A Theory Vision for the Higgs Boson

- Ian Low
- Argonne/Northwestern

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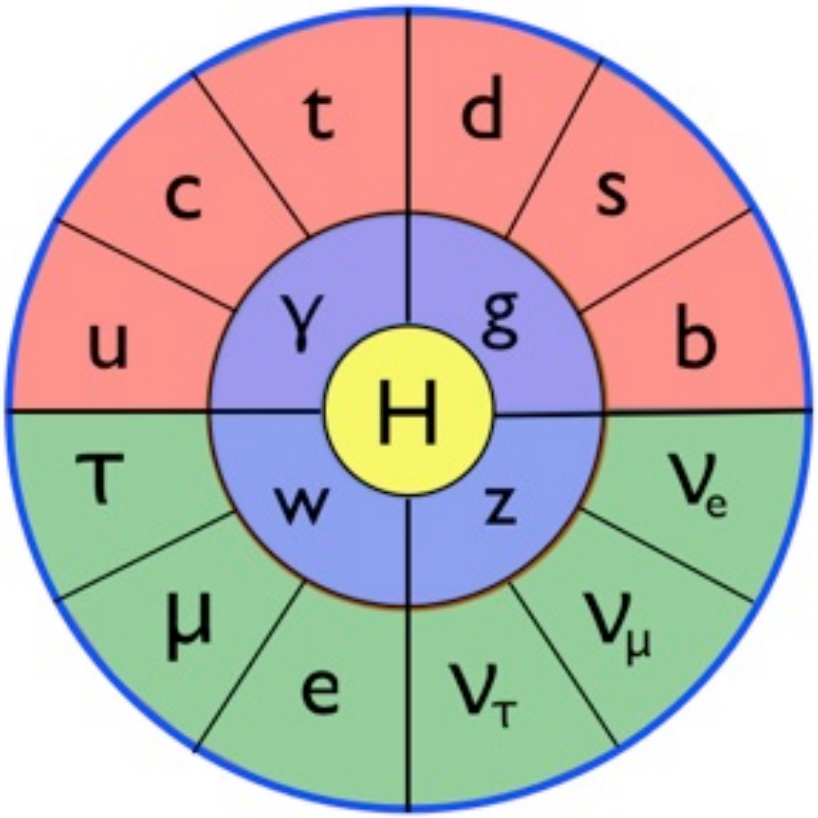
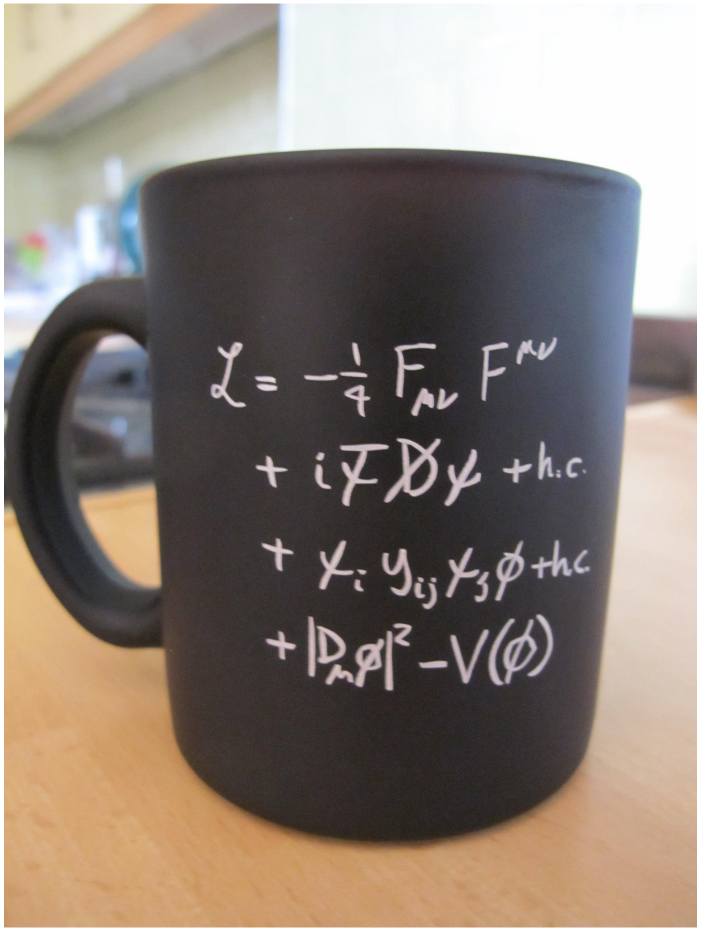
Higgs as a Probe of New Physics 2023

大阪大学
OSAKA UNIVERSITY

The Standard Model is UV-complete after the discovery of the Higgs:





Are we done then?

A reminder:

throughout the course of history, UV completion always fails to predict the completeness of the theory!

- 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.

What is the path forward?

- 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

Testing Predictions of 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 →

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

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

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

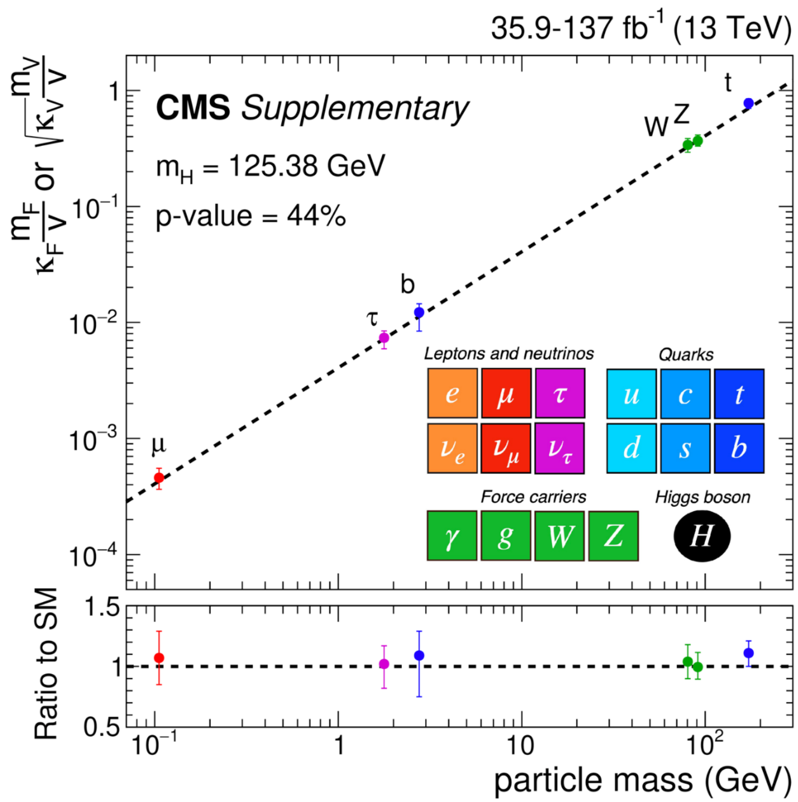
Self-couplings → $\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$

A highly non-trivial prediction:

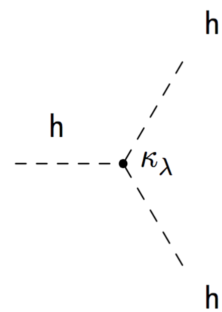
There is no free parameters (once all masses are measured)!

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

Yukawa couplings to 1st and 2nd generation fermions.

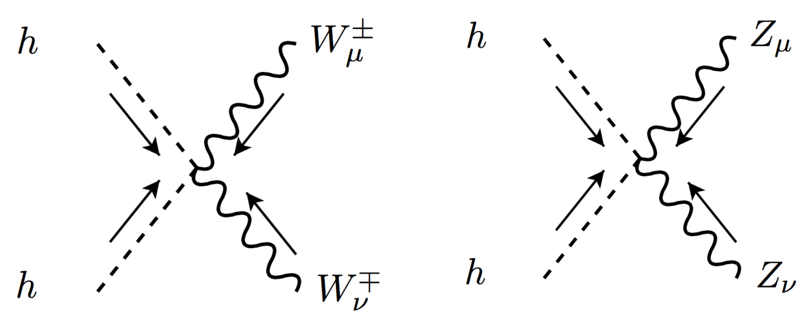


Trilinear Higgs self-coupling – we have NOT measured the Higgs potential.

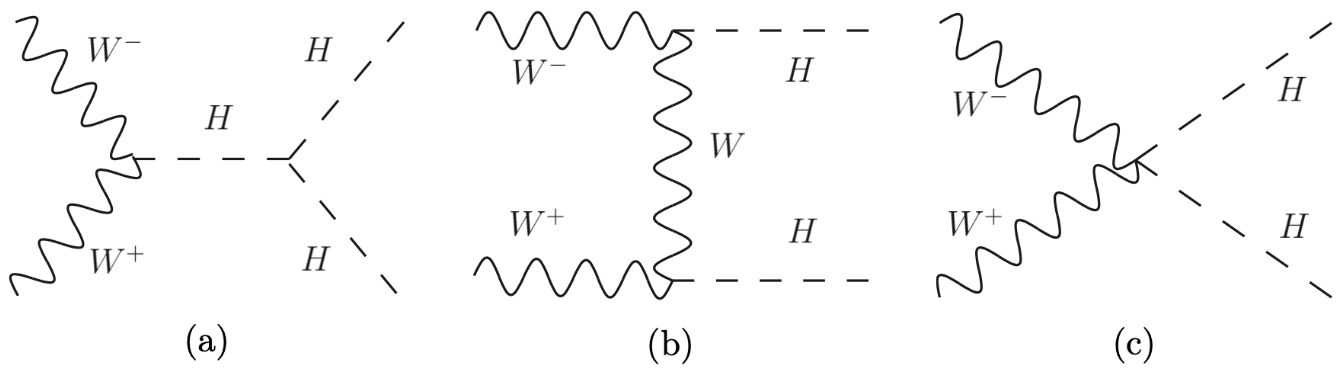


4-pt HHVV coupling – prediction of gauge invariance.

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



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



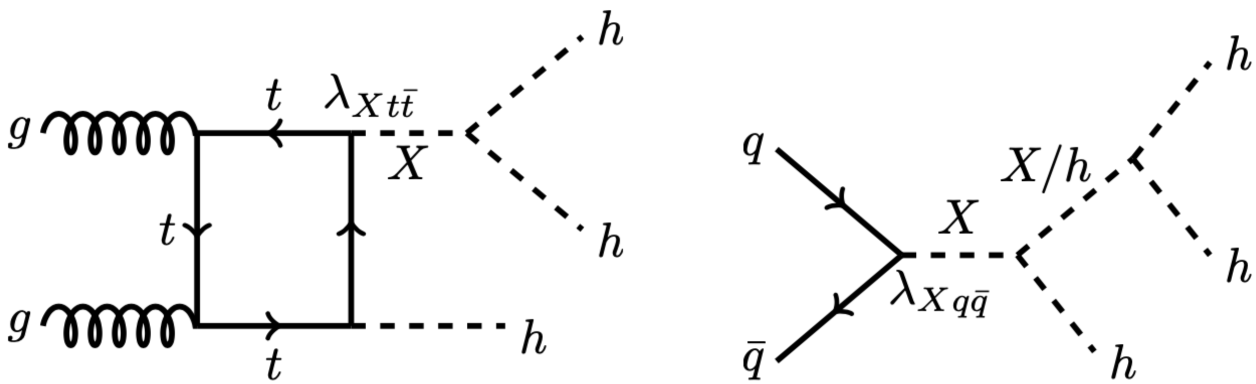
- **As we go to very high energies, why stop at two Higgses?**

  3H and 4H final states have not been searched for experimentally.

  What are the NLO/NNLO SM predictions for 3H and 4H??

- **A new frontier waiting to be explored at both the hadron and lepton colliders!**

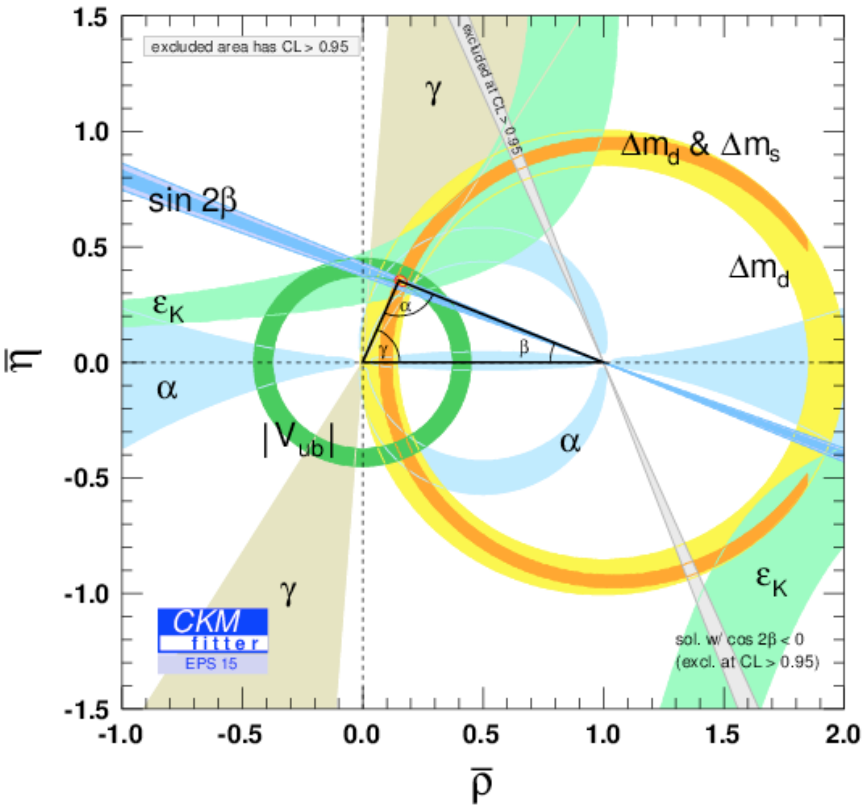
- Simple extensions of the scalar sector (2HDM or SM+ singlet) could produce 3H and 4H final states with significant rates at a hadron collider:



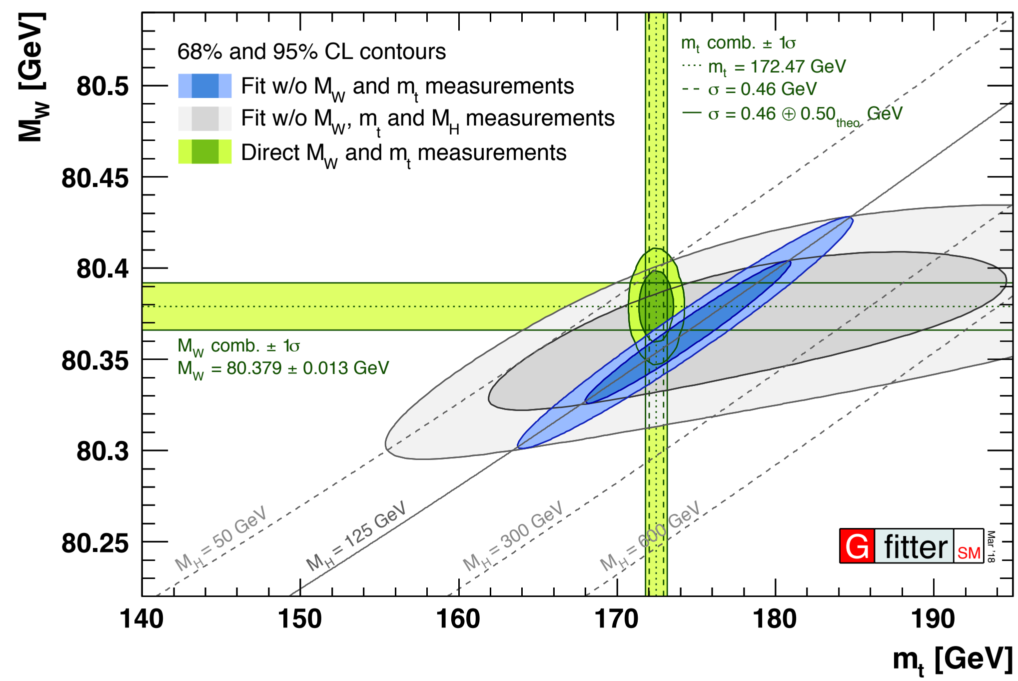
IL, N. Shah, X. Wang: 2012.00773;
Egana-Ugrinovic, Homiller, Meade: 2101.04119
C.-W. Chiang, T.-K. Kuo, IL: 2202.02954

- **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:



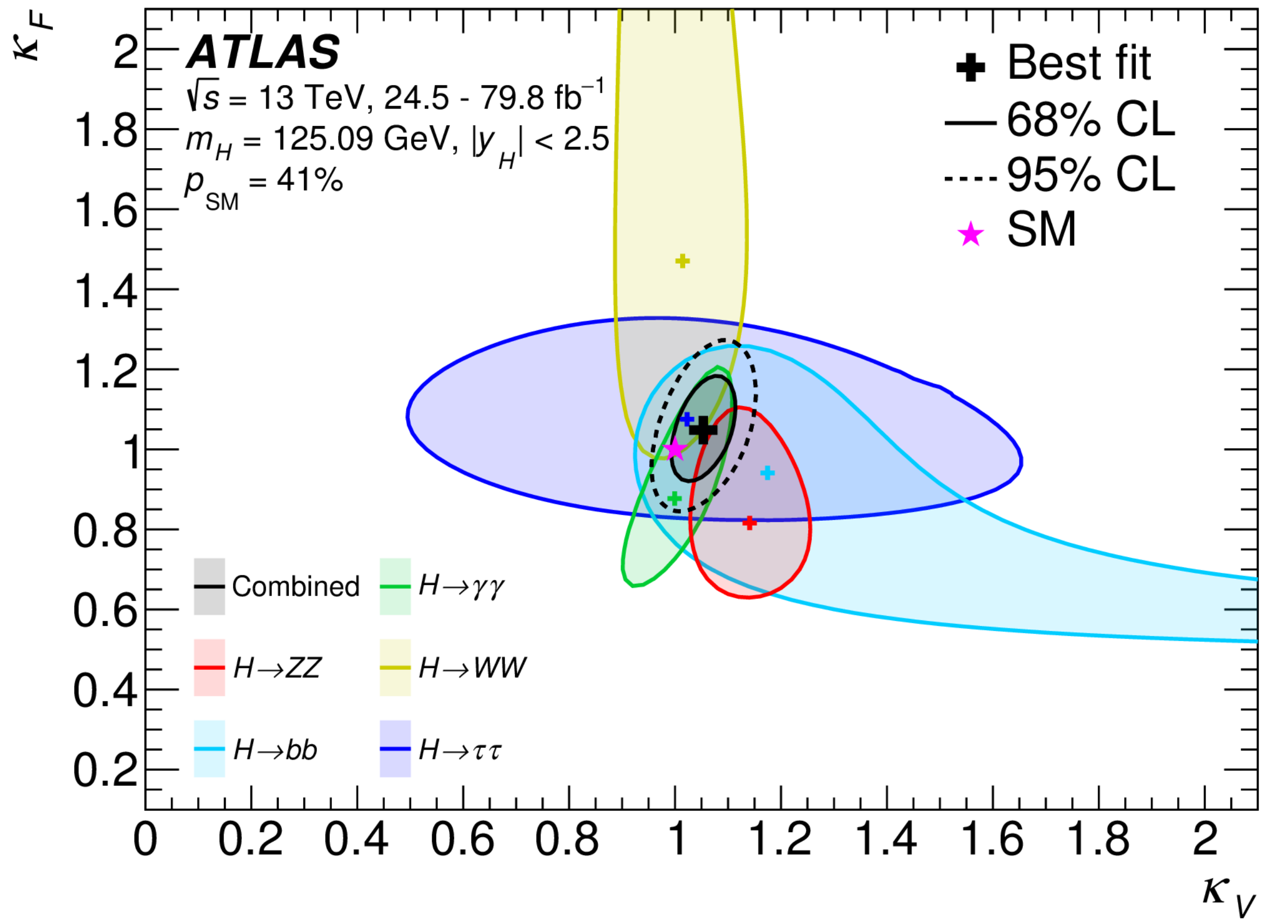
Unitarity triangle



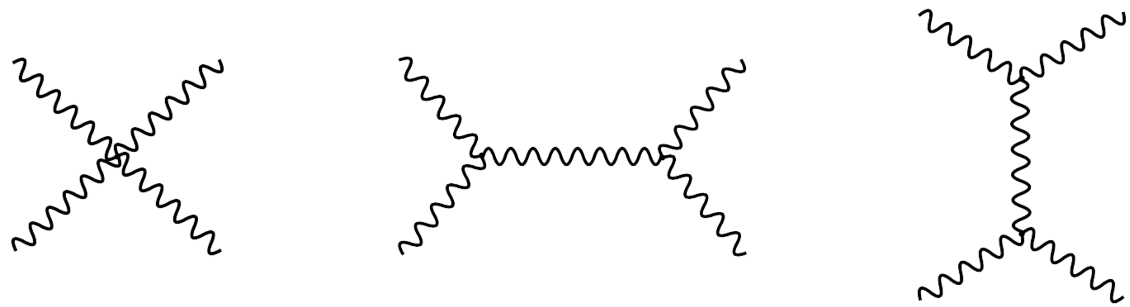
Precision Electroweak Measurements

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

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

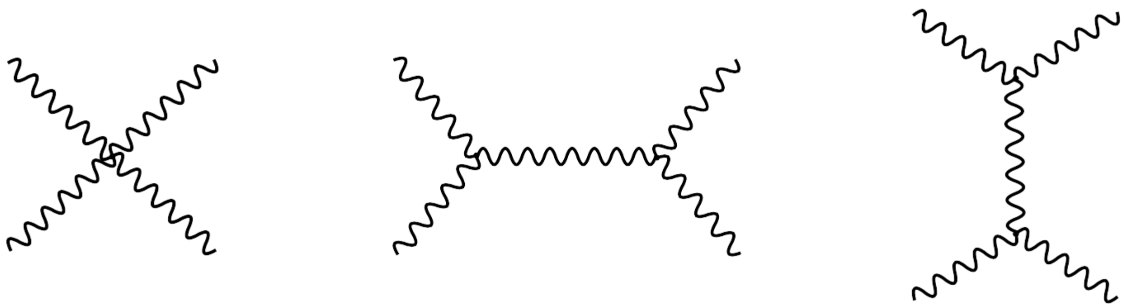


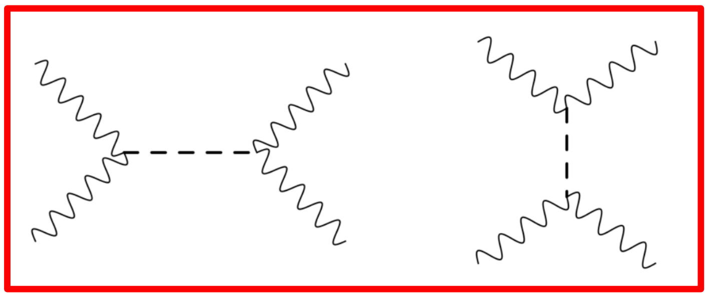
- One very important prediction of SM Higgs to be measured precisely:
  Without the Higgs, WW scattering amplitude violates unitarity:



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

- One very important prediction of SM Higgs to be measured precisely:
  Including the Higgs contribution allows the growth to be cancelled completely,





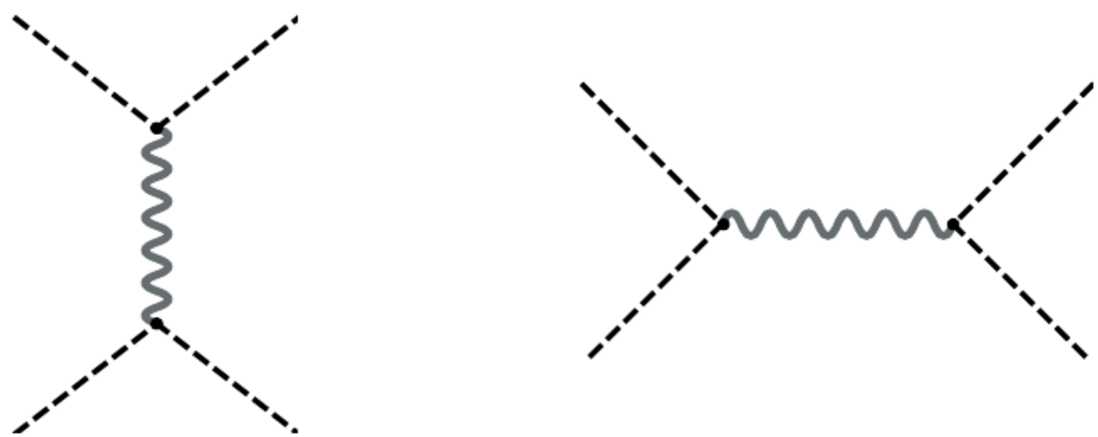
provided the HWW coupling have precisely the form in the SM!

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!)

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 unitarizes 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 how precise is precise enough??

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

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

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

If the precision improved,

ECFA 1905.03764

	HL-LHC	ILC250	ILC500	CLIC380	CLIC1500	CEPC	FCCee240	FCCee350
hZZ	3.6	0.47	0.22	0.66	0.27	0.52	0.47	0.26
hWW	3.2	0.48	0.23	0.65	0.24	0.51	0.46	0.27
hbb	5.1	0.83	0.52	1.0	0.47	0.67	0.70	0.56
hcc	-	1.8	1.2	4.0	1.9	1.9	1.4	1.3
$h\tau\tau$	3.5	0.85	0.60	1.3	0.93	0.70	0.70	0.57
hgg	2.2	1.1	0.79	1.3	0.97	0.79	0.95	0.82
$h\gamma\gamma$	3.7	1.3	1.1	1.4	1.2	1.2	1.2	1.2

$$\delta_{hWW} \sim 1\% \quad \Rightarrow \quad f \sim 1.7\ \text{TeV}$$
$$\delta_{hWW} \sim 0.1\% \quad \Rightarrow \quad f \sim 5.5\ \text{TeV}$$

Asking the right questions

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

What is the Higgs made of?

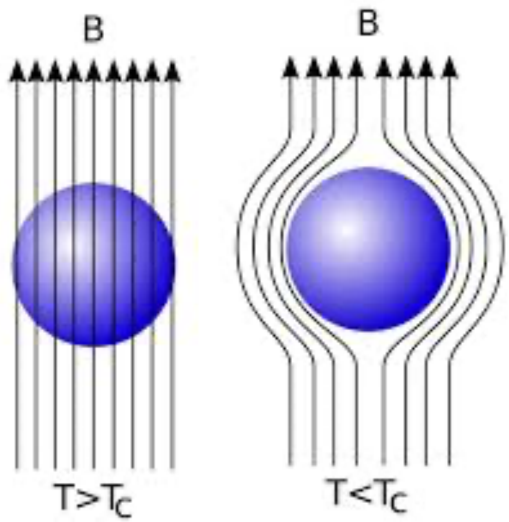
There is a more sophisticated version of the question:

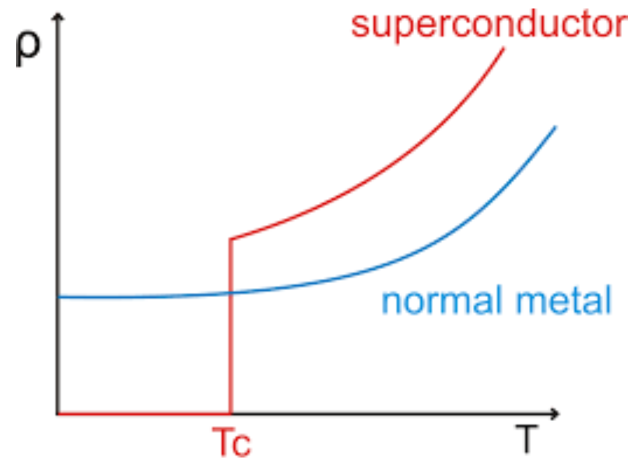
What is the microscopic theory that gives rise to the Higgs boson and its potential?

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

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:





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

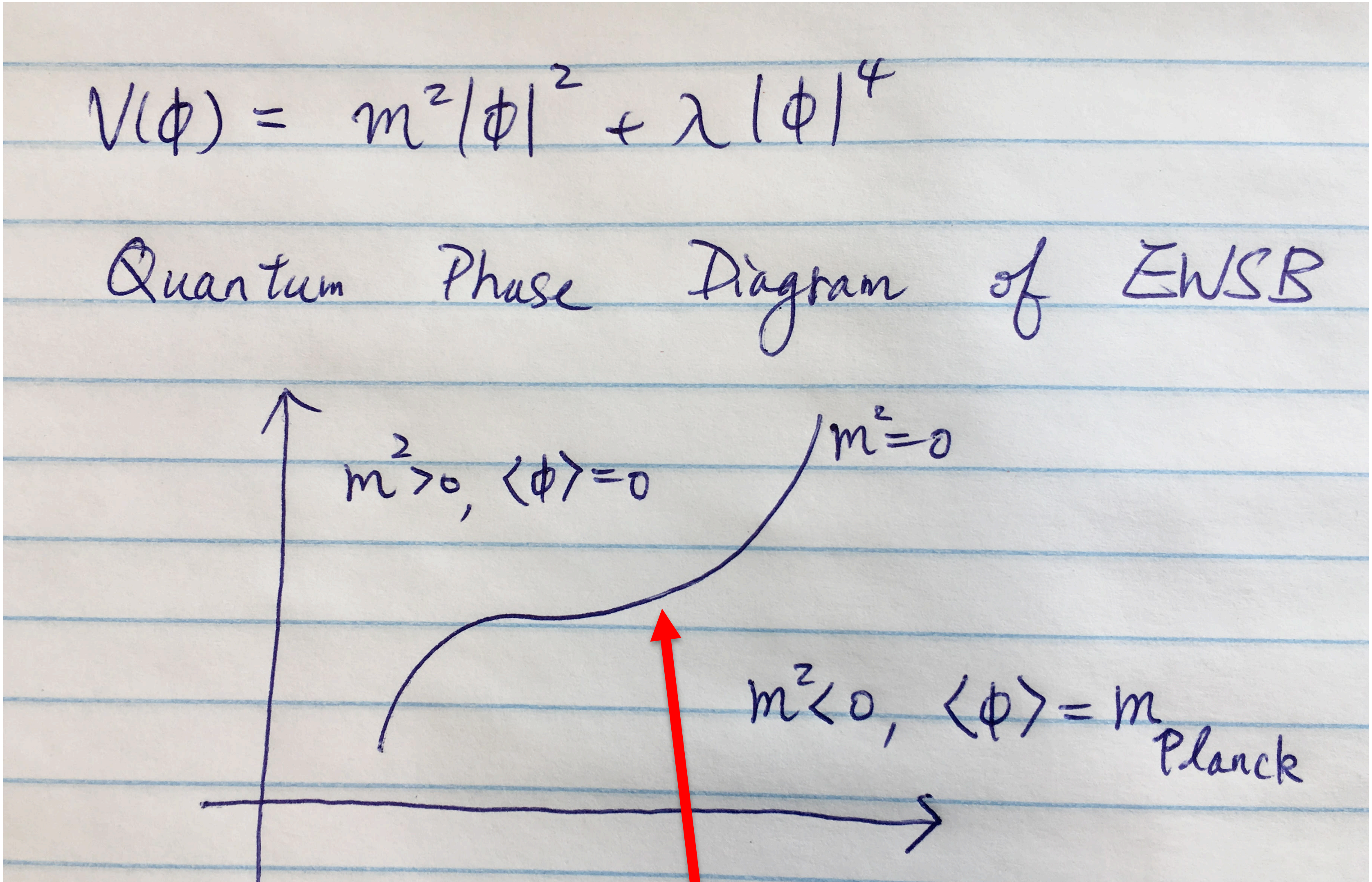
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

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

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**:



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.

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

by a prominent HEP theorist.

Besides technicolor, there are two popular “explanations:”

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

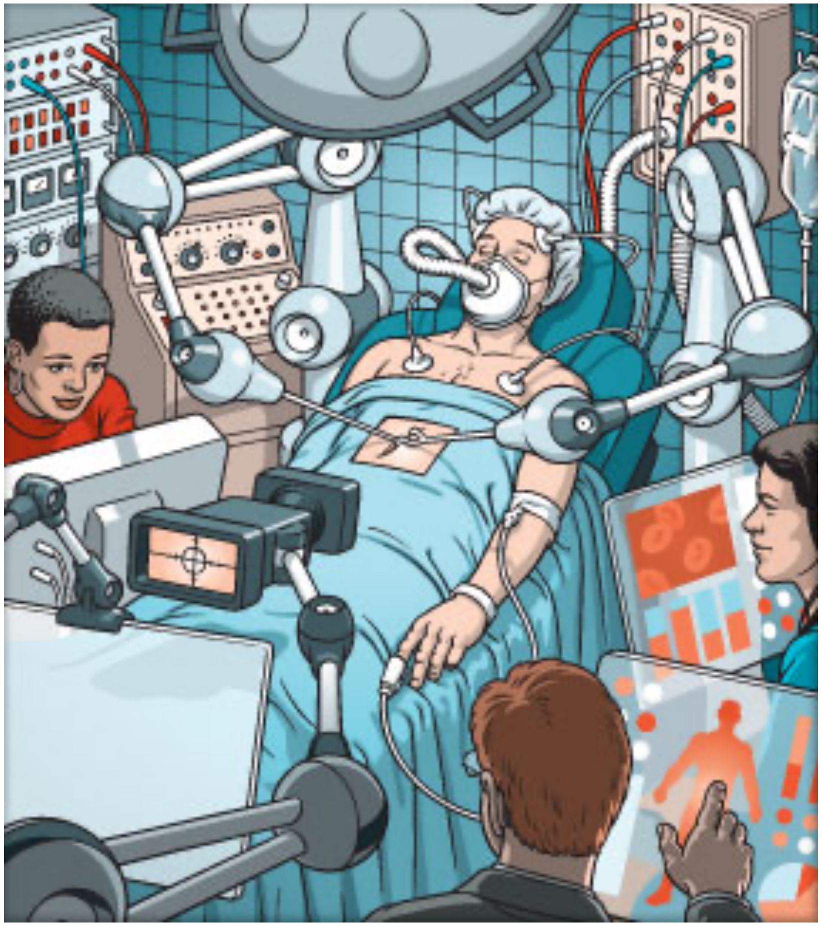
➔ This class goes by the name of “composite Higgs models.”

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

➔ This is the (broken) supersymmetry.

Supersymmetry v.s. Composite Higgs:

Neither of them is doing great --



Although that may be a difference of opinion…

Every day we don't observe any signs of new physics, the mystery deepens and the plot thickens:

Why are we sitting close to the critical line of EWSB??

An esteemed condensed matter colleague once told me "I have a microscopic theory for EWSB!"

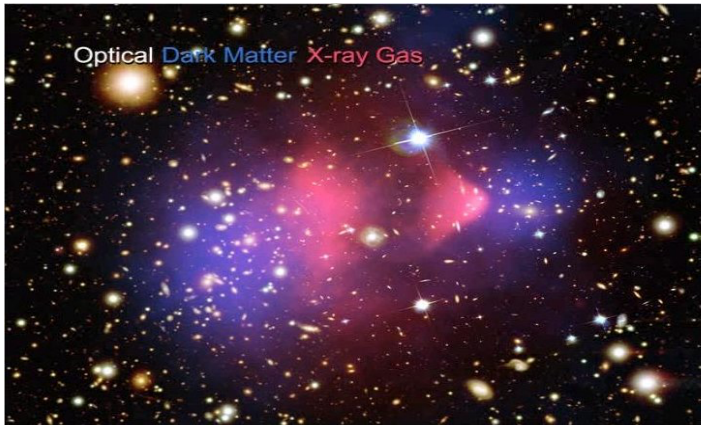
I asked him "So tell me, do you have Higgs and nothing else?"

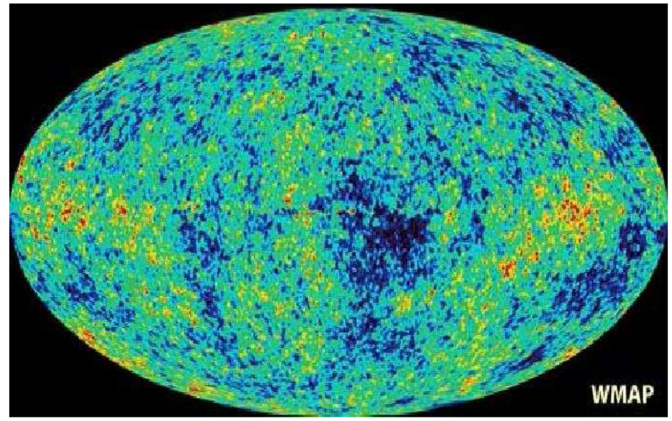
Then he shut up…

EWSB is the most exotic state of quantum criticality.

Some excellent empirical questions SM cannot answer:

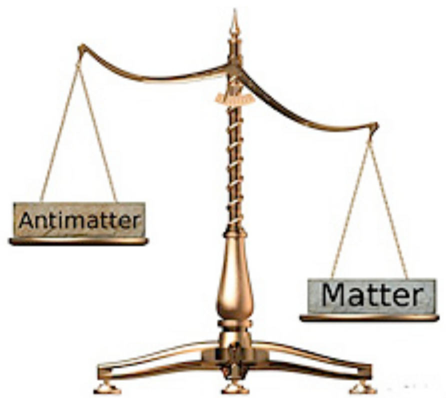
- Dark matter/Dark sector.





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.

An important benchmark:

Coupling structures in HVV and HHVV – many well-motivated BSM models predict new coupling structures, in addition to the SM ones.

Some examples of $O(p^4)$ operators modifying HVV and HHVV couplings

$$
\begin{aligned}
\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} &+ \left(2C_0^h \frac{h}{v} + C_0^{2h}\frac{h^2}{v^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right) \\
&+ C_5^h \left(\frac{h}{v} W_\mu^+ \mathcal{D}^{\mu\nu} W_\nu^- + \text{h.c.}\right) + C_6^h \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu} \\
&+ C_5^{2h} \left(\frac{h^2}{v^2} W_\mu^+ \mathcal{D}^{\mu\nu} W_\nu^- + \text{h.c.}\right) + C_6^{2h} \frac{h^2}{v^2} W_{\mu\nu}^+ W^{-\mu\nu} \\
&+ C_9^{2h} \frac{(\partial_\nu h)^2}{v^2} W_\mu^+ W^{-\mu} + C_{10}^{2h} \frac{\partial^\mu h \partial^\nu h}{v^2} W_\mu^+ W_\nu^- \,,
\end{aligned}
$$

Rare and exotic Higgs decays:

- Rare mesonic exclusive and flavor-violating decays:
  - Providing a unique window into the H(125) couplings to light quark flavors.
  - Testing the “flavor symmetry” of the SM Lagrangian.

- New particles in the decay of H(125):
  - New intermediate particles into SM final states.
  - New “invisible particles” in the decays of H(125).
  - New long-lived particles in the decay.

Mass of the Higgs is only 125 GeV, searches often face experimental challenges in triggering, detector response, MC simulations of signal samples, and etc.

→ Nice playground for theorists and experimentalists alike!

- Top partners can be either spin-0 in supersymmetry (the top squark) or spin-1/2 in composite Higgs models (the vector-like quark).

Their existence provides a “microscopic origin” for the special “minus sign” in the Higgs potential:

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

This sign could be generated by top partners at the loop-level through the celebrated Coleman-Weinberg mechanism.

This is the most salient feature common to popular models explaining the naturalness problem.

Their presence often modifies the top Yukawa coupling.

Where are the additional Higgs bosons?

Gunion and Haber, hep-ph/0207010

V. A SM-LIKE HIGGS BOSON WITHOUT DECOUPLING

We have demonstrated above that the decoupling limit (where $m_A^2 \gg |\lambda_i| v^2$) implies that $|c_{\beta-\alpha}| \ll 1$. However, the $|c_{\beta-\alpha}| \ll 1$ limit is more general than the decoupling limit. From eq. (36), one learns that $|c_{\beta-\alpha}| \ll 1$ implies that either (i) $m_A^2 \gg \lambda_A v^2$, and/or (ii) $|\widehat{\lambda}| \ll 1$ subject to the condition specified by eq. (33). Case (i) is the decoupling limit described in

"Alignment without decoupling" was (re)discovered by two groups:

- MSSM augmented by a triplet scalar in 1303.0800 by Delgado, Nardini and Quiros.
- Studies on the parameter space of general THDMs by Craig, Galloway and Thomas in 1305.2424.

See also Carena, IL, Shah, Wagner: 1310.2248; Carena, Haber, IL, Shah and Wagner: 1410.4969

Concluding Remarks:

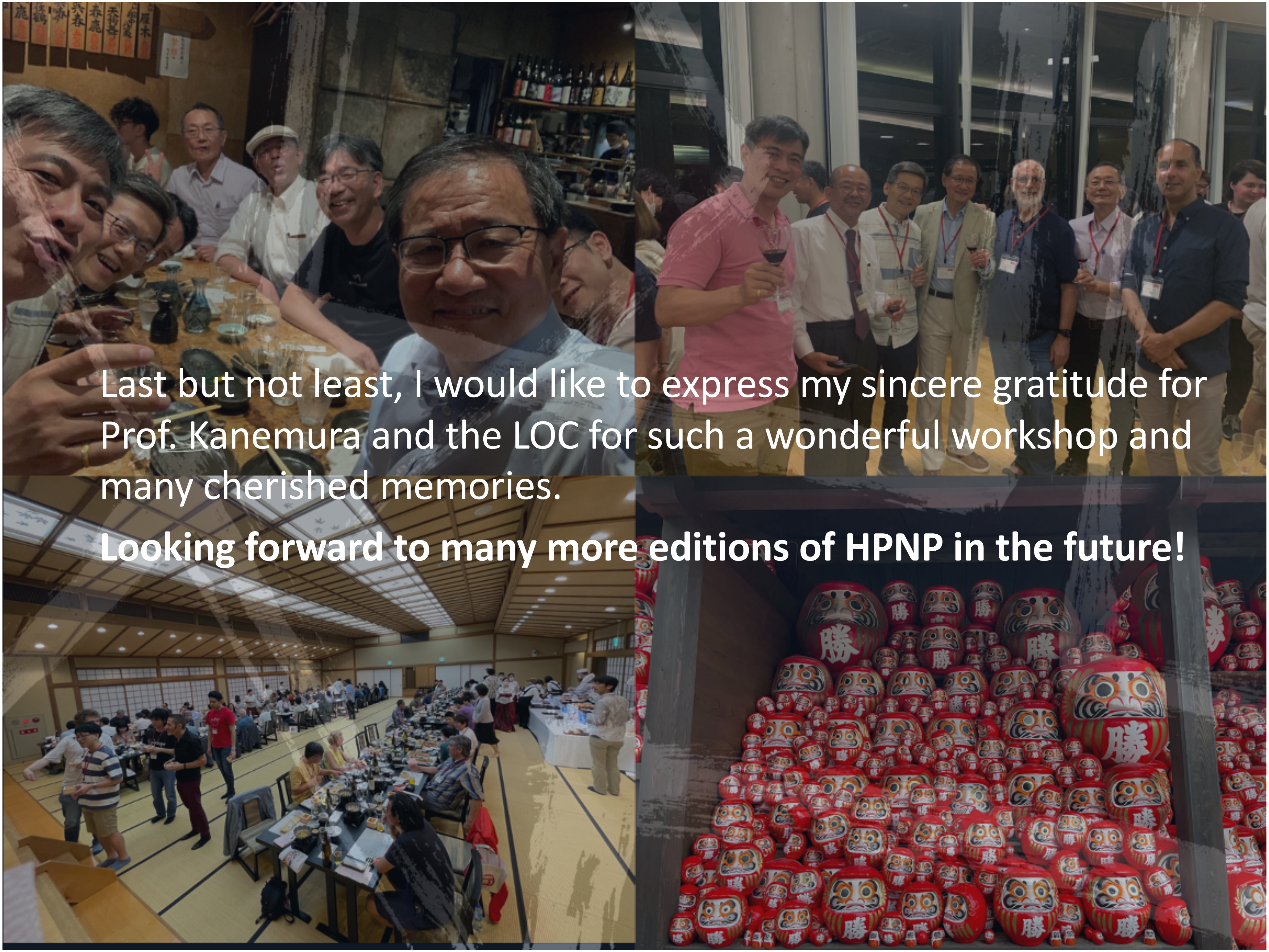
- The Higgs boson is the most exotic state of matter in Nature. The electroweak criticality is the most bizarre type of quantum criticality.

- 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 percent-level precision Higgs factory.**

- **Having a Higgs factory (and/or a very high energy collider), we will be exploring some of the deepest puzzles in physics.**



Last but not least, I would like to express my sincere gratitude for Prof. Kanemura and the LOC for such a wonderful workshop and many cherished memories.

Looking forward to many more editions of HPNP in the future!