Bridging HEP and NP with a Muon Collider

Patrick Meade
Yang Institute for Theoretical Physics
Stony Brook University

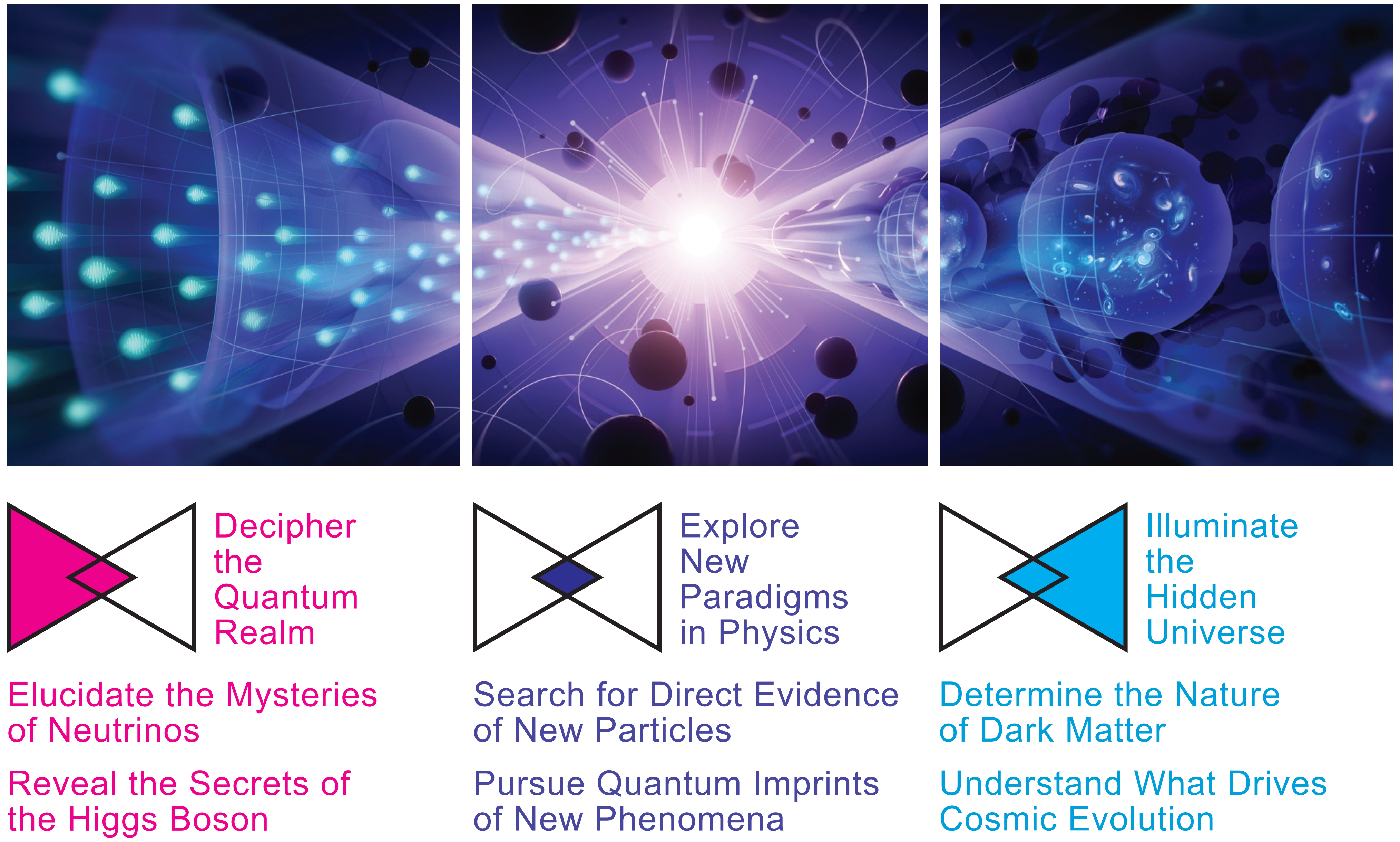
MUON COLLIDER

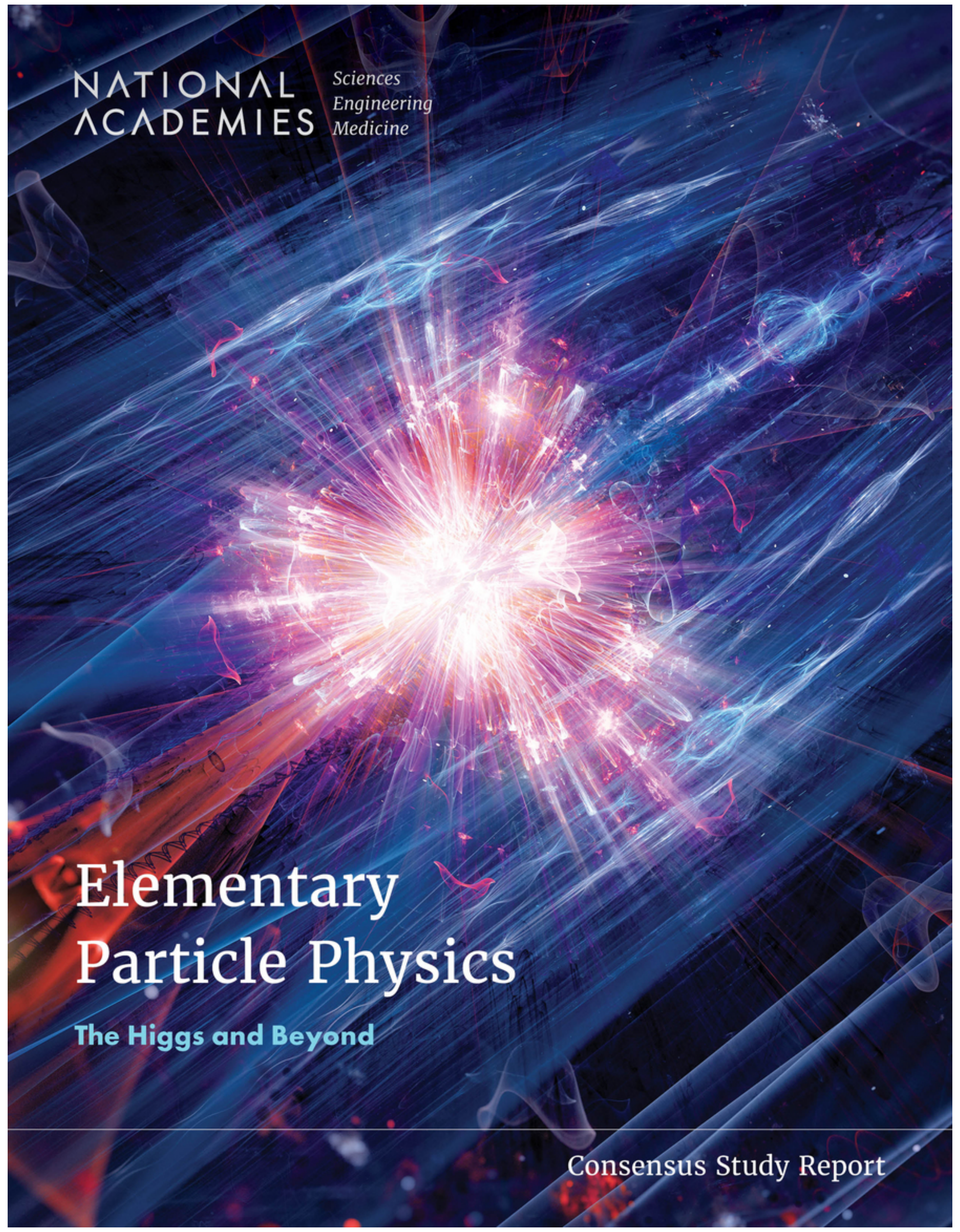
https://www.muoncollider.us/

Outline

- Why does the US HEP community want a muon collider?
- What does a muon collider look like?
- How could a muon collider benefit NP?

US HEP* planning via P5 and National Academy





P5 recommended R&D towards a 10 TeV pCM collider, singling out our "muon shot" in the US

NAS highest recommendation: an immediate R&D program towards the US hosting a muon collider around the middle of the century

At the most basic level a muon collider is a path to higher energies

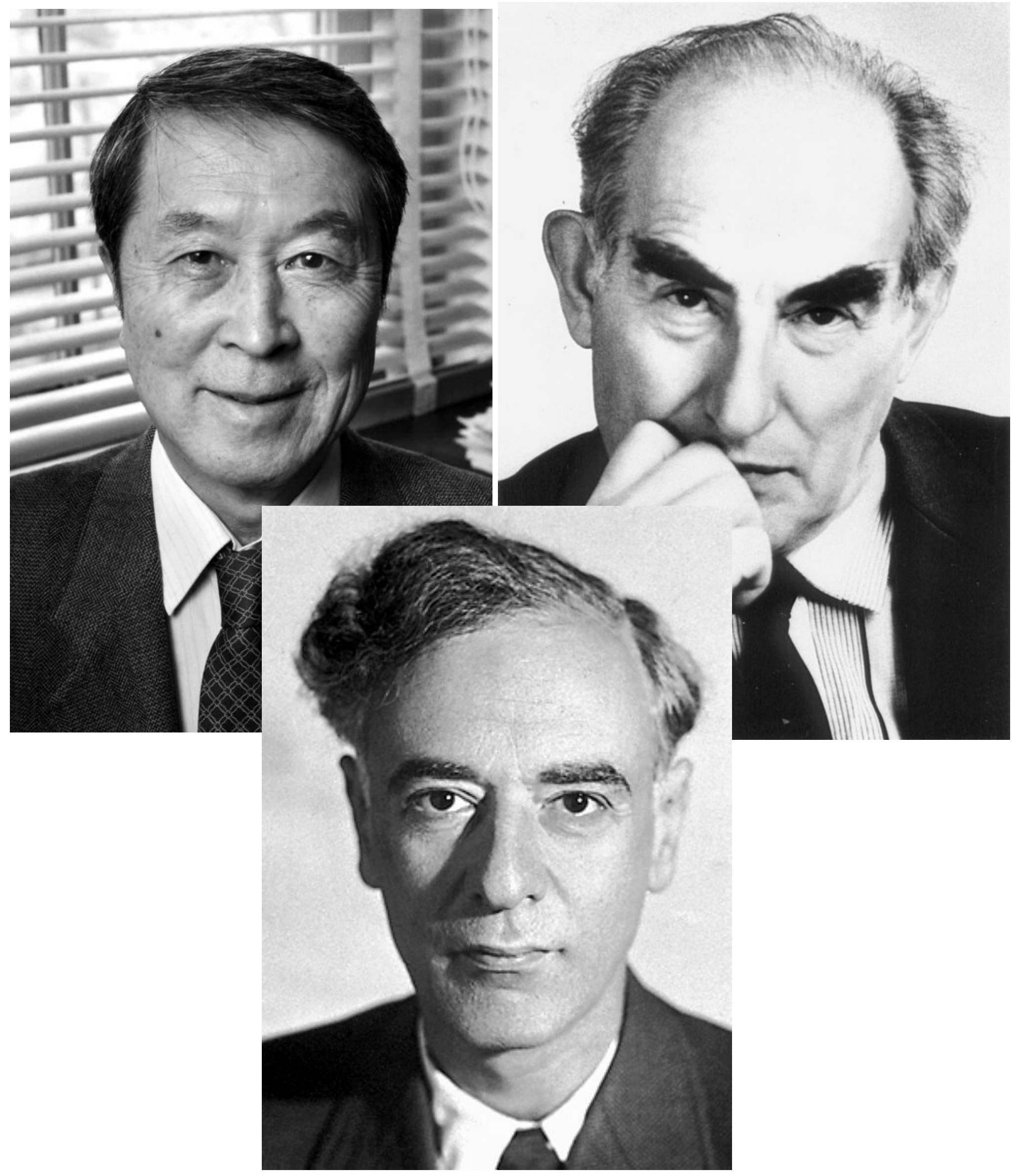
Certain questions about nature ***require*** going to high energies/shorter distances

The LHC has given us more questions than answers!

Why are we here?

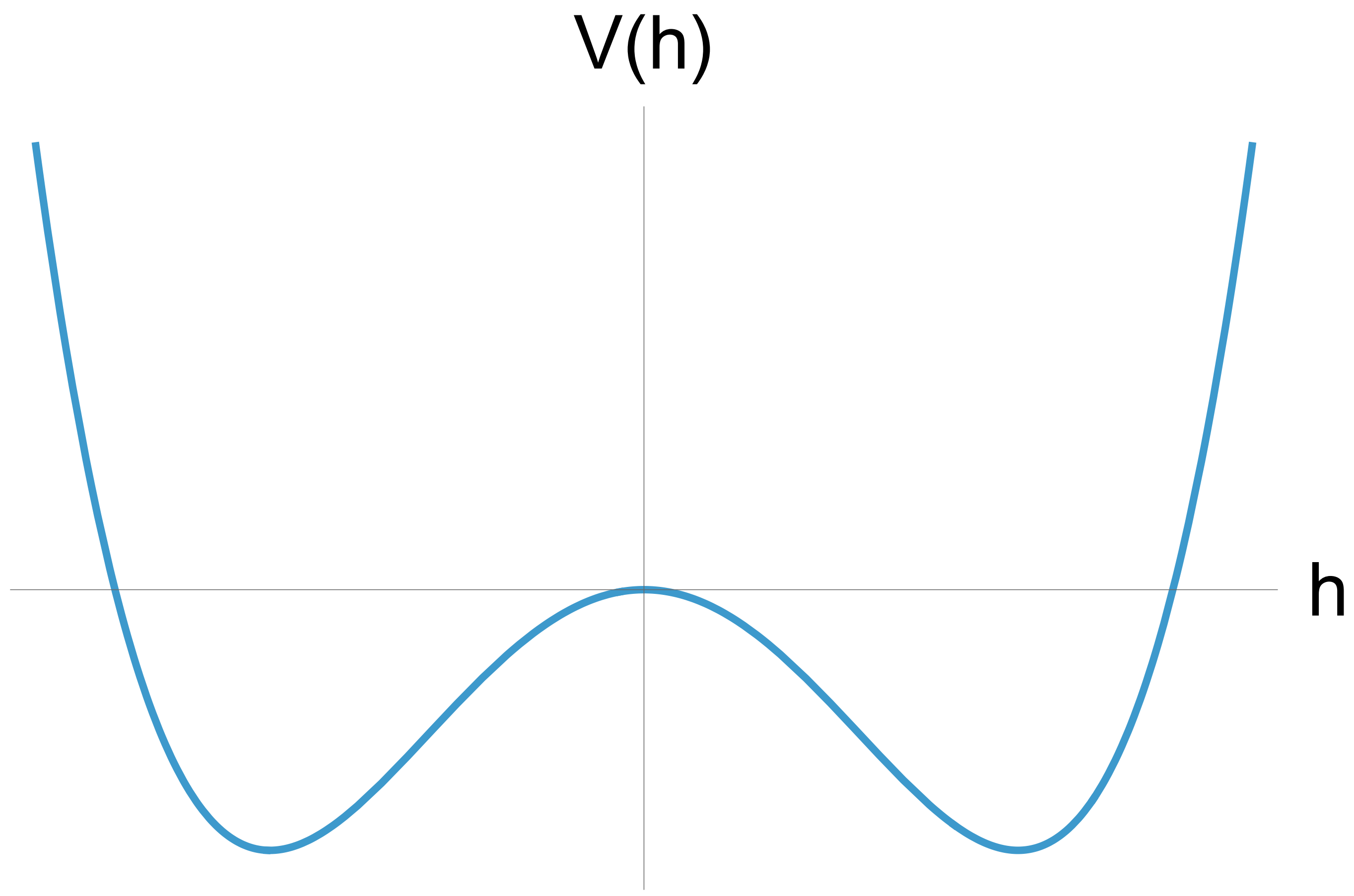
Where did we come from?

Where are we going?



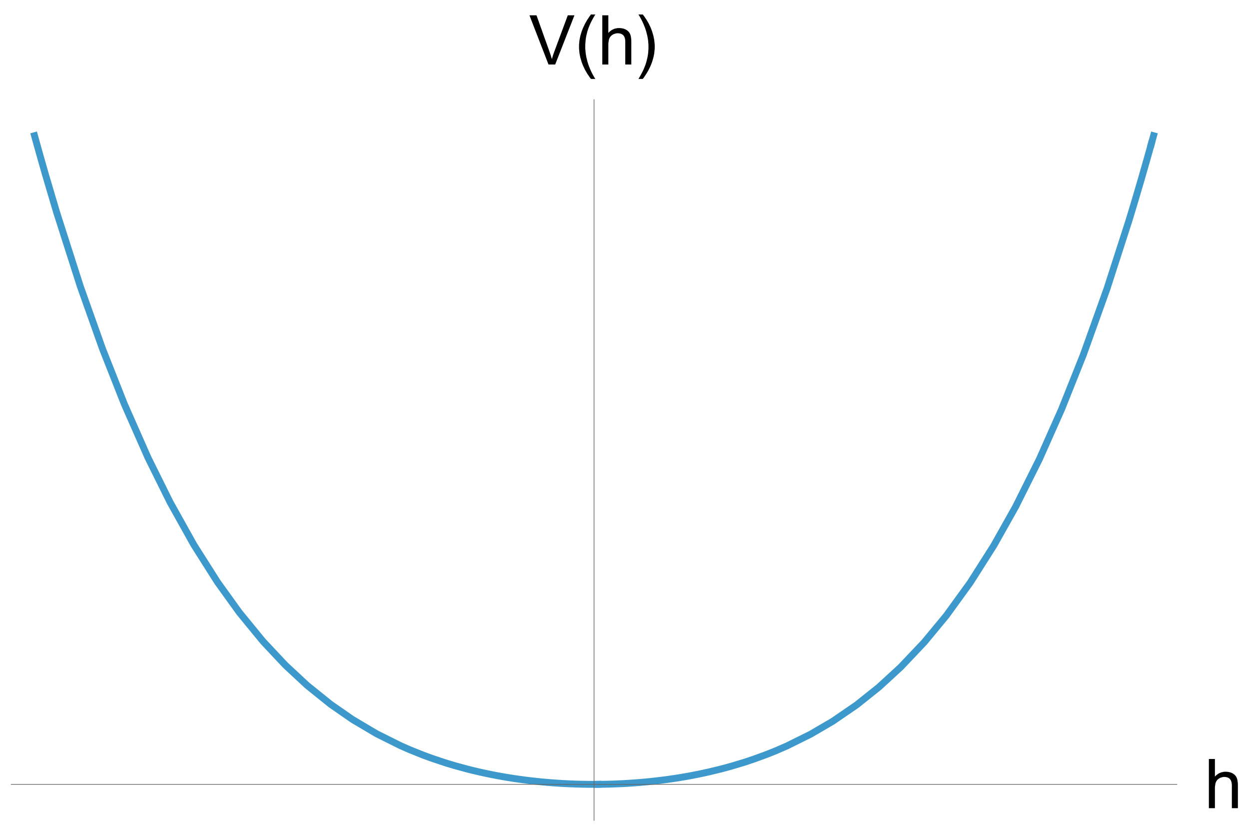
Spontaneous Symmetry Breaking and *our* place in the universe

Why



,

not



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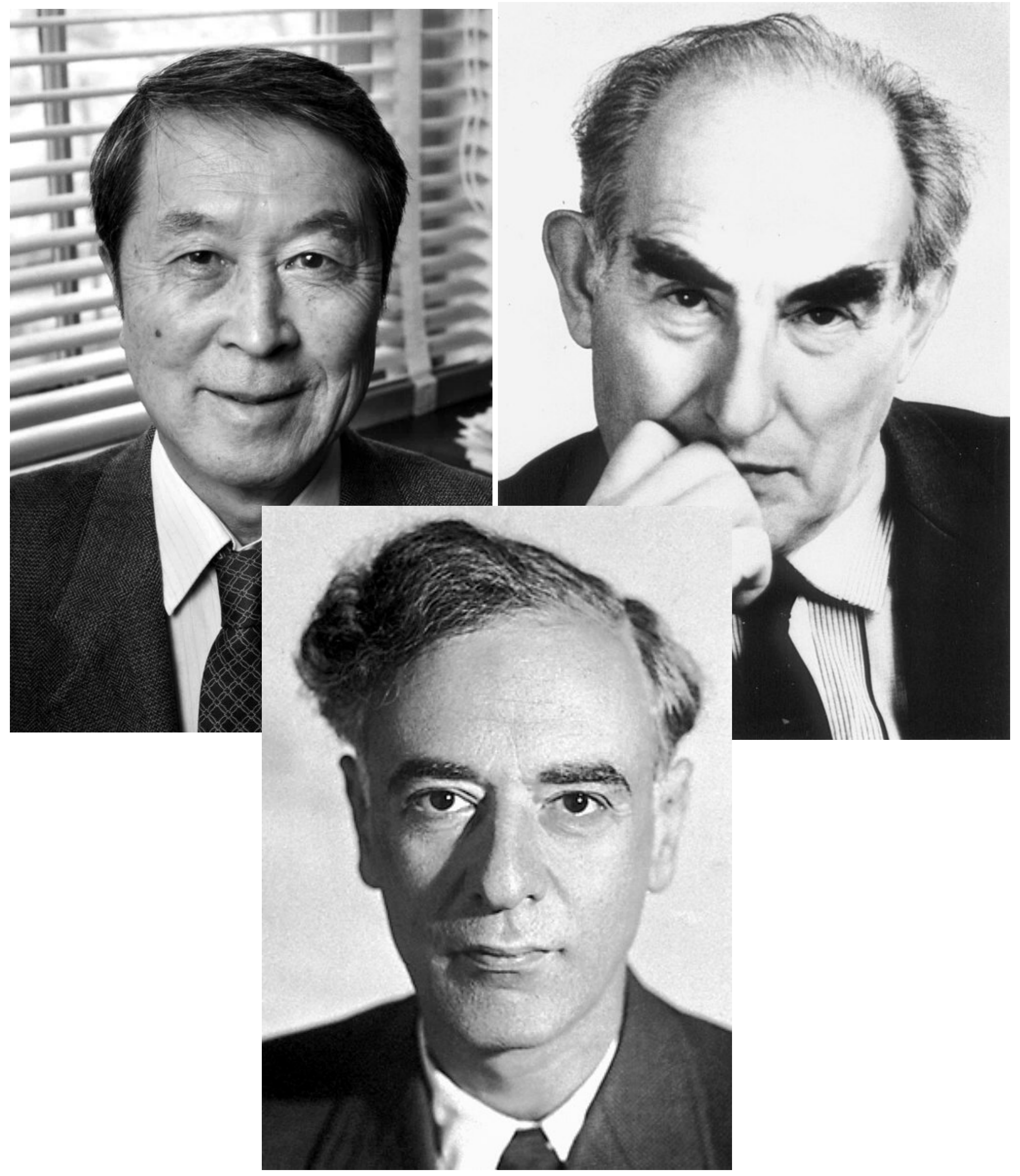
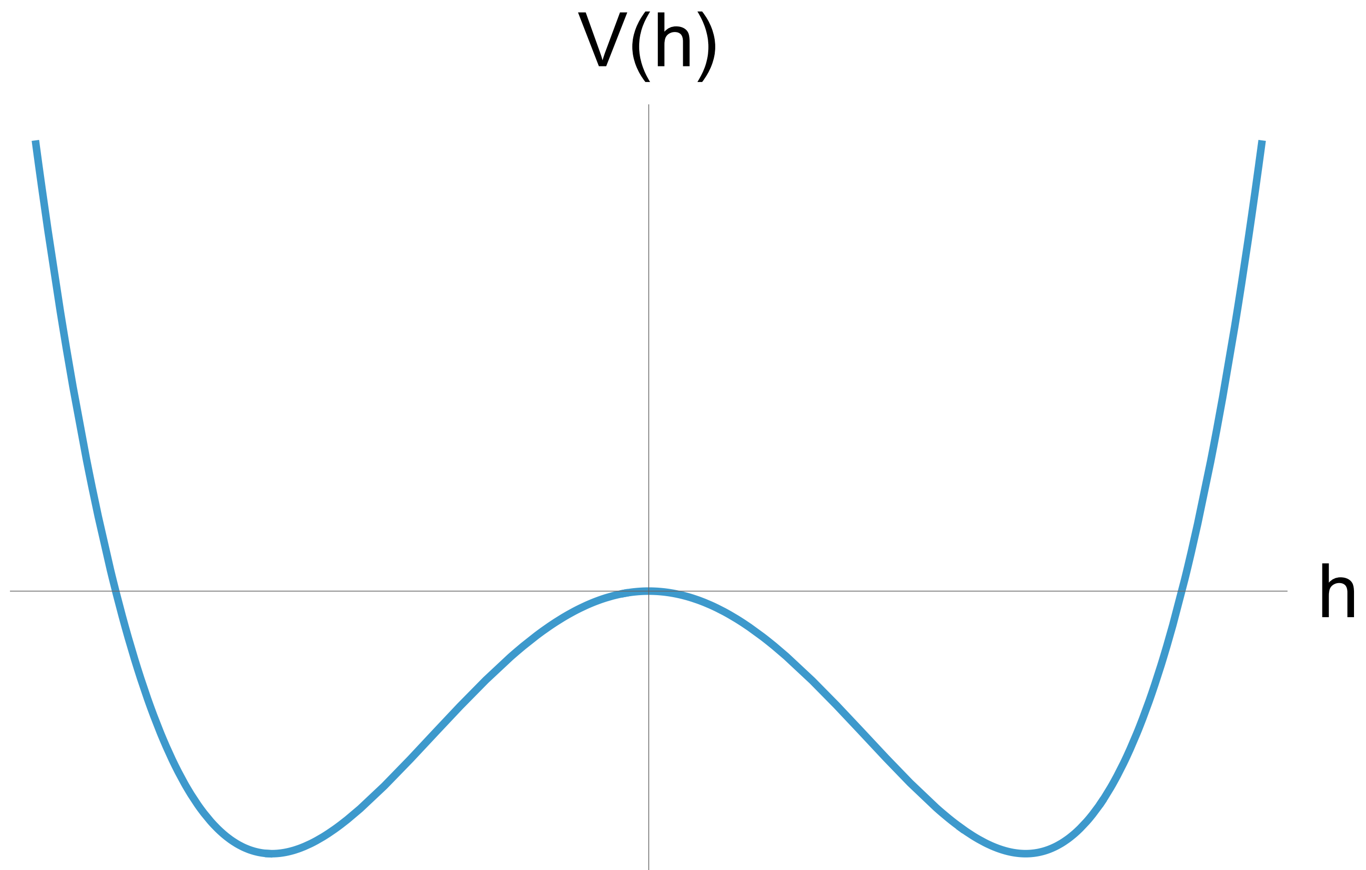
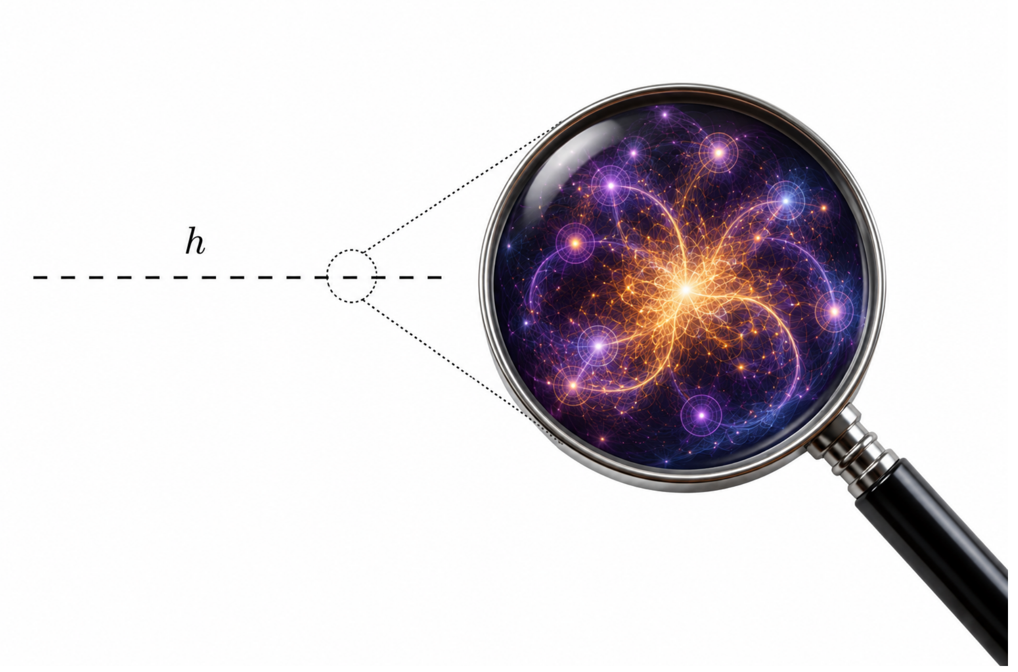


Spontaneous Symmetry Breaking and *our* place in the universe

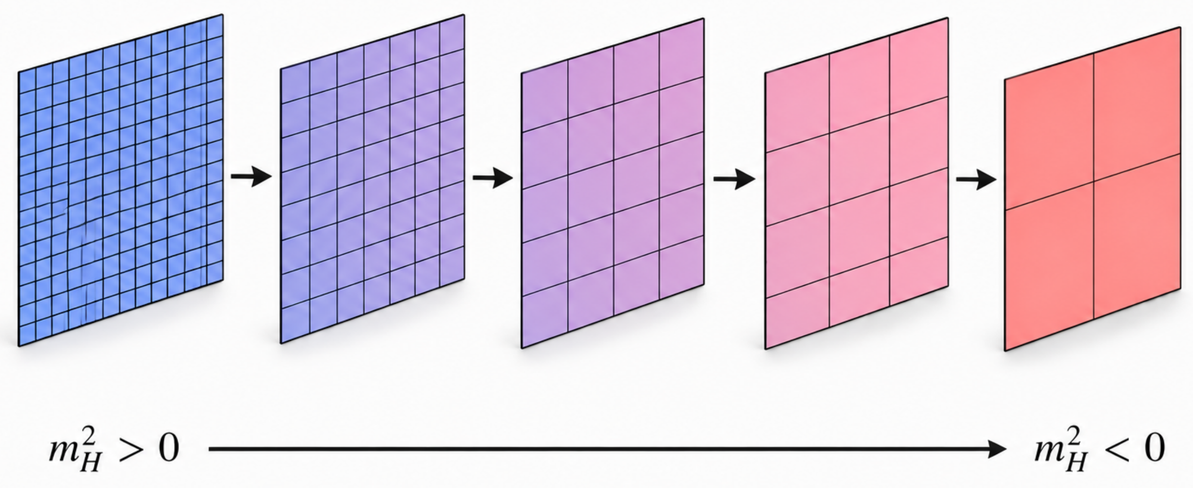


Underlying dynamics

Composite Higgs



Radiative Symmetry Breaking



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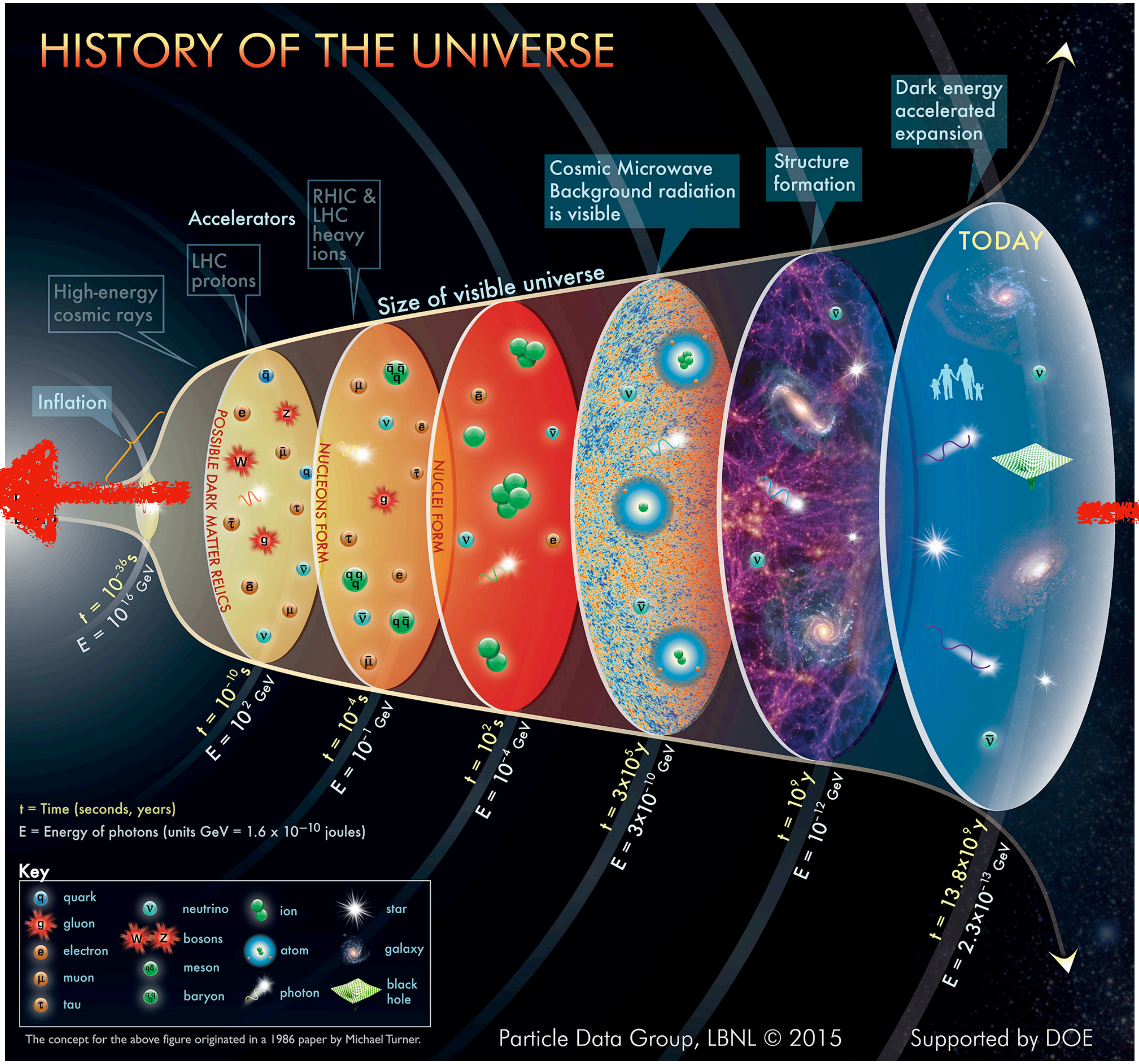
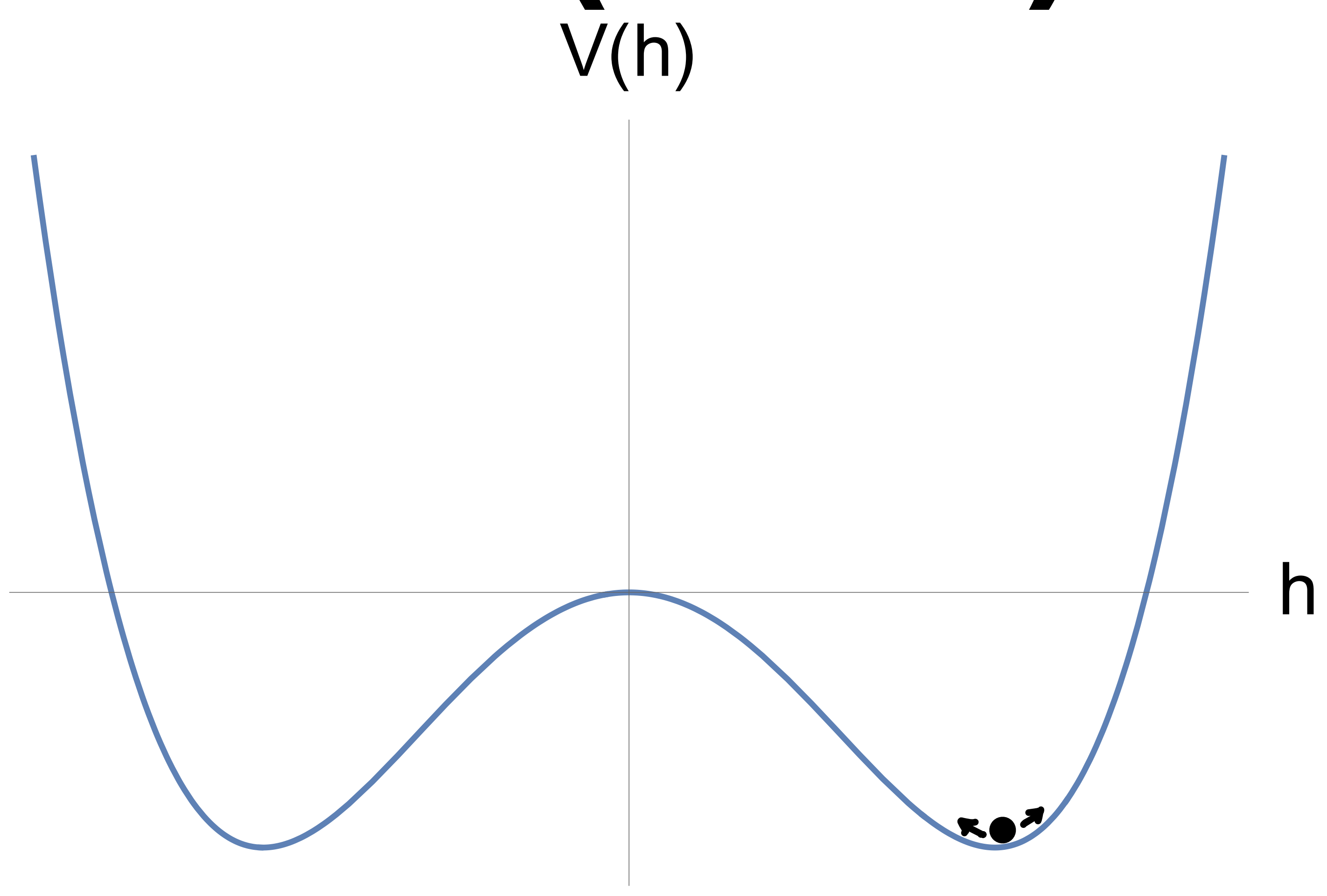
Origin and Fate of the Universe?

Higher T



Stability of Vacuum?

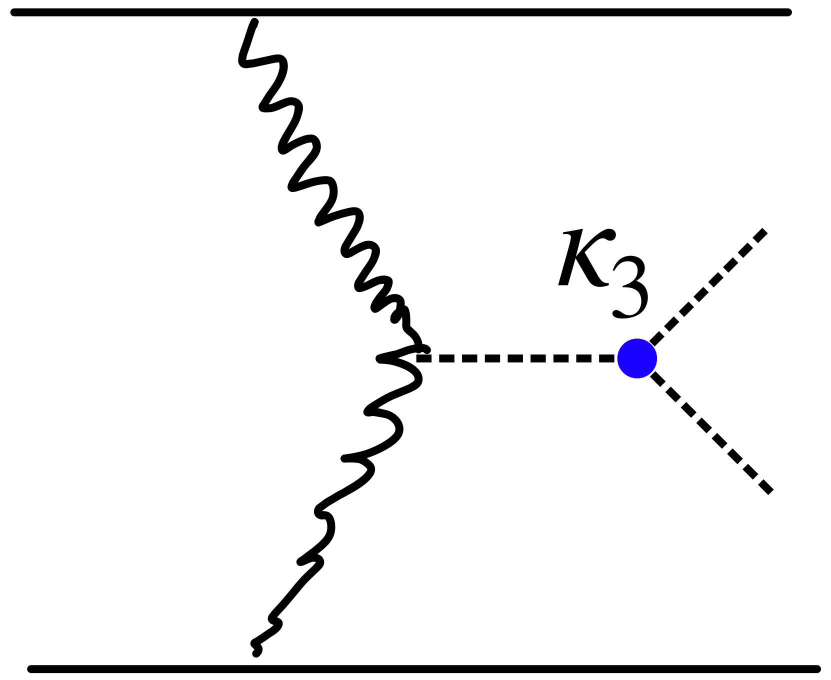
We often (*over*)simplify this for exposition

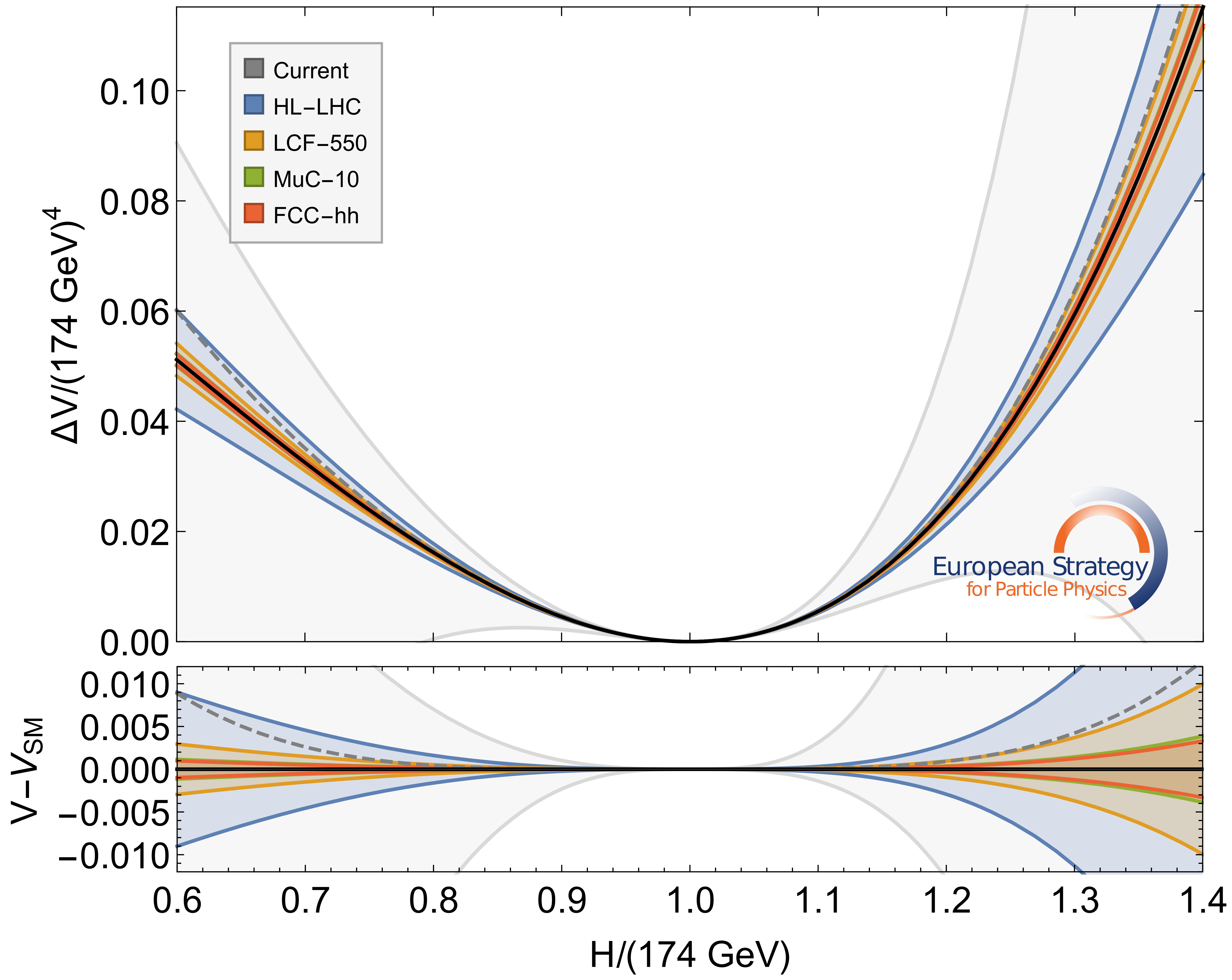


$$\left.\frac{\partial V(h)}{\partial h}\right|_{h=v} = 0$$

$$\left.\frac{\partial^2 V(h)}{\partial h^2}\right|_{h=v} = m_h^2$$

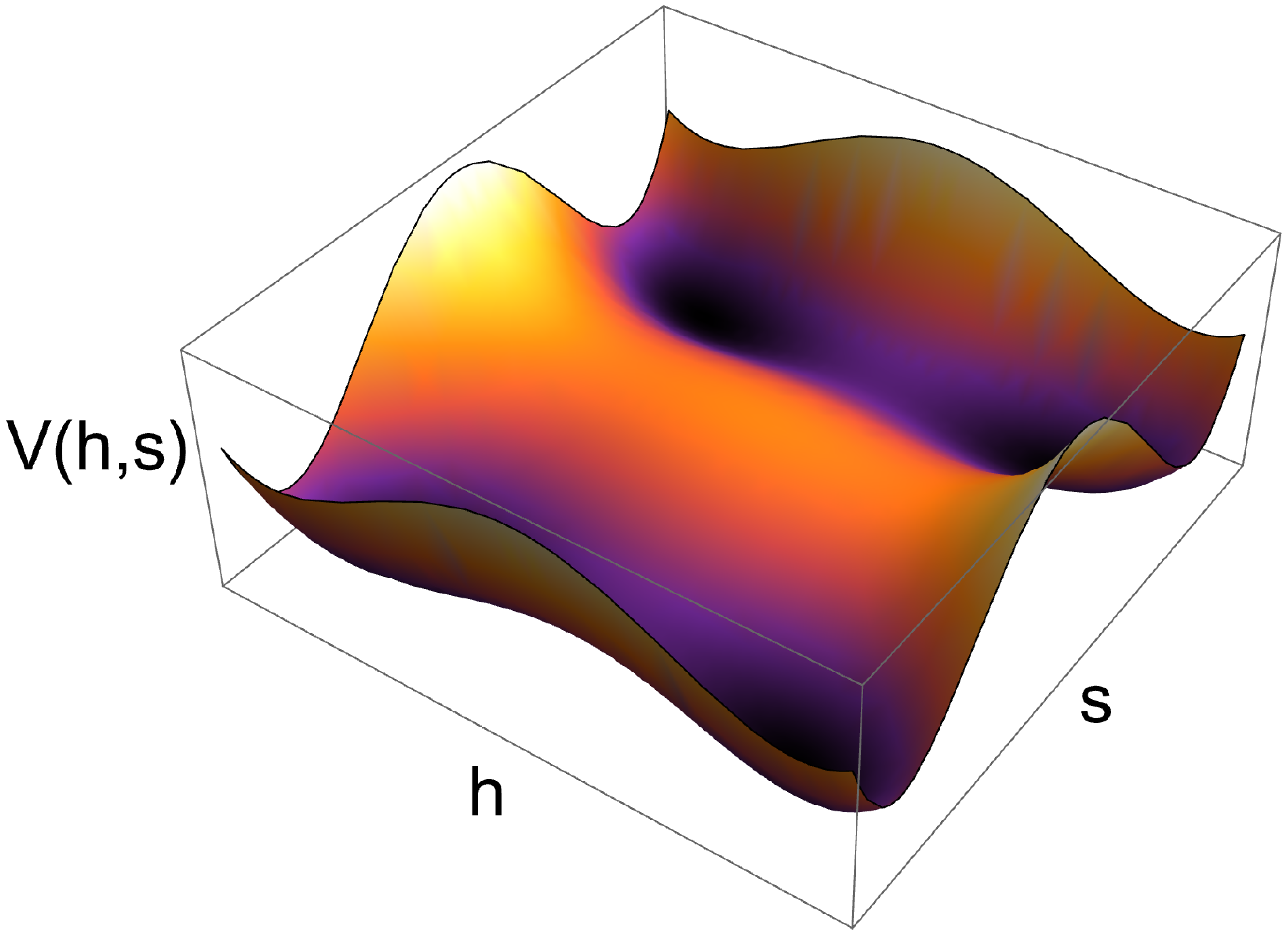
$$\left.\frac{\partial^n V(h)}{\partial h^n}\right|_{h=v} = \text{self interactions}$$



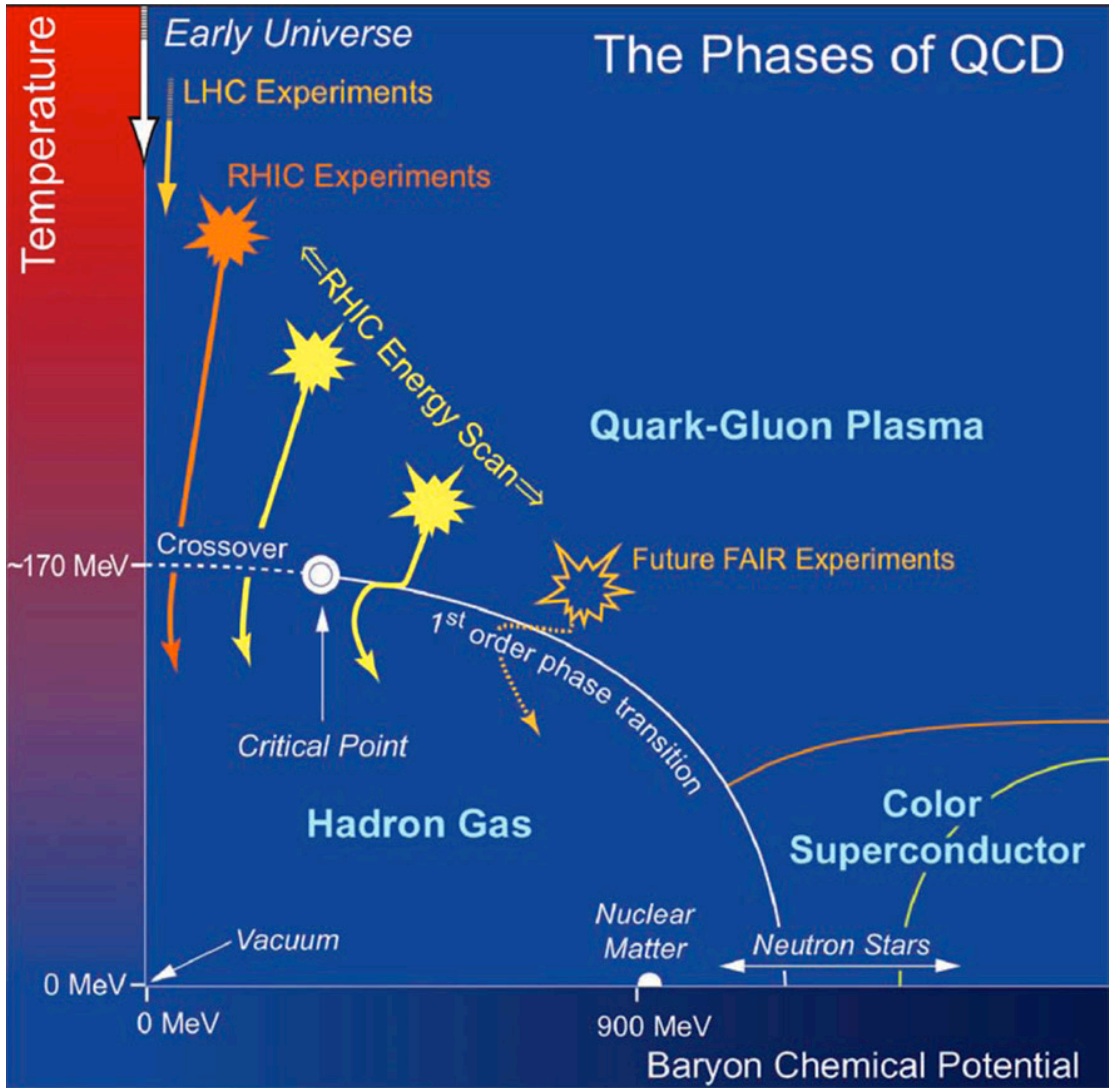


It makes it easy to understand why ***energy*** matters, however, exploring/measuring the vacuum of our universe is ***more than*** κ_3

Any deviation in a SM parameter must have *an origin*



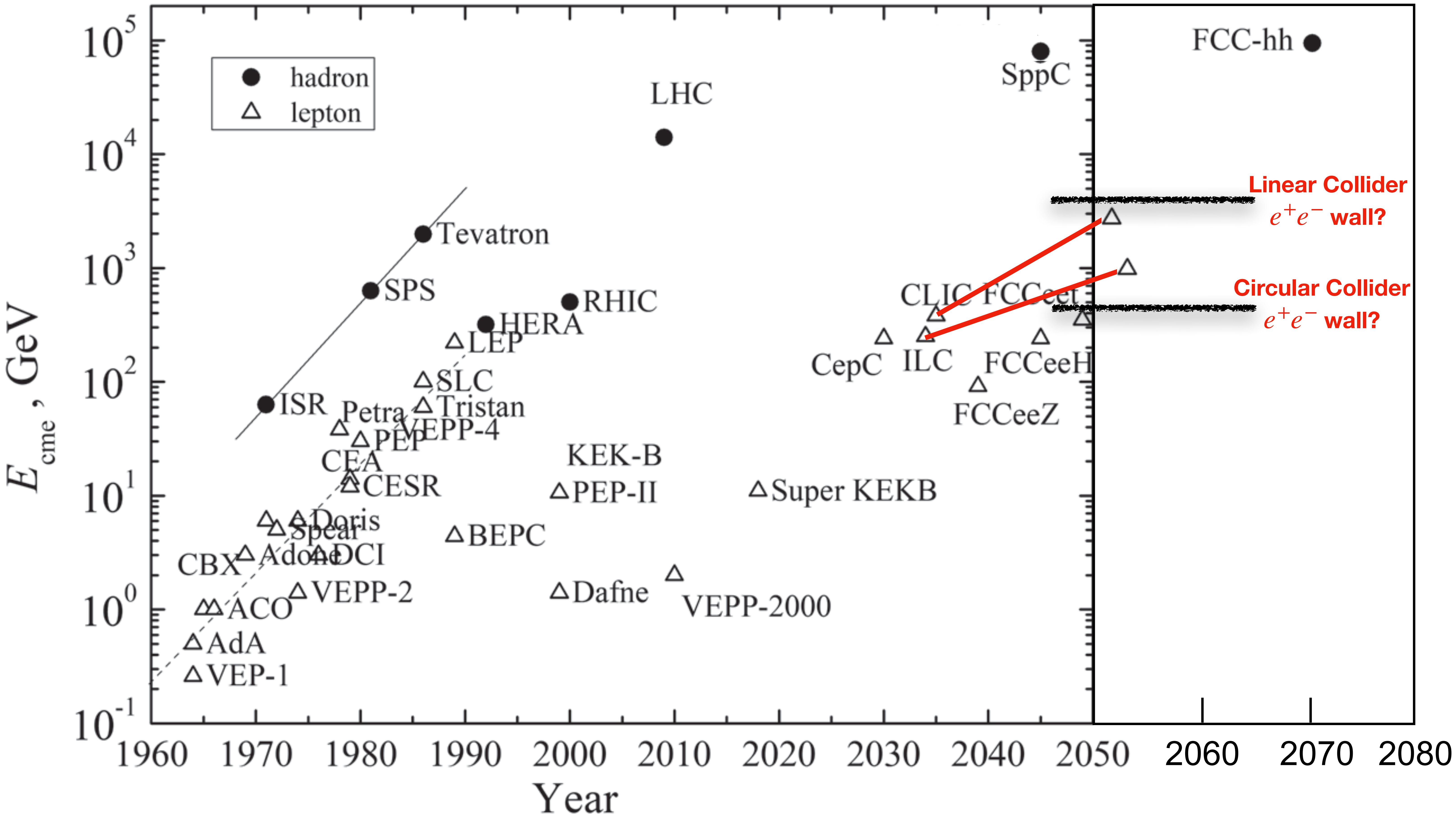
A more complex vacuum



(STAR whitepaper)

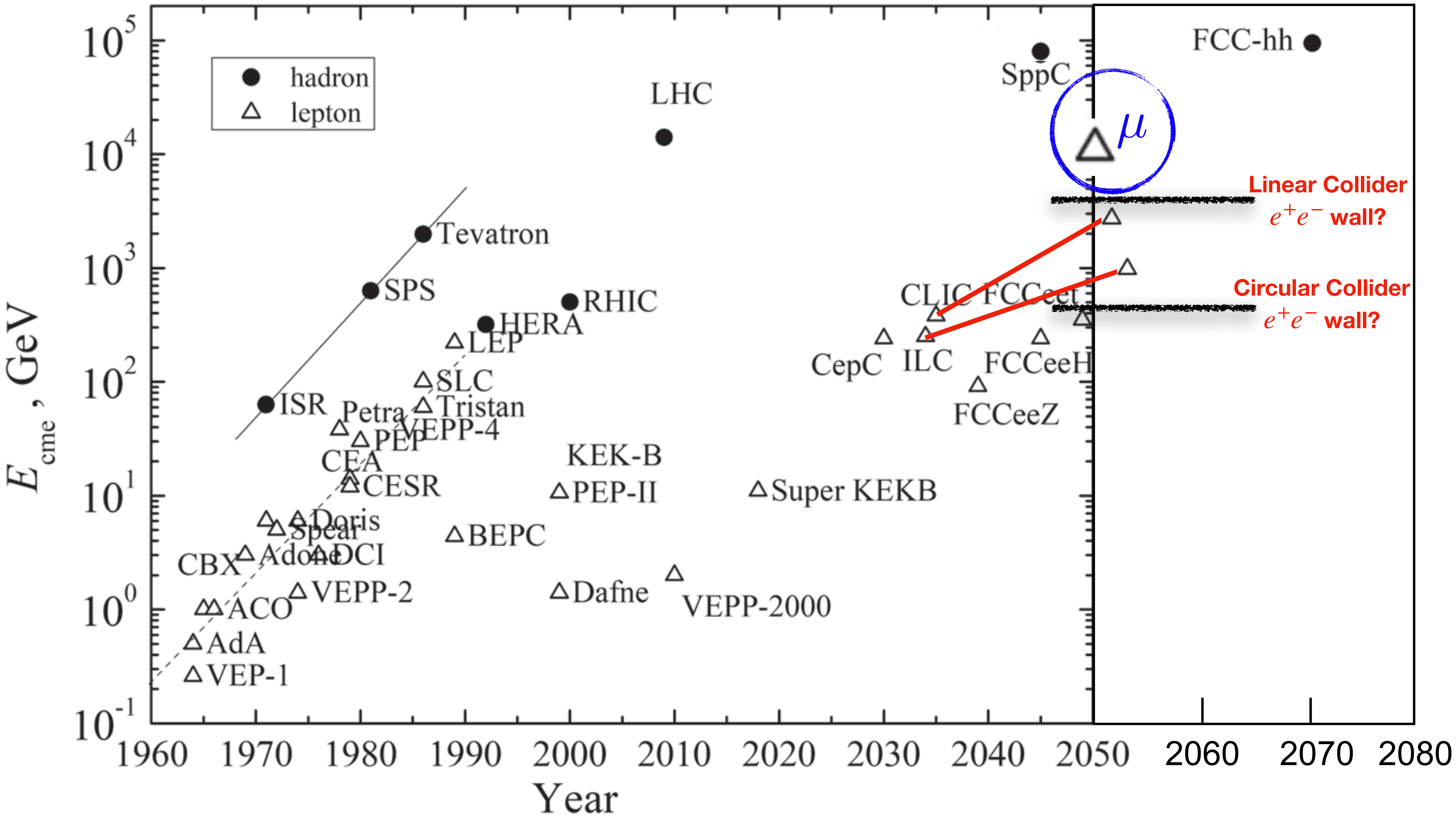
We'd like to understand the ***EW phase diagram*** analogously to the ***QCD phase diagram***

What are the paths to the highest energies?



Modern Livingston Plot (Shiltsev and Zimmerman)

Muons unlock a new way!



$$P_{sync}^{loss} \sim \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

$$\frac{m_\mu}{m_e} \sim 200$$

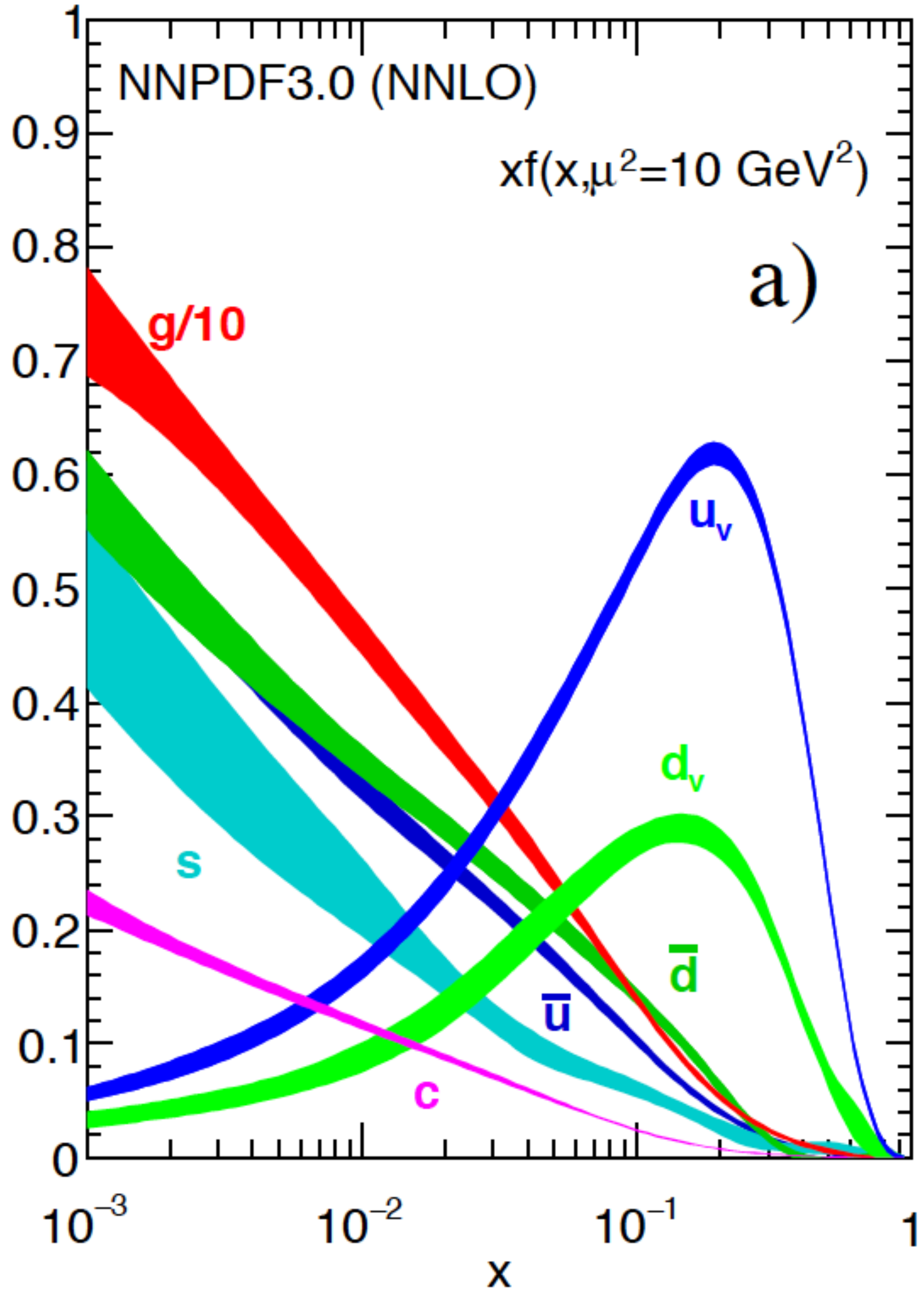
Muons avoid synchrotron/ beamstrahlung issues until ridiculously high energies

Modern Livingston Plot (Shiltsev and Zimmerman)

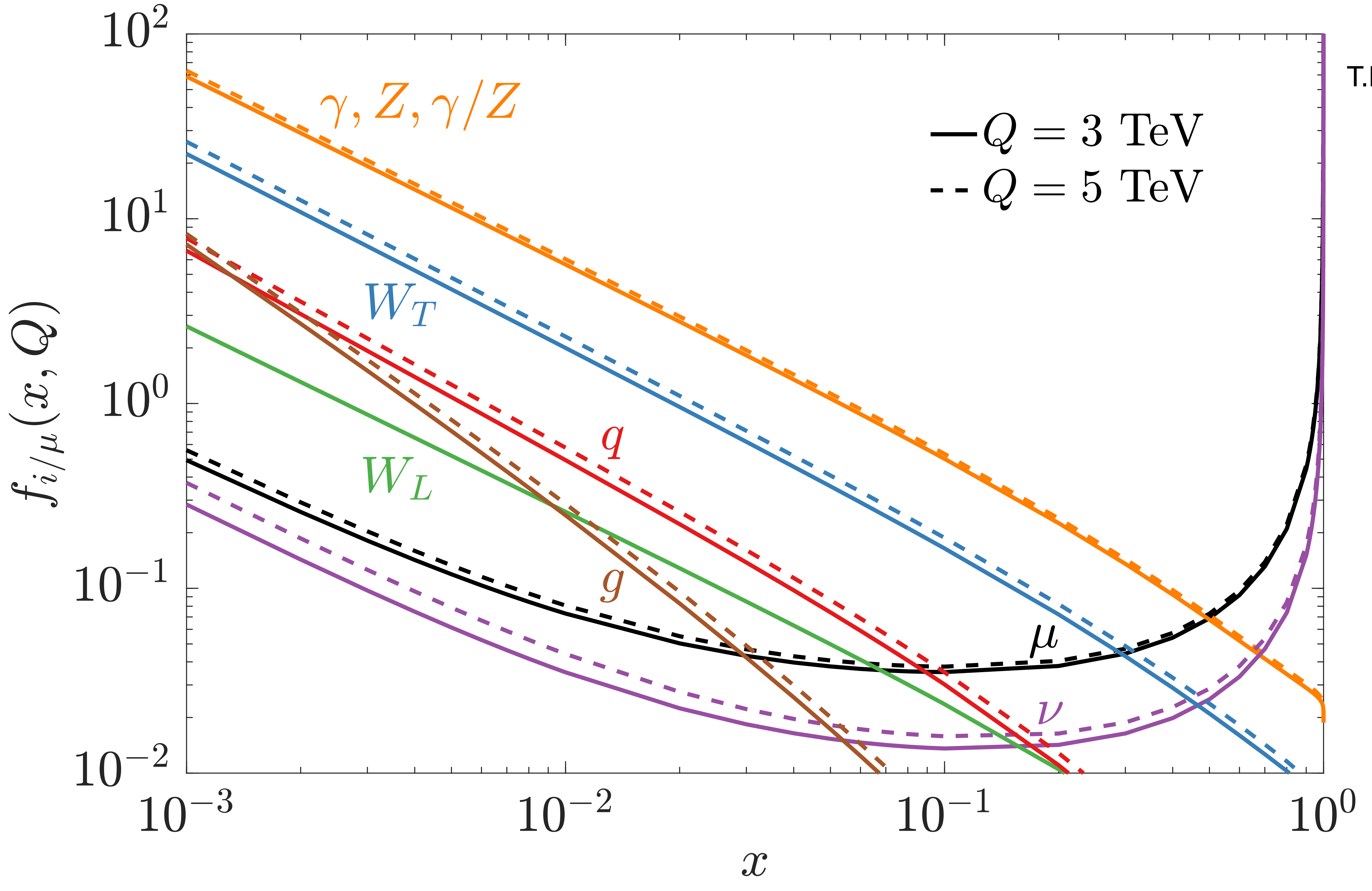
Why not just wait for FCC-hh at CERN?

The potential to do something sooner isn't the most well received argument when budgets are extremely tight…

Composite versus Fundamental* and 10 TeV pCM



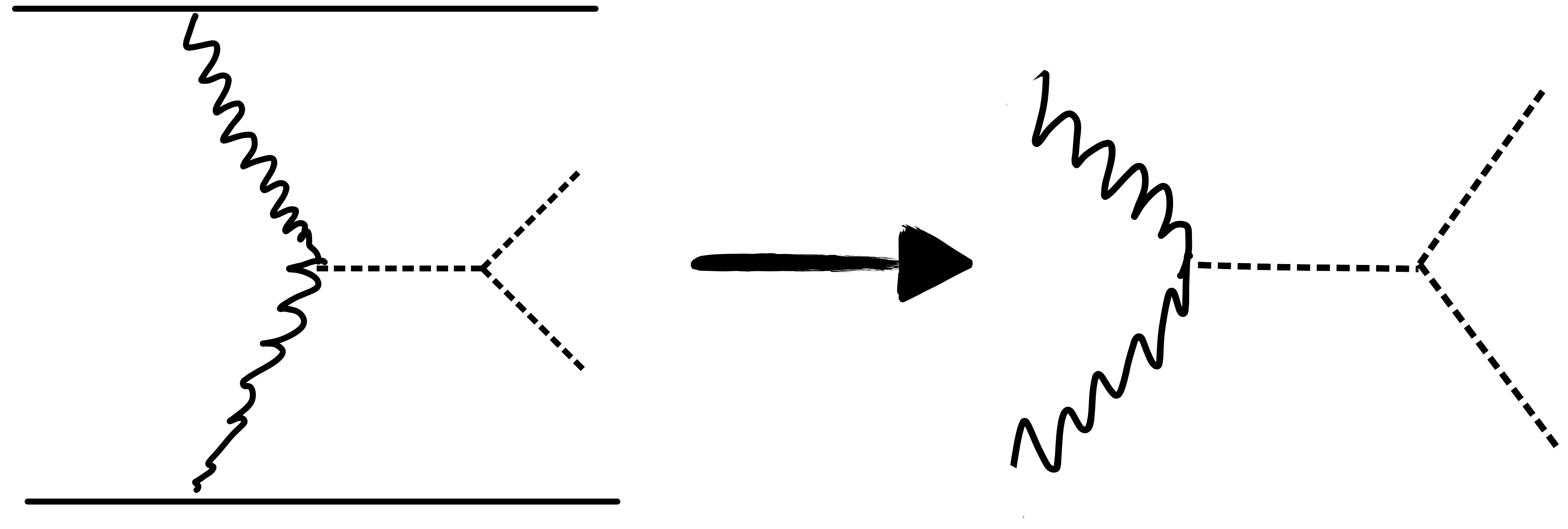
Protons
valence peaks at x~.2
sea of quarks and gluons below



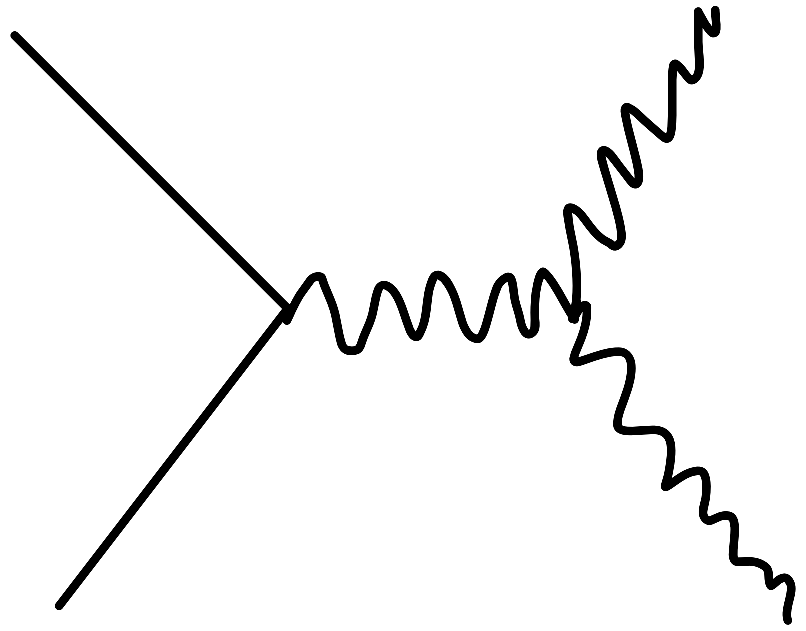
Muons
muons and neutrinos peak at x~1
EW + more sea

A more compact collider with lower backgrounds

A muon collider is an <u>ideal</u> EW probe
“Second Generation Higgs Factory”



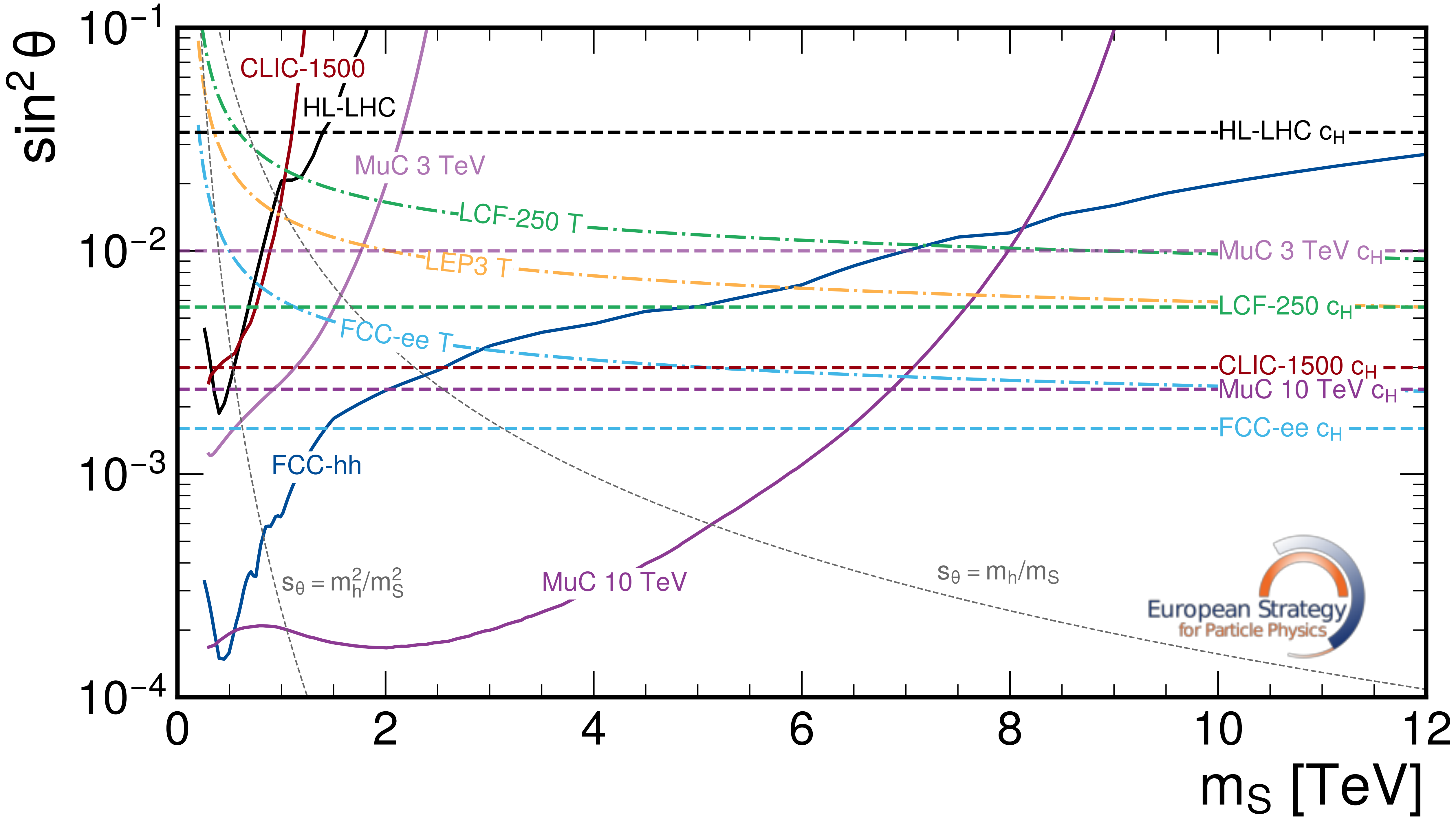
EW boson collider
with large cross sections

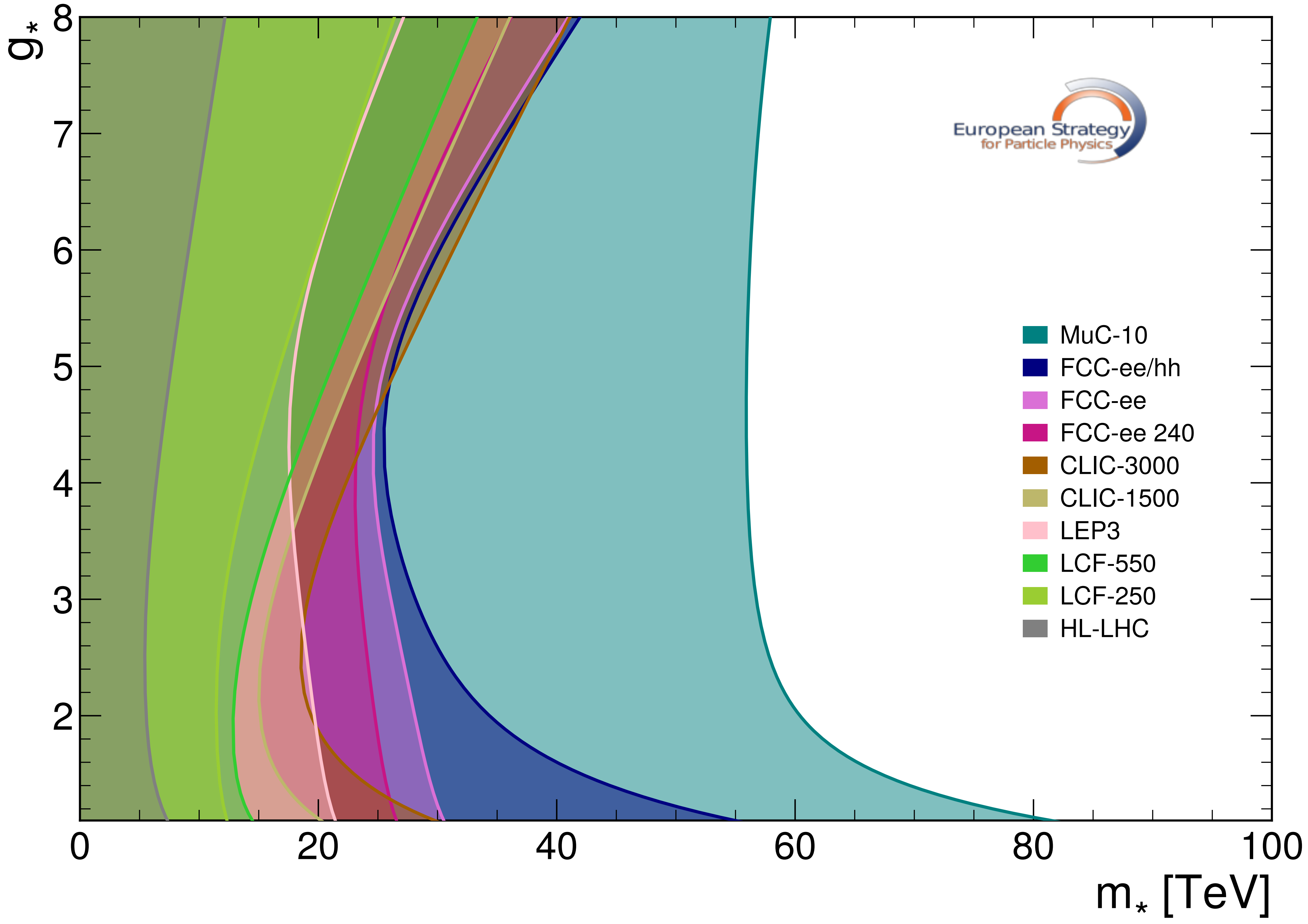


Highest Energy w/sufficient
luminosity and small backgrounds

Energy + Precision and large dynamic $\sqrt{\hat{s}}$ range

Energy + Precision *generically* unlocks the EW phase diagram





Exploring a more complex vacuum

Composite Higgs imprints ≫ 10 TeV

So there's a clear physics reason to pursue muon colliders ***even*** if others pursue a proton collider

How do you build a muon collider?

Clearly a great idea if you can do it, but not a *new* idea either

УСКОРИТЕЛИ И ВСТРЕЧНЫЕ ПУЧКИ

Г. И. БУДКЕР

Институт ядерной физики, Новосибирск.

Accelerators and colliding beams

G.I. Budker (Novosibirsk, IYF) (Aug, 1969)

Published in: *Conf.Proc.C* 690827 (1969) 33-39

"On the other hand, of obvious interest are the lepton collisions at energies of a few hundred GeV (in the center of mass system). For this, the most convenient particles are mu-mesons. One can consider two variants:

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

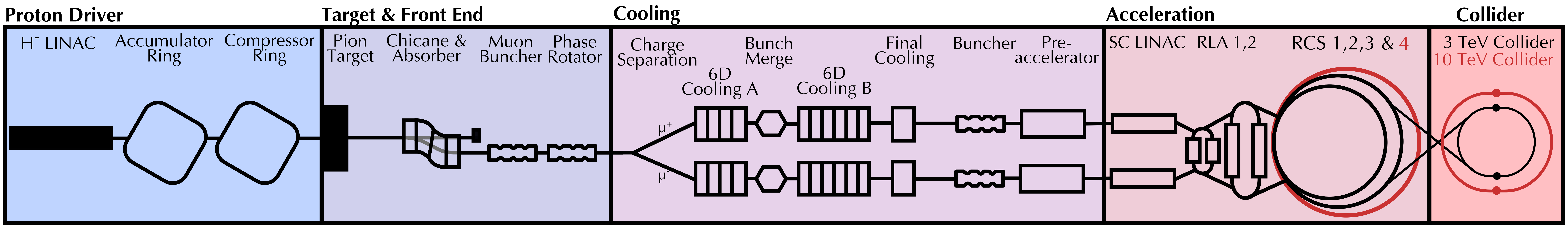
VBA

L. M. Lederman

Columbia University, New York, N.Y. 10027

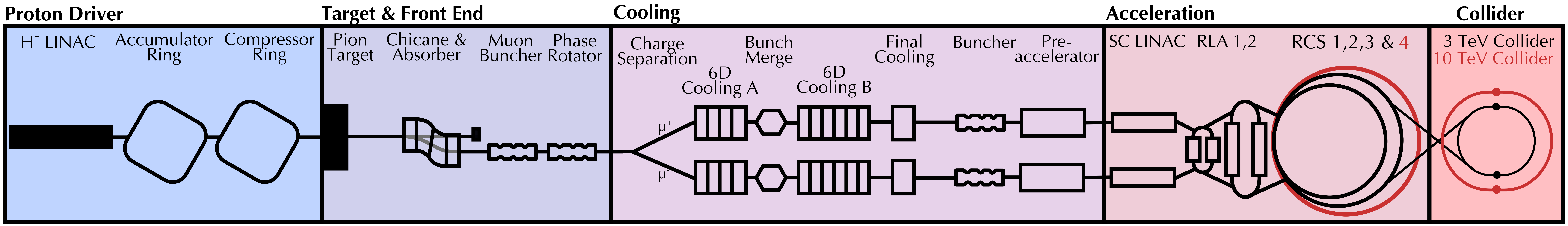
Collisions of electrons and protons in storage rings and competing high intensity muon beams can be used to study quark dynamics. It is easy to see that 10 TeV muon beams of very high luminosity ($\sim 10^{36}cm^{-2} sec^{-1}$) can be achieved.

Sometimes simple conceptual paradigm changes are hard to implement *technologically,* in this case because the muon **decays!**



Production
Cooling
Acceleration
Detection

} Unique aspects to each



Parameter	Symbol	Unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2} s^{-1}$	2.1	21	5 (tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_r	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_p	10^{14}	5	5	5	5
Proton energy on target	E_p	GeV	5	5	5	5

IMCC parameter table - 10 TeV 10/ab goal

Remarkably what goes into a muon collider design concept now roughly exists for other purposes

- **Proton Driver**
  - multi MW exist/being built - SNS, ESS, J-PARC, Fermilab
- **Target**
  - T2K MW, LBNF 2.4 MW
- **Capture Solenoid**
  - Large bore ~ 2 m high field, similar to ITER main solenoid (not the project!)
- **Ionization Cooling** (synchrotron, laser, stochastic etc too slow)
  - MICE experiment, $(g-2)_\mu$,Final cooling solenoid 30T small bore - NHFML exists
- **High Field Dipoles**
  - HL-LHC dipoles

Hard engineering challenges still, demonstrator needed… but we* *ARE* miracle workers everyday!

National Lab Accelerator Study Group for a Muon Collider

Purpose and Scope

- Identify the **key accelerator challenges** for a **10 TeV Muon Collider**
- Define the **necessary R&D steps**
- Estimate **timeframes for major R&D areas**
- Evaluate and build on existing **U.S. and IMCC plans**
- Identify **gaps, overlaps, and coordination issues**:
- Strong focus on:
  - **U.S. national lab collaboration**
  - **Alignment with international efforts**
- Goal: ensure **high-impact, complementary U.S. contributions**

The study is about **prioritizing and organizing the critical R&D needed now**—not designing the collider itself—so future planning can be grounded in realistic technical progress.

Membership

Argonne: Philippe Piot

Berkeley: Jean-Luc Vay, Chad Mitchel

Brookhaven: Steve Peggs

Fermi: Steve Gourlay (Chair)

JLab: Robert Rimmer

Los Alamos: Steve Russel

Oak Ridge: Fulvia Pilat

SLAC: Emilio Nanni

Scientific Secretary, Diktys Stratakis, Fermi

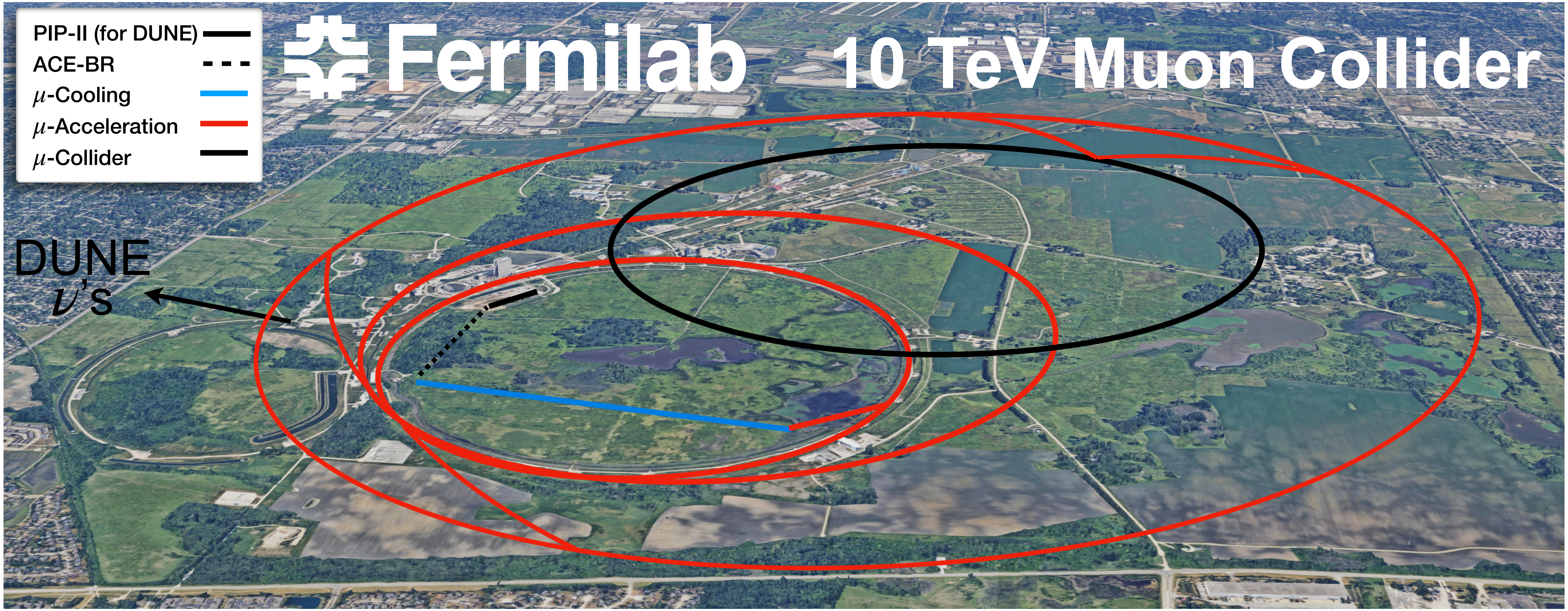
Held 17 Seminars on systems and technologies – report writing in progress – aiming for July 31th

IMO two of the most exciting reasons for a **US** muon collider R&D program:

What it builds on

Physics Synergies/Unifying Facility

A muon collider *could* be a facility that builds on existing investments



Compact enough to reuse existing infrastructure and modular enough for synergistic physics along the way

Synergy Examples

Proton Driver (Extend CW Linac) → CLFV, Kaon Physics:

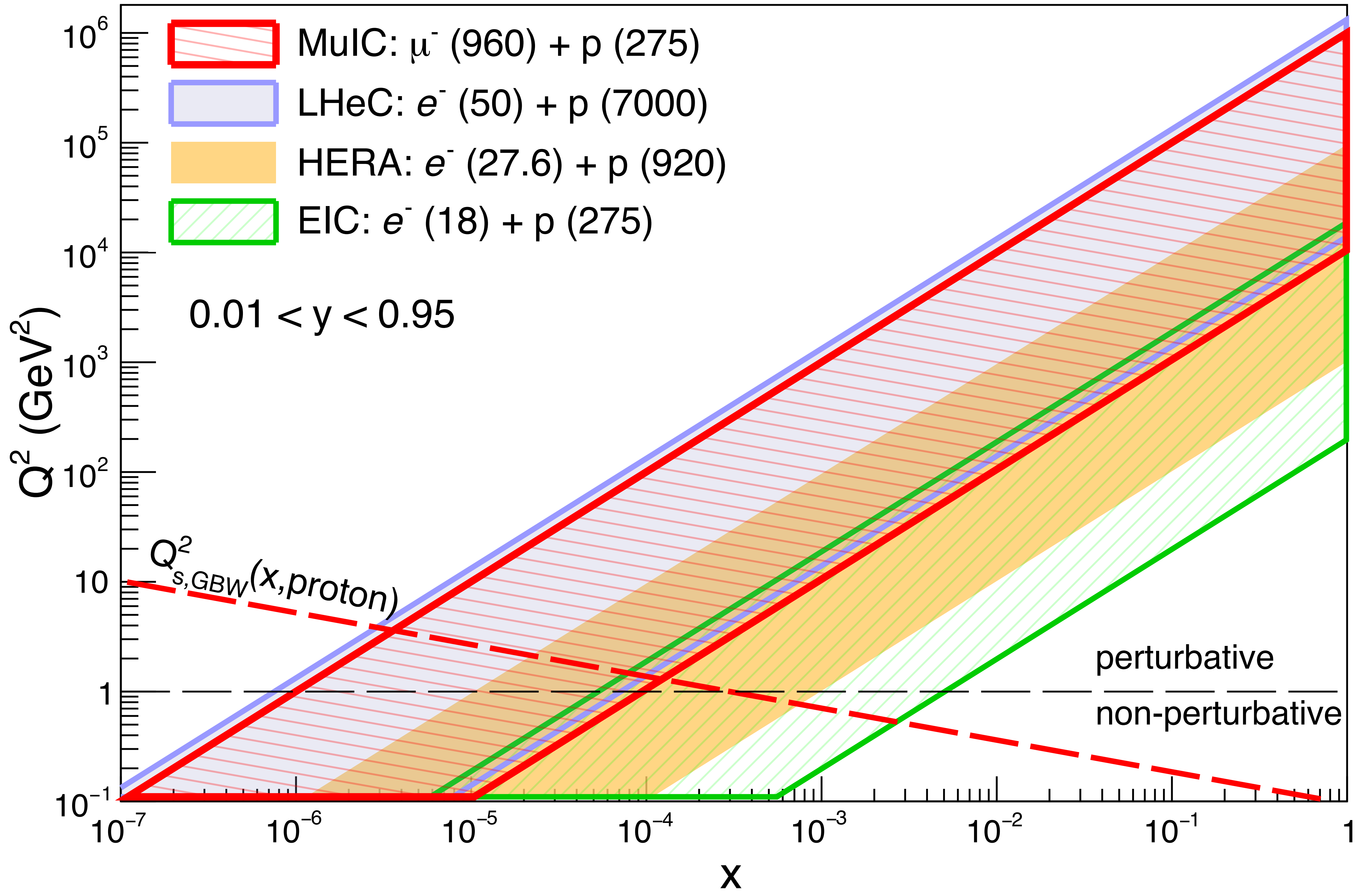
- $K_L \to \pi^0 \bar{\nu}\nu$ **Unobserved in KOTO, sensitive to SM in KOTO-II, potentially ~1000 events at muC facility**
- $K^+ \to \pi^+ \bar{\nu}\nu$ **Consistent with SM ~ 20 events NA62, potentially ~1000 events at muC facility**

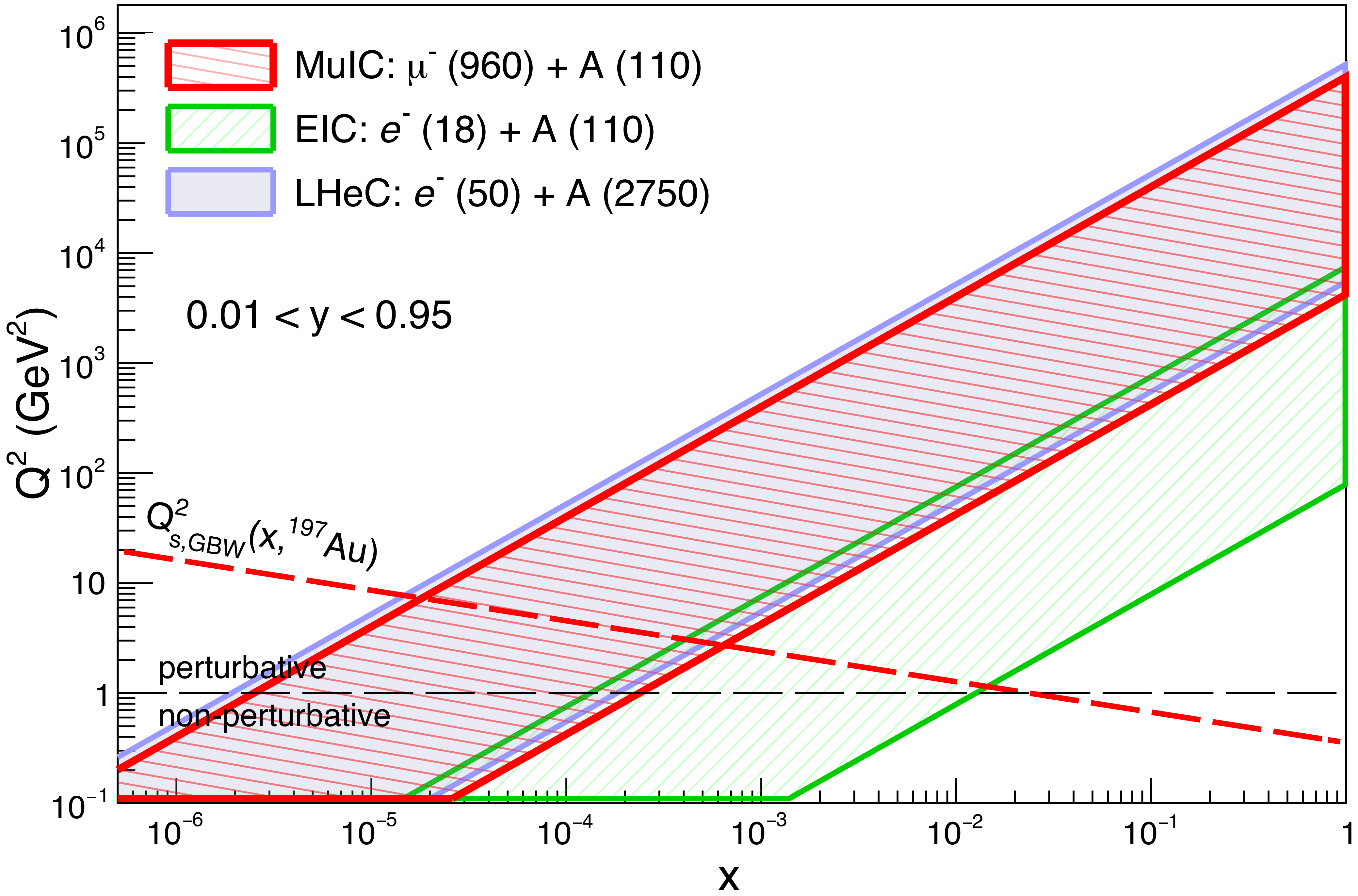
Muon Storage Rings → Neutrino Factories

- Pure flavor and energy calibrated ν beams
- Access to ν_τ
- Systematic improvement for $\sigma(\nu N)$ (DUNE/ICECUBE)
- Reuse of DUNE FD/ND ~ $\mathcal{O}(10^2)$ stats improvement?

What does it have to do with NP?
What opportunities are there?

Once muon beam technology is demonstrated it can be applied for purposes other than a MuC





EIC→MuIC

D. Acosta, W. Lei
2107.02073

Same concept of $e \rightarrow \mu$ as an alternative to higher energy hadrons

Alternatively, use the Muon beam at a Muon Collider Facility to extend EIC to higher precision

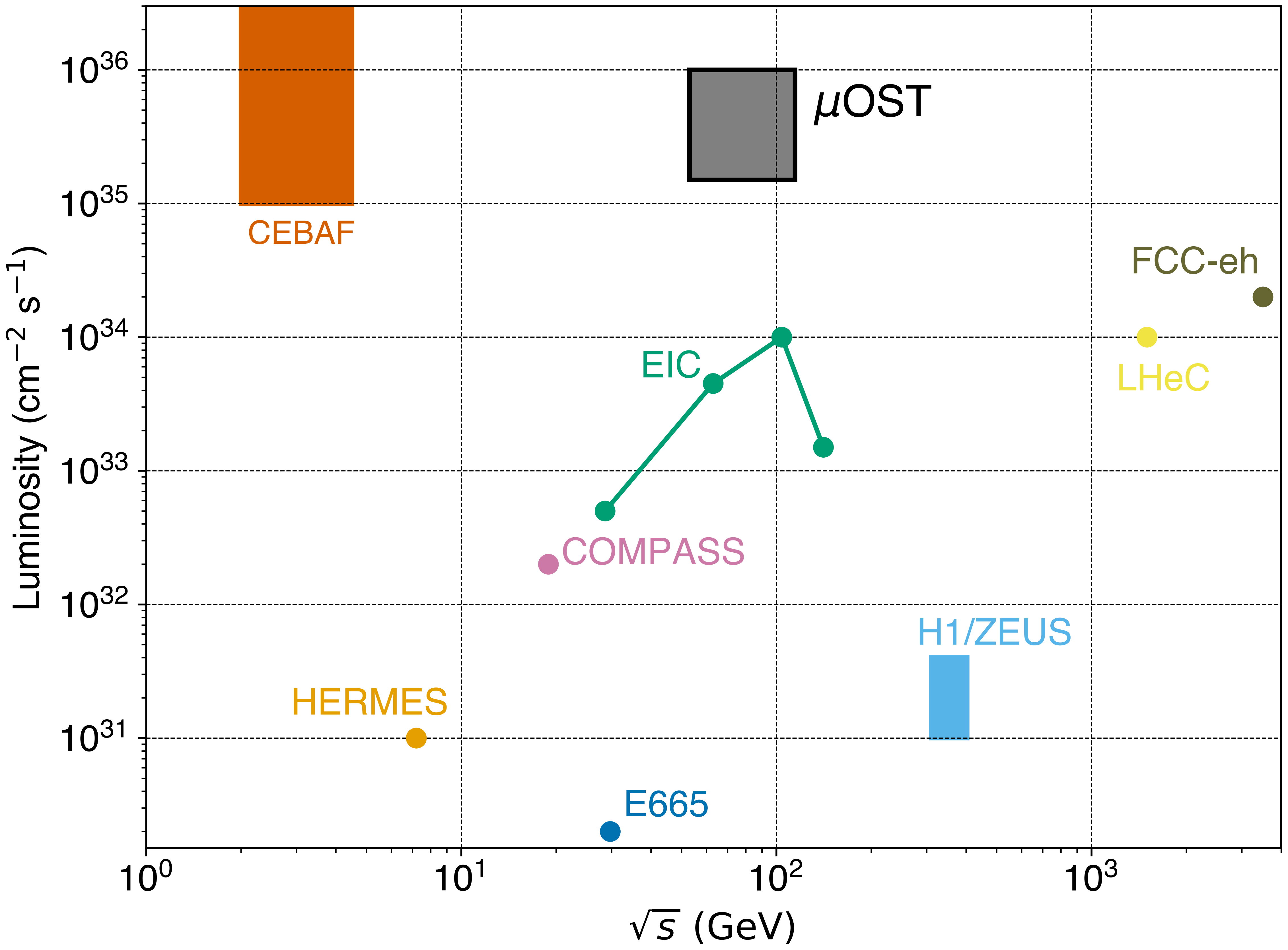


FIG. 1: Comparison of luminosity and energy for lepton-scattering facilities. The μOST box corresponds to 1% of the 1.5 to 7 TeV collider beam being dumped on a 1- to 6-meter long target.

μ DIS

μ On Stationary Target (μOST)

H. Klest
2506.19301

Neutrino DIS possibilities?

$\mathcal{O}(10^{20})$ usable Muons at different energies*

Complementary F_3 structure function measurements to PVDIS?

Improved PDFs
CKM measurements

...

Even if we can't achieve the ultimate collider, there are many off-ramps/ synergies/staging opportunities that make *muon beam* R&D worthwhile

A potential joint HEP + NP accelerator R&D roadmap

Conclusions

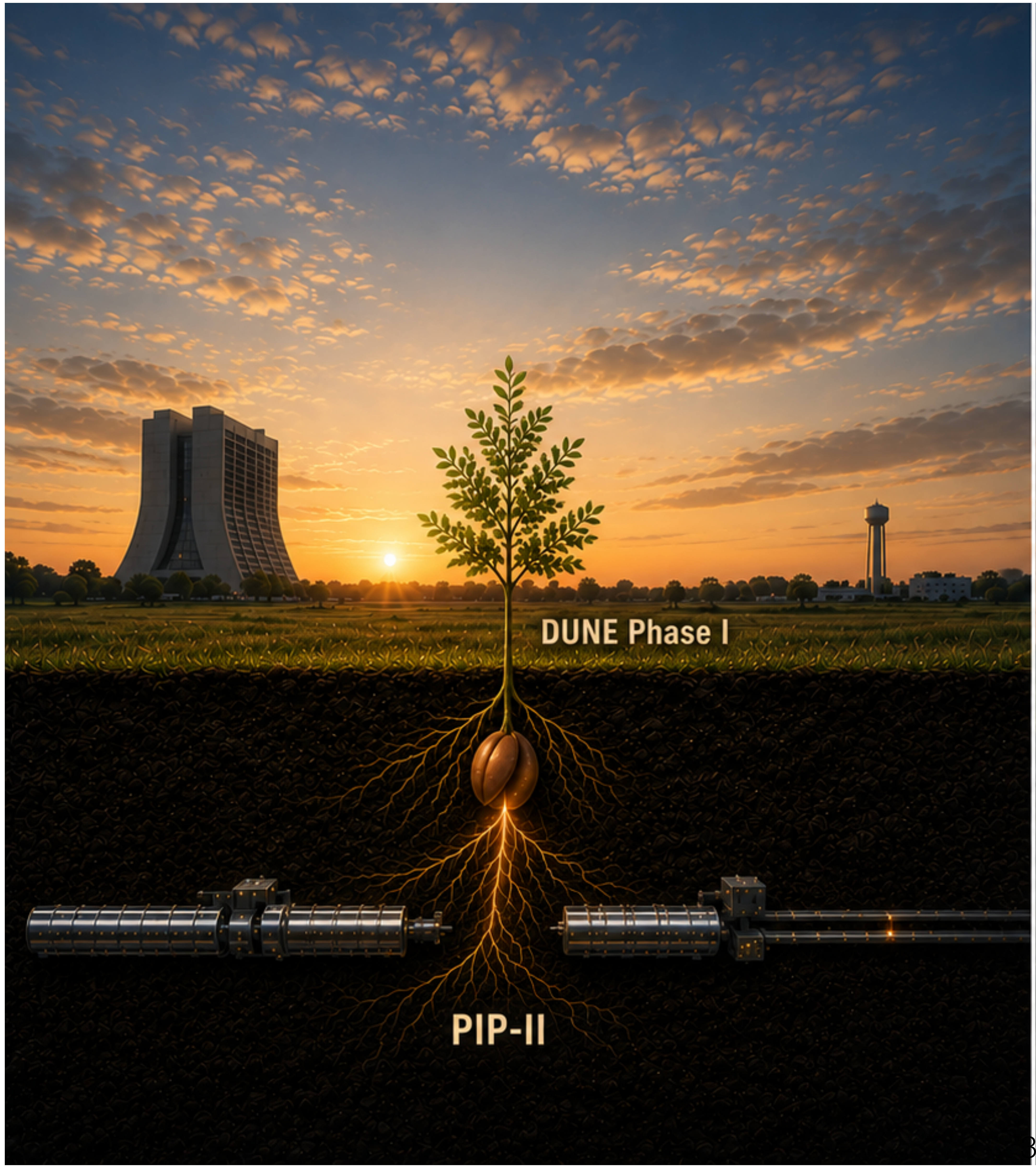
- A muon collider represents a paradigm change for HEP with unparalleled abilities to access the physics of EW symmetry breaking

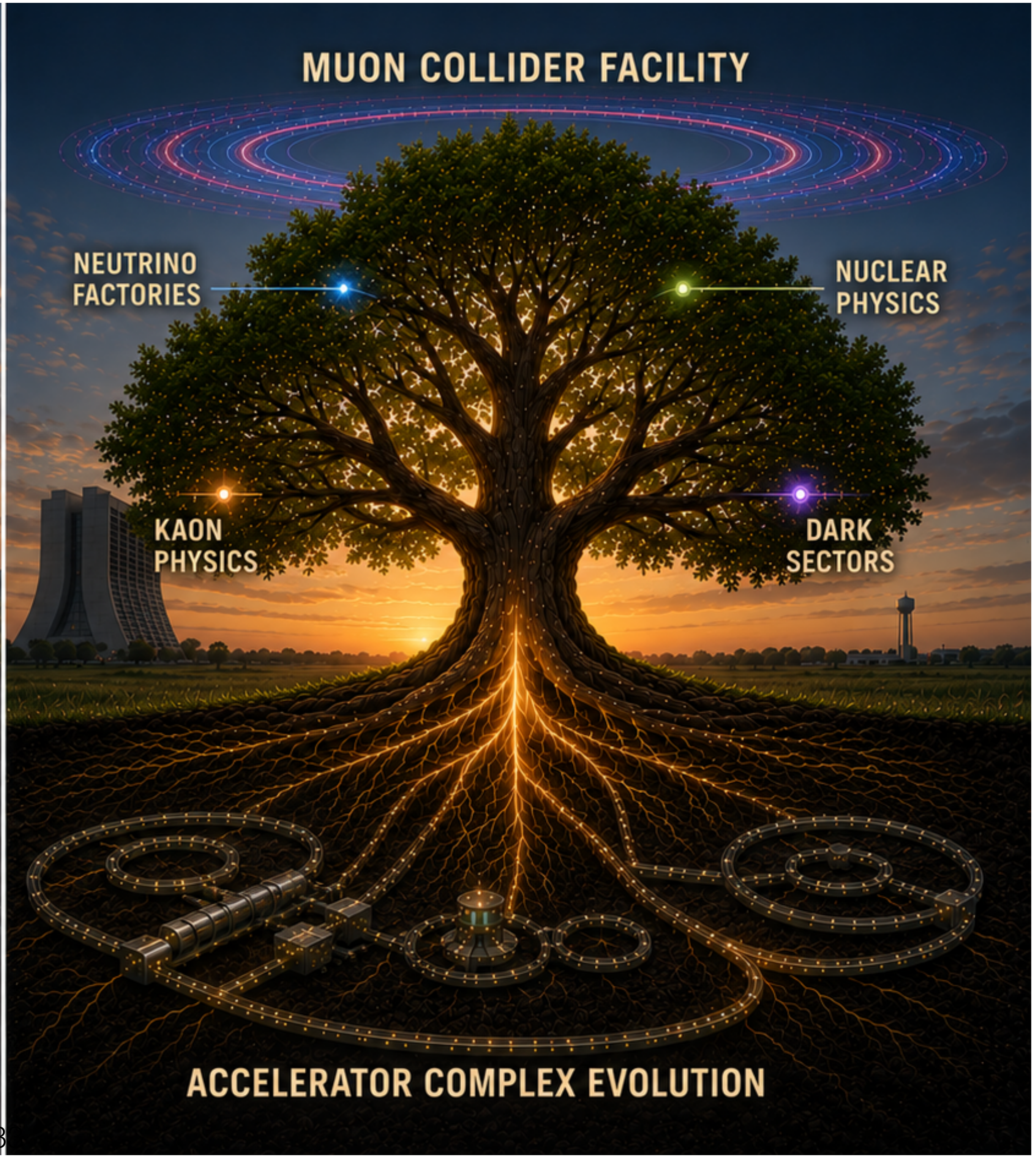
- A muon collider is a *facility* that can span HEP+NP, which makes sense for the HENP merger

- A muon collider isn't a binary choice on a mega project, muon beam R&D provides off-ramps and synergies across fields

- No new DOE starts until 2030s could turn out to be a feature not a bug ***if*** we work together as a community to identify the most promising opportunities

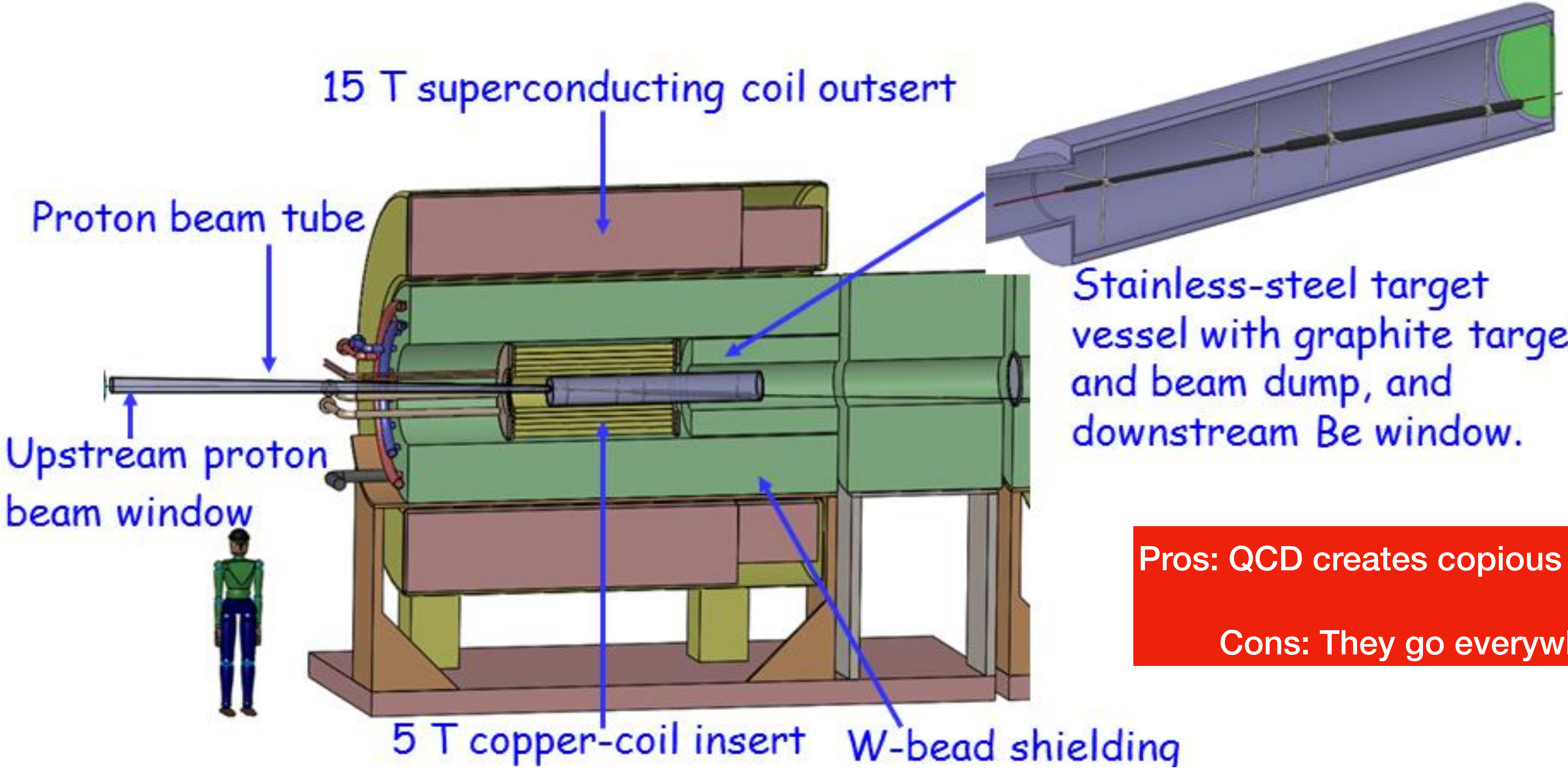
Who knows maybe we’ve already planted the HENP seed?





Backup

Create and Capture muons



Pros: QCD creates copious μ^- AND μ^+

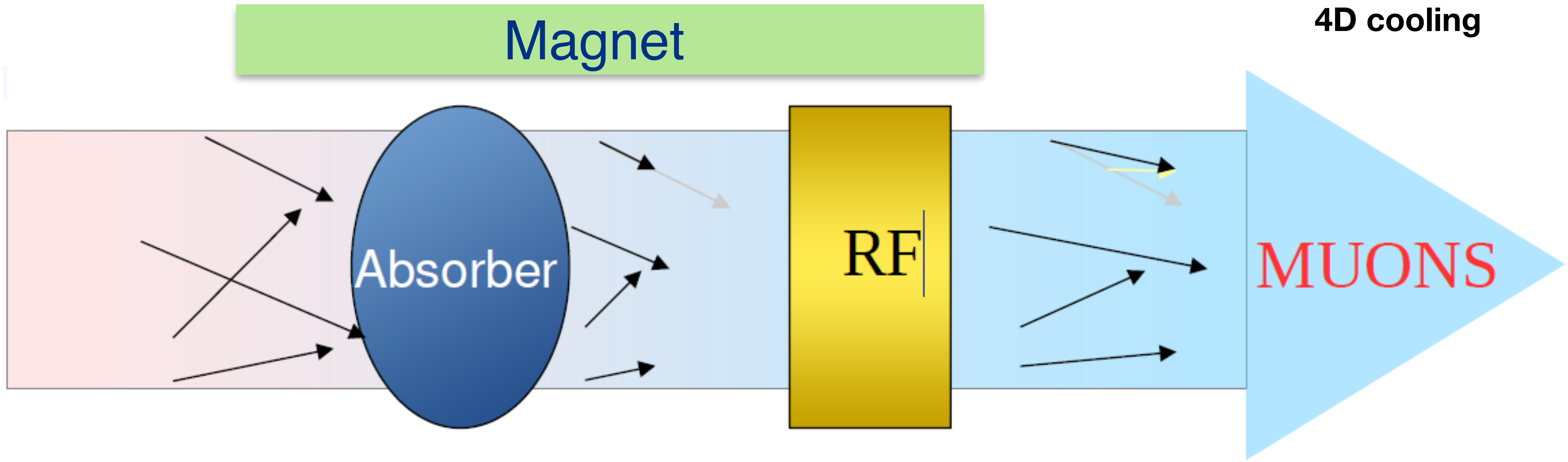
Cons: They go everywhere…

Cool the muons to make a beam

And you've got a few microseconds to do it

Typical cooling methods don't
work on this timescale!

Ionization Cooling



Physics is of the 1930's Bethe-Bloch formula, putting the components together is the tricky part!