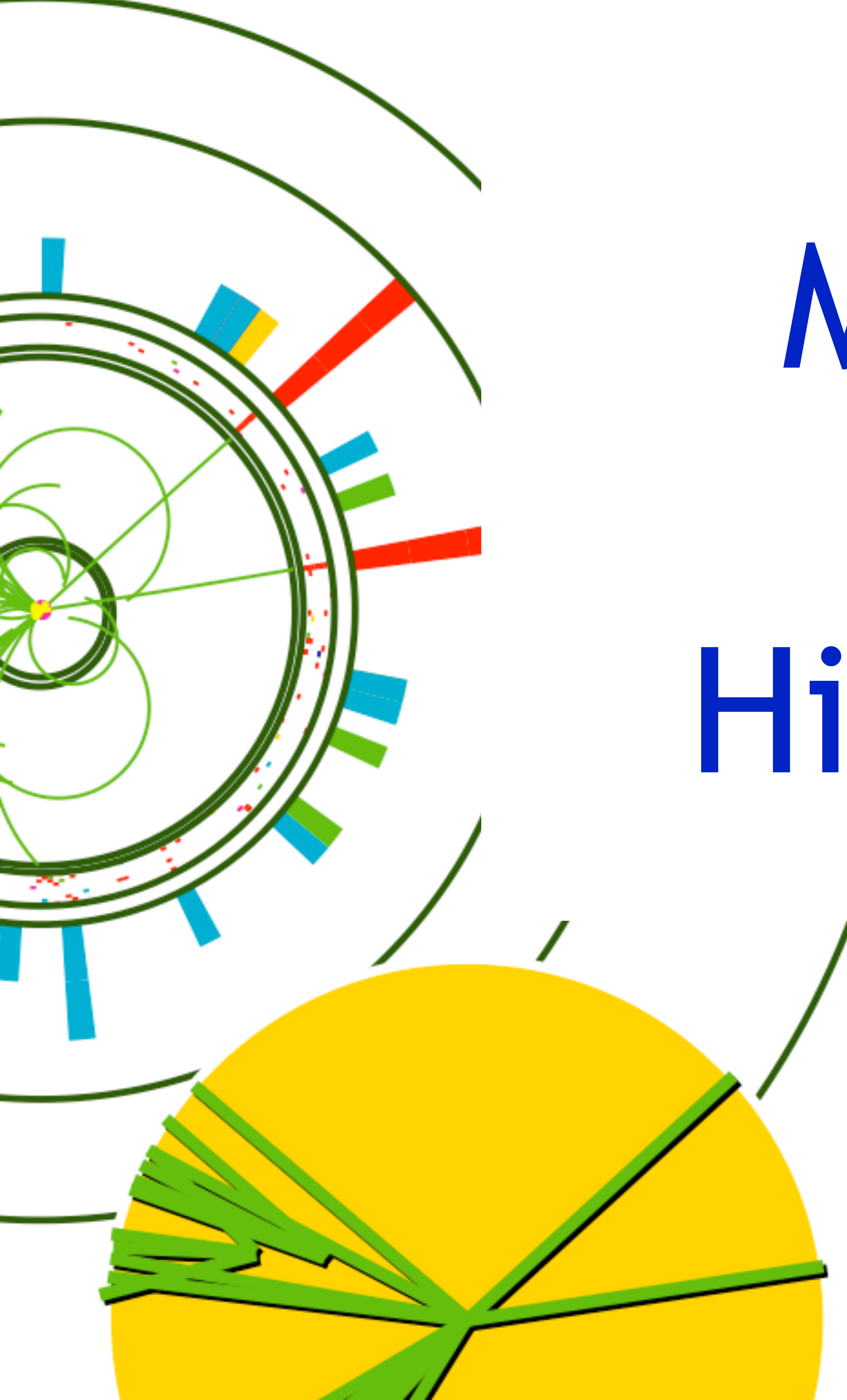


Mysteries of the Higgs Boson

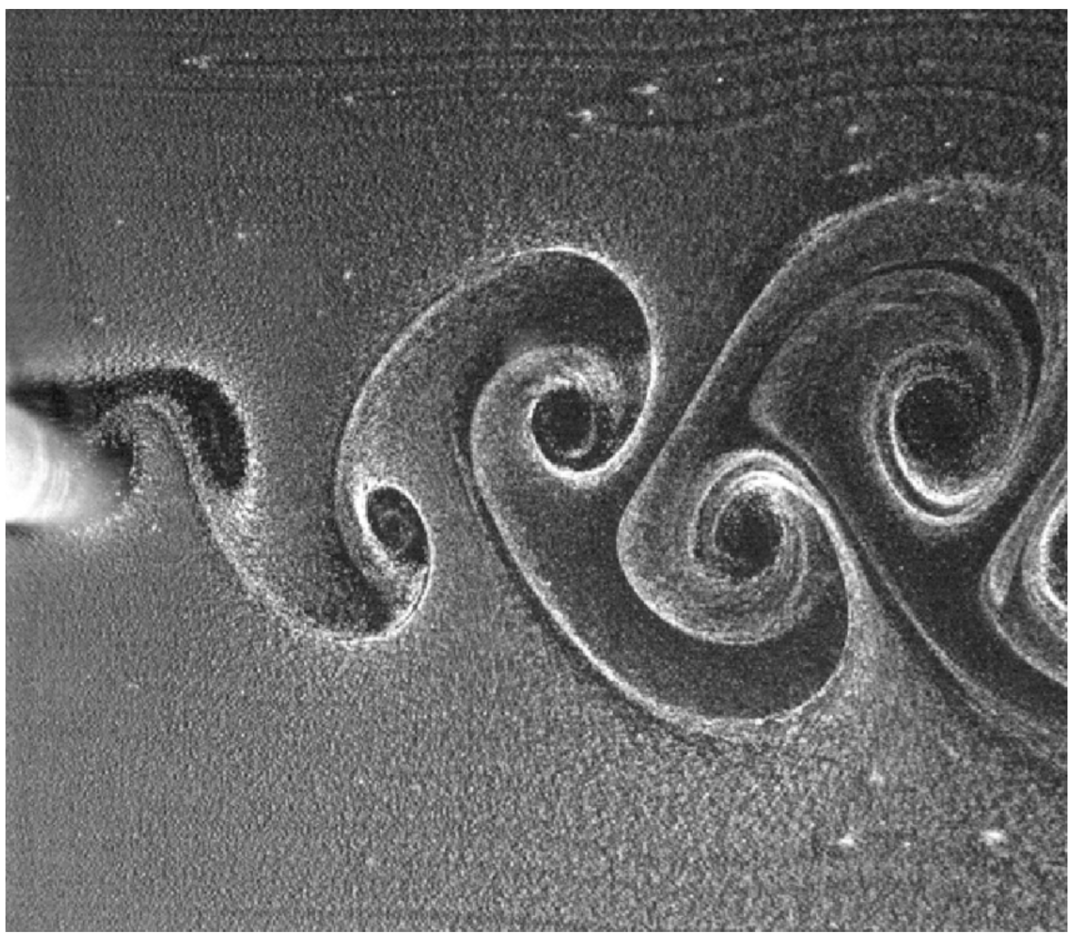
M. E. Peskin
April 2025

In this lecture, I will discuss the current status of elementary particle physics and the problems that we hope to solve in the future.

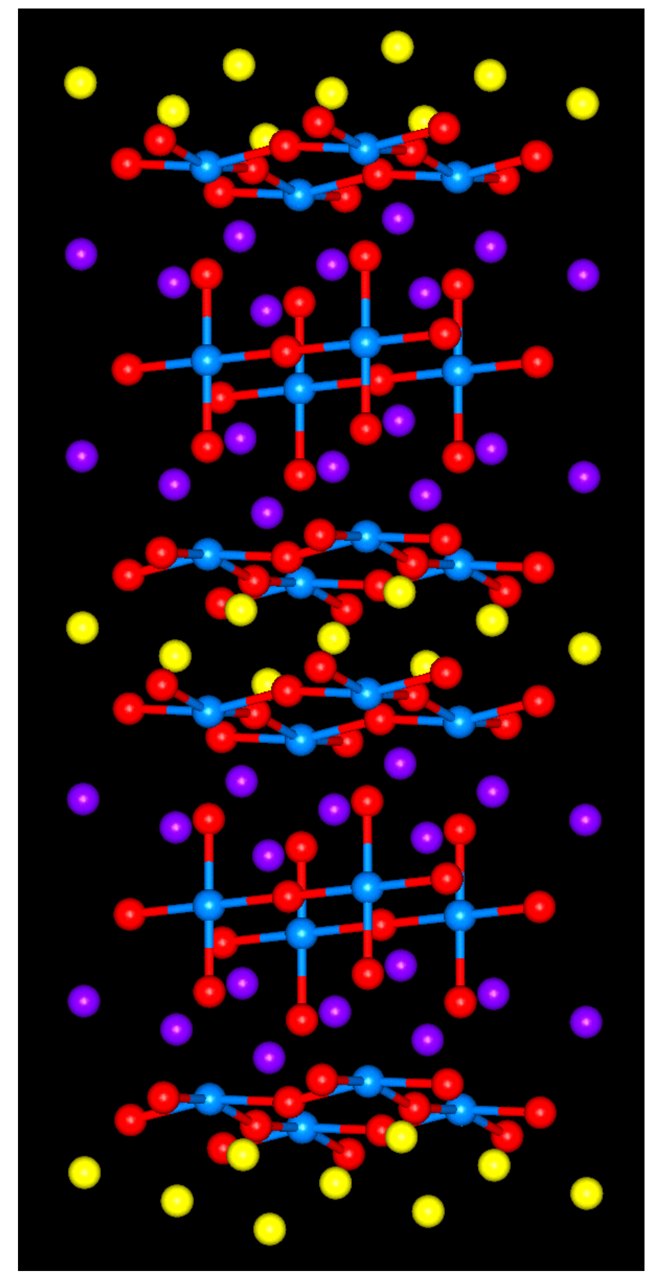
We have achieved tremendous success, but we are still far from our goal. I will discuss what next large step is required, and how we might get there.

Particle physics is different from other branches of physics.

Nature has a tremendous diversity of physical systems, each of which has its own fascinating behavior.



UCL OpenFOAM



D. Otway
Imperial
College

In particle physics, we are concerned with only one of these
— the underlying, fundamental equations of the universe.

Why do we want to know these ?

Basic curiosity about the origin of everything

Ultimate unification of all interactions

A highly symmetrical and yet subtle problem;
a source of concepts for other fields of science

A tremendous technical challenge;
a source of technology for other fields of science

Whatever the motivation, this is what drives us

to build the largest and most expensive pieces of experimental equipment

to organize the largest collaborations of physicists

to gather the largest experimental databases

discovery of the Higgs boson — 45 years after it was postulated, > $ 10 B spent, 6000 physicists in the discovery collaborations. …

and, yet, our problems are not solved.

The answers are still further from the human scale, requiring further advances in technology and insight.

How far have we come ?

The Standard Model of particle physics:

$$\mathcal{L} = -\frac{1}{4}\sum_a (F^a_{\mu\nu})^2 + |D_\mu \Phi|^2 - V(\Phi^\dagger \Phi)$$
$$+ \sum_f \left\{ \overline{\psi}_{f\,L,R}(i\gamma \cdot D_{f\,L,R})\psi_{f\,L,R} - y_f \overline{\psi}_L \cdot \Phi \psi_R + h.c \right\}$$

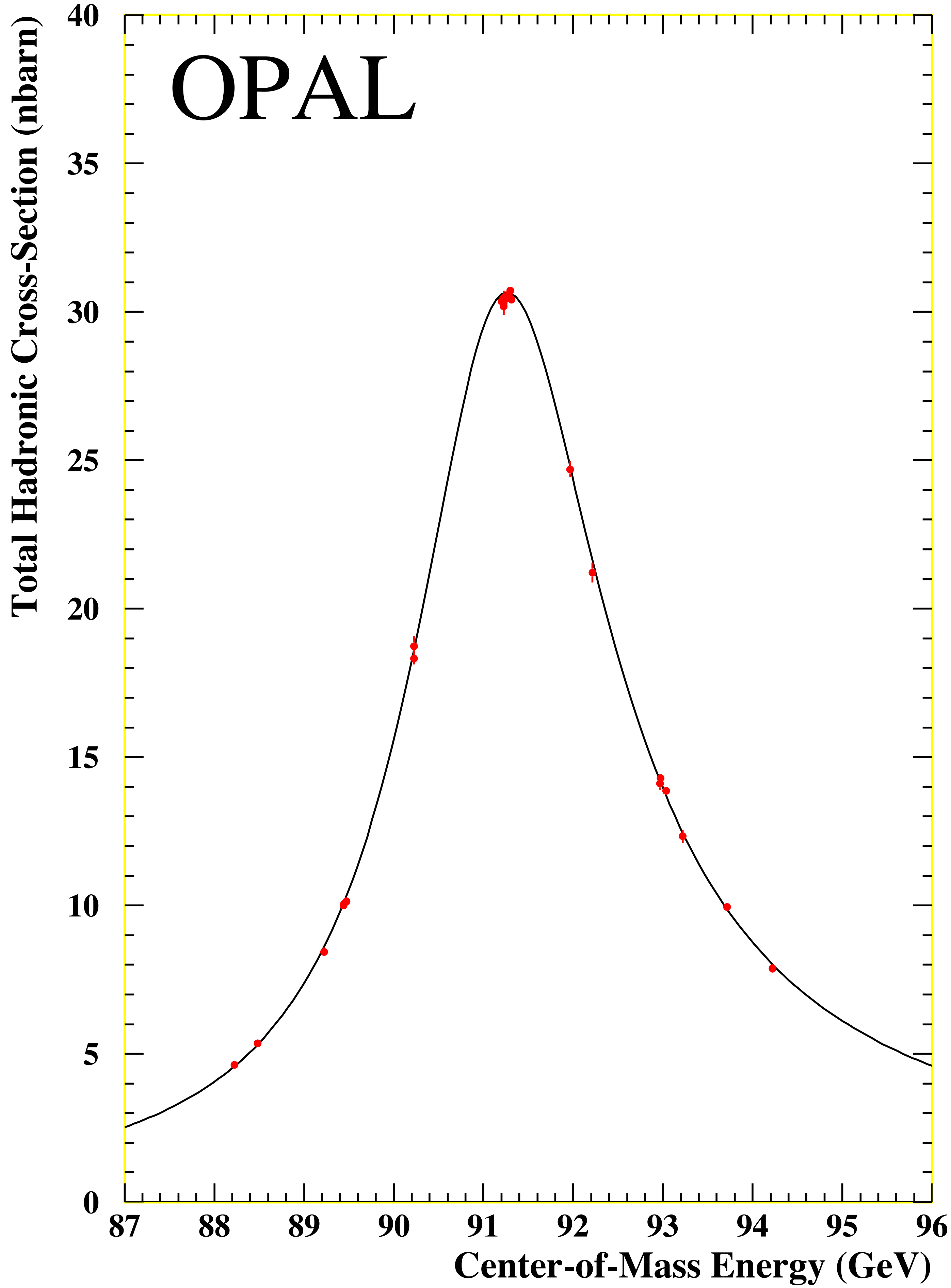
with $$D_\mu = \partial_\mu - i \sum_a g_a A^a_\mu t^a$$

Not as simple as it could be, but not so bad.

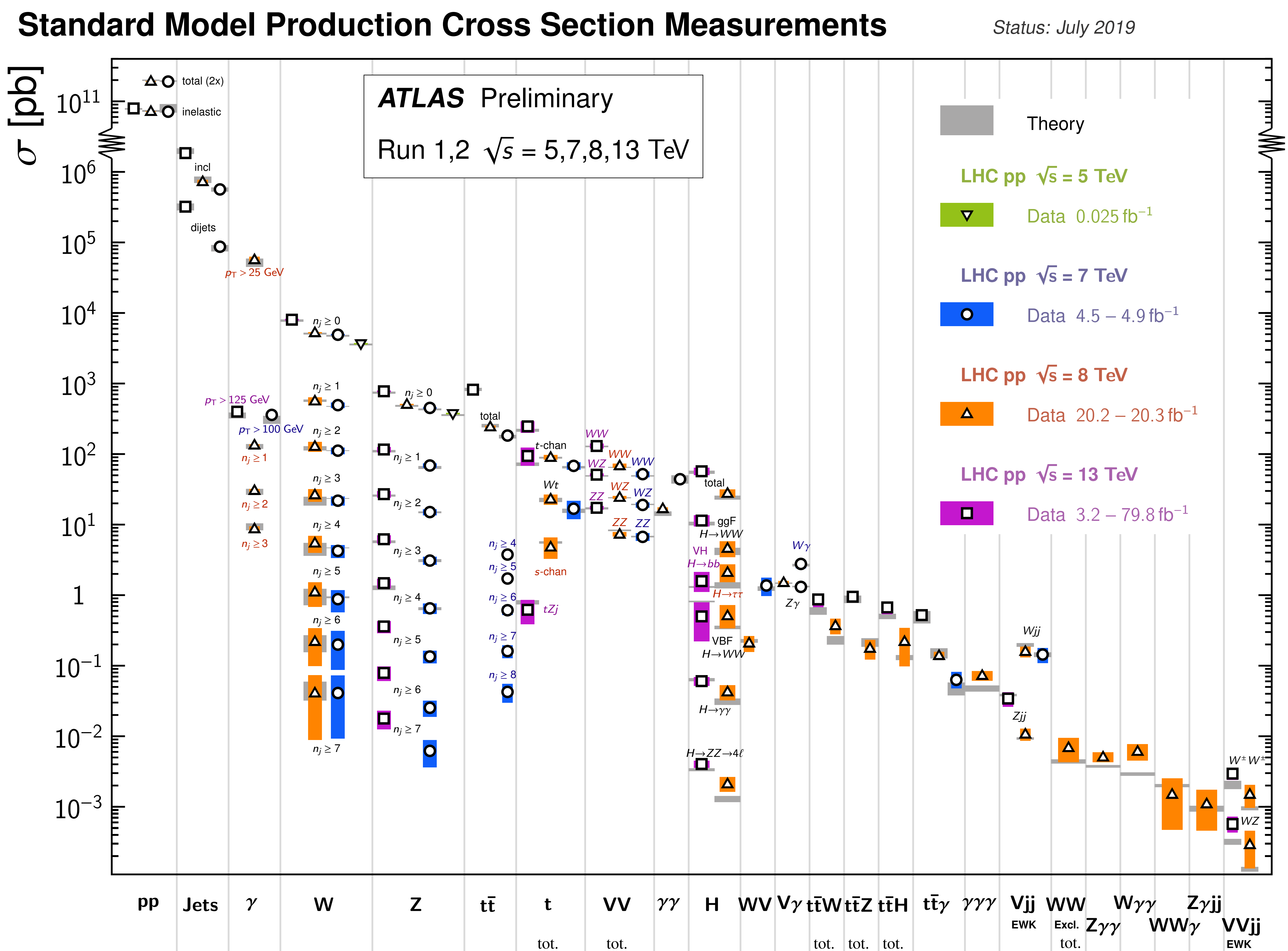
This will keep nuclear, CM, fluid, optical physicists occupied for centuries.

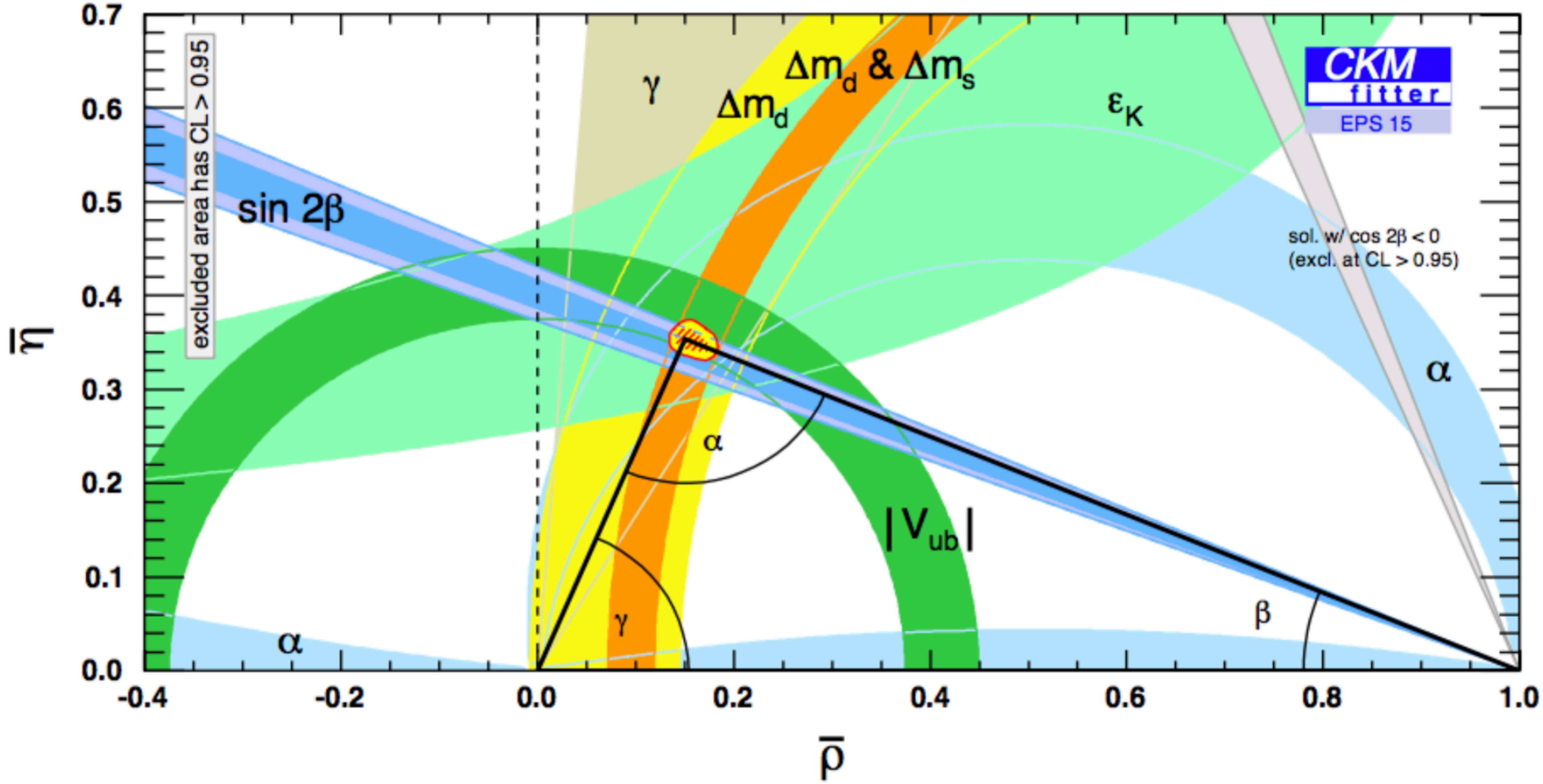
The couplings of all included particles to the strong, weak, and electromagnetic interactions are specified by the structure of D_μ ("the gauge principle").

This includes many nontrivial features which are now verified in detail by experiments.



thanks to T. Mori


Standard Model Production Cross Section Measurements
Status: July 2019
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 5 TeV
Data 0.025 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
total (2x)
inelastic
incl
dijets
pT > 25 GeV
pT > 125 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
tZj
ggF H→WW
VH H→bb
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
Wjj
Zjj
W±W±
WZ
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Vjj EWK
WW Excl.
Zγγ
Wγγ
WWγ
Zγjj
VVjj EWK
tot.



CKMfitter: data from BaBar, Belle, CDF

Although we understand half of the Standard Model strikingly well, there is another half of the Standard Model that we hardly understand at all.

This is the set of interactions that involve the Higgs field Φ.

The Higgs field is often described as the source of mass for all elementary particles.   Let's discuss a little about why that is necessary.

Maybe we should ask first,

Doesn’t stuff just have mass ?

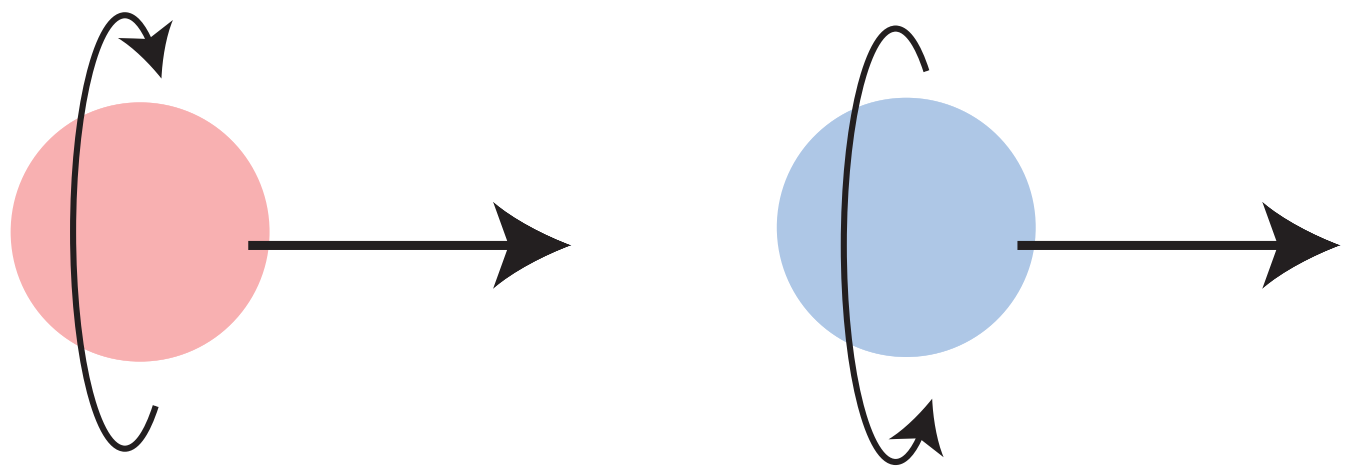
In classical physics, this is correct.

In relativistic quantum physics, it may be wrong.

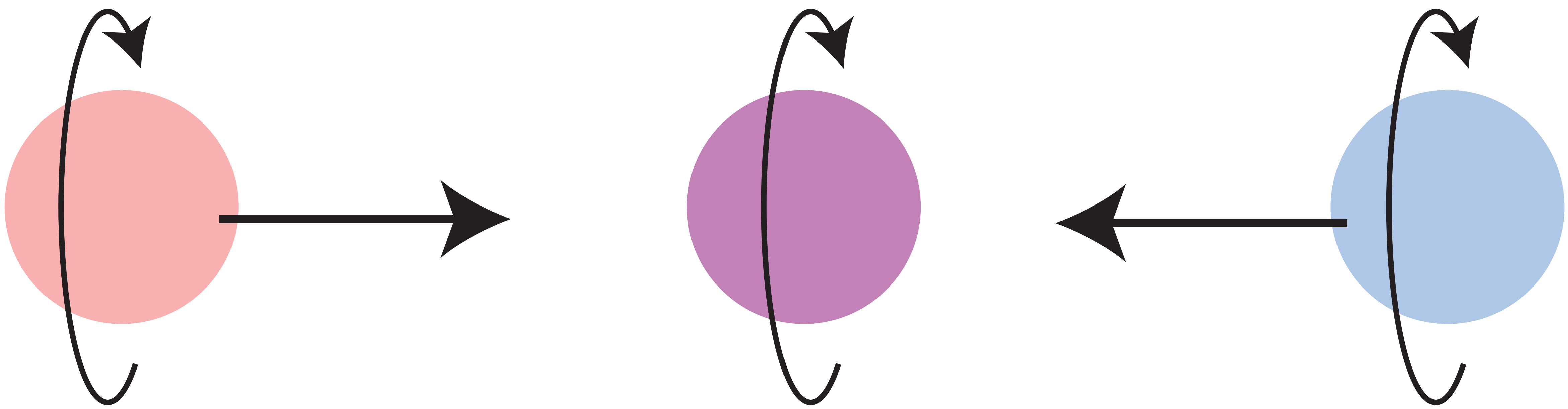
There are known fields whose particles are forbidden to obtain mass.

Actually, everything that we know is made out of such particles.

massless spin 1/2 particles



massive spin 1/2 particles ??

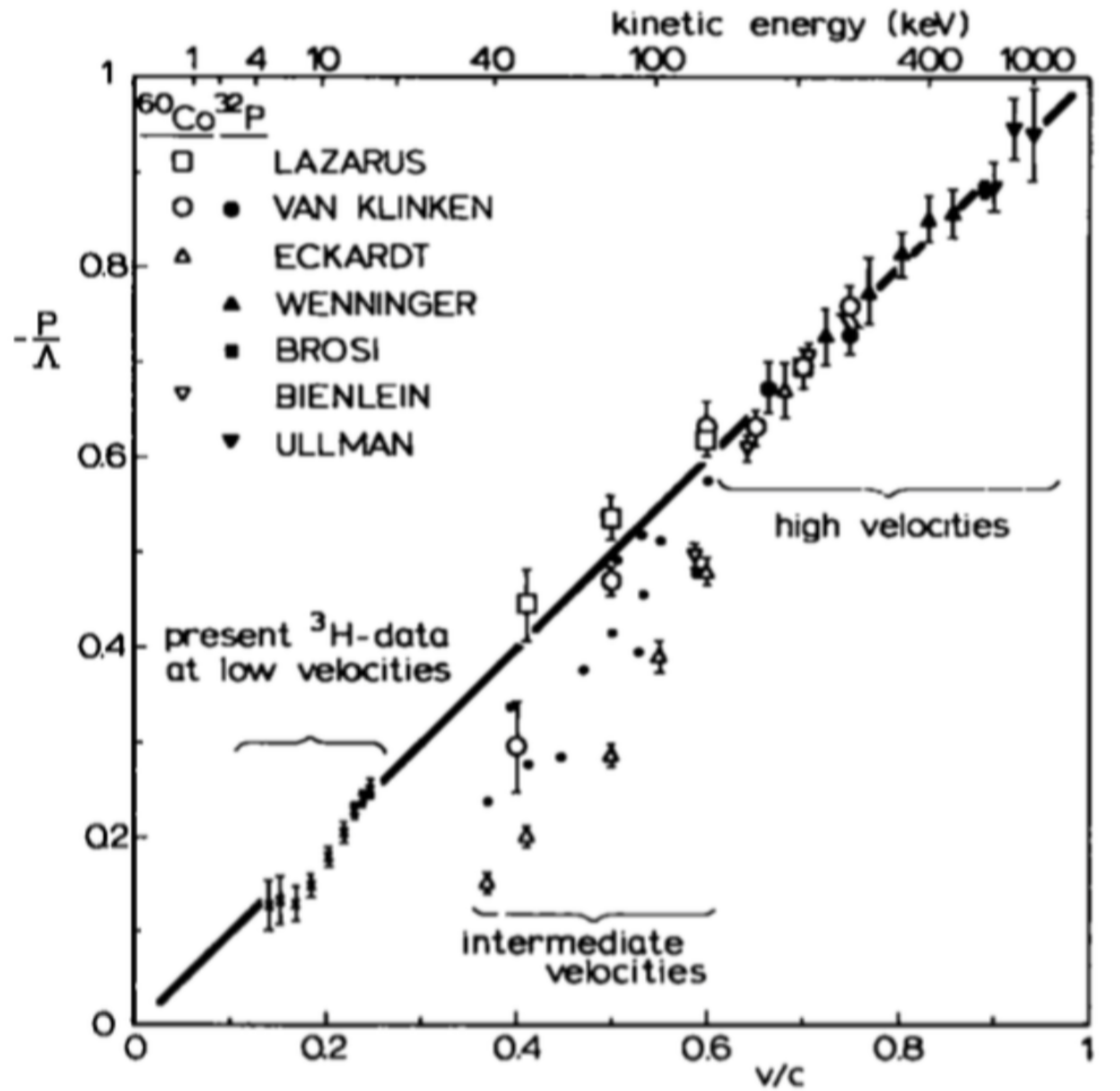


But don't electrons come in both left- and right- handed spinning states ?

Actually, these states are different particles, with different quantum numbers under the weak interactions.   This is an aspect of the gauge principle as it applies to the Standard Model.

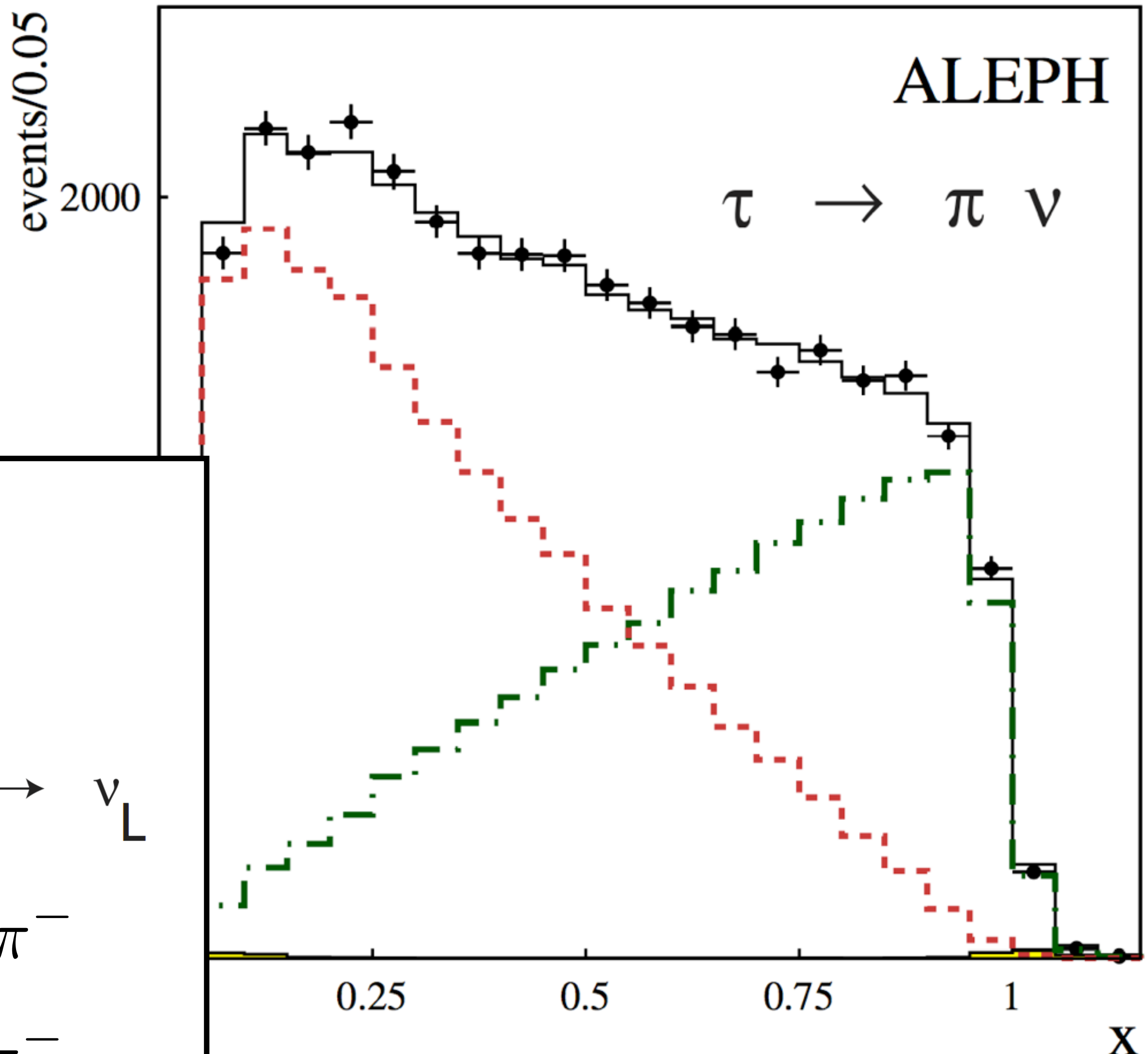
Because of this, in the Standard Model, it is not possible to write a mass term for the electron that respects all of its symmetries.

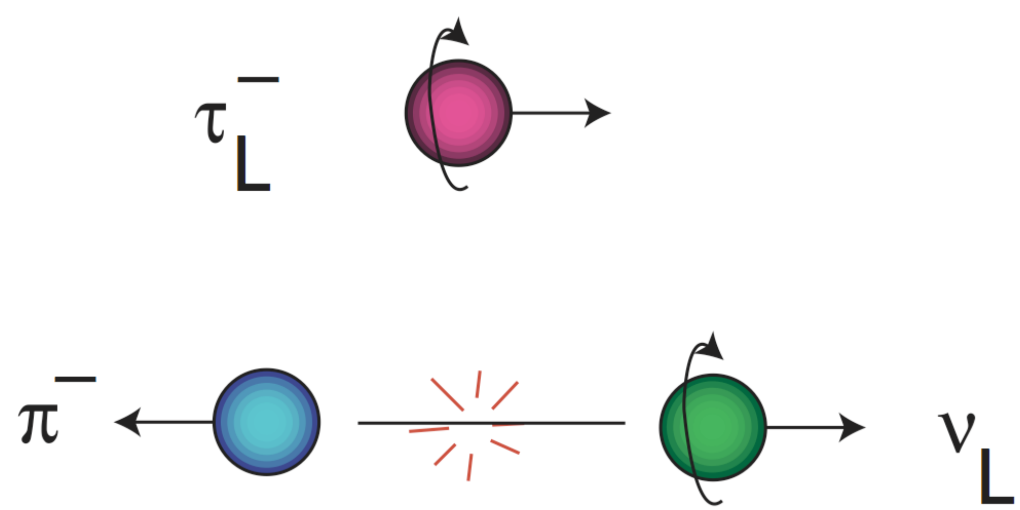
parity violation in beta decay:



Koks and van Klinken

$$e^+e^- \to Z^0 \to \tau^+\tau^-$$





$\tau^-_L \to$ slow π^-

$\tau^-_R \to$ fast π^-

The Standard Model fixes this problem by the coupling the left- and right-handed quark and lepton states together via the Higgs boson.

$$\mathcal{L} = -y_e \, \overline{e}_L \cdot \Phi e_R + h.c.$$

$$m_e = \frac{y_e}{\sqrt{2}} \langle \Phi \rangle$$

The Higgs field Φ must also transform under the gauge symmetry (SU(2)xU(1)).

A separate input parameter is needed to give mass to each individual quark or lepton.

$\langle \Phi \rangle \neq 0$ is a spontaneous symmetry breaking, similar to the appearance of the superconducting condensate in metals or magnetism in ferromagnets.

This idea is directly testable at the CERN Large Hadron collider.

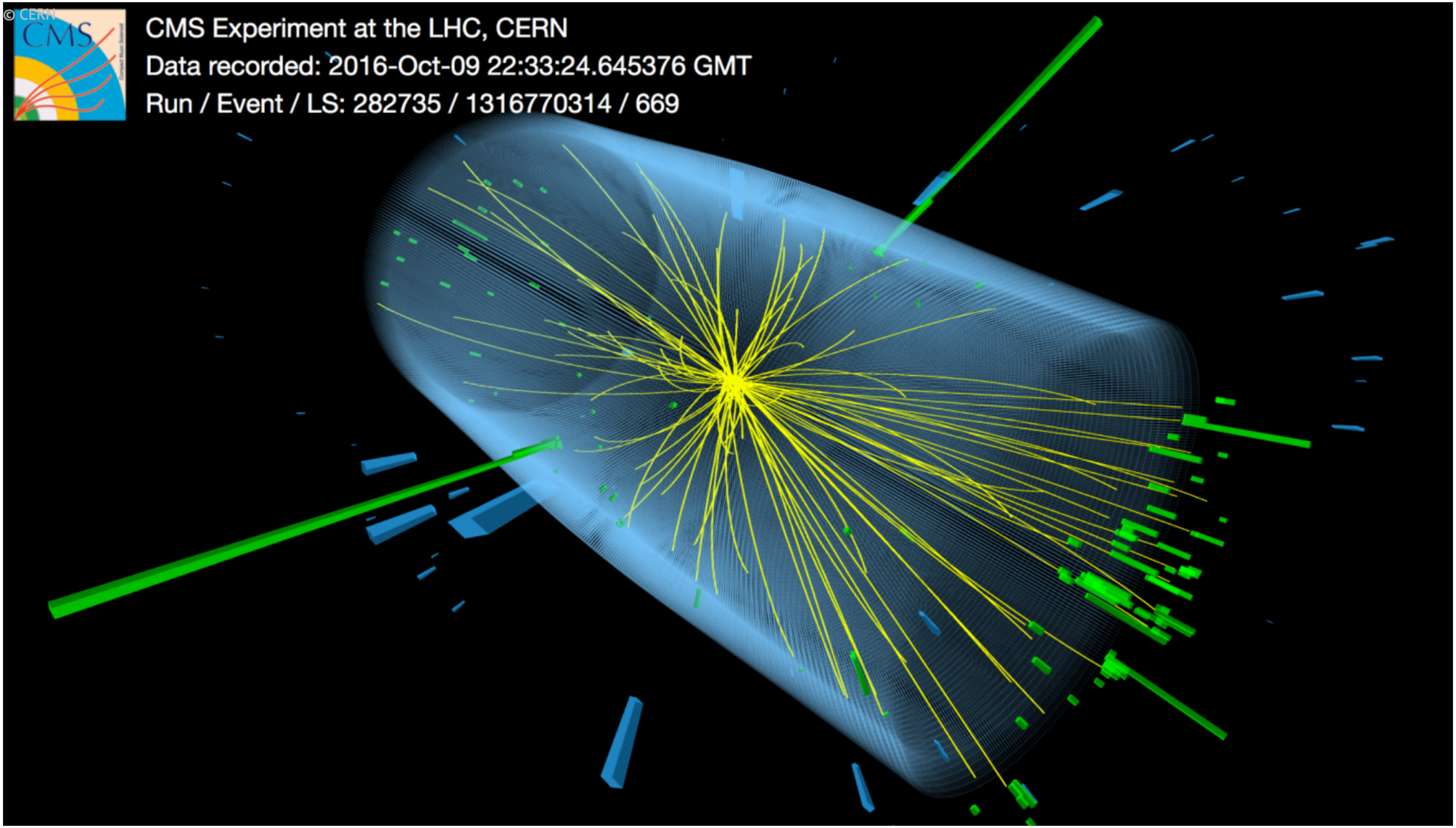
Higgs must couple to all massive particles.

This leads to 10 decay modes with branching ratios greater than 0.01%

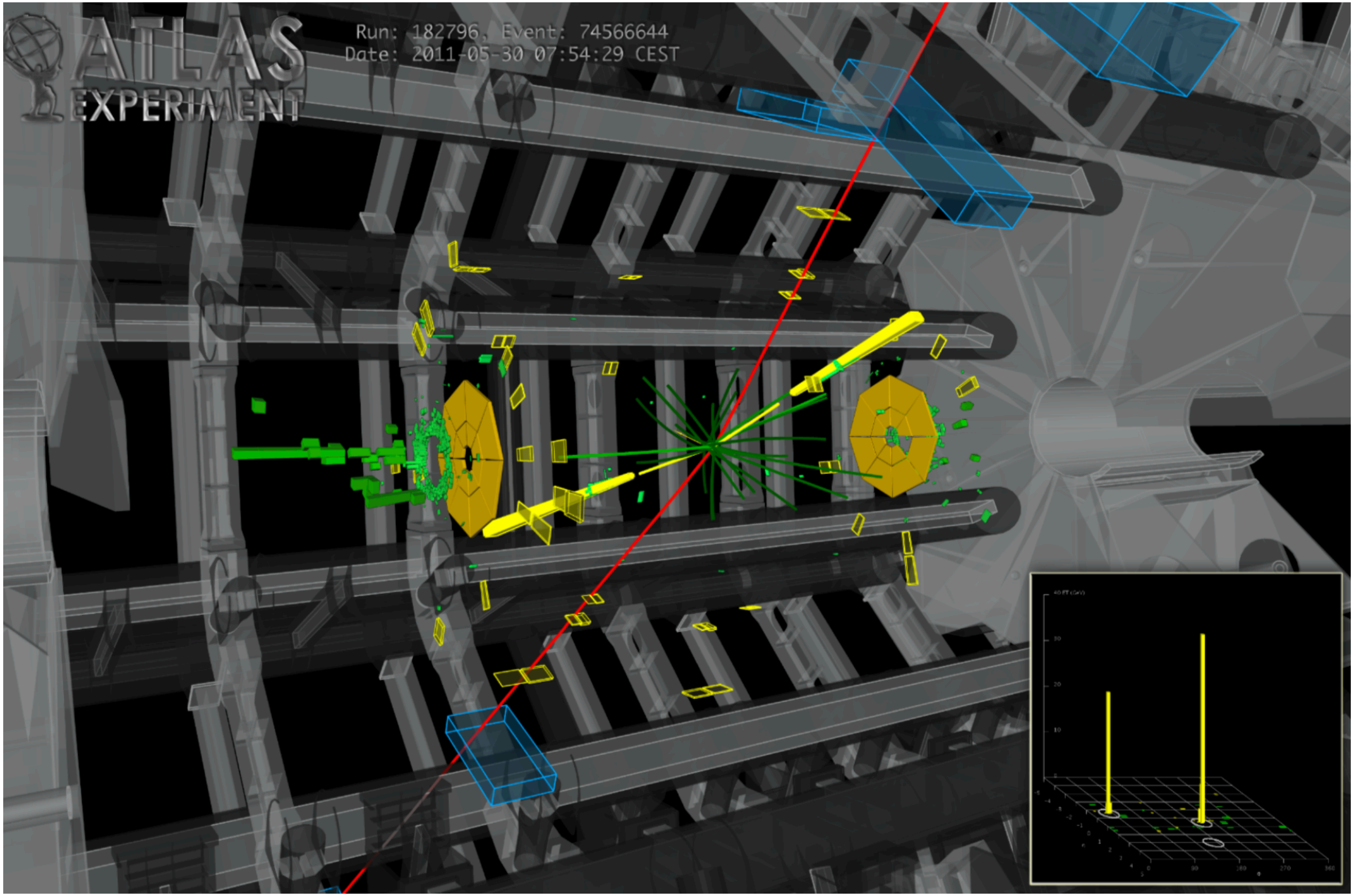
Higgs couplings are proportional to measured masses.

Measure these from the decay widths.

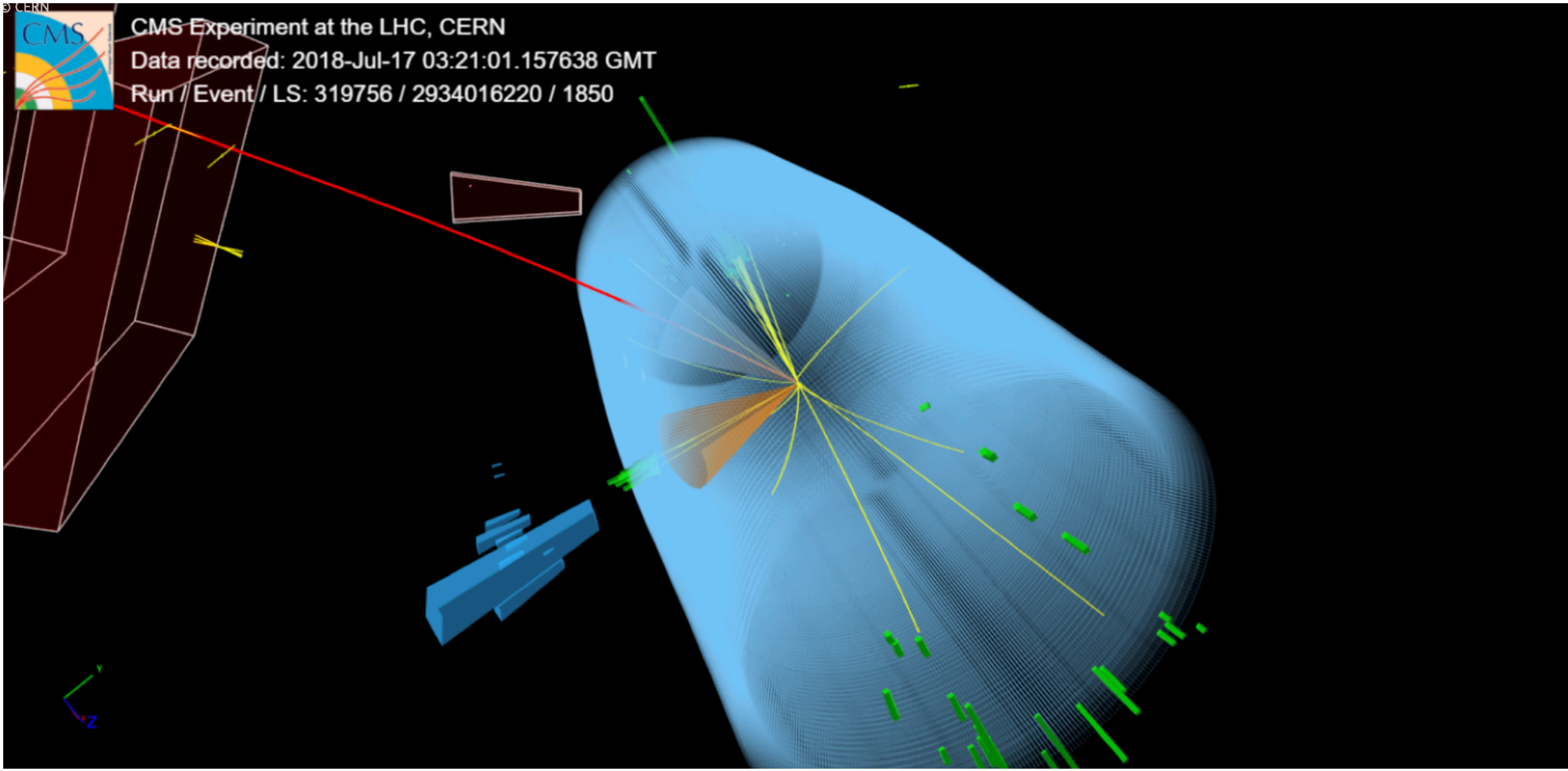
$h \to \gamma\gamma$ candidate



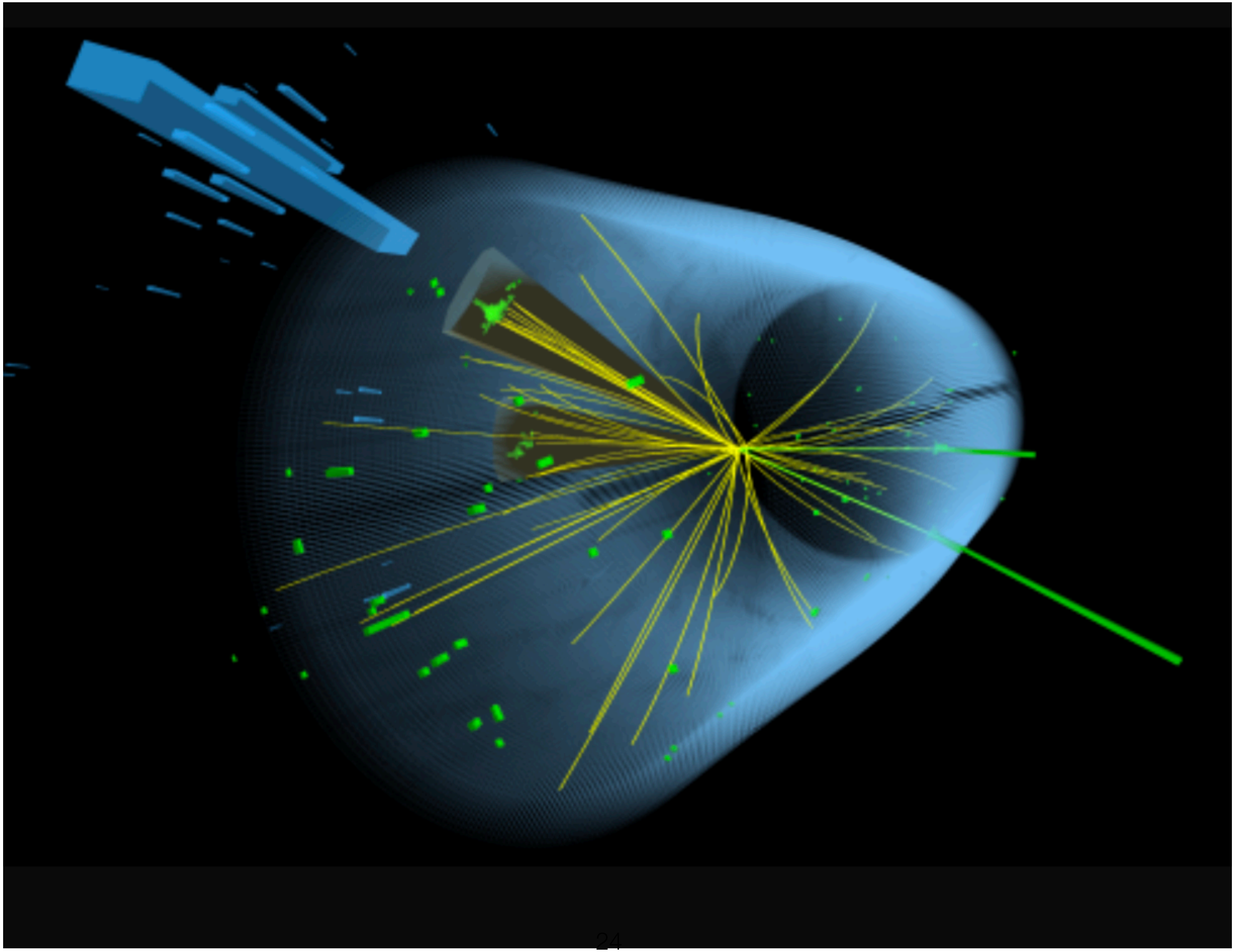
$h \to ZZ \to e^+e^-\mu^+\mu^-$ candidate



$h \to \tau^+\tau^-$ candidate



$h \to b\bar{b}$ candidate using Higgsstrahlung with Z



Tests of qualitative properties predicted for the Higgs boson:

$\gamma\gamma$ decay mode ✔

ZZ decay mode ✔

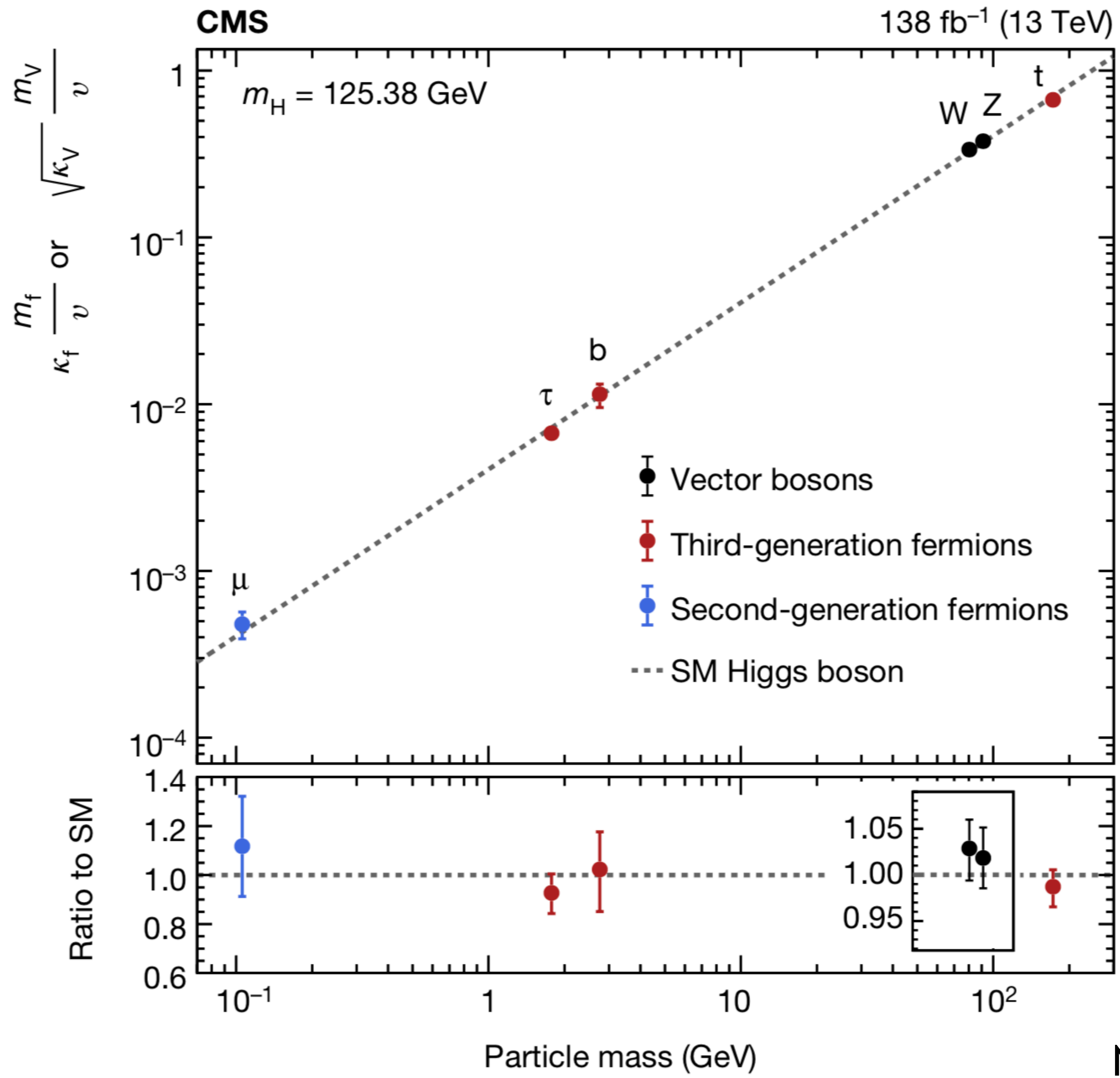
WW decay mode ✔

$\tau^+\tau^-$ decay mode ✔

bb decay mode ✔ (2017!)

tt coupling ✔ (2018!)

spin-parity 0+ ✔



CMS
Nature 2022

Still, something important is missing.

We understand how mass is generated for quarks and leptons, but the Standard Model gives us no understanding of why ?

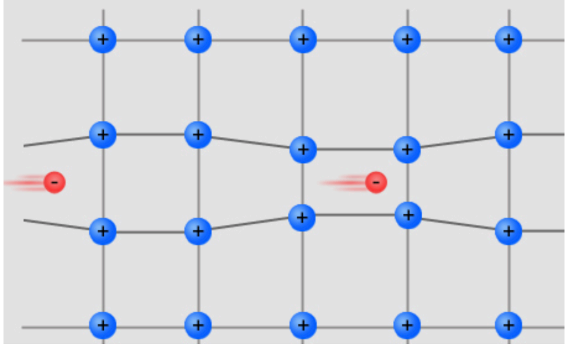
Not only the quark and lepton masses, but also the weak interaction transitions among these particles, the origin of neutrino masses, the origin of CP violation, are all put in by hand.

The Standard Model just gives up in explaining these phenomena.

At the center, the Standard Model gives no explanation of why electroweak symmetry is spontaneously broken in the first place.

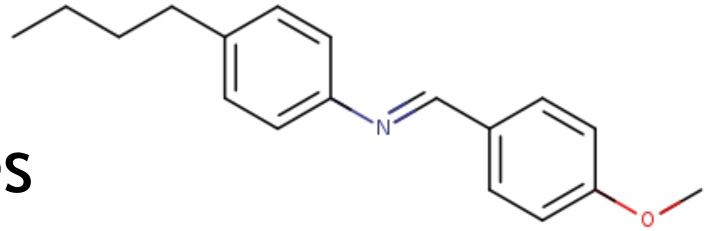
We have many examples of spontaneous symmetry breaking in condensed matter physics.   In all cases, these is a physics mechanism, and each mechanism has its own fascinating properties.

superconductivity: Cooper pairing



magnetism: Hund's rule

liquid crystals: unique molecular shapes



Is there a similar story in particle physics ?

In superconductivity, there is the Landau-Ginzburg theory (1950). This is a phenomenological theory that describes the interaction of a superconductor with electromagnetic fields.

It predicts the thermodynamics of the phase transition, the Meissner effect, the critical current, the existence of Type I and Type II superconductors, and the Abrikosov flux state.

What is does not explain is why superconductivity exists in the first place.

In particle physics, we are still at the Landau-Ginzburg stage.

We might actually know half of the story.

The spectrum of quark and lepton masses spans 5 orders of magnitude

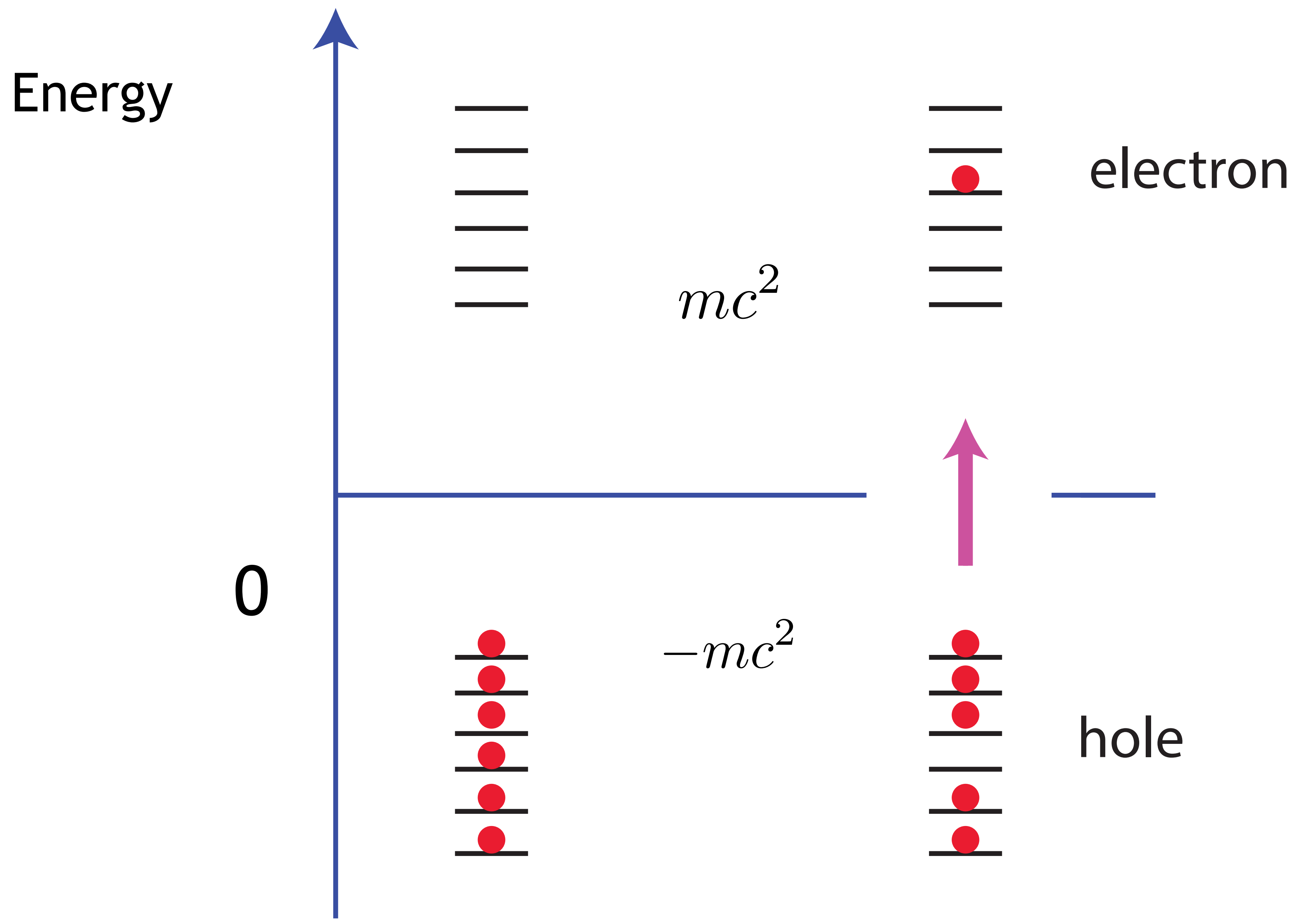
e	0.00051	d	0.0048	u	0.0023
μ	0.106	s	0.095	c	1.28
τ	1.777	b	4.18	t	$173.$

(masses in GeV; $m_p = 0.938\ \mathrm{GeV}$)

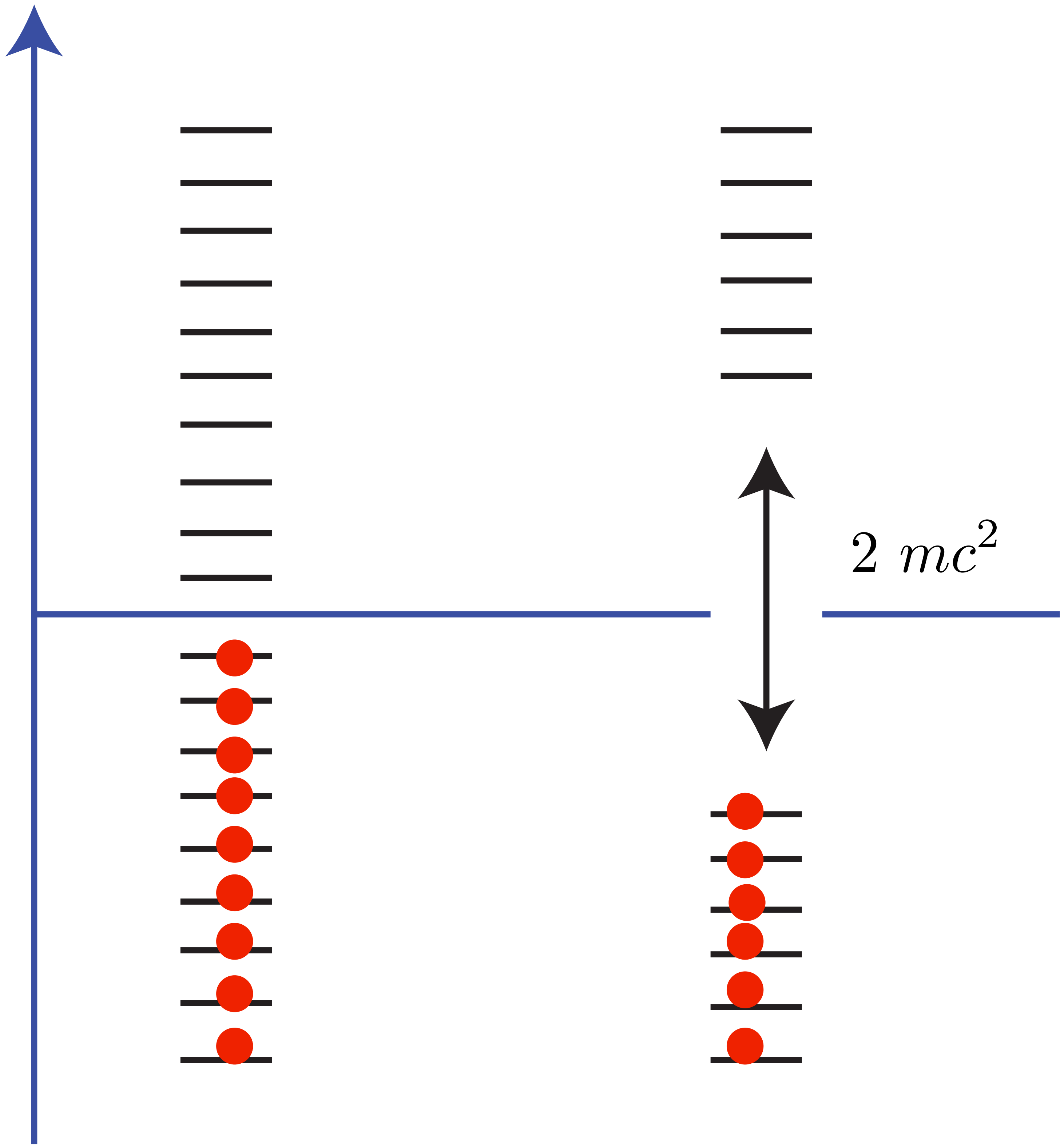
This is one of the mysteries that the Standard Model does not explain.

A striking feature is that one quark — the top quark — is especially heavy. It is the heaviest particle in the Standard Model, heavier than the Higgs boson and the W and Z bosons.

The states of a relativistic fermion can be described as a Dirac sea.

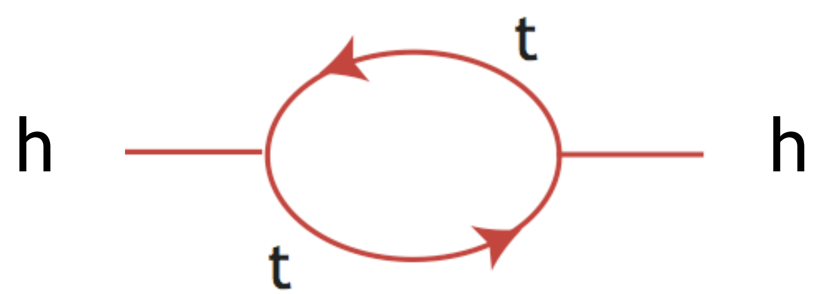


In the Standard Model without symmetry-breaking, there is no gap. Turning on a Higgs field expectation value makes the top quark massive and opens a gap in the spectrum. This lowers the energy of the ground state (vacuum state).



The problem is that the mass gap does not stabilize at a fixed value. As we make the gap larger, the energy continues to decrease indefinitely. The vacuum is unstable.

We can also see this problem in the Feynman diagram computation of the corrections to the mass of the Higgs boson. The diagram

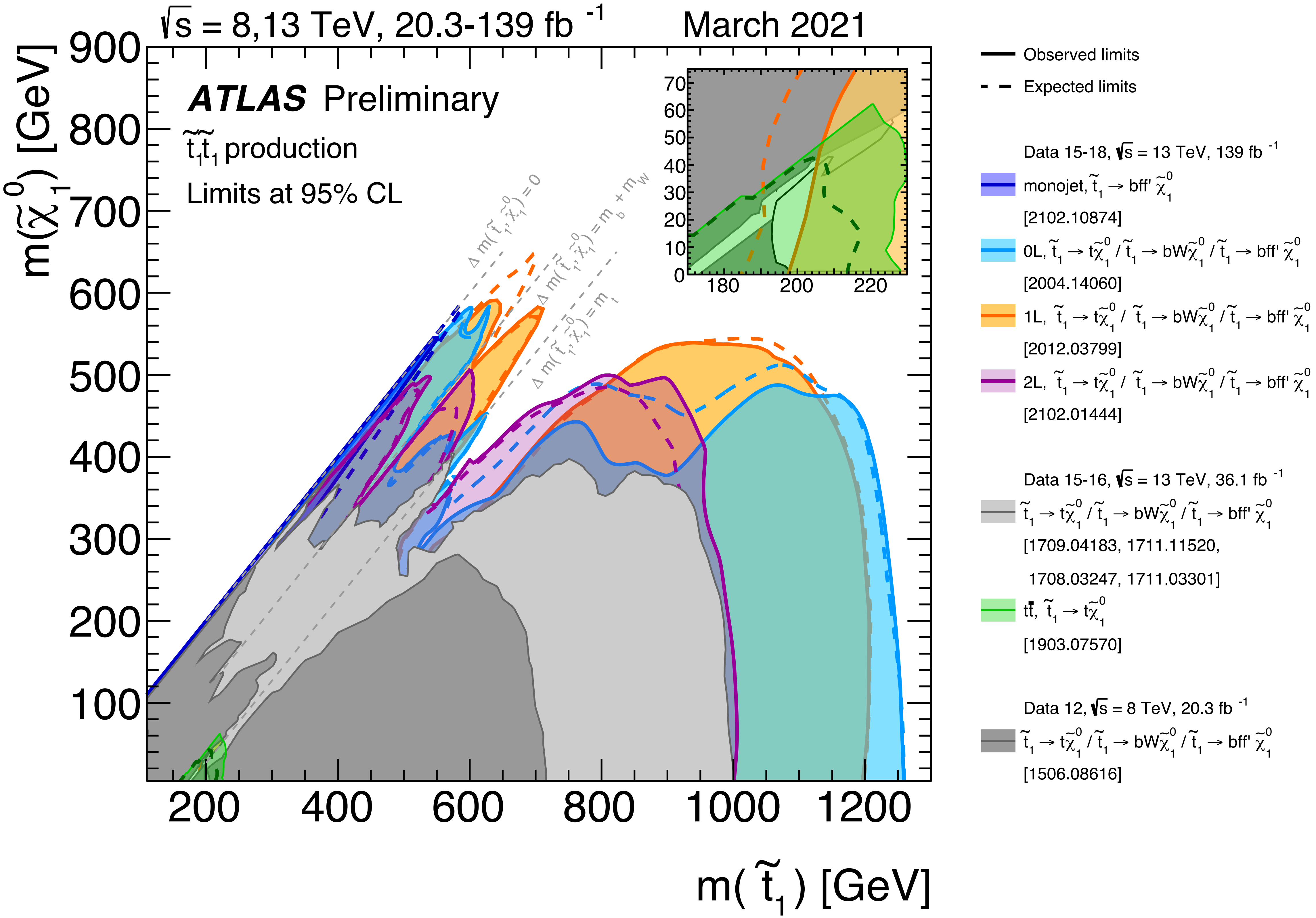


gives $$\Delta m_h^2 = -\frac{3\alpha_t}{2\pi}(\infty)^2$$

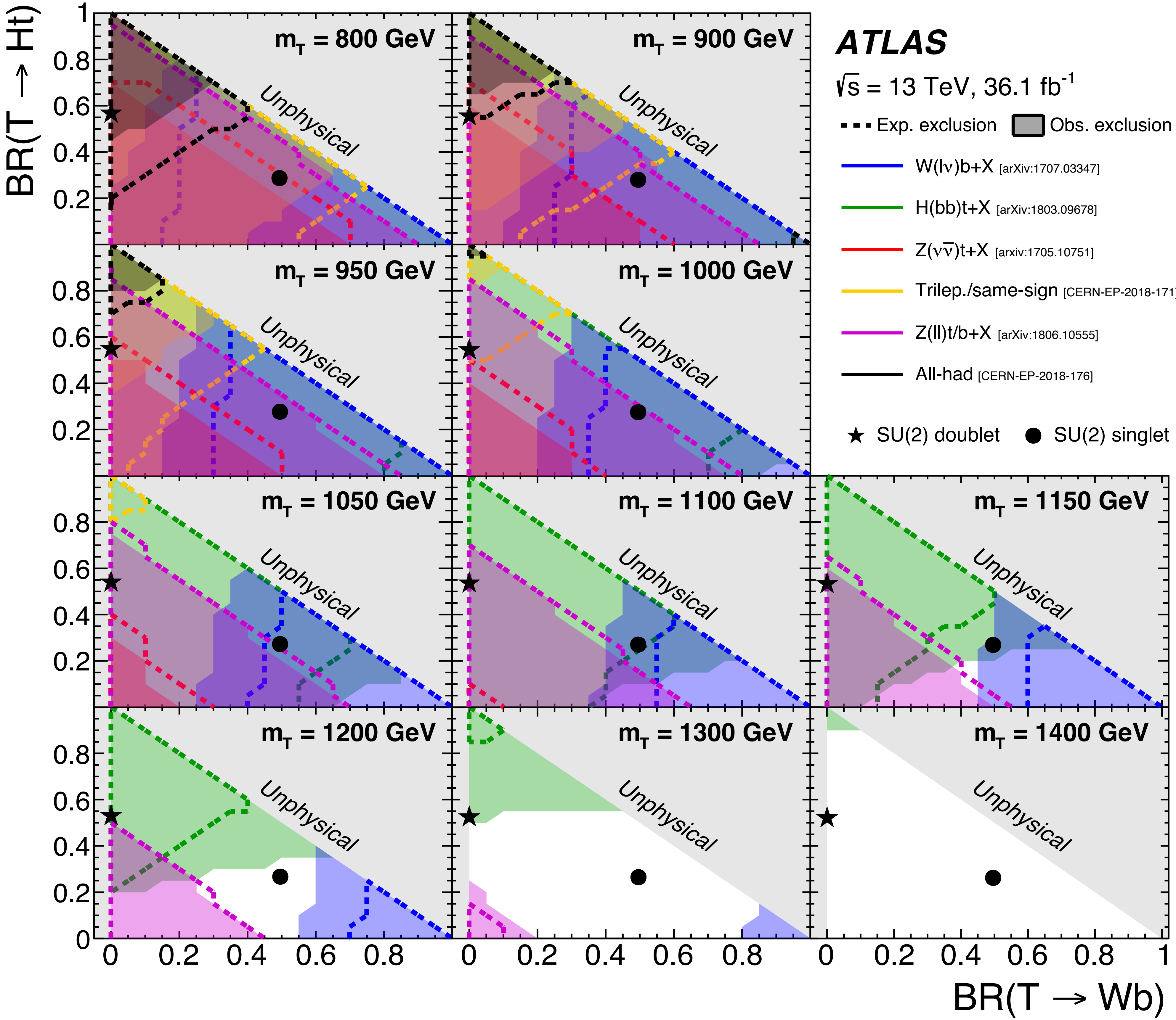
A predictive theory of the Higgs potential should provide an additional contribution that keeps the instability but gives a finite answer for the mass parameter.   Then, additional, balancing contributions to the energy functional are needed.

This suggests the presence of new particles with masses in of order a few x 100 GeV or above. Such particles — predicted by different models — have been searched for intensively at the Large Hadron Collider.

So far, none have been seen.



supersymmetric top quark partner



heavy fermion top quark partner

Can we ask the Higgs boson itself ?

We can improve the precision of measurements of Higgs boson couplings and look for the imprint of undiscovered particles and forces.

This is not as easy as it might seem.

The masses of quarks and leptons measure the Higgs couplings at momentum transfer $Q = 0$.

The decays of quarks and leptons measure the Higgs couplings at momentum transfer $Q = m_h$.

A difference between these values due to the influence of a heavy particle of mass M is then naturally of the order of

$$m_h^2/M^2 \quad \sim \quad \text{few percent}$$

for heavy particles out of the range where they can be observed at the LHC.

Despite the excellent agreement shown on a previous slide, the current LHC measurements are too coarse to speak to this program. The LHC is not in the game yet.

Still, it seems very important to pursue this program if it is possible.

There is a bonus: Each Higgs coupling has its own personality and is sensitive to a different type of new physics:

coupling to fermions -   multiple Higgs doublets, SUSY

coupling to gauge bosons - Higgs compositeness

coupling to $\gamma\gamma$, gg - heavy top quark partners

coupling to tt -   top quark compositeness

These ideas give strong motivation for a program of precision measurements of the Higgs boson couplings.

The goal should be to measure the individual partial widths to an accuracy of 1%, and better if possible.

This requires a comprehensive program of measurements of Higgs production and decay processes.

It would be best if the experiments were also highly sensitive to invisible and exotic Higgs decays, which might contribute to Γ_h and also signal new physics in their own right.

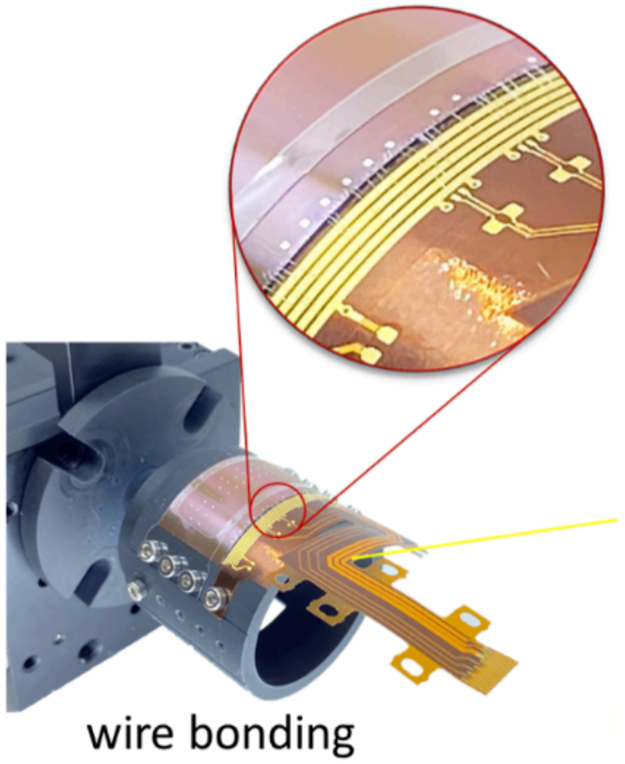
Eventually, the LHC experiments will bring the uncertainties on Higgs boson coupling to the few % level. But to have a significant and confirmed discovery, we will need to do better. For this, a new experimental setting is needed — the e+e- Higgs factory.

To achieve high precision, we need to design an experiment in which achieving low precision is straightforward. This first step is already not possible at the LHC, where we create 1 Higgs boson for each billion proton-proton collisions.

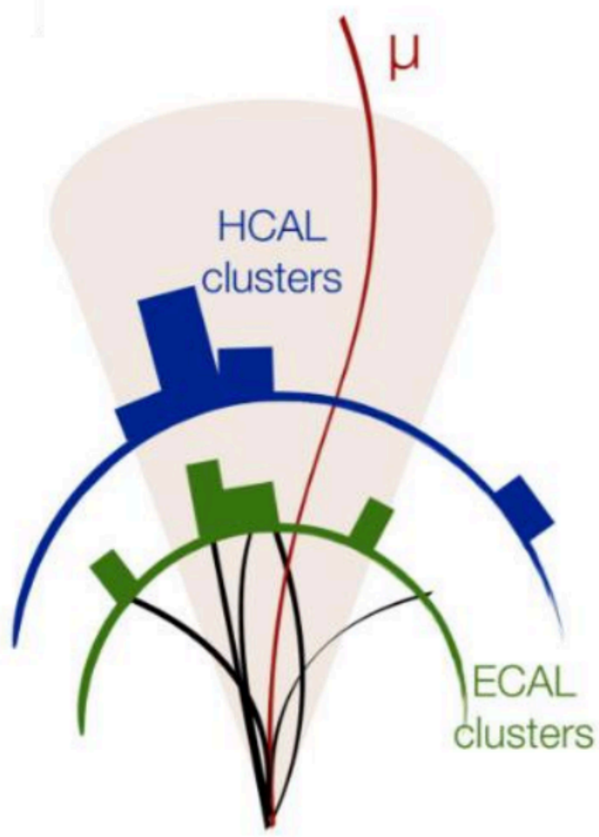
At an e+e- collider, we create 1 Higgs boson in each 100 e+e- annihilation events. Then we can put our effort into creating the best experiment possible for that environment.

Highest-precision measurements will benefit from new detector technologies under development now:

MAPS: monolithic active pixel sensors
— bendable silicon sensors thinned to 50 μ;
10% of the material in the CMS tracker

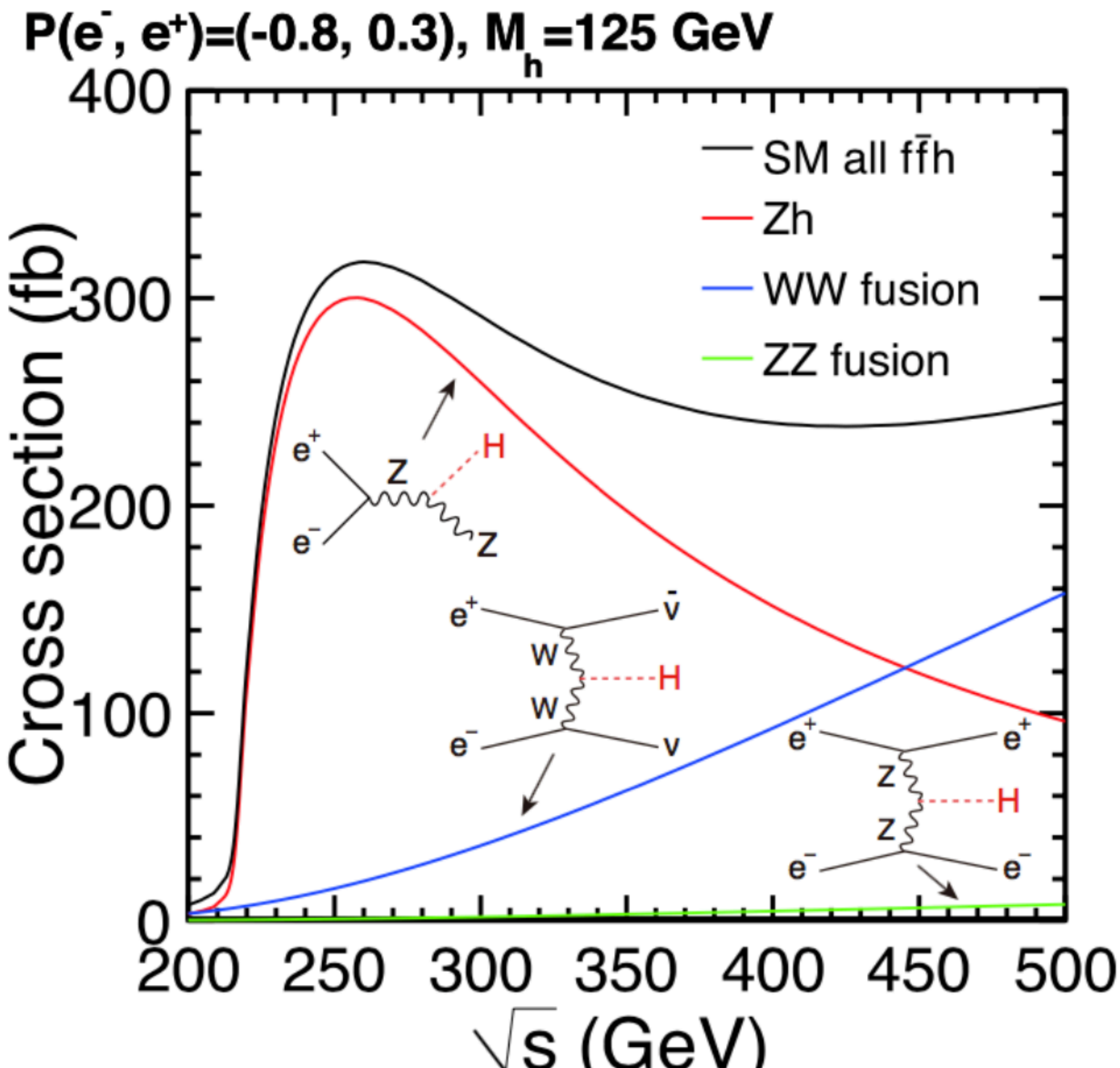


Particle Flow vs. Dual readout calorimetry
— hadron calorimetry with high-granularity, measuring and tracking the details of the shower evolution — inclusion of timing
improvement of a factor 2 over LHC



In-sensor intelligence, machine learning at all levels

Production cross sections for Higgs production processes:



First energy stage: 240-250 GeV

Higgs production dominated by the Higgsstrahlung process

Higgs bosons are tagged by the recoil Z boson at a lab energy of 110 GeV. This allows:

direct measurement of Higgs boson branching ratios

searches for invisible, partially invisible, and other exotic Higgs final states

measurement of $\sigma(e^+e^- \to hZ)$ independently of the Higgs boson final state. This allows determination of the absolute normalization of Higgs partial widths.

measurement of the Higgs boson mass in recoil to 10 MeV (10^{-4} precision)

Second energy stage: 350 - 550 - 1000 GeV

Higgs production dominated by the WW fusion process

This is gives an independent data set that can confirm anomalies found at the first stage.

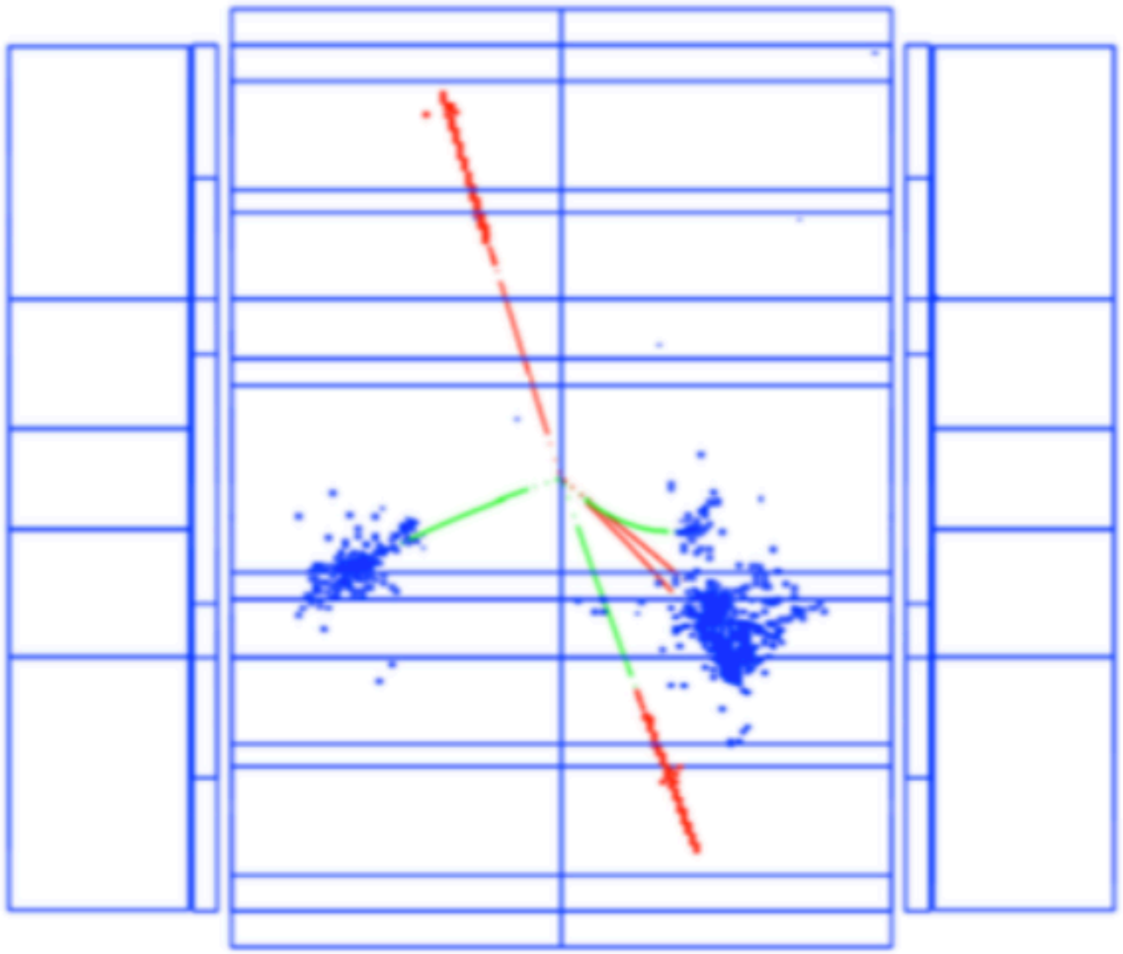
Additional and complementary Higgs measurements:

top-Higgs coupling: $e^+e^- \to t\bar{t}h$

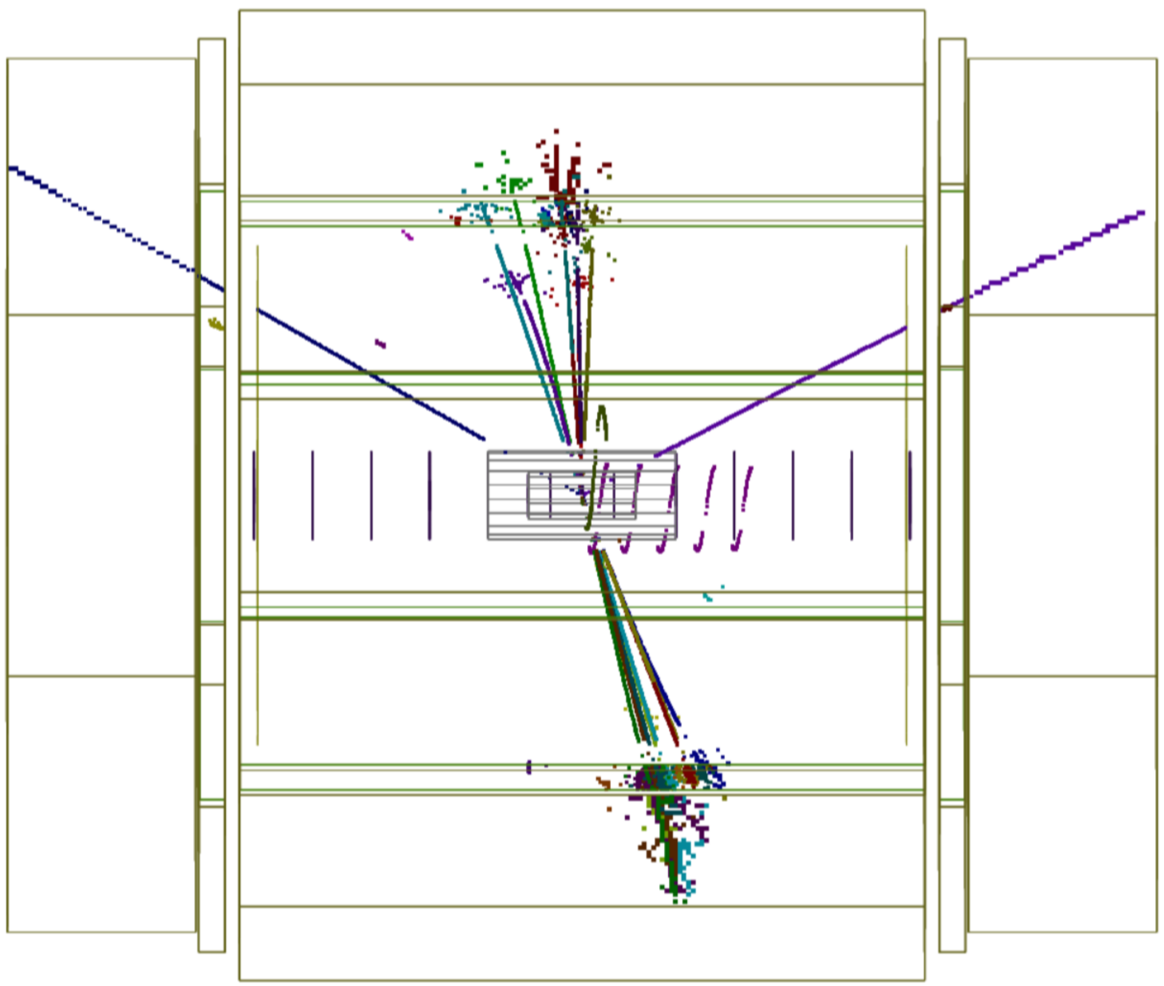
Higgs self-coupling: $e^+e^- \to Zhh$ $e^+e^- \to \nu\bar{\nu}h$

precision measurement of top quark electroweak form factors in $e^+e^- \to t\bar{t}$

ILD simulation of $e^+e^- \to Zh\ ,\ Z \to \mu^+\mu^-$



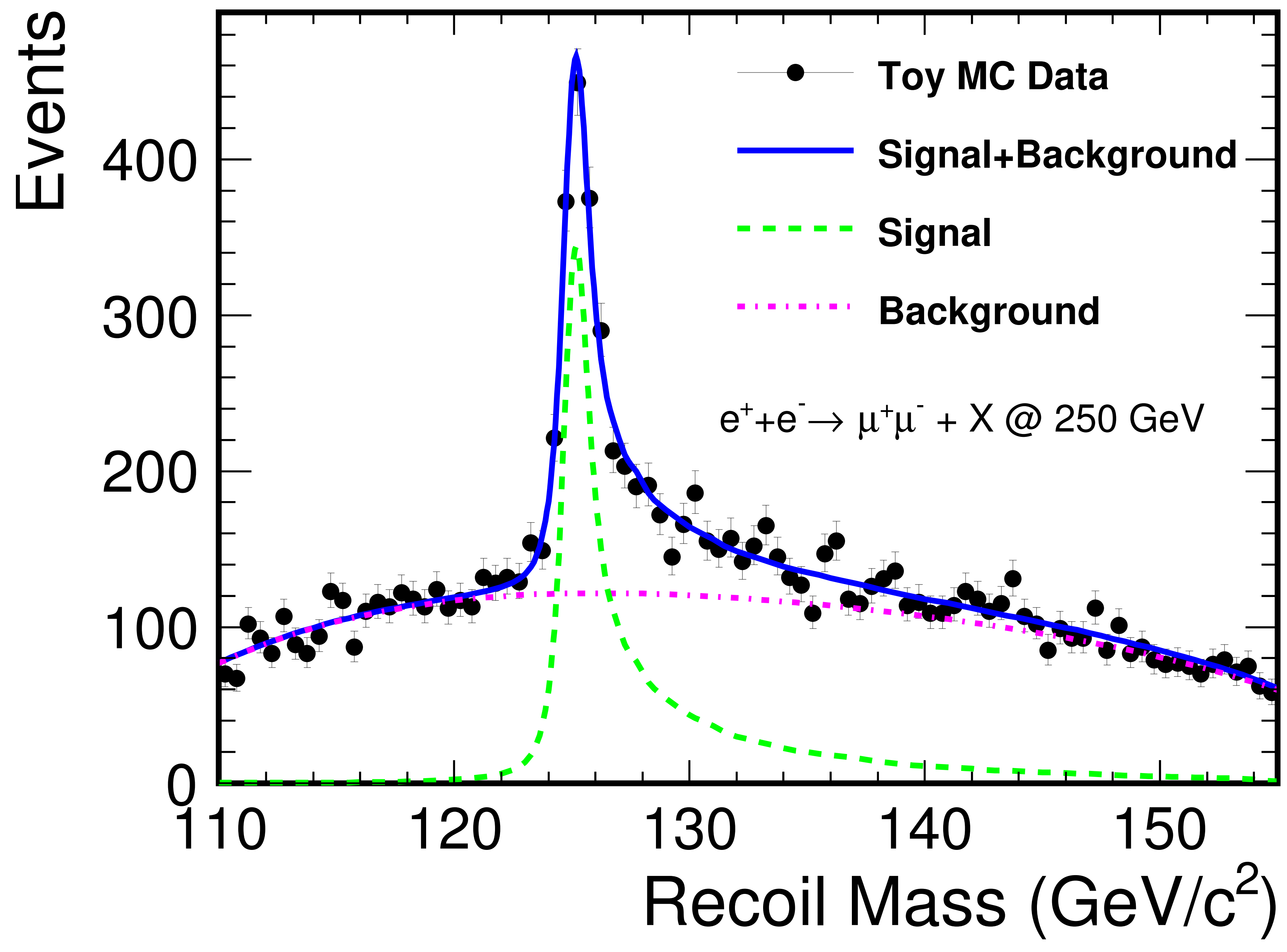
$h \to \tau^+\tau^-$



$h \to b\bar{b}$

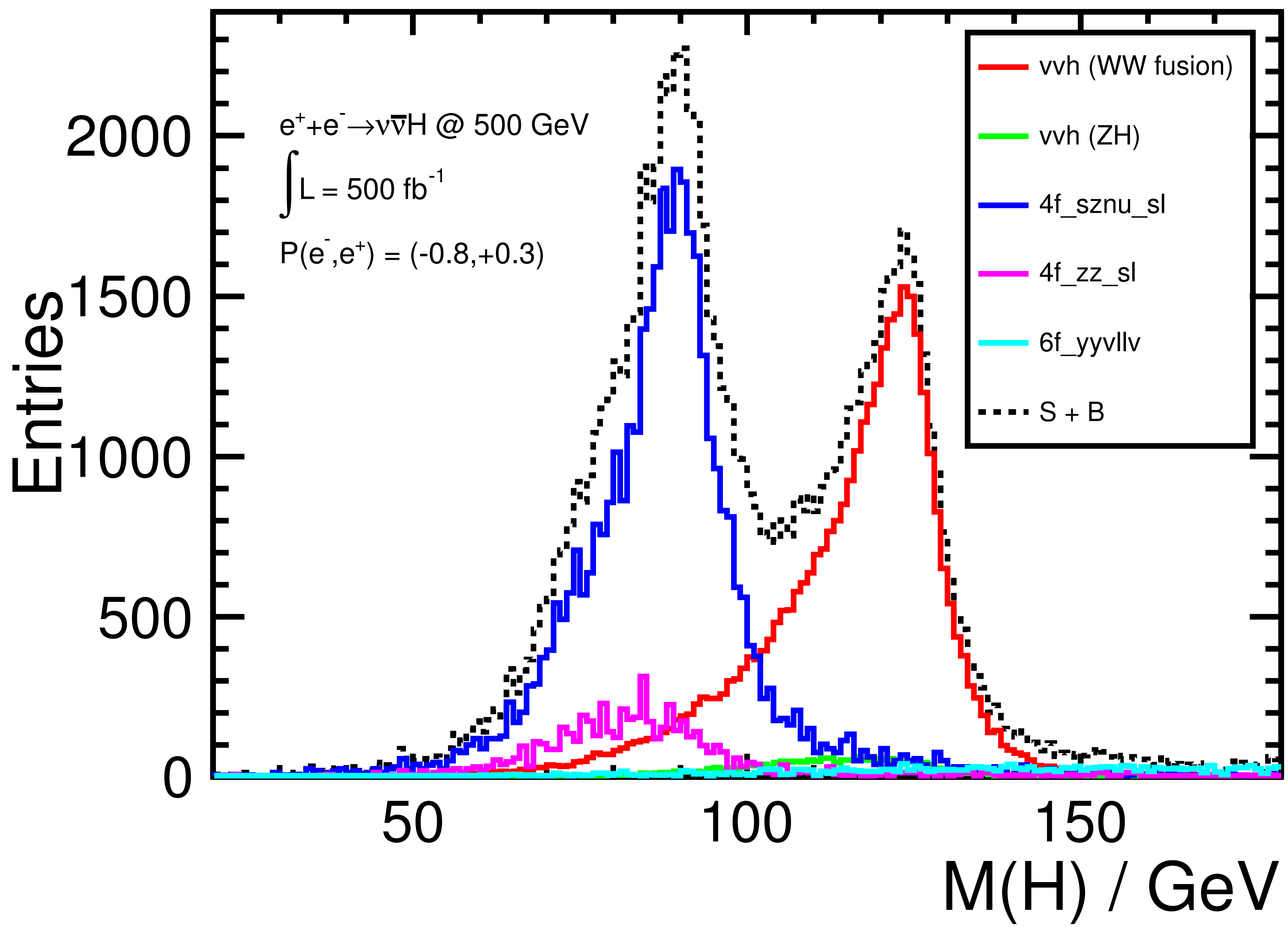
(thanks to M. Ruan)

measurement of the Higgs boson mass by the recoil technique

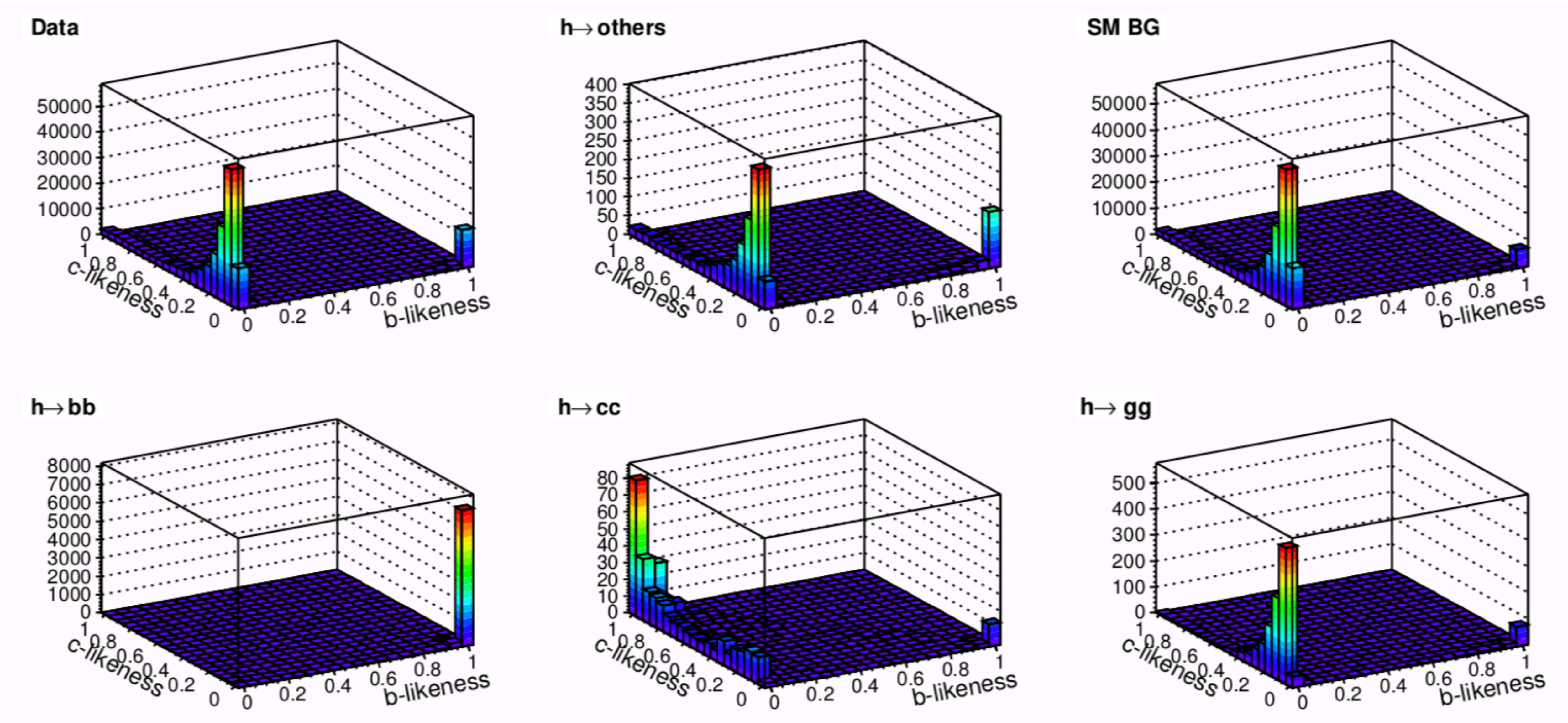


arXiv:1903.01629

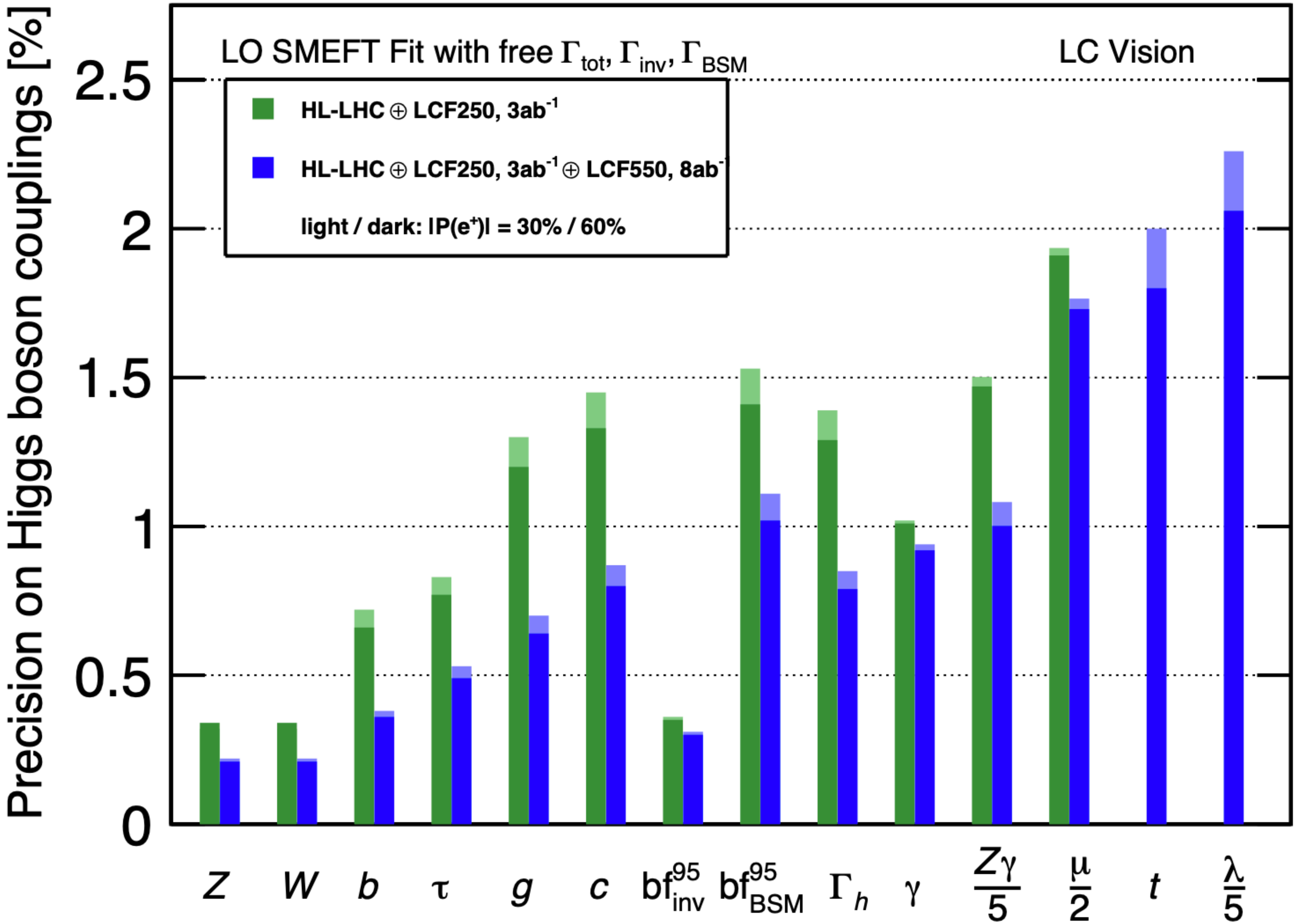
$$e^+e^- \to \nu\overline{\nu} + b\overline{b}$$



arXiv:1903.01629



discrimination of hadronic Higgs decays - ILD simulation



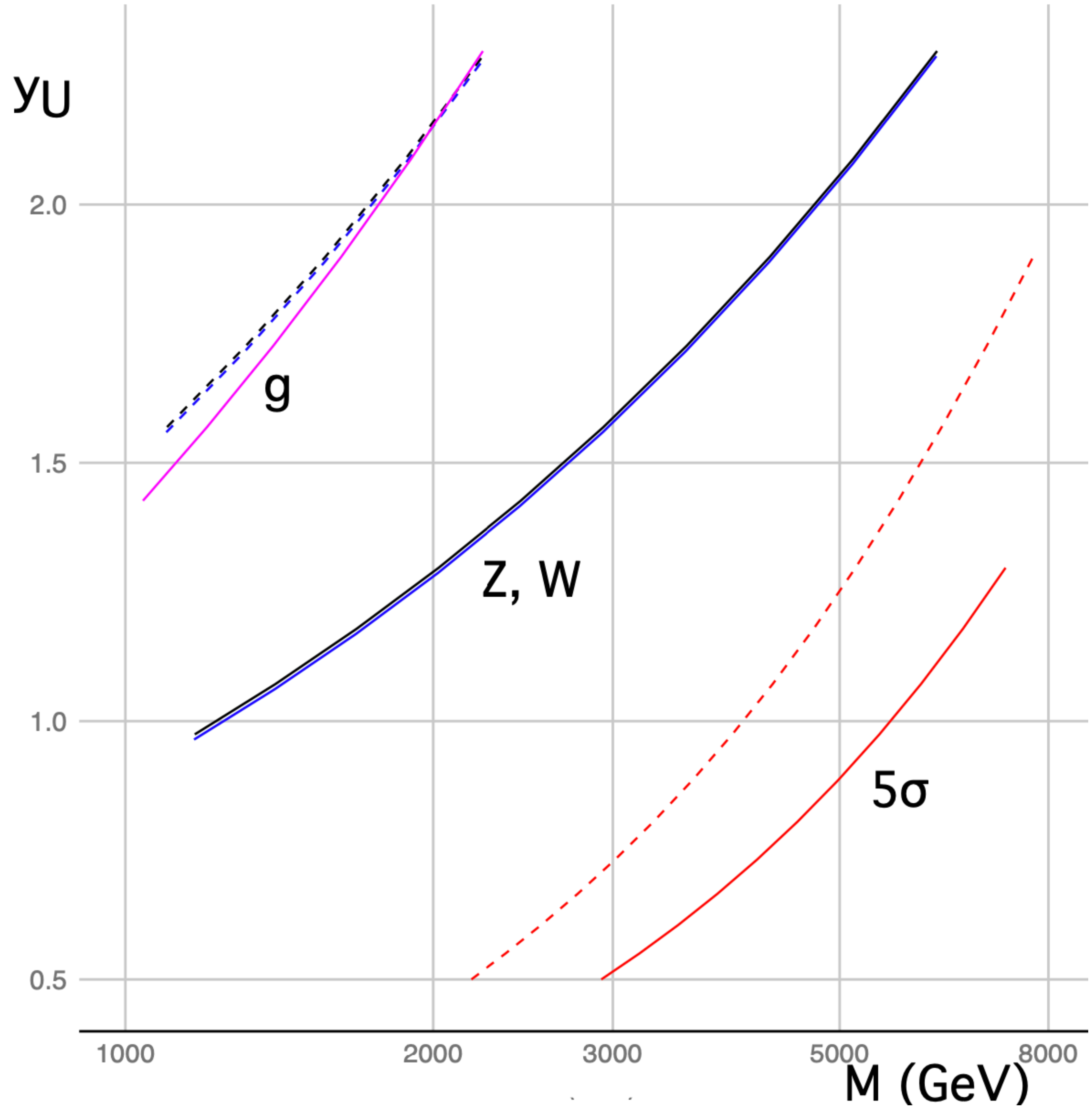
LO SMEFT Fit with free Γ_{tot}, Γ_{inv}, Γ_{BSM}
LC Vision
HL-LHC ⊕ LCF250, 3ab^{-1}
HL-LHC ⊕ LCF250, 3ab^{-1} ⊕ LCF550, 8ab^{-1}
light / dark: |P(e$^+$)| = 30% / 60%
Precision on Higgs boson couplings [%]
0
0.5
1
1.5
2
2.5
Z
W
b
τ
g
c
bf^{95}_{inv}
bf^{95}_{BSM}
Γ_h
γ
$\frac{Z\gamma}{5}$
$\frac{\mu}{2}$
t
$\frac{\lambda}{5}$

Not every Beyond-Standard-Model scenario becomes visible in this way. But there are many possibilities for discovery of new physics far beyond the expected reach of the HL-LHC.

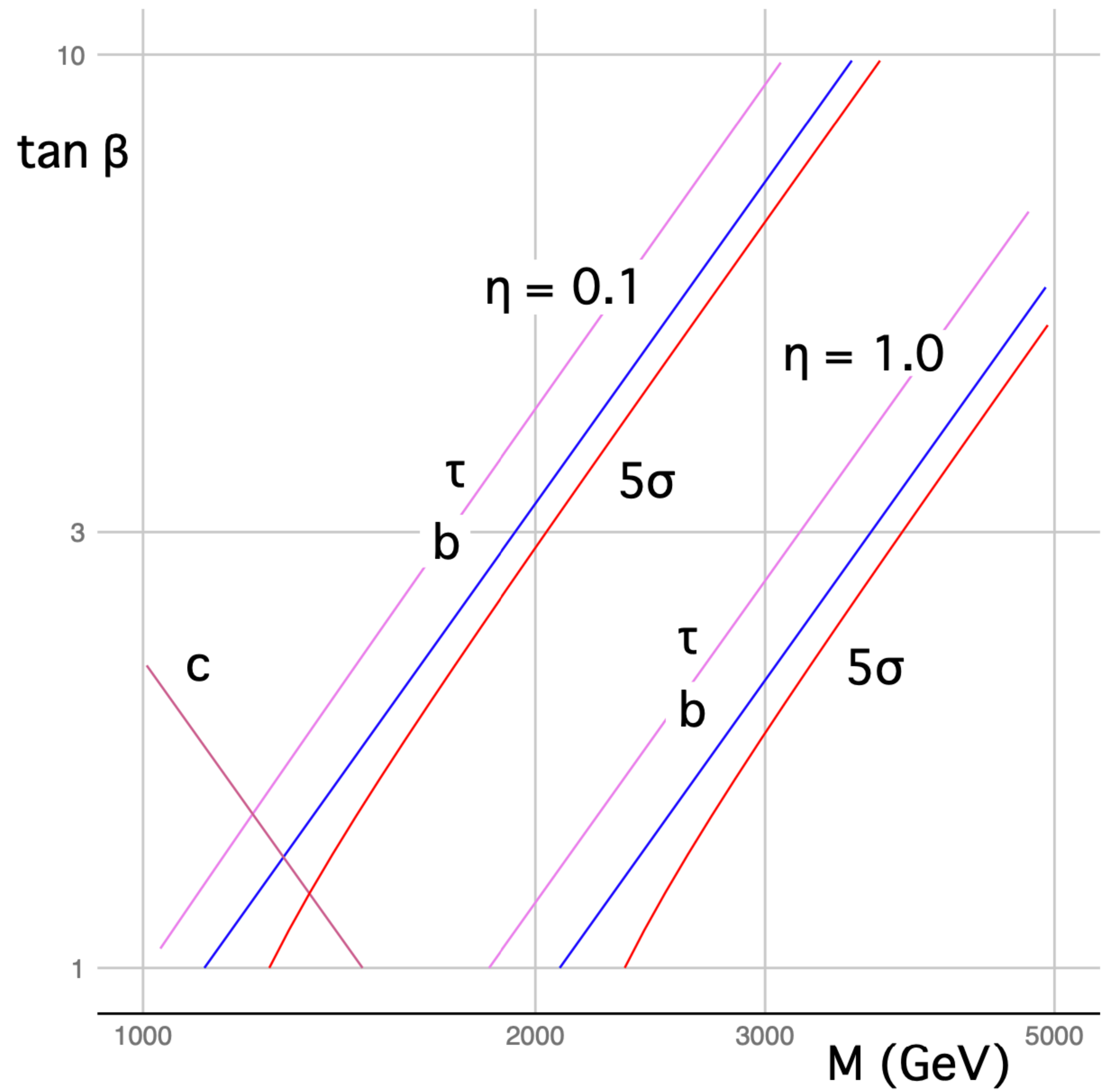
Model with vector-like top quark partners:

3σ deviation in one coupling

5σ deviation in the complete fit



2 Higgs doublet models



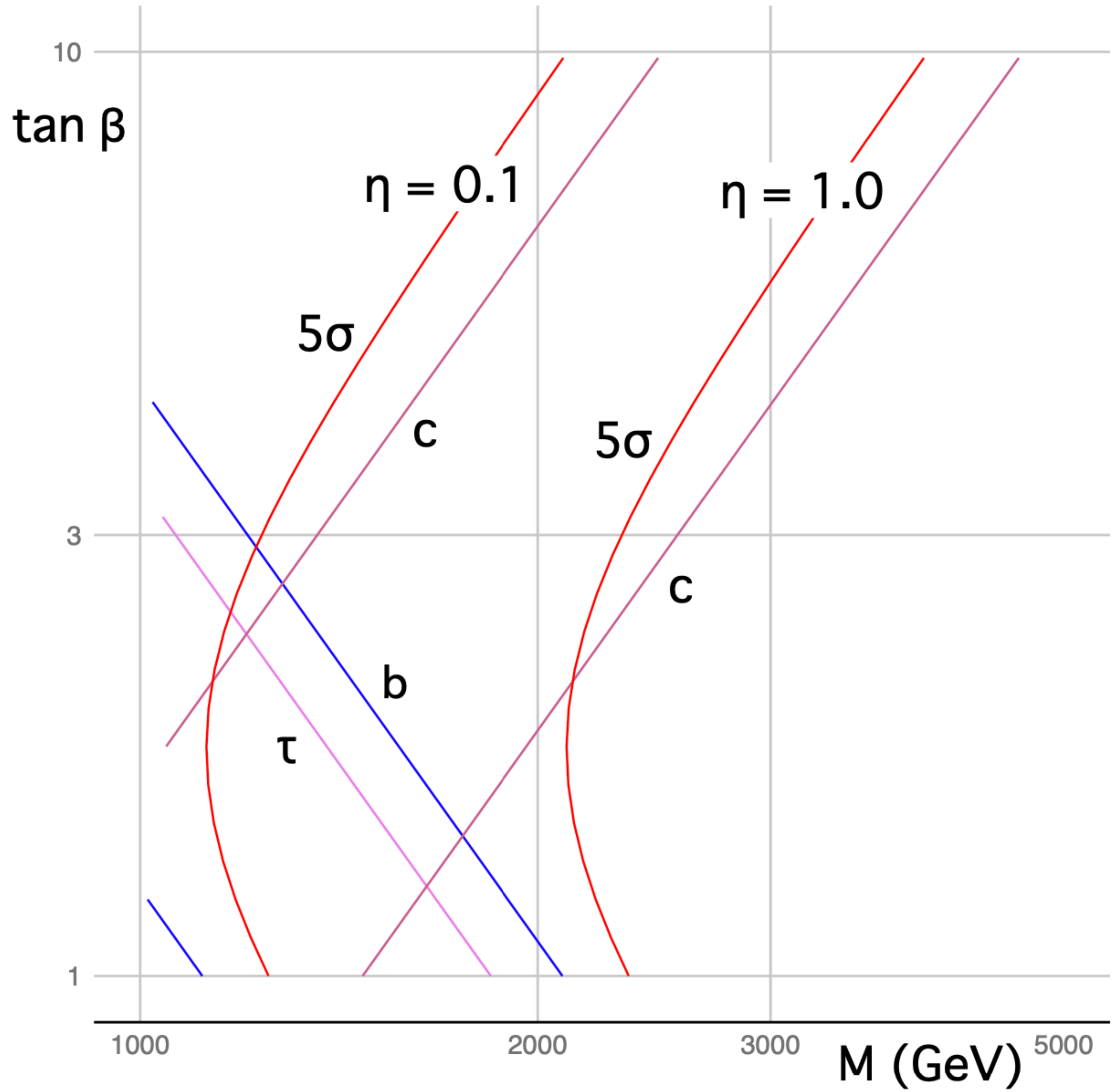
3σ deviation
in one coupling

5σ deviation in
the complete fit

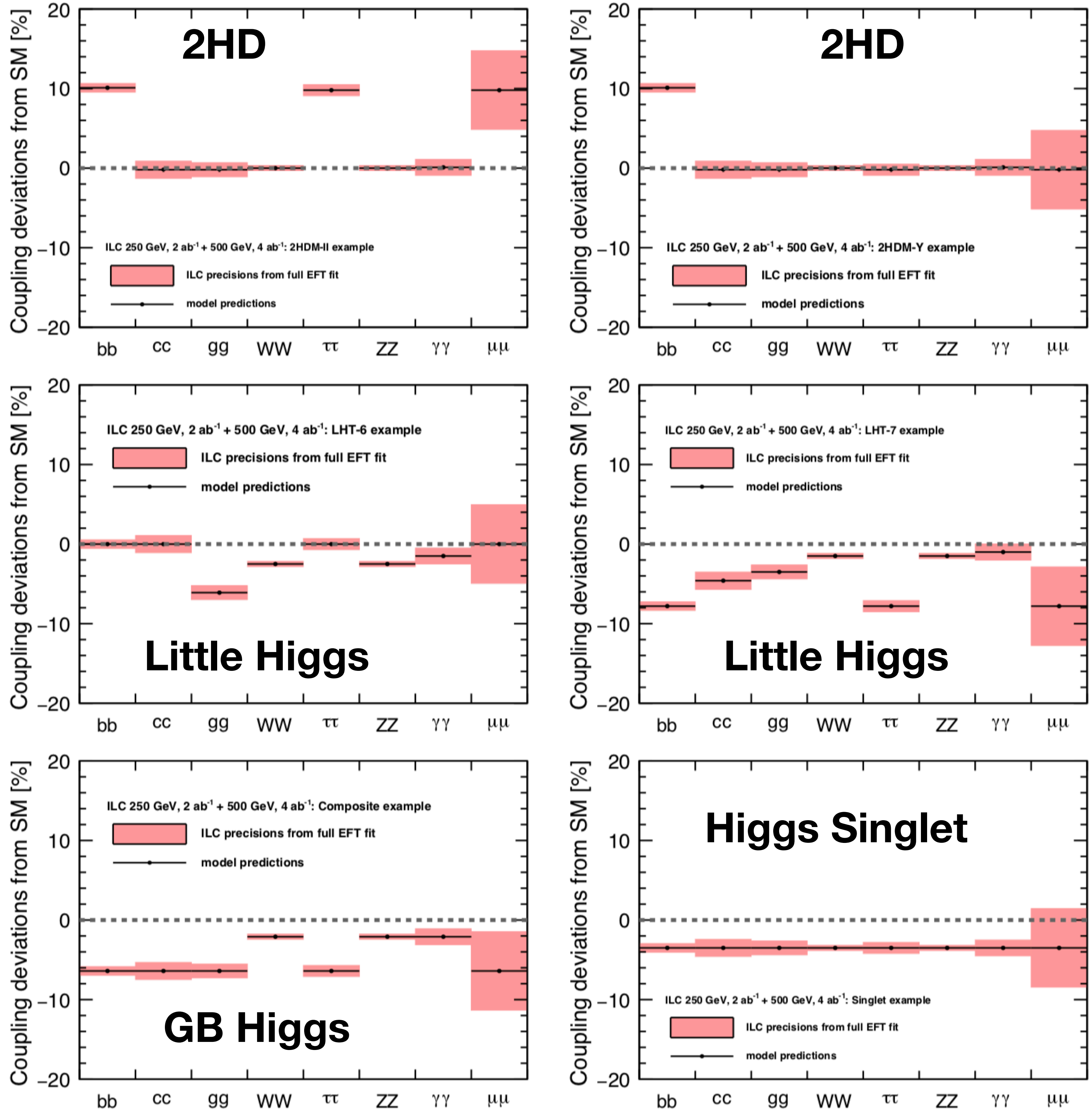
2-Higgs doublet model with different Higgs for 3rd and 2nd generation:

3σ deviation in one coupling

5σ deviation in the complete fit



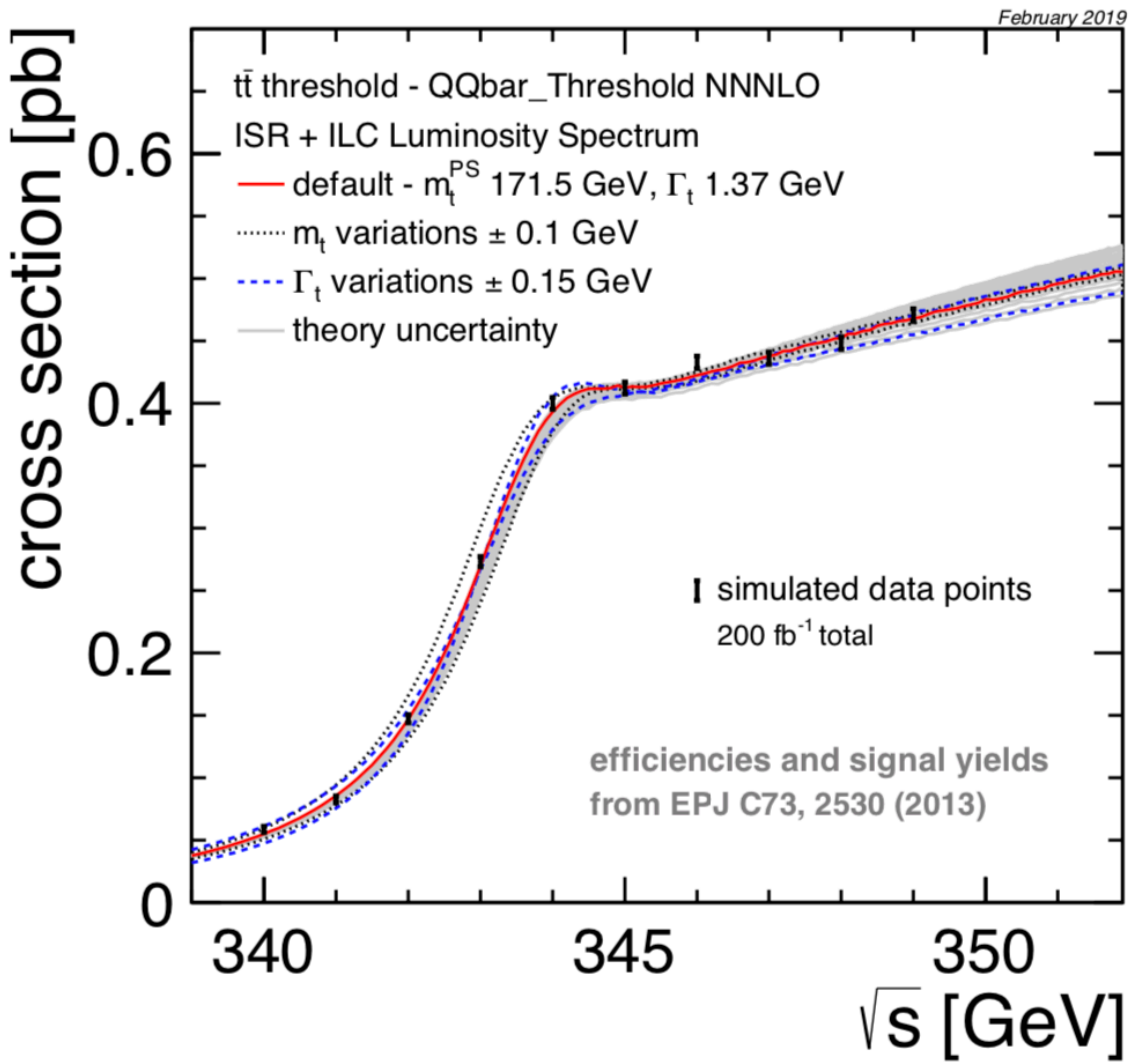
Every model of new physics has its own distinctive imprint on the pattern of anomalies in Higgs boson couplings.

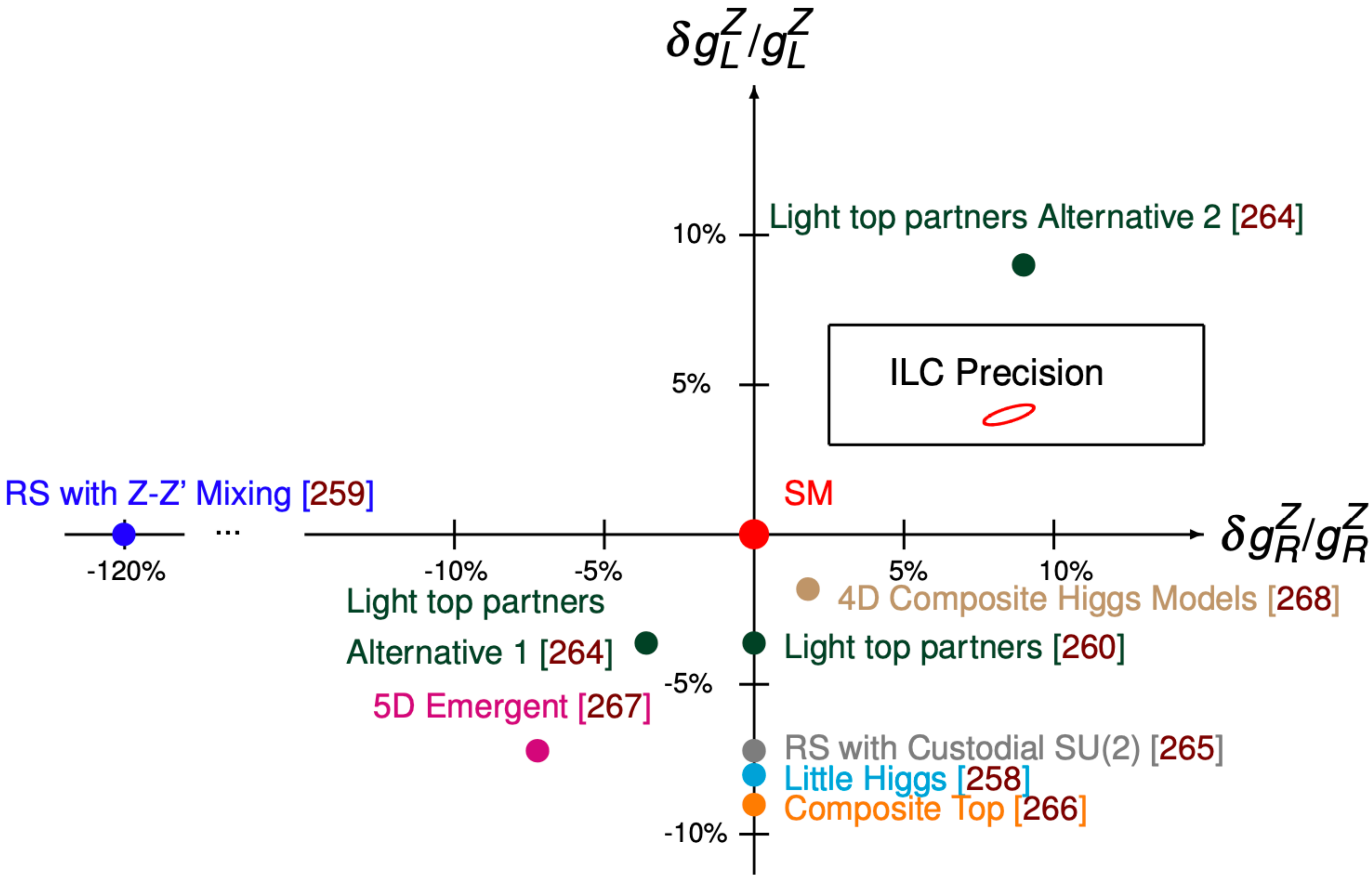


ILC report: arXiv:2203.07622

I have emphasized that top quarks are potentially also important in the story of the Higgs spontaneous symmetry breaking. So it is important that a “Higgs factory” will also be a top quark factory.

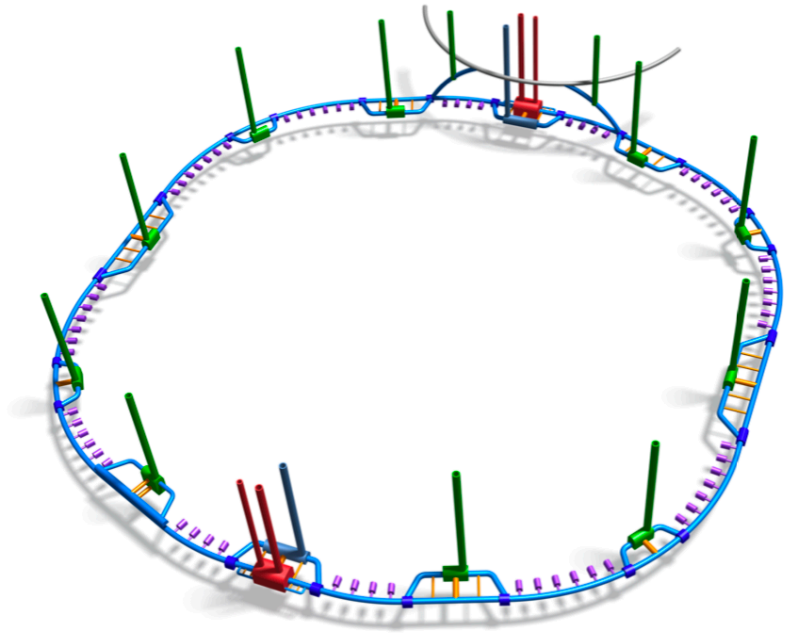
precision top quark mass measurement

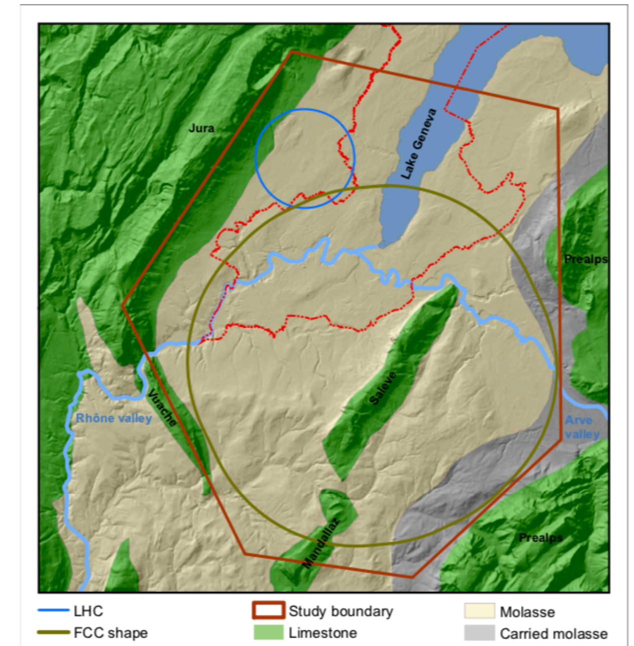


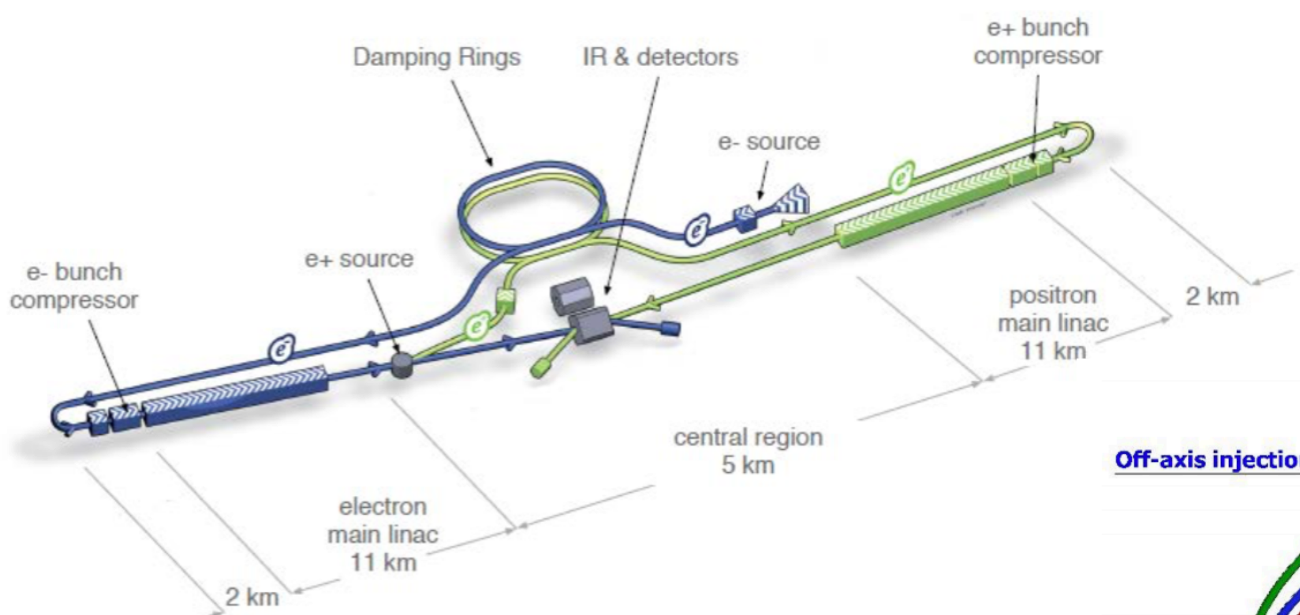

$\delta g_L^Z / g_L^Z$
$\delta g_R^Z / g_R^Z$
10%
5%
-5%
-10%
-120%
...
-10%
-5%
5%
10%
Light top partners Alternative 2 [264]
ILC Precision
RS with Z-Z' Mixing [259]
SM
4D Composite Higgs Models [268]
Light top partners
Alternative 1 [264]
Light top partners [260]
5D Emergent [267]
RS with Custodial SU(2) [265]
Little Higgs [258]
Composite Top [266]

Collider proposals for e+e- Higgs factories:

FCC-ee
a circular
collider in a
91 km tunnel

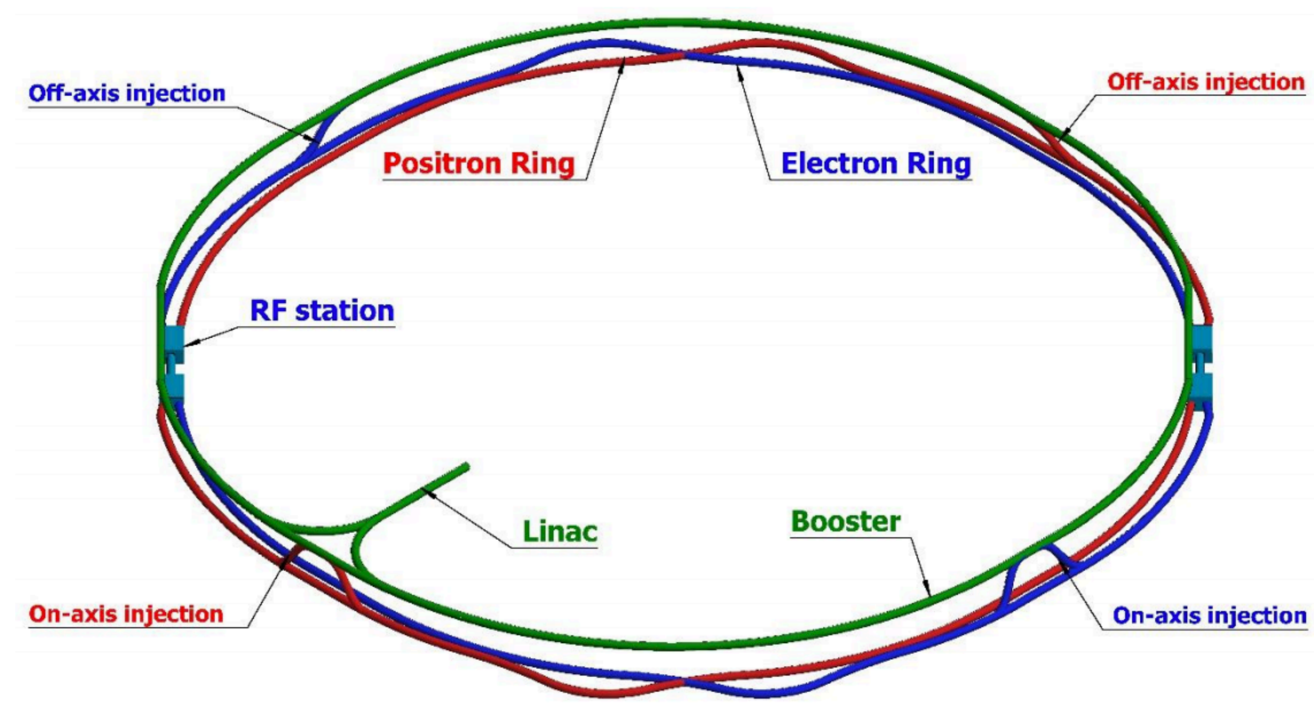






LCF, a 21 km linear collider,
expandable to 1 TeV e+e- energy

CEPC, a circular collider
proposal in China



The Higgs boson has many secrets that are still hidden. But it is within our power to find them out.

We are looking forward to a new frontier accelerator that will measure the Higgs boson properties in detail and give a window into these secrets.