

# Muon LFV experiments with pulsed beam (COMET/Mu2e/DeeMe)

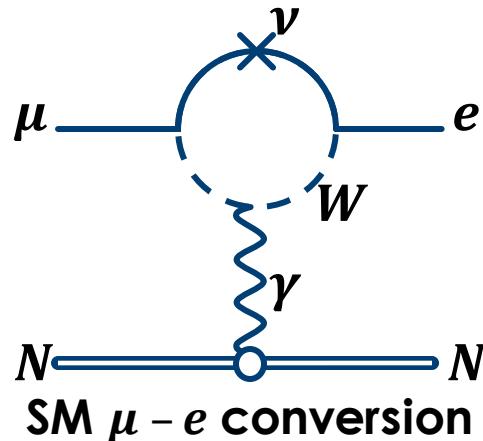
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Phill Litchfield  
(COMET collaboration)

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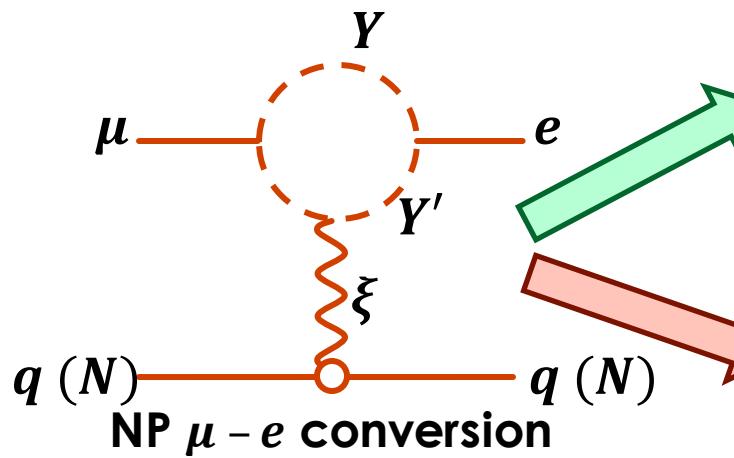
$\mu - e$  conversion

# $\mu$ to $e$ conversion

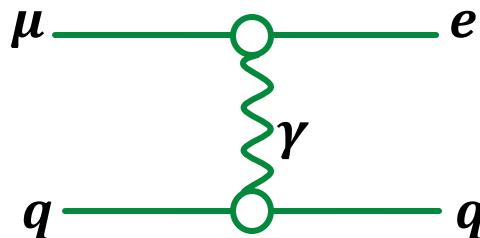


In the **SM**  $\mu N \rightarrow e N$  is suppressed by  $O(10^{-54})$  because of the mass disparity between the  $W$  and neutrino.

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

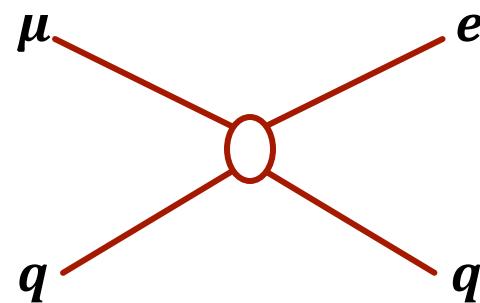


$$\mathcal{L} = \frac{1}{1 + \kappa} \mathcal{L}_d + \frac{\kappa}{1 + \kappa} \mathcal{L}_4$$



**Dipole coupling**

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



**Four-fermion coupling**

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

# A giant leap...



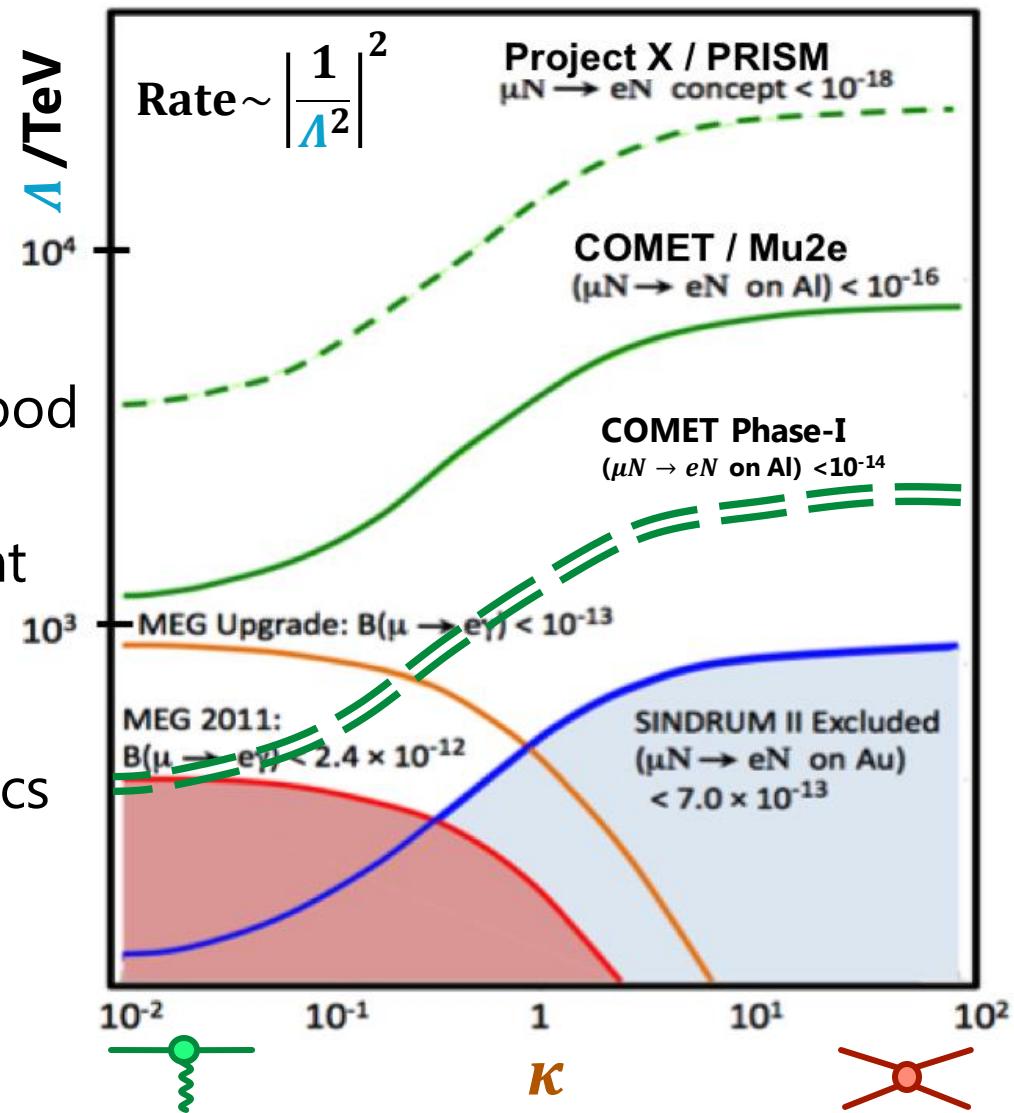
For the full COMET experiment sensitivity improvement over SINDRUM-II is **4 orders of magnitude**.

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**

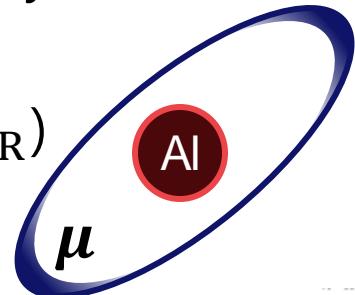


# Muon decays



Muons allowed stop in suitable target.

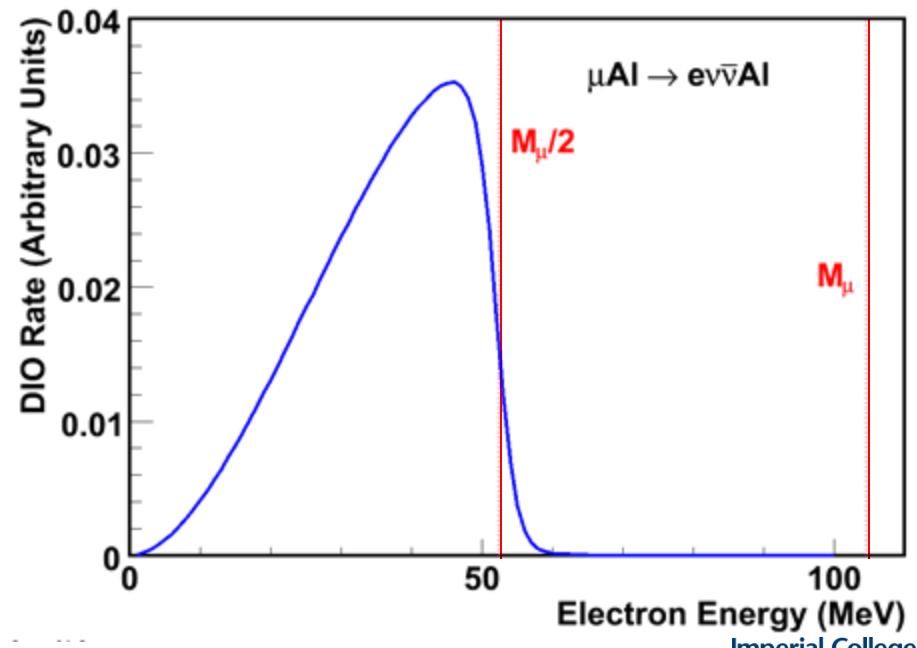
- Initially **Aluminium**, but other materials (Ti) under study.
- Conversion from 1s orbital:  $\mu N \rightarrow e N$  gives a **mono-energetic electron** at 105MeV ( $\approx m_\mu - B_{1s}^\mu - E_R$ )



'Normal' decays are backgrounds

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

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



# Backgrounds



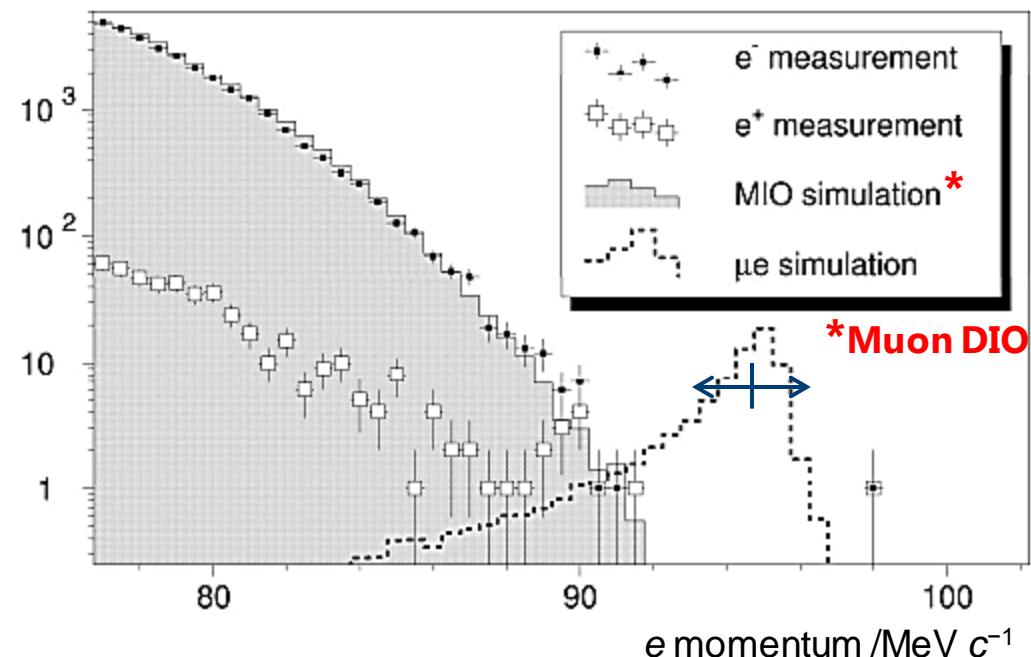
Three main background processes:

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

- **Decay in flight:**  
Electrons from energetic muons ( $p > 77\text{MeV}$ ) can be boosted to 105MeV.
  - Use momentum selection in muon transport

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

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



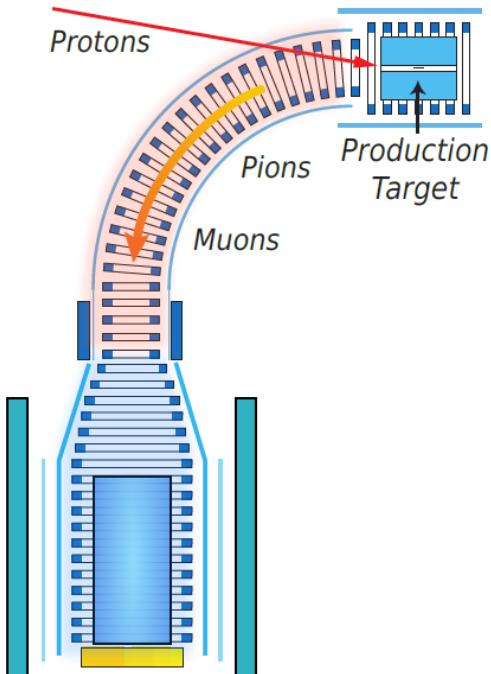
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# COMET design and construction

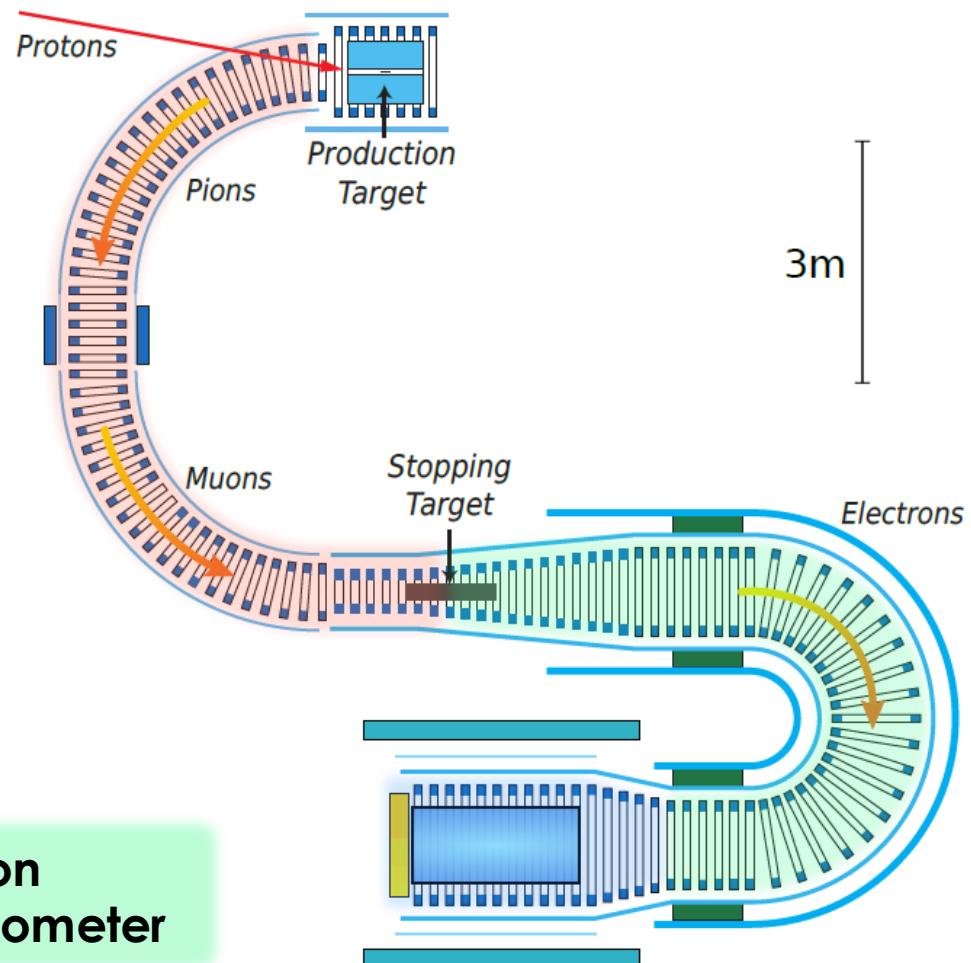
# COMET, Phase I and II



## Phase I



## Phase II



Pion & muon transport

Detector

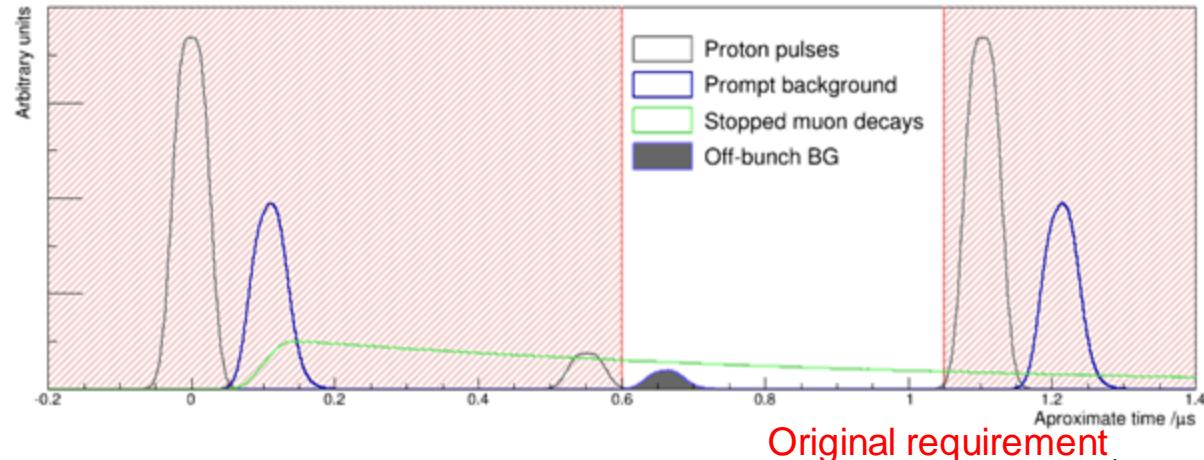
Electron spectrometer

# Primary beamline

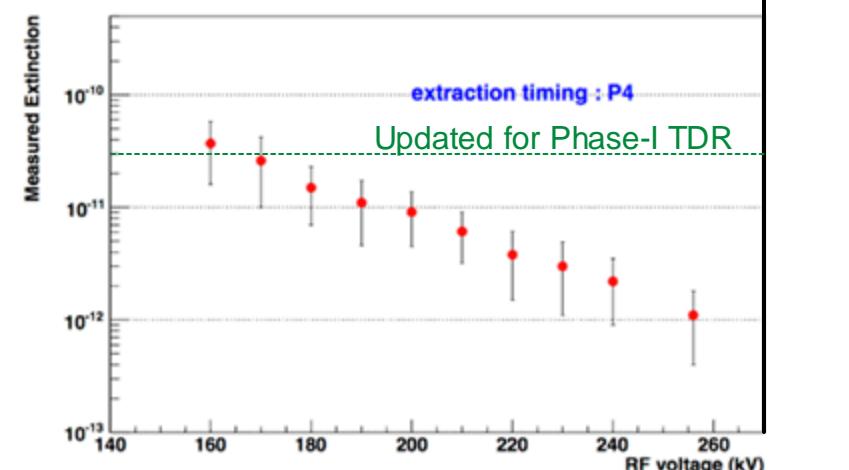
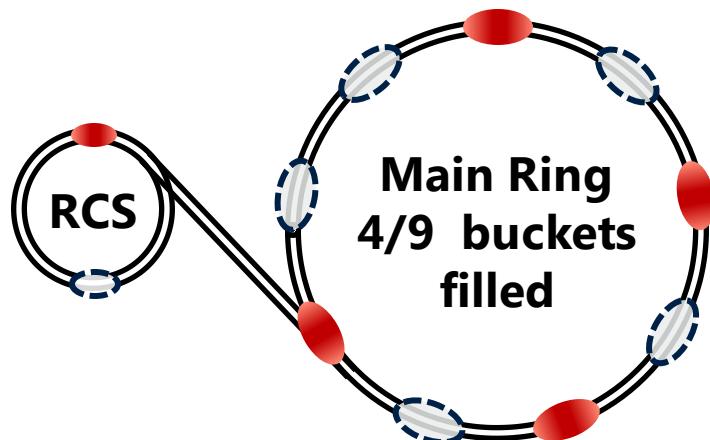


Main driver of sensitivity: Need lots of low energy muons!

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



Original requirement

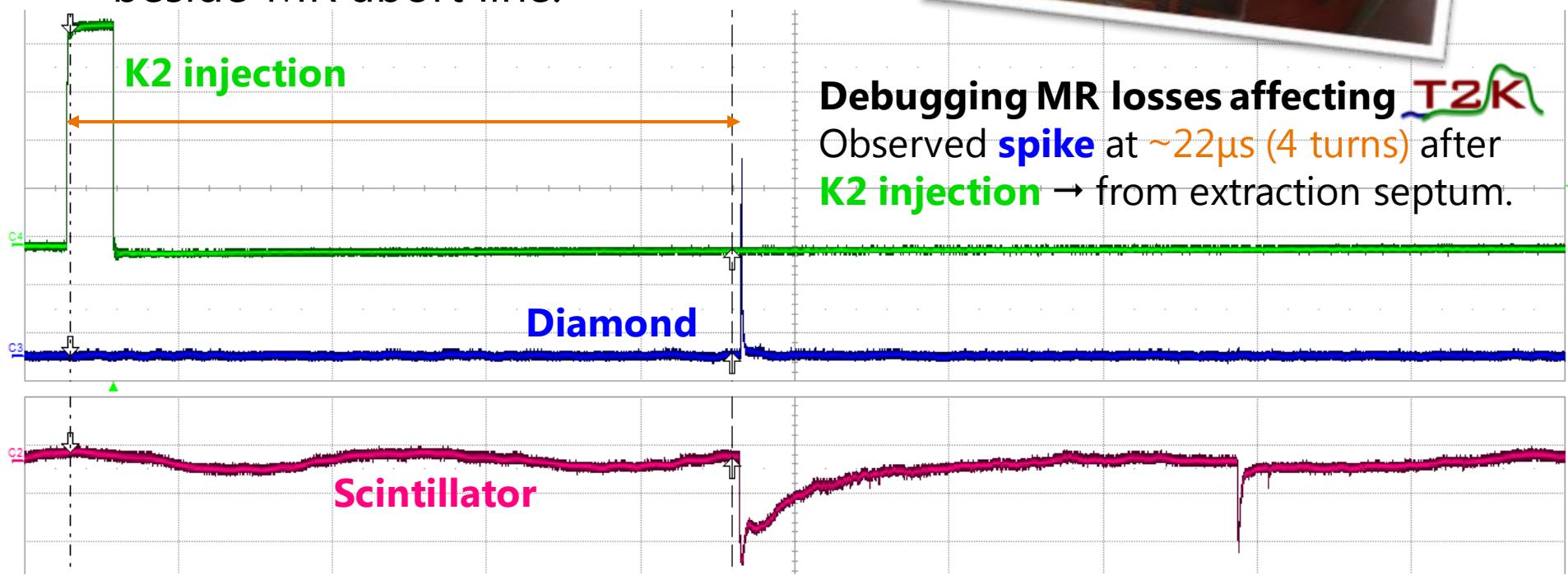
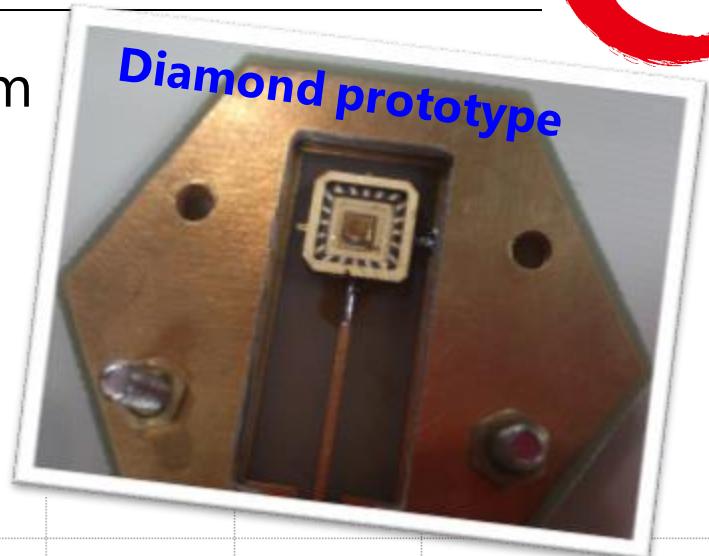


# Beam monitoring



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

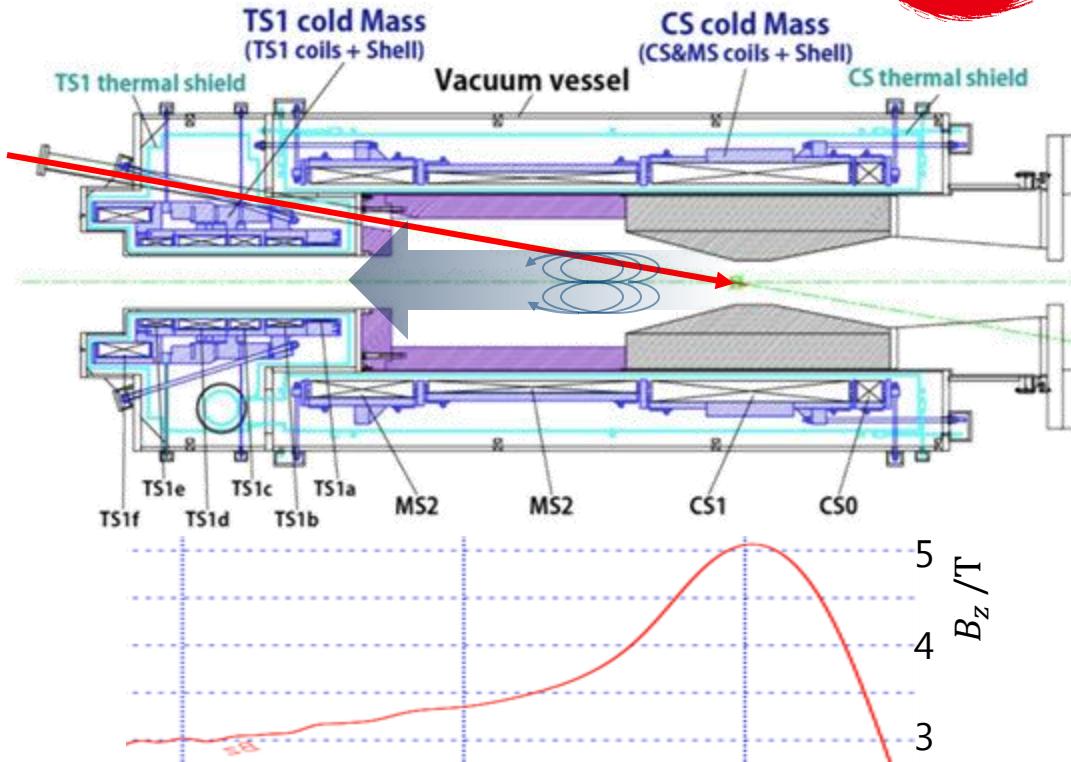
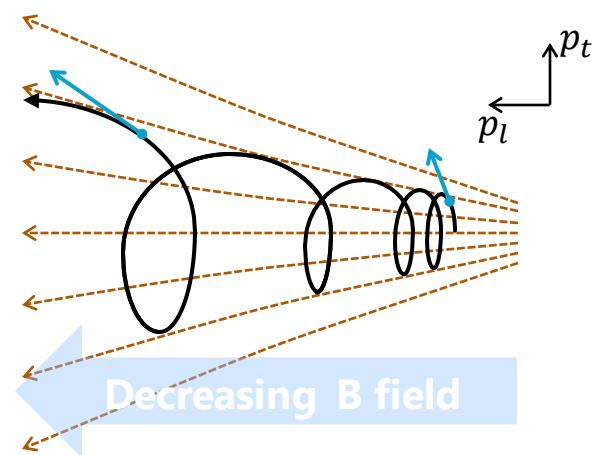
- Mainly for extinction monitor, but could have position monitor as well.
- Prototype tested (11/24~) beside MR abort line.



# Muon source

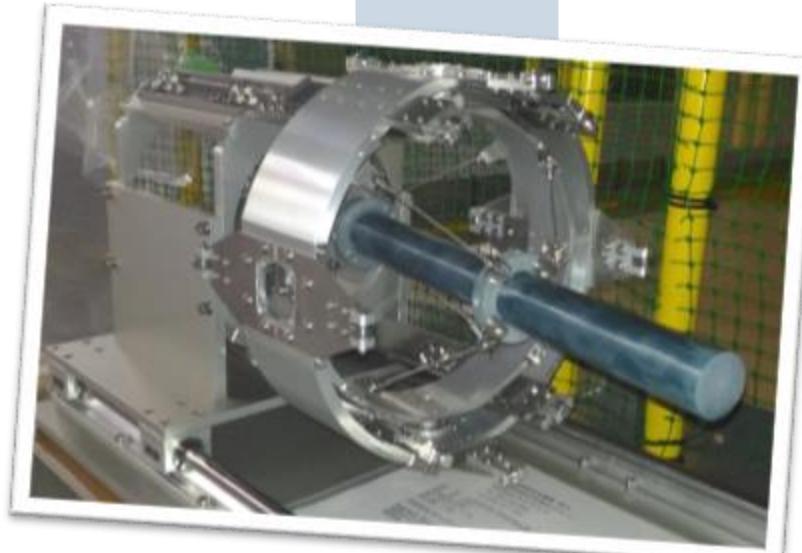
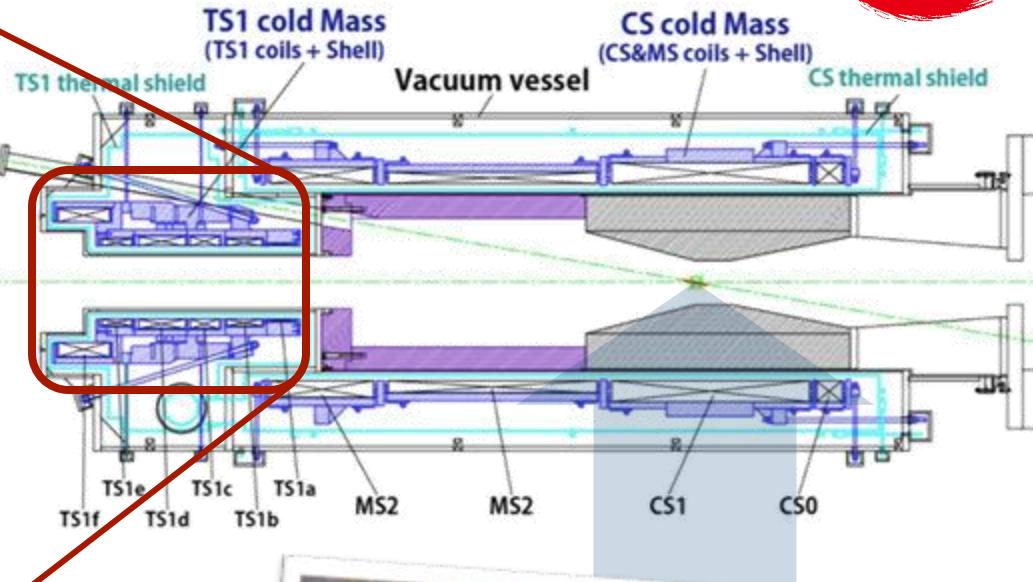
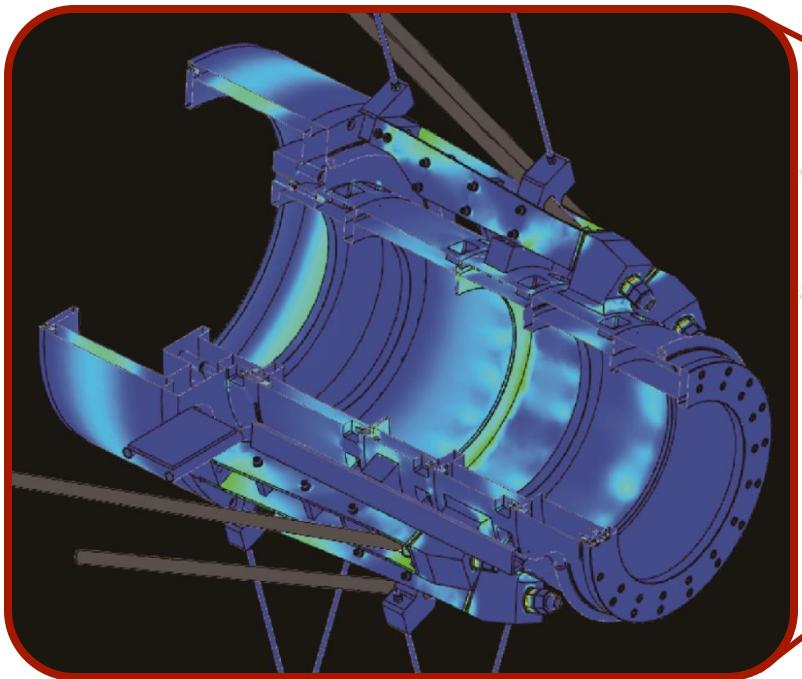


- Collect **backward-going pions** with capture solenoid
- Maximise field at target to give larger aperture angle



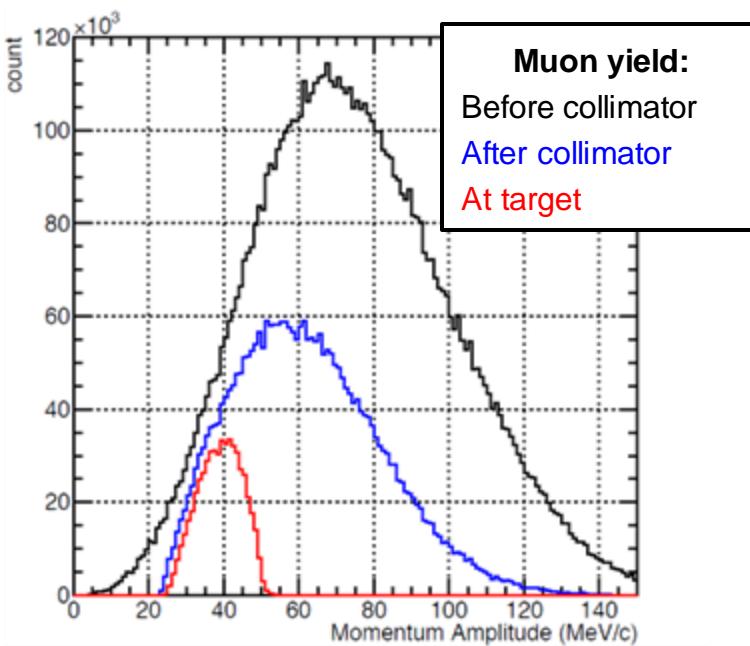
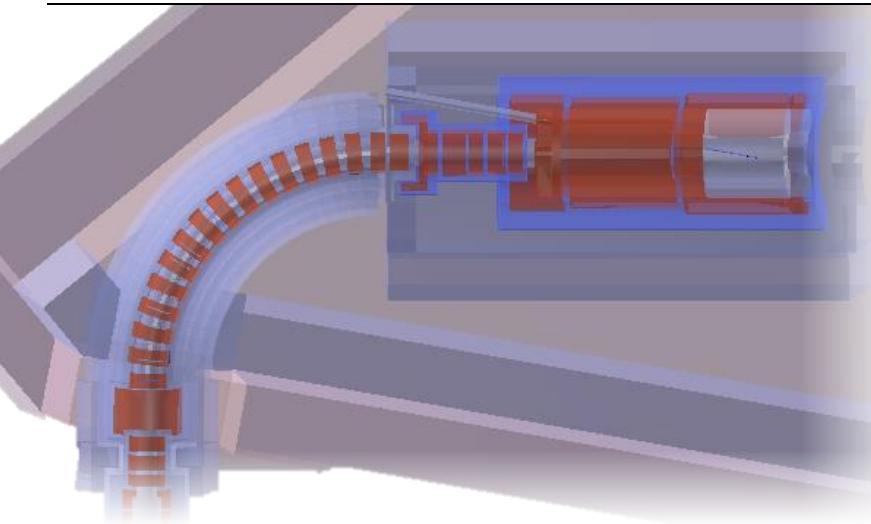
- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. The curved transport line helps to eliminate direct line-of sight.

# Production target developments



- ▲ Stress calculation for TS1 (first transport solenoid). Coil winding is almost complete.
- ▶ Pion target (graphite: IG-43) and insertion mount constructed

# Muon transport



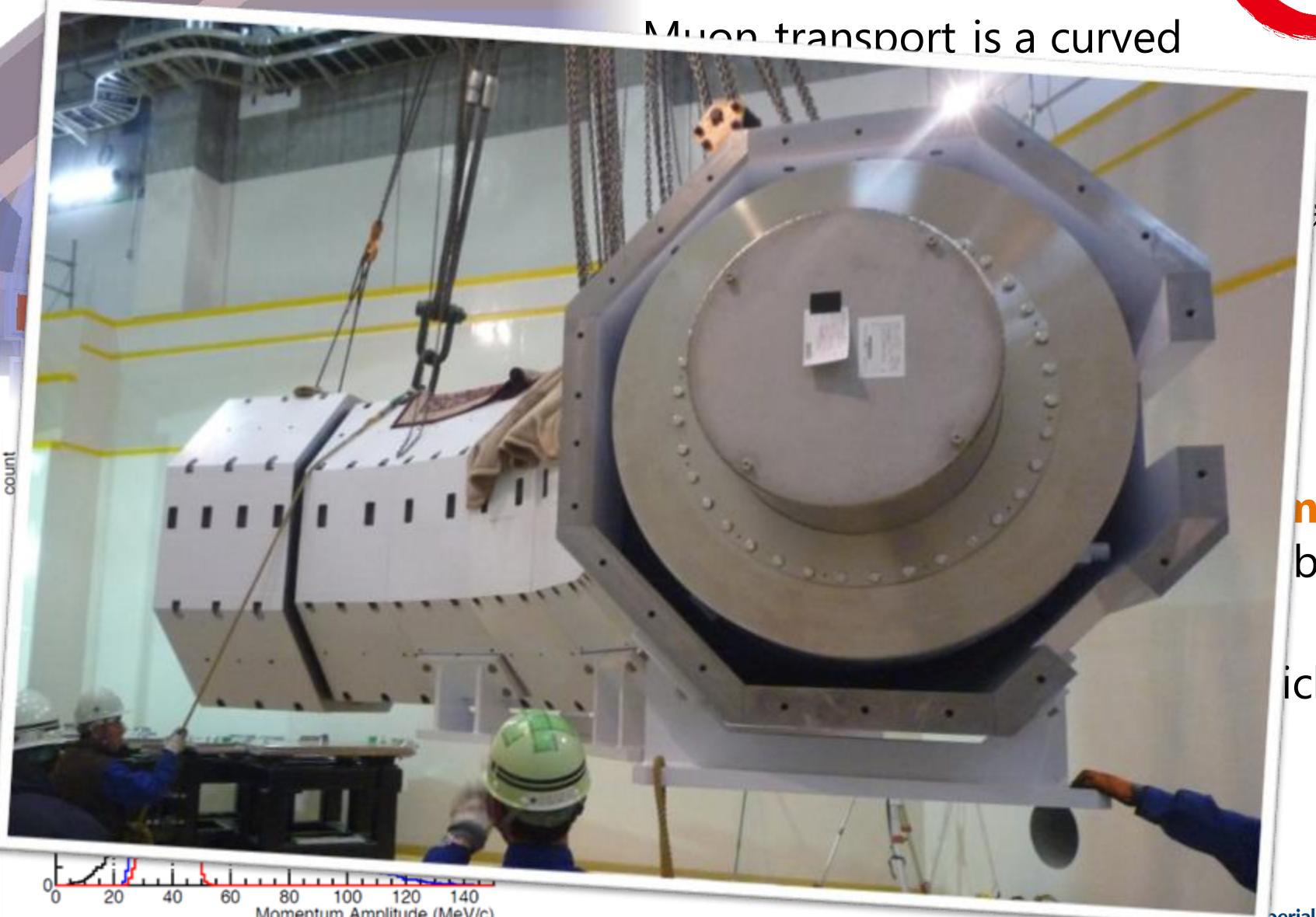
Muon transport is a curved solenoid:

- 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



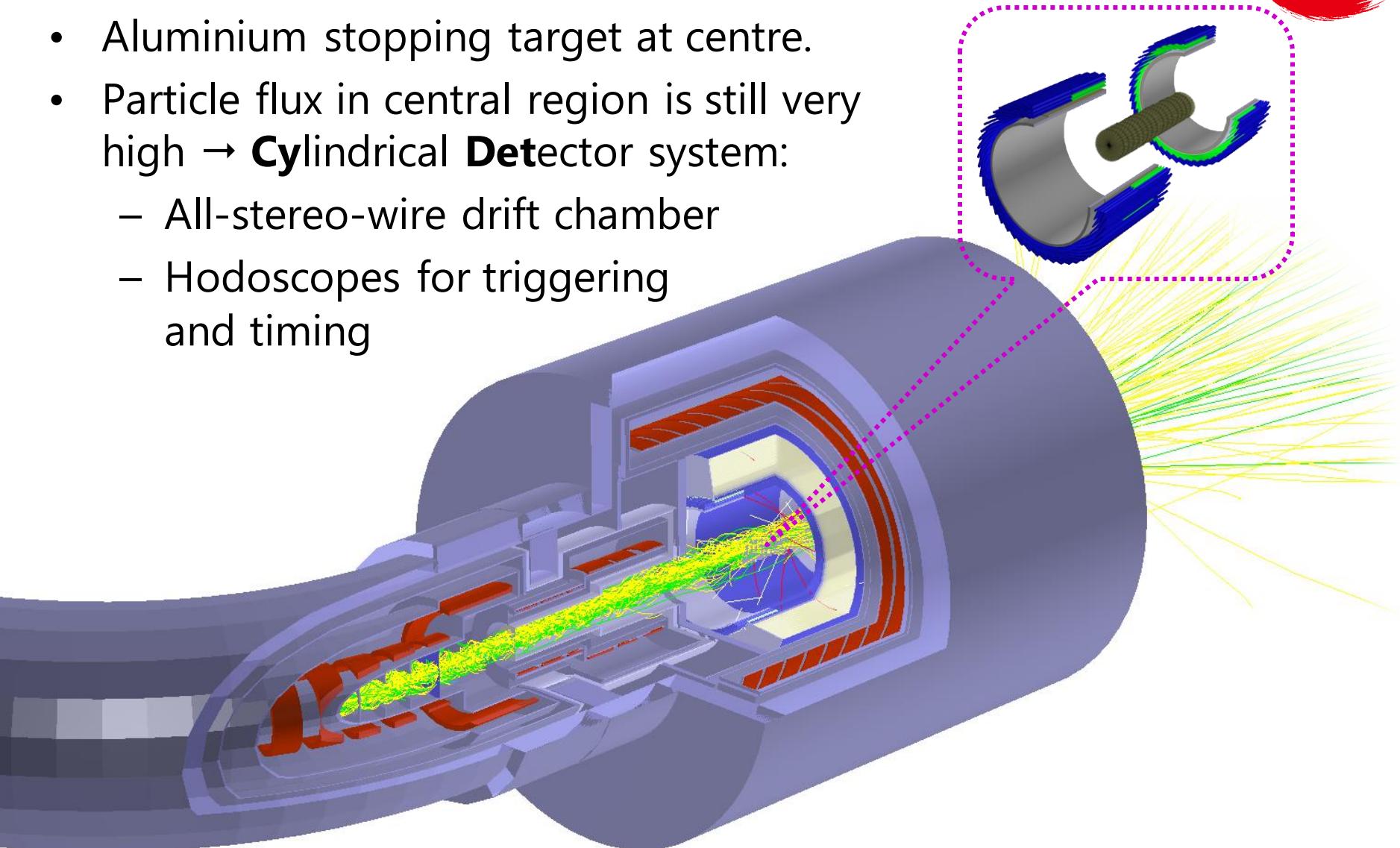
Muon transport is a curved



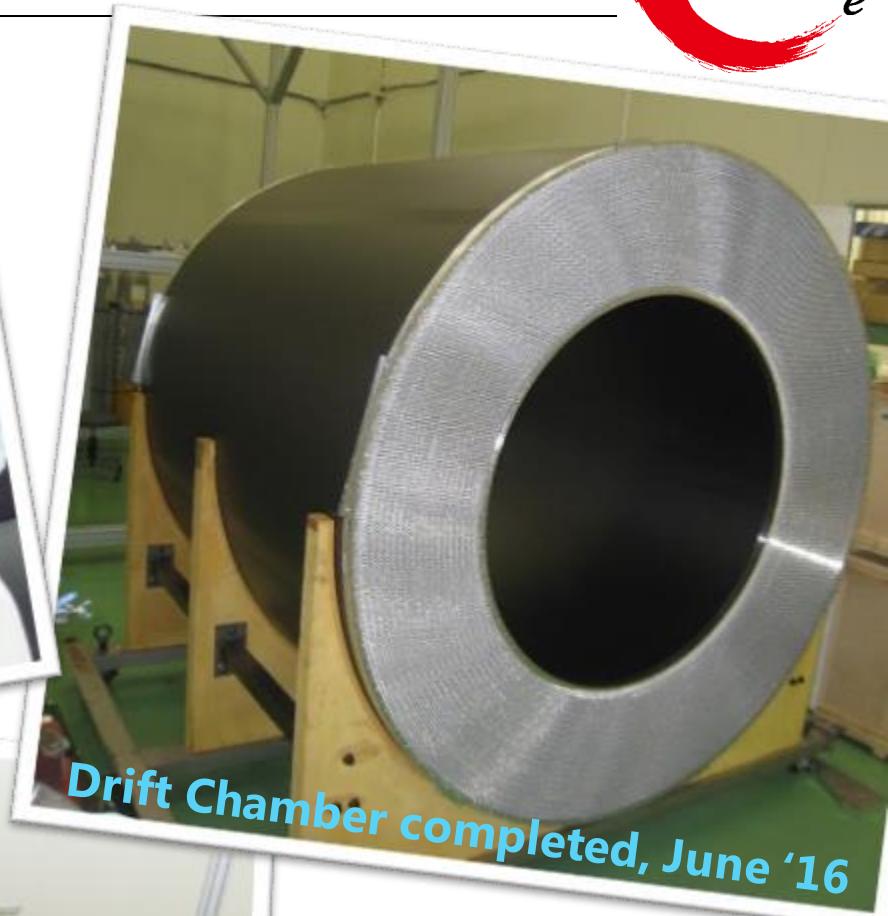
# Phase I detector (CyDet)



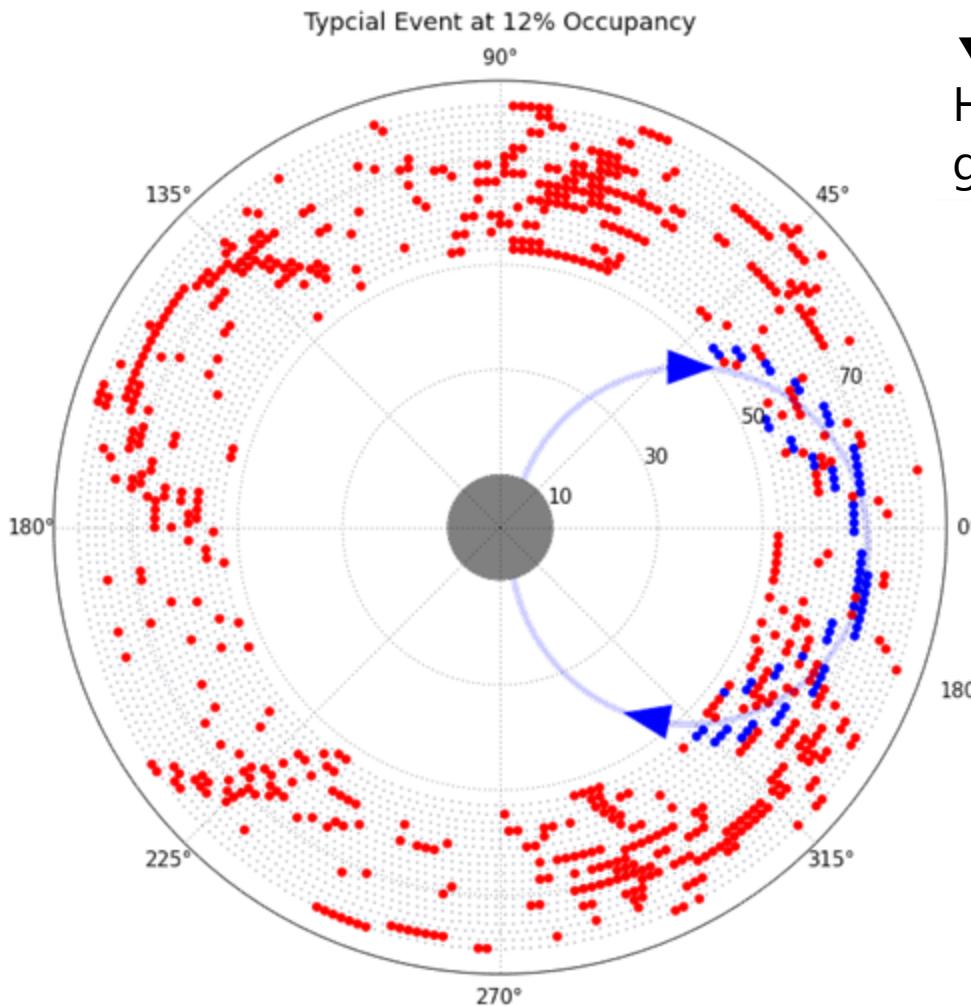
- Aluminium stopping target at centre.
- Particle flux in central region is still very high → **Cylindrical Detector** system:
  - All-stereo-wire drift chamber
  - Hodoscopes for triggering and timing



# CyDet construction

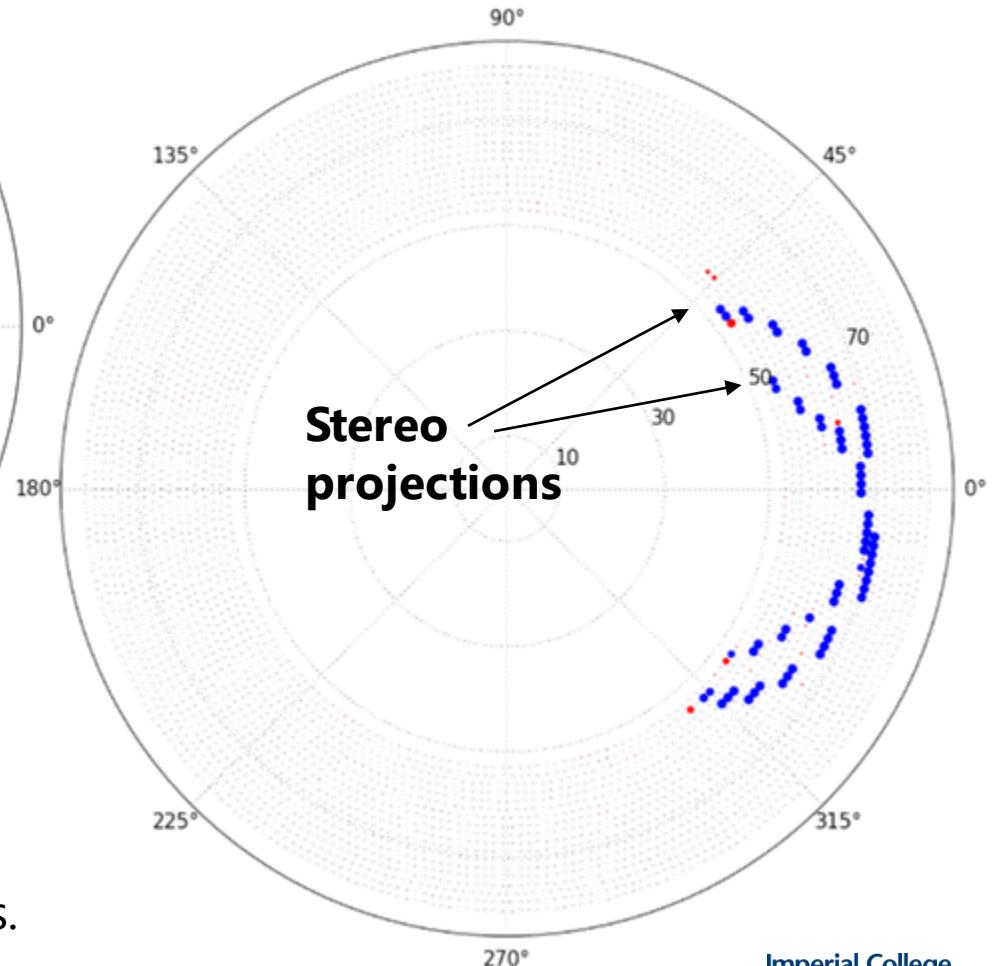


# CyDet reconstruction



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

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

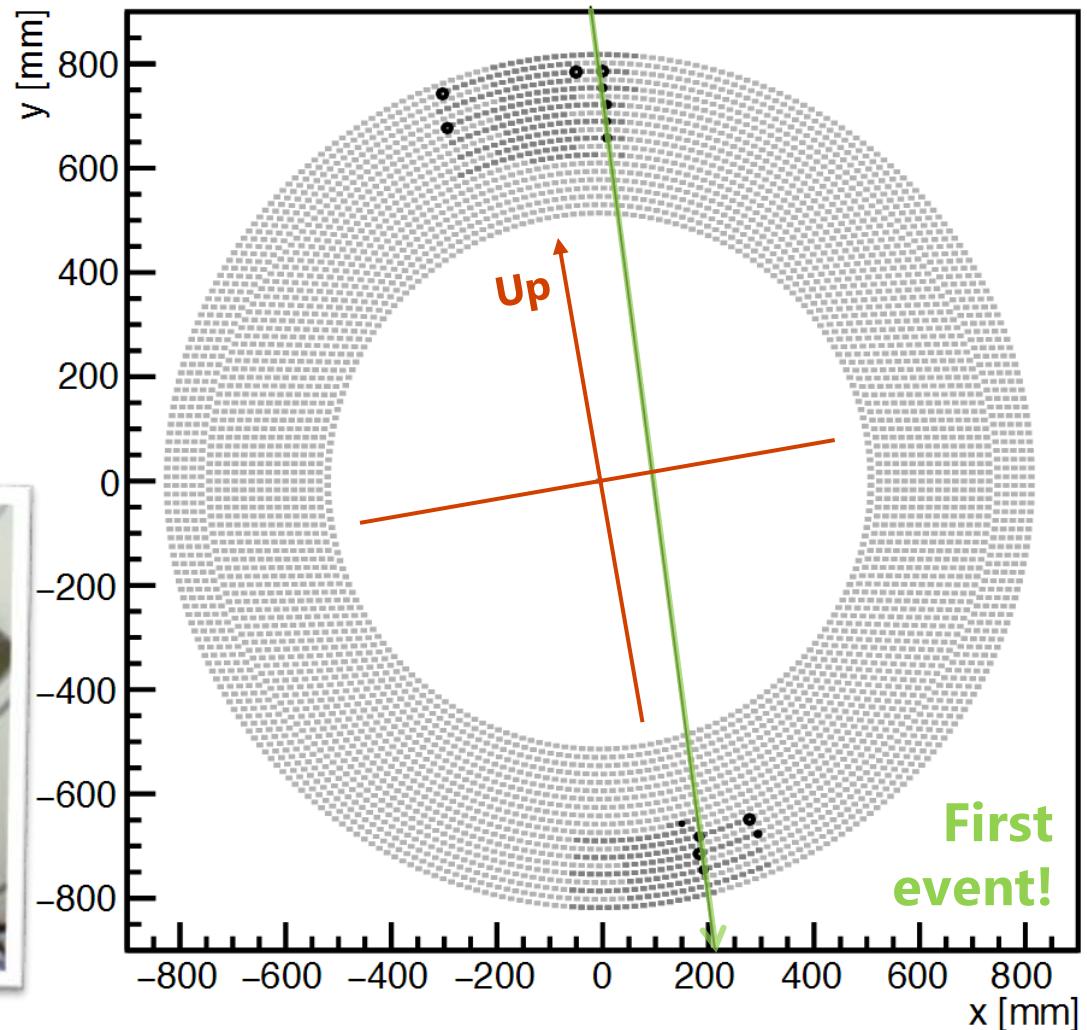
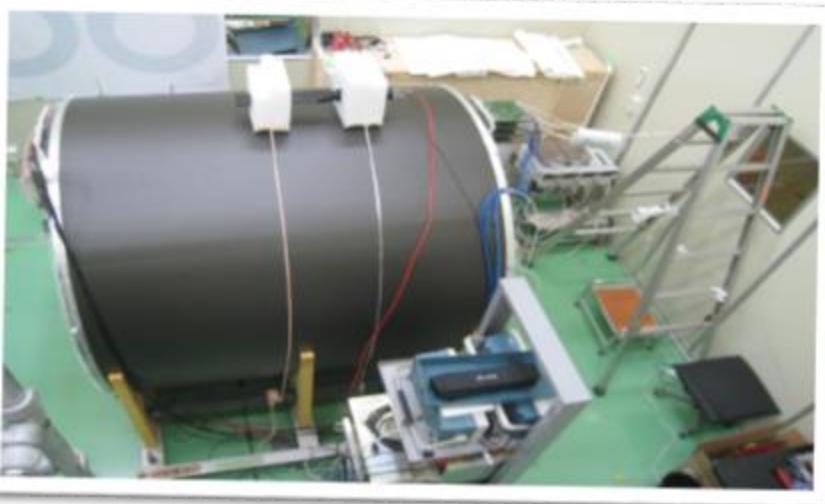


# CyDet Cosmic ray tests



CR test setup at KEK:

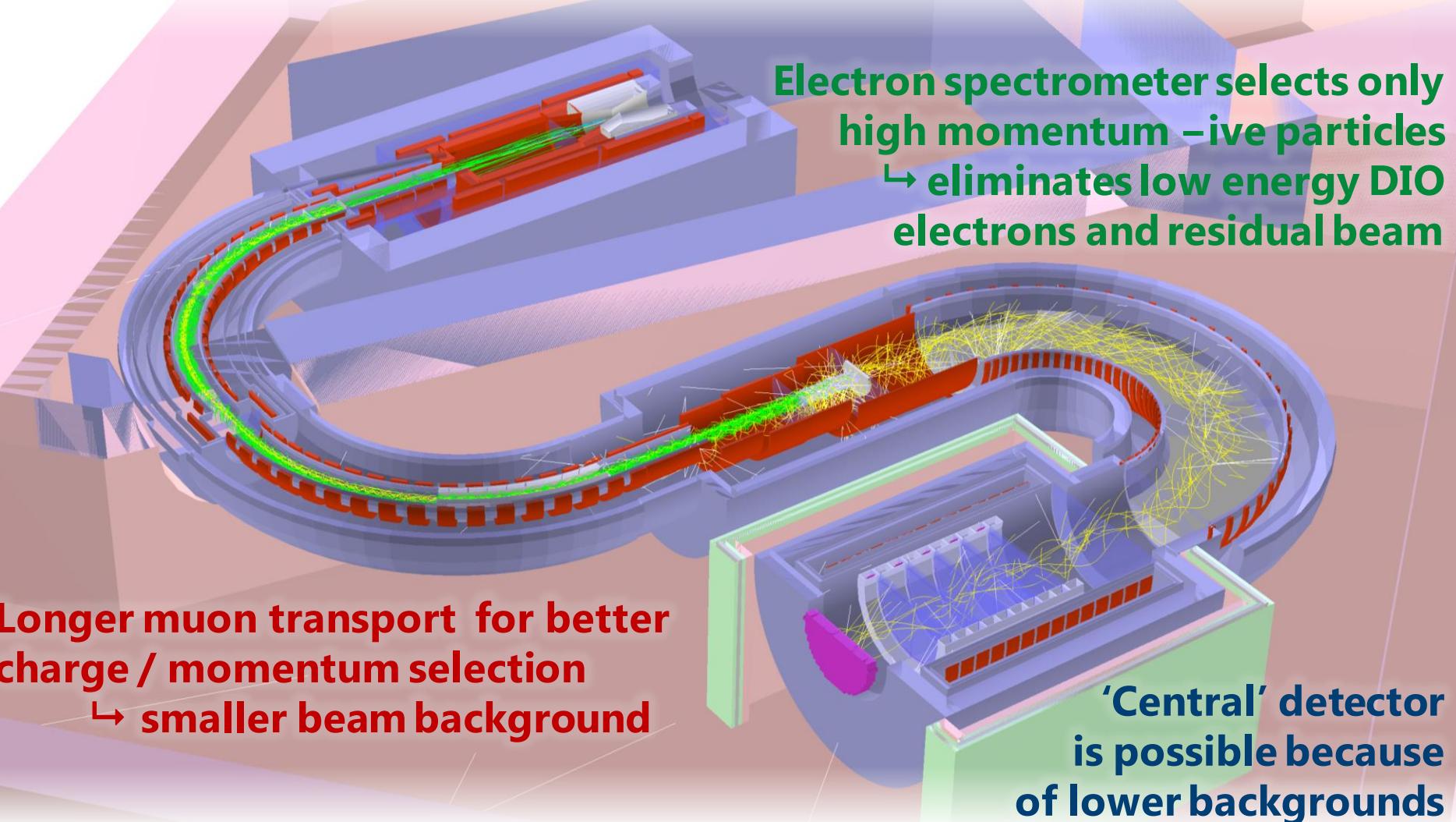
- Instrument detector with development DAQ
- Trigger with external hodoscope counters at top and bottom.



# COMET Phase II



Upgrade the experiment for  $100\times$  better sensitivity

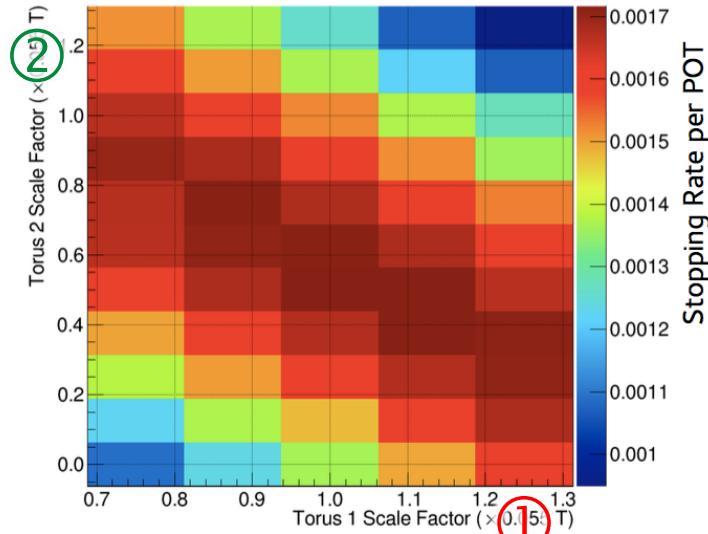


Longer muon transport for better charge / momentum selection  
↳ smaller beam background

Electron spectrometer selects only high momentum -ive particles  
↳ eliminates low energy DIO electrons and residual beam

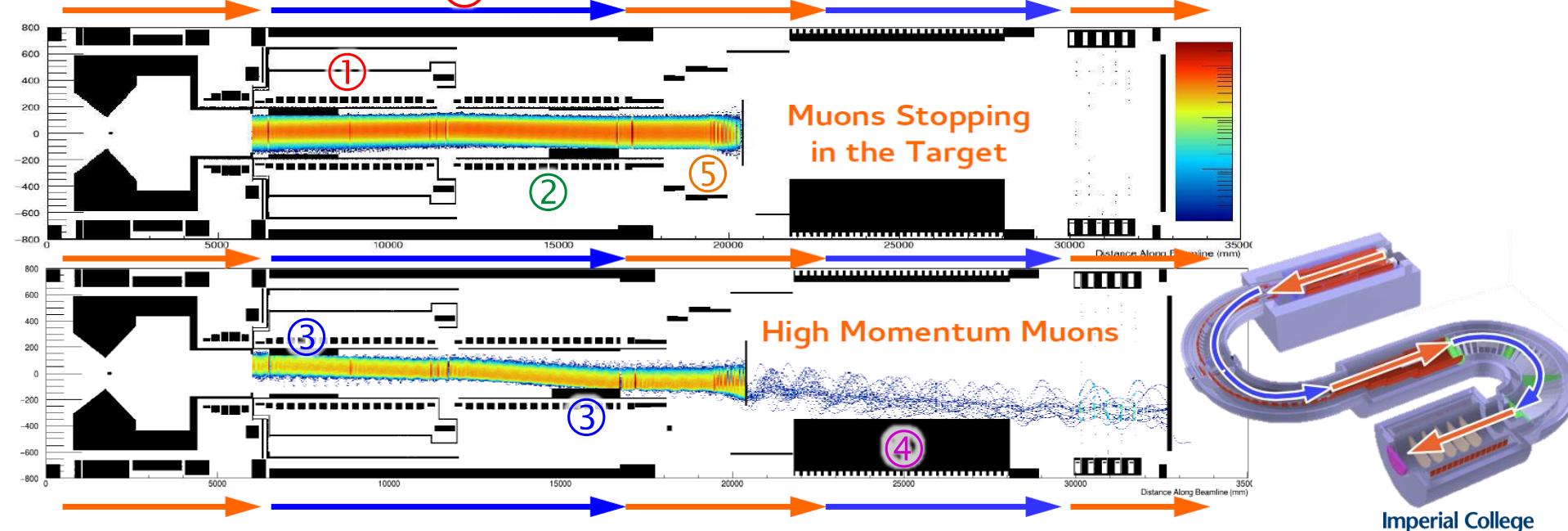
'Central' detector is possible because of lower backgrounds

# Phase II beamline optimisation

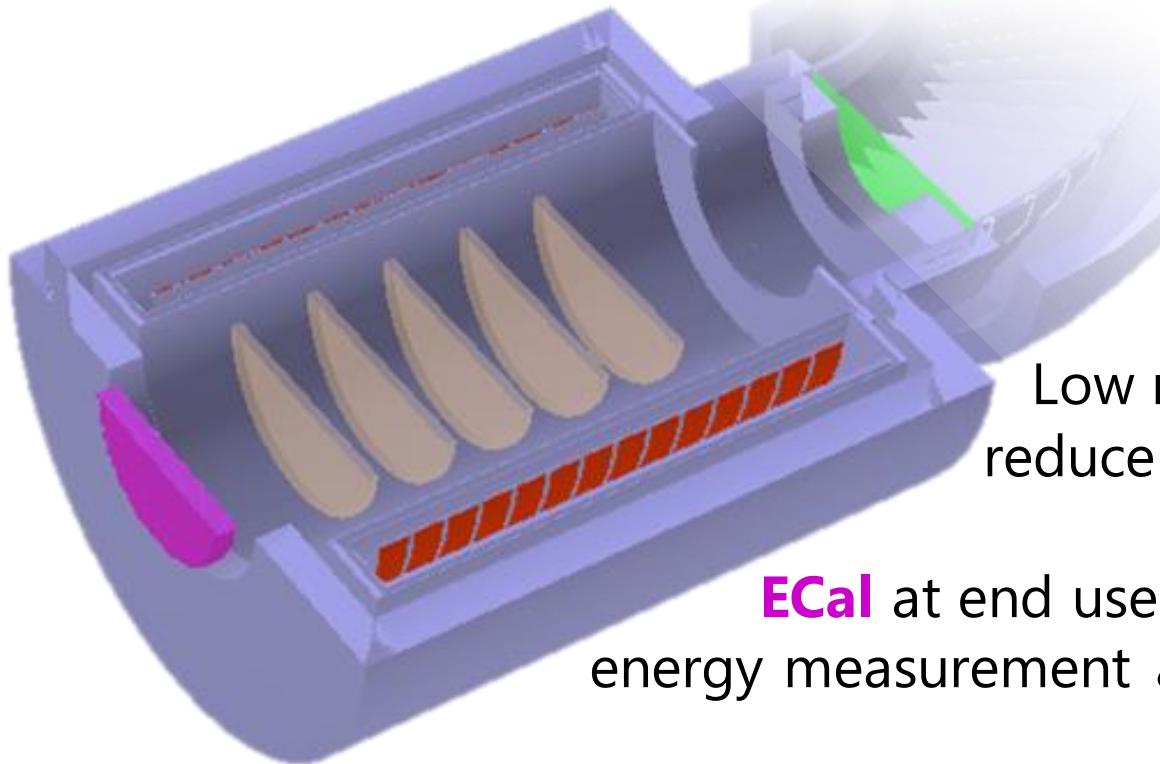


In parallel with Phase I construction, Phase II design is being optimised using integrated COMET simulation. Examples:

- 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.

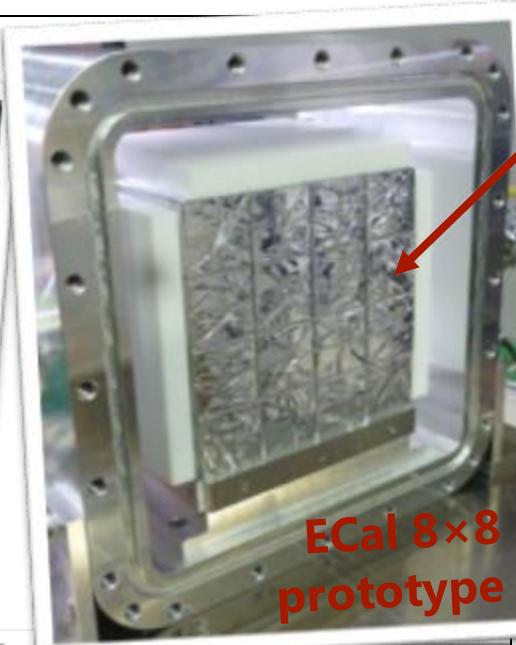
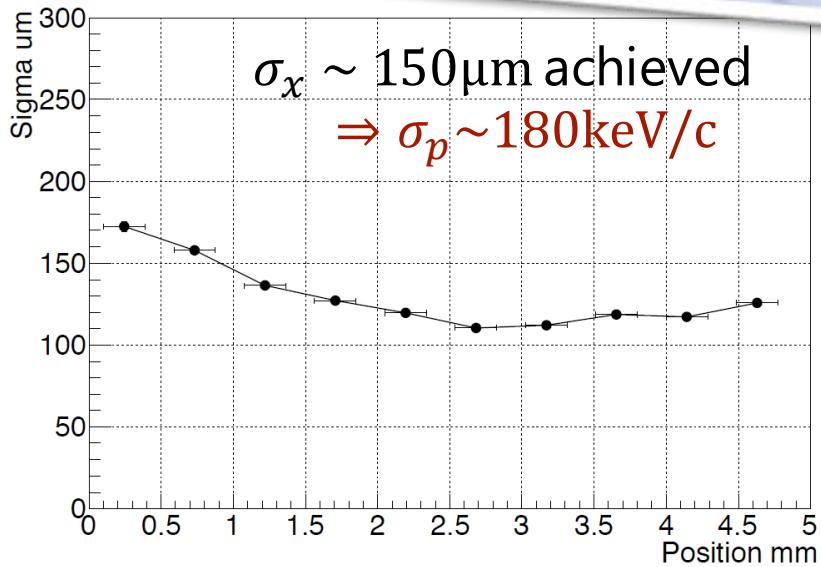
Low mass straw design to reduce scattering.

**ECal** at end uses  $\sim$ 2000 LYSO crystals for energy measurement and triggering.

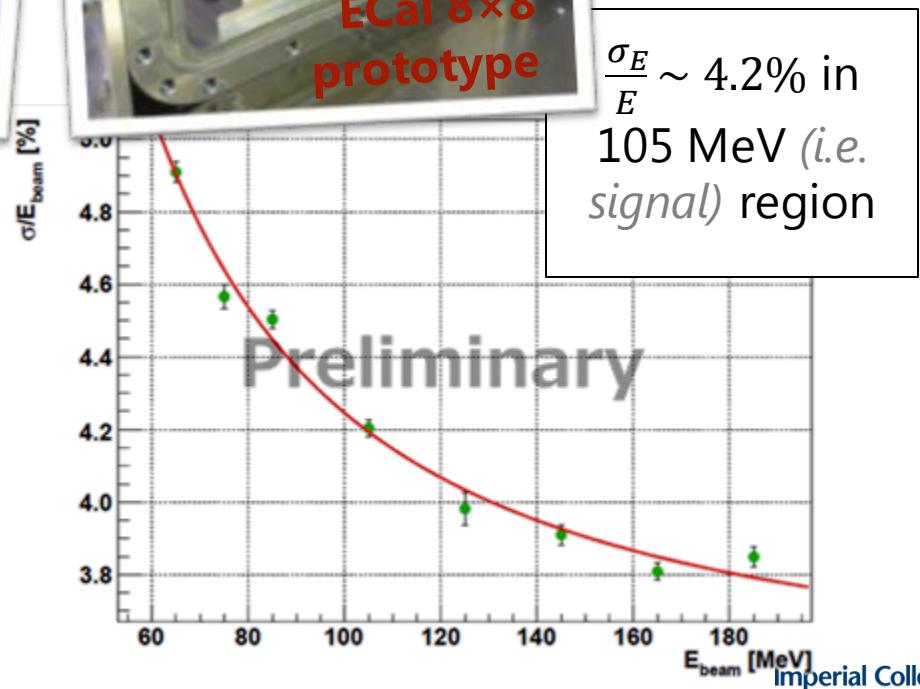
Prototype version detector in development for Phase I, can be installed in place of CyDet.

- 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)

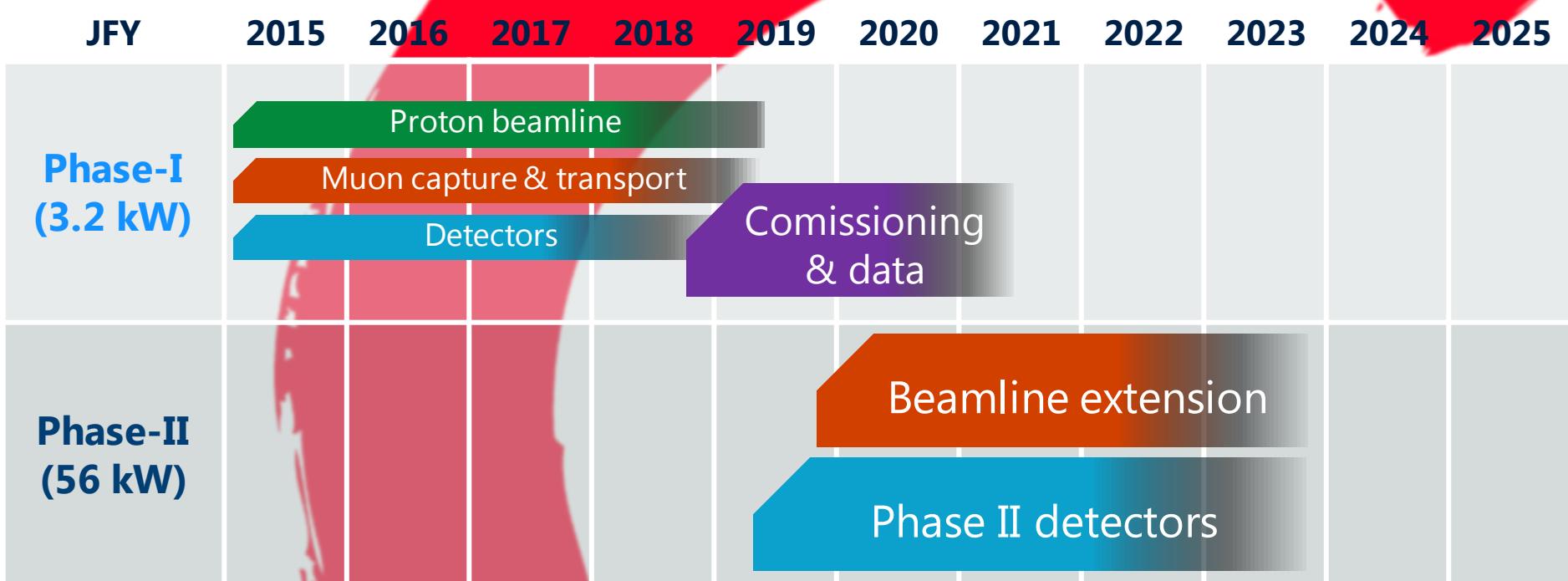
# ECal & Straw testing



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



# COMET Timeline



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

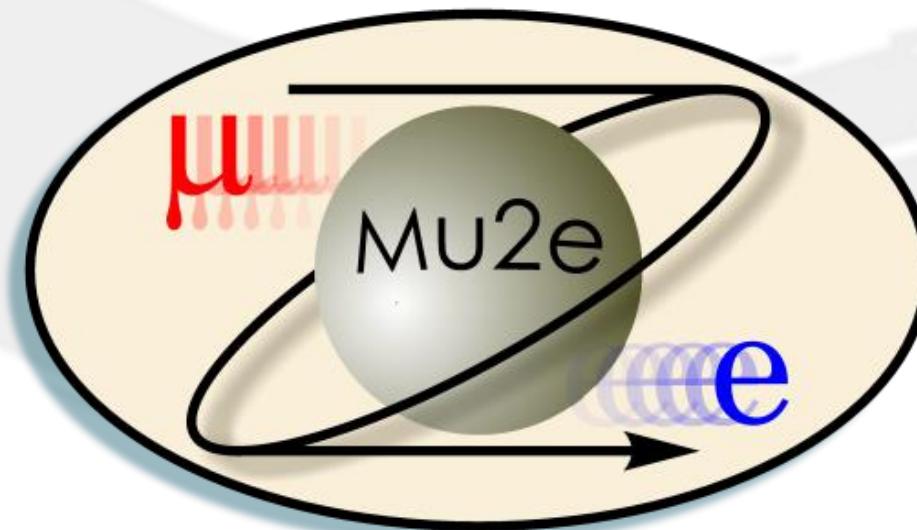
~2018: Start COMET Phase I; goal  $3 \times 10^{-15}$  S.E.S. (~ 5 mo)

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

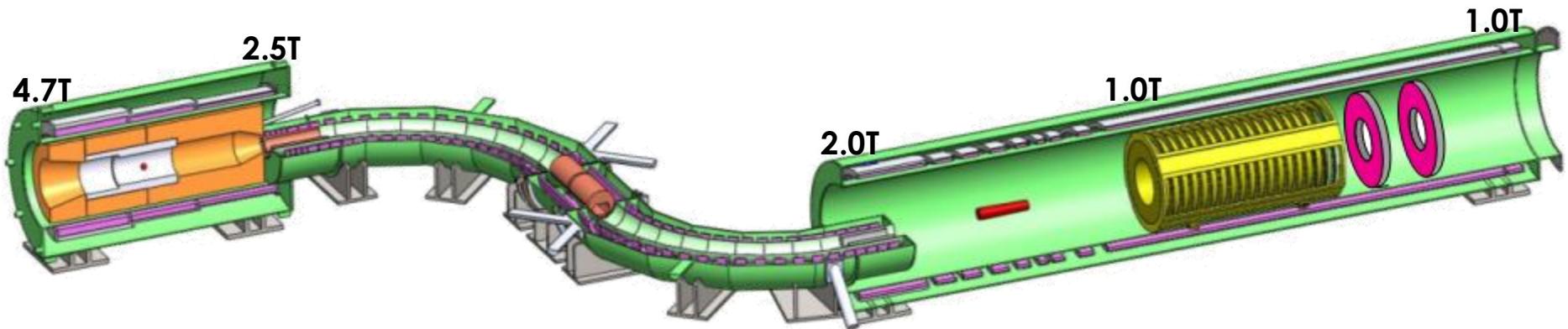
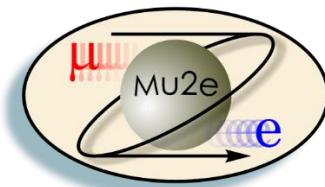
- Accumulates statistics very quickly thanks to high power 56kW beam from J-PARC main ring

# Mu2e Experiment at Fermilab

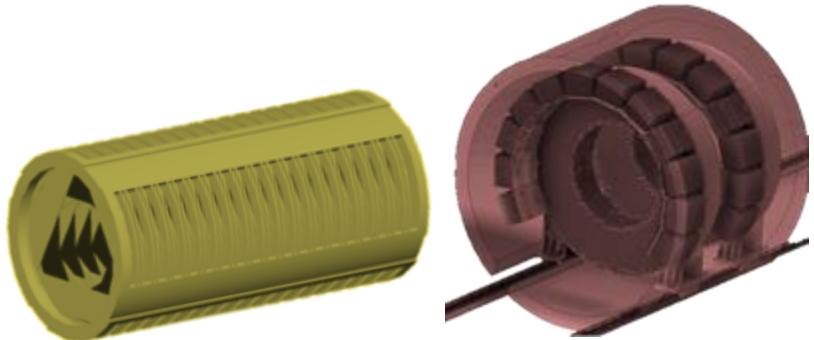
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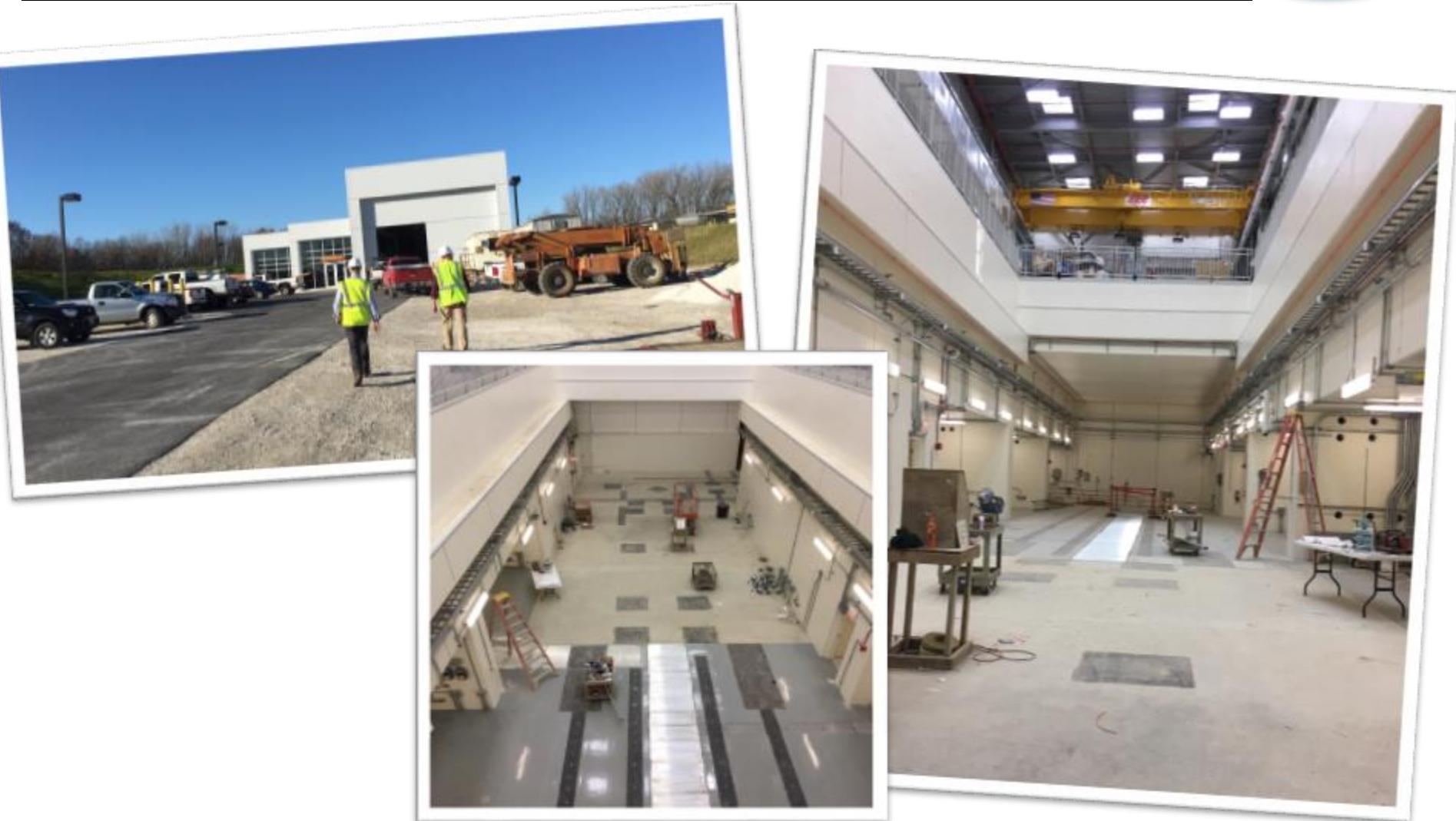
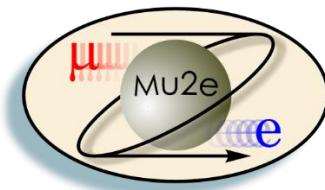
# Mu2e: Overview



- **S-shape** and off-centre collimators that can rotate for BG studies
- Stopping **target** is  $17 \times 0.2\text{mm}$  Al foils
- Target & detector in same solenoid
  - “Minimum radius” configuration similar to COMET Phase-I
- Electrons spiral from target to **straw tracker** and **EM calorimeter**
- No sign selection, can look  $e^+$  tracks (B/G, double charge exchange)

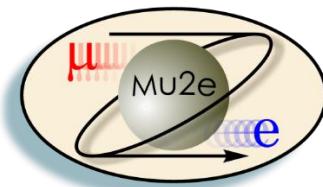


# Mu2e Developments

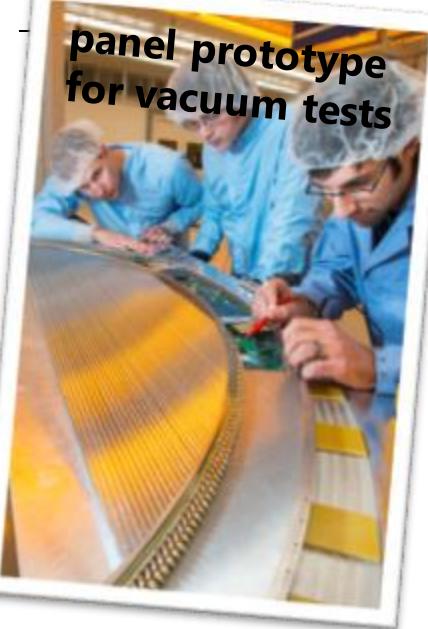


"We are getting beneficial occupancy of our building very soon"

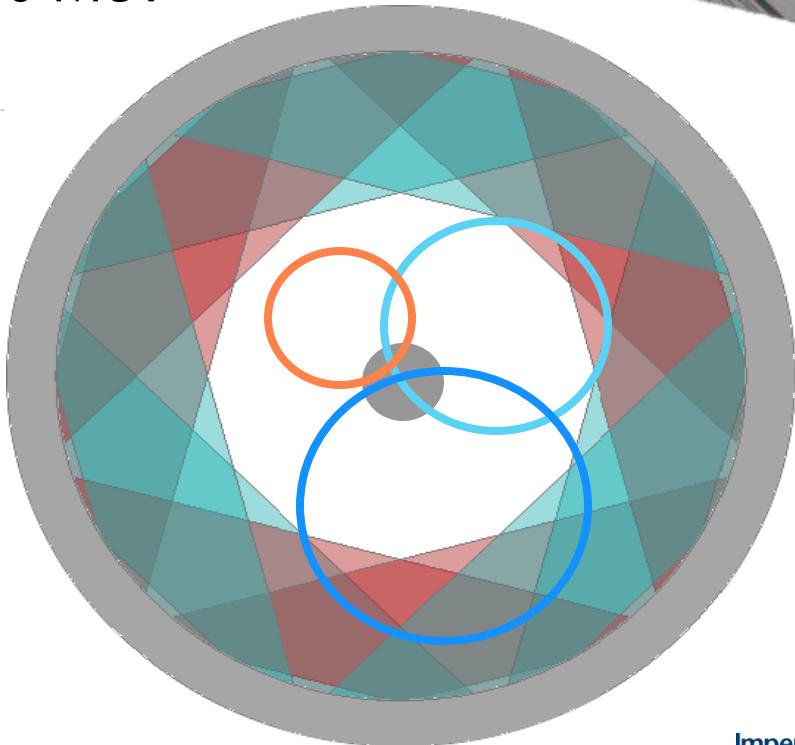
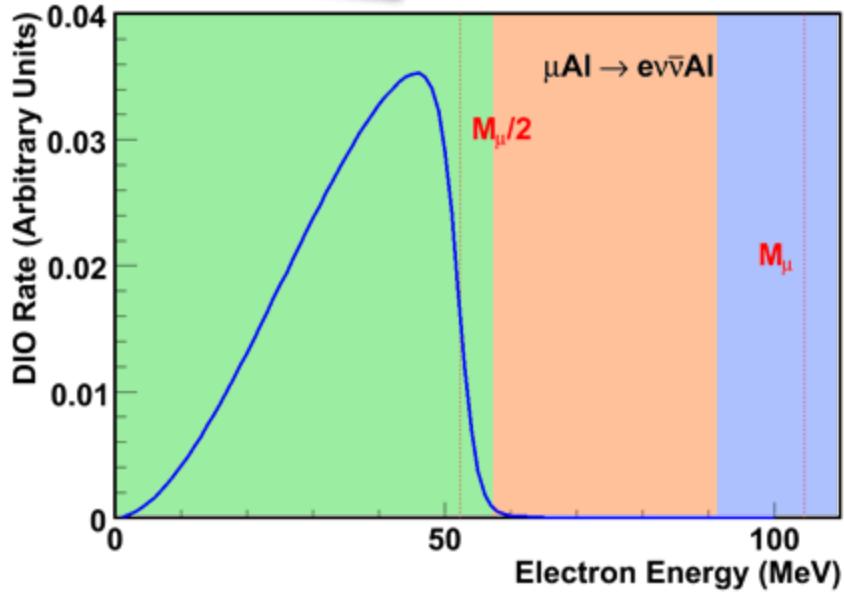
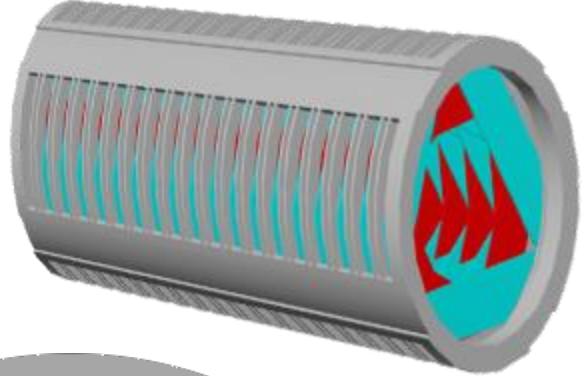
# Mu2e Tracker



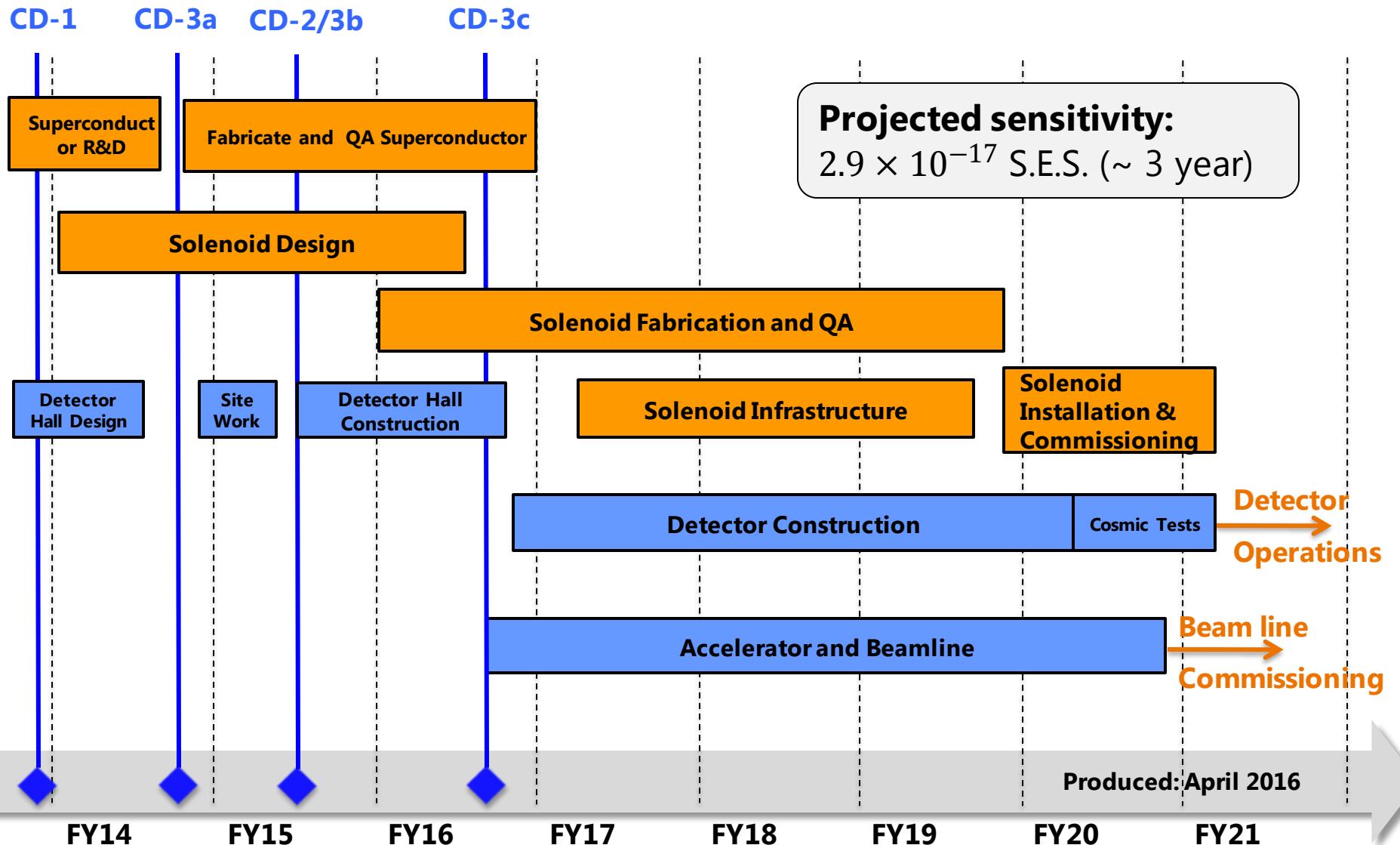
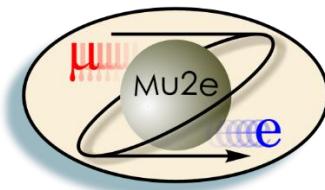
panel prototype  
for vacuum tests



- Tracker made from straw tubes
- Minimum radius of 380mm corresponds to momentum of  $\sim 60\text{MeV}$
- 'Complete' tracks need momentum  $> 90\text{ MeV}$



# Mu2e Schedule



# DeeMe at J-PARC MLF



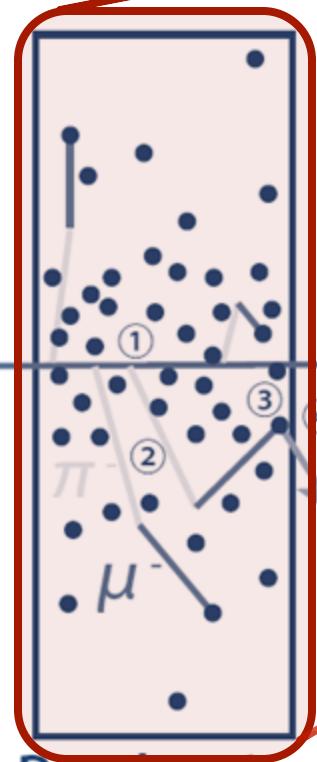
# DeeMe concept



If pion momentum is small,  $\pi^- \rightarrow \mu^- \bar{\nu}$  decays and muon capture can happen in one target

- Large sample of muon decays without needing to build solenoid channel

Proton



Production Target

Secondary Beamline

high-P Signal

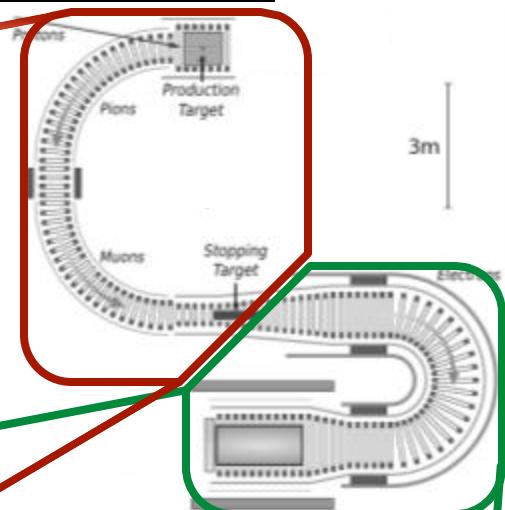
low-P BG

$e^-$

Magnet

Spectrometer

3m

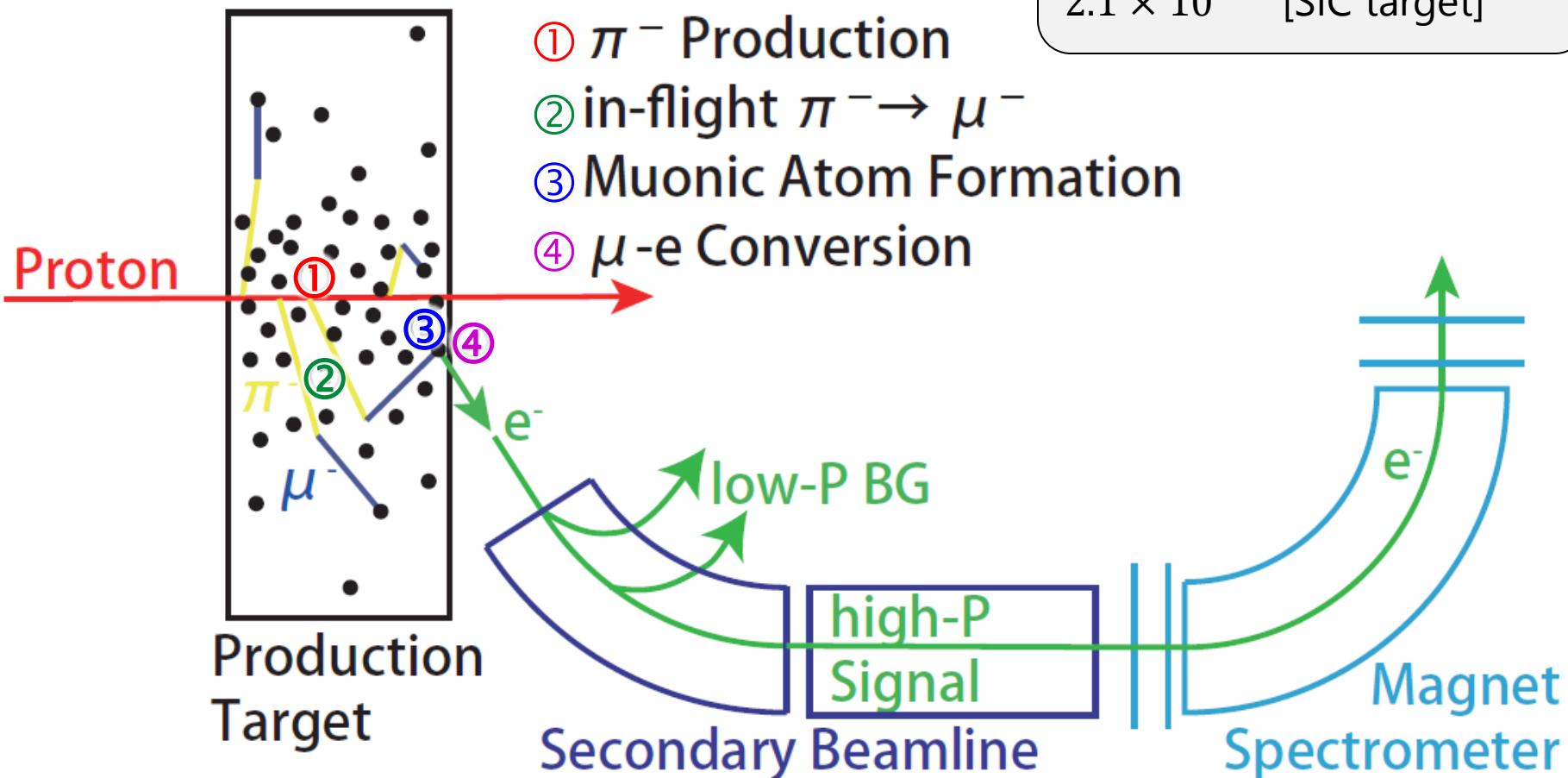


# DeMee design & goals



- **Study DIO tail** (see Nagao-san's poster)
- **$\mu - e$  conversion**

$\mu - e$  1 year S.E.S.  
 $1.2 \times 10^{-13}$  [Carbon target]  
 $2.1 \times 10^{-14}$  [SiC target]



# DeeMe in MUSE H-line (Technology)



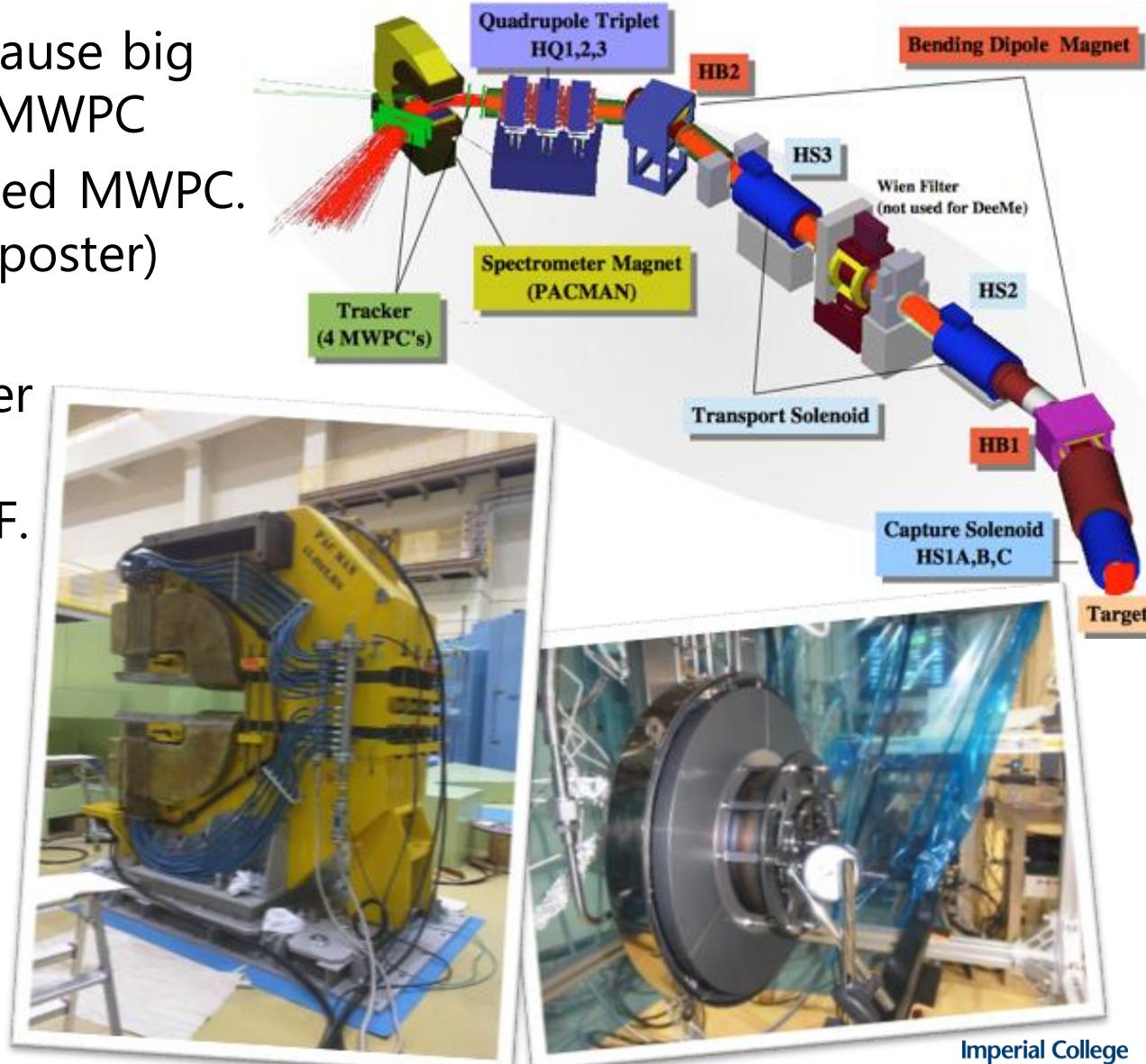
Prompt burst would cause big problems for normal MWPC

- Develop fast-switched MWPC.  
(see Teshima-san's poster)

PACMAN spectrometer magnet from PIENU experiment @ TRIUMF.

- $B = 0.4\text{T}$  at centre.  
For 105MeV, gives a  $70^\circ$  bend.

Prototype of rotating SiC target fabricated, updating design.



# Summary



**Suppresion of CLFV in SM is *accidental*, which make it an excellent place to look for new physics.**

**“Pulsed-beam experiments” =  $\mu - e$  conversion**

**Several new experiments coming online in next few years to make good use of new high power facilites**

- At J-PARC MLF, **DeeMe** can get  $\sim 25$  improvement over current limit.
- Next up, **COMET Phase-I** can get  $O(10^2)$  improvement as well as improve understanding of beam for Phase-II.
- After that **Mu2E** and **COMET Phase-II** will deliver  $O(10^4)$  improvement.

# Reserves

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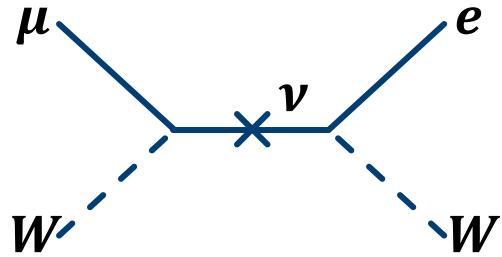
Caveat emptor: mostly from old talks, not  
guaranteed to be up to date

# Charged lepton flavour violation

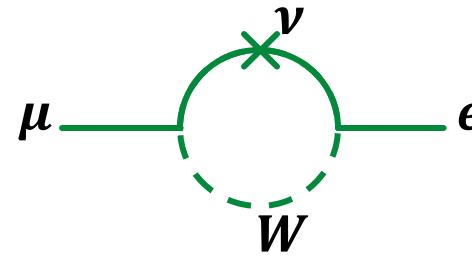


We already know that lepton flavour is not conserved

- 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)

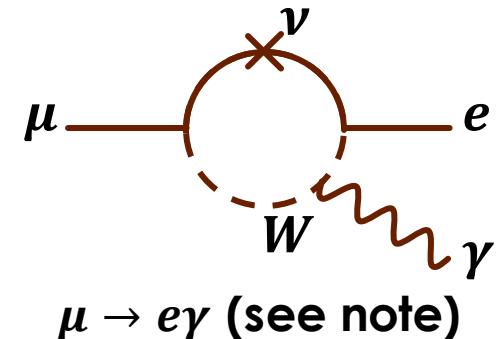
- The basic SM amplitudes can be related to the neutrino oscillation parameters, but requires some radiation to conserve energy & momentum.
- The  $\mu - e$  system is particularly simple because the radiated 'mass' must be neutral, and lighter than a muon.

# Options for decaying muons



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

$$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow evv)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim 0(10^{-54})$$

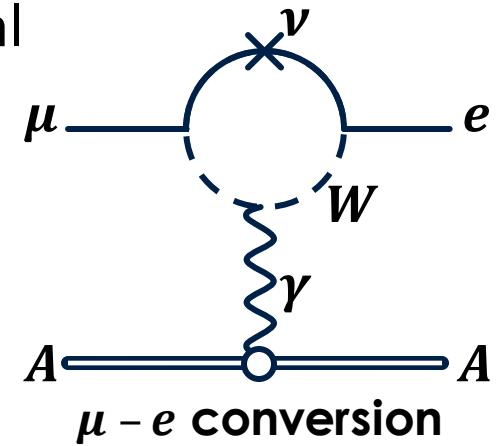


For a free muon,  $\gamma$  or  $ee$  are the only options...

...but in a muonic atom the radiation can be virtual

The nucleus absorbs it, and recoils slightly.

- 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...



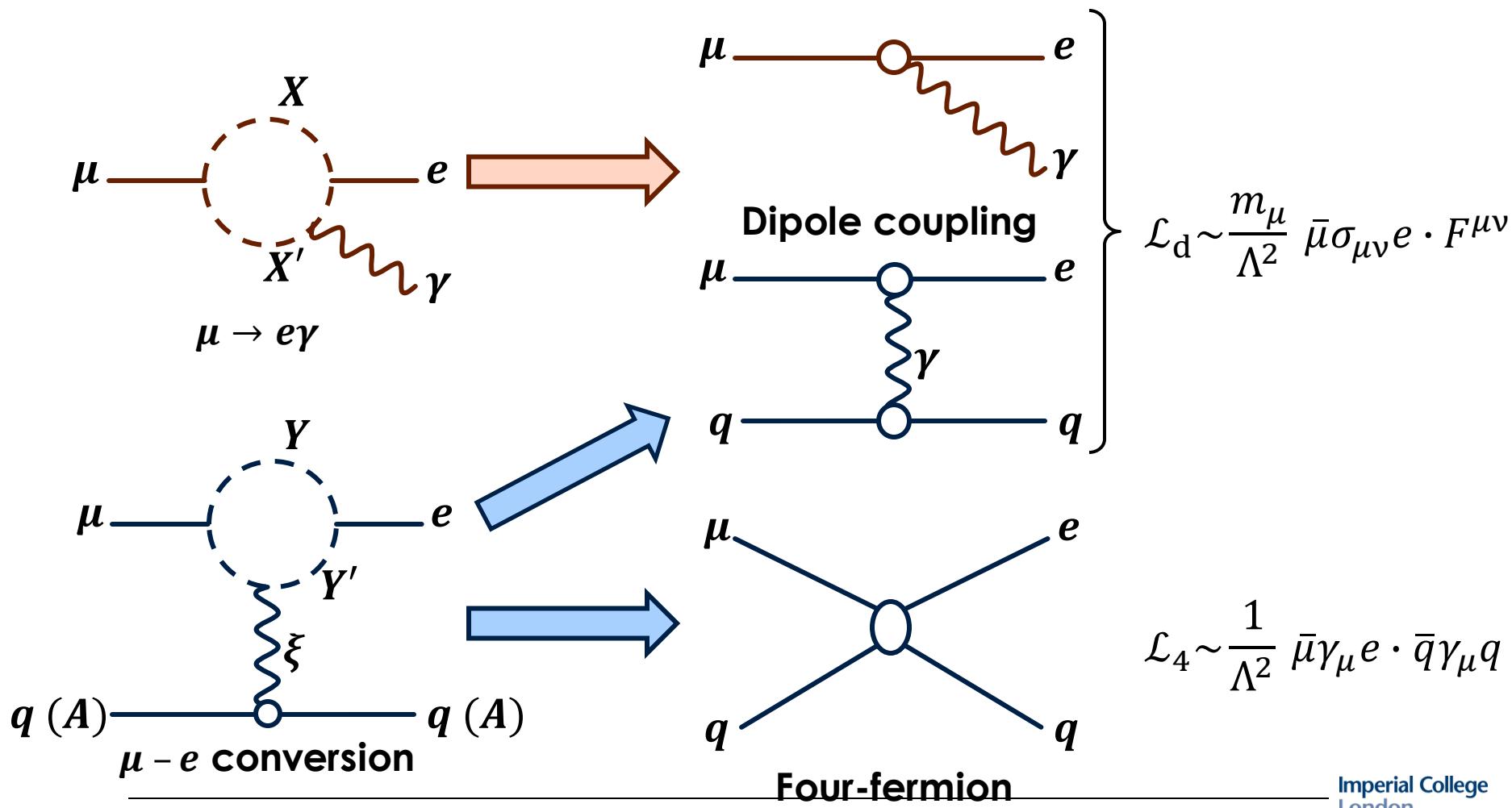
**Note:** The  $\gamma$  can connect anywhere, not just in the loop

# New physics



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

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

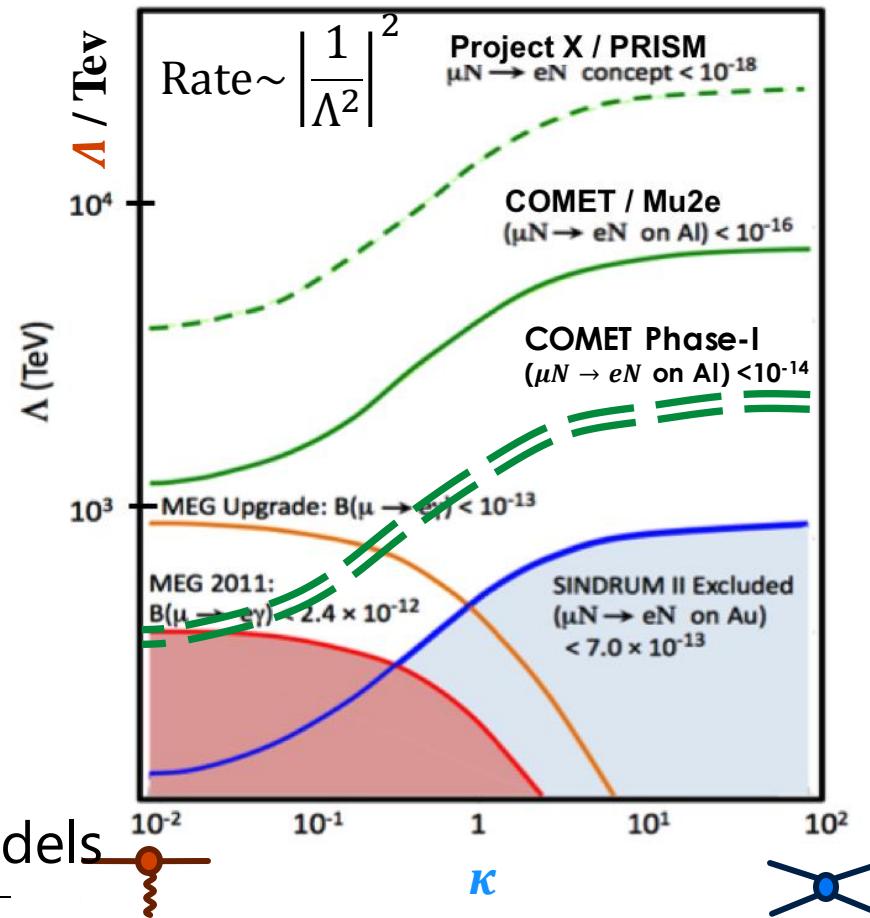


$$\mathcal{L}_{\mu e} \sim \frac{1}{\Lambda^2} \left[ \frac{1}{\kappa + 1} m_\mu \bar{\mu} \sigma_{\mu\nu} e \cdot F^{\mu\nu} + \frac{\kappa}{\kappa + 1} \bar{\mu} \gamma_\mu e \cdot \bar{q} \gamma_\mu q \right]$$

- New physics  $\rightarrow$  CLFV in rare muon decays.
- Energy scale  $\Lambda$  affects the rate of all such processes.
- Parameter  $\kappa$  depends on the nature of the new physics

**Both  $\mu \rightarrow e\gamma$  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



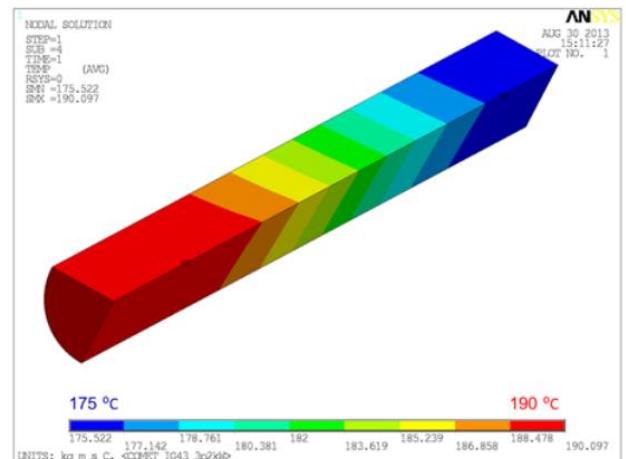
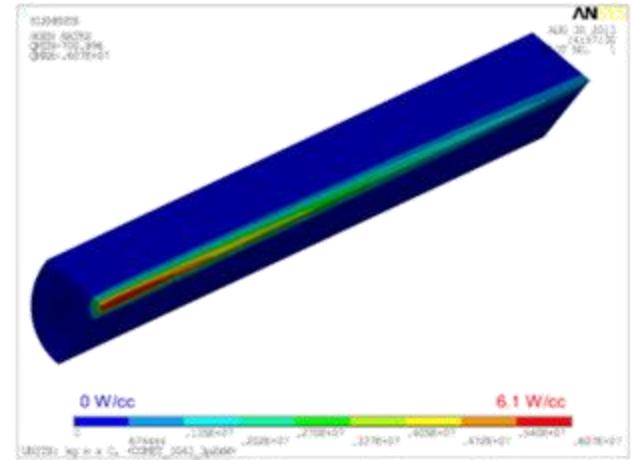
# Production target



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:

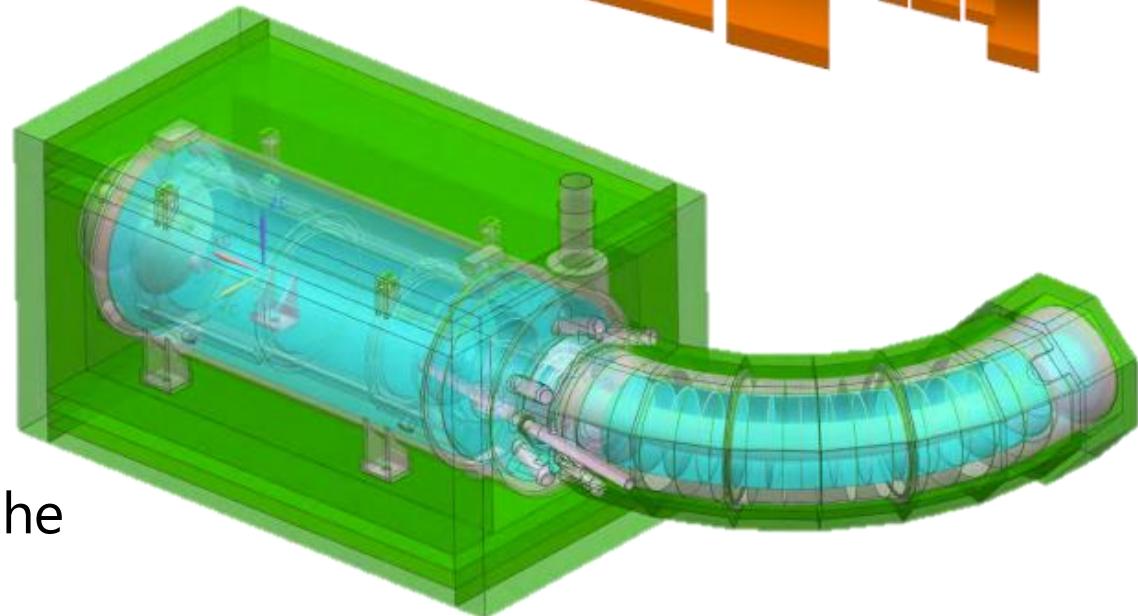
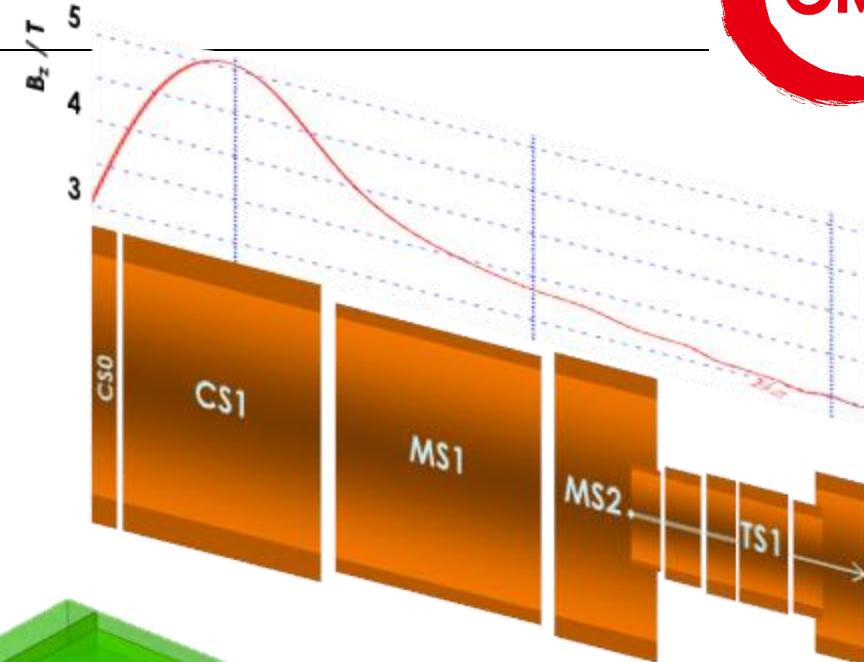
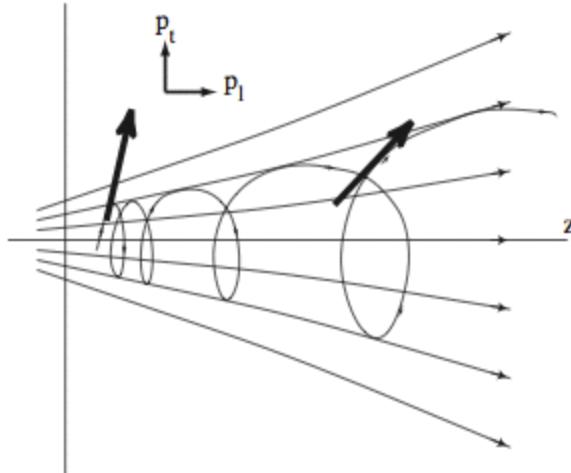
- IG-43 is used for T2K target (FX, >200kW beam) so is known to be capable of handling our beam.
- Lower irradiation of target and shield makes removal and storage safer in case of replacement in Phase-II
- At Phase-I power, radiative cooling is sufficient for this target.



# Capture Solenoid



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



**Gradient field** converts  
transverse momentum into  
longitudinal momentum.

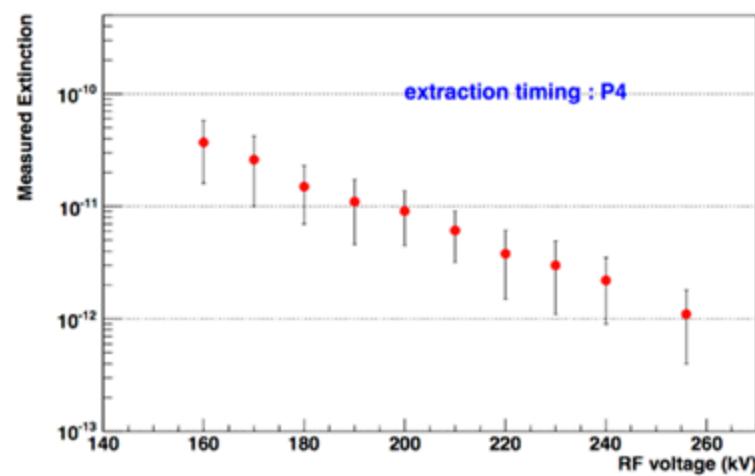
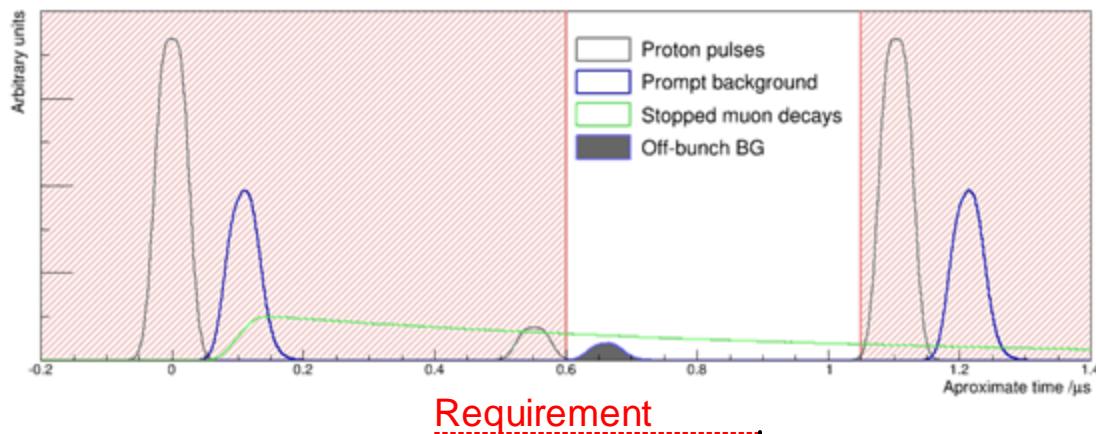
- Effectively increases the solid angle aperture into the transport solenoid.

# Primary beamline

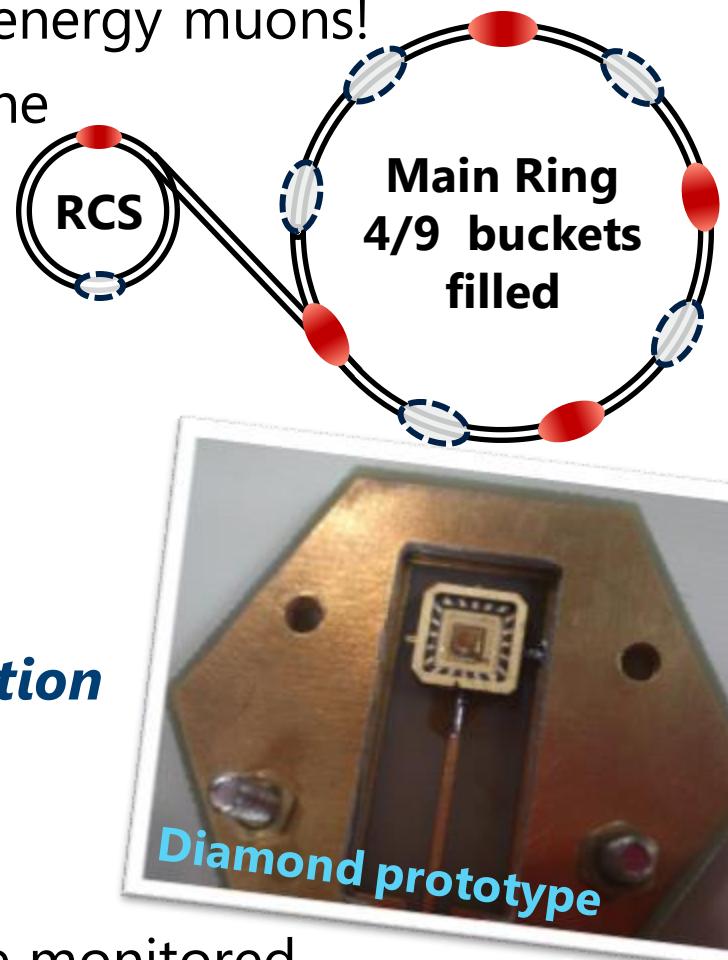


Main driver of sensitivity: Need lots of low energy muons!

- 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.

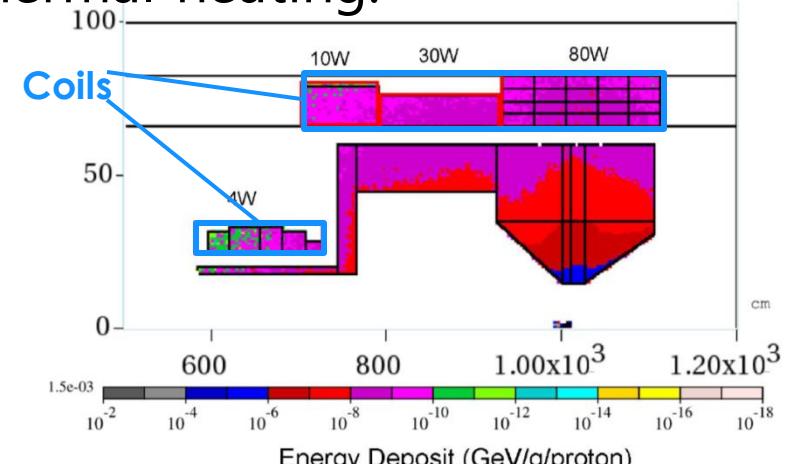
- And therefore cryogenically cooled...

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  $\sim 15W$ ]

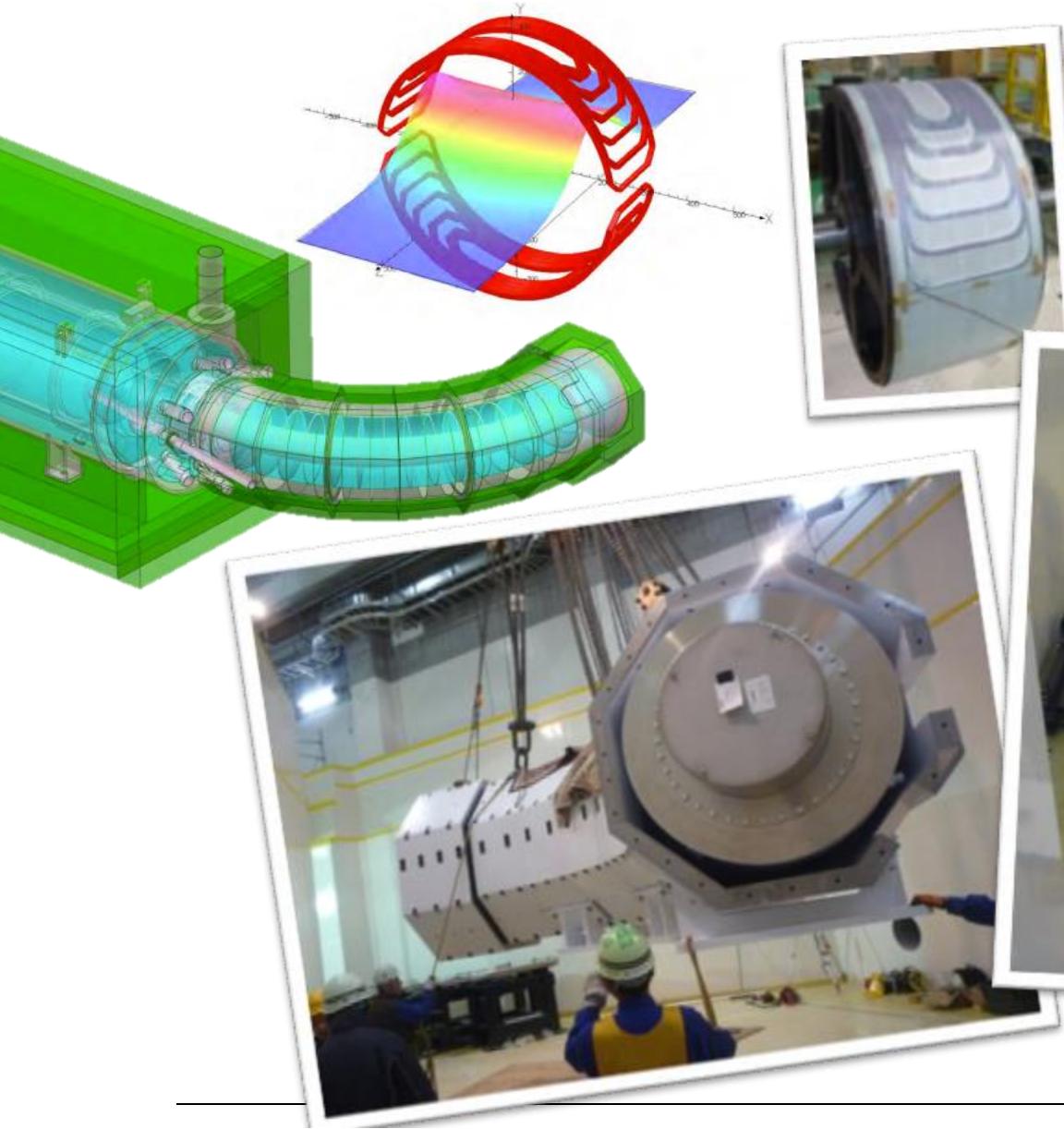
**Shielding** is needed, for radiation and thermal heating.

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



**Non-trivial engineering challenge!**

# Transport Solenoid

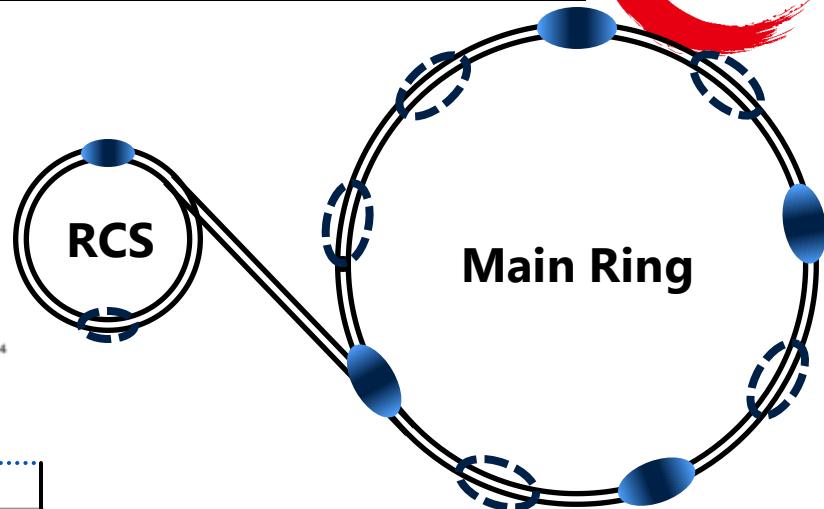
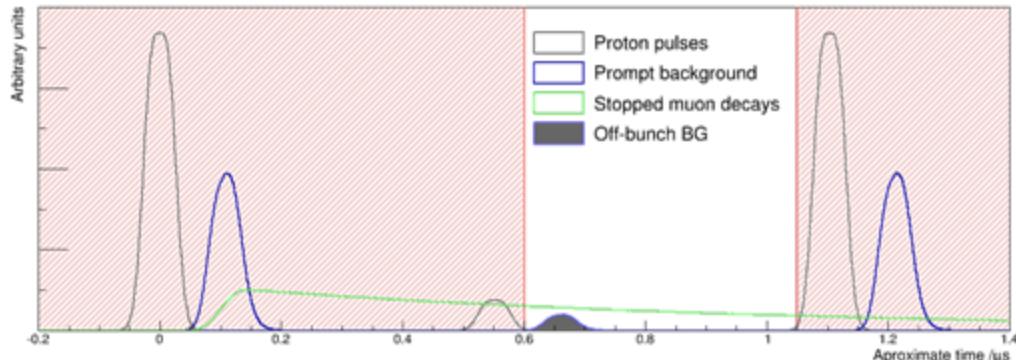


◀ Corrective dipoles

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

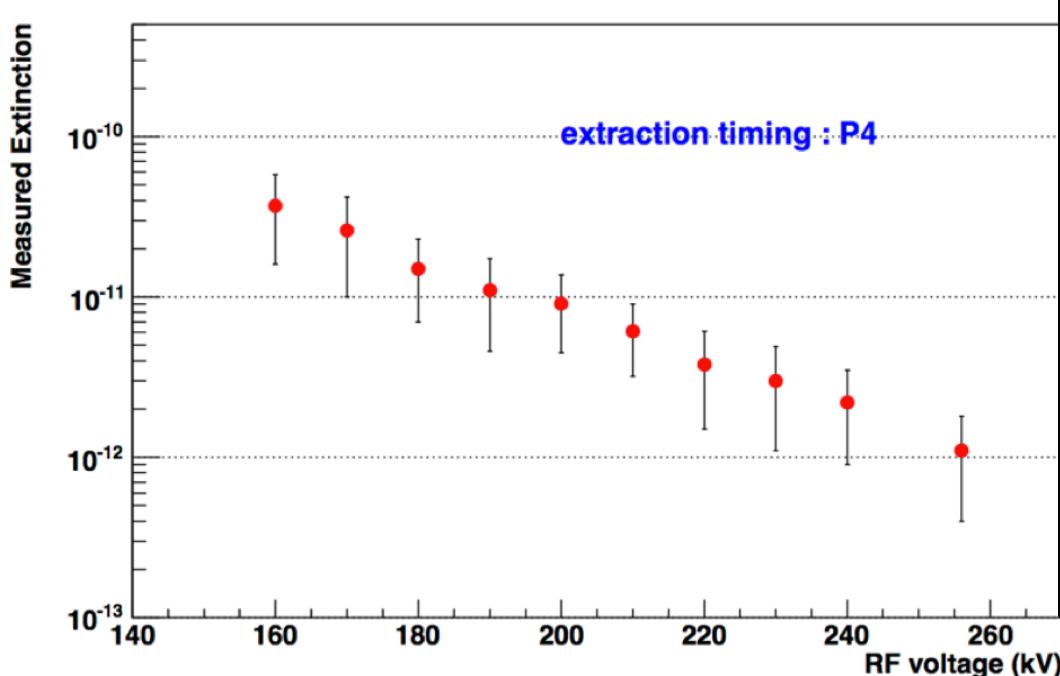


# Extinction test



Extinction @ J-PARC MR Abort

Requirement



Comet requires extinction:

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

Important test in May 2014:  
**Excellent results!**

# Phase-I Detector



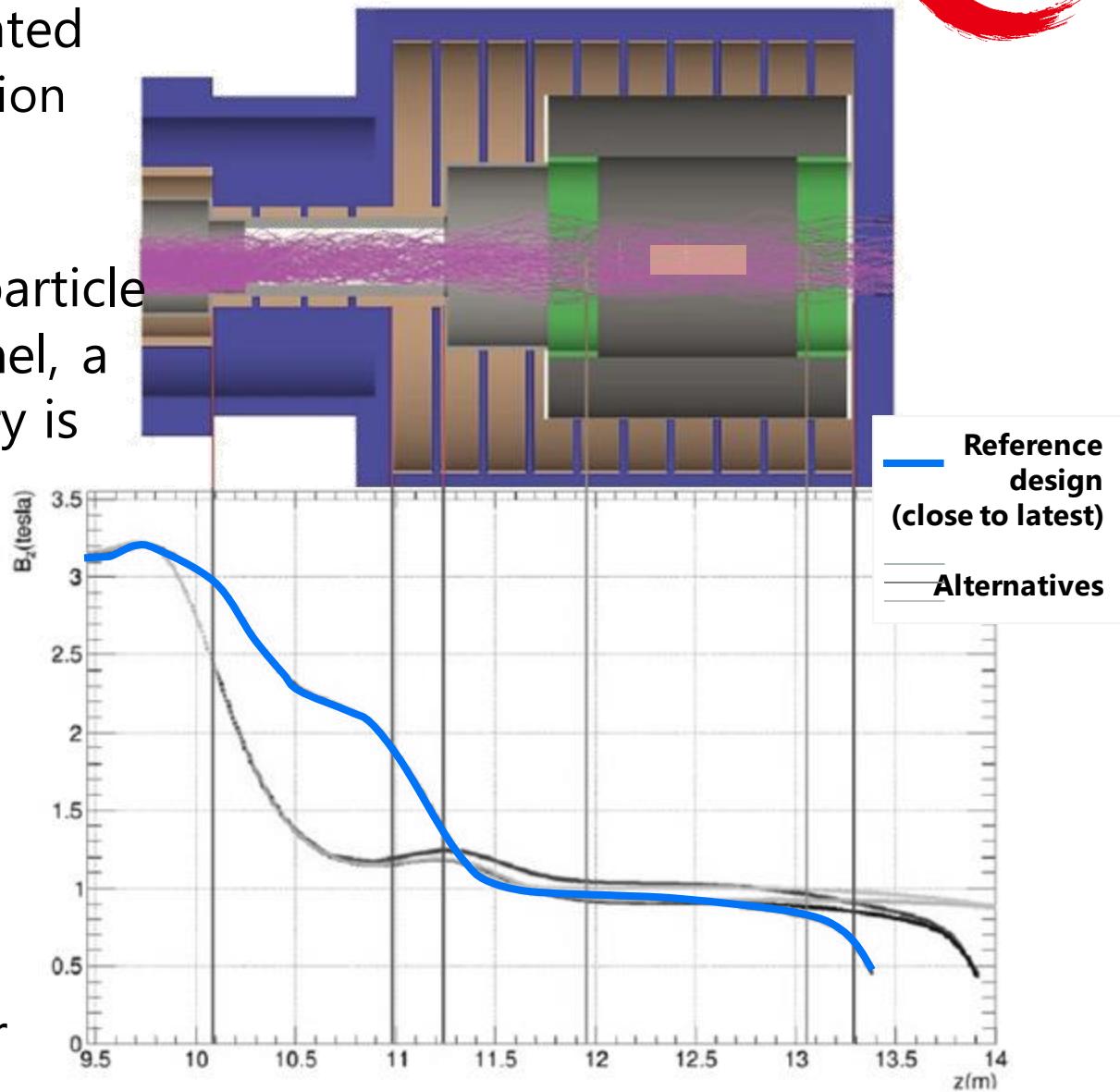
Phase-I will have a dedicated detector for  $\mu \rightarrow e$  conversion measurements.

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

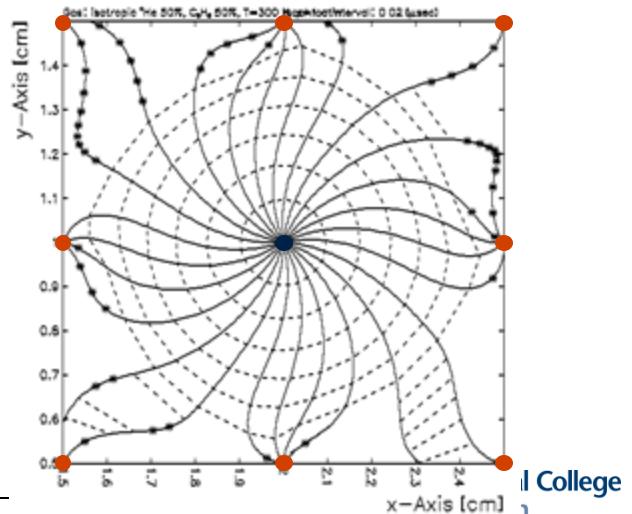
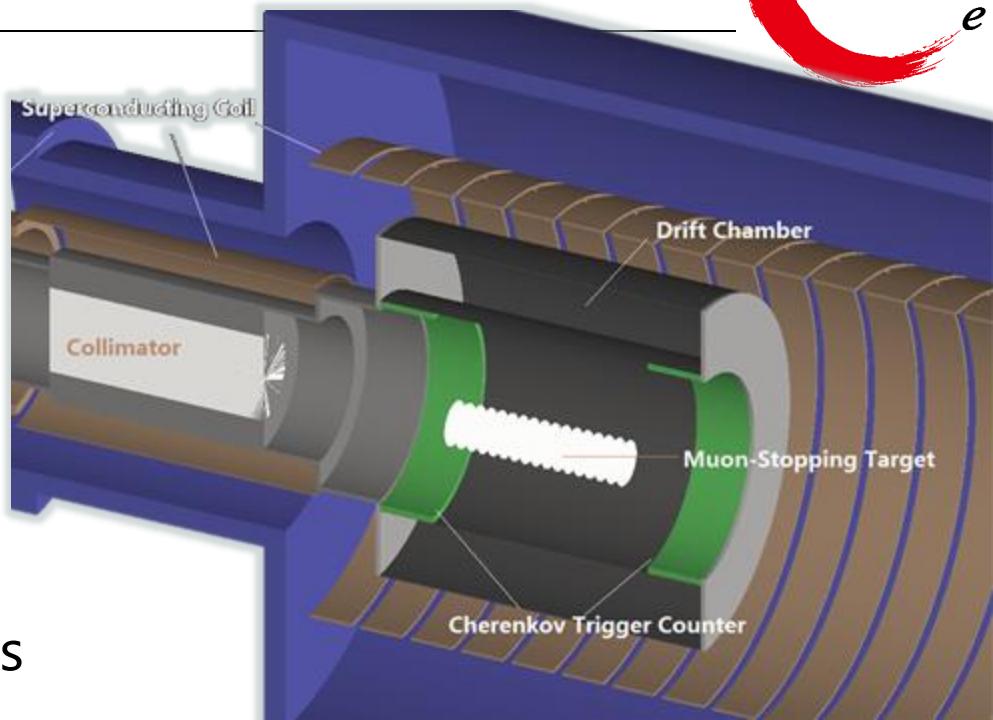


# CyDet



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

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

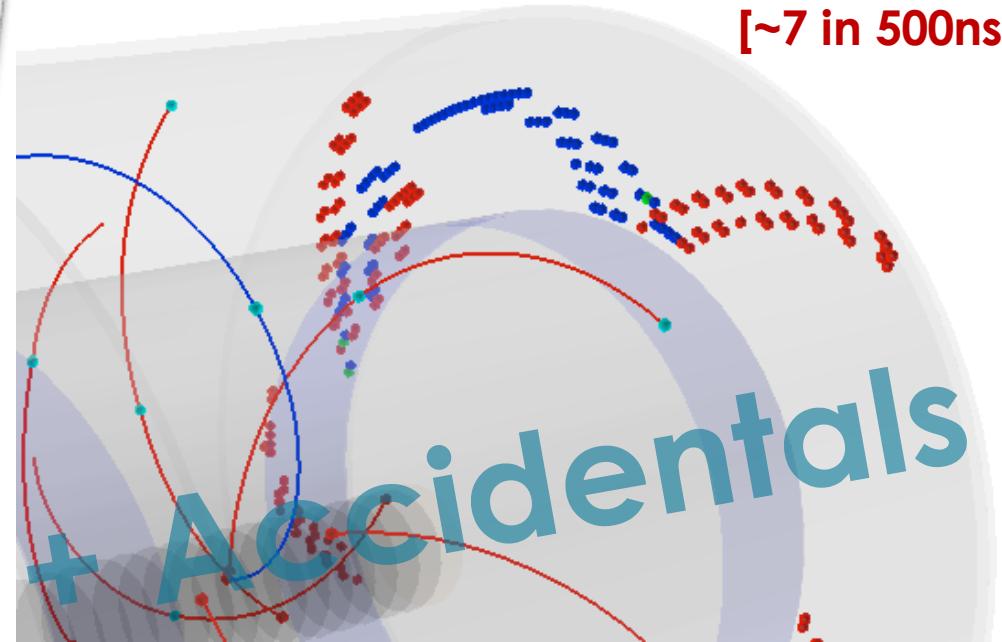


# Drift chamber progress

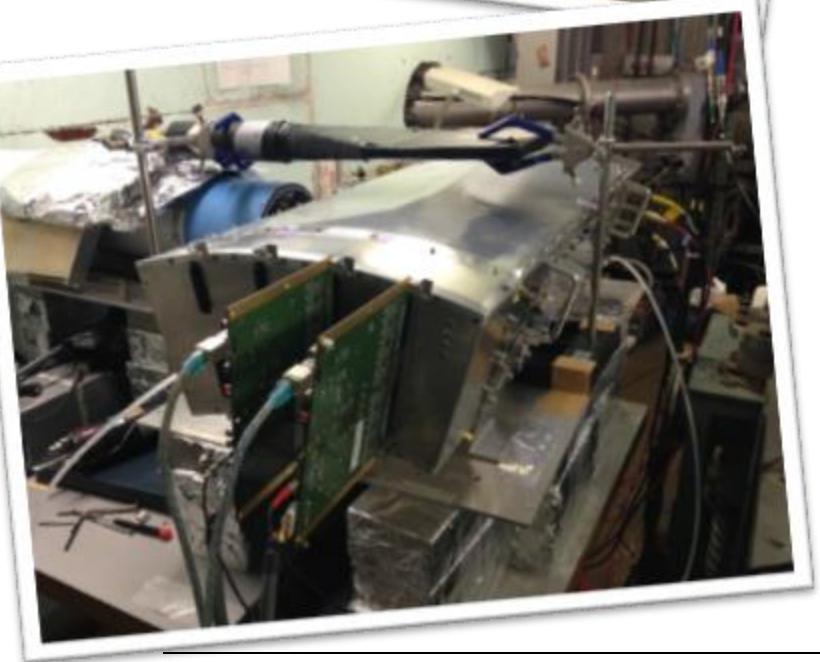
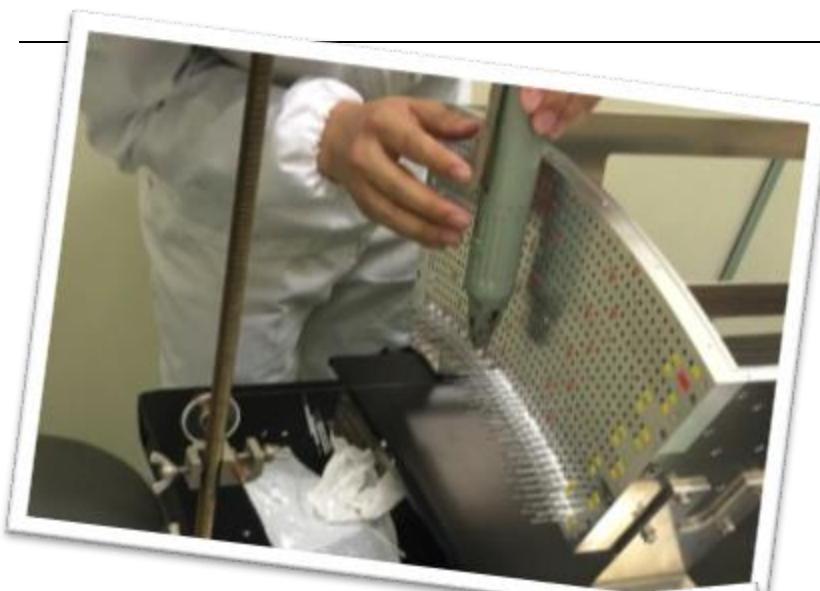


Electron track [~3Hz]

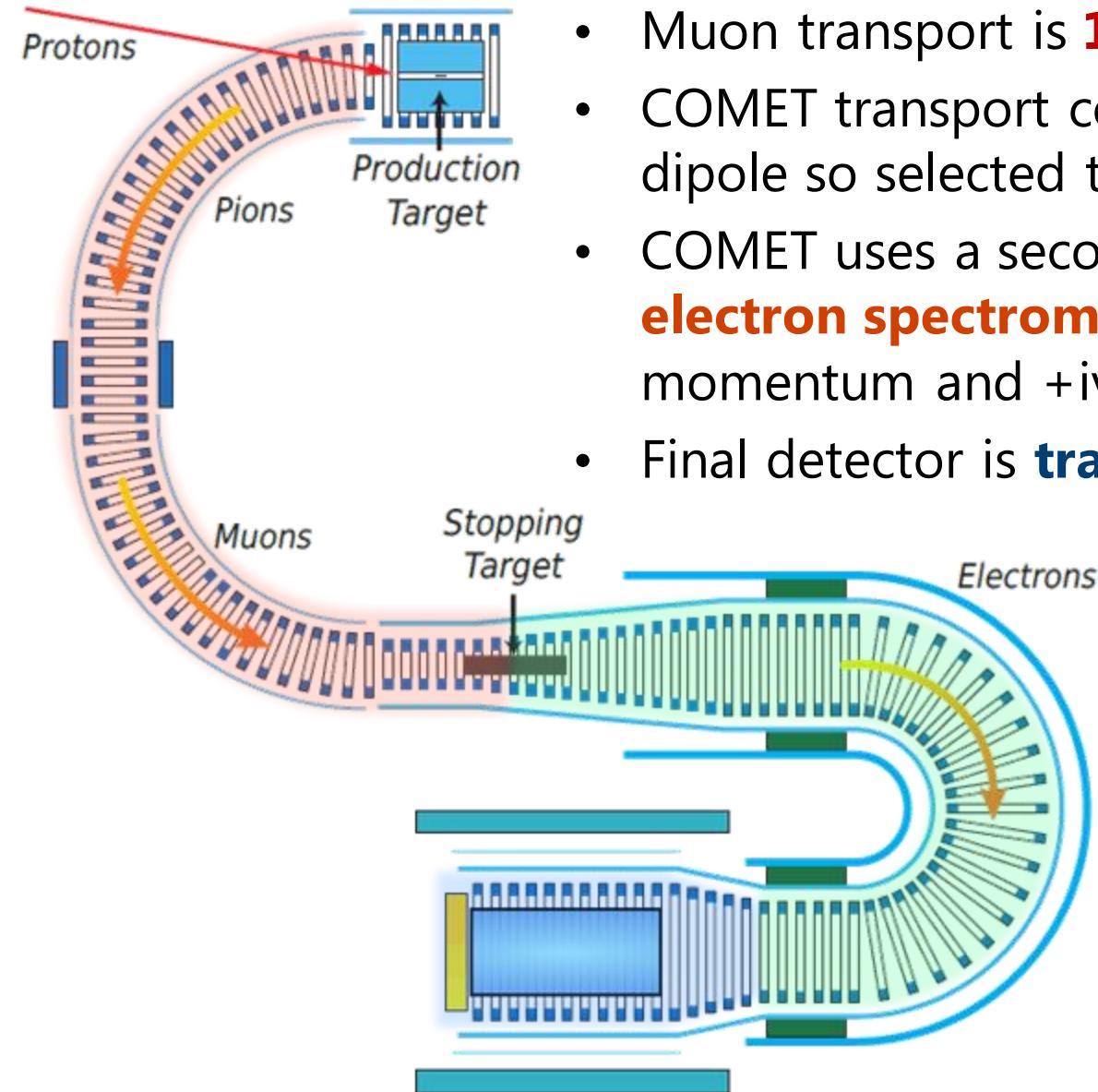
Proton tracks  
[~7 in 500ns]



- ▲ 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



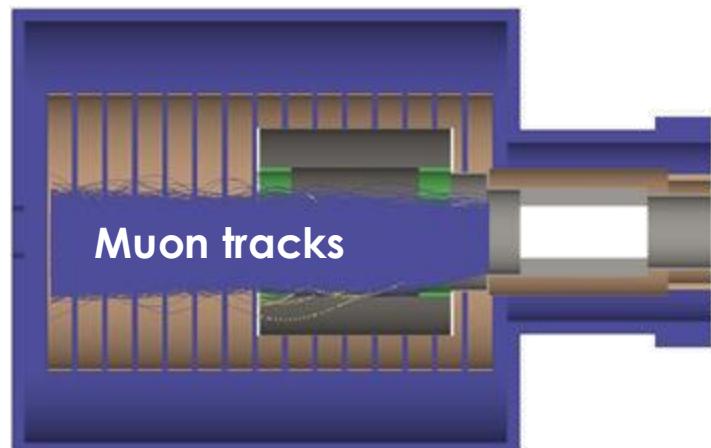
Phase I has 2 goals:

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

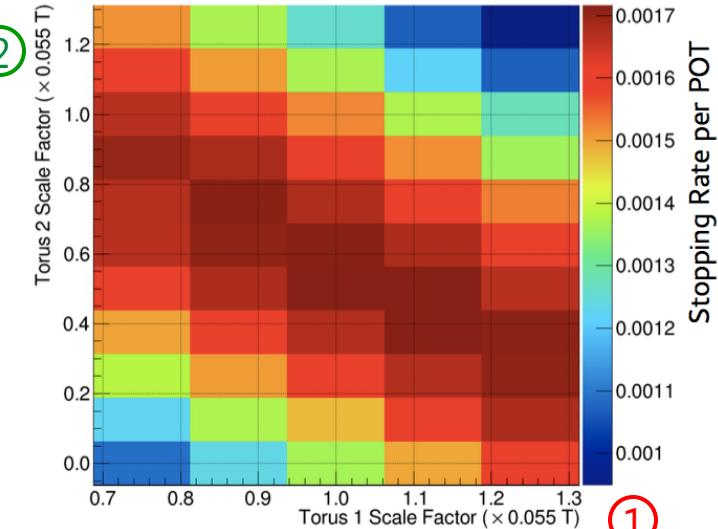
For Phase I measurement use a **cylindrical drift chamber** around the stopping target.

- Triggering by **auxillary hodoscopes**

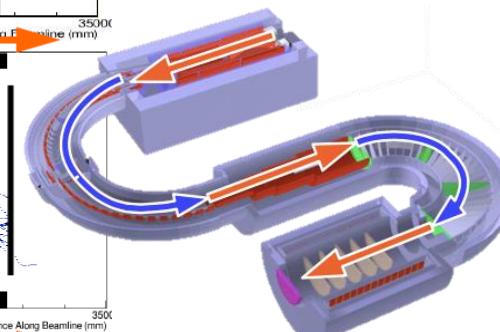
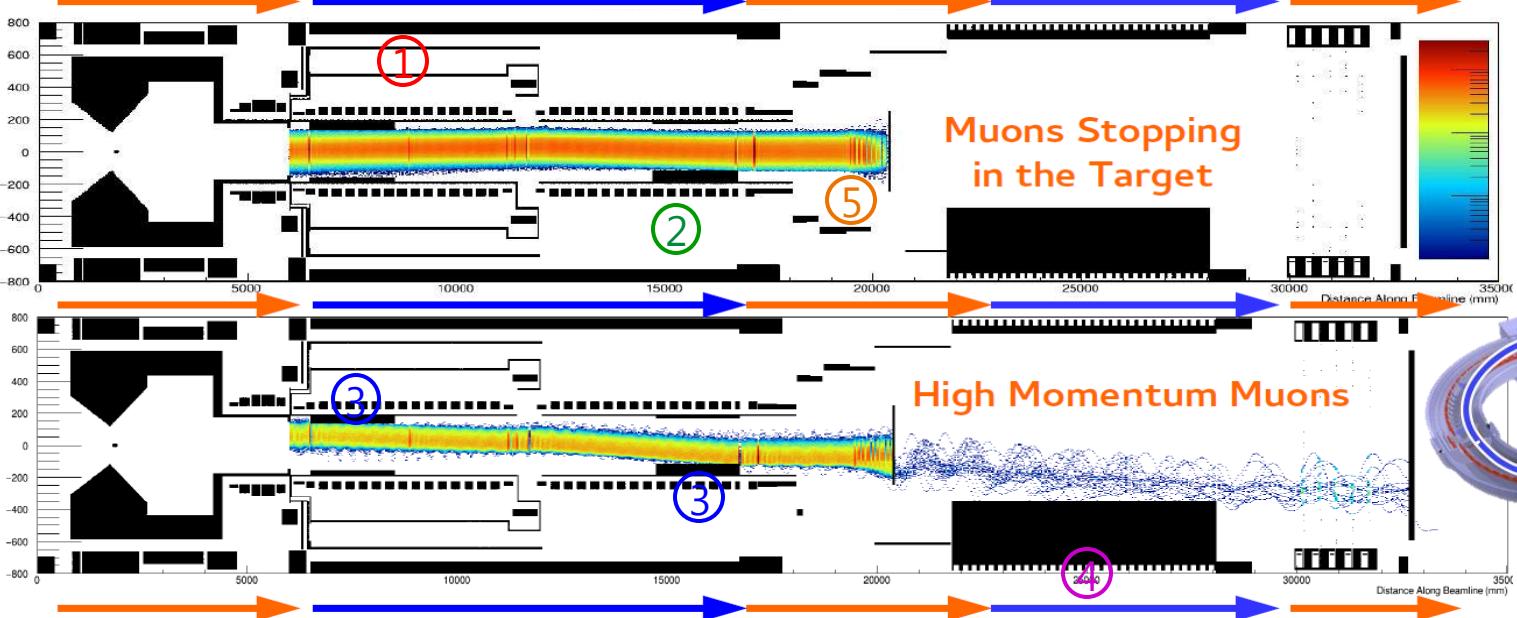
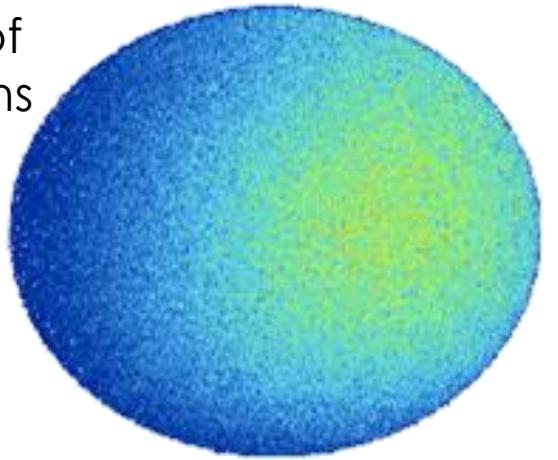
Also include prototypes/partial elements of Phase II detectors for development and characterising backgrounds at low current



# Phase II beamline optimisation



► Distribution of stopped muons



# COMET developments



◀ COMET hall construction completed!



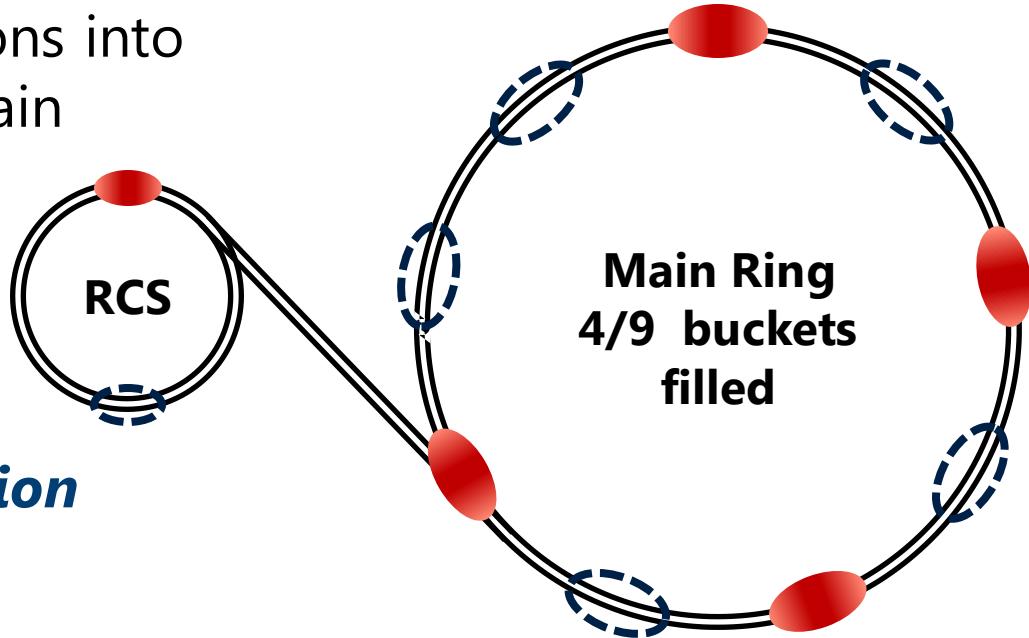
▲ Magnets laid-out for new beam switchyard

# Really beam-free windows?

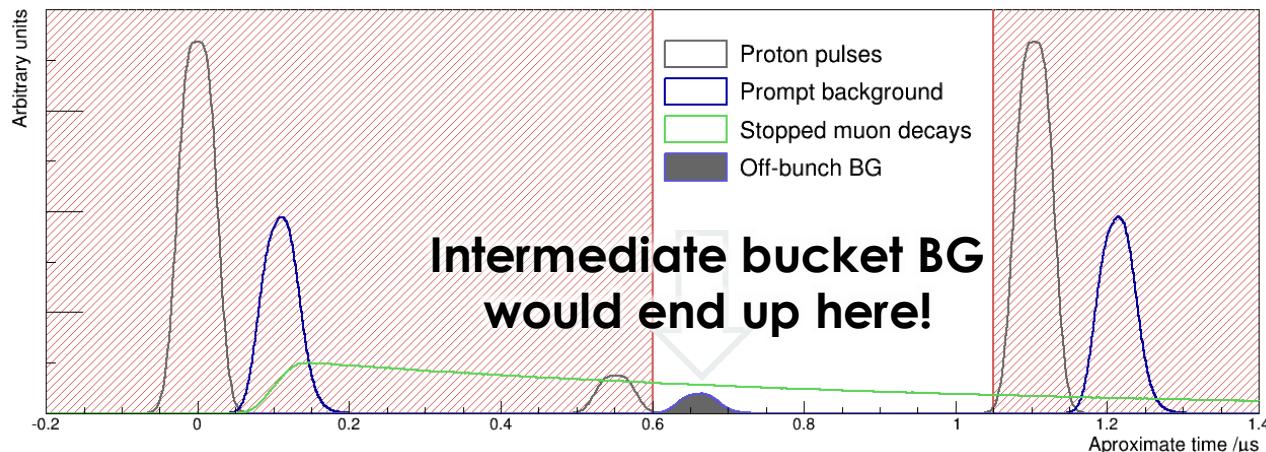


Synchrotrons have stable acceleration buckets

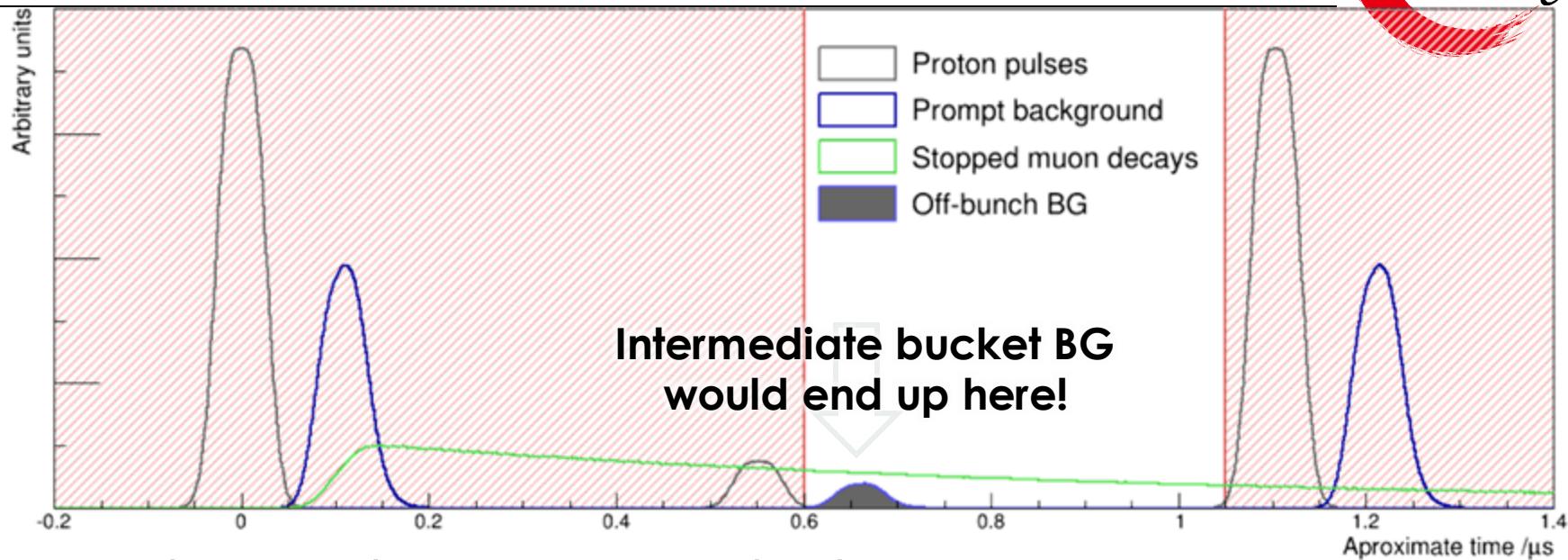
- Even if you don't inject protons into them, stray protons can remain in stable acceleration.



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



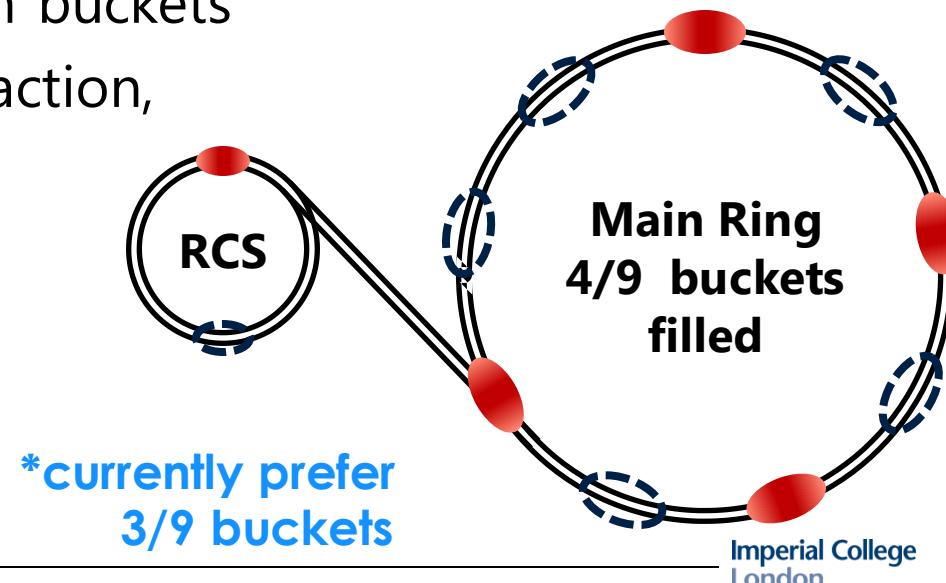
# Beam extinction



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



# Extinction measurement

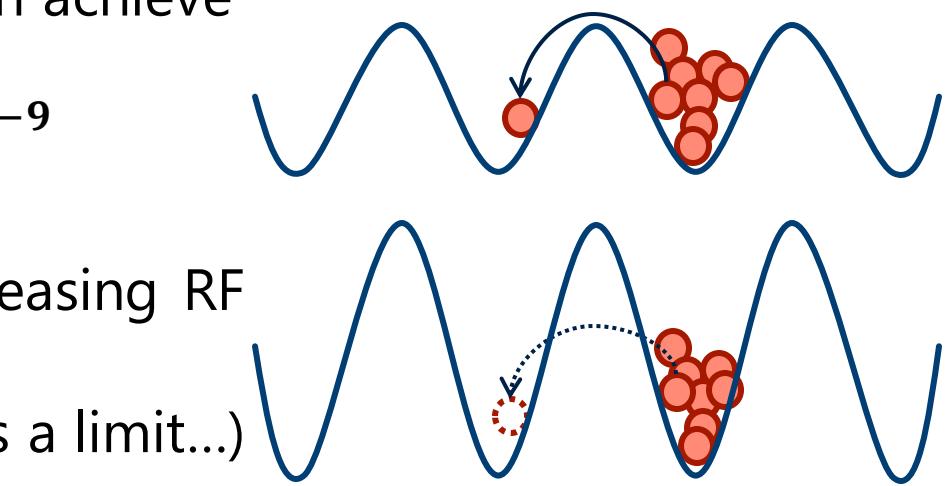
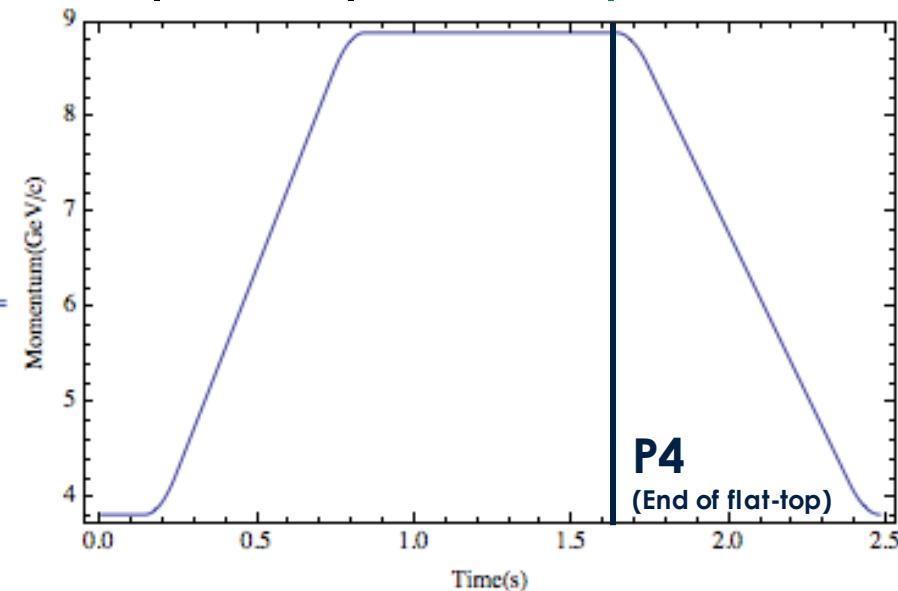


COMET design requires that we can achieve an extinction:

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

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

Accelerate **Maintain RF** (And there is a limit...)



**2012 test at 30 GeV demonstrated this is possible**

**Now also (comfortably) demonstrated at 8 GeV**

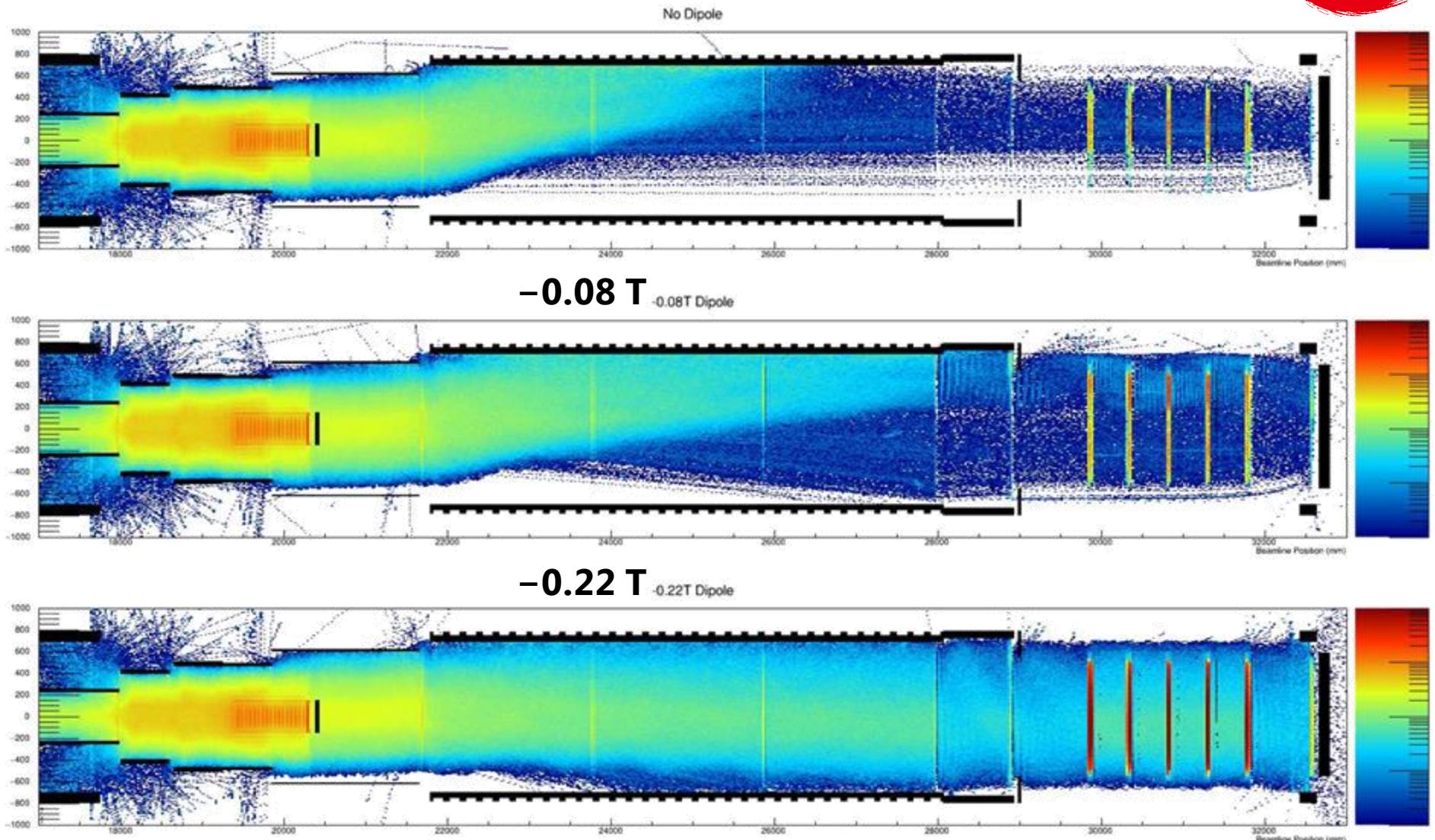
# Background budget (Phase-I)



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	$\leq 0.0038$
	Radiative pion capture	0.0028
Delayed Beam	Neutrons	$\sim 10^{-9}$
	Beam electrons	$\sim 0$
	Muon decay in flight	$\sim 0$
	Pion decay in flight	$\sim 0$
	Radiative pion capture	$\sim 0$
Others	Anti-proton induced backgrounds	0.0012
	Cosmic rays <sup>†</sup>	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

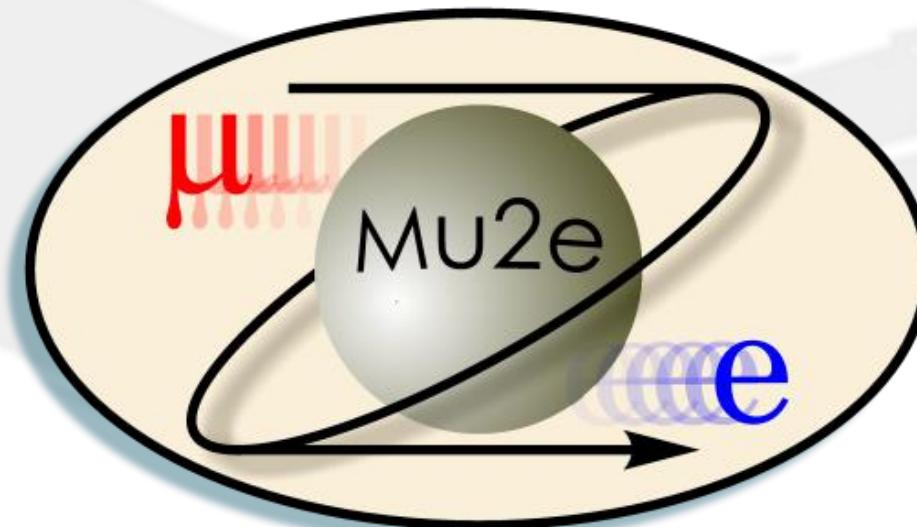
# Spectrometer dipole tuning



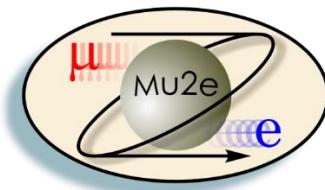
# Mu2e slides kindly provide by Jim Miller (Boston)

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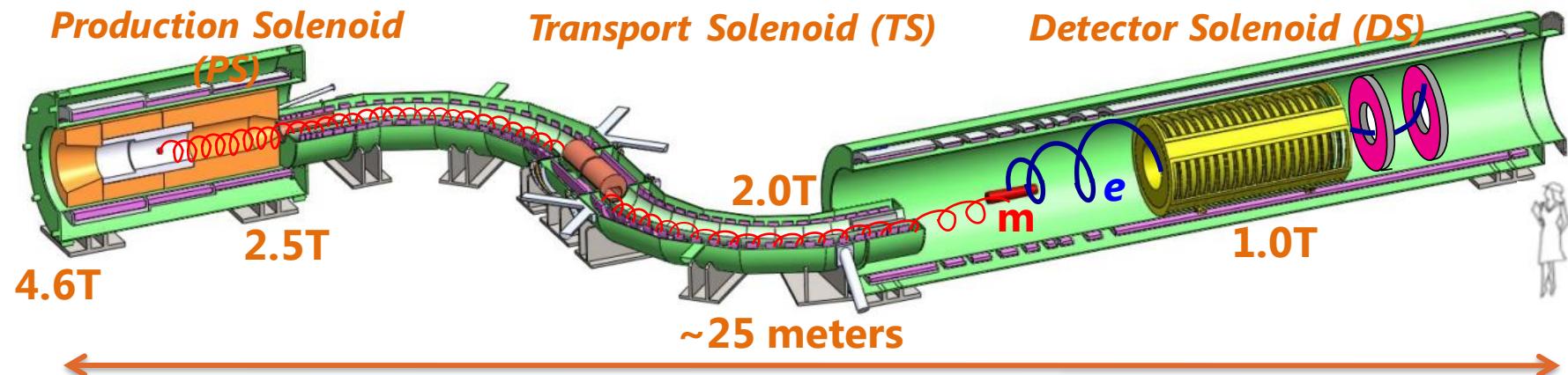
<http://mu2e.fnal.gov>



# The Mu2e Experiment



## A System of superconducting solenoids and an intense muon beam

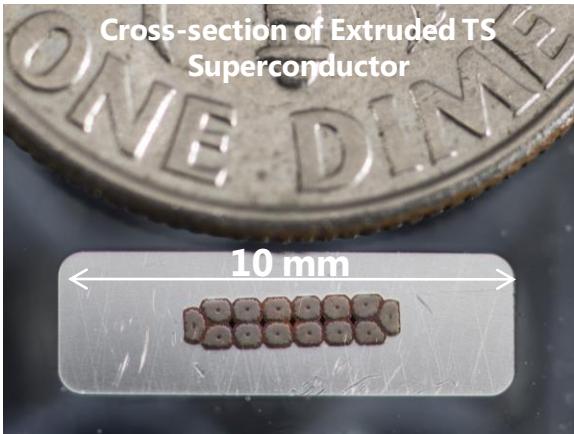


- A search for Charged Lepton Flavor Violation:  $\mu N \rightarrow e N$ 
  - Expected sensitivity of  $6 \times 10^{-17}$  @ 90% CL, x10,000 better than **SINDRUM-II**
  - Probes effective new physics mass scales up to  $10^4$  TeV/c<sup>2</sup>
  - **Discovery sensitivity to broad swath of NP parameter space**

- Experiment scope includes
  - Proton Beam line
  - Solenoid systems
  - Detector elements (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - **Experimental hall**
  - **Commissioning begins in 2020**

# Mu2e Solenoids

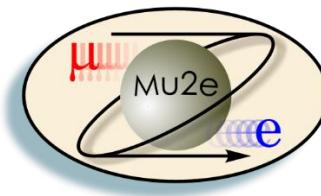
Fermilab, INFN Genova, Northwestern, ANL



- Production length superconductor being fabricated
  - 65 km (out of 75 km total) delivered to FNAL and accepted
- Fabrication of TS coils has started
  - Prototype provided by INFN Genova
  - Exceeded specs.
- Final design and fabrication for PS & DS by General Atomics

# Mu2e Tracker

ANL, Berkeley, CUNY, LBNL, Duke, Fermilab, Houston, Minnesota, Rice



- 20k Straw tubes oriented transverse to beam line
  - $R_{in} = 38$  cm,  $R_{out} = 70$  cm,  $L = 300$  cm
  - Readout and support at large radii, outside active volume
- High efficiency, excellent resolution
  - Momentum resolution 120 keV/c core for 105 MeV electrons

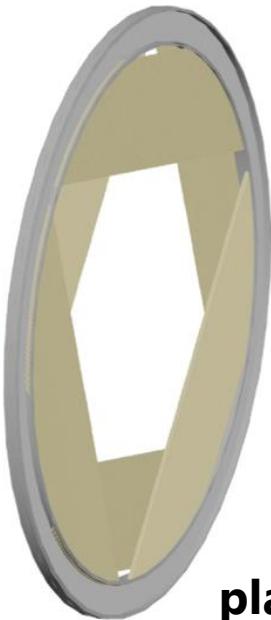
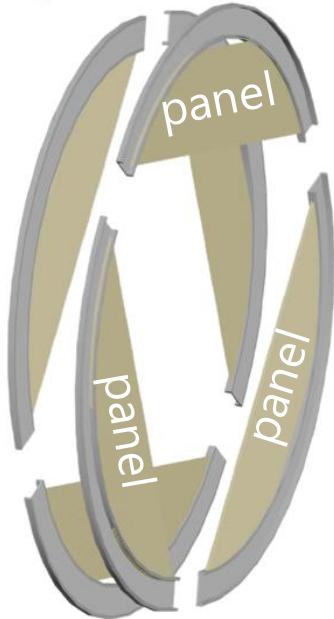
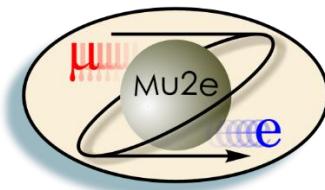


- 5 mm diameter straw
- 25 mm Au-plated W sense wire
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al

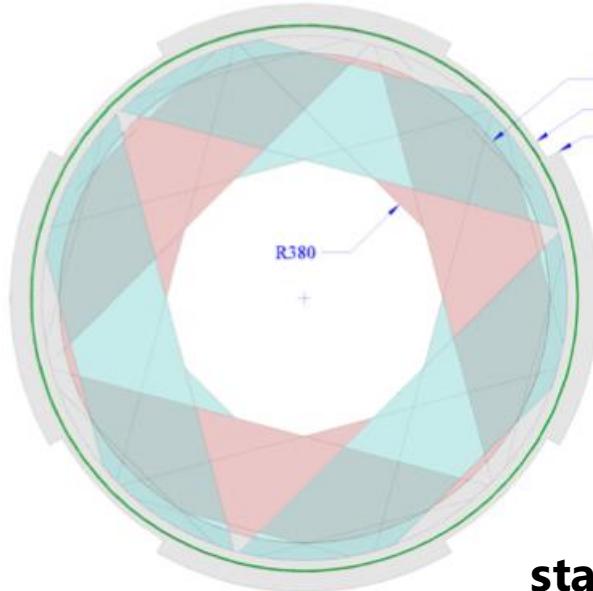


panel prototype (96 straws)  
for vacuum tests

# Mu2e Tracker

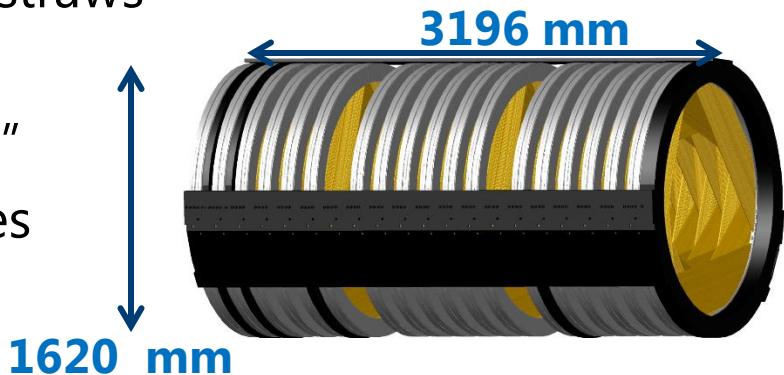


**plane**



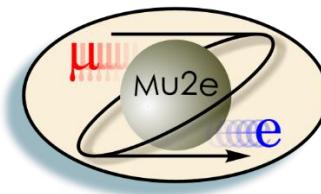
**station**

- Self-supporting “panel” consists of 96 straws
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- Final tracker 18-20 stations long

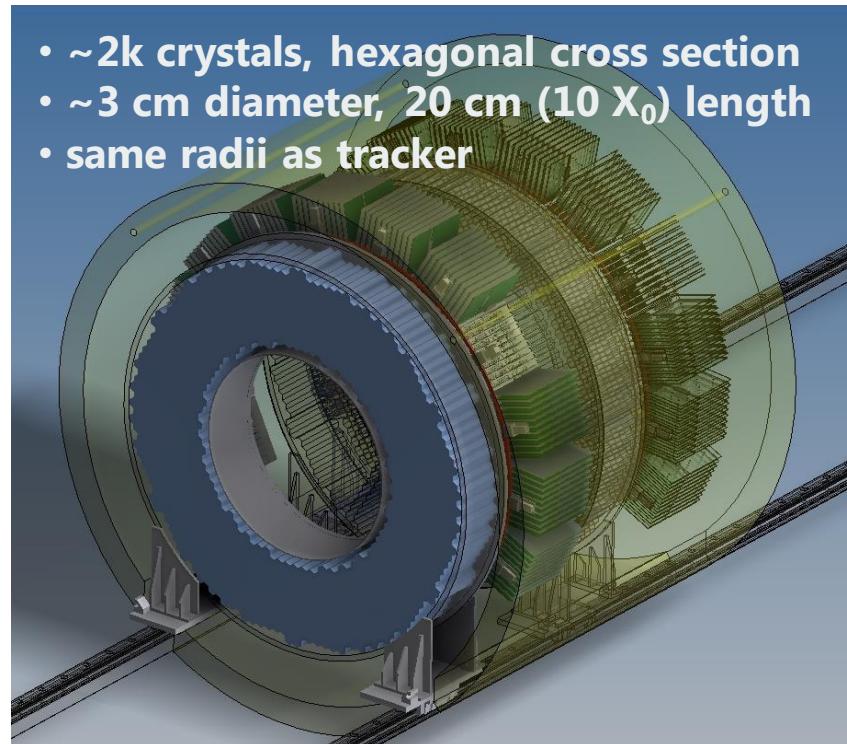
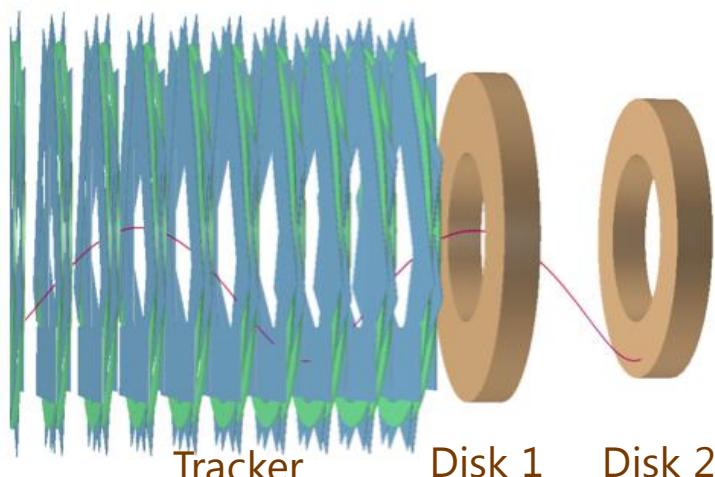


# Mu2e Calorimeter

Frascati, Pisa, Lecce, Roma, Caltech, Dubna, FNAL, HZDR

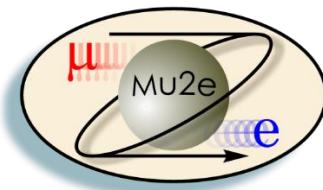


- CsI crystal calorimeter
  - Important for particle ID
  - 5% energy resolution @ 105 MeV
  - <500 ps timing resolution
- 2 disks oriented transverse to beam line, 70 cm apart
- Readout : 2 photo-sensors per crystal

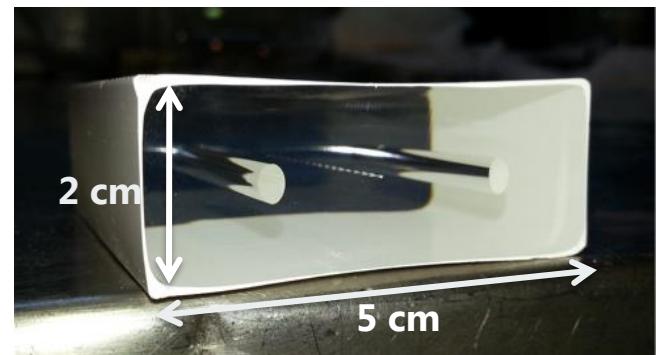
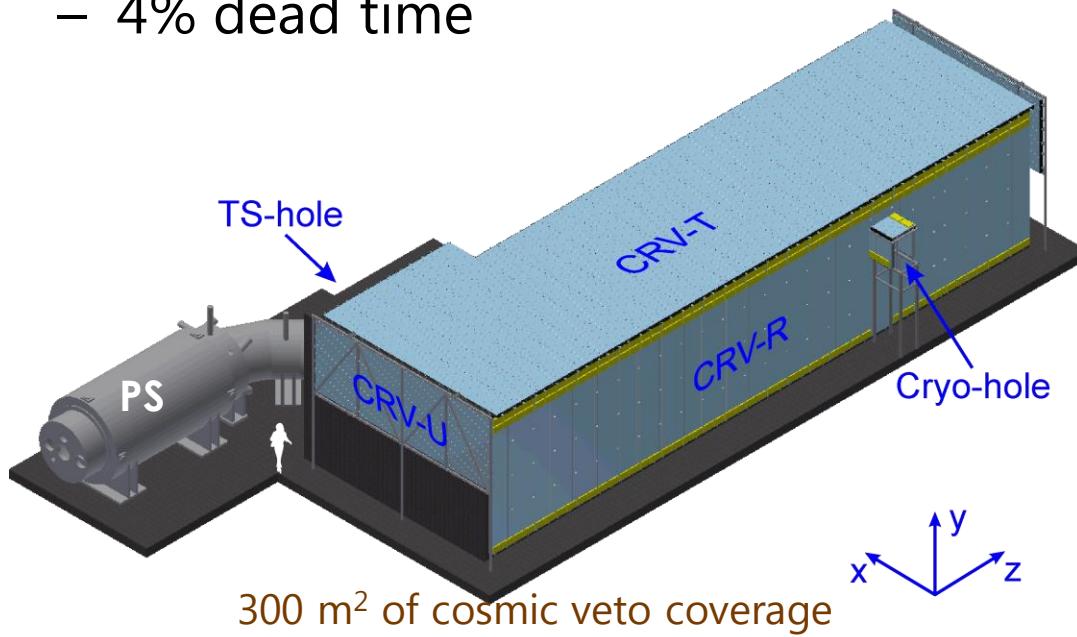


# Mu2e Cosmic Veto

Virginia, NIU, ANL, S. Alabama, BNL, JINR Dubna, KSU

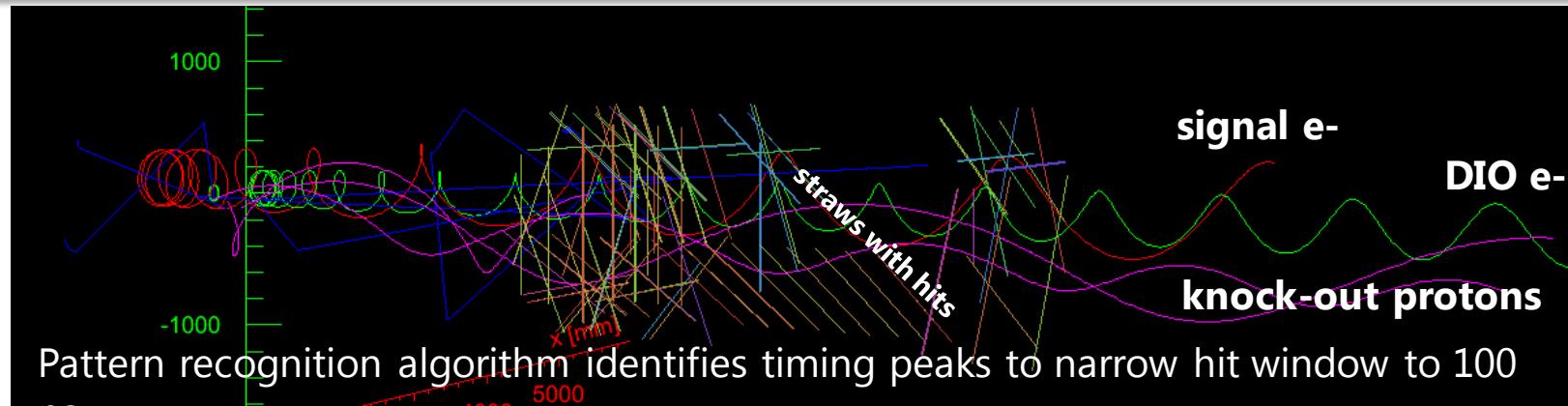
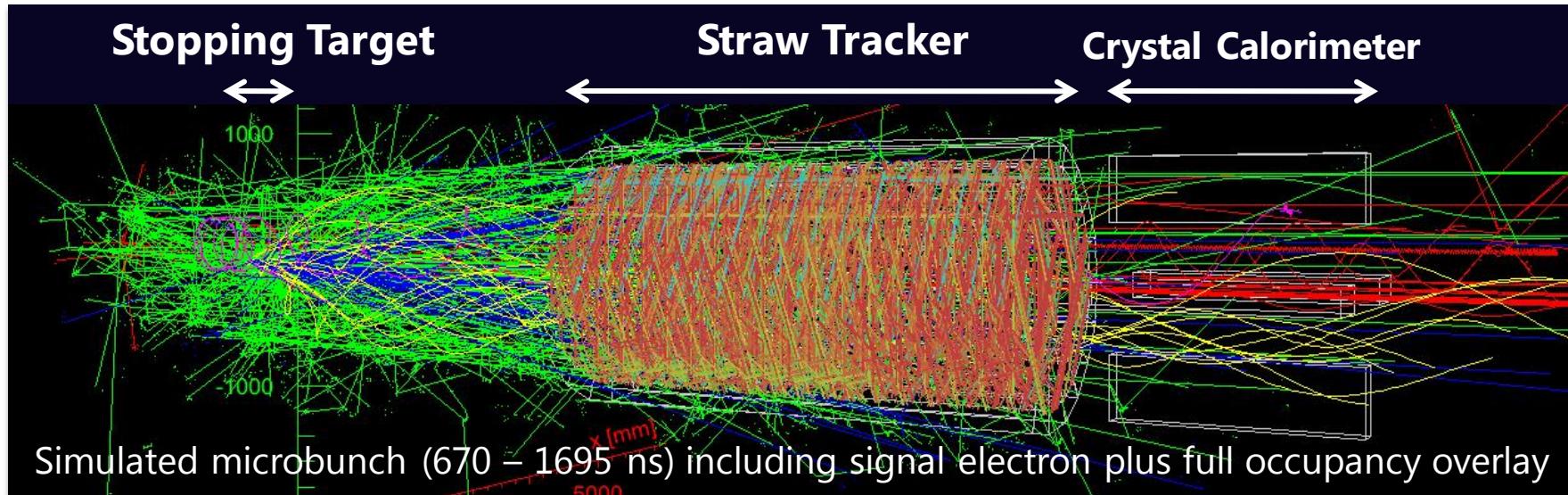
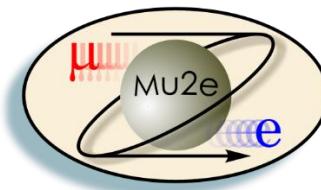


- 4 layers of plastic scintillator
  - WLS fiber + dual-ended SiPM readout
- Coincidence in 3-of-4 layers gives 99.99% veto efficiency
  - 5 ns coincidence window
  - 125 ns veto window
  - 4% dead time



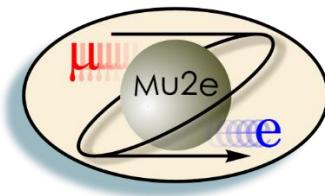
# Mu2e Simulations

BNL, Fermilab, Irvine, Boston, Virginia, NIU, Caltech, Louisville, Pisa, Novosibirsk, Frascati, CUNY, Muons Inc., Northwestern, Sun Yat-Sen, Berkeley



Utilize a detailed, hit-level GEANT4 simulation, realistic occupancy overlays, full reconstruction, pattern recognition, and track fitting. Full systematic error analysis.

# Mu2e Sensitivity



## Estimated background yields for $3.6 \times 10^{20}$ POT

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	$0.199 \pm 0.092$
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	$0.023 \pm 0.006$
	Muon decay-in-flight ( $\mu$ -DIF)	$<0.003$
	Pion decay-in-flight ( $\pi$ -DIF)	$0.001 \pm <0.001$
Miscellaneous	Beam electrons	$0.003 \pm 0.001$
	Antiproton induced	$0.047 \pm 0.024$
	Cosmic ray induced	$0.082 \pm 0.018$
Total background:		$0.36 \pm 0.10$

## Estimated signal sensitivity for $3.6 \times 10^{20}$ POT

Parameter	Value
Physics run time @ $2 \times 10^7$ s/yr.	3 years
Protons on target per year	$1.2 \times 10^{20}$
$\mu^-$ stops in stopping target per proton on target	0.0019
$\mu^-$ capture probability	0.609
Total acceptance x efficiency for the selection criteria of Section 3.5.3	$(8.5 \pm 1.1)\%$
Single-event sensitivity with Current Algorithms	$(2.87 \pm 0.32) \times 10^{-17}$
Goal	$2.4 \times 10^{-17}$

- Total background yield:  $(0.36 \pm 0.10)$  events
- Total signal acceptance x efficiency:  $(8.5 \pm 1.0)\%$
- Single-event-sensitivity:  $(2.9 \pm 0.3) \times 10^{-17}$
- Expected Limited:  $6 \times 10^{-17}$  @90% CL
- New Physics reach:  $L_{\text{eff}} < 10^4 \text{ TeV}/c^2$

End

