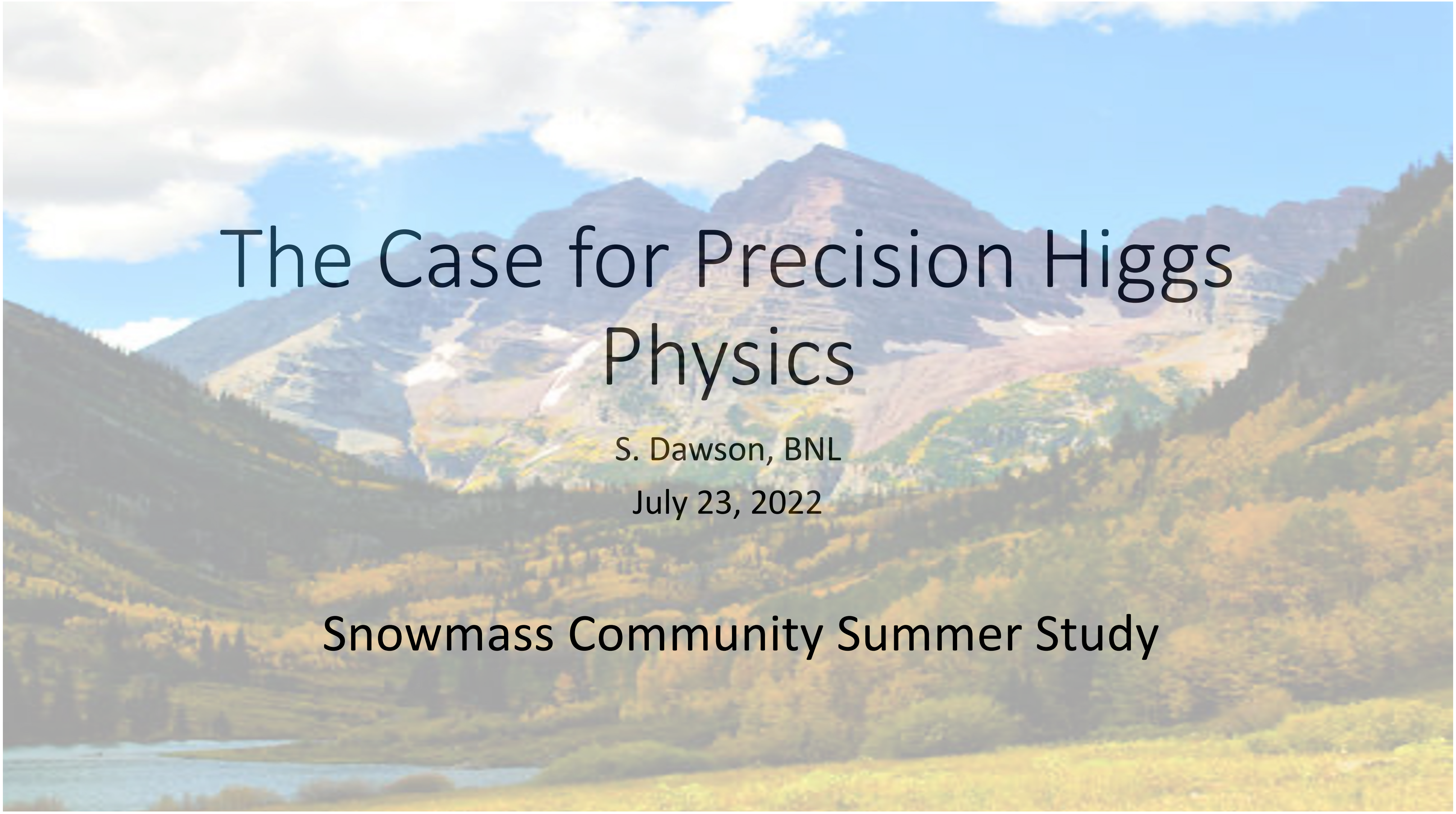


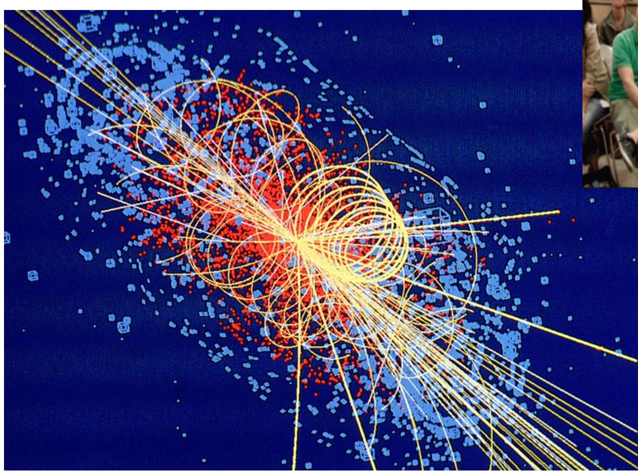
The Case for Precision Higgs Physics

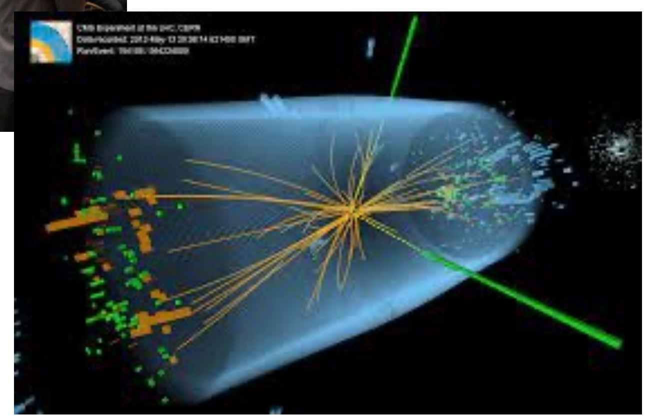
S. Dawson, BNL

July 23, 2022

Snowmass Community Summer Study

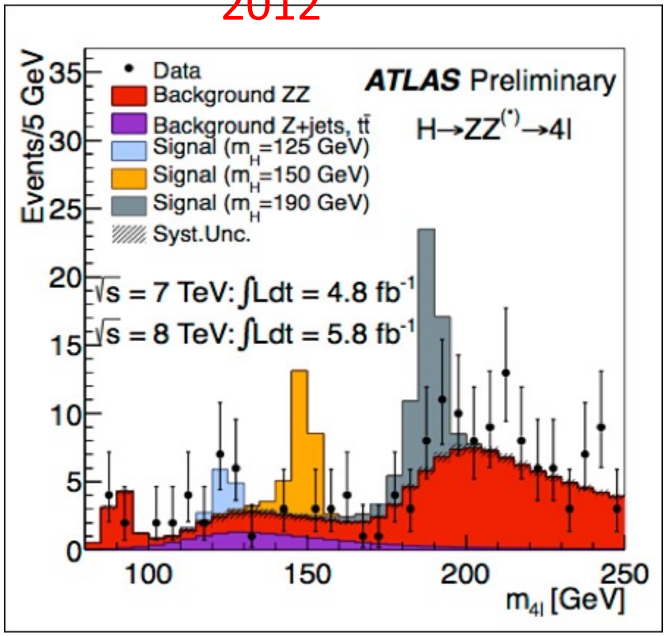
The landscape has changed since the Higgs discovery in 2012



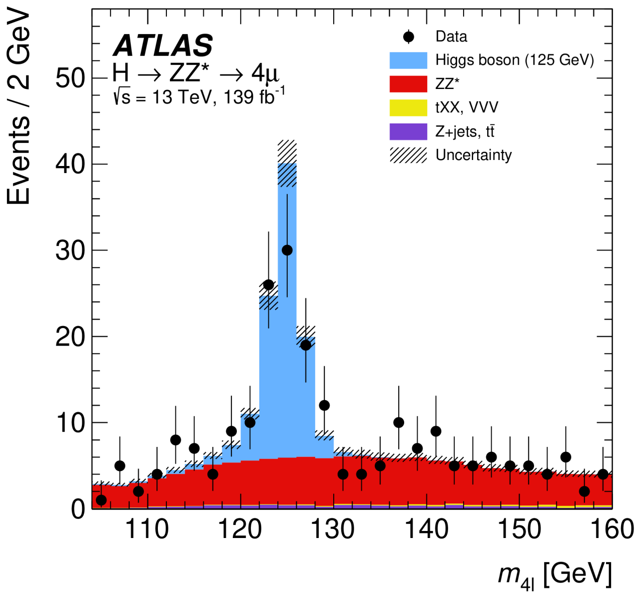


Higgs physics is ***precision physics*** at the LHC

2012



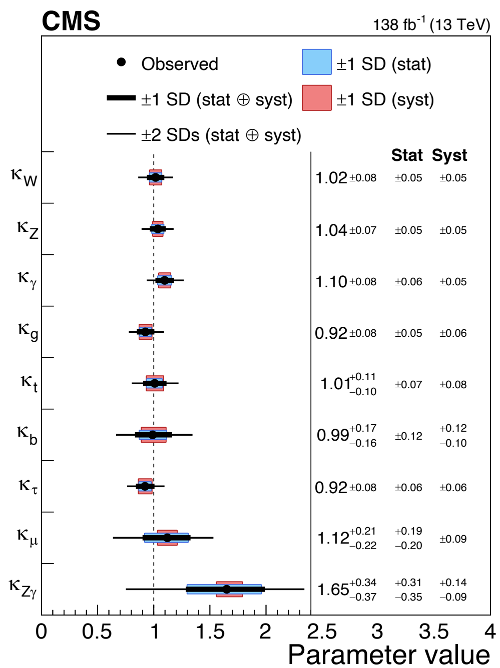
2022

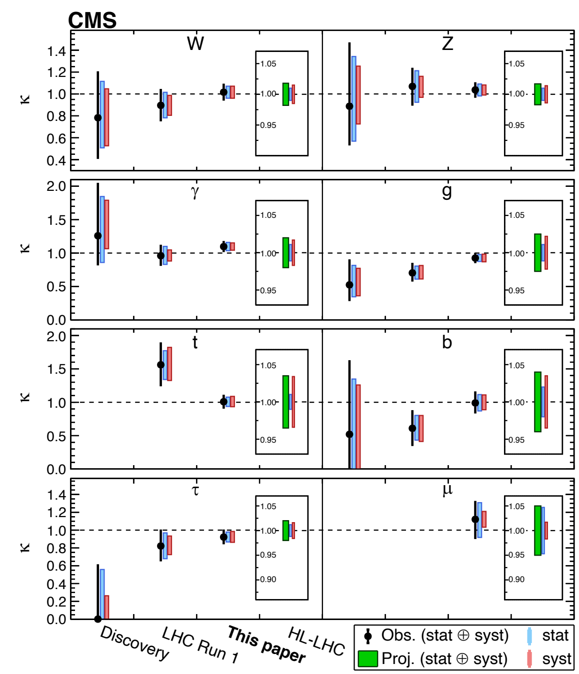


Higgs physics is ***precision physics*** at the LHC

Higgs couplings to fermions and gauge bosons measured at the 5-10% level by both ATLAS and CMS

Always compare measurements with expectations: κ=1 is SM

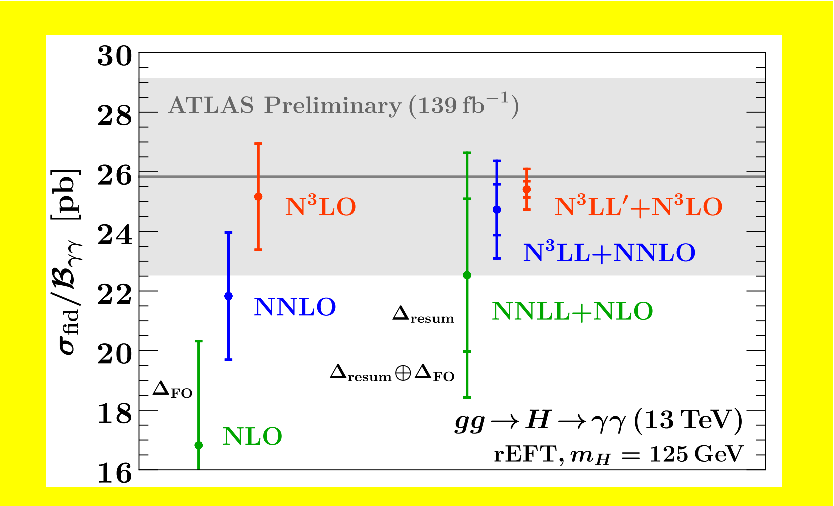




Evolution in time of Higgs coupling measurements

Triumph of the Standard Model

- Precision calculations of Higgs quantities
- New theoretical calculations allow for precision testing of Standard Model *(cf LEP program)*
  - *New tools for calculations*
  - *Incredibly precise predictions*
  - *Standard model is benchmark*



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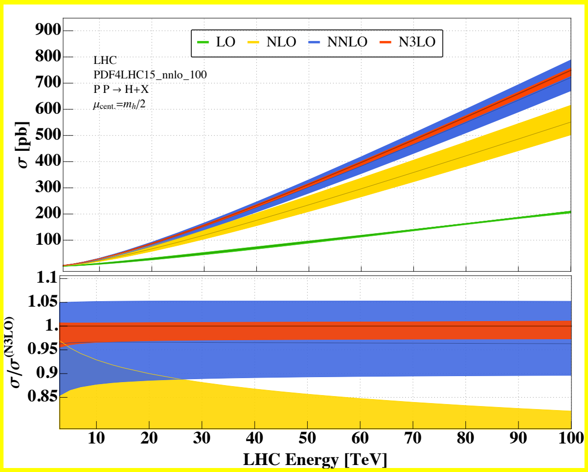
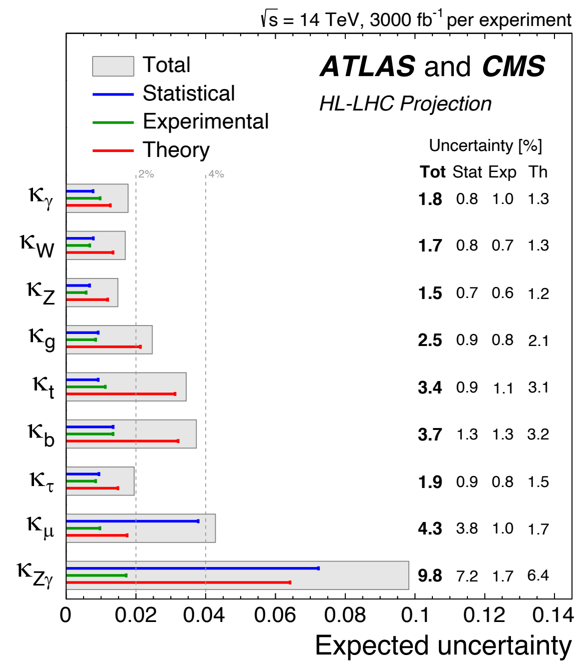
It's all about the uncertainties

Gluon fusion production of Higgs



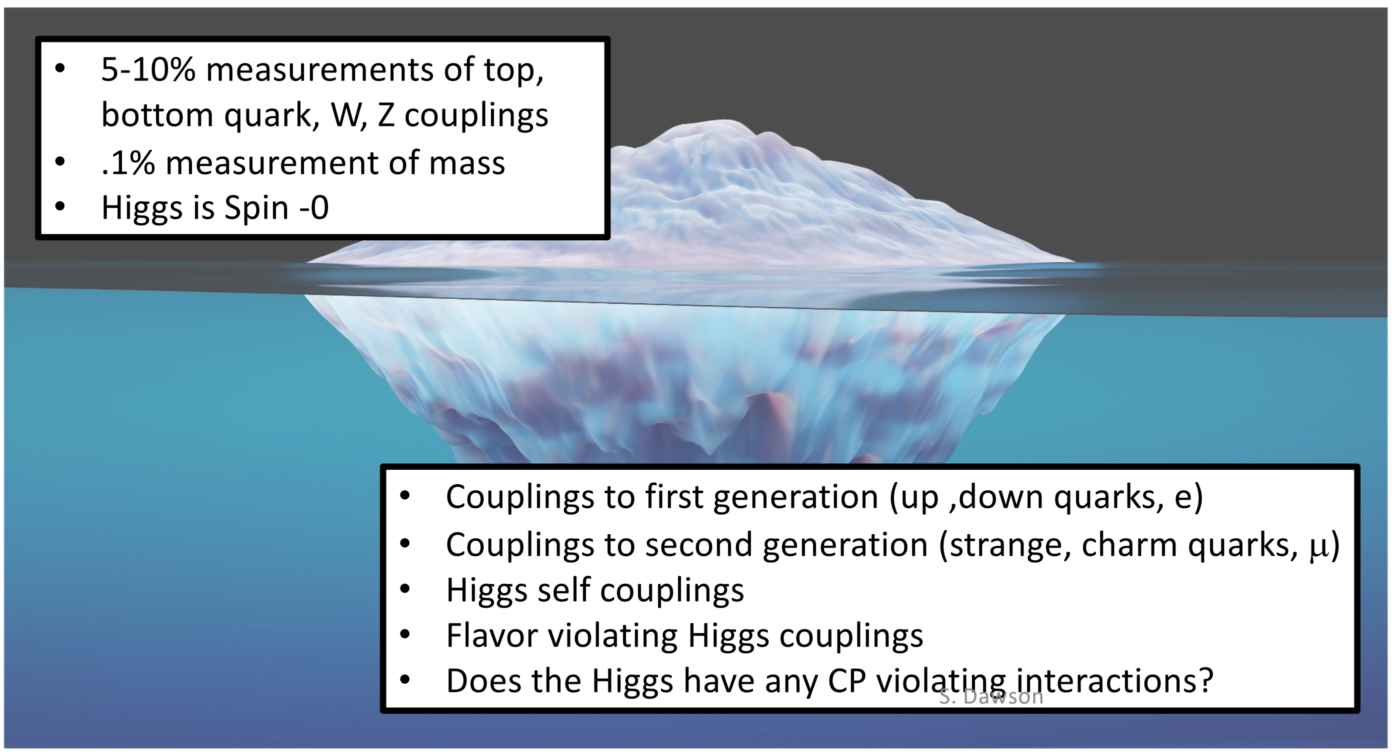
Bands are uncertainties at different orders

More work needed so that theory uncertainties do not limit understanding of Higgs measurements, despite immense theory progress



Our understanding is incomplete

- Just the tip of the iceberg with Higgs physics



The study of the Higgs is just beginning

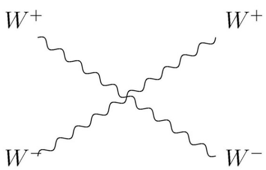
We know there must be new physics

- What is dark matter?
- Why is there a matter-antimatter asymmetry?
- What sets the pattern of fermion masses?
  - Why is the top so heavy and why are neutrinos so light?
- Why are the W and Higgs so much lighter than the Planck scale?
- Why is the Standard Model so simple with only one Higgs doublet?

Many of the possible answers to these questions involve the Higgs boson

The new paradigm

- Either M_h < 800 GeV or perturbative unitarity violated around 3 TeV



Cross sections grow with energy without Higgs

- Led to the powerful idea of a ”no-lose” theorem
- “The LHC had to find a Higgs or something else at an accessible scale”
- Today we do not know where new physics might be

Need broad searches

Lee, Quigg, and Thacker

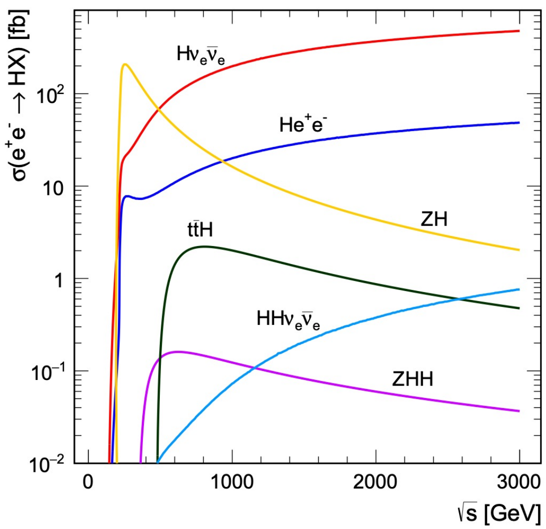
Exploring the Higgs sector

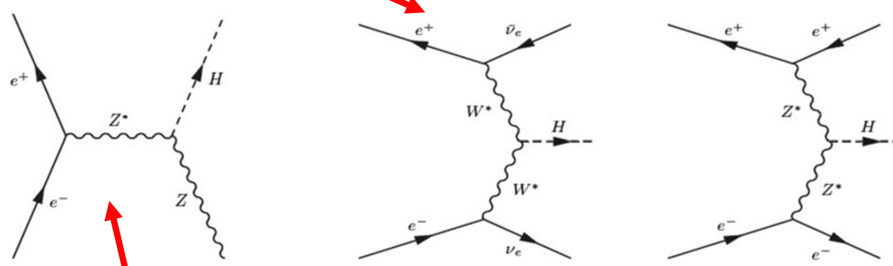
Complementary approaches

Goal: Compare Higgs properties with Standard Model predictions as accurately as possible

Lepton colliders offer new opportunities

- Running at 250 GeV enhances the Zh rate
- Running at higher energy gives access to WW→h (dominant at μ10TeV)





Very precise Higgs couplings

Opportunities Abound

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C[3] c.o.m almost similar	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm 80/0$ $\pm 80/0$ $\pm 80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Higgs factories offer many possibilities for discovery with multiple stages

- I am focusing on Higgs measurements, but these machines make many measurements and have a rich physics program
- Running at the Z pole gives extremely precise measurements of SM quantities
- WW measurements probe the structure of the SU(2) x U(1) gauge structure
- QCD program

Targets for precision

- What scales are precision measurements probing?
  - Naïve estimate for deviation from Standard Model is $\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 1.5\% \left(\frac{\Lambda}{2\ TeV}\right)^2$
- Look at some motivated models
- Add gauge singlet: $\delta\kappa < O(4\%)$
- Add extra Higgs doublet:
- Maybe the Higgs is composite?

$$\delta\kappa_t \sim -.4\% \left(\frac{2\ TeV}{M_A}\right)^2 \cot^2\beta$$

$$\delta\kappa_b \sim .4\% \left(\frac{2\ TeV}{M_A}\right)^2$$

$$\delta\kappa_V \sim .001\% \left(\frac{2\ TeV}{M_A}\right)^4$$

$$\delta\kappa_V \sim -1\% \left(\frac{2\ TeV}{f}\right)^2$$

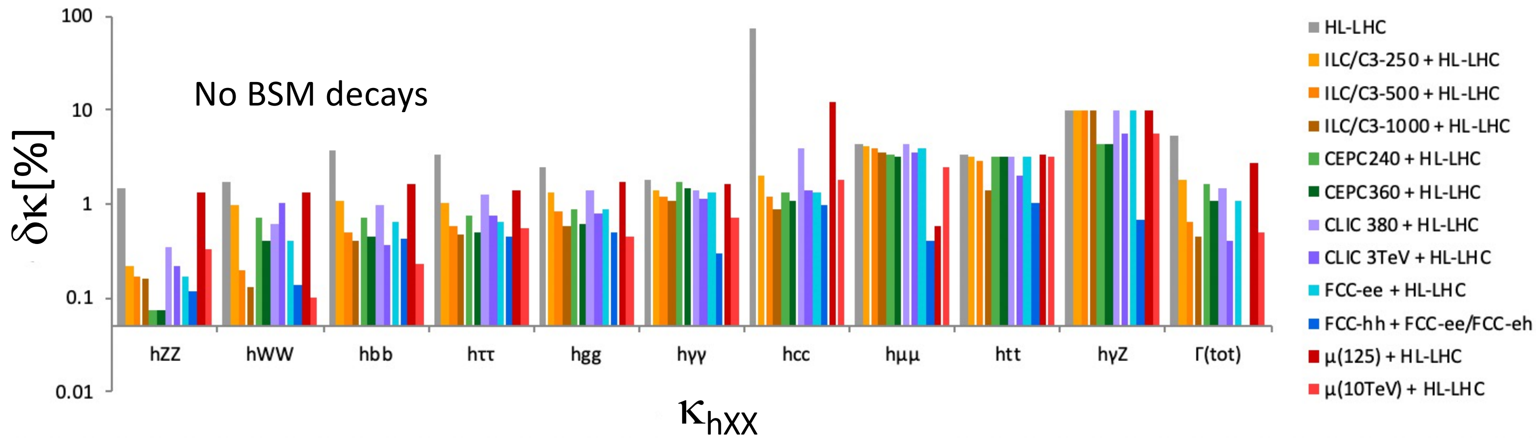
$$\delta\kappa_f \sim -2\% \left(\frac{2\ TeV}{f}\right)^2$$

These are examples where new physics arises at tree level

Look for patterns of deviations from the Standard Model

Measurements of Higgs Couplings

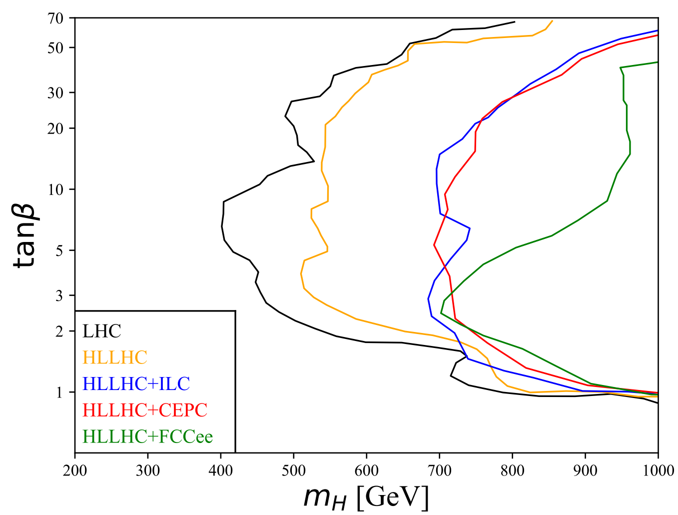
- Stringent test of Standard Model (absolute predictions)
- Sensitive to new physics at the TeV scale
- Future colliders offer opportunities to improve our knowledge significantly *(note log scale)*
  - Now (~5-10%) → HL-LHC (~2-5%) → e^+e^- (~< 1%)



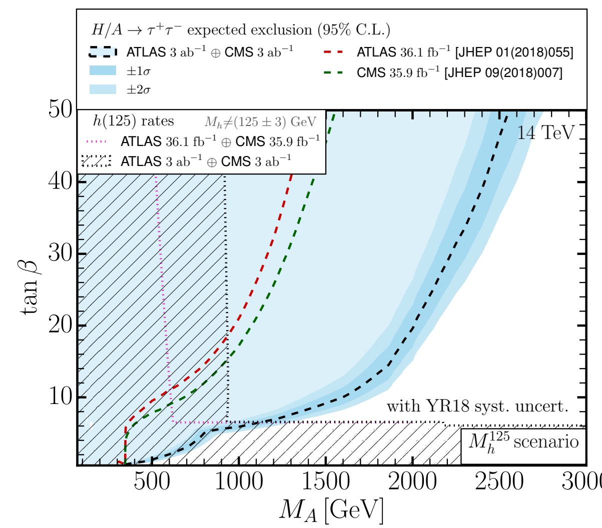
Why should there be only one Higgs boson?

- 2 Higgs doublet model: 2 neutral Higgs bosons, 1 charged and 1 pseudoscalar scalar
- Look for new Higgs bosons and measure Higgs couplings for complementary information

Higgs coupling measurements



Direct search at HL-LHC



2005.14536 , ATL-PHYS-PUB-2022-018.pdf

The Higgs potential

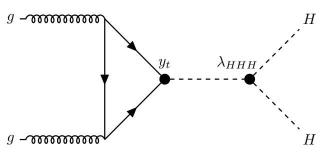
- Our understanding of the Standard Model rests on the assumption that electroweak symmetry breaking occurs through a scalar potential
- NO experimental evidence that this is the case!

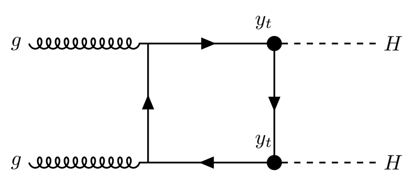
$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

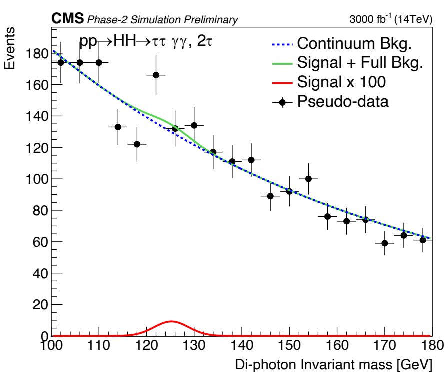
Probe through triple Higgs production

Probe through double Higgs production or through loop corrections to single Higgs production

Double Higgs Production



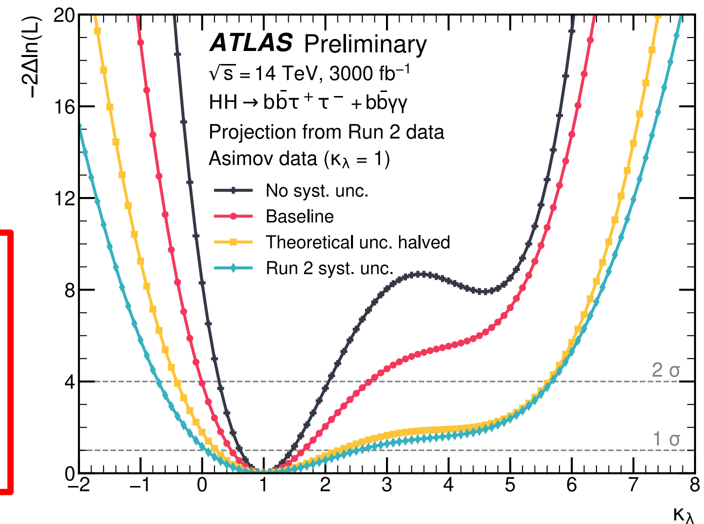




[CMS-PAS-FTR-21-003](CMS-PAS-FTR-21-003)

- Lots of progress
- Current Run-2 results exceed projections
- Hope for 5σ HH with 3 ab^{-1}

For Snowmass, CMS updated γγbb, added γγWW, γγττ, ttHH



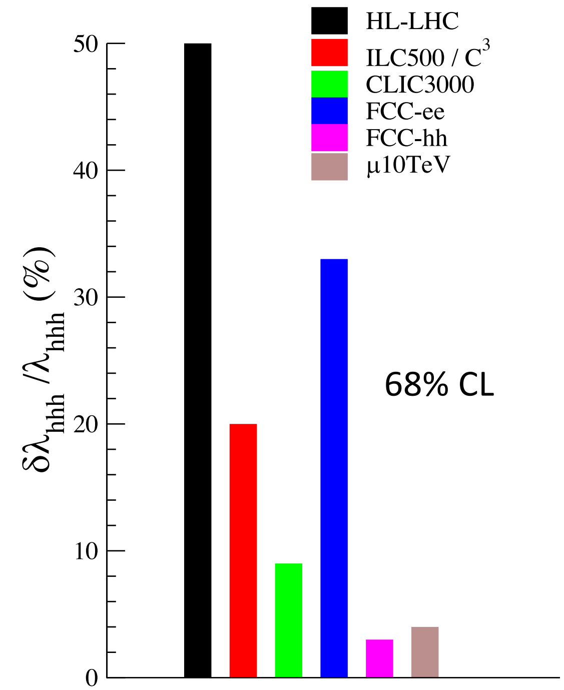
3.2σ with systematic uncertainty

ATLAS-2022-005

The Higgs potential

- Rate for hh production depends on hhh coupling and tests our understanding of electroweak symmetry breaking
  - ***(absolute prediction of Standard Model)***
- Extremely sensitive to new resonances that couple to Standard Model Higgs boson and can be significantly enhanced in BSM models

> - Full run of HL-LHC gets 50% measurement
> - FCC-hh or μ collider, needed for ~ 5% precision measurement of Standard Model Higgs self coupling

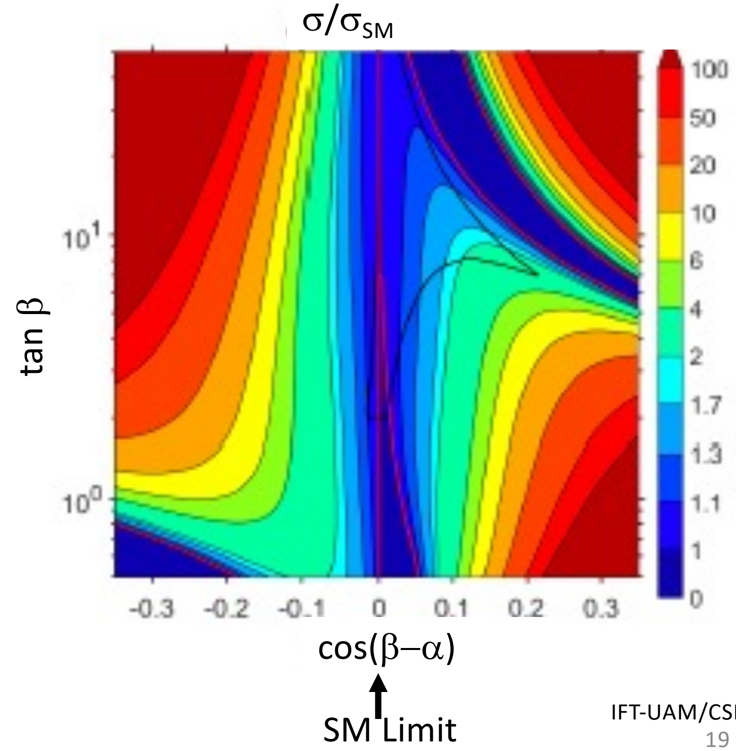


Double Higgs production and new physics

- Double Higgs production can be significantly enhanced in models with new physics
- Can be new resonant effects in double Higgs production

Proposed future colliders sensitive to this enhancement of hh rate

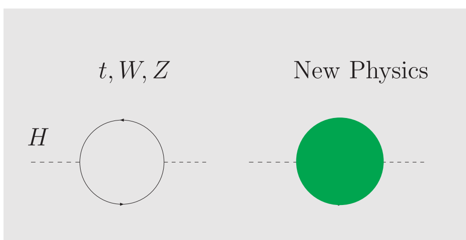
Enhancement of hh production in Type-1 2HDM Model



IFT-UAM/CSIC-22-073

New physics in the Higgs sector?

- Naturalness argument still relevant
  - Light fundamental scalars raise theoretical issues
- Quantum corrections to scalar masses sensitive to high scale physics



$$\Delta M_H^2 \sim M_{NEW}^2$$

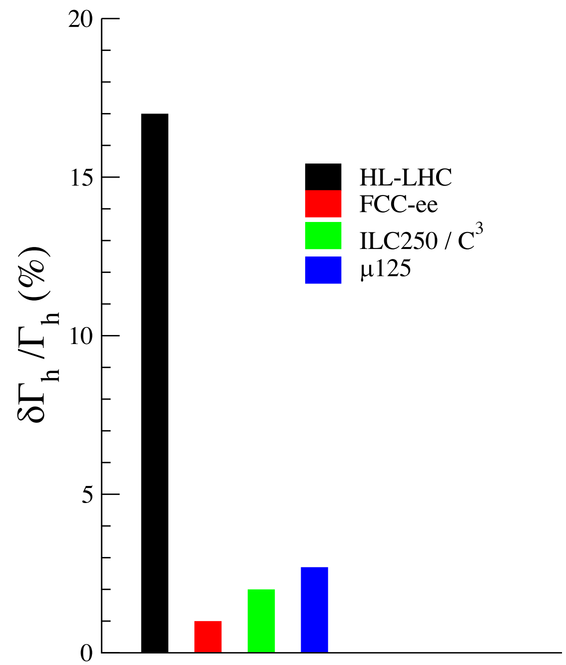
New physics that solves naturalness problem interacts with Higgs

(Physical mass)^2 ~ (bare mass)^2 +(M_{NEW})^2
Light scalars ➡ Fine tuning

These new particles would change the Higgs width

Why does the Higgs width matter?

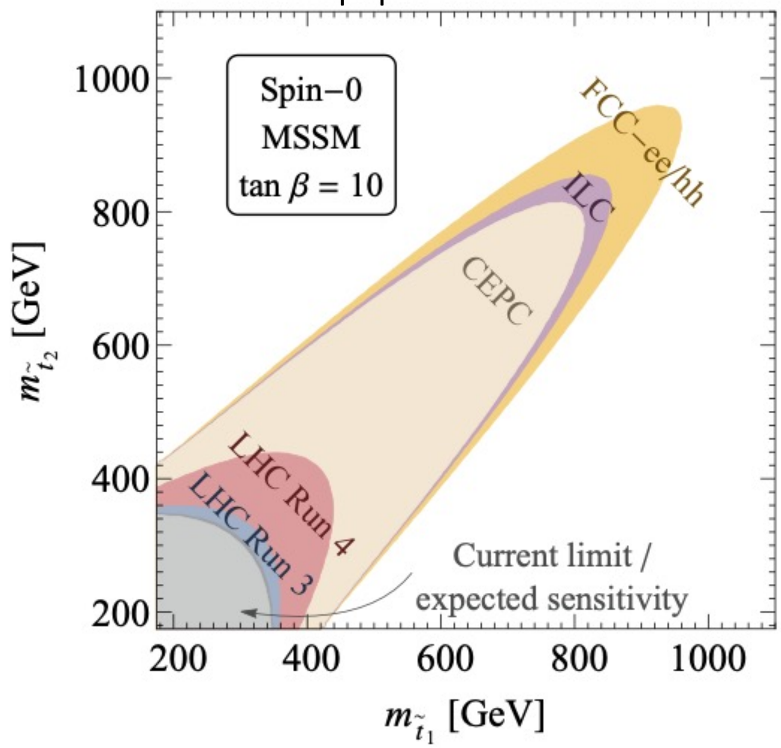
- In the Standard Model the Higgs width is very small (4 MeV) and accurately predicted
- The Higgs width is sensitive to new particles that enter in loops
  - (particles that may be motivated by solving the naturalness problem)
- Future lepton colliders give extremely precise and model independent measurements of width



Why does the Higgs width matter?

- Width is sensitive to new particles occurring in loops
- These particles also change Higgs couplings
- Future lepton colliders extend HL-LHC reach

Sensitivity to Scalar partners of top quark in MSSM



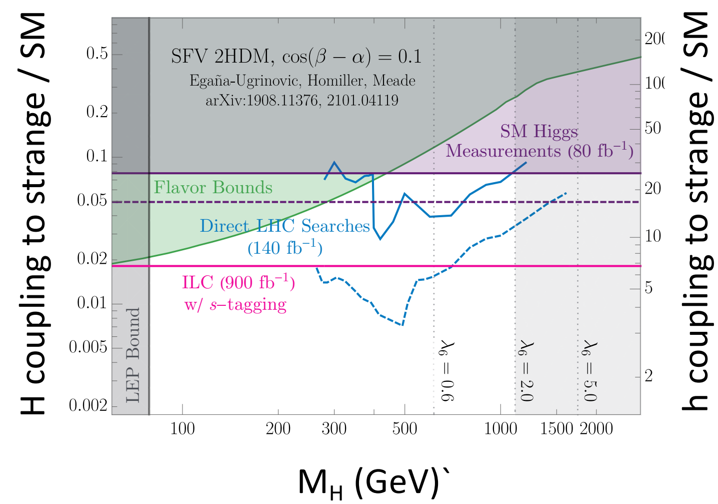
1707.03399

Higgs and flavor

- B decays suggest maybe something new with flavor?
- In the Standard Model all Higgs couplings are flavor diagonal.
  - ***Why?*** This doesn't have to be the case in more complicated models
  - Easy to construct 2 Higgs doublet models with flavor violation in the Higgs sector that is allowed by all current data

*Advances in strange quark tagging at ILC

Higgs coupling to strange quarks in flavor violating 2HDM

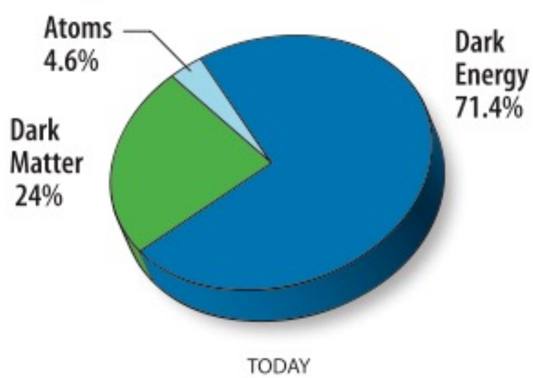


HI-LHC and future e+e- colliders probe flavor violation in Higgs sector

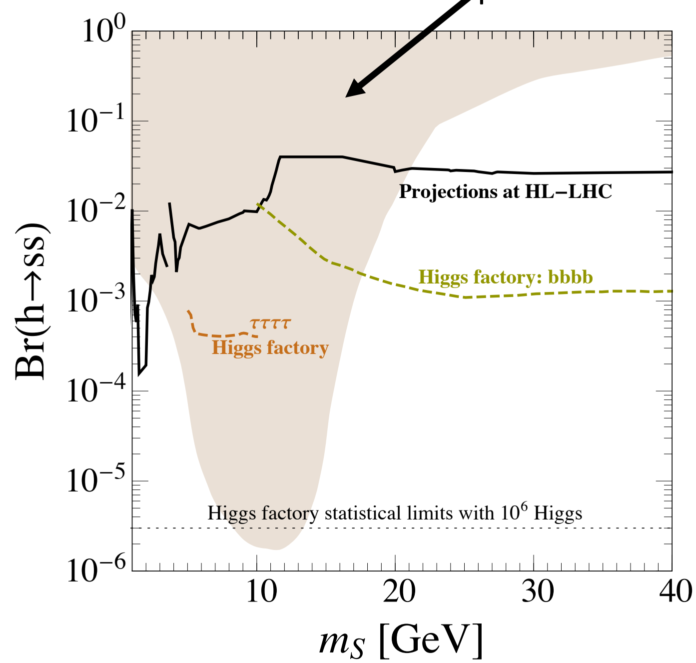
2203.07535

Higgs can be a portal to dark matter

- Simple model: Higgs couples to light dark matter scalar, S
- Can explain baryon- antibaryon asymmetry of the universe
- Changes Higgs couplings to SM particles



Region with 1st order electroweak phase transition



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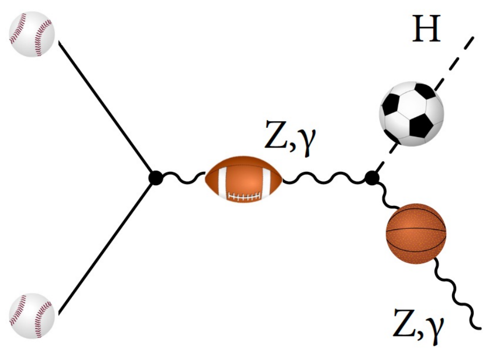
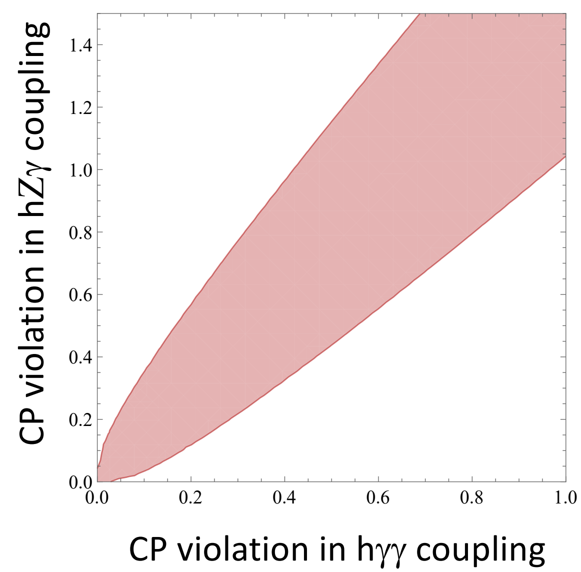
CP violation

- What is the source of CP violation?
- Is there (small) CP violation in the Higgs sector?
  - Collider measurements of fermion –Higgs CP violation
- Complementary information from colliders and EDMs on CP violation in ZZh, Zγh, γγh interactions



CP violating Higgs observables in EDMS



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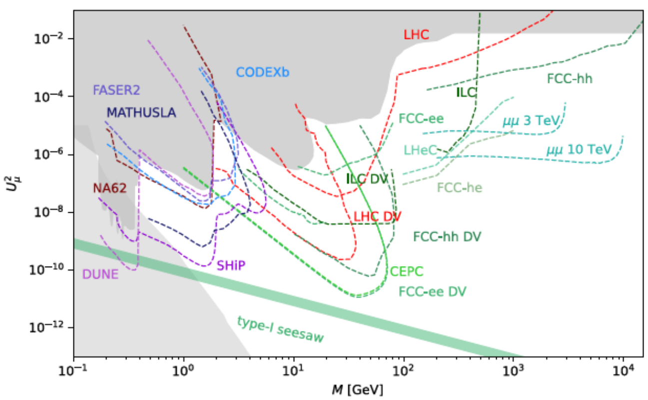
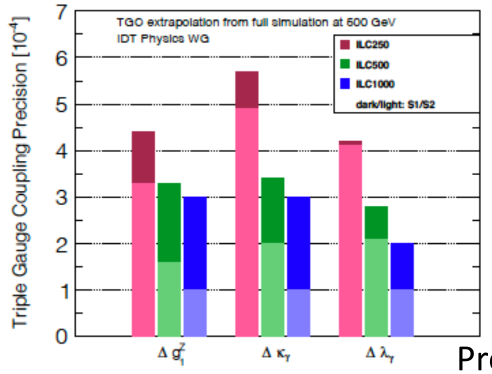
Rich EW program beyond Higgs in e^+e^- machines

Search for new physics: Heavy neutral leptons

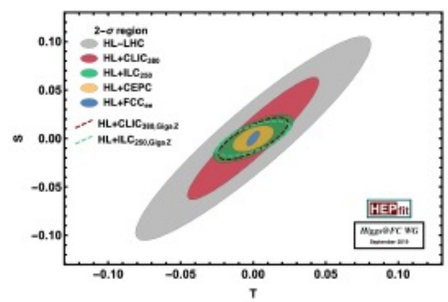


Measurements of anomalous gauge boson couplings



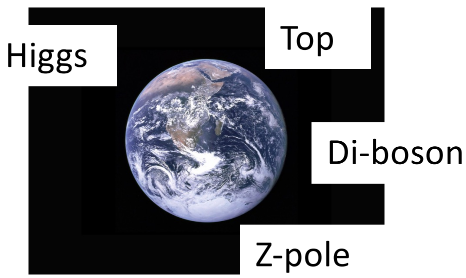
Plus much more…

Precision measurements of SM quantities

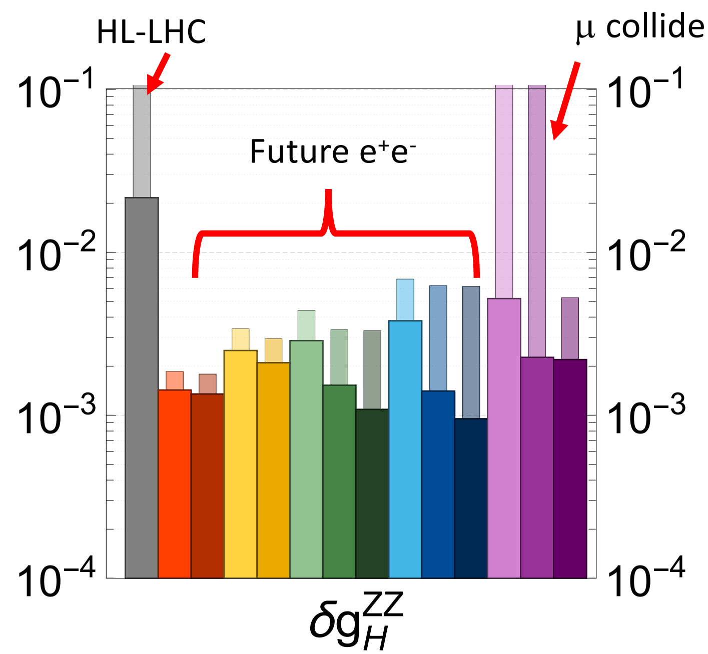


Connecting the Higgs

- Current data suggests the Standard Model is an excellent low energy effective field theory



- Effective field theory framework connects physics in different sectors
  - HL-LHC top quark measurements are connected to Higgs measurements
    - Probes Yukawa structure of SM
  - Future Z-pole and di-boson measurements connected to Higgs measurements
    - Probes gauge structure of SM



A lot of WHY????

- Tests of the Standard Model at the % level achievable
- The future precision Higgs program can address many of the fundamental questions of particle physics
  - Is there an extended Higgs sector?
  - Does the Higgs really come from the simple potential of the Standard Model?
  - Why is there dark matter and a baryon-antibaryon asymmetry?
  - Is there CP violation in the Higgs sector?
  - Why is the weak scale so much lighter than the Plank scale?
  - What about flavor?

Answers to these questions are likely to be found in the future precision Higgs program

Energy Frontier Vision

- ***The physics case for further exploring the Higgs and electroweak sectors is compelling!***
  - The full run of the HL-LHC will make major advances in our knowledge of the Higgs
  - The next step in understanding electroweak symmetry breaking will come from future e^+e^- machines with significant gains in precision
  - Many groundbreaking measurements, searches, discoveries
  - A path with countless physics results, opportunities for students
- Following an e^+e^- machine, the EF endorses R&D toward a high energy μ collider or 100 TeV pp Collider
  - Discoveries at a Higgs factory will inform the path forward