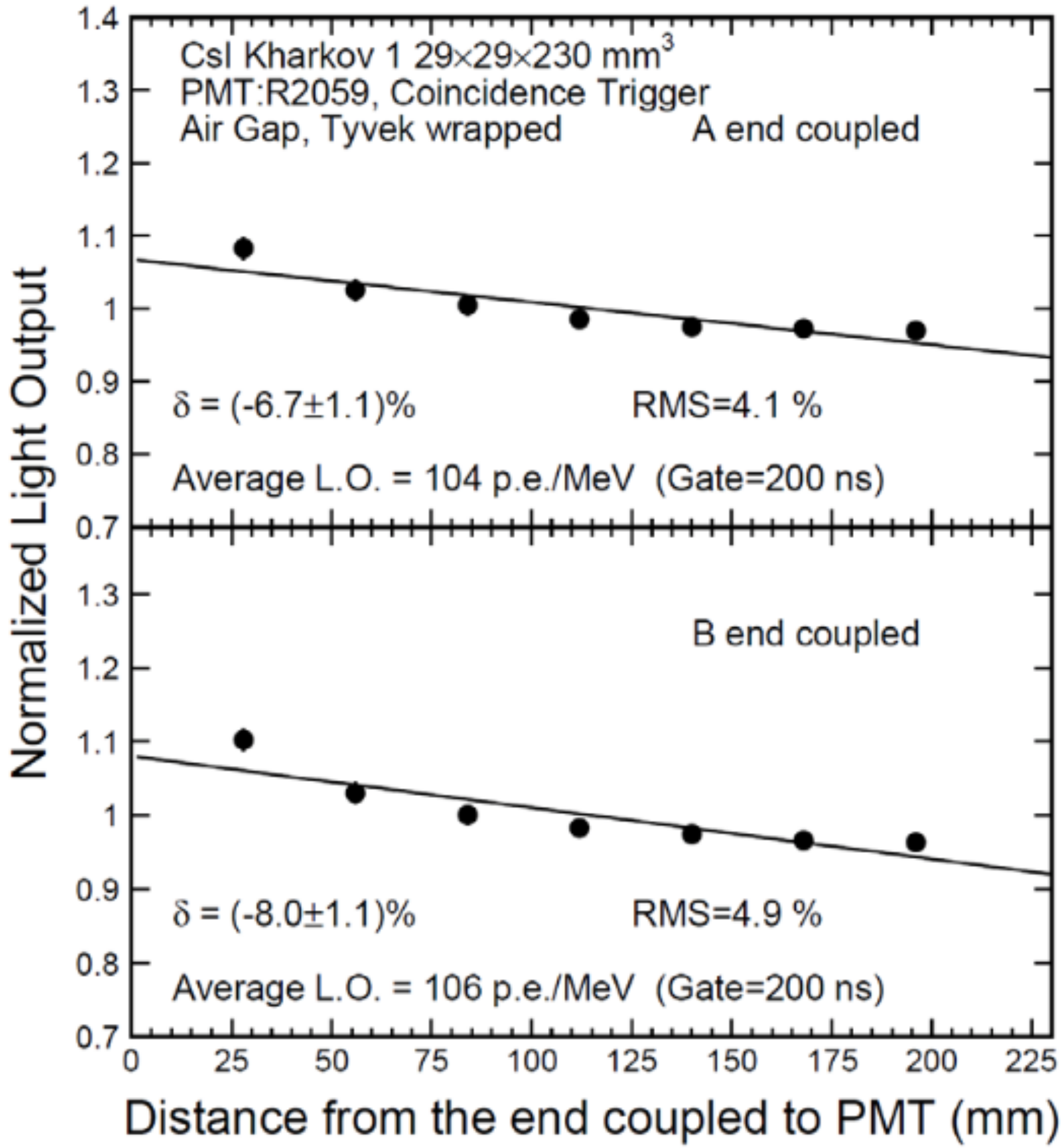
- where LT(λ) is the light transmittance and Em(λ) is the emission spectrum



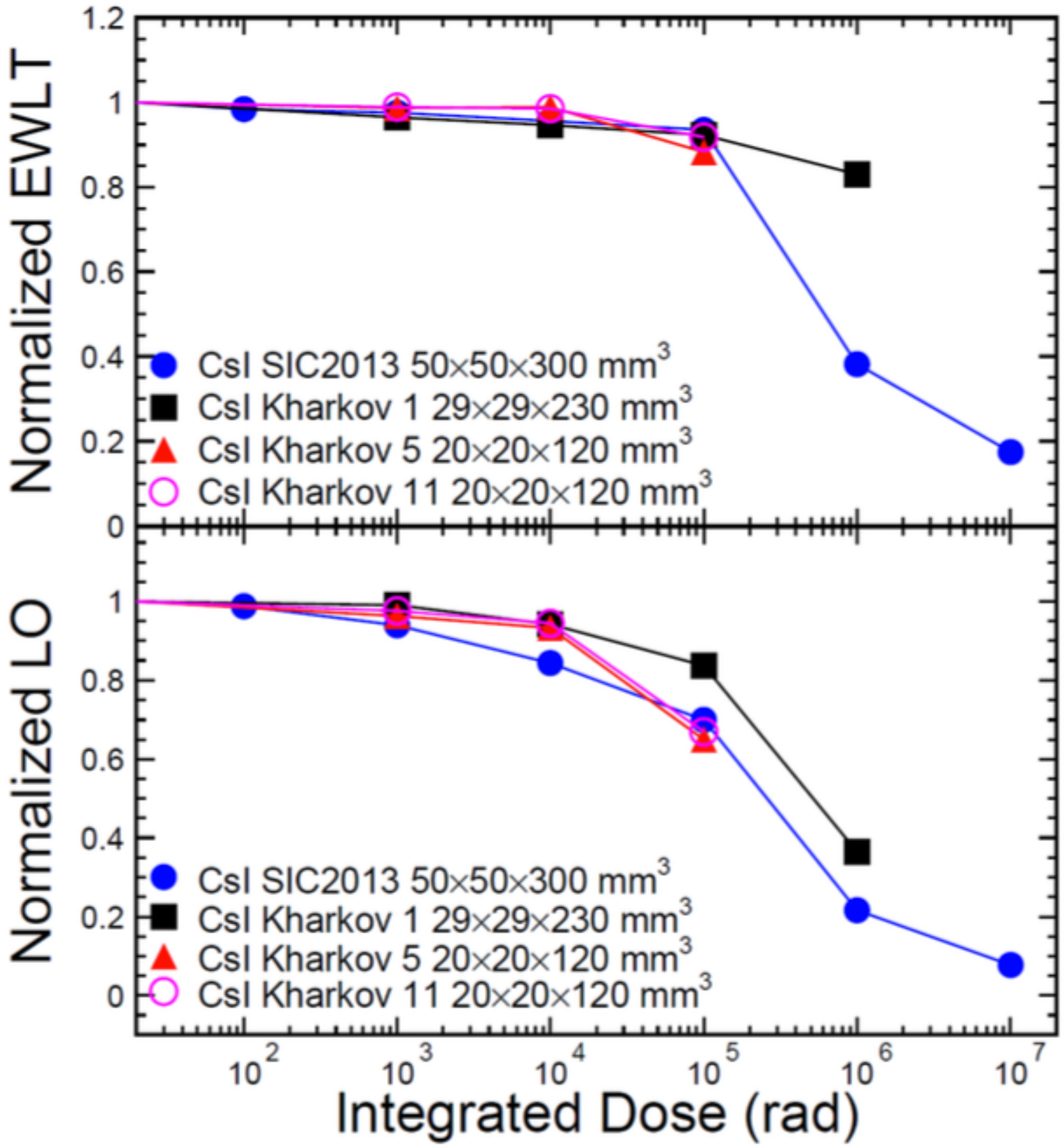
CsI Light Output



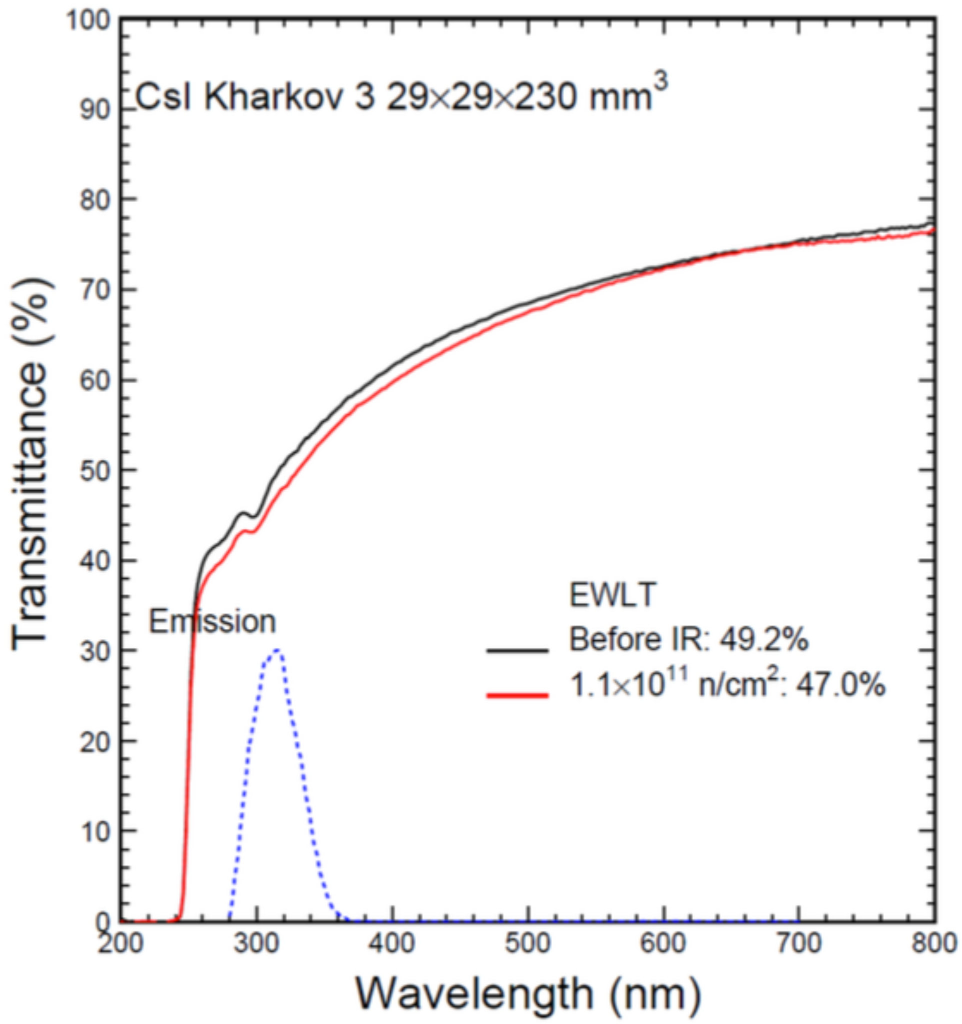
CsI LRU

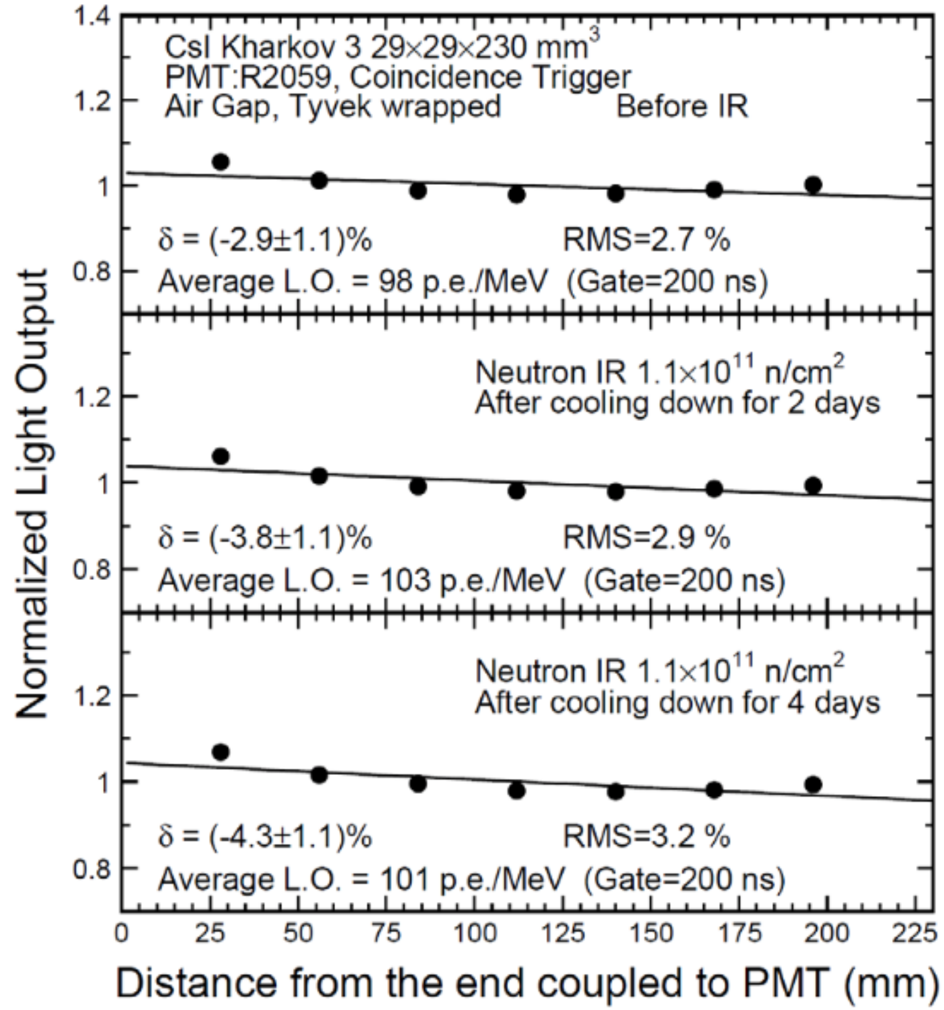

CsI Kharkov 1 29×29×230 mm3
PMT:R2059, Coincidence Trigger
Air Gap, Tyvek wrapped
A end coupled
δ = (-6.7±1.1)%
RMS=4.1 %
Average L.O. = 104 p.e./MeV (Gate=200 ns)
B end coupled
δ = (-8.0±1.1)%
RMS=4.9 %
Average L.O. = 106 p.e./MeV (Gate=200 ns)
Normalized Light Output
Distance from the end coupled to PMT (mm)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0
25
50
75
100
125
150
175
200
225

CsI rad damage



CsI neutron damage

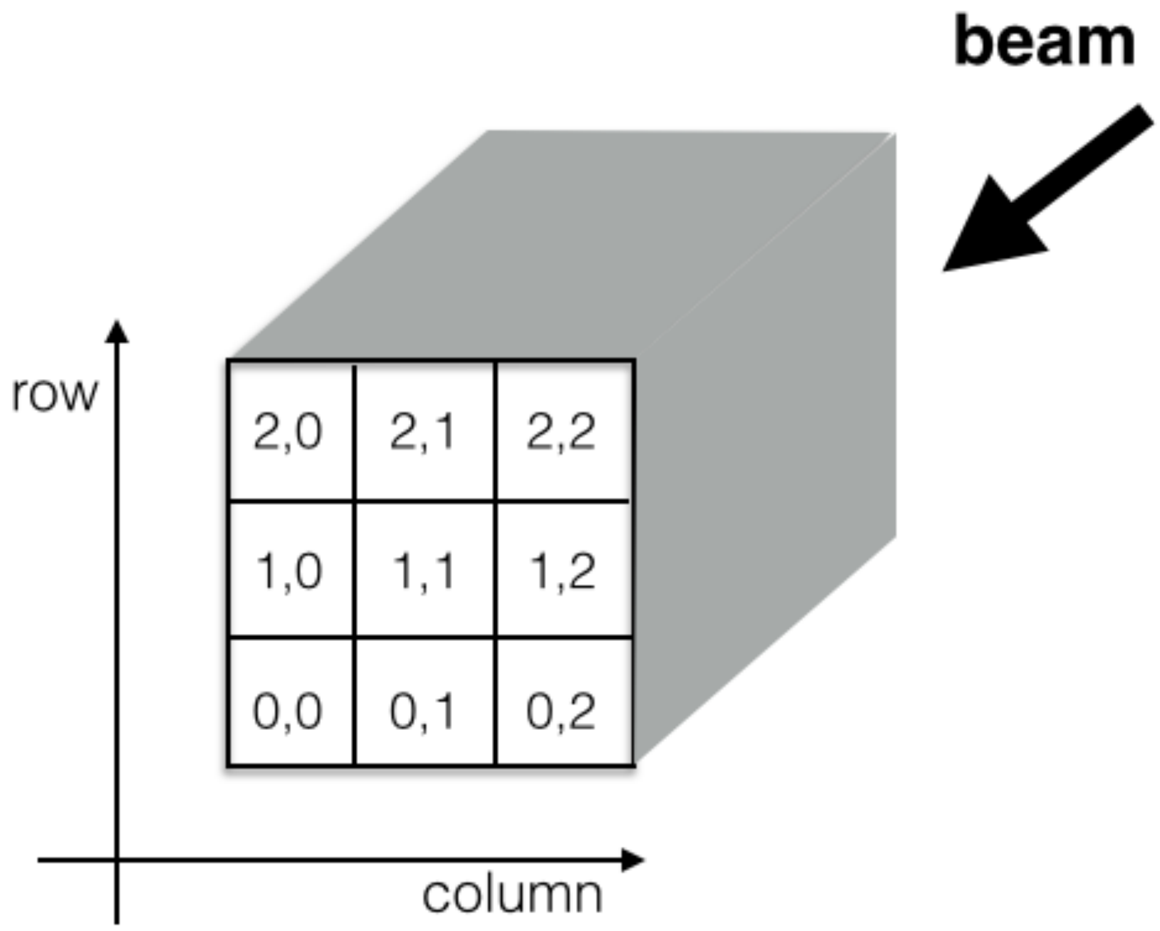




backup slides

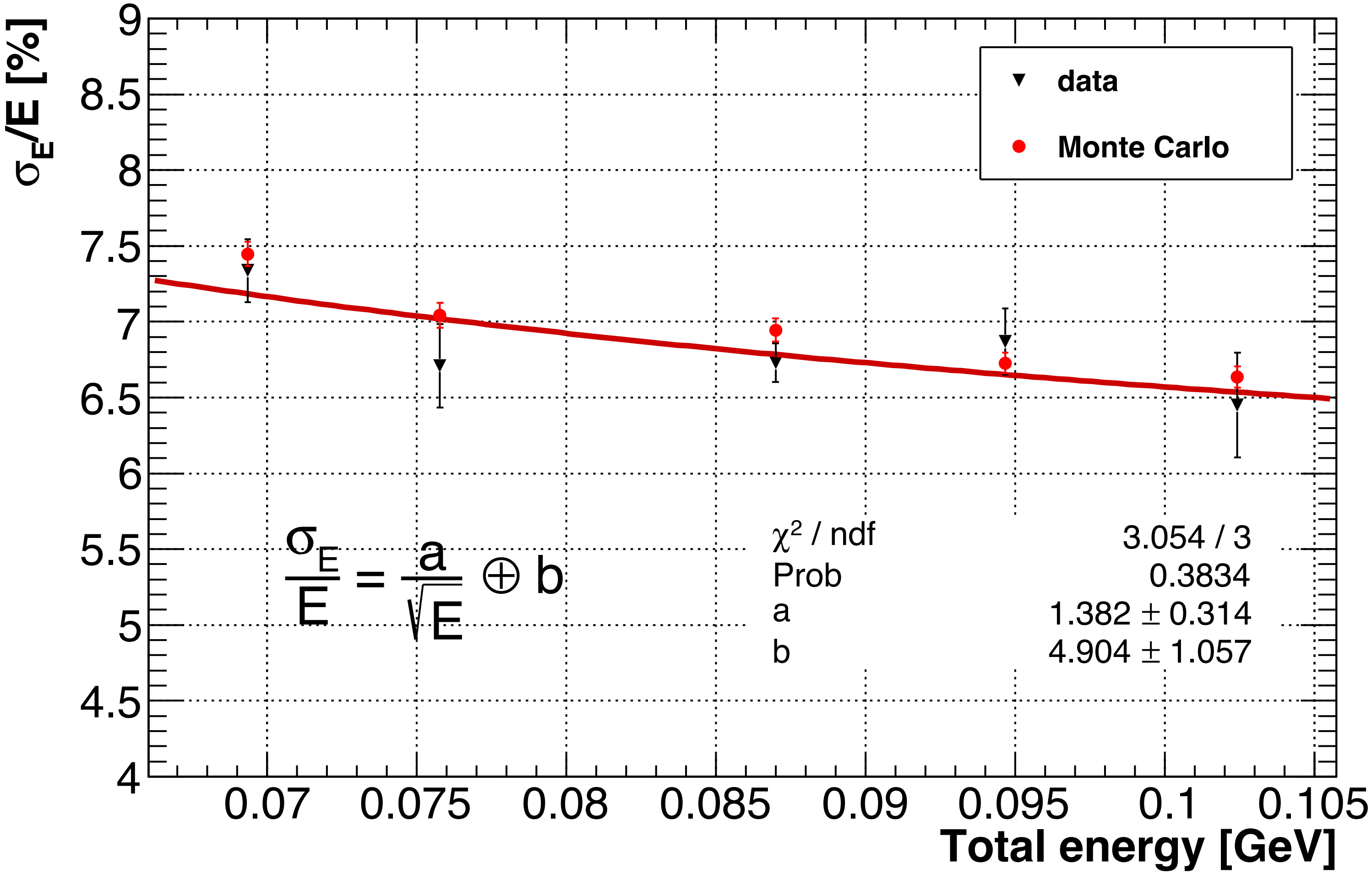
beam test

Numbering convention



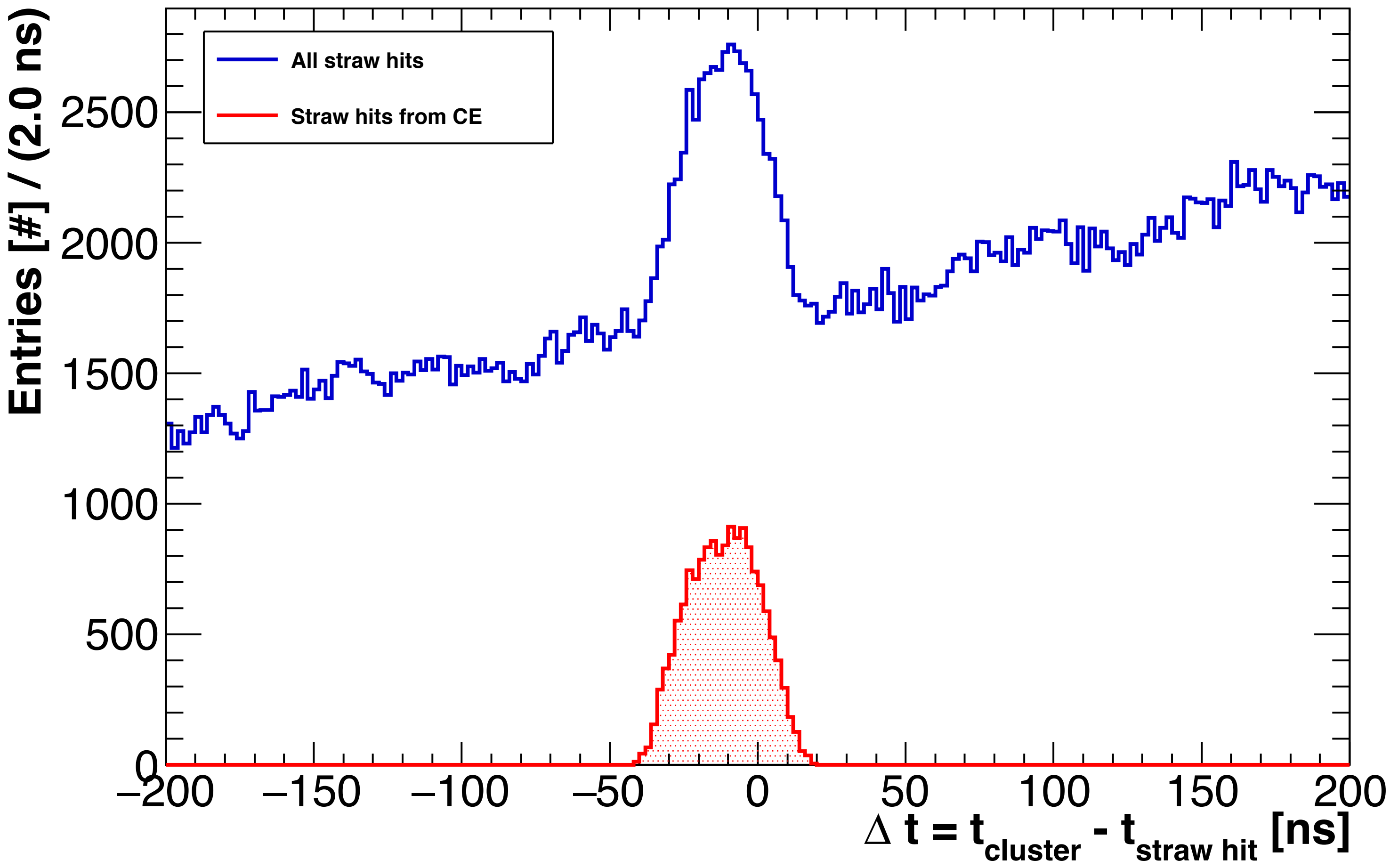
Energy resolution

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



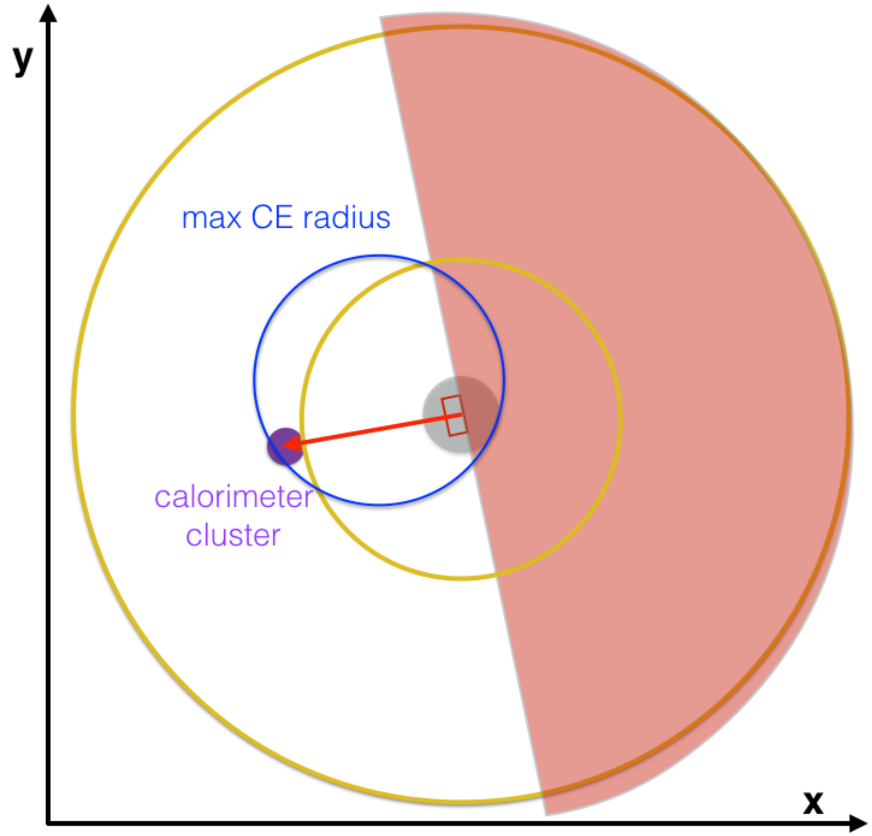
backup slides
track reconstruction

Cluster time window



- 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 positon 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:

$$r_{\mathrm{drift}} = v_{\mathrm{drift}} \cdot (t_{\mathrm{measured}} - \mathrm{T}_0 - t_{\mathrm{flight}})$$

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