The Awesome Workshop Matplotlib for HEP

matplotlib

Alexander Moreno Briceño

UAN UNIVERSIDAD ANTONIO NARIÑO

April 21-22, 2022

HSF HEP Software Foundation iris hep

Outline of Training

- Introduction
- Physics background
- A HEP-based example: the Higgs search
- HEP style plotting with mplhep
- One more challenge: plot the dimuon spectrum

Outline of Training

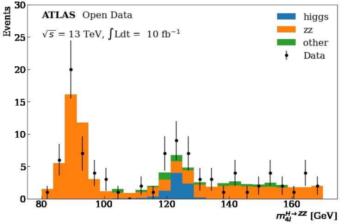
- Introduction
- **Physics background**
- A HEP-based example: the Higgs search
- HEP style plotting with mplhep
- One more challenge: plot the dimuon spectrum

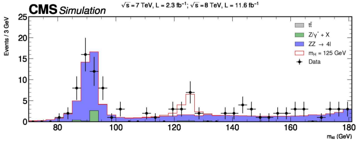
We are here to help!

There is no such thing as a "stupid question"!
There is no such thing as a "silly question"!

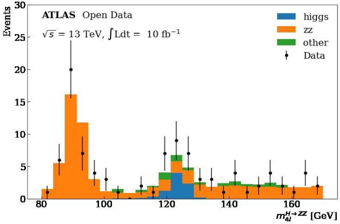
PHYSICS BACKGROUND

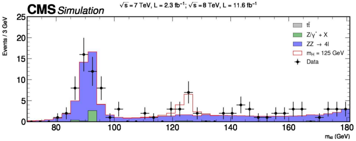
PHYSICS BACKGROUND





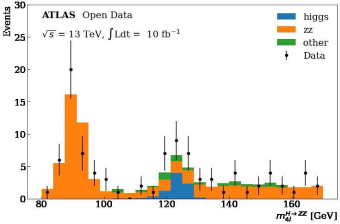
PHYSICS BACKGROUND

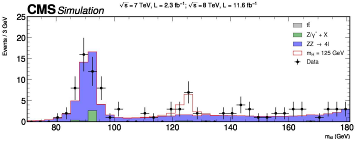




- What is the physics behind the data?

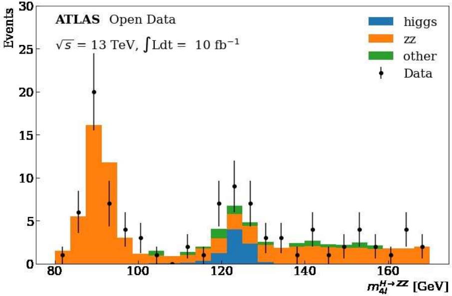
PHYSICS BACKGROUND





- What is the physics behind the data?
- Learn the basics of the physics processes present in the data

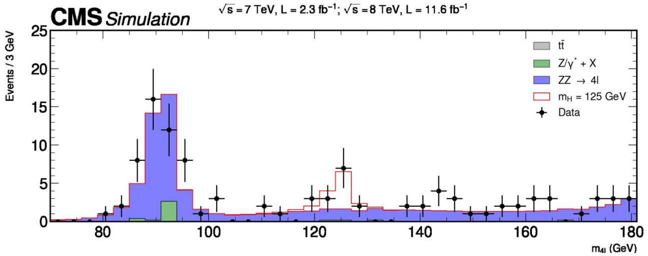
A HEP-based example: the Higgs search



The decay of the Standard Model Higgs boson to two Z bosons and subsequently to four leptons, this is known as a golden channel.

Using the ATLAS data collected during 2016 at a center-of-mass energy of 13 TeV, equivalent to 10 fb^{-1} of integrated luminosity.

HEP style plotting with mplhep



The decay of the Standard Model Higgs boson to two Z bosons and subsequently to four leptons, this is known as a golden channel.

Using the CMS data collected during 2011 – 2012.

Outline

Outline

- The LHC Experiments

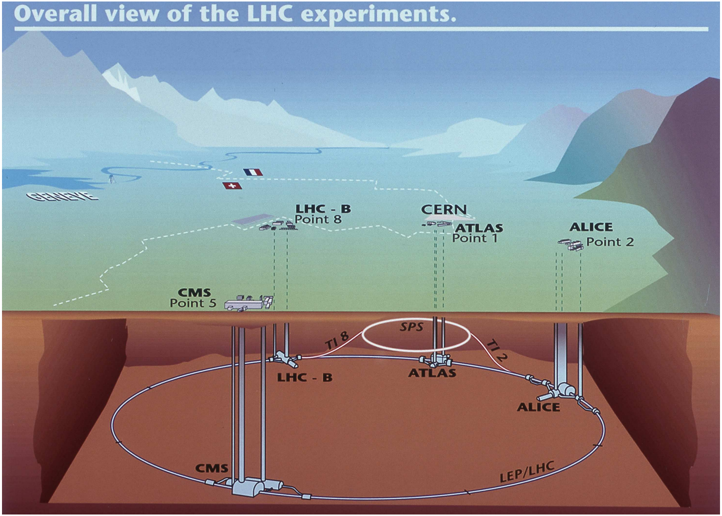
Outline

- The LHC Experiments
- The Standard Model (SM)

Outline

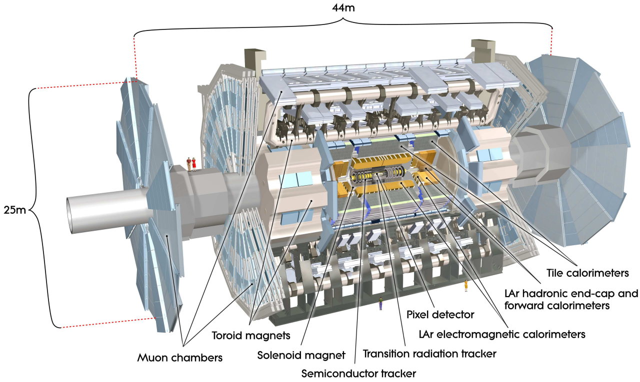
- The LHC Experiments
- The Standard Model (SM)
  - Spontaneous Symmetry Breaking (SSB) and Mass Generation: The Higgs Mechanism in the SM
  - Decays of the SM Higgs Boson

The LHC Experiments



https://cds.cern.ch/record/40525

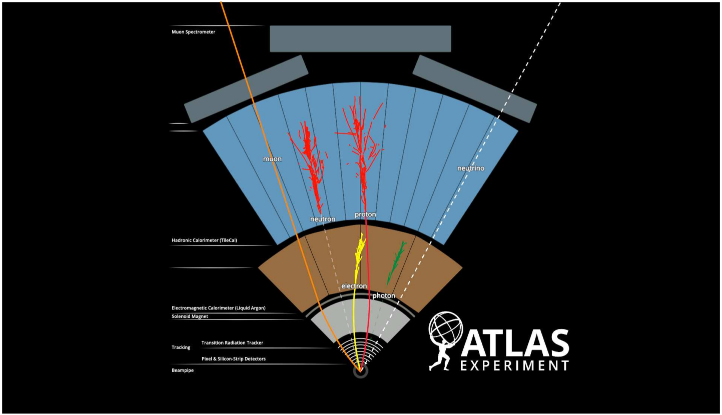
A Toroidal LHC Apparatus: The ATLAS Detector



https://cds.cern.ch/record/1095924

The ATLAS detector has the dimensions of a cylinder, 46 *m* long, 25 *m* in diameter, and weighs 7,000 tonnes.

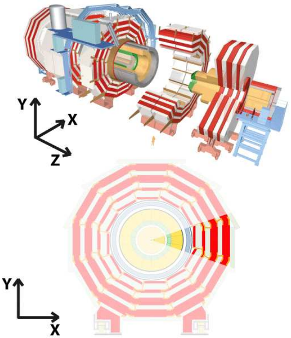
A Toroidal LHC Apparatus: The ATLAS Detector

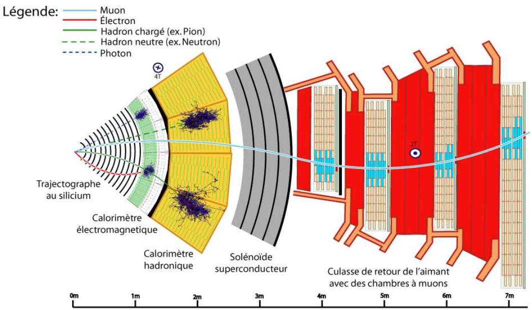


https://cds.cern.ch/record/2770815

The ATLAS detector has the dimensions of a cylinder, 46 *m* long, 25 *m* in diameter, and weighs 7,000 tonnes.

Compact Muon Solenoid: The CMS Detector

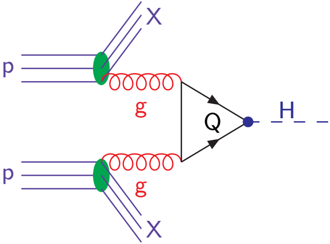




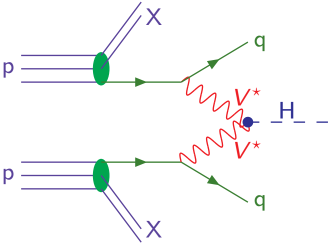
https://cds.cern.ch/record/2204863

The CMS detector has the dimensions of a cylinder, 21 m long, 15 m in diameter, and weighs 14,000 tonnes.

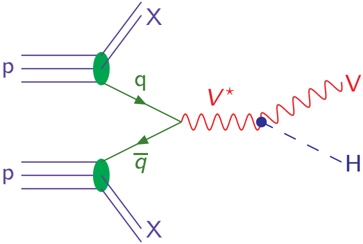
Higgs Production Mechanisms at the LHC



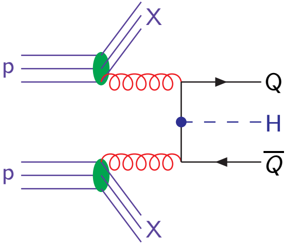
Gluon Fusion



Vector Boson Fusion

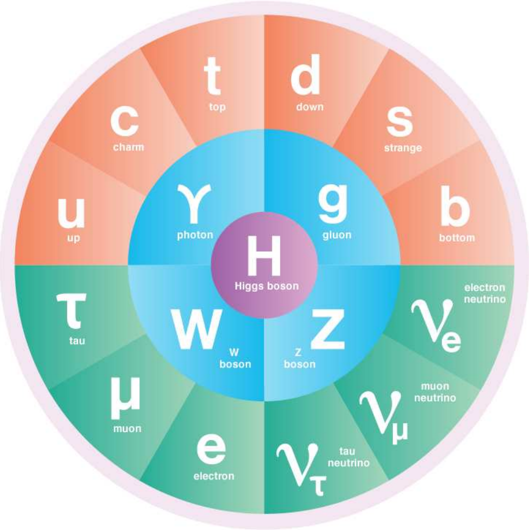


Higgs-strahlung



in Association with $Q\overline{Q}$

The Standard Model (SM)



https://www.symmetrymagazine.org/standard-model/

The SM Lagrangian

The SM Lagrangian

The SM is a quantum field theory that is based on the gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y .$$

The SM Lagrangian

The SM is a quantum field theory that is based on the gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y.$$

This gauge group includes the symmetry group of the strong interactions, $SU(3)_C$, and the symmetry group of the electroweak (EW) interactions, $SU(2)_L \times U(1)_Y$.

The EW theory is based on the $SU(2)_L \times U(1)_Y$ lagrangian

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{fermions} + \mathcal{L}_{gauge} + \mathcal{L}_{Scalar} + \mathcal{L}_{Yuk}$$

The EW theory is based on the $SU(2)_L \times U(1)_Y$ lagrangian

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{fermions} + \mathcal{L}_{gauge} + \mathcal{L}_{Scalar} + \mathcal{L}_{Yuk}$$

where

$$\mathcal{L}_{fermions} = \overline{L}_i iD_\mu \gamma^\mu L_i + \overline{e}_{Ri} iD_\mu \gamma^\mu e_{Ri} + \overline{Q}_i iD_\mu \gamma^\mu Q_i + \overline{u}_{Ri} iD_\mu \gamma^\mu u_{Ri} + \overline{d}_{Ri} iD_\mu \gamma^\mu d_{Ri}$$

where $D_\mu = \partial_\mu - ig_2 T_a W_\mu^a - ig_1 \frac{Y_q}{2} B_\mu$.

The EW theory is based on the $SU(2)_L \times U(1)_Y$ lagrangian

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{fermions} + \mathcal{L}_{gauge} + \mathcal{L}_{Scalar} + \mathcal{L}_{Yuk}$$

where

$$\mathcal{L}_{fermions} = \overline{L}_i iD_\mu \gamma^\mu L_i + \overline{e}_{Ri} iD_\mu \gamma^\mu e_{Ri} + \overline{Q}_i iD_\mu \gamma^\mu Q_i + \overline{u}_{Ri} iD_\mu \gamma^\mu u_{Ri} + \overline{d}_{Ri} iD_\mu \gamma^\mu d_{Ri}$$

where $D_\mu = \partial_\mu - ig_2 T_a W_\mu^a - ig_1 \frac{Y_q}{2} B_\mu$.

The gauge part is

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

where $W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon^{abc} W_\mu^b W_\nu^c$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ are the field strength tensors for the $SU(2)$ and $U(1)$ gauge fields, respectively.

The EW theory is based on the $SU(2)_L \times U(1)_Y$ lagrangian

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{fermions} + \mathcal{L}_{gauge} + \mathcal{L}_{Scalar} + \mathcal{L}_{Yuk}$$

The scalar part of the lagrangian is

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

where $V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$.

The EW theory is based on the $SU(2)_L \times U(1)_Y$ lagrangian

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{fermions} + \mathcal{L}_{gauge} + \mathcal{L}_{Scalar} + \mathcal{L}_{Yuk}$$

The scalar part of the lagrangian is

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

where $V(\Phi^{\dagger}\Phi) = \mu^2\Phi^{\dagger}\Phi + \lambda(\Phi^{\dagger}\Phi)^2$.

The Yukawa lagrangian is

$$\mathcal{L}_{Yuk} = -\lambda_e \overline{L}\Phi e_R - \lambda_d \overline{Q}\Phi d_R - \lambda_u \overline{Q}\tilde{\Phi} u_R + h.c.$$

Spontaneous Symmetry Breaking and Mass Generation: The Higgs Mechanism in the SM

Spontaneous Symmetry Breaking and Mass Generation: The Higgs Mechanism in the SM

Experimentally, the weak bosons are massive. We give mass to the gauge bosons through the *Higgs Mechanism*: generate mass terms from the *kinetic energy term* of a *scalar doublet field* Φ that undergoes spontaneous symmetry breaking.

Spontaneous Symmetry Breaking and Mass Generation: The Higgs Mechanism in the SM

Experimentally, the weak bosons are massive. We give mass to the gauge bosons through the *Higgs Mechanism*: generate mass terms from the *kinetic energy term* of a *scalar doublet field* Φ that undergoes spontaneous symmetry breaking.

Introduce a *complex $SU(2)$ doublet of scalar fields*

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; Y_\Phi = +1$$

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

Spontaneous Symmetry Breaking and Mass Generation: The Higgs Mechanism in the SM

Experimentally, the weak bosons are massive. We give mass to the gauge bosons through the *Higgs Mechanism*: generate mass terms from the *kinetic energy term* of a *scalar doublet field* Φ that undergoes spontaneous symmetry breaking.

Introduce a *complex $SU(2)$ doublet of scalar fields*

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; Y_\Phi = +1$$

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

with

$$D_\mu = \partial_\mu - i g_s T_a G_\mu^a - i g_2 T_a W_\mu^a - i g_1 \frac{Y_q}{2} B_\mu$$

$$V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

For $\mu^2 < 0$, the neutral component of Φ will develop a vev

$$< \Phi >_0 \equiv < 0|\Phi|0 > = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

with

$$v = \left(-\frac{\mu^2}{\lambda} \right)^{1/2}$$

For $\mu^2 < 0$, the neutral component of Φ will develop a vev

$$< \Phi >_0 \equiv < 0|\Phi|0 > = \begin{pmatrix} 0 \\ \frac{\upsilon}{\sqrt{2}} \end{pmatrix}$$

with

$$\upsilon = \left(-\frac{\mu^2}{\lambda} \right)^{1/2}$$

The W and Z bosons acquire their masses, while the photon remains massless

$$M_W = \frac{1}{2}\upsilon g_2,$$
$$M_Z = \frac{1}{2}\upsilon\sqrt{g_2^2 + g_1^2},$$
$$M_A = 0$$

What About the Fermion Masses?

We can use the same scalar field Φ to generate the fermion masses, with $Y = +1$, and the isodoublet $\tilde{\Phi} = i\tau_2\Phi^\star$, with $Y = -1$. For any fermion generation, we introduce the $SU(2)_L \times U(1)_Y$ invariant Yukawa lagrangian

$$\mathcal{L}_{Yuk} = -\lambda_e \overline{L}\Phi e_R - \lambda_d \overline{Q}\Phi d_R - \lambda_u \overline{Q}\tilde{\Phi} u_R + h.c.$$

and repeat the same procedure as before.

What About the Fermion Masses?

We can use the same scalar field Φ to generate the fermion masses, with $Y = +1$, and the isodoublet $\tilde{\Phi} = i\tau_2\Phi^\star$, with $Y = -1$. For any fermion generation, we introduce the $SU(2)_L \times U(1)_Y$ invariant Yukawa lagrangian

$$\mathcal{L}_{Yuk} = -\lambda_e \overline{L}\Phi e_R - \lambda_d \overline{Q}\Phi d_R - \lambda_u \overline{Q}\tilde{\Phi} u_R + h.c.$$

and repeat the same procedure as before. Taking for instance only the electron, we get

$$\begin{aligned}\mathcal{L}_{Yuk} &= -\frac{1}{\sqrt{2}} \begin{pmatrix}\overline{\nu}_e & \overline{e}_L\end{pmatrix} \begin{pmatrix}0 \\ \upsilon + H\end{pmatrix} e_R + \dots \\ &= -\frac{1}{\sqrt{2}}\lambda_e(\upsilon + H)\overline{e}_L e_R + \dots\end{aligned}$$

What About the Fermion Masses?

We can use the same scalar field Φ to generate the fermion masses, with $Y = +1$, and the isodoublet $\tilde{\Phi} = i\tau_2 \Phi^\star$, with $Y = -1$. For any fermion generation, we introduce the $SU(2)_L \times U(1)_Y$ invariant Yukawa lagrangian

$$\mathcal{L}_{Yuk} = -\lambda_e \overline{L} \Phi e_R - \lambda_d \overline{Q} \Phi d_R - \lambda_u \overline{Q} \tilde{\Phi} u_R + h.c.$$

and repeat the same procedure as before. Taking for instance only the electron, we get

$$\begin{aligned} \mathcal{L}_{Yuk} &= -\frac{1}{\sqrt{2}} \begin{pmatrix} \overline{\nu}_e & \overline{e}_L \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} e_R + \ldots \\ &= -\frac{1}{\sqrt{2}} \lambda_e (\upsilon + H) \overline{e}_L e_R + \ldots \end{aligned}$$

The constant term in front of $\overline{f}_L f_R$ (and h.c.) is identified with the fermion mass

$$m_e = \frac{\lambda_e \upsilon}{\sqrt{2}}, m_u = \frac{\lambda_u \upsilon}{\sqrt{2}}, m_d = \frac{\lambda_d \upsilon}{\sqrt{2}}$$

The Higgs Particle in the SM

The kinetic part of the Higgs field, $\frac{1}{2}(\partial_\mu H)^2$, comes from the term involving the covariant derivative $|D_\mu \Phi|^2$, while the mass and self-interaction parts, come from the scalar potential

$$
\begin{aligned}
V(\Phi) &= \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \\
&= \frac{\mu^2}{2} \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} + \frac{\lambda}{4} \left| \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} \right|^2
\end{aligned}
$$

The Higgs Particle in the SM

The kinetic part of the Higgs field, $\frac{1}{2}(\partial_\mu H)^2$, comes from the term involving the covariant derivative $|D_\mu \Phi|^2$, while the mass and self-interaction parts, come from the scalar potential

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$
$$= \frac{\mu^2}{2} \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} + \frac{\lambda}{4} \left| \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} \right|^2$$

Using the relation $\upsilon^2 = -\mu^2/\lambda$, we get

$$V = -\frac{1}{2}\lambda \upsilon^2 (\upsilon + H)^2 + \frac{1}{4}\lambda(\upsilon + H)^4$$

The Higgs Particle in the SM

The kinetic part of the Higgs field, $\frac{1}{2}(\partial_\mu H)^2$, comes from the term involving the covariant derivative $|D_\mu \Phi|^2$, while the mass and self-interaction parts, come from the scalar potential

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$
$$= \frac{\mu^2}{2} \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} + \frac{\lambda}{4} \left| \begin{pmatrix} 0 & \upsilon + H \end{pmatrix} \begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix} \right|^2$$

Using the relation $\upsilon^2 = -\mu^2/\lambda$, we get

$$V = -\frac{1}{2}\lambda \upsilon^2 (\upsilon + H)^2 + \frac{1}{4}\lambda(\upsilon + H)^4$$

The lagrangian containing the Higgs field H is given by

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V$$
$$= \frac{1}{2}(\partial^\mu H)^2 - \lambda \upsilon^2 H^2 - \lambda \upsilon H^3 - \frac{\lambda}{4} H^4$$

The Higgs Particle in the SM

The kinetic part of the Higgs field, $\frac{1}{2}(\partial_\mu H)^2$, comes from the term involving the covariant derivative $|D_\mu \Phi|^2$, while the mass and self-interaction parts, come from the scalar potential

$$
\begin{aligned}
V(\Phi) &= \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \\
&= \frac{\mu^2}{2} \begin{pmatrix} 0 & v+H \end{pmatrix} \begin{pmatrix} 0 \\ v+H \end{pmatrix} + \frac{\lambda}{4} \left| \begin{pmatrix} 0 & v+H \end{pmatrix} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \right|^2
\end{aligned}
$$

Using the relation $v^2 = -\mu^2/\lambda$, we get

$$
V = -\frac{1}{2}\lambda v^2 (v+H)^2 + \frac{1}{4}\lambda (v+H)^4
$$

The lagrangian containing the Higgs field H is given by

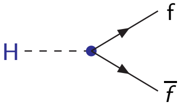
$$
\begin{aligned}
\mathcal{L}_H &= \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V \\
&= \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4
\end{aligned}
$$

From this lagrangian, we have that the Higgs boson mass is given by

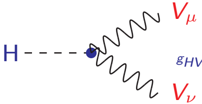
$$
m_H^2 = 2\lambda v^2 = -2\mu^2
$$

HSF iris hep

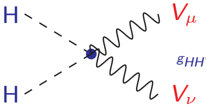
Feynman Rules for Higgs Couplings



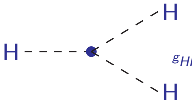
$$g_{Hff} = i\frac{m_f}{v} = (\sqrt{2}G_\mu)^{1/2} m_f$$



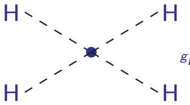
$$g_{HVV} = -2ig_{\mu\nu}\frac{M_V^2}{v} = -2ig_{\mu\nu}(\sqrt{2}G_\mu)^{1/2} M_V^2$$



$$g_{HHVV} = -2ig_{\mu\nu}\frac{M_V^2}{v^2} = -2ig_{\mu\nu}\sqrt{2}G_\mu M_V^2$$



$$g_{HHH} = 3i\frac{m_H^2}{v} = 3i(\sqrt{2}G_\mu)^{1/2} m_H^2$$

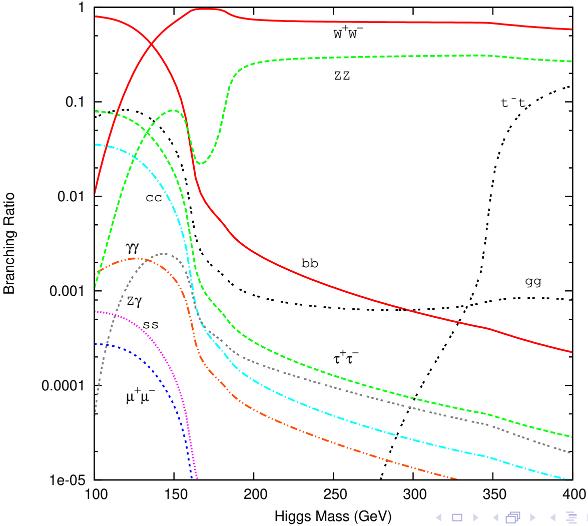


$$g_{HHHH} = 3i\frac{m_H^2}{v^2} = 3i\sqrt{2}G_\mu m_H^2$$

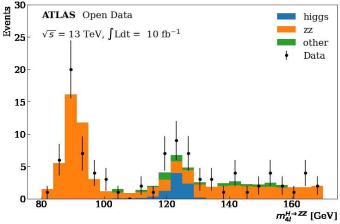
Decays of the SM Higgs Boson

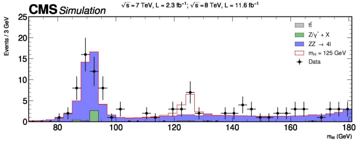
Branching ratios within the SM (Hdecay)

$$Br(H_{SM} \rightarrow X) = \frac{\Gamma(H_{SM} \rightarrow X)}{\Gamma_{Total}}$$



PHYSICS BACKGROUND





- What is the physics behind the data?
- Learn the basics of the physics processes present in the data