The Standard Model of particle physics

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The Standard Model of particle physics

1. Symmetries in Particle Physics
    - Continuous symmetry
    - Discrete Symmetry
    - Gauge symmetry
2. Standard Model
    - EWSB
    - Higgs mechanism
    - Higgs Discovery
3. Higgs boson production
    - LEP
    - LHC
    - ILC

The Standard Model of particle physics

This lecture provide a basic introduction to the Standard Model (SM) of particle physics. While there are several reasons to believe that the Standard Model is just the low energy limit of a more fundamental theory, the SM has been successfully tested at an impressive level of accuracy and provides at present our best fundamental understanding of the phenomenology of particle physics.

The perspective I will take will not be historical, I will instead take advantage of our present understanding to find the most direct logical motivations. As the level of the audience is quite diverse, I will summarize the main theoretical preliminaries needed to make sense of what will follow.

The Standard Model of particle physics

The study of Nature involves probing deeper into the structure of matter, achieving ever-increasing spatial resolution to examine smaller objects.Throughout the history of natural sciences, several particles have been considered elementary

- Anaximenes and Democritus introduced the concept of four indivisible atoms
  (a-tom = not divisible).
- Dalton and Mendeleev developed the idea of elements/atoms.
- Rutherford identified the atomic nucleus.
- The discovery of elementary particles included the proton, neutron, electron, and neutrino.
- Between 1930 and 1960, hundreds of particles were discovered, necessitating a new understanding of elementariness, leading to the development of the quark model.
- The quark model proposed that protons and neutrons are composite particles, while the electron remains an elementary particle.

This progression culminated in the creation of the Standard Model (SM) in the late 1960s, which remains the prevailing global theory of matter, supported by extensive theoretical and experimental evidence.

The Standard Model of particle physics

Particle

- Mass
- charge
- energy

- Spin
- Flavor
- Color charge
- Other Quantum numbers

Please see:

https://pdg.lbl.gov

- Quantum mechanics
- Quantum Field theory
- Statistical mechanics
- Computationnel physics

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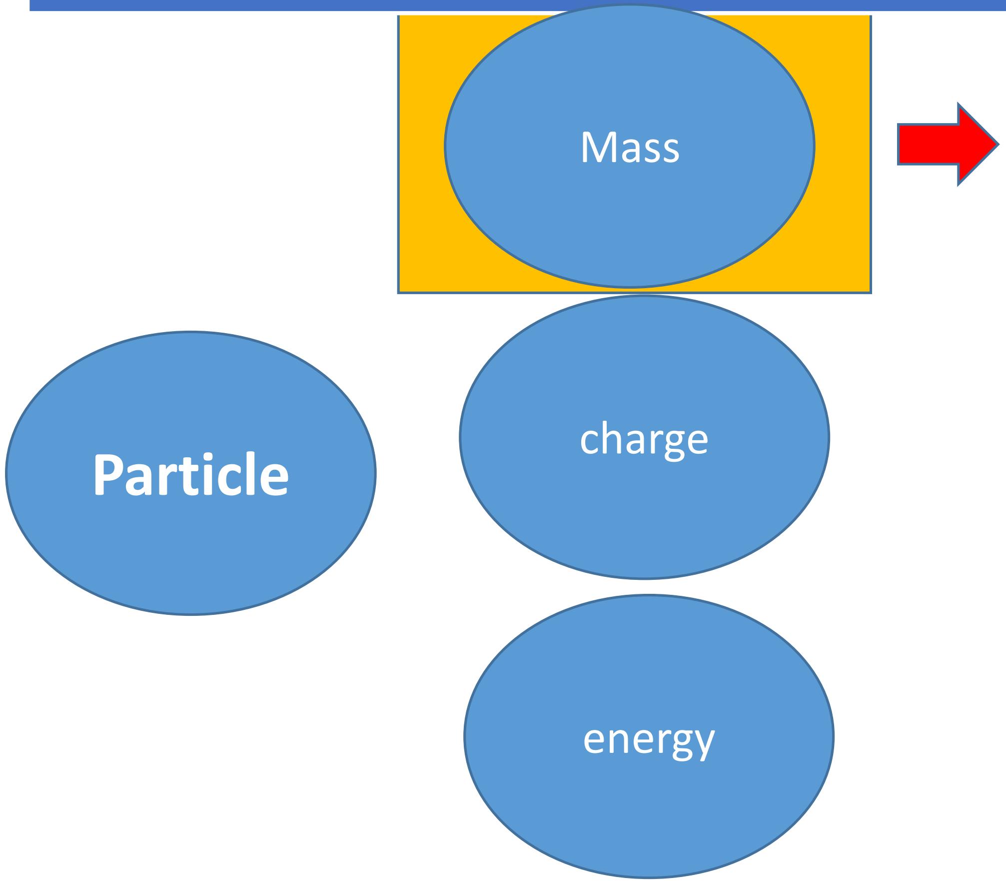

Concepts ranging from classical mechanics to quantum mechanics and general relativity:

- Gravitational Mass
- Inertial Mass
- Rest Mass
- Relativistic Mass
- Effective Mass

The Standard Model of particle physics

Particle

Mass

charge

energy

Concepts ranging from classical mechanics to quantum mechanics and general relativity:

- ❖Gravitational Mass
- ❖Inertial Mass
- ❖Rest Mass
- ❖Relativistic Mass
- ❖Effective Mass

But still not easy the understand the mechanism of generating « mass »

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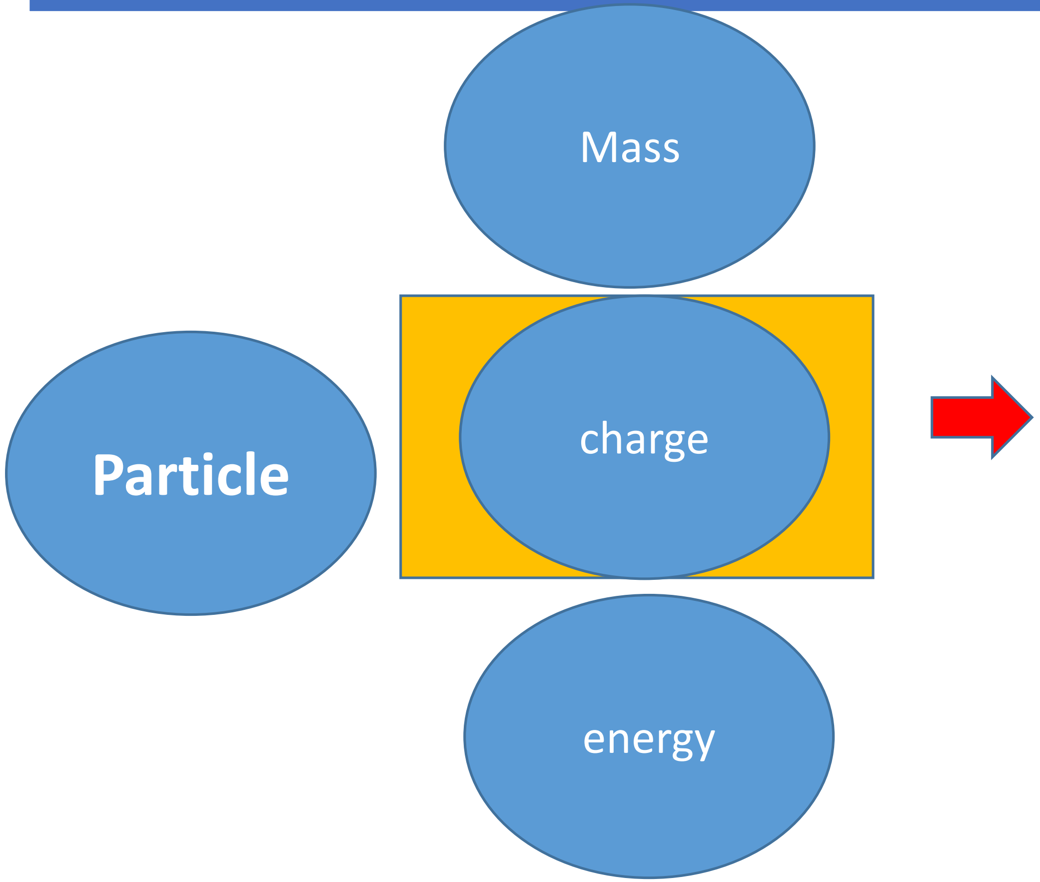

- Operator
- Quantum number
- Quantified number
- Conserved number
- Symmetry

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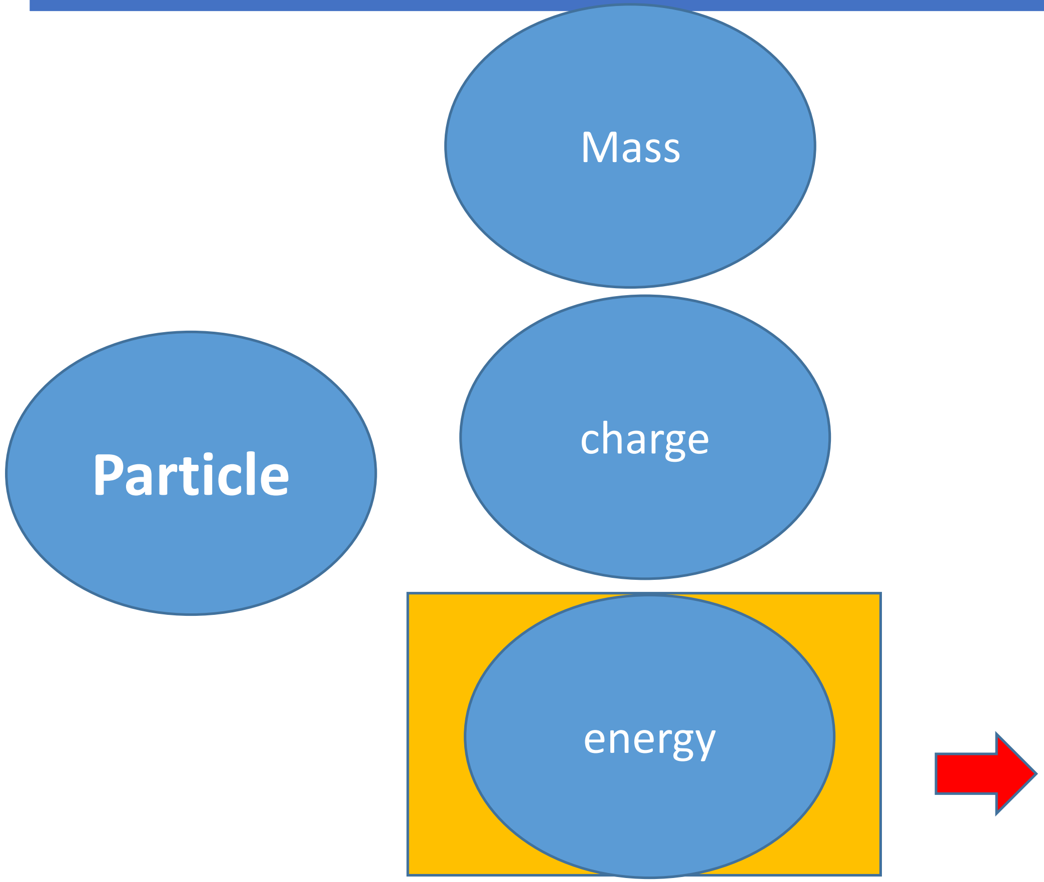

The concept of energy is central to both classical and quantum mechanics:

- ❖Continue in CM
- ❖Eigenvalues in QM
- ❖Quantified
- ❖Conserved quantity
- ❖Observable quantity

The Standard Model of particle physics

Particle

Mass

charge

energy

/Symmetry/

Spin

Flavor

Color charge

Quantum numbers

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Particle

- Mass
- charge
- energy

/Symmetry/

every continuous symmetry of a physical system corresponds to a conserved quantity

Noether's theorem

Key point

- Spin
- Flavor
- Color charge
- Quantum numbers

The Standard Model of particle physics

Continuous Symmetry → Invariance → Conservation law

Time-Translation Symmetry:

- **Symmetry**: The laws of physics do not change over time; they are the same now as they were in the past.
- **Invariance**: The Lagrangian/Hamiltonien’s system remains unchanged under shifts in time.
- **Conservation**: Energy is conserved.

$$\boxed{\text{Invariance of the equations of motion}}$$

$$\Updownarrow$$

$$\boxed{\text{Operator commutes with } H}$$

$$\Updownarrow$$

$$\boxed{\text{Symmetry of } H}$$

$$\Updownarrow$$

$$\boxed{\text{Conserved quantity}}$$

The Standard Model of particle physics

Continuous Symmetry → Invariance → Conservation law

Time-Translation Symmetry:

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Invariance of the equations of motion

$\Updownarrow$

Operator commutes with H

$\Updownarrow$

Symmetry of H

$\Updownarrow$

Conserved quantity

It is a widely accepted principle in physics that behind every fundamental law, there is often an underlying symmetry.

The Standard Model of particle physics

Continuous Symmetry → Invariance → Conservation law

In quantum mechanics, we say that there is a symmetry only if there is a transformation of which the studied system is an invariant.

Let U be a unitary transformation on the states. Indeed, we can write:

$$|i'\rangle = U|i\rangle$$

$$|f'\rangle = U|f\rangle.$$

The transition from the initial state to the final state requires the matrix S such that:

$$\langle f|S|i\rangle = \langle f'|S|i'\rangle = \langle f|U^{+}SU|i\rangle$$

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$$\Rightarrow S = U^\dagger S U \Rightarrow US = UU^\dagger S U$$

Given that U is a unitary transformation, $UU^\dagger = I$, we have:

$$\Rightarrow US - SU = 0 \Rightarrow [S, U] = 0$$

and since S is related to the Hamiltonian H, U must also commute with H so that the system is invariant.

$$\Rightarrow [H, U] = 0.$$

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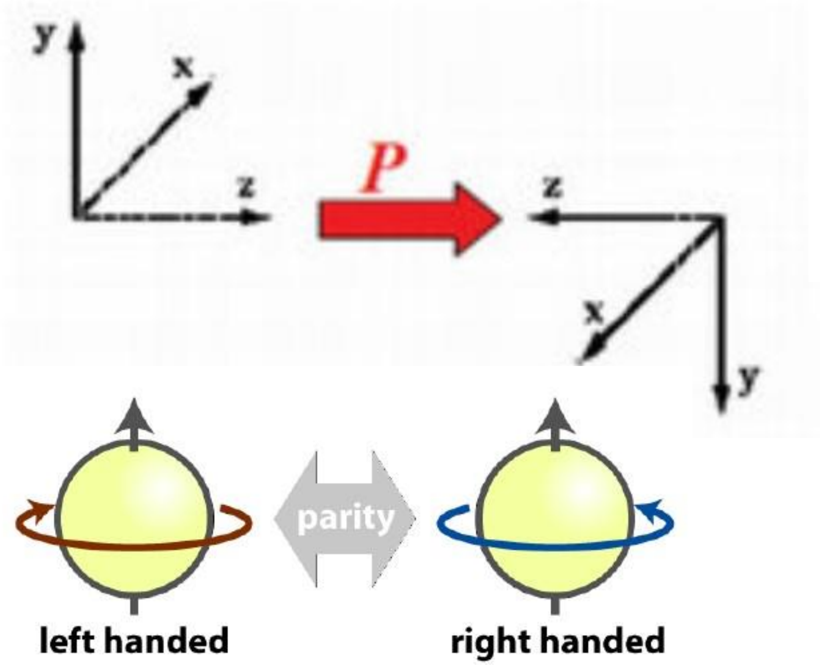
Discrete symmetry

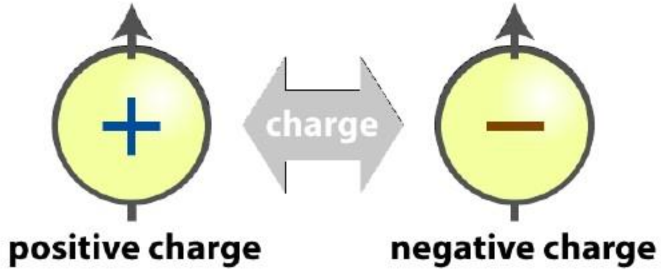
Parity (P)

Parity symmetry involves flipping the spatial coordinates (x,y,z)→(−x,−y,−z)



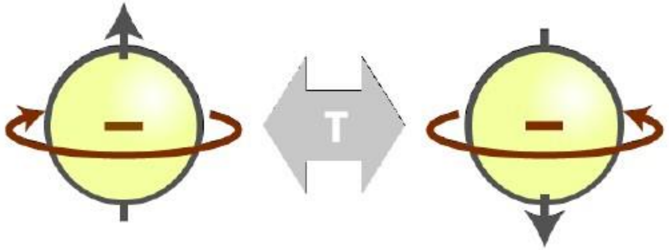
Charge Conjugation (C)

Charge conjugation transforms particles into their antiparticles.



Time Reversal (T)

Time reversal symmetry involves reversing the direction of time t→−t.



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Parity (P)

It is a transformation that corresponds to a reflection in the space $x \longrightarrow x' = -x$. The action of the parity operator $\mathcal{P}$ on a wave function $\psi(t, \vec{x})$ is defined by:

$$\psi(t, \vec{x}) \longrightarrow \psi'(t, \vec{x}) = \mathcal{P}\psi(t, \vec{x}) = \psi(t, -\vec{x}).$$

It is a discrete transformation.

For the eigenstates and eigenvalues of $\mathcal{P}$, we have:

$$\mathcal{P}\psi_p(t, \vec{x}) = \eta_p \psi_p(t, \vec{x}).$$

After two reflections the system returns to its initial state

$$\mathcal{P}^2\psi_p(t, \vec{x}) = \psi_p(t, \vec{x}) = \eta_p^2 \psi_p(t, \vec{x})$$

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Parity (P)

$$\Rightarrow \eta_p^2 = 1 \Rightarrow \begin{cases} \eta_p = +1 & \text{pour} \quad \psi(t,\vec{x}) \quad \text{even} \\ \eta_p = -1 & \text{pour} \quad \psi(t,\vec{x}) \quad \text{odd} \end{cases} . \tag{2.31}$$

- **Eigenvalue +1**: If $\psi(\mathbf{r})$ is an eigenfunction of the parity operator with eigenvalue +1, then $\psi(\mathbf{r}) = \psi(-\mathbf{r})$. Such a function is called **even** under parity.
- **Eigenvalue -1**: If $\psi(\mathbf{r})$ is an eigenfunction of the parity operator with eigenvalue -1, then $\psi(\mathbf{r}) = -\psi(-\mathbf{r})$. Such a function is called **odd** under parity.

A system that conserves parity is described by a Hamiltonian H which commutes with the operator $\mathcal{P}$, $\quad [\mathcal{P}, H] = 0$.

The parity is a conserved quantity in the electromagnetic and strong interactions but not in the weak interactions:

$$[\mathcal{P}, H_{\text{em}}] = 0\,;\ [\mathcal{P}, H_{\text{strong}}] = 0\,;\ [\mathcal{P}, H_{\text{weak}}] \neq 0$$

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Parity (P)

The orbital angular momentum l of the state determines the parity

$$\boxed{\mathcal{P}Y_{lm}(\theta,\varphi) = \eta_p Y_{lm}(\theta,\varphi)}$$

$$\eta_p = \begin{cases} +1 & \text{for the states} \quad l = 0, 2, 4\,(s, d, g) \\ -1 & \text{for the states} \quad l = 1, 3, 5\,(p, f, h...) \end{cases}$$

$$J^n \quad \text{where} \quad n = \pm 1$$

and J is the spin of the particle.

Spin 0:

$o^{\dagger}$: Scalar particle:

o^{-} : Pseudo-scalar particle:

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Spin 1:

1^+ : Pseudo-vector particle.

1^- : Vector particle:

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Parity (P)

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By convention, one chooses

$$\eta_p(\text{fermion}) = +1$$

$$\eta_p(\text{anti-fermion}) = -1$$

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Parity (P)

The orbital angular momentum l of the state determines the parity

$$\boxed{\mathcal{P}Y_{lm}(\theta,\varphi) = \eta_p Y_{lm}(\theta,\varphi)}$$

$$\eta_p = \begin{cases} +1 & \text{for the states} \quad l = 0, 2, 4\,(s, d, g) \\ -1 & \text{for the states} \quad l = 1, 3, 5\,(p, f, h...) \end{cases}$$

The photon, as a particle associated with the electromagnetic field, has a parity of −1.

$$\hat{P}|\mathbf{k},\epsilon\rangle = -|\mathbf{k},\epsilon\rangle \quad \mathbf{B}(\mathbf{r}) \to -\mathbf{B}(-\mathbf{r}) \quad \mathbf{E}(\mathbf{r}) \to -\mathbf{E}(-\mathbf{r})$$

This shows that the photon has an intrinsic parity of −1.

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Parity (P)

$$|i\rangle = |a\rangle|b\rangle...|n\rangle. \qquad \eta_p^i = \eta_p^a.\eta_p^b.\eta_p^n,$$

$$|f\rangle = |p\rangle.|q\rangle...|z\rangle \qquad \eta_p^f = \eta_p^p.\eta_p^q.\eta_p^z.$$

The conservation law of parity requires $\boxed{\eta_p^i = \eta_p^f}$.

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Parity (P)

$$|i\rangle = |a\rangle|b\rangle...|n\rangle.$$

$$\eta_p^i = \eta_p^a.\eta_p^b.\eta_p^n,$$

$$|f\rangle = |p\rangle.|q\rangle...|z\rangle$$

$$\eta_p^f = \eta_p^p.\eta_p^q.\eta_p^z.$$

The conservation law of parity requires $\boxed{\eta_p^i = \eta_p^f}$.

$$\eta_p^{\text{totale}} = (\prod_a \eta_p^a) \times \eta_p^{\text{orbitale}}.$$

orbital angular momentum

$$\eta_p^{\text{orbitale}} = (-1)^{l_{1,2}}$$

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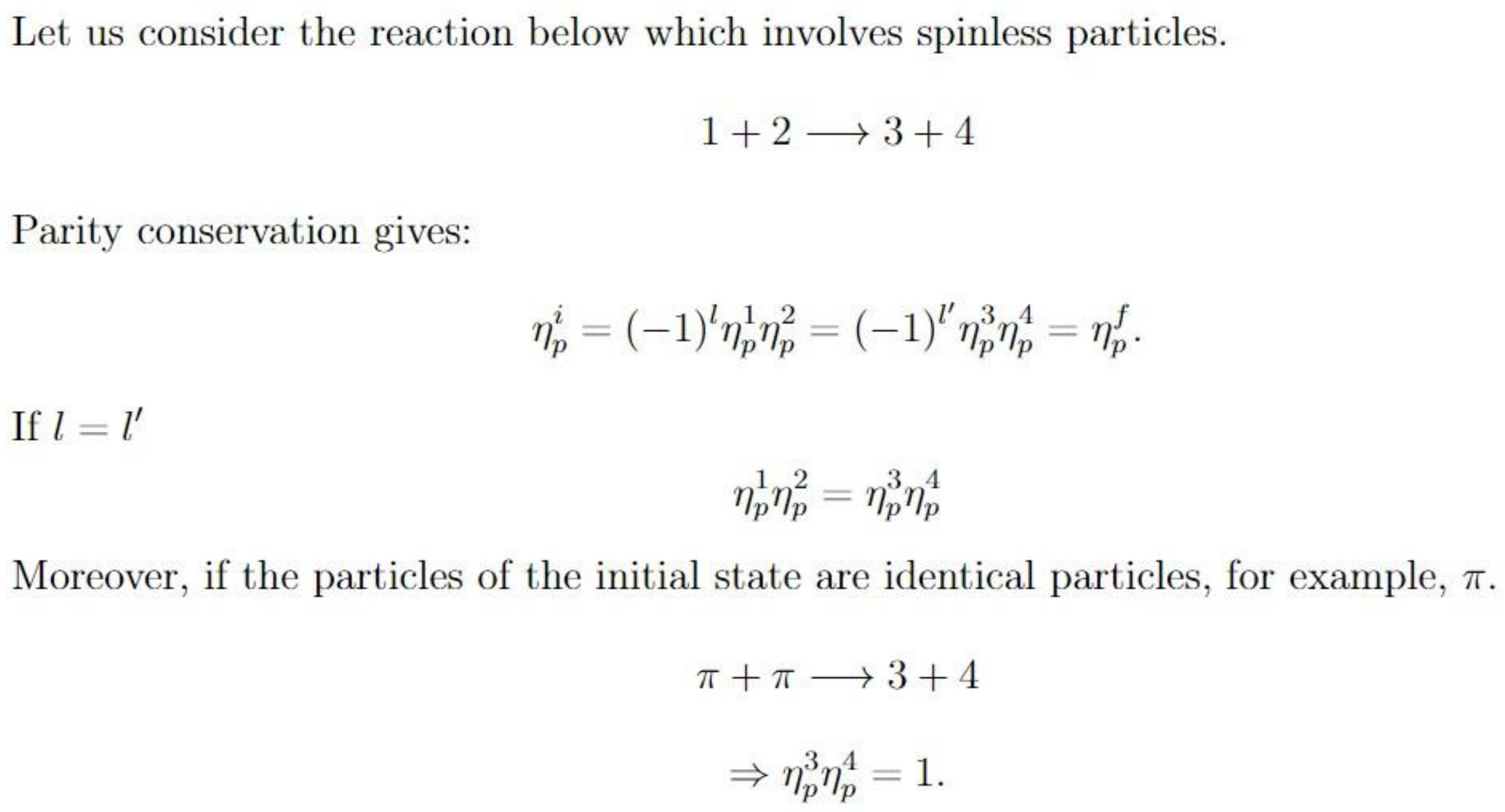
Example 1;



Let us consider the reaction below which involves spinless particles.

$$1 + 2 \longrightarrow 3 + 4$$

Parity conservation gives:

$$\eta_p^i = (-1)^l \eta_p^1 \eta_p^2 = (-1)^{l'} \eta_p^3 \eta_p^4 = \eta_p^f.$$

If $l = l'$

$$\eta_p^1 \eta_p^2 = \eta_p^3 \eta_p^4$$

Moreover, if the particles of the initial state are identical particles, for example, π.

$$\pi + \pi \longrightarrow 3 + 4$$

$$\Rightarrow \eta_p^3 \eta_p^4 = 1.$$

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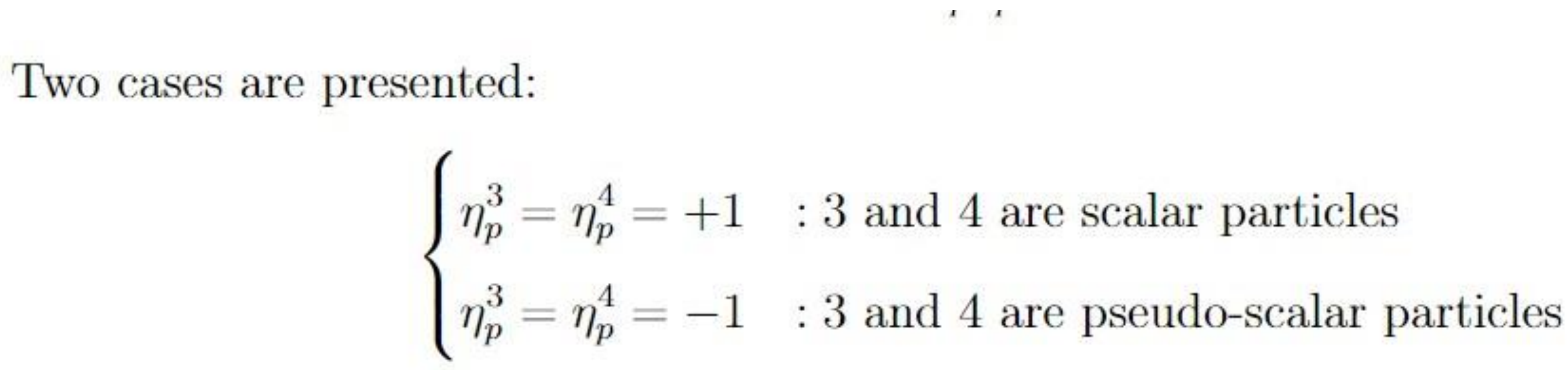
Example 1;



Two cases are presented:

$$\begin{cases} \eta_p^3 = \eta_p^4 = +1 & : \text{3 and 4 are scalar particles} \\ \eta_p^3 = \eta_p^4 = -1 & : \text{3 and 4 are pseudo-scalar particles} \end{cases}$$

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Charge conjugation

$$\hat{C}|\psi\rangle = \eta_c|\psi\rangle = |\bar{\psi}\rangle. \qquad \eta_c = \pm 1.$$

$$\hat{C}|f\bar{f}\rangle = \eta_c^{f\bar{f}}|f\bar{f}\rangle = (-1)^{l+s}|f\bar{f}\rangle \quad \Rightarrow \quad \eta_c^{f\bar{f}} = (-1)^{l+s}.$$

The charge conjugation is a quantum number that is conserved in the electromagnetic and strong interactions but not in the weak interactions.

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Charge conjugation

$$\hat{C}|\psi\rangle = \eta_c|\psi\rangle = |\bar{\psi}\rangle. \qquad \eta_c = \pm 1.$$

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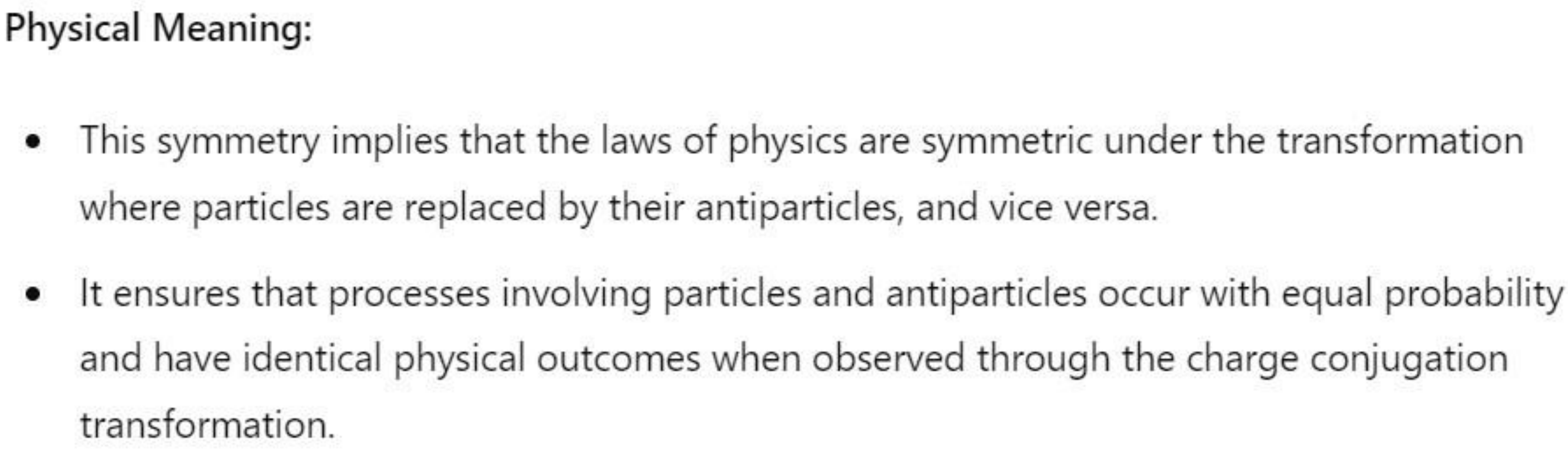

Physical Meaning:

- This symmetry implies that the laws of physics are symmetric under the transformation where particles are replaced by their antiparticles, and vice versa.
- It ensures that processes involving particles and antiparticles occur with equal probability and have identical physical outcomes when observed through the charge conjugation transformation.

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Time reversal T :

It corresponds to looking at a system while events are running backwards in time

$$t \longrightarrow t' = -t$$
$$\vec{x} \longrightarrow \vec{x'} = \vec{x}.$$

The effect of T on the wave functions is as follows:

$$\psi(t,\vec{x}) \longrightarrow \psi'(t,\vec{x}) = T(\psi(t,\vec{x})) = \psi(-t,\vec{x}).$$

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Time reversal T :

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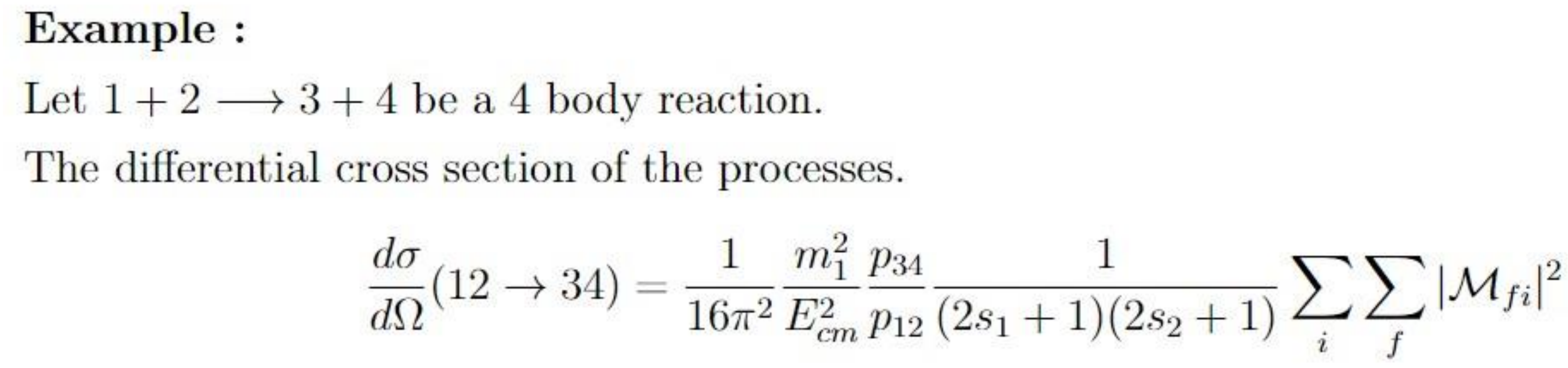

Example :

Let $1+2 \longrightarrow 3+4$ be a 4 body reaction.

The differential cross section of the processes.

$$\frac{d\sigma}{d\Omega}(12 \to 34) = \frac{1}{16\pi^2}\frac{m_1^2}{E_{cm}^2}\frac{p_{34}}{p_{12}}\frac{1}{(2s_1+1)(2s_2+1)}\sum_i\sum_f |\mathcal{M}_{fi}|^2$$

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Time reversal T :

It corresponds to looking at a system while events are running backwards in time

The cross section of the processes inverse $3 + 4 \longrightarrow 1 + 2$ such that

$$\sum_i \sum_f |\mathcal{M}_{fi}|^2 = \sum_i \sum_f |\mathcal{M}_{if}|^2.$$

The differential cross section is written in this case:

$$\frac{d\sigma}{d\Omega}(12 \to 34) = \frac{p_{34}^2}{p_{12}^2} \frac{(2s_3+1)(2s_4+1)}{(2s_1+1)(2s_2+1)} \frac{d\sigma}{d\Omega}(34 \to 12)$$

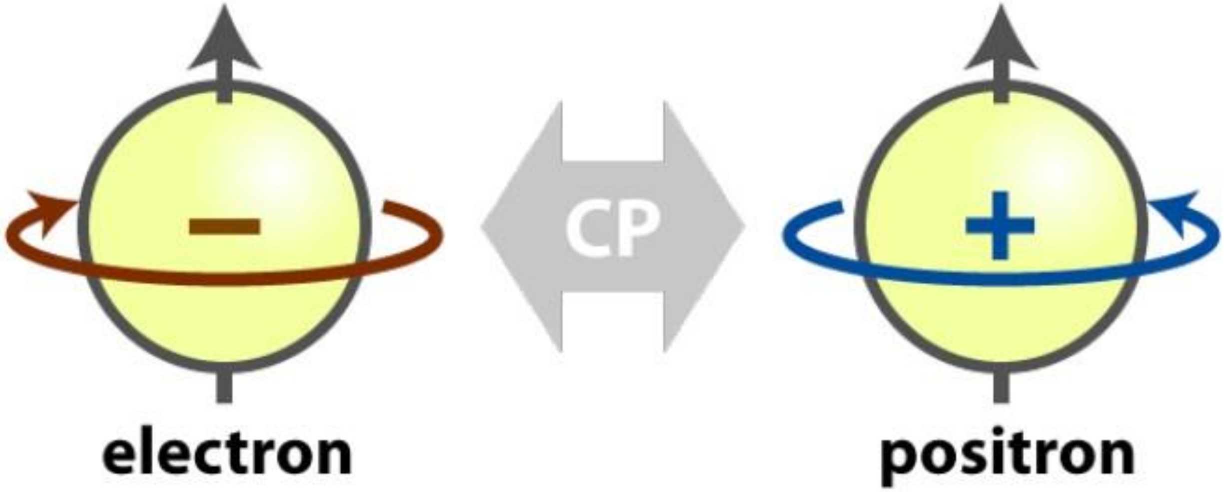
It is noted that the electromagnetic and strong interactions are invariant with respect to a time reversal.

The Standard Model of particle physics

CP Symmetry

Both charge conjugation and parity are found to be maximally violated in weak decays.

However, experimental results suggest the combination CP is a nearly a conserved symmetry. CP turns a particle into its antiparticle with opposite helicity: it is a symmetry between matter and anti-matter CP is a conserved quantity in absolutely strong and electromagnetic interactions



CP Violation in the mixing amplitude
CP Violation in the amplitude
CP Violation in the interference

CKM Matrix

The Standard Model of particle physics

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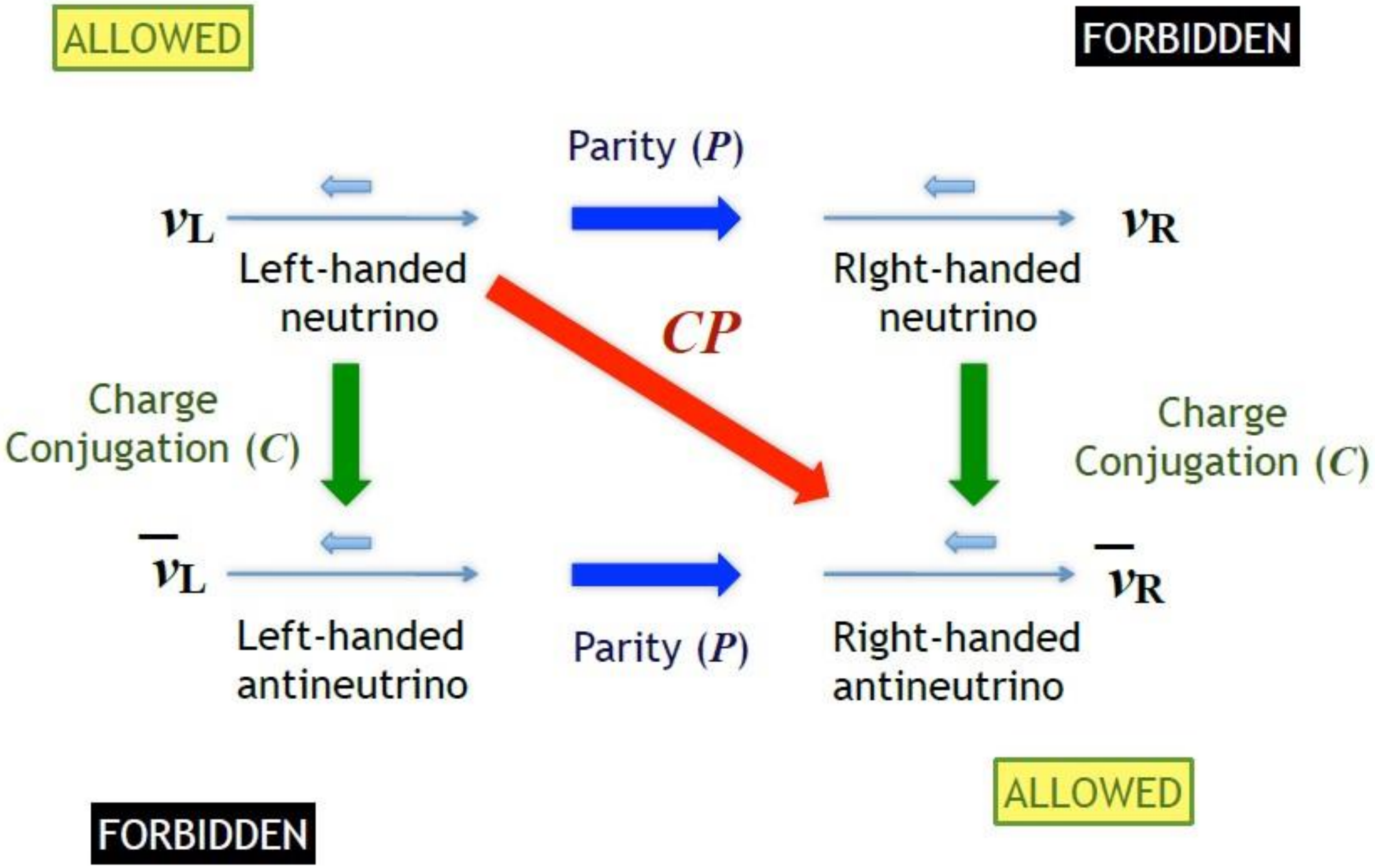

CP Violation in the mixing amplitude
CP Violation in the amplitude
CP Violation in the interference

CKM Matrix

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CPT theorem

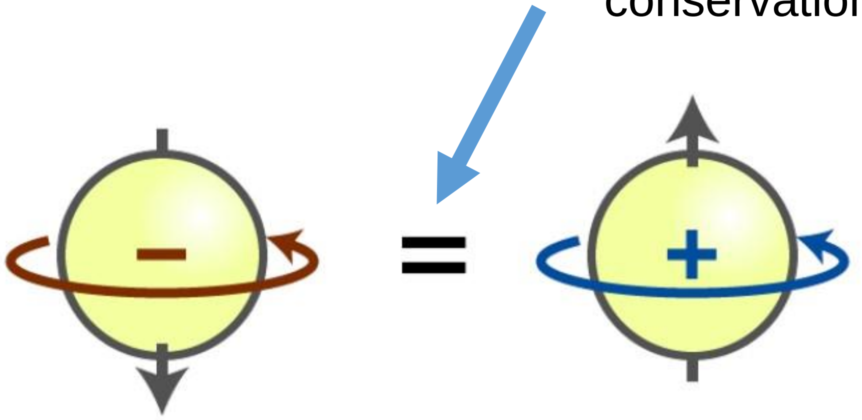
The CPT theorem predicts that particles and antiparticles must have the same mass and lifetime, but opposite electric charge and magnetic moment. Experimental tests of the CPT theorem have shown very precise agreement.

The CPT theorem also means that the transformation properties of gauge theories under the discrete symmetries C, P and T are related to each other:

$$CP \leftrightarrow T \qquad CT \leftrightarrow P \qquad PT \leftrightarrow C$$

It can be thought of as a statement about the invariance of Feynman diagrams under particle/antiparticle interchange, and interchange of the initial and final states.

The equals sign represents CPT conservation



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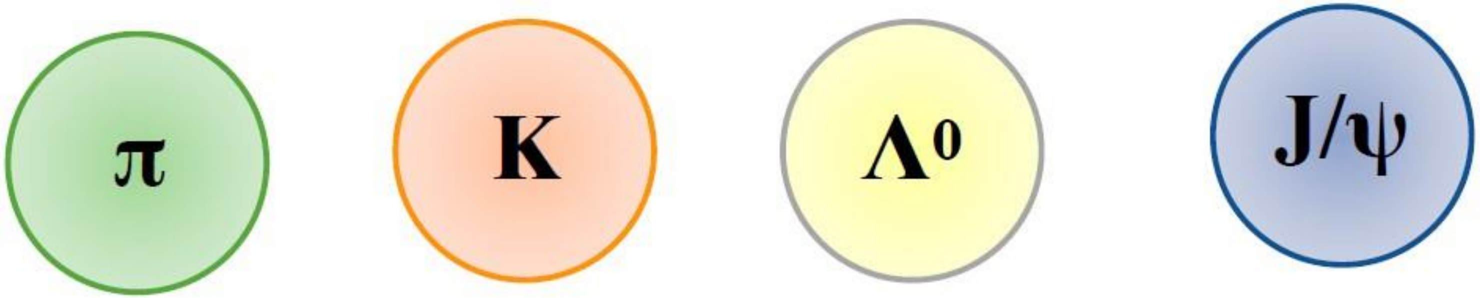
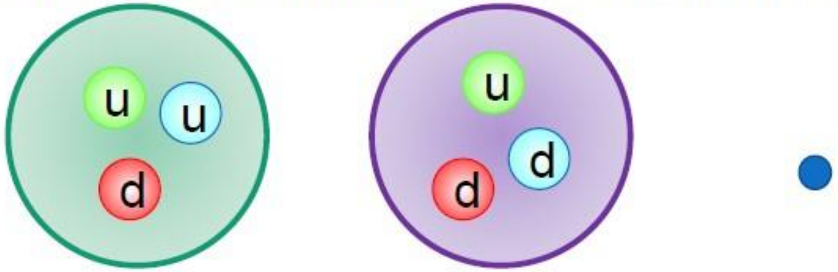
An abundance of particles

- 1947 to 1964: More and more “elementary” particles discovered



- Solution: all of these *hadrons* are different combinations of even smaller particles, called quarks



Proton (+) Neutron (0) Electron (-)

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- **Baryon number:** baryons=+1, antibaryons=-1, mesons, leptons=0.
- **Lepton number:**
  - electron number: $e^-, \nu_e = 1,\ e^+, \overline{\nu_e} = -1$
  - muon number: $\mu^-, \nu_\mu = 1,\ \mu^+, \overline{\nu_\mu} = -1$
  - τ number: $\tau^-, \nu_\tau = 1,\ \tau^+, \overline{\nu_\tau} = -1$

	Strong Interactions	**Electromagnetic Interactions**	**Weak Interactions**
Baryon number	yes	yes	yes
Lepton number (all)	yes	yes	yes
Angular momentum	yes	yes	yes
Isospin	yes	no	no
Flavour	yes	yes	no
Parity	yes	yes	no
Charge conjugation	yes	yes	no
CP	yes	yes	almost

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Internal Symmetries

Any transformation that act on the internal degrees of freedom of a physical system but not related to space-time.

Gauge symmetry

$$\psi(x) \longrightarrow \psi'(x) = e^{-ie\alpha}\psi(x),$$

- If $\alpha = cte$ is independent of x, the transformation is called **global**,
- If $\alpha(x)$ is a position dependent function, the transformation is called **local**.

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Internal Symmetries

Any transformation that act on the internal degrees of freedom of a physical system but not related to space-time.

$$\psi(x) \longrightarrow \psi'(x) = e^{-ie\alpha}\psi(x),$$

Gauge symmetry

$$\mathcal{L}_D = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$$

$$\overline{\psi}(x)\partial_\mu\psi(x) \longrightarrow \overline{\psi}(x)\partial_\mu\psi(x) - i\overline{\psi}(x)[\partial_\mu\alpha(x)]\psi(x)$$

$$D_\mu\psi(x) = (\partial_\mu + iea_\mu)\psi(x) \qquad a_\mu(x) \longrightarrow a'_\mu(x) = a_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)$$

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Internal Symmetries

Any transformation that act on the internal degrees of freedom of a physical system but not related to space-time.

Gauge symmetry

$$\psi(x) \longrightarrow \psi'(x) = e^{-ie\alpha}\psi(x),$$

$$\mathcal{L}_D = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$$

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x)$$

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Internal Symmetries

Any transformation that act on the internal degrees of freedom of a physical system but not related to space-time.

Gauge symmetry → Group symmetry

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^{\mu} D_{\mu} - m)\psi - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x)$$

U(1) symmetry → QED

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Group U(1) symmetry

- $U(1)$ stands for the unitary group of degree 1. It consists of all complex numbers of magnitude 1, typically represented as $e^{i\theta}$, where θ is a real number.
- In gauge theories, $U(1)$ symmetry corresponds to local phase transformations of the complex field. This means that the phase of the field can vary from point to point in spacetime.
- The gauge principle for $U(1)$ symmetry leads to the introduction of a gauge field, which in the case of Quantum Electrodynamics (QED), is the electromagnetic field.
- Physical laws remain invariant under local $U(1)$ transformations. This invariance necessitates the introduction of the electromagnetic potential A_μ, which transforms in such a way as to cancel the changes introduced by the local phase transformation.

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Group SU(2) symmetry

Let U be a unit operator such that:

$$|\varphi'\rangle = U|\varphi\rangle$$

$$\langle\varphi|\varphi\rangle = \langle\varphi'|\varphi'\rangle \Rightarrow \det(U) = 1.$$

. The operator U must:

- be a unitary matrix: $U^\dagger U = 1$ to preserve the hermeticity and generate real eigenvalues.
- preserve the scalar product

$$U = e^{i\omega}.$$

$$U^\dagger U = 1 \Rightarrow \quad 4\,\text{equations}$$

$$\det(U) = 1 \Rightarrow \quad 1\,\text{equation}$$

Where omega is a complex(2×2) matrix which depends on 8 parameters (4 real and 4 imaginary)

Then 4degrees of freedom 4−1 = 3independent degrees of freedom

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Group SU(2) symmetry

$$\omega = \omega^i \sigma_i \,, \quad i = 1, 2, 3.$$

σ are identified as generators of the group $SU(2)$ and are the famous Pauli matrices:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad , \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad , \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} .$$

They obey to the following switching rules:

$$[\sigma_i, \sigma_j] = i\epsilon_{ijk}\sigma_k. \longrightarrow$$

SU(2) is no abelian group

$$Tr(\sigma_i) = 0 \Rightarrow Tr(\omega) = 0.$$

For all $U = e^A$, we have:

$$\det(U) = e^{Tr(A)} \Rightarrow Tr(A) = 0 \Rightarrow \det(U) = 1$$

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SU(3) symmetry of QCD

3x3 -1 = 8

$$U = e^{-i\alpha_a \cdot \lambda^a} \qquad \mathrm{q} \rightarrow (1 + i\alpha_a\lambda^a)\mathrm{q} \qquad G^a_\mu \rightarrow G^a_\mu - \frac{1}{g_s}\partial_\mu\alpha_a - f_{abc}\alpha_b G^c_\mu$$

The Lagrangian for QCD is written:

$$L = \bar{\mathrm{q}}(i\gamma_\mu\partial^\mu - m)\mathrm{q} + g_s\bar{\mathrm{q}}\gamma_\mu\lambda^a G^\mu_a \mathrm{q} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

Where q represent the quark spinors, and compared to QED, the gluon states G^a_μ replace the photon, and g_s replaces e. The gluon field energy contains a term for the self-interactions of the gluons:

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f_{abc} G^b_\mu G^c_\nu$$

The Standard Model of particle physics

SU(3) symmetry of QCD

$$U = e^{-i\alpha_a \cdot \lambda^a}$$

The λ matrices can be identified with the eight gluon states

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

$$\lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad \lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \qquad \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

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

The Standard Model of particle physics

SU(3) symmetry of QCD

$$U = e^{-i\alpha_a \cdot \lambda^a}$$

The λ matrices can be identified with the eight gluon states

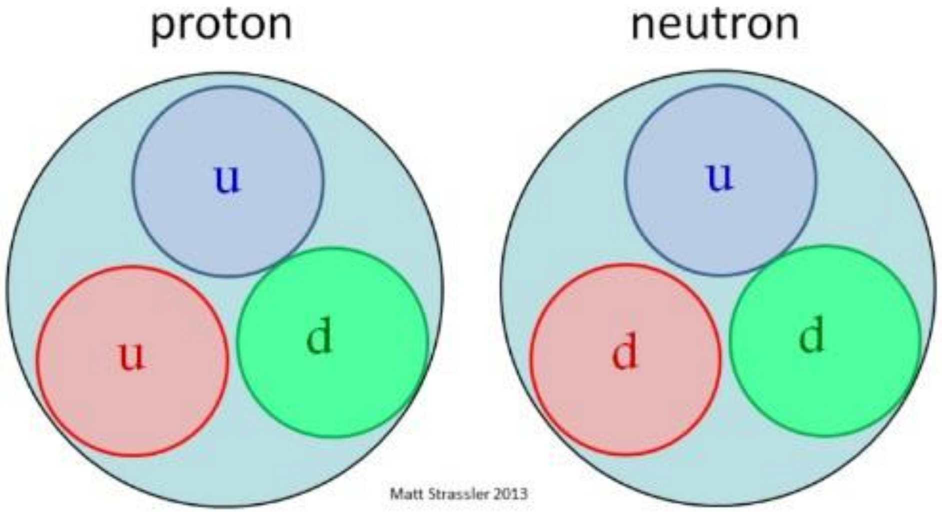

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Fig. 1: An oversimplified vision of protons as made from two up quarks and a down quark, and neutrons as made from two down quarks and an up quark — and nothing else.

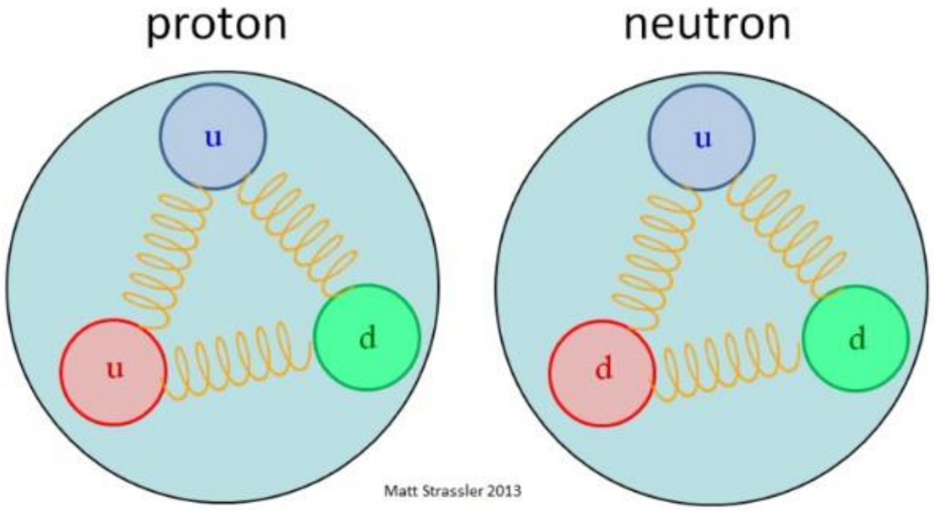

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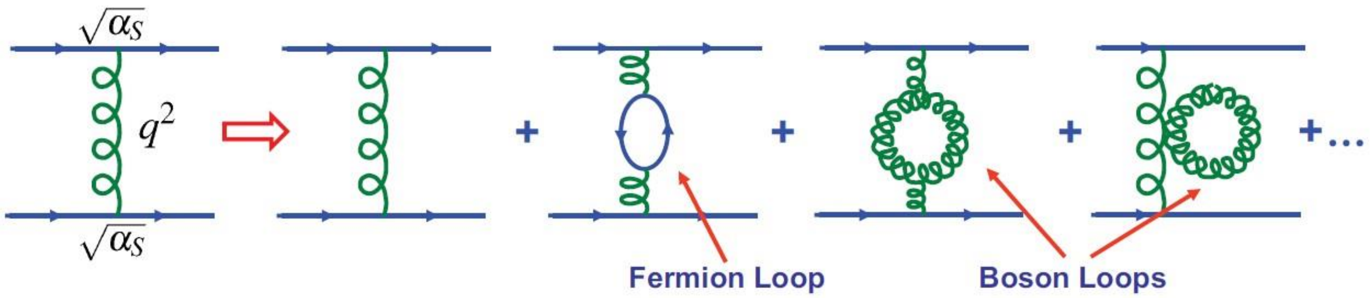
Fig. 2: This figure improves on Figure 1 by emphasizing the important role of the strong nuclear force in holding the quarks in the proton. Usually (and confusingly) the drawn springs are intended to schematically indicate that there are gluons in the proton.

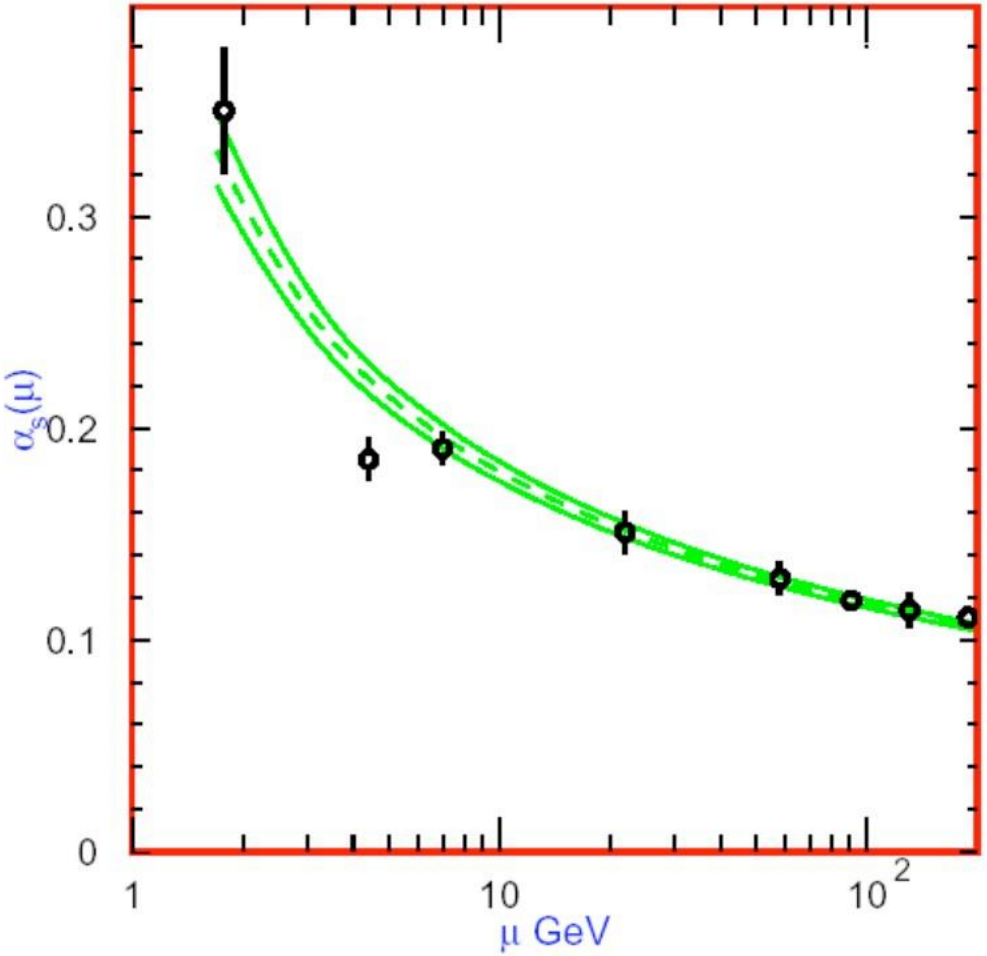
The Standard Model of particle physics

SU(3) symmetry of QCD

$$U = e^{-i\alpha_a \cdot \lambda^a}$$

$$\alpha_S(q^2) = \frac{\alpha_S(\mu^2)}{1+\frac{\alpha_S(\mu^2)}{12\pi}(11n_C - 2n_f)\ln\left(\frac{q^2}{\mu^2}\right)}\alpha_S(q^2)$$





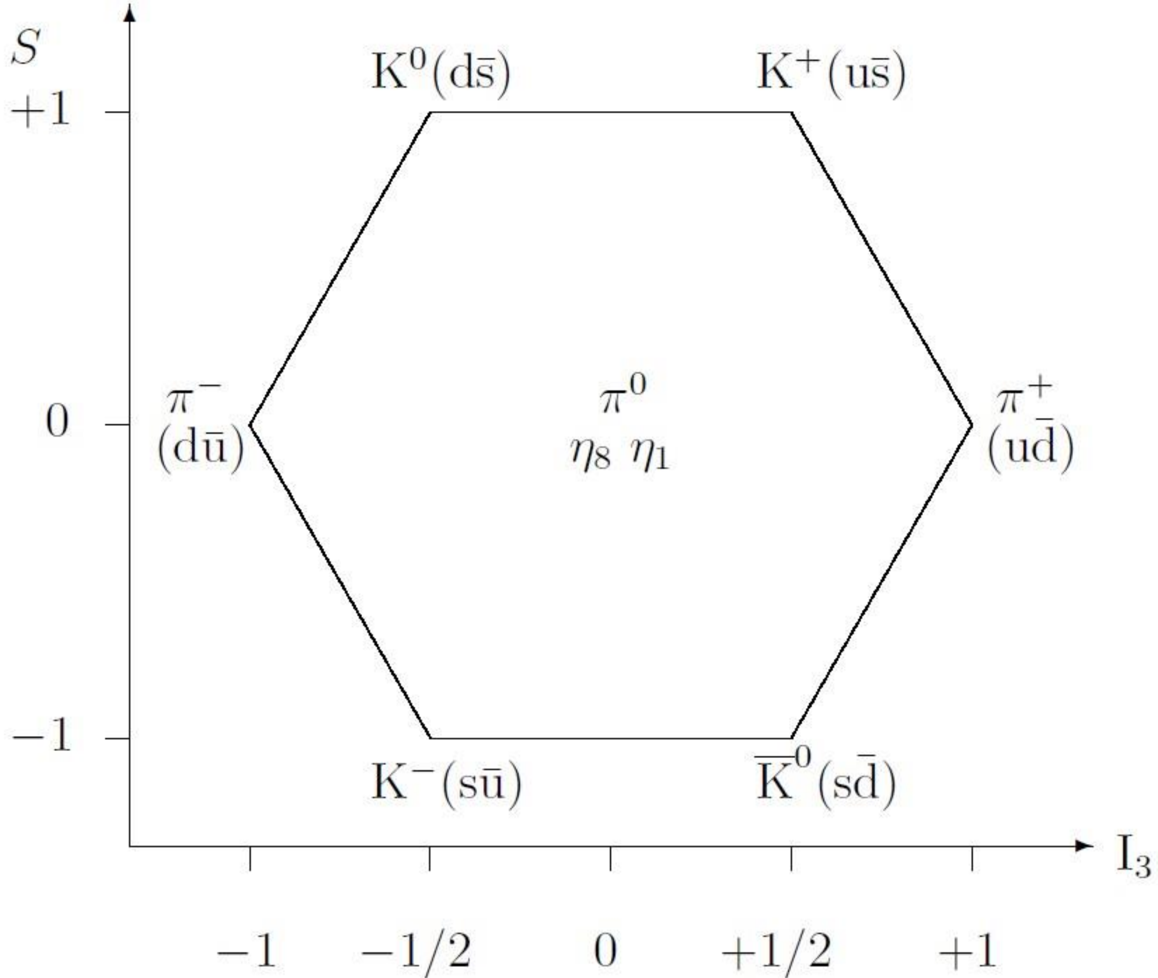
The Standard Model of particle physics

SU(3) symmetry of QCD

Hadron Multiplets

Pseudoscalar mesons

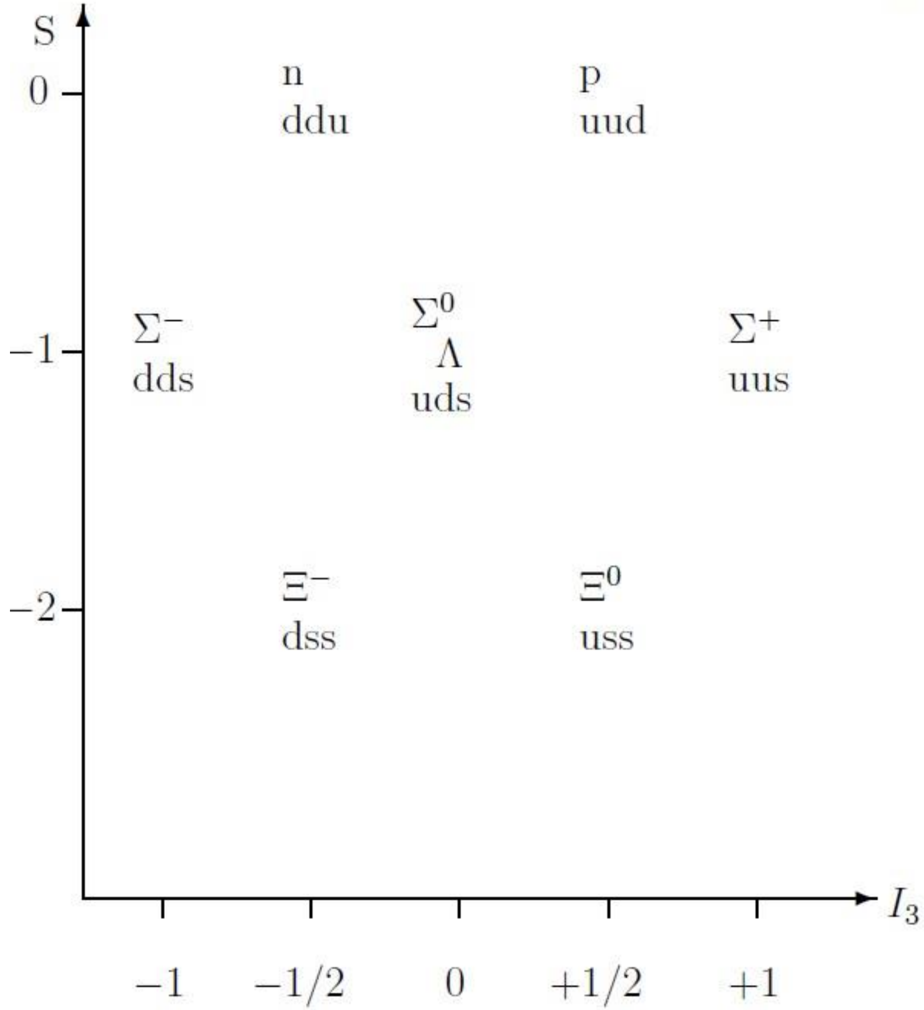
$J = 0$



SU(3) symmetry of QCD

Hadron Multiplets

$J = 1/2.$

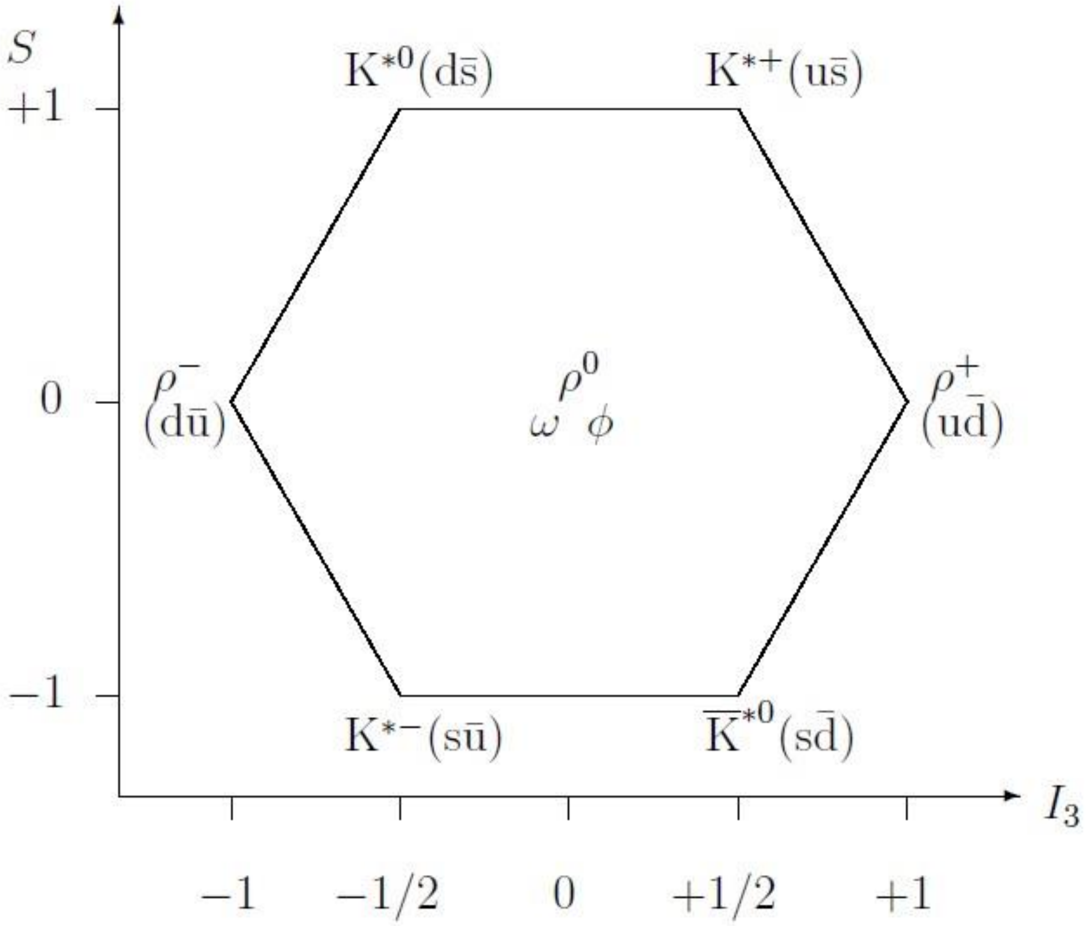


SU(3) symmetry of QCD

Hadron Multiplets

Vector mesons

$J = 1$

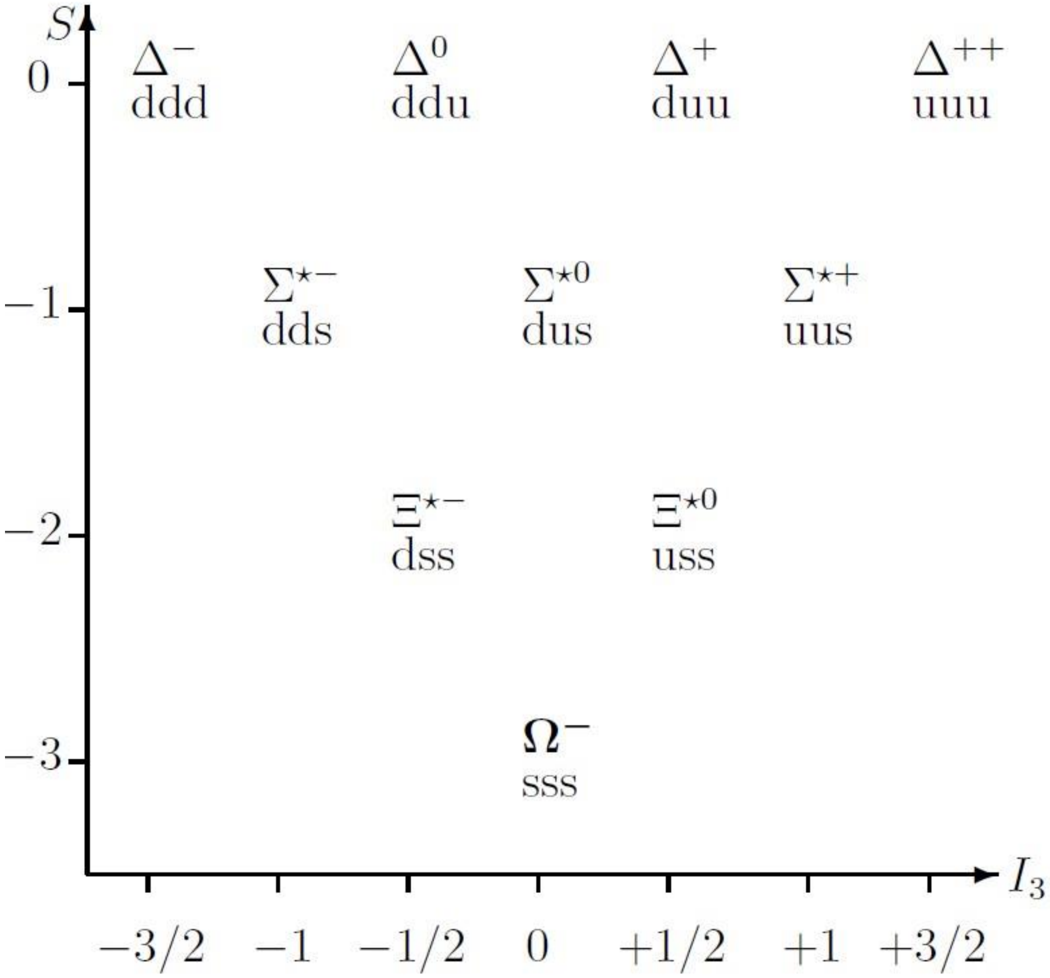


The Standard Model of particle physics

SU(3) symmetry of QCD

Hadron Multiplets

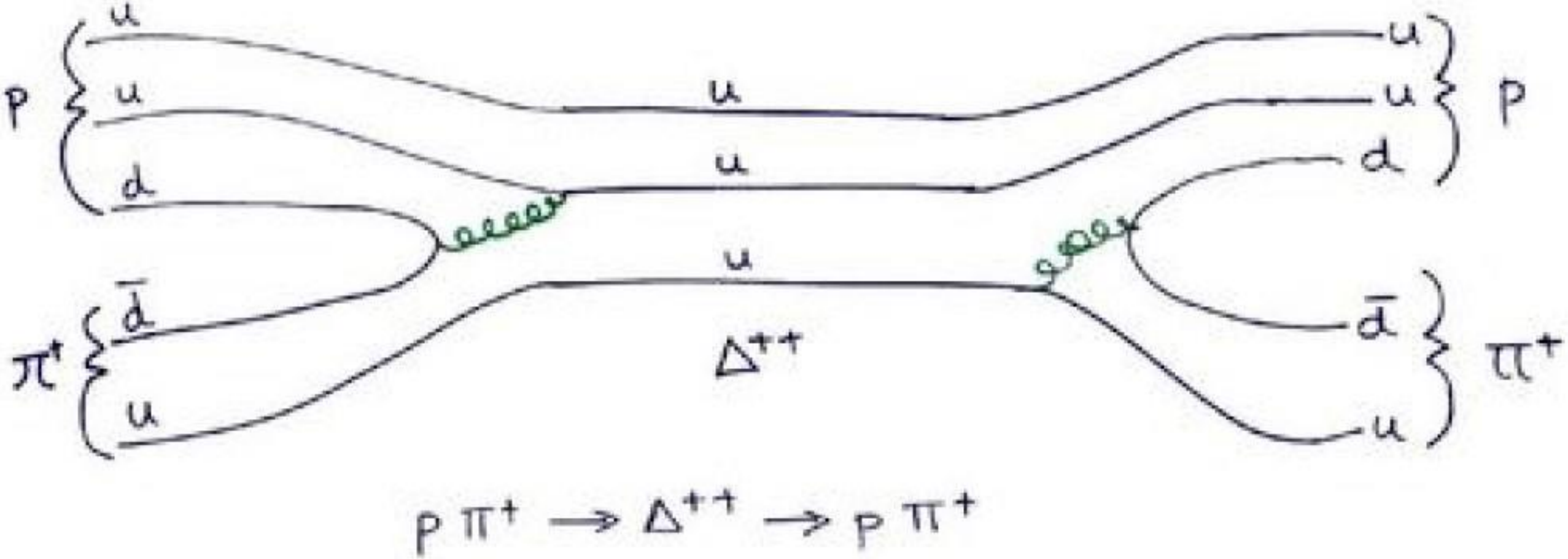
$J = 3/2$ baryons states.



The Standard Model of particle physics

SU(3) symmetry of QCD

Hadron Multiplets



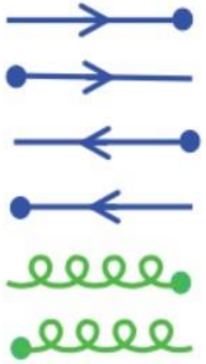
Feynman diagram for $p\pi^+ \to \Delta^{++} \to p\pi^+$ scattering.

The Standard Model of particle physics

SU(3) symmetry of QCD

- **External Lines**

spin 1/2	incoming quark	$u(p)$
	outgoing quark	$\overline{u}(p)$
	incoming anti-quark	$\overline{v}(p)$
	outgoing anti-quark	$v(p)$
spin 1	incoming gluon	$\varepsilon^{\mu}(p)$
	outgoing gluon	$\varepsilon^{\mu}(p)^{*}$



- **Internal Lines (propagators)**

spin 1 gluon

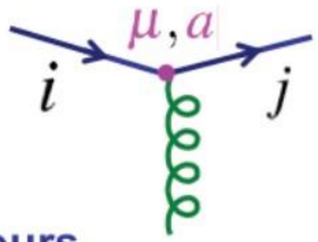
$$\boxed{\frac{g_{\mu\nu}}{q^2}\delta^{ab}}$$

a, b = 1,2,…,8 are gluon colour indices

- **Vertex Factors**

spin 1/2 quark

$$\boxed{g_s\frac{1}{2}\lambda^{a}_{ji}\gamma^{\mu}}$$



i, j = 1,2,3 are quark colours,

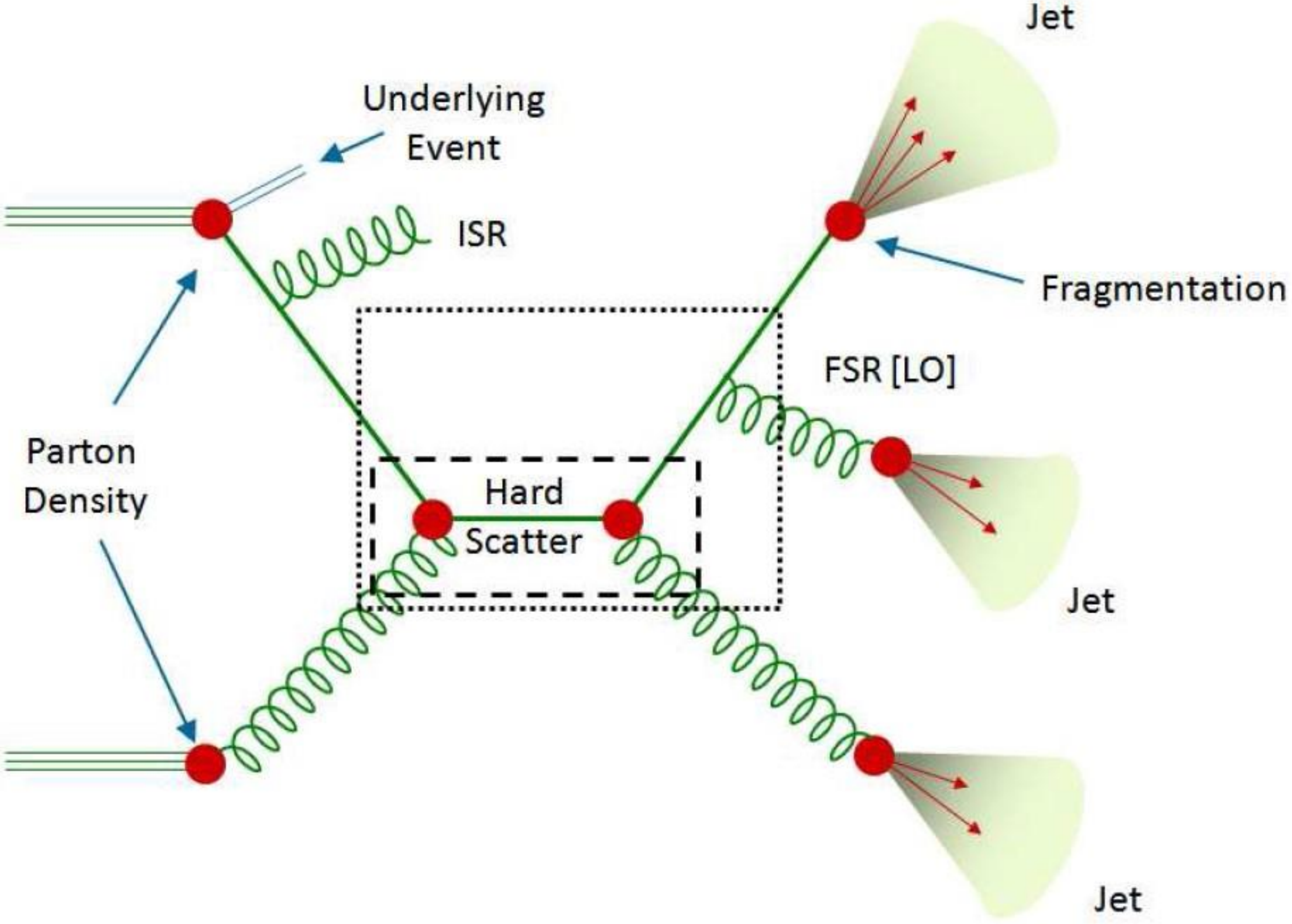
λ^{a} a = 1,2,..8 are the Gell-Mann SU(3) matrices

The Standard Model of particle physics

At Hadron Collider

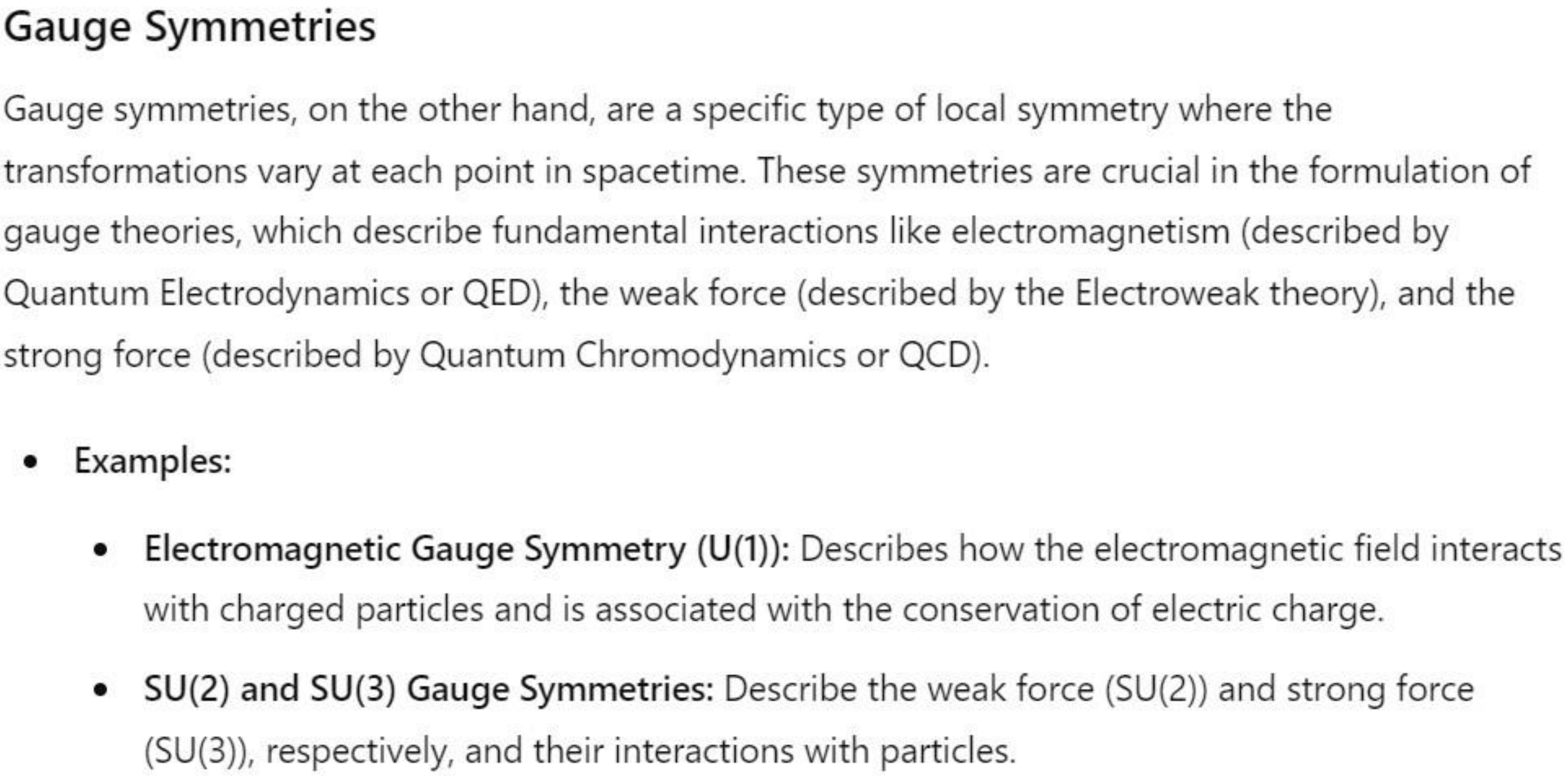
Jet production at hadron colliders

- Initial and final state radiation (ISR and FSR) are high energy gluon emissions from the scattering partons.
- Fragmentation is the process of producing final state particles from the parton produced in the hard scatter.
- A hadronic jet is a collimated cone of particles associated with a final state parton,
- produced through fragmentation.



Production of Jets at a Hadron Collider

The Standard Model of particle physics

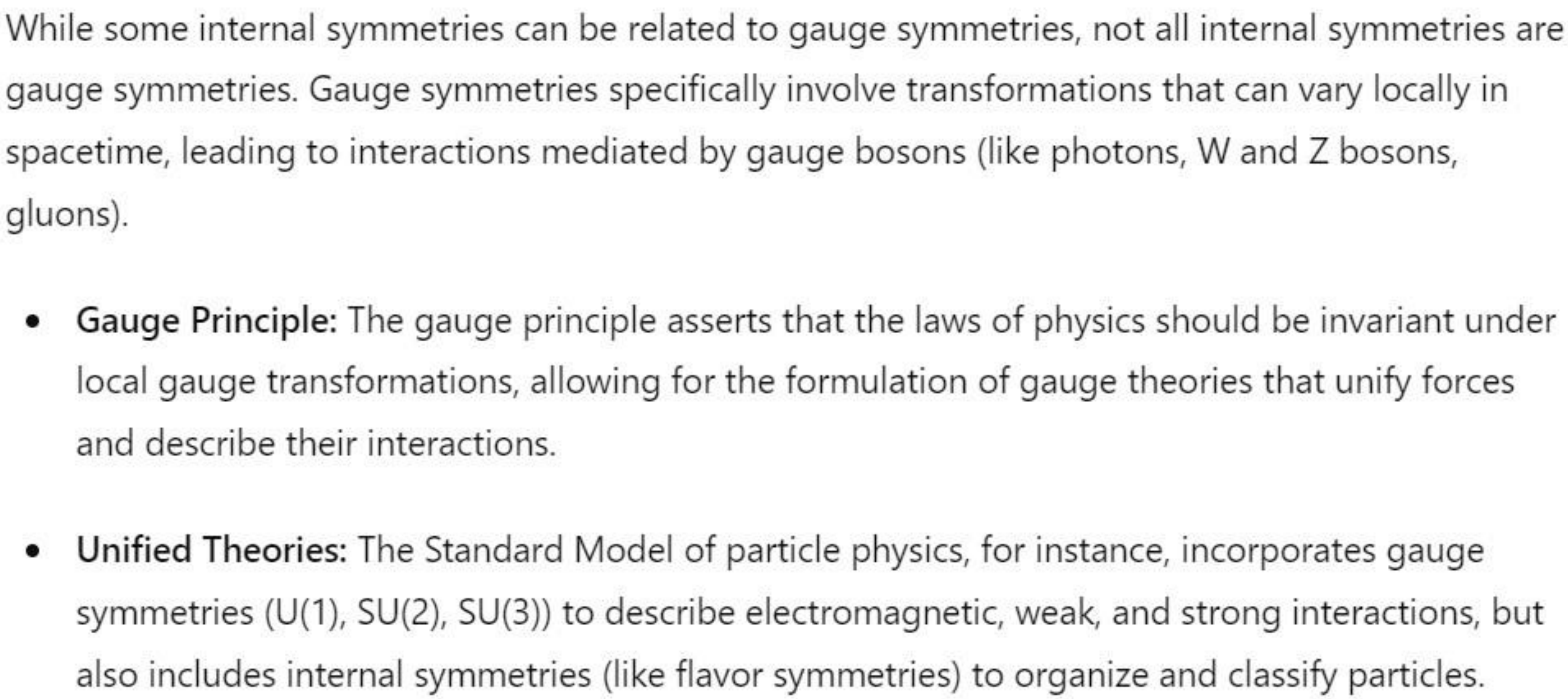


Gauge Symmetries

Gauge symmetries, on the other hand, are a specific type of local symmetry where the transformations vary at each point in spacetime. These symmetries are crucial in the formulation of gauge theories, which describe fundamental interactions like electromagnetism (described by Quantum Electrodynamics or QED), the weak force (described by the Electroweak theory), and the strong force (described by Quantum Chromodynamics or QCD).

- Examples:
  - **Electromagnetic Gauge Symmetry (U(1)):** Describes how the electromagnetic field interacts with charged particles and is associated with the conservation of electric charge.
  - **SU(2) and SU(3) Gauge Symmetries:** Describe the weak force (SU(2)) and strong force (SU(3)), respectively, and their interactions with particles.

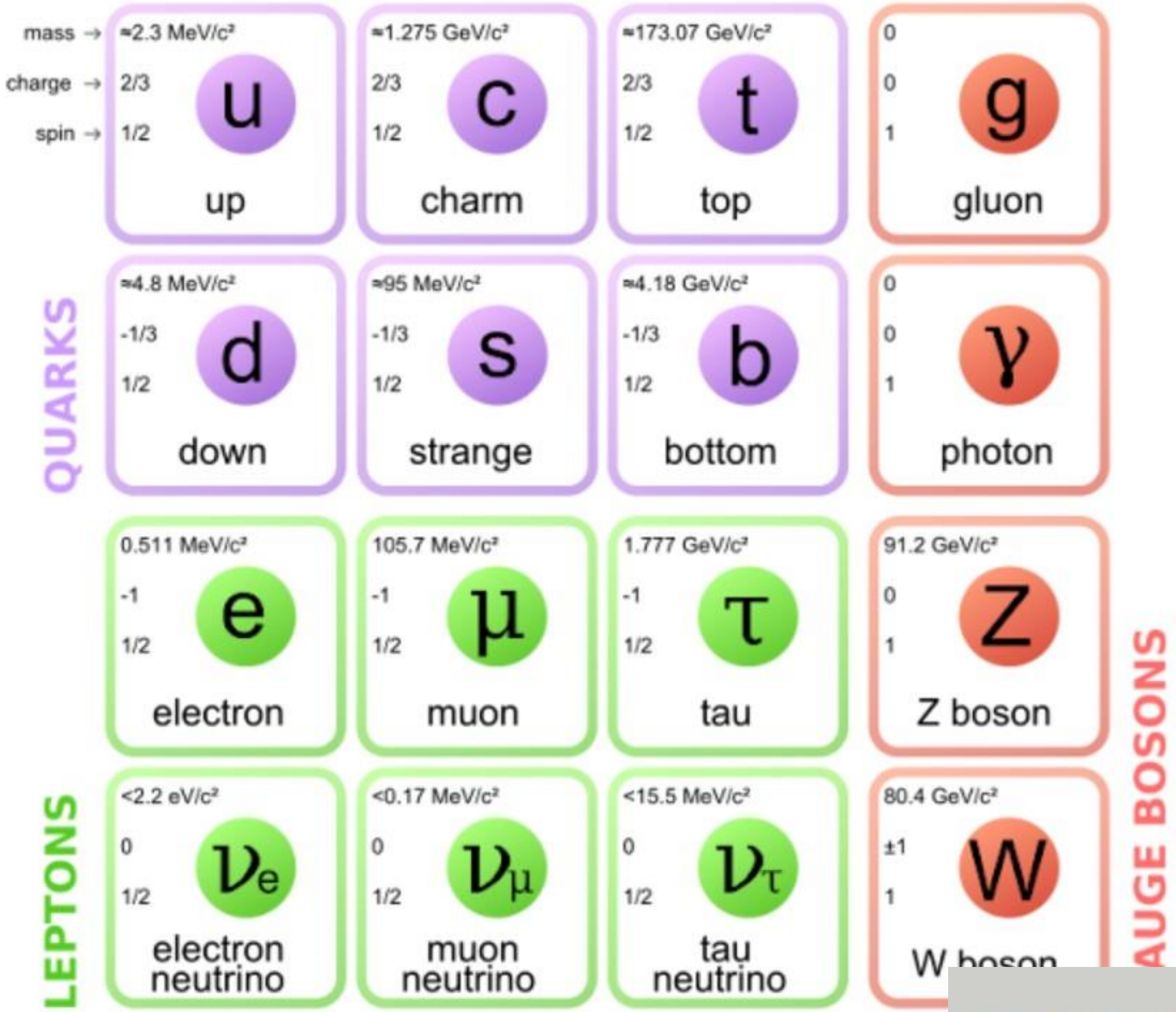
The Standard Model of particle physics



While some internal symmetries can be related to gauge symmetries, not all internal symmetries are gauge symmetries. Gauge symmetries specifically involve transformations that can vary locally in spacetime, leading to interactions mediated by gauge bosons (like photons, W and Z bosons, gluons).

- **Gauge Principle:** The gauge principle asserts that the laws of physics should be invariant under local gauge transformations, allowing for the formulation of gauge theories that unify forces and describe their interactions.
- **Unified Theories:** The Standard Model of particle physics, for instance, incorporates gauge symmetries (U(1), SU(2), SU(3)) to describe electromagnetic, weak, and strong interactions, but also includes internal symmetries (like flavor symmetries) to organize and classify particles.

The Standard Model of particle physics



mass → charge → spin →	≈ 2.3 MeV/c^2 2/3 1/2 u up	≈ 1.275 GeV/c^2 2/3 1/2 c charm	≈ 173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon
QUARKS	≈ 4.8 MeV/c^2 -1/3 1/2 d down	≈ 95 MeV/c^2 -1/3 1/2 s strange	≈ 4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson

AUGE BOSONS

✓ All ordinary matter is made from up quarks, down quarks, and Electrons

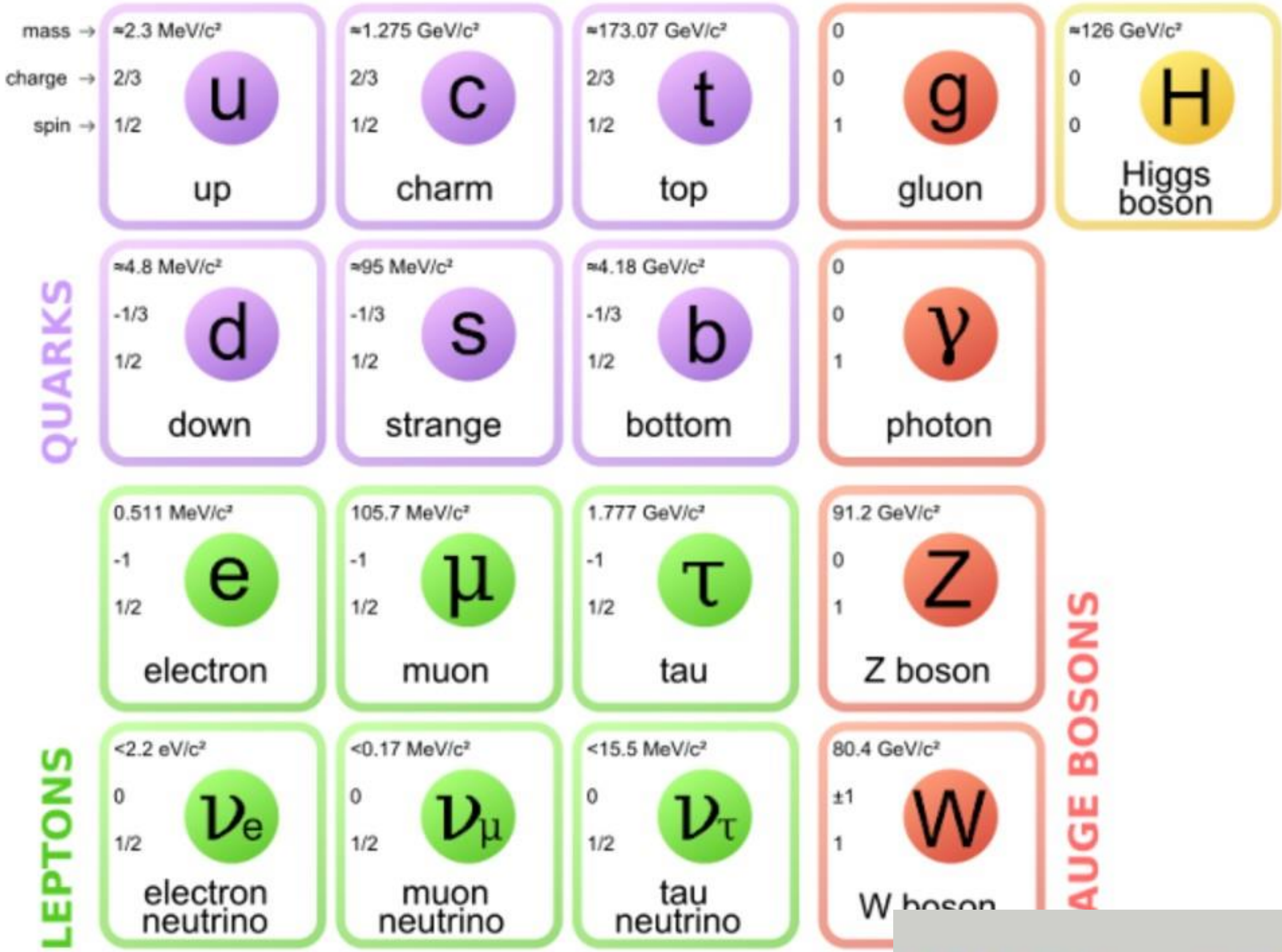
✓ There are three copies, or
✓ *generations*, of quarks and leptons

✓ Same properties, only heavier
Leptons also include neutrinos, one for each generation

✓ All of these are *matter* particles, or fermions

$SU(3)_C \times SU(2)_L \times U(1)_Y$ ``symmetry"

The Standard Model of particle physics



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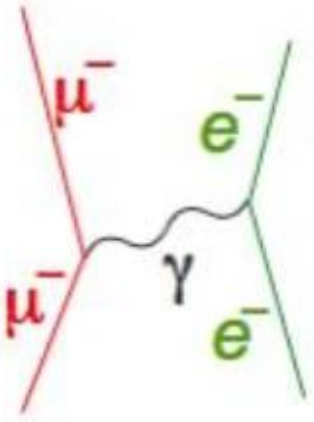
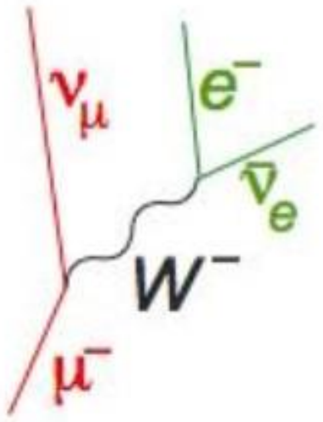
The Standard Model of particle physics



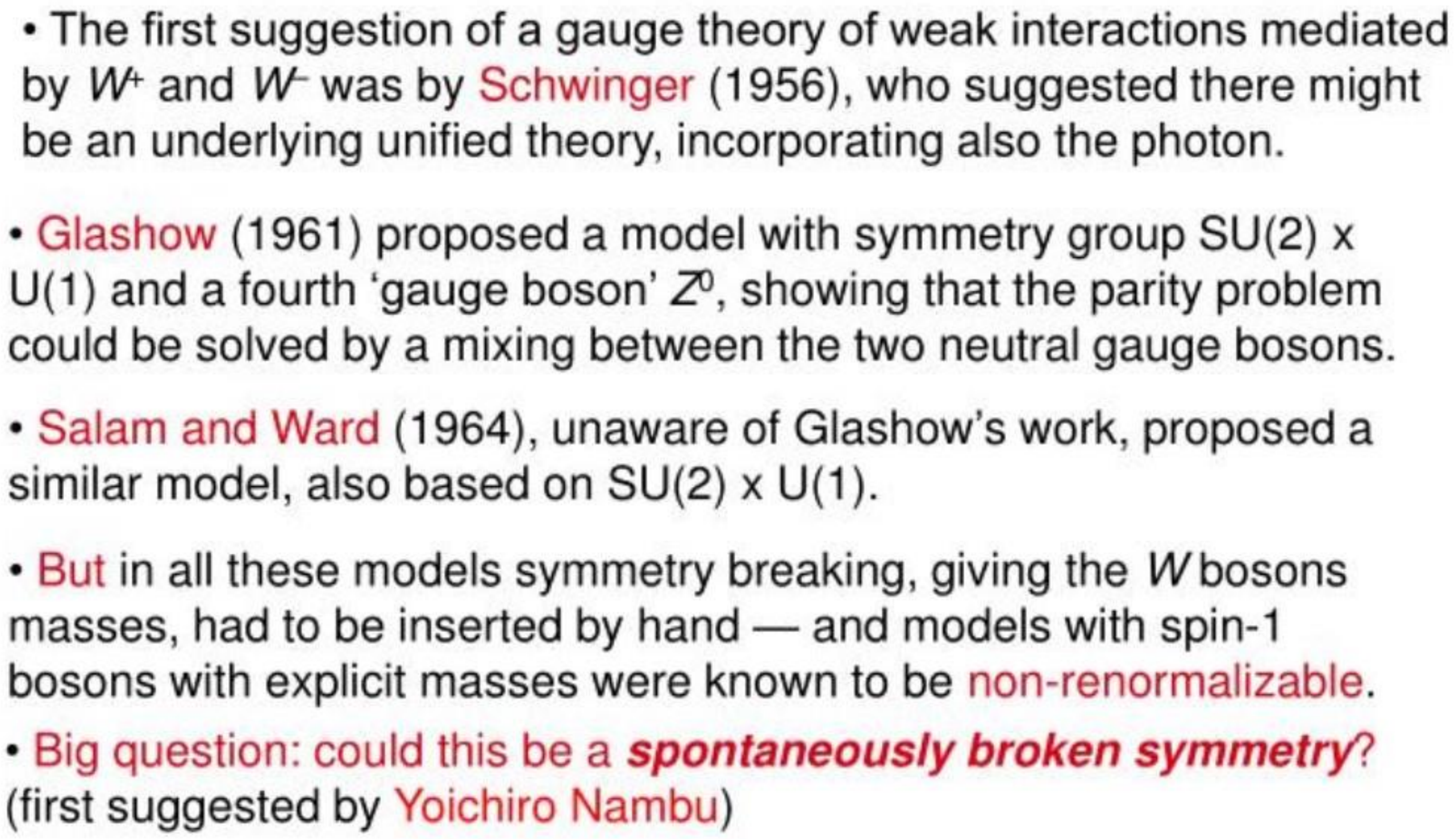
Electromagnetic interaction	***Weak interaction***
exchange of spin-1 γ	exchange of spin-1 $W^{\pm}$
But	
long range $\Rightarrow M_\gamma = 0$	short range $\Rightarrow M_W$ large
parity conserving (mirror-symmetric)	parity violating (non-mirror-symmetric)



So: Can there be a ***symmetry*** relating γ and $W^{\pm}$?

If so it must be ***broken***

The Standard Model of particle physics



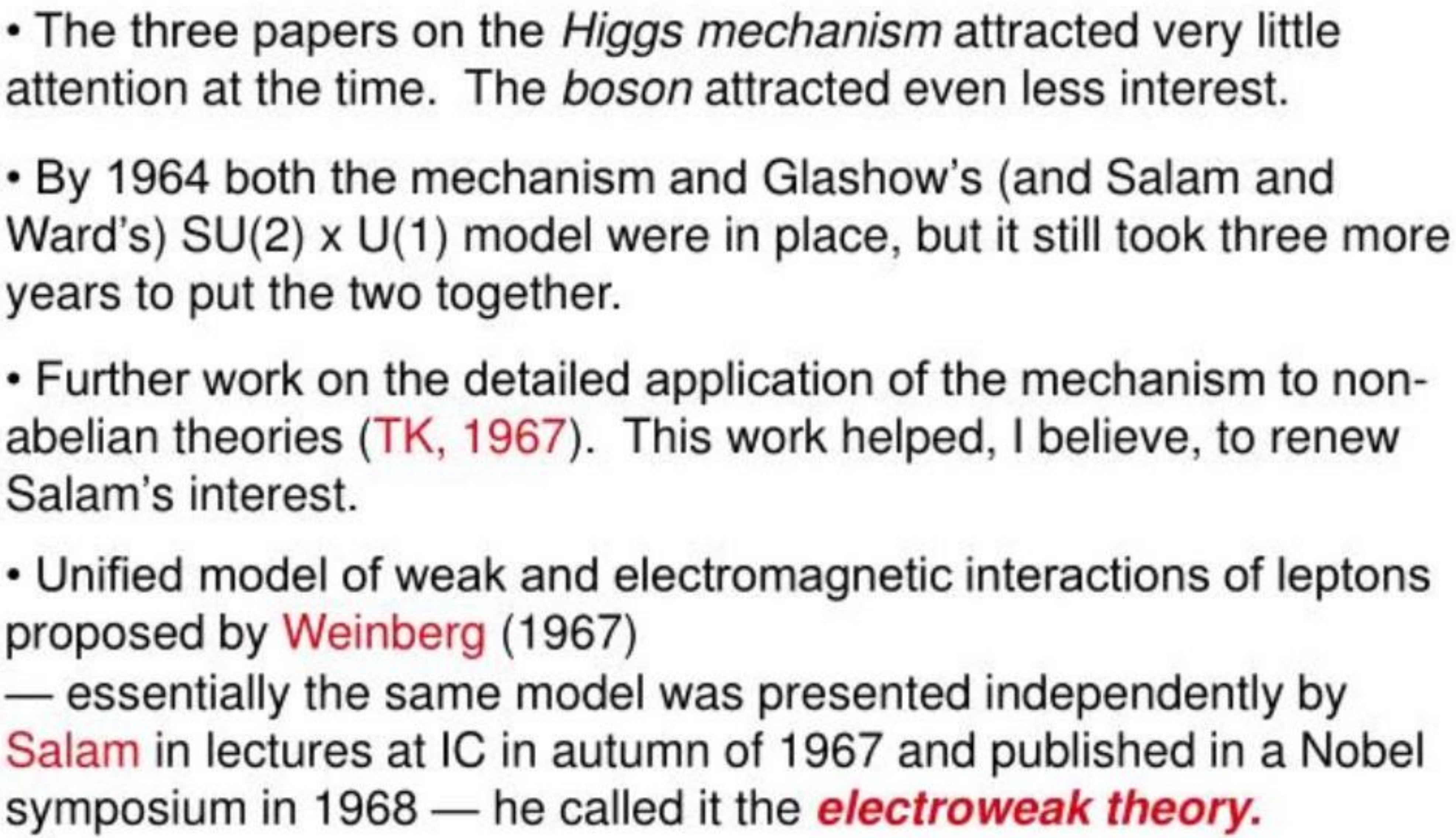
- The first suggestion of a gauge theory of weak interactions mediated by W^+ and W^- was by Schwinger (1956), who suggested there might be an underlying unified theory, incorporating also the photon.
- Glashow (1961) proposed a model with symmetry group SU(2) x U(1) and a fourth 'gauge boson' Z^0, showing that the parity problem could be solved by a mixing between the two neutral gauge bosons.
- Salam and Ward (1964), unaware of Glashow's work, proposed a similar model, also based on SU(2) x U(1).
- But in all these models symmetry breaking, giving the W bosons masses, had to be inserted by hand — and models with spin-1 bosons with explicit masses were known to be non-renormalizable.
- Big question: could this be a ***spontaneously broken symmetry***? (first suggested by Yoichiro Nambu)

The Standard Model of particle physics

- Solution was found by three groups
  — Englert & Brout (1964), Higgs (1964), Guralnik, Hagen & TK (1964)
  — gauge theories are not like other field theories: masslessness of Nambu–Goldstone bosons and gauge bosons 'cancels out', combining to create massive gauge bosons.

- All three proposed (from different viewpoints) essentially the same model for spontaneous symmetry breaking in the simplest U(1) gauge theory, i.e. a broken version of electrodynamics
  — it involves introducing a new scalar (spin-0) field, with 'sombrero' potential (as in Goldstone model)
  — spontaneous symmetry breaking occurs when this field acquires a non-zero average value
  — this gives mass to other fields it interacts with, in particular the gauge bosons.

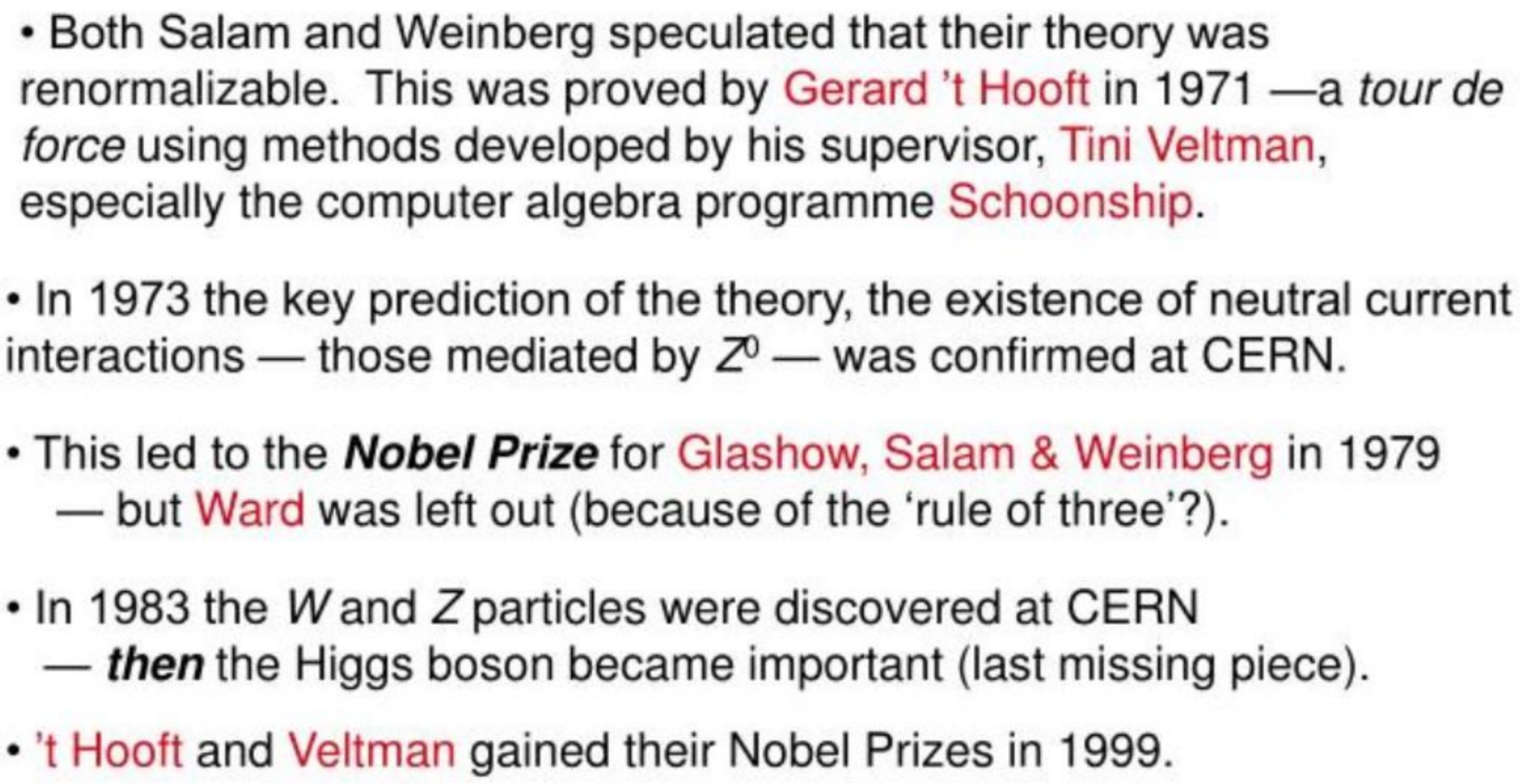
The Standard Model of particle physics



- The three papers on the *Higgs mechanism* attracted very little attention at the time. The *boson* attracted even less interest.
- By 1964 both the mechanism and Glashow's (and Salam and Ward's) SU(2) x U(1) model were in place, but it still took three more years to put the two together.
- Further work on the detailed application of the mechanism to non-abelian theories (TK, 1967). This work helped, I believe, to renew Salam's interest.
- Unified model of weak and electromagnetic interactions of leptons proposed by Weinberg (1967)

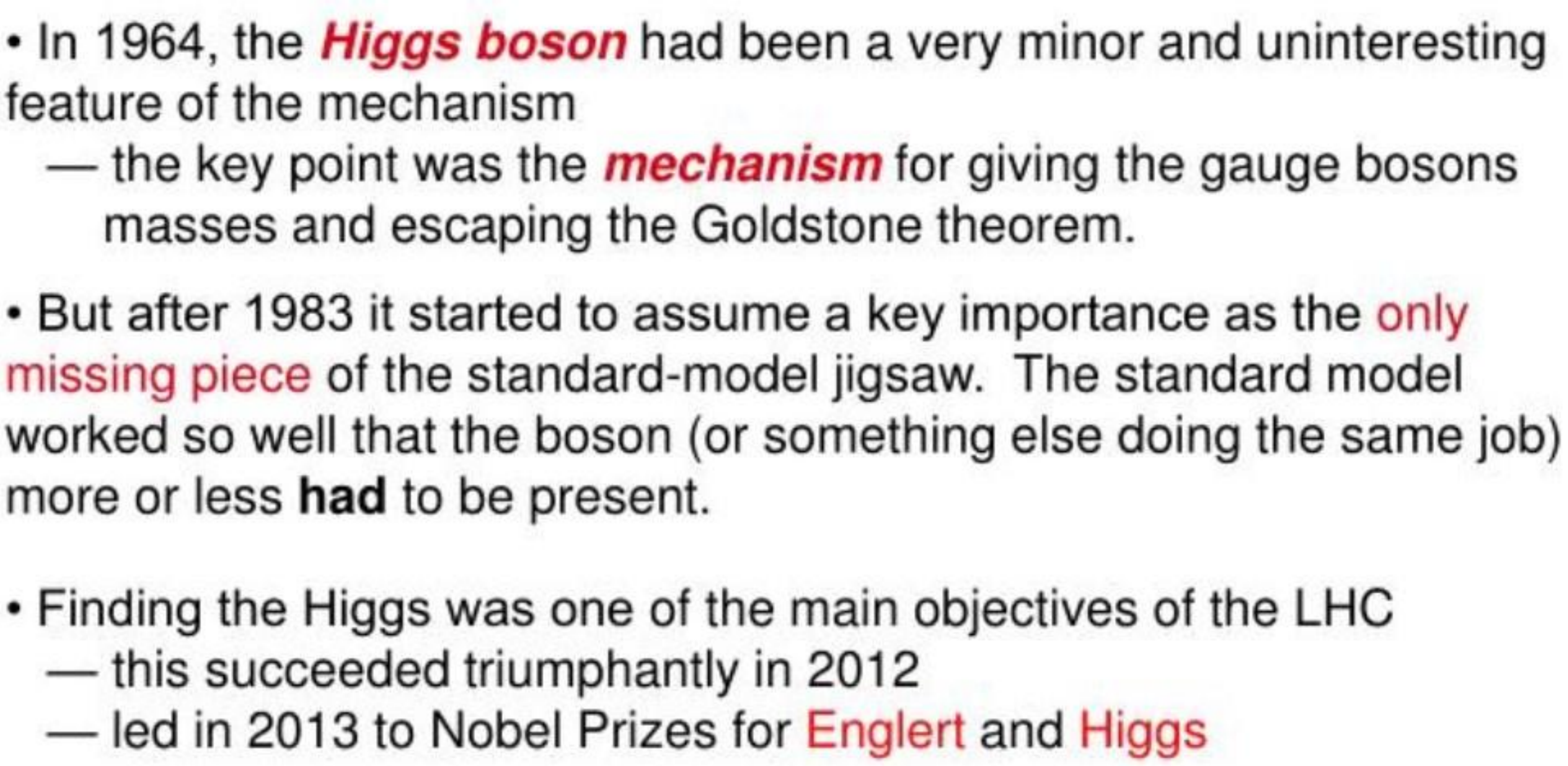
— essentially the same model was presented independently by Salam in lectures at IC in autumn of 1967 and published in a Nobel symposium in 1968 — he called it the ***electroweak theory.***

The Standard Model of particle physics



- Both Salam and Weinberg speculated that their theory was renormalizable. This was proved by Gerard ’t Hooft in 1971 —a *tour de force* using methods developed by his supervisor, Tini Veltman, especially the computer algebra programme Schoonship.
- In 1973 the key prediction of the theory, the existence of neutral current interactions — those mediated by Z^0 — was confirmed at CERN.
- This led to the ***Nobel Prize*** for Glashow, Salam & Weinberg in 1979 — but Ward was left out (because of the ‘rule of three’?).
- In 1983 the W and Z particles were discovered at CERN — ***then*** the Higgs boson became important (last missing piece).
- ’t Hooft and Veltman gained their Nobel Prizes in 1999.

The Standard Model of particle physics



- In 1964, the ***Higgs boson*** had been a very minor and uninteresting feature of the mechanism
  — the key point was the ***mechanism*** for giving the gauge bosons masses and escaping the Goldstone theorem.

- But after 1983 it started to assume a key importance as the only missing piece of the standard-model jigsaw. The standard model worked so well that the boson (or something else doing the same job) more or less **had** to be present.

- Finding the Higgs was one of the main objectives of the LHC
  — this succeeded triumphantly in 2012
  — led in 2013 to Nobel Prizes for Englert and Higgs

The Standard Model of particle physics

Standard Model

Everything we have learned in the last several decades about fundamental particles and their interactions

The theory describing the properties of, and interactions between all *known* elementary particles

(… hence, in principle, of everything made of these particles!)

A theory based on a *gauged* $SU(3)_C \times SU(2)_L \times U(1)_Y$ ``symmetry"

Physics Translation:

Describes spin-1 (quantum) fields coupled to the other fields (i.e. spin-1/2 and spin-0) through the Noether currents of a *global* $SU(3)_C \times SU(2)_L \times U(1)_Y$ internal symmetry:

$$\mathcal{L}_{\mathrm{SM}} = \cdots + \underbrace{J_3^{\mu\, a} G_\mu^a}_{\text{8 color currents}} + \underbrace{J_2^{\mu\, i} W_\mu^i}_{\text{3 weak isospin currents}} + \underbrace{J_1^{\mu} B_\mu}_{\text{hypercharge current}} + \cdots$$

Until recently: all collider-experiment results could be understood just in terms of these interactions!

Furthermore:

The electroweak (EW) sector, i.e. $SU(2)_L \times U(1)_Y$, is ``*spontaneously broken*”

Translation: the vacuum we live in is not invariant under the EW transformations, so that it selects a particular direction in the internal $SU(2)_L \times U(1)_Y$ space…

… much as the ground state of a ferromagnet, at sufficiently low temperatures, selects one direction, even if the underlying physics is perfectly rotationally invariant.

Consequence: three of the EW spin-1 particles are massive (hence mediate short-range interactions) and one is massless (mediating long range interactions).

These are the W^+, W^-, the Z^0 and the photon.

Physics: ``weak” lifetimes (e.g. beta-decay or muon decay) much longer than those of EM or strongly induced decays.

A striking difference between the (massless) photon and the (massive) $W^{\pm}$ and Z^0:

- The photon has *two* physical polarizations
- The massive vector bosons have *three* physical polarizations

Clearly, the three extra d.o.f. must arise from the EW symmetry breaking sector

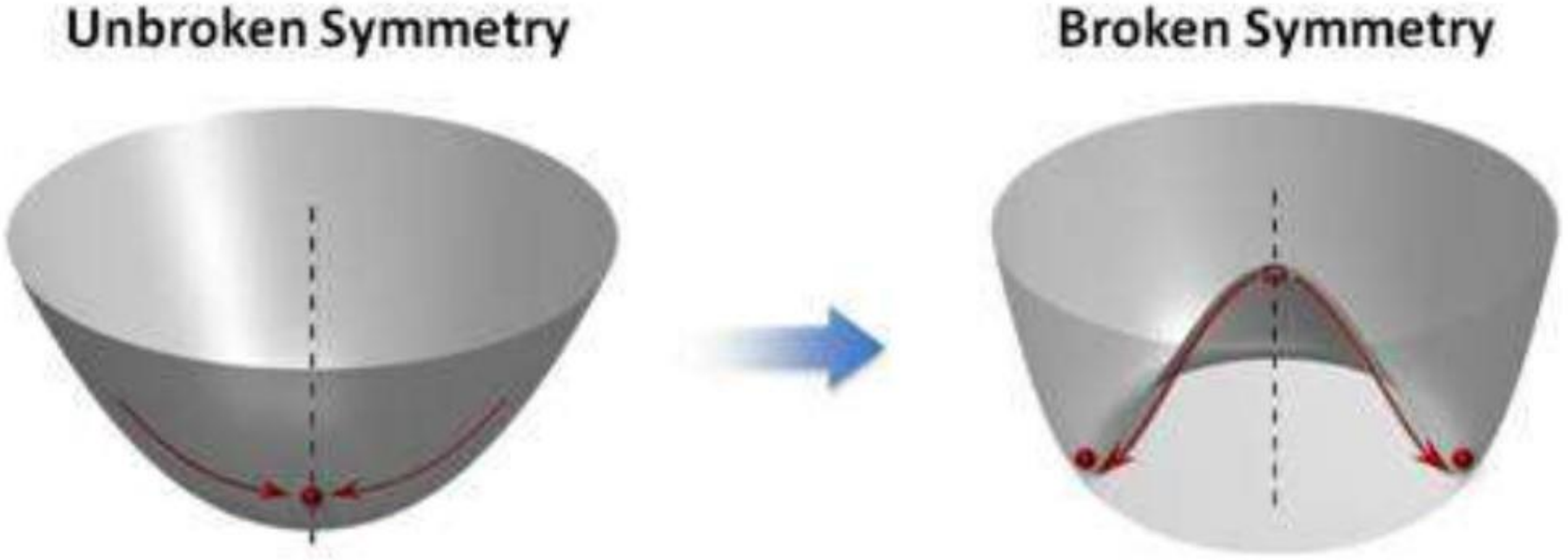
(and we have been studying their properties for decades)

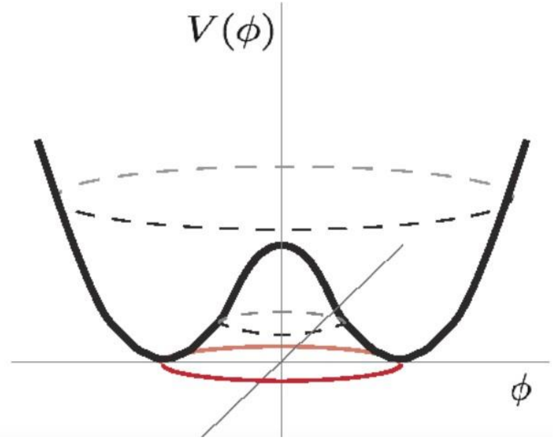
These, together with the 125 GeV resonance discovered in 2012, nicely fit into the simplest imaginable picture (at least as measured by counting d.o.f.) for the symm. breaking sector!

The Standard Model posits the existence of a scalar (spin-0) field, transforming as a doublet of $SU(2)_L$ and with hypercharge $Y = 1/2$. In the vacuum, this ``Higgs doublet" has a vacuum expectation value (VEV):

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

(The direction is conventional
and arbitrary, given the
SU(2) x U(1) invariance)


Unbroken Symmetry
Broken Symmetry


$V(\phi)$
ϕ

The Standard Model posits the existence of a scalar (spin-0) field, transforming as a doublet of $SU(2)_L$ and with hypercharge $Y = 1/2$. In the vacuum, this ``Higgs doublet" has a vacuum expectation value (VEV):

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

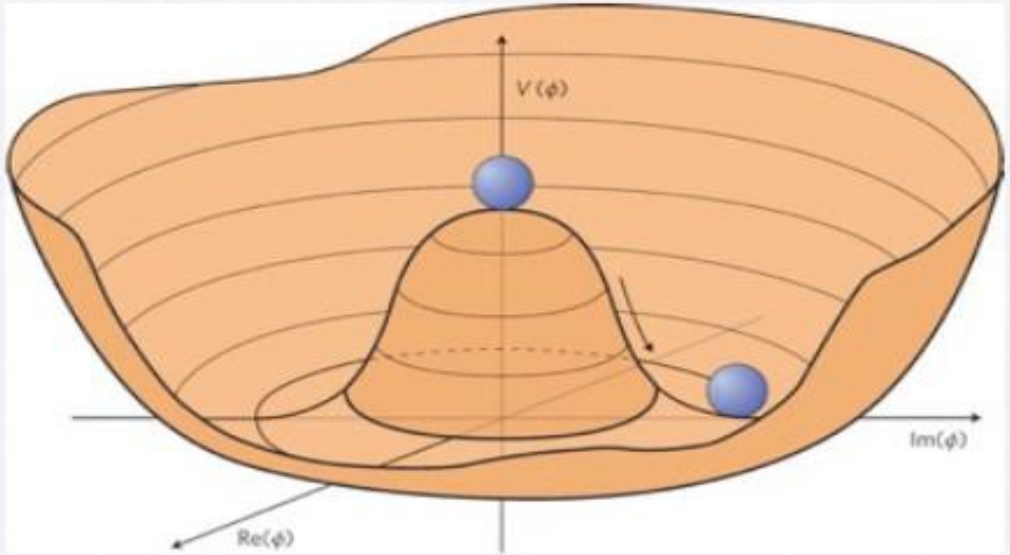
(The direction is conventional and arbitrary, given the SU(2) x U(1) invariance)

The observed d.o.f. can be parametrized as follows:

$$H = e^{i\,\vec{x}\cdot\vec{\tau}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}\,h \end{pmatrix} \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

`eaten NGB's"

The 125 resonance (the ``Higgs boson")



``Higgs field" potential:

(Most general renormalizable one)

$$V(H) = \lambda \left(H^\dagger H - v^2\right)^2 \longrightarrow |\langle H \rangle| = v \approx 174 \text{ GeV}$$

$$V(H) = \lambda \left(H^\dagger H - v^2\right)^2 \quad \longrightarrow \quad |\langle H \rangle| = v \approx 174 \text{ GeV}$$

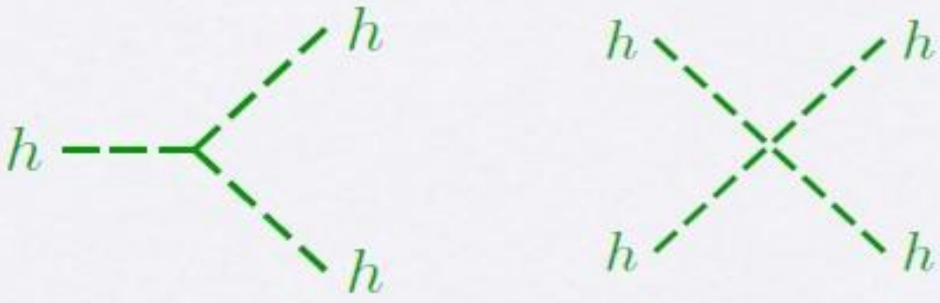
$$= 2\lambda v^2 h^2 + \sqrt{2}\lambda v h^3 + \frac{1}{4}\lambda h^4 \quad \longrightarrow \quad m_h^2 = 4\lambda v^2$$

Thus, within the SM, a measurement of the Higgs mass fixes the remaining free parameter:

$$m_h \approx 125 \text{ GeV} \quad \longrightarrow \quad \lambda \approx 0.13$$

But so far we have no *direct* evidence for λ, i.e. from cubic and quartic Higgs self-interactions!

Measuring these interactions directly would constitute a non-trivial check of the SM



Alternatively: any deviations would indicate a more complicated symmetry breaking sector, i.e. physics beyond the SM!

Gauge boson masses arise from the Higgs “kinetic term”:

$$\mathcal{L}_{\rm SM} \supset (D_\mu H)^\dagger D^\mu H \qquad \text{where} \qquad D_\mu H = (\partial_\mu - igW_\mu - ig'/2\, B_\mu)H$$

↳ **Minimal coupling prescription:** $\partial_\mu \to D_\mu$

The construction that leads to consistent interactions of spin-1 fields:

$$\partial_\mu W^{\mu\nu\, a} = J^{\nu\, a}_{\rm Noether}$$ ← conserved source

Can use gauge invariance to choose:

$$H = e^{i\vec{\chi}\cdot\vec{\tau}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}\, h \end{pmatrix} \quad \longrightarrow \quad H' = U(x)H = \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}\, h \end{pmatrix} \quad \text{with} \;\; U(x) = e^{-i\,\vec{\chi}(x)\cdot\vec{\tau}}$$

In this (unitary) gauge:

$$(D_\mu H')^\dagger D^\mu H' = \frac{1}{2}\partial_\mu h \partial^\mu h + (v + \frac{1}{\sqrt{2}} h)^2 \times \begin{pmatrix} 0 & 1 \end{pmatrix} (gW'_\mu + g'/2\, B'_\mu)^2 \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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$$(D_\mu H')^\dagger D^\mu H' = \frac{1}{2}\partial_\mu h \partial^\mu h + (v + \frac{1}{\sqrt{2}}h)^2 \times \begin{pmatrix} 0 & 1 \end{pmatrix} (g W'_\mu + g'/2\, B'_\mu)^2 \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

From the h-independent terms, we read the gauge boson masses:

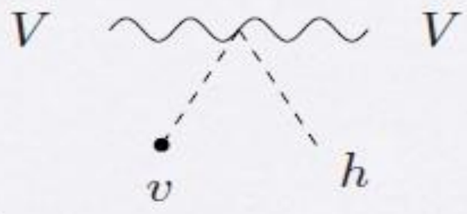
$$M_W = g\, v/\sqrt{2} \qquad\qquad M_Z = \sqrt{g^2 + g'^2}\, v/\sqrt{2}$$

where

$$W^\pm_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp i W^2_\mu) \qquad Z^0_\mu = c_W W^3_\mu + s_W B_\mu \qquad t_W = \tan\theta_W = g'/g$$

This leads to one important prediction: $M_W = c_W M_Z$

The interactions between the Higgs boson and the massive gauge bosons are also fixed:



$ig M_V \eta_{\mu\nu}$

Knows about EWSB!

$i(M_V^2/v^2)\eta_{\mu\nu}$

The SM fermions come in the simplest (smallest) representations: singlets or fundamental

$$\underbrace{\begin{matrix} Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \\ \\ L_L^i = \begin{pmatrix} \nu_L^i \\ l_L^i \end{pmatrix} \end{matrix}}_{SU(2)_L \text{ doublets}} \qquad \underbrace{\begin{matrix} u_R^i \\ d_R^i \\ \\ l_R^i \end{matrix}}_{\text{singlets}} \qquad \begin{matrix} \left.\vphantom{\begin{matrix} u \\ d \end{matrix}}\right\} SU(3)_C \text{ triplets} \\ \\ \left.\vphantom{\begin{matrix} u \\ d \end{matrix}}\right\} SU(3)_C \text{ singlets} \end{matrix}$$

$$\boxed{\begin{aligned} Y_Q &= 1/6 \\ Y_u &= 2/3 \\ Y_d &= -1/3 \\ Y_L &= 1/2 \\ Y_l &= -1 \end{aligned}}$$

($i = 1, 2, 3$ label the three generations)

The EW part is chiral, i.e. the quantum numbers for LH and RH fermions are different!

With the SM Higgs doublet, we can write the following gauge invariant terms:

$$\mathcal{L}_{\text{SM}} \supset -\overline{Q}_L \tilde{H} \lambda_u u_R - \overline{Q}_L H \lambda_d d_R - \overline{L}_L H \lambda_e l_R + \text{h.c.} \qquad \tilde{H} \equiv i\sigma^2 H^* = \begin{pmatrix} H^{0*} \\ -H^- \end{pmatrix}$$

Yukawa matrices

With the SM Higgs doublet, we can write the following gauge invariant terms:

$$\mathcal{L}_{\rm SM} \supset -\overline{Q}_L \tilde{H} \lambda_u u_R - \overline{Q}_L H \lambda_d d_R - \overline{L}_L H \lambda_e l_R + \text{h.c.}$$

$$= -(v + \frac{1}{\sqrt{2}} h) \left[\overline{u}_L \lambda_u u_R + \overline{d}_L \lambda_d d_R + \overline{l}_L \lambda_e l_R + \text{h.c.} \right]$$ (in unitary gauge)

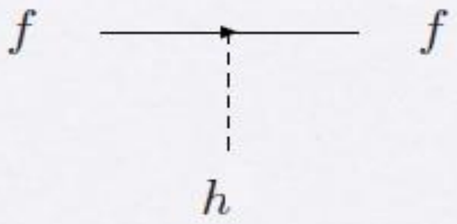
One can furthermore diagonalize the Yukawa matrices (and choose real, positive eigenvalues) by rotating independently the LH and RH components (in generation space)

(the rotation matrices appear only in the interactions with the charged W's: the CKM matrix)

One notices that:

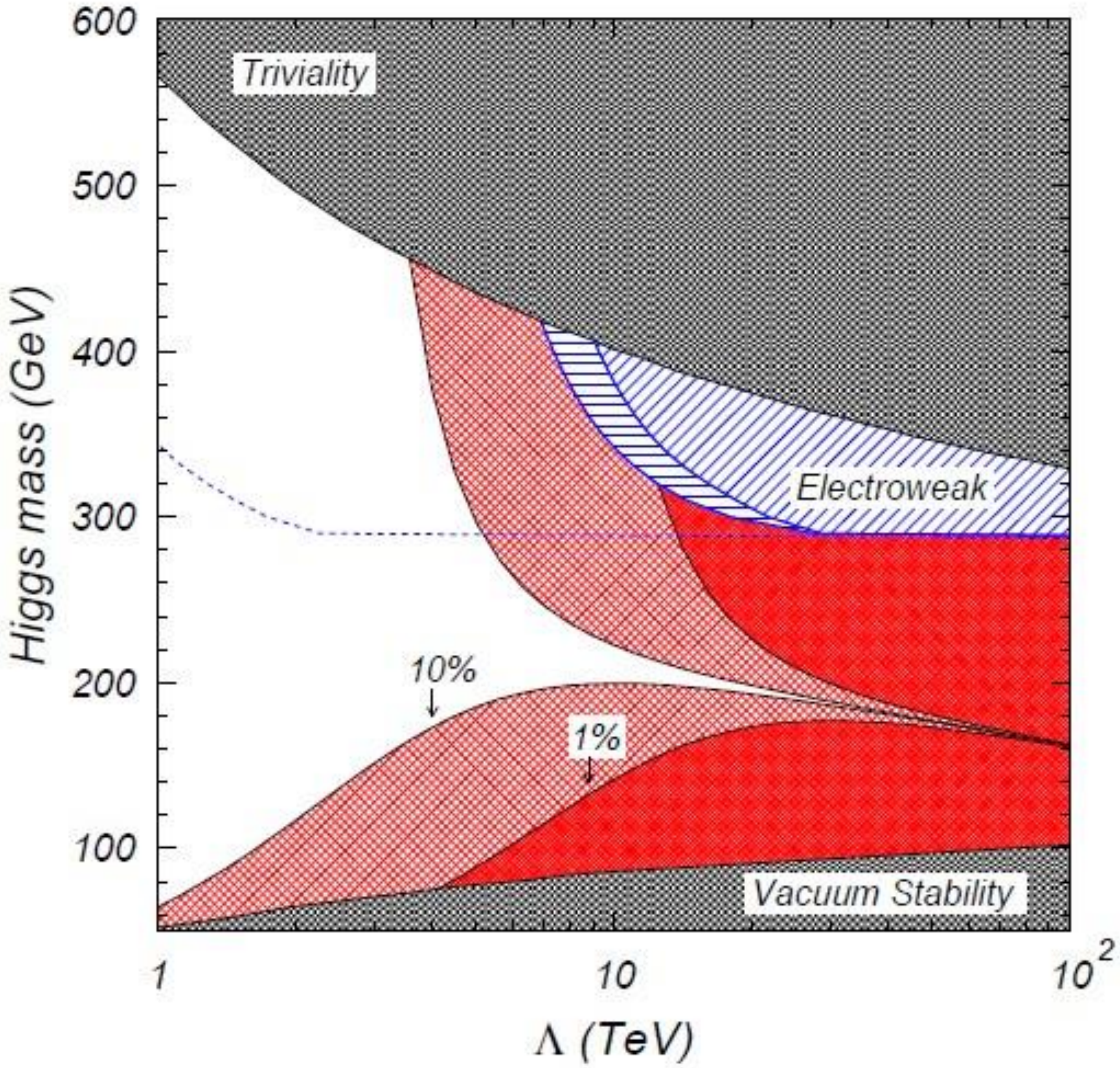
the eigenvalues above

- The Higgs VEV leads to fermion masses: $m_f = \lambda_f v$
- There are Yukawa interactions proportional to the fermion mass:



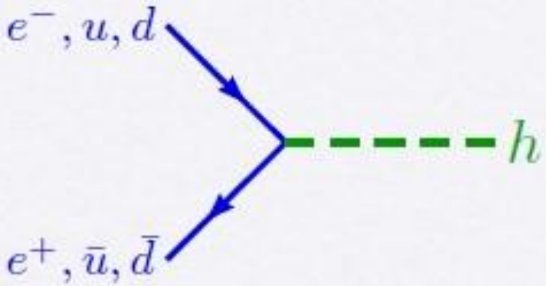
Hence the discovery of the Higgs boson amounts to the discovery of new, non-gauge interactions!

… and with a very distinctive pattern of strengths!


Triviality
Electroweak
10%
1%
Vacuum Stability
Higgs mass (GeV)
600
500
400
300
200
100
1
10
10^2
Λ (TeV)

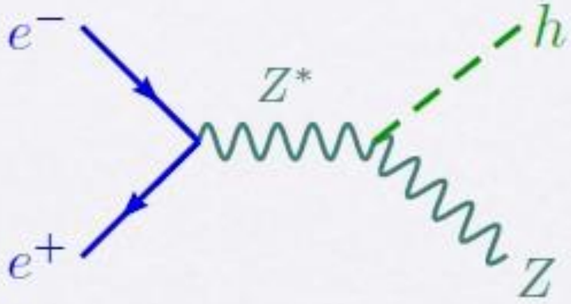
We have seen that the Higgs couples most strongly to the heavier particles…

… but our beams (and, modulo DM, our universe) are made mostly of the lightest particles!

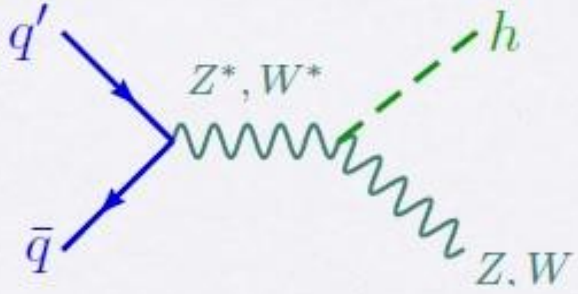


Hopeless!

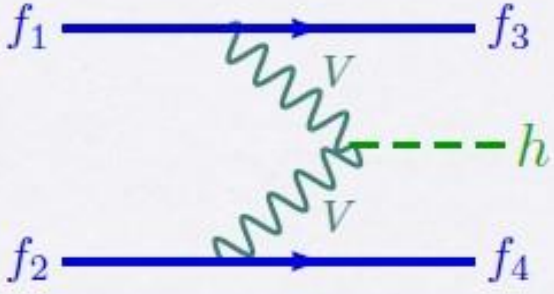
Rather, look for processes involving the heavy gauge bosons:



(At leptons colliders)

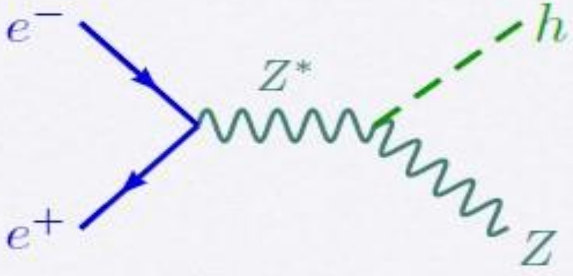


(At hadron colliders)

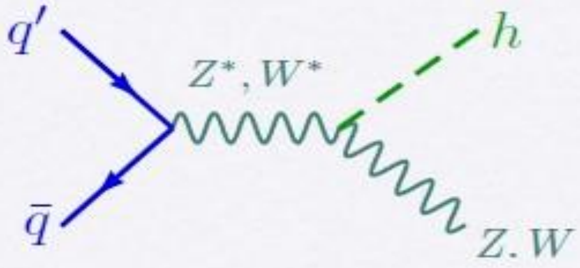


(Vector Boson Fusion or VBF)

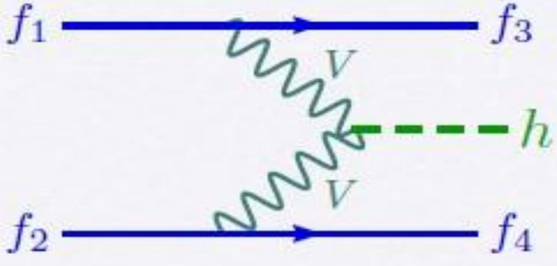
Rather, look for processes involving the heavy gauge bosons:



(At leptons colliders)

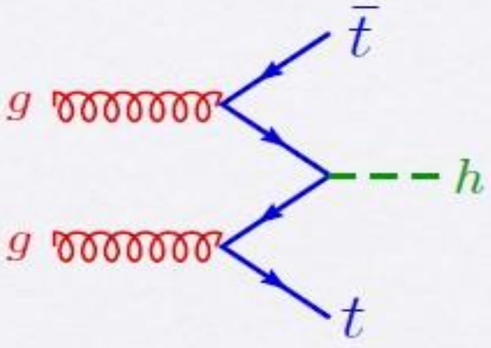


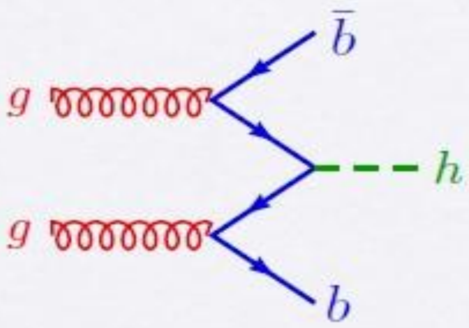
(At hadron colliders)



(Vector Boson Fusion or VBF)

Or the heavier fermions:

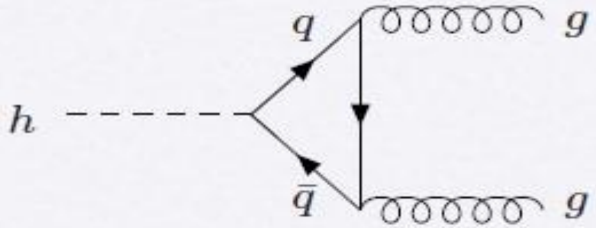




- **Directly sensitive to the top Yukawa coupling!**
- **Pays phase space price**
- **Challenging, but doable at the LHC**

- **Pays price of small bottom Yukawa coupling**
- **Pays phase space price**
- **Enhanced in some BSM scenarios!**

There is another way in which heavy particles can affect Higgs physics: while, being colorless, the Higgs boson does not couple to gluons at tree-level, at loop level one has:



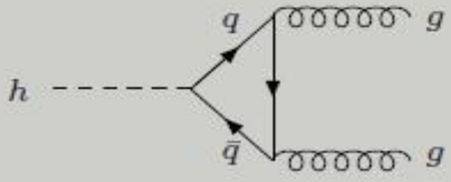
$$\boxed{\mathcal{L}_{hgg}^{\rm eff} = \frac{g\alpha_s N_g}{24\pi M_W}\, h\, G_{\mu\nu}^a G_a^{\mu\nu}}$$

$$N_g = \frac{3}{4}\sum_i A_{1/2}(\tau_i) \qquad \tau_i = \frac{m_h^2}{4m_{q_i}^2}$$

$$A_{1/2}(\tau) \to \begin{cases} 4/3 & \text{for } \tau \ll 1 \\ 0 & \text{for } \tau \gg 1 \end{cases}$$

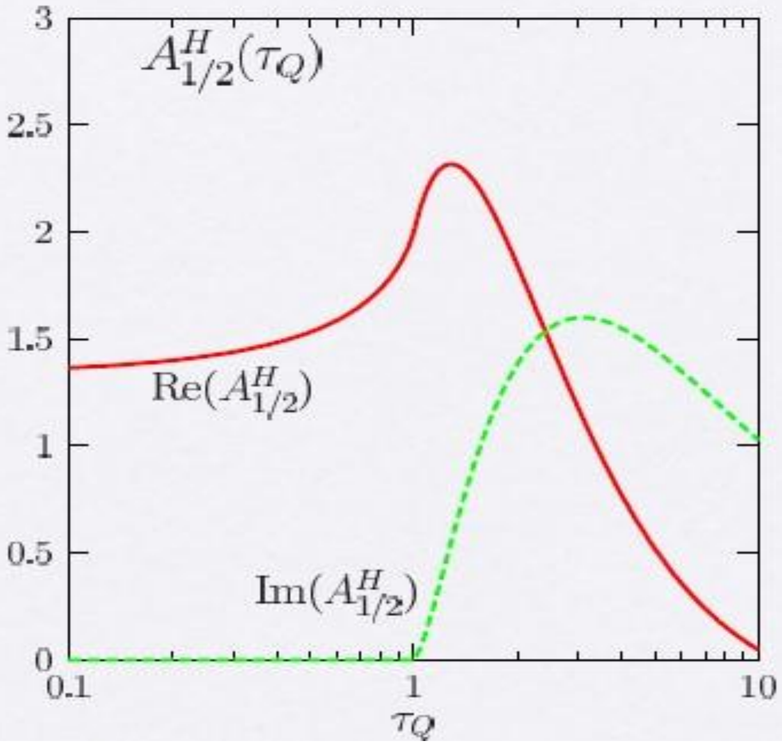
N_g counts roughly the number of quarks heavier than h (the top in the SM case)

Aside: *non-decoupling*

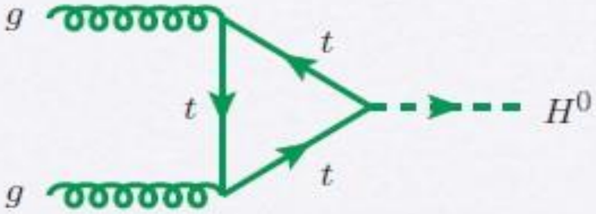


$$\sim \frac{\lambda_t g_s^2}{16\pi^2} \times \frac{1}{m_t} \sim \frac{g_s^2}{16\pi^2 v}$$

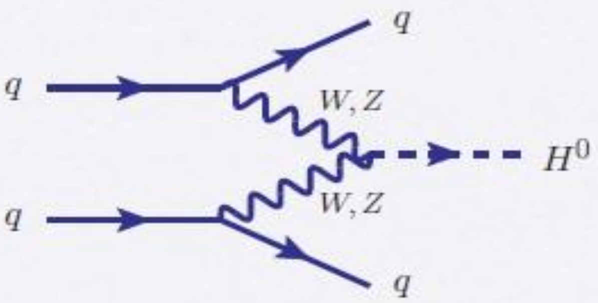
- Fourth generation of quarks would induce a cross section about nine times larger, hence highly disfavored!
- However, heavy fermions that do not owe most of their mass to EWSB can be allowed.



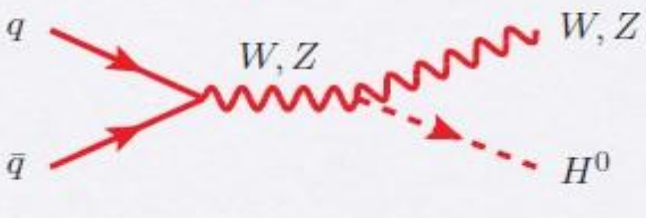
"Gluon fusion"



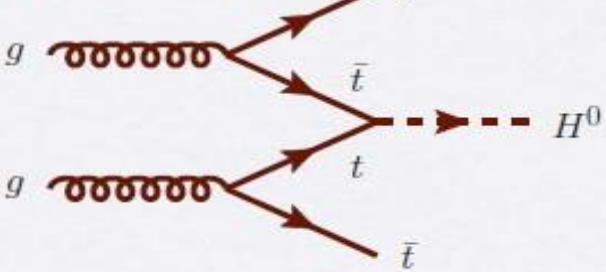
"Vector boson fusion" or $qq \to qqh$



"Associated production with W or Z"



tth

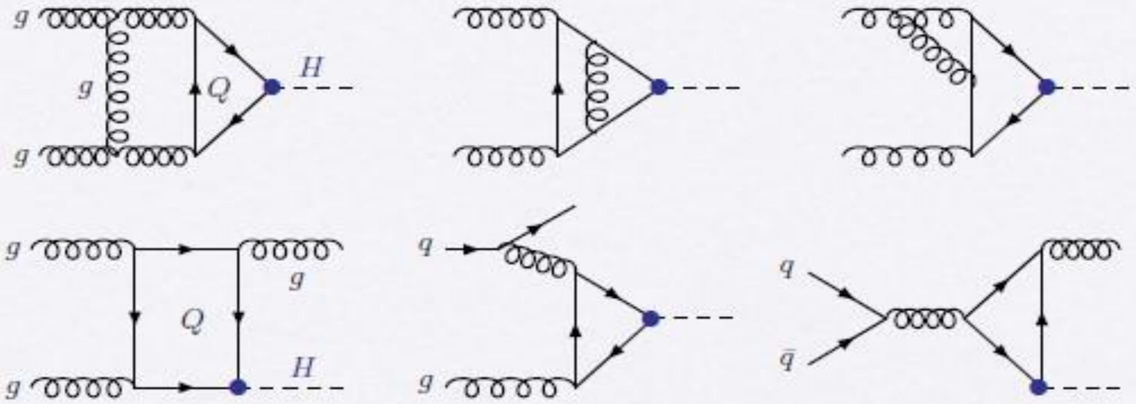


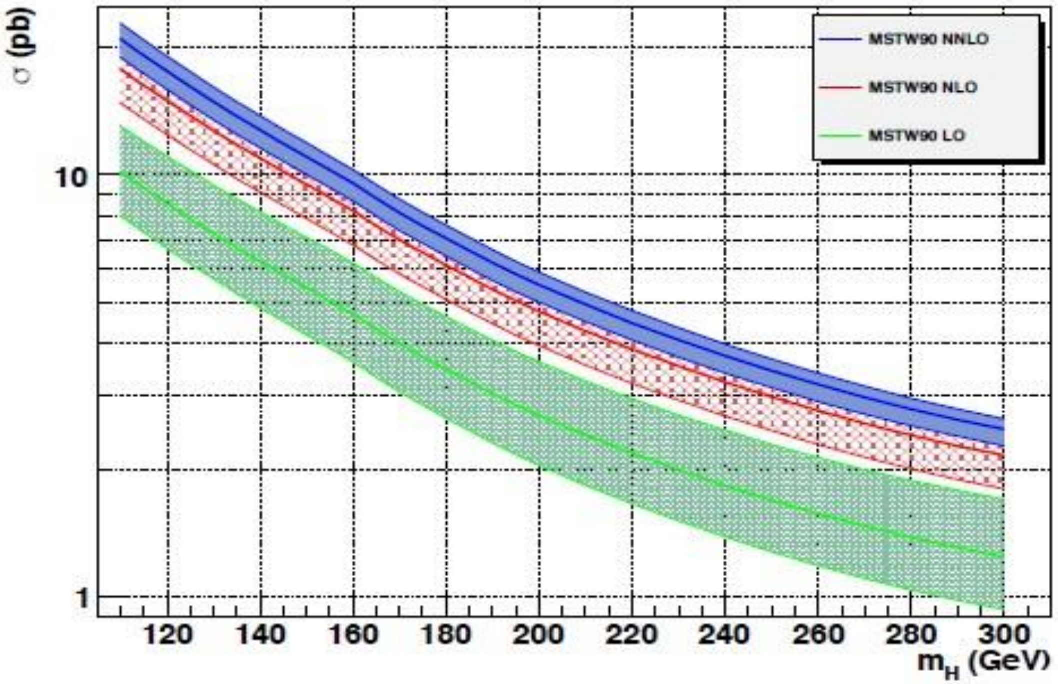
It turns out that the previous ``leading order" contribution to ``gluon fusion" receives large radiative corrections from QCD (even EW corrections must be included).

Some representative examples of next-to-leading order (NLO) diagrams are shown:

$$K_{\mathrm{NLO}} \equiv \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \sim 1.6 \ !$$

Higher-order corrections exhibit convergence

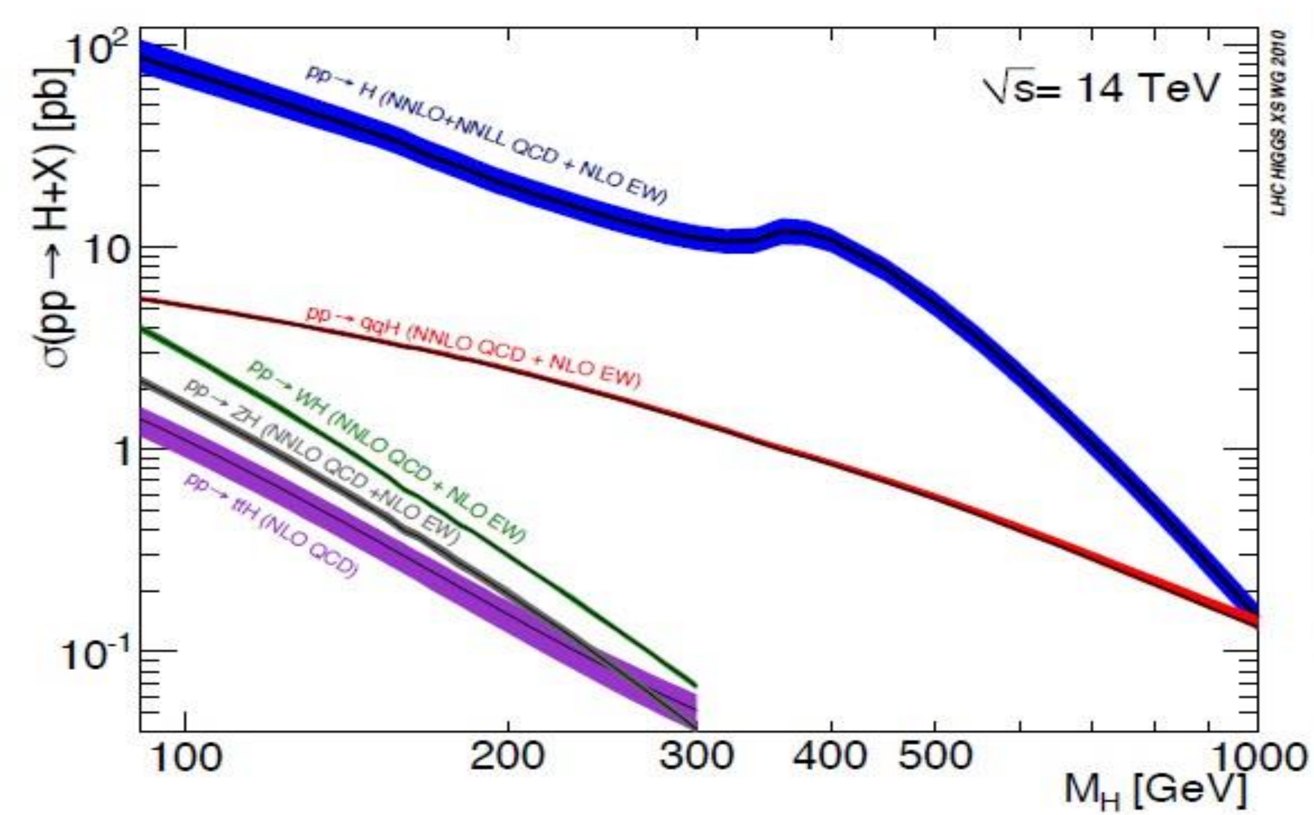




Anastasiou et. al. arXiv:1107.0683

Inclusive production cross section:

- QCD at NNLO:
  - Bottom + top quark mass effects exact to NLO
  - NNLO in large top mass limit
- NNLO partons
- NLO EW corrections (5%)
- Partial QCD N3LO partons
- Estimate for mixed EW-QCD corrections



Leading-order convolution with PDF's:

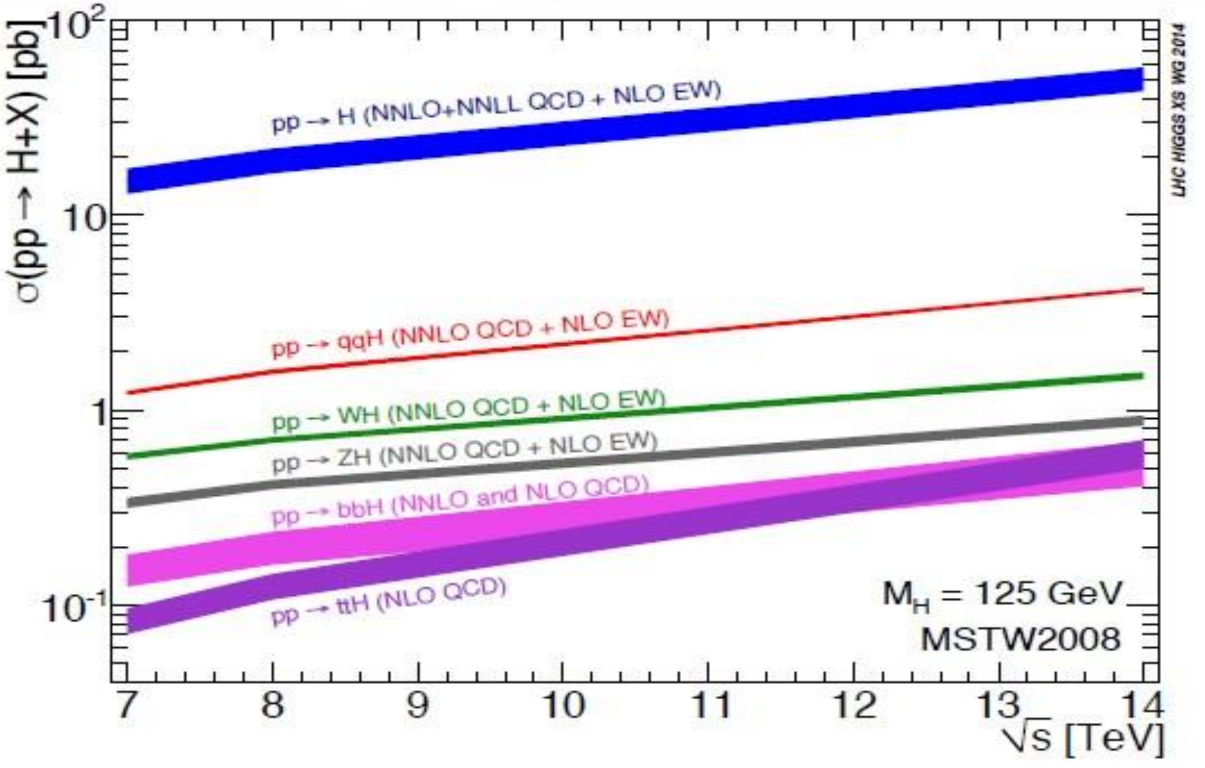
$$\sigma_{\rm LO}(pp \to h) = \sigma_0\, \tau\, \frac{d\mathcal{L}^{gg}}{d\tau}$$

$$\sigma_0 = \frac{G_\mu \alpha_s^2(\mu_R^2)|N_g|^2}{288\sqrt{2}\pi}$$

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x, \mu_F^2) g(\tau/x, \mu_F^2)$$

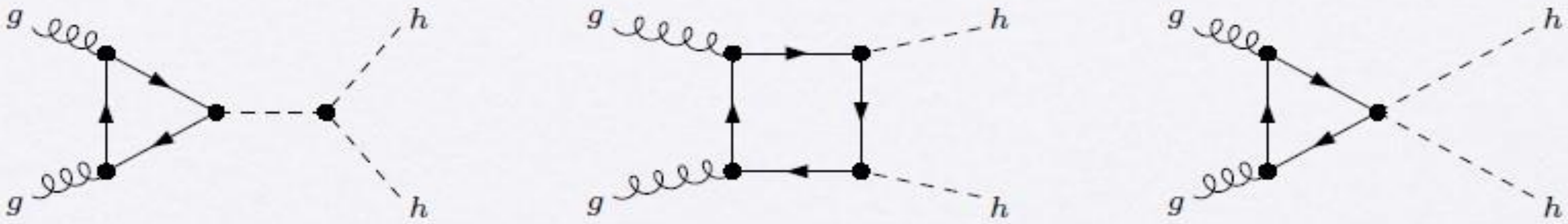
8 TeV → 14 TeV

Factor of ~ 3

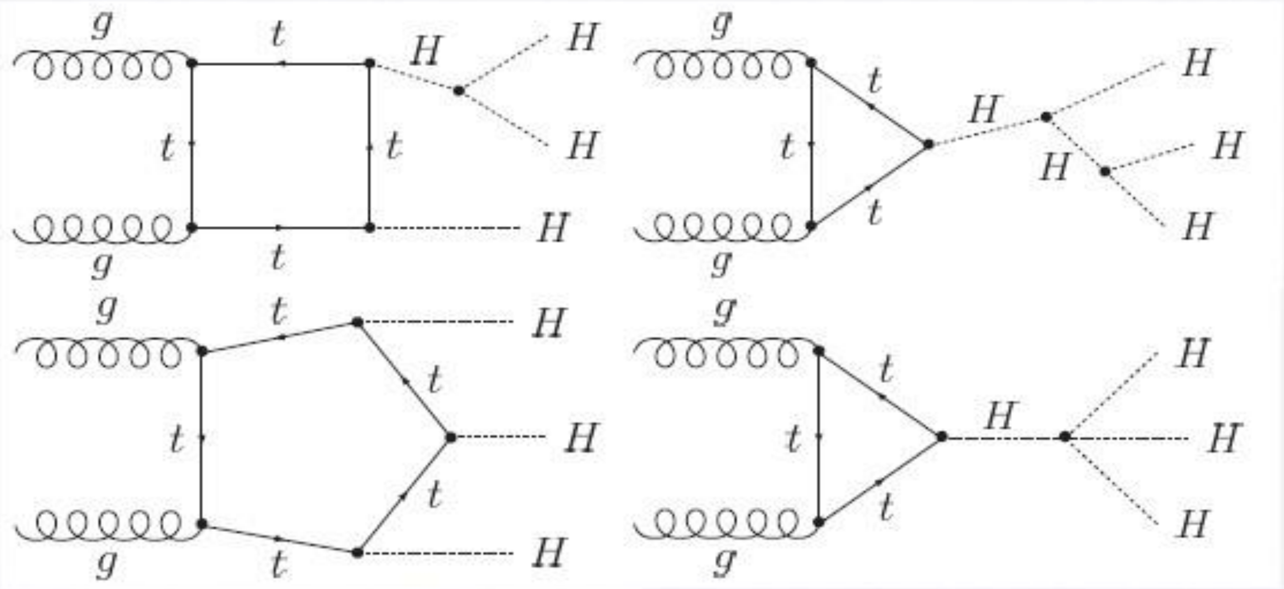


The Higgs boson can also be pair produced. At the LHC, the main production channel is again gluon fusion, and again the higher-order corrections need to be included.

From a theoretical perspective, double-Higgs production gives a handle on the trilinear interaction:



Aside comment:



The quartic self-interaction would enter in triple-Higgs production.

Unfortunately, this appears extremely challenging at any foreseeable collider…

Given that $m_h \approx 125 \text{ GeV}$, the two-body decays $h \to t\bar{t}$, $h \to ZZ$ and $h \to W^+W^-$ are forbidden by energy conservation.

Therefore, the 2-body decays are dominated by $b\bar{b}$, followed by $\tau^+\tau^-$, $c\bar{c}$. The decays into lighter fermions $(s, \mu, d, u, e, \nu' s)$ are much further suppressed.

Using that the relevant fermions are much lighter than the Higgs:

$$\Gamma(h \to l^+l^-) \approx \frac{G_\mu m_h}{4\sqrt{2}\pi}\, \bar{m}_l^2(m_h)$$

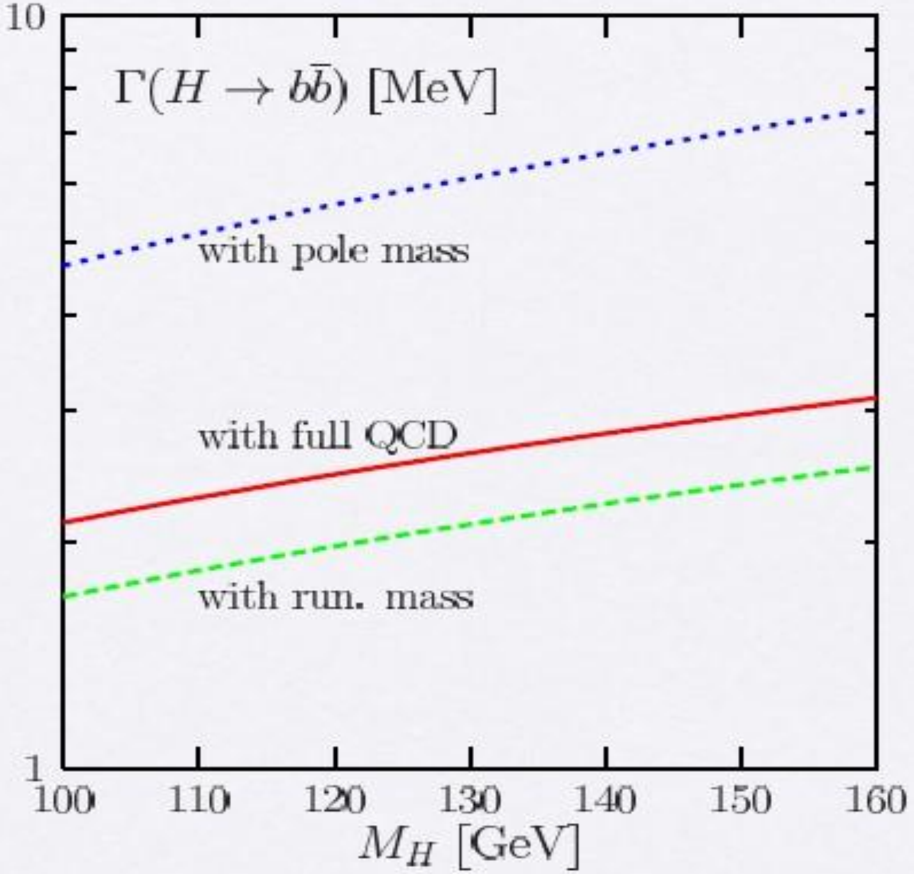
$$\Gamma(h \to q\bar{q}) \approx \frac{3G_\mu m_h}{4\sqrt{2}\pi}\, \bar{m}_q^2(m_h) \left[1 + 5.67\, \frac{\bar{\alpha}_s(m_h)}{\pi} + \mathcal{O}(\bar{\alpha}_s^2)\right]$$

Note that:

$$m_b^{\text{pole}} \approx 4.9 \text{ GeV} \quad \Big| \quad \bar{m}_b(m_h) \approx 2.8 \text{ GeV}$$

$$m_c^{\text{pole}} \approx 1.7 \text{ GeV} \quad \Big| \quad \bar{m}_c(m_h) \approx 0.6 \text{ GeV}$$

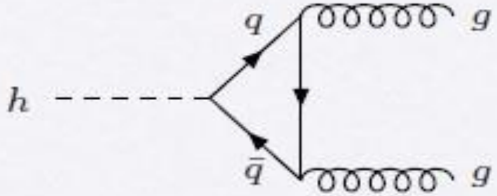
$$m_\tau^{\text{pole}} \approx 1.7 \text{ GeV} \quad \Big| \quad \bar{m}_\tau(m_h) \approx 1.7 \text{ GeV}$$



We have seen that the loop-induced coupling to gluons ends up being the dominant one for Higgs production. Also that the dominant 2-body decay is into bottom quark pairs. Since

$$\lambda_b = \frac{m_b}{v} \approx 0.02 \ \sim \ \frac{1}{16\pi^2}$$

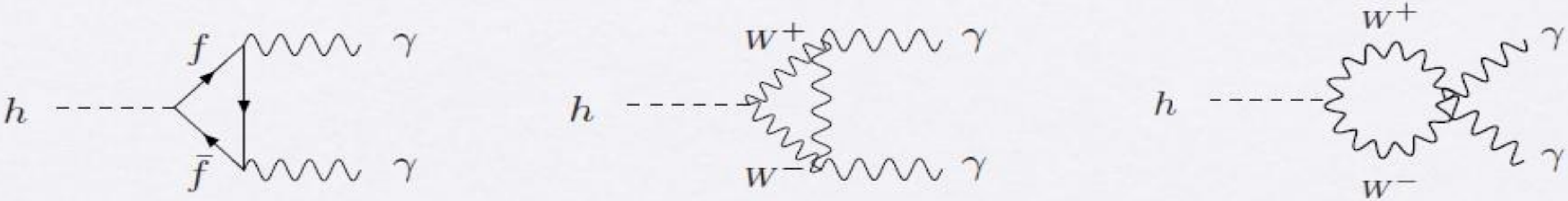
Can expect the decay into gluons to be sizable



$$\Gamma_{\mathrm{LO}} = \frac{8m_h^3}{\pi^2}\,\sigma_0$$

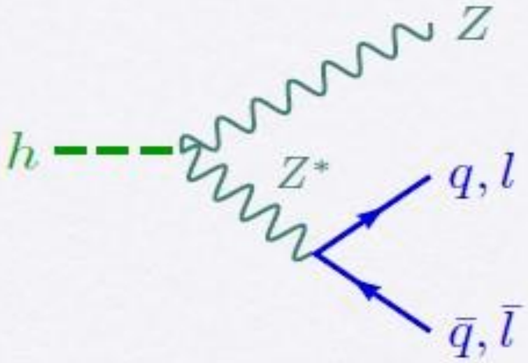
tree-level gluon fusion (parton level)

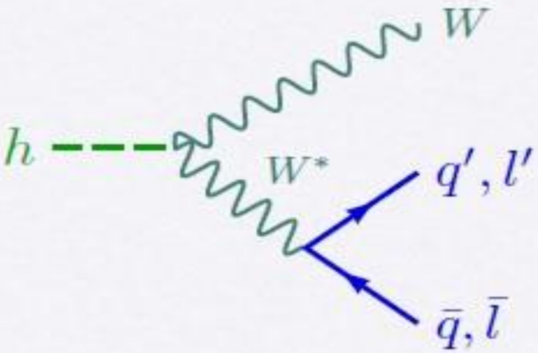
Similarly, a coupling of the (neutral) Higgs boson to two photons is induced at 1-loop order:



While suppressed, due to the great sensitivity to photons of our detectors, this loop-induced coupling is extremely important (discovery channel)! *There is also a coupling of photon + Z.*

Each additional particle in the final state leads to a suppression of about one-loop factor. Hence, we should expect the following 3-body decays to be relevant.



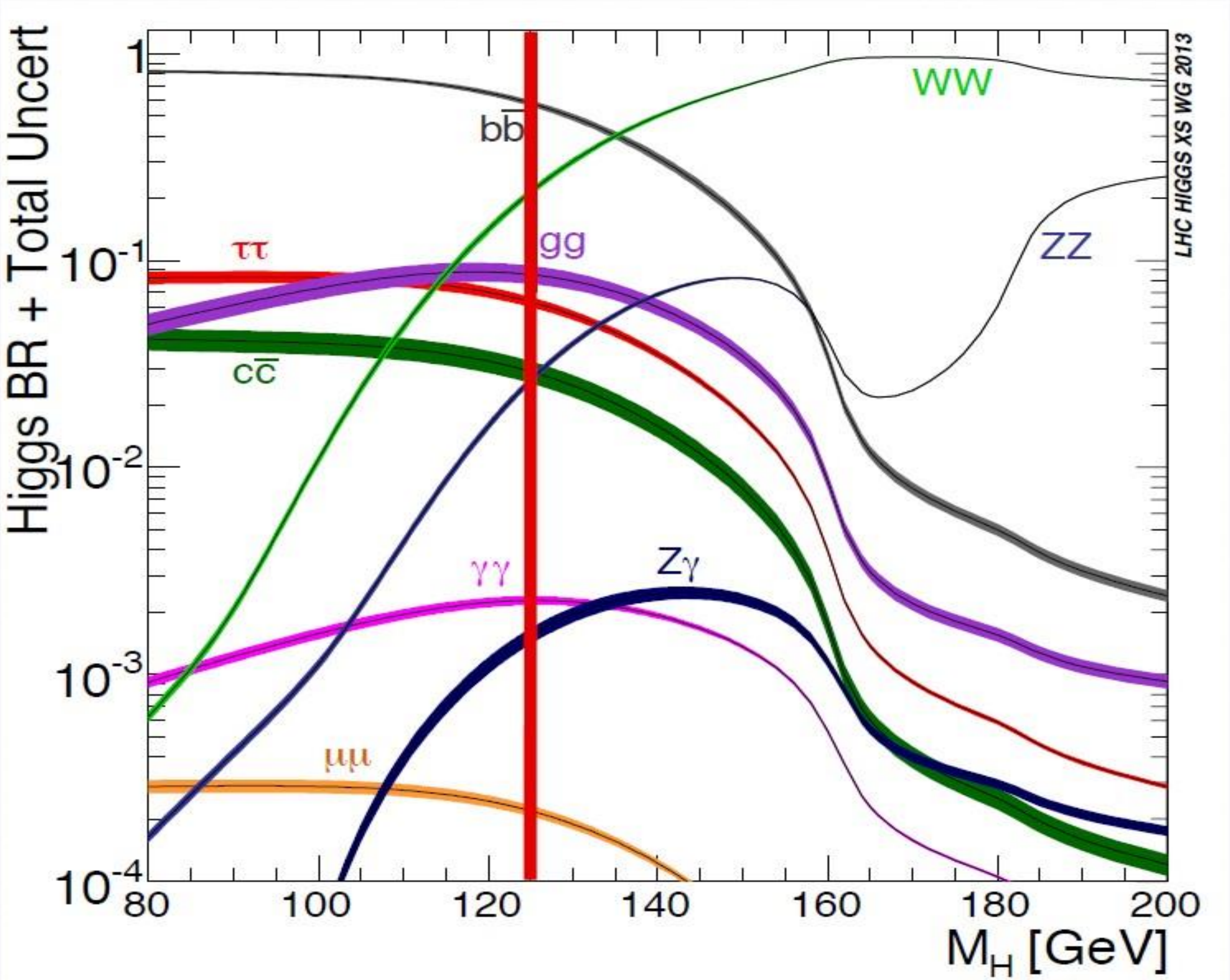


Recall that these vertices are a direct consequence of EWSB!

$$\Gamma(h \to VV^*) = \frac{3G_\mu^2 M_V^4}{16\pi^3}\, m_h \delta'_V R_T(M_V^2/m_h^2)$$

$$\delta'_W = 1,\ \delta'_Z = \tfrac{7}{12} - \tfrac{10}{9}\sin^2\theta_W + \tfrac{40}{9}\sin^4\theta_W$$

$$R_T(x) = \frac{3(1-8x+20x^2)}{(4x-1)^{1/2}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)\log x$$



$m_h \approx 125$ GeV

$\mathrm{BR}(b\bar{b}) \approx 0.6$

$\mathrm{BR}(WW) \approx 0.20$

$\mathrm{BR}(gg) \approx 0.077$

$\mathrm{BR}(\tau\bar{\tau}) \approx 0.06$

$\mathrm{BR}(c\bar{c}) \approx 0.026$

$\mathrm{BR}(ZZ) \approx 0.025$

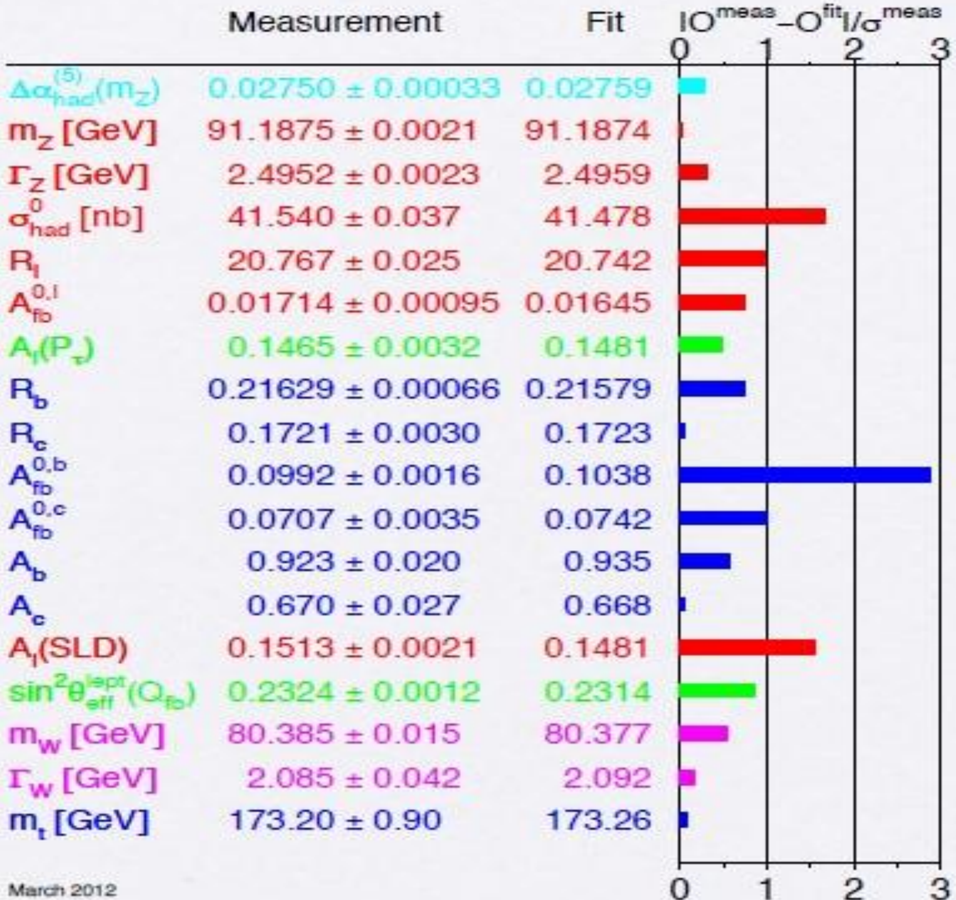
$\mathrm{BR}(\gamma\gamma) \approx 0.002$

$\mathrm{BR}(Z\gamma) \approx 0.001$

$\Gamma_{\mathrm{Tot}} \approx 4.4$ MeV

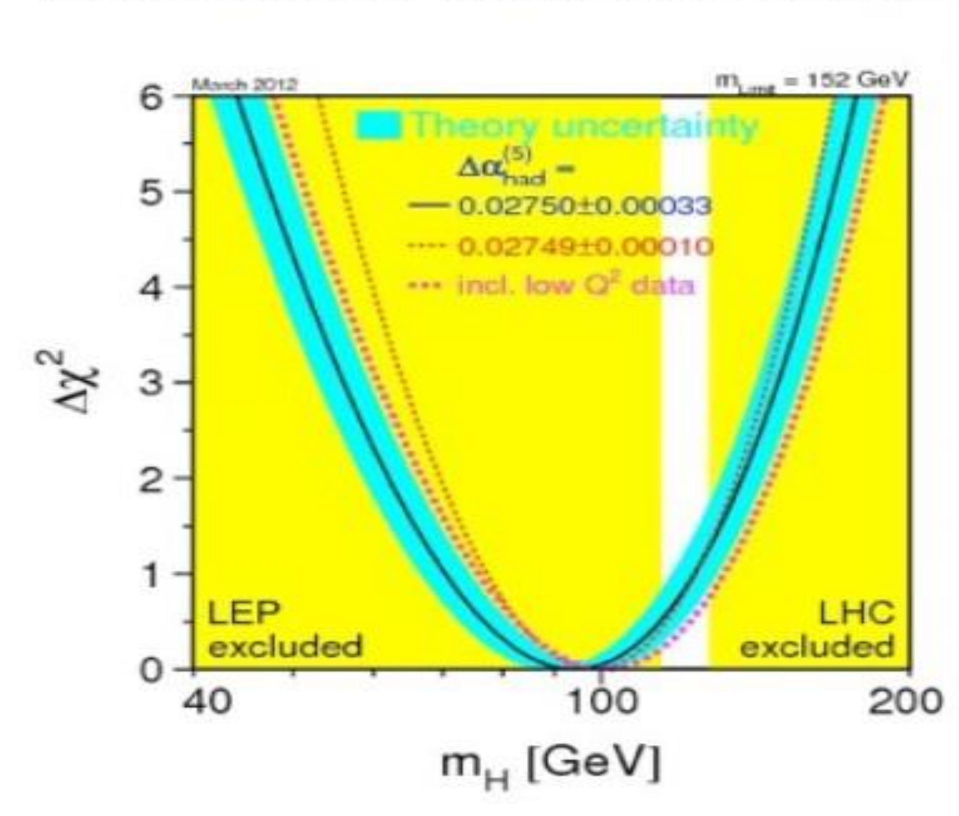
The W and Z masses receive corrections that depend logarithmically on m_h

These self-energy contributions affect several EW observables (oblique corrections)

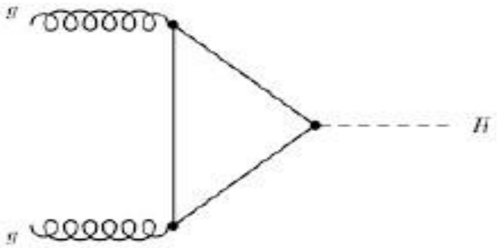


	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	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

Previous indirect determination of m_h



LHC is the Higgs factory and the only place to study Higgs physics directly today



At 13 TeV, the production cross section for the Higgs boson, dominated by gluon-gluon fusion, is ~50 pb

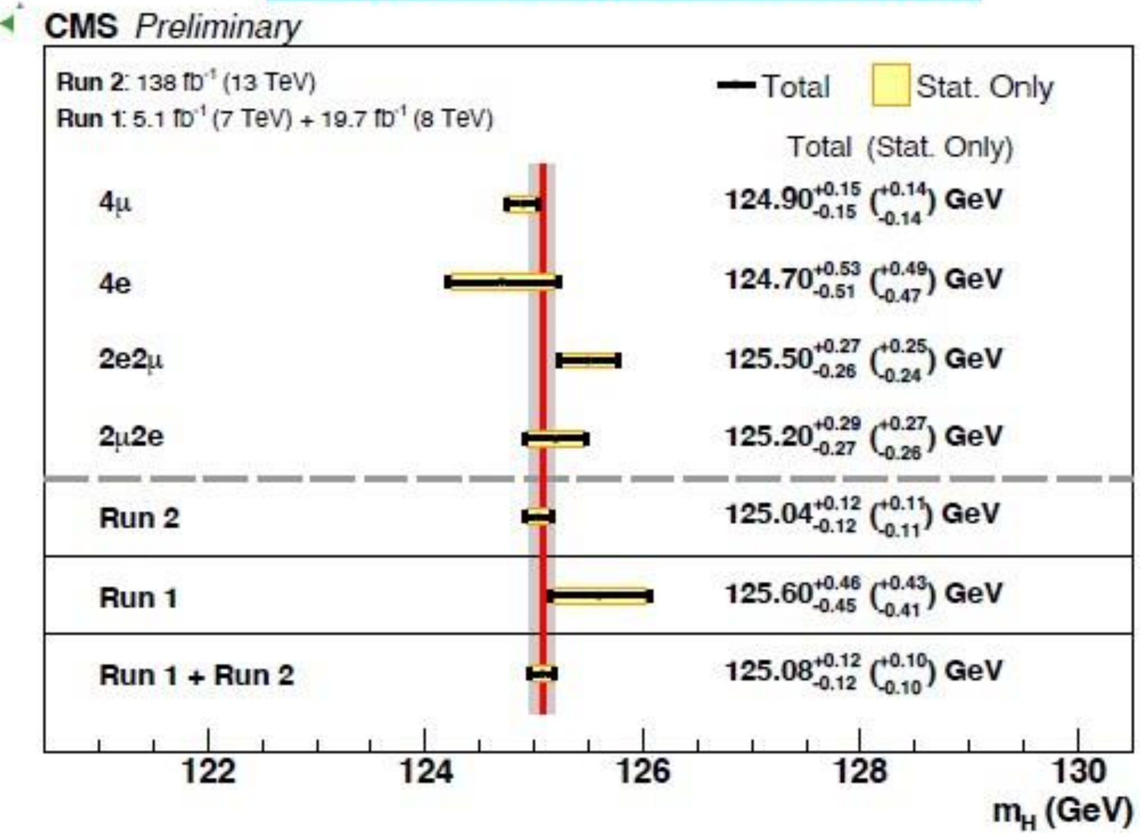
- 15M Higgs bosons delivered by the LHC in Run 2!
- By now ATLAS and CMS *could* have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
- With the cross section @13.6 TeV of ~60 pb another 12M have been already delivered in Run 3!

But: triggering is a big challenge:

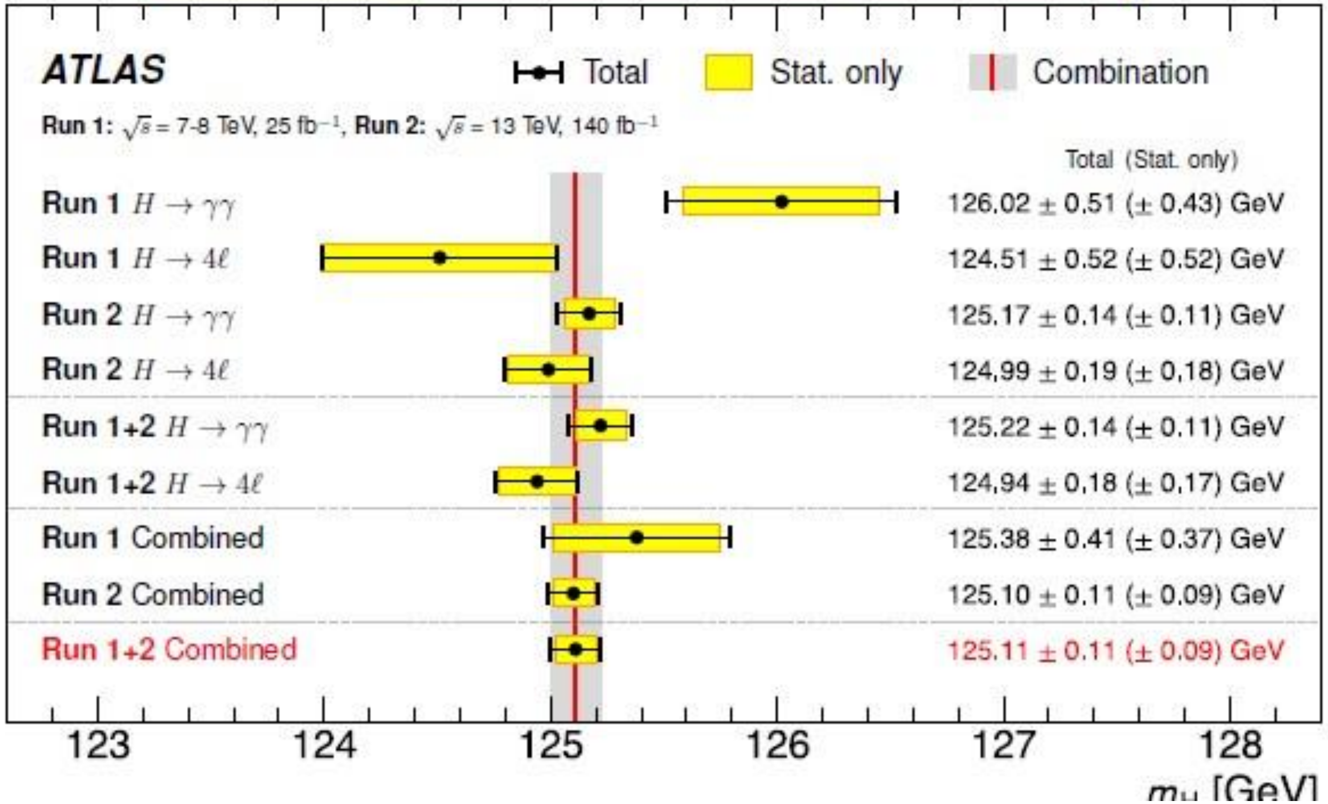
- Most of gg → H(bb) events were never put on tape, which is how half of Higgs bosons at the LHC are produced and decay

Need to pursue aggressive triggering strategies and go for lower cross section production mechanisms to observe all possible Higgs boson decays and couplings

CMS PAS HIG-21-019



ATLAS PRL 131 (2023) 251802



An important constraint arises from the “rho parameter”. At tree-level it reads

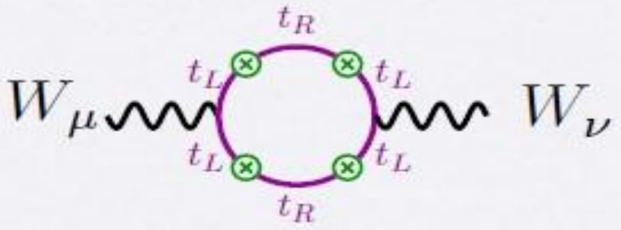
$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = \frac{\sum_{T,Y} [T(T+1) - Y^2] |V_{T,Y}|^2 c_{T,Y}}{\sum_{T,Y} 2Y^2 |V_{T,Y}|^2}$$

which has been written for an arbitrary Higgs sector. Here we have

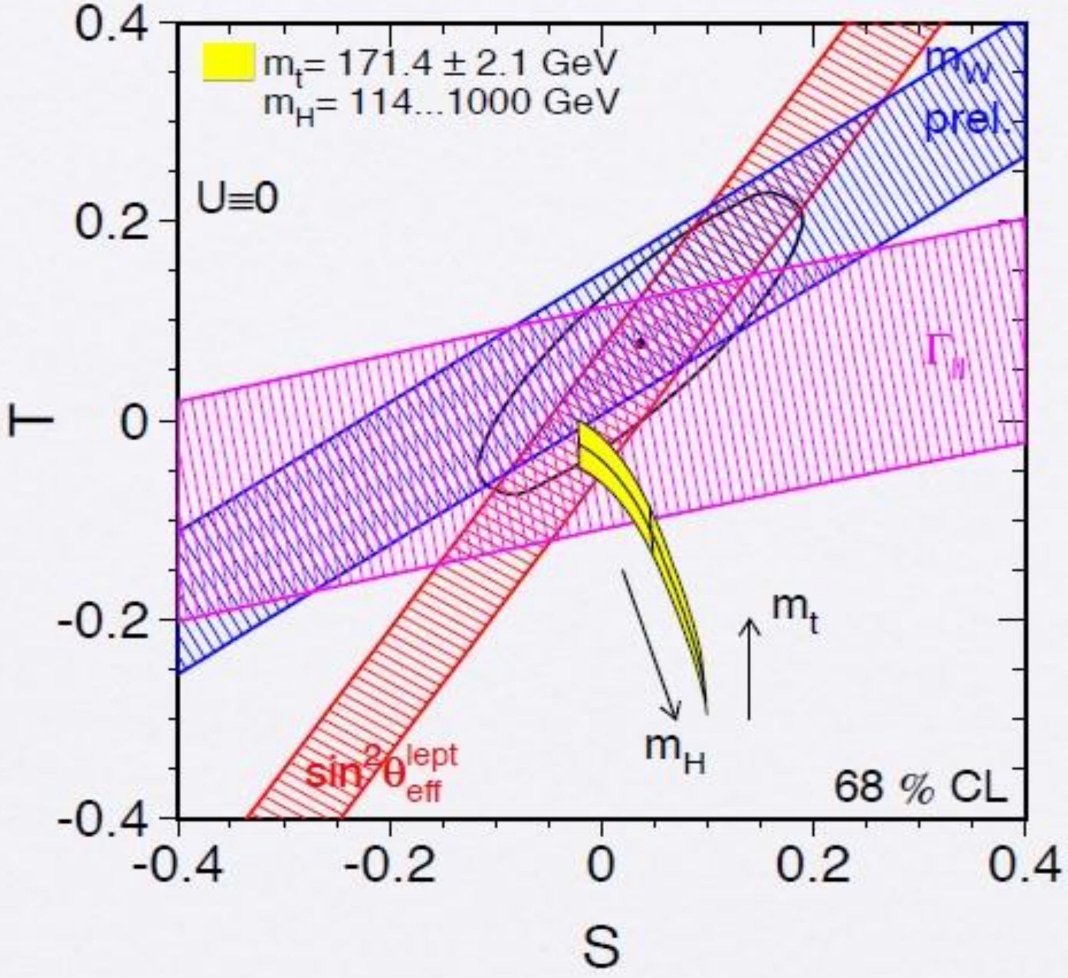
- T and Y : total SU(2) isospin and hypercharge of Higgs representation
- $V_{T,Y} = \langle \phi(T,Y) \rangle$, the vev of the corresponding Higgs with quantum numbers T and Y
- $c_{T,Y} = \begin{cases} 1 & (T,Y) \in \text{complex representation} \\ \frac{1}{2} & (T,Y=0) \in \text{real representation} \end{cases}$
- Normalization: $Q = T^3 + Y$

Experimentally, rho is very close to one, as predicted in the SM $(T = Y = 1/2)$

There are also small loop corrections, most importantly from the top quark



The oblique corrections (dominant) are often parameterized in terms of the Peskin-Takeuchi S and T parameters. A fit to the EW observables looks like this...



This is another way of displaying the preference, within the SM, for a light Higgs

However, indirect measurement were never considered definitive, since new physics typically gives important contributions to S and T!

(that could allow reentering the ellipse)

The fact that the Higgs turned out to be light gives further indication that nature does not like to play dirty tricks (conspiracies that lead to cancellations)!

$$\rho = 1 + \alpha T$$

The Standard Model of particle physics

Conclusions

The Standard Model of particle physics

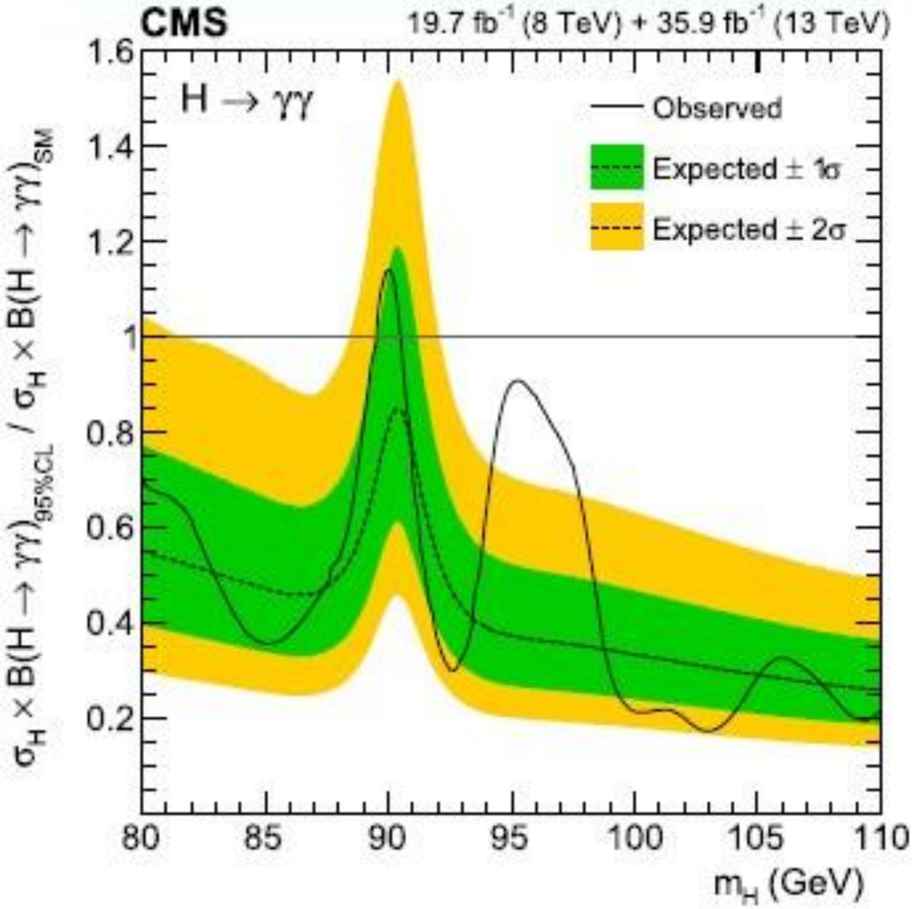
Conclusions

Wait, there is more

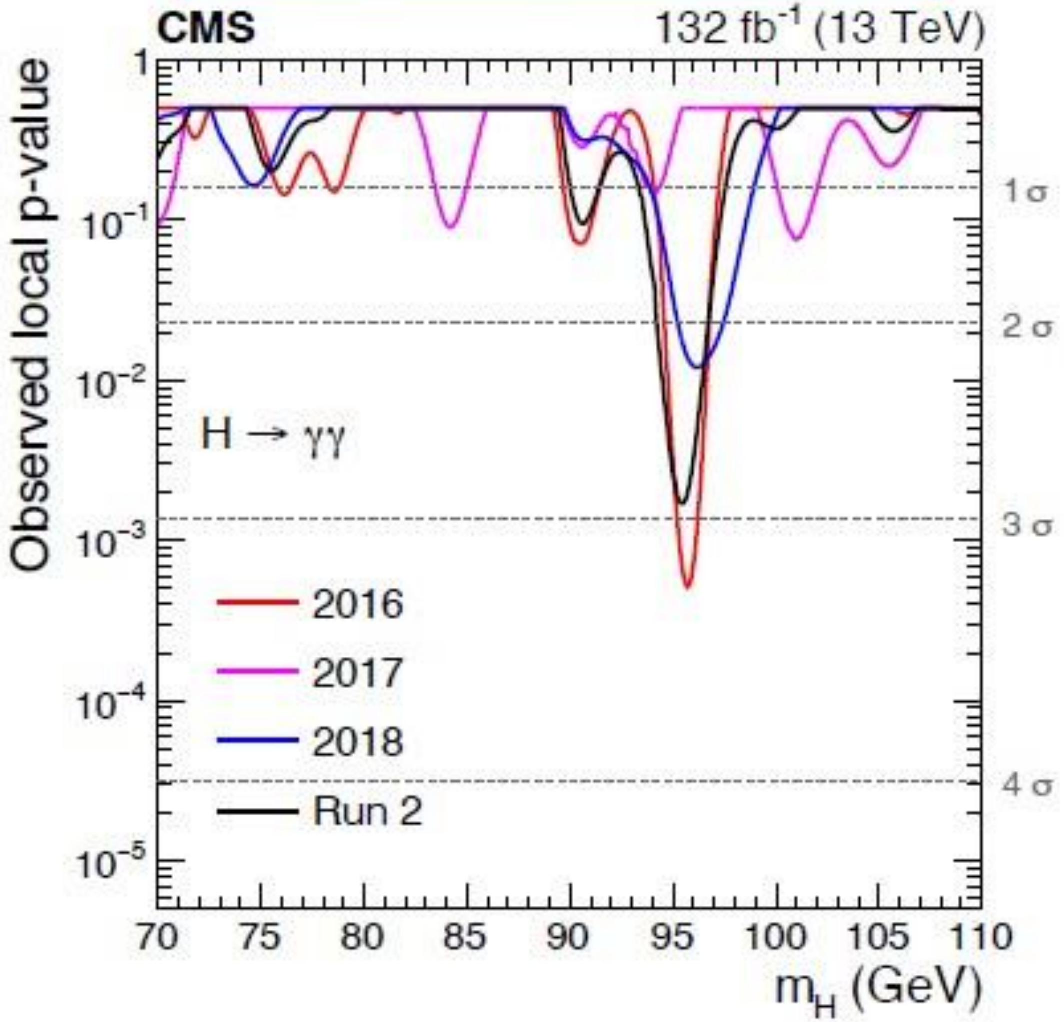
Beyond Standard Model

The 95 GeV Puzzle

CMS PLB 793 (2019) 320

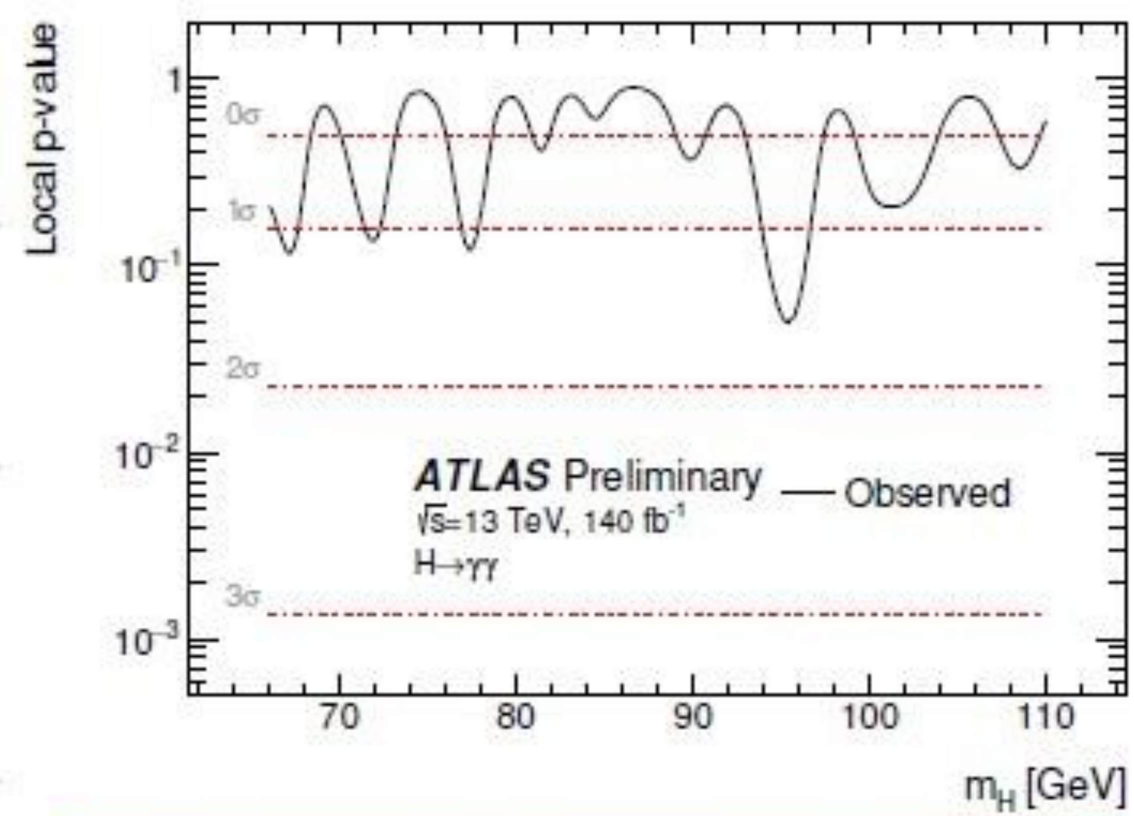


CMS arXiv:2405.18149



The Standard Model of particle physics

The 95 GeV Puzzle



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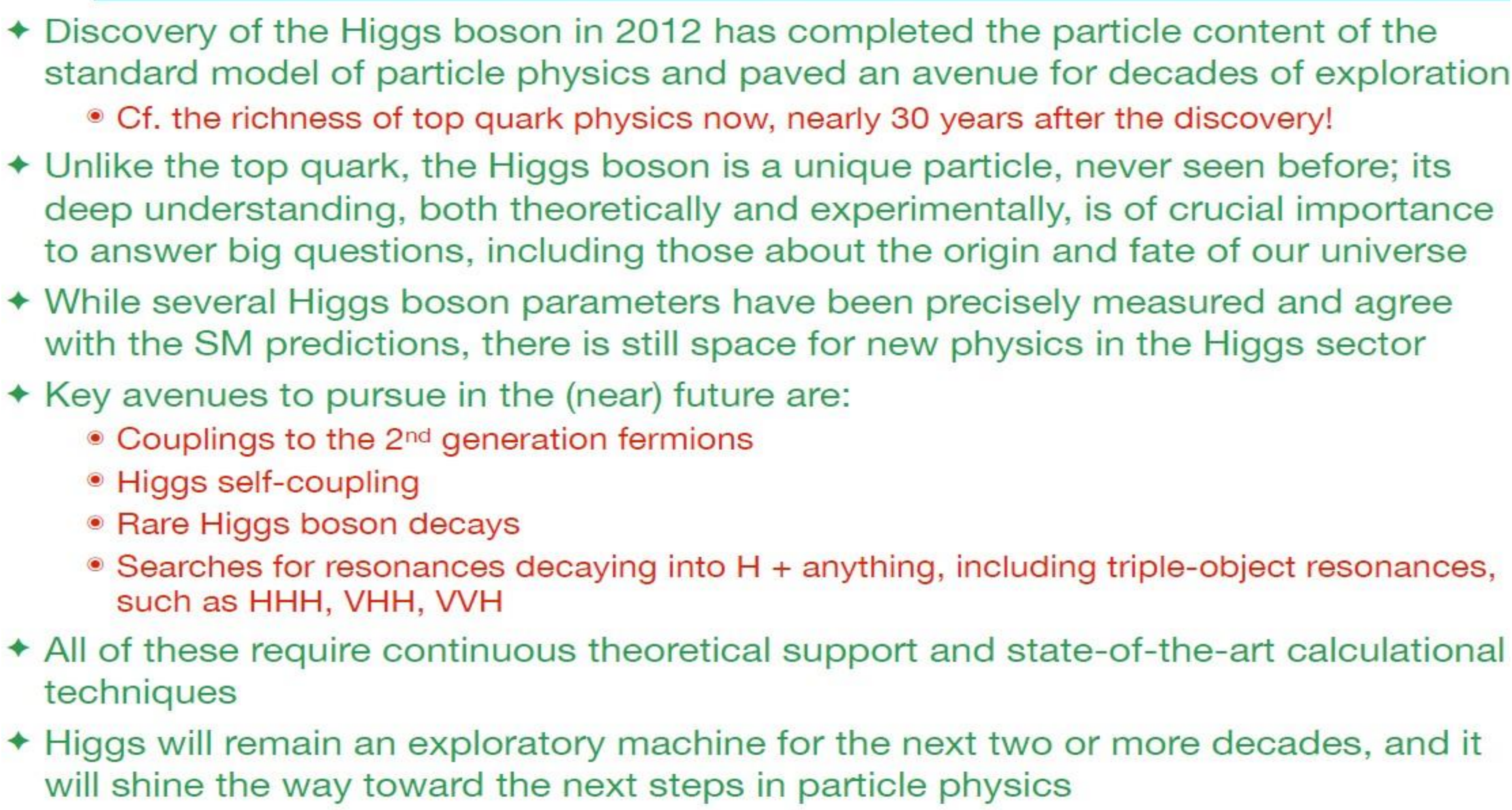
The Standard Model of particle physics



- Discovery of the Higgs boson in 2012 has completed the particle content of the standard model of particle physics and paved an avenue for decades of exploration
  - Cf. the richness of top quark physics now, nearly 30 years after the discovery!
- Unlike the top quark, the Higgs boson is a unique particle, never seen before; its deep understanding, both theoretically and experimentally, is of crucial importance to answer big questions, including those about the origin and fate of our universe
- While several Higgs boson parameters have been precisely measured and agree with the SM predictions, there is still space for new physics in the Higgs sector
- Key avenues to pursue in the (near) future are:
  - Couplings to the 2nd generation fermions
  - Higgs self-coupling
  - Rare Higgs boson decays
  - Searches for resonances decaying into H + anything, including triple-object resonances, such as HHH, VHH, VVH
- All of these require continuous theoretical support and state-of-the-art calculational techniques
- Higgs will remain an exploratory machine for the next two or more decades, and it will shine the way toward the next steps in particle physics