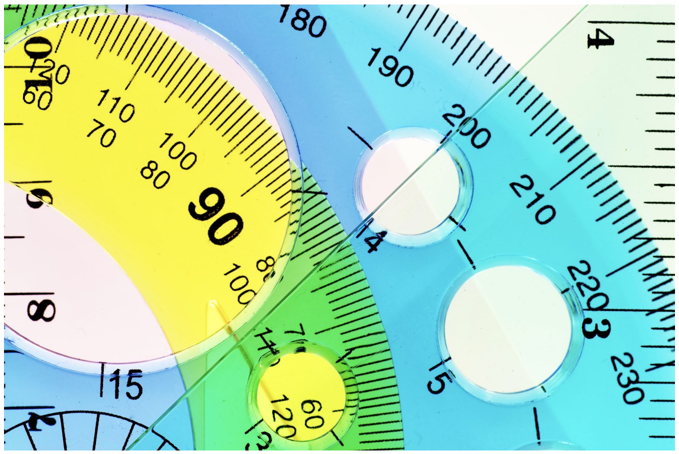
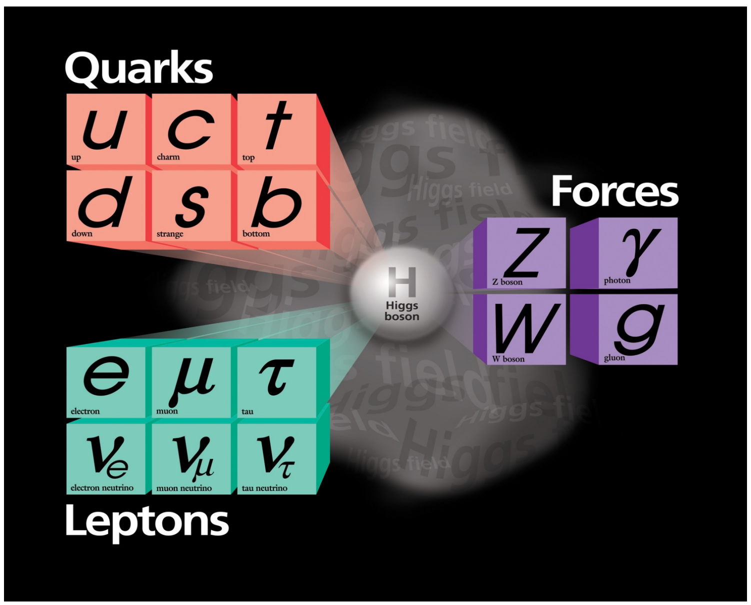


The Standard Model of Particle Physics

S. Dawson, BNL, June 29, 2026

Standard Model is a framework

- Particle physics has a "Standard Model" of particles and their interactions

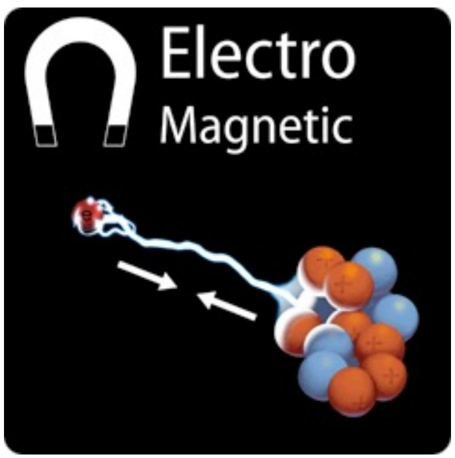


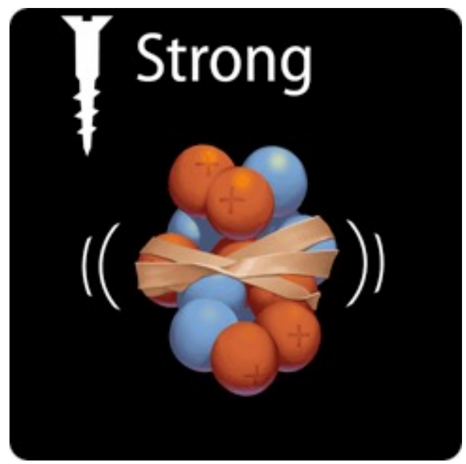
- Quarks come in pairs with charge 2/3 e and -1/3 e
- Each lepton has its own neutrino
- Force carriers communicate between quarks and leptons

Muon ν discovered at BNL in 1962

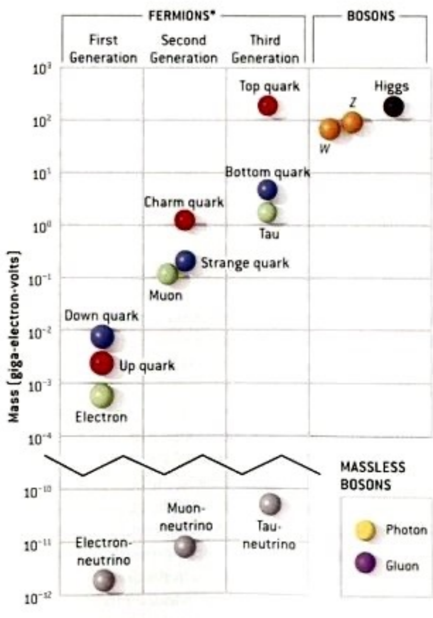
Forces

- Electromagnetism explains electricity and magnetism (Maxwell)
- Weak force explains radioactivity (Fermi, 1933)
- Strong force explains why quarks are bound in protons
- Gravity seems simple…..





We know so little



$$m_{top} = 175\ GeV$$
$$m_{electron} = .5\ MeV$$

$$\boxed{\frac{m_{top}}{m_{electron}} = 350,000}$$

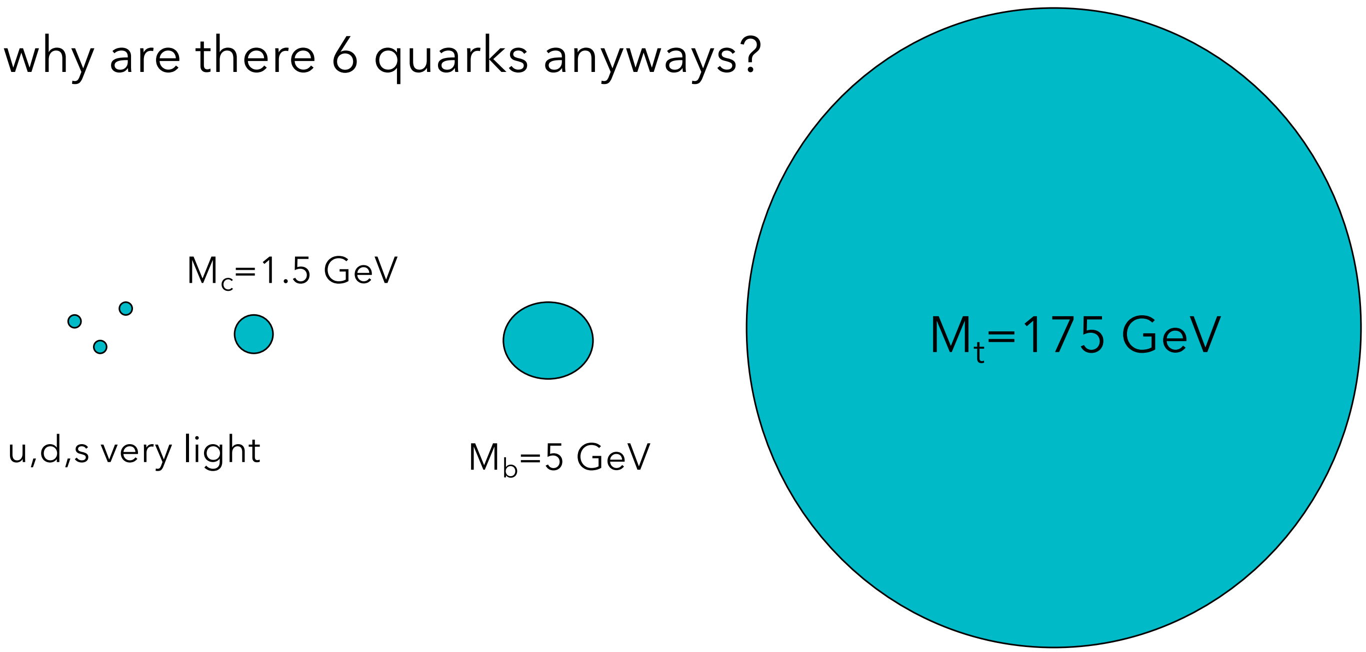
- Model accommodates masses, but doesn't predict them
- Masses are put in by hand

WE DON'T UNDERSTAND MASS

1000 MeV= 1 GeV
Proton mass ~ 1 GeV

Why?

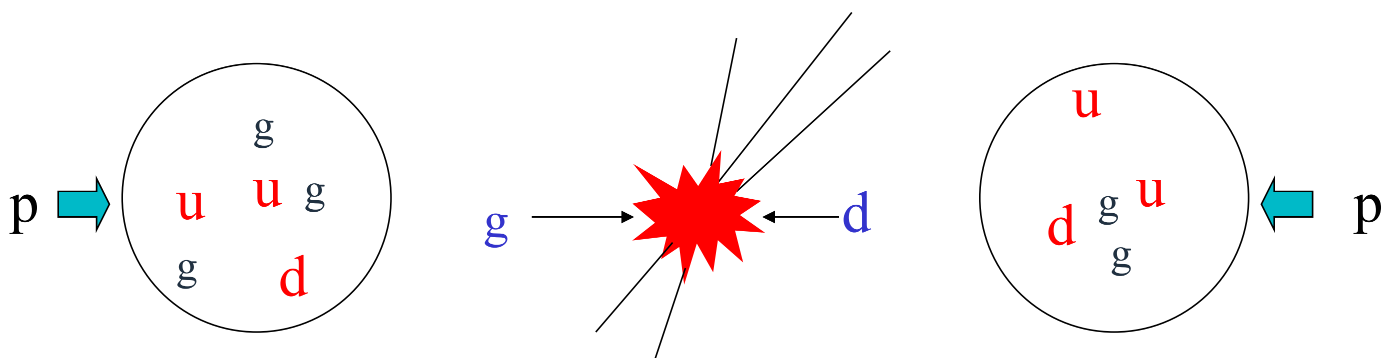
- And why are there 6 quarks anyways?



I won't talk about this because nobody has any good ideas

The Particles

- Leptons (e, μ, τ,ν) and quarks are point-like
- Quarks don't exist outside of hadrons with integral charge
- Proton p = uud + (infinite number of $q\bar{q}$ pairs and gluons)



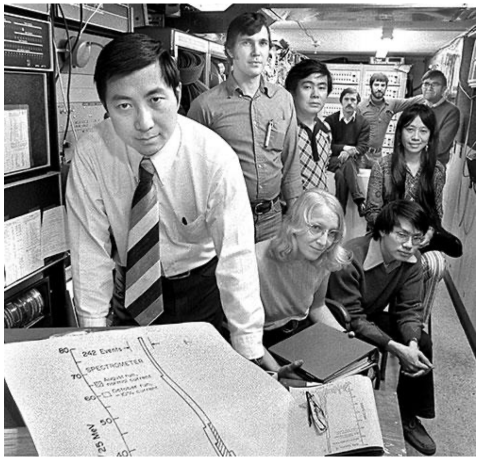
Typical interaction energy at LHC ~ 1 TeV

Particle spectroscopy

- In nature, we see pions:

$$\pi^+ = (u\bar{d}) \qquad \pi^- = (d\bar{u}) \qquad \pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

  - Pion was discovered in cosmic rays in 1947

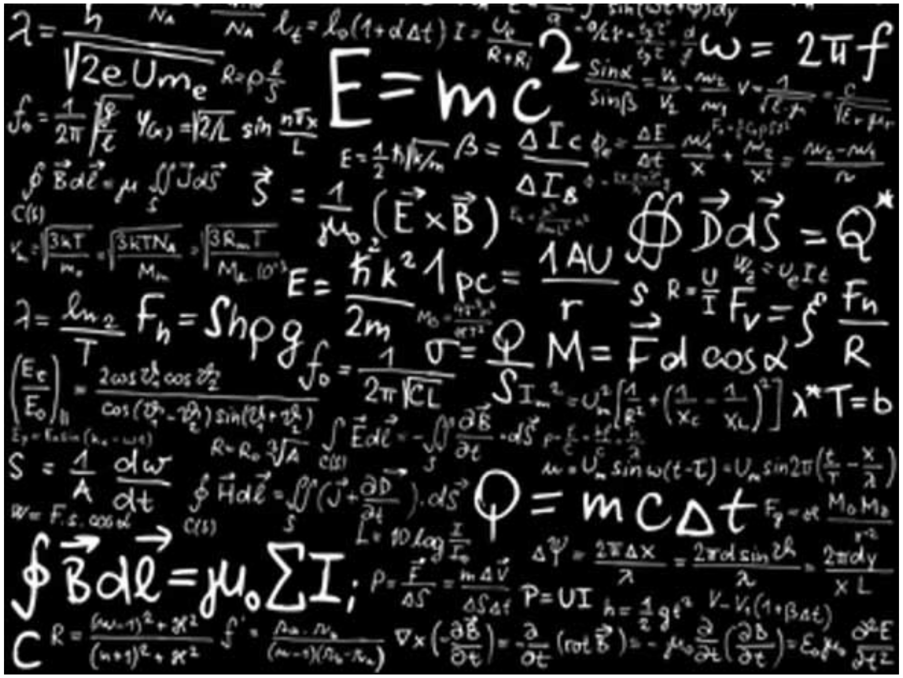


- Kaons also seen in cosmic rays

$$K^+ = (u\bar{s})$$

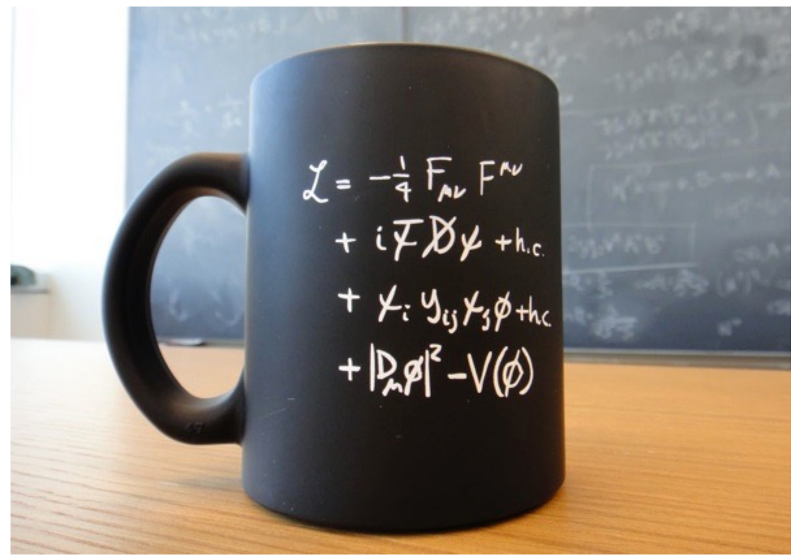
- (sss) (Ω^-) discovered at BNL in 1964
- Heavier quarks have to be made at accelerators
- $J/\psi = (c\bar{c})$ discovered at BNL/SLAC in November, 1974

Since the 1960's we have constructed a picture of how the forces interact with particles



The Standard Model is Simple and predictive

- It is a gauge theory: SU(3) x SU(2) x U(1)
- An SU(N) gauge group has N^2-1 spin-1 particles that act as "force carriers"
- SU(3) is QCD with 8 massless gluons
- SU(2) is the weak force with 3 spin-1 particles W,B (they are massless at the moment)
- U(1) has 1 spin-1 gauge boson



Gauge theories for particle physics started with Yang-Mills @ BNL in 1953

Why is mass a problem?

- Lagrangian for gauge field, A_μ, (spin 1 photon):

$$L=-\frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu$$

- L is invariant under transformation:

$$A_\mu(x) \rightarrow A_\mu(x)-\partial_\mu\eta(x)$$

- ***Gauge invariance is guiding principle***
- Mass term for gauge boson: $\frac{1}{2} m^2 A_\mu A^\mu$
- Violates gauge invariance
- We understand why photon is massless

You can derive Maxwell's equations from this Lagrangian

Quantum mechanics: photon is a particle and/or photon is a field

The Standard Model without the Higgs has massless particles

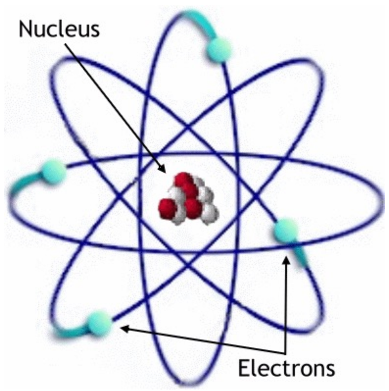
- The gauge bosons are massless without the Higgs
  - Experimentally: M_W=80 GeV, M_Z=91 GeV, m_g, m_γ=0
- The fermions are massless without the Higgs
  - Experimentally: m_{top}=173 GeV

Not a small effect

The entire reason for the Higgs boson is to explain masses

Higgs Boson needs to explain electron mass

- Radius of atoms depend on electron mass



Radius is proportional to 1/mass(electron)

- Atoms wouldn't form without the Higgs boson!

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)

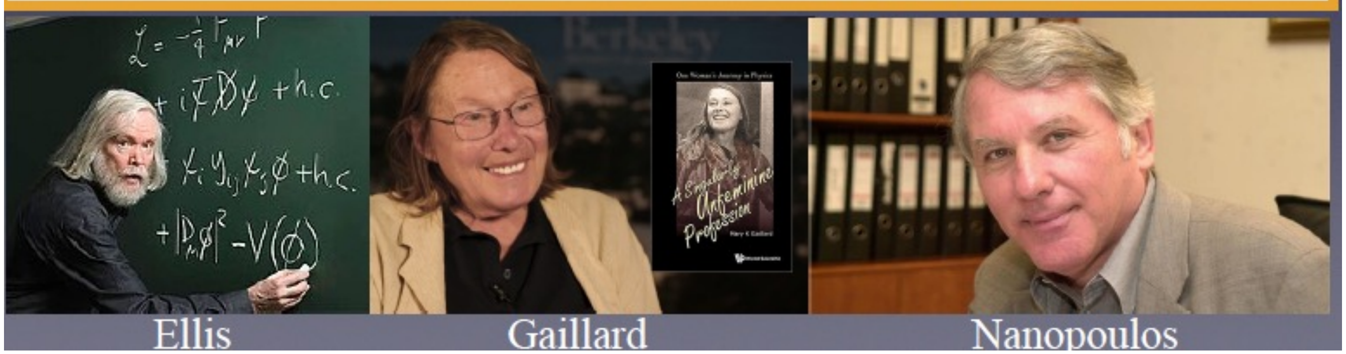
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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 guides search for new physics

First Serious Study of the Higgs, 1976

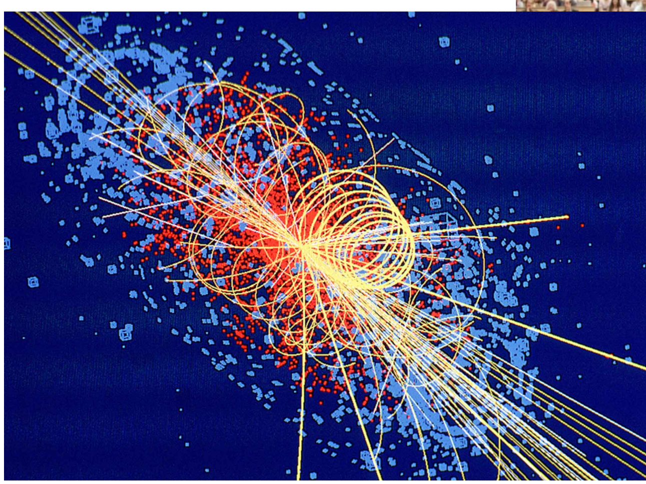
> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.



This started theorists thinking!

In the last 15 years...

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



Announced on July 4, 2012 at 9 am Geneva time

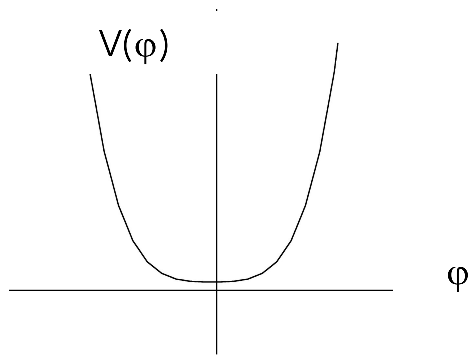
Scalar particle in Potential

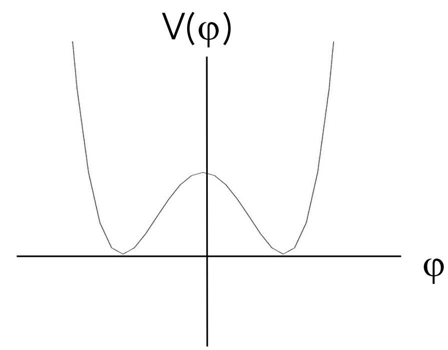
$$V = \mu^2\phi^2 + \lambda\phi^4$$

- Case 1: $\mu^2 > 0$
    - Unique minimum at φ=0

- Case 2: $\mu^2 < 0$
    - Minimum is not at 0
    - Once you pick a minimum you have broken the symmetry of $\phi \rightarrow -\phi$

Location of minima called vacuum expectation value: called v



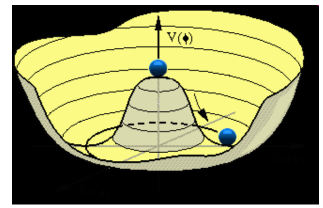


Physical particle at minimum energy state at 0: $h=\phi-v$

Standard Model postulates a Higgs particle

- Standard Model includes complex Higgs SU(2) doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



- Self-interactions of Higgs described by potential

$$V = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$ Invariant under $\phi \to -\phi$

- If $\mu^2 < 0$, then minimum of potential not at 0
- Minimum of potential at:

$$\phi = e^{\frac{\omega \cdot \sigma}{v}} \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

σ are Pauli matrices, come from SU(2) symmetry

  - Choice of minimum breaks gauge symmetry

Standard Model

- Higgs doublet interacts with massless SU(2) spin-1 doublet, $\mathcal{W}$, and massless spin-1 singlet, $\mathcal{B}$
- 4 degrees of freedom (3 in $\mathcal{W}$ and 1 in $\mathcal{B}$)
- 3 combinations of fields get mass proportional to v, $M_W=gv/2$
  - $W^\pm$ (charge ±1), Z (charge 0)
  - Prediction: $M_W=\cos\theta\, M_Z$ (ie $M_Z>M_W$, $\cos\theta$ proportional to SU(2) and U(1) coupling strengths which are arbitrary parameters)
- 1 combination of fields remains massless and is the photon

Massive W and Z bosons discovered in 1983

Need Higgs boson….

Fermions in the Standard Model

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R, \quad d_{R,} \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R, \quad s_{R,} \quad \begin{pmatrix} \nu \\ \mu \end{pmatrix}_L, \quad \mu_R$$

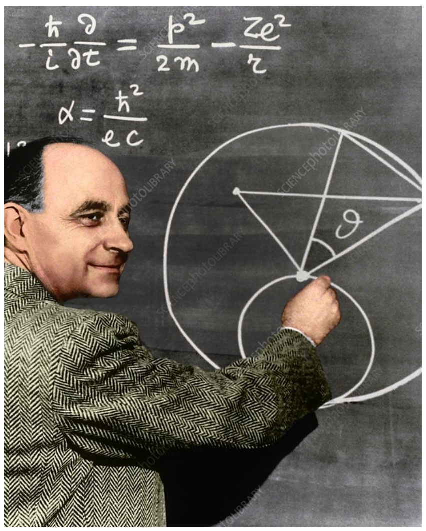
$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R, \quad b_{R,} \quad \begin{pmatrix} \nu \\ \tau \end{pmatrix}_L, \quad \tau_R$$

ASSUME left-handed fermions are in SU(2) doublets and right-handed fermions are SU(2) singlets

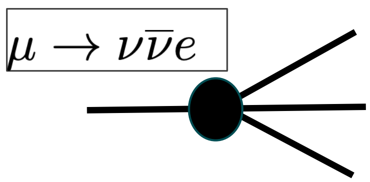
Only left-handed fermions interact with the weak force: We know this from measurements of muon decay

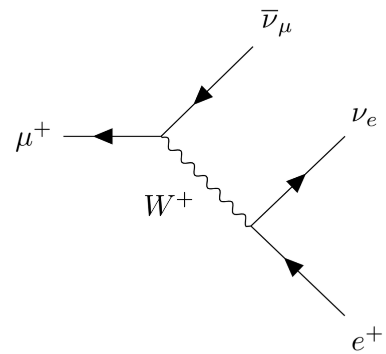
When the muon was discovered (1936), I. I. Rabi famously said: "Who ordered that?"

The VEV v is not a free parameter



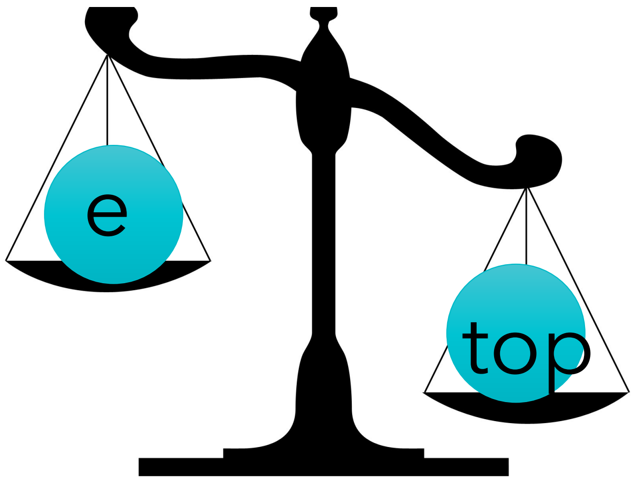
- Fermi theory ($\mu \to \nu\overline{\nu}e$) predicts rate for muon decay, G_μ
- Standard Model shows that muon decay is mediated by exchange of W boson





Match: $\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$ v=246 GeV

Masses for particles



Theory does not predict the values of particle masses (other than the W boson)

- Higgs particle accommodates quark and electron masses
- The more a particle interacts with the Higgs boson, the heavier it is

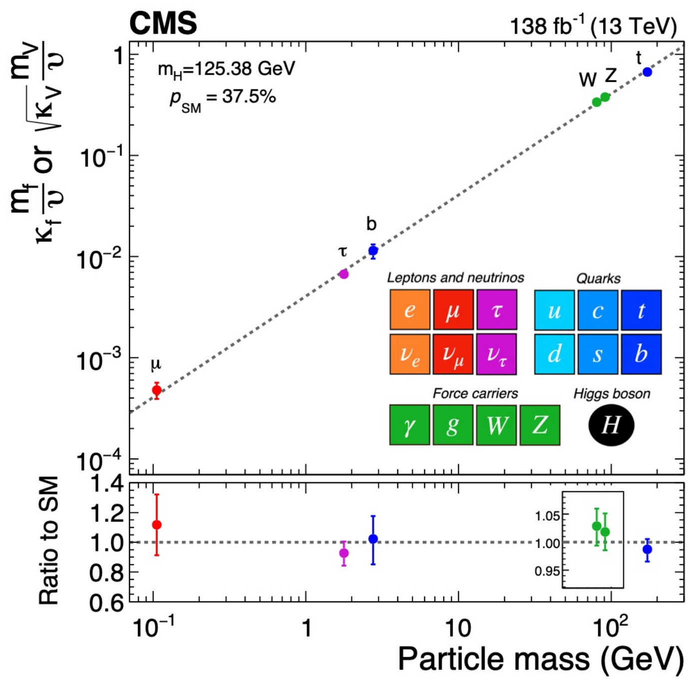
UNSATIFACTORY STATE OF AFFAIRS!

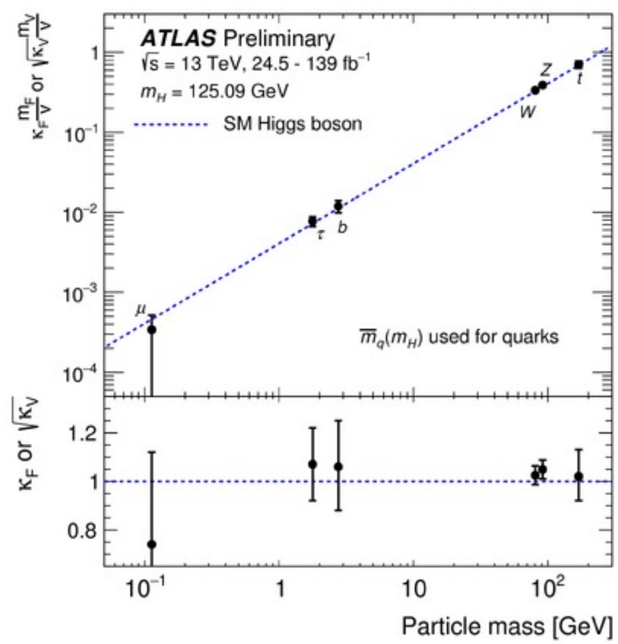
Count free parameters

- Masses of fermions: 6 quarks, 3 charged leptons
  - Also 3 x 3 mixing matrix involving quark masses (3 angles, 1 phase)
  - By definition, neutrinos are massless in the Standard Model
  - Incorporating neutrino masses requires extension of Standard Model
- 3 gauge coupling constants
- Higgs boson mass is completely free parameter
- A CP parameter

All particle interactions predicted in terms of these 18 parameters:
A PREDICTIVE THEORY

Higgs couplings look "SM-like"





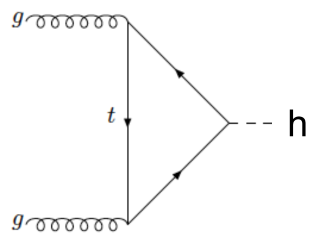
No free parameters in plots

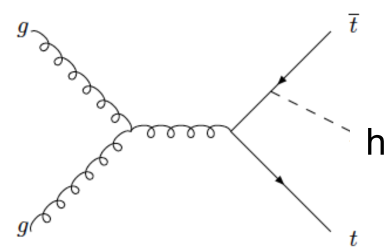
Dashed lines are predictions

Higgs couplings proportional to mass

Higgs Production

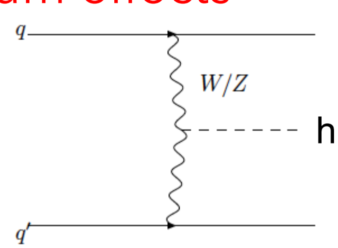
Most important processes:

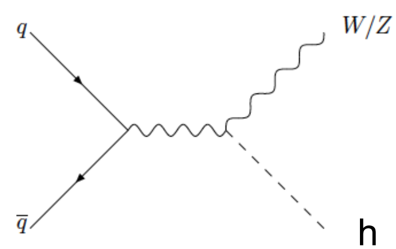




Direct measurement of tth coupling: Largest Higgs fermion coupling

Depends on physics in loop: quantum effects

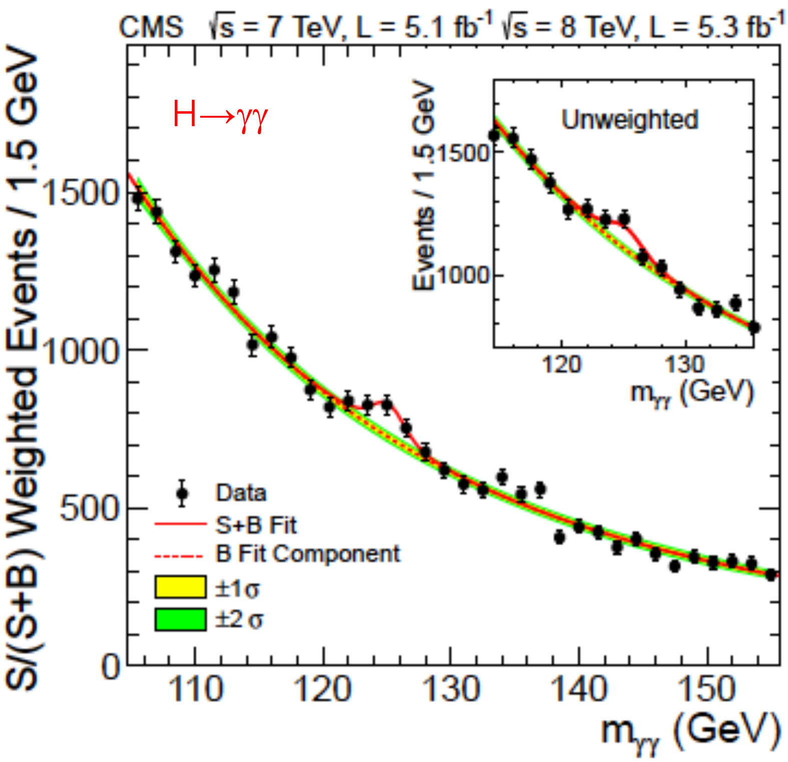




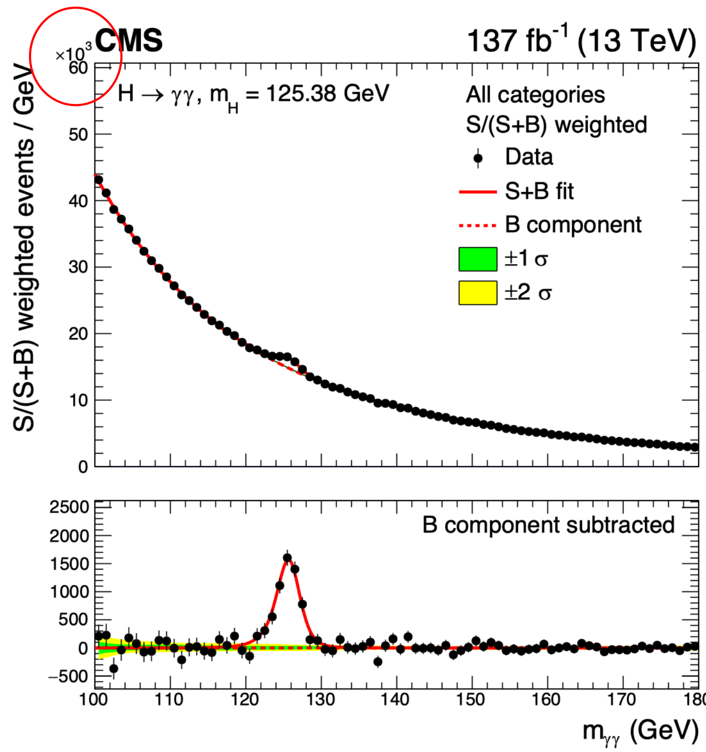
Vanish if v=0

Discovery to precision

2012

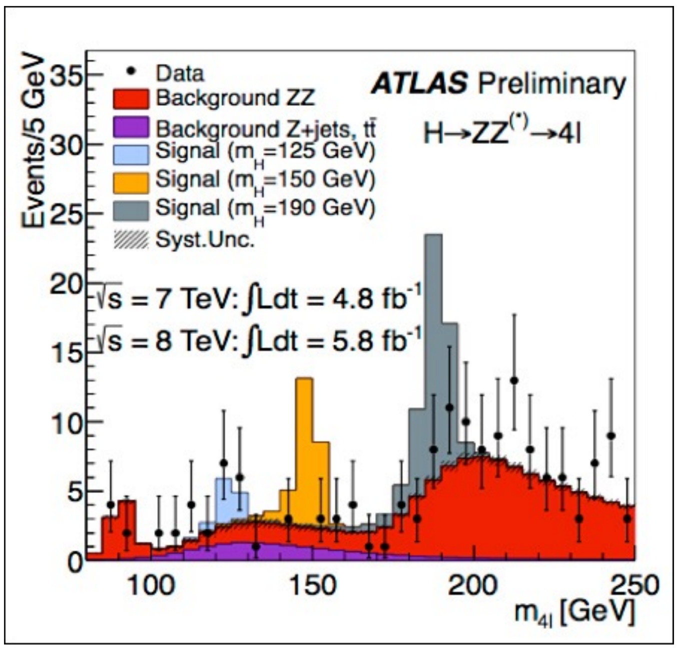


2022

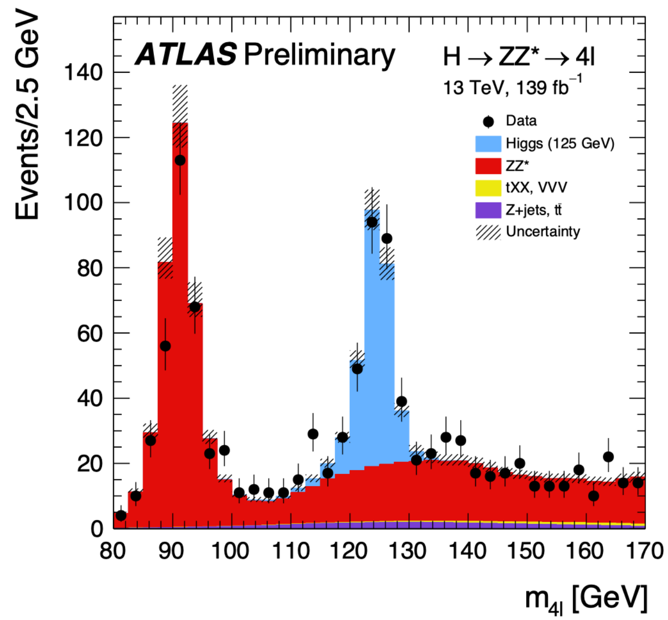


Discovery to precision

2012



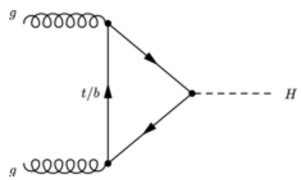
2022



More events, smaller uncertainties

Measurements compared to Theory

- Dominant production of Higgs boson is gluon fusion



DEPENDS ON INTERACTION
OF HIGGS WITH TOP QUARK

- Rate is power series in strong coupling constant, $\alpha_s \sim .118$

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

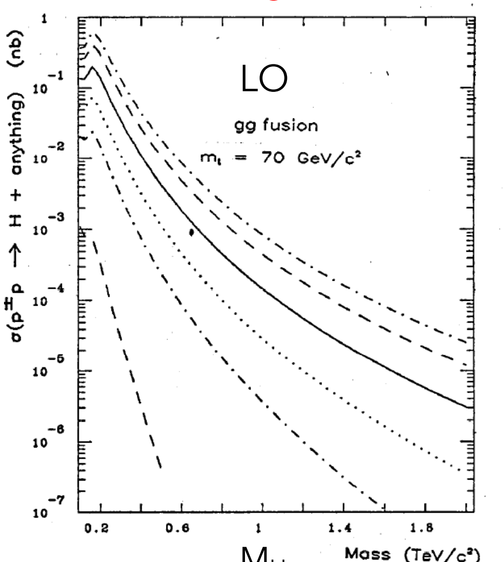
We can predict!!!!

1977 → 1995 → 2002 → 2015

Precision physics at a Hadron Collider

- Can you do precision physics at a hadron collider? YES!

1984



M_H

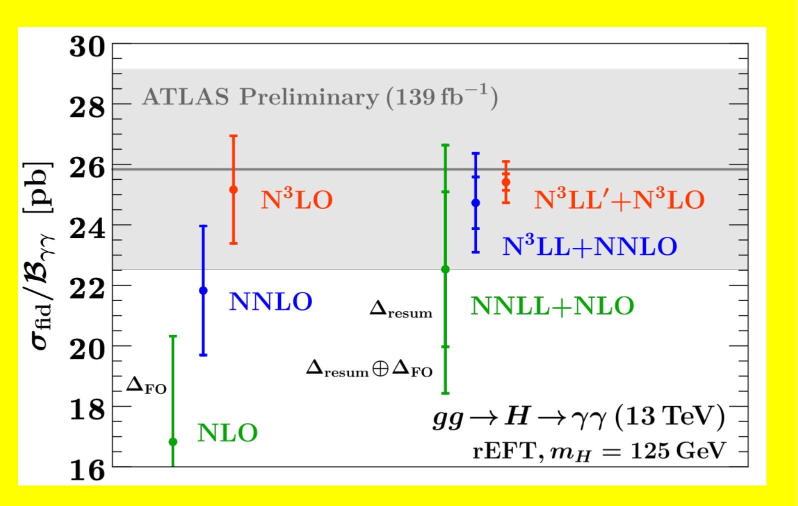
$\sqrt{S}$=2,10,20,40,70,100 TeV

EHLQ

Major lesson from last 14 years at LHC: Higgs physics is precision physics

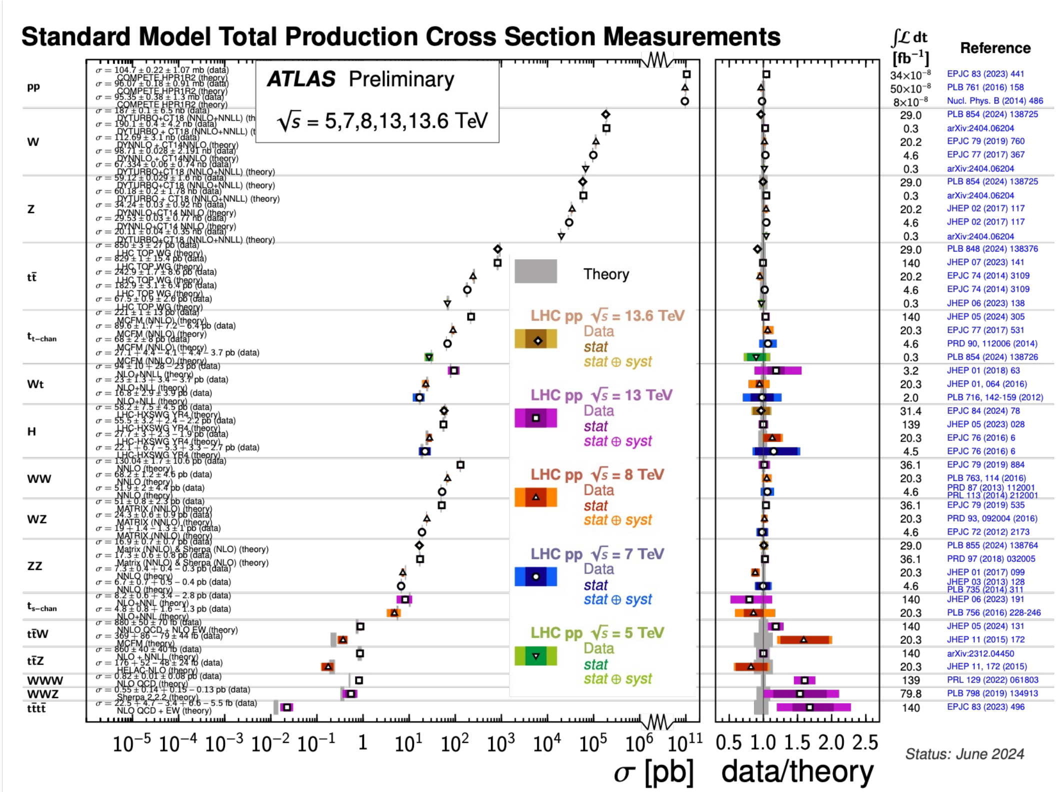
Despite progress, theory uncertainties are expected to dominate Higgs results at LHC

2025



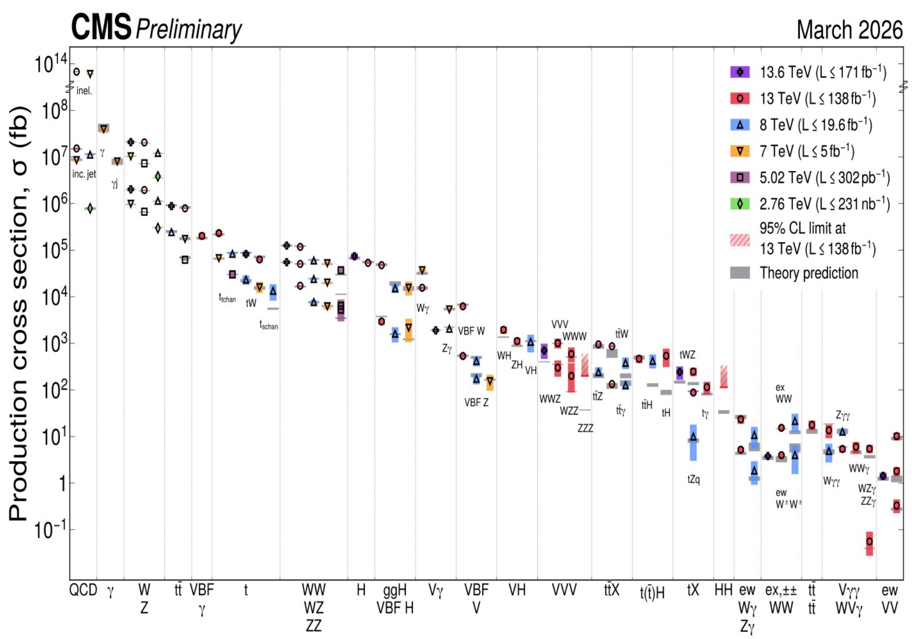
Current uncertainty ~O(3%)

LHC measurements look "SM-like"

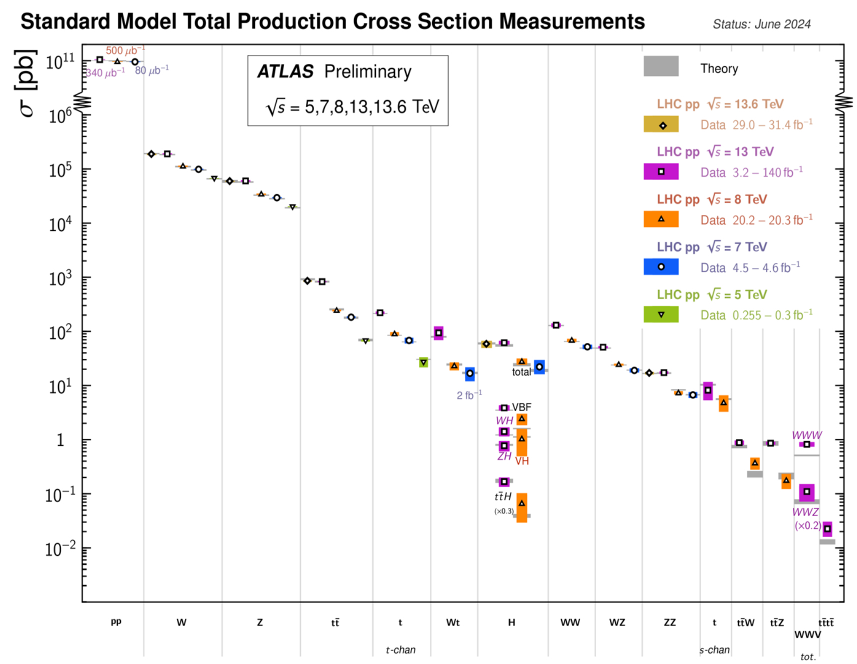


Impressive theory/experiment agreement over many orders of magnitude and in many varied processes

Precision



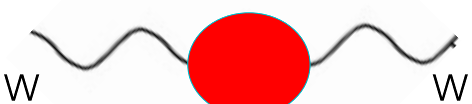
CMS Preliminary
March 2026
Production cross section, σ (fb)
13.6 TeV (L ≤ 171 fb⁻¹)
13 TeV (L ≤ 138 fb⁻¹)
8 TeV (L ≤ 19.6 fb⁻¹)
7 TeV (L ≤ 5 fb⁻¹)
5.02 TeV (L ≤ 302 pb⁻¹)
2.76 TeV (L ≤ 231 nb⁻¹)
95% CL limit at 13 TeV (L ≤ 138 fb⁻¹)
Theory prediction
QCD γ W Z tt̄ VBF γ t WW WZ ZZ H ggH VBF H Vγ VBF V VH VVV tt̄X t(t̄)H tX HH ew Wγ Zγ ex,±± WW tt̄ tt̄ Vγγ WVγ ew VV



Standard Model Total Production Cross Section Measurements
Status: June 2024
ATLAS Preliminary
$\sqrt{s}$ = 5,7,8,13,13.6 TeV
σ [pb]
Theory
LHC pp $\sqrt{s}$ = 13.6 TeV Data 29.0 – 31.4 fb⁻¹
LHC pp $\sqrt{s}$ = 13 TeV Data 3.2 – 140 fb⁻¹
LHC pp $\sqrt{s}$ = 8 TeV Data 20.2 – 20.3 fb⁻¹
LHC pp $\sqrt{s}$ = 7 TeV Data 4.5 – 4.6 fb⁻¹
LHC pp $\sqrt{s}$ = 5 TeV Data 0.255 – 0.3 fb⁻¹
pp W Z tt̄ t t-chan Wt H WW WZ ZZ t s-chan tt̄W tt̄Z WWV tt̄tt̄ tot.

Model is consistent at quantum level

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



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

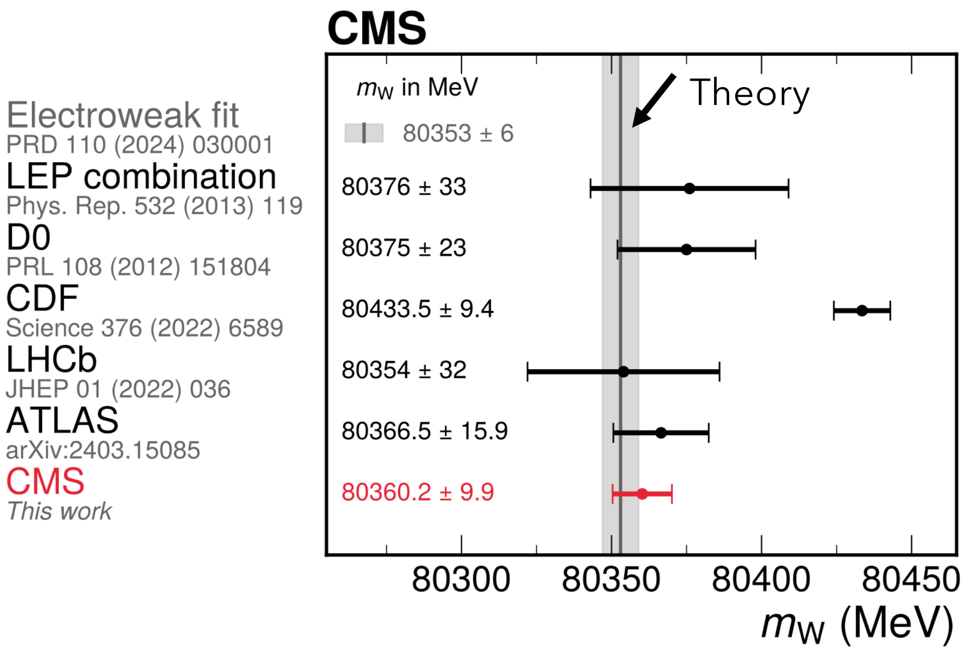
calculable

$$M_W[\mathrm{exp}] = 80.3625 \pm 0.0077\ \mathrm{GeV}$$

- Example of learning from precision measurements!

* M_W [theory] is infinite without Higgs boson

Model works at Quantum Level



Predictions include quantum corrections

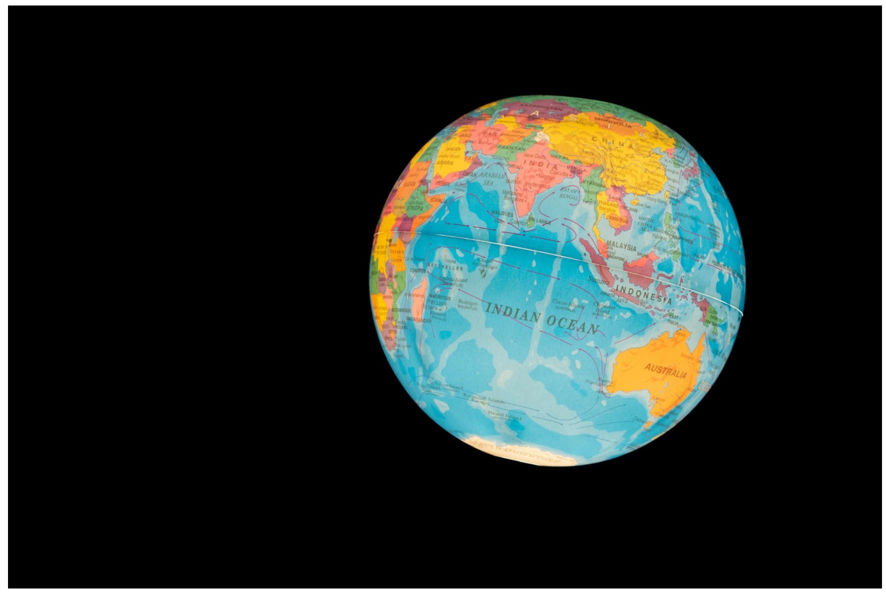
Standard Model fits data very well at the quantum level

Everything we have measured

(Almost) everything is consistent with this picture of physics above 1 TeV

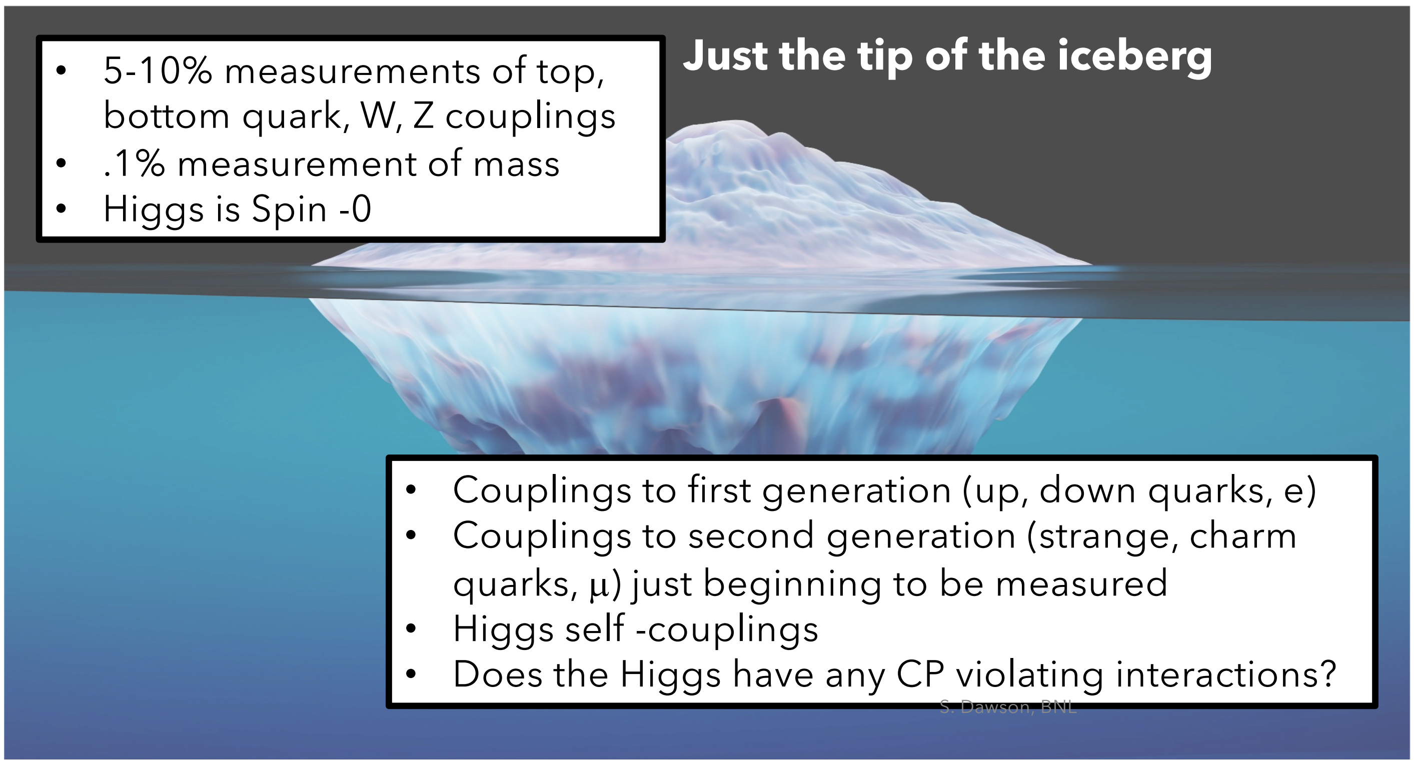
But we are not finished

- The discovery of the Higgs changed everything
- But yet, it leaves us with many unanswered questions
- Opportunities for discovery!



It's the beginning, not the end of the story

Our understanding is incomplete



- 5-10% measurements of top, bottom quark, W, Z couplings
- .1% measurement of mass
- Higgs is Spin -0

- Couplings to first generation (up, down quarks, e)
- Couplings to second generation (strange, charm quarks, μ) just beginning to be measured
- Higgs self -couplings
- Does the Higgs have any CP violating interactions?

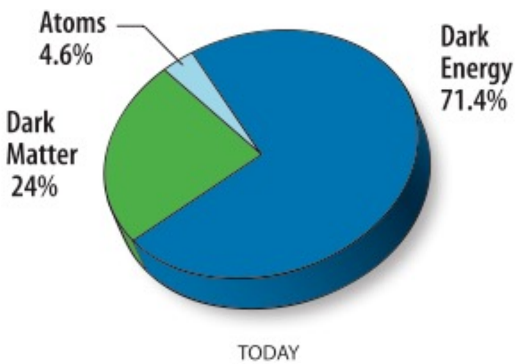
These are just Higgs questions…..many more questions

The study of the SM cannot be complete yet

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

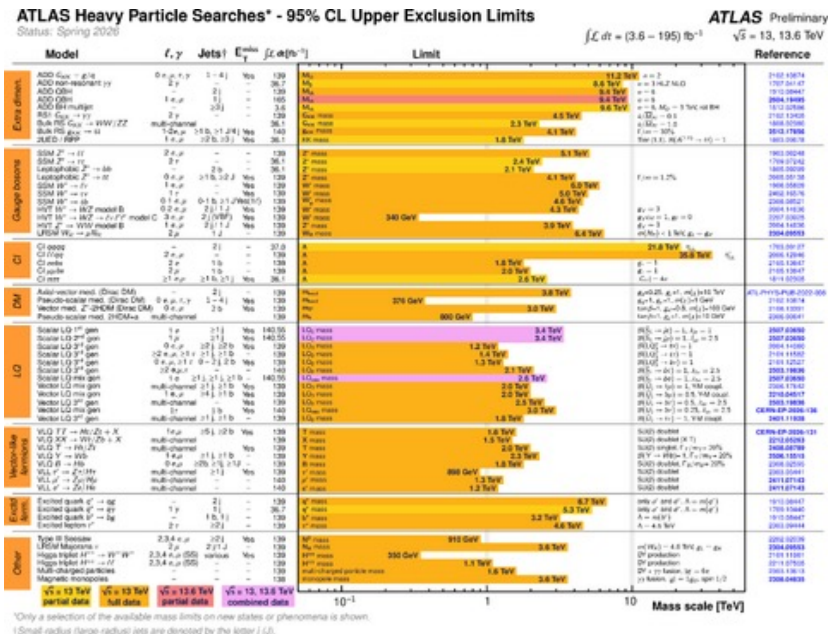


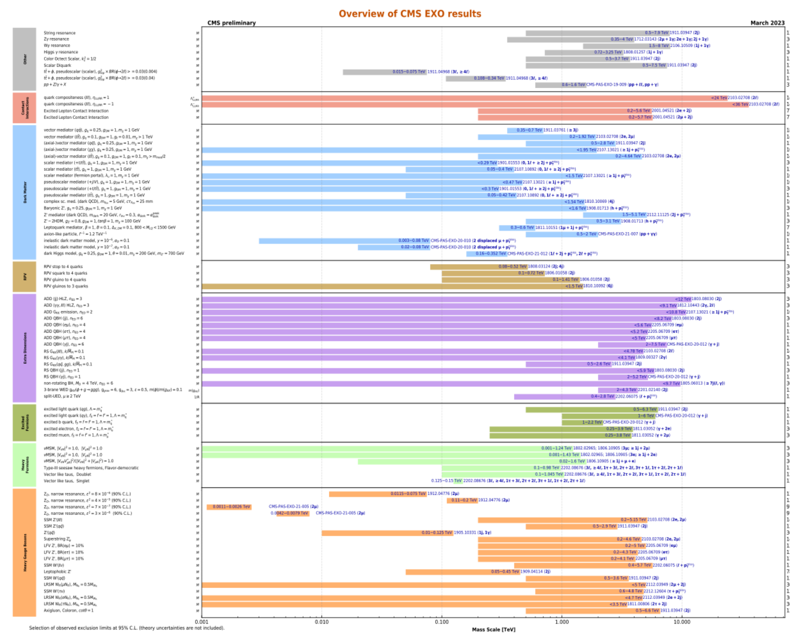
Many questions

- Want to explain why the top quark is heavy
- Want to explain why neutrinos are light
- Want to explain why $M_W <<$ Mplanck ~ 10^{19} GeV (~Scale of Gravity)
- Want to figure out what dark matter is

- All of these questions have led to vast amounts of creative theory
- Typically, theory attempts to address these questions end up postulating many new particles

No new particles discovered *(yet?)*

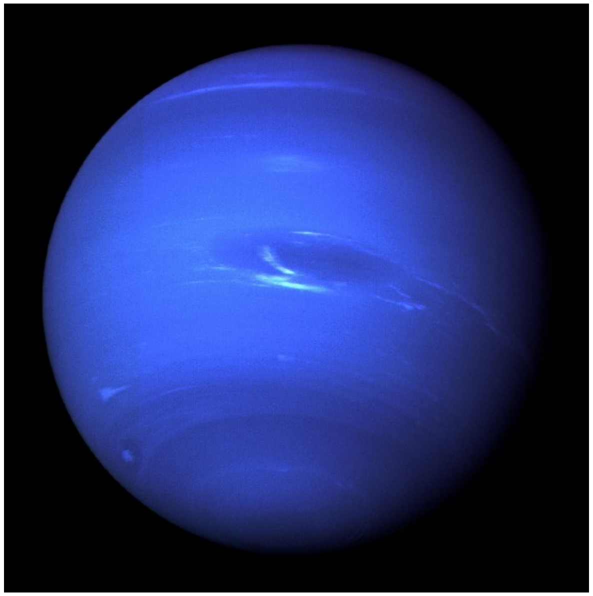




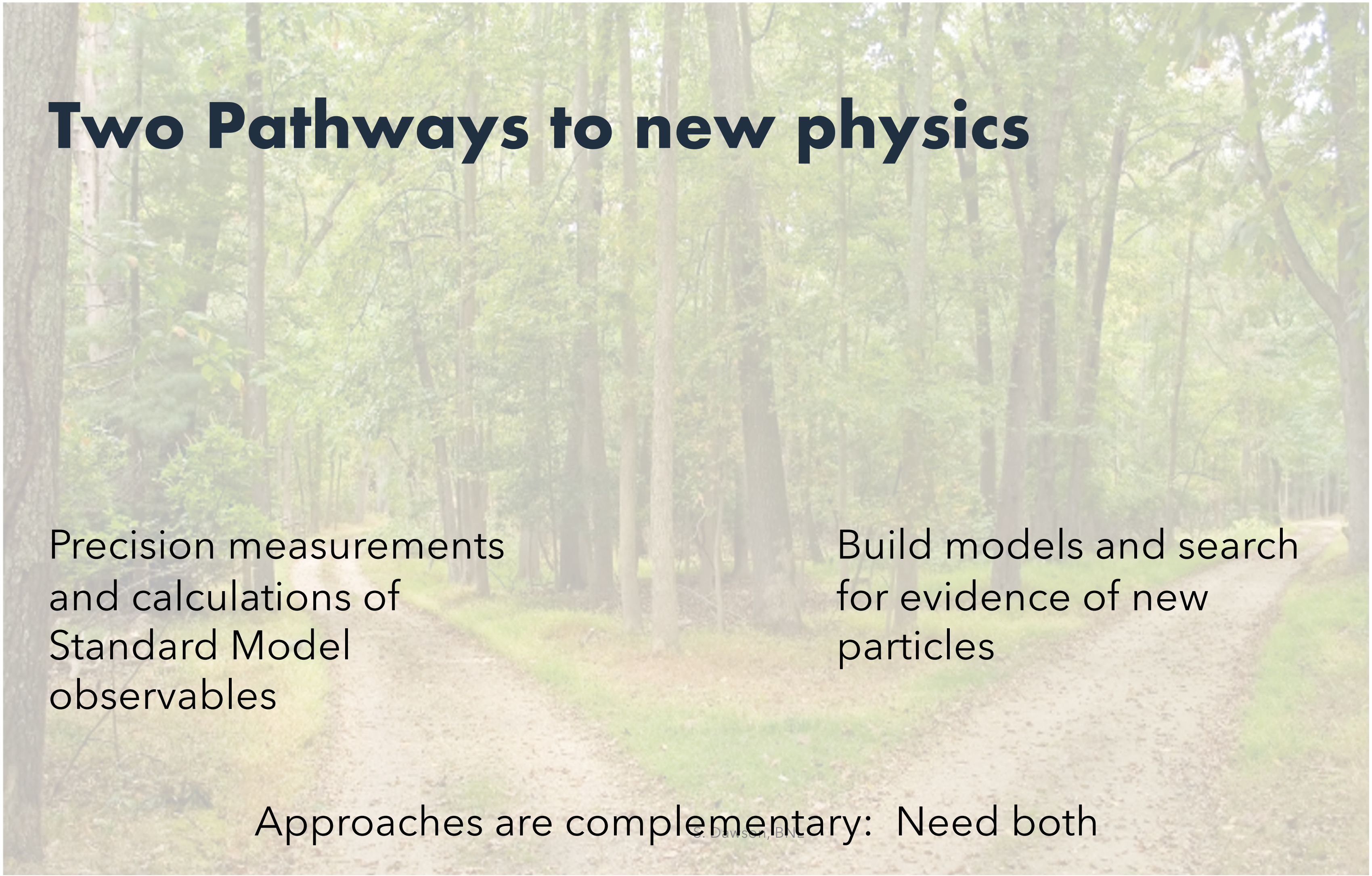
Many limits exceed 1 TeV

New physics isn't always new particles

- This wouldn't be the first time that we discover new physics by careful calculation and measurement



- Nov. 10, 1845: Urbain Le Verrier reports small discrepancies in the orbit of Uranus, uncovered through precision calculation
- June 1, 1846: he posits a new planet, whose presence could explain the observed perturbations
- Sep. 24, 1846: *Neptune* is discovered, exactly where predicted by Johann Galle in Berlin



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

To go further

- We need to improve precision on Higgs measurements
- We need to improve quantum tests of Standard Model
- We need to see double Higgs production (See Brost talk)
- We want to further search for new physics

- We will need new colliders
- Many machines have been proposed