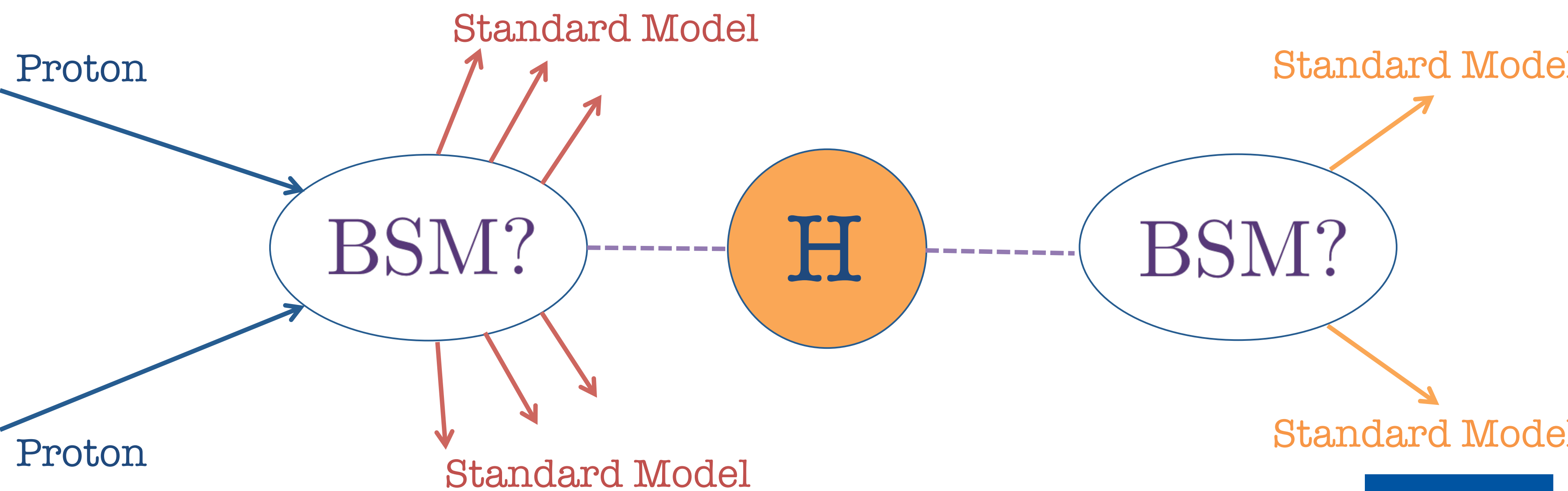
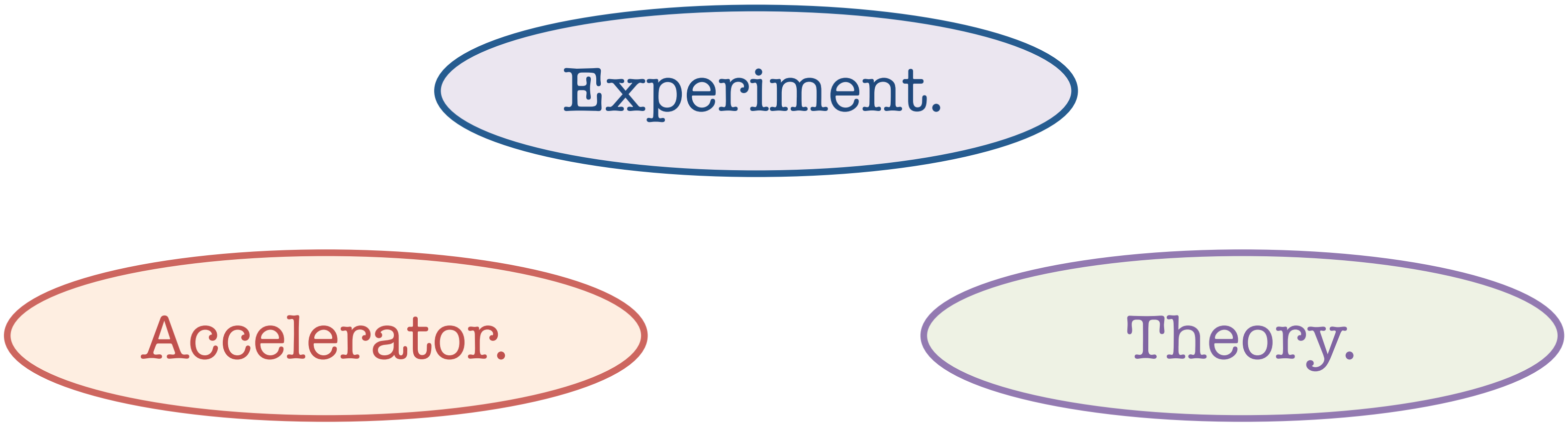
Physics Opportunities at Future Hadron Colliders



Matthew McCullough

Where are we now?

After decades of combined effort…



We now have the correct effective theory (symmetries and particles) to describe all of the known fundamental particles.

This is a remarkable scientific achievement!

Where are we now?

After decades of combined effort…

Experiment.

Accelerator.

Theory.

The Higgs boson was the keystone,

bringing us to a new era of fundamental physics.

Where are we now?

The Higgs is the end of the first chapter…

and the beginning of the next, but the LHC cannot address new frontiers of fundamental questions.

Where are we going?

This talk will focus on 100 TeV proton-proton collider physics:

However, HE-LHC also falls into the bracket of Future Hadron Colliders, and FCC studies.

In some sense, HL-LHC is also a Future Hadron Collider, but will not be discussed here.

Ginzburg-Landau

- The G-L Theory of superconductivity involves a complex scalar field and the photon (magnetic vector potential)

$$A$$

First, a little historical context...

- The free energy

$$F = |(\nabla + 2ieA)\Phi|$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + ...$$

- Where the mass depends on the temperature.

Ginzburg-Landau

- The G-L Theory of superconductivity involves a complex scalar field and the photon (magnetic vector potential)

$$\Phi \qquad\qquad A$$

- The free energy for this theory is

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

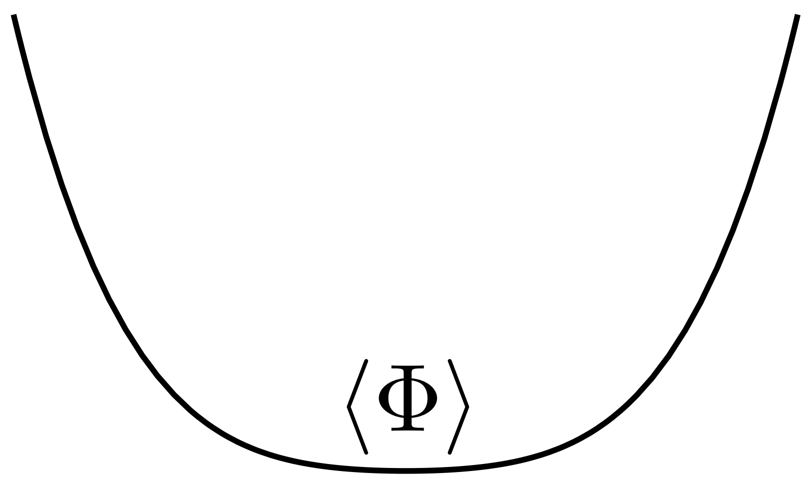
- Where the mass depends on the temperature.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

- At high temperatures the mass-squared is positive:



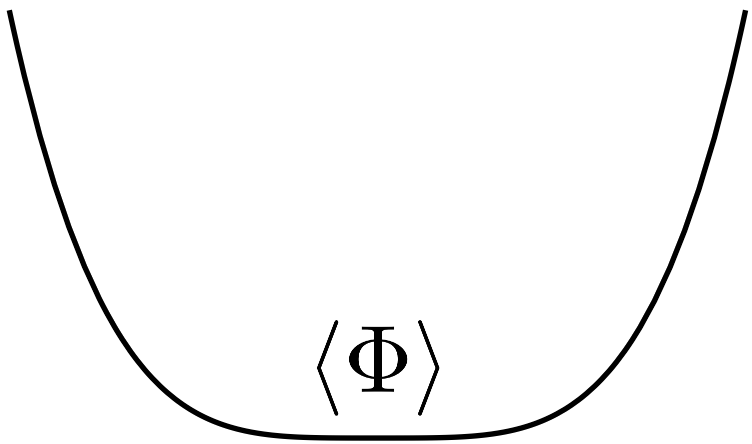
- Just a hot metal.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

- At the critical temperature the mass-squared vanishes:



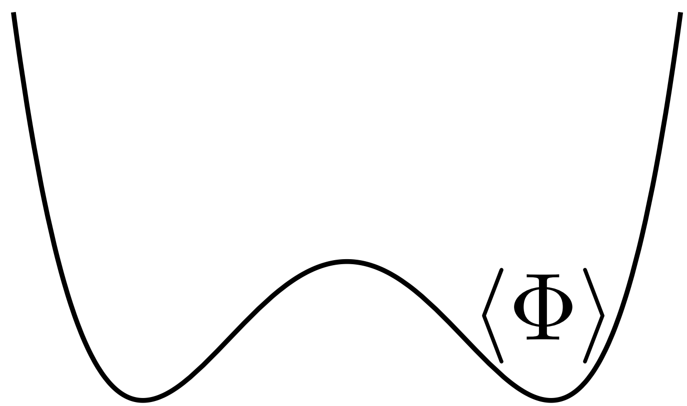
- Strange theory with massless fluctuations.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

- Below the critical temperature the mass-squared is negative:



- Photon has become massive: $m_A \sim e\langle\Phi\rangle$

What does this have to do with particle physics?

Higgs Mechanism

- The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

- The Lagrangian for this theory is

$$\mathcal{L} = \left|(\partial_\mu + ig\sigma^a W_\mu^a)H\right|^2$$

$$-m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

- This is a relativistic non-Abelian version of Ginzburg-Landau.

Higgs Mechanism

- The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

- [illegible]

$$\mathcal{L} = \left|\left(\partial_\mu + ig \ldots\right.\right.$$

$$- m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

Cosmological history is analogous to reducing the temperature of a superconductor.

- This is a relativistic non-Abelian version of Ginzburg-Landau.

The Elephant in the Room

G-L model of superconductivity is just a phenomenological model, with no explanation of parameters. The macroscopic parameters follow from the detailed microscopic BCS theory.

At low temperature the scalar field is actually secretly a composite of electrons.

The Elephant in the Room

G-L … f superconductivity is just a phe… with no explanation of pa… eters fo… y.

At low temperature … y secretly a composite of electrons.

Imagine if we had stopped at G-L, without pushing for the fundamental description?

Right now for the Higgs sector we are at G-L stage, but what is the microscopic story?

The Higgs and the Universe..

What does cosmology have to do with symmetry breaking and the Higgs?

This question is not merely academic.
It strikes right at the heart of how we perceive our place in the Universe!

Why might

- The nature of dark matte
- The origin of the matter-antimatter imba
- The ultimate fate of the Universe?

And perhaps more.

The Higgs and the Universe..

What does cosmology have to do with symmetry breaking and the Higgs?

H

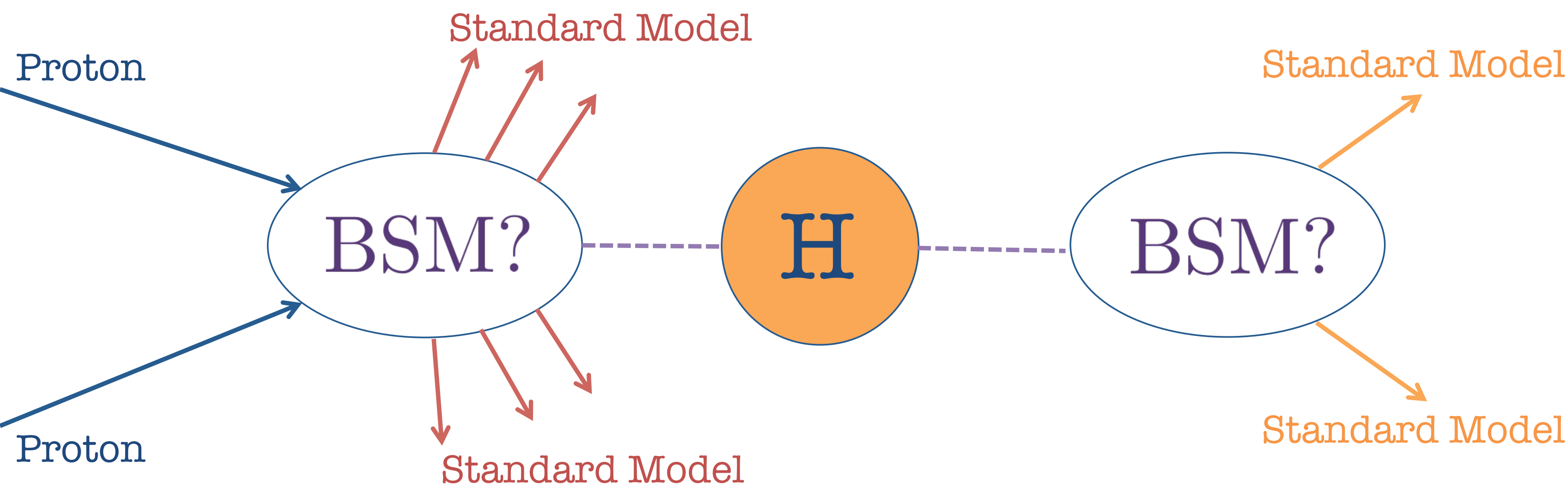
Why might the Higgs lead us to understand:

- The nature of dark matter?
- The origin of the matter-antimatter imbalance?
- The ultimate fate of the Universe?

And perhaps more.

The question defines the machine...

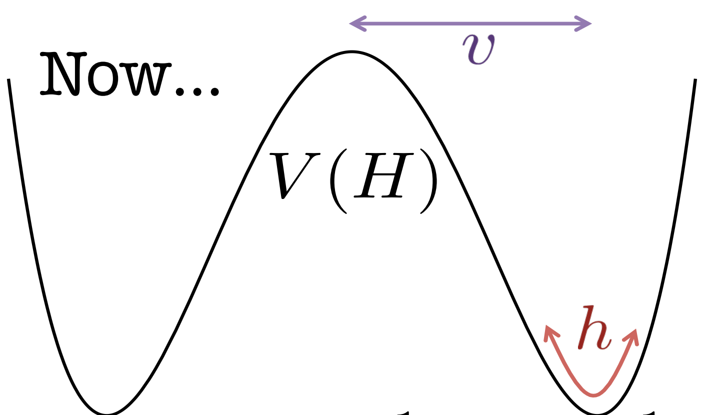
The physics of the Higgs boson dictates some very clear physics targets.



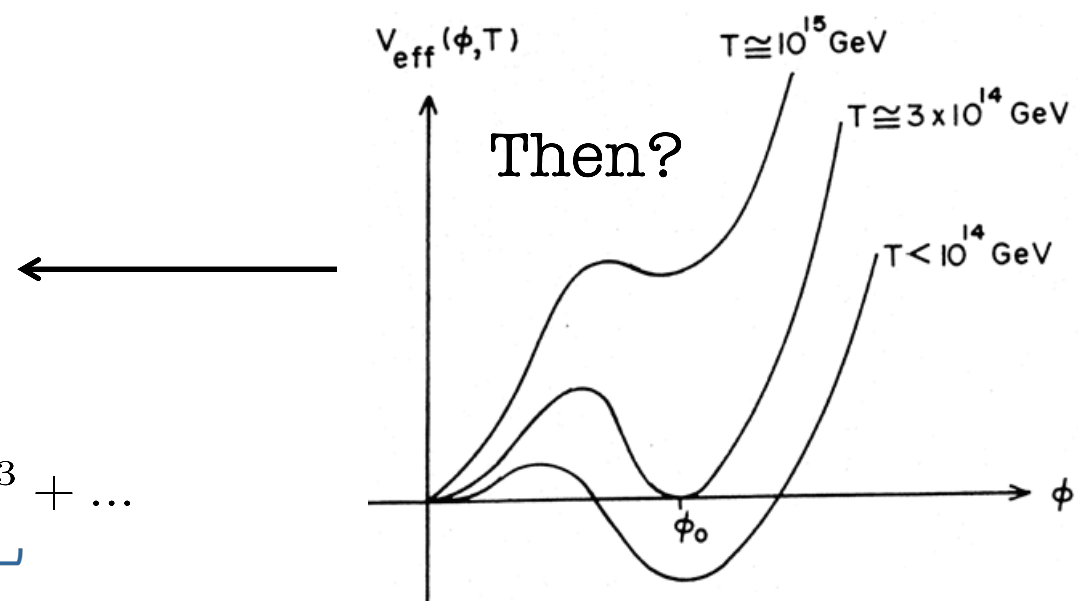
Every measurement probes new physics. What physics targets should we aim for?

The Dynamics of EWSB

How did the electroweak phase transition occur in the primordial Universe?



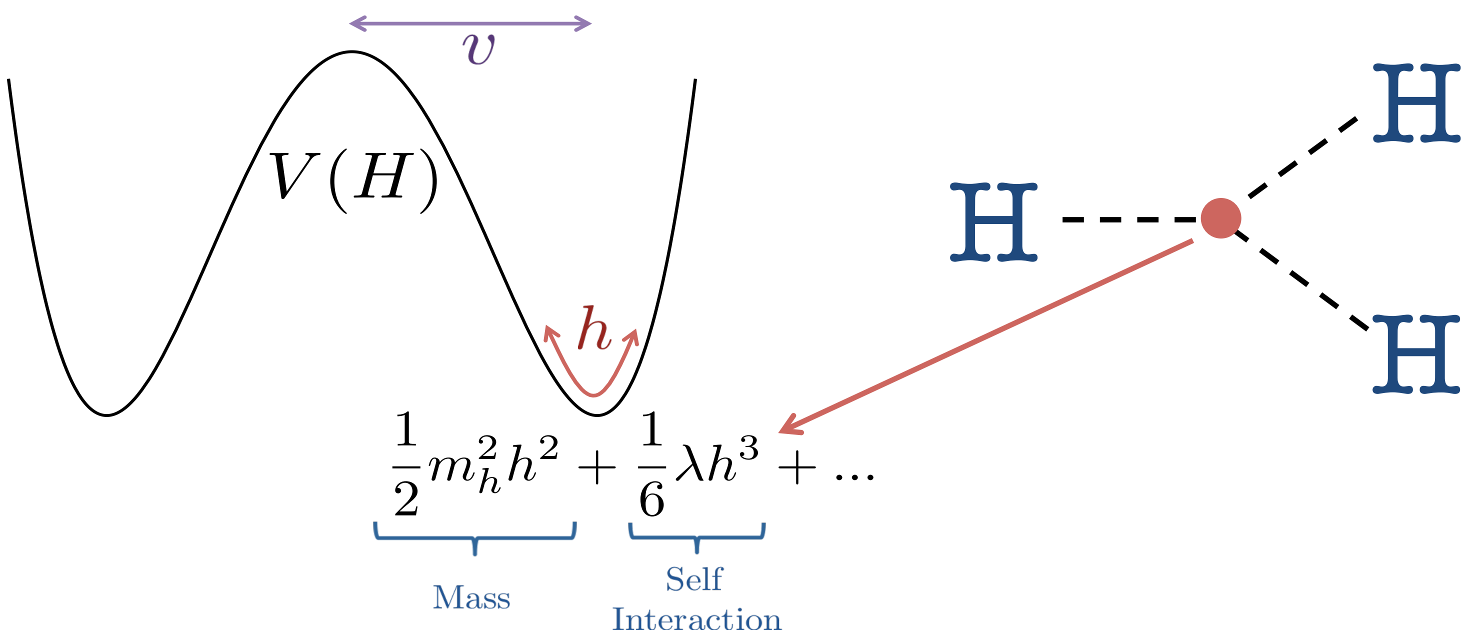
$$\underbrace{\frac{1}{2}m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$



The question and answer have important consequences...

The Higgs Potential...

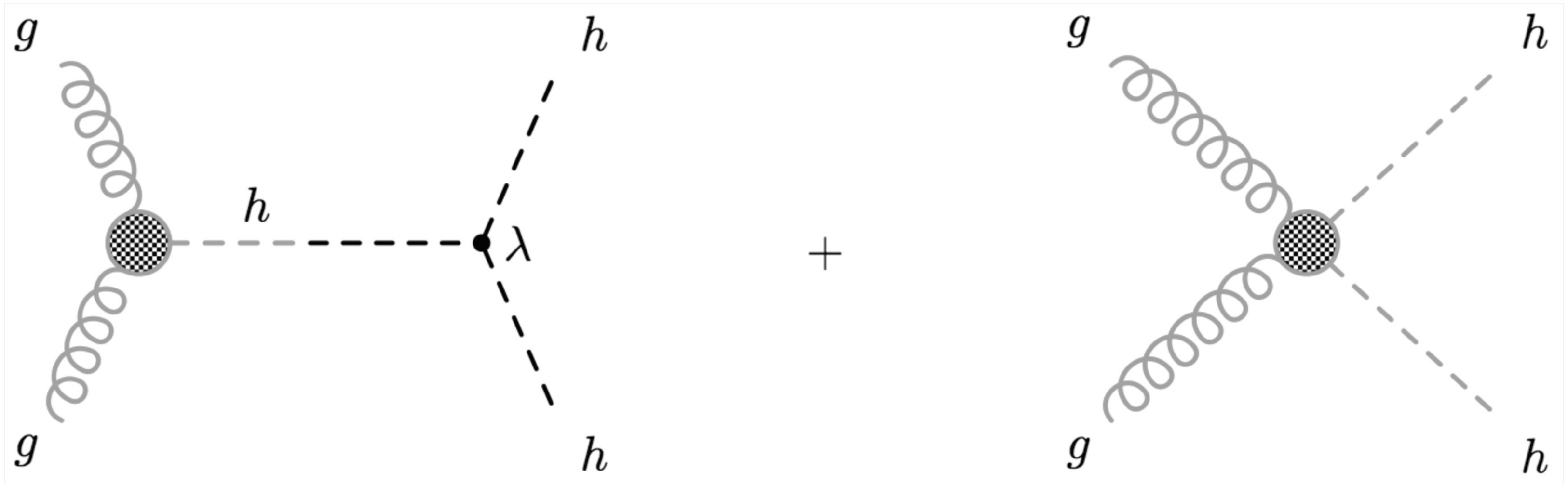
Measuring the Higgs self-coupling is the only way to measure the structure of the Higgs potential.



Discovering the Higgs was difficult enough, now we want to know how it behaves in private...

The Higgs Potential...

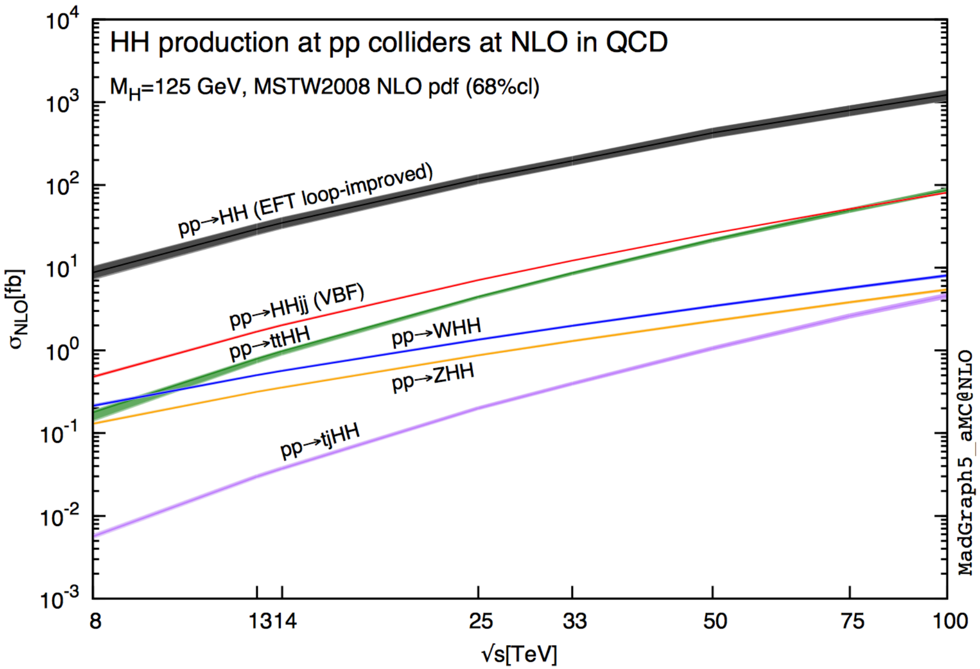
At hadron colliders gain sensitivity to self-interactions by searching for pair production:



There are many decay channels to consider, however most promising is:

$$hh \to b\bar{b}\gamma\gamma$$

The Higgs Potential...



Compared to the LHC, at 100 TeV pair production cross section grows by a factor of 40. Note that this is a much greater increase than in CM energy...

From FCC Report

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Huge increase in event numbers translates directly to a precise measurement of the nature of the Higgs potential!

Electroweak Evolution

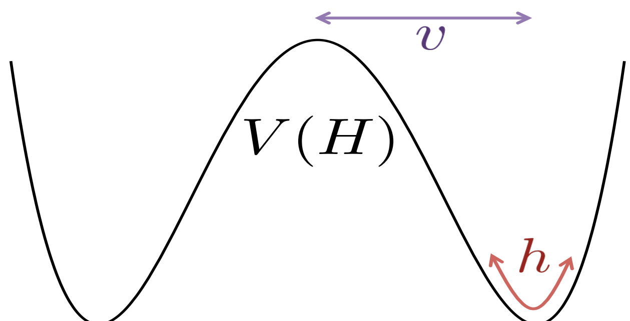
We got the symmetries: LEP.

$$SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

Then we got the mechanism: LHC.

$$\langle H \rangle = v + h$$

Now it's time to get the dynamics: Future colliders.



$$\underbrace{\frac{1}{2}m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$

What's the Matter?

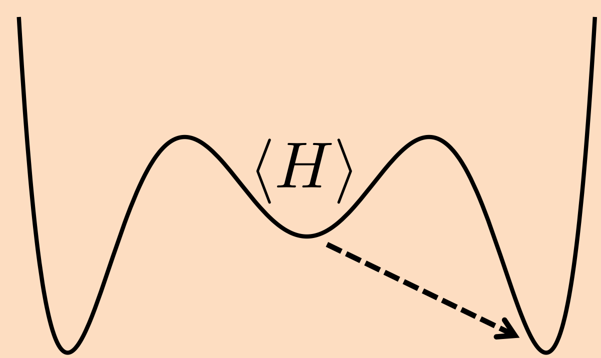
To generate more matter than antimatter, would have to satisfy Sakharov conditions:

I demand:

- Baryon-number violation
- CP-violation
- Out-of-equilibrium processes

If the phase transition had been strongly first order we could have satisfied these conditions.

But it was not (we think) ...



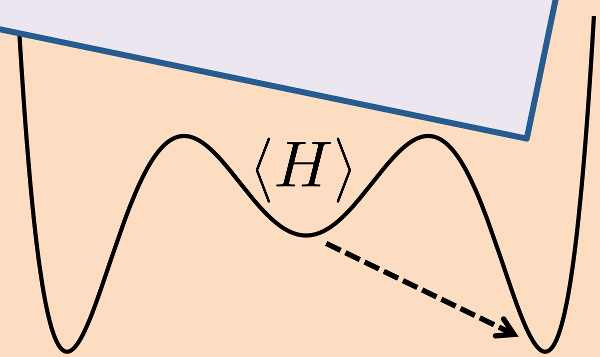
What's the Matter?

To generate more matter than antimatter,
wo… to satisfy Sakharov conditions:

Relatively minor modifications of the Higgs sector of Standard Model can actually generate the observed matter-antimatter imbalance. I.e. You and me!

If the phase transition had been strongly first order we could have satisfied these conditions.

But it was not (we think) …

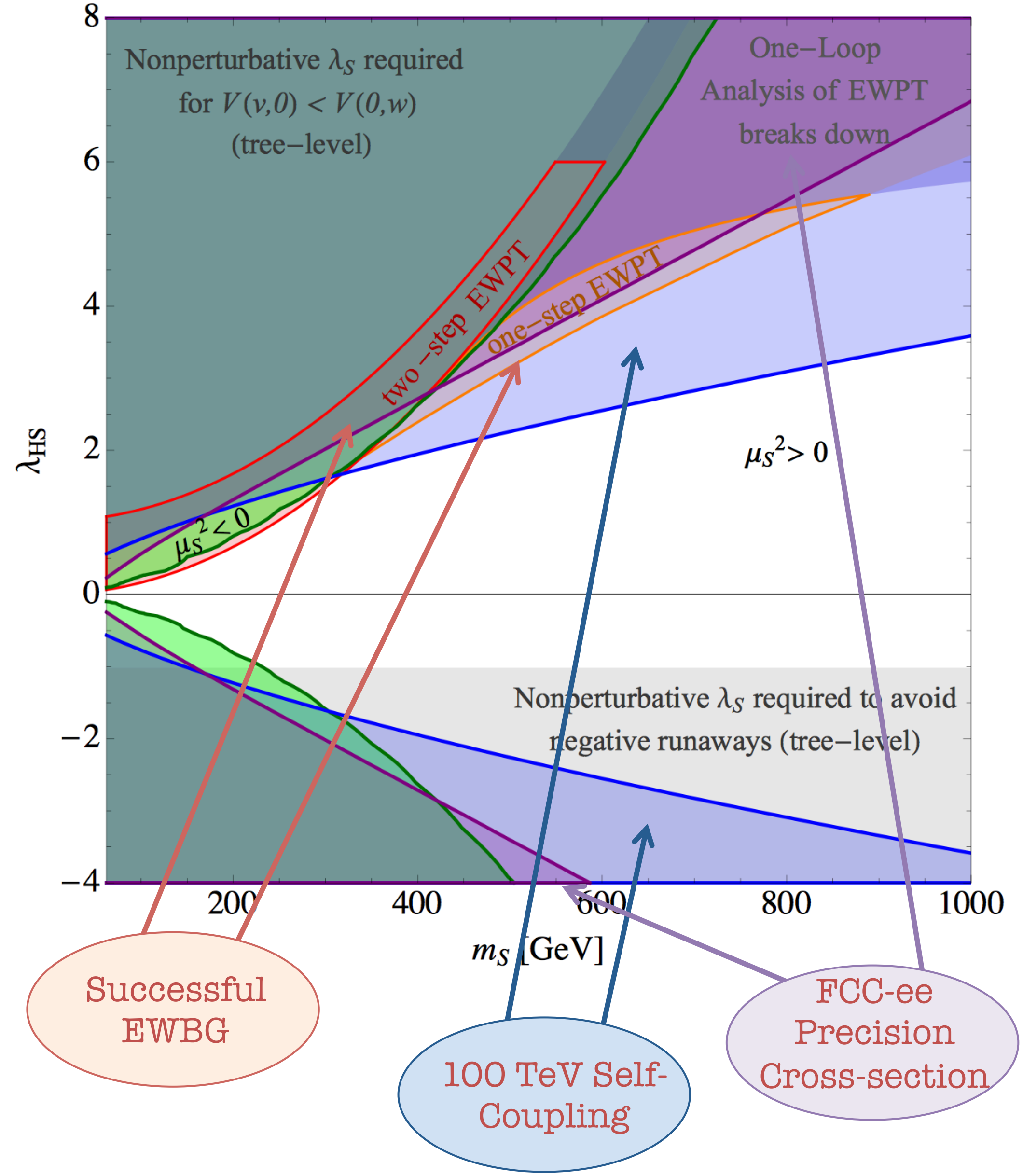


The origins of matter…

The matter-antimatter imbalance can be generated during the primordial electroweak phase-transition.

This needs to be strongly first-order. SM does not work, however scenarios modifying the Higgs potential, through the influence of new particles, can.

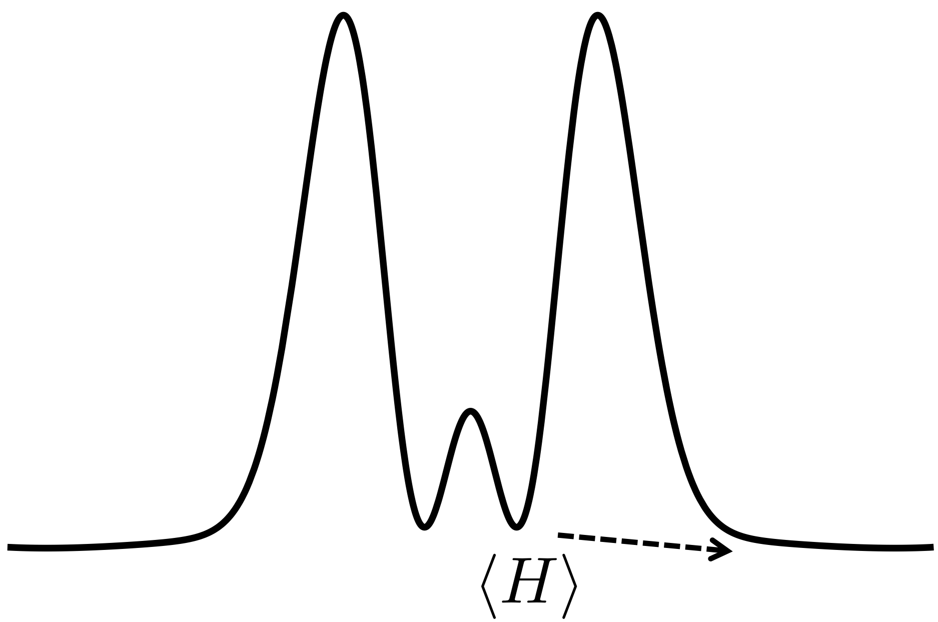
The “Nightmare scenario”: A gauge singlet scalar, is the most difficult to discover.



This plot assumes 10% accuracy.

The Fate of Fate

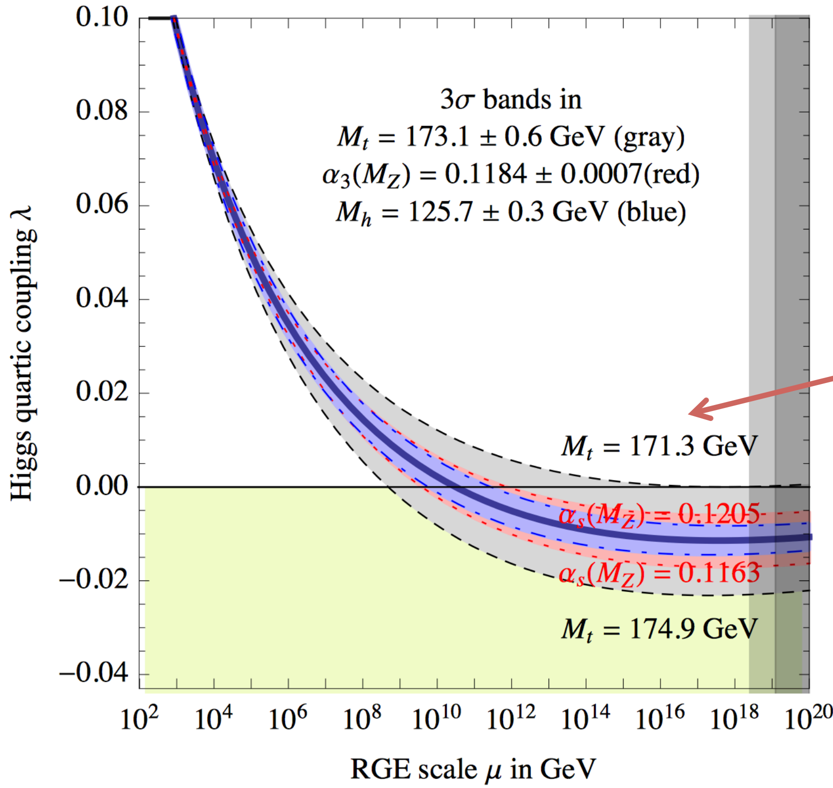
Let's look to the distant future...

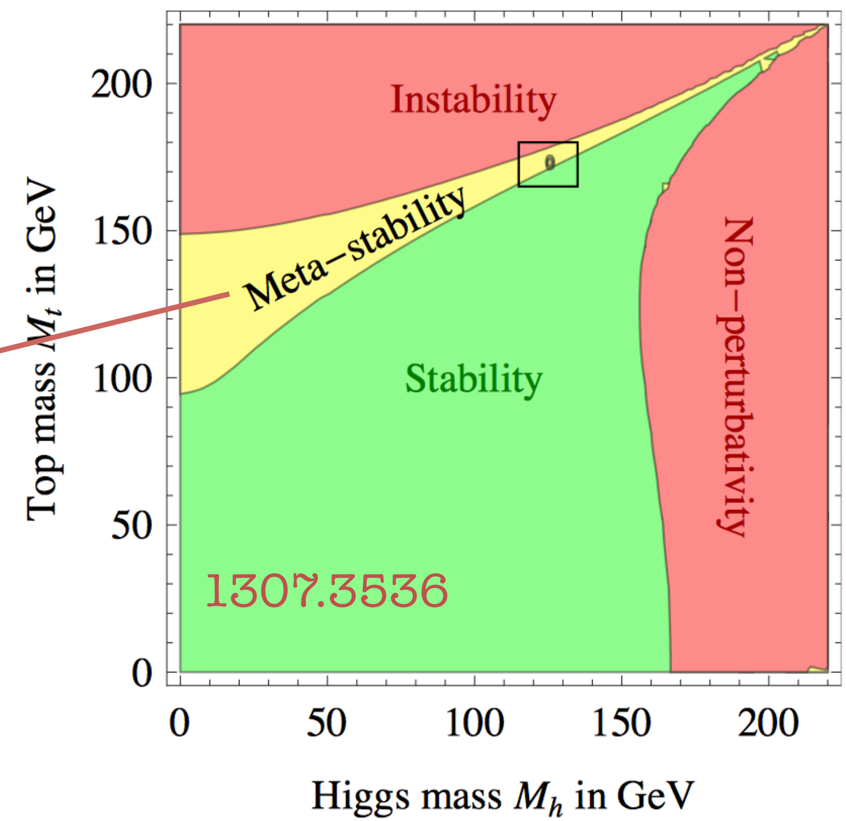


The Higgs potential may have yet another minimum that I wasn't telling you about. May be at lower energies...

The Fate of Fate...

The Higgs potential has another minimum...

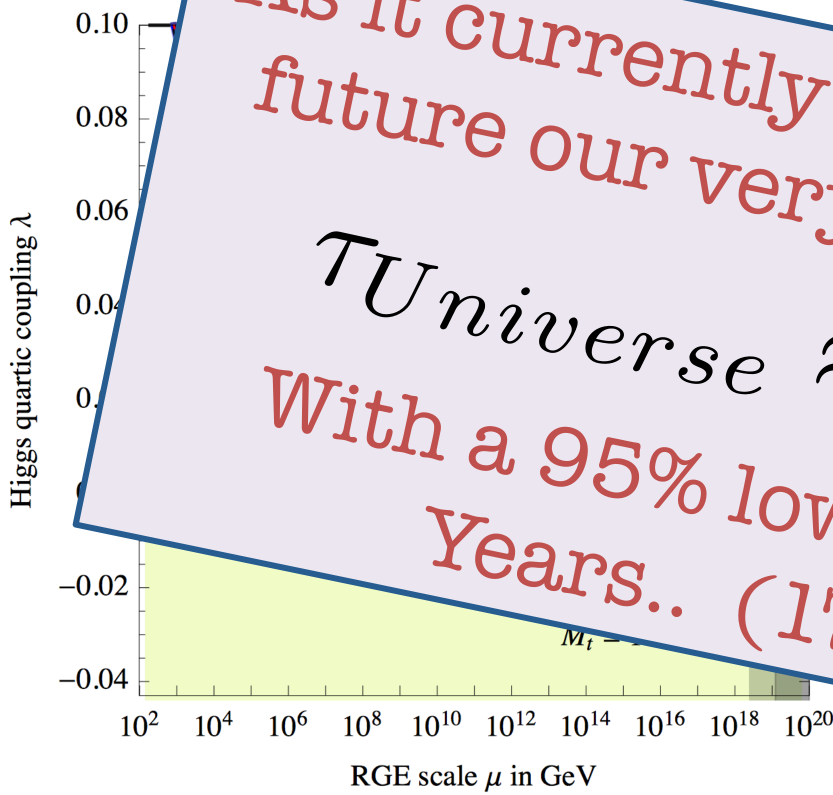


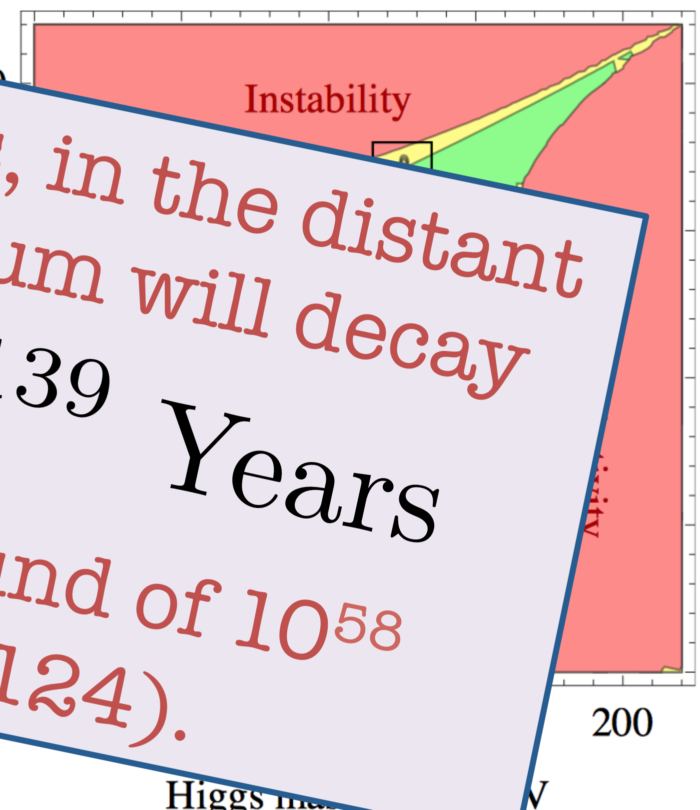


From current LHC measurements it looks like our current location on the Higgs potential is unstable!

The Fate of Fate...

The Higgs potential has another minimum...





As it currently stands, in the distant future our very vacuum will decay

$$\tau_{Universe} \approx 10^{139} \text{ Years}$$

With a 95% lower bound of 10^{58} Years.. (1707.08124).

From current LHC measurements it looks like our current location on the Higgs potential is unstable!

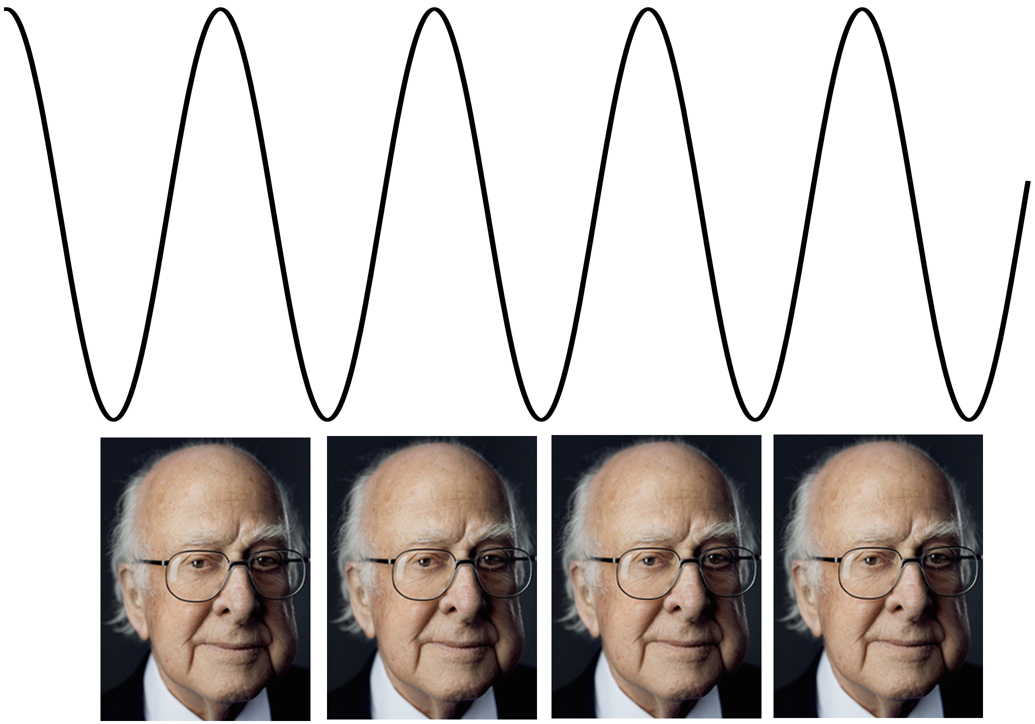
The Elephant in the Room

Is the Higgs a composite?

Since the equations are pretty much identical to Ginzburg-Landau, then maybe if we look closely enough we'll see what the Higgs is really made of?

The size of the Higgs boson…

- The Higgs boson has a size/wavelength. We can look inside…



Measurements are different ways of probing the "compositeness of the Higgs".

No substructure has yet shown up…

$$\lambda_h \approx 10^{-17} \text{ m}$$

$$\lambda_{10 \text{ TeV}} \approx 10^{-19} \text{ m}$$

Composite Higgs Models

If the Higgs is made up of constituents

$$H = \bar{f} f \sim f \qquad \xi \sim \frac{v^2}{f^2}$$

Then no fundamental scalar at high energies!

These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

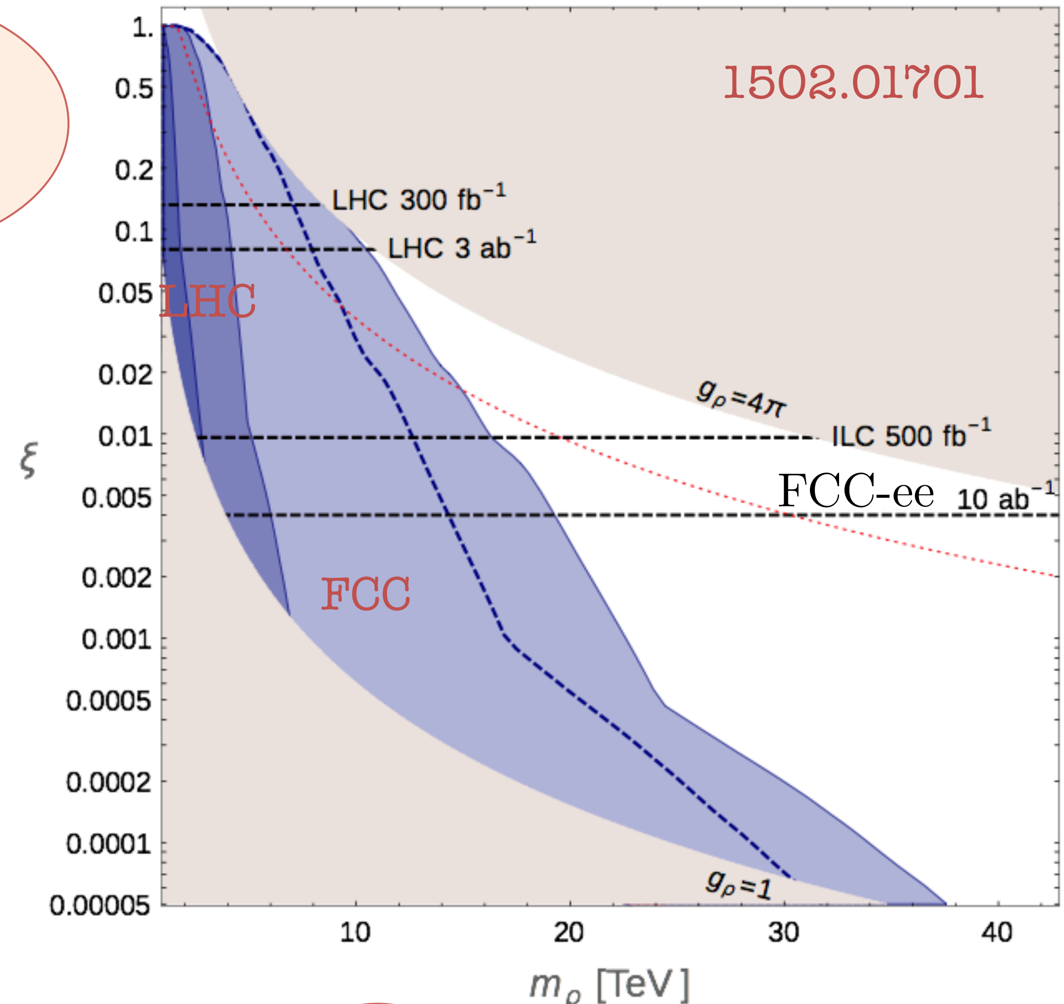
$$\rho = \bar{f} f \sim \Lambda$$

Should also get other heavy resonances then!

Composite Higgs Models

$$\xi \sim \frac{v^2}{f^2}$$

Combining precision measurements with high mass resonance searches, can fully answer the question of Higgs compositeness.



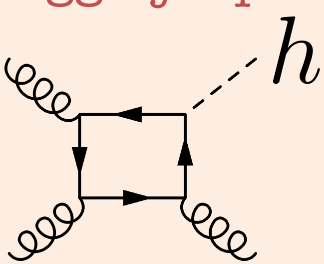
$$\rho = \bar{f} f$$

100 TeV at Higgs Intensity frontier.

At FCC-hh TEN BILLION Higgs bosons produced.
Allowing to study extremely rare behaviour.

Higgs Production

Higgs+jet production



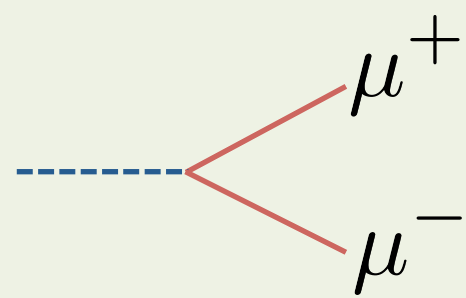
$+\dots$ other diagrams

Would occur at Higgs p_T's as large as 7 TeV!

This is 56 times the mass, in other words, speed of 0.9998c.

Higgs Decays

Higgs coupling to muons



Would be measured to 1%. The interaction strength to Higgs is $\lambda_\mu \approx 6 \times 10^{-4}$

Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.

Dark Matter!

- We have no idea what 80% of the matter in nature is. We have to change this.

Dark Matters

Evidence for dark matter is now overwhelming

- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

?

Dark Times

The Higgs portal term is the <u>only renormalizable</u> interaction between a Standard Model particle and a new <u>stable</u> neutral particle

$$\lambda |H|^2 X^2$$

This property is known as the "Higgs Portal". Since we know other stable neutral particles exist (Dark Matter) then the Higgs portal could be the only window into the dark sector!

Dark Times

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$$\lambda |H|^2 X^2$$

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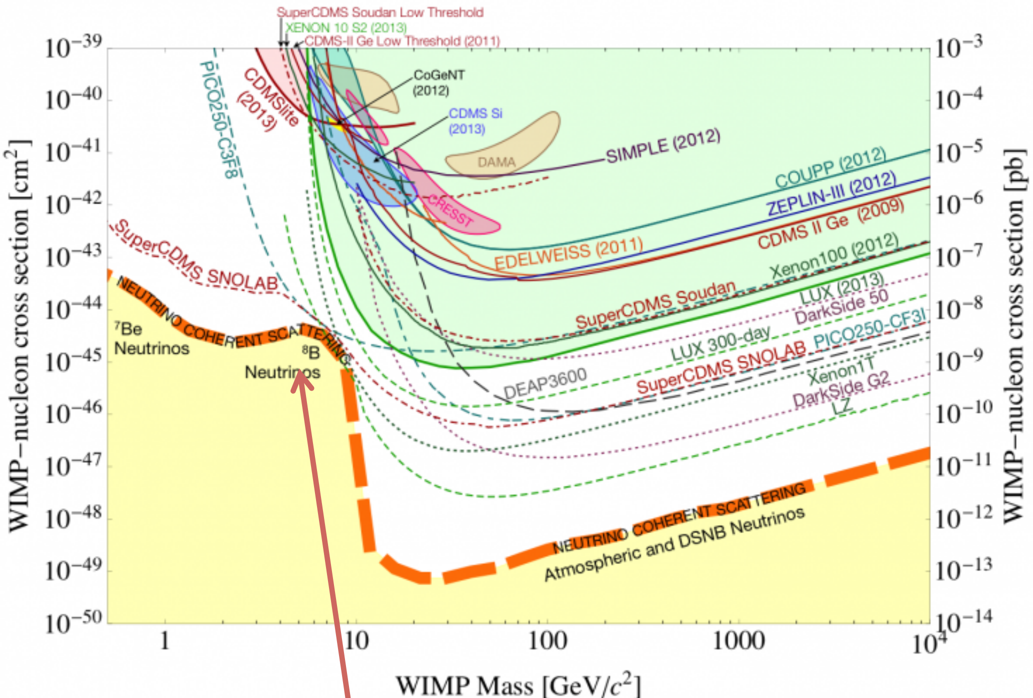
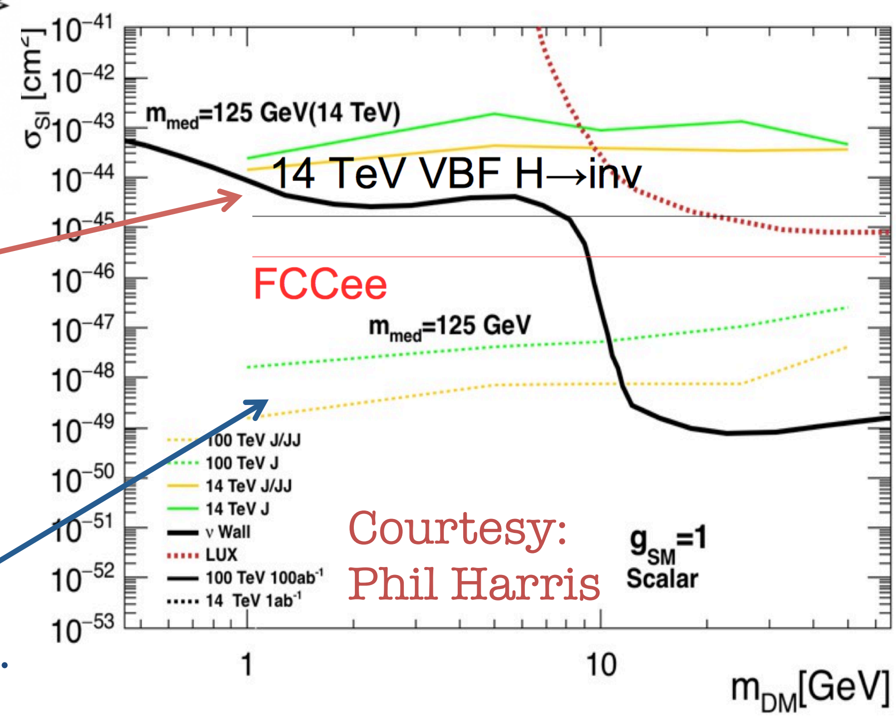
A Portal to Hidden Worlds…



100 TeV Missing Energy searches, for example for decays of the Higgs to dark sector states, will hit the per-mille branching ratio level!

The laboratory search for dark matter will hit a difficult background, called the "neutrino floor".

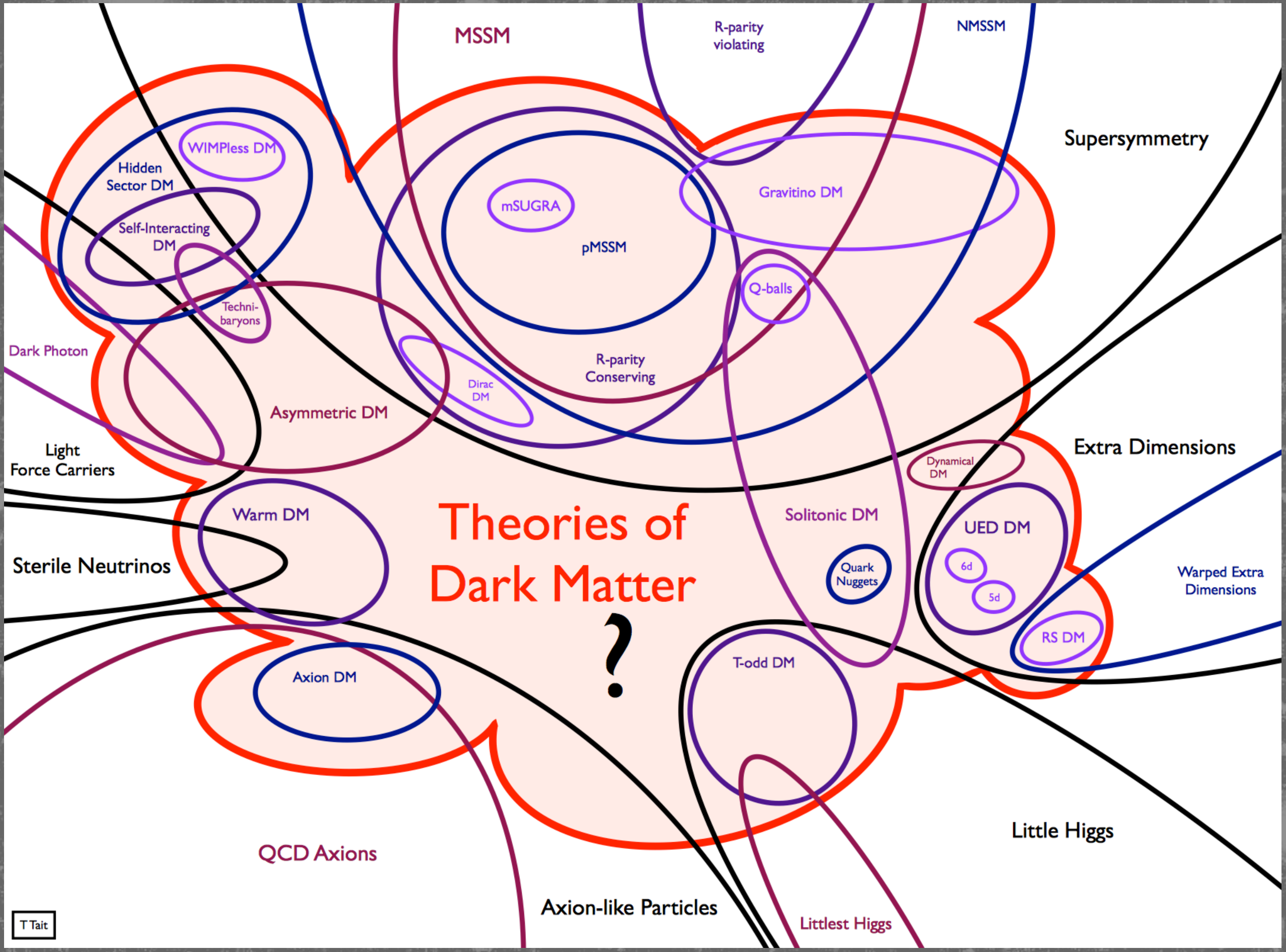


Courtesy: Phil Harris

May not be a good thermal DM candidate…

Dark Matters

There are other ideas...



Stolen from slides of Tim Tait

Dark Matter at 100 TeV

Despite overwhelming evidence for its existence, the particle nature of dark matter is unknown.

Cosmology provides a strong motivation for direct and collider searches...

- Thermal freeze-out predicts observed abundance for:

$$M_{DM} \sim \mathcal{O}(\text{few GeV}) \to \mathcal{O}(10\text{'s TeV})$$

↑ Cosmological constraints

↑ Unitarity bounds

Motivates dark matter searches in ballpark of 100 TeV collider <u>independent</u> of hierarchy problem.

Simplified Dark Matter Models

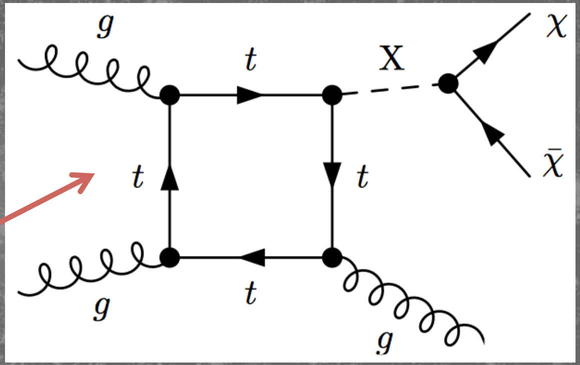
Write down simple scenarios to model production of dark matter at colliders:

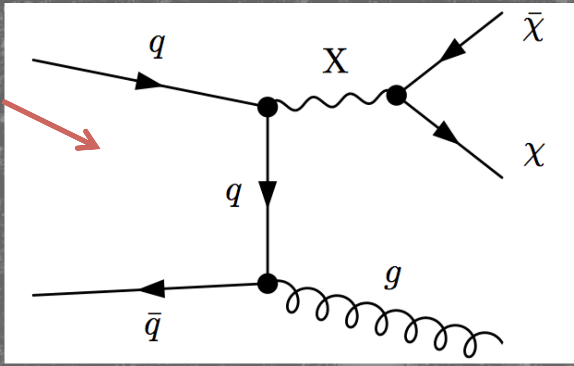
$$\mathcal{L}_{\rm S} \supset -\sum_q c_S \lambda_{h,q} S\,\bar{q}q - \frac{1}{2}m_{\rm MED}^2 S^2 + \mathcal{L}(S,\bar{\chi},\chi)\,,$$

$$\mathcal{L}_{\rm P} \supset -\sum_q i c_P \lambda_{h,q} P\,\bar{q}\gamma^5 q - \frac{1}{2}m_{\rm MED}^2 P^2 + \mathcal{L}(P,\bar{\chi},\chi)\,,$$

$$\mathcal{L}_{\rm V} \supset -\sum_q c_V V_\mu \bar{q}\gamma^\mu q - \frac{1}{2}m_{\rm MED}^2 V_\mu V^\mu + \mathcal{L}(V,\bar{\chi},\chi)\,,$$

$$\mathcal{L}_{\rm A} \supset -\sum_q c_A A_\mu \bar{q}\gamma^\mu\gamma^5 q - \frac{1}{2}m_{\rm MED}^2 A_\mu A^\mu + \mathcal{L}(A,\bar{\chi},\chi)\,,$$



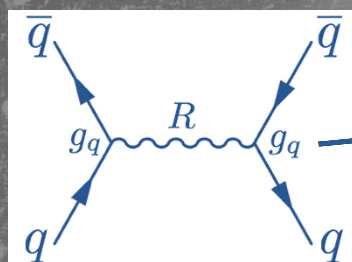


100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.

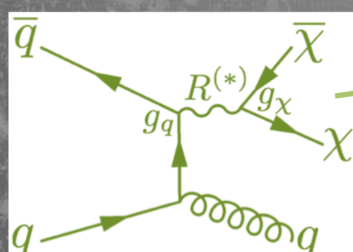
100 TeV: Resonances and Dark Matter

Consider a scenario where dark matter interacts via a new Z' boson:

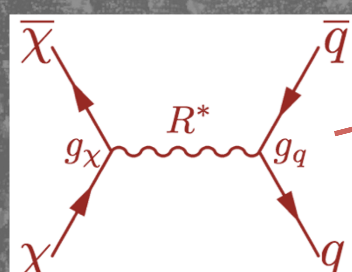
Dijet Resonances

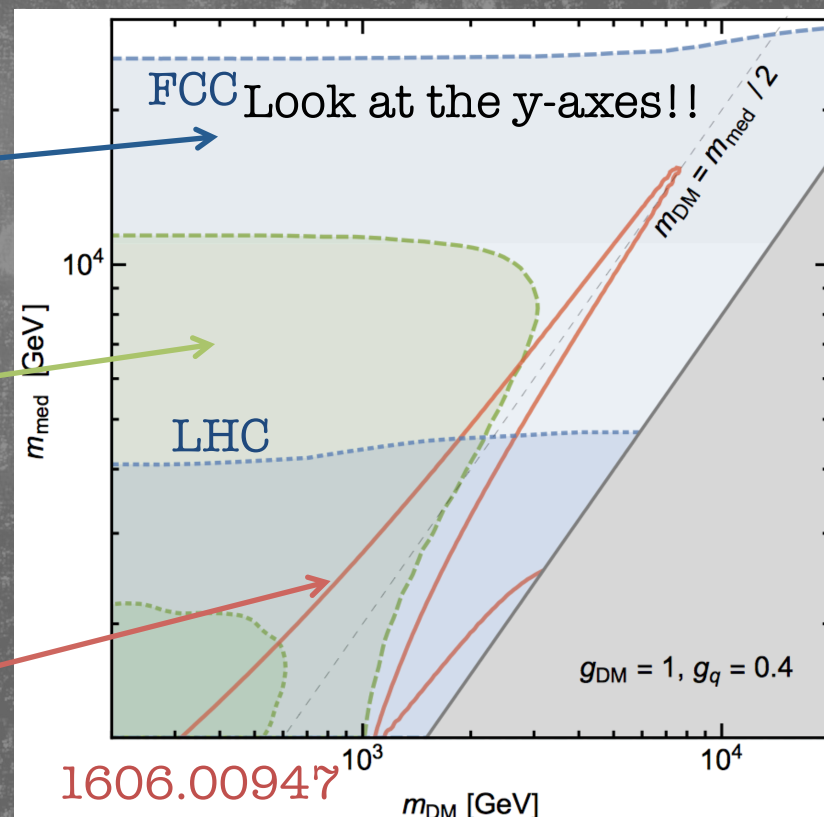


Missing Energy



Relic Density



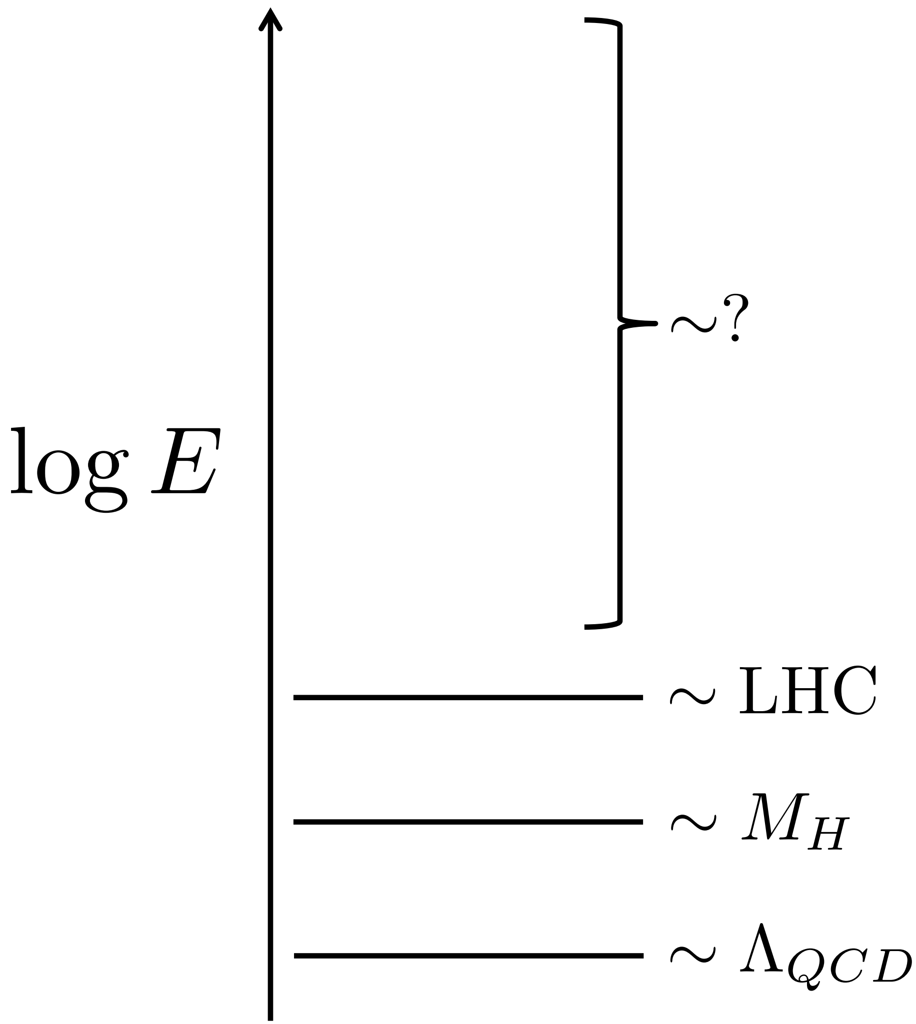


Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

Looking to the sky.

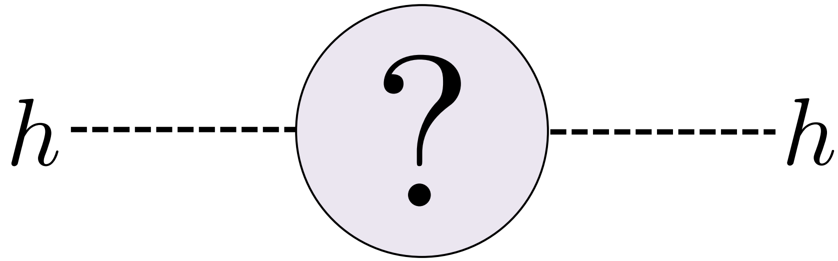


We do not know what new physics lies above, but we have hints...

- Neutrino masses?
  $$M_N \gtrsim 10^{10} \text{ GeV}$$
- Strong CP?
  $$M_{\rm PQ} \gtrsim 10^{10} \text{ GeV}$$
- Unification?
  $$M_{\rm GUT} \sim 10^{15} \text{ GeV}$$
- Quantum gravity?
  $$M_P = 2 \times 10^{18} \text{ GeV}$$
- Hypercharge Landau pole?
  $$M_{\Lambda_Y} \gg M_P$$

The Naturalness Paradox

This has implications at the weak scale...



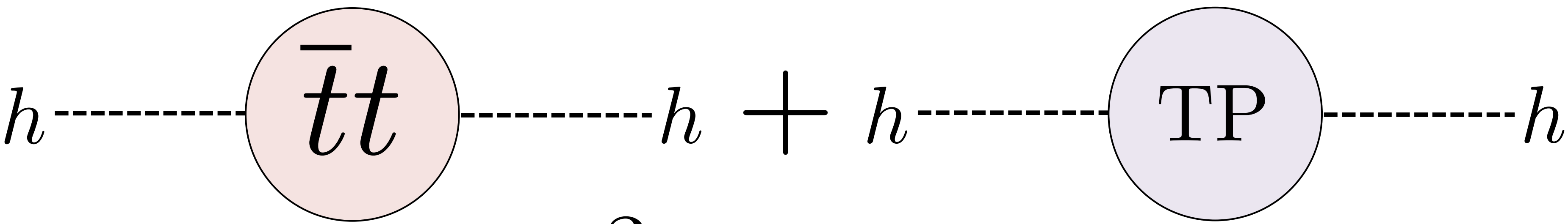
At quantum level, new physics will correct Higgs mass, pulling it up to $m_h \sim \Lambda$.

Should expect $m_H \sim \Lambda$. But I just argued $\Lambda \gg M_W$ so how can we reconcile with

$$m_h = 125 \text{ GeV } ?$$

The Naturalness Paradox

Hierarchy problem solutions typically involve a "Top Partner":



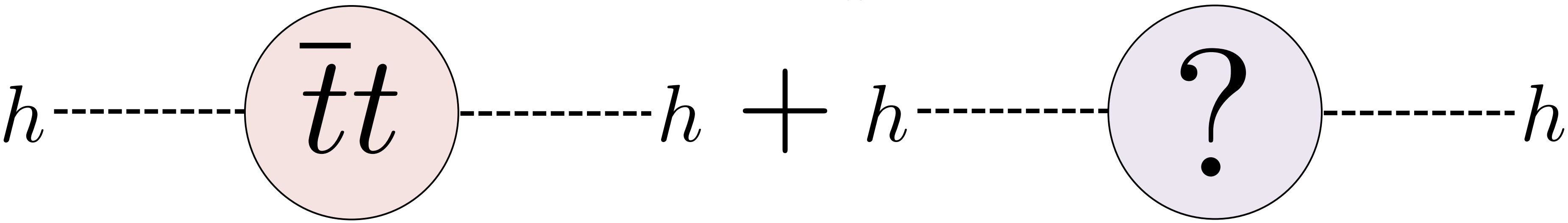
$$\approx \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda$$

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

For naturalness expect $m_{TP} \lesssim 400 \text{ GeV}$.

Neutral Naturalness

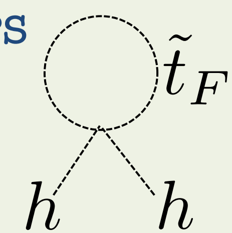
Could there be a hidden "Top Partner"?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

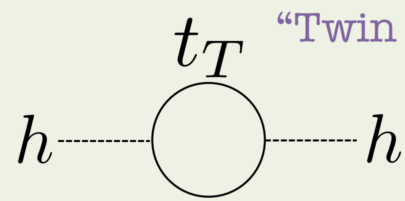


"Folded Stops"

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

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



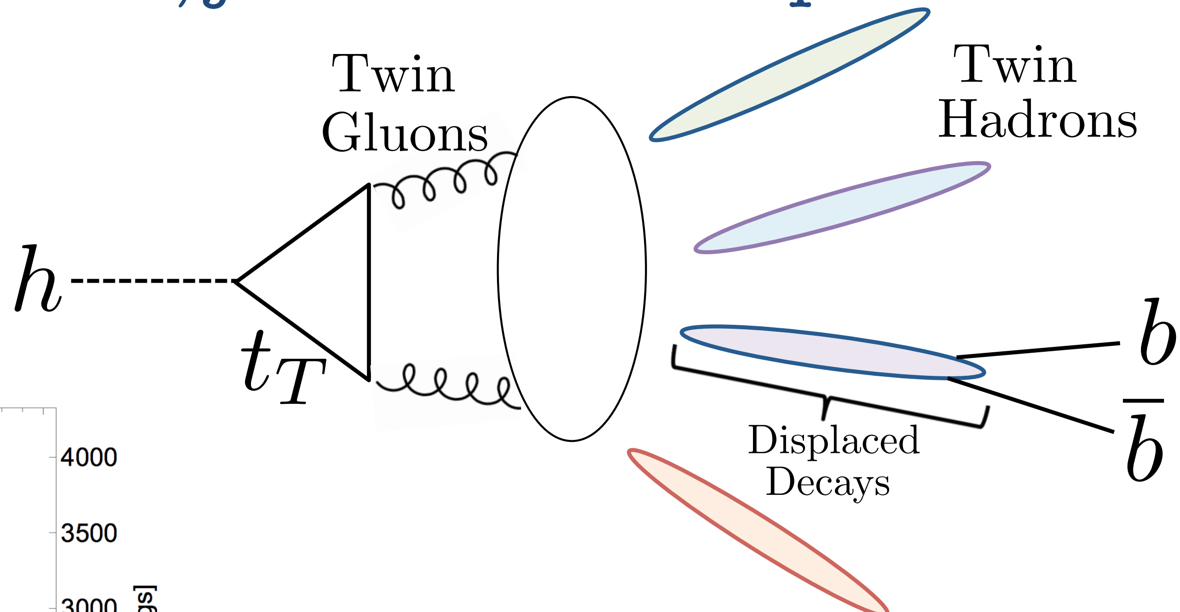
"Twin Tops"

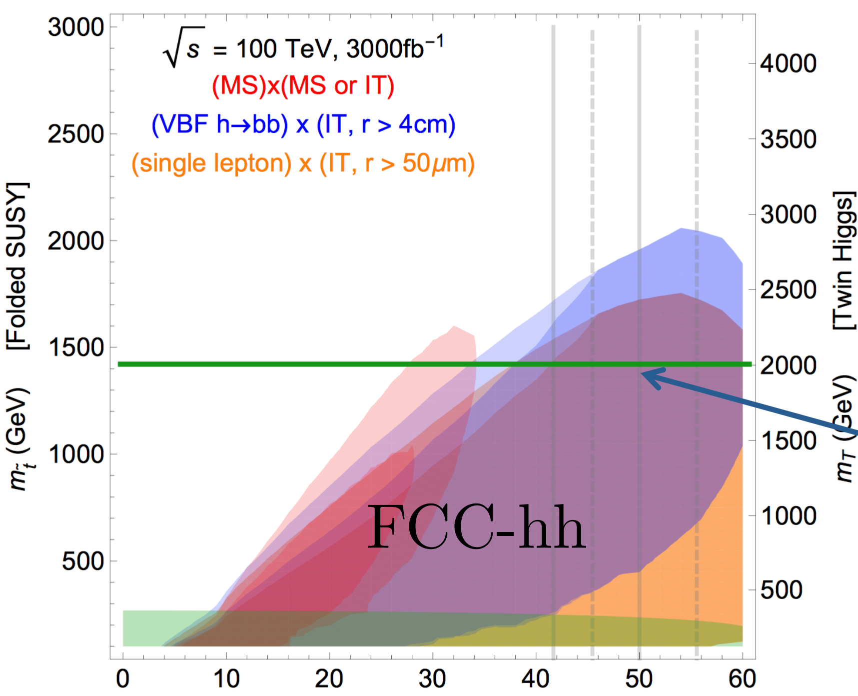
...but they must be charged under new hidden QCD'.

Neutral Naturalness

Naturalness not hidden, just look in new places…

New hidden sector introduces exotic Higgs decays:





Curtin, CV 1506.06141

100 TeV can thoroughly probe larger Twin scales through displaced searches.

Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!

- Sometimes we overlook the role of future high energy colliders as intensity frontier machines.

Intensity Frontier

There are models in which there is no preferred mass scale for new particles.

An "Axion-like particle" (ALP) is a canonical example:

$$a$$

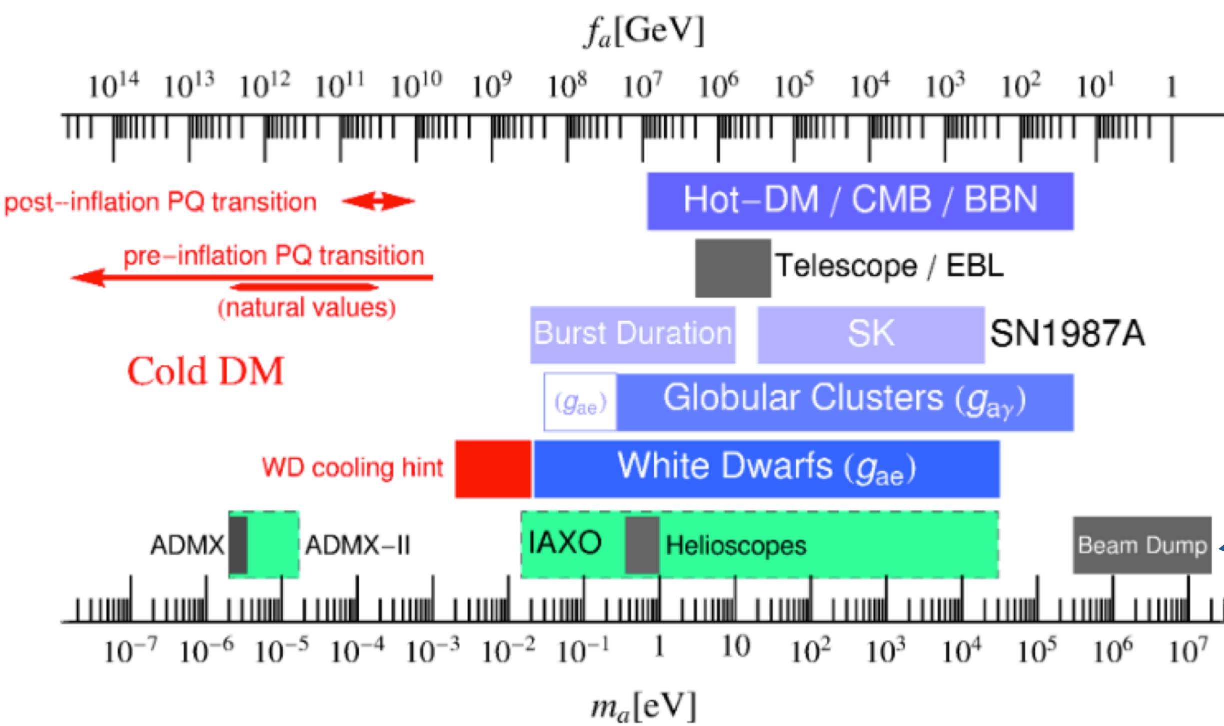
ALPs emerge as pseudo-Goldstone bosons of spontaneously broken global symmetries.

Since the parameter that gives mass breaks a symmetry, it can be naturally small.

Intensity Frontier

ALPs can also couple to photons, gluons etc,

$$\mathcal{L} \supset \frac{a}{f} B^{\mu\nu} \widetilde{B}_{\mu\nu}$$

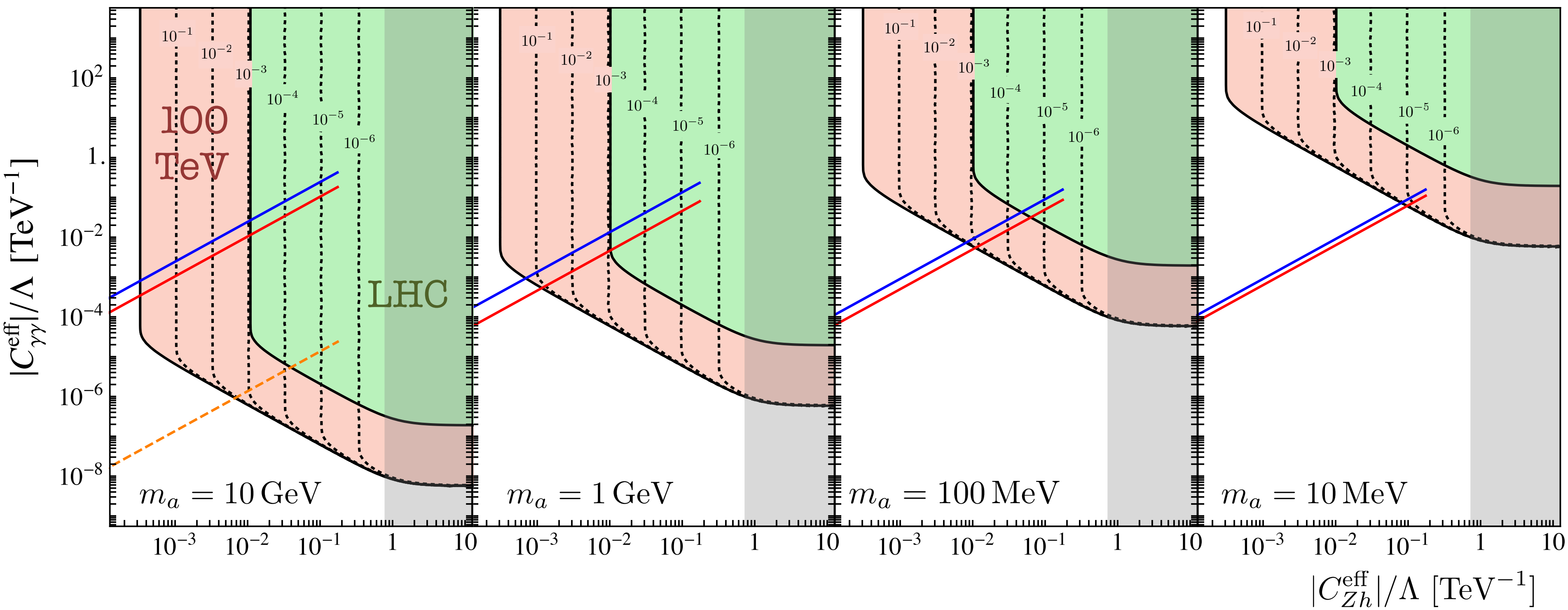


This is why we consider ALPs searches over many orders of magnitude…

But why do so many plots end here?

Intensity Frontier

100 TeV collider would push intensity frontier an additional three orders of magnitude in some cases:



Plot kindly provided by Martin Bauer, Mathias Neubert, and Andrea Thamm.

Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!

- Sometimes we overlook the role of future high energy colliders as intensity frontier machines.

The Unexpected!

- Avoid hubris: No one knows what exists above LHC energies unless we actually go there! Completely uncharted territory.

Conclusions.

The G… theory is a great phenomenological model,
but w… …tood superconductivity when
with… …BCS).

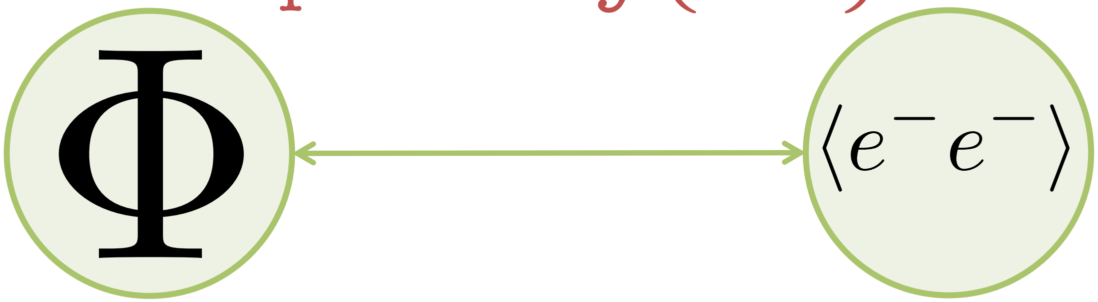
We… …el,
but it's …
opportunity at a fu…
uncover the microscopic natur… …se.

Clearly the physics opportunities at a future hadron collider are vast!

Afford me one last comment on how I see the current experimental situation with the Higgs…

Conclusions.

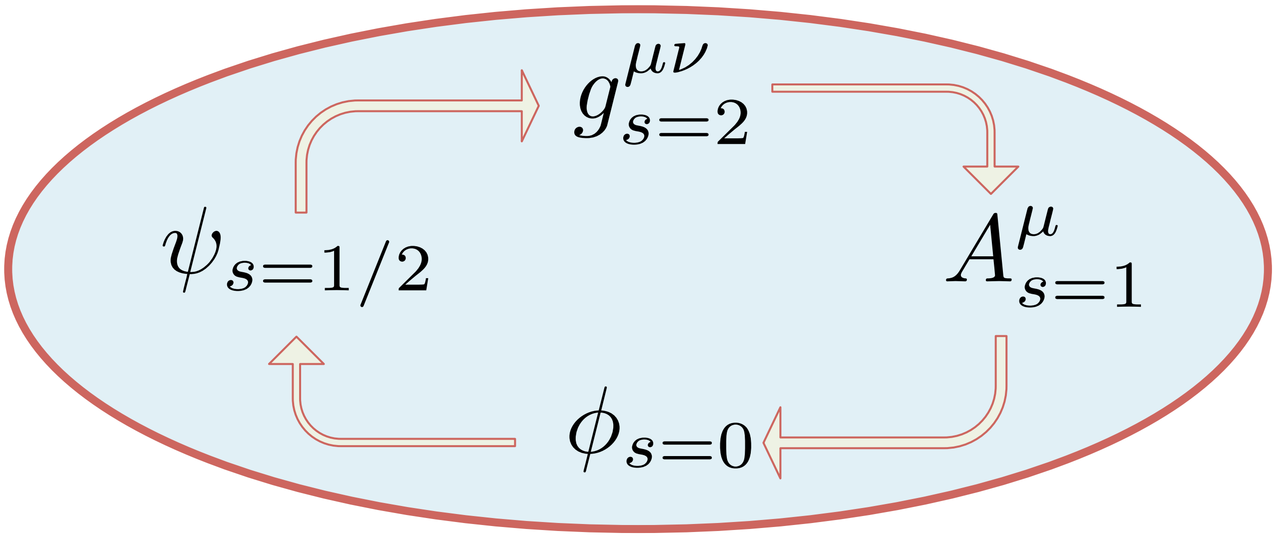
The G-L theory is a great phenomenological model, but we only understood superconductivity when with the microscopic theory (BCS).



We currently have a great phenomological model, but it’s not the final story. One physics opportunity at a future hadron collider is to uncover the microscopic nature of our Universe.

Supersymmetry

What is supersymmetry?



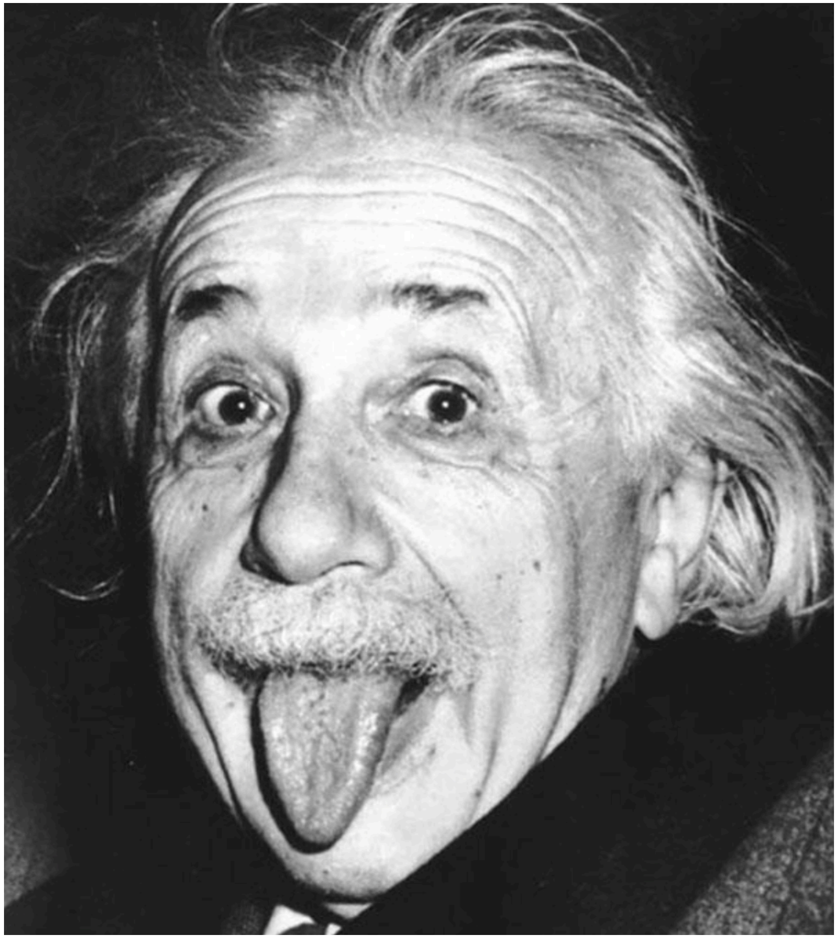
Entirely new spacetime symmetry!

Unifies fields into superfields, transforming into one another!

Also predicts... $\tilde{g}_{s=3/2}$

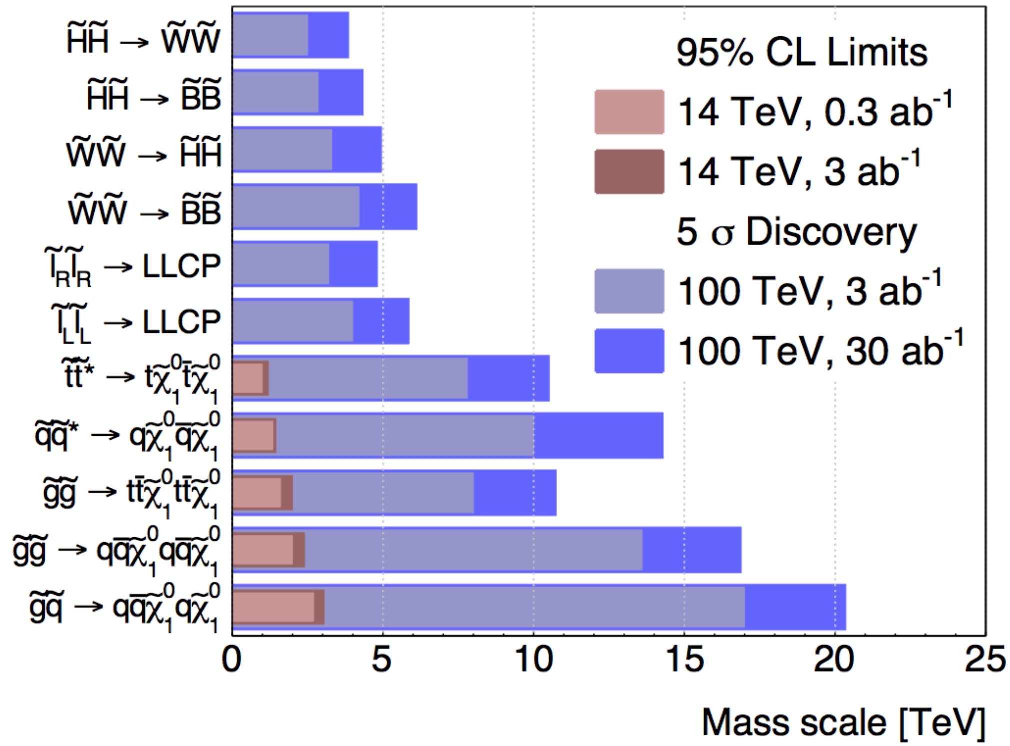
Supersymmetry

The last time a spacetime symmetry was discovered...



Supersymmetry

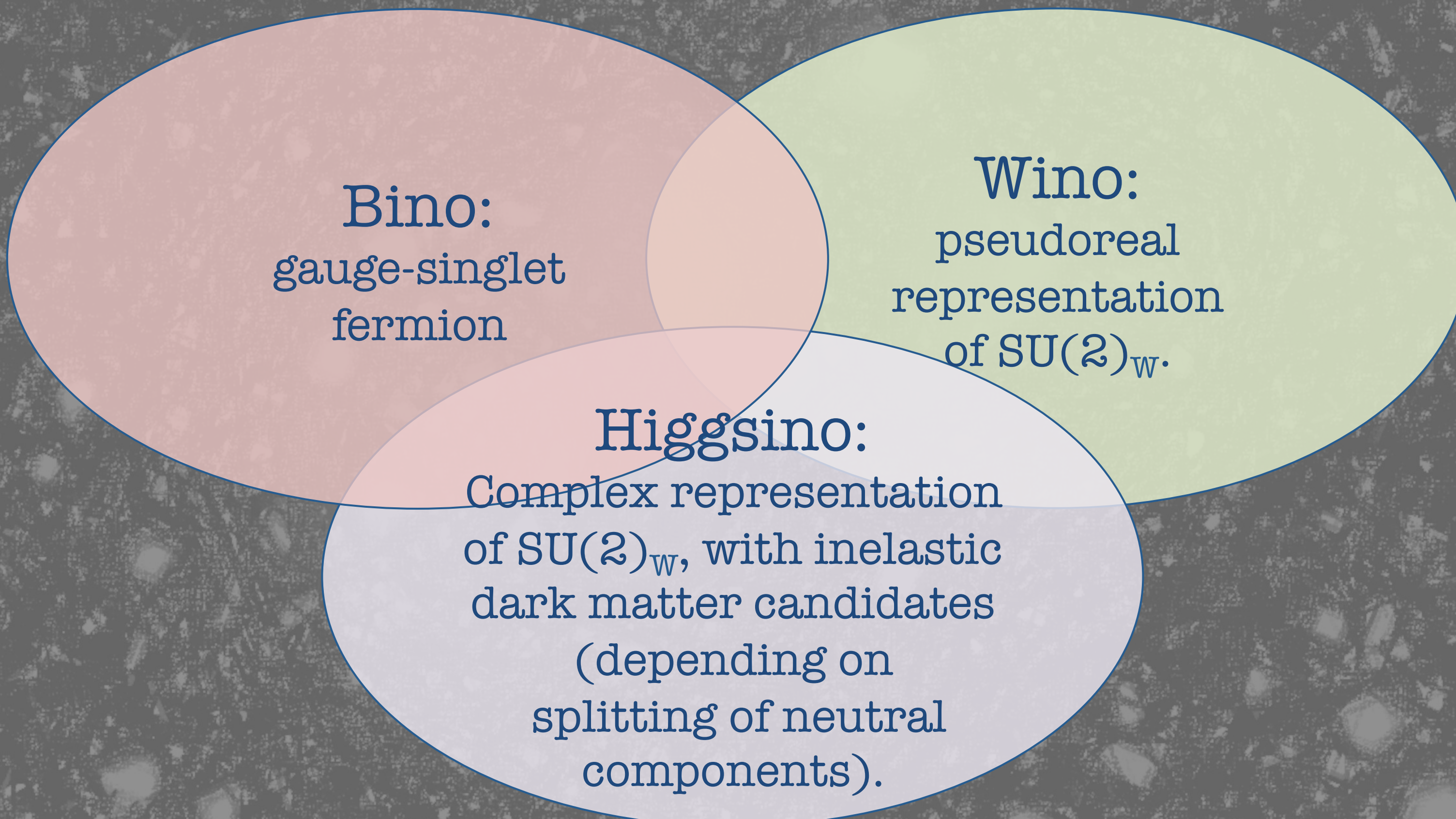
Summary from FCC Report:



The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.

Supersymmetry

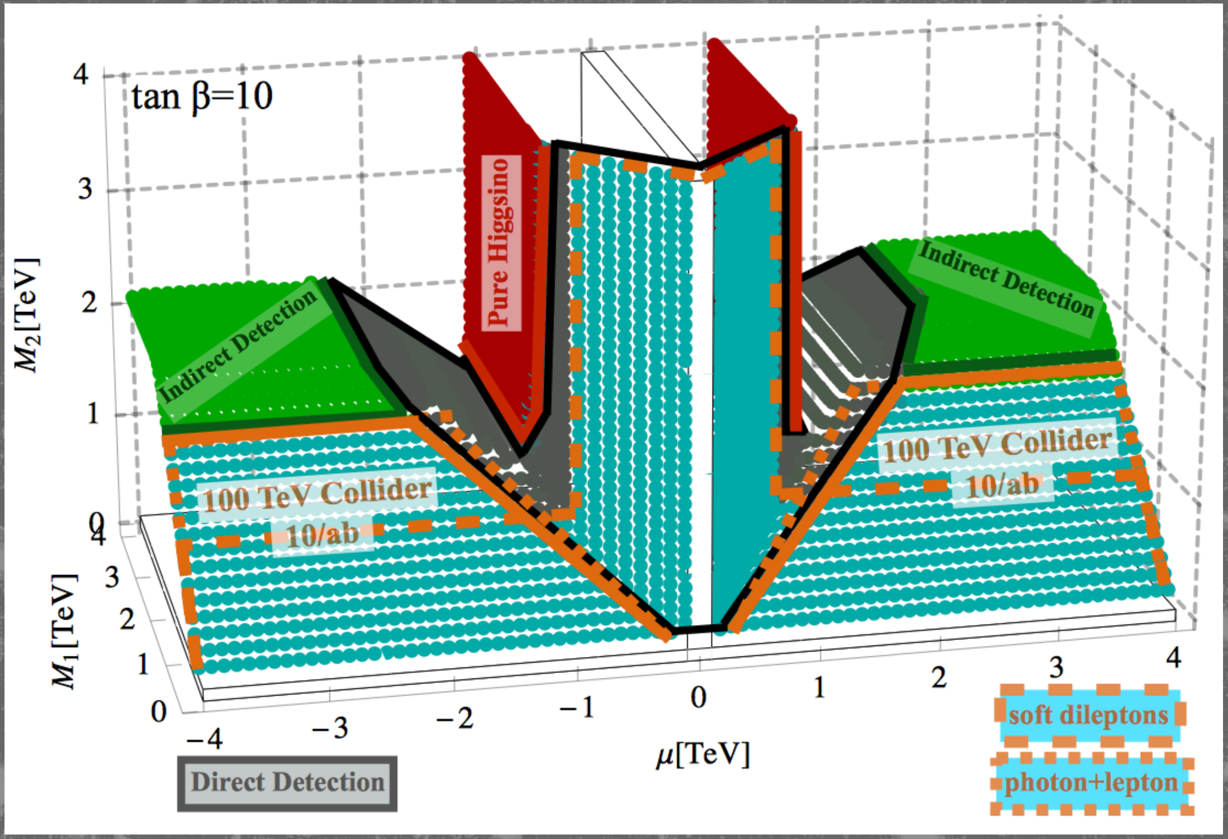
Dark Matter: Neutralino is a compelling ingredient of the SUSY setup:



Relic density points towards no more than few TeV!

Relic Neutralino Surface

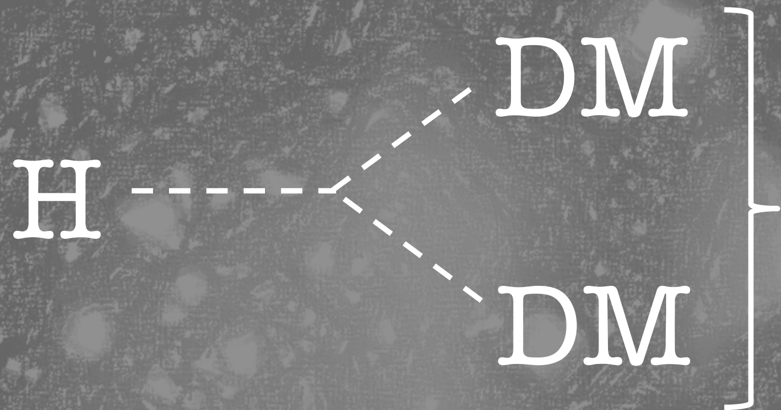
Collider signatures considered: MET + Jet and either soft dileptons or lepton+photon



100 TeV Study: Bramante, Desai, Fox, Martin, Ostdiek, Plehn. 2015.

Dark Times

This means that we can search for new dark sector states by searching for exotic Higgs decays



We don't know what's out there, but there is something, and the Higgs is a great place to look.

Or other quantum modifications of Higgs properties

How can we get there?

How we answer the next fundamental questions will boil down to the uncertainty principle:

Energy Frontier

To probe nature at the smallest distance scales, we must push to the highest momentum scales:

$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

If new particles exist with a tiny Compton wavelength, high energy is the only way to observe them directly.

Intensity Frontier

Alternatively, we may gain indirect access to physics at the highest energies with high precision measurements:

$$\Delta E \geq \frac{\hbar}{2\Delta t}$$

If new interactions exist, beyond the Standard Model, the first cracks could show up in high precision.

Hadron colliders fit both categories.

How can we get there?

How we answer the next fundamental questions will boil down to the uncertainty principle:

Energy Frontier

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$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

If new particles exist with a tiny Compton wavelength, high energy is the only way to observe them directly.

I… rontier

Altern… indire… the h… h prec…

If … be… el, the … w up in high precision.

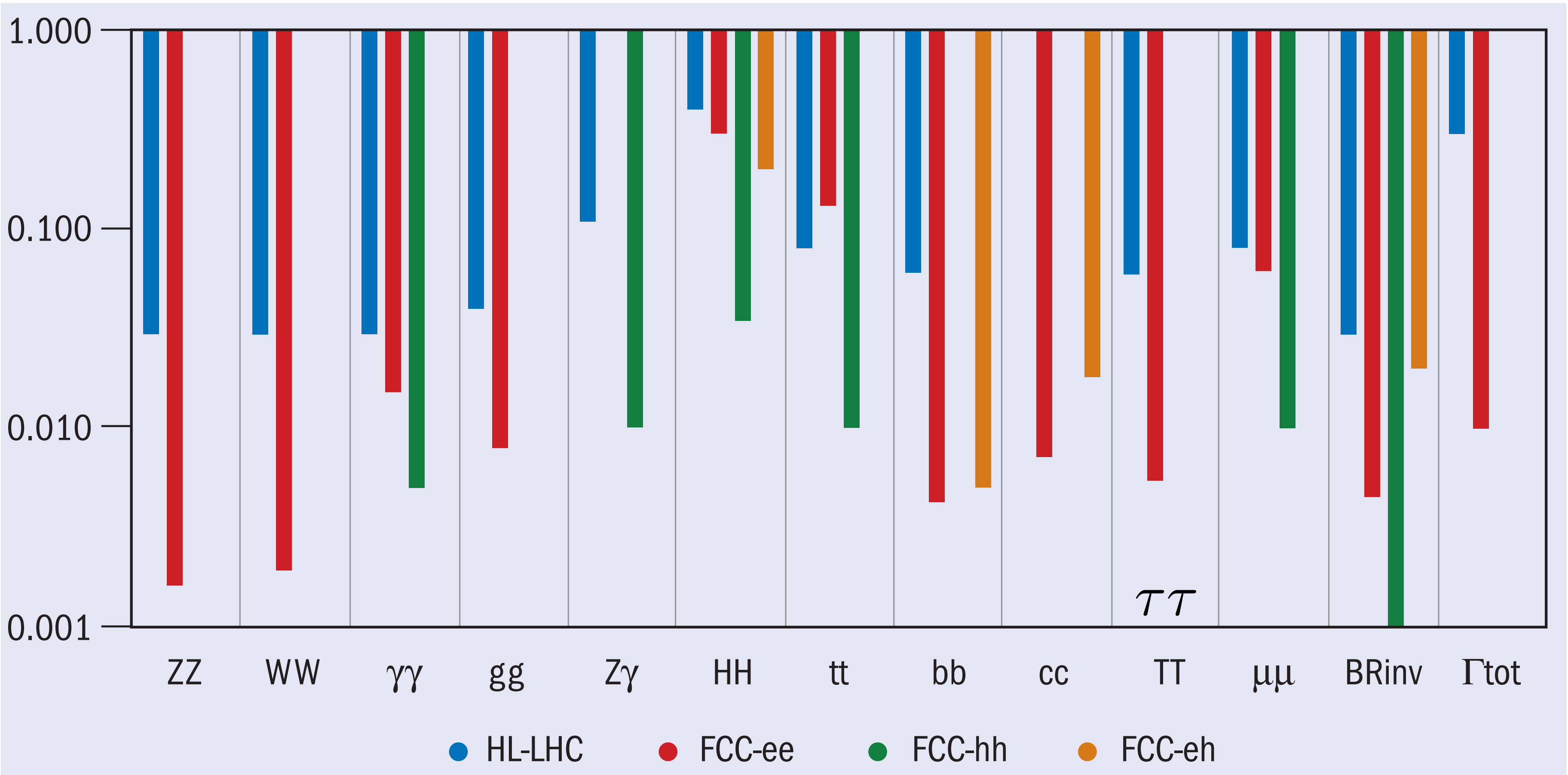
This one not trivial. Consider Breit-Wigner, (amplitude depends on width far from resonance), and:

$$\Gamma = \frac{\hbar}{\tau}$$

Hadron colliders fit both categories.

Higgs at 100 TeV.

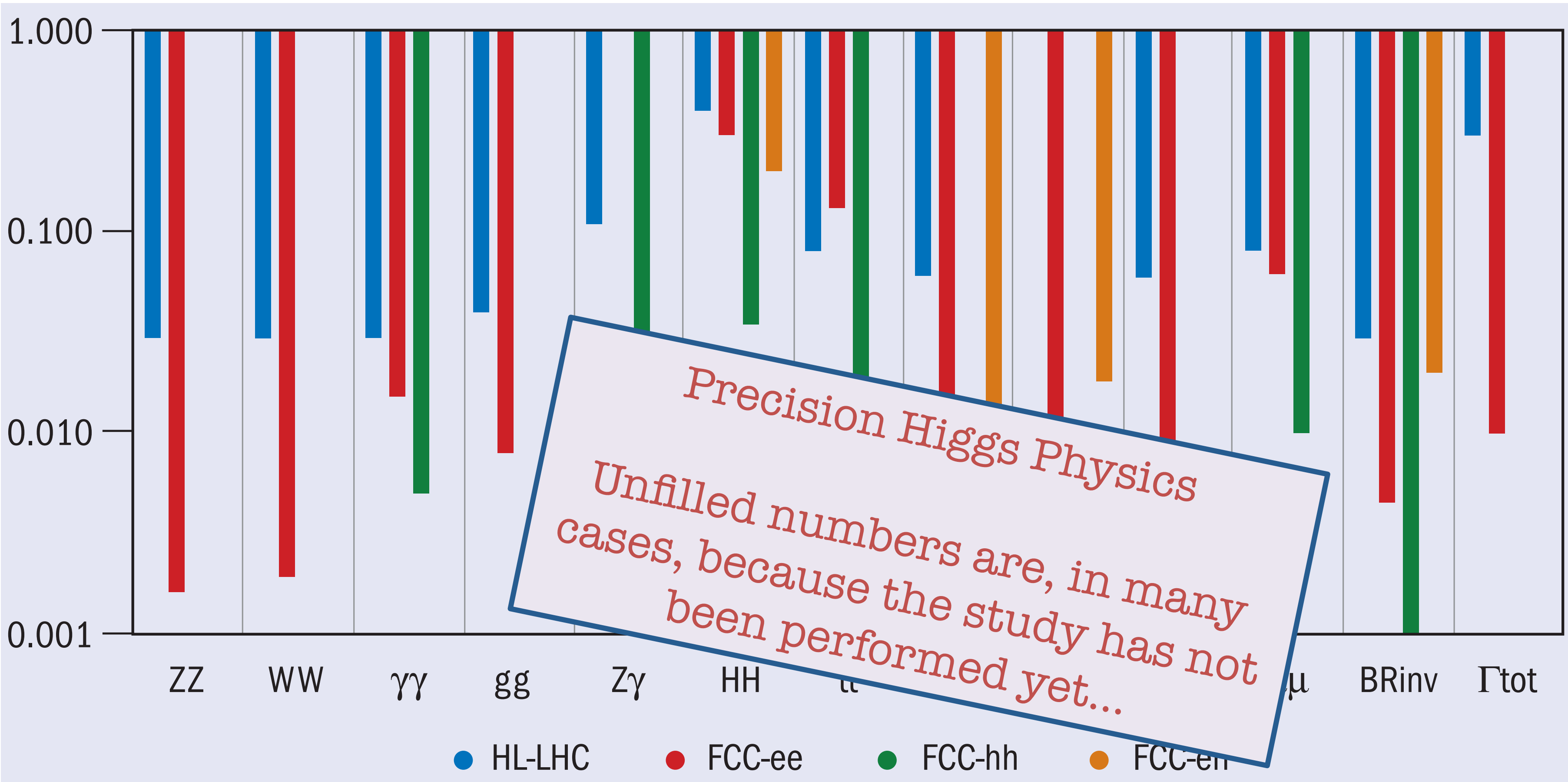
To summarise the Higgs programme…



Note that y-axis is logarithmic!

Higgs at 100 TeV.

To summarise the Higgs programme...



Note that y-axis is logarithmic!

Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.

Dark Matter!

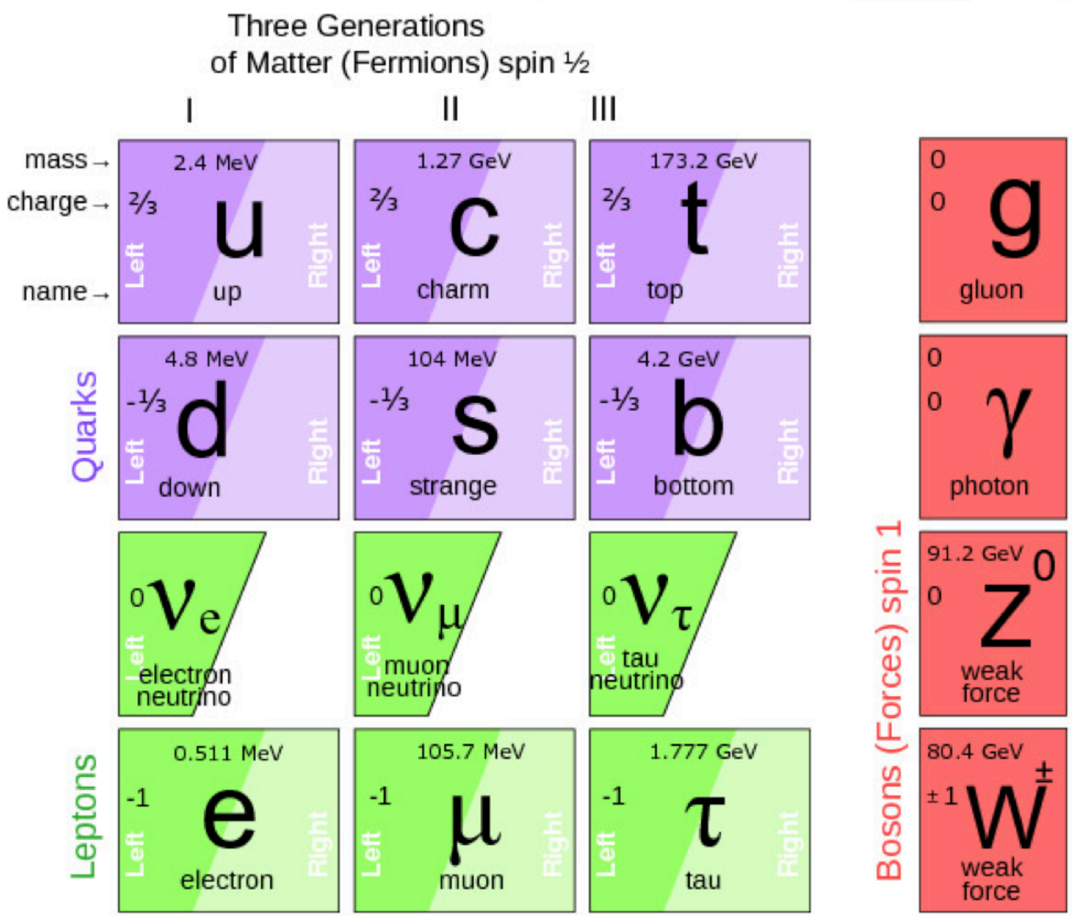
- We <u>have no idea</u> what 80% of the matter in nature is. We have to change this.

Neutrino Masses!

- The renormalisable Standard Model cannot explain this, so what is their origin?

Neutrino Masses!

Someone didn't show up to the party...



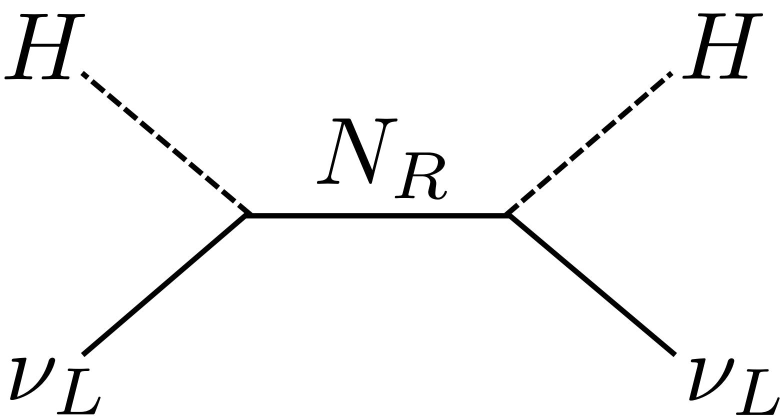
Shaposhnikov et al.

Neutrino masses might be Dirac, but then why such a small interaction with the Higgs? They are all below the eV range...

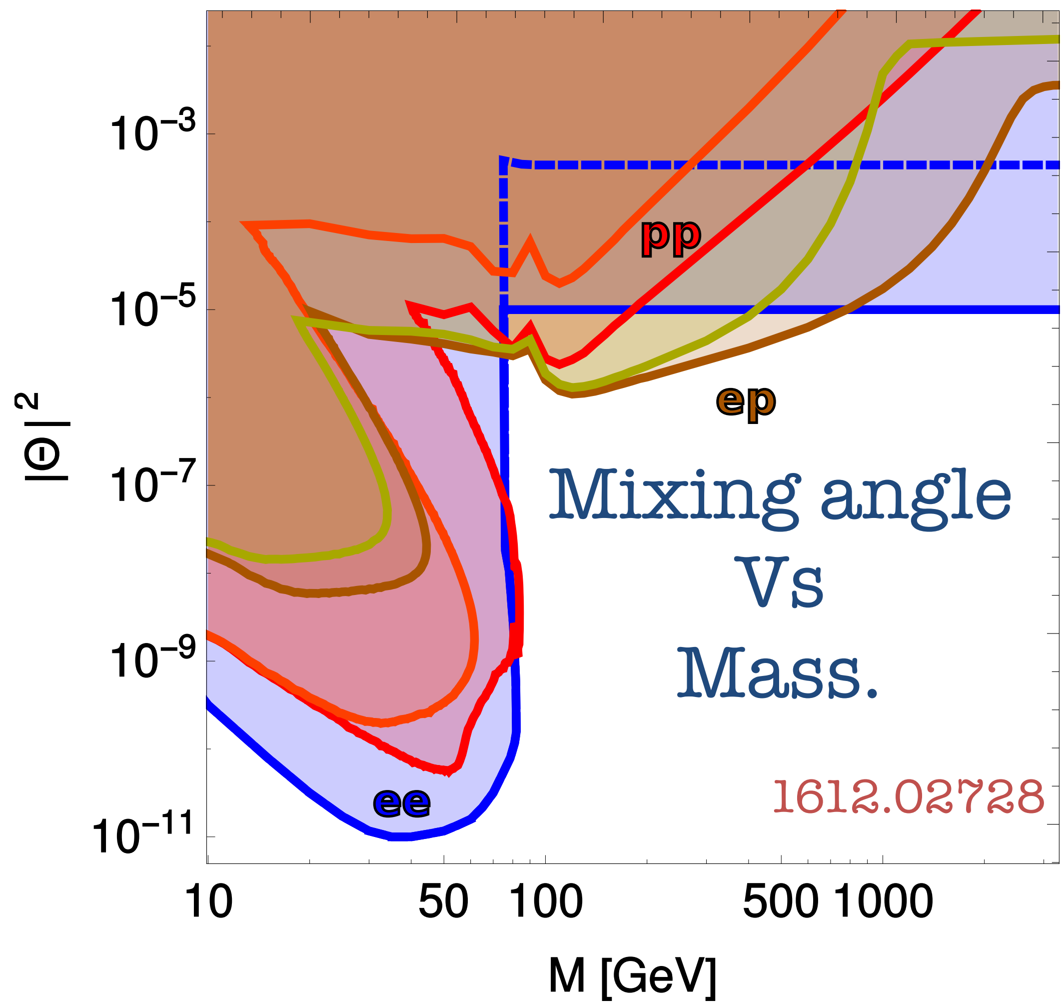
Or Majorana, but then where is the right-handed neutrino?

Neutrino Masses!

Neutrino masses: Long-standing puzzle in fundamental physics.

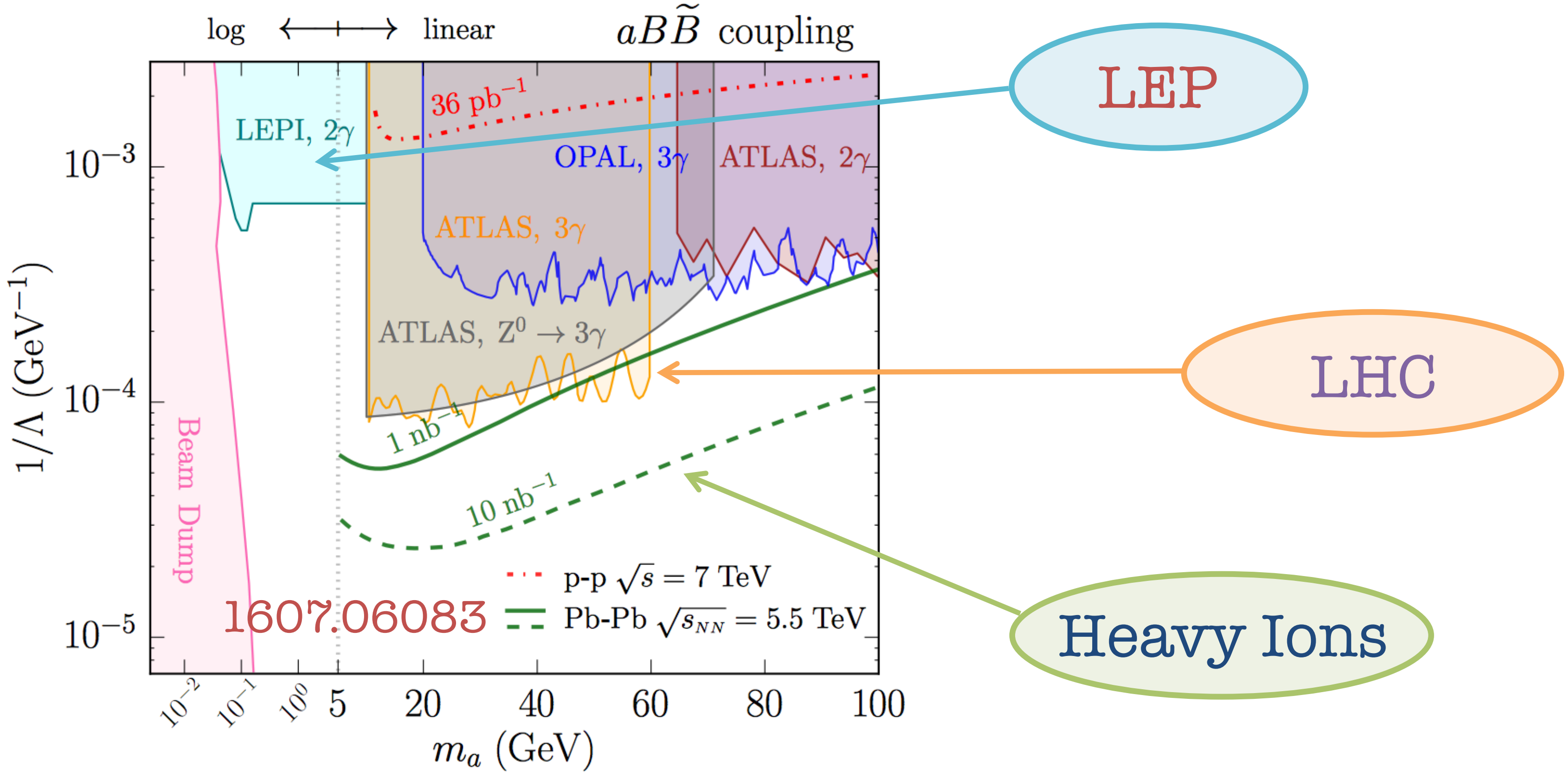


New heavy right-handed neutrinos can generate mass and be at collider energy scales.



Intensity Frontier

LEP+LHC already proven effective



Together they fill the gap from beam dumps to weak scale, but not at "intensity frontier"-level cross sections...

Heavy New Physics

It is a very good idea to consider luminosity ratio plots. They tell us about a vast physics program if e.g. a heavy resonance is discovered...

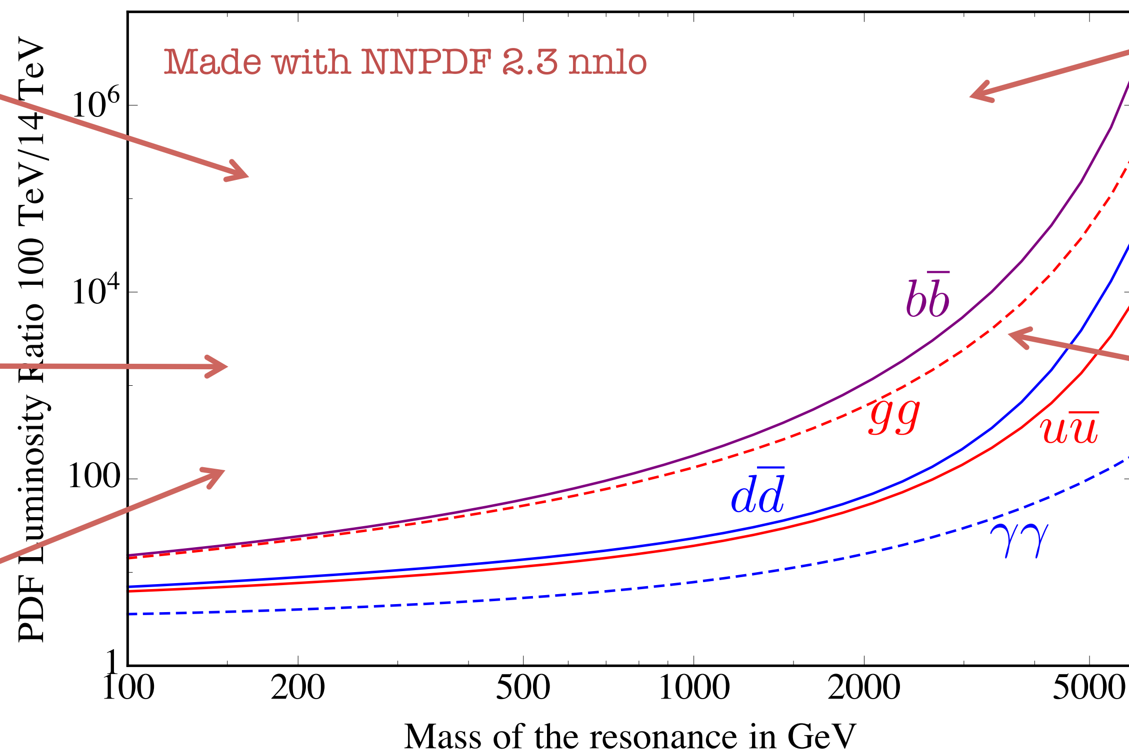
High precision in dominant production modes.

Differential distributions.

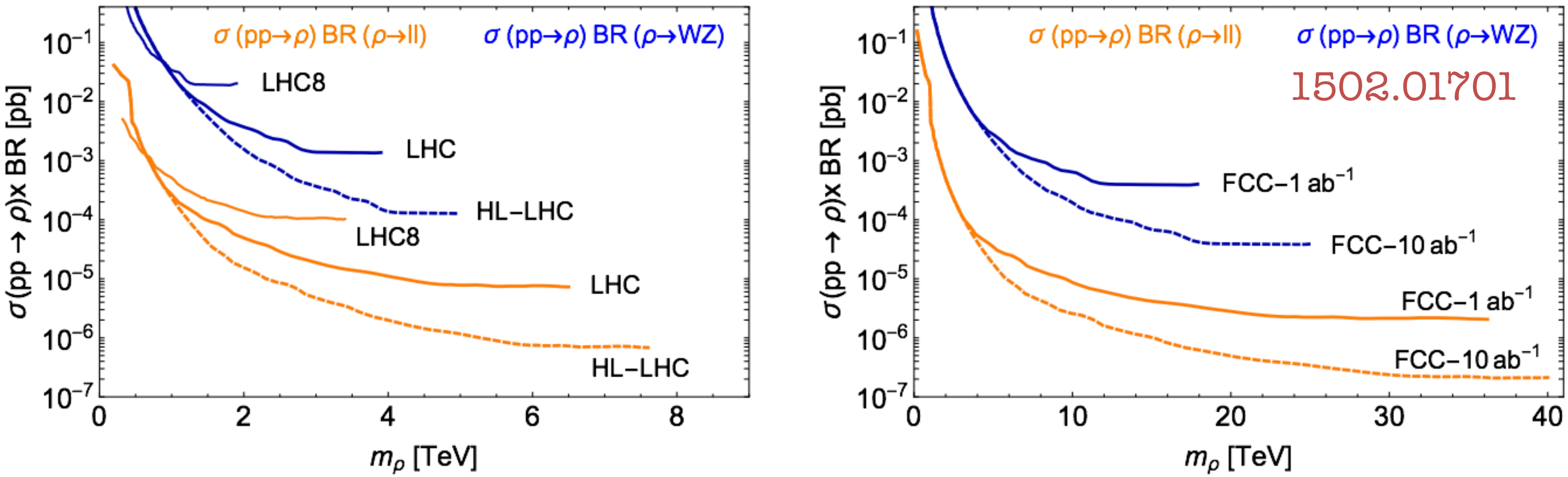
Rare/ associated production modes

Rare/ exotic decays.

For exotic signatures can take full advantage of cross section if background is small. E.g. displaced vertices.



Composite Higgs Models



These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

$$\rho = \bar{f} f \sim \Lambda$$

Should also get other heavy resonances then!