Study of Muon Capture for Muon to Electron Conversion Experiments

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on behalf of the AlCap Collaboration

PSI BVR Meeting, January 15, 2013

Outline

- Importance and Urgency
  - overview of μ-e conversion searches:
    - Mu2e (FNAL) and COMET (J-PARC)
- The AlCap Collaboration (jointly formed by Mu2e and COMET)
- Overview of the Work Packages (WP1, WP2 and WP3) of This Proposal
  - WP1 (proton emission after muon capture)
  - WP2 (gamma and X-ray emission after muon capture)
  - WP3 (neutron emission after muon capture)
- Beam Requirements and Beam Time Request
- Summary

μ-e Conversion Search

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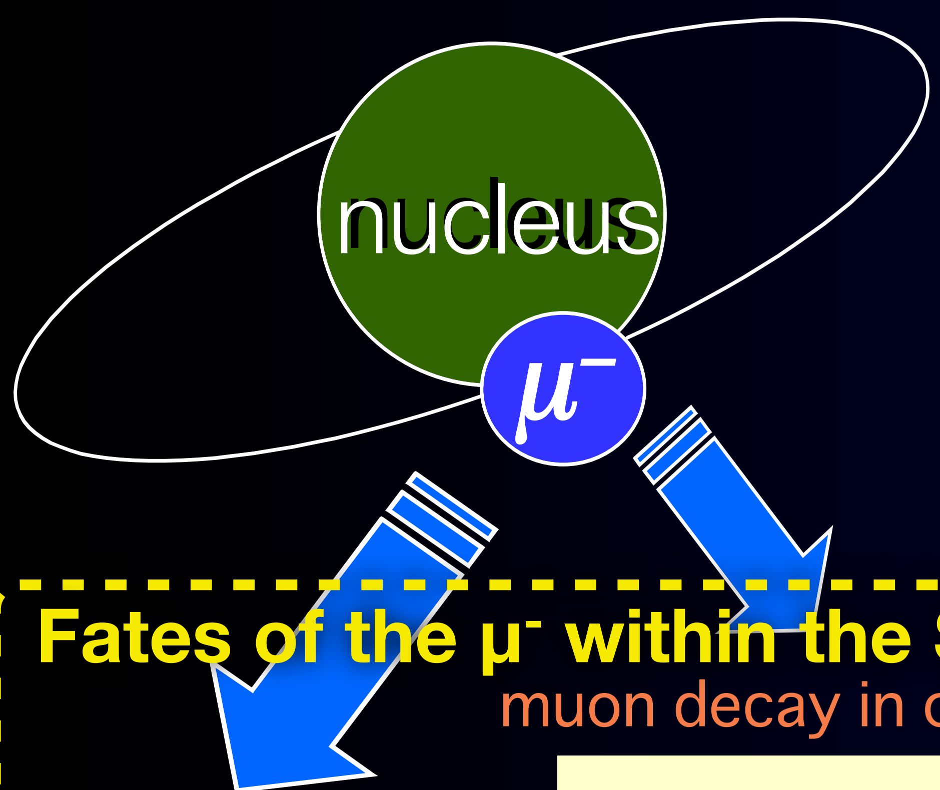

Fates of the μ^- within the SM

muon decay in orbit

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

nuclear muon capture

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

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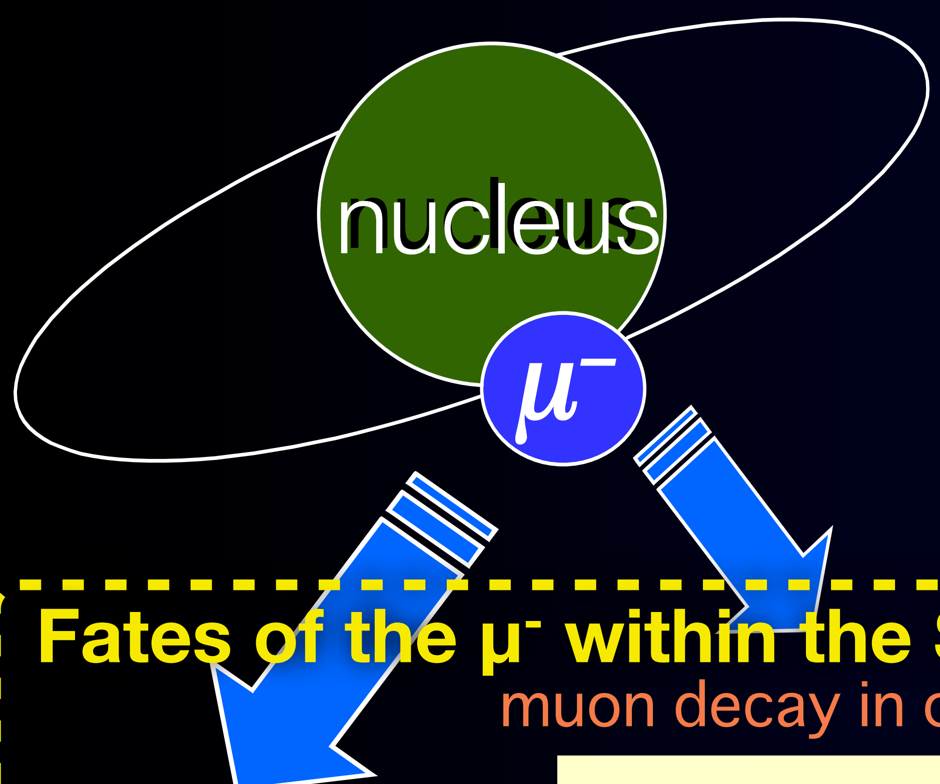

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Beyond the SM

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

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 ~$O(10^{-54})$

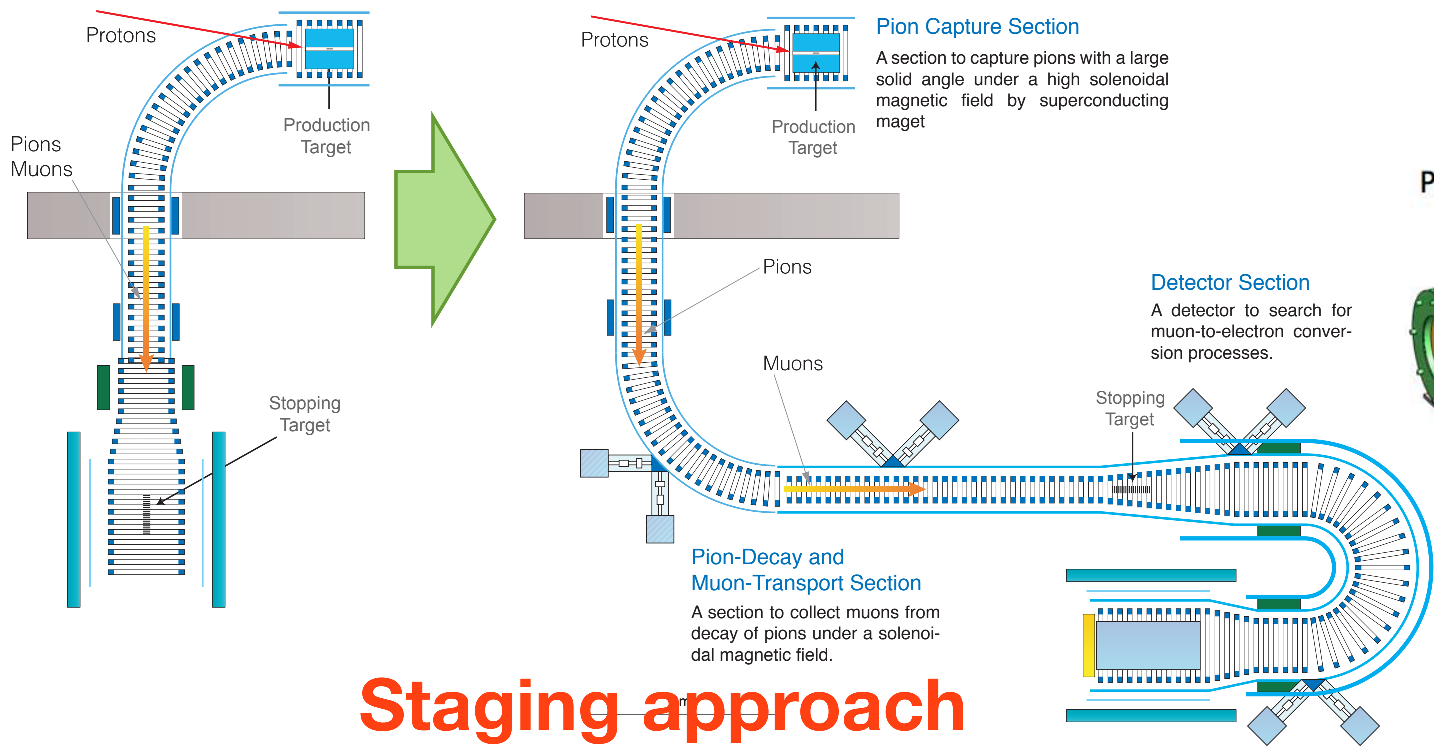
Discovery of the μ-e conversion is a clear evidence of new physics beyond the SM.

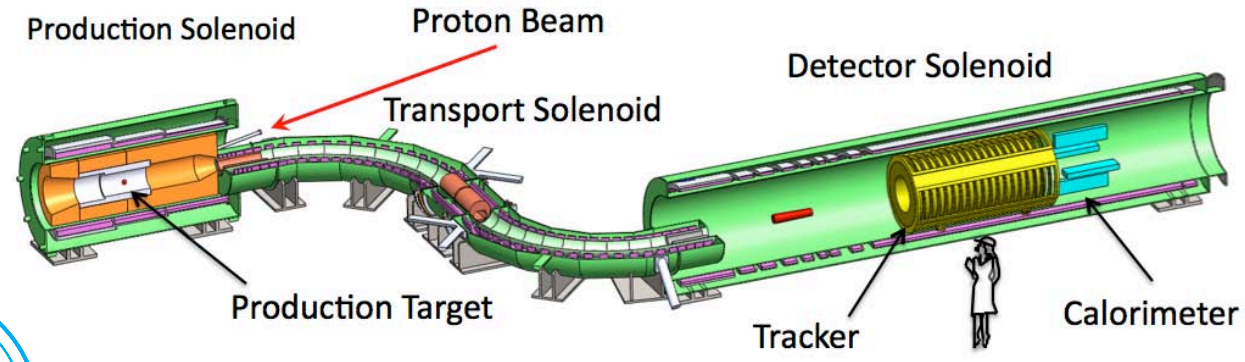
in the SM + new physics

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

COMET @J-PARC

Mu2e @FNAL





Staging approach

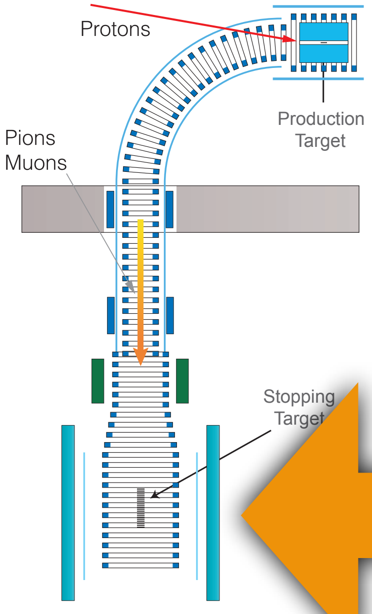
COMET Phase-I :	COMET Phase-II :	Mu2e :
physics run 2017-	physics run 2021-	physics run 2021-
BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL	BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL	BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL
*8GeV-3.2kW proton beam, 6x10^{9} μ/s, 18 days	*8GeV-56kW proton beam, 10^{11}μ/s, 2x10^{7}s	*8GeV-8kW proton beam, 3 years
*90deg. bend solenoid, cylindrical detector	*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter	*2x90deg. S-shape bend solenoid, straw tracker+calorimeter
*Background study for the phase2		

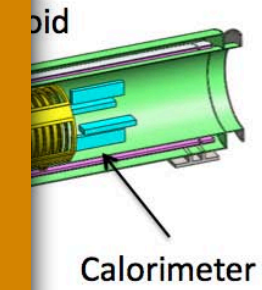
a factor of 10,000 better sensitivity than the current upper limit (SINDRUM II)

- **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 in July 2012!
- These experiments are now optimizing their parameter to get the final design.

COMET @ J-PARC

Mu2e @FNAL





Stag

COMET Phase-I :

physics run 2017-

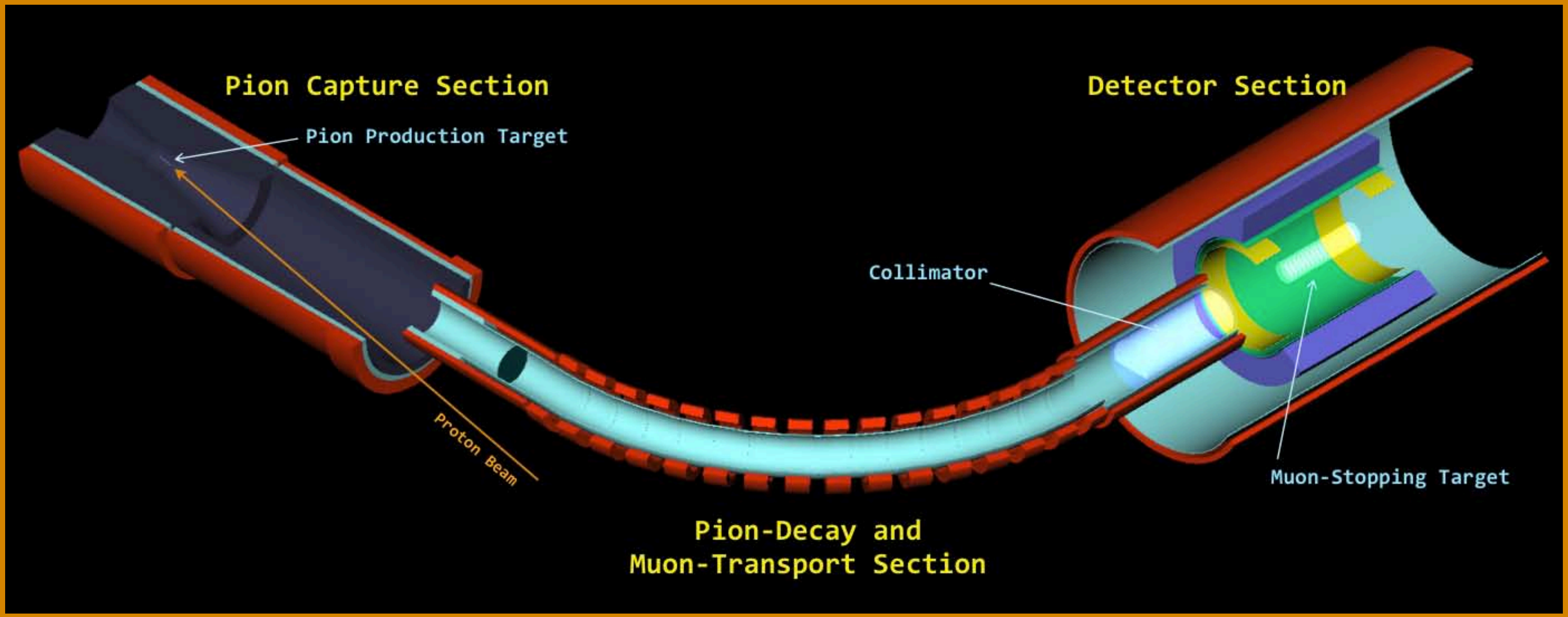
BR(μ+Al→e+Al)<7x10^{-15} @ 9

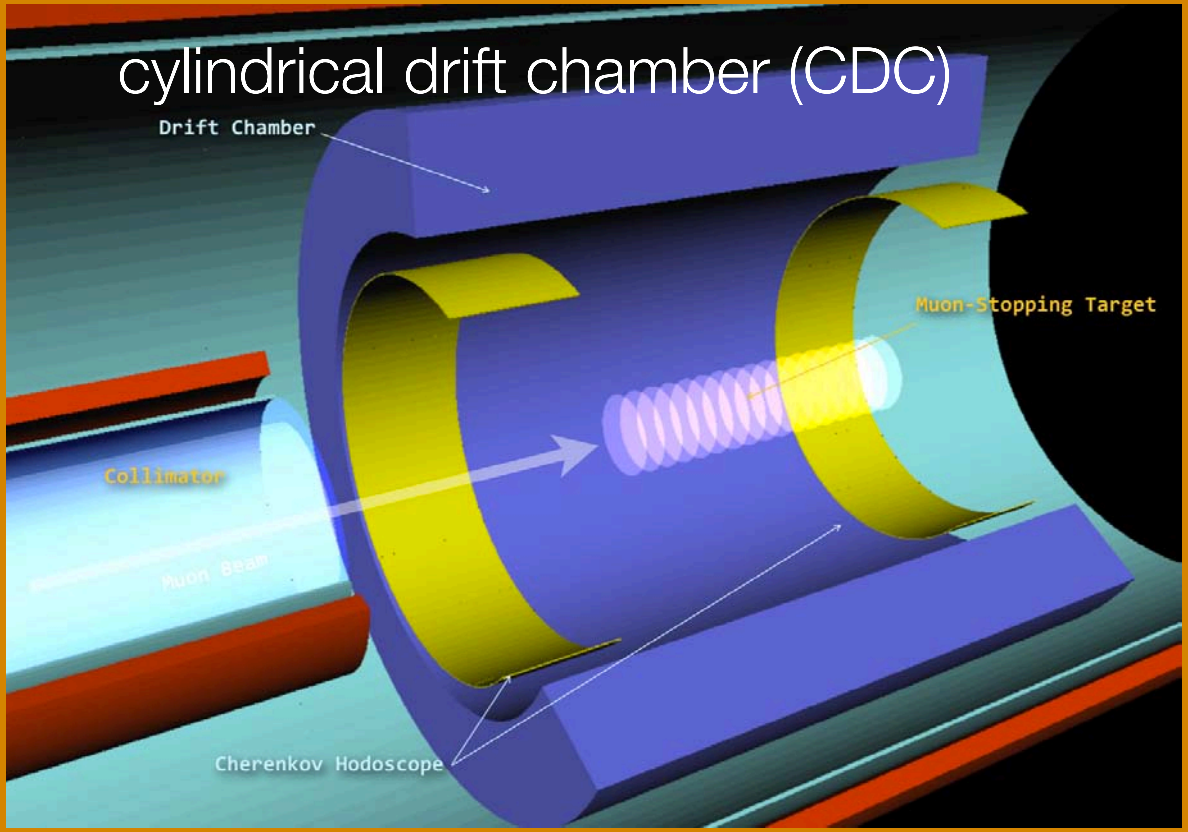
*8GeV-3.2kW proton beam, 6x10^{9} μ/s

*90deg. bend solenoid, cylindrical

*Background study for the phase2

COMET Phase-I and CDC





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  - COMET : "
    - The IPN … beam line and the … y plan.
    - … 2012)
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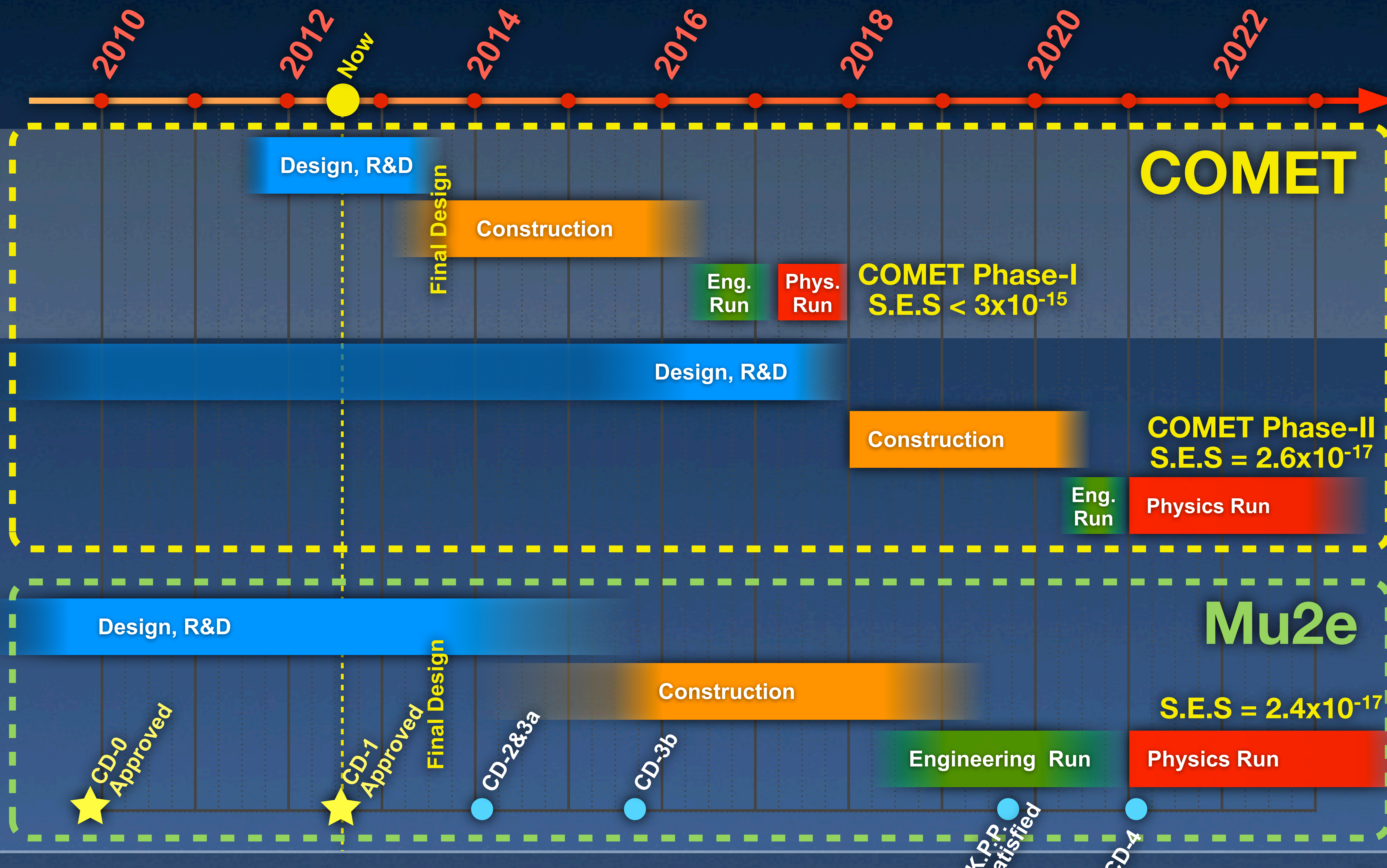
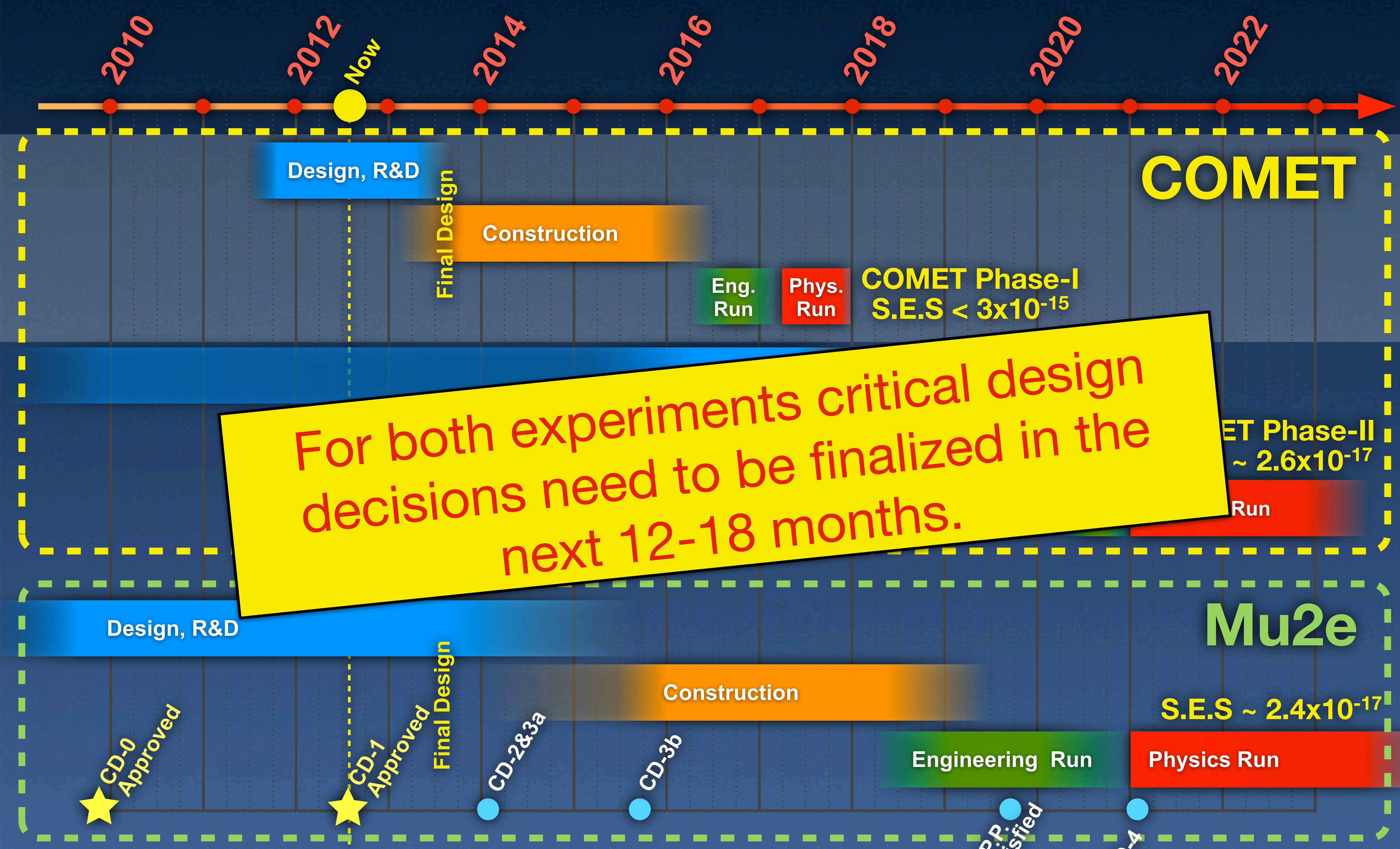
Schedule of COMET and Mu2e



Schedule of COMET and Mu2e



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

This Proposal

Three Work Packages

- WP1: Charged Particle Emission after Muon Capture
  - Kammel (Washington) and Kuno (Osaka)
  - Rate and spectrum with precision 5% down to 2.5 MeV
- WP2: Gamma and X-ray Emission after Muon Capture
  - Lynn (PNNL) and Miller (Boston)
  - X-ray and gamma-ray for normalization (by Ge detector), and radiative muon decay (by a NaI detector)
- WP3: Neutron Emission after Muon Capture
  - Hungerford (Houston) and Winter (ANL)
  - rate and spectrum from 1 MeV up to 10 MeV
  - BG for calorimeters and cosmic-ray veto, damage to electronics

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ready to start in spring 2013

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plan to carry out early 2014

The AlCap Collaboration Joint force

- 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

COMET

- 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. Rusu
- Pacific North National Laboratory
  - D. M. Asner, R. Bonicalzi, M. Schram, G.Warren, L. Wood

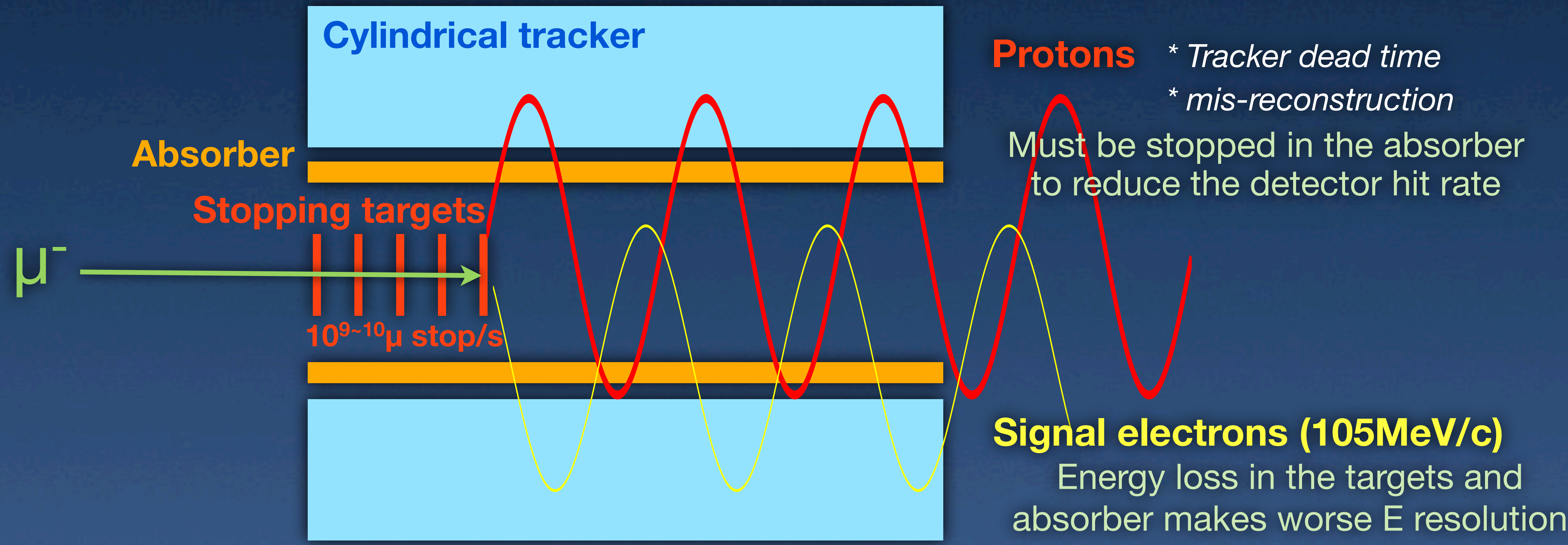
Mu2e

WP1: Charged Particle Emission after Muon Capture

WP1: Design issue with protons

- 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**

WP1 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)

WP1 Current Exp. Data : E dist.

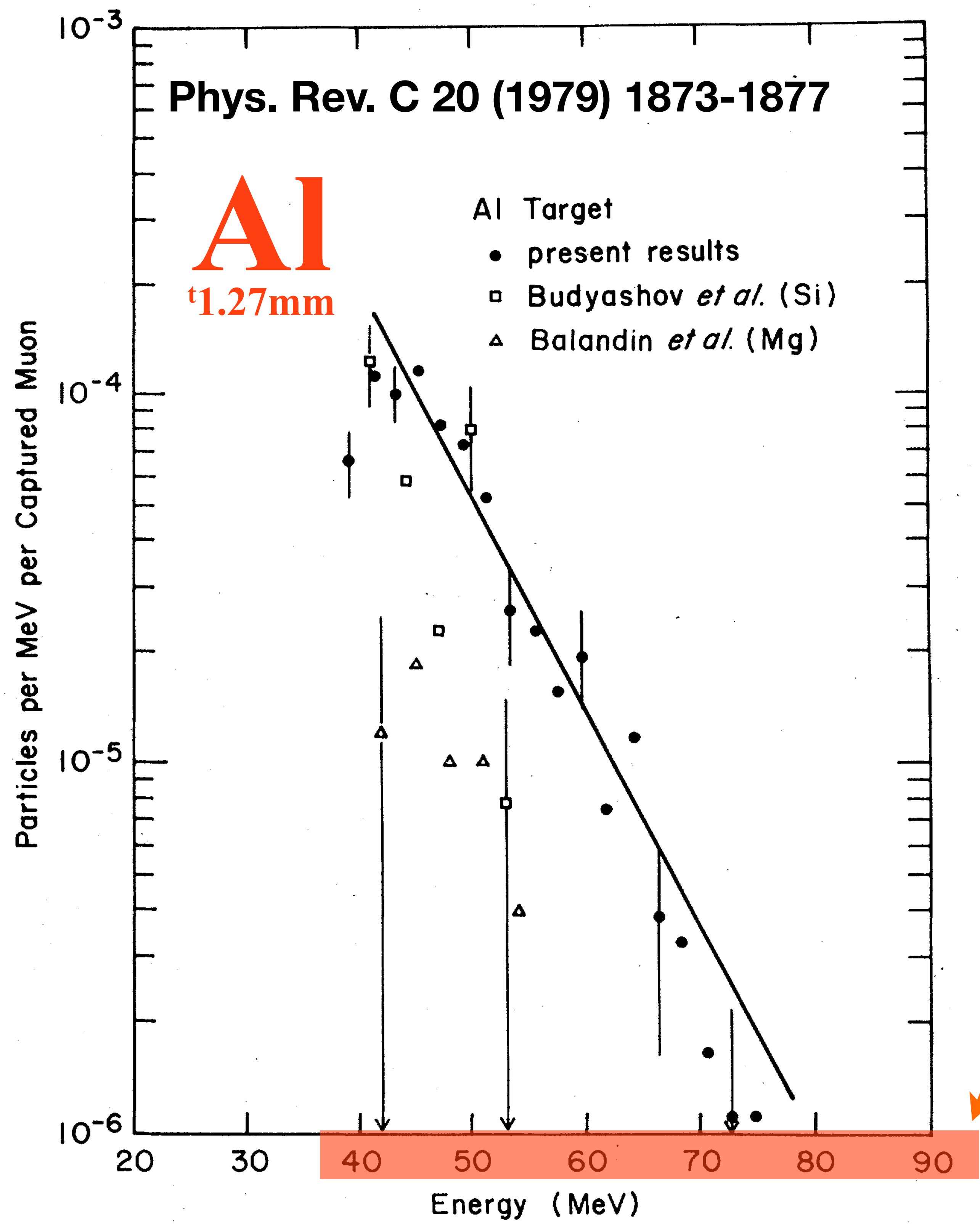
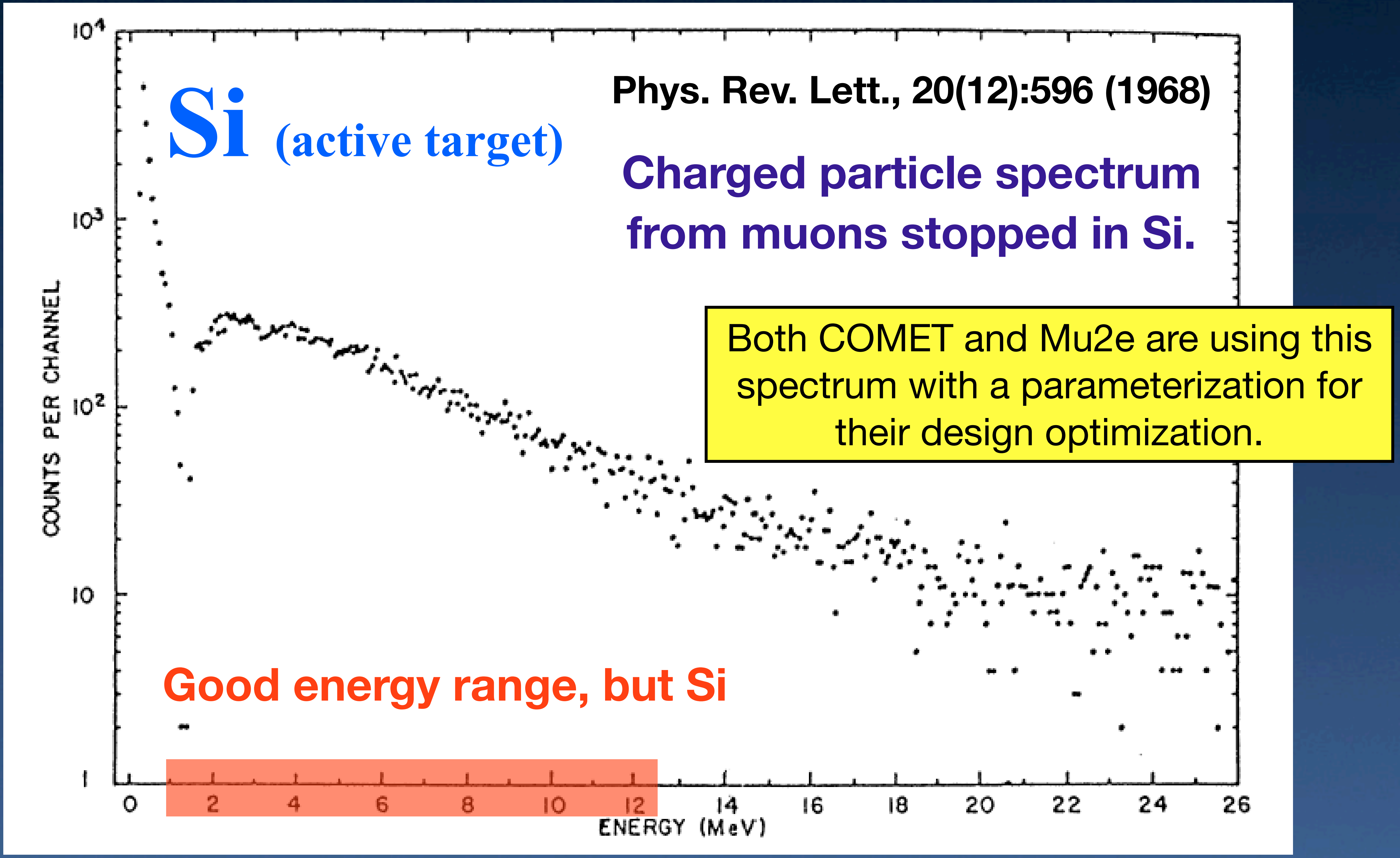


FIG. 2. Yield of charged particles following μ^- capture in aluminum target. The filled circles represent results of the present work, with representative error bars shown. The straight line is an exponential fit to the data with $E > 40$ MeV. The open squares represent results of Budyashov *et al*.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

WP1 Current Exp. Data : E dist.

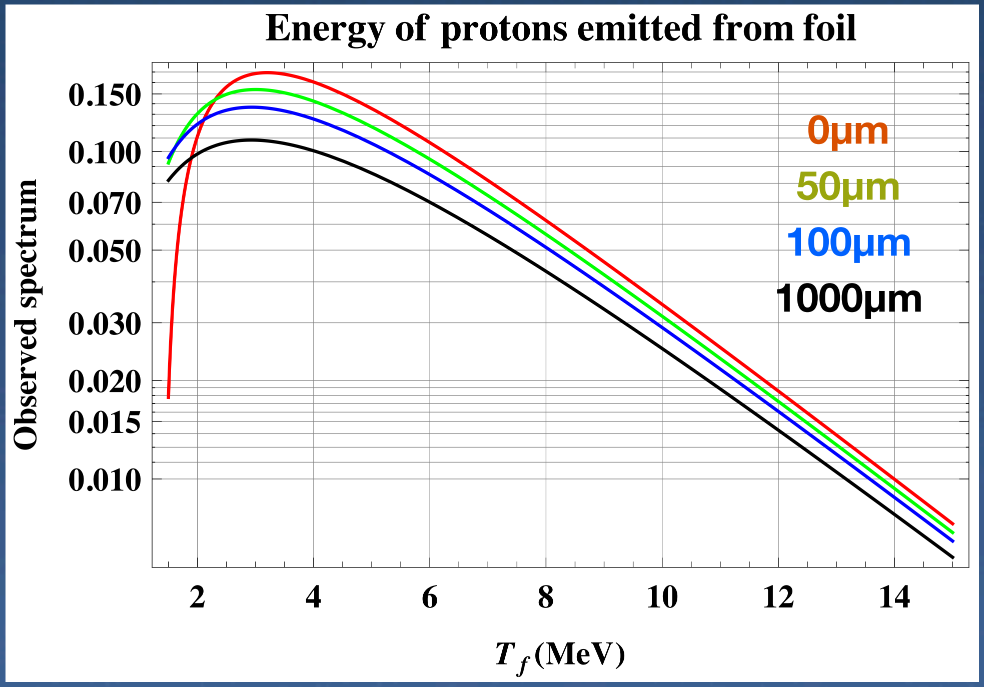


WP1 Current Exp. Data : Summary

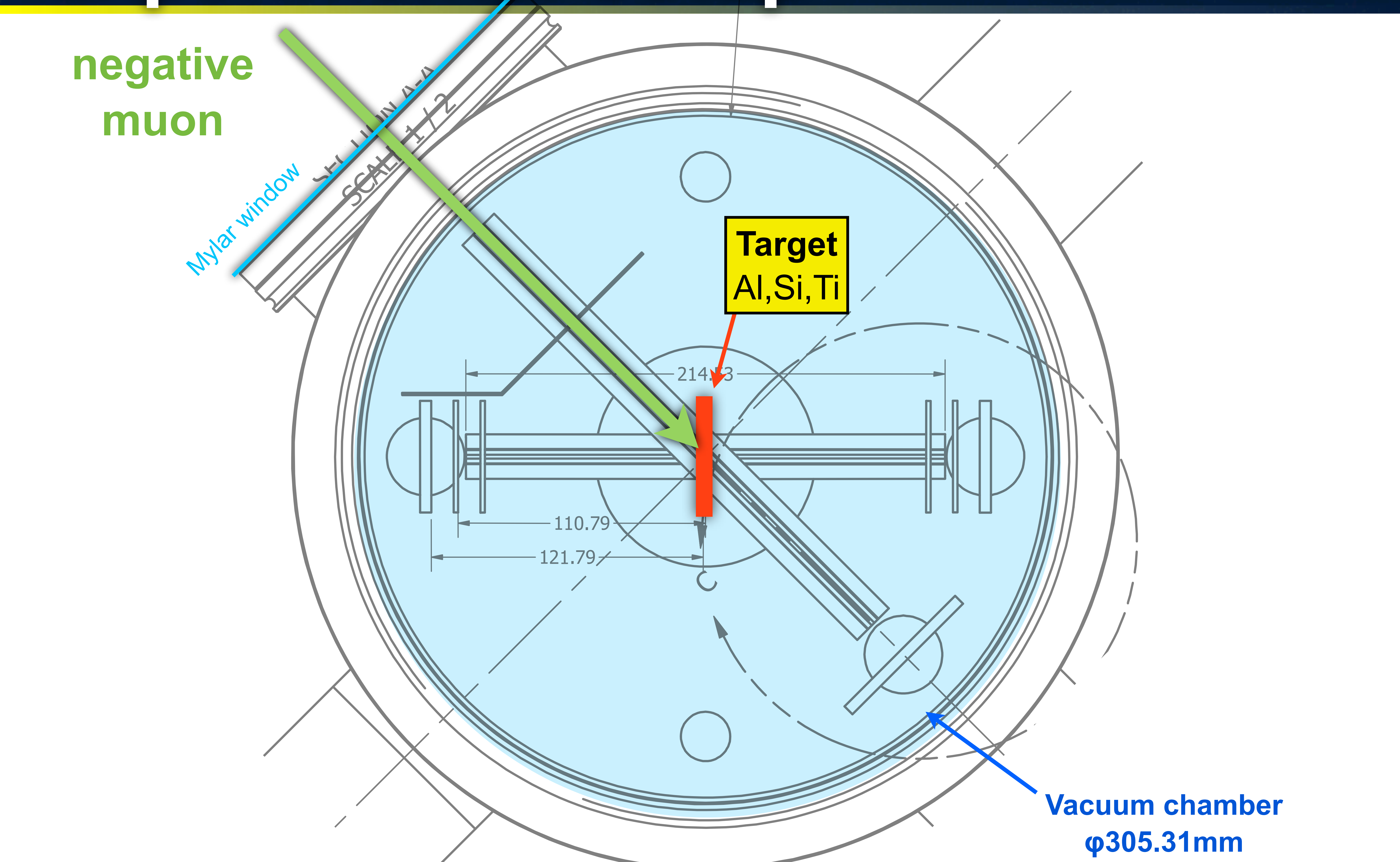
- **There are no data**, in the relevant energy range, on the products of muon nuclear capture from an Al target (and Ti).
  - ratio of p:d:α
  - the absolute proton rate
  - energy distribution
- Mu2e and COMET are presently using parameterization of the muon-capture data taken from Si in 1968.
- Uncertainties in the proton spectra have significant ramifications for the design of COMET Phase-I and Mu2e.
- **We must measure them. This WP1 proposal.**

WP1: Experiment

- **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. (2.5 MeV~71 MeV/c for proton).
- **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.



Experimental Setup



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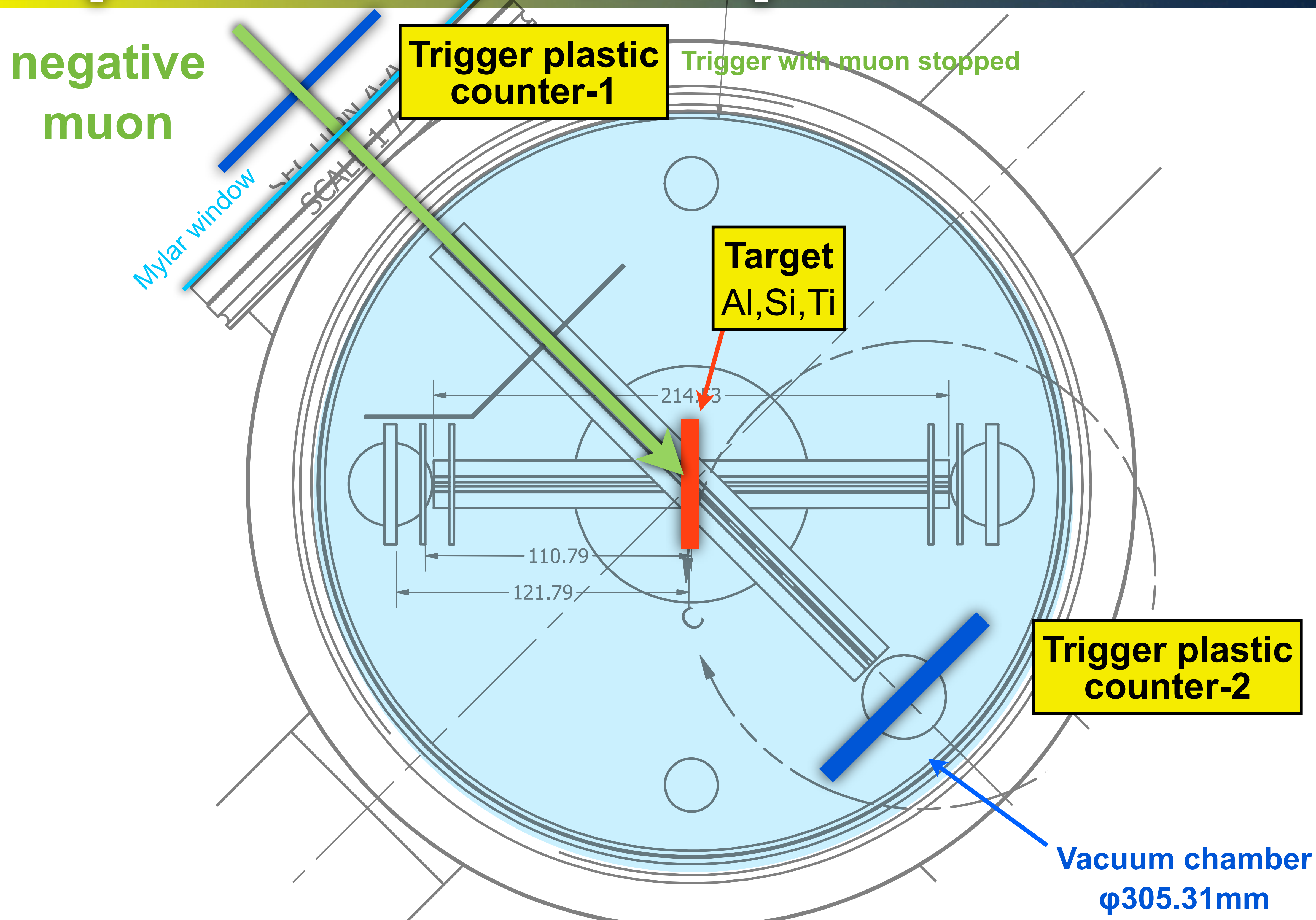

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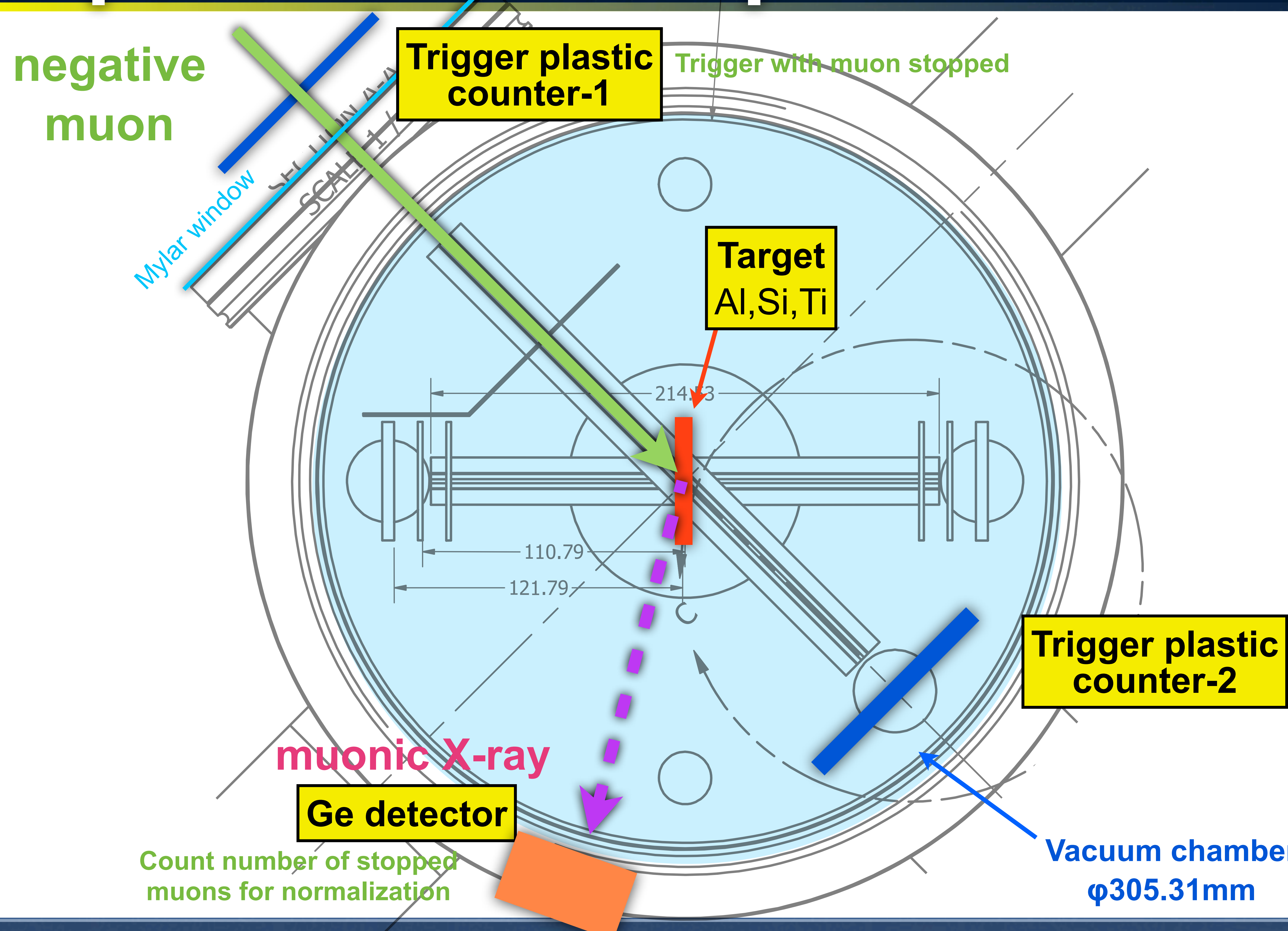

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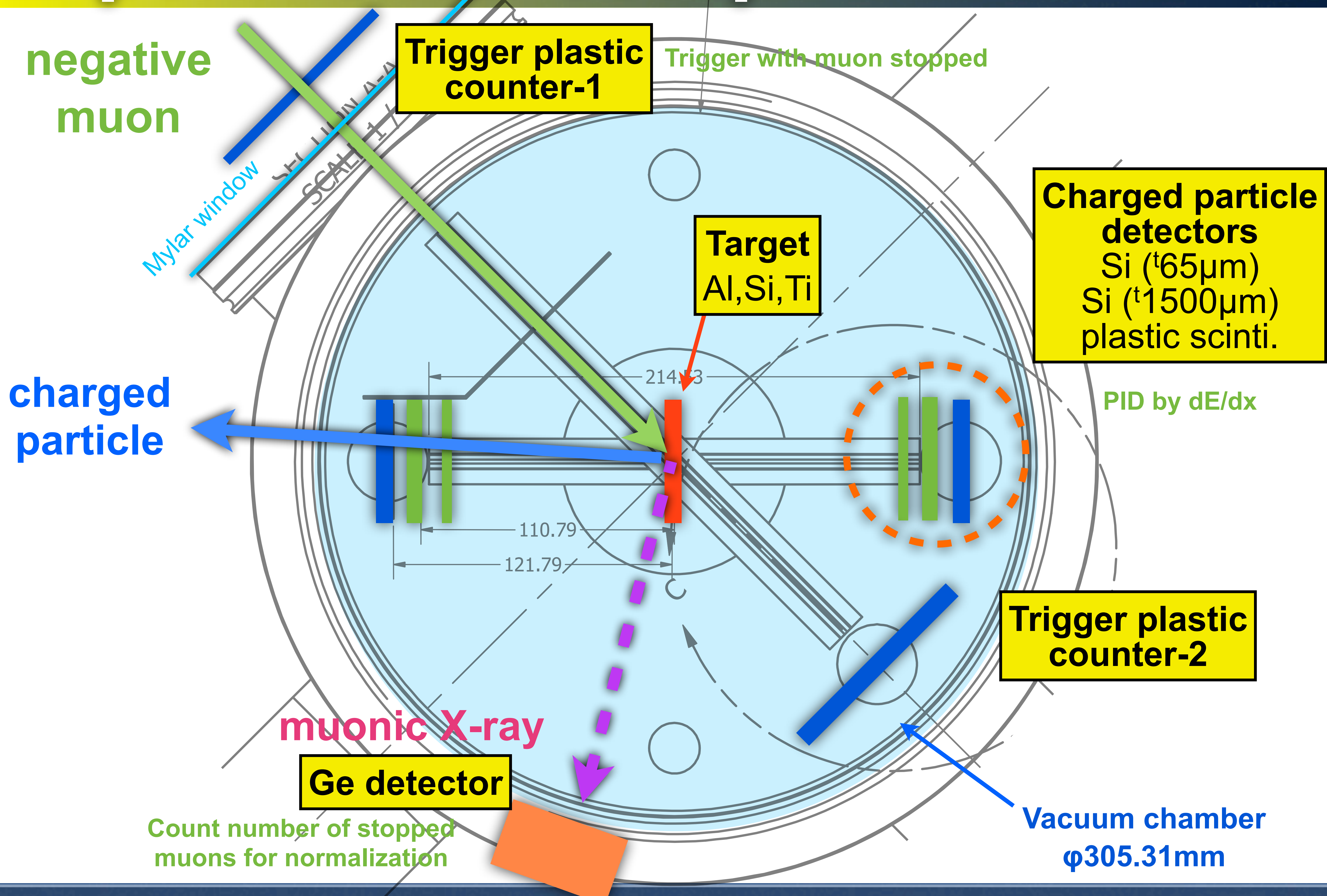
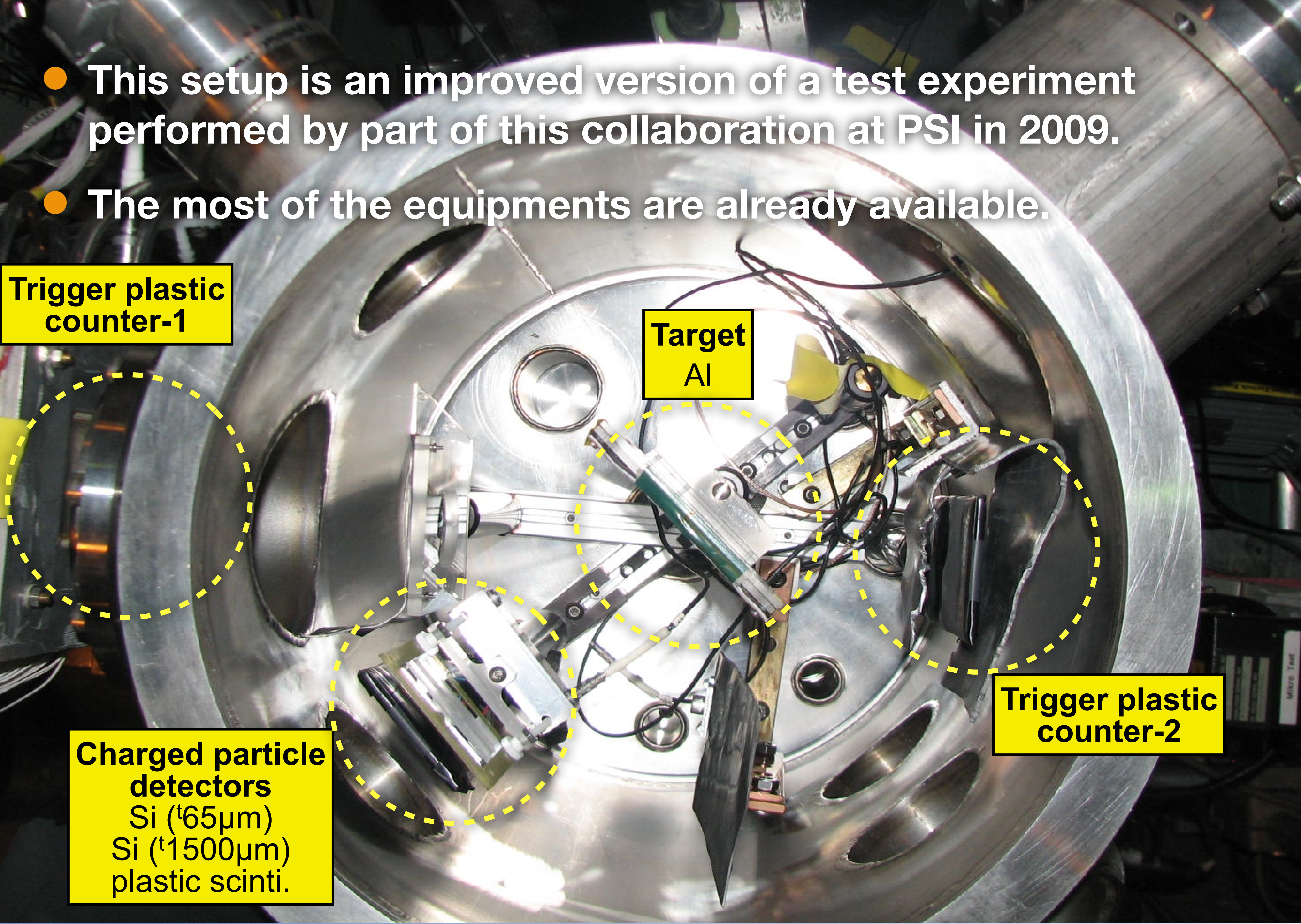
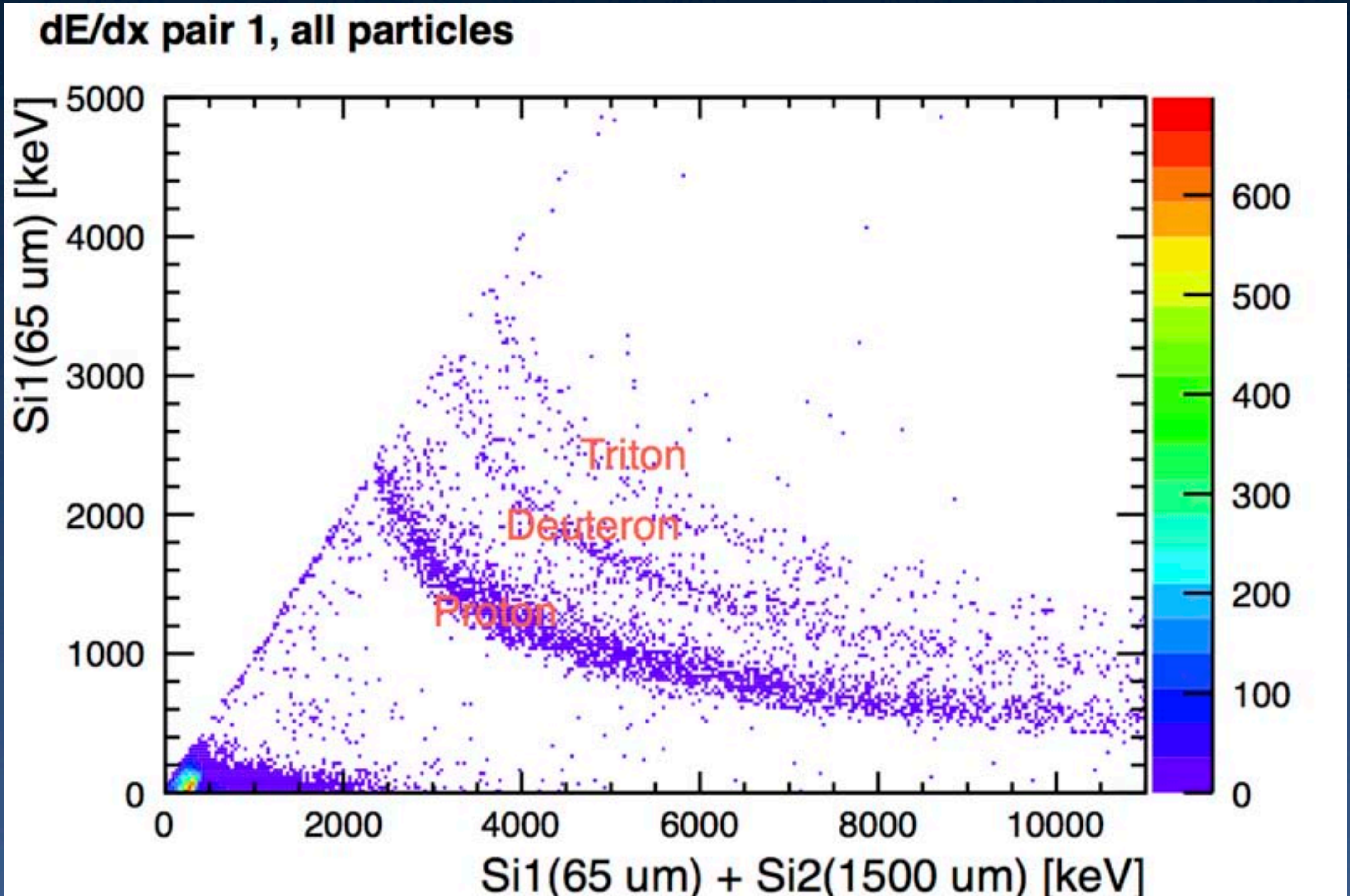


- This setup is an improved version of a test experiment performed by part of this collaboration at PSI in 2009.
- The most of the equipments are already available.



Particle Identification by dE/dx



Assumed energy resolution: 140 keV for Si1 and 40 keV for Si2

WP1 Rates estimation

Target thickness (μm)	Muon momentum (MeV/c)	% Stopping in target	Event rate (Hz) All particles	Event rate (Hz) Protons
50	26	22.2	34.8	4.6
100	27	32.9	48.5	5.4
150	28	38.5	54.5	4.8
200	28	51.2	47.7	4.5

- Event rates were estimated using Geant4 simulations. The total event rate is below 100 Hz for all the considered targets.
- the rates of protons are rather low (5 Hz) and as such approximately 1.5 days of data taking will be required to accumulate the necessary statistics (~0.5 M events) for a given target.

WP1 Systematic Uncertainties

- **Response Function**
  - Uncertainties can be minimized using
    - an optimal cloud muon beam at πE1 and
    - the use of the active Si target
      - where both the initial and final proton energies can be determined.
- **Absolute Rate**
  - The proton detection efficiency will be determined from detailed GEANT4 simulations of the Si detectors.
  - The number of stopped muons will be determined independently from both
    - the Ge detector and
    - the electron telescope and
    - a cross-checked using data from the active silicon target.

WP1 Systematic Uncertainties

- **Particle Identification Efficiency**
  - Particle identification will be made
    - using dE/dx vs. E in the Si detectors, with the efficiency determined from the GEANT4 simulation.
- **Backgrounds**
  - Electron background will be determined using
    - using dE/dX vs. E and the veto counter.
  - Muon scattering background will be eliminated by putting lead shields.
  - A GEANT4-based evaluation of backgrounds from muons that stop in the lead shields.

WP1 Estimation of Running time

- **A precision of 5%** for **energy spectra (2.5 - 10MeV)** is required for **both the rate and the energy spectra**.
  - 500 k proton events needed for each sample.
    - energy bin size = 0.1 MeV → 75 bins
    - average 6k events for each bin
  - proton rate ~5 Hz → 100k sec ~ 30 hours for each
  - about 1.5 days for each sample.
    - including a time for changing targets, pumping chamber, beam tuning
  - 3 sample each for Al and Ti (6 in total), plus 2 Si active targets (8 samples in total)
  - total: about 12 days for proton measurement.

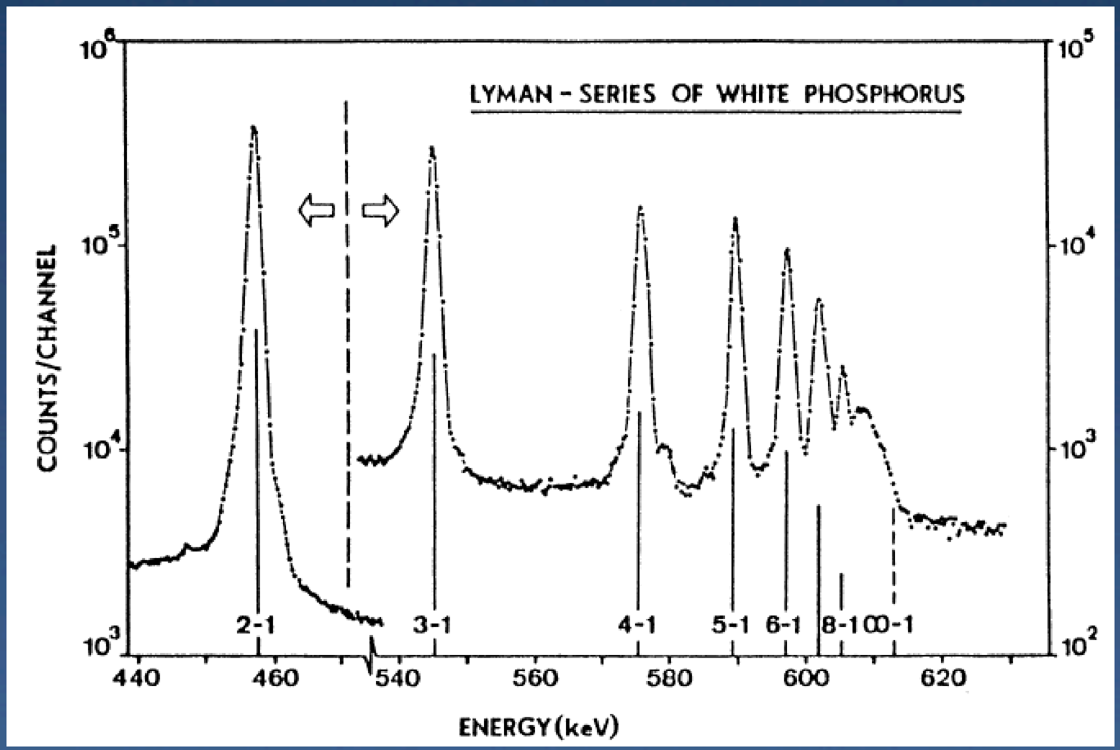
WP1: Readiness

- Most of equipments are already available:
  - chamber, pump, targets, lead shields, detector mounts
  - Si and plastic scintillator detectors
  - preamps, PMT, ...
- A vacuum chamber has been tested at UW
- Si and plastic scintillators have been tested at UW and OU
- A custom DAQ based on “Midas” is being developed, and tested with the detectors (OU)
- A study of Monte Carlo simulation is being done to the optimize geometry (OU)

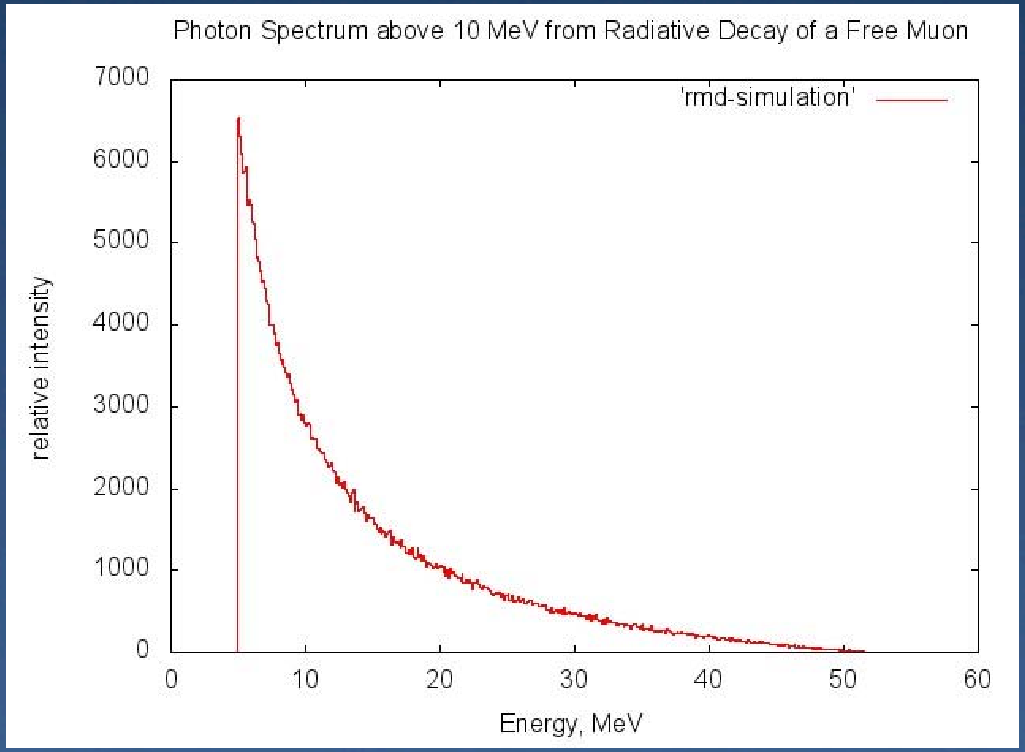
WP2: Gamma and X-ray Emission after Muon Capture

WP2 Present Knowledge

- When a negative muon is captured in an atomic orbit, it cascades down to the 1s level with 10^{-13} s by emitting X-rays and Auger electrons. The muonic X-ray from 2p to 1s transition occurs ~80% of the time.
- Muonic X-rays can be used to count a number of muons stopped in the target.
- Radiative muon decays (RMD) have been measured.



a typical muonic X-ray spectrum



radiative muon decay (simulation)

WP2 Relevance for μ-e conversion

- A method of proper normalization of a number of stopping muons has to be established.
  - (1) Measurement of muonic X-rays in a pulsed beam will be used as the primary method.
  - (2) As an alternative, delayed gamma-rays after muon capture can be measured in a spill-off time. For Al, 1.01 MeV and 843.76 MeV delayed gamma from excited state of Al, where ^{27}Mg lifetime is 9.5 min.
  - (3) As an another alternative, bound radiative muon decays can be used, in particular energy range of 55 MeV to 75-85 MeV (BR~10^{-5})
- Ge detectors are used for (1) and (2), whereas a NaI detector is used for (3).
- PNNL develops a high-rate segmented Ge detector with fast amp.

Table 6: Energies of muonic X-rays in selected target elements.

Transition	Si (keV)	Al (keV)	Ti (keV)
$2p \to 1s$	400	347	1021
$3p \to 1s$	477	413	1210
$4p \to 1s$	504	436	1277
$3d \to 2p$	77	66	189

WP2 Experiment

- The AlCap collaboration propose to test several schemes to monitor the number of stopped muons in the muon-stopping target.
- High purity Germanium detector
  - We will install a high-purity germanium (HPG) detector at the port of the vacuum chamber for WP1 to measure muonic X-rays. A typical resolution of 2 keV for 1 MeV photon. The normalization method can be cross-checked with an active Si target run in WP1.
  - A high-speed 14-16 bit data acquisition system will be used to record high-resolution raw waveform data, in addition to online monitoring.
  - The measurements would include muonic X-rays and delayed gamma-rays.
  - The study of both immediate and long-term effects of neutrons on the HPG detector.
- NaI Detector
  - A NaI detector will be used to measure high energy photons from the muon stopping target, with the primary goal of evaluating alternative means of monitoring the stopped muon rate.
  - The NaI detector has 9 PMTs and their signals are digitized by waveform digitizers. The rate of photons, up to about 80-90 MeV, will be measured.

WP3: Neutron Emission after Muon Capture

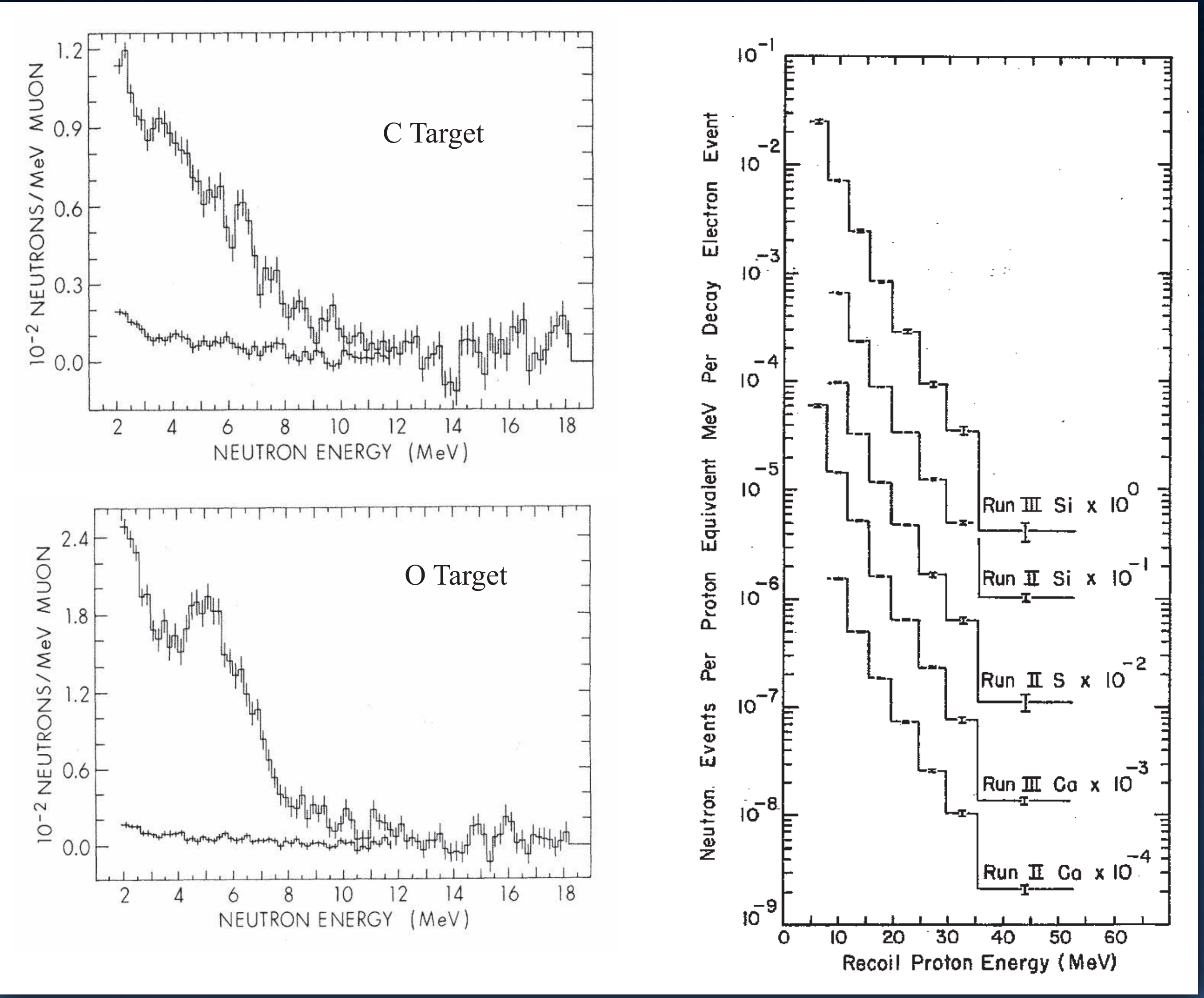
WP3 Present Knowledge

- Neutron emission after muon capture is not well understood, and can be described by direct and evaporation processes (via giant dipole resonances).
- High energy neutrons (above 10 MeV) come from direct emission with an exponential decrease as a function of increasing energy.
- Low energy neutrons that may come from evaporation processes depend on nuclear structure and is less well defined.

$$\mu^- + A(N,p) \rightarrow \nu_\mu + A(N+1,p-1)^*$$
$$A(N+1,p-1)^* \rightarrow xN + x'p + x''\gamma$$

two steps via evaporation

- Average neutron multiplicity from measurements are shown in right



neutron energy spectra of low (left) and high (right).

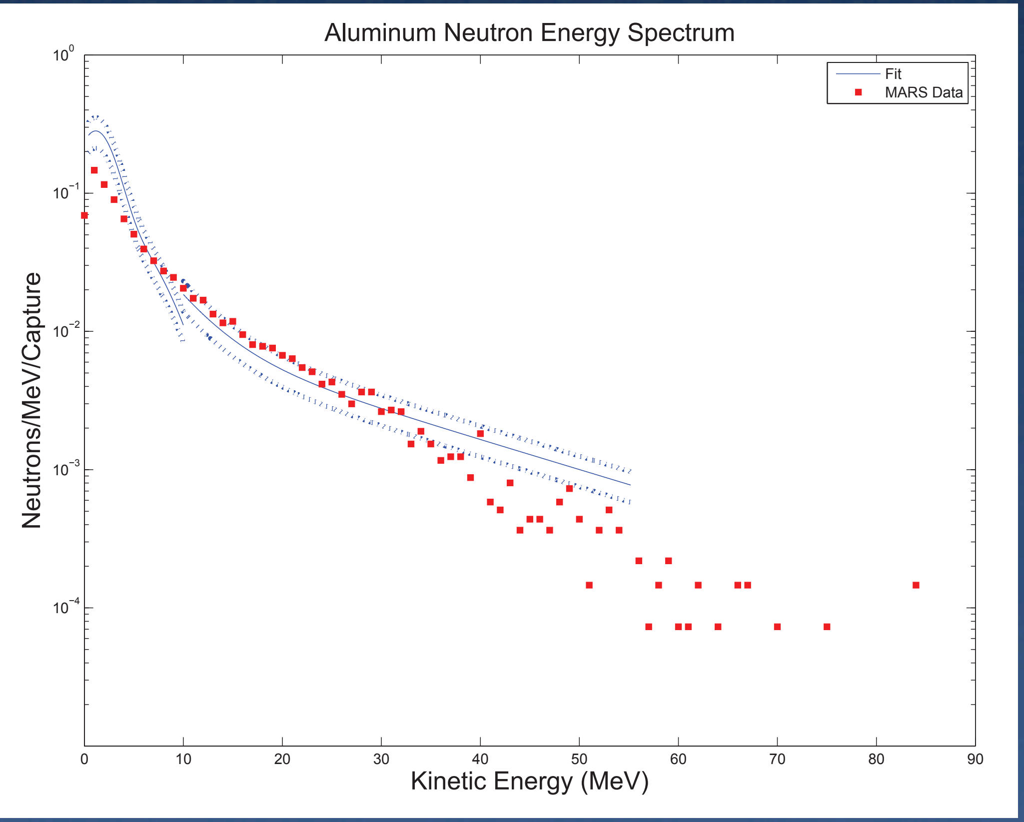
Target	Avg. Mult.	Multiplicity 0	1	2	3
Al	1.262 ± 0.059	0.449 ± 0.027	0.464 ± 0.028	0.052 ± 0.0013	0.036 ± 0.007
Si	0.864 ± 0.072	0.611 ± 0.042	0.338 ± 0.042	0.045 ± 0.0018	0.000 ± 0.008
Ca	0.746 ± 0.032	0.633 ± 0.021	0.335 ± 0.022	0.025 ± 0.0009	0.004 ± 0.006
Fe	1.125 ± 0.041	0.495 ± 0.018	0.416 ± 0.019	0.074 ± 0.0011	0.014 ± 0.005

WP3 Relevance for μ-e conversion

- Neutrons emitted from muon capture at the muon-stopping target (beam stop) at Mu2e and COMET would become a problem for single rates of the electron calorimeters and the cosmic-ray veto, although tracking chambers are not sensitive to neutrons.
  - Estimated calorimeter rates of neutrons and gammas are about 300 kHz and 85 kHz respectively.
  - Simulation shows those introduces pileup probability of 40% and 20% (with energy deposition of 0.5 MeV and 0.7 MeV) respectively.
- Fast neutrons will cause damages on the front-end electronics.
  - From the MARS simulation, a dose of 5×10^4 n/s/cm^2 is obtained. For a IC ship of 1cm^2 area, 4×10^7 second running time is allowed to get the tolerant level of about 10^{12} neutrons.
- Therefore, it would be important to understand the rate and spectrum of neutrons emitted after muon capture.

Table 4: Neutron Background Sources on the Tracker as a function of Neutron Kinetic Energy, T

	Neutrons/cm^2 ($\times 10^{10}$)		
Source	Thermal($T < 1$ eV)	Epithermal (1eV $< T <$ 1 MeV)	Fast ($T > 1$ eV)
Stopping Target	16	77	100
Muon Beam Stop	0.2	2	0.8
Beam Flash	0.2	1	2
Production Solenoid	0.6	0.09	0



neutron energy spectrum from Al from the MARS simulation

WP3 Experiment

- Rate and spectrum of neutrons emitted from muon capture on Al target will be measured.
- Neutron counters from the MuSun experiment will be used. They are six cylindrical cells of 13cm diameter and 13cm depth, containing 1.2 liters of BC501A organic liquid scintillator. They are coupled to PMT.
- Instead of TOF, the neutron spectrum unfolding technique is considered with a detector response function.
- The 12-bit, 170 MHz waveform digitizers (from MuSun) will be used for readout. The digitization allows separation of neutrons from gammas by pulse shape discrimination (PSD).

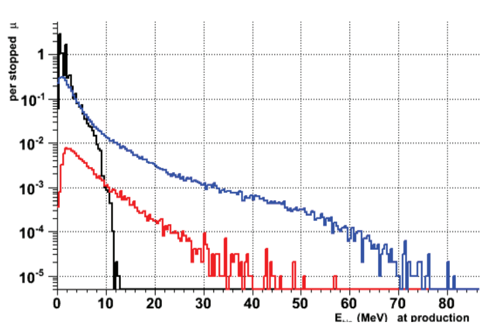


Figure 15: The FLUKA simulated spectrum for proton(red), neutron(blue), and gamma(black) emission per μ stop after μ capture on Al

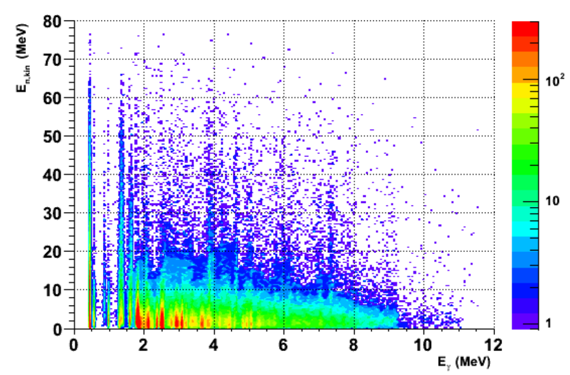
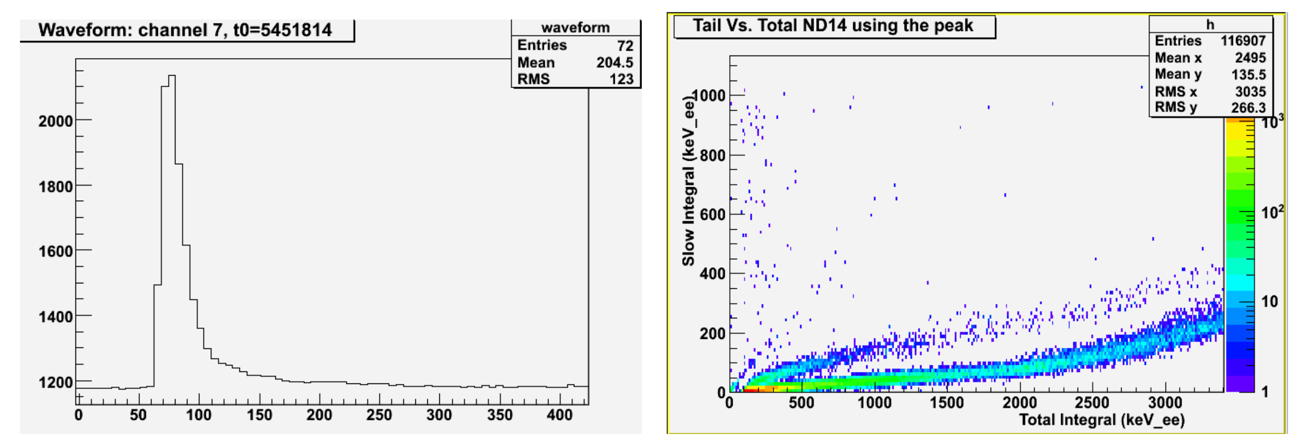


Figure 16: A FLUKA simulation of the energy correlation between neutron (vertical) and prompt gamma (horizontal) emission after μ capture on Al



(a) (b)

Figure 17: a) Digitized signal from a BC501A neutron detector (x-axis in ns). b) Neutron-gamma separation via pulse shape discrimination. The slow integral corresponds to the sum of the bins 5 to 20 to the right of the peak of the digitized signal. The lower band contains γs and the upper band the neutrons.

Beam Requirements and Beam Request

Beam Requirement

- Experiment area:
  - πE1 beam line
- Required beam properties:
  - particle: μ-
  - momentum: 25-35 MeV/c
  - momentum bite: < 2% FWHM
  - beam spot: <2 cm in diameter
  - intensity: $2 \times 10^4\ s^{-1}$
  - beam purity: < 10 % electrons

Beam Time Request

- We request two **two 4 week PSI beam blocks. One is scheduled in 2013, and the next one is in 2014.**
- **In spring 2013,** we like to carry out **WP1 (proton emission)** with **WP2 (muonic X-ray emission).**
  - week 1: setup. commission beam counters and detectors, a vacuum chamber.
  - week 2: beam optimization,
  - week 3: high statistics measurements with 3 targets of Al and Ti, 25-200μm.
  - week 4: high statistics measurements (continued). Last days dedicated neutron measurements.
- **In early 2014,** we like to carry out **WP3 (neutron emission)** with **WP2 (muonic gamma-ray emission and RMD).**

Organization and Responsibilities

- main responsibilities for work packages of the AlCap experiment.

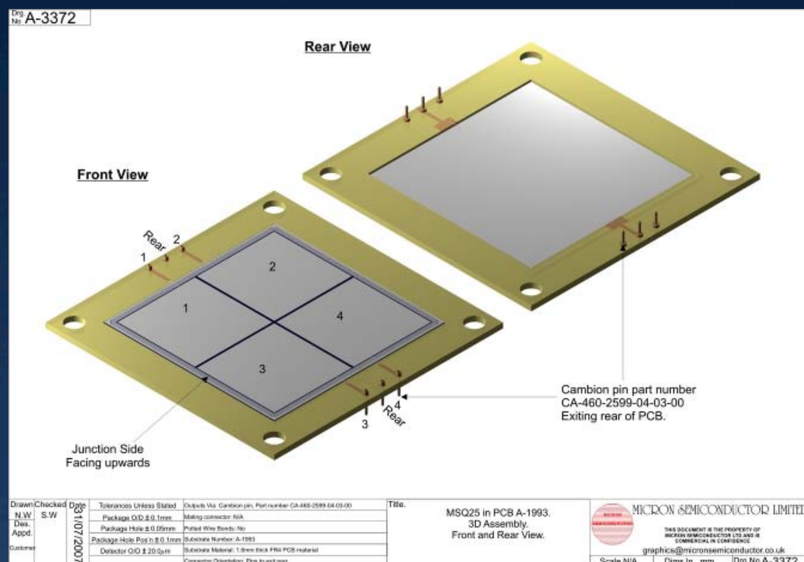
Work Package	Set-up	Detectors	Electronics	DAQ	Simulation/Analysis
WP1	UW, OU	UW, OU, FNAL	UW, OU	OU, UCL	OU, UCL, UW
WP2	PNNL	PNNL, BU	PNNL,UW	PNNL, OU	PNNL, BU
WP3	UH, ANL	UH, UW	ANL	ANL, OU	UH, ANL

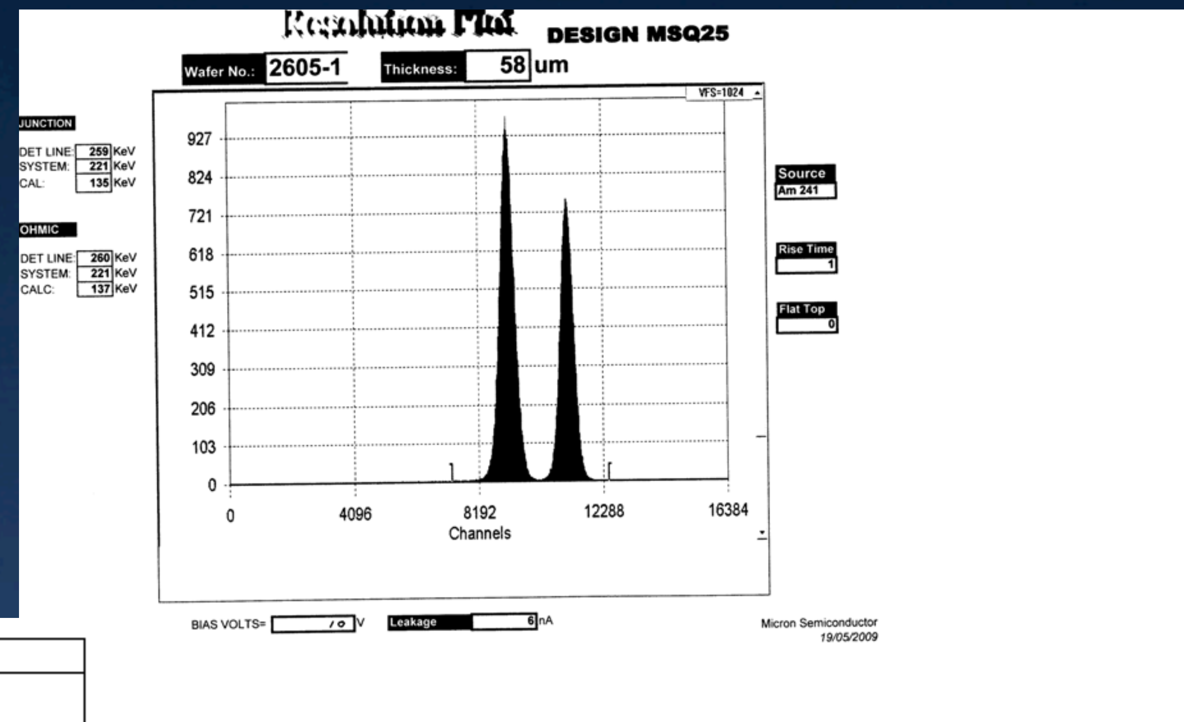
Summary

- Search for μ-e conversion would have a great potential to find an evidence of physics beyond the Standard Model.
- The two experiments in preparation, Mu2e at FNAL and COMET (Phase-I in particular) at J-PARC, need to finalize their detector design in one year. For design optimization, we need accurate data sets of particle emission from muon capture.
- The AlCap collaboration, formed jointly by Mu2e and COMET, proposes an experiment to measure the rate and energy of particle emissions after muon capture at the πE1 beam channel, in two 4-week blocks of the beam time in spring 2013 and early 2014.

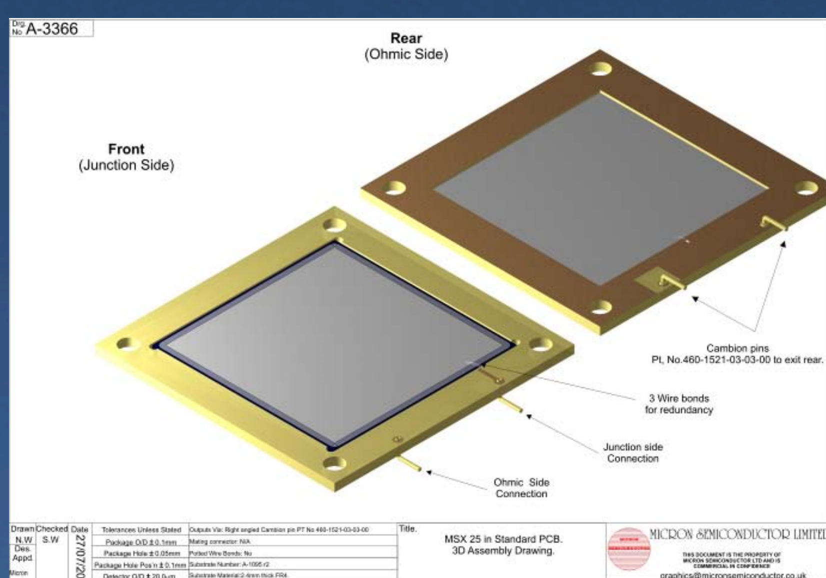
Backup Slides

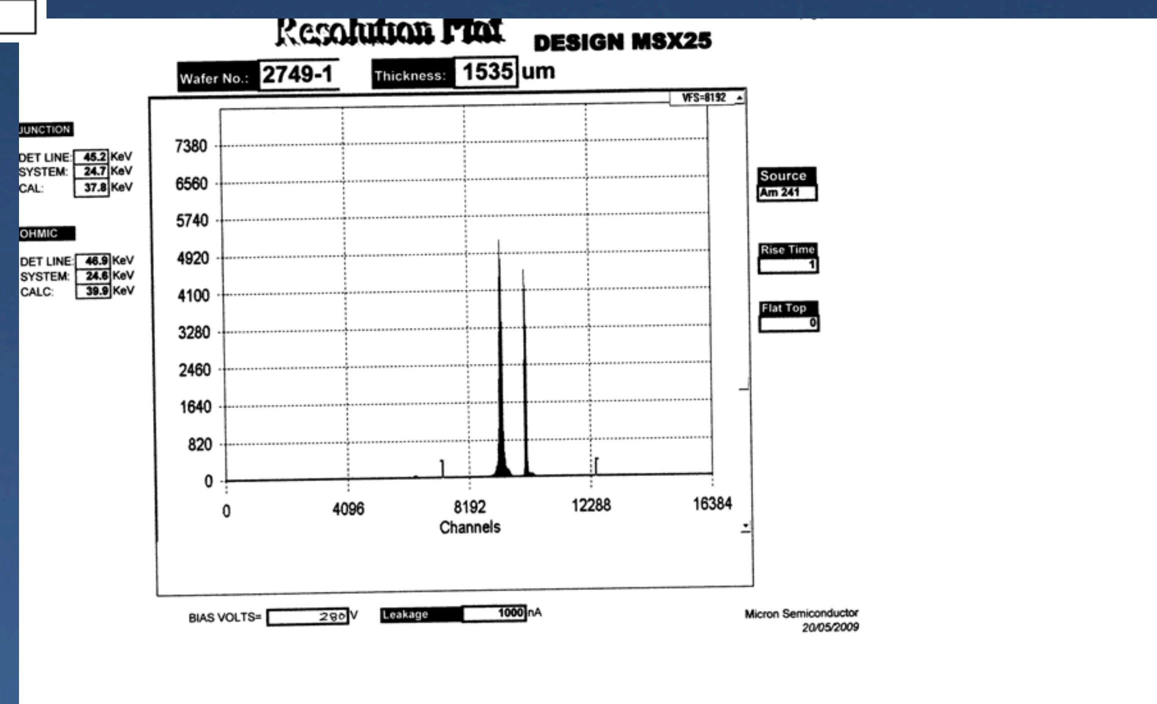
Silicon Detectors

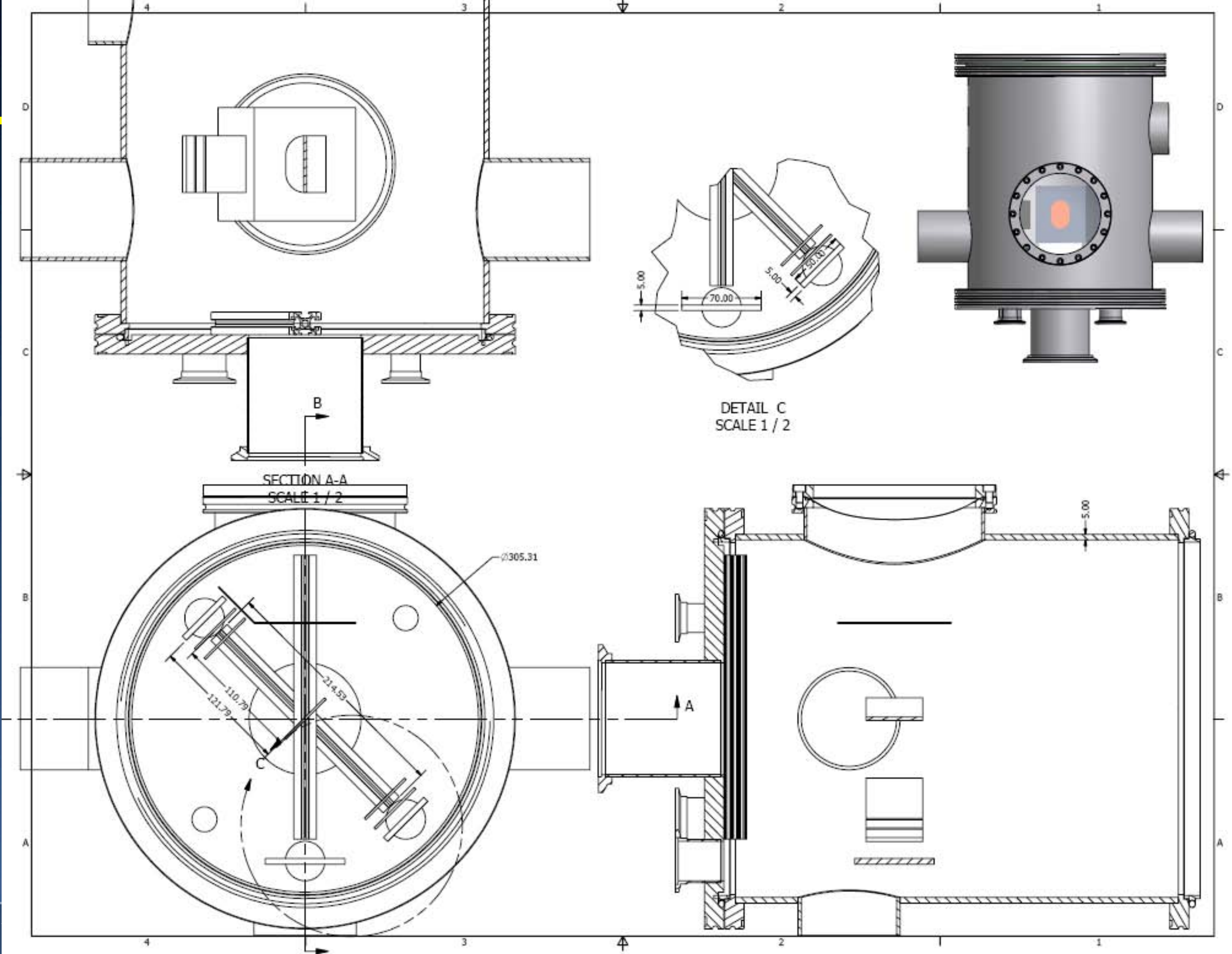




Quantity	Design	Capacitance
2	MSQ25-65 (65 microns)	4,000 pF total 1,000 pF per quadrant
2	MSX25-140 (140 microns)	2,000 pF
2	MSX25-1500 (1500 microns)	300 pF
All detectors will be in PCB frames and are totally depleted.		







DETAIL C
SCALE 1 / 2
SECTION A-A
SCALE 1 / 2
5.00
70.00
30.00
Ø305.31
214.53
110.79
121.79
A
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