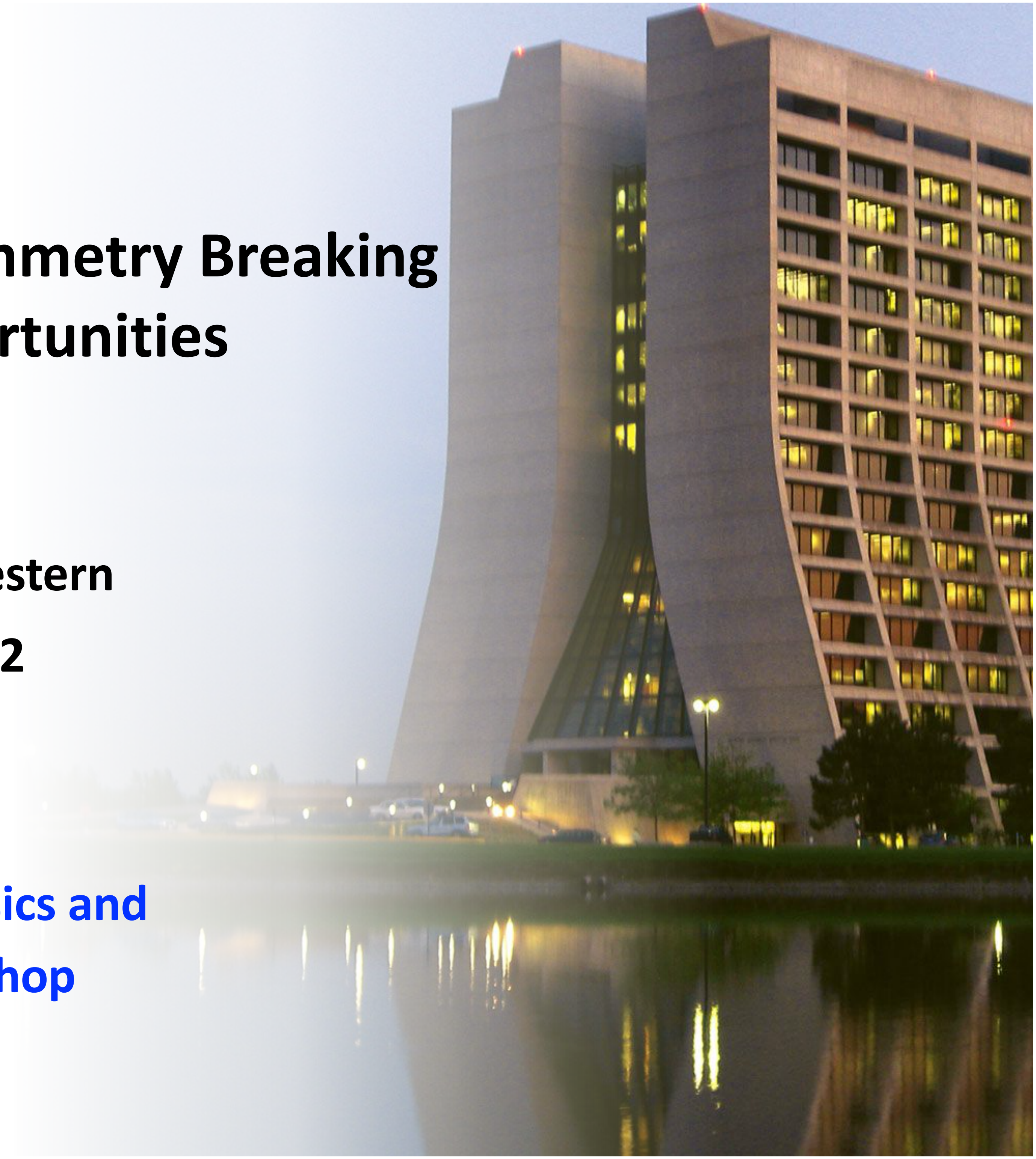
Electroweak Symmetry Breaking and Physics Opportunities

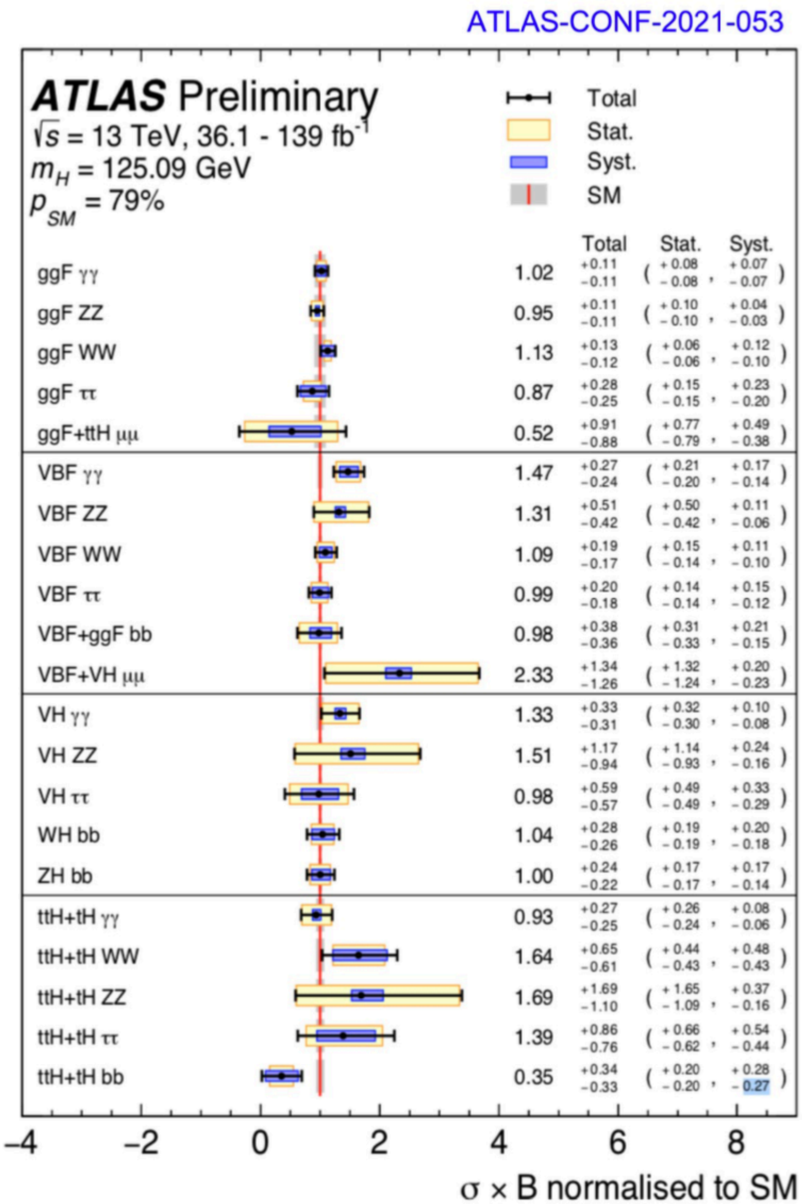
- Ian Low
- Argonne/Northwestern
- December 15, 2022

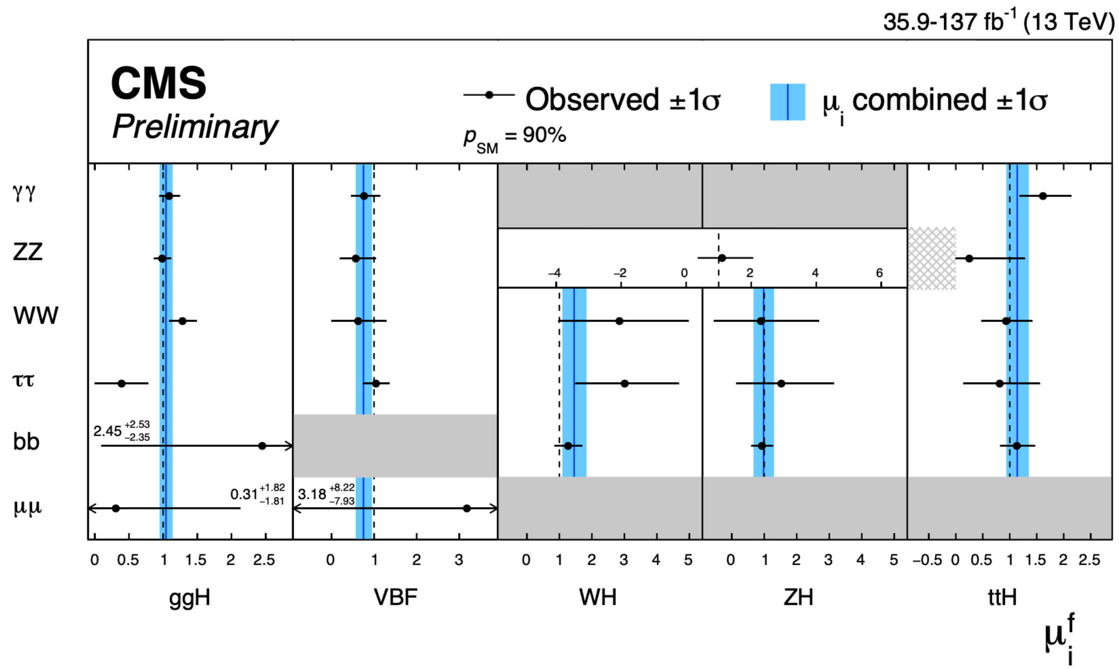


Muon Collider Physics and Detector Workshop

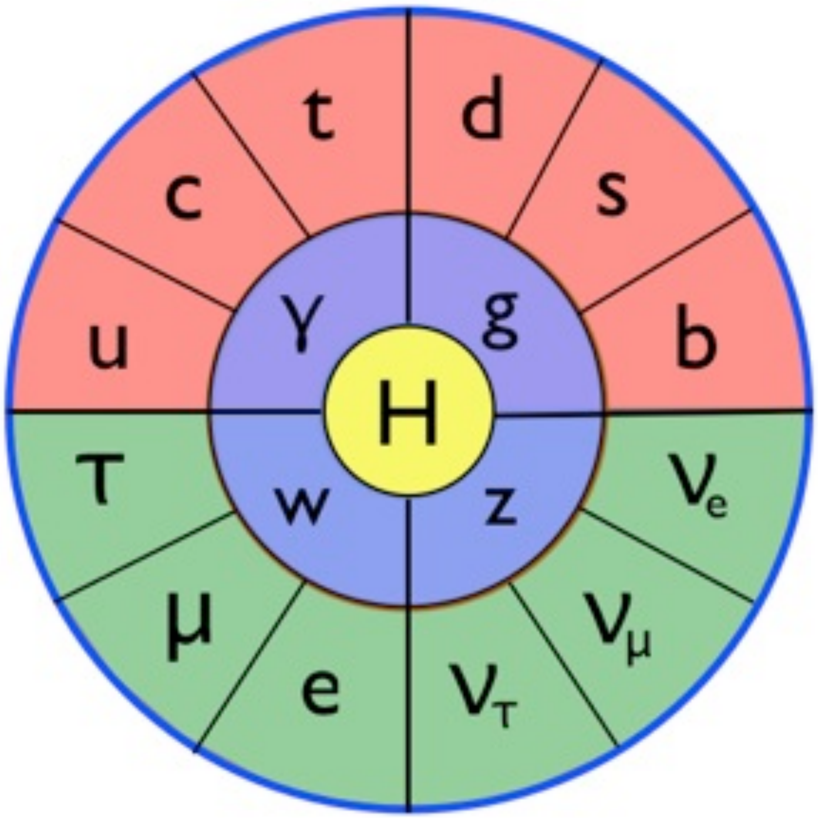
Higgs at 2012:

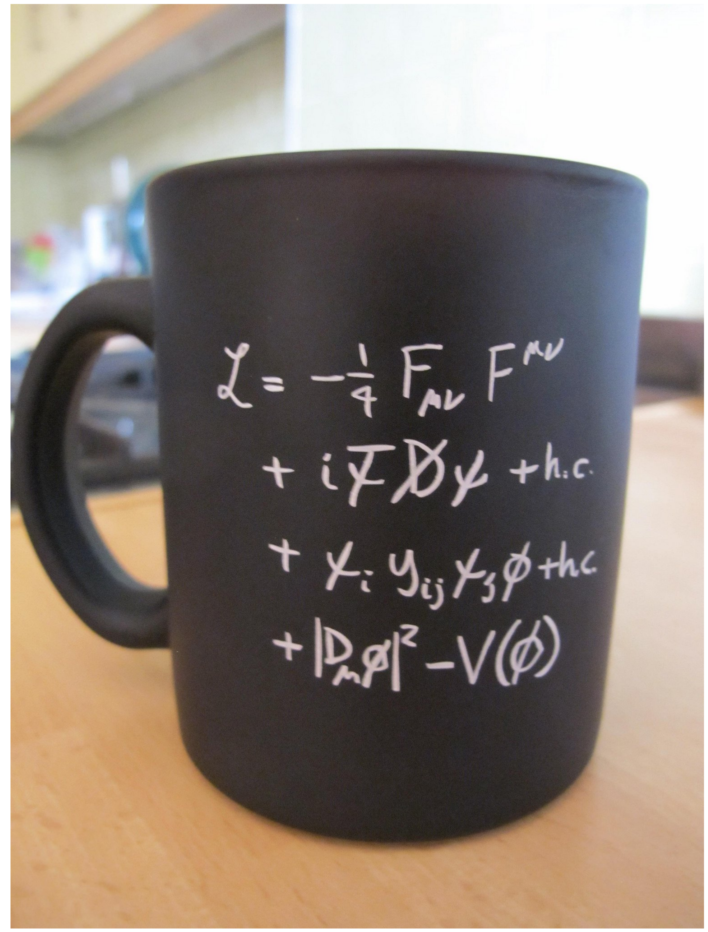
Higgs at 2022:





The Standard Model is self-consistent after the discovery of the Higgs:





Self-consistent $\neq$ Complete

(UV complete) (No BSM)

This is a fallacy that has been refuted throughout the course of history:

Self-consistent $\neq$ Complete

(UV complete) (No BSM)

This is a fallacy that has been refuted throughout the course of history:

- QED (photons+electrons) is UV-complete. But physics didn't stop there.
- QCD (gluons+quarks) is UV-complete. Again physics didn't stop there.
- SM with one generation of fermion is UV-complete. "WHO ORDERED THAT?"

Not to mention the empirical evidence for BSM physics:
dark matter, dark energy, baryon asymmetry and etc.

Where are the physics opportunities then?

Where are the physics opportunities then?

- Testing predictions of SM
  - Prioritize couplings that have yet to be established experimentally
  - Over-constrain couplings that have already been measured

- Asking the right questions
  - conceptual questions that can’t be answered by the SM
  - empirical questions that can’t be answered by the SM

The SM Higgs boson is very special:

Couplings to massive gauge bosons →
$$\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\,\mu}+\frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g\frac{\alpha_s}{12\pi v}h\,G^a_{\mu\nu}G^{a\,\mu\nu}+c_\gamma\frac{\alpha}{8\pi v}h\,F_{\mu\nu}F^{\mu\nu}+c_{Z\gamma}\frac{\alpha}{8\pi v s_w}\,h\,F_{\mu\nu}Z^{\mu\nu}$$

$$c_g^{(SM)}(125\ \text{GeV})=1\ ,\qquad c_\gamma^{(SM)}(125\ \text{GeV})=-6.48\ ,\qquad c_{Z\gamma}^{(SM)}(125\ \text{GeV})=5.48\ .$$

Couplings to fermions →
$$\sum_f\frac{m_f}{v}h\bar{f}f$$

Self-couplings →
$$\frac{1}{2}m_h^2h^2+\frac{m_h^2}{v}h^3+\frac{2m_h^2}{v^2}h^4$$

The SM Higgs boson is very special:

Couplings to massive gauge bosons → $$\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w}\, h\, F_{\mu\nu} Z^{\mu\nu}$$

$$c_g^{(SM)}(125 \text{ GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125 \text{ GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125 \text{ GeV}) = 5.48\ .$$

Couplings to fermions → $$\sum_f \frac{m_f}{v} h \bar{f} f$$

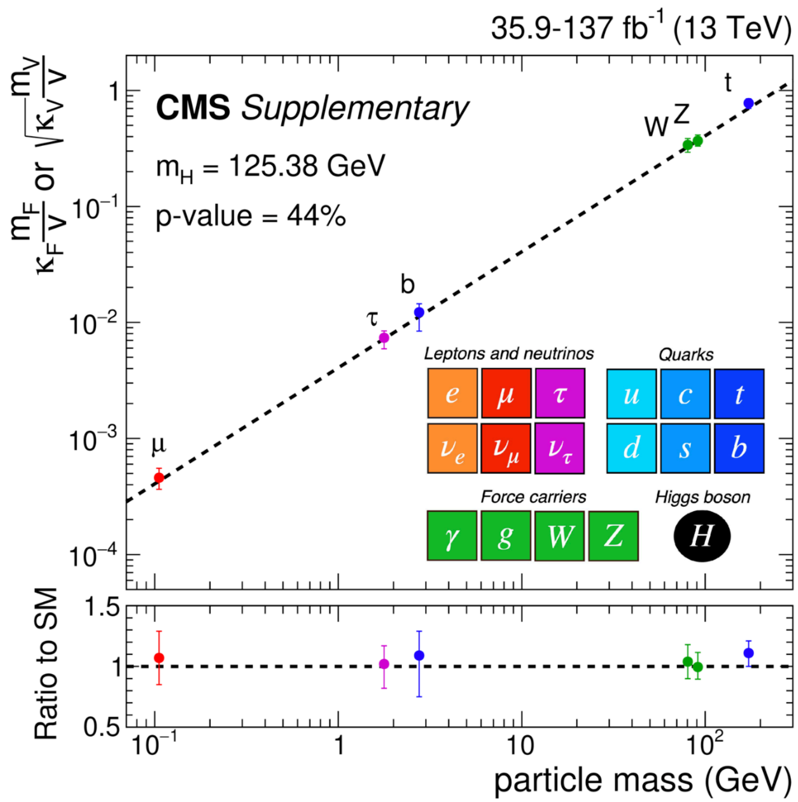
Self-couplings → $$\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$$

A non-trivial prediction:

once all masses are measured, there is no more free parameters!

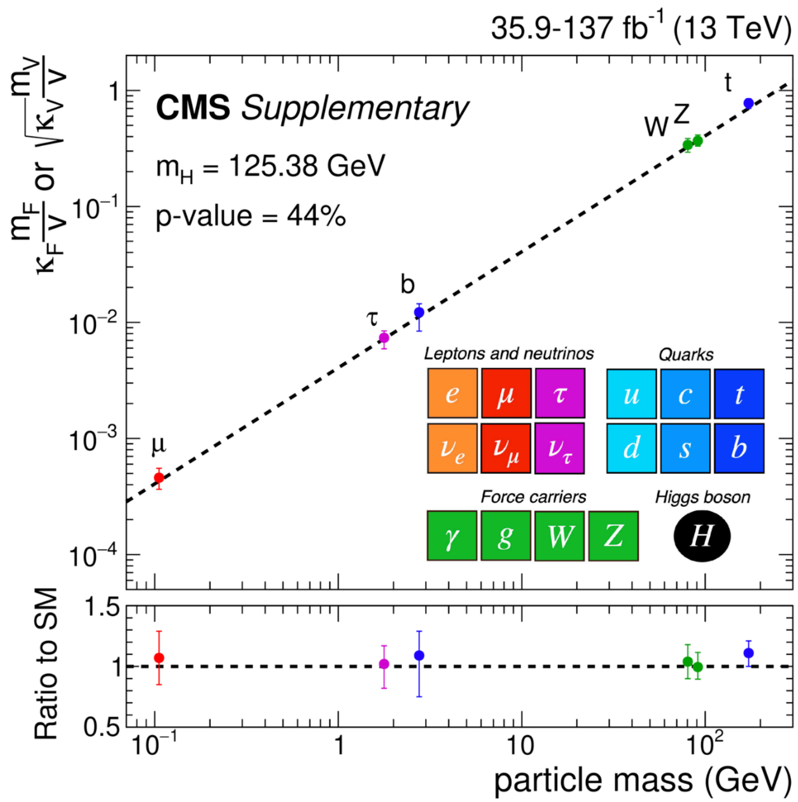
- **Prioritize couplings which have yet to be established experimentally:**

Yukawa couplings to 1st and 2nd generation fermions.

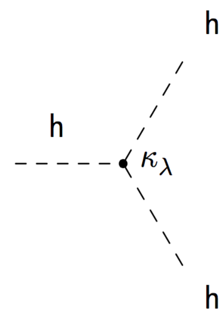


- **Prioritize couplings which have yet to be established experimentally:**

Yukawa couplings to 1st and 2nd generation fermions.



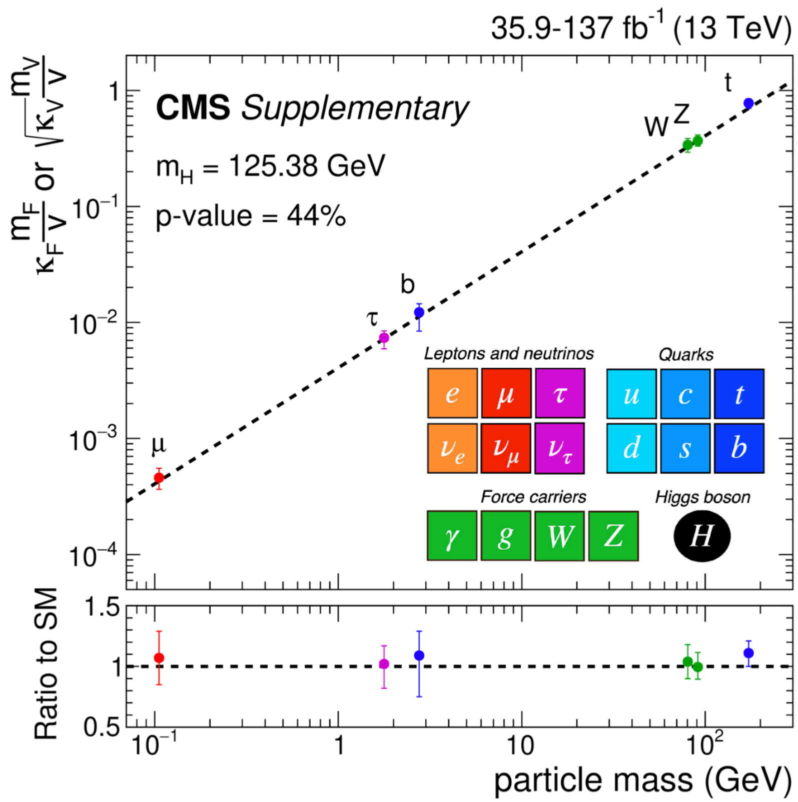
Trilinear Higgs self-coupling – we have NOT measured the Higgs potential.

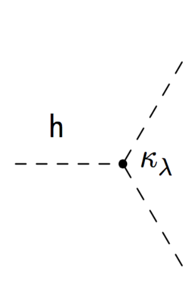


- **Prioritize couplings which have yet to be established experimentally:**

Trilinear Higgs self-coupling – we have NOT measured the Higgs potential.

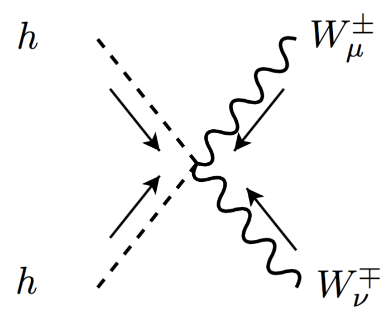
Yukawa couplings to 1st and 2nd generation fermions.

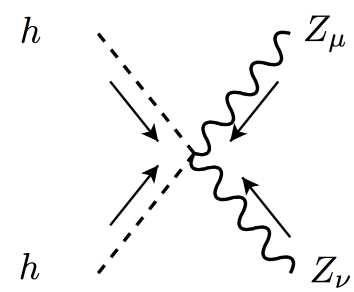




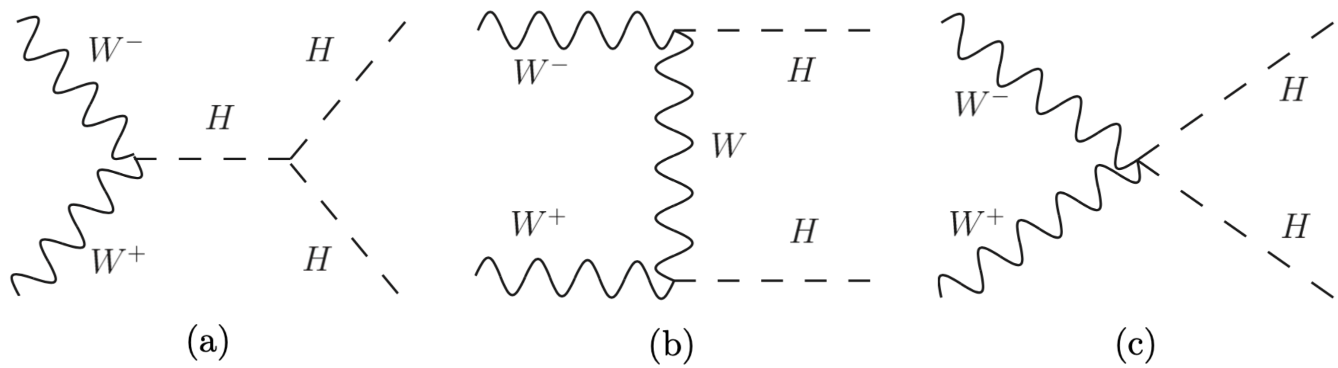
4-pt HHVV coupling – prediction of gauge invariance.

$$D_\mu H^\dagger D^\mu H \supset g^2 h^2 V_\mu V^\mu$$





- At a lepton collider, both the trilinear and quartic couplings can be probed in double Higgs production through VBF:



Notice the process is sensitive to **both** HHH and WWHH couplings!

- Using the M_{HH} shape information, it is possible to constrain both couplings at the same time:

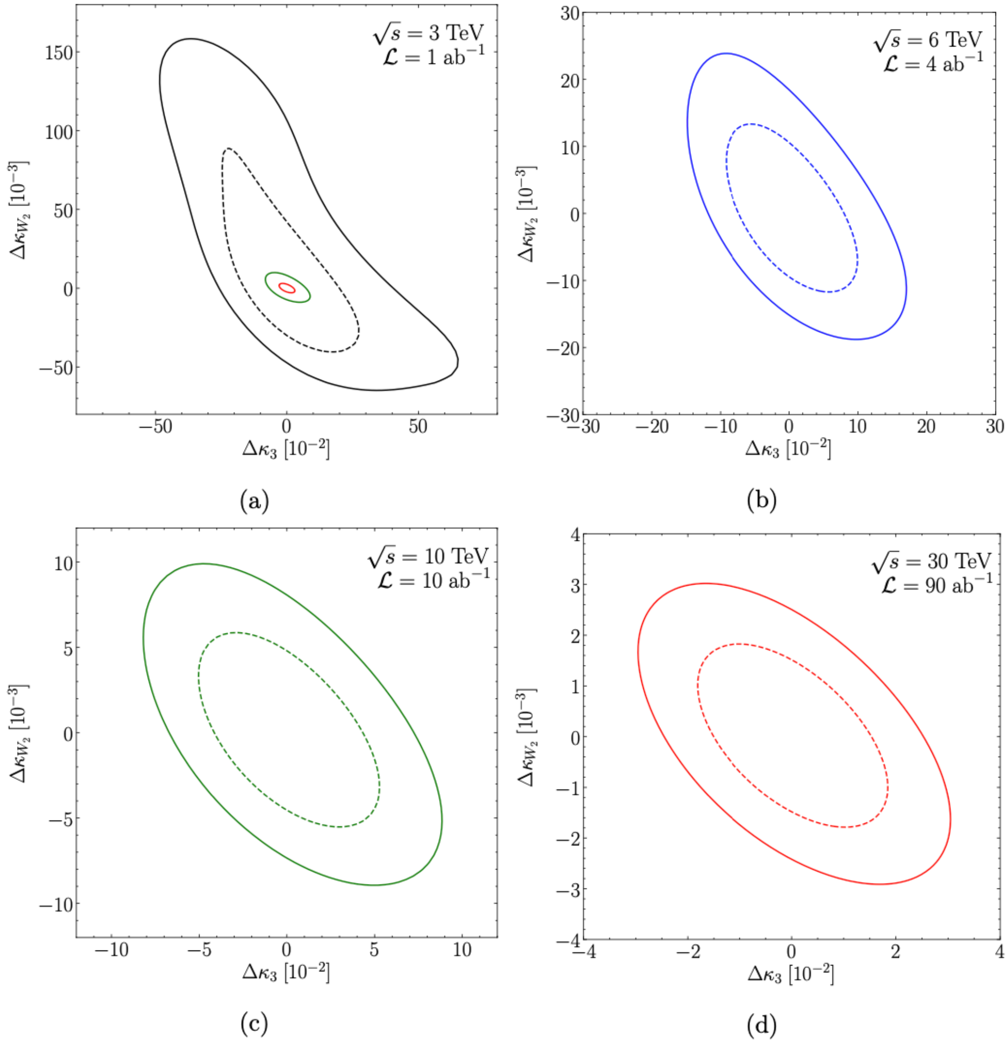
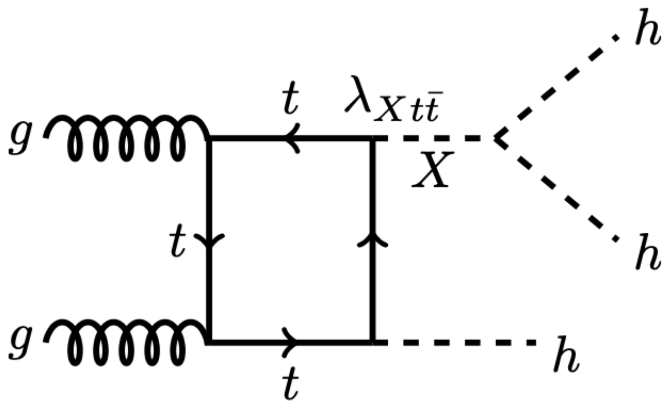


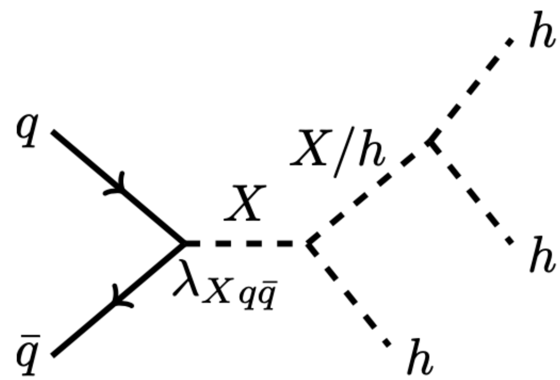
Figure 7: Correlated bounds with 95% C.L. (solid) and 68% C.L. (dashed) in the $\Delta\kappa_{W_2}$-$\Delta\kappa_3$ plane for $\sqrt{s} = 3, 6, 10, 30$ TeV, respectively. In (a), inner ellipses (solid) include the 95% C.L. results for 10 TeV and 30 TeV for comparison.

T. Han, D. Liu, IL, X. Wang: 2008.12204

As we go to very high energies, why stop at two Higgses?

- HHH and HHHH have not been searched for experimentally.
- These final states can be produced in simple extensions (2HDM or SM+ singlet) with significant rates.



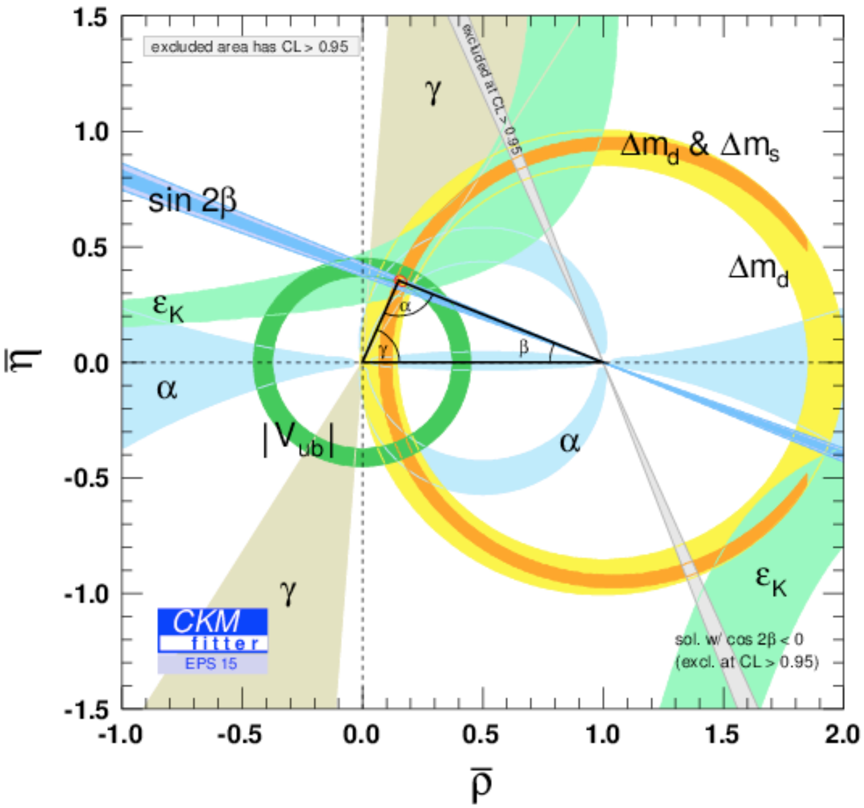


Egana-Ugrinovic, Homiller, Meade: 2101.04119
(See also IL, Shah, Wang: 2012.00773;
Chiang, Kuo, IL: 2202.02954)

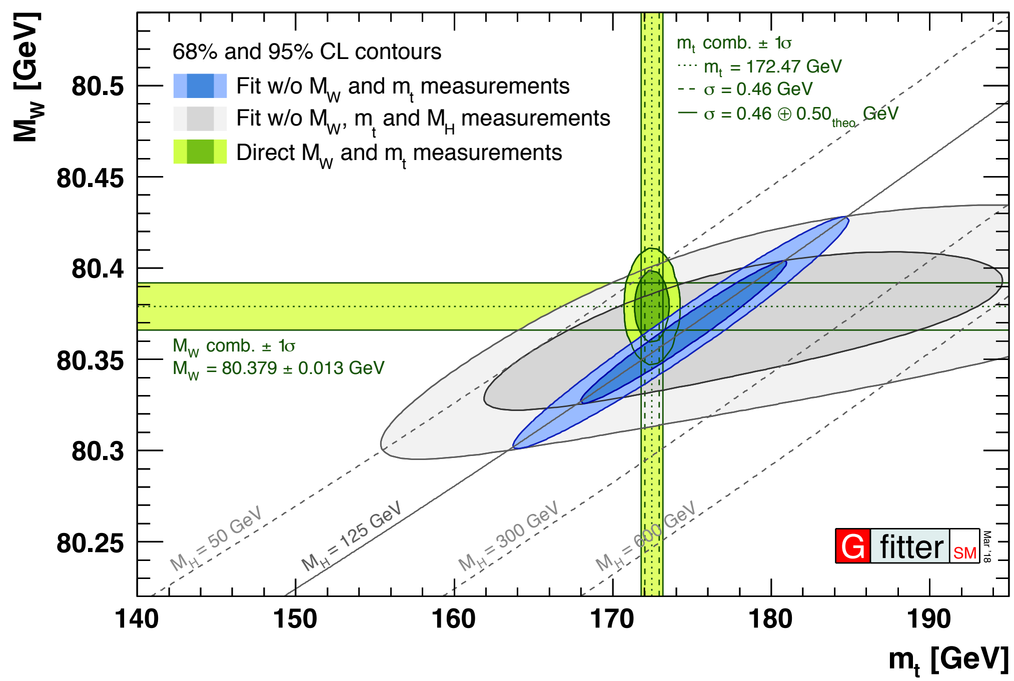
This is a new frontier waiting to be explored at both the hadron and lepton colliders!

- **For couplings which have been established, we need to over-constrain.**

  Our colleagues in flavor physics and from LEP era are very good at this:



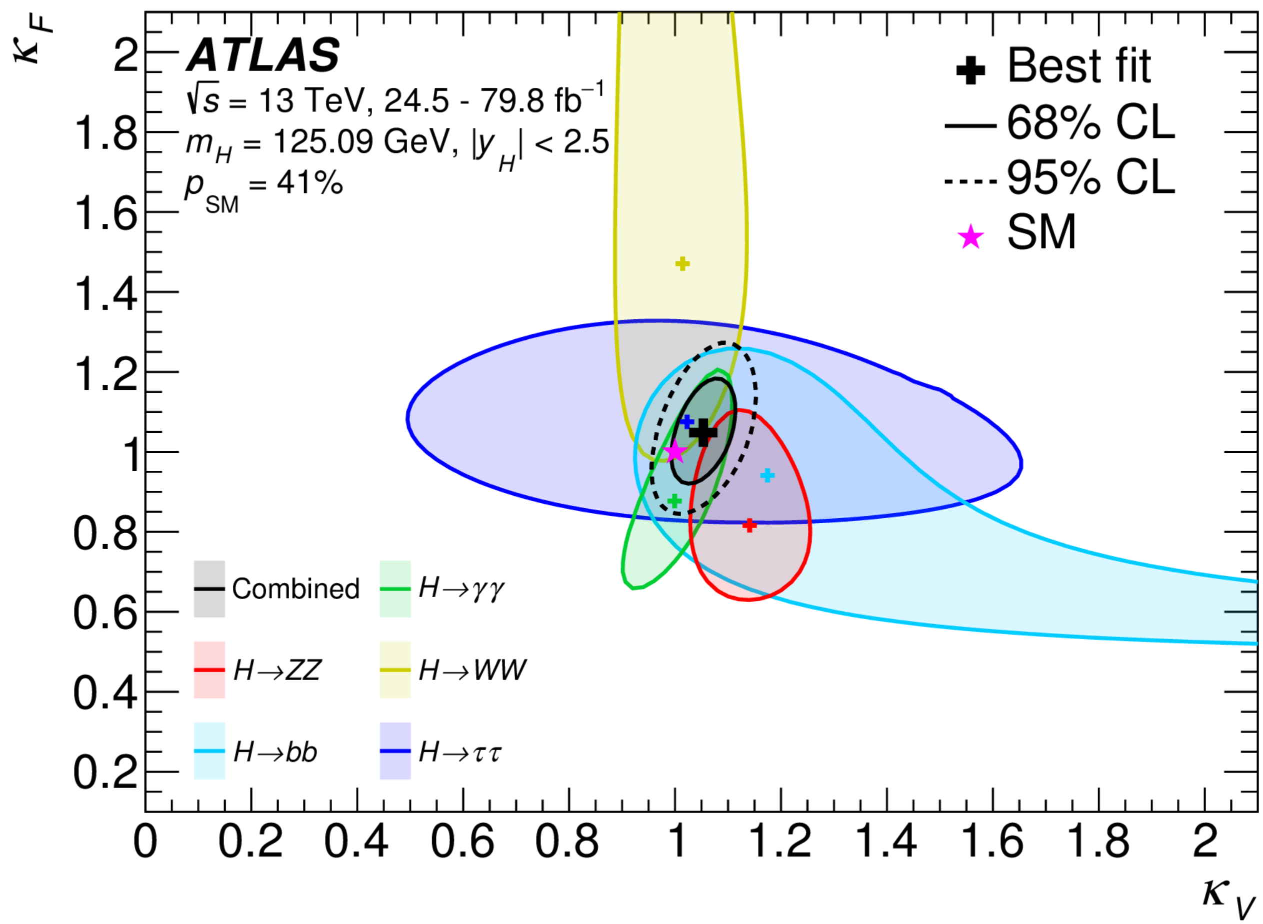
Unitarity triangle



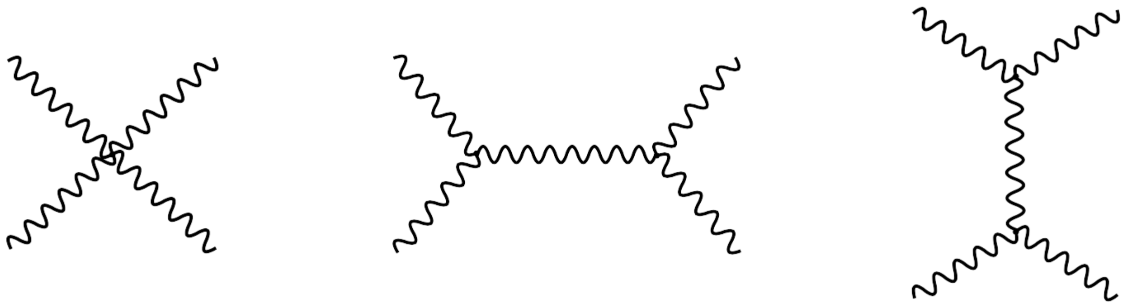
Precision Electroweak Measurements

- **For couplings which have been established, we need to over-constrain.**

At the LHC this has been pursued, but we need much better precision!



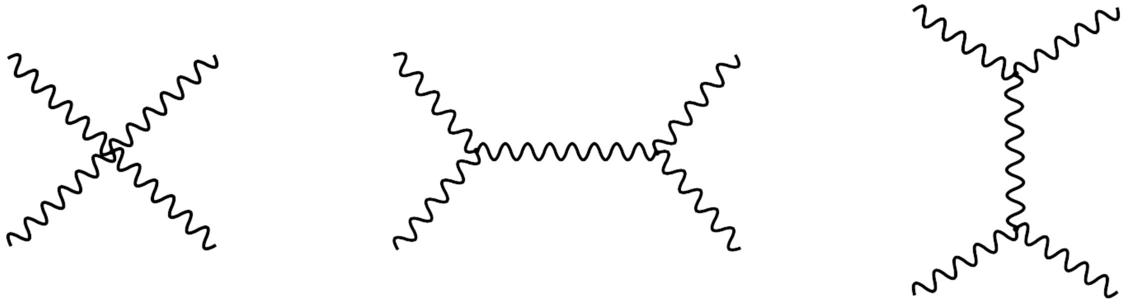
- One very important prediction of SM Higgs to be measured precisely:
  Without the Higgs, WW scattering amplitude violates unitarity:

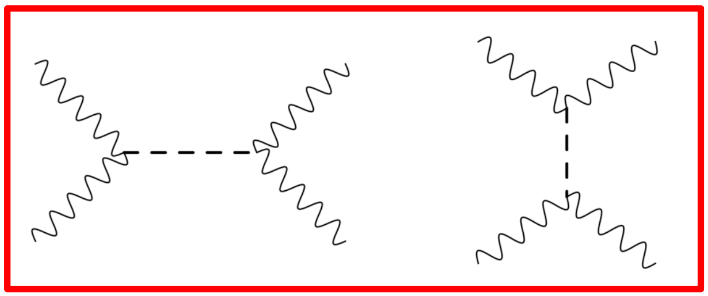


$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \frac{g^2}{4m_W^2}(s+t)\ .$$

- One very important prediction of SM Higgs to be measured precisely:

  Including the Higgs contribution allows the growth to be cancelled completely,





provided the HWW coupling have precisely the form in the SM!

This is an extremely simple and economical solution, except…

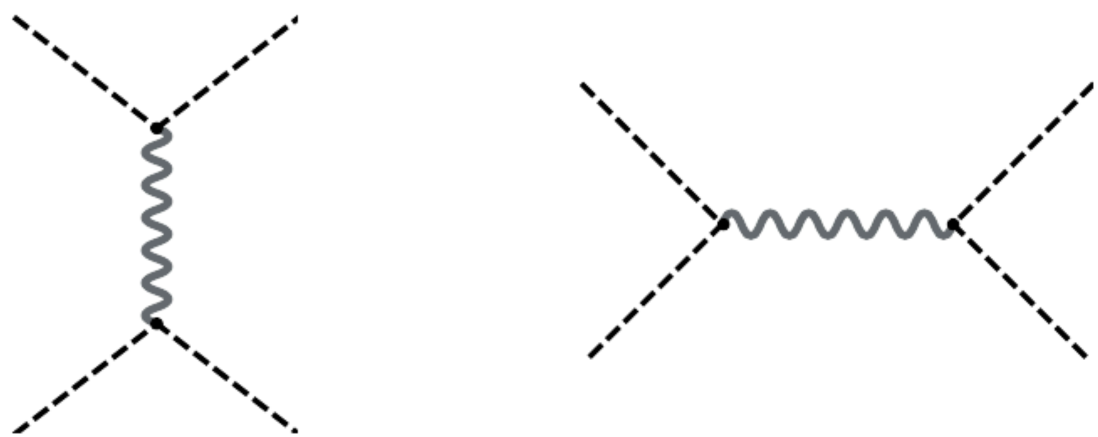
Nature has never chosen this simple solution before…

(Recall we have NOT observed a fundamental scalar previously!)

Nature has never chosen this simple solution before…

(Recall we have NOT observed a fundamental scalar previously!)

For example, pi-pi scattering in low-energy QCD is unitarized by a series of heavy resonances, including the spin-1 rho meson:



Each resonance only partially unitarizes the pi-pi scattering.

If the 125 GeV Higgs only partially unitarize the VV scattering

→ the HVV coupling will deviate from the SM expectation!!

Unitarization in VV scattering is only tested with O(10%) uncertainty.

→ Clearly not sufficient!

If the 125 GeV Higgs only partially unitarize the VV scattering

→ the HVV coupling will deviate from the SM expectation!!

Unitarization in VV scattering is only tested with O(10%) uncertainty.

→ Clearly not sufficient!

In the end of the day, precision is the key!

But what kind of precision is needed?

By accident, generic deviations from SM are quadratic in $1/M_{new}$:

$$\mathcal{O}\left(\frac{v^2}{M_{\rm new}^2}\right) \sim 5\% \times \left(\frac{1\ \rm TeV}{\Lambda}\right)^2$$

To establish credible deviations we need Higgs factories with percent level precision!

By accident, generic deviations from SM are quadratic in $1/M_{new}$:

$$\mathcal{O}\left(\frac{v^2}{M_{\rm new}^2}\right) \sim 5\% \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

To establish credible deviations we need Higgs factories with percent level precision!

At a high energy muon collider, single Higgs production goes through the VBF topology. Moreover, both WW and ZZ fusion need to be considered:

$$\begin{aligned} \mu^+\mu^- &\to \nu_\mu\bar{\nu}_\mu\ H \qquad (WW\ \text{fusion}), \\ \mu^+\mu^- &\to \mu^+\mu^-\ H \qquad (ZZ\ \text{fusion}). \end{aligned}$$

This lead to the notion of a “inclusive process” similar to a hadron collider!

(Electroweak PDF of the muon is among the most fascinating physics opportunities at a muon collider!)

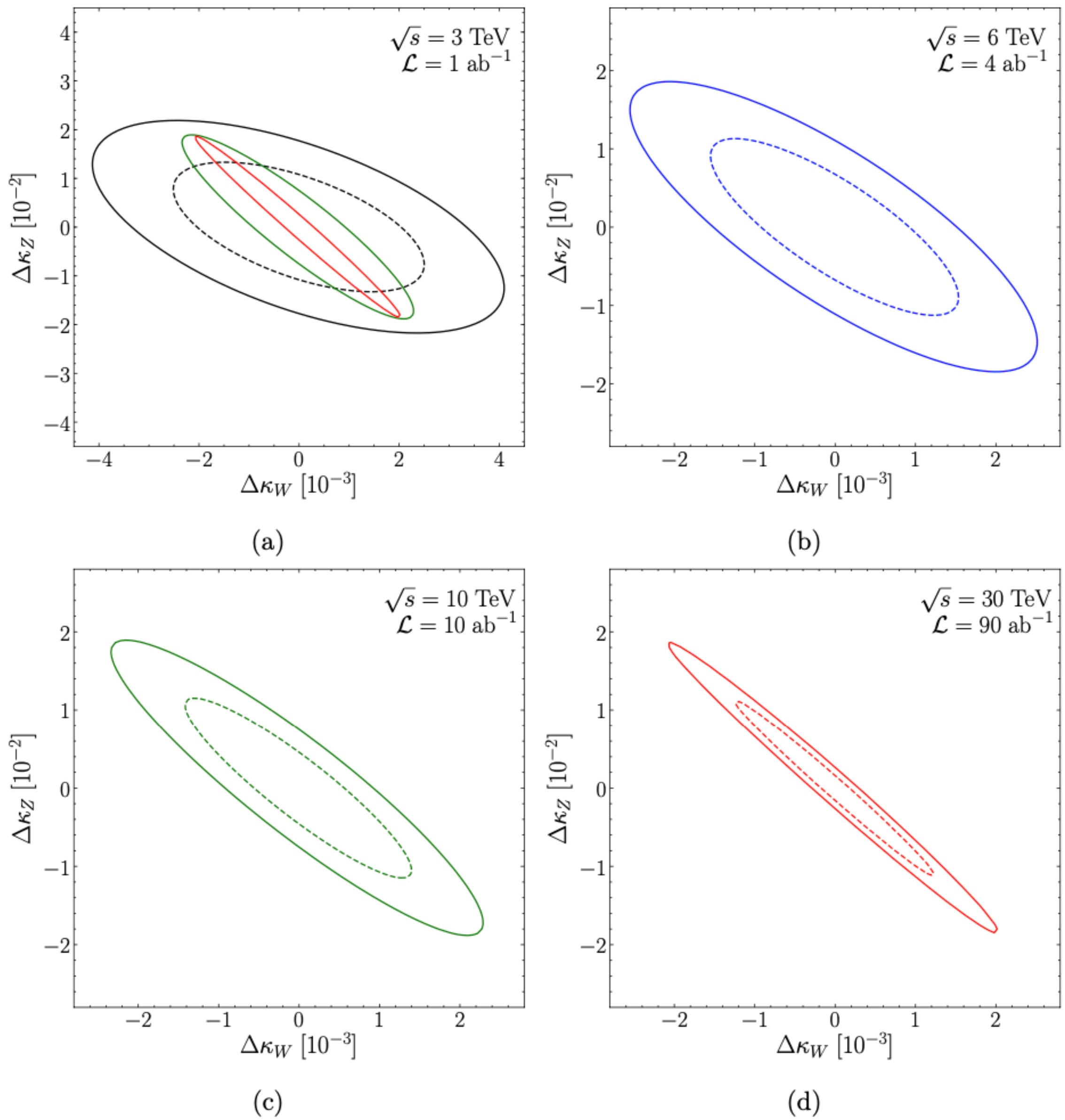


Figure 6: Correlated bounds with 95% C.L. (solid) and 68% C.L. (dashed) in the $\Delta\kappa_W$-$\Delta\kappa_Z$ plane for $\sqrt{s} = 3, 6, 10, 30$ TeV, respectively. In (a), inner ellipses (solid) include the 95% C.L. results for 10 TeV and 30 TeV for comparison.

T. Han, D. Liu, IL, X. Wang: 2008.12204

One example of a conceptual question the SM has no answer to:

What is the Higgs made of?

One example of a conceptual question the SM has no answer to:

What is the Higgs made of?

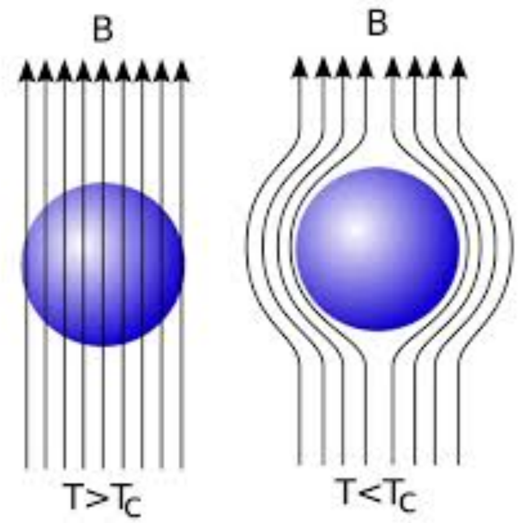
There is a more sophisticated version of the question:

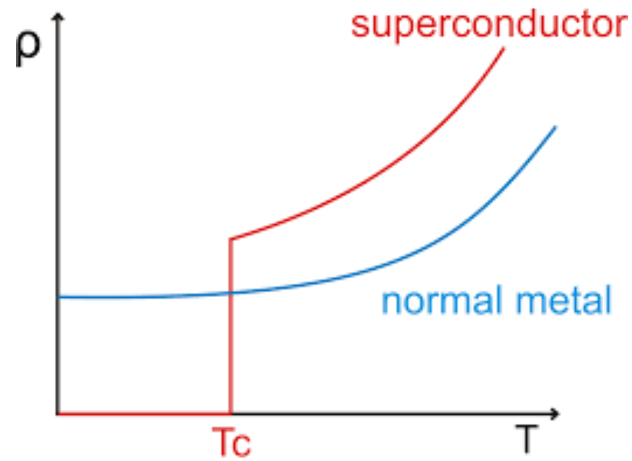
What is the microscopic theory that gives rise to the Higgs boson and its potential?

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

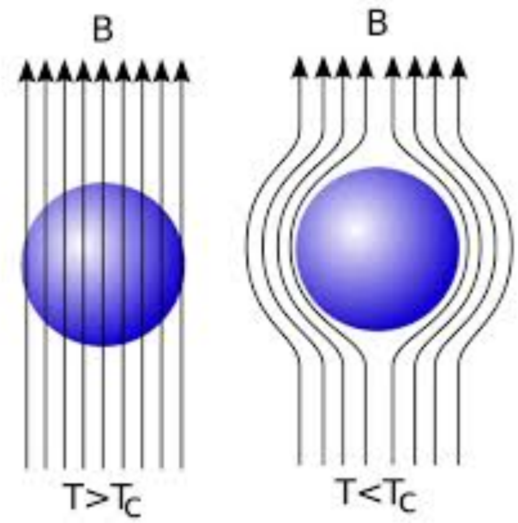
Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.

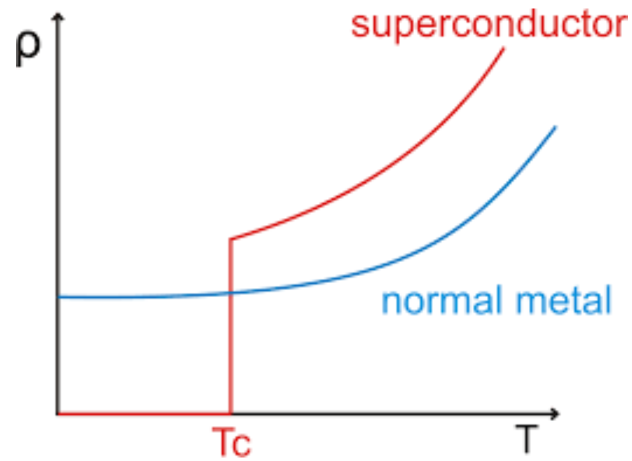
One of the most beautiful examples is the superconductivity discovered in 1911:





One of the most beautiful examples is the superconductivity discovered in 1911:

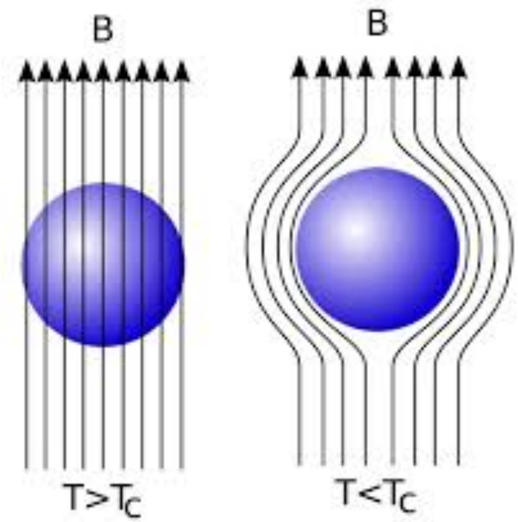


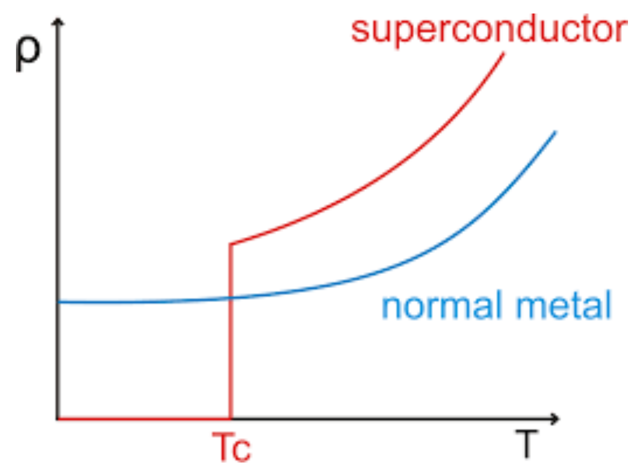


Ginzburg-Landau theory from 1950 offered a **macroscopic** (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

One of the most beautiful examples is the superconductivity discovered in 1911:





Ginzburg-Landau theory from 1950 offered a **macroscopic** (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

What is the **microscopic** origin of the Ginzburg-Landau potential for superconductivity?

In 1957 Bardeen, Cooper and Schrieffer provided the **microscopic** (fundamental) theory that allows one to

1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

In 1957 Bardeen, Cooper and Schrieffer provided the **microscopic** (fundamental) theory that allows one to

1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

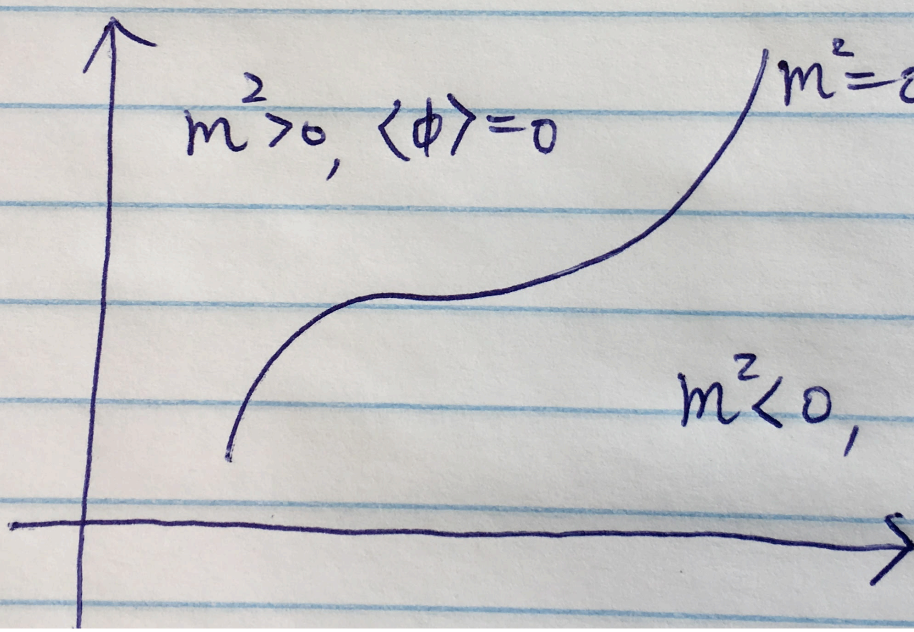
We do not have the corresponding **microscopic** theory for the Higgs boson.

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!

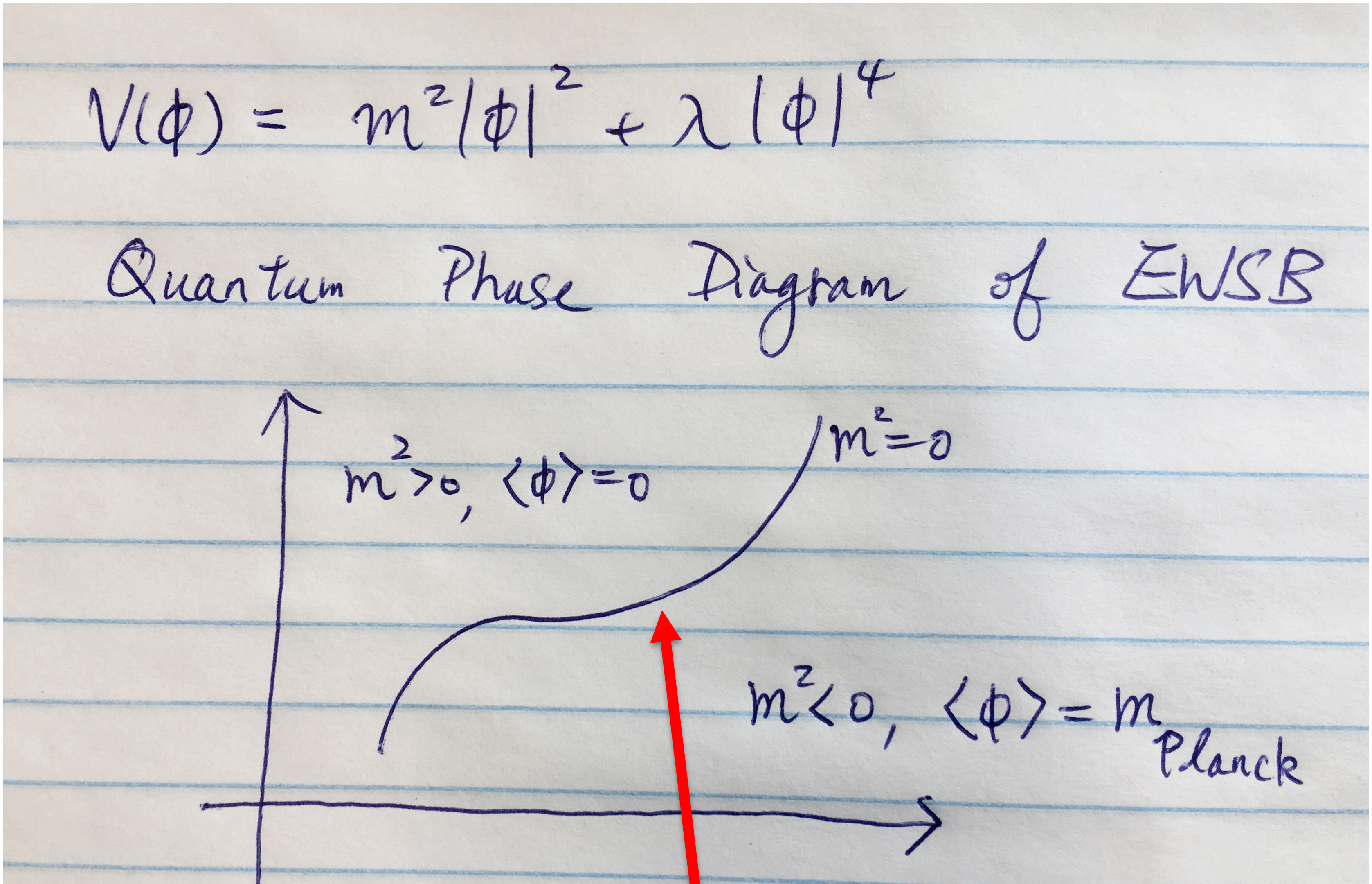
The question can be reformulated in terms of **Quantum Criticality**:

$$V(\phi) = m^2|\phi|^2 + \lambda|\phi|^4$$

Quantum Phase Diagram of EWSB



The question can be reformulated in terms of **Quantum Criticality**:



Mh=125 GeV. We are sitting extremely close to the criticality. **WHY??**

One appealing possibility – the critical line is selected dynamically.

This is the analogy of BCS theory for electroweak symmetry breaking. It goes by the name of “technicolor,” which is strongly disfavored experimentally.

One appealing possibility – the critical line is selected dynamically.

This is the analogy of BCS theory for electroweak symmetry breaking. It goes by the name of "technicolor," which is strongly disfavored experimentally.

Two popular "explanations:"

1. Postulate new global symmetries above the weak scale, and the Higgs boson arises as a (pseudo) Nambu-Goldstone boson.

➔ This class goes by the name of "composite Higgs models."

2. The critical line is a locus of enhanced symmetry.

➔ This is the (broken) supersymmetry.

We have not seen any signs of SUSY or CHM.

This only **deepens** the mystery, of why we are sitting close to the critical line of EWSB!

It is a humbling experience to realize that, after 40 years, our understanding of the electroweak criticality is still at the level of Ginzburg-Landau level.

We have not seen any signs of SUSY or CHM.

This only **deepens** the mystery, of why we are sitting close to the critical line of EWSB!

It is a humbling experience to realize that, after 40 years, our understanding of the electroweak criticality is still at the level of Ginzburg-Landau level.

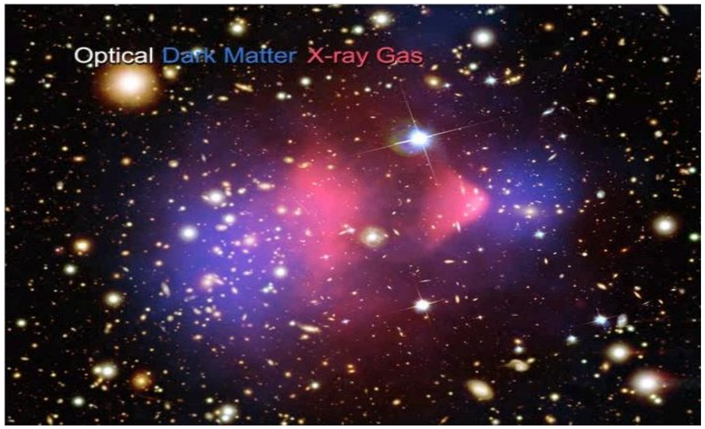
However, we do know that electroweak symmetry breaking more exotic than the BCS theory of superconductivity.

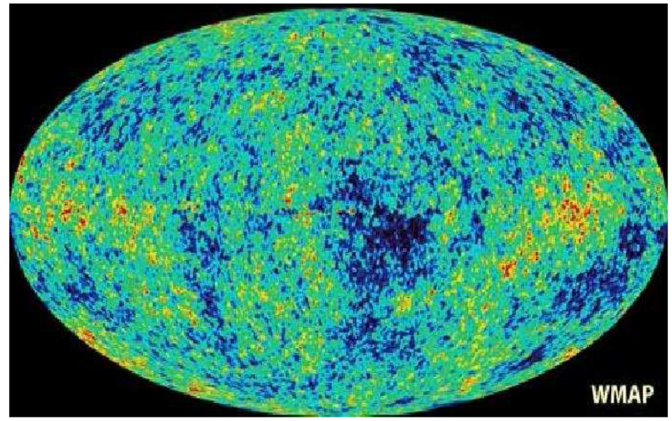
“The Universe is not a piece of crappy metal!”

by a prominent HEP theorist.

Some excellent empirical questions SM cannot answer:

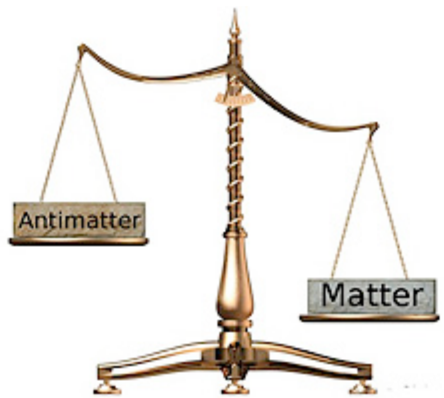
- Dark matter/Dark sector.





Higgs as a portal to dark matter/dark sector?

- CP-violation and baryon asymmetry.



New sources of CP-violation in the Higgs couplings?

These questions require us to look for

- Deviations in the coupling <u>structure</u> of the Higgs boson.
- Rare and new decay channels of the Higgs boson.
- Partners of the SM top quark that couple significantly to the Higgs.
- Additional Higgs bosons.

Concluding Remarks:

- The Higgs boson is the most exotic state of matter in Nature. The electroweak criticality is the most bizarre type of quantum criticality.

- Our understanding is still preliminary, at the level of Ginzburg-Landau theory for the superconductivity.

  Need to pin down a microscopic picture.

- **There is a rich program to be pursued at a high energy muon collider.**

- **We will be exploring some of the deepest puzzles in physics!**