Charged Lepton Flavour Violation Experiments

NUFACT2014, XVIth International Workshop on Neutrino Factories and Future Neutrino Facilities

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Imperial College London

Outline

- Brief introduction.
  - Motivation.
  - History.

- Focus on muon based experiments.
  - Muon to electron conversion, i.e. $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
    - COMET, Mu2e, PRISM.
  - $\mu^+ \rightarrow e^+\gamma$
    - MEG
  - $\mu^+ \rightarrow e^+e^+e^-$
    - Mu3e

- Summary.

Related Talks This Week

- See these for details.
  - Monday:
    - “The search for CLF violation in the MEG & MEG II experiments”, F. Tenchini.
    - “The Mu3e Experiment - Introduction and Current Status”, M. Kiehn.
    - “tau cLFV decays”, G. Onderwater.
  - Tuesday:
    - “Search for muon to electron conversion at J-PARC MLF : Recent status on DeeMe”, Y. Nakatsugawa.
    - “Status of the Alcap experiment”, P. Litchfield.
  - Thursday
    - “Status of MuSIC facility”, Y. Matsumoto.
    - “COMET Phase-I”, P. Litchfield.
    - “Mu2e”, Y. Kolomensky.
    - “PRISM”, J.Pasternak.
  - Friday
    - “Backgrounds studies for the COMET Phase-I and Phase-II”, A. Sato.
    - “COMET Phase-II”, A. Kurup.
- Thanks to everyone for the material I’ve used for this talk!

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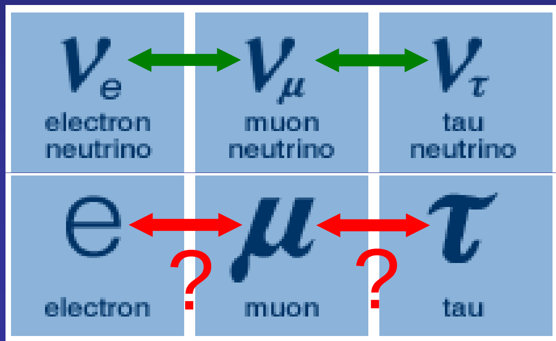
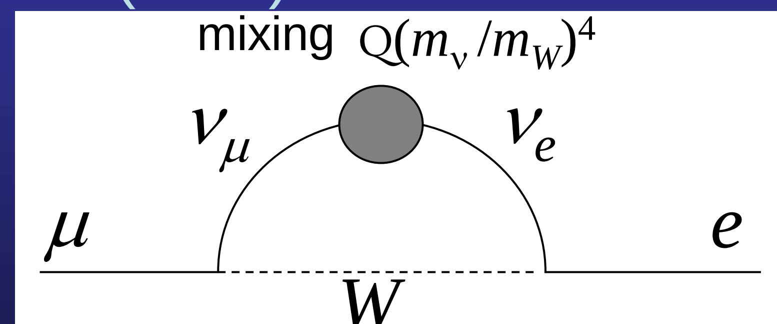
Physics Motivation

- Neutrinos in the SM are massless but observation of neutrino oscillations is direct evidence that neutrinos have mass.
  - Proof that neutral lepton flavour number is not conserved.



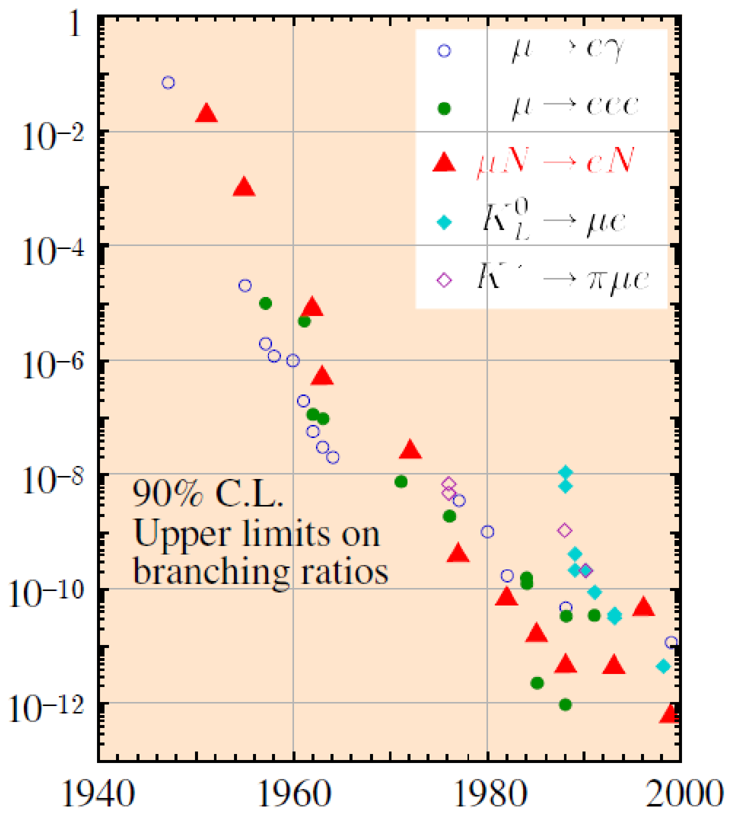
- $\tau \rightarrow \mu\gamma$
- $\tau \rightarrow 3\mu$
- $\tau \rightarrow 3e$
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^+ \rightarrow e^+\gamma$

- Simplest extension to the SM to include neutrino mixing
  - e.g. BR($\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$) = O($10^{-54}$)



- A number of BSM models predict rates to be much higher
  - e.g. BR($\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$) = O($10^{-13} - 10^{-15}$)

Previous Experimental Searches

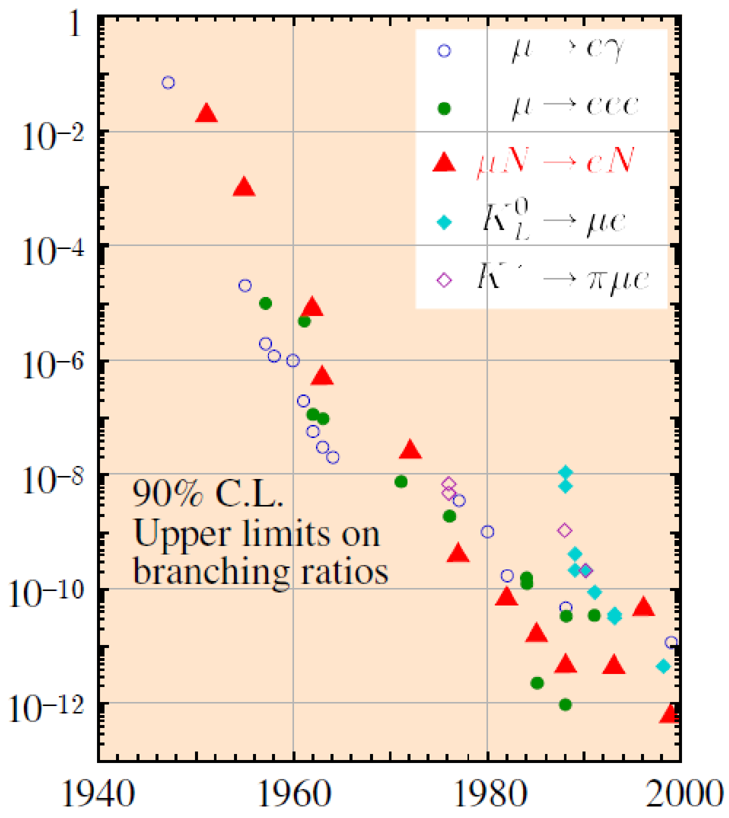


First CLFV search by Hincks and Pontecorvo in 1947 for $\mu^+ \to e^+ + \gamma$

"Search for gamma-radiation in the 2.2-microsecond meson decay process".

Phys. Rev. Lett. **73**, 257–258.

Previous Experimental Searches



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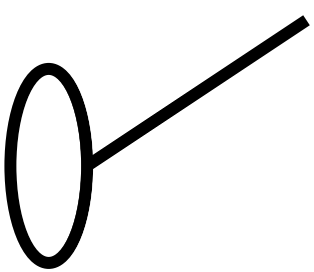
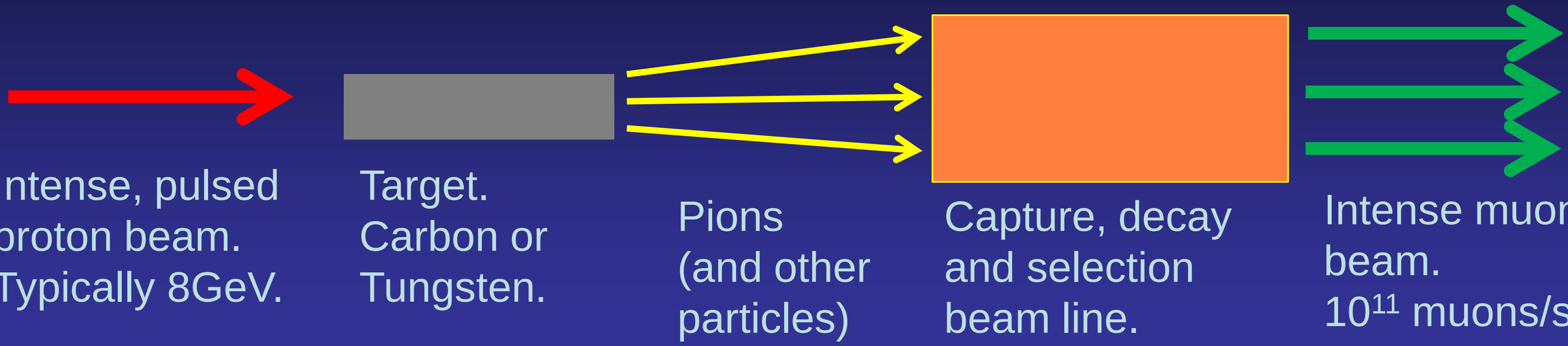


With advances in accelerator and detector technology we can expect to probe as low as here (i.e. 10^{-16}– 10^{-19}).

MUON TO ELECTRON CONVERSION EXPERIMENTS

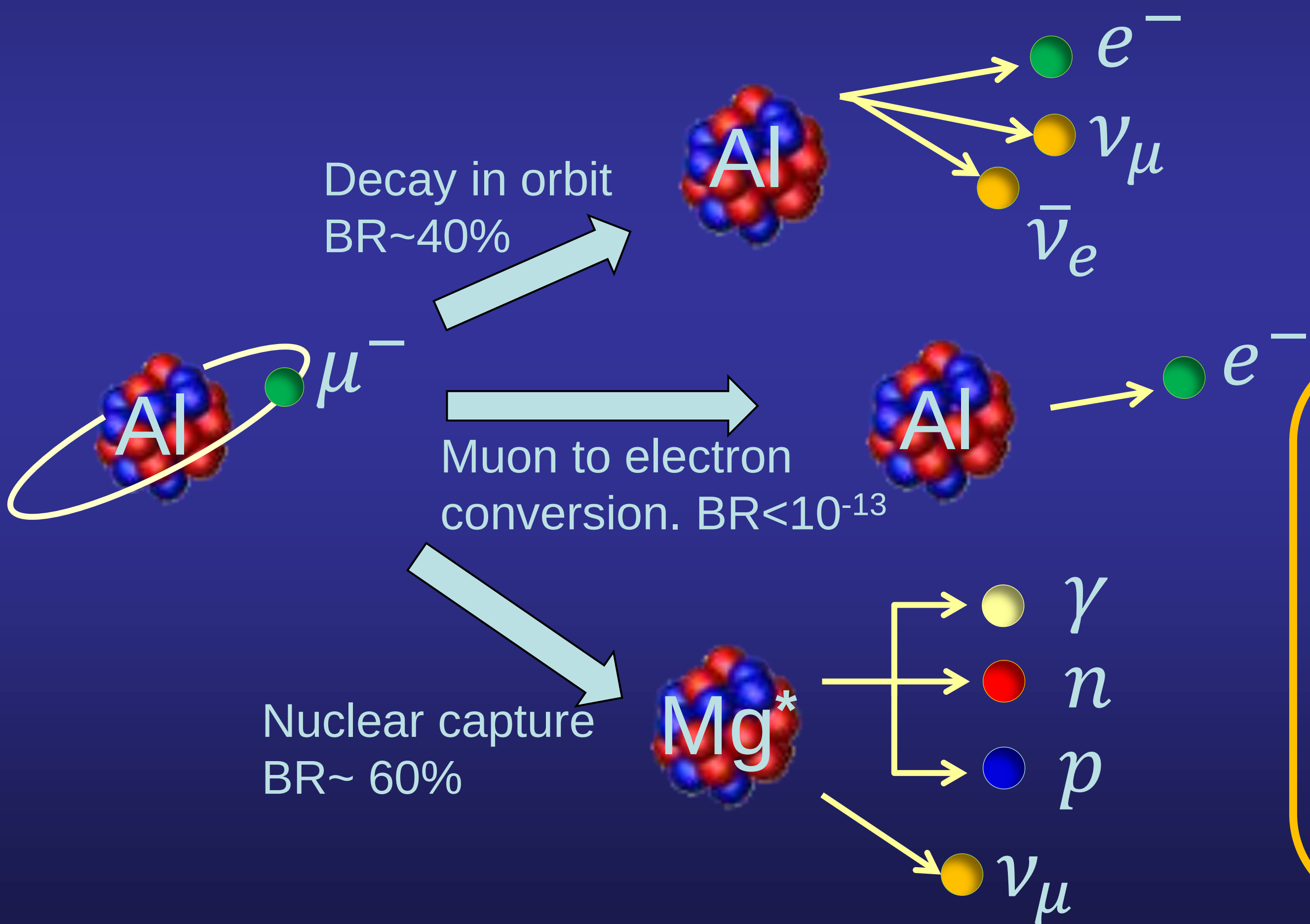
General Principle

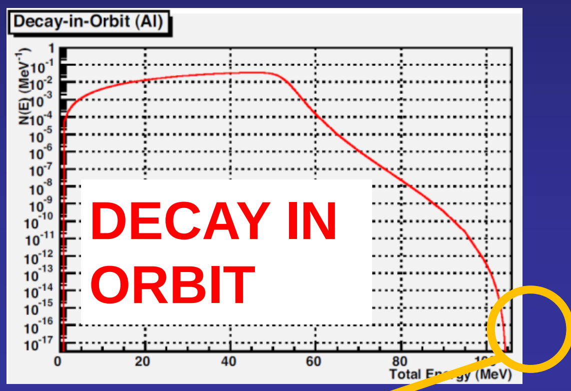


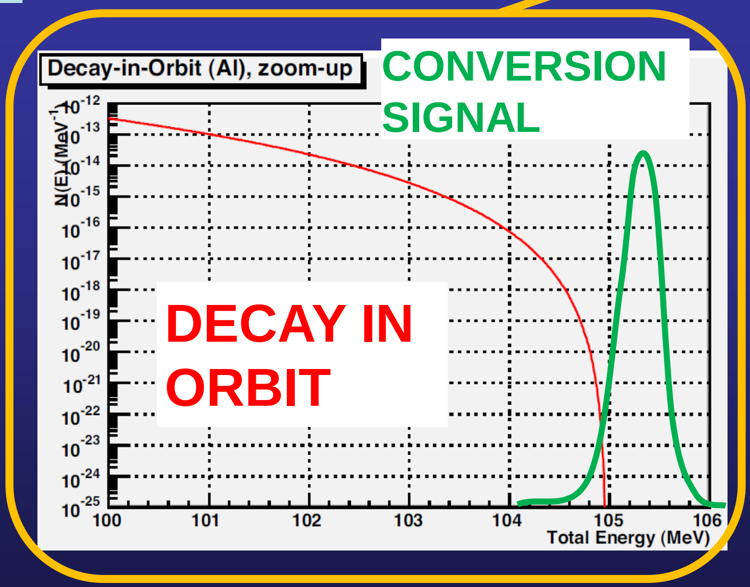
- Use intense muon beam (10^{11} muons/s) with P~40±30MeV/c.
  - Start with a proton beam (~8GeV) and collide with a target.
  - Capture and transport beam line aims to deliver as many muons as possible while removing background particles.
    - Acts as the decay channel for pions – Length is important.
    - Performs charge and momentum selection.
- Synergy with the Neutrino Factory.

General Principle

- Stop muons in a target (Al or carbon) → muonic atoms.
  - SM processes produce intrinsic backgrounds.
  - BSM processes can lead to conversion.

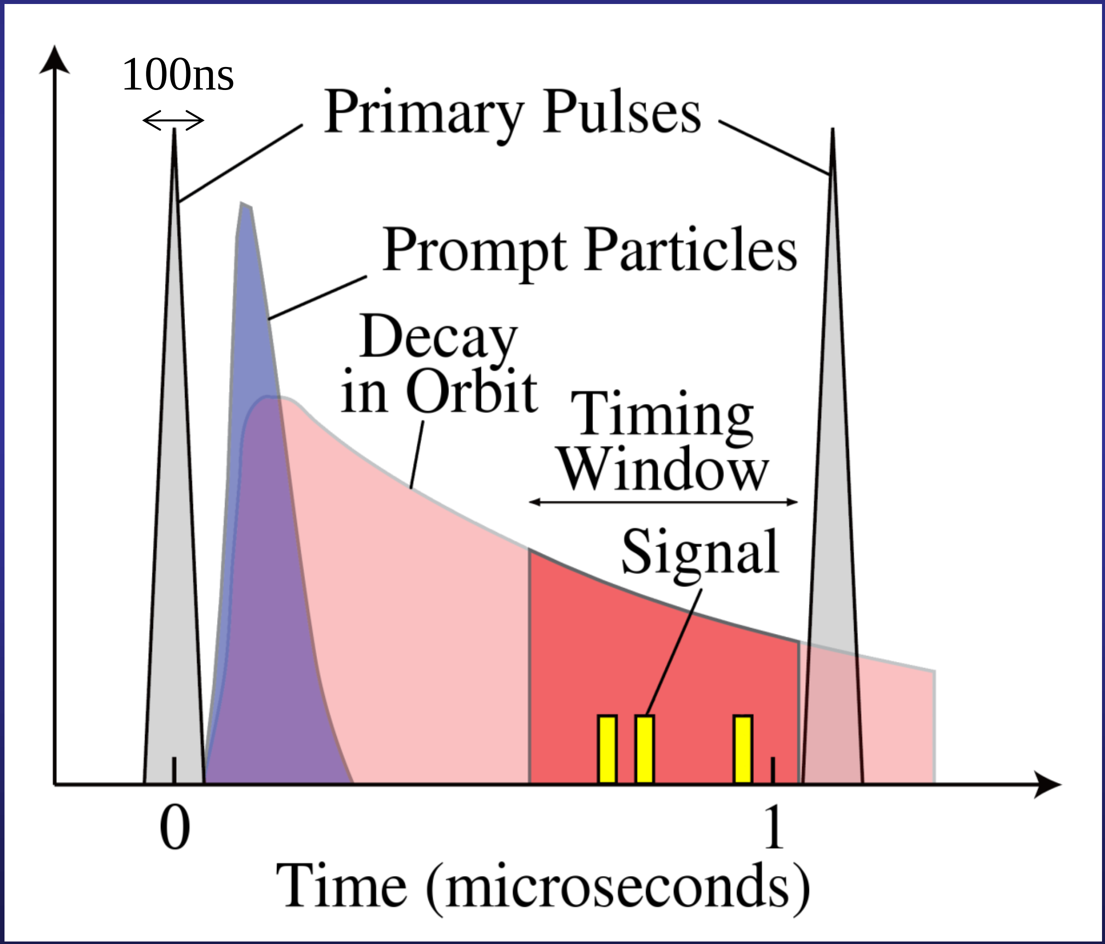






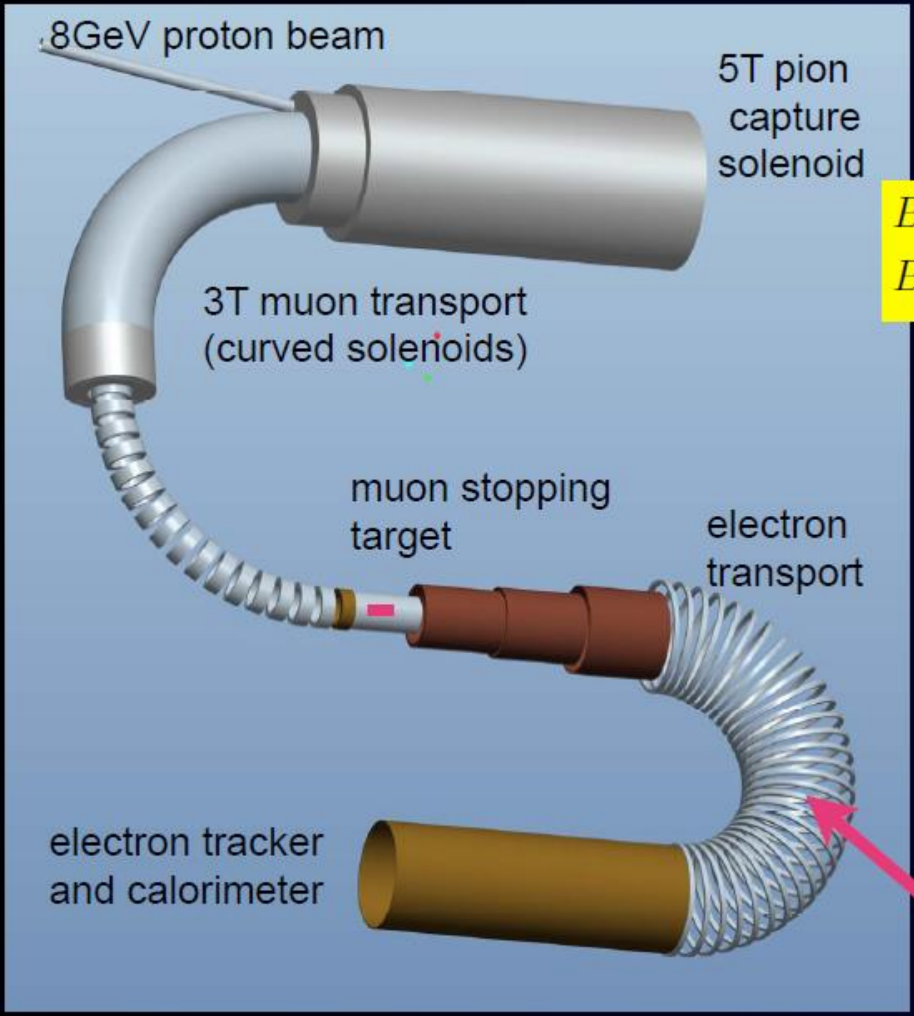
Time Structure of the Proton Beam

- Beam related backgrounds requires using a pulsed beam.
- Muon lifetime is dependent on the stopping target material.
  - Defines the time between pulses.
- Extinction is defined as the ratio of protons in the main pulse to the protons between pulses.
  - Required to be $<10^{-9}$
- May need special device in the proton delivery line depending on intrinsic extinction of the beam extracted from the ring.
- Important to measure this.



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

- COherent Muon to Electron Transition experiment



Experimental Goal of COMET

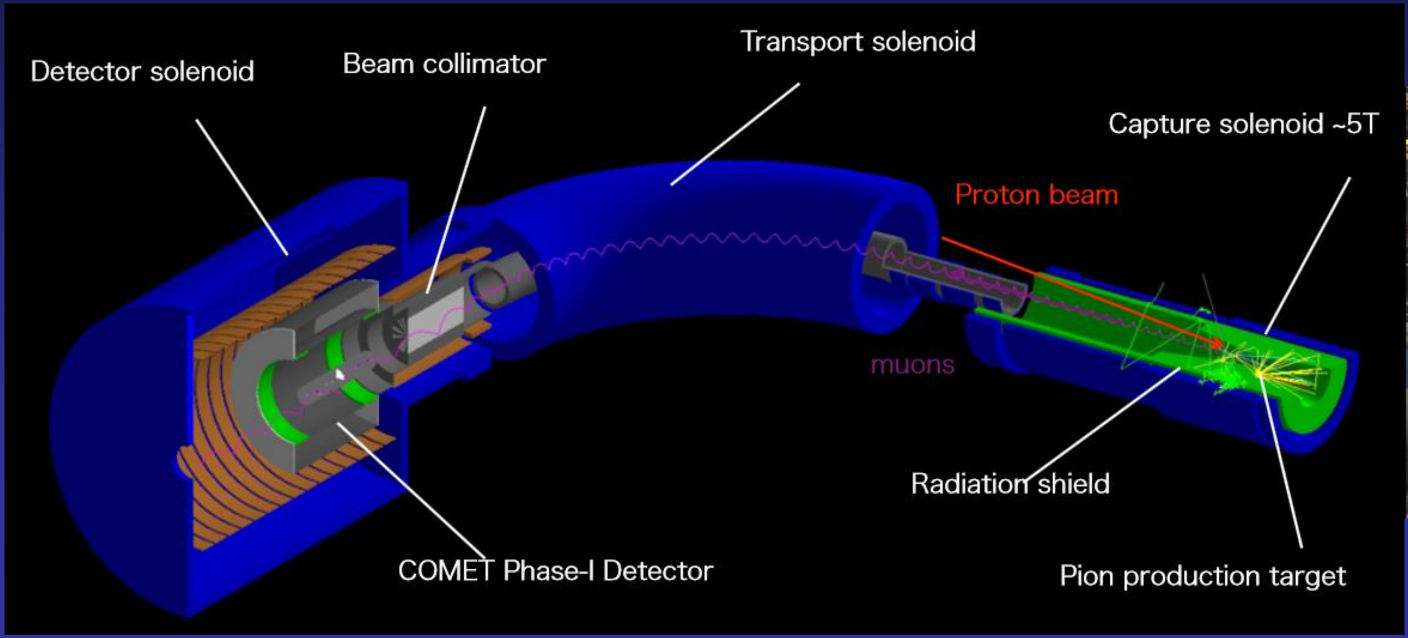
$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$

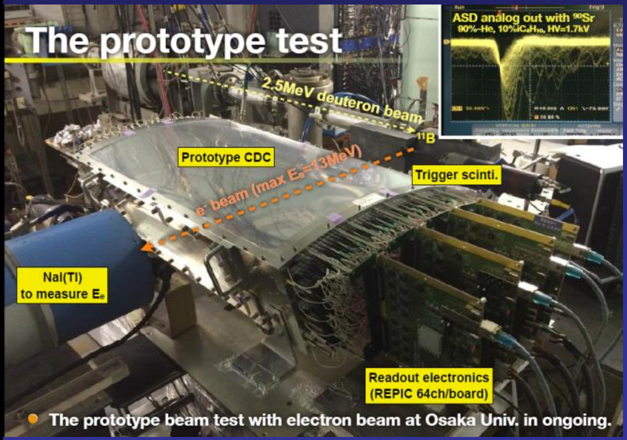
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: COMET Phase-I

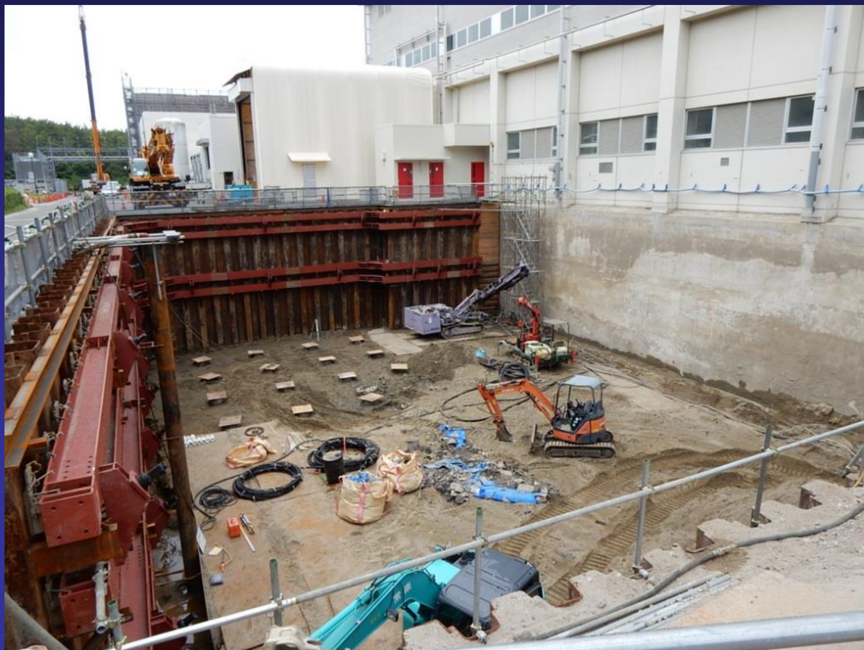




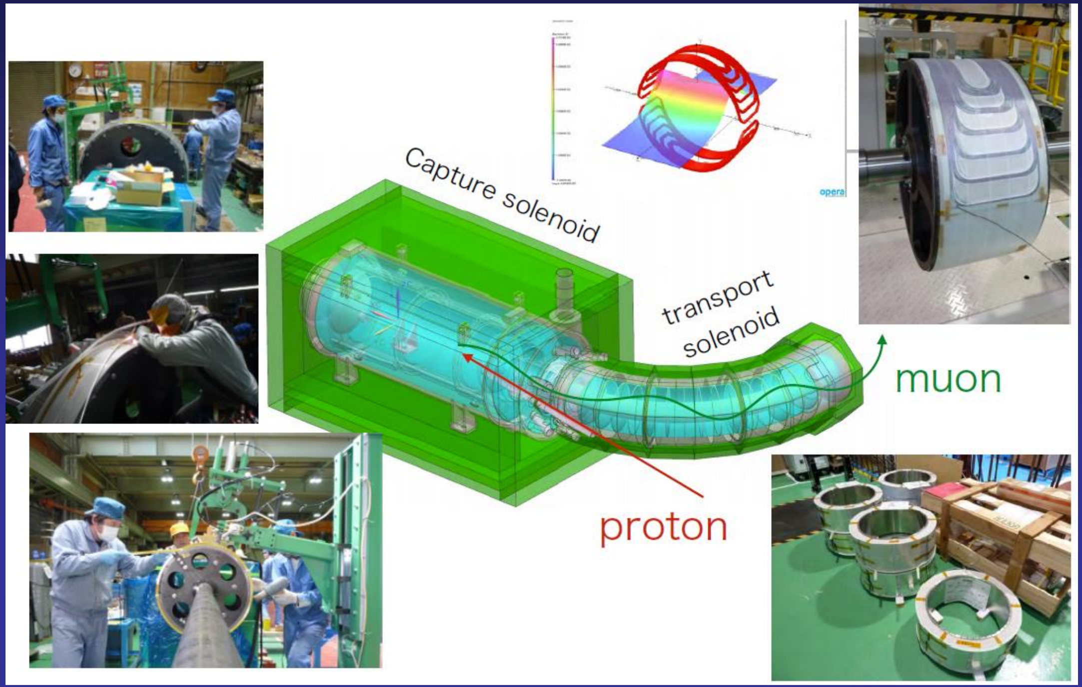
CDC Prototype test

- The experiment will be built in two stages.
  - Allows important measurements of the beam.
    - Understand muon yields and background rates.
    - Validation of simulations.
  - Test prototypes of the detector systems.
- Sensitivity of $3\text{x}10^{-15}$ with 90 days of running.

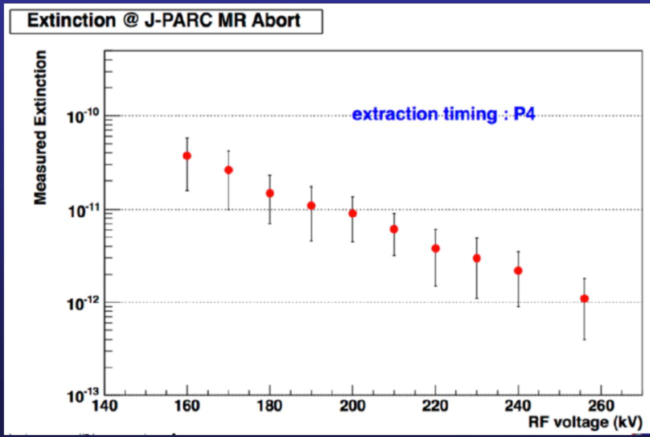
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: COMET



Construction of COMET experimental hall and proton beam line.



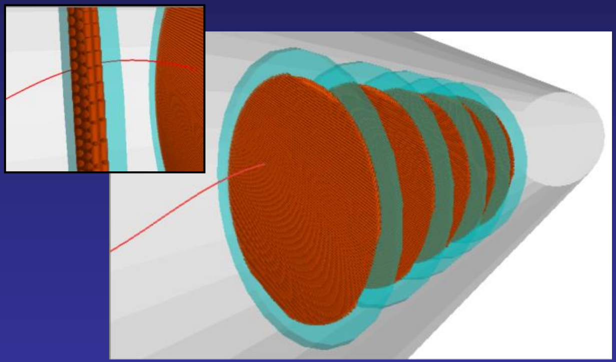
Construction of solenoids.



Beam extinction measured in May 2014. 8GeV beam without the slow extraction.

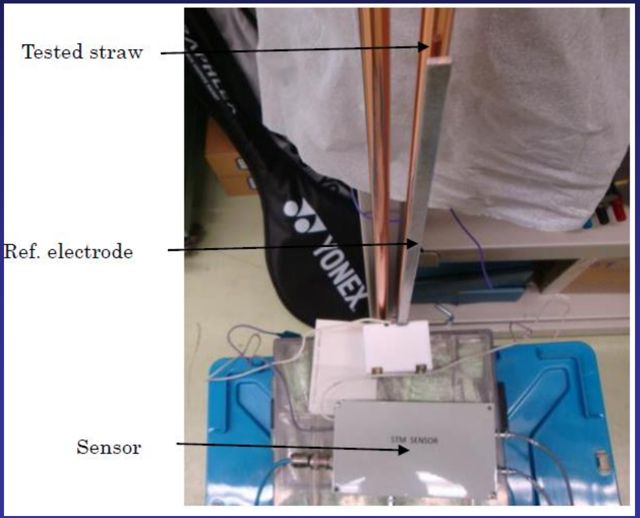
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: COMET

STRAW TUBE TRACKER R&D

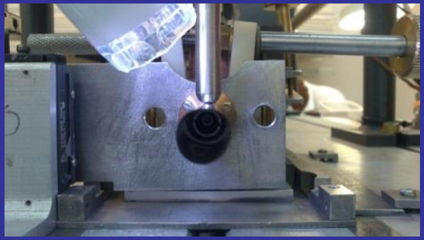


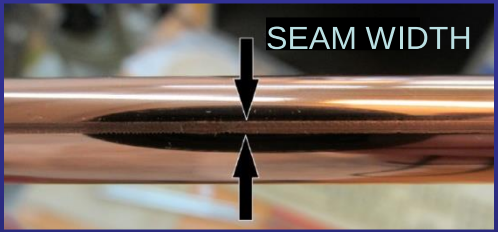
Requirements

- operate in a 1T solenoid field.
- operate in vacuum (to reduce multiple scattering of electrons).
- 0.4% momentum and 700μm spatial resolution.



Straw tube tensioning tests





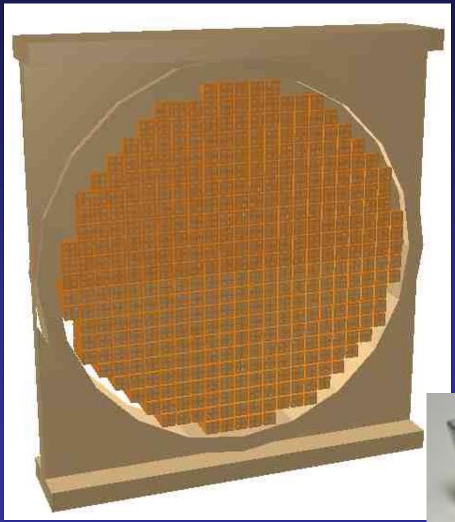
20-100 cm straw tubes produced by ultra-sonic welding at JINR. Seam width is 0.6 – 0.9mm, which will not deteriorate the electric field.
Investigating thicknesses 12-36μm and Cu+Au and Al+mylar coatings.

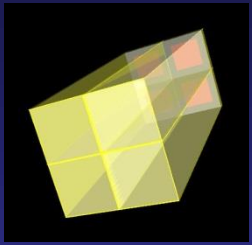
Prototype construction at KEK

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

CALORIMETER R&D

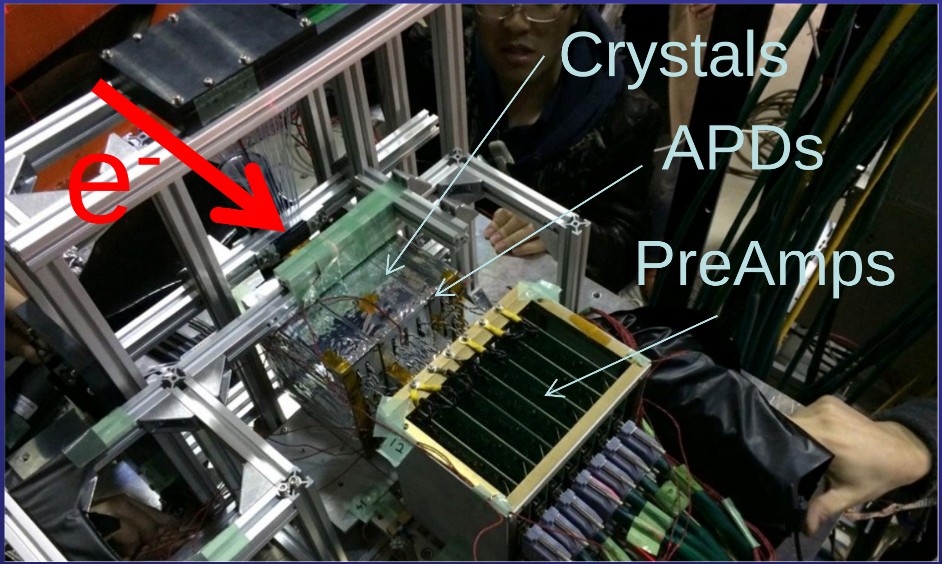
- Calorimeter crystal choice: GSO or LYSO
  - Size: GSO 20x20x150mm^3, LYSO 20x20x120mm^3
  - Radiation length: GSO 10.9 X_0, LYSO 10.5 X_0
  - Light yield: GSO ~ $^1/_3$ × LYSO
  - Cost: GSO ~ $^1/_2$ × LYSO
- Test both crystals meet <5% resolution requirement.



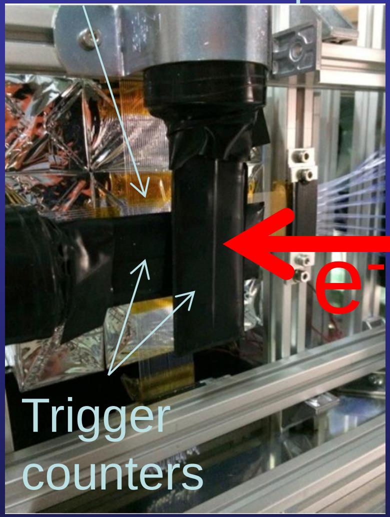


2x2 crystal module

Prototype 2x2 crystal module wrapped with teflon and Al-mylar and 4 APDs.



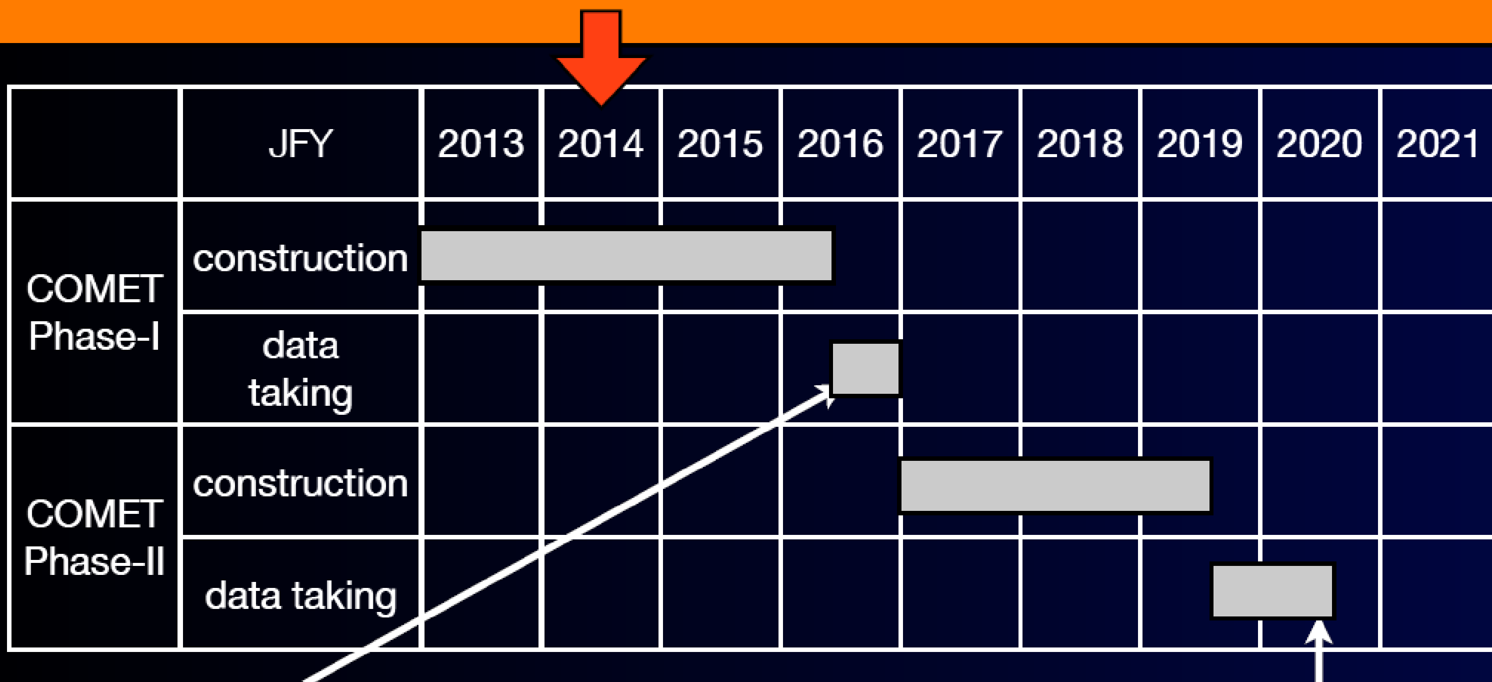
Fibres to measure beam size and position



- Beam tests in Tohoku March 2014.
  - Preliminary results are promising.
  - Final analysis results will be available soon.

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

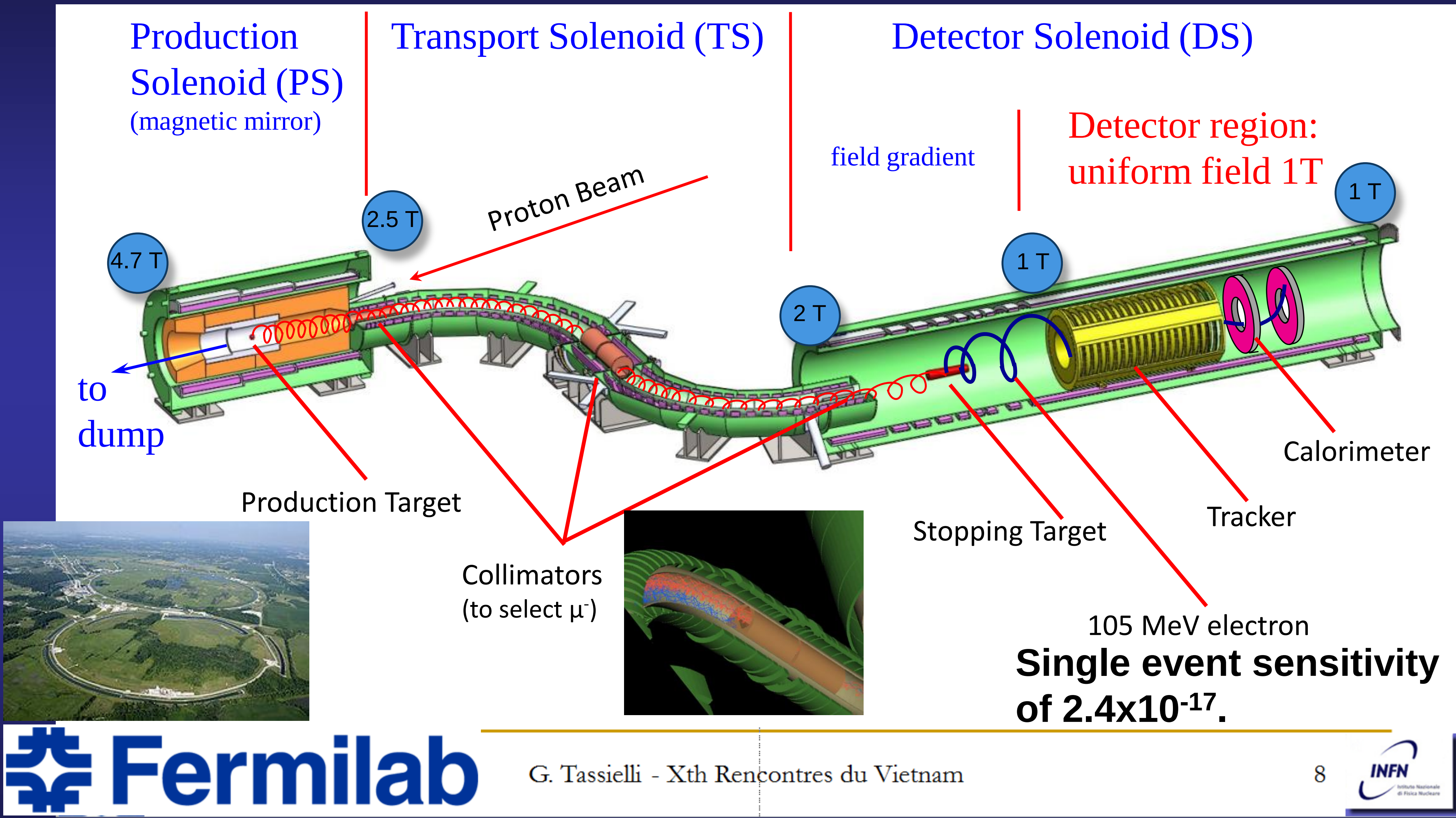
Schedule of COMET Phase-I and Phase-II



COMET Phase-I :
2016 ~
S.E.S. ~ 3×10^{-15}
(for 90 days
with 3,2 kW proton beam)

COMET Phase-II :
2019~
S.E.S. ~ 3×10^{-17}
(for 2×10^{7} sec
with 56 kW proton beam)

$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: Mu2e

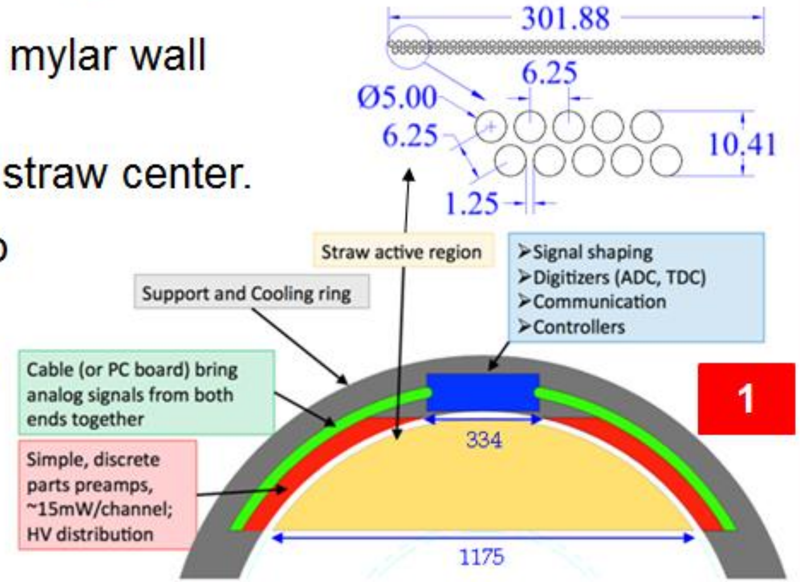


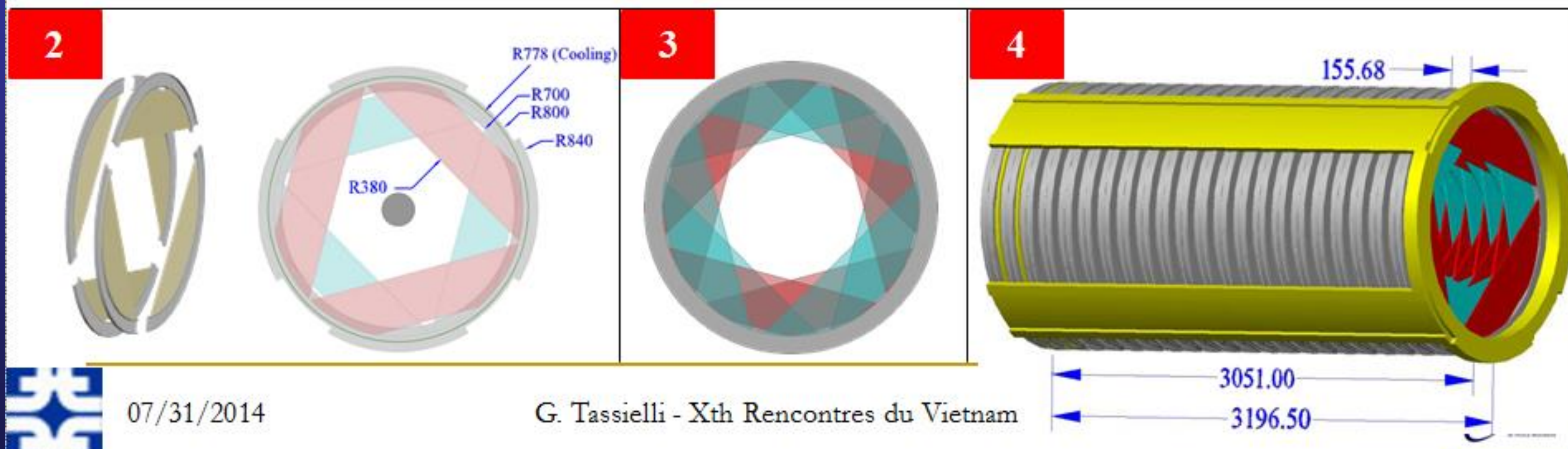
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: Mu2e

Tracker: strawtubes operating in vacuum

- Straws: 5 mm OD; 15 μm metalized mylar wall (~ 23000).
- Will employ time division: ~5 mm at straw center.

1. 2 layer of 48 straws are arranged to make a panel;
2. 6 rotated panels and placed in two different surfaces make a plane;
3. 2 rotated planes make a station;
4. 20 station form the tracker.

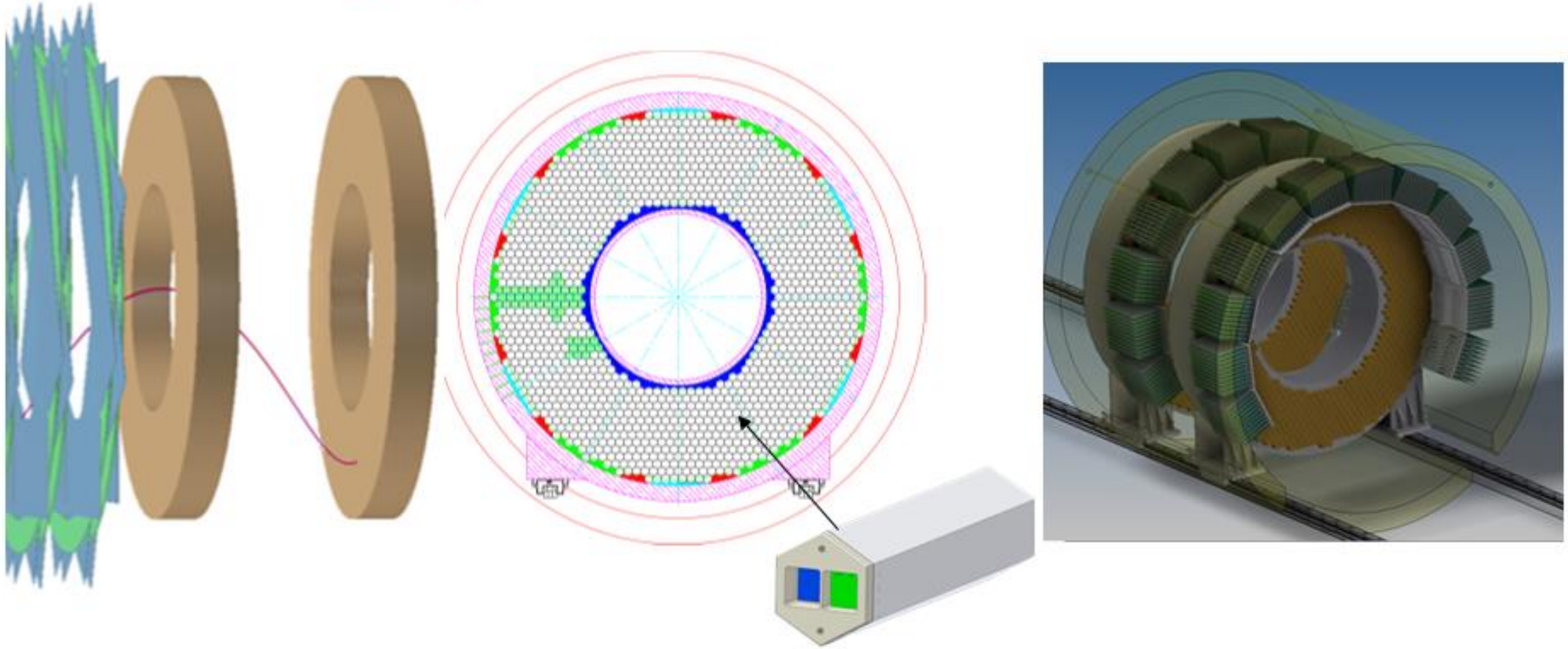




07/31/2014 G. Tassielli - Xth Rencontres du Vietnam

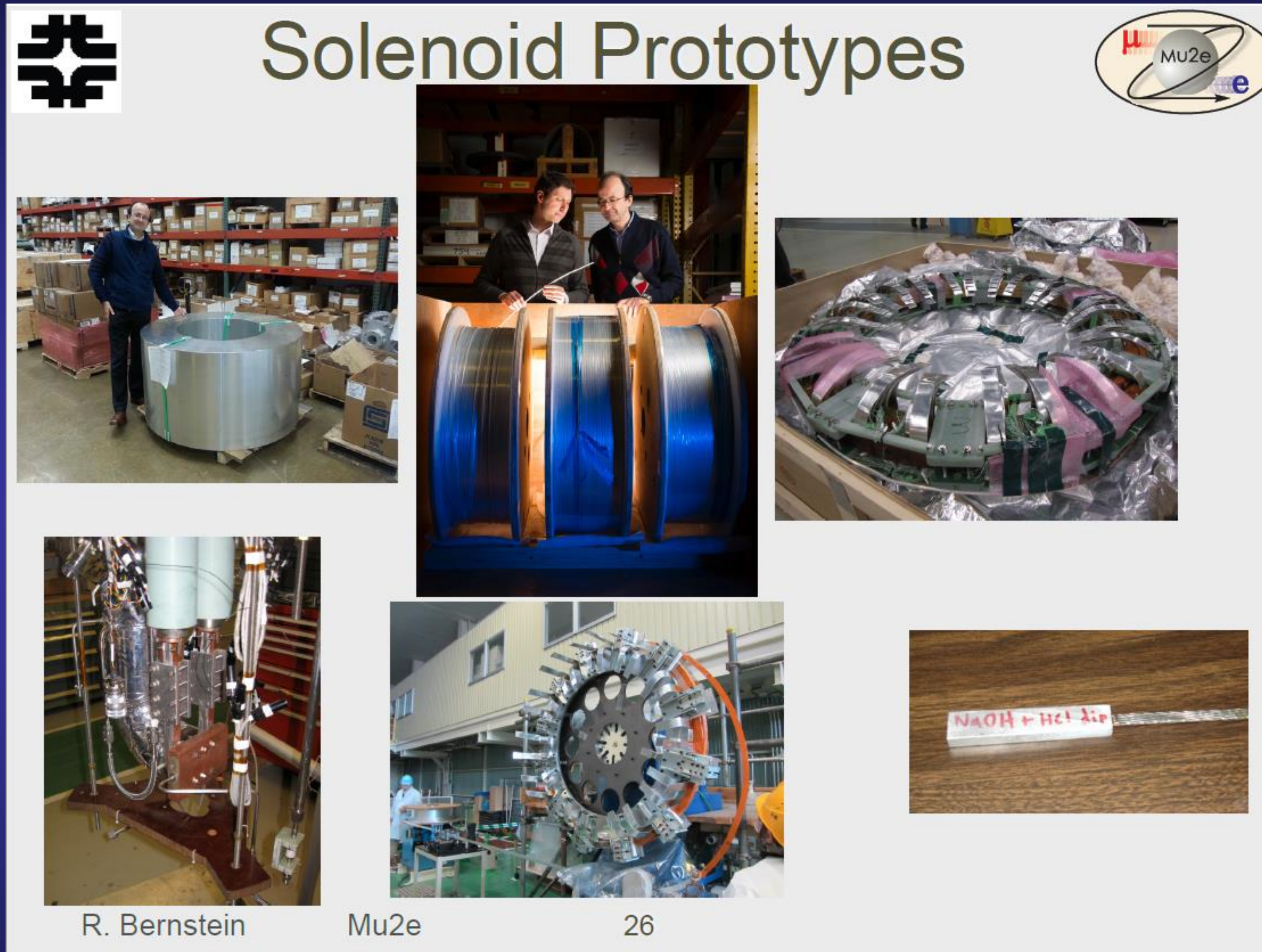
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: Mu2e

Scintillating crystal calorimeter



- Two disk geometry (inner radius 351 mm, outer radius 660 mm);
- Hexagonal BaF2 crystals (33 mm x 180 mm, ~1900); two (10 x 10 mm^2) APD or SiPM readout;
- Provides precise timing (< 1 ns), PID (μ/e), background rejection, alternate track seed and possible calibration trigger.

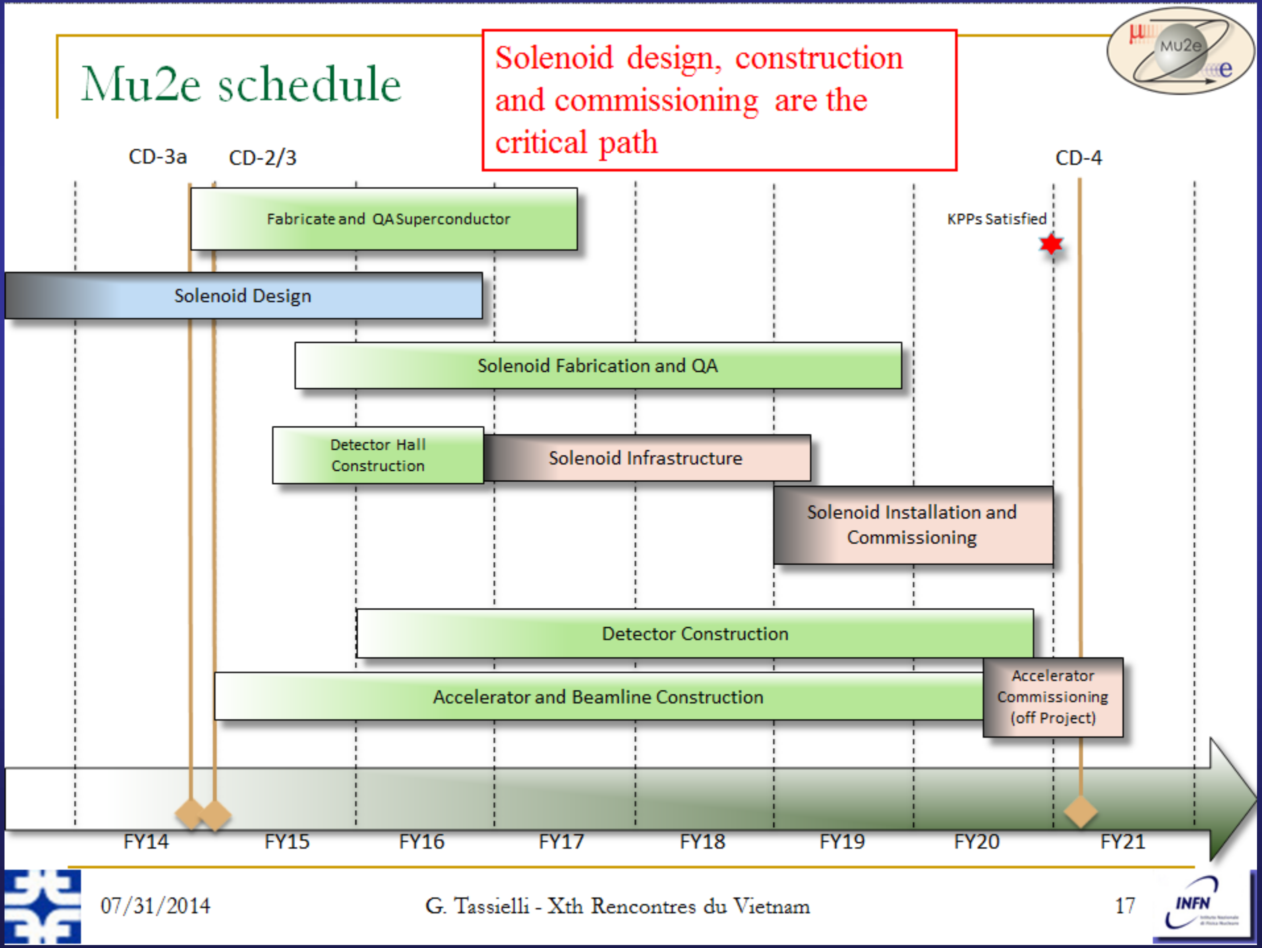
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: Mu2e



- Order for final solenoids being placed.

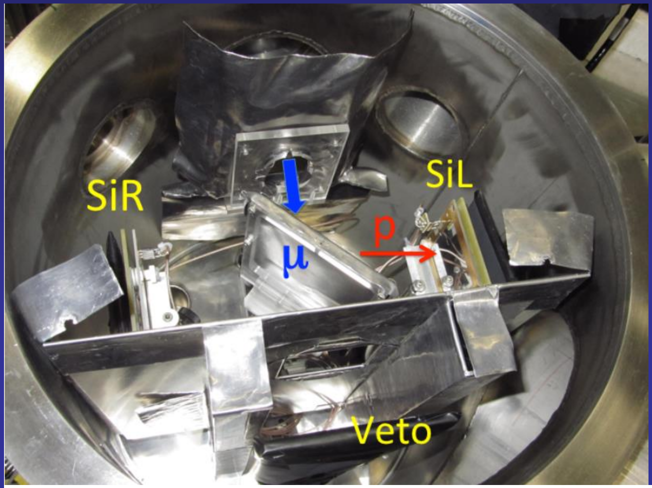
$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: Mu2e

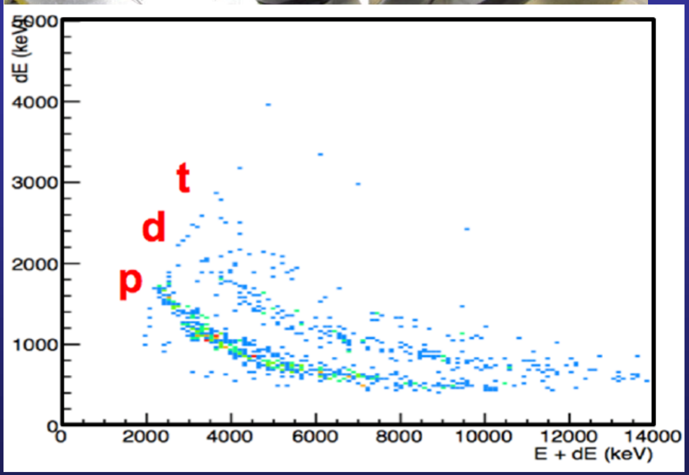
- P5 recommendation
  - Highlights the importance of muon to electron conversion searches and that Mu2e is considered a flagship experiment



AlCap

- Joint experiment at PSI between COMET and Mu2e.
- Measure particle emission rates for muon nuclear capture in Aluminium.

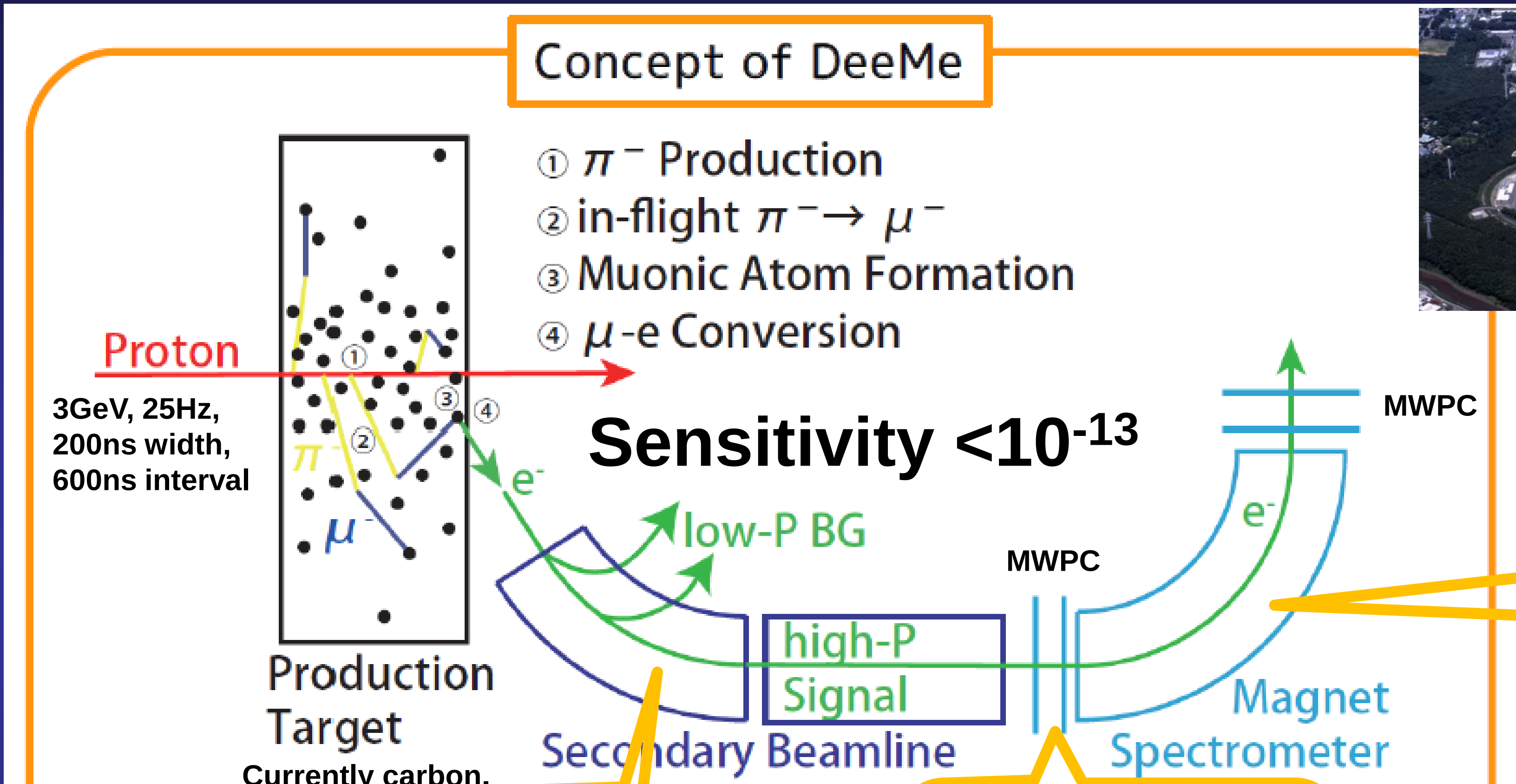


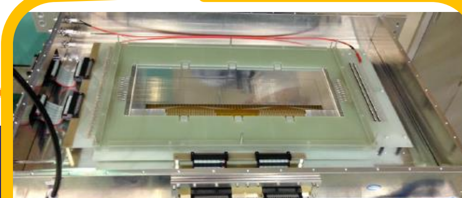


Initial analysis.

- Details in Phil's talk on Tuesday.

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





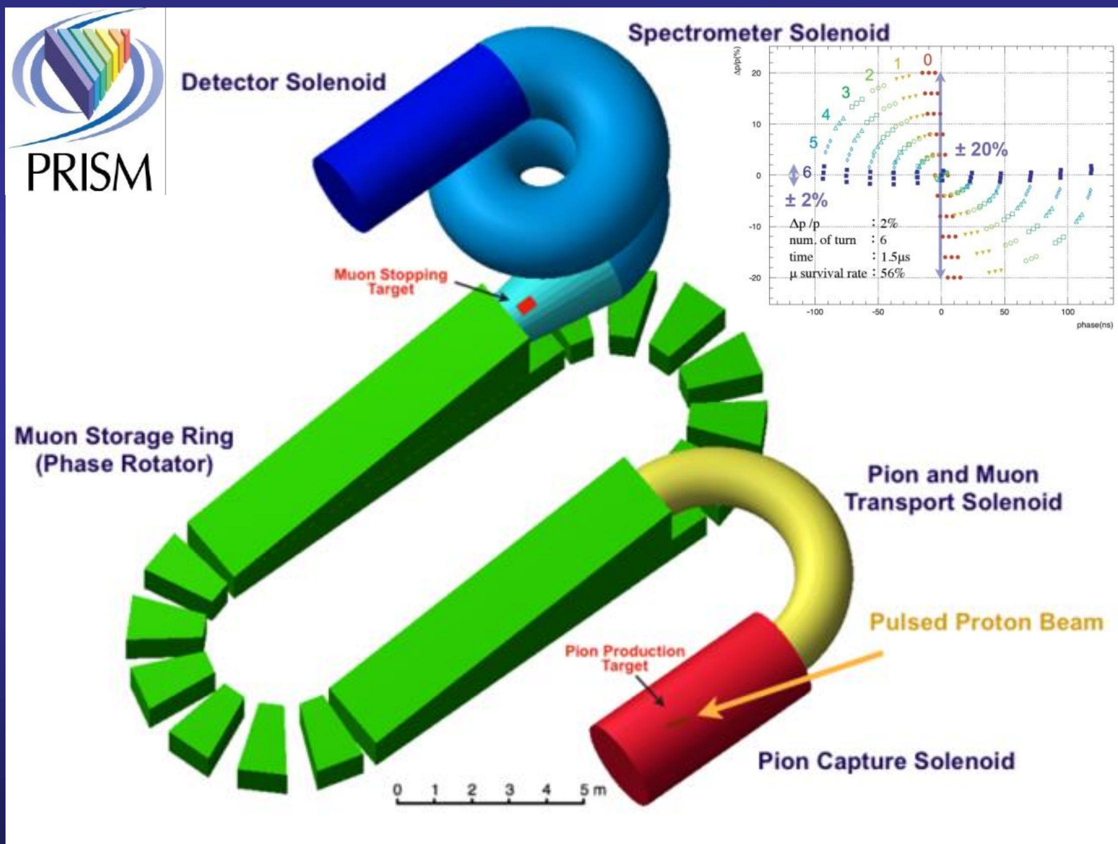
Prototype chamber

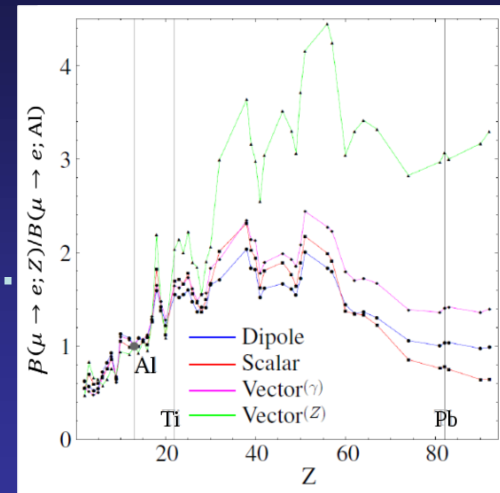
Spectrometer magnet shipped from TRIUMF.

- Details in Nakatsugawa-san’s talk on Tuesday.

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

- Phase Rotated Intense Source of Muons.
- Single event sensitivity $<10^{-19}$.
- Can look at different stopping target materials.

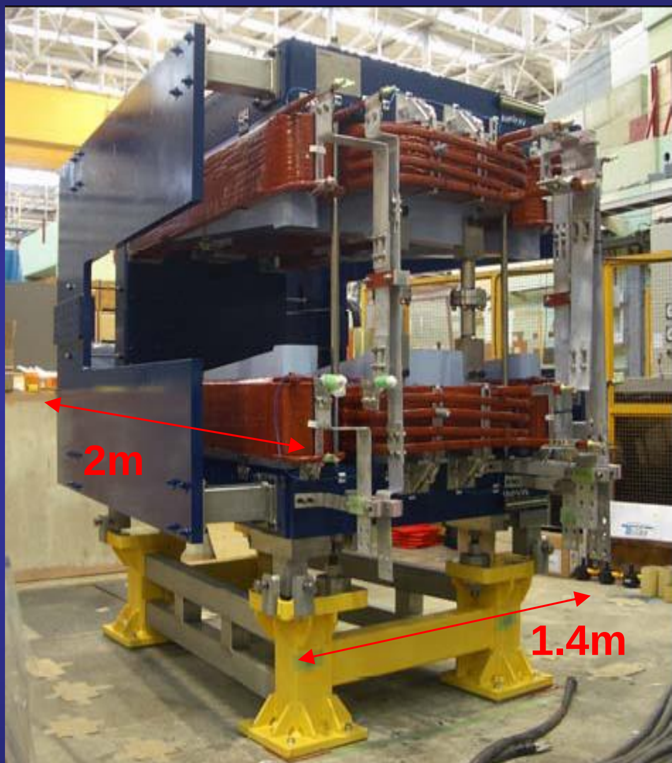




Cirigliano, Kitano, Okada and Tuzon, arXiv:0904.0957.

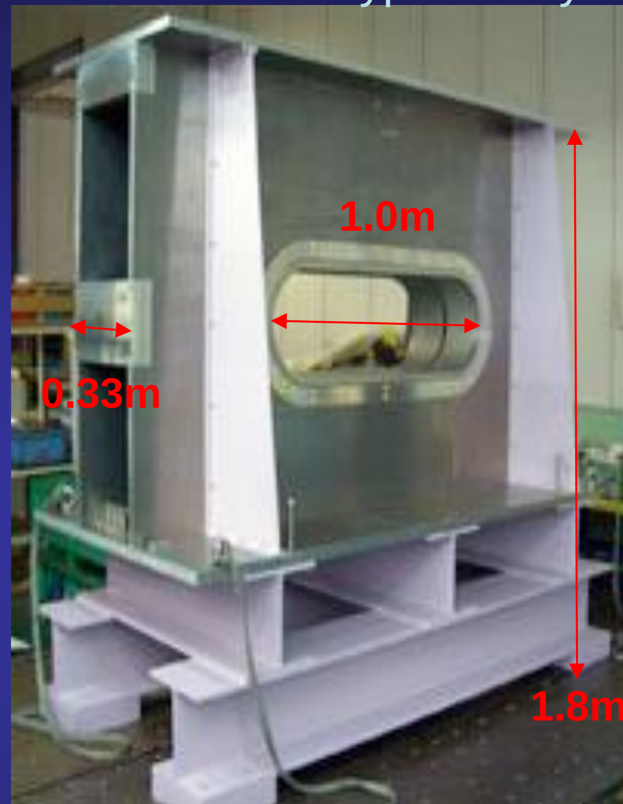
- Accelerator challenges:
  - Matching and injection to the ring.
  - High voltage, wideband RF cavities.
- PRISM task force addressing these issues.

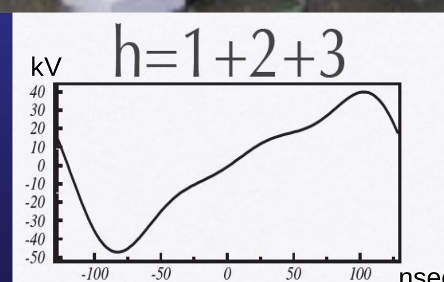
Accelerator Technology R&D



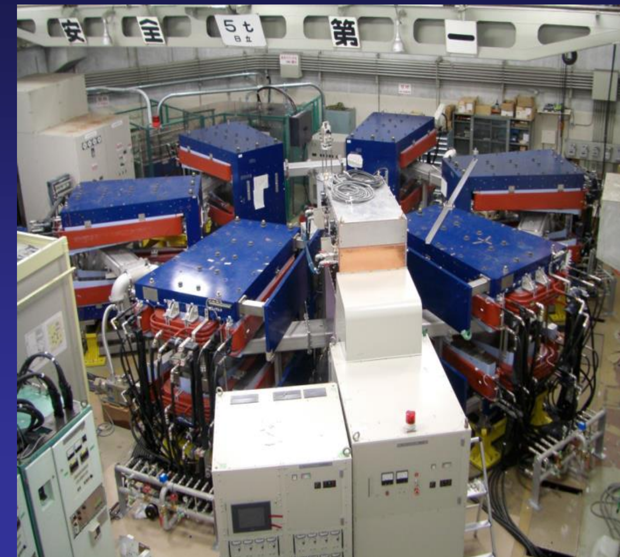
k=4.6 DFD triplet scaling FFAG magnet

PRISM Prototype Cavity

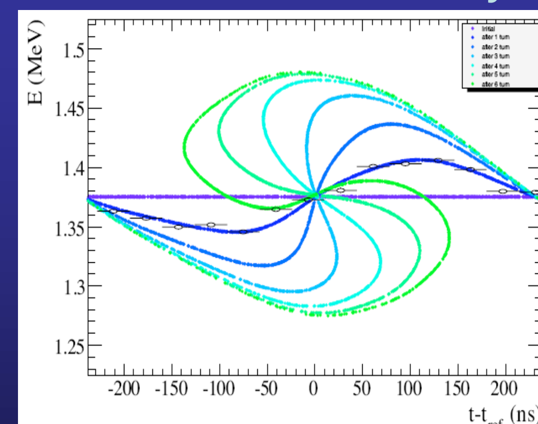




Sawtooth Approximation

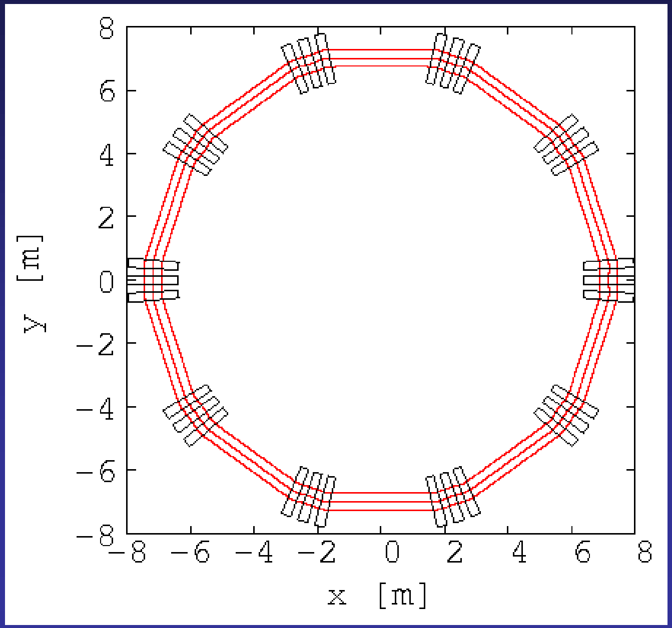


6-cell demonstration ring at RCNP, Osaka University.

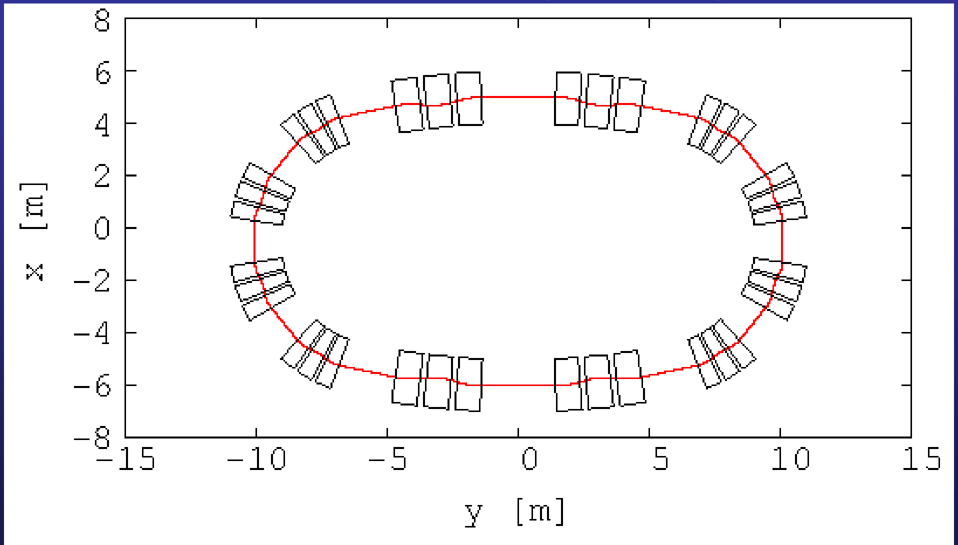


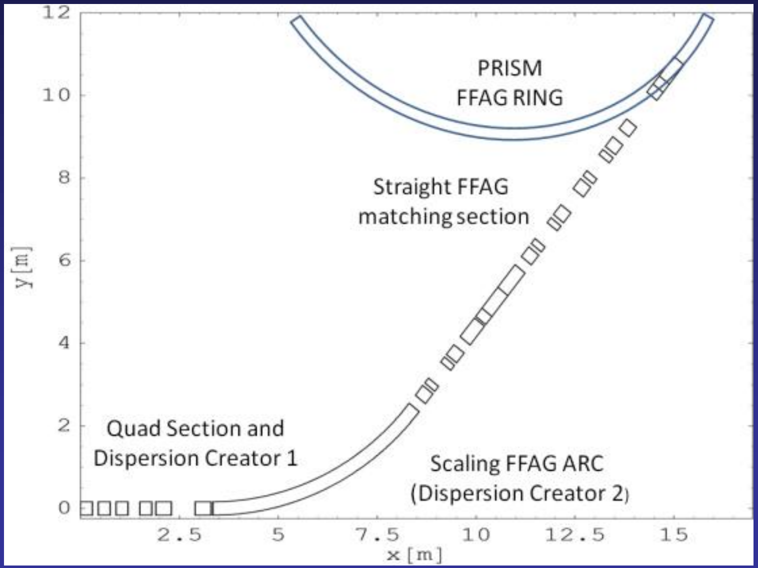
First demonstration of longitudinal phase rotation with an FFAG.

Simulation Studies

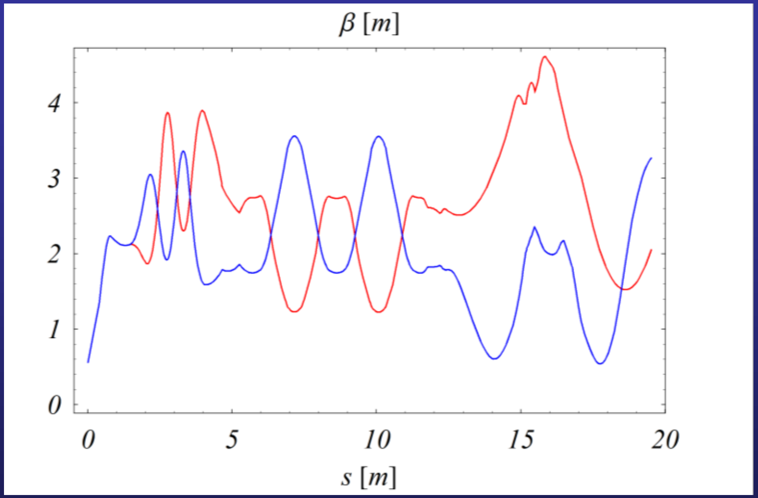


Alternative ring designs





Matching into the ring



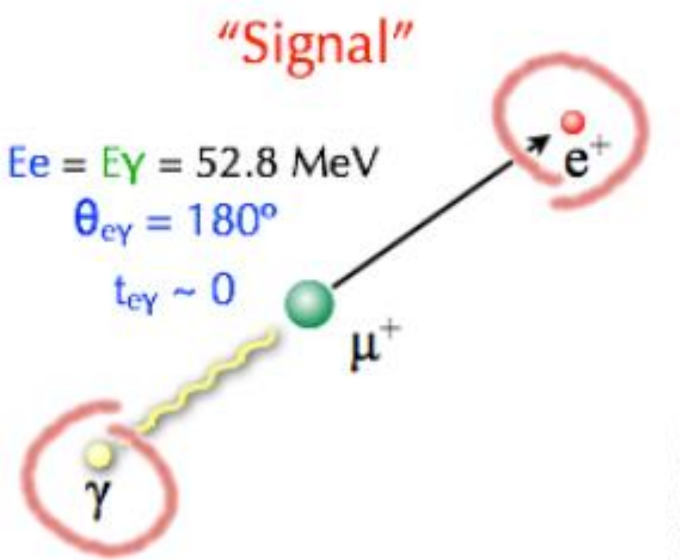
Horizontal (red) and vertical (blue) betatron functions in the PRISM front end.

$$\mu^{+} \rightarrow e^{+}\gamma$$

MEG

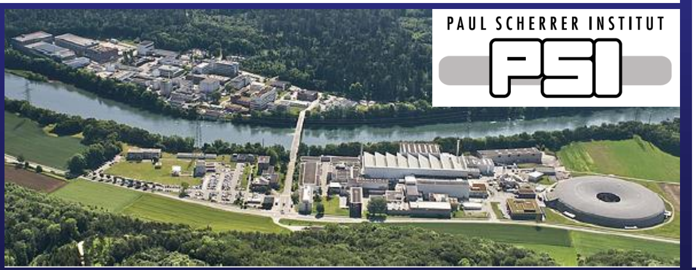
$\mu^+ \to e^+\gamma$: MEG

THE MEG EXPERIMENT



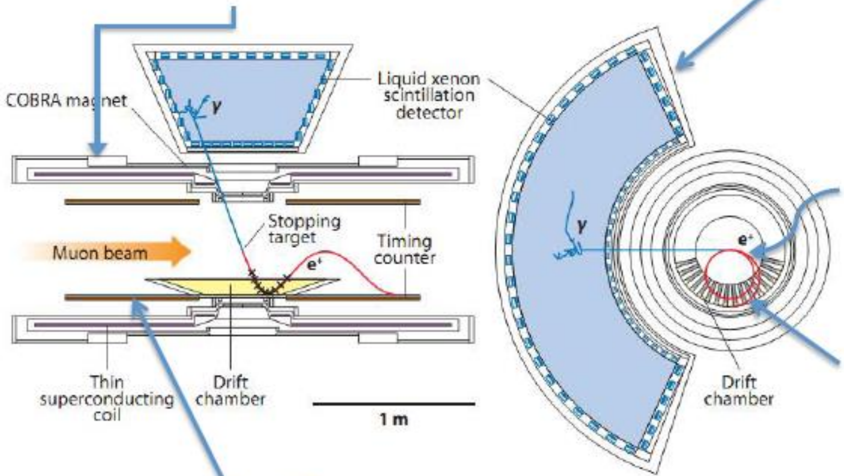
$P_\mu = 28\text{MeV/c}$

$I_\mu = 3 \times 10^7 \mu^+ \text{ stopped}/s$



MEG Detector Overview

Gradient magnetic field
(constant bending radius)



LXe gamma calorimeter

- Fast (6/22/45 ns)
- High LY and X_0

Thin CH_2 target (205 μm)

Low mass **drift chambers**
(2×10^{-3} X_0)

Timing counter

- Time of flight with plastic scintillator
- Scintillation fibers for fast hit detection

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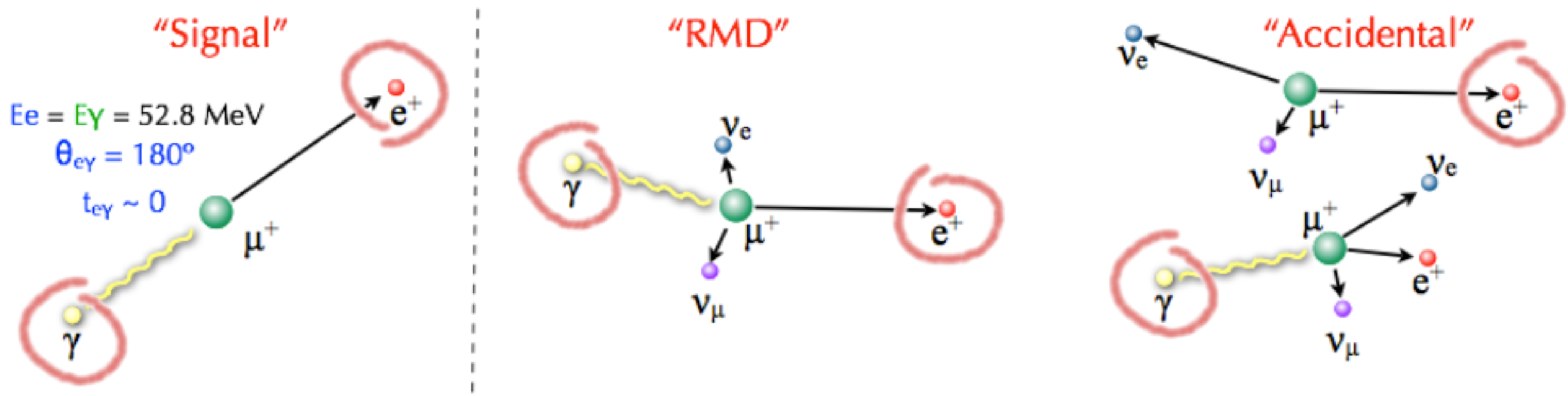
$\mu^+ \to e^+\gamma$: MEG

The μ → eγ decay



A straightforward decay channel:

- **Back-to-back** decay at rest with $E_e = E_\gamma = 52.8$ MeV
- **Dominated by accidental background** determined by muon beam rate and resolutions: $B_{acc} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$
- $\boldsymbol{B}_{\mathbf{RMD}} \approx 0.1\ \boldsymbol{B}_{\mathbf{acc}}$

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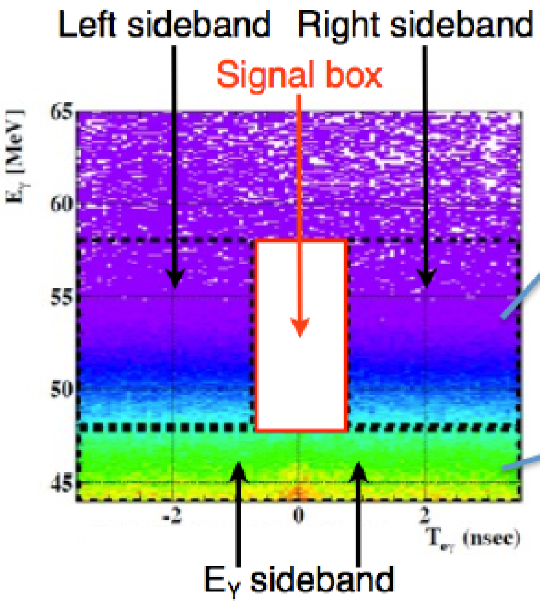
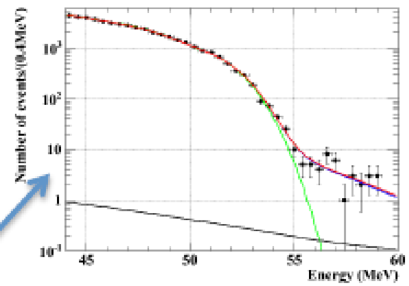
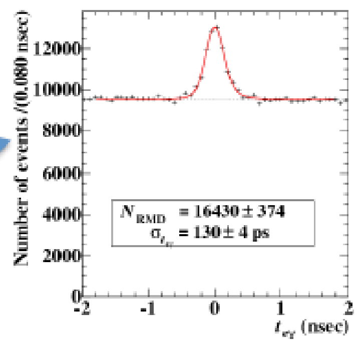
Analysis strategy: Blinding Box

- Events characterized by five observables **(E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$)**
- **Blinding box** left unopened
- **Resolutions** and **PDFs** evaluated outside signal region





Accidental background



RMD background

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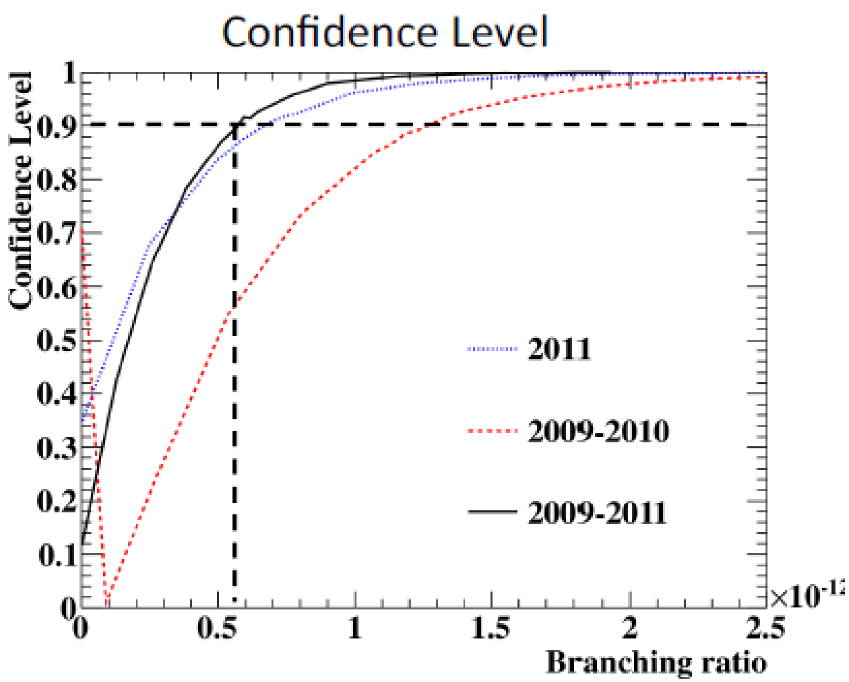
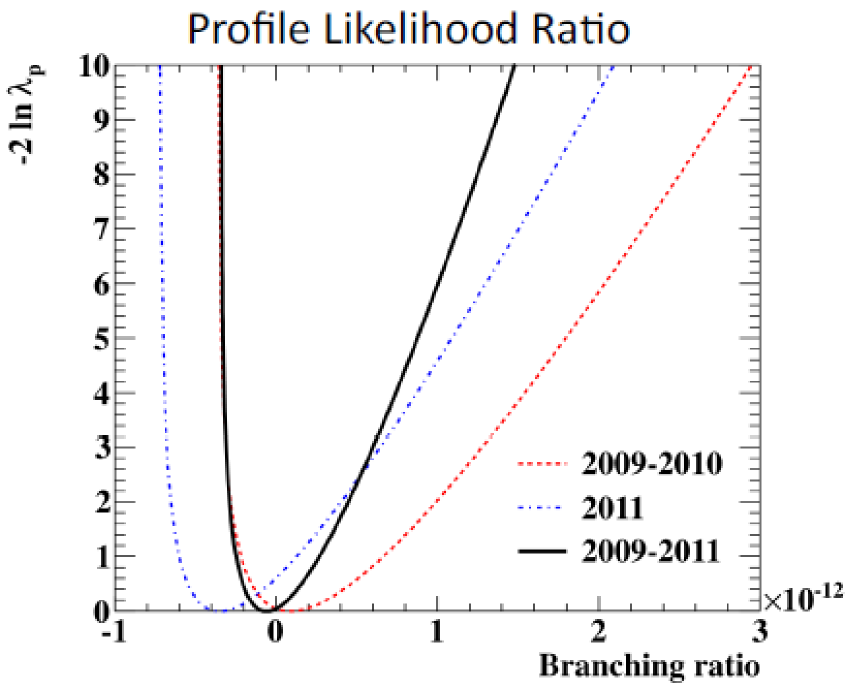
$\mu^+ \to e^+\gamma$: MEG

Most Recent Result (2009-2011)

J.Adam et al., Phys. Rev. Lett. 110, 201801 (2013)





BR (μ → eγ):

- Sensitivity: **7.7 x 10^{-13}**
- Upper Limit at 90% C.L.: **5.7 x 10^{-13}**

$\mu^+ \to e^+\gamma$: MEG-II

Upgrade Outline

- **Short term** upgrade aiming at a sensitivity of **5 x 10^{-14}** (10 times higher than MEG).
- **Use existing assets when possible!**
  - Cryostat, beamline, magnet, calibrations…
- Build on the **knowledge and expertise** of over a decade.

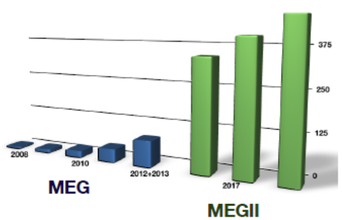
- Already approved and funded
- **Ongoing R&D**

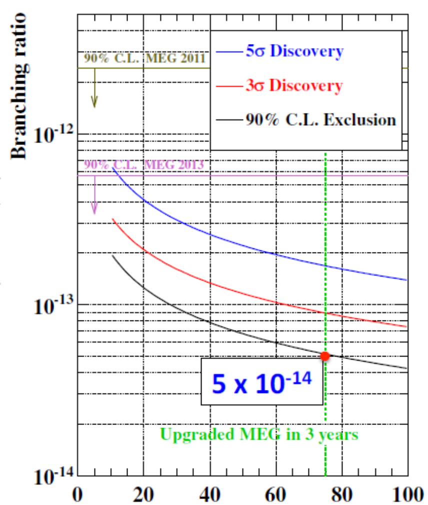
2013 2014 2015 2016 2017 2018 2019

Design | Construction | Eng.Run | Run | Run | Run

Sensitivity Expectations

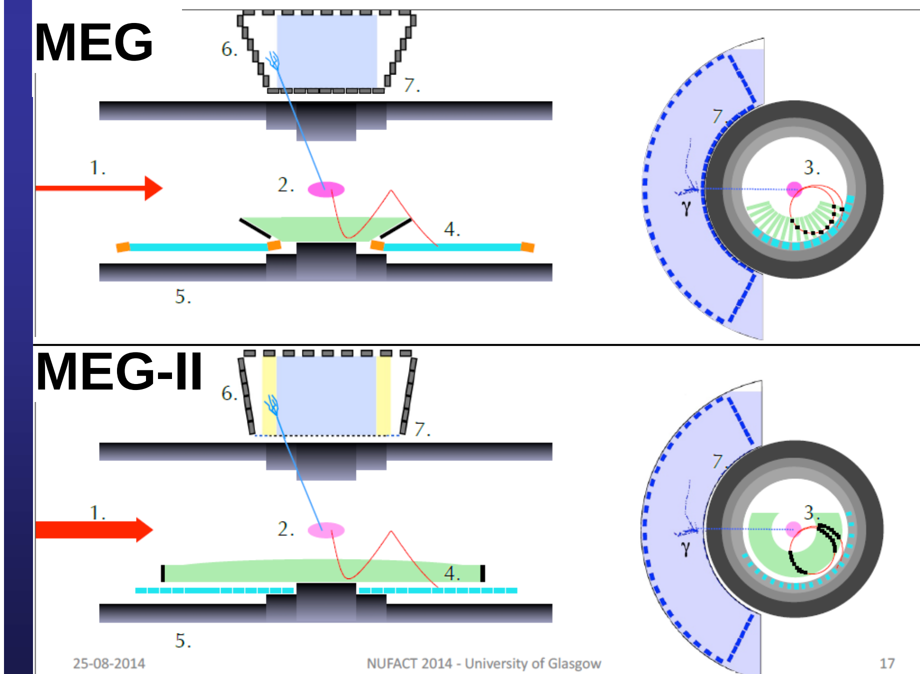
PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88



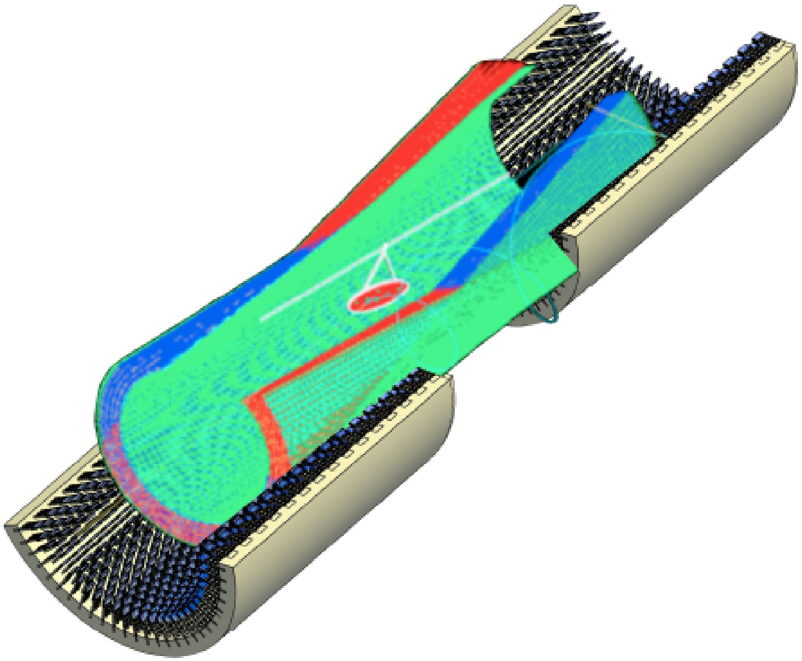


Key Upgrade Points

1. Increase **μ⁺ stopped** on target to **7 x 10^7 μ/sec.**
2. Reduced target thickness (**140 μm**).
3. New **positron tracker** with riduced radiation length, improved granularity and resolution.
4. Improved **positron tracking and timing integration**, by measuring the positron trajectory to the TC interface.
5. Improved timing counter **granularity** and **resolution** for improved **timing and reconstruction.**
6. Expanded calorimeter volume – **more uniform response** at edges.
7. Improved calorimeter resolution for **shallow events.**
8. Integrating **splitter, trigger and DAQ** while maintaining a high bandwidth.



Positron Spectrometer



- Single volume stereoscopic (7-8°) drift chamber
- Single cell: **7x7 mm²** (varies)
- Closer to the target for better track reconstruction
- Increased hits per track
- Low mass (**1.7×10^{-3} X_0**)
- **He/iC_4H_{10} (85:15)** gas mixture
- Ultra fast electronics (~1 GHz) for cluster timing

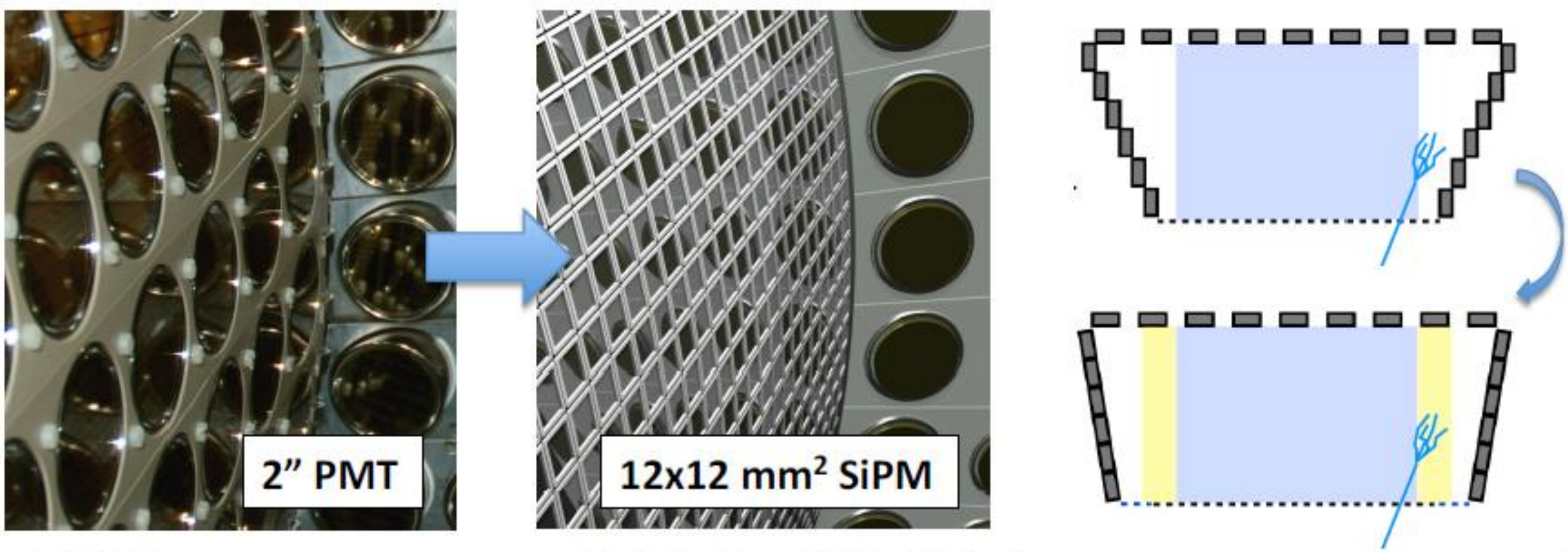
Expected performance from MC (assuming **120 μm** single hit resolution)

- Tracking efficiency: **> 85%**
- Momentum resolution: **130 keV**
- Angular resolution: **3.7 mrad (φ), 5.3 mrad (θ)**

$\mu^+ \to e^+\gamma$: MEG

Xenon Calorimeter

- Replacing 216 inner face PMTs with **specially developed VUV SiPM**
- Better detector **granularity**
  - Better **energy** and **position** resolution → $B_{\text{acc}} \approx R_\mu \Delta E_e \boxed{\Delta E_\gamma^2 \Delta\theta^2} \Delta t$
  - Reduced pile-up
- Less material in inner face: **9% more transparent** to 52.8 MeV gamma.
- Improved layout for lateral PMTs: **improved uniformity** at edges.



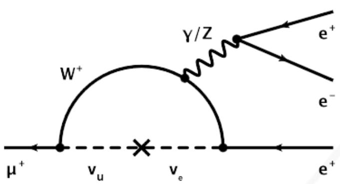
$$\mu^{+} \rightarrow e^{+} + e^{+} + e^{-}$$

Mu3e

$\mu^+ \to e^+ + e^+ + e^-$: Mu3e

$\mu \to$ eee in the Standard Model

3



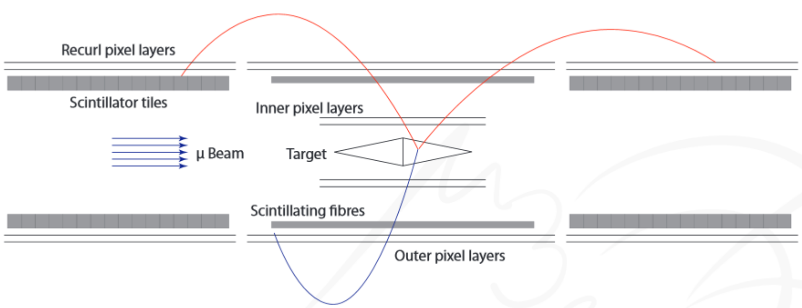
Features

- Charged lepton flavor violating
- Via neutrino mixing
- Expected BR($\mu \to$ eee) $\ll 10^{-50}$
- Current Limit from Sindrum
  BR($\mu \to$ eee) $< 1 \cdot 10^{-12}$ @90 % CL
  Nucl.Phys. B299(1)

Importance

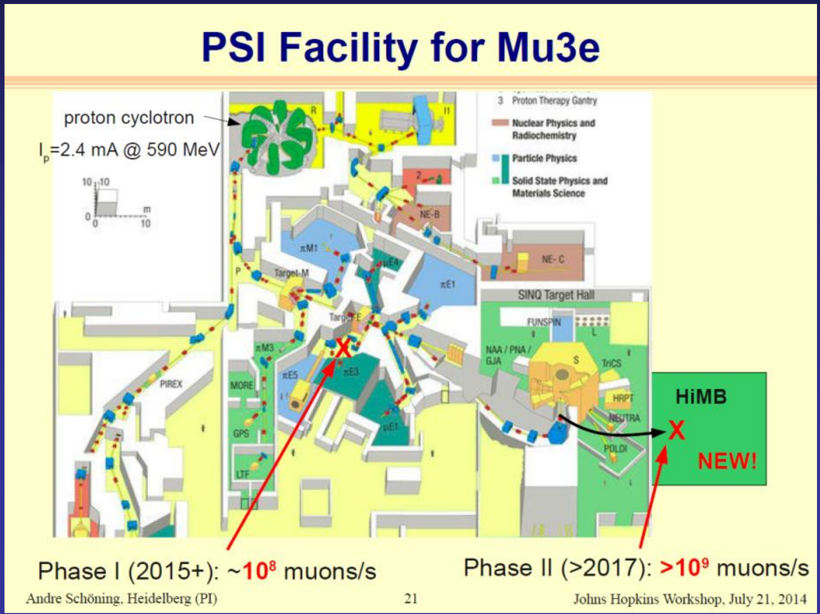
- Observable rate only from New Physics
- Sensitive New Physics Search

Detector Concept



Environment

- $> 10^9$ μ^+ Decays/s
- Electrons p $<$ 53 MeV
- Multiple scattering dominates



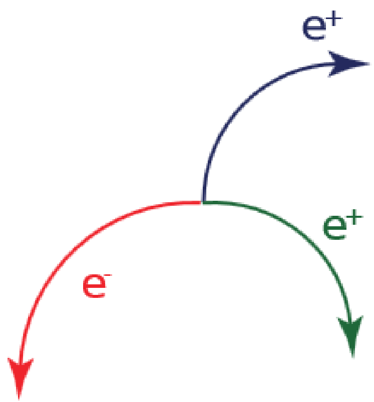
- Aim for sensitivity of 10^{-14} – 10^{-16}.
- Approved in Jan 2013.

$\mu^+ \rightarrow e^+ + e^+ + e^-$: Mu3e

Signal and Backgrounds

6

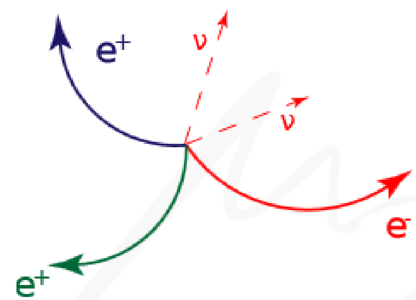
Signal



- Common vertex
- $\sum \vec{p}_i = 0$
- $p < 53\,\text{MeV}$

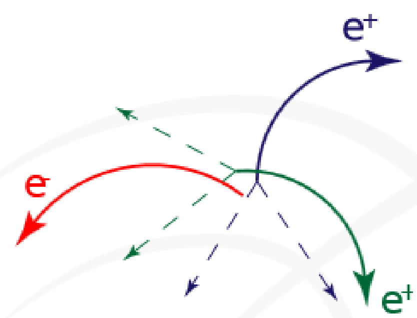
Backgrounds

Internal Conversion



- Common vertex
- $\sum \vec{p}_i \neq 0$
- In-time

Combinatorial



- No common vertex
- Out-of-time

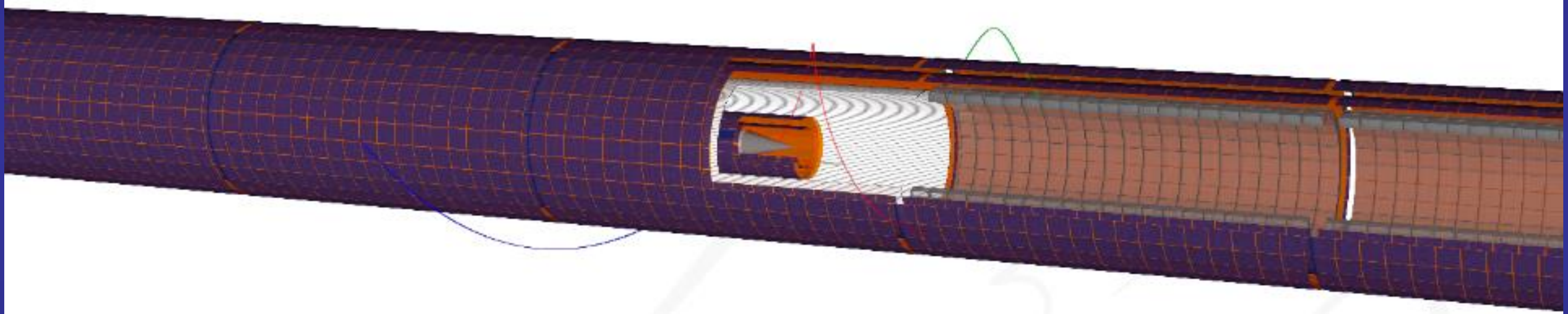
Requires $\sigma_p < 0.5\,\text{MeV}$
$\sigma_t < 1\,\text{ns}$

- Continuous beam is best to reduce combinatorial backgrounds.

$\mu^+ \rightarrow e^+ + e^+ + e^-$: Mu3e

Full Detector

Magnetic field $\sim 1\,\text{T}$
Continuous readout



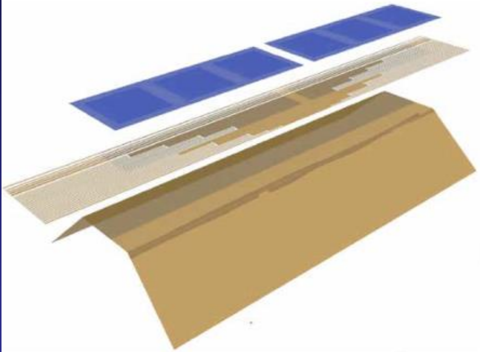
Tracker Requirements

- Fast serial readout $\sim 20\,\text{MHz}$
- Thin $< 1\,‰\,X_0$
- $80\,\mu\text{m} \times 80\,\mu\text{m}$ pixel
- $1\,\text{cm} \times 2\,\text{cm}$ sensor area

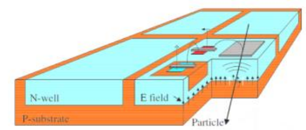
Timing

- Resolution $< 1\,\text{ns}$

$\mu^+ \to e^+ + e^+ + e^-$: Mu3e



Monolithic Active Pixel Sensors



I. Peric, P. Fischer et al. NIMA 582(2007)876

- HV ~ 70 V (HV-MAPS)
- Fast charge collection by drift
- Thin active zone < 20 µm
- Cheap, commercial process

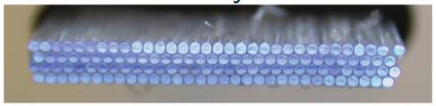
Pixel Tracker

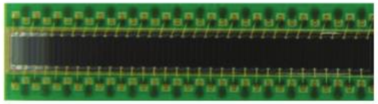
- 50 µm Silicon sensor
- 25 µm Kapton flexprint
- 25 µm Kapton support frame

→ ~ 1 ‰ Radiation length

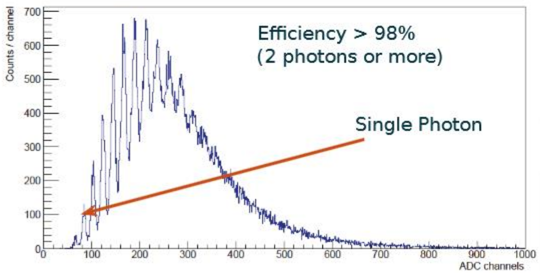
Scintillating Fibres

Fibre and SiPM Array





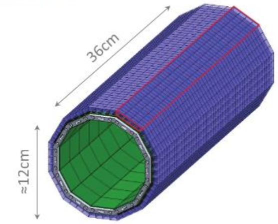
Signal Spectrum



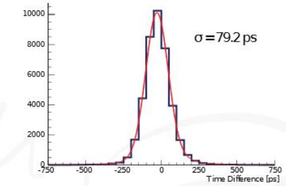
- 3-5 layers of fibres
- Readout with SiPM and custom ASIC (StiC)
- Time resolution ~ 1 ns (^{22}Na-source)

Scintillating Tiles

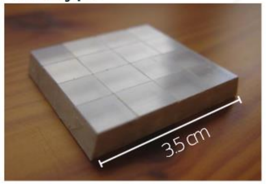
Tile Station



Time Resolution



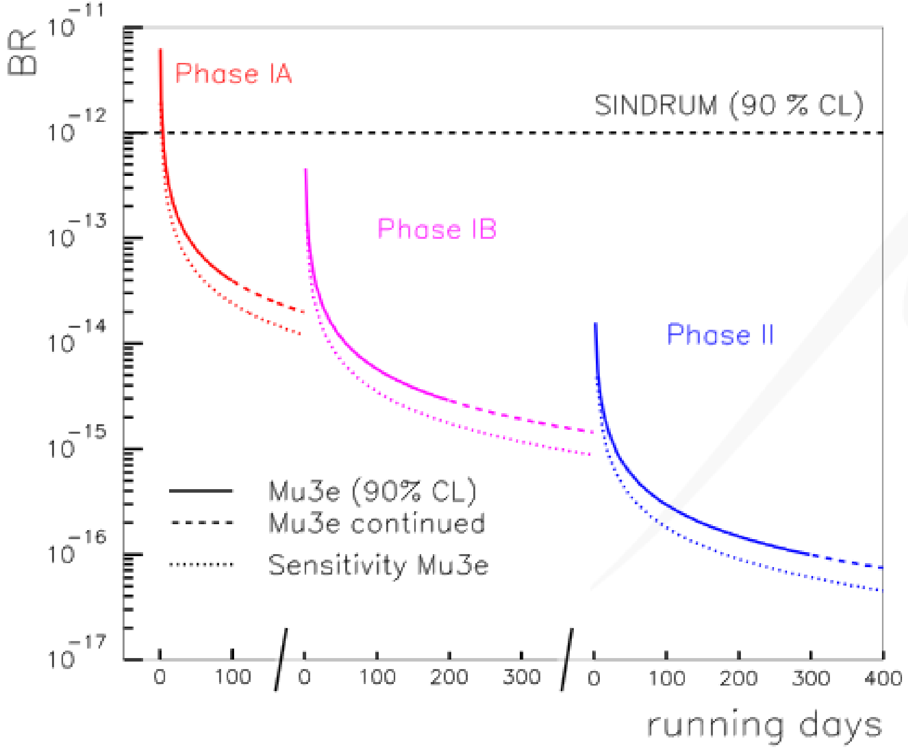
Tile Prototype



- ~ 0.5 cm^3 per tile
- Readout with SiPM and custom ASIC (StiC)
- Time resolution ~ 80 ps (testbeam)

$\mu^+ \rightarrow e^+ + e^+ + e^-$: Mu3e

Expected Sensitivity



Phase IA: earliest 2016

- $2 \cdot 10^7\ \mu/s$
- Central pixel layers

Phase IB: 2017+

- $1 \cdot 10^8\ \mu/s$

\+ Timing

\+ 1^{st} recurl stations

Phase II: 2019+

- $2 \cdot 10^9\ \mu/s$
- Full detector
- Future Muon Beamline

Summary

- Upcoming experiments will have significant improvements in sensitivity.
  - $\mu^+ \rightarrow e^+\gamma$: 10, MEG→MEG-II.
  - $\mu^+ \rightarrow e^+e^+e^-$: 10^3 for Mu3e.
  - $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: 10^4 for COMET and Mu2e.
- Future experiments such as PRISM can make use of advances in accelerator technology to deliver intense muon beams with a small energy spread.
  - Sensitivity $<10^{-18}$ for muon to electron conversion.
- Synergies with neutrino factory accelerator complex.
- Very exciting potential for discovering new physics!