# Physics Opportunities at $e^+e^-$ Colliders

HEP 2021

IAS Hong Kong (Virtually)

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CERN

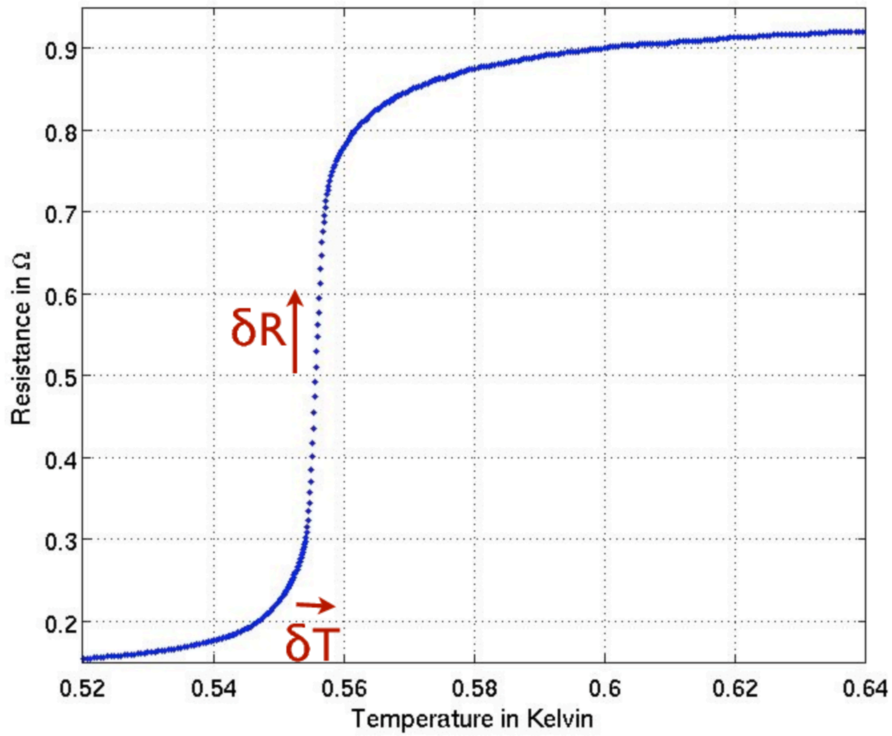
This will, inevitably, be a perspective which is biased, but I'll do my best to cover a few different areas of interest.

Our Universe is like a Superconductor...

and we have no idea why!

# Superconductors in the Lab

At high-T a superconductor does nothing special…




- Taken from 1309.5383

Reduce the temperature and a dramatic phase transition occurs. Vanishing resistance, Meissner effect, etc…

# Ginzburg-Landau

The G-L Theory of superconductivity involves a complex scalar field and the photon

$$\Phi \qquad\qquad A$$

The Free energy for this theory is

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

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

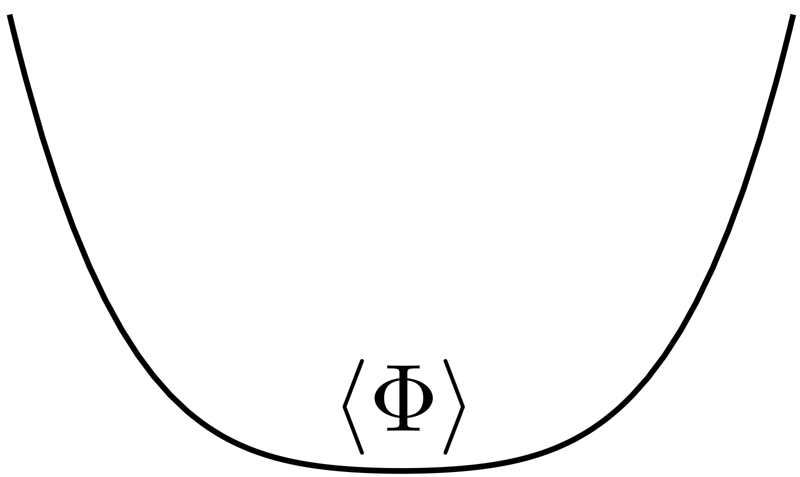
where the mass depends on the temperature.

# 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

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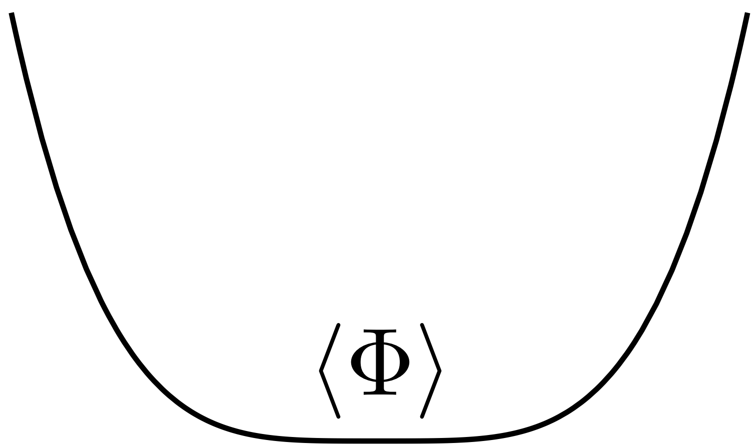


Strange theory with massless fluctuations.

# Ginzburg-Landau

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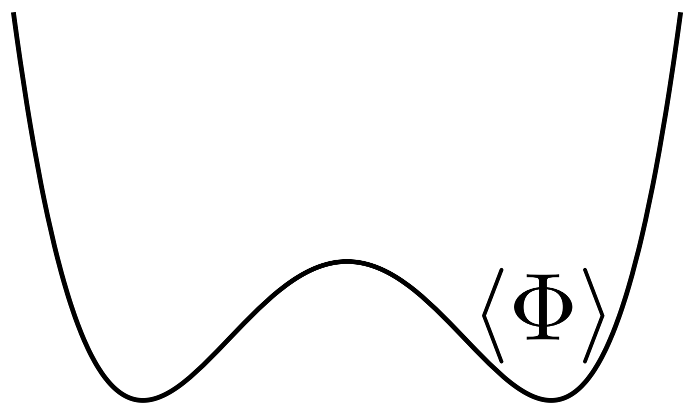
Below the critical temperature the mass-squared is negative:




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

# What does this have to do with the Higgs Boson?

# 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 just like a relativistic, non-Abelian, version of Ginzburg-Landau.

# Higgs Mechanism

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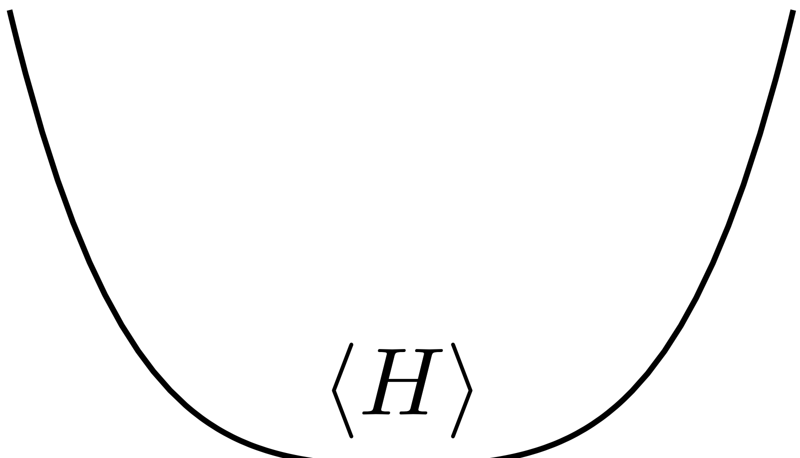


Just a hot relativistic gas.

# Higgs Mechanism

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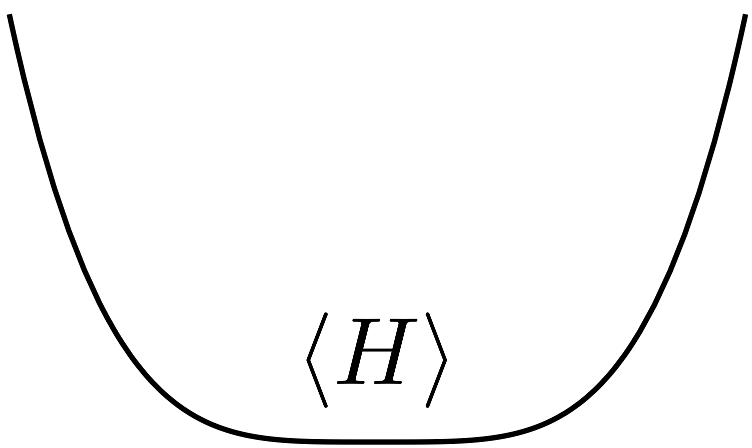


Higgs boson is massless at this point.

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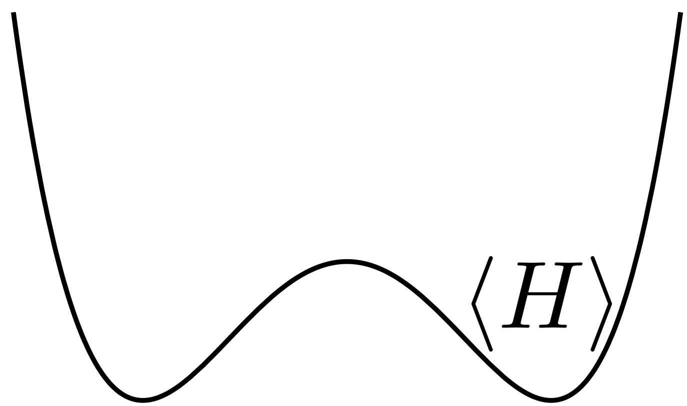



Gauge bosons become massive: $M_W \sim g\langle H \rangle$

# The Elephant in the Room

Ginzburg-Landau is a phenomenological model, with no explanation of parameters.


Fortunately, however, we can understand the origins of superconductivity from the detailed microscopic BCS theory (Gor'kov).

# The Elephant in the Room

Like GL, the Higgs sector is a phenomenological model, with no explanation of parameters.


Unlike GL, we have no understanding of the microscopic origins of the Weak Scale! (No BCS for the Higgs sector, yet...).

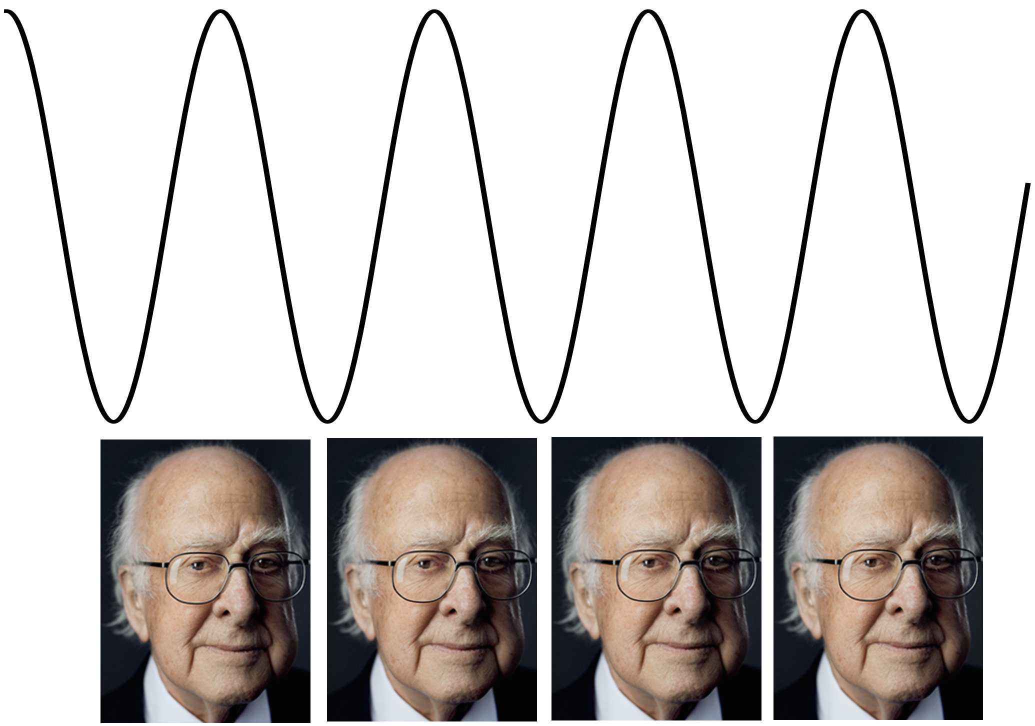
# Next Steps:

An $e^+e^-$ Higgs factory is the blindingly obvious next step!

Put the Higgs boson under a magnifying glass!

# Higgs Factories

- The Higgs boson has a size/wavelength. What's inside?



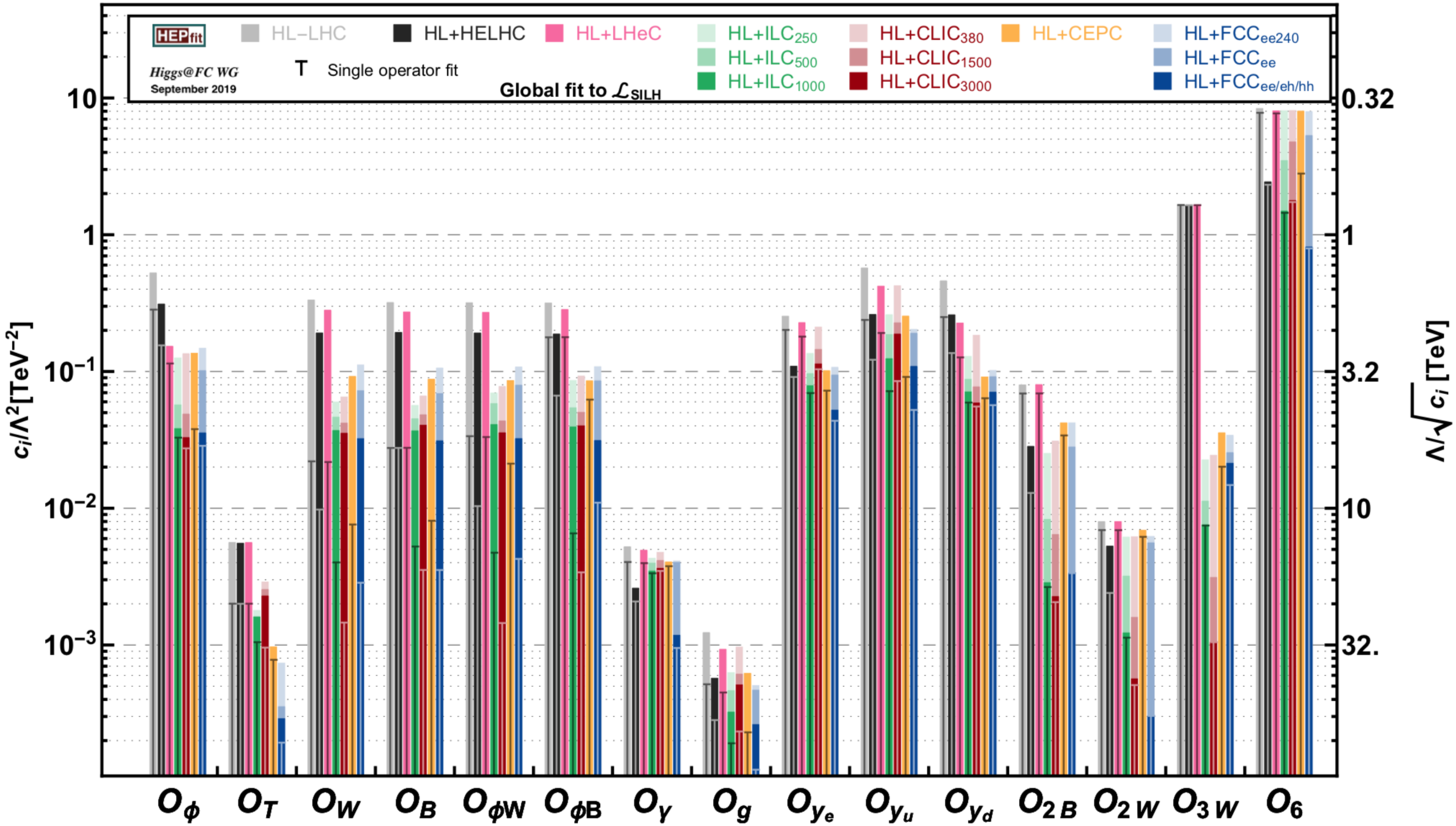
Precision measurements are different ways of probing the "compositeness of the Higgs".

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

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

# Higgs Factories

- Unprecedented examination of the Higgs boson:

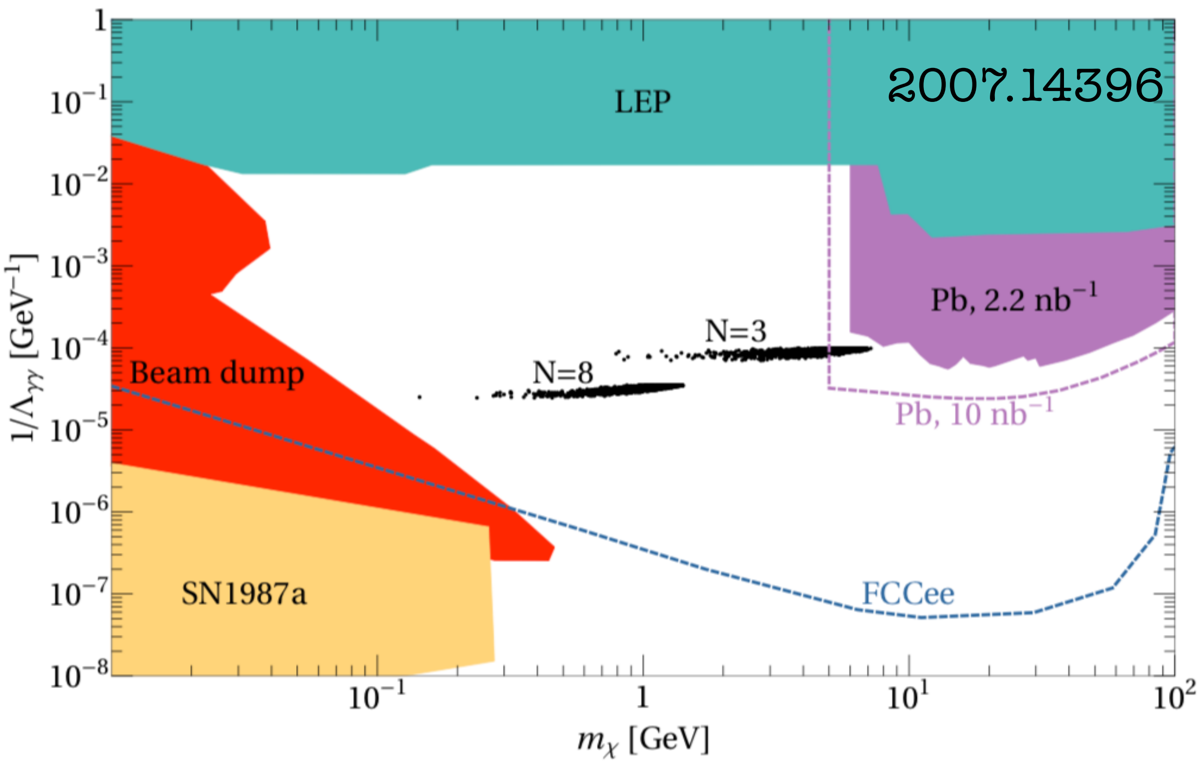



$$\lambda_h \approx 10^{-17}\ \text{m}$$

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

# Origins of the Weak Scale

Theorists have been exploring many connections between the origin of the Higgs mass and the cosmology. One example: "Crunching Dilaton".

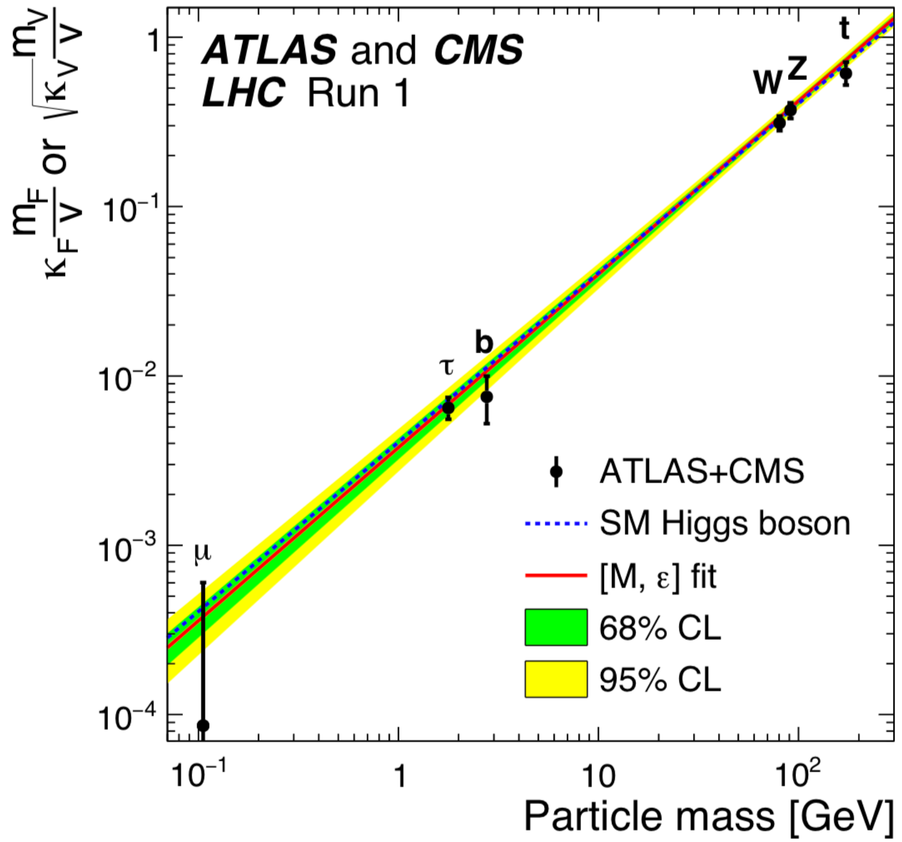



Future Z-factories are by far the most comprehensive probes of this scenario!

# The origin of mass.

# Higgs Couplings

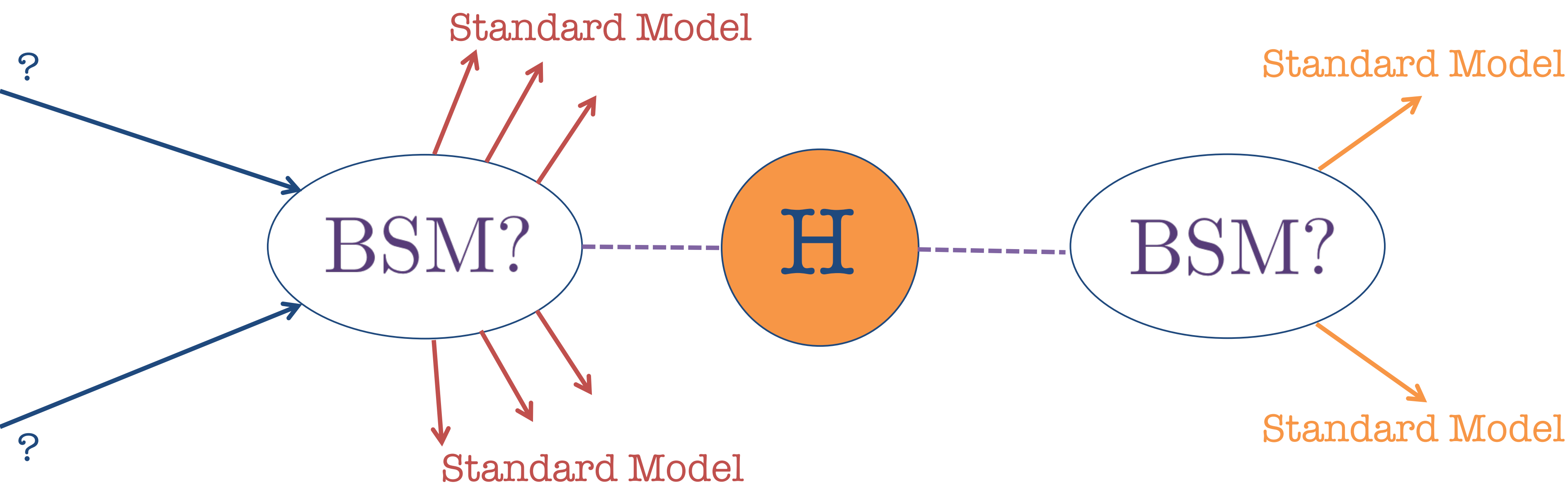
By measuring how a massive fundamental particle interacts with the Higgs boson




we measure how that particle got mass.

# Higgs Couplings

Production and decay of Higgs through couplings:




What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery it exists: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

# Higgs Factories

## Summary:

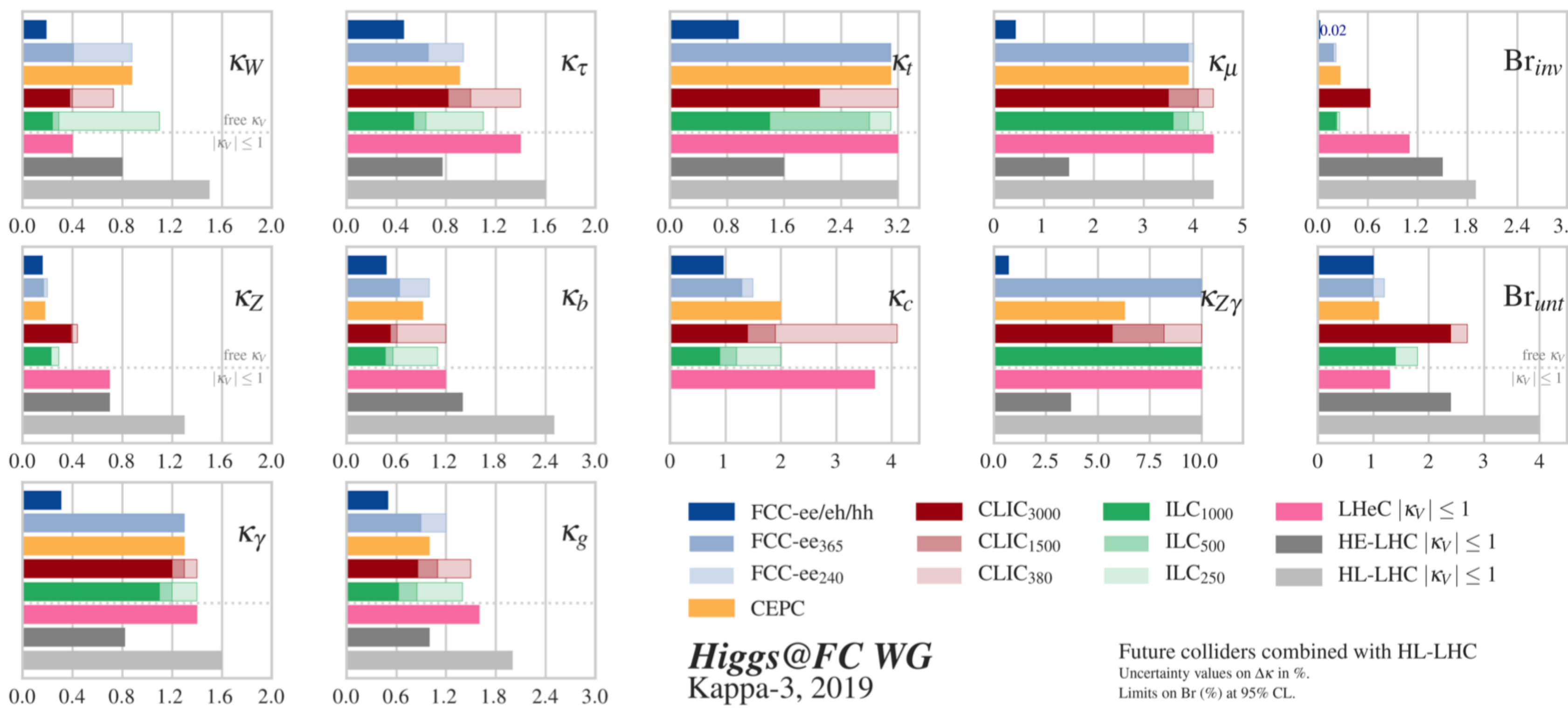
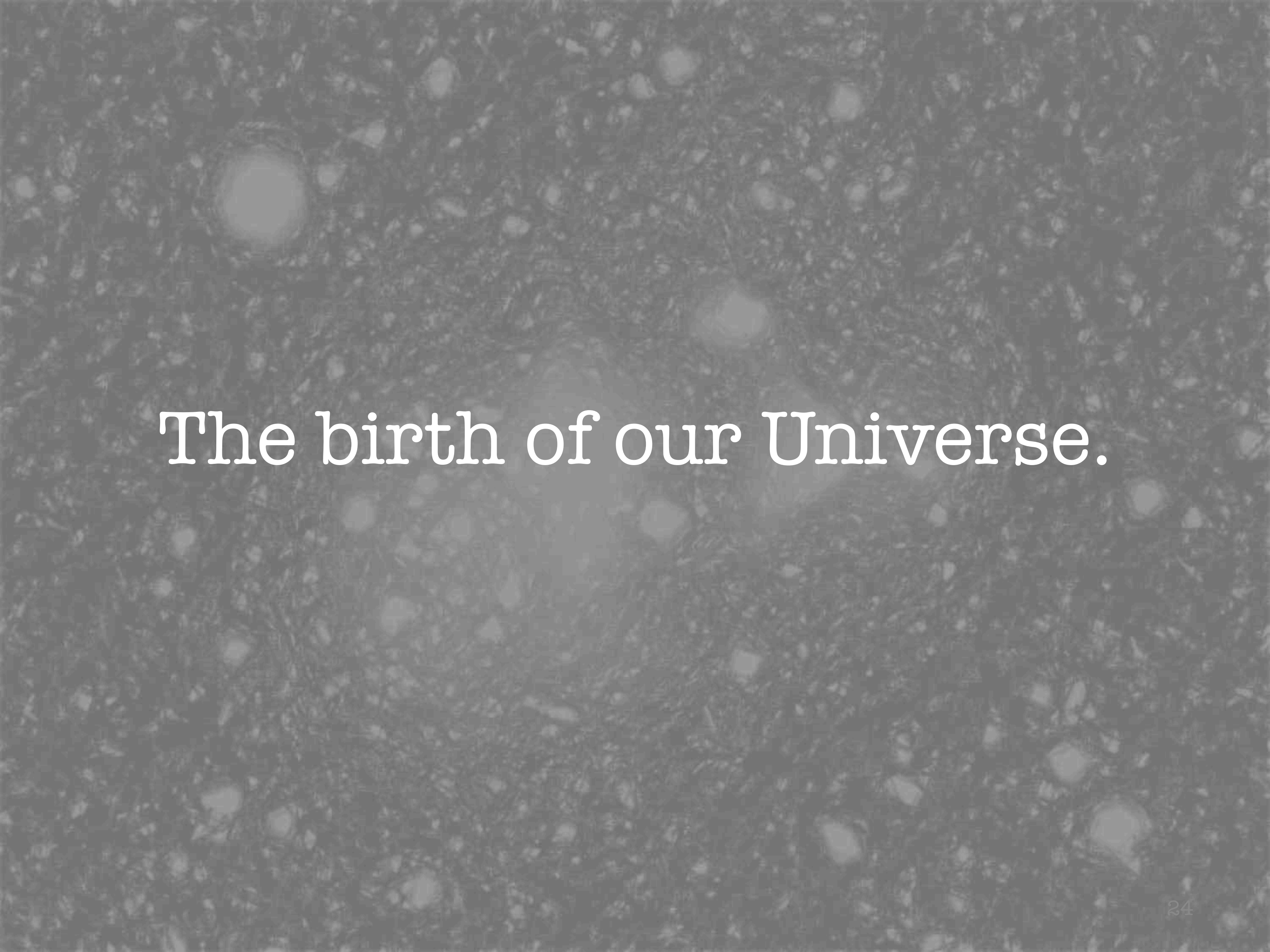


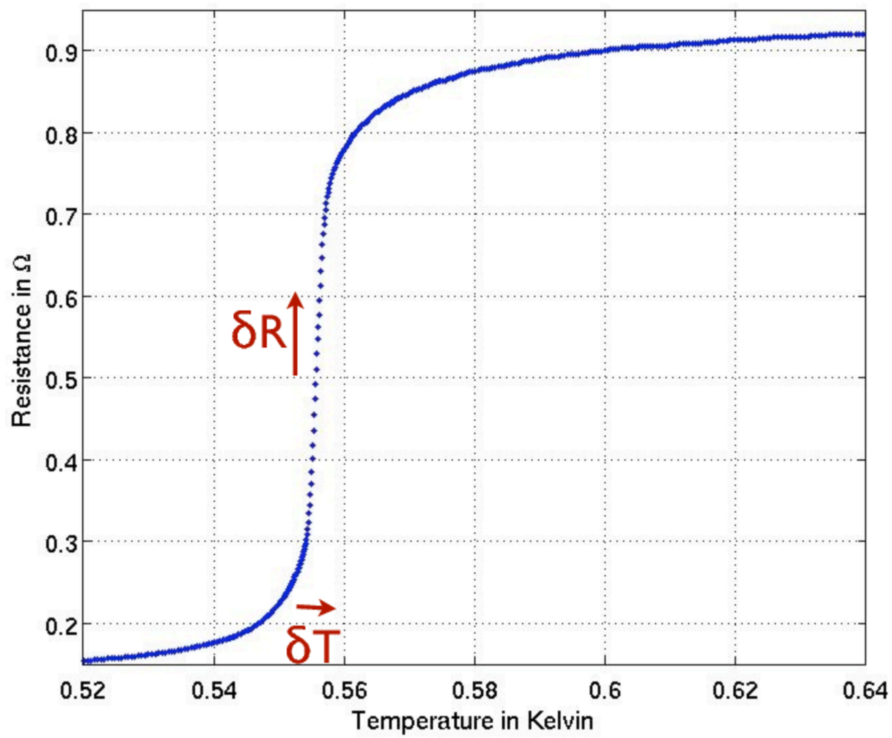

**Figure 2.** Expected relative precision (%) of the $\kappa$ parameters in the kappa-3 scenario described in Section 2. For details, see Tables 4 and 5. For HE-LHC, the S2' scenario is displayed. For LHeC, HL-LHC and HE-LHC a constrained $\kappa_V \leq 1$ is applied.

Higgs factories offer enormous precision, digging deep into quantum structure of the Higgs boson!


The birth of our Universe.

# The Electroweak Phase Transition

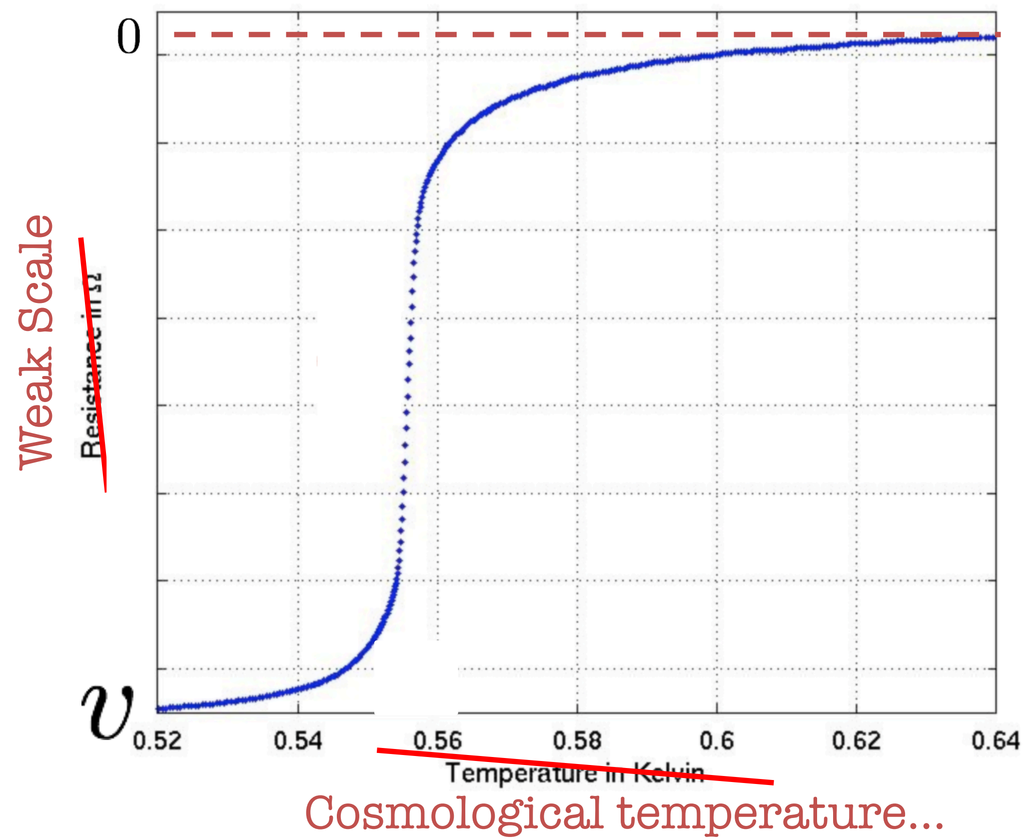
With a superconductor we can tune the temperature up and down




and study the details of the phase transition.

# The Electroweak Phase Transition

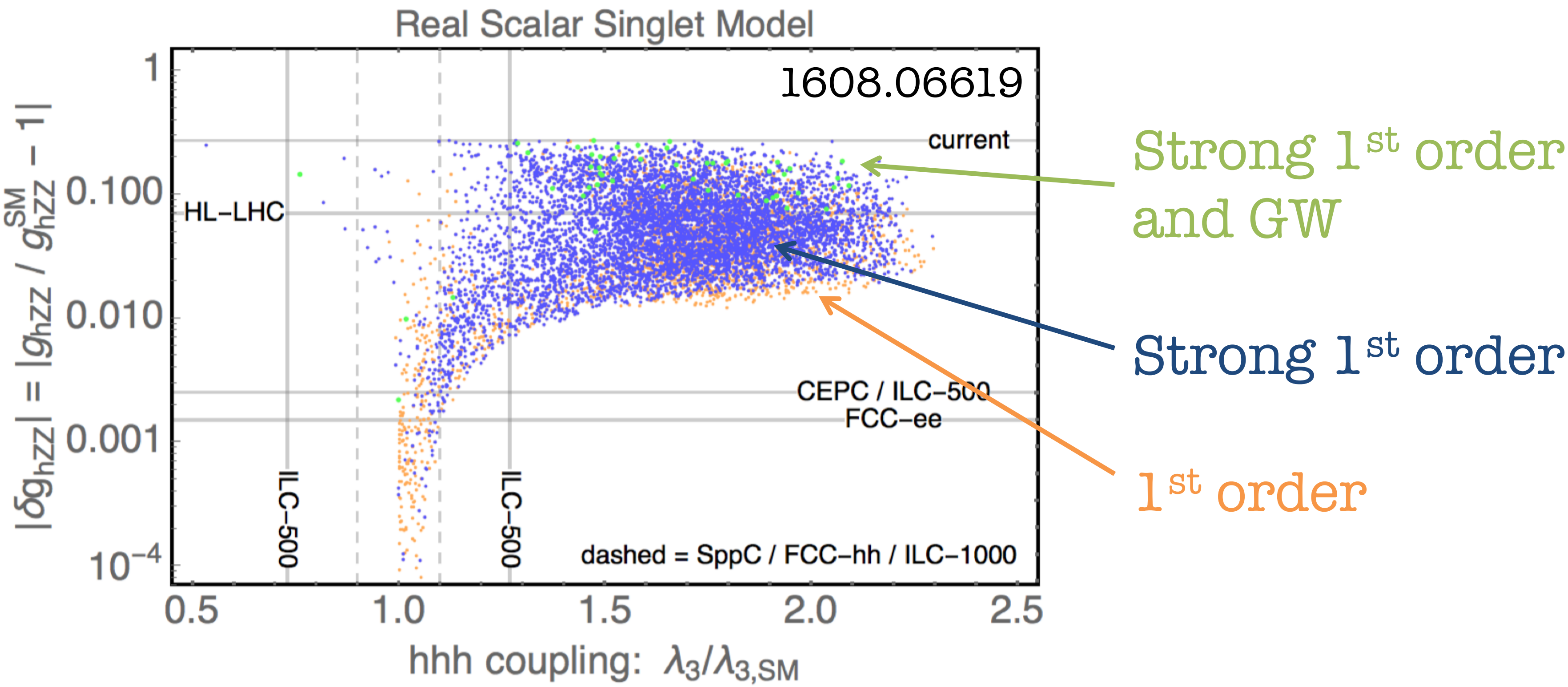
The EW phase transition only happened once, a long long time ago. How can we tell what happened,




and study the details of the phase transition?

# The Electroweak Phase Transition

Difficult to make model-independent statements, however scenarios with modified EWPT produce correlated deviations in precision Higgs. Example:




Very simple: Add a singlet scalar.

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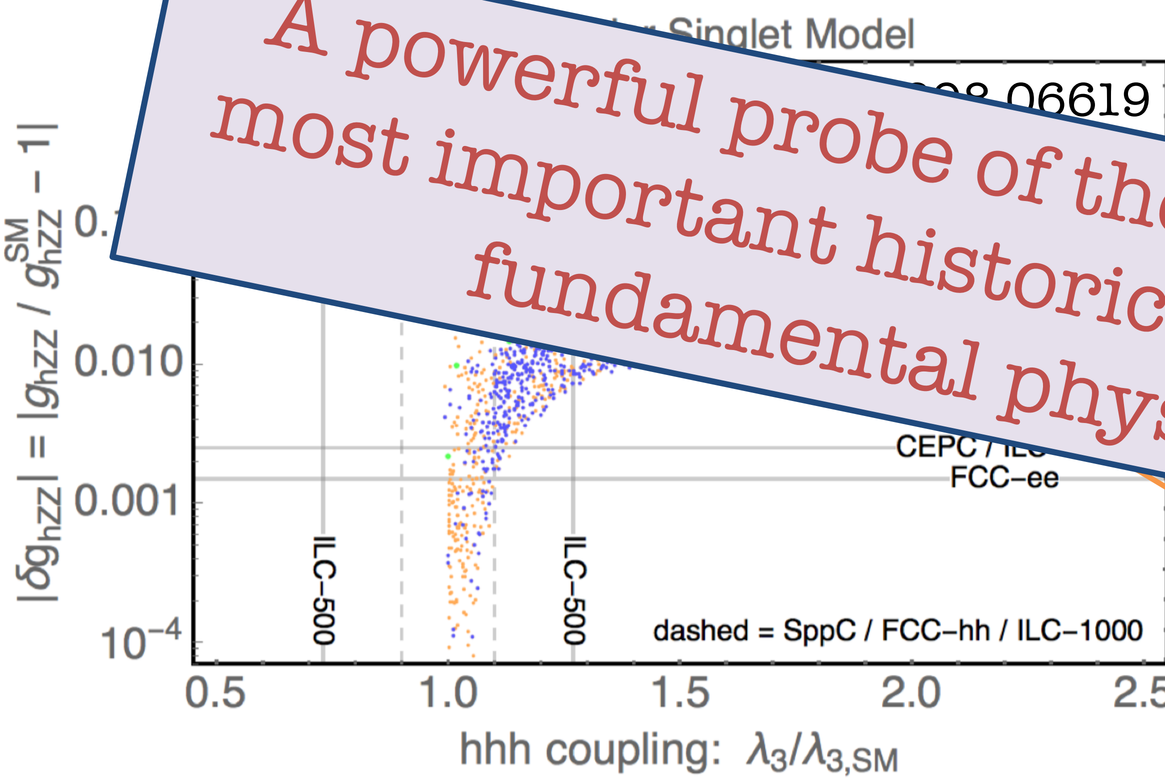



Strong 1$^{st}$ order

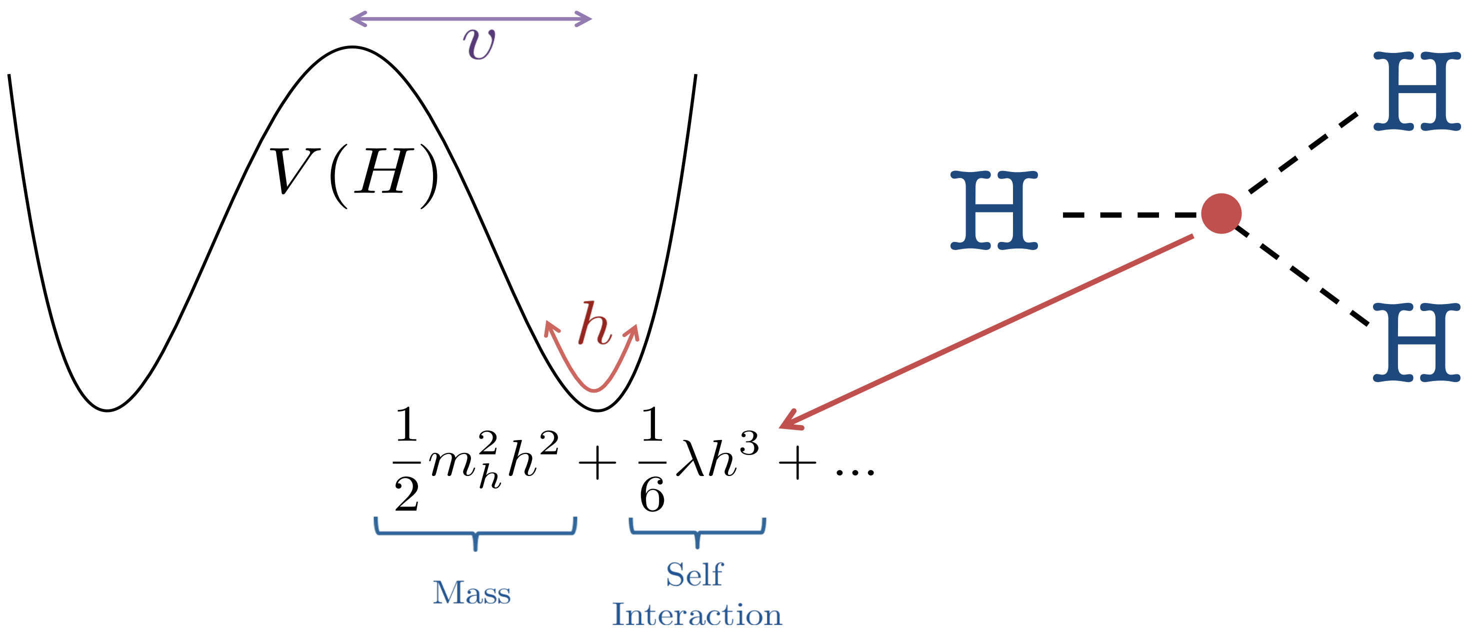
1$^{st}$ order

A powerful probe of the one of the most important historical events in fundamental physics.

Very simple: Add a singlet scalar.

# The Shape of the Potential

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




Discovering the Higgs was difficult enough, now we want to know how it interacts with itself...

# A Unique Operator

However,

$$\mathcal{O}_6 = \frac{c_6}{M^2} |H|^6$$

is also very very special, since:

$$[c_6] = C^4 \quad , \quad [\hbar] = C^{-2}$$

At one-loop we have:

$$[\hbar c_6] = C^2$$

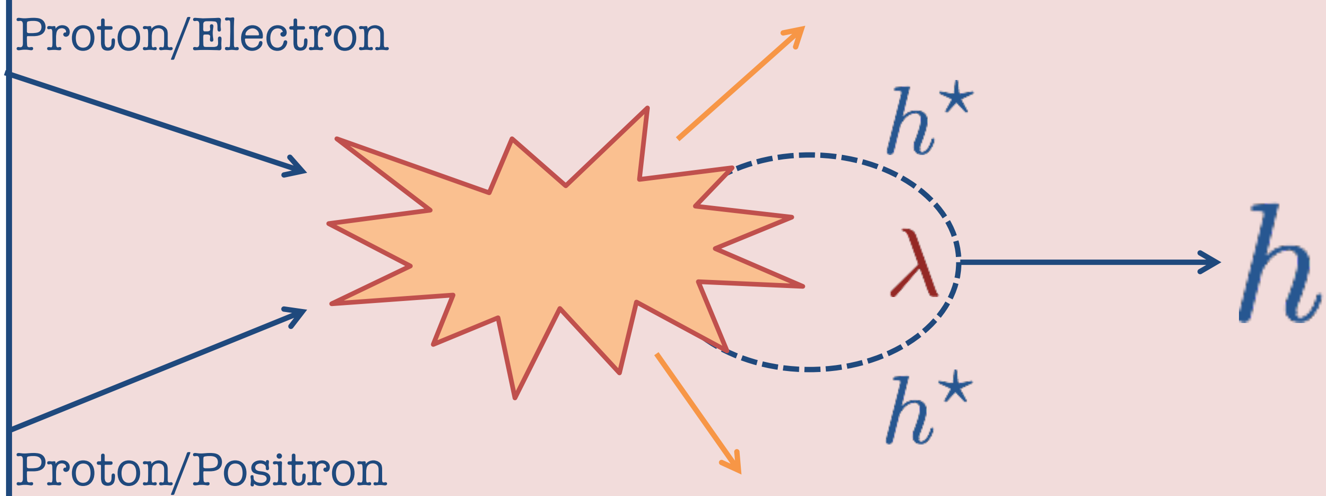
Thus, if <u>any</u> other coupling enters the game, coupling dimension is too large to match any other dim-6 operator!

# A Unique Operator

Observation:

$$\mathcal{O}_6 \xrightarrow{\text{One-loop running}} \mathcal{O}_6$$

This operator is a mountain-top in RG-space.




Insert into any one-loop diagram and no dim-6 counterterms will be required, result always finite!

# A Unique Operator

Observation:

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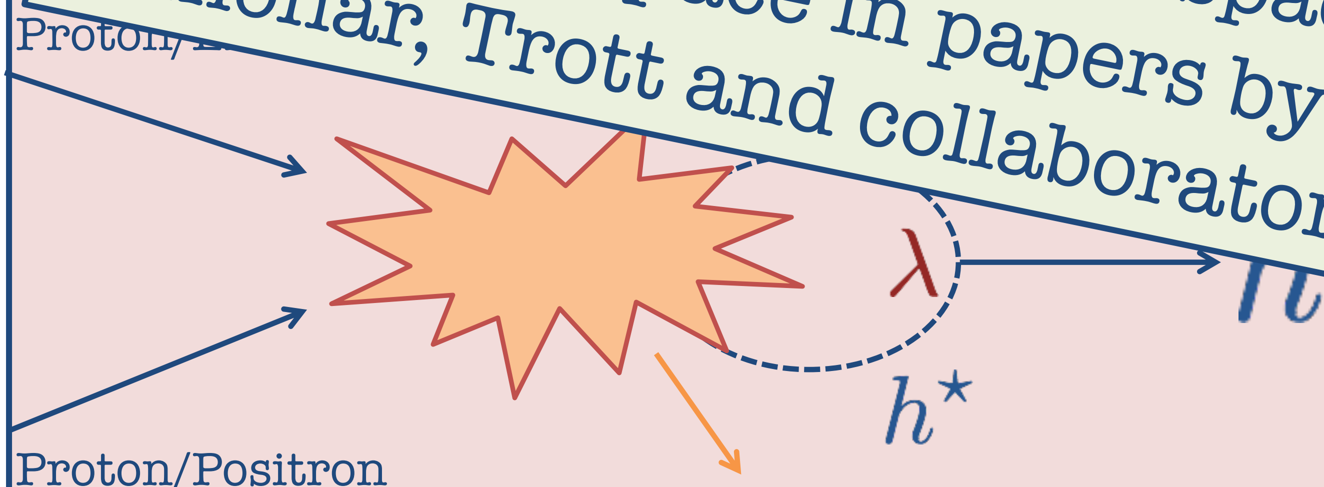
…ain-top in RG-space.

Can see where it lies in the space of Dim-6 operator RG space in papers by Jenkins, Manohar, Trott and collaborators…

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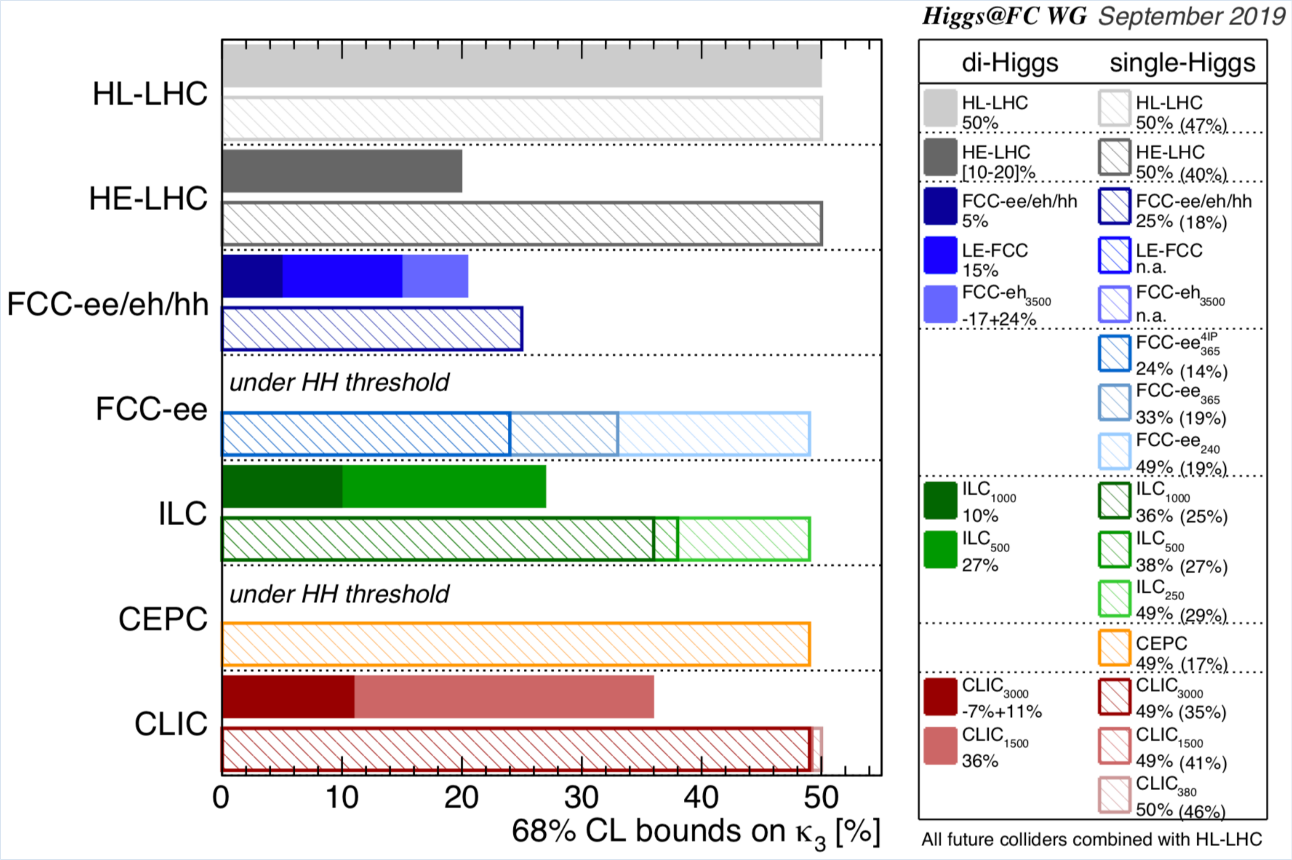
# A Unique Operator

At high energies we can use Higgs pair production, at low energies quantum effects:




ECFA Higgs Working Group Report 1905.03764

This is the future of the Higgs self coupling (Higgs potential)…

# Dark Sectors

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!

?

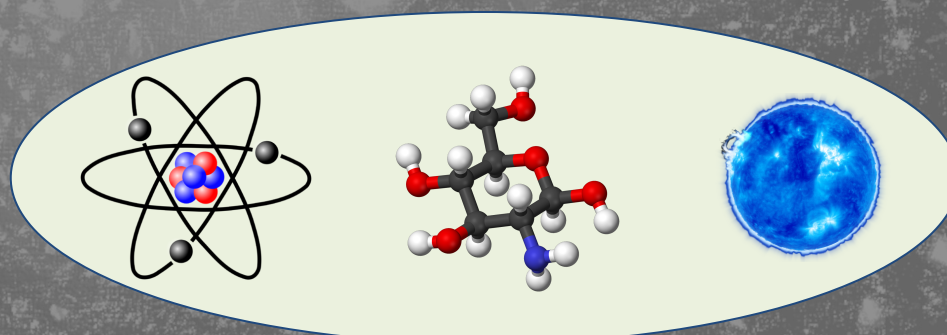
Only 18% of all matter in Universe is visible.

$e \quad u \quad d \quad Z \quad h$

$\mu \quad c \quad s \quad g$

$\tau \quad t \quad b \quad \gamma \quad W$

Within that 18% we observe extraordinary complexity.

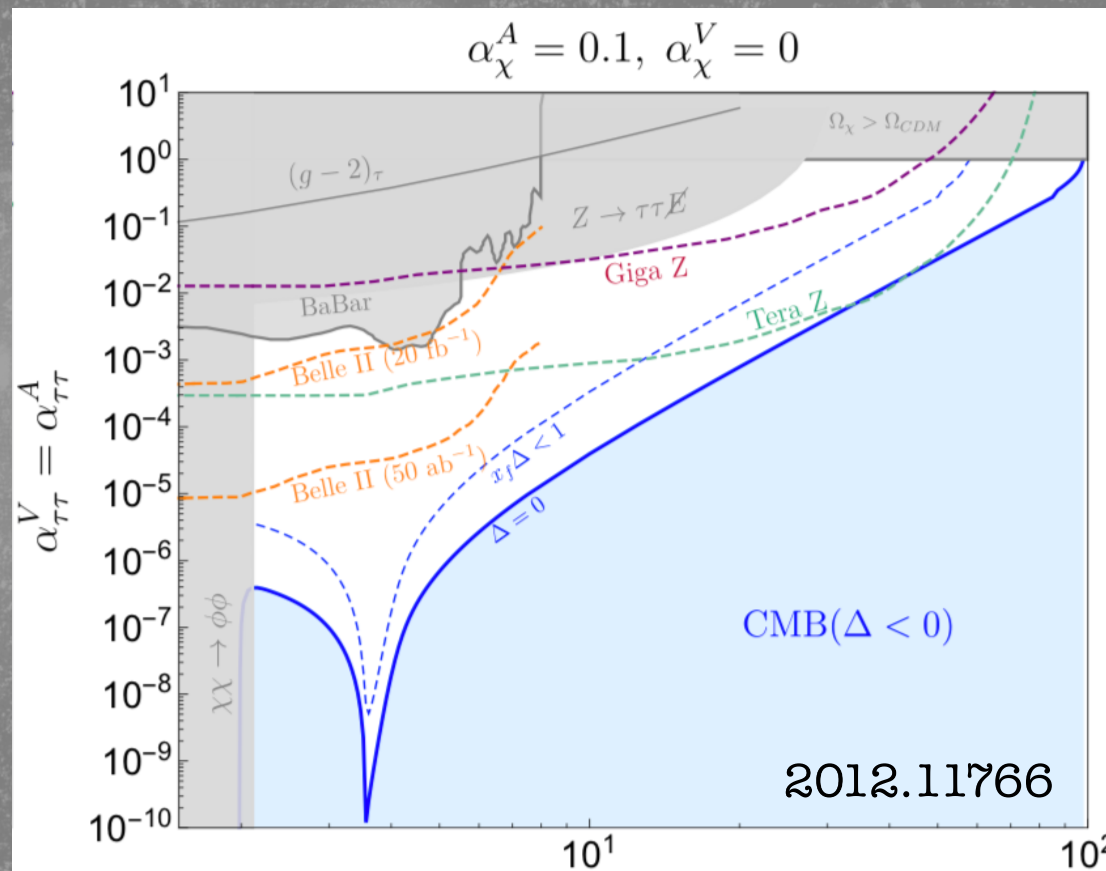


Similarly, the dark sector, and dark matter, may be much more complex than just a single state.

# New Models – New Searches

Theorists are constantly developing new models to understand the origin of dark matter. Forbidden dark matter is one example

$$\chi\chi \rightarrow \tau\tau$$




where a Tera-Z program offers a unique probe!

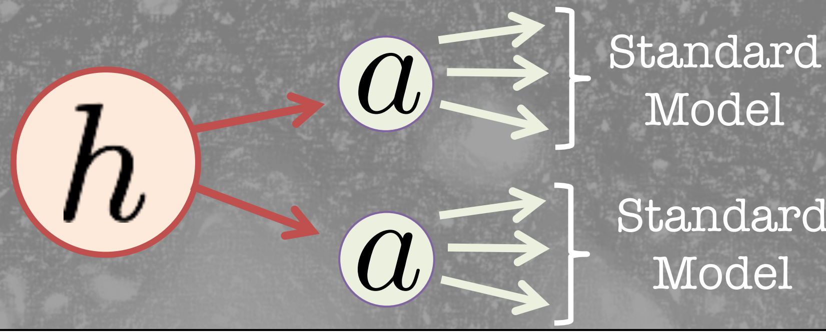
# Comment: On Energy

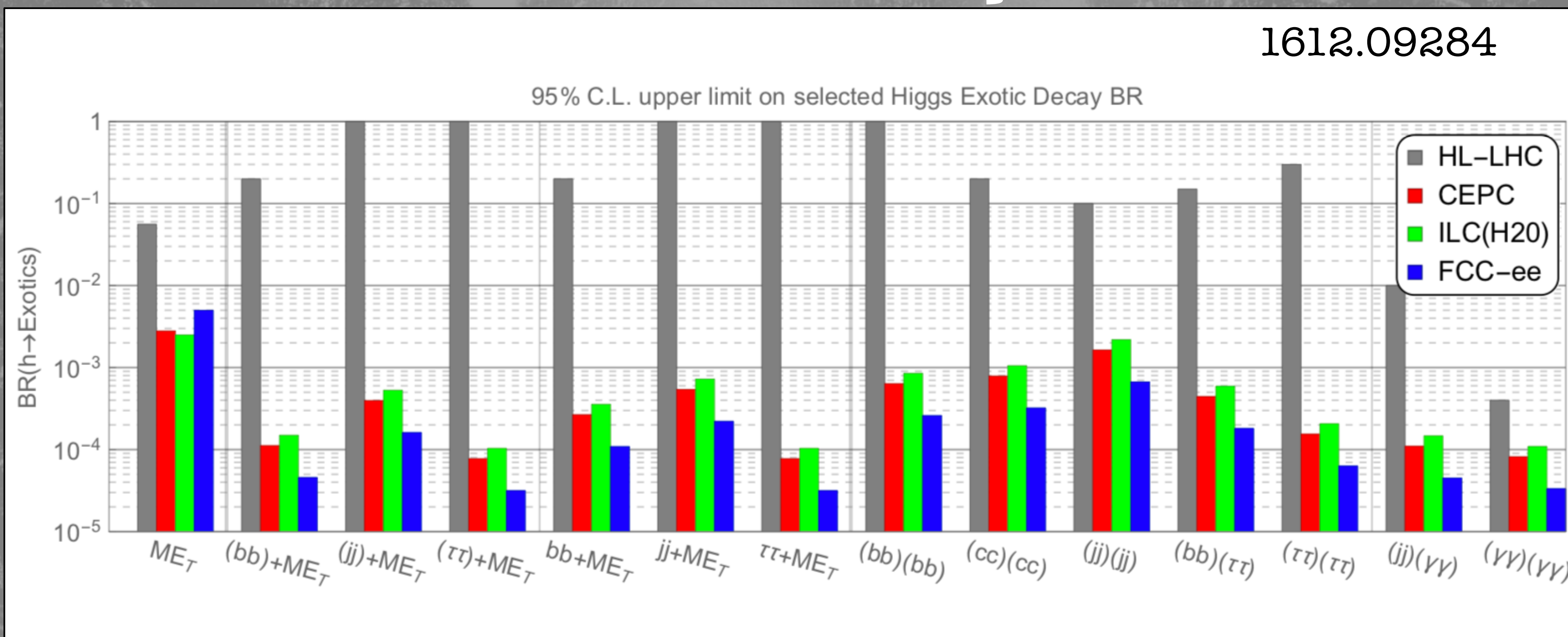
It is tempting to associate the weakly coupled frontier with the low mass range. Why?

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

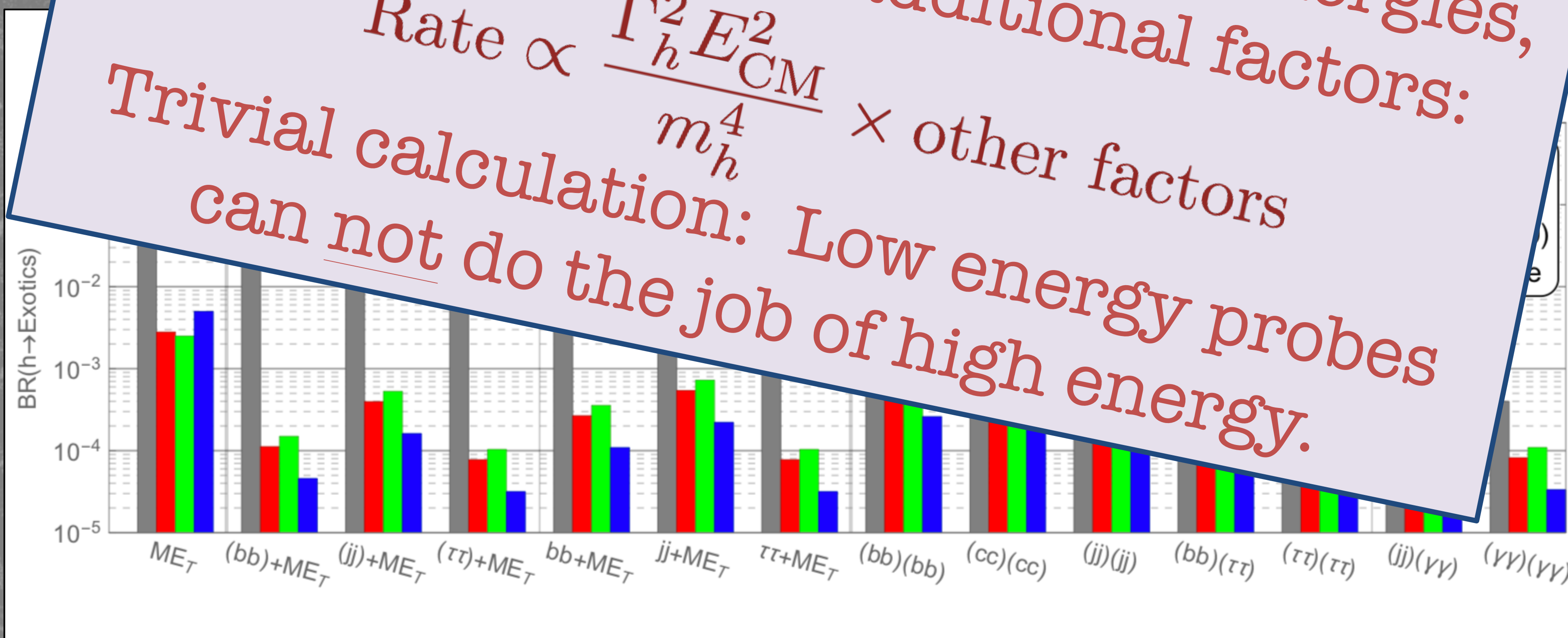
The […] is totally different from other particles and […] window to the dark sector:

Standard

The only way to search for such scenarios is with a Higgs boson. At lower energies, suppressed by tiny additional factors:

$$\text{Rate} \propto \frac{\Gamma_h^2 E_{\text{CM}}^2}{m_h^4} \times \text{other factors}$$

Trivial calculation: Low energy probes can not do the job of high energy.



# Conclusions

After the discovery of the Higgs Boson fundamental physics is now poised to ask the big, structural, questions.


The only way we can hope to understand the origin of this weird superconducting Universe we live in is to measure every facet of the Higgs.