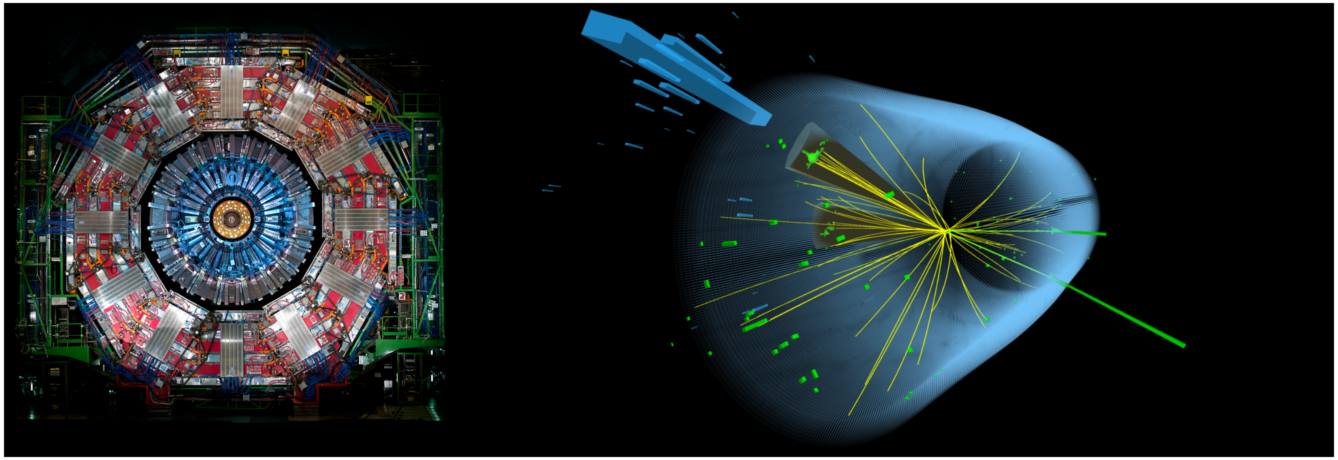

Tests of the Standard Model and beyond

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For CAU Particle Physics Lecture Series
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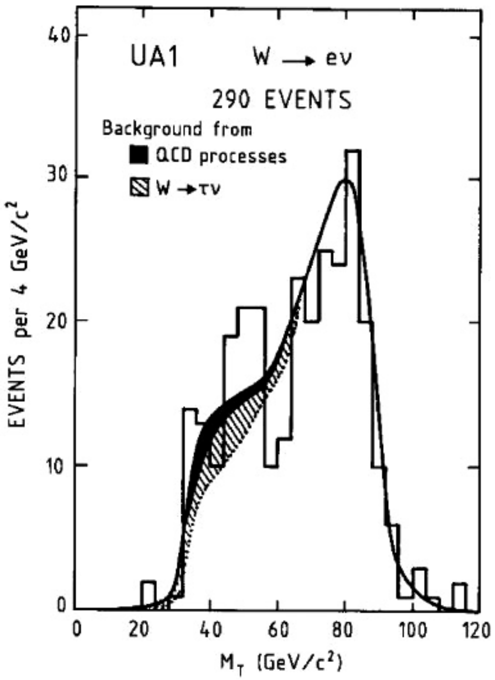
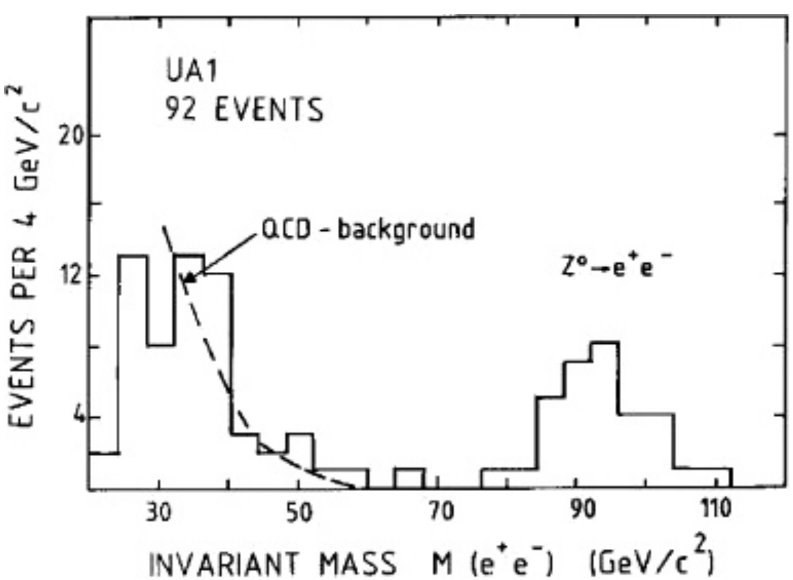
Weak interaction gauge group

- Responsible for many physical processes of fundamental particle decay
- Muon, Tau decays and Neutrino interactions
- Some mesons and baryons can decay through weak interaction
- Force carrier particles for the weak interaction: Z^0 and $W^{\pm}$



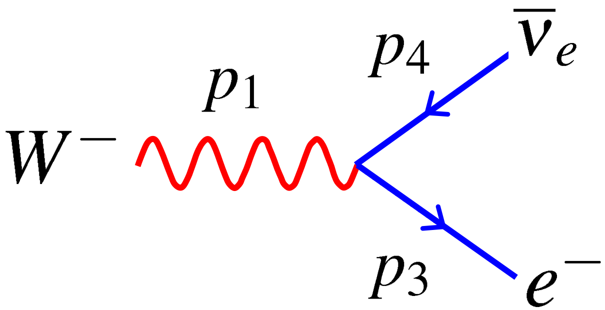
U1 experiment between 1982 to 1985



- $W^{\pm}$ boson mass 80.4 GeV
- Z^0 boson mass 91.2 GeV

W boson decay

- To calculate the W boson decay rate, first consider $W^- \rightarrow e^- \overline{\nu}_e$
- We want matrix element for



Incoming W-boson : $\epsilon_\mu(p_1)$

Out-going electron : $\bar{u}(p_3)$

Out-going : $\bar{\nu}_e$ $v(p_4)$

Vertex factor : $-i\frac{g_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$

V-A

- Using Feynman diagram : product all components
- In the ultra-relativistic limit, only LH particles and RH anti-particles participate in the weak interaction
- Should consider the three possible W-Boson polarization states

$$\Gamma(W^- \rightarrow e^- \overline{\nu}) = \frac{g_W^2 m_W}{48\pi}$$

- **The calculation for the other decay modes (neglecting final state particle masses) is the same. For quarks, need to account for coloar and CKM matrix. No decays to top : the top mass (173 GeV) is greater than the W boson mass (80 GeV)**

$$
\begin{aligned}
W^- &\to e^-\overline{\nu}_e \qquad & W^- &\to d\overline{u} \quad \times 3|V_{ud}|^2 \qquad & W^- &\to d\overline{c} \quad \times 3|V_{cd}|^2 \\
W^- &\to \mu^-\overline{\nu}_\mu \qquad & W^- &\to s\overline{u} \quad \times 3|V_{us}|^2 \qquad & W^- &\to s\overline{c} \quad \times 3|V_{cs}|^2 \\
W^- &\to \tau^-\overline{\nu}_\tau \qquad & W^- &\to b\overline{u} \quad \times 3|V_{ub}|^2 \qquad & W^- &\to b\overline{c} \quad \times 3|V_{cb}|^2
\end{aligned}
$$

- **Unitarity of CKM matrix gives, e.g.** $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

- **Hence** $BR(\mathrm{W} \to qq') = 6BR(\mathrm{W} \to \mathrm{e}\nu)$

  and thus, the total decay rate :

$$
\Gamma_W = 9\Gamma_{W\to e\nu} = \frac{3g_W^2 m_W}{16\pi} = 2.07\,\mathrm{GeV}
$$

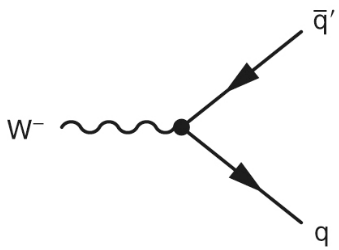
Experiment: 2.14±0.04 GeV
(our calculation neglected a 3% QCD correction to decays to quarks)

- **W boson branching fraction (Γ_i/Γ_{total})**

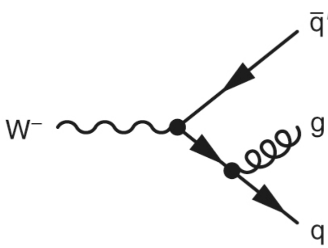
$$
Br(W^- \to \text{hadrons}) \approx 0.67 \qquad Br(W^- \to \mathrm{e}^-\overline{\nu}_\mathrm{e}) \approx 0.11
$$

$$
Br(W^- \to \mu^-\overline{\nu}_\mu) \approx 0.11 \qquad Br(W^- \to \tau^-\overline{\nu}_\tau) \approx 0.11
$$

QCD correction



The lowest-order Feynman diagram for $W^- \rightarrow q\bar{q}'$



The first-order Feynman diagram for $W^- \rightarrow q\bar{q}'g$

- QCD correction → $k_{QCD} = \left[1 + \frac{\alpha_S(m_W)}{\pi}\right] \approx 1.038$

- The branching ratio of the W boson to hadronic final states is

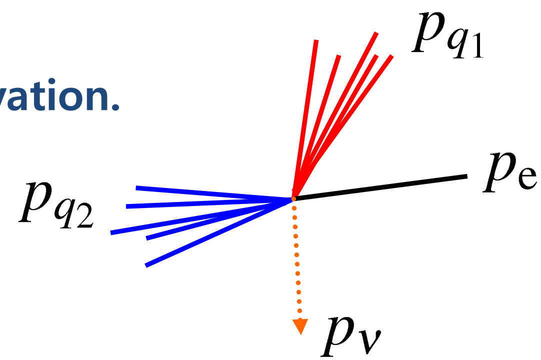
$$BR(W \rightarrow q\bar{q}') = \frac{6k_{QCD}}{3 + 6k_{QCD}} = 67.5\%$$

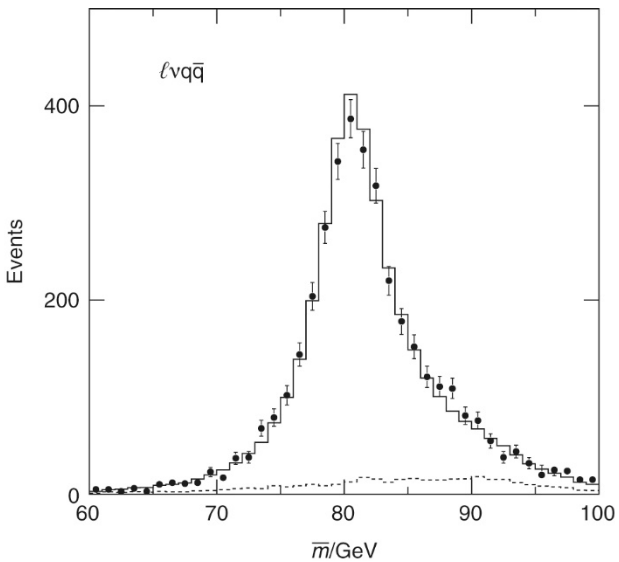
W boson mass at the LEP

- **Unlike $e^+e^- \to Z$, the process $e^+e^- \to W^+W^-$ is not a resonant process**

  → Different method to measure W-boson Mass

- **Let's consider this decay :** $W^+W^- \to q\bar{q}e^-\bar{\nu}$
- **Neutrino four-momentum from energy-momentum conservation.**
  - $p_{q1} + p_{q2} + p_e + p_\nu = (\sqrt{s}, 0)$





$$\approx \frac{1}{2}(M_+ + M_-)$$

- **Reconstruct masses of two W bosons**

$$M_+^2 = E^2 - \vec{p}^2 = (p_{q1} + p_{q2})^2$$
$$M_-^2 = E^2 - \vec{p}^2 = (p_e + p_\nu)^2$$

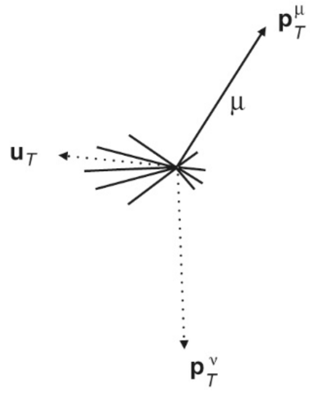
- **Peak of reconstructed mass distribution**

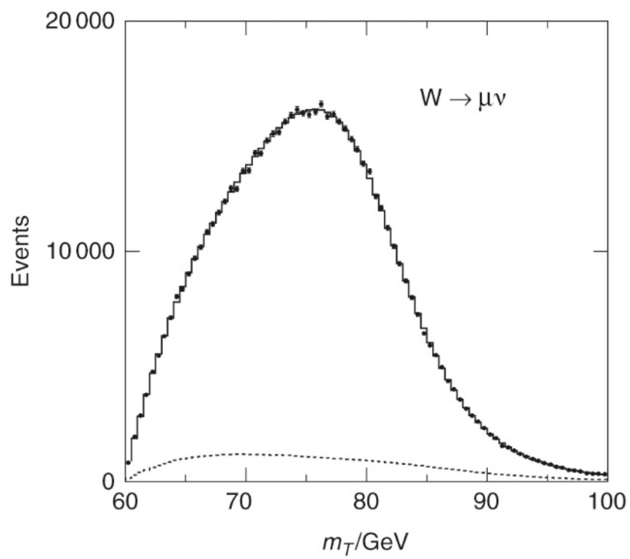
$$m_W = 80.376 \pm 0.033\,\mathrm{GeV}$$

- **Width of reconstructed mass distribution**

$$\Gamma_W = 2.196 \pm 0.083\,\mathrm{GeV}$$

W boson mass at the Tevatron and LHC





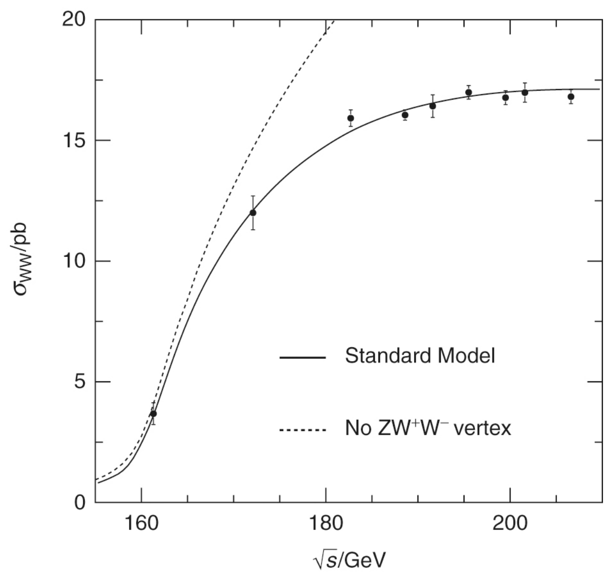
- **In $p\bar{p}$ collision, the center of the mass energy of the $q\bar{q}$ annihilation process is not known on an event-by-event basis.**
- **Consequently, the final state W boson will be boosted along the bean (z) axis.**
- **The Z component of the momentum of the neutrino is not known.**
- **It is only possible to reconstruct the transverse mass in x-y plane.**

$$m_T \equiv \sqrt{2\left(p_T^\mu p_T^\nu - p_T^\mu \cdot p_T^\nu\right)}$$

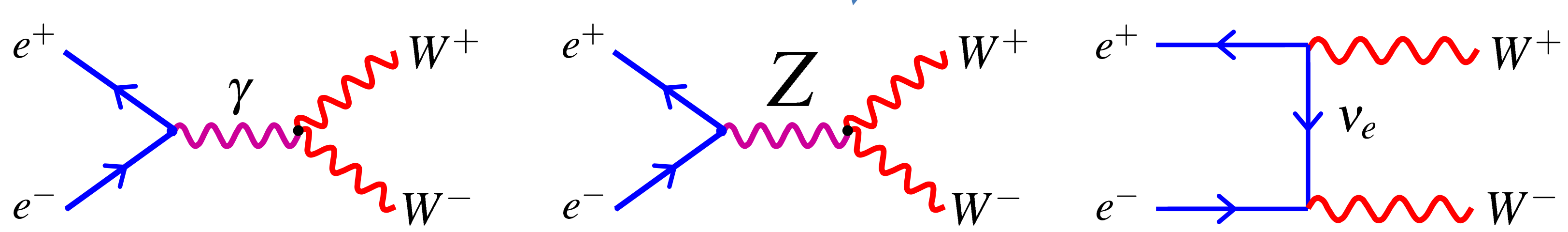
$$m_W = 80.385 \pm 0.015 \text{ GeV} \text{ and } \Gamma_W = 2.085 \pm 0.042 \text{ GeV}$$

From W to Z

- The $W^{\pm}$ bosons carry the EM charge – suggestive Weak are EM forces are related



Problem can be "fixed" by introducing a new boson, the Z. The new diagram interferes negatively with the above two diagrams fixing the unitarity problem



$$|M_{\gamma WW} + M_{ZWW} + M_{\nu WW}|^2 < |M_{\gamma WW} + M_{\nu WW}|^2$$

- Only works if Z, γ, W couplings are leated → need **ELECTROWEAK UNIFICATION**

Z Branching ratios

- (Neglecting fermion masses) obtain the same expression for the other decays

$$\Gamma(Z \to f\bar{f}) = \frac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$$

- Using values for c_V and c_A,

$$Br(Z \to e^+e^-) = Br(Z \to \mu^+\mu^-) = Br(Z \to \tau^+\tau^-) \approx 3.5\%$$
$$Br(Z \to \nu_1\bar{\nu}_1) = Br(Z \to \nu_2\bar{\nu}_2) = Br(Z \to \nu_3\bar{\nu}_3) \approx 6.9\%$$
$$Br(Z \to d\bar{d}) = Br(Z \to s\bar{s}) = Br(Z \to b\bar{b}) \approx 15\%$$
$$Br(Z \to u\bar{u}) = Br(Z \to c\bar{c}) \approx 12\%$$

- The Z Boson therefore predominantly decays to hadrons

$$Br(Z \to \text{hadrons}) \approx 69\%$$

Mainly due to factor 3 from colour

- Also predict total decay rate (total width)

$$\Gamma_Z = \sum_i \Gamma_i = 2.5\,\text{GeV}$$

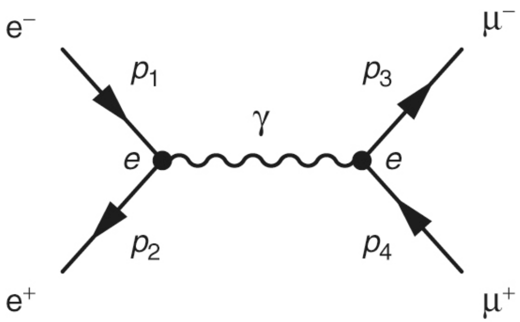
Experiment:

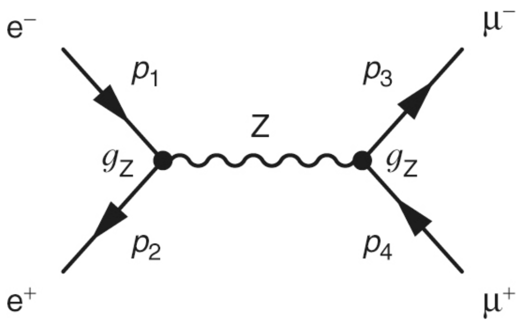
$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$$

The Z resonance

- The unified electroweak model provides precise predictions for the properties of the Z boson
- Tested at Large Electron-Positron (LEP) collider at CERN
- The lowest-order Feynman diagrams for the annihilation process

$$e^+e^- \to \mu^+\mu^-$$





$$M_\gamma \propto \frac{e^2}{q^2} \qquad M_Z \propto \frac{g_Z^2}{q^2 - m_Z^2}$$

QED process dominates	Z boson process dominates	both are important
at $\sqrt{s} \ll \mathrm{m_Z}$	at $\sqrt{s} = \mathrm{m_Z}$	at $\sqrt{s} \gg \mathrm{m_Z}$

The Breit-Wigner Resonance

- Need to consider carefully the propagator term $\frac{1}{s-m_Z^2}$ which diverges when C.o.M energy is equal to the rest mass of the Z boson
- To do this, need to account for the fact that the Z boson is an unstable particle
- The time dependence of the quantum mechanical wavefunction for a stable particle, as measured in its rest frame is given by e^{-imt}
- For unstable particle, this must be modified taking decay rate $\Gamma = \frac{1}{\tau}$ into account

$$\psi \propto e^{-imt} \rightarrow \psi \propto e^{-imt} e^{-\Gamma t/2}$$

so that the particle probability decays away exponentially

$$\psi^* \psi \sim e^{-\Gamma t} = e^{-t/\tau} \qquad \text{with } \tau = \frac{1}{\Gamma_Z}$$

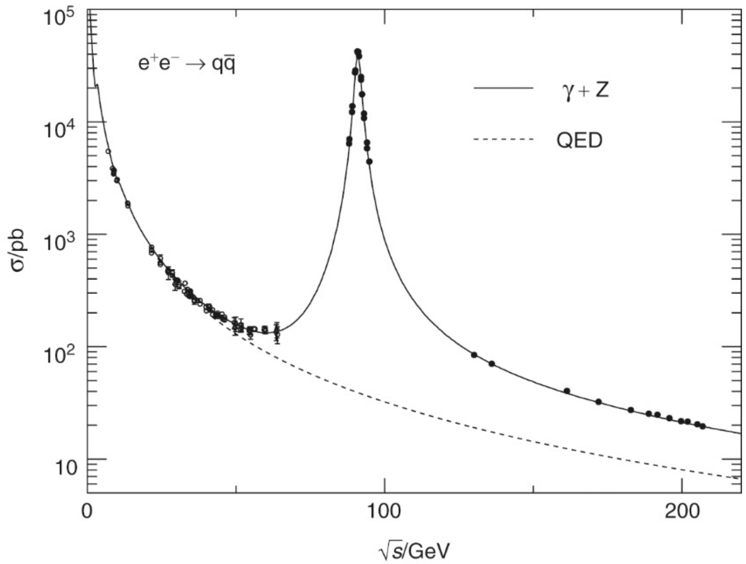
- Equivalent to making the replacement $m \rightarrow m - i\Gamma/2$

$$m_Z^2 \rightarrow \left(m_Z - \frac{i\Gamma_Z}{2}\right)^2 = m_Z^2 - i m_Z \Gamma_Z - \frac{1}{4}\Gamma_Z^2$$

- For the Z boson, total decay width $\Gamma_Z \ll m_Z$, last term can be neglected
- The Z boson propagator becomes

$$\frac{1}{q^2 - m_Z^2} \rightarrow \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z}$$

The Breit-Wigner Resonance



$$|M|^2 = \left|M_\gamma + M_Z\right|^2$$

- **The cross section for $e^+e^- \to Z \to \mu^+\mu^-$ with $q^2 = s$, is proportional to**

$$\sigma \propto |M|^2 \propto \left|\frac{1}{s - m_Z^2 + i m_Z \Gamma_Z}\right|^2 = \frac{1}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}$$

- **$e^+e^- \to Z$ annihilation cross section peaks sharply at $\sqrt{s} = m_Z$, and the resulting Lorentzian dependence on the centre-of-mass energy is referred to as a Briet-Wigner resonance.**

Measurements of the Z Line-shape

- Measurements of the Z resonance line-shape determine:
  - m_Z : peak of the resonance
  - Γ_Z : FWHM of resonance
  - Γ_f : Partial decay widths
  - N_ν : Number of light neutrino generations
- Total cross section, expressed in terms of the partial decay width, is

$$\sigma(e^+e^- \to Z \to \mu^+\mu^-) = \frac{12\pi s}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\left(s - m_Z^2\right)^2 + m_Z^2\Gamma_Z^2}$$

- Maximum value occurs at $\sqrt{s} = m_Z$ with peak cross section equal to

$$\boxed{\sigma_{ff}^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_{\mathrm{ee}}\Gamma_{\mathrm{ff}}}{\Gamma_Z^2}}$$

- The cross section falls to half of its peak value at

$$\sqrt{s} = m_Z \pm \frac{\Gamma_Z}{2}$$

- Γ_Z is not only the total decay rate of the Z boson, it is also the full-width-at-half-maximum (FWHM) of the cross section as a function of centre-of-mass energy

- In principle, the measurement of m_Z and Γ_Z is rather simple: run accelerator at different energies, measure cross sections, account for ISR, then find peak and FWHM.

$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}, \ \Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

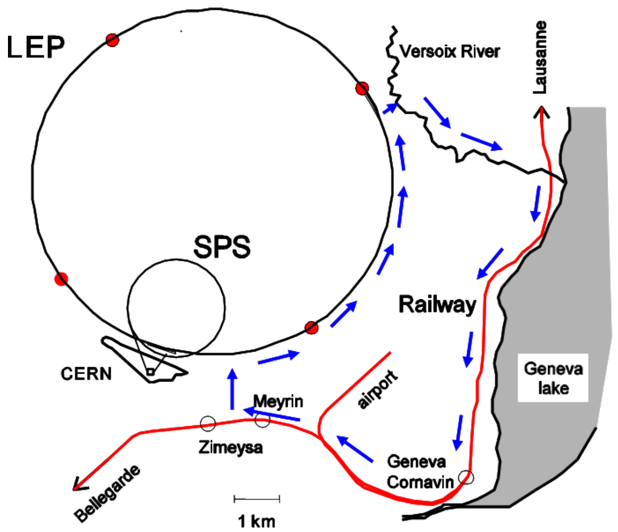
- 0.002% measurement of m_Z!
- To achieve this level of precision, we need to know energy of the colliding bea ms to better than 0.002% : sensitive to unusual systematic effects…

Moon:

- As the moon orbits the Earth it distorts the rock in the Geneva area very slightly !
- The nominal radius of the accelerator of 4.3 km varies by ±0.15 mm
- Changes beam energy by ~10 MeV : need to correct for tidal effects !

Trains:

- Leakage currents from the TGV railway line return to Earth following the path of least resistance.
- Travelling via the Versoix river and using the LEP ring as a conductor.
- Each time a TGV train passed by, a small current circulated LEP slightly changing the magnetic field in the accelerator
- LEP beam energy changes by ~10 MeV

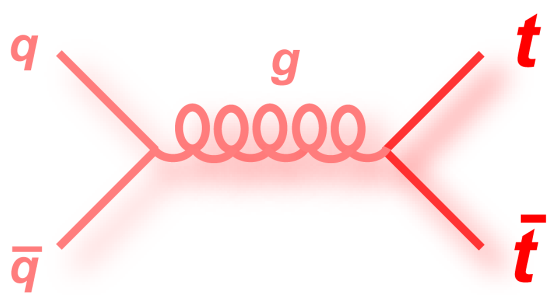


Top quark

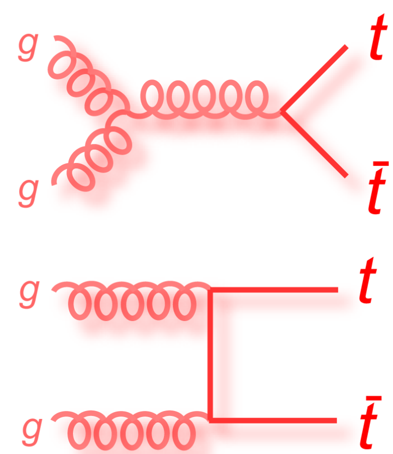
- Predicted as isospin partner of bottom quark (bottom quark was discovered in 1977)
- From virtual loop corrections and precise LEP data can predict the top quark mass
- The top quark is the most massive of the quarks ~ 173 GeV in the standard model : m(t) > m(H) > m(Z) > m(W)
- Because of its mass, it was not observed directly at the LEP.
- In 1995 top quark is observed at the Tevatron, proton anti-proton collider at Fermilab.
- Owing to its large mass, the lifetime is very short

$$\tau = \frac{1}{\Gamma} = 4\times10^{-25}s, \qquad \Gamma = 1.5\ \mathrm{GeV}. \qquad \boxed{\sim10^{-16}\mathrm{m}}$$

- It decays before it can form strongly interacting bound states (hadronization).
- The top quark properties can be studied without non-perturbative effects.



Quark annihilation



Gluon-gluon fusion

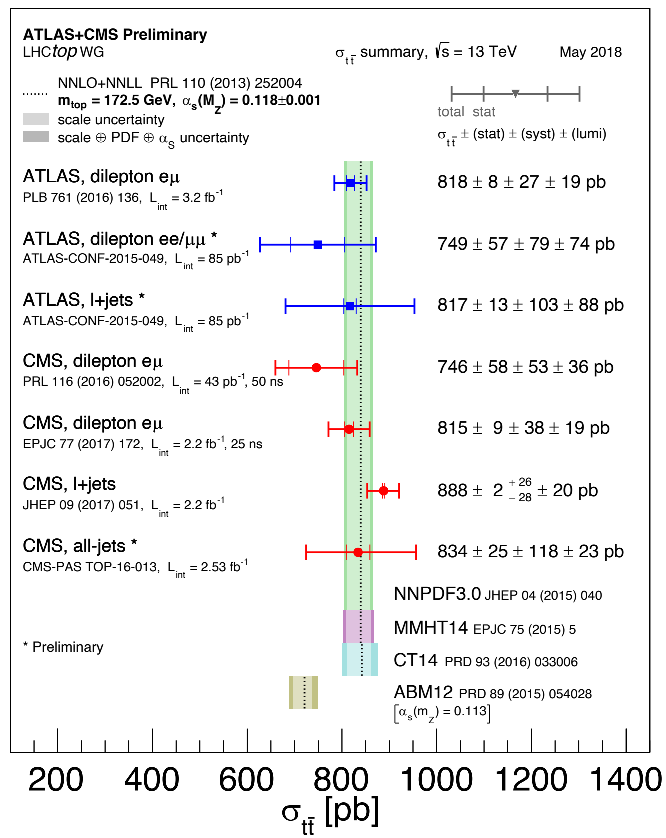
Production cross section

- **The presence of the propagators for the two virtual top quarks implies that**

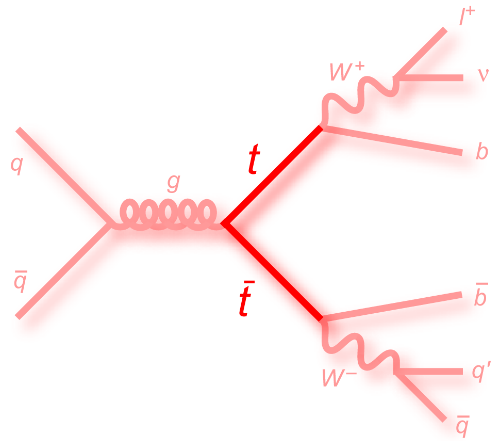
$$|M|^2 \propto \frac{1}{(q_1^2 - m_t)^2 + m_t^2\Gamma_t^2} \times \frac{1}{(q_2^2 - m_t^2)^2 + m_t^2\Gamma_t^2}$$

- **The invariant masses of each of W^+b and $W^-\bar{b}$ systems, produced in the top decay, will be distributed according to Lorentzian centered on m_t with width Γ_t**

LHC top quark cross section results at $\sqrt{s} = 13$ TeV →

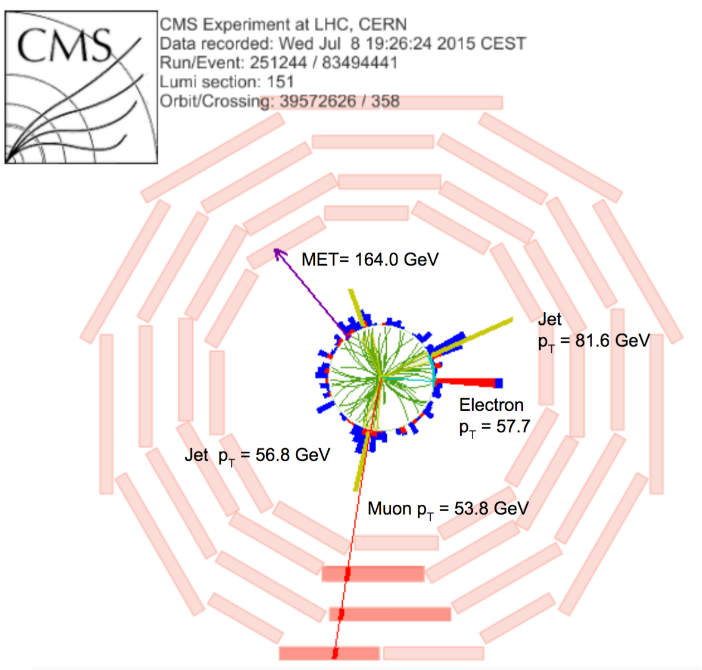


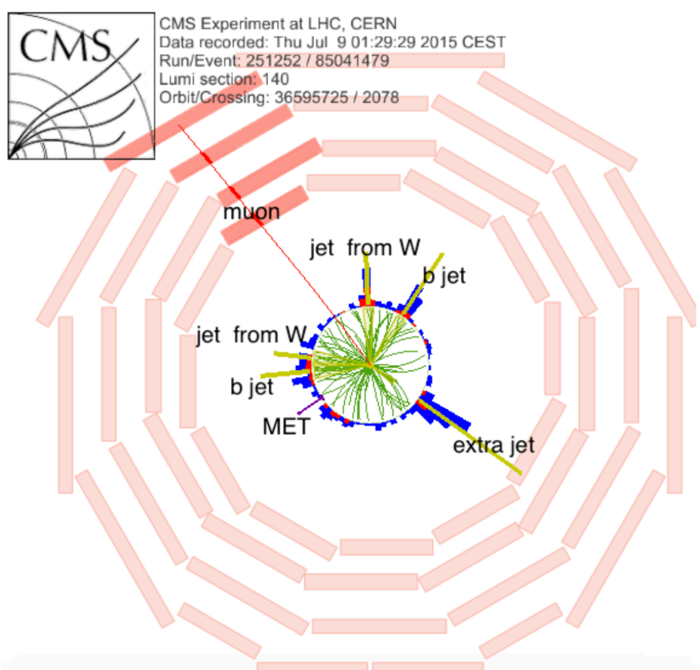
Top quark decay



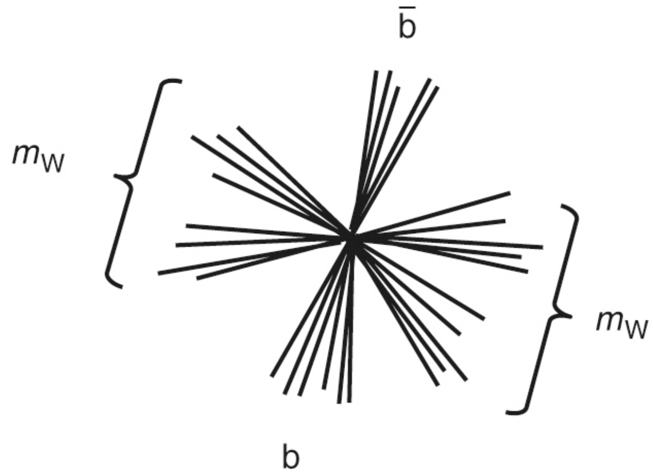
- **The top quark almost exclusively decays to a bottom quark.**
- **Complicated final state topologies**

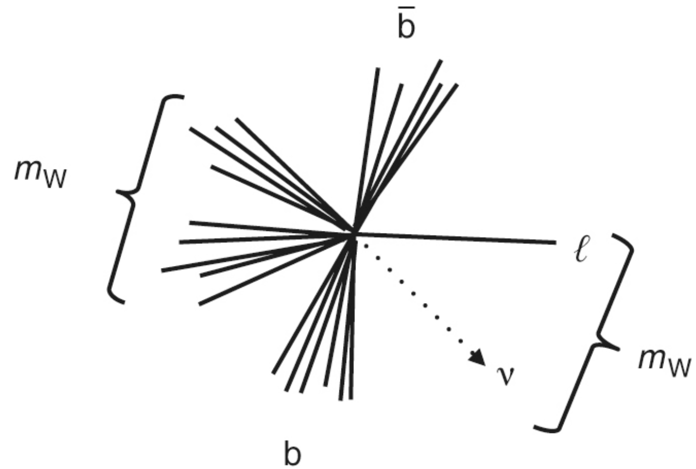
$$t\bar{t} \rightarrow b\bar{b}q\bar{q}q\bar{q} \rightarrow 6\,jets$$
$$t\bar{t} \rightarrow b\bar{b}q\bar{q}l\nu \rightarrow 4\,jets + l + \nu$$
$$t\bar{t} \rightarrow b\bar{b}l\nu l\nu \rightarrow 2\,jets + 2l + 2\nu$$

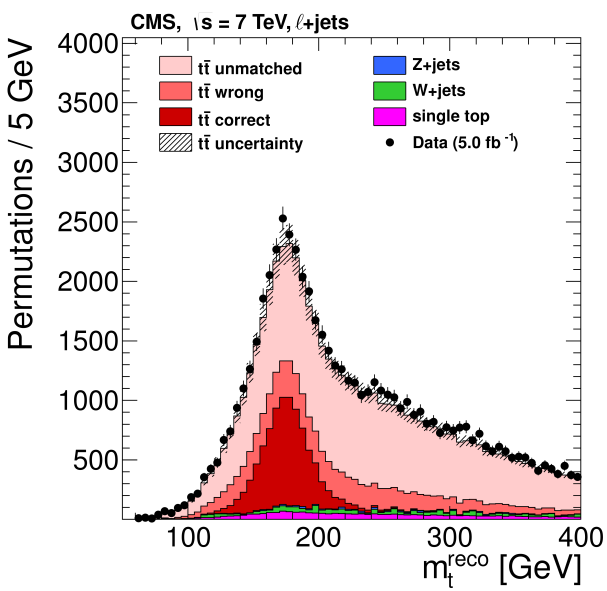


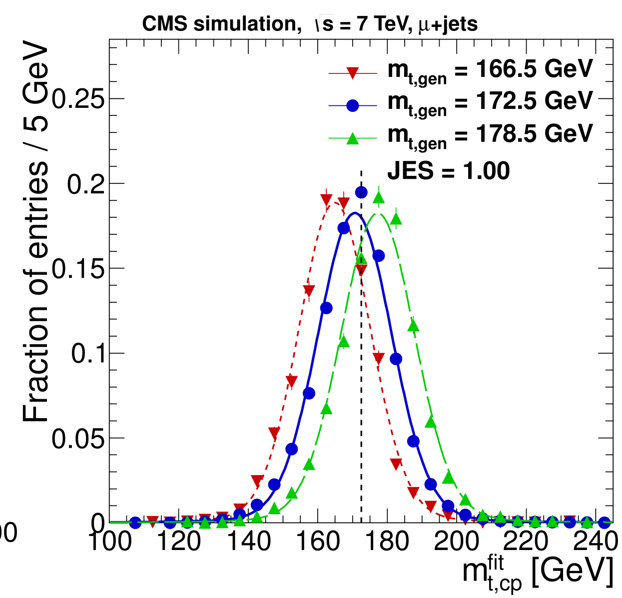


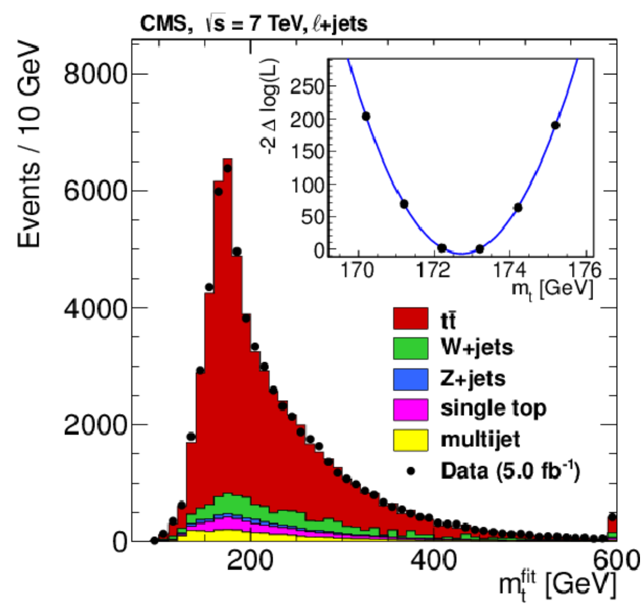
Top quark mass measurement



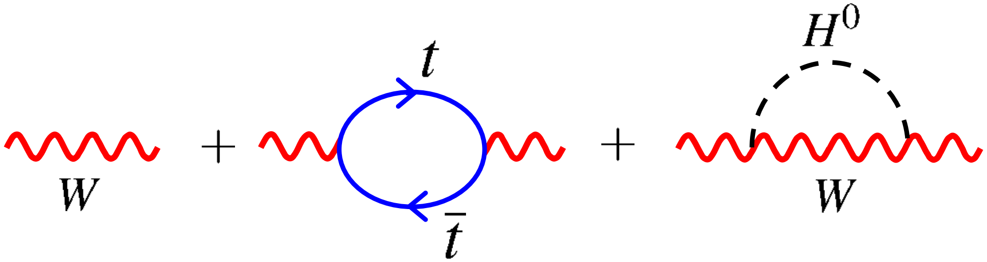




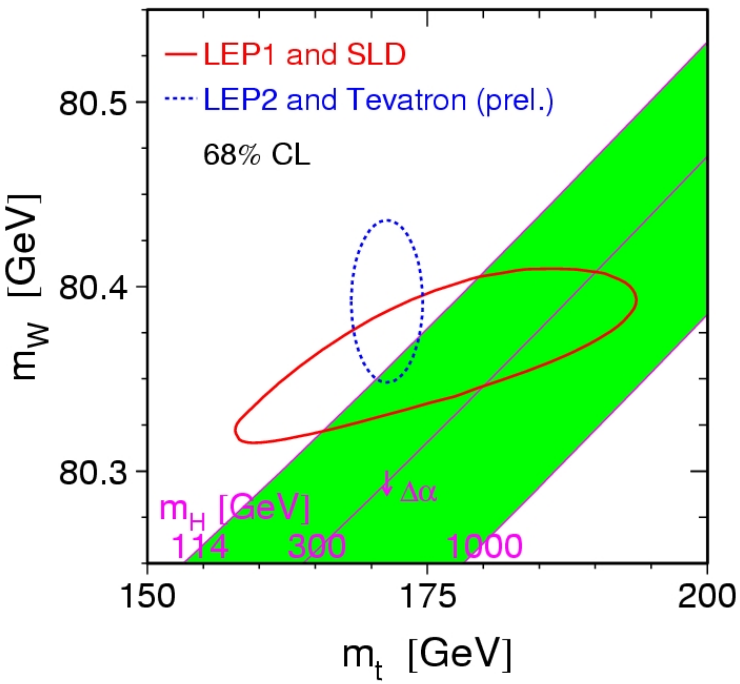




- **The W mass also depends on the Higgs mass**



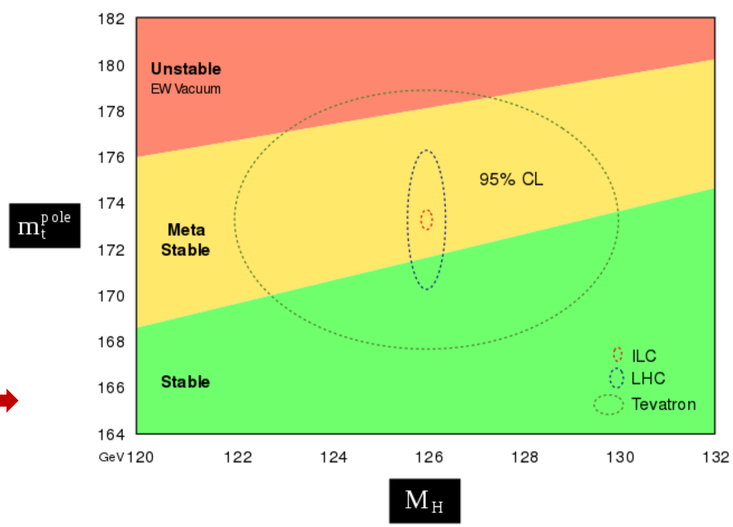
$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$



- **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**
- **Data favor a light Higgs**

arXiv:1207.0980

Higgs potential and top quark mass



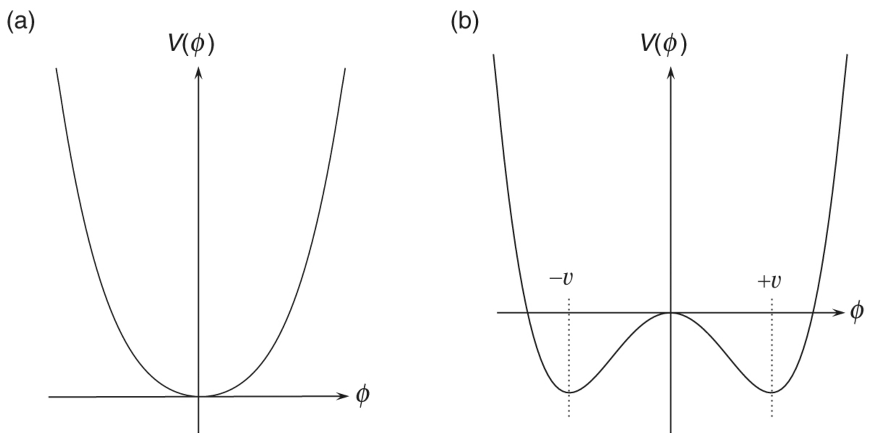
Higgs - The theory of 1964

- In 1964, six theoretical physicists hypothesized a new field (like an electromagnetic field) that would permeate all of space and solve a critical problem for our understanding of the universe
- Robert Brout, Francois Englert published the first paper about the (Brout-Englert-Higgs) BEH field and Peter Higgs published his paper later on.

The Higgs Mechanism

- The idea of gauge symmetries and electroweak unification only work for massless gauge bosons
- Introducing masses violate the underlying gauge symmetry
- The Higgs mechanism provides a way of giving the gauge bosons mass

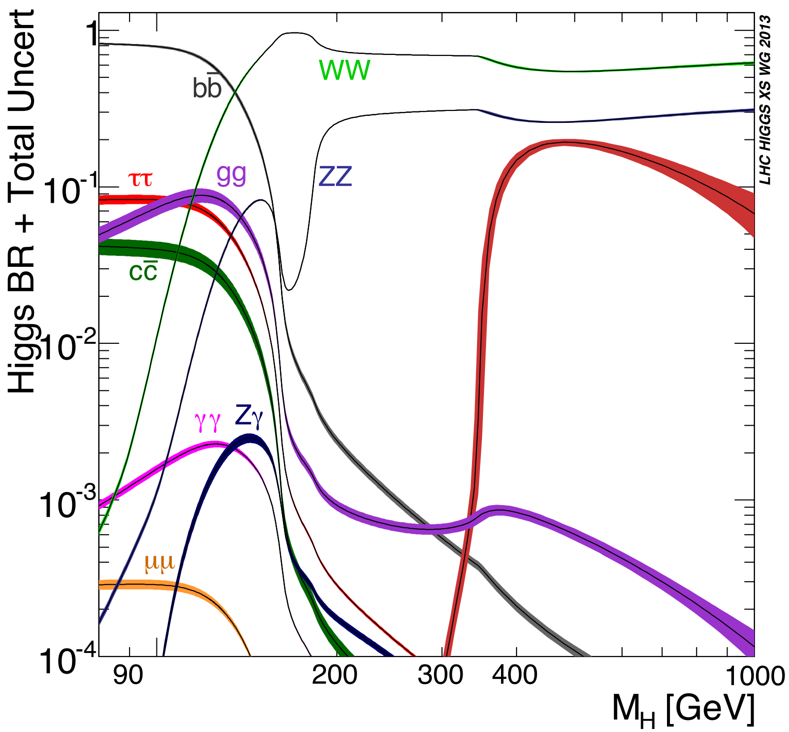
$$L = \frac{1}{2}(\partial_\mu \Phi)(\partial^\mu \Phi) - V(\Phi) = \frac{1}{2}(\partial_\mu \Phi)(\partial^\mu \Phi) - \frac{1}{2}\mu^2\Phi^2 - \frac{1}{4}\lambda\Phi^4$$



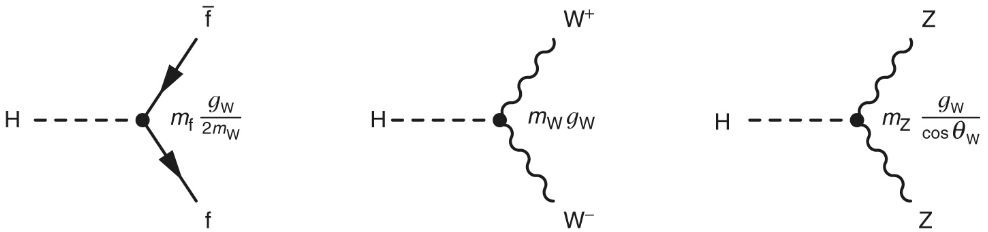
$\mu^2 > 0$ $\mu^2 < 0$

The choice of the vacuum state breaks the symmetry of the Lagrangian
→ spontaneous symmetry breaking

History of hunting the Higgs



- **Higgs boson couplings proportional to mass**
- **Higgs decays predominantly to heaviest particles which are energetically allowed**

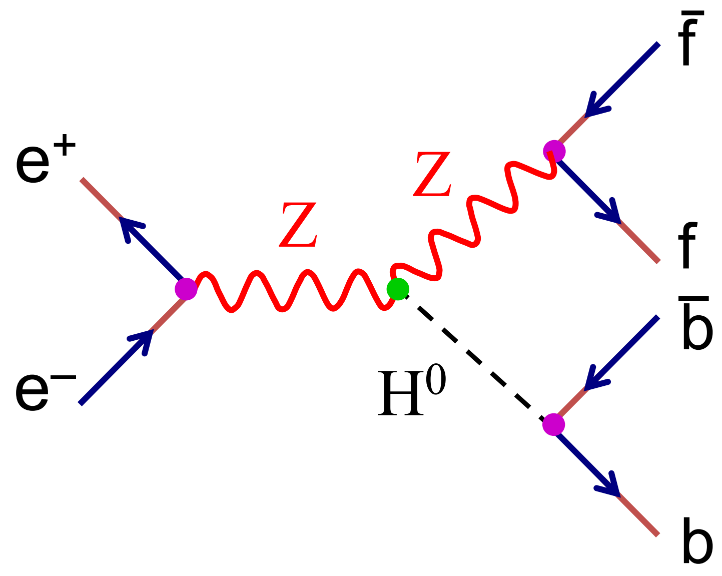


$m_H < 2m_W$ mainly $H^0 \to b\bar{b}$ + ~10% of $H^0 \to \tau^+\tau^-$
$2m_W < m_H < 2m_t$ almost entirely $H^0 \to W^+W^-$ + $H^0 \to ZZ$
$m_H > 2\,m_t$ either $H^0 \to W^+W^-$, $H^0 \to ZZ$, $H^0 \to t\bar{t}$

- **We had to search the whole mass range because there is no prediction of the Higgs mass**

A Hint from LEP

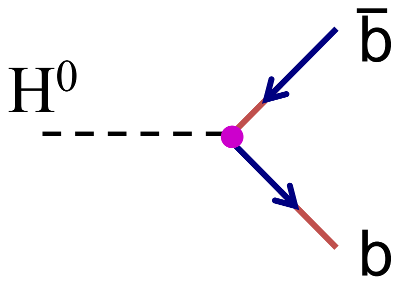
- LEP operated with a C.o.M. energy up to 207 GeV
- For this energy, the main production mechanism would be the "Higgsstrahlung" process
- Need enough energy to make a Z and H
  - Could produce the Higgs boson if $\mathrm{m_H} < 207\ \mathrm{GeV} - \mathrm{m_Z}$
    i.e. if $\mathrm{m_H} < 116\ \mathrm{GeV}$

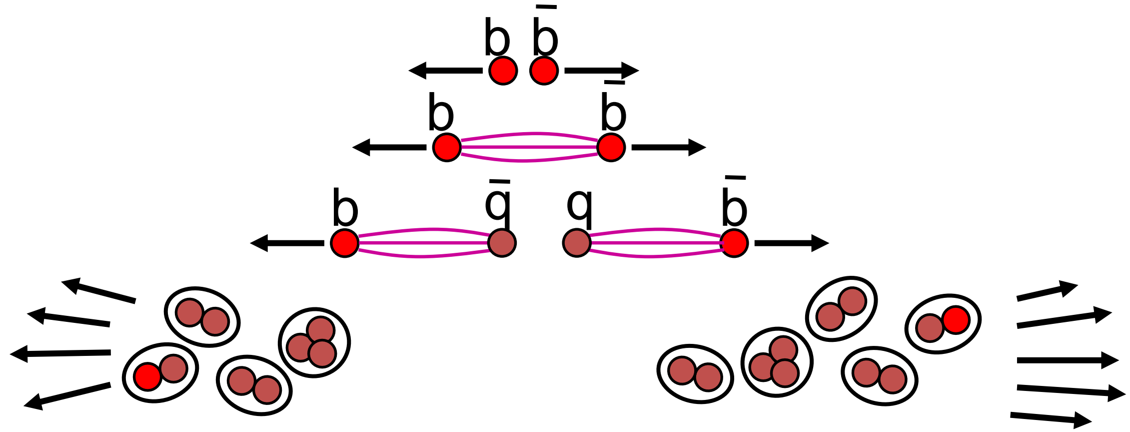


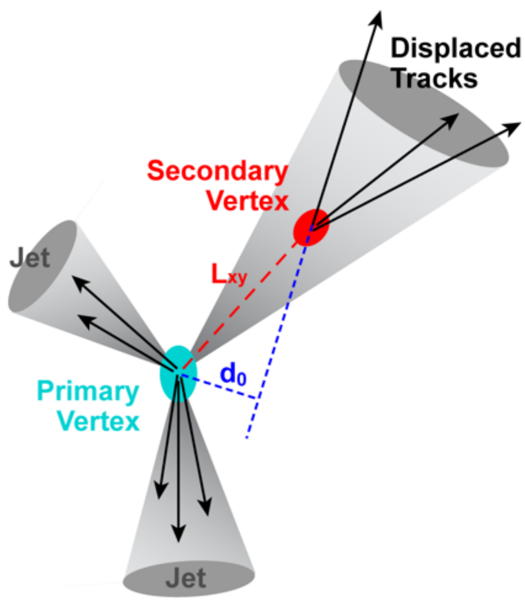
- The Higgs predominantly decays to the heaviest particle possible
- For $m_H < 116$ GeV, this is the b-quark (not enough mass to decay to WW/ZZ/$t\bar{t}$)
- $Br(Z \to l^+ l^-) \approx 10\%$, $Br(Z \to q\bar{q}) \approx 70\%$, $Br(Z \to \nu\bar{\nu}) \approx 20\%$,

Tagging the Higgs Boson Decays

- The most dominant signature for a Higgs boson decay is the production of two b quarks

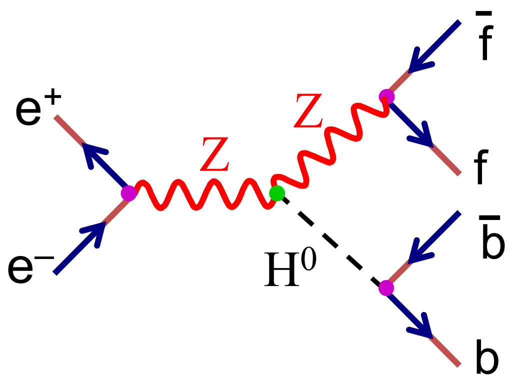






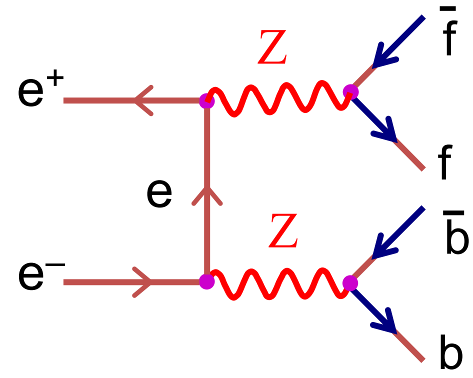
- To identify jet from b-quark flavor
  - mass = 4.2 GeV,
  - lifetime = 1.5 ps
  - ~1.8 mm before decay
  - secondary vertex
  - high track multiplicity

- **How do we distinguish the signal?**



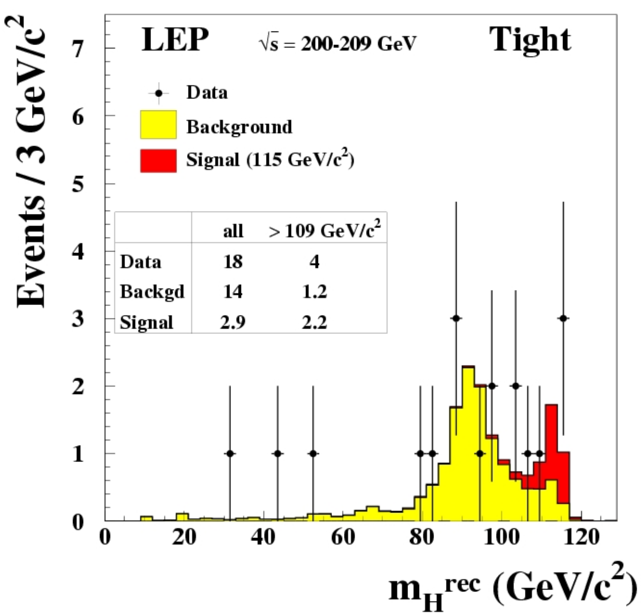
$M_{b\bar{b}} = M_{Higgs}$

from



$M_{b\bar{b}} = M_Z$

- **The only way is to form the invariant mass of the jets from the boson decays**
- **Boson mass** $\mathbf{M_{b\bar{b}}} = \sqrt{(E_b + E_{\bar{b}})^2 - \vec{p}_b \cdot \vec{p}_{\bar{b}}}$



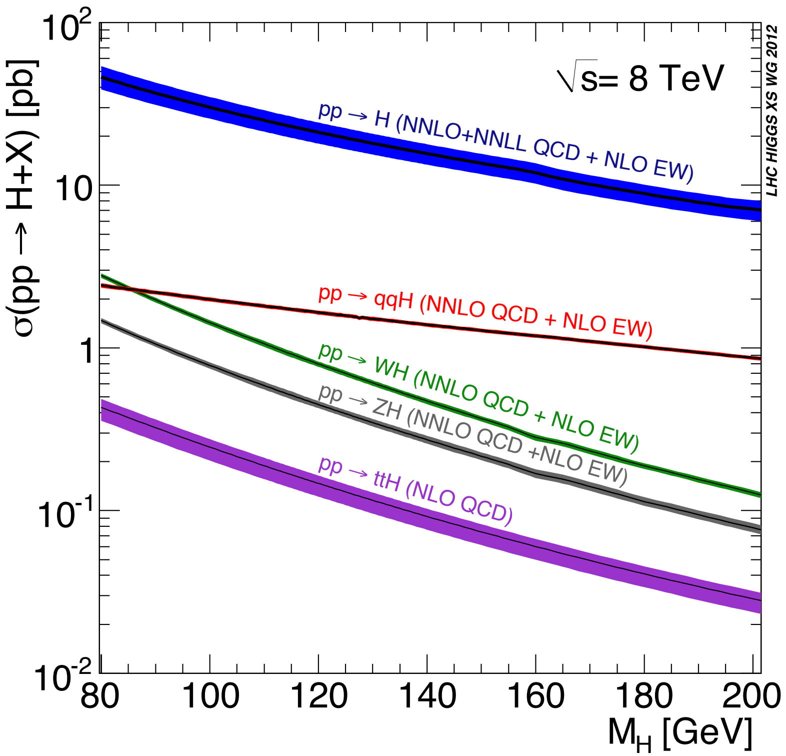
Phys. Lett. B565 (2003) 61-75

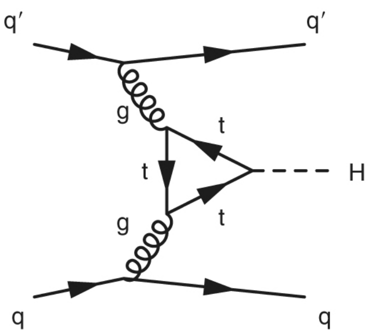
- **Final combined LEP results are inconclusive**
- **A hint rather than strong evidence**
- **All that can be concluded**

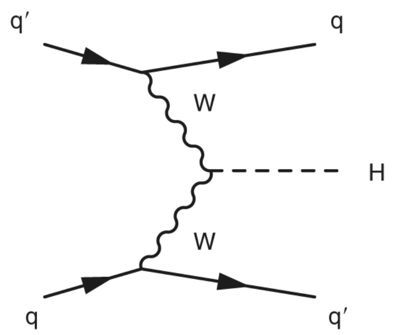
  $m_H > 114$ **GeV**

Higgs searches at the LHC

Production processes at the LHC



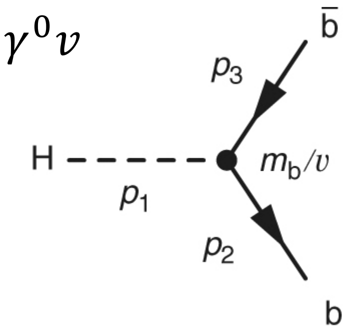




- **Total production cross section for a Higgs boson with $m_H = 125$ GeV is approximately 20 pb**
- **The first observation of the Higgs boson were based on 20 fb^{-1} of data (ATLAS and CMS combined)**
- **This corresponds to a total of approximately** $N = \sigma L = 400\,000$ **Higgs bosons**

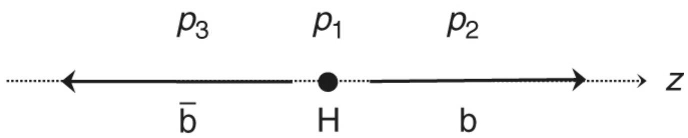
Higgs decay

$$M = \frac{m_b}{v}\bar{u}(p_2)v(p_3) = \frac{m_b}{v}u^{\dagger}\gamma^0 v$$



$$E = m_H/2$$

$$p_3 \approx (E, 0,0, -E) \qquad p_2 \approx (E, 0,0, E)$$



- **In the ultra-relativistic limit, the spinors for the two possible helicity states for each of the b-quark and the anti-b-quark are**

$$u_{\uparrow}(p_2) = \sqrt{E}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}, u_{\downarrow}(p_2) = \sqrt{E}\begin{pmatrix}0\\1\\0\\-1\end{pmatrix}, v_{\uparrow}(p_3) = \sqrt{E}\begin{pmatrix}1\\0\\-1\\0\end{pmatrix}, v_{\downarrow}(p_4) = \sqrt{E}\begin{pmatrix}0\\-1\\0\\-1\end{pmatrix}$$

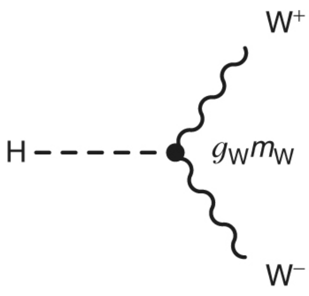
$$M_{\uparrow\uparrow} = -M_{\downarrow\downarrow} = \frac{m_b}{v}2E$$

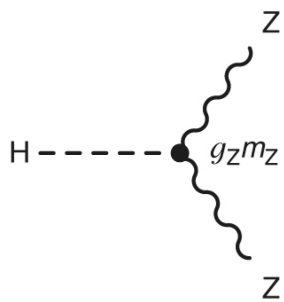
$$< |M|^2 > = |M_{\uparrow\uparrow}|^2 + |M_{\downarrow\downarrow}|^2 = \frac{m_b^2}{v^2}8E^2 = \frac{2m_b^2 m_H^2}{v^2}$$

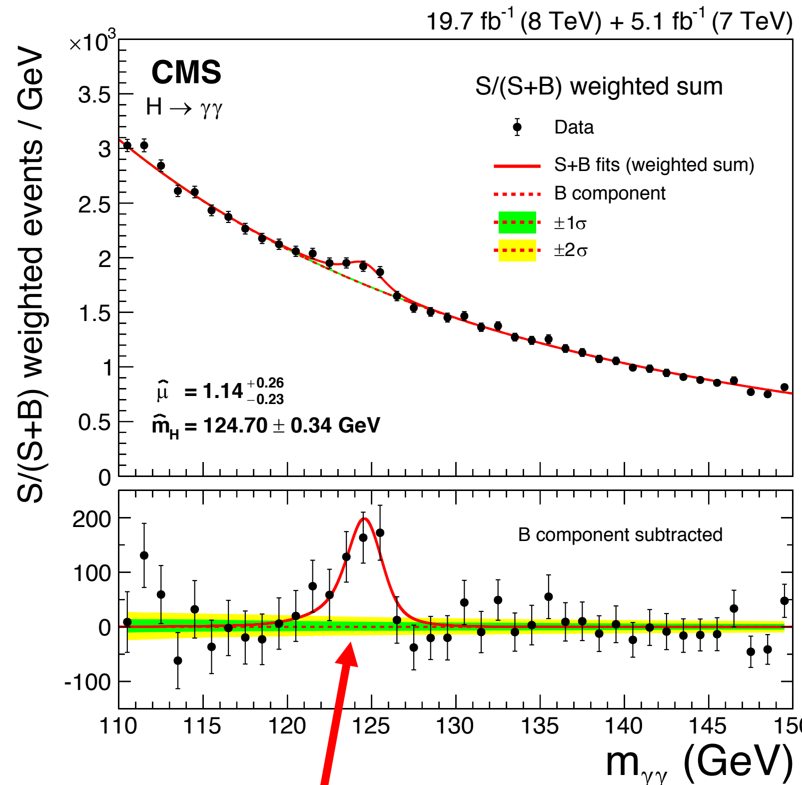
$$\Gamma(H \to b\bar{b}) = 3 \times \frac{m_b^2 m_H}{8\pi v^2}$$

Higgs searches at the LHC

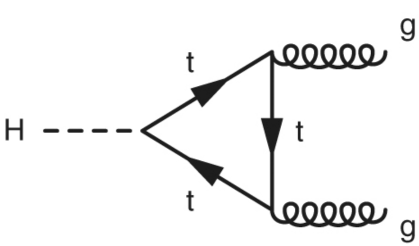
- Higgs decays to W and Z gauge bosons

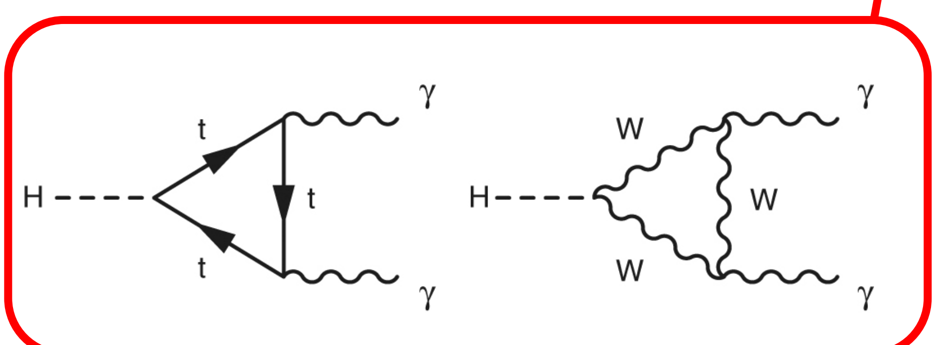






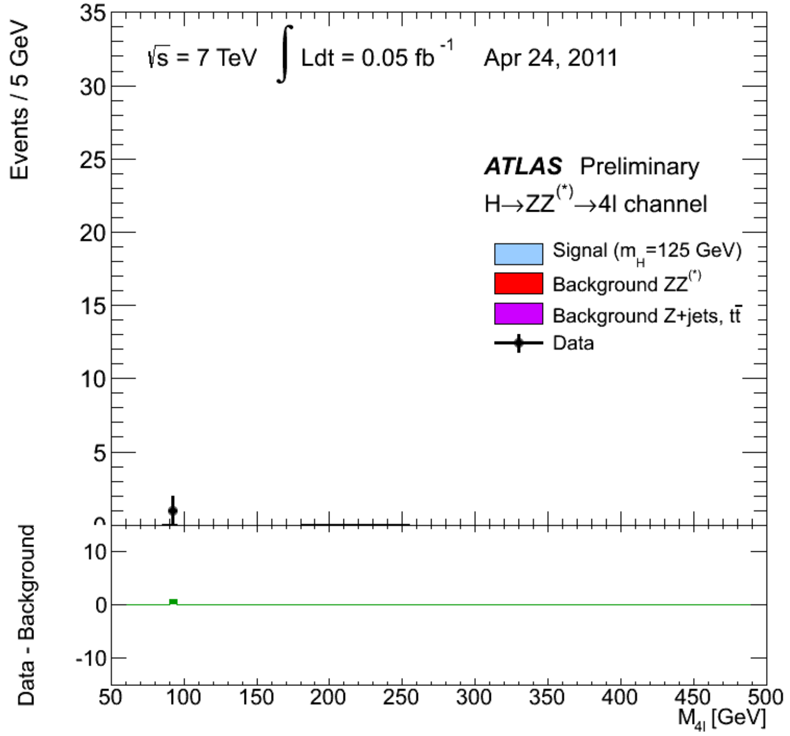
- Higgs also decays to massless particles through loops of virtual top quark and W bosons

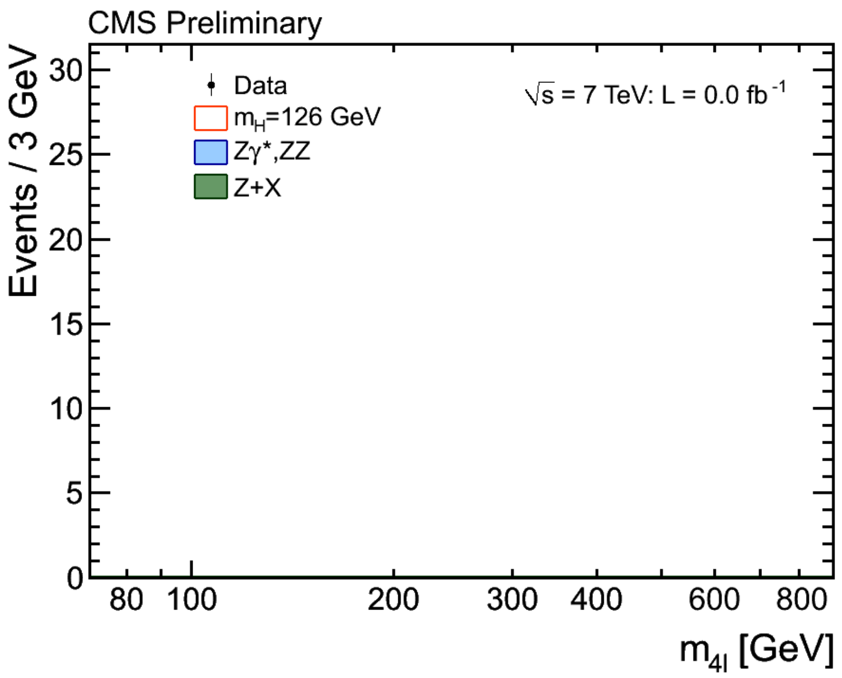




Higgs discovery at the LHC

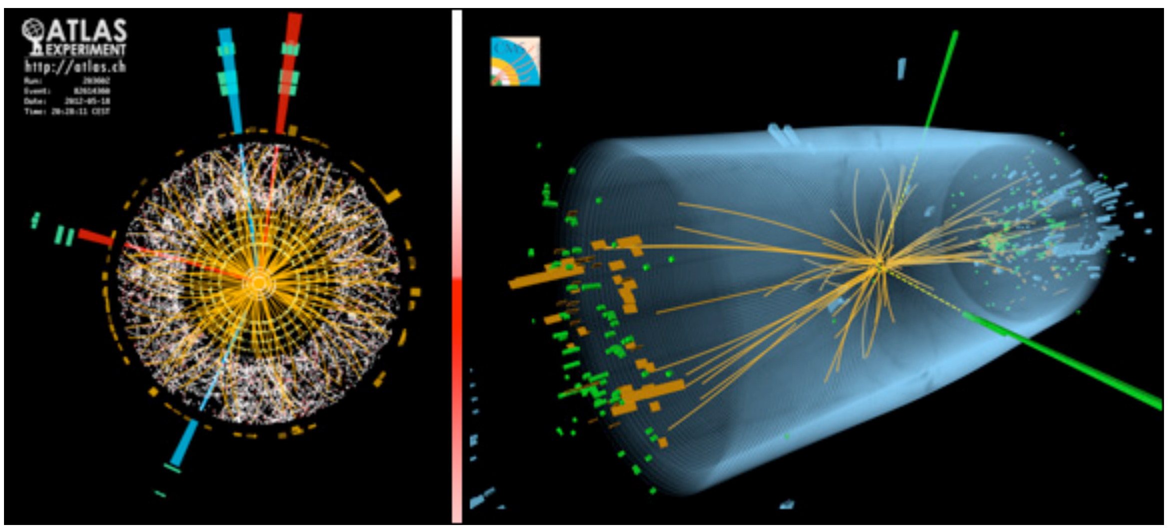
- Accumulating enough data allows to discover the signal from the large background
- 5 σ discovery at the LHC → the probability of having this peak due to statistical fluctuation is 0.00005%





Fireworks on the 4th of July

- On July 4, 2012, the leaders of the ATLAS and CMS experiments at the LHC reported we had evidence for a “Higgs-like” boson with a mass around 125 GeV.
- The evidence was far from weak; they were five sigma results, meaning less than one chance in a million of the data being only a statistical fluctuation.
- After half a century of waiting, the drama was intense. Physicists slept overnight outside the auditorium to get seats for the seminar at the CERN lab in Geneva, Switzerland.



Combined result at the LHC

- When a new boson was discovered, it was not possible to say conclusively that the Higgs boson has been discovered.
- Many experimental results have showed that a new particle is compatible with the expected properties of the Higgs boson in the SM
- Its production cross section is consistent with the SM
- Its mass is compatible with the indirect determinations from its presence in quantum loop corrections, as inferred from the precision electroweak measurements.
- So the new particle is the Higgs boson with the mass

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

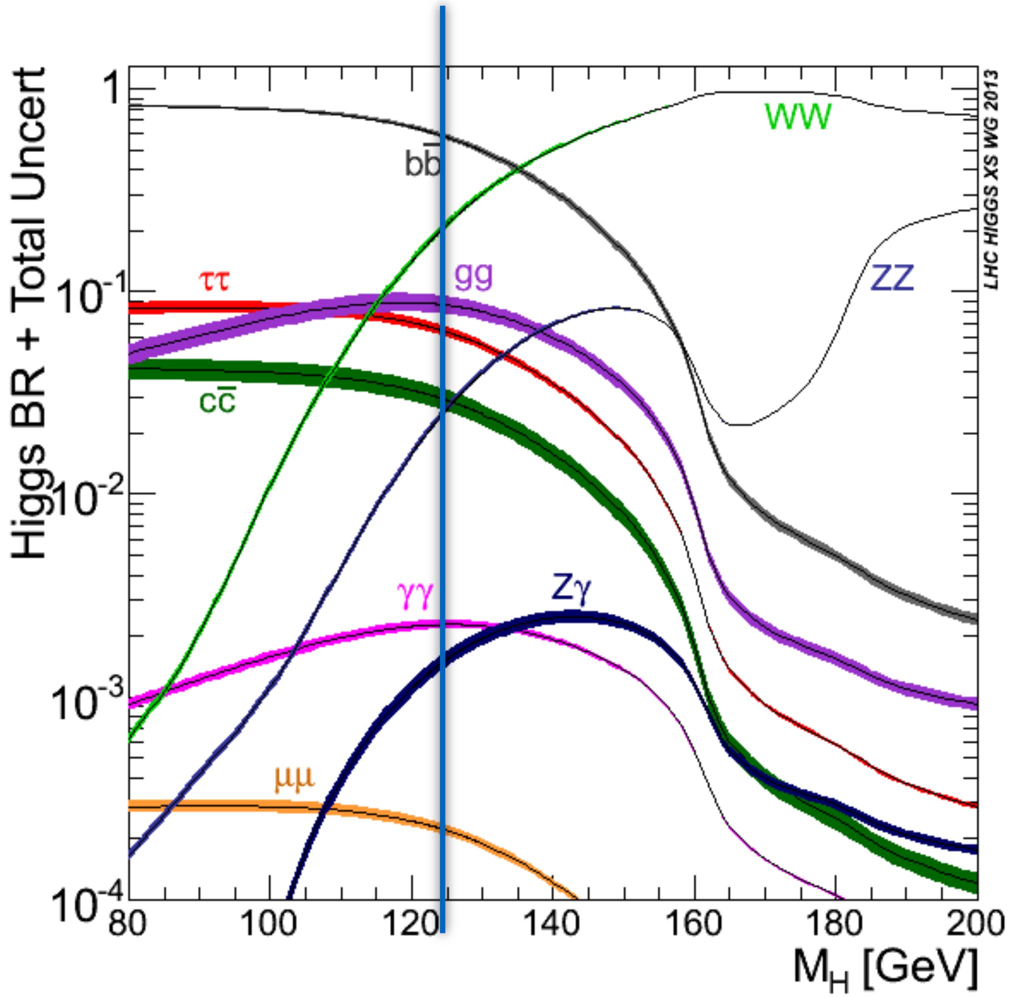
- Since the discovery of the W and Z bosons in the mid 1980s, the search for the Higgs boson has been the highest priority in particle physics.
- Its discovery finally completed the particle spectrum of the SM

More about Higgs

- **If the scalar boson discovered in 2012 is a Higgs boson predicted in the Standard Model, the coupling with other particle should be consistent with the SM predictions at 125 GeV**

- **For example,**
  - **in the third generation :** $H \rightarrow b\bar{b}$, $H \rightarrow \tau\tau$
  - **In the second generation:** $H \rightarrow \mu\mu$, $H \rightarrow c\bar{c}$

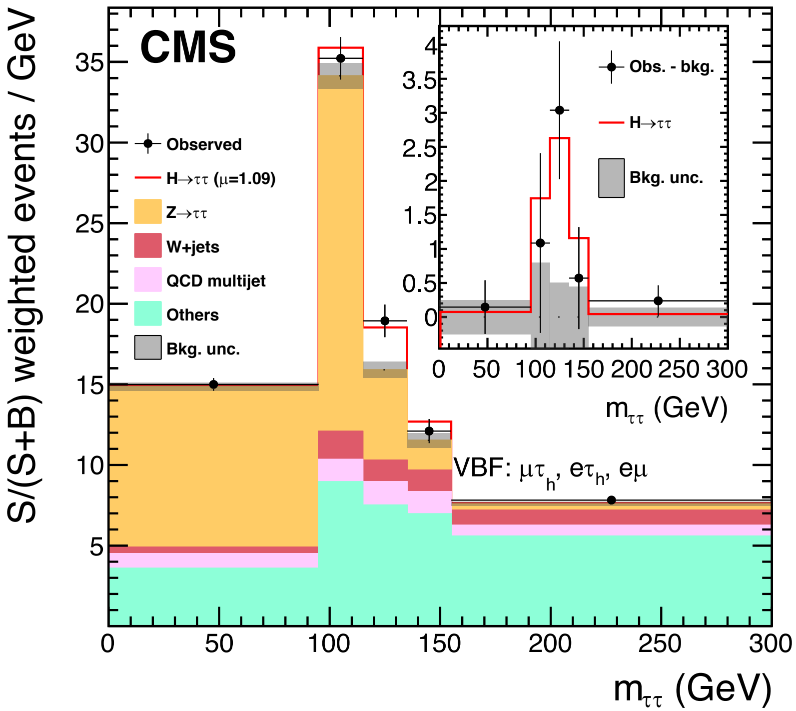
- **How about coupling with a top quark?**



Coupling with third generation particles

$H \rightarrow \tau\tau$

5.9 σ (5.9 σ expected)

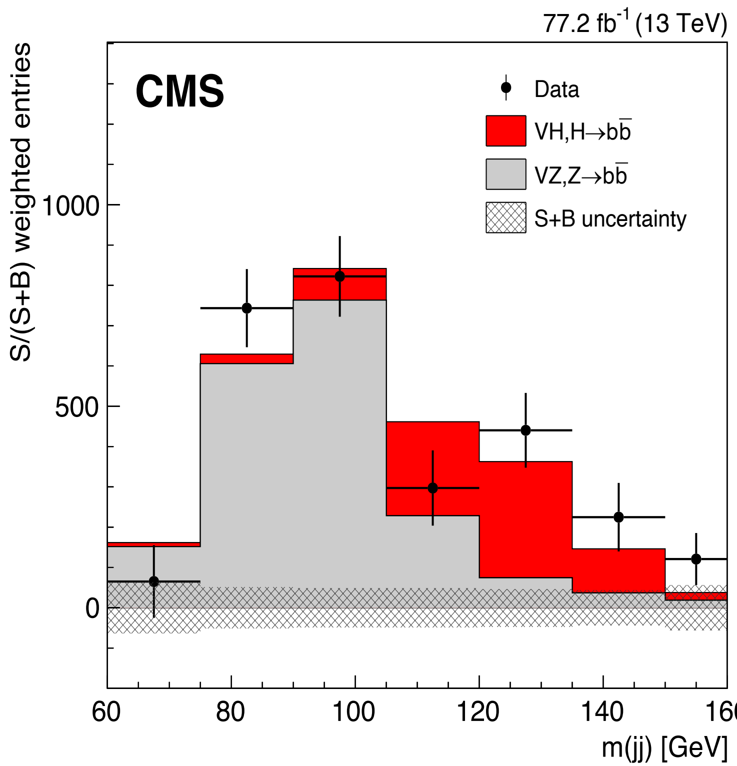


Summer in 2017

PLB 779 (2018) 283

$H \rightarrow b\bar{b}$

5.6 σ (5.5 σ expected)



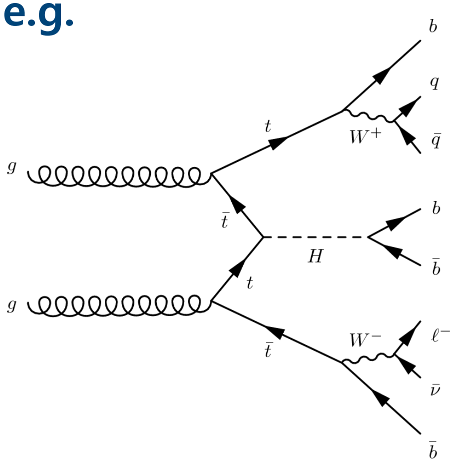
Summer in 2018

PRL 121 (2018) 121801

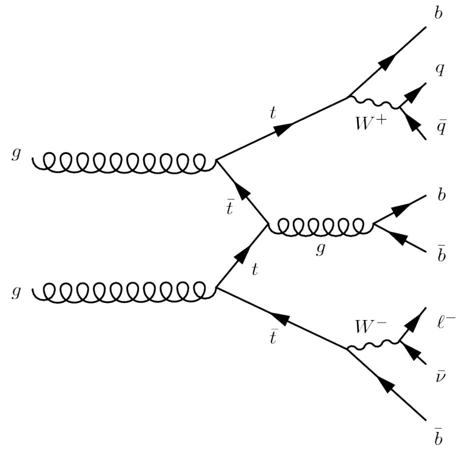
Coupling with a top quark

- In $H \rightarrow \gamma\gamma$ decay, Higgs couples with top quarks and W bosons
- Direct measurement of coupling from the production $t\bar{t}$ associated with the Higgs

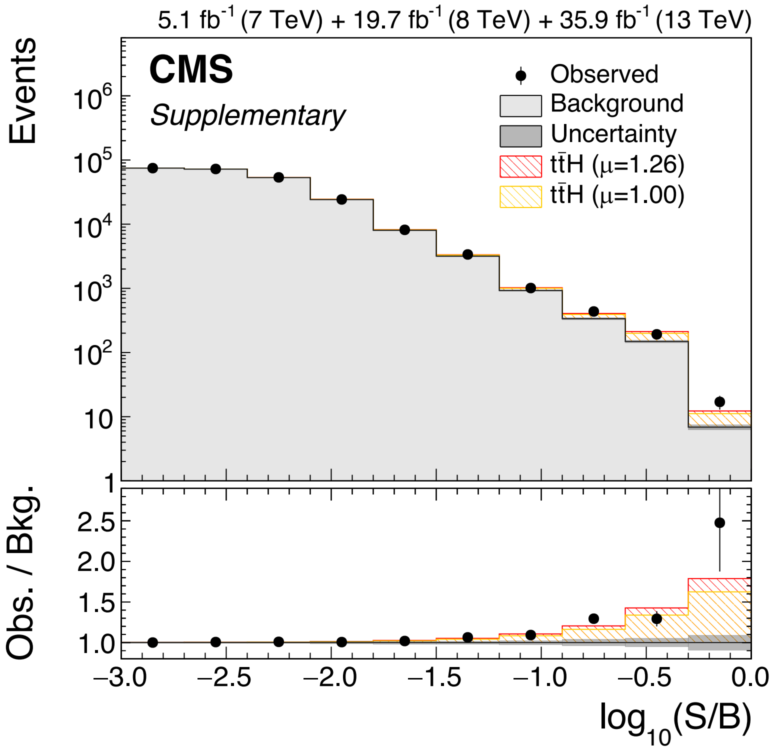
e.g.



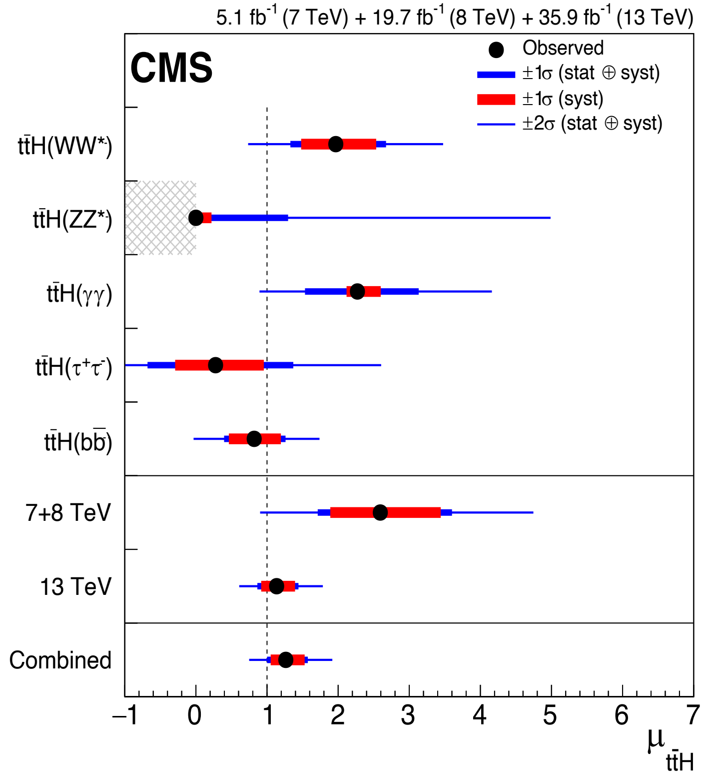
Signal
$t\bar{t}H(b\bar{b})$



Background
$t\bar{t}b\bar{b}$



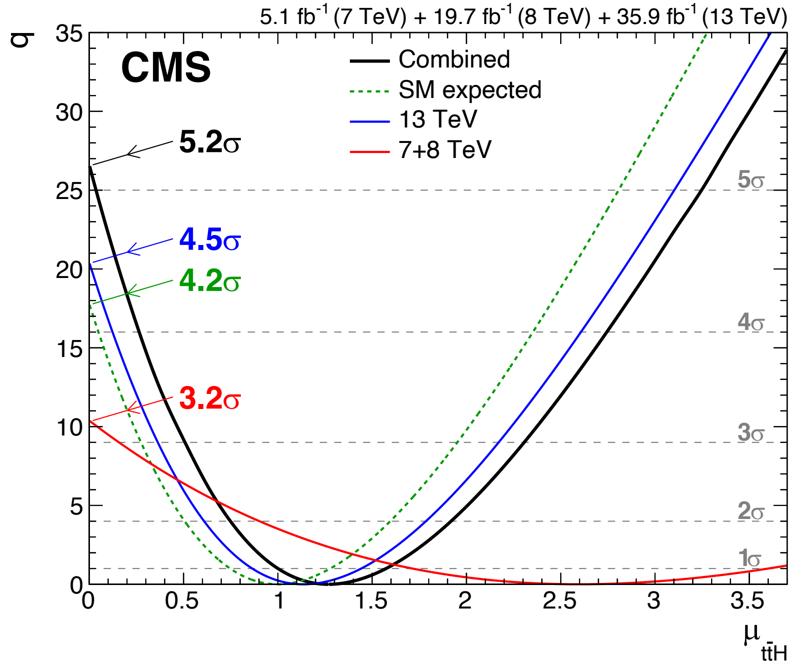
Discovery of $t\bar{t}H$



Signal strength

ttH

5.2 σ (4.2 σ expected)



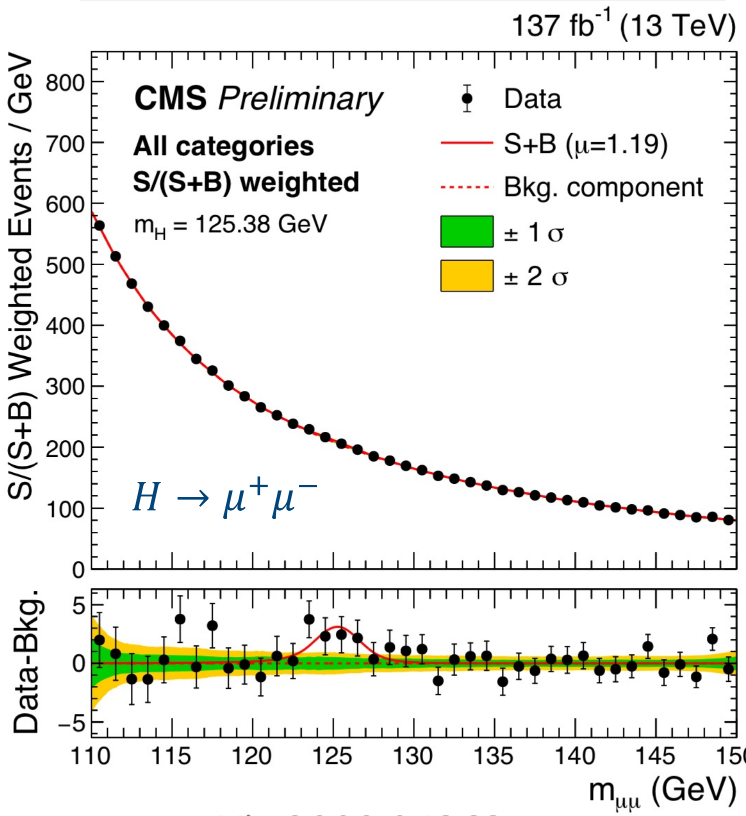
Spring in 2018

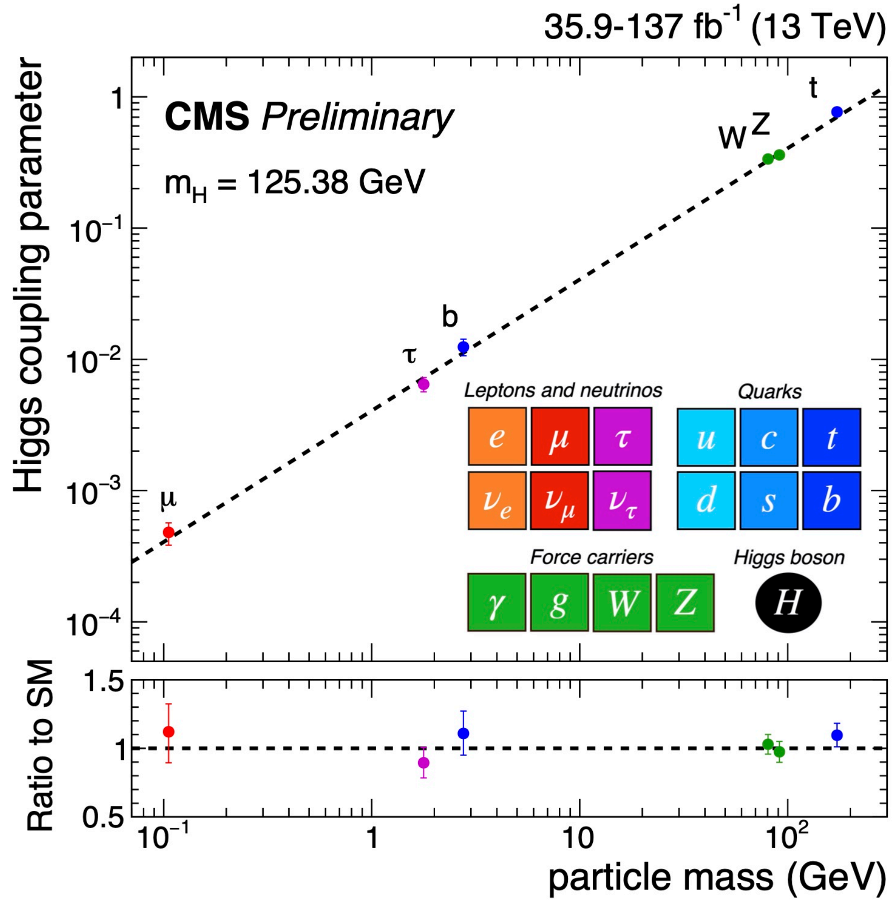
PRL 120 (2018) 231801

Coupling with the SM particles

- Recently, first evidence of Higgs coupling with the 2nd generation fermion
- Look for a narrow resonance peak at 125 GeV with $BR(H \rightarrow \mu\mu) = 2.1 \times 10^{-4}$
- Measured signal strength $\hat{\mu} = 1.19^{+0.44}_{0.42}$
- Continuous success of the Standard Model!

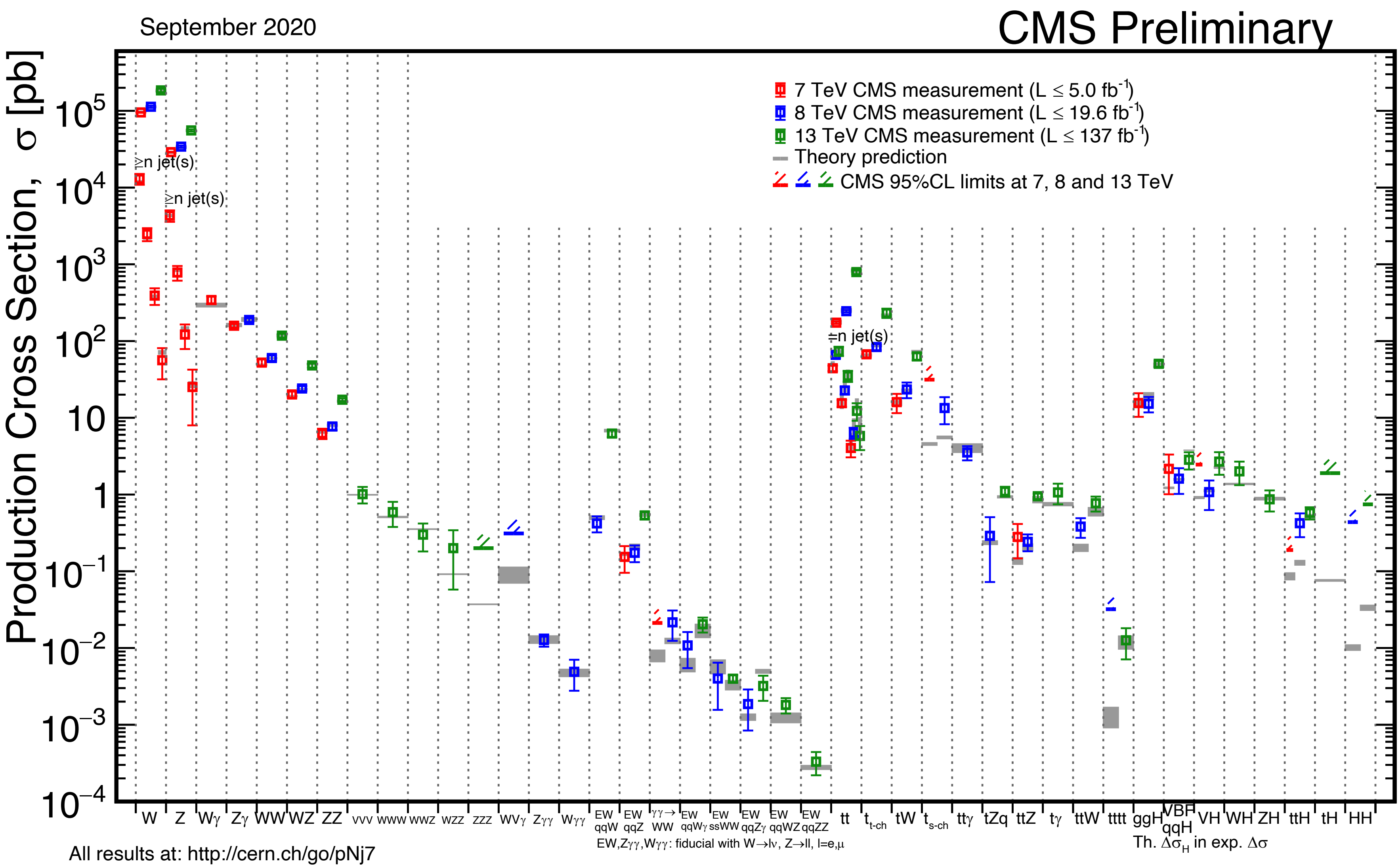
Significance 3σ obs. (2.5σ exp.)



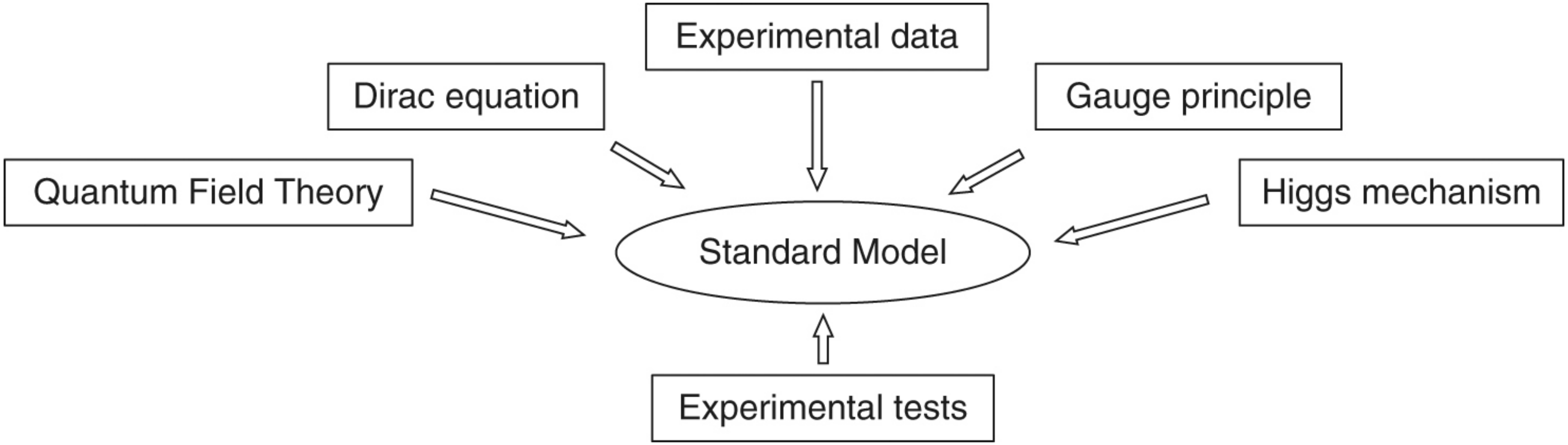


arXiv:2009.04363

Our understanding of the standard model



Parameters of the SM



- 25 free parameters
  - Masses of the twelve fermions
  - Three coupling constants describing the strengths of the gauge interactions
  - Higgs potential (vacuum expectation value) and the mass of the Higgs
  - Eight mixing angles of the PMNS and CKM matrices
- These parameters are chosen to match the observations rather than theoretical principle
- Patterns emerge between the different parameters suggesting the presence of some, yet unknown, symmetry principle

Outlook

- **The discovery of the Higgs boson is not the end of the story**
- **In supersymmetry, there could be five Higgs bosons.**
- **It is not clear whether the observed Higgs boson is a fundamental scalar particle or whether it might be composite**
- **A detailed understanding of all the properties of the Higgs boson may open up completely new avenues in our understanding of the Universe and point to what lies beyond the Standard Model**

Beyond the Standard Model

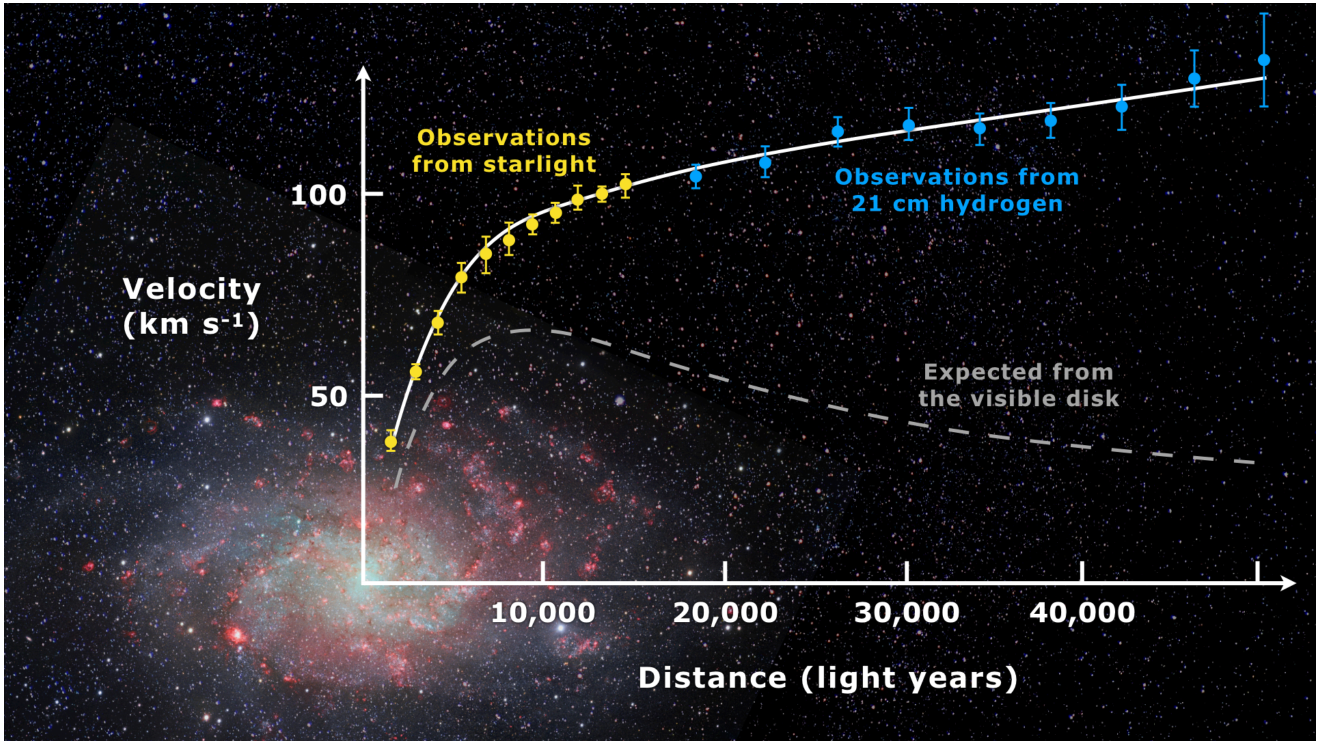
- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
- Why can't the Standard Model predict a particle's mass?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- Why are there exactly three generations of quarks and leptons?
- How does gravity fit into all of this?

Dark Matter

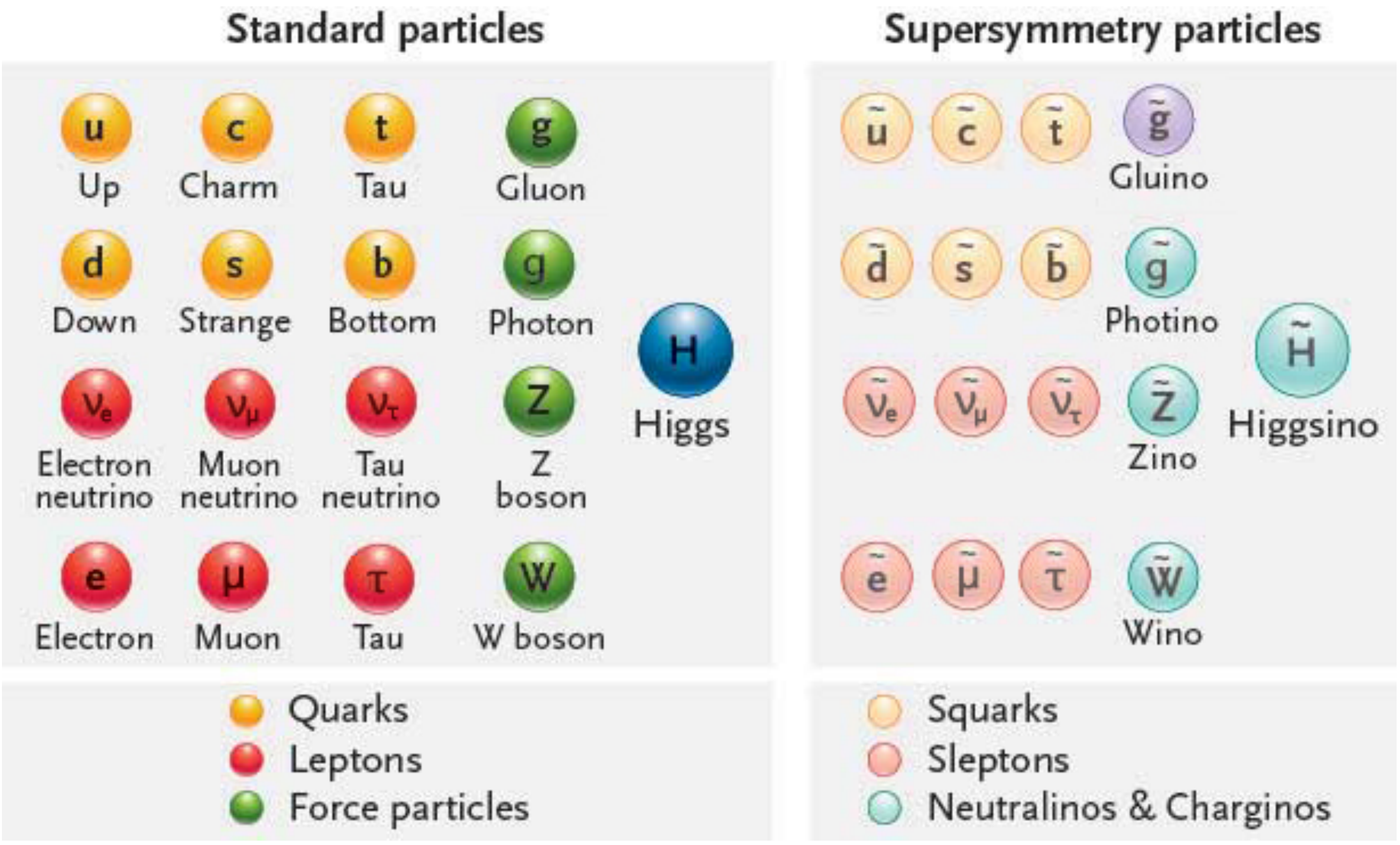
- $M(r)$ is the total mass within a radius r
- The tangential velocities of the stars should decrease as $r^{-\frac{1}{2}}$.
- But this is not consistent with the observed velocity distributions which decrease only slowly with r.

- Majority of the universe may not be made of the same type of matter as the Earth. We infer from gravitational effects the presence of this dark matter, a type of matter that we cannot see. There is strong evidence that it might not be made up of protons, neutrons, and electrons.

$$\frac{mv^2}{r} = \frac{Gm}{r^2} M(r)$$



Suppersymmetry

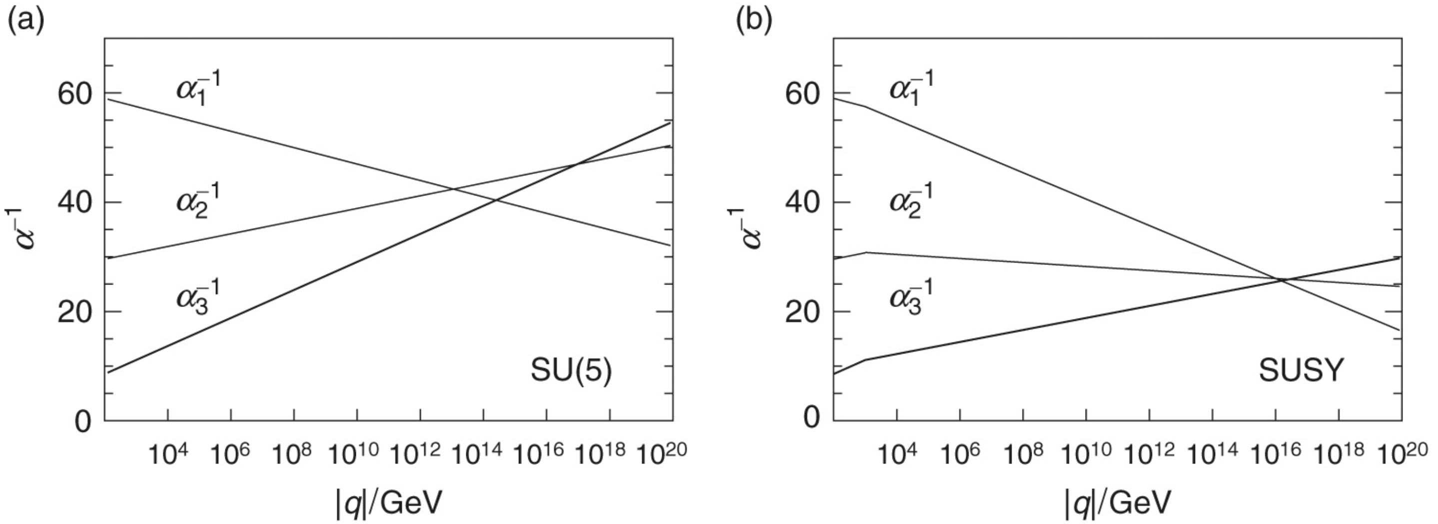


Suppersymmetry

- At the electroweak scale of $q^2 = m_Z^2$,

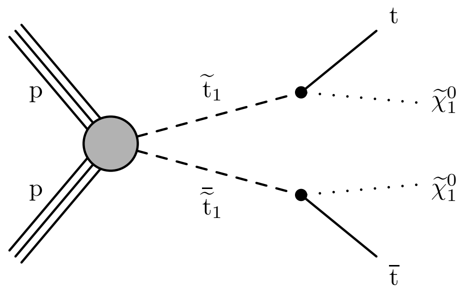
$$\alpha^{-1} : \alpha_W^{-1} : \alpha_S^{-1} \approx 128 : 30 : 9$$

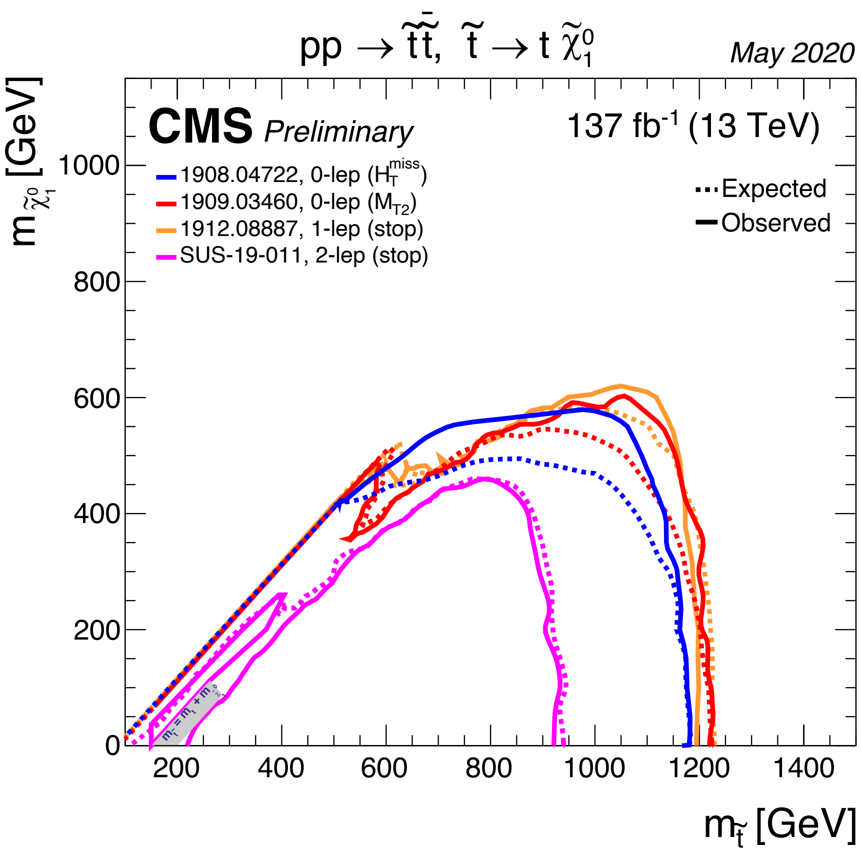
- Supersymmetric particles at a scale of $\Lambda_{SUSY} = 1$ TeV would modify the couplings
- The coupling constants converge to a single value of $\alpha_{GUT} \approx 1/26$ at $q \sim 10^{16}$ GeV



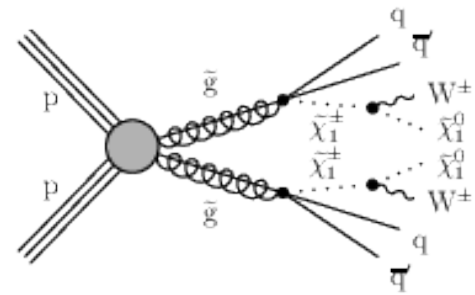
Search for SUSY

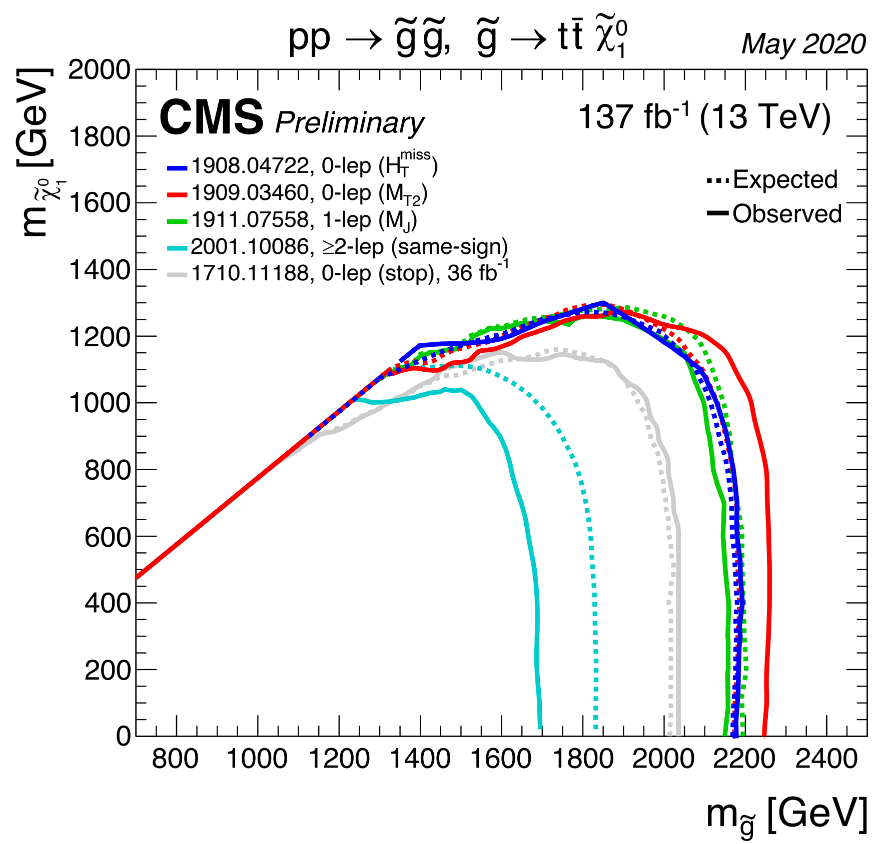
Squark pair production





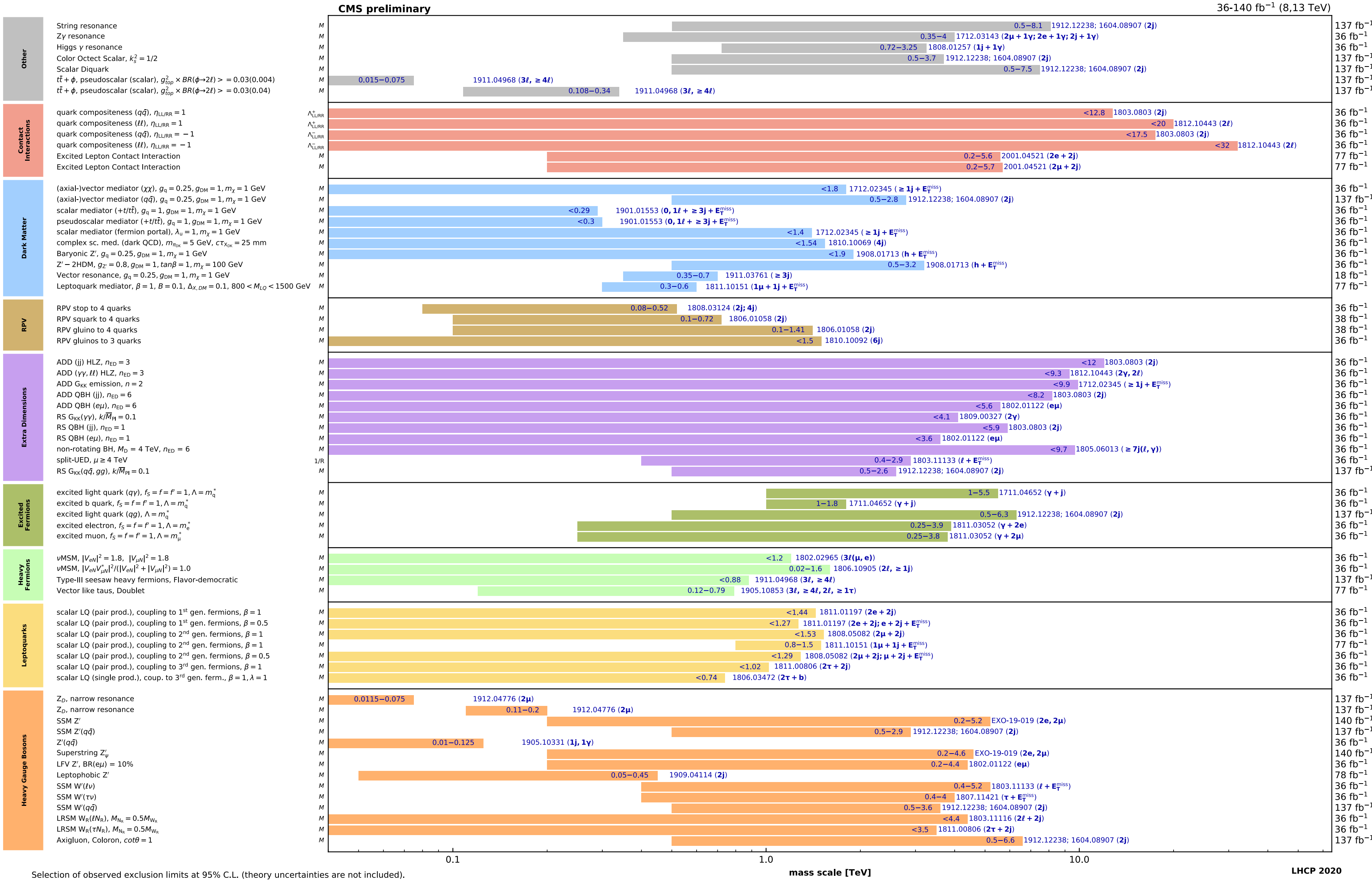
Gluino pair production



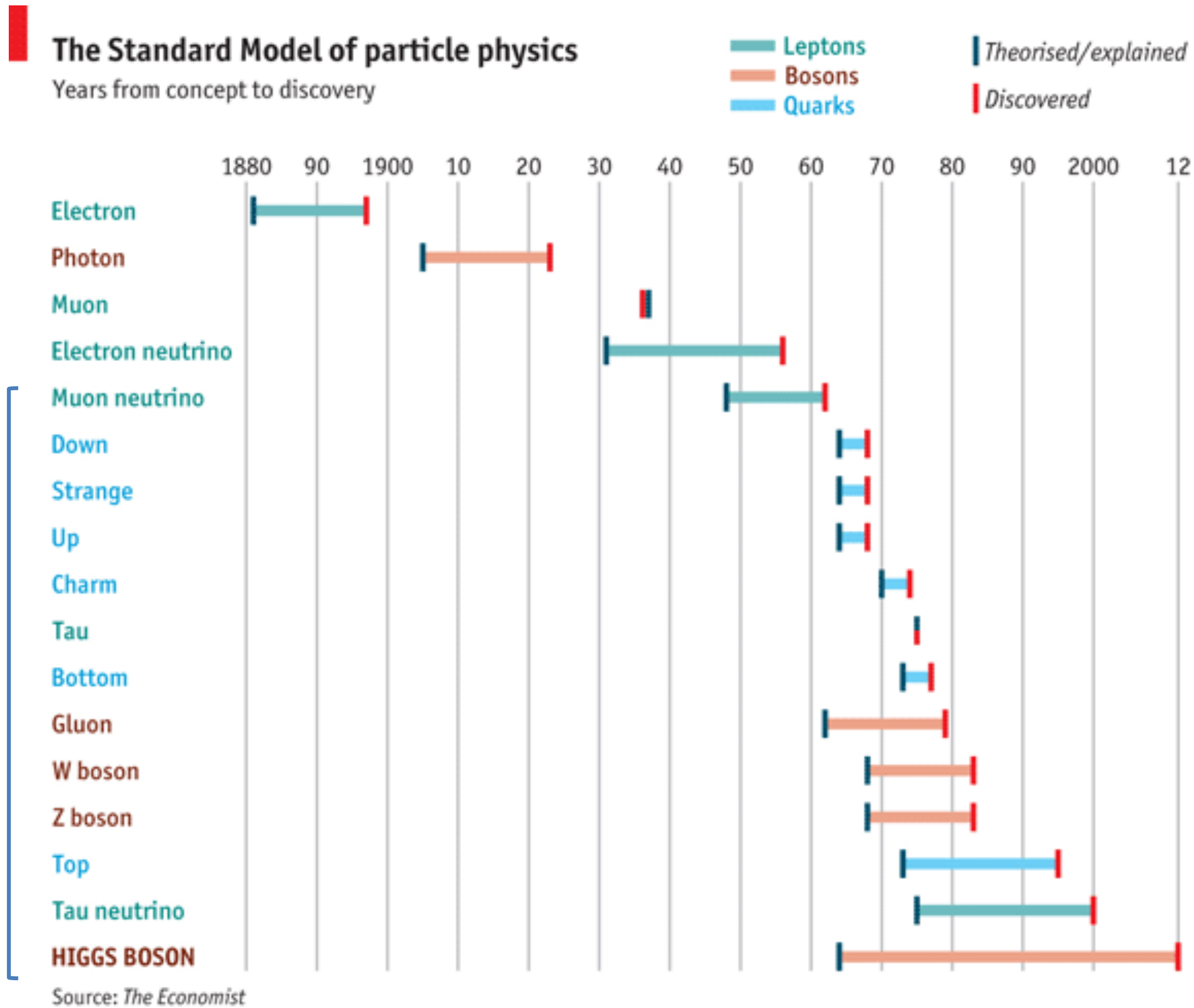


Search for Exotica particle

Overview of CMS EXO results



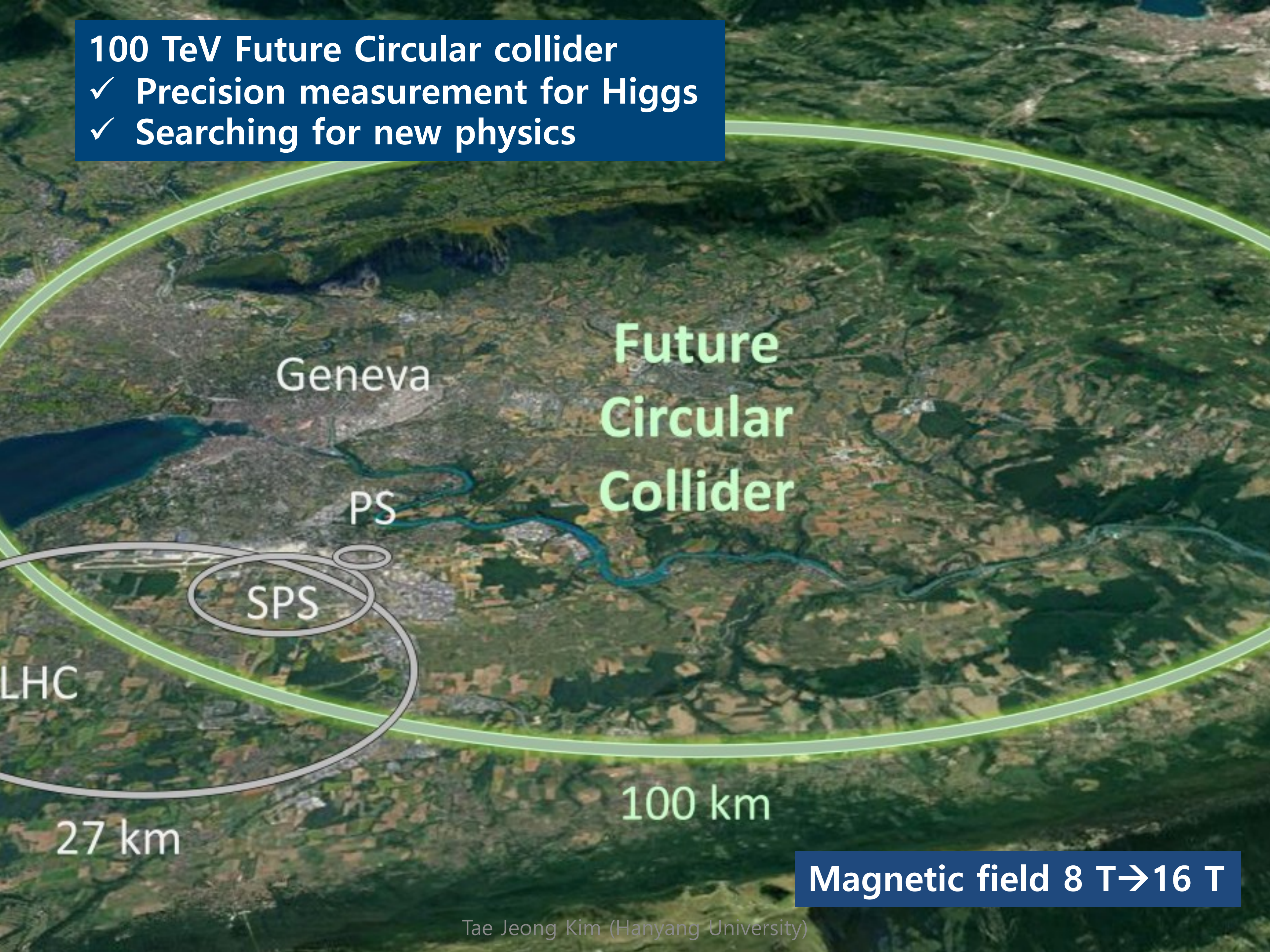
History of Particle discovery



Collider Physics

100 TeV Future Circular collider

- ✓ Precision measurement for Higgs
- ✓ Searching for new physics



Magnetic field 8 T→16 T

Conclusion

- From 1960 to 2012, this period represented a giant leap forward in our understa nding of out nature
- In this lecture, tried to overview the whole story of the Standard model which is one of the central pillars of modern physics
- We just learned that SM is not the end of the story: there are too many unknow n phenomena
- Our nature is there to be discovered and understood
- In coming years, more data from the LHC will tell us whether there will be the direct detection of dark matter, the discovery of supersymmetry or even unexpected discovery
- Feel lucky we are living in very interesting times