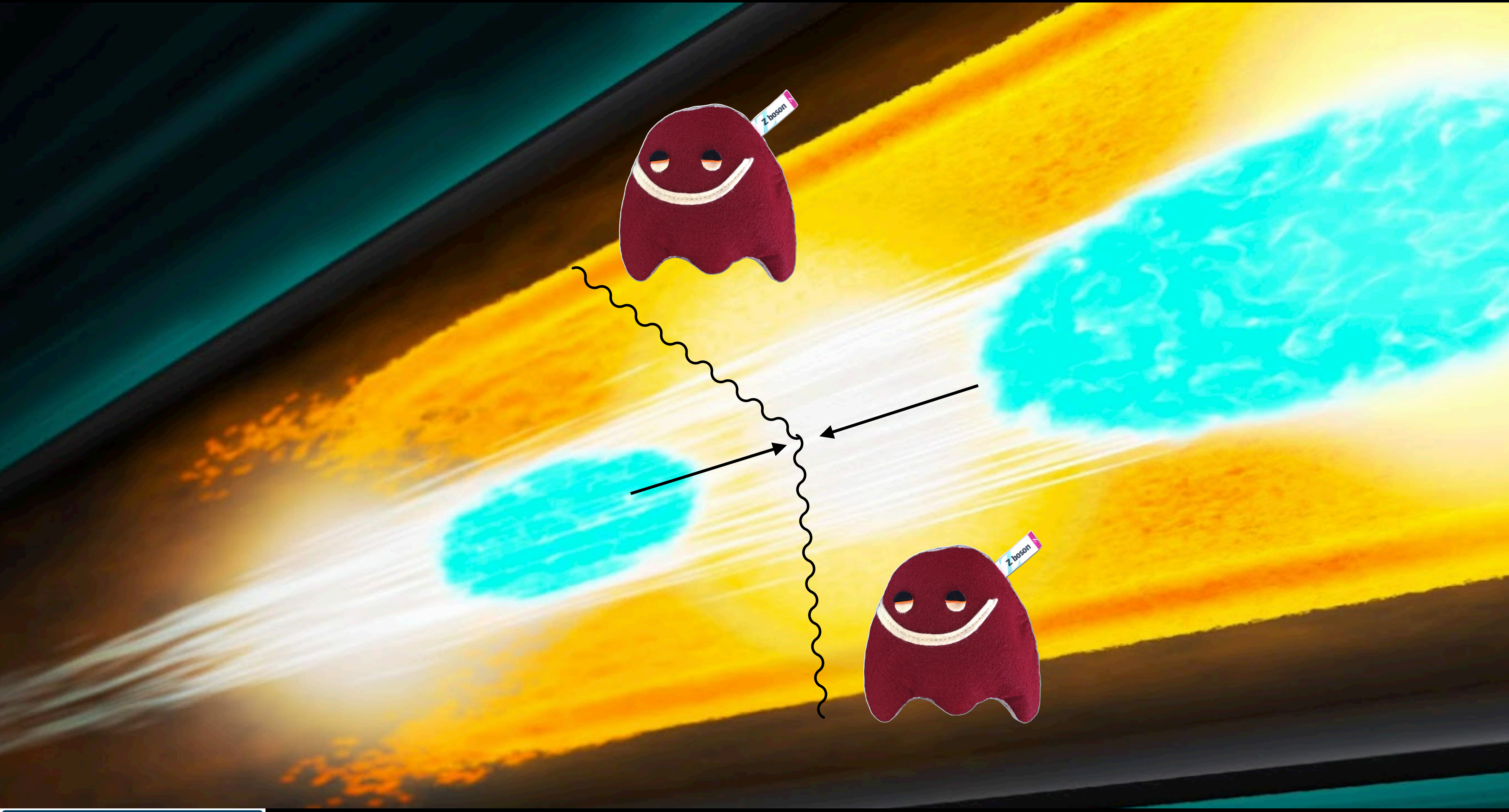
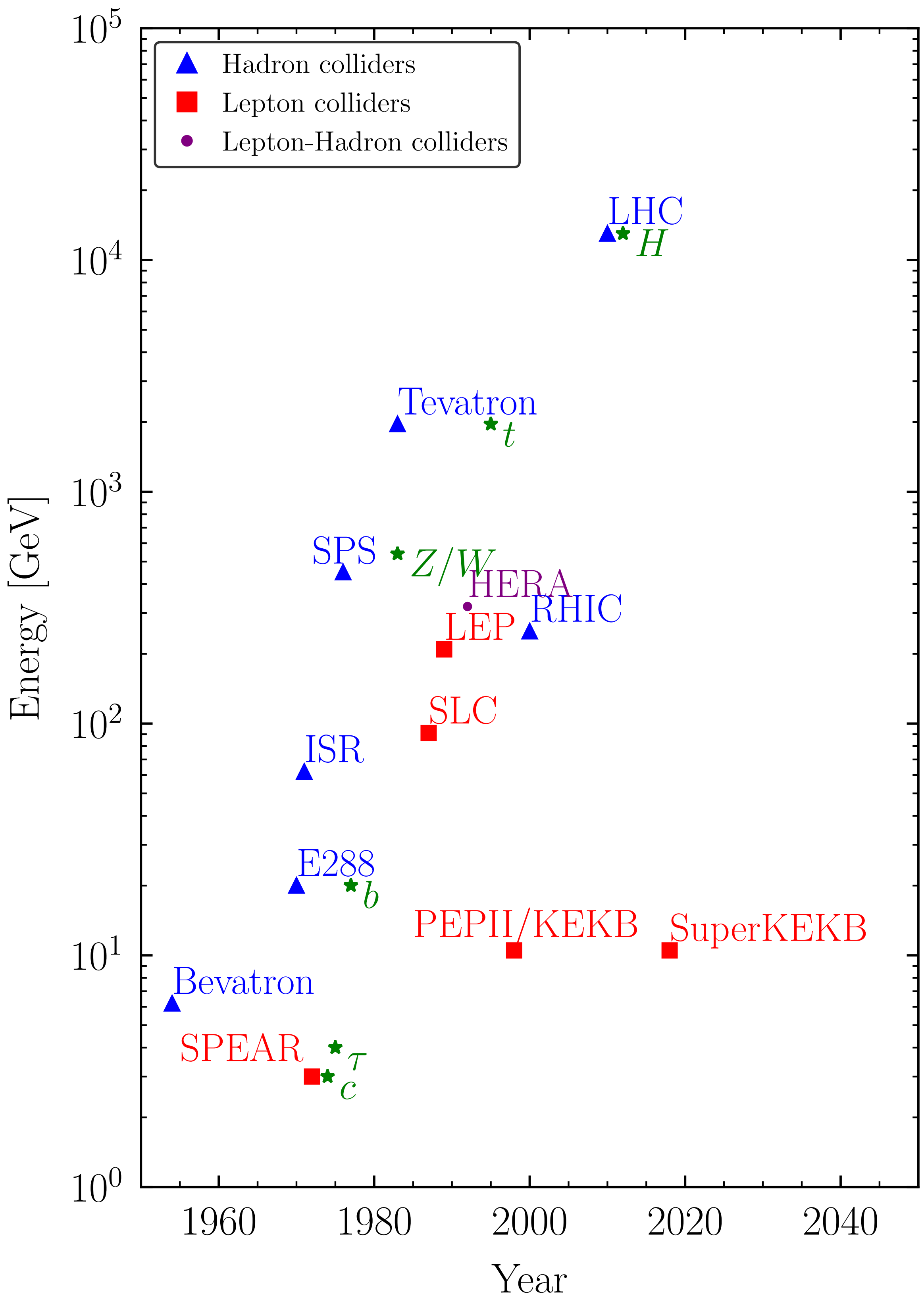
Physics at a 10 TeV lepton collider



Simon Knapen
Lawrence Berkeley National Laboratory
BERKELEY LAB

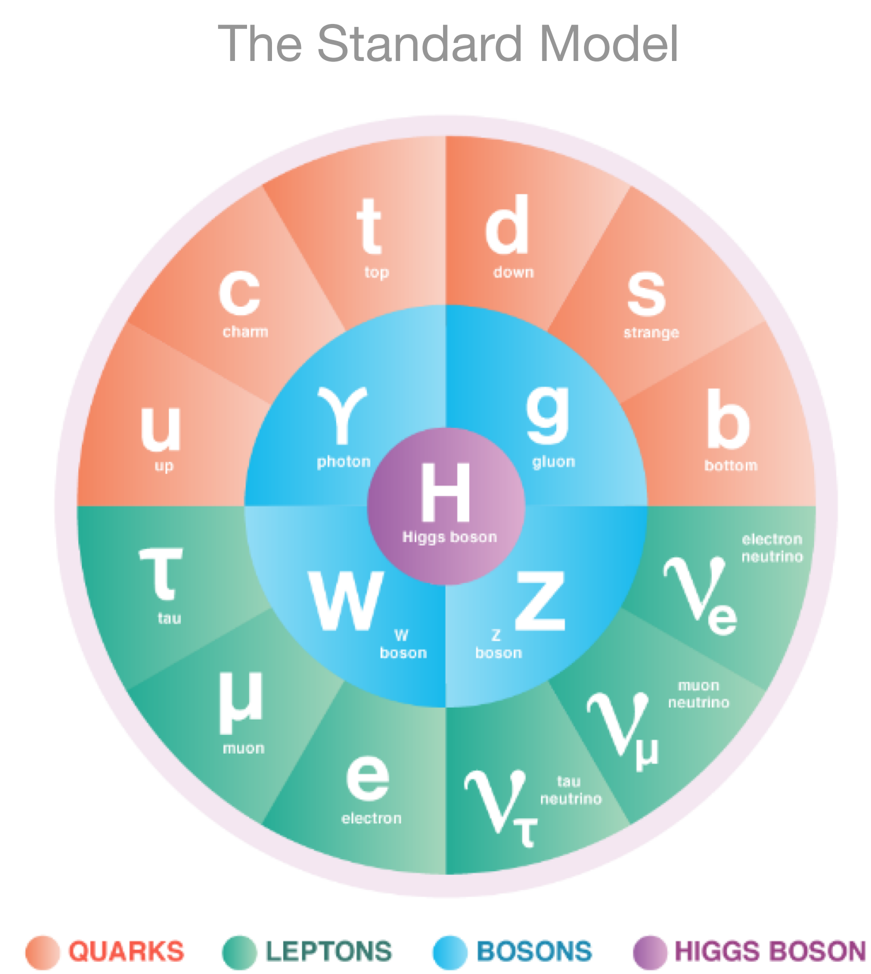
Why do we build colliders?



We want to probe the shortest distances we can

Historically, this has meant discovering new particles

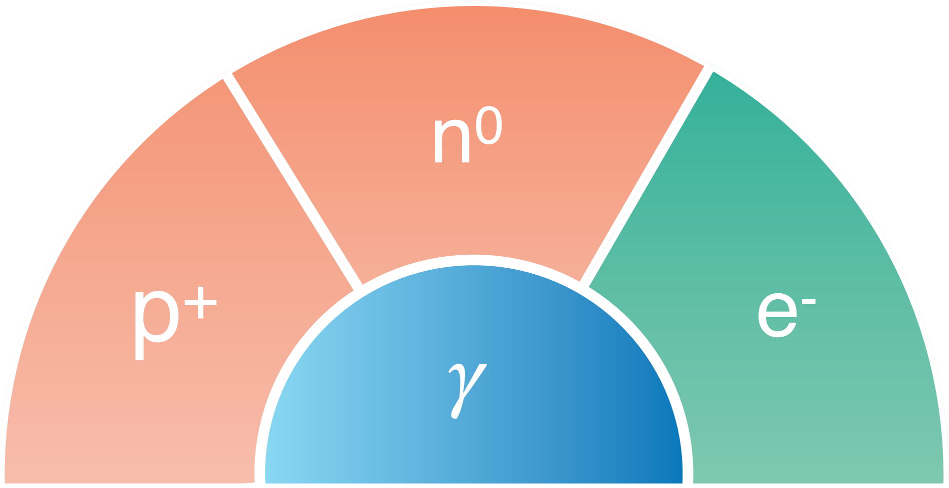
Will this continue to be the case as we push to shorter distances?



Particle Fever 2013

Back to 1932

Standard model in 1932



Some open questions:

- Why are is the electron so much lighter than the proton and neutron?
- How to protons and neutrons stick together in nuclei?
- How does radioactivity work?

Back to 1932

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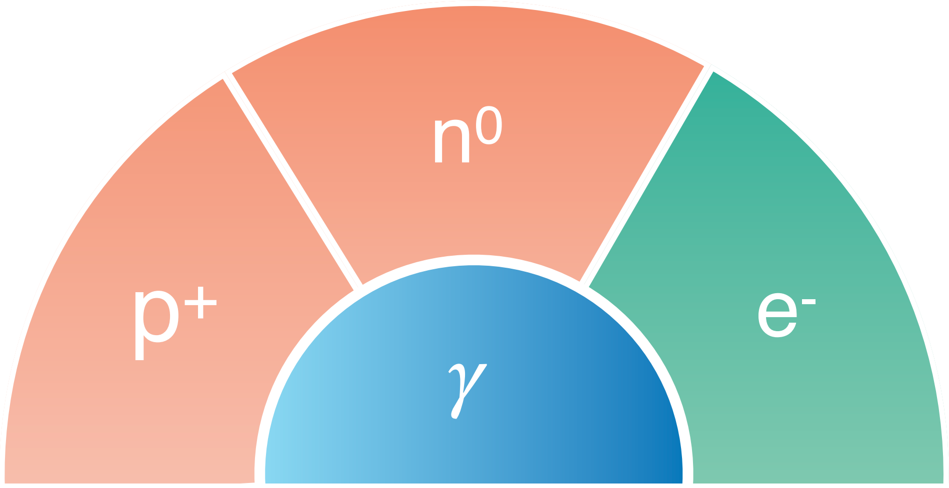

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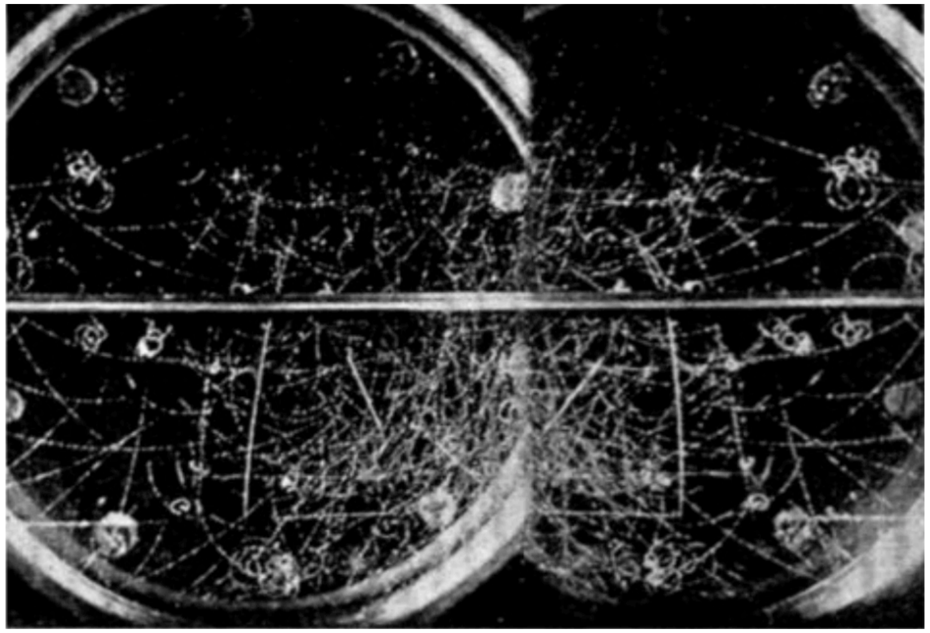
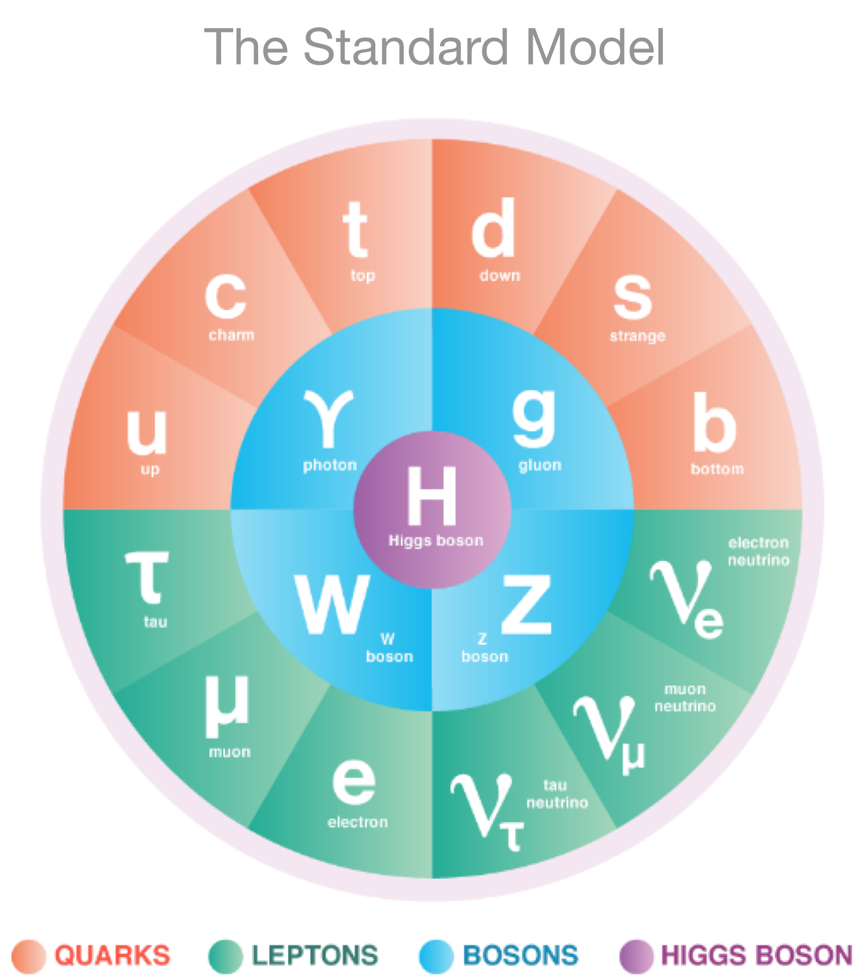
Muon discovered in 1936



How about now?



A very satisfying diagram!

But still some deep open questions:

- What is the origin of mass?
- What is the dark matter?
- Why is there more matter than antimatter?
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- Why are there 3 generations?
- What breaks CP symmetry?
- Why do neutrinos have mass?

On the origin of mass

Standard Model theory prediction for particle masses without Higgs

On the origin of mass

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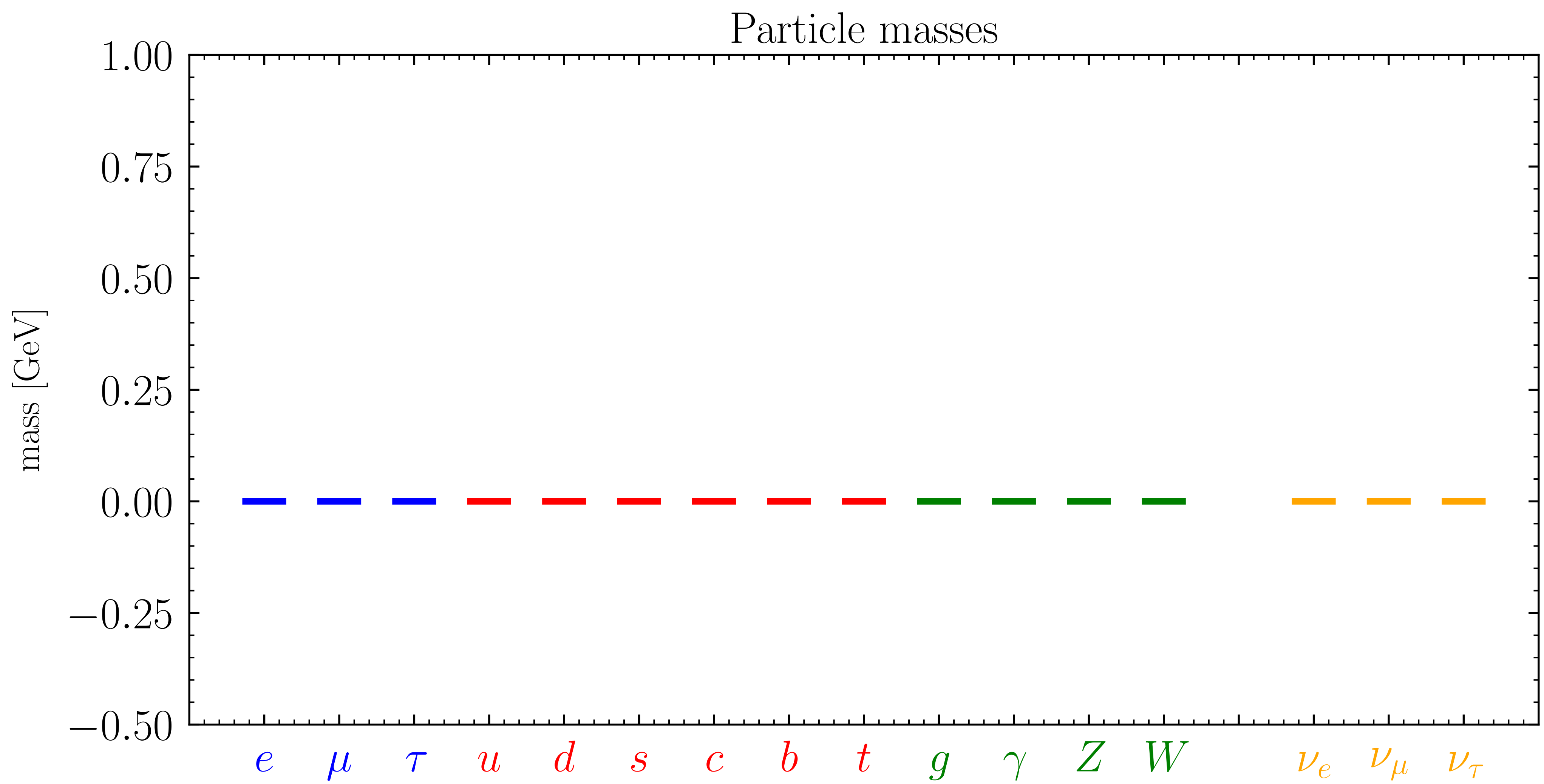
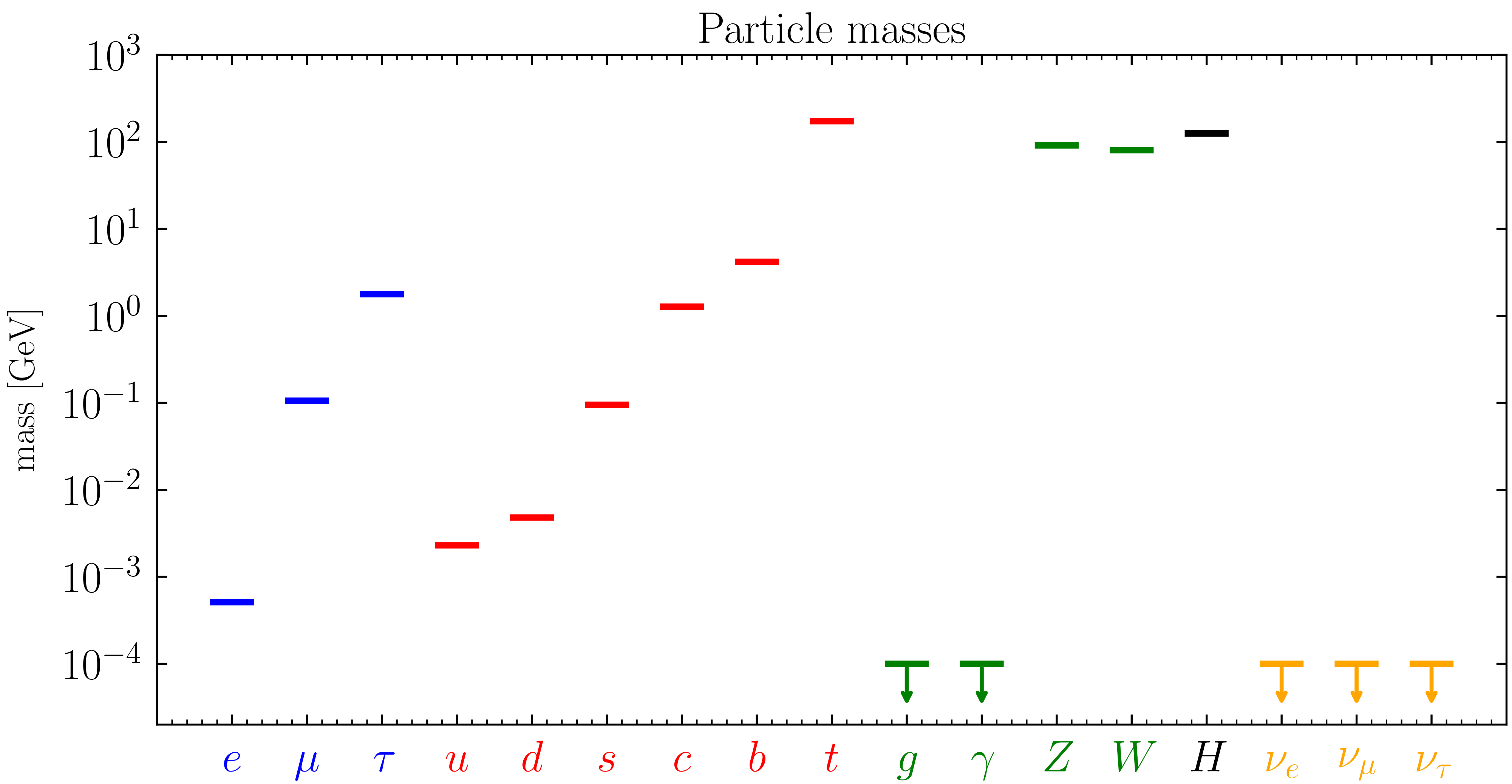


On the origin of mass

Experimental reality

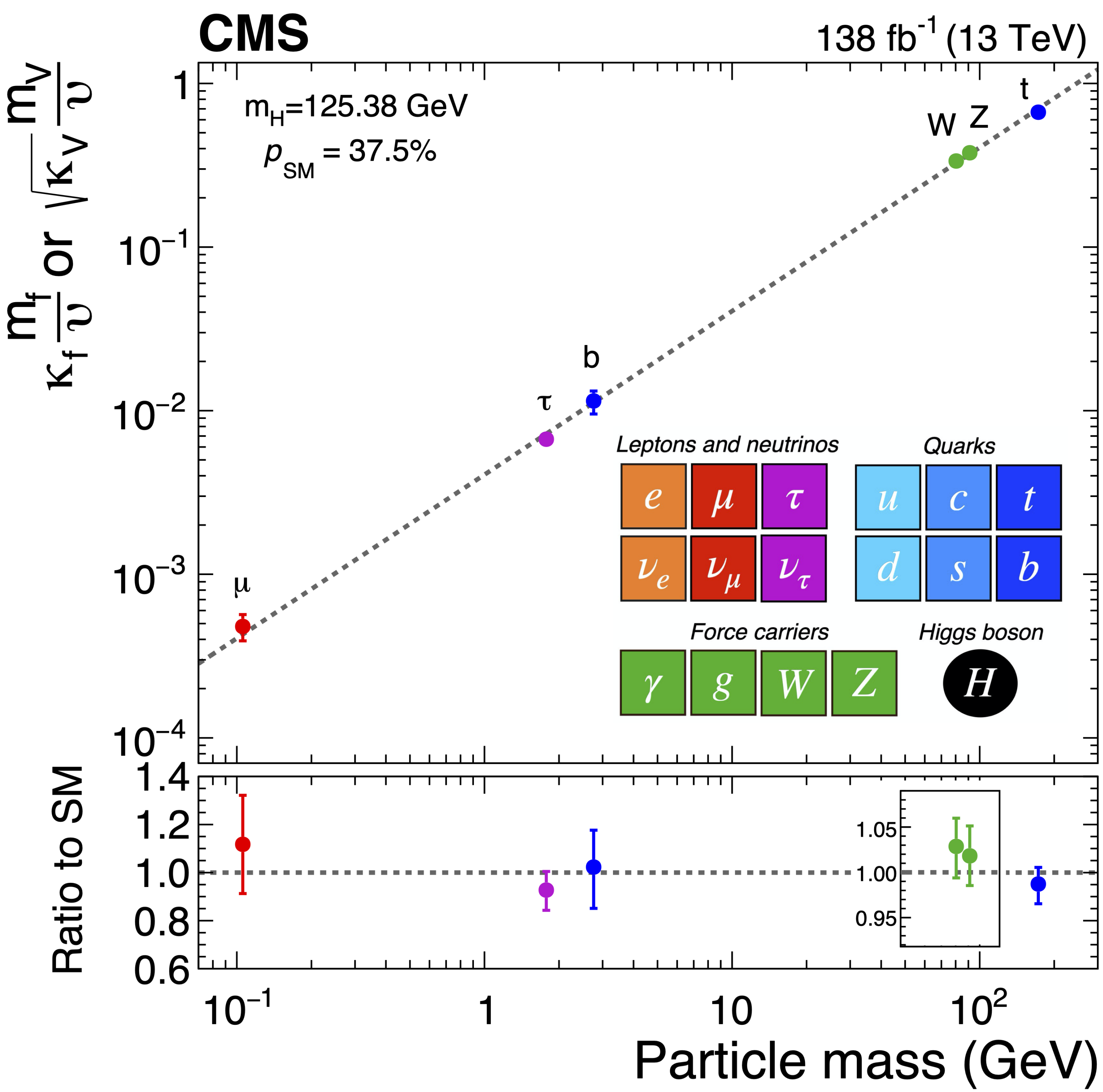


With the Higgs, the Standard Model does not predict the particle masses

but at least it no longer predicts all particles must be massless

On the origin of mass

The Standard Model does predict a *relation* between the particle masses and their coupling to the Higgs boson



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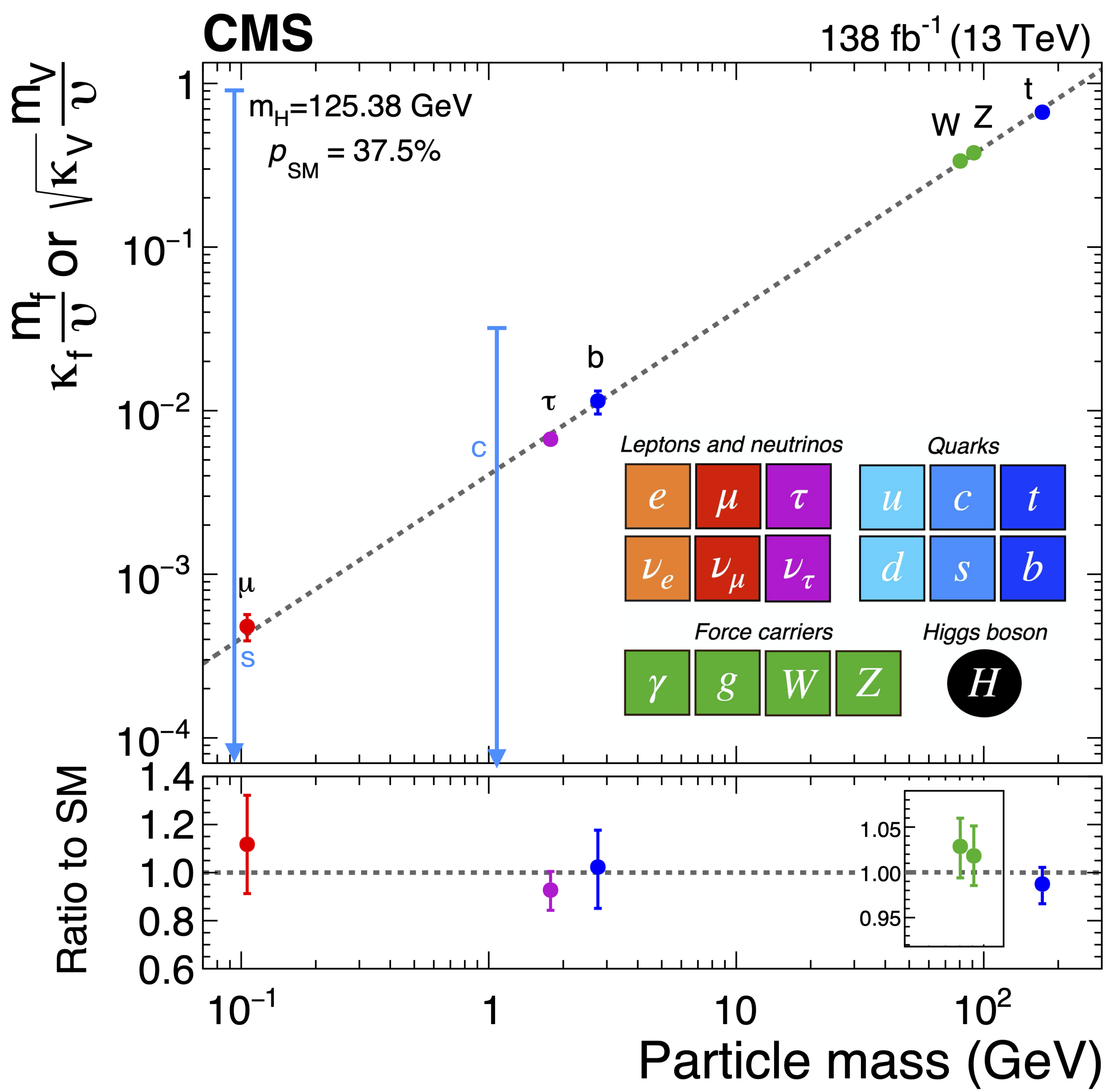

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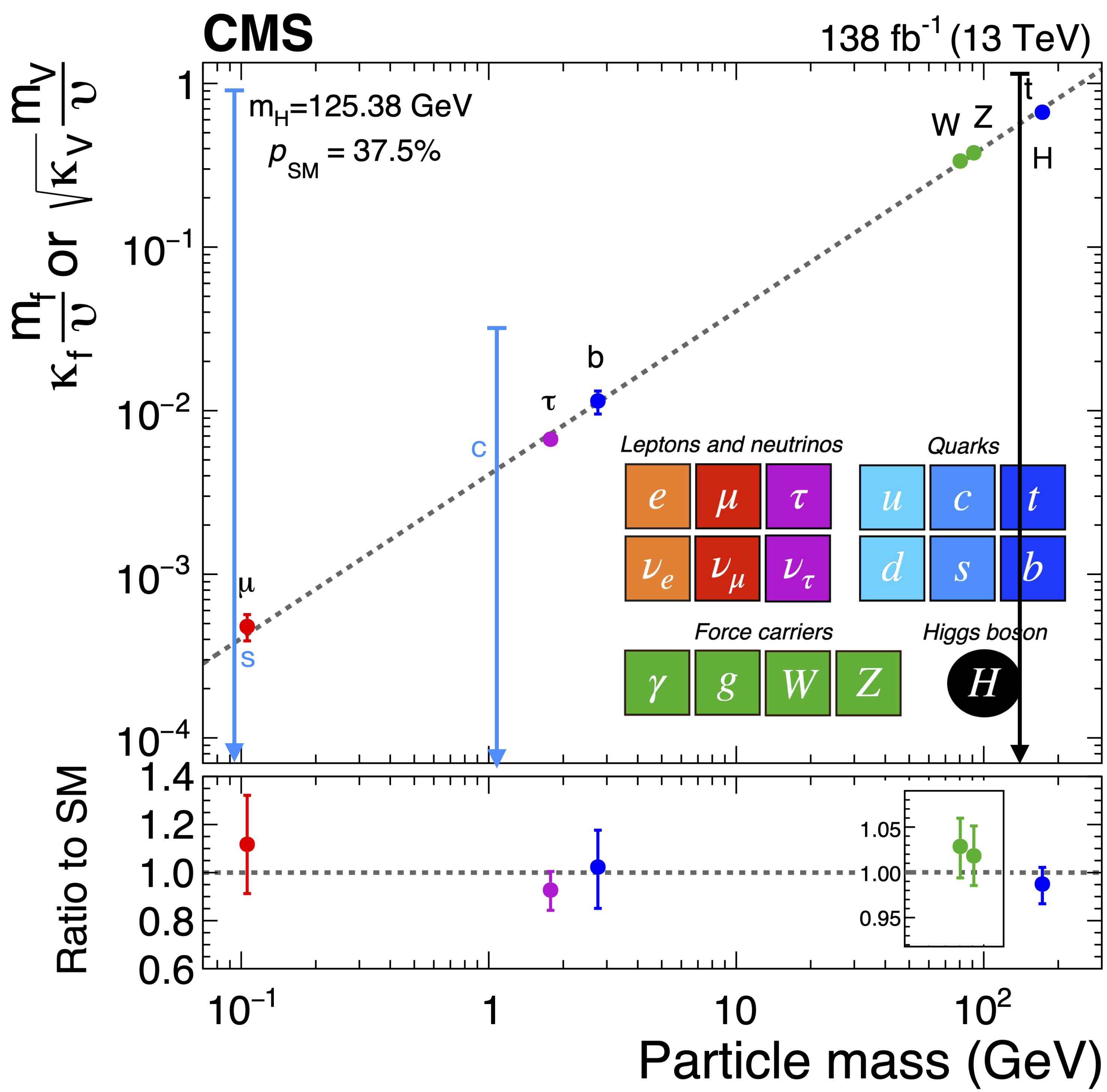
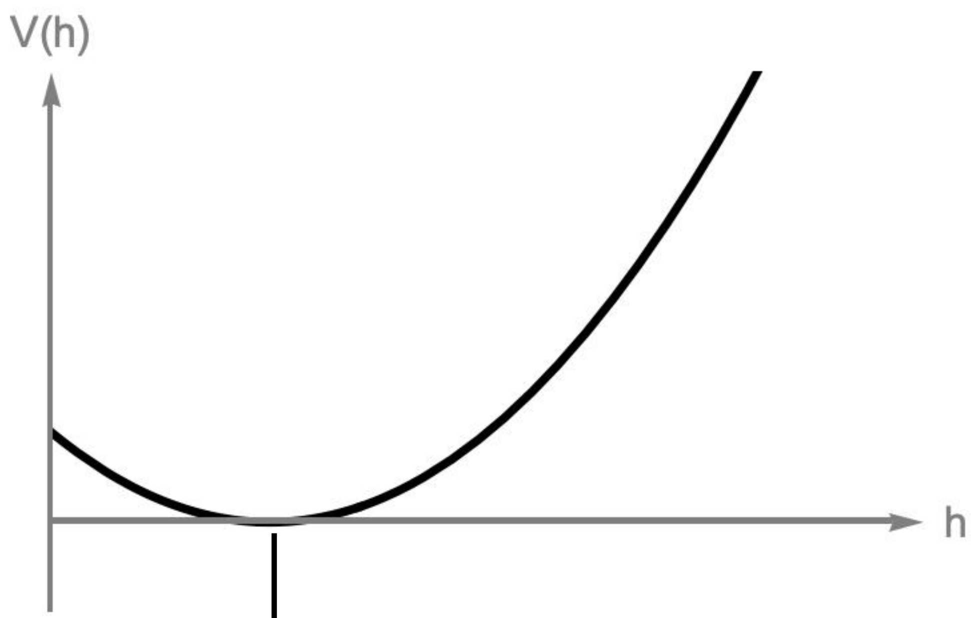


The Higgs potential



Taylor expand around minimum

$$V(h) = v + c_2 h^2 + c_3 h^3 + c_4^4 h^4$$

G_F (measured)

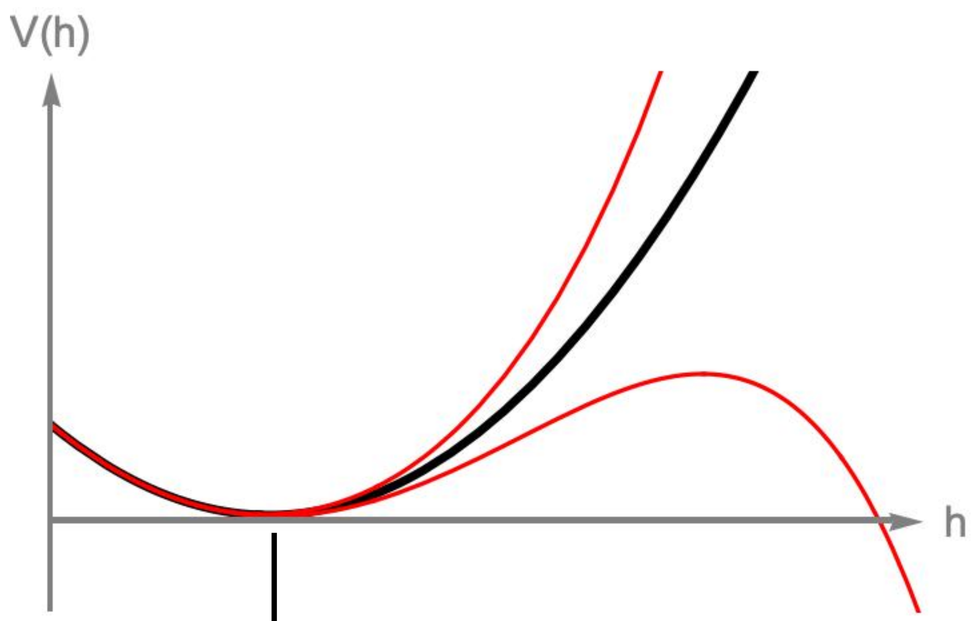
mass (measured)

predicted

The Higgs field permeates the vacuum of all of space

All fundamental particles derive their mass (or lack thereof) from their interaction with this background field

The Higgs potential



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c_3, c_4 → predicted

The Higgs field permeates the vacuum of all of space

All fundamental particles derive their mass (or lack thereof) from their interaction with this background field

Important open questions:

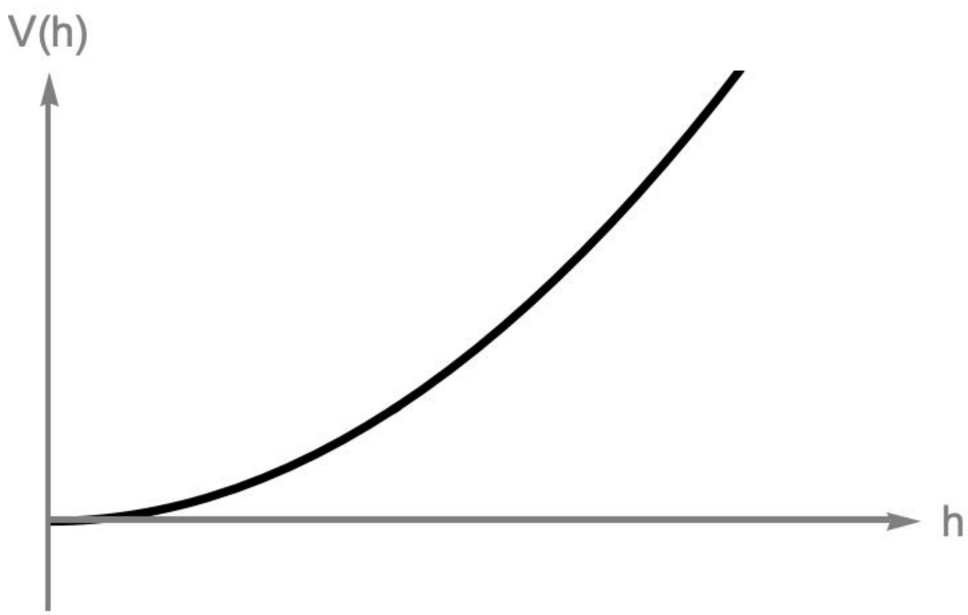
- Are the Standard Model predictions correct?
- What does the potential look like away from the minimum?
- Are there more directions? (= additional Higgs fields)

Big implications for birth and death of our universe

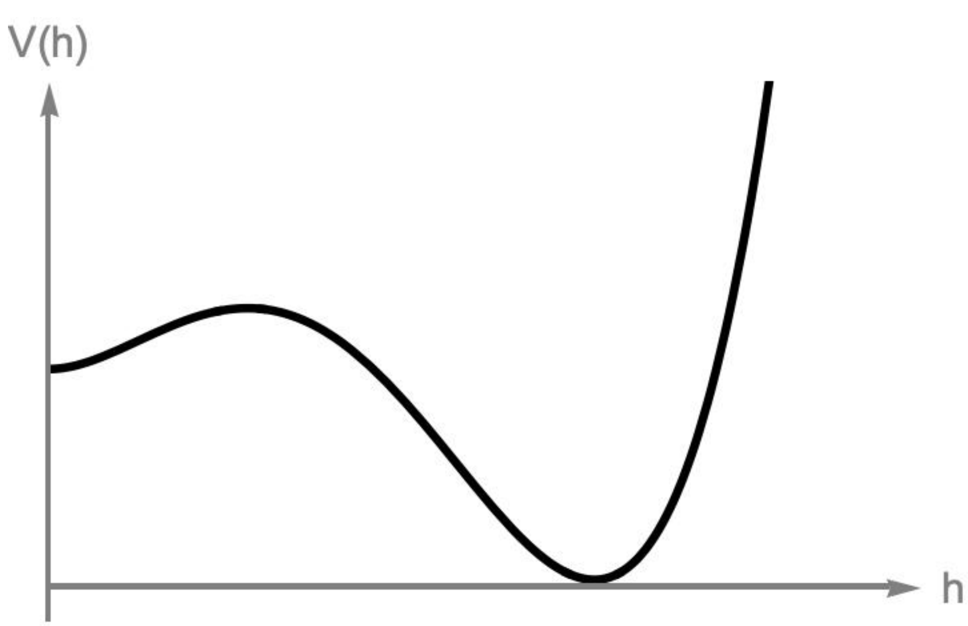
The birth of the universe

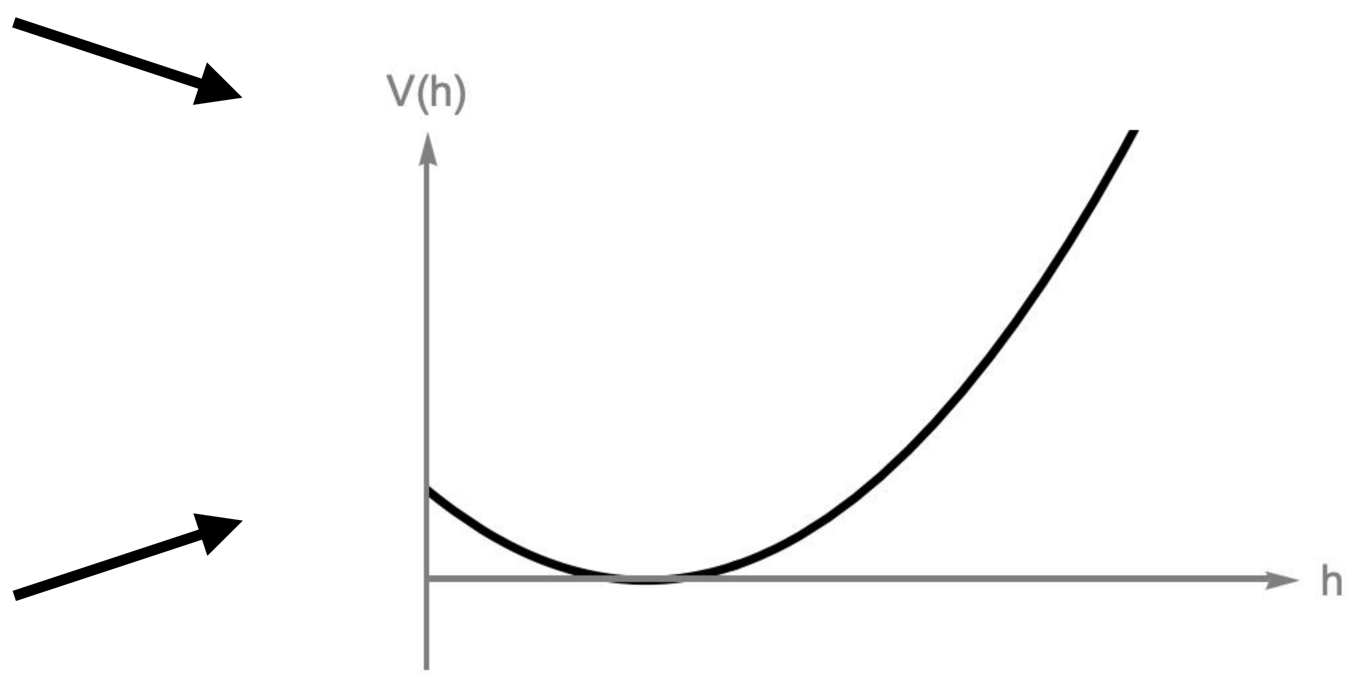
During early universe (very hot)

Today (very cold)



Or





We cannot recreate the conditions in the early universe

But the shape of today's Higgs potential contains imprints of the high temperature physics

The birth of the universe

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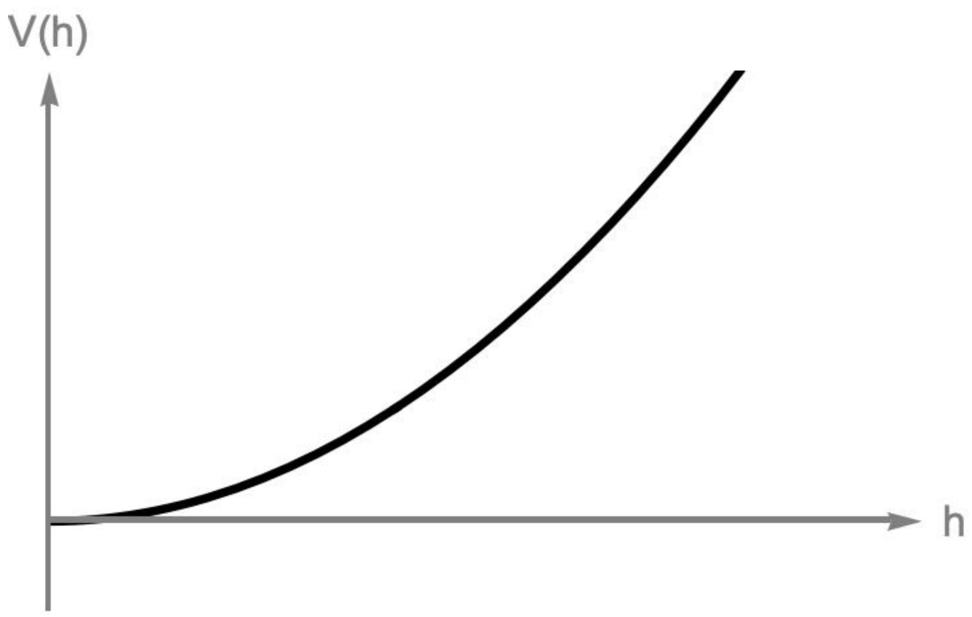

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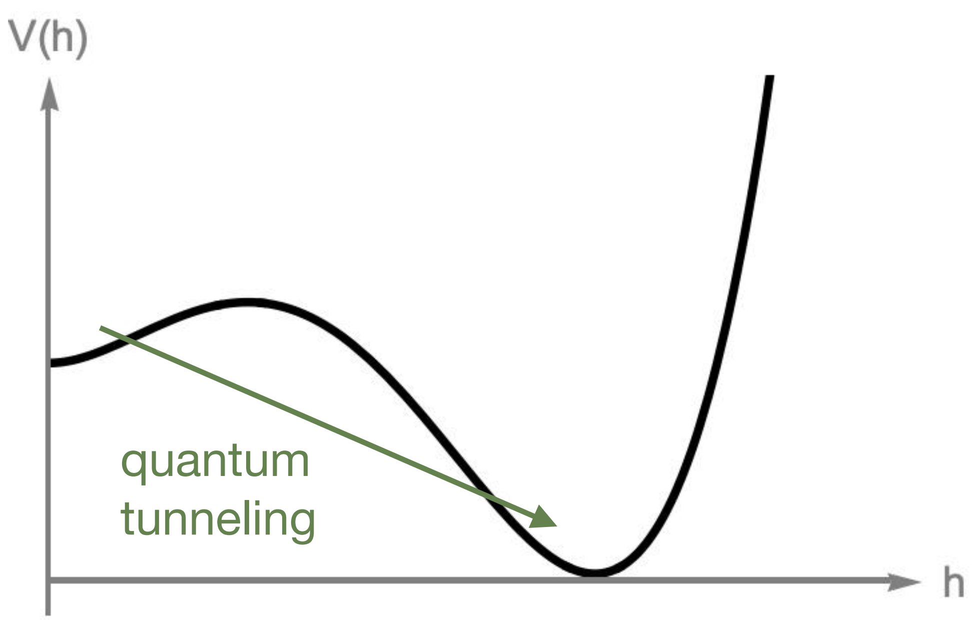
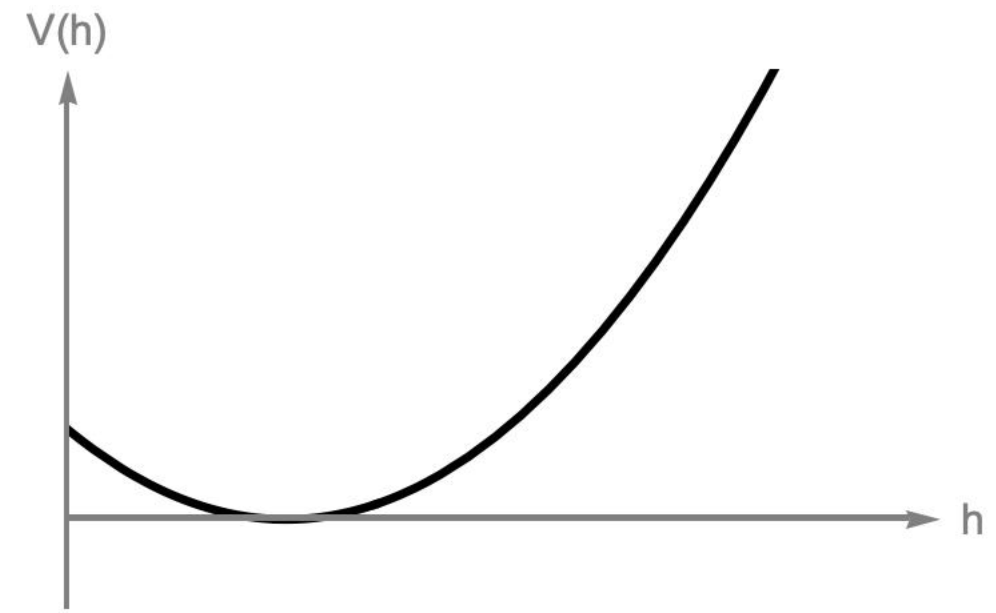


Today (very cold)



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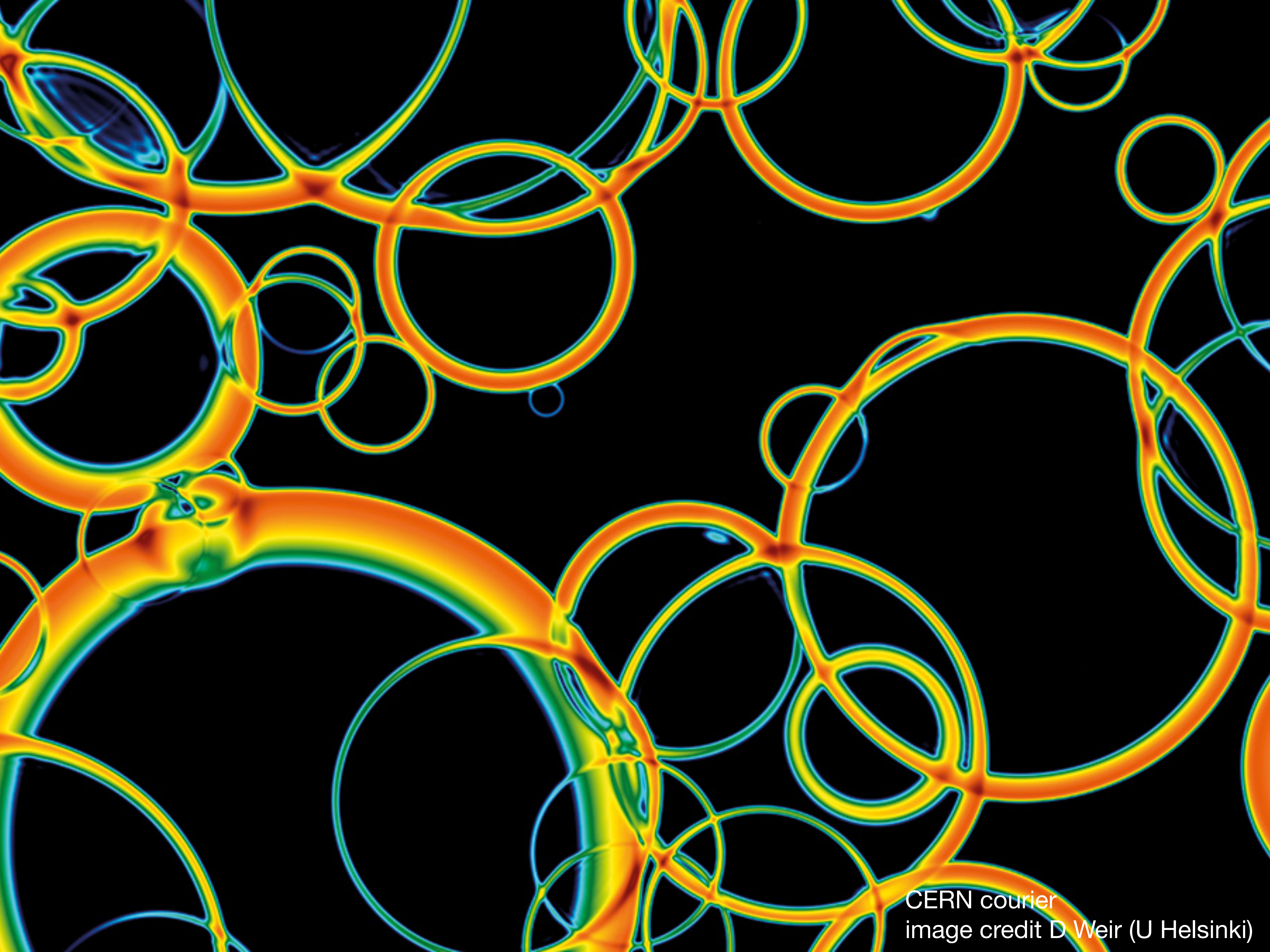
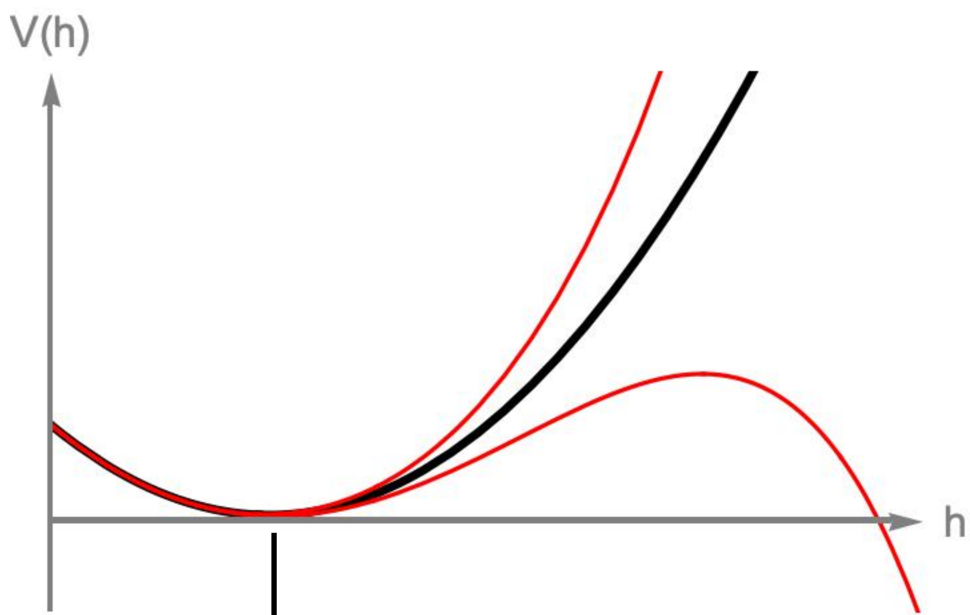


CERN courier
image credit D Weir (U Helsinki)

Measuring the Higgs potential



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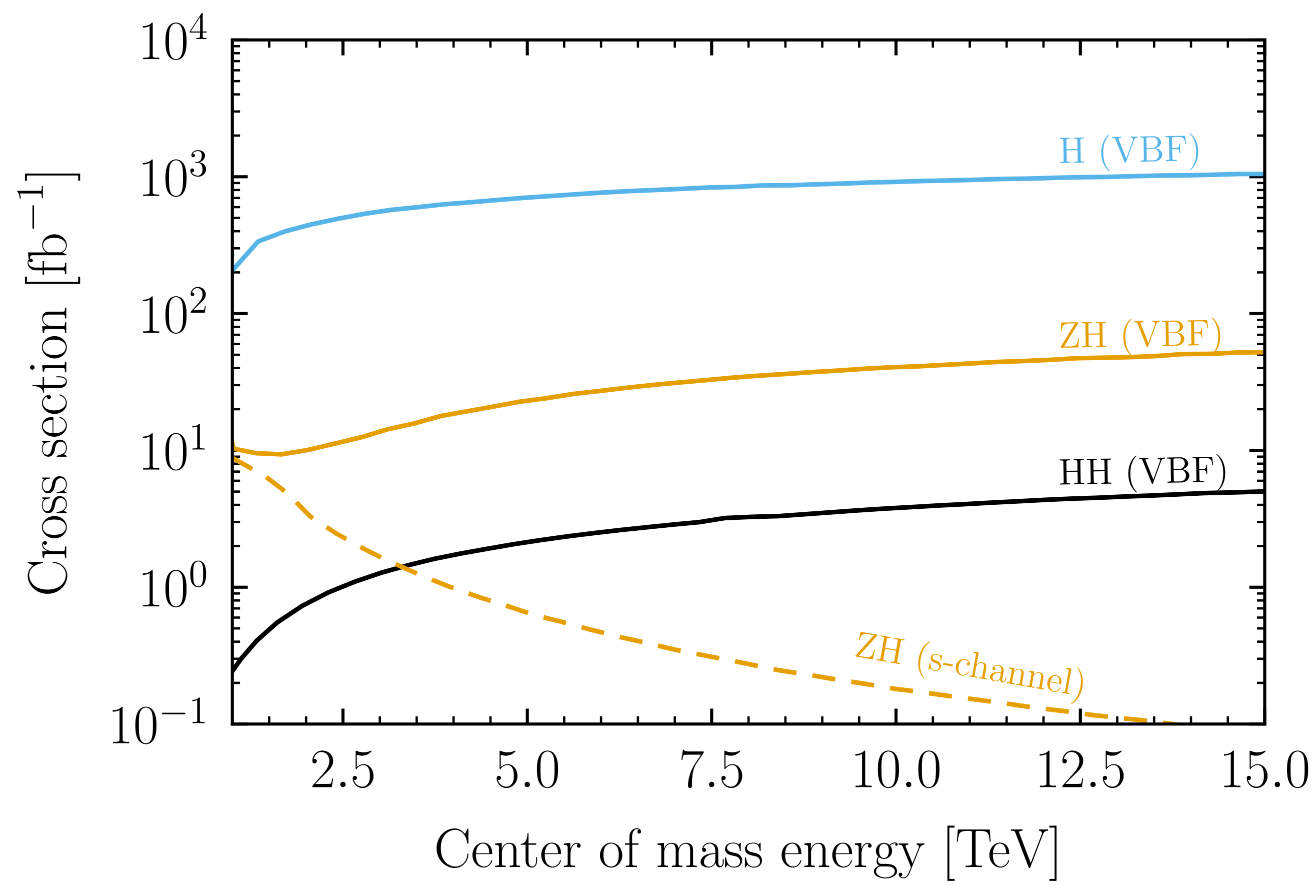
adapted from T. Han, Y. Ma and K. Xie arXiv: 2007.14300



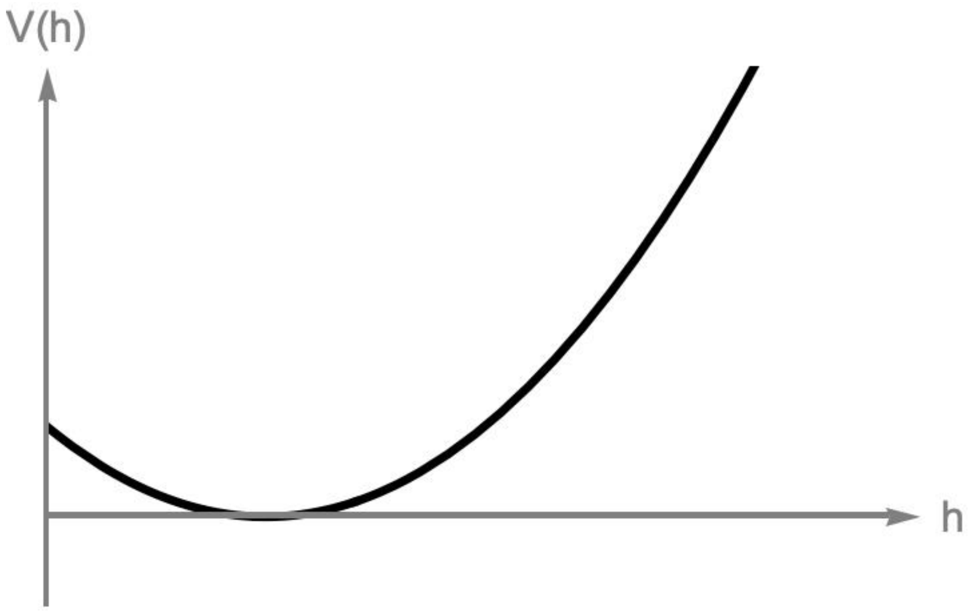
Vector Boson Fusion (VBF) cross section grows with energy

Annihilation channels (e.g. Drell-Yann) are falling

Wakefield sensitivity should be similar to muon collider

Some interesting subtleties however
(see Kevin Langhoff's talk in the afternoon session.)

Are there other directions in the Higgs potential?



If the Higgs boson we already saw is part of a larger Higgs sector, we expect:

- An additional neutral scalar (H^0)
- An additional pseudo-scalar (A^0)
- An additional charged scalar ($H^\pm$)

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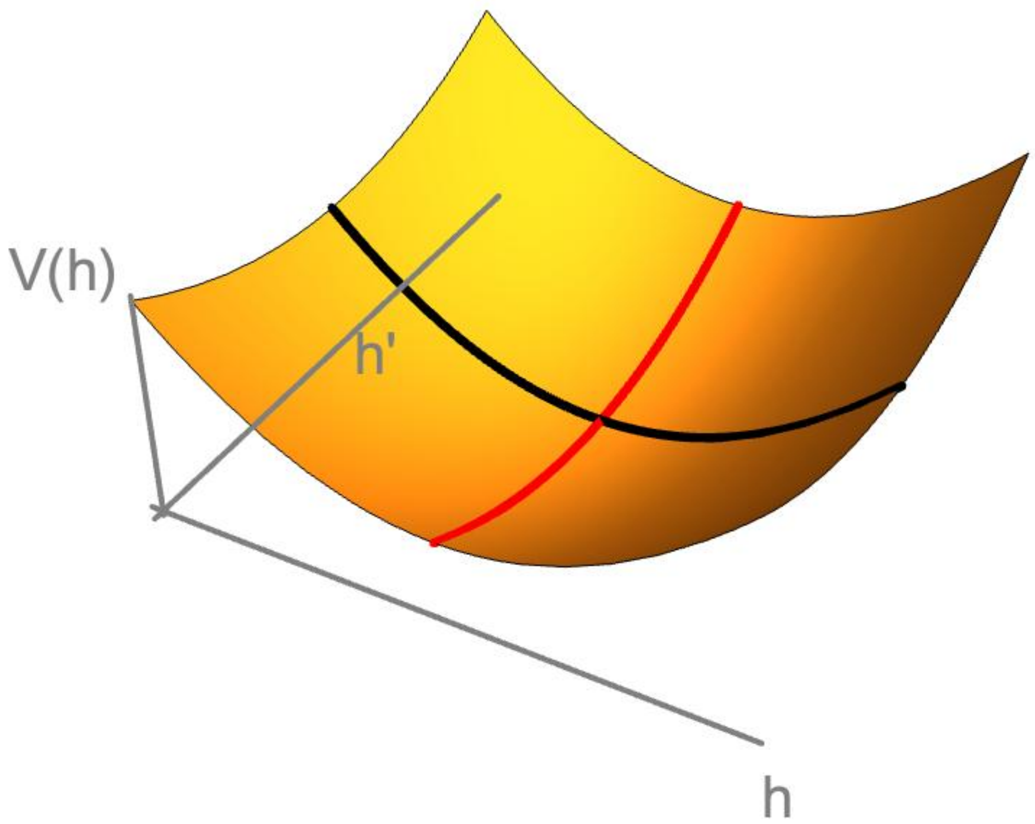

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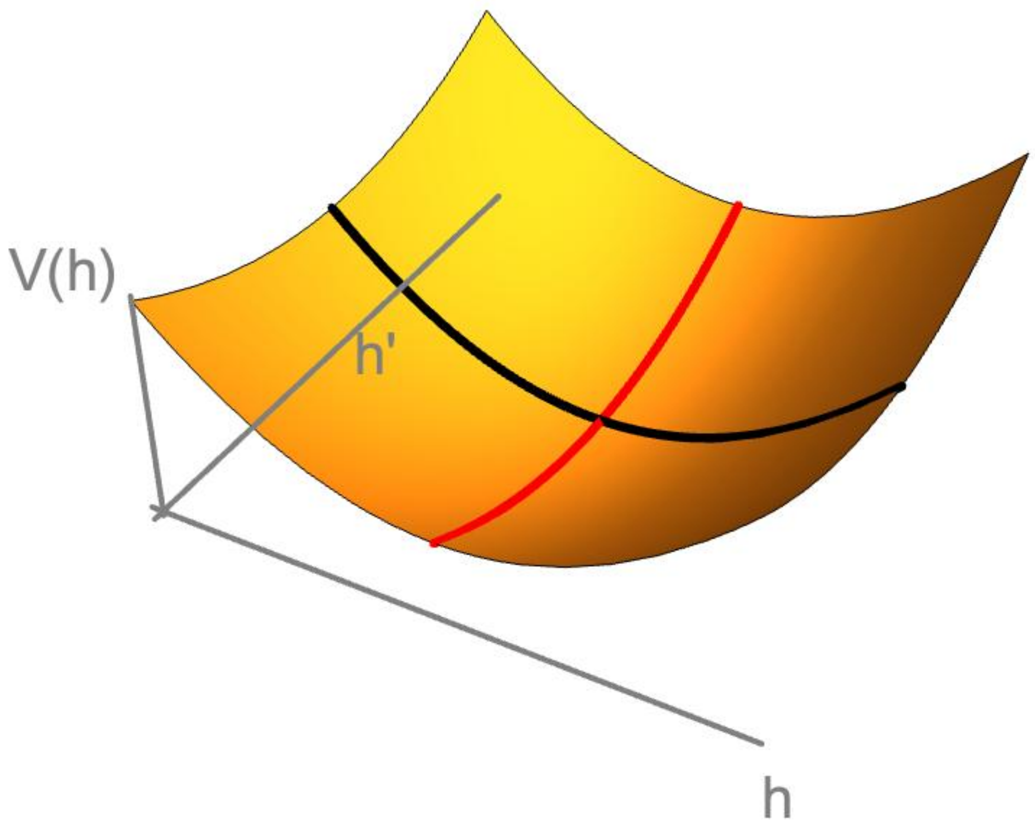

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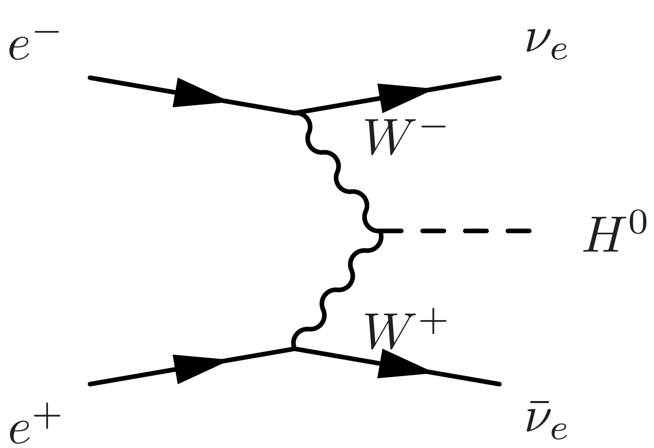
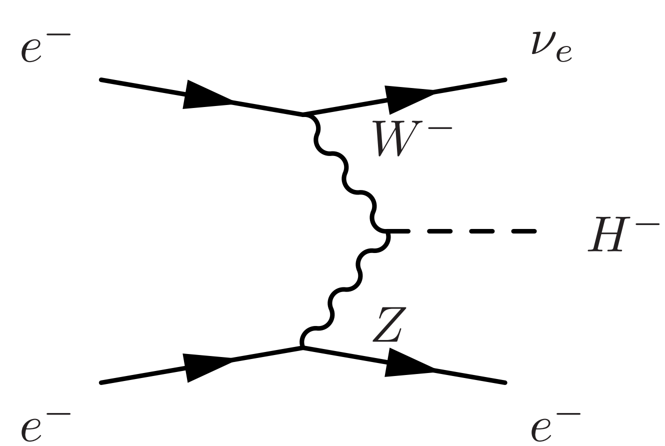
We can produce these particles in multiple ways e.g.

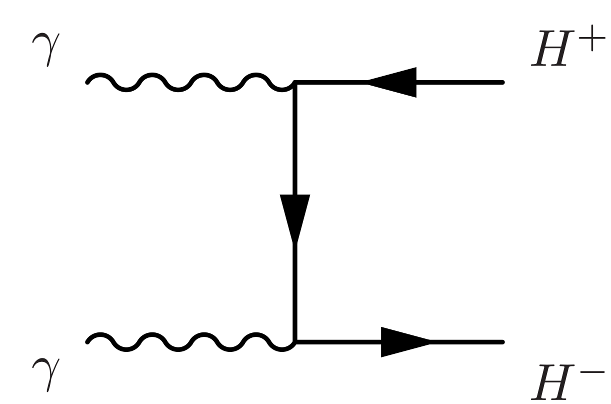
WW fusion



WZ fusion



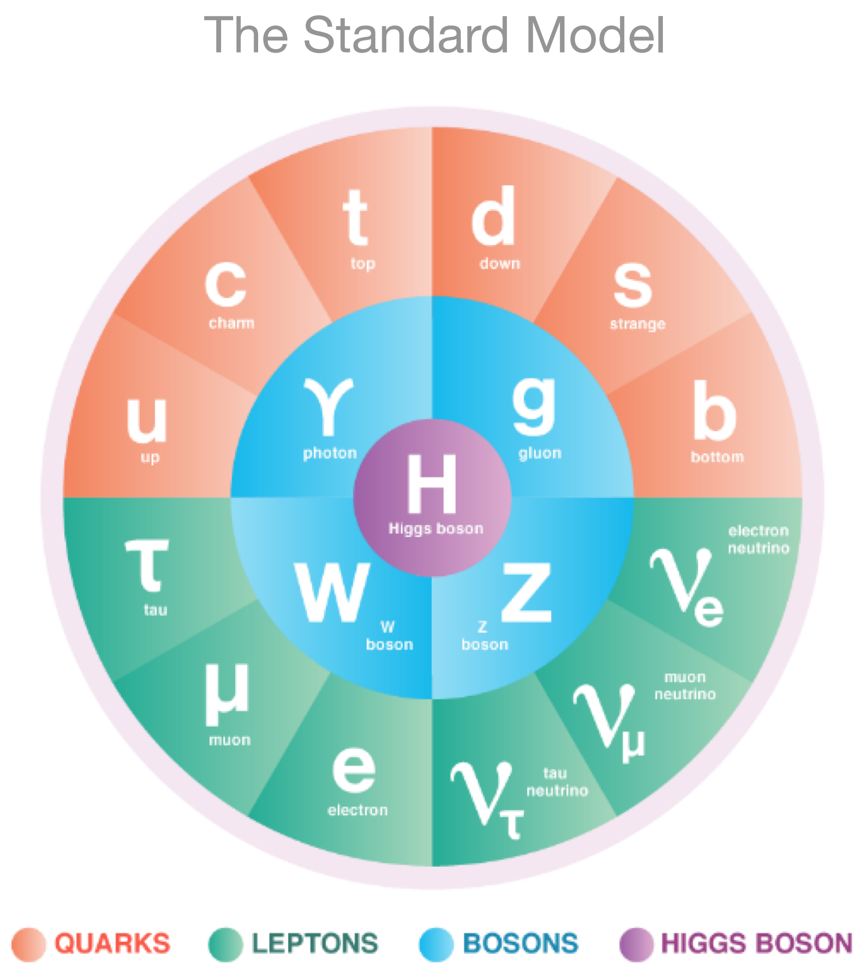
photon initial states



Study is under way, no results yet

(See e.g. Butazzo et.al. 1807.04743 for muon collider study)

How about now?



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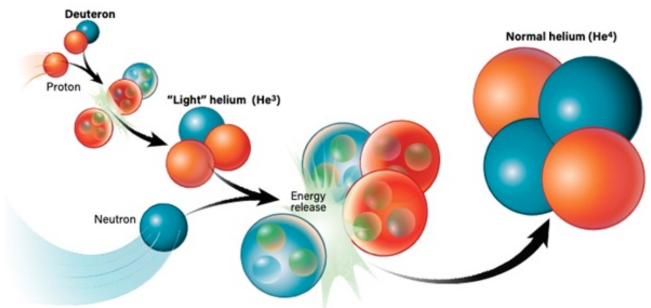
Muon shot and the future of particle physics: N. Craig @ KITP

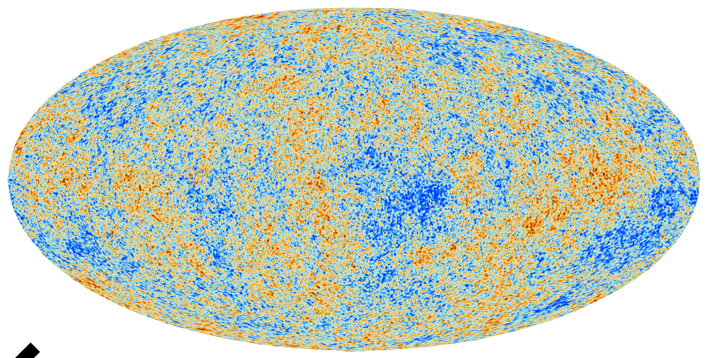
Evidence for dark matter

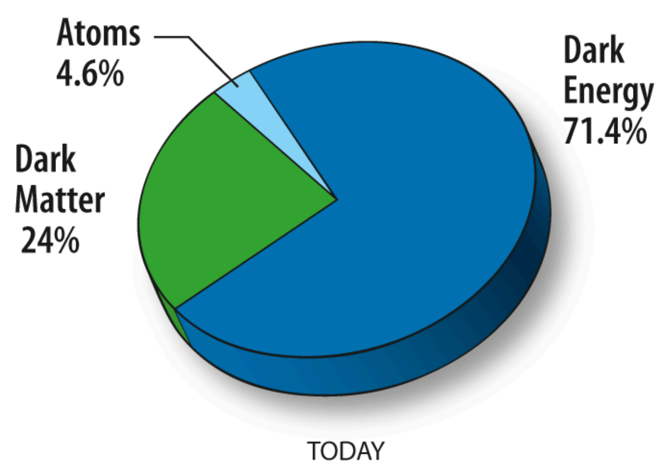
Early universe

Big Bang Nucleosynthesis (BBN)



Cosmic Microwave Background (CMB)

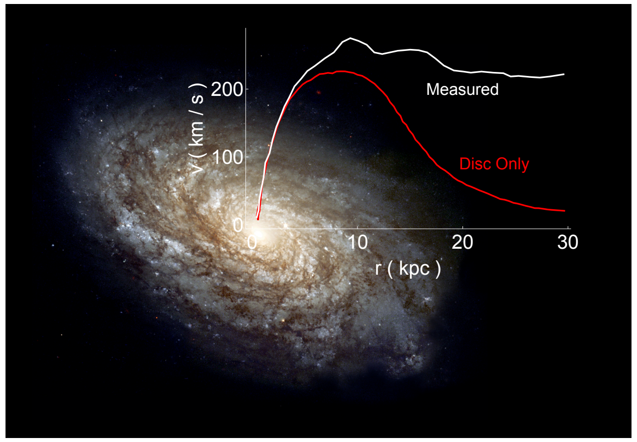




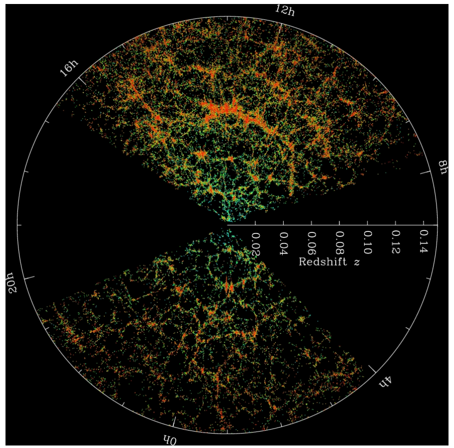
All evidence is from interactions with Dark Matter's gravity

Late universe

Rotation curves



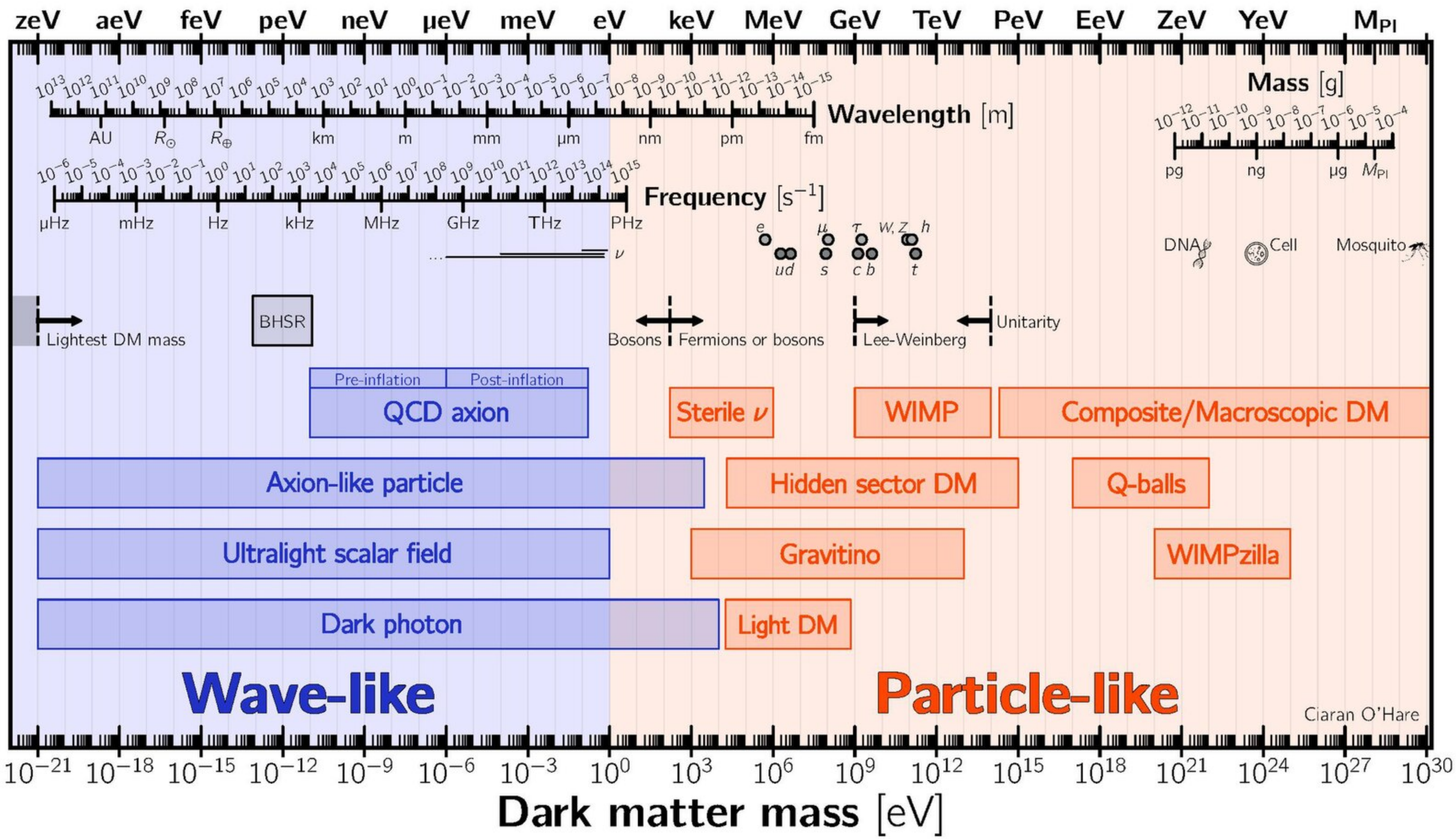
Structure surveys



Galaxy cluster mergers

Evidence for dark matter

Gravity does not care about the dark matter mass



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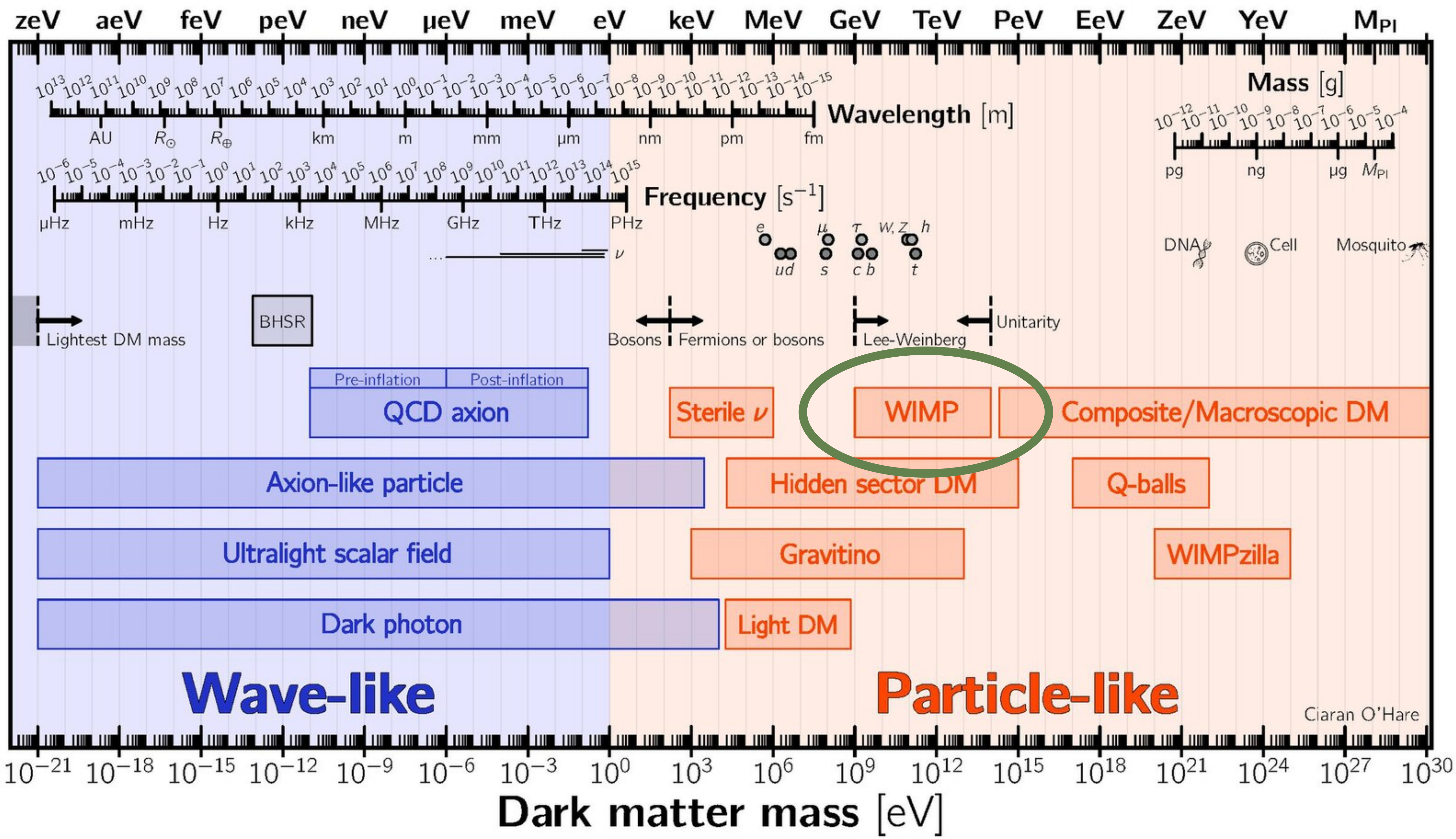

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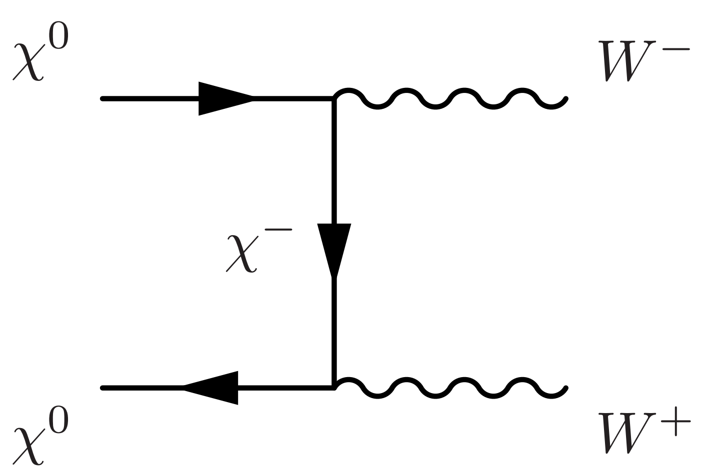
Weakly Interacting Massive Particles

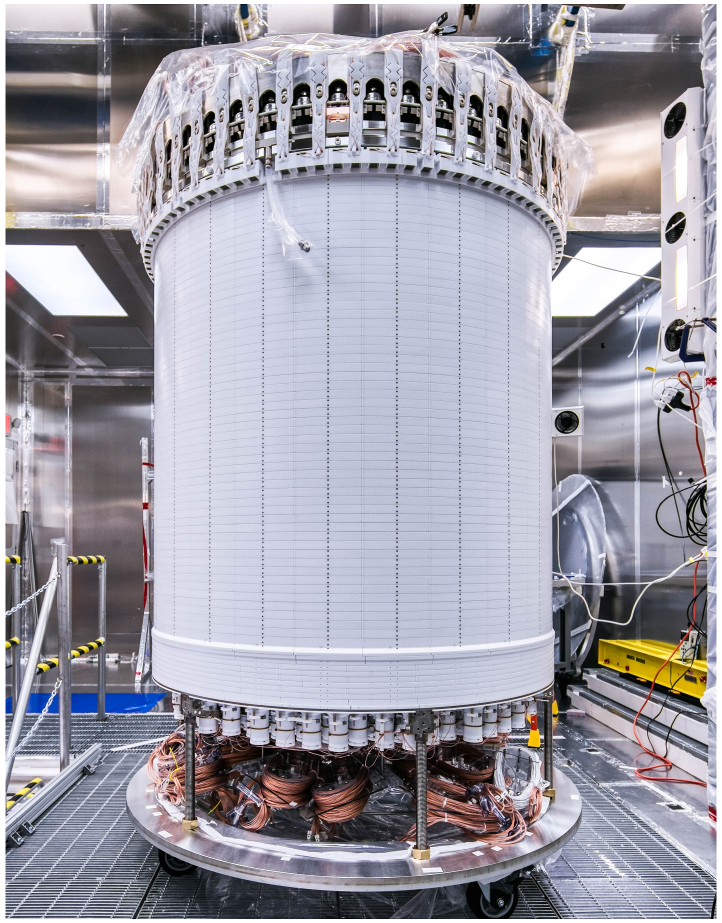
What if the dark matter interacts with us through the weak force?



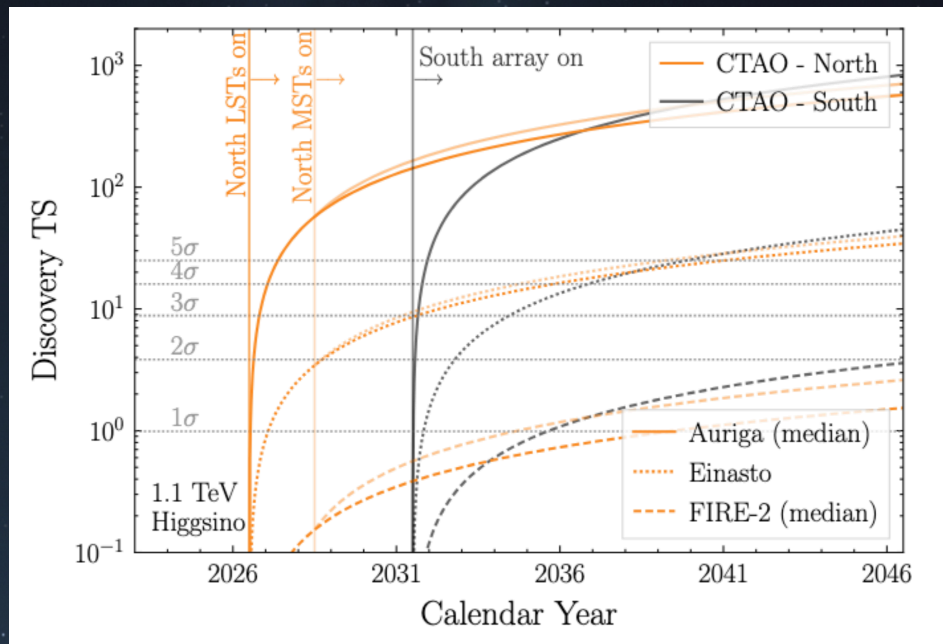
It’s annihilation rate in the early universe reproduces the dark matter relic density if m_χ ~ 1 - 10 TeV range

Direct detection experiments such as LZ may or may not see it

The LHC unfortunately cannot



The Cherenkov Telescope Array (CTA) can detect some WIMP candidates soon



L. Xu et al (in progress)

If either LZ or CTA observes a WIMP, this would enormously strengthen the case for a multi-TeV lepton collider *as soon as possible*

WIMP at high energy colliders

The WIMP is actually *two* particles

$$\begin{pmatrix} \chi^{\pm} \\ \chi^{0} \end{pmatrix}$$

Very similar to the W and Z are in a multiplet

$$\begin{pmatrix} W^{\pm} \\ Z^{0} \end{pmatrix}$$

This one is the dark matter

Conveniently, it turns out that the $\chi^{\pm}$ tends to be a bit heavier than χ^0

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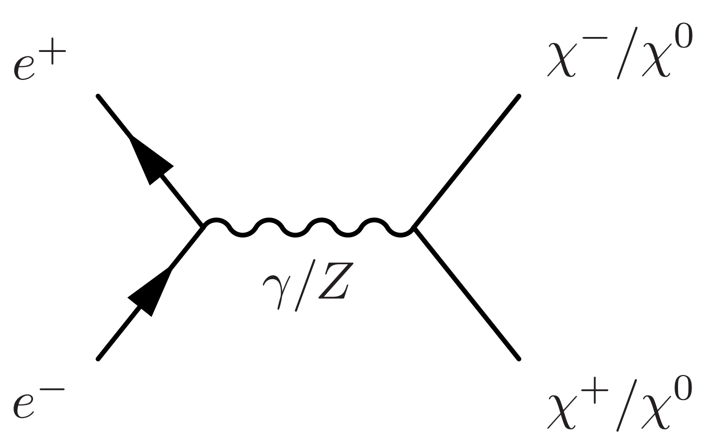
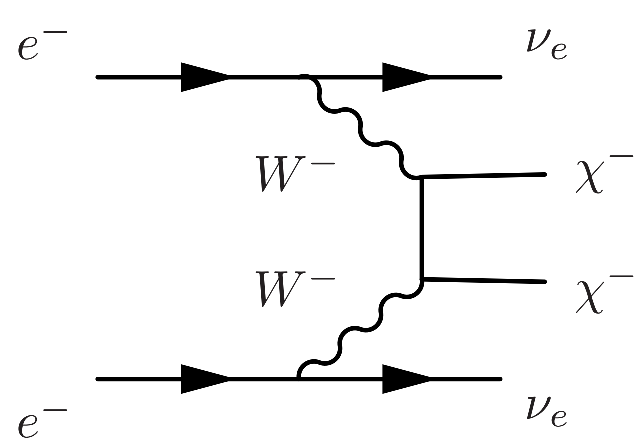
These particles must be produced in pairs, e.g.

Drell-Yann



WW fusion



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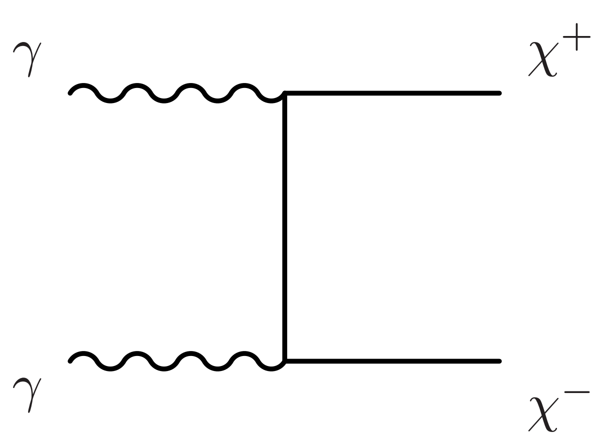


See So Chigusa's talk this afternoon

(See e.g. Tao Han et.al. 2009.11287 for muon collider study)

Back to wakefield colliders & design study

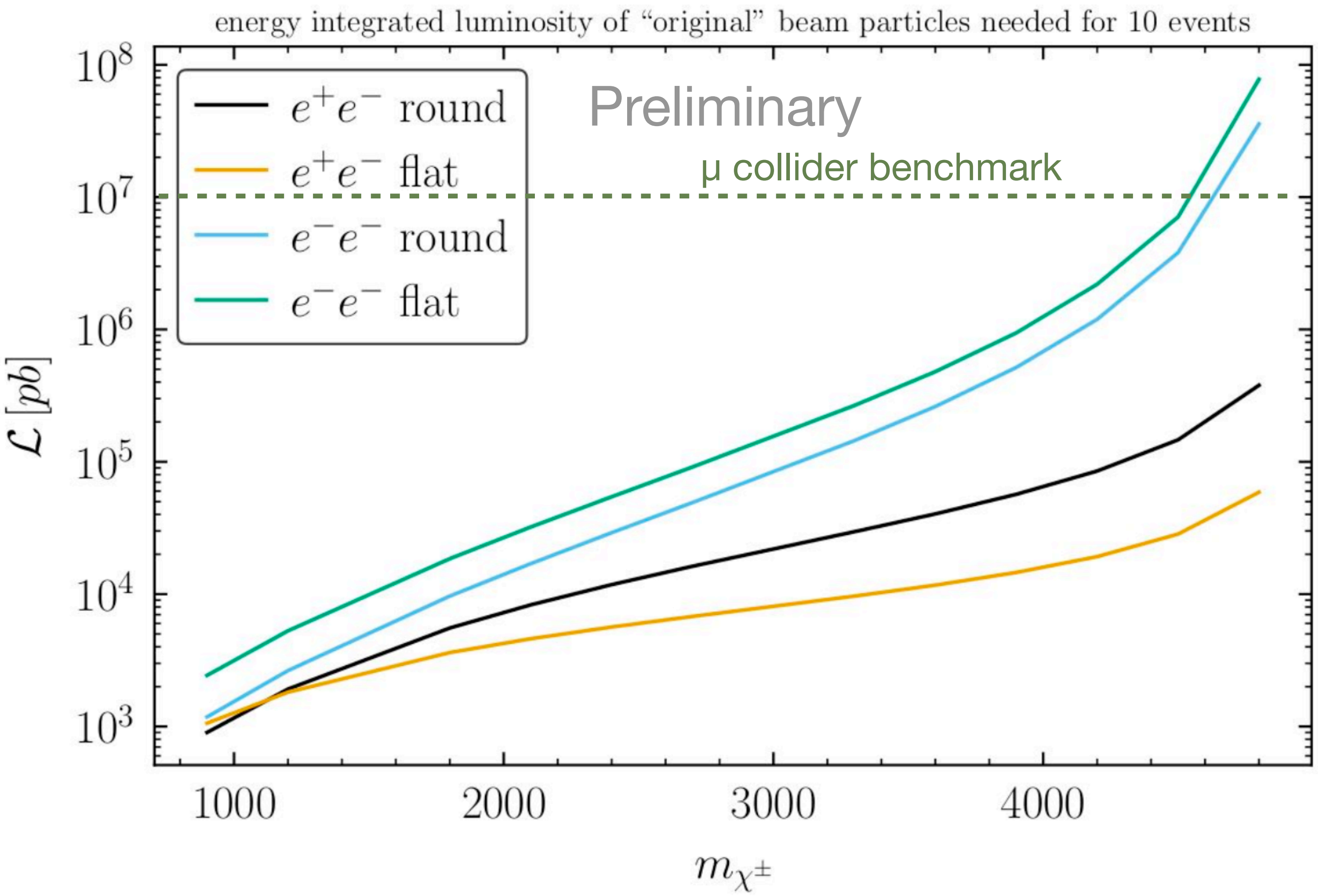
What do we know?

What open questions do we need to answer?

How much luminosity do we need ?

For electroweak particles the cross sections are fully predictable

But how many events are needed for a discovery?



L. Xu, T. Opferkuch, I. Savoray, C. Scherb, S. Chigusa, SK in progress

See So Chigusa's talk for more details

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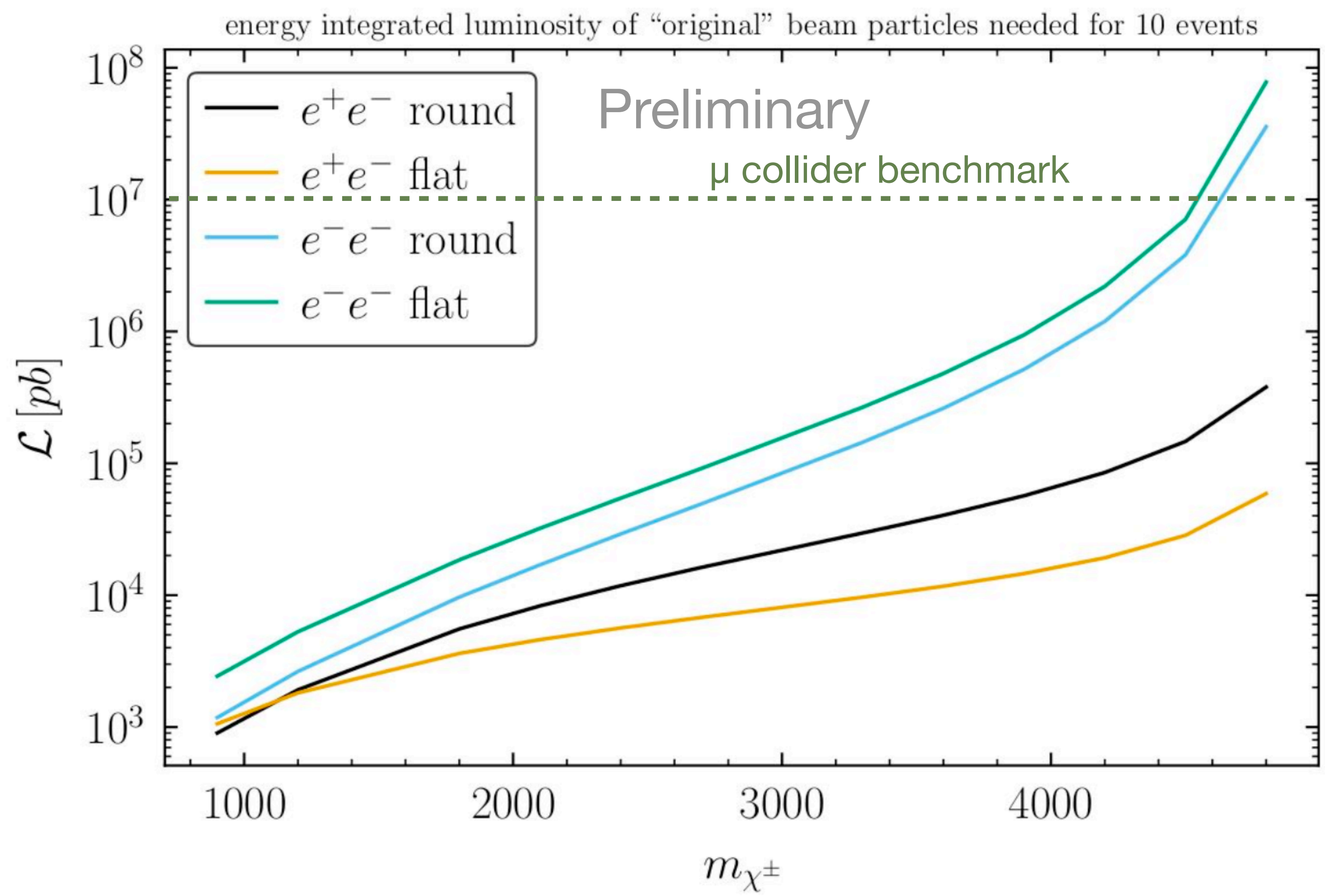
But how many events are needed for a discovery?

It depends…

- What is the detection efficiency?
- What are the backgrounds?



L. Xu, T. Opferkuch, I. Savoray, C. Scherb, S. Chigusa, SK in progress

See So Chigusa's talk for more details

The answers to these questions depend strongly on the model we consider

The best we can do is to consider a broad enough set of models and take some sort of envelope

e^+e^- or e^-e^- or $\gamma\gamma$?

It depends on what luminosity you think is achievable for each option

Some preliminary thoughts:

1. Drell-Yan is important when looking for heavy new particles
   but we can make use of secondary e^+ and γ in e^-e^- configurations

2. Standard Model production is mostly through Vector Boson Fusion (VBF)
   ZZ-fusion is substantially smaller than WW-fusion

3. $\gamma\gamma$ is more limited
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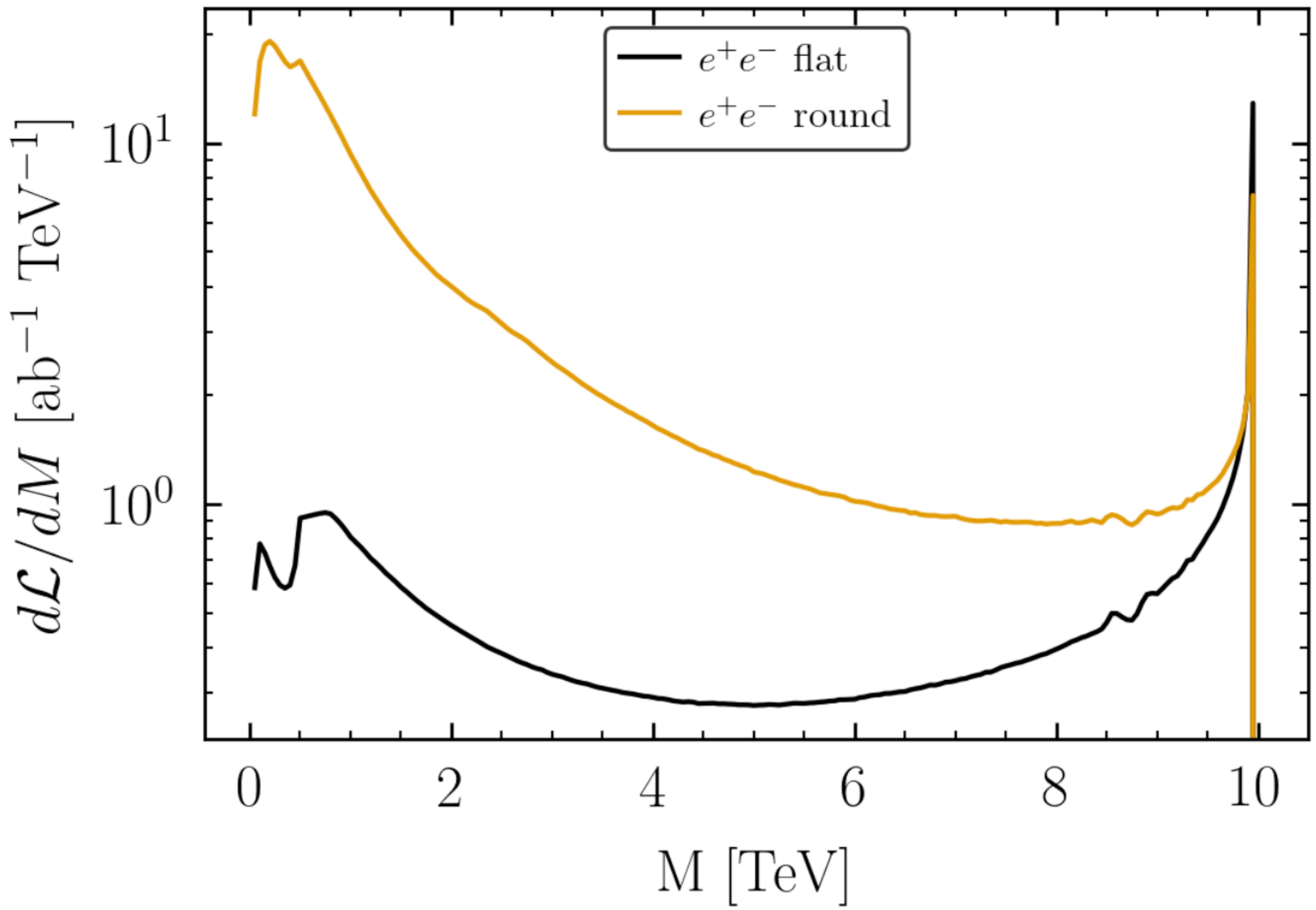
This answer is also model-dependent, and dependent on the achievable luminosity

We will calculate the luminosities need for discovery for a class of example models that is as broad as possible *(subject to person-power availability)*

Round or flat beams?

How “useful” is beam strahlung?



Adapted from A. Fromenti, S. S. Bulanov, A. Huebl, R. Lehe, J. Osterhoff, C. Schroeder, J.L. Vay (in progress) with WarpX simulation code

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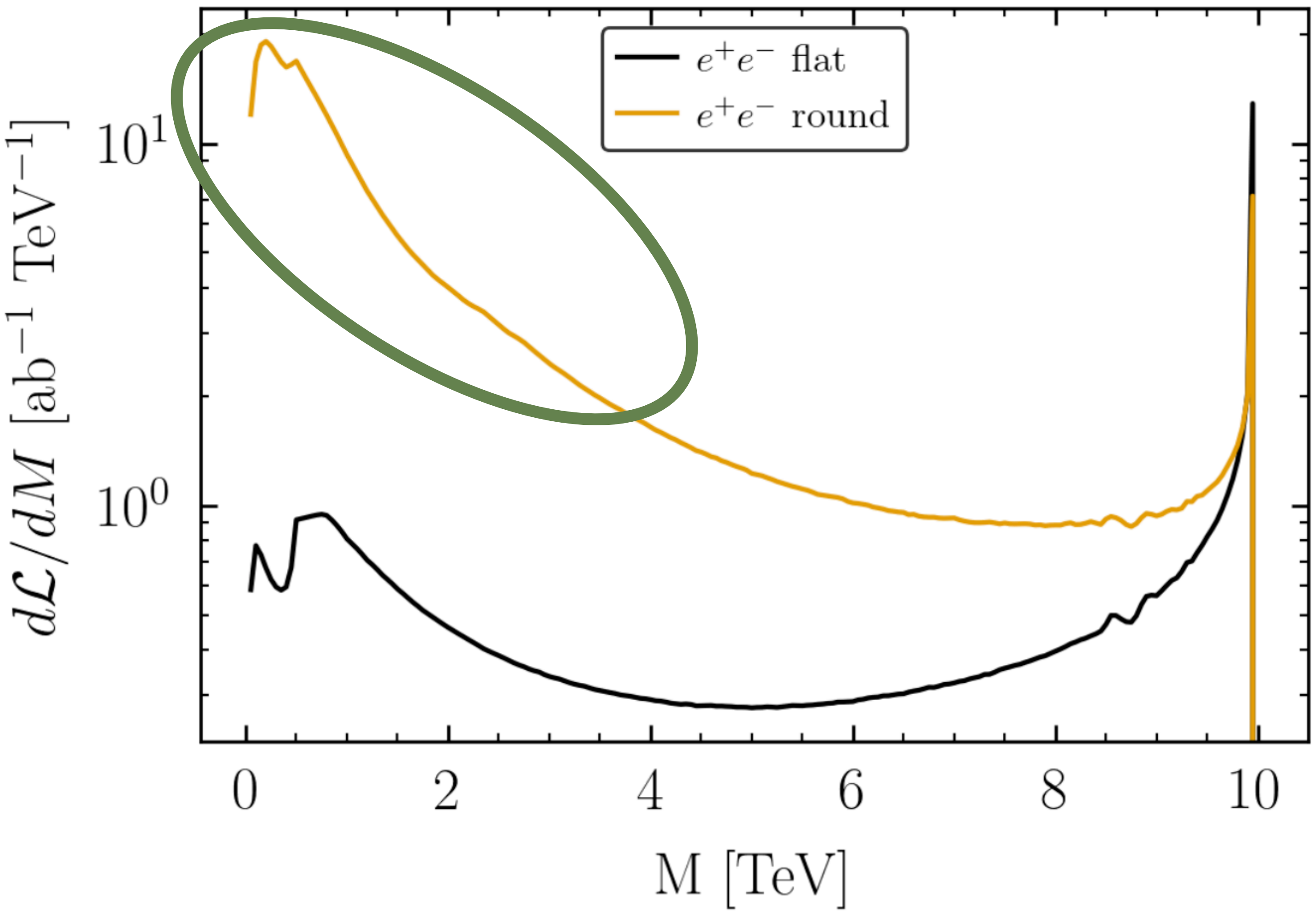
- VBF only grows ~ log(M)



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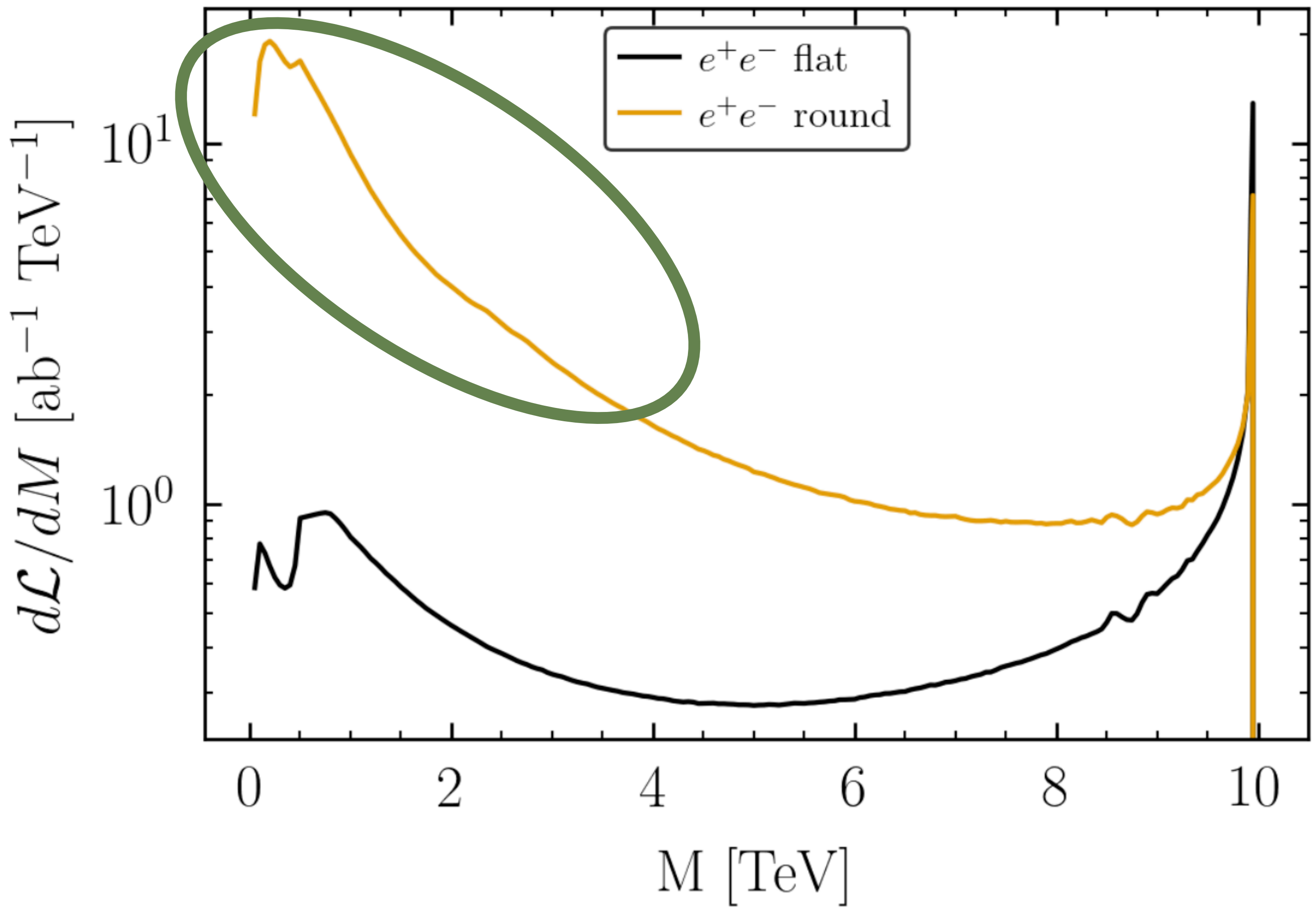
For Standard Model processes and ~ TeV scale new particles, the low energy tail can dominate

Especially for e^-e^- beams secondary e^+ and γ are important



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With your help, we can quantify the importance of these effects

Conclusion

I believe the future of particle physics hinges on whether we can build a multi-TeV collider

We will help where we can