Imperial College London

MICE

A Brave New World of Muon Accelerators for High Energy Physics

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20th July, 2015

The Ideal Accelerator...

1. Enables the search for physics beyond the Standard Model

2. Produces beams with no backgrounds or uncertainties

3. Has high luminosity (rate)

The Standard Model of Particle Physics

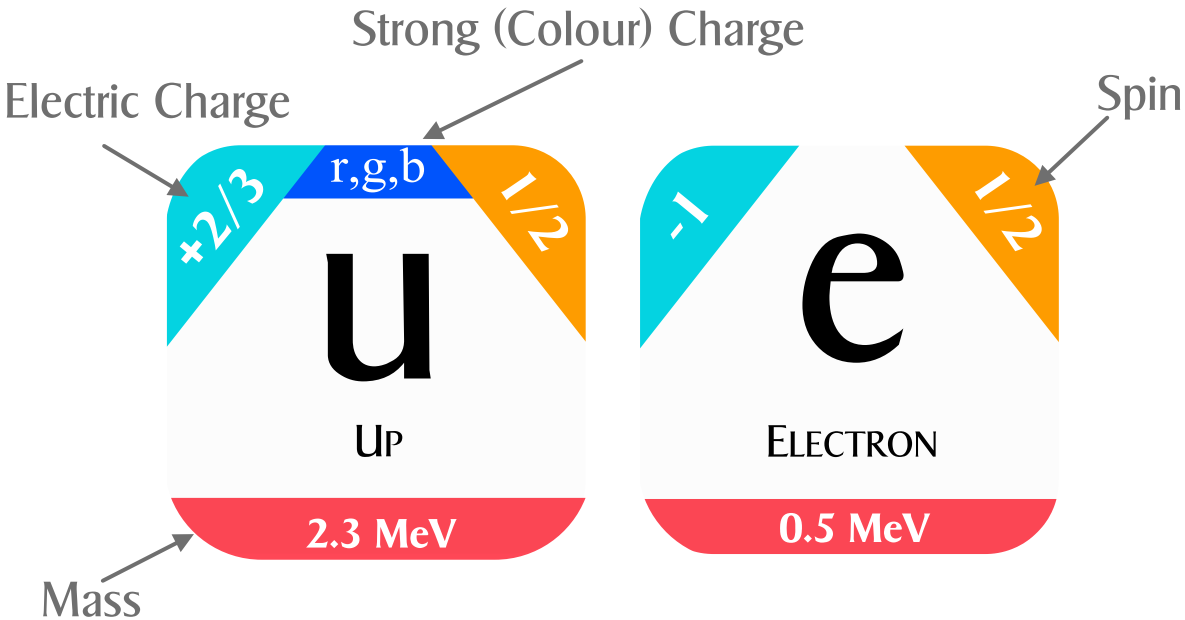
(... and what exists beyond it...)

The Standard Model

Describes the interaction of the fundamental particles with 3 (of 4) fundamental forces.

Fermions

- Fundamental particles that make up 'everyday' and 'exotic' matter
- Non-integer spin

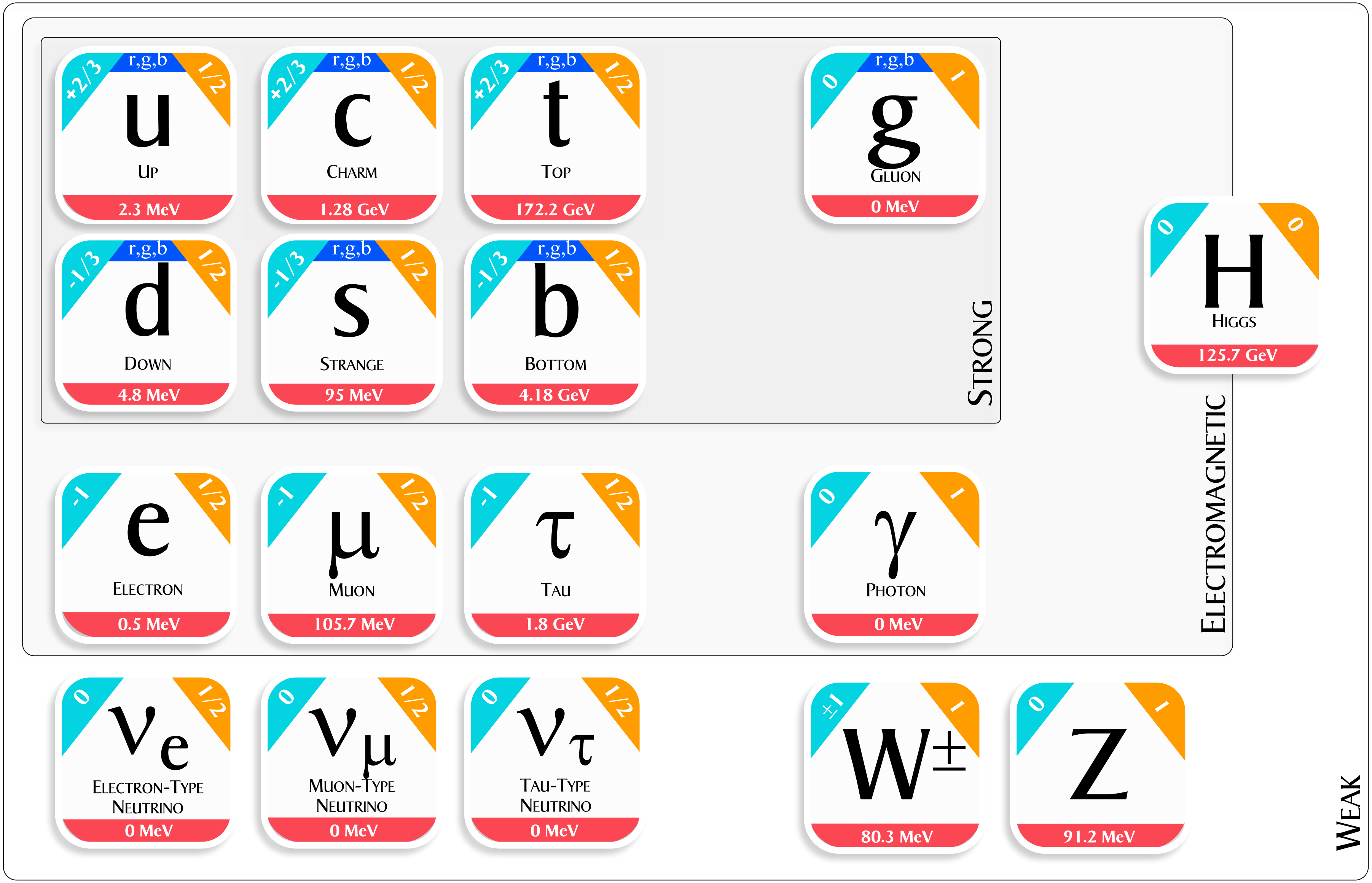


Bosons

- Force-carrying particles
- Integer spin

The Standard Model

+ Antimatter

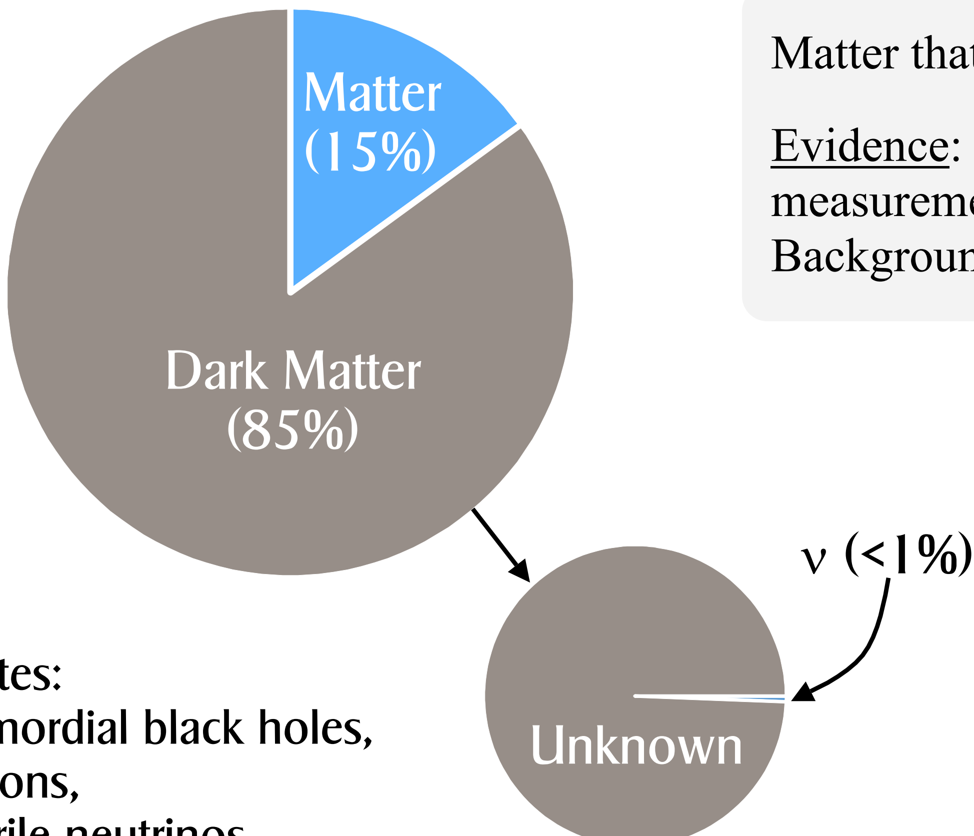


5 Reasons to Keep Searching

1. Dark Matter
2. CP Violation
3. Baryogenesis
4. Gravity
5. Massive ν

5 Reasons to Keep Searching

Dark Matter



Matter that does not reflect or absorb light

Evidence: galactic rotation curves, measurements of the Cosmic Microwave Background (CMB)

Candidates:
- Primordial black holes,
- Axions,
- Sterile neutrinos,
- Weakly Interacting Massive Particles (WIMPs)

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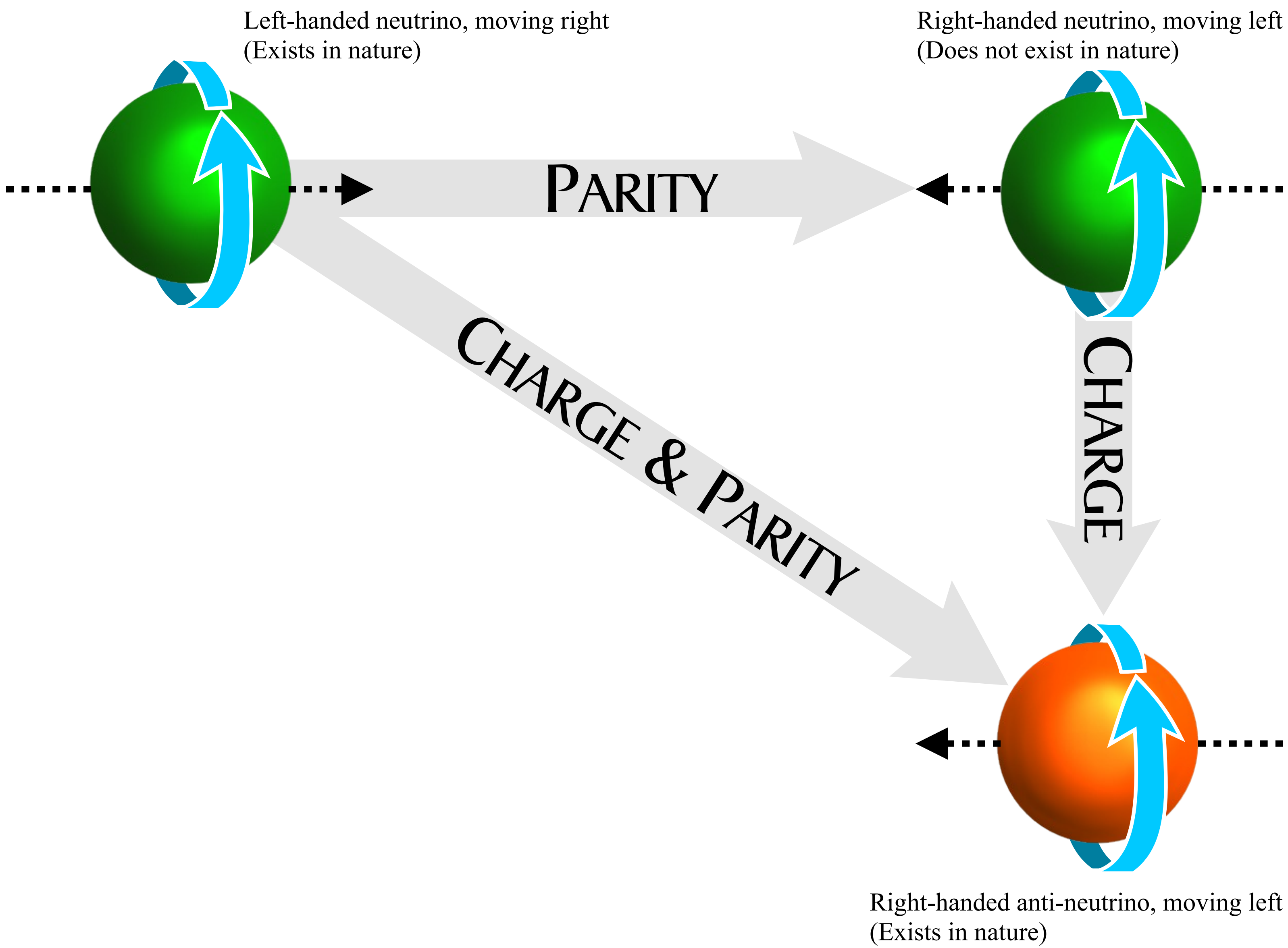
CP Violation



(Adapted from http://universe-review.ca/R02-14-CPviolation.htm)

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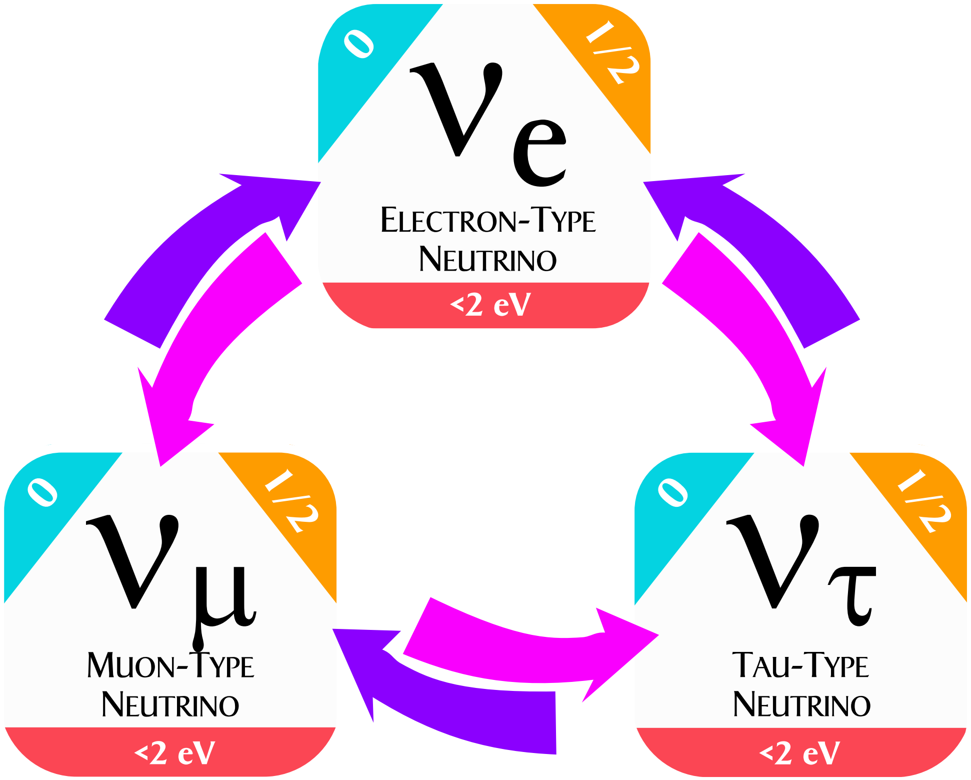
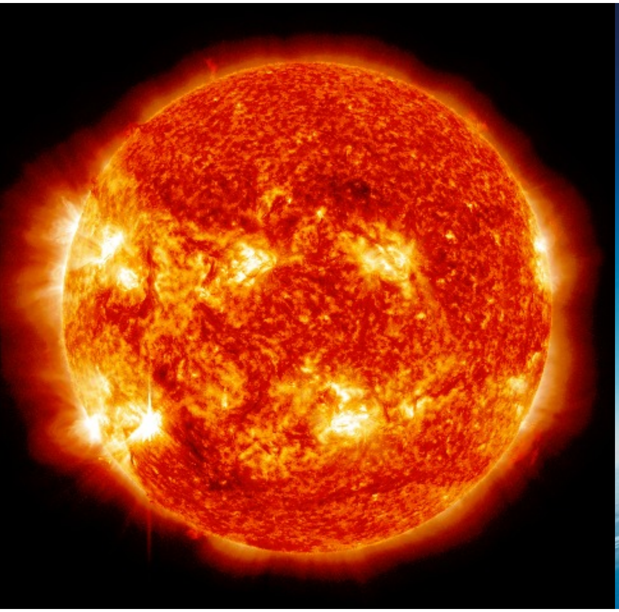
Neutrino Oscillations



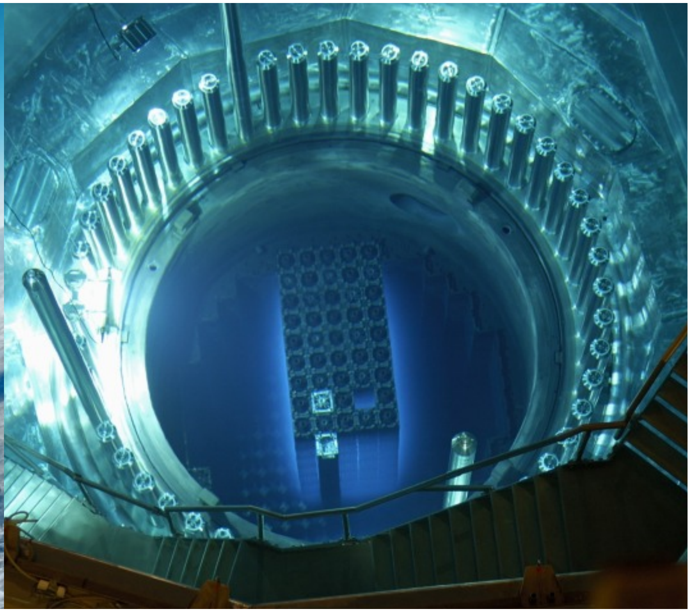
Neutrinos change flavour

Neutrino Oscillations



Solar Neutrino
Deficit

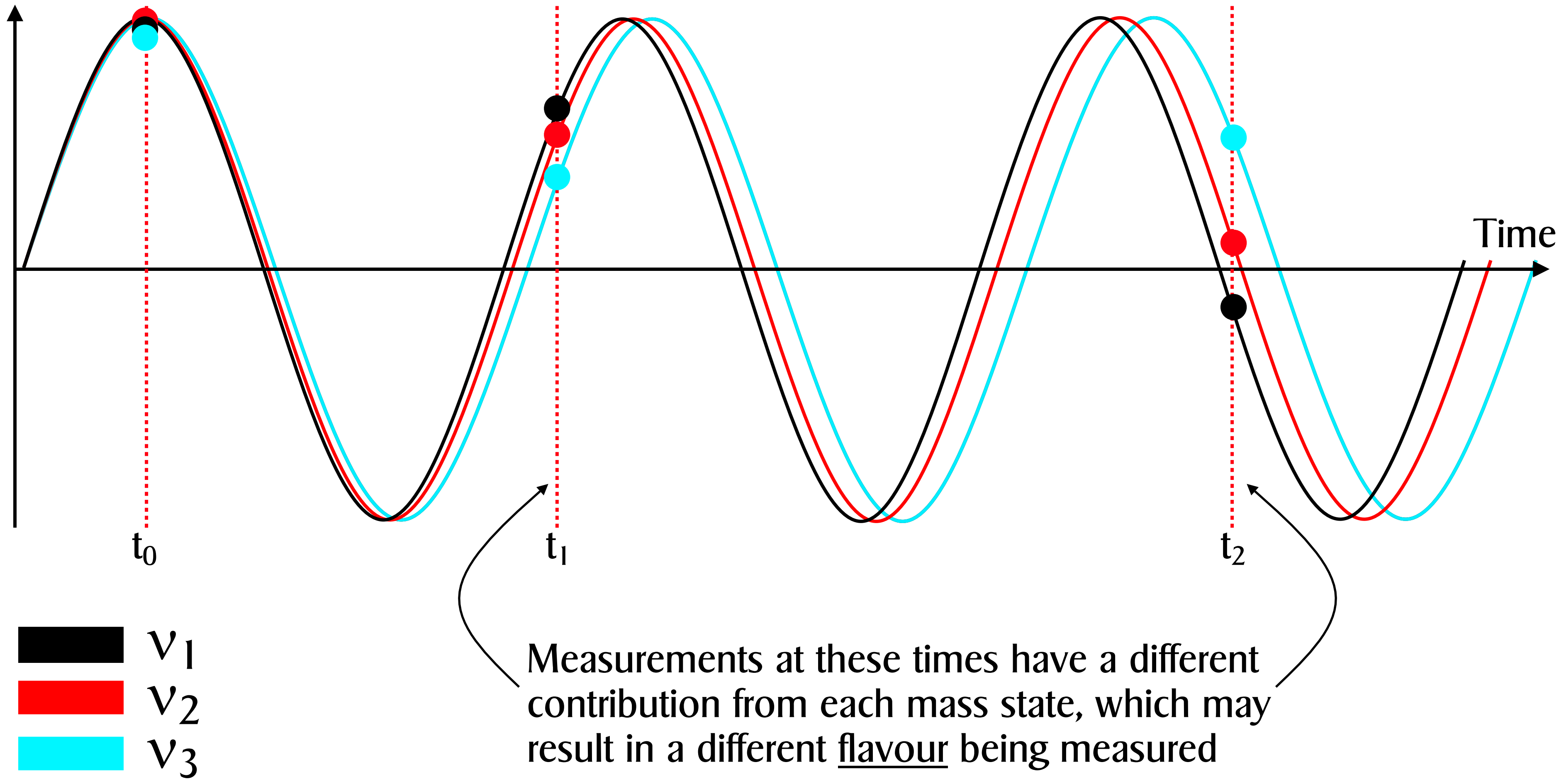
Atmospheric Neutrino
Anomaly



Reactor Neutrino
Anomaly

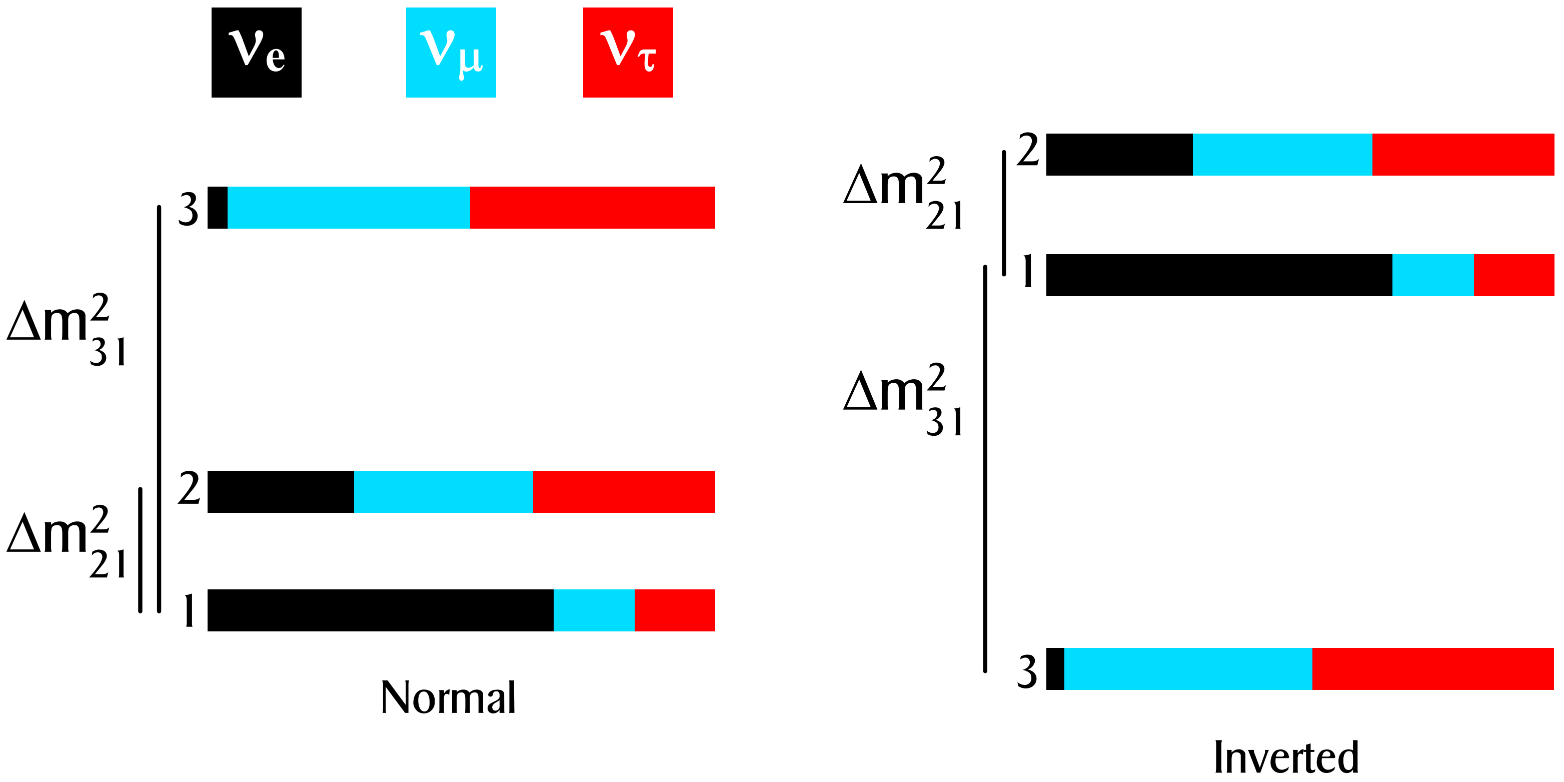
Neutrino Oscillations

Neutrinos are defined by more than flavour
→ Three underlying mass states: ν_1, ν_2, ν_3



Neutrino Oscillations

Which mass state is heaviest?



(Adapted from http://cerncourier.com/cws/article/cern/49351)

Neutrino Oscillation Open Questions

What changes must be made to the Standard Model to allow for neutrino oscillations?

Is there CP violation in the neutrino sector?

Why are the neutrino mixing angles large?

Do sterile neutrinos exist?

Precision neutrino beams can help answer these questions!

What Makes a Good Accelerator?

(... and why are muons best ...)

The Ideal Accelerator...

1. Enables the search for physics beyond the Standard Model

   i.e. Collisions > 1TeV and/or new particle beam sources

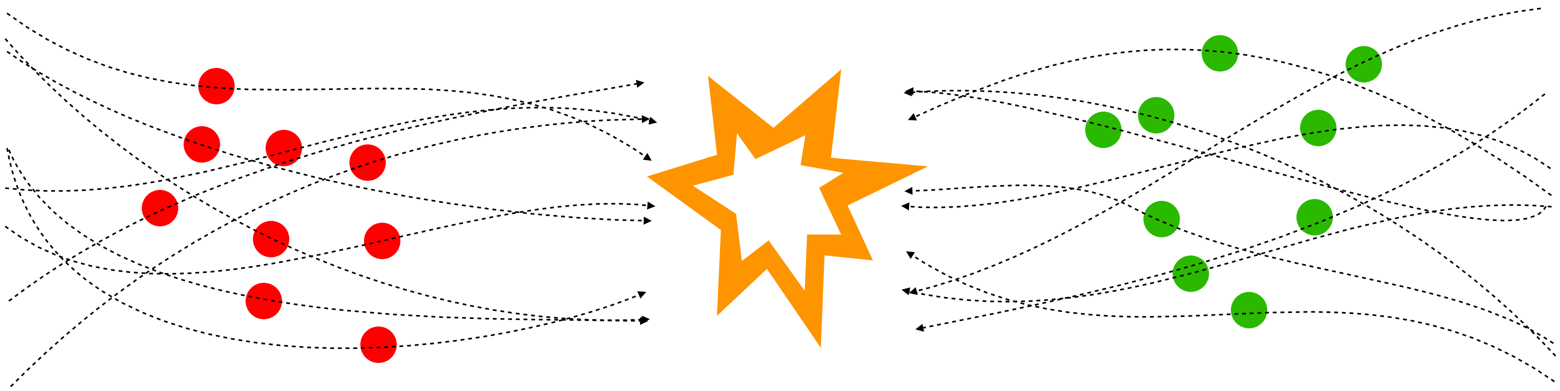
2. Produces beams with no backgrounds or uncertainties

   i.e. Well understood point-particle collisions with known energy/momentum distributions and flavour

3. Has high luminosity (rate)

   i.e. Collisions frequent enough to maximise the probability of observing interesting new physics

Intricacies of Particle Collisions



No. expected events

$$N_{exp} = \sigma_{exp} \int \mathscr{L}(t)\, dt$$

"Luminosity"

Cross-section of interest

$$\mathscr{L} = f_{coll} \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Particles per bunch

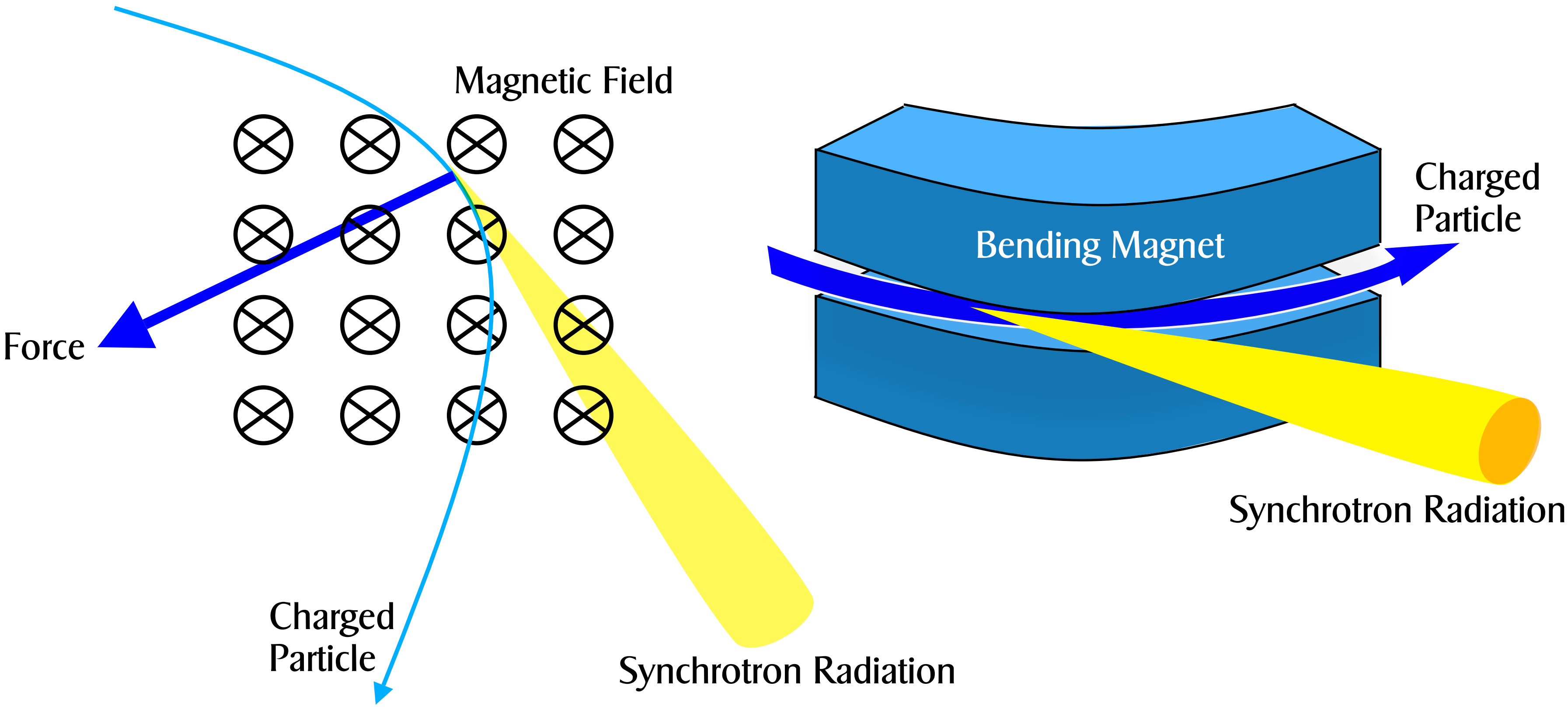
Collision frequency

Transverse beam size

Why Choose Muons?

	Point Particle	σ_{exp} enhancement ($\propto m^2$)	Energy spread
e	Yes	1	TLEP 2.3% / ILC 0.1%
μ	Yes	40'000	4 TeV μColl 0.003%
p	No	25 – 100 (Depends on colliding quarks)	LHC/VHE-LHC 0.1%

Why Choose Muons?



The more massive the particle, the less energy lost to synchrotron radiation

→ Smaller bend radii possible with more massive particles
→ Impacts machine size

Why Choose Muons?

RAL


4 TeV μColl
716 m
500 m
0
126 GeV
μ-Higgs Factory
Satellite Applications
Catapult
MRC Harwell
Newbury Rd
A4185
Science and
Technology Facilities
Chilton, a Wyevale
Garden Centre
CHILTON FIELD


14 TeV LHC (pp) or LHeC (7 TeV p, 0.06 TeV e)
4 TeV μColl
Milton
Steventon
Grove
Milton Hill
Didcot
Rowstock
Harwell
East Hendred
Ardington
East Hagbourne
Harwell Oxford
Upton
Chilton
Blewbury
West Ilsley
Farnborough
East Ilsley


TLEP (0.2TeV ee) or VHE-LHC (50 TeV pp)
LHC / LHeC
μColl
Cumnor
Radley
Abingdon
A420
Faringdon
the Vale
Milton
Didcot
Grove
Wantage
Sparsholt
Wallingford
Watlington
Compton
Aldbourne
M4
Ramsbury
Hermitage
Bradfield
Calcot

TLEP (0.2TeV ee) or VHE-LHC (50 TeV pp)
LHC / LHeC
μColl
ILC (0.5–1TeV ee)
Cumnor
Radley
Abingdon
Faringdon
Stanford in the Vale
Milton
Didcot
Grove
Wantage
Sparsholt
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Watlington
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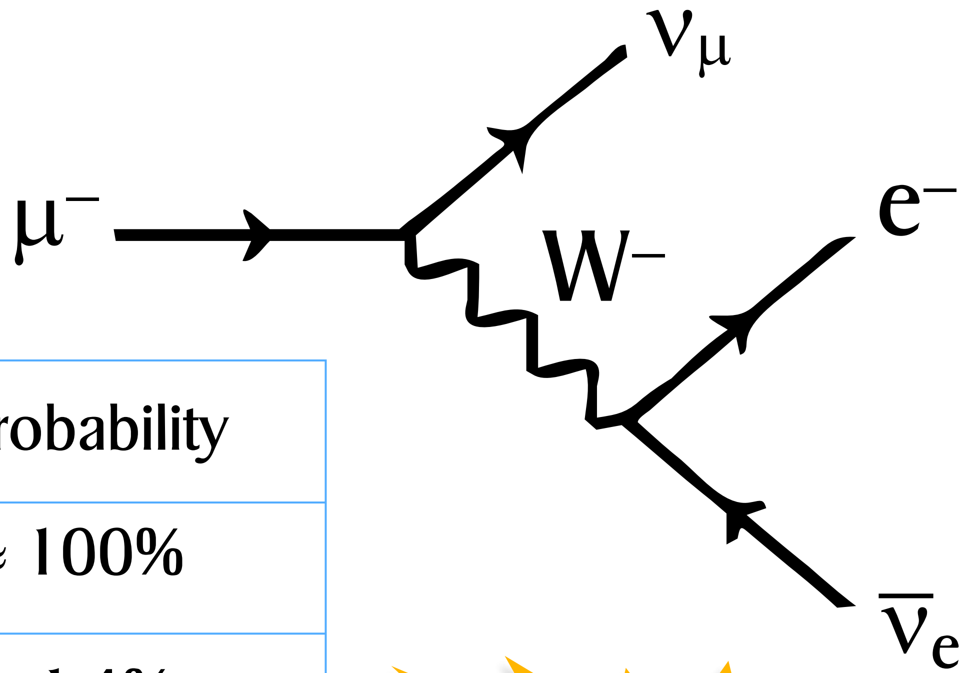
Why (Not) Choose Muons?



Decay Mode	Probability
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$
$\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma$	$\approx 1.4\%$
$\mu^- \to e^- \bar{\nu}_e \nu_\mu e^+ e^-$	$\approx 0.003\%$

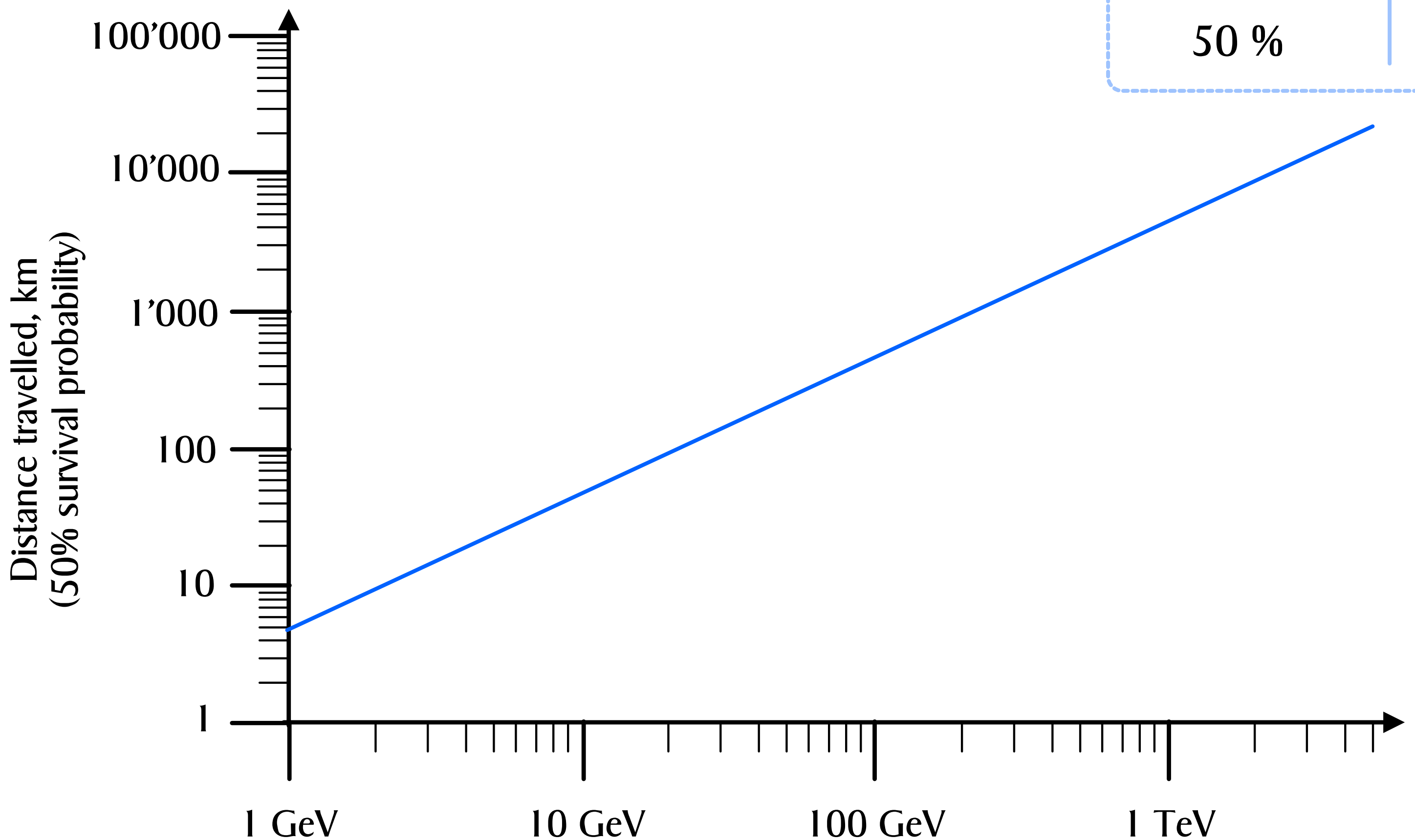
Muon beams are perfect neutrino sources!

$\tau_\mu = 2.2\ \mu s$ → Must produce, accelerate and collide muon beams before decay losses become large!

Why (Not) Choose Muons?

At 5 TeV:

Survival Rate	Distance (km)
99.6 %	100
96 %	1’000
50 %	20’000



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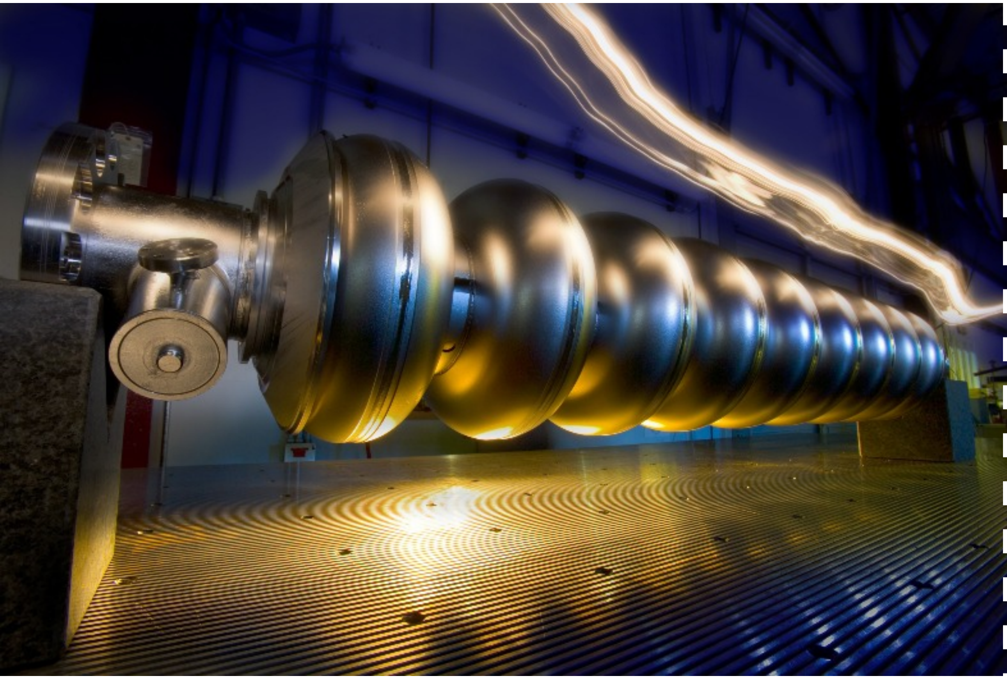
RF Acceleration

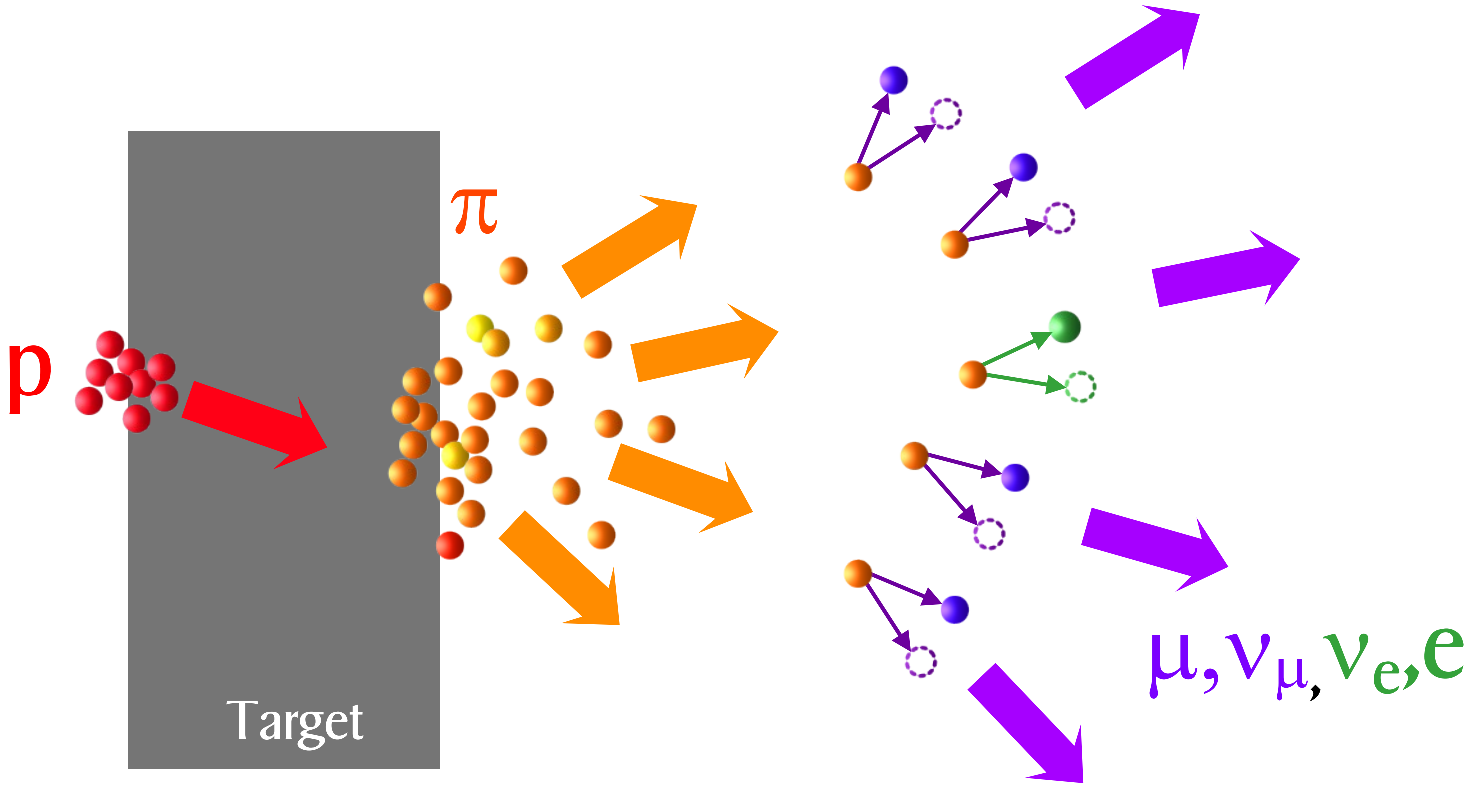


ILC Superconducting RF Cavities

MICE Normal Conducting RF Cavities

$$“\pounds \propto r^2”$$

The **Real** Trouble with Muon Beams



Muons are tertiary particles
→ Large physical size
→ Large divergence
→ Large emittance

Needs a **lot** of work

$$\mathscr{L} = f_{coll} \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Muon Beam Challenges

High intensity muon source

(So we have enough of them to collide)

Reduce beam emittance

(Reduced physical size and divergence)

Develop RF acceleration

(Ultra-relativistic, ASAP!)

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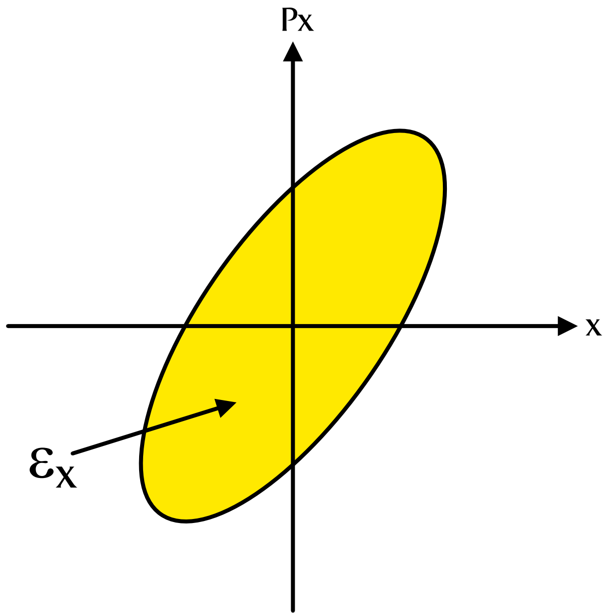
Beam Emittance

Liouville's Theorem: Conservation of Phase Space



$$\varepsilon_x = \sqrt{\det\begin{vmatrix}\sigma_{xx} & \sigma_{x\,p_x}\\ \sigma_{x\,p_x} & \sigma_{p_x\,p_x}\end{vmatrix}}$$

$$\sigma_{ab} = \langle ab\rangle - \langle b\rangle\langle b\rangle$$

The Muon Ionization Cooling Experiment

Emittance Reduction within the Muon Lifetime

What is "Cooling"?

The process of reducing the emittance of a particle beam

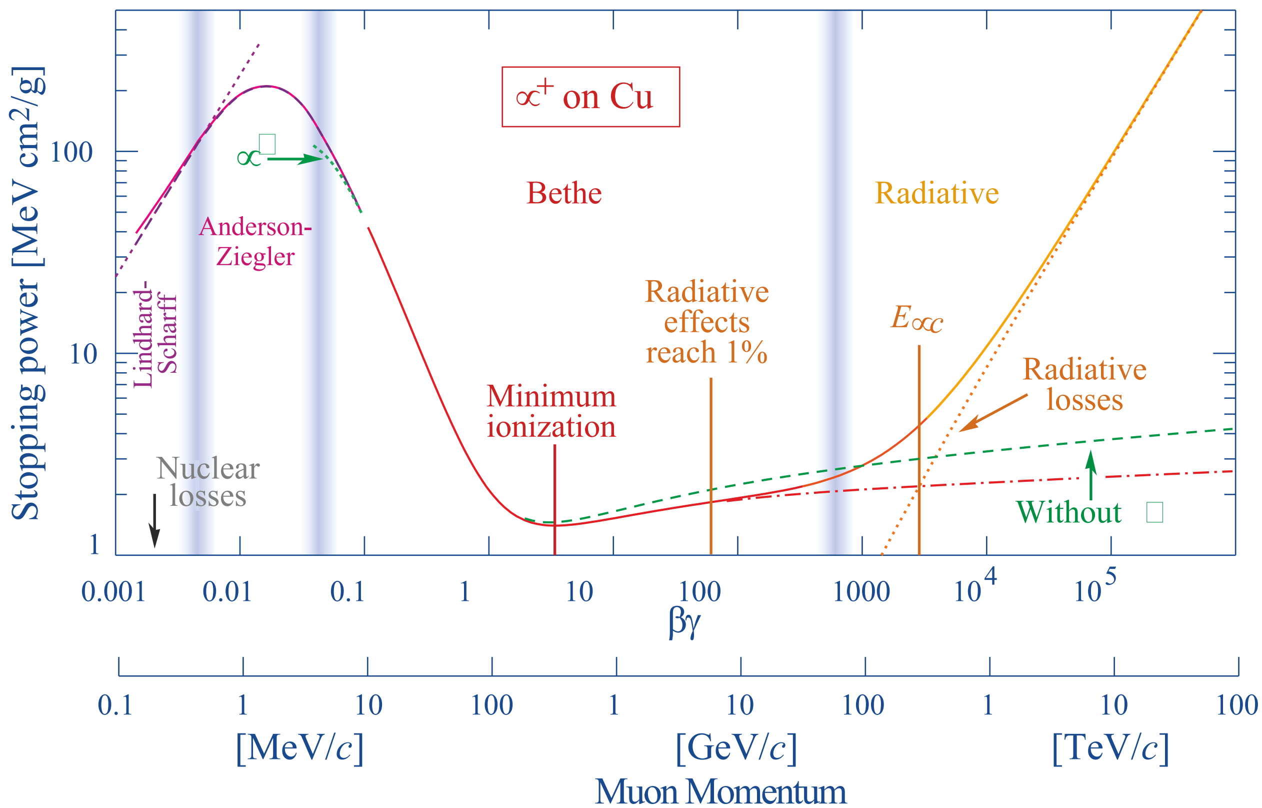
Standard techniques cannot act within the muon lifetime

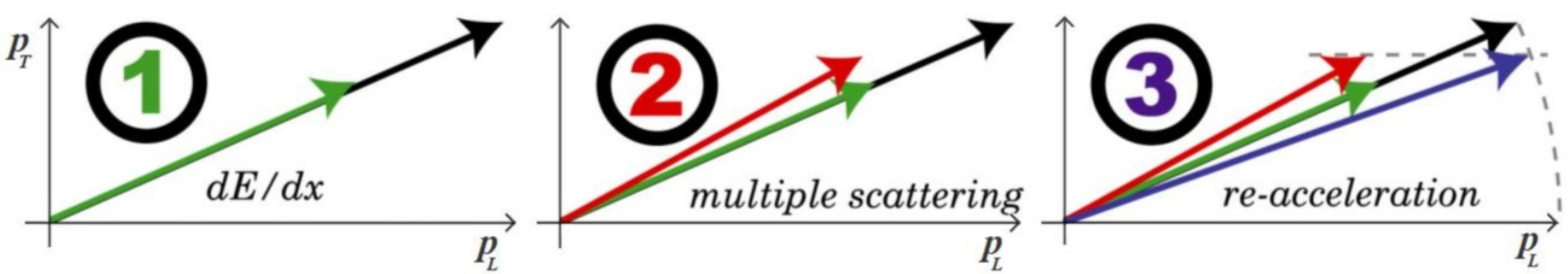
Beams must be "cooled" before they can be efficiently accelerated

MICE aims to demonstrate:
→ That an ionization cooling channel can be built and operated
→ That ionization cooling reduces the emittance of muon beams

* Figure from the Particle Data Group

Ionization Cooling





Ionization Cooling

Magnetic field properties

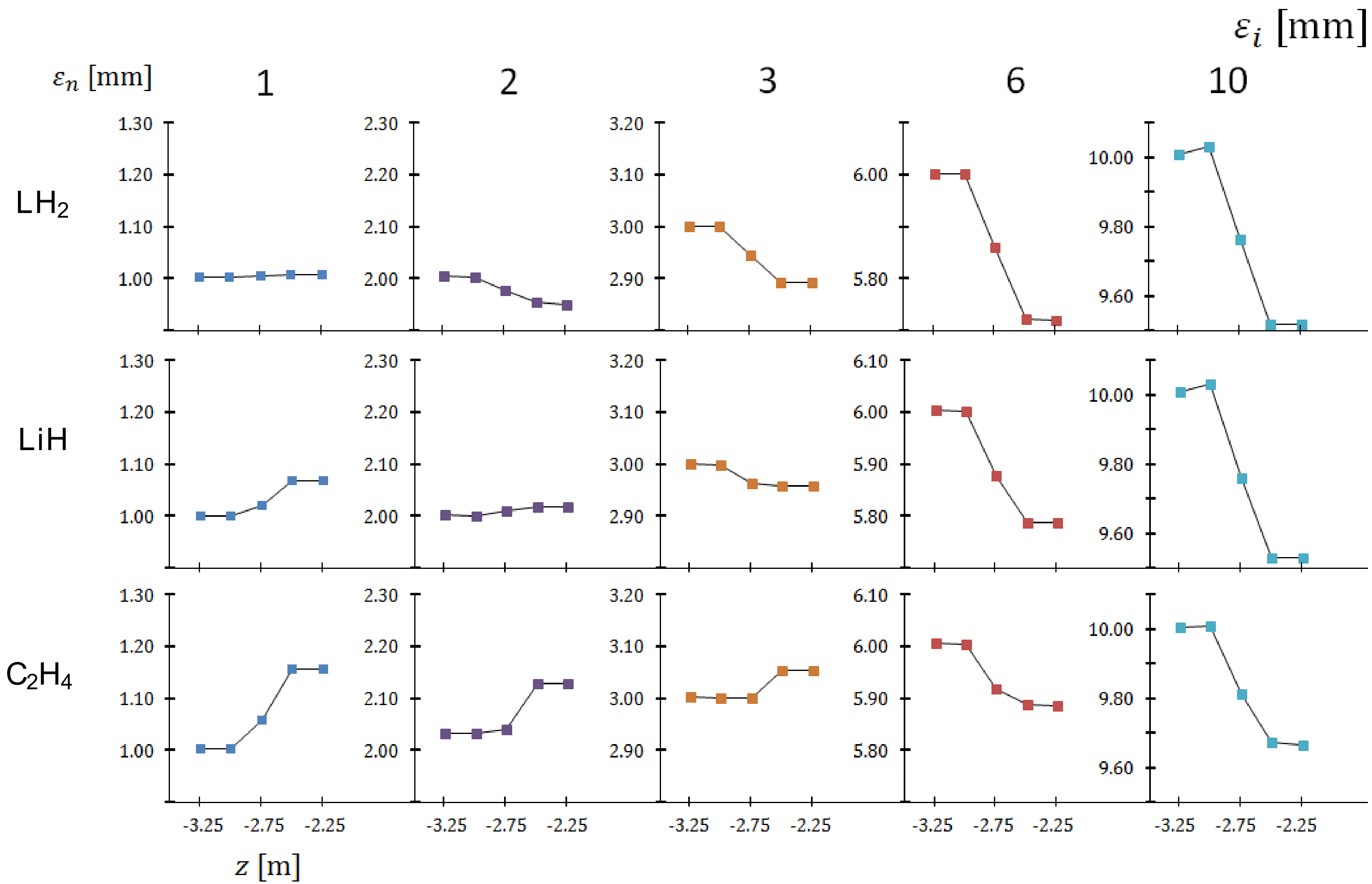
Cooling | Heating

$$\frac{d\varepsilon}{ds} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (13.6\ \mathrm{MeV})^2}{2\,\beta^3 E\, m_\mu X_0}$$

Relativistic quantities

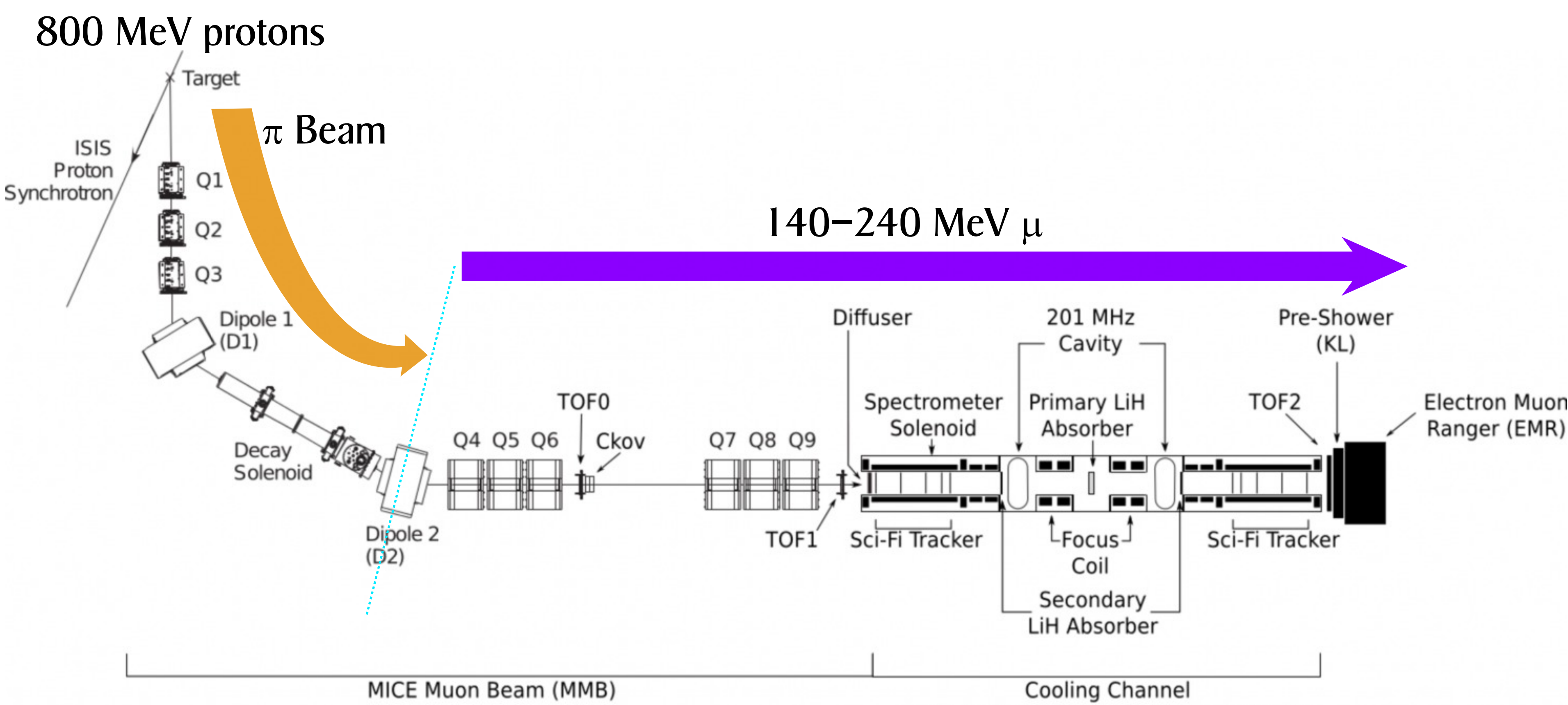
Absorber properties

Emittance Reduction Across an Absorber



* Figure from thesis of T. Carlisle, University of Oxford
"Step IV of the Muon Ionization Cooling Experiment (MICE) and the multiple scattering of muons"

How to Build a Cooling Cell in ~~6~~ 3 Easy Steps



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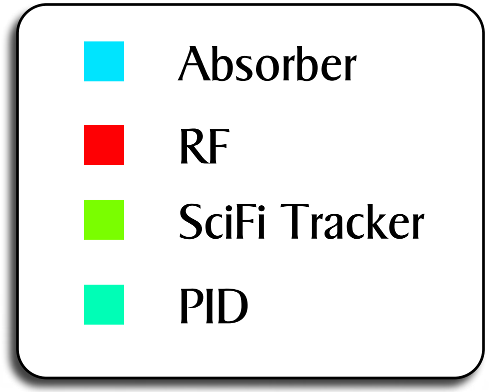

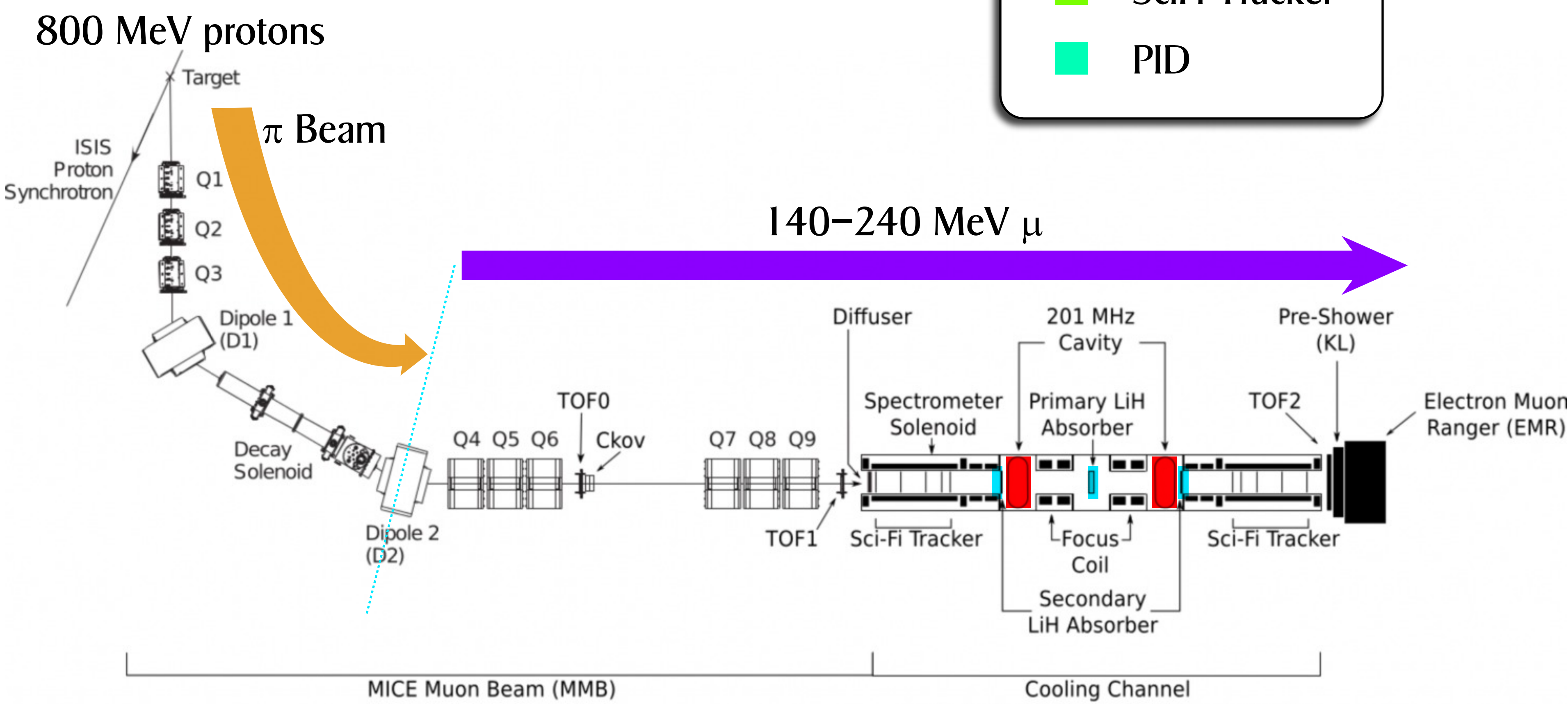

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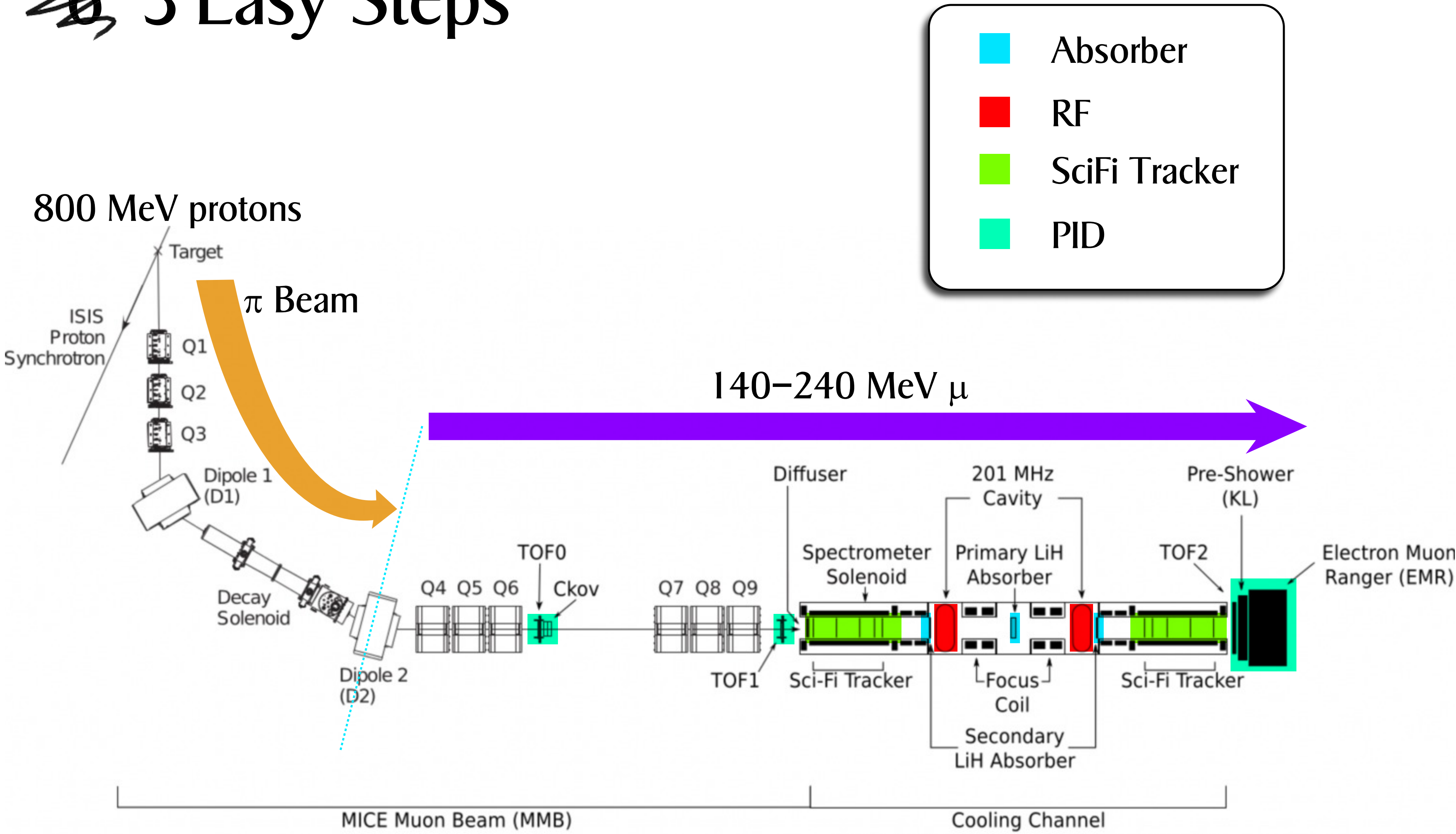

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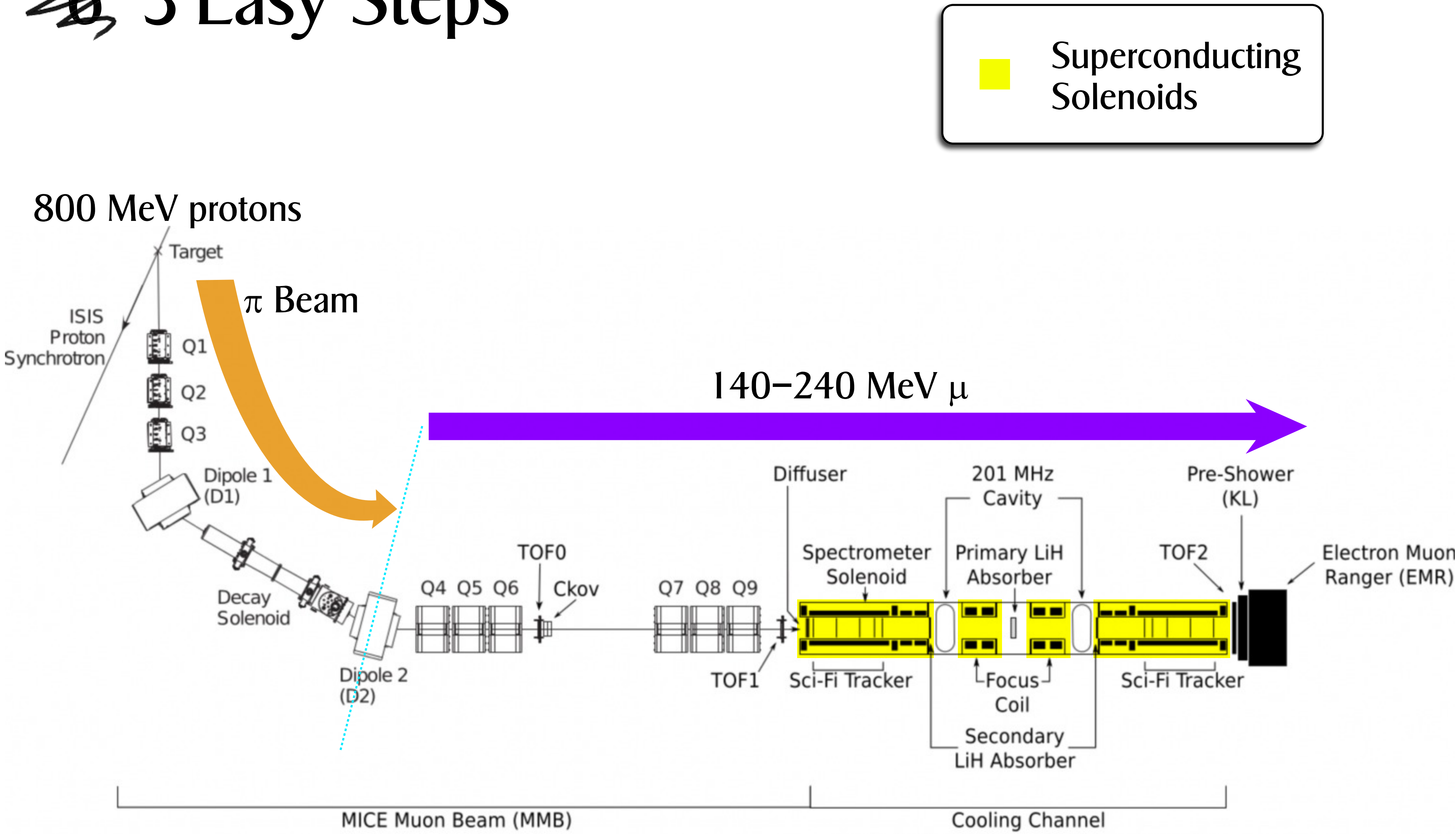
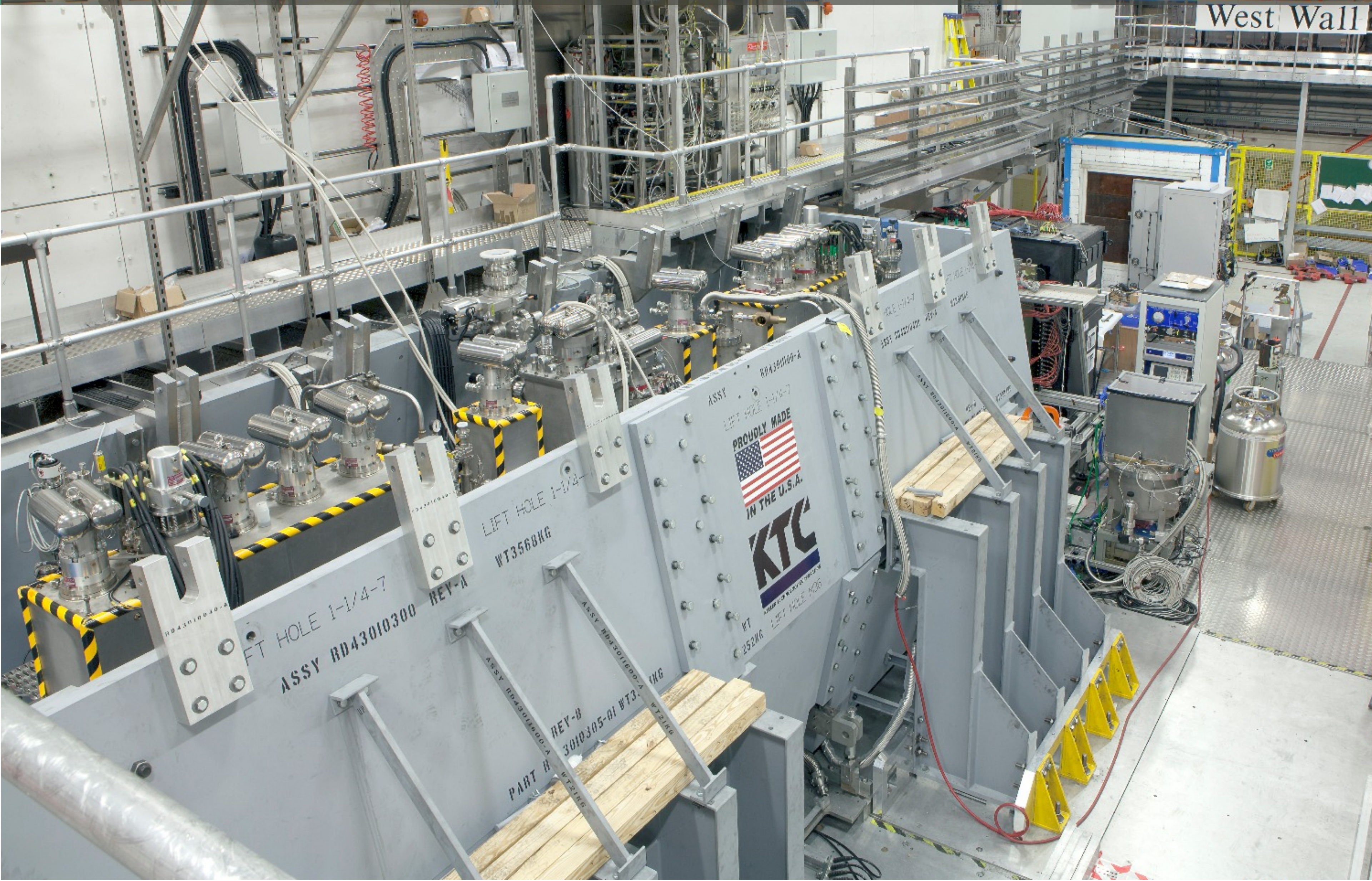


The MICE Experiment

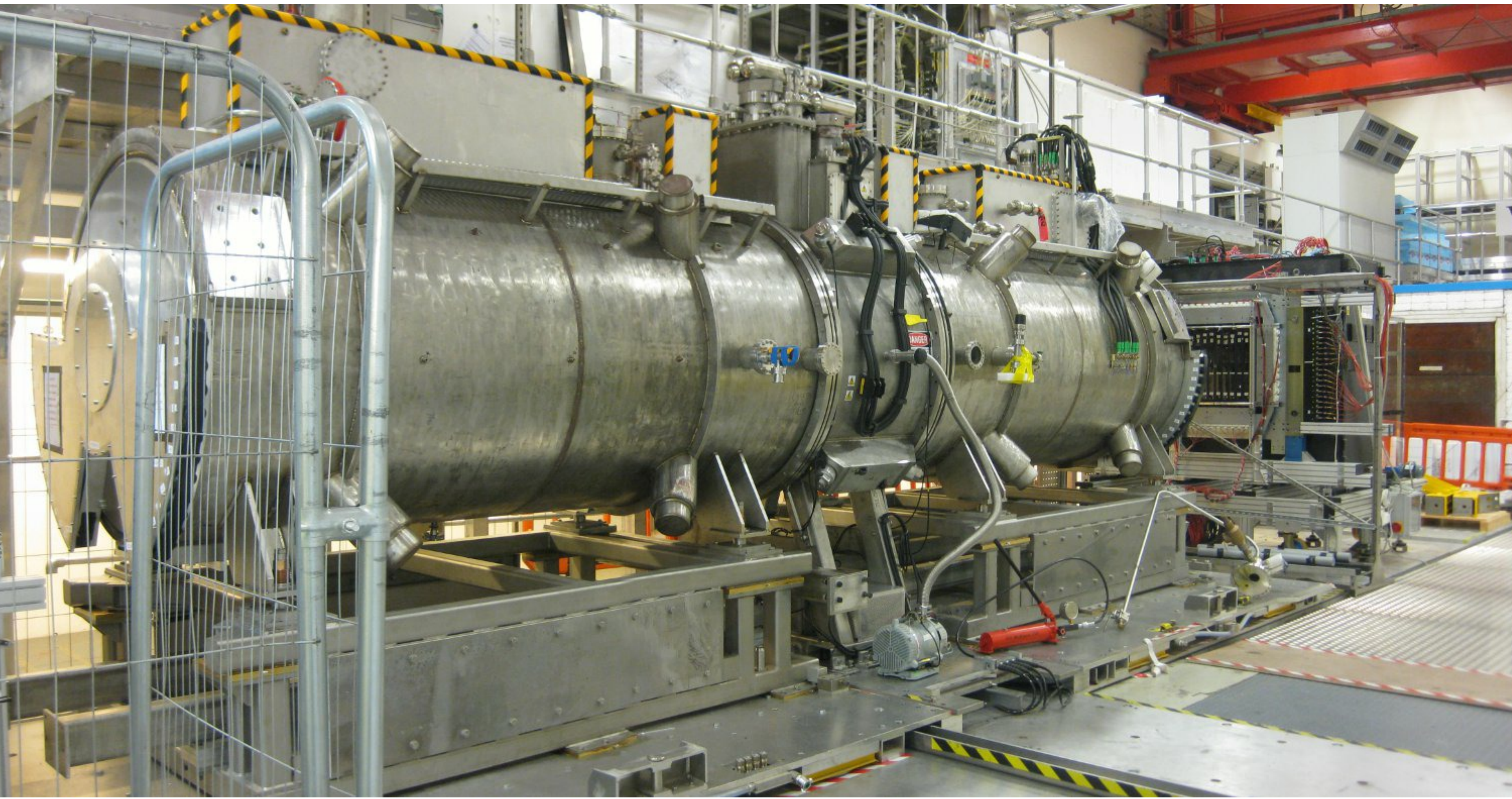
First studies of cooling imminent!



The MICE Experiment

An older, but clearer, view

Spectrometer Solenoid & Tracker — Focus Coil & Absorber — Spectrometer Solenoid & Tracker — PID



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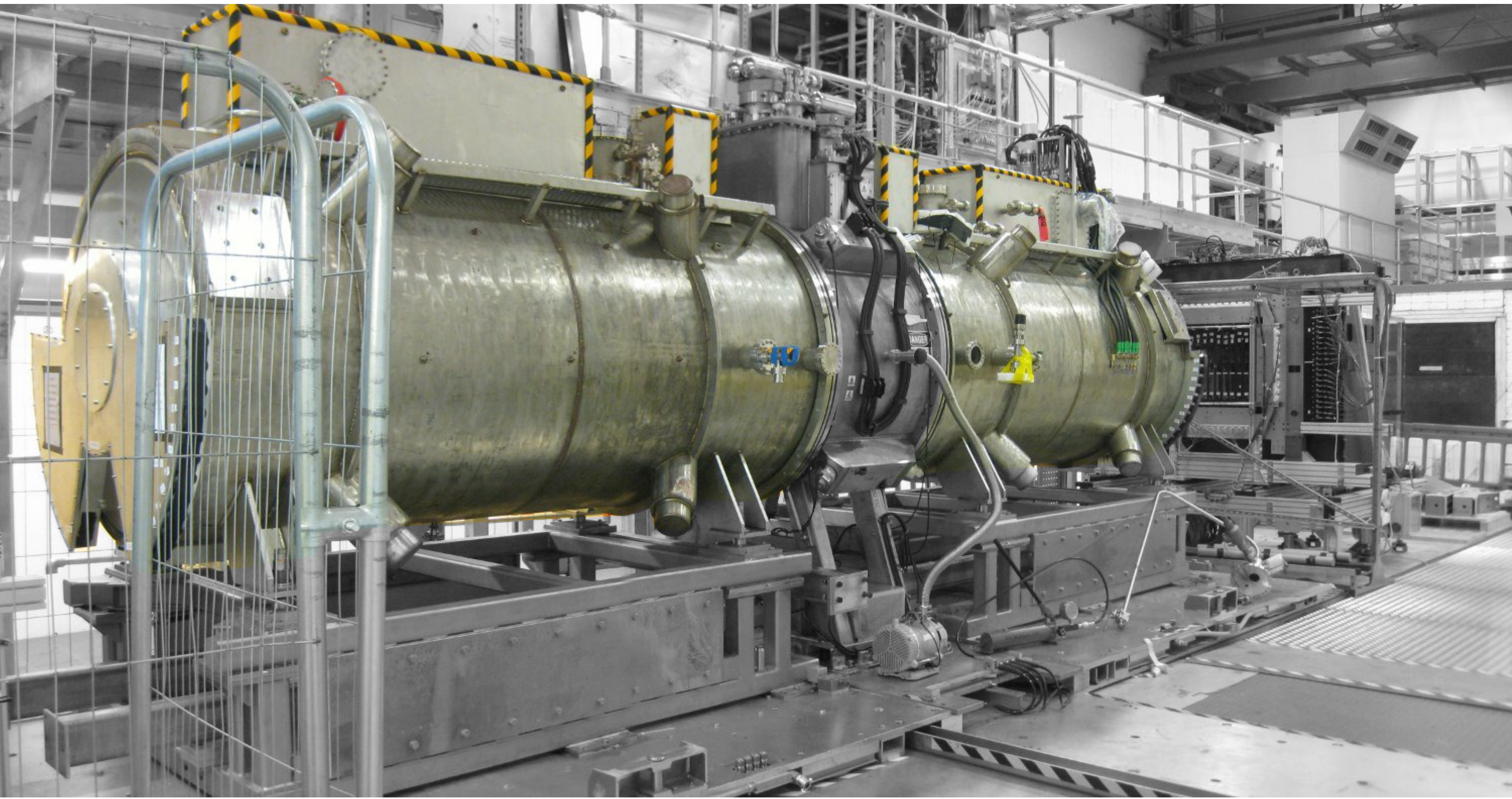

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Focus Coil & Absorber

Spectrometer Solenoid & Tracker

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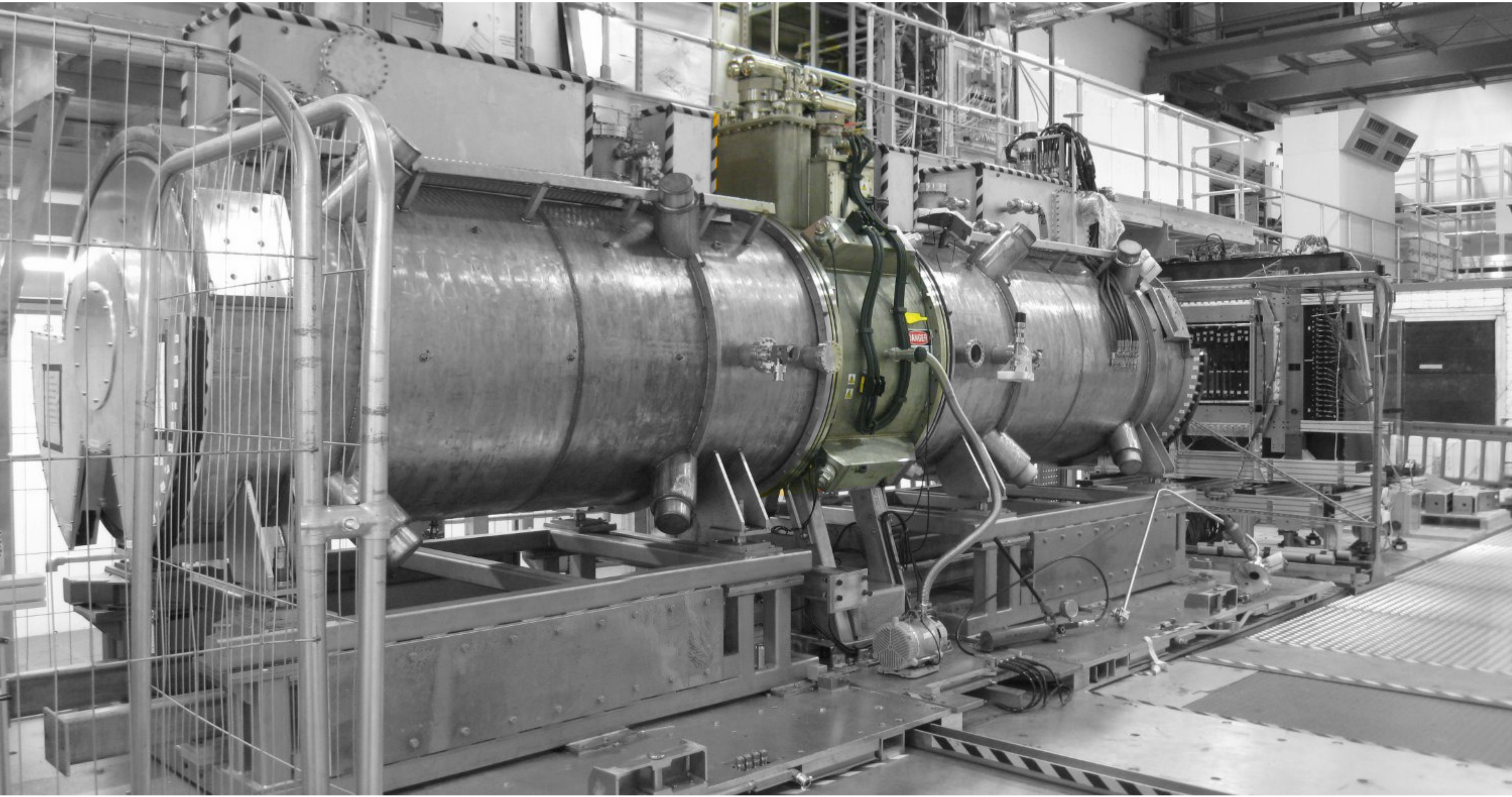

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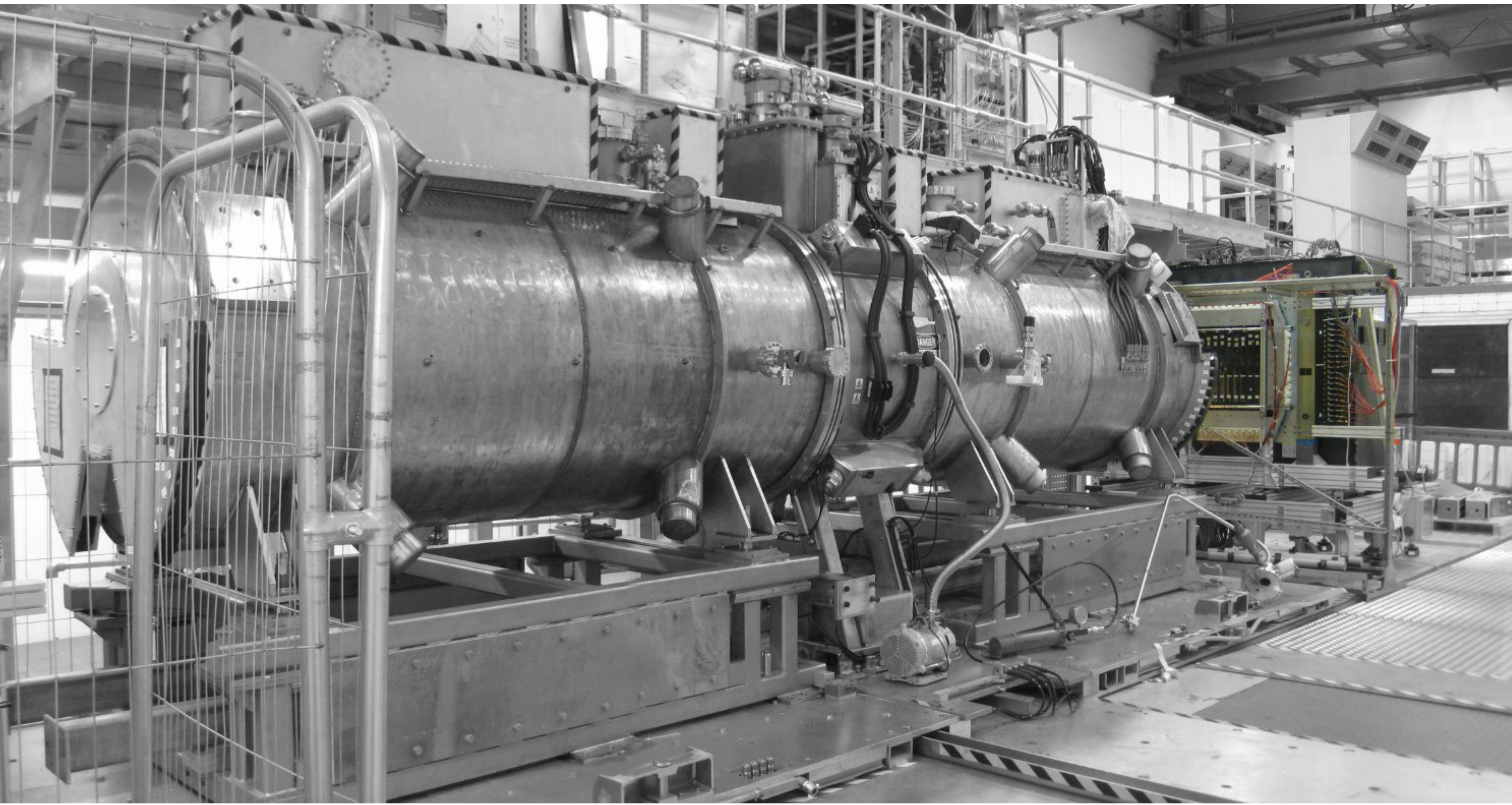


The MICE Experiment

Measuring muon beams with Particle Physics Detectors

MICE Timeline

Now

Experiment assembled to study absorber properties
Superconducting magnet training in progress
Initial detector commissioning in progress

Sep 2015+

ISIS User Run 2: Begin absorber studies
First measurements of emittance reduction in liquid hydrogen and lithium hydride

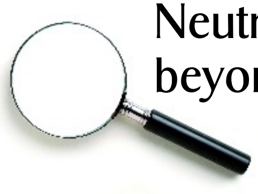
Q3 2016

Conclude absorber studies
Install RF cavities for final cooling demonstration

2017

Demonstrate ionization cooling of muon beams with reacceleration

Summary

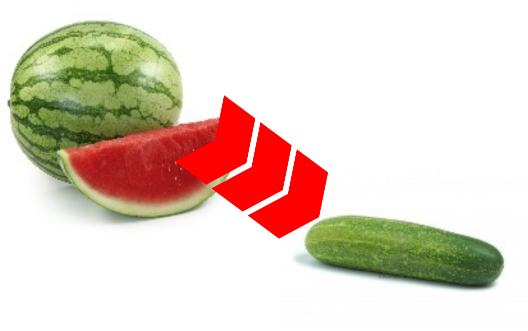


Neutrino oscillations are evidence of physics beyond the Standard Model of Particle Physics

Precision neutrino measurements require precision neutrino beams

Precision TeV-scale measurements require precision lepton beams

! Muon-based accelerators are the perfect solution, but are non-trivial to build !



Large muon beam size and divergence must be reduced before acceleration and before muons decay

MICE will demonstrate the only approach that can do this within the muon lifetime: Ionization Cooling

Muon beams could be the future:
nuSTORM → Neutrino Factory → μHiggs Factory → μCollider