The E.M. calorimeter of the Mu2e experiment at Fermilab: a tool to improve the background suppression

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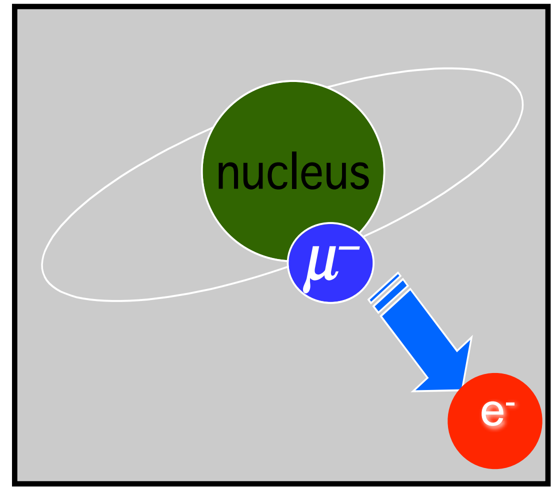
What is μ to e conversion

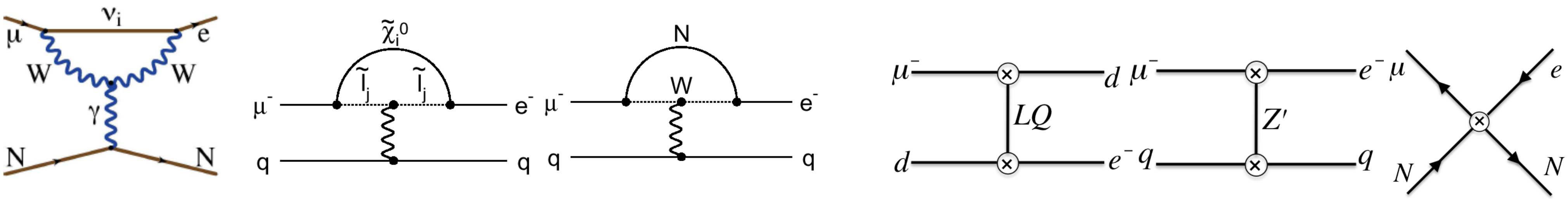
μ converts to an electron in the presence of a nucleus

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



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

for Aluminum: $B_\mu(Z)$ is the muon binding energy (0.48 MeV); $C(A)$ is the nuclear recoil energy (0.21 MeV)



nuMSM Muon conversion : $R \approx 10^{-54}$ | Supersymmetry : $R \leq 10^{-13}$ | Heavy neutrino | Lepto-quark exchange | Z' exchange | Effective contact interaction

Mu2e goal

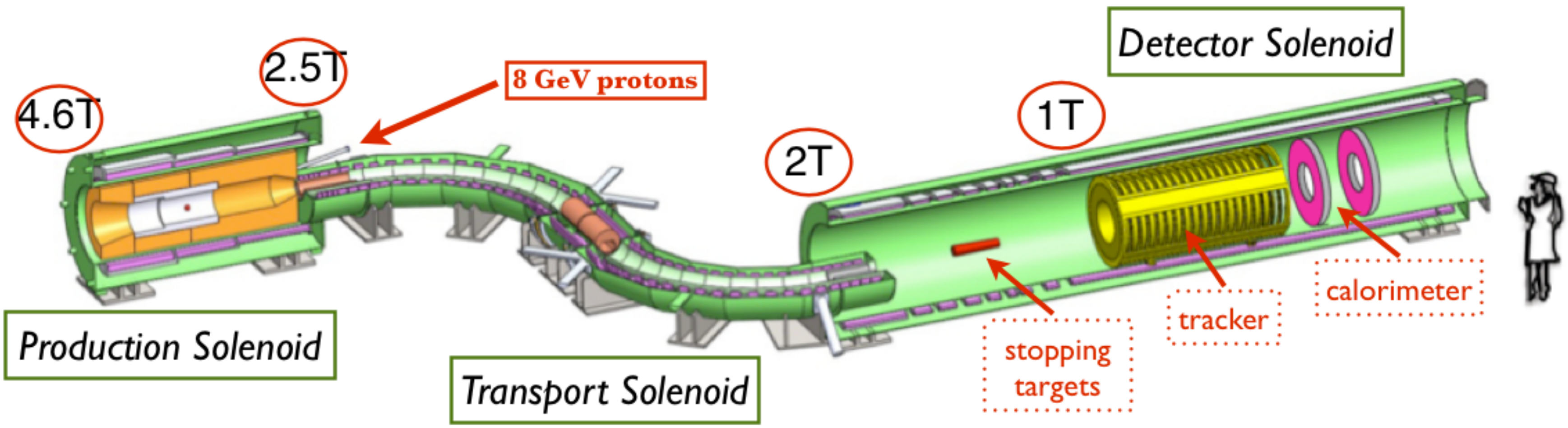
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

Mu2e will start data taking at Fermilab in the second half of 2019

Mu2e experiment set up

- *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



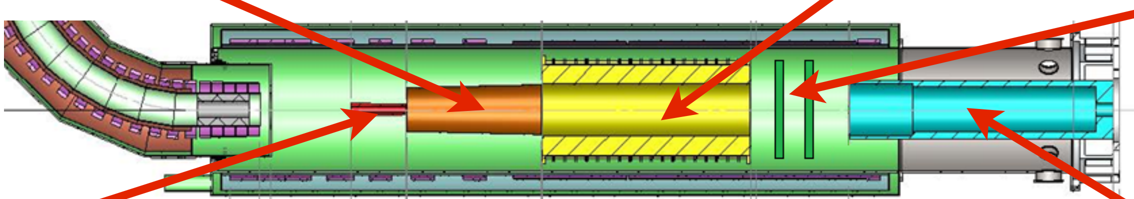
- *Transport Solenoid:*
➡ Select low momentum, negative muons
➡ Antiproton absorber in the mid-section

Mu2e detector

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

- *Tracker:*
  - ❖ 21600 tubes arranged in planes on stations, the tracker has 21 stations
  - ❖ Expected momentum resolution ~ 120 keV/c

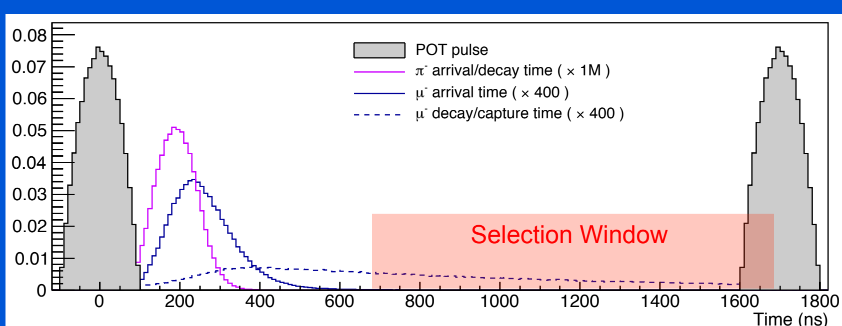
- *Calorimeter:*
  - ❖ 2 disks composed of BaF2 crystals and separated by 1/2 wavelength

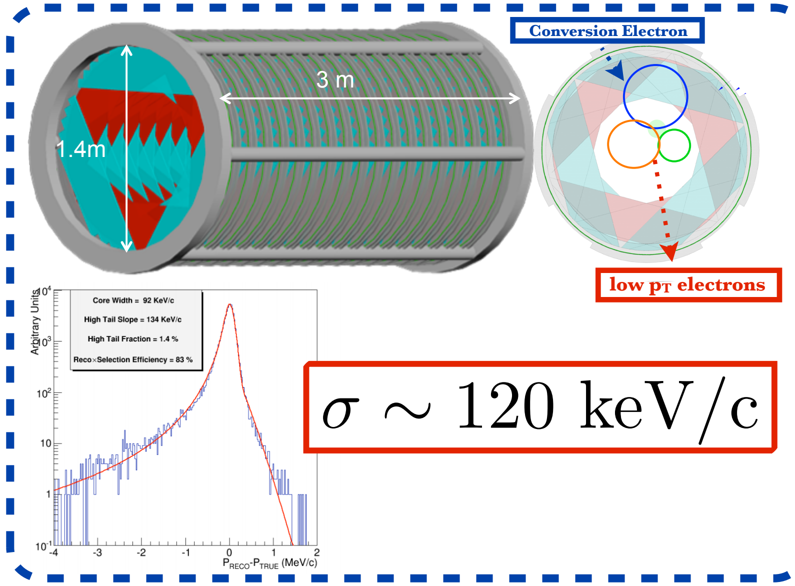


- *Muon beam stop:*
  - ❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

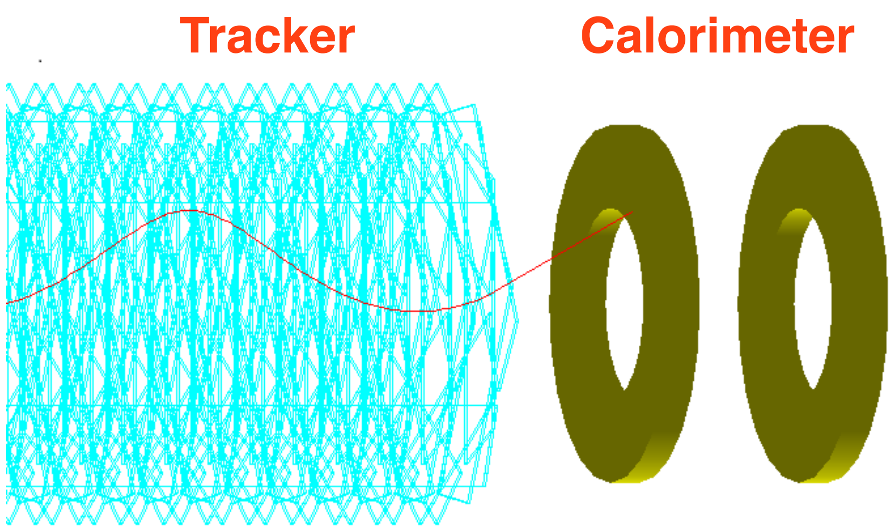
- *Targets:*
  - ❖ 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

Beam structure

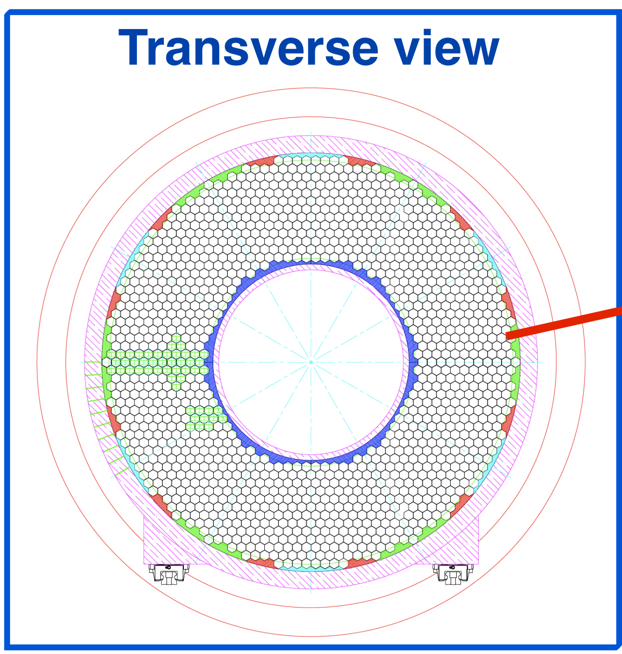


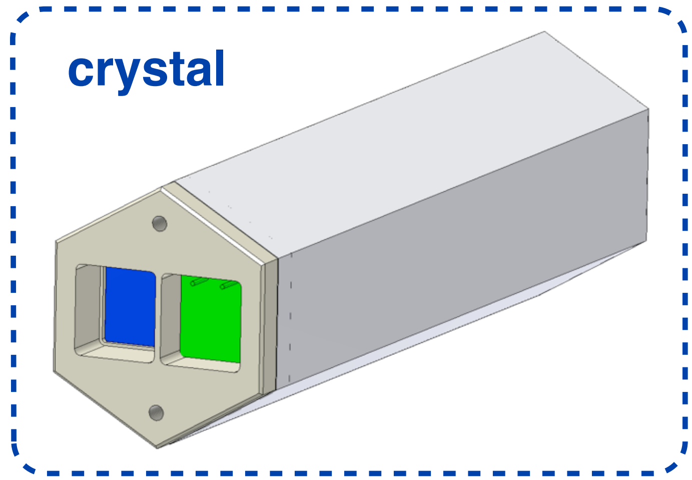


Calorimeter



- ✓ The baseline design consists of two disks; each disk contains 930 hexagonal BaF_2 crystals
- ✓ CDR choice LYSO now substituted with BaF_2 due to excessive increase of cost (x 2.5)
- ✓ Disk separation ~ 70 cm
- ✓ Inner/outer radii: 35.1/66 cm





- ✓ Hexagonal crystals 20 cm length, 1.65 cm apothem
- ✓ 2 APD's/crystal used as readout

Physics backgrounds

Background source	Background fraction with respect to DIO
Electrons from muon Decay-In-Orbit (DIO)	100%
Cosmic induced background	48%
Antiproton induced background	24%
Radiative pion capture	12%
Beam electrons	2%

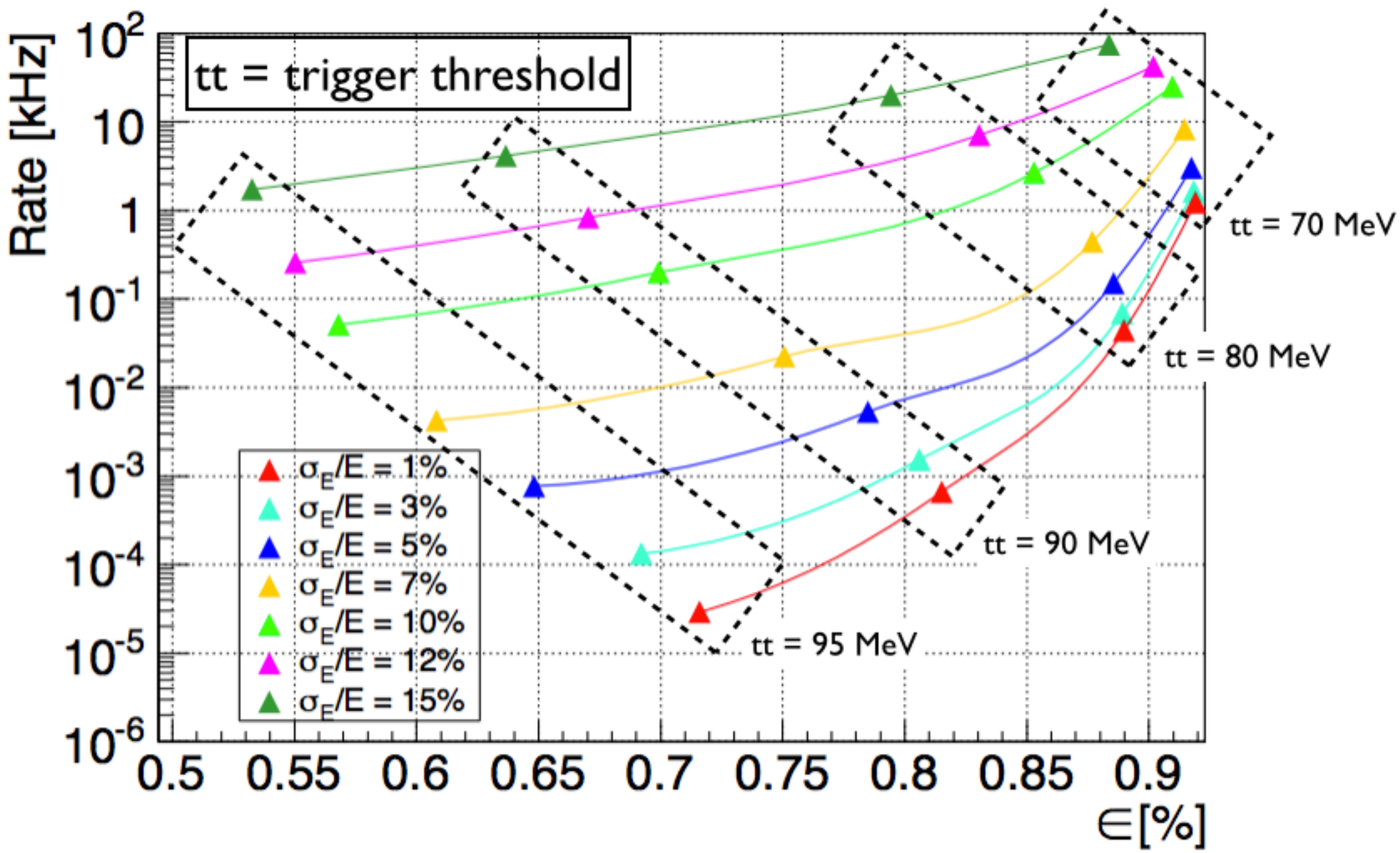
EMC background suppression

- EMC information can be used for suppressing several background sources
- Suppression may be obtained:

1. At the trigger level (setting an energy threshold)
2. By particle identification (PID)
3. By rejection of DIO events, using timing, position and angle information provided by the EMC

Calorimeter trigger

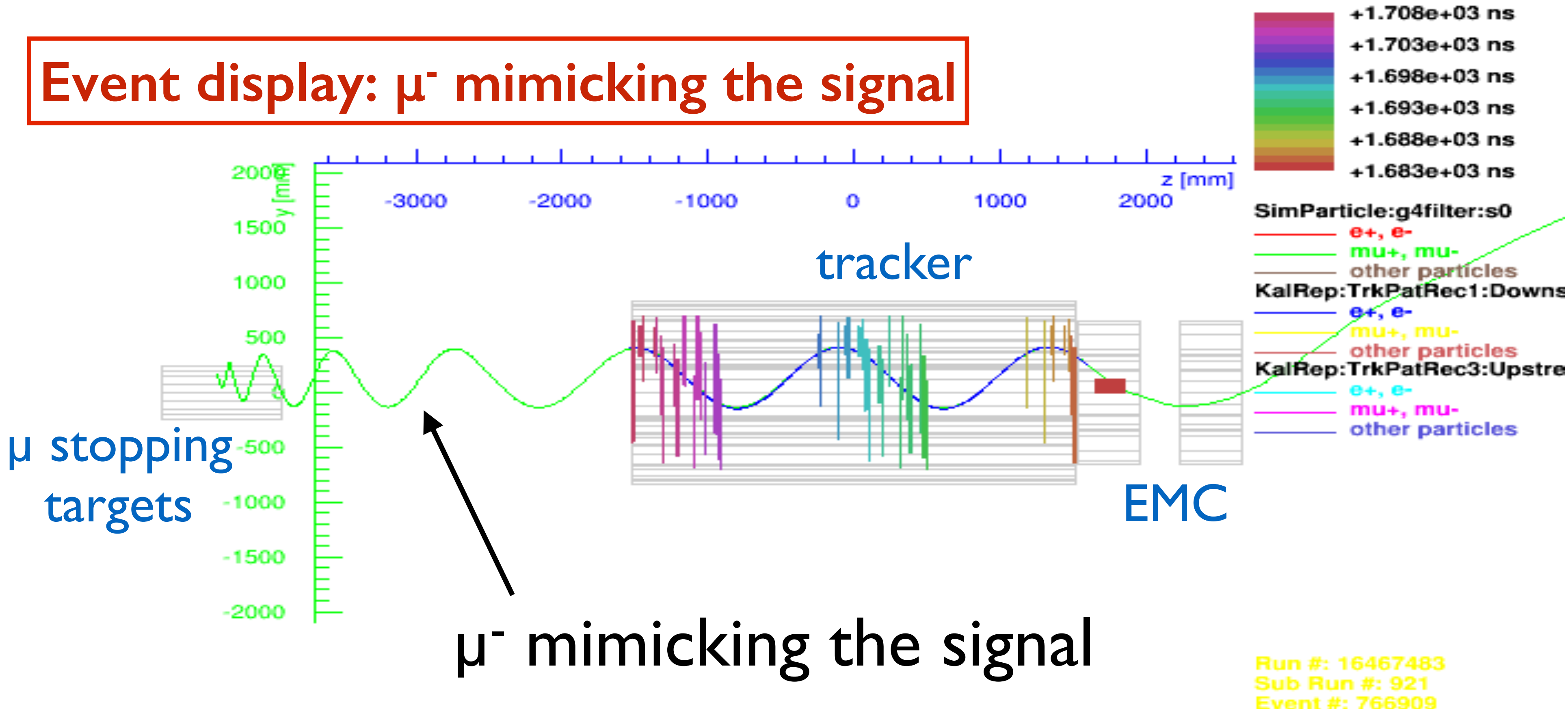
- Threshold on deposited energy in EMC
- sigmaE ~ 5 - 10 % and a threshold @ 70 MeV, DAQ rate ~ 2-20 kHz



Cosmic induced background

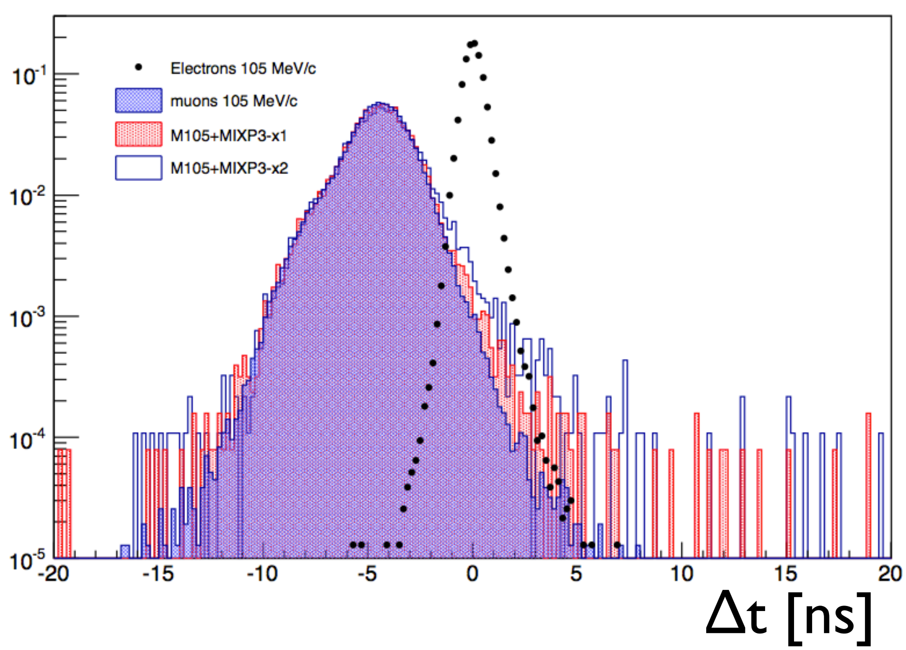
- Simulation showed that a **μ rejection factor > 200** is needed

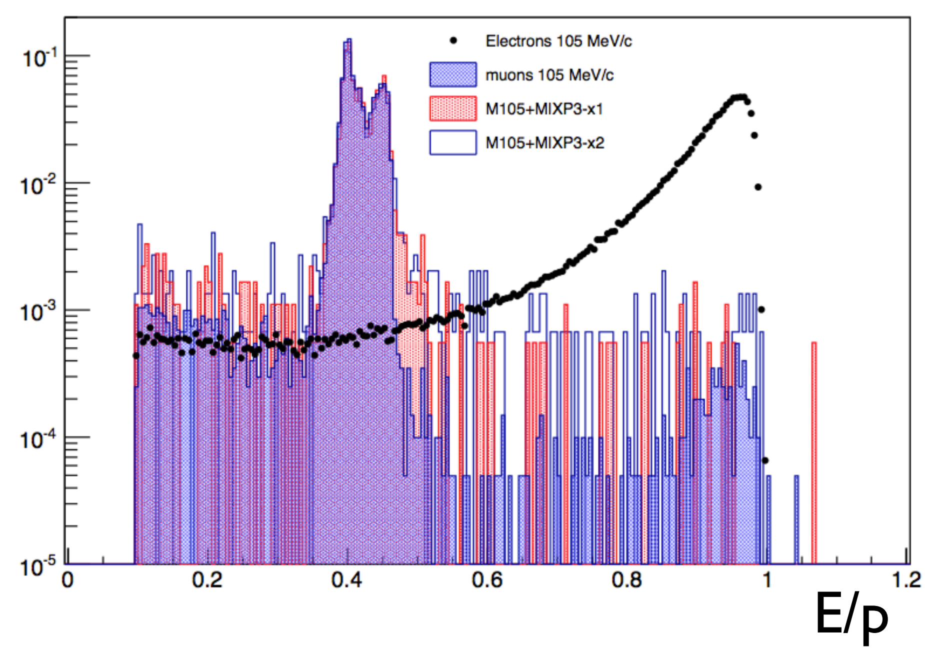
Event display: μ⁻ mimicking the signal



PID - basic idea

- Compare the reconstructed track and the calorimeter information:
    A. $\Delta t = t_{track} - t_{emc}$, where t_{track} is the track time extrapolated to the calorimeter and t_{emc} is the reconstructed EMC cluster time
    B. E/p, where E is the energy deposition in the EMC and p is the reconstructed momentum





PID - algorithm

Two steps used for doing the PID:

1. Define a likelihood using distributions in E/p and Δt:

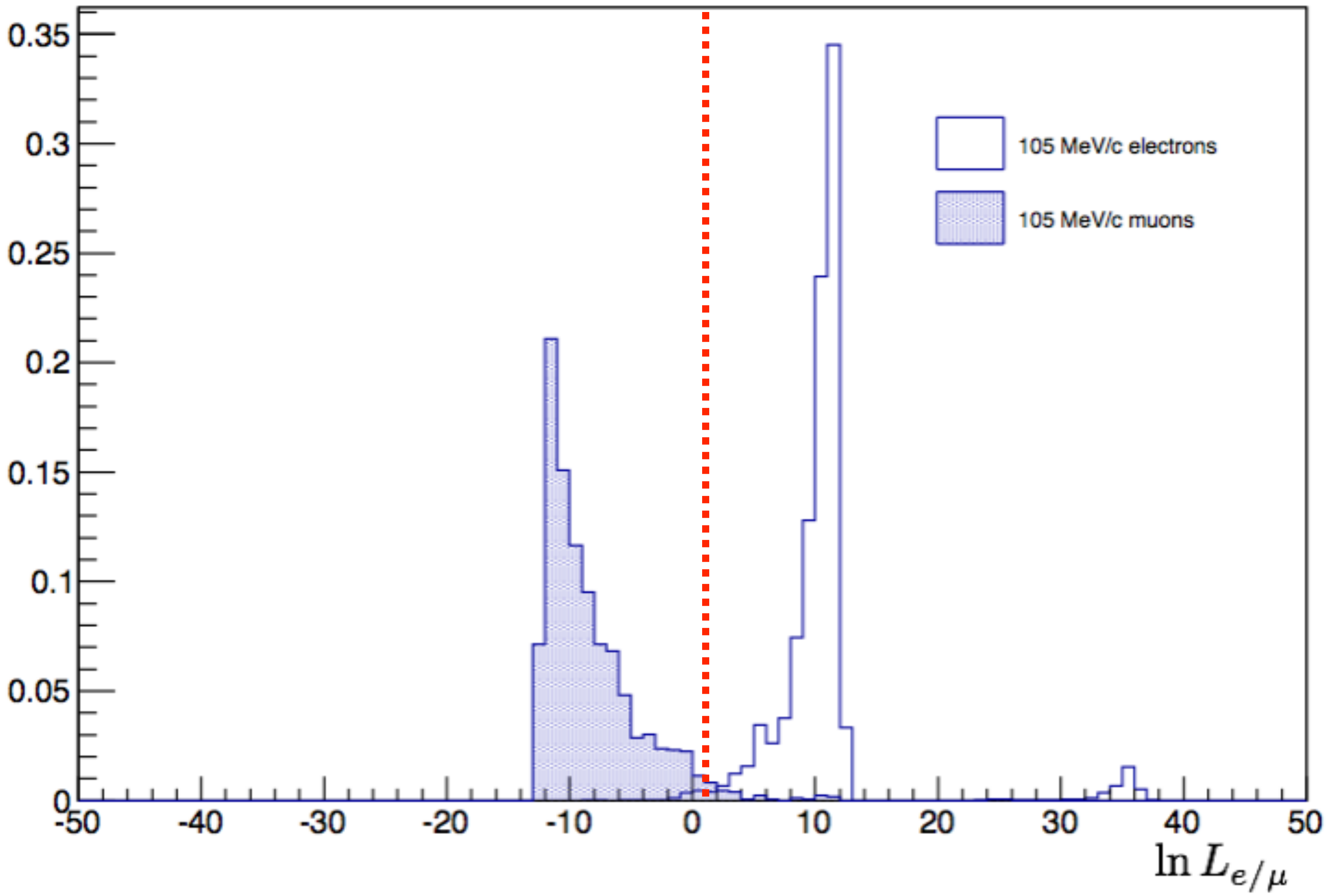
$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E_{cluster}/p_{track})$$

   $P_{e,\mu}(\Delta t)$ and $P_{e,\mu}(E/p)$ are the probability densities for e and μ respectively

2. The ratio of the likelihoods is the final parameter used:

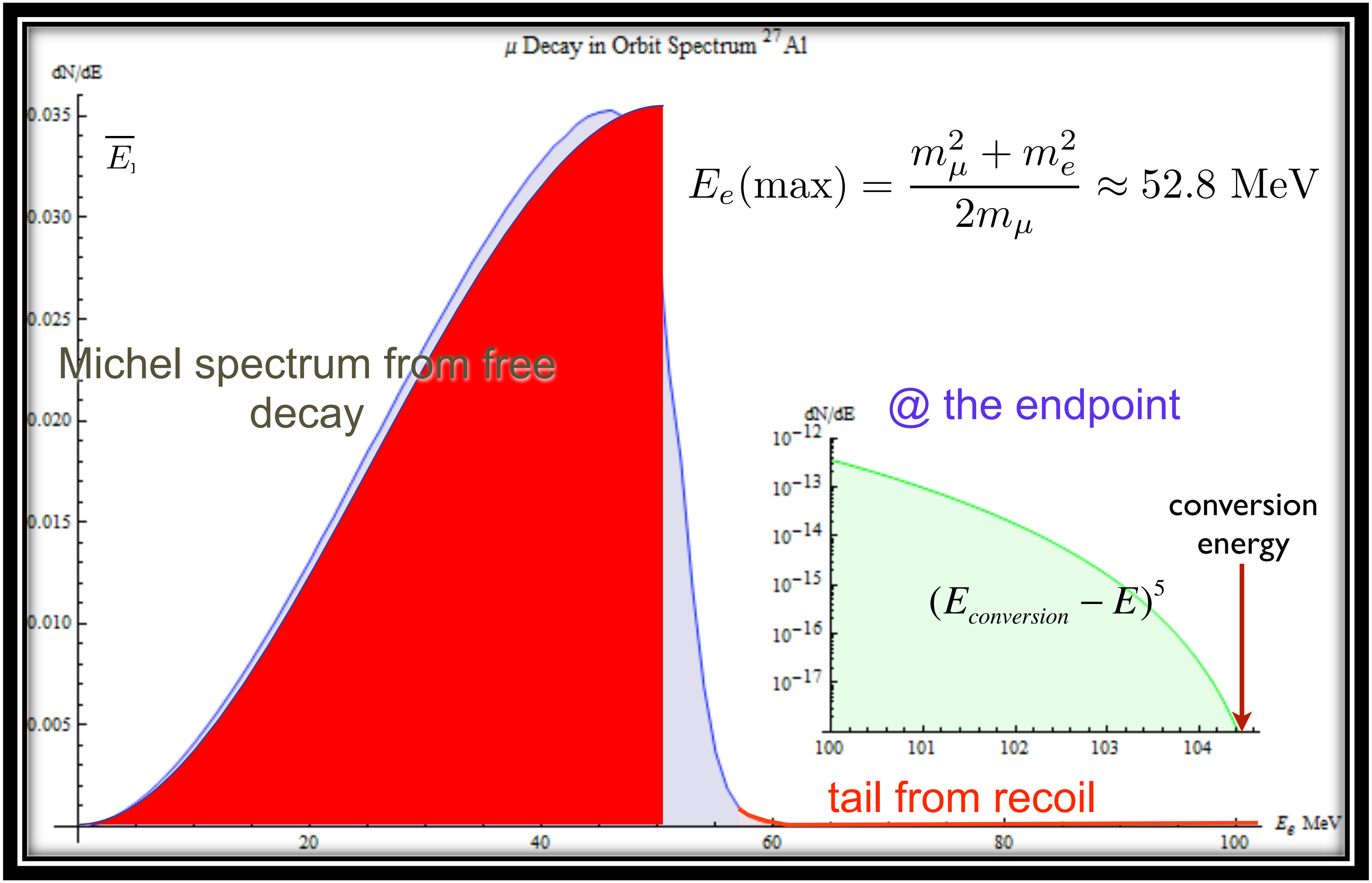
$$\ln L_{e/\mu} = \ln \frac{L_e}{L_\mu} = \ln L_e - \ln L_\mu$$

PID - likelihood ratio



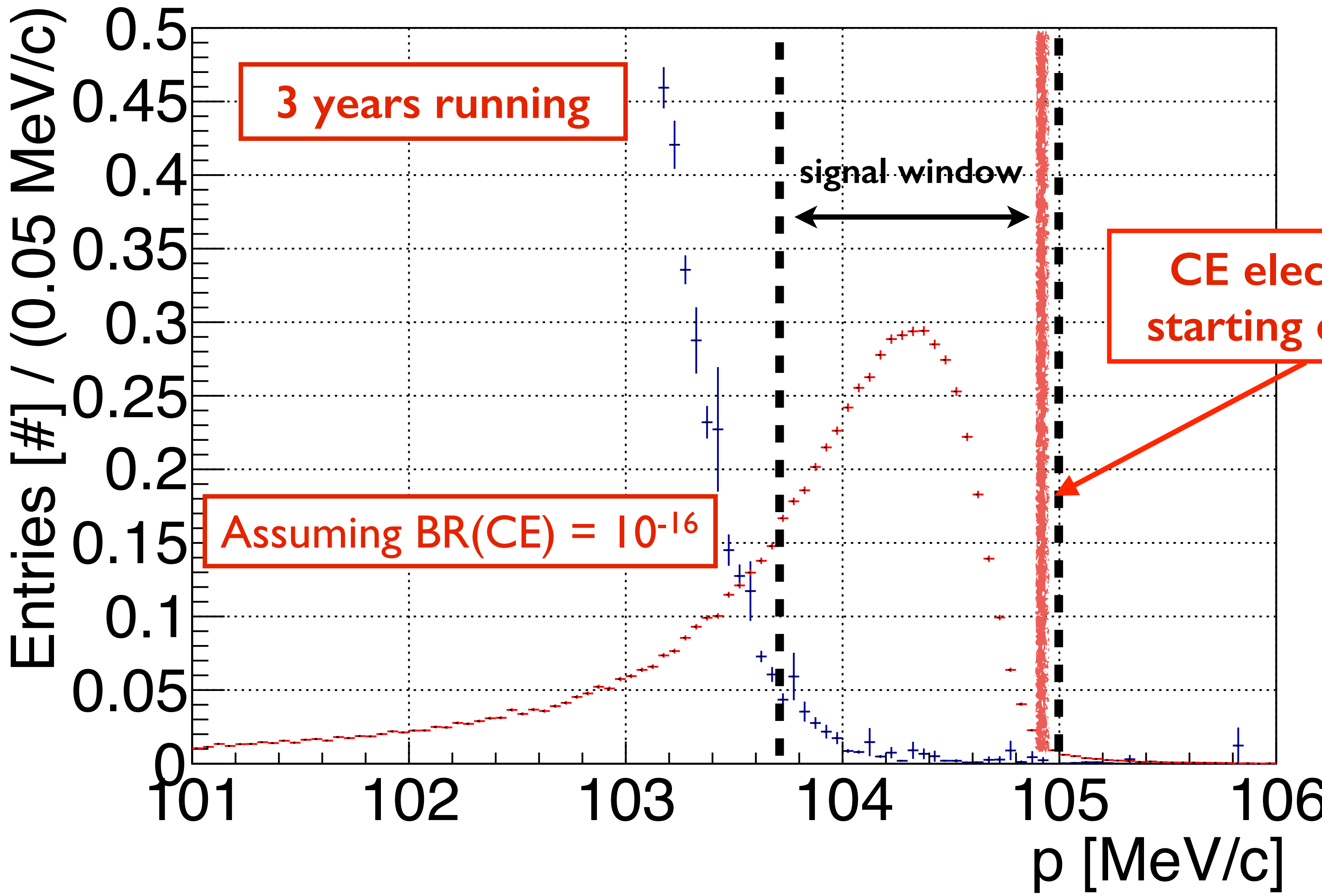
- Open histogram: CE. Blue filled: 105 MeV/c μ^-
- Cutting @ ln $L_{e/\mu}$ >1.5 provides a μ rejection of 200 and ε_e ~ 96%

μ decay-in-orbit



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

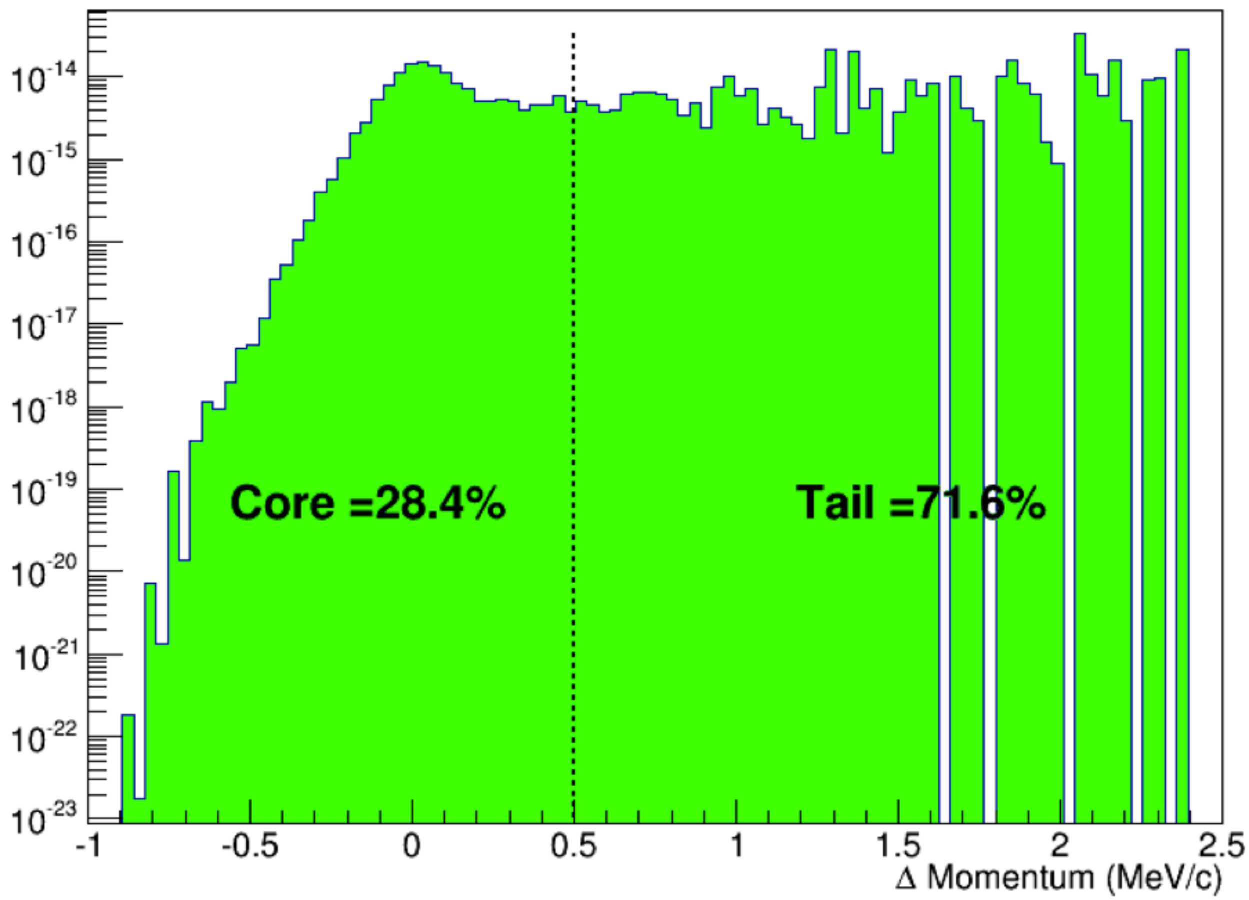
CE vs DIO: tracker only



- Blue markers: DIO's. Red markers: CE's.
- **signal window**: 103.75 < p < 105.00 MeV/c

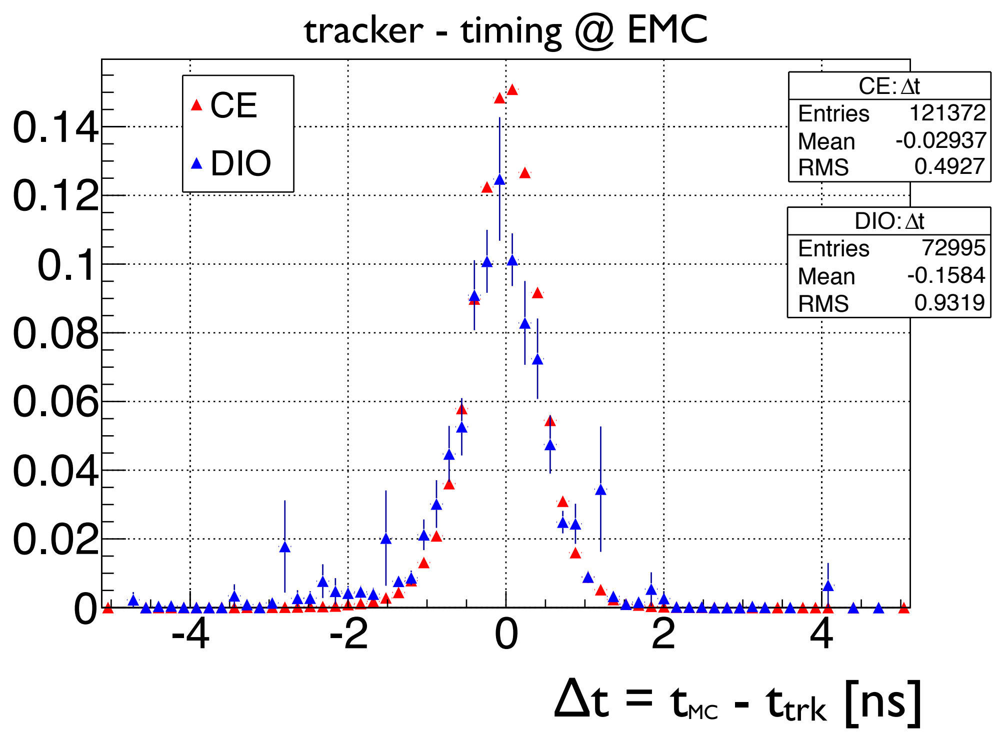
DIO suppression

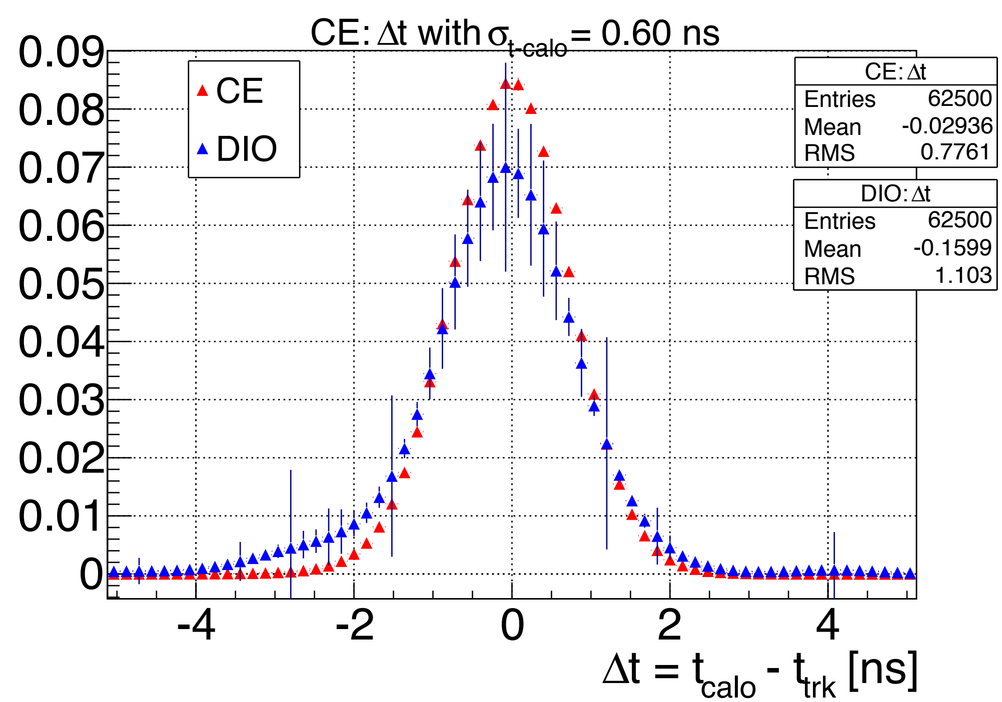
- More than 70% of the DIO have $\Delta p = p_{trk} - p_{MC} > 500$ keV
- Comparing track and calorimeter information a candidate is either validated or rejected



Calorimeter timing

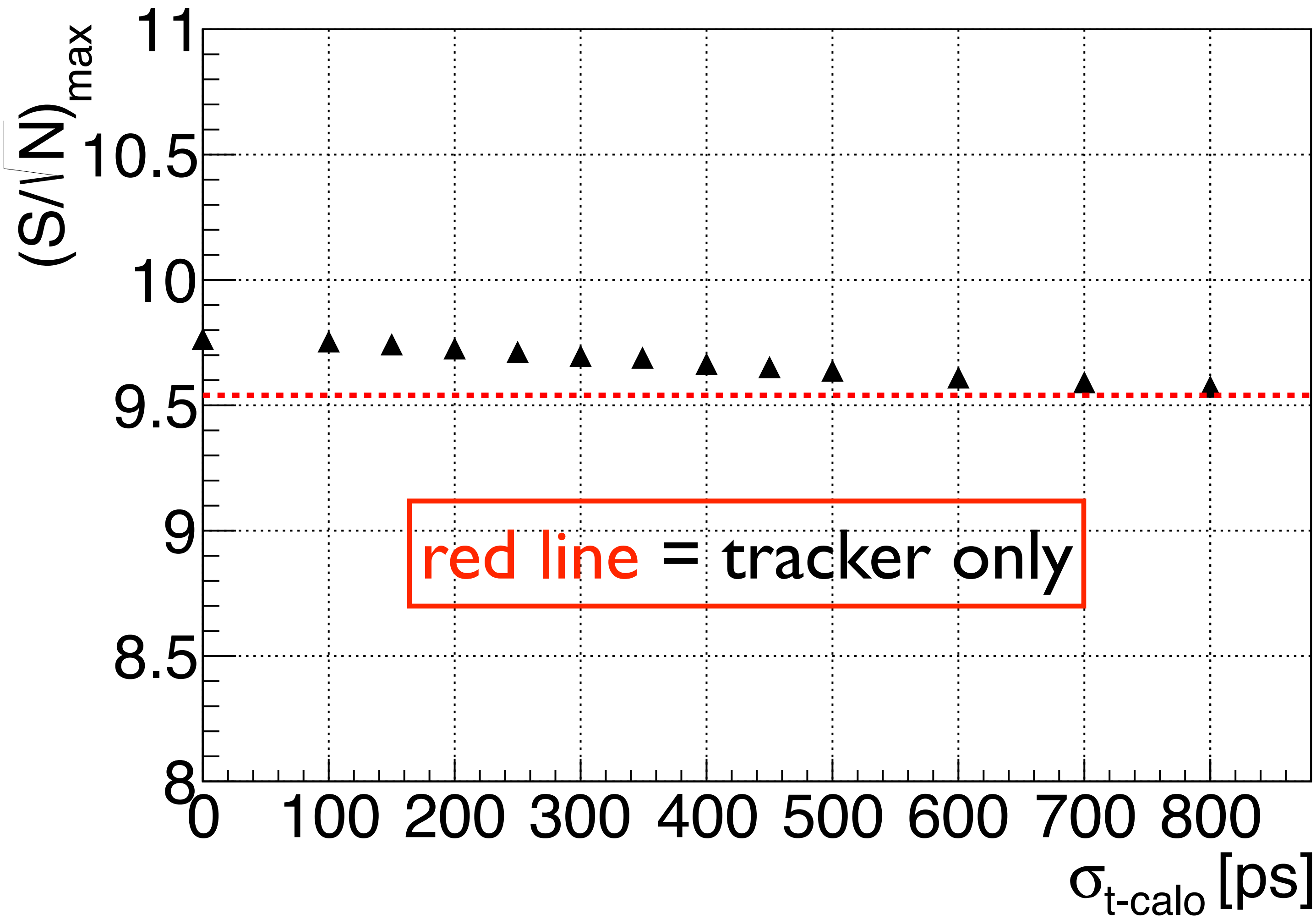
- Red markers: CE. Blue: DIO electrons
- Include effect of the calorimeter time resolution in different scenarios using Gaussian smearing; $\sigma_{t-calo} \in [100, 800]$ ps
- Apply cuts on $|\Delta t|$ and use the value of $S/\sqrt{N}$ (S=CE and N = # DIO) as figure-of-merit (fom)





DIO rejection vs timing resolution

- Maximum of the fom vs calorimeter time resolution
- ~ 3% improvement in $S/\sqrt{N}$ reached with sigmaT < 300 ps



Conclusions

- Improvement in the calorimeter based trigger are under study
- Calorimeter PID satisfies the Mu2e requirements, but improvements including other information in the likelihood are underway

Future prospects:

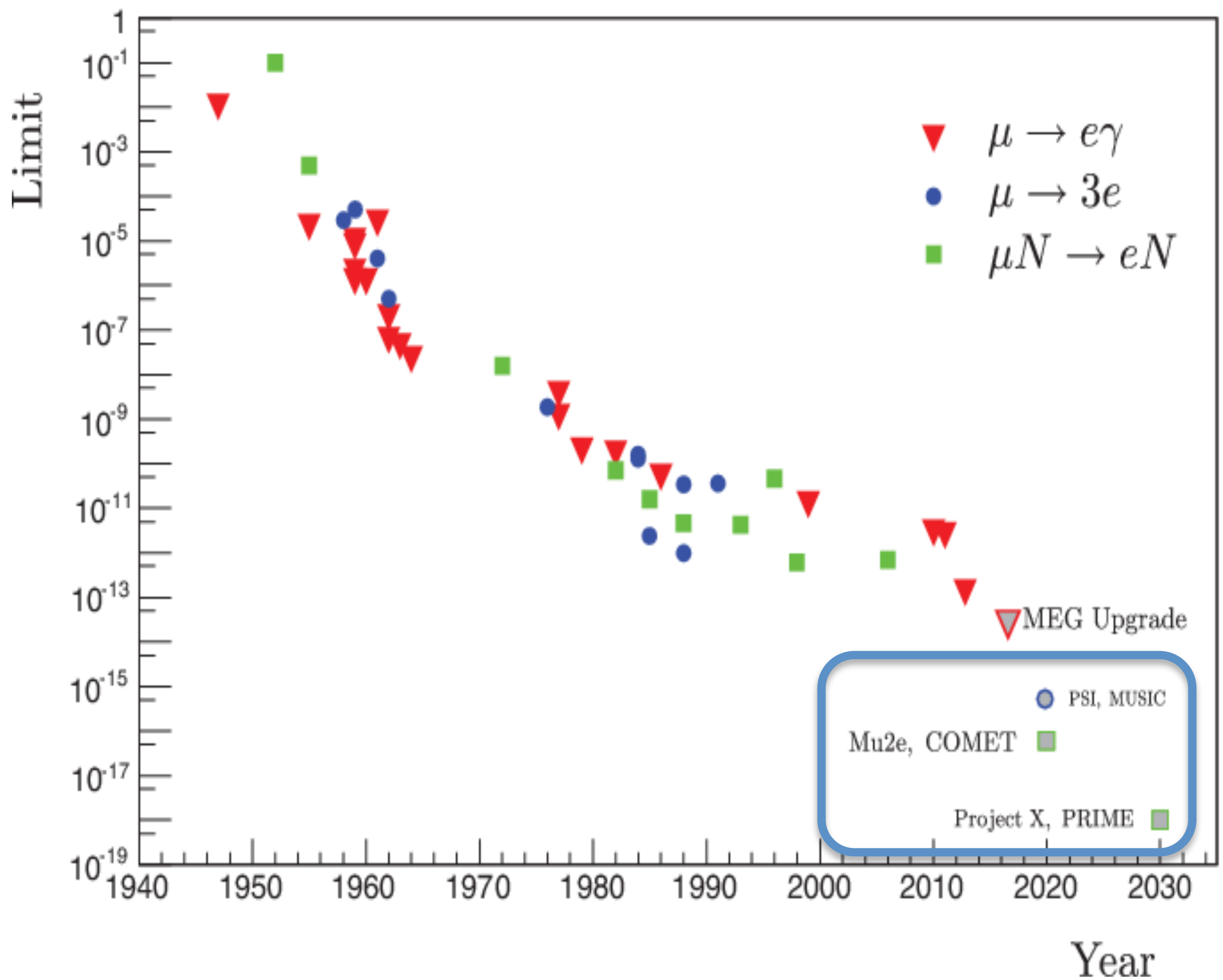
- Improve the DIO rejection analyses including ALL the calorimeter observables
- test performance of the calorimeter prototype: crystals, photosensors and fee electronics
- At the end of this analyses process, an implementation of the EMC will be also discussed

Backup slides

Why to look for cLFV

Charged Lepton Flavor Violation (cLFV) predicts many processes:

$$\mu^- N \rightarrow e^- N,\ \ \mu \text{ or } \tau \rightarrow e\gamma, e^+e^-e^-,\ \ K_L \rightarrow \mu^\pm e^\mp,\ \text{ and more}$$



Crystal choice

✓ At CDR the baseline was LYSO, but high variation (x2.5) of the cost made this option not more affordable. We have studied alternative crystals and opted for BaF2

BaF2 presents several advantages:

✓ **Small decay time**

✓ **Non-hygroscopic**

✓ **Rad hard**

Crystal	BaF_2	LYSO	CsI	$PbWO_4$
Density (g/cm^3)	4.89	7.28	4.51	8.28
Radiation length (cm) X_0	2.03	1.14	1.86	0.9
Molière radius (cm) Rm	3.10	2.07	3.57	2.0
Interaction length (cm)	30.7	20.9	39.3	20.7
dE/dx (MeV/cm)	6.5	10.0	5.56	13.0
Refractive Index at λ_{max}	1.50	1.82	1.95	2.20
Peak luminescence (nm)	220, 300	402	310	420
Decay time τ (ns)	0.9, 650	40	26	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	3.6	0.3, 0.1
Light yield variation with temperature (% / °C)	0.1, -1.9	-0.2	-1.4	-2.5
Hygroscopicity	None	None	Slight	None

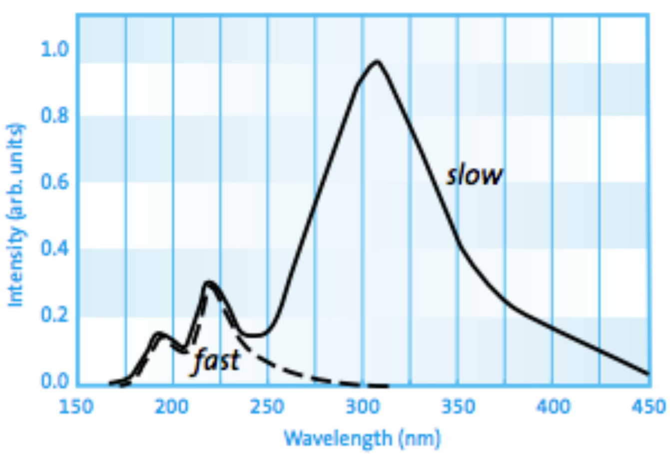


Figure 1. Scintillation emission spectrum of BaF_2

It presents also some drawbacks:

✓ The fast component is @ 220 nm

✓ the slow component has a tau of 650 ns