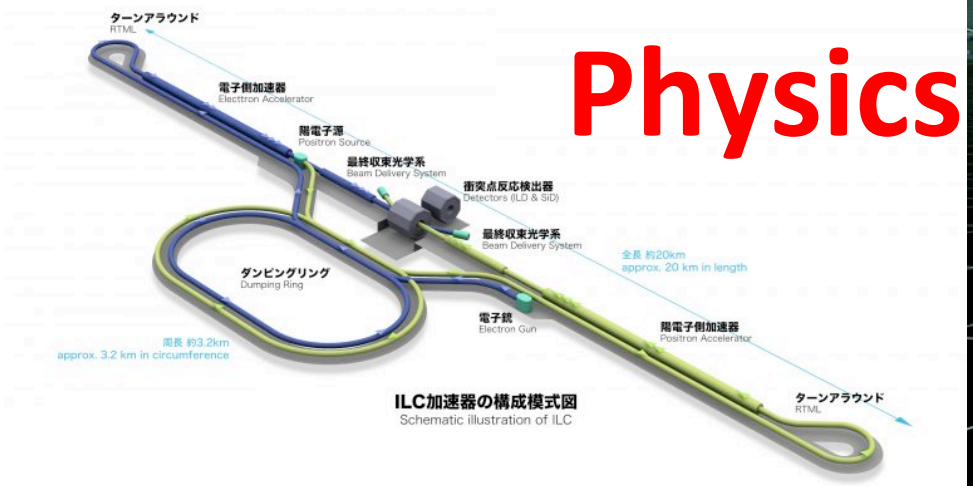
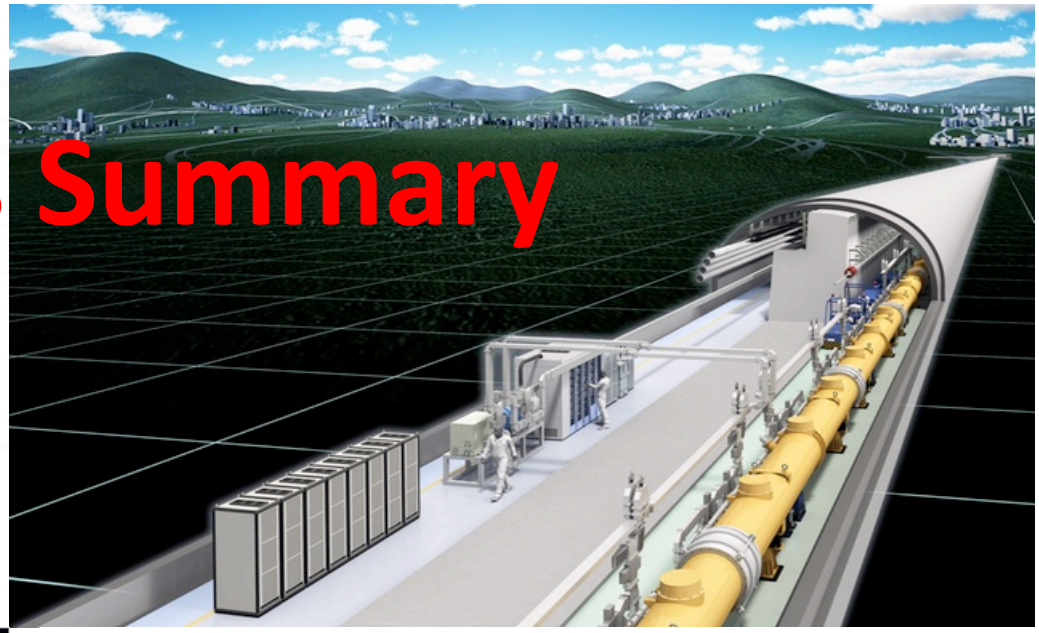
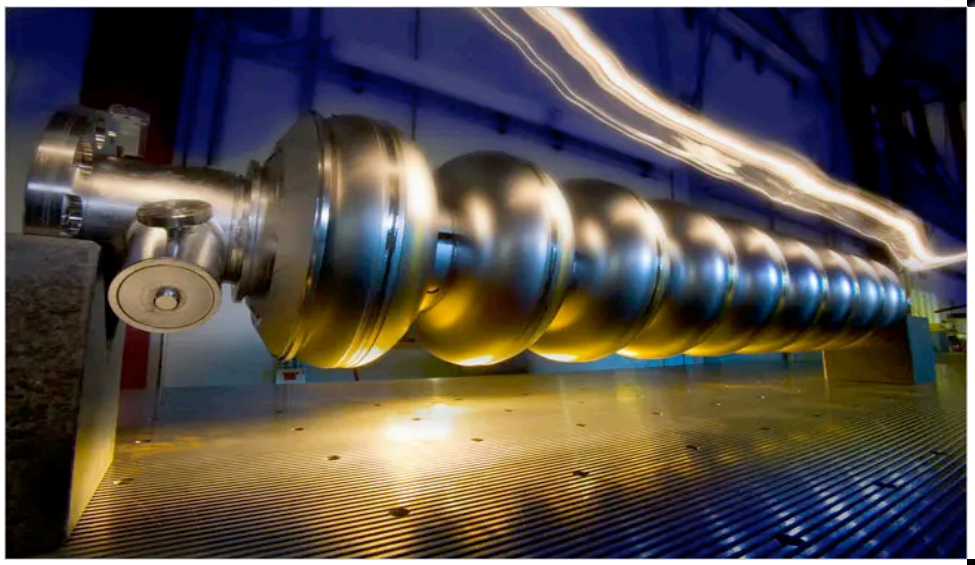
Physics Summary







Ian Low
Argonne/Northwestern

November 1, 2019

Our charge:

The physics and detector parallel sessions will have three tracks:

Track 1: Physics at e+e- colliders, models of new physics, tests of the Standard Model through global fits

Track 2: Analysis and reconstruction of e+e- processes, event simulation, physics performance

Track 3: Detector R&D for e+e- Colliders

Track 1 conveners

(Replace "_at_" to "@" in [ ] to send emails.)

- Stefania Gori [sgori_at_ucsc.edu] (UC Santa Cruz)
- Shinya Kanemura [kanemu_at_het.phys.sci.osaka-u.ac.jp] (Osaka)
- Ian Low [ilow_at_anl.gov] (Argonne)
- Junping Tian [tian_at_icepp.s.u-tokyo.ac.jp] (Tokyo)
- Marcel Vos [Marcel.Vos_at_ific.uv.es] (Valencia)
- Dirk Zerwas [zerwas_at_lal.in2p3.fr] (Orsay)
- Sven Heinemeyer [Sven.Heinemeyer_at_cern.ch] (CERN)

Track 2 conveners

(Replace "_at_" to "@" in [ ] to send emails.)

- Patrizia Azzi [Patrizia.Azzi_at_cern.ch] (Padova)
- Mikael Berggren [mikael.berggren_at_desy.de] (DESY)
- Frank Gaede [frank.gaede_at_desy.de] (DESY)
- Daniel Jeans [daniel.jeans_at_kek.jp] (KEK)
- Manqi Ruan [manqi.ruan_at_ihep.ac.cn] (IHEP)
- Jan Strube [jan.strube_at_pnnl.gov] (PNNL)
- Filip Zarnecki [Filip.Zarnecki_at_fuw.edu.pl] (Warsaw)

Disclaimer

- Track 1: 32 contributions
- Track 1/2 joint: 17 contributions
- Track 2: 12 contributions

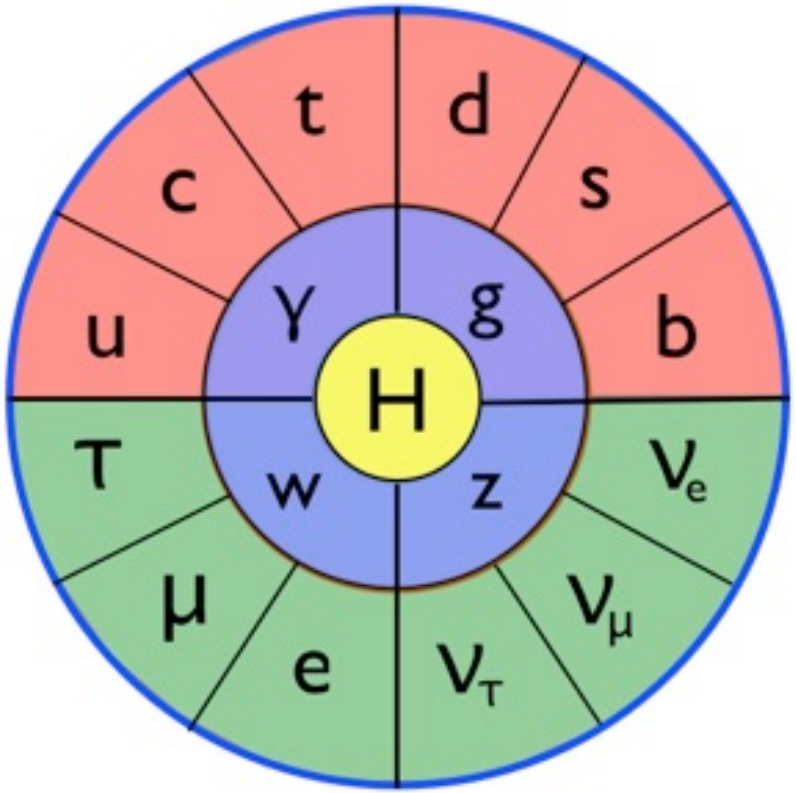
Suppose to cover ~ 60 talks in 30 minutes…

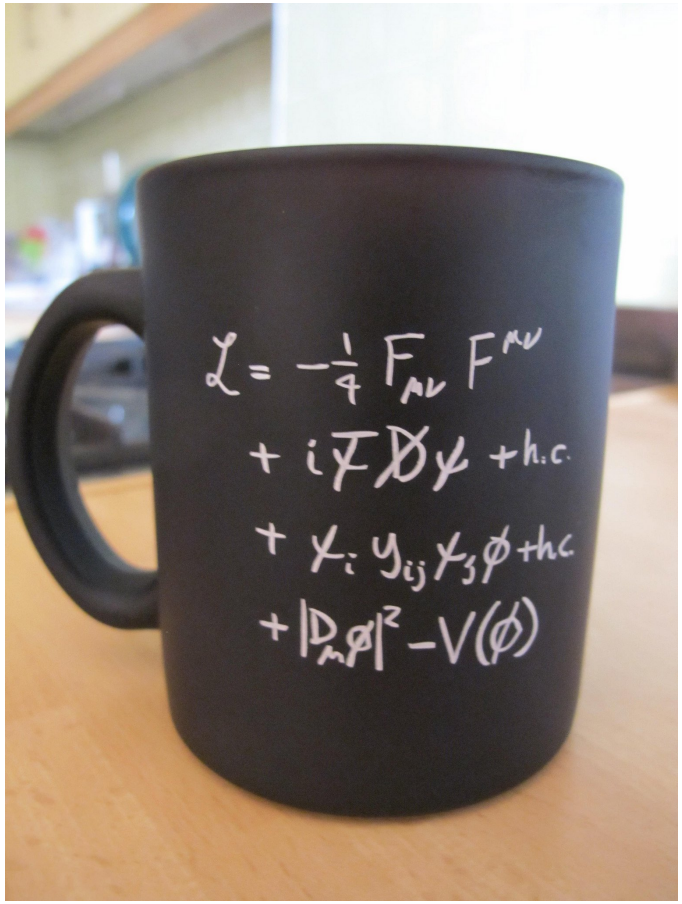
Will try to

- Give a broad context of the physics goals of ILC and skip details
- Provide a roadmap to various contributions

Choice of topics reflects my ignorance – don't know everything well enough to comment on everything!

After the discovery of the Higgs, the Standard Model is self-consistent :





Self-consistent ≠ Complete

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

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

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

“But the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

We find path forward by

- 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

But first we need to acknowledge the foundations of any measurements

- Detector performance
- Object/event reconstruction
- Event simulations

Construct Deep Jet Clustering

17:36 - 17:56

Generating the full SM at ILC

10:50

(Conference building)

Preparing SHERPA for e+e-

16:24 - 16:48

Tau finding and lepton ID studies at CEPC

pySiDR: Python Event Reconstruction for SiD

10:55 - 11:15

Room5 (Confere

R&D of the flavor-tag method based on Machine Learning for high energy experiments

A study of e+e--->tau+tau- at ILC500

14:00 - 14:20

Room5 (Confere

Presenter Keita Y

Jet reconstruction performances and distinguish between multi-jet events

16:00 - 16:20

Room1 (Conference building)

Presenter Peizhu Lai

Improving jet energy reconstruction for ILC Higgs precision measurement with kinematic fits

16:48

Study of ee->cc

NLO QCD and BSM with WHIZARD

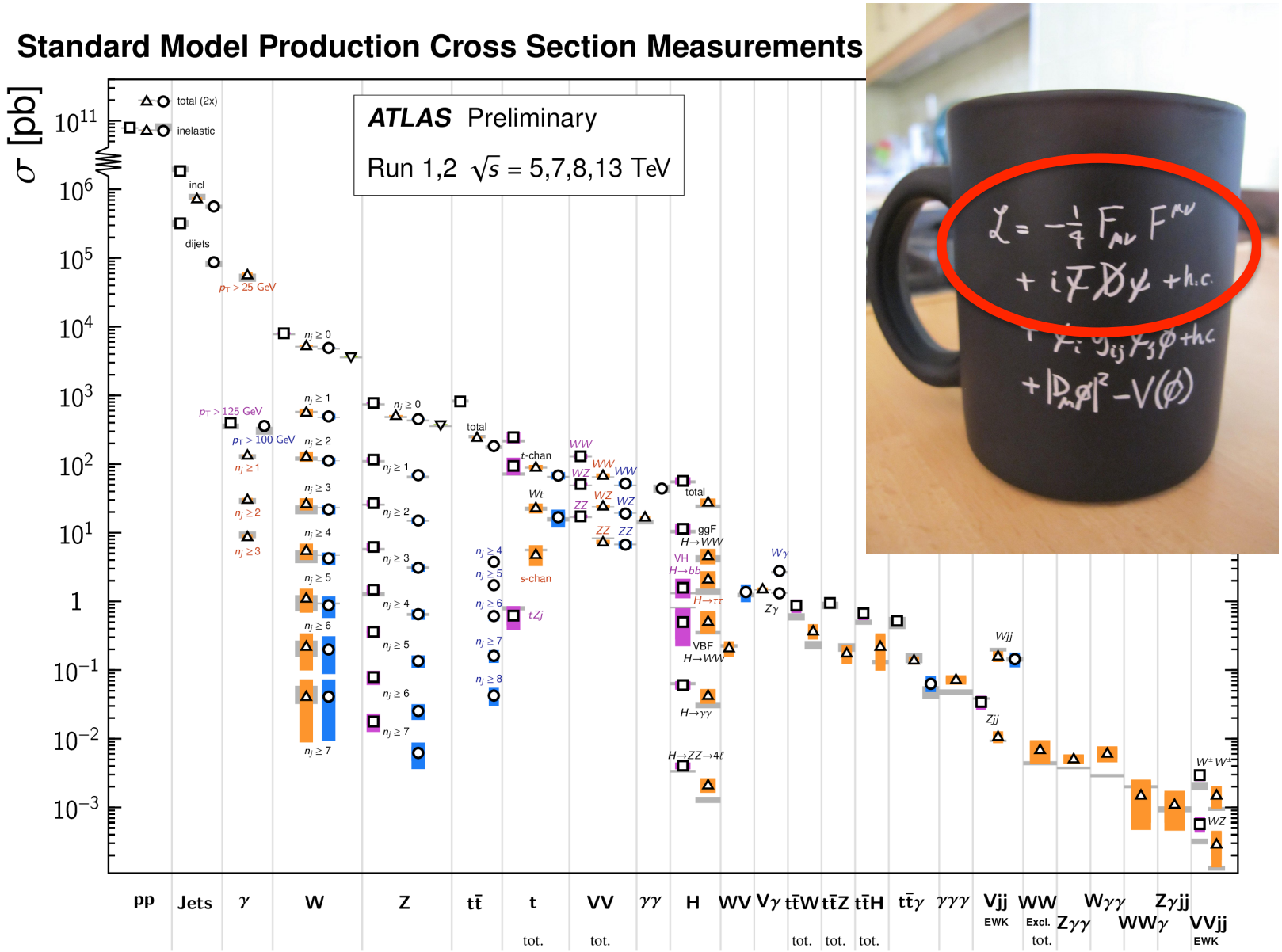
16:00 - 16:24

Room5 (Conference building)

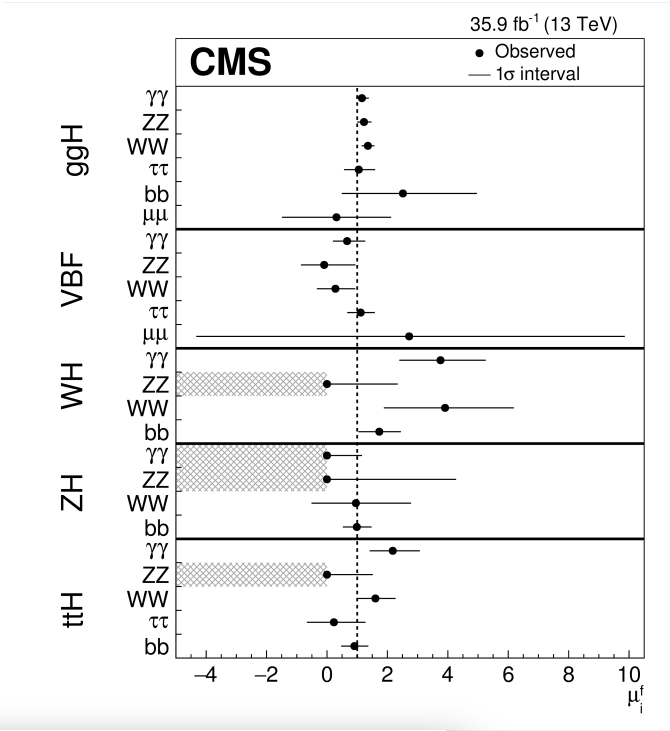
Presenter Jürgen Reuter

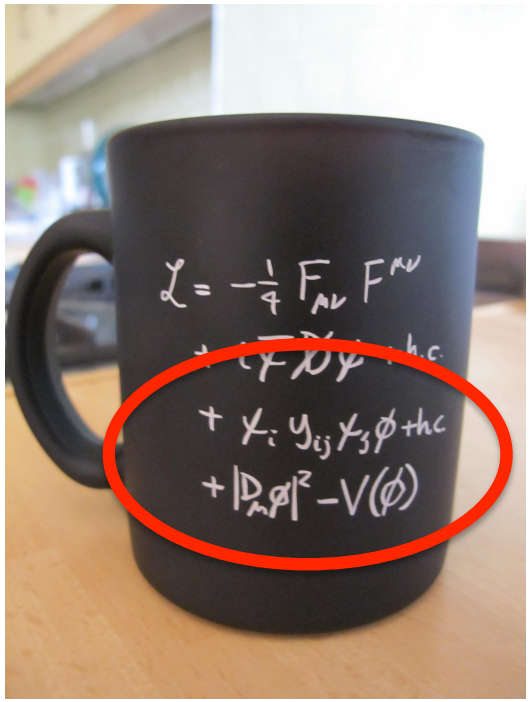
- Testing predictions of SM
  - Prioritize couplings that have yet to be established experimentally
  - Over-constrain couplings that have already been measured

We have established many SM gauge interactions:



as well as Higgs interactions:





Current Fit to Higgs Signal Strength

14:15 - 14:40

Room6 (Cor

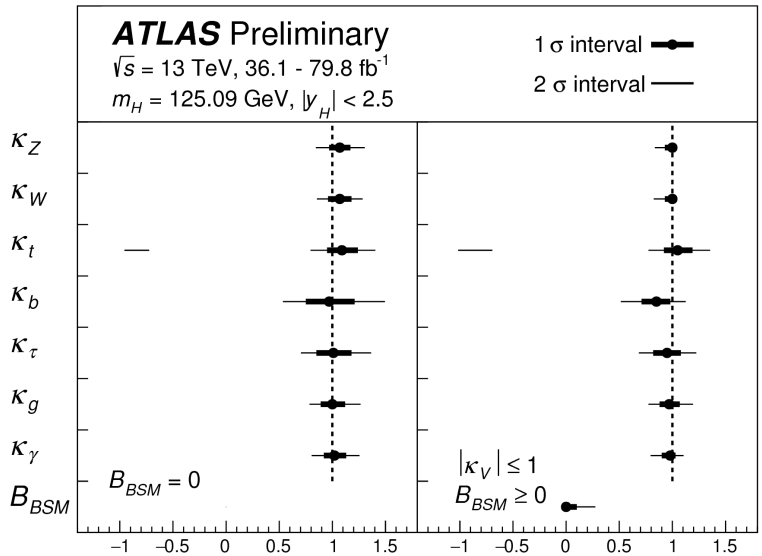
Presenter Kir

Higgs overview at the CMS

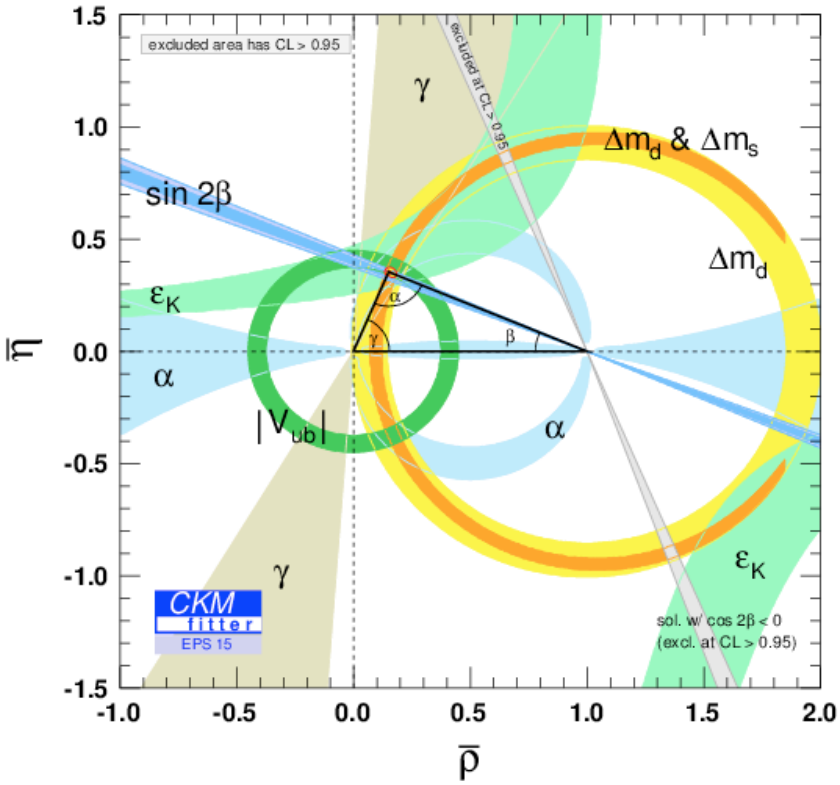
08:30 - 09:00

Room6 (Conference building)

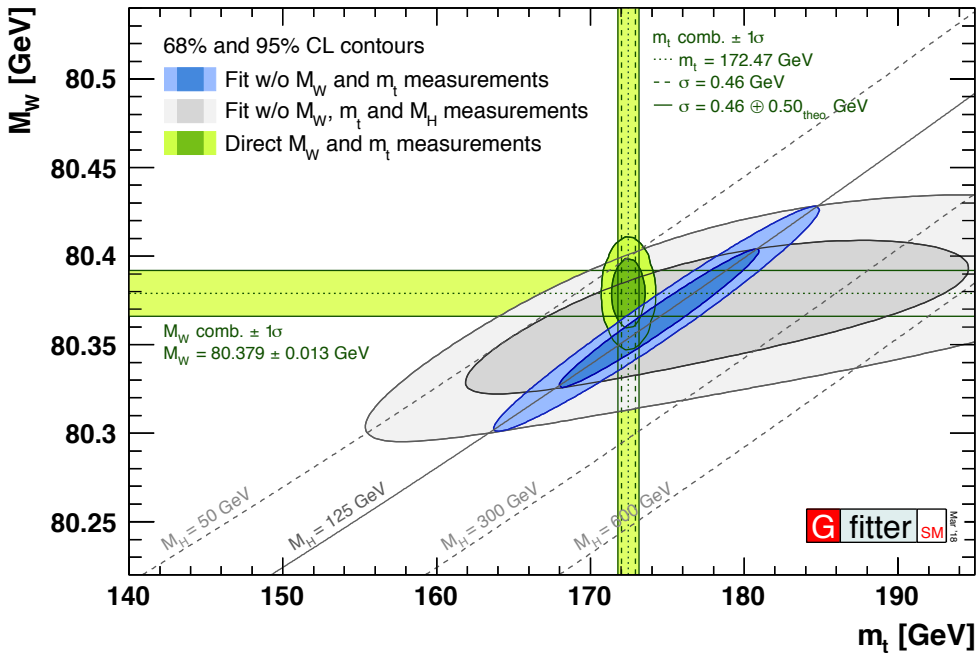
Presenter Giuseppe Bagliesi



Once a coupling is established, we need to over-constrain by making precision measurements and calculations



Unitarity triangle



Precision Electroweak Measurements

Talks on over-constraining the SM masses and cross-sections:

Measurement of the tt cross section at the LC

ilding)

wa

Precise predictions for e+e- -> tt

11:05 - 11:30

Room6 (Conference building)

Presen

MW from threshold / direct reco

11:44 - 12:04

uilding)

son

Precision b-quark mass determination

17:10 - 17:35

Room6 (Conference building)

Presenter Yukinari Sumino

Extracting the top quark mass and yukawa coupling from the threshold scan at CLIC

14:15 -

Room1

Study of systematic errors in high precision heavy quark analyses

e building)

oeschl

Precision measurement of Triple Gauge Couplings at future electron-positron colliders

10:54

Room

Presenter

top mass in radiative events

11:30 - 11:55

Room6 (Conference building)

Presenter Marcel Vos

The Higgs boson plays a special role in the SM

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 →

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

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

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

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

NO free parameters in its couplings!

So far we have measured a subset of couplings with O(10-30%) uncertainty:

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 →

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

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

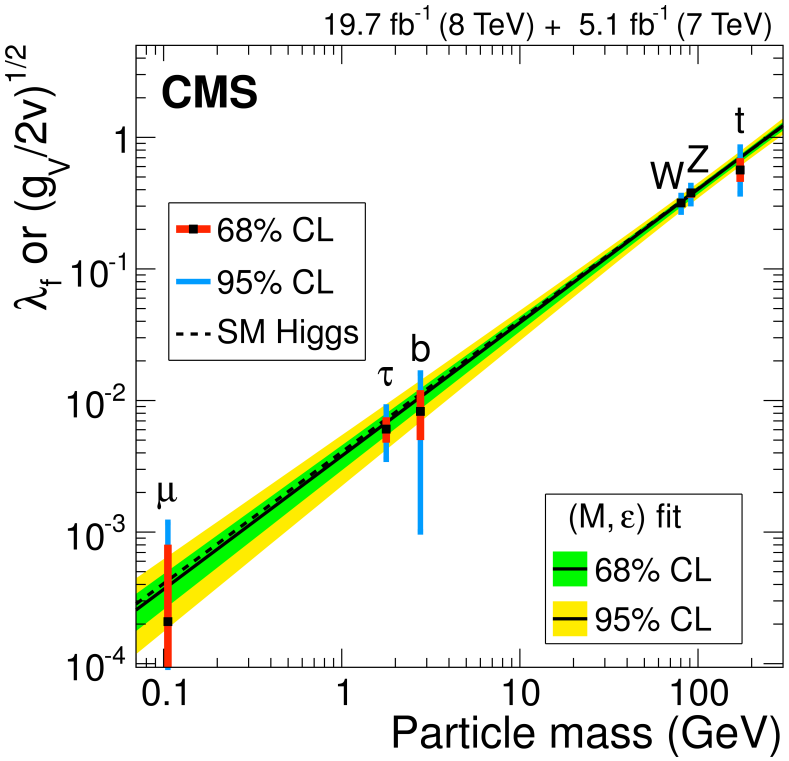
Couplings to fermions → $\sum_f \frac{m_f}{v} h \bar{f} f$ for *bb*, *tt*, and *ττ* only!

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

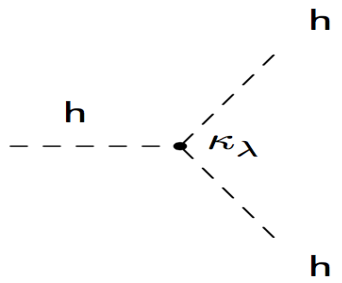
A "SM Higgs" is hardly vindicated!

- Unverified couplings of the 125 GeV Higgs:

Yukawa couplings to 1st and 2nd generation fermions.

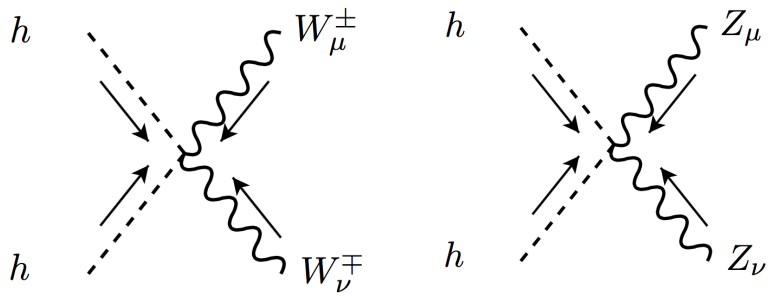


Trilinear Higgs self-coupling – we have NOT measured the Higgs potential.



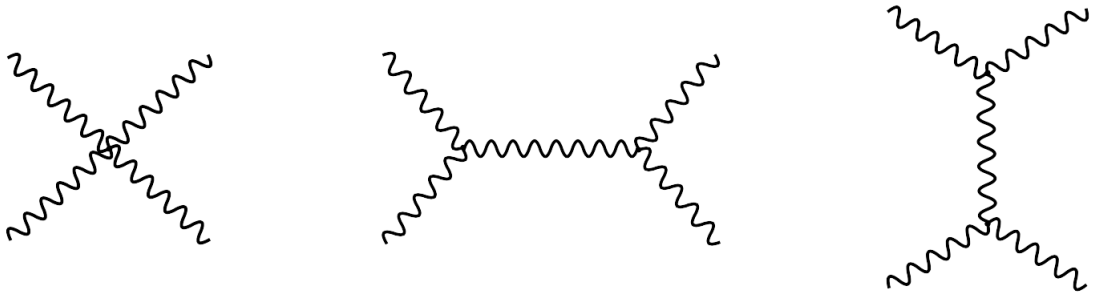
4-pt HHVV coupling – prediction of gauge invariance.

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



- One very important prediction of SM need to be pin-down precisely:

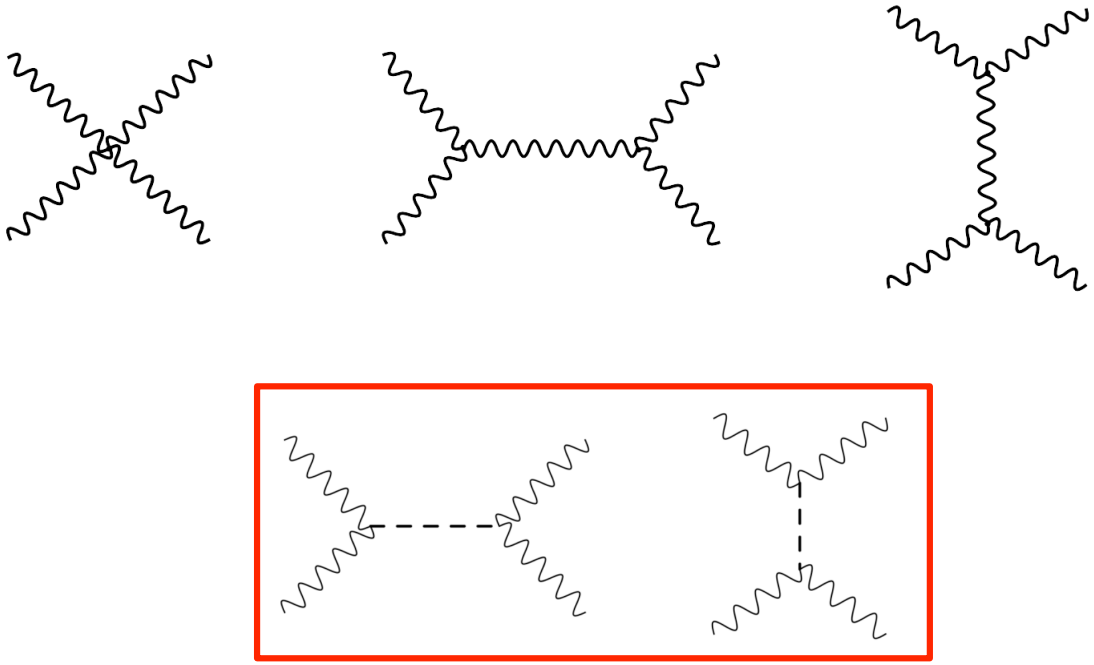
Without the Higgs, WW scattering amplitude violates unitarity:



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

- One very important prediction of SM need to be pin-down precisely:

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

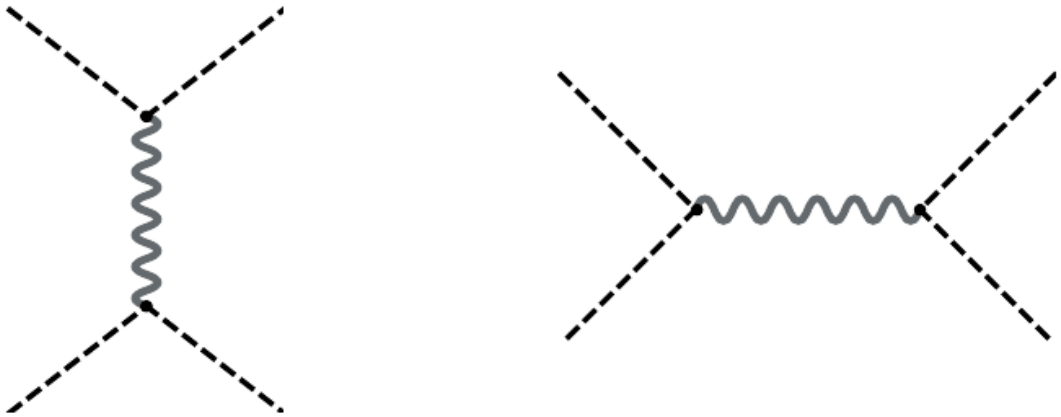


provided the HWW coupling have precisely the form in the SM!

This is an extremely simple and economical solution, except…

Nature has never chosen this particular 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 does NOT 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!

To test this prediction we need to make

- More precise measurements of HVV couplings.
- Direct measurements of vector boson scatterings.

In considering deviations in the couplings, it is useful to recall the generic expectation:

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

To establish credible deviations would require a precision at the percent level!

No need to feel distressed for lack of deviations in current data!!

If the precision improved,

	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

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

Talks on Higgs mass/couplings:

A new method for measuring the Higgs mass at e+e-

11:55
Room

Combined EFT fit Higgs/top

e building)

n Jung

Di-boson studies at e+e- colliders

10:30 - 10:50
Room1 (Conference building)

Presenter

Complementarities between Higgs and electroweak measurements at future lepton colliders

15:05 - 15:30
Room6 (Conference building)

Presenter Gauthier Durieux

EWPO with dim-6 operators

16:4
Roo

Presente

Higgs → gamma Z

09:30 - 09:50
Room5 (Conference building)

Prospects for measuring Higgs Boson decays into muon pairs at the ILC

09:10 - 09:30
Roo

Presente

Model independent determination of triple Higgs coupling

14:00 - 14:25
Room6 (Conference building)

Presenter Michael Peskin

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

A few years ago my (then) 7-year-old asked one such question:

What is the Higgs boson made of?

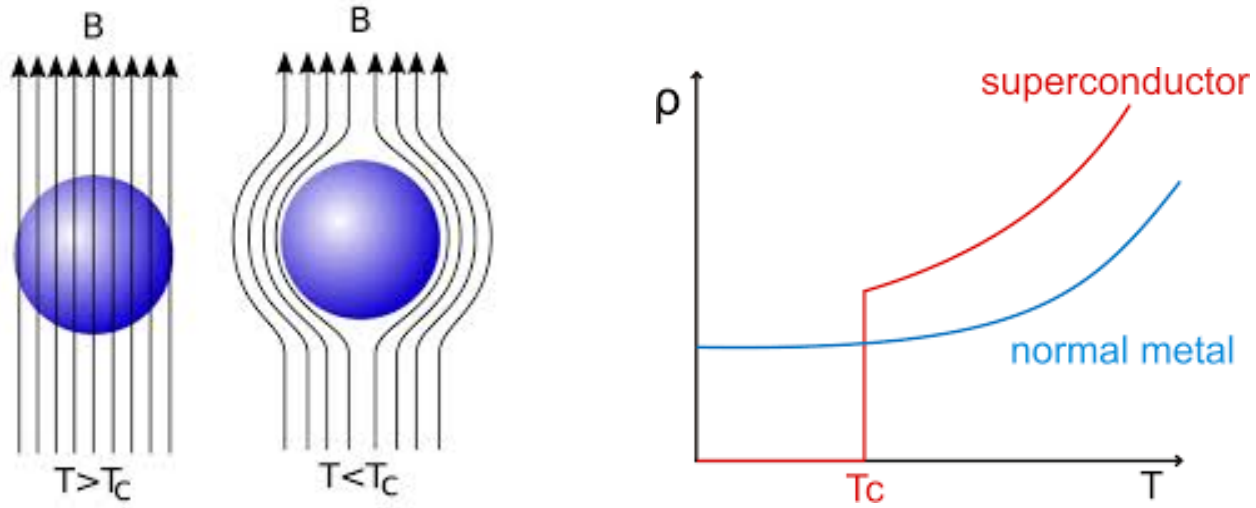
A physics Ph.D. could rephrase slightly:

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

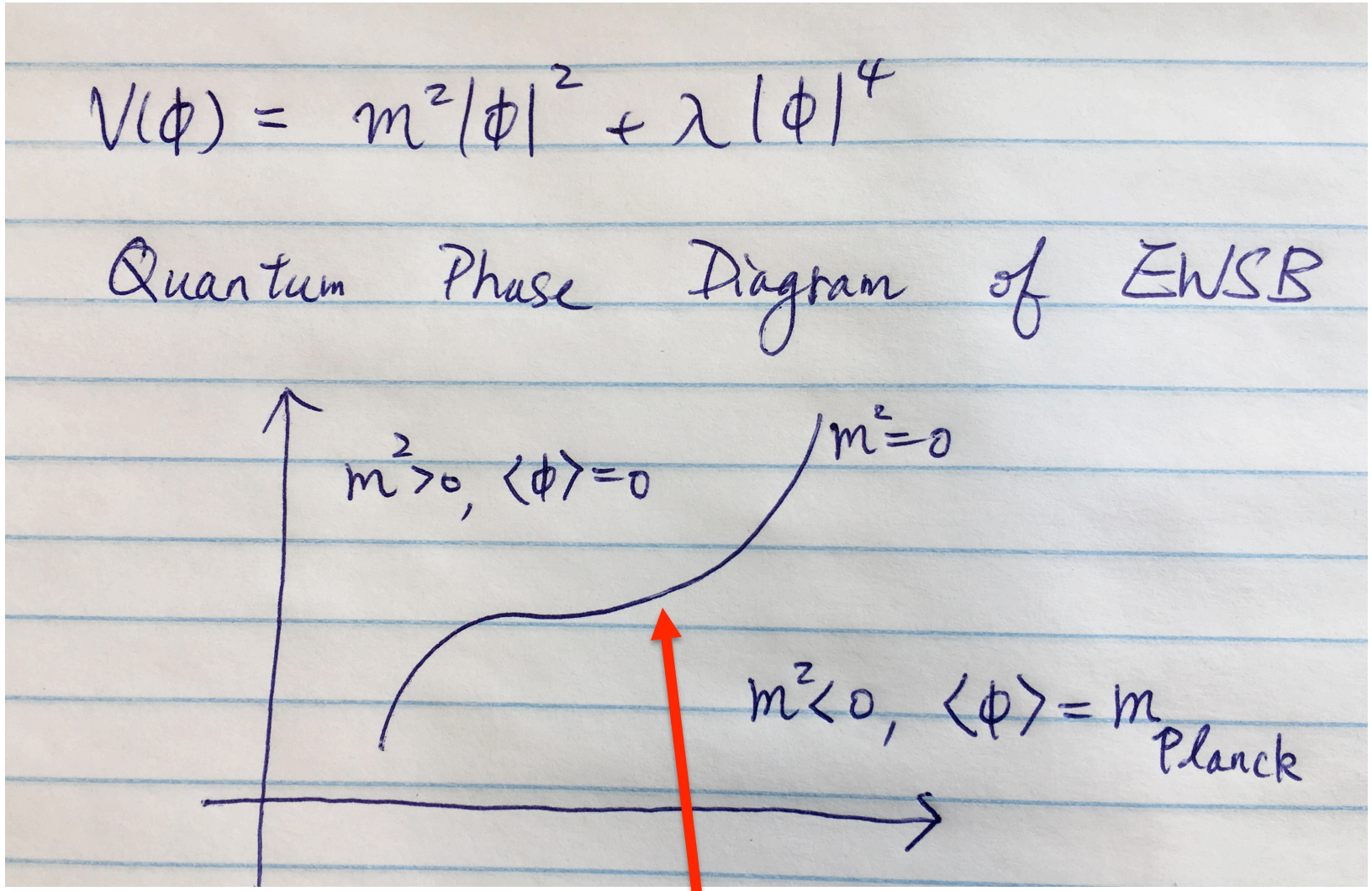
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

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.

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 signs of new physics, but not ready to give up yet:

J. Ellis @ HKUST, January 2019

The mystery, of why we are sitting close to the critical line of EWSB, **deepens** day by day :

The Higgs boson is the most exotic state of matter in the Universe!

After 40 years, our understanding of the electroweak symmetry breaking is still at the level of Ginzburg-Landau level!

In order to understand the *microscopic* nature of the Higgs, we need to look for

- Rare and new decay channels of H(125).
- Additional Higgs bosons.
- Partners of the SM top quark that couple significantly to H(125).

No shortage of talks on models of Electroweak symmetry breaking:

ILC Pheno of Gauge Higgs Unification

Anatomy of TTHH Coupling

Inert Doublet Model signatures at Future e+e- Colliders

Forward-backward asymmetry in the gauge-Higgs unification at the International Linear Collider.

Analysis of the Higgs Potential in Extended Gauge-Higgs Unification Models

Reaching the LC precision in SUSY Higgs predictions

Chargino search at the ILC

Precise calculations of Higgs decays in various extended Higgs sectors

Impact of LC measurements of H_125 on SUSY scenarios

ILC Pheno of Composite Higgs models

Two loop calculation to the hhh coupling in nonminimal Higgs models

15:05 - 15:25

Room6 (Conference building)

Presenter Johannes Braathen

Double Higgs boson production at future colliders in the two-Higgs-doublet model: non-alignment case

14:25 - 14:45

Room6 (Conference building)

Presenter Takuto Nagura

SUSY at future colliders - an overview

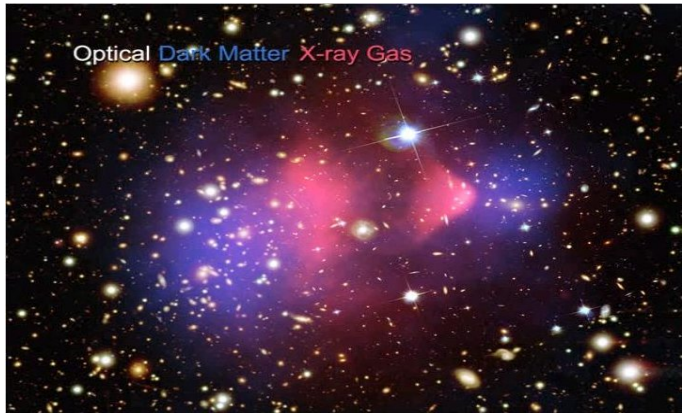
15:05 - 15:30

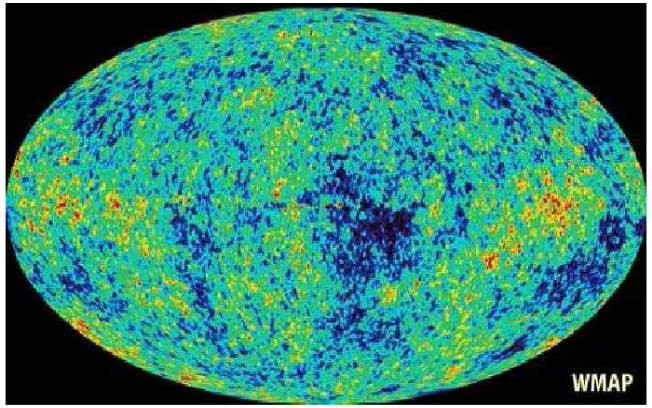
Room6 (Conference building)

Presenter Mikael Berggren

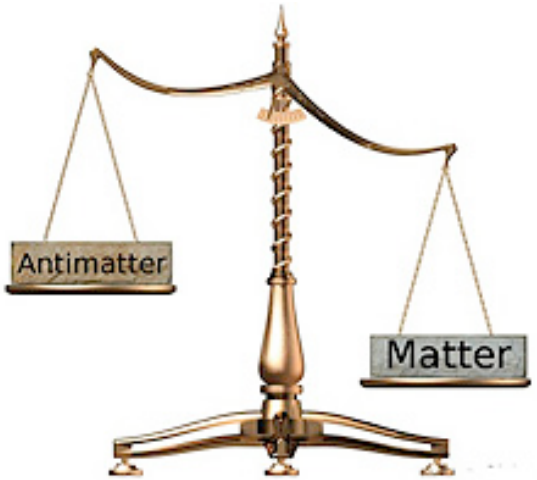
- Asking the right questions
  - conceptual questions that can't be answered by the SM.
  - **empirical questions that can't be answered by the SM.**

- We are all convinced about the existence of dark matter.
  What is it??





- We owe our existence to matter − antimatter asymmetry in the Universe.
  Why is there more matter than antimatter?



Some talks addressing these issues:

Searching for beyond the standard model physics from heavy resonance at the linear collider

11:00 - 11:20
Room6 (

Presenter

Higgs LFV decays in the model for Dirac neutrino masses and dark matter

nce building)

Enomoto

WIMP search at the ILC

14:20 - 14:40
Room6 (Conference building)

Presenter

Higgs invisible decays at the ILC

08:50 - 09:10
Room5 (Conference building)

Presenter Yu Kato

Electroweak Baryogenesis

11:40 - 12:05
Room6 (Conference building)

amsey-Musolf

Studying Electroweakly Interacting Particles at Future Colliders

09:00 - 09:25
Room6 (C

Presenter

WIMP DM phenomenology and ILC

09:25 - 09:50
Room6 (Conference building)

umoto

Sensitivity to new physics scenarios in invisible Higgs boson decays at CLIC

08:30 - 08:50
Room5 (Conference building)

Presenter Aleksander Filip Zarnecki

Concluding Remarks:

- For the first time we are staring down the edge of the Standard Model.

  Anything we discover from this point on will be revolutionary.

- Standard Model is a self-consistent theory, but it is by no means a complete theory -- it cannot explain the existence of dark matter, nor the observed matter--anti-matter asymmetry, just to name a few.

  Something has to be out there!

- 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 picture for the superconductivity.

  Need to pin down a microscopic picture.

The International Linear Collider will help us unlock all of these mysteries!