The BSM Landscape at CEPC

CEPC International Workshop

Shanghai
Oct 27th 2020

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CERN

Wherefore art thou BSM?

Dark Sectors

Evidence for dark matter is now overwhelming

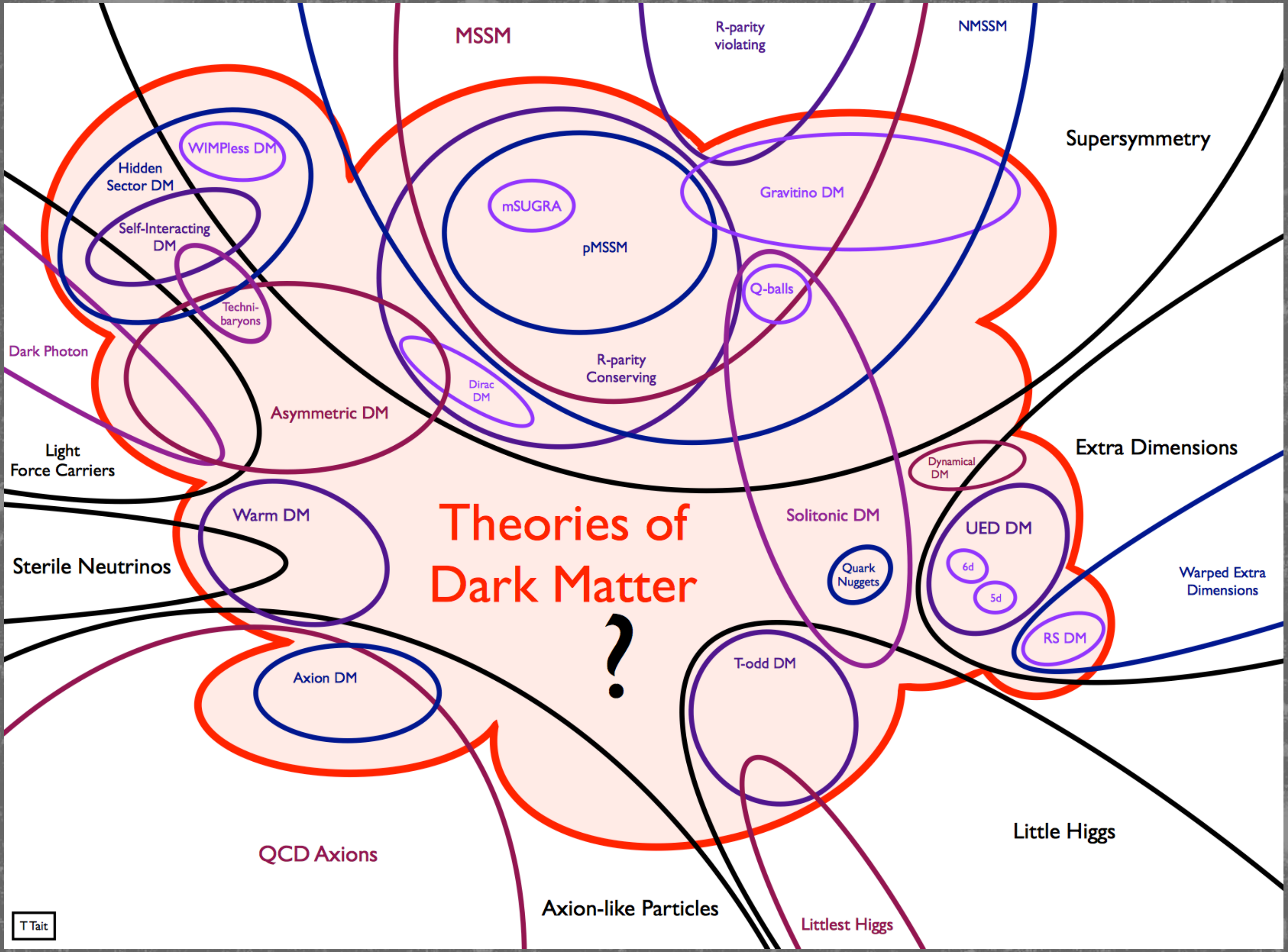
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

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

?

Dark Matters

But there are some ideas…



Stolen from slides of Tim Tait

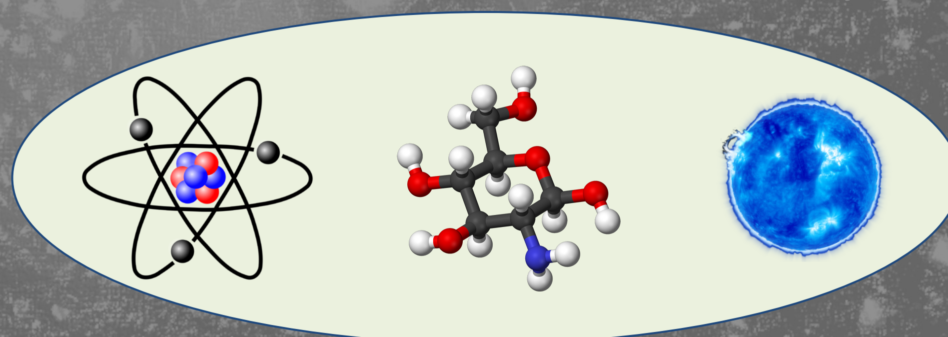
Only 18% of all matter in Universe is visible.

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

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

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

Within that 18% we observe extraordinary complexity.



The photon, despite not being matter itself, gave us our first tool to explore the visible sector.

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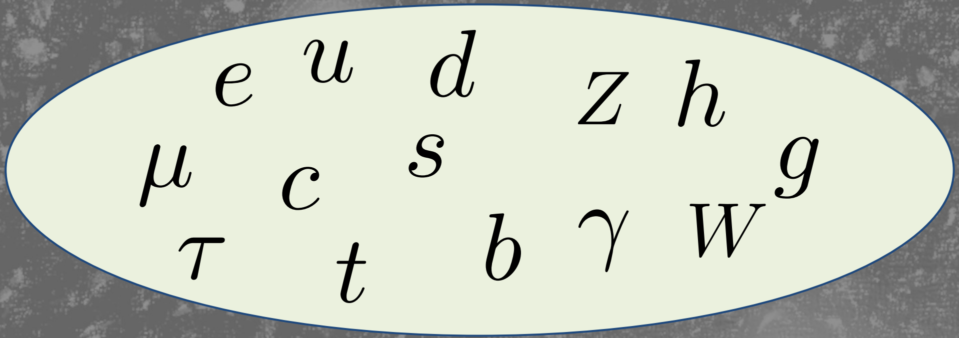

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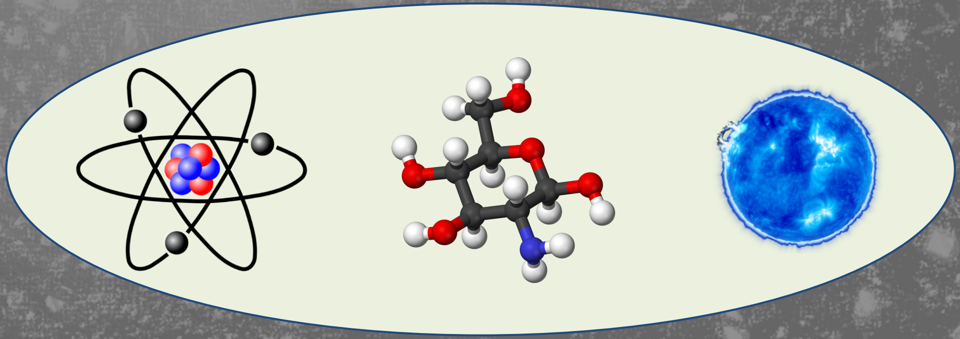


Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

ALPs

The standard model provides two examples of neutral bosons which can comfortably be light and have arbitrarily weak interactions:

Standard Model	Dark Sector
Z	Z'
π	a

ALPs

I will here focus on this case:

π	a
Standard Model	Dark Sector

Pseudo-Goldstone Bosons can be naturally light.
Typically called "Axion-Like Particles (ALPs)".

$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

Many possible interactions, but focus on these.

ALPs

I will here focus on this case:

π a

See also the talks by Andrea Thamm (many of Andrea's results shown here) and by Xiaoping Wang!

Pseudo-Goldstone Bosons

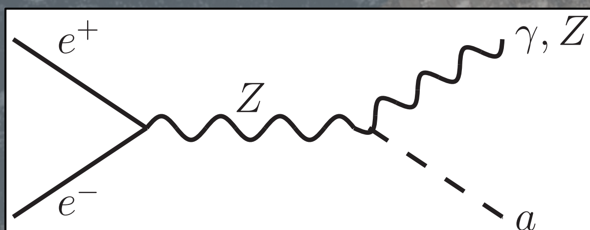
Typically called "Axion-Like Particles

$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

Many possible interactions, but focus on these.

ALPs: FCC-ee/CEPC

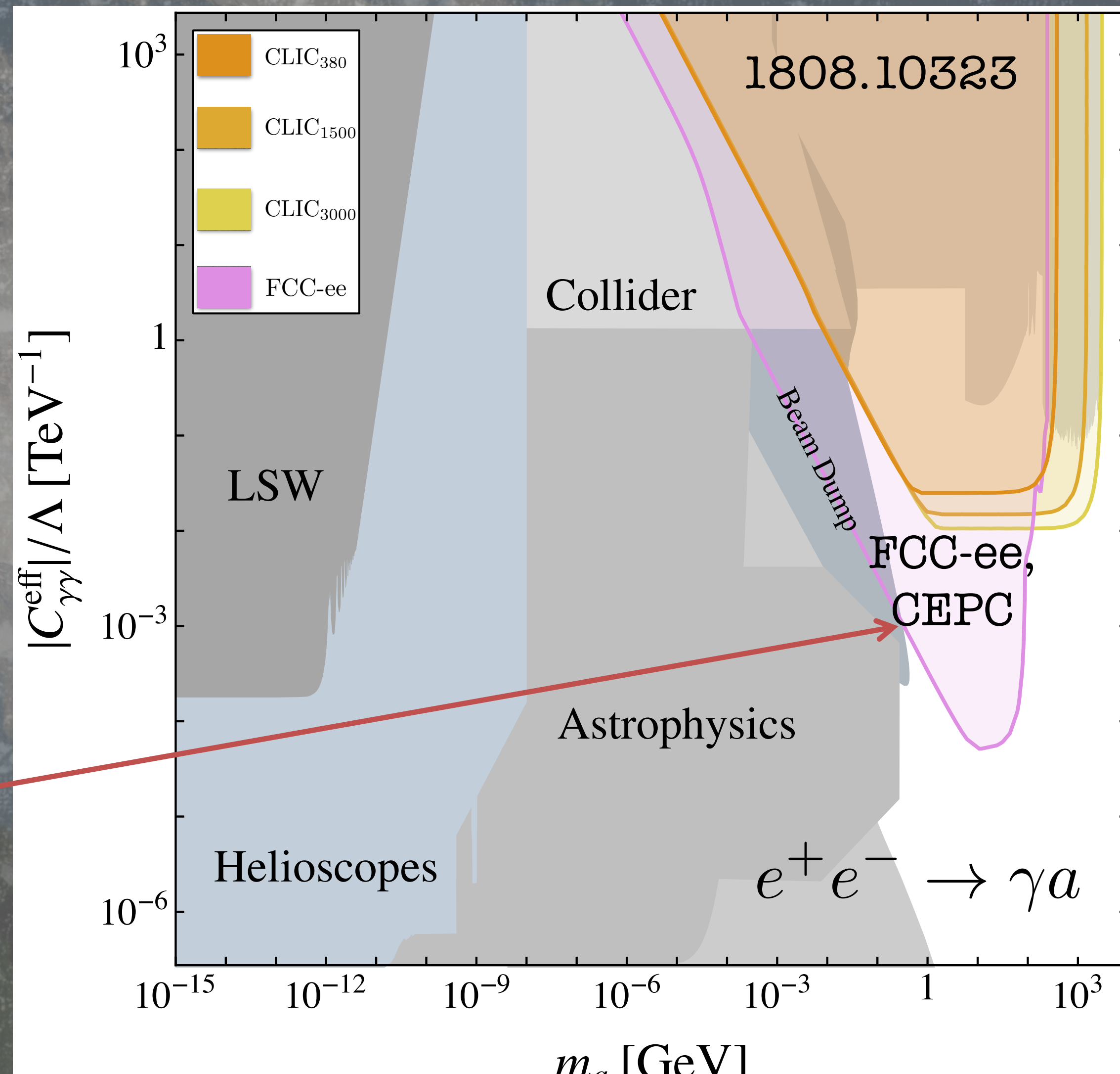
Key production channel:



Followed by:

$$a \to \gamma\gamma$$

CEPC is an <u>intensity frontier</u> machine!!!



ALPs

We will here focus on this case:

π

Standard Model

a

Dark Sector

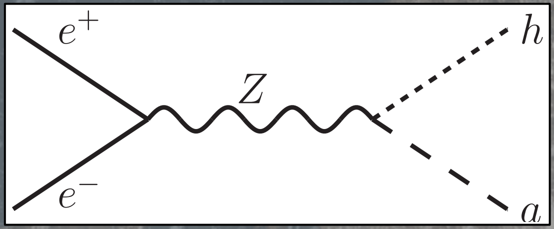
Pseudo-Goldstone Bosons can be naturally light.
Typically called “Axion-Like Particles (ALPs)”.

$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}}{\Lambda^3}\,(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots\,,$$

Can also have interactions with the Higgs.

ALPs: FCC-ee/CEPC

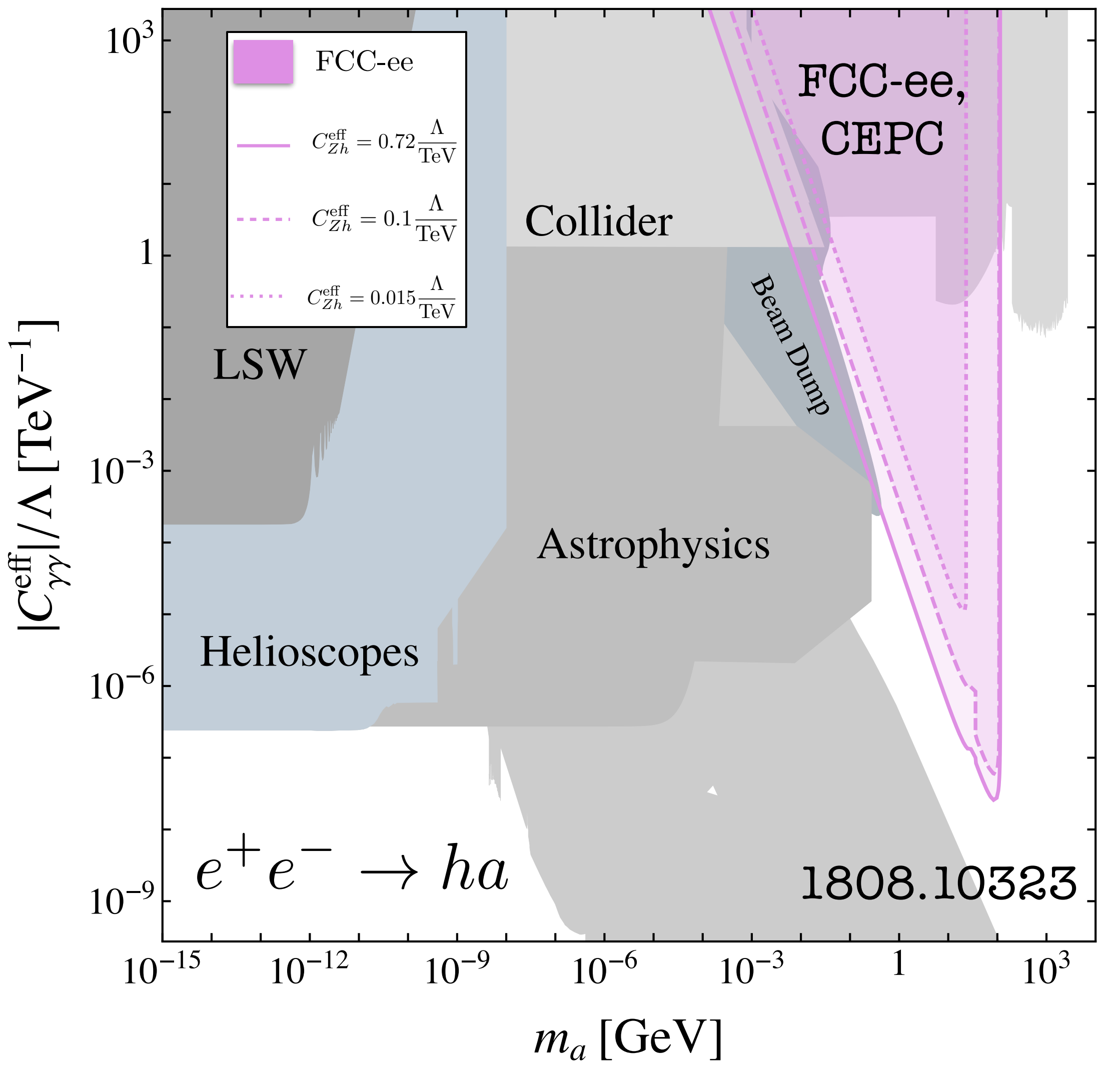
The Higgs is a key player:



Followed by:

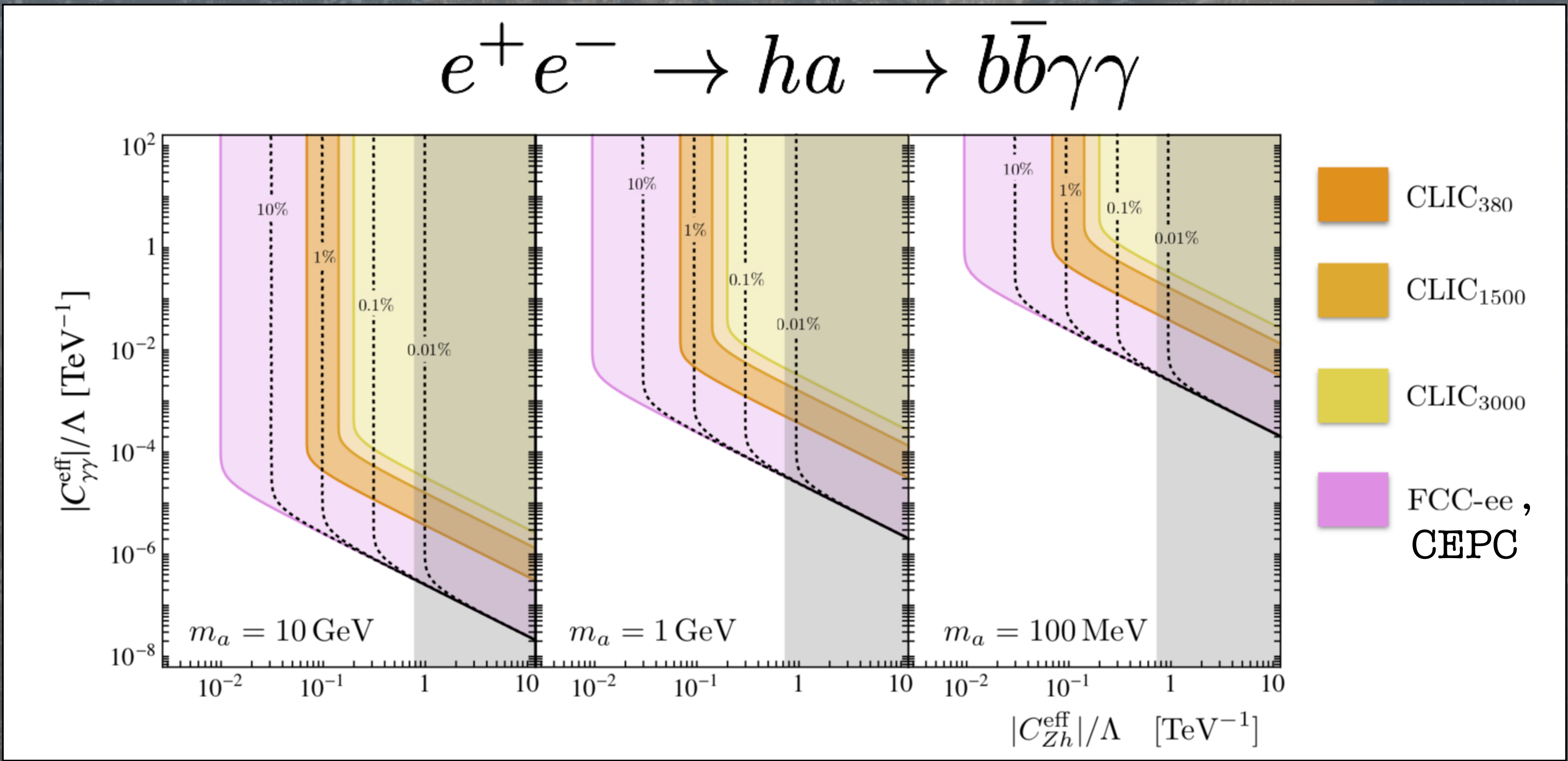
$$a \to \gamma\gamma$$

FCC-ee/CEPC can probe extremely high scales through the Higgs.



ALPs: FCC-ee/CEPC

Possible to probe multi-TeV couplings across a range of parameter space:



Revealing light remnants of high scale physics!

ALPs + Dark Photon

What about an ALP and a dark photon?

Z $\qquad$ Z'

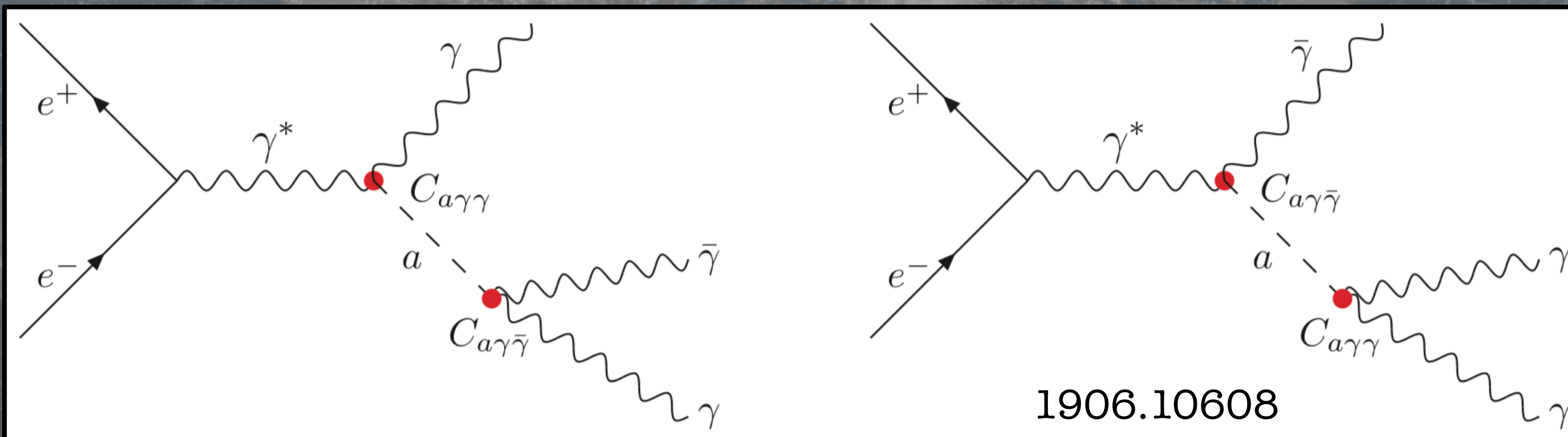
π $\qquad$ a

Standard Model $\qquad$ Dark Sector

$$\mathcal{L}_{eff} = \frac{C_{a\,\gamma\gamma}}{\Lambda} a\, F^{\mu\nu}\tilde{F}_{\mu\nu} + 2\frac{C_{a\gamma\bar{\gamma}}}{\Lambda} a\, F^{\mu\nu}\tilde{\bar{F}}_{\mu\nu}$$

ALPs + Dark Photon

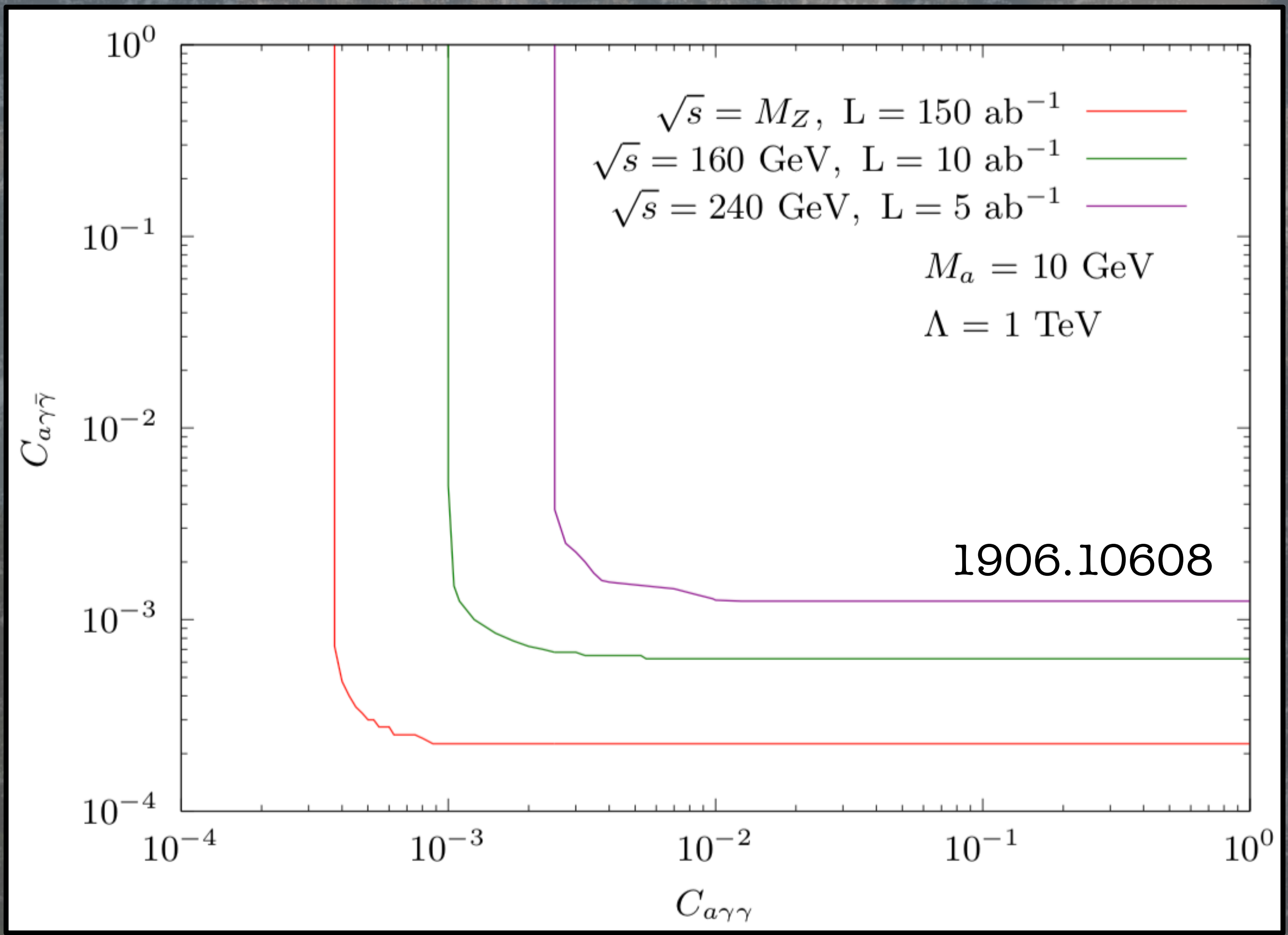
With this addition the signatures change somewhat:



Leading to the additional handle of missing energy!

ALPs + Dark Photon

Future lepton colliders also have extreme sensitivity to high scale physics in this case:



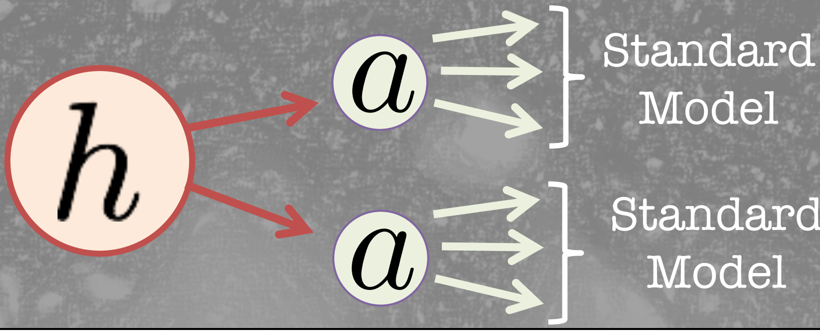
Comment: On Energy

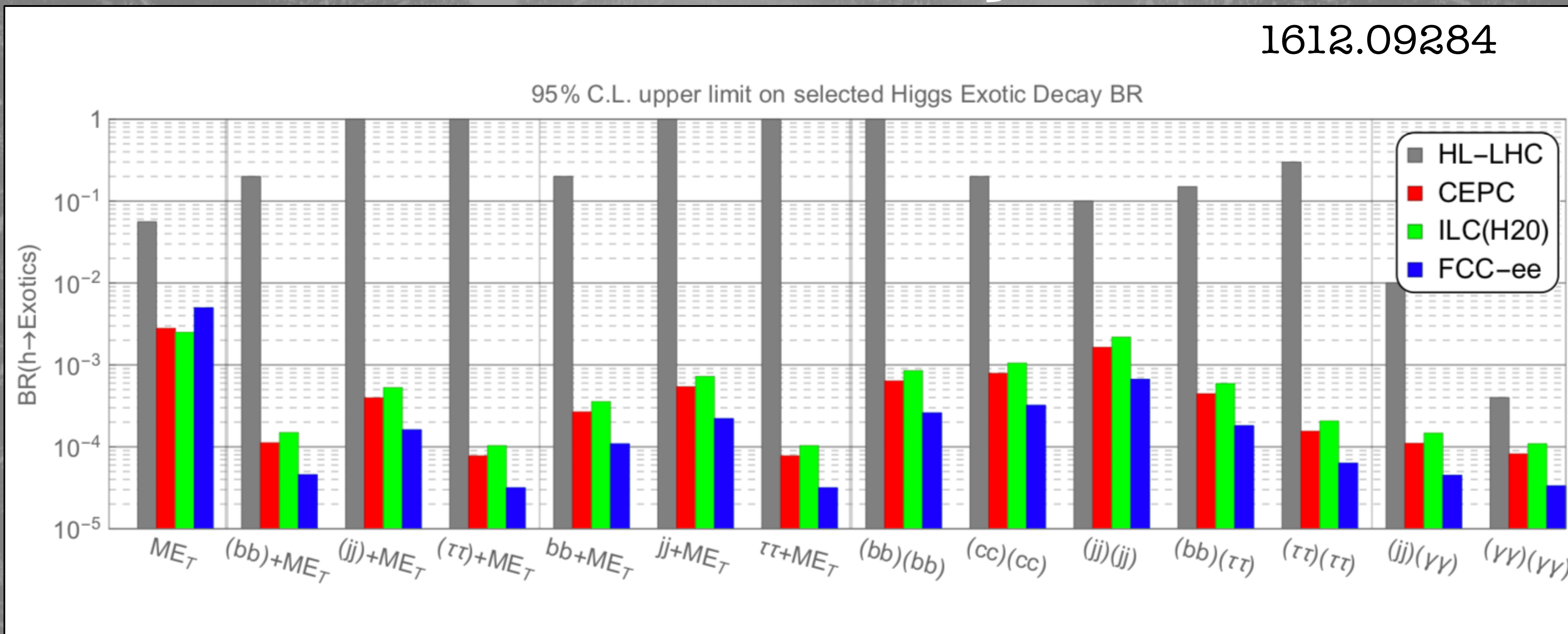
It is tempting to associate the weakly coupled frontier with the low mass range. Why?

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

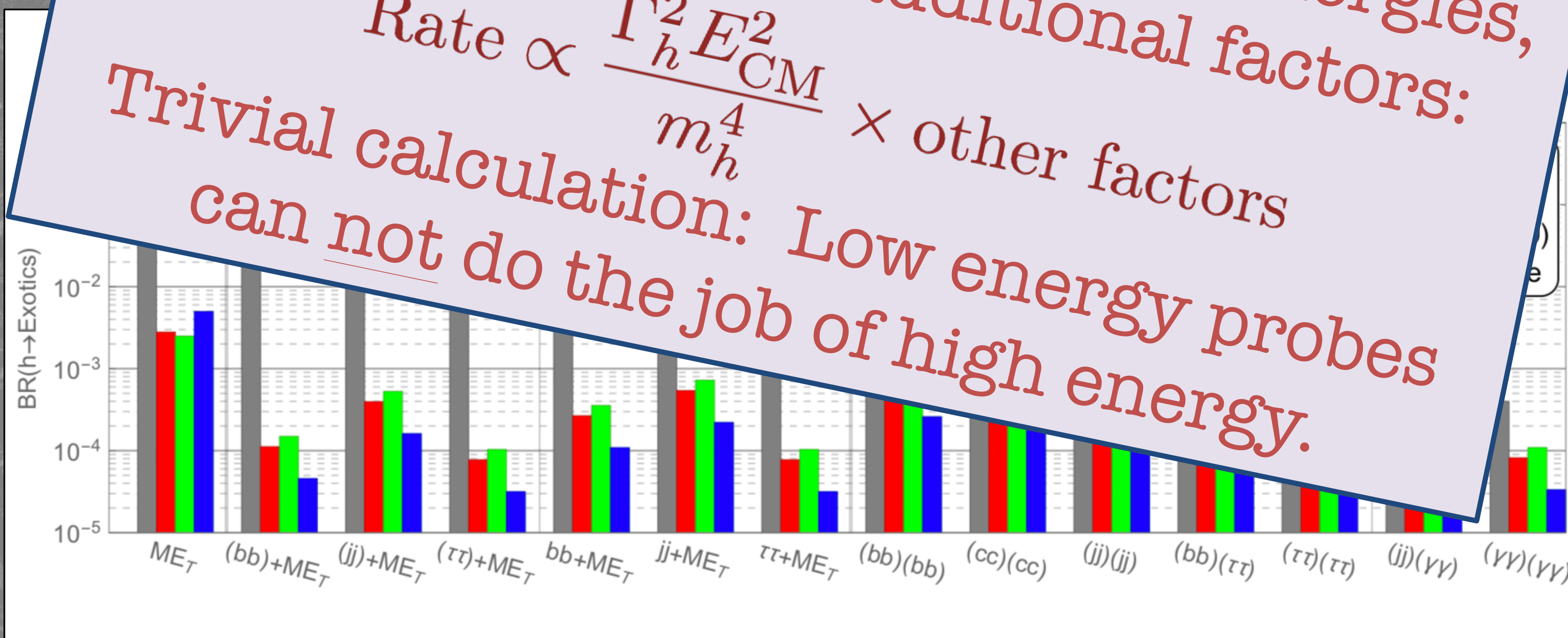
The … is totally different from other particles and … window to the dark sector:

Standard

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

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

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



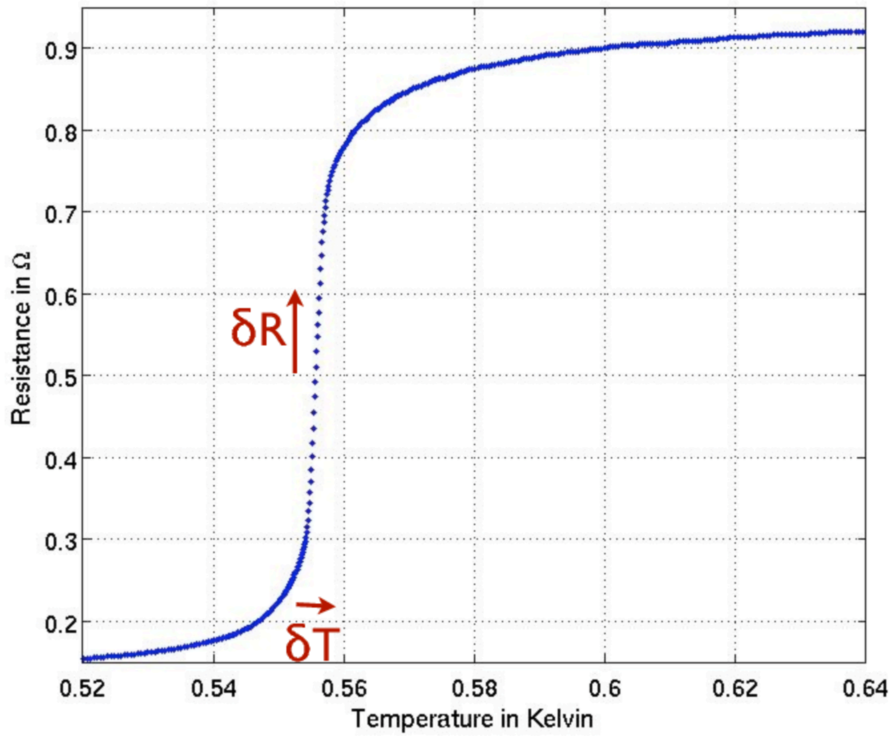
Our Universe is like a Superconductor...

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

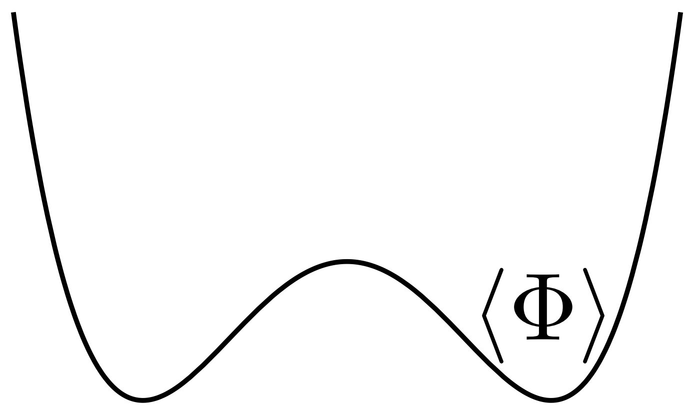
Reduce the temperature and a dramatic phase transition occurs. Vanishing resistance, Meissner effect, etc…

Ginzburg-Landau

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

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

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 the Higgs Boson?

Higgs Mechanism

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

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

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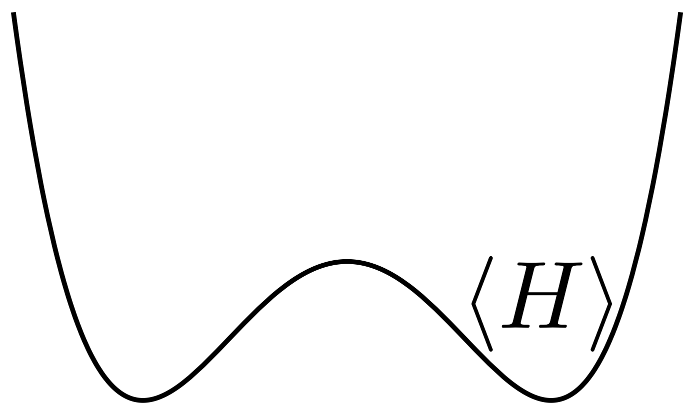


Gauge bosons become massive: $M_W \sim g\langle H \rangle$

The Higgs sector, and all of the known Universe, is like a form of relativistic superconductor...

We should at least try to understand the Higgs sector as well as we understand superconductors...

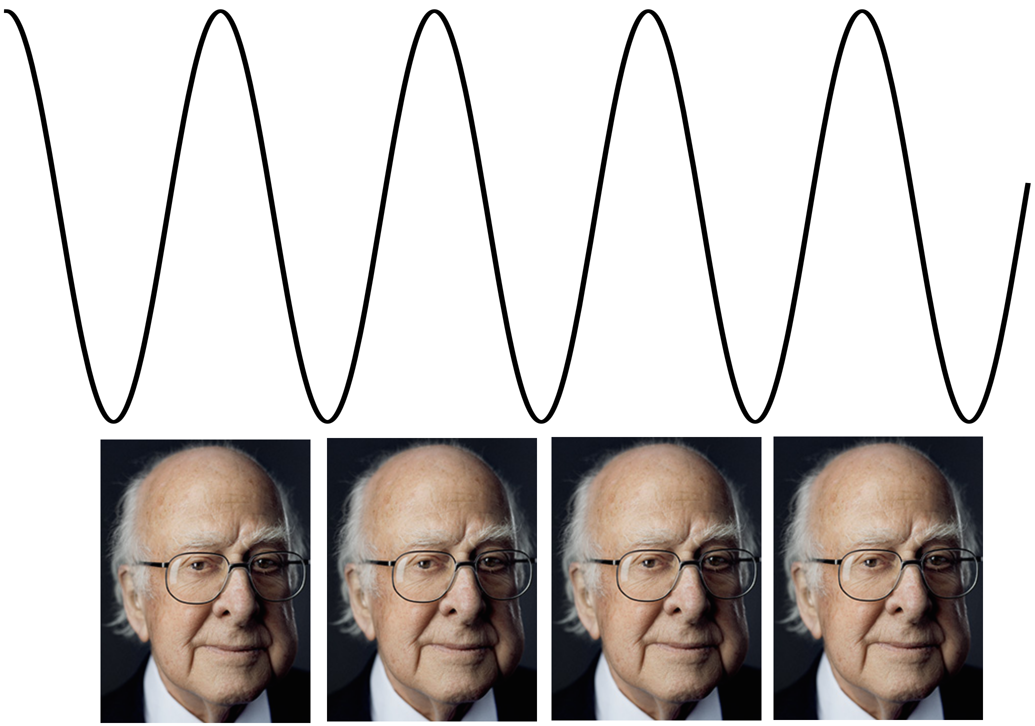
Next Steps:

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?



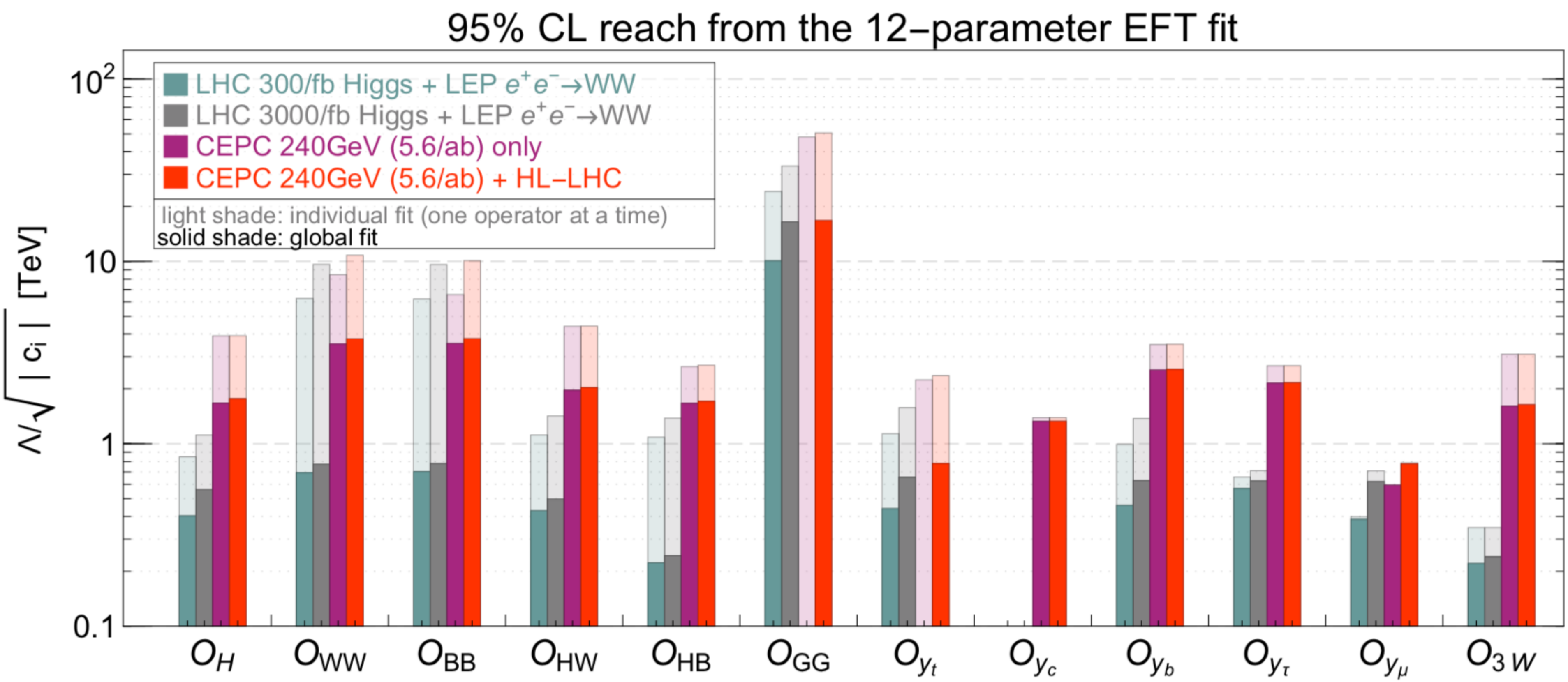
Precision measurements are different ways of probing the "compositeness of the Higgs".

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

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

Higgs Factories

- Unprecedented examination of the Higgs boson:

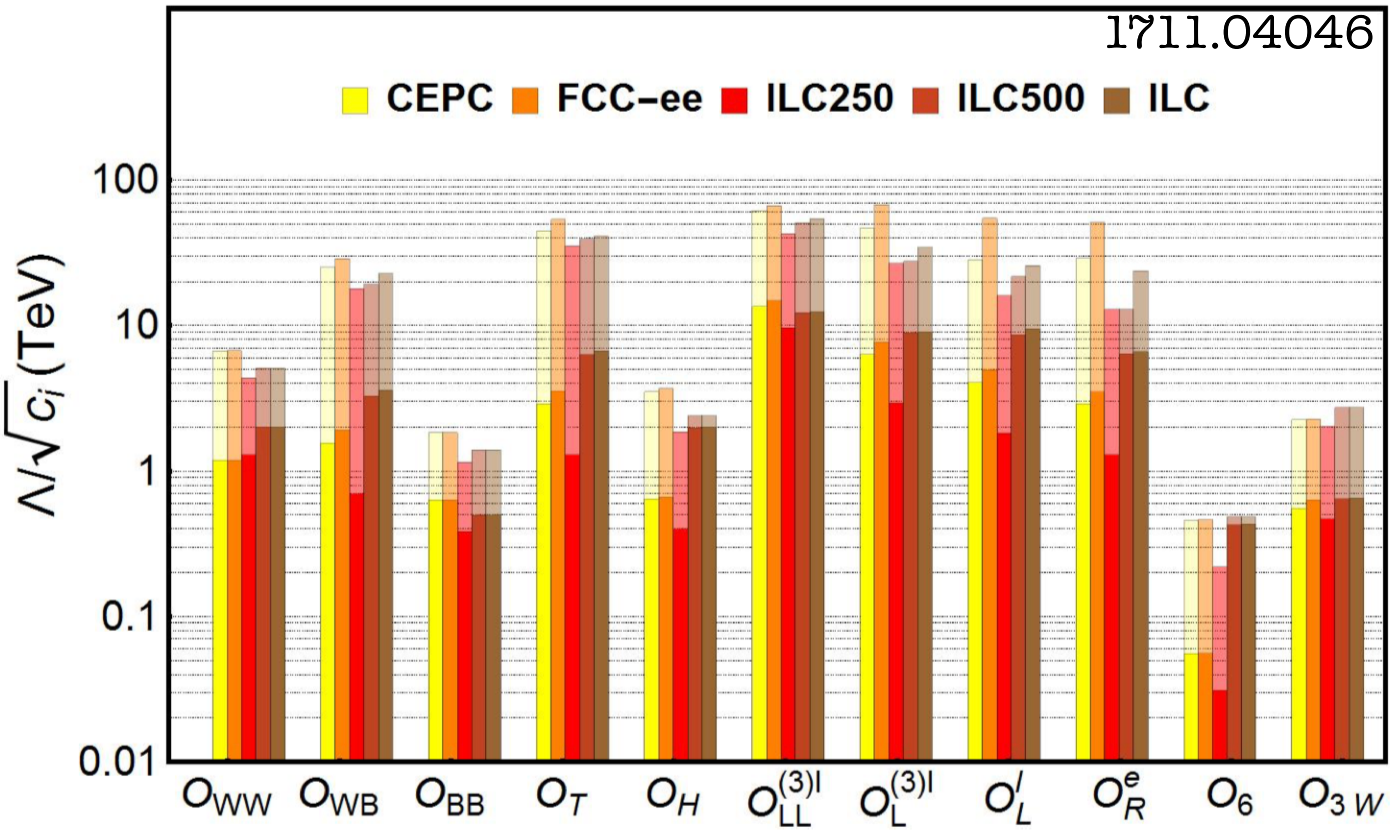


$$\lambda_h \approx 10^{-17} \text{ m}$$

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

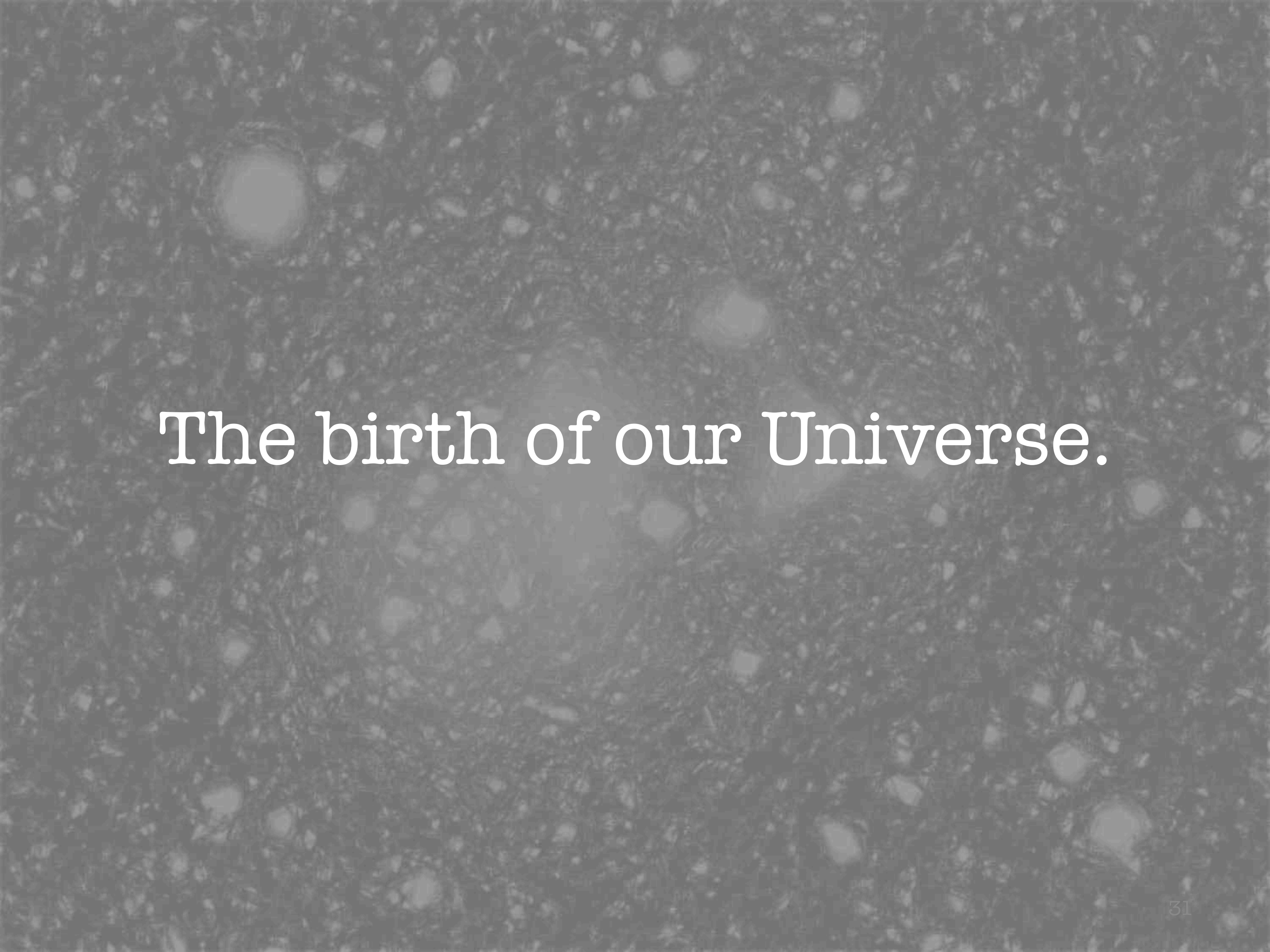
Higgs Factories

The more precision measurements we can get at heavy thresholds, Z, h, tt, the better!



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

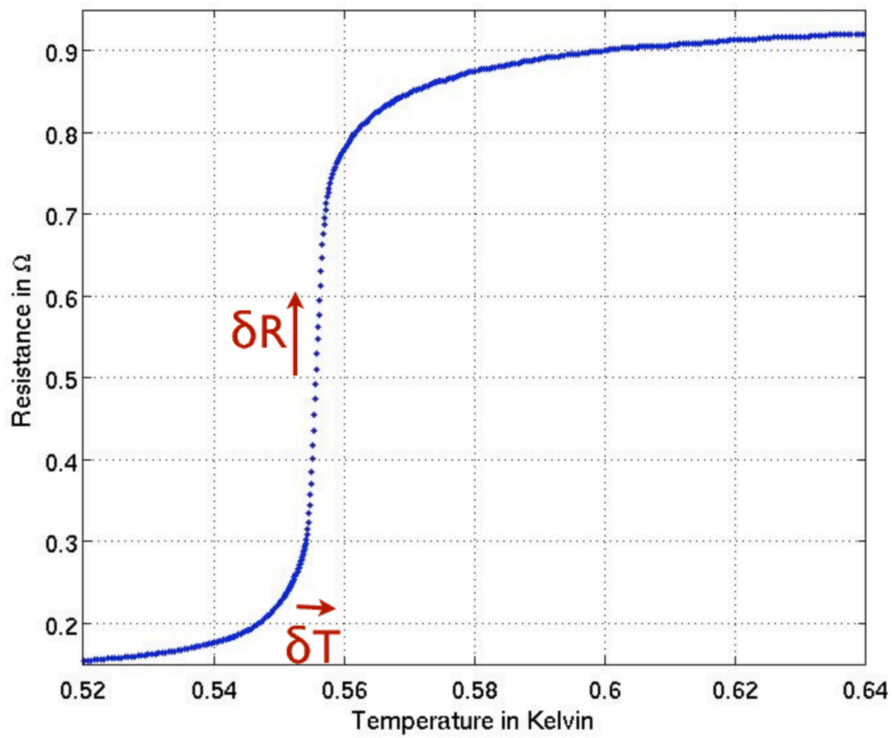
$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}$ m



The birth of our Universe.

The Electroweak Phase Transition

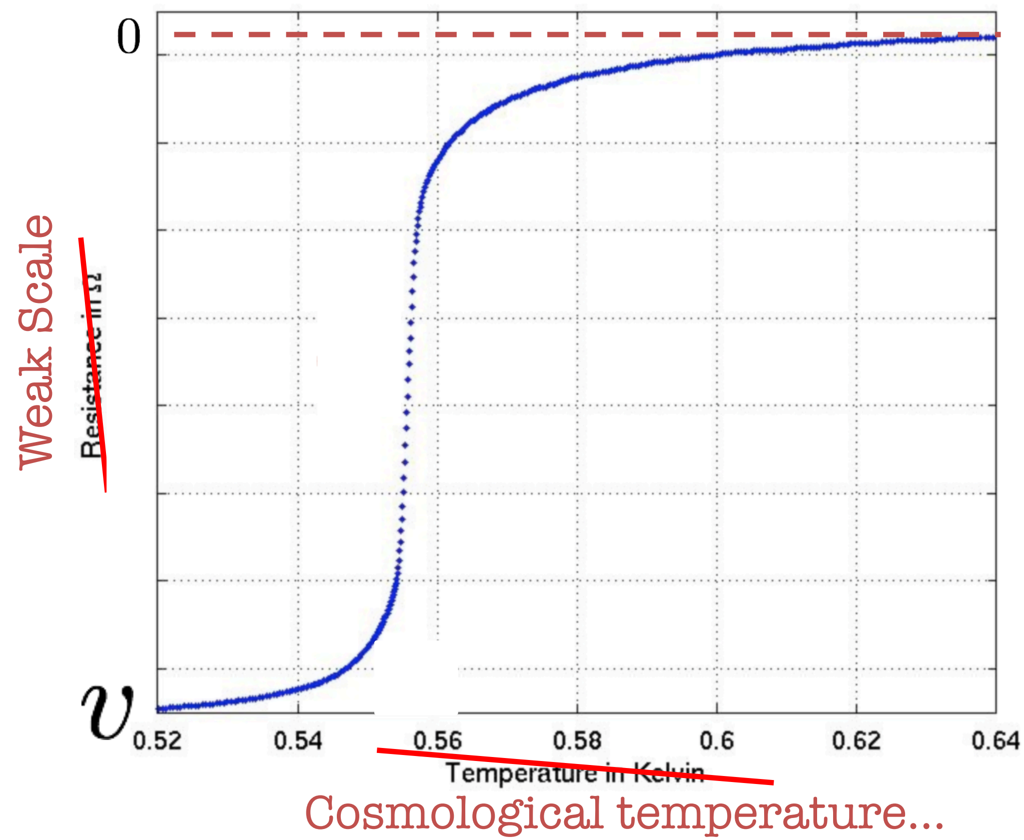
With a superconductor we can tune the temperature up and down



and study the details of the phase transition.

The Electroweak Phase Transition

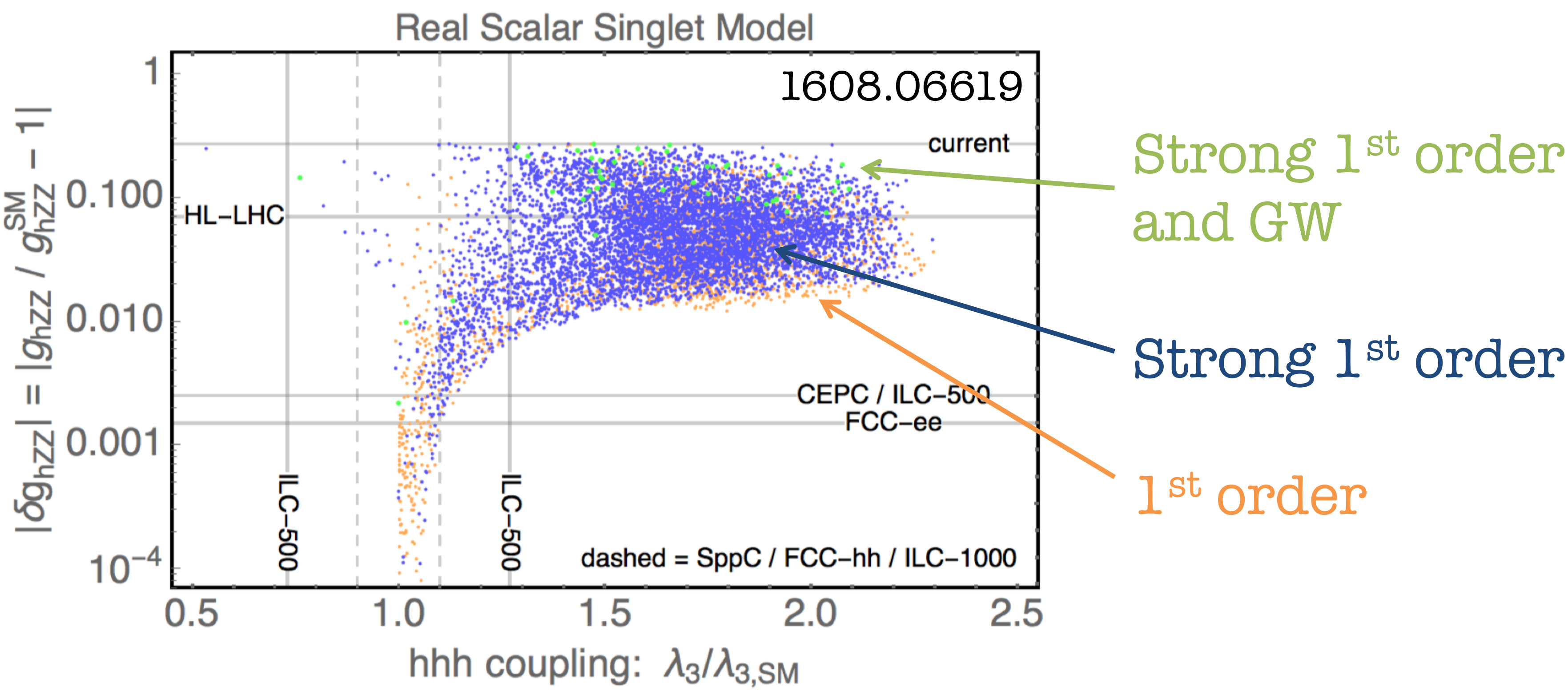
The EW phase transition only happened once, a long long time ago. How can we tell what happened,



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.

The Electroweak Phase Transition

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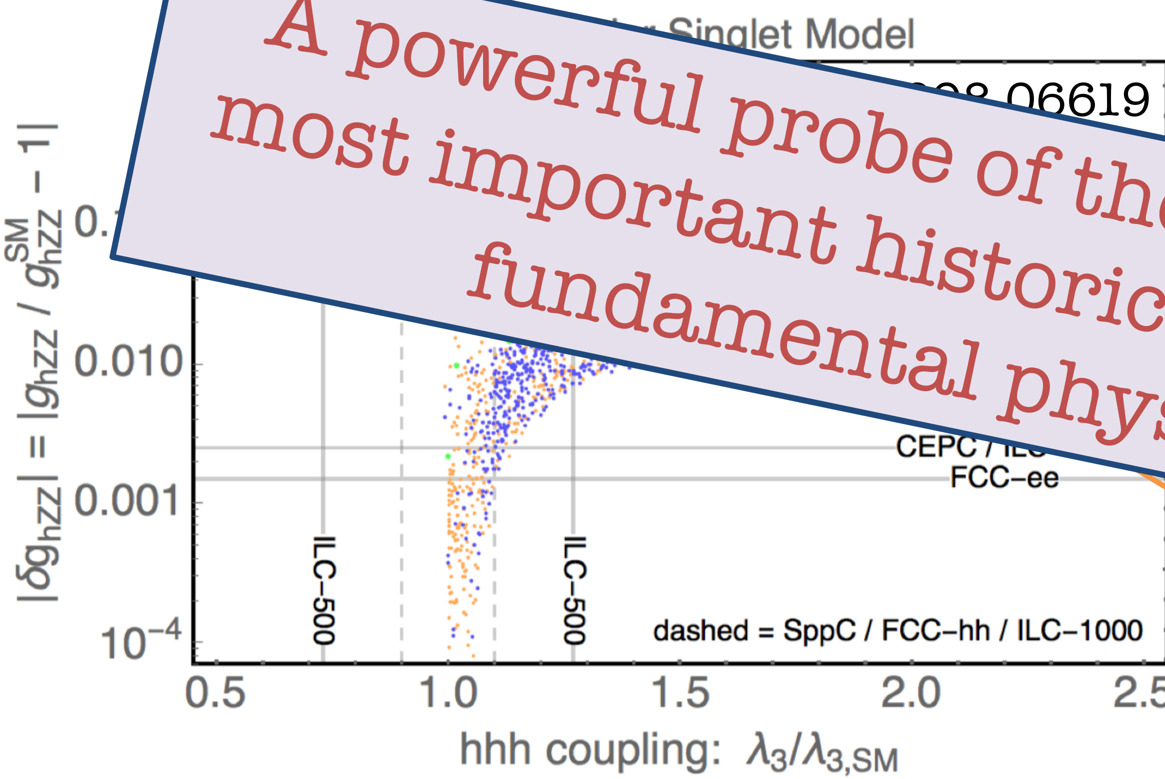

Strong 1^{st} order

1^{st} order

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

Very simple: Add a singlet scalar.

We are embarking on an entirely new era of fundamental physics…

Do you know what to expect?