S1371

Study of Muon Capture for μ-e Conversion Experiments

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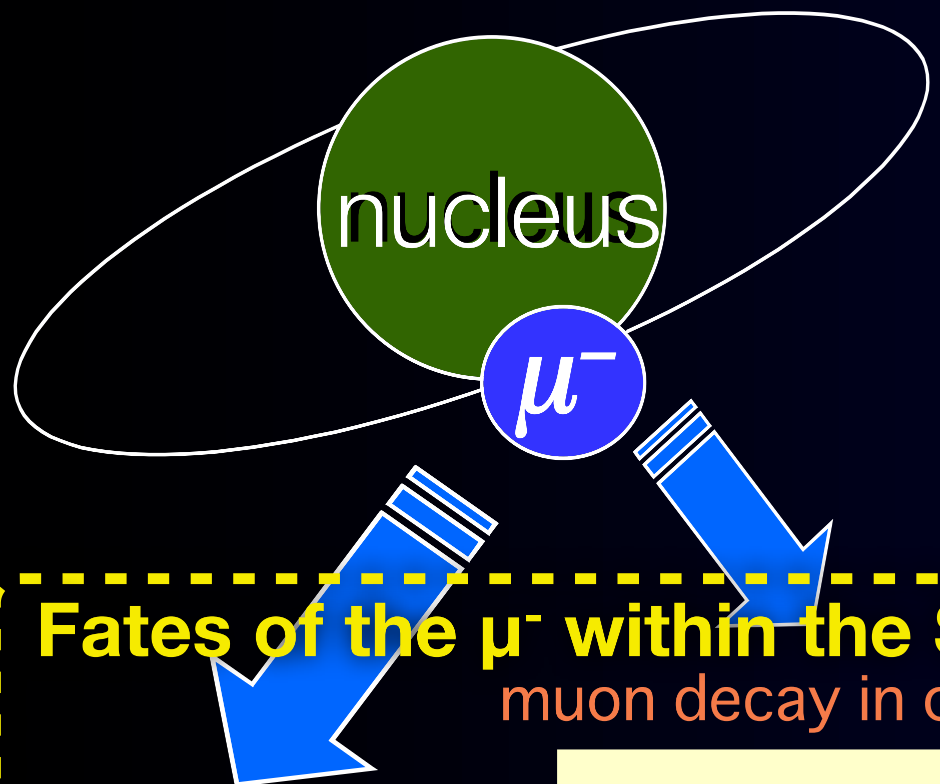
Outline

- Importance and urgency
  - overview of μ-e conversion searches:
    - COMET, Mu2e
  - proton emission from μ-capture process
- Experiment
  - overview
  - setup and readiness
  - simulation
  - beam time requirements

μ-e Conversion Search

- Two experiments are going to start to search for the μ-e conversion process: COMET@J-PARC and Mu2e@FNAL.
- These are stopped muon experiments. When a μ^- in stopped in a material, ...

1s state in a muonic atom



Fates of the μ^- within the SM

muon decay in orbit

$$\mu^- \to e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$$

Beyond the SM

$$\mu^- + (A,Z) \to e^- + (A,Z)$$

μ-e conversion

Forbidden by the SM, because
the lepton flavor is changed to μ-flavor to e-flavor.

Event signature :

a single mono-energetic electron of 100MeV

in the SM + ν masses

μ-e conversion can be occur via ν-mixing, but expected rate is well below the experimentally accessible range. Rate ~$O(10^{-54})$

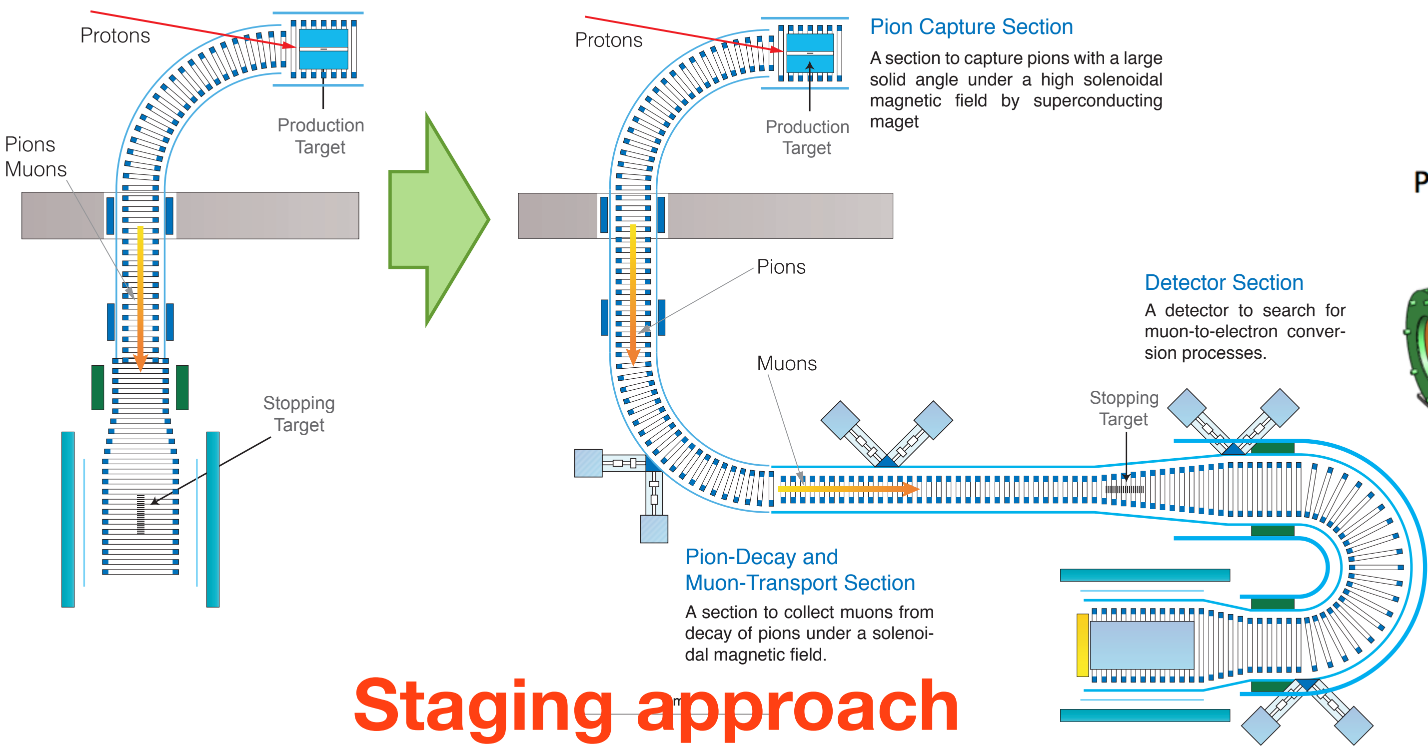
Discovery of the μ-e conversion is a clear evidence of new physics beyond the SM.

in the SM + new physics

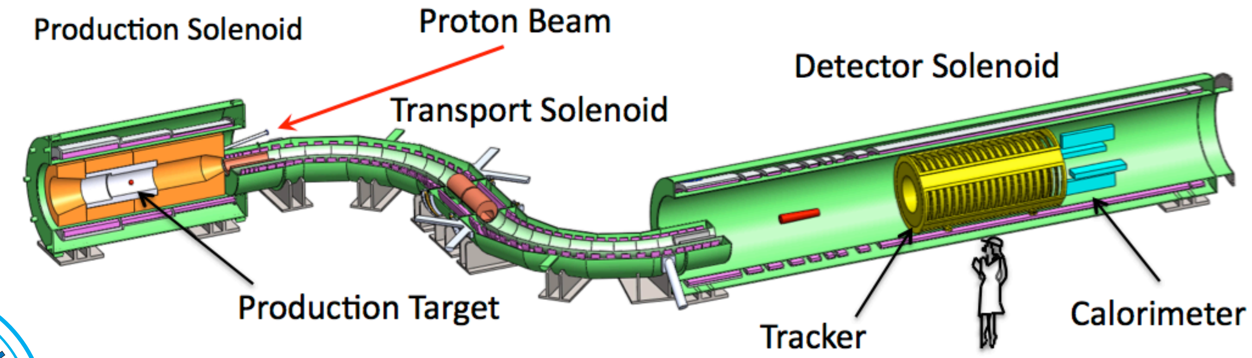
A wide variety of proposed extensions to the SM predict observable μ-e conversion rate.

COMET @J-PARC

Mu2e @FNAL



Staging approach



COMET Phase-I :
physics run 2017-
BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL
*8GeV-3.2kW proton beam, 12 days
*90deg. bend solenoid, cylindrical detector
*Background study for the phase2

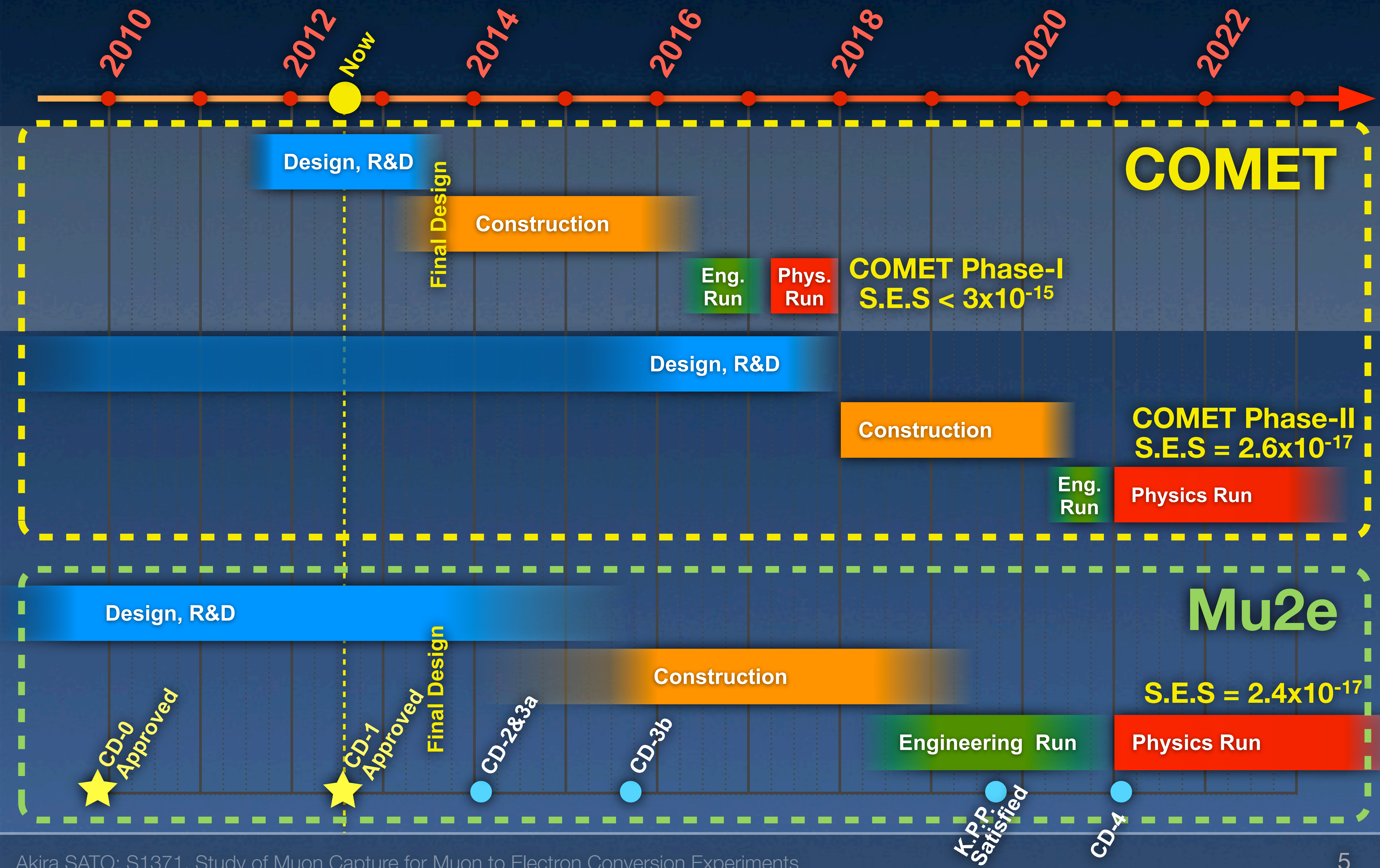
COMET Phase-II :
physics run 2019-
BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL
*8GeV-56kW proton beam, 2 years
*180deg. bend solenoid, bend spectrometer,
transverse tracker+calorimeter

Mu2e :
physics run 2019-
BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL
*8GeV-8kW proton beam, 3 years
*2x90deg. S-shape bend solenoid,
straw tracker+calorimeter

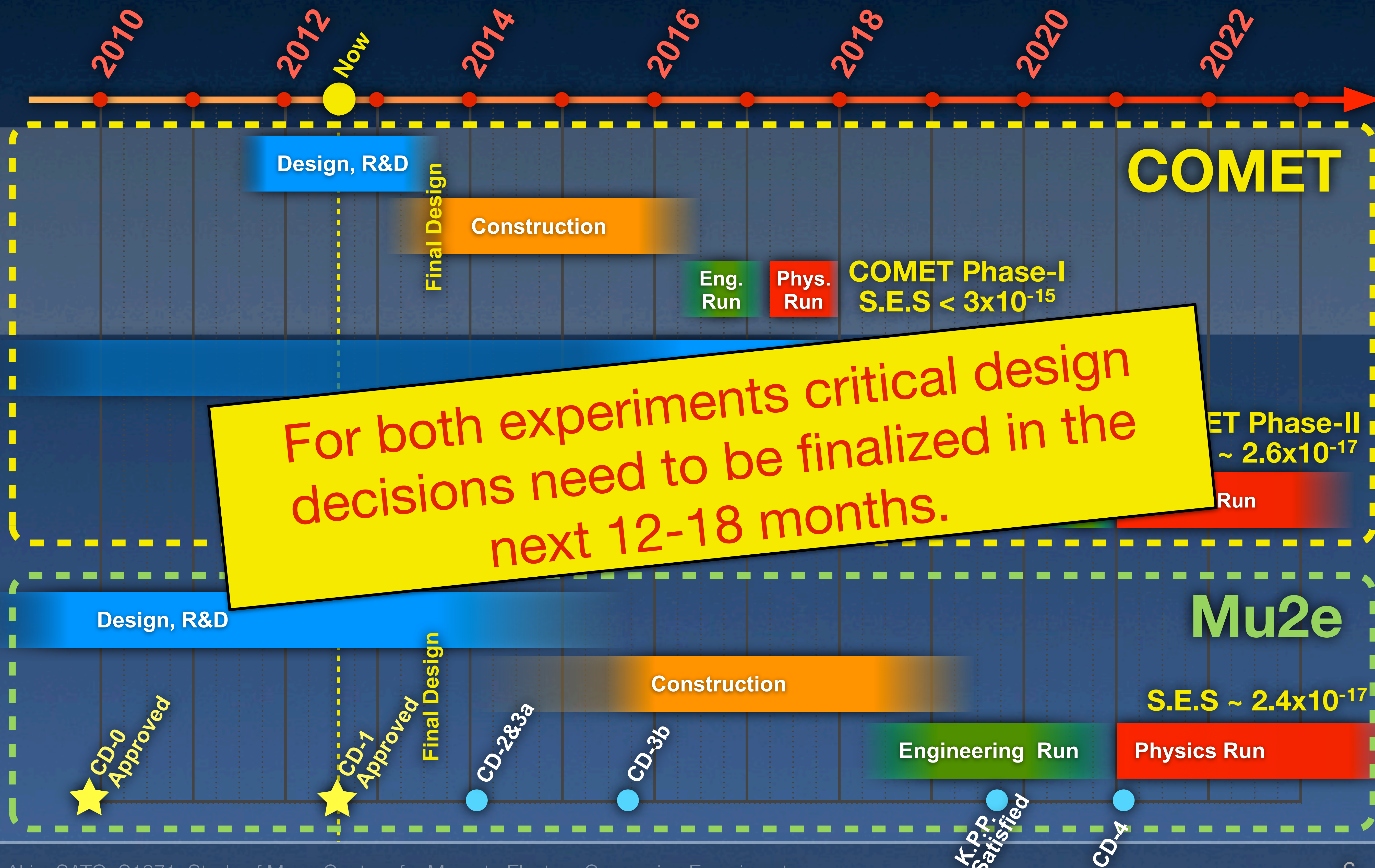
a factor of 10,000 better sensitivity than the current upper limit (SINDRUM II)

- **Both experiments have received strong endorsements from Japan and US communities.**
  - **COMET** : "is a high priority component for the J-PARC program." (KEK/J-PARC-PAC March/2012)
    - The IPNS proposed, as the first priority item in the next 5-year plan, to construct a proton beam line and the 1st half of solenoid magnets for COMET Phase-I. The PAC endorsed the laboratory plan.
  - **Mu2e** : "should be strongly encouraged in all budget scenarios considered by the panel." (P5 report)
    - got the CD-1 approval two days ago!
- These experiments are now optimizing their parameter to get the final design.

Schedule of COMET and Mu2e



Schedule of COMET and Mu2e

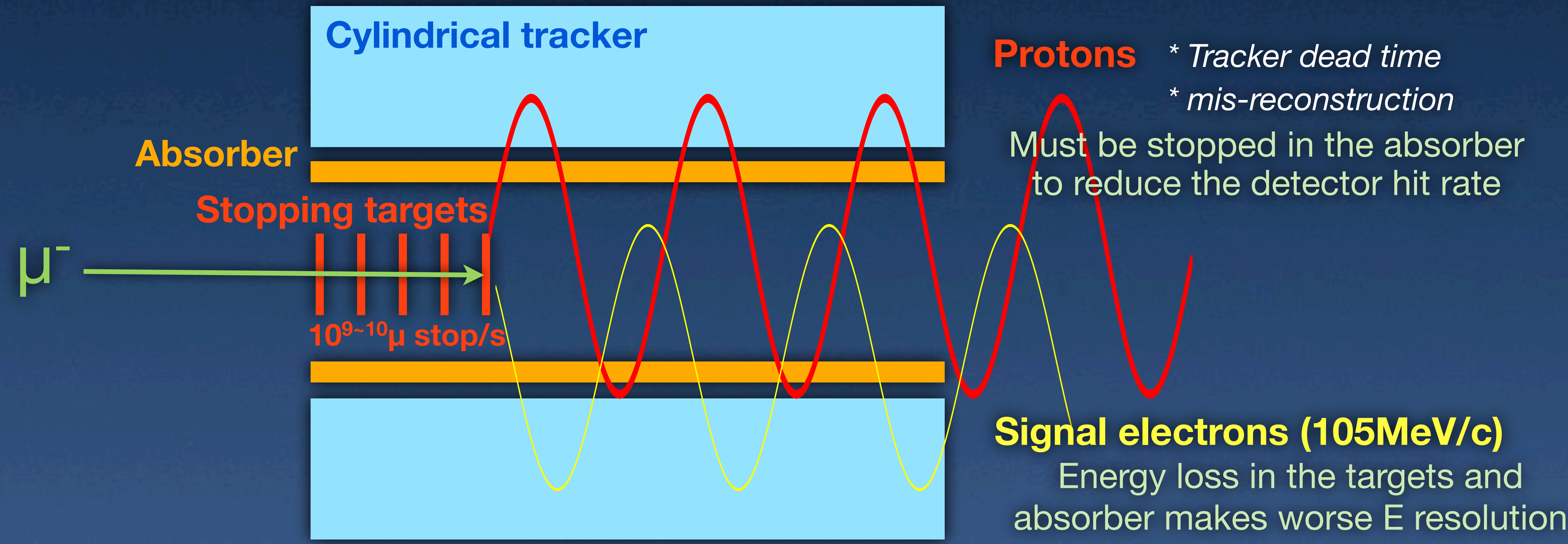


For both experiments critical design decisions need to be finalized in the next 12-18 months.

Design issue from μ capture process

- A crucial component in optimizing the designs is the background from the products of the nuclear capture process. In particular, protons are a significant source of hits in the tracking detectors. Probability of proton emission would be 0.05~0.15 per muon.

Optimization of the target thickness and the absorber



- **Both COMET Phase-I and Mu2e need the rate and energy spectra of proton emission as a function of the target thickness**

Current Exp. Data : Rate

D.F Measday, Phys. Rep. 354 (2001) 243–409

Table 4.14

Probabilities in units of 10^{-3} per muon capture for the reaction ${}^{A}_{Z}X(\mu,\nu p)^{A-1}_{Z-2}Y$ and for inclusive proton emission calculated by Lifshitz and Singer [343,348]. The experimental data are from Wyttenbach et al. [333], except when otherwise referenced. For $\Sigma(\mu,\nu p(xn))$ the experimental figures are lower limits, determined from the actually measured channels. The figures in crescent parentheses are estimates for the total inclusive rate derived from the measured exclusive channels by the use of the approximate regularity noted in Ref. [333], viz: $(\mu,\nu p):(\mu,\nu pn):(\mu,\nu p2n):(\mu,\nu p3n) = 1:6:4:4$

Capturing nucleus	$(\mu,\nu p)$ calculation	Experiment	$\Sigma(\mu,\nu p(xn))$ calculation	Experiment	Est.
${}^{27}_{13}$Al	9.7	(4.7)	40	$> 28 \pm 4$	(70)
${}^{28}_{14}$Si	32	53 ± 10[a]	144[b]	150 ± 30[b]	
${}^{31}_{15}$P	6.7	(6.3)	35	$> 61 \pm 6$	(91)
${}^{39}_{19}$K	19	32 ± 6[a]	67		
${}^{41}_{19}$K	5.1	(4.7)	30	$> 28 \pm 4$	(70)
${}^{51}_{23}$V	3.7	2.9 ± 0.4	25	$> 20 \pm 1.8$	(32)
${}^{55}_{25}$Mn	2.4	2.8 ± 0.4	16	$> 26 \pm 2.5$	(35)
${}^{59}_{27}$Co	3.3	1.9 ± 0.2	21	$> 37 \pm 3.4$	(50)
${}^{60}_{28}$Ni	8.9	21.4 ± 2.3[c]	49	40 ± 5[c]	
${}^{63}_{29}$Cu	4.0	2.9 ± 0.6	25	$> 17 \pm 3$	(36)
${}^{65}_{29}$Cu	1.2	(2.3)	11	$> 35 \pm 4.5$	(36)
${}^{75}_{33}$As	1.5	1.4 ± 0.2	14	$> 14 \pm 1.3$	(19)
${}^{79}_{35}$Br	2.7		22	[22][d]	
${}^{107}_{47}$Ag	2.3		18	[11][d]	
${}^{115}_{49}$In	0.63	(0.77)	7.2	$> 11 \pm 1$	(12)
${}^{133}_{55}$Cs	0.75	0.48 ± 0.07	8.7	$> 4.9 \pm 0.5$	(6.7)
${}^{165}_{67}$Ho	0.26	0.30 ± 0.04	4.1	$> 3.4 \pm 0.3$	(4.6)
${}^{181}_{73}$Ta	0.15	0.26 ± 0.04	2.8	$> 0.7 \pm 0.1$	(3.0)
^{208}Pb	0.14	0.13 ± 0.02	1.1	$> 3.0 \pm 0.8$	(4.1)

no Ti data

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no Ti data

Activation experiment

A. Wyttenbach, et al, Nucl. Phys. A294 (1978) 278-292

Reaction probabilities per captured muon [a])

Target A, Z	Product Reaction Factor / target purity (%)	$A-1, Z-2$ (μ^-, p) (10^{-4})	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-3, Z-2$ $(\mu^-, p2n)$ (10^{-3})	$A-4, Z-2$ $(\mu^-, p3n)$ (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
${}^{23}_{11}Na$	> 99.5					11 ±1.5 (3)
${}^{27}_{13}Al$	99.99	no data	28 ±4 (2)	no data	no data	7.6 ±1.1 (2)
${}^{31}_{15}P$	99.5		38 ±5 (2)	23 ±3 (2)		13 ±2 (2)

Current Exp. Data : E distribution

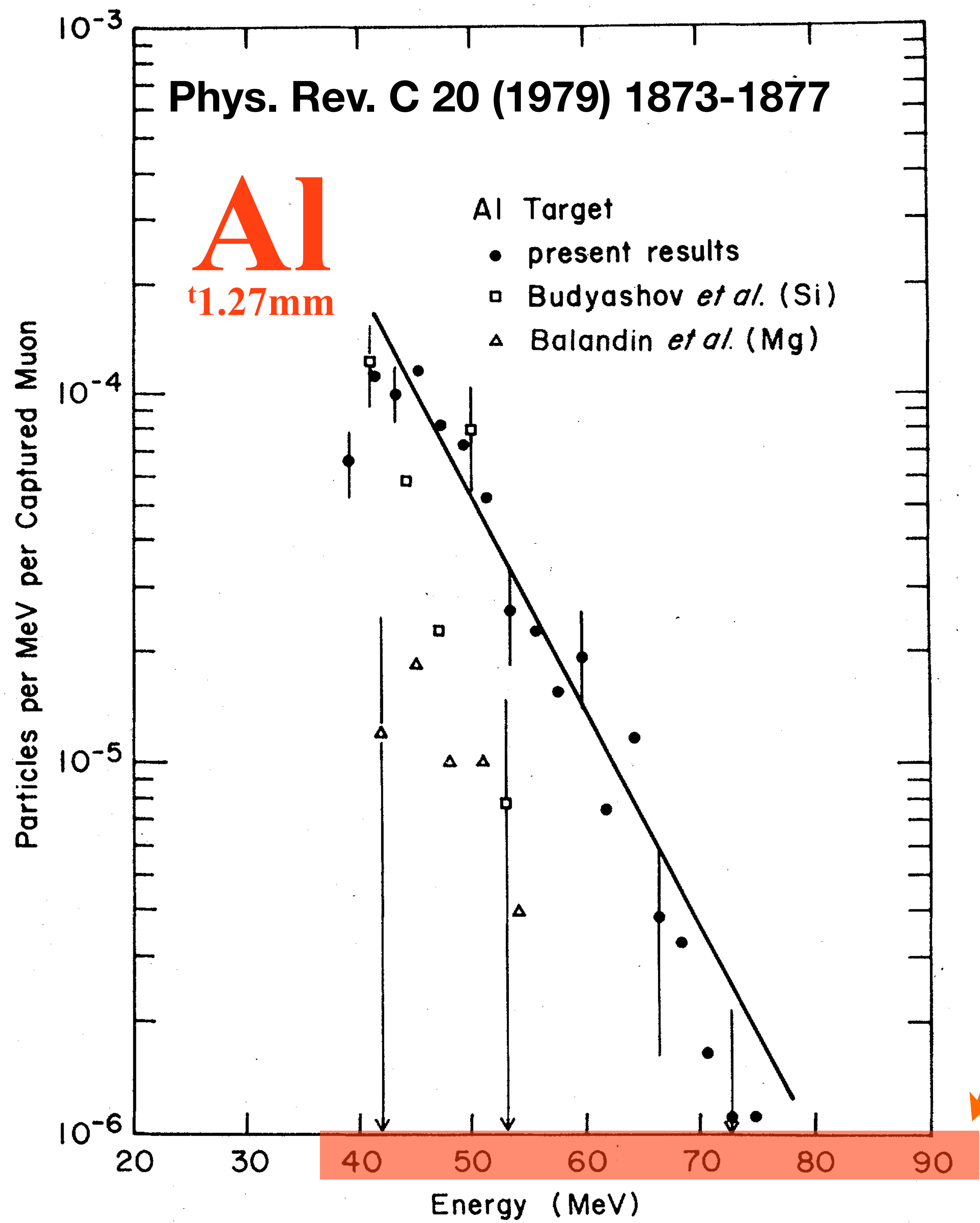
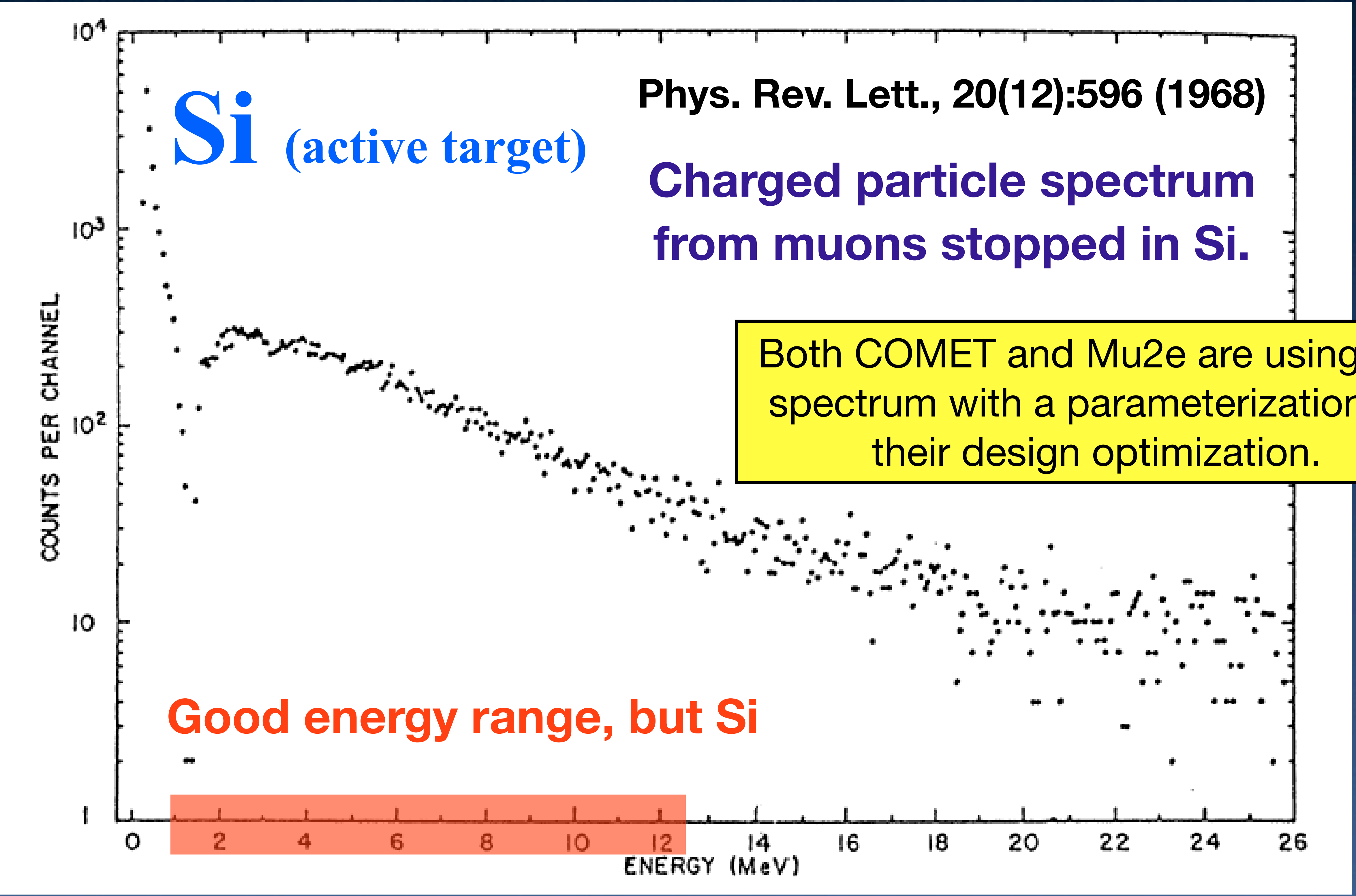


FIG. 2. Yield of charged particles following μ^- capture in aluminum target. The filled circles represent results of the present work, with representative error bars shown. The straight line is an exponential fit to the data with $E > 40$ MeV. The open squares represent results of Budyashov *et al*. (Ref. 12) for silicon. The open triangles represent results of Balandin *et al*. (Ref. 13) for magnesium.

Energy range is too high for our purpose.

- Beam quality was not enough to stop muons in a thin target.
    - thick target : 1.27mm
    - no low energy data
    - large background rate

Current Exp. Data : E distribution



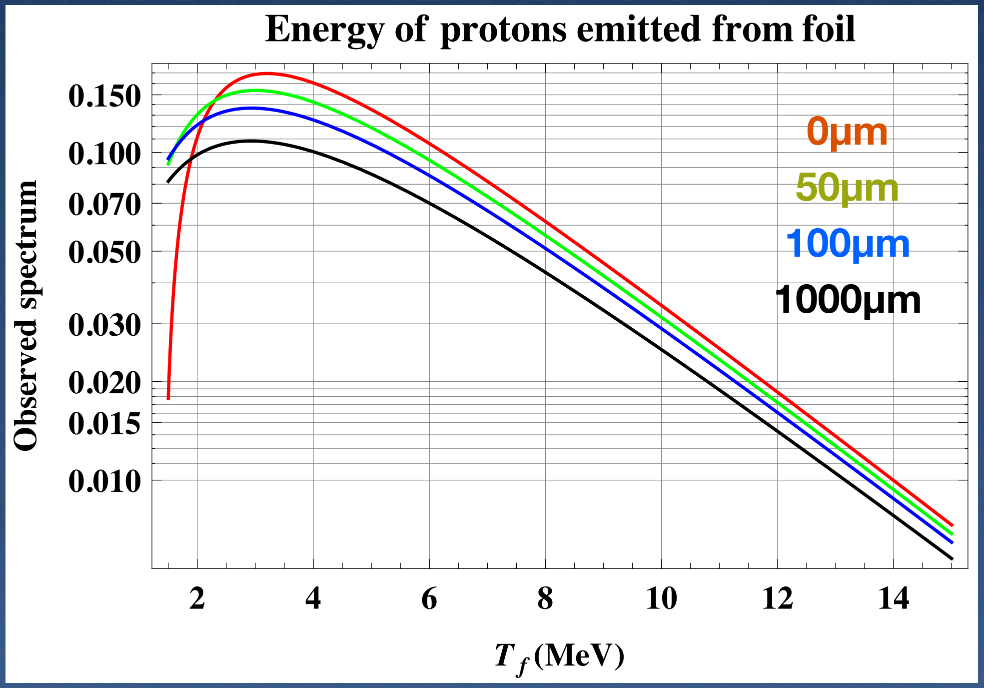
Both COMET and Mu2e are using this spectrum with a parameterization for their design optimization.

Current Exp. Data : Summary

- **There are no data**, in the relevant energy range, on the products of muon nuclear capture from an Al target (and Ti).
  - ratio of p:d:α
  - the absolute proton rate
  - energy distribution
- Mu2e and COMET are presently using a parameterization of muon-capture data taken from the Si target in 1968.
- Uncertainties in the proton spectra have significant ramifications for the design of COMET Phase-I and Mu2e.
- **We must measure them. This proposal**

Experiment (TRIUMF-S1371)

- **Goal of the experiment**
  - to measure the rate and energy spectra of the charged particles (p, d, α) emitted after muon captured on some targets:
    - **Al** : the default stopping target for COMET and Mu2e
    - **Ti** : possible target for future μ-e conv. experiments.
    - **Si (active)** : for cross-check against the previous data and systematics studies
  - A precision of 5% down to an energy of 2.5 MeV is required for both the rate and the energy spectra.
- **Essential points**
  - Thin targets and a low energy muon beam with a small Δp/p
    - to achieve a high and well determined rate of stopped muons
    - Due to ΔE of the charged particles in the target, we need to correct the energy spectra by a response function. To reduce the systematic uncertainty from the response function, the ΔE in the target must be small enough.



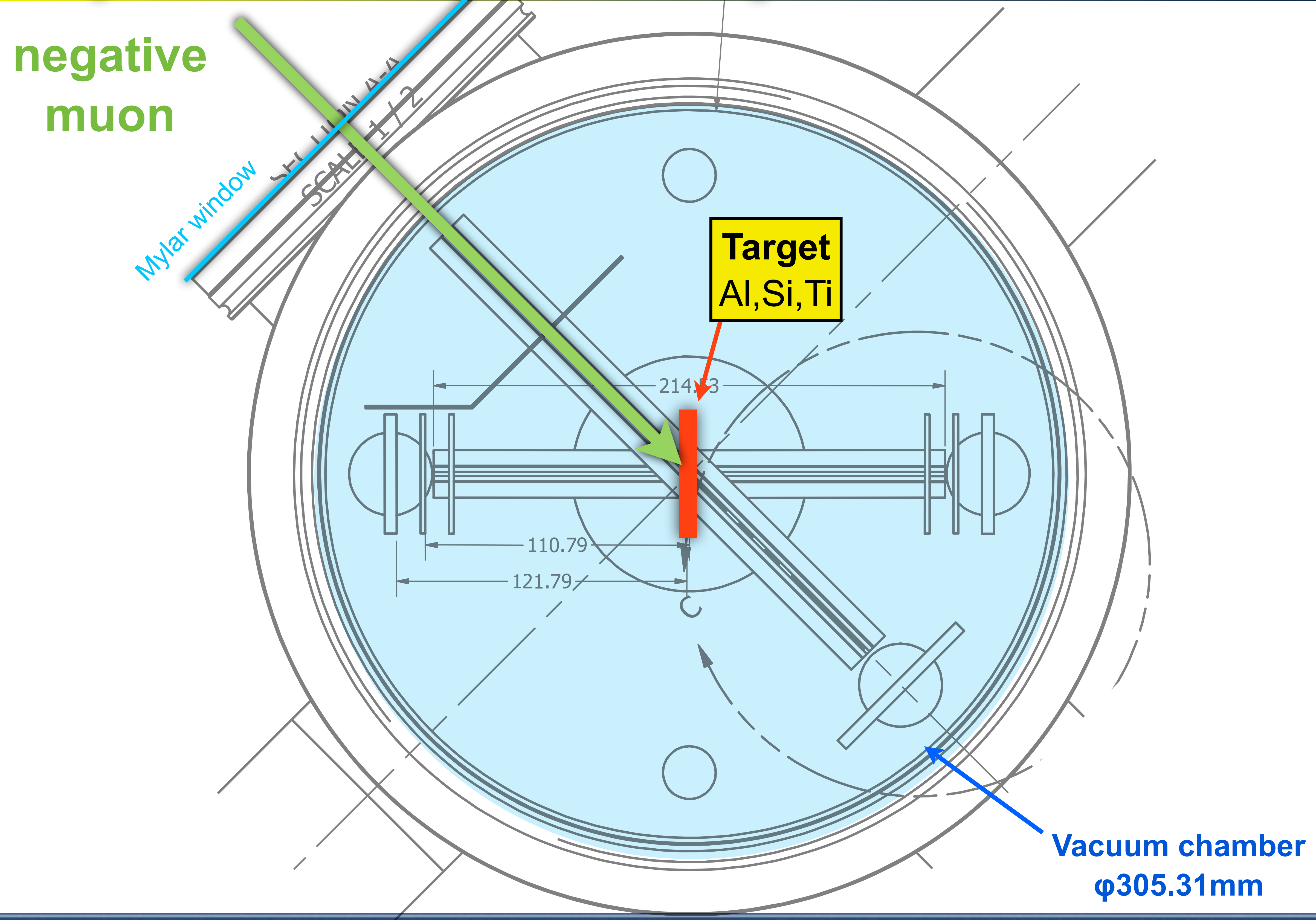
Members for TRIUMF-S1371

- Osaka University
  - **Y. Kuno**, H. Sakamoto, T. Itahashi, Y. Hino, A. Sato. T. Yai, T.H. Nam
- Univ. College London
  - M. Wing, M. Lancaster, A. Edmonds
- Imperial College London
  - B. Krikler, A. Kurup, Y. Uchida
- TRIUMF
  - T. Numao
- Univ. Washington
  - **P. Kammel**, D. Hertzog, F. Wauters, M. Murray
- Boston University
  - J. Miller, E. Barnes, A. Kolarkar
- Univ. Massachusetts Amherst
  - D. Kawall, K. Kumar
- FermiLab
  - R. Bernstein, V. Ruso

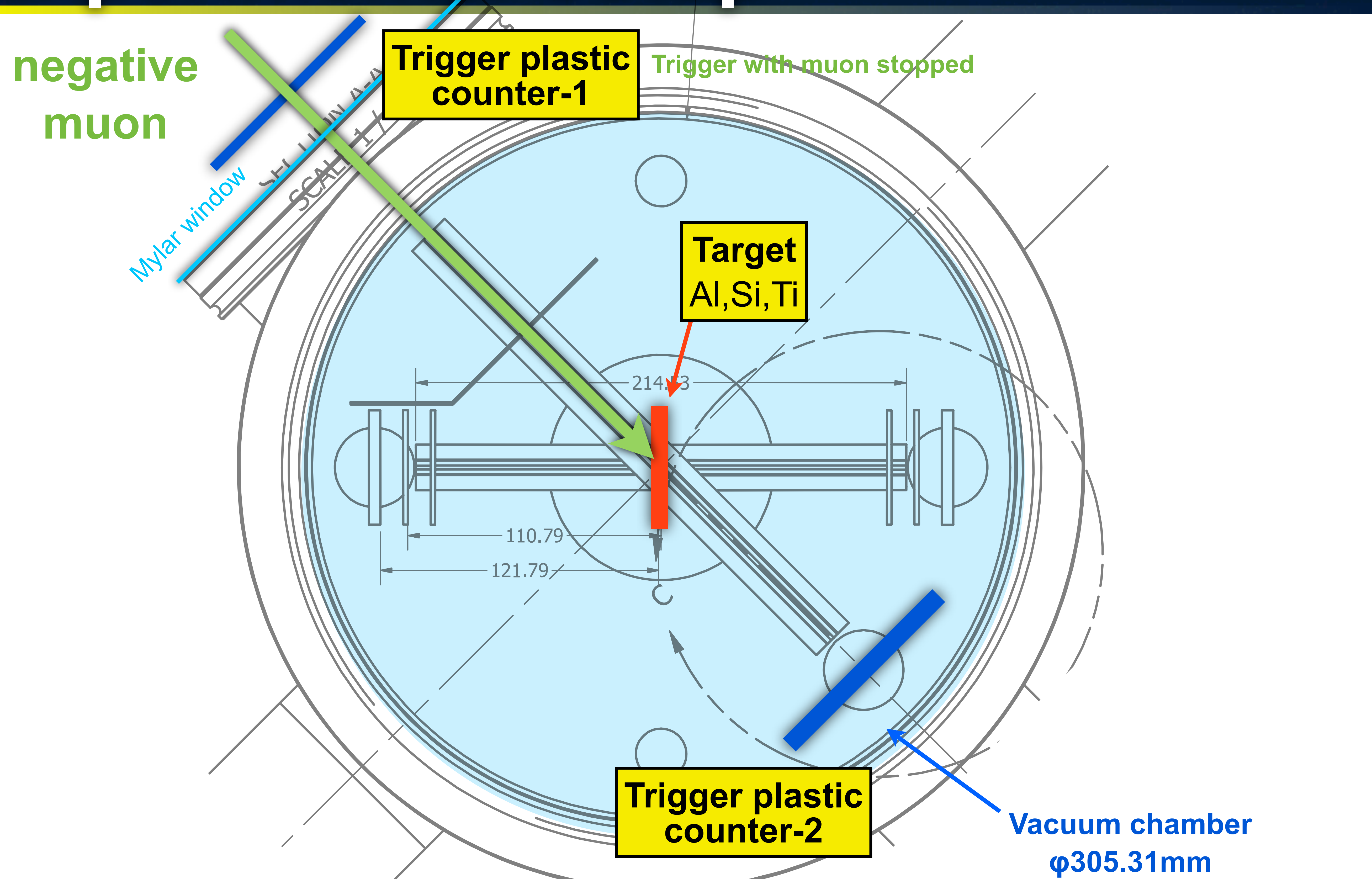
COMET **Mu2e**

Joint Collaboration

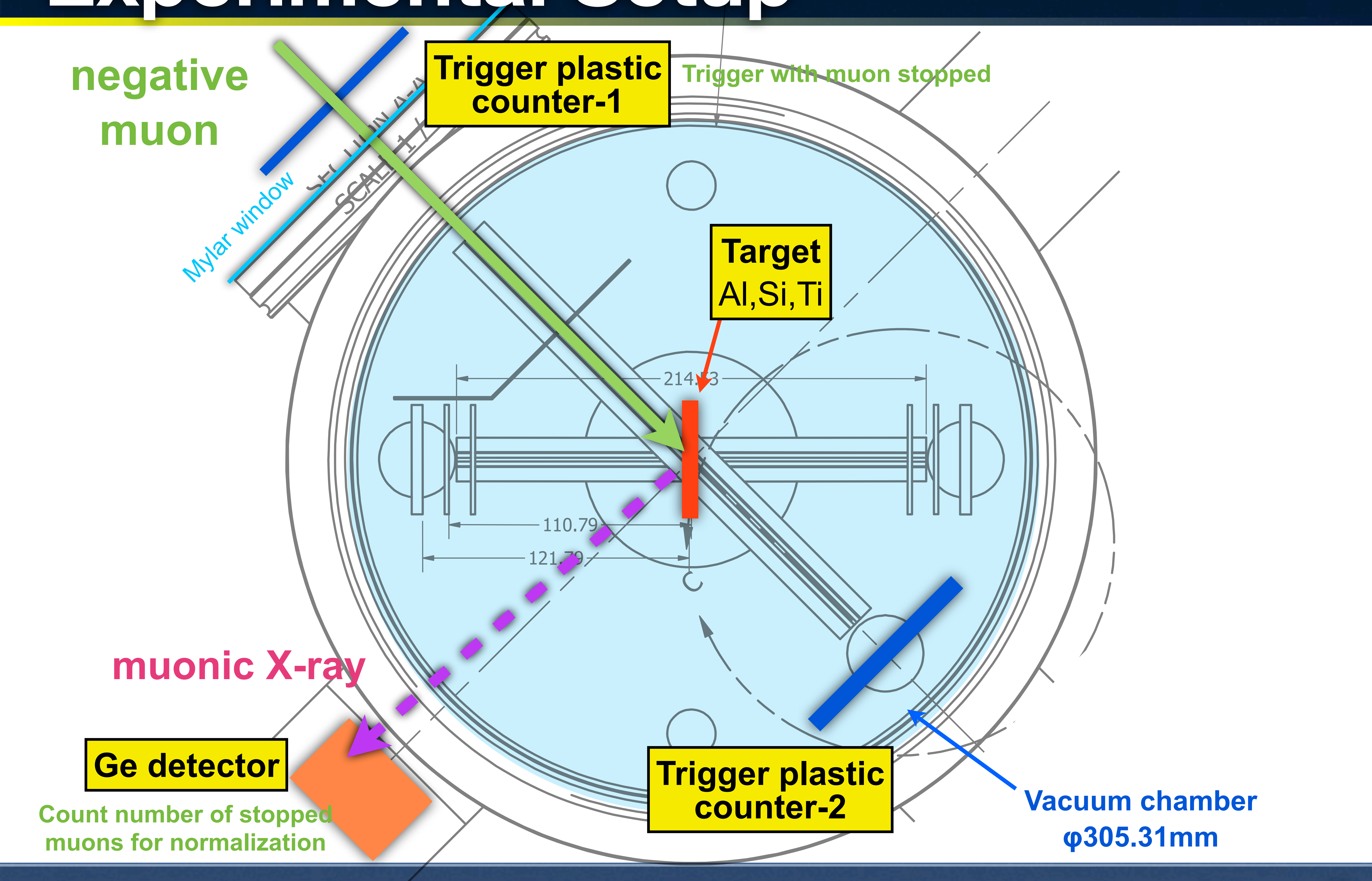
Experimental Setup



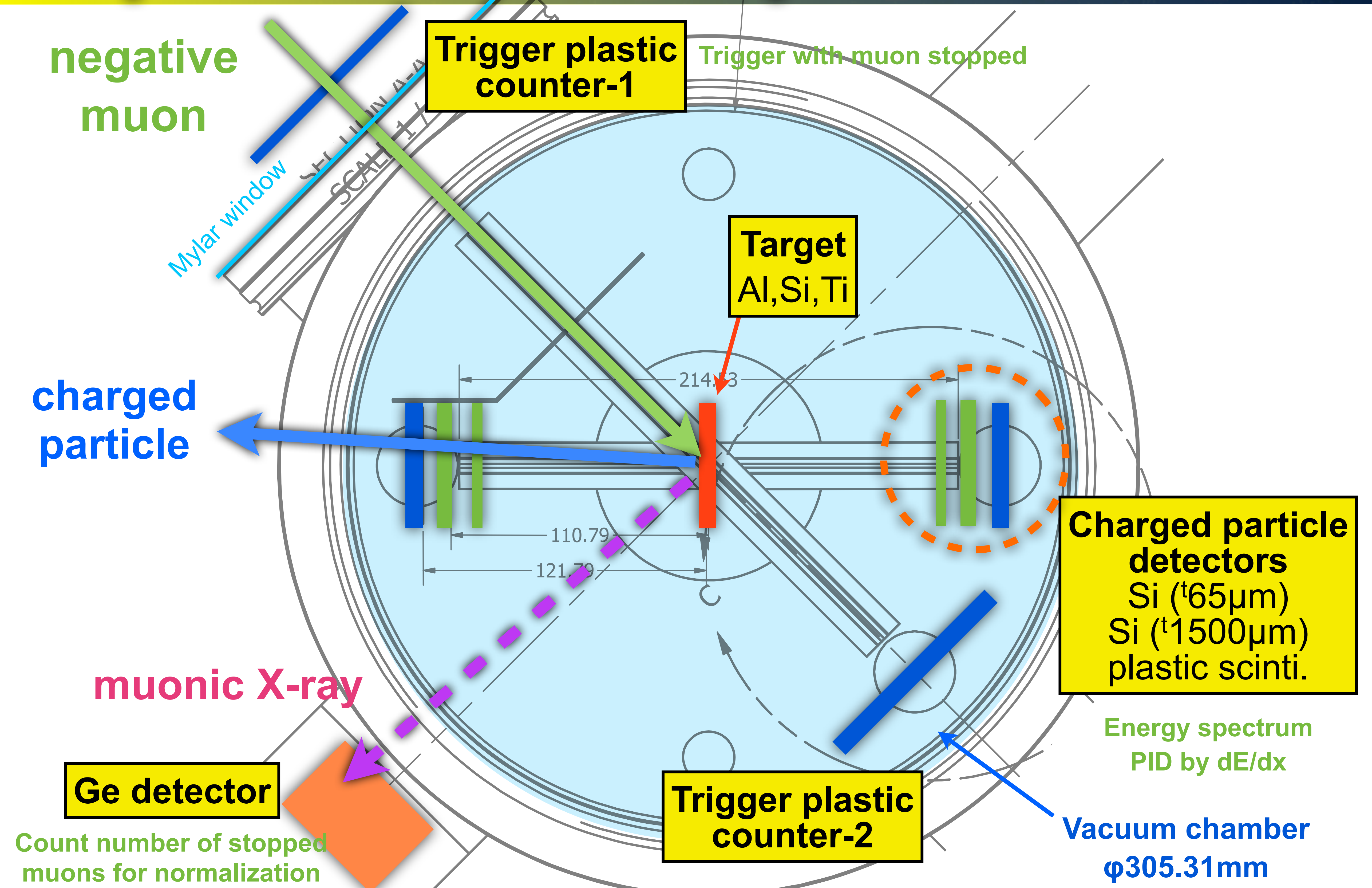
Experimental Setup



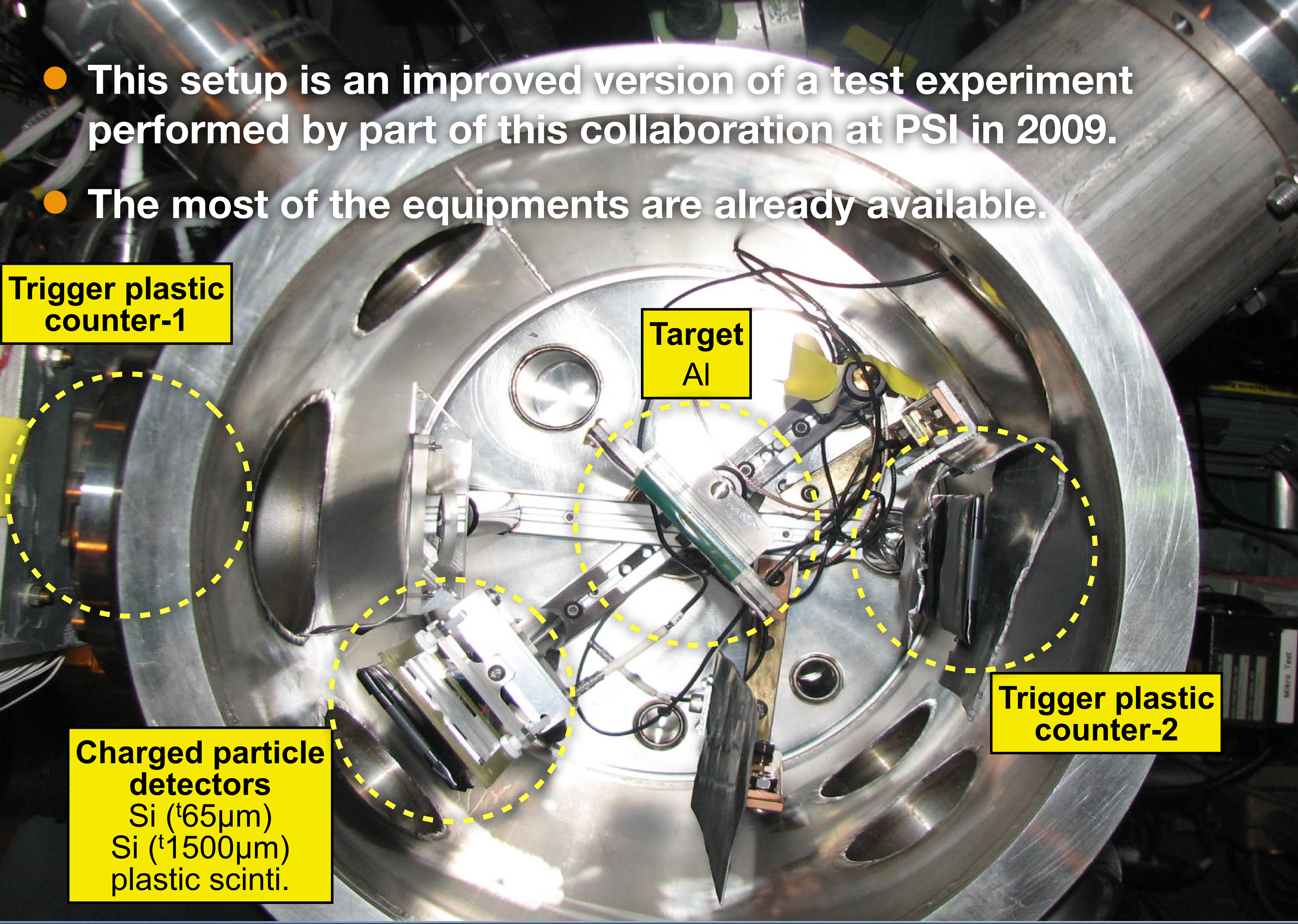
Experimental Setup



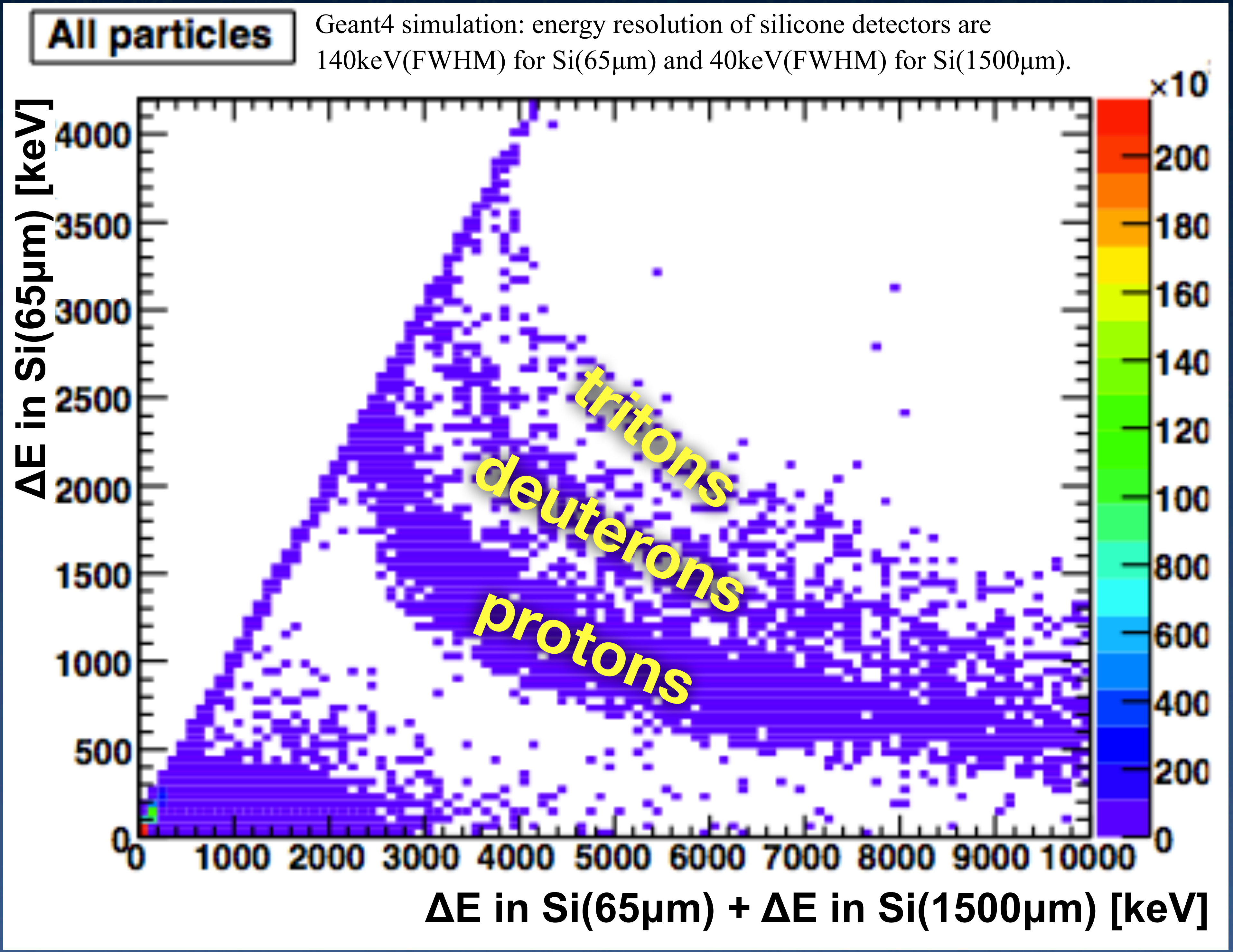
Experimental Setup



- This setup is an improved version of a test experiment performed by part of this collaboration at PSI in 2009.
- The most of the equipments are already available.



Particle Identification by dE/dx



- PID is possible using ΔE in the two Si detectors. That will allow some discrimination between protons, deuterons, muons and electrons across the energy range 2.5–12 MeV required by COMET and Mu2e.

Event Rates

Target thickness (μm)	% Stopping in target	Event rate (Hz) all particles	Event rate (Hz) protons
50	2	8.1	1.0
100	16	21.3	1.5
150	38	39.9	2.1
200	53	51.1	2.4

- Event rates were estimated using geant4 simulations. The total event rate is below 100 Hz for all considered targets but the rate of protons for the thinnest target for is rather low (1 Hz) and as such approximately 7 days of data taking will be required to accumulate the necessary statistics for a given target.

Systematic Uncertainties

- **Response Function**
  - Uncertainties can be minimized using an optimal cloud muon beam and
  - through the use of the active Si target
    - both the initial and final proton energies can be determined.
- **Absolute Rate**
  - The proton detection efficiency will be determined from a detailed GEANT4 simulation of the Si detectors.
    - The number of stopped muons will be determined independently from both
      - the Ge detector and
      - the electron telescope and
      - cross-checked using data from the active silicon target.
- **Particle Identification Efficiency**
  - Particles will be identified
    - using dE/dx in the Si detectors with the efficiency determined from the GEANT4 simulation.
    - A cross check using time of flight with the active Si target will also be investigated.
- **Backgrounds**
  - The electron background will be determined using
    - positive muons and
    - the neutron recoils by using a proton absorber before the silicon detectors.
  - A careful GEANT4-based evaluation will be made of the background from muons that stop in the chamber walls.

Beam Time Requests

- A low-momentum separated cloud μ beam of 30-34 MeV/c from a surface muon channel. **M20 (or M15) has an extra beam quality.**
  - for a high stopping rate with low backgrounds and smaller systematic uncertainties
- **in late 2012/early 2013 : Main Beam Time (this proposal)**
  - 36 shifts (3 weeks)
    - 2 days : installation
    - 5 days : tuning and optimization of beam and system
    - 14 days : for two targets
      - including systematic studies with a Si active target
- **in September 2012 : Test**
  - to gather initial experience at **M9B**