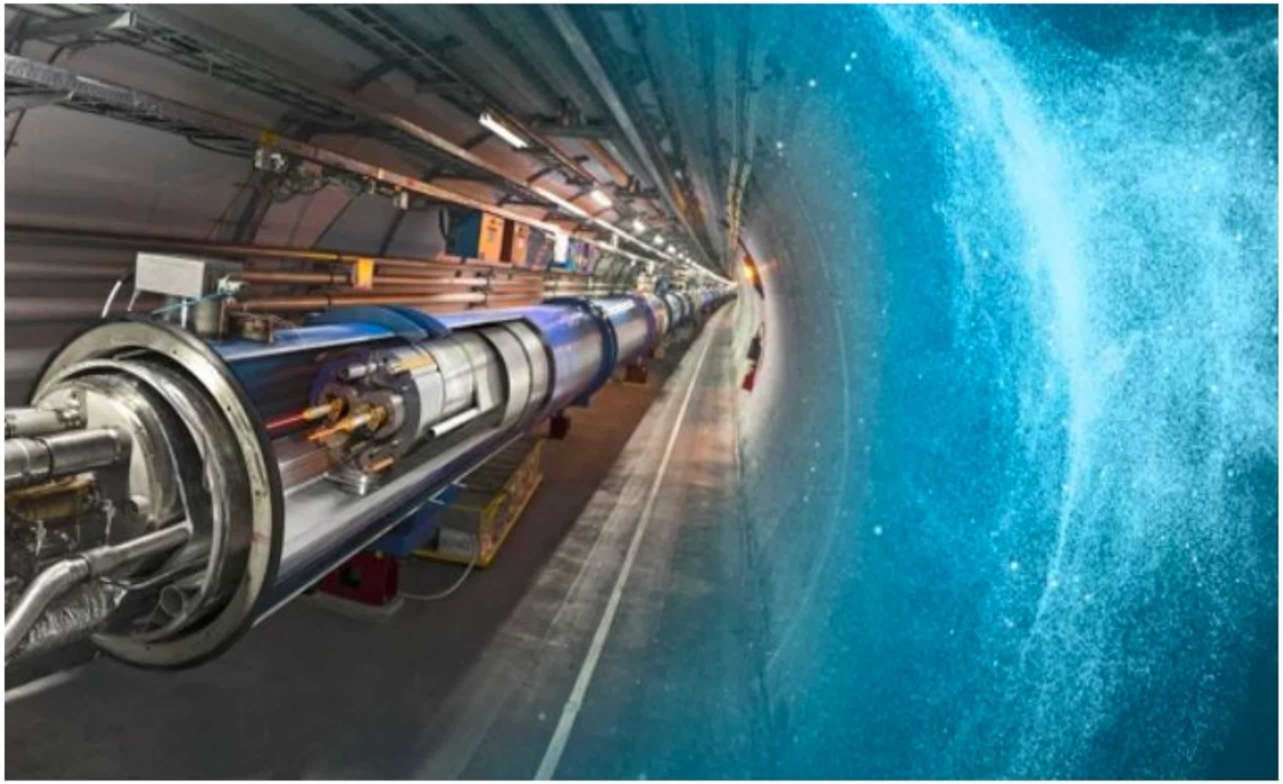
# Introduction to the Standard Model

## Summer Student Lecture 2023 – Part III




Alvaro Lopez Solis

Deutsches
Elektronen
Synchrotron


24th-26th July 2023

HELMHOLTZ ASSOCIATION


Many thanks to Sarah Heim and Thorsten Kuhl for their lectures and help


DESY

# Content

- 0) Introduction
  - What is the Standard Model?
  - Coupling constants, masses and charges
  - Units and scales

- 1) Interactions
  - Relativistic kinematics
  - Symmetries and conserved quantities
  - Feynman diagrams
  - Running couplings and masses

- 2)Quantum electrodynamics
  - Test of QED: Magnetic momentum of the muon
  - Test of QED: High energy colliders

# Content

- 3) Strong Interaction: Quantum-Chromodynamics
  - A short history of hadrons and quarks
  - DIS and gluons
  - QCD and its properties

- **4) Electroweak interactions**
  - **History of the weak interaction : β-decays**
  - **Parity violation**
  - **CP-violation**
  - **GSW mechanism and CKM**
  - **Experimental verification**

- **5) The Higgs**
  - **Why is it necessary ?**
  - **How was it found ?**

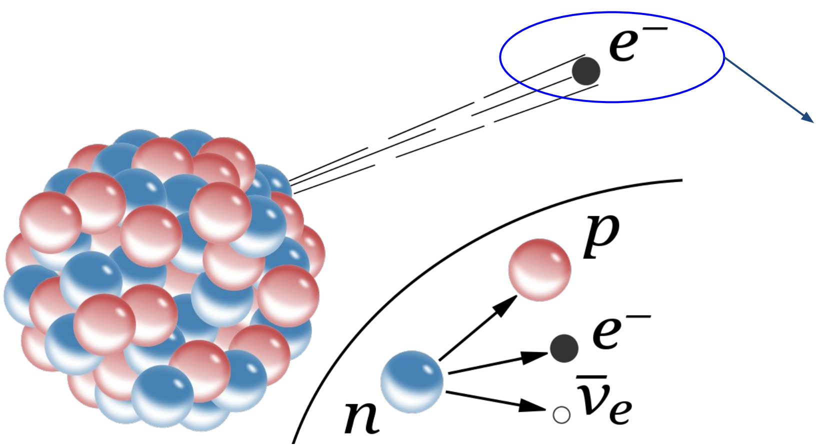
- **Beyond the Standard Model (brief)**

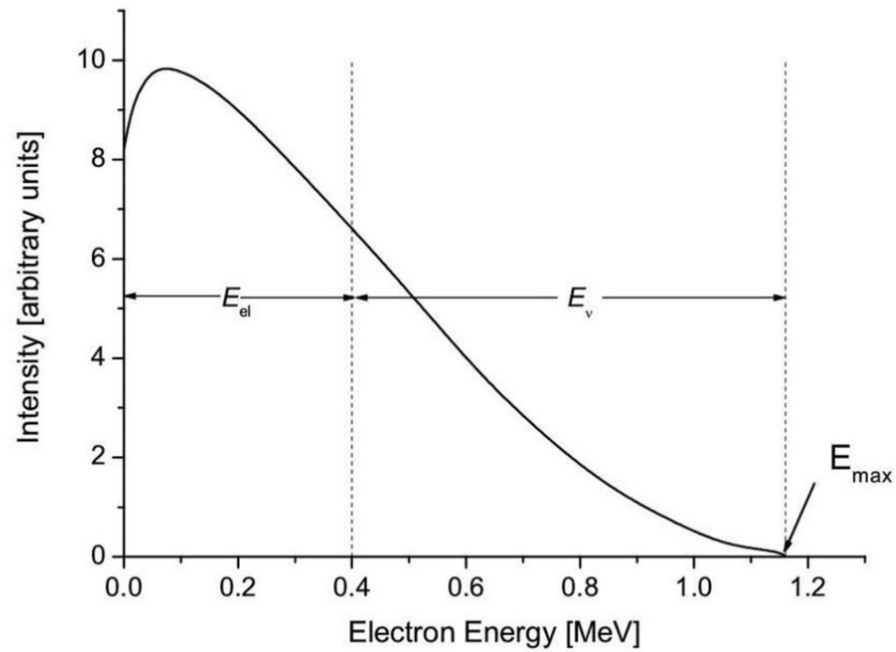
# Weak interaction

# A little bit of history: the β⁻ decays and radiation

- Discovered with radioactivity. Initially, only observed that nuclei emitted one electron and the atomic number was unchanged.
- Puzzling at the time:
  - Spin of the nuclei unchanged or integer change → electron with spin ½. How ?
  - Energy conservation: if only electron is emitted, energy should have a defined value → But continuous
- Pauli's proposal: neutrino

  Detected in 1956 ([Cowan,Reines](Cowan,Reines))



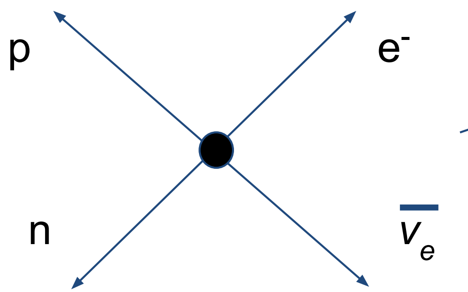



DESY

# A little bit of history: Weak interactions

- $\beta^-$ decays usually have a long lifetime ( e.g. isolated neutron having a half life of 10 mins)
  - Lifetime depends on the probability of the decay to happen
  - Probability of decay depends on interaction strength → Weak interaction !
- Before full QFT developed, Fermi theory proposed as explanation of beta-decay

  → four point interaction




$$\mathcal{M} = \frac{G_F}{\sqrt{2}}(\bar{\psi}_p \gamma^\mu \psi_n)(\bar{\psi}_e \gamma_\mu \psi_{\bar{\nu}}),$$

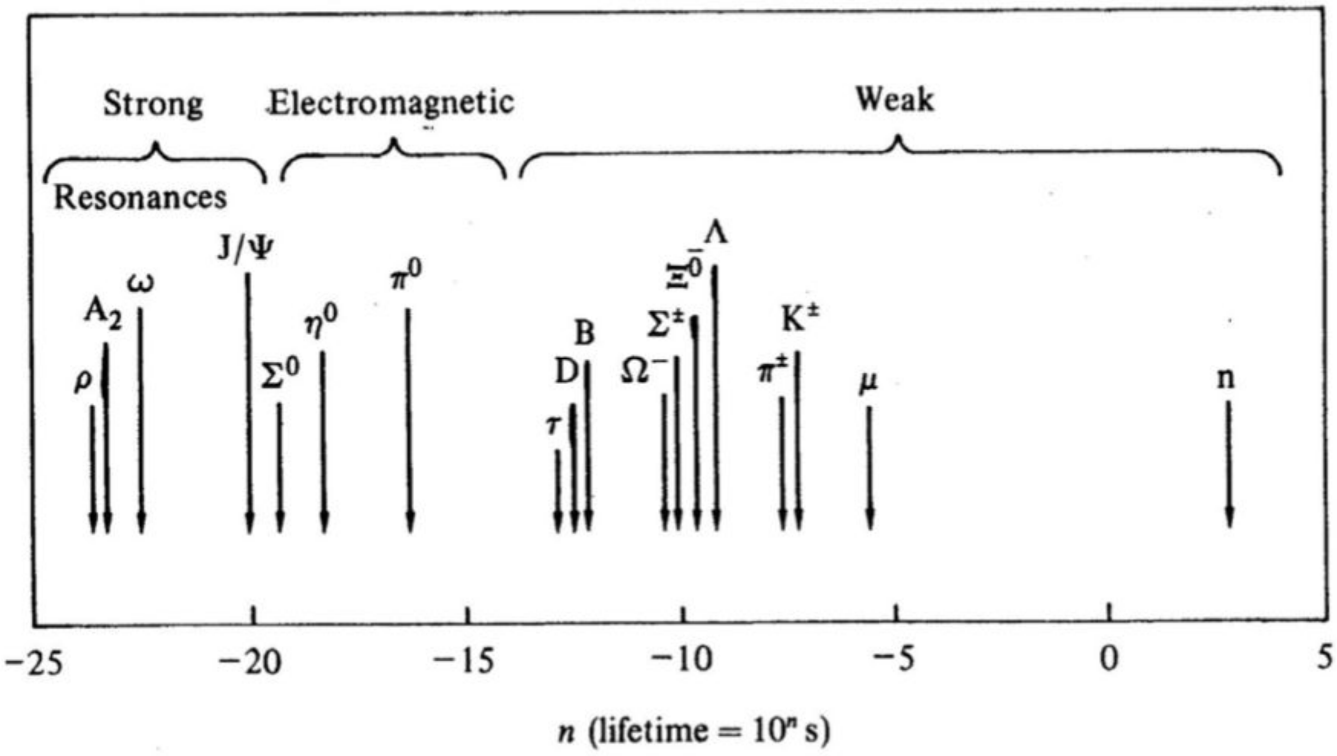
$G_F = 1.6637 \times 10^{-5}\ \mathrm{GeV}^{-2}$
measured from lifetime of muon

- Fermi's theory successfully described decays but incomplete.

Weak interaction decays started to show strange behaviours w.r.t electromagnetic and strong interactions

# Hadrons and weak interactions

> Yesterday we saw the appearances of hadrons in the 50's and 60's. At the same time, these hadrons are not stable and decay
> Lifetimes very different.



# Hadrons and weak interactions

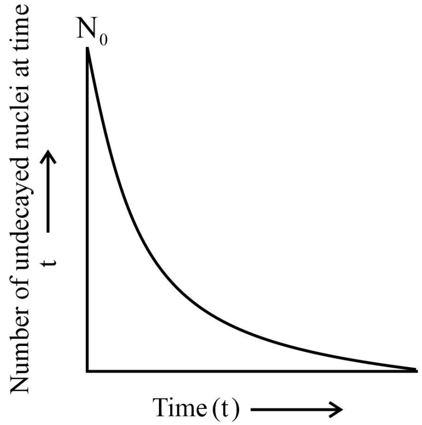
> The probability of finding a particle after a certain time is given by:

$$\psi(t) \propto e^{-iMt} e^{-\Gamma t/2} = e^{-i(M-i\Gamma/2)t},$$

$$P(t) = |\psi(t)|^2 \propto e^{-\Gamma t}$$

$$\Gamma = 2\Delta E = \frac{\hbar}{\tau}$$

Decay width




Decay width proportional to the amplitude of the process to happen

$$d\Gamma = \frac{(2\pi)^4 \delta^{(4)}(P_f - p_R)}{2E_R} \overline{|\mathcal{M}_{fi}|^2} \prod_{j=f} \frac{d^3 p_j}{2E_j (2\pi)^3}.$$

- More likely process (e.g strong ) → Larger decay width → shorter lifetime
- Less likely process (e.g weak interaction ) → Smaller decay width → larger lifetime

# Hadrons and weak interactions

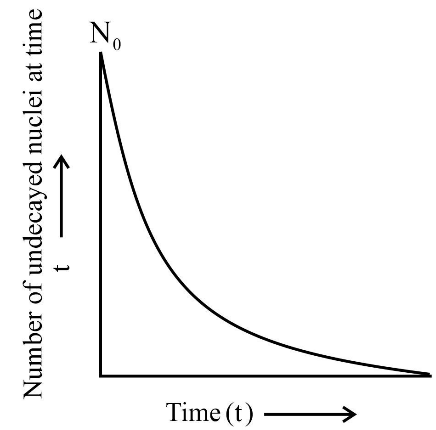
> The probability of finding a particle after a certain time is given by:

$$\psi(t) \propto e^{-iMt} e^{-\Gamma t/2} = e^{-i(M - i\Gamma/2)t},$$

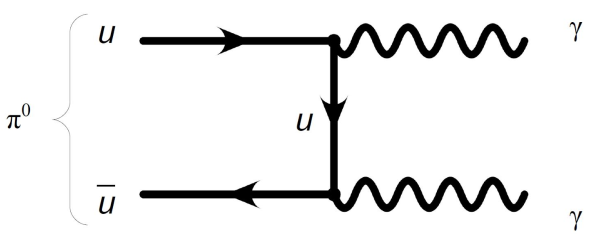
$$P(t) = |\psi(t)|^2 \propto e^{-\Gamma t}$$

$$\Gamma = 2\Delta E = \frac{\hbar}{\tau}$$

Decay width

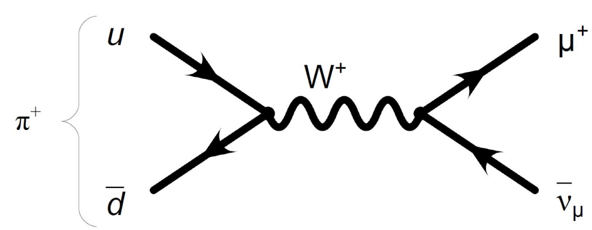



Decay width proportional to the amplitude of the process to happen




electromagnetic interaction

$$\text{Mean life } \tau = (8.52 \pm 0.18) \times 10^{-17}\ \text{s}$$

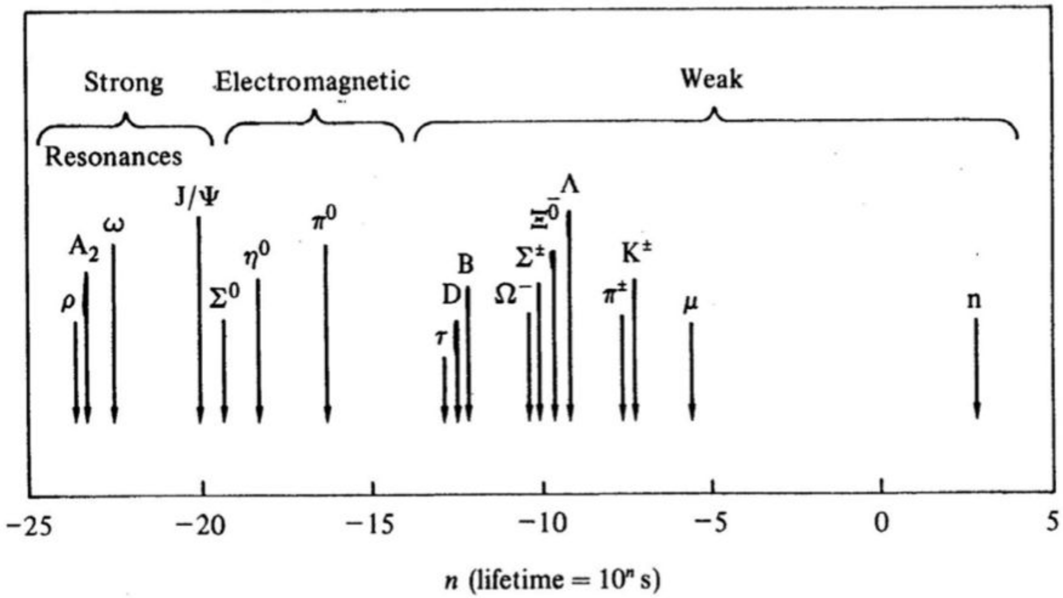



weak interaction

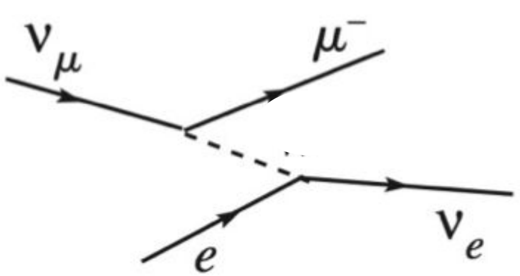
$$\text{Mean life } \tau = (2.6033 \pm 0.0005) \times 10^{-8}\ \text{s}$$

# Hadrons and weak interactions

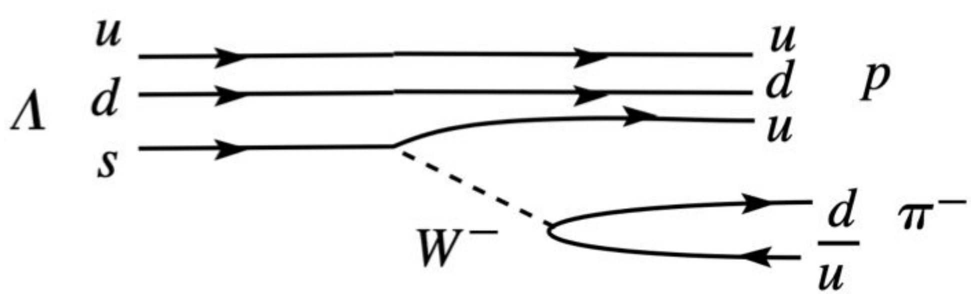
- Weak interactions mediating the decays of many of the hadrons .. And other features observed




Charge currents




Changes in flavour (ΔS = 1 )



# The $\tau$-$\theta$ puzzle (1956)

- In the 50's, two particles were observed: $\tau^+$ and $\theta^+$.$\tau$-$\theta$ puzzle

$$\tau^+ \rightarrow \pi^+\pi^+\pi^- \qquad P(\tau^+) = P(\pi^+\pi^+\pi^-) = -1$$

$$\theta^+ \rightarrow \pi^+\pi^0 \qquad P(\theta^+) = P(\pi^+\pi^0) = +1$$

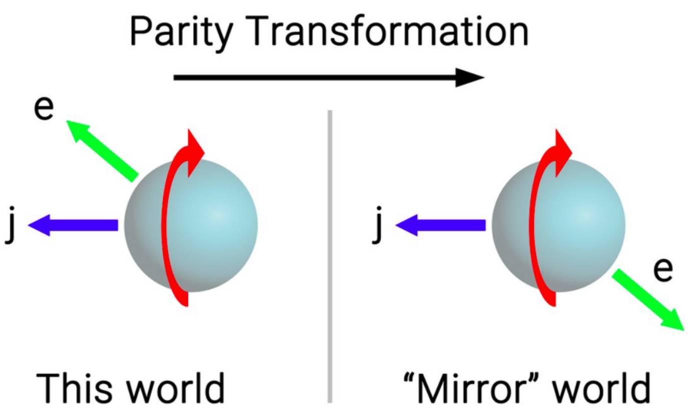
- Decaying into different states and different parity …. Same mass, lifetime, charge, spin ….

- Proposal that both particles are actually the same particle ($K^+$) but parity violation in the interaction.

# Reminder 1st lecture

## Parity

Mirror the coordinates of the particle.
Changes sign of momentum, coordinates
Spin doesn't change sign.




## Time reversal

If I revert the time, would the interaction take place in the same way ?

## Charge conjugation

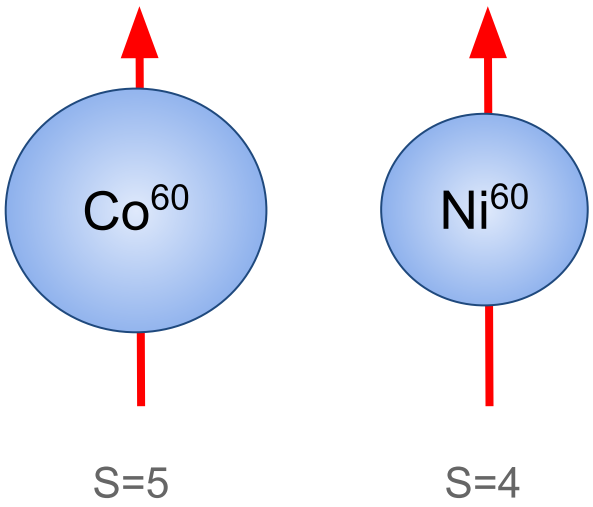
Change a particle by its anti-particle

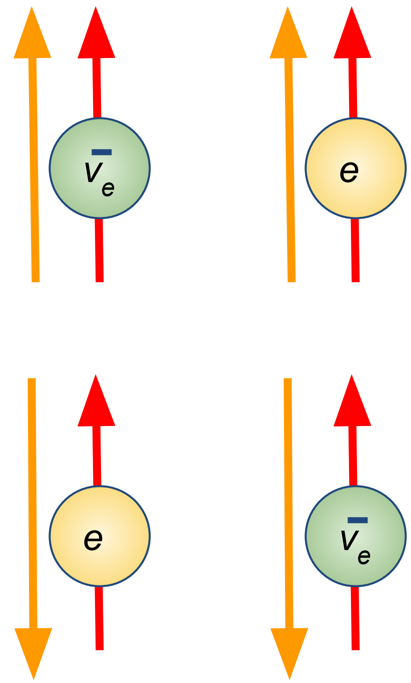

And combinations: CP, CPT ?

# β-decays of $Co^{60}$: Parity violation of the weak interaction

## $Co^{60}$ atoms aligned with magnetic field

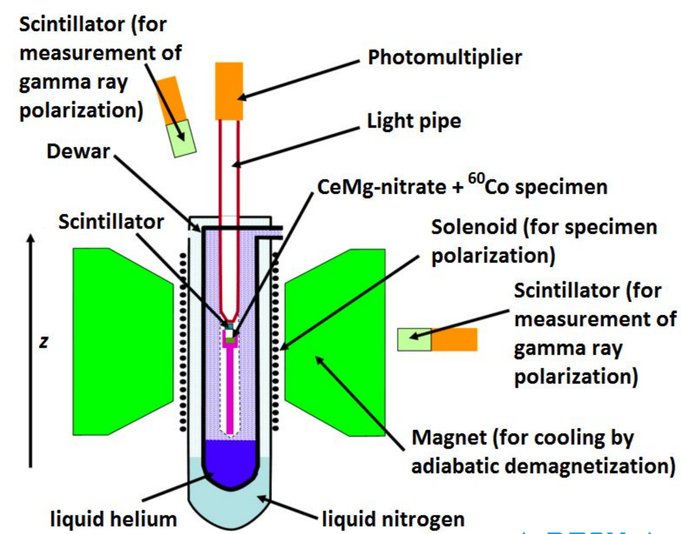
$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$




### Experiment of Madame Wu

Check decays of $Co^{60}$ into $Ni^{60}$. Align $Co^{60}$ using a uniform magnetic field and reduce thermal motion with low-temperature experiment. 2γ from Ni* de-excitation, isotropic. Anisotropy would show how $Co^{60}$ was aligned. If parity symmetry, no preferred direction of the electron from this decay.

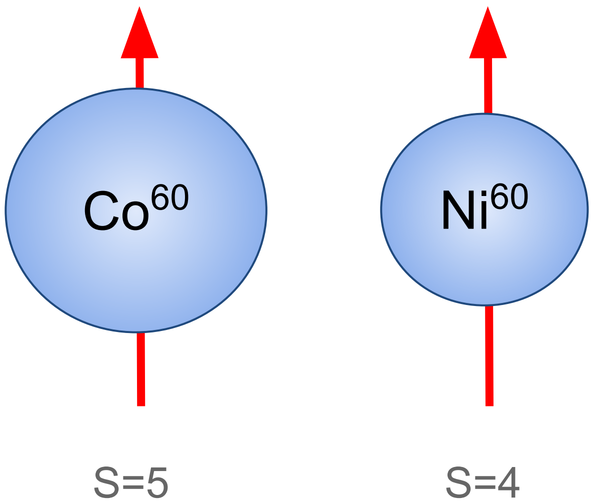


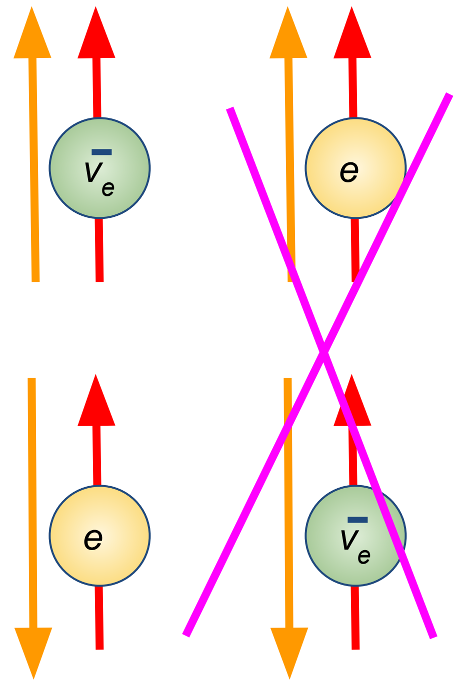
# β-decays of $Co^{60}$: Parity violation of the weak interaction

## $Co^{60}$ atoms aligned with magnetic field

If parity symmetry, no preferred direction of flight for the electron

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$



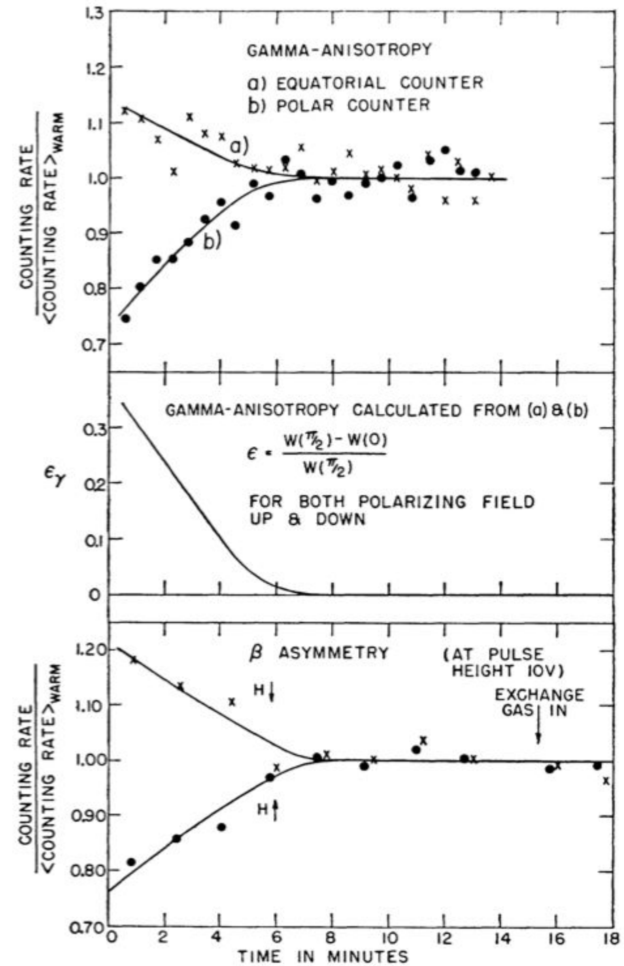




Fig. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Observed that electrons are preferentially emitted in opposite direction to nucleus spin

**Weak interaction violates parity (maximally). What about the C and CP ?**

# Further problem: $K^0_S$ and $K^0_L$ and CP-violation

## Experiment of Christenson-Fitch-Cronin-Turlay: [link]

Two neutral kaons (meson with one strange quark) were known with same mass and properties but two different lifetimes and decay types: $K^0_S$ and $K^0_L$

$K^0_S$, $\tau = 9.0 \cdot 10^{-11}$ s ($c\tau = 2.7$ cm)

$K^0_L$, $\tau = 5.1 \cdot 10^{-8}$ s ($c\tau = 15$ m)

$$K^0_S \rightarrow \pi^0\pi^0/\pi^+\pi^- \quad ; \quad CP = +1$$

$$K^0_L \rightarrow \pi^0\pi^0\pi^0/\pi^+\pi^-\pi^0 \quad ; \quad CP = -1$$

- Lifetimes typical of weak interaction
- Experiment with a beam of neutral kaons. If beam long enough, enriched with $K^0_L$.
- If only 3π decays, no CP violation.

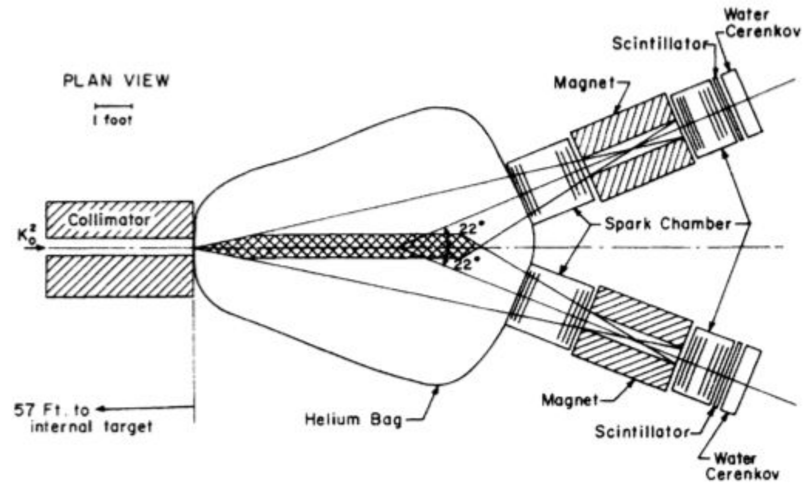



FIG. 1. Plan view of the detector arrangement.

# Further problem: $K^0_S$ and $K^0_L$ and CP-violation

## Experiment of Christenson-Fitch-Cronin-Turlay: [link]

Two neutral kaons (meson with one strange quark) were known with same mass and properties but two different lifetimes and decay types: $K^0_S$ and $K^0_L$

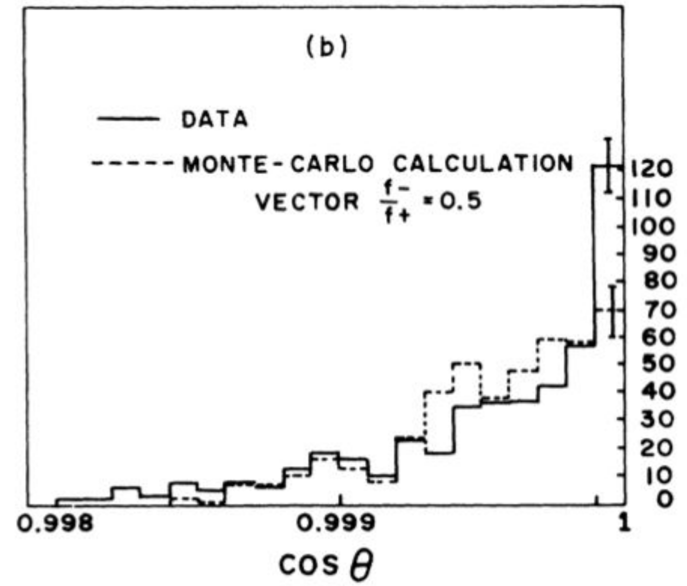
$K^0_S$, $\tau = 9.0 \cdot 10^{-11}$ s ($c\tau = 2.7$ cm)

$K^0_L$, $\tau = 5.1 \cdot 10^{-8}$ s ($c\tau = 15$ m)

$$K^0_S \to \pi^0\pi^0/\pi^+\pi^- \quad ; \quad CP = +1$$

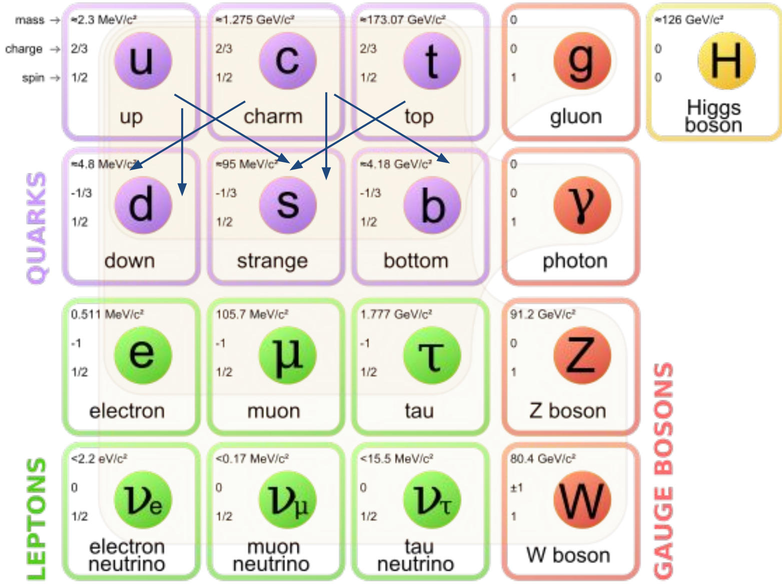
$$K^0_L \to \pi^0\pi^0\pi^0/\pi^+\pi^-\pi^0 \quad ; \quad CP = -1$$

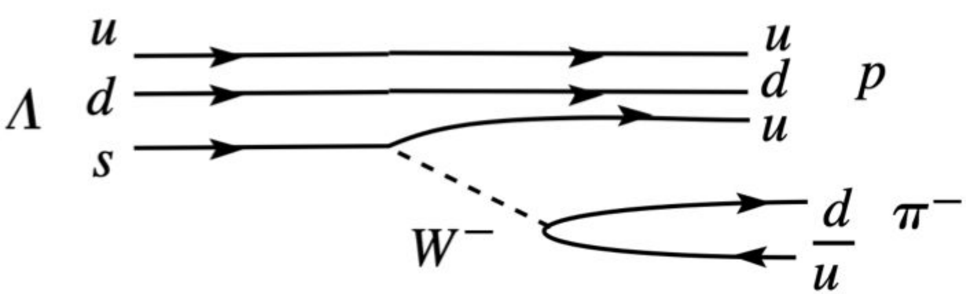
- Lifetimes typical of weak interaction
- Experiment with a beam of neutral kaons. If beam long enough, enriched with $K^0_L$.
- Observed more events than expected and associated to production of 2π! → CP-violation !



# Flavour and weak interaction: CKM matrix

- In the 60's, together with parity and CP-violation, observed:
  - $u - d$, $e^- - \nu_e$, $\mu^- - \nu_\mu$ transitions with weak interaction had same probability to happen
  - Charged currents do not seem to conserve flavour
  - $\Delta S = 1$ transitions had ¼ of probability of occuring than $\Delta S = 0$



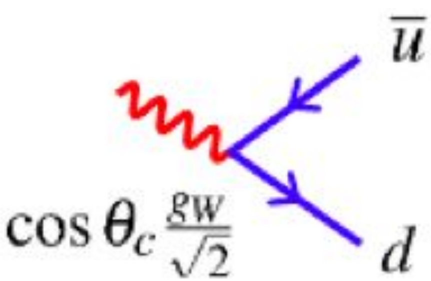
# Flavour and weak interaction: Cabibbo angle

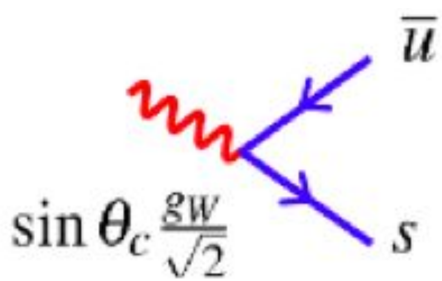
- Reason for the change in flavour → weak interaction eigenstates are not mass eigenstates→ mixture of quarks
- Nicola Cabibbo introduced mixing angle

Weak eigenstate

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Mass eigenstate

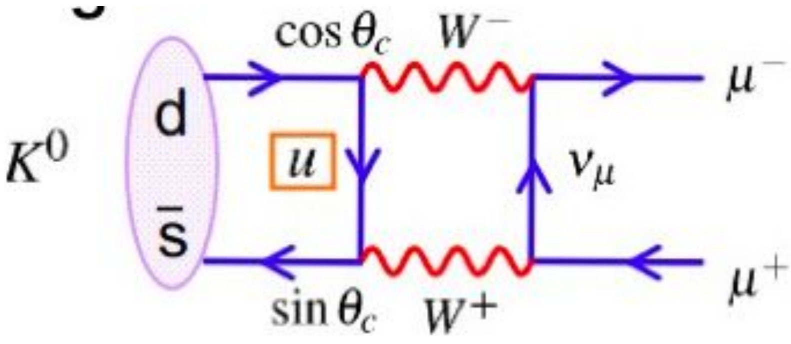



- Interaction of the u-quarks with the d-quark and s-quark dependent on the $\theta_C$.
- Allows change in flavour and generations.
- Small angle allows to explain the different probability in ΔS transitions

# Flavour and weak interaction: GIM mechanism

- At the time, calculated probability of some processes had large discrepancies with observations
  - Kaon decay into muons

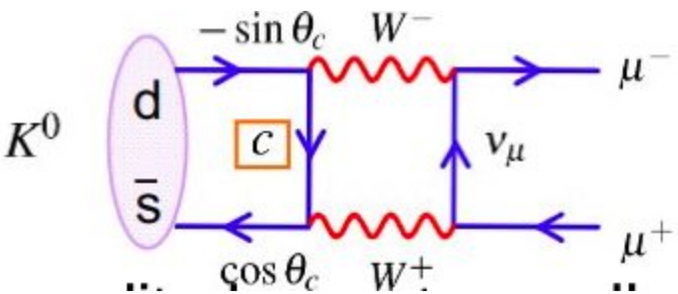



$$M_1 \propto g_W^4 \cos\theta_c \sin\theta_c$$

| $K^0_S$ DECAY MODES | | Fraction $(\Gamma_i/\Gamma)$ |
|---|---|---|
| $\mu^+\mu^-$ | S1 | $< 2.1 \times 10^{-10}$ |

| $K^0_L$ DECAY MODES | | Fraction $(\Gamma_i/\Gamma)$ |
|---|---|---|
| $\mu^+\mu^-$ | S1 | $(6.84 \pm 0.11) \times 10^{-9}$ |

- GIM: using Cabibbo theory, cannot explain $K^0$ - $K^0$ mixing → Introduced the c-quark




$$M_2 \propto -g_W^4 \cos\theta_c \sin\theta_c$$

Cancellation of the diagrams → c-quark discovered in

# Flavour and weak interaction: CKM matrix

> **CKM matrix:** Cabibbo-Kobayashi-Maskawa observed that the current Cabibbo matrix (2d and u,d,s,c) couldn't explain CP violation (can rotate 2d matrix to absorb any phase)
  - Added a 3rd generation in order to include a CP-violation phase
  - CKM matrix explaining mixing in charged currents with quarks

> Measurement show diagonal terms dominant. Off-diagonal, lower probability

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}.$$

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}} \left[ \overline{u}_i \, \gamma^\mu \, \frac{1-\gamma^5}{2} \, M_{ij}^{\mathrm{CKM}} \, d_j + \overline{\nu}_i \, \gamma^\mu \, \frac{1-\gamma^5}{2} \, e_i \right] W_\mu^+ + \mathrm{h.c.}\,,$$

# Flavour and weak interaction: CKM matrix

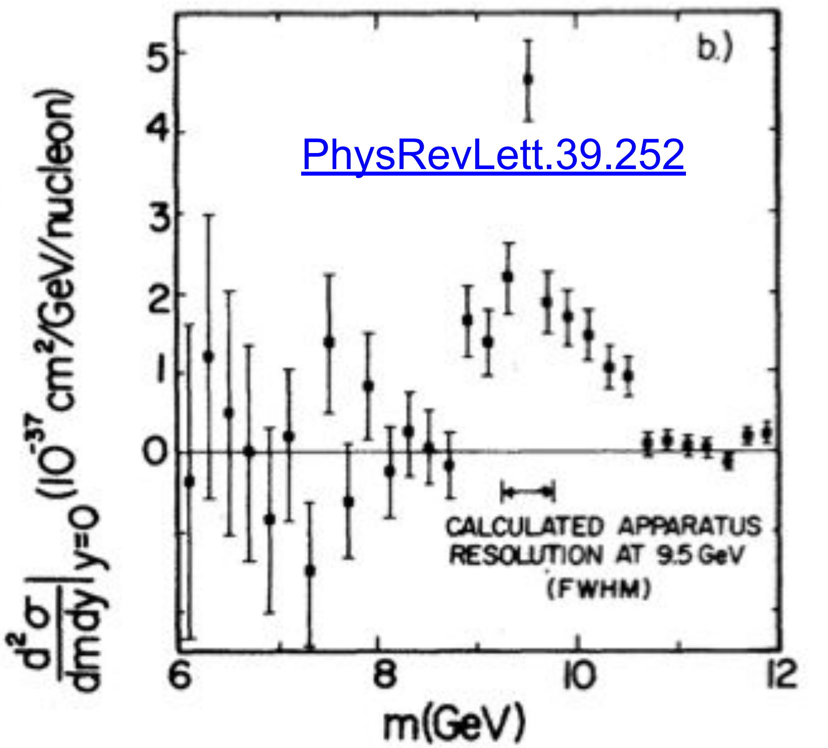
> **CKM matrix:** Cabibbo-Kobayashi-Maskawa observed that the current Cabibbo matrix (2d and u,d,s,c) couldn't explain CP violation (can rotate 2d matrix to absorb any phase)
  - Added a 3rd generation in order to include a CP-violation phase
  - CKM matrix explaining mixing in charged currents with quarks

> Mea … diagonal, lower probability

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \quad \cdots \begin{matrix} 0014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 04 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{matrix} \Bigg] .$$

$$\begin{bmatrix} 1 & \cdots \\ 0 & c \cdots \\ 0 & - \cdots \end{bmatrix} \cdots \begin{matrix} s_{12} & 0 \\ c_{12} & 0 \\ 0 & 1 \end{matrix} \Bigg]$$

$$= \Bigg[ \begin{matrix} \cdots \\ - \cdots \\ s \cdots \end{matrix} \cdots \begin{matrix} s_{13}e^{-i\delta_{13}} \\ s_{23}c_{13} \\ c_{23}c_{13} \end{matrix} \Bigg] .$$




[PhysRevLett.39.252](PhysRevLett.39.252)

Discovery of bottom-quark in 1977 at Fermilab !

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\,\gamma^\mu\,\frac{1-\gamma^5}{2}\,M^{\rm CKM}_{ij}\,d_j + \overline{\nu}_i\,\gamma^\mu\,\frac{1-\gamma^5}{2}\,e_i\right]W^+_\mu + \text{h.c.}\,,$$

# Flavour and weak interaction: CKM matrix

> **CKM matrix:** Cabibbo-Kobayashi-Maskawa observed that the current Cabibbo matrix (2d and u,d,s,c) couldn't explain CP violation (can rotate 2d matrix to absorb any phase)

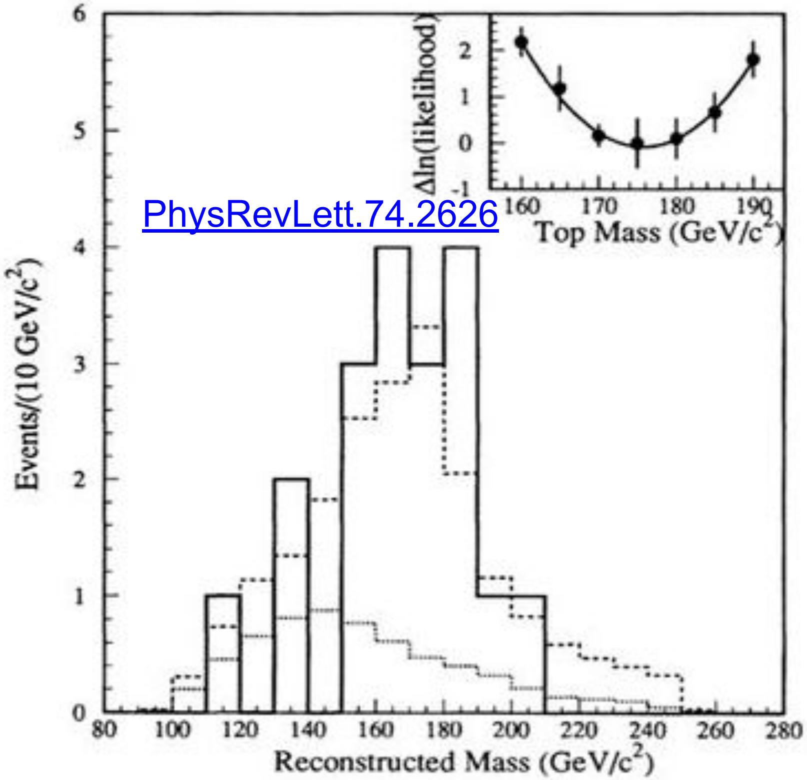
- Added a 3rd generation in order to include a CP-violation phase
- ... s with quarks

> Meas ... onal, lower probability

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} \ldots & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ \ldots & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ \ldots & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix} \ldots$$

$$\begin{bmatrix} 1 & 0 & \ldots \\ 0 & c_{2\ldots} & \ldots \\ 0 & -s\ldots & \ldots \end{bmatrix} \ldots \begin{bmatrix} \ldots & 0 \\ \ldots & 0 \\ \ldots & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \ldots & \ldots & \ldots_{13} e^{-i\delta_{13}} \\ -s_{1\ldots} & \ldots & s_{23}c_{13} \\ s_{1\ldots} & \ldots & c_{23}c_{13} \end{bmatrix}.$$



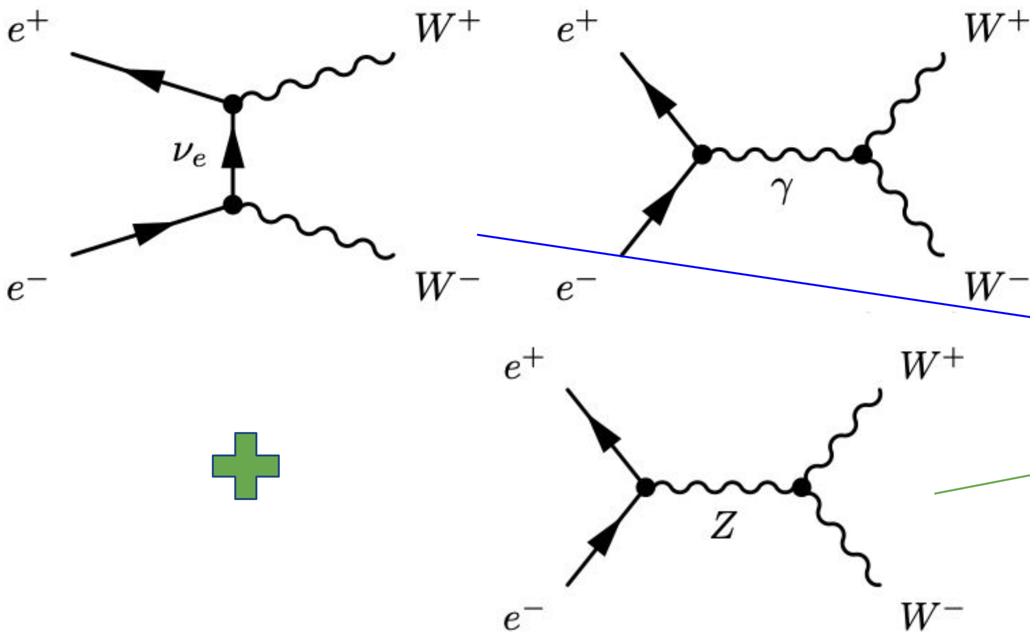

Discovery of the top-quark at Tevatron in 1995 !

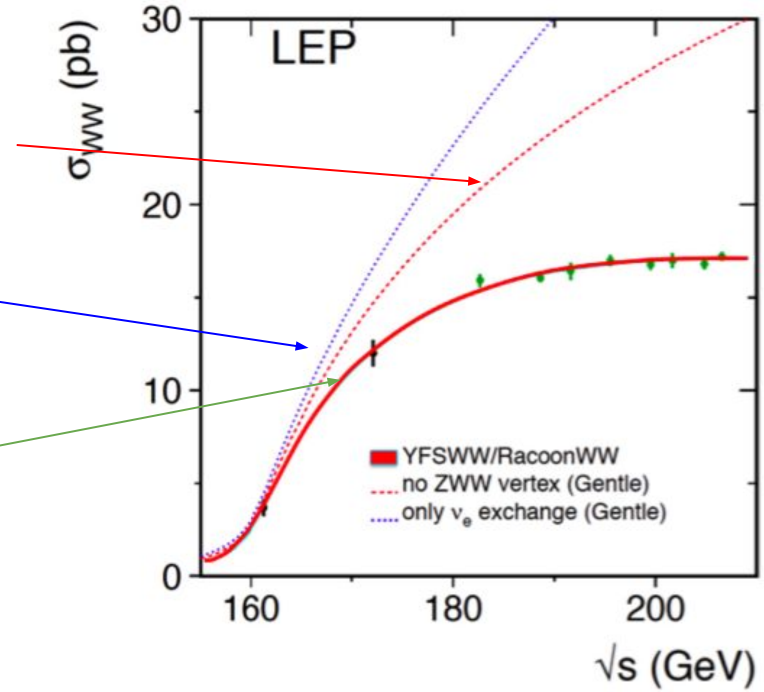
$$\mathcal{L}_C = -\frac{g}{\sqrt{2}} \left[ \overline{u}_i \gamma^\mu \frac{1-\gamma^5}{2} M^{\mathrm{CKM}}_{ij} d_j + \overline{\nu}_i \gamma^\mu \frac{1-\gamma^5}{2} e_i \right] W^+_\mu + \mathrm{h.c.}\ ,$$

# Electroweak unification

# Towards a QFT of weak interactions → Electroweak

- Weak interactions present so far via a  charge current (exchange of a charged mediator)
  - Mediators might be massive → W+,W- bosons
- W-boson charged → interaction with the photon. Consider ee → WW




- Cross-section diverges at high energies
- Cured if introducing  a coupling to a neutral current
- Only possible if γ, W and Z boson couplings are related → Electroweak unification

# Electroweak unification !!!

- Glashow, Salam and Weinberg proposed a gauge theory with two separate symmetry groups SU(2) x U(1)
- SU(2) : interactions of particles that have a weak isospin $I_{wea.}$ Coupling g
  - Three bosons mediating this force : $W_1$, $W_2$, $W_3$
- U(1): interaction of particles that have an hypercharge Y. Coupling g'
  - One single boson mediating this force : B-boson

$$D_\mu \equiv \partial_\mu - i\,\frac{g'}{2}\,Y\,B_\mu - i\,\frac{g}{2}\,T_j\,W_\mu^j$$

$$\mathcal{L}_g = -\frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}\,,$$

# Electroweak interactions

| Fermion family | Left-chiral fermions | | | | Right-chiral fermions | | | |
|---|---|---|---|---|---|---|---|---|
| | | Electric charge $Q$ | Weak isospin $T_3$ | Weak hyper-charge $Y_W$ | | Electric charge $Q$ | Weak isospin $T_3$ | Weak hyper-charge $Y_W$ |
| Leptons | $\nu_e, \nu_\mu, \nu_\tau$ | 0 | $+\frac{1}{2}$ | −1 | No interaction, if they even exist | | | 0 |
| | $e^-, \mu^-, \tau^-$ | −1 | $-\frac{1}{2}$ | −1 | $e_R^-, \mu_R^-, \tau_R^-$ | −1 | 0 | −2 |
| Quarks | u, c, t | $+\frac{2}{3}$ | $+\frac{1}{2}$ | $+\frac{1}{3}$ | $u_R, c_R, t_R$ | $+\frac{2}{3}$ | 0 | $+\frac{4}{3}$ |
| | d, s, b | $-\frac{1}{3}$ | $-\frac{1}{2}$ | $+\frac{1}{3}$ | $d_R, s_R, b_R$ | $-\frac{1}{3}$ | 0 | $-\frac{2}{3}$ |

| Interaction mediated | Boson | Electric charge $Q$ | Weak isospin $T_3$ | Weak hypercharge $Y_W$ |
|---|---|---|---|---|
| Weak | $W^\pm$ | ±1 | ±1 | 0 |
| | $Z^0$ | 0 | 0 | 0 |
| Electromagnetic | $\gamma^0$ | 0 | 0 | 0 |

from wikipedia

# Electroweak unification !!!

- Formulated as a gauge theory (a theory that leaves the lagrangian invariant under local transformation, in this case of hypercharge and weak isospin)
- There is a feature of gauge theories though → The gauge bosons cannot be massive because it violates the invariance of the lagrangian under transformations
- Solution, use a mechanism that allows you to have massive gauge boson at the same time that, formally, the lagrangian is still invariant

# Electroweak unification !!!

# Electroweak unification !!!


Patience, let's go back to EW unification

# Electroweak unification !!!

- Glashow, Salam and Weinberg unified electromagnetic and weak interactions to electroweak interaction
- Gauge fields are linear combinations of
  $B^0$ ($U(1)_Y$ weak hypercharge with coupling $g'$), and
  $W^{1,2,3}$ ($SU(2)_L$ weak isospin with coupling $g$)

$$W^{\pm} = \frac{1}{\sqrt{2}}(W^1 \mp iW^2)$$

$$Z = \cos\theta_W W^3 - \sin\theta_W B^0$$

$$A = \sin\theta_W W^3 + \cos\theta_W B^0$$

- with the masses related (at tree level): $m_W = m_Z \cos\theta_W$ and $\theta_W$ the weak mixing angle with

$$\sin\theta_W = \frac{g'}{\sqrt{g'^2 + g^2}}$$

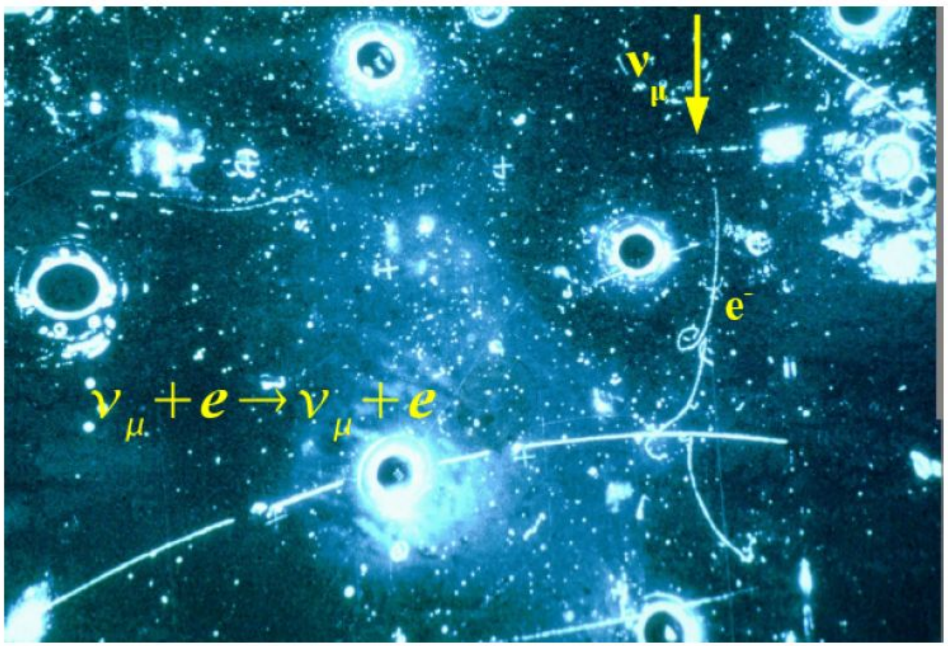
$$G_F^0 = \frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2 c^4} = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

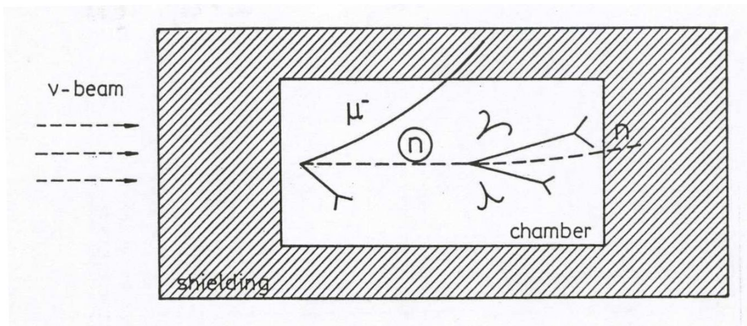


$$Y_W = Q - T_3$$

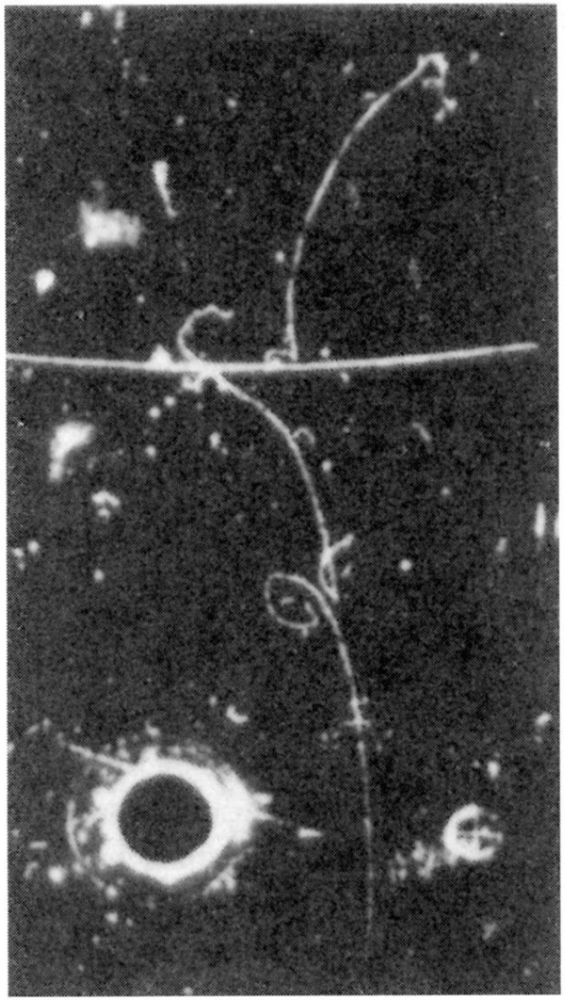
# Evidence of GSW validity: neutral weak interaction

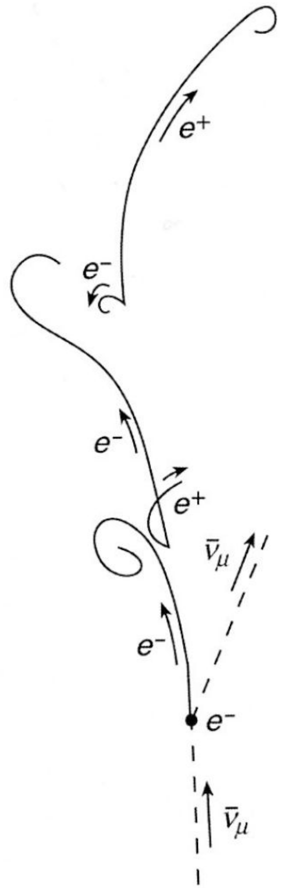
- Neutral current discovered in 1973 with *Gargamelle* at CERN by observing $e\nu \rightarrow e\nu$
- First evidence of neutral current in leptons
- Confirmation of the existence of neutral weak currents !



# Evidence of GSW validity: neutral weak interaction






The first picture of a neutral weak process

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$.

The neutrino enters from below (leaving no track), and strikes an electron. which moves upwards, emitting two photons (visible via the e+e- pairs from subsequent conversions)

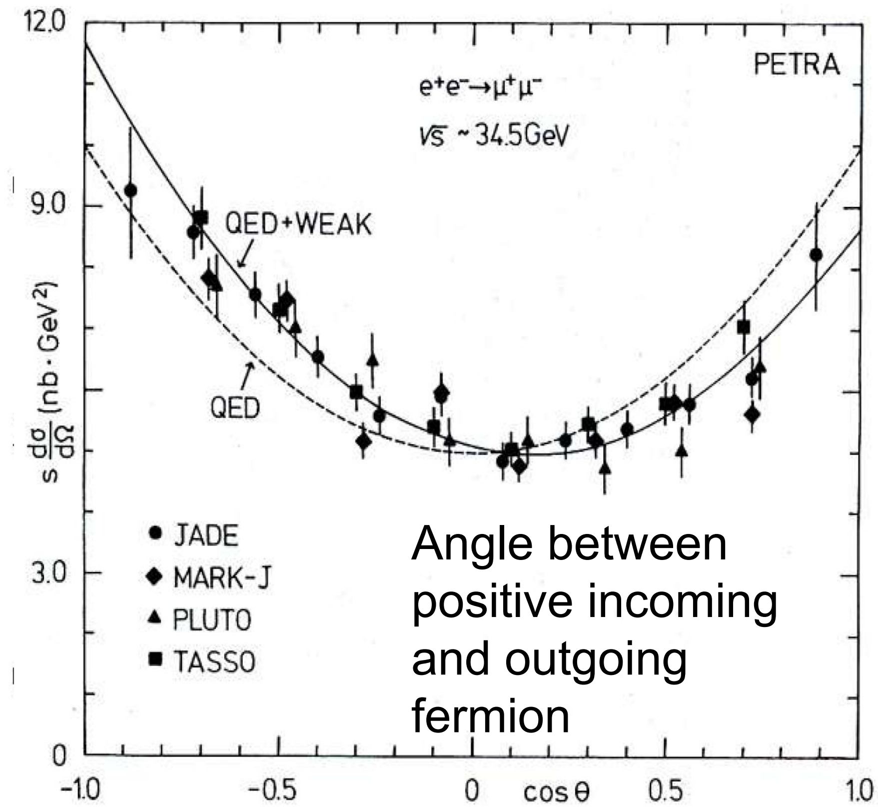
# Evidence of GSW validity: Angular relations

- Angular distributions changed by electroweak interactions

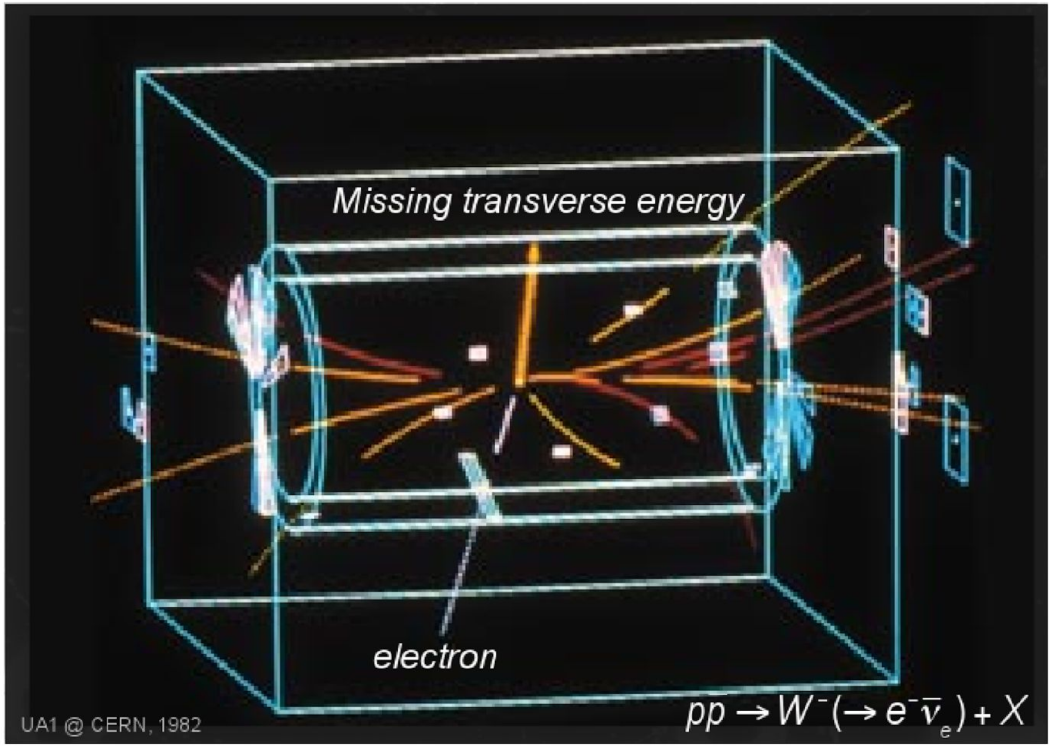
$$\frac{d\sigma_0^{\mathrm{EW}}}{d\Omega} = \frac{\alpha^2}{4s}\left(1 + \cos^2\vartheta + A\cos\vartheta\right)$$

- Total cross sections unchanged

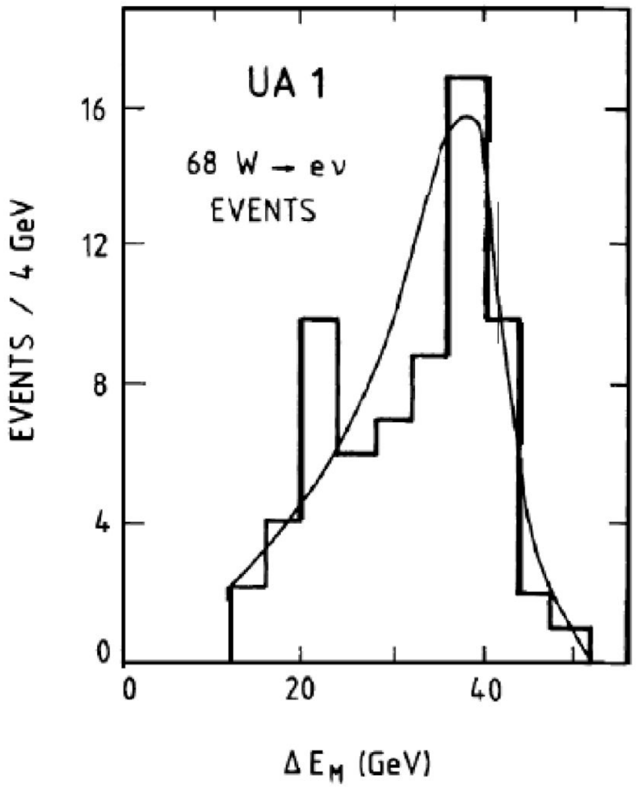
- Reason: V-A structure of neutral current (NC)



# Evidence of GSW validity: Discovery of W boson



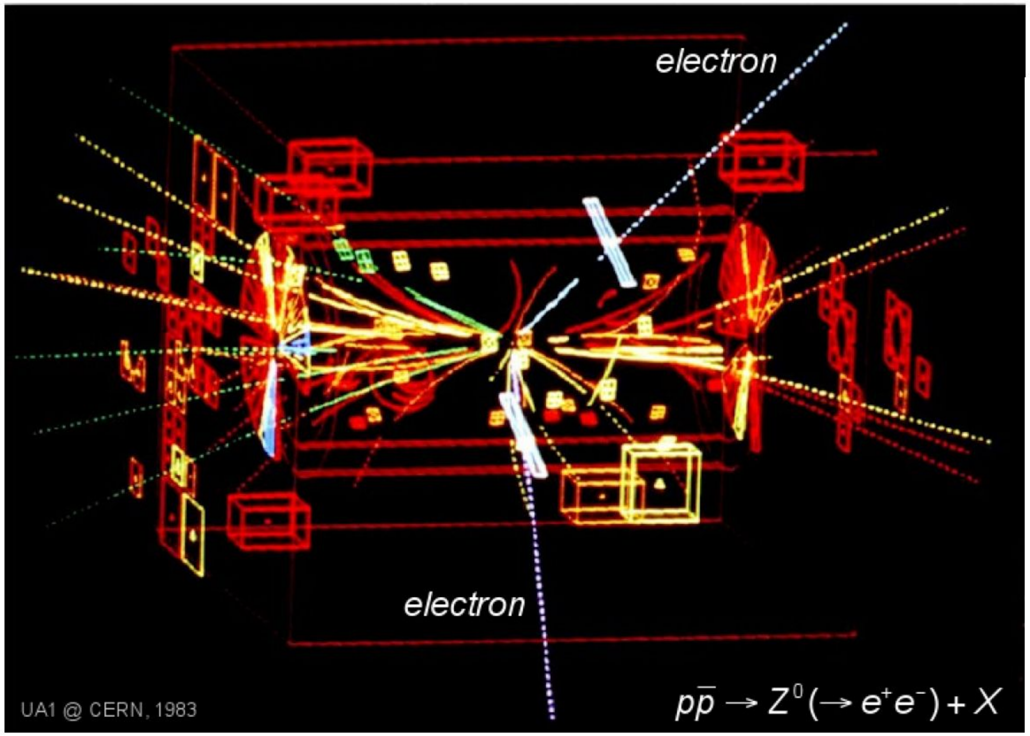

Missing transverse energy in events with $E_e$ > 15 GeV

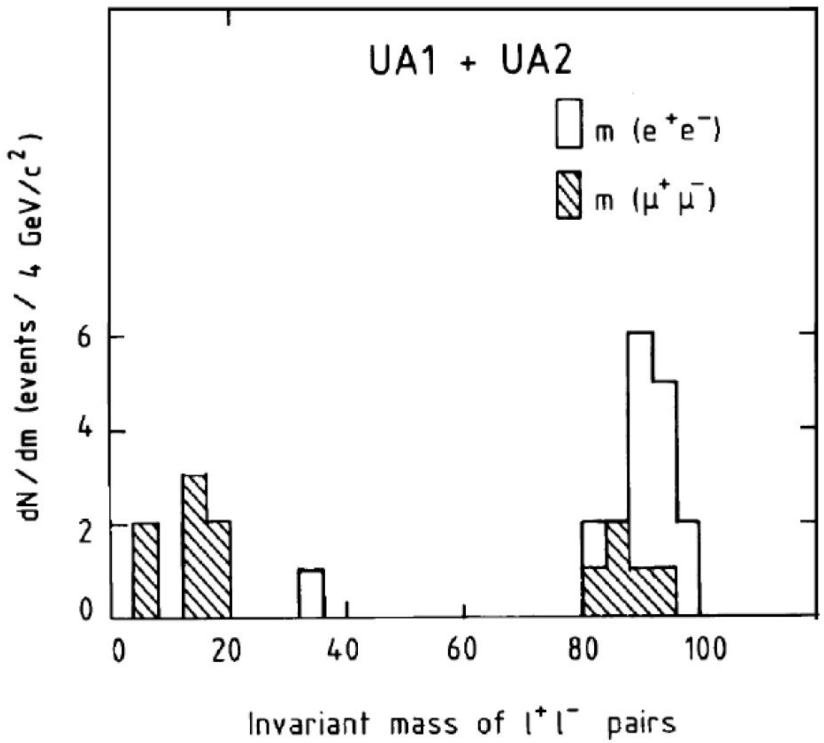



$$m_W = (80.9 \pm 1.5 \pm 2.4)\ \mathrm{GeV}$$

C. Rubbia, Nobel Lecture, 1984

# Evidence of GSW validity: Discovery of Z boson

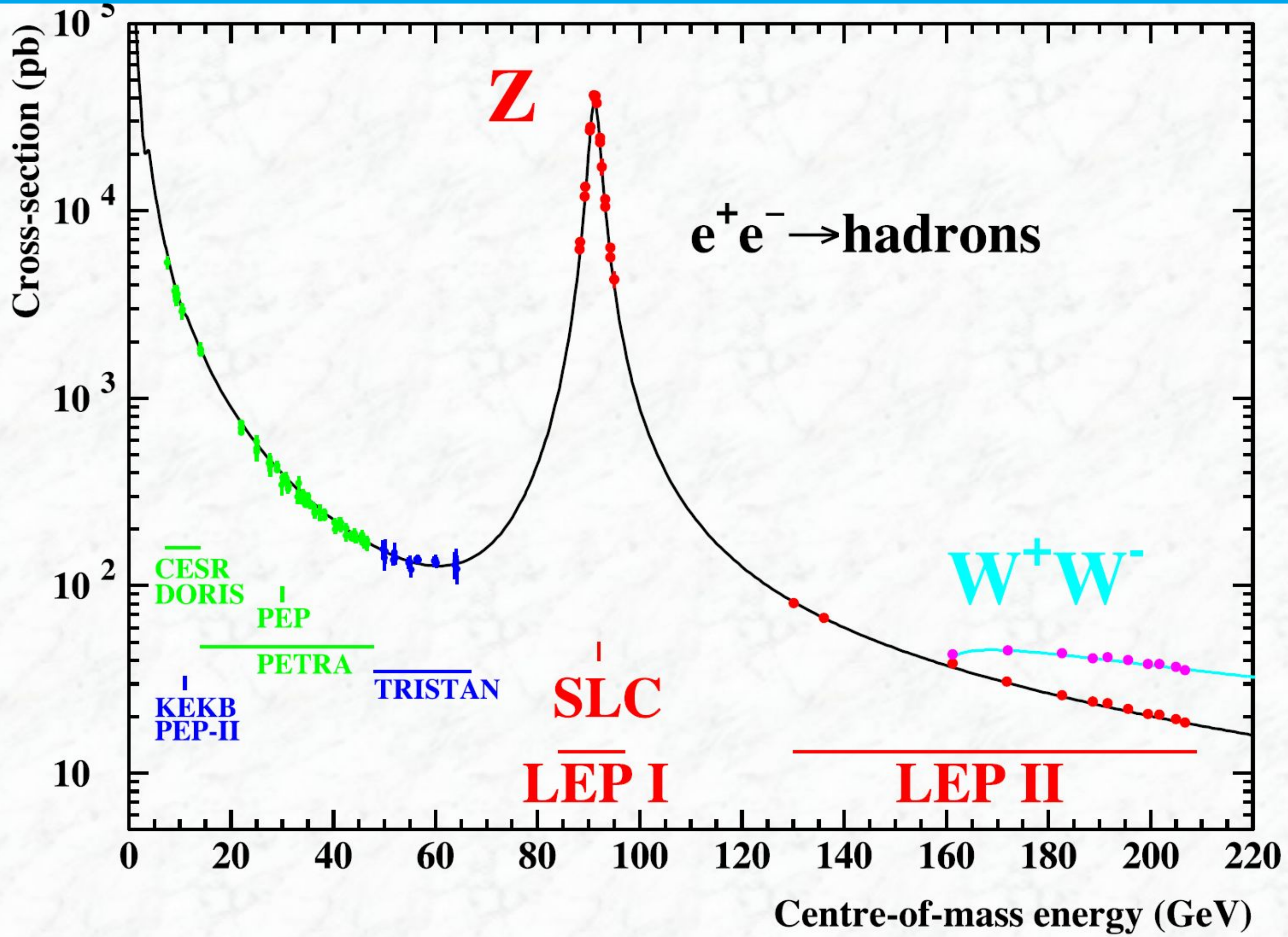



$$m_Z = (95.1 \pm 2.5)\ \mathbf{GeV}$$

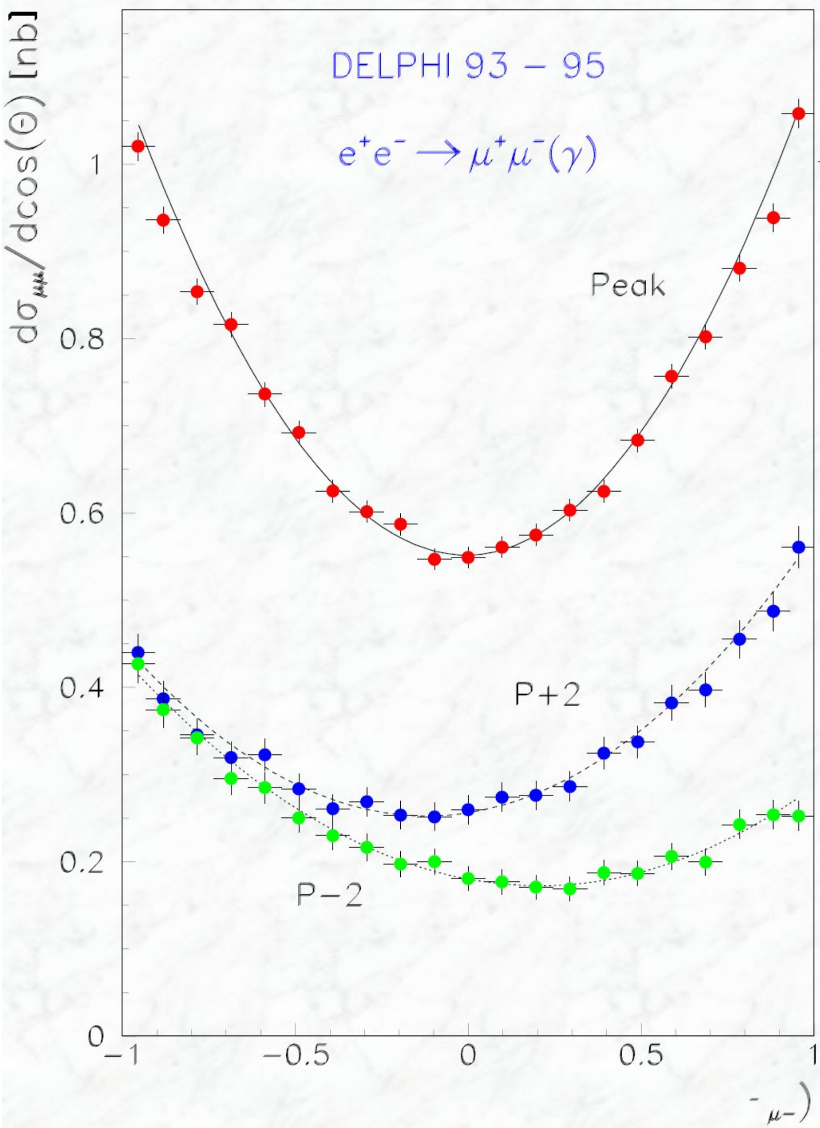
- 1983: first signals with 6 W → eν and 4 Z → ee events
- 1984: Nobel prize for C. Rubbia (UA1) and S. van der Meer

# EWK tests: $\sigma(e^+e^- \rightarrow W/Z)$ production at LEP




Precision tests of the Z sector

Tests of the W sector




$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W \cos^4\theta_W}[(g_V^{e^2} + g_A^{e^2})(g_V^{\mu^2} + g_A^{\mu^2})(1+\cos^2\theta) +$$

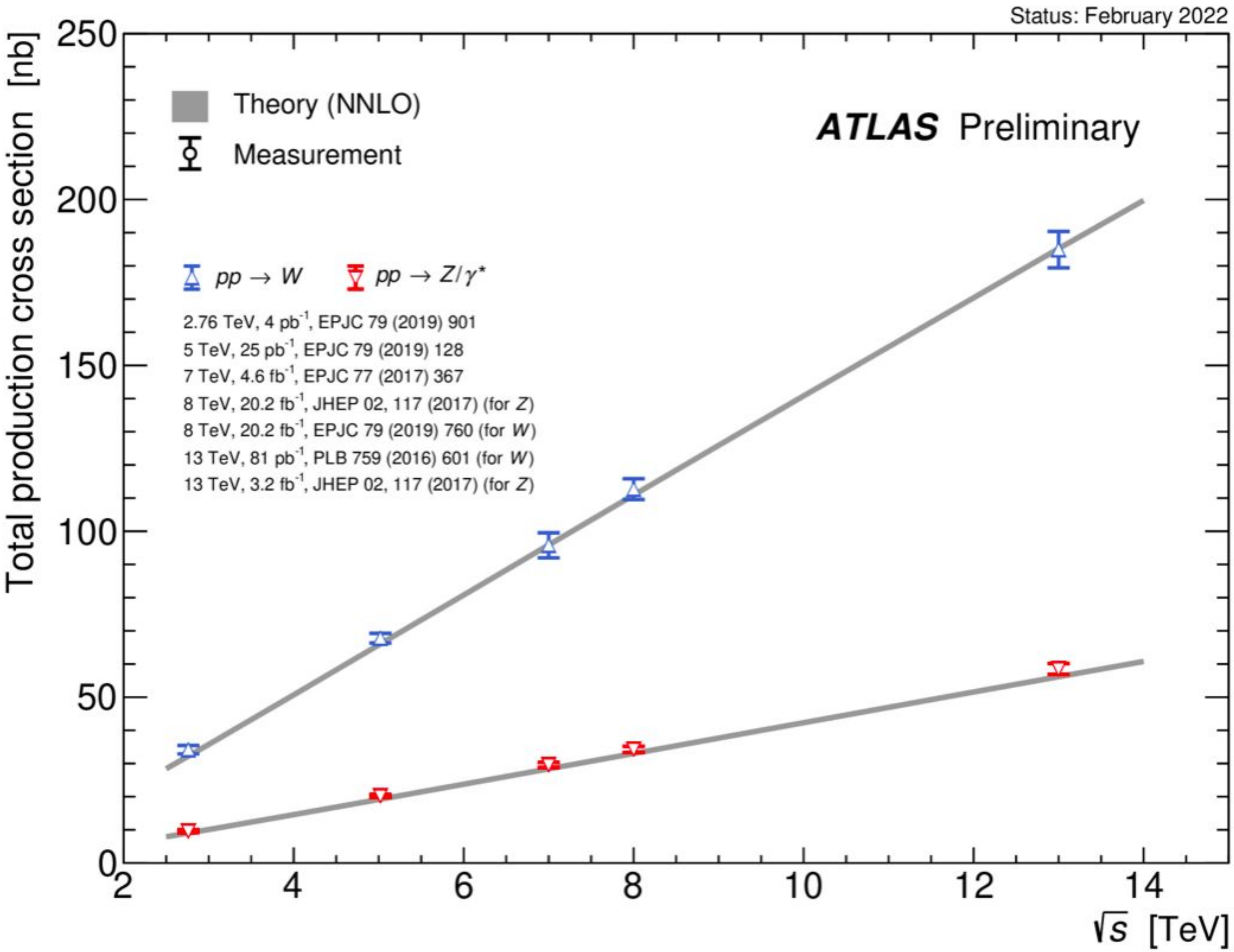
$$8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]$$

Terms ∝ cosθ in dσ/dcosθ
→ asymmetry

$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

# EWK tests: σ(*pp* → W/Z) production at LHC



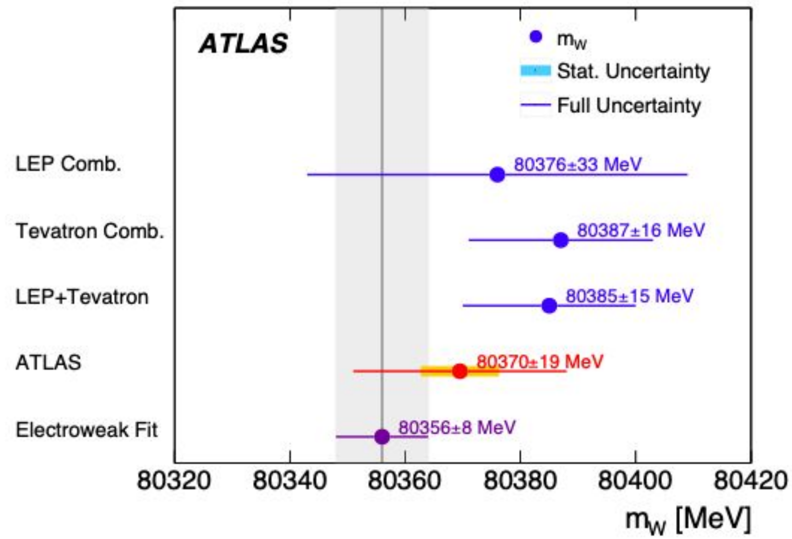
# Consistent picture of electroweak parameters

## LEP

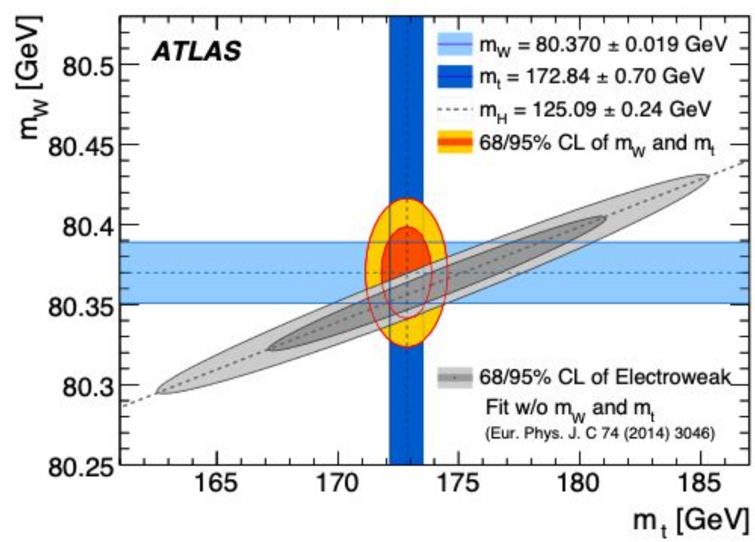
| | Measurement | Fit | $\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02750 ± 0.00033 | 0.02759 | |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 | |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 | |
| $\sigma^0_{had}$ [nb] | 41.540 ± 0.037 | 41.478 | |
| $R_l$ | 20.767 ± 0.025 | 20.742 | |
| $A^{0,l}_{fb}$ | 0.01714 ± 0.00095 | 0.01645 | |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1481 | |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 | |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 | |
| $A^{0,b}_{fb}$ | 0.0992 ± 0.0016 | 0.1038 | |
| $A^{0,c}_{fb}$ | 0.0707 ± 0.0035 | 0.0742 | |
| $A_b$ | 0.923 ± 0.020 | 0.935 | |
| $A_c$ | 0.670 ± 0.027 | 0.668 | |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1481 | |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 | |
| $m_W$ [GeV] | 80.385 ± 0.015 | 80.377 | |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 | |
| $m_t$ [GeV] | 173.20 ± 0.90 | 173.26 | |



## ATLAS W-mass measurement




## $m_W$-$m_t$-$m_H$ dependence



# Higgs boson mechanism

# But why was the Higgs predicted?

- **Problem with electroweak unification:** Gauge invariance implied massless gauge bosons and fermions
  - Mass terms are not allowed for gauge bosons

Lagrangian of the QED (U(1))

$$\mathcal{L} = \bar{\psi}(i\hbar c\gamma^\mu D_\mu - mc^2)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

+ mass term for gauge bosons

$$+\frac{1}{2}m^2 A_\mu A^\mu$$

Mass term + gauge transform

$$A_\mu \to A_\mu + \partial_\mu \Lambda(x)$$

$$+\frac{1}{2}m^2 A_\mu A^\mu \to +\frac{1}{2}m^2 A_\mu A^\mu + m^2 A_\mu \partial^\mu \Lambda + \frac{1}{2}m^2 \partial_\mu \Lambda \partial^\mu \Lambda$$

Breaking of gauge symmetry → Forbidden mass terms

# How can we get massive gauge bosons → BEH mechanism

We know weak interaction must have massive gauge bosons but gauge theories don't allow them→ Spontaneous symmetry breaking

Underlying physics law keeps the symmetry (Lagrangian is still symmetric), but in reality, the ground state of the theory doesn't preserve the symmetry.

- Add scalar field with a particular potential
- If $\mu^2 > 0$, potential follows the "Mexican" hat form
  - Minimum of potential is not for <Φ> = 0 but for:

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

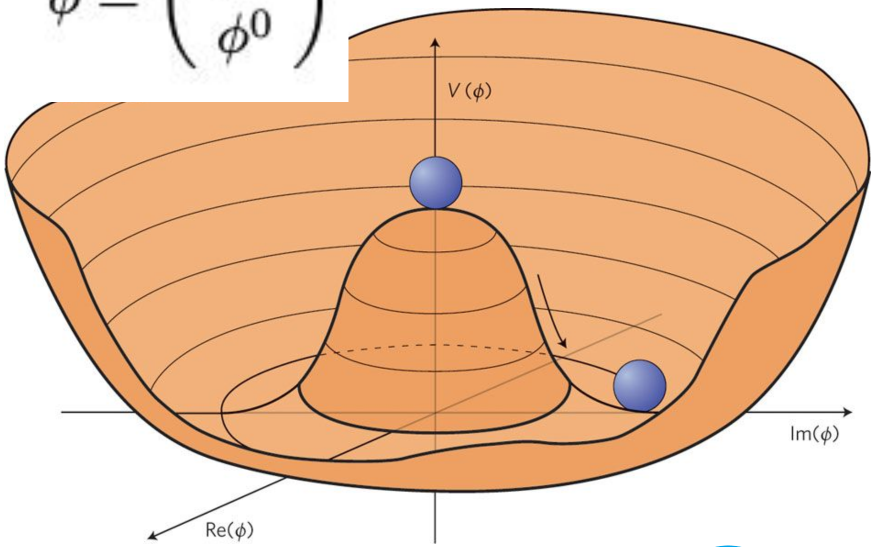
v = Vacuum expectation value (VEV)

- Ground state of field, a certain value with $v = \mu^2/\lambda$
- Excitations around VEV. Quanta of the field → Higgs bosons

$$\mathcal{L}_{Higgs} = (D^\mu\phi)^\dagger (D_\mu\phi) - V(\phi)$$

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

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



# Brout-Englert-Higgs mechanism → Masses

- When spontaneously breaking the GSW $SU(2)_L$ X $U(1)_Y$, got a residual symmetry $U(1)_Q$ → Associated to QED

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$$

- 3 massive bosons (electroweak bosons)
- Massive scalar (Higgs)
- Electric charge as function of weak isospin and hypercharge.

$$Q = T_3 + \frac{1}{2} Y_W$$

VEV leading to mass terms

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Mass terms for gauge bosons

$$(D^\mu \phi)^\dagger (D_\mu \phi) = \left| \left( \partial_\mu + \frac{i}{2} g \tau^k W_\mu^k + \frac{i}{2} g' B_\mu \right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2$$

$$= \frac{v^2}{8} \left| \left( g \tau^k W_\mu^k + g' B_\mu \right) \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right|^2$$

$$= \frac{v^2}{8} \left| \begin{pmatrix} g W_\mu^1 - i g W_\mu^2 \\ -g W_\mu^3 + g' B_\mu \end{pmatrix} \right|^2$$

$$= \frac{v^2}{8} \left[ g^2 \left( (W_\mu^1)^2 + (W_\mu^2)^2 \right) + (g W_\mu^3 - g' B_\mu)^2 \right].$$

$$m_W = \frac{1}{2} v \, | \, g \, | \, ,$$

$$m_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$

# Brout-Englert-Higgs mechanism → Masses

- When spontaneously breaking the GSW $SU(2)_L$ X $U(1)_Y$, got a residual symmetry $U(1)_Q$ → Associated to QED
  - 3 massive bosons (electroweak bosons)
  - Massive scalar (Higgs)
  - Electric charge as function of weak isospin and hypercharge.

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$$

$$Q = T_3 + \frac{1}{2} Y_W$$

VEV leading to mass terms

$$\langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Mass fermion ∝ Yukawa coupling of Higgs to fermions

$$m_i = -\frac{f_i\, v}{\sqrt{2}}, \qquad i = e,\, u,\, d$$

Mass term for fermions

$$\mathcal{L}_{Yuk} = f_e\, \bar{l}_L\, \phi\, e_R + f_u\, \bar{q}_L\, \tilde{\phi}\, u_R + f_d\, \bar{q}_L\, \phi\, d_R + h.c.$$

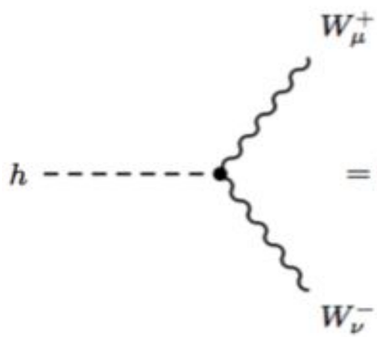
$$\mathcal{L}_{Yuk} = \frac{f_e\, v}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L) + \frac{f_u\, v}{\sqrt{2}}(\bar{u}_L u_R + \bar{u}_R u_L) + \frac{f_d\, v}{\sqrt{2}}(\bar{d}_L d_R + \bar{d}_R d_L)$$

# Brout-Englert-Higgs mechanism → Higgs boson !

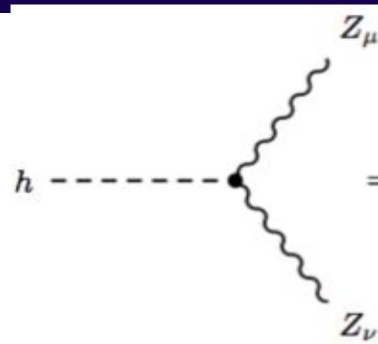
- Oscillations around VeV → Higgs bosons !
- Due to the interaction with gauge fields/fermions → Higgs couplings

$$\mathcal{L}_{\mathcal{H}-\mathcal{W}/\mathcal{Z}} = \frac{1}{2}(\mathrm{v}+\mathrm{H})^2 \left[ \frac{\mathrm{g}_2^2}{2} \mathrm{W}_\mu^+ \mathrm{W}^{-\mu} + \frac{\mathrm{g}_2^2 + \mathrm{g}_1^2}{4} \mathrm{Z}_\mu \mathrm{Z}^\mu \right]$$

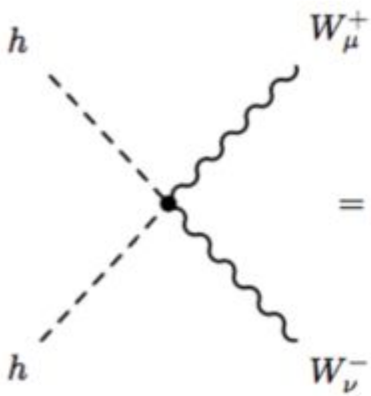
$g^2 = g \,;\, g^1 = g'$



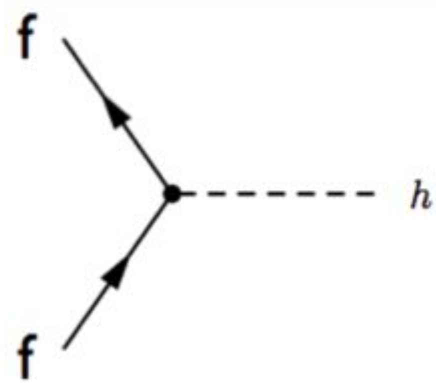

$$= i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$




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




$$= i\frac{g^2}{4} \cdot 2g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu}$$



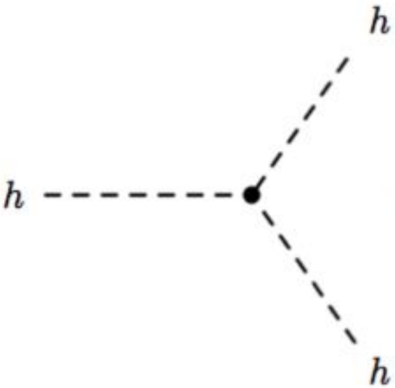

$$= -i\frac{h_f}{\sqrt{2}} = -i\,\frac{m_f}{v}$$

# Brout-Englert-Higgs mechanism → Higgs boson!

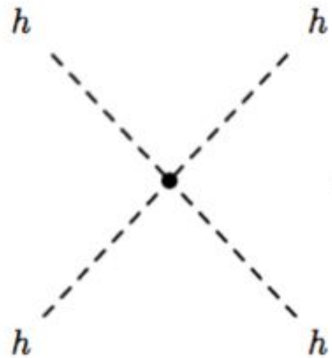
- Oscillations around VeV → Higgs bosons !
- Due to the V(Φ)potential shape, Higgs interacting with itself → Higgs self-couplings

$$V = \lambda\, v^2 h^2 + \lambda\, v\, h^3 + \frac{\lambda}{4}\, h^4$$

$$m_{\mathrm{H}} = \sqrt{2\mu_{\mathrm{H}}^2} \equiv \sqrt{2\lambda v^2}$$




$$= -i\lambda v \cdot 3! = -6i\lambda v = -3i\frac{m_h^2}{v}$$




$$= -i\frac{\lambda}{4} \cdot 4! = -6i\lambda = -3i\frac{m_h^2}{v^2}$$

# Where is it ? The Standard Model's biggest triumph

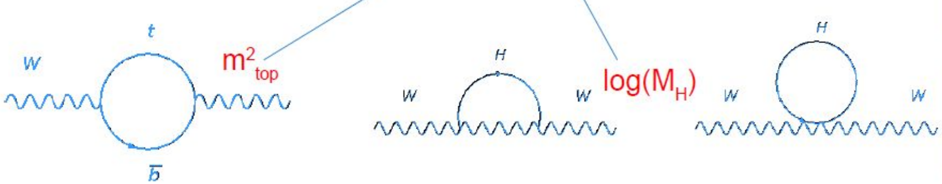
As you may have observed, the mass of the Higgs boson depends on λ
→ Mass of the Higgs boson is a free parameter of the SM

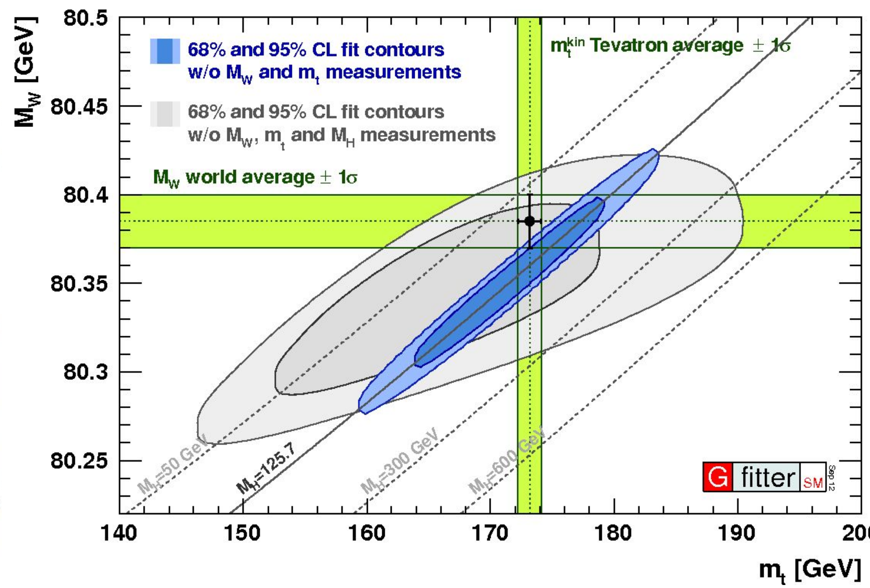
However, indirect constraints on the Higgs mass could be searched for

Radiative corrections to W-boson mass

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

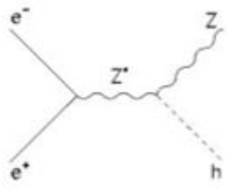
radiative corrections

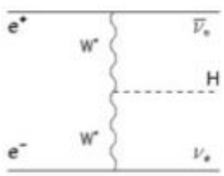


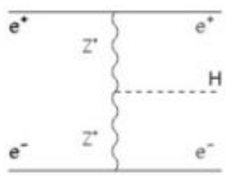



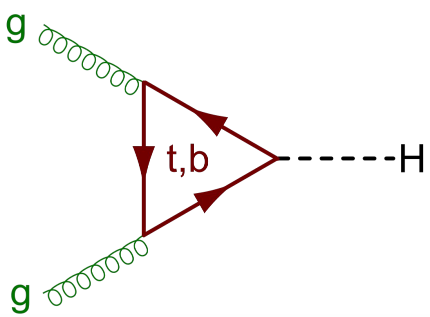
# The Higgs boson before LHC

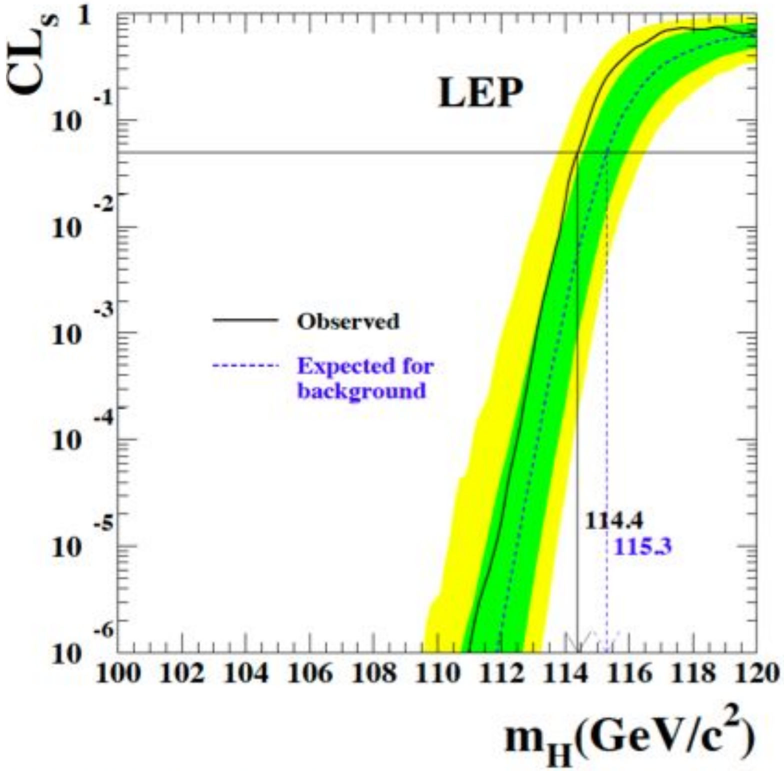
LEP ($e^+e^-$) and Tevatron ($p\bar{p}$) indicated Higgs around 120-130 GeV

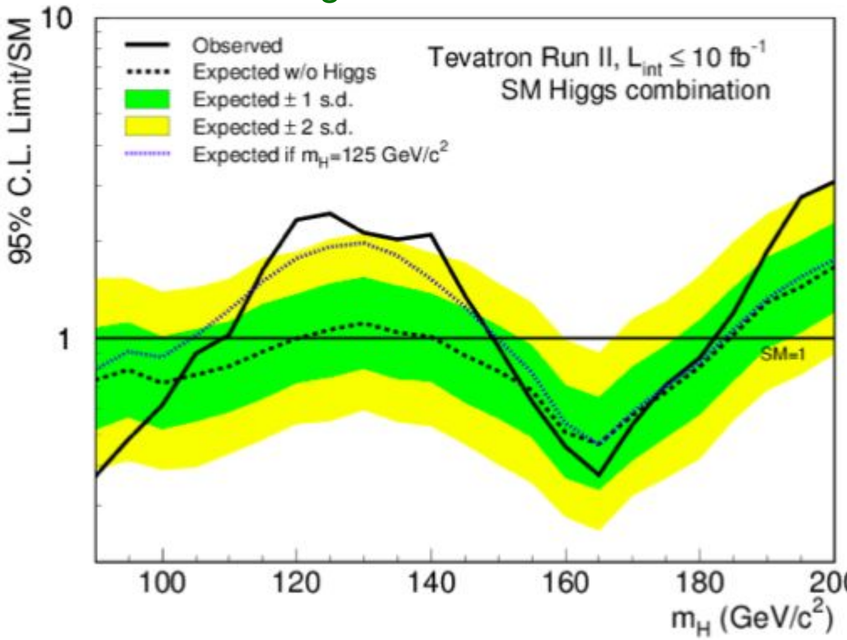


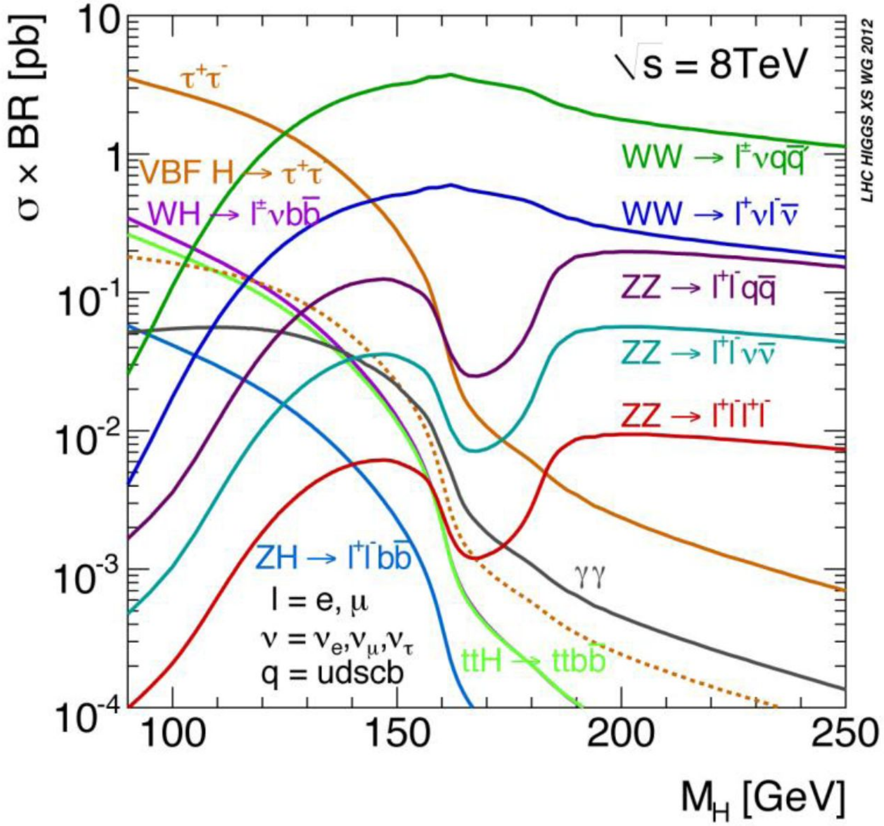



# Measurements of the Higgs boson at LHC




## Low mass ($\lesssim$ **140 GeV**)

$H \to \gamma\gamma$

Rare decay, but distinct signal

$H \to \tau\tau$

Enhanced in MSSM, also contributes to SM search

$H \to b\bar{b}$

Main search channel at LEP and Tevatron, important to study Higgs properties

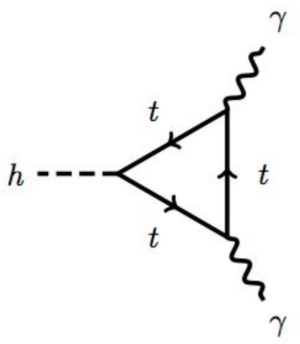
## Intermediate and large $m_H$ ($\gtrsim$ **130 GeV**)

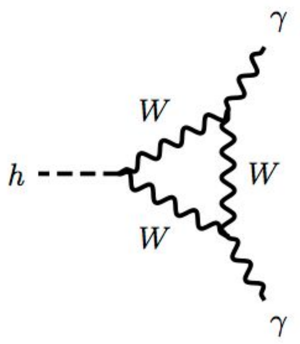
$H \to WW$

Large signal yield

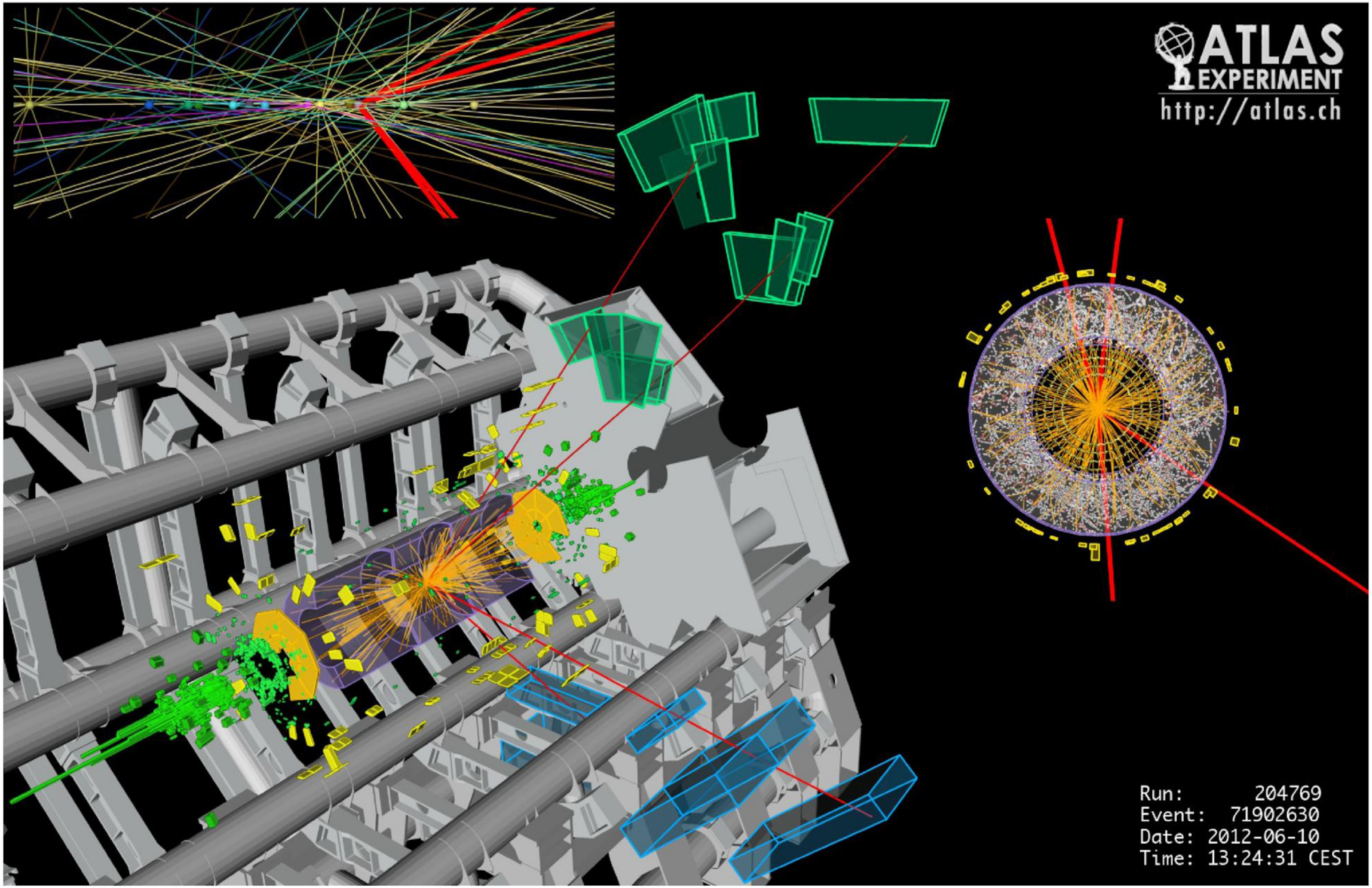
$H \to ZZ$

Very clean signal if both $Z \to \ell\ell$



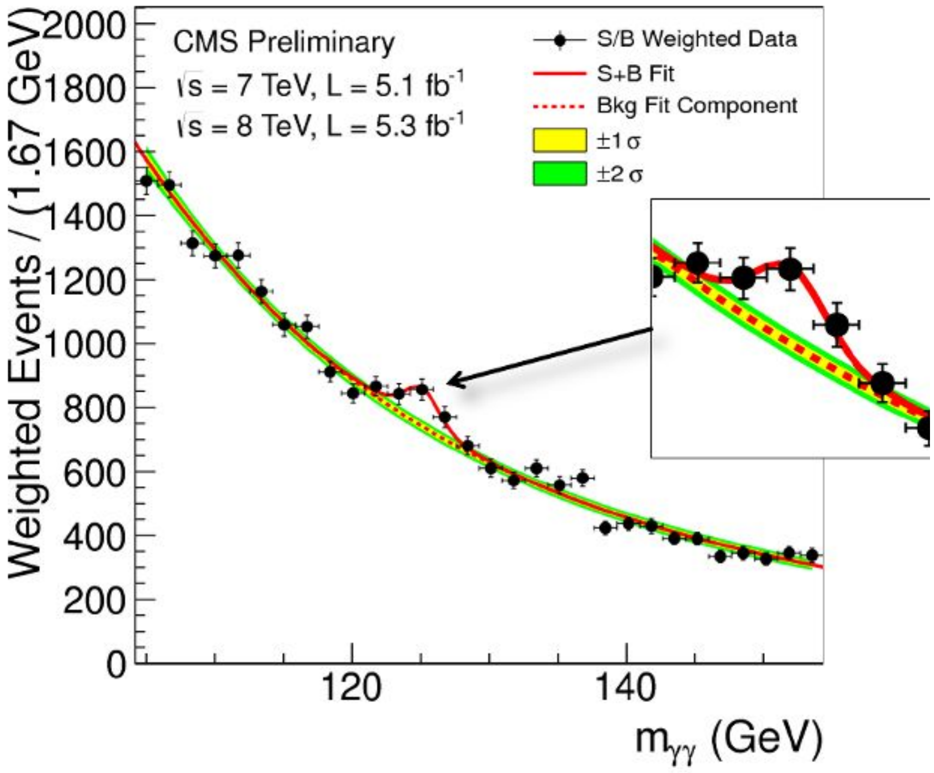



# The Higgs is there !

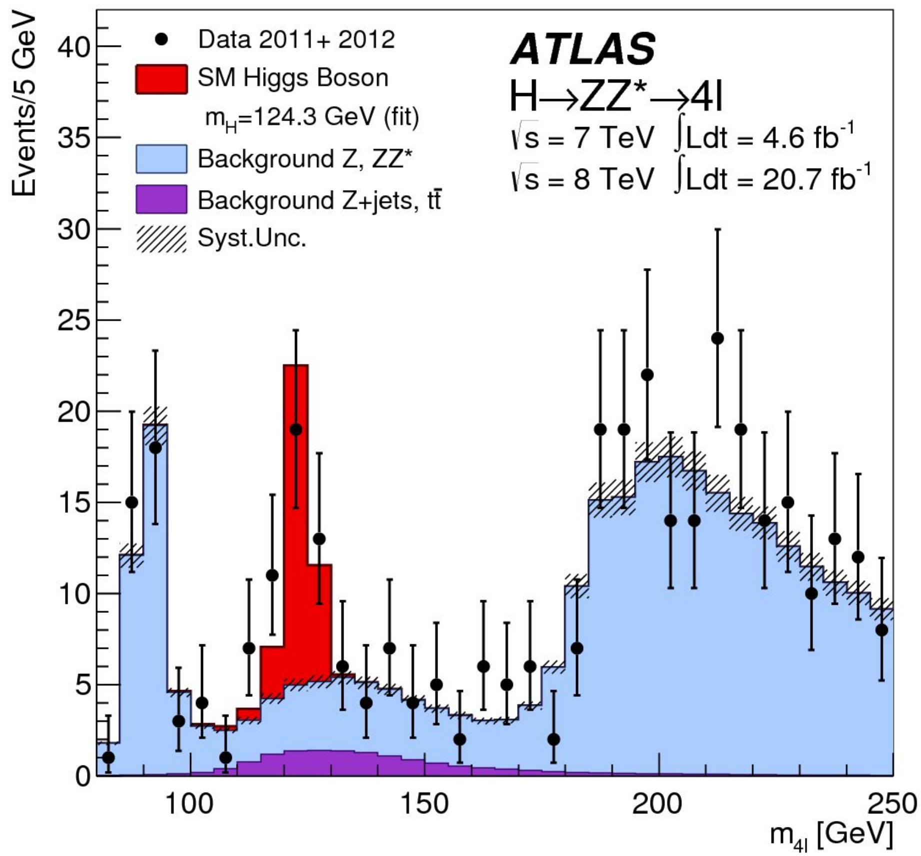


# The Higgs is there !

$H \rightarrow \gamma\gamma$



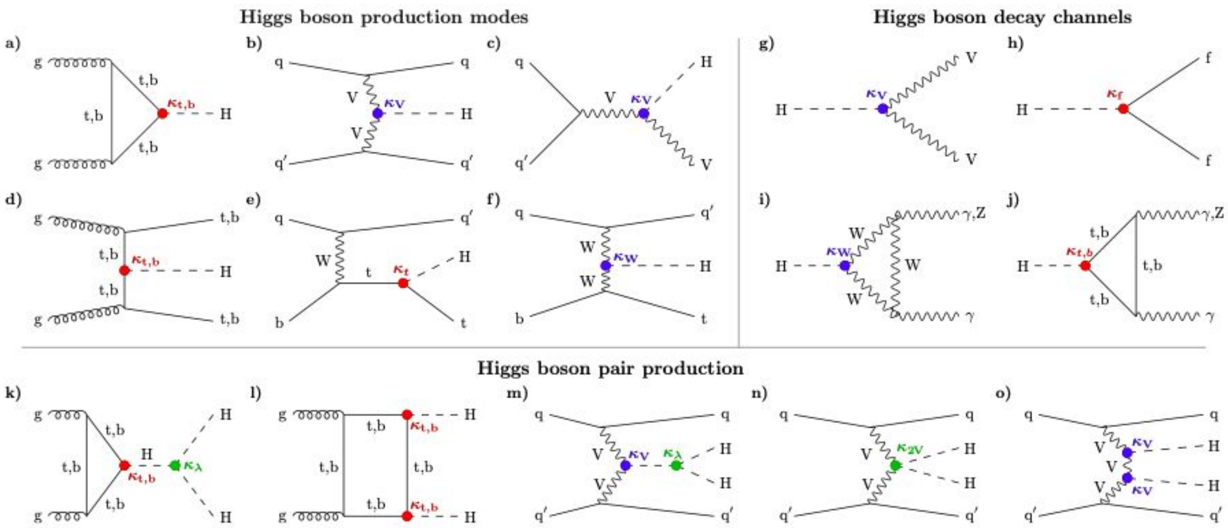

$H \rightarrow ZZ$

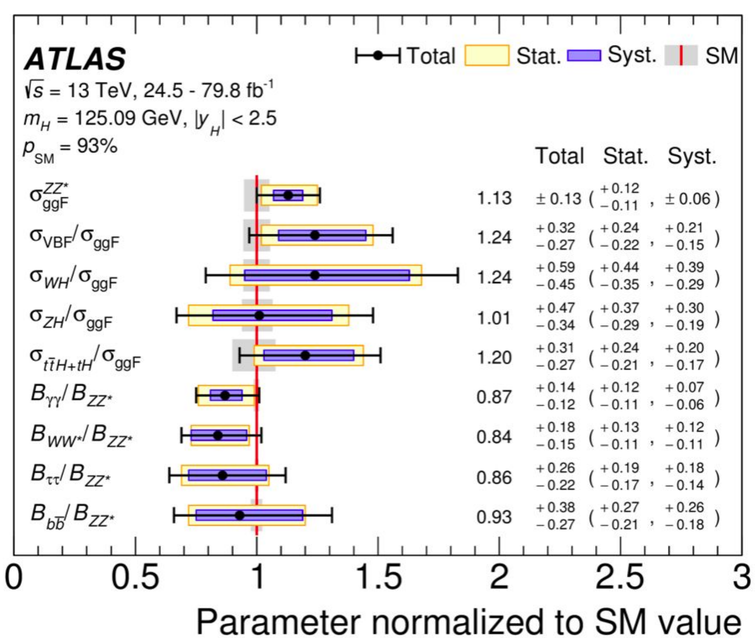


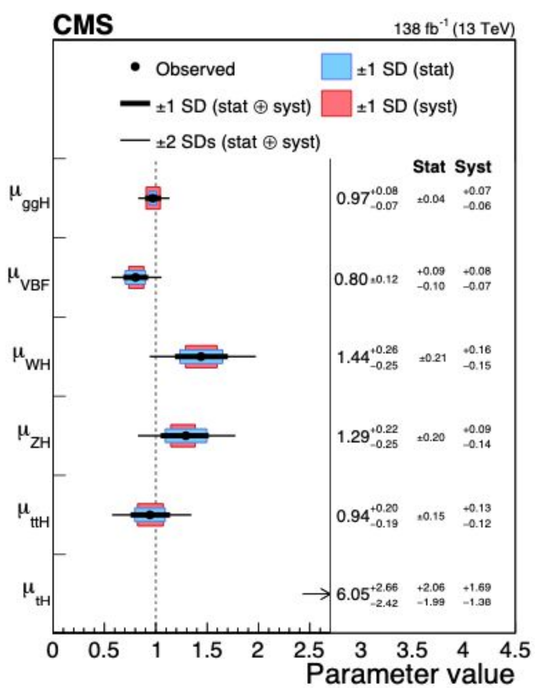

LHC is running at 13 TeV since 2015 → much bigger sample will be corrected in the next year → precision Higgs physics, possibility to discover the open ttH coupling

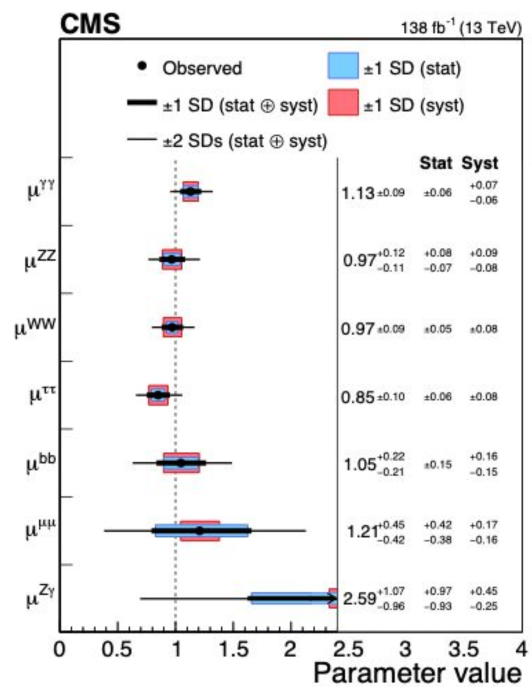
# The last missing piece in the Standard Model


# The last missing piece in the Standard Model



# Beyond Standard Model

# The Standard Model: Free parameters

## The standard model establish relations between different parameters

However, some of its parameters cannot be known a priori → Experiments

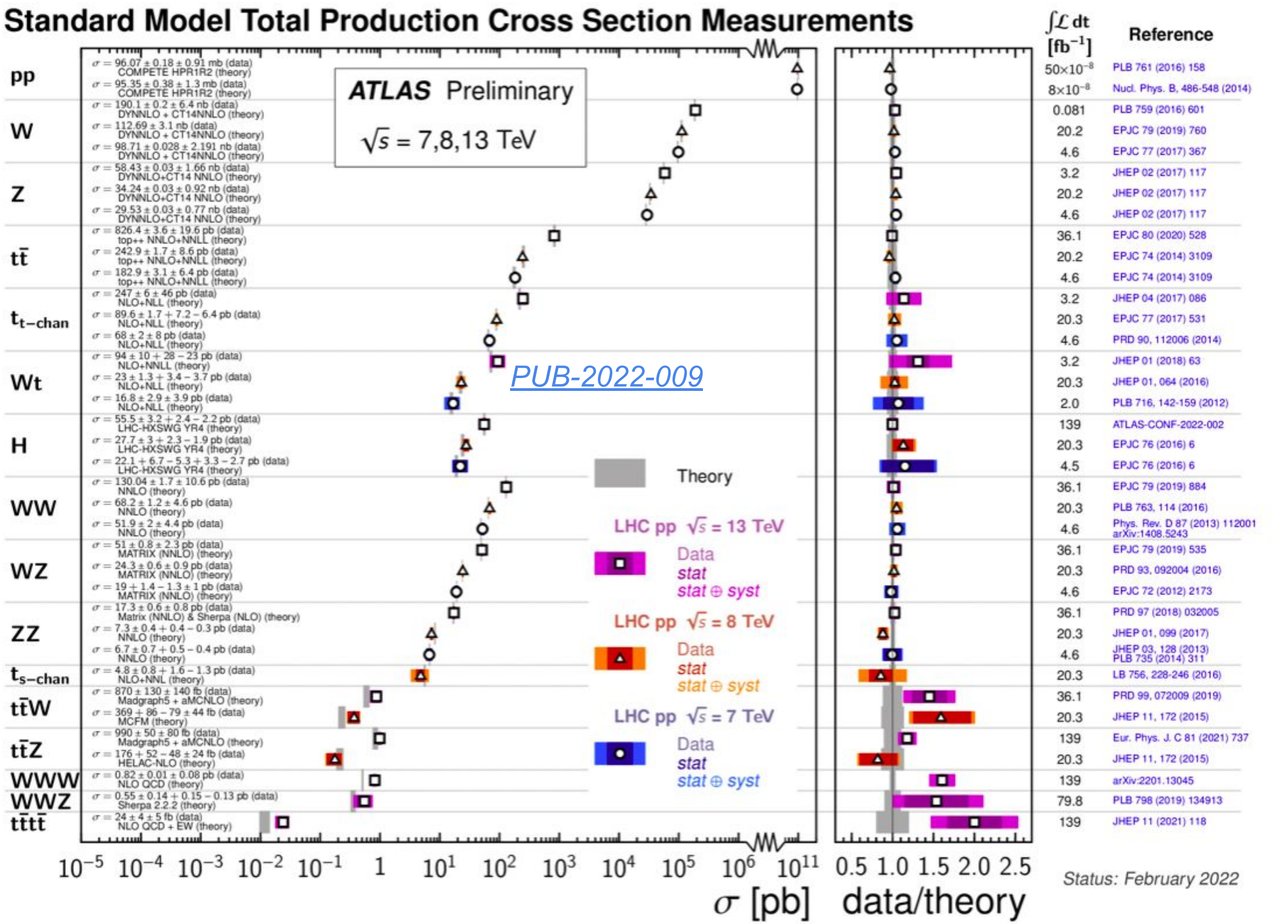
- Particle masses
- CKM parameters
- Gauge couplings at a given energy: strength of forces
- CP properties of QCD
- Parameters of electroweak symmetry breaking: v and $m_H$

Parameters of the Standard Model [hide]

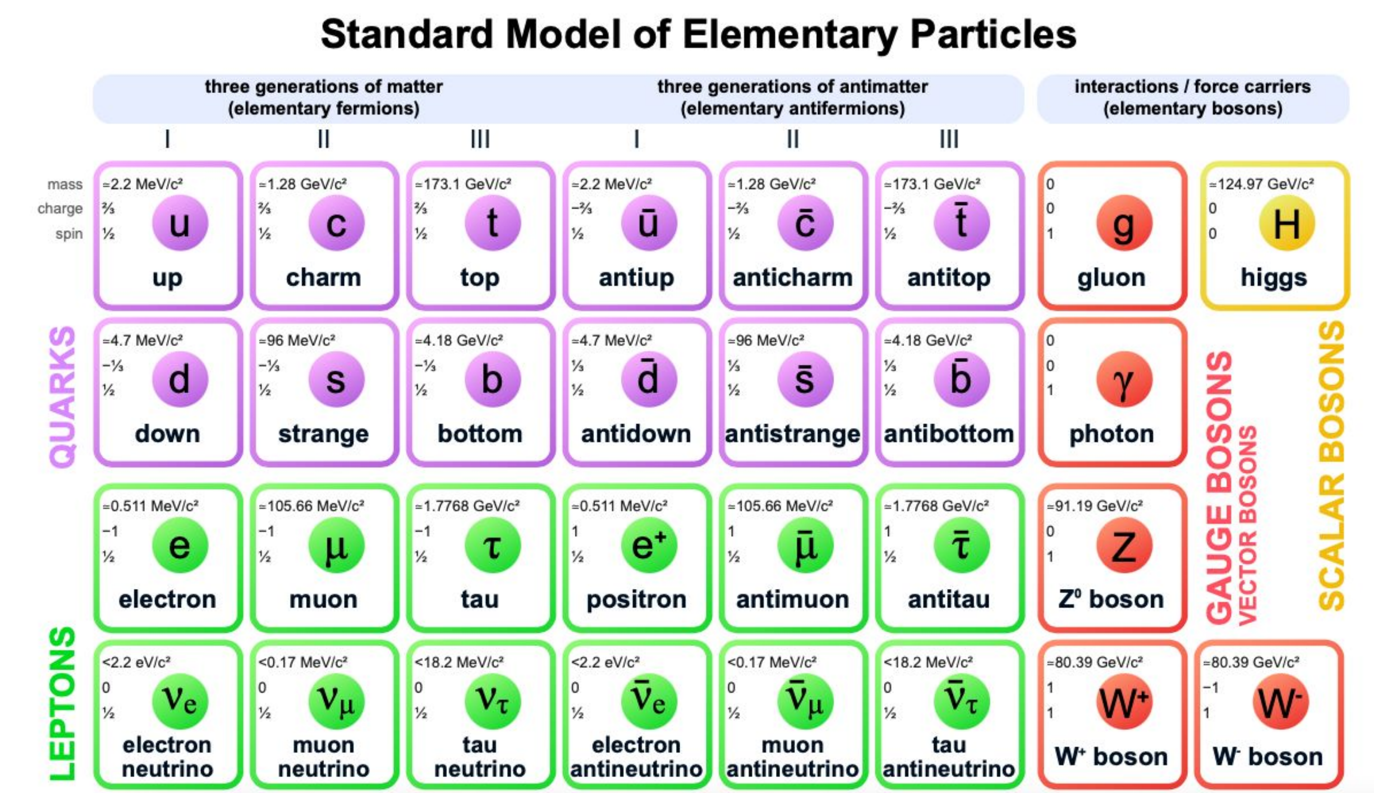
| # | Symbol | Description | Renormalization scheme (point) | Value |
|---|---|---|---|---|
| 1 | $m_e$ | Electron mass | | 0.511 MeV |
| 2 | $m_\mu$ | Muon mass | | 105.7 MeV |
| 3 | $m_\tau$ | Tau mass | | 1.78 GeV |
| 4 | $m_u$ | Up quark mass | $\mu_{\overline{MS}}$ = 2 GeV | 1.9 MeV |
| 5 | $m_d$ | Down quark mass | $\mu_{\overline{MS}}$ = 2 GeV | 4.4 MeV |
| 6 | $m_s$ | Strange quark mass | $\mu_{\overline{MS}}$ = 2 GeV | 87 MeV |
| 7 | $m_c$ | Charm quark mass | $\mu_{\overline{MS}} = m_c$ | 1.32 GeV |
| 8 | $m_b$ | Bottom quark mass | $\mu_{\overline{MS}} = m_b$ | 4.24 GeV |
| 9 | $m_t$ | Top quark mass | On shell scheme | 173.5 GeV |
| 10 | $\theta_{12}$ | CKM 12-mixing angle | | 13.1° |
| 11 | $\theta_{23}$ | CKM 23-mixing angle | | 2.4° |
| 12 | $\theta_{13}$ | CKM 13-mixing angle | | 0.2° |
| 13 | $\delta$ | CKM CP violation Phase | | 0.995 |
| 14 | $g_1$ or $g'$ | U(1) gauge coupling | $\mu_{\overline{MS}} = m_Z$ | 0.357 |
| 15 | $g_2$ or $g$ | SU(2) gauge coupling | $\mu_{\overline{MS}} = m_Z$ | 0.652 |
| 16 | $g_3$ or $g_s$ | SU(3) gauge coupling | $\mu_{\overline{MS}} = m_Z$ | 1.221 |
| 17 | $\theta_{QCD}$ | QCD vacuum angle | | ~0 |
| 18 | $v$ | Higgs vacuum expectation value | | 246 GeV |
| 19 | $m_H$ | Higgs mass | | 125.09 ±0.24 GeV |

# The Standard Model: Extremely predictive

Once parameters are known, everything else is “fixed”



# What is missing ? Beyond Standard Model Physics




## Is the SM complete ?

Presented the SM during the last days. Very successful and predictive theory but …..

- We know gravity to be one interaction of nature. Why is it not included ?
- Naturalness problem
- Hierarchy problem
- Matter-antimatter asymmetry



H. Murayama

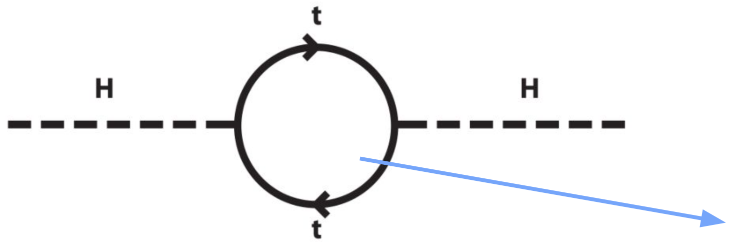
# Naturalness problem (some might call it hierarchy)

## Mass corrections to the Higgs

As we have seen, some Feynman diagrams might diverge and renormalization of couplings and masses helps to remove these divergences.

- Correction to the Higgs mass include loops with creation of fermions.
- Cannot absorb this correction. Dependent on cut-off Λ.

Radiative correction to Higgs mass very large, if no other new physics of mass Λ




$$\Delta m_h^2 \sim \frac{3}{4\pi^2}\left( -\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda \right)\Lambda^2$$

$$M < \left(\frac{10\%}{\text{tuning}}\right) 1\ \text{TeV}$$

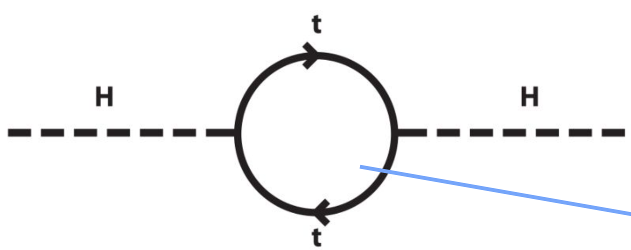
# Naturalness problem (some might call it hierarchy)

## Mass corrections to the Higgs

As we have seen, some Feynman diagrams might diverge and renormalization of couplings and masses helps to remove these divergences.

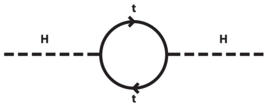
- Correction to the Higgs mass include loops with creation of fermions.
- Cannot absorb this correction. Dependent on cut-off Λ.
- Very typical new theory to solve Naturalness problem : Supersymmetry !

Radiative correction to Higgs mass very large, if no other new physics of mass Λ





$$\Delta m_h^2 \sim \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

(-1)* 

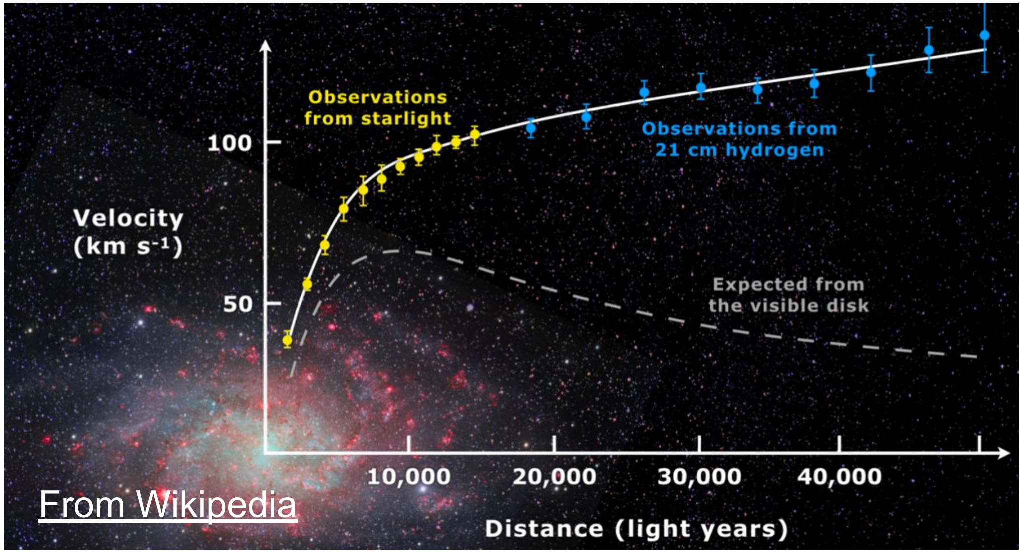
A super-partner of the top (boson) would generate same correction but with negative value → Cancellation

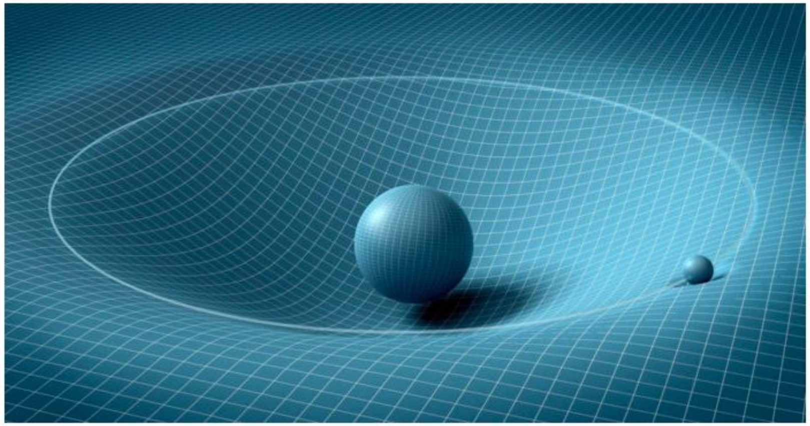
# Gravity, dark matter, matter-antimatter asymmetry, …..

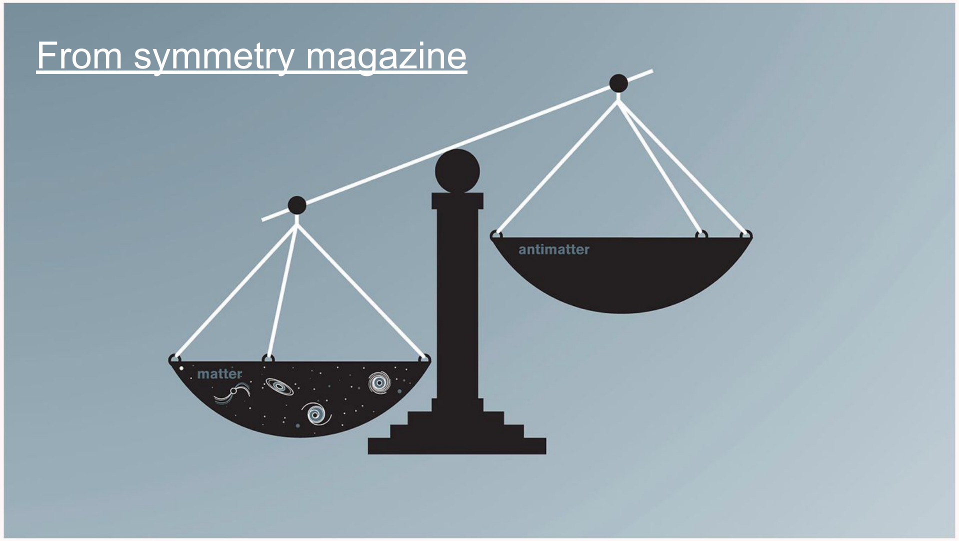
## More missing pieces

- Gravity: non-renormalizable theory
- Dark Matter: no candidate particle in SM
- We live in a matter dominated Universe. CP violation in EWK and CKM/PMNS cannot explain it. Why ?
- Strong CP problem

And many more missing pieces !





# So what else is out there?


H. Murayama

# So what else is out there?


More and better in the BSM talks by Ben Brueers!

H. Murayama