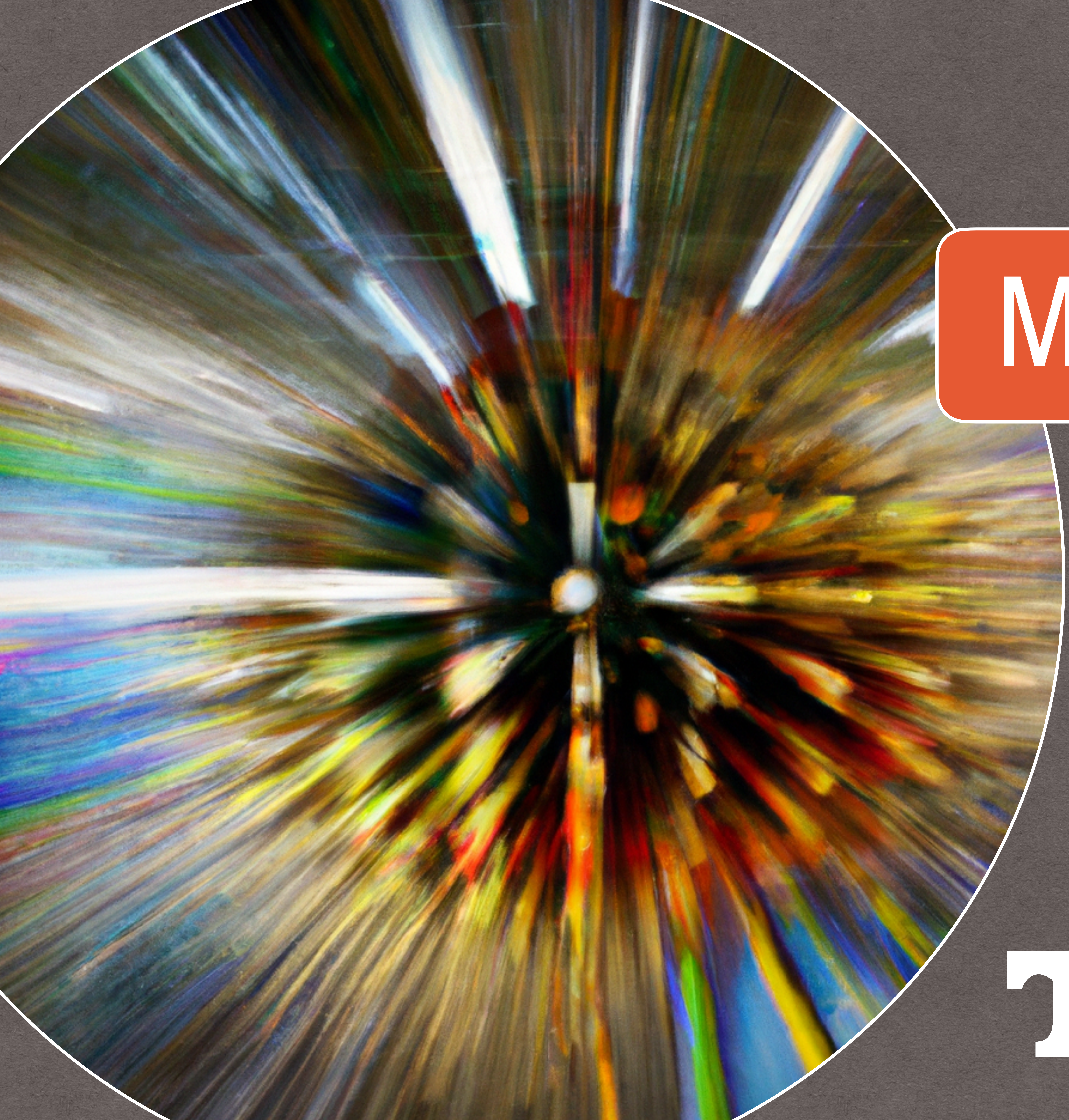


U.S. DEPARTMENT OF ENERGY | Office of Science

MUON COLLIDERS

THE FUTURE OF THE ENERGY FRONTIER?

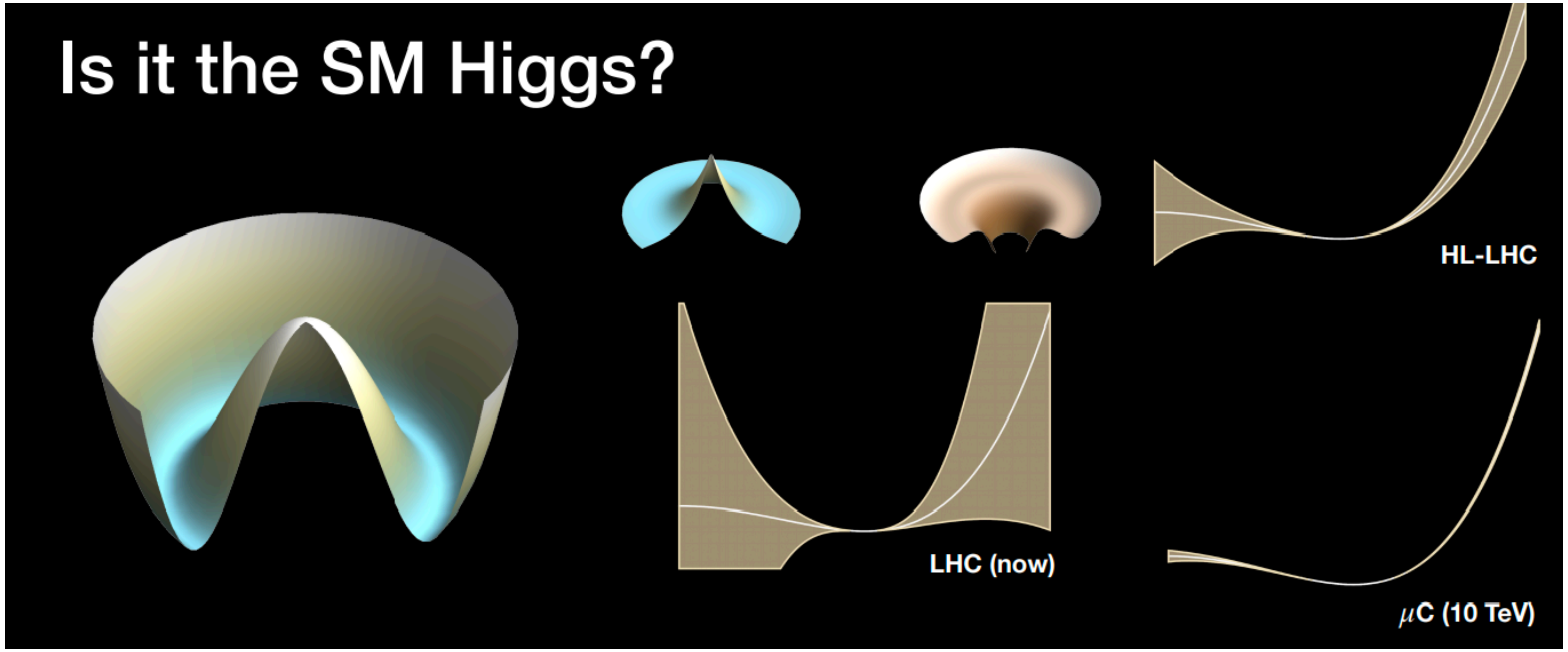
TOVA HOLMES, U. OF TENNESSEE
MELFEST, MAY 21, 2023
UNIVERSITY OF CHICAGO

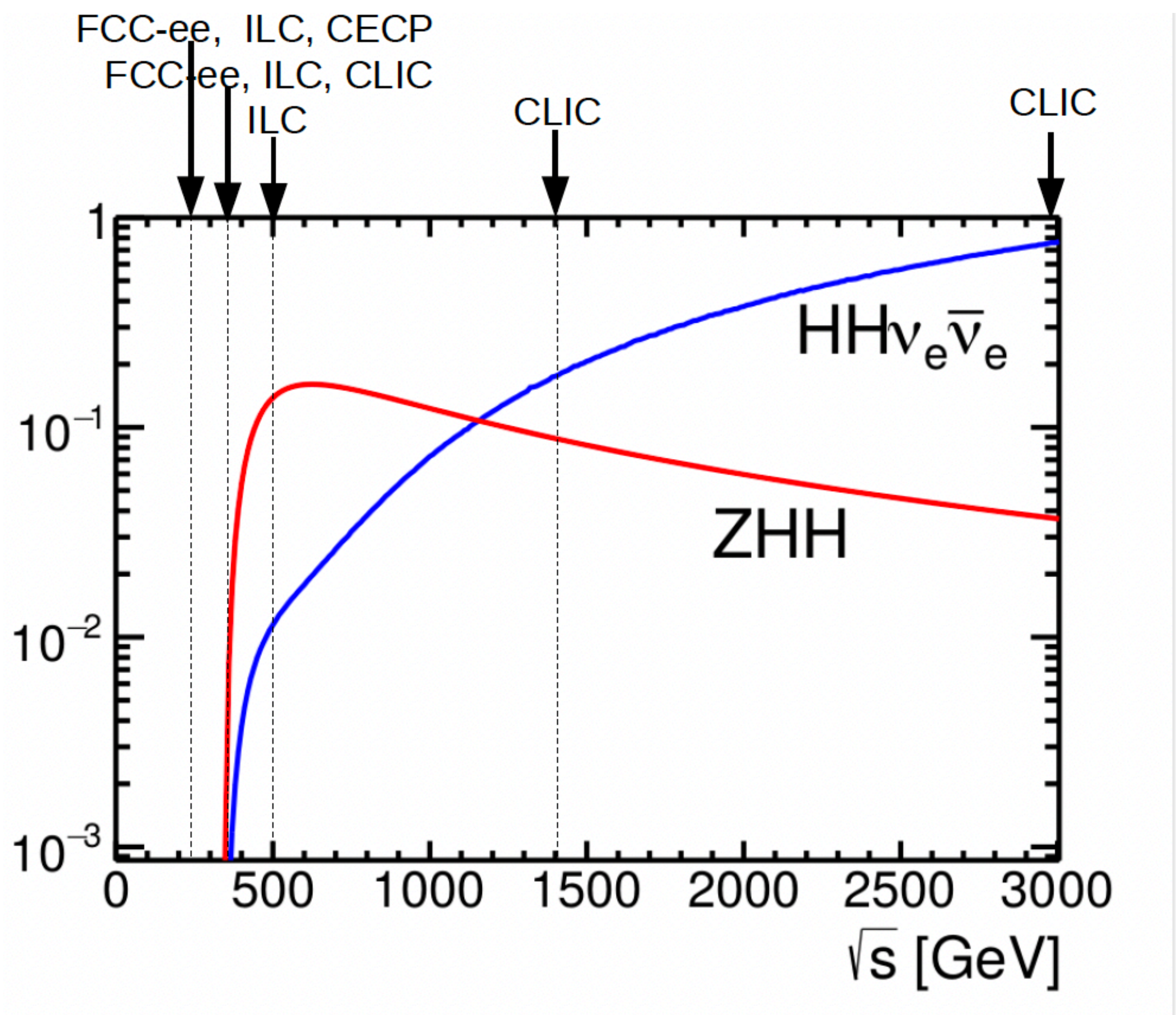
Why does the energy frontier need a future?

Science drivers for High Energy Physics:

- ★ Use the Higgs boson as a new tool for discovery
- ☆ Pursue the physics associated with neutrino mass
- ☆ Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- ★ Explore the unknown: new particles, interactions, and physical principles.

Why does the energy frontier need a future?





$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

need to produce and study **high-energy** higgses to probe the potential!

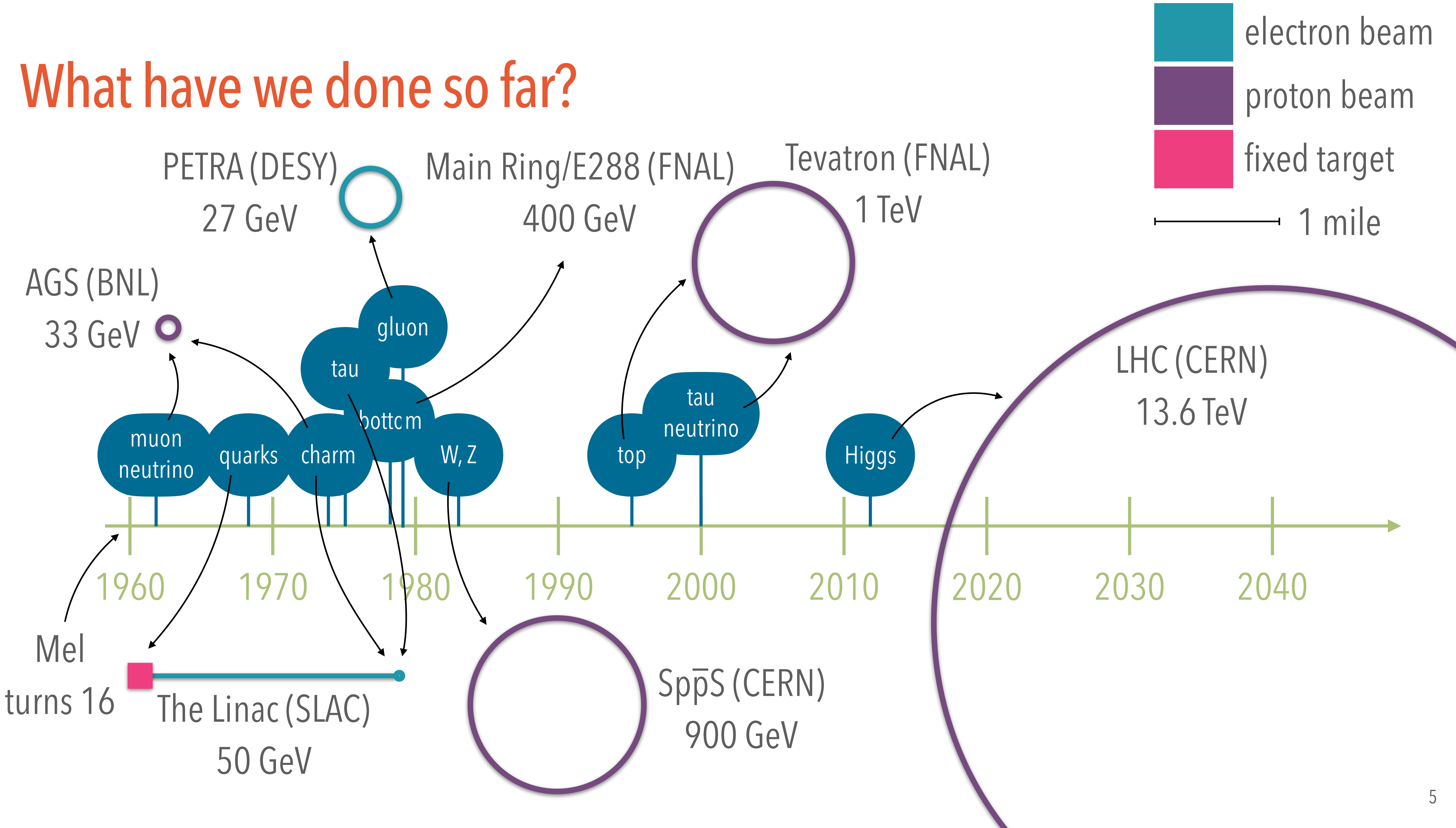
N. Craig, E. Petit

What have we done so far?

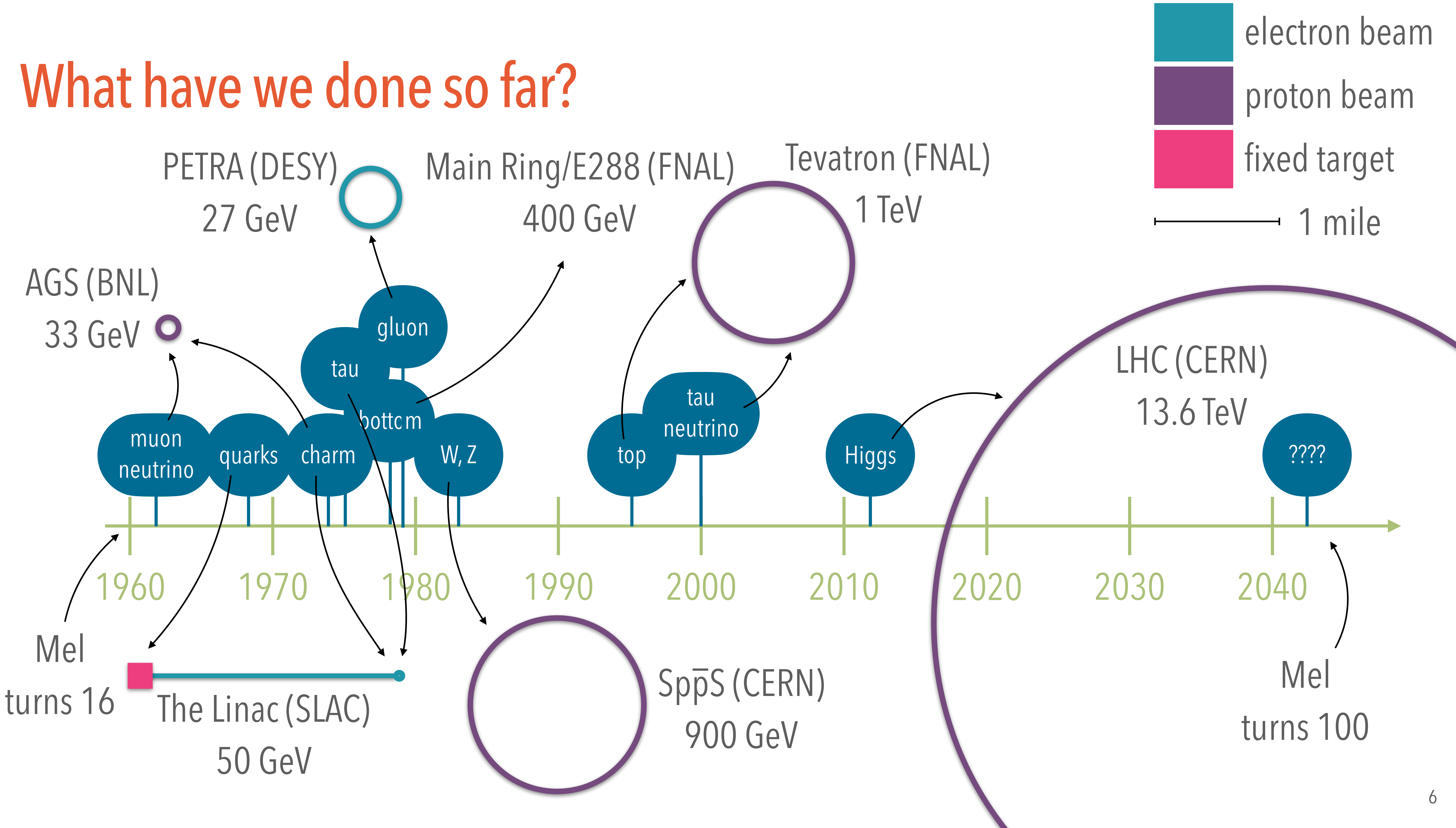
- The **reasonable** thing!
  - Take advantage of our readily accessible, stable, charged particles: e & p

- What have we done with them?
  - A **lot!**

What have we done so far?



What have we done so far?



How do we go forward?

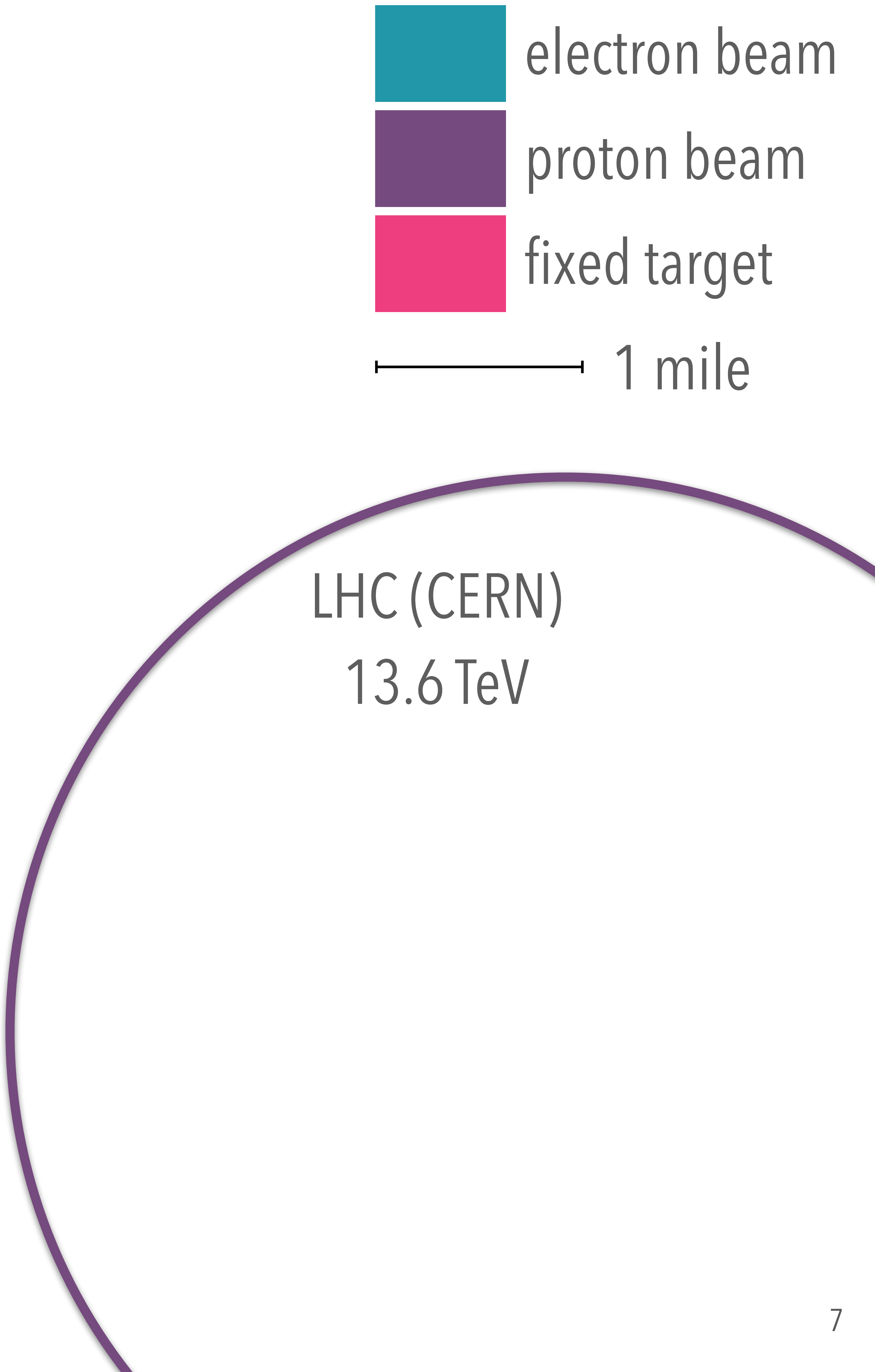
can we go to higher energies?

$$B \approx 3\left(\frac{E}{1\ \mathrm{TeV}}\right)\left(\frac{1\ \mathrm{km}}{R}\right)\ \mathrm{T}$$

to go from 14 to 100 TeV, could do:

same magnets, 7x ring size

2x magnetic field, 3.5x ring size



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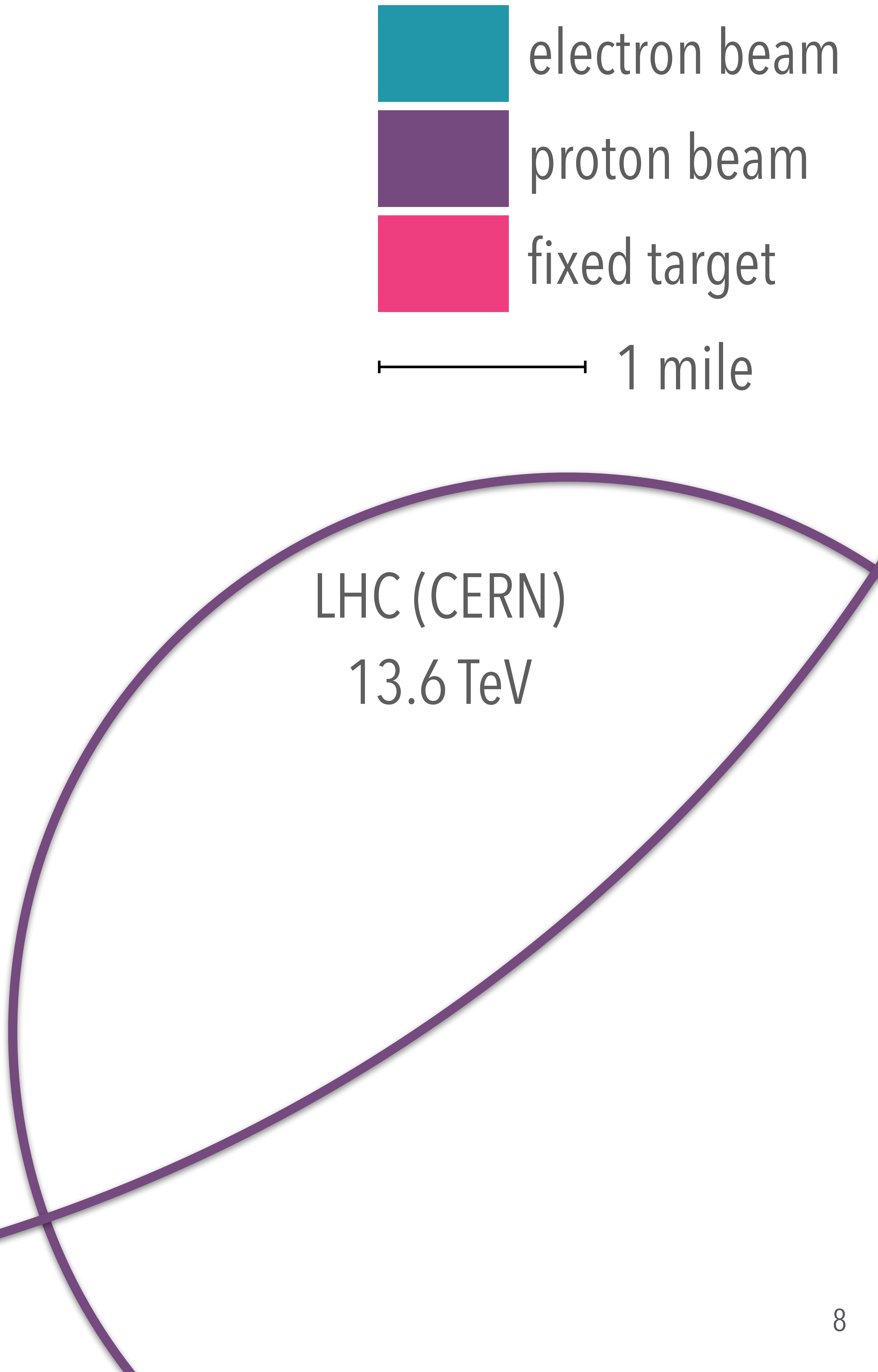
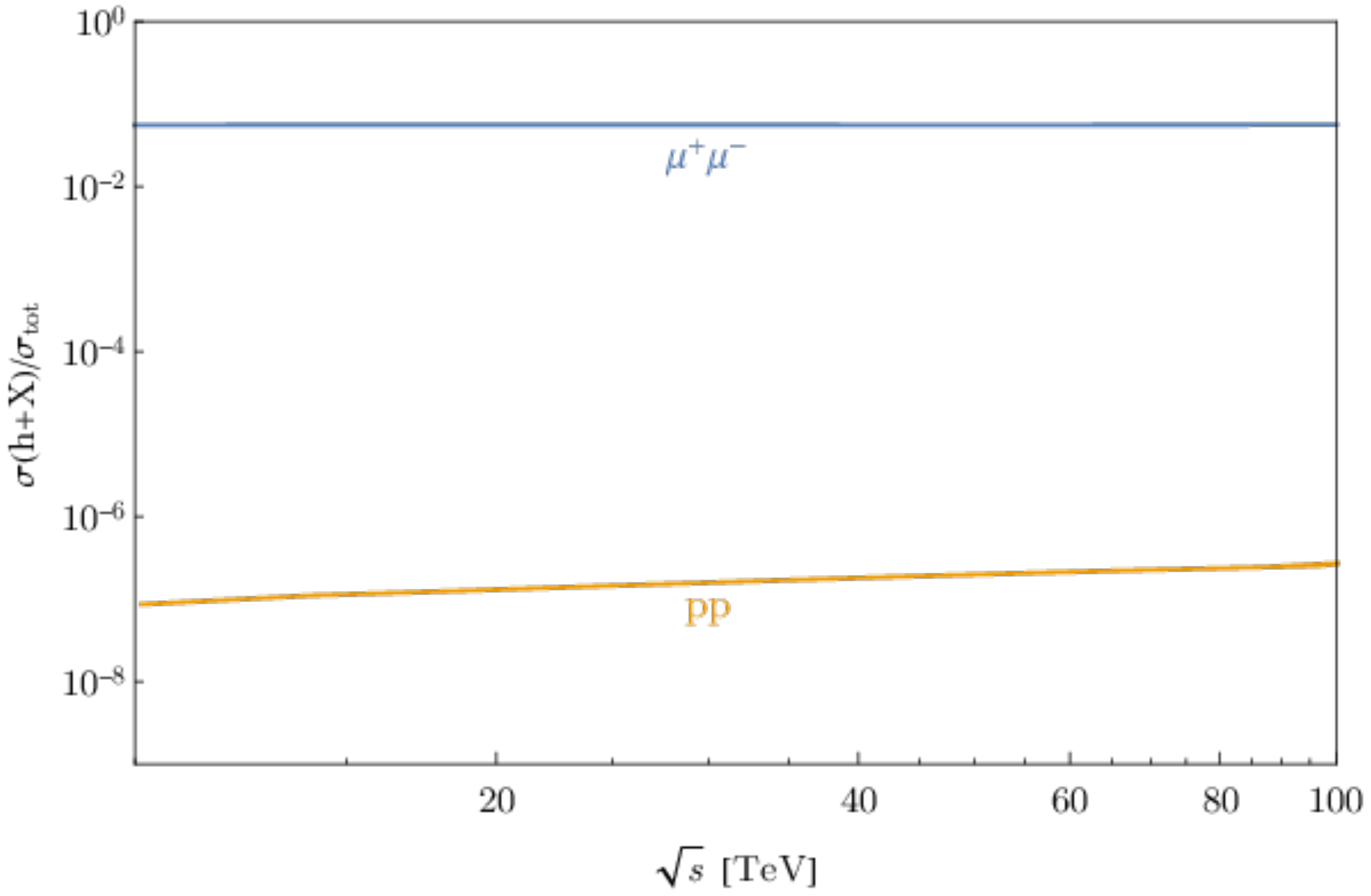
to go from 14 to 100 TeV, could do:
same magnets, 7x ring size
2x magnetic field, 3.5x ring size

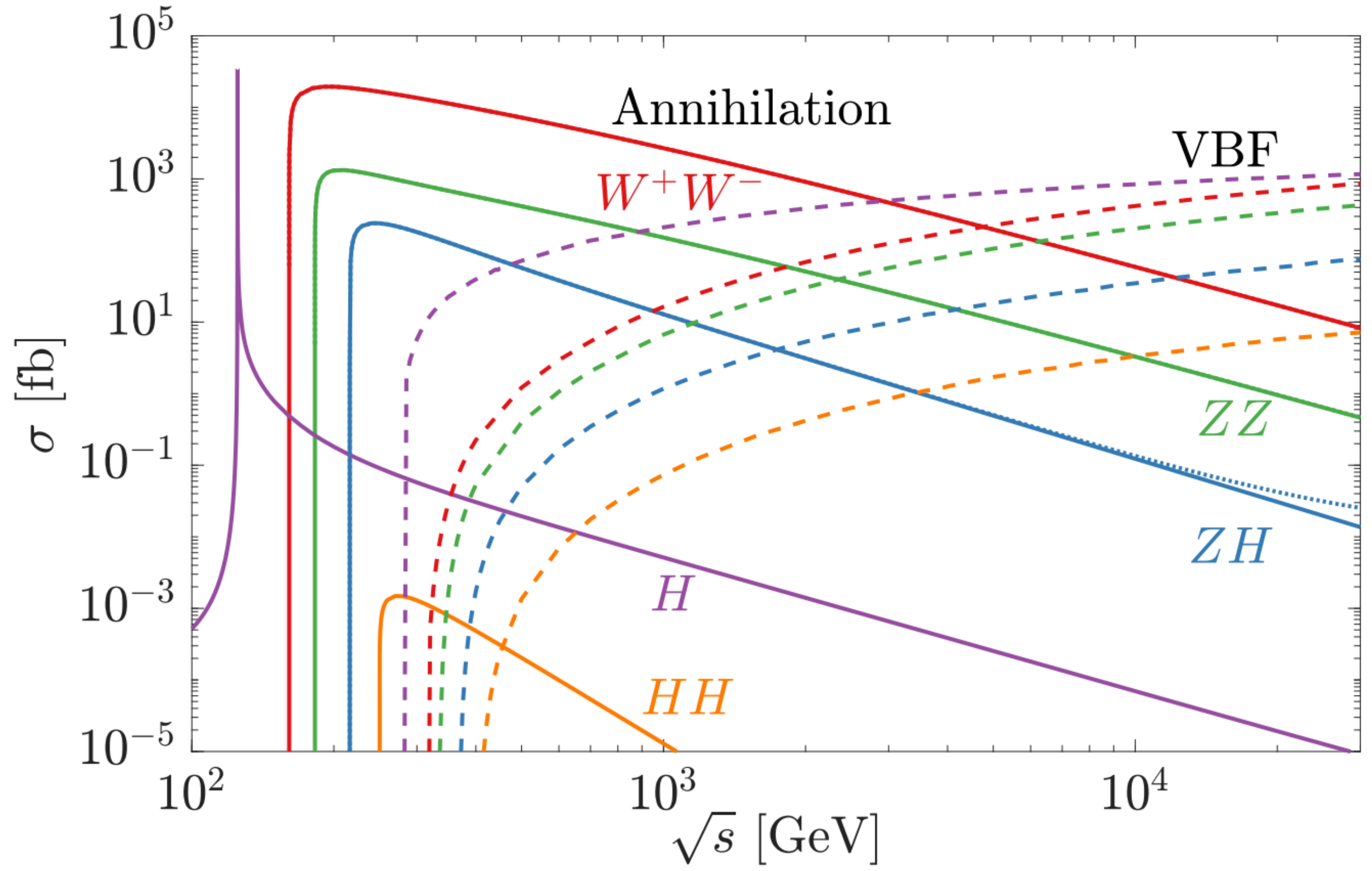
LHC: 8 T magnets, 27 km size
FCC-hh: ~16 T magnets, ~90 km size



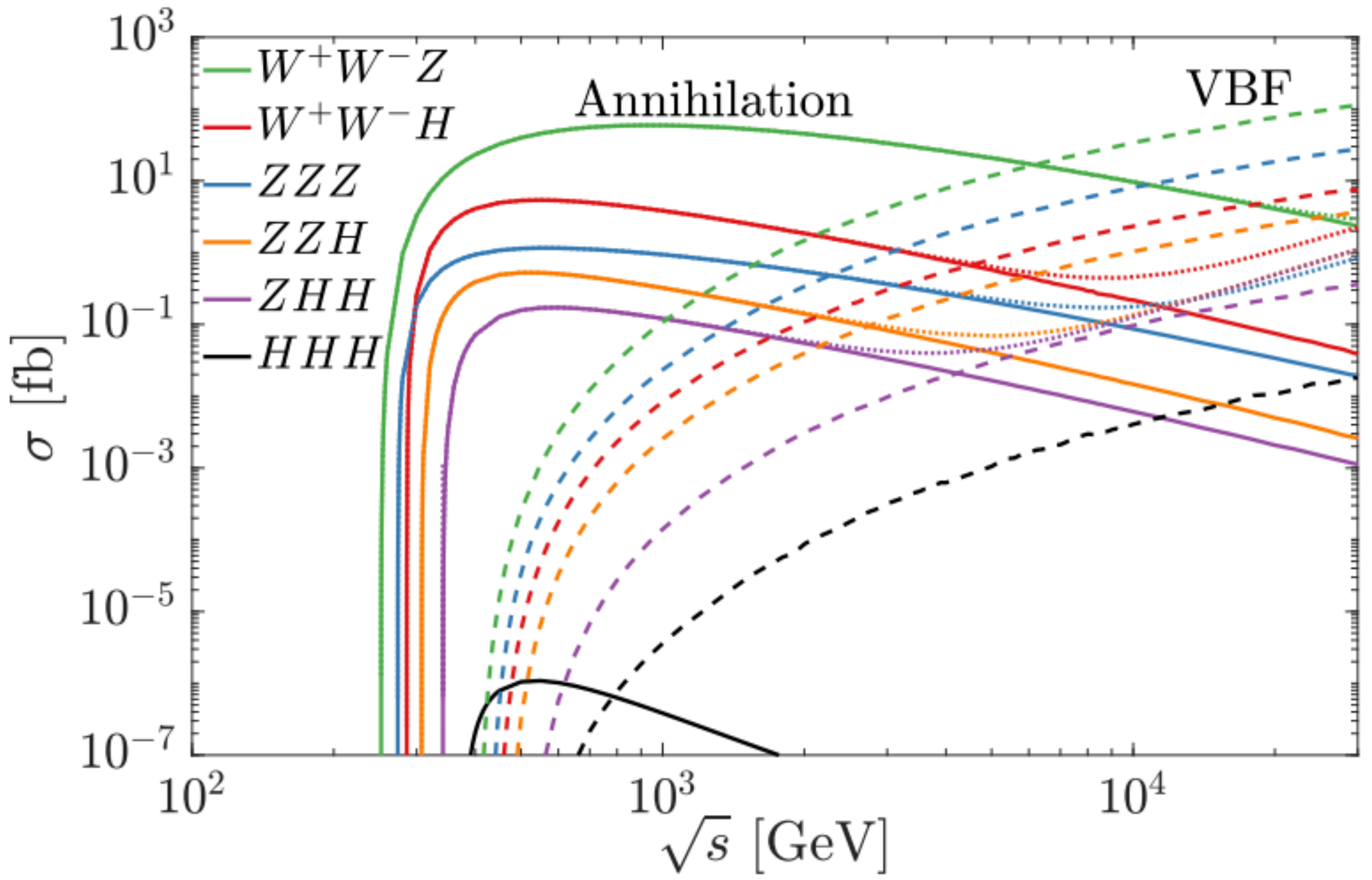
How do we go forward?

If we want to study the mysteries of EWK symmetry breaking maybe an EWK machine would be nice?



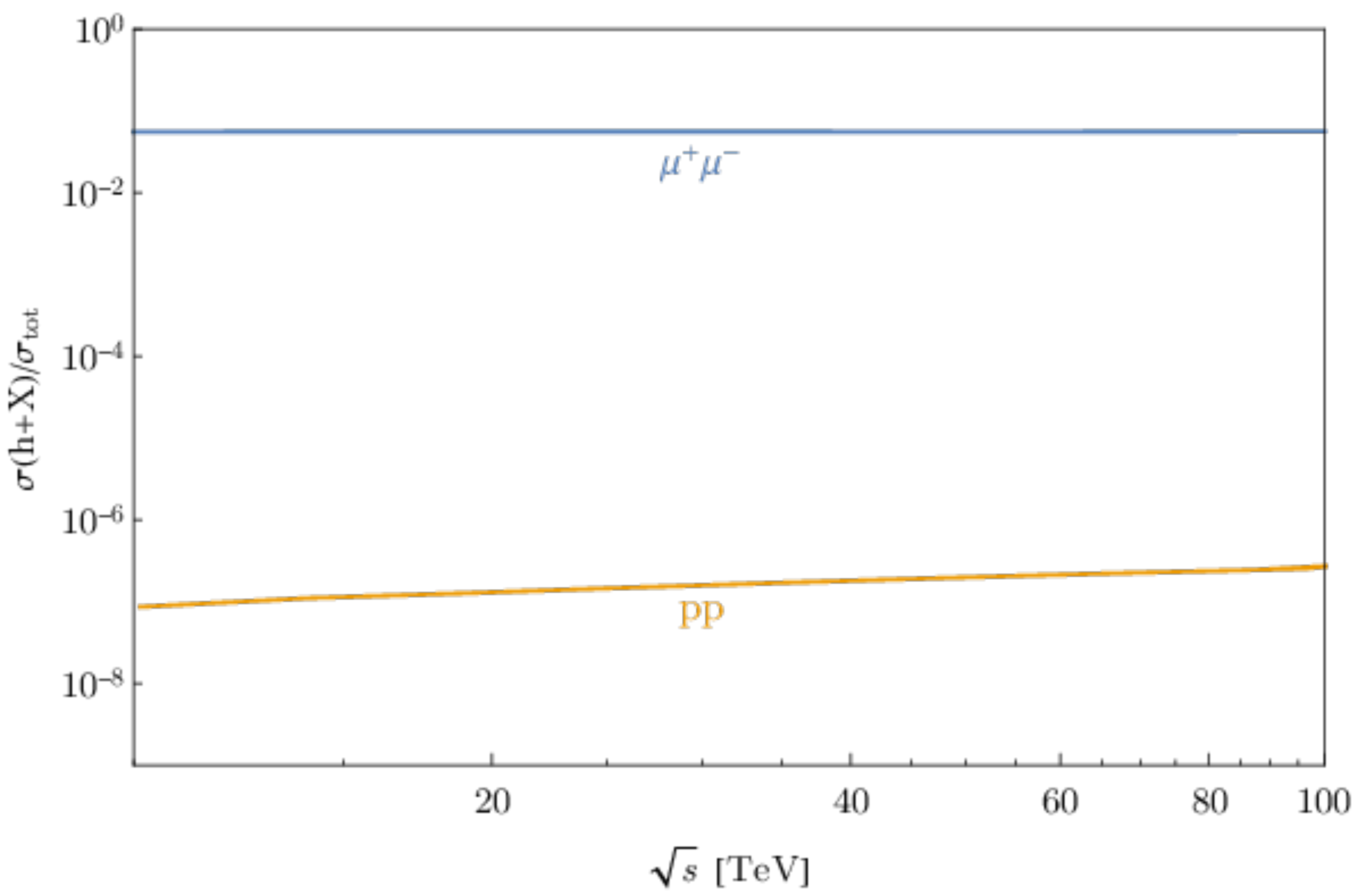


ee or μμ?



The Muon Smasher's Guide, J. Reuter et al

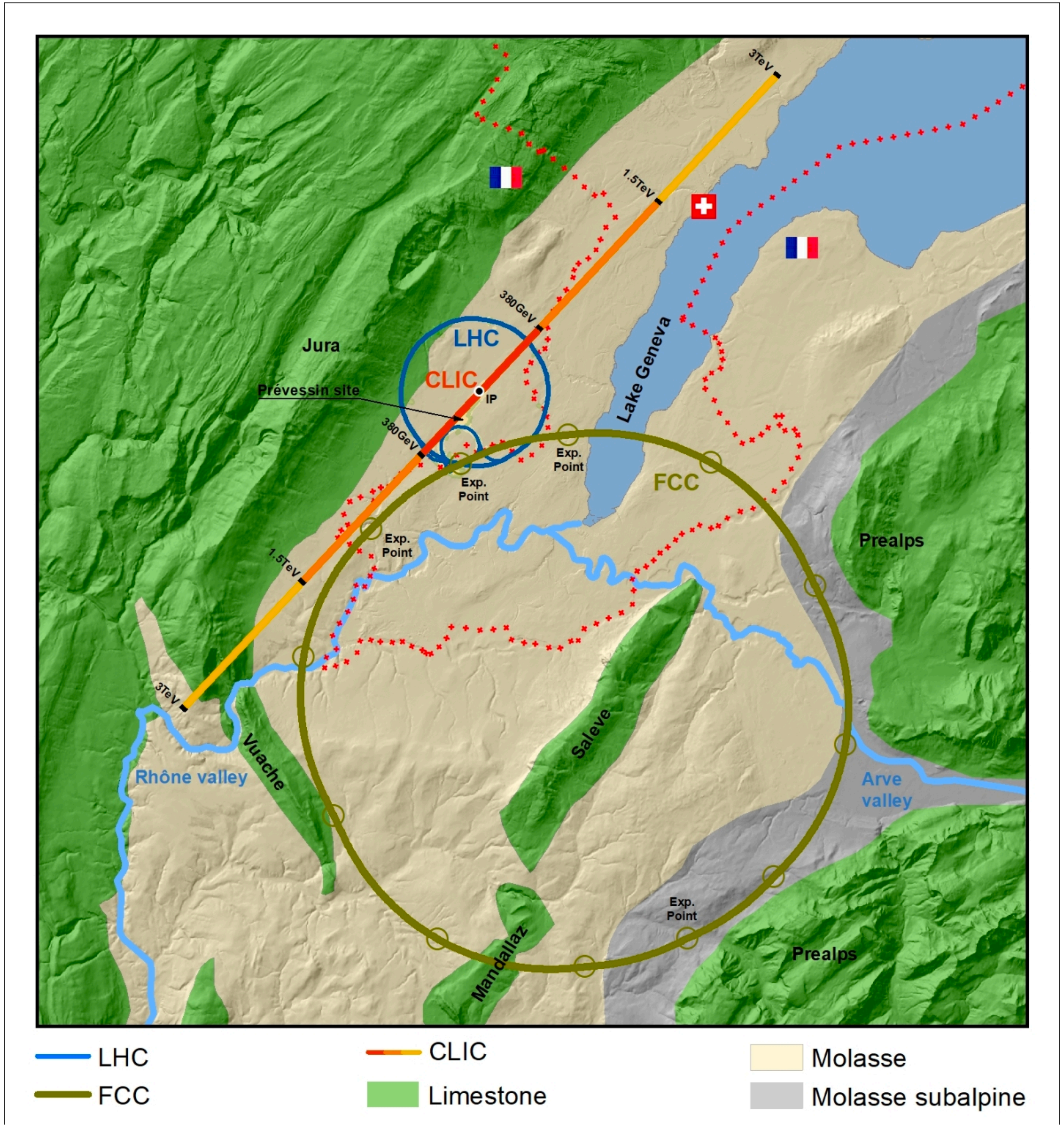
How do we go forward?



- **Not on the plot!**
  - Highest energy explored for e+e- is 3 TeV

$$E = \left(\frac{G}{100\ \mathrm{MeV/m}}\right)\left(\frac{L}{10\ \mathrm{km}}\right)\ \mathrm{TeV}$$

J. Osborne et al

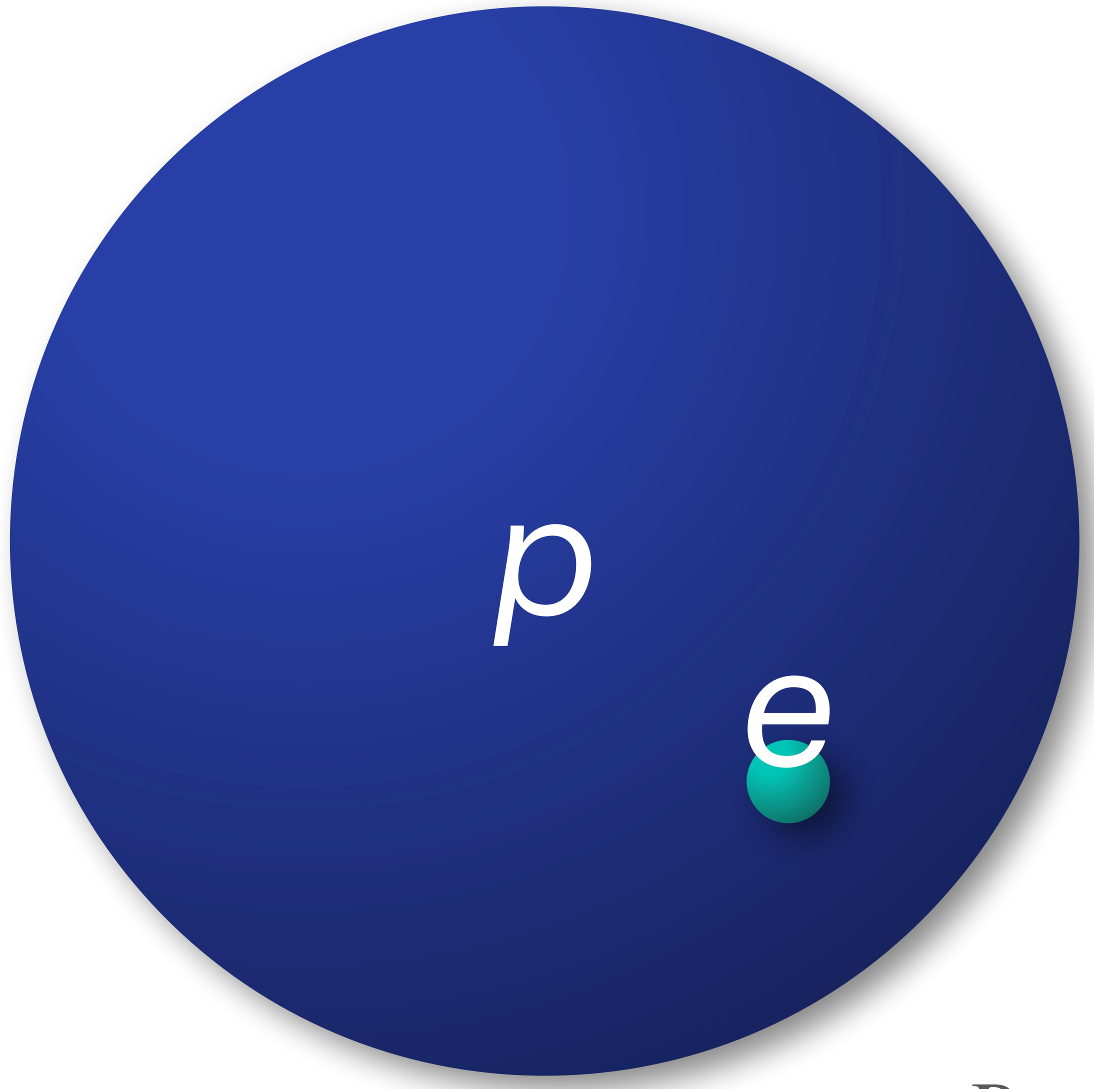


How do we go forward?

- **Using electrons...**
  - Synchrotron radiation means we can't make high energy circular colliders
  - Linear collider lengths are proportional to their energy
- **Using protons...**
  - Effective center of mass energy ~1/10 of beam, and ring size set to beam energy
  - EWK cross-section tiny compared to QCD

$$P \approx 3 \times 10^{-7} \left(\frac{1\ \text{km}}{R}\right)^2 \left(\frac{E}{m}\right)^4 \text{eV/s}$$

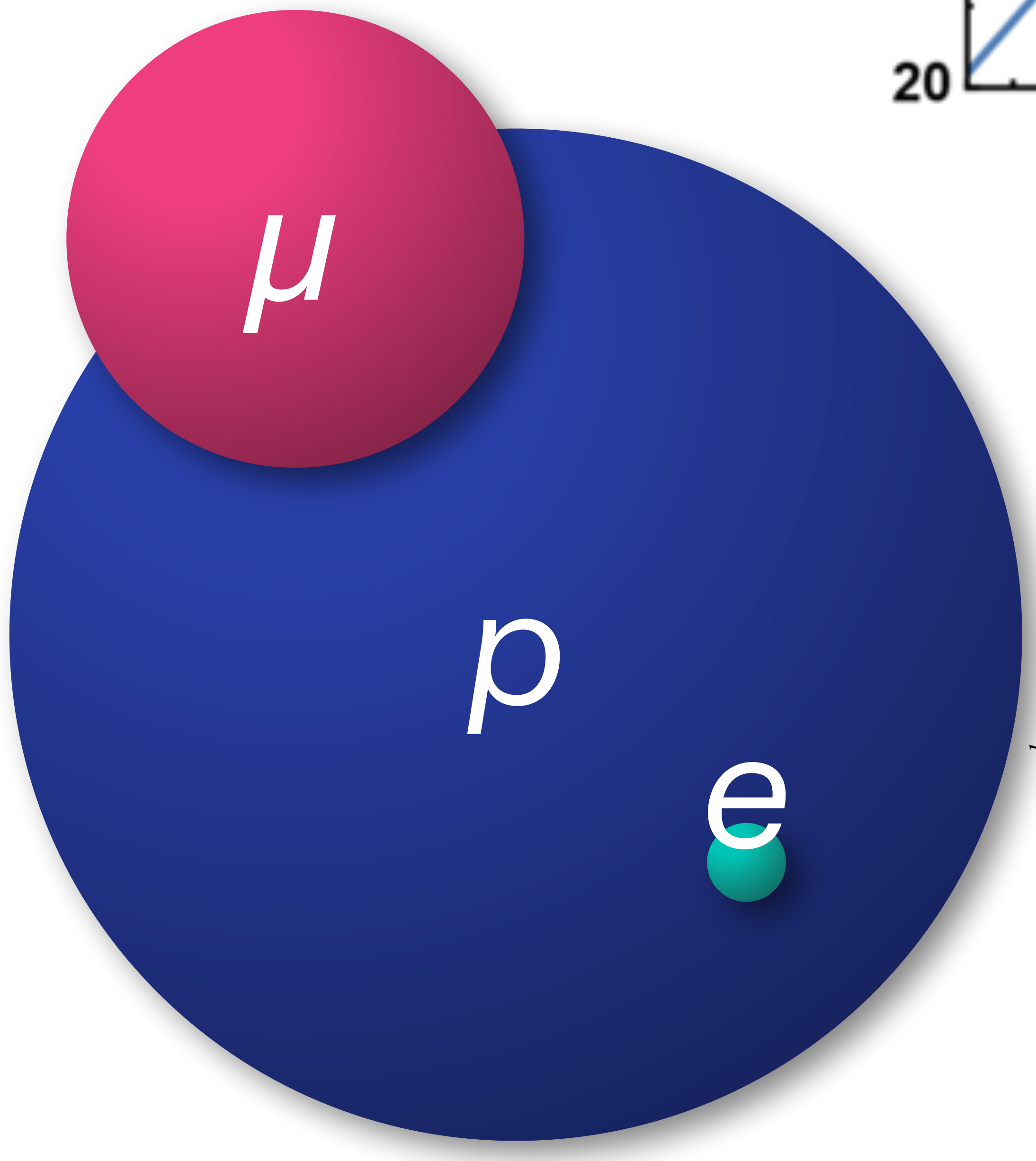
$$E = \left(\frac{G}{100\ \text{MeV/m}}\right)\left(\frac{L}{10\ \text{km}}\right) \text{TeV}$$

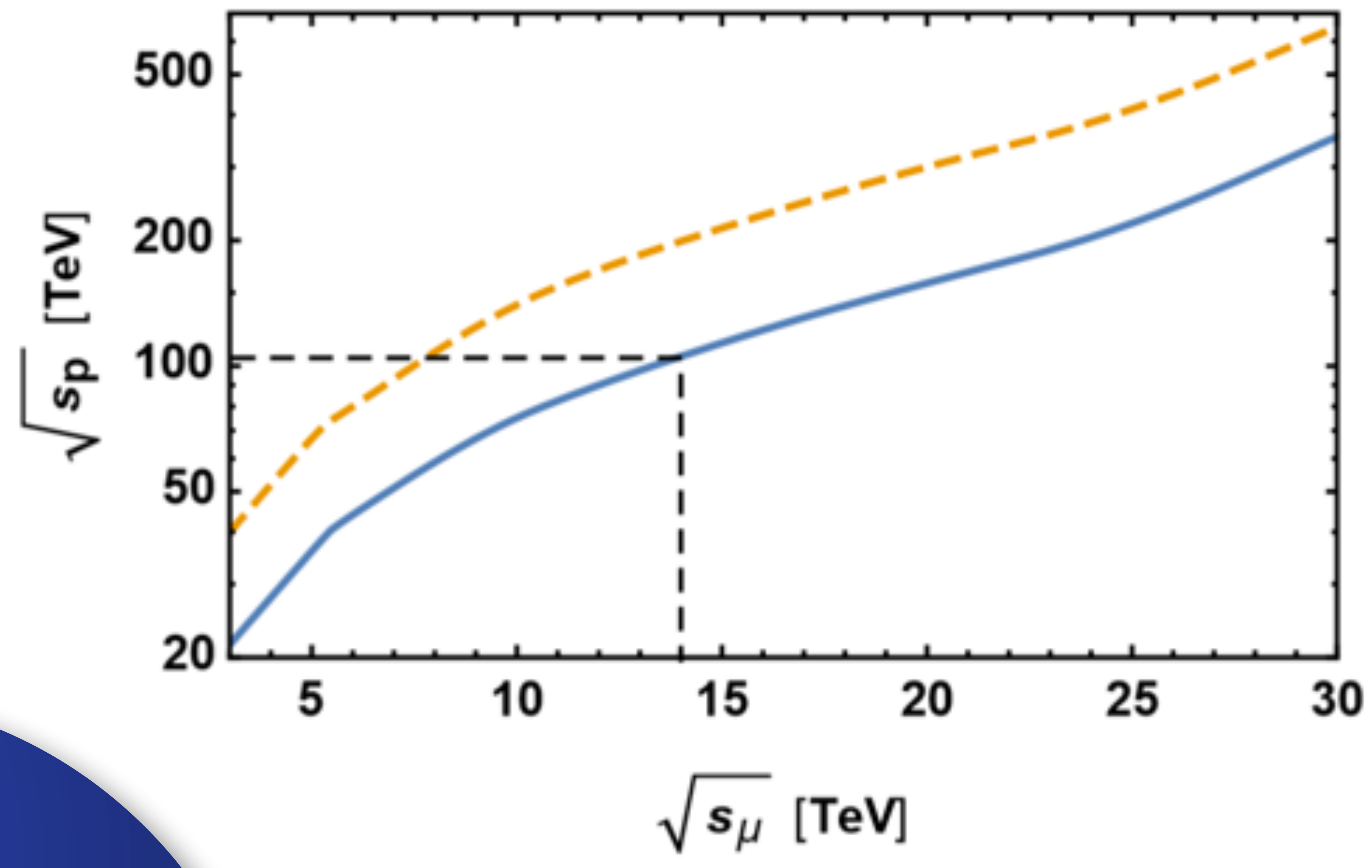


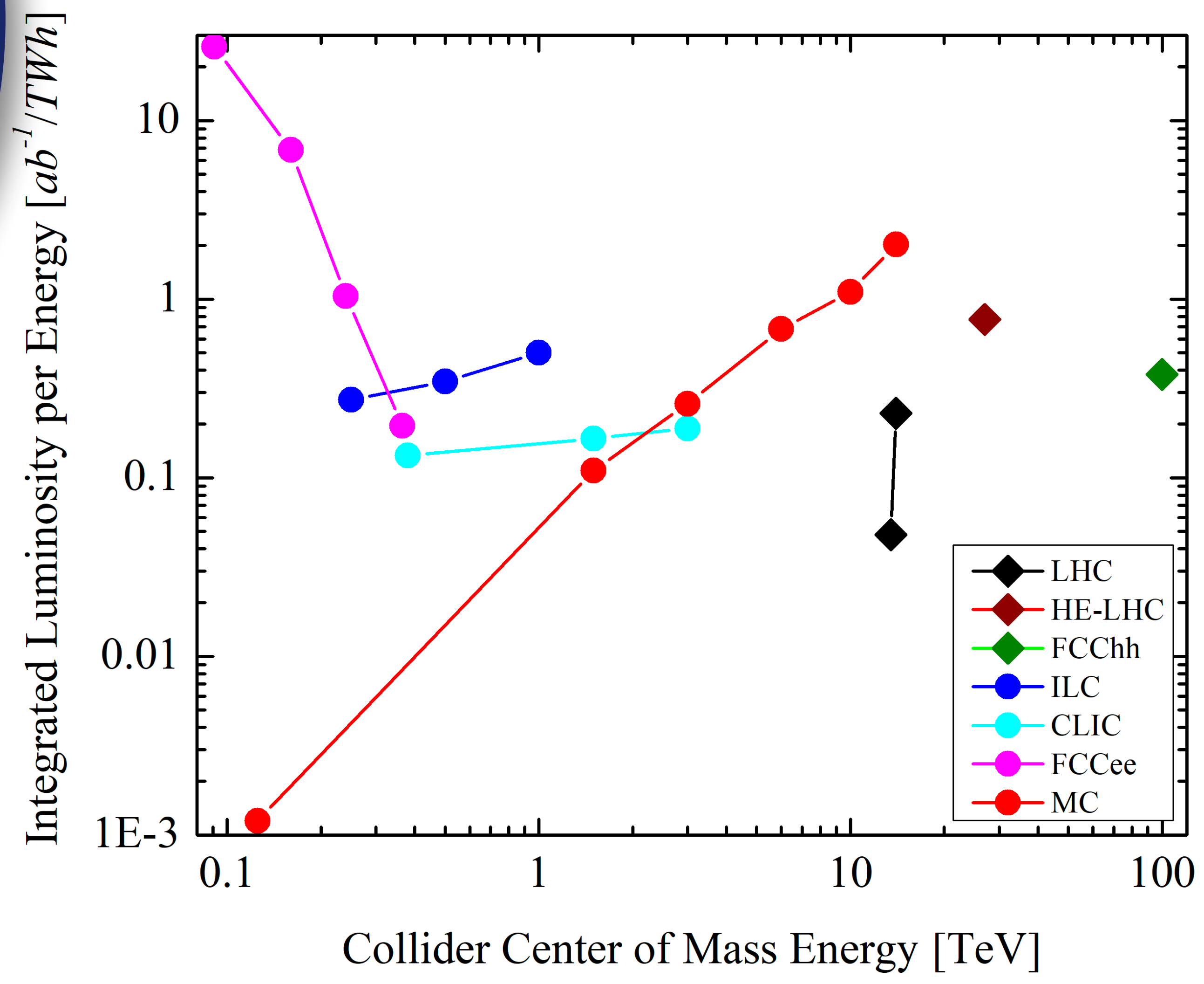
$$B \approx 3 \left(\frac{E}{1\ \text{TeV}}\right)\left(\frac{1\ \text{km}}{R}\right) \text{T}$$

How do we go forward?

- **Enter the muon!**
  - High mass – avoids synchrotron limitations, can do a circular collider
  - Fundamental particle – can get higher energy reach with lower energy beam compared to protons
  - Bonus: luminosity increases linearly with energy for fixed power



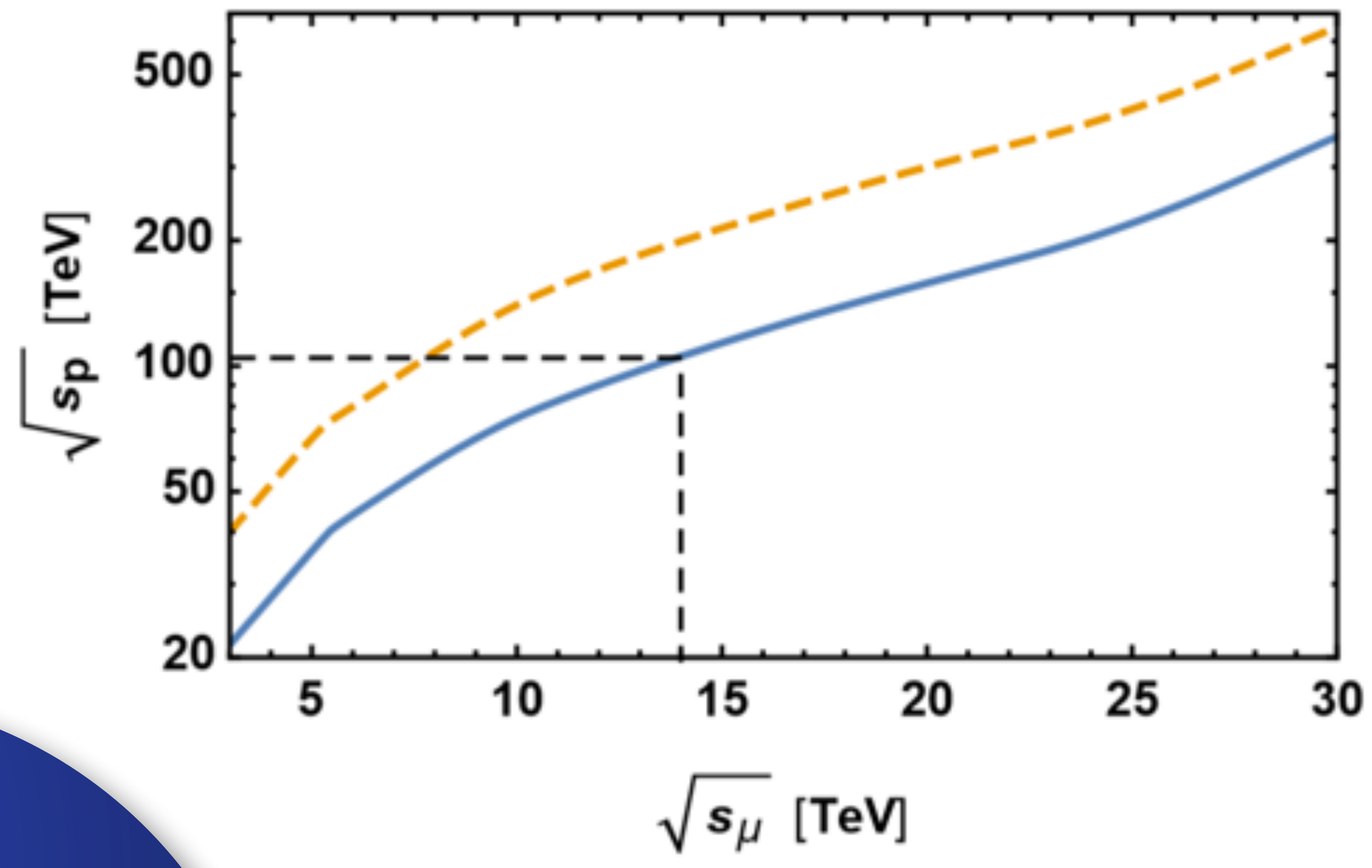


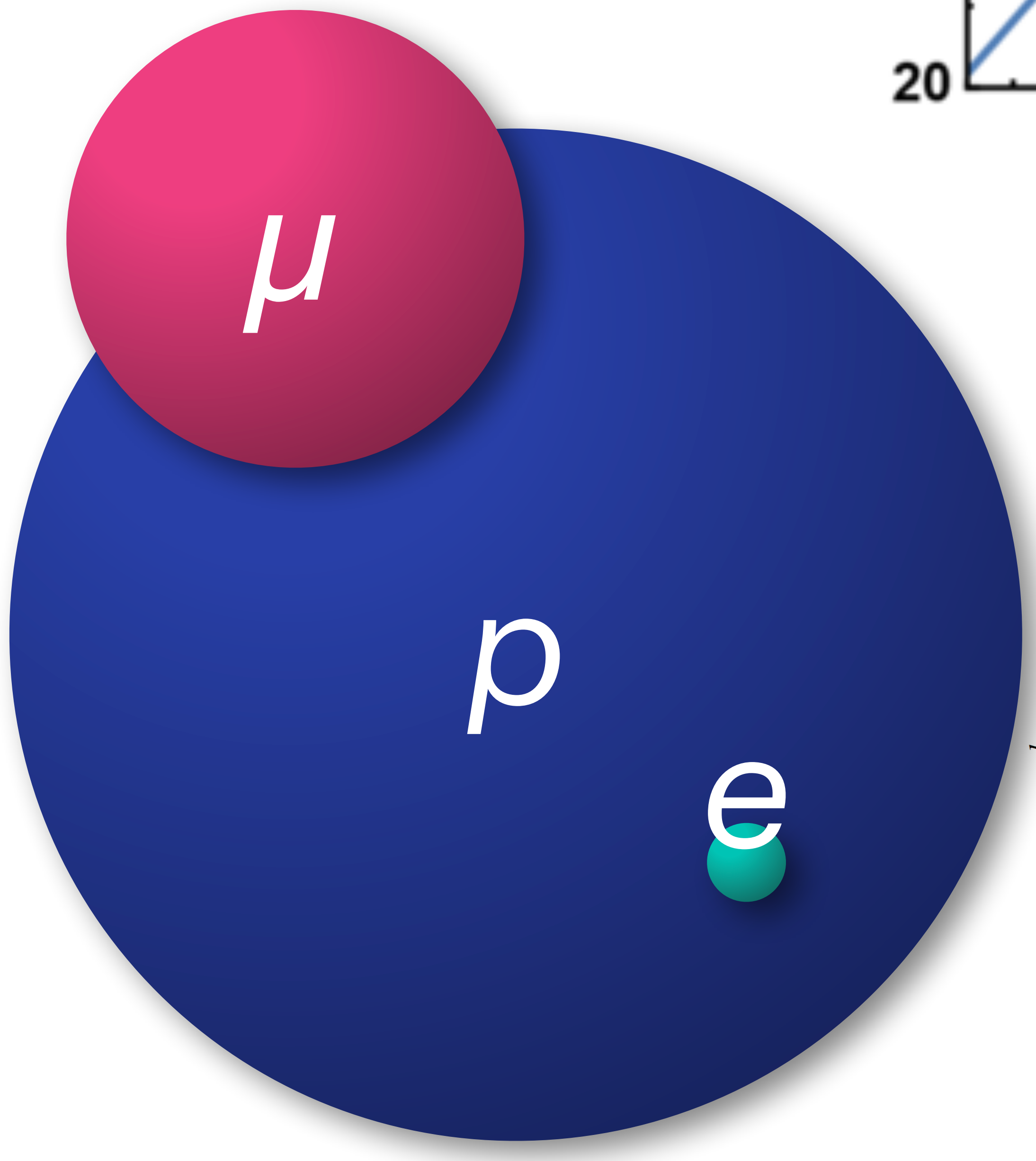


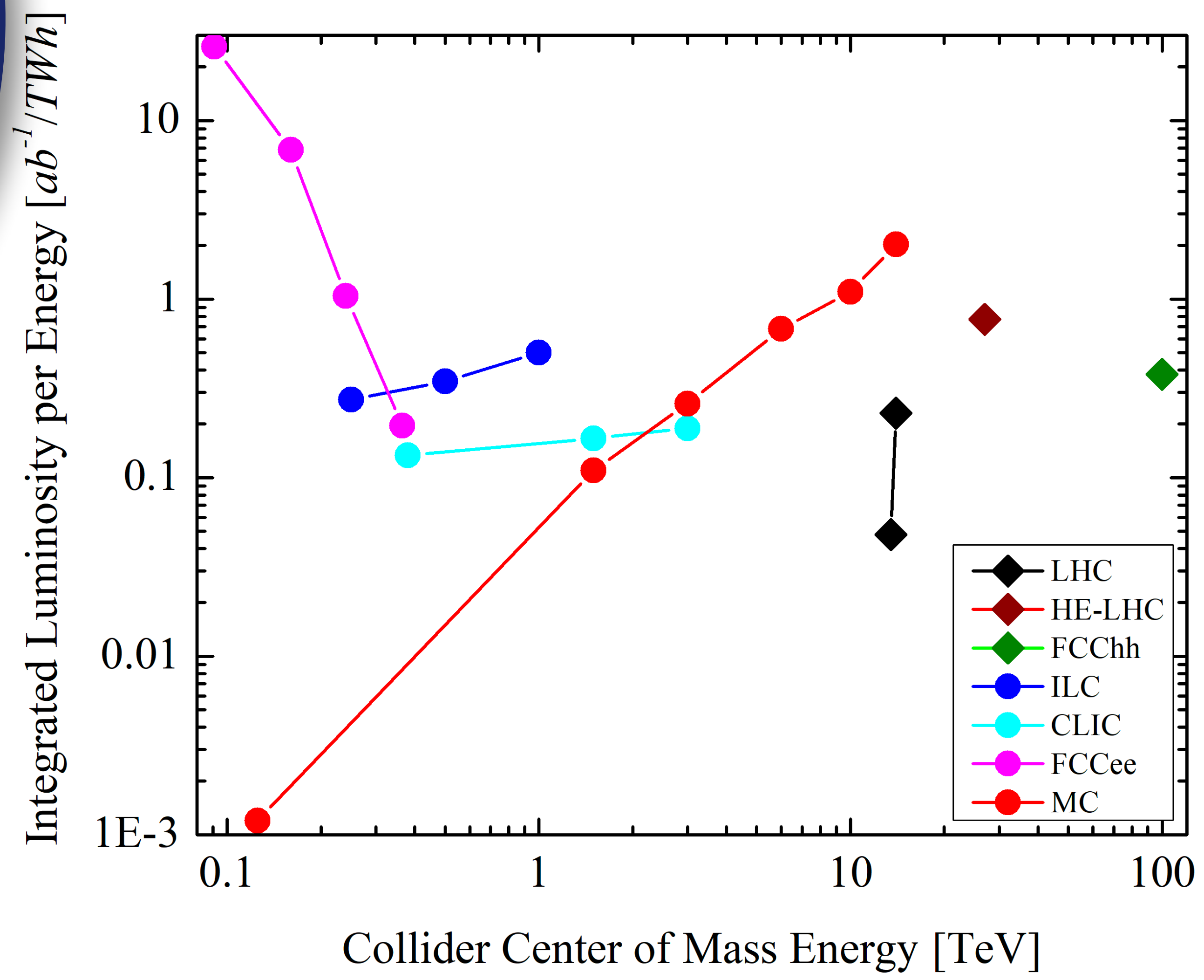
K. Long et al

How do we go forward?

- **Enter the muon!**
  - High mass – avoids synchrotron limitations, can do a circular collider
  - Fundamental particle – can get higher energy reach with lower energy beam compared to protons
  - Bonus: luminosity increases linearly with energy for fixed power
  - Downside: muons decay…



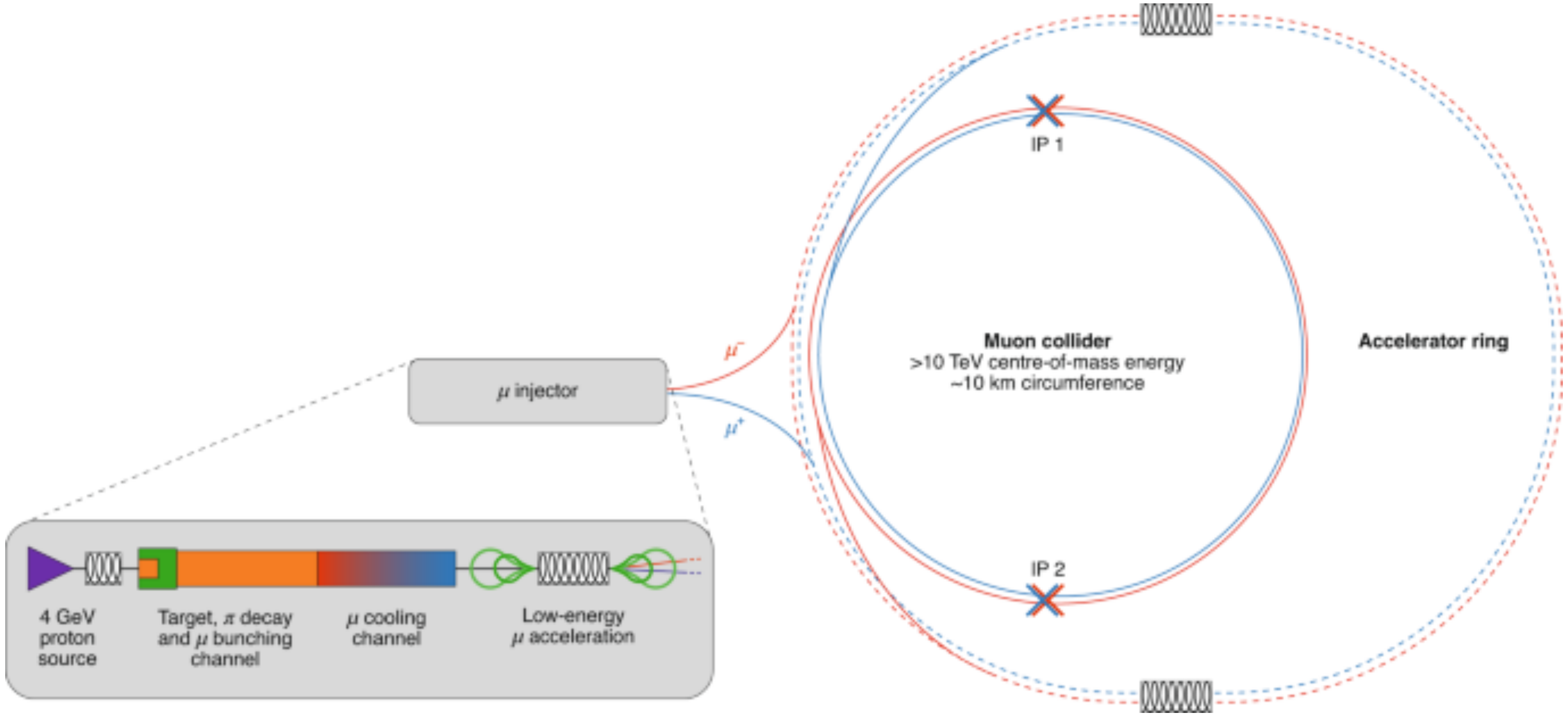




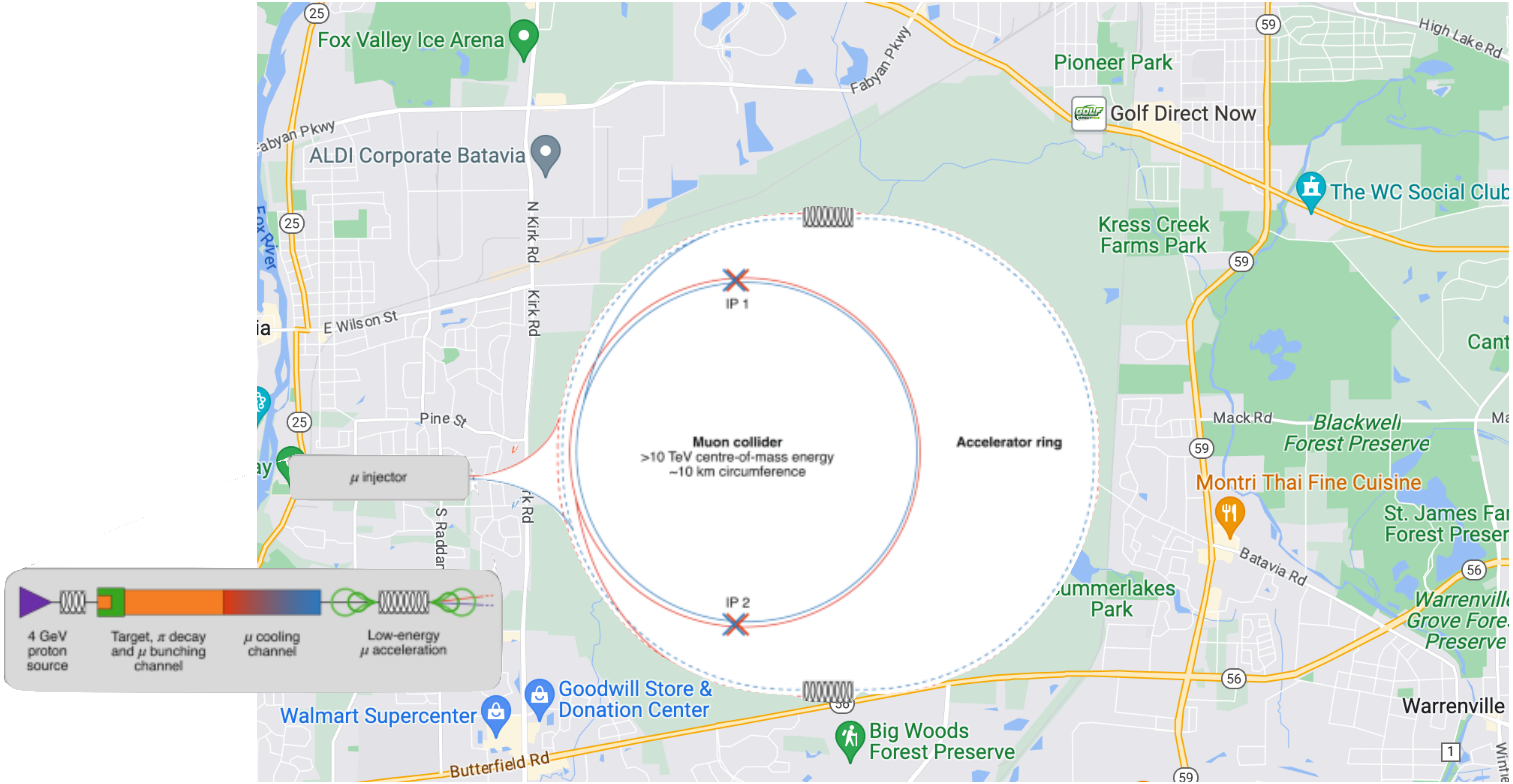
K. Long et al

How do we go forward?

a multi-TeV muon collider?



How do we go forward?



A spherical cow muon collider

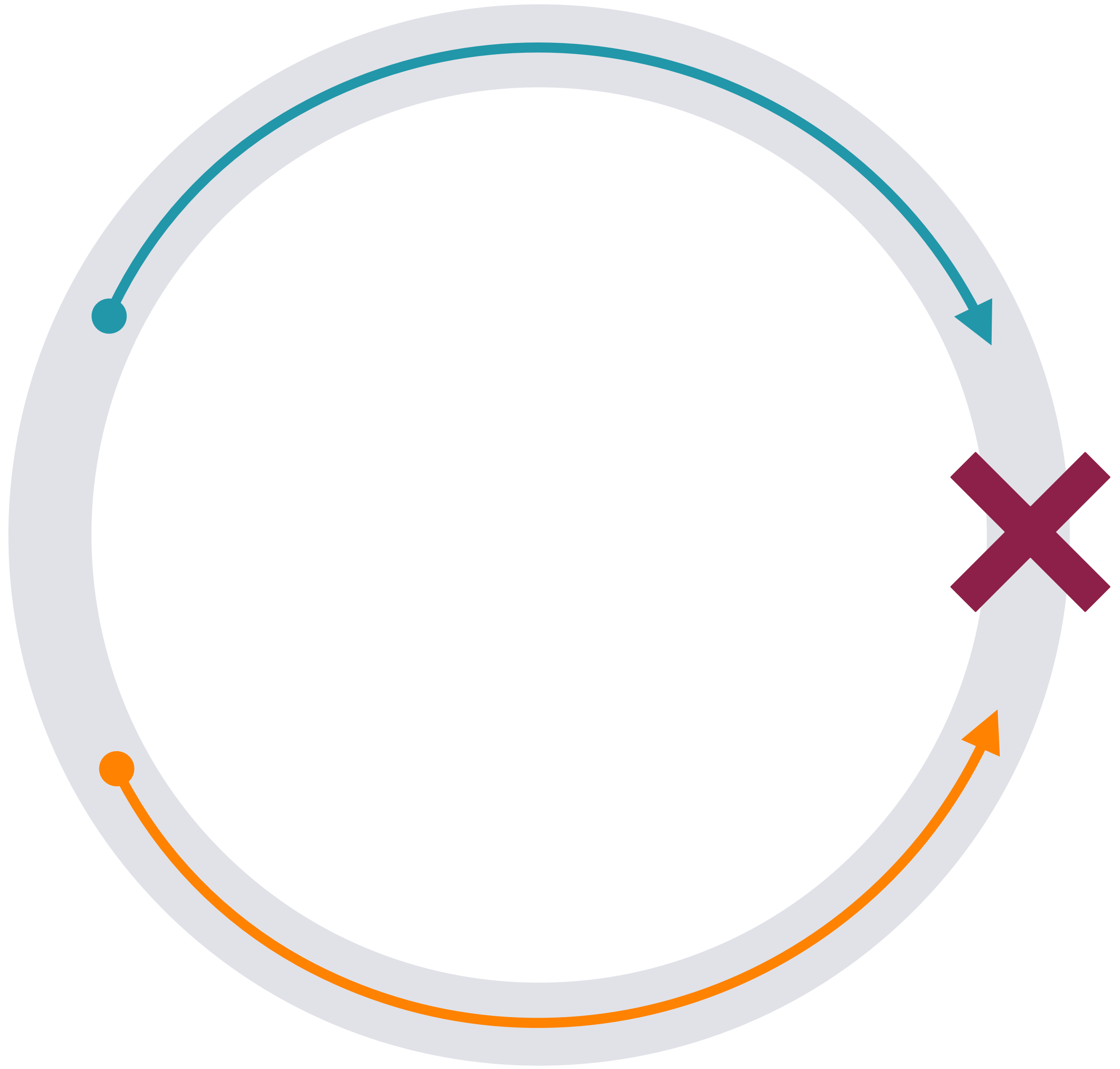
- Muons aren't just sitting around
  - Production limited, so concentrate them in two bunches
  - Circulate pairs of bunches until they're depleted
- What happens to the bunches?
  - muon lifetime $\tau_\mu = 2.2\ \mu s$
  - Lorentz factor $\gamma = 9{,}400 \times \left(\frac{E}{1\ \mathrm{TeV}}\right)$

$L = \text{circumference}$
$E = \text{beam energy}$

A spherical cow muon collider

Need to re-inject at:
~100 Hz for 0.5 TeV beam
~10 Hz for 5 TeV beam

- Muons aren't just sitting around
  - Production limited, so concentrate them in two bunches
  - Circulate pairs of bunches until they're depleted
- What happens to the bunches?
  - muon lifetime $\tau_\mu = 2.2\ \mu s$
  - Lorentz factor $\gamma = 9{,}400 \times \left(\frac{E}{1\ \mathrm{TeV}}\right)$
  - average decay time in lab frame $\tau'_\mu = 21\ \mathrm{ms} \times \left(\frac{E}{1\ \mathrm{TeV}}\right)$

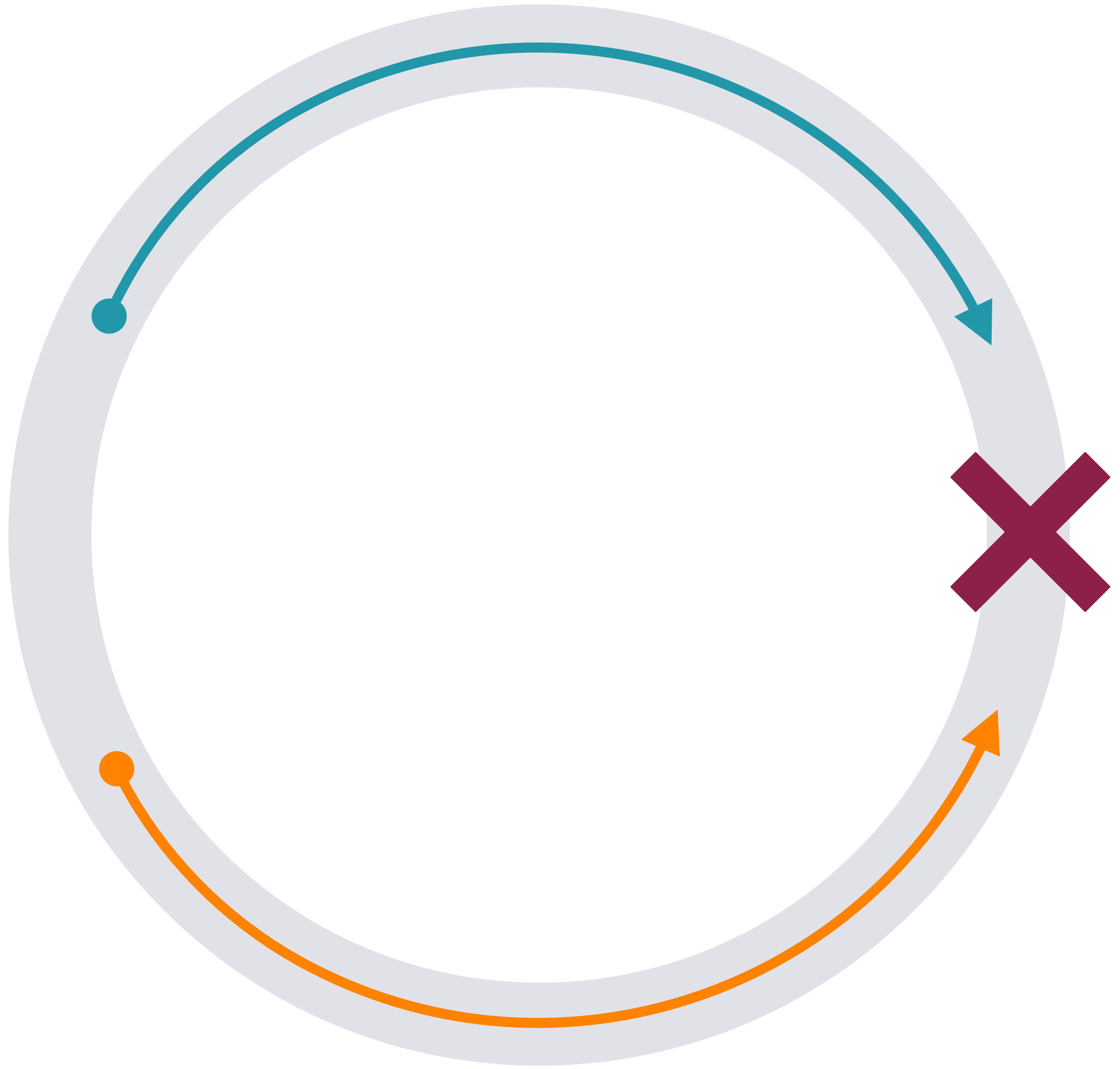


L = circumference
E = beam energy

A spherical cow muon collider

- Muons aren't just sitting around
  - Production limited, so concentrate them in two bunches
  - Circulate pairs of bunches until they're depleted
- What happens to the bunches?
  - time between collisions $t = 33\ \mu s \times \left(\frac{L}{10\ \text{km}}\right)$

Large spacing between collisions, ~1000x lower rate than LHC



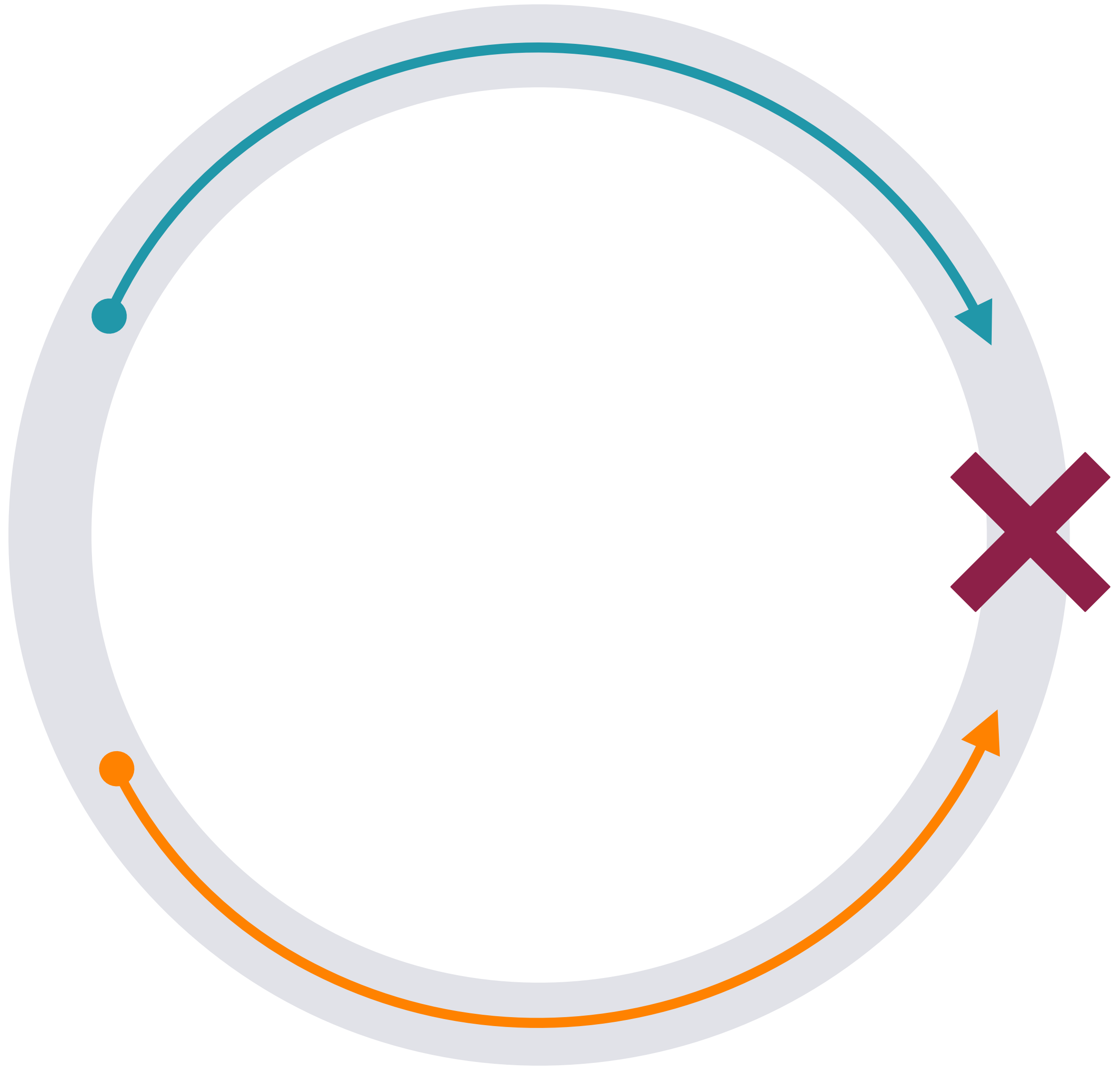
$L = \text{circumference}$
$E = \text{beam energy}$

A spherical cow muon collider

- average decay time in lab frame $\tau'_\mu = 21\ \mathrm{ms} \times \left(\frac{E}{1\ \mathrm{TeV}}\right)$
- average beam crossings for each injected muon:

$$\langle n_{\mathrm{crossings}} \rangle = 620 \times \left(\frac{E}{1\ \mathrm{TeV}}\right) \times \left(\frac{10\ \mathrm{km}}{L}\right)$$

Luminosity increases proportionally to energy



$L = \mathrm{circumference}$
$E = \mathrm{beam\ energy}$

A spherical cow muon collider

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- average beam crossings for each injected muon:

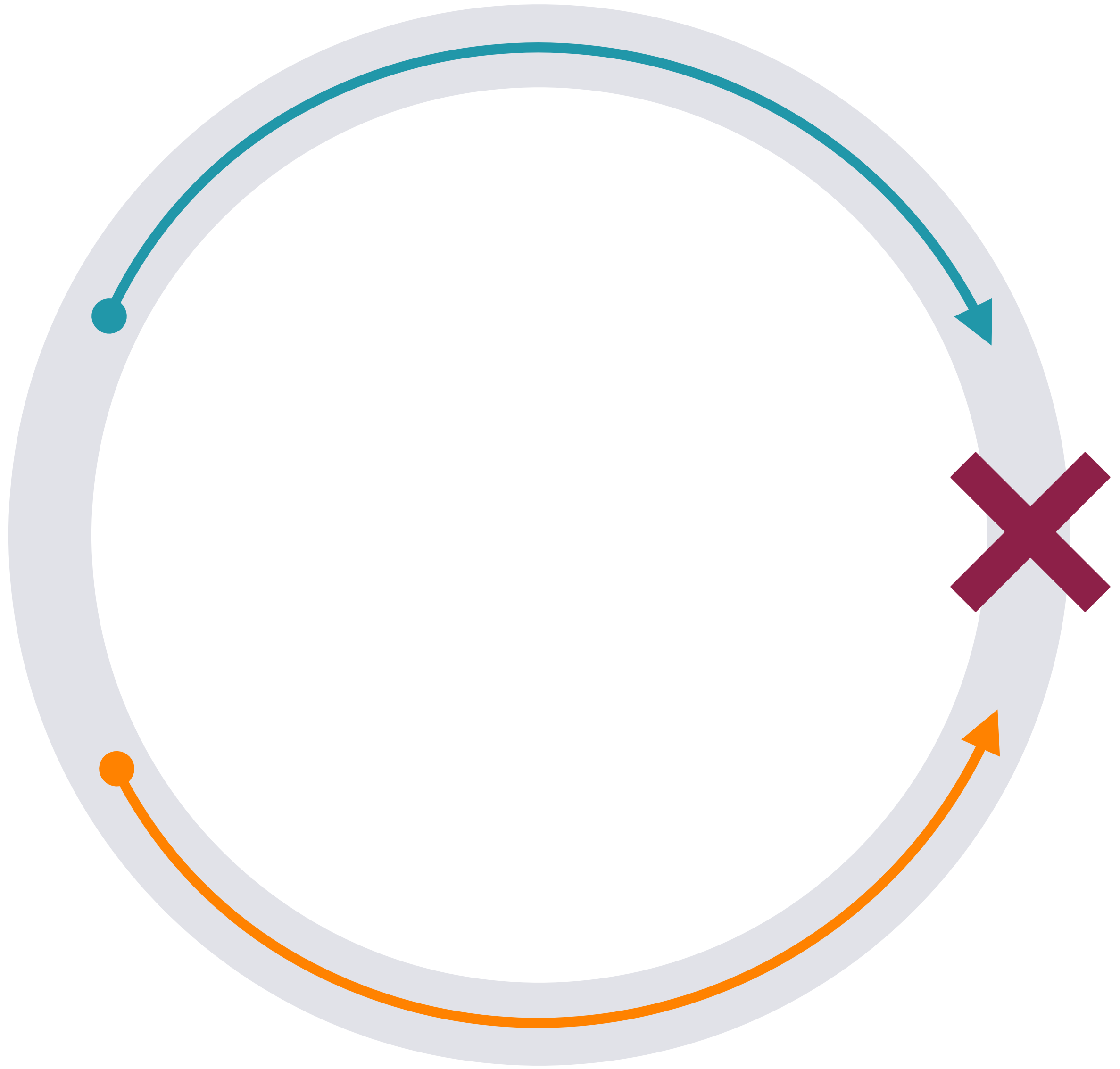
$$\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1\ \text{TeV}}\right) \times \left(\frac{10\ \text{km}}{L}\right)$$

- fraction of muons decaying within 20m of the interaction point:

$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

inversely proportional to energy

For each bunch of $2\text{x}10^{12}$, expect around 10^7 decays in this region



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A spherical cow muon collider

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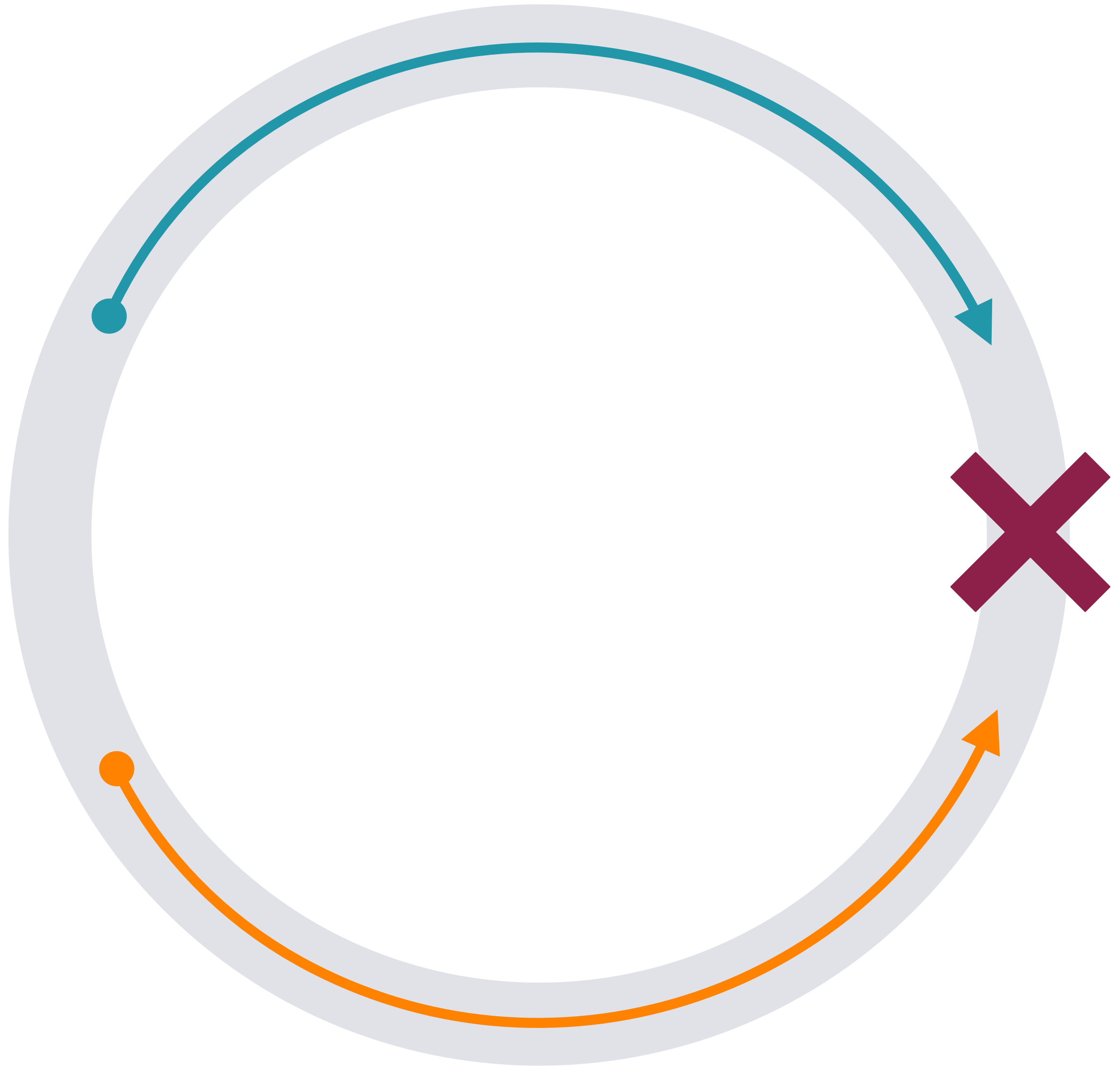
$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

- total energy of decay products within 20m of the interaction point

$$E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$$



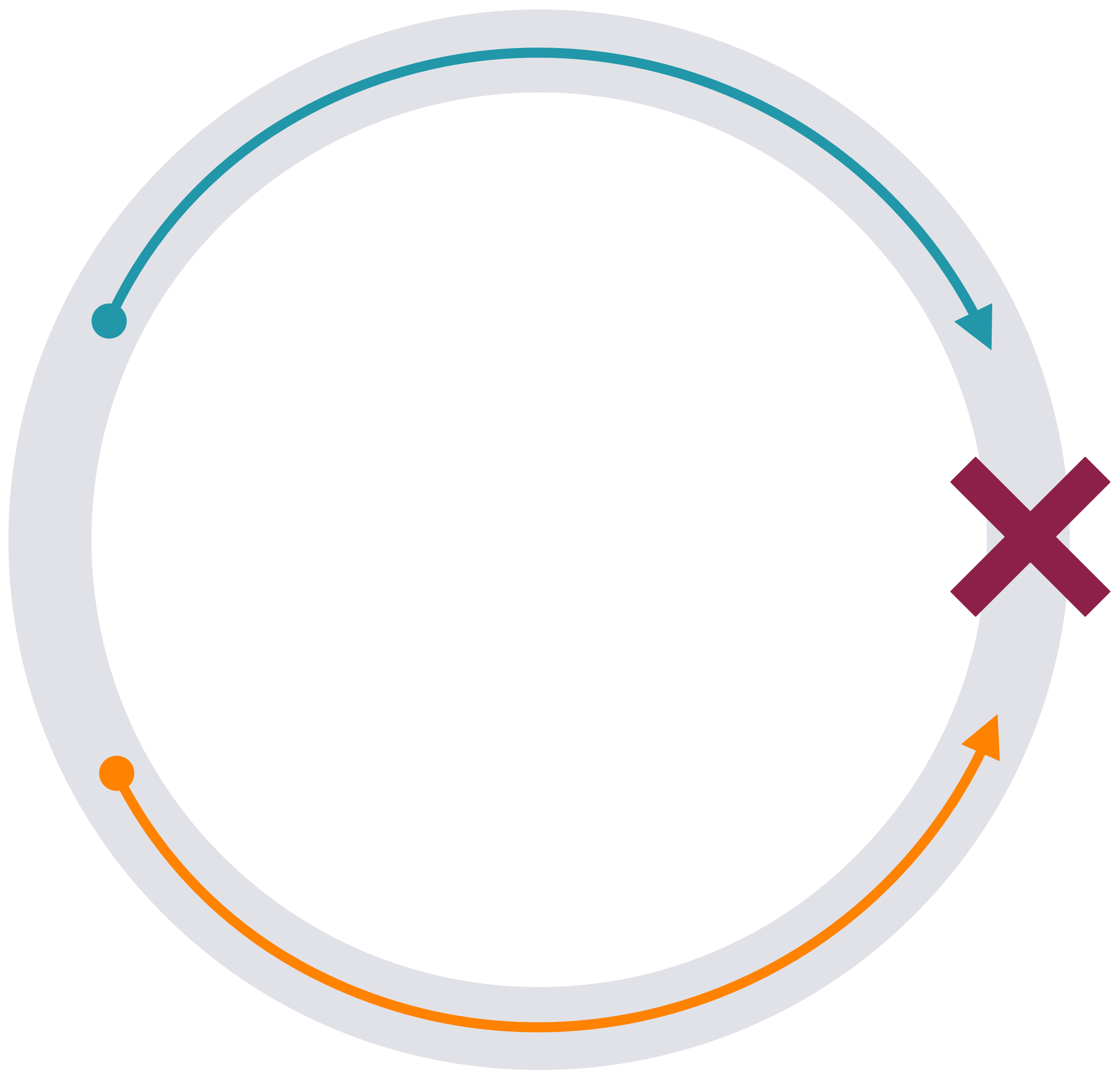
$L = \text{circumference}$

$E = \text{beam energy}$

does not depend on E!

A spherical cow muon collider

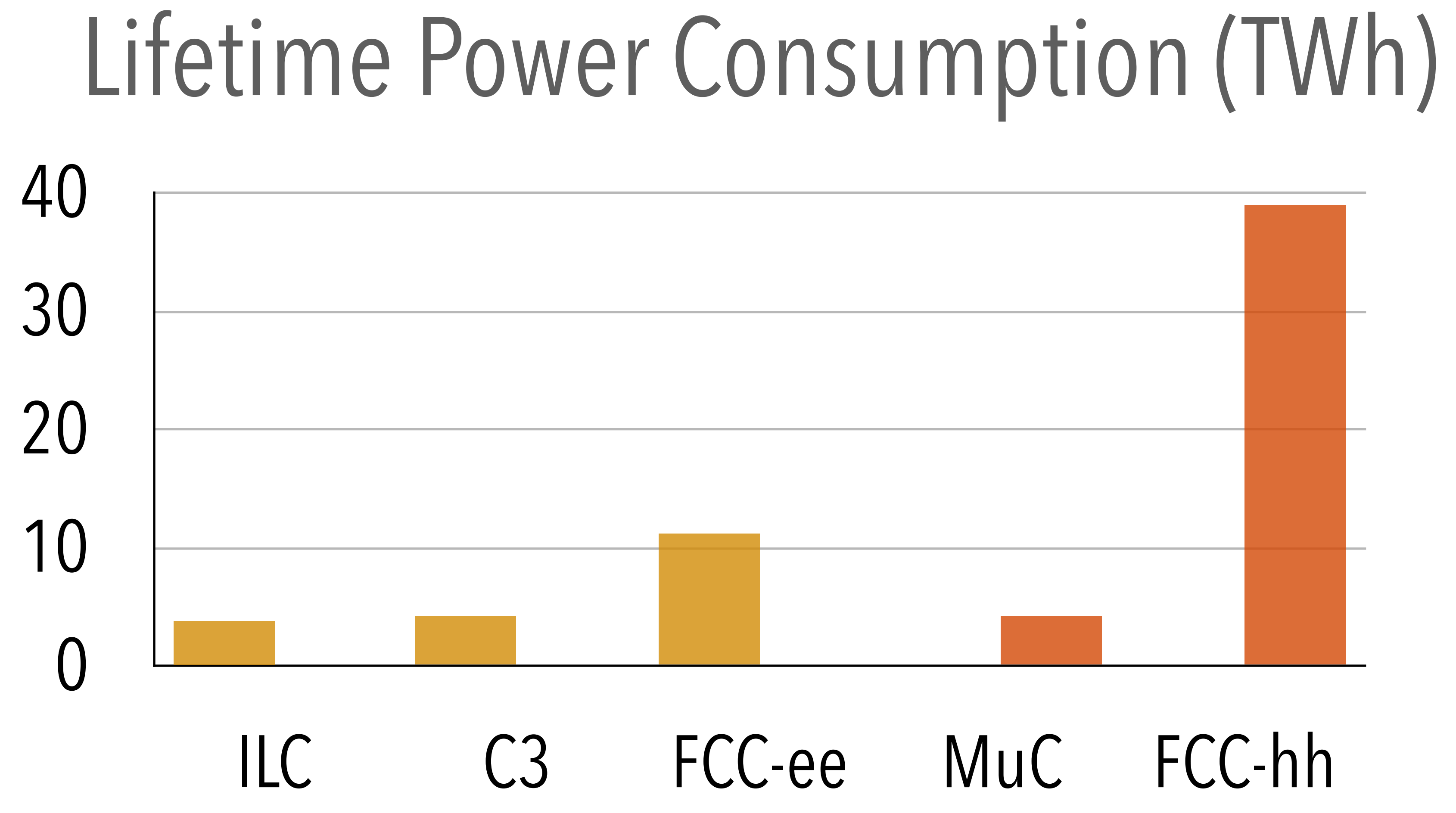
- Takeaways:
  - Key **ee** challenges get **harder** with E
    - synchrotron radiation at a circular collider
    - power and size constraints on a linear collider
  - Key **pp** challenges get **harder** with E
    - large ring size needed for high energy beams
  - Key **μμ** challenges get **easier** with E
    - higher luminosity due to circulating beams
    - fewer beam decays

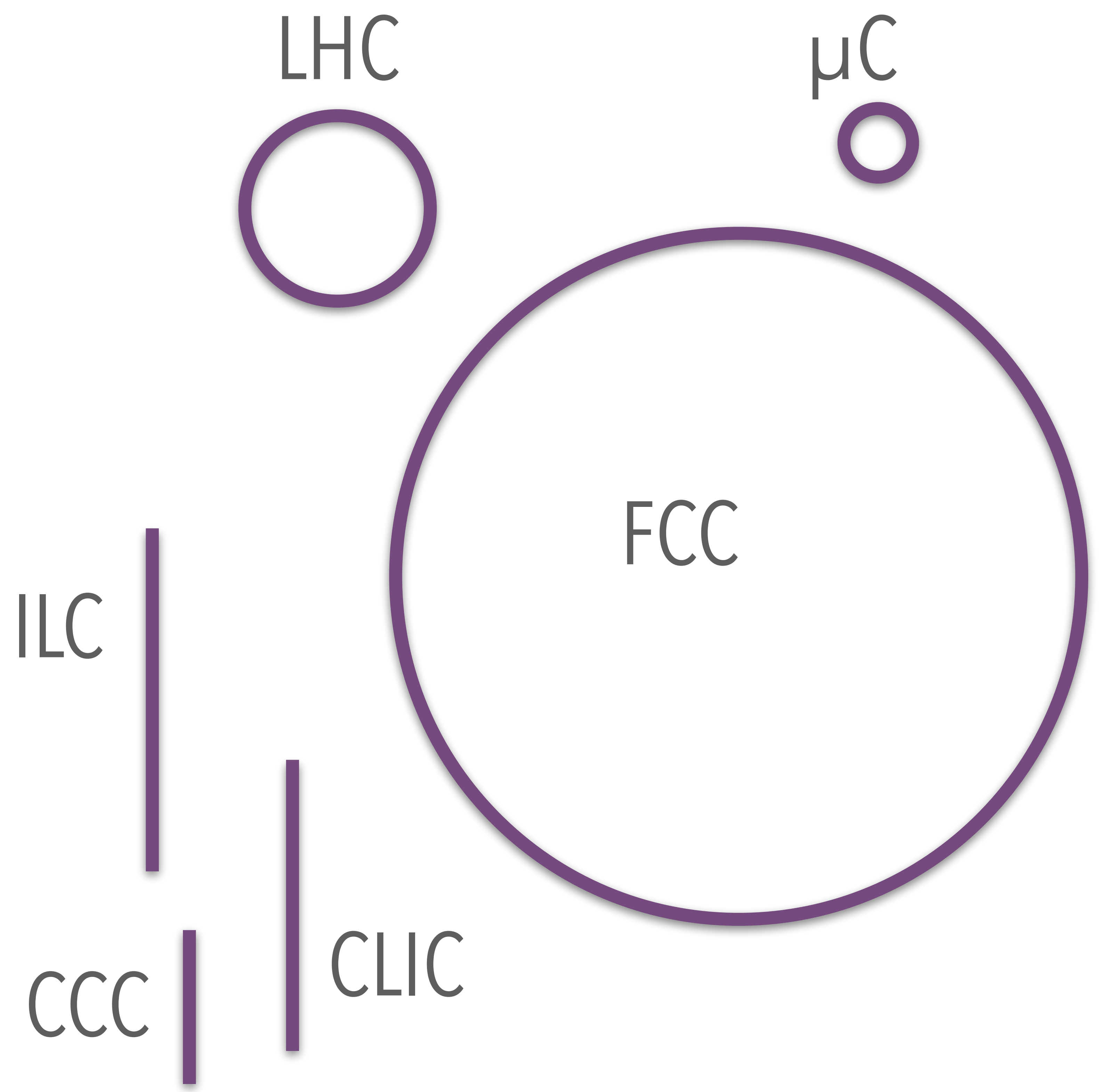


$$L = \text{circumference}$$
$$E = \text{beam energy}$$

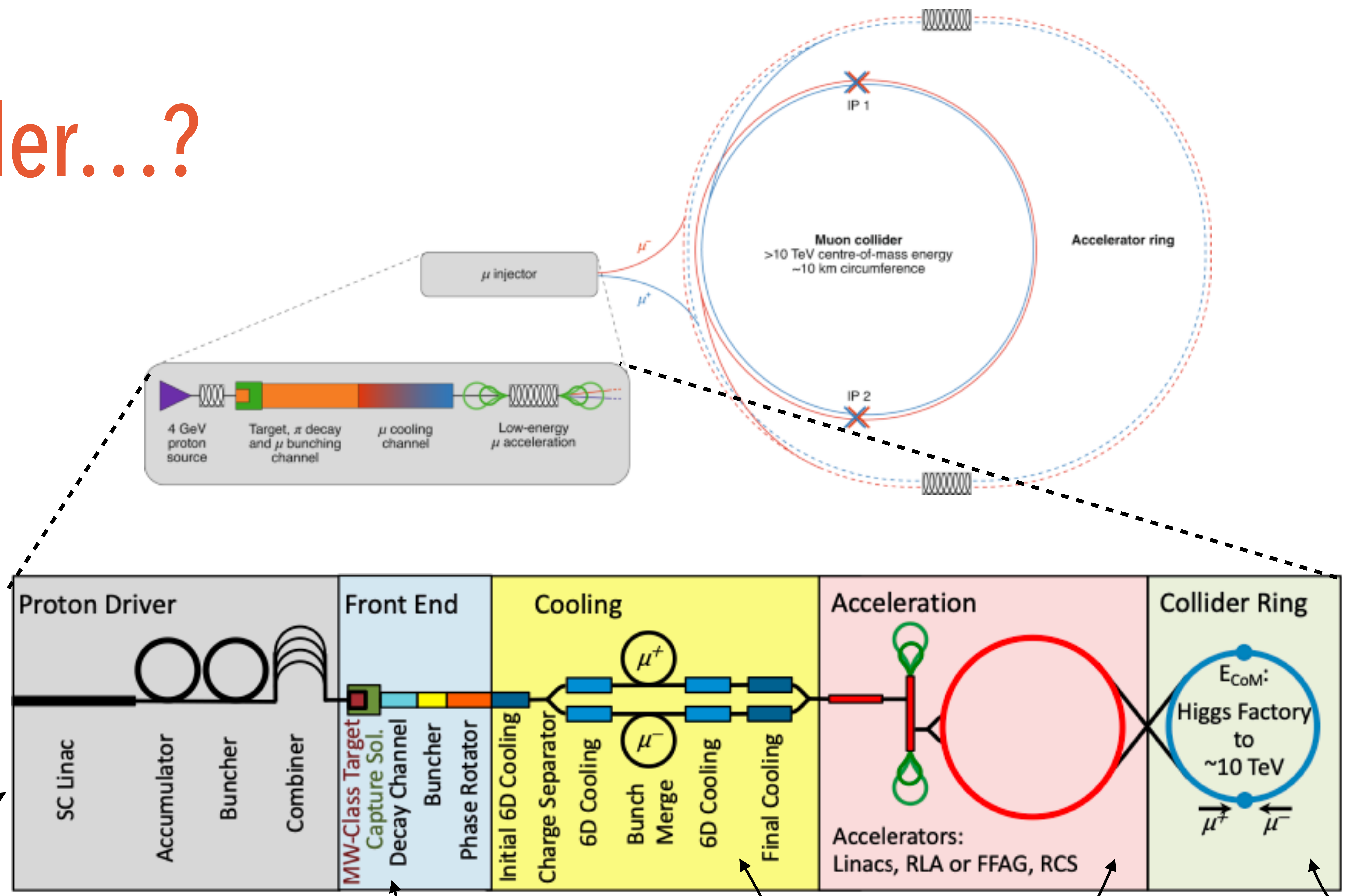
A spherical cow muon collider

- Some other selling points:
    - **Compact** size and low power means lower cost and carbon footprint
    - Potential **Fermilab** siting, which means it could be complimentary to a CERN program
    - Most of cost goes into **new technology**; good for return on investment and international buy-in
    - Path **beyond** the 10 TeV scale!





A real muon collider…?



MW-scale proton driver

Target for muon production + solenoid for capture

6D ionization cooling

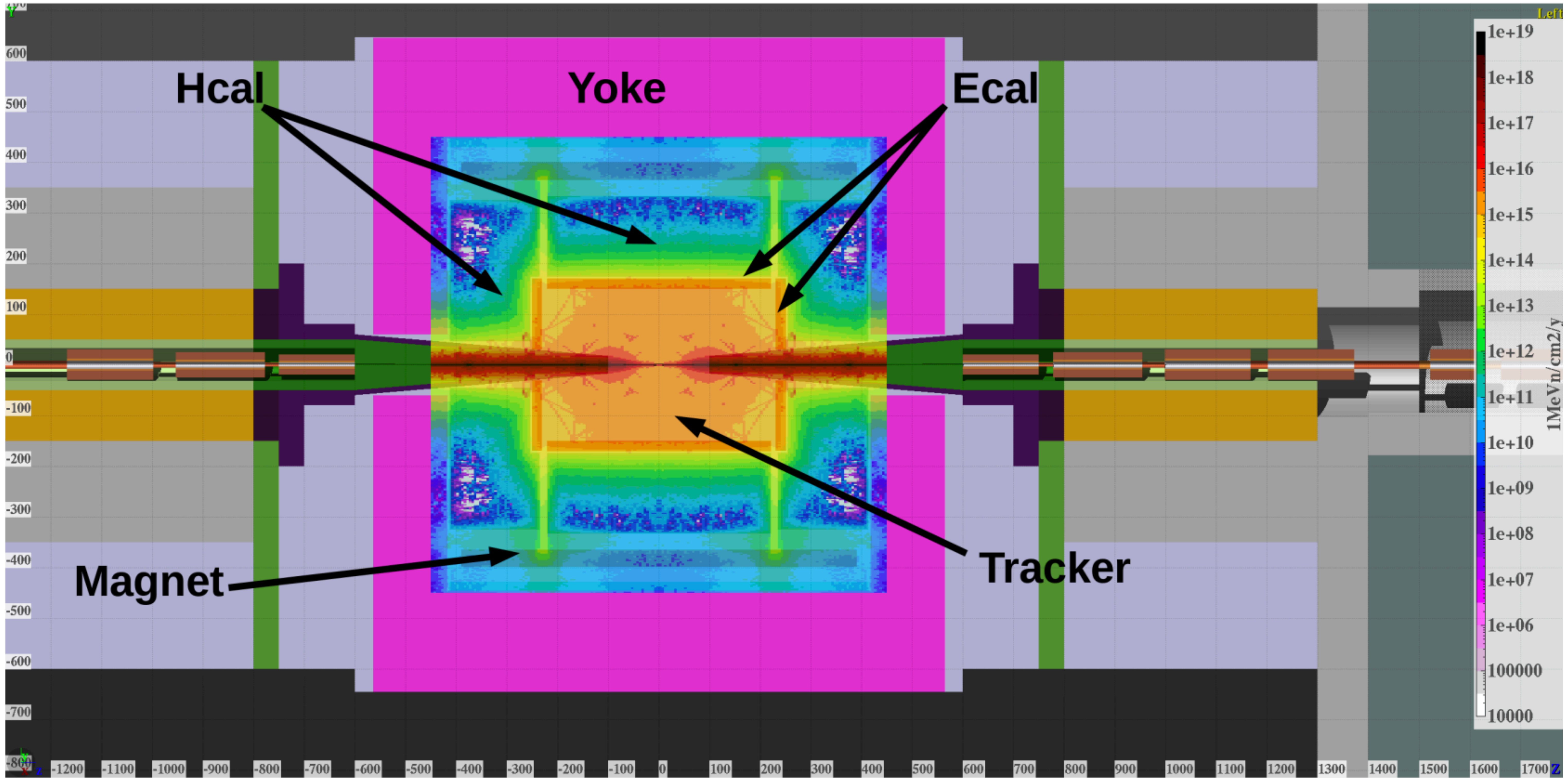
Accelerator ring

Collider ring

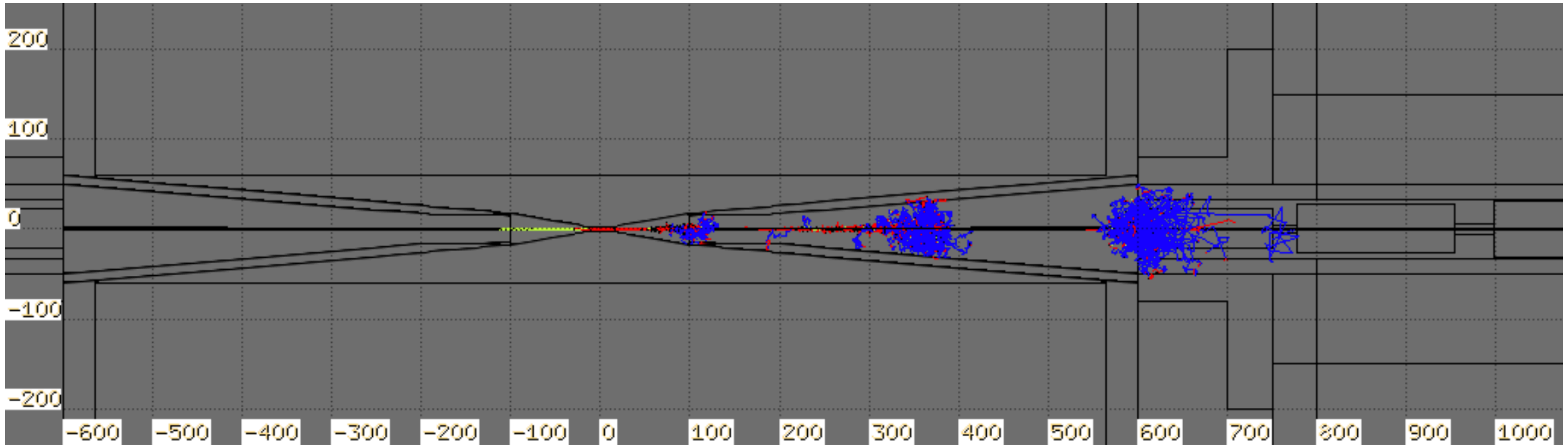
D. Stratakis

A real muon collider…?

In the detector, tungsten nozzles block high energy products of decaying beam



particles resulting from one muon decay



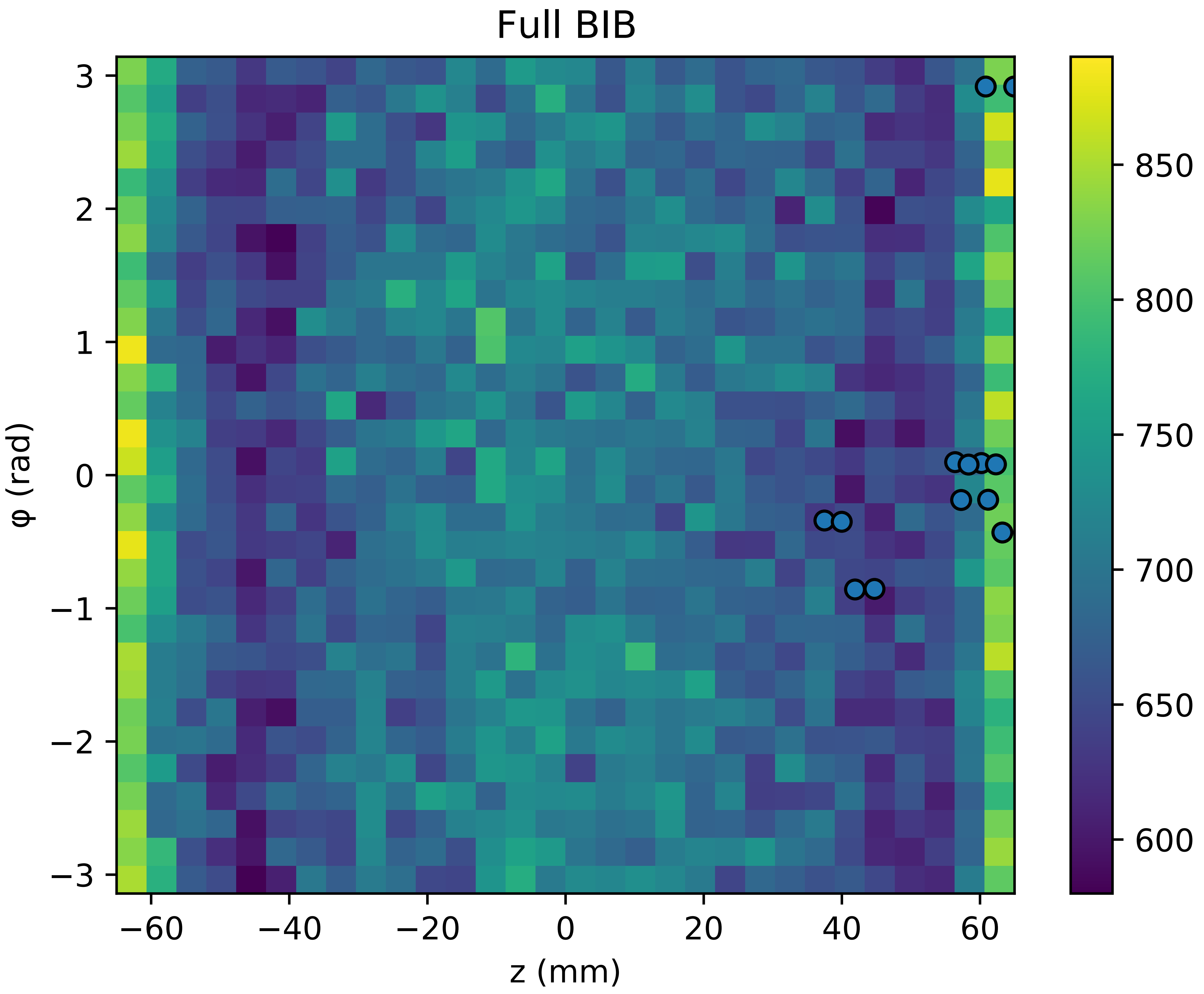
we expect ~10^7 of these

F. Collamati et al

A real muon collider…?

In the detector, tungsten nozzles block high energy products of decaying beam

In the vertex detector…



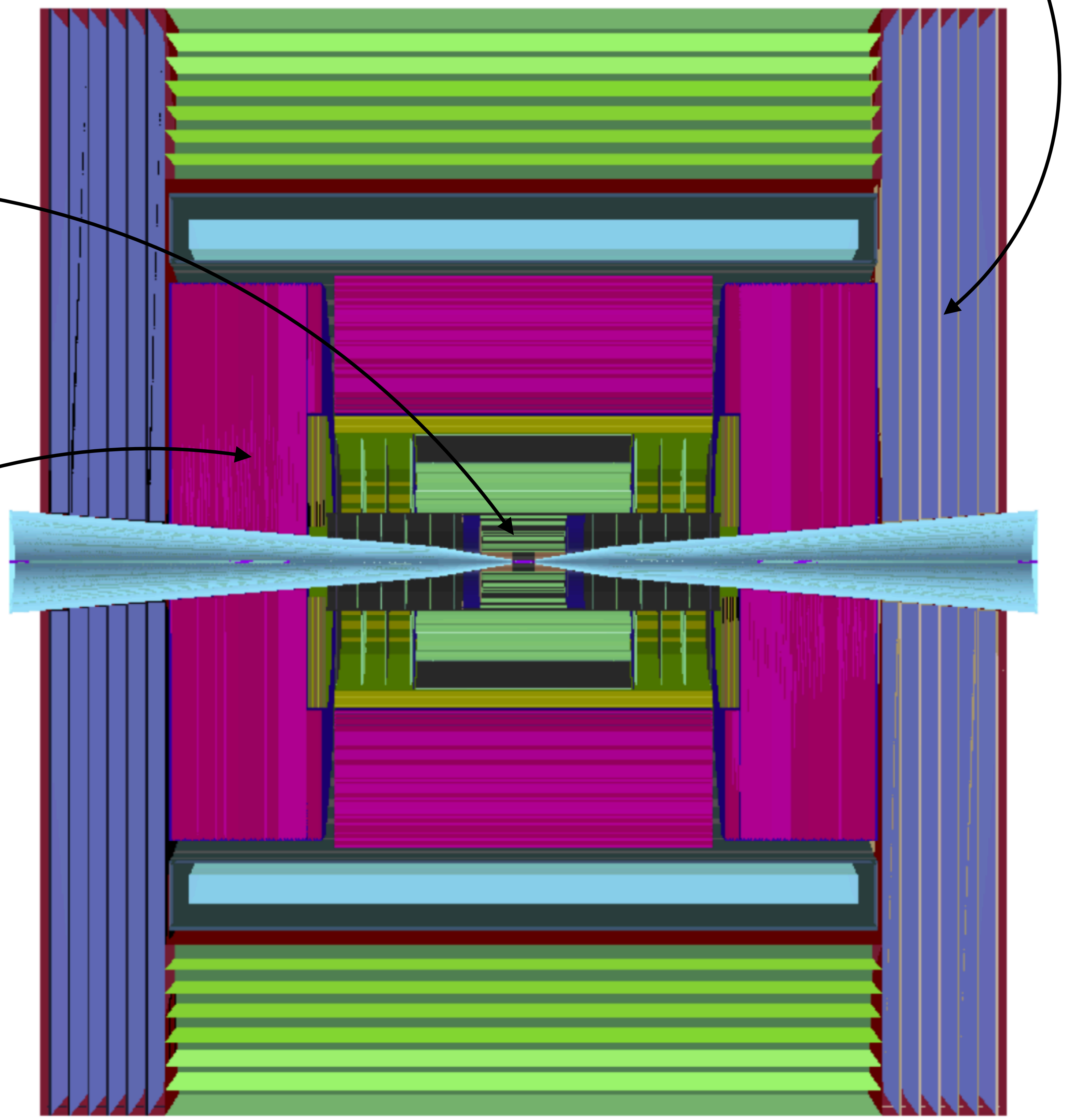
A real muon collider…?

High rate muon system (esp. in endcaps)

4D tracker, potentially with pointing information

Radiation hard electronics with on-chip intelligence for triggerless readout

High granularity calorimeter with precision timing

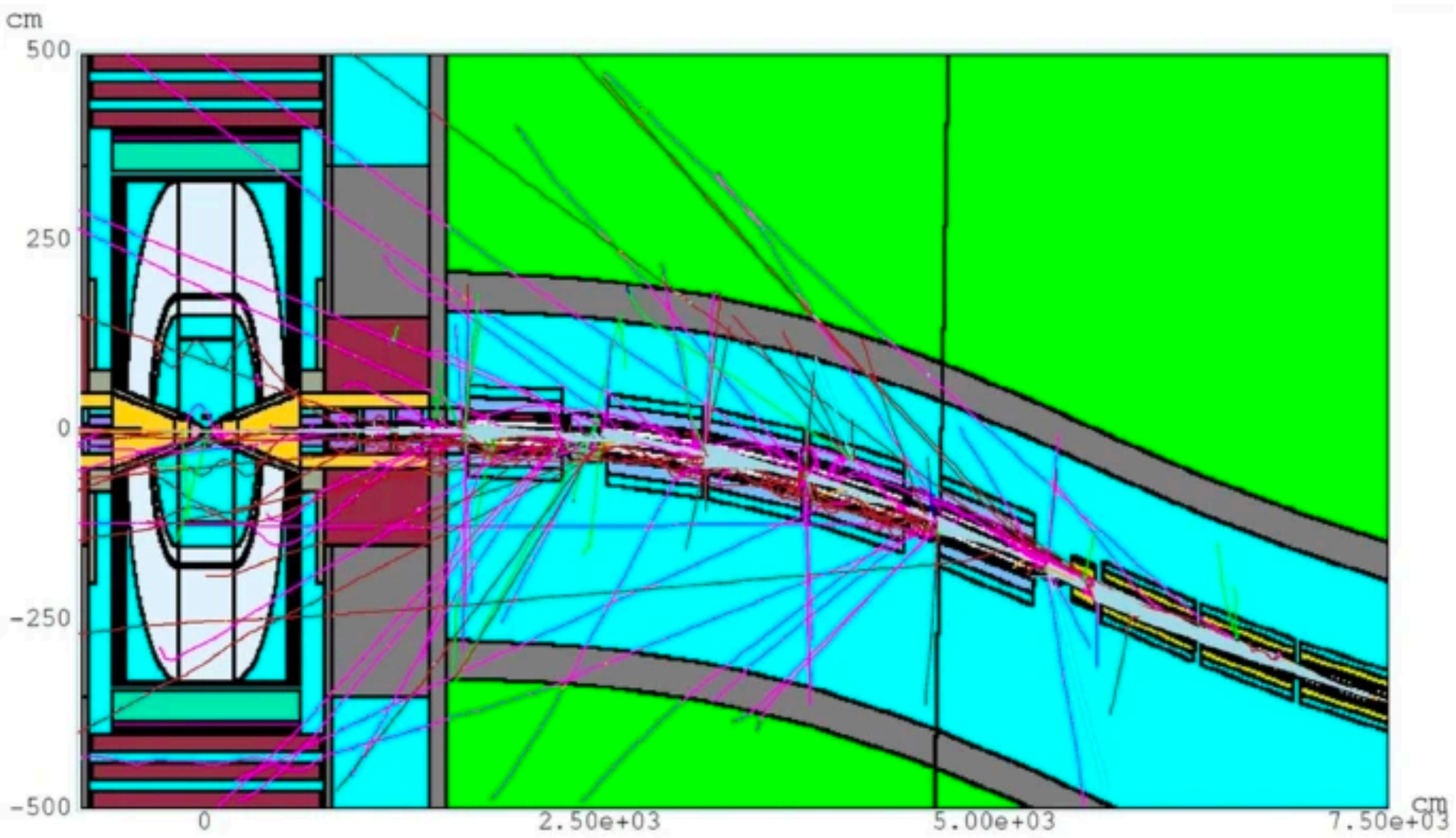


Design for forward systems for tagging and luminosity

A real muon collider…?

Everything is interconnected!

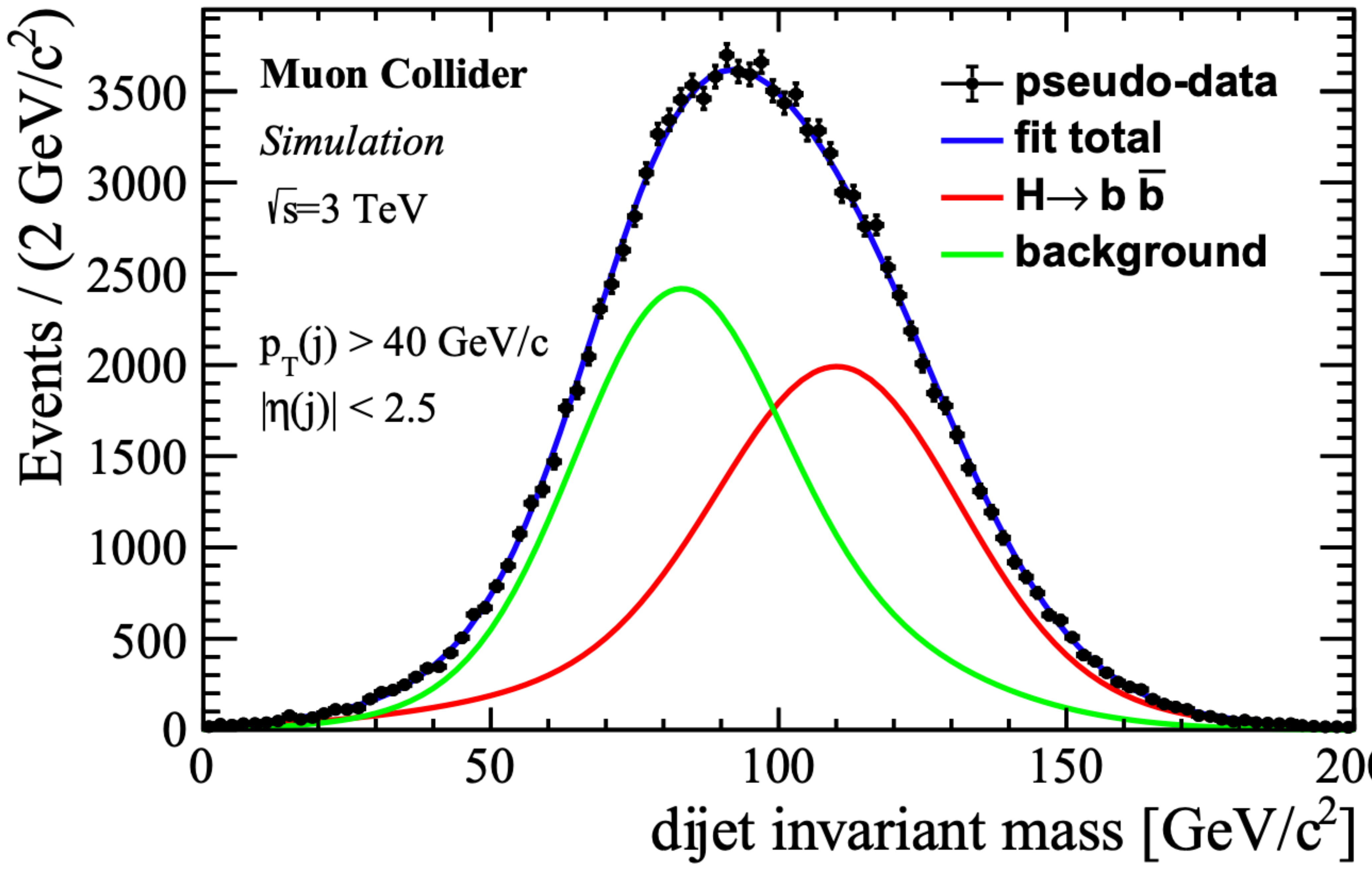
Tweaks to beam parameters or machine-detector-interface completely change detector requirements, physics performance

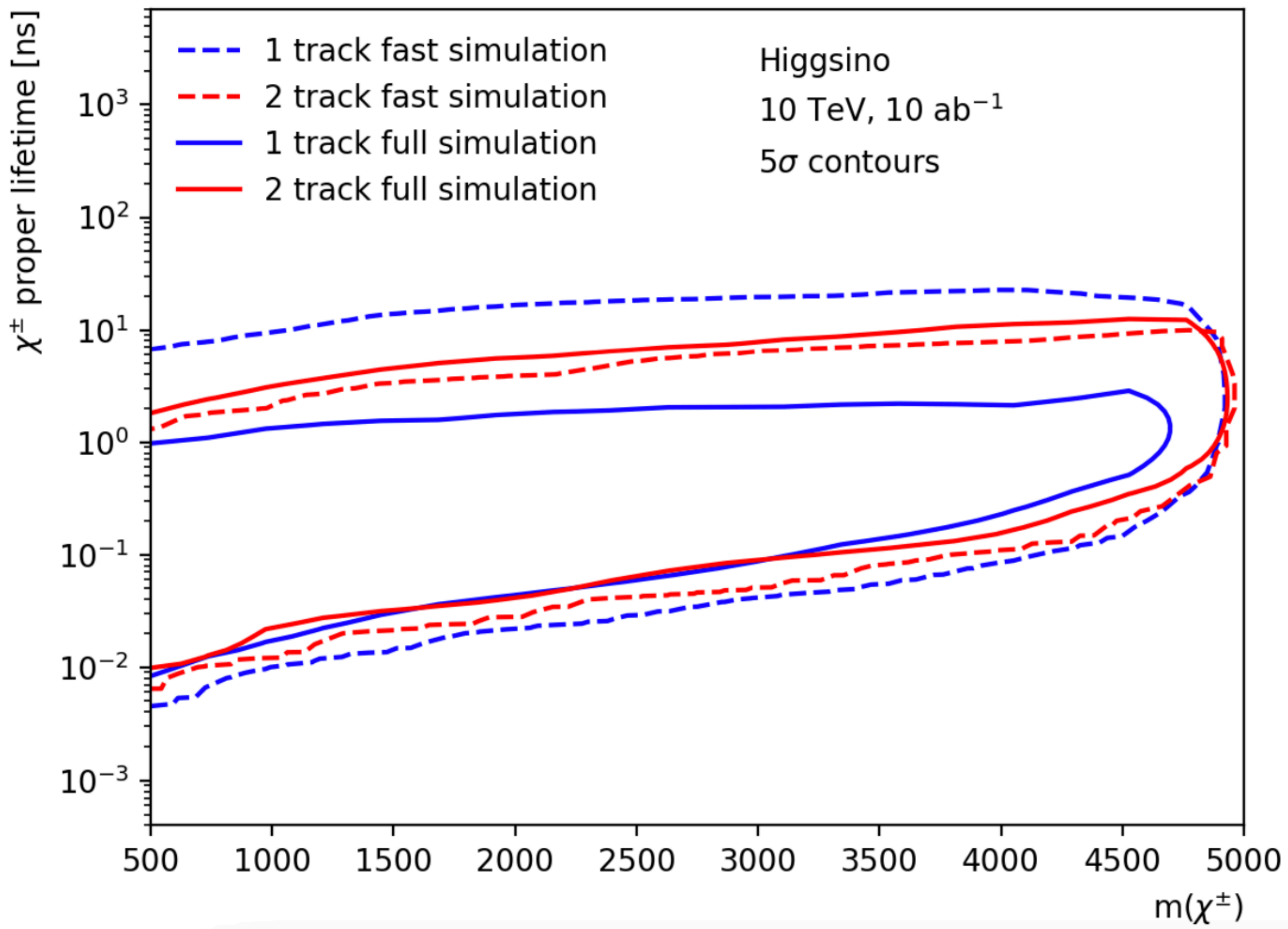


An opportunity to bring accelerator, experiment, and theory together – already happening.

N. Bartosik et al

A real muon collider…?

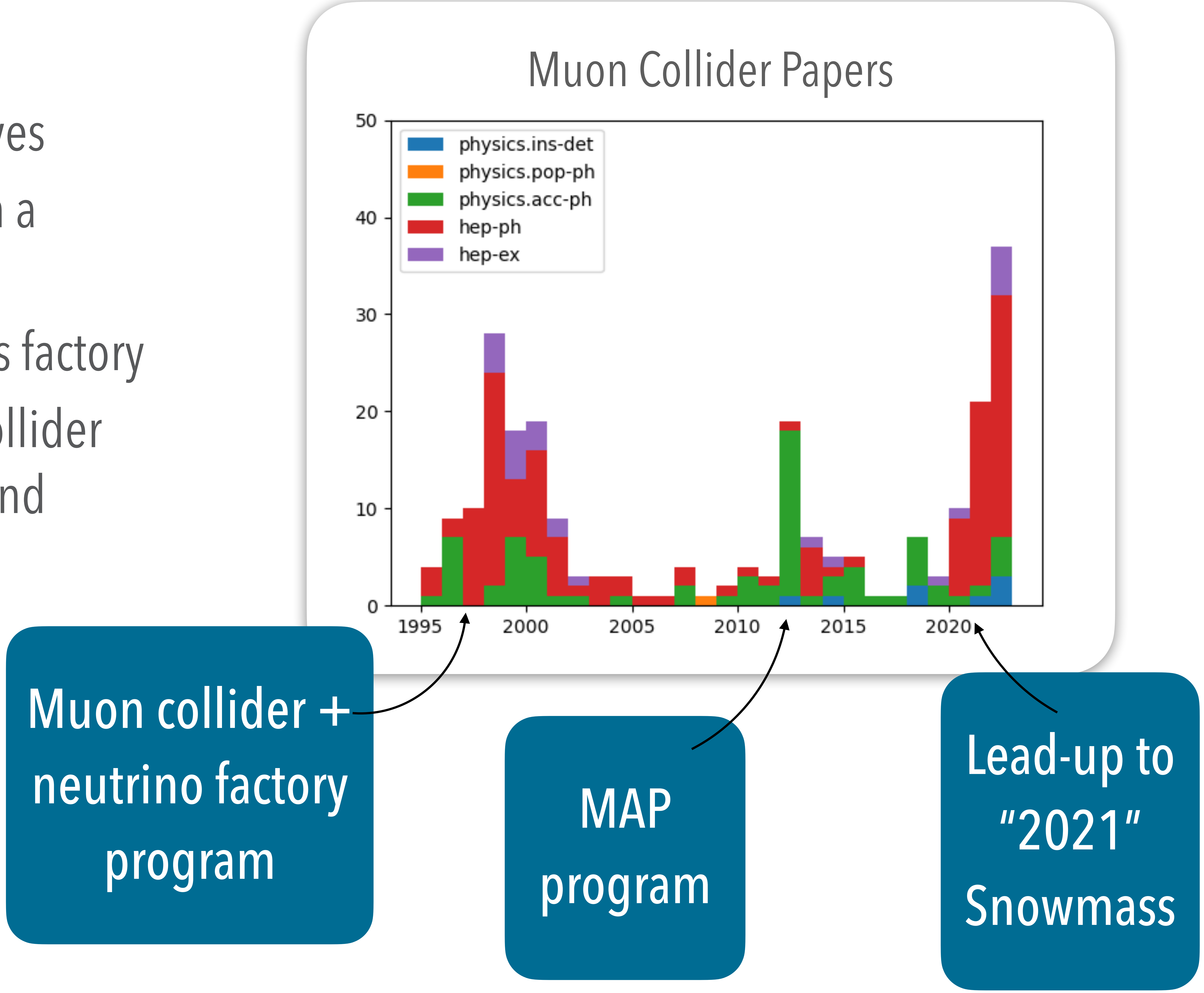




Muon Collider Forum Report

A real muon collider…?

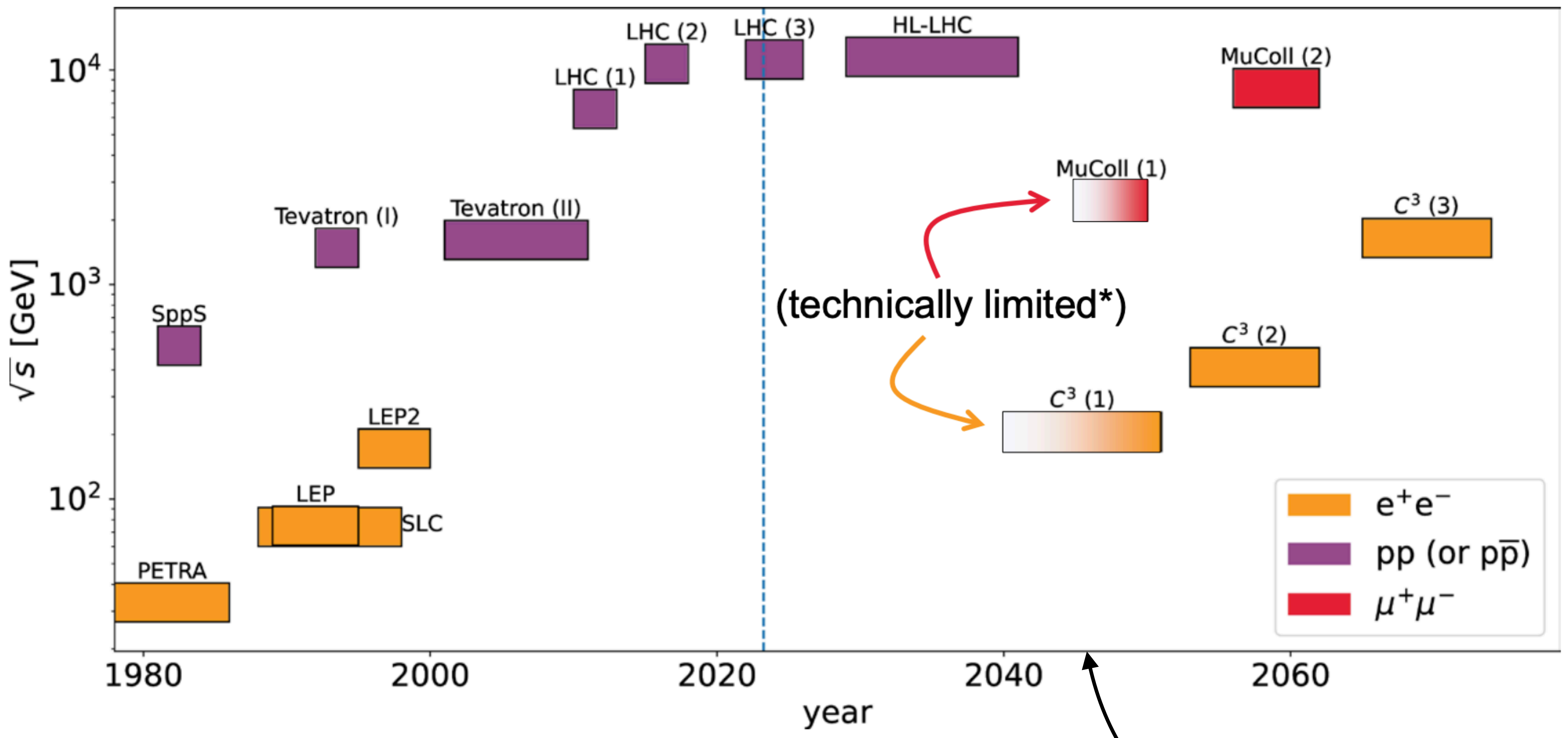
- Muon collider interest comes in waves
  - First proposed in connection with a neutrino factory at BNL or FNAL
  - MAP program focused on a Higgs factory
  - Now, shifted focus to multi-TeV collider with connections back to Higgs and neutrinos



A real muon collider…?

Community already well-tested in design and production

A real muon collider…?



Mel turns 100

Exciting opportunity to continue the exploration of the energy frontier – maybe even in Chicagoland!

Thank you!