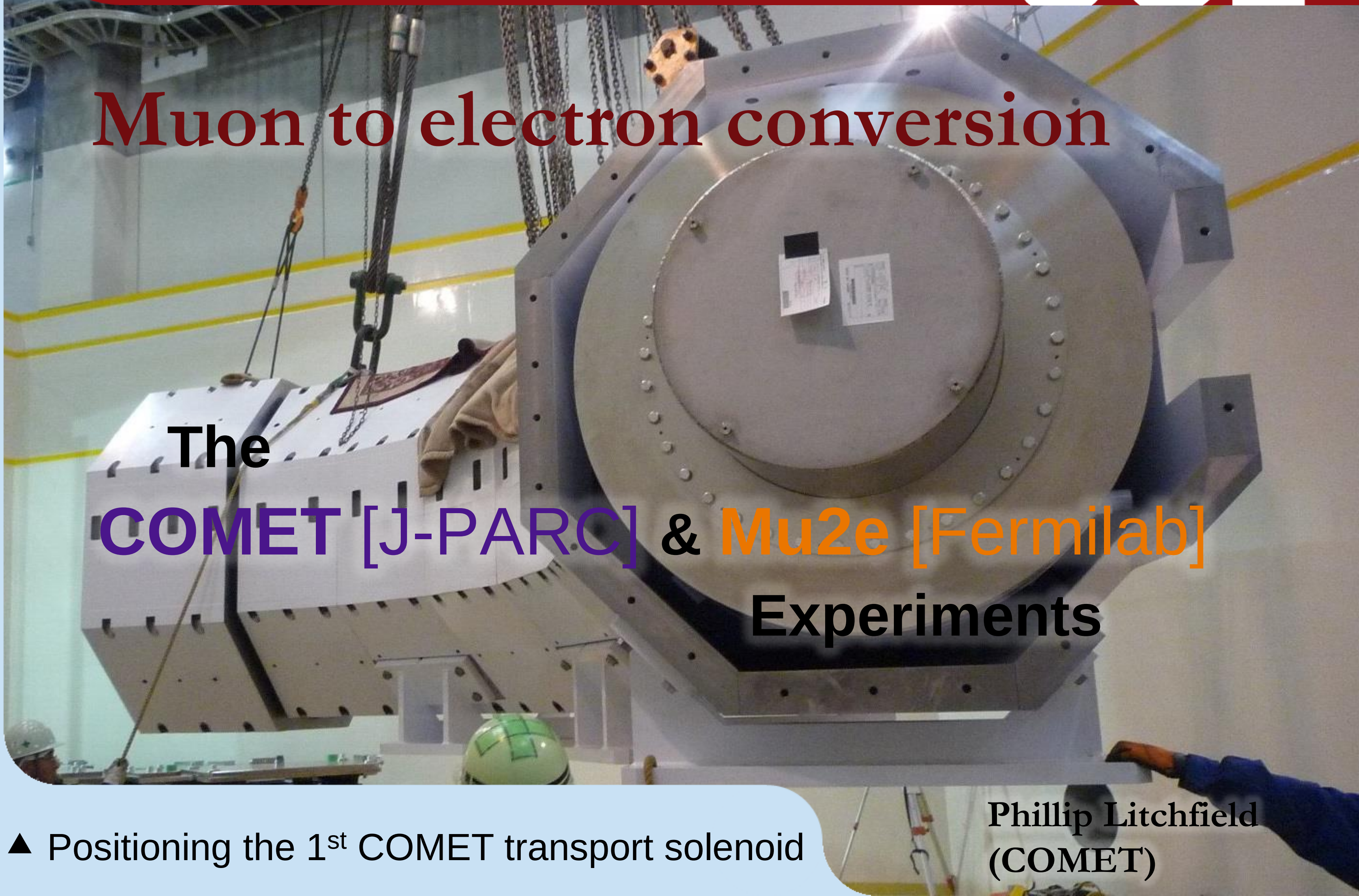
Muon to electron conversion

The COMET [J-PARC] & Mu2e [Fermilab] Experiments



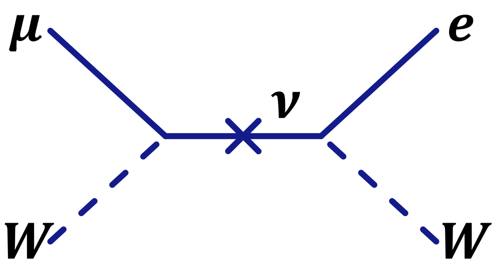
▲ Positioning the 1st COMET transport solenoid

Phillip Litchfield
(COMET)

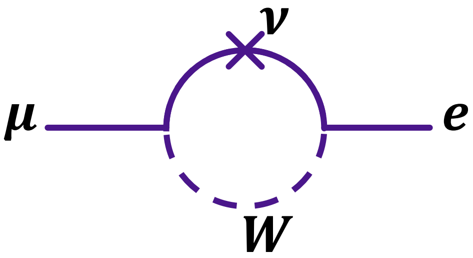
Charged lepton flavour violation

We already know that lepton flavour is not conserved

- Weak mixing mechanism & non-degenerate neutrino masses
- Neutrino (lack of) mass & charge means this is easiest to observe in neutrino oscillations, but can also lead to **CLFV**:



Neutrino oscillation



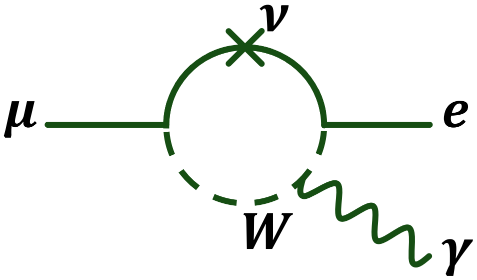
$\mu - e$ transition
(without radiation)

- The basic SM amplitudes can be related to the neutrino oscillation parameters, but requires some radiation to conserve energy & momentum.
- The $\mu - e$ system is particularly simple because the radiated ‘mass’ must be neutral, and lighter than a muon.

Options for decaying muons

The most obvious candidate for the transition to radiate is a photon, and the branching ratio is:

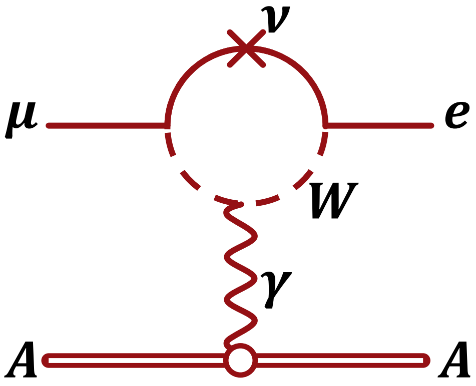
$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim O(10^{-54})$$



$\mu \to e\gamma$ (see note)

For a free muon, γ (or ee) is the only option…

…but in a muonic atom the radiation can be virtual
The nucleus absorbs it, and recoils slightly.



$\mu - e$ conversion

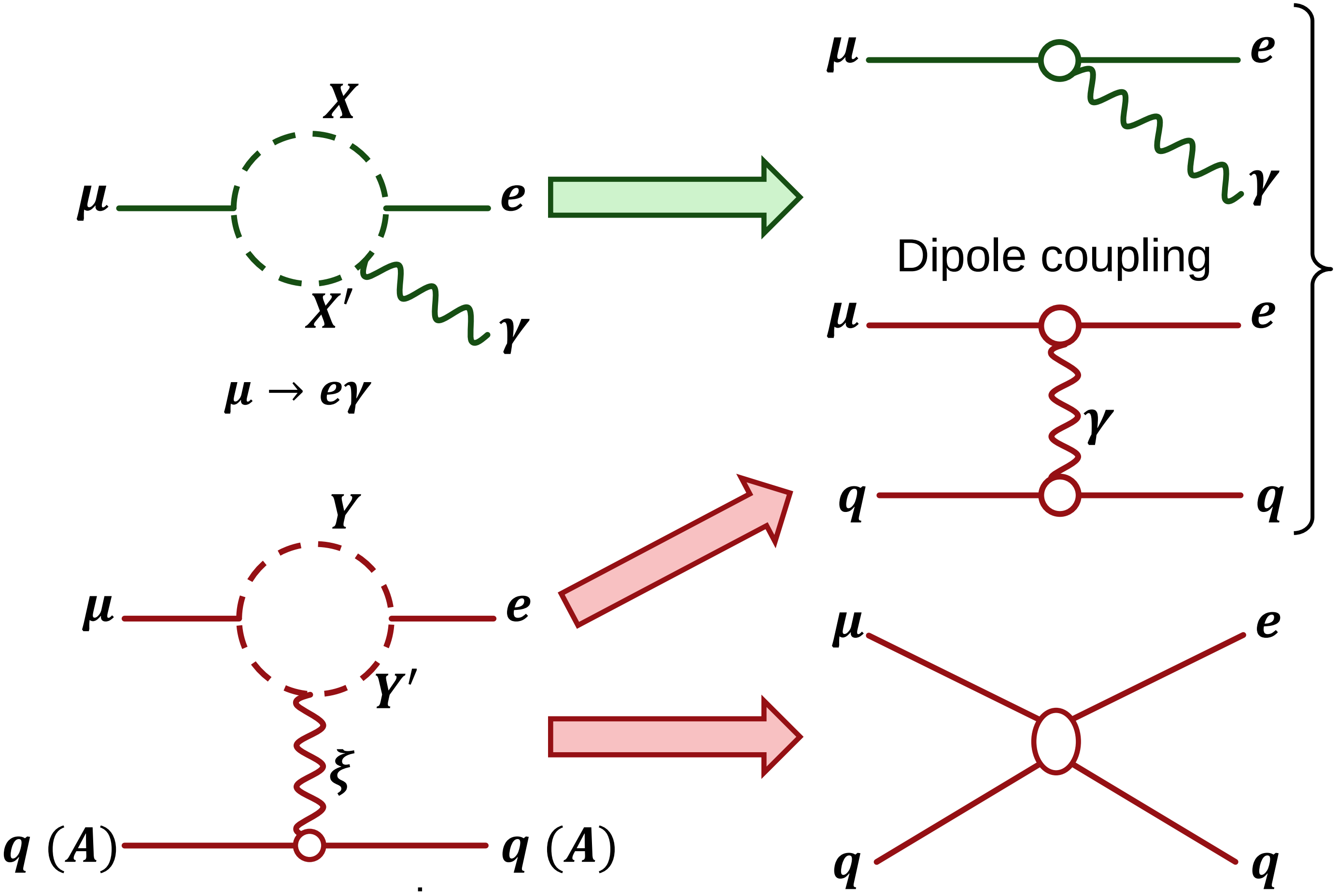
- Because of the relatively large nuclear mass, the electron is effectively mono-energetic.
- Because the process does not require a ‘real’ photon, other diagrams are possible…

Note: The γ can connect anywhere, not just in the loop

New physics

Similar processes exist in a wide variety of new physics scenarios.

- Muon decay is at low energy, so reduce to effective operators:



$\mu \to e\gamma$

Dipole coupling

$\mu - e$ conversion

Four-fermion coupling

$$\mathcal{L}_{\mathrm{d}} \sim \frac{m_\mu}{\Lambda^2}\ \bar{\mu}\sigma_{\mu\nu}e \cdot F^{\mu\nu}$$

$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2}\ \bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q$$

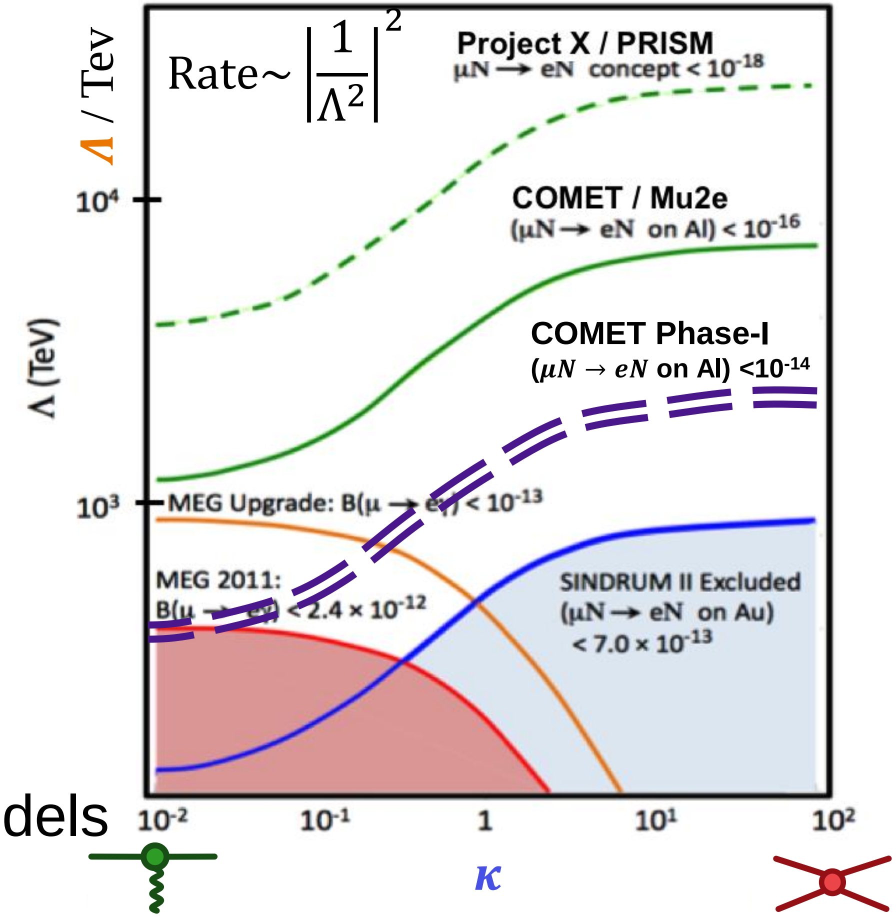
$\mu N \to eN$ and $\mu \to e\gamma$

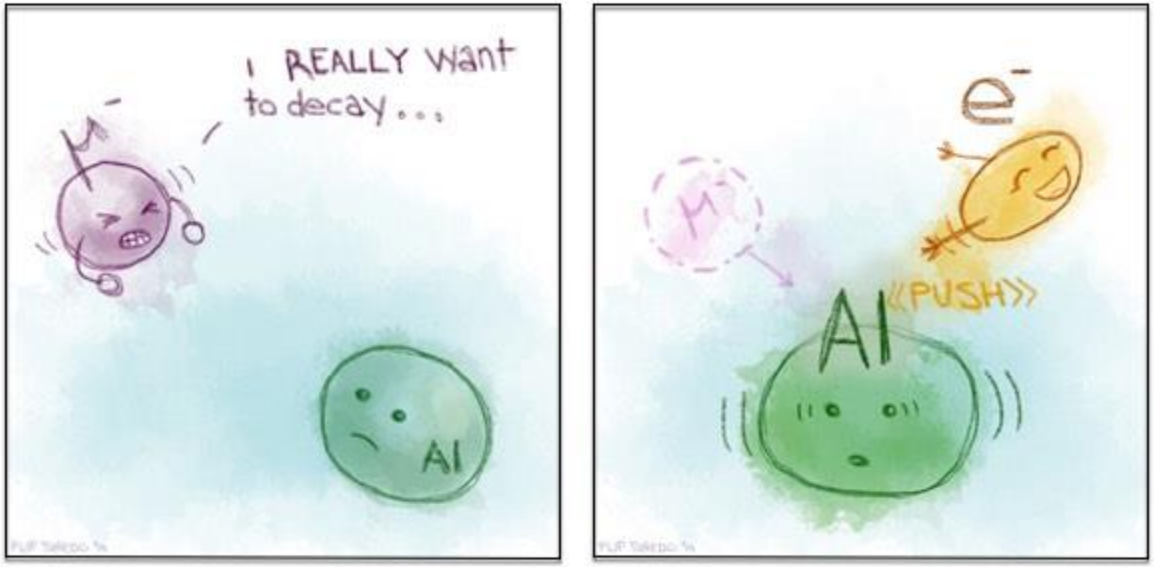
$$\mathcal{L}_{\mu e} \sim \frac{1}{\Lambda^2}\left[\frac{1}{\kappa+1} m_\mu \bar{\mu}\sigma_{\mu\nu} e \cdot F^{\mu\nu} + \frac{\kappa}{\kappa+1}\bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q\right]$$

- New physics → CLFV in rare muon decays.
- Energy scale Λ affects the rate of all such processes.
- Parameter κ depends on the nature of the new physics

Both $\mu \to e\gamma$ and $\mu - e$ conversion are sensitive to dipole terms, but $\mu - e$ conv. is also sensitive to 4-femion terms.

- More sensitive to some models.
- (If signal seen) the comparison allows discrimination between models





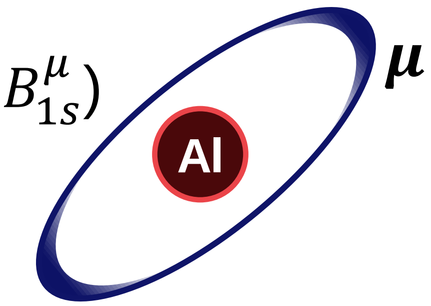
Basics of a (modern) $\mu - e$ conversion experiment

Cartoon: Flip Tanedo `http://www.particlebites.com/`

Muon decays

Muons allowed stop in suitable target.

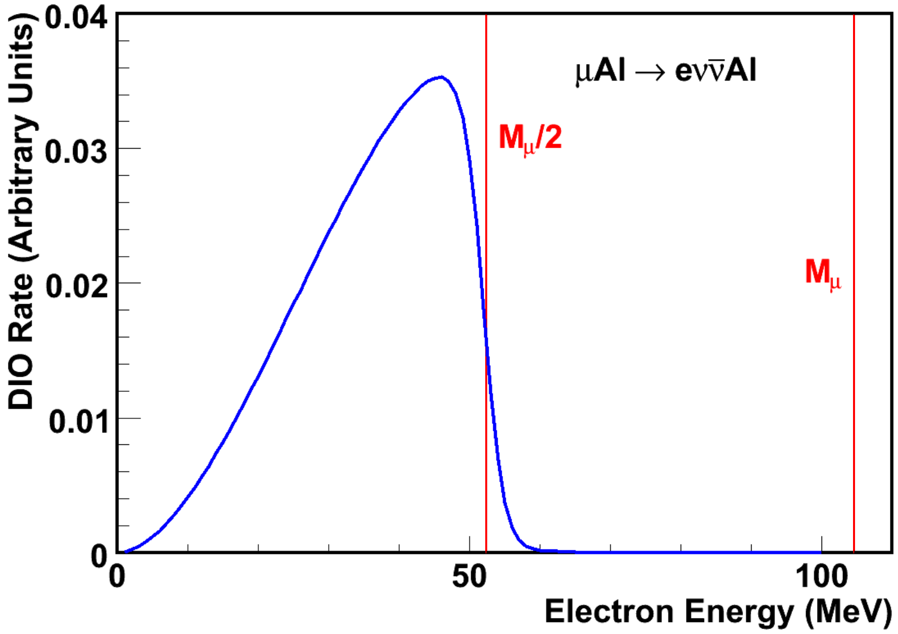
- Initially **Aluminium**, but other materials (Ti) under study.
- Conversion from 1s orbital: $\mu N \to eN$ gives a ***mono-energetic electron*** at 105MeV ($\approx m_\mu - B^{\mu}_{1s}$)



'Normal' decays are backgrounds

- Nuclear muon capture: $\mu N(Z) \to \nu N(Z-1)$
- **Decay in Orbit [DIO]:**
  $\boldsymbol{\mu N \to e\nu\bar{\nu}N}$

  For a free muon, cuts off at $\frac{1}{2}m_\mu$, but bound state has a small tail up to m_μ



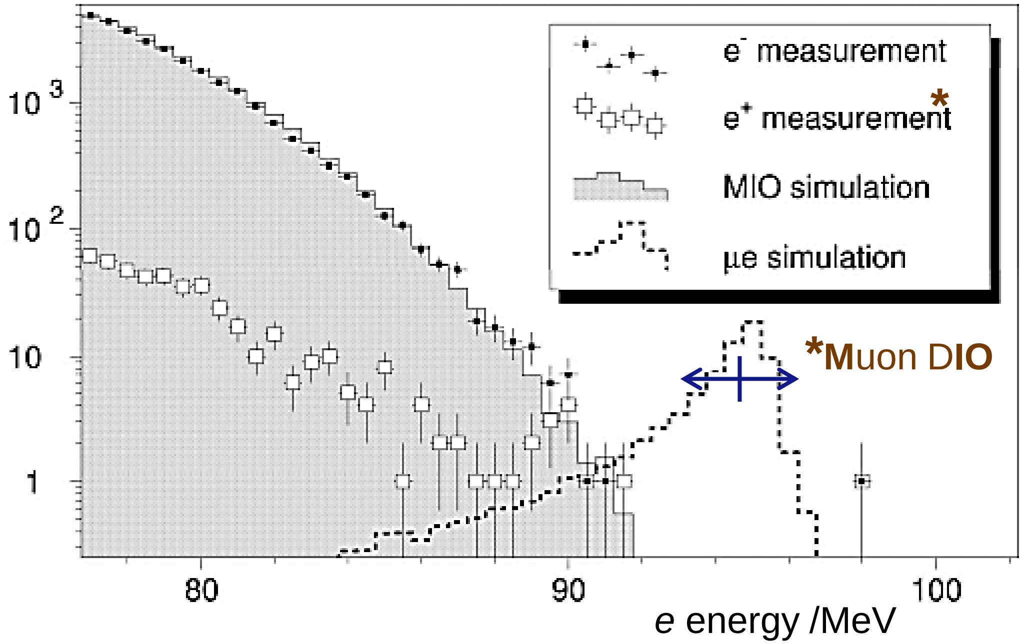
Backgrounds

Three main background processes:

- **Decay in orbit**, as before ▶ **Energy resolution!**

- **Decay in flight**: Electrons from energetic free muons can be boosted to 105MeV.
  - – Use momentum selection in muon transport (see later)

Results from SINDRUM-II (BR <7 $\times 10^{-13}$ @ 90%CL)



*Muon DIO

- **Beam backgrounds**: Significant number of prompt e^- and π^- produced by beam. Can eliminate this with timing *if* we have reliably beam-free time windows.

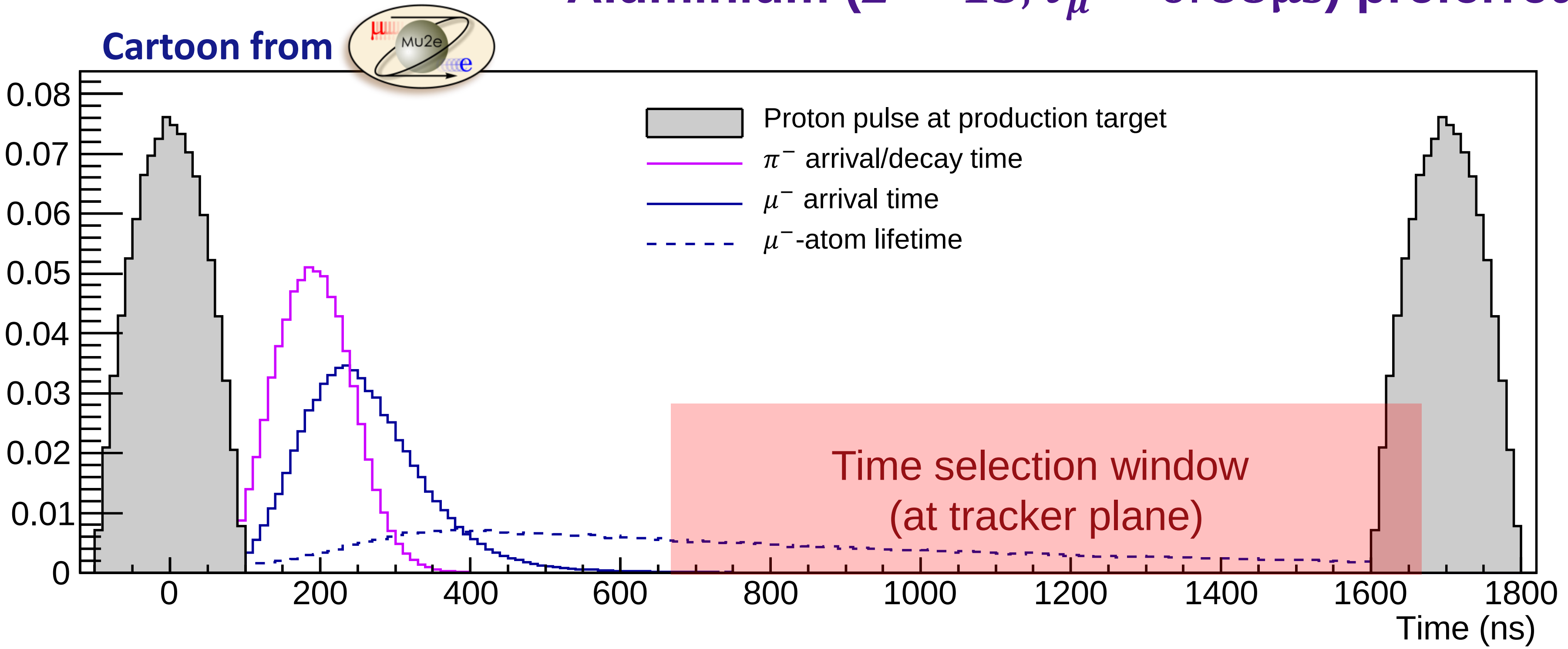
Beam-free windows?

Naïvely, this sounds easy, but…

- High intensity pulsed muon beams are uncommon → new facilities
- Need $\tau_\mu \gg \sigma_{\text{Pulse}}$ so choose stopping targets with long lifetime
  ↳ low Z, conflicts with high A preferred for coherent signal.

Aluminium ($Z = 13, \tau_\mu = 0.88\mu s$) preferred

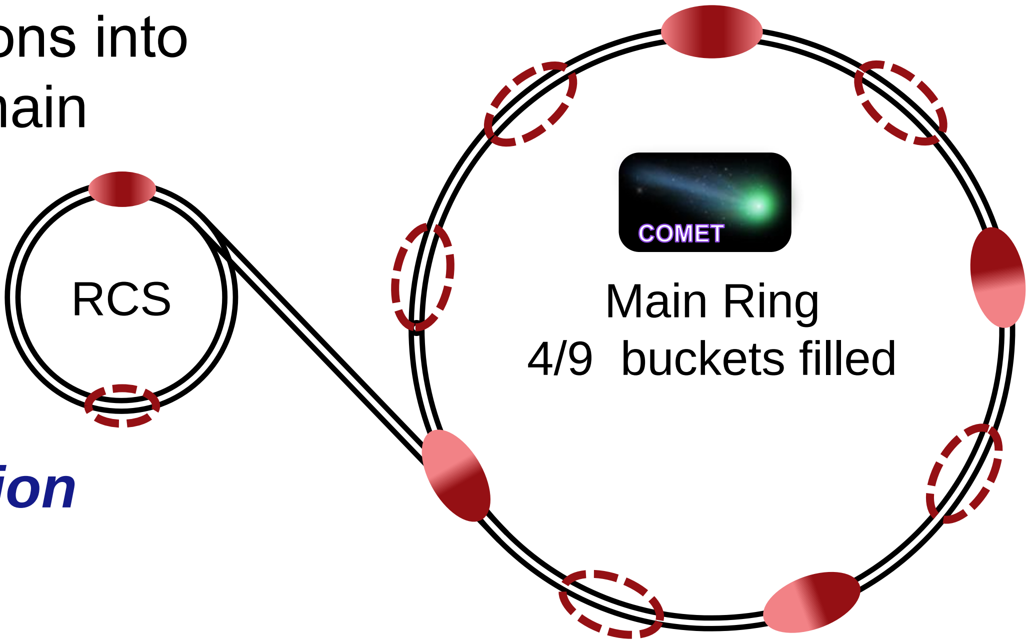
Cartoon from



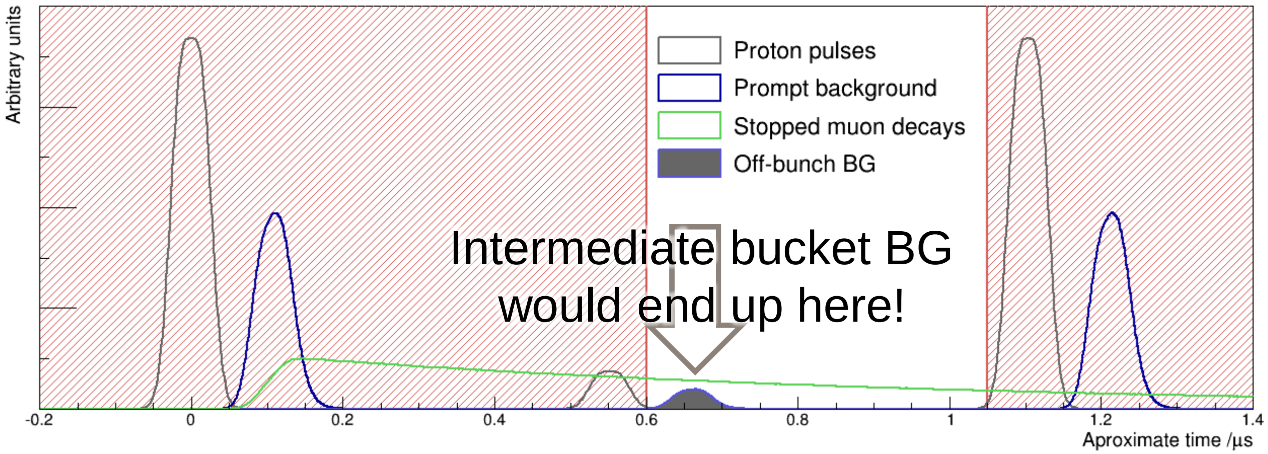
Really beam-free windows?

Synchrotrons have stable acceleration buckets

- Even if you don’t inject protons into them, stray protons can remain in stable acceleration.



The signal process is rare, so requirements on the ***extinction*** between pulses is very strict

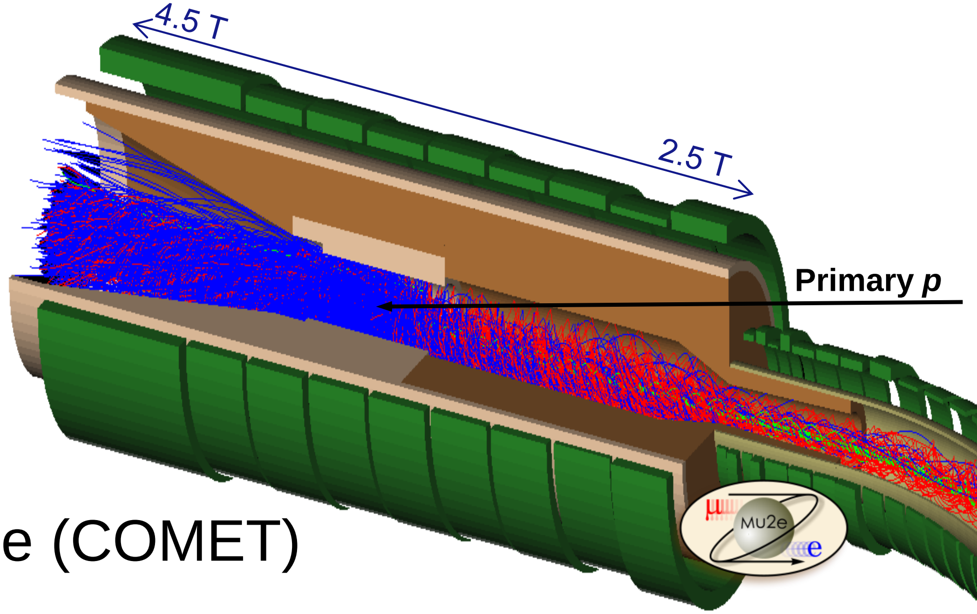


Intermediate bucket BG would end up here!

Muon source

Main driver of sensitivity: Need lots of low energy muons!

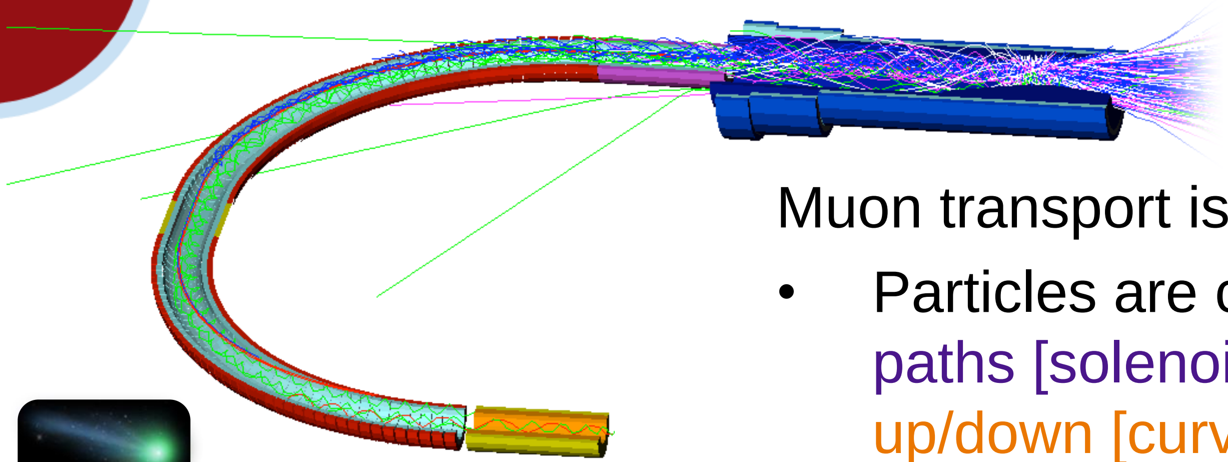
- Use dedicated high-power *pulsed* proton beam lines (~8 GeV)
- Resonant slow extraction onto pion production target



- Collect *backward*-going pions with capture solenoid
- Can use gradient field to reflect low-energy forward pions. (Mu2e ▶)
- Maximise field at target to give larger solid angle apperture (COMET)

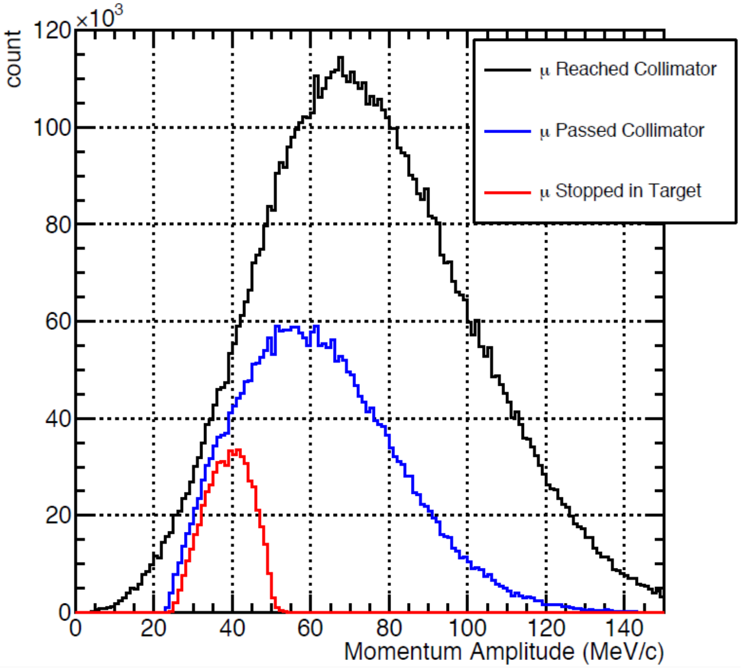
- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. The curved transport line helps to eliminate direct line-of sight.

Muon transport

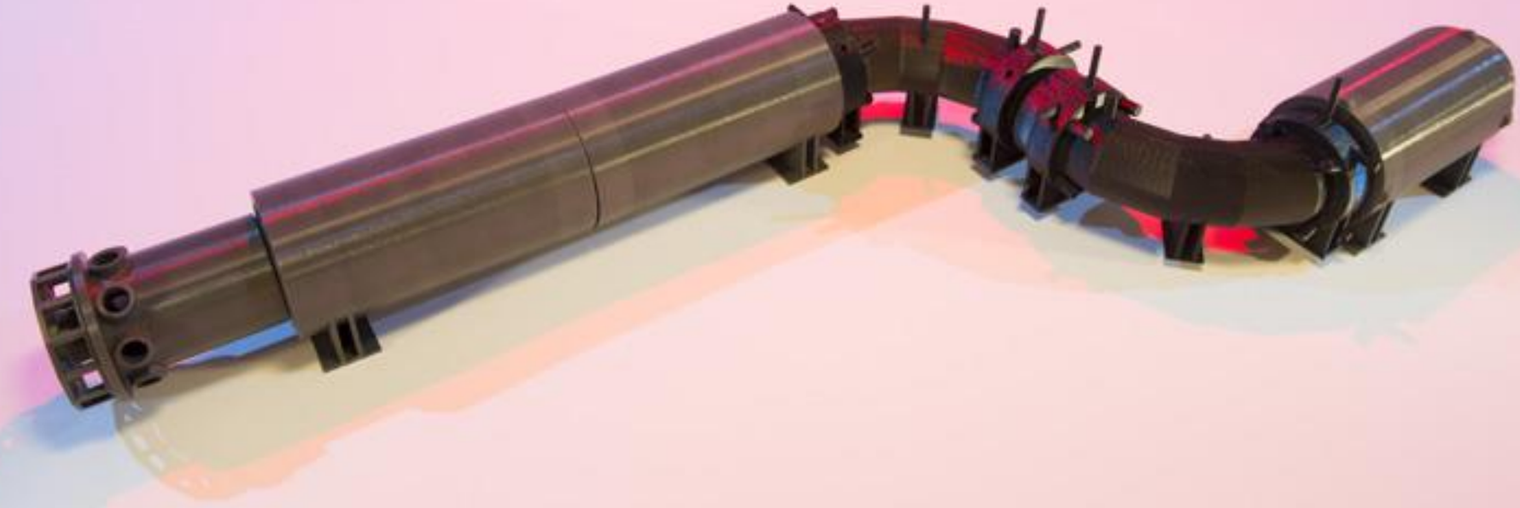


Muon transport is a curved solenoid

- Particles are channelled in spiral paths [solenoid], which naturally tend up/down [curvature] depending on momentum and charge
- Gives charge sign and momentum selection, which can be enhanced by using a collimator.
- Use to eliminate high momentum muons, other particles.
- Eliminates line-of-sight from production target

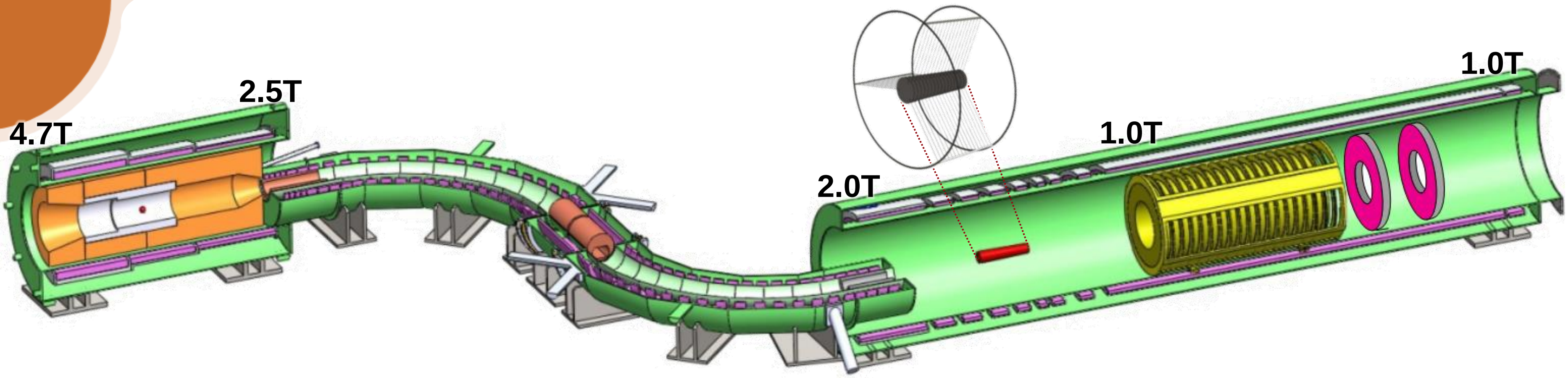


Mu2e



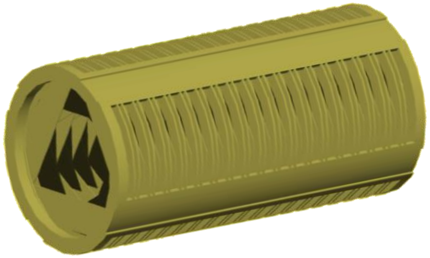
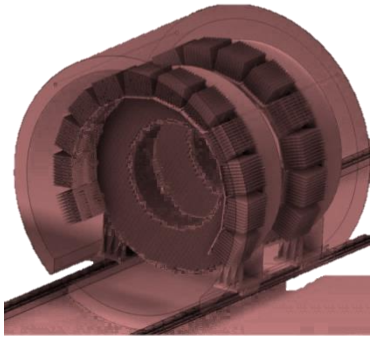
▲ 3D printed model of Mu2e solenoids

Mu2e overview



- S-shape and off-centre collimators that can rotate for BG studies
- Stopping **target** is 17 × 0.2mm Al foils

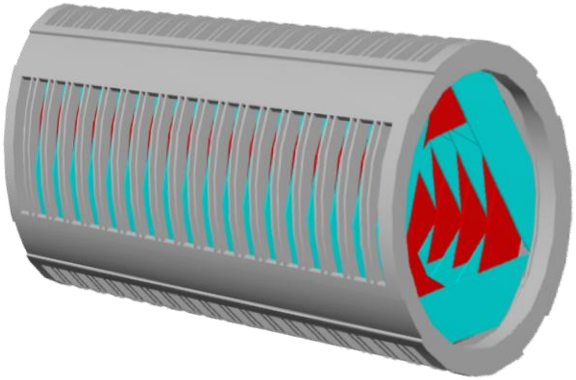
- Target & detector surrounded by solenoid
  - Electron transport
  - Magnetic mirror

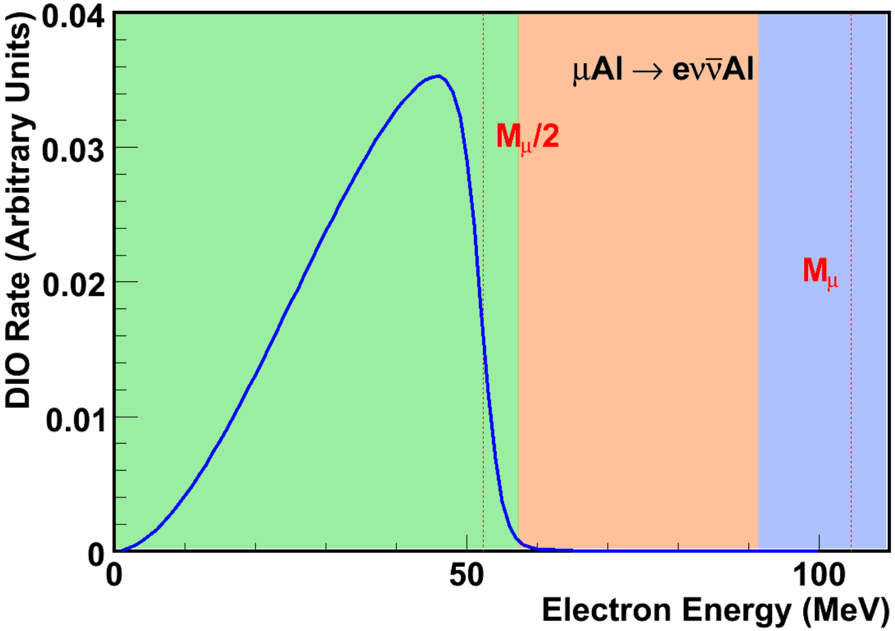



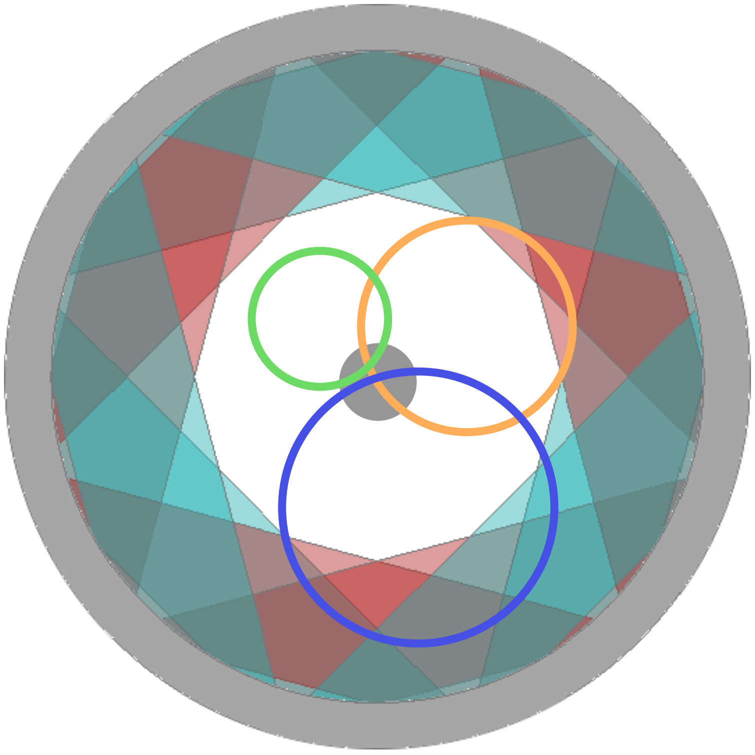
- Electrons spiral from target to **tracker** and **EM calorimeter**

Mu2e Tracker

- Tracker made from straw tubes to measure particle momentum
- Minimum radius of 380mm corresponds to momentum ~ 60MeV
- ‘Complete’ tracks need mom > 90 MeV

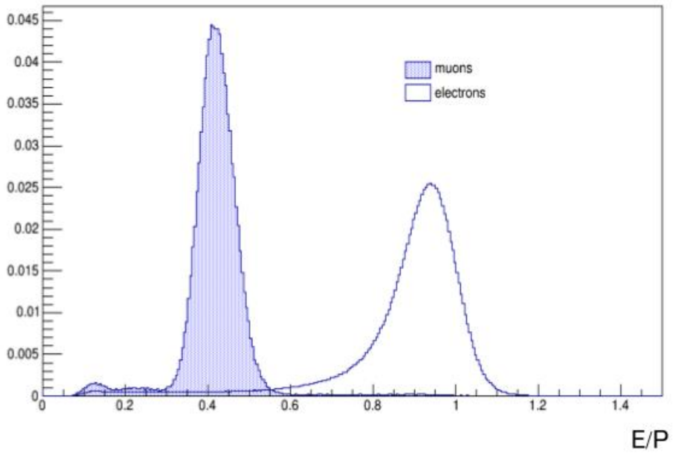


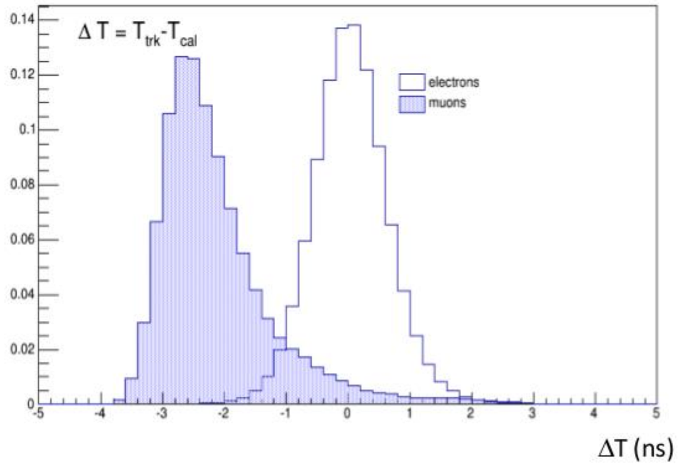


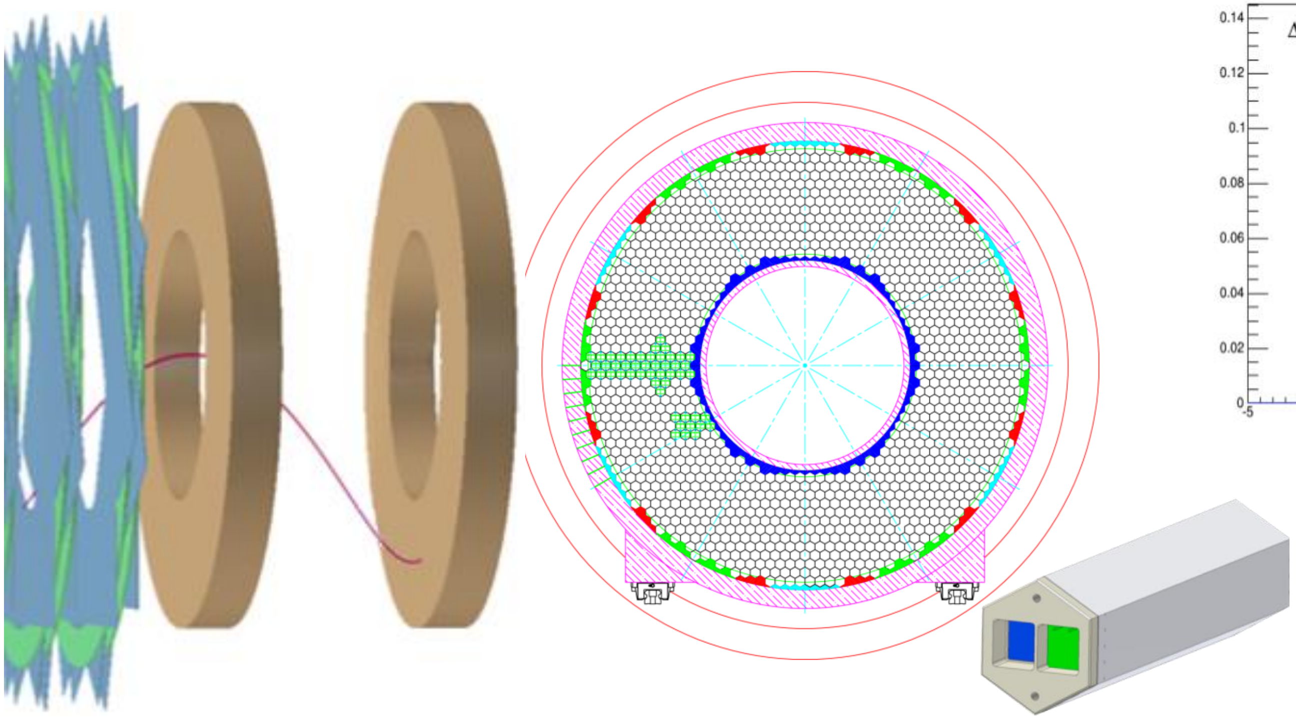


Mu2e calorimeter

- Inorganic scintillator crystals
- Provides fast response for trigger
- Energy measurement combined with momentum from tracker gives excellent μ/e discrimination







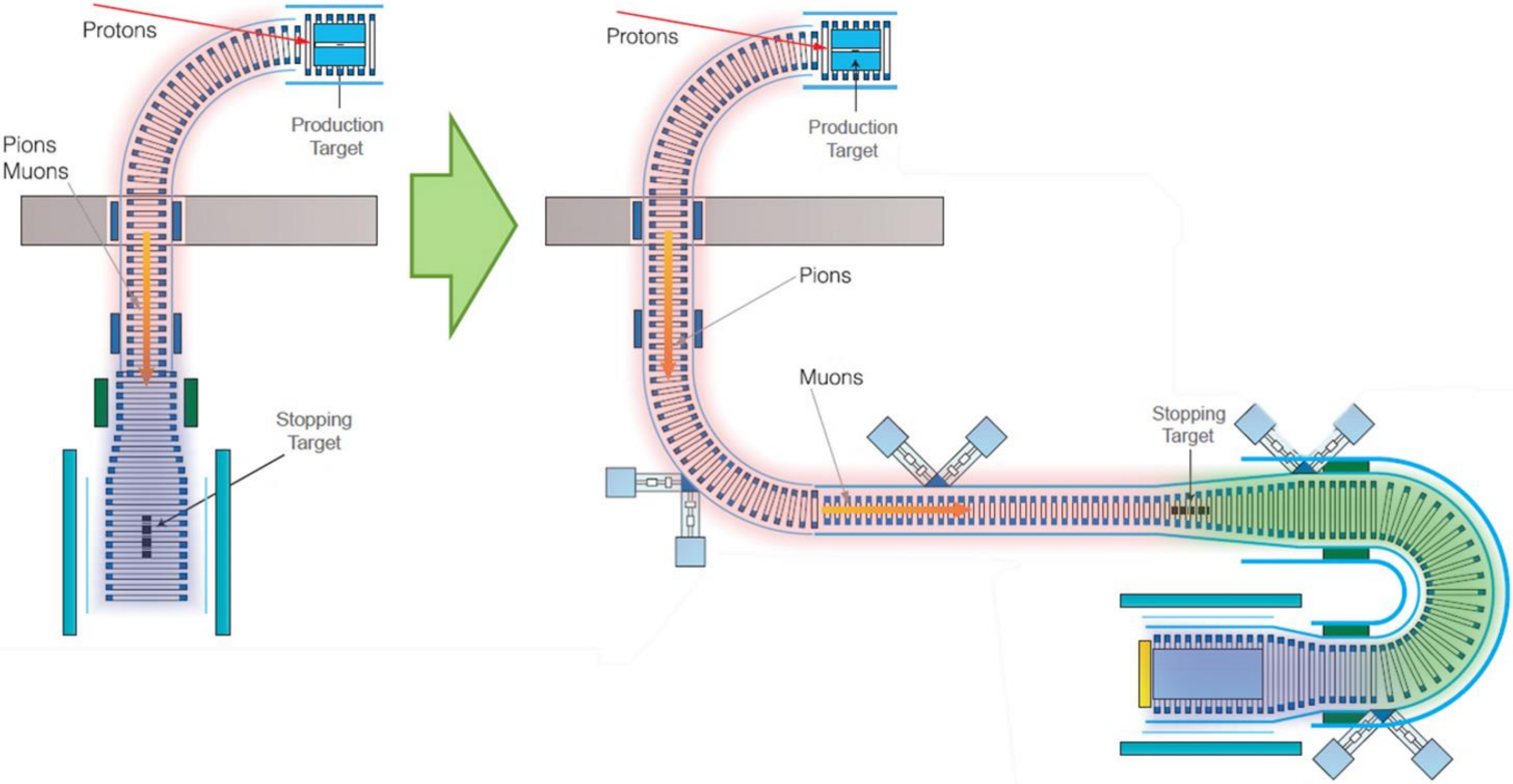
COMET

▲ View from (newly furnished) COMET Counting Room

Two phases of COMET

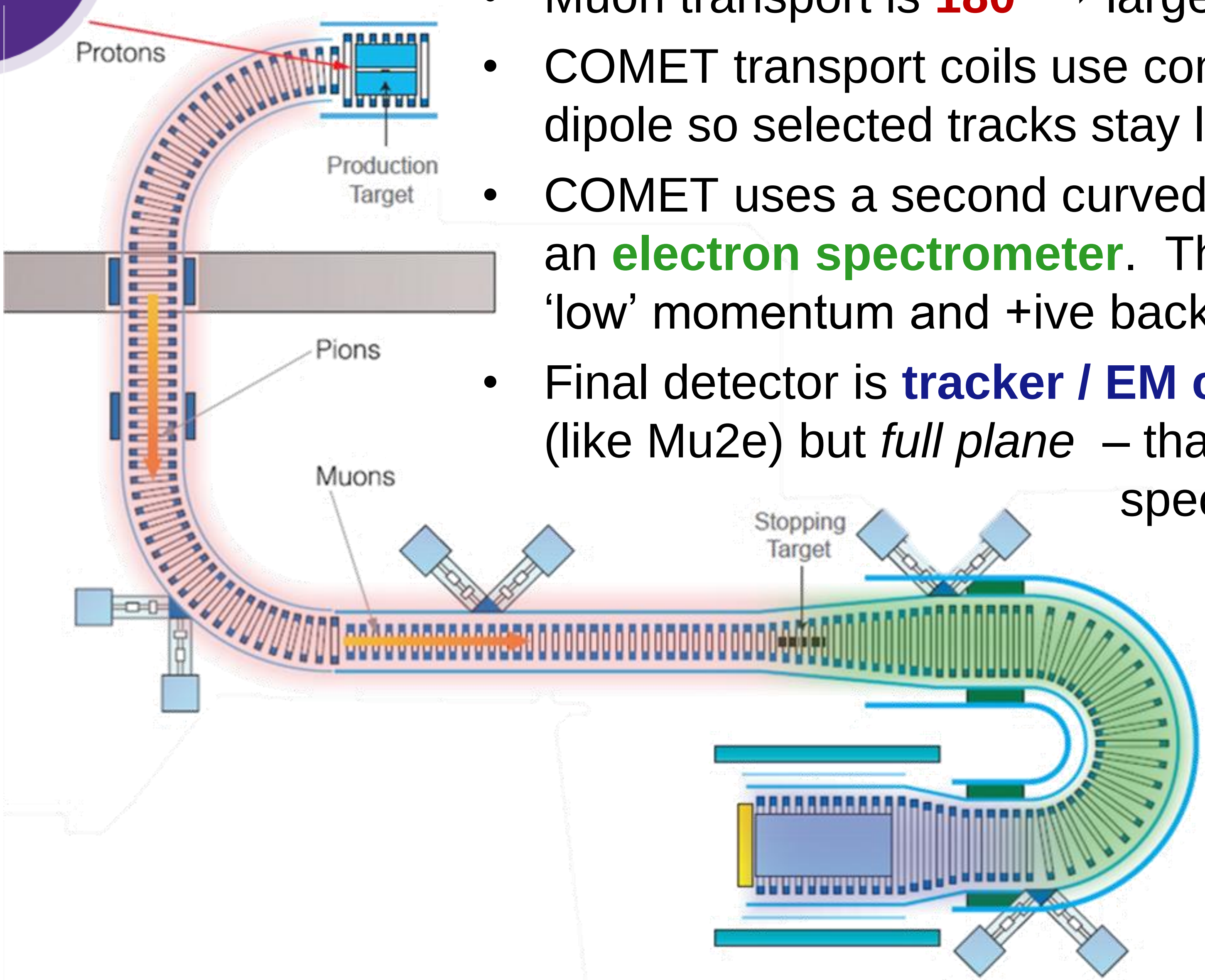
Phase I

Phase II



In time-revered order: Phase II…

- Muon transport is **180°** → larger dispersion.
- COMET transport coils use compensating dipole so selected tracks stay level.
- COMET uses a second curved solenoid as an **electron spectrometer**. This filters out ‘low’ momentum and +ive backgrounds
- Final detector is **tracker / EM calorimeter** (like Mu2e) but *full plane* – thanks to spectrometer.



…and Phase I

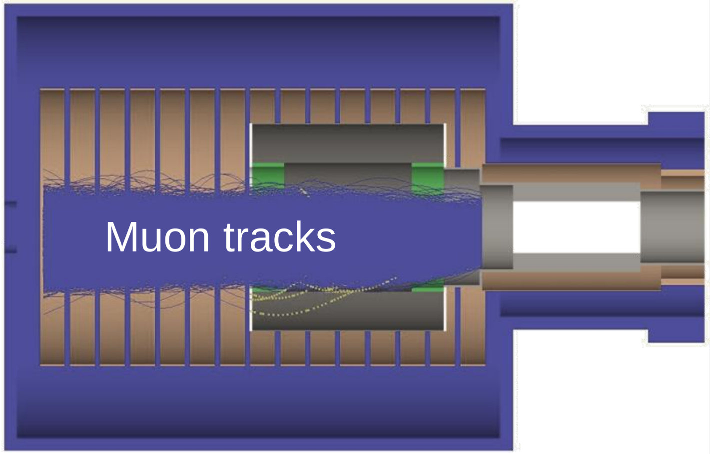
Phase I has 2 goals:

- Investigate backgrounds for phase II
- Perform search at 100× sensitivity of SINDRUM-II

For Phase I measurement use a **cylindrical drift chamber** around the stopping target.

- Triggering by **auxillary hodoscopes**

Also include prototypes/partial elements of Phase II detectors for development and characterising backgrounds at low current



COMET developments


June 2014


April 2015

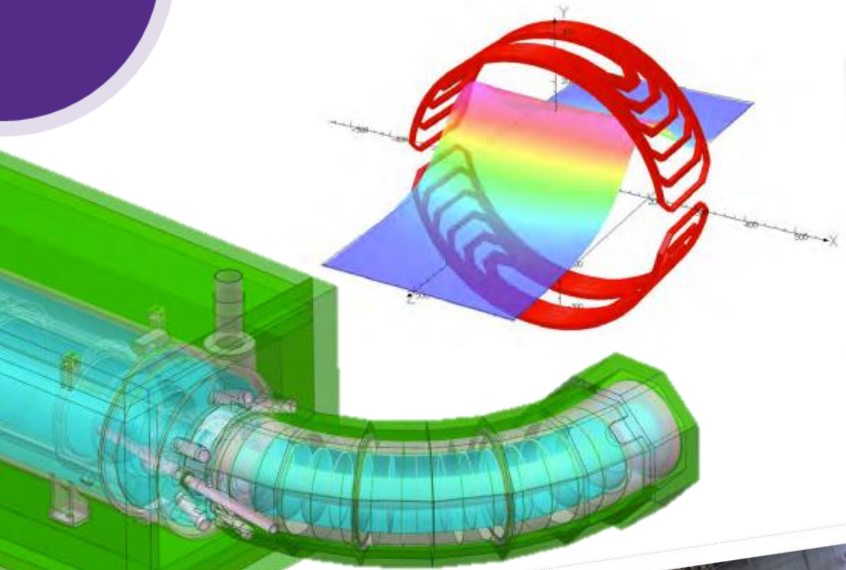
◄ COMET hall construction completed!

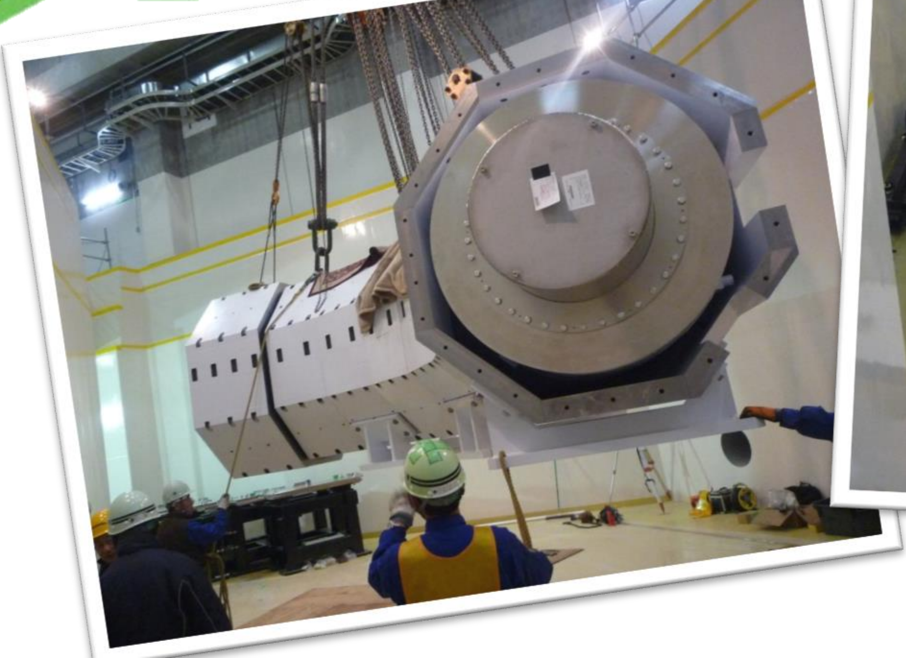
▲ Magnets laid-out for new beam switchyard

Transport Solenoid

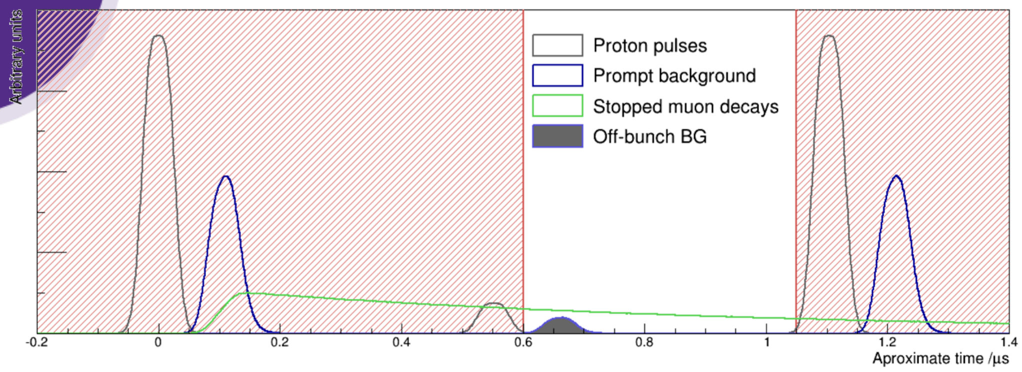
◀Corrective dipoles

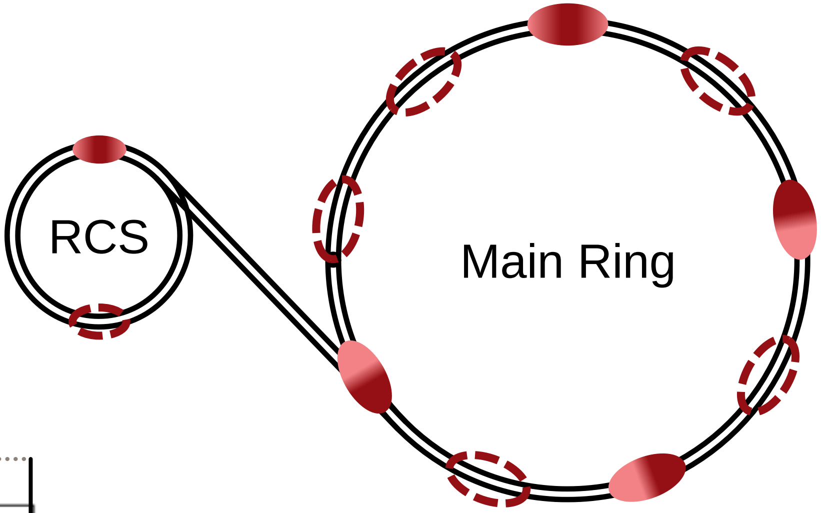
▼Completed 90° muon transport arc (including octagonal return yoke)

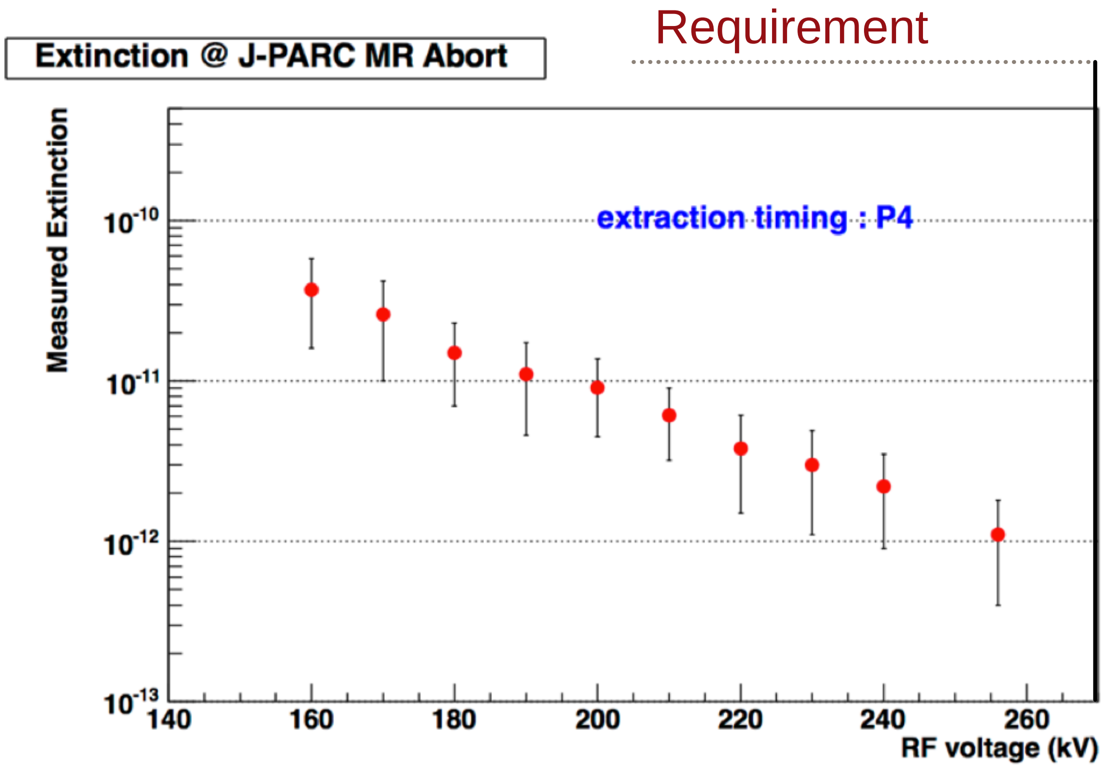




Extinction test







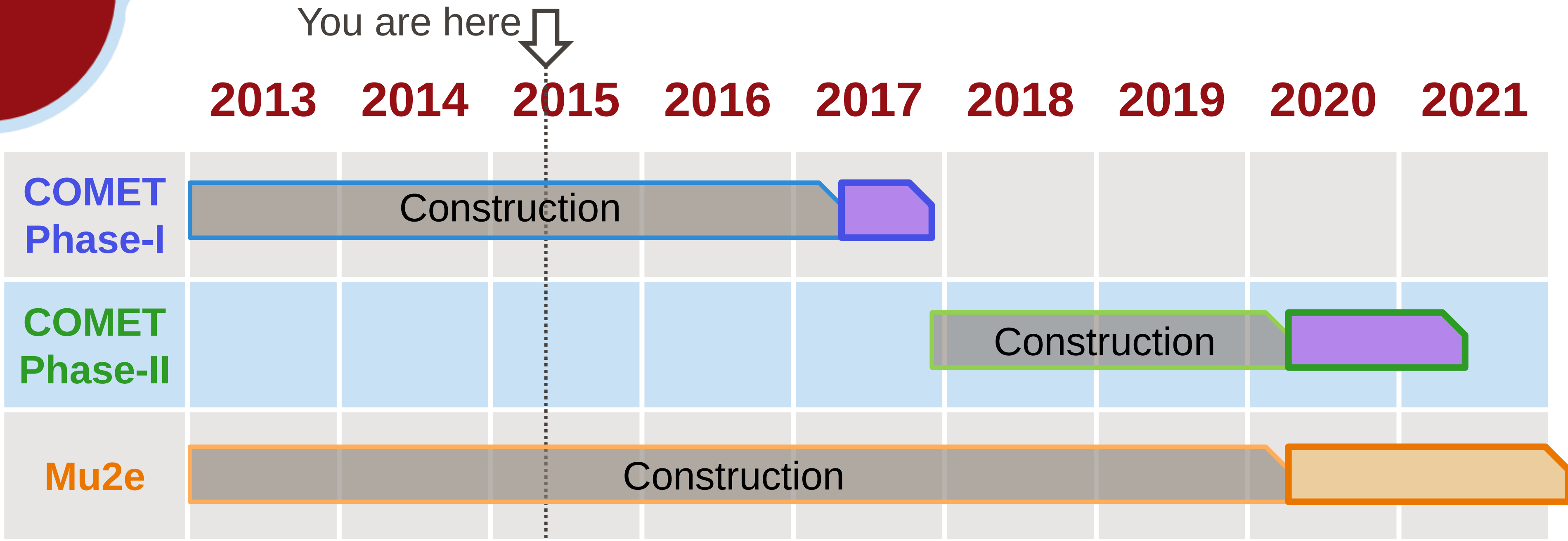
Comet requires extinction:

$$E = \frac{N_{Empty}}{N_{Filled}} < 10^{-9}$$

Important test in May 2014:

Excellent results!

Timelines



You are here

2013 2014 2015 2016 2017 2018 2019 2020 2021

COMET Phase-I: Construction

COMET Phase-II: Construction

Mu2e: Construction

2014: 7×10^{-13} **90% U.L.** [SINDRUM-II] (since 2004)

~2017: 3×10^{-15} **S.E.S.** [COMET Phase-I] (~ 6mo)

~2021: 3×10^{-17} **S.E.S.** [COMET Phase-II & Mu2e]

beyond 2021: PRISIM /PRIME @J-PARC**?** [Goal 3×10^{-19}]

Mu2e × ProjectX @FNAL**?**

Summary

- **Charged lepton flavour violation** is ‘natural’ in new physics scenarios.

- The (arguably) SM process is driven by neutrino mixing, and is **hugely suppressed**: $\mathbf{O\left(10^{-54}\right)}$

- Complimentary approaches from $\mu \rightarrow e\gamma$ $\mu \rightarrow eee$ and

  $\boldsymbol{\mu - e}$ **conversion**

- Current limit is $\mathbf{O\left(10^{-12}\right)}$ from SINDRUM-II

- COMET & Mu2e can improve on this by **4 orders of magnitude** in 5~10 years

- Information on *what* the NP is through similar experiments.

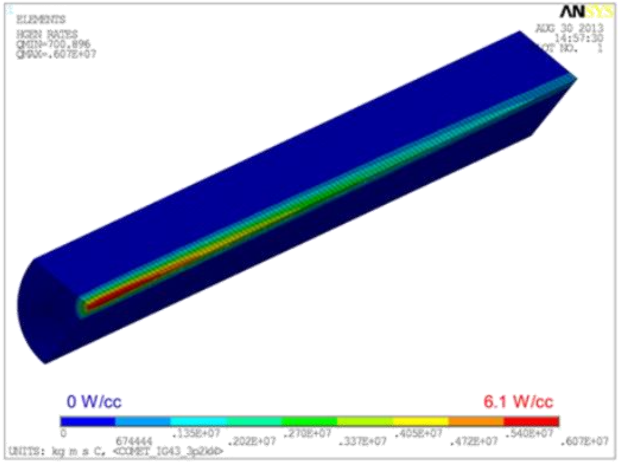
Reserves

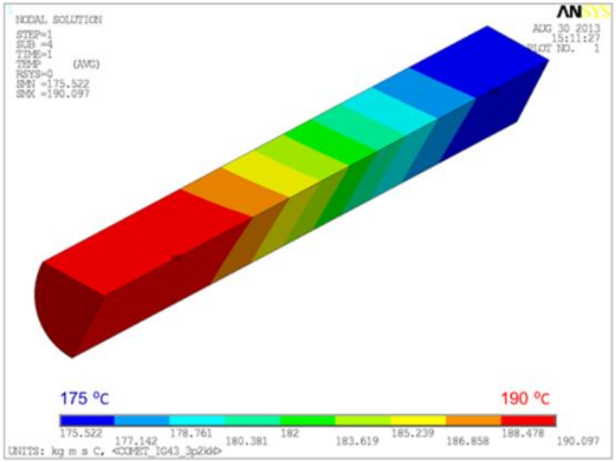
Production target

Phase-I baseline (unlikely to change):
60cm × 2cm dia. graphite (IG-43) target.

Higher Z is better for pion production,
but **graphite** is a ‘safer’ choice:

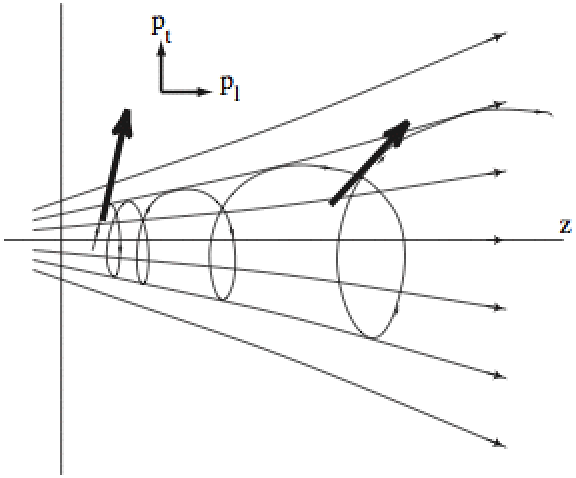
- IG-43 is used for T2K target (FX, >200kW beam) so is known to be capable of handling our beam.
- Lower irradiation of target and shield make safer in case of replacement in Phase-II
- At Phase-I power, radiative cooling is suffic





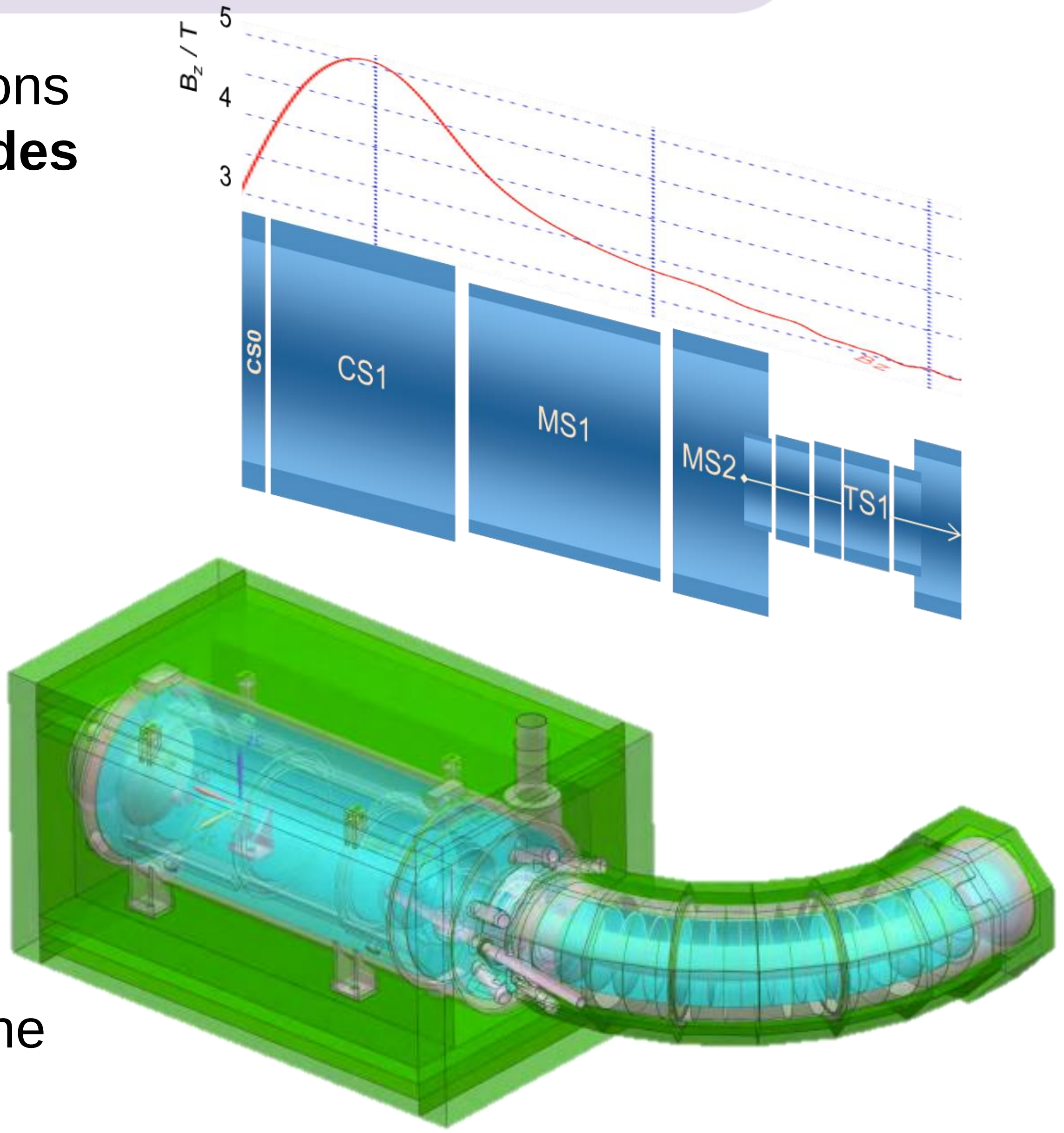
Capture Solenoid

Comet needs *low energy* pions so collect from **back and sides** of target.



Gradient field converts transverse momentum into longitudinal momentum.

- Effectively increases the solid angle aperture into the transport solenoid.



Cooling and shielding

A 5T solenoid is (unsurprisingly?) superconducting.

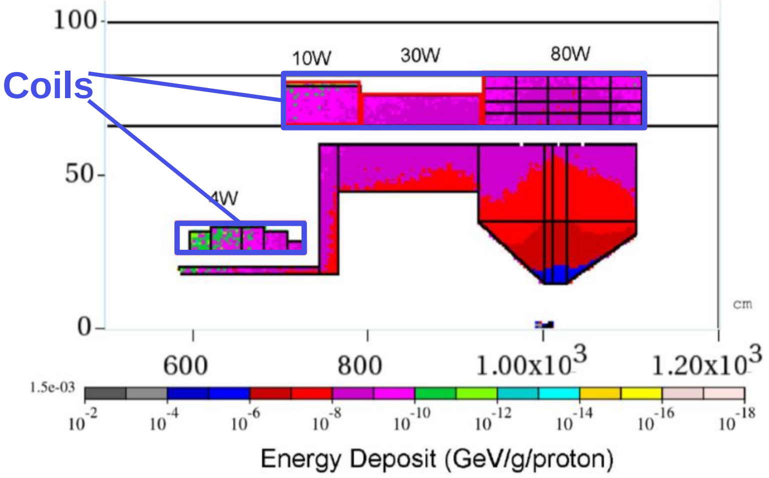
- And therefore cryogenically cooled…

But there is a high power beam hitting a target in the middle!

- Phase I: this heating is estimated up to 30W
- Phase II: heating can be 120W [c.f. other sources ~15W]

Shielding is needed, for radiation and thermal heating.

- Copper and tungsten shield
- Cooled with water
- Will probably need upgrade for Phase II, gets very (radioactively) hot.



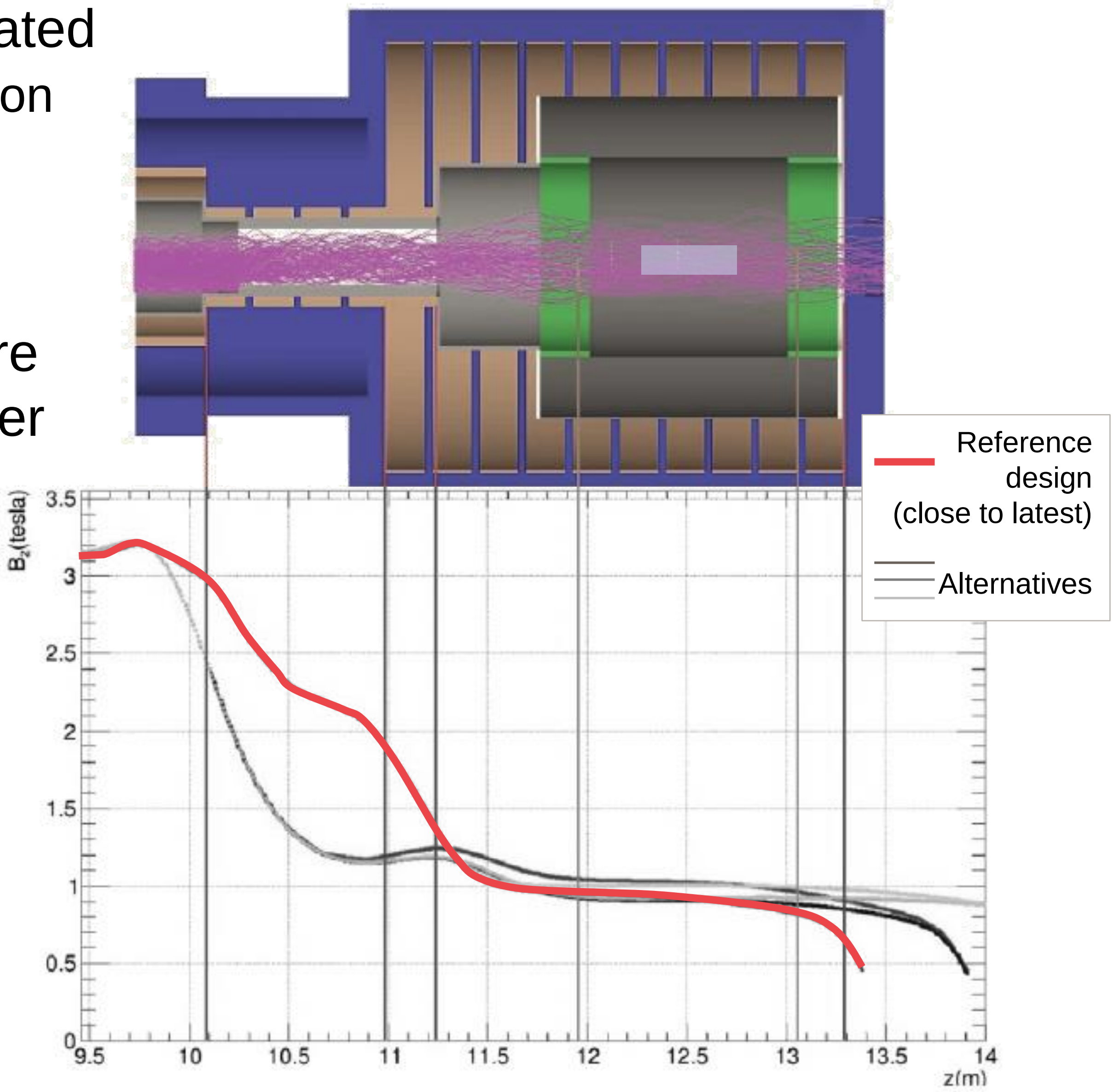
Non-trivial engineering challenge!

Phase-I Detector

Phase-I will have a dedicated detector for $\mu \rightarrow e$ conversion measurements.

Because of the charged particle tracks in the centre channel, a co-axial cylinder geometry is used.

↳ **CyDet**

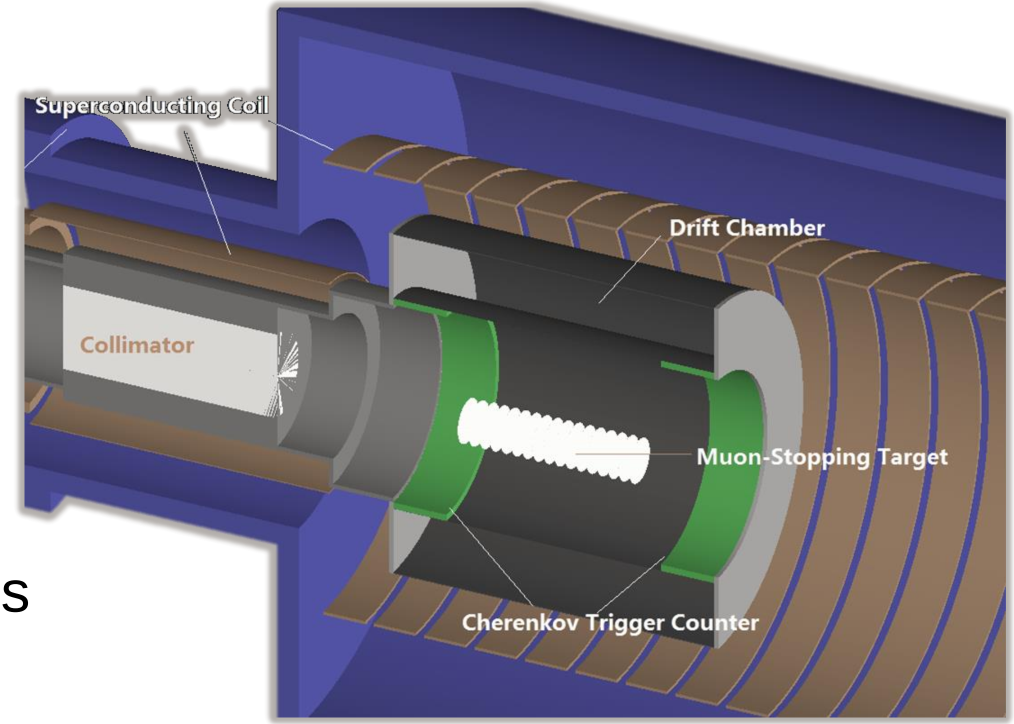


The detector and capture target will sit within a 1T solenoid field.

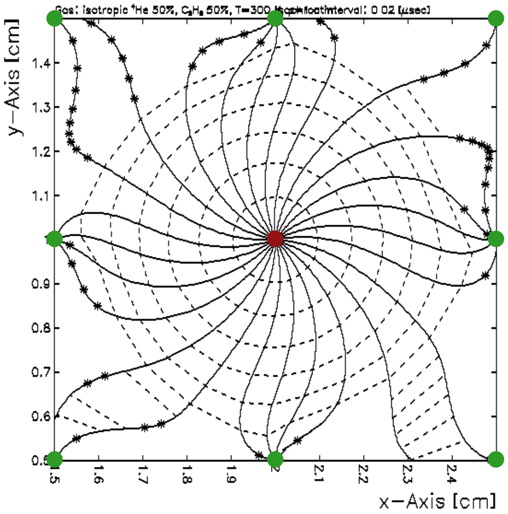
Low momentum particles do not reach the detector

CyDet

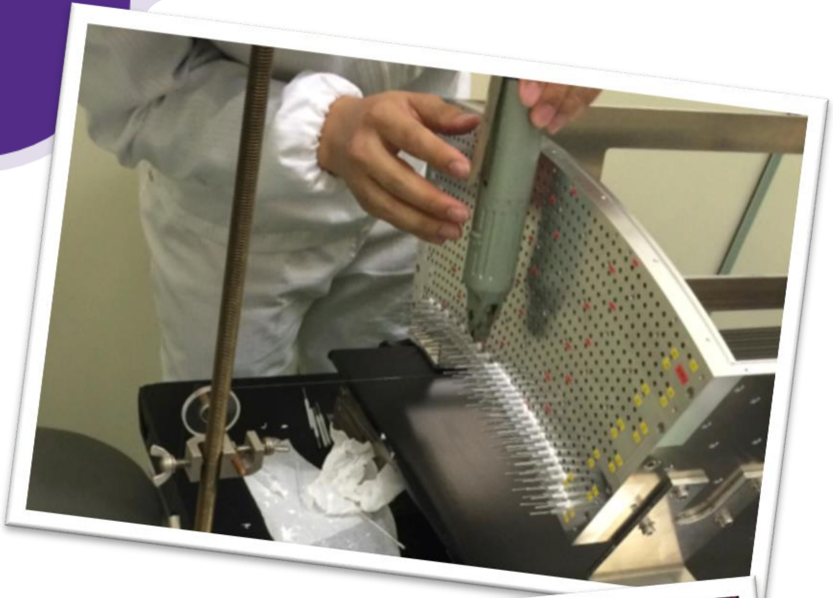
The main part of the detector is a coaxial **drift chamber**

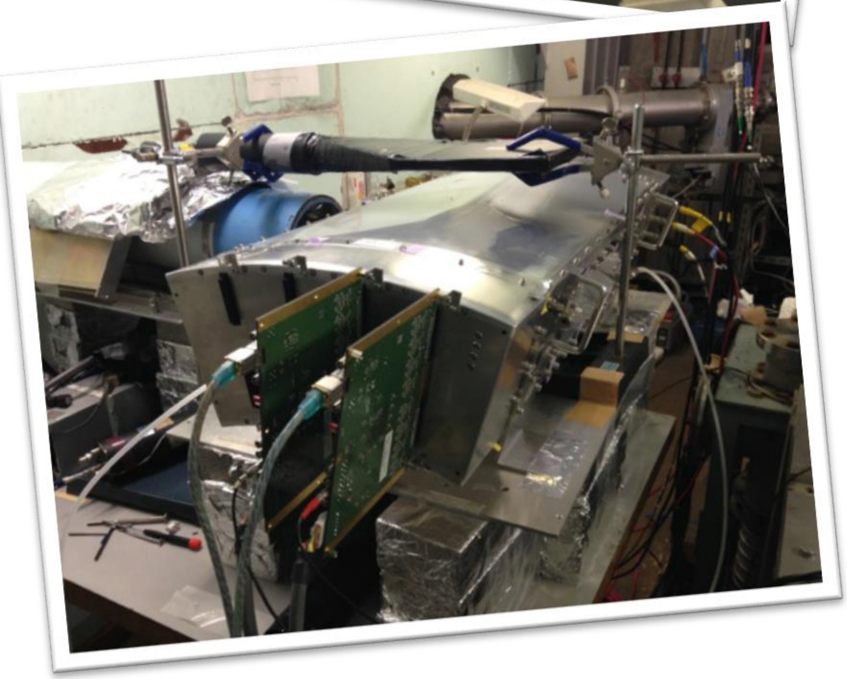


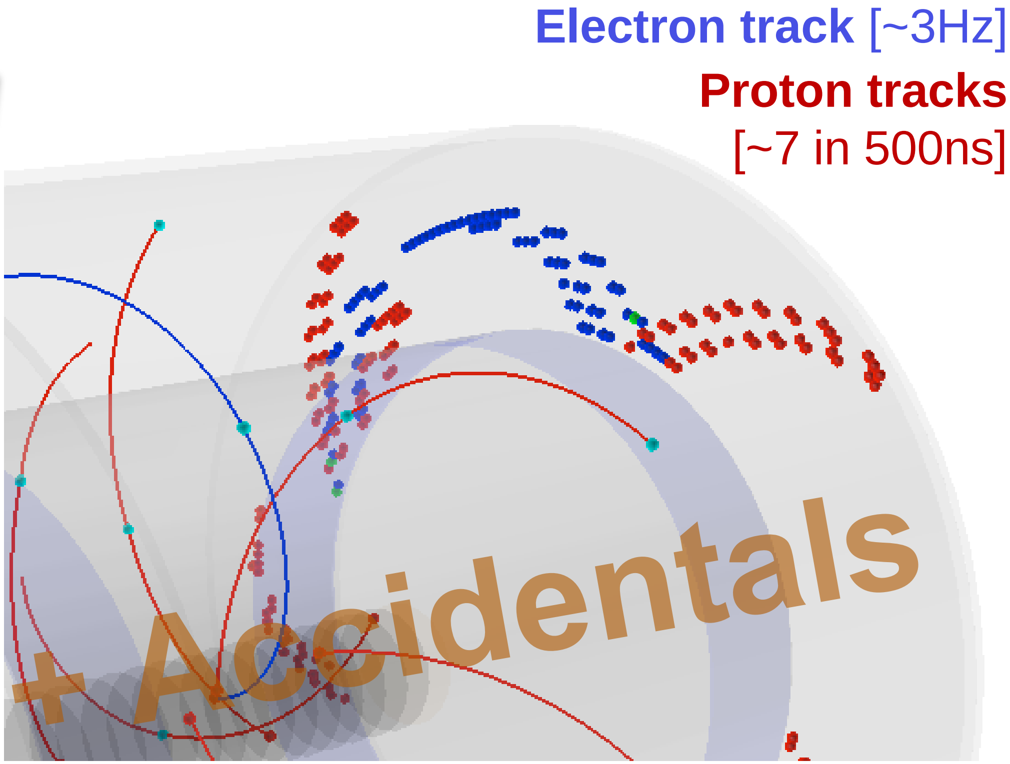
- Helium-based gas mixture to reduce multiple scattering.
  - Resolution ~ 200 keV
- *z* measurement by stereo layers
- Large inner radius to reduce DIO hit rate
  - Dim: 150cm × 84cm(outer) // 50cm(inner)
- 19 concentric sense layers
- Triggering from **hodoscopes** at ends



Drift chamber progress



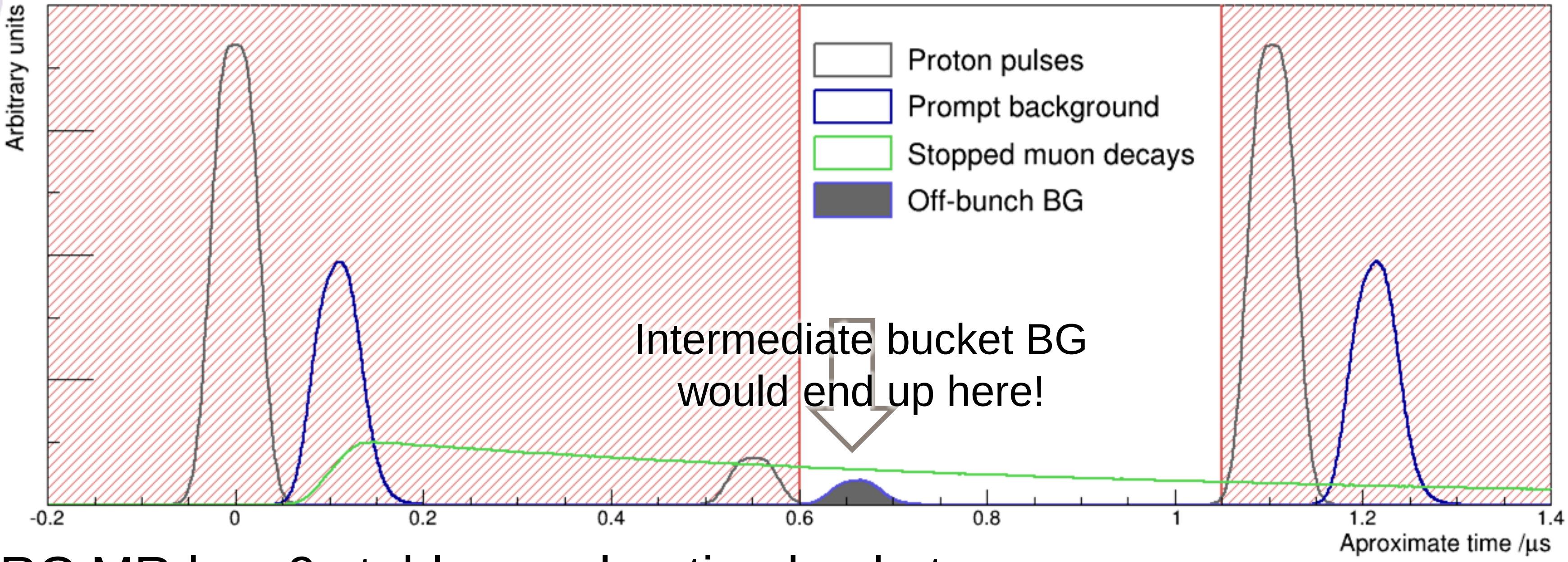




▲ Event display showing event projection

◀ Stringing wires and CR test of prototype section

Beam extinction

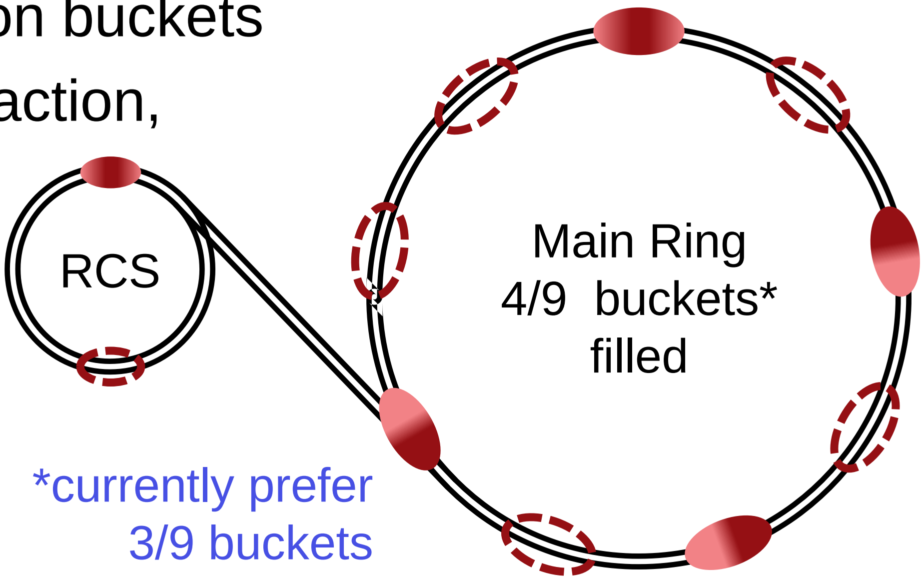


Intermediate bucket BG would end up here!

J-PARC MR has 9 stable acceleration buckets

- Need to maintain RF during extraction, so that bunch structure remains.
- If RF is not strong enough, protons will ‘leak’ into empty buckets.

Signal process is rare so even a small leak is a major background

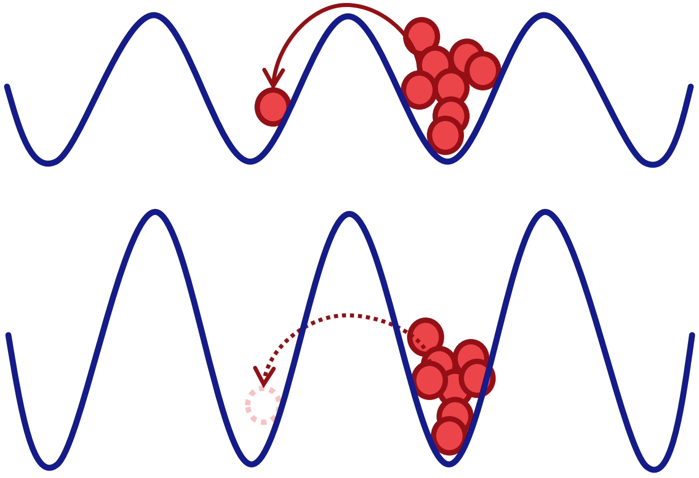


*currently prefer 3/9 buckets

Extinction measurement

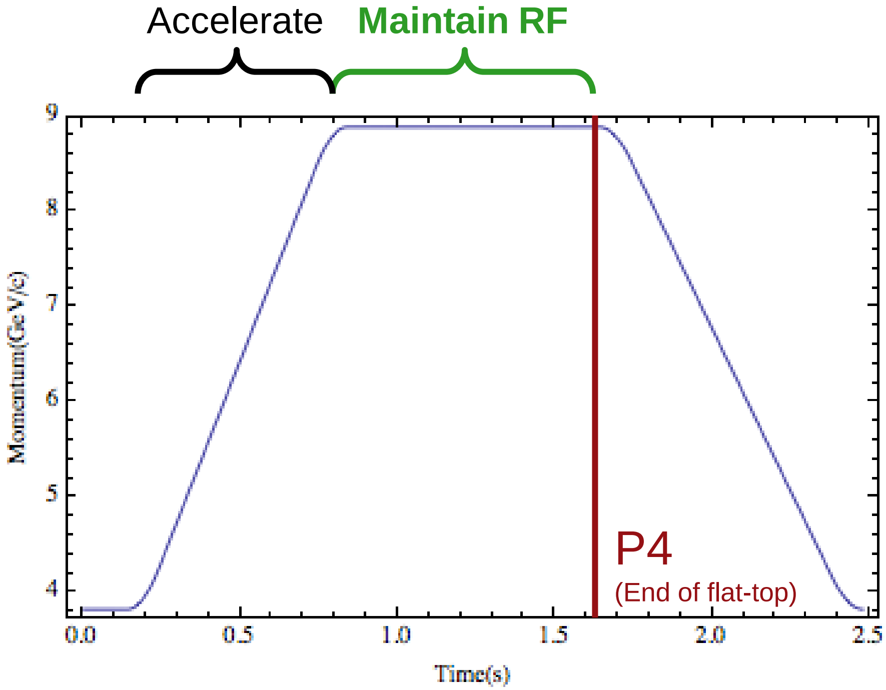
COMET design requires that we can achieve an extinction:

$$E = \frac{N_{Empty}}{N_{Filled}} < \mathbf{10^{-9}}$$



Extinction can be improved by increasing RF voltage, but this heats the cavities.

(And there is a limit…)



Accelerate

Maintain RF

P4

(End of flat-top)

2012 test at 30 GeV demonstrated this is possible for RF > 120kV,

But study time at 8 GeV not allocated until this year…