Universität Zürich[UZH]

Physik-Institut

PAUL SCHERRER INSTITUT

PHY213 Kern- und Teilchenphysik II
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Extensions of the Standard Model

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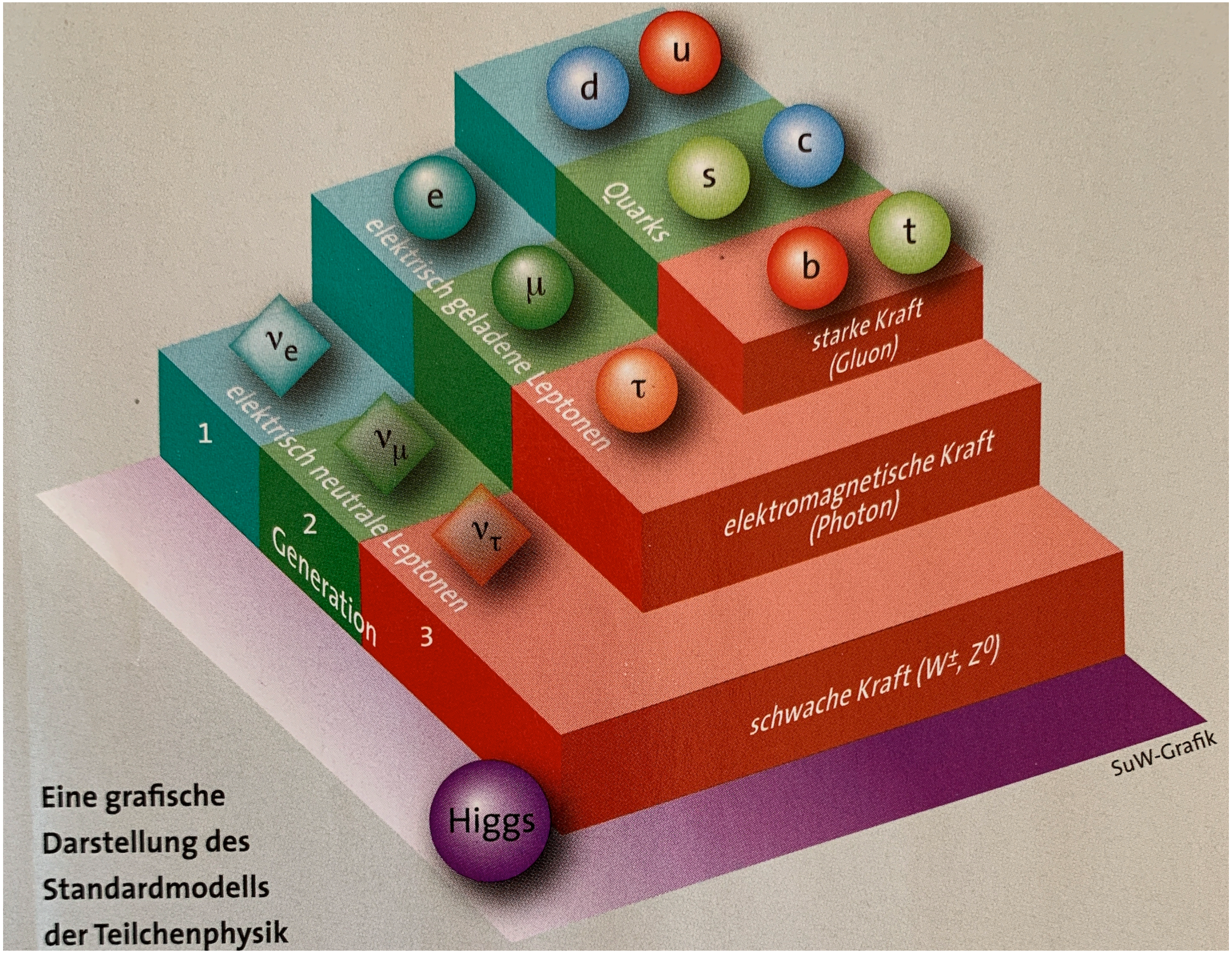
The Standard Model



Multiplets of the electroweak interaction

				T_3	Y	Q
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	-1	0 -1
	e_R	μ_R	τ_R	0	-2	-1
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$
	u_R	d_R	c_R	0	$+\frac{4}{3}$	$-\frac{1}{3}$
	s_R	b_R	t_R	0		
Bosons	$W^\pm$			± 1	0	± 1
	Z			0	0	0
	γ			0	0	0
	H			$-\frac{1}{2}$	$+1$	0

Particle interactions: The SM Lagrangian

- Putting together all ingredients for the SM Lagrangian

Electroweak

$$\mathcal{L} = -\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$W^{\pm}, Z, \gamma$ kinetic energy and self-interaction

$$+\bar{\psi}_L\gamma^{\mu}(i\partial_{\mu} - g\frac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu})\psi_L)$$

$$+\bar{\psi}_R\gamma^{\mu}(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu})\psi_R)$$

lepton and quark kinetic energies and their interaction with $W^{\pm}, Z, \gamma$

$$+\left|(i\partial_{\mu} - g\frac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu})\phi\right|^2 \quad -V(\phi)$$

$W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$+\frac{g_f}{\sqrt{2}}(\bar{\psi}_L\phi\psi_R + \bar{\psi}_R\phi\psi_L) + h.c.$$

QCD

$$\mathcal{L} = \underbrace{\bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q}_{E_{kin}(q)} - \underbrace{g(\bar{q}\gamma^{\mu}T_{\alpha}q)G^{\alpha}_{\mu}}_{\text{quark-gluon interaction}} - \underbrace{\frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{gluon } E_{kin} \text{ and self-interaction}}$$

Fermion masses

The mass term in the Dirac Langrangian is not gauge invariant under $SU(2)_L \times U(1)_Y$ transformations.

$$m\overline{\psi}_R\psi_L$$

One can make it gauge invariant either by setting m = 0 (i.e., getting rid of it by making all fermions massless), or by using the so-called Yukawa interaction between fermions and the Higgs field:

$$\mathcal{L}_f = \frac{g_f}{\sqrt{2}}\left[\overline{\psi_L}\phi\psi_R + \overline{\psi_R}\phi\psi_L\right] + \text{ h.c.}$$

And after spontaneous symmetry breaking, setting ϕ = v + H, we obtain:

$$\mathcal{L}_f = \frac{g_f v}{\sqrt{2}}\left[\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right] + \frac{g_f H}{\sqrt{2}}\left[\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right] + \text{h.c.}$$

Where the first term gives the fermion masses, and the second term describes the interaction of fermions with the Higgs field.

Fermion masses

The previous slide glosses over important details of the Yukawa interaction. Unpacking it one step further we have more generally:

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= Y_{ij}\overline{\psi_{Li}}\phi\psi_{Ri} + \text{ h.c.}\\ &= Y^d_{ij}\overline{d_{Li}}\frac{v}{\sqrt{2}}d_{Ri} + Y^u_{ij}\overline{u_{Li}}\frac{v}{\sqrt{2}}u_{Ri} + \ldots\\ &= M^d_{ij}\overline{d_{Li}}d_{Ri} + M^u_{ij}\overline{u_{Li}}u_{Ri} + \ldots\end{aligned}$$

Here, Y_{ij} are the Yukawa couplings between the Higgs field and the fermion **flavor eigenstates.**

$$M^d_{ij} = Y^d_{ij}\frac{v}{\sqrt{2}}, \text{ etc}$$

To get to the **mass eigenstates** we need to apply a rotation:

$$M^d_{\text{diag}} = V^d_L M^d V^{d\dagger}_R,\ M^u_{\text{diag}} = V^u_L M^u V^{\text{u}\dagger}_R$$

The rotation matrices V that take us from flavor to mass eigenstates are essentially the CKM matrix:

$$V_{\text{CKM}} = V^d_L V^{u\dagger}_L$$

Parameters of the Standard Model

Need to be experimentally measured !

Charged lepton masses	3
Quark masses	+ 6
Quark mixing angles (CKM)	+ 3
Quark CP violation (CKM phase)	+ 1
SU(2)xU(1) gauge couplings g,g'	+ 2
SU(3) gauge coupling g_S	+ 1
QCD vacuum angle	+ 1
Higgs vacuum expectation value v	+ 1
Higgs boson self-coupling λ	+ 1
Total	**19**

Note:
M_W and M_Z are determined by three parameters:
v, g, g'

$$\boxed{\begin{aligned} &M_H = \lambda v, \\ &M_W = \frac{1}{2} g\, v = \frac{e\, v}{2 \sin\theta_W}, \\ &M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v = \frac{e\, v}{2 \sin\theta_W \cos\theta_W} = \frac{M_W}{\cos\theta_W} \\ &M_\gamma = 0. \end{aligned}}$$

Neutrino sector**:

Neutrino mixing angles (PMNS) + 3 (we know that neutrinos mix)

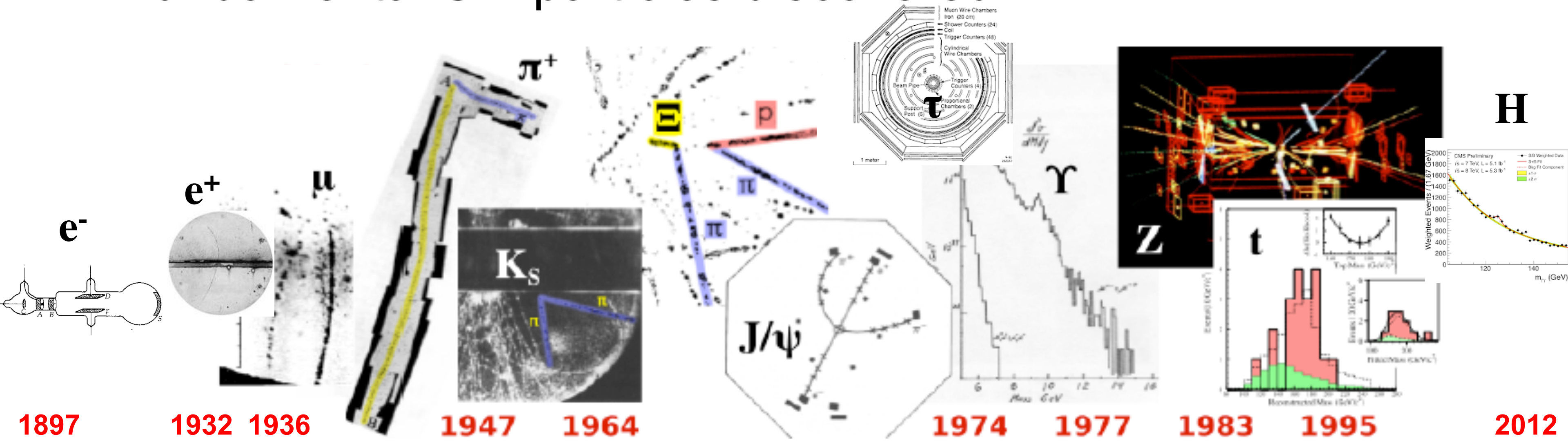
– Neutrino CP violation (PMNS phase) + 1

Neutrino masses + 3 ? (we don't know how neutrinos get mass yet)

** Still fuzzy

Tests of the Standard Model

All fundamental SM particles discovered!



- 1897: Electron: Thomson (cathode ray tube)
- 1932: Positron: Anderson (cosmic rays)
- 1936: Muon: Anderson and Neddermeyer (cosmic rays)
- 1956: ν_e: Cowan and Reines (reactor neutrinos)
- 1962: ν_μ: Ledermann, Schwartz, Steinberger (p fixed target)
- 1974: Tau: Perl (SLAC e^+e^-)
- 2000: ν_τ DONUT collaboration (Fermilab)

- 1964: quark model
- 1974: charm quark (J/psi), Richter and Ting
- 1977: bottom quark (Y), Ledermann
- 1995: top quark, CDF and D0, Fermilab

- 1900: photon Villard
- 1983: W, Z boson, UA1, CERN
- 2012: Higgs boson, CMS and ATLAS, CERN

Precision tests of the Standard Model

★ From LEP and elsewhere have precise measurements – can test predictions of the Standard Model !

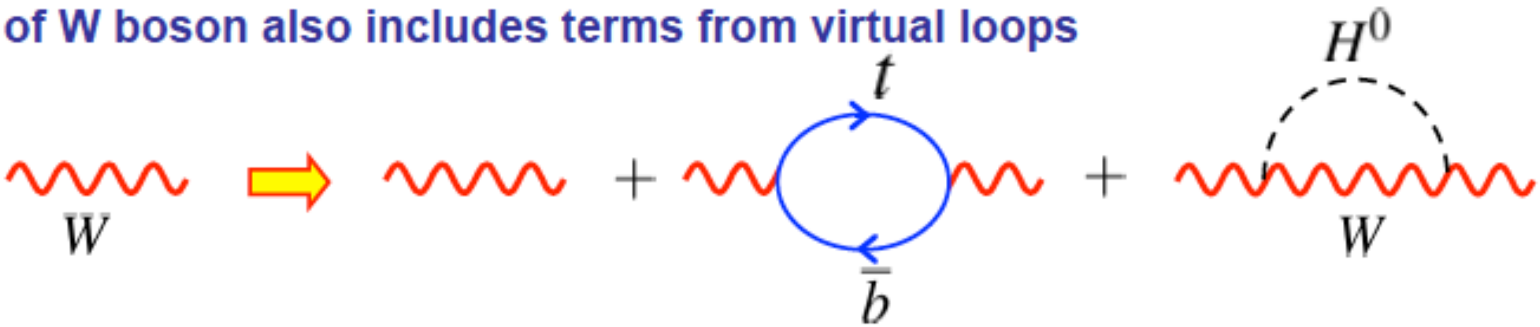
•e.g. predict: $\boxed{m_W = m_Z \cos\theta_W}$ measure $\boxed{m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}}$ $\boxed{\sin^2\theta_W = 0.23154 \pm 0.00016}$

•Therefore expect:

$\boxed{m_W = 79.946 \pm 0.008\,\mathrm{GeV}}$ but measure $\boxed{m_W = 80.376 \pm 0.033\,\mathrm{GeV}}$

★ Close, but not quite right – but have only considered lowest order diagrams

★ Mass of W boson also includes terms from virtual loops



$$\boxed{m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)}$$

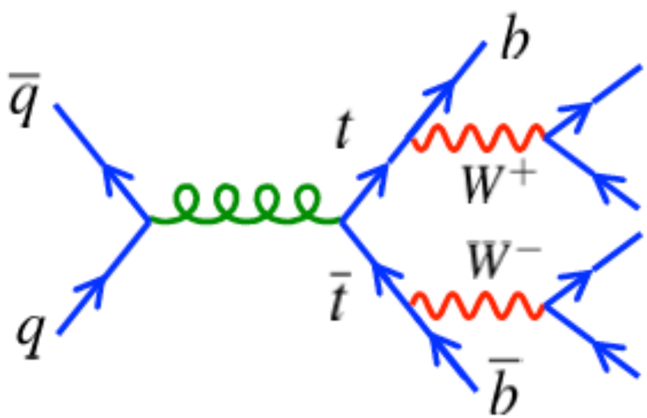
★ Above "discrepancy" due to these virtual loops, i.e. by making very high precision measurements become sensitive to the masses of particles inside the virtual loops !

The top quark

★ From virtual loop corrections and precise LEP data can predict the top quark mass:

$$\boxed{m_t^{\mathrm{loop}} = 173 \pm 11\,\mathrm{GeV}}$$

★ In 1994 top quark observed at the Tevatron proton anti-proton collider at Fermilab – with the predicted mass !



★ The top quark almost exclusively decays to a bottom quark since

$$|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$$

★ Complicated final state topologies:

$$t\bar{t} \rightarrow b\bar{b}q\bar{q}q\bar{q} \rightarrow 6\text{ jets}$$

$$t\bar{t} \rightarrow b\bar{b}q\bar{q}\ell\nu \rightarrow 4\text{ jets} + \ell + \nu$$

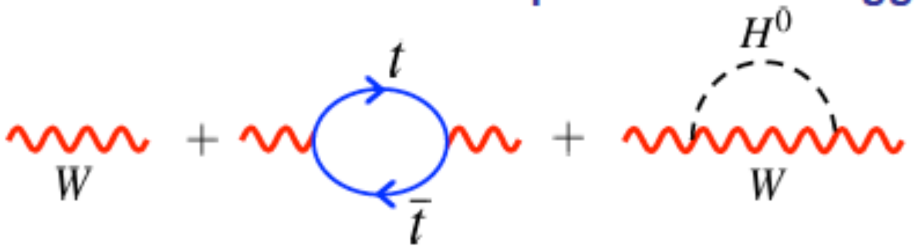
$$t\bar{t} \rightarrow b\bar{b}\ell\nu\ell\nu \rightarrow 2\text{ jets} + 2\ell + 2\nu$$

★ Mass determined by direct reconstruction

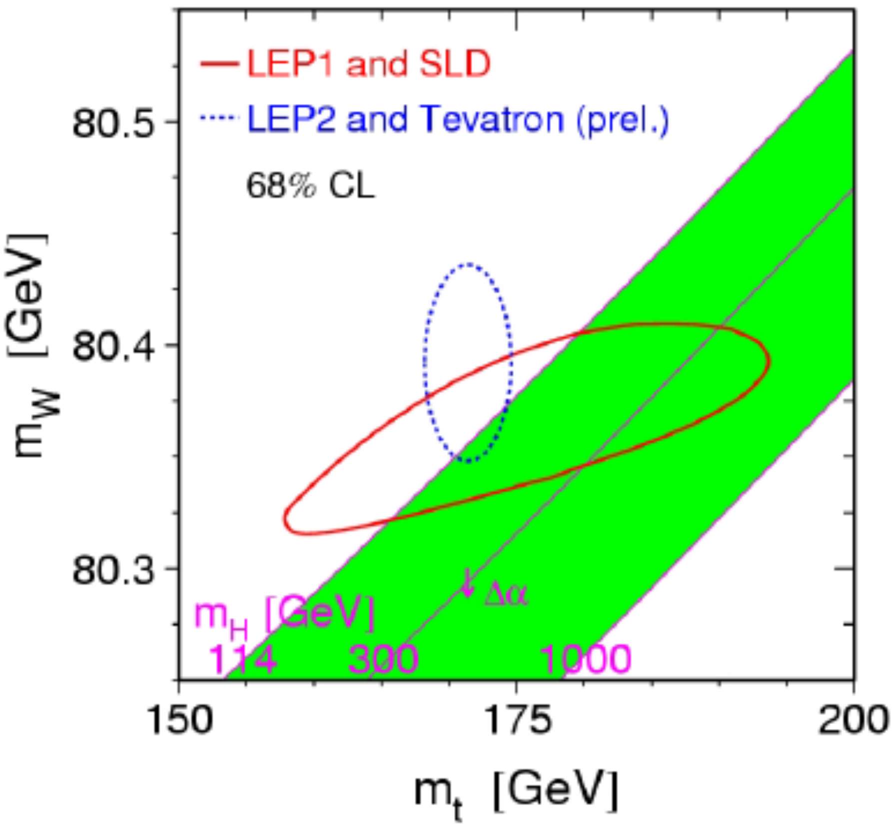
$$\boxed{m_t^{\mathrm{meas}} = 174.2 \pm 3.3\,\mathrm{GeV}}$$

Constraining the Higgs boson mass

★ But the W mass also depends on the Higgs mass (albeit only logarithmically)



$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$



★ Measurements are sufficiently precise to have some sensitivity to the Higgs mass

★ Direct and indirect values of the top and W mass can be compared to prediction for different Higgs mass

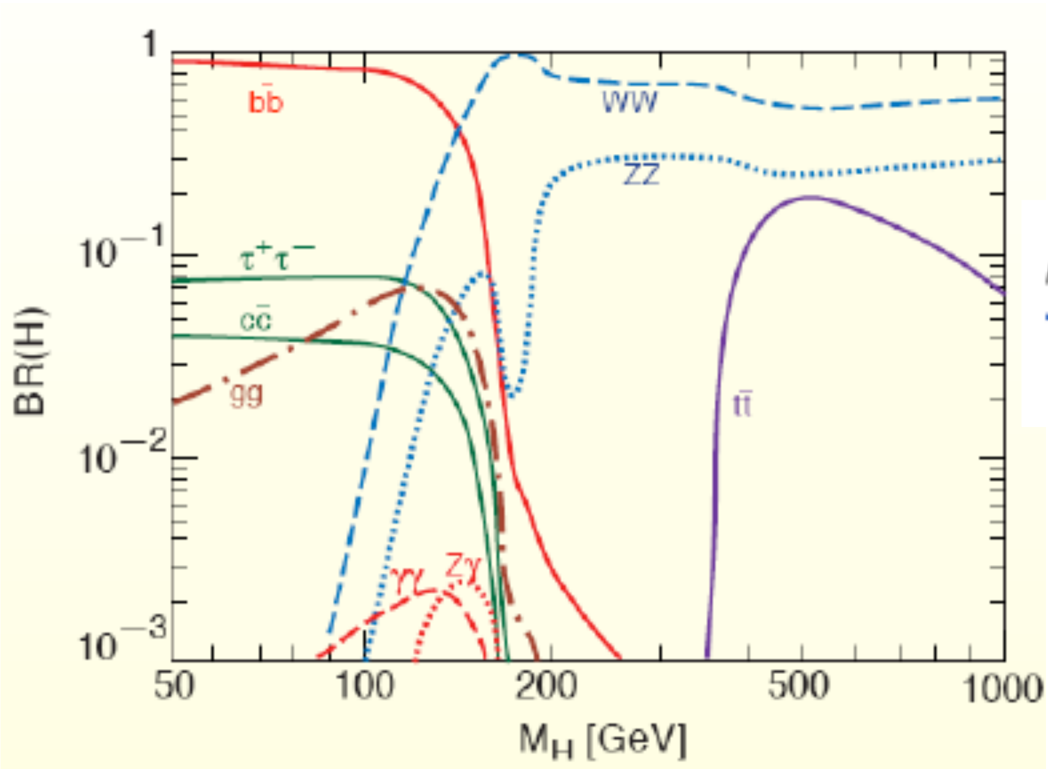
- **Direct:** W and top masses from direct reconstruction
- **Indirect:** from SM interpretation of Z mass, θ_W etc. and

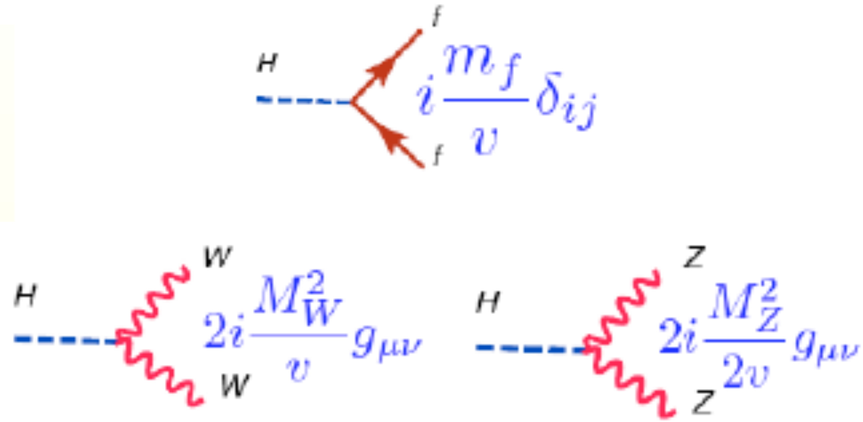
★ Data favour a light Higgs:

$$\boxed{m_H < 200\,\text{GeV}}$$

Hunting the Higgs boson

- For the search, need to know how the Higgs boson decays: The Higgs boson decays into the heaviest massive particles that is allowed by phase space





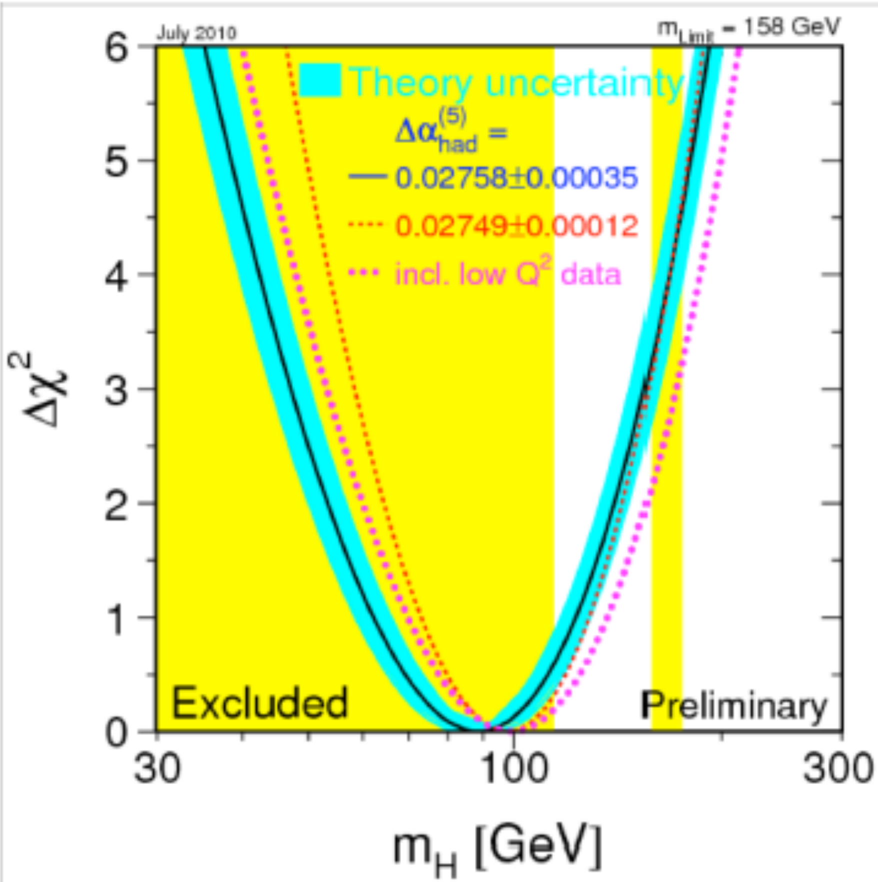
Higgs coupling to:

- fermions grow with their mass
- bosons grow as m^2

Heaviest available fermion dominates until WW,ZZ threshold opens up

The Higgs boson before LHC

From LEP and Tevatron (1983-2011) experiments:



https://inspirehep.net/record/880855/

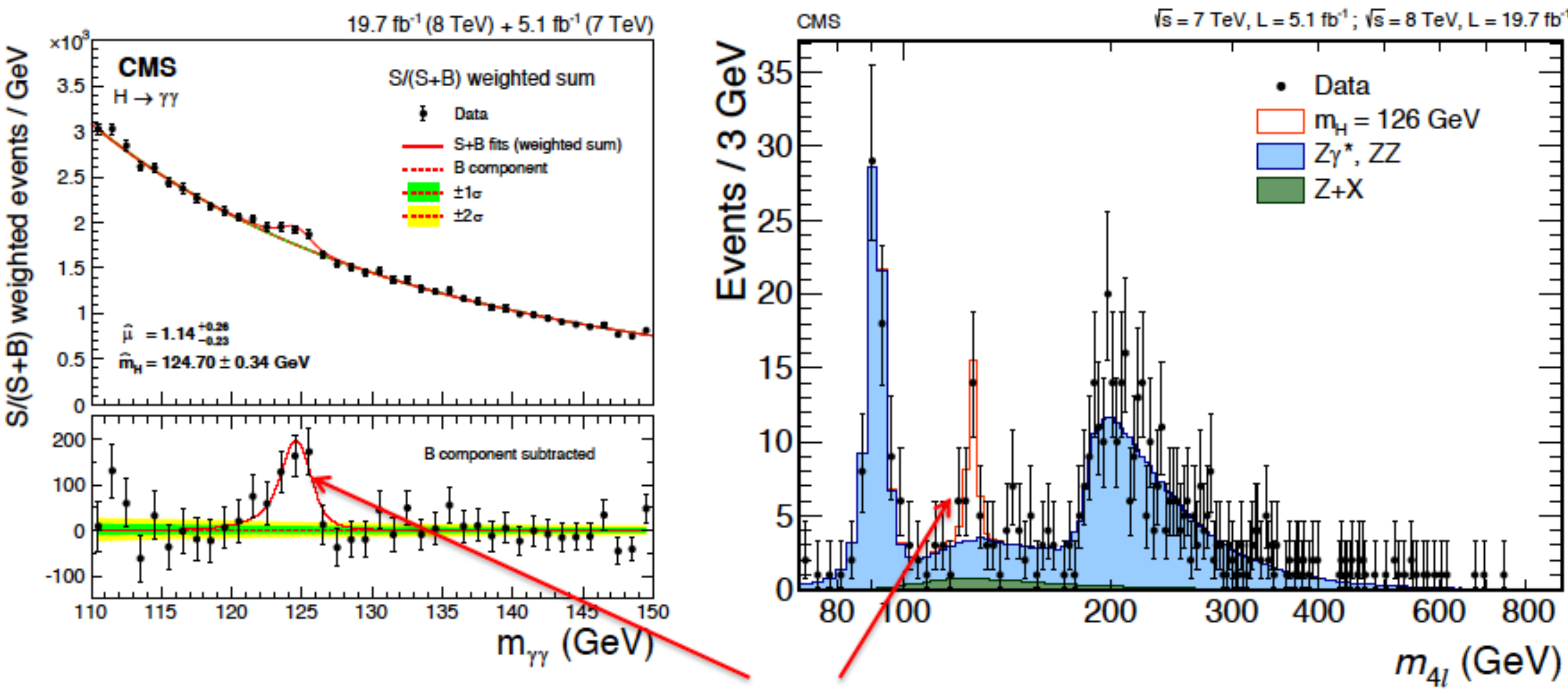
Direct exclusion:

- m_H > 114.4 GeV (LEP)
- m_H < 158 GeV or > 175 GeV (Tevatron)

Preferred value from indirect measurements: $m_H = 89^{+35}_{-26}$ GeV

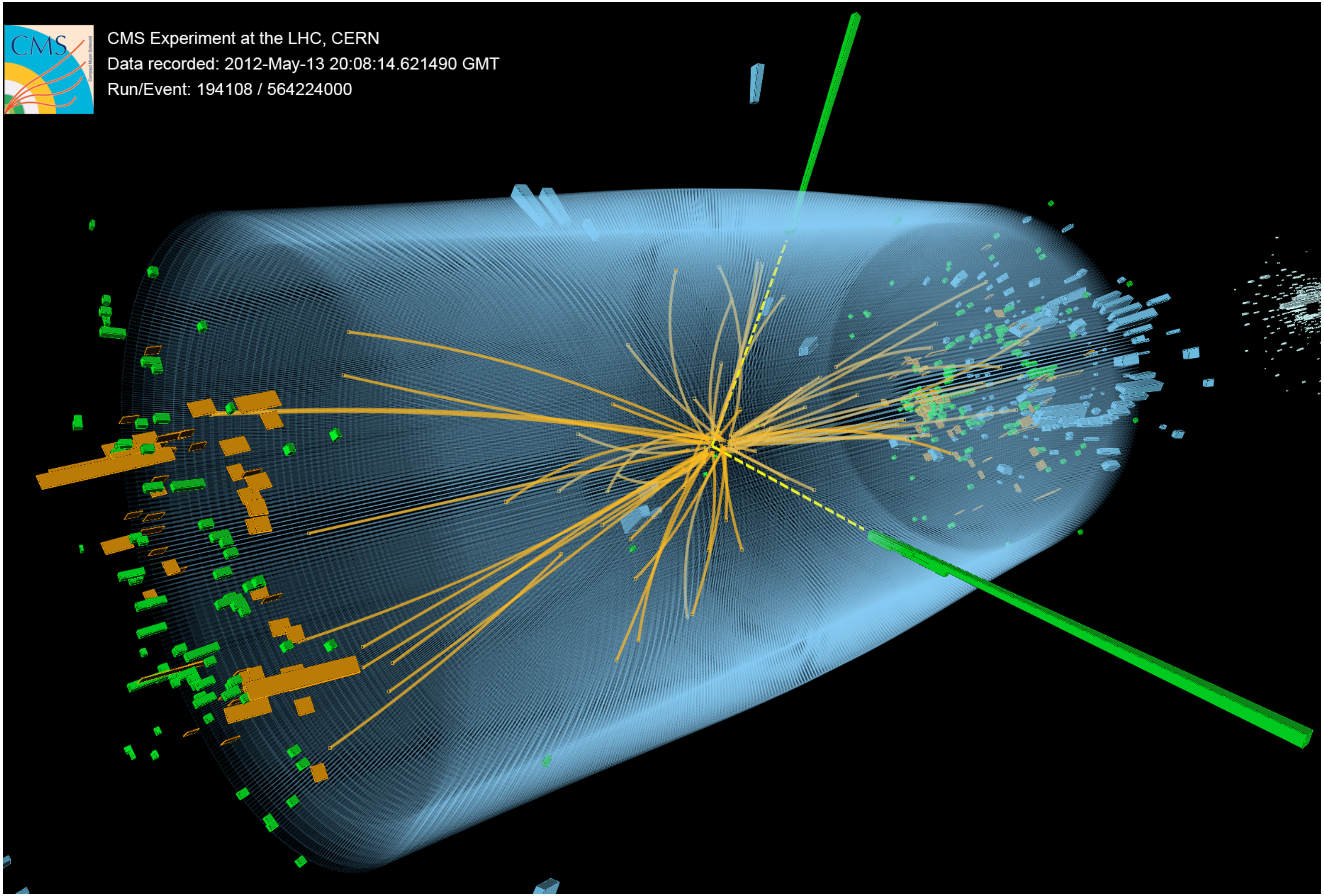
⇒ Waiting for LHC data to solve the controversy...

At CMS in July 2012

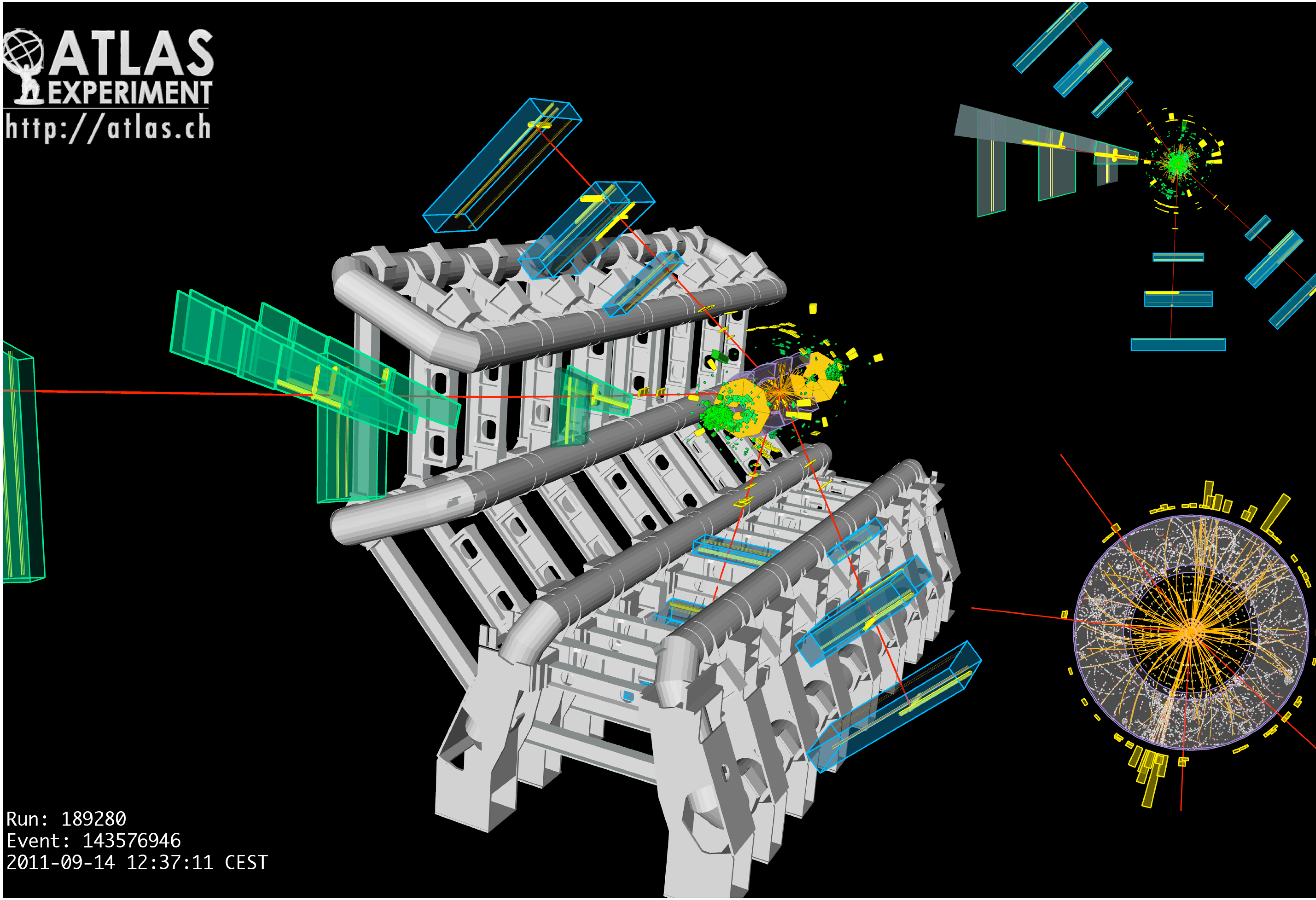


excess of events over expected background,
in two different “channels”

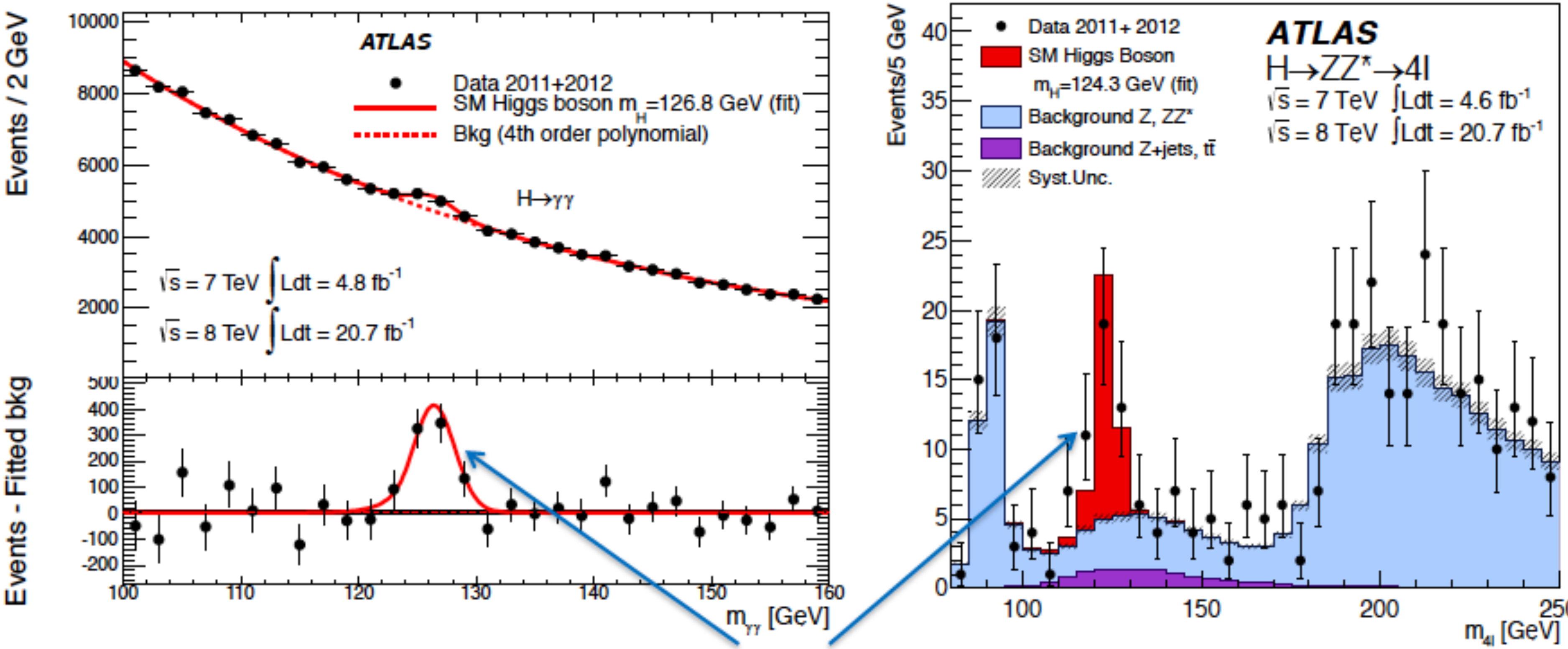
H → γγ at CMS


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

H → ZZ → 4μ at ATLAS

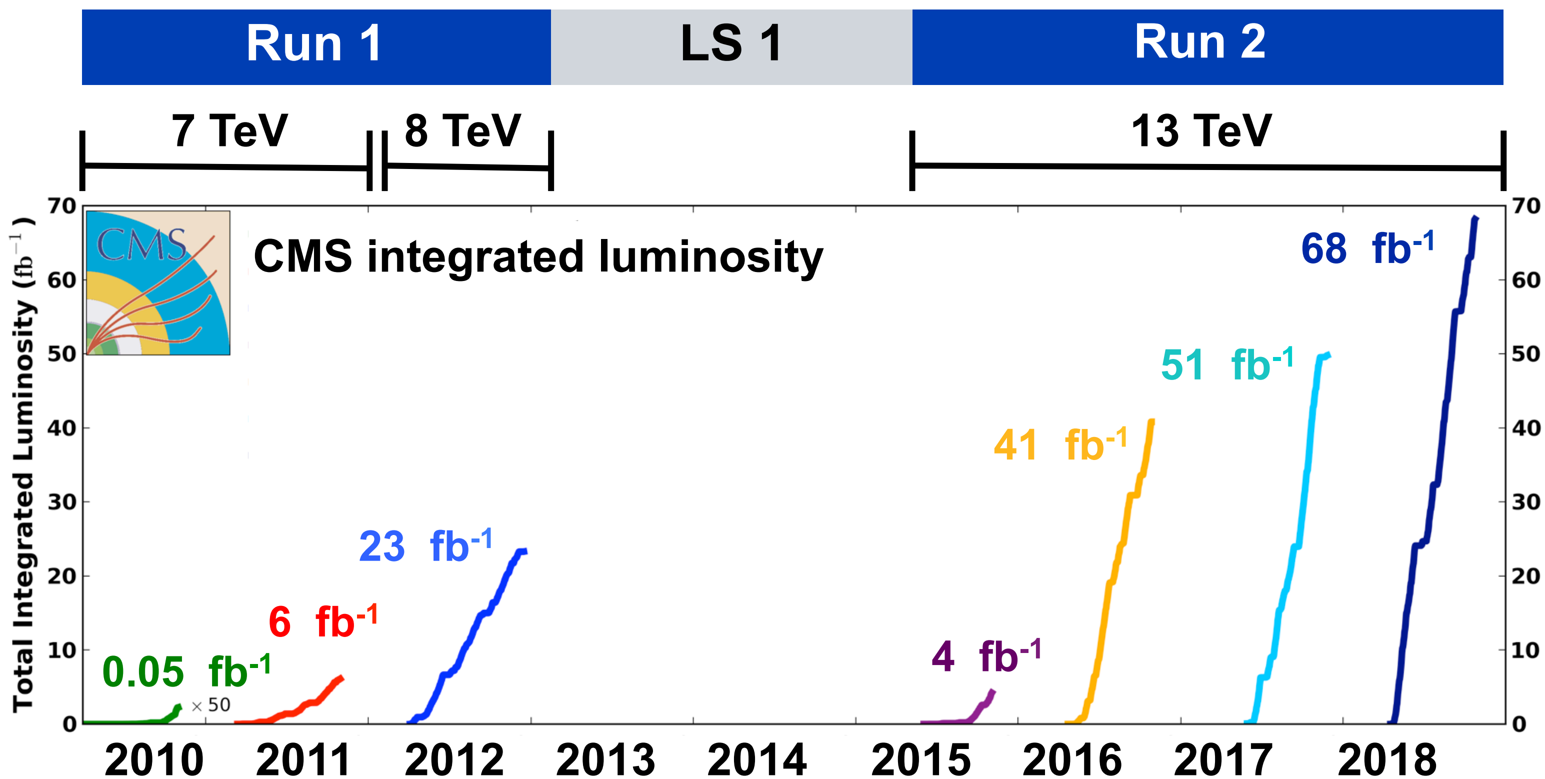


and at ATLAS in July 2012



excess of events over expected background,
in two different “channels”

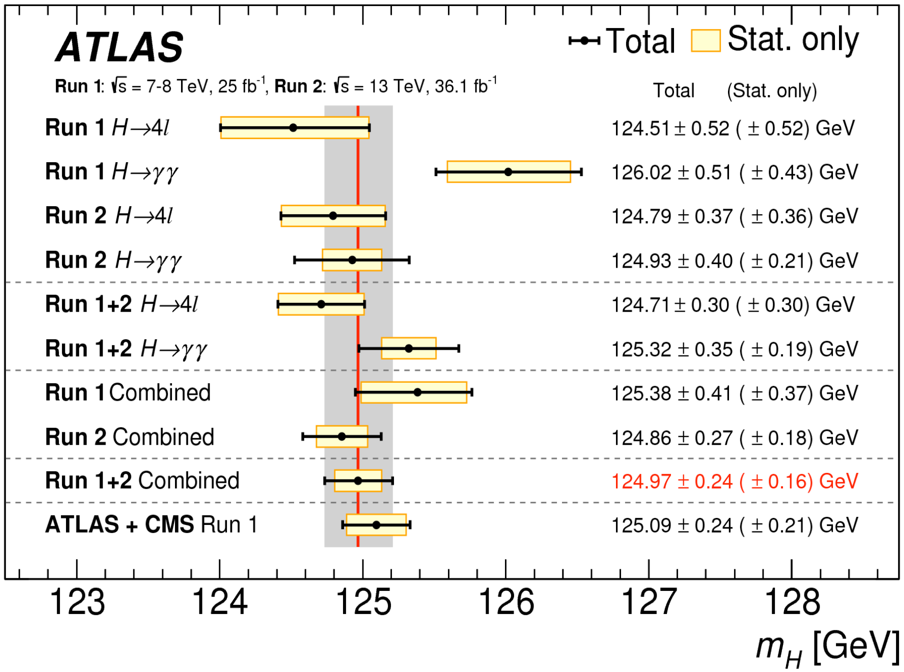
LHC data Run 1 and Run 2

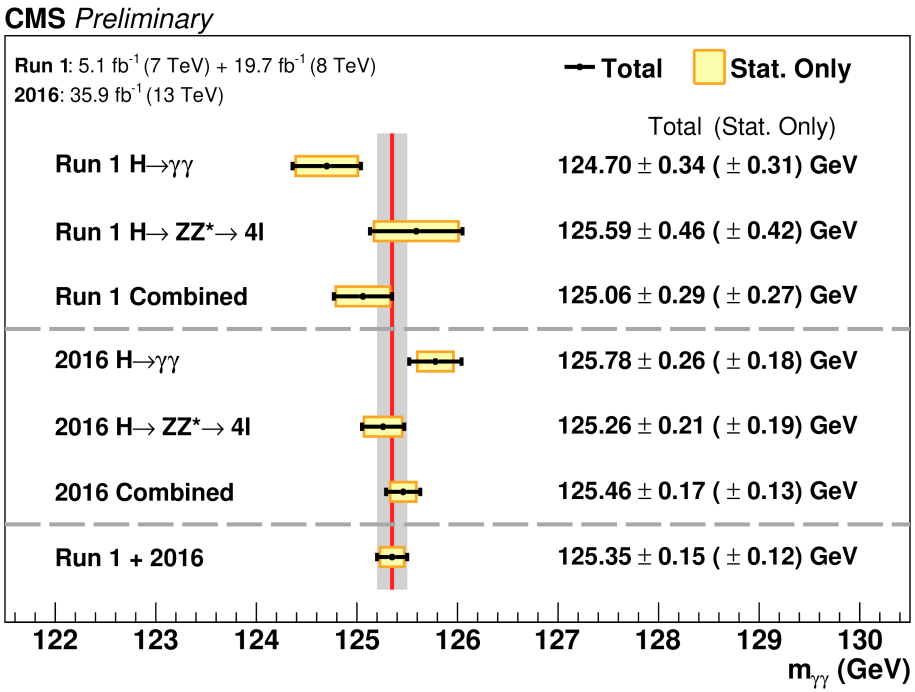


Higgs boson discovery (ZZ,γγ)
200k Higgs bosons produced

Run 2: 7M Higgs bosons produced!
Allows to study Higgs boson properties

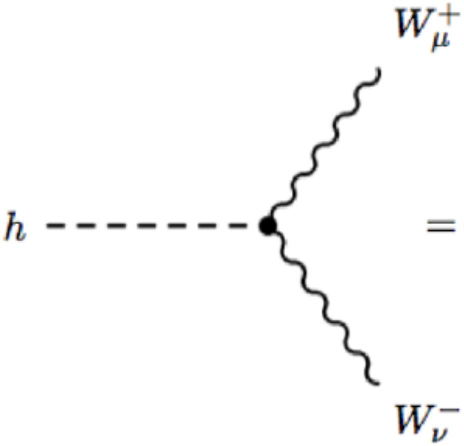
Higgs mass



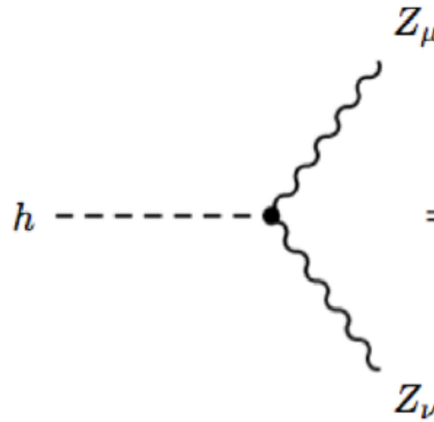


Higgs mass measured to better than 0.1%!

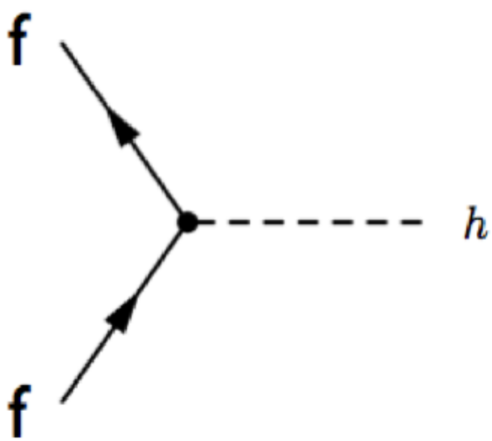
Higgs boson couplings



$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$

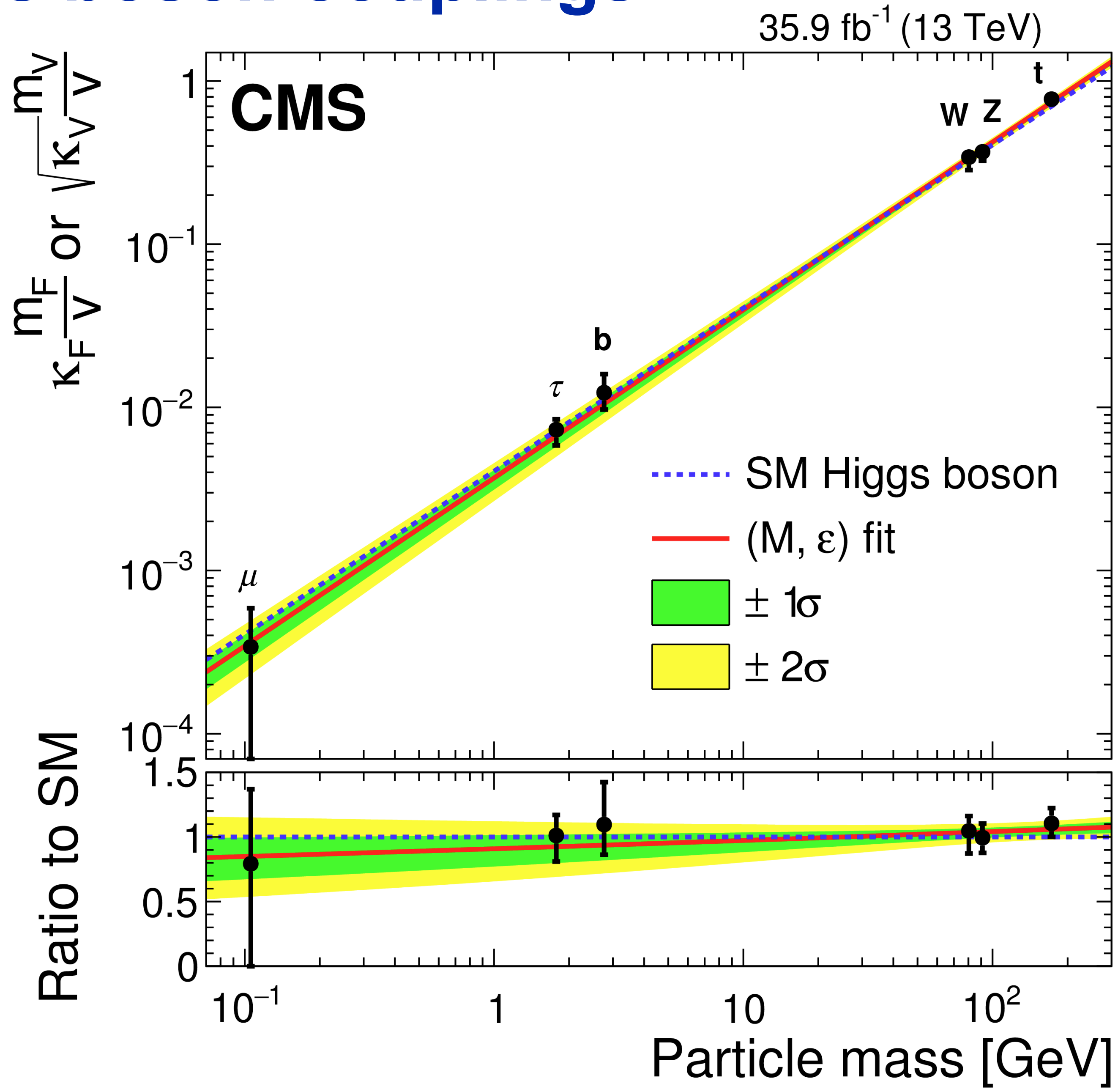


$$= i\frac{(g^2 + g'^2)v}{4} \cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$$



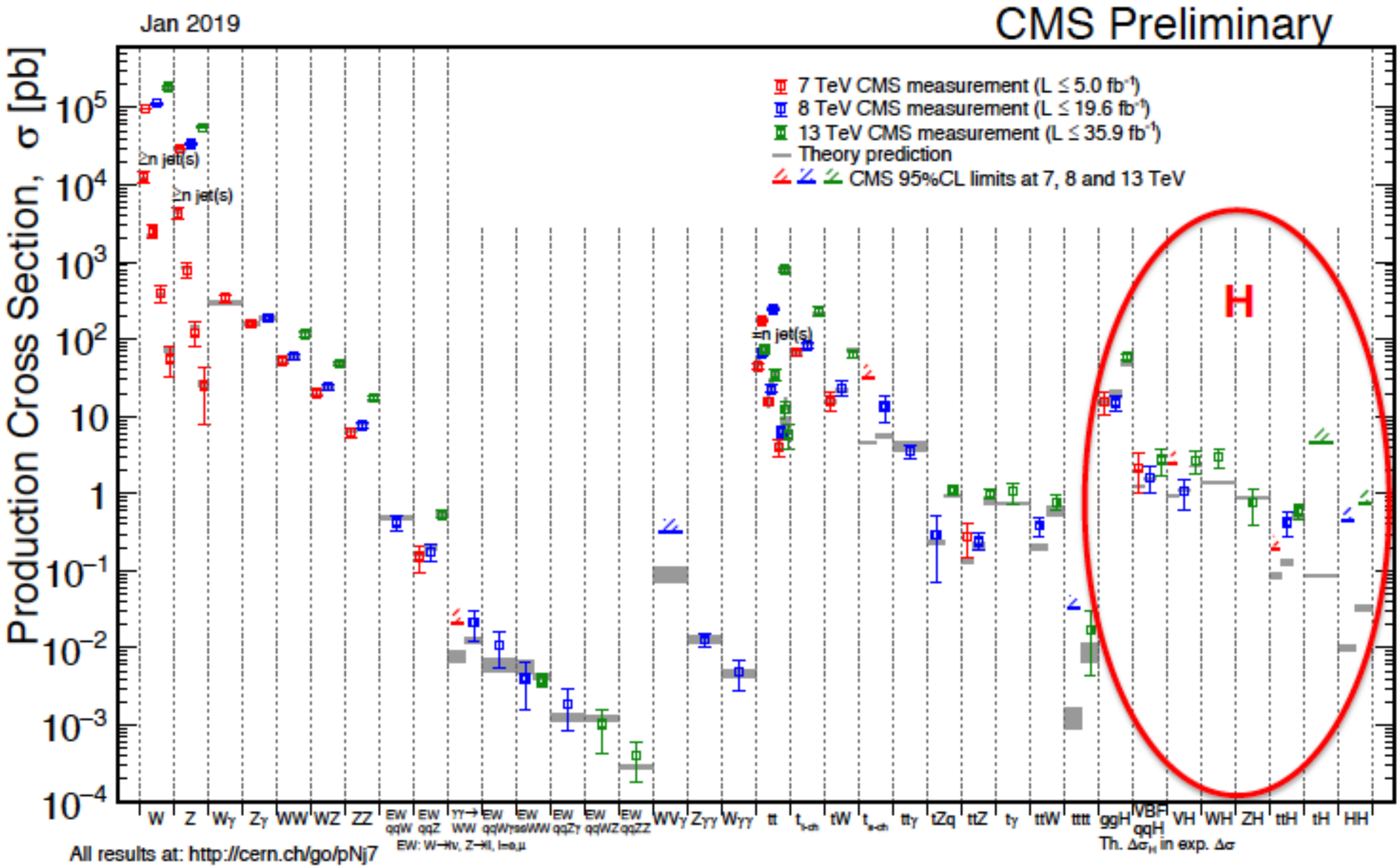
$$= -i\frac{h_f}{\sqrt{2}} = -i\ \frac{m_f}{v}$$

Higgs boson couplings



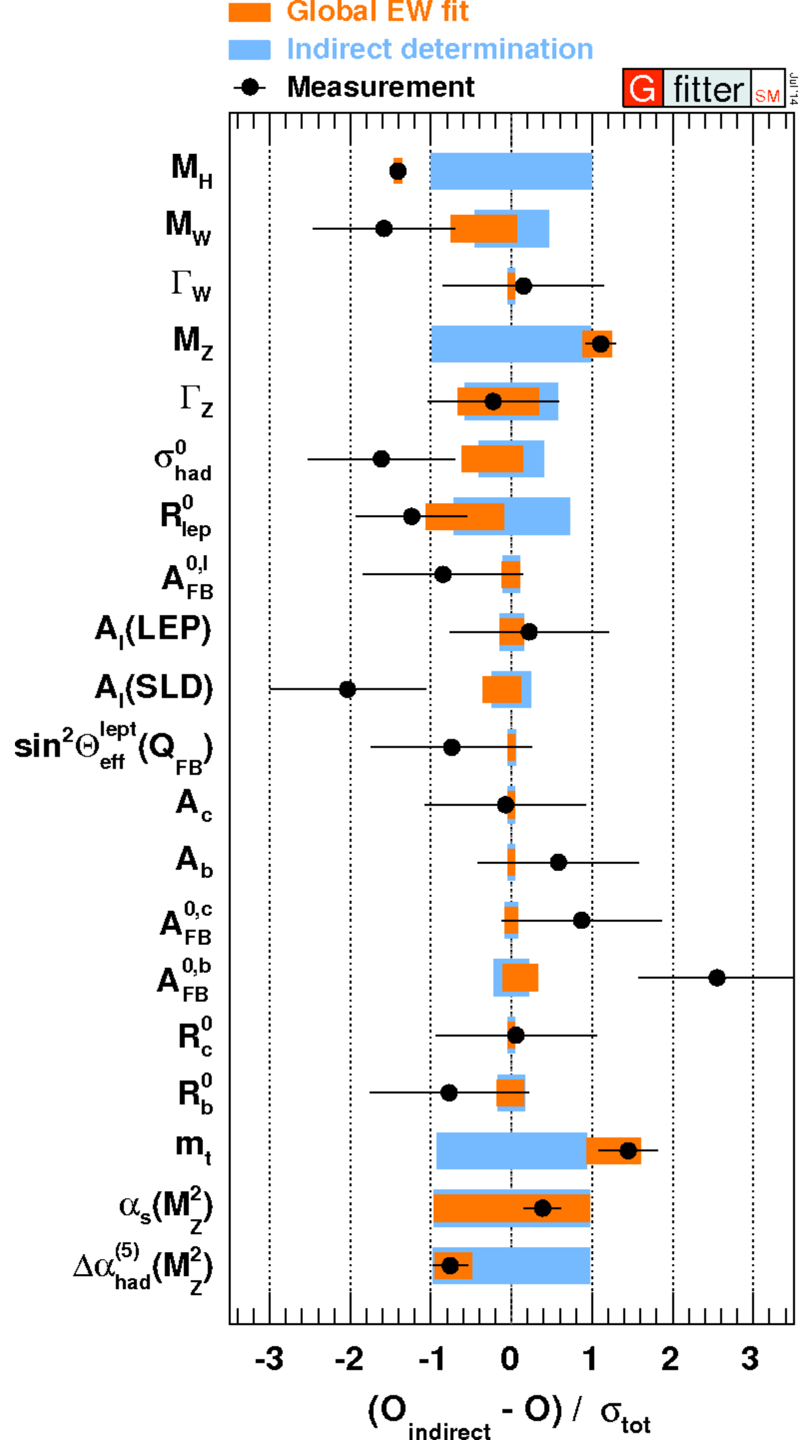
Standard Model precision tests at LHC

- High precision measurements
- Large number of different processes with very different cross sections



Global electroweak fit

Comparison of SM fit results (orange bars) with indirect determinations (blue bars) and direct measurements (data points): pull values for the SM fit defined as deviations to the indirect determinations. The total error is taken to be the error of the direct measurement added in quadrature with the error from the indirect determination.



Beyond the Standard Model

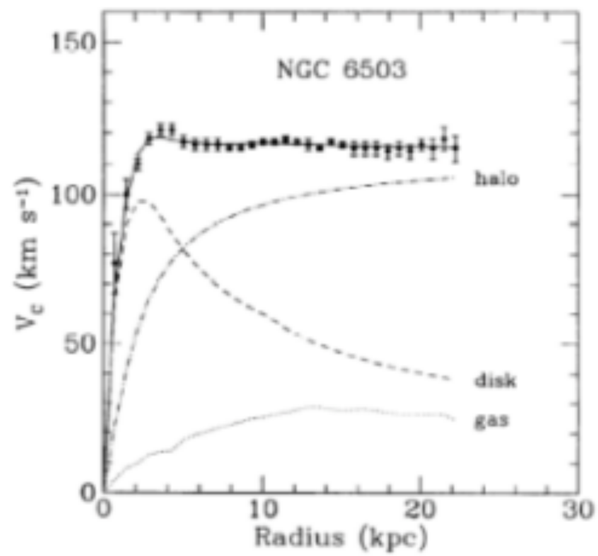
- Despite the excellent agreement of the predictions of the SM with almost all experimental data, we know that it cannot be a complete theory of nature
- Many important problems left open:

- ❑ SM accounts for only 4% of the energy in the universe. What is dark matter? What is dark energy?
- ❑ Today's universe is matter dominated. Where did all the anti-matter go?
- ❑ What mechanism generates neutrino masses?
- ❑ What causes the mass hierarchy in the fermion sector? Why 3 families?
- ❑ Why are there so many parameters in the SM?
- ❑ Why is gravity 10^{40} times weaker than the electroweak force?
- ❑ Why is so much fine-tuning needed to get the Higgs boson mass?
- ❑ Can gravity be included in an extension of the SM?
- ❑ Can the four forces be unified?
- ❑ Why are $m_Z, m_W << m_{Planck}$?
- ❑ Are there more dimensions?
- ❑ ...???

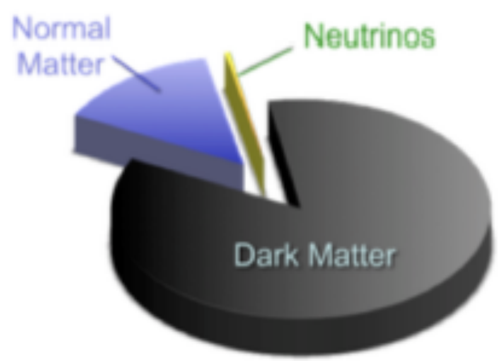
Dark matter and dark energy

- Rotation curves
- Gravitational lensing
- Hot gas in clusters
- Bullet cluster

Existence of DM established !



Quantify ?

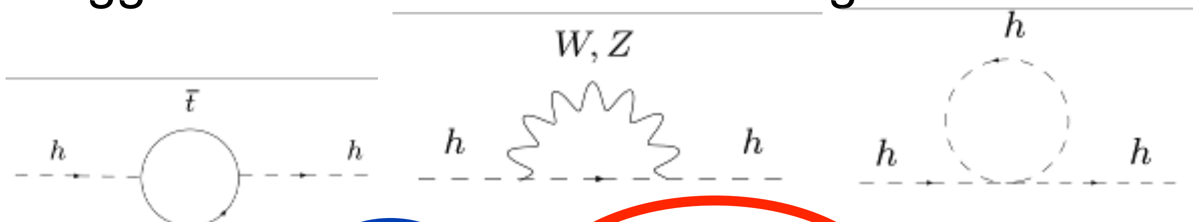


From Cosmic Microwave Background measurements + large scale structures + Big bang nucleosynthesis:

About 84% of matter in Universe is Dark matter

Higgs sector: Fine tuning

- Observed (Higgs boson mass)^2: 10^{32} times smaller than predicted
- Radiative corrections to the Higgs boson mass lead to divergencies that would force the Higgs boson mass to be much larger than the measured mass



$$\Delta m_H^2 = m_H^2 - m_{\mathrm{bare}}^2 = \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

Λ can be as large as the Planck scale

3612789098478930739452093287892833023 -

3612789098478930739452093287892817398 =

= m^2_H = 125^2

Is this natural ?

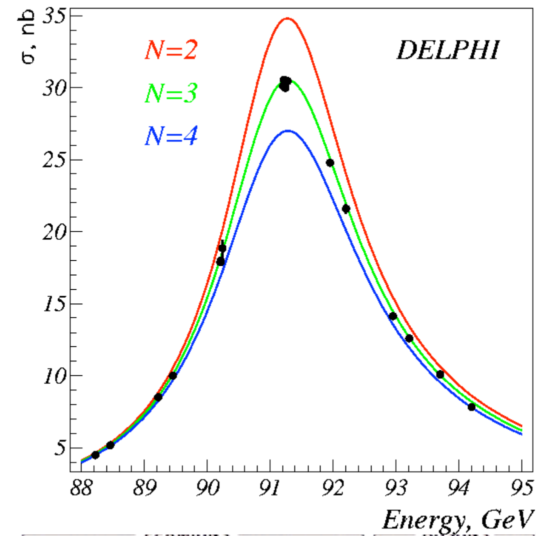
=

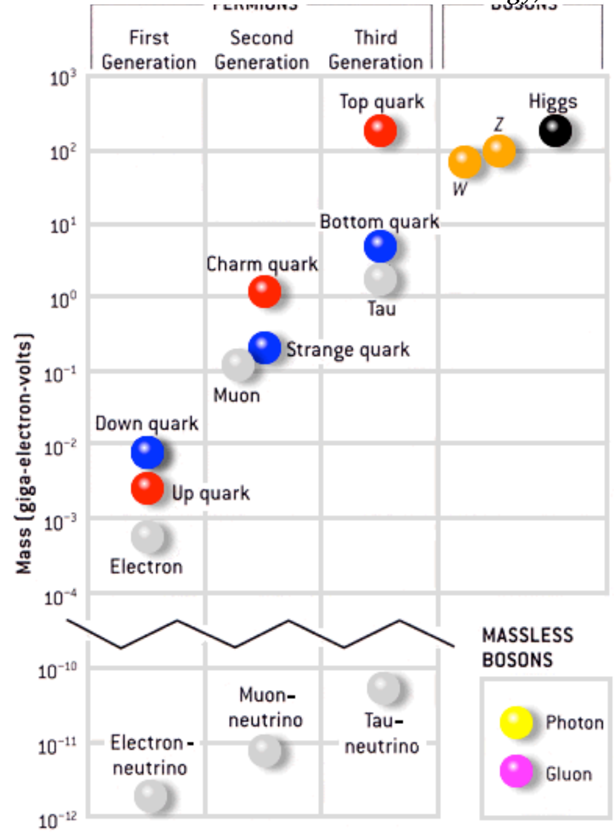
-

pinch of salt | 9.999999… billion tons of salt | 10 billion tons of salt

Flavor sector

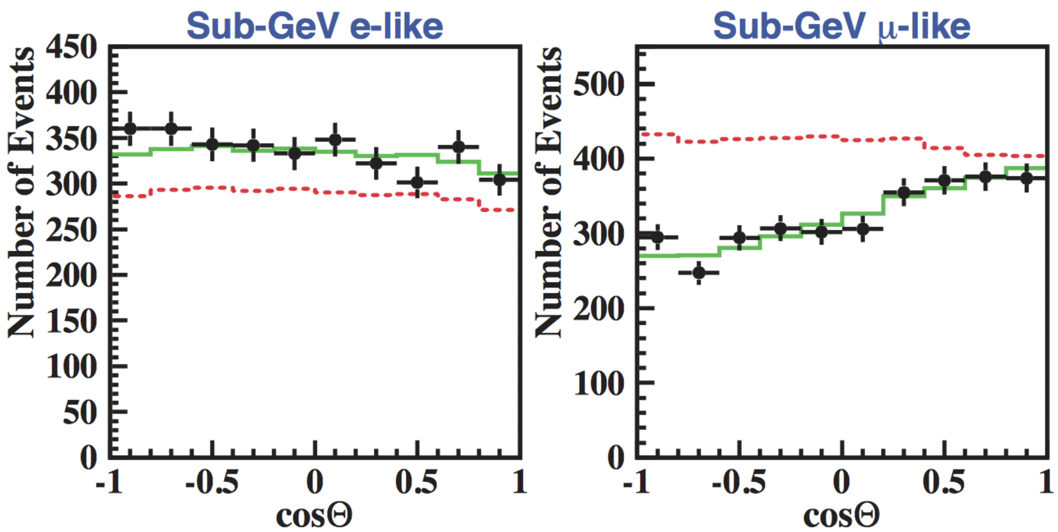
- Fermion masses are free parameters in the SM
- Why are the masses of the fermions so much smaller than the masses of the force particles?
- Is there are reason for the observed pattern in the fermion masses (i.e. in the Yukawa couplings in the SM)?
- Why are there three families?
- What causes the hierarchy in the entries of the CKM matrix?
- Is there insight hiding in the suppressed flavor changing currents?

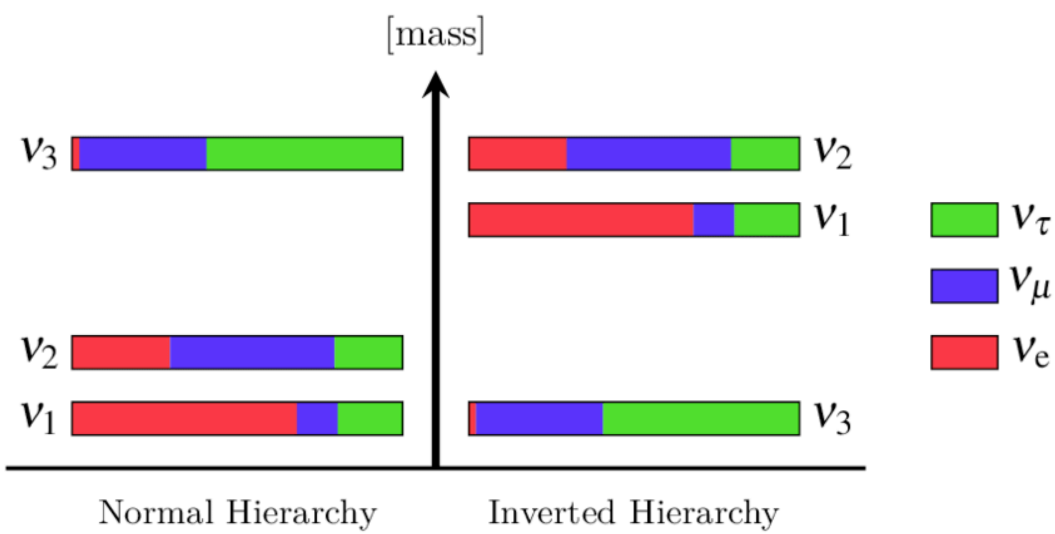




Neutrino sector

- We know that neutrinos have mass because of the measurement of neutrino oscillations
- No right-handed neutrinos in the SM → neutrinos cannot get mass through Higgs mechanism. What other mechanism generates masses of neutrinos? Or do right-handed neutrinos exist?
- Why are neutrino masses so small? What is the hierarchy in neutrino masses?





Beyond SM

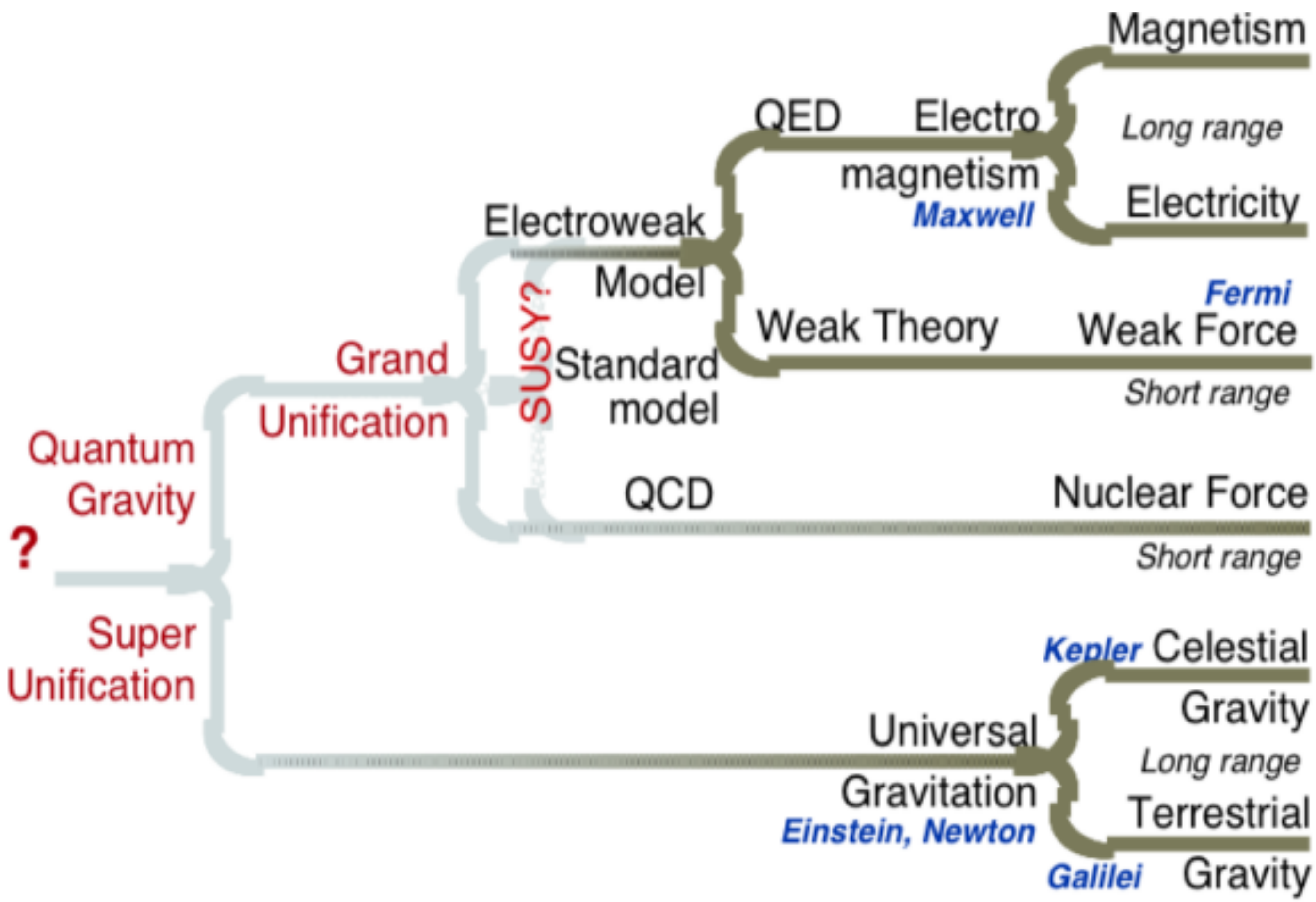
- All these questions imply physics beyond the Standard Model
- The Standard Model itself should be regarded as effective theory, i.e. the limit (in the range of energies and effective couplings probed so far) of a more fundamental theory with new degrees of freedom
- A good new theory should:

  ✧Incorporate the SM and extend it

  ✧Solve one or several of the SM defects

  ✧Describe present and future experimental results

Grand unification theories (GUT)



Theories:

STRINGS ? RELATIVISTIC/QUANTUM CLASSICAL

Simplest GUT model

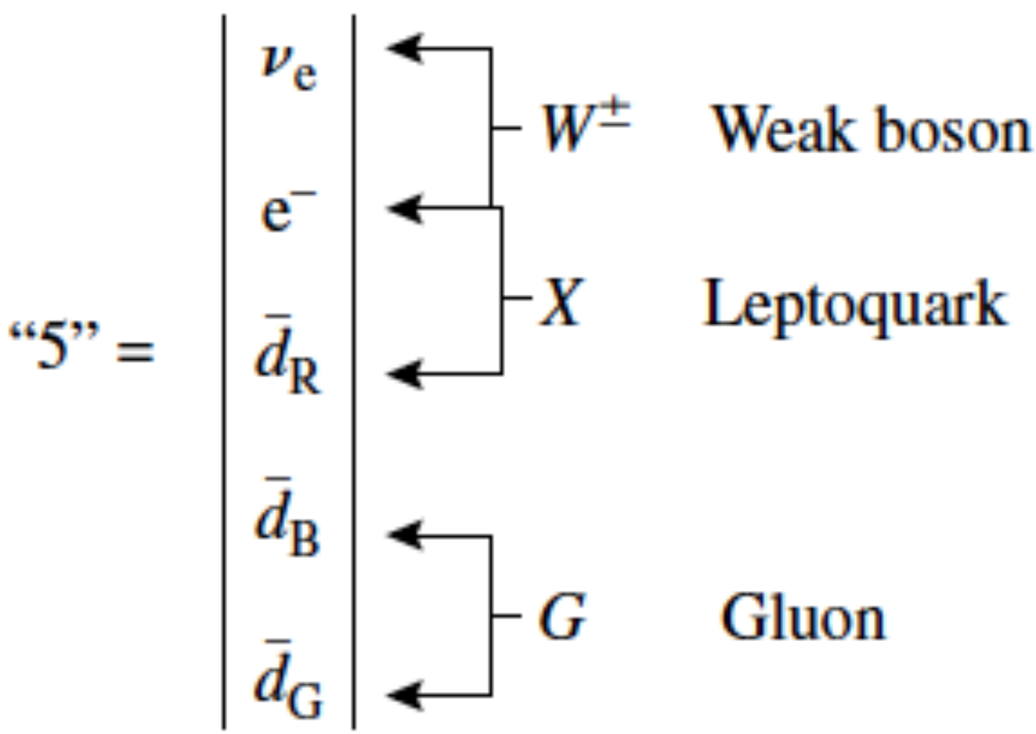
- Basic idea: SU(2)xU(1) (broken symmetry at low energy) and SU(3) (exact symmetry) might be encompassed by a more global symmetry
- This global symmetry would manifest at some high unification energy and again be broken at low energies

- Simplest GUT model proposed by Gregori and Glashow 1974

$$SU(5) \supset SU(3) \times SU(2) \times U(1) \text{ minimal group}$$
$$24 \text{ generators } T^a \Longrightarrow 24 \text{ gauge bosons}$$

Minimal SU(5) model

- Incorporates both, leptons and quarks, into multiplets
- Leptons and quarks can transform into one another via the exchange of massive 'leptoquark' bosons
- Leptoquarks X and Y with charges 4/3 and 1/3



Representation of SU(5)

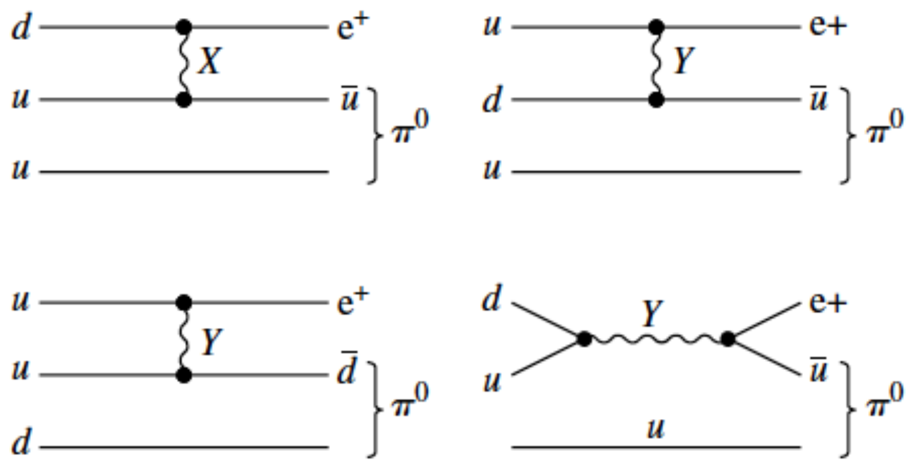
Minimal SU(5) model - Pros

- Total charge within a multiplet is zero
  - Provides explanation for fractional charges of quarks
- Electric charge is generator of SU(5) → get only discrete Eigenvalues → explanation of charge quantization
- Electroweak couplings (g,g') and strong coupling (g_s) can be derived from one coupling in SU(5)
- Value of $\sin^2\Theta_W \approx 0.20$ predicted → consistent with measurements

- GUT scale in the region of 10^{14} GeV

Minimal SU(5) model - Cons

- Exchange of leptoquarks allows for proton decay

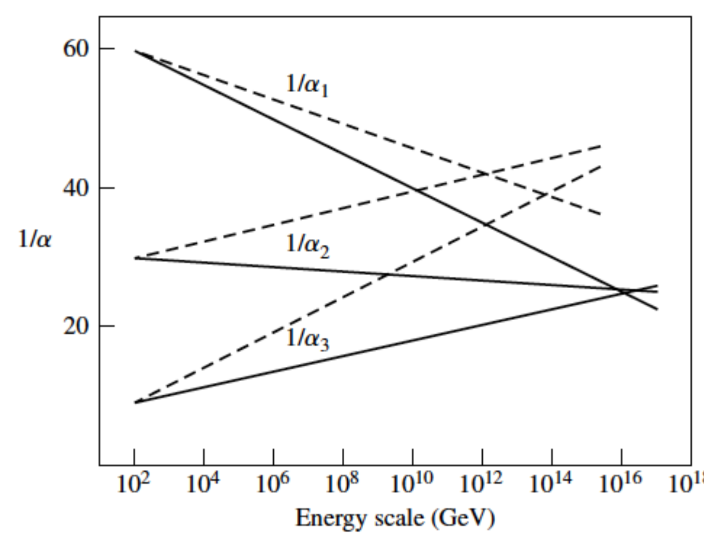


Predicted proton lifetime $10^{(30\pm0.5)}$ years

→ In contradiction with measured value of $> 1.7 \times 10^{34}$ years

- No experimental evidence for existence of leptoquarks
- Couplings do not run to exactly the same value

→ Go to models with larger gauge groups SO(10)...

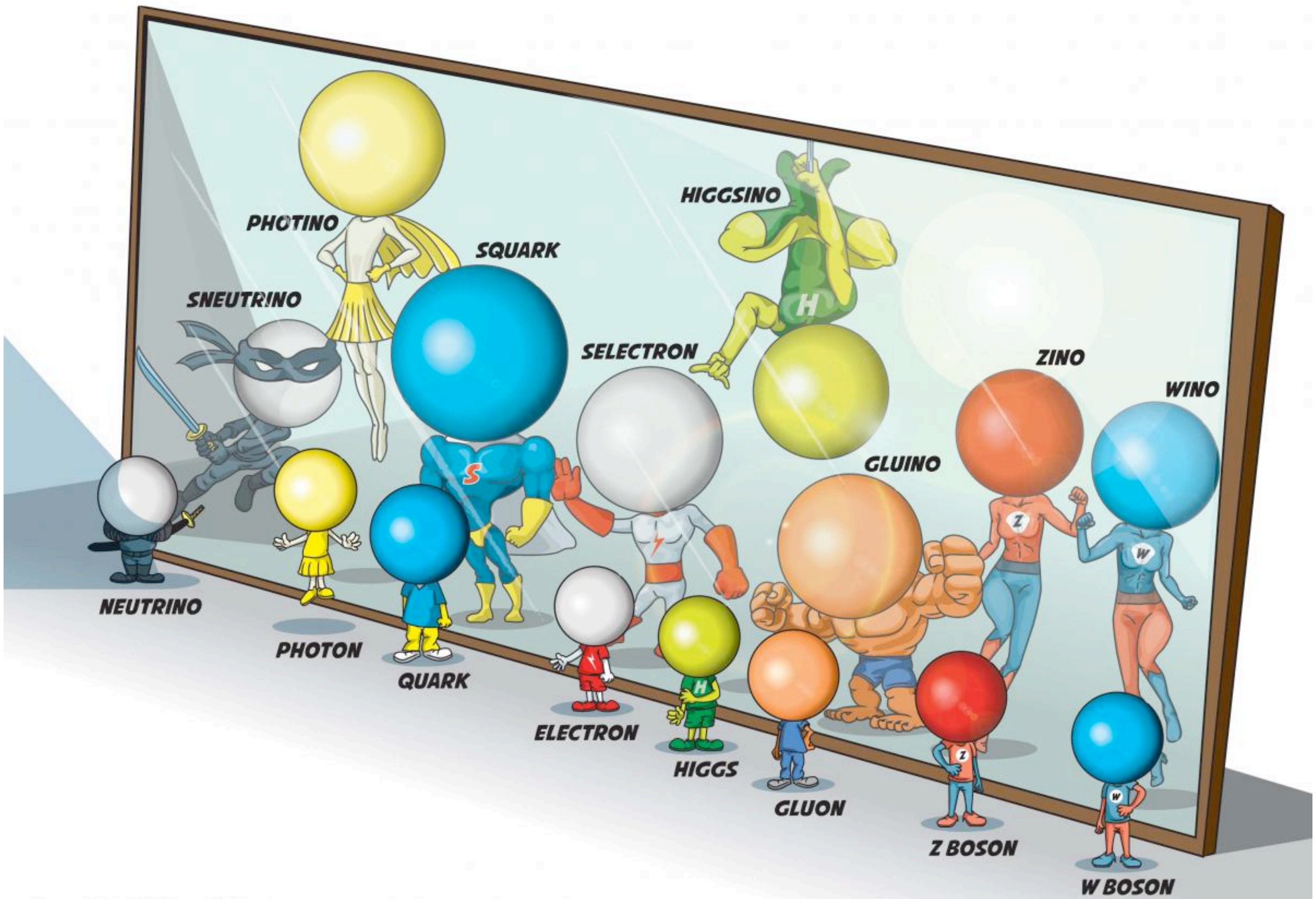


--- SM

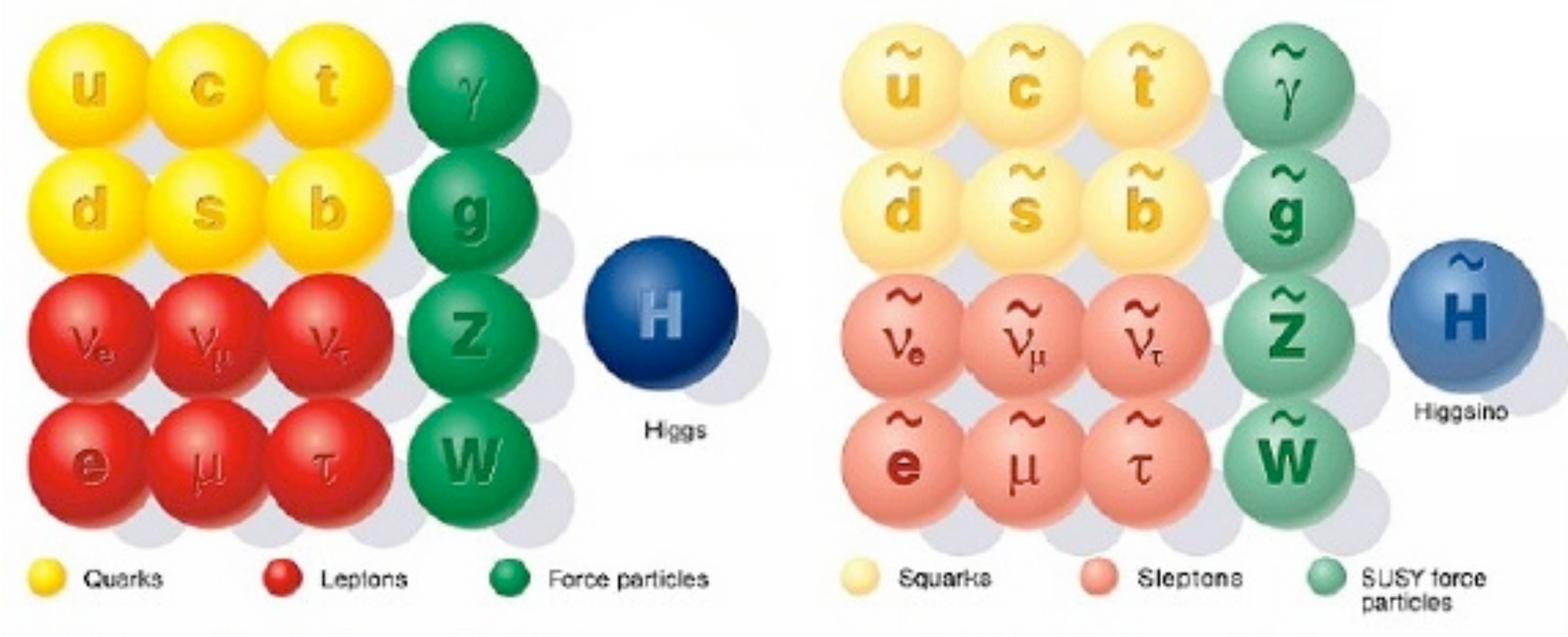
—— SU(5)

Supersymmetry

- A possible extension to the SM: A new symmetry between fermions and bosons



SUPERSYMMETRY



Standard particles **SUSY particles**

- Introduce supersymmetric partners for all SM particles:
  - Differ by ½ unit in spin
  - sfermions (squarks, selectrons, smuon, ...): spin 0 → bosons
  - gauginos (chargino, neutralino, gluino,...): spin ½ → fermions
- No new interactions

MSSM – Minimal Supersymmetric Standard Model

Minimal Supersymmetric Standard Model (MSSM) requires

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \widetilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

+1 gravitino in GMSB

34 new particles

- 9 scalar leptons (3x3 families)
- 12 scalar quarks (4x3 families)
- 1 gluino
- 1 bino, 3 winos
- 4 higgsinos
- 4 additional higgses

Higgs sector: must assume two higgs doublets (anomaly cancellation):

- 4 SM bosons, higgses (H_u^+, H_u^0), (H_d^0, H_d^-)
- 4 SUSY fermions, higgsinos $(\tilde{H}_u^+, \tilde{H}_u^0)$, $(\tilde{H}_d^0, \tilde{H}_d^-)$

In general, gauge eigenstates ≠ mass eigenstates: mixing

- 3rd generation
- 4 higgsinos mix with winos and bino to give 4+4 massive charginos and neutralinos

Supersymmetry breaking

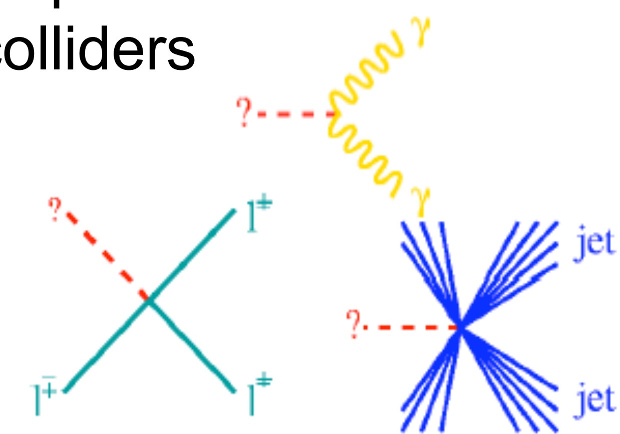
- In unbroken SUSY all particles would have the same mass as their SUSY partners
- No SUSY particles found as of yet → SUSY must be broken
- Most general term in the Lagrangian

$$\delta\mathcal{L}_{\mathrm{soft}} = -\sum_{\tilde{q},\tilde{l},H_{\mathrm{d,u}}} m^2_{0,i}|\Phi_i|^2 + (-\tfrac{1}{2}m_{1/2,a}\lambda_a\lambda_a - A_{0,i}W_{3,i} - B_0\mu H_{\mathrm{u}}H_{\mathrm{d}}) + \text{h.c.}$$

> 100 new parameters !!

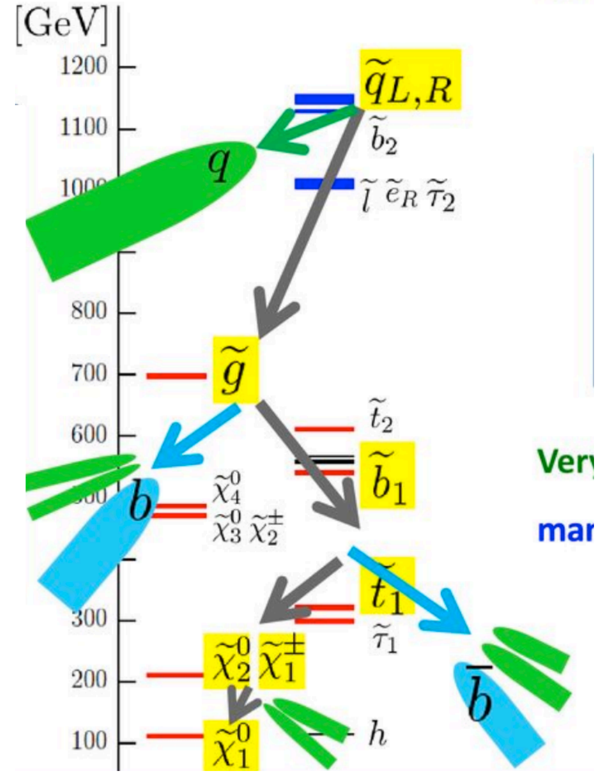
$m_{0,i}$ – scalar masses, $m_{1/2,a}$ – gaugino masses, $A_{0,i}$ – trilinear couplings, μ – higgsino mass parameter

- Breaking mechanism determines particle spectrum and thus phenomenology and search strategy at colliders

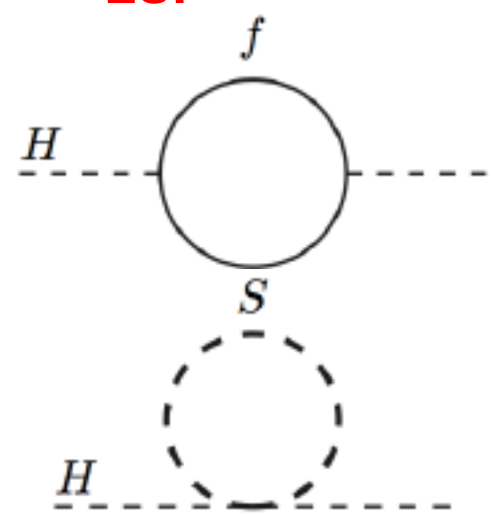


What's nice about SUSY

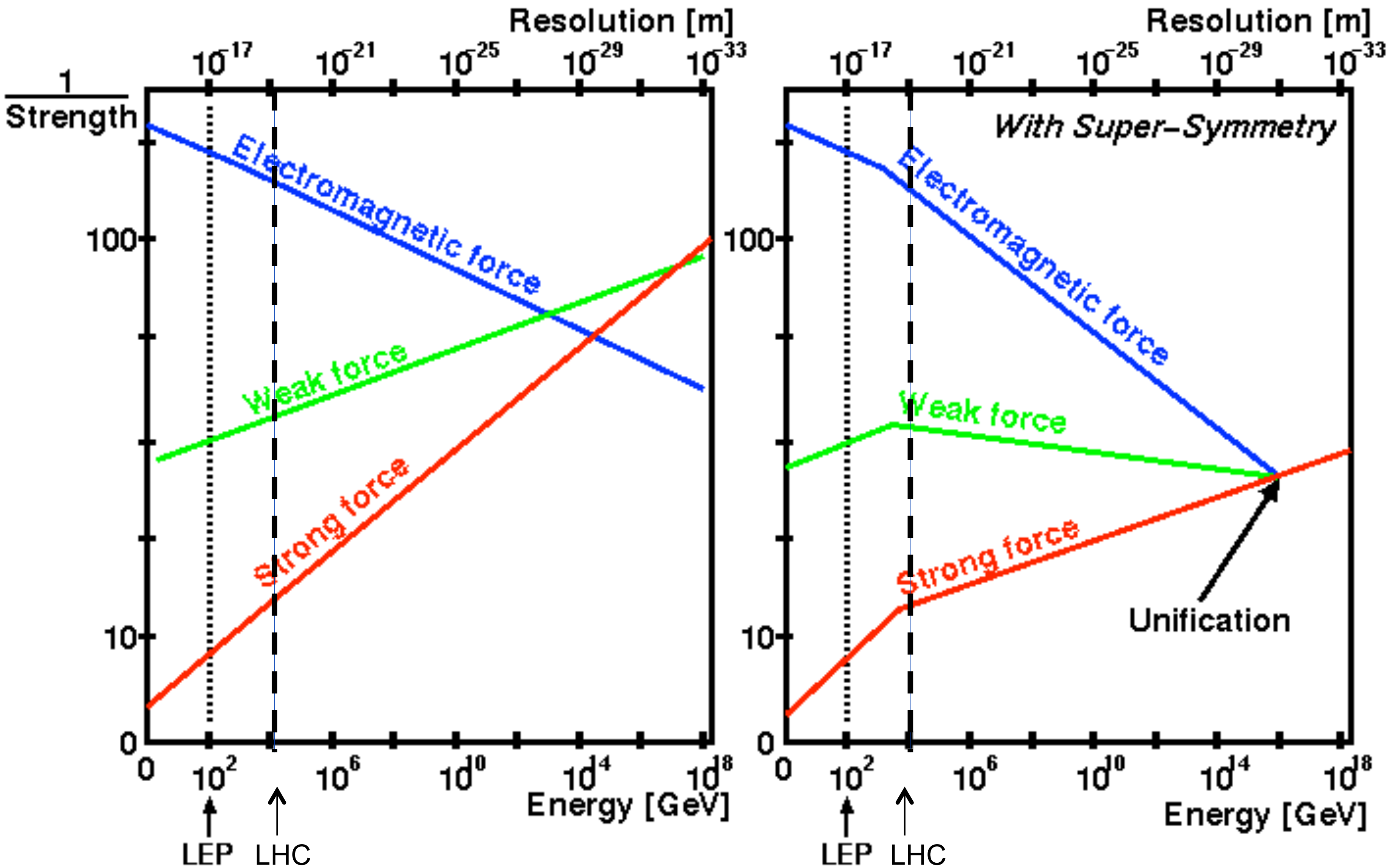
- Introduces symmetry between fermions and bosons
- Unification of strong and electroweak force possible
- Dark matter candidate exists:
  - The lightest neutral gaugino
  - Consistent with cosmology data
- No fine-tuning required
  - Radiative corrections to Higgs mass acquire SUSY corrections
  - Cancellations of fermion and sfermion loops
- Also consistent with electroweak precision measurements of m_W and m_{top}
  - but may change relationship between m_{top}, m_W and m_H



LSP

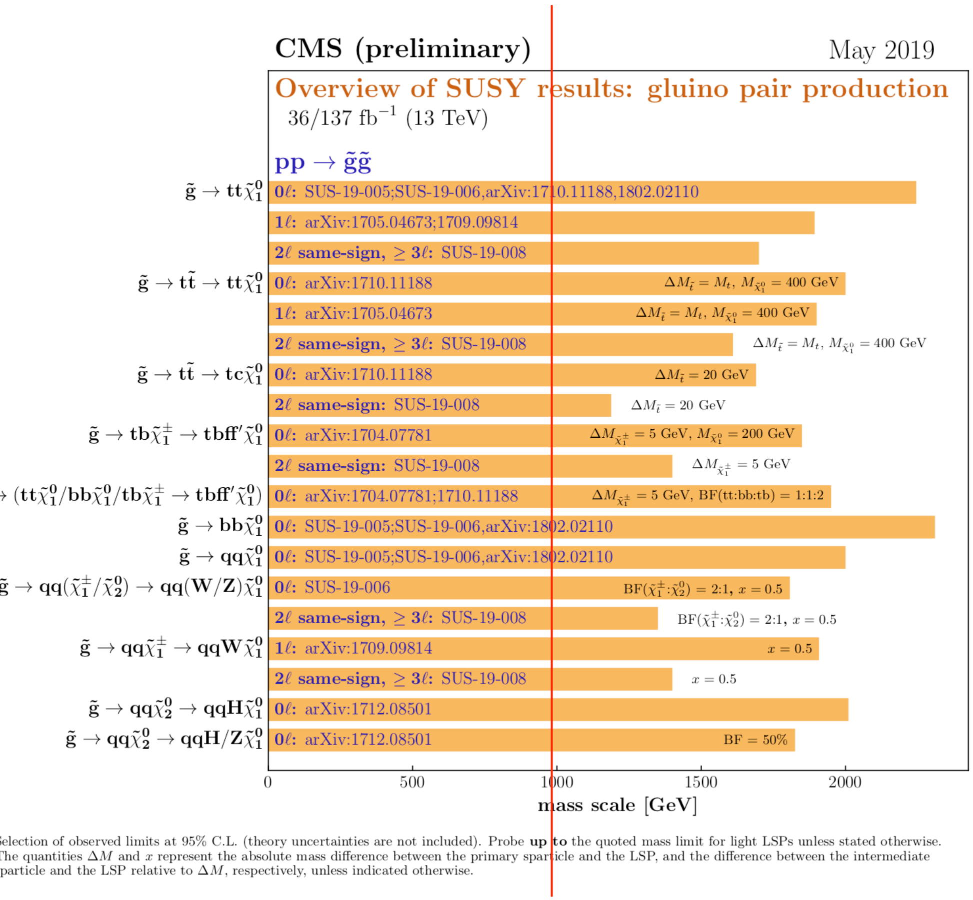


Unification of electroweak and strong force

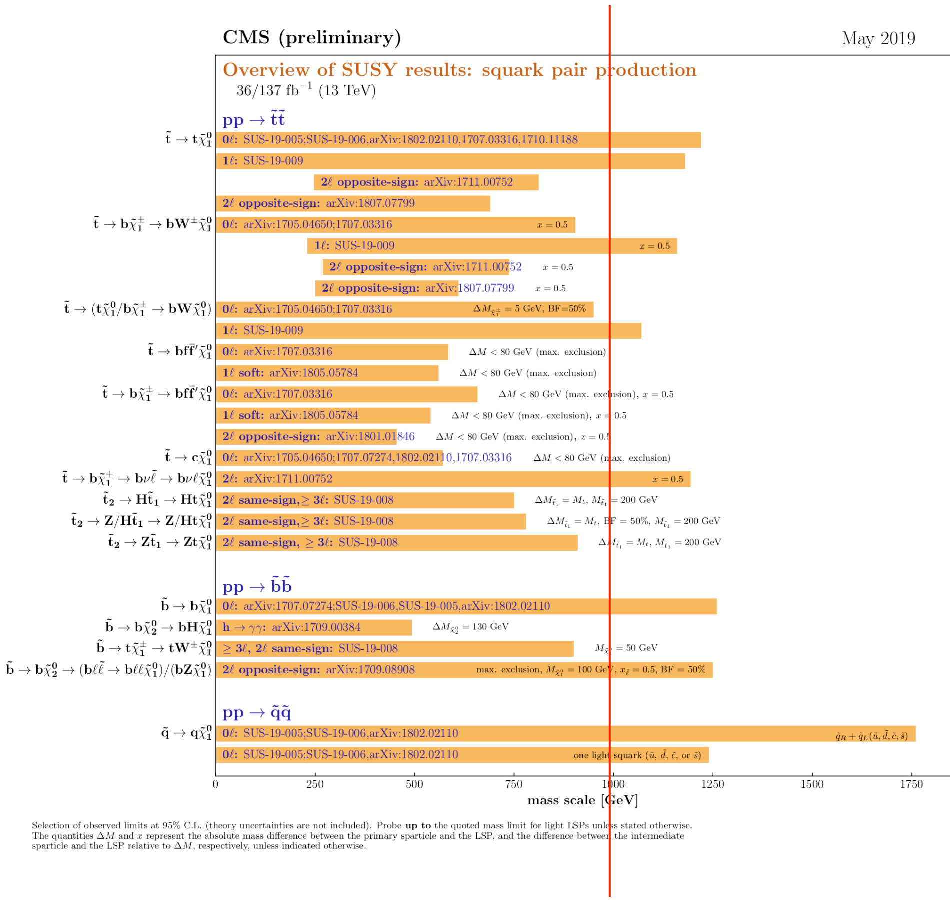


However...

- So far no experimental evidence for the existence of any SUSY particle



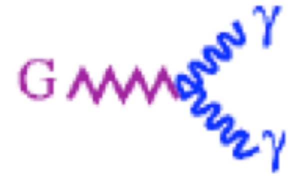
1 TeV



1 TeV

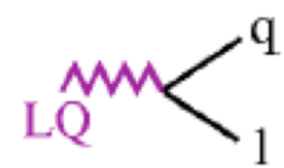
Need to keep looking

- For example for..
- **Extra spatial dimensions**
  - addresses hierarchy problem, gravity strong at TeV scale

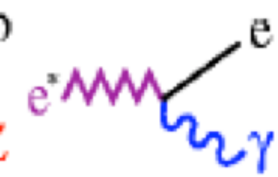


- **Additional gauge groups**
  - occur naturally in GUT scale theories

- **Leptoquarks**
  - combines quark and lepton sector



- **New/excited fermions**
  - more generations, right-handed neutrinos



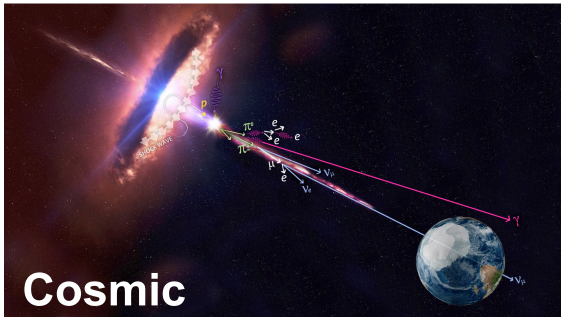
- **Composite Higgs boson**
  - solves fine-tuning, addresses hierarchy in fermion masses
- **Preons**
  - atoms → nucleons → quarks → preons?

- **New ideas???**

And how do we do this?

- Extensive experimental program in particle physics

Accelerators...



Man-made

world's highest-current accelerator @PSI

world's highest-energy accelerator @CERN

... and experiments

Road to discovery

Start with

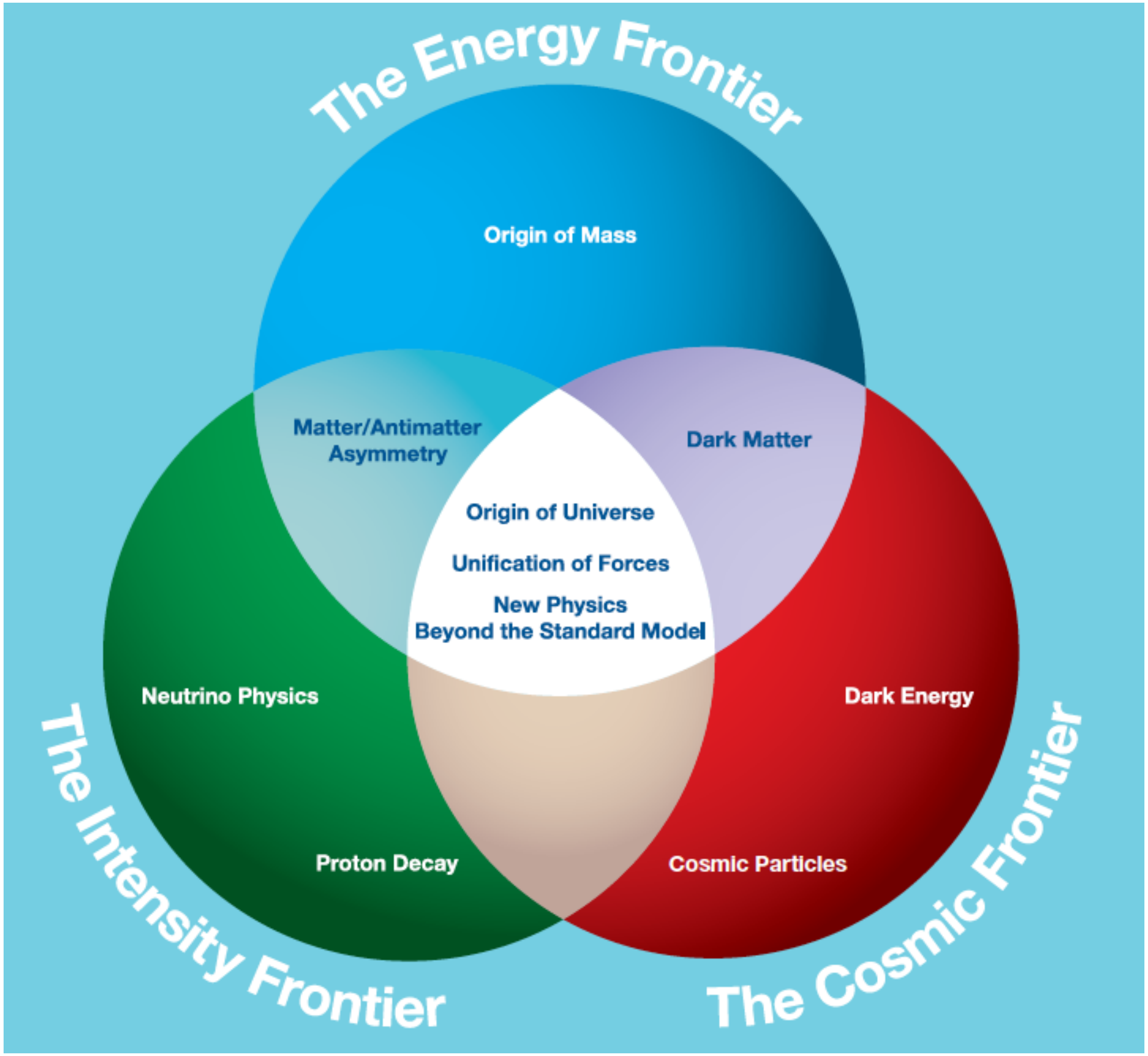
- Identify a source of particles or build a powerful accelerator
- Build high performance detectors

Once this is done

1) Understand the basic physics objects to be measured in the detector: electrons, muons, photons, jets, ...
2) Calibrate against know processes (either measured or predicted by Standard Model)
3) Start looking for anomalies...anywhere...
4) Interpret signals, measure properties

Increasing collected data

Three frontiers



Extra dimensions

Closer to Truth with Lisa Randall
"Are there extra dimensions?"
https://www.youtube.com/watch?v=DJUnw8CHzsk

Closer to Truth with Michio Kaku
"Are there extra dimensions?"
https://www.youtube.com/watch?v=RUIVFzI_BJs

References

- Lecture includes material prepared by C. Anastasiou, L. Baudis, F. Canelli, A. de Cosa, B. Heinemann, F. Pauss, D. Perkins, M. G. Ratti, N. Serra, M. Spira