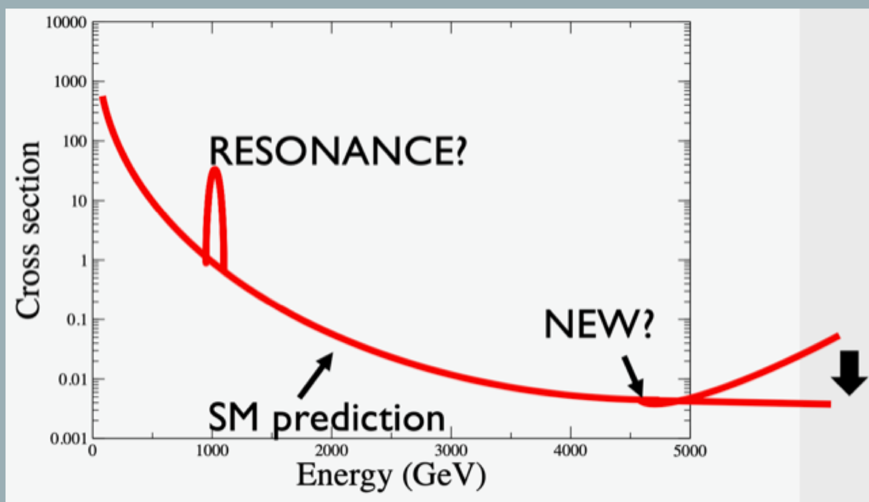
THE SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

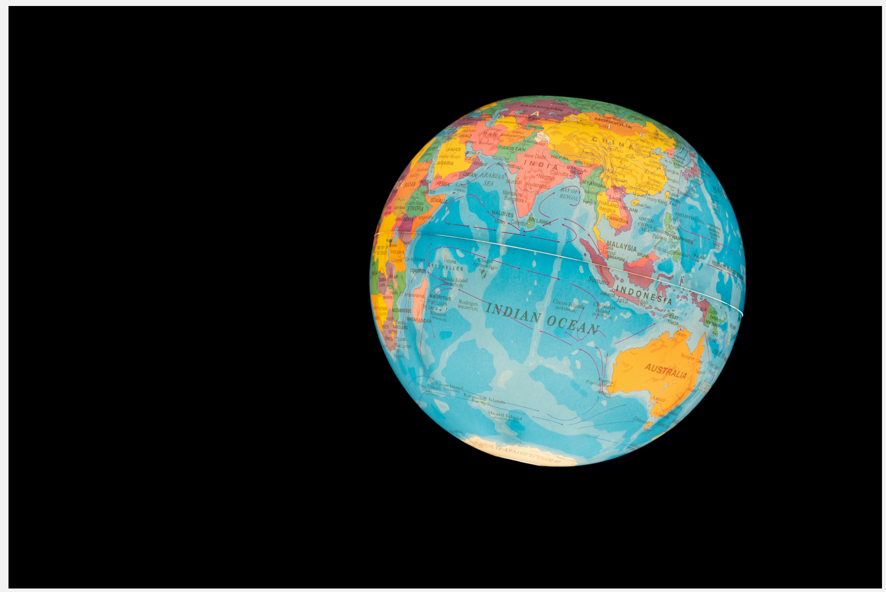


S. Dawson, BNL

DESY, 2021

THE PARTICLE PHYSICS WORLD HAS CHANGED DRAMATICALLY IN THE LAST DECADE

- The triumph of the Standard Model
- European Strategy Study and Snowmass Study inspire us to think about the future



A HIGGS PARTICLE PREDICTED IN 1964

Peter Higgs in the LHC tunnel in 2012

A LONG JOURNEY

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The idea of symmetry still guides search for new physics

FIRST STUDY OF THE HIGGS, 1976

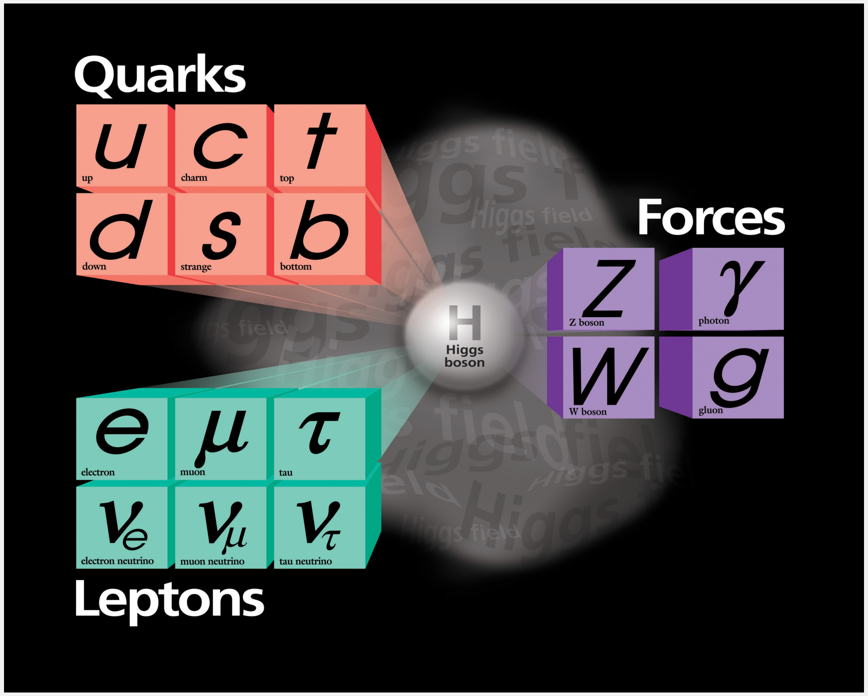
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Ellis Gaillard Nanopoulos

WHY IS THE HIGGS BOSON SO IMPORTANT?

A well understood and well defined model

Model doesn't make sense without Higgs or something like it

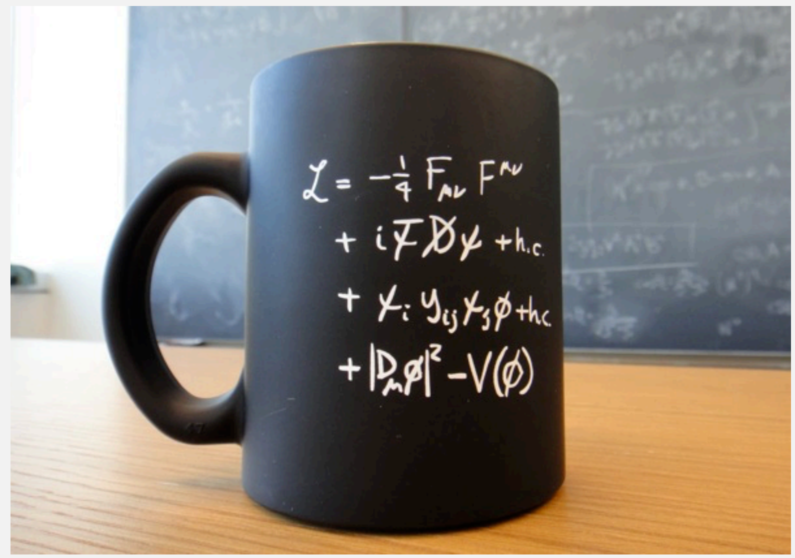


Particles that interact by exchanges of forces carried by *gauge bosons*

STANDARD MODEL

THE SM IS SIMPLE AND PREDICTIVE

- SU(3) x SU(2) x U(1)
  - Gauge interactions describe forces
- Electroweak sector described in terms of masses and 3 inputs
  - Typically G_F, α, M_Z
- Particle couplings fixed

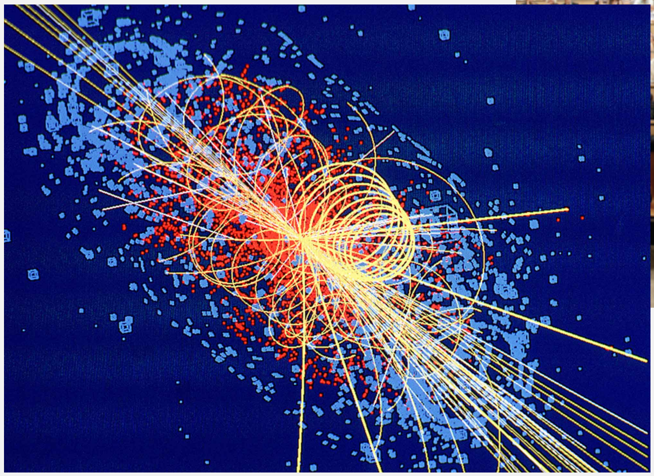


Testable model !

Only unknown parameter is Higgs mass

IN THE LAST 9 YEARS….

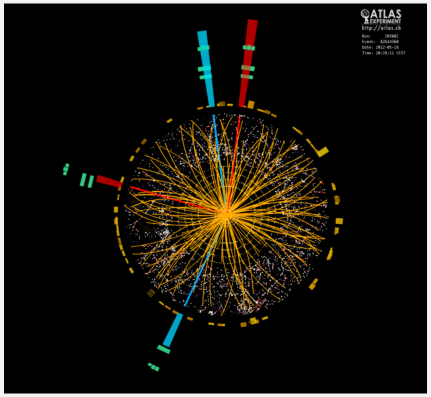
- 2012: LHC discovered a Higgs boson; it appears to have predicted properties



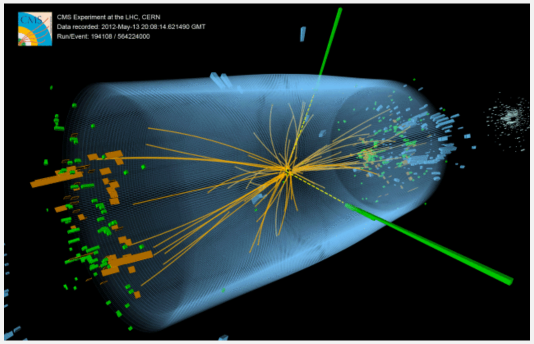
HIGGS PRODUCTION AND DECAY

- Predicted in terms of Higgs mass
- Discovery through Higgs decays to 2 photons and Higgs decays to ZZ (and subsequent decays of Z's to electrons and muons)
- Small rates, but observation signals are clean

$H \to ZZ \to e^+e^-e^+e^-$

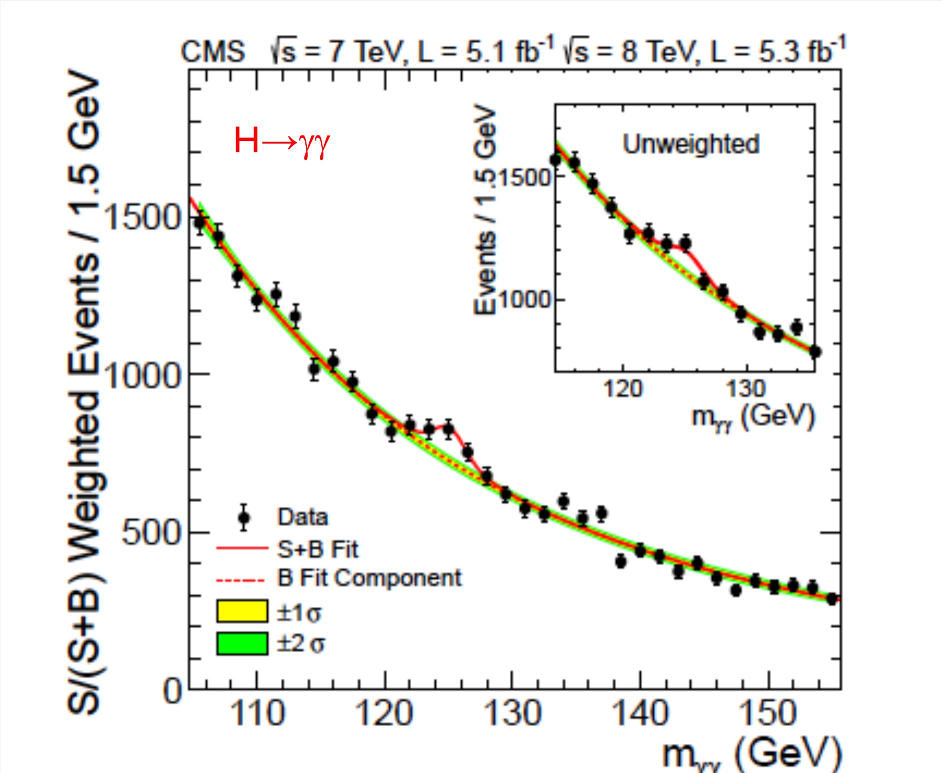


$H \to \gamma\gamma$



DISCOVERY TO PRECISION

2012



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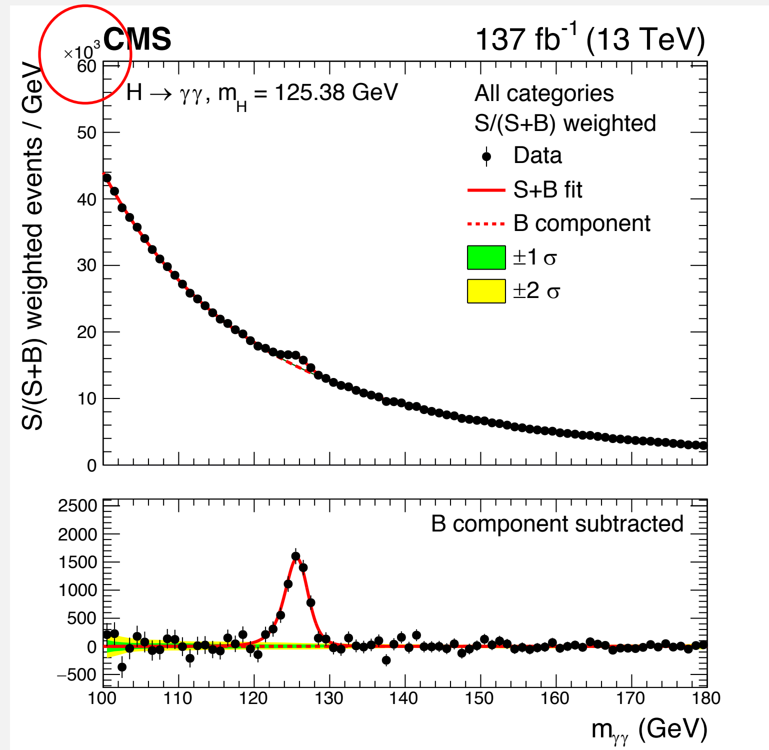
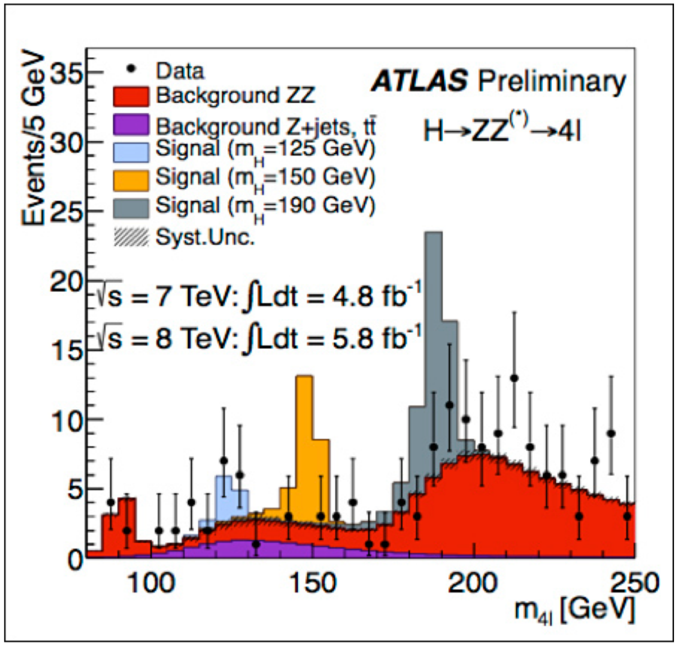
2021

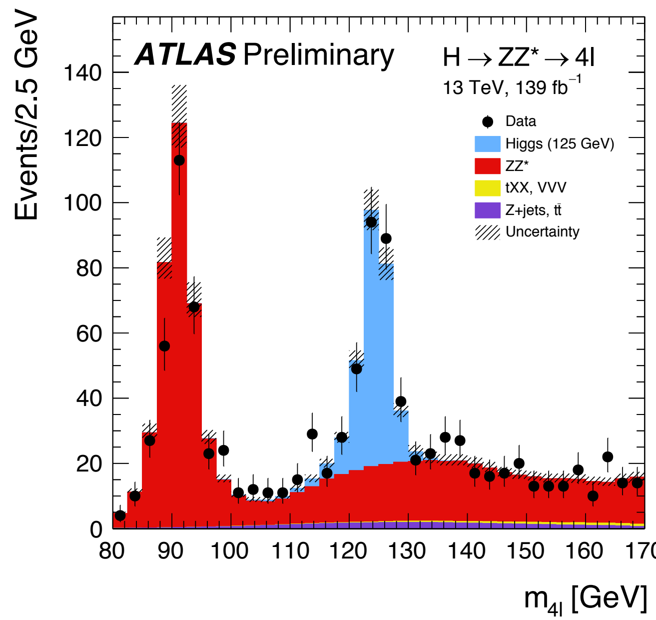


DISCOVERY TO PRECISION

2012



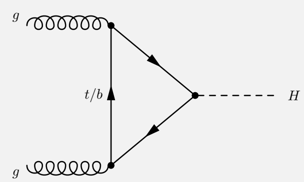
2021



More events, smaller uncertainties

MEASUREMENTS COMPARED TO EXPECTATIONS

- Dominant production of Higgs boson is gluon fusion



- Rate is power series in strong coupling constant, α_s~.118

$$\sigma(gg \to H) = \alpha_s^2 \Big(\sigma_{LO} + \alpha_s \delta\sigma_{NLO} + \alpha_s^2 \delta\sigma_{NNLO} + \alpha_s^3 \delta\sigma_{NNNLO} + \dots \Big)$$

1977 → 1995 → 2002 → 2015

THEORY CRITICAL FOR INTERPRETING DATA

- Calculation of Higgs production to NNNLO required:
  - New analytic techniques
  - New computational techniques
  - Surprisingly large corrections to gluon fusion production:

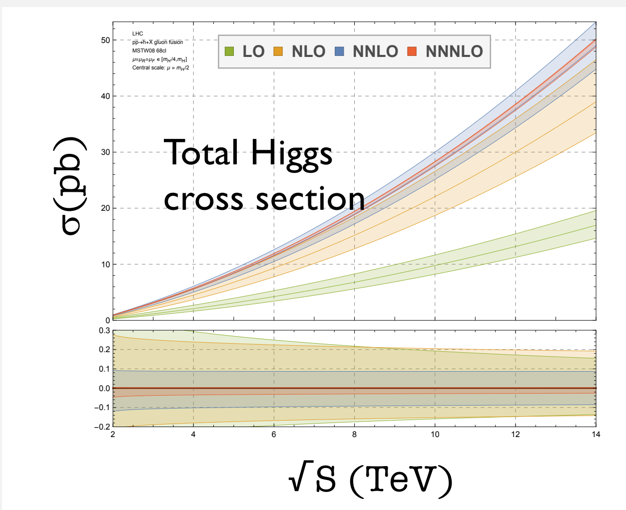
LO → NLO → NNLO → NNNLO

100% increase | 20% increase | 2% increase

1977 → 1995 → 2002 → 2015

INTERPRETING MEASUREMENTS

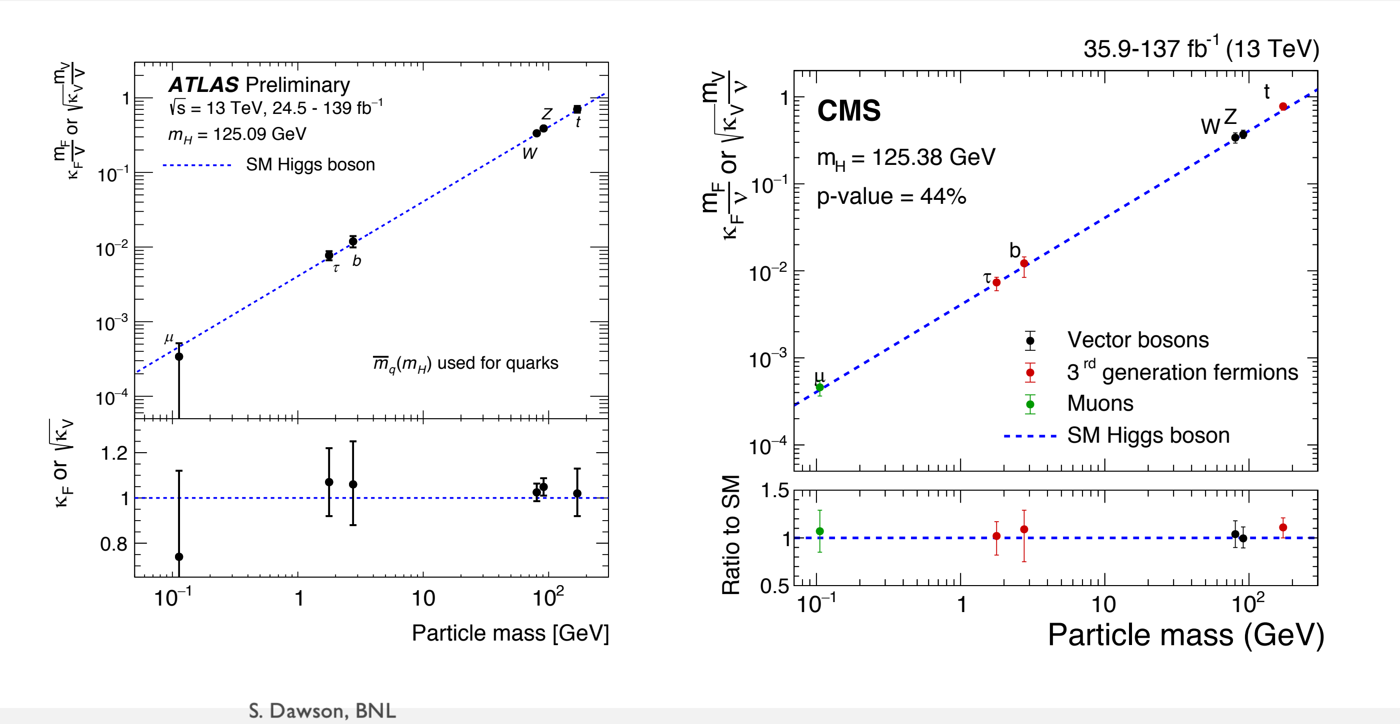
- Motivates a huge theory program of calculating Standard Model predictions
- Good convergence of calculations at high perturbative orders in strong coupling



Bands are estimates of theory uncertainties

1503.06056

FROM DISCOVERY TO PRECISION MEASUREMENTS

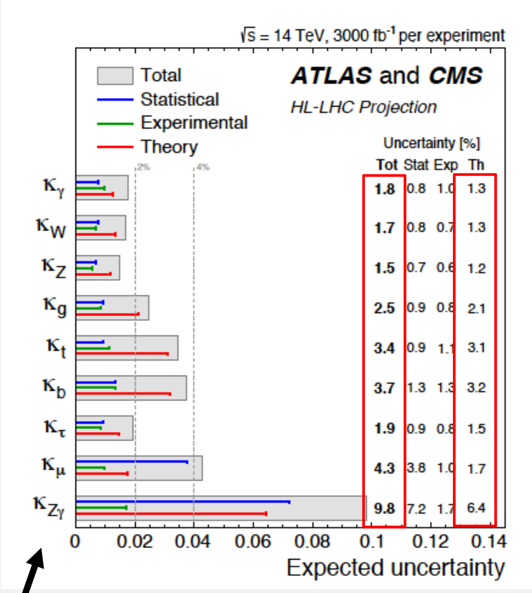


- Higgs couplings to fermions and gauge bosons *fixed in SM*
- *Couplings proportional to mass*
- *A deviation from this pattern signals new physics!*

THEORY UNCERTAINTIES

- Despite huge theory progress, the theory uncertainties will be significant at HL-LHC
- Corollary: assigning new physics interpretations to Higgs measurements limited by understanding Standard Model predictions

FUTURE

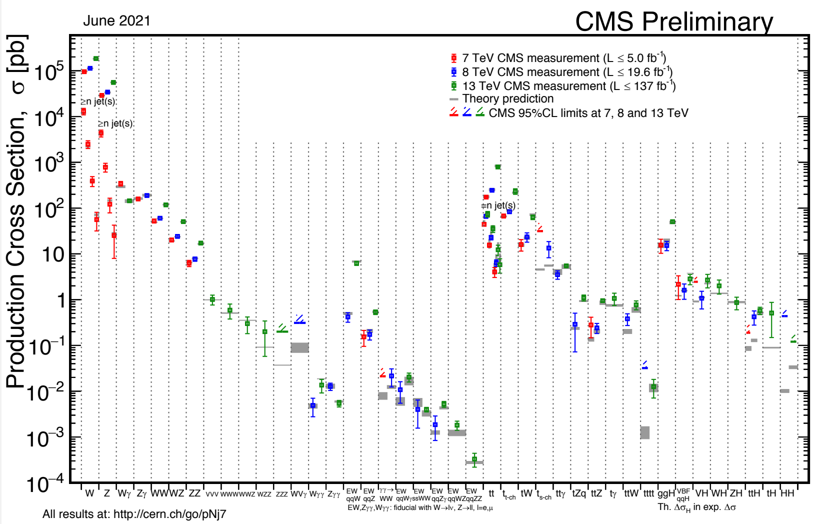


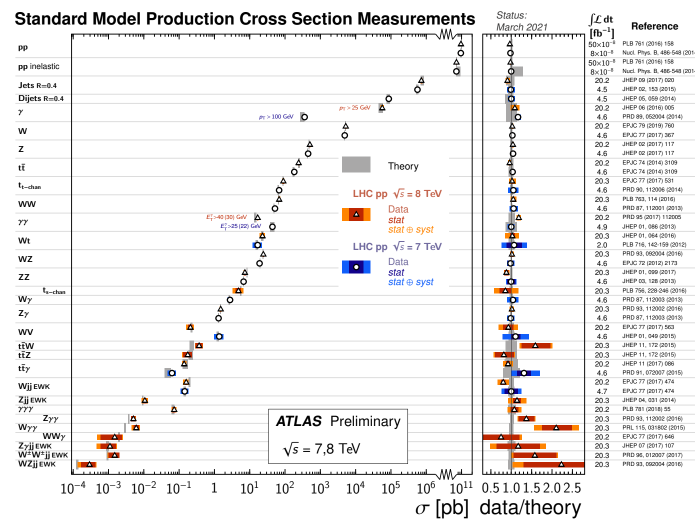
Can't talk about new physics without understanding Standard Model theory and experiment

Deviation from SM prediction

IT'S NOT JUST THE HIGGS

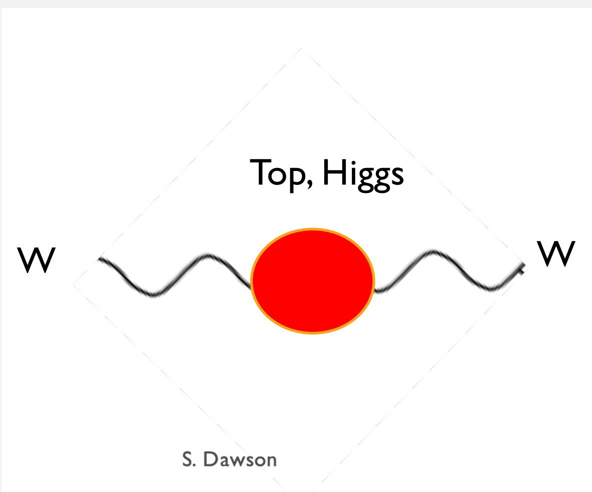
Theory/experimental agreement over many orders of magnitude and in many processes





CONSISTENCY AT THE QUANTUM LEVEL

- W boson mass is a prediction of the theory
- At the quantum level contributions from the top quark and the Higgs boson



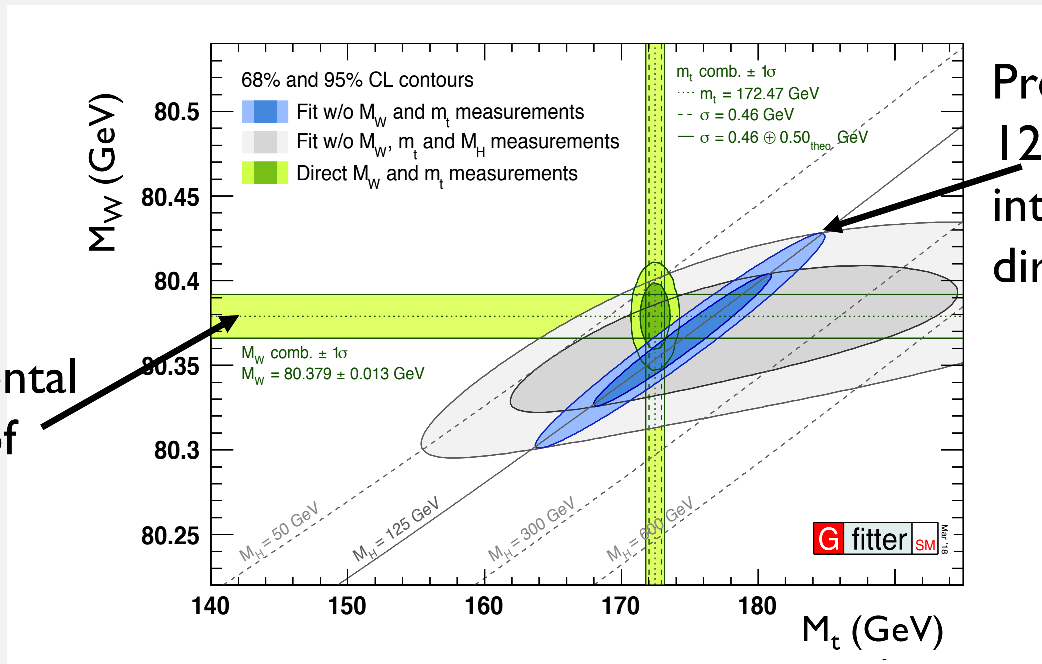
$$M_W \sim 80.94\ GeV + (\ldots)\frac{M_t^2}{(246\ GeV)^2} + (\ldots)\log(M_H^2) + .$$

calculable

* Infinite without Higgs boson

THE SM WORKS AT THE QUANTUM LEVEL

Direct experimental measurements of M_W and M_t



Prediction of M_W and M_t for 125 GeV Higgs boson from interpreting data not including direct measurements

Standard Model fits data very well at the quantum level

ALL DATA SO FAR CONSISTENT WITH....

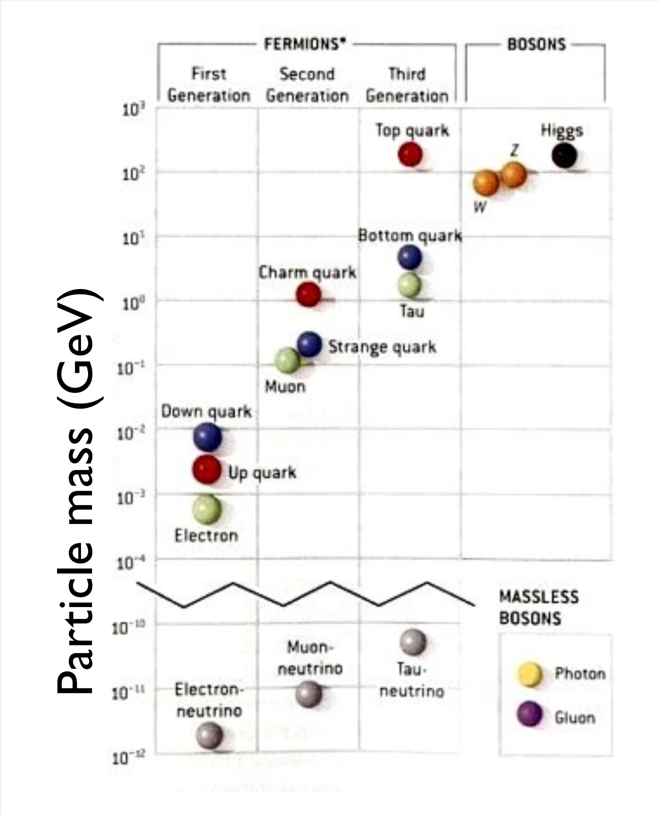
SO WHY ARE WE TALKING?

Beautiful model that works….
But…..

THE SM CAN'T BE COMPLETE

- It doesn't explain:
  - Neutrino masses
  - The pattern of fermion masses

Can't predict masses or explain large hierarchy



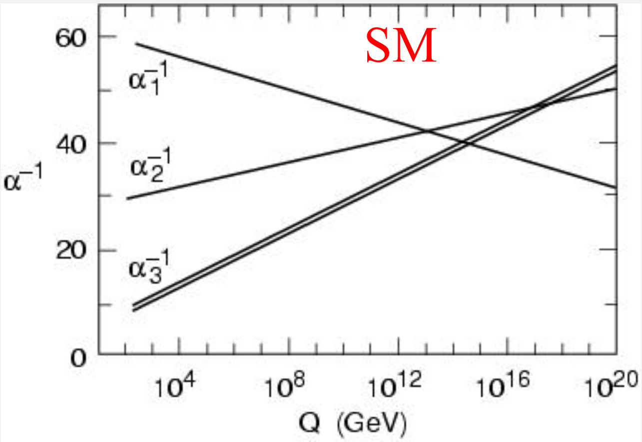
THE SM CAN'T BE COMPLETE

- It doesn't explain the strength of the gauge interactions
- Maybe there is a unified explanation at high energy?

$$\alpha_s(M_Z) \sim 0.1179$$

$$\alpha(M_Z) \sim 0.0078$$

$$\alpha_{weak}(M_Z) \sim .035$$



Couplings run with enerty

*Numbers from PDG

WHY DOES THE UNIVERSE HAVE MORE BARYONS THAN ANTI-BARYONS?

- At beginning of universe

1,000,000,001 Matter

1,000,000,001 Anti-Matter

→

- Shortly after

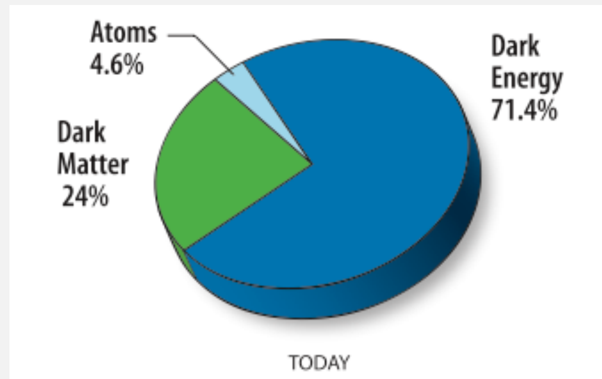
1,000,000,002 Matter

1,000,000,000 Anti-Matter

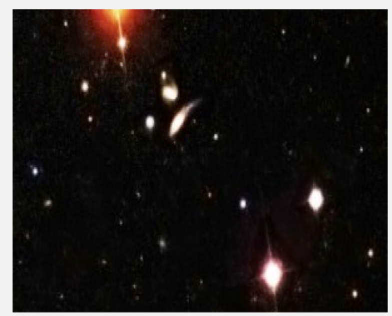
$$\frac{(n_B - n_{\overline{B}})}{n_\gamma} \sim 6 \times 10^{-10}$$

THEORY UNHAPPINESS WITH SM CONTINUES

- What is dark matter and dark energy?
- Attempt to answer this question has inspired countless models

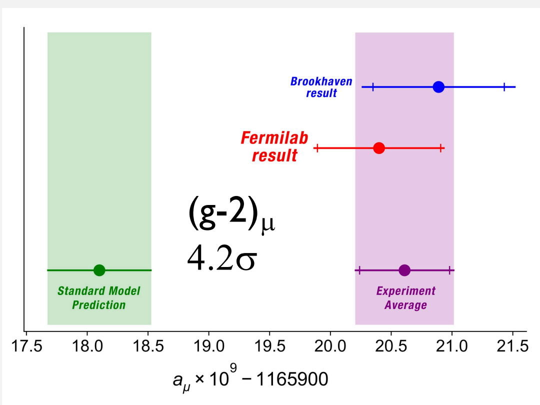


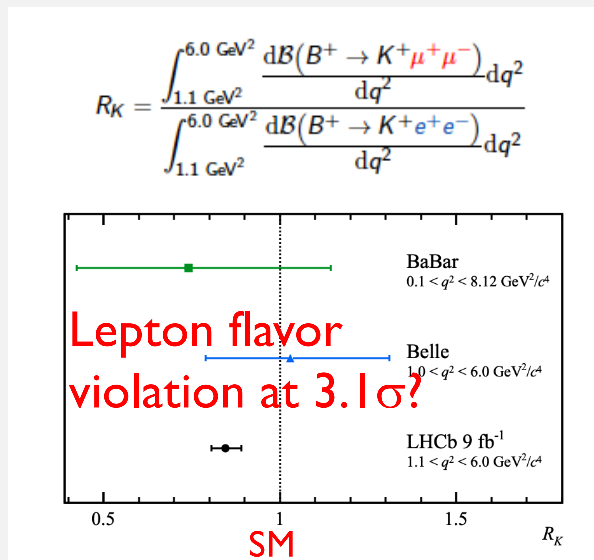
A theory of everything would answer these questions



A LITTLE EXPERIMENTAL EVIDENCE

- A few experimental indications support the theory view that there might be physics beyond the Standard Model





+ other ~ 3 σ indications from B physics

TAKE SERIOUSLY THE NEED FOR EXTENDING THE SM

- How do we investigate cracks in the Standard Model?
- Can we get a handle on where new physics might be?

PREDICTIONS…..

Physics in 2006

S. Dawson

Physics Department[1]
Brookhaven National Laboratory
Upton, N.Y. 11973

12433v1 20 Dec 1999

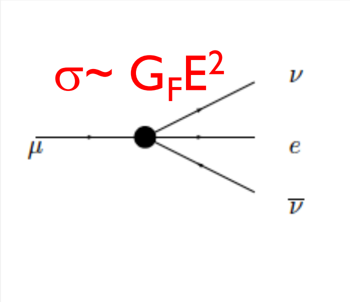
Abstract. Any consideration of future physics facilities must be made in the context of the Tevatron and the LHC. I discuss some examples of physics results which could emerge from these machines and the resulting questions which would remain for a high energy e^+e^- collider. Particular attention is 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.

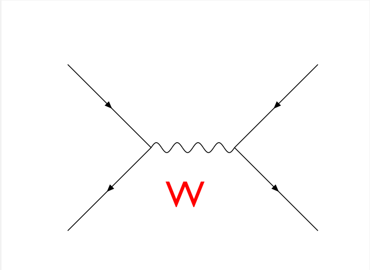
The future is unclear….

*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

- Before the Standard Model, Fermi theory explained the rate for $\mu \rightarrow e\overline{\nu}_e \nu_\mu$ in terms of an effective 4-fermion interaction
- Problem: Scattering rate becomes non-perturbative at Energy ~ 600 GeV (violates unitarity)
- W boson saved the day



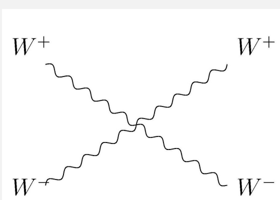


$G_F E^2 \rightarrow G_F M_W^2$

W boson or something like it had to be there

WHAT ENERGY HAS NEW PHYSICS?

- Hints from Higgs physics
- Scattering amplitudes grow with energy without Higgs below 800 GeV
- This logic gives generic upper bounds on new physics

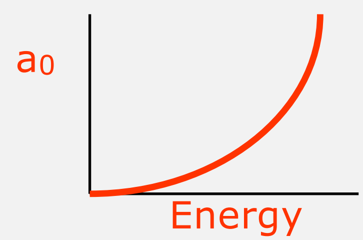


$\Rightarrow \infty$

Must have a Higgs boson or something that plays it role for perturbative theory

Not allowed in perturbative theory

$\Rightarrow$



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 (approximately) the scale of new physics

Future : No guarantees, need to examine many possibilities

Look for new physics in many places

TWO PATHWAYS TO NEW PHYSICS

Precision measurements and calculations of Standard Model observables

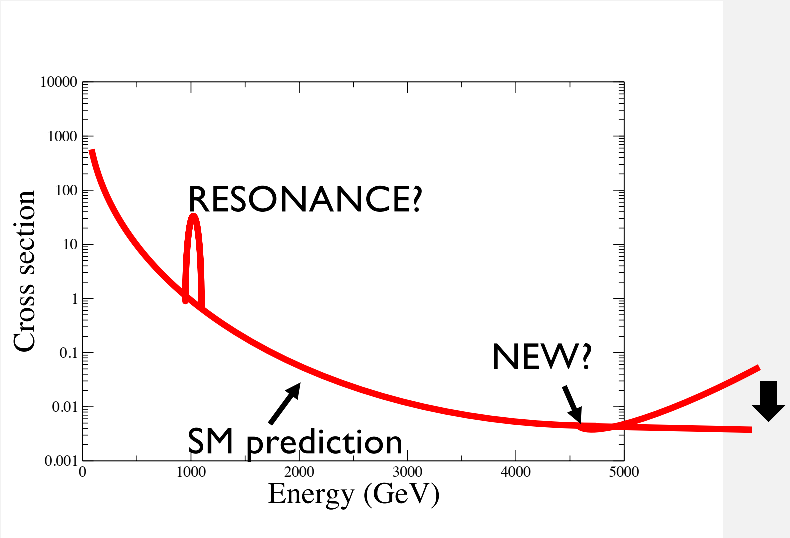
Build models and search for evidence of new particles

Approaches are complementary: Need both

NO SIGN OF ANY NEW PARTICLES

- No shortage of models predicting more particles
  - But no evidence yet….

What do we learn from precision measurements?



NEW PHYSICS FROM HIGGS COUPLINGS

- Higgs couplings fixed in Standard Model
- Deviation from Standard Model prediction would be evidence for new physics
- But we wouldn't know source of new physics

- Currently know Higgs couplings to W and Z gauge bosons at 8-12%
- Higgs couplings to 3rd generation fermions (t,b,τ) at 15-20%

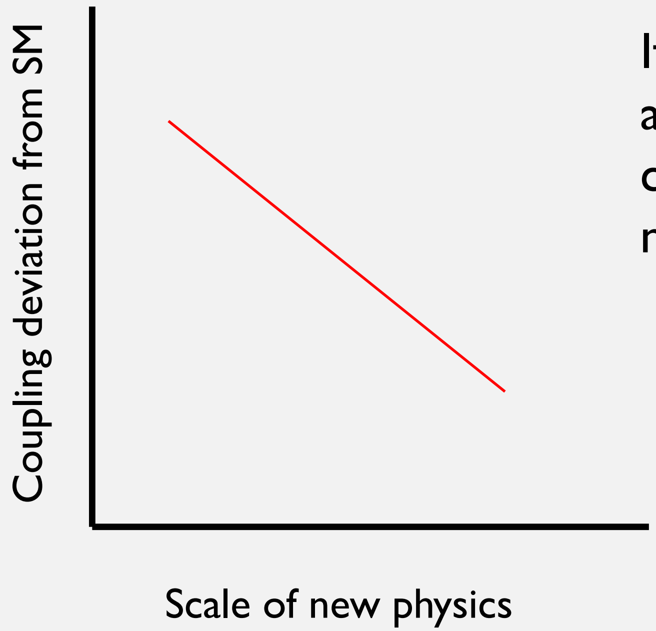
We are just getting to the interesting regime:
Generically expect deviations

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

← Scale of new physics (Λ)

*very dependent on model

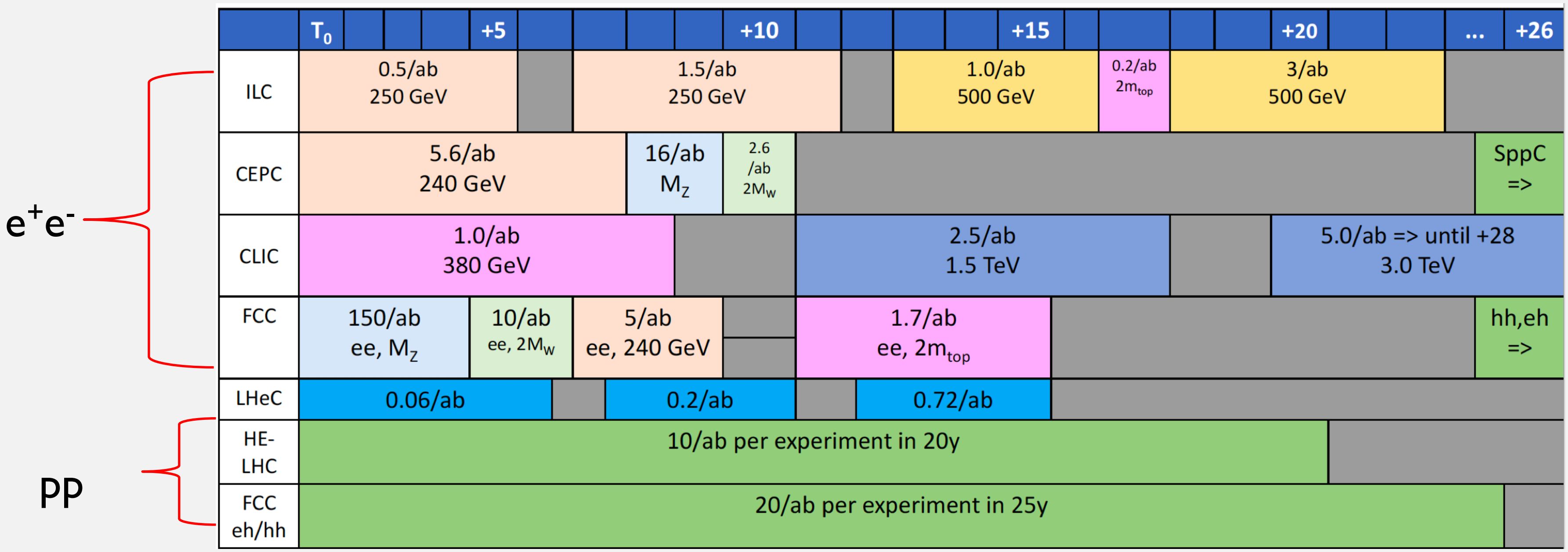
WHAT WE HOPE FOR



If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

For this to work, we have to understand the SM first (Remember precision measurements at LEP!)

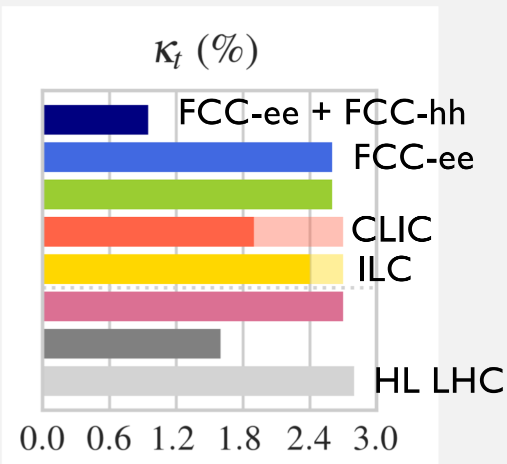
MANY POSSIBLE TOOLS



FUTURE COLLIDERS

- If new physics explains why top quark is heavy, maybe top –Higgs coupling will deviate from prediction

Precision of top quark coupling to the Higgs

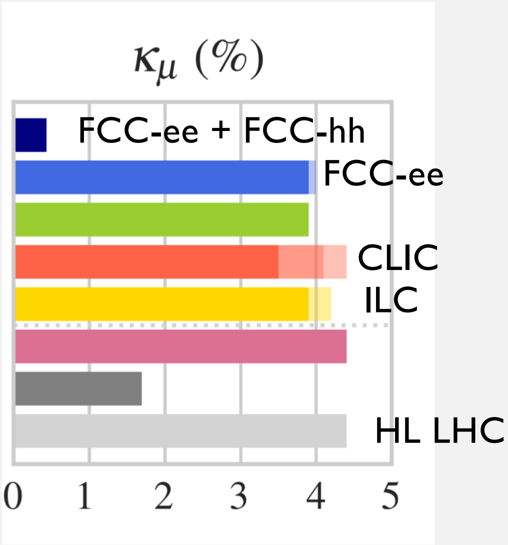


- Possibilities for couplings at the % level with future colliders
- Motivates theory calculations at the % level

arxiv:1905.03764

FUTURE COLLIDERS

- If $(g\text{-}2)_\mu$ is an indication of new physics, maybe muon –Higgs coupling will deviate from prediction

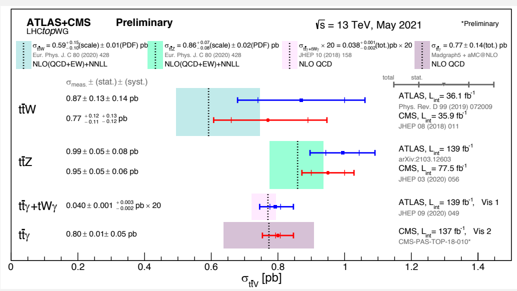


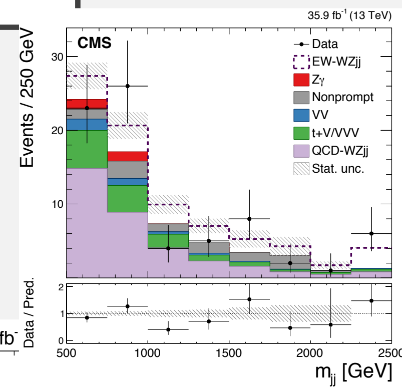
- Possibilities for couplings at the % level with future colliders
- Motivates theory calculations at the % level

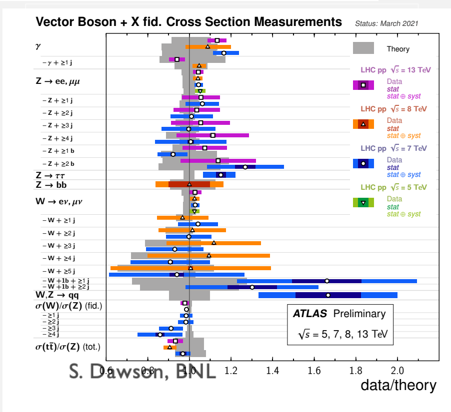
arxiv:1905.03764

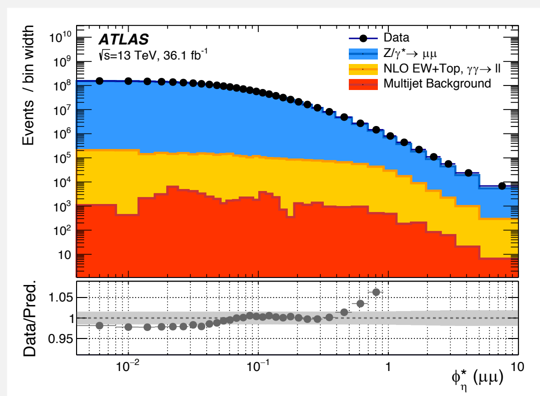
IT'S NOT JUST THE HIGGS

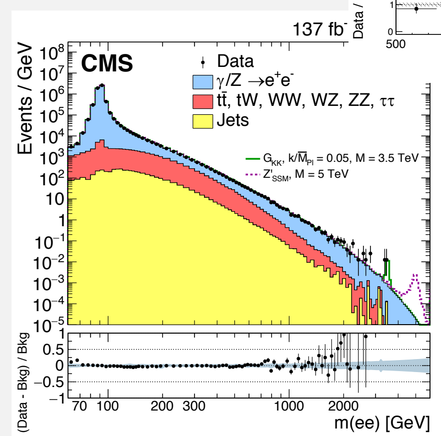
- Top quark, Drell Yan, di-boson production….
- Need to connect information from different types of measurements





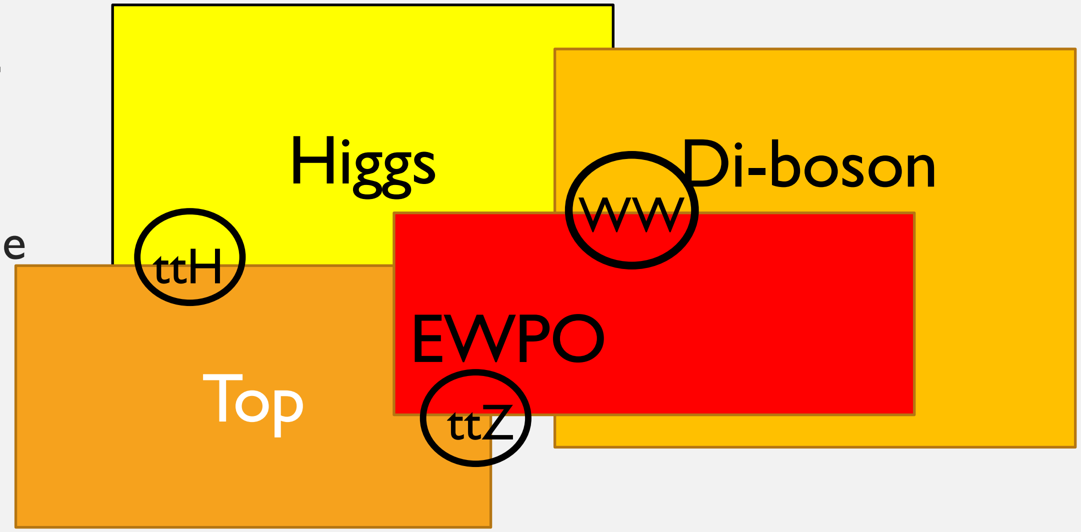






NEED CONSISTENT FRAMEWORK

- The precision program at the LHC and future colliders needs a theoretical framework to include multiple types of measurements



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

This is sad scenario where there is no intermediate scale physics

M_W Only SM particles in theory at low scales

Learn about high scale physics by measuring coefficients of effective operators with global fits

EFFECTIVE FIELD THEORY PROVIDES FRAMEWORK

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

$$L \sim L_{SM} + \Sigma_i \frac{C_i O_i}{\Lambda^2} + \Sigma_j \frac{C'_j O'_j}{\Lambda^4} + ...$$

Expansion in powers of $1/\Lambda^2$

  - O: Higher dimension gauge invariant operators constructed from SM fields
  - All Beyond the Standard Model effects in coefficients, C
  - Allows for a systematic parameterization of deviations from SM predictions without affecting agreement with low energy measurements

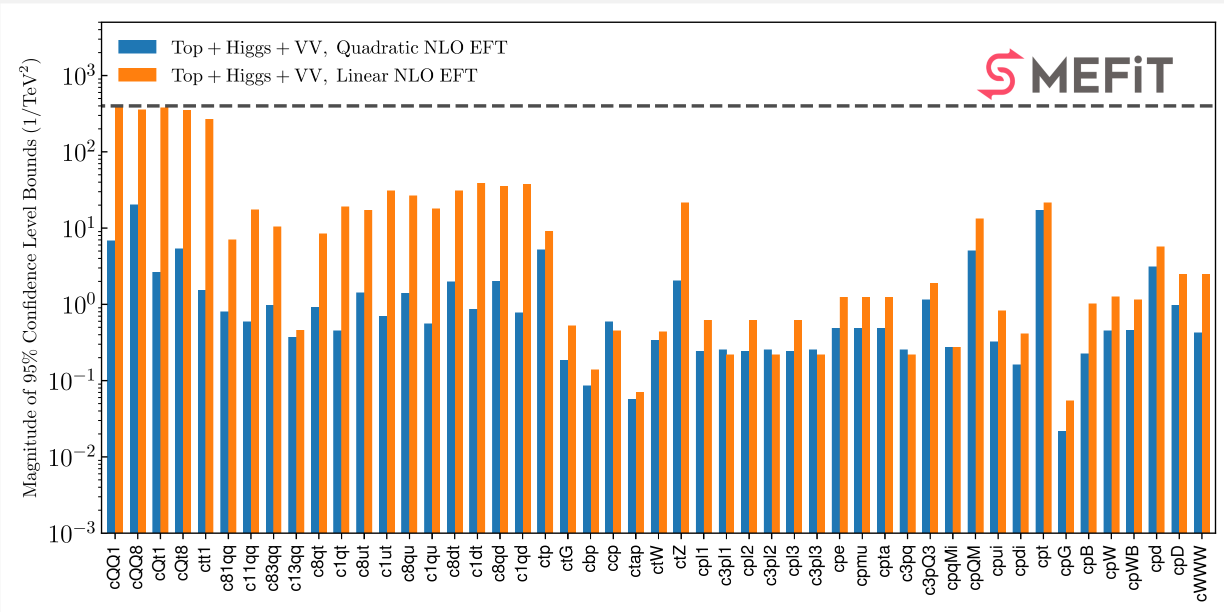
MANY SOPHISTICATED GLOBAL FITS

- Include Higgs data, WW, WZ production with kinematic distributions, top quark data
- Include precision observables from LEP/SLD
- Compare with "best SM theory"
- Calculate to NLO QCD in the effective field theory
- Some fits include flavor observables

Precision program has a lot of pieces

*LHC-EFT working group is spanning efforts in different areas

EXAMPLE OF GLOBAL FIT



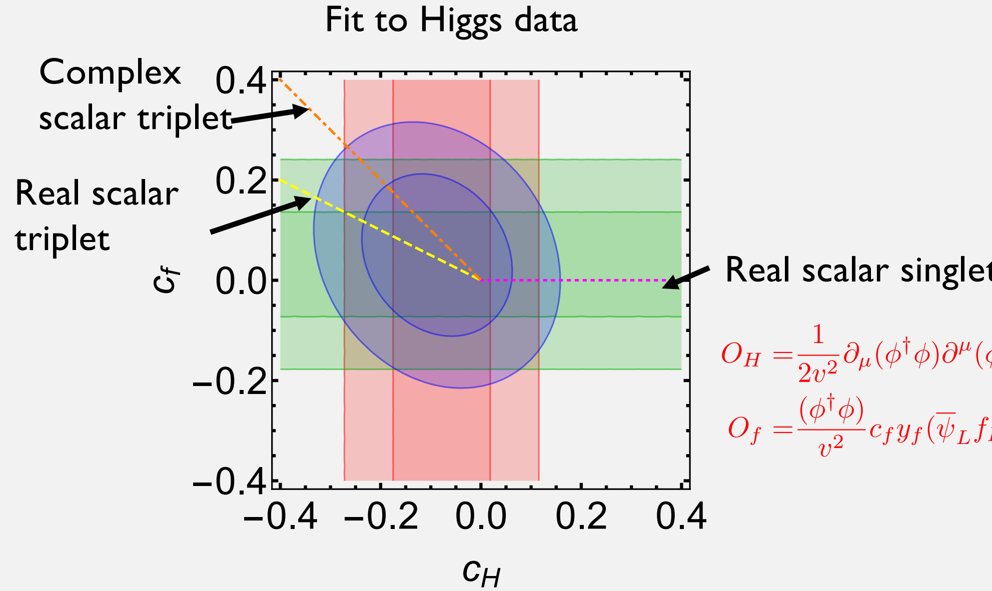
- Precision of limits very different for different operators
- Orange and Blue are different approaches to expansion in $1/\Lambda^2$

[2105.00006](https://arxiv.org/abs/2105.00006)

WHAT DO WE LEARN BY FITTING EFT COUPLINGS?

- In any given high scale model, coefficients of EFT predicted in terms of small number of parameters
- Different operators are generated in different models
- By measuring the pattern of coefficients, information is gleaned about high scale physics

Example with new scalars at very high mass scales



$$O_H = \frac{1}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

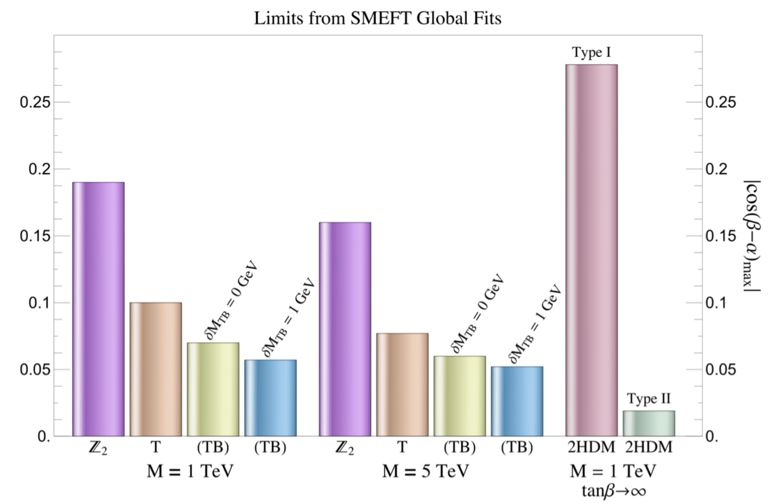
$$O_f = \frac{(\phi^\dagger\phi)}{v^2} c_f y_f(\overline{\psi}_L f_R \phi)$$

Dawson, Murphy, 1704.07851

PATTERNS OF COEFFICIENTS

- Compare models with new scalars or new heavy top/bottom quarks at the high energy scale
- Do global fits to just the sets of operators generated in these models
- Fits can restrict high scale models

Coupling strength (mixing angle) of high scale new physics



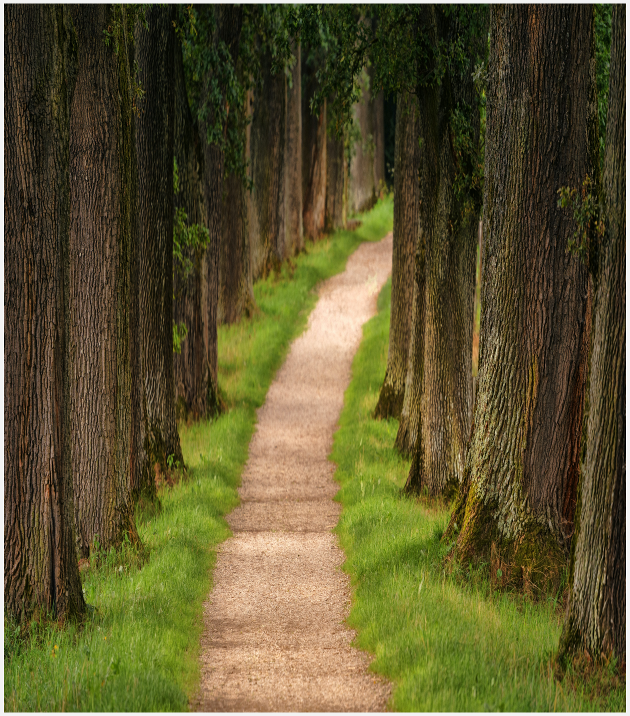
Scale of new physics

2007.01296

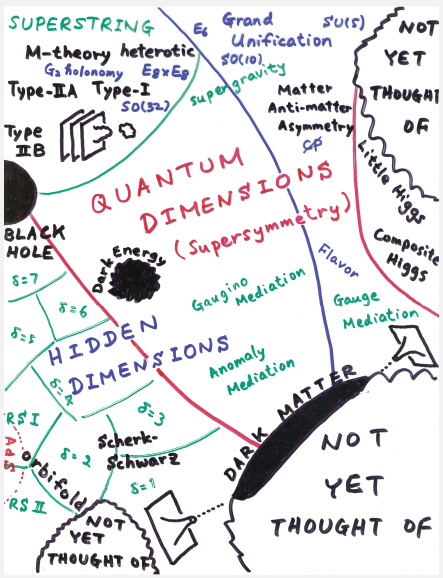
*These are particularly simple toy models

THE OTHER PATH

- Build a model that explains (some) of the mysteries of the Standard Model
- Test model predictions experimentally
- PROS:
  - Typically get quite strong limits
- CONS:
  - No generally accepted preferred model
  - Limits often have lots of fine print



MANY POSSIBILITIES FOR NEW PHYSICS

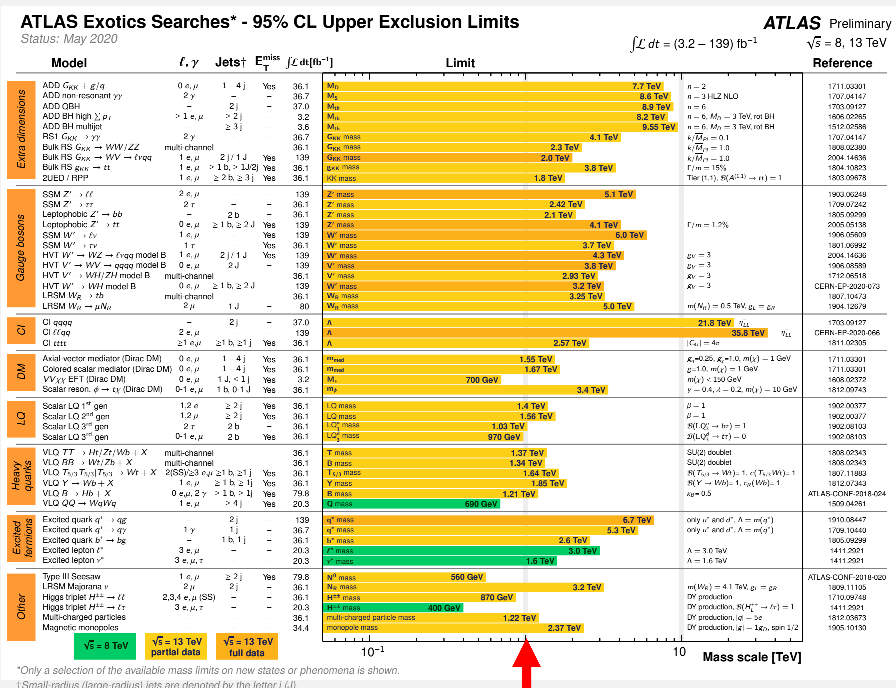


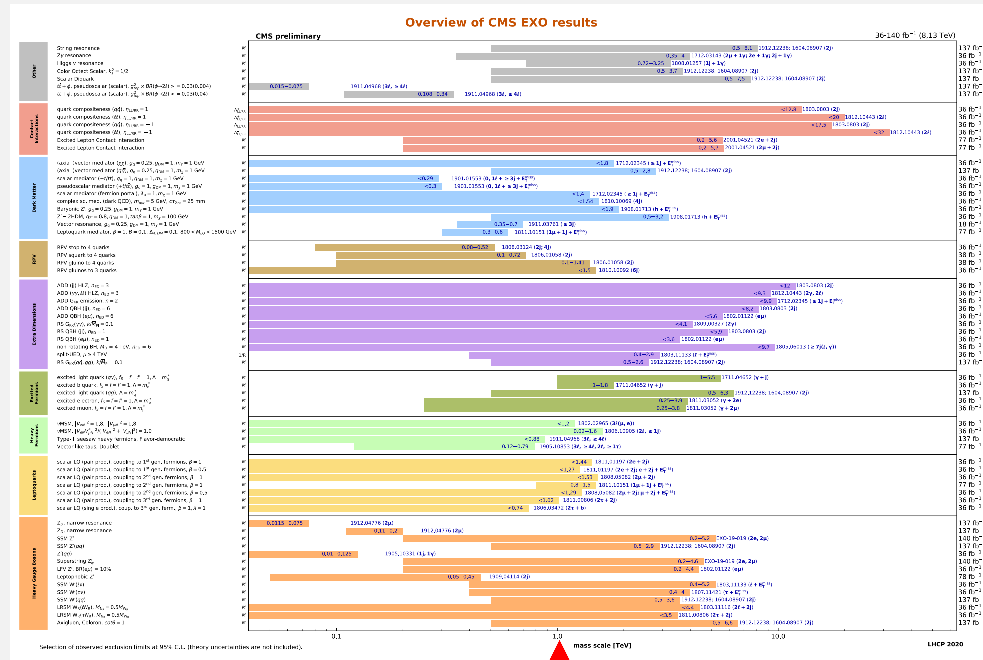
[Murayama]

Models predict deviations from SM predictions and typically as yet unobserved heavy particles

Only experiment can tell us which (if any) model is correct

CURRENT LIMITS IN THE 1-10 TEV RANGE



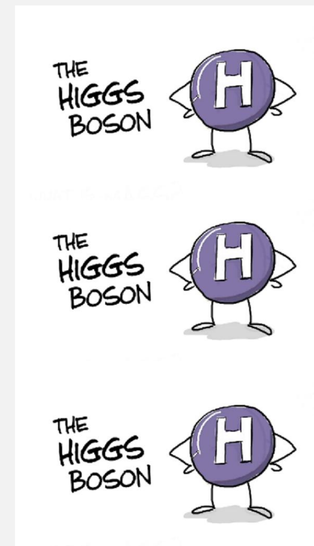


S. Dawson, BNL

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

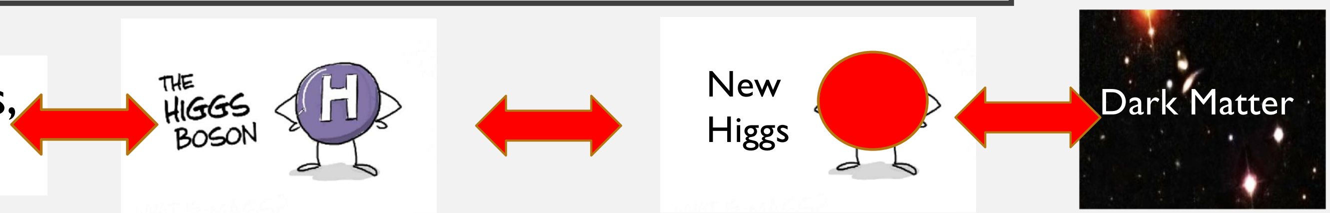
LOOK AT A FEW EXAMPLE MODELS

- Models with more Higgs particles
  - No theoretical reason not to have more Higgs particles
  - Look at model where new Higgs doesn't interact with anything other than SM Higgs (this can be used to construct models explaining dark matter and to explain why there are more baryons than anti-baryons)
  - And a model with a 2nd identical copy of the SM Higgs
- Models with a heavy copy of the top quark
  - Why not? (Might explain why top is heavy)



ADD 1 MORE HIGGS PARTICLE

All the other particles, quarks, leptons, gauge bosons



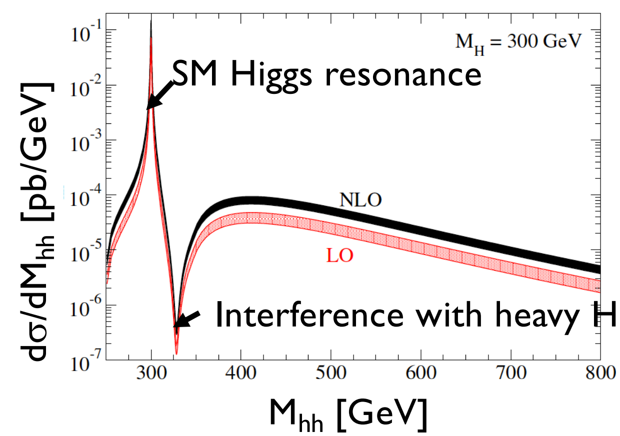
- Add a Higgs that only talks to the Standard Model Higgs
- Simple and predictive
- Predictions:
  - Couplings of Standard Model Higgs to known particles reduced by constant factor (same for all particle)
  - There is a new heavy Higgs particle that we can search for

HIGGS SELF COUPLING

- The Standard Model predicts the magnitude of the Higgs self coupling
- When you add more Higgs bosons, you change the self coupling, and introduce the possibility of observing a new resonant interaction/interference

This class of models can enhance the rate for producing 2 Higgs bosons by up to a factor of 10

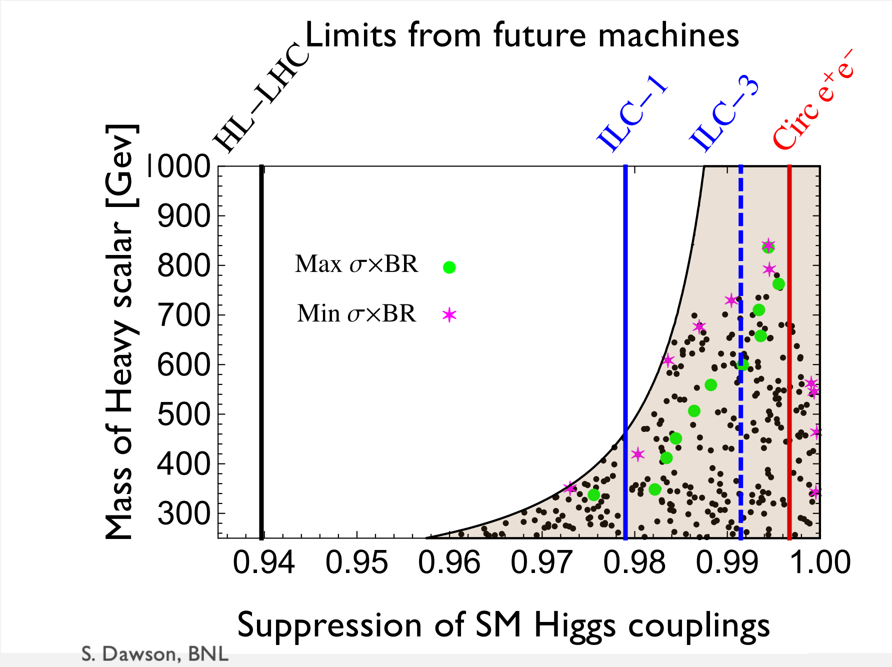
Cartoon of double Higgs production



*Haven't seen 2 Higgs production yet!

DOUBLE HIGGS PRODUCTION CAN GIVE INFORMATION ON ELECTROWEAK PHASE TRANSITION

- Models with scalar singlets can allow first order electroweak phase transition

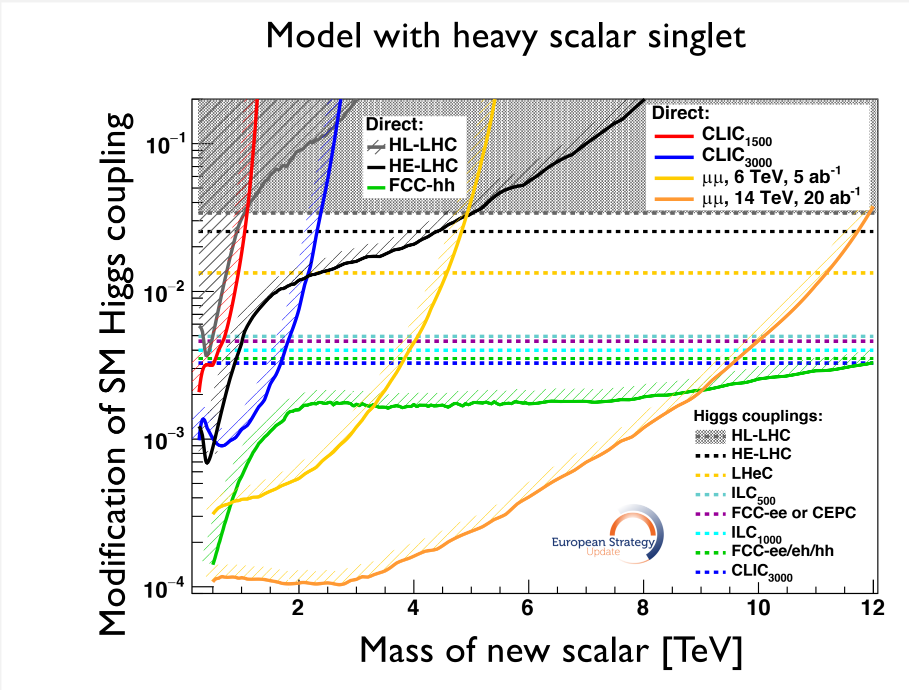


- Motivation for high energy colliders
- Can probe region with EW phase transition in hh production (dots are parameter points where this happens)

Kotwal, Ramsey-Musolf, No, Winslow, 1605.06123

HOW HIGH IN SCALE CAN WE GO?

- Future e^+e^- colliders give increasingly precise measurements of Higgs couplings
- Higher energy machines can look for new Higgs-like particle as a resonance
- *COMPLEMENTARITY OF APPROACHES*

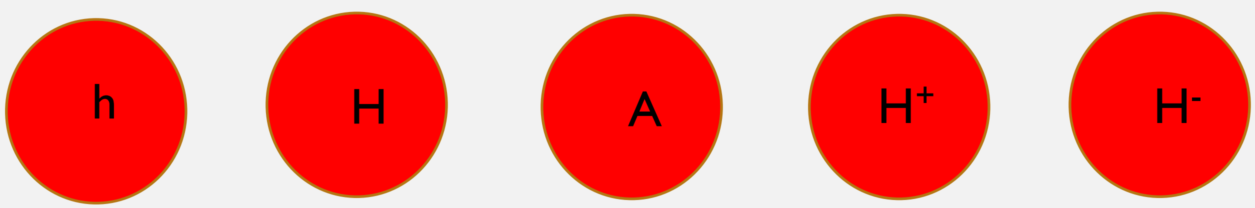


* 0 is SM

[European Strategy Report](#)

2 HIGGS DOUBLET MODEL

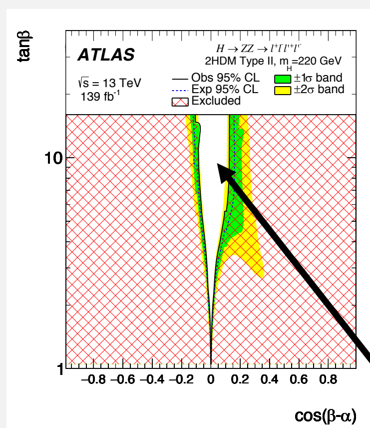
- Add an exact copy of the Standard Model Higgs
- Predicts: Couplings of Standard Model like Higgs to W's and Z's suppressed
- Couplings of Higgs to top, bottom, muons, other fermions can be expressed in terms of 2 new variables (call them α and β)
- Predicts: 5 Higgs bosons! 2 are electrically neutral, 1 is electrically neutral but with different CP properties from SM, 2 are electrically charged

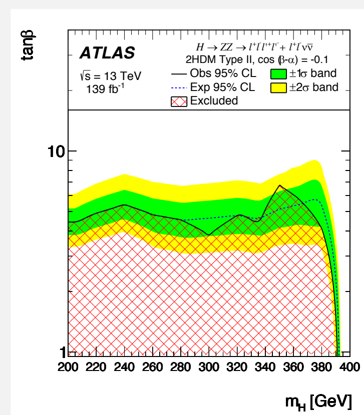


2 HIGGS DOUBLET MODELS

- These models are highly motivated because they can be part of a supersymmetric model which explains why $M_h << M_{planck}$
- More than one way to couple fermions to the 2 Higgs doublets

- Restrictions from Higgs coupling measurements
- White is allowed region
- $\cos(\beta-\alpha)=0$ is SM



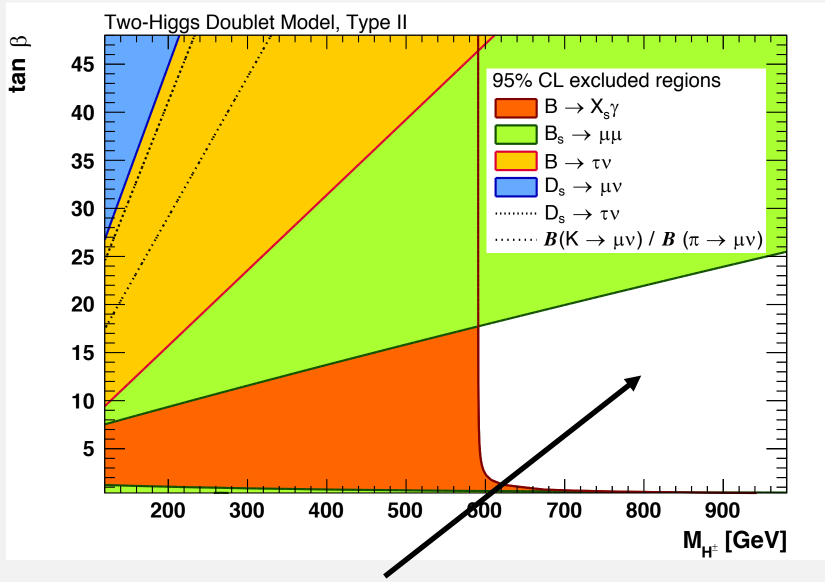


Closing in on the SM

LOOK FOR NEW HIGGS PARTICLES AND NEW SIGNATURES

- This class of models has rich set of predictions with new signatures
- Look for $H^+ \to tb$, $H^+ \to \tau\nu$, $pp \to A \to ZH$ (for example)
- Charged Higgs contributions limited from B physics measurements $B \to s\gamma$, $B \to \mu\mu$, etc

Consistent picture requires input from many types of measurements



White is allowed region from B physics

Gfitter, 0811.0009

LAST EXAMPLE

- New physics can happen in many sectors (not just the Higgs)
- Simple example: Add a heavy charge 2/3 fermion (heavy top)
  - (This particle interacts differently with the Z boson than the usual top)
- Now we have Standard Model top quark t, and heavy T
- Such a particle occurs in many extensions of the Standard Model
- This heavy T can be produced at the LHC and then decays to Wb, Zt, or Ht
- Limits on mass consider all possible decays: $M_T > 1400$ GeV

OPPORTUNITIES FOR DISCOVERY ABOUND

- We are just at the cusp of where we expect to see deviations in couplings from Standard Model predictions
  - Advances in precision theoretical calculations make this possible
- Vast possibilities for discovering new particles in motivated models
  - Look for new signatures
  - Look for new resonances