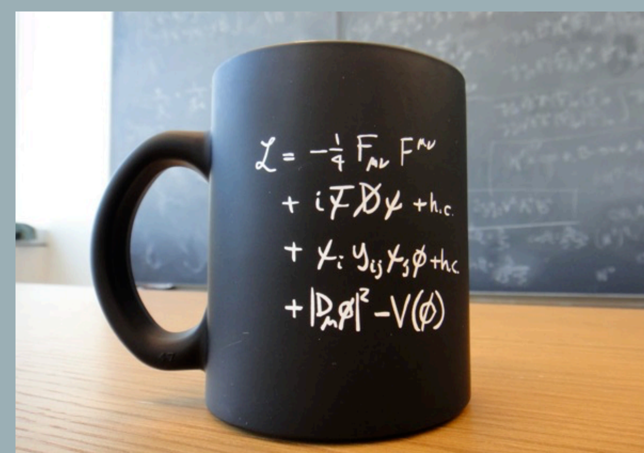
THE SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

S. Dawson, BNL

DIS, 2021



PREDICTIONS.....

Physics in 2006

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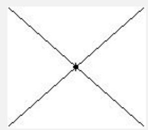
Abstract. Any consideration of future physics facilities must be made in the context of the Tevatron and the LHC. I discuss some examples of physics results which could emerge from these machines and the resulting questions which would remain for a high energy e^+e^- collider. Particular attention is paid to the electroweak symmetry breaking sector. If a light Higgs boson exists, it will be observed at the LHC and the role of any later accelerator will be to map out the Higg's boson mass and couplings and then determine the space of possible models. If there is no light Higgs boson then some effects of a strongly interacting electroweak symmetry breaking sector will be observed at the LHC and I discuss the role of a high energy linear collider in exploring this scenario.

The future is unclear….

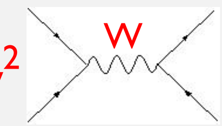
*In 2006 I thought we were going to measure everything possible about the Higgs or observe strongly interacting WW scattering

HISTORY: PREDICTING THE SCALE OF NEW PHYSICS

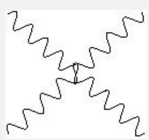
- Fermi theory becomes non-perturbative at E ~ 600 GeV
- W boson saves the day



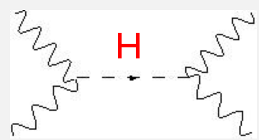
$G_F E^2 \rightarrow G_F M_W^2$



- WW scattering grows with energy and violates unitarity at E ~ 3 TeV
  - Higgs boson < 800 GeV restores unitarity



$E^2/v^2 \rightarrow O(1)$



NO LOSE THEOREMS

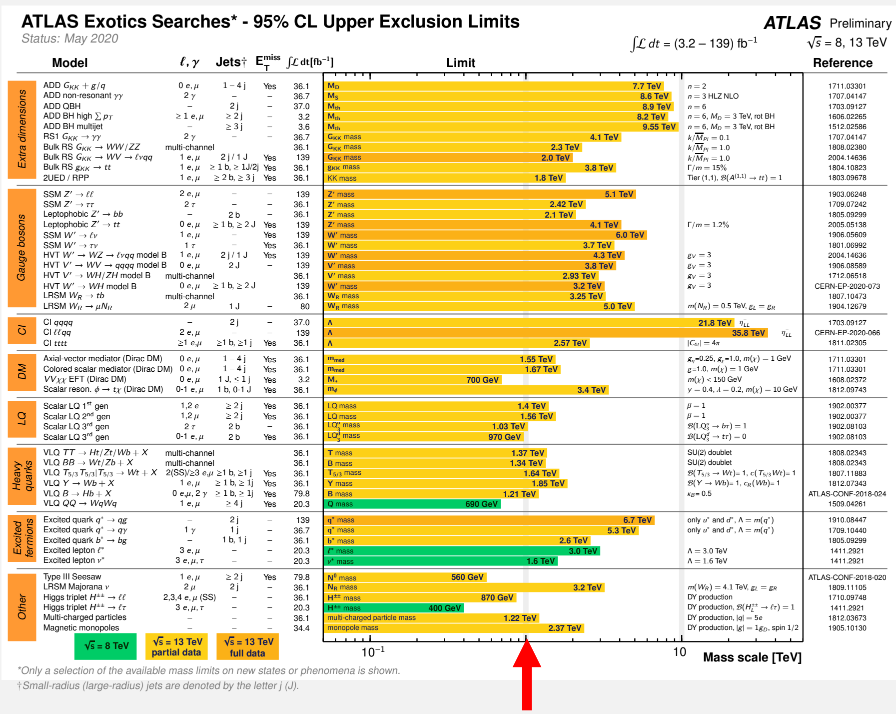
THE NEW PARADIGM

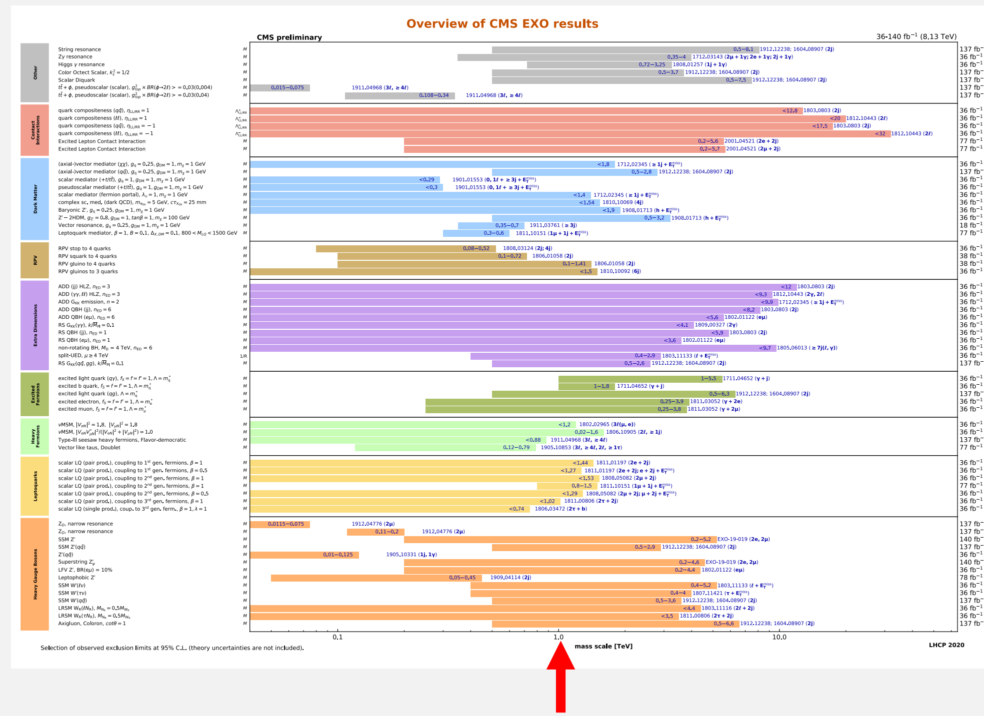
- Past: Guaranteed discoveries ensured by no-lose theorems
  - Beyond the Fermi theory (the W)
  - Beyond the bottom quark (the top)
  - Beyond the electroweak theory (the Higgs)
    - Scattering amplitudes grow with energy without W, top, Higgs….
    - Knew the scale of new physics

Future : No guarantees, need to examine many possibilities

Look for new physics in many places

CURRENT LIMITS IN THE 1-10 TEV RANGE

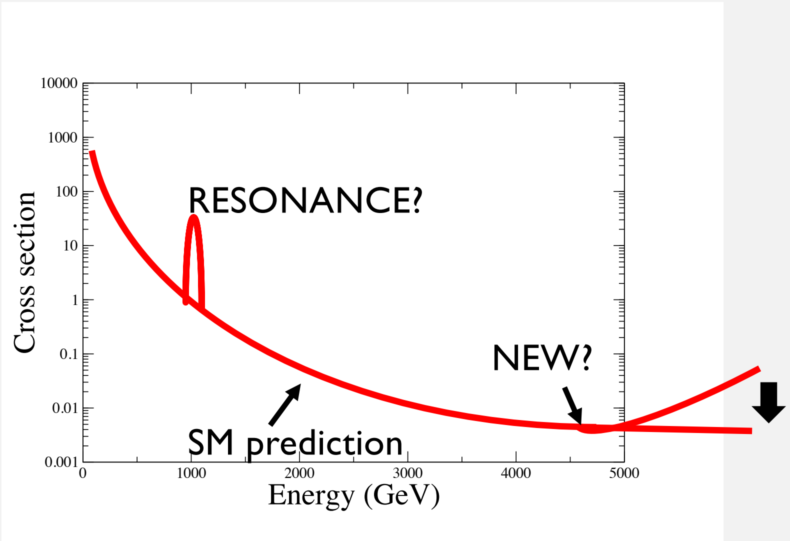




****But we don't really have a target mass****

NO SIGN OF ANY NEW PARTICLES

- No shortage of models predicting more particles
  - But no evidence yet….
- Look for new physics in tails of distributions
  - Requires precision calculations of SM predictions for comparison
  - This is much harder than looking for resonances



NEW PHYSICS AT HIGH SCALES: NO NO LOSE THEOREM

Use effective field theory: precision calculations

NO?

Can we determine source of new physics from EFT?

Is there a light (weak scale) resonance?

YES?

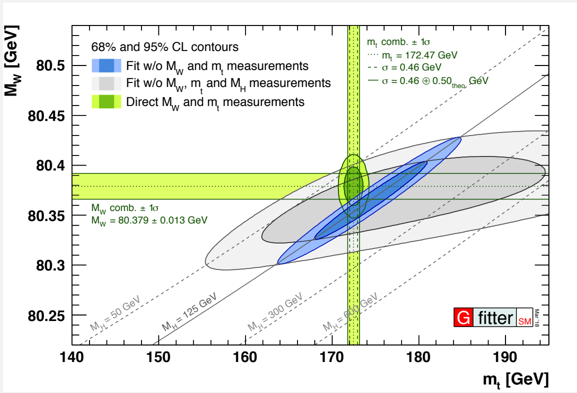
Current limits will be strengthened at HL-LHC

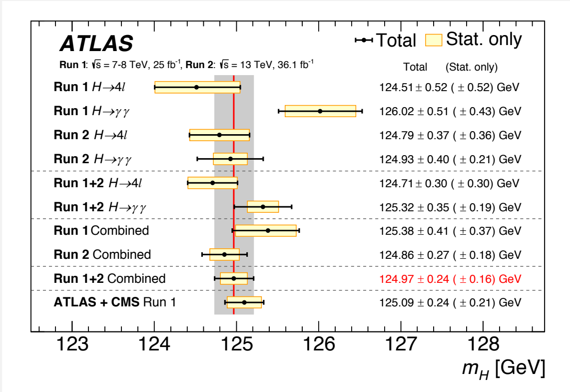
Find resonance!

At high scales this is a well defined program

PRECISION CONSTRAINS NEW PHYSICS

- Use precision measurements to constrain BSM physics (long history starting with LEP and SLD)
- Higgs mass is precision observable

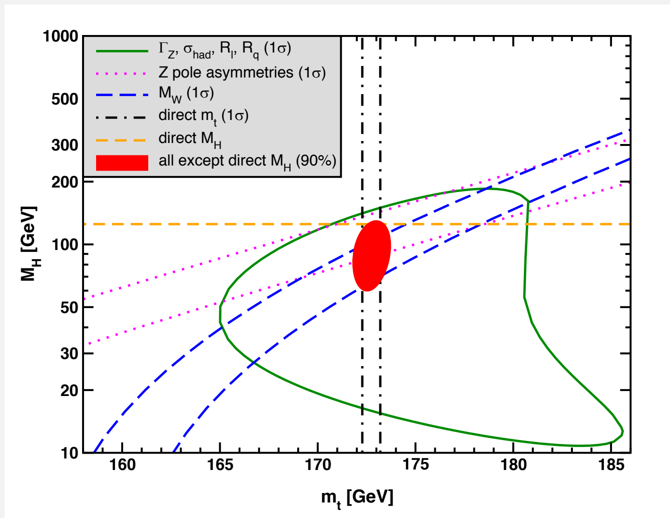




SM predicts relationship between M_t, M_W, and M_H

At the loop level

M_H FROM INDIRECT MEASUREMENTS

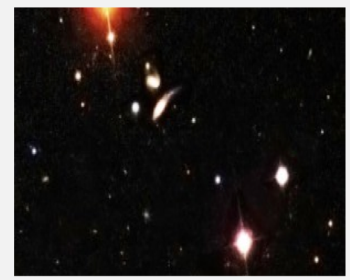


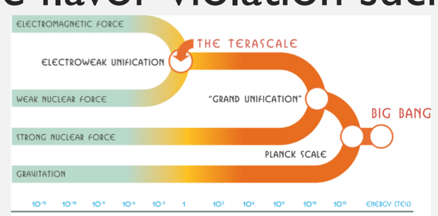
1908.07327

Consistent picture, but room for new physics

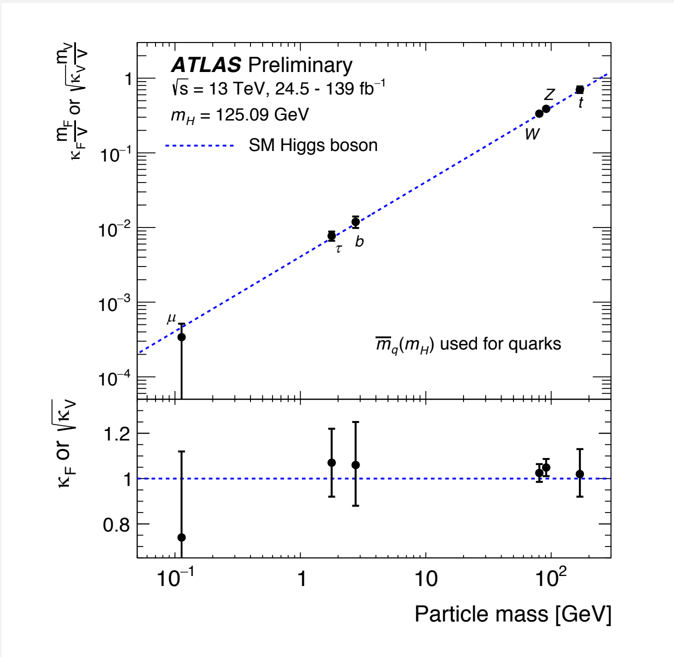
WHY MIGHT NEW PHYSICS HIDE IN HIGGS SECTOR?

- Many *unanswered questions*: dark matter, the pattern of fermion masses (including neutrinos), baryogenesis, strong CP violation, EW hierarchy….
- Why does the SM only have one Higgs doublet?
  - No good answer to this question
- Higgs can be portal to dark matter
  - Motivates models with extra Higgs gauge singlet
- Higgs models can be constructed to have flavor violation such as $H \rightarrow \mu e$
  - Motivates 2HDM type models





FROM DISCOVERY TO PRECISION MEASUREMENTS



- Higgs couplings to fermions and gauge bosons *fixed in SM*
- What if we allowed couplings to deviate by constant rescaling?
- SM is excellent approximation of Higgs sector

FIRST STEP TO HIGGS COUPLINGS: κ APPROACH

- κ_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)
  - Simple rescaling; no momentum dependence
  - Gauge invariance of SM requires κ=1
- Assuming loops resolved and no BSM:

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl

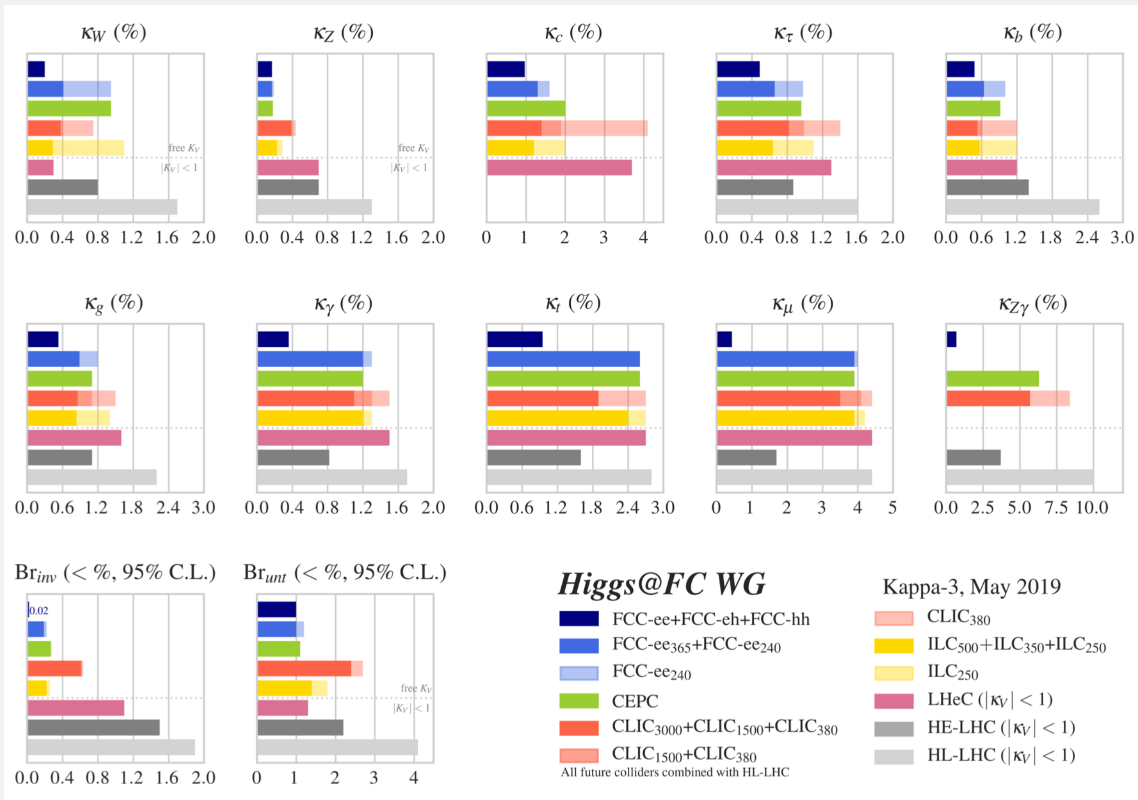
- Couplings to gauge bosons at 8-12%
- Couplings to 3rd generation fermions at 15-20%

We are just getting to the interesting regime: Generically expect deviations

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 6\% \left(\frac{1000\ TeV}{\Lambda}\right)^2$$

CMS, arXiv:1809.10733
ATLAS, ATLAS-CONF-2019-005

PROJECTIONS

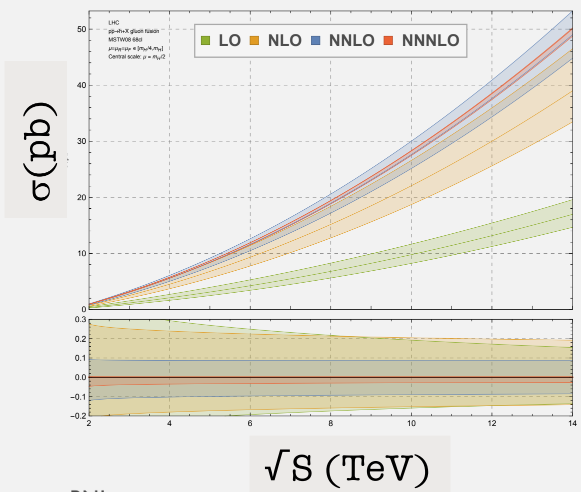


Possibilities for couplings at the % level

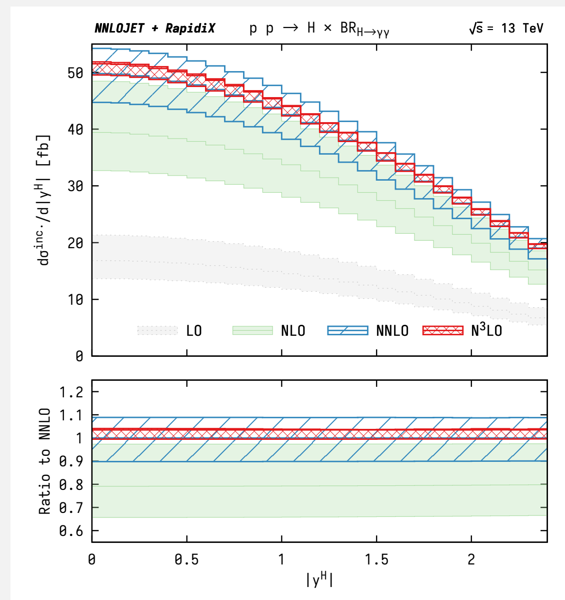
arxiv:1905.03764

CAN WE CALCULATE LHC HIGGS PROCESSES TO ~5% ACCURACY?

- Dominant Higgs production mechanism is gluon fusion
- Higgs production from gluon fusion known at N^{3}LO



[1503.06056](1503.06056)



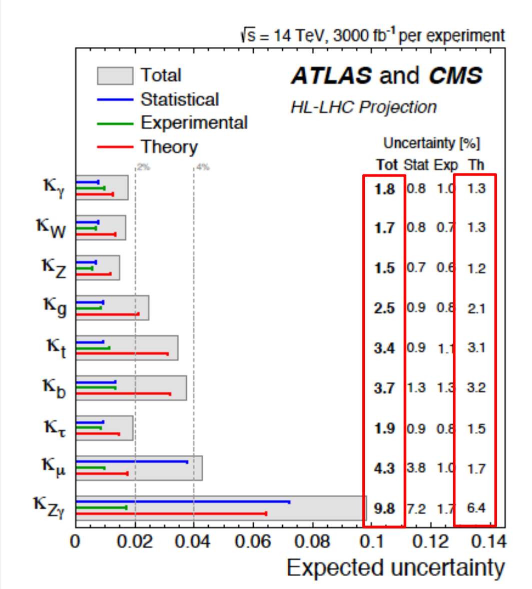
[2102.07607](2102.07607)

THEORY ERRORS DOMINATE EXPERIMENTAL EXTRACTIONS OF HIGGS PARAMETERS

ATLAS, Global Higgs signal strength

Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

FUTURE



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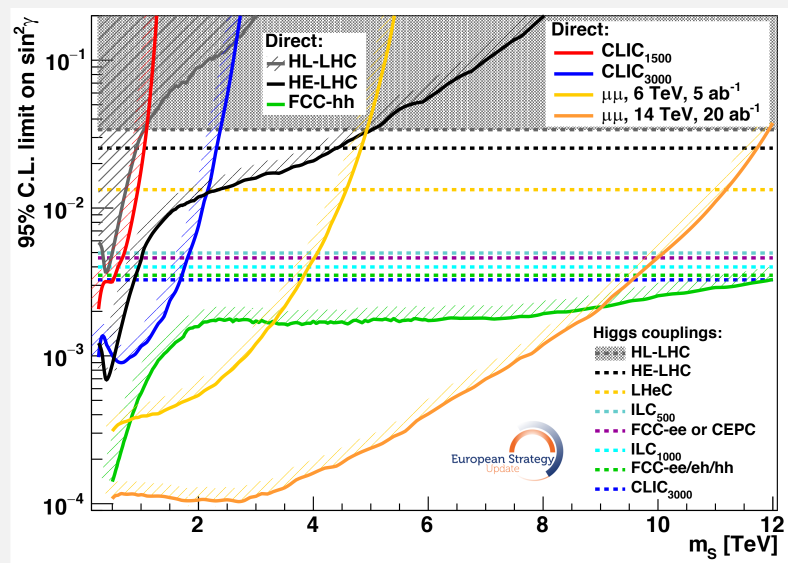
Lots of theoretical work needed!

HOW HIGH IN SCALE CAN WE GO?

- No evidence for any TeV scale resonance
- Theorists are being increasingly clever at devising scenarios that evade limits
- Precision calculations ever more precise
- Strategy: Look for new physics in precision Higgs measurements: *COMPLEMENTARITY OF APPROACHES*

Model with heavy scalar singlet



European Strategy Report

HIGGS SELF COUPLINGS COMPLETELY UNKNOWN

- We know that the Higgs couples to fermions and gauge bosons at the 10-20% accuracy level
- We postulate that the Higgs interactions come from a scalar potential:

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- The potential could just as easily be an effective theory:

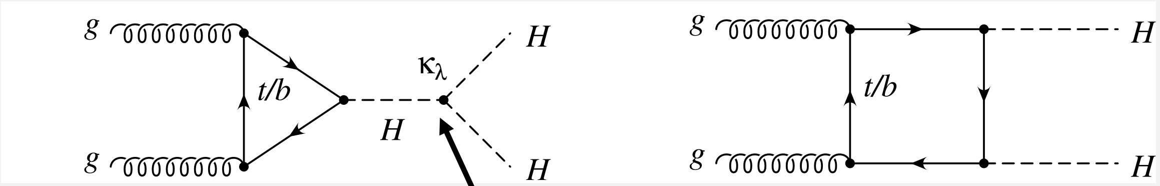
$$V \to -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

$\boxed{\text{We have few handles on measuring } \lambda_4}$

Must measure $\lambda_3 = \frac{M_H^2}{2v} = .13v$

HH PRODUCTION

- HH first occurs at one-loop



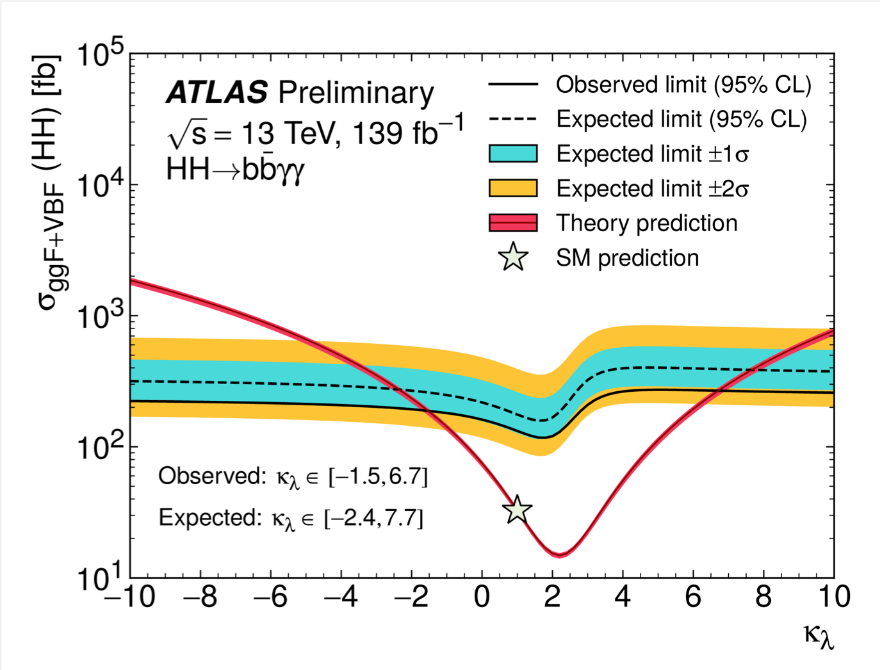
Goal: Measure $\lambda/\lambda_{SM}=\kappa_\lambda$

- Large cancellation between diagrams
- Very small rate at LHC

Measurement of Higgs tri-linear coupling necessary to confirm structure of Higgs potential

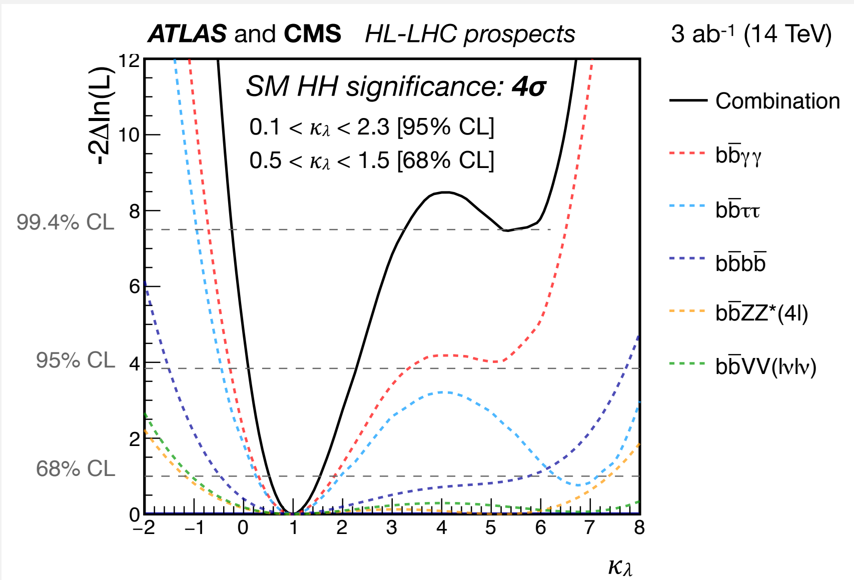
The next big thing…..

CURRENT STATUS OF HH SEARCHES: RESULTS WITH 137 FB^{-1}



- This search is sensitive to models with heavy neutral scalars and is a sensitive probe of new physics

HIGGS TRI-LINEAR COUPLING IN THE FUTURE



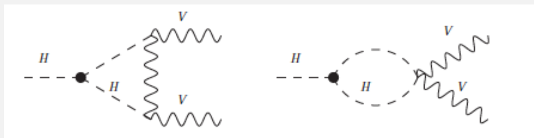
Collider	Accuracy on κ_λ	Running Years
HL-LHC	50%	12
HE-LHC	10-20%	20
ILC(500)	27%	21
CLIC(1500)	36%	15
CLIC(3000)	+11%, -7%	23
FCC(hh)	5%	13

Difficult measurement at all colliders!

[arxiv.1902.00134.pdf](), [arxiv:1905.03764]()

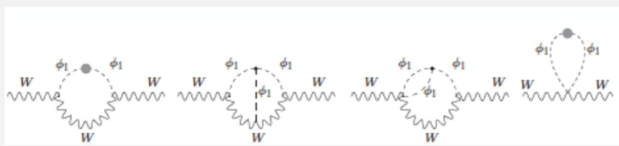
COMPLEMENTARITY WITH PRECISION MEASUREMENTS

- Indirect constraints on HHH coupling from Higgs coupling measurements



+ …

- Indirect constraints from precision observables such as M_W



- Combining HH searches with indirect constraints gives limit

$$\boxed{-1.8 < \lambda/\lambda_{SM} < 9.2}$$

2102.07651

*This before new bbγγ limit

NO RESONANCES?
ASSUME A HIERARCHY OF SCALES

$\Lambda >> M_W$ where complete theory exists

- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed

M_W Only SM particles in theory at low scales

SCALES

- High scale, Λ: Complete model with unknown heavy states
  - Integrate out heavy particles to get non-renormalizable effective Lagrangian
  - Renormalization group evolve to low scales

This is sad scenario where there is no intermediate scale physics

- Weak Scale, M_W: Standard Model + remnants of high scale model
  - Described by effective field theory

MODEL INDEPENDENT PARAMETERIZATION OF NEW PHYSICS: SMEFT

- Useful to have a model independent formulation of new physics
  - SM works at the EW scale with SM-like Higgs
  - Treat SU(3) x SU(2) x U(1) as good symmetry with doublet Higgs, ϕ

$$\boxed{L = L_{SM} + \Sigma_{n=1}^{\infty} \Sigma_k \frac{c_{n,k}}{\Lambda^n} O_{n,k}}$$

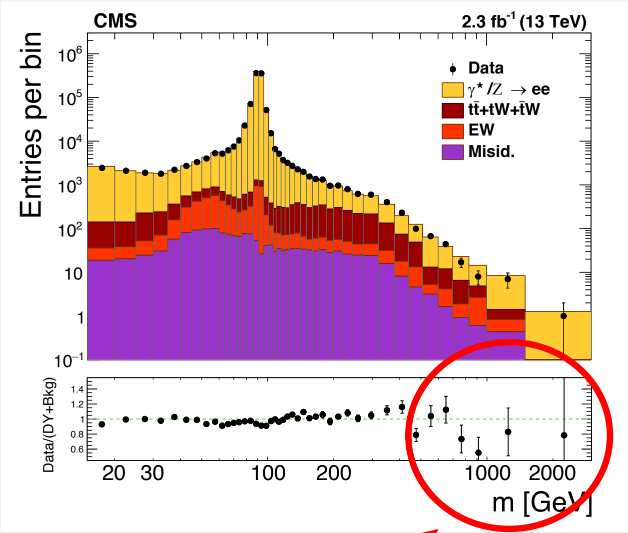
  - $O_{n,k}$: Gauge invariant 4+n dimensional operators constructed from SM fields
  - All BSM effects in coefficients, $c_{n,k}$
  - Allows for a systematic parameterization of deviations from SM predictions without affecting agreement with low energy measurements

DRELL-YAN

- Extremely precisely known in SM (NNLO QCD+…)
- Large number of events: potential sensitivity to SMEFT operators that contribute effects $O(p_T^2/\Lambda^2)$
- In SMEFT, tree level 4-fermion contributions (extensive literature)
- Can also be 1-loop corrections from new SMEFT operators

Look in tails of distributions

$pp \rightarrow \gamma, Z \rightarrow e^+e^-$

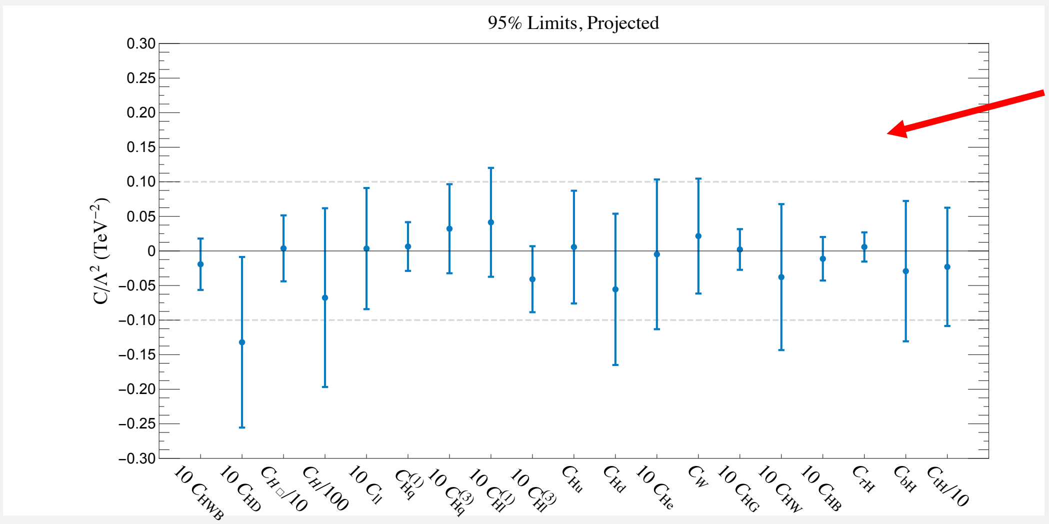


Room for new physics?

PDFs extracted from tails

LEARNING FROM SMEFT

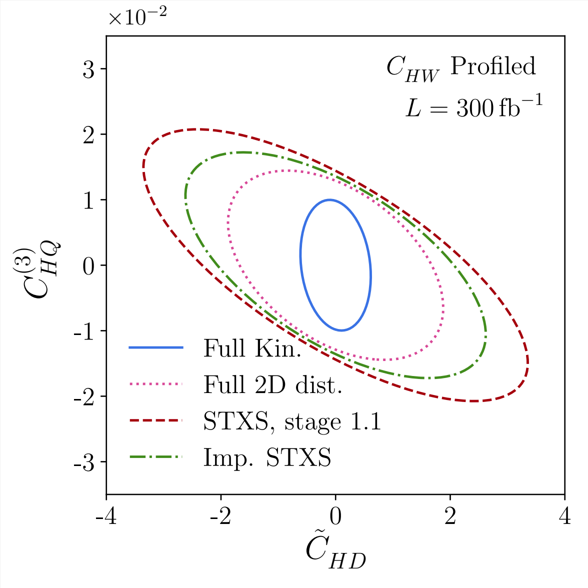
- Global fits include LEP precision data, VV production, Higgs production….
  - Effective field theory connects different processes with large correlations
  - Precision requires a complete set of operators, not just one at a time



- Includes subset of higher order corrections in fit
- No indication of new physics from this type of approach
- MANY! Independent global fits

NEW TECHNIQUES

- Machine learning to extract possible deviations from SM



- Much more precise results from full kinematics (machine learning) than from looking at distributions (STXS)
- MADMINER: automated tool

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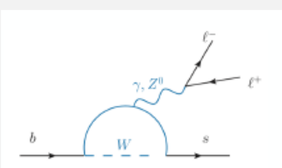
1908.06980

SEARCH IN NEW PLACES

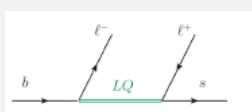
- Maybe the new physics is not apparent at high energy scales

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

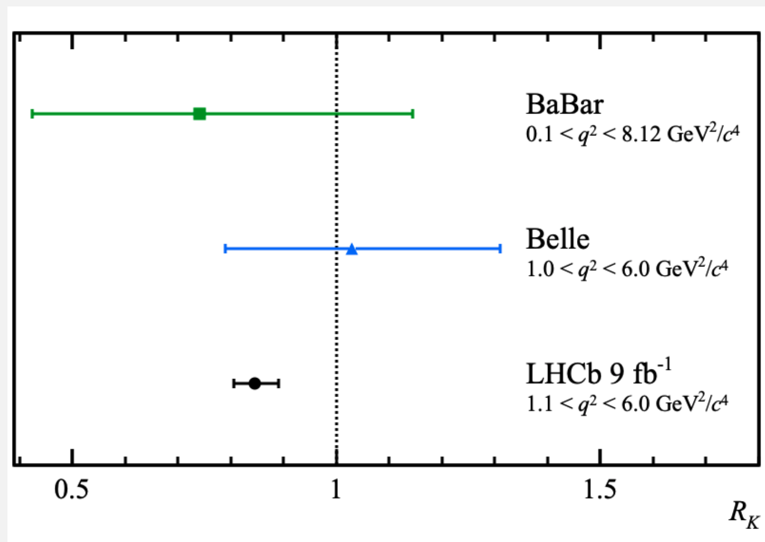
= 1 + (radiative corrections) in SM



Small CKM angles



Leptoquark?



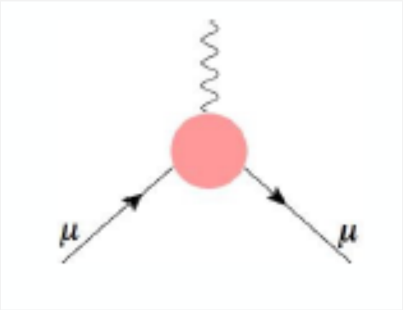
SM

Lepton flavor violation at 3.1σ?

LHCb, [2103.11769]

SEARCH IN NEW PLACES

- $(g\text{-}2)_\mu$ is now 4.2σ from SM (up from 3.7σ)
- Has inspired immense theory effort
- Can be explained with new particle contributions
- Many possibilities, many models



CONCLUSIONS

- No evidence so far for new physics at the LHC
- Need to look for new heavy resonances and tease out small effects from precision measurements
- Very hard!

Case for the existence of new physics remains strong: we just don't know where it will be!