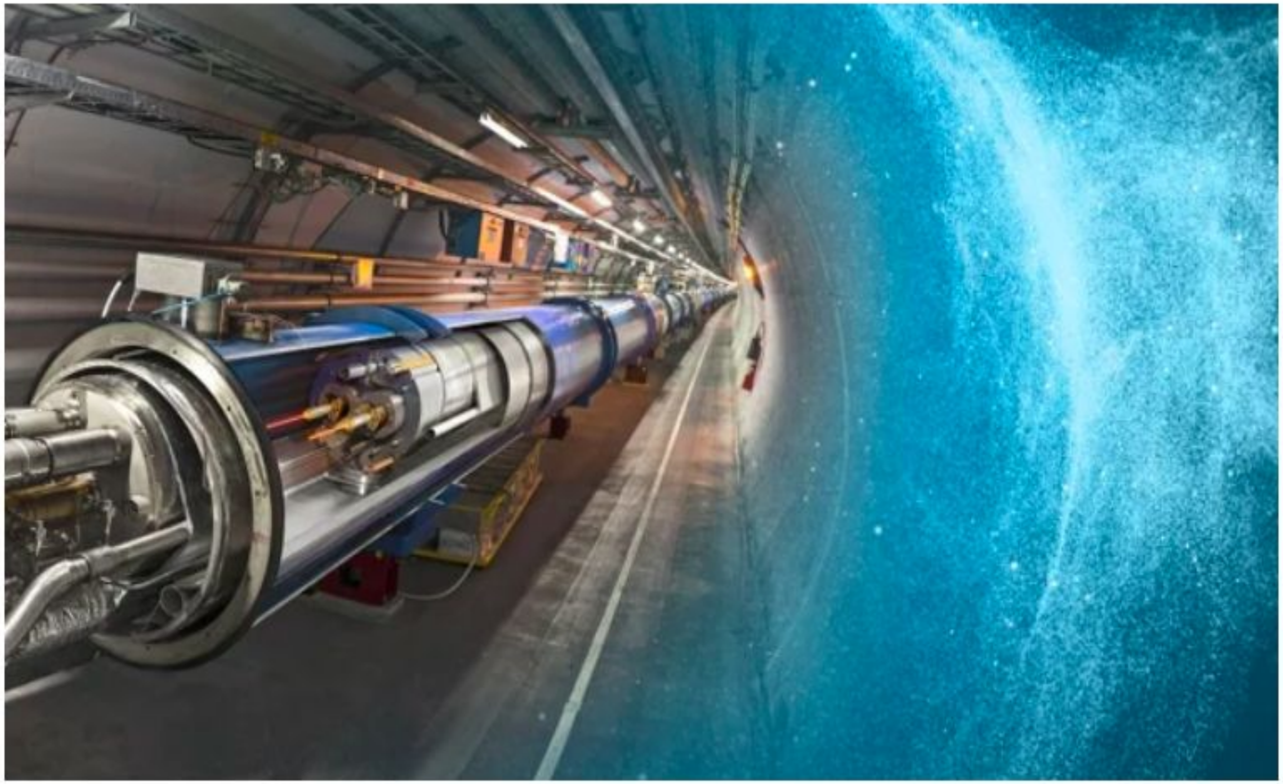
Introduction to the Standard Model

Summer Student Lecture 2022 – Part III



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Deutsches Elektronen Synchrotron

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HELMHOLTZ ASSOCIATION

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

DESY

Content

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- 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 ?**

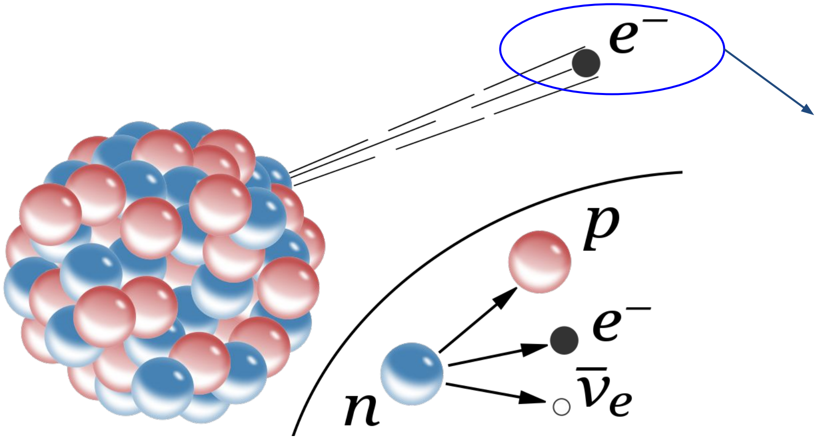
- **Beyond the Standard Model (brief)**

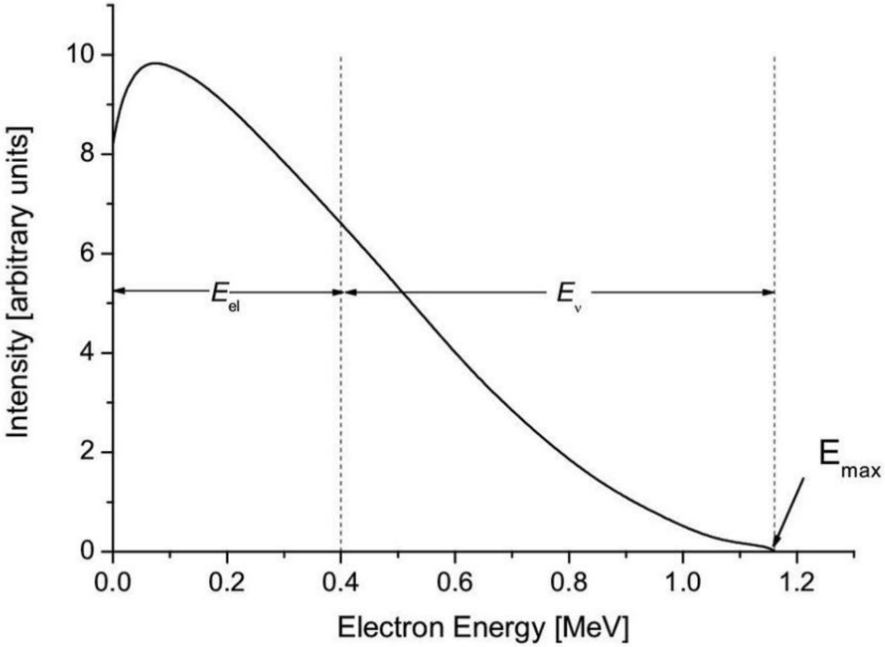
Weak interactions: Electroweak unification

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)

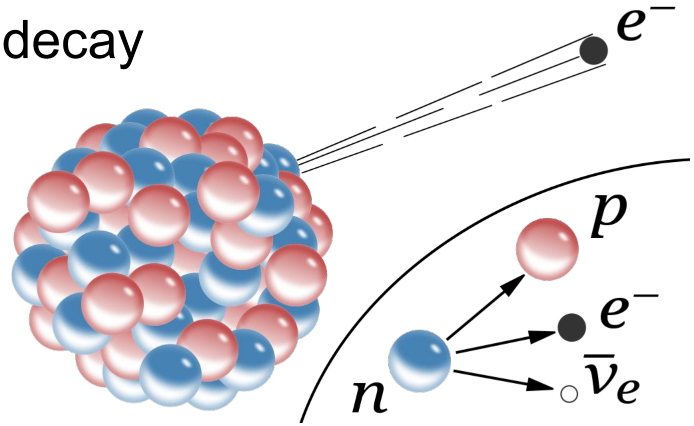




A little bit of history: Weak interactions

- In addition, β^- decays usually have a long lifetime (e.g. isolated neutron having a half life of 10 mins)
    - Lifetime depends on interaction’s strength → Weak interaction !

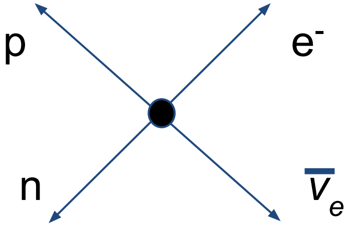
- Fermi theory proposed as explanation of beta-decay
  → four point interaction



- Coupling constant G_F measured from lifetime of muon: 1.6637×10^{-5} GeV^{-2}

- Suggested generic four point interaction (a la QED)

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



- Fermi's theory successfully described decays but incomplete.

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

Let’s go back to the properties of an interaction

Helicity

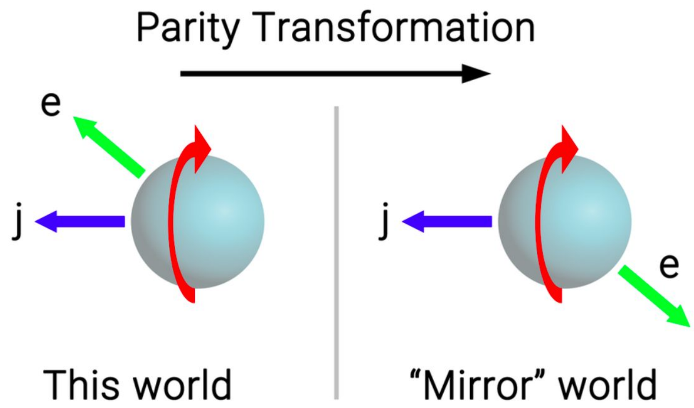
Particles whose momentum direction aligns with spin → right-handed particles

Particles whose momentum direction aligns with spin → left-handed particles

Dependent on the reference frame.

Parity

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



Charge conjugation

Change a particle by its anti-particle

Let’s go back to the properties of an interaction

Chirality

Identical to helicity in the massless case but something more complicated

It tells how two separate components of a fermionic field change under Lorentz boost (space-time change) → Weyl spinors. Each fermion has a left-handed component and a right-handed one

Parity transformations change chirality

General Lorentz transformation

$$S = \exp\begin{bmatrix} \frac{1}{2}i\boldsymbol{\sigma}\cdot\boldsymbol{\theta} - \frac{1}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\phi} & 0 \\ 0 & \frac{1}{2}i\boldsymbol{\sigma}\cdot\boldsymbol{\theta} + \frac{1}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\phi} \end{bmatrix}$$

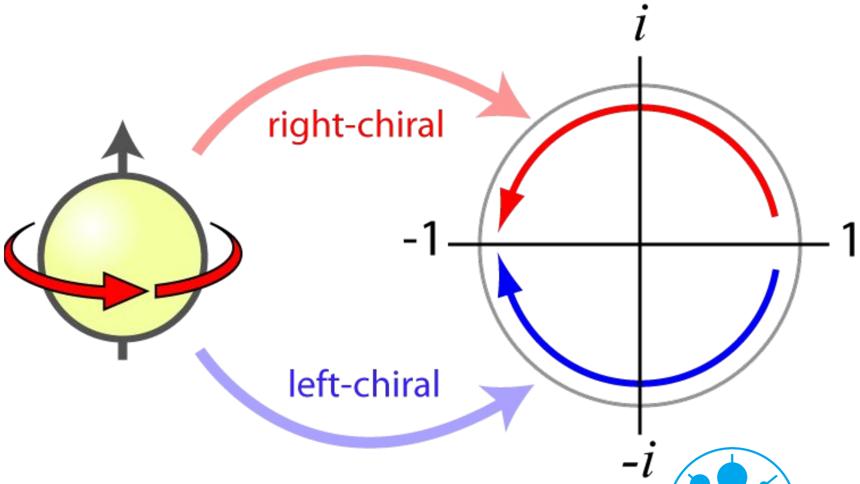
θ: angle in space rotations

Φ: boost (time and space rotation)

Spinor of fermion: 2 terms (Weyl spinor) with 2 components

$$\Psi = \begin{bmatrix} \psi_R \\ \psi_L \end{bmatrix}$$

$$\begin{aligned} \psi'_R &= \exp\left(\frac{1}{2}i\boldsymbol{\sigma}\cdot\boldsymbol{\theta} - \frac{1}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\phi}\right)\psi_R \\ \psi'_L &= \exp\left(\frac{1}{2}i\boldsymbol{\sigma}\cdot\boldsymbol{\theta} + \frac{1}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\phi}\right)\psi_L \end{aligned}$$

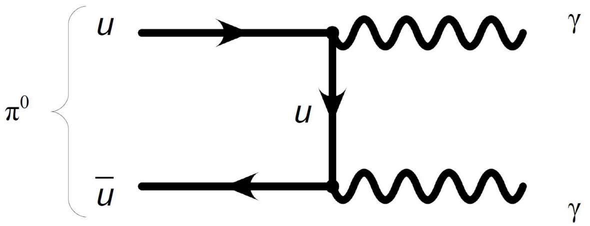


Mass terms in Lagrangian

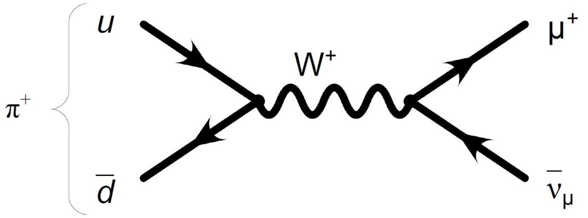
$$-m\bar{\Psi}\Psi = -m\left(\bar{e}_L e_R + \bar{e}_R e_L\right)$$

What's the strange behaviour ? The τ-θ puzzle (1956)

- Additional measurements showed interactions similar like the β-decay.



electromagnetic interaction



weak interaction

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

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

- In the 50's, two particles were observed: τ^+ and θ^+.τ-θ puzzle

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

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

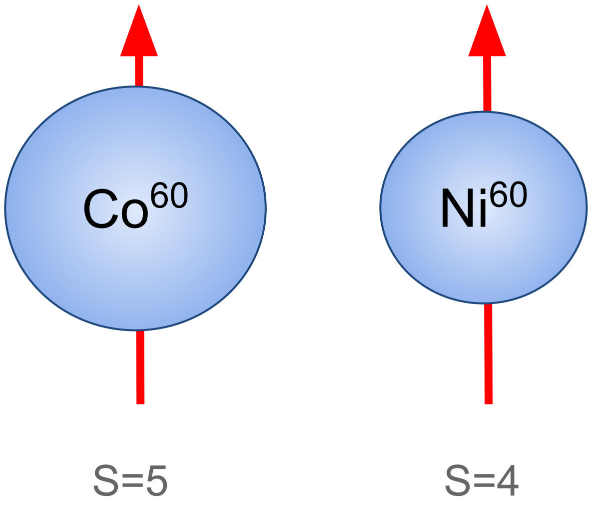
- Decaying into different states and different parity …. Same mass, lifetime, charge, spin ….

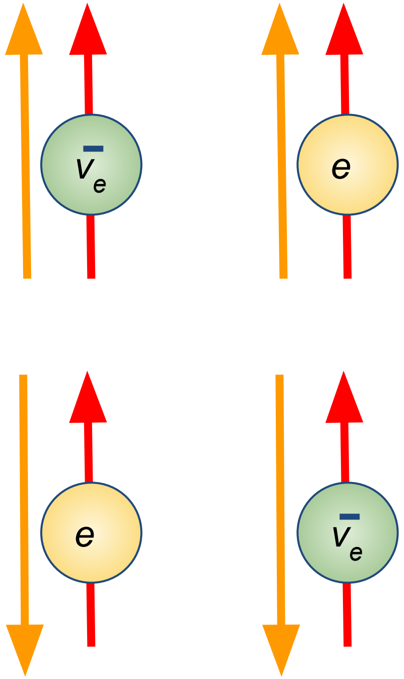
- Proposal that both particles are actually the same particle (K^+)but parity violation in the interaction.

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

Co^{60} atoms aligned with magnetic field

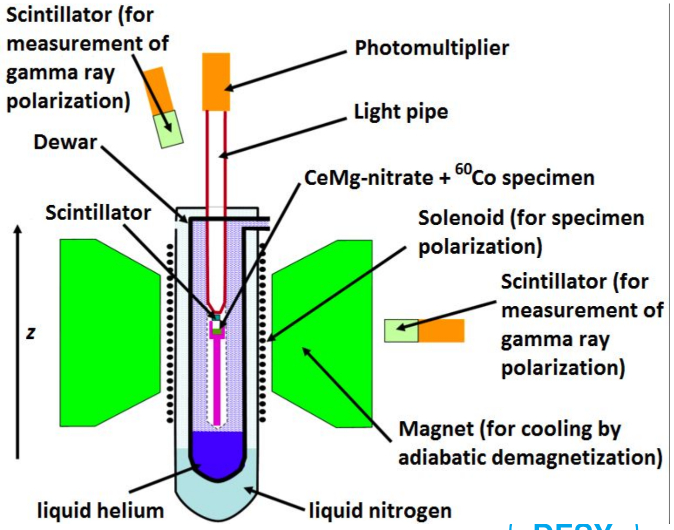
$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$





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.



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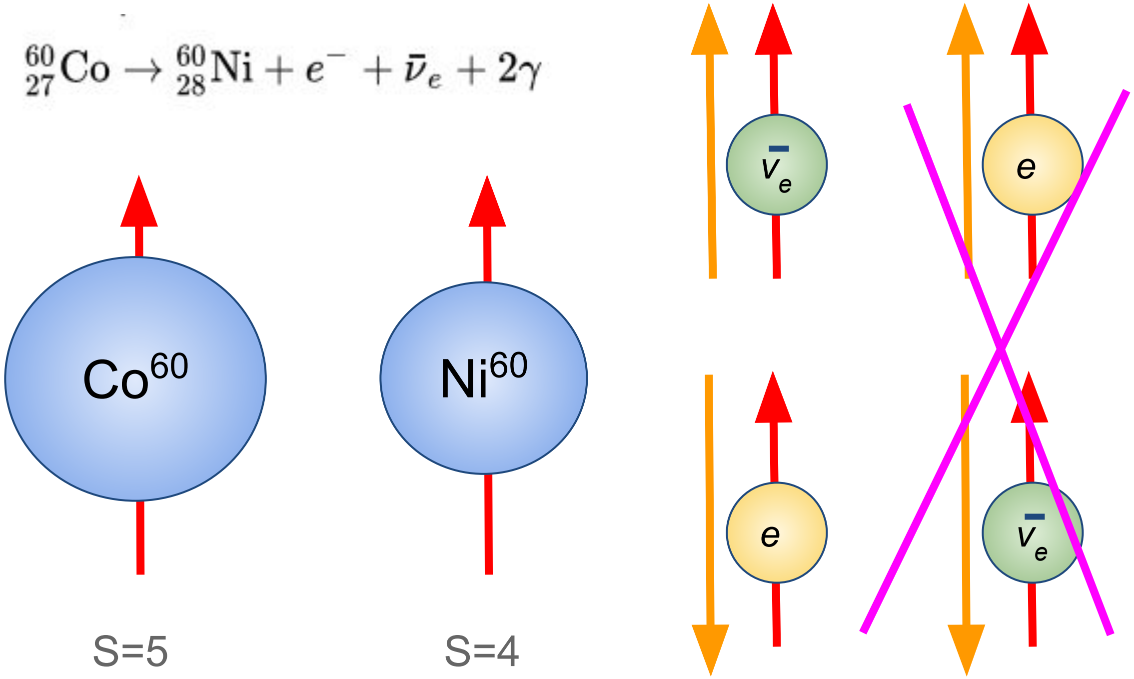


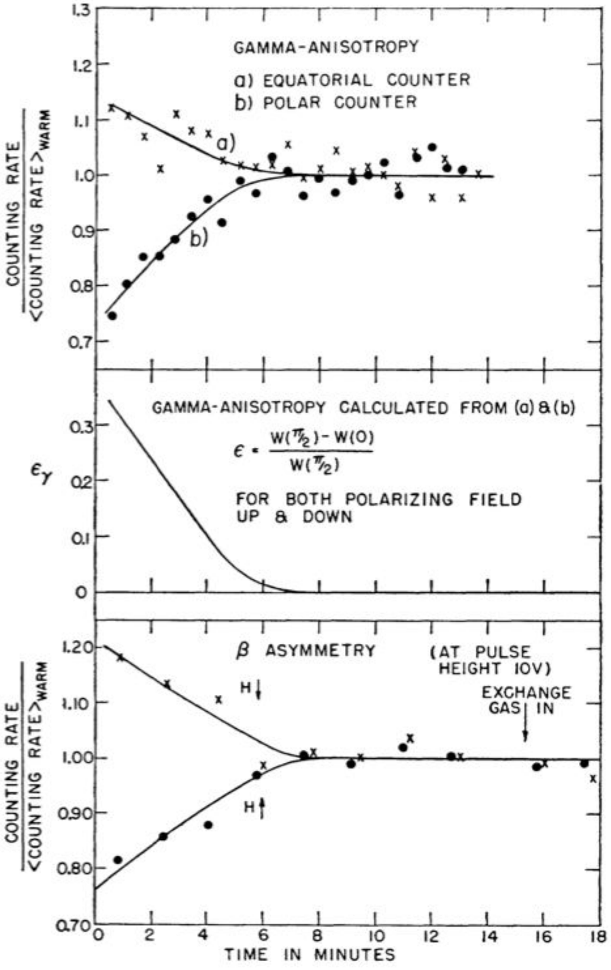


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

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

Weak interaction violates parity (maximally)

First proposal of a QFT for weak interactions

Feynman and Gell-Mann proposed a QFT where the force field is V-A interaction

Explanation of Wu's experiment : weak interaction only with left-handed states of particles (and right-handed anti-particles)

Vector-axial symmetry → Interaction only happens between left-handed particles (or right-handed antiparticles).

$$e_L = \tfrac{1}{2}(1-\gamma_5)e$$

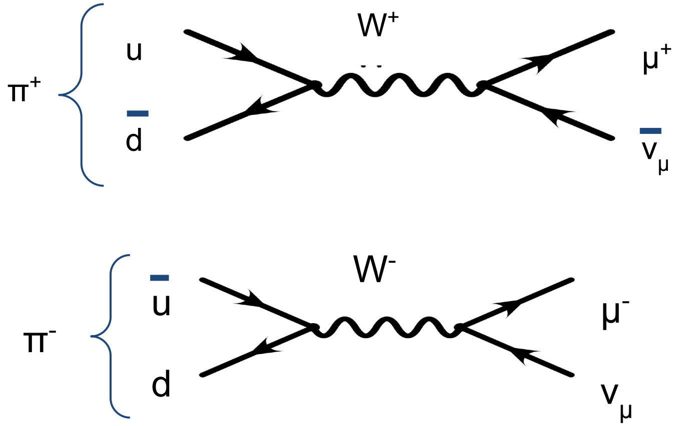
$$e_R = \tfrac{1}{2}(1+\gamma_5)e$$

$$\mathcal{L}_\mu = \frac{G_\mu}{\sqrt{2}}\left[\bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu\right]\left[\bar{e}\gamma_\lambda(1-\gamma_5)\nu_e(x)\right] + \text{c.c.}\ .$$

QFT theory still allows the CP-symmetry

Change parity of the interaction and change particles by anti-particles → Same probability.

Experiment of Wu didn't show any problem CP-symmetry



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)

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

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

- 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.

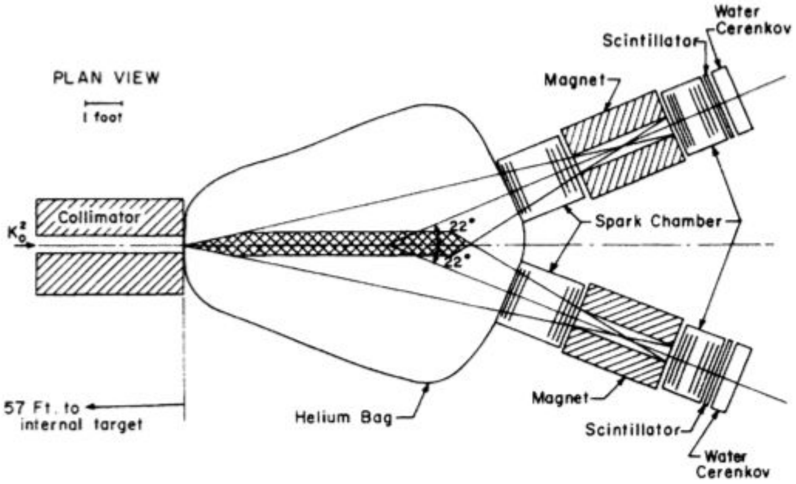


FIG. 1. Plan view of the detector arrangement.

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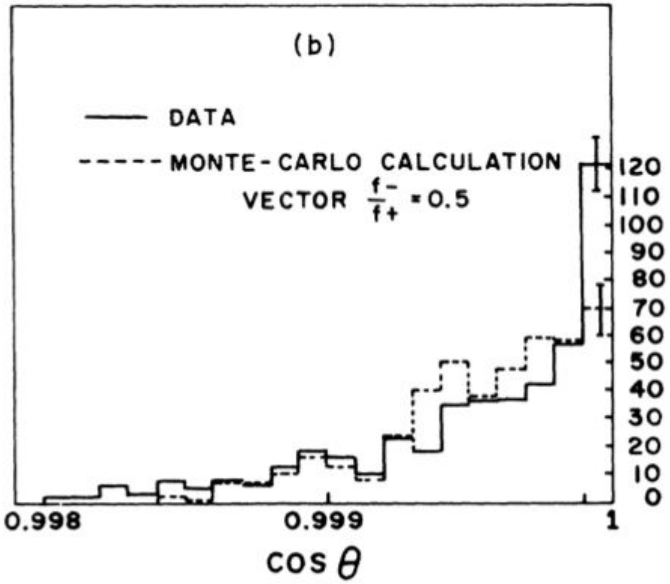
- Lifetimes typical of weak interaction
- Experiment with a beam of neutral kaons. If beam long enough, enriched with K^0_L.
- Observed more events than expected and associated to production of 2π!



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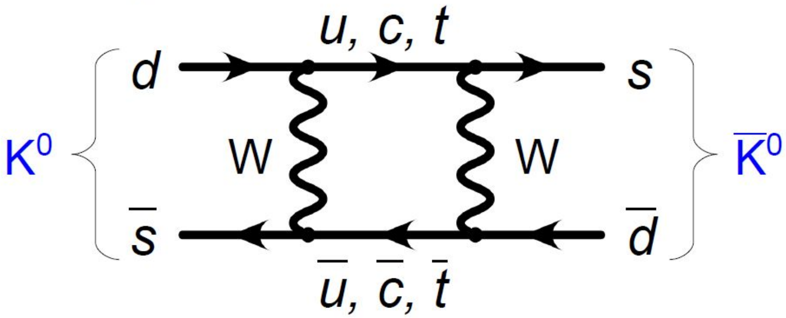
$$K^0_L \to \pi^0\pi^0\pi^0/\pi^+\pi^-\pi^0 \quad ;\mathrm{CP} = -1$$

- As we know today, the reason is that K^0_S and K^0_L are actually a mixing of the strong interaction eigenstates K^0 and $\overline{K}^0$
- Mass and charge of the interaction determined by QCD and QED (this is the particle we see).
- But QCD eigenstate is not weak eigenstate. QCD eigenstate = composition of weak eigenstates → Turn CP=1 state into CP = -1 → **CP-violation!**

K^0 and $\overline{K}^0$ can turn from one into the other:

"oscillation"



Towards a QFT of weak interactions → Electroweak

- Problem: Divergences! Theory only valid at low energies

$$\mathcal{L}_\mu = \frac{G_\mu}{\sqrt{2}}\left[\bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu\right]\left[\bar{e}\gamma_\lambda(1-\gamma_5)\nu_e(x)\right] + \text{c.c.}\ .$$

$$\longrightarrow \quad \sigma^{e^- + \nu_e \to e^- \nu_e} = \frac{4G_F^2}{\pi} E_{\rm CM}^2$$

Additional problems:

- Radiative corrections divergent (but needed)
- Unitarity violated at high energy (cross-section goes to very large values)
- Loop processes such as K^0 mixing meaningless/incorrect
- Need theory which includes Feynman theory but does not diverge at high energies

1960-1968: Formulation of electroweak unification
(Glashow, Salam, Weinstein) → **massive W/Z bosons + massless γ**

Gauge theory for the weak interaction → Electroweak

A gauge theory is a QFT theory that is invariant under local transformations

Local transformation = transformation that is not the same in all space → x+Δx with Δx = f(x)

This is the way that interactions are introduced in the SM → Find a variable/symmetry of the interaction and formulate a theory including a new gauge boson that would make the lagrangian invariant.

Lagrangian of the free Dirac field

$$\mathcal{L} = \bar{\psi}(i\hbar c\gamma^{\mu}\partial_{\mu} - mc^2)\psi$$

Invariance under phase transformations?

Physics should be similar

$$\psi(x) \rightarrow e^{iq\Lambda(x)/\hbar}\psi(x)$$
$$\bar{\psi}(x) \rightarrow \bar{\psi}(x)e^{-iq\Lambda(x)/\hbar}$$

$$\mathcal{L} \rightarrow \bar{\psi}e^{-iq\Lambda(x)/\hbar}(i\hbar c\gamma^{\mu}\partial_{\mu} - mc^2)e^{iq\Lambda(x)/\hbar}\psi =$$
$$= \bar{\psi}(i\hbar c\gamma^{\mu}(\partial_{\mu} + iq\partial_{\mu}\Lambda(x)/\hbar) - mc^2)\psi$$

Introduce A_{μ} to absorb δΛ(x)

$$A_{\mu} \rightarrow A_{\mu} + \partial_{\mu}\Lambda(x) \qquad D_{\mu} = \partial_{\mu} - \frac{i}{\hbar}qA_{\mu}$$

$$\mathcal{L} = \bar{\psi}(i\hbar c\gamma^{\mu}(\partial_{\mu} - iqA_{\mu}/\hbar) - mc^2)\psi$$

Lagrangian of the QED (U(1))

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

Gauge theory for the weak interaction → Electroweak

Transformations are described by a Lie group of transformations → Includes the whole ensemble of NxN matrices that make a transformation possible in a space defined by N-sized vectors.

In QFT, we us unitary matrices U(N) and SU(N) (with det(U))=1

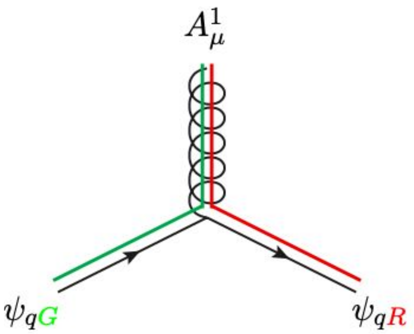
- Each transformation can be described by a set of N^2-1 matrices → generators
- In the context of QFT, one gauge boson per generator

A complex example: SU(3) or also called QCD !!

- Strong interaction behaves equally for 3 different colors → Gauge invariance from color transformations → 3 different directions : red, blue and green
- Transformations between 3 colors leave invariant the lagrangian
- 8 different generators → One gauge boson per generator ! 8 glu

gluon

$$(D_\mu)_{ij} = \delta_{ij}\partial_\mu - ig_s t^a_{ij} A^a_\mu$$



$$\begin{array}{ccccc} \propto & -\frac{i}{2}g_s & \bar{\psi}_{qR} & \lambda^1 & \psi_{qG} \\ = & -\frac{i}{2}g_s & \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \end{array}$$

generators of rotation in SU(3)

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix}$$

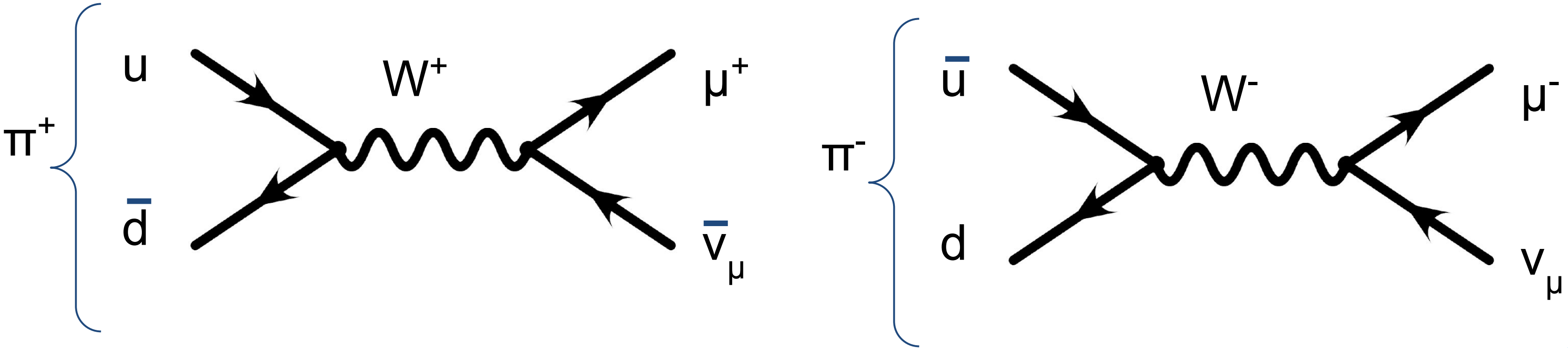
Electroweak interactions

Usually observed charged (positive and negative) interactions with long-lifetime → Propose mediated by two charged heavy bosons!

- Consider W+/W- as doublets of the charge current
- Introduce in QFT → Postulate SU(2)$_L$ symmetry acting only on the left-handed fermions.
  - Observed that weak interaction between two distinct particles → Introduction of weak isospin
  - A 3rd gauge field → Introduction of *neutral current !*

$$\psi_L = \begin{pmatrix} e_L \\ \nu_e \end{pmatrix}$$

- Try preserving SU(2)$_L$ and U(1)$_Q$ symmetry → Introduce Hypercharge Y$_L$ to preserve U(1)$_Y$
- Arrive at a unified interaction with massive W/Z boson +massless γ



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)

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

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

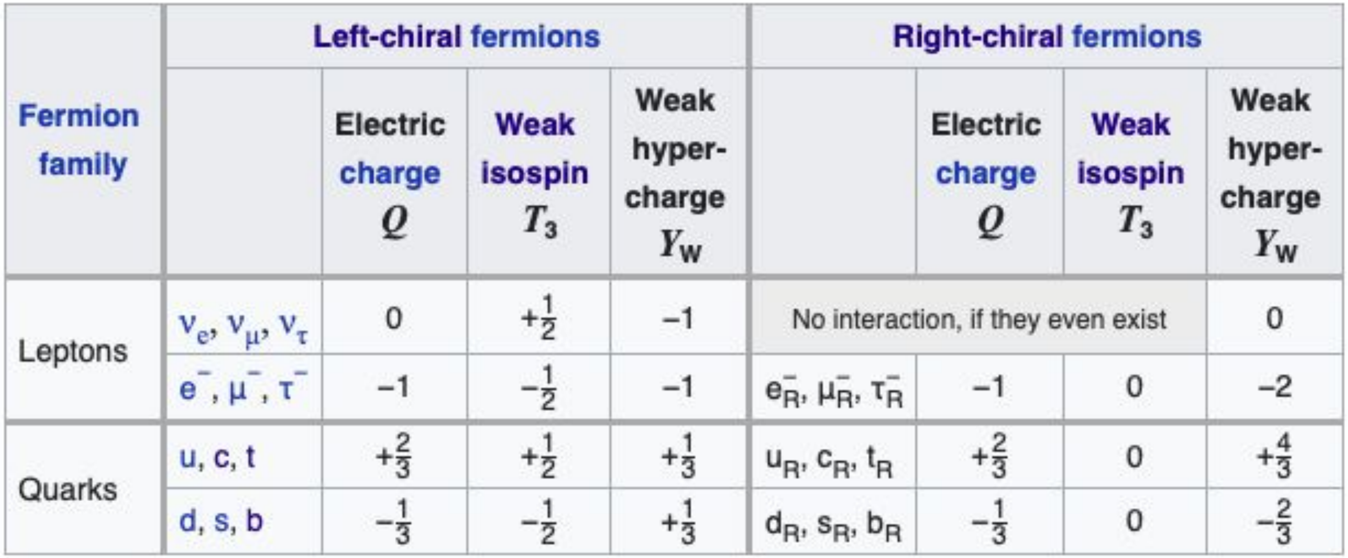
$$A = \sin\theta_W W^3 + \cos\theta_W B^0$$

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

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

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

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	ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	−1	No interaction, if they even exist			0
	e^-, μ^-, τ^-	−1	$-\frac{1}{2}$	−1	e^-_R, μ^-_R, τ^-_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	γ^0	0	0	0

from wikipedia

Flavour and weak interaction: CKM matrix

- In the 60's, together with parity and CP-violation, observed:
  - u – d, e^- – v_e, μ^- – v_μ transitions with weak interaction had same probability to happen
  - $\Delta S = 1$ transitions had ¼ of probability of occuring than $\Delta S = 0$

- We have seen that weak interaction eigenstates are not electric or strong interaction eigenstates → Mixture of quarks are weak interaction
- Nicola Cabibbo introduced mixing angle

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

$$\tan\theta_c = \frac{|V_{us}|}{|V_{ud}|} = \frac{0.22534}{0.97427} \quad \Rightarrow \quad \theta_c = 13.02^\circ$$

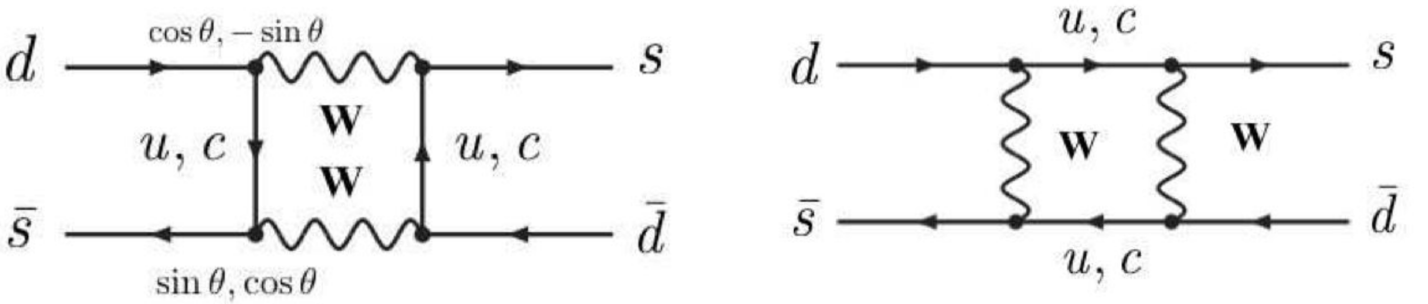
Weak eigenstate

$$\left\{ \begin{aligned} d' &= \cos\theta_c \, d + \sin\theta_c \, s \\ s' &= -\sin\theta_c \, d + \cos\theta_c \, s \end{aligned} \right\}$$

Strong eigenstate

Flavour and weak interaction: CKM matrix

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



- **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
  - CKM matrix explaining mixing in charged currents with quarks

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\text{ud}} & V_{\text{us}} & V_{\text{ub}} \\ V_{\text{cd}} & V_{\text{cs}} & V_{\text{cb}} \\ V_{\text{td}} & V_{\text{ts}} & V_{\text{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Same matrix for leptons (PMNS)

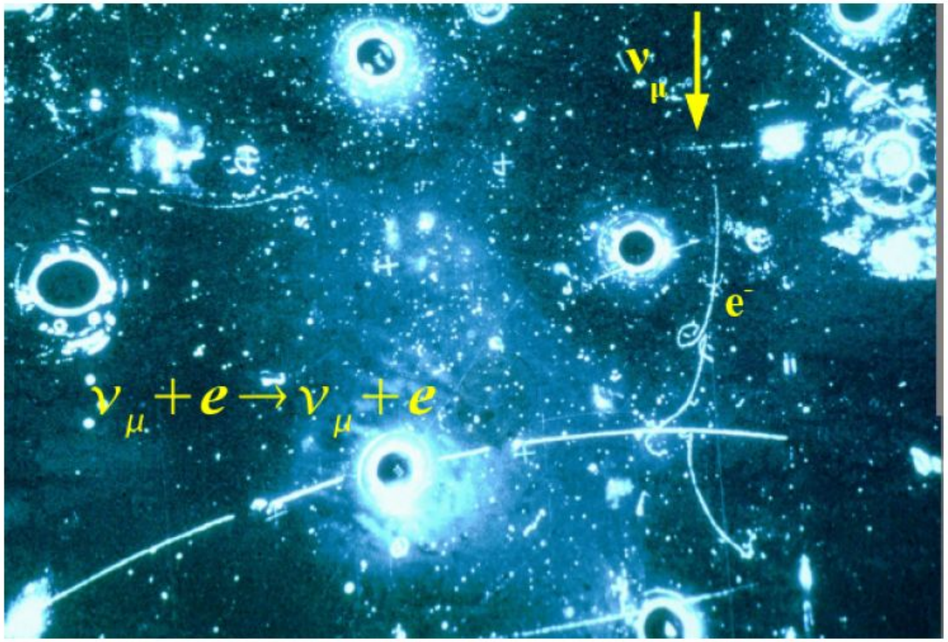
$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} &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

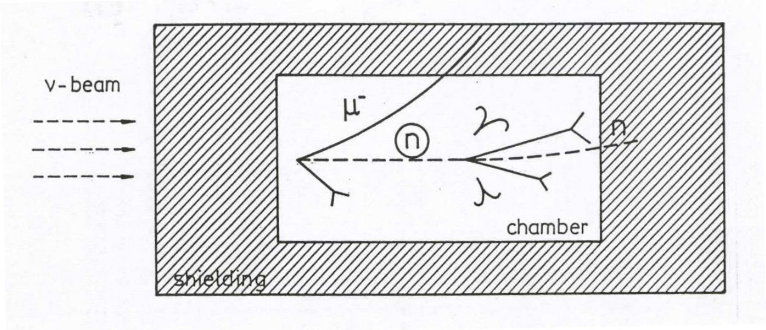
$$\mathcal{L}_C = -\frac{g}{\sqrt{2}} \left[\overline{u}_i\, \gamma^\mu\, \frac{1-\gamma^5}{2} \boxed{M^{\text{CKM}}_{ij}}\, d_j + \overline{\nu}_i\, \gamma^\mu\, \frac{1-\gamma^5}{2}\, e_i \right] W^+_\mu + \text{h.c.}\,,$$

Evidence of GSW validity: neutral weak interaction

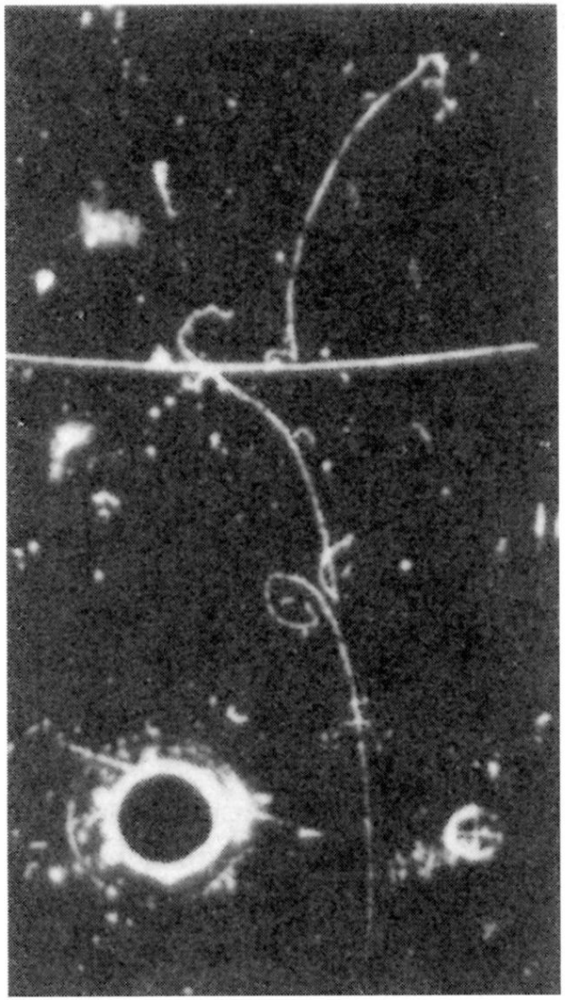
- Neutral current discovered in 1973 with *Gargamelle* at CERN by observing eν → eν

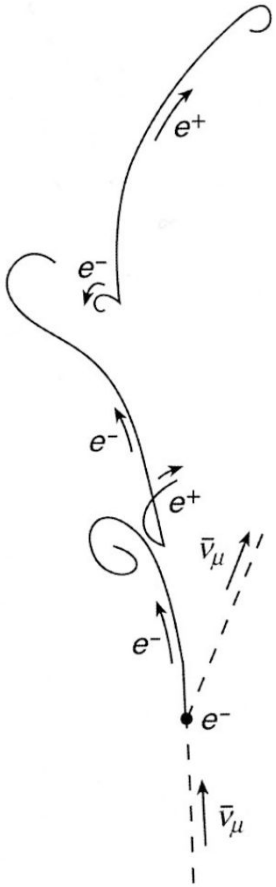
- Before this: no observation/indication of neutral weak currents





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)

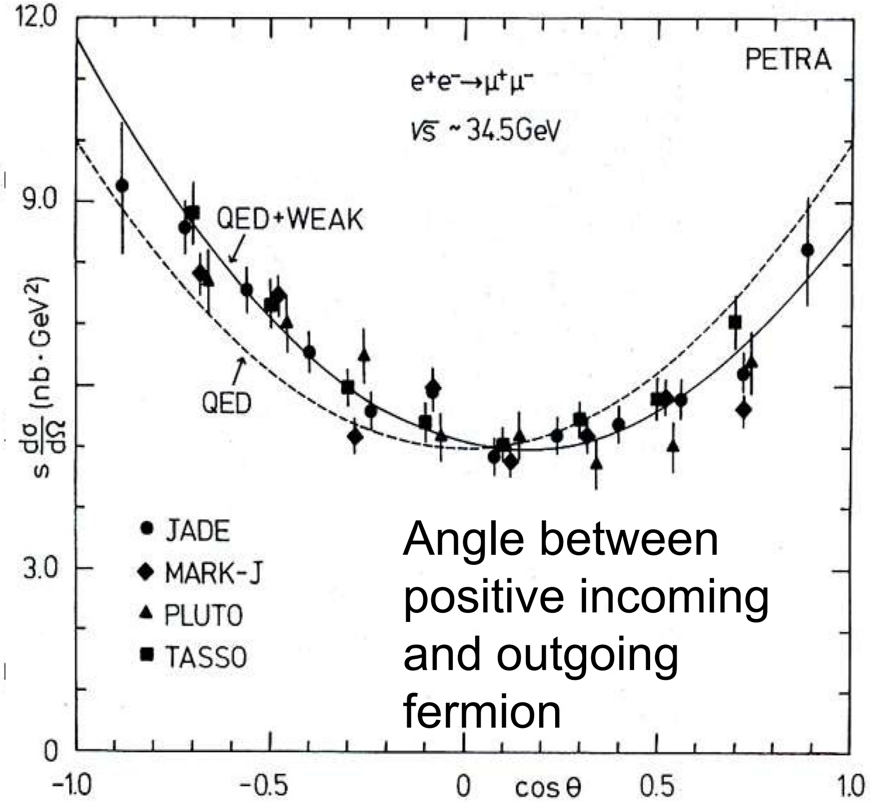
Evidence of GSW validity: Angular relations

- Angular distributions changed by electroweak interactions

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

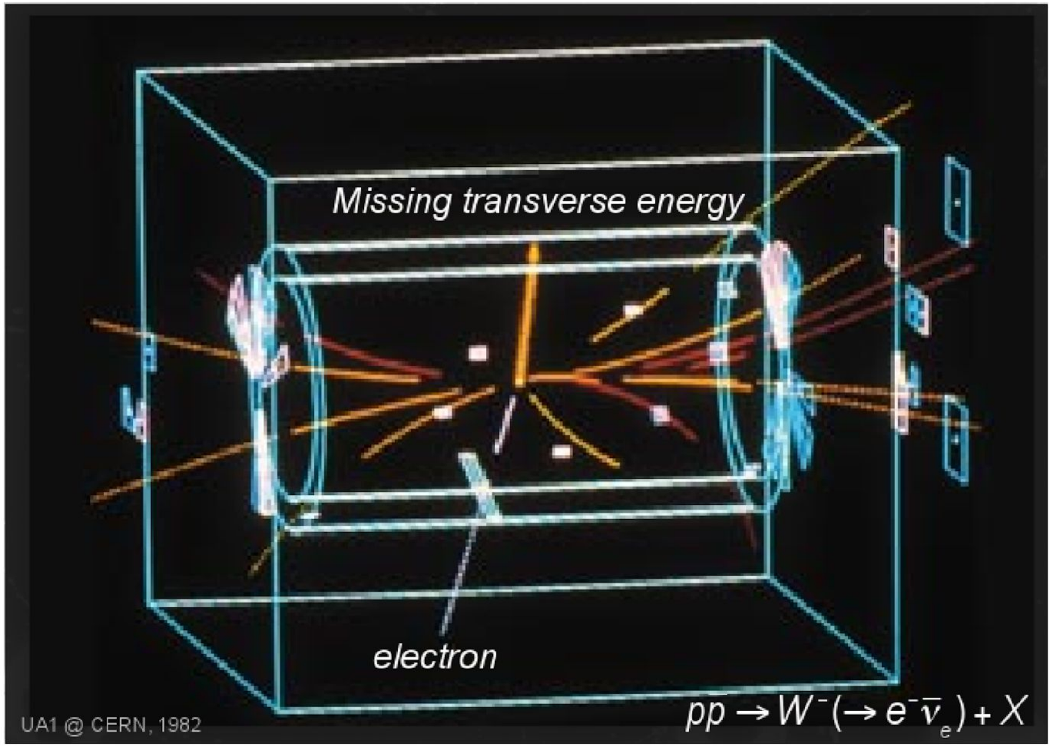
- Total cross sections unchanged

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

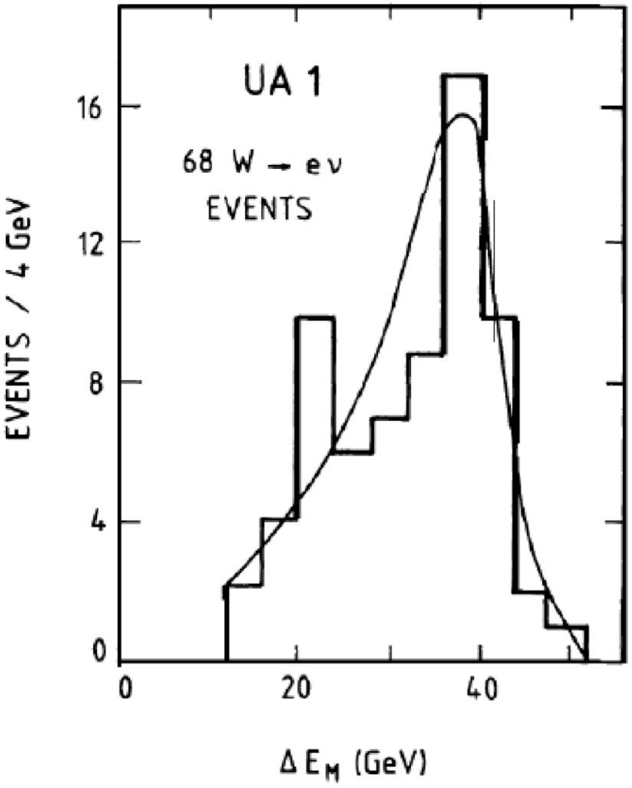


Angle between positive incoming and outgoing fermion

Evidence of GSW validity: Discovery of W boson



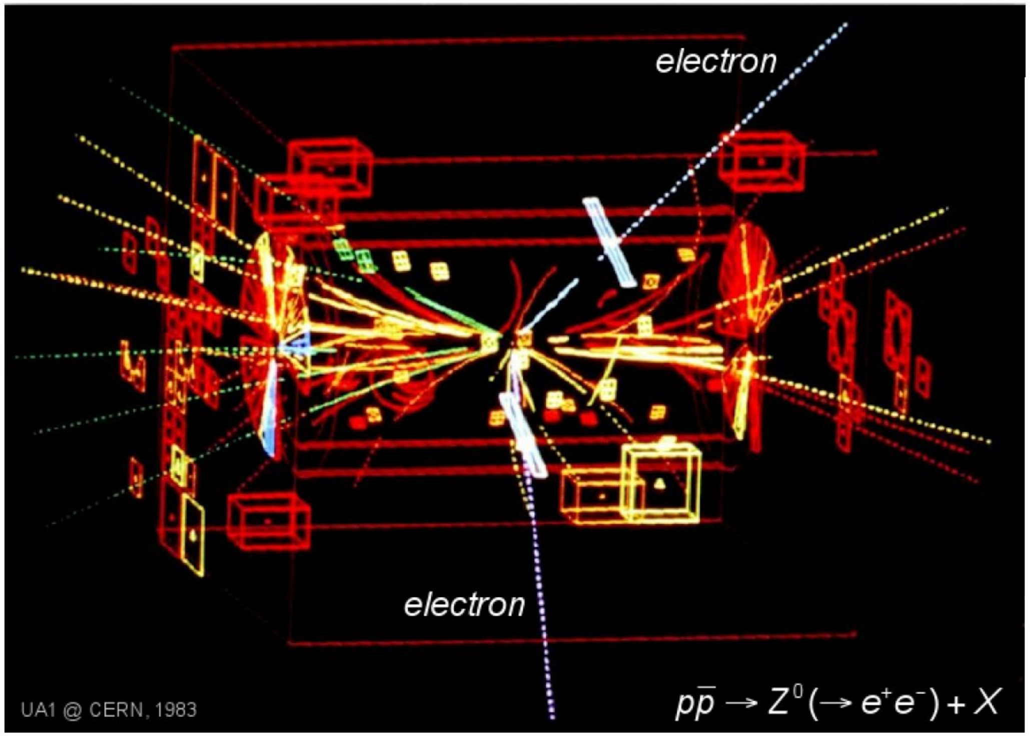
Missing transverse energy
in events with E_e > 15 GeV

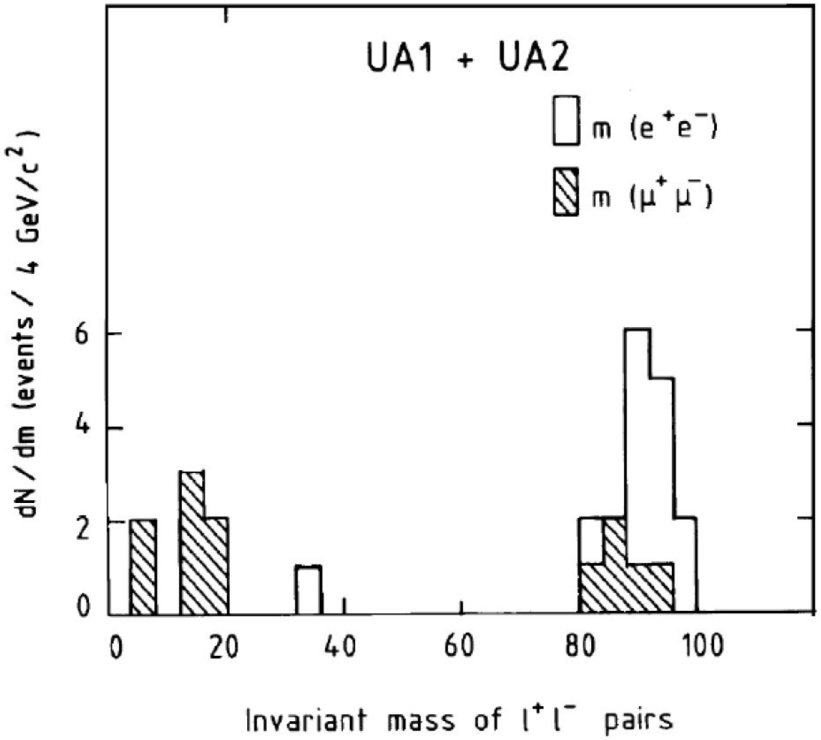


$$m_W = (80.9 \pm 1.5 \pm 2.4)\ \text{GeV}$$

C. Rubbia, Nobel Lecture, 1984

Evidence of GSW validity: Discovery of Z boson

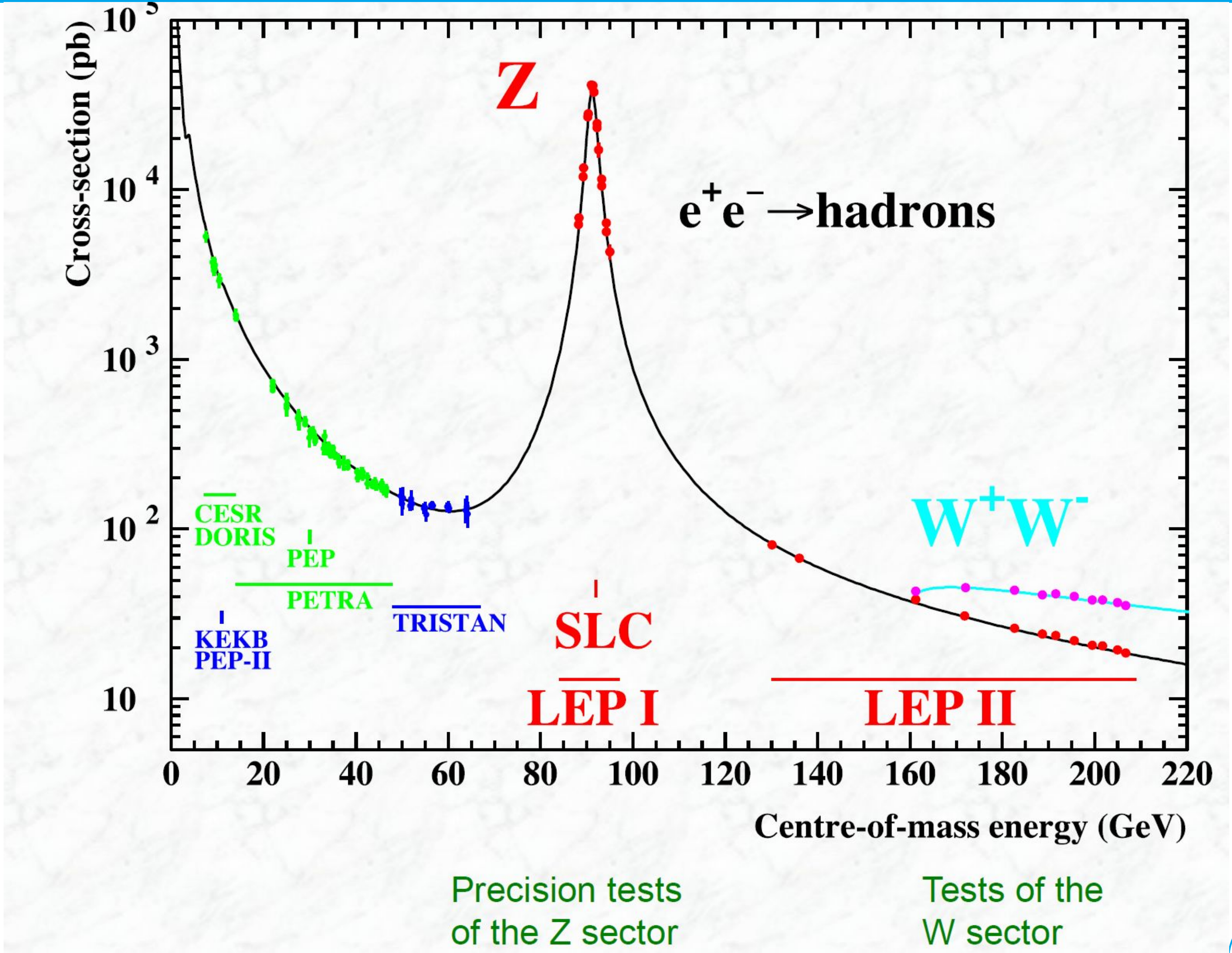




$$m_Z = (95.1 \pm 2.5)\ \mathrm{GeV}$$

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

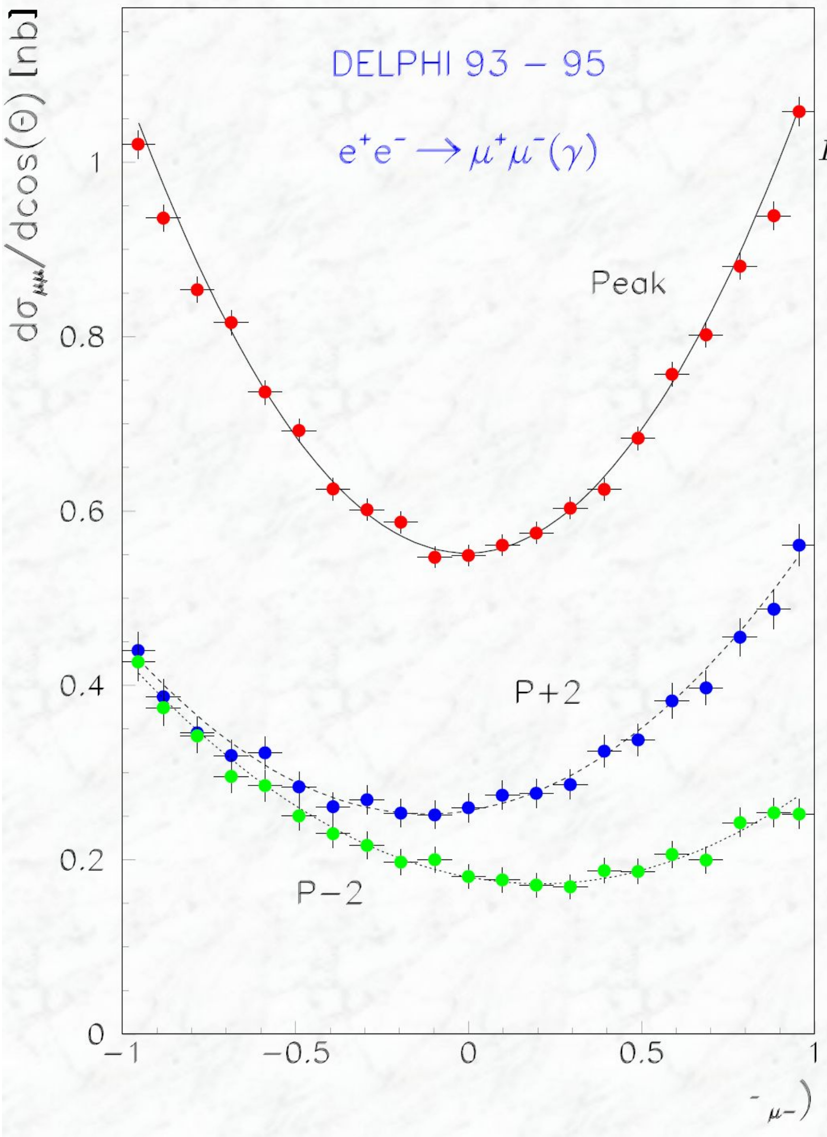
EWK tests: $\sigma(e^+e^- \rightarrow W/Z)$ production at LEP



Precision tests of the Z sector

Tests of the W sector

LEP: Cross section of $e^+e^- \rightarrow \mu^+\mu^-$



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

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

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

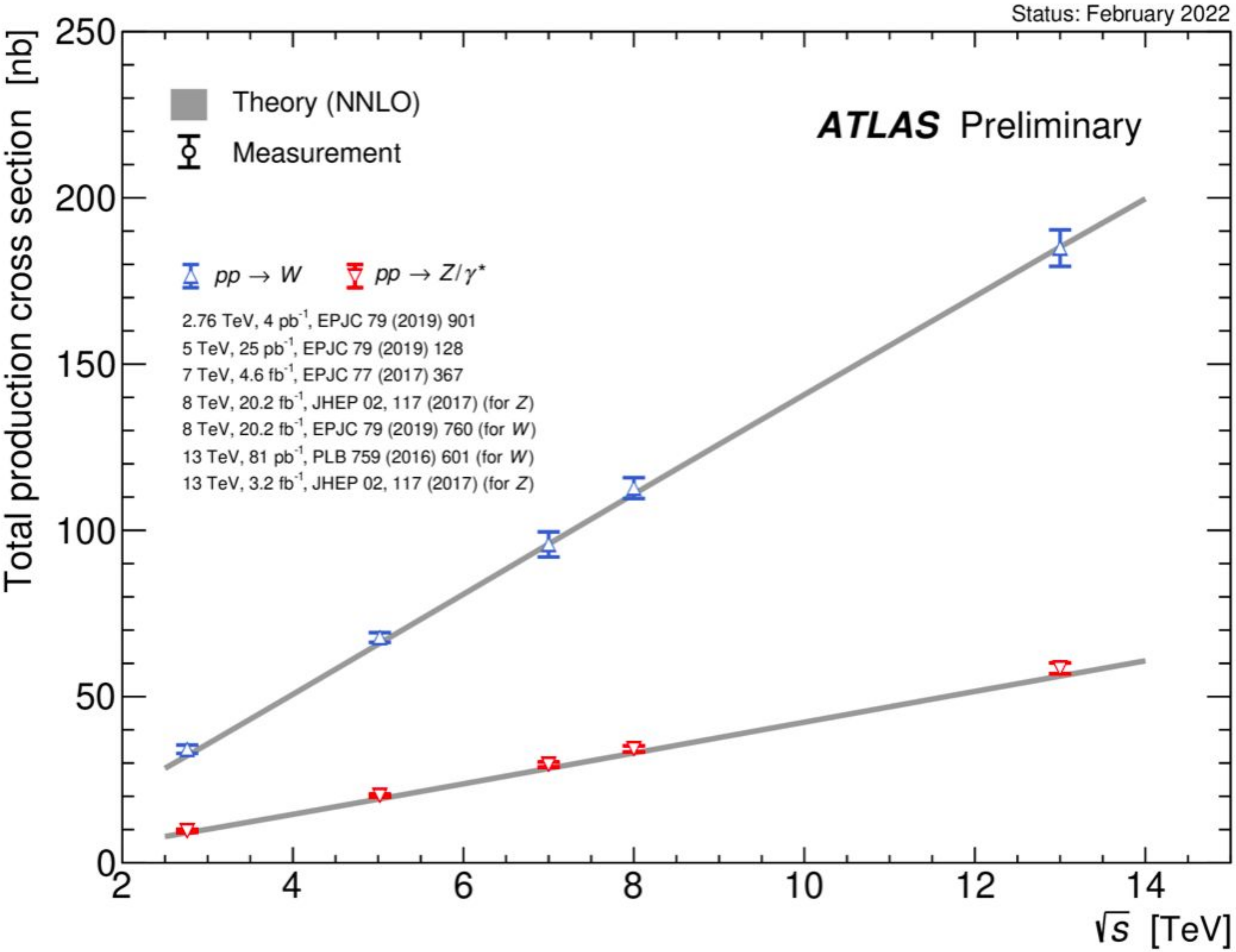
$$8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]$$

Terms ∝ cosθ in dσ/dcosθ
→ asymmetry

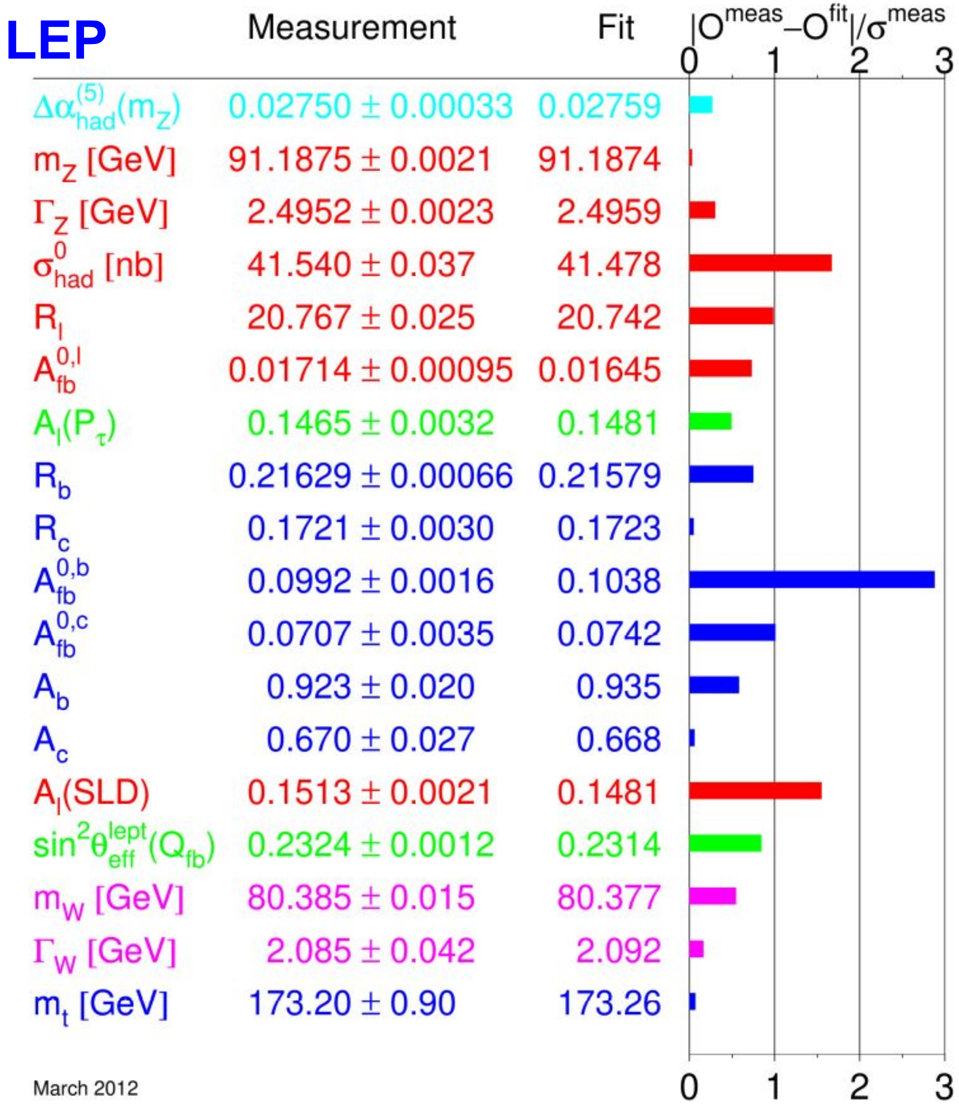
$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

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

EWK tests: $\sigma(pp \rightarrow W/Z)$ production at LHC



Consistent picture of electroweak parameters

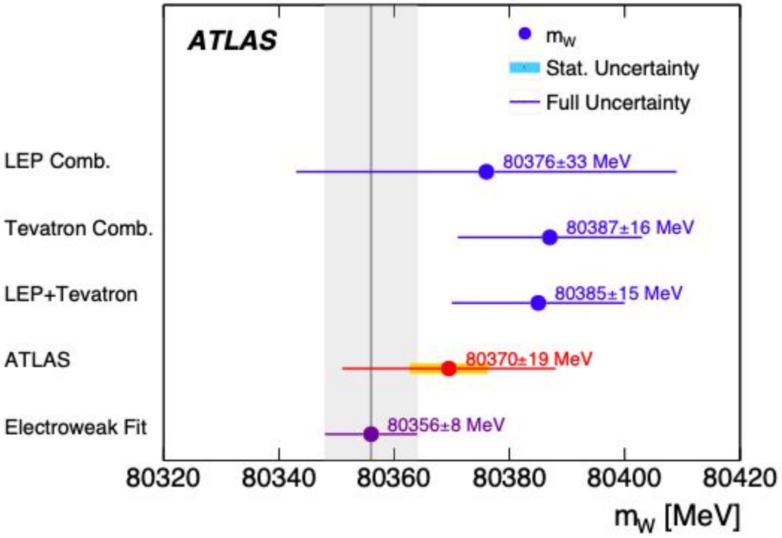


LEP

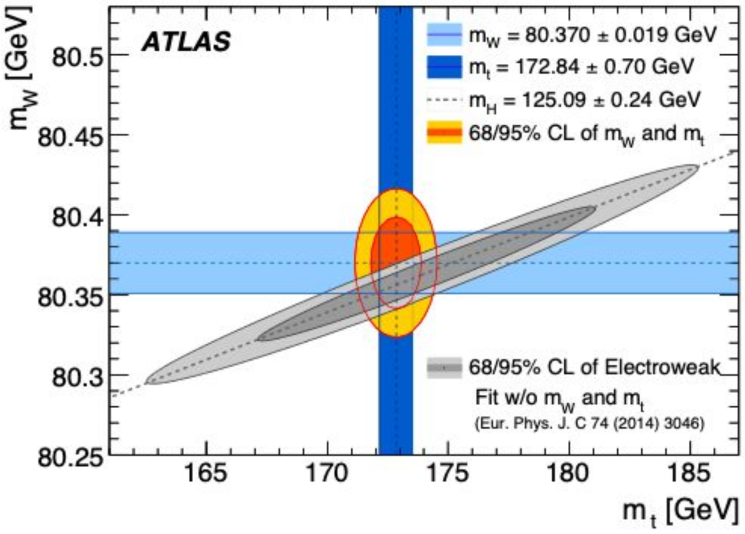
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

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 mass less 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

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

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

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→ Spontaneous symmetry breaking

Symmetry is formally kept in the Lagrangian, but in reality, the ground state of the theory doesn't preserve the symmetry.

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

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

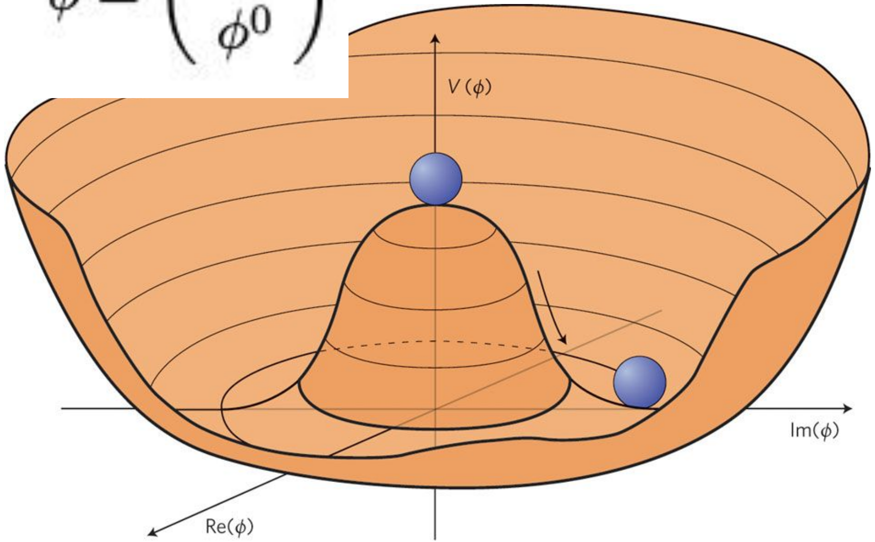
$$V(\phi) = -\mu^2\phi^{\dagger}\phi + \lambda\left(\phi^{\dagger}\phi\right)^2$$

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

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

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



Brout-Englert-Higgs mechanism → Higgs boson

- 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.

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

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

Mass terms for gauge bosons

$$\begin{aligned}
(D^\mu\phi)^\dagger (D_\mu\phi) &= \left|\left(\partial_\mu + \frac{i}{2} g\tau^k W_\mu^k + \frac{i}{2} g' B_\mu\right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}\right|^2 \\
&= \frac{v^2}{8} \left|\left(g\tau^k W_\mu^k + g' B_\mu\right) \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right|^2 \\
&= \frac{v^2}{8} \left|\begin{pmatrix} gW_\mu^1 - igW_\mu^2 \\ -gW_\mu^3 + g'B_\mu \end{pmatrix}\right|^2 \\
&= \frac{v^2}{8}\left[g^2\left((W_\mu^1)^2 + (W_\mu^2)^2\right) + (gW_\mu^3 - g'B_\mu)^2\right].
\end{aligned}$$

Mass term for fermions

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

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

Where is it ? The Standard Model's biggest triumph

Even before the direct discovery, indirect constraints on Higgs mass though connections with W and top

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

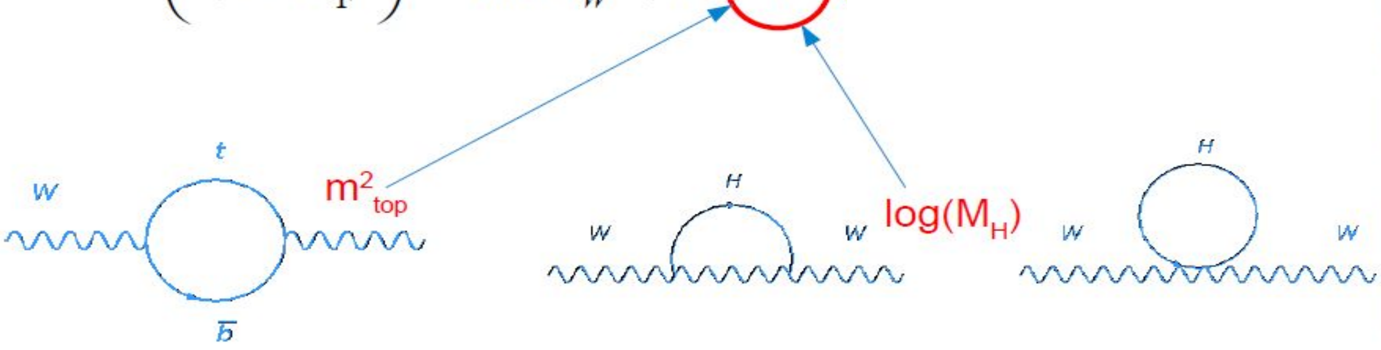
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & \sin\theta_\mathrm{W} \\ -\sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

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

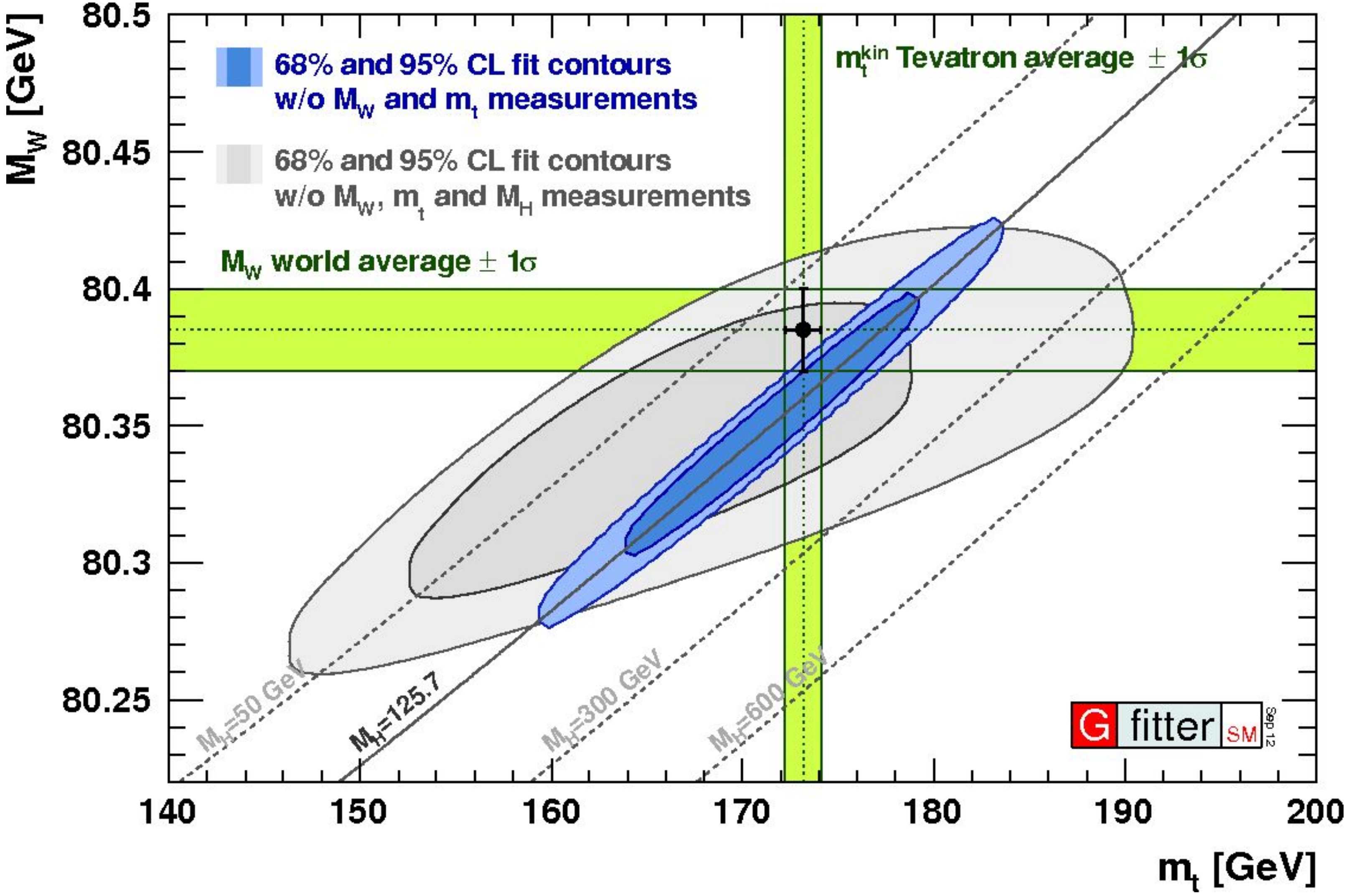
$$m_\mathrm{Z} = \frac{m_\mathrm{W}}{\cos\theta_\mathrm{W}}$$

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

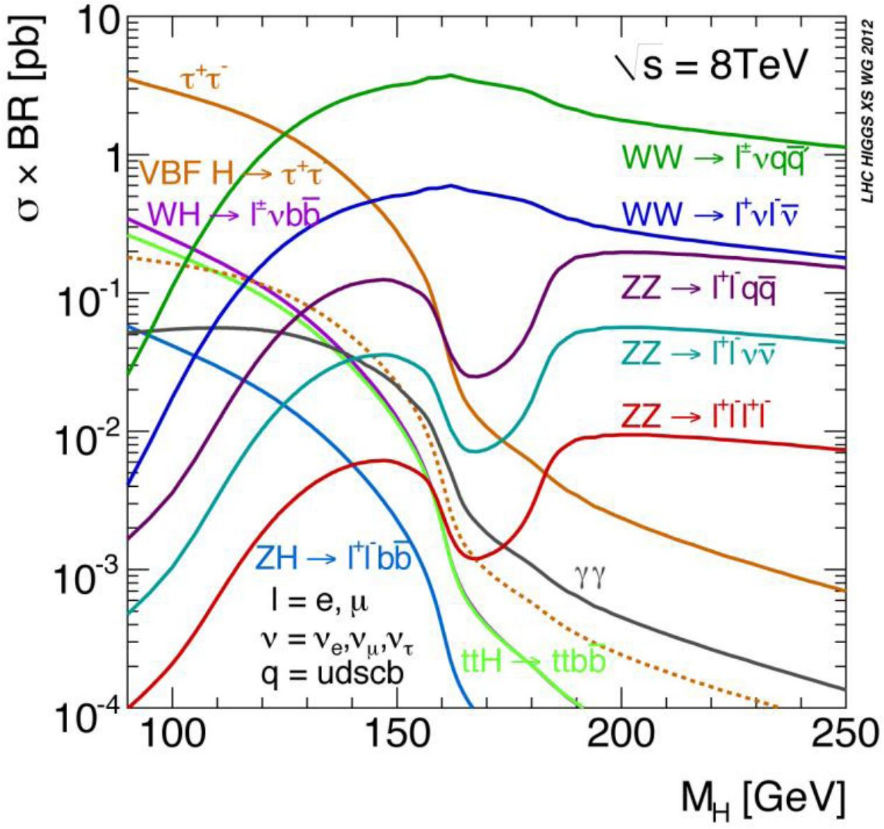
radiative corrections



LEP: Quantum corrections and the Higgs



Higgs



Low mass ($\lesssim \mathbf{140\,GeV}$)

$\boldsymbol{H \to \gamma\gamma}$

Rare decay, but distinct signal

$\boldsymbol{H \to \tau\tau}$

Enhanced in MSSM, also contributes to SM search

$\boldsymbol{H \to b\bar{b}}$

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

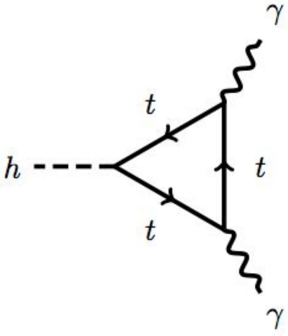
Intermediate and large m_H ($\gtrsim \mathbf{130\,GeV}$)

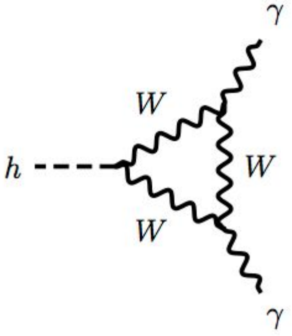
$\boldsymbol{H \to WW}$

Large signal yield

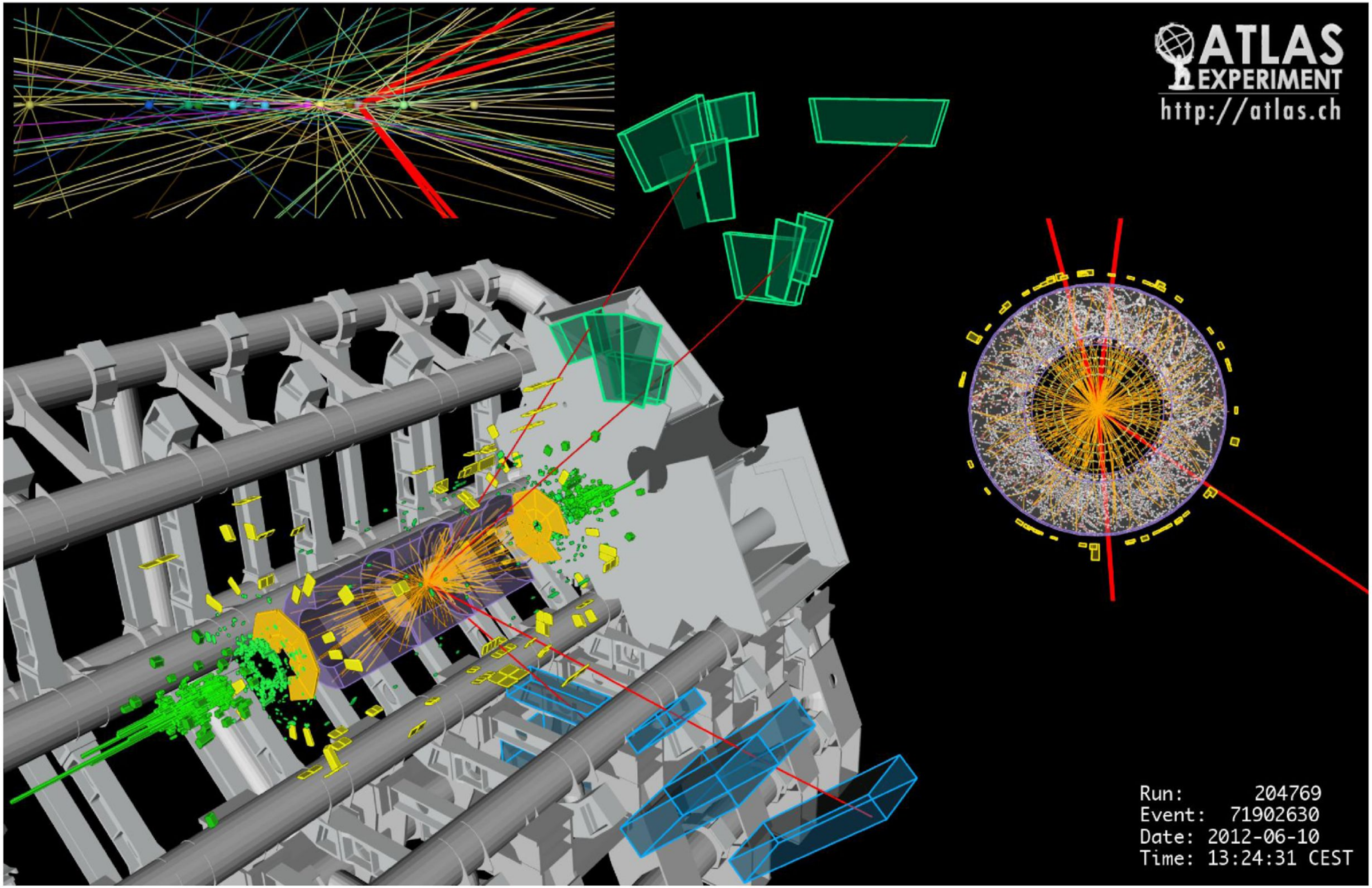
$\boldsymbol{H \to ZZ}$

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





Higgs

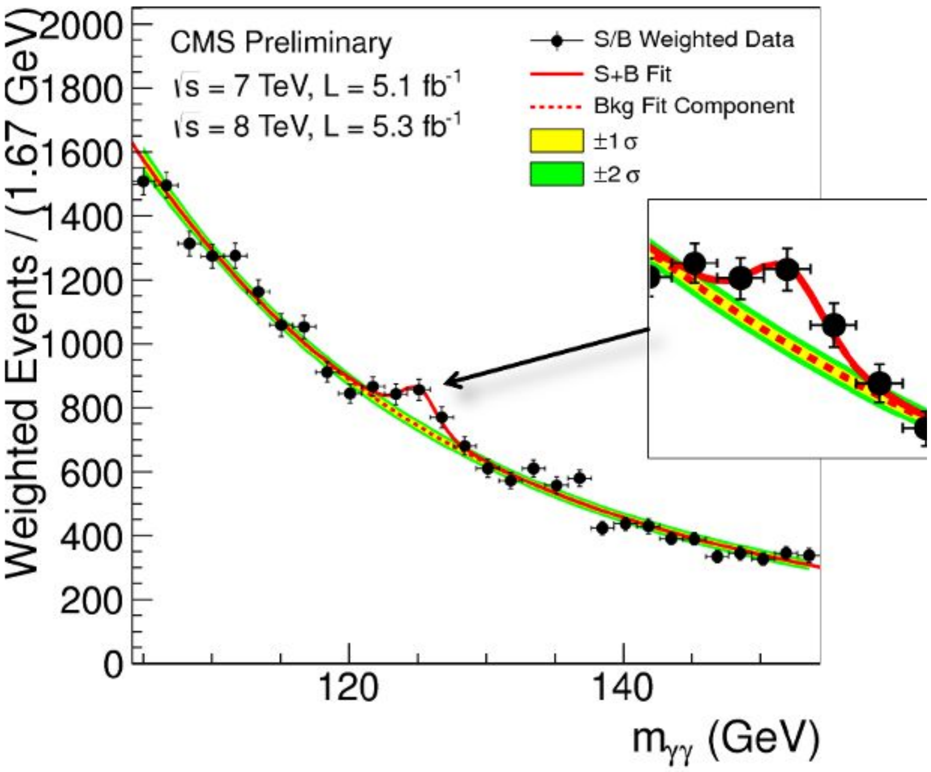


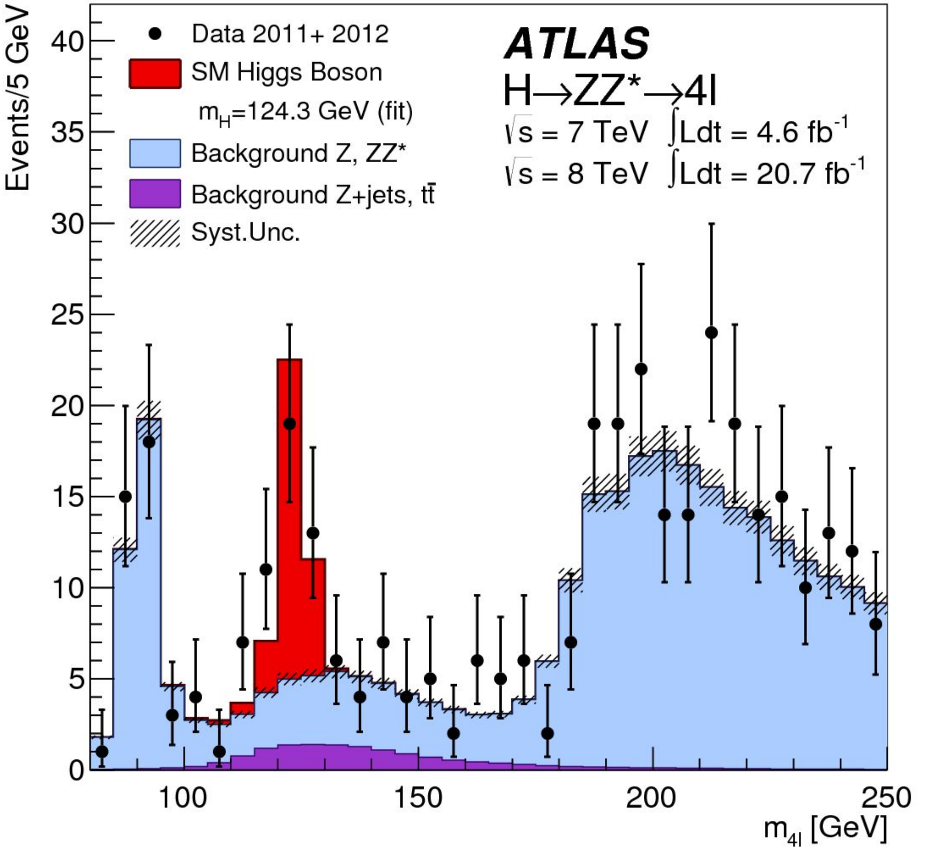
ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs

H → γγ

H → ZZ

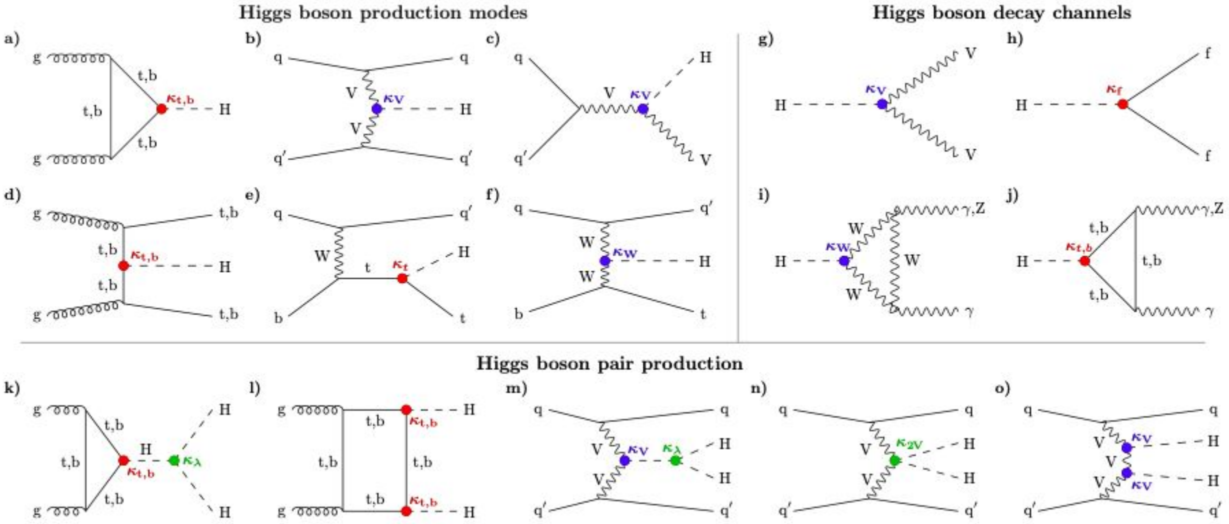


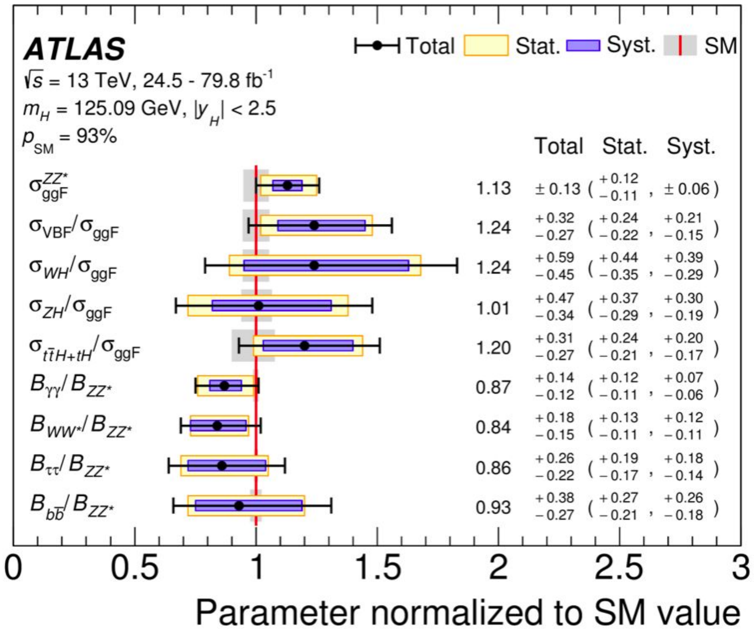


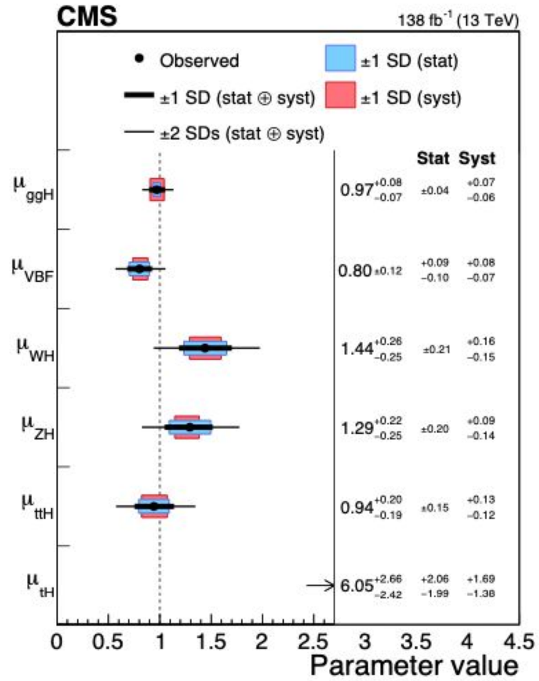
LHC is running at 13 TeV since 2015 → much bigger sample will be corrected in the next year → precision Higgs physics, possibility to discover the open ttH coupling

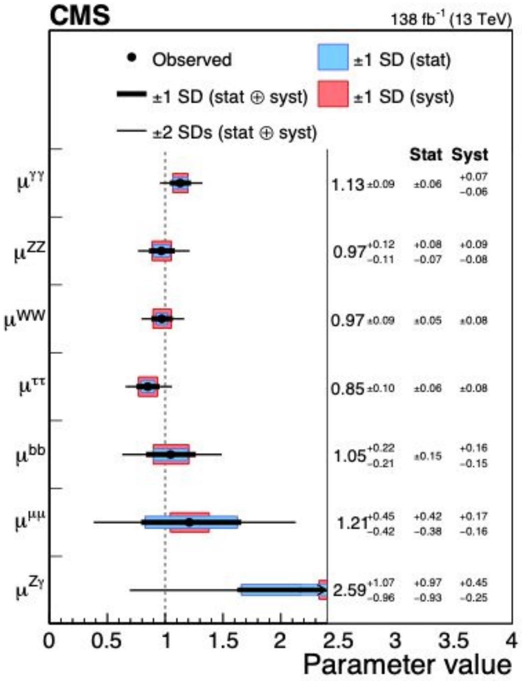
The last missing piece in the Standard Model

The last missing piece in the Standard Model









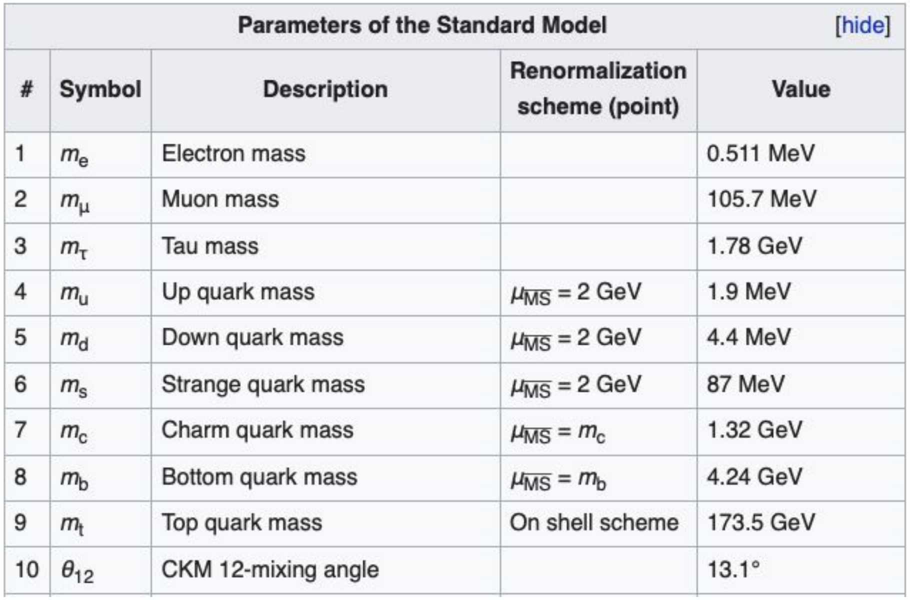
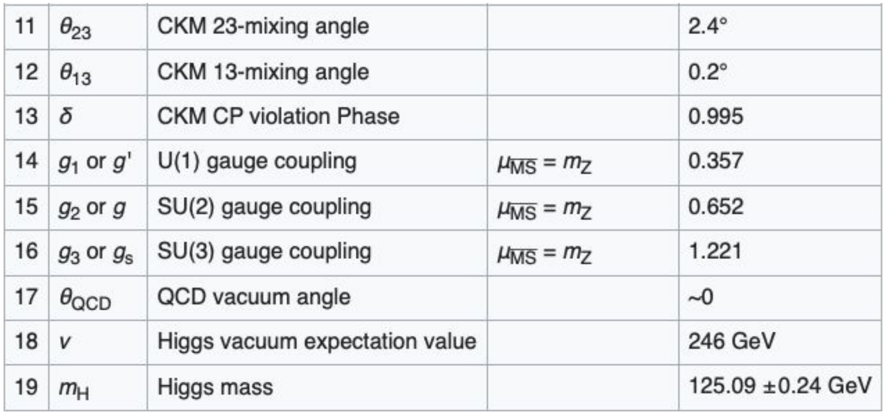
Beyond Standard Model

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

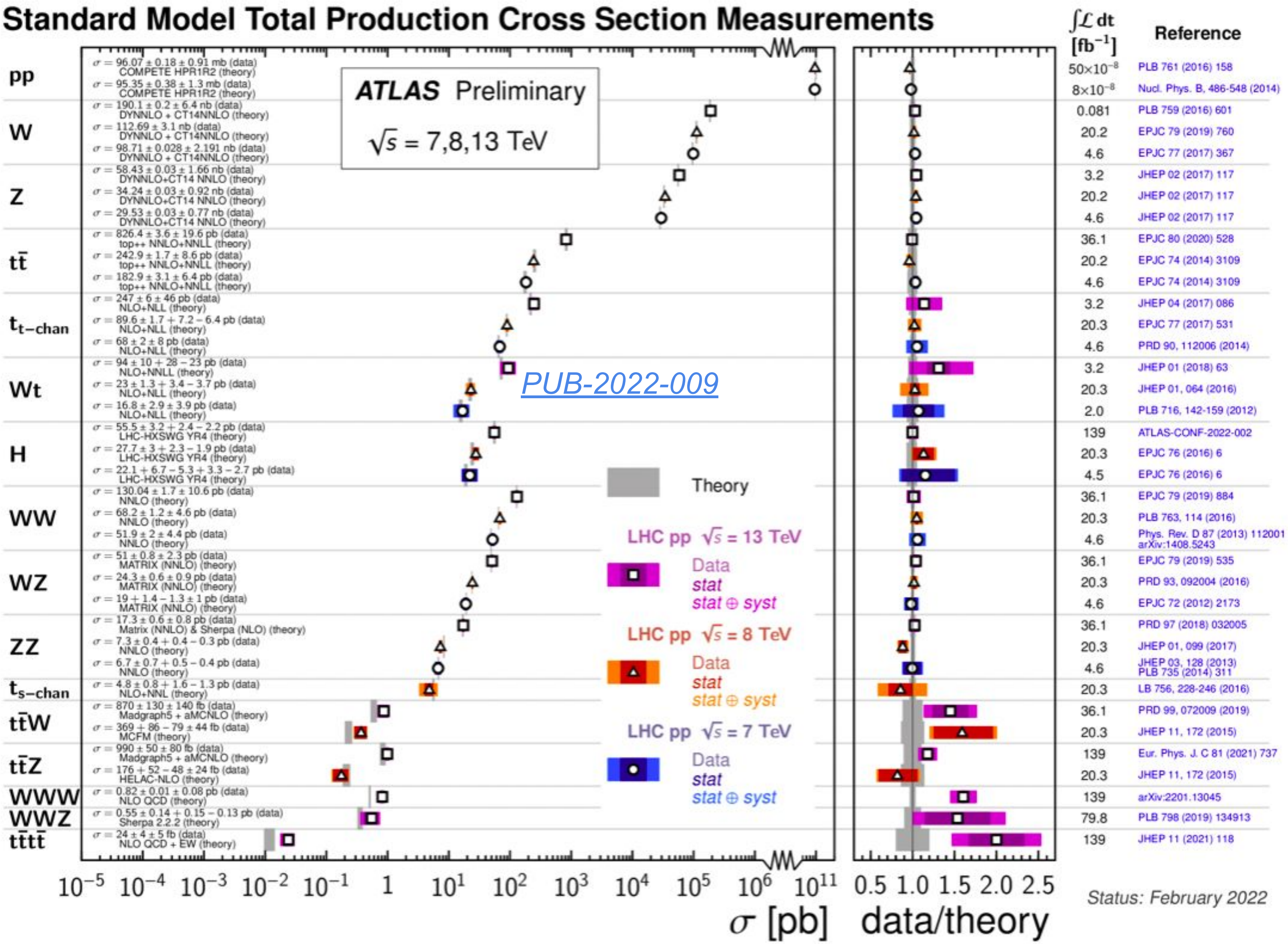



Parameters of the Standard Model [hide]

#	Symbol	Description	Renormalization scheme (point)	Value
1	m_e	Electron mass		0.511 MeV
2	m_μ	Muon mass		105.7 MeV
3	m_τ	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	θ_{12}	CKM 12-mixing angle		13.1°
11	θ_{23}	CKM 23-mixing angle		2.4°
12	θ_{13}	CKM 13-mixing angle		0.2°
13	δ	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	θ_{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”



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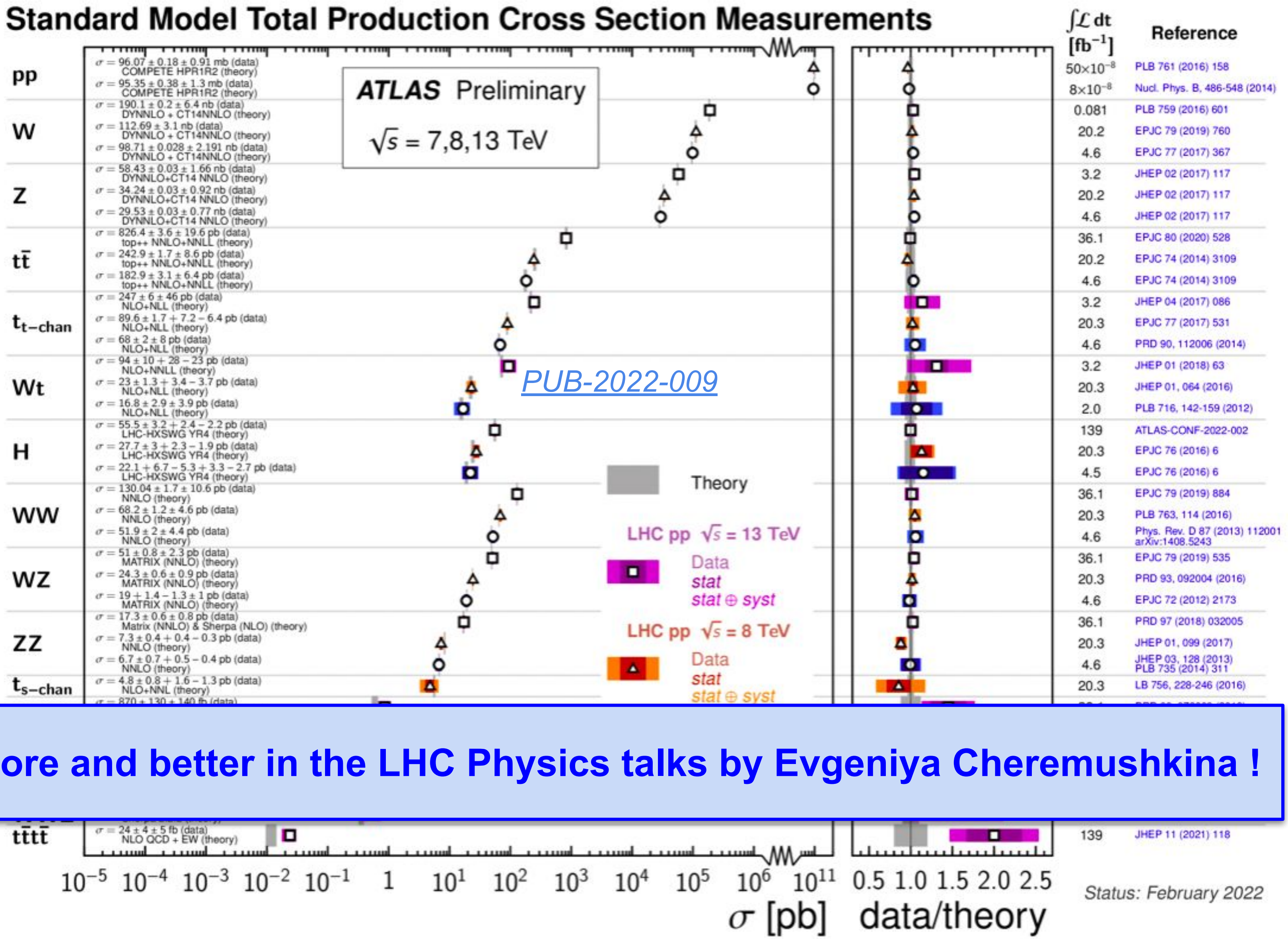
The Standard Model: Extremely predictive

Once parameters are known, everything else is “fixed”



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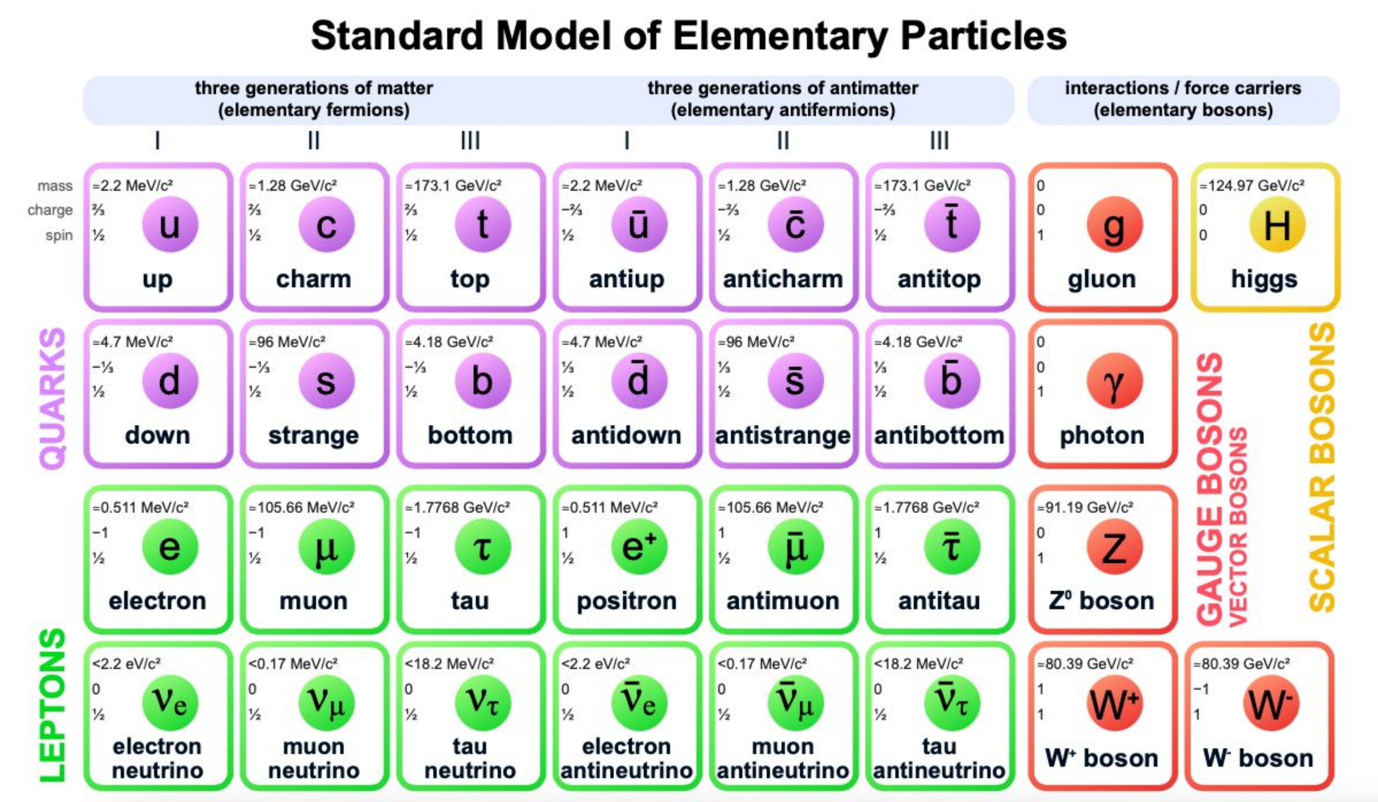
More and better in the LHC Physics talks by Evgeniya Cheremushkina !

What is missing ? Beyond Standard Model Physics



Standard Model of Elementary Particles

		three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
		I	II	III	I	II	III		
QUARKS	mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top	≈2.2 MeV/c^2 −⅔ ½ $\bar{u}$ antiup	≈1.28 GeV/c^2 −⅔ ½ $\bar{c}$ anticharm	≈173.1 GeV/c^2 −⅔ ½ $\bar{t}$ antitop	0 0 1 g gluon	≈124.97 GeV/c^2 0 0 H higgs
		≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom	≈4.7 MeV/c^2 ⅓ ½ $\bar{d}$ antidown	≈96 MeV/c^2 ⅓ ½ $\bar{s}$ antistrange	≈4.18 GeV/c^2 ⅓ ½ $\bar{b}$ antibottom	0 0 1 γ photon	
LEPTONS		≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	≈0.511 MeV/c^2 1 ½ e^+ positron	≈105.66 MeV/c^2 1 ½ $\bar{\mu}$ antimuon	≈1.7768 GeV/c^2 1 ½ $\bar{\tau}$ antitau	≈91.19 GeV/c^2 0 1 Z Z^0 boson	
		<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	<2.2 eV/c^2 0 ½ $\bar{\nu}_e$ electron antineutrino	<0.17 MeV/c^2 0 ½ $\bar{\nu}_\mu$ muon antineutrino	<18.2 MeV/c^2 0 ½ $\bar{\nu}_\tau$ tau antineutrino	≈80.39 GeV/c^2 1 1 W^+ W^+ boson	≈80.39 GeV/c^2 −1 1 W^- W^- boson

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

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

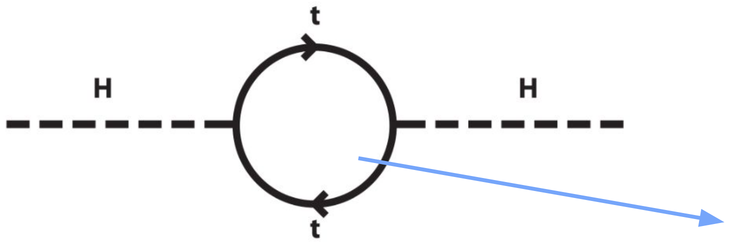
Naturalness problem (some might call it hierarchy)

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



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

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

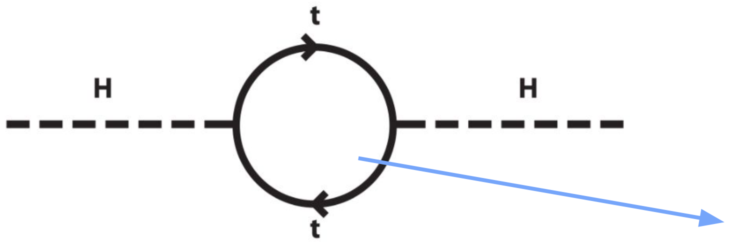
Naturalness problem (some might call it hierarchy)

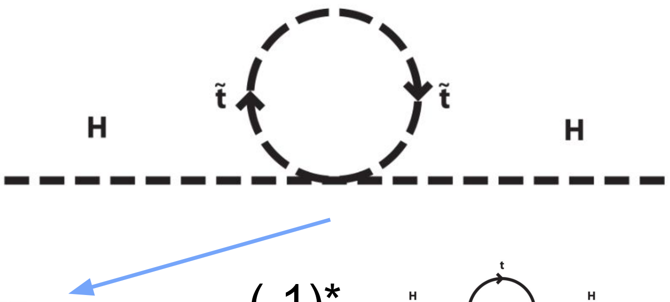
Mass corrections to the Higgs

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 !

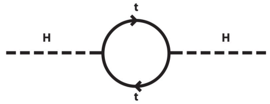
Radiative correction to Higgs mass very large, if no other new physics of mass Λ





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

(-1)*



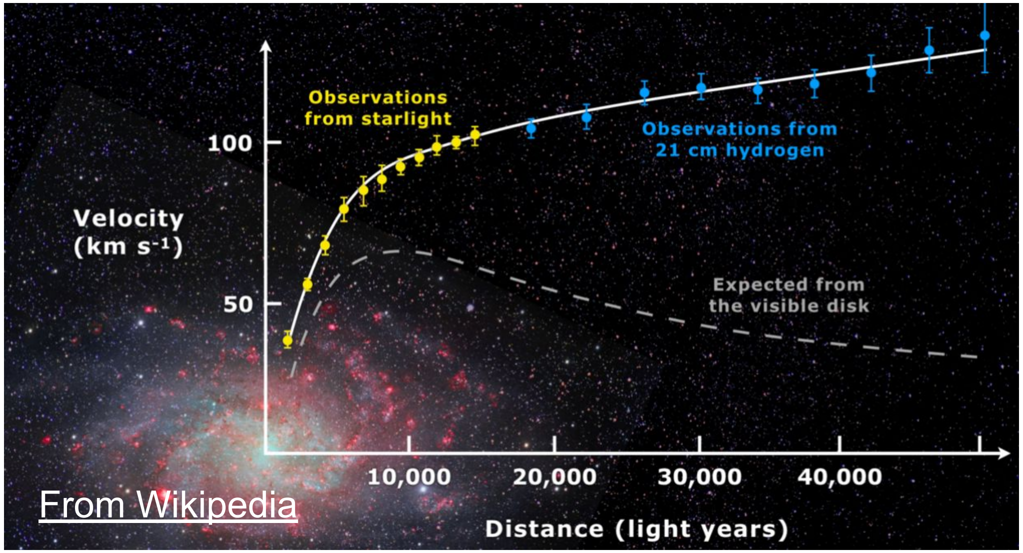
A super-partner of the top (boson) would generate same correction but with negative value → Cancellation

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

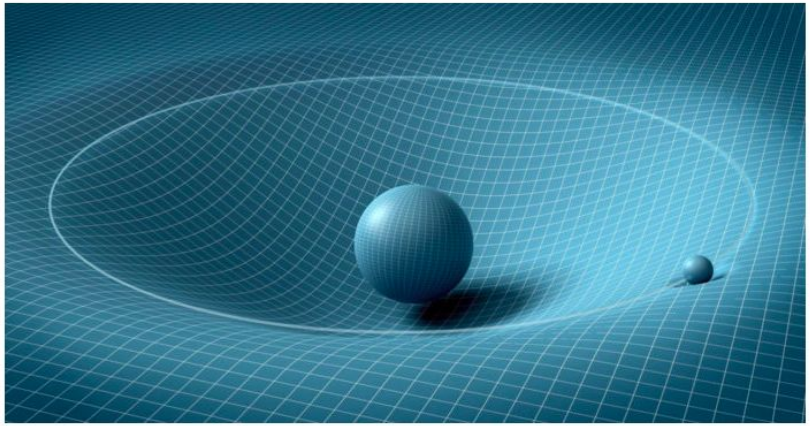
More missing pieces

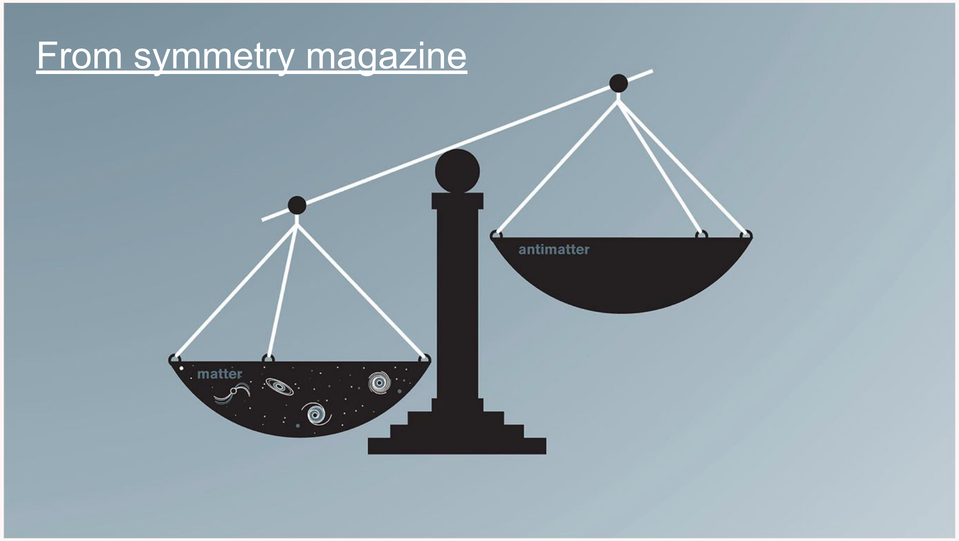
- Gravity: non-renormalizable theory
- Dark Matter: no candidate particle in SM
- We live in a matter dominated Universe. CP violation in EWK and CKM/PMNS cannot explain it. Why ?
- Strong CP problem

And many more missing pieces !



From Wikipedia



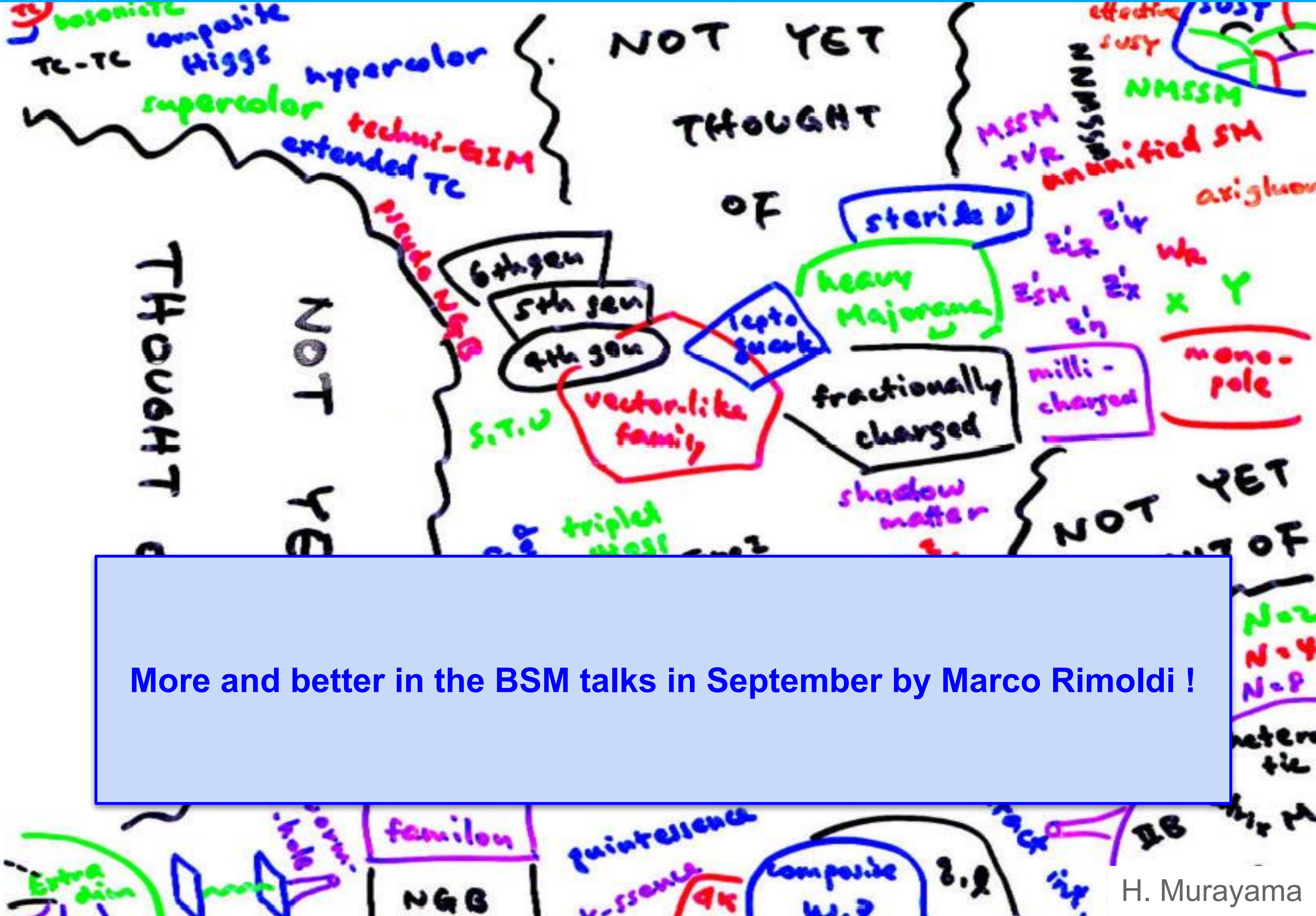


From symmetry magazine

So what else is out there?

H. Murayama

So what else is out there?

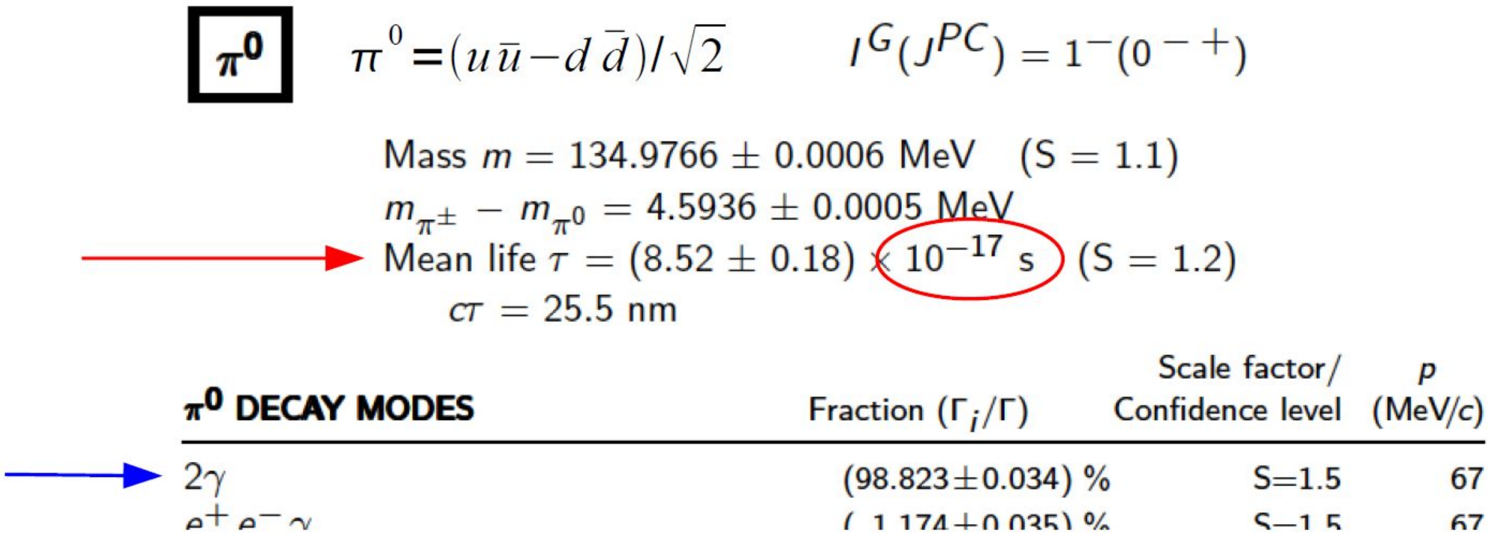


More and better in the BSM talks in September by Marco Rimoldi !

H. Murayama

Backup

Handed-ness and hadronic decays: The Pion



$\boxed{\pi^0}$ $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ $I^G(J^{PC}) = 1^-(0^{-+})$

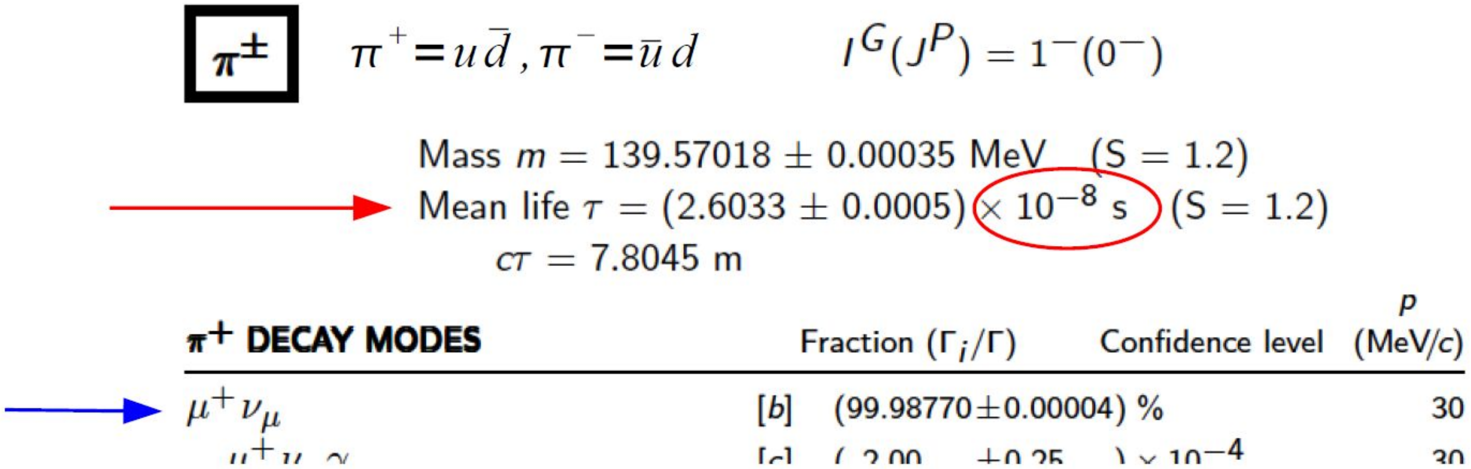
Mass $m = 134.9766 \pm 0.0006$ MeV $(S = 1.1)$

$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV

Mean life $\tau = (8.52 \pm 0.18) \times 10^{-17}$ s $(S = 1.2)$

$c\tau = 25.5$ nm

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$	(1.174 ± 0.035) %	S=1.5	67



$\boxed{\pi^\pm}$ $\pi^+ = u\bar{d}, \pi^- = \bar{u}d$ $I^G(J^P) = 1^-(0^-)$

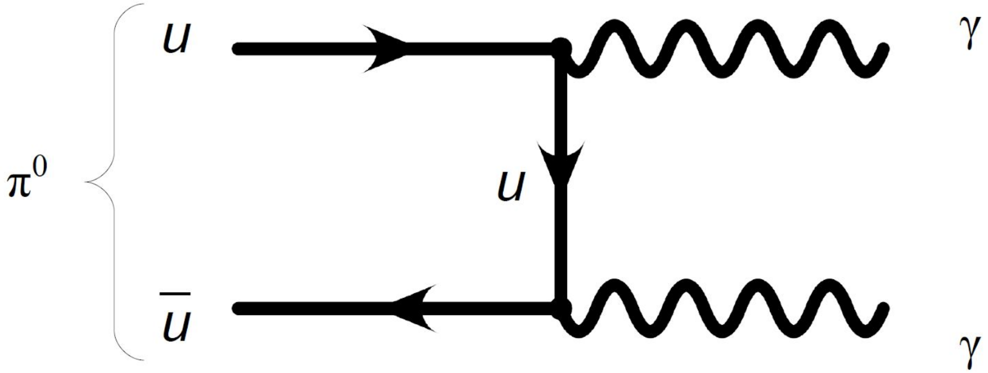
Mass $m = 139.57018 \pm 0.00035$ MeV $(S = 1.2)$

Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $(S = 1.2)$

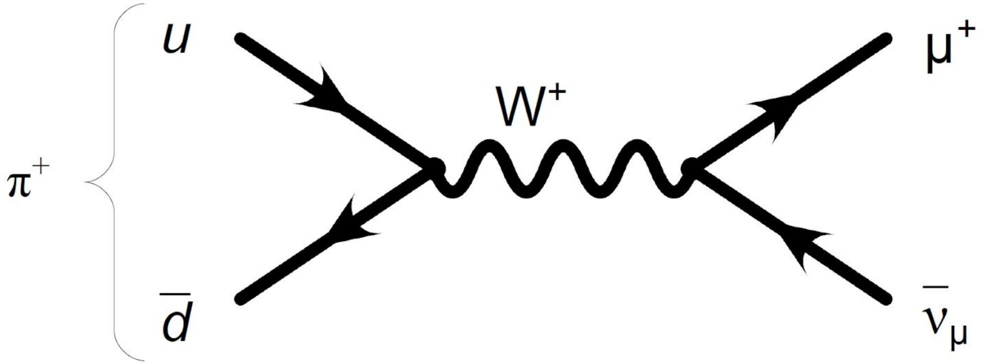
$c\tau = 7.8045$ m

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30

Handed-ness and hadronic decays: The Pion

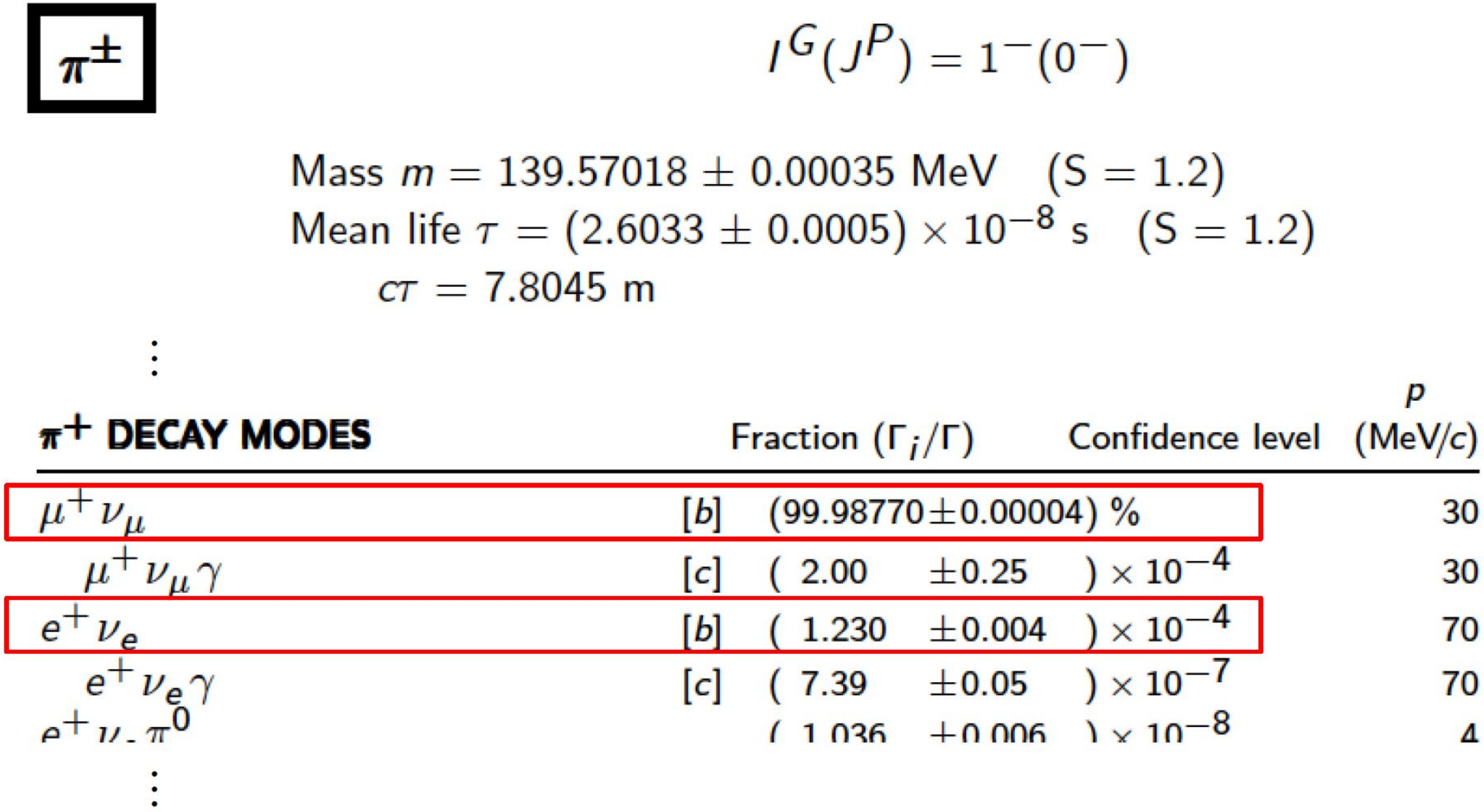


electromagnetic
interaction



weak
interaction

Handed-ness and hadronic decays: The Pion



$\pi^\pm$

$$I^G(J^P) = 1^-(0^-)$$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)

Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)

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⋮

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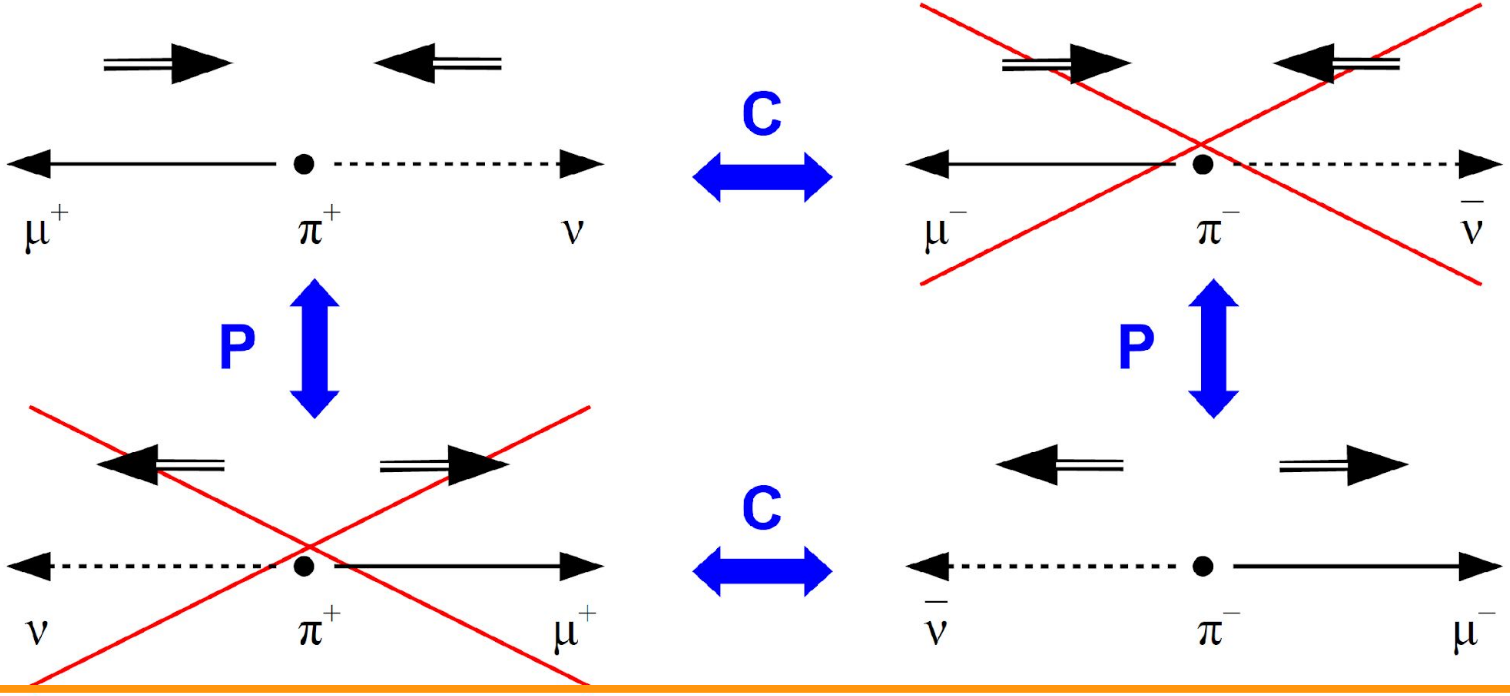
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm0.006) \times 10^{-8}$		4

⋮

why is the decay to muon and neutrino so much more likely than the decay to electron and neutrino, although the muon is much heavier than the electron?

Handed-ness and hadronic decays: The Pion

- neutrino is left-handed, π has spin 0
  ⇒ charged lepton also has to be left-handed, which is the "wrong" spin
- the heavier the charged lepton, the less suppressed is the wrong helicity, proportional to (1-v/c)



- left-handedness of neutrinos also means that weak interaction violates C, but CP can be conserved (and indeed CP violation is much smaller)

LEP: Cross section of $e^+e^- \rightarrow \mu^+\mu^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ $\qquad$ γ/Z interference $\qquad$ Z

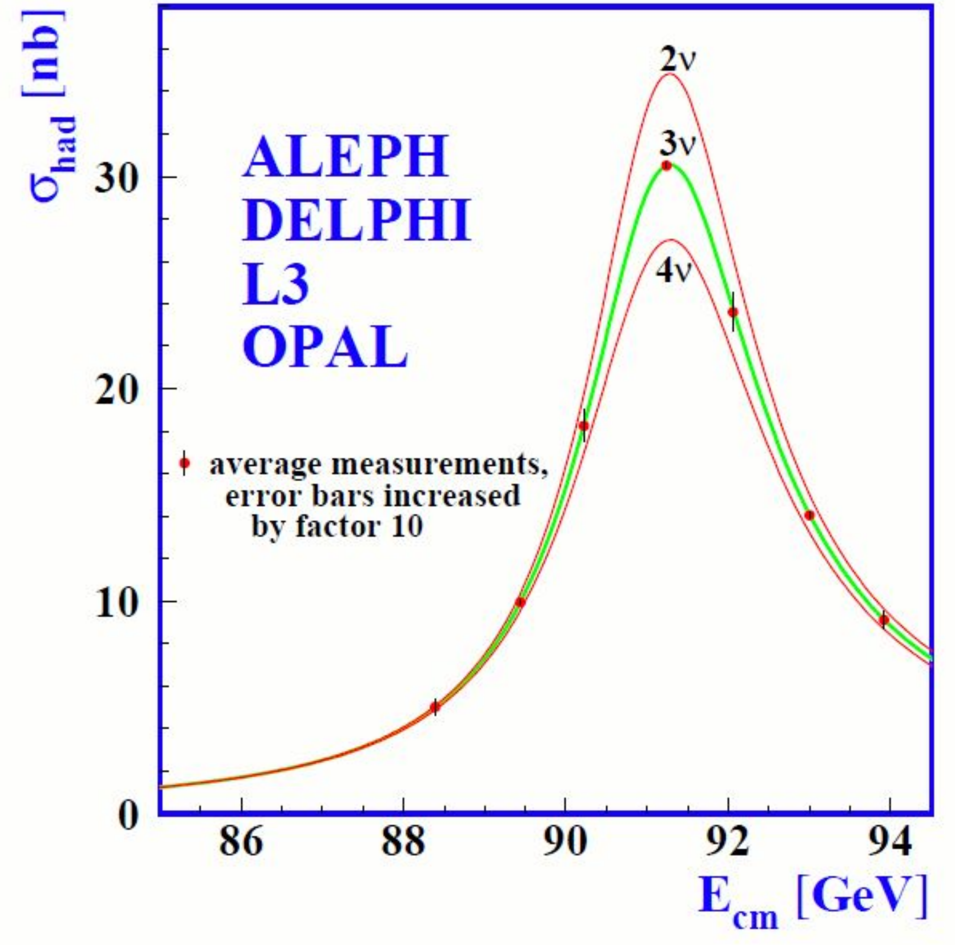
vanishes at $\sqrt{s} \approx M_Z$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta]
\end{aligned}$$

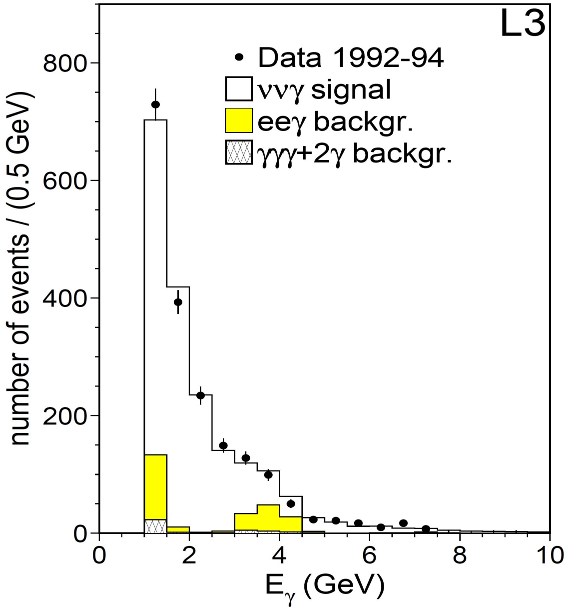
$\alpha = \alpha(m_Z)$: running electromagnetic coupling [$\alpha(m_Z) = \alpha/(1-\Delta\alpha)$ with $\Delta\alpha \approx 0.06$]

g_V, g_A = c_V, c_A: effective coupling constants (vector and axial vector)

LEP: Number of light neutrinos



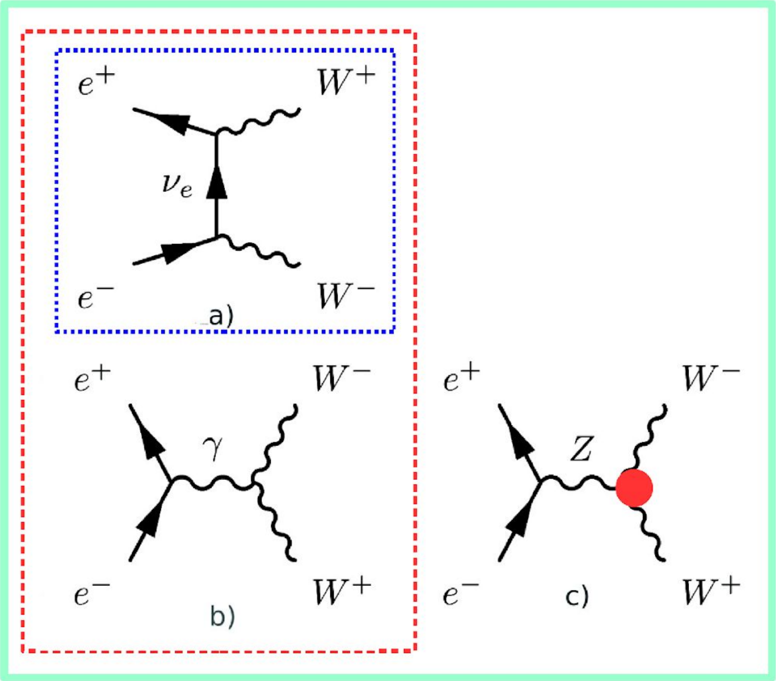
- Data selected using invisible Z decays with photon radiation



- Width of Z boson depends of the number of decay channels

LEP: WW production and the TGC vertex

- LEP also proved self-interaction of weak bosons through indirect measurement of triple gauge coupling vertex
- Interference between all three diagrams leads to “safe” energy behavior



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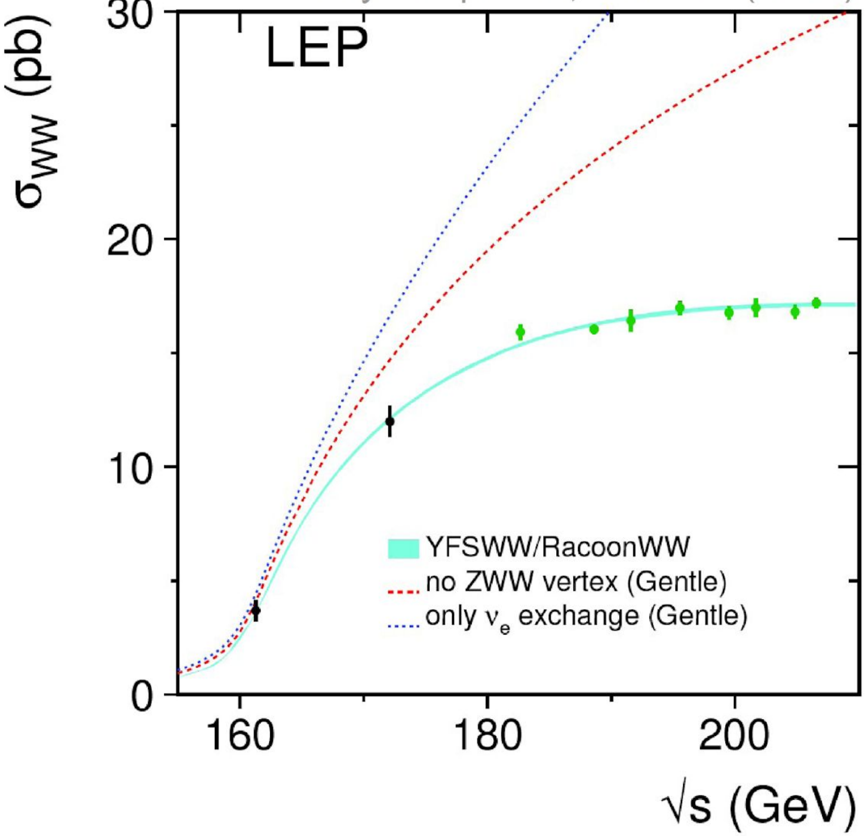

Gauge invariance and Noether's theorem

Noether's theorem (informal version):
If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

quantity	interaction			invariance
	strong	elm.	weak	
energy	yes	yes	yes	translation in time
momentum	yes	yes	yes	translation in space
angular momentum	yes	yes	yes	rotation in space

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0,$$

As in classical mechanics, equations of motions (e.g. Dirac equation) can be obtained from Lagrangian (or rather: can construct Lagrangian to further analyse equations of motions)

Gauge invariance and Noether's theorem

- Invariance of field equations describing electromagnetic and weak interaction (→ Lagrangian)
- Gauge (phase) transition possible (without changing effect of interaction) for electron (→ U(1) symmetry: U(A)U(B) = U(B)U(A):
-

$$\psi(x) \rightarrow e^{i\alpha}\psi(x),$$

$$\partial_\mu\psi \rightarrow e^{i\alpha}\partial_\mu\psi,$$

$$\bar{\psi} \rightarrow e^{-i\alpha}\bar{\psi}.$$

- Apply to field questions
- These extra phase terms cancel in the equations and we are left with:

$$\partial_\mu j^\mu = 0,$$

- Global gauge invariance → α fixed to one value everywhere

>Conservation of electrical charge!

Gauge invariance and Noether's theorem

- More general: local gauge invariance, α depends on space points

- With some tweaking to make this gauge invariance work, we arrive at the Lagrangian for the QED (Quantum electrodynamics):
-

- Note: This was done posteriori (i.e. after QED was already know)

- One take away message however for theorists: It only works, if the photon is massless (and this also explains problems with the weak boson masses)
- Works well also for QCD (and naturally requires gluon self-interaction)

- **Find a solution that allows for gauge invariance in EWK interactions including massive W and Z bosons**