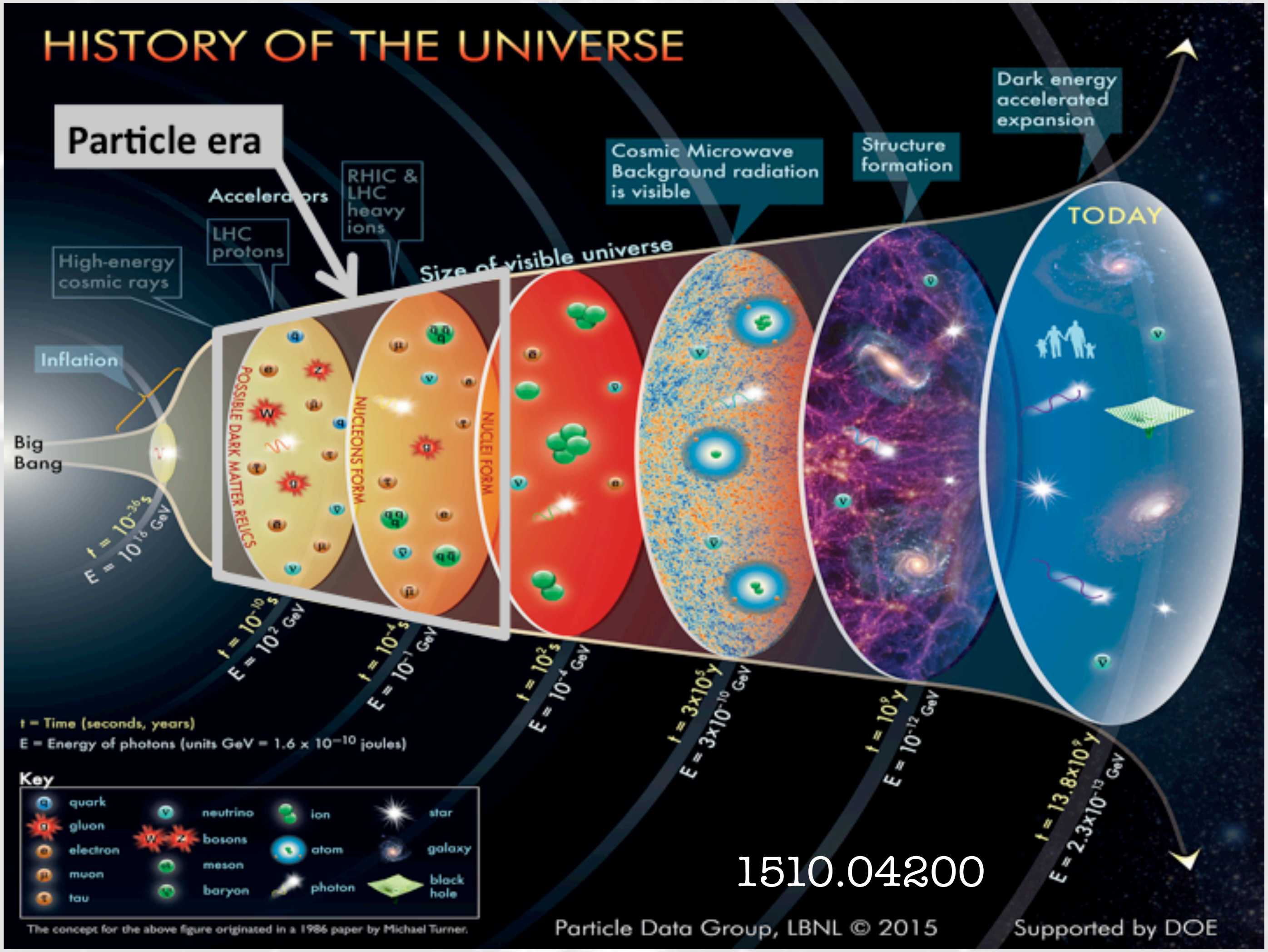
LLPs

UK HEP Forum 2020

Matthew McCullough

Comment: A Cosmological Bridge

We are all familiar with diagrams like this:



With an important message for particle physics…

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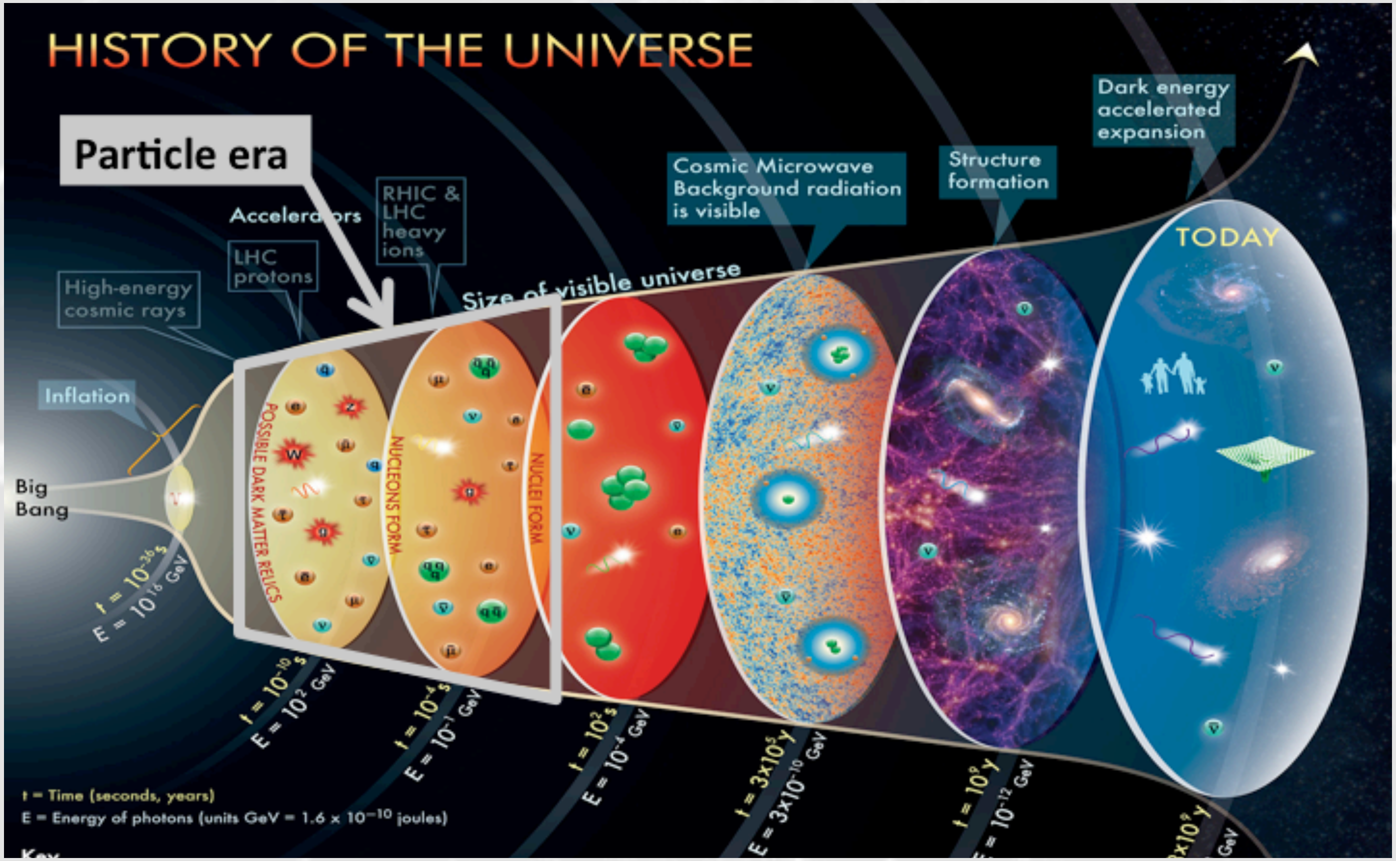

Particles with this lifetime are our responsibility.

BBN and CMB greatly constrain this region.

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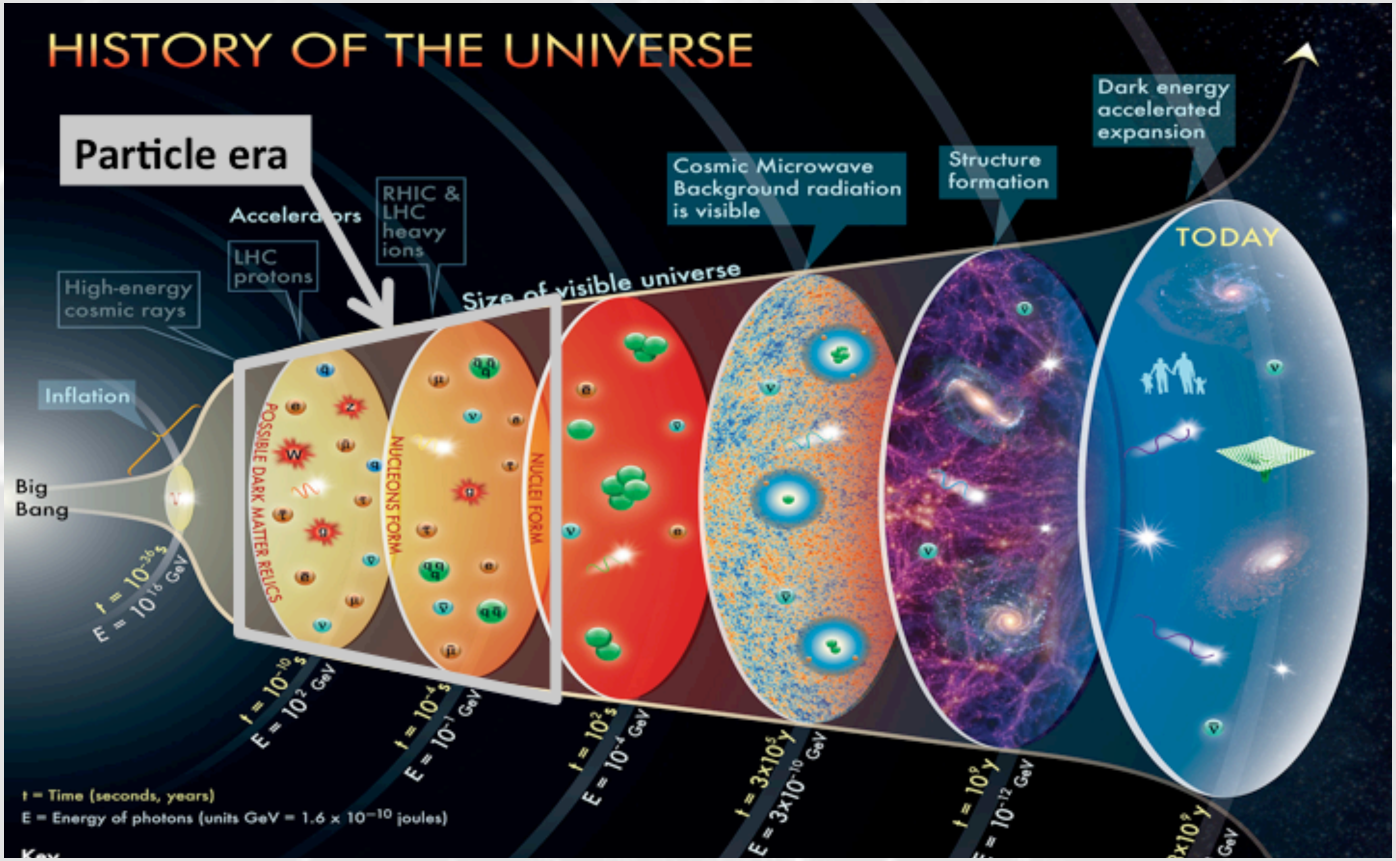

We should consider this a lifetime target for our field:

$$c\tau \sim 10^7 - 10^8 m$$

For a particle to be long-lived it must have a very weak coupling, or a small phase space. Consider former.

What is a weak coupling?

On Couplings

Dimensional analysis unambiguously determines what a “coupling” is. Seen by reinserting ħ into action.

$$\mathcal{L}_{\hbar \neq 1}$$

In terms of these dimensionful quantities:

$$[\hbar] = EL \ , \quad [\mathcal{L}] = EL^{-3} \ , \quad [\phi] = [A_\mu] = E^{1/2}L^{-1/2} \ , \quad [\psi] = E^{1/2}L^{-1}$$

$$[\partial] = [\tilde{m}] = L^{-1} \ , \quad [g] = [y] = E^{-1/2}L^{-1/2} \ , \quad [\lambda] = E^{-1}L^{-1}$$

we see that couplings carry a label.

On Couplings

Studying the following assignments:

$$[\hbar] = EL\ , \quad [\mathcal{L}] = EL^{-3}\ , \quad [\phi] = [A_\mu] = E^{1/2}L^{-1/2}\ , \quad [\psi] = E^{1/2}L^{-1}$$

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Then if we have <u>any</u> parameter κ with dimensions of coupling then the quantity:

$$\hbar\kappa^2$$

is dimensionless. As a result, if

$$\hbar\kappa^2 \ll 1$$

then we have a weak coupling.

Nature 😍 Weak Couplings

Electron Yukawa

Interaction: $\mathcal{L} = \lambda_e h \bar{e} e$

Dimension: $[\lambda_e]$ ← Coupling

For example, the scalar force mediated by the Higgs:

$$\hbar \lambda_e^2 \approx 10^{-11}$$

is extremely weak.

Nature 😍 Weak Couplings

Fermi Scale

Interaction: $\mathcal{L} \sim \frac{\psi^4}{\Lambda^2}$

UV-completion

Dimension: $[\Lambda] = [G_F^{-1/2}] = \frac{[M_W]}{[g]}$

Coupling

For example, for muon decays we have

$$\hbar G_F m_\mu^2 \approx 10^{-7}$$

and the muon is long-lived due to a tiny coupling (standard coupling times small mass-ratio).

We know there is a lot we don't know, but nature has clearly demonstrated an affinity for weak couplings...

We should avoid excessive theoretical hubris and explore all frontiers, including the weakest of couplings.

Organizing the Unknown

Some quantum operator $\mathcal{O}^{\mu\nu..}$ Contains the hidden sector fields. Interaction with SM is of the form

$$\mathcal{L}_{\text{Int}} = \frac{1}{\Lambda^{D_{\mathcal{O}}+D_{\mathcal{O}}^{\text{SM}}-4}} \mathcal{O}^{\mu\nu..} \mathcal{O}^{\text{SM}}_{\mu\nu..}$$

The lower the 'dimension' of the interaction, the more relevant it will remain at low energies, since amplitudes will scale as

$$\mathcal{M} \propto \left(\frac{E}{\Lambda}\right)^{D_{\mathcal{O}}+D_{\mathcal{O}}^{\text{SM}}-4}$$

This enables us to isolate promising targets.

Kinetic Mixing

If the hidden sector contains a light neutral vector $\mathcal{O}_{\mu\nu} = F'_{\mu\nu}$, then we have

$$\mathcal{L}_{\text{Int}} = -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

which also remains relevant at all energies.

Motivation: Nothing prevents new force carriers from being light. To explore possibility of new forces, this is the obvious place to look!

$$\hbar\epsilon^2 e^2 \ll 1$$

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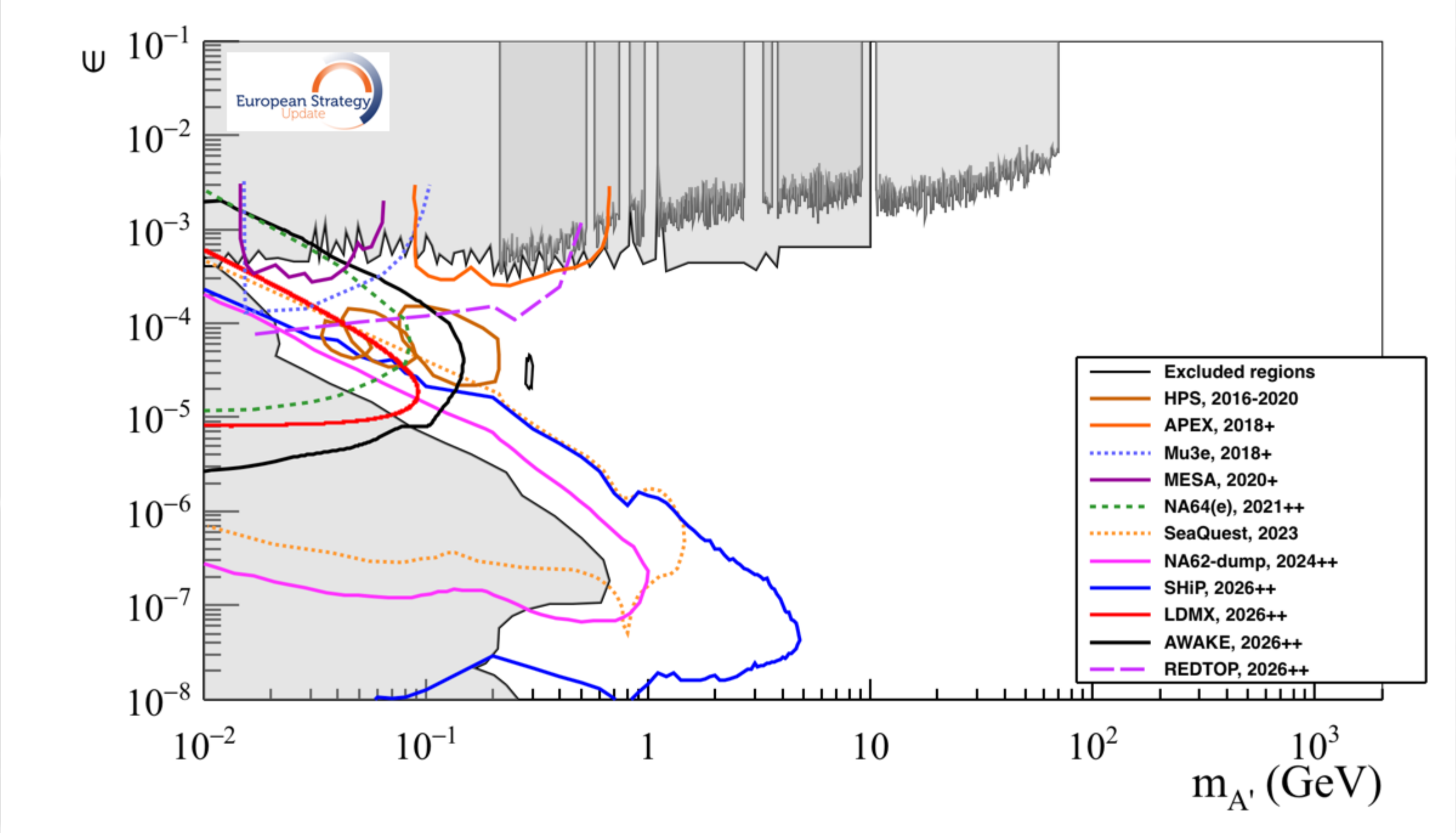

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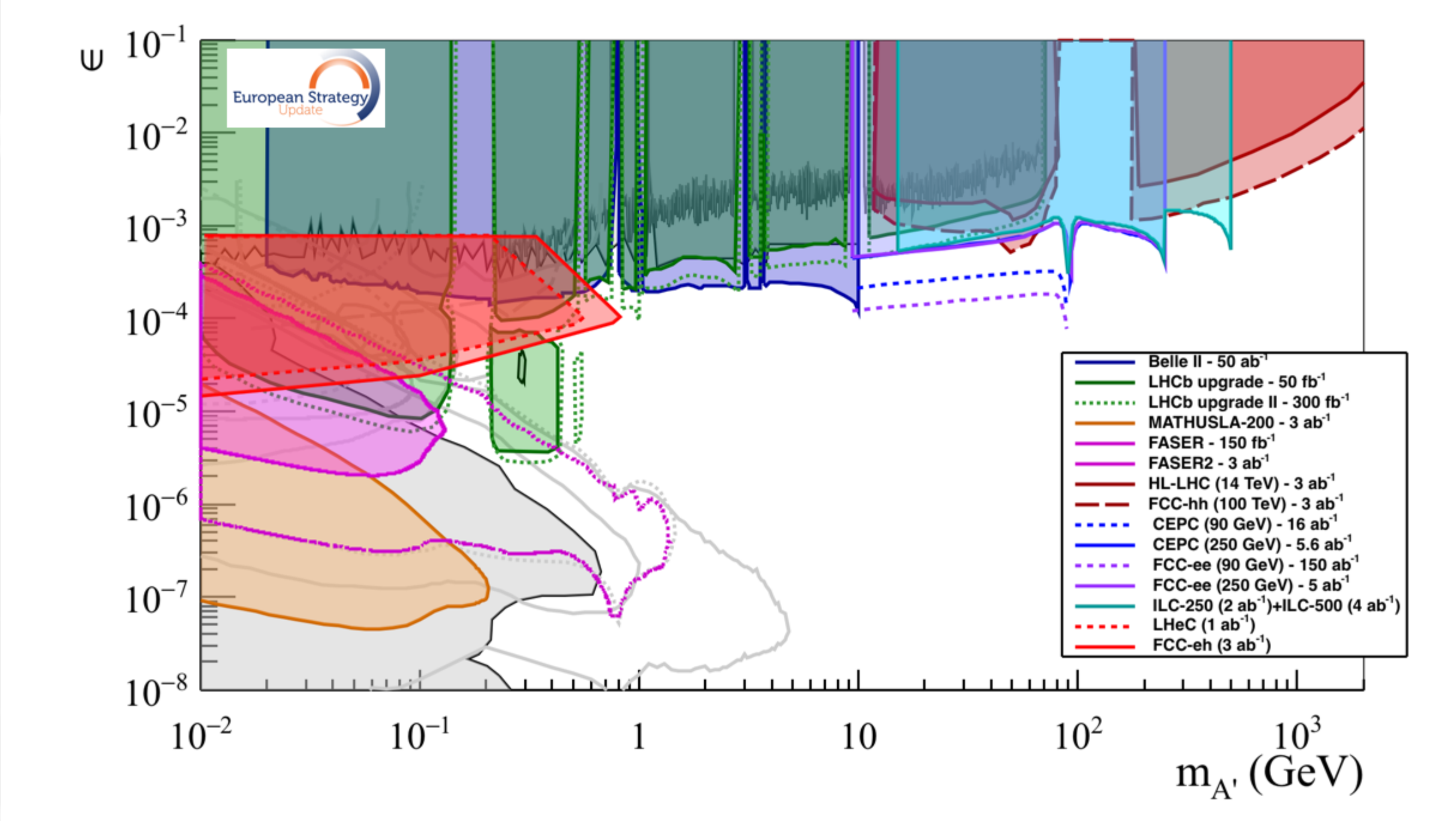

Sterile Fermions

If the hidden sector contains a gauge-neutral spin-1/2 operator $\mathcal{O}_\alpha = N_\alpha$, then we have

$$\mathcal{L}_{\text{Int}} = yNLH$$

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Motivation: Could explain the origin of matter-antimatter asymmetry, could explain microscopic origin of neutrino masses, etc...

$$\hbar y^2 \ll 1$$

Sterile Fermions

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These states can have big mixing angles with SM neutrinos:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Int}} + \mathcal{L}^{L}_{\text{Mass}} + \mathcal{L}^{\not{L}}_{\text{Mass}}$$

Generates large mixing with SM neutrinos

Generates SM neutrino masses.

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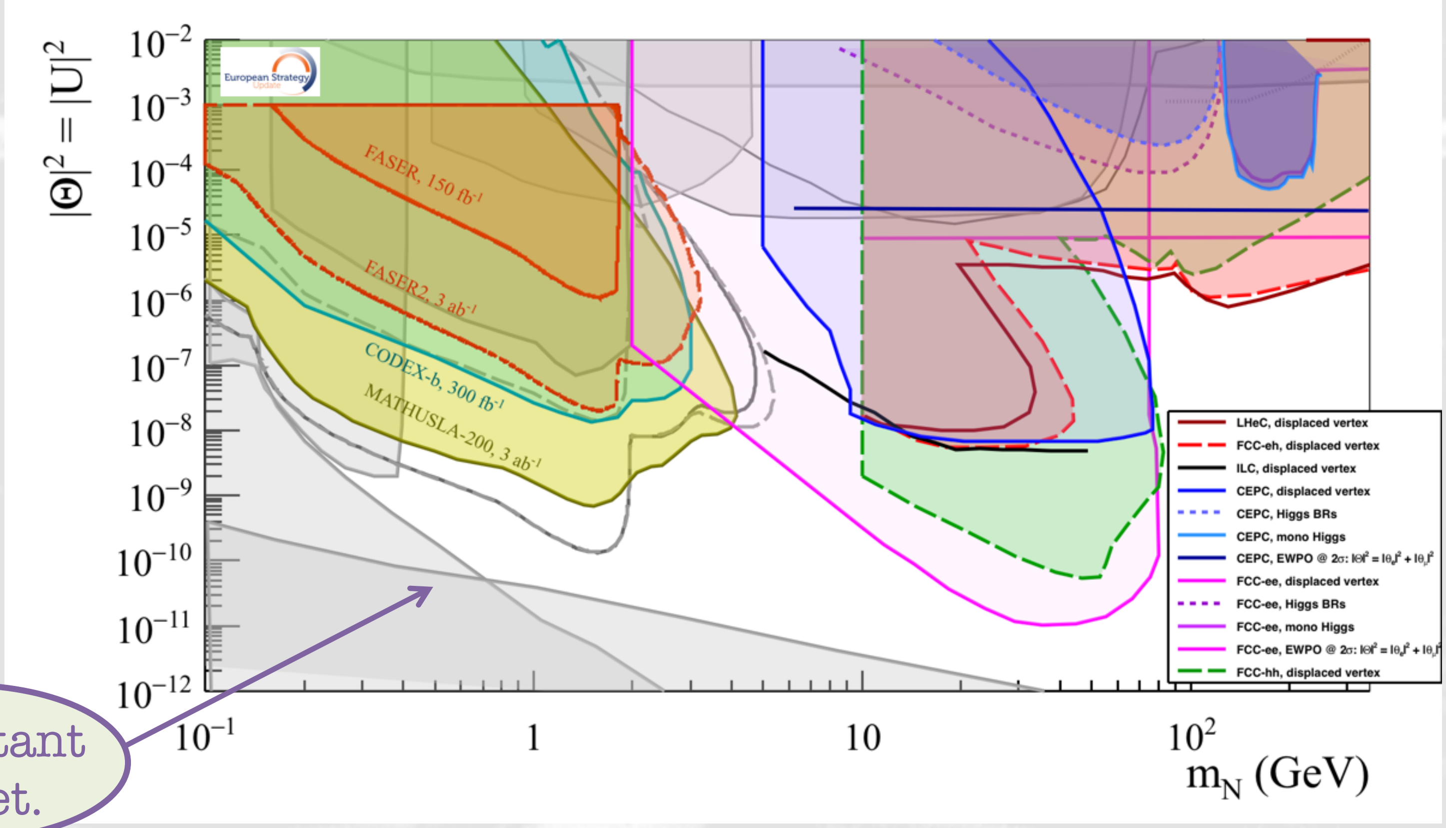


Important target.

Higgs Portal

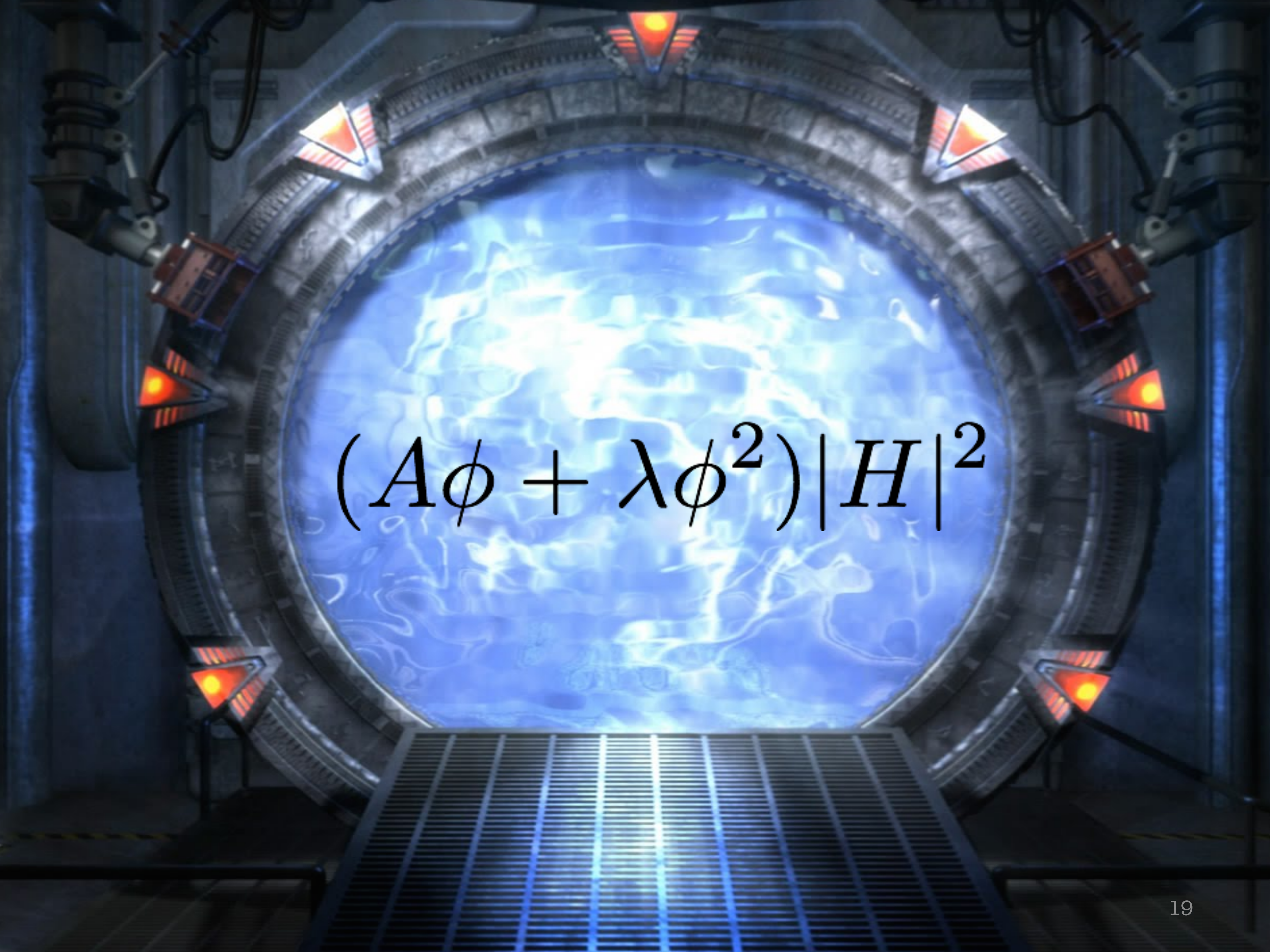
If the hidden sector contains a gauge-neutral spin-0 operator $\mathcal{O} = A\phi,\ \ \lambda\phi^2$, then we have

$$\mathcal{L}_{\mathrm{Int}} = (A\phi + \lambda\phi^2)|H|^2$$

which also remains relevant at all energies.

Motivation: Could explain the origin of matter-antimatter asymmetry, relate to dark sector, etc...

$$\hbar A^2/m_h^2\ ,\ \ \hbar\lambda \ll 1$$



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1905.03764

kappa-3 scenario	HL-LHC+ ILC$_{250}$	ILC$_{500}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
BR$_{\rm inv}$ ($<$%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024

For no mixing, one can get a glimpse into the hidden sector through invisible decays.

Incredibly effective probes possible.

Higgs Portal

If the hidden sector contains a gauge-neutral spin-0 operator $\mathcal{O} = A\phi,\ \lambda\phi^2$, then we have

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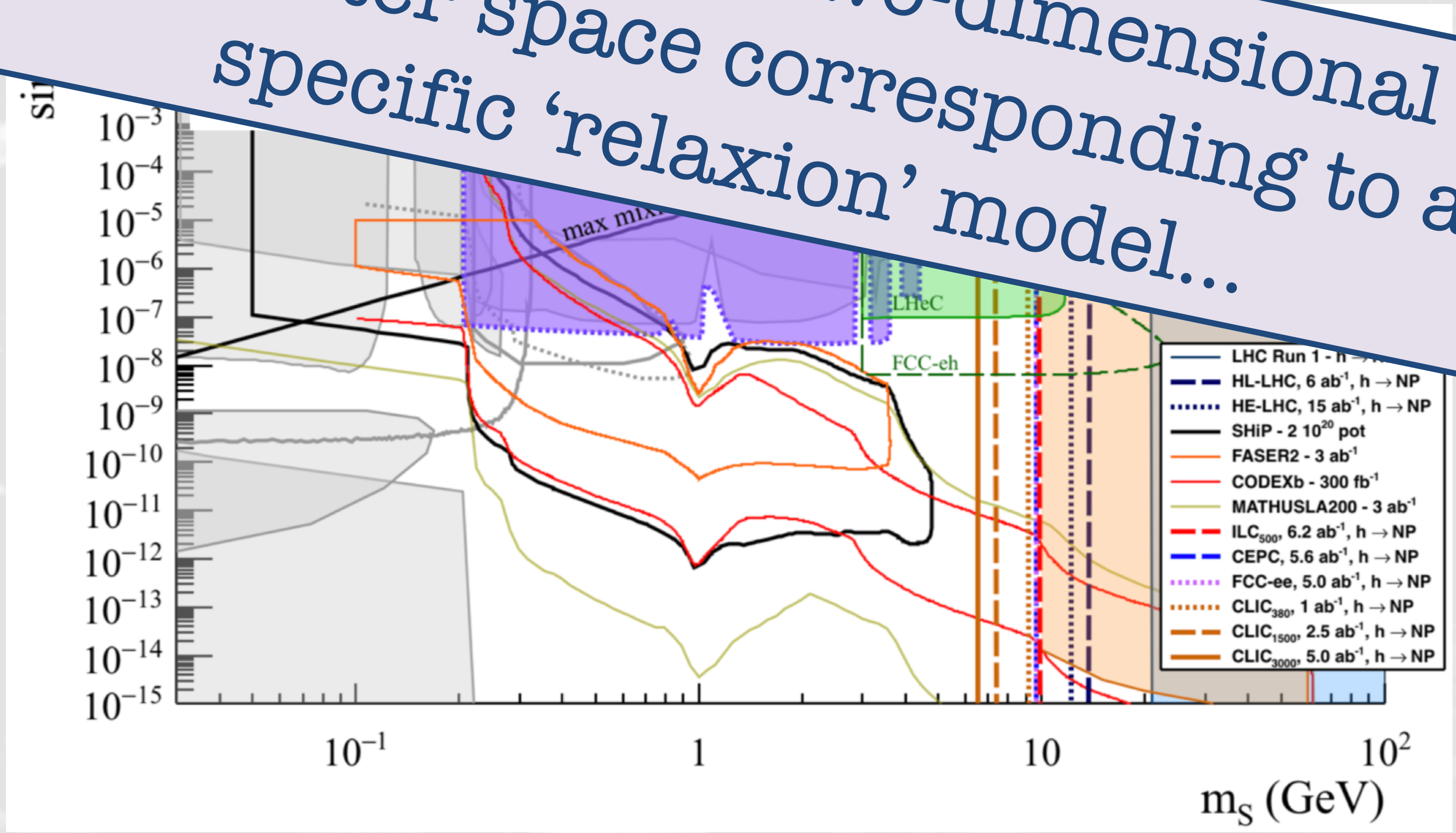
wh ... energies.

Collapsing into a two-dimensional parameter space corresponding to a specific 'relaxion' model...



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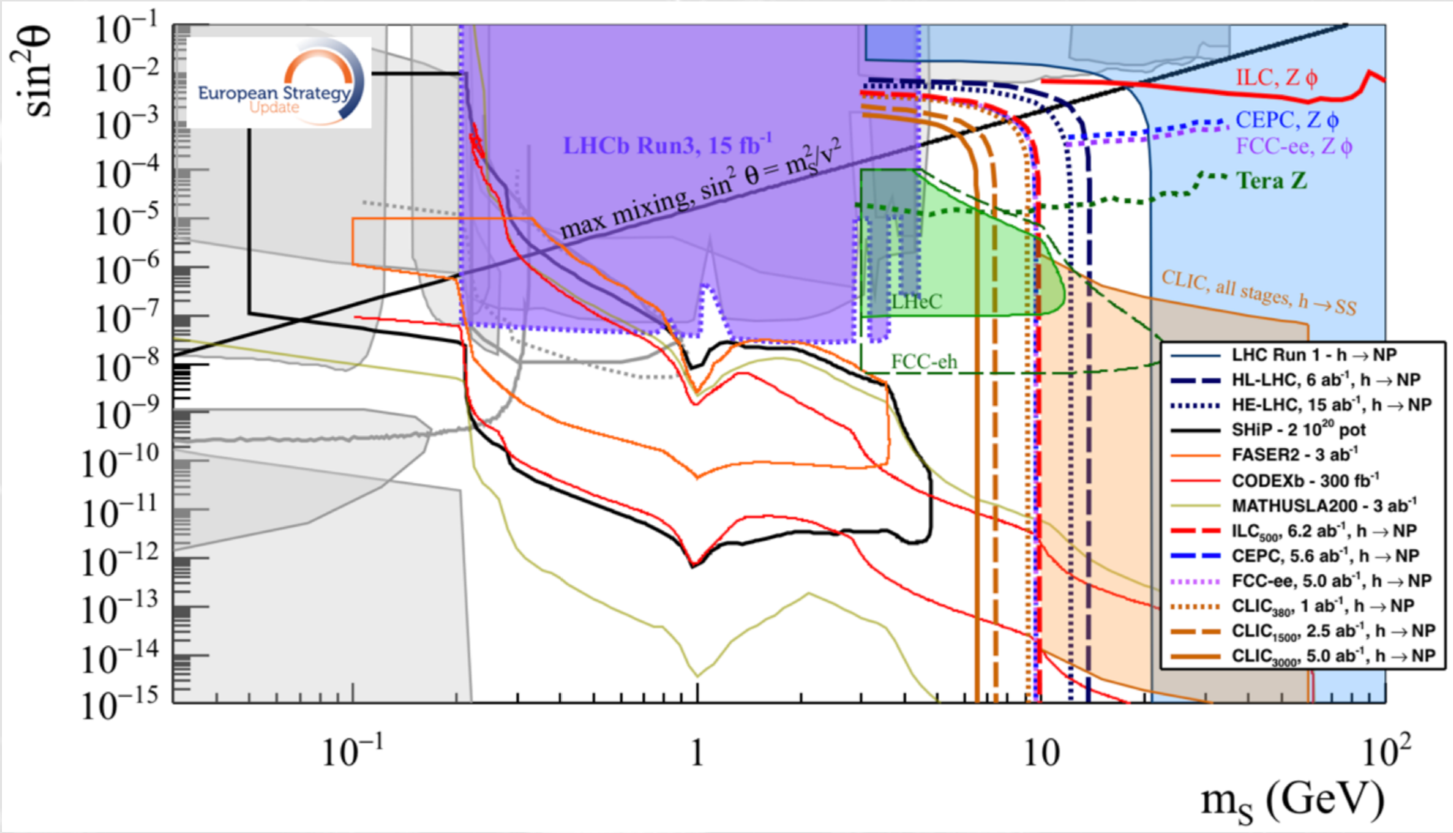
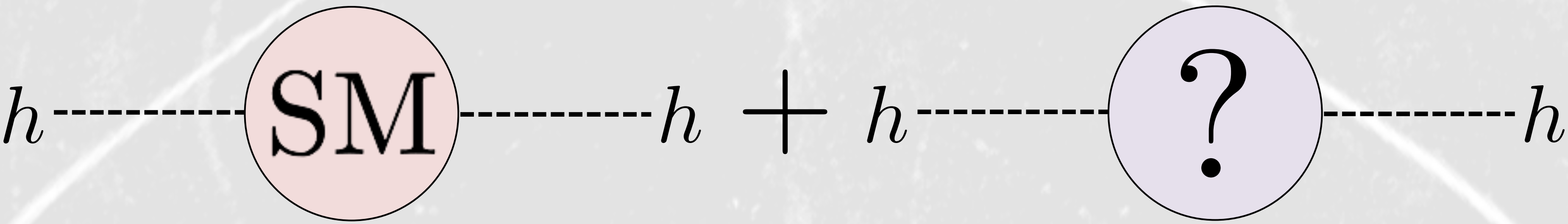


A UV Perspective on the Higgs Portal

Neutral Naturalness

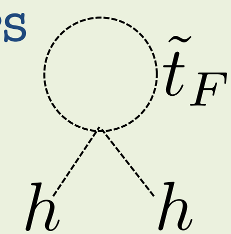
Could there be totally hidden states which tame sensitivity to physics at the cutoff?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners



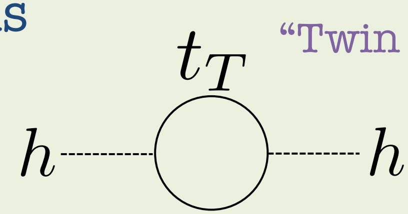
"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions

"Twin Tops"

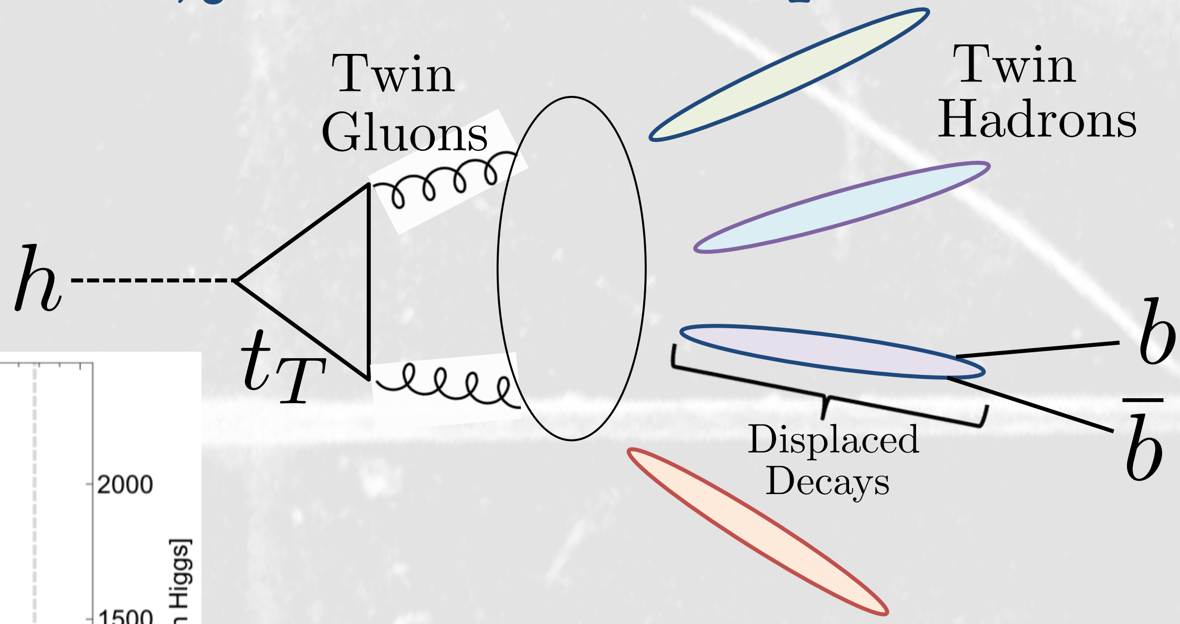


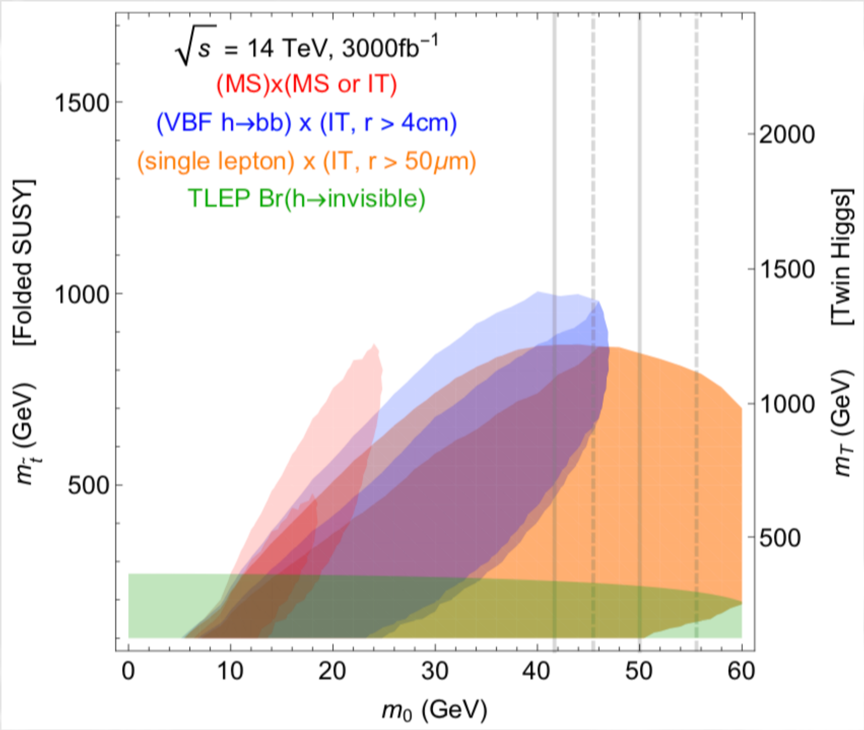
...but they must be charged under new hidden QCD'.

Neutral Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:





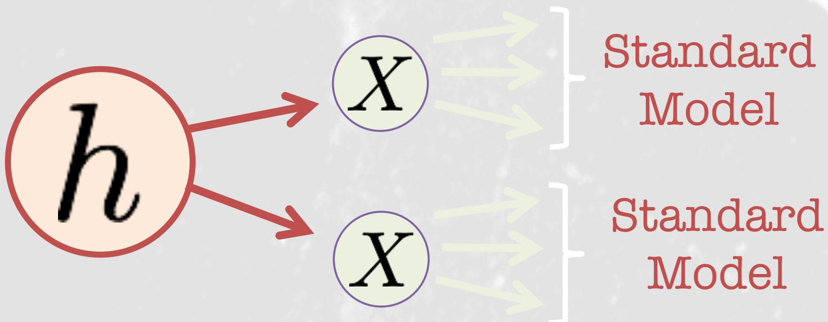
Comment: On Energy

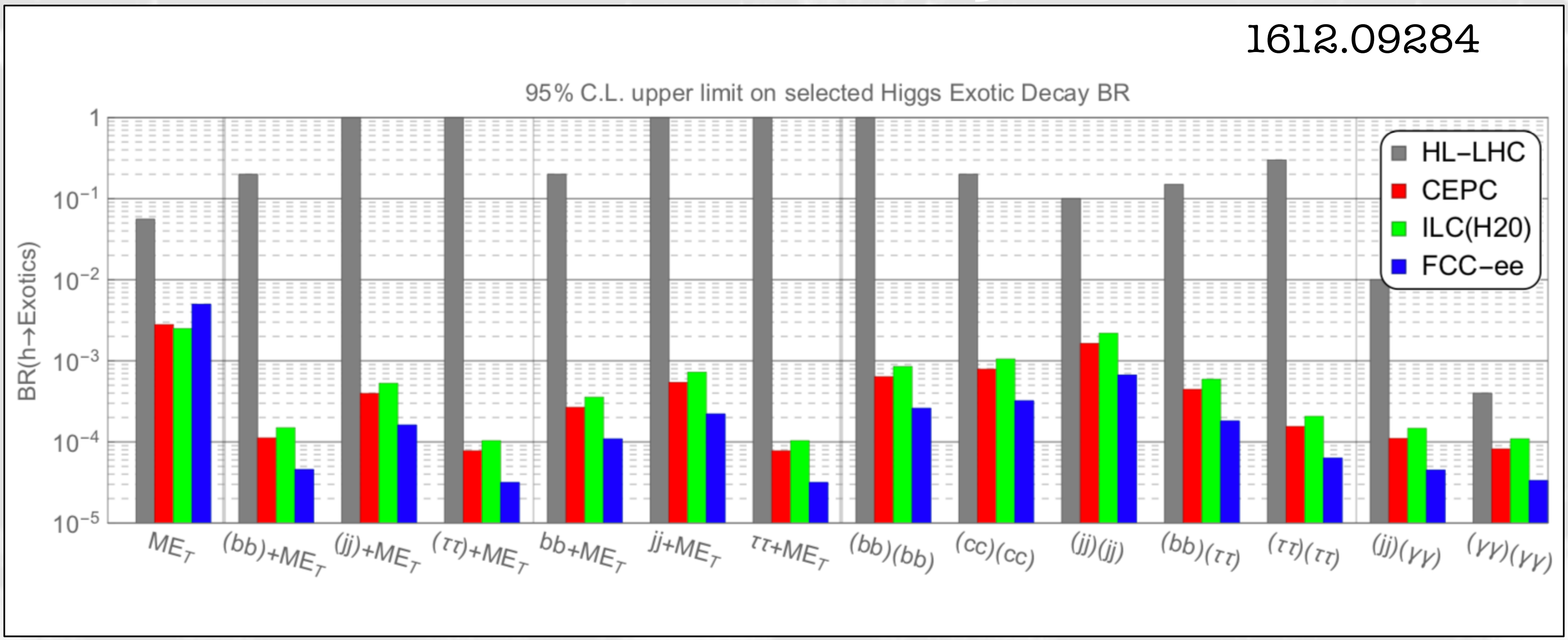
It is tempting to associate the weakly coupled frontier with the low mass range. Why?

Case study: The Higgs boson is the most mysterious particle in nature. If it has rare decays then the only shot at discovering them is through Higgs boson decays.

Higgs

The Higgs is totally different from other particles and could be our new window to the dark sector:





Higgs

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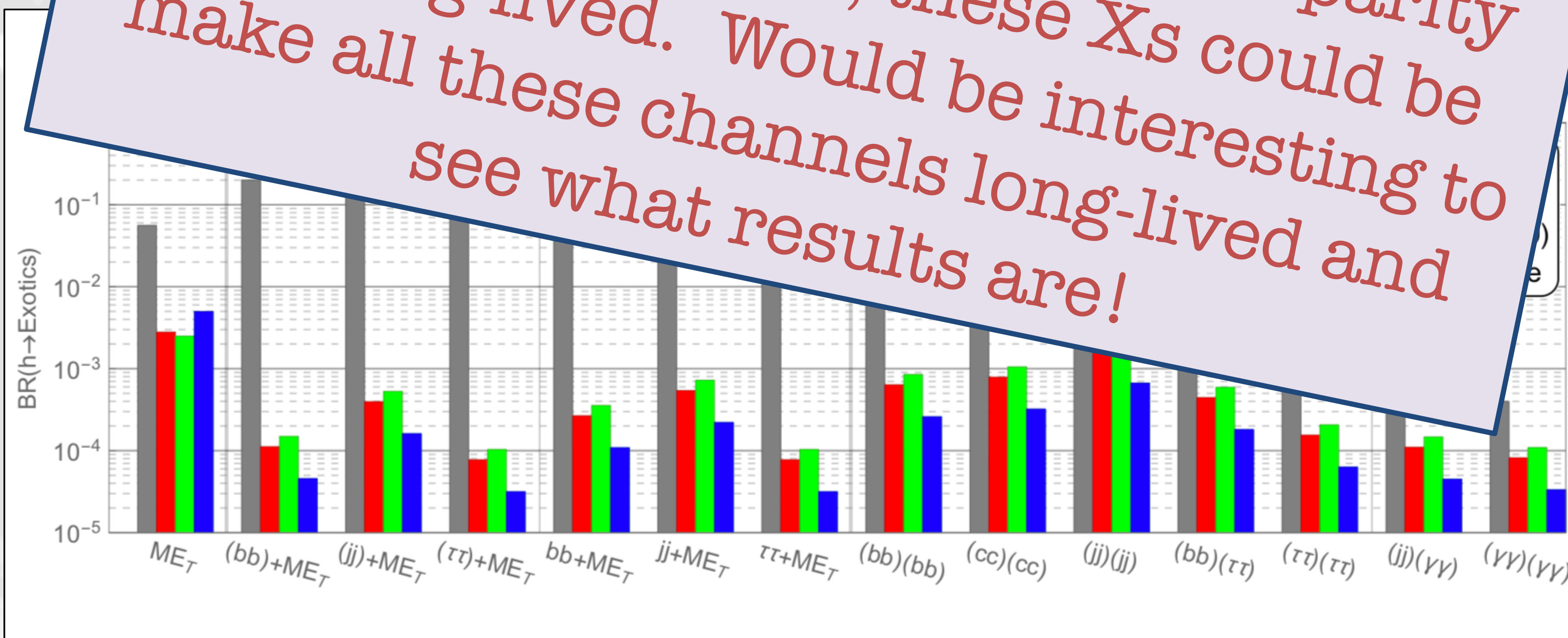
Since the Higgs decay respects a parity symmetry for the X, these Xs could be easily long-lived. Would be interesting to make all these channels long-lived and see what results are!



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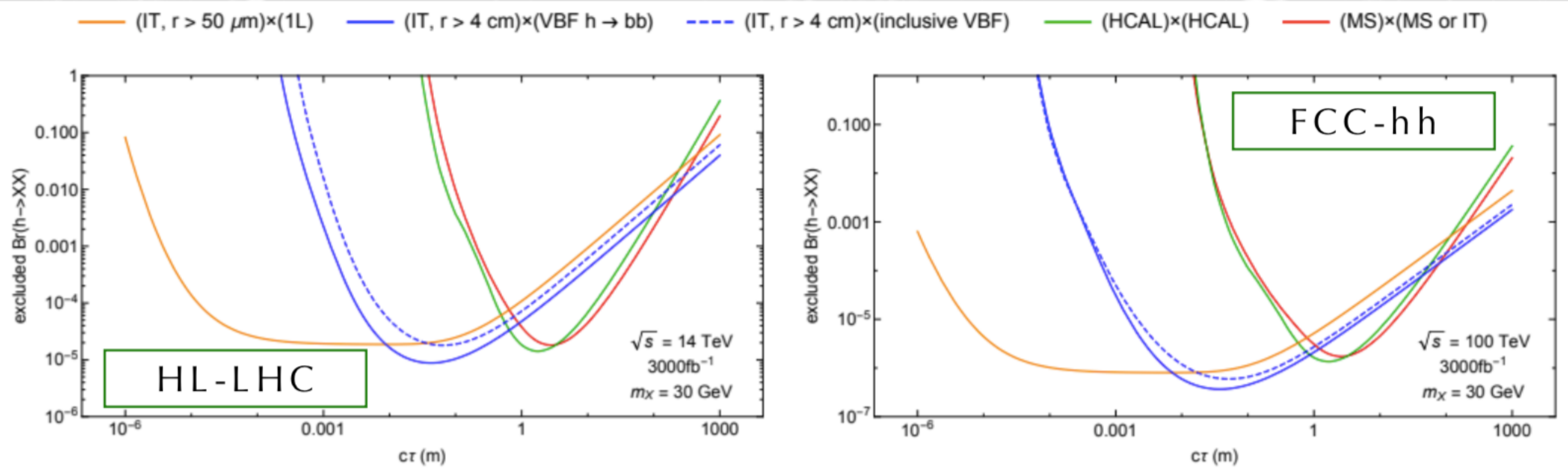

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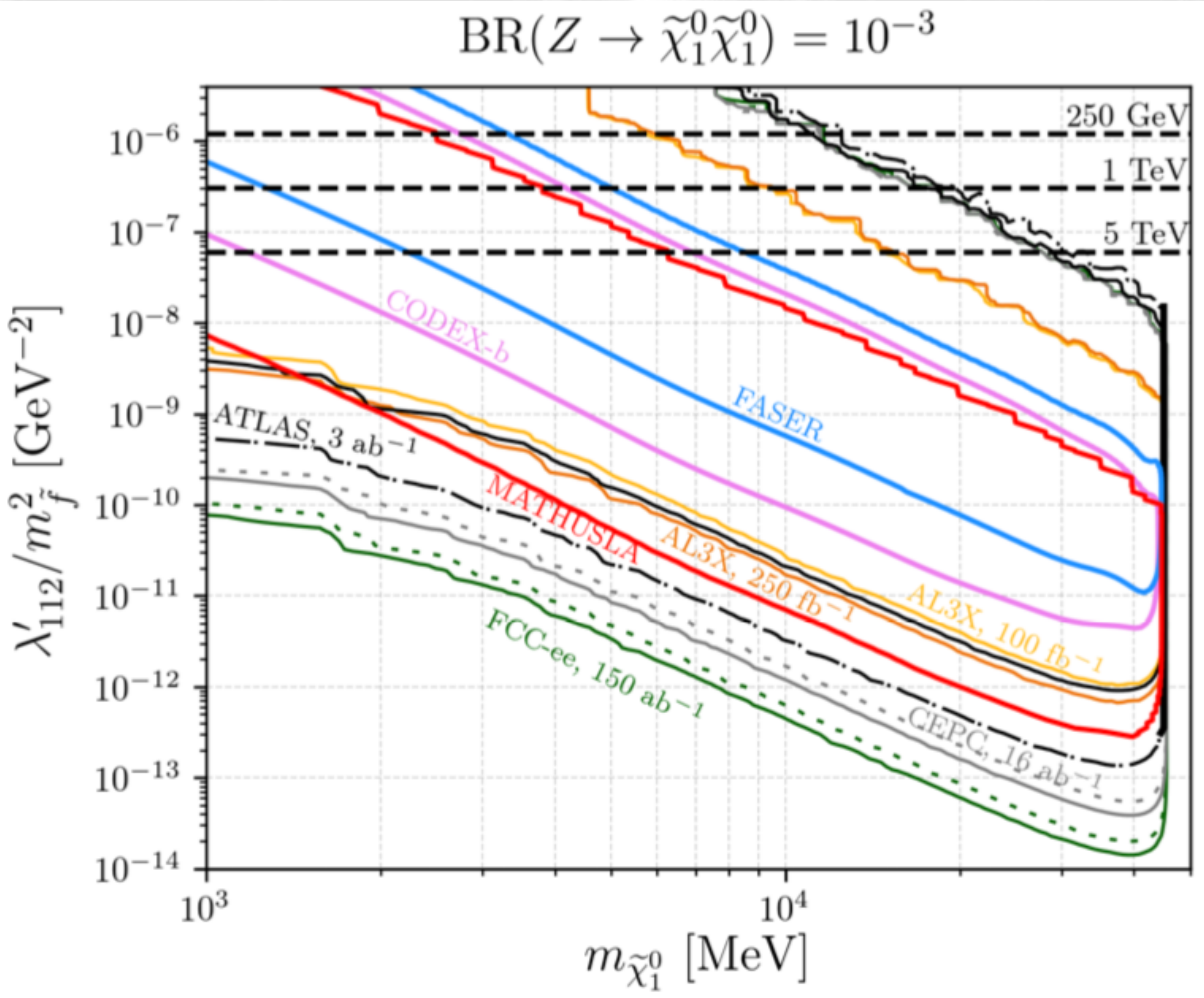
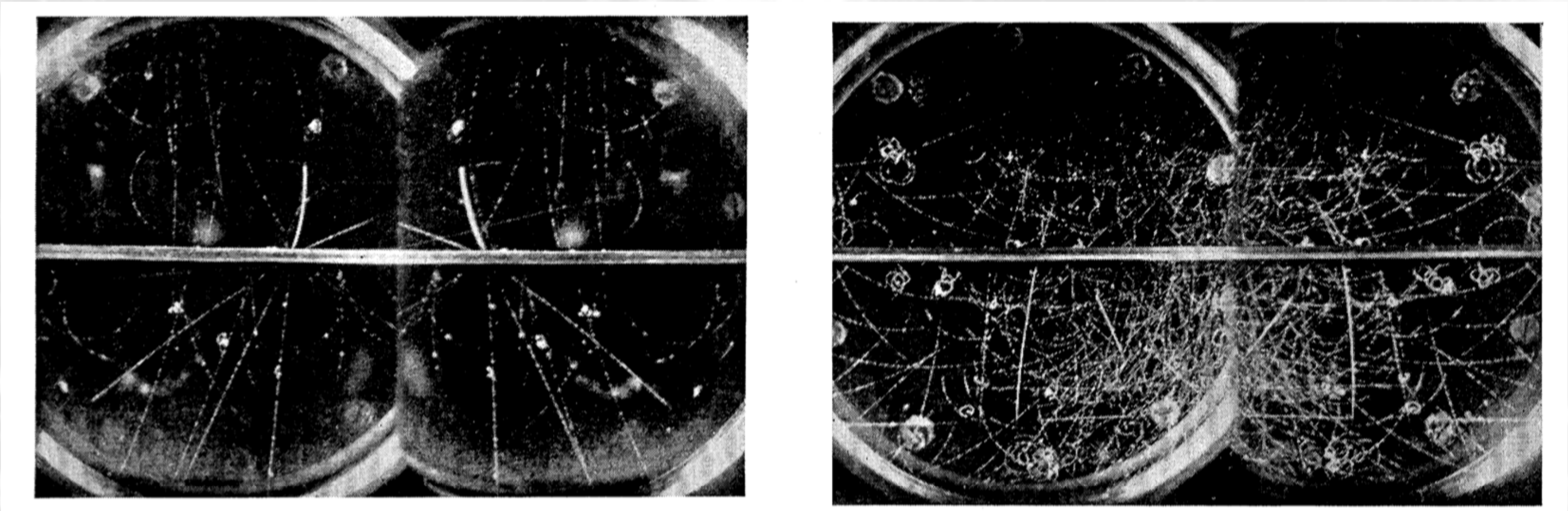
Last but not least… SUSY (ish)

1904.10661 - Neutralinos



The Punchline



Who recognises this?

The Punchline

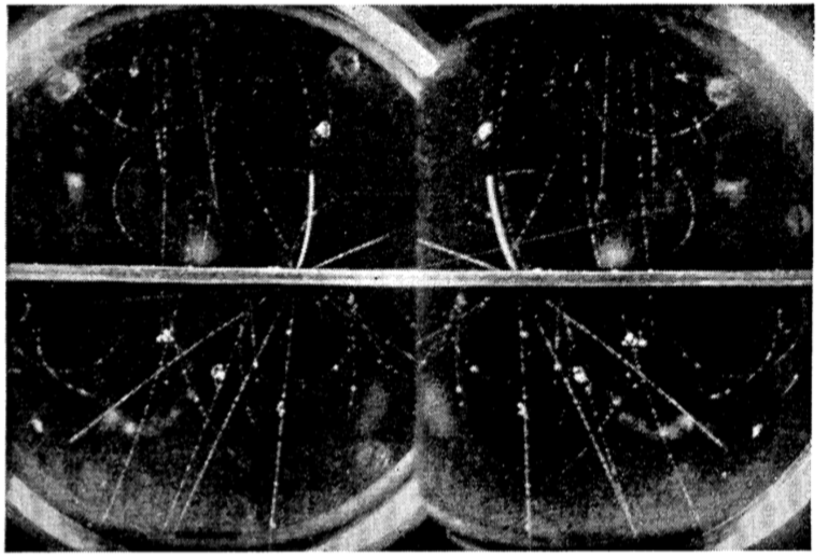


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to estimate to what extent scattering may have modified the curvature in this case. The particle is therefore tentatively interpreted as a proton. The other particle ejected upward to the right may be either an electron or a fast proton. The four particles ejected downward are positively charged and do not ionize sufficiently strongly to represent protons of the curvatures shown. If they are positrons their

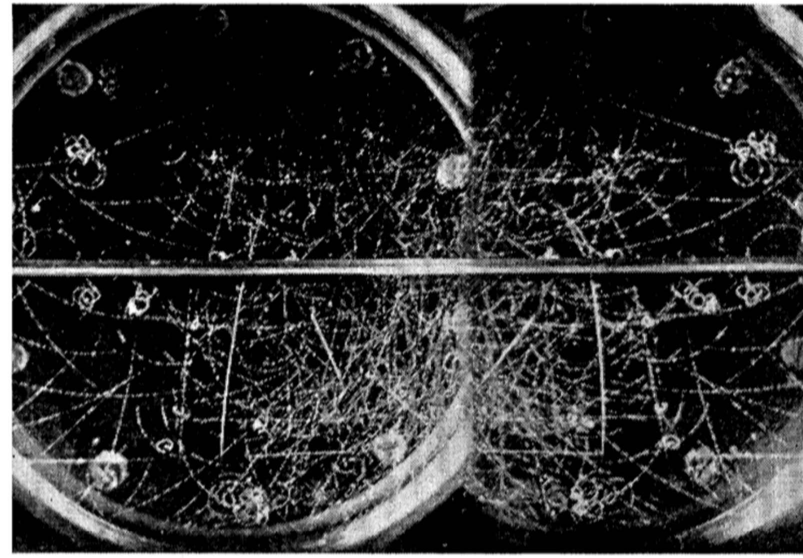


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

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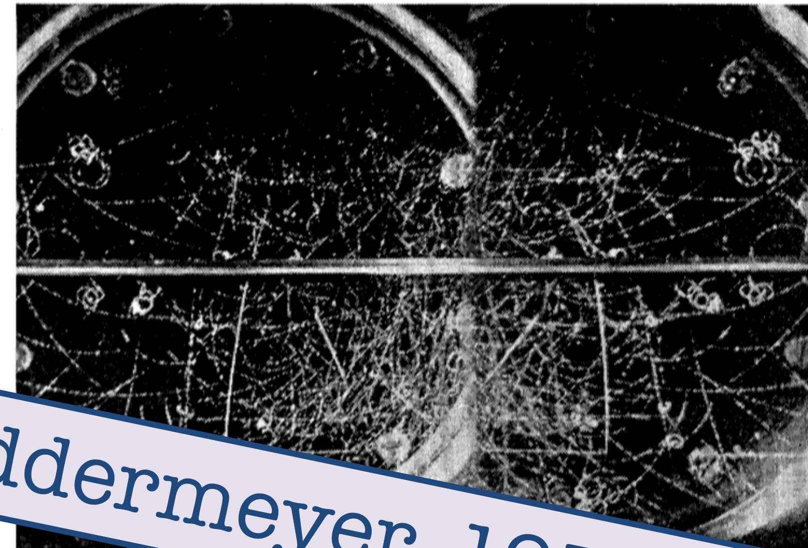

Anderson and Neddermeyer, 1936.

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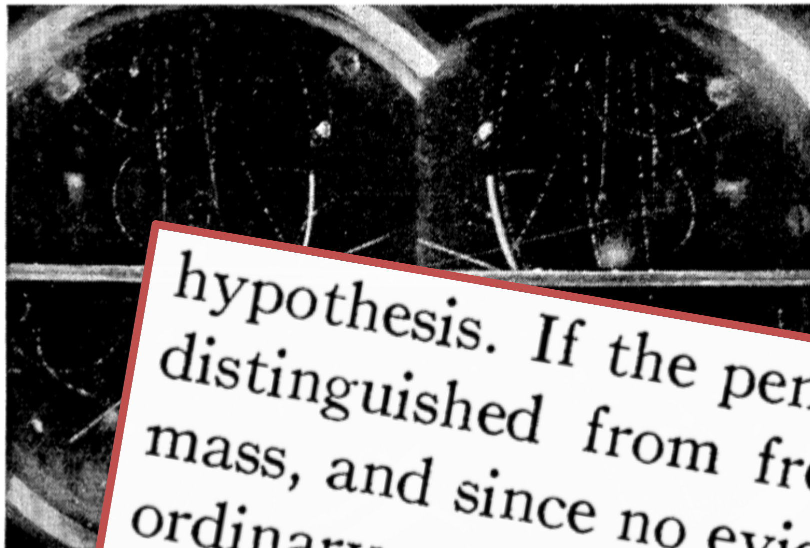

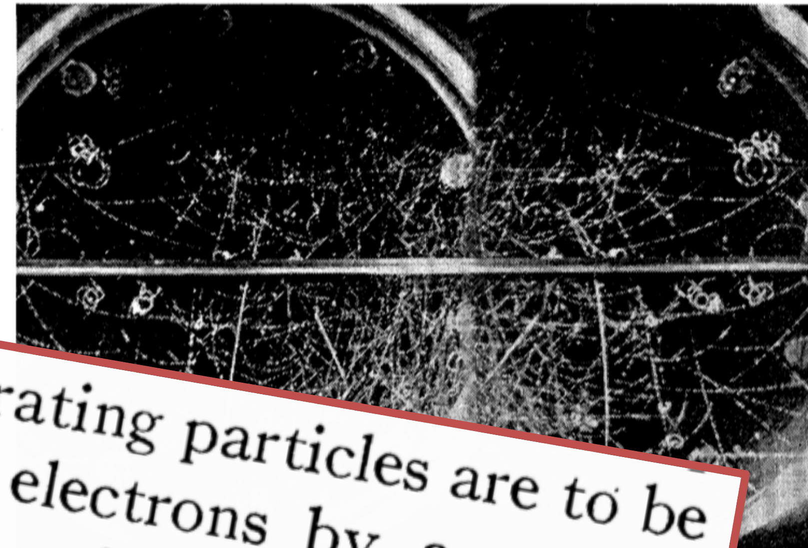

hypothesis. If the penetrating particles are to be distinguished from free electrons by a greater mass, and since no evidence for their existence in ordinary matter obtains, it seems likely that there must exist some very effective process for removing them.

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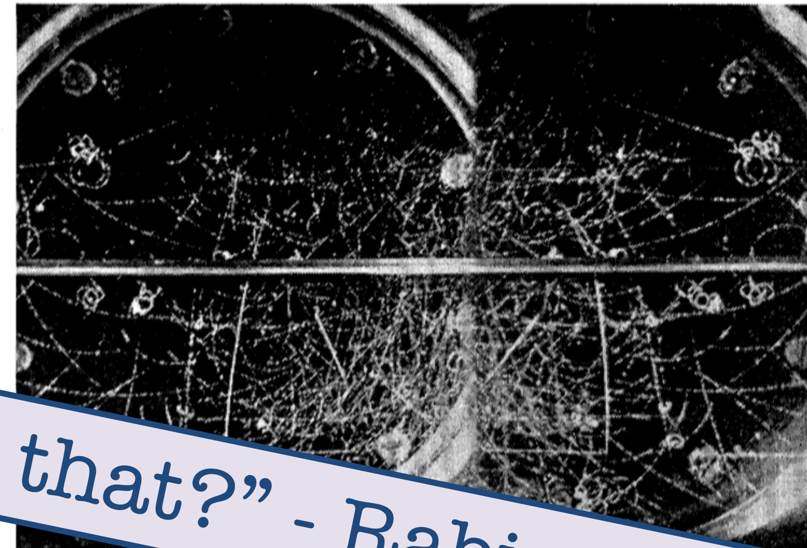

“Who ordered that?” - Rabi

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Listen to History

No theorist predicted, never mind guaranteed(!), the discovery of the muon.

It occurred by great experimentalists making great measurements of known phenomena.

Theoretical models are a good litmus test for possibility of a signal, but discoveries need not be guaranteed. Most important is to measure!

Will still don't know who ordered it.