# Muon Accelerators and Results from the MICE Experiment

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Physics Colloquium
Fermilab
Batavia, IL
19 Feb. 2020

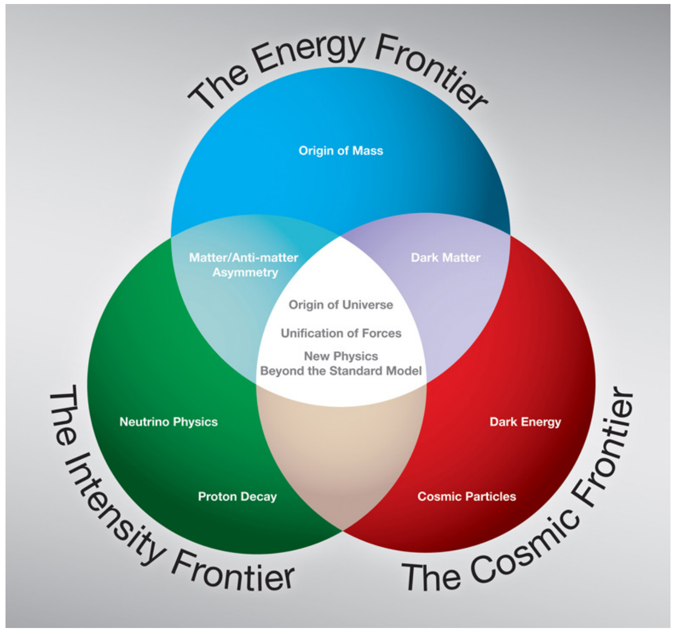
# Outline

- Future particle accelerators
  - hadron & electron-positron colliders
  - muon accelerators: muon colliders and neutrino factories
- Muon cooling
- MICE
- Conclusions

# Once & Future Particle Accelerators

# Once & Future Particle Accelerators

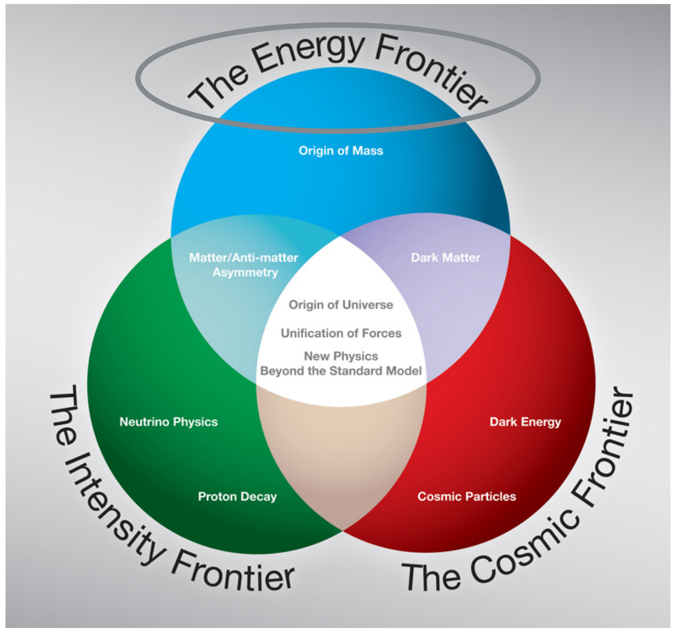
One way to subdivide particle physics:



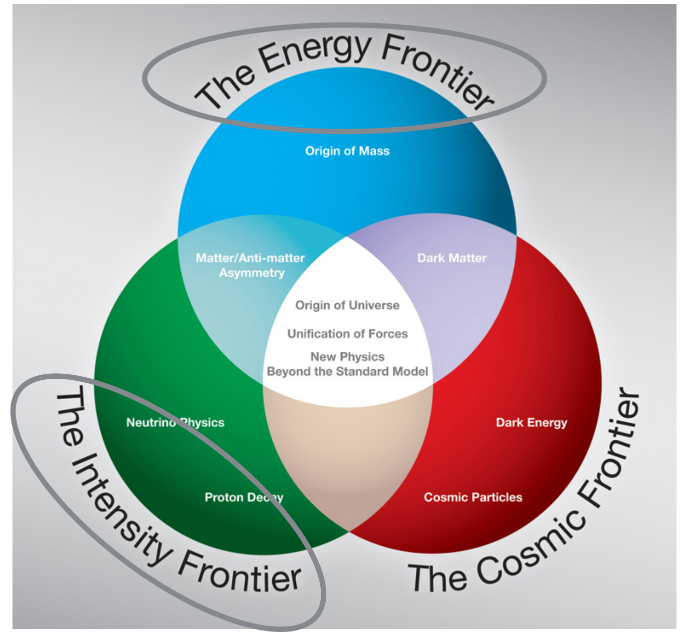
# Once & Future Particle Accelerators

One way to subdivide particle physics:

- Energy frontier
  - require highest *energy*: hadron ("discovery") colliders and lepton ("precision") colliders



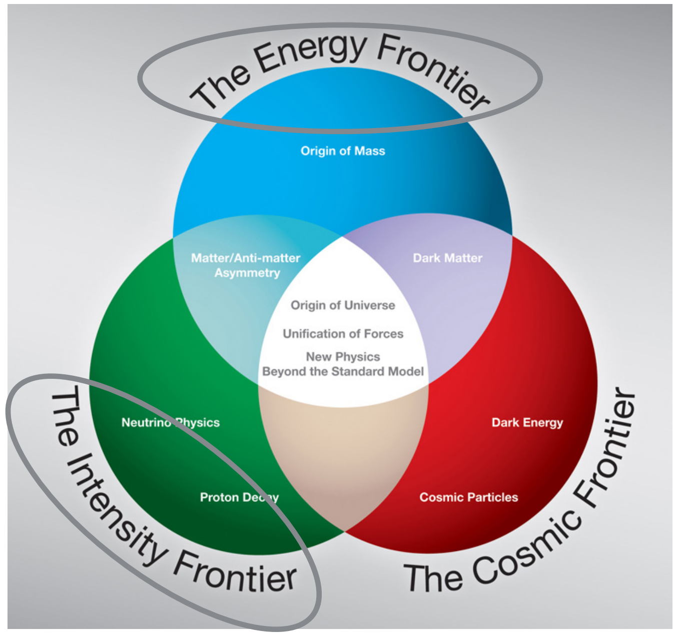
# Once & Future Particle Accelerators

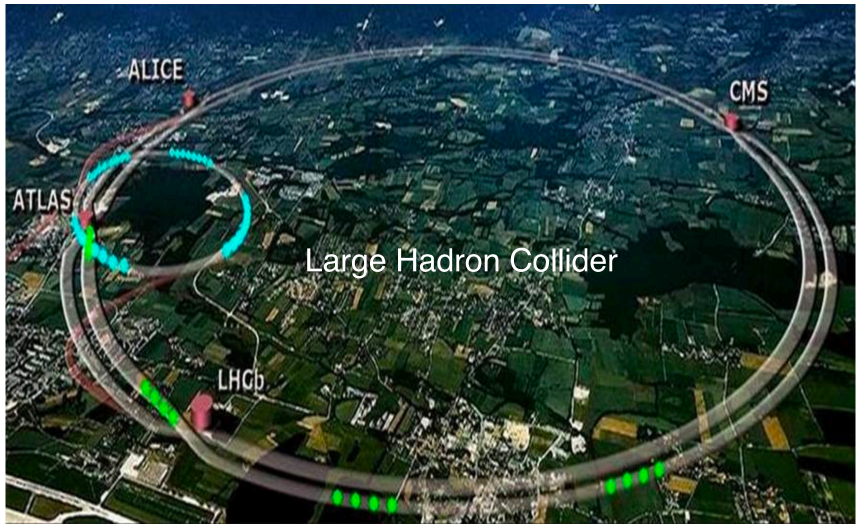



One way to subdivide particle physics:

- Energy frontier
  - require highest *energy*: hadron ("discovery") colliders and lepton ("precision") colliders
- Intensity frontier
  - require highest *intensity*: e.g., neutrino and rare-decay experiments (e.g., Mu2e)

# Once & Future Particle Accelerators




One way to subdivide particle physics:

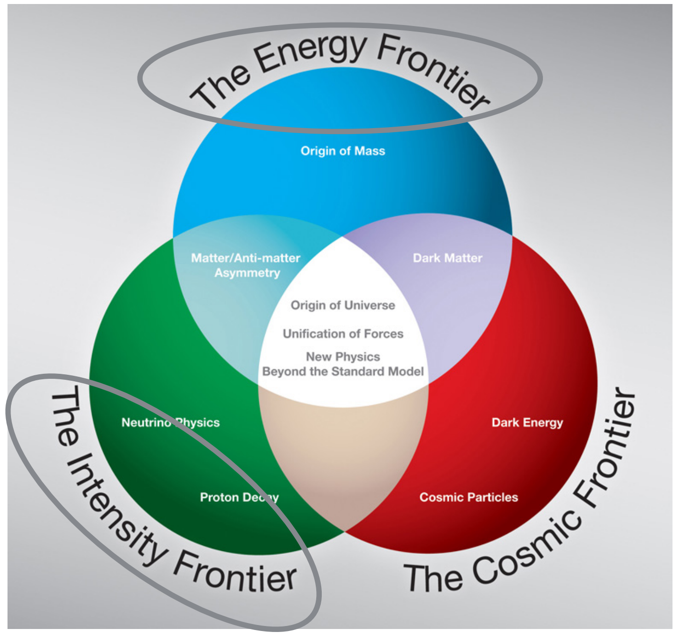
- Energy frontier
  - require highest *energy*: hadron ("discovery") colliders and lepton ("precision") colliders
- Intensity frontier
  - require highest *intensity*: e.g., neutrino and rare-decay experiments (e.g., Mu2e)
- Now: CERN LHC @ energy frontier

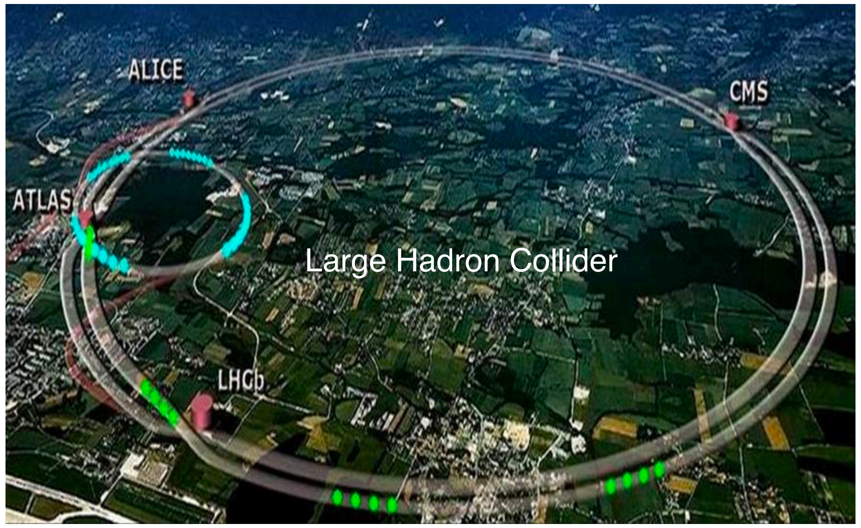
# Once & Future Particle Accelerators

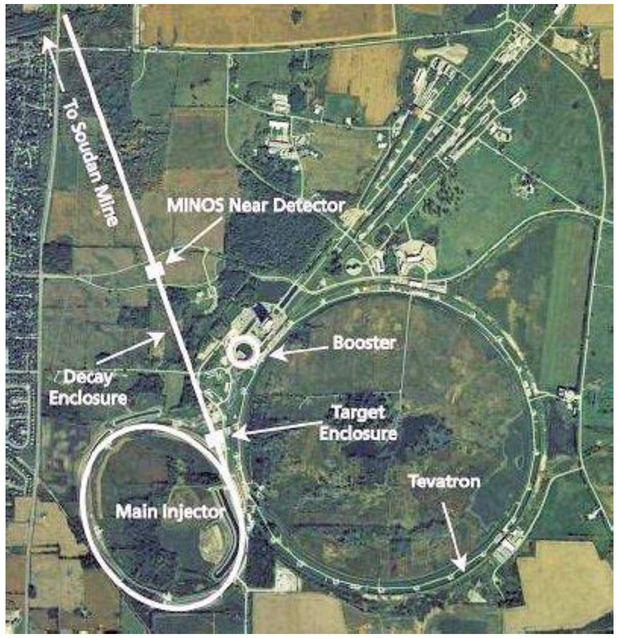
One way to subdivide particle physics:

- Energy frontier
  - require highest *energy*: hadron ("discovery") colliders and lepton ("precision") colliders
- Intensity frontier
  - require highest *intensity*: e.g., neutrino and rare-decay experiments (e.g., Mu2e)
- Now: CERN LHC @ energy frontier

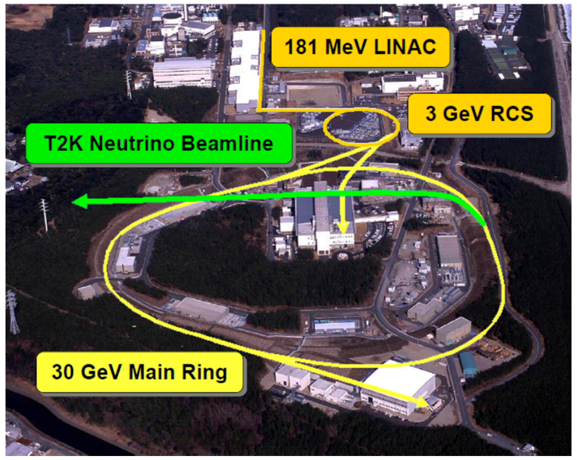
  FNAL Booster & Main Injector and J-PARC @ intensity frontier




Fermilab




J-PARC

# Once & Future Particle Accelerators

- Now: CERN LHC @ energy frontier

  FNAL Booster & Main Injector and
  J-PARC @ intensity frontier

# Once & Future Particle Accelerators

- Now: CERN LHC @ energy frontier

  FNAL Booster & Main Injector and
  J-PARC @ intensity frontier

*What comes next?*

# Once & Future Particle Accelerators

- Now: CERN LHC @ energy frontier

  FNAL Booster & Main Injector and
  J-PARC @ intensity frontier

*What comes next?*

- Open question!

(See https://europeanstrategy.cern/)

# Once & Future Particle Accelerators

- Now: CERN LHC @ energy frontier

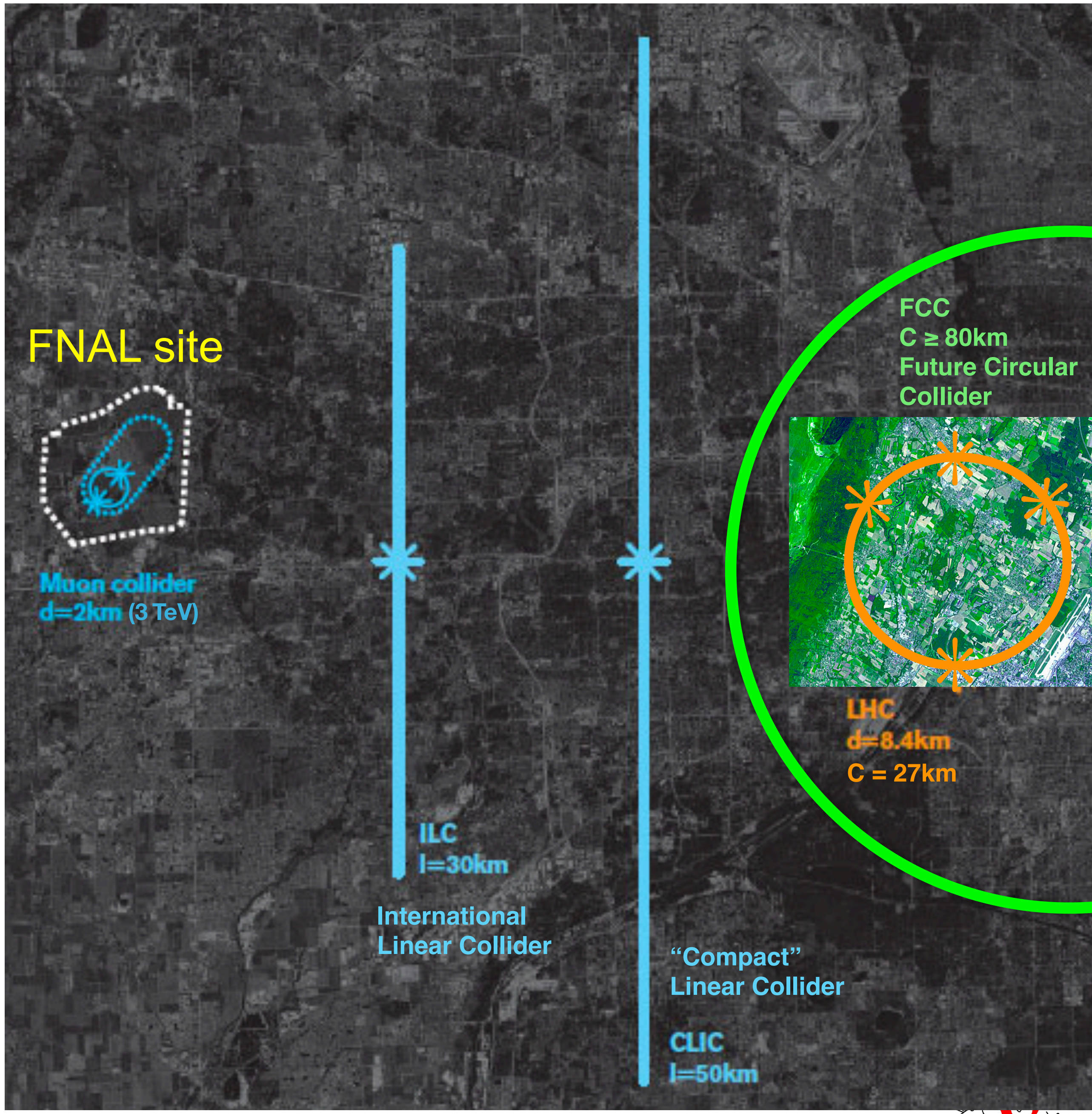
  FNAL Booster & Main Injector and J-PARC @ intensity frontier

*What comes next?*

- Open question!

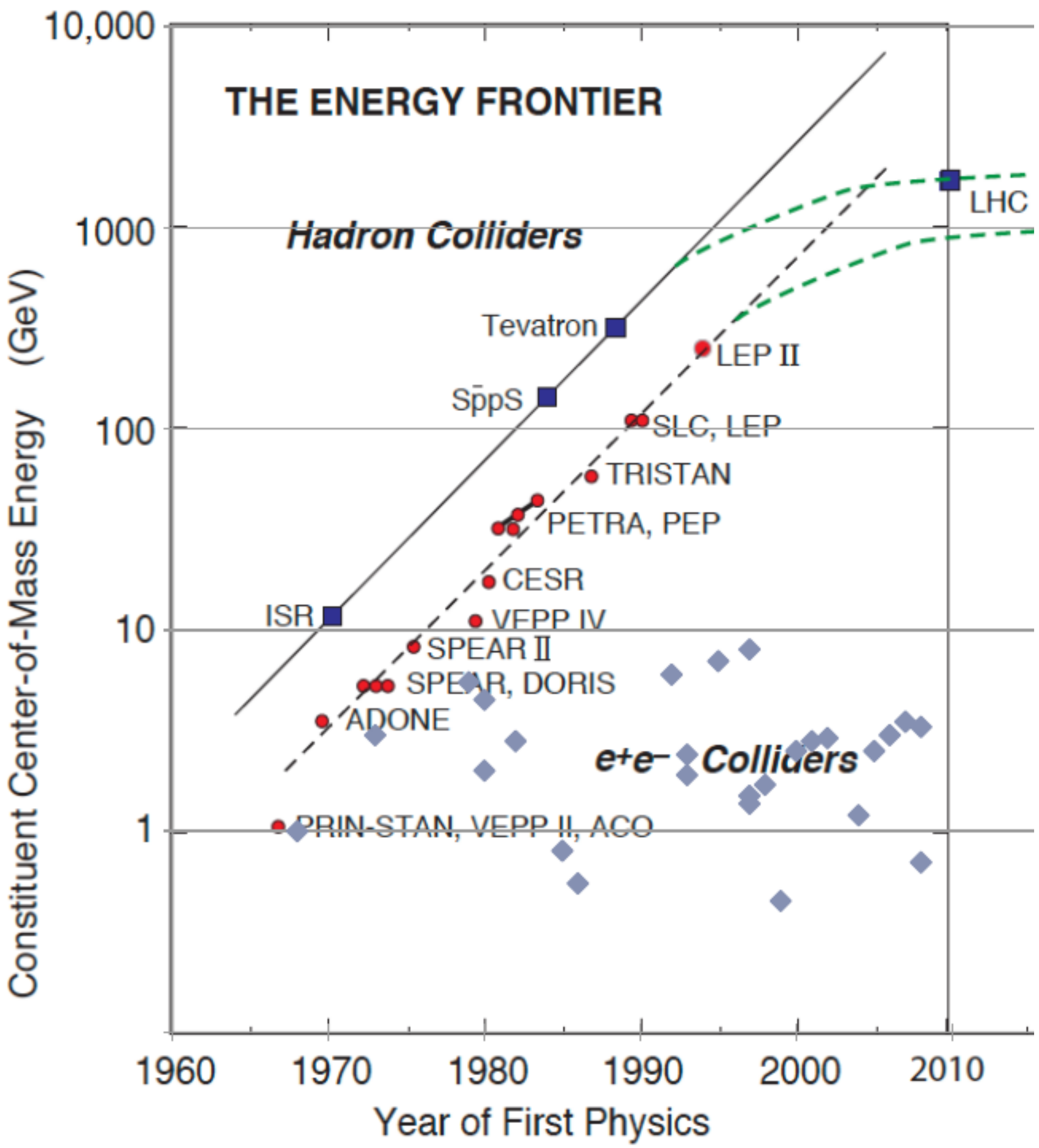
  (See https://europeanstrategy.cern/)

- Much R&D:
  - FCC? ($e^+e^-$, then $pp$)
  - ILC, CLIC? ($e^+e^-$)
  - Muon Collider? ($\mu^+\mu^-$)



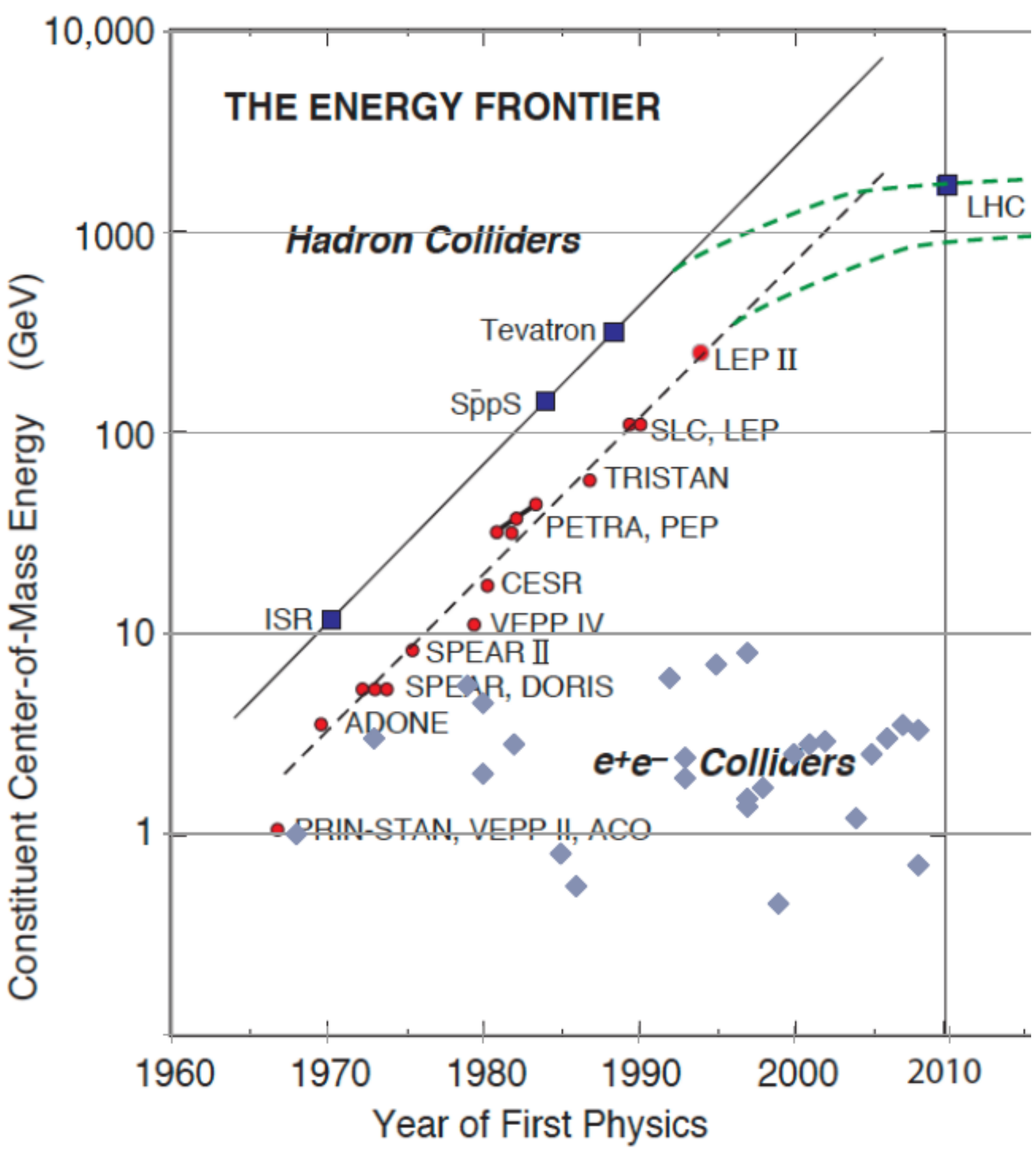
# Once & Future Particle Accelerators

- "Livingston" plot:



# Once & Future Particle Accelerators

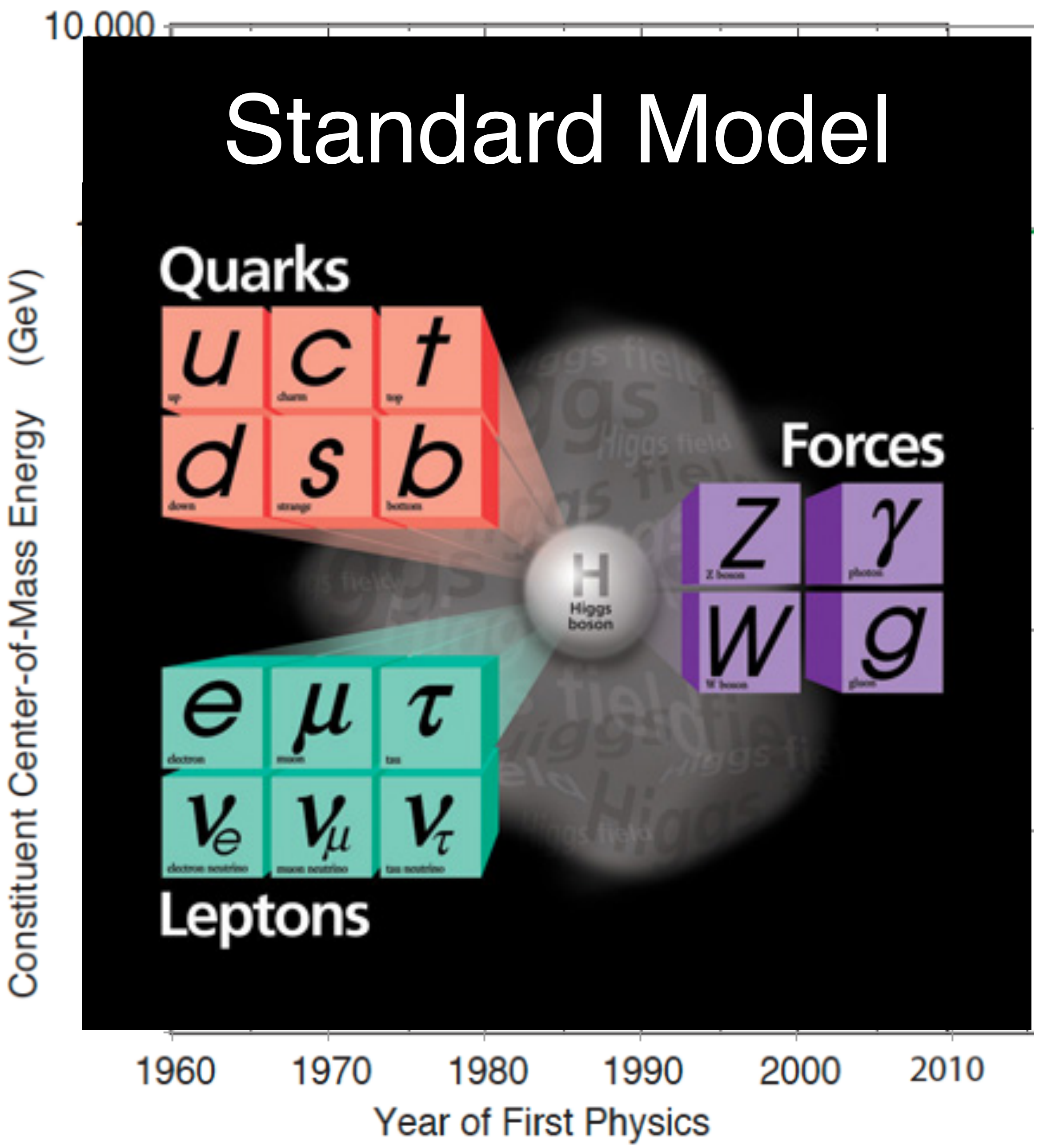
- "Livingston" plot:




  - *exponential growth* in particle energy led to series of key discoveries

# Once & Future Particle Accelerators

- "Livingston" plot:



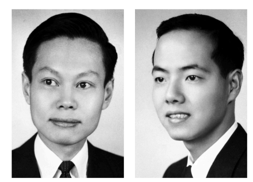
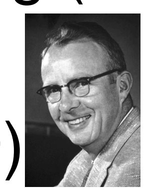

- *exponential growth* in particle energy led to series of key discoveries

| | |
|---|---|
| 1950-60s: | strange particles, quarks, parity violation, 2 neutrinos, CP viol. |
| 1974: | charm quark, tau lepton |
| 1977: | bottom quark |
| 1995: | top quark |
| 2000: | tau neutrino |
| 2012: | Higgs boson |

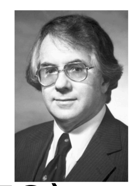
# Once & Future Particle Accelerators

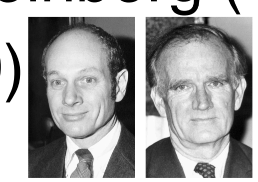
- "Livingston" plot:

## …& Nobel prizes:

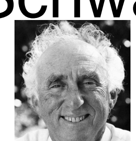
T.D. Lee & C.N. Yang (1957)

L.W. Alvarez (1968)

M. Gell-Mann (1969)

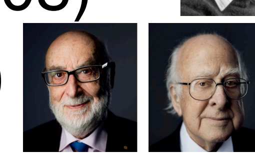
B. Richter & S.C.C. Ting (1976)

S.L. Glashow, A. Salam, S. Weinberg (1979)



J.W. Cronin & V.L. Fitch (1980)

C. Rubbia & S.v.d.Meer(1984)

L.M. Lederman, M. Schwartz, J. Steinberger (1988)

M.L. Perl (1995)

M. Kobayashi & T. Maskawa (2008)

F. Englert & P.W. Higgs (2013)


1960 1970 1980 1990 2000 2010

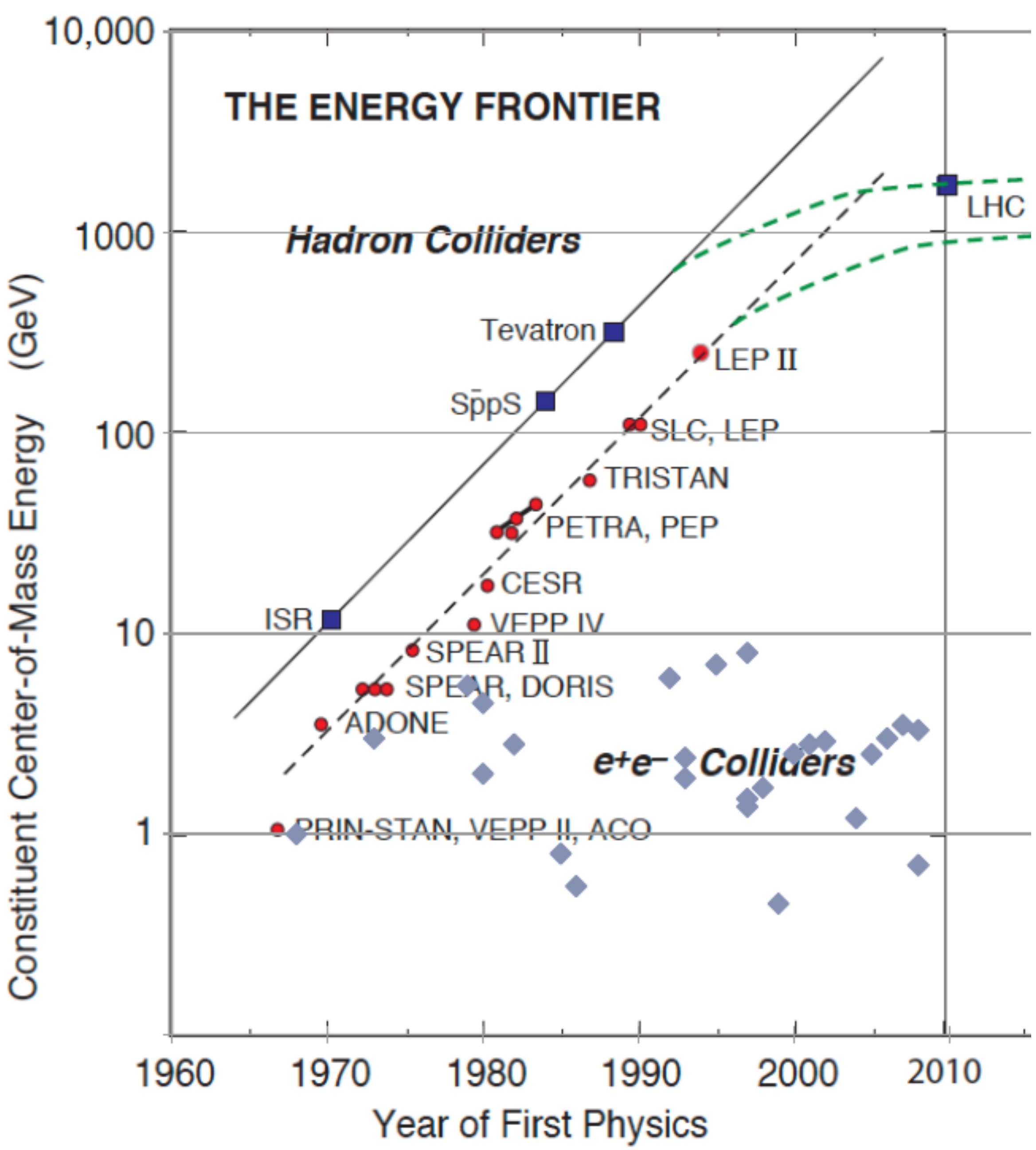
Year of First Physics

- *exponential growth* in particle energy led to series of key discoveries

| | |
|---|---|
| 50-60s: | strange particles, quarks, parity violation, 2 neutrinos, CP viol. |
| 1974: | charm quark, tau lepton |
| 1977: | bottom quark |
| 1995: | top quark |
| 2000: | tau neutrino |
| 2012: | Higgs boson |

# Once & Future Particle Accelerators

- "Livingston" plot:




- *exponential growth* in particle energy led to series of key discoveries

| | |
|---|---|
| 1950-60s: | strange particles, quarks, parity violation, 2 neutrinos, CP viol. |
| 1974: | charm quark, tau lepton |
| 1977: | bottom quark |
| 1995: | top quark |
| 2000: | tau neutrino |
| 2012: | Higgs boson |

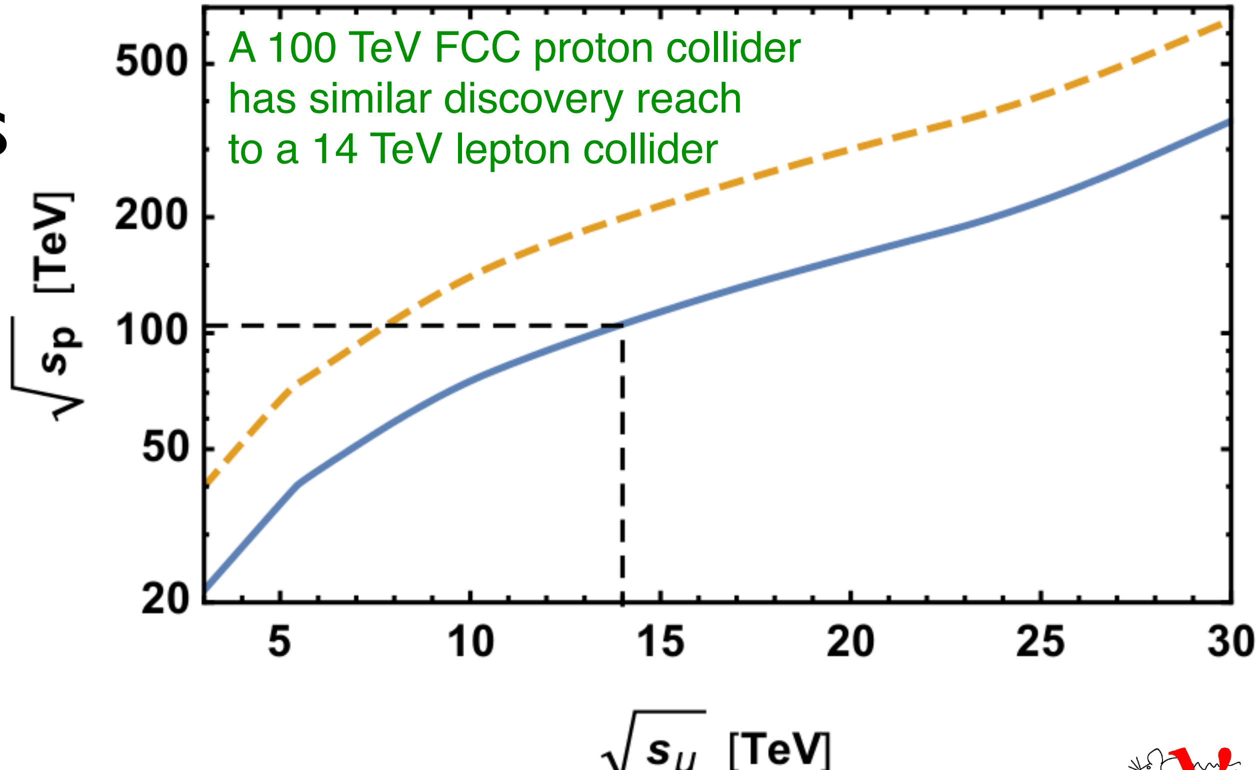
…but we've "fallen off the exponential" as machines & their costs have grown

# Once & Future Particle Accelerators

- Energy frontier
  - goal: world's highest *energy density*
    - pack the most energy into the tiniest space, to make (via $E = mc^2$) and discover new particles
  - *problem:* LHC uses protons, made of quarks & gluons

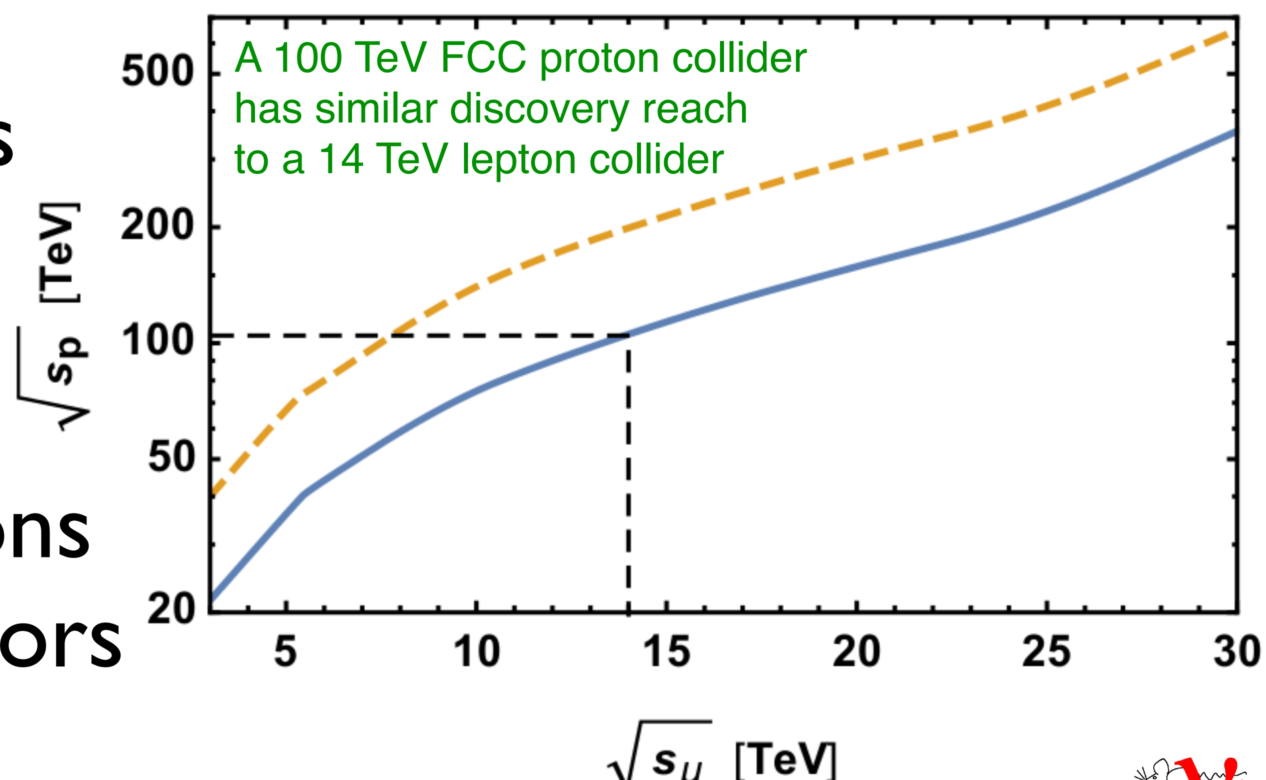
# Once & Future Particle Accelerators

- Energy frontier
  - goal: world's highest *energy density*
    - pack the most energy into the tiniest space, to make (via $E = mc^2$) and discover new particles
  - *problem:* LHC uses protons, made of quarks & gluons
    - so colliding quarks or gluons carry only a small fraction of proton-beam energy



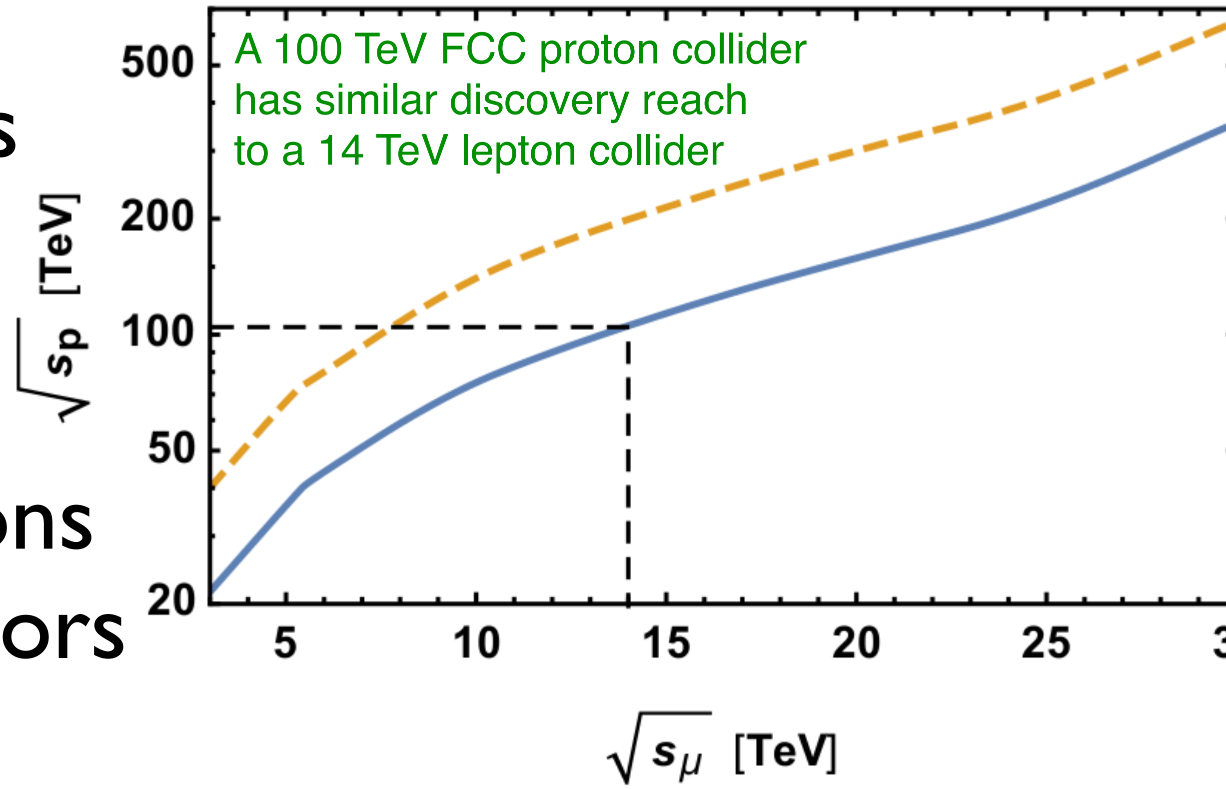
# Once & Future Particle Accelerators

- Energy frontier
  - goal: world's highest *energy density*
    - pack the most energy into the tiniest space, to make (via $E = mc^2$) and discover new particles
  - *problem:* LHC uses protons, made of quarks & gluons
    - so colliding quarks or gluons carry only a small fraction of proton-beam energy
    - & remaining quarks and gluons create background in detectors



# Once & Future Particle Accelerators

- Energy frontier
  - so colliding quarks or gluons carry only a small fraction of proton-beam energy
  - & remaining quarks and gluons create background in detectors

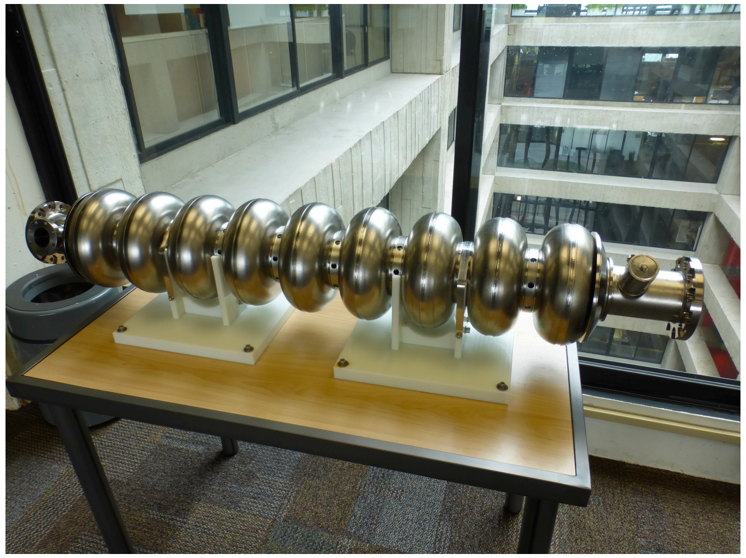



- a *lepton collider* thus provides a cleaner environment than a hadron collider, and requires less energy
- *but:* electrons lose energy (by radiating X rays) when deflected around a circle by magnets

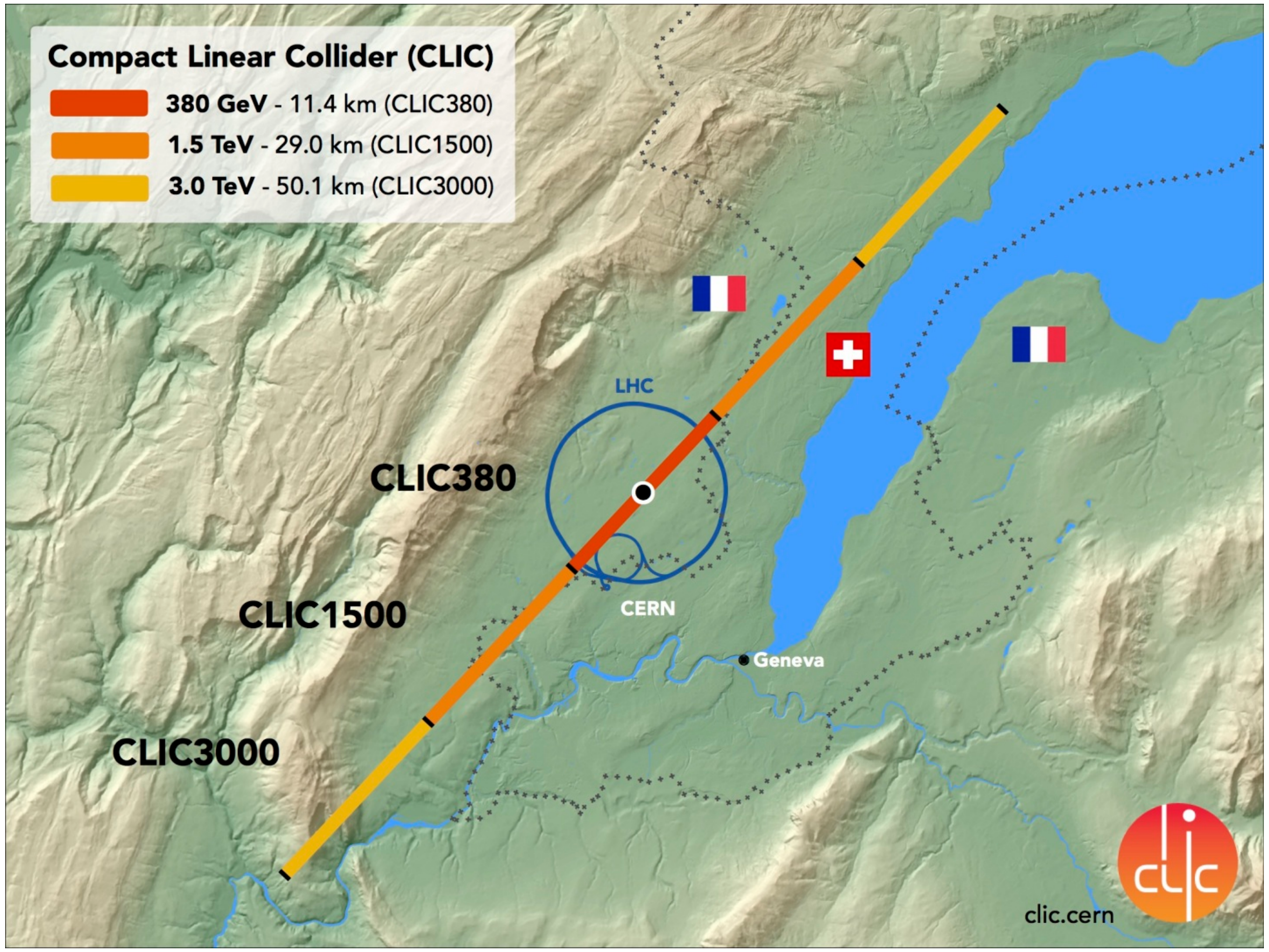
# Once & Future Particle Accelerators

- a *lepton collider* thus provides a cleaner environment than a hadron collider, and requires less energy
- *but:* electrons lose energy (by radiating X rays) when deflected around a circle by magnets
- solution: *linear* electron-positron colliders!
  - *but:* then each particle passes through each radio-frequency accelerating cavity only once, and can collide only once

➡ expensive way to accelerate and collide leptons



# E.g., Proposed CLIC @ CERN



# How to Do Better?

# Muon Accelerators?

# Muon Accelerators?

- (First, what's a muon?

# Muon Accelerators?

- (First, what's a muon?
  - an unstable, heavy "cousin" of the electron

# Muon Accelerators?

- (First, what's a muon?
  - an unstable, heavy "cousin" of the electron
  - very penetrating:
    - Alvarez famously used them to "x-ray" the 2nd Pyramid of Gizeh (see e.g. http://www2.lns.mit.edu/fisherp/AlvarezPyramids.pdf)

# Muon Accelerators?

- (First, what's a muon?
  - an unstable, heavy "cousin" of the electron
  - very penetrating:
    - Alvarez famously used them to "x-ray" the 2nd Pyramid of Gizeh (see e.g. http://www2.lns.mit.edu/fisherp/AlvarezPyramids.pdf)
    - also proposed for cargo scanning
  - the predominant component of cosmic radiation at sea level

# Muon Accelerators?

- (First, what's a muon?
  - an unstable, heavy "cousin" of the electron
  - very penetrating:
    - Alvarez famously used them to "x-ray" the 2nd Pyramid of Gizeh (see e.g. http://www2.lns.mit.edu/fisherp/AlvarezPyramids.pdf)
    - also proposed for cargo scanning
  - the predominant component of cosmic radiation at sea level
    - dozens of muons pass harmlessly through our bodies every second

# Muon Accelerators?

- (First, what's a muon?
  - an unstable, heavy "cousin" of the electron
  - very penetrating:
    - Alvarez famously used them to "x-ray" the 2nd Pyramid of Gizeh (see e.g. http://www2.lns.mit.edu/fisherp/AlvarezPyramids.pdf)
    - also proposed for cargo scanning

  - the predominant component of cosmic radiation at sea level
    - dozens of muons pass harmlessly through our bodies every second
  - decay into electrons, neutrinos, and antineutrinos)

# Muon Accelerators?

- Muons are 207 times as massive as electrons
  - radiate less energy by factor $(207)^4$ = 1.8 billion

    $\Rightarrow$ can use *circular* muon accelerators & collider rings 😊

# Muon Accelerators?

- Muons are 207 times as massive as electrons
  - radiate less energy by factor $(207)^4$ = 1.8 billion

    $\Rightarrow$ can use *circular* muon accelerators & collider rings 😊
- But – muons unstable: average lifetime = 2.2 μs ☹️
  - need to *make* the muons before accelerating them, and accelerate them as rapidly as possible
    - once muons accelerated to high energy, relativistic time dilation lengthens their lifetime substantially: $\tau = \tau_0 \, E/mc^2$

# Muon Accelerators?

- Muons are 207 times as massive as electrons
  - radiate less energy by factor $(207)^4$ = 1.8 billion

    ⇒ can use *circular* muon accelerators & collider rings 😊
- But – muons unstable: average lifetime = 2.2 μs ☹️
  - need to *make* the muons before accelerating them, and accelerate them as rapidly as possible
    - once muons accelerated to high energy, relativistic time dilation lengthens their lifetime substantially: $\tau = \tau_0\, E/mc^2$
- And muons at production "go in all directions"
  - need to "cool" the beam before acceleration ☹️
  - to increase beam brightness and collider "luminosity"

# Muon Accelerators?

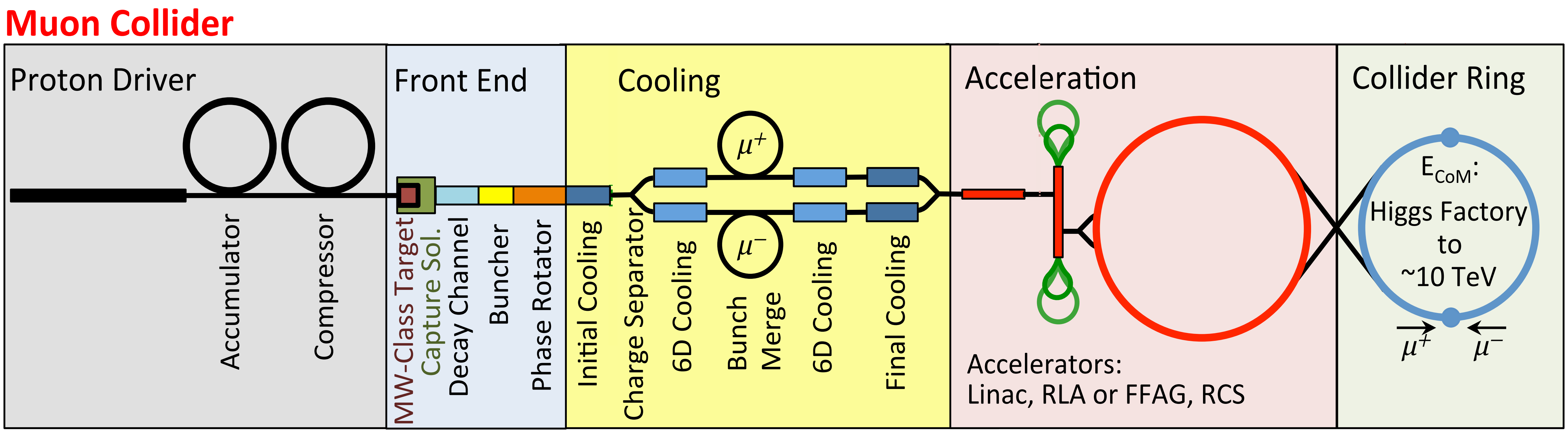
- Given solution to muon cooling problem (see below), muon accelerators could play 3 important roles:

1. Precision "Higgs factory,"
2. Energy-frontier collider,

   and, since muon decay makes neutrinos,

3. Uniquely powerful "Neutrino Factory"

# Muon Collider Concept




Prepare high-intensity (> MW) proton beam

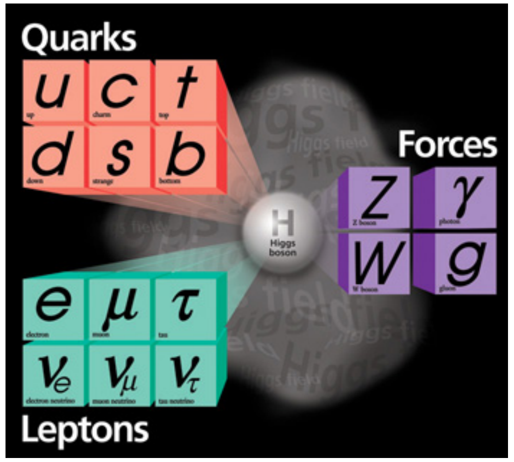
Protons hit target, make pions; muons captured & prepared for cooling

"6D" cooling (in the directions both transverse to & along the beam)

Muon & antimuon bunches accelerated via repeated traversal of superconducting RF cavities

Muon & antimuon beam bunches circulate & collide ~1000 times before decaying

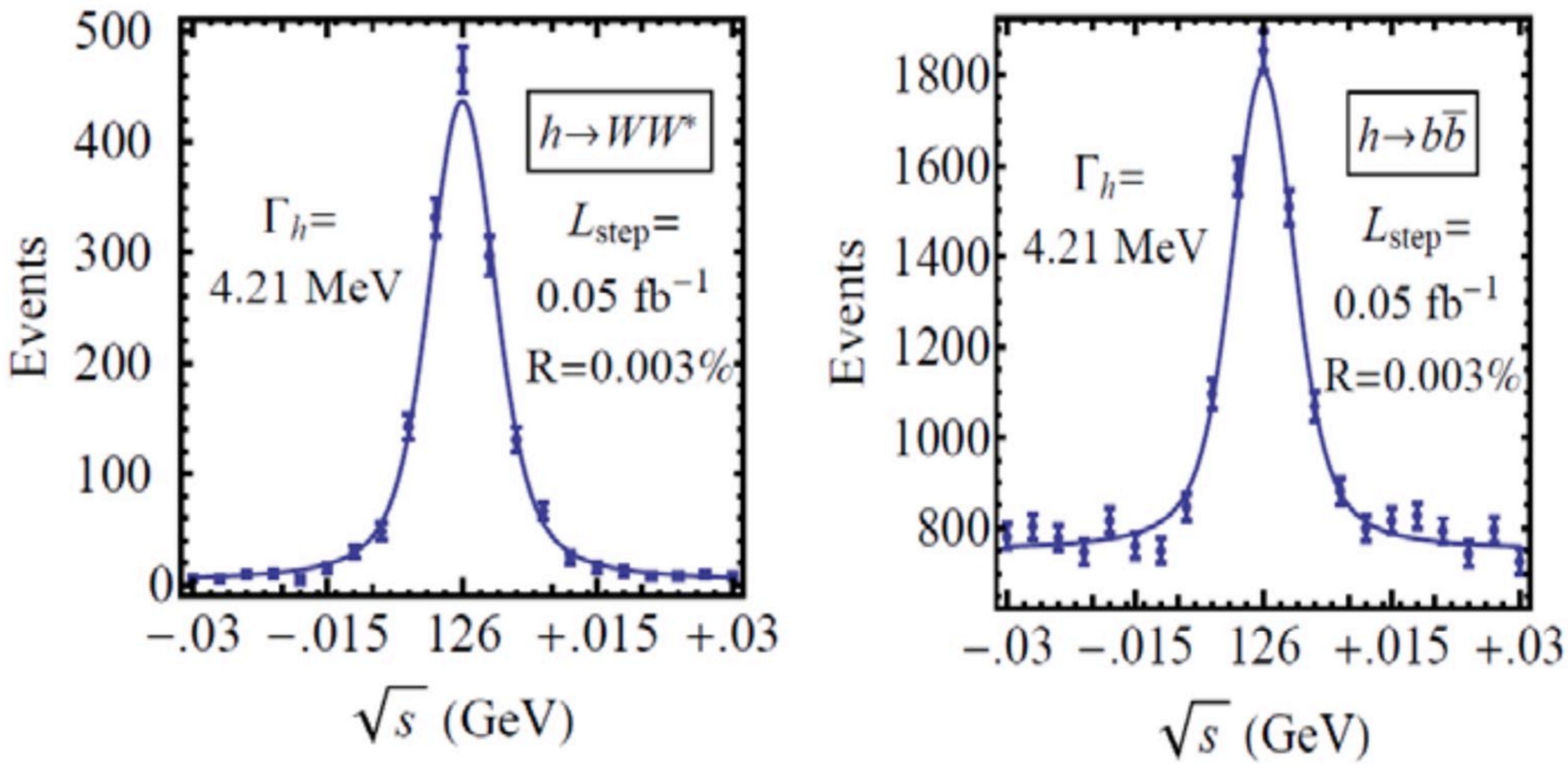
# I. Higgs Factory




- Role of Higgs boson in Standard Model:
  - provide mechanism for some particles to be heavy and others to be light
  - thus it couples more strongly to heavier particles
- Higgs boson discovered in 2012 in LHC *pp* collisions – now need to study it in detail
  - $\mu^+\mu^-$ annihilation to Higgs boson is ideal: $\mu^+\mu^- \rightarrow h$
  - allows direct measurement of key properties — mass, width, and line shape — as well as decay probabilities to various final states

# 1. Higgs Factory

- Simulated scans of muon-collider energy across the Higgs-boson peak

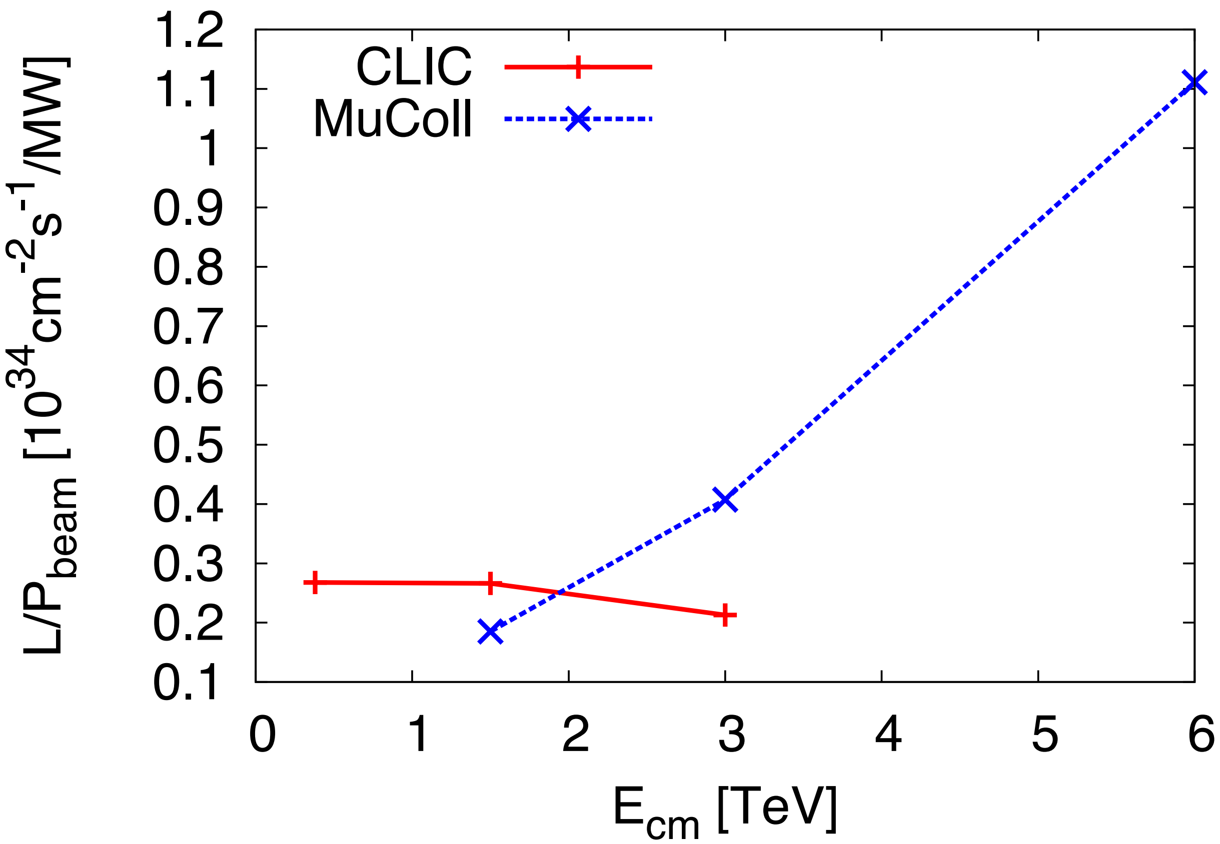



From C. Rubbia, "Further searches of the Higgs scalar sector at the ESS," arXiv:1908.05664 (2019)

  - directly determine Higgs mass, line shape & width & precisely measure decay probabilities

# 2. Energy Frontier Muon Collider

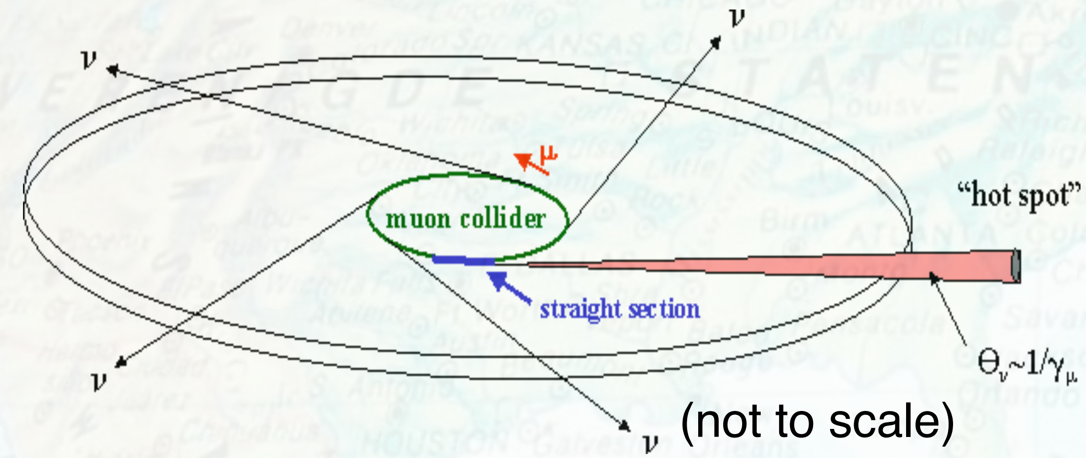
- Muon Collider luminosity rises with energy
  - unlike $e^+e^-$, which requires more electrical power (higher costs) the higher the energy




- Designs sketched up to 14 TeV (reusing LHC tunnel), exceeding FCC discovery reach

D. Neuffer and V. Shiltsev, "On the feasibility of a pulsed 14 TeV c.m.e. muon collider in the LHC tunnel," JINST **13** (2018 ) T10003

# MC Energy Limit?




(not to scale)

- ∃ maximum MC energy?
  - most of the muons decay in the collider ring
    - many of the decay neutrinos reach the surface
    - where they interact, they create hadrons
    - interaction probability rises with neutrino energy
    - neutrino intensity rises as neutrino-energy squared, falls inversely with storage-ring depth underground
  - above ≈14 TeV, anyone living 24/7 at a neutrino "hotspot" would receive radiation dose near or above federal limit for general public

B.J. King, "Neutrino radiation challenges and proposed solutions for many TeV muon colliders," *AIP Conf. Proc.* **530** (2000) 165 [*hep-ex/0005006*].

- interaction probability rises with neutrino energy
- neutrino intensity rises as neutrino-energy squared, falls inversely with storage-ring depth underground

- above ≈ 14 TeV, anyone living 24/7 at a neutrino "hotspot" would receive radiation dose near or above federal limit for general public

B.J. King, "Neutrino radiation challenges and proposed solutions for many TeV muon colliders," *AIP Conf. Proc.* **530** (2000) 165 [hep-ex/0005006].

- potential ways to mitigate hazard:
  - minimize length of straight sections
  - use helical beam orbits to spread neutrino cones
  - site facility on mountaintop, or on island far from residences (e.g., St. Croix)

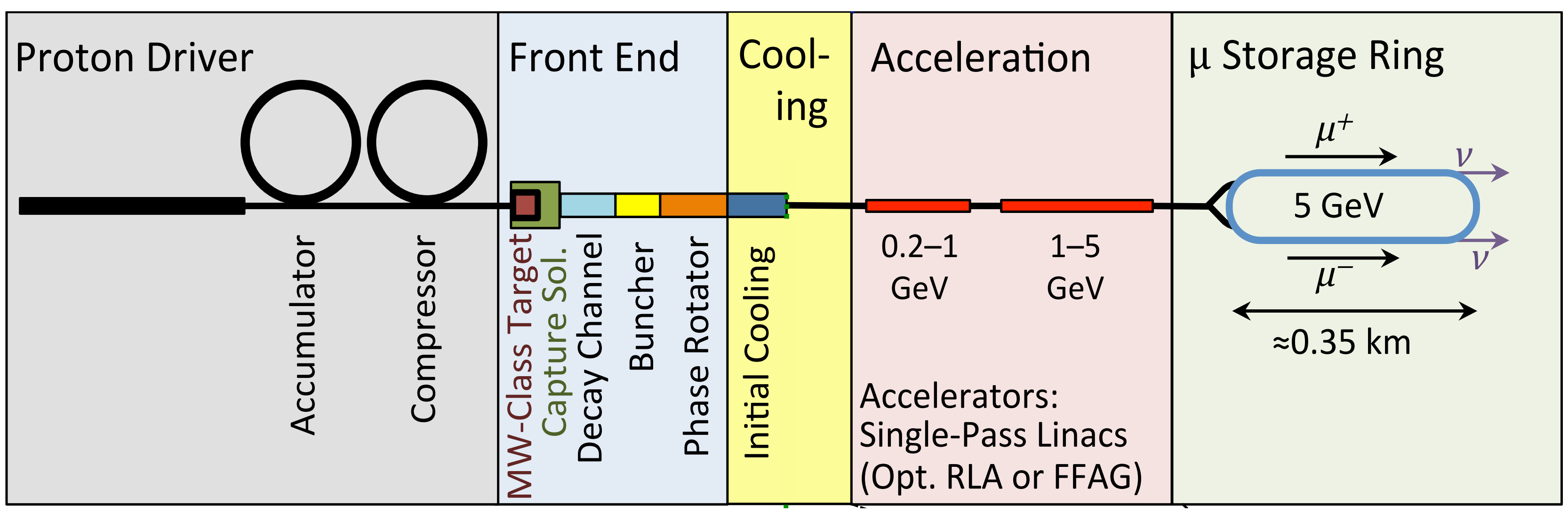
- eventually a problem, but not for foreseeable future

# 3. Neutrino Factory

- King's realization (muon storage ring a prolific source of neutrinos) inspired Steve Geer to invent "Neutrino Factory":

S. Geer, "Neutrino beams from muon storage rings: Characteristics and physics potential," Phys. Rev. D **57**, 6989 (1998).

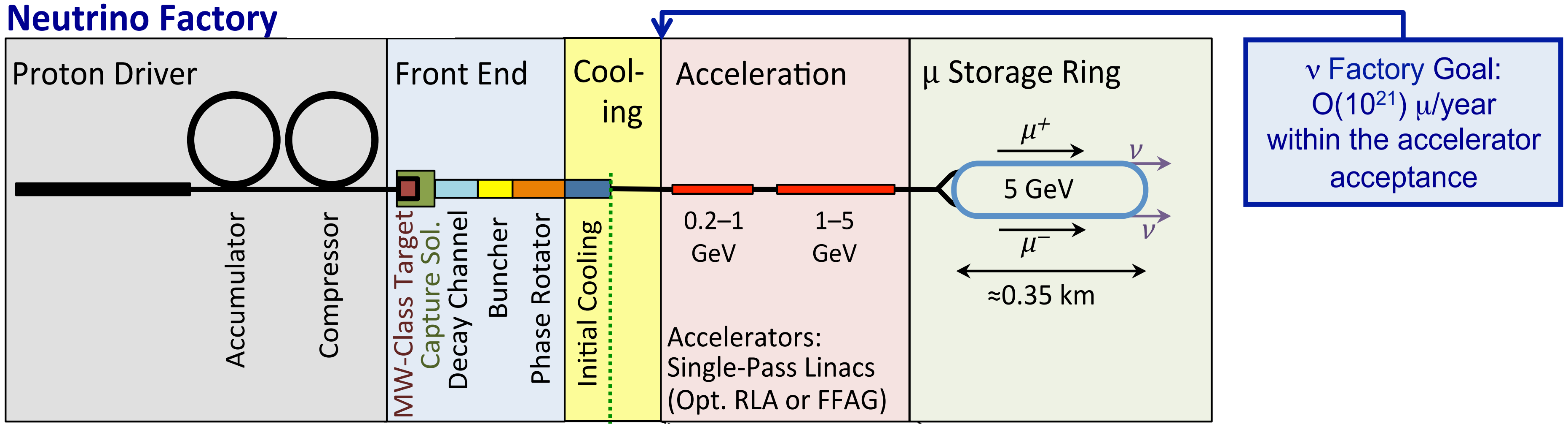
  - cooled high-intensity muon storage ring with long straight sections




ν Factory Goal:
$O(10^{21})$ μ/year
within the accelerator acceptance

# NF and MC Compared

**Neutrino Factory**

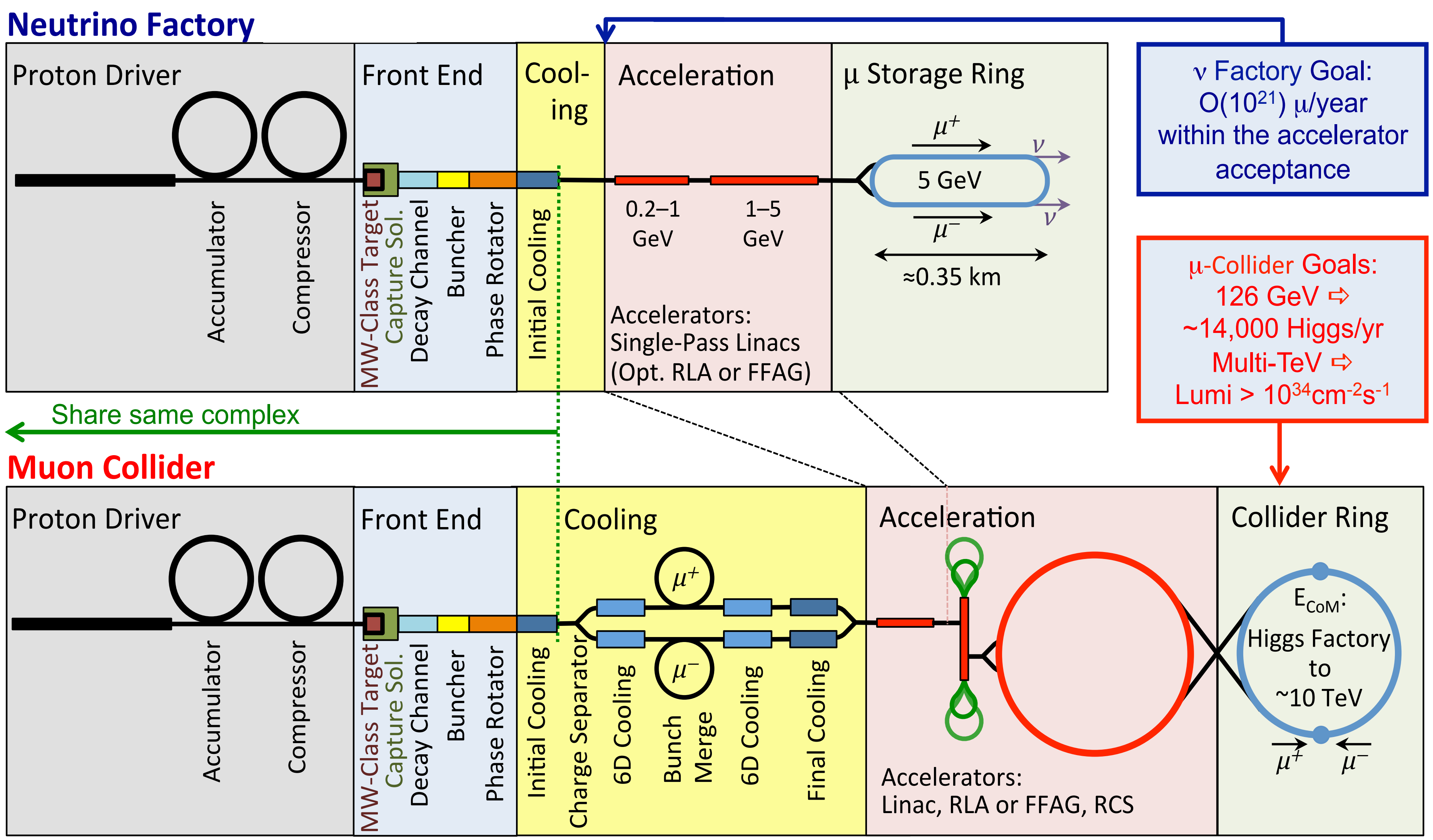



Key Features:

~ $10^{21}$ ν/year to remote detectors

$\nu_e$ beam → sub-percent precision

# NF and MC Compared




**Key Features:**

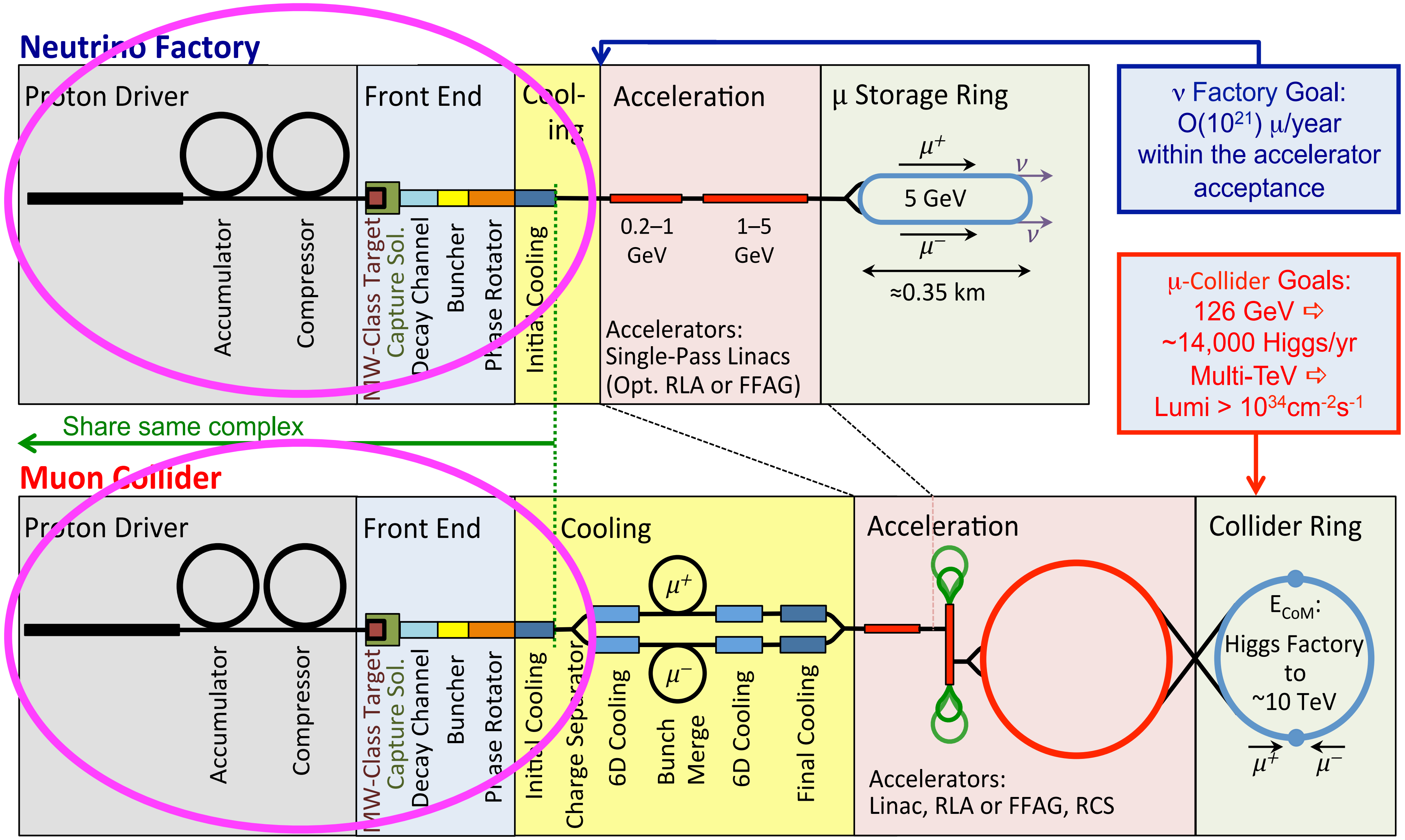
~ $10^{21}$ ν/year to remote detectors

$\nu_e$ beam → sub-percent precision

$\mathcal{L} > 10^{34}$ /cm²/s

$E_{CM}$ up to 10 TeV and beyond

# NF and MC Compared




**Key Features:**

~ $10^{21}$ ν/year to remote detectors

$\nu_e$ beam → sub-percent precision

$\mathcal{L} > 10^{34}$ /cm²/s

$E_{CM}$ up to 10 TeV and beyond

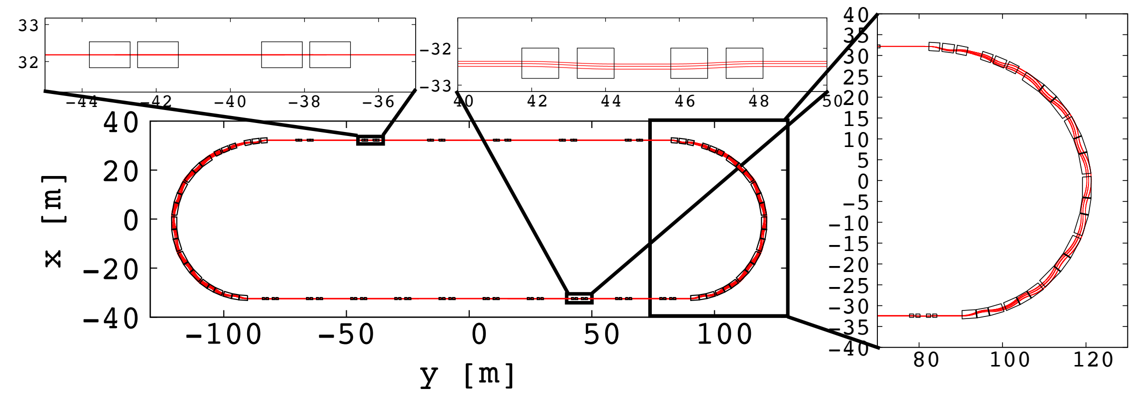
- Strong similarities! (1st 3 stages of NF reusable in MC)
  - both start with ~MW $p$ beam on high-power tgt → π → $\mu$, then cool, accelerate, & store

# NF and MC Compared

- Suggests natural upgrade path:

0. Build "conventional" muon storage ring: "nuSTORM"

D. Adey et al. (nuSTORM Collaboration), Phys. Rev. D 89, 071301(R) (2014)




  - testbed for muon cooling R&D
  - provide operational experience with stored-μ neutrino source
  - measure $\nu_e$ cross sections with precision needed for DUNE & T2HK + very sensitive search for sterile neutrinos

1. Build Neutrino Factory
2. Upgrade to Higgs Factory
3. Upgrade to Energy-Frontier Muon Collider

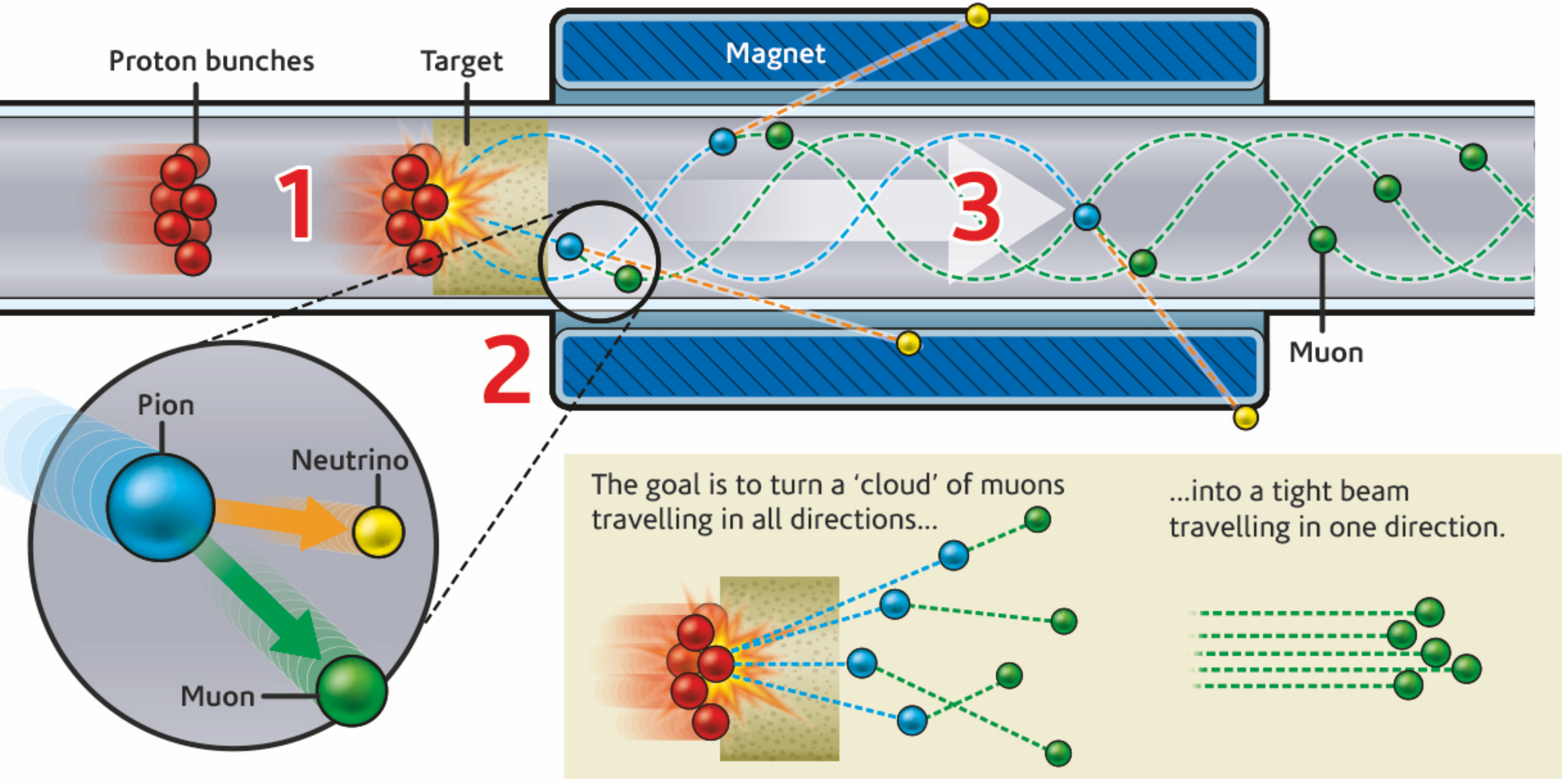
# Muon Cooling

# Muon Cooling

- Cooling = reducing the random motions of particles

# Muon Cooling

- Cooling = reducing the random motions of particles



# Muon Cooling

- Various beam cooling techniques developed since 1970s to cool beams of antiprotons or ions (electron cooling, stochastic cooling, laser cooling)
  - require the beam to circulate in a ring for minutes to hours
  - far too slow for muons!

- How cool muons in < microseconds???

# Muon Cooling

- How cool muons in < microseconds???

# Muon Cooling

- How cool muons in < microseconds???
- Solution proposed in 1970s by Budker, Skrinsky, Parkhomchuk, Balbekov, *et al.* at Budker Institute of Nuclear Physics, Novosibirsk, Russia:

# Muon Cooling

- How cool muons in < microseconds???
- Solution proposed in 1970s by Budker, Skrinsky, Parkhomchuk, Balbekov, *et al.* at Budker Institute of Nuclear Physics, Novosibirsk, Russia:

*Ionization* Cooling

- elaborated at Fermilab, Brookhaven, and elsewhere
- now confirmed experimentally by the Muon Ionization Cooling Experiment (MICE):

M. Bogomilov *et al*., "Demonstration of cooling by the Muon Ionization Cooling Experiment," Nature **578**, 53 (2020), www.nature.com/articles/s41586-020-1958-9

Article | Open Access | Published: 05 February 2020

# Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

*Nature* **578**, 53–59(2020) | Cite this article



Associated Content

*Nature* | News & Views
**Muon colliders come a step closer**
Robert D. Ryne



## Abstract

The use of accelerated beams of electrons, protons or ions has furthered the development of nearly every scientific discipline. However, high-energy muon beams of equivalent quality have not yet been delivered. Muon beams can be created through the decay of pions produced by the interaction of a proton beam with a target. Such 'tertiary' beams have much lower brightness than those created by accelerating electrons, protons or ions. High-brightness muon beams comparable to those produced by state-of-the-art electron, proton and ion accelerators could facilitate the study of lepton–antilepton collisions at extremely high energies and provide well characterized neutrino beams[1,2,3,4,5,6]. Such muon beams could be realized using ionization cooling, which has been proposed to increase muon-beam brightness[7,8]. Here we report the realization of ionization cooling, which was confirmed by the observation of an increased number of low-amplitude muons after passage of the muon beam through an absorber, as well as an increase in the corresponding phase-space density. The simulated performance of the ionization cooling system is consistent with the measured data, validating designs of the ionization cooling channel in which the cooling

# Muon Cooling

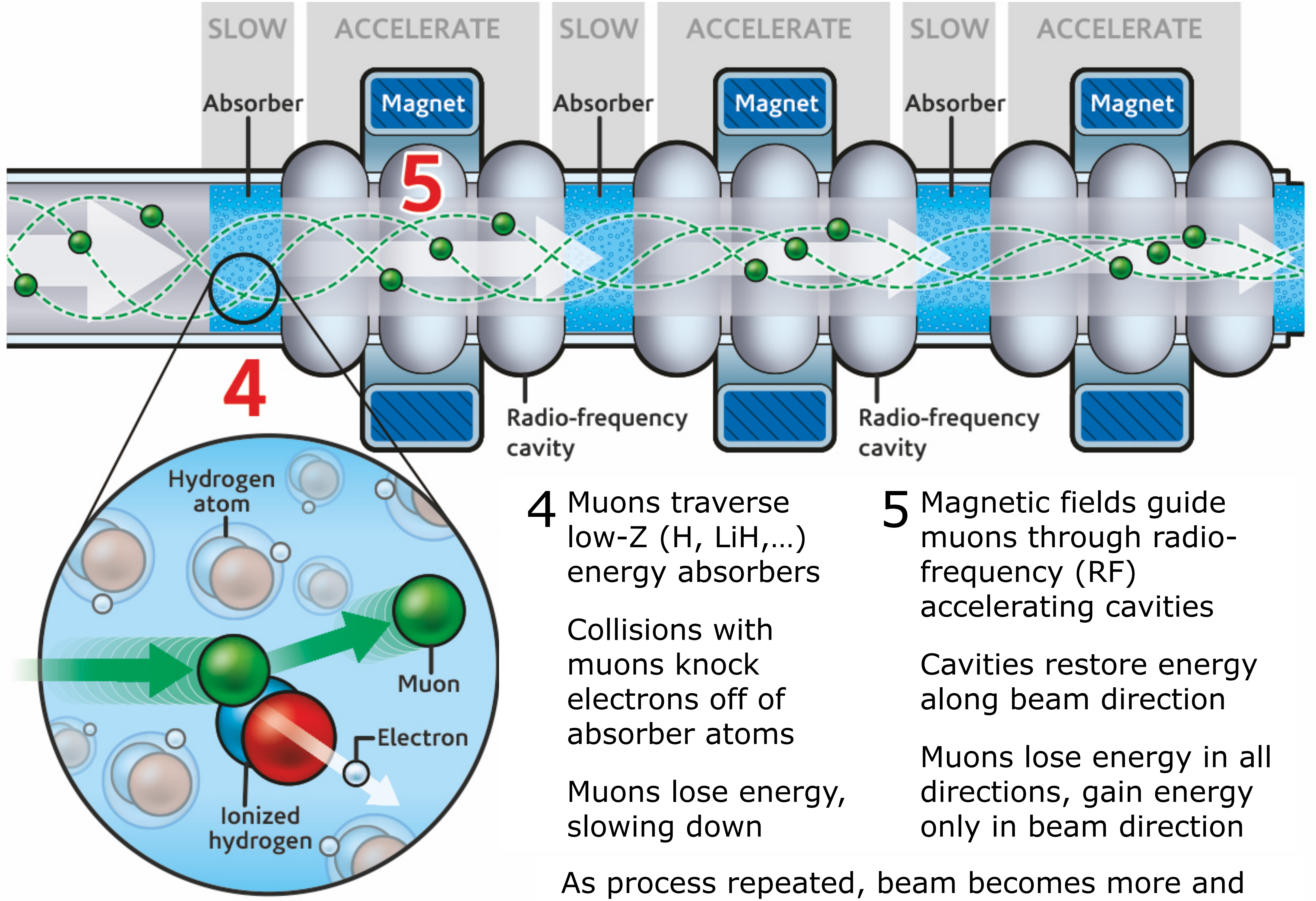
- How cool muons in < microseconds???
- Solution proposed in 1970s by Budker, Skrinsky, Parkhomchuk, Balbekov, *et al.* at Budker Institute of Nuclear Physics, Novosibirsk, Russia:

*Ionization* Cooling

- elaborated at Fermilab, Brookhaven, and elsewhere
- now confirmed experimentally by the Muon Ionization Cooling Experiment (MICE):

M. Bogomilov *et al.*, "Demonstration of cooling by the Muon Ionization Cooling Experiment," Nature **578**, 53 (2020), www.nature.com/articles/s41586-020-1958-9

# Ionization Cooling




*Infographic: STFC, Ben Gilliland*

4 Muons traverse low-Z (H, LiH,…) energy absorbers

Collisions with muons knock electrons off of absorber atoms

Muons lose energy, slowing down

5 Magnetic fields guide muons through radio-frequency (RF) accelerating cavities

Cavities restore energy along beam direction

Muons lose energy in all directions, gain energy only in beam direction

As process repeated, beam becomes more and more parallel, suitable for main accelerator

# Muon Cooling

- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" ε

(3 position coordinates + 3 momentum coordinates = 6 dimensions)

# Muon Cooling

- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" ε

(3 position coordinates + 3 momentum coordinates = 6 dimensions)

- Physics of multi-TeV lepton collisions calls for luminosity $\mathcal{L} \gtrsim 10^{34}$ events/cm²/s

# Muon Cooling

- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" $\varepsilon$

(3 position coordinates + 3 momentum coordinates = 6 dimensions)

- Physics of multi-TeV lepton collisions calls for luminosity $\mathcal{L} \gtrsim 10^{34}$ events/cm$^2$/s

- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$

# Muon Cooling

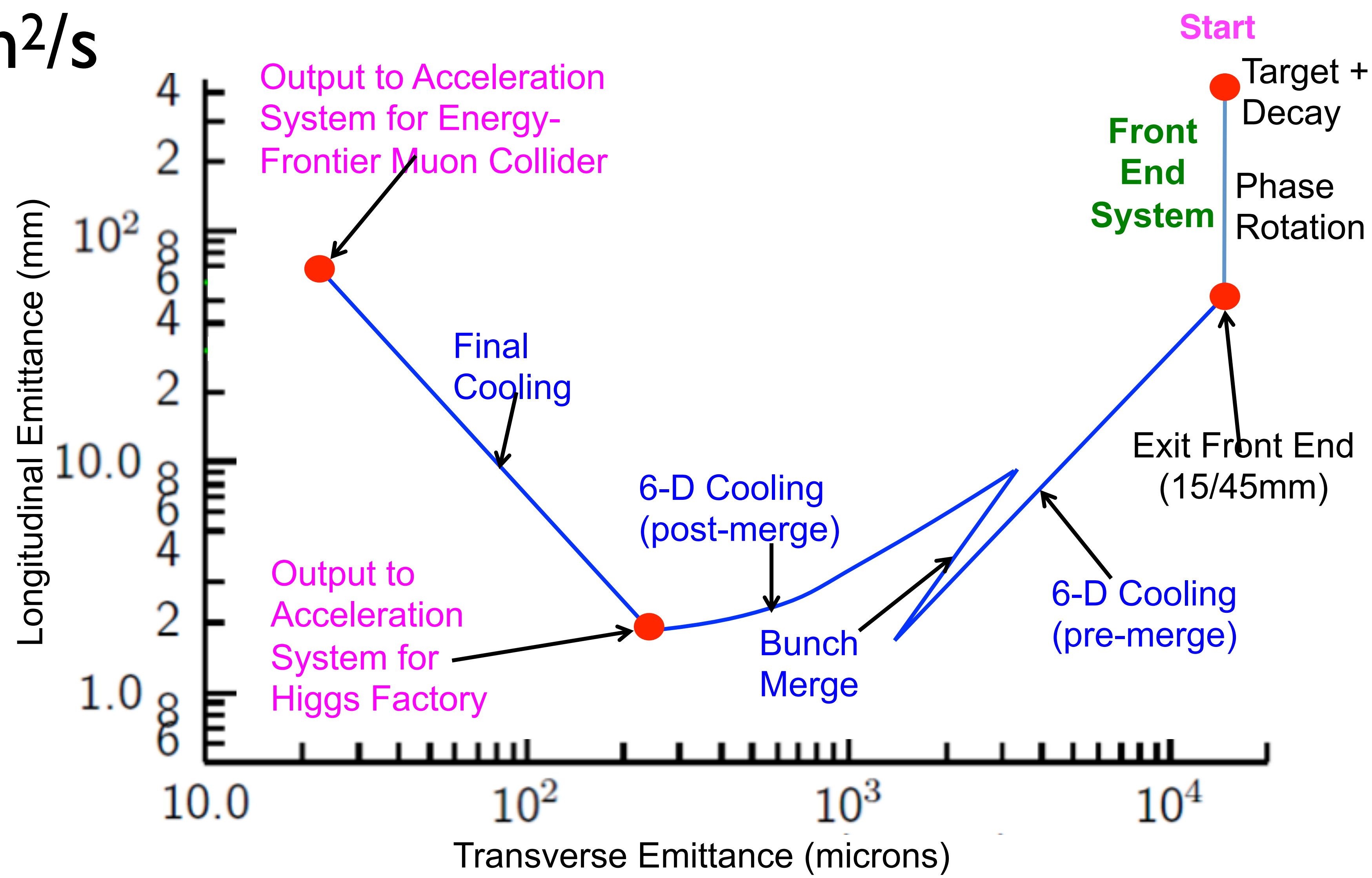
- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" ε

  (3 position coordinates + 3 momentum coordinates = 6 dimensions)

- Physics of multi-TeV lepton collisions calls for luminosity $\mathcal{L} \gtrsim 10^{34}$ events/cm²/s

- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$

- How to get there: (one scenario)



# Muon Cooling

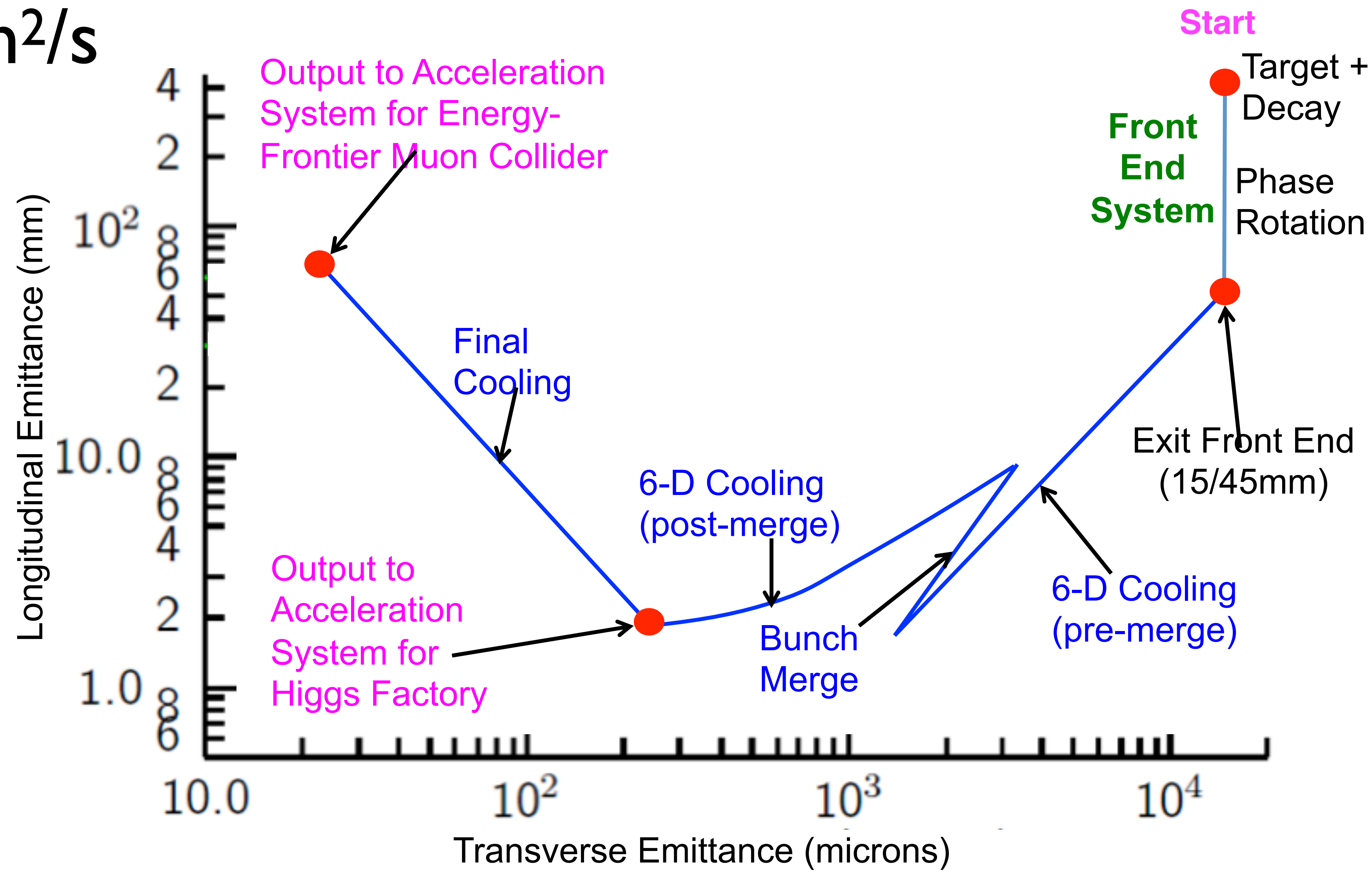
- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" ε

(3 position coordinates + 3 momentum coordinates = 6 dimensions)

- Physics of multi-TeV lepton collisions calls for luminosity $\mathcal{L} \gtrsim 10^{34}$ events/cm²/s

- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$

- How to get there: (one scenario)
  - must cool both $\varepsilon_\perp$ and $\varepsilon_{||}$



# Muon Cooling

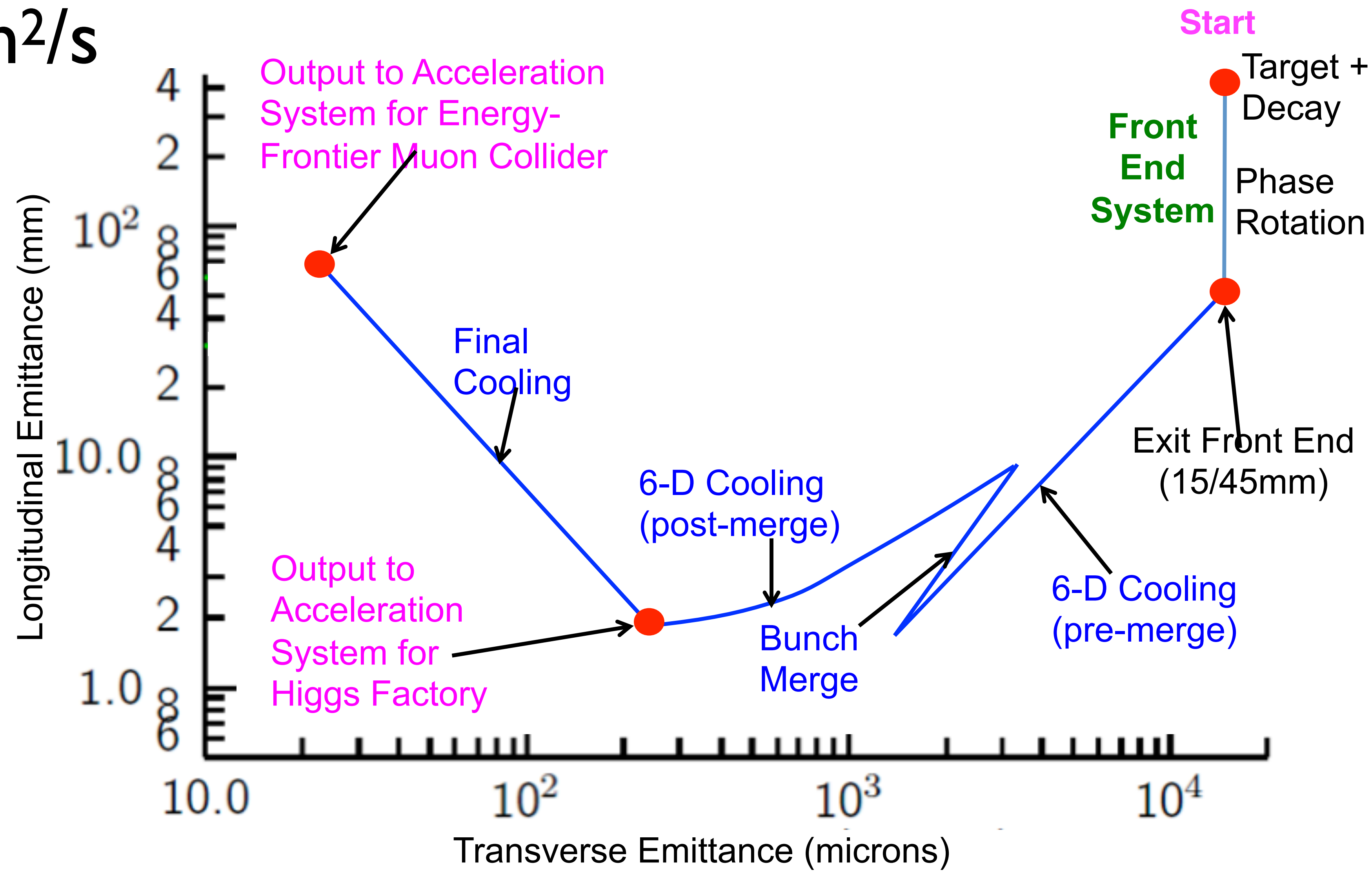
- Cooling best thought of in terms of generalized beam size in 6-dimensional "phase space": "emittance" ε

(3 position coordinates + 3 momentum coordinates = 6 dimensions)

- Physics of multi-TeV lepton collisions calls for luminosity $\mathcal{L} \gtrsim 10^{34}$ events/cm²/s

- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$

- How to get there: (one scenario)
  - must cool both $\varepsilon_\perp$ and $\varepsilon_{||}$
  - need factor $\gtrsim 10^6$ in total 6D emittance reduction (from "basketball" to "grain of rice")

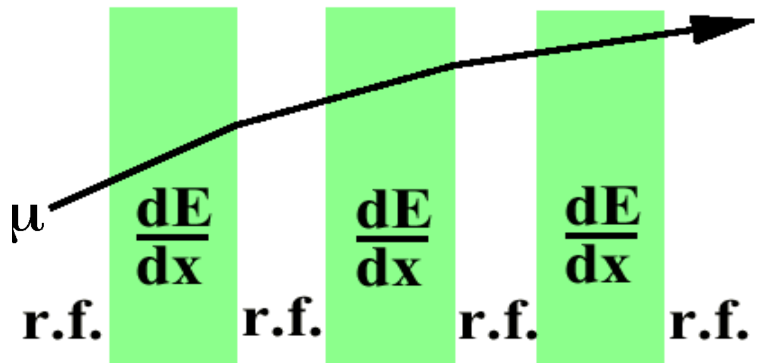


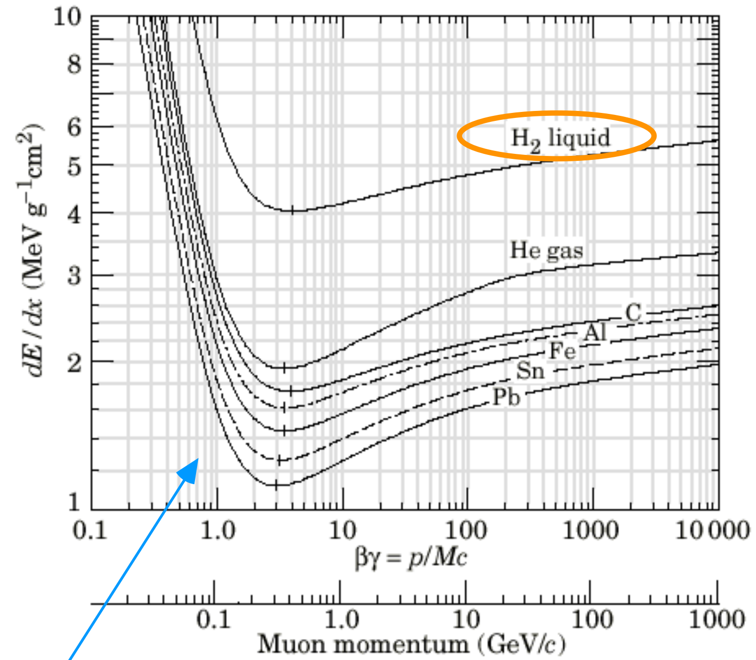
# Transverse Ionization Cooling

- Muons cool via ionization *dE*/*dx* in low-*Z* medium:

# Transverse Ionization Cooling

- Muons cool via ionization *dE*/*dx* in low-*Z* medium:




  – Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

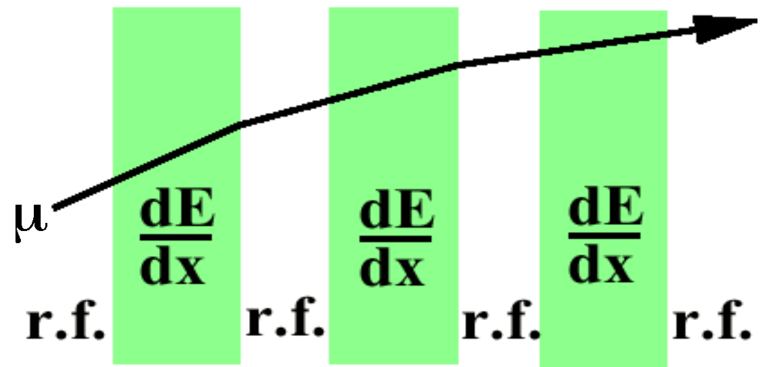
  – RF cavities between absorbers replace $\Delta E$

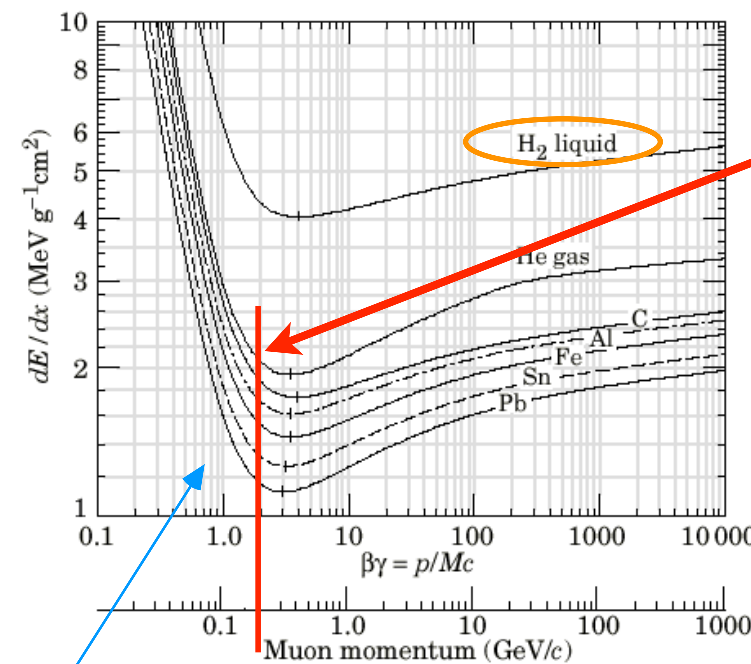
  – Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling:

$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2} \left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

# Transverse Ionization Cooling

- Muons cool via ionization *dE/dx* in low-*Z* medium:




- optimal working point is ≈ ionization minimum

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

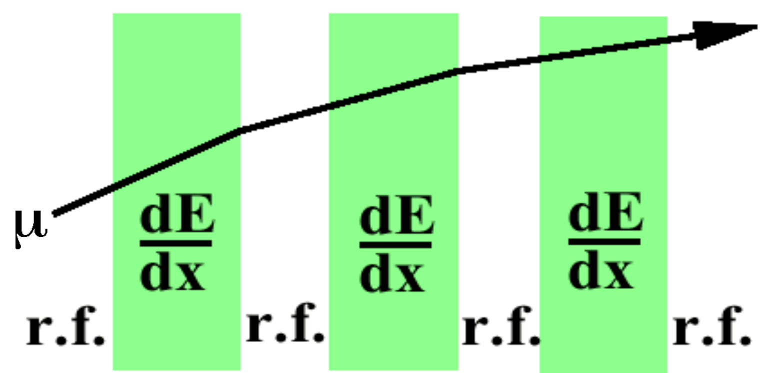
– RF cavities between absorbers replace $\Delta E$

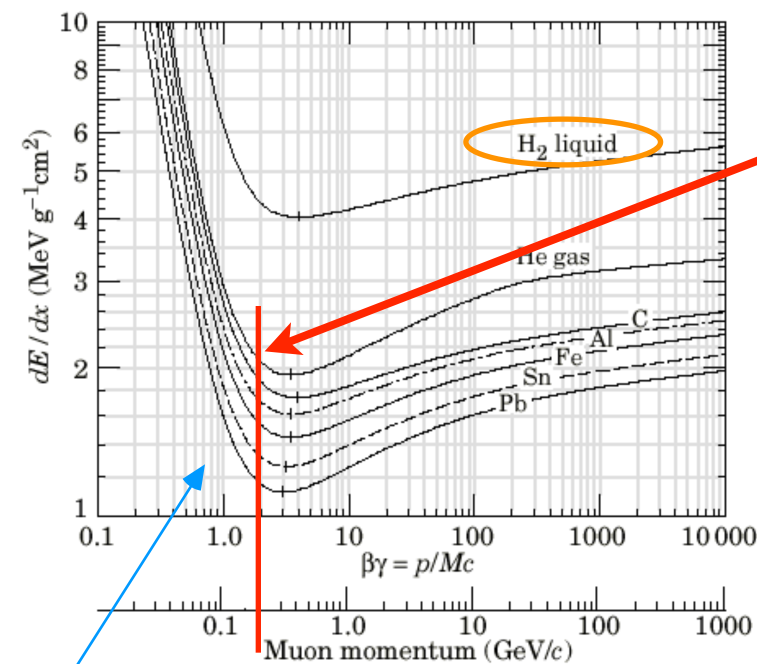
– Net effect: reduction in $p_\perp$ at constant $p_{\|}$, i.e., transverse cooling:

$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2} \left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

# Transverse Ionization Cooling

- Muons cool via ionization *dE/dx* in low-*Z* medium:




- optimal working point is ≈ ionization minimum

– Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

– RF cavities between absorbers replace $\Delta E$

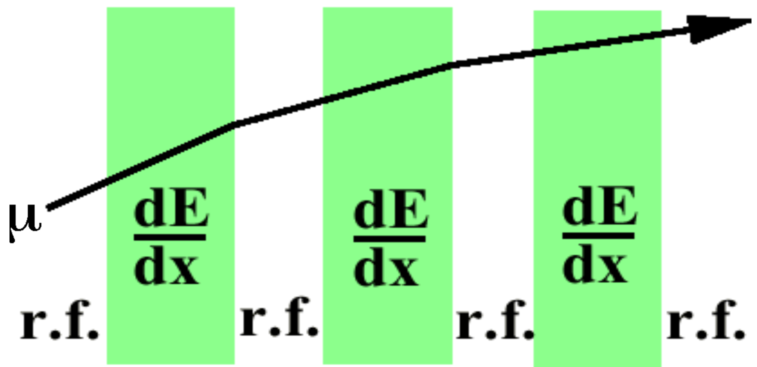
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling:

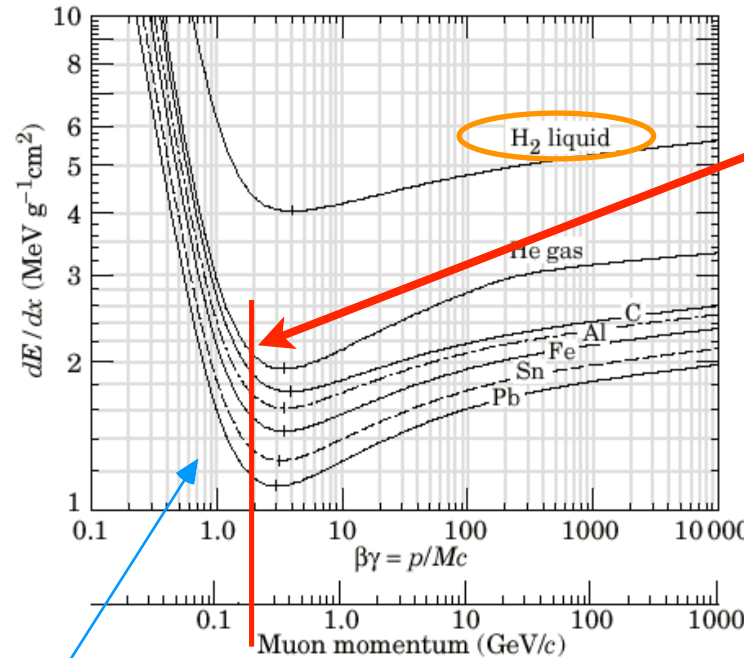
$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2} \left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

- 2 competing effects
  ⇒ equilibrium emittance:
  $\varepsilon_0 \propto \beta_\perp \langle dE/dx \rangle X_0$

# Transverse Ionization Cooling

- Muons cool via ionization *dE*/*dx* in low-*Z* medium:




- optimal working point is ≈ ionization minimum

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

– RF cavities between absorbers replace Δ*E*

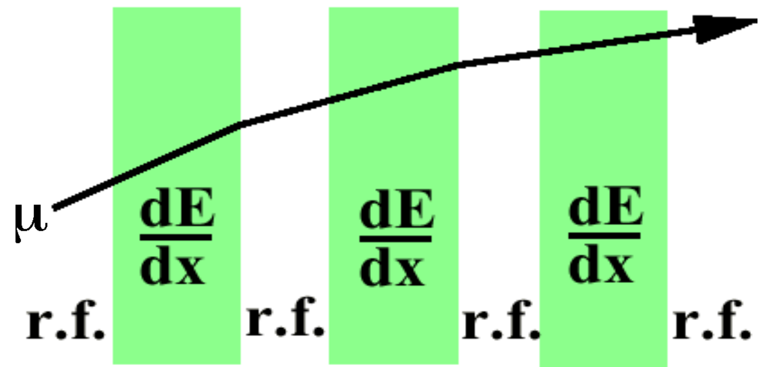
– Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling:

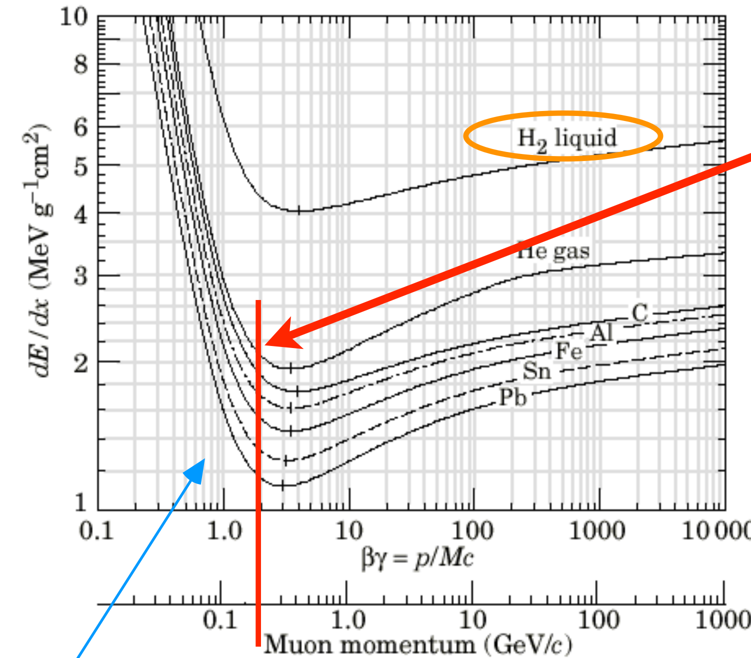
$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2}\left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

- 2 competing effects ⇒ equilibrium emittance: $\varepsilon_0 \propto \beta_\perp \langle dE/dx \rangle X_0$

# Transverse Ionization Cooling

- Muons cool via ionization *dE*/*dx* in low-Z medium:




- optimal working point is ≈ ionization minimum

  – Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

- 2 competing effects ⇒ equilibrium emittance: $\varepsilon_0 \propto \beta_\perp \langle dE/dx \rangle X_0$

  – RF cavities between absorbers replace $\Delta E$

  – Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling:

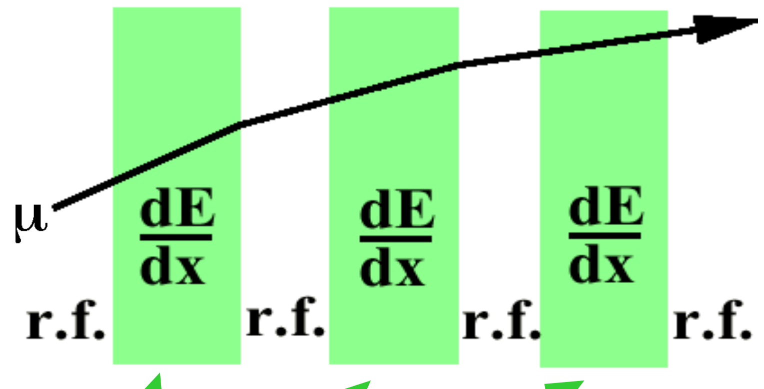
$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2} \left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

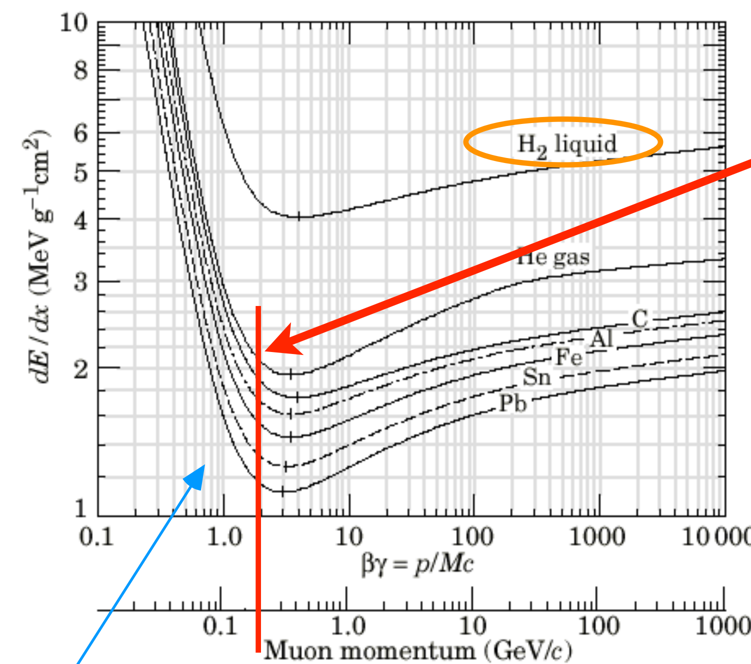
- Only* practical way to cool within $\mu$ lifetime

*unless optical stochastic cooling workable [IOTA]

# Transverse Ionization Cooling

- Muons cool via ionization *dE/dx* in low-Z medium:




- optimal working point is ≈ ionization minimum

  – Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering off nuclei

- 2 competing effects
  ⇒ equilibrium emittance: $\varepsilon_0 \propto \beta_\perp \langle dE/dx \rangle X_0$

  – RF cavities between absorbers replace $\Delta E$

  – Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling:

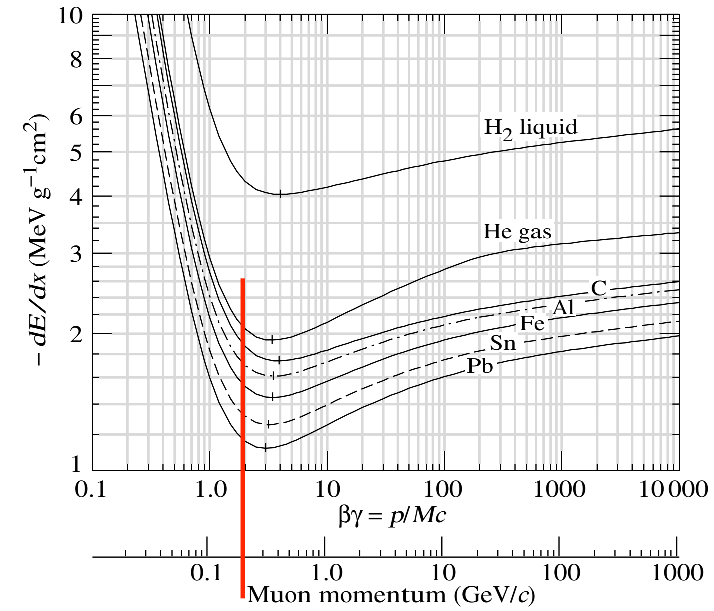
$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2}\left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

- Only* practical way to cool within $\mu$ lifetime
- Expt'l demo: MICE

*unless optical stochastic cooling workable [IOTA]

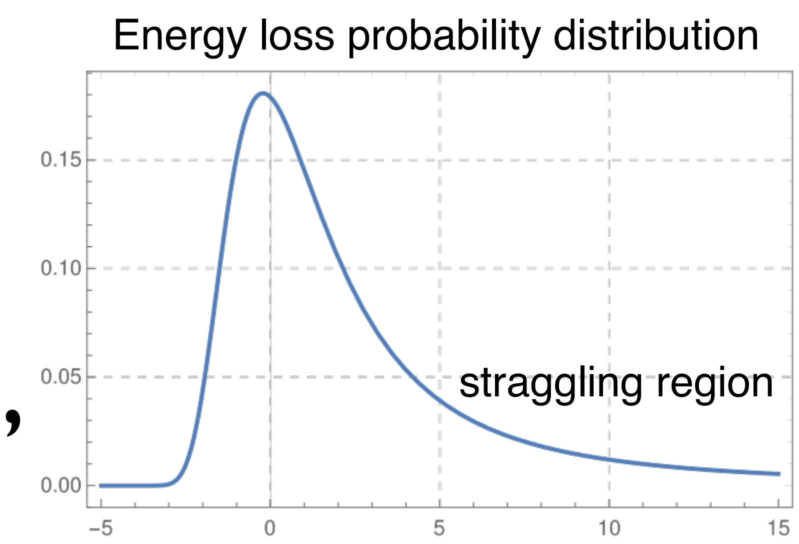
# How to cool in 6D?

- Work above ionization minimum to get negative feedback in $p_z$?



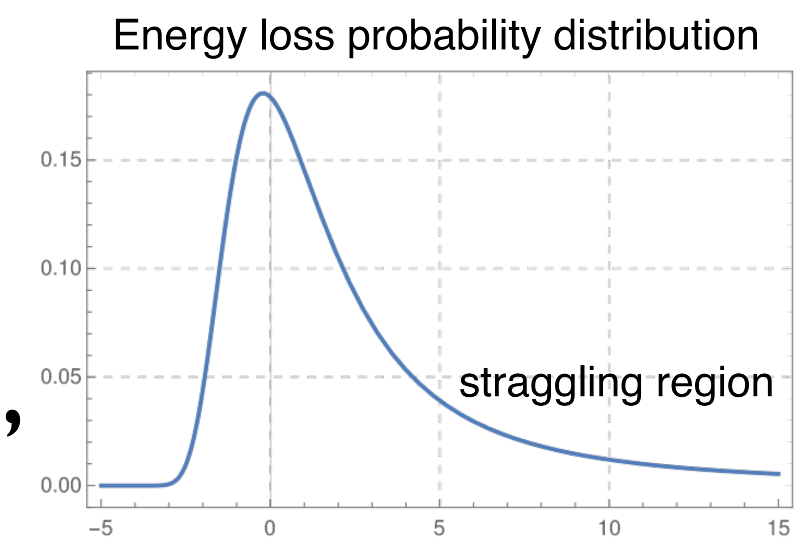
# How to cool in 6D?

- Work above ionization minimum to get negative feedback in $p_z$?
- No – ineffective due to "straggling"



# How to cool in 6D?

- Work above ionization minimum to get negative feedback in $p_z$?
- No – ineffective due to "straggling"

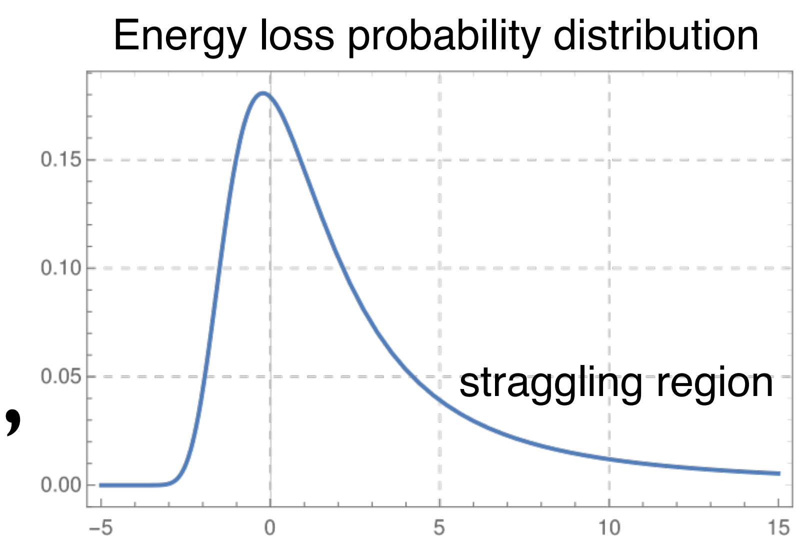



$\Rightarrow$ cool longitudinally via *emittance exchange*:

David Neuffer, "$\mu^+\mu^-$ Colliders," CERN-YELLOW-99-12

# How to cool in 6D?

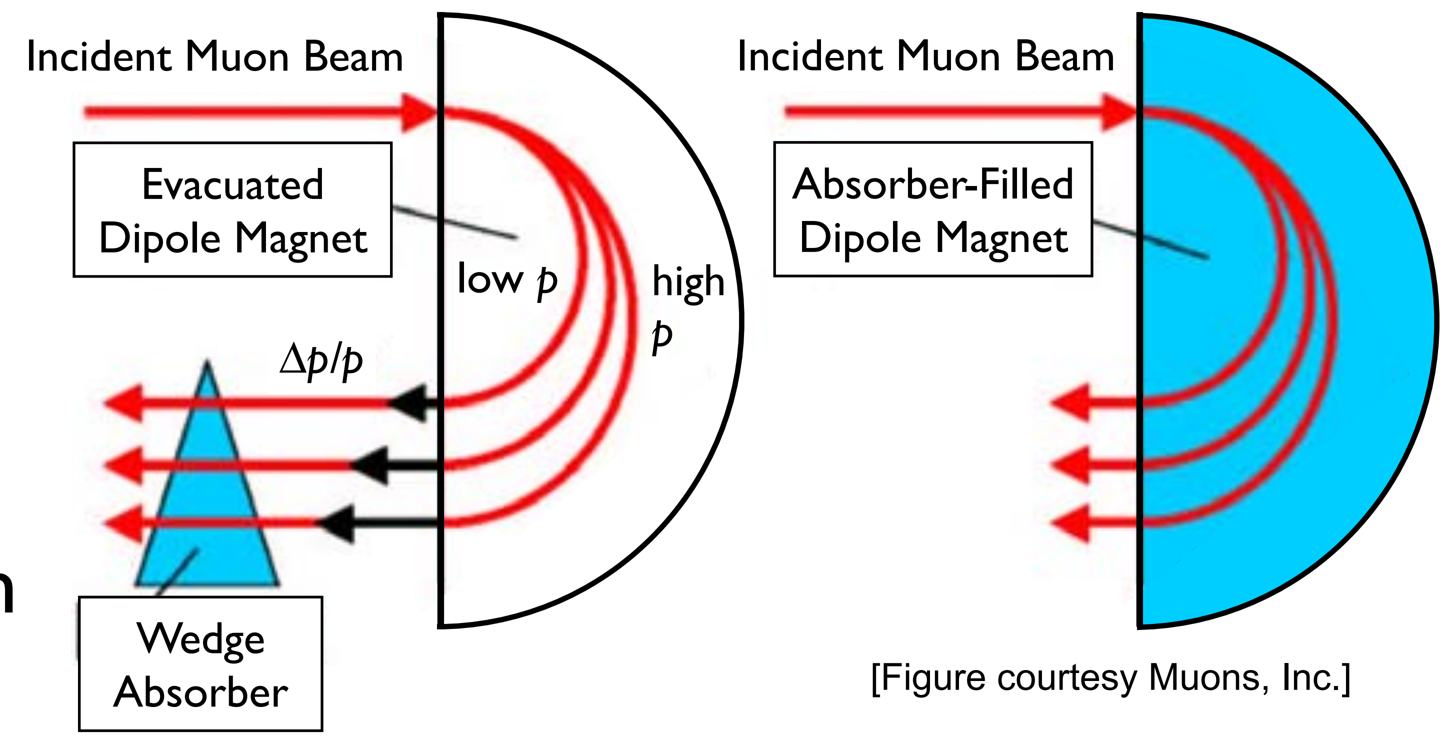
- Work above ionization minimum to get negative feedback in $p_z$?
- No – ineffective due to "straggling"




$\Rightarrow$ cool longitudinally via *emittance exchange*:

David Neuffer, "μ⁺μ⁻ Colliders," CERN-YELLOW-99-12

- use "dispersion" (spread muons apart magnetically) to correlate momentum with position
- wedge absorbers then equalize momenta



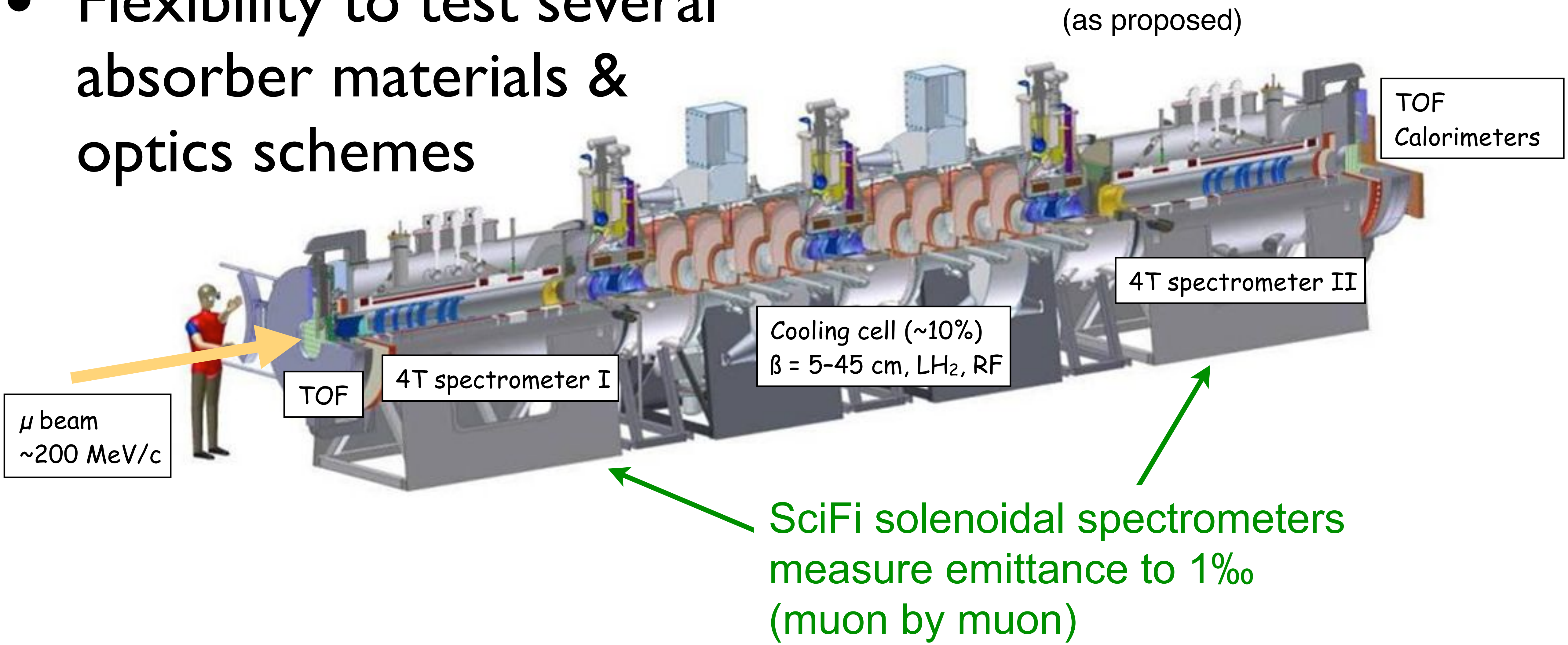

[Figure courtesy Muons, Inc.]

- Cool $\varepsilon_\perp$, exchange $\varepsilon_\perp$ & $\varepsilon_{||}$ → 6D cooling

# MICE

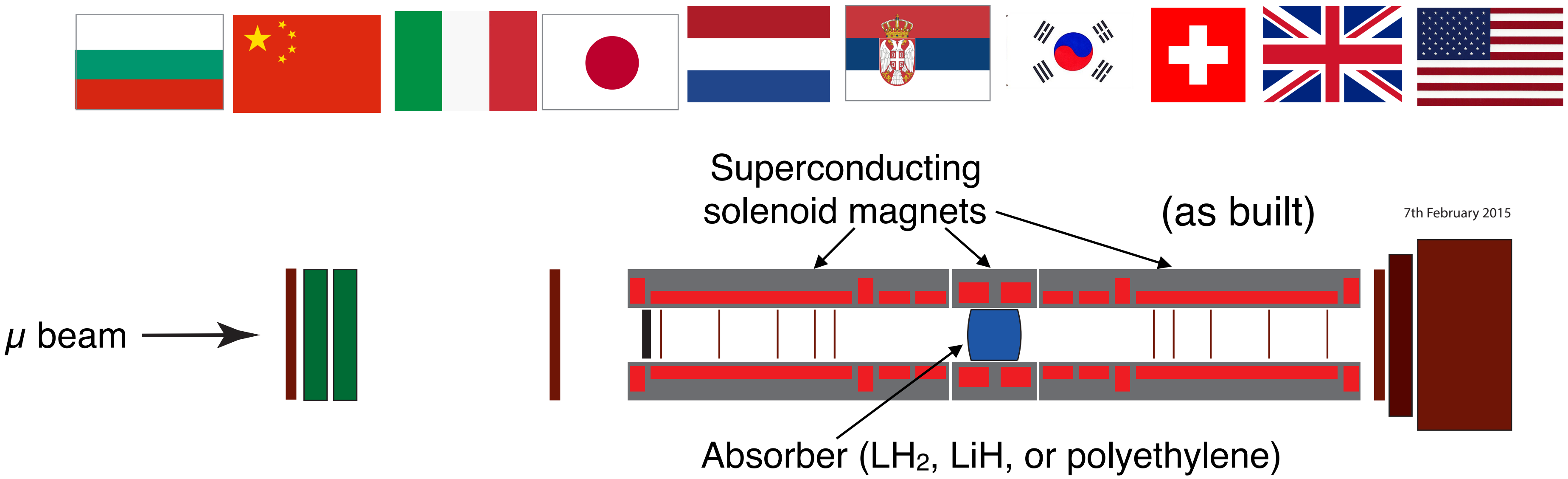
- International Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory (RAL)

- Flexibility to test several absorber materials & optics schemes



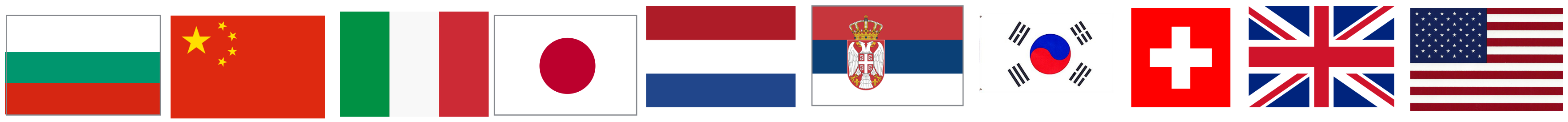

- Status: data-taking complete, 1st results published, further analyses in progress

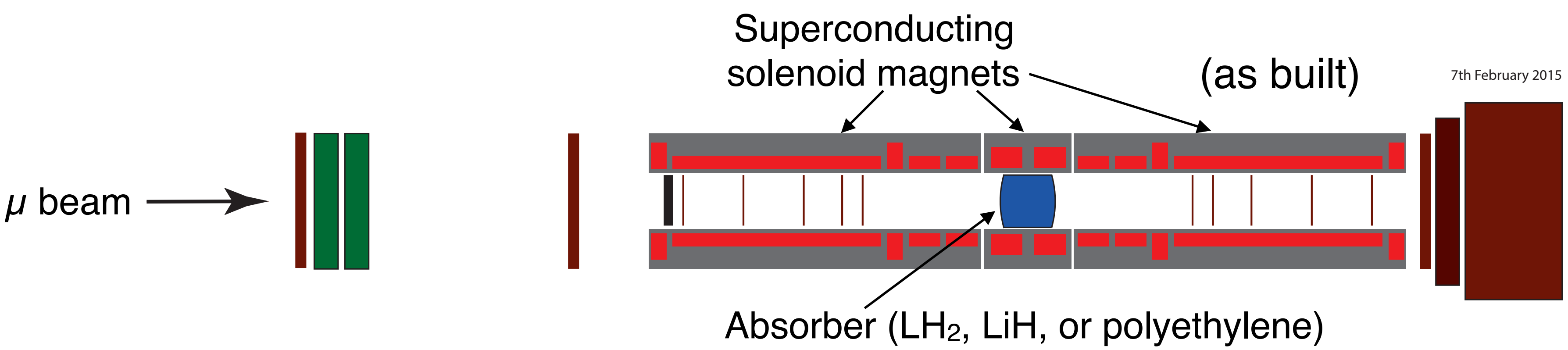
# MICE




- International collaboration of >100 scientists and engineers, from >30 institutions in 11 countries

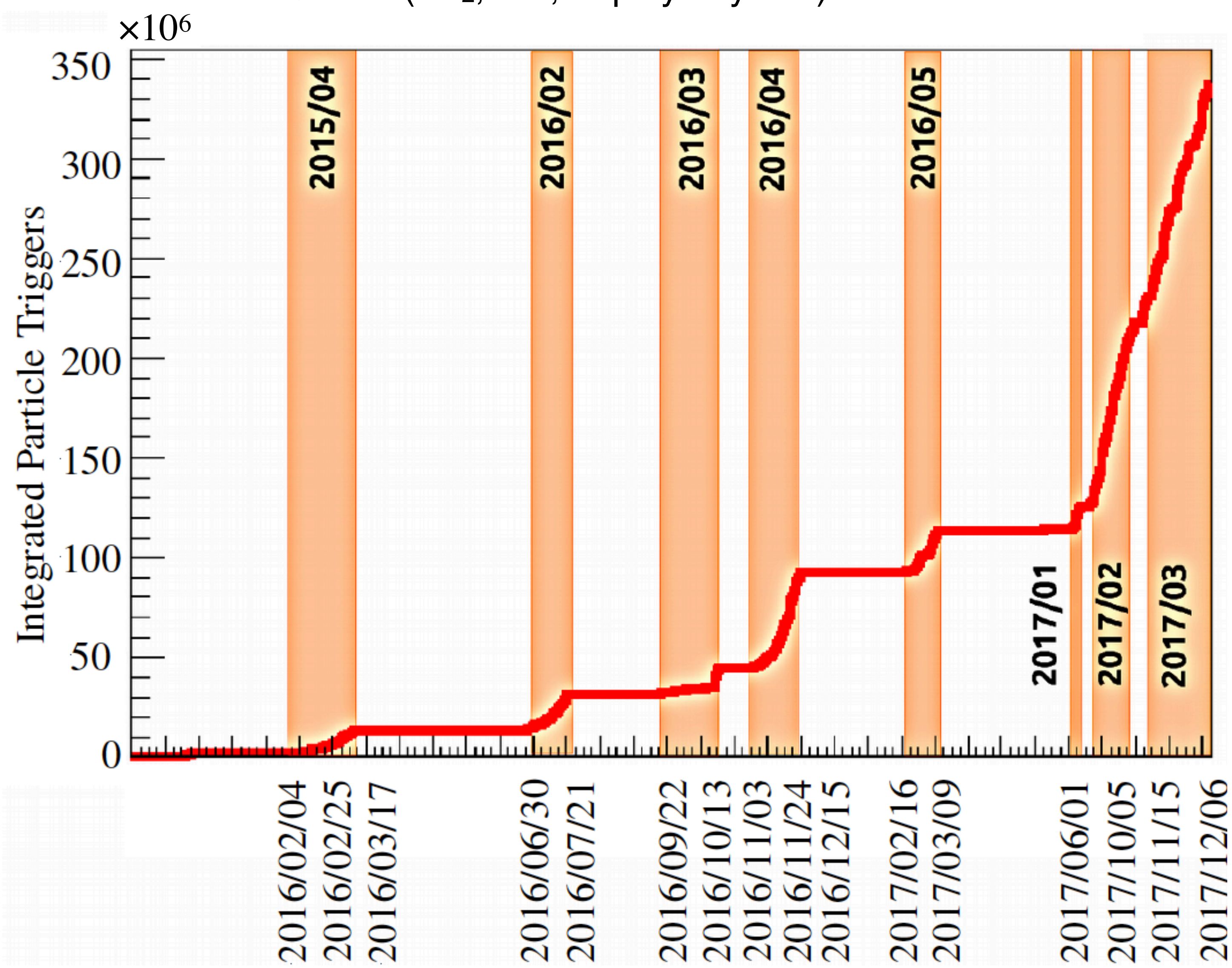
# MICE



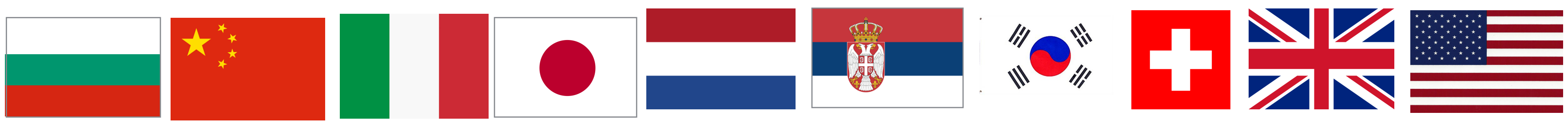


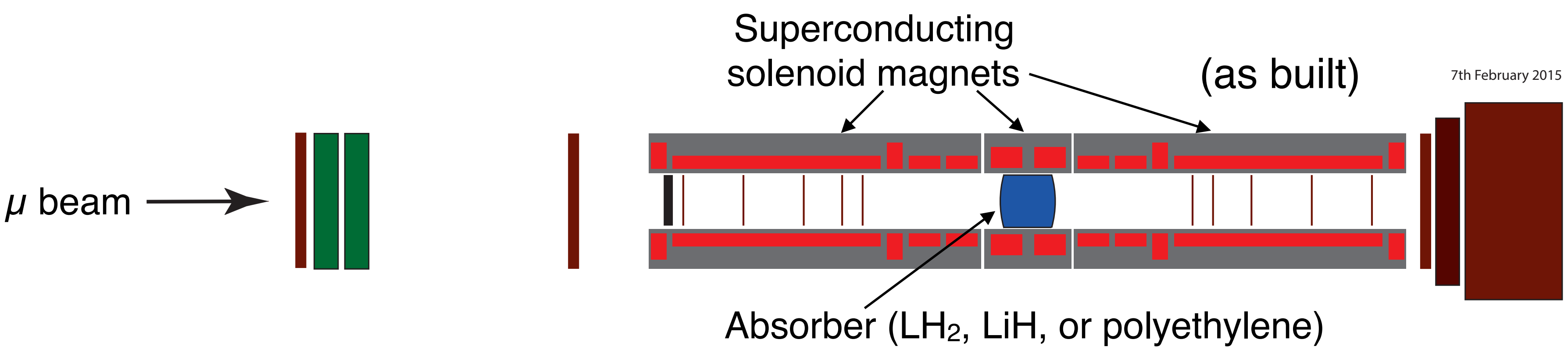

- International collaboration of >100 scientists and engineers, from >30 institutions in 11 countries

- Successful data-taking campaign finished in 2017



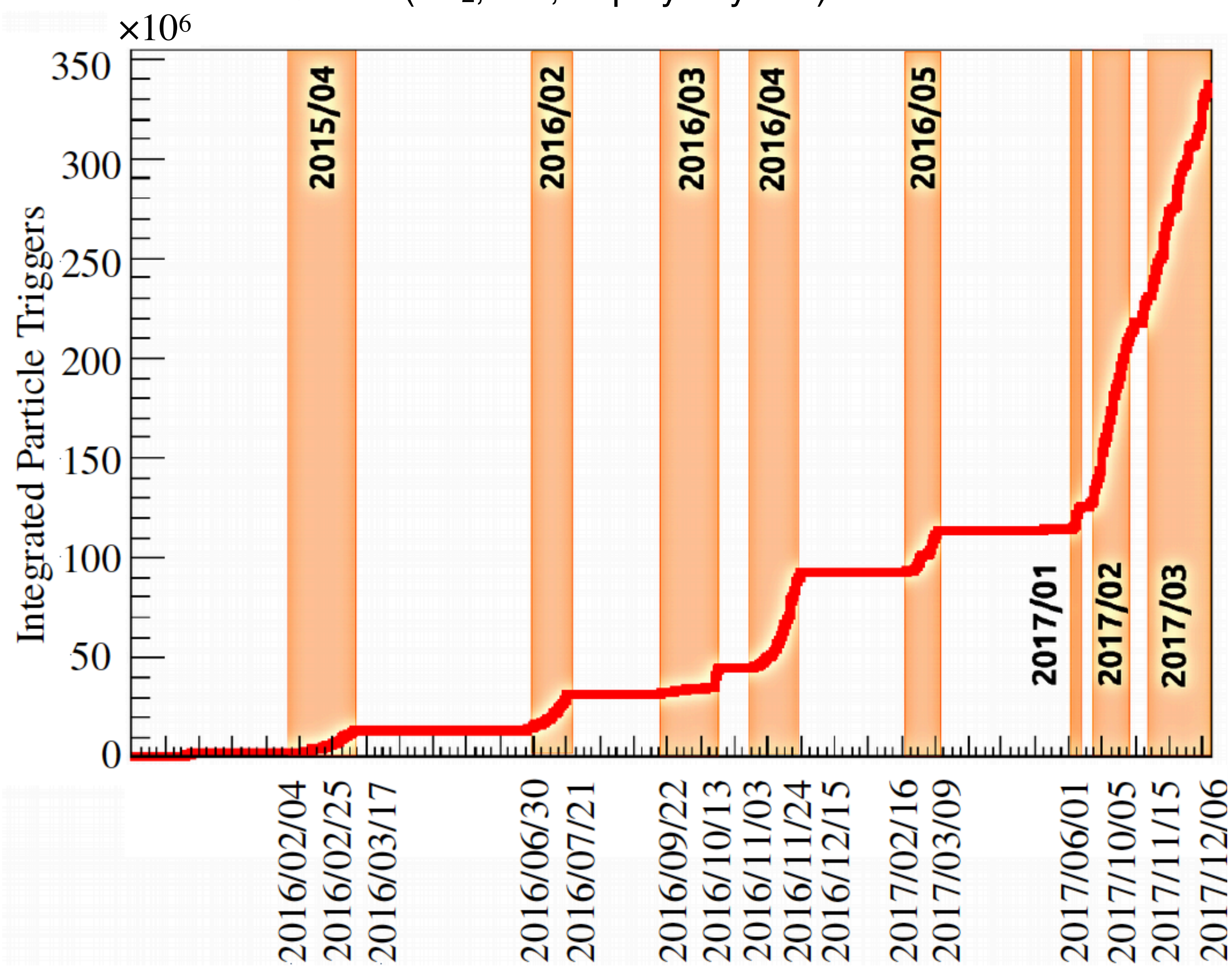
# MICE






- International collaboration of >100 scientists and engineers, from >30 institutions in 11 countries

- Successful data-taking campaign finished in 2017




- $3.5 \times 10^8$ triggers recorded

# Principles of MICE

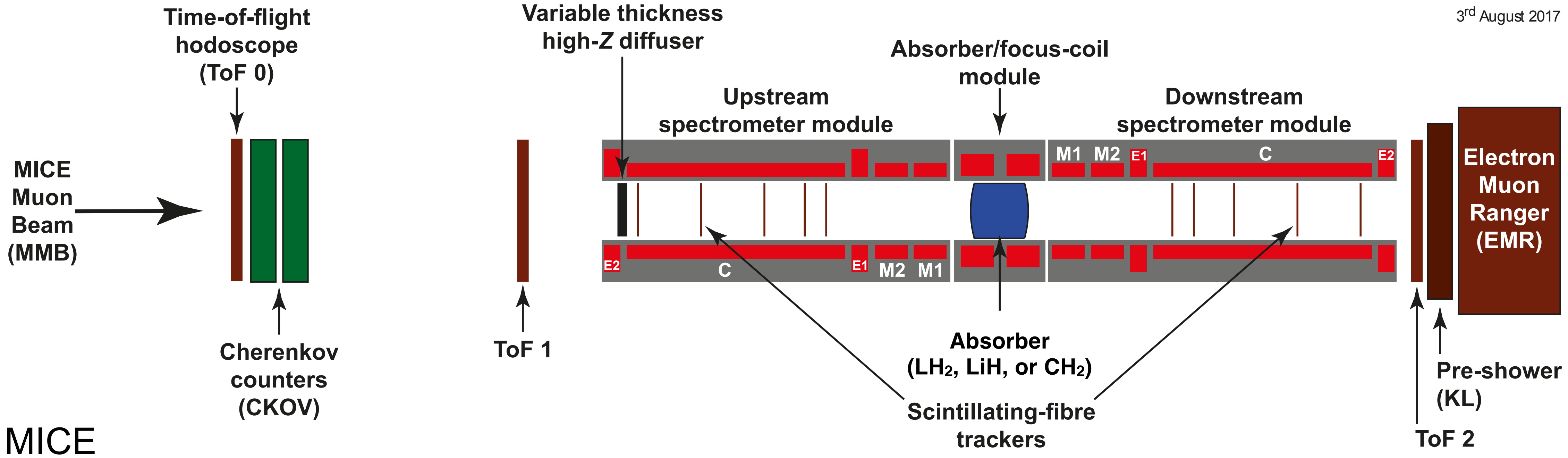
- Cost-effective: uses minimal cooling channel
  - proposed one cooling cell → ~10% cooling effect
    - in the end we built only a single "absorber–focus-coil" module → ~5% cooling effect
- Measure emittance with 0.1% precision
  - allows even small cooling effects near equilibrium emittance to be well measured

  ⇒ need to measure muon beam one muon at a time! (unlike typical accelerator-experiment ~10% precision)
- Vary all parameters to explore full performance range & validate simulation tools

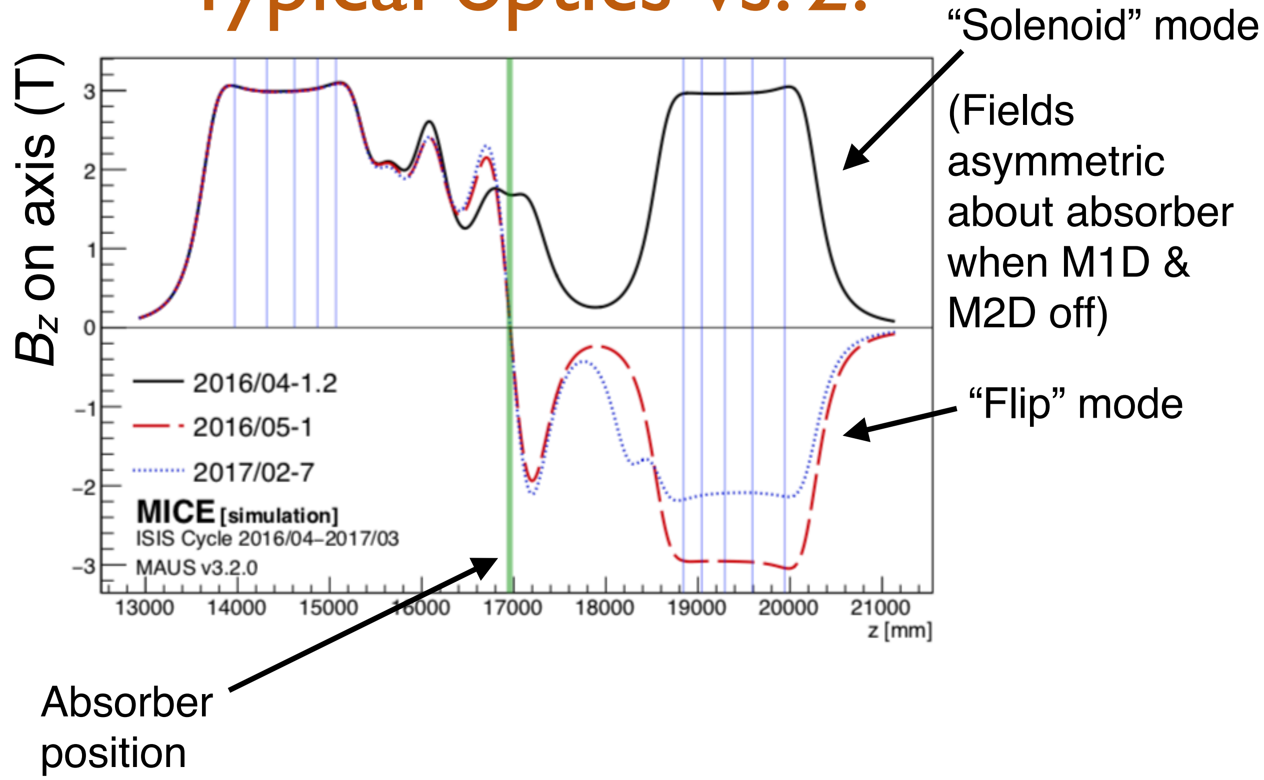
# Key Questions

- Can we safely operate liquid hydrogen absorbers?
- Can we operate such a tightly packed lattice?
- Do we see the expected emittance change?
- Do we see the expected beam transmission?

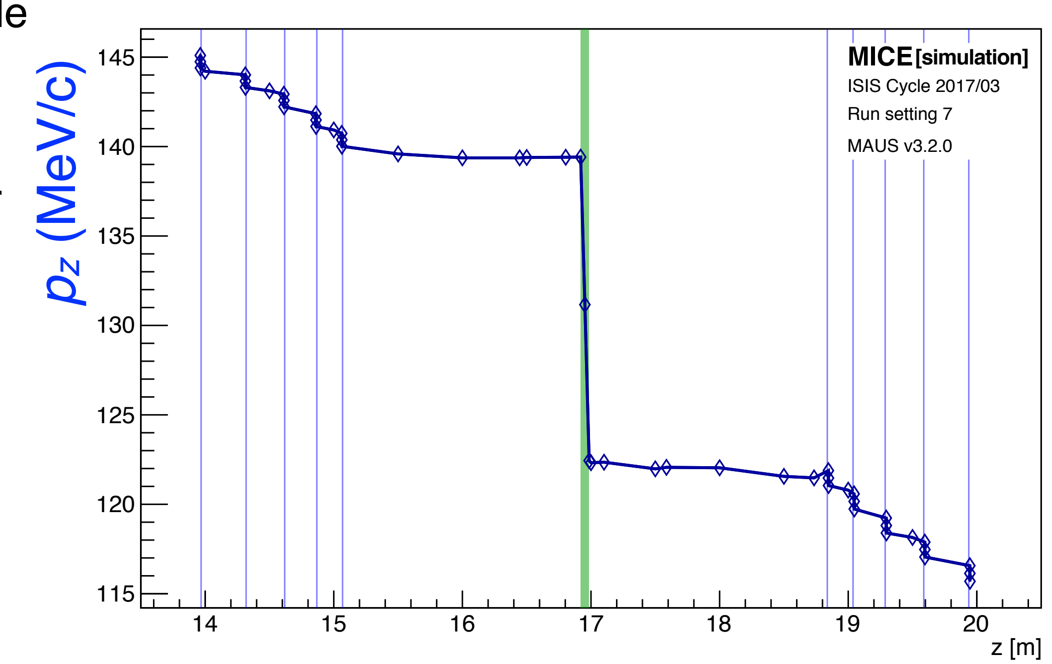
# Principles of MICE



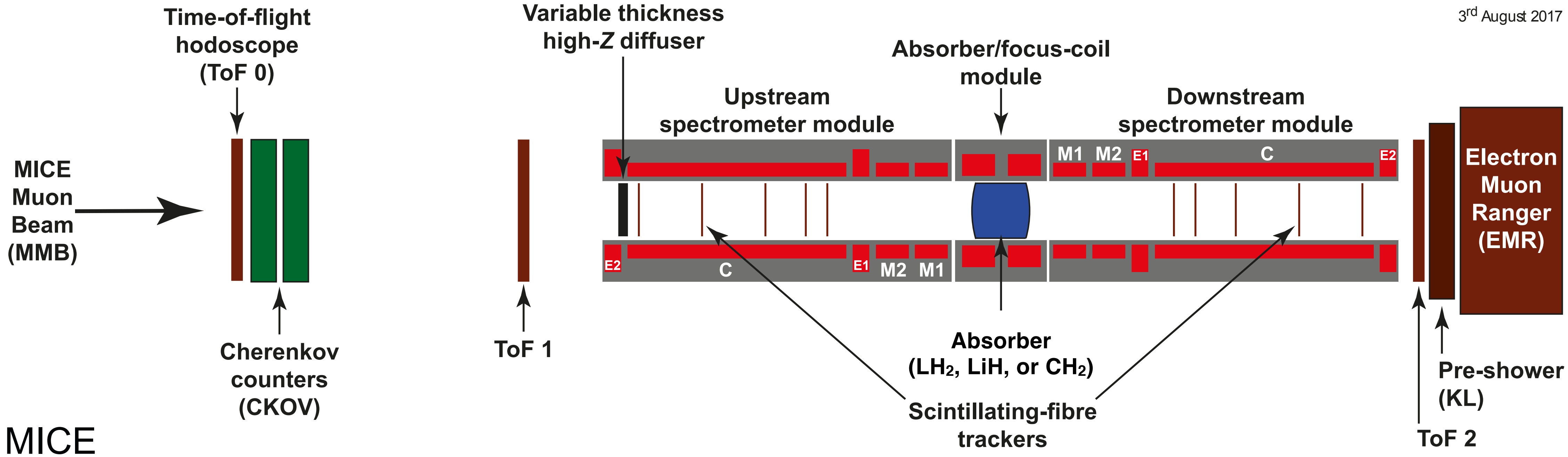

- Typical optics vs. z:




- Beam behavior vs. z:

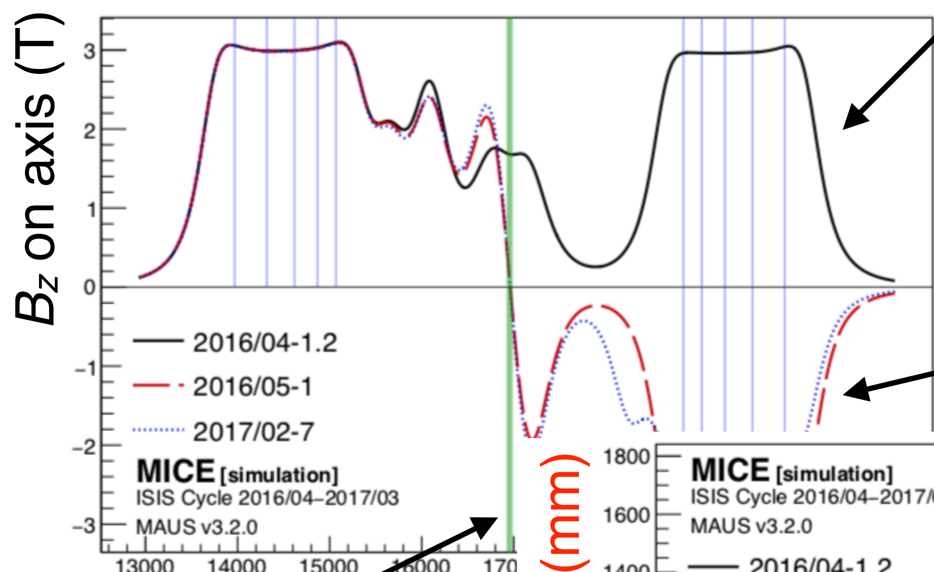


# Principles of MICE




MICE

- Typical optics vs. z:
- Beam behavior vs. z:

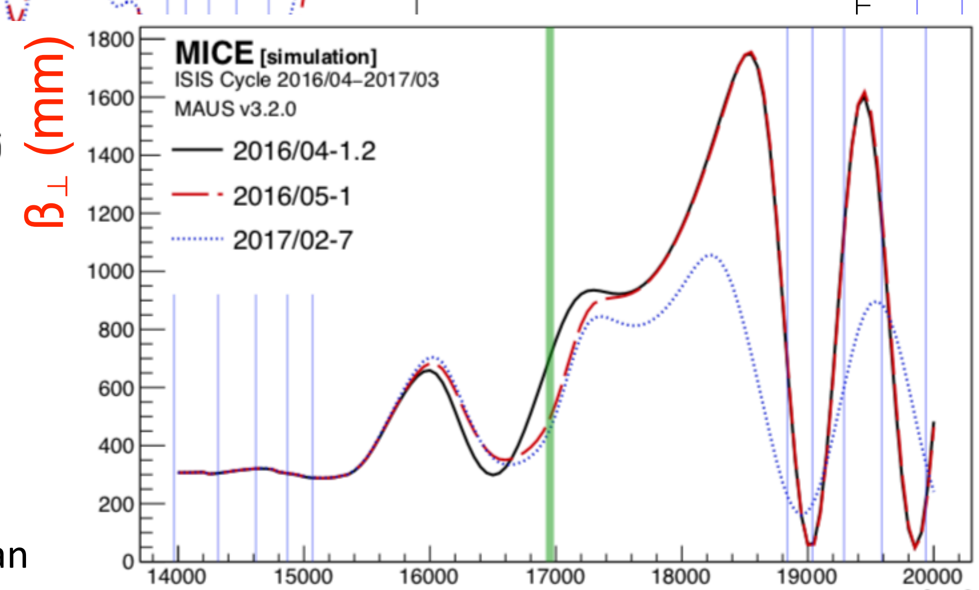


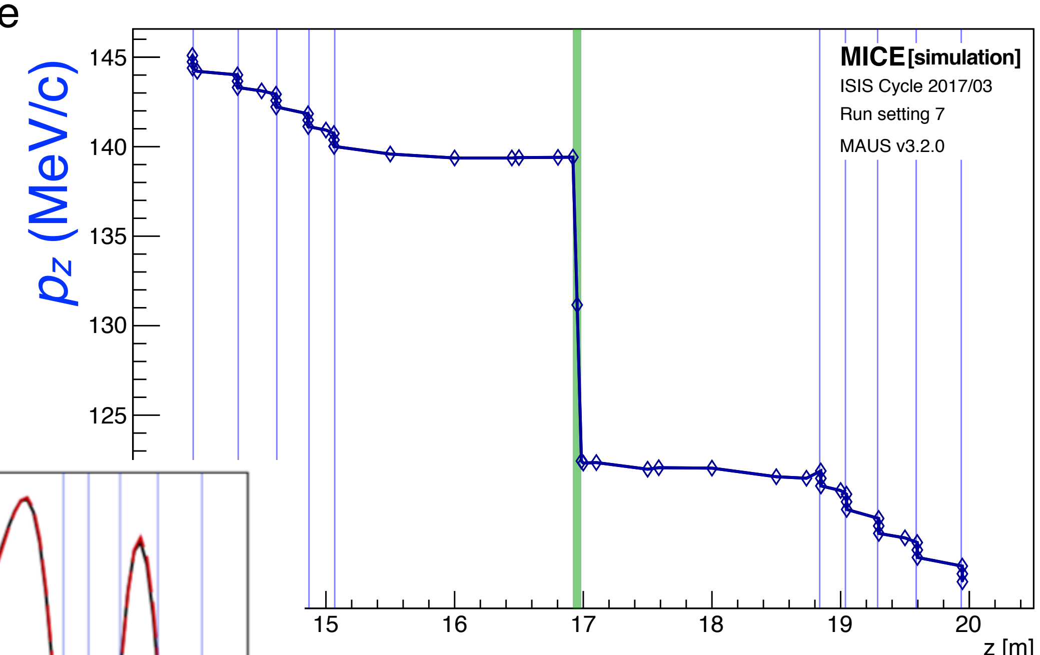

“Solenoid” mode

(Fields asymmetric about absorber when M1D & M2D off)

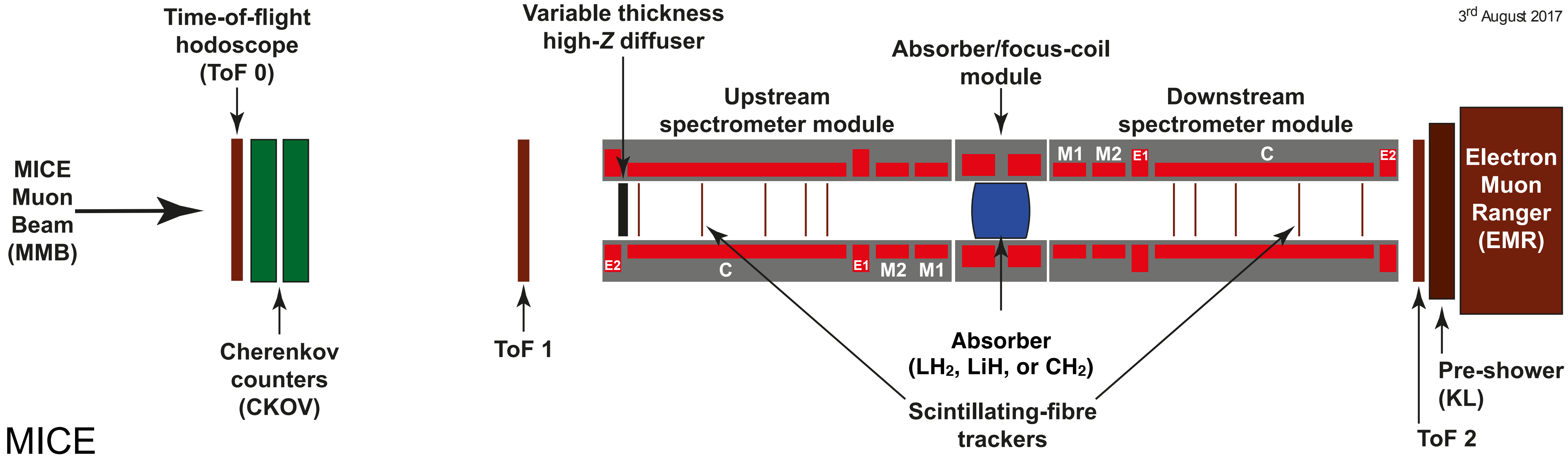
“Flip” mode

Absorber position



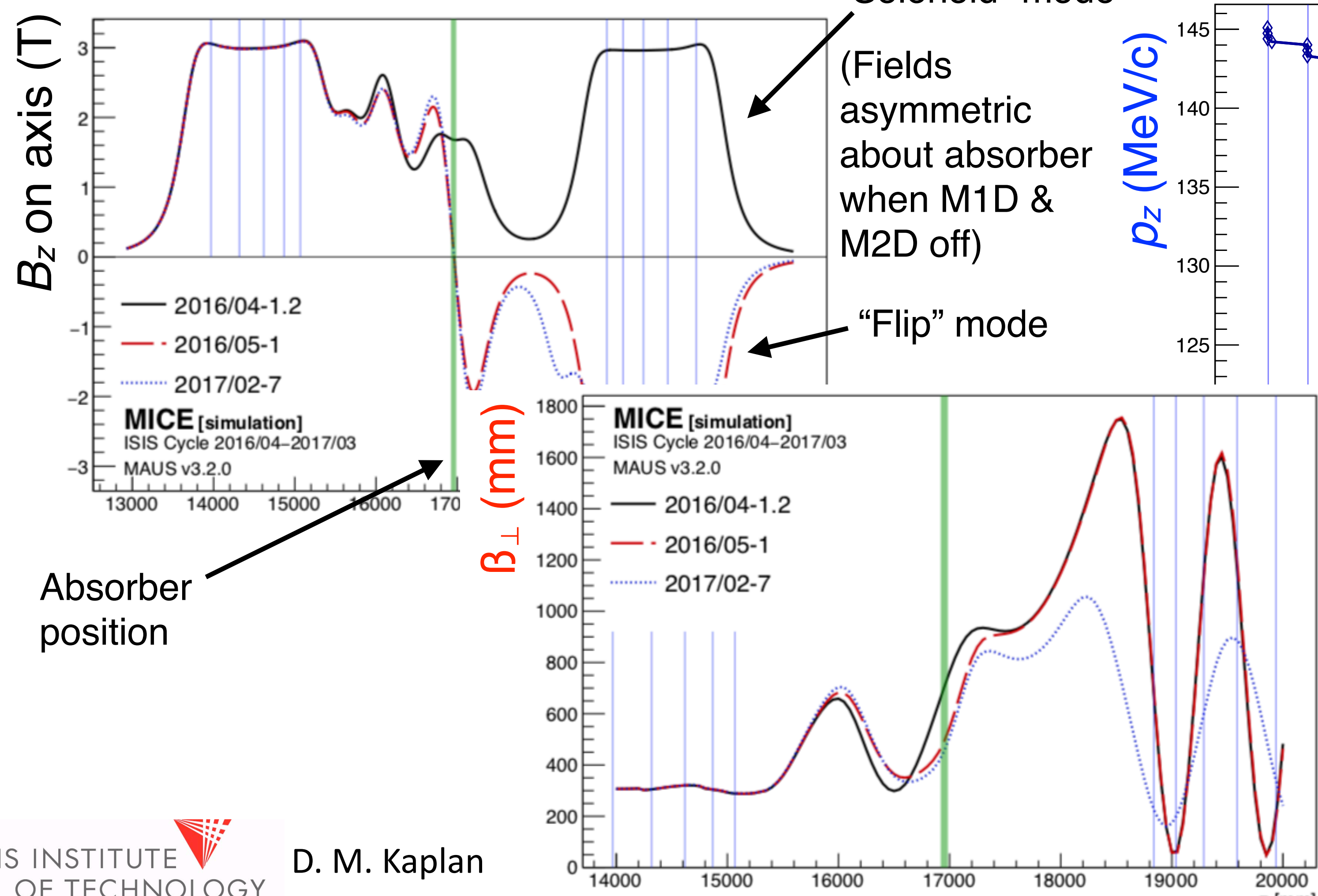



# Principles of MICE




MICE

- Typical optics vs. z:



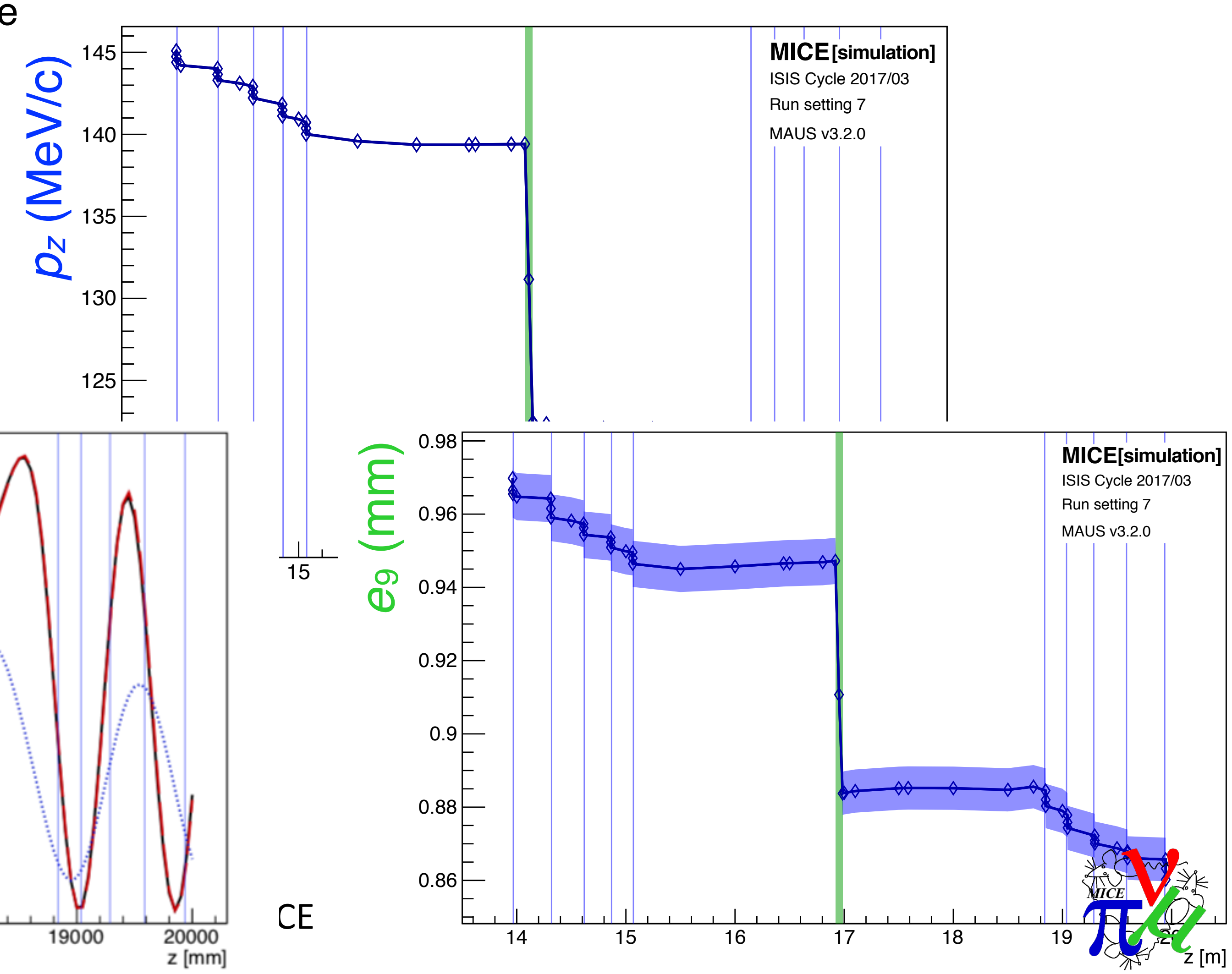

"Solenoid" mode

(Fields asymmetric about absorber when M1D & M2D off)

"Flip" mode

Absorber position

- Beam behavior vs. z:

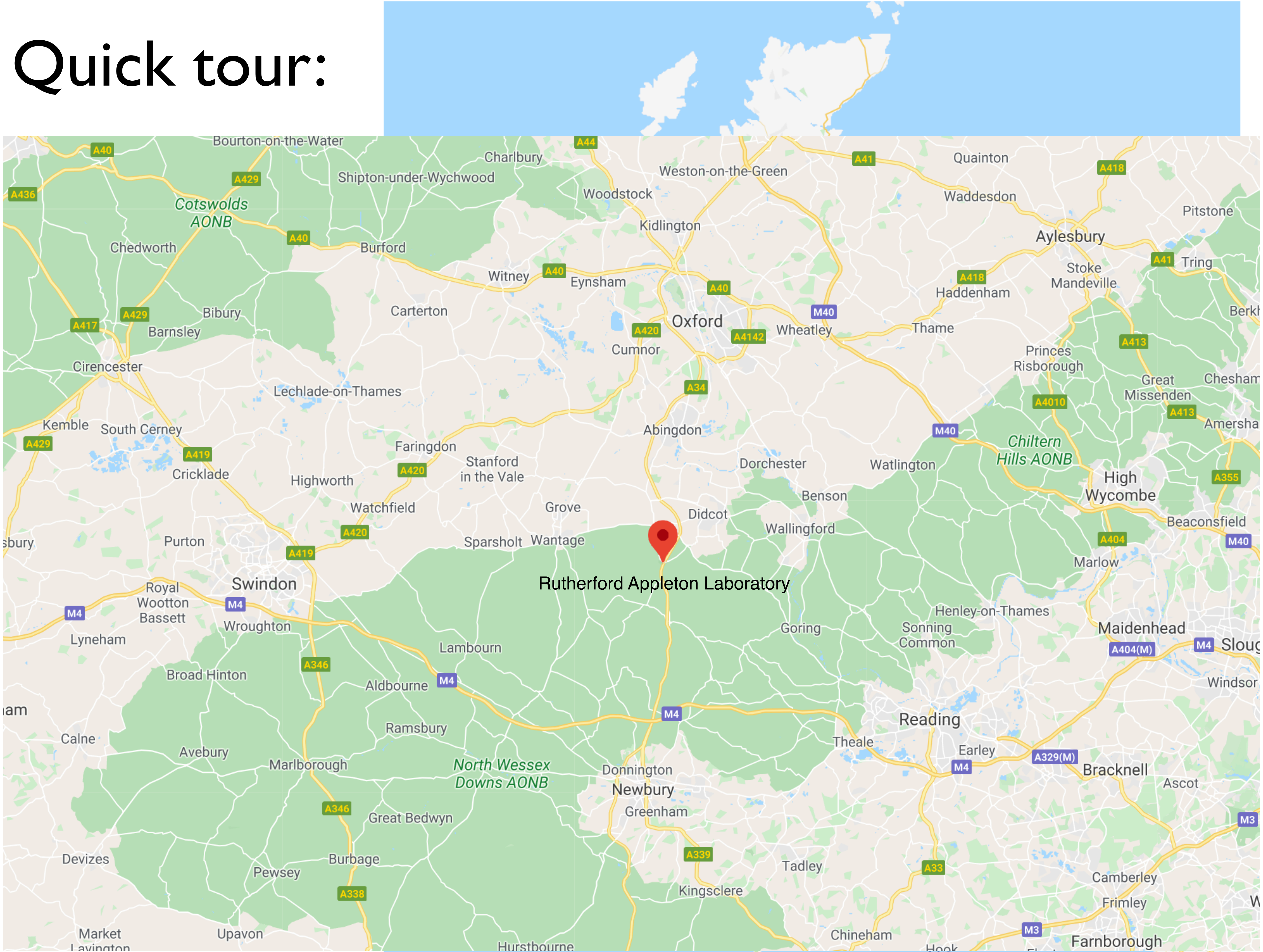


# MICE Apparatus

- Quick tour:

# MICE Apparatus

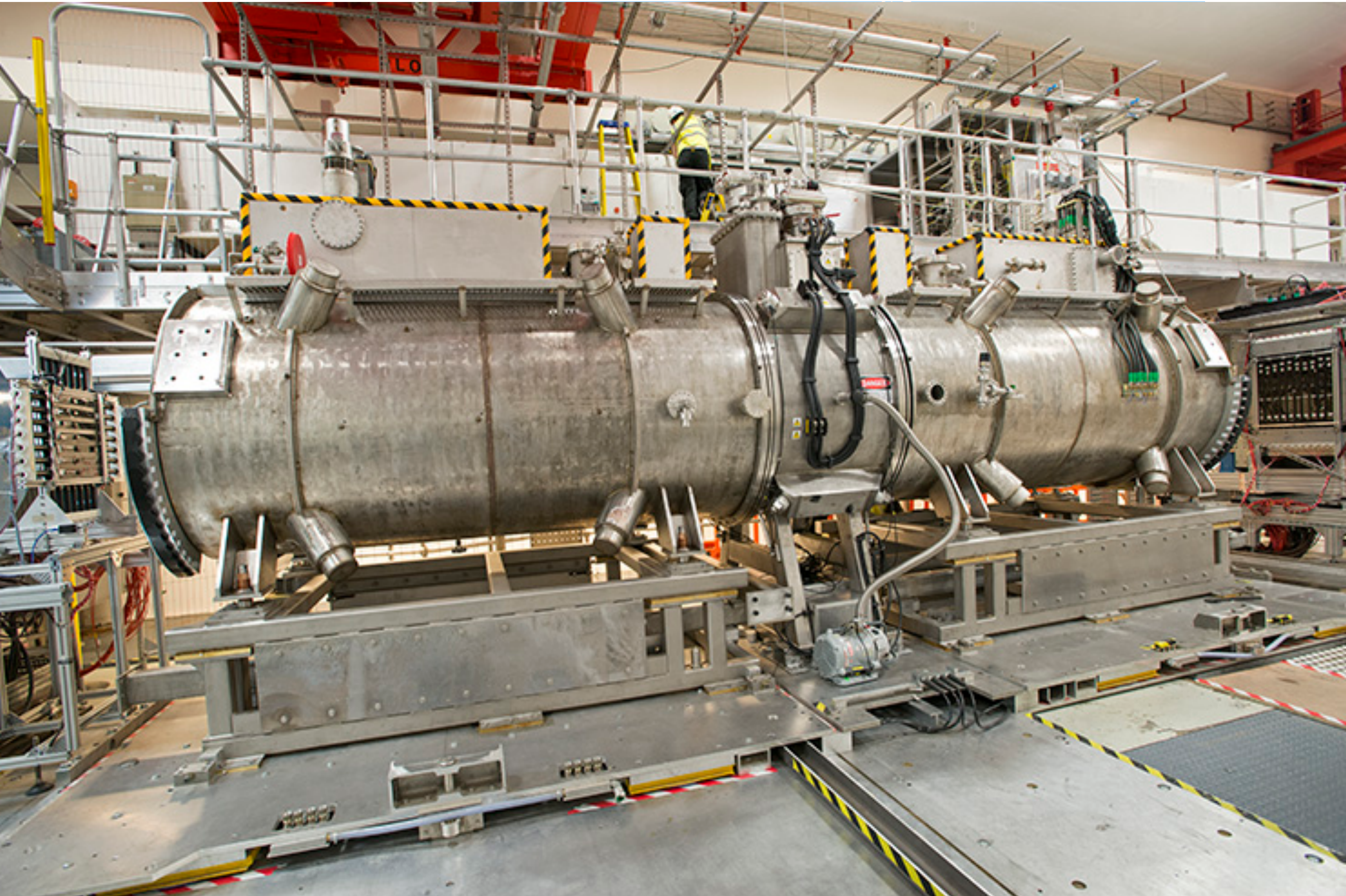
- Quick tour:



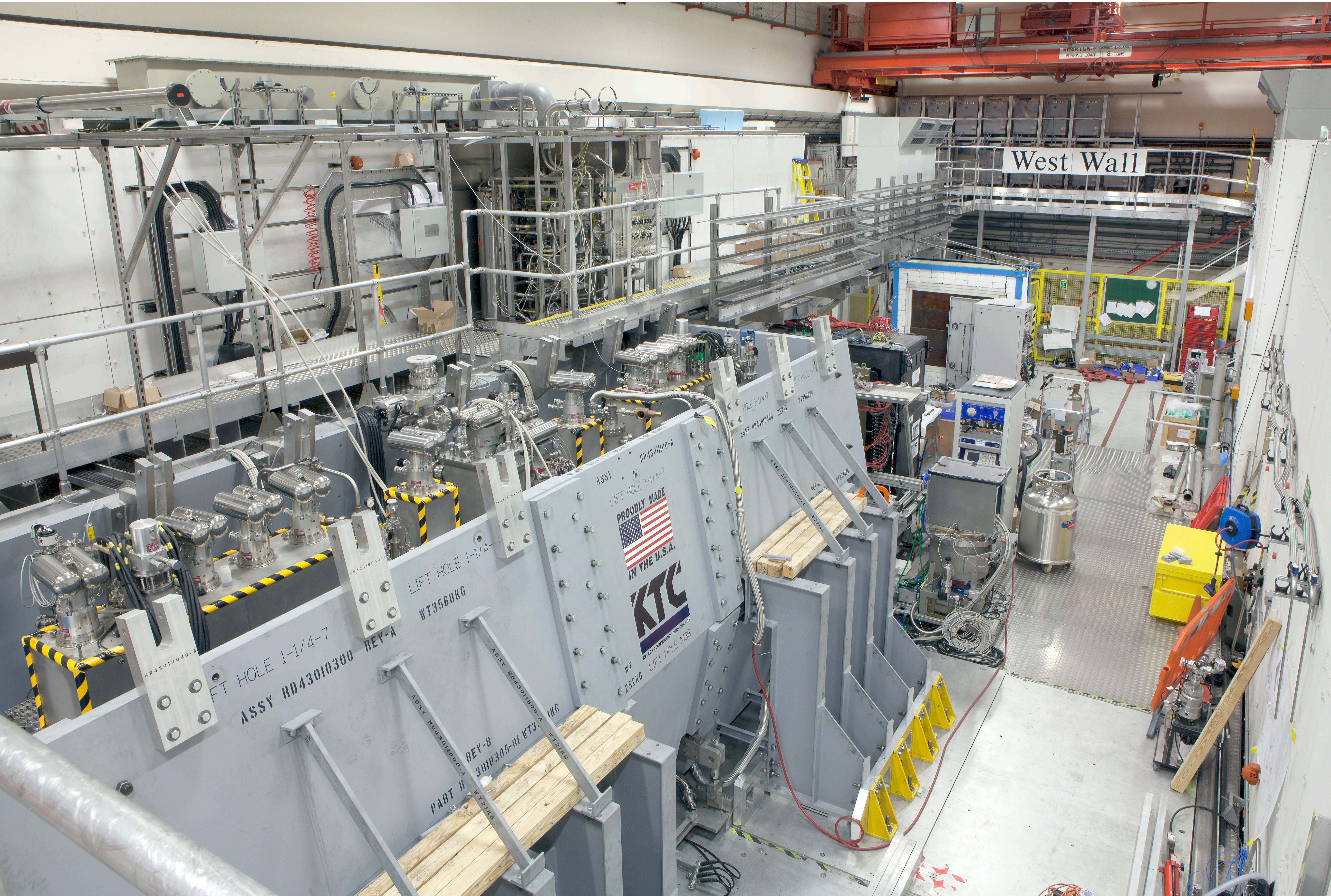
# MICE Apparatus

- Quick tour:

# MICE Apparatus



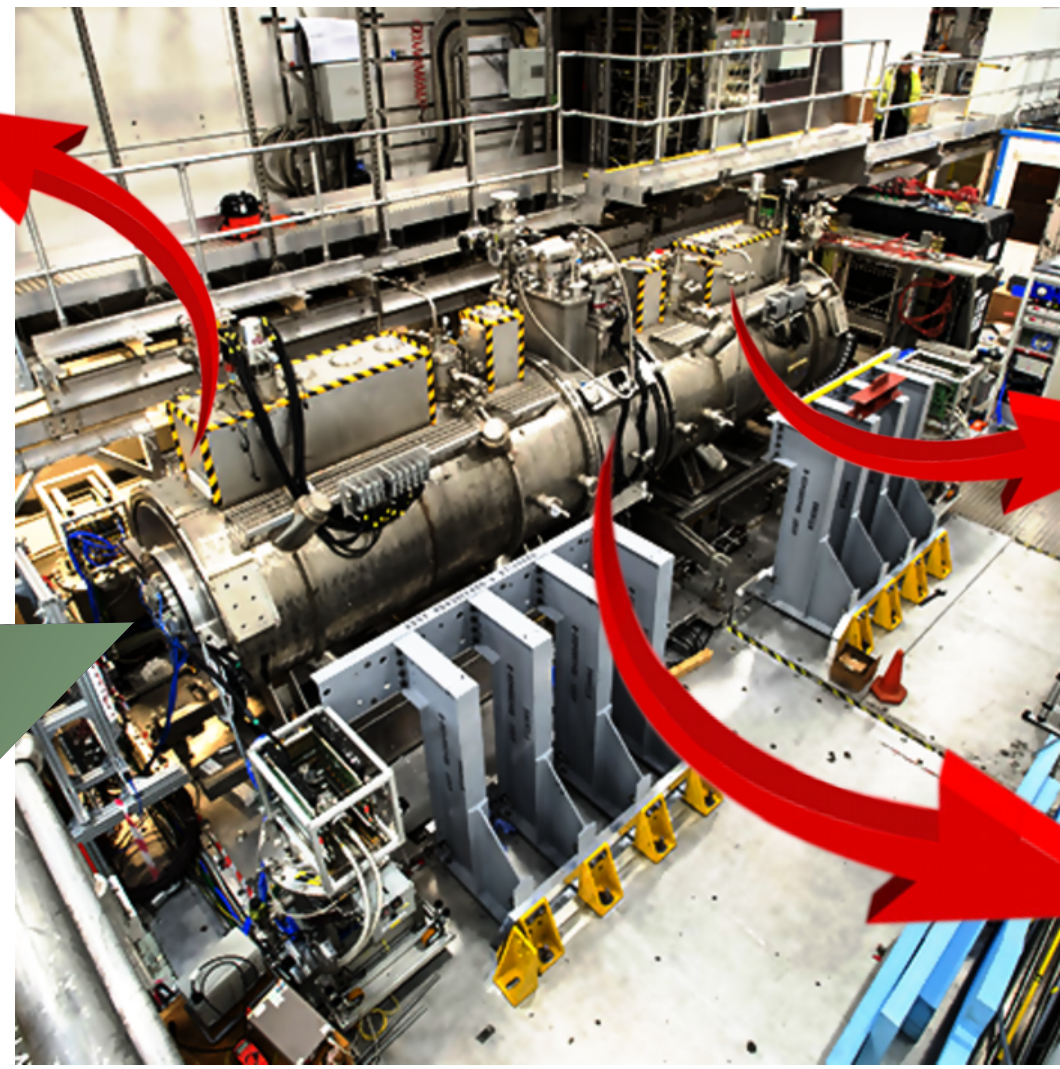
# MICE Apparatus



# What It Does

**Measure** muon position and momentum upstream

Beam



**Measure** muon position and momentum downstream

**Cool** the muon beam using LiH, $LH_2$, or polyethylene wedge absorbers

# Beam Characterization

- Muon-beam emittance determined from measured individual-muon positions & momenta

# Beam Characterization

- Muon-beam emittance determined from measured individual-muon positions & momenta
  - 4D transverse phase-space of muons: ($x$, $p_x$, $y$, $p_y$ )

→ normalized RMS transverse emittance:

$$\varepsilon_n = \frac{\sqrt[4]{|\Sigma_4 D|}}{mc}$$

$\Sigma_4$: 4D covariance matrix of coordinates

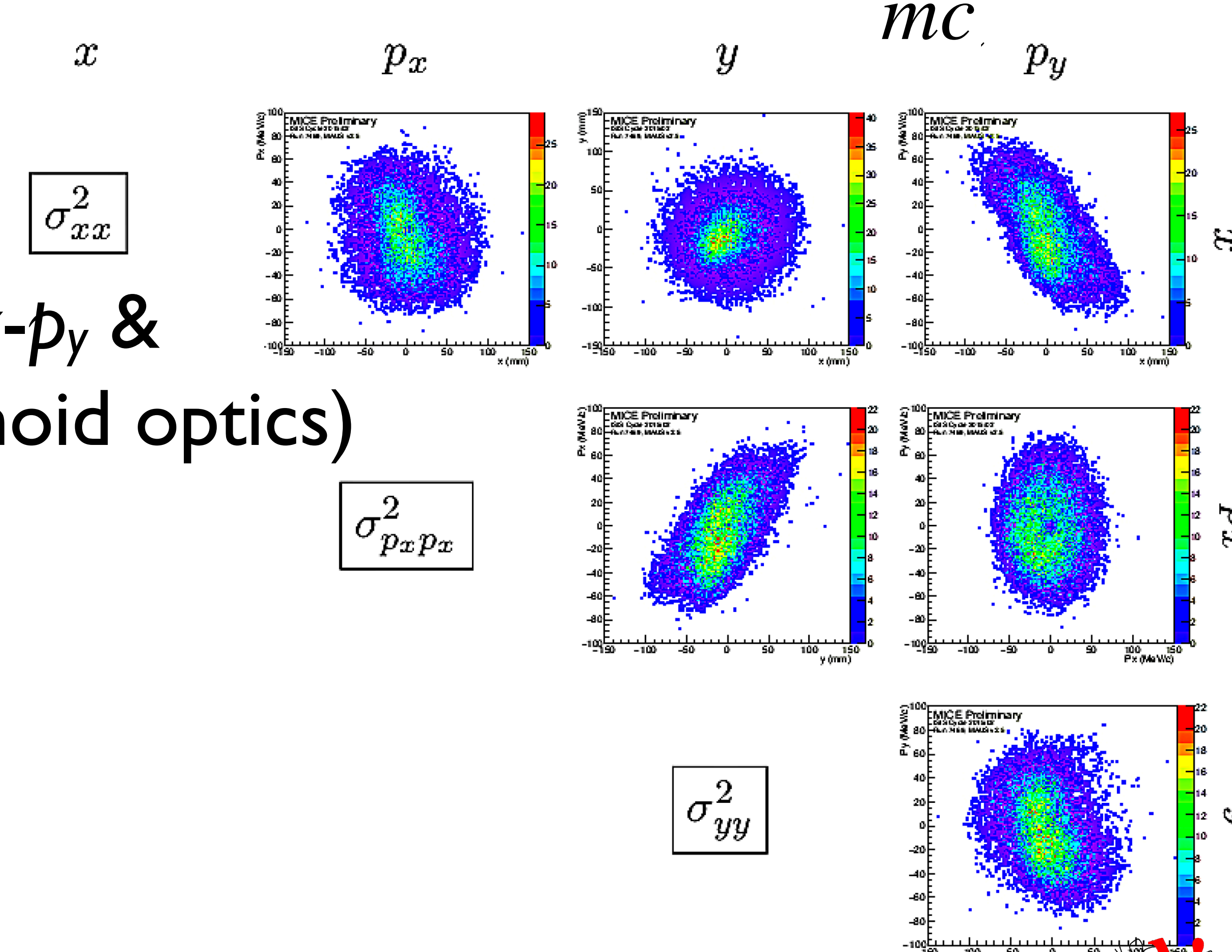
# Beam Characterization

- Muon-beam emittance determined from measured individual-muon positions & momenta
  - 4D transverse phase-space of muons: ($x$, $p_x$, $y$, $p_y$ )

→ normalized RMS transverse emittance: $$\varepsilon_n = \frac{\sqrt[4]{|\Sigma_4 D|}}{mc}$$

$\Sigma_4$: 4D covariance matrix of coordinates

(phase-space distributions $x$-$p_y$ & $y$-$p_x$ correlated due to solenoid optics)

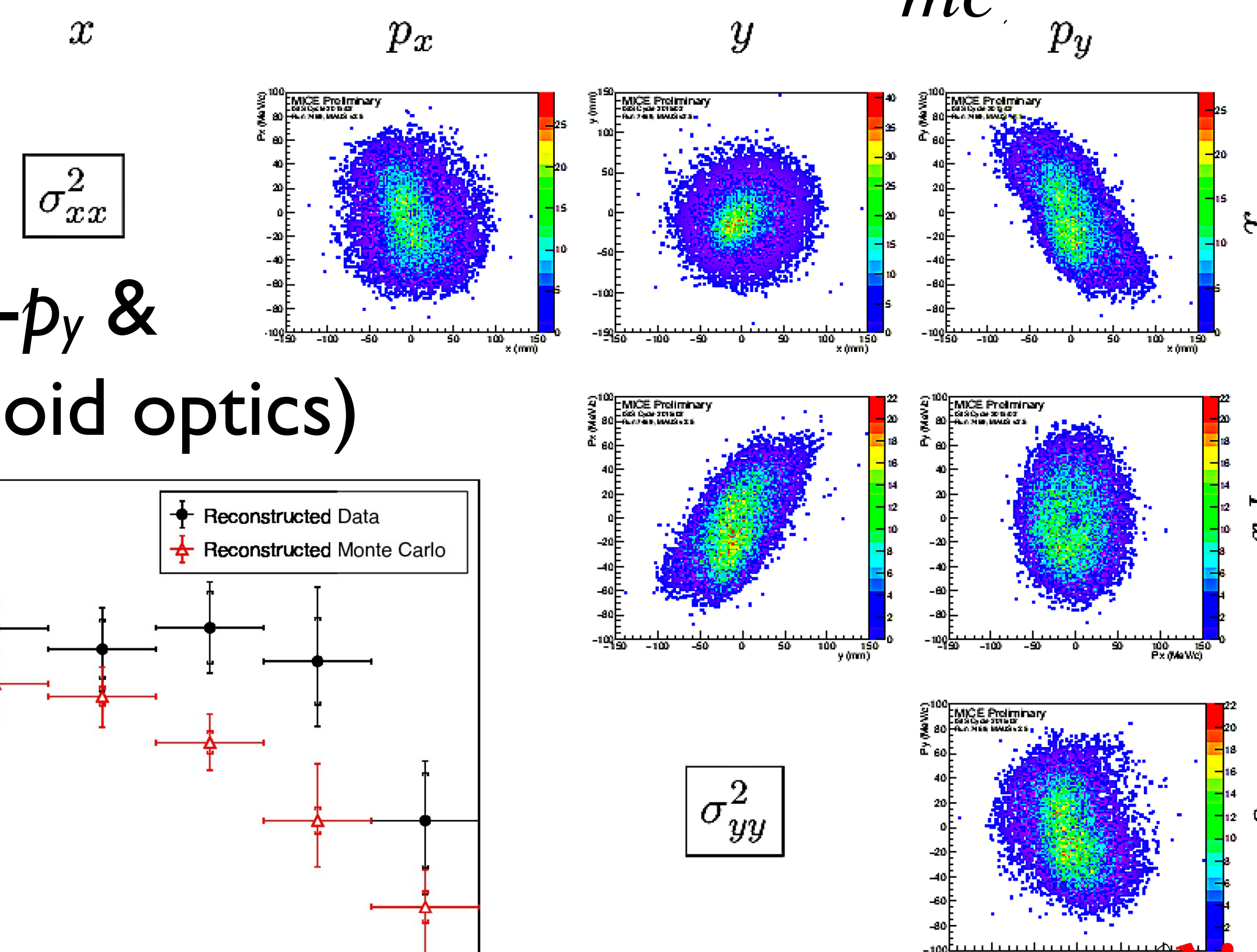


# Beam Characterization

- Muon-beam emittance determined from measured individual-muon positions & momenta
  - 4D transverse phase-space of muons: $(x, p_x, y, p_y)$

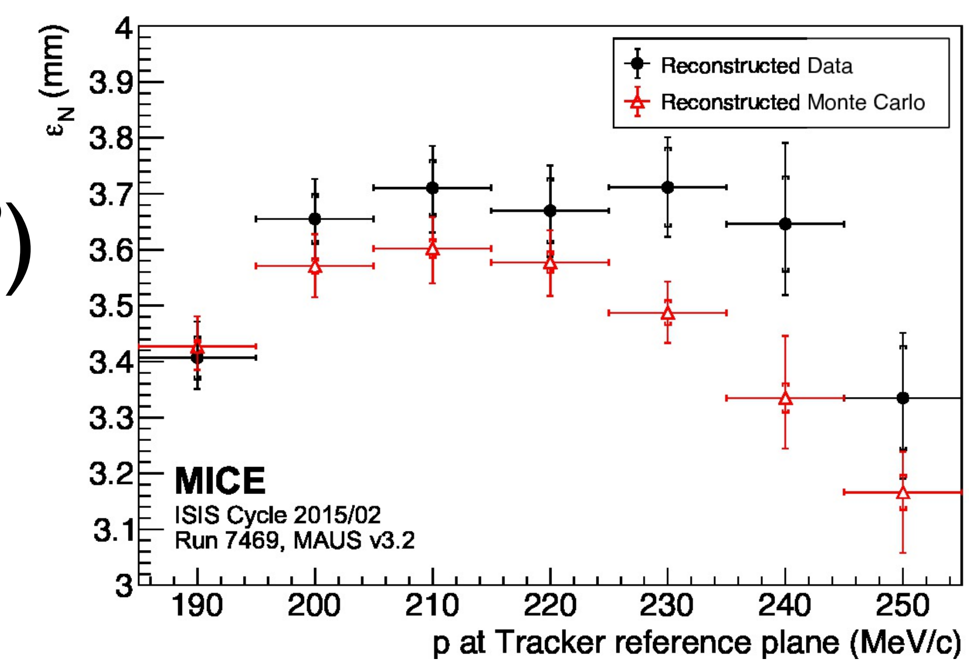
$\rightarrow$ normalized RMS transverse emittance: $$\varepsilon_n = \frac{\sqrt[4]{|\Sigma_4 D|}}{mc}$$

$\Sigma_4$: 4D covariance matrix of coordinates



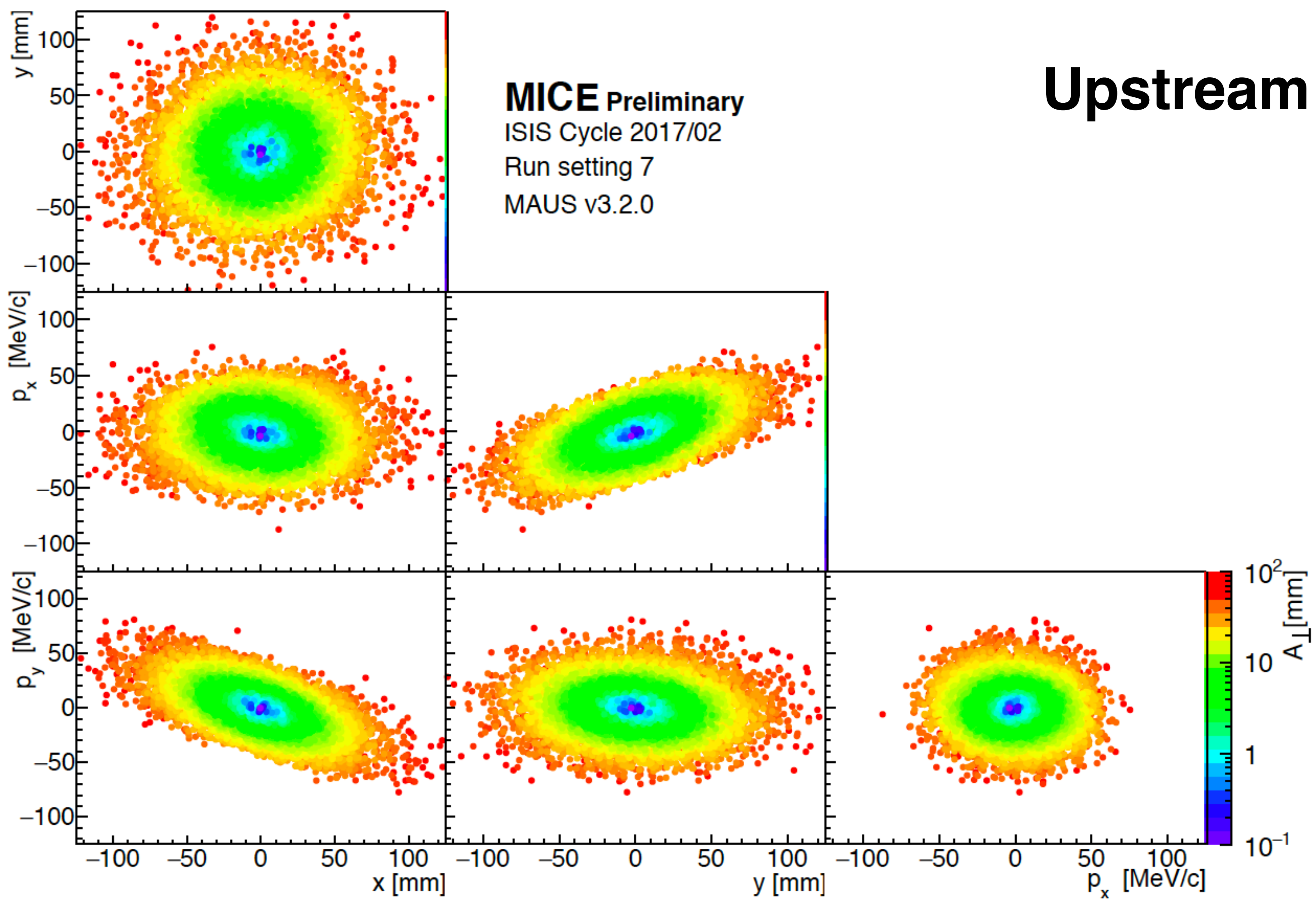

(phase-space distributions $x$-$p_y$ & $y$-$p_x$ correlated due to solenoid optics)

  - give $\varepsilon_n$ vs. $p_z$ in typical ("3 mm") beam setting



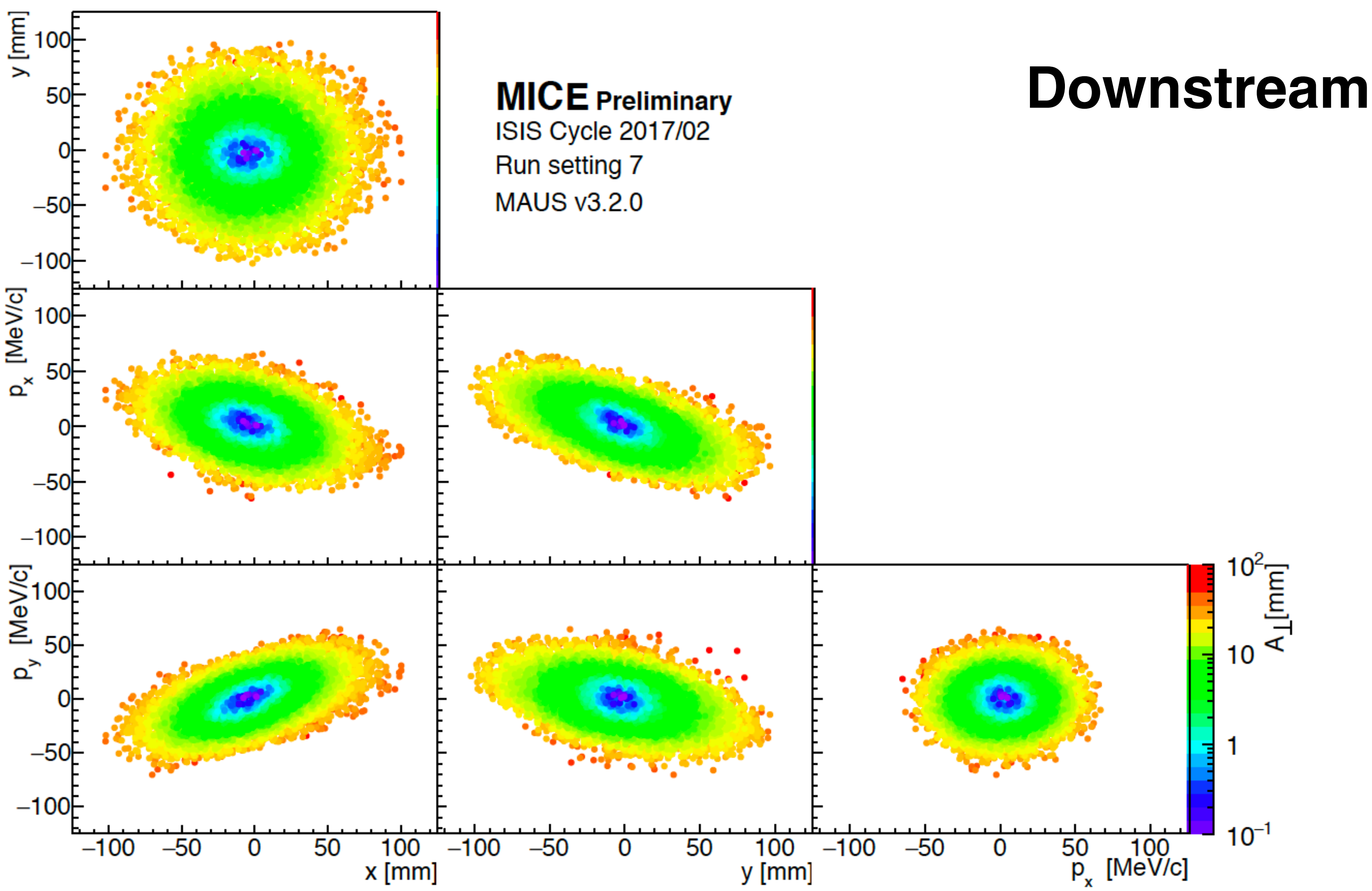
# Cooling Measurements

- Since we know *each muon's* coordinates, can compute individual-muon *amplitudes*
  - 4D distance of each muon from beam center
  - more informative than emittance



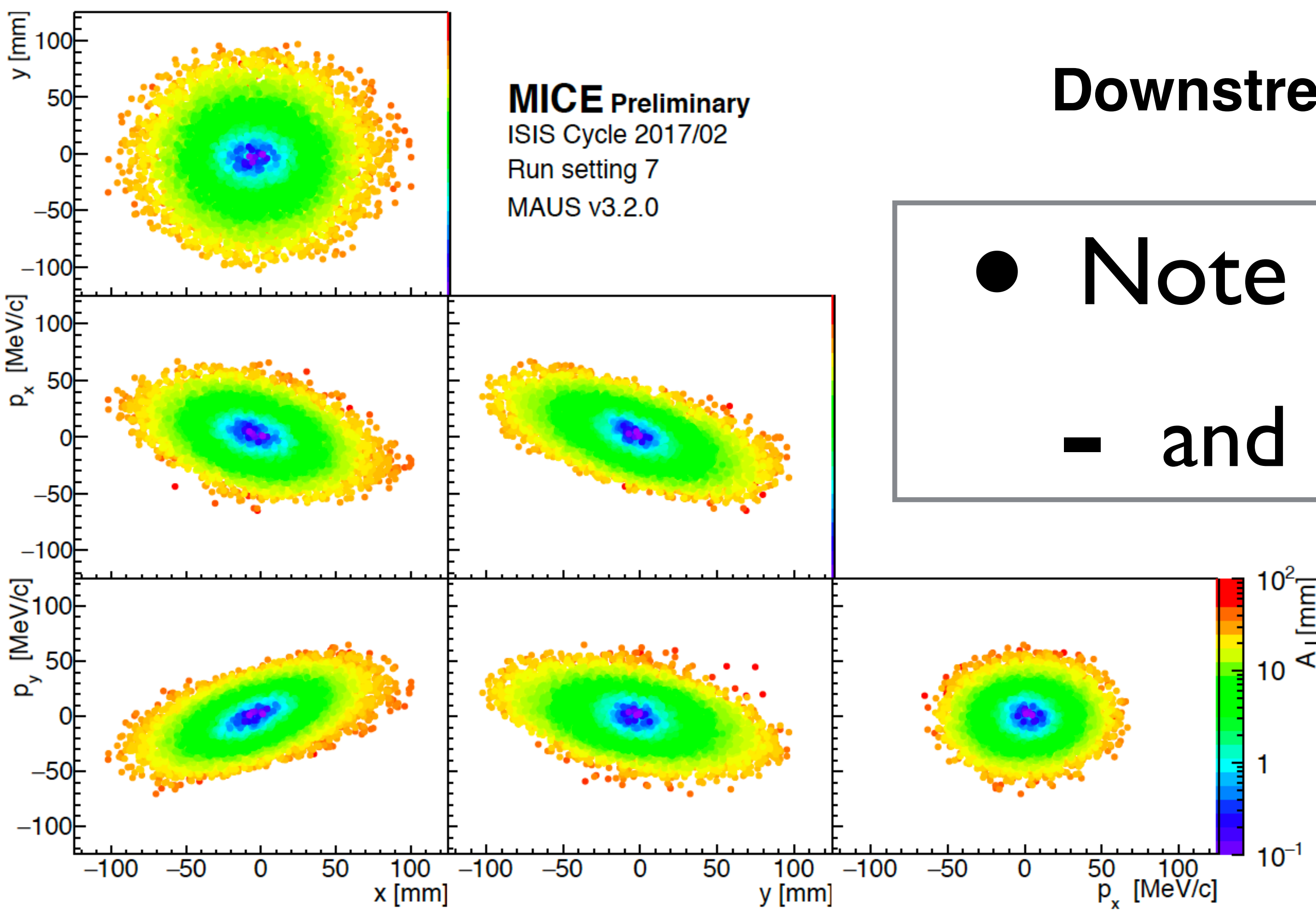
# Cooling Measurements

- Since we know *each muon's* coordinates, can compute individual-muon *amplitudes*
  - 4D distance of each muon from beam center
  - more informative than emittance



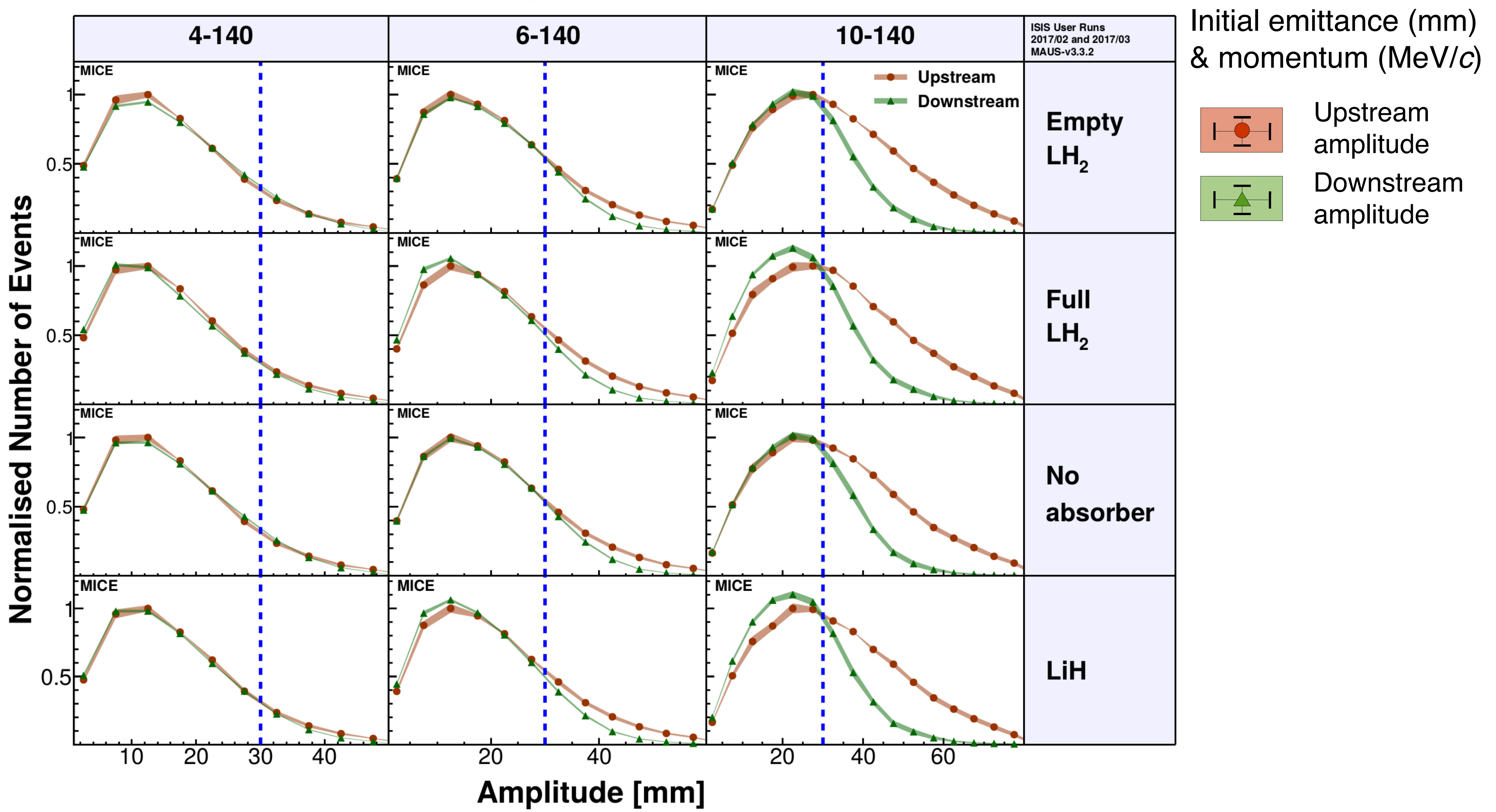
# Cooling Measurements

- Since we know *each muon's* coordinates, can compute individual-muon *amplitudes*
  - 4D distance of each muon from beam center
  - more informative than emittance




- Note cooling of beam core
  - and scraping of tails

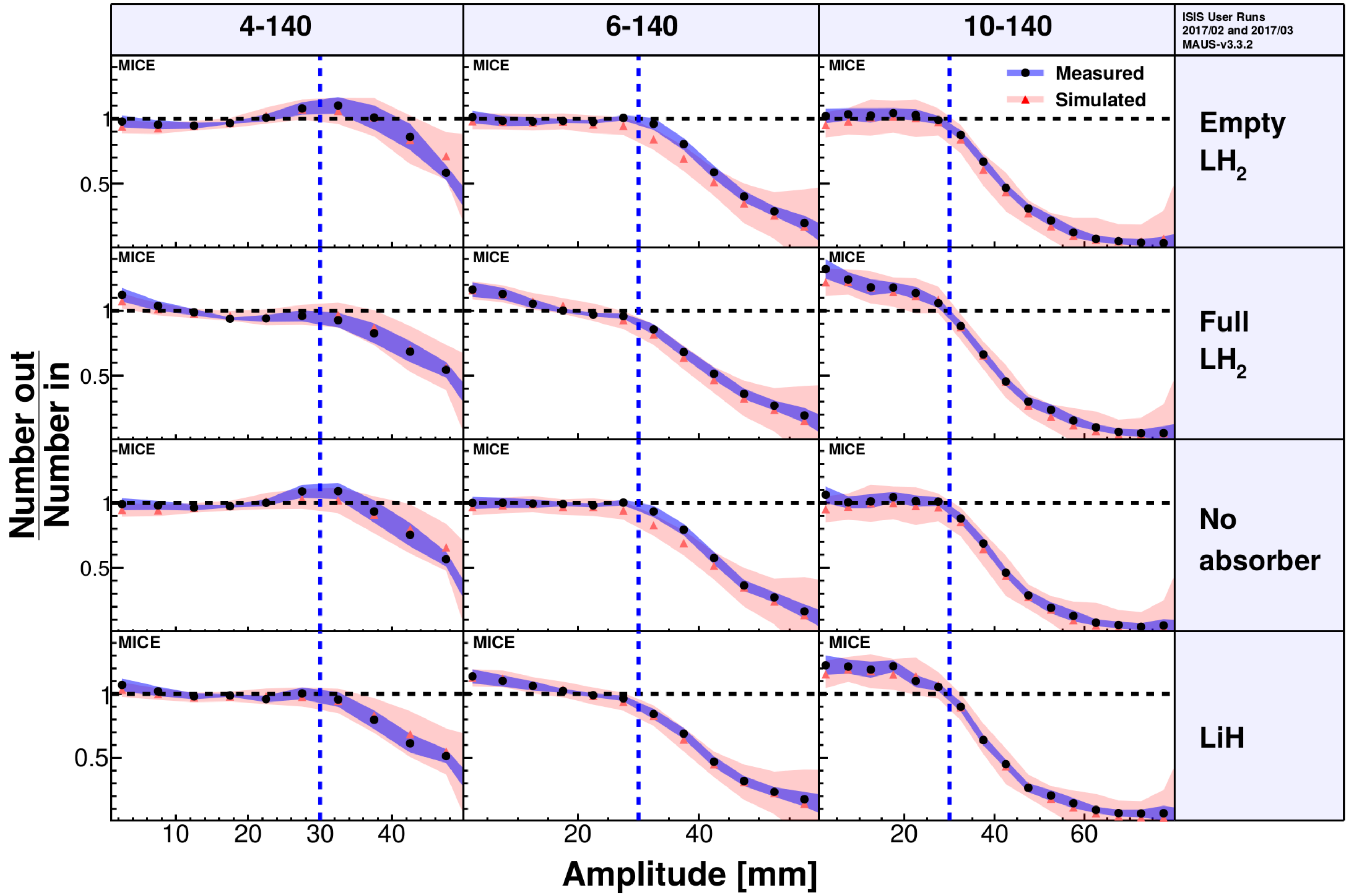
# Change in Amplitude Distribution




- No absorber → no change in number of core muons
- With absorber → increase in number of core muons
- Bigger initial emittance (beam size) → bigger increase

➡ cooling signal

# Ratio of Amplitude Distributions




- Core density increase for $LH_2$ and LiH absorber → cooling
- More cooling for higher initial emittances

➡ observed cooling signal agrees with simulation

# Key Questions

- Can we safely operate liquid hydrogen absorbers?
- Can we operate such a tightly packed lattice?
- Do we see the expected emittance change?
- Do we see the expected beam transmission?

# Key Questions

- Can we safely operate liquid hydrogen absorbers? √
- Can we operate such a tightly packed lattice?
- Do we see the expected emittance change?
- Do we see the expected beam transmission?

# Key Questions

- Can we safely operate liquid hydrogen absorbers? √
- Can we operate such a tightly packed lattice? √
- Do we see the expected emittance change?
- Do we see the expected beam transmission?

# Key Questions

- Can we safely operate liquid hydrogen absorbers? √
- Can we operate such a tightly packed lattice? √
- Do we see the expected emittance change? √
- Do we see the expected beam transmission?

# Key Questions

- Can we safely operate liquid hydrogen absorbers? √
- Can we operate such a tightly packed lattice? √
- Do we see the expected emittance change? √
- Do we see the expected beam transmission? √

# Key Questions

- Can we safely operate liquid hydrogen absorbers? √
- Can we operate such a tightly packed lattice? √
- Do we see the expected emittance change? √
- Do we see the expected beam transmission? √

**(More detailed presentation on MICE by Yagmur Torun at Fermilab Accelerator Physics and Technology Seminar, 3/2/20)**

# Conclusions

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above $\tau$ threshold & low-*E* systematics

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above $\tau$ threshold & low-*E* systematics

- High-luminosity Muon Collider looks feasible

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

  → most sensitive way to study neutrino mixing?

    - & only practical way to get above $\tau$ threshold & low-$E$ systematics

- High-luminosity Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above $\tau$ threshold & low-$E$ systematics

- High-luminosity Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way!

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above $\tau$ threshold & low-$E$ systematics

- High-luminosity Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way!

- First results from MICE validate efficacy of ionization cooling; more detailed results on the way

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above $\tau$ threshold & low-*E* systematics

- High-luminosity Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way!
- First results from MICE validate efficacy of ionization cooling; more detailed results on the way
  - eliminate last in-principle obstacle to high-brightness muon accelerators

# Conclusions

- $10^{21}$ ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc. (2011), arXiv:1112.2853 [hep-ex]

→ most sensitive way to study neutrino mixing?

  - & only practical way to get above *τ* threshold & low-*E* systematics

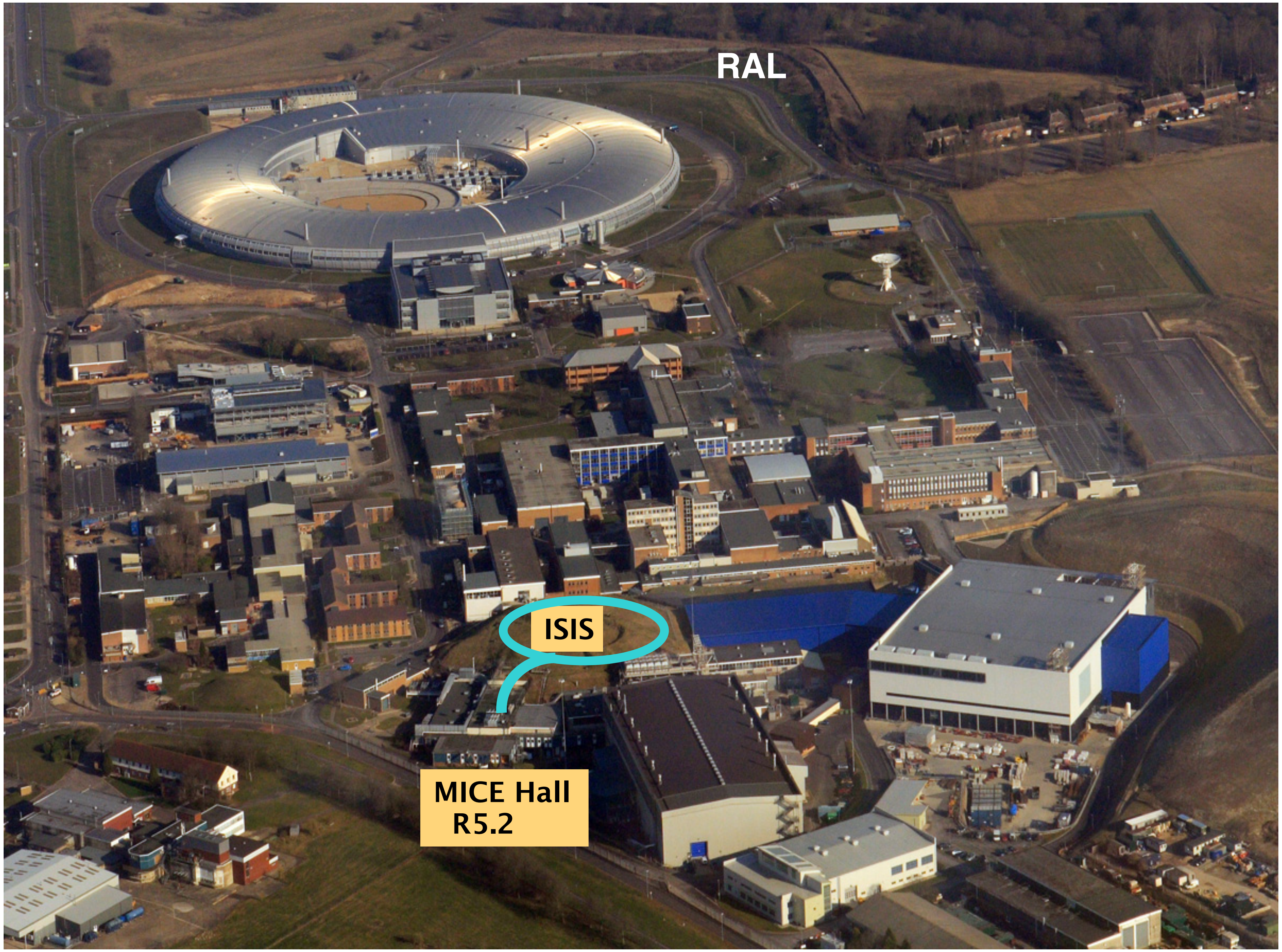
- High-luminosity Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way!
- First results from MICE validate efficacy of ionization cooling; more detailed results on the way
  - eliminate last in-principle obstacle to high-brightness muon accelerators

➡ such machines can be designed & built with confidence

# Backups

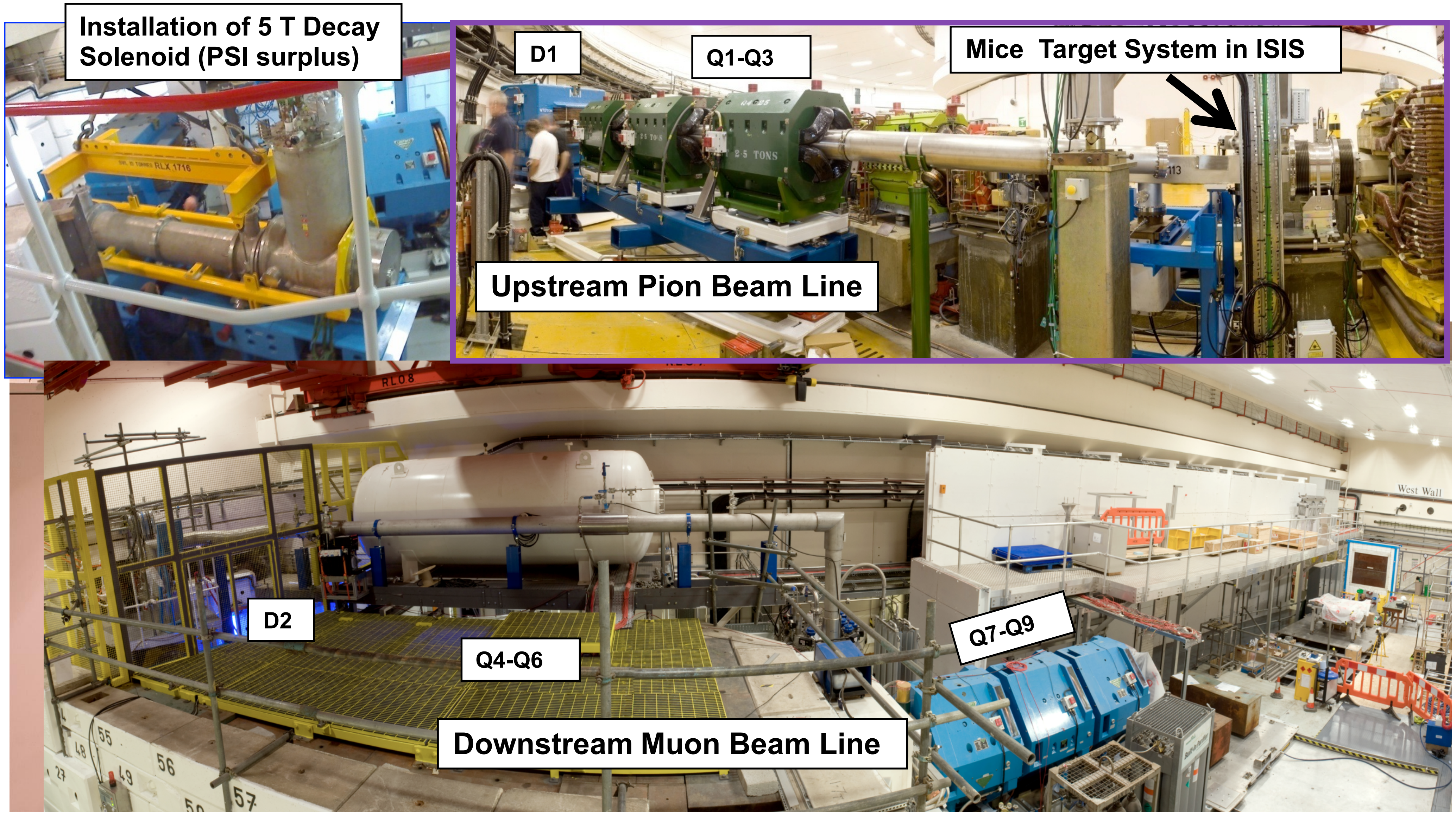
# MICE Apparatus

- Quick tour:



# MICE Apparatus

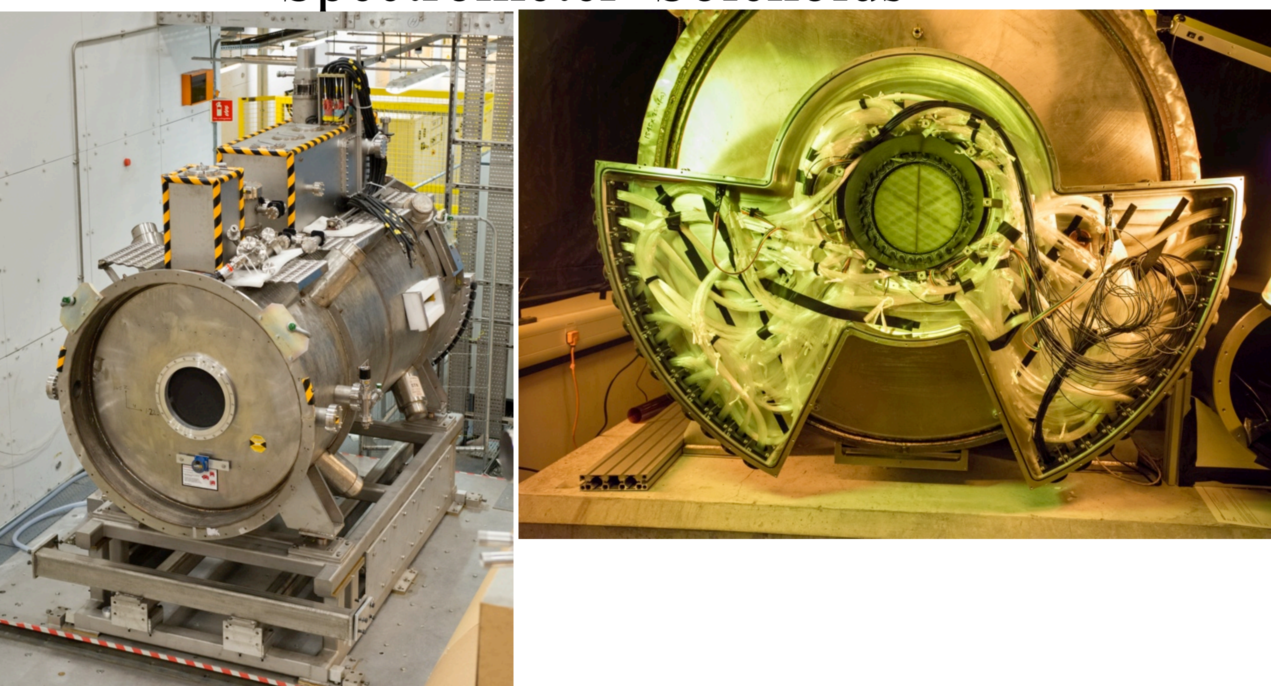
- Quick tour:



# MICE Apparatus

- Quick tour:

Spectrometer Solenoids

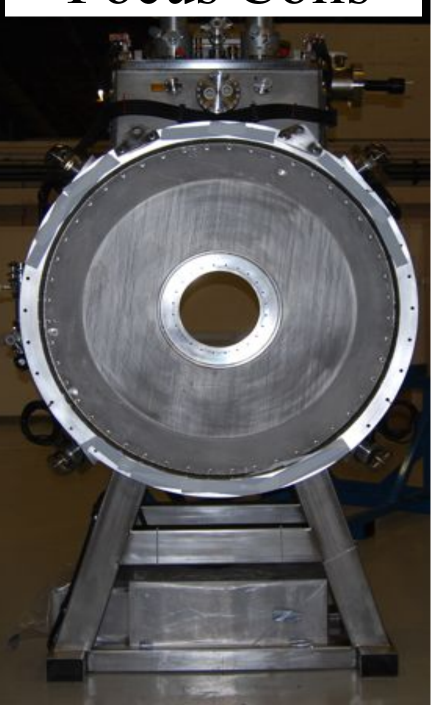


SciFi Trackers

Diffuser

KL & EMR

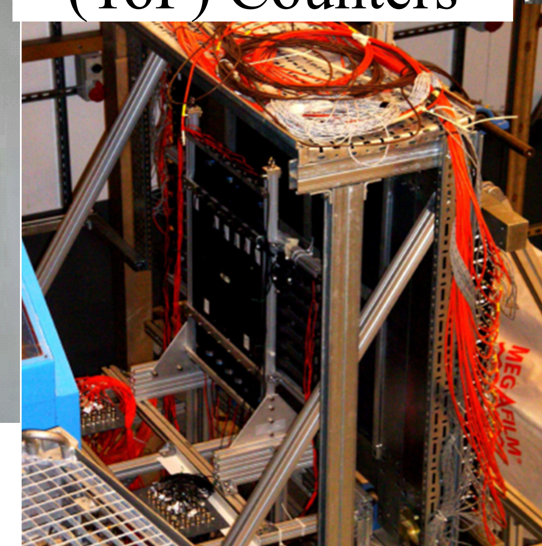
Focus Coils



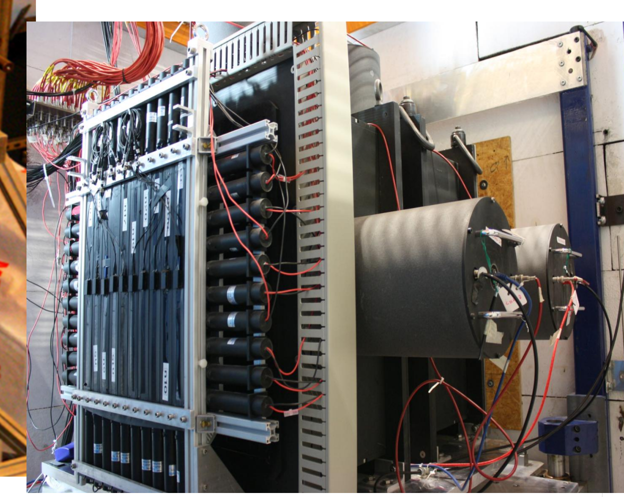
LiH Absorber

$LH_2$ Absorber

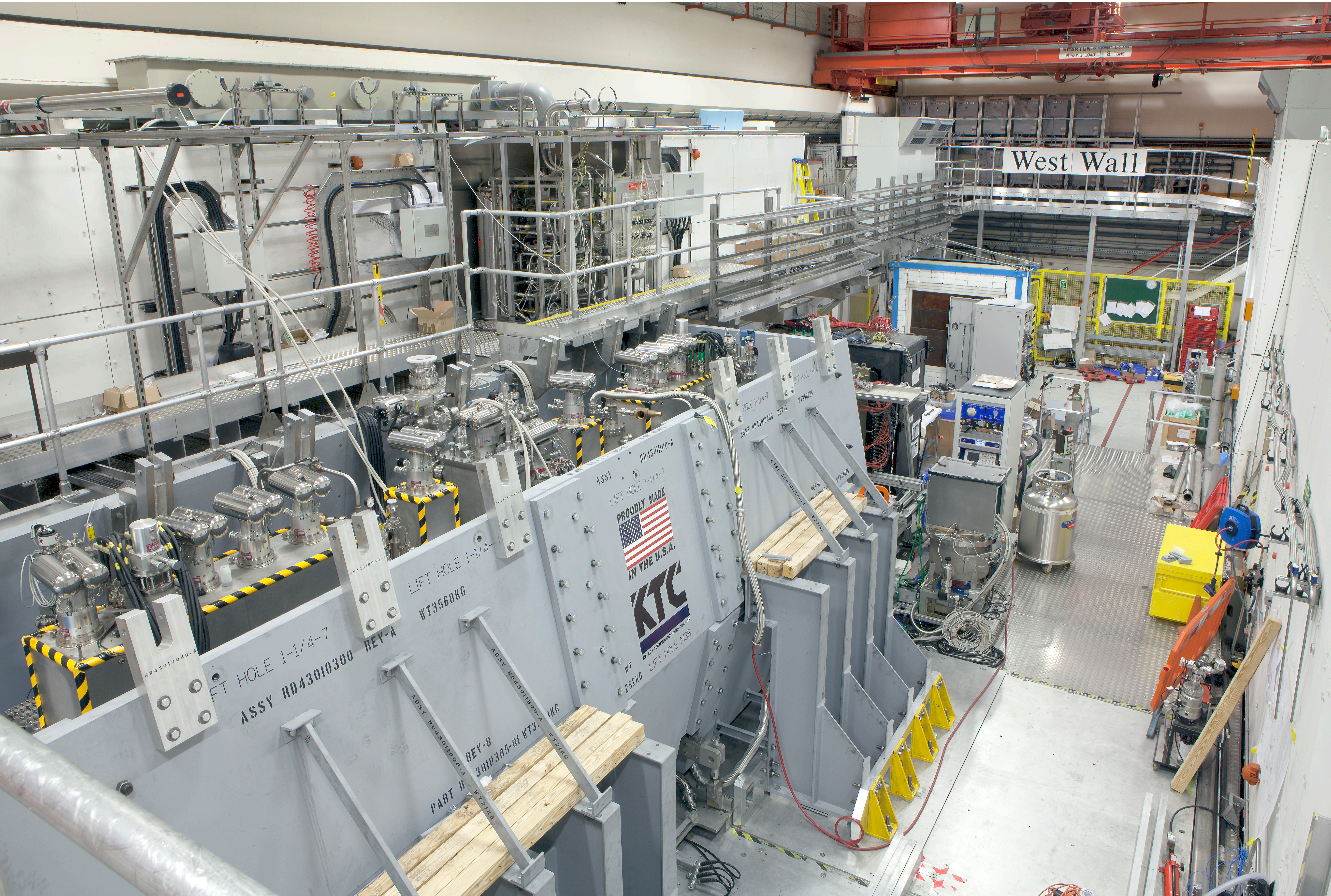
Time-of-Flight (ToF) Counters



ToF & Ckov Counters



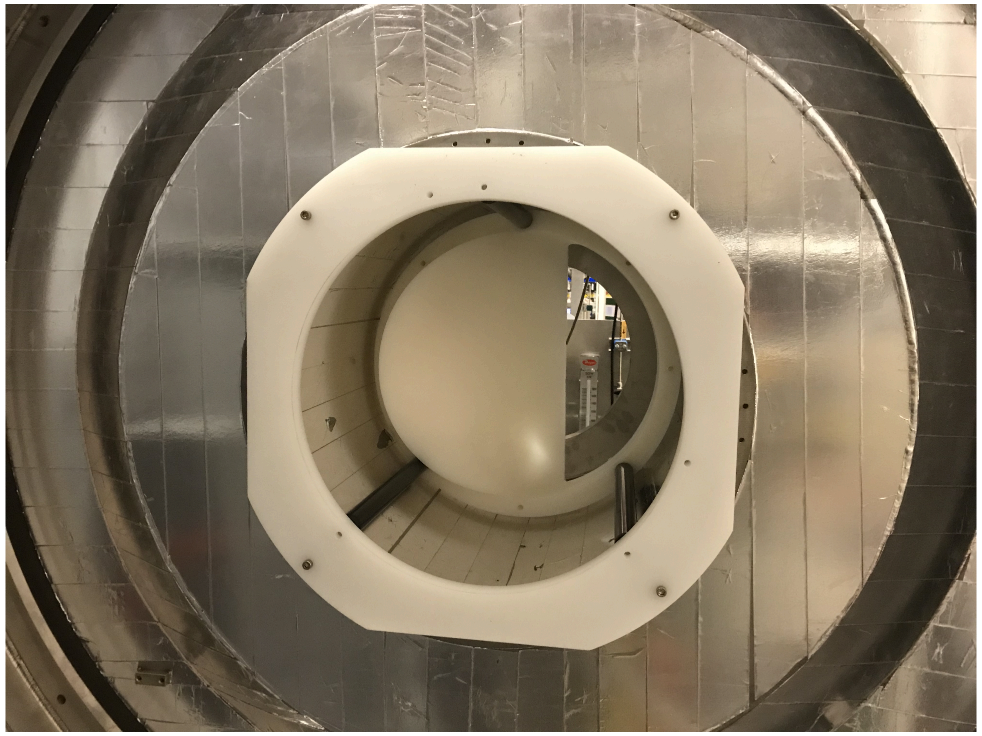
# MICE Apparatus

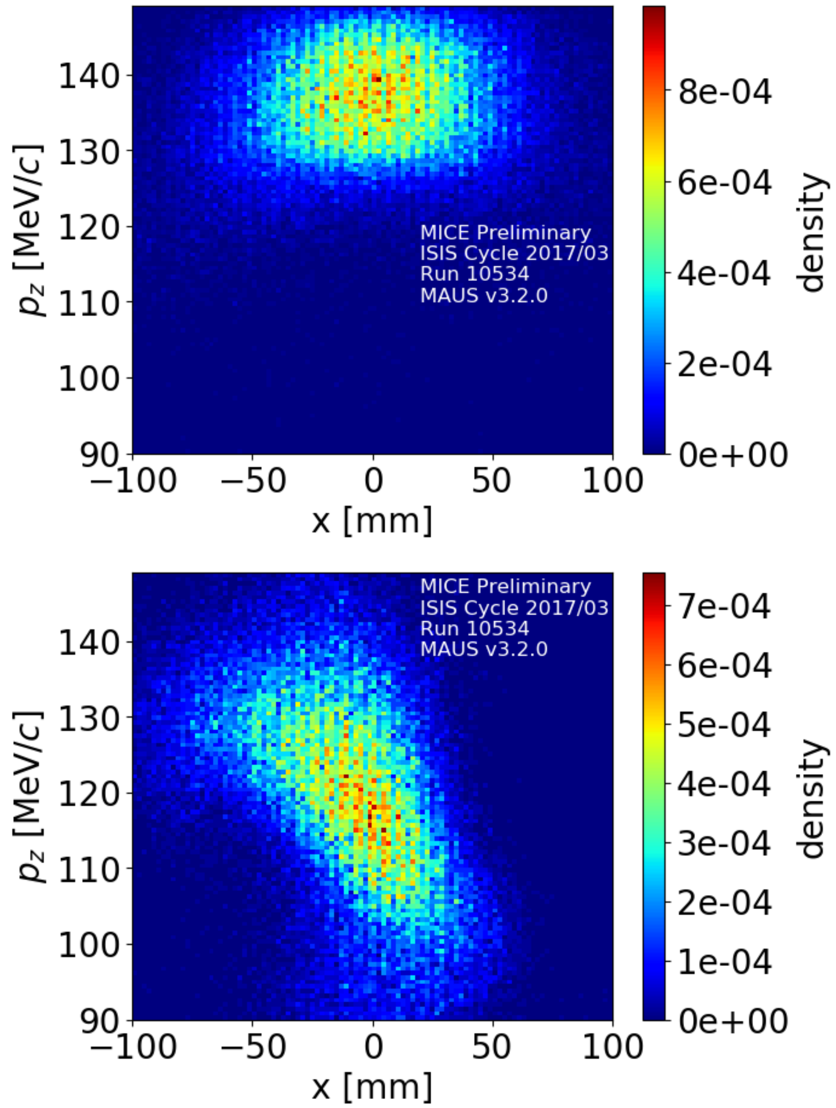


# Also – 1st 6D cooling test:

- Aspects of 6D cooling / emittance exchange tested by inserting wedge absorbers in MICE

- MICE data with 45° polyethylene wedge:
  - test *reverse* emittance exchange






  - wedge increases momentum spread while reducing $\varepsilon_n$
  - can be used to increase collider luminosity

# Muon Accelerator Technical Challenges

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam

e.g., SNS, ESS, PIP II SC Linac

# Muon Accelerator Technical Challenges

## 1. High-power (up to 4 MW) *p* beam* and target

- Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

* unless LEMMA shown to work

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions

* unless LEMMA shown to work

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions
   - μ unstable, $\tau_\mu$ = 2.2 μs ⇒ must cool *quickly*!...

* unless LEMMA shown to work

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions
   - μ unstable, $\tau_\mu$ = 2.2 μs ⇒ must cool *quickly*!...
3. *Rapid* acceleration

* unless LEMMA shown to work

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions
   - μ unstable, $\tau_\mu$ = 2.2 μs ⇒ must cool *quickly*!...

* unless LEMMA shown to work

3. *Rapid* acceleration
   - Linac–RLAs–(FFAGs)–RCS [EMMA@DL, 2011]

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions
   - μ unstable, $\tau_\mu$ = 2.2 μs ⇒ must cool *quickly*!...
3. *Rapid* acceleration
   - Linac–RLAs–(FFAGs)–RCS [EMMA@DL, 2011]
4. High storage-ring bending field (to maximize # cycles before decay) and small $\beta_\perp$, for high $\mathscr{L}$

* unless LEMMA shown to work

# Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

2. Muon beam cooling in all 6 dimensions
   - μ unstable, $\tau_\mu$ = 2.2 μs ⇒ must cool *quickly*!...

* unless LEMMA shown to work

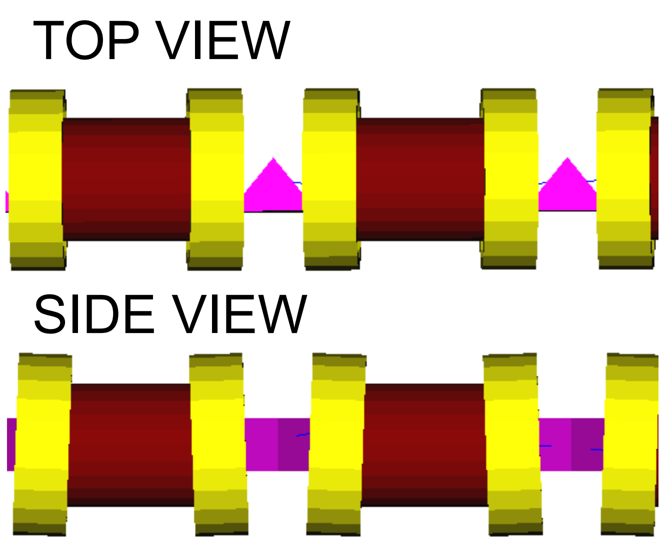
3. *Rapid* acceleration
   - Linac–RLAs–(FFAGs)–RCS [EMMA@DL, 2011]
4. High storage-ring bending field (to maximize # cycles before decay) and small $\beta_\perp$, for high $\mathcal{L}$
   - Solutions devised by MAP (FNAL), *B* ~ 10 T, $\beta_\perp$ ~ 1 cm

# How to cool in 6D?

- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport

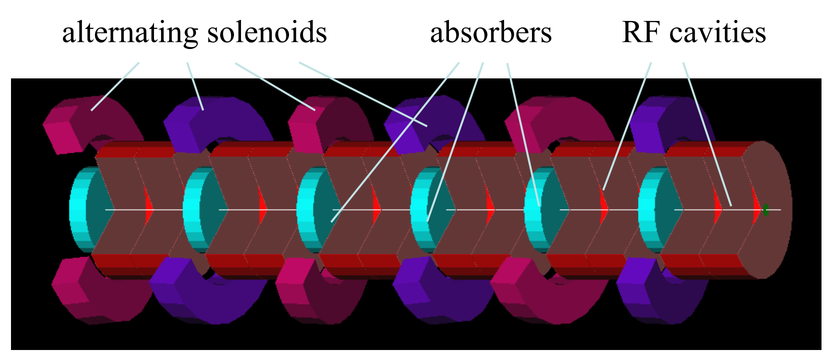
- 3 types of solutions found viable in simulation:

Rectilinear FOFO



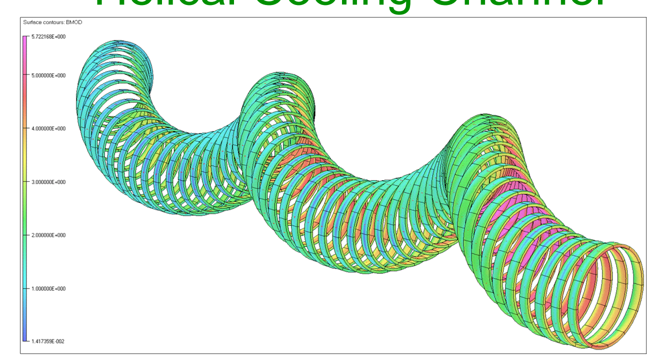

BNL & FNAL

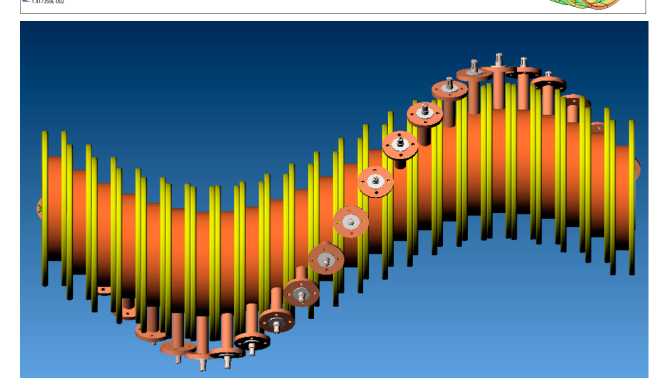
FOFO Snake




Y. Alexahin, FNAL

Helical Cooling Channel

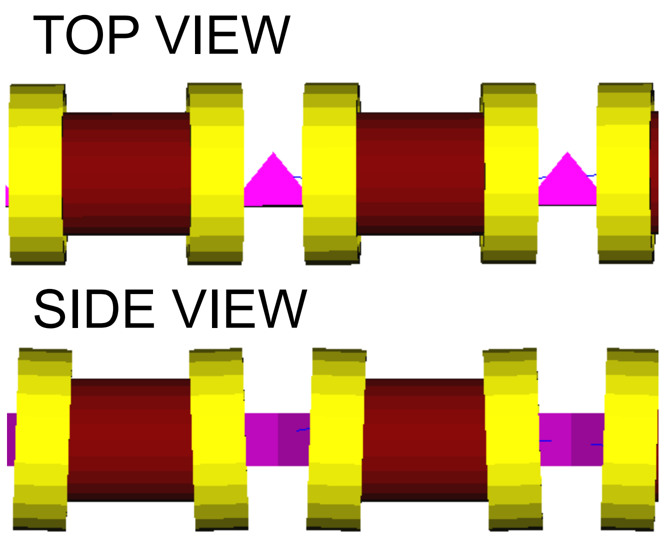




Muons, Inc. & FNAL

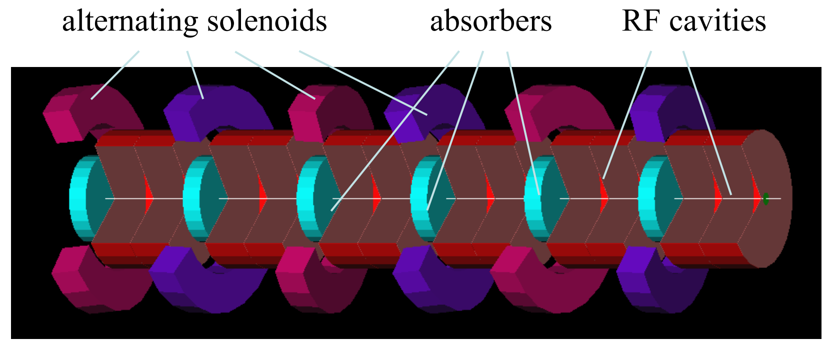
# How to cool in 6D?

Rectilinear FOFO



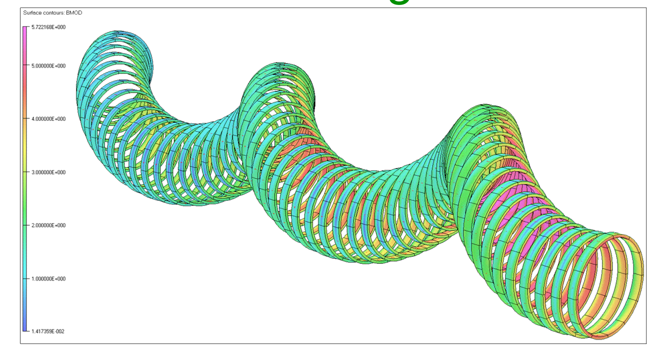

BNL & FNAL

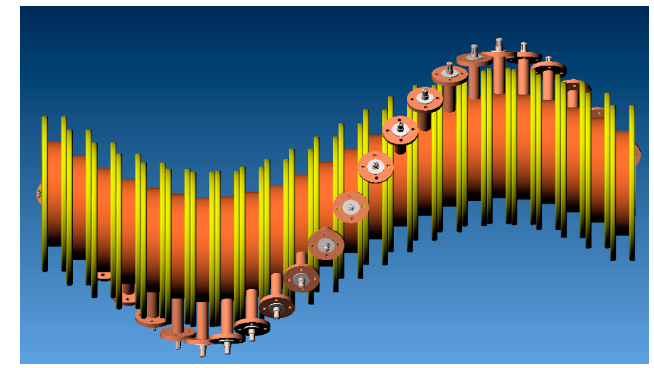
FOFO Snake




Y. Alexahin, FNAL

Helical Cooling Channel





Muons, Inc. & FNAL

- FOFO Snake can cool both signs at once but may be limited in $\beta_{\perp,min}$ ⇒ may be best for initial 6D cooling
- HCC may be most compact
- Performance limits of each not yet clear, nor which is most cost-effective

# Beyond 6D Cooling

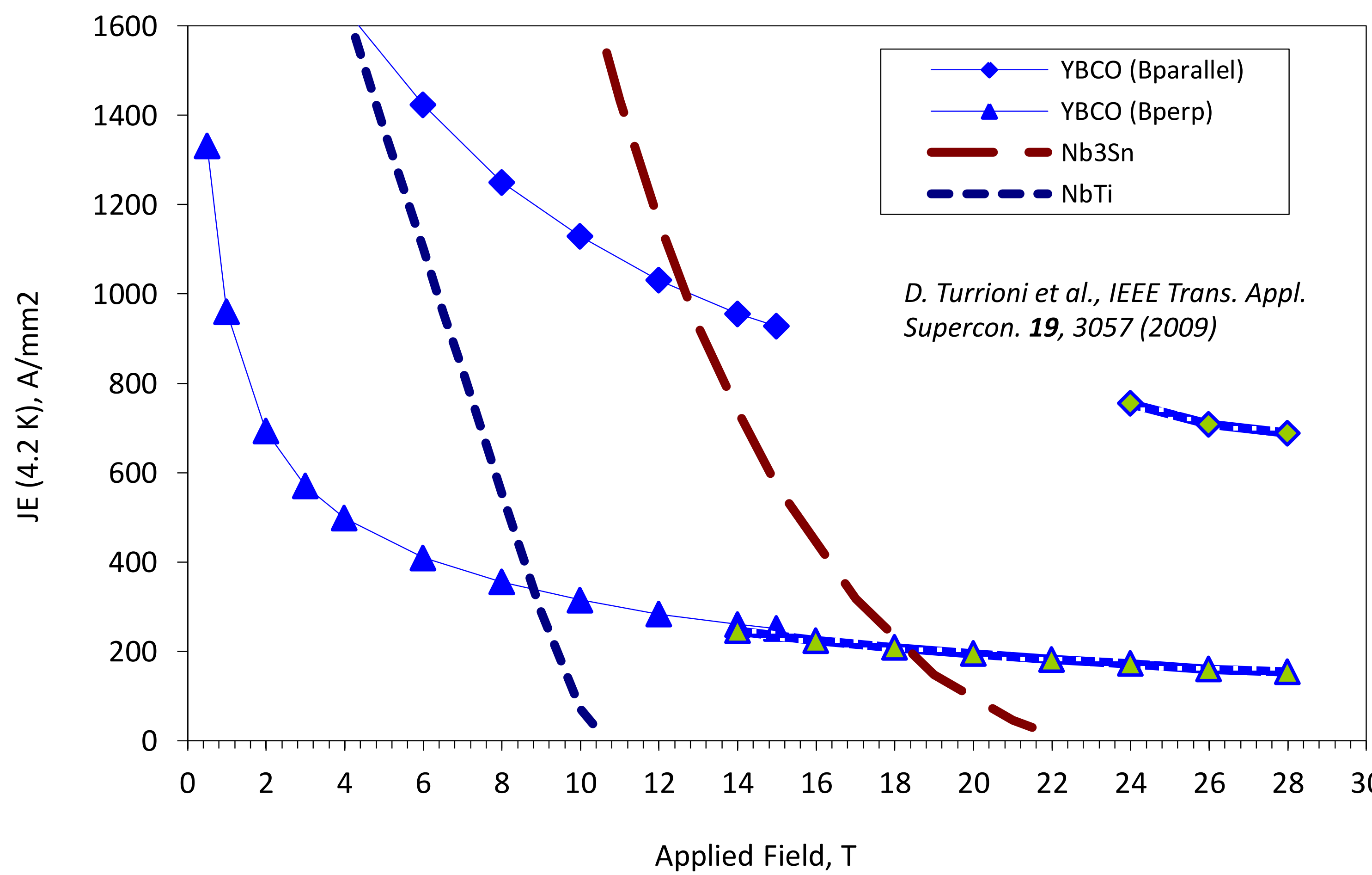
- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above

- One approach (Palmer "Final Cooling"):

  - cool transversely with $B$ ~ 30 T at low momentum

  - gives lower β & higher $dE/dx$:

$$\beta_\perp \sim \frac{p}{B}$$

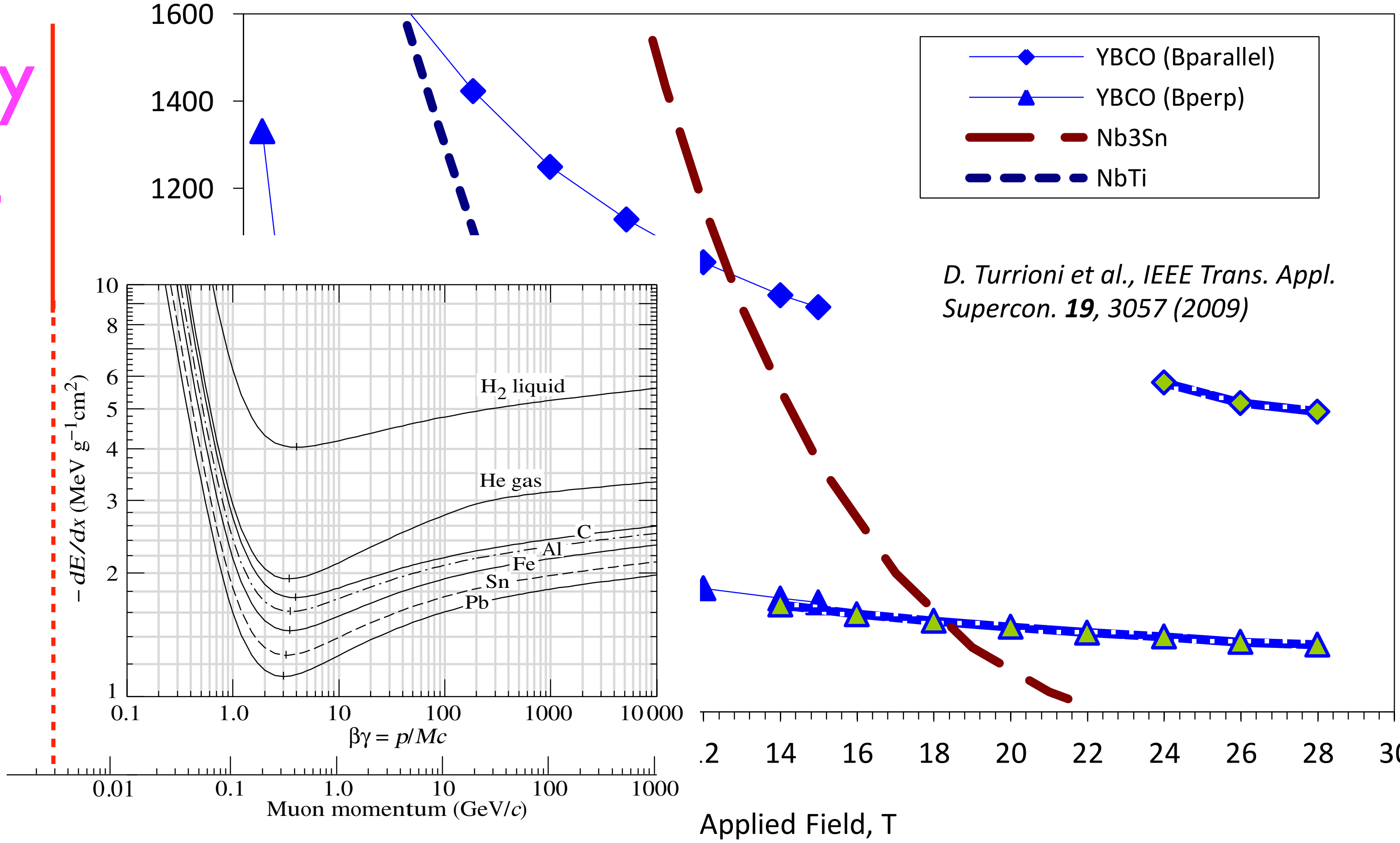



- Lower-$B$ options under study as well (Derbenev PIC, REmEx, lithium lenses)

# Beyond 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 30 T at low momentum
  - gives lower β & higher *dE/dx*:

$$\beta_\perp \sim \frac{p}{B}$$

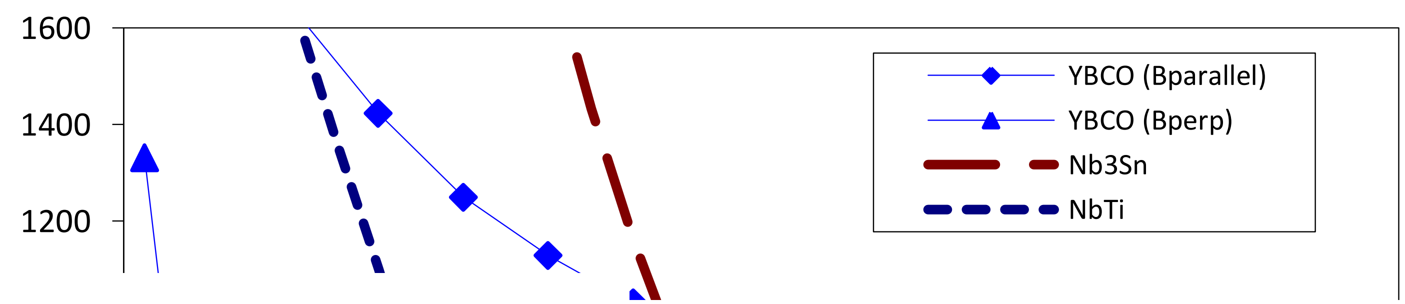


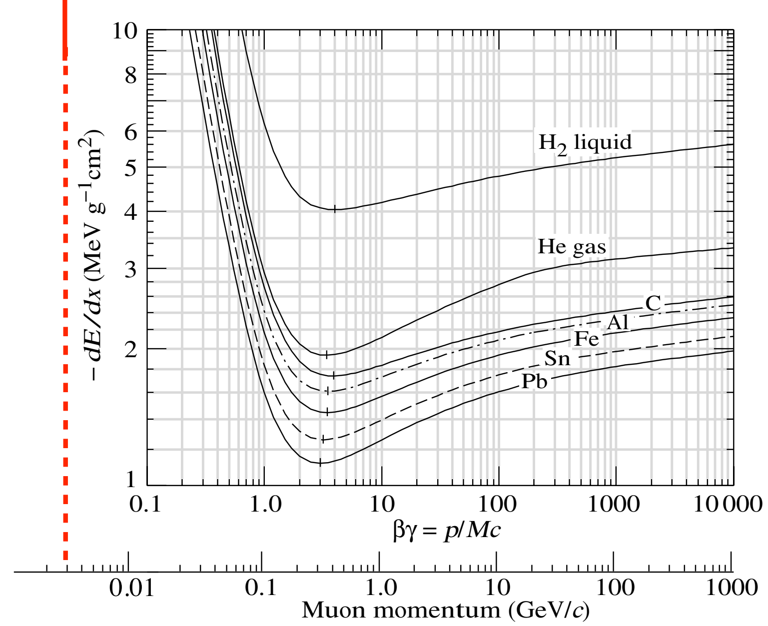

- Lower-*B* options under study as well (Derbenev PIC, REmEx, lithium lenses)

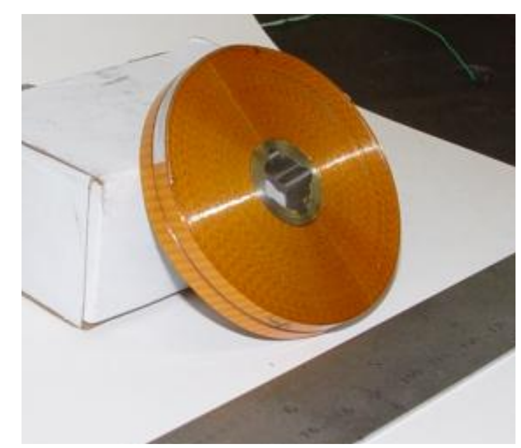
# Beyond 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 30 T at low momentum
  - gives lower β & higher *dE*/*dx*:

$$\beta_\perp \sim \frac{p}{B}$$



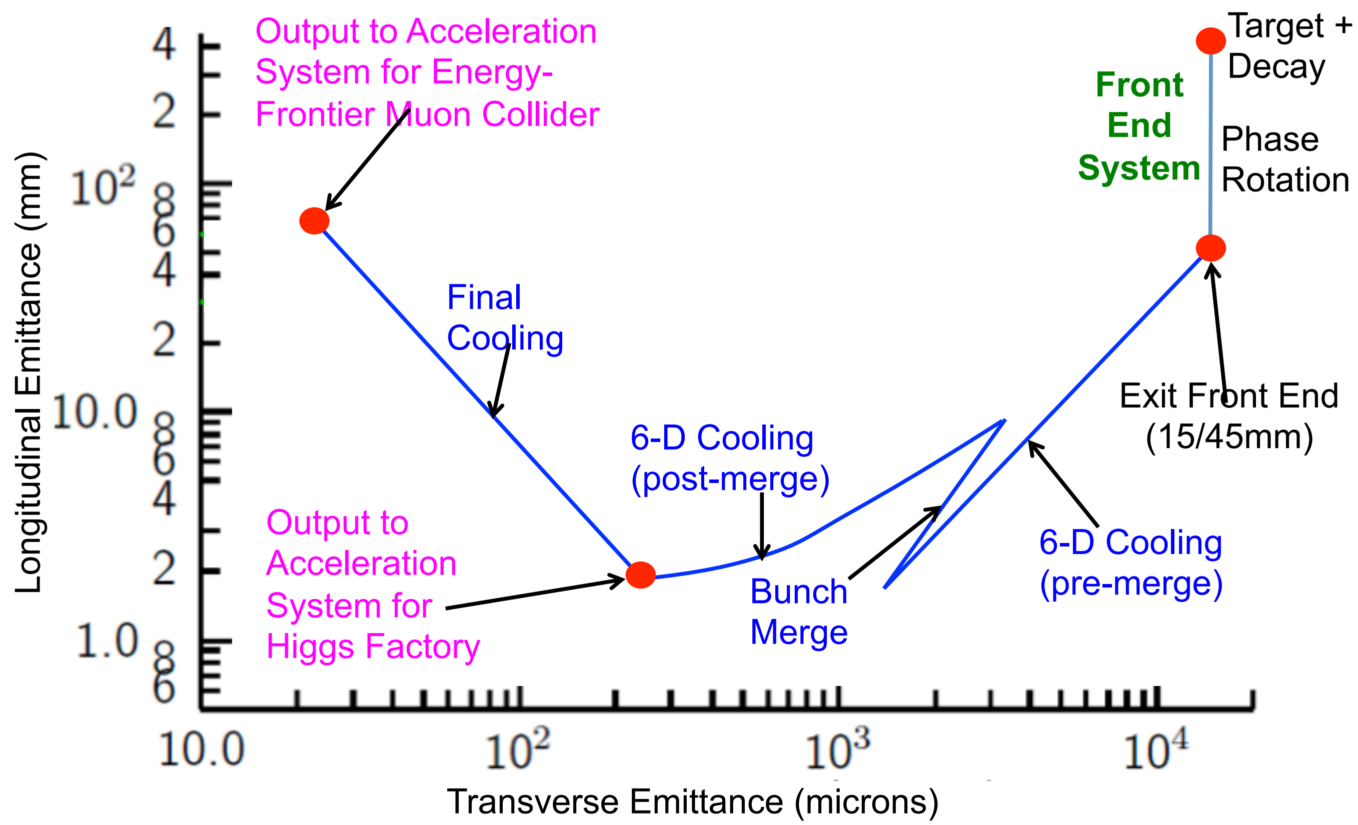



High-field YBCO solenoid (BNL/Particle Beam Lasers, Inc.)

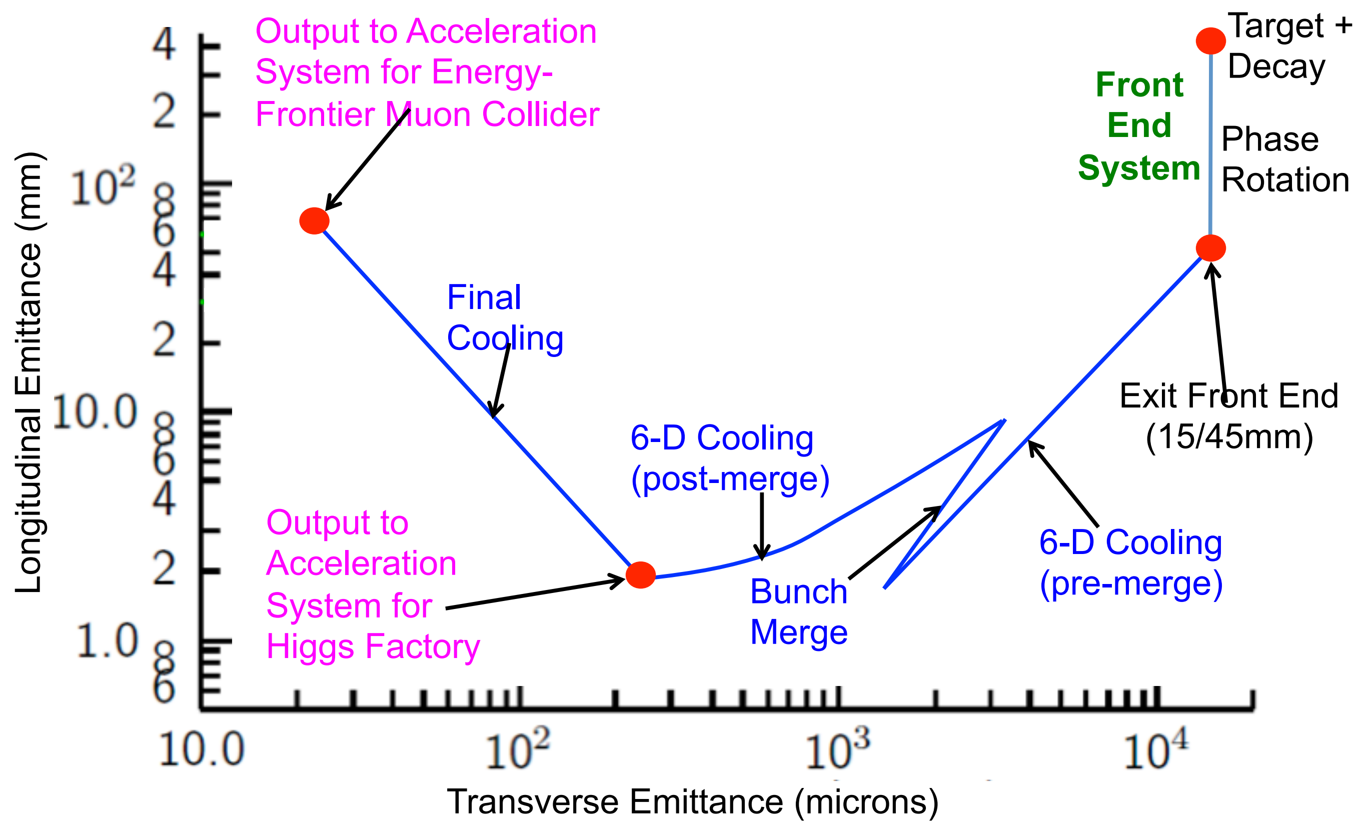
- Lower-*B* options under study as well (Derbenev PIC, REmEx, lithium lenses)

# Higgs Factory Cooling



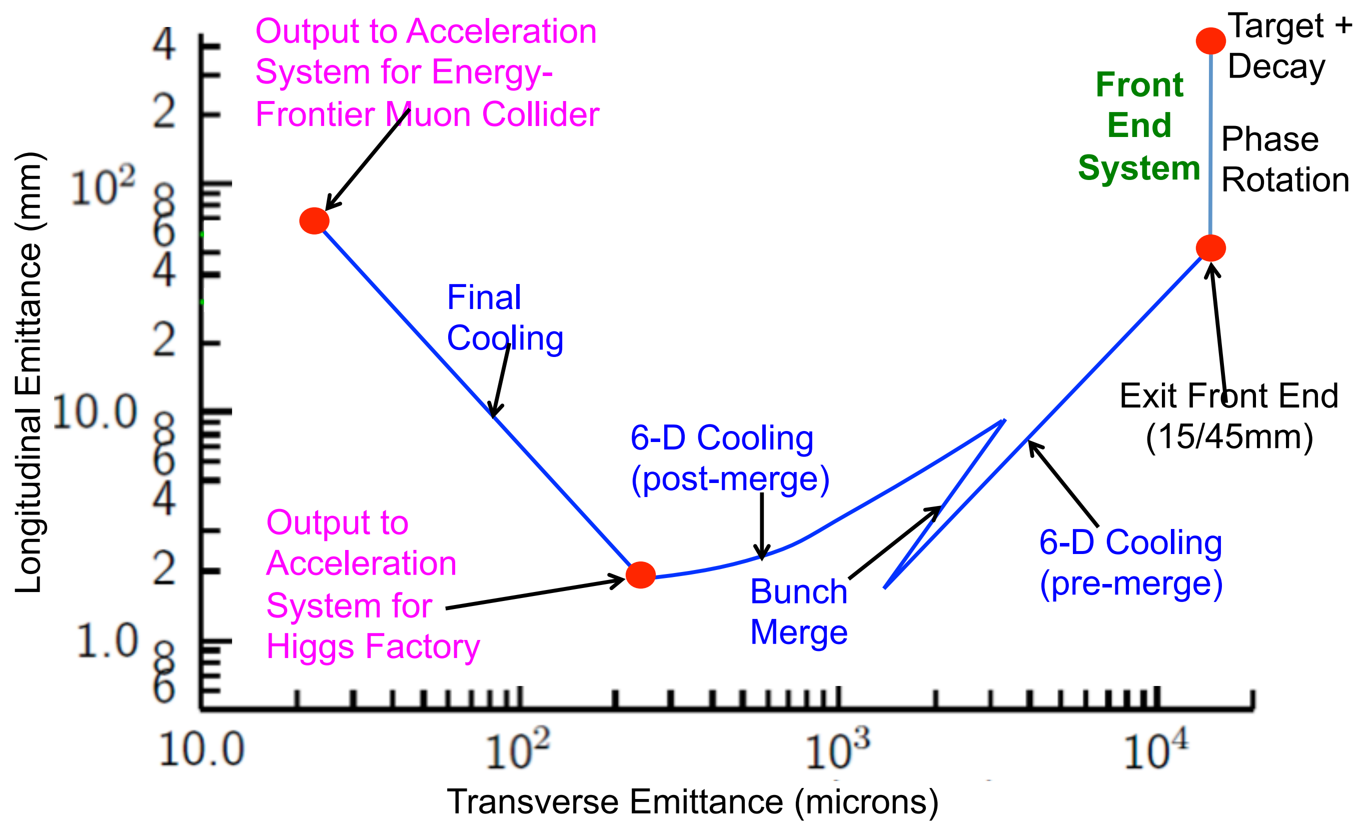
# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:



# Higgs Factory Cooling

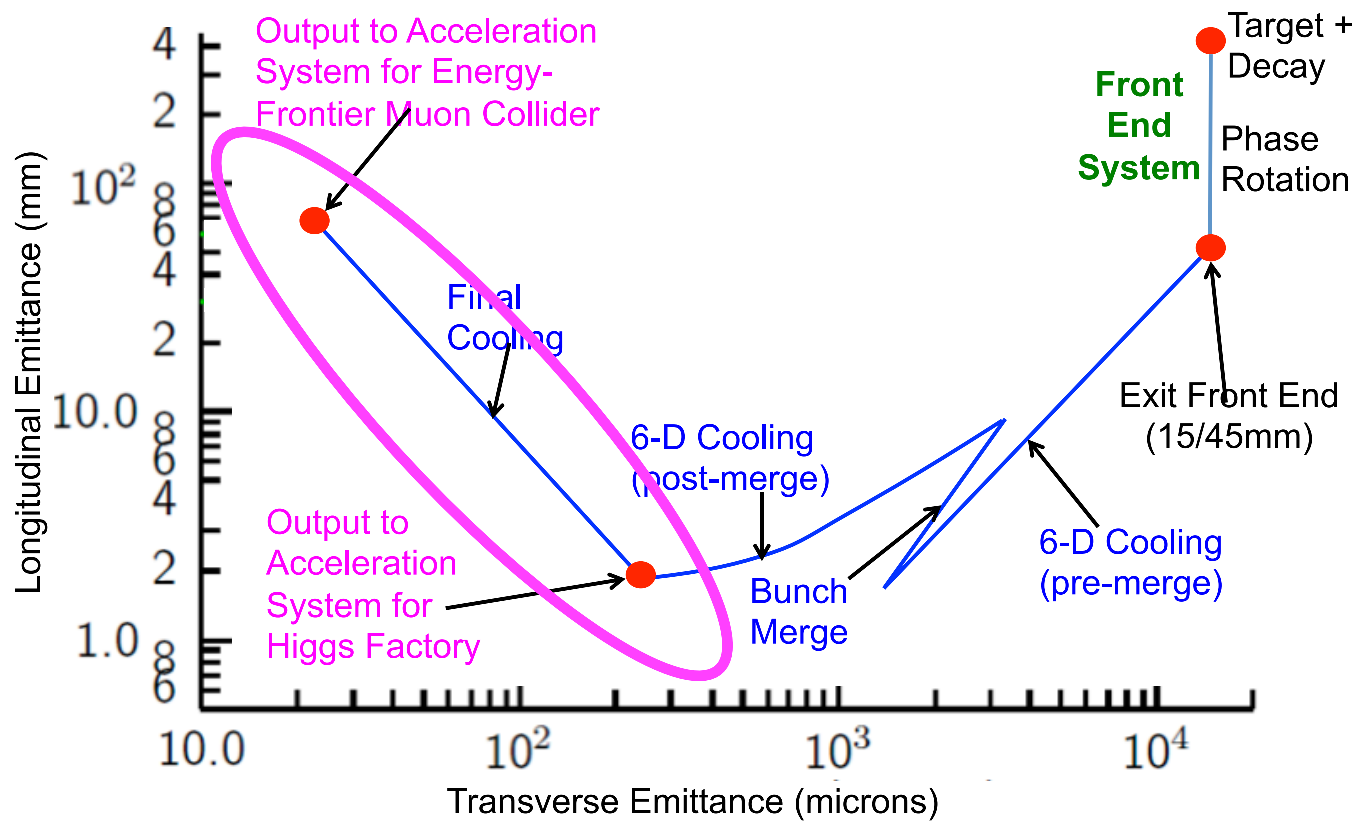
- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV



# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

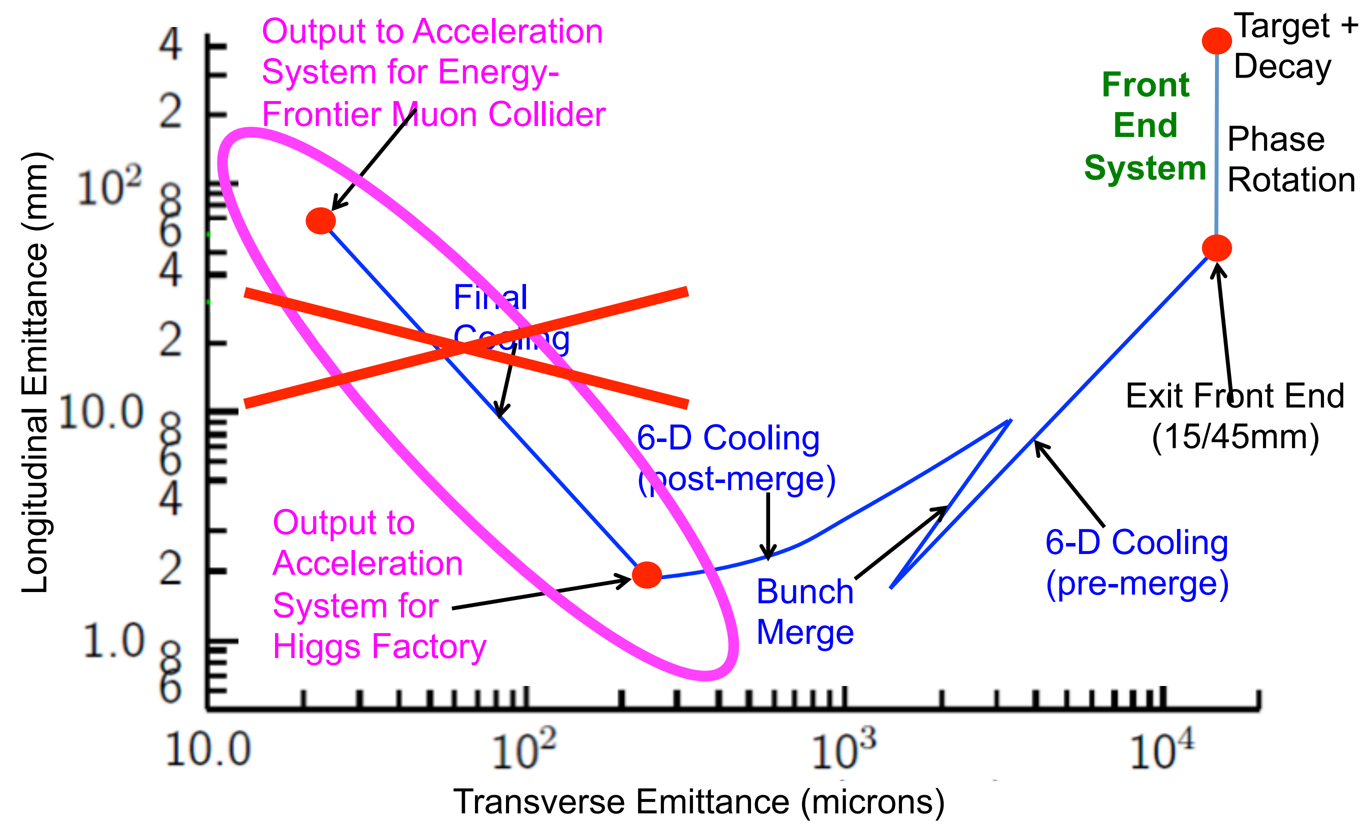
$\Longrightarrow$ omit final cooling



# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

⇒ omit final cooling

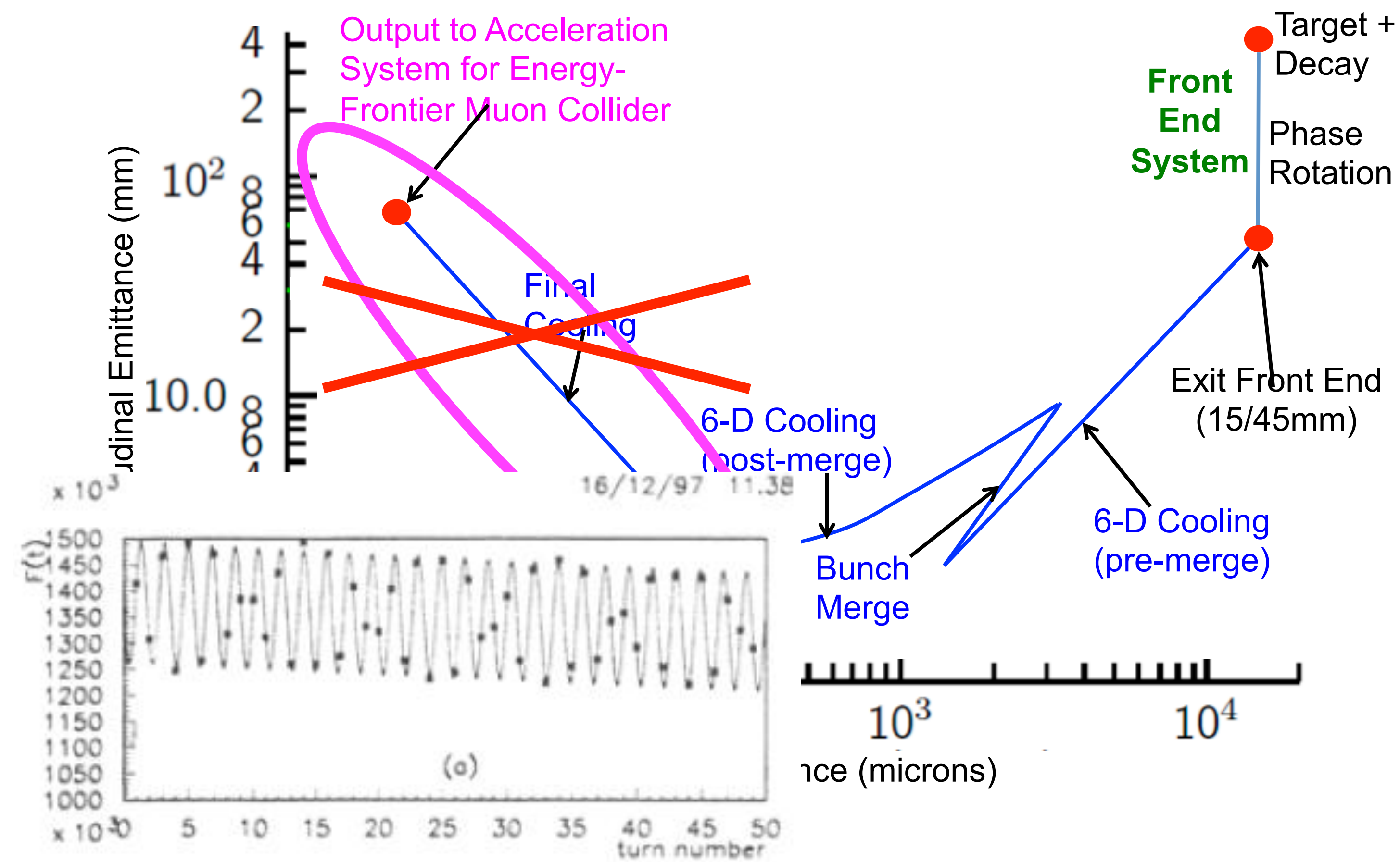


# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \rightarrow h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

  ⇒ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!

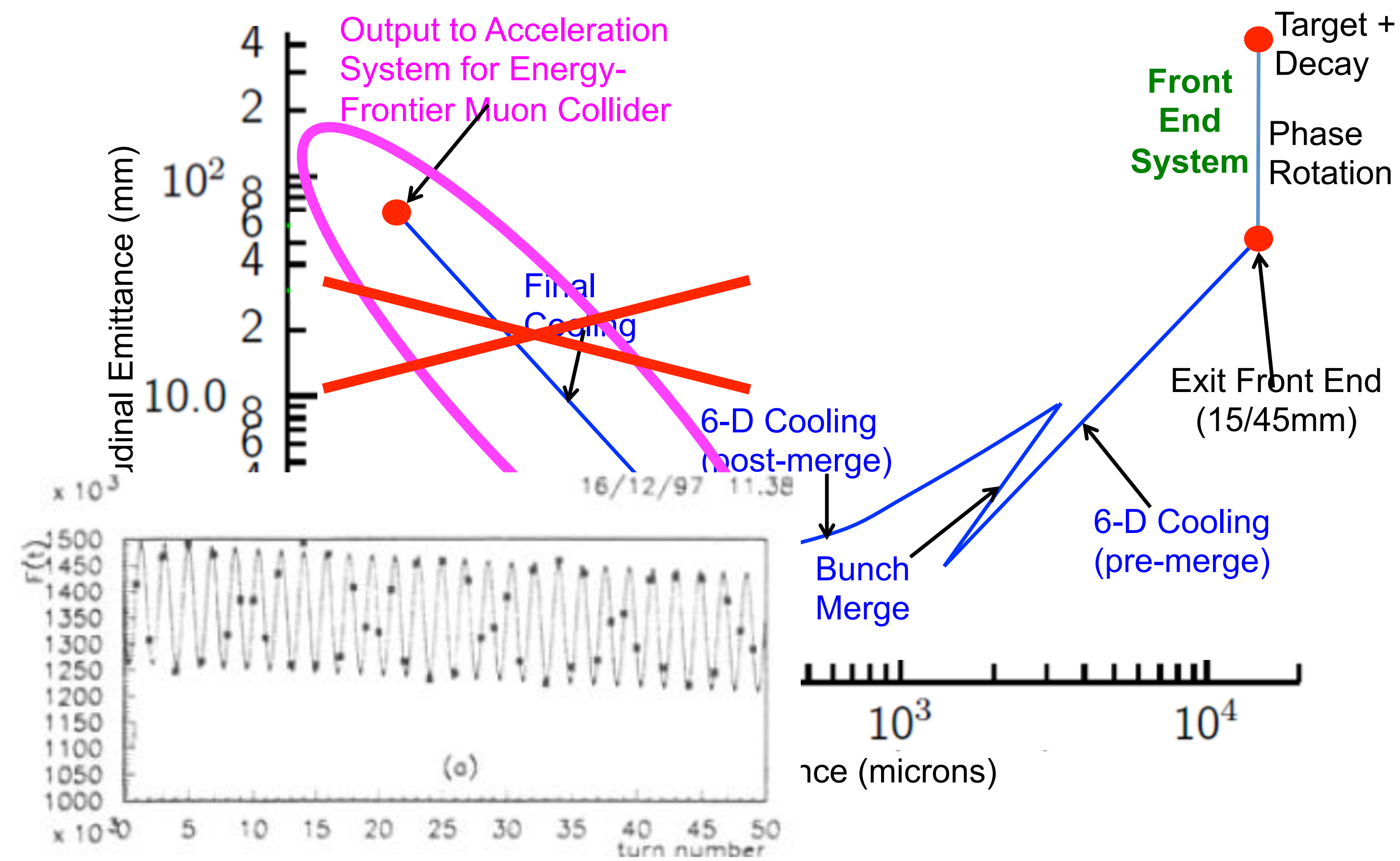


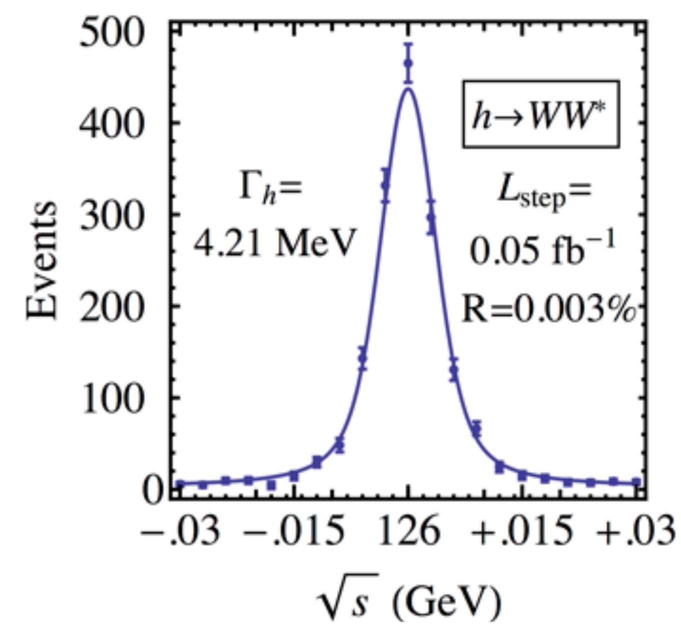
# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

⇒ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan



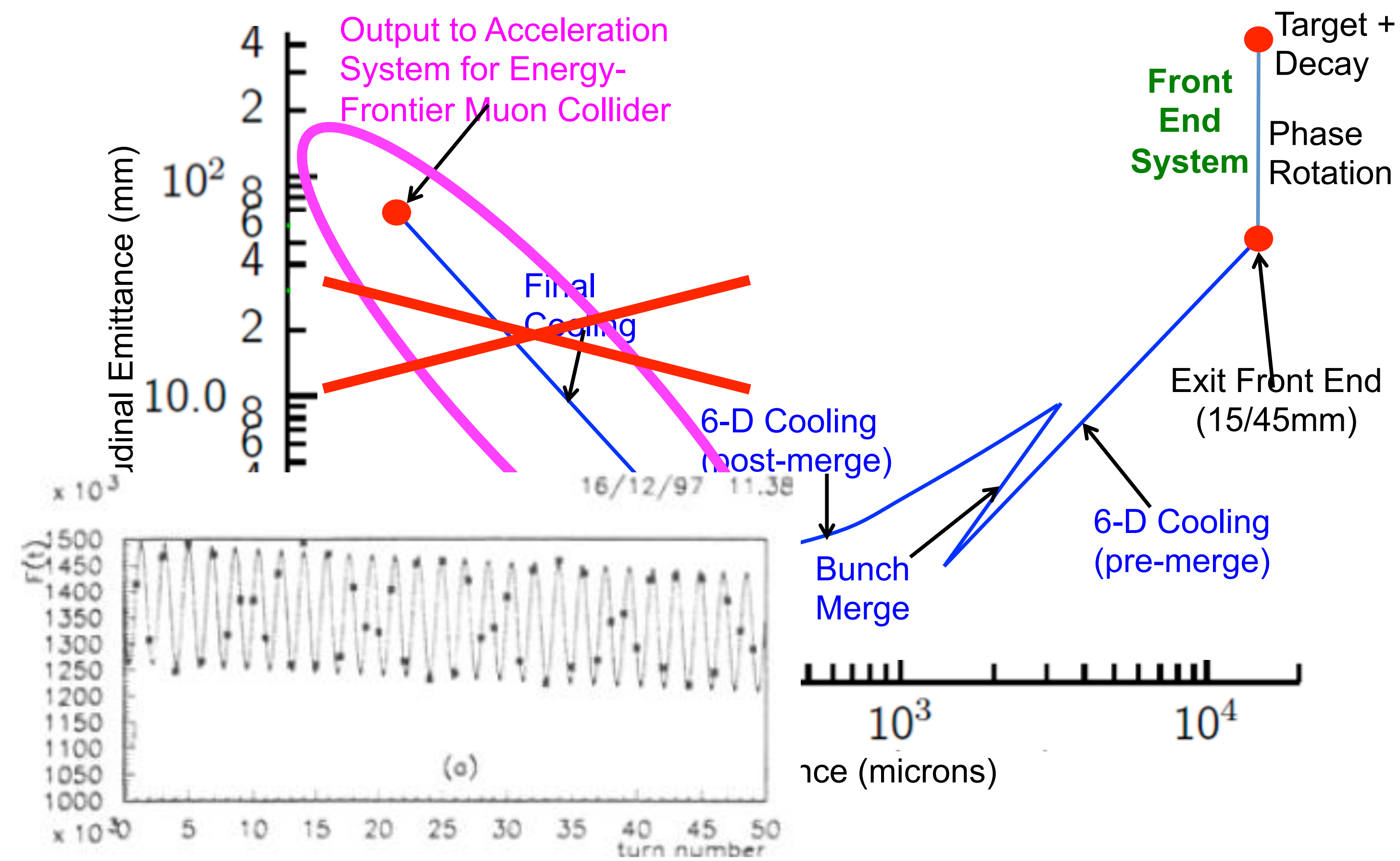

[P. Janot, HF2012]

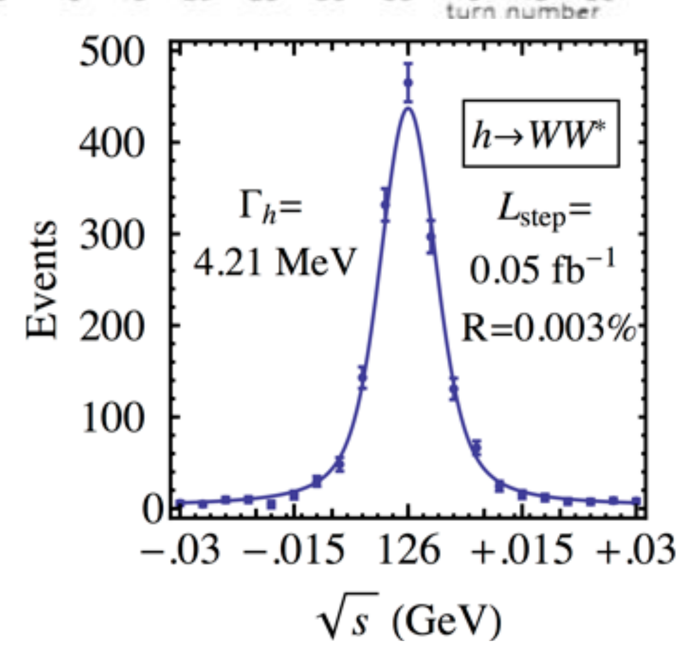
# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \rightarrow h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

    ⇒ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan
    - o the only way to do so!



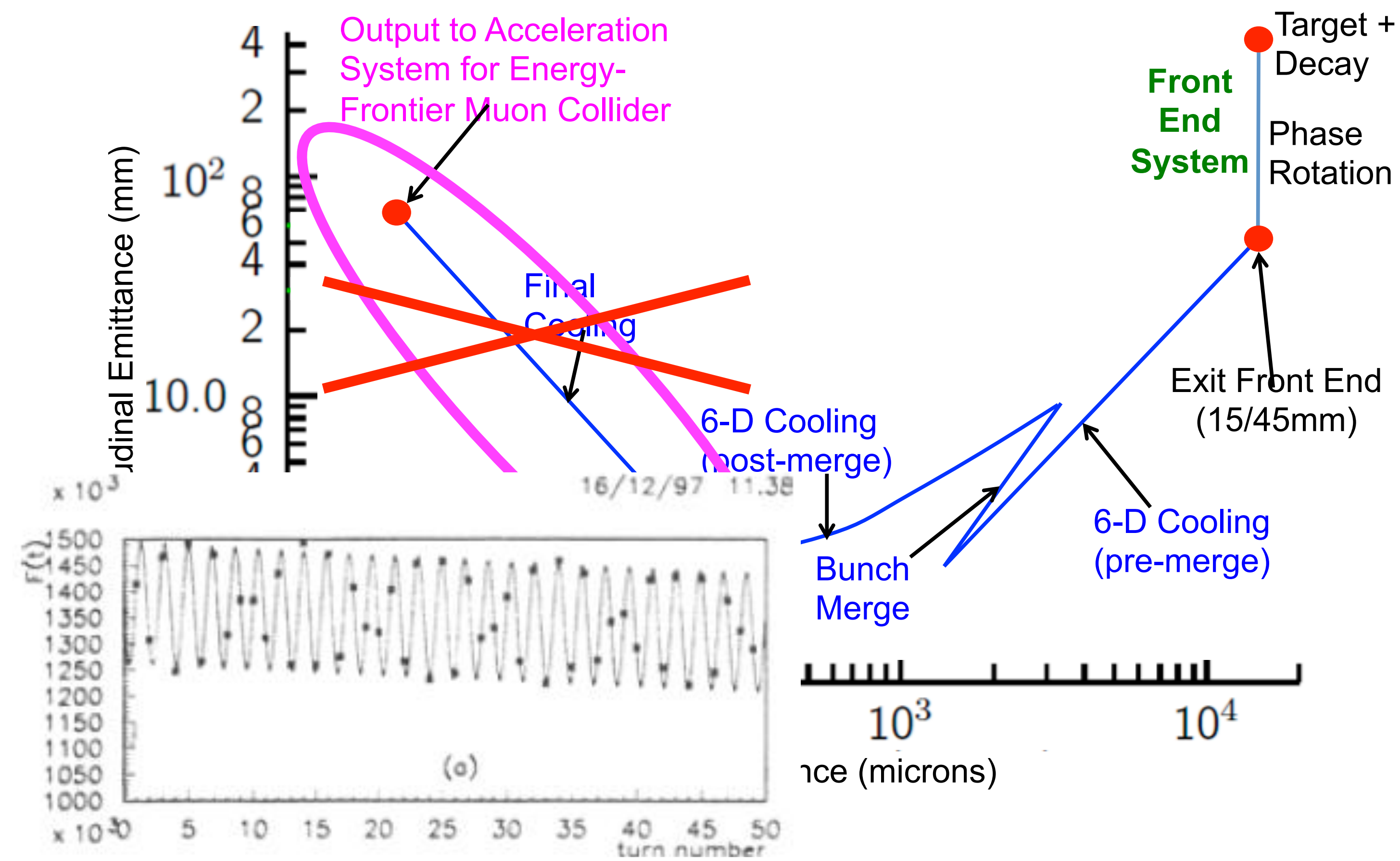




[P. Janot, HF2012]

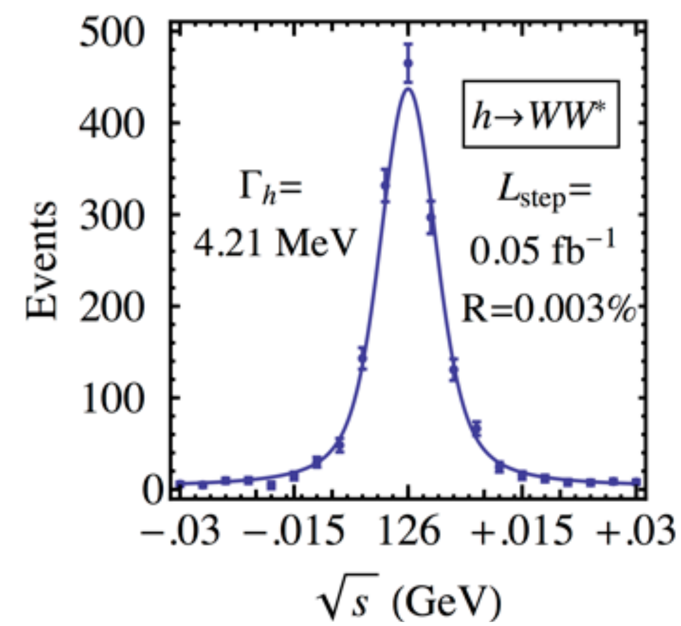
# Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

  ⇒ omit final cooling




  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan
    - the only way to do so!
    - and a key test of the SM




[P. Janot, HF2012]

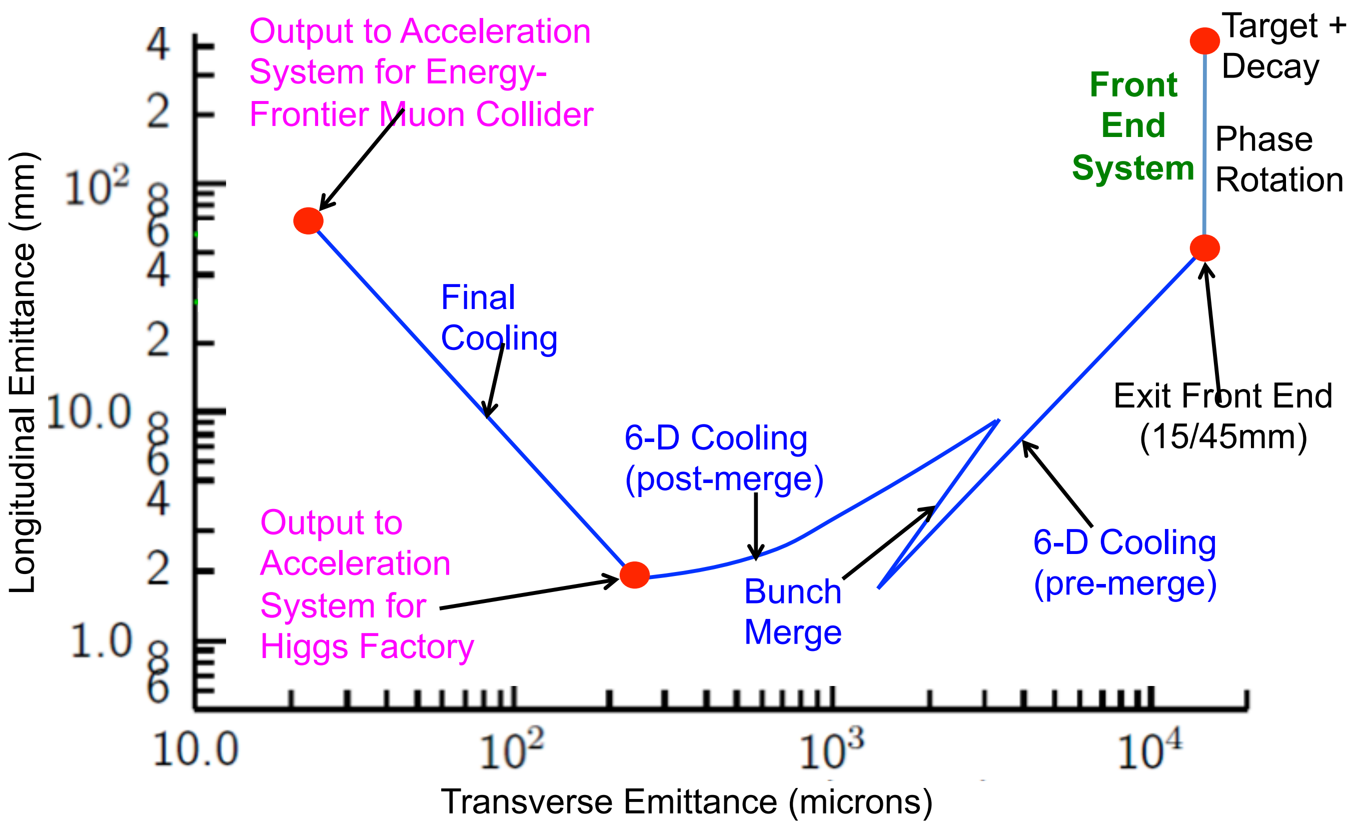
# Selected MICE Results…

# Some MC/NF source material:

- **Neutrino Factory Feasibility Study II report** [BNL-52623 (2001)]
- Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration [PRST Accel. Beams 6, 081001 (2003)]
- **Neutrino Factory and Beta Beam Experiments and Development** [arXiv:physics/0411123, www.aps.org/policy/reports/multidivisional/neutrino/upload/Neutrino_Factory_and_Beta_Beam_Experiments_and_Development_Working_Group.pdf (2004)]
- Recent innovations in muon beam cooling [AIP Conf. Proc. 821, 405 (2006)]
- **International Design Study for the Neutrino Factory**, Interim Design Report [arXiv:1112.2853]
- **Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.**: A White Paper Submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields of the American Physical Society [arXiv:1308.0494]
- Pressurized $H_2$ RF Cavities in Ionizing Beams and Magnetic Fields [PRL 111 (2013) 184802]
- Muon Colliders, R.B. Palmer [Rev. Accel. Sci. Tech. 7 (2014) 137]
- Operation of normal-conducting RF cavities in multi-tesla magnetic fields for muon ionization cooling: a feasibility demonstration [arXiv:1807.03473]
- map.fnal.gov; www.cap.bnl.gov/mumu/; mice.iit.edu
- **JINST Special Issue on Muon Accelerators** [iopscience.iop.org/journal/1748-0221/page/extraproc46]

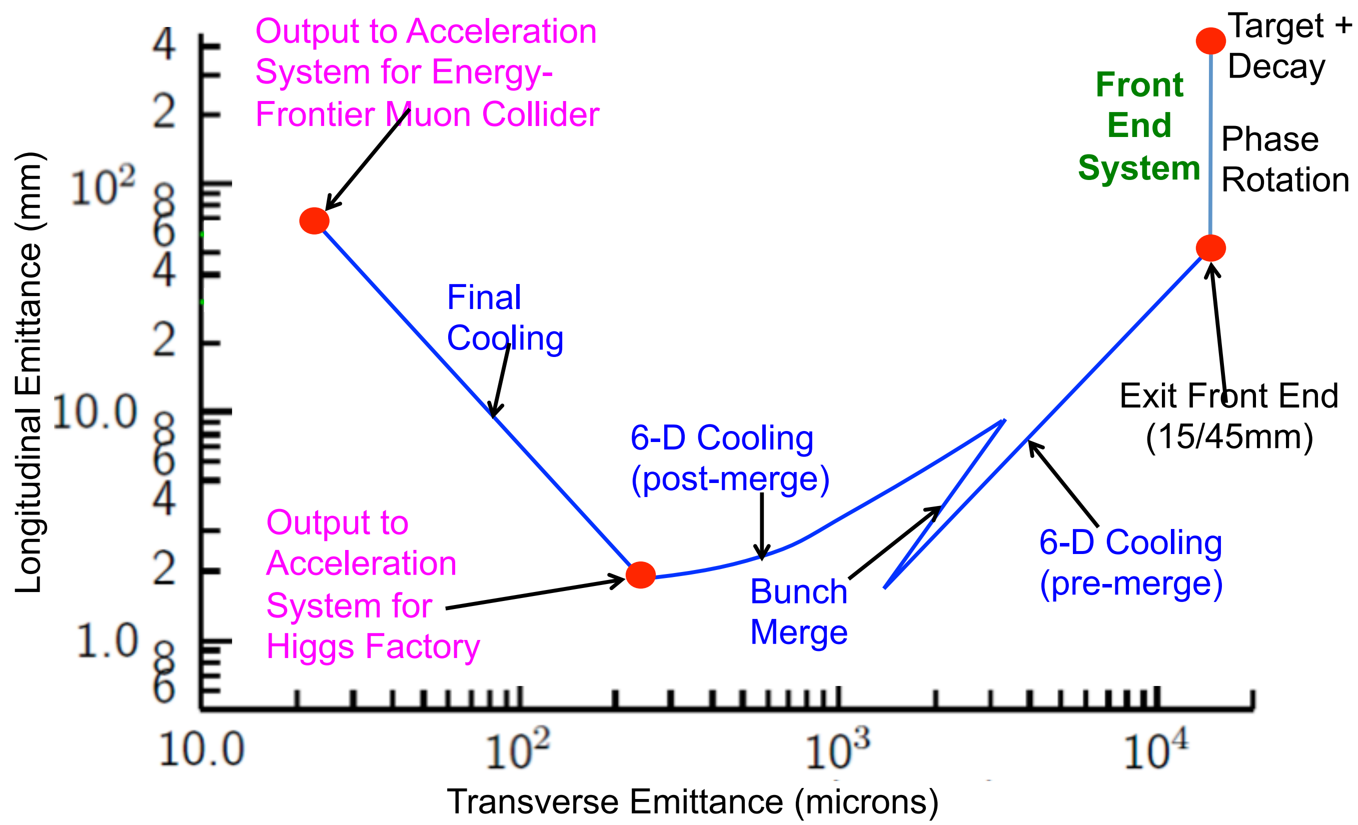
Repository for final MAP and MICE papers

# Higgs Factory



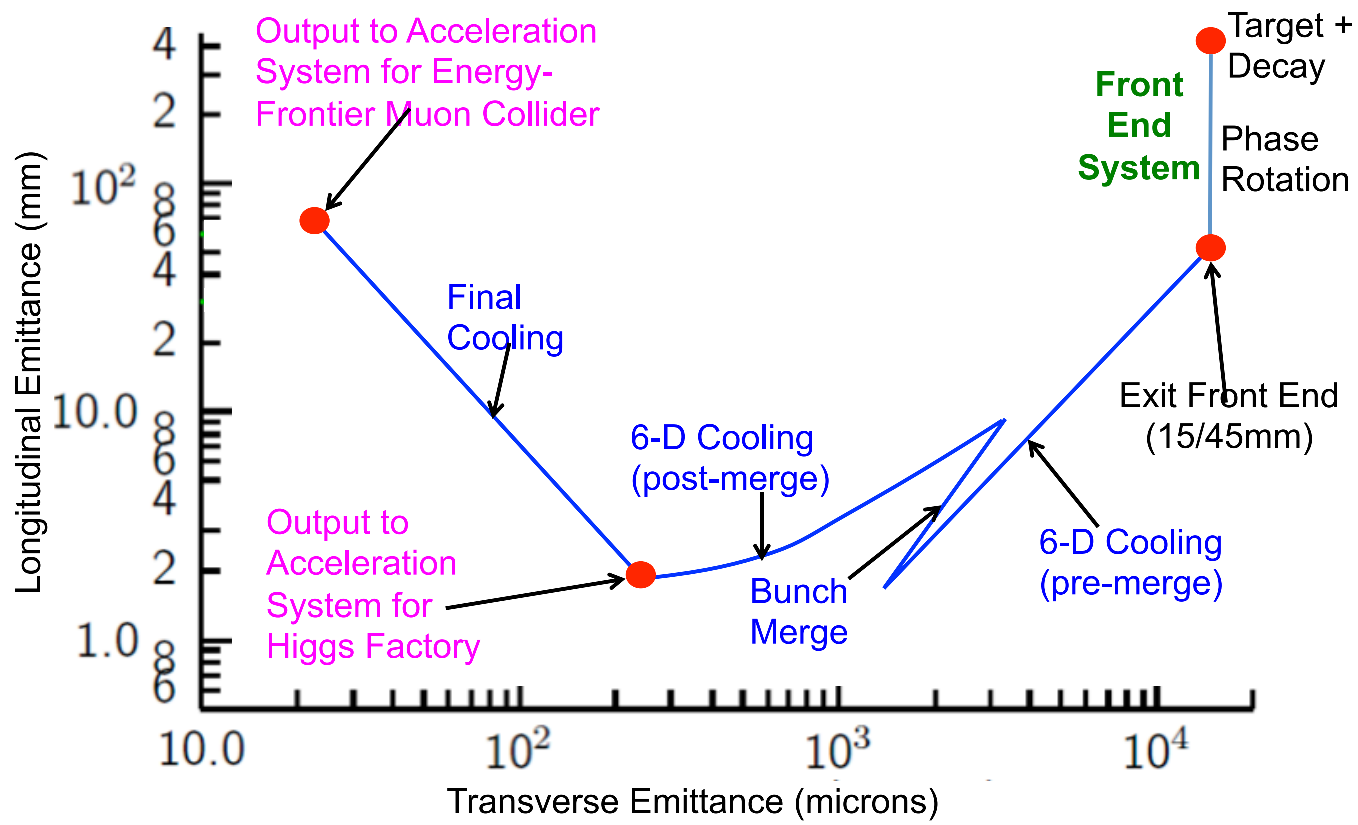
# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:



# Higgs Factory

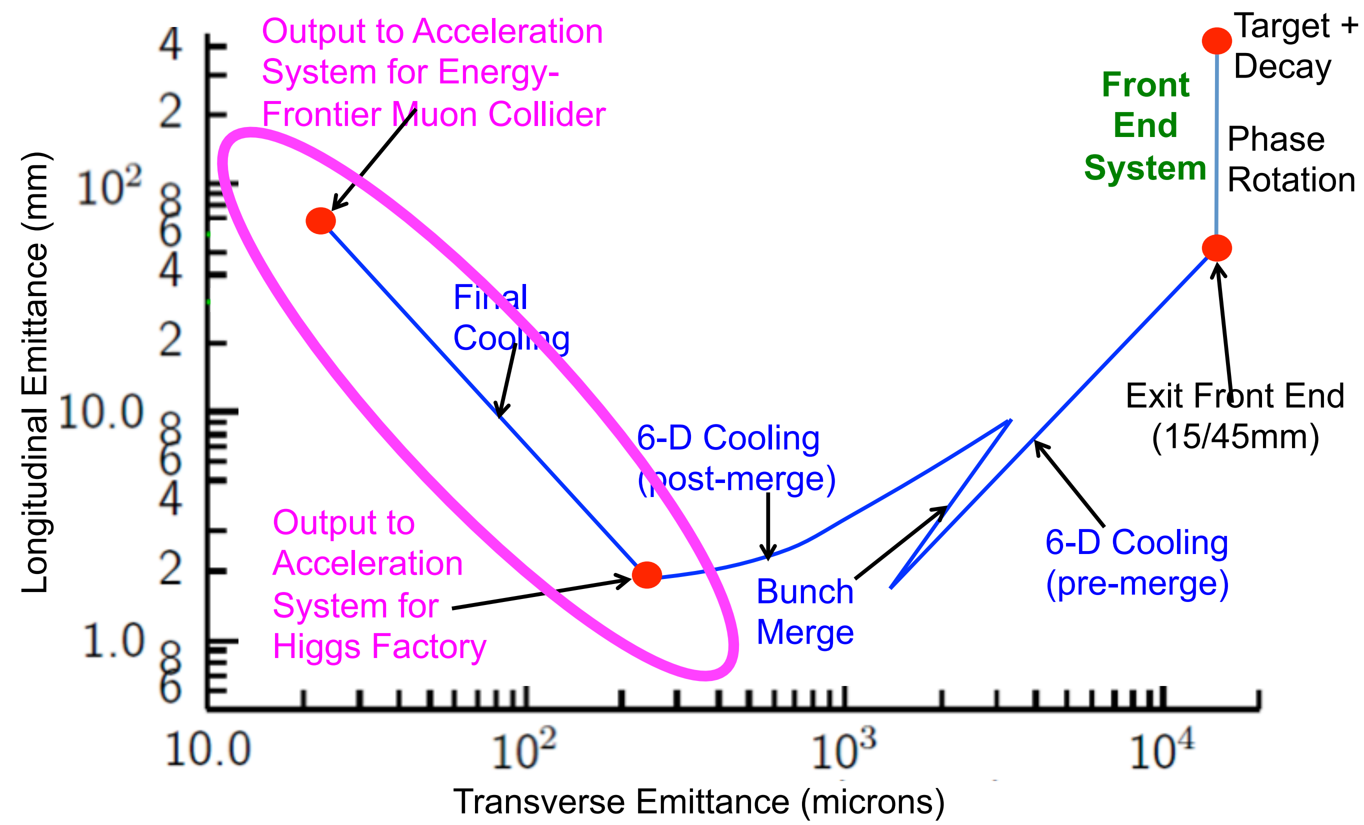
- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \rightarrow h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV



# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

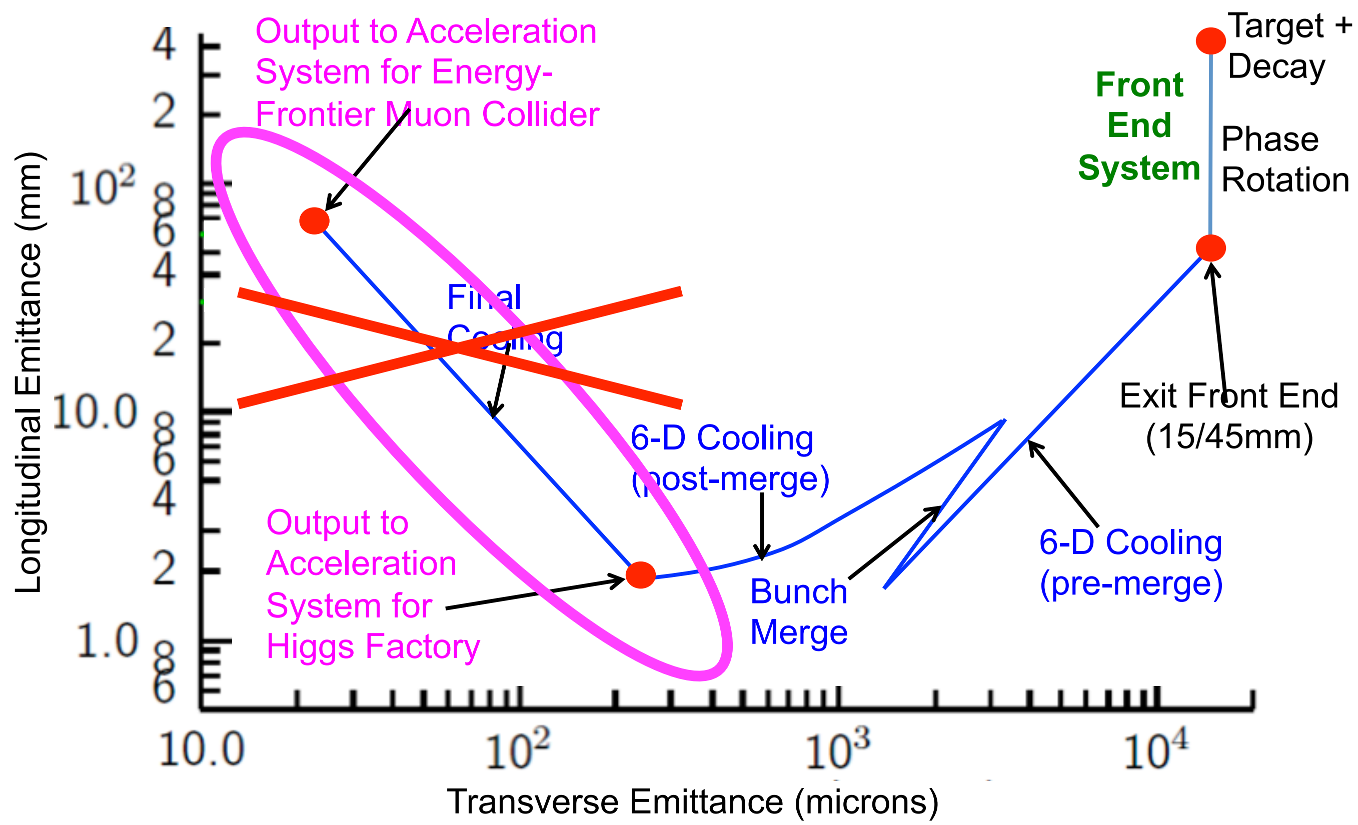
$\Rightarrow$ omit final cooling



# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

$\Rightarrow$ omit final cooling

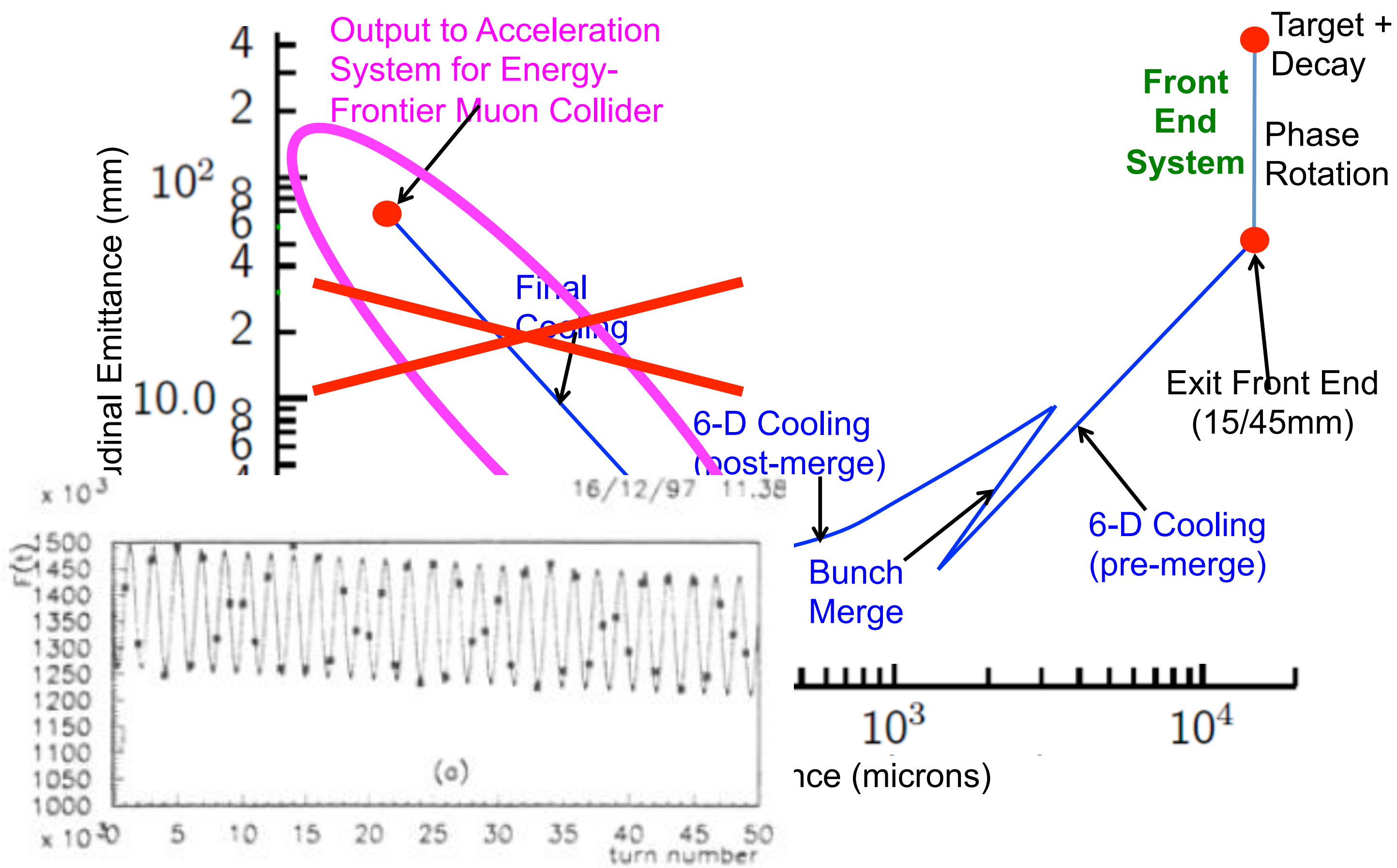


# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

    $\Rightarrow$ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!

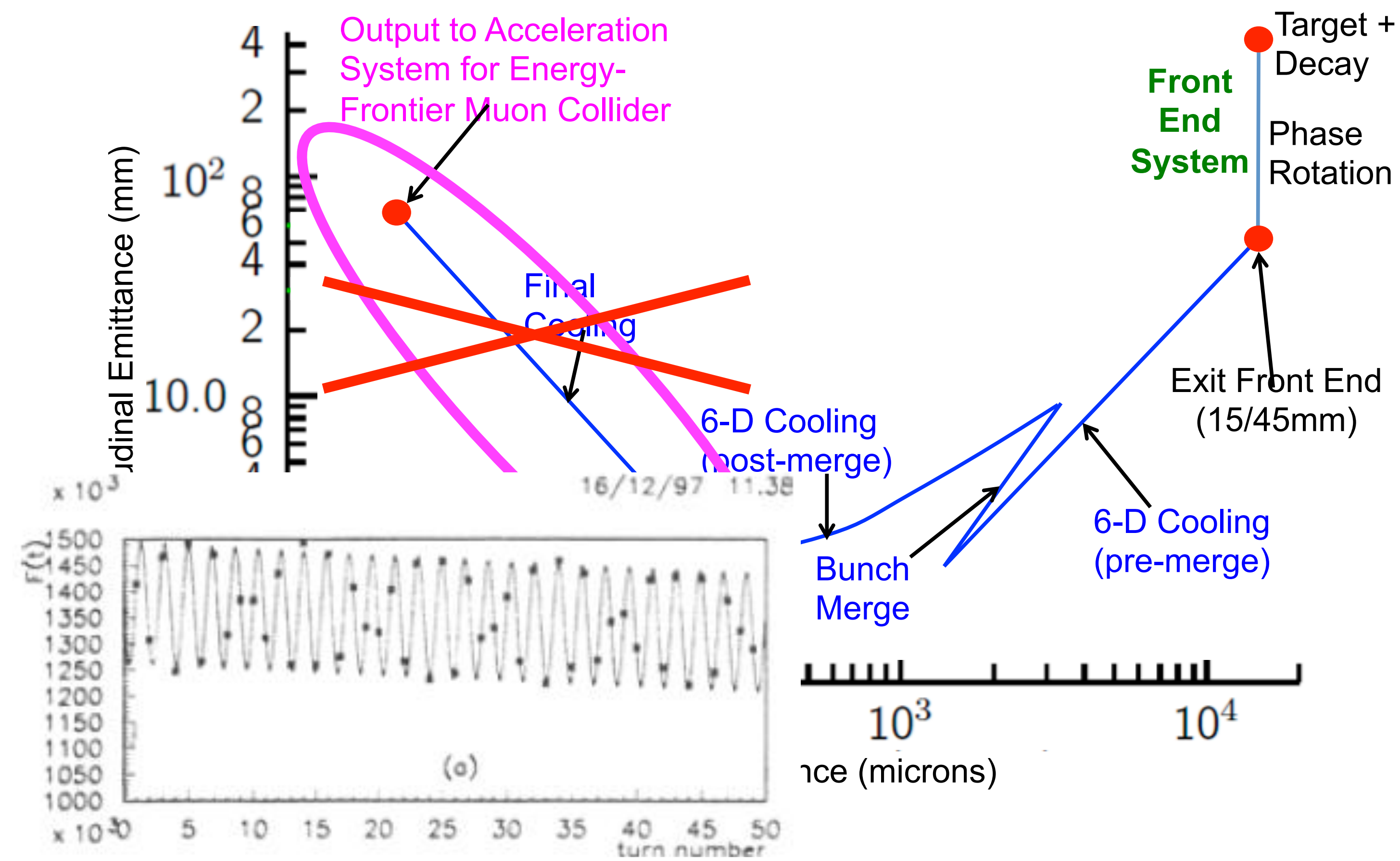


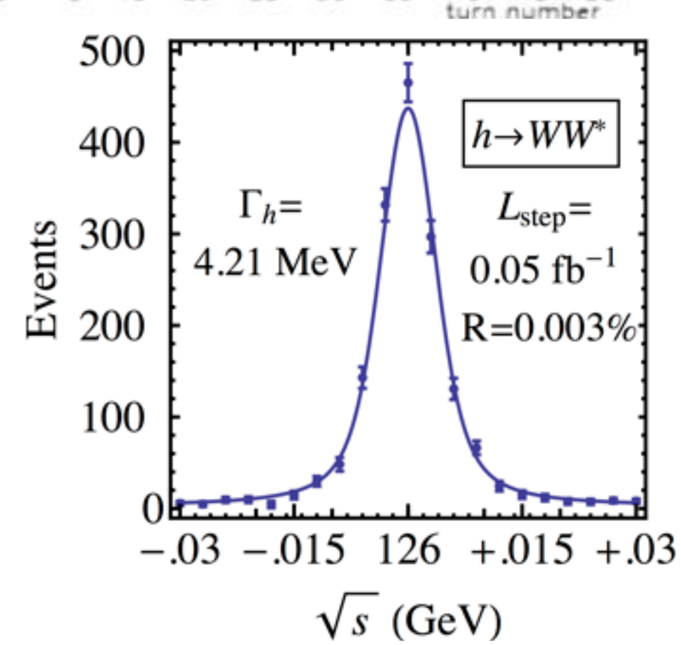
# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

$\Rightarrow$ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan



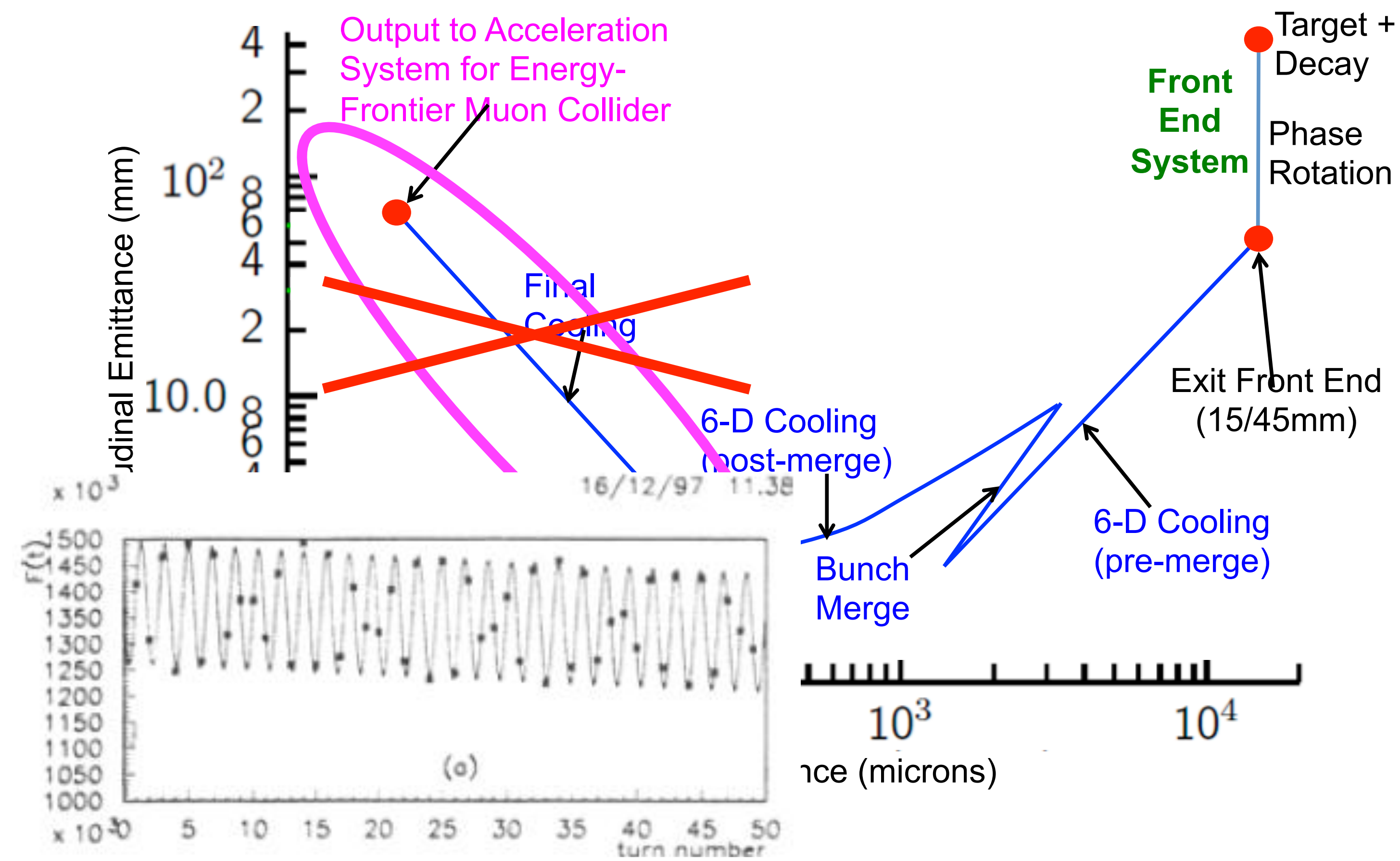

[P. Janot, HF2012]

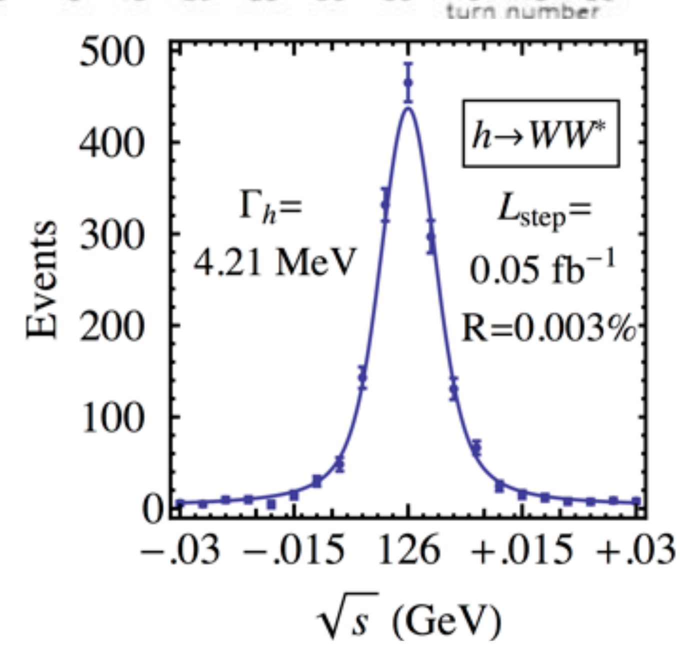
# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

  $\Rightarrow$ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan
    - o the only way to do so!



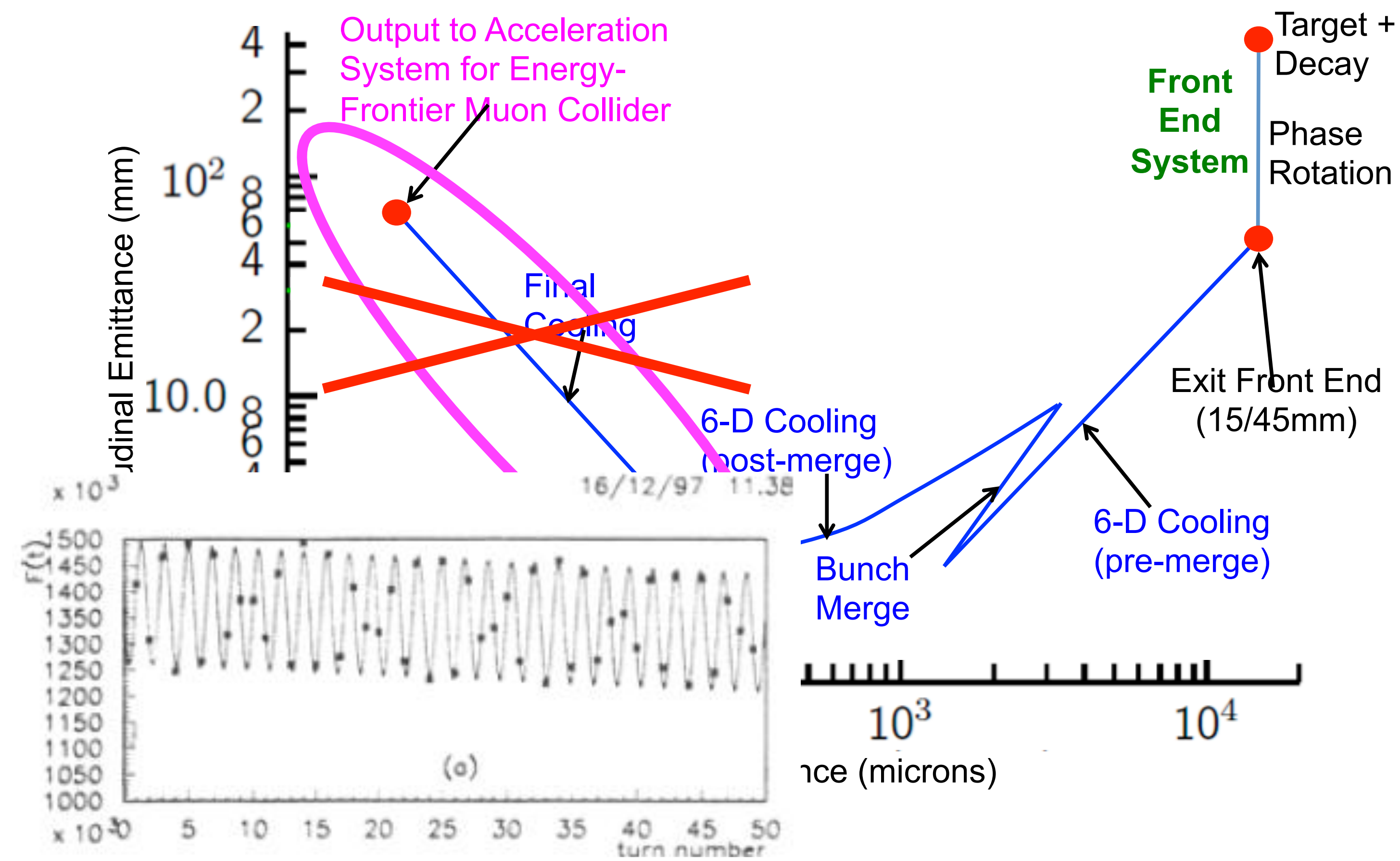

[P. Janot, HF2012]

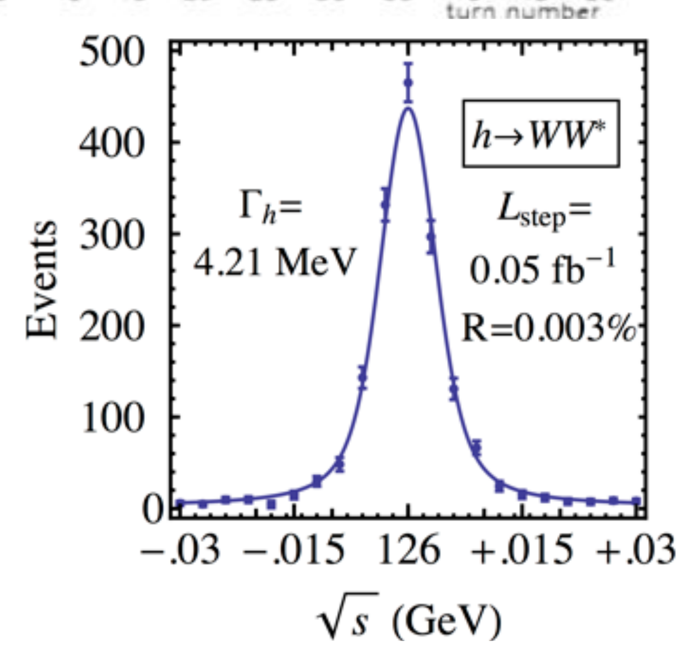
# Higgs Factory

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

  ⇒ omit final cooling

  - $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!
  - measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan
    - the only way to do so!
    - and a key test of the SM



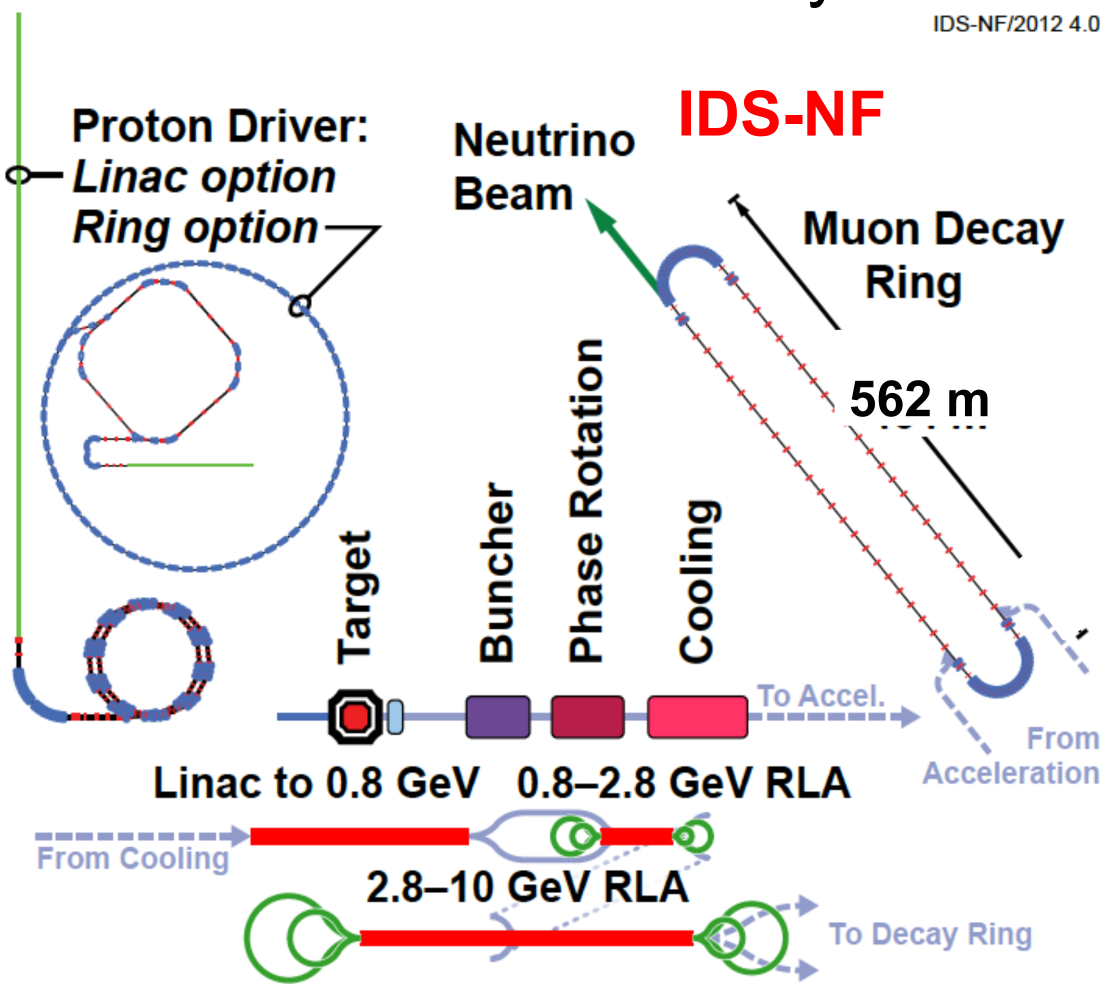



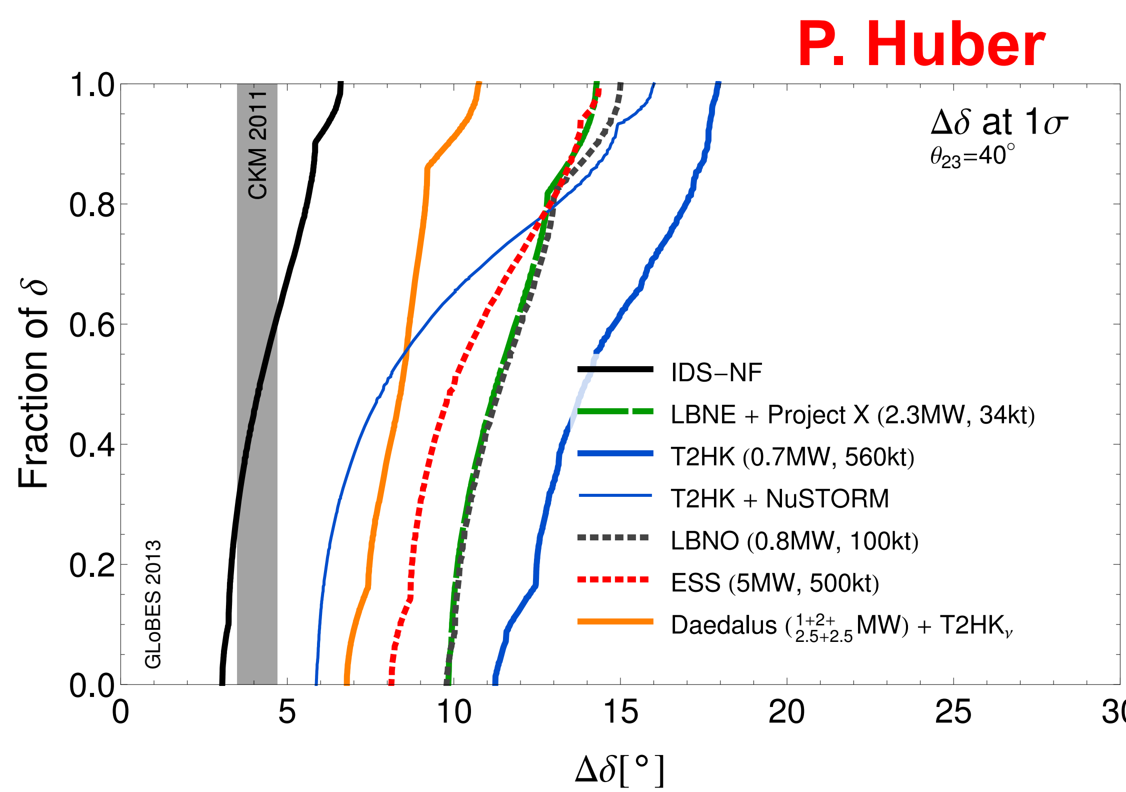

[P. Janot, HF2012]

# Neutrino Factory Physics Reach

[from P. Soler]

- International Design Study for a Neutrino Factory (IDS-NF):
  - Most sensitive facility for the study of CP violation in neutrinos




**Can reach uncertainty in $\delta_{CP}$ of 5°**

**Test three-neutrino mixing paradigm**

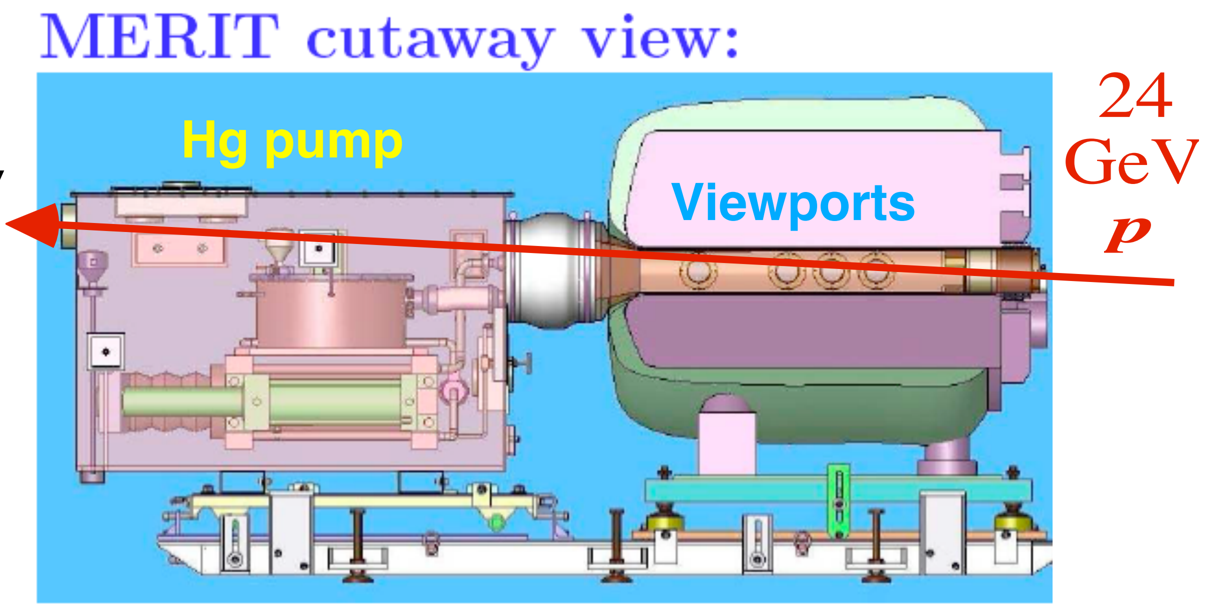
# 1. High-Power Target

- Multi-MW beam likely to melt almost any solid target!
  - so why not use liquid?
  - Hg (high-*A*) makes ≈equal #s of $\mu^+$ and $\mu^-$
    - can remove radioactive spallation products by distillation
  - container risky (erosion, shock), so free Hg jet
- Proof of principle: MERcury Intense Target (MERIT) Experiment @ CERN

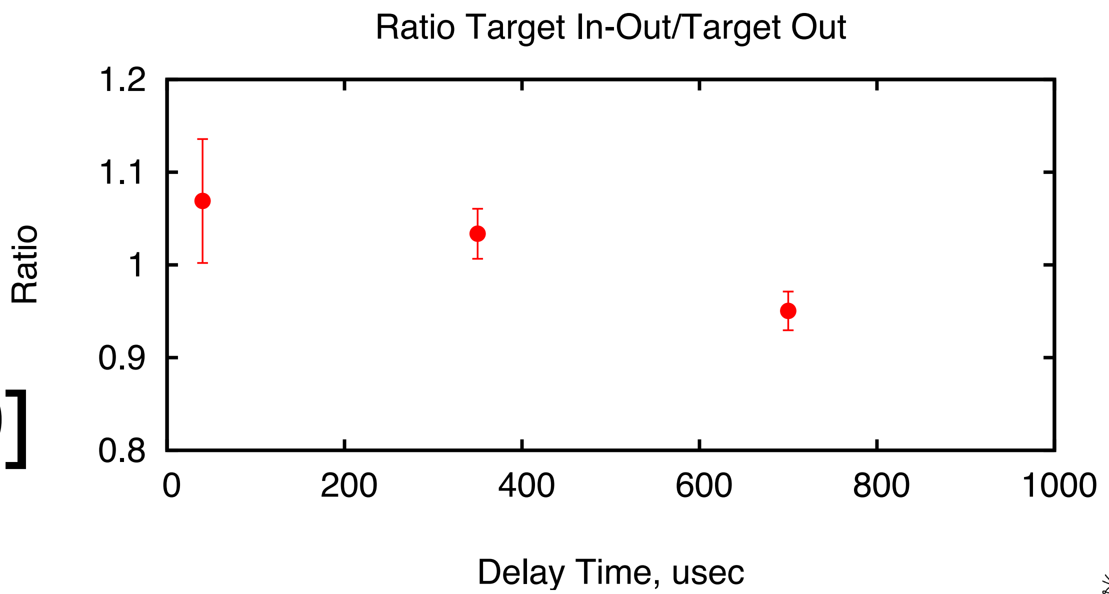
# MERIT

- Experiment carried out @ CERN nTOF facility in 2007
- BNL/CERN/KEK/ORNL/ Princeton collaboration
  - Hg jet, 1 cm diam, 20 m/s, jet axis at 33 mrad to magnet axis ($B \leq 15$ T)
  - concept demonstrated workable up to ≈8 MW

[K. McDonald *et al.*, Proc. IPAC'10]



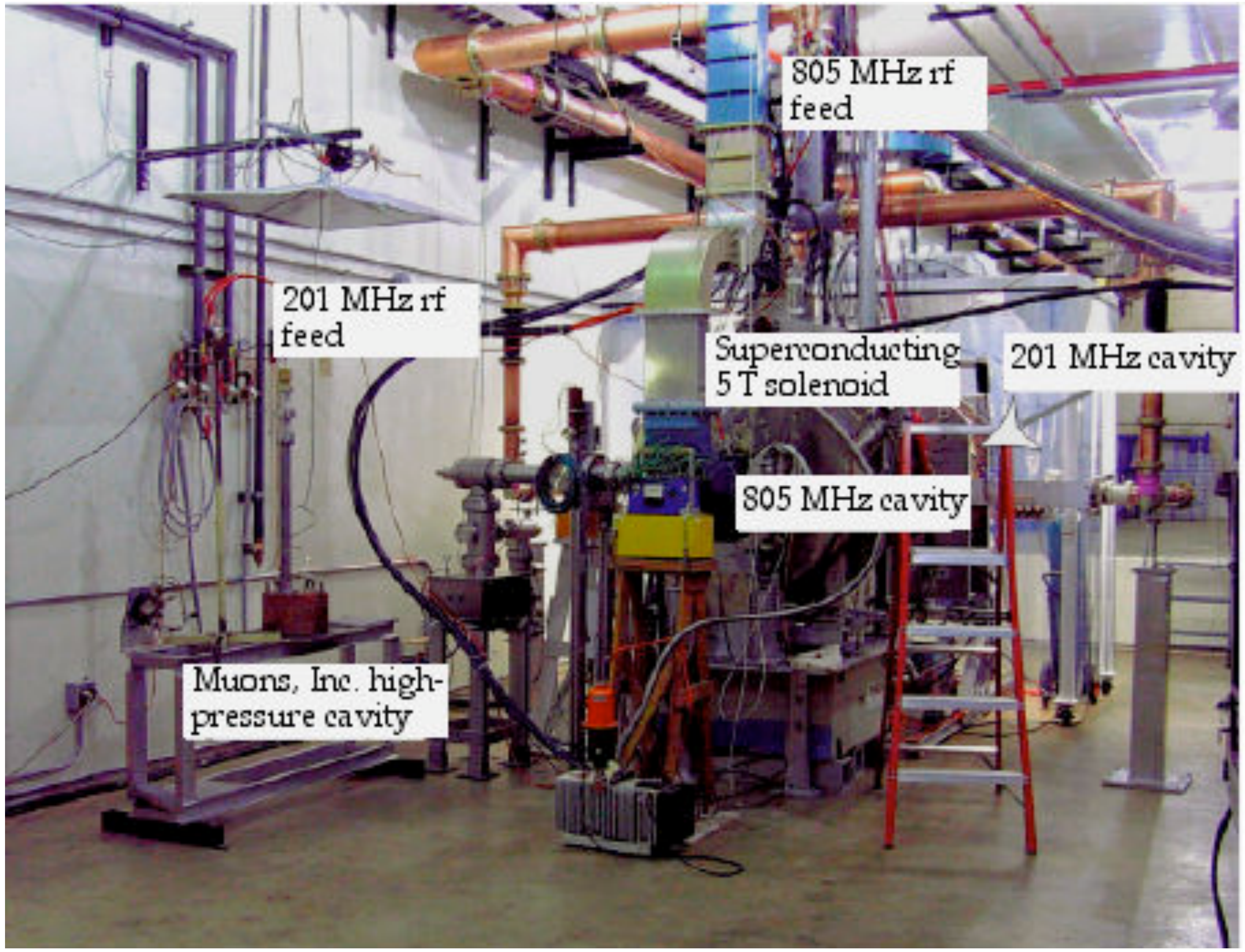




# RF Cavities in B Fields

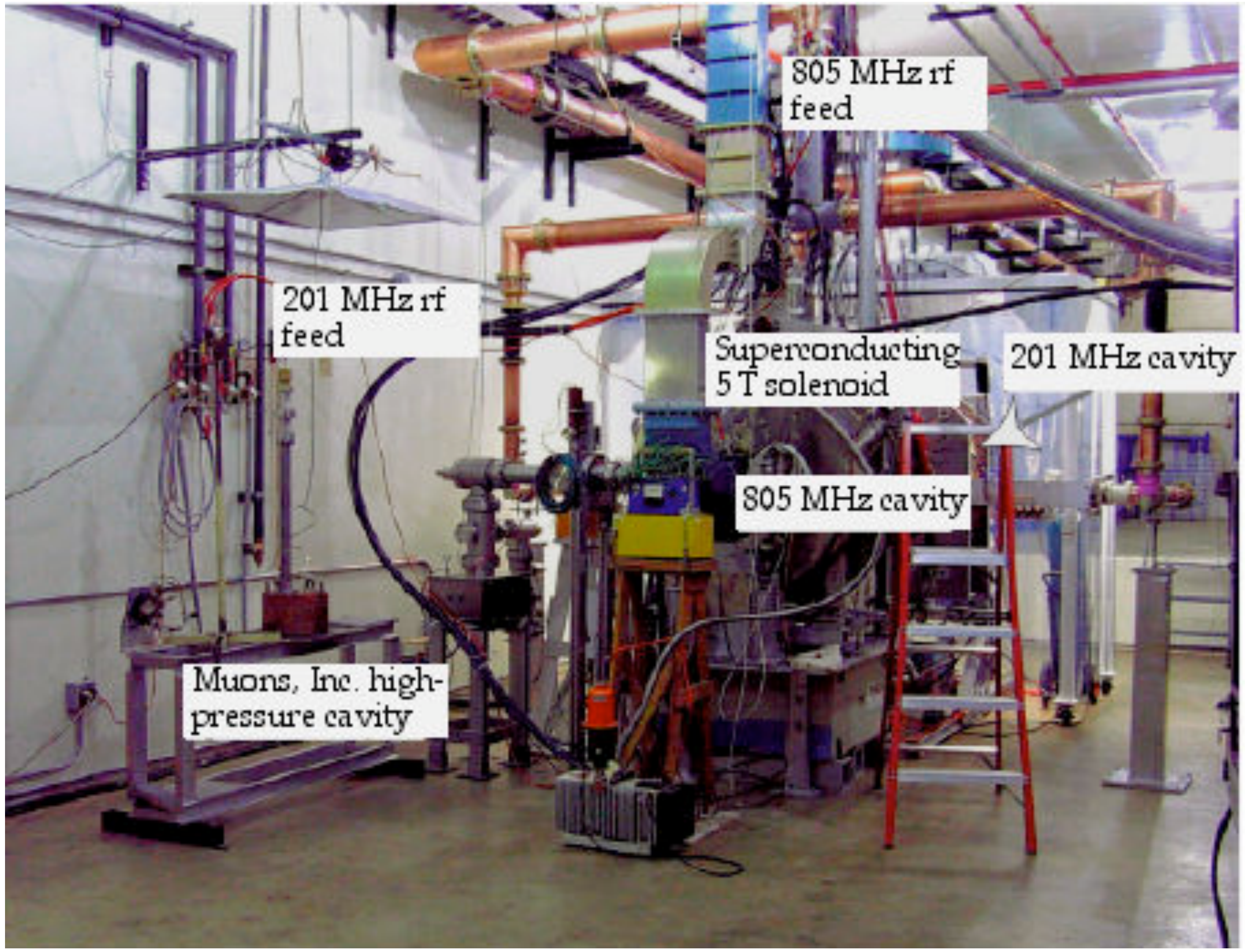
# RF Cavities in B Fields

- Muon cooling lattices put high-gradient normal-conducting RF cavities close to focusing solenoids
- Effect studied at Fermilab MuCool Test Area (MTA)
- MTA has:



# RF Cavities in B Fields

- Muon cooling lattices put high-gradient normal-conducting RF cavities close to focusing solenoids
- Effect studied at Fermilab MuCool Test Area (MTA)

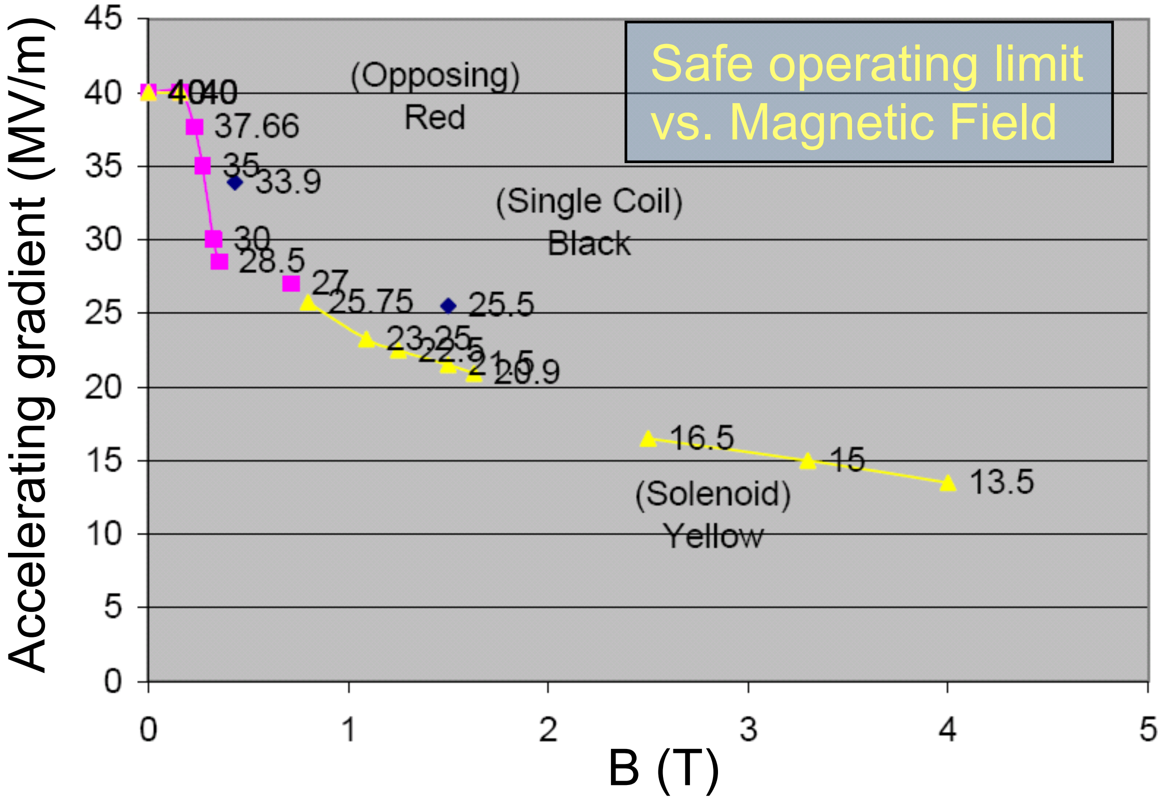



- MTA has:
  - 5 T solenoid
  - 201 and 805 MHz RF power
  - cryogenics infrastructure
  - high-intensity 400 MeV $H^{-}$ beam

# RF Cavities in B Fields

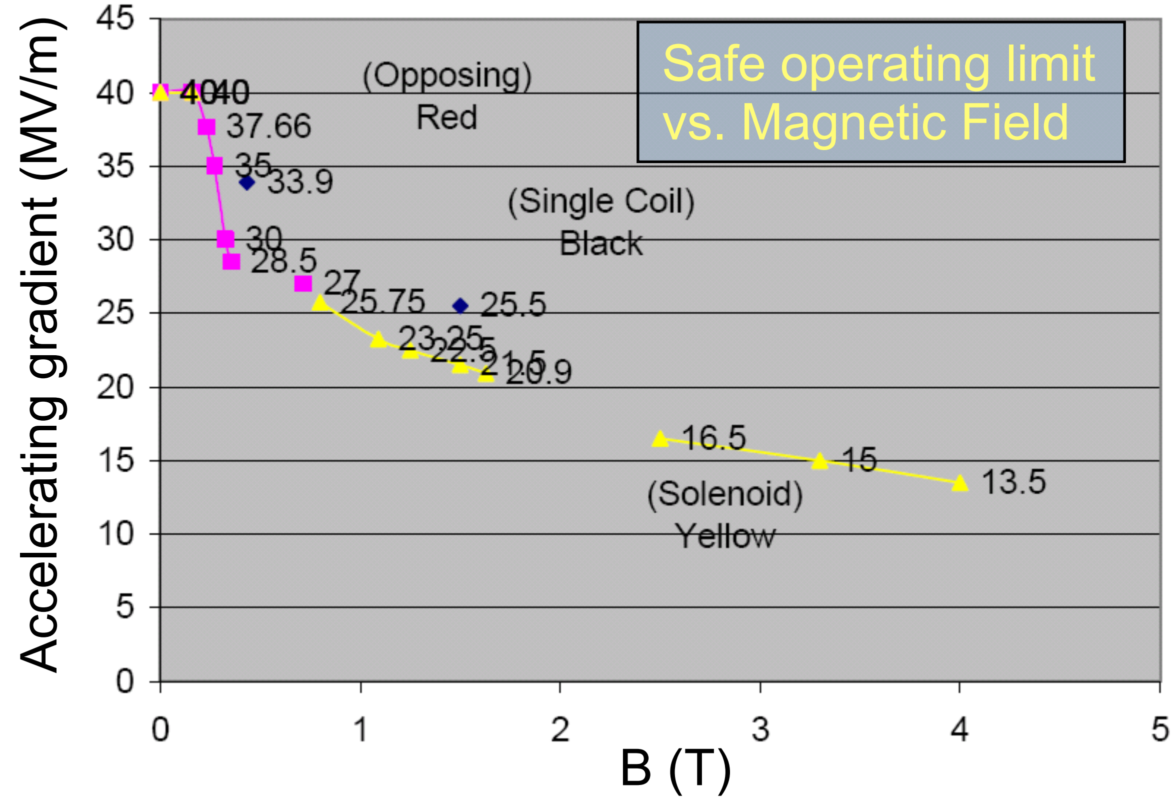
# RF Cavities in B Fields

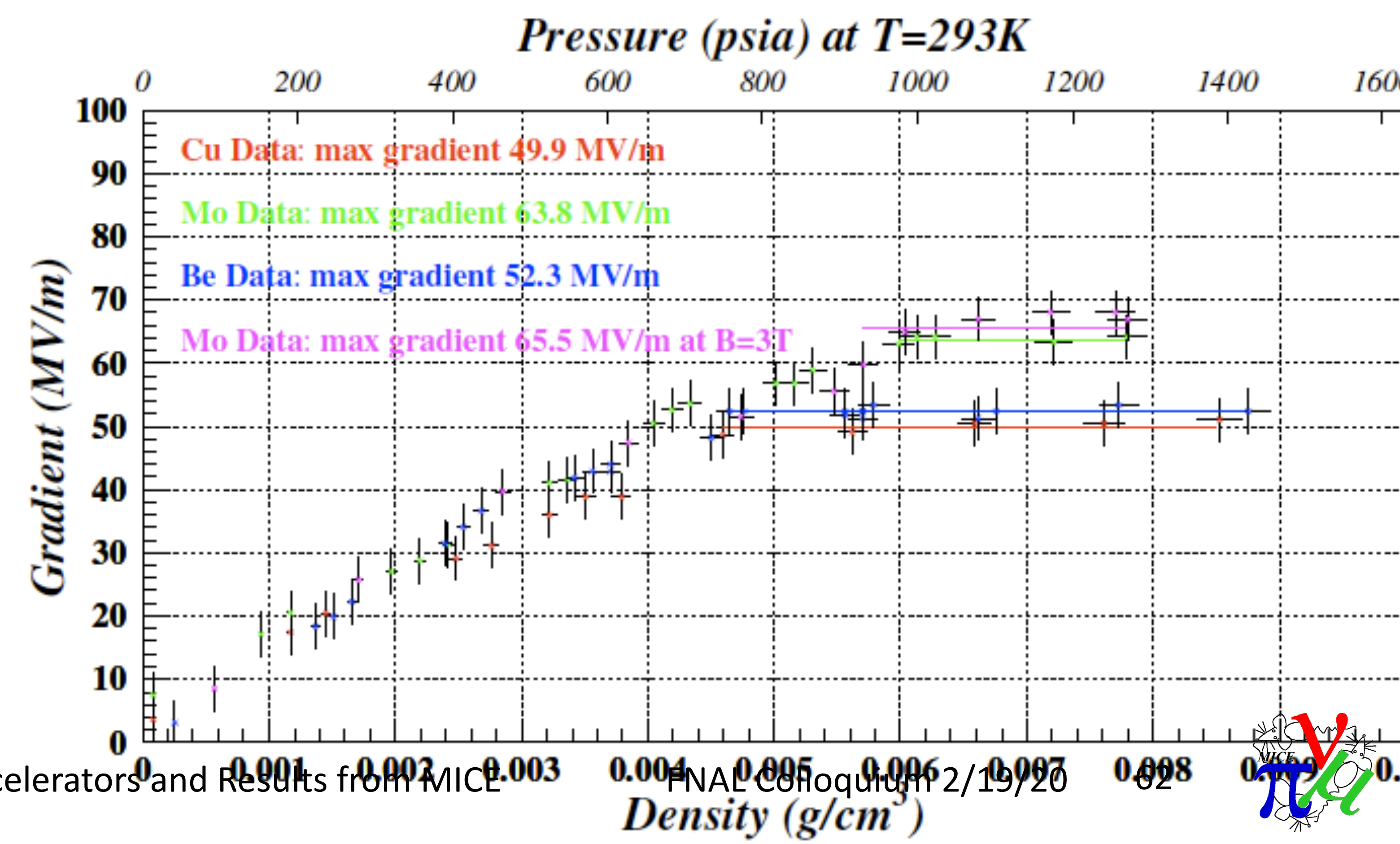
- Observe performance degradation for *B* ~ T



# RF Cavities in B Fields

- Observe performance degradation for *B* ~ T
- Possible solutions:
  - surfaces that
    - suppress breakdown (very smooth and/or special materials/coatings)
    - minimize breakdown-induced damage
  - high-pressure cavities
    - $H_2$ gas; *dE*/*dx* absorber, as well as breakdown suppressant

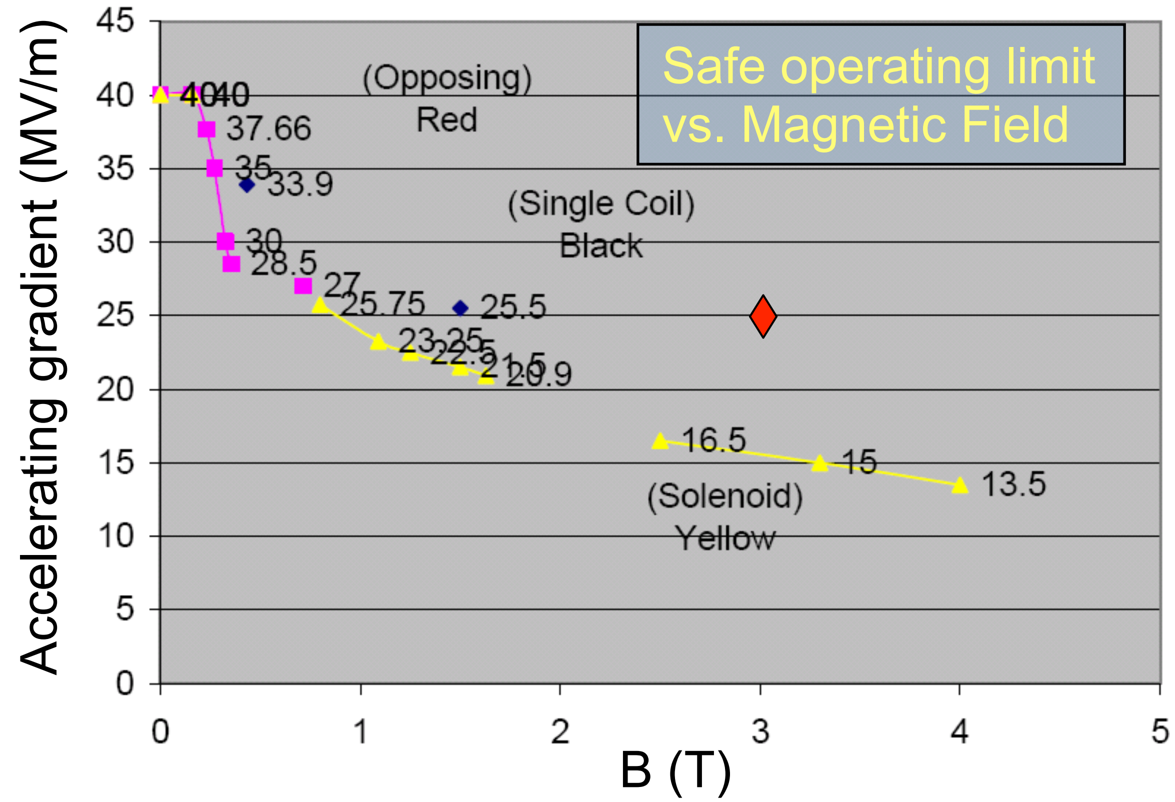


# RF Cavities in B Fields

- Observe performance degradation for *B* ~ T

- Possible solutions:
  - surfaces that
    - suppress breakdown (very smooth and/or special materials/coatings)
    - minimize breakdown-induced damage
  - high-pressure cavities
    - $H_2$ gas; *dE/dx* absorber, as well as breakdown suppressant



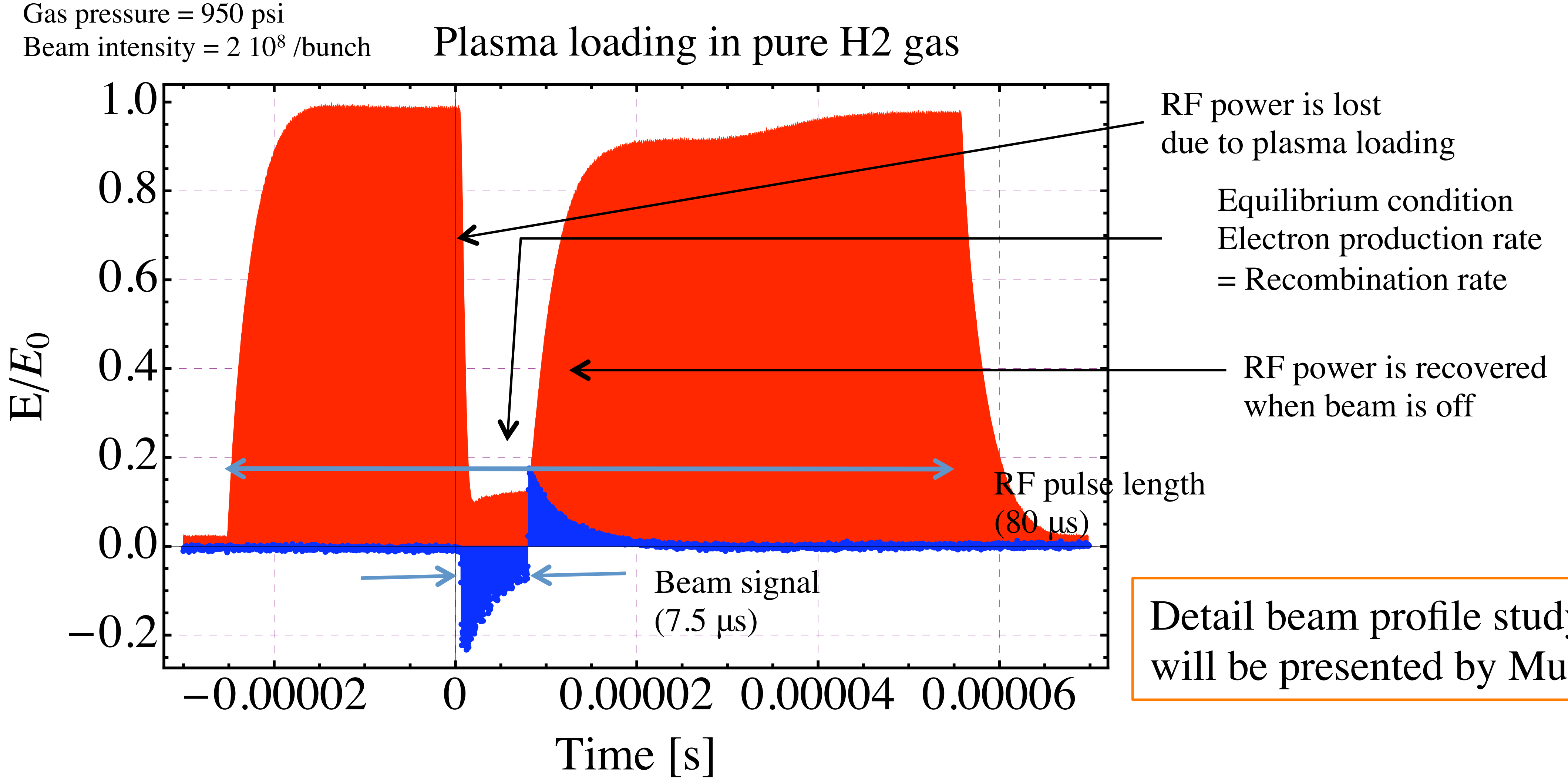

All are under study...

- one possibility: RF coupler issues at high *B*
  - supported by recent "all-seasons-cavity" result: 25 MV/m at 3 T

➡ will learn more this year

# Study interaction of intense beam with dense H2 in high gradient RF field

ν= 802 MHz
Gas pressure = 950 psi
Beam intensity = 2 $10^8$ /bunch



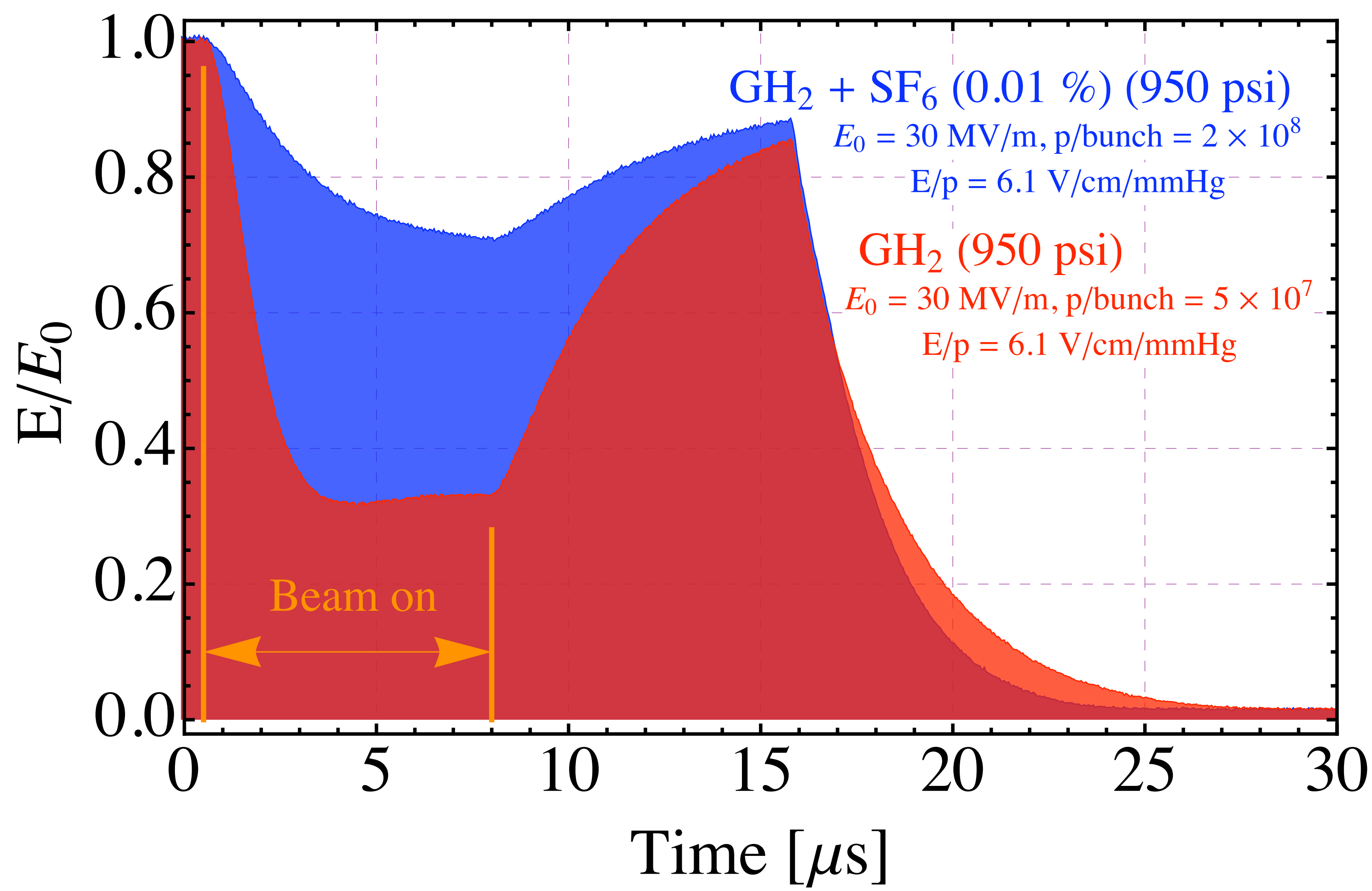

Detail beam profile study will be presented by Mukti

Ionization process

$p + H_2 \rightarrow p + H_2^+ + e^-$

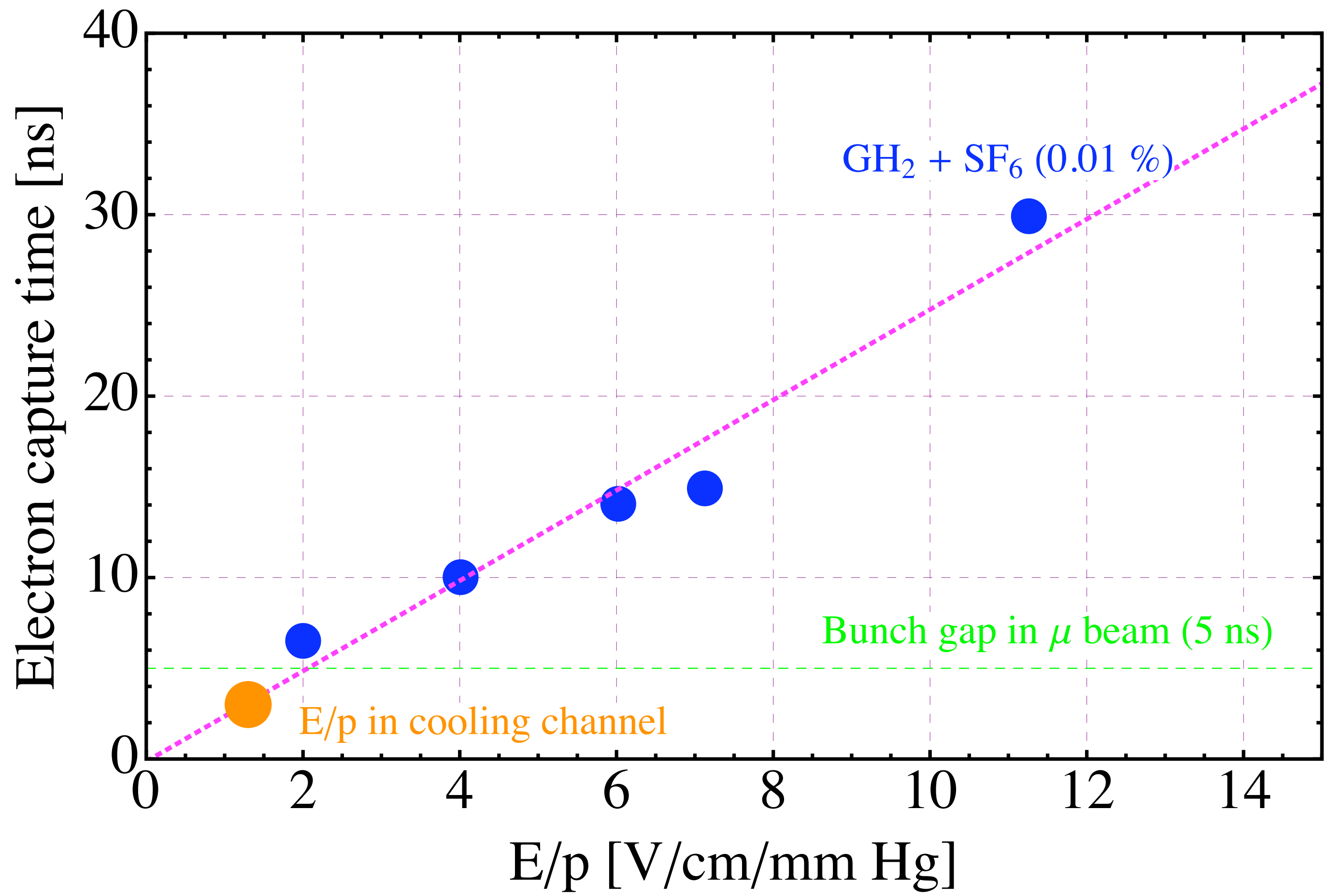
1,200 $e^-$/cm are generated by incident p @ K = 400 MeV

# Study electronegative gas effect




SF6 removes residual electrons

# Compare with muon beam structure




- E/p in helical 6D cooling channel is 1.6 V/cm/mm Hg
- Bunch gap is 5 ns
- Electron capture time looks to be fast enough for real application

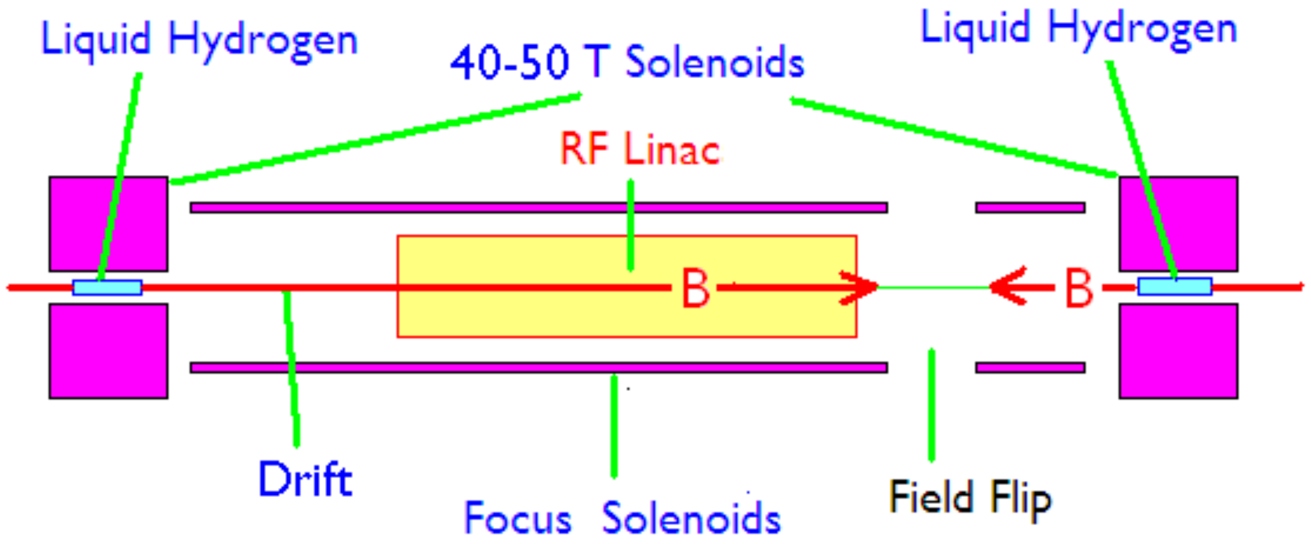
# Final Cooling

# Final Cooling

- Palmer final-cooling cell:

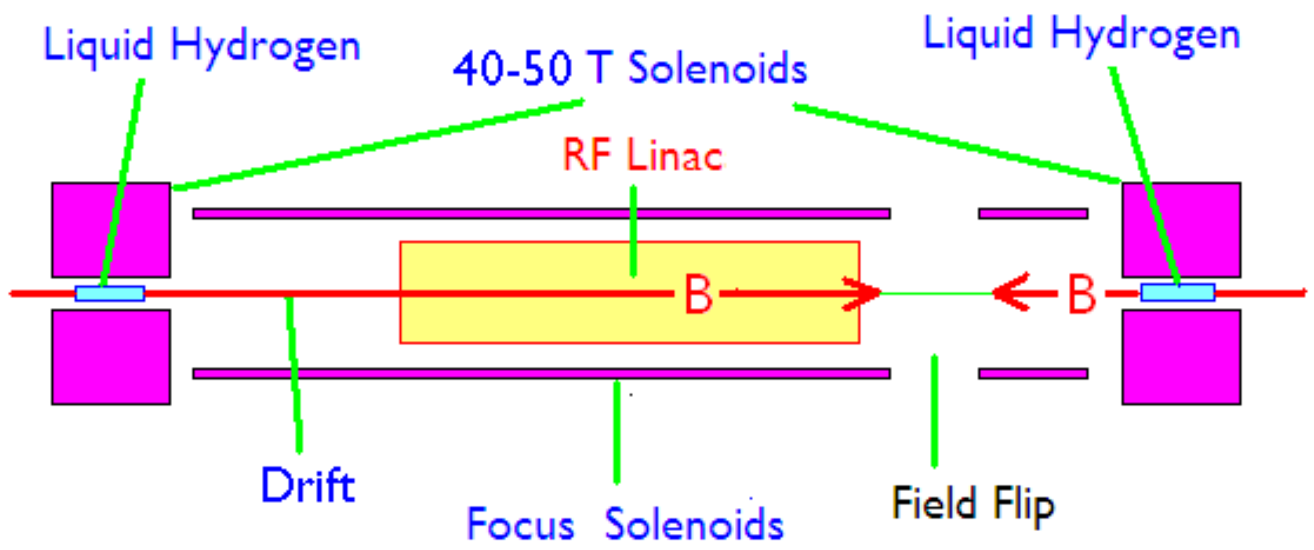
# Final Cooling

- Palmer final-cooling cell:

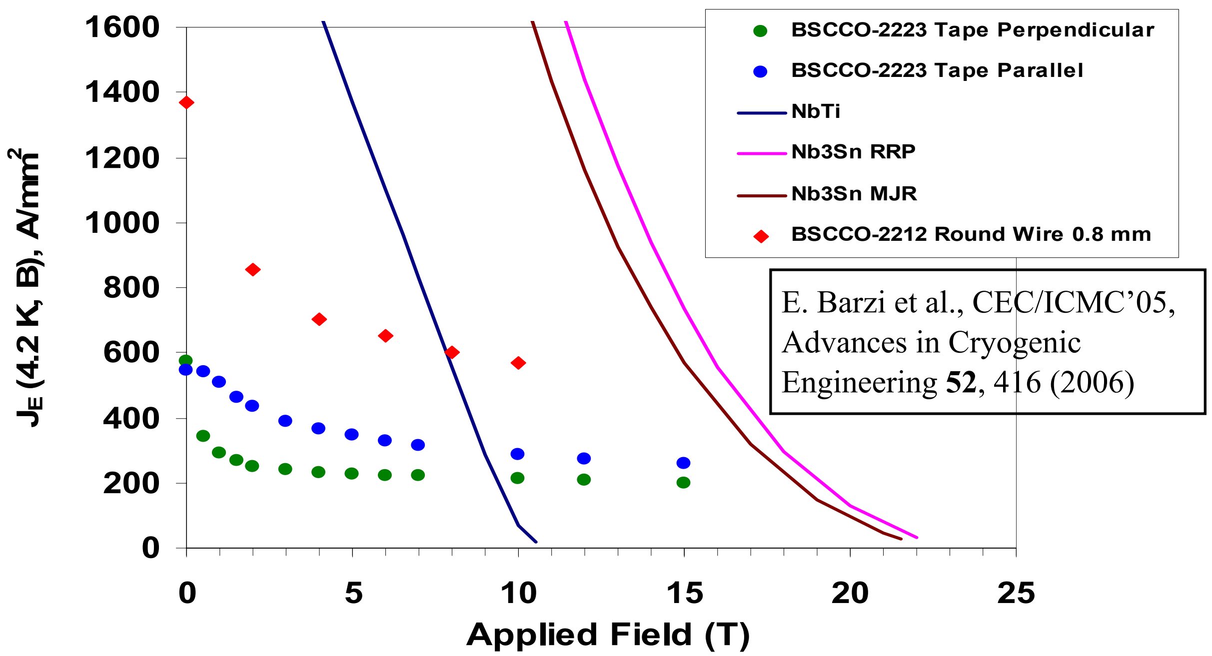


# Final Cooling

- Palmer final-cooling cell:



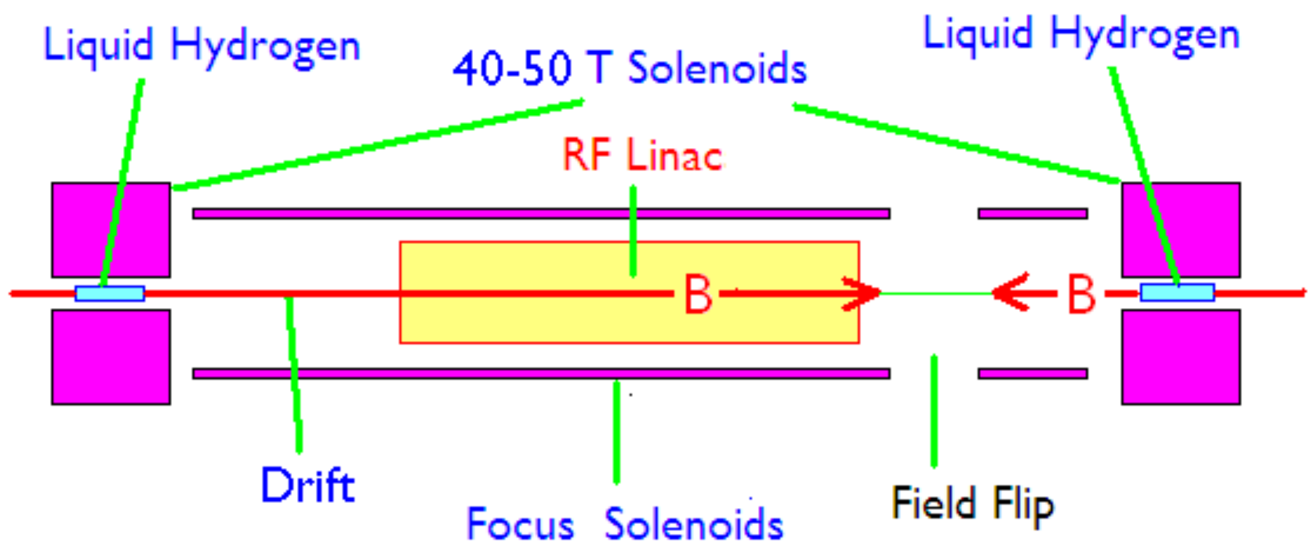

- HTS $J_E$ @ 4.2 K quite flat vs B:



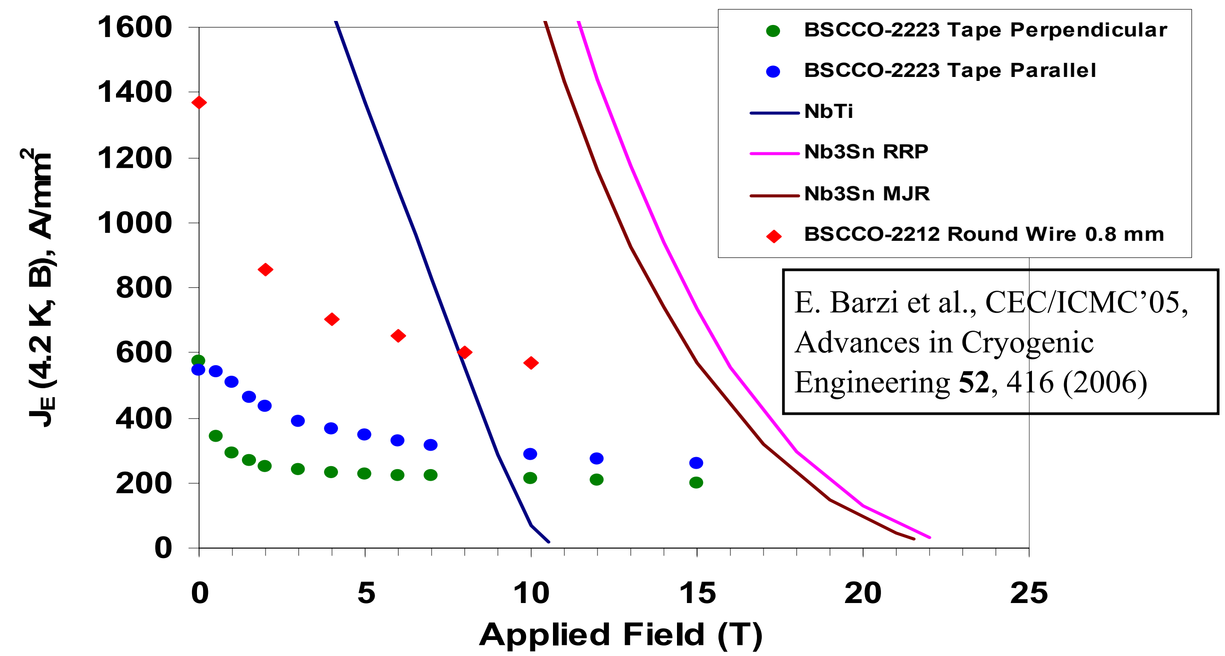

(∃ YBCO 33.8 T hybrid solenoid @ NHMFL)

# Final Cooling

- Palmer final-cooling cell:




- HTS $J_E$ @ 4.2 K quite flat vs B:

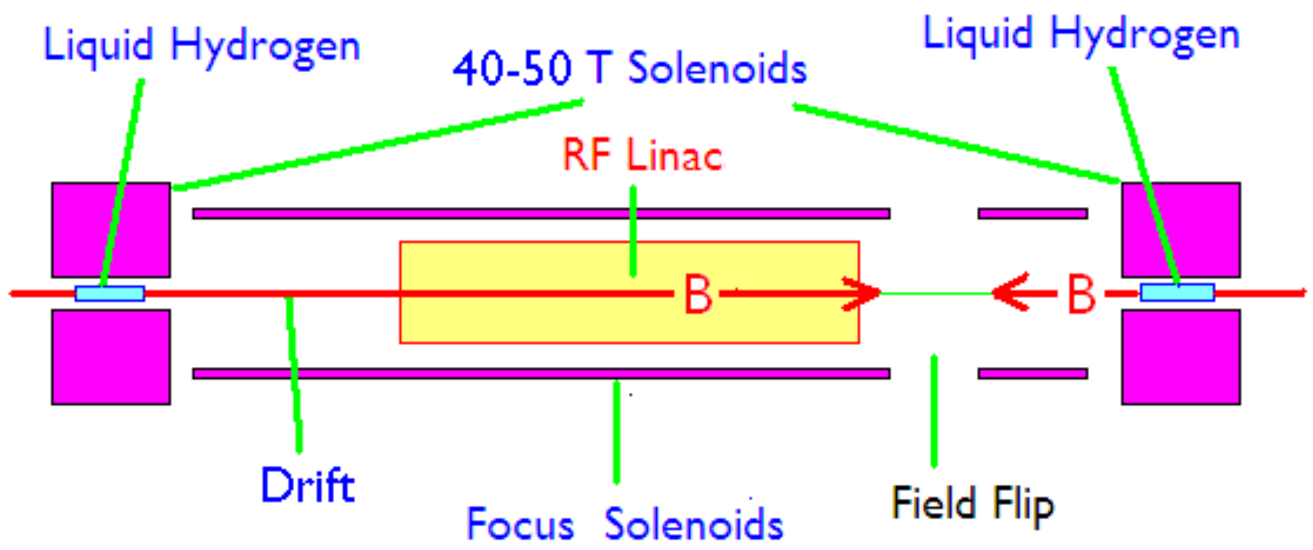



(∃ YBCO 33.8 T hybrid solenoid @ NHMFL)

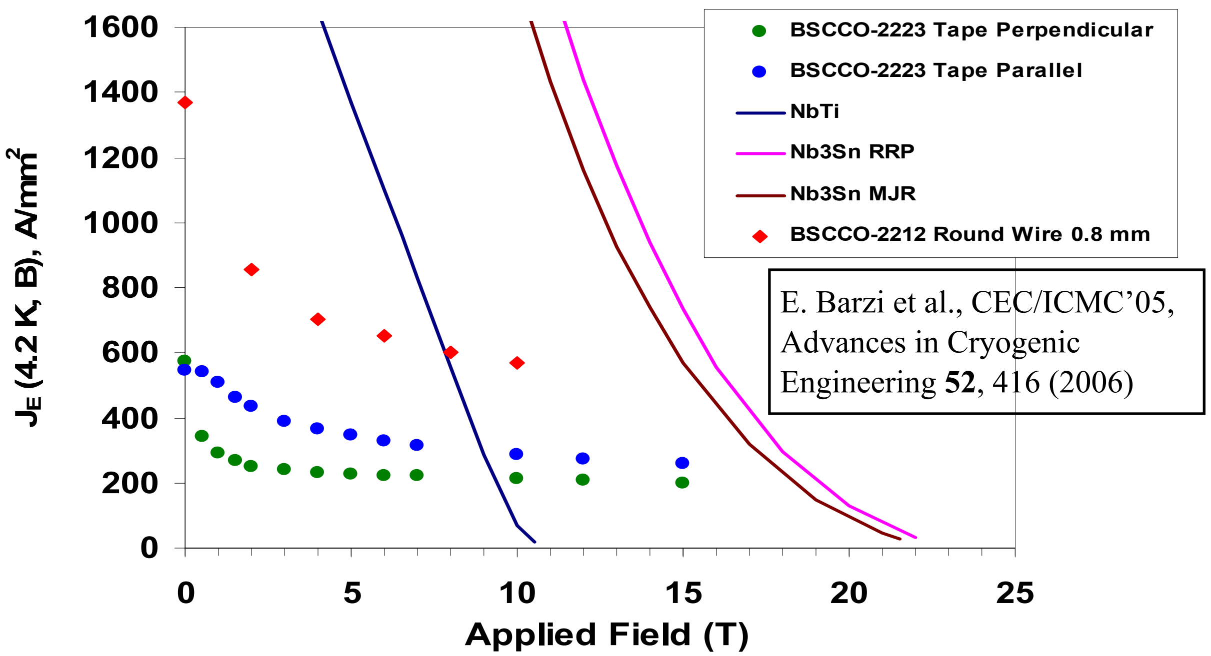
- Simulation of 13 stages:

# Final Cooling

- Palmer final-cooling cell:

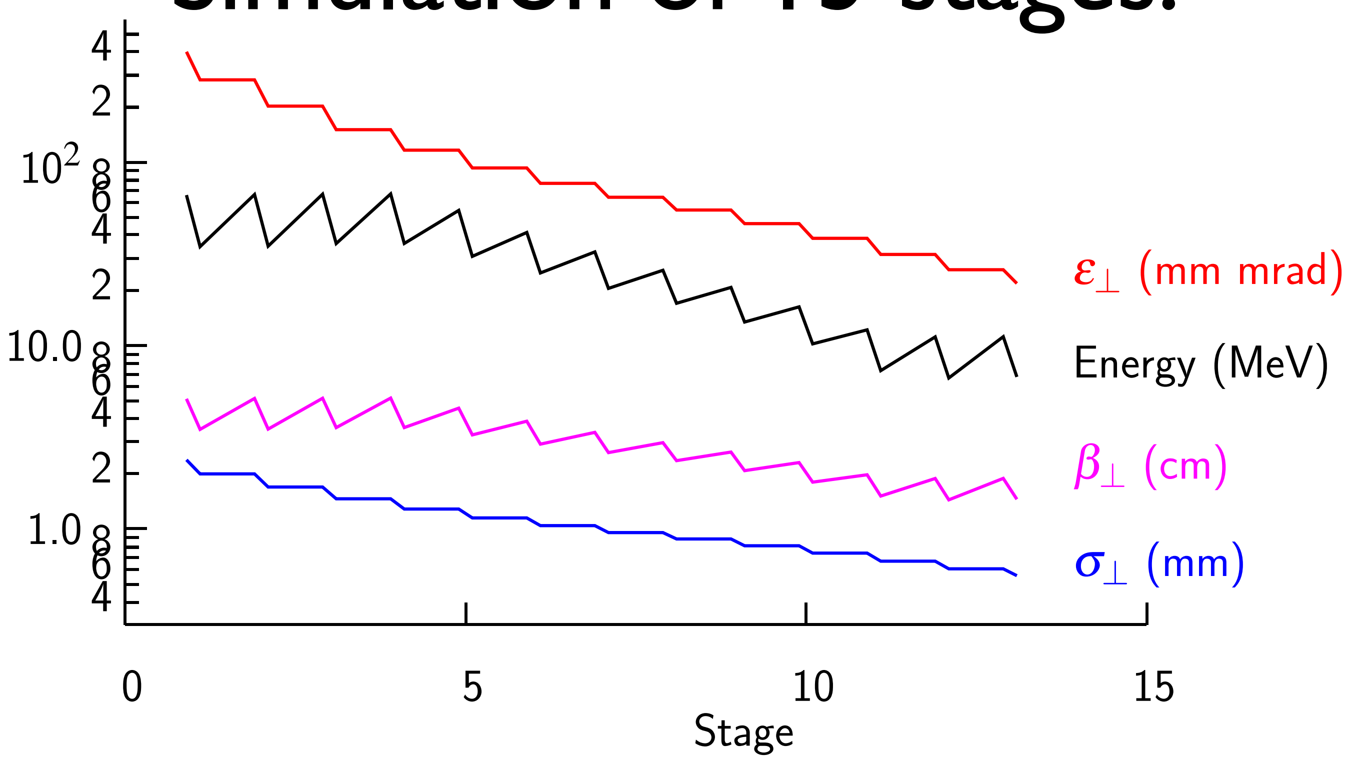



- HTS $J_E$ @ 4.2 K quite flat vs B:



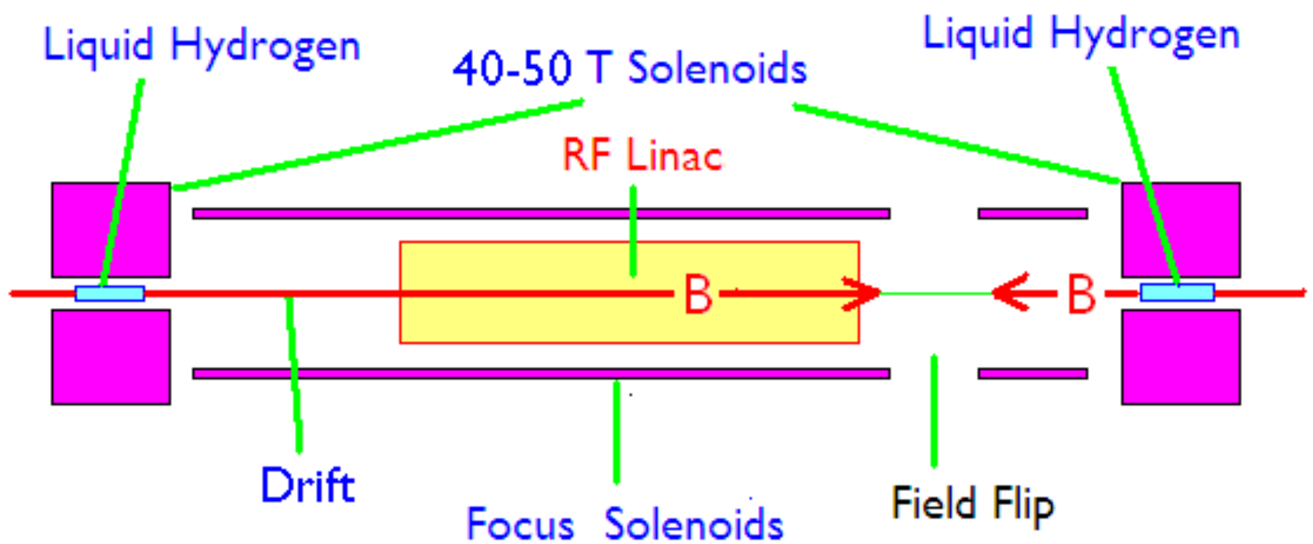

(∃ YBCO 33.8 T hybrid solenoid @ NHMFL)

- Simulation of 13 stages:

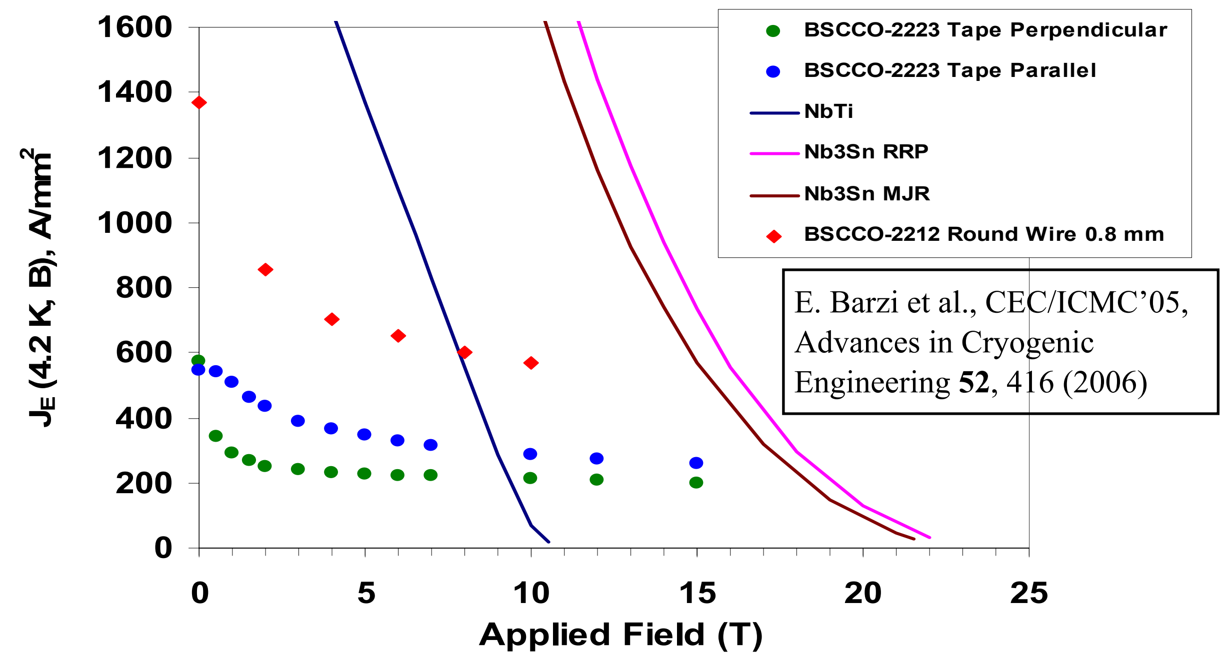


# Final Cooling

- Palmer final-cooling cell:

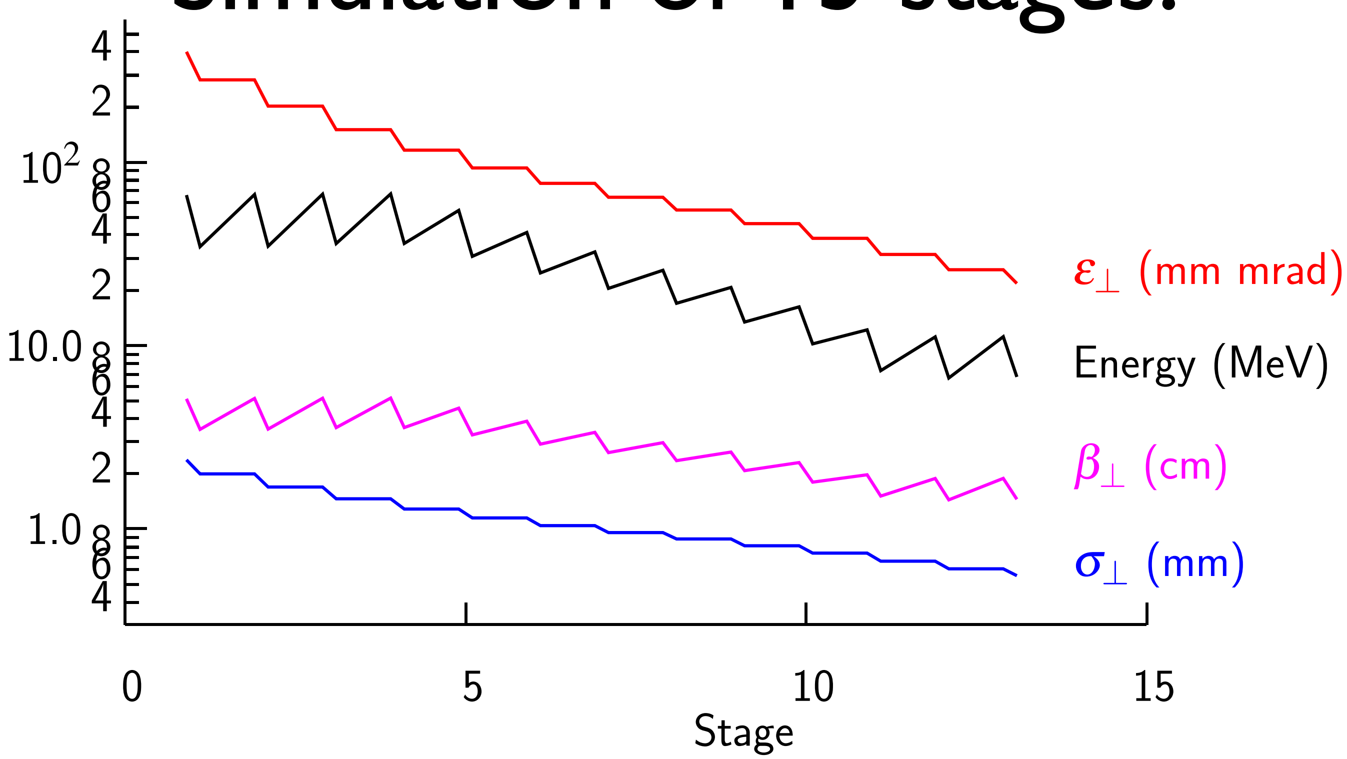



- HTS $J_E$ @ 4.2 K quite flat vs B:




(∃ YBCO 33.8 T hybrid solenoid @ NHMFL)

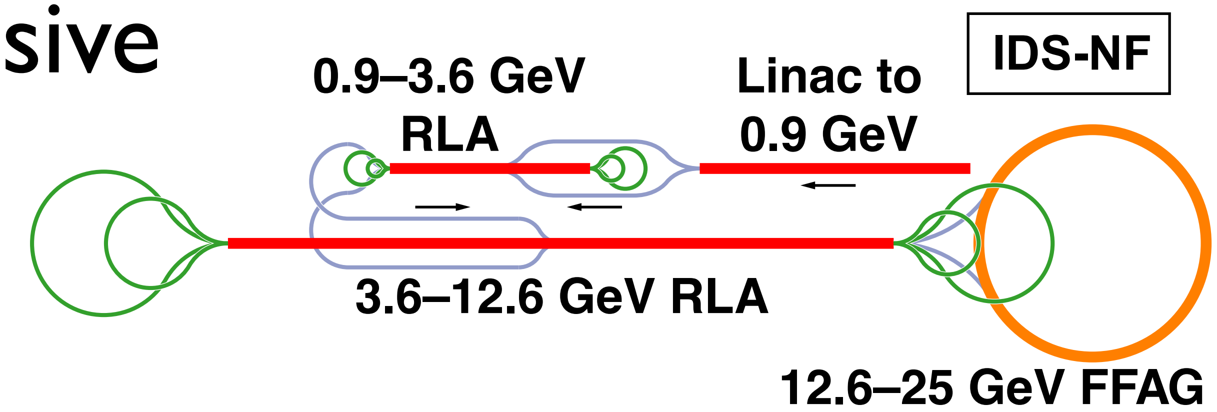
- Simulation of 13 stages:




- Beam energy falls from 70 MeV (135 MeV/c) to ≈ 6 MeV
- Bunch length rises from 5 cm to 300 cm rms
- Beam rms radius falls from 2 cm to 6 mm, $\varepsilon_\perp$ to 23 μm
- 65% transmission

# 3. Muon Acceleration

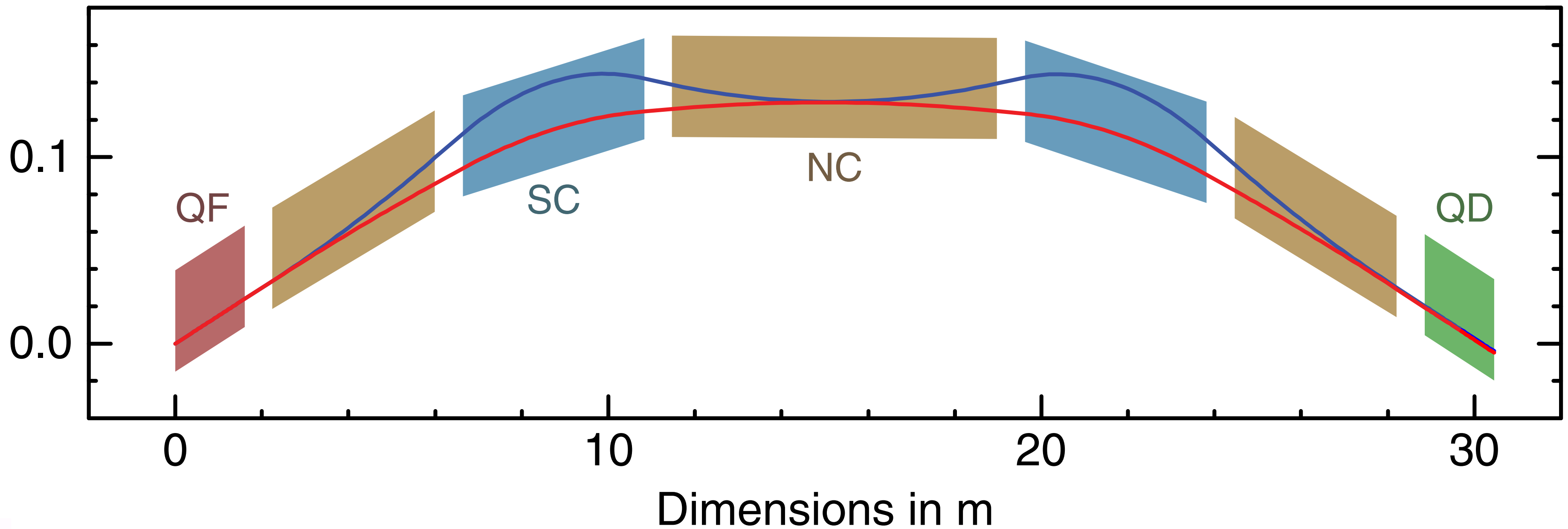
- Typically the most expensive subsystem




- Initial linac
- Then recirculating linacs (RLA) & FFAG(s)
- Finally, rapid-cycling synchrotrons (RCS)

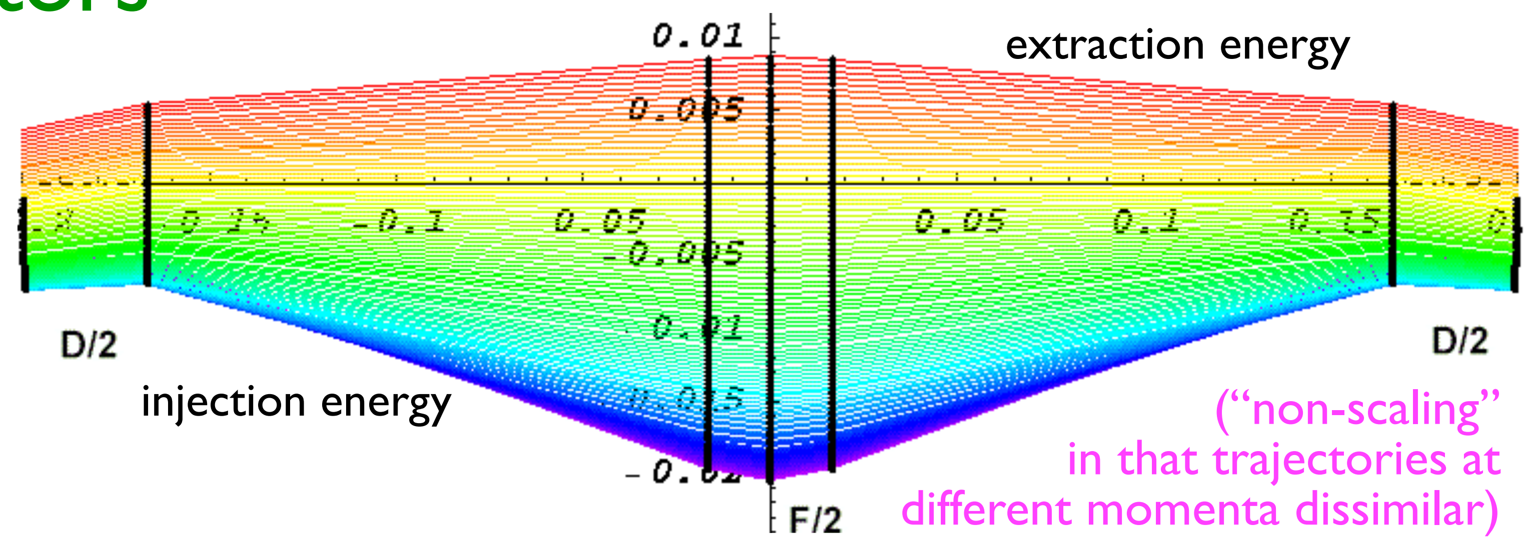
} increasingly cost-effective

- RCS (to 750 GeV) uses hybrid 8T SC and –1.8 to +1.8 T pulsed dipoles



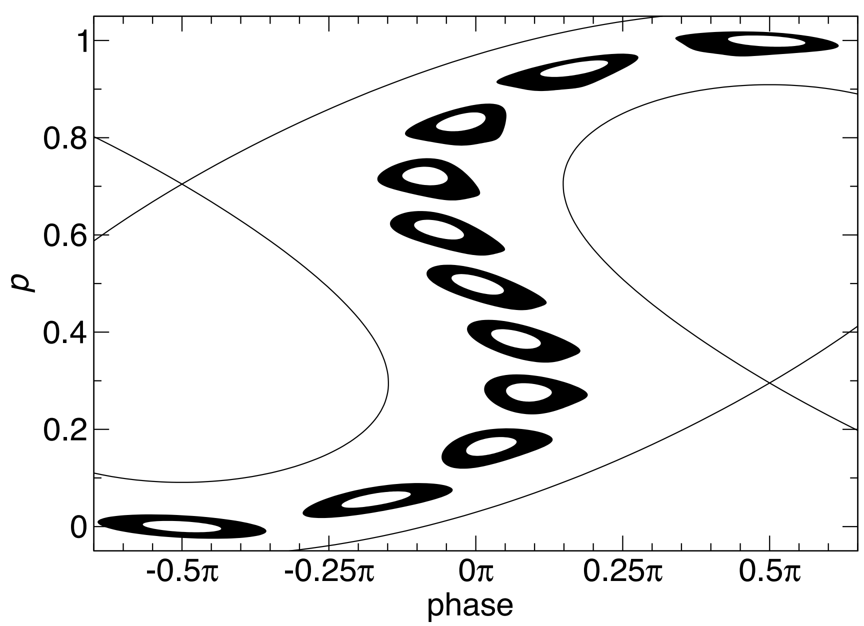
# 3. Muon Acceleration

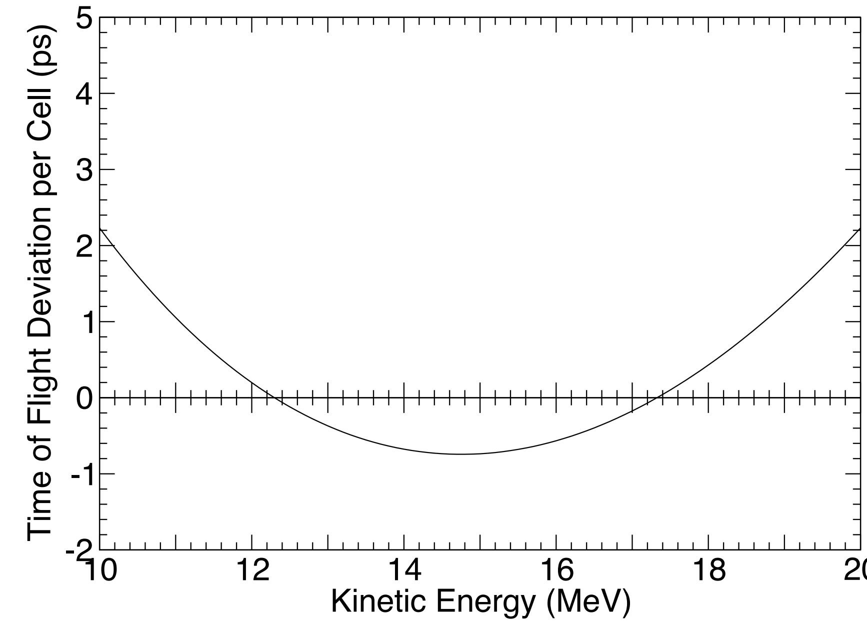
- Baseline designs use novel, non-scaling, fixed-field alternating-gradient (FFAG) accelerators
  - lattice includes both in- & out-bends for large $\Delta p/p$ acceptance




(“non-scaling” in that trajectories at different momenta dissimilar)

  - “serpentine” acceleration, between buckets, quickly crossing multiple resonances



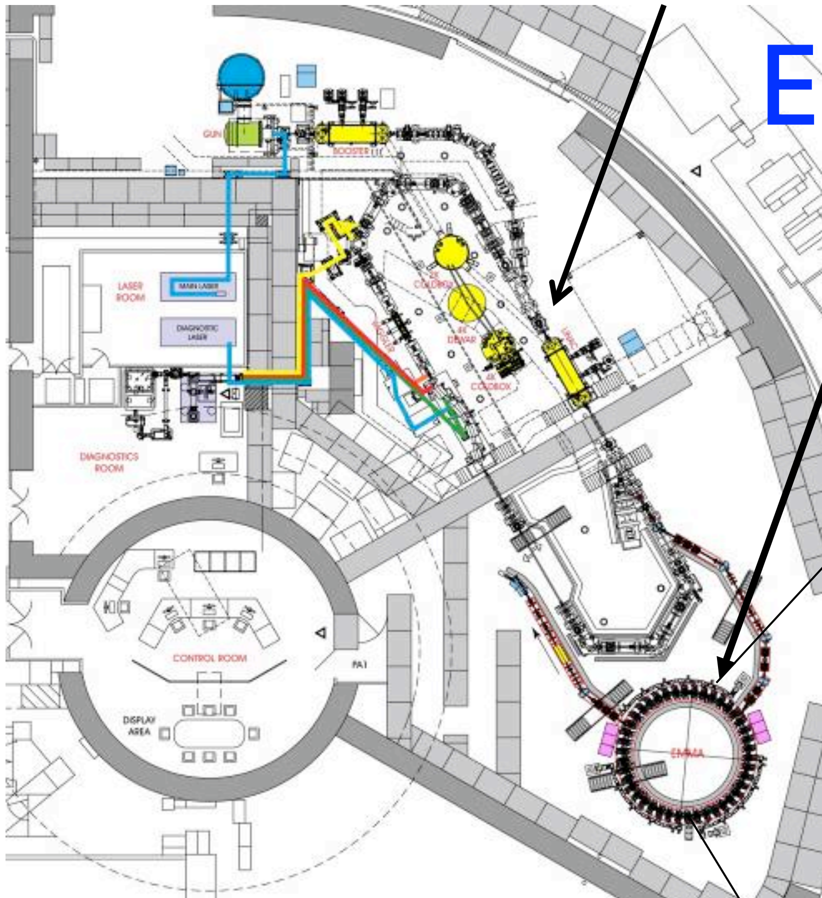




  - proof of principle: Electron Machine with Many Applications (EMMA) @ Daresbury Lab

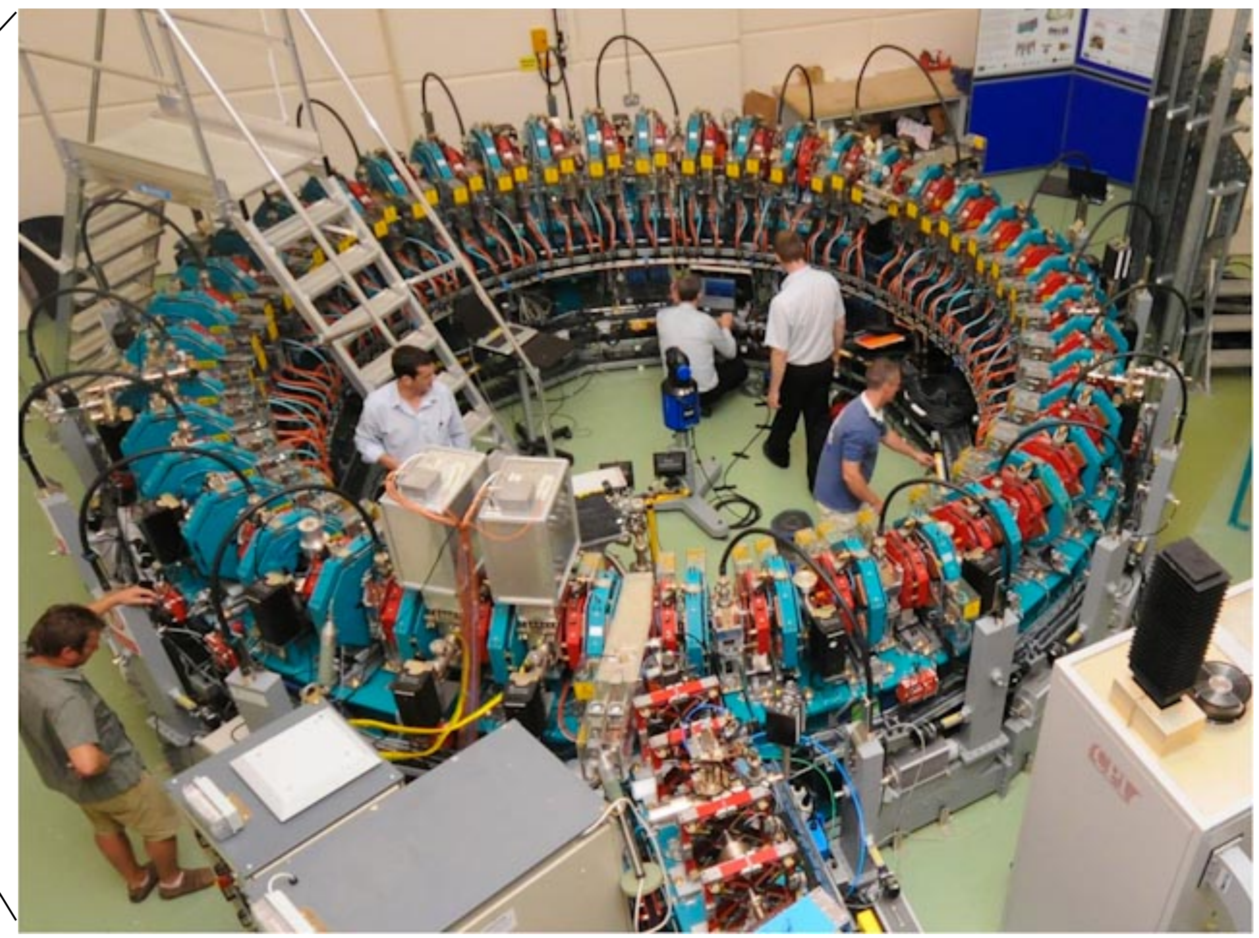
# 3. Muon Acceleration

ALICE

EMMA



- Proposed NS-FFAG applications include proton drivers, muon accelerators, cancer therapy, subcritical U&Th fission reactors...



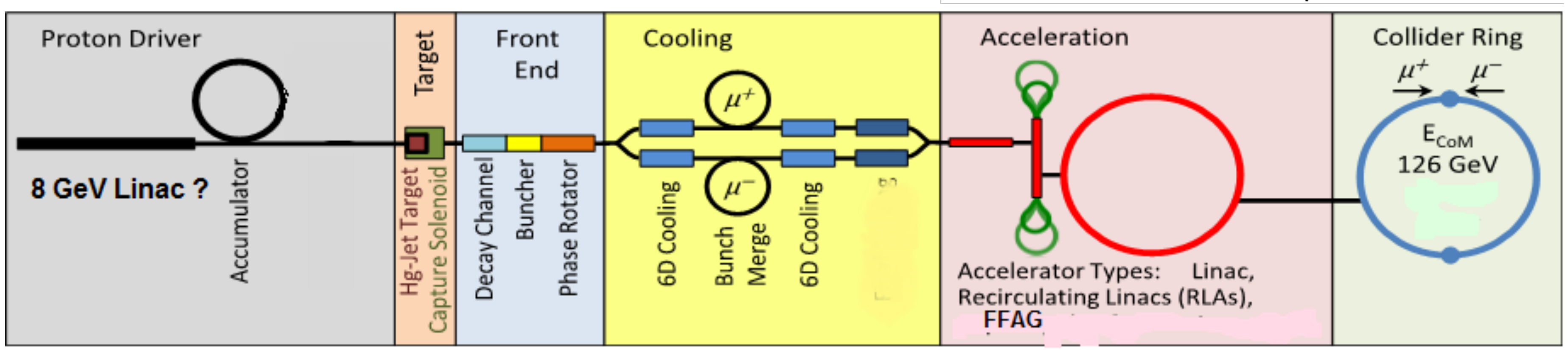
- Started 2007
- 1st beam 2010
  - electron acceleration successful

From D. Neuffer:

# 126 GeV $\mu^+$-$\mu^-$ Collider

- **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch
- **$\pi\rightarrow\mu$ collection, bunching, cooling**
  - $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
    - $10^{12}$ μ/ bunch
- **Accelerate, Collider ring**
  - $\delta E$ = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - $\delta E_{error}$ → 0.1 MeV

| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+},E_{\mu-}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0004m |
| Longitudinal emittance | $\varepsilon_{LN}$ | 0.002m |
| Energy spread | $\delta E$ | 4MeV |
| Collision $\beta^*$ | $\beta^*$ | 0.05 m |
| Beam size at collision | $\sigma_{x,y}$ | 0.02cm |
| Beam size (arcs) | $\sigma_{x,y}$ | 1.0cm |
| Beam size IR quad | $\sigma_{max}$ | 5.4cm |
| Storage turns | $N_t$ | 1000 |
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 60 Hz |
| Protons per bunch | $N_p$ | $5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |




22

From D. Neuffer:

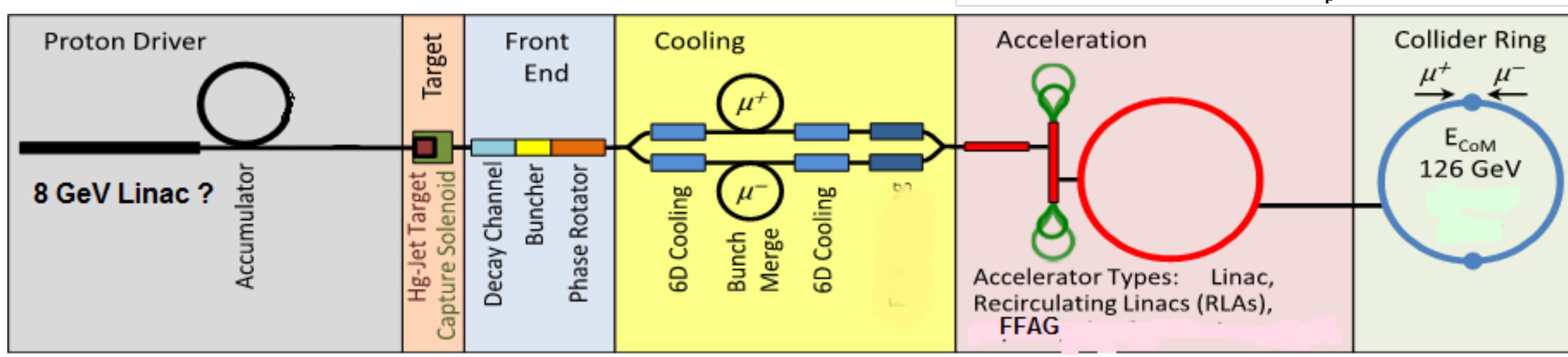
# 126 GeV $\mu^+$-$\mu^-$ Collider

- Note *s*-channel enhancement:

  $(m_\mu/m_e)^2 \rightarrow \times$ 43,000 in cross section vis-à-vis $e^+e^-$

- **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch
- **π→μ collection, bunching, cooling**
- $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
  - $10^{12}$ μ/ bunch
- **Accelerate, Collider ring**
  - δE = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - $\delta E_{error}$ → 0.1 MeV

| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+}$,$E_{\mu\_}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0004m |
| Longitudinal emittance | $\varepsilon_{LN}$ | 0.002m |
| Energy spread | δE | 4MeV |
| Collision $\beta^*$ | $\beta^*$ | 0.05 m |
| Beam size at collision | $\sigma_{x,y}$ | 0.02cm |
| Beam size (arcs) | $\sigma_{x,y}$ | 1.0cm |
| Beam size IR quad | $\sigma_{max}$ | 5.4cm |
| Storage turns | $N_t$ | 1000 |
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 60 Hz |
| Protons per bunch | $N_p$ | $5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |




22

From D. Neuffer:

# 126 GeV $\mu^+$-$\mu^-$ Collider

- Note *s*-channel enhancement:

  $(m_\mu/m_e)^2 \rightarrow \times$ 43,000 in cross section vis-à-vis $e^+e^-$

- So $10^{31}$ suffices

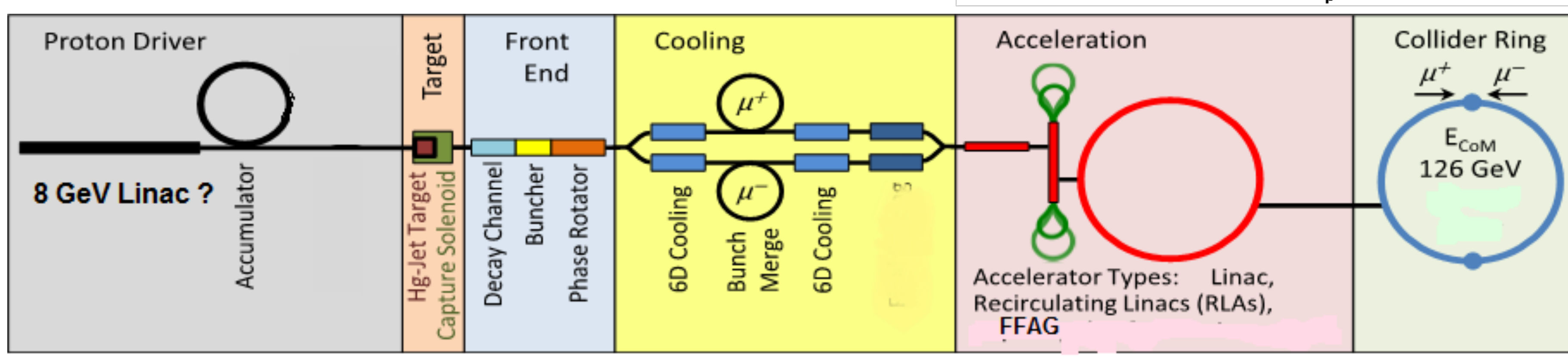
➢ **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch

➢ **π→μ collection, bunching, cooling**

➢ $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
  - $10^{12}$ μ/ bunch

➢ **Accelerate, Collider ring**
  - δE = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - $\delta E_{error} \rightarrow$ 0.1 MeV

| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+}, E_{\mu-}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0004m |
| Longitudinal emittance | $\varepsilon_{LN}$ | 0.002m |
| Energy spread | δE | 4MeV |
| Collision β* | β* | 0.05 m |
| Beam size at collision | $\sigma_{x,y}$ | 0.02cm |
| Beam size (arcs) | $\sigma_{x,y}$ | 1.0cm |
| Beam size IR quad | $\sigma_{max}$ | 5.4cm |
| Storage turns | $N_t$ | 1000 |
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 60 Hz |
| Protons per bunch | $N_p$ | $5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |




22

From D. Neuffer:

# 126 GeV $\mu^+$-$\mu^-$ Collider

- Note *s*-channel enhancement:

  $(m_\mu/m_e)^2 \rightarrow \times$ 43,000 in cross section vis-à-vis $e^+e^-$

- So $10^{31}$ suffices

- Commission on the $Z^0$ ("giga-*Z*")

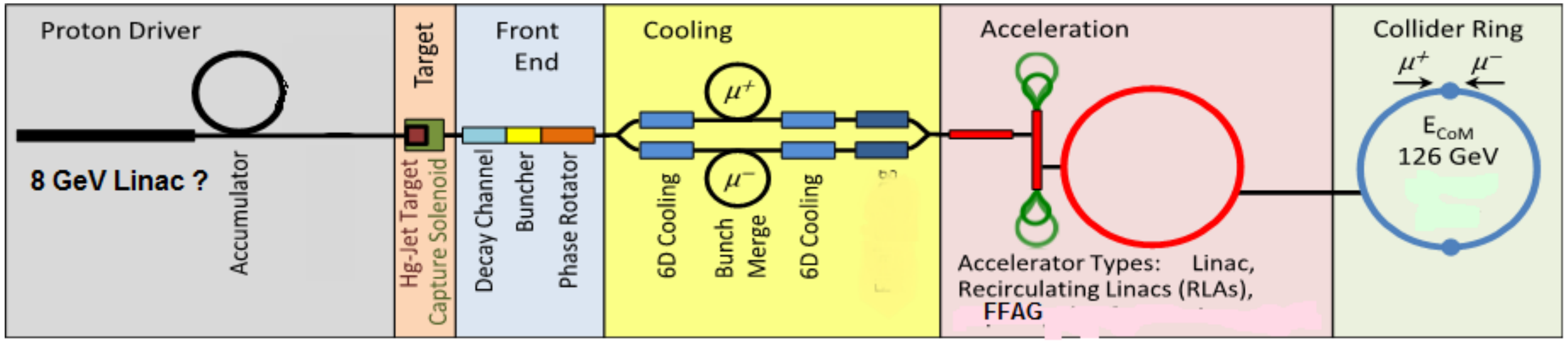
➢ **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch

➢ **π→μ collection, bunching, cooling**

➢ $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
  - $10^{12}$ μ/ bunch

➢ **Accelerate, Collider ring**
  - δE = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - $\delta E_{error}$ → 0.1 MeV

| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+}, E_{\mu-}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0004m |
| Longitudinal emittance | $\varepsilon_{LN}$ | 0.002m |
| Energy spread | δE | 4MeV |
| Collision β* | β* | 0.05 m |
| Beam size at collision | $\sigma_{x,y}$ | 0.02cm |
| Beam size (arcs) | $\sigma_{x,y}$ | 1.0cm |
| Beam size IR quad | $\sigma_{max}$ | 5.4cm |
| Storage turns | $N_t$ | 1000 |
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 60 Hz |
| Protons per bunch | $N_p$ | $5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |




22

# From D. Neuffer:

- Note *s*-channel enhancement:

  $(m_\mu/m_e)^2 \rightarrow \times$ 43,000 in cross section vis-à-vis $e^+e^-$

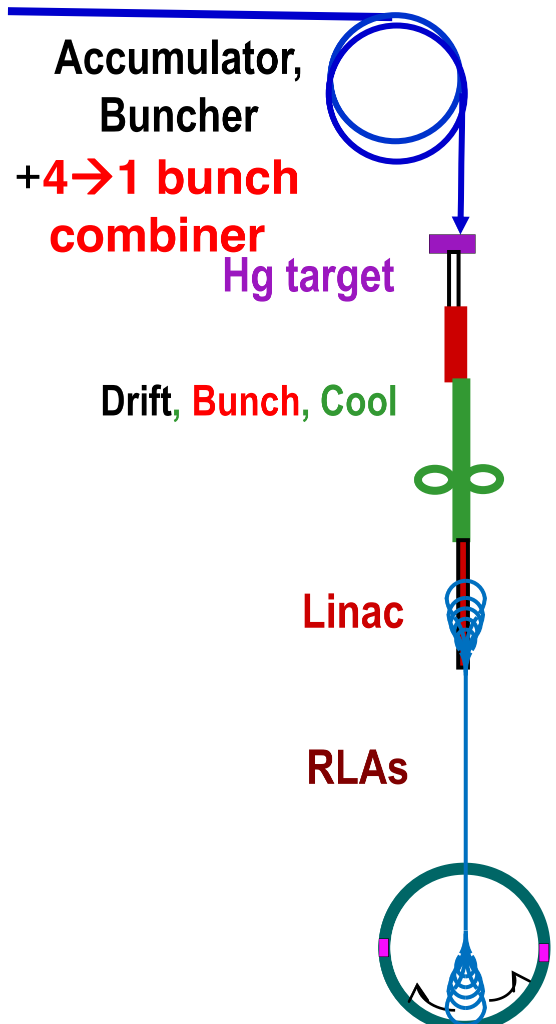
- So $10^{31}$ suffices
- Commission on the $Z^0$ ("giga-$Z$")
- Subsequently upgrade to $10^{32}$

## 126 GeV $\mu^+$-$\mu^-$ Collider

- **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch
- **π→μ collection, bunching, cooling**

| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+},E_{\mu\_}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t\ N}$ | 0.0004m |

## Higgs MC Parameters -Upgrade




$\delta v_{BB}$ =0.027

- Reduce transverse emittance to 0.0002m
- More Protons/pulse (15 Hz)

| Parameter | Symbol | Value |
|---|---|---|
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 15 Hz |
| Protons per bunch | $N_p$ | $4\times5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |
| Number of muon bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $5\times10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0002m |
| Collision $\beta^*$ | $\beta^*$ | 0.05m |
| Collision $\beta_{max}$ | $\beta^*$ | 1000m |
| Beam size at collision | $\sigma_{x,y}$ | 200000nm |
| Beam size (arcs) | $\sigma_{x,y}$ | 0.3cm |
| Beam size IR quad | $\sigma_{max}$ | 4cm |
| Collision Beam Energy | $E_{\mu+},E_{\mu\_}$ | 62.5(125geV total) |
| Storage turns | $N_t$ | 1300 |
| **Luminosity** | $L_0$ | $10^{32}$ |

**50000 H/yr**

From D. Neuffer:

# 126 GeV $\mu^+$-$\mu^-$ Collider

- 8 GeV, 4MW Proton Source
  - 15 Hz, 4 bunches $5\times10^{13}$/bunch
- $\pi\rightarrow\mu$ collection, bunching, cooling

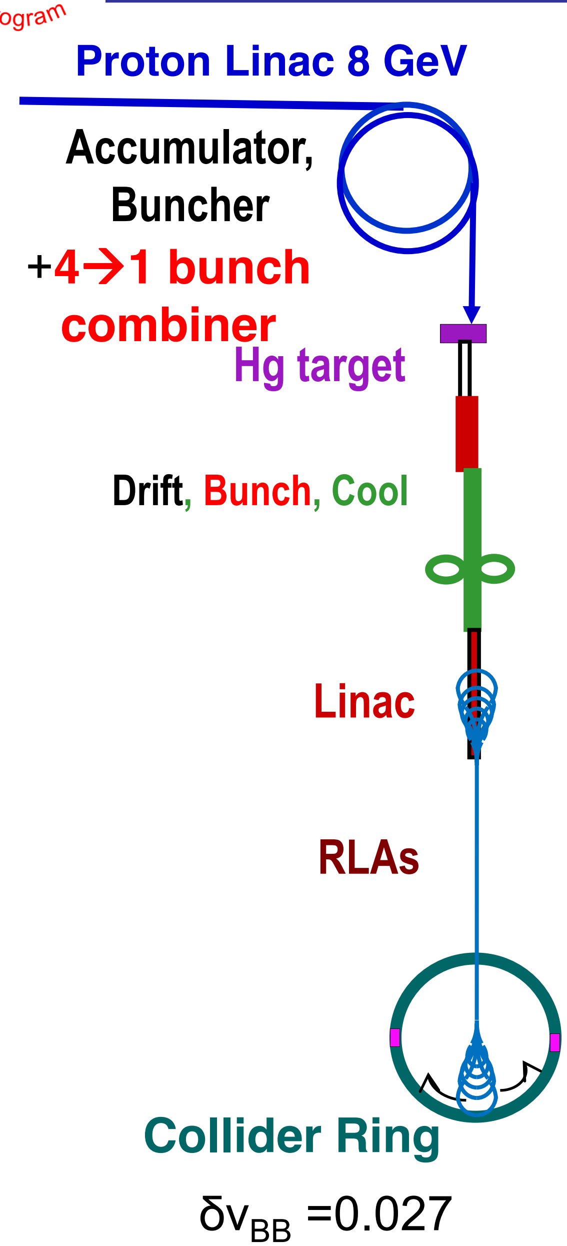
| Parameter | Symbol | Value |
|---|---|---|
| Collision Beam Energy | $E_{\mu+}, E_{\mu\_}$ | 63GeV |
| Luminosity | $L_0$ | $10^{31}$ |
| Number of μ bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $10^{12}$ |
| Transverse emittance | $\varepsilon_{t\,N}$ | 0.0004m |

- Note *s*-channel enhancement:

  $(m_\mu/m_e)^2 \rightarrow \times$ 43,000 in cross section vis-à-vis $e^+e^-$

- So $10^{31}$ suffices
- Commission on the $Z^0$ ("giga-$Z$")
- Subsequently upgrade to $10^{32}$

# Higgs MC Parameters -Upgrade




- Reduce transverse emittance to 0.0002m
- More Protons/pulse (15 Hz)

| Parameter | Symbol | Value |
|---|---|---|
| Proton Beam Power | $P_p$ | 4 MW |
| Bunch frequency | $F_p$ | 15 Hz |
| Protons per bunch | $N_p$ | $4\times5\times10^{13}$ |
| Proton beam energy | $E_p$ | 8 GeV |
| Number of muon bunches | $n_B$ | 1 |
| $\mu^{+/-}$/ bunch | $N_\mu$ | $5\times10^{12}$ |
| Transverse emittance | $\varepsilon_{t,N}$ | 0.0002m |
| Collision $\beta^*$ | $\beta^*$ | 0.05m |
| Collision $\beta_{max}$ | $\beta^*$ | 1000m |
| Beam size at collision | $\sigma_{x,y}$ | 200000nm |
| Beam size (arcs) | $\sigma_{x,y}$ | 0.3cm |
| Beam size IR quad | $\sigma_{max}$ | 4cm |
| Collision Beam Energy | $E_{\mu+}, E_{\mu\_}$ | 62.5(125geV total) |
| Storage turns | $N_t$ | 1300 |
| **Luminosity** | $L_0$ | $10^{32}$ |

50000 H/yr

# 4. Collider Ring

- Example 2.5 km storage ring for $\sqrt{s}$ = 1.5 TeV:

[Y. Alexahin *et al.*, FNAL]

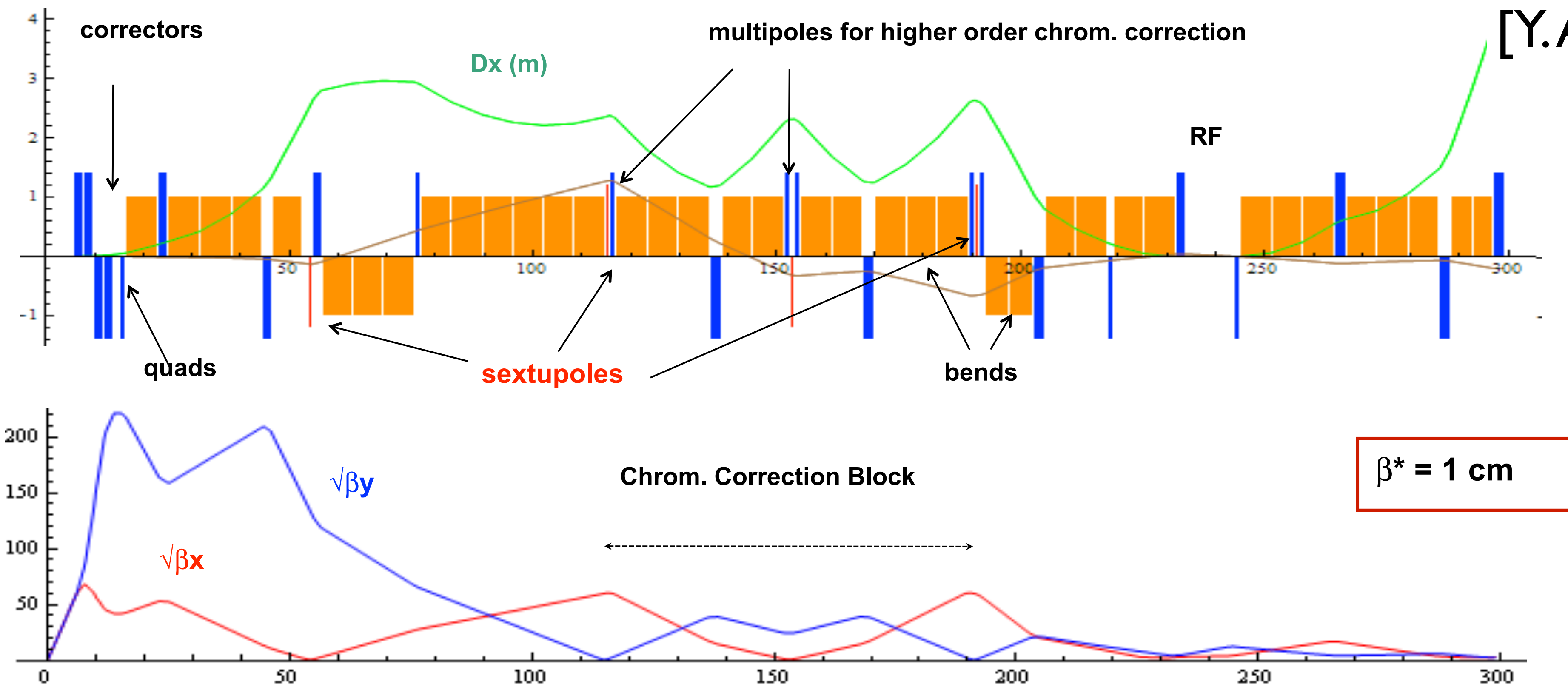



Table 2. Example parameters for a 1.5 TeV (c.m.) muon collider [26].

| | LEMC | HEMC |
|---|---|---|
| Avg. luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.7 | 1 |
| Avg. bending field (T) | 10 | 8 |
| Proton driver repetition rate (Hz) | 65 | 15 |
| $\beta^*$ (cm) | 0.5 | 1 |
| Muons per bunch ($10^{11}$) | 1 | 20 |
| Muon bunches in collider (each sign) | 10 | 1 |
| Norm. Transv. Emittance (μm) | 2.1 | 25 |
| Norm. Long. Emittance (m) | 0.35 | 0.07 |
| Energy spread (%) | 1 | 0.1 |

# 4. Collider Ring

- Example 2.5 km storage ring for $\sqrt{s}$ = 1.5 TeV:

[Y. Alexahin *et al.*, FNAL]

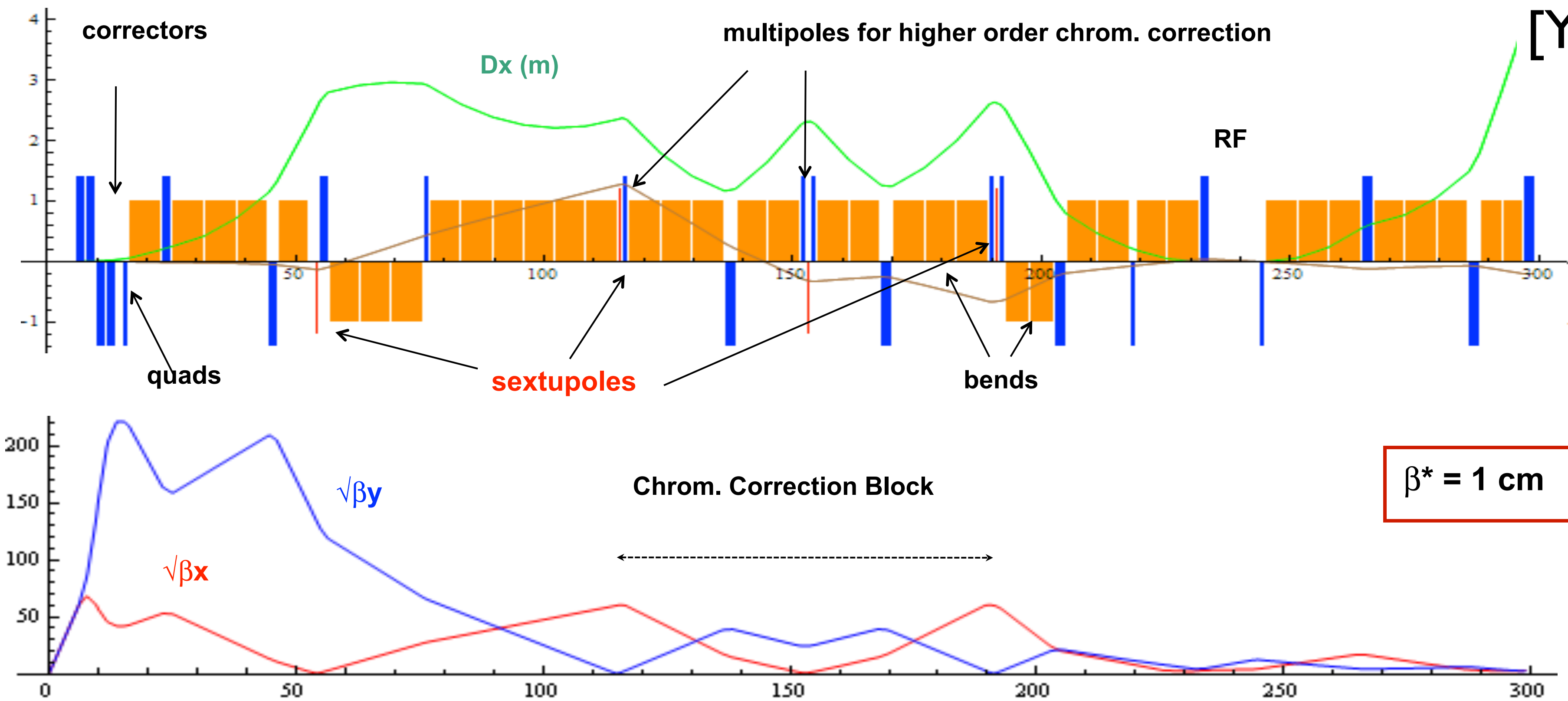



Table 2. Example parameters for a 1.5 TeV (c.m.) muon collider [26].

| | LEMC | HEMC |
|---|---|---|
| Avg. luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.7 | 1 |
| Avg. bending field (T) | 10 | 8 |
| Proton driver repetition rate (Hz) | 65 | 15 |
| $\beta^*$ (cm) | 0.5 | 1 |
| Muons per bunch ($10^{11}$) | 1 | 20 |
| Muon bunches in collider (each sign) | 10 | 1 |
| Norm. Transv. Emittance (μm) | 2.1 | 25 |
| Norm. Long. Emittance (m) | 0.35 | 0.07 |
| Energy spread (%) | 1 | 0.1 |

# 4. Collider Ring

- Example 2.5 km storage ring for $\sqrt{s}$ = 1.5 TeV:

[Y. Alexahin *et al.*, FNAL]

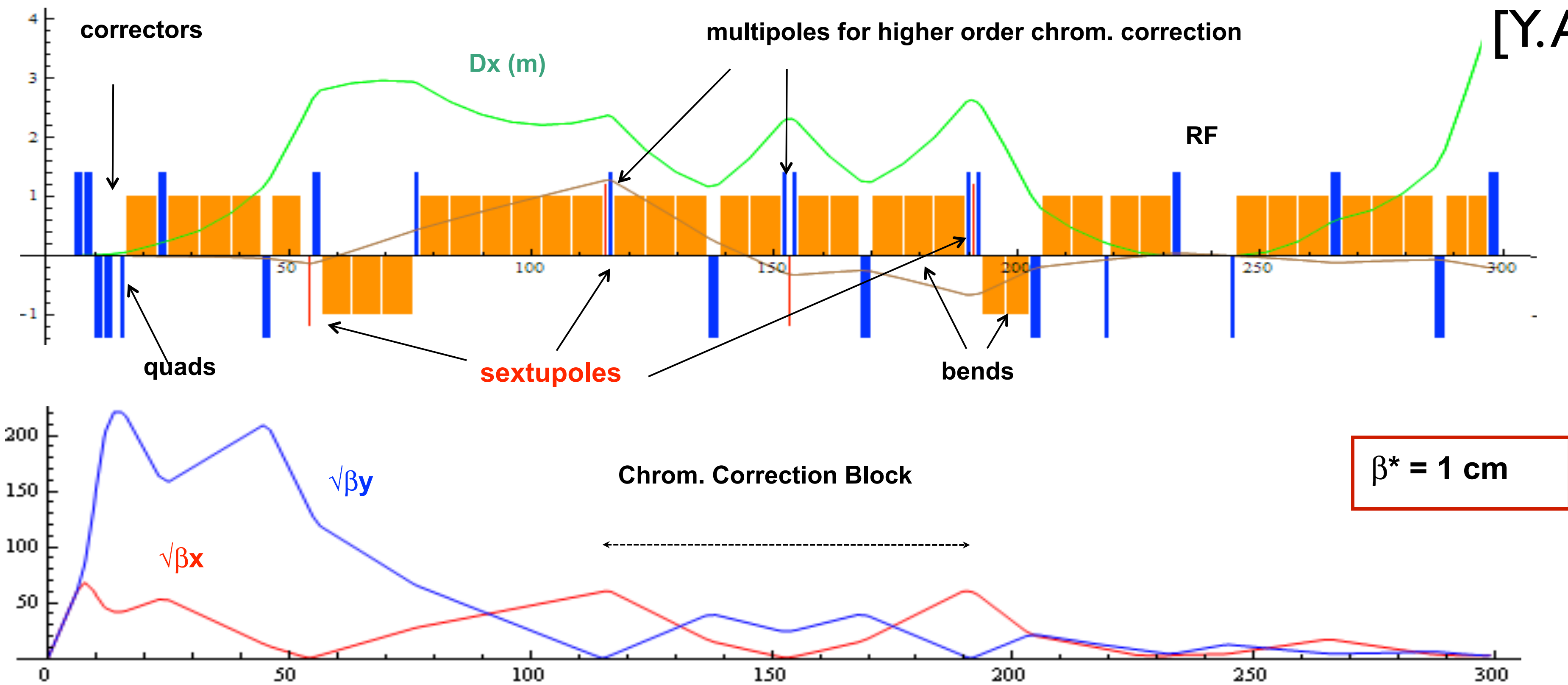



Table 2. Example parameters for a 1.5 TeV (c.m.) muon collider [26].

| | LEMC | HEMC |
|---|---|---|
| Avg. luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.7 | 1 |
| Avg. bending field (T) | 10 | 8 |
| Proton driver repetition rate (Hz) | 65 | 15 |
| $\beta^*$ (cm) | 0.5 | 1 |
| Muons per bunch ($10^{11}$) | 1 | 20 |
| Muon bunches in collider (each sign) | 10 | 1 |
| Norm. Transv. Emittance (μm) | 2.1 | 25 |
| Norm. Long. Emittance (m) | 0.35 | 0.07 |
| Energy spread (%) | 1 | 0.1 |

# 4. Collider Ring

- Example 2.5 km storage ring for $\sqrt{s}$ = 1.5 TeV:

[Y. Alexahin *et al.*, FNAL]

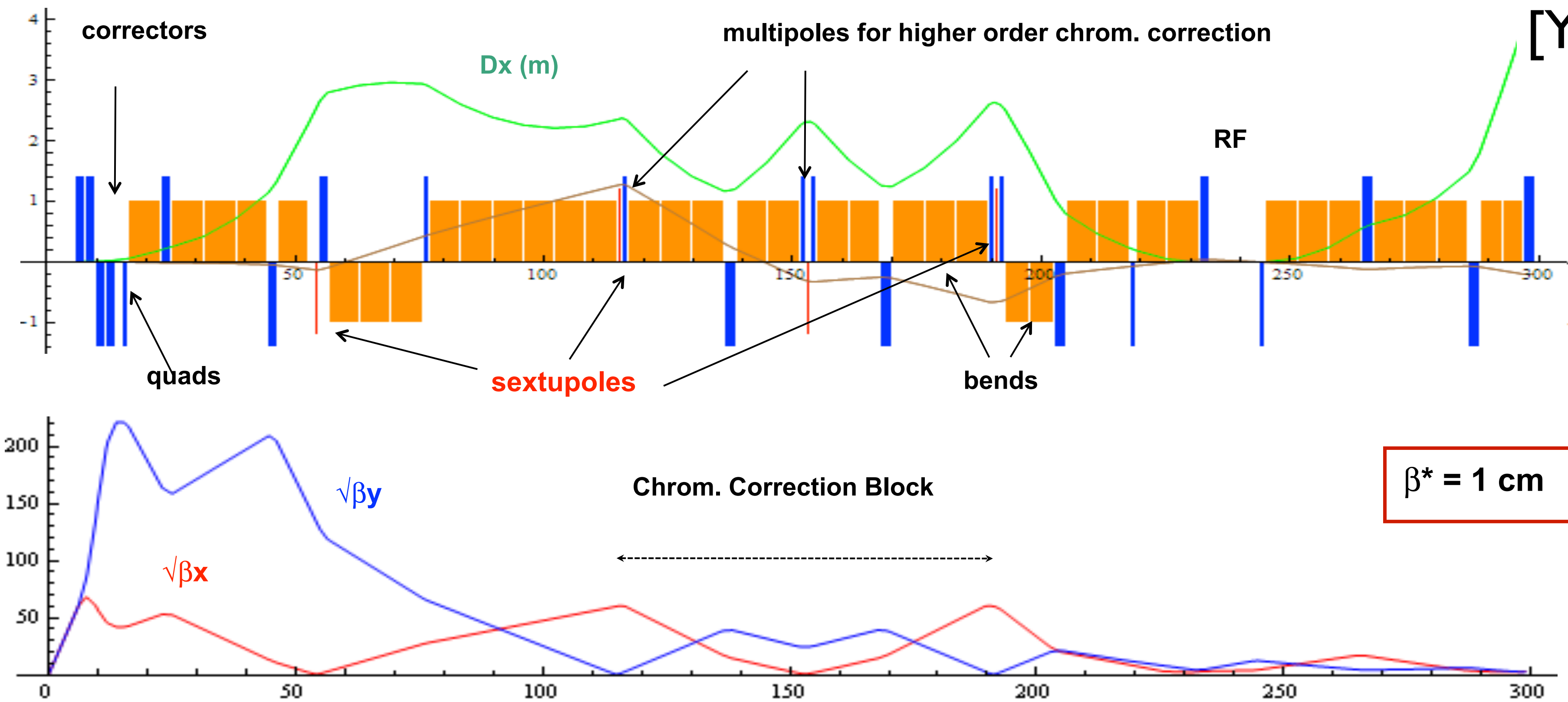



Table 2. Example parameters for a 1.5 TeV (c.m.) muon collider [26].

| | LEMC | HEMC |
|---|---|---|
| Avg. luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.7 | 1 |
| Avg. bending field (T) | 10 | 8 |
| Proton driver repetition rate (Hz) | 65 | 15 |
| $\beta^*$ (cm) | 0.5 | 1 |
| Muons per bunch ($10^{11}$) | 1 | 20 |
| Muon bunches in collider (each sign) | 10 | 1 |
| Norm. Transv. Emittance (μm) | 2.1 | 25 |
| Norm. Long. Emittance (m) | 0.35 | 0.07 |
| Energy spread (%) | 1 | 0.1 |