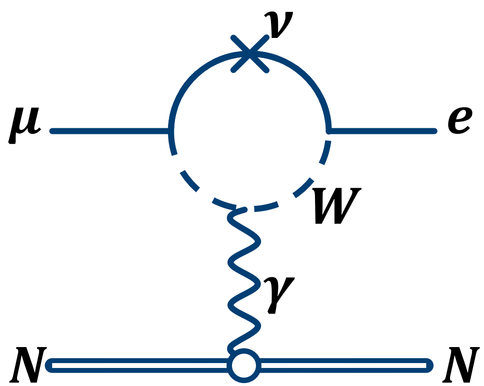
Imperial College London

Status of the COMET experiment

Phill Litchfield
for the COMET collaboration

$\mu - e$ conversion

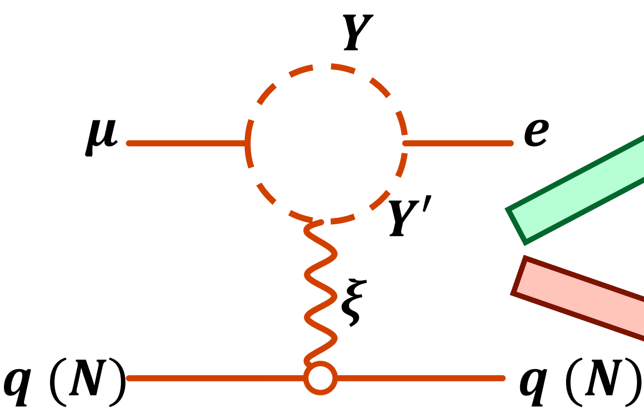
μ to e conversion



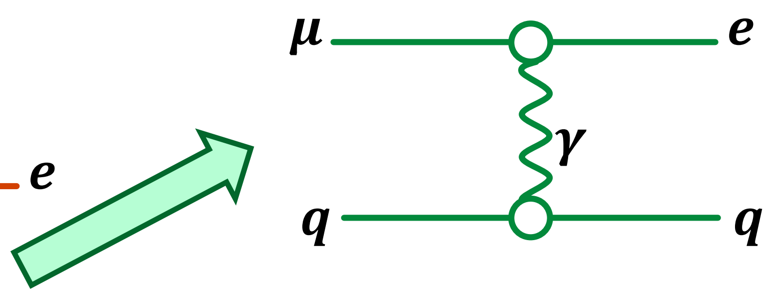
SM $\mu - e$ conversion

In the **SM** $\mu N \rightarrow eN$ is supressed by $O(10^{-54})$ because of the mass disparity between the W and neutrino.

This is 'accidental'; **new physics** scenarios typically give CLFV much higher than SM.

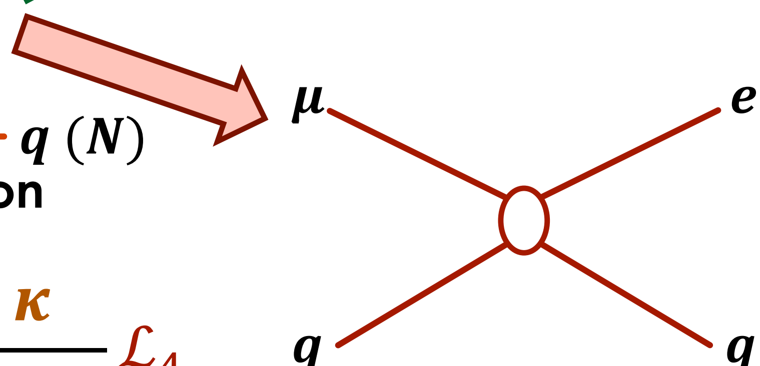


NP $\mu - e$ conversion



Dipole coupling

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



Four-fermion coupling

$$\mathcal{L}_{4} \sim \frac{1}{\Lambda^2}\ \bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q$$

$$\mathcal{L} = \frac{1}{1+\kappa}\mathcal{L}_d + \frac{\kappa}{1+\kappa}\mathcal{L}_4$$

Bound muon fates

Muons allowed stop in suitable target.

- Initially **Aluminium**, but (Ti) also suitable.

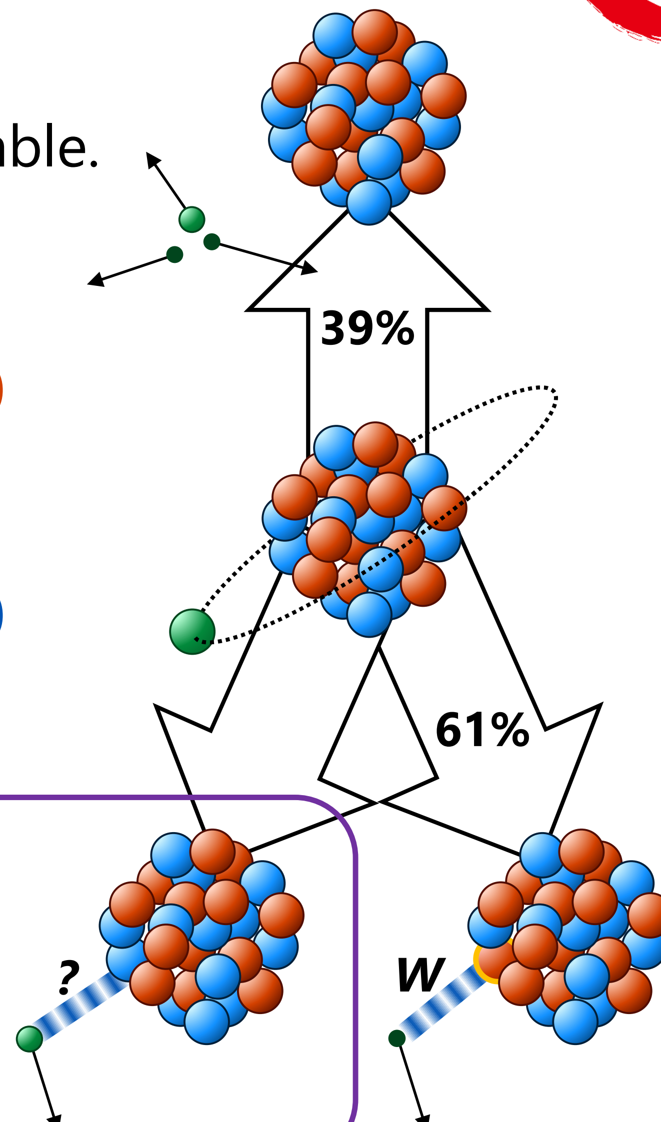
'Normal' fates are:

- Decay in Orbit [DIO]: (39% in Al)

  $\mu N \rightarrow e\nu\bar{\nu}N$

- Nuclear muon capture: (61% in Al)

  $\mu N(Z) \rightarrow \nu N'(Z-1)$



Looking for the conversion:

$\mu N \rightarrow eN$

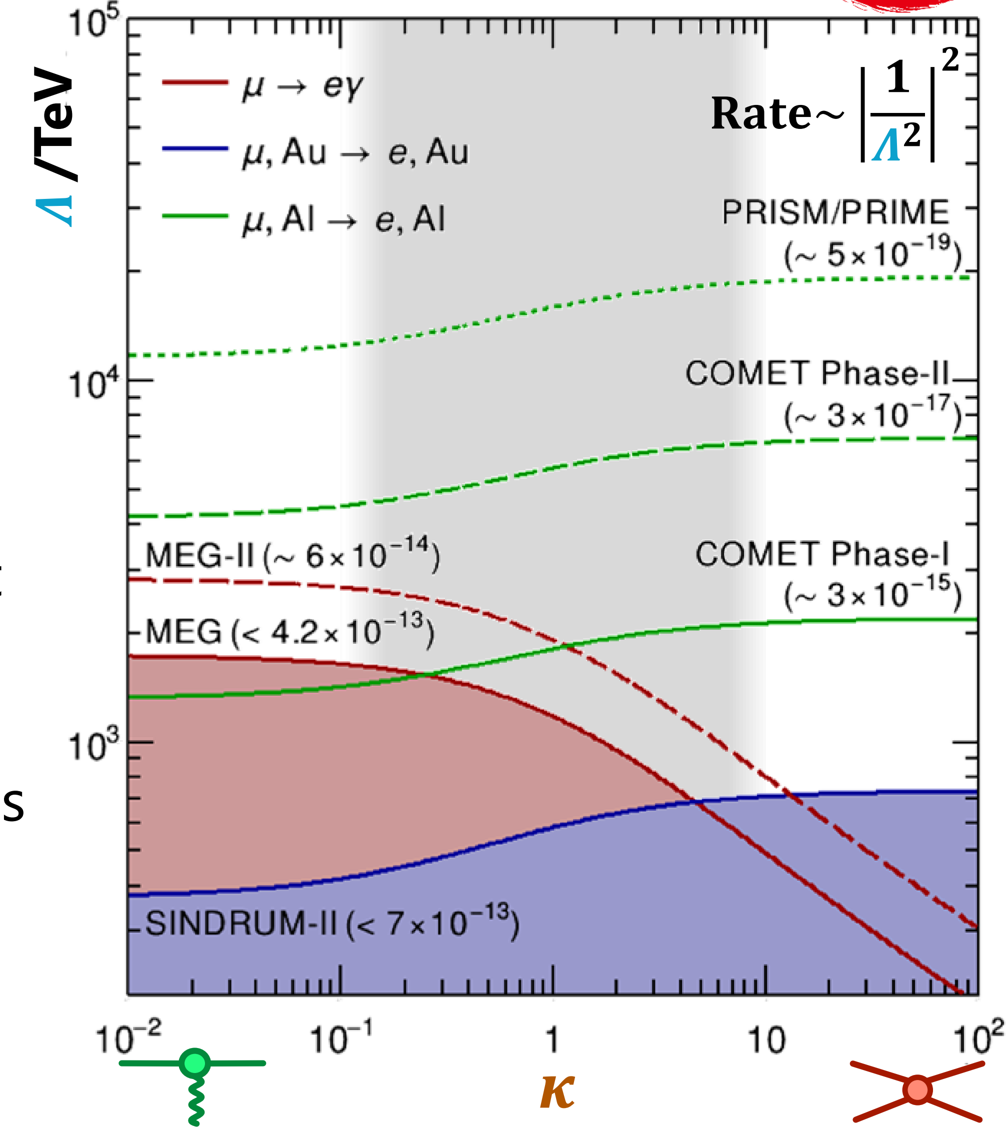
From 1s orbital: ***mono-energetic electron*** at 105MeV ($\approx m_\mu - B_{1s}^{\mu} - E_{\mathrm{R}}$)

A giant leap…

For the full COMET experiment sensitivity improvement over SINDRUM-II is **4 orders of magnitude.**

MC of background processes [especially '*tails*'] may not be good enough for optimal design

- Intermediate-scale experiment can measure background sources and inform design.
- Can still do competitive physics with a smaller apparatus

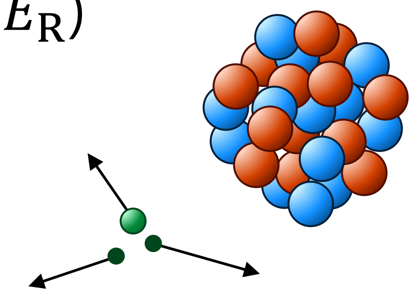


Include in COMET programme:

COMET Phase-I

Background from bound muons

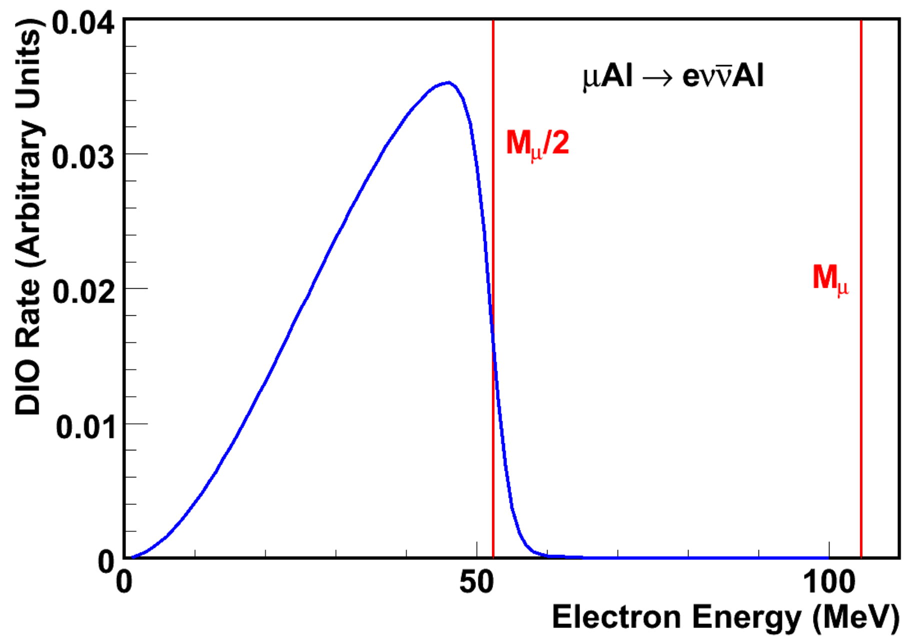
Signal process: coherent $\mu N \rightarrow eN$ from 1s orbital
mono-energetic electron at 105MeV ($\approx m_\mu - B_{1s}^{\mu} - E_{\mathrm{R}}$)



Decay in Orbit [DIO] $\mu N \rightarrow e\nu\bar{\nu}N$ is important

For a free muon, cuts off at $\frac{1}{2}m_\mu$, but bound state has a small tail up to $m_\mu - B_{1s}^{\mu} - E_{\mathrm{R}}$

Nuclear muon capture
is more common, but does not produce energetic electrons

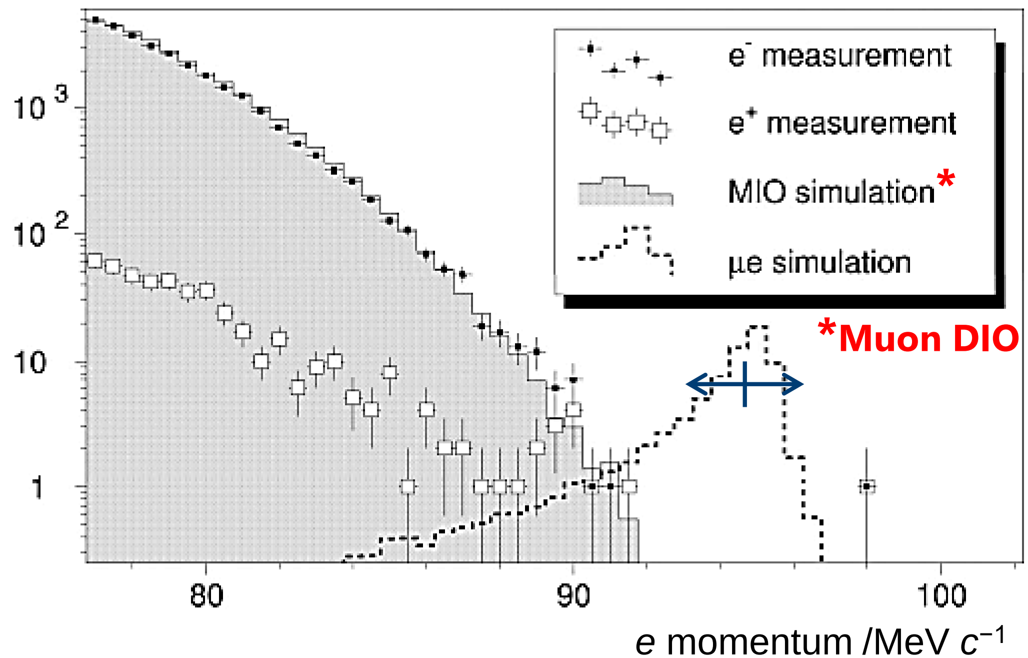


Backgrounds

Three main background processes:

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

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

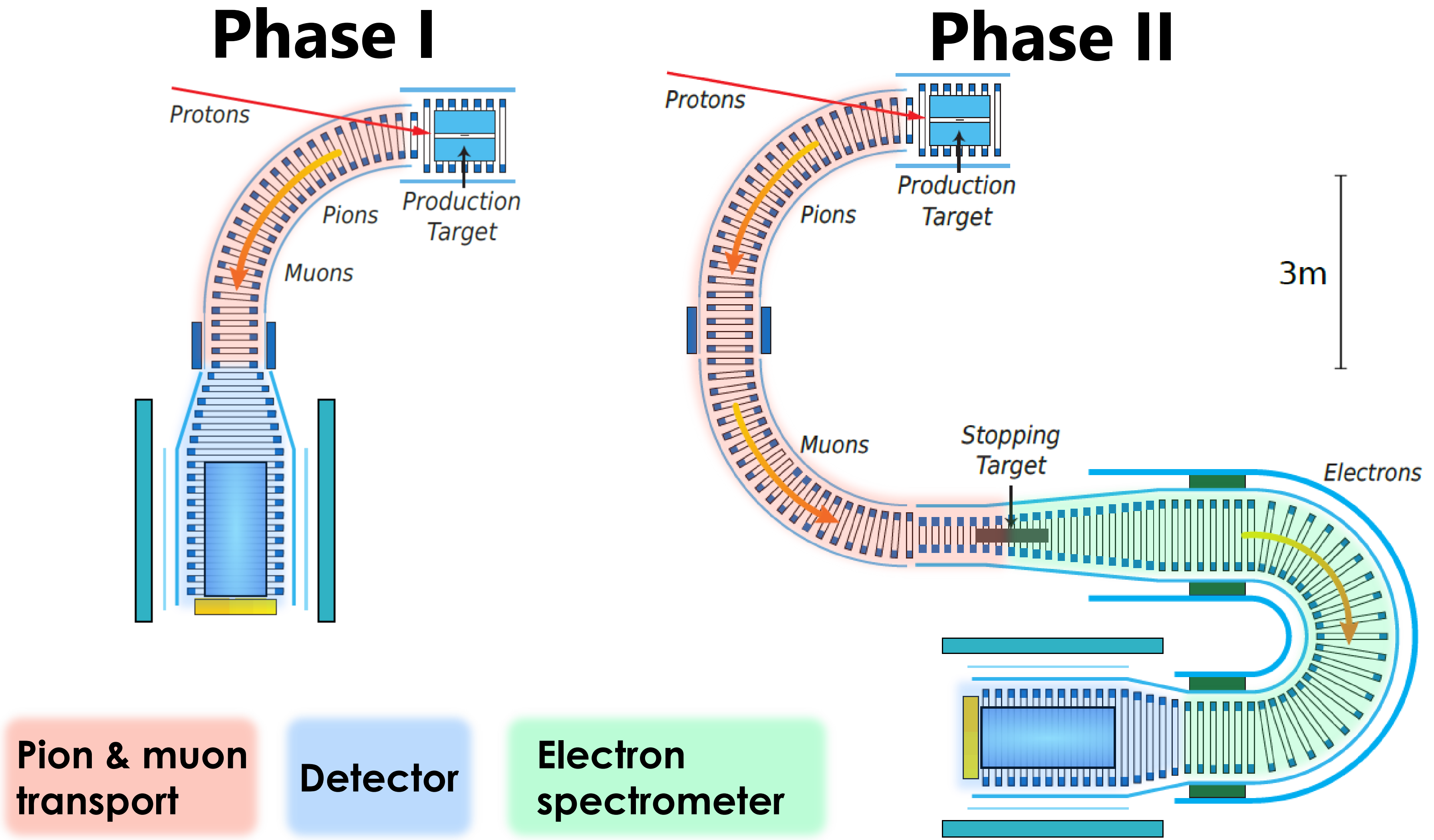


- **Decay in flight**:
  Electrons from energetic muons (p>77MeV) can be boosted to 105MeV.
  – Use **momentum filtering** in muon transport

- **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 ▶ **Pulsed beam**

COMET design and construction

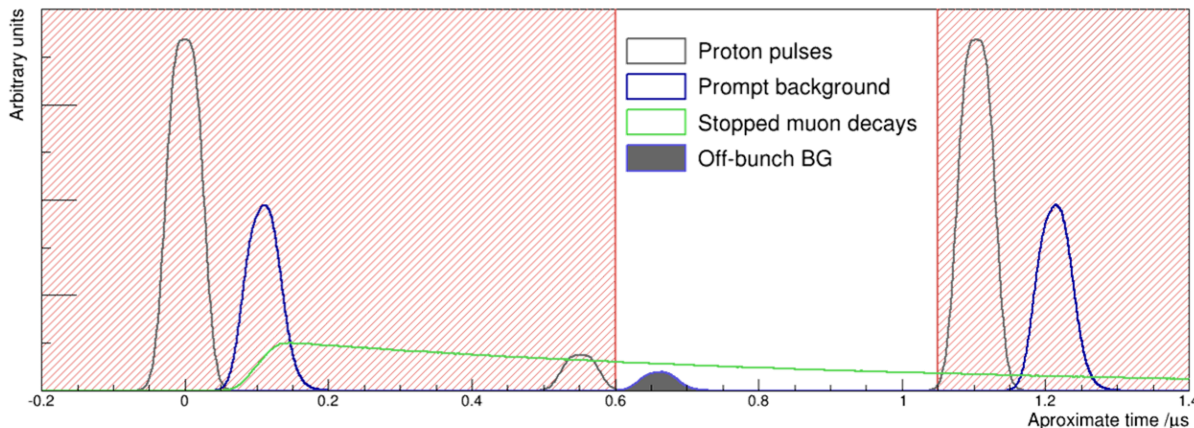
COMET, Phase I and II

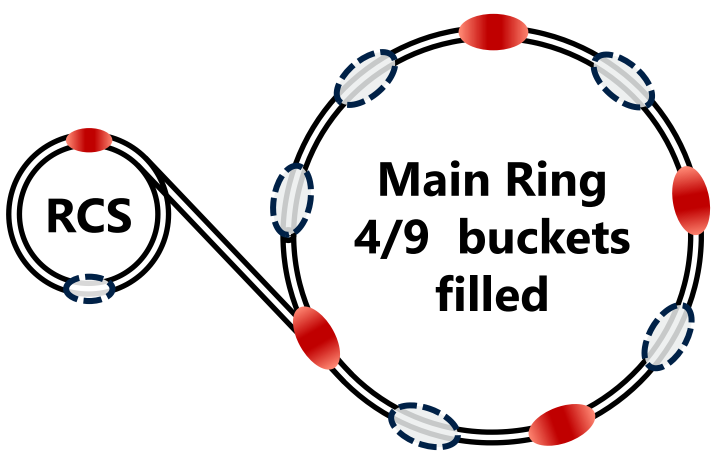


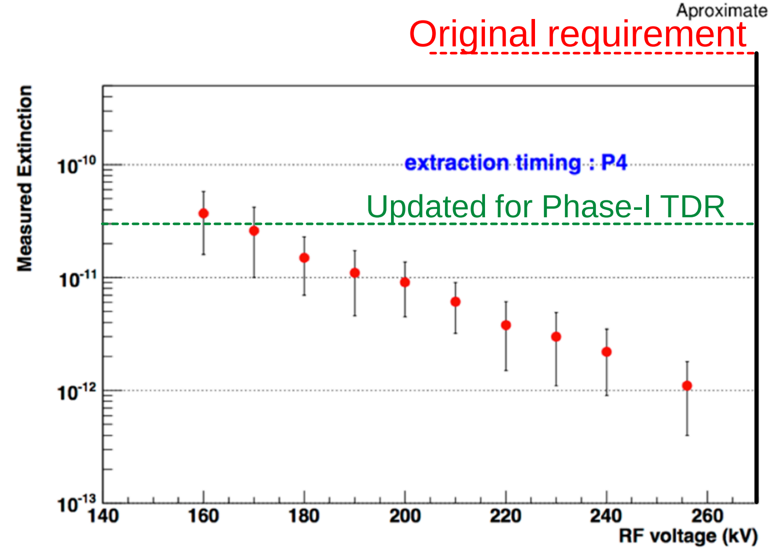
Primary beamline

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

- Use high-power ***pulsed* proton beam** line (8 GeV) with resonant slow extraction.
- Empty buckets could contain protons and create background
- Strict ***extinction*** requirement $< 10^{-9}$

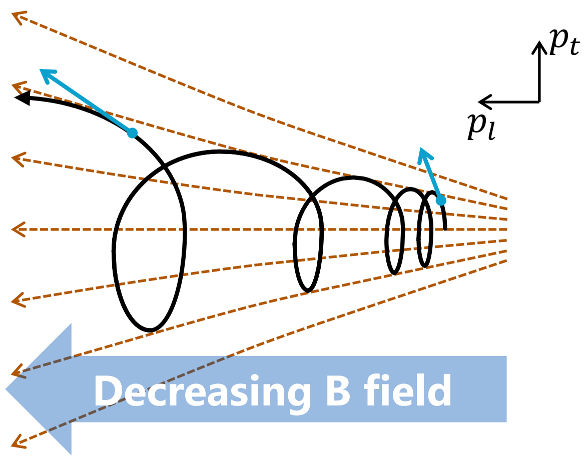


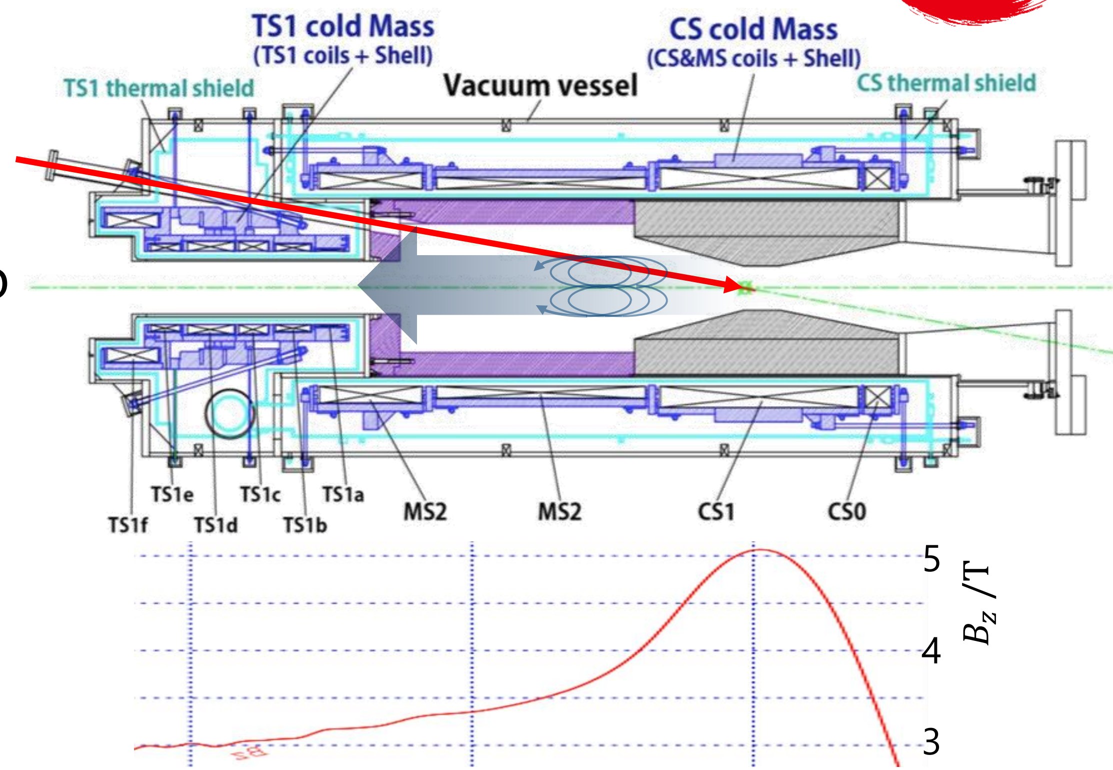




Muon source

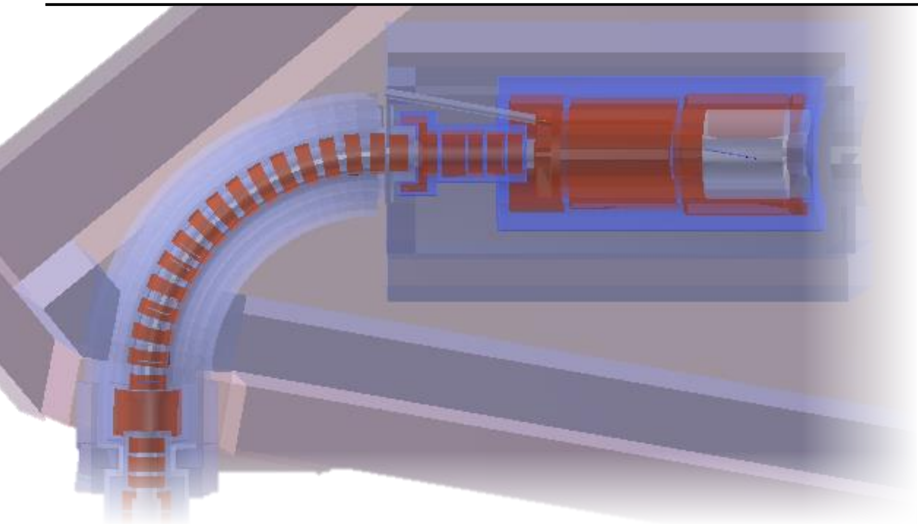
- Collect ***backward*-going pions** with capture solenoid
- Maximise field at target to give larger aperture angle

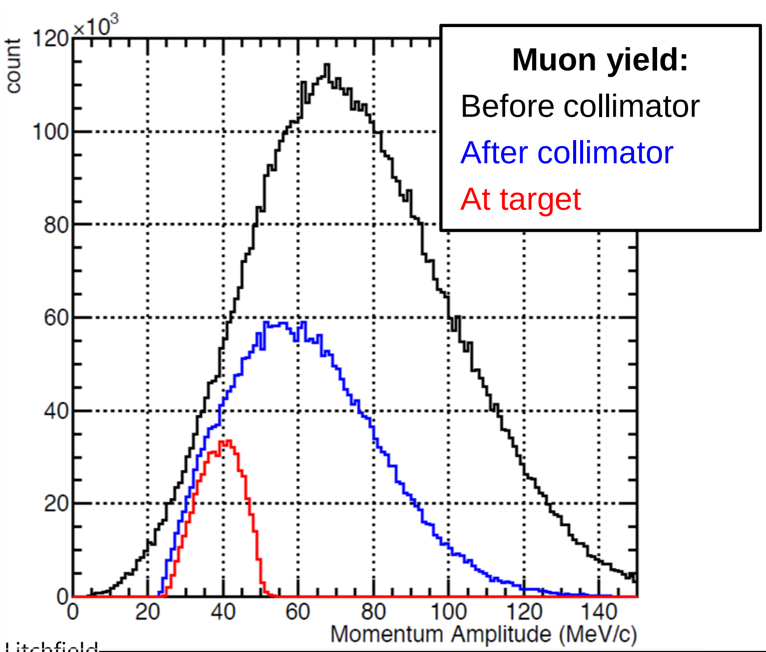




- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. The curved transport line helps to eliminate direct line-of sight.

Muon transport





Muon transport is a curved solenoid:

- Particles are channelled in **spiral paths [solenoid]**, which naturally tend **up/down [curvature]** depending on *p* and charge
- Dipole keeps desired lower-*p* –ive muons on level trajectory
- Gives **charge and momentum selection**, which is enhanced by using a collimator.
- Eliminates high-*p* muons (which won't stop) & other particles.
- Eliminates line-of-sight from production target

Muon transport

Muon transport is a curved

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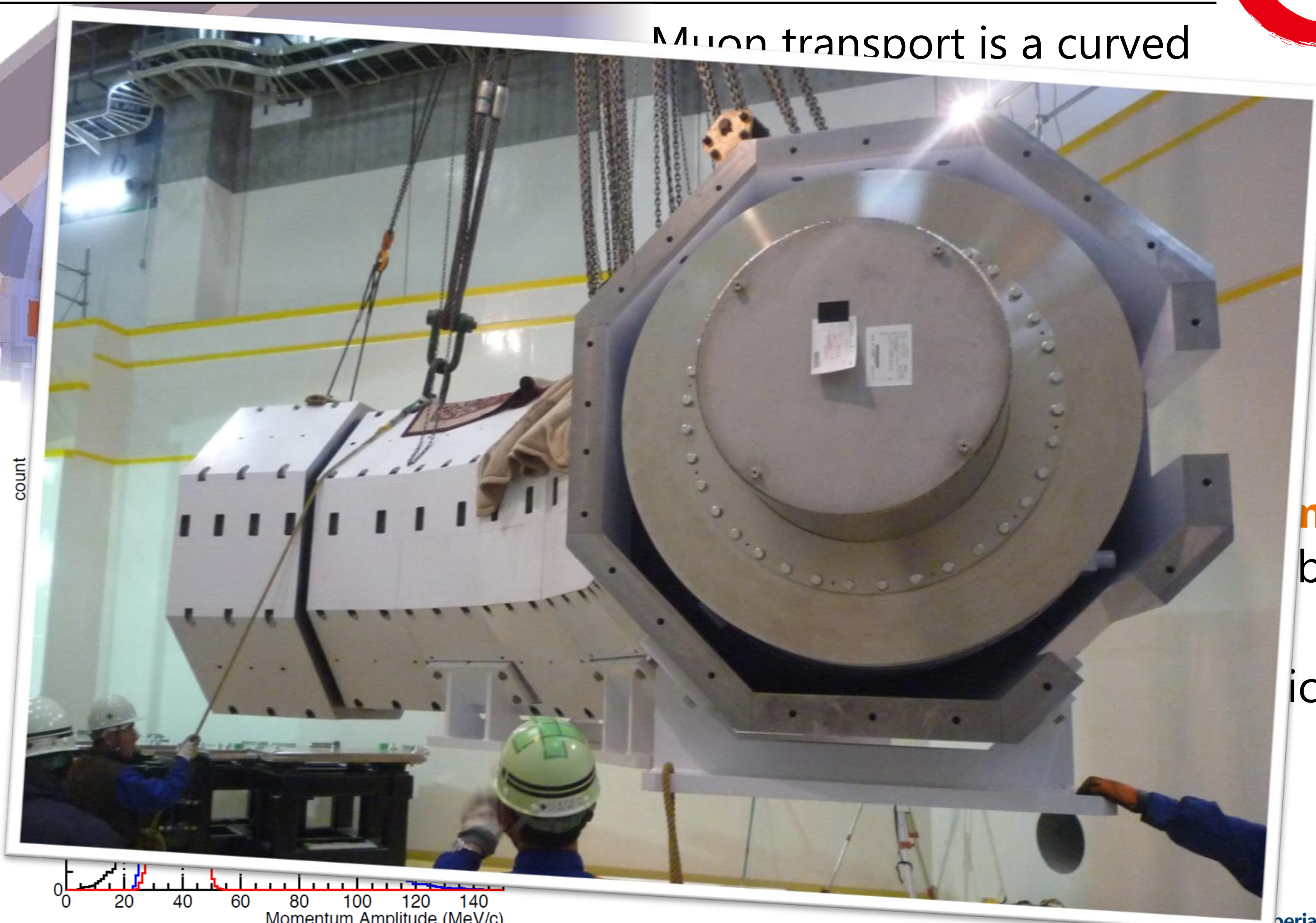
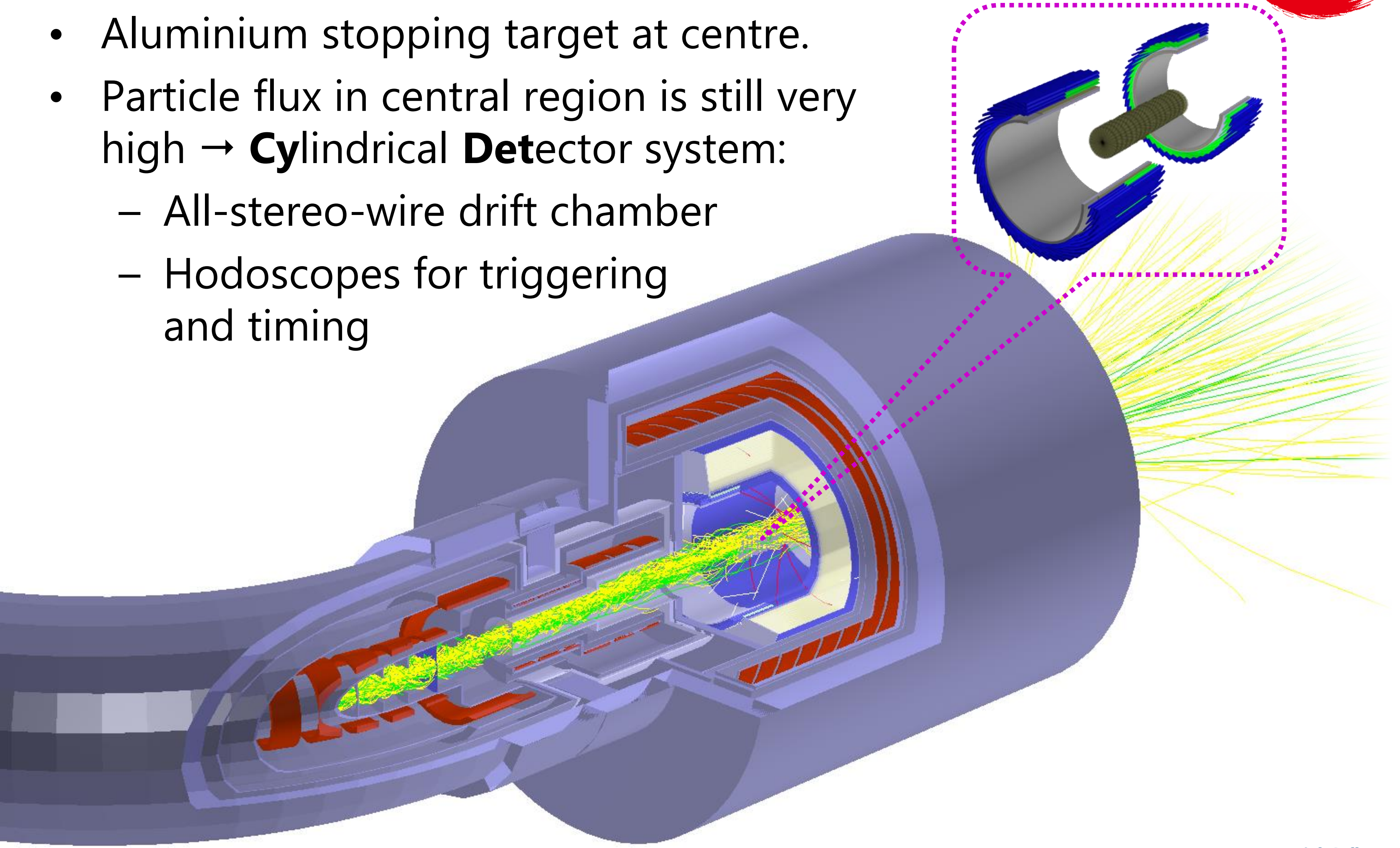


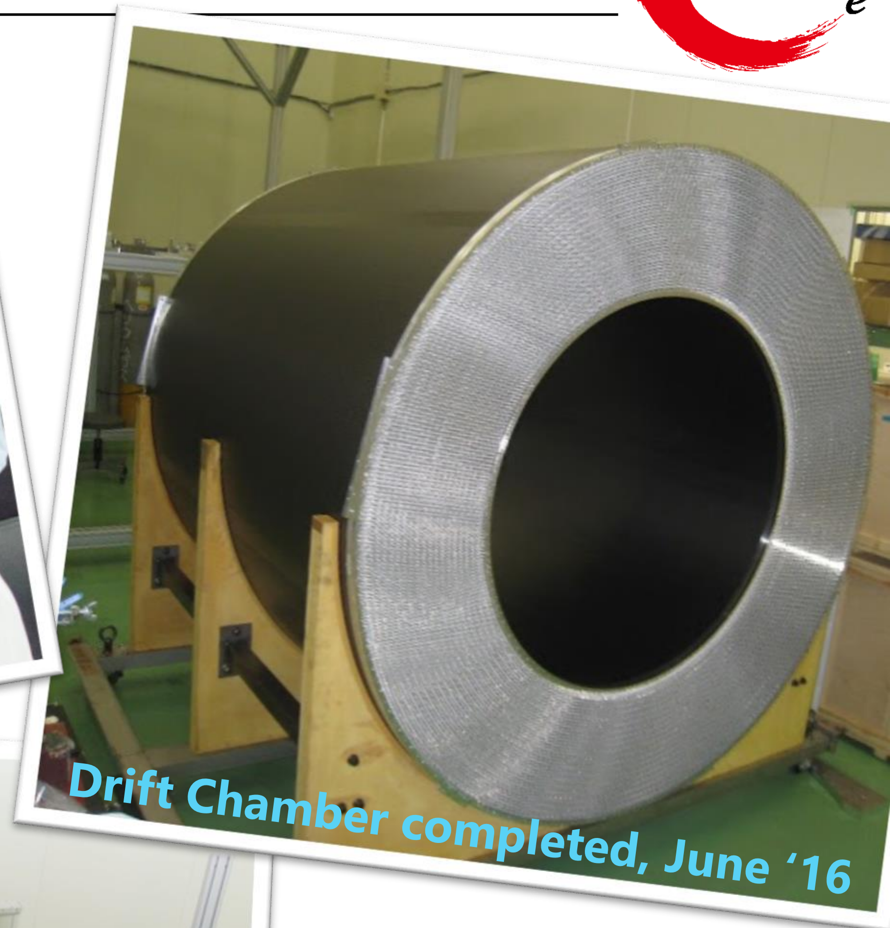
Phase I detector (CyDet)

- Aluminium stopping target at centre.
- Particle flux in central region is still very high → **Cy**lindrical **Det**ector system:
  - All-stereo-wire drift chamber
  - Hodoscopes for triggering and timing



CyDet construction

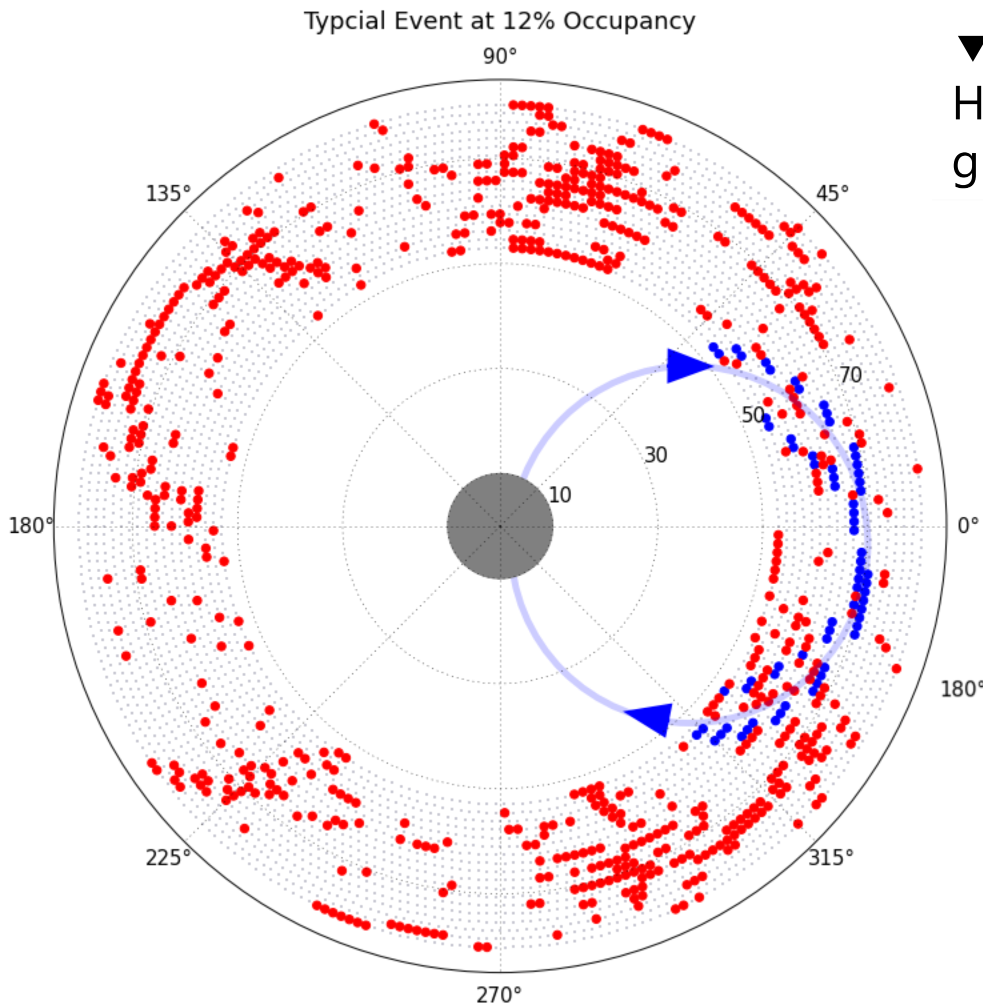
Checking wires, Dec '15



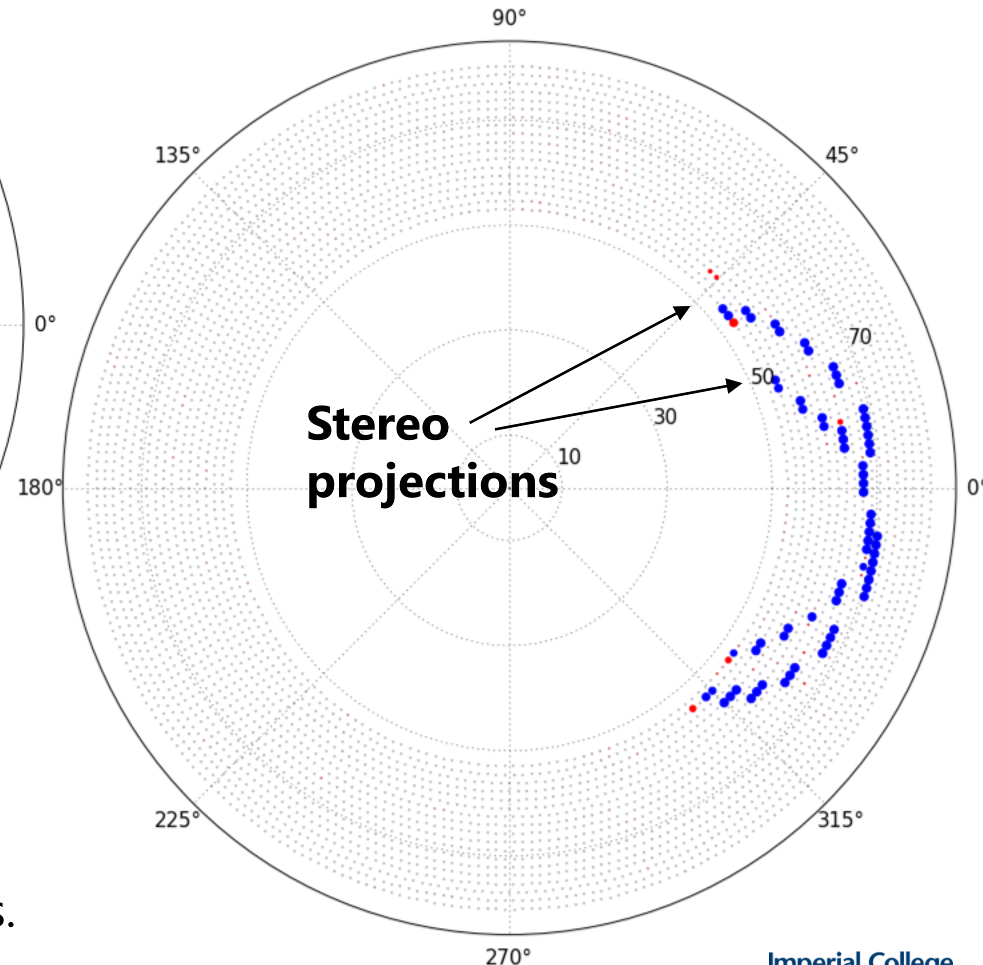
Drift Chamber completed, June '16

Installing inner wall

CyDet reconstruction



▼ **Signal** tracks picked out using Hough transform based discriminator, then given to Kalman filter for reconstruction.

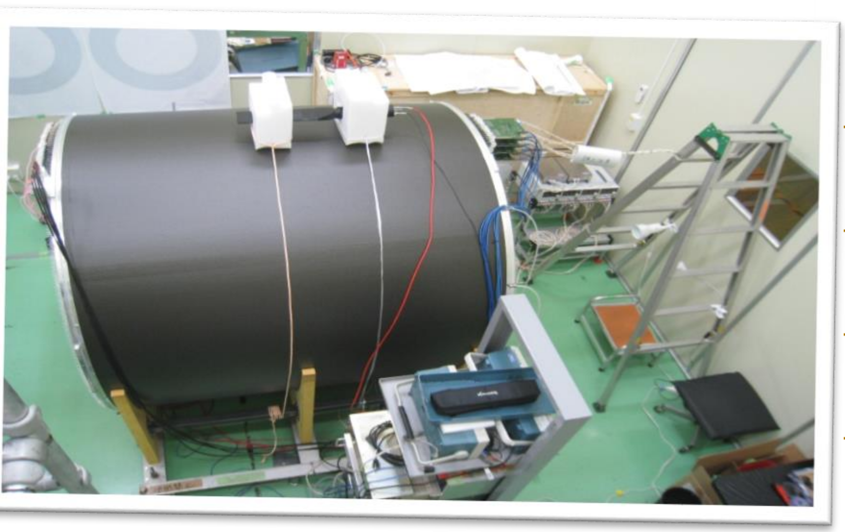


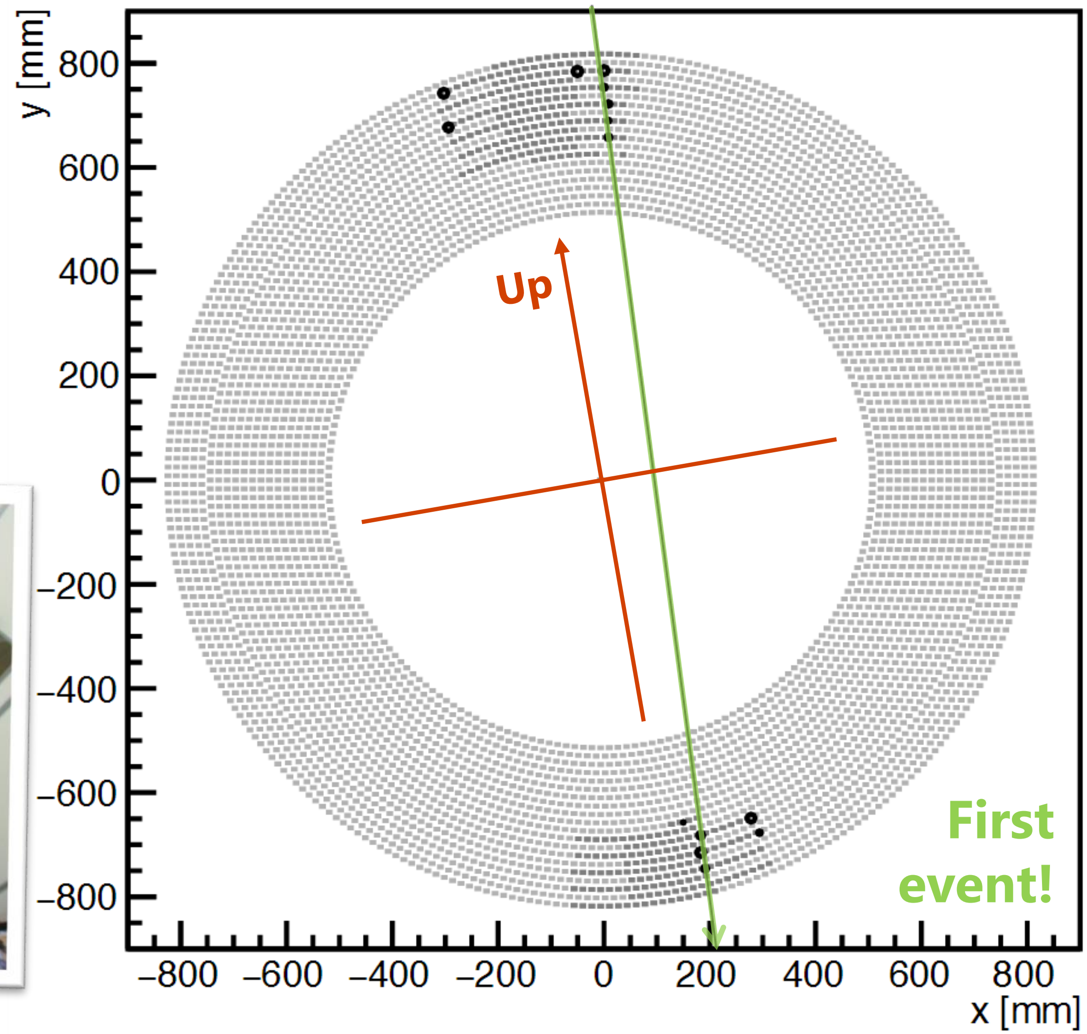
▲ Most **background** hits are rejected based on timing, charge, & local features.

CyDet Cosmic ray tests

CR test setup at KEK:

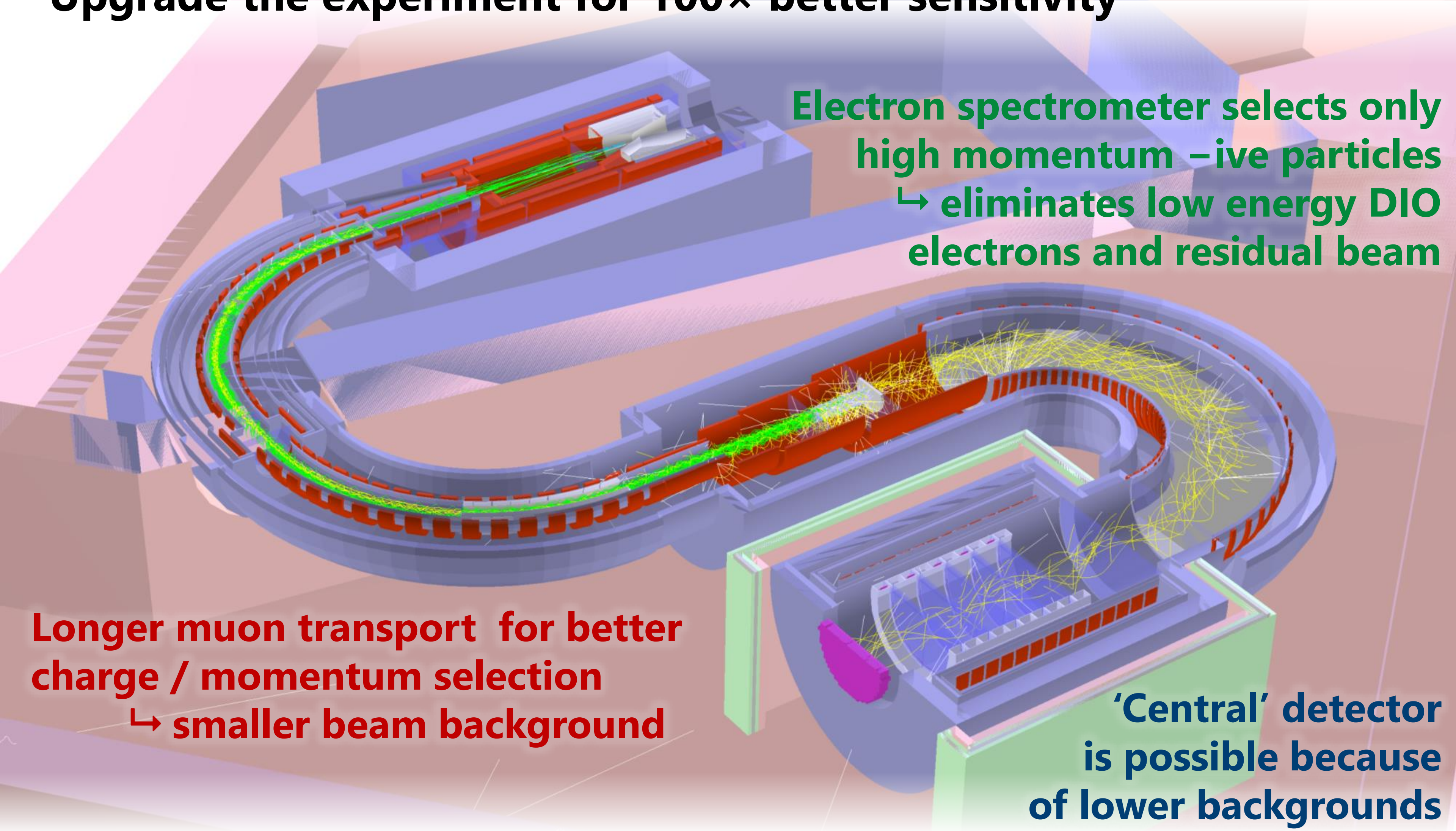
- Instrument detector with development DAQ
- Trigger with external hodoscope counters at top and bottom.



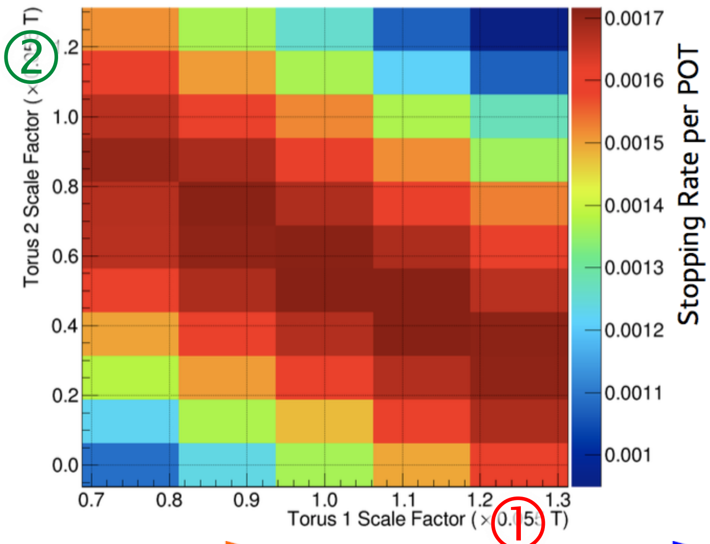


COMET Phase II

Upgrade the experiment for 100× better sensitivity



Phase II beamline optimisation

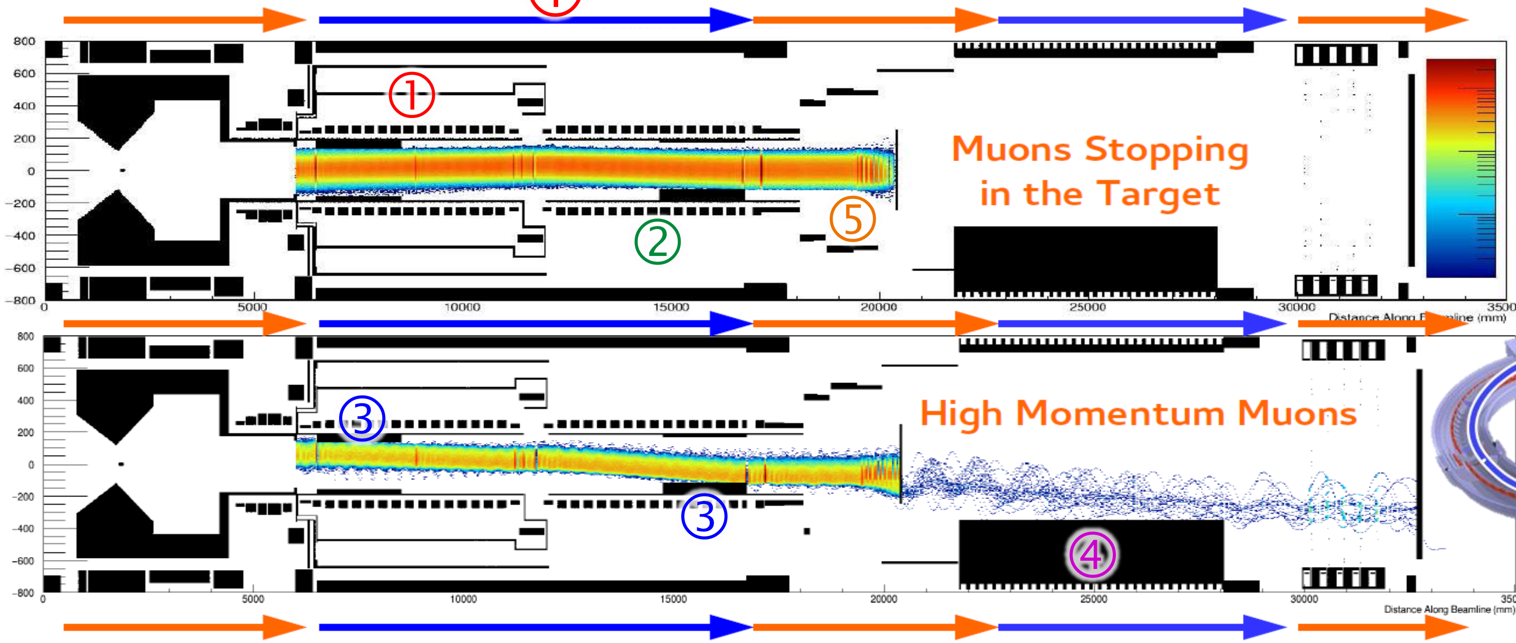


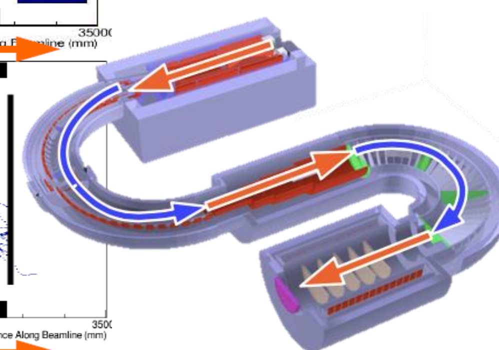
In parallel with Phase I construction, Phase II design is being optimised using integrated COMET simulation. Examples:

① ② Correcting dipole field strength

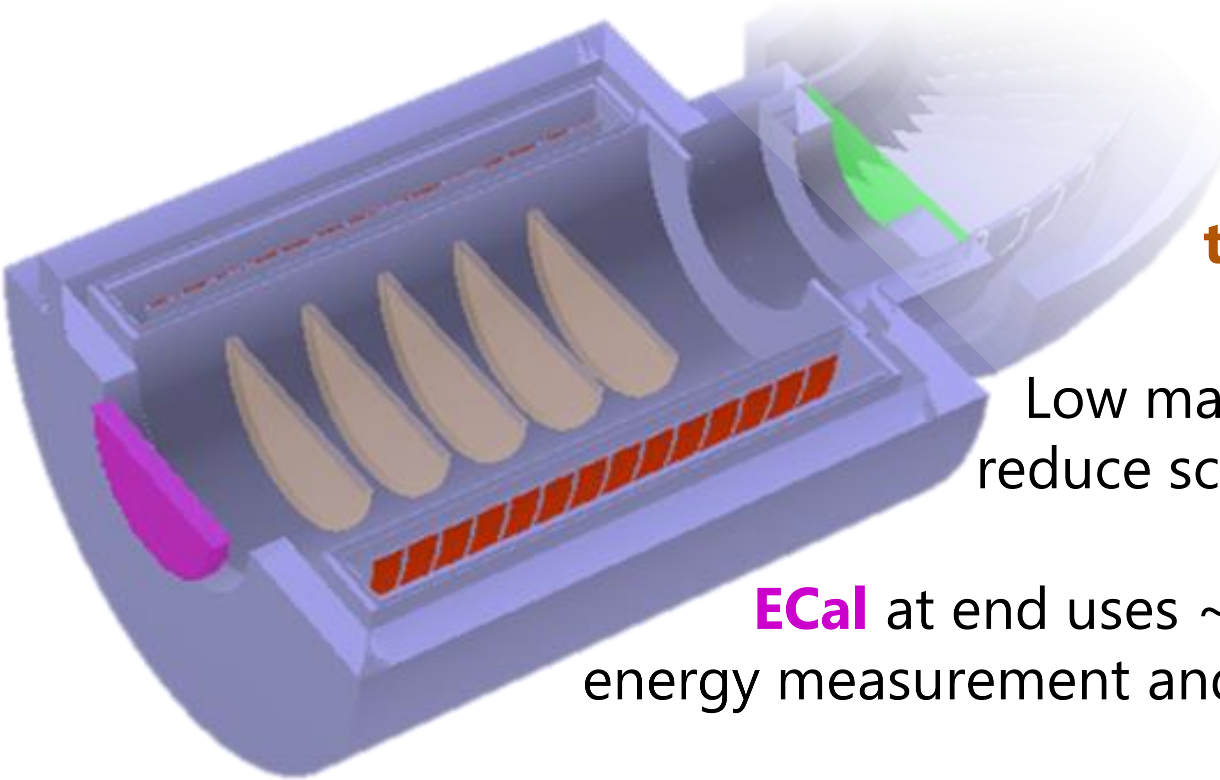
③ ④ Collimator positions

⑤ Target position & shape





Phase II detectors



5x4 planes (in base-line design) of **straw tubes** for tracking.

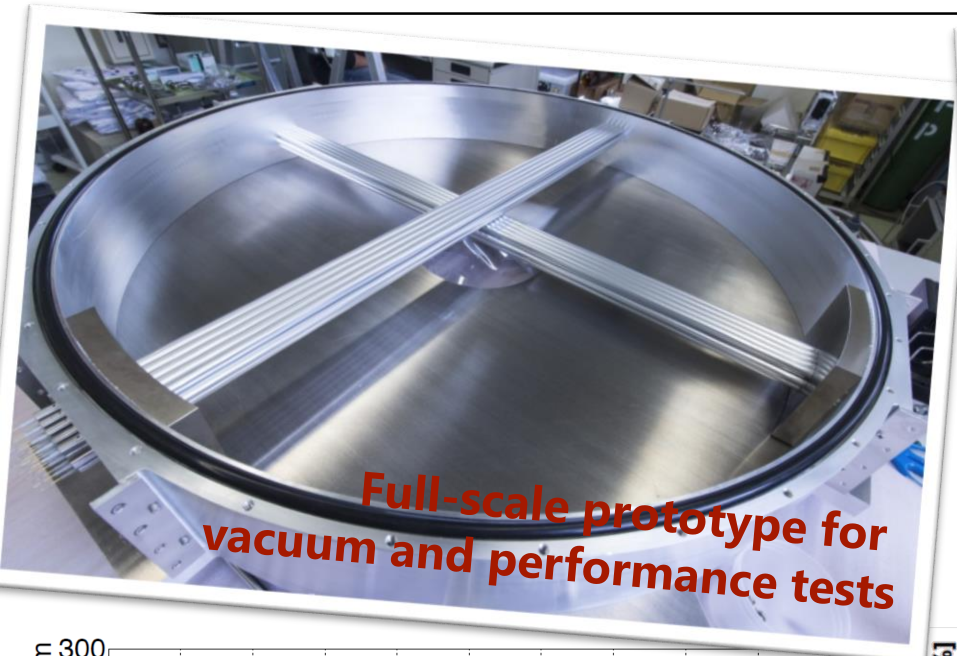
Low mass straw design to reduce scattering.

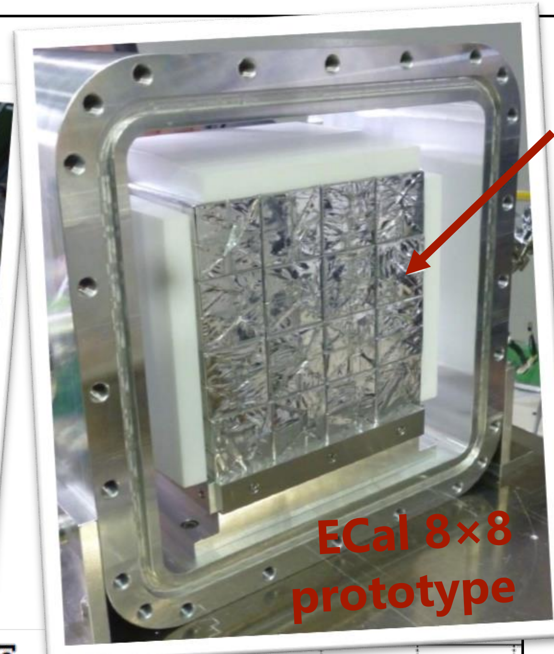
ECal at end uses ~2000 LYSO crystals for energy measurement and triggering.

Prototype version detector in development for Phase I, can be installed in place of CyDet.

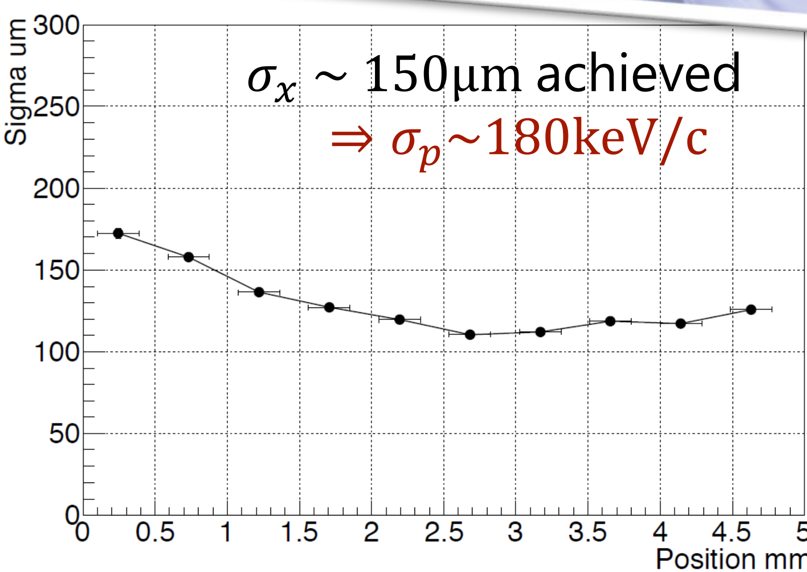
- Test design (e.g. new straw weld for lower mass) and readout
- Study particle content of secondary beamline to improve MC prediction (esp. for Phase II analysis)

ECal & Straw testing



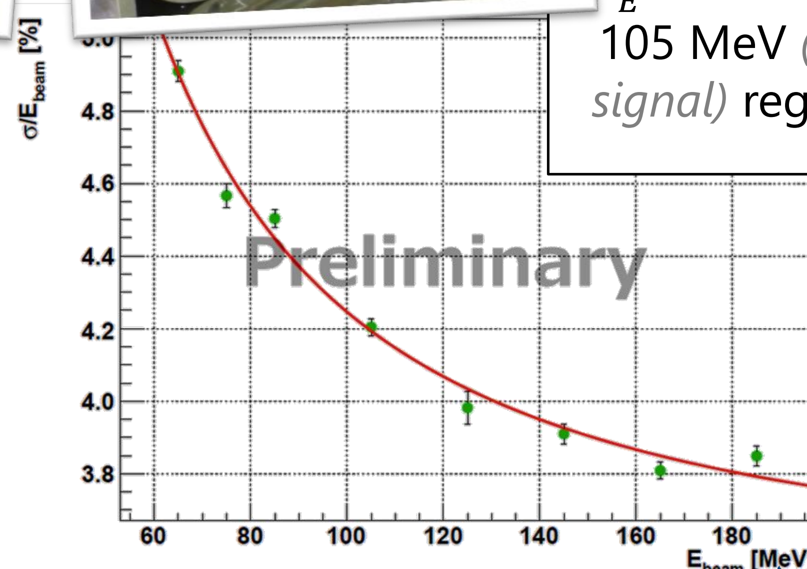


ECal Crystals
(2x2 bundle in
Al-mylar.)



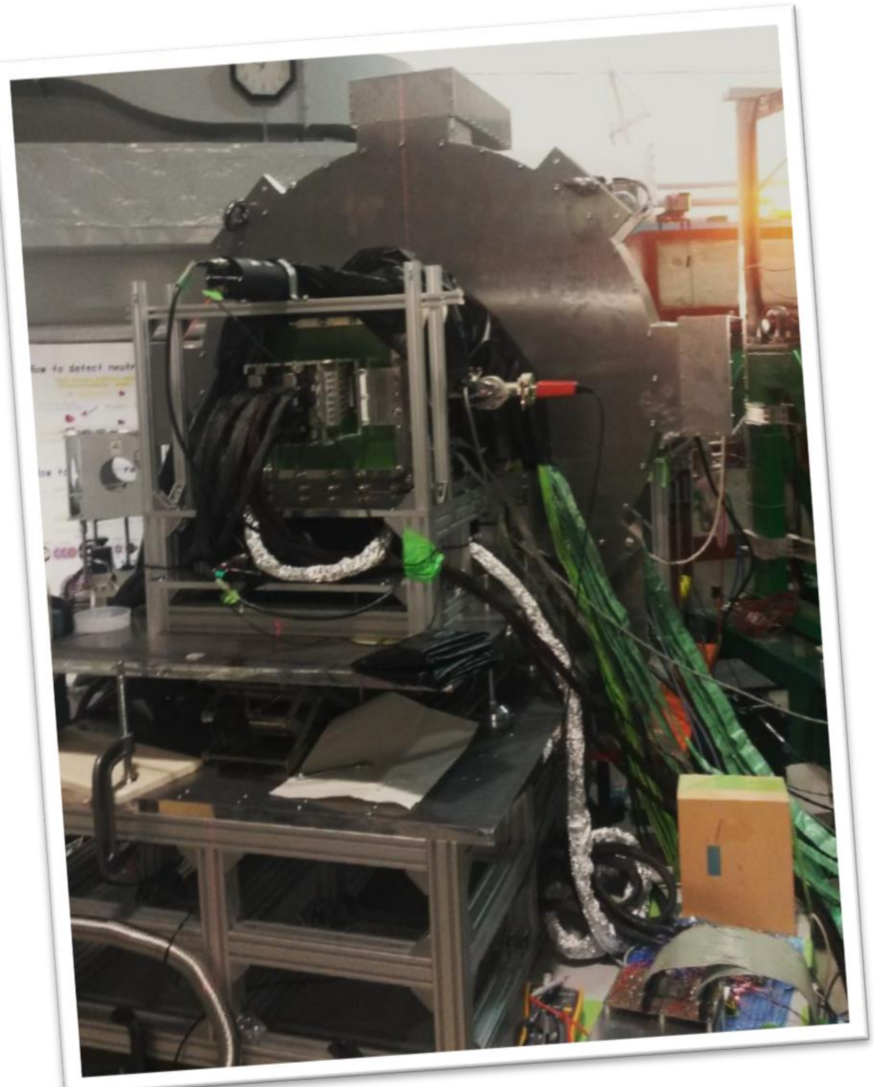
$\sigma_x \sim 150\mu\text{m}$ achieved

$\Rightarrow \sigma_p \sim 180\text{keV/c}$



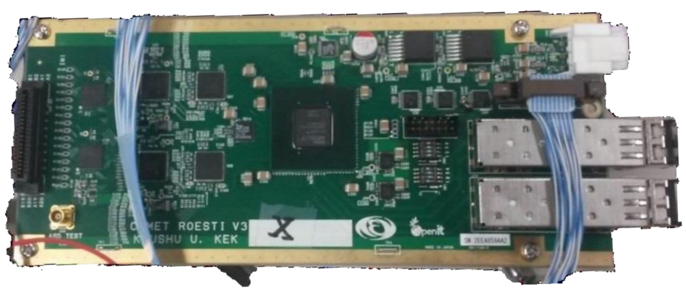
$\frac{\sigma_E}{E} \sim 4.2\%$ in 105 MeV *(i.e. signal)* region

Integrated test beam



Prototypes tested in combination at test beam (2017/03).
Included also prototypes for:

- Readout via ROESTI front ends



- DAQ based on MIDAS
- Fast control using FC7 board (from CMS)

Very successful! Finished all planned tests and more.

Sensitivity

Expressed in terms of $\mathcal{R} = \frac{\Gamma(\mu N \to e N)}{\Gamma(\mu N \to \nu N')}$

Define single event sensitivity (S.E.S.):

Value of $\mathcal{R}$ s.t. mean expectation is 1 signal event.

$$\therefore \text{S.E.S.} = \frac{1}{N_\mu \cdot g \cdot f \cdot A} \quad \text{where:}$$

$g = 0.9$ prob. for N to remain in ground state

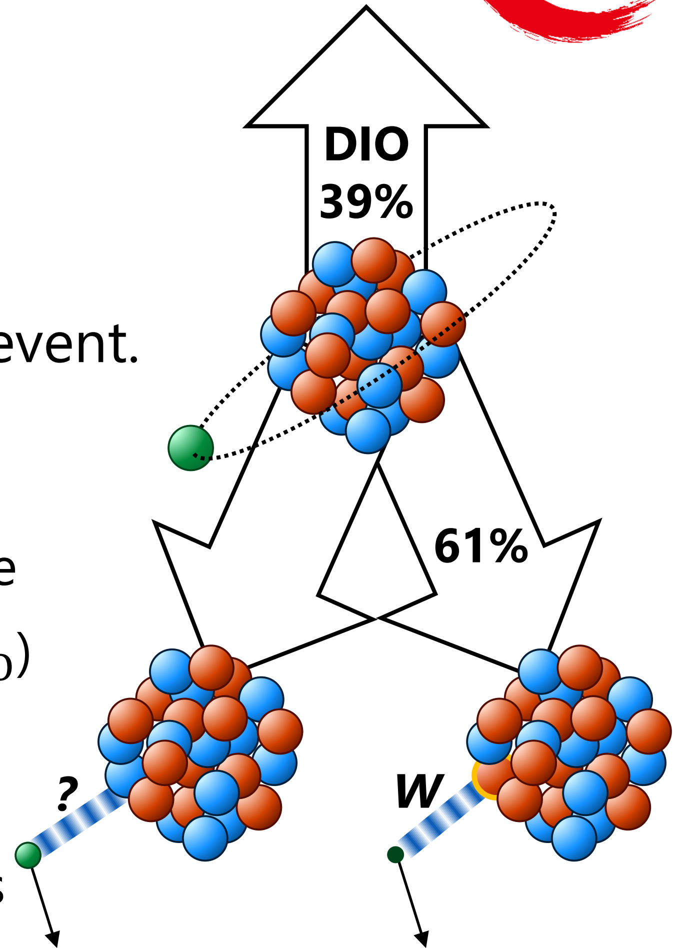
$f = 0.61$ fraction of nuclear capture $(1 - P_{\text{DIO}})$

In phase-1:

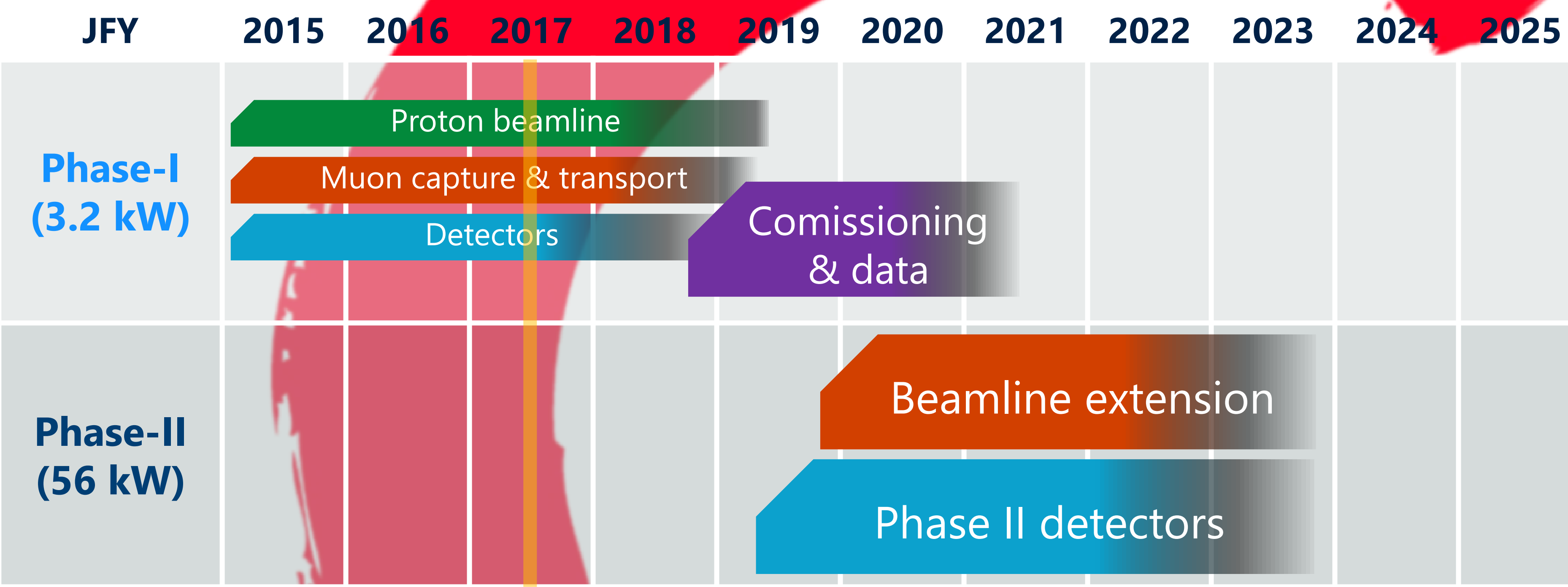
$N_\mu = 1.5 \times 10^{16}$ number of stopped muons

$A = 4.1\%$ is the signal acceptance

- Dominated by geometric (18%) and time (30%) acceptance.
- Selection for B/G of 0.03 events



COMET Timeline



Current limit [SINDRUM-II]: $\mathbf{7 \times 10^{-13}}$ **90% U.L.**

~2018: Start COMET Phase I; goal $\mathbf{3 \times 10^{-15}}$ **S.E.S.** (~ 5 mo)

COMET Phase II goal $\mathbf{2.6 \times 10^{-17}}$ **S.E.S.** (~ 1 year)

- Accumulates statistics very quickly thanks to high power 56kW beam from J-PARC main ring

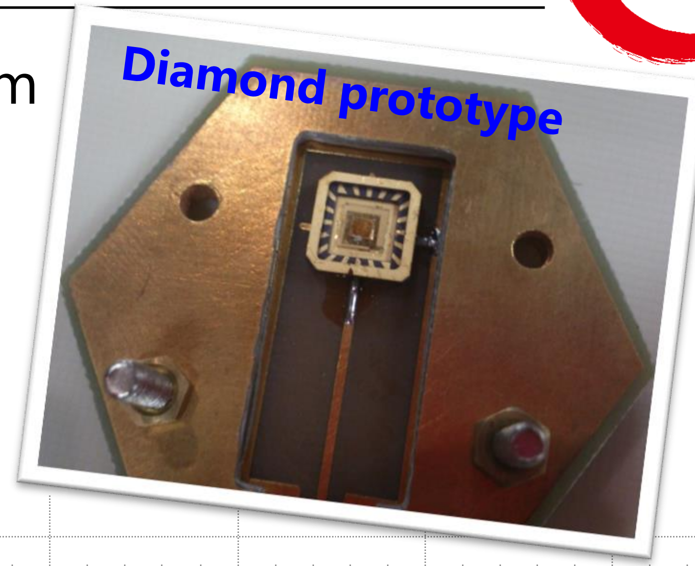
Reserves

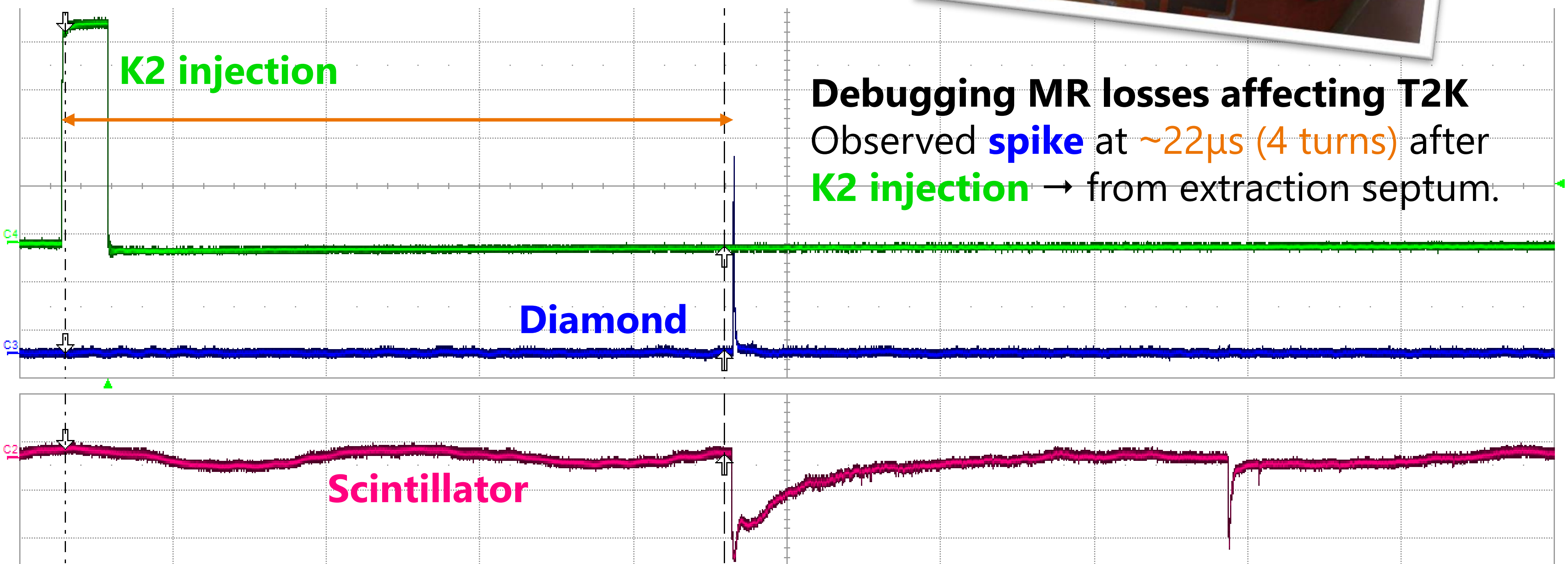
Caveat emptor: mostly from old talks, not guaranteed to be up to date

Beam monitoring

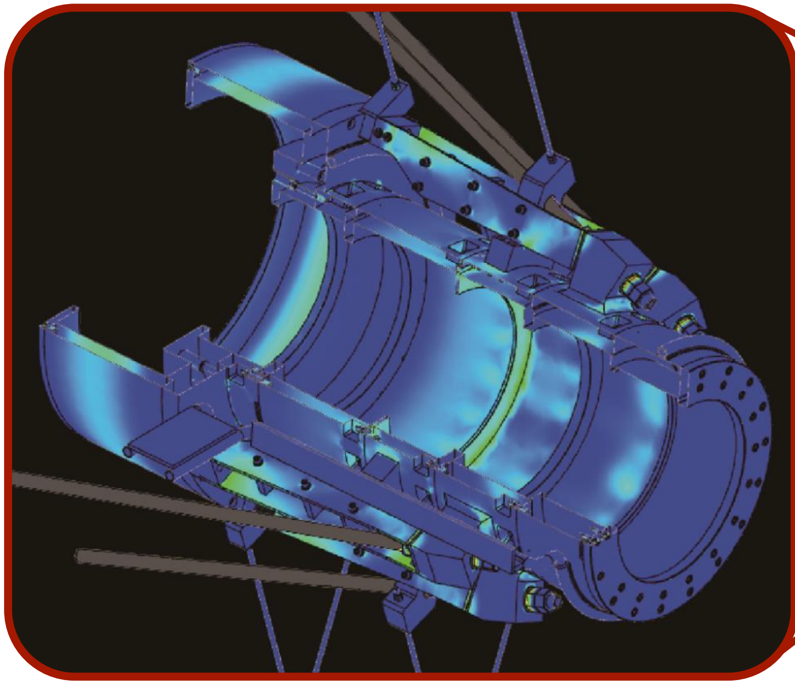
Plan to use diamond detector(s) for beam monitoring.

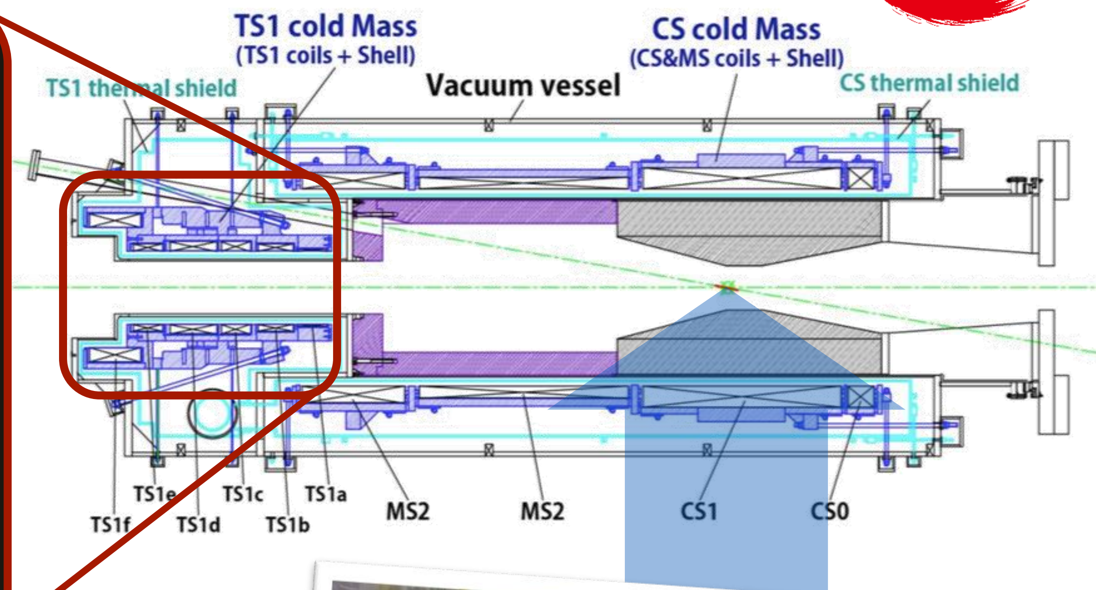
- Mainly for extinction monitor, but could have position monitor as well.
- Prototype tested (2016/11/24~) beside MR abort line.





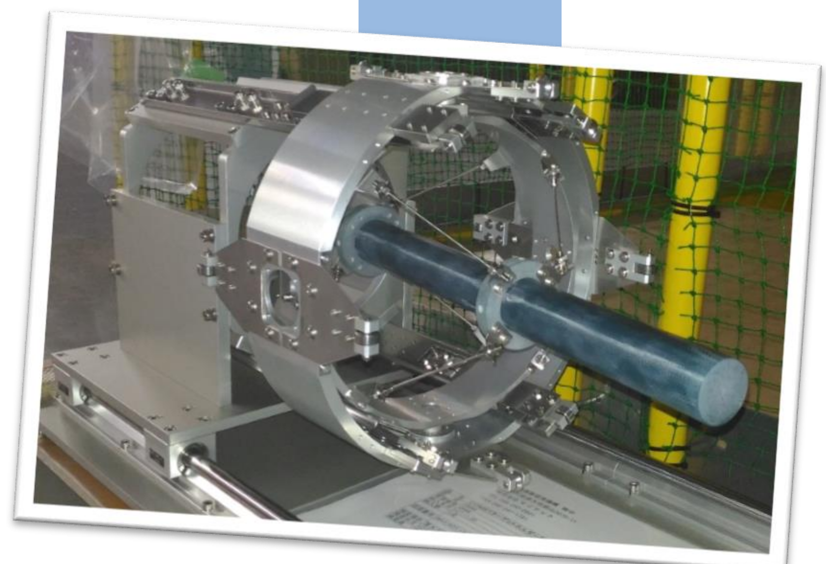
Production region developments





▲ Stress calculation for TS1 (first transport solenoid). Coil winding is almost complete.

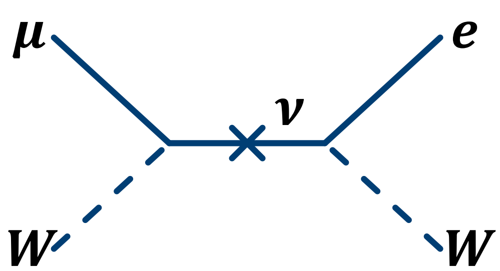
▶ Pion target (graphite: IG-43) and insertion mount constructed



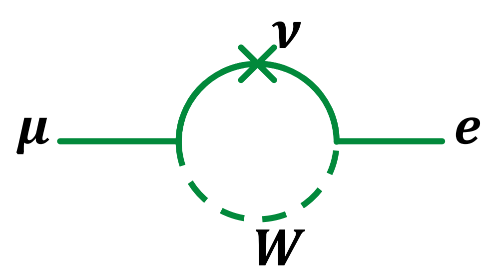
Charged lepton flavour violation

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



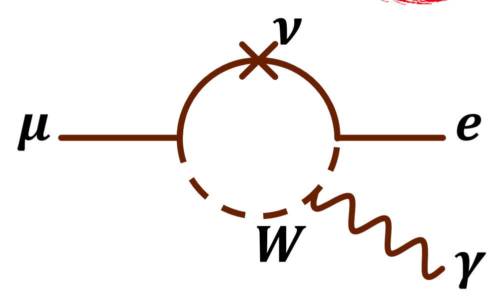
$\mu - e$ transition (without radiation)

- 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:

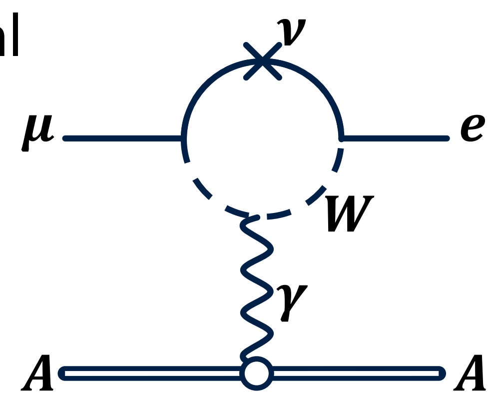
$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim O(10^{-54})$$



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

For a free muon, γ or ee are the only options…

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



$\mu - e$ conversion

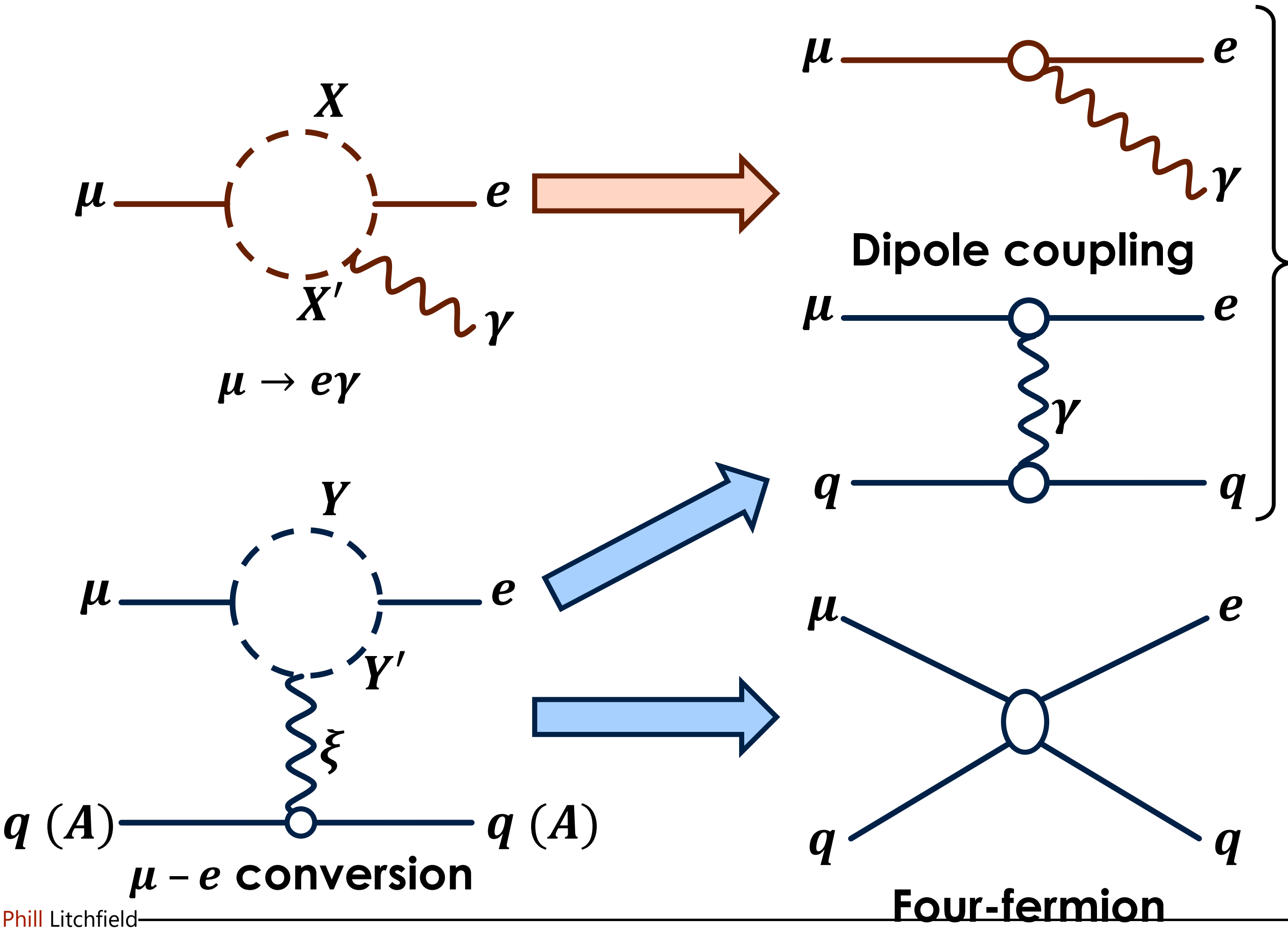
- Because of the relatively large nuclear mass, the electron is effectively mono-energetic.
- Because the process does not require a 'real' photon, other diagrams are possible…

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:



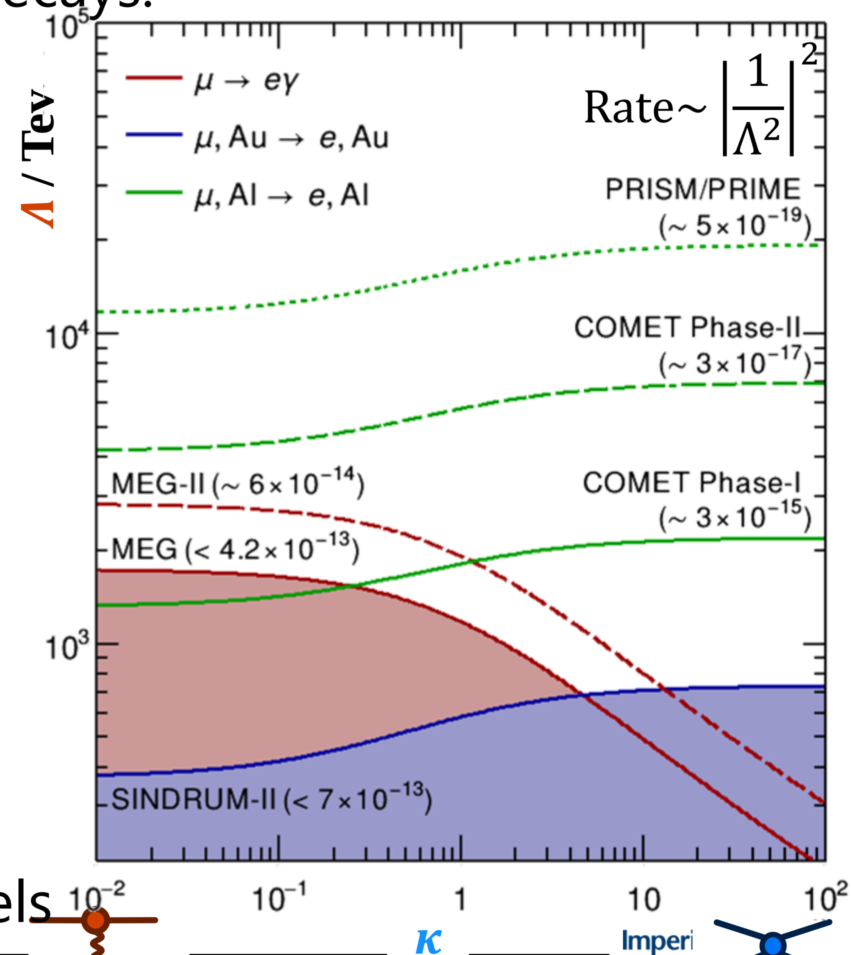
$$\mathcal{L}_{\mathrm{d}} \sim \frac{m_\mu}{\Lambda^2}\ \bar{\mu}\sigma_{\mu\nu}e \cdot F^{\mu\nu}$$

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

$\mu N \to eN$ 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.

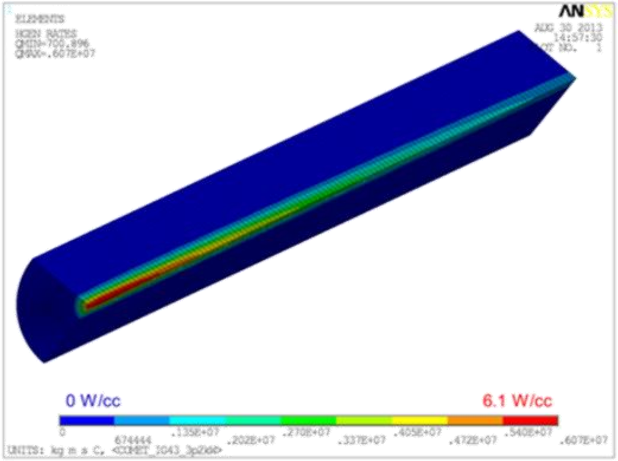
- More sensitive to some models.
- (If signal seen) the comparison allows discrimination between models

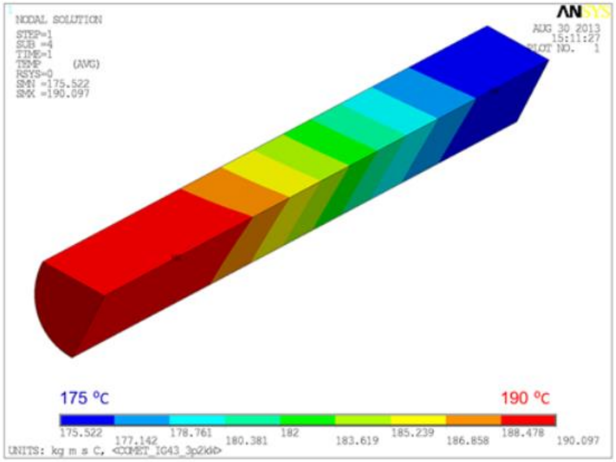
Production target

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:

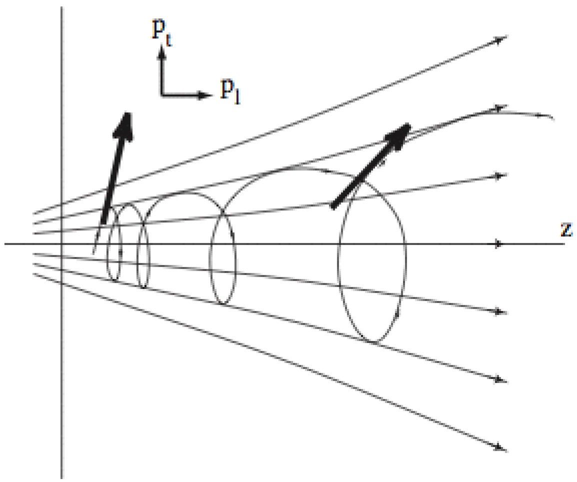
- IG-43 is used for T2K target (FX, >200kW beam) so is known to be capable of handling our beam.
- Lower irradiation of target and shield makes removal and storage safer in case of replacement in Phase-II
- At Phase-I power, radiative cooling is sufficient for this target.

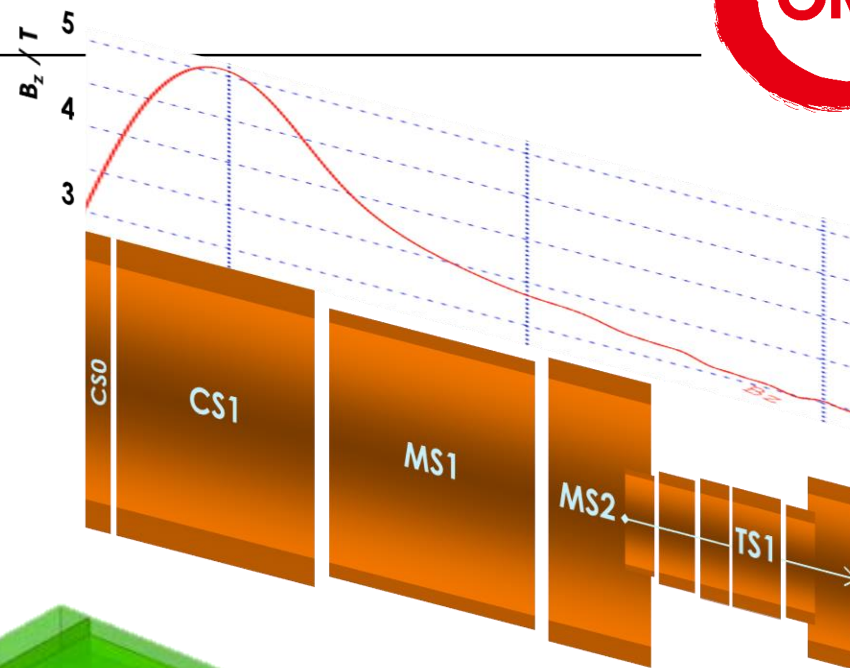


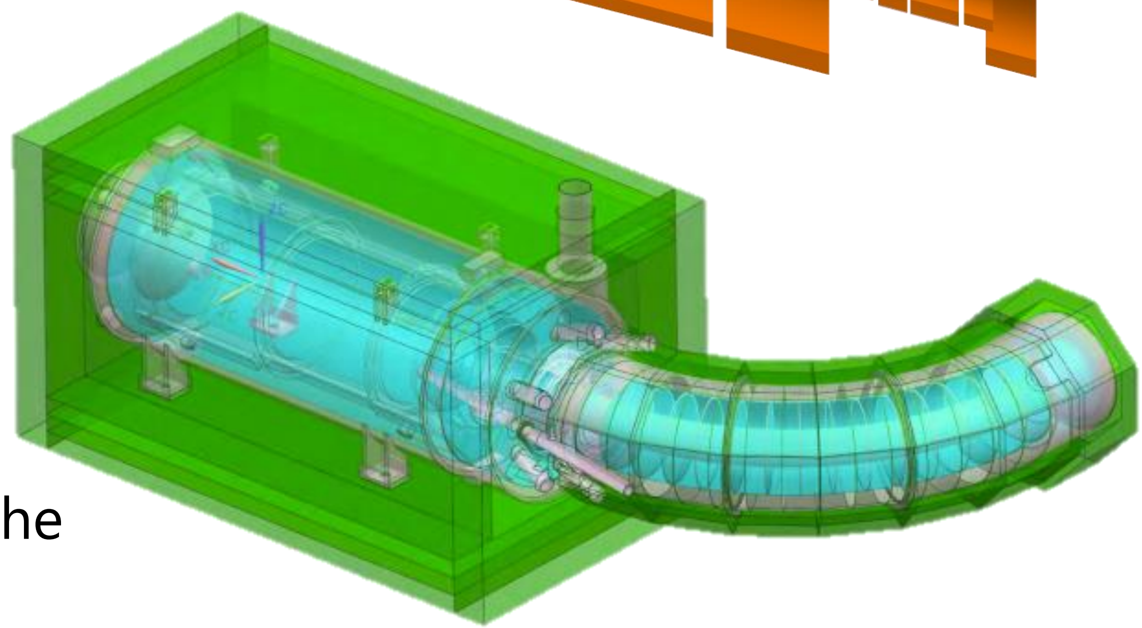


Capture Solenoid

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







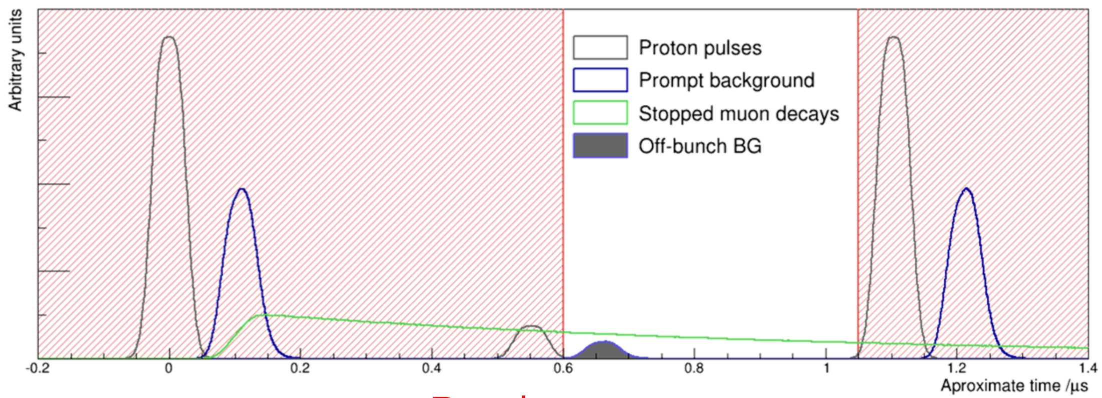
Gradient field converts transverse momentum into longitudinal momentum.

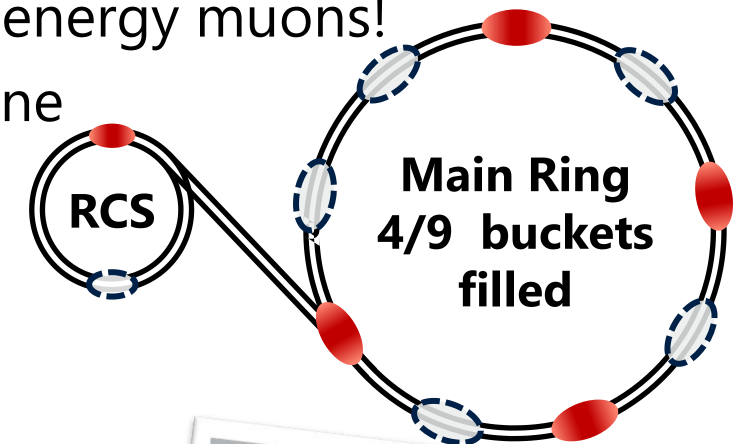
- Effectively increases the solid angle aperture into the transport solenoid.

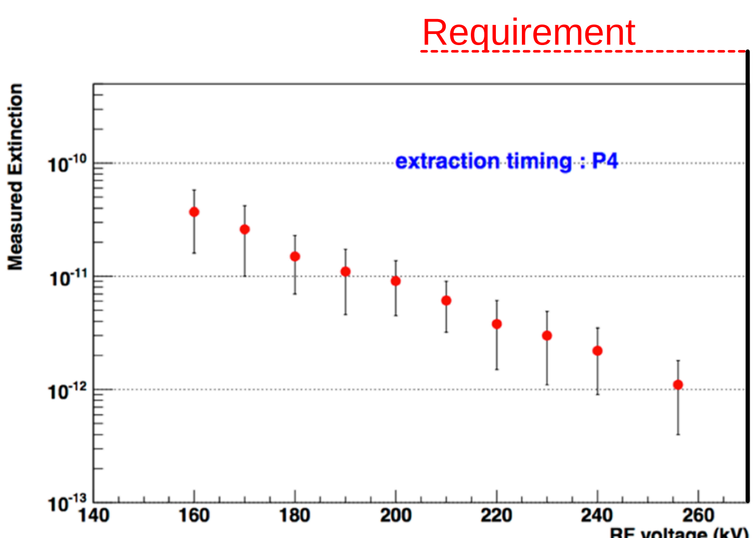
Primary beamline

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

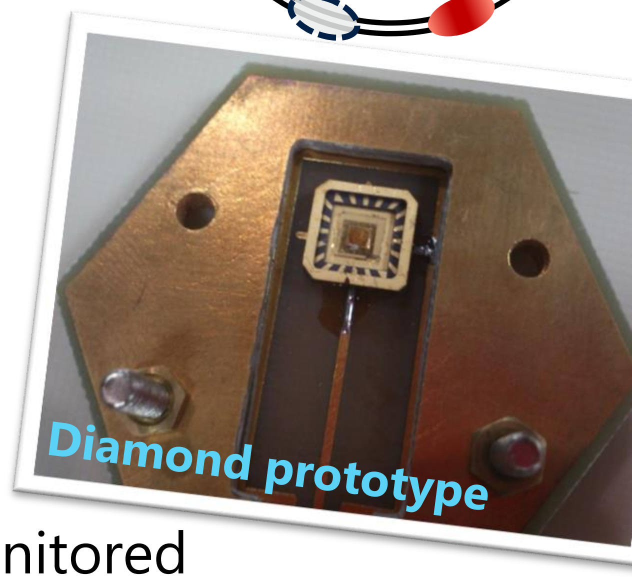
- Use high-power ***pulsed* proton beam** line (8 GeV) with resonant slow extraction







Strict ***extinction*** requirement of $< 10^{-9}$.



Beam will be monitored with diamond detector

Cooling and shielding

A 5T solenoid is (unsurprisingly?) superconducting.

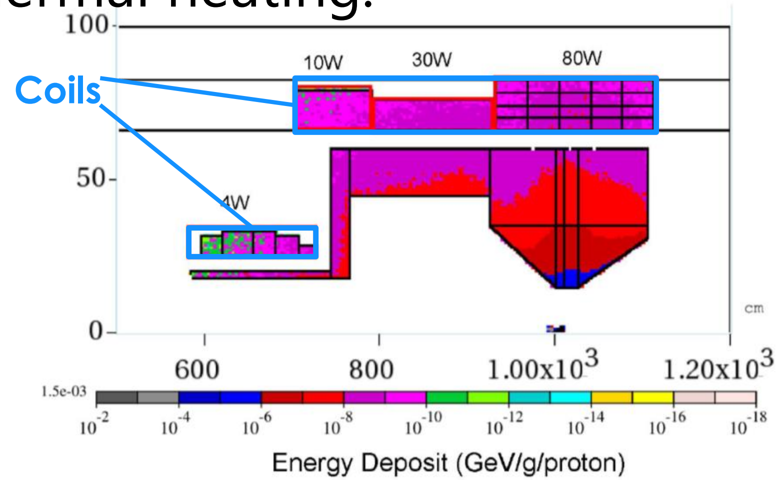
- And therefore cryogenically cooled…

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]

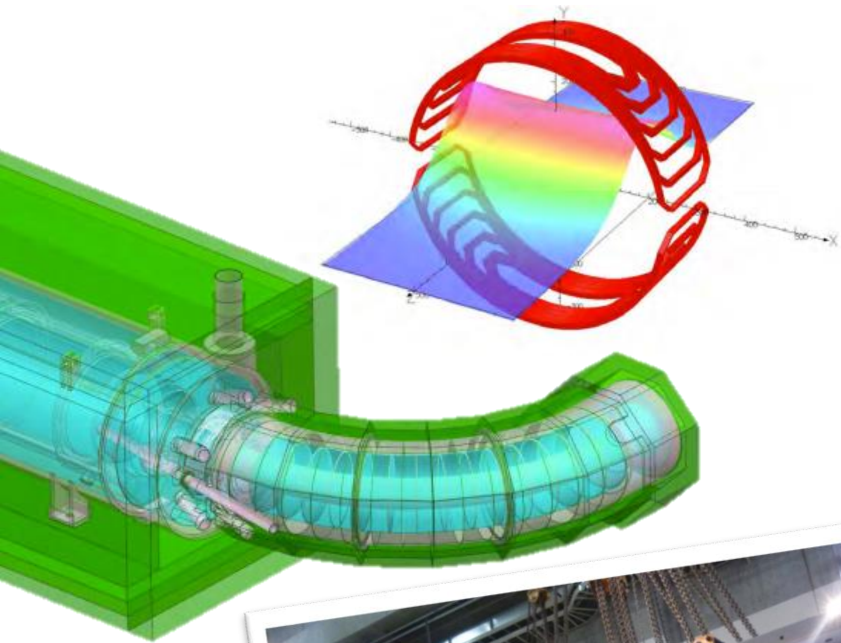
Shielding is needed, for radiation and thermal heating.

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



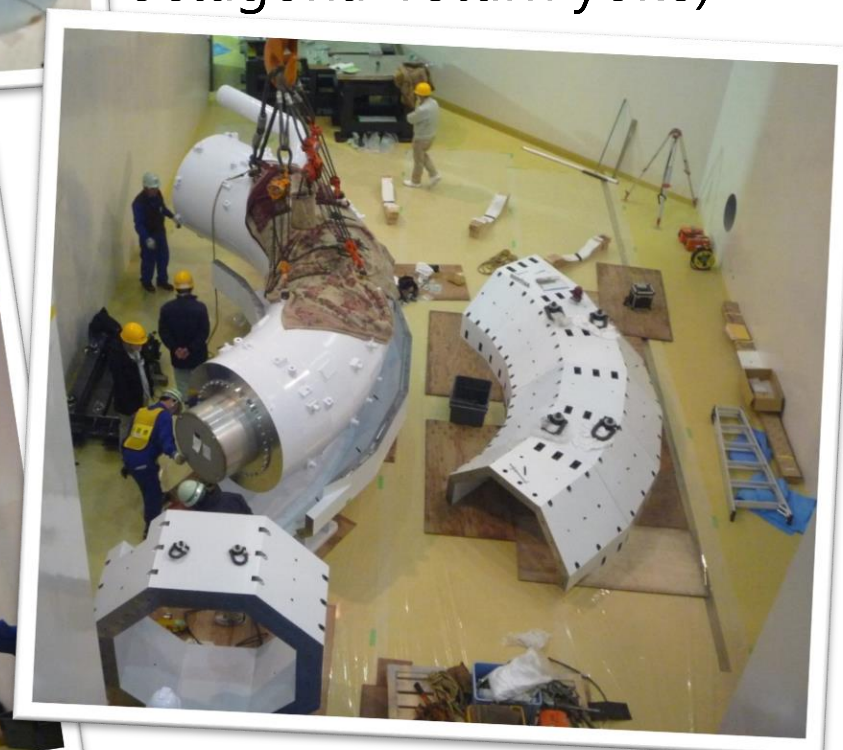
Non-trivial engineering challenge!

Transport Solenoid

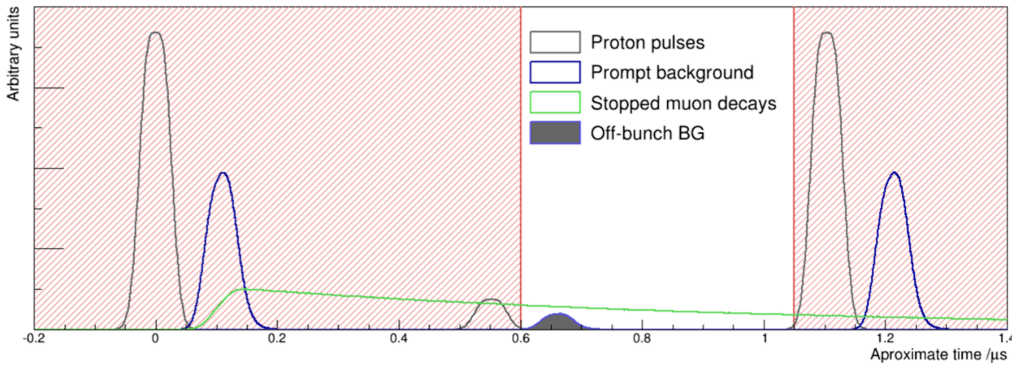


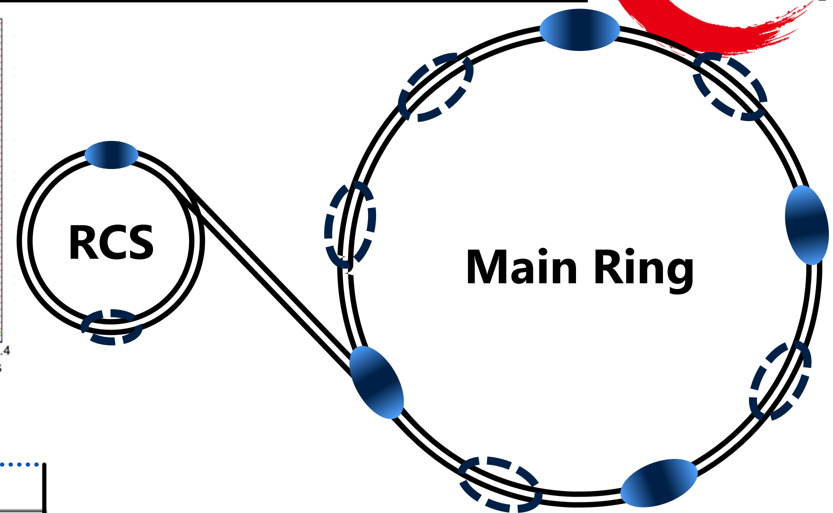
◀ Corrective dipoles

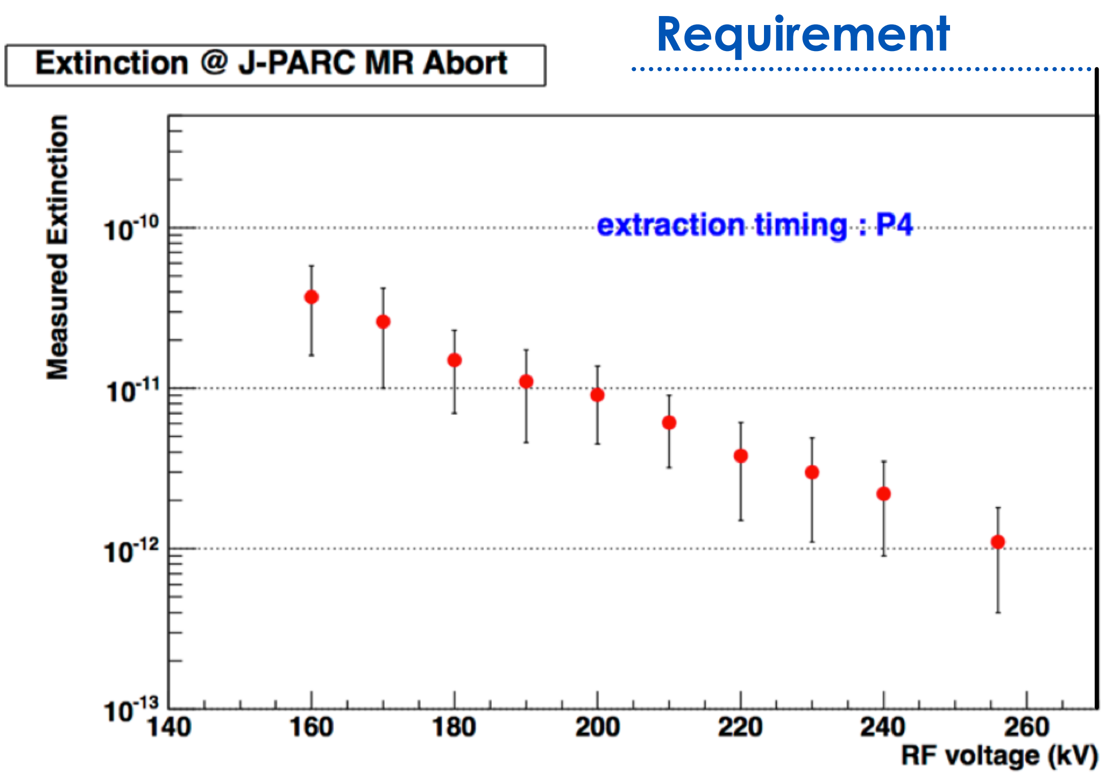
▼ Completed 90° muon transport arc (including octagonal return yoke)



Extinction test







Comet requires extinction:

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

Important test in May 2014:

Excellent results!

Phase-I Detector

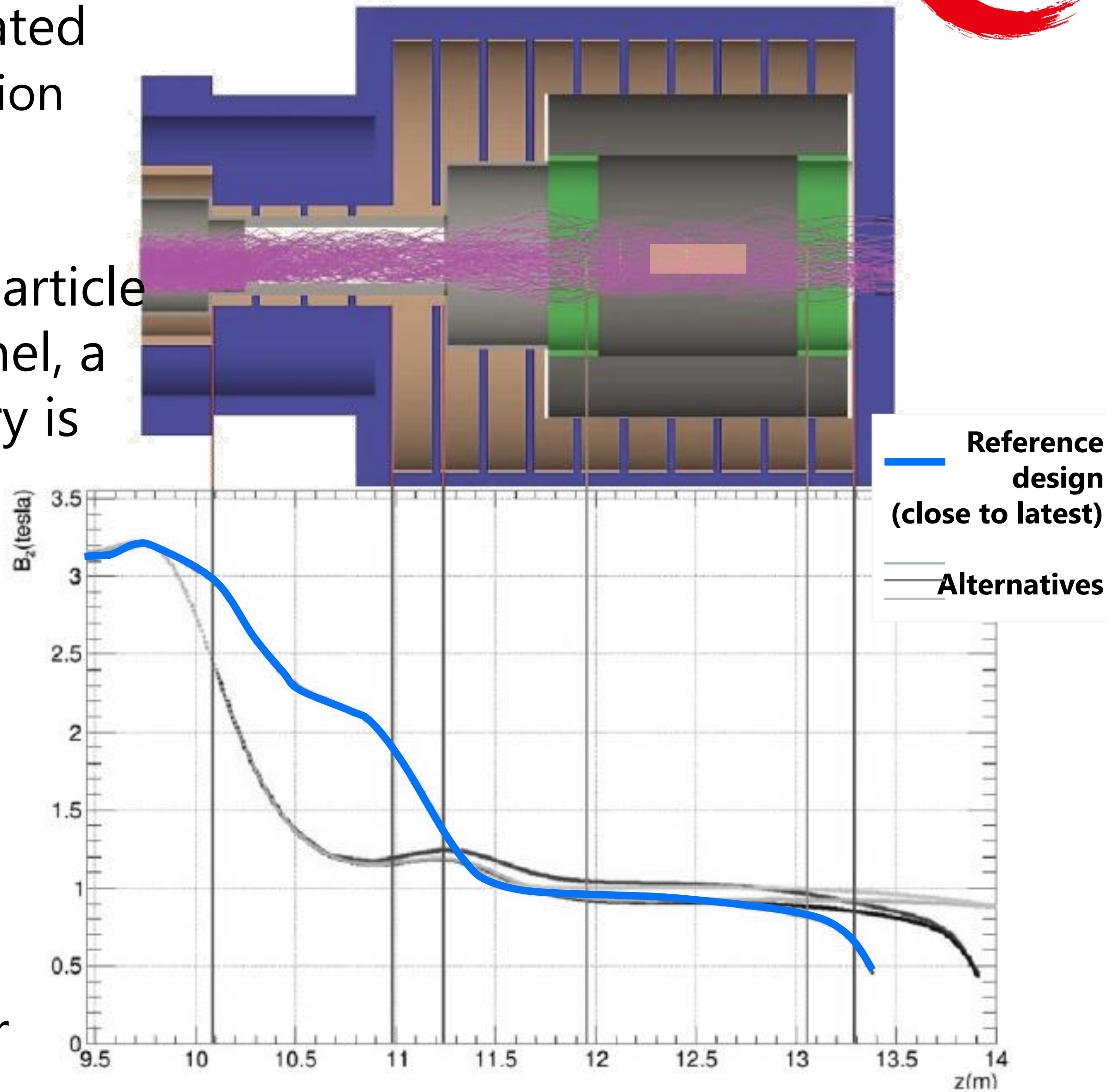
Phase-I will have a dedicated detector for $\mu \rightarrow e$ conversion measurements.

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

↳ **CyDet**

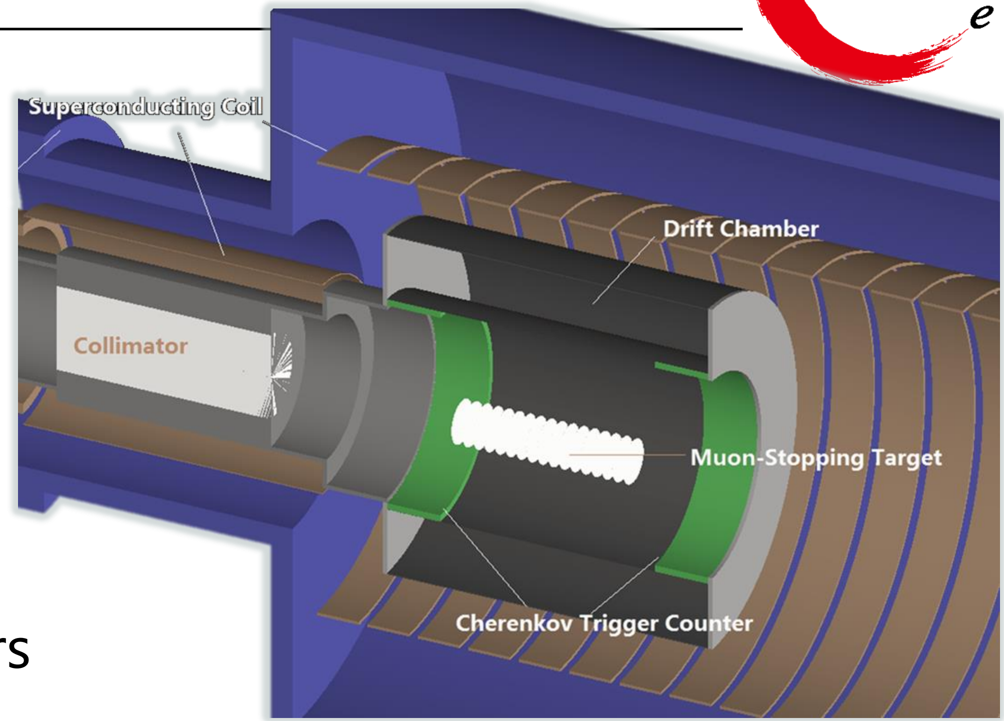
The detector and capture target will sit within a 1T solenoid field.

Low momentum particles do not reach the detector

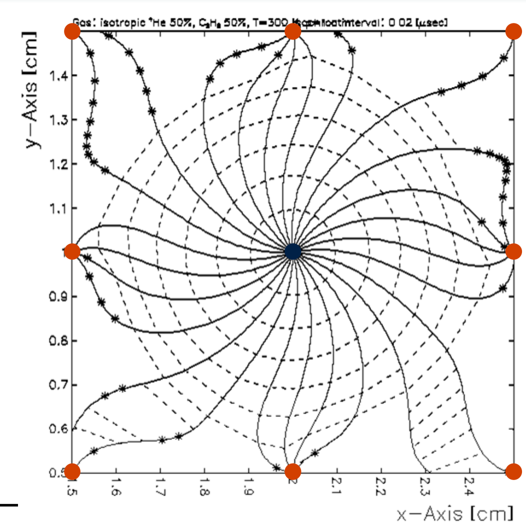


CyDet

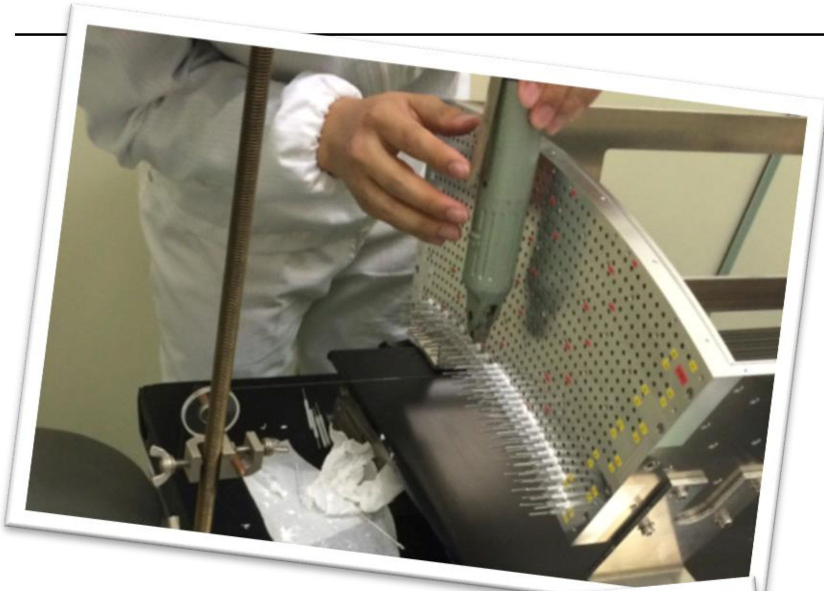
The main part of the detector is a coaxial **drift chamber**

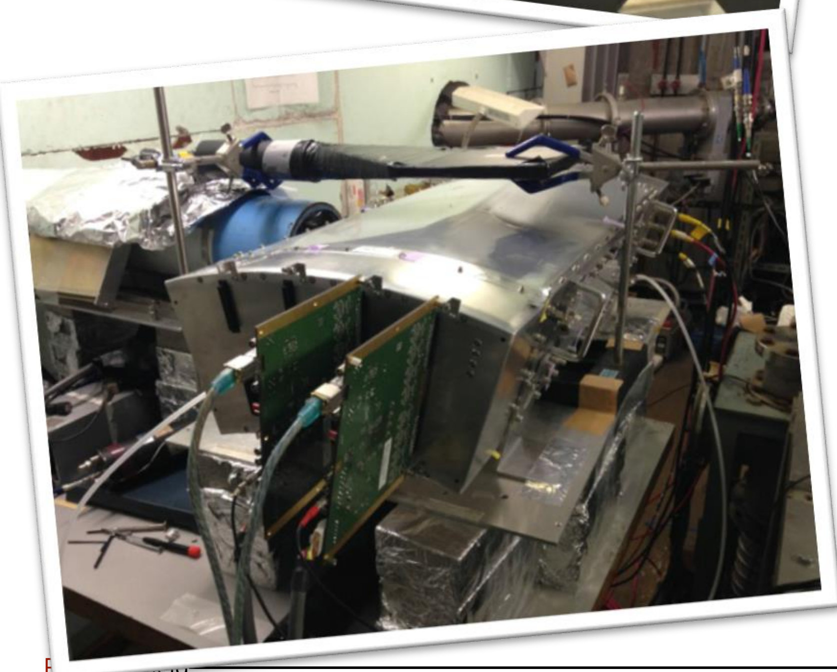


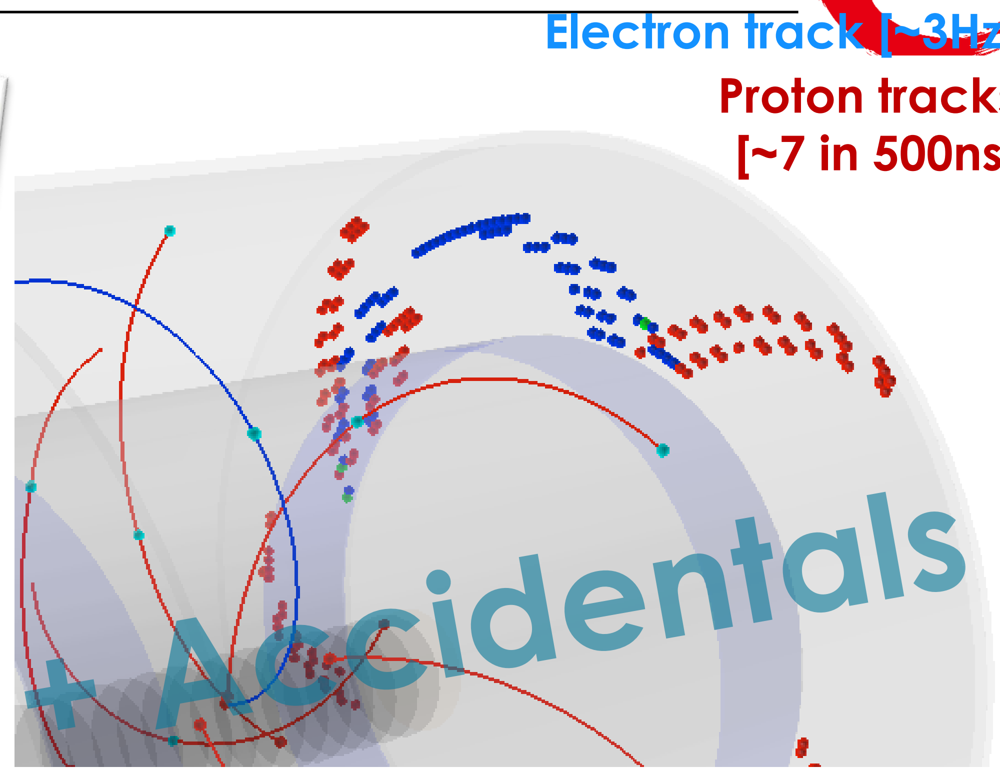
- Helium-based gas mixture to reduce multiple scattering.
  - Resolution ~ 200 keV
- z measurement by stereo layers
- Large inner radius to reduce DIO hit rate
  - Dim: 150cm × 84cm(outer) // 50cm(inner)
- 19 concentric sense layers
- Triggering from **hodoscopes** at ends



Drift chamber progress

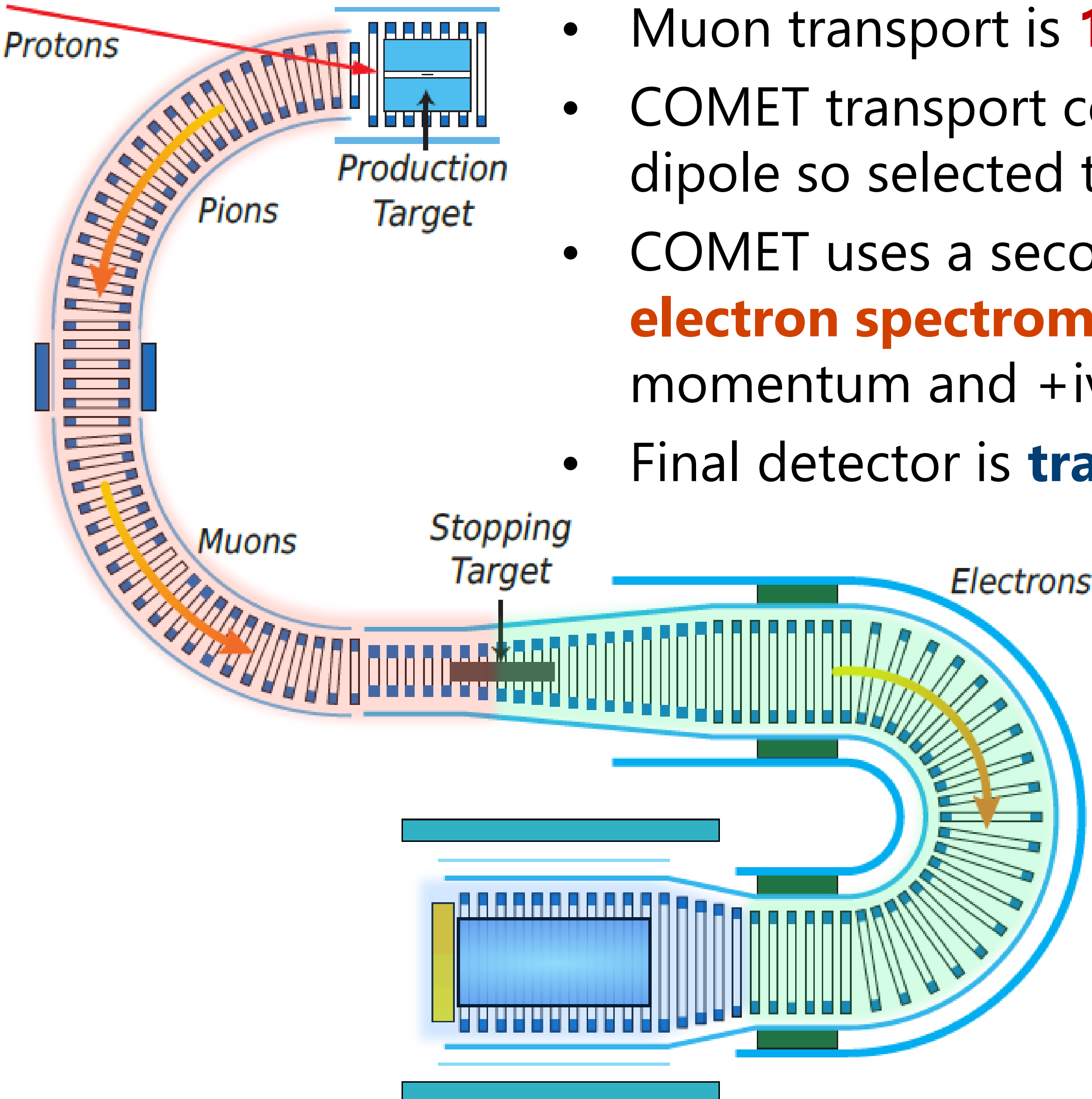






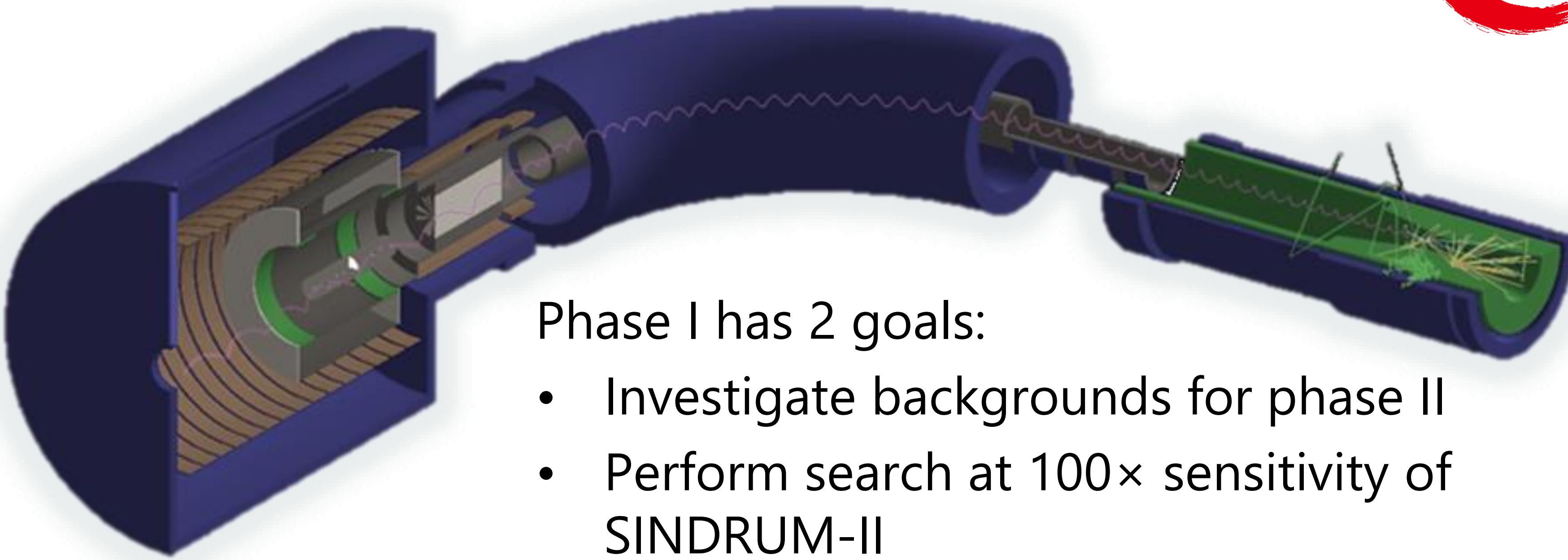
- ▲ Event display showing event projection
- ◀ Stringing wires and CR test of prototype section

In time-reversed 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



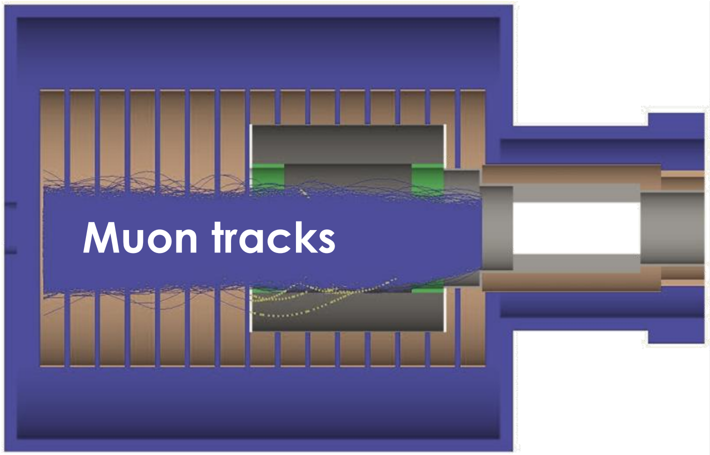
Phase I has 2 goals:

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

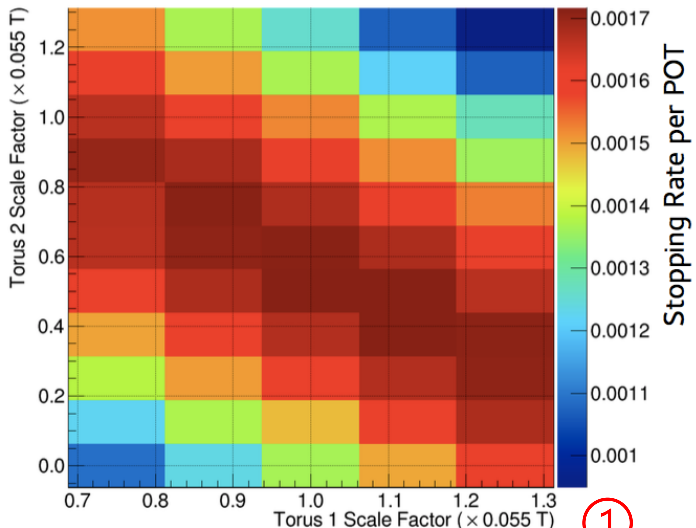
For Phase I measurement use a **cylindrical drift chamber** around the stopping target.

- Triggering by **auxillary hodoscopes**

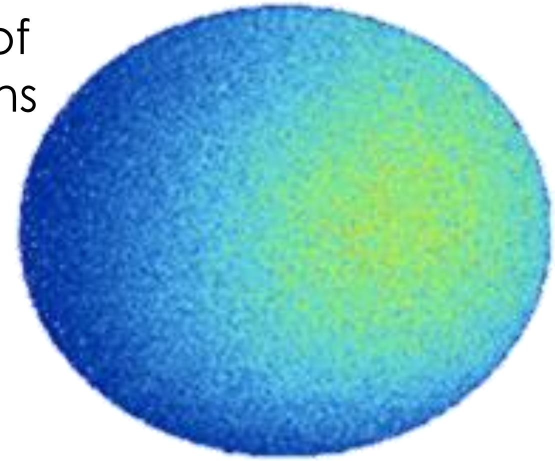
Also include prototypes/partial elements of Phase II detectors for development and characterising backgrounds at low current

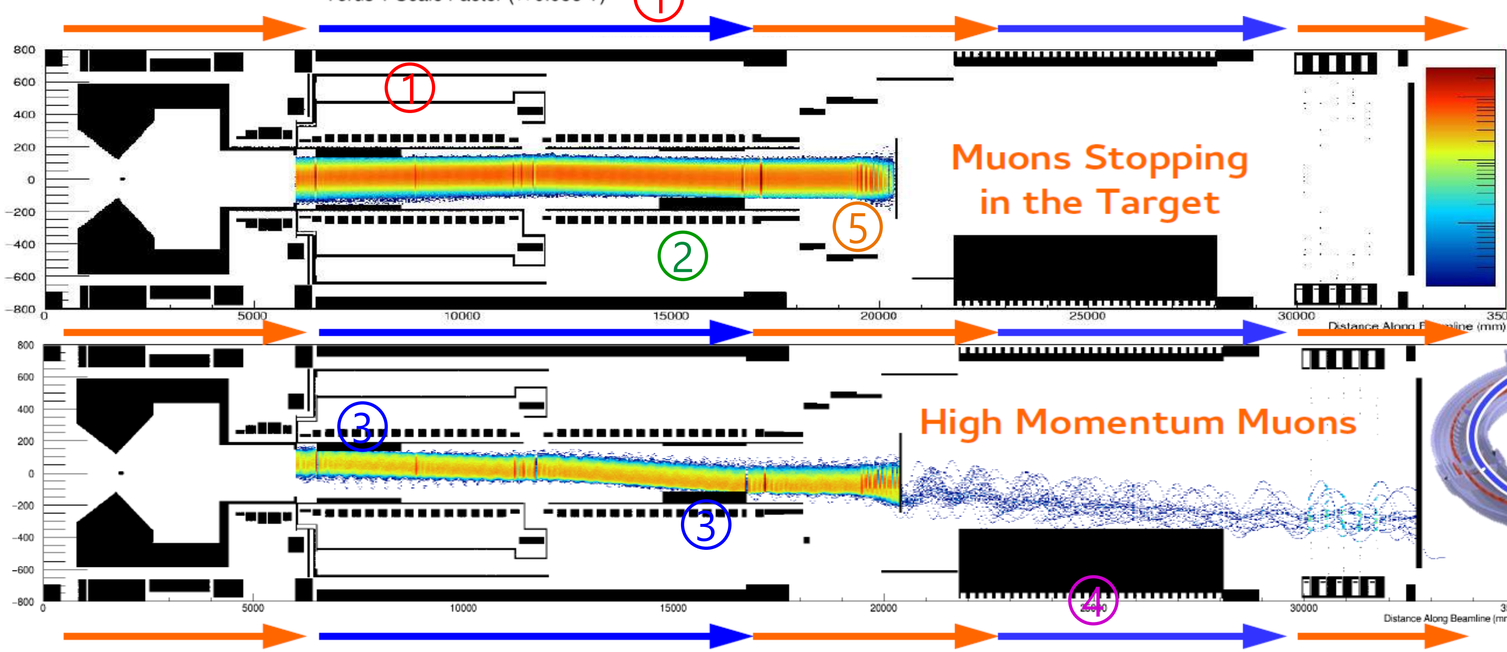


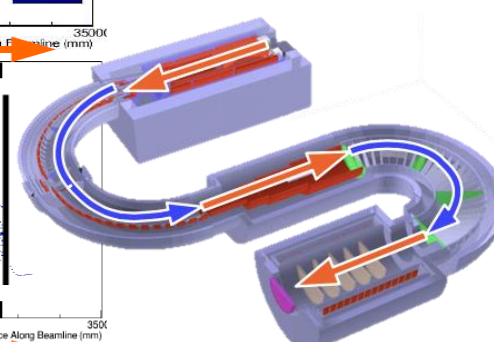
Phase II beamline optimisation



- Distribution of stopped muons







COMET developments

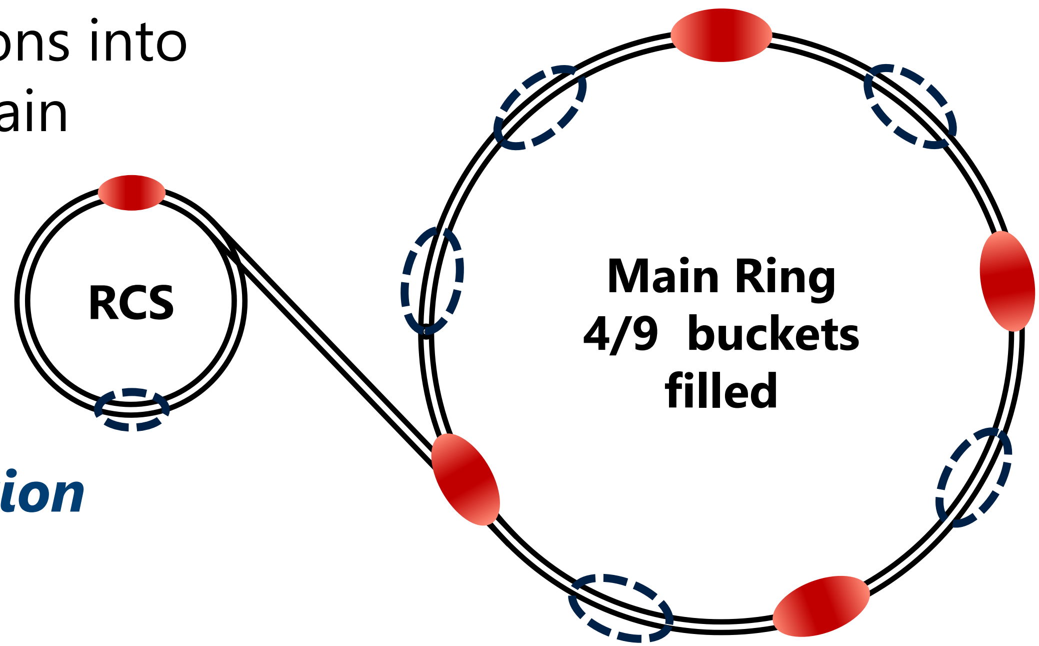
◄ COMET hall construction completed!

▲ Magnets laid-out for new beam switchyard

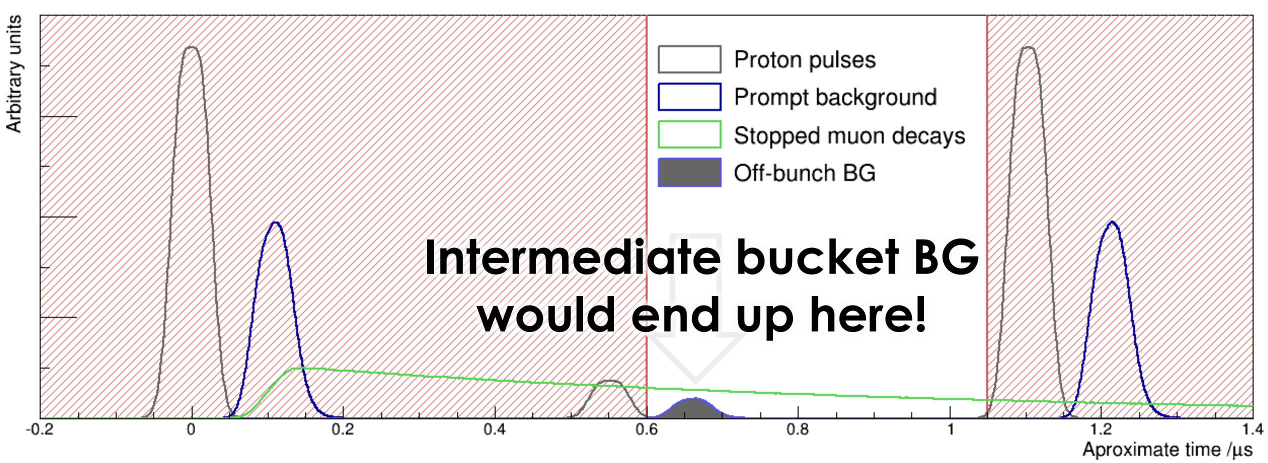
Really beam-free windows?

Synchrotrons have stable acceleration buckets

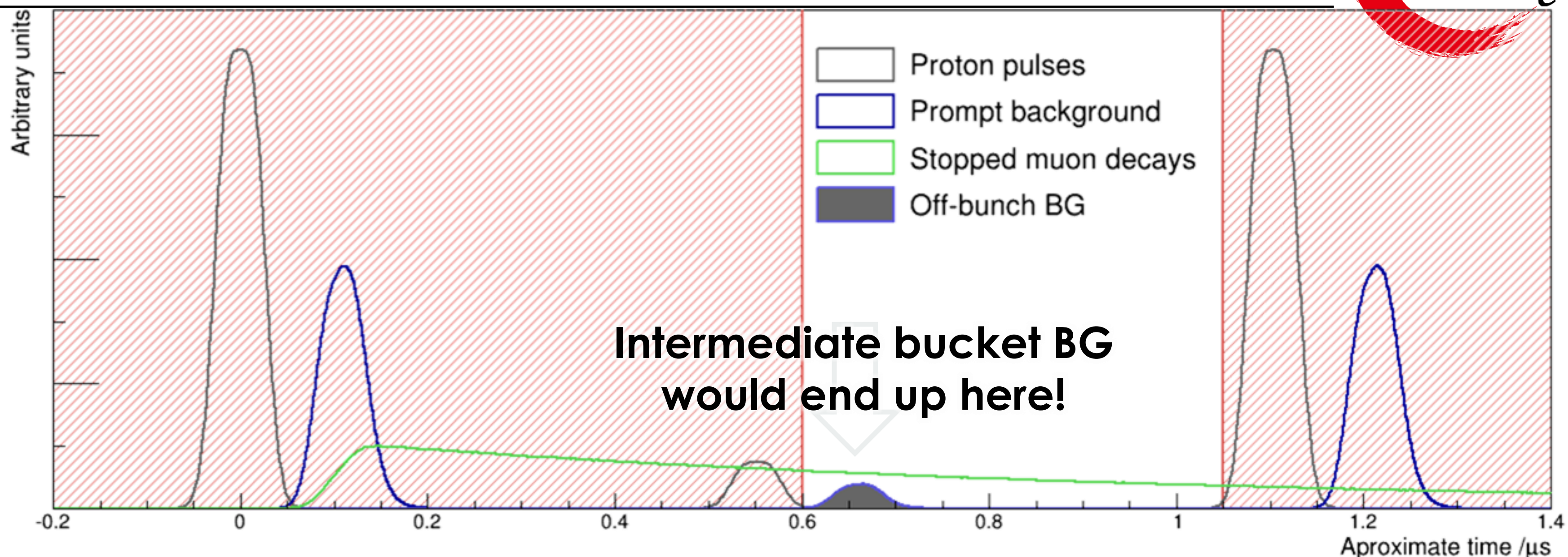
- Even if you don't inject protons into them, stray protons can remain in stable acceleration.



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



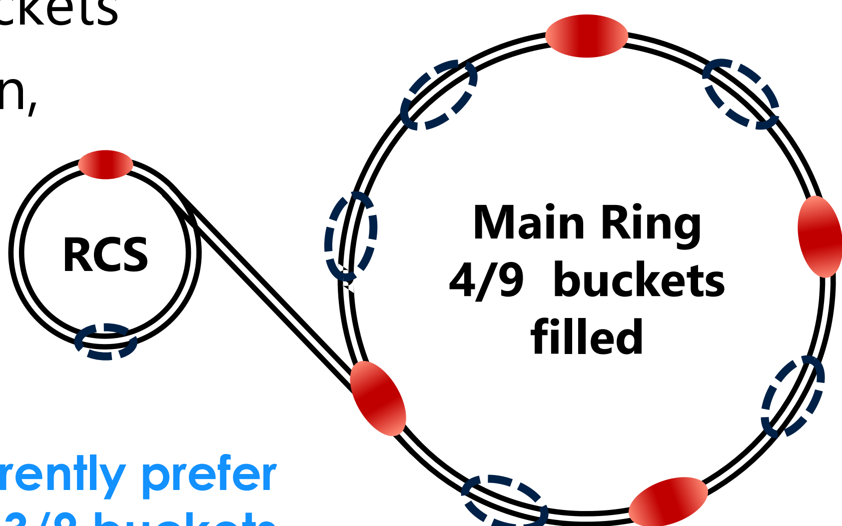
Beam extinction



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

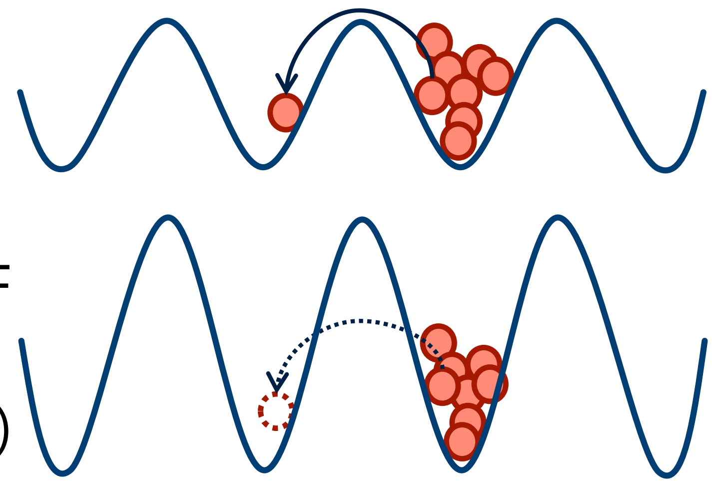


*currently prefer 3/9 buckets

Extinction measurement

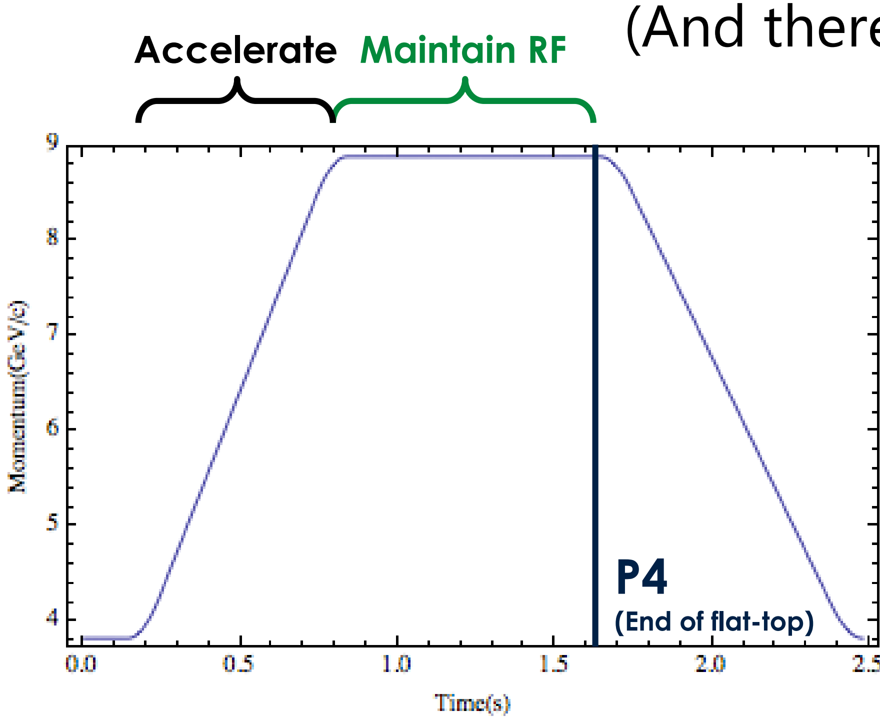
COMET design requires that we can achieve an extinction:

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



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

(And there is a limit...)



2012 test at 30 GeV demonstrated this is possible

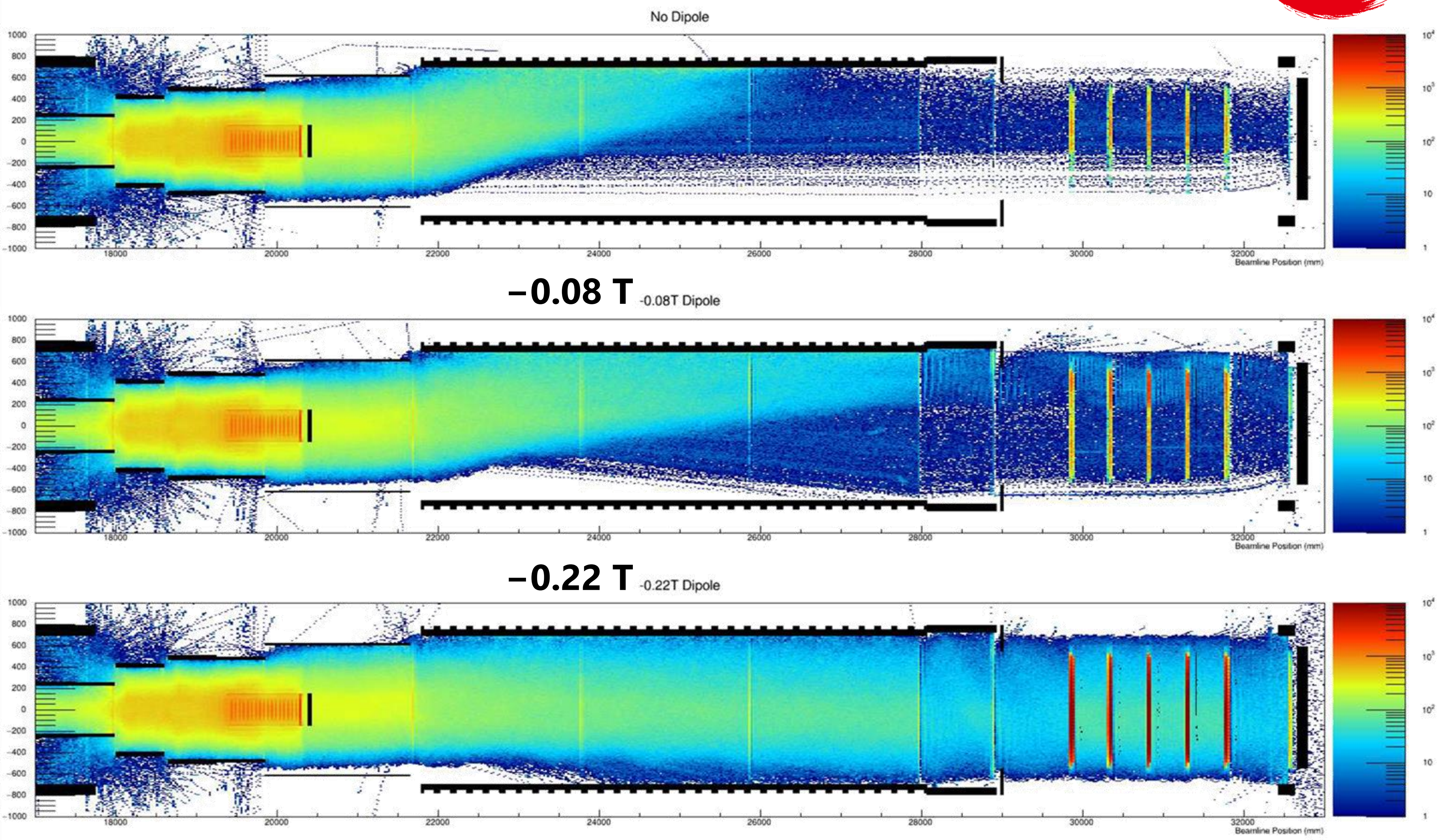
Now also (comfortably) demonstrated at 8 GeV

Background budget (Phase-I)

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Spectrometer dipole tuning



End