Department of Physics

A 2.4σ observation of the Higgs Boson through the $H \rightarrow ZZ \rightarrow 4\ell$ golden channel

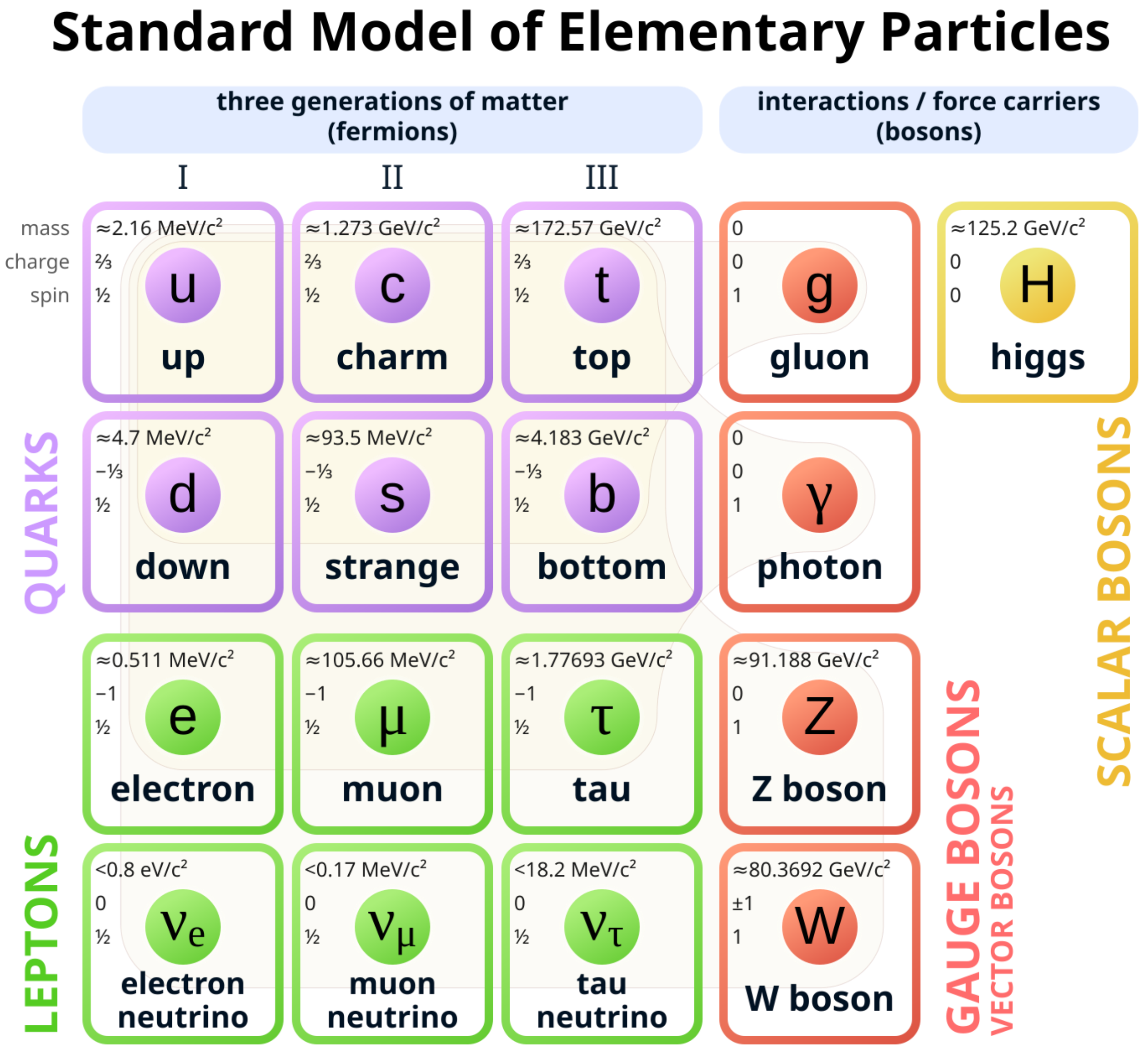
Vinh Q. Tran

Vinh Q. Tran
BSc Physics Candidate at MIT

April 22nd, 2025

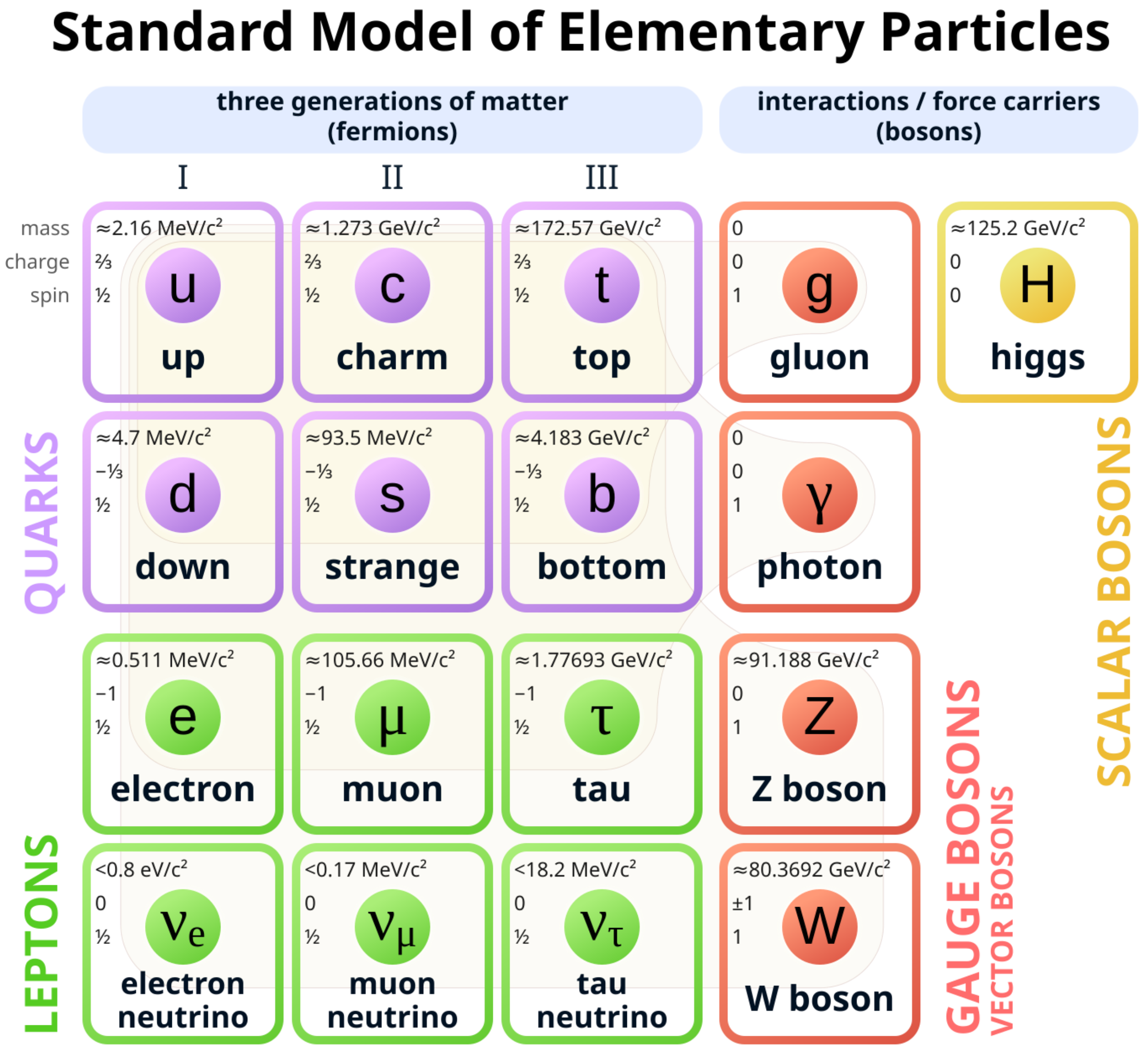
The Standard Model

- Describe particles and phenomenon in terms of interactions between fundamental fields.



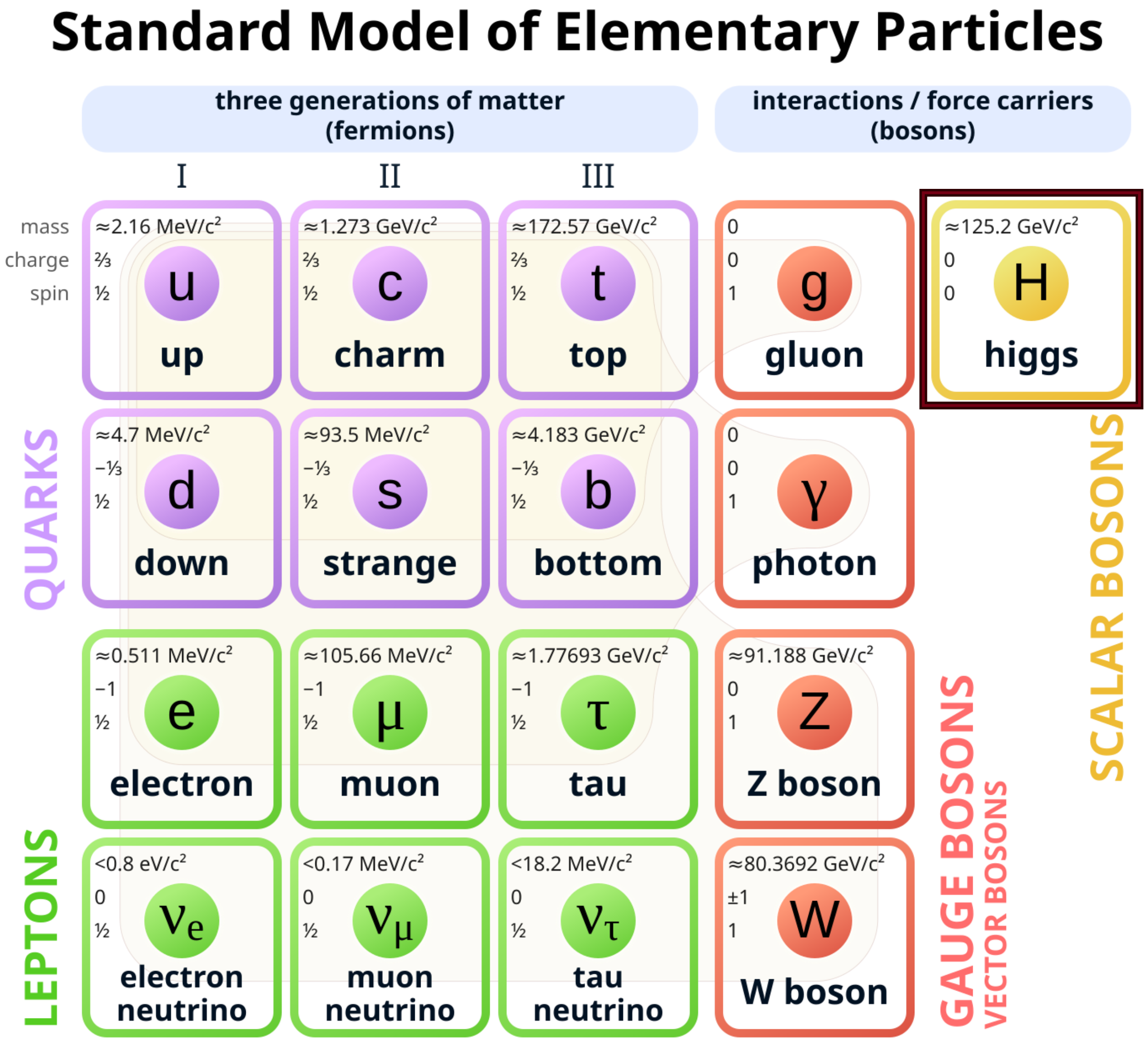
The Standard Model

- Describe particles and phenomenon in terms of interactions between fundamental fields.
- Success in explaining three of the four fundamental forces.



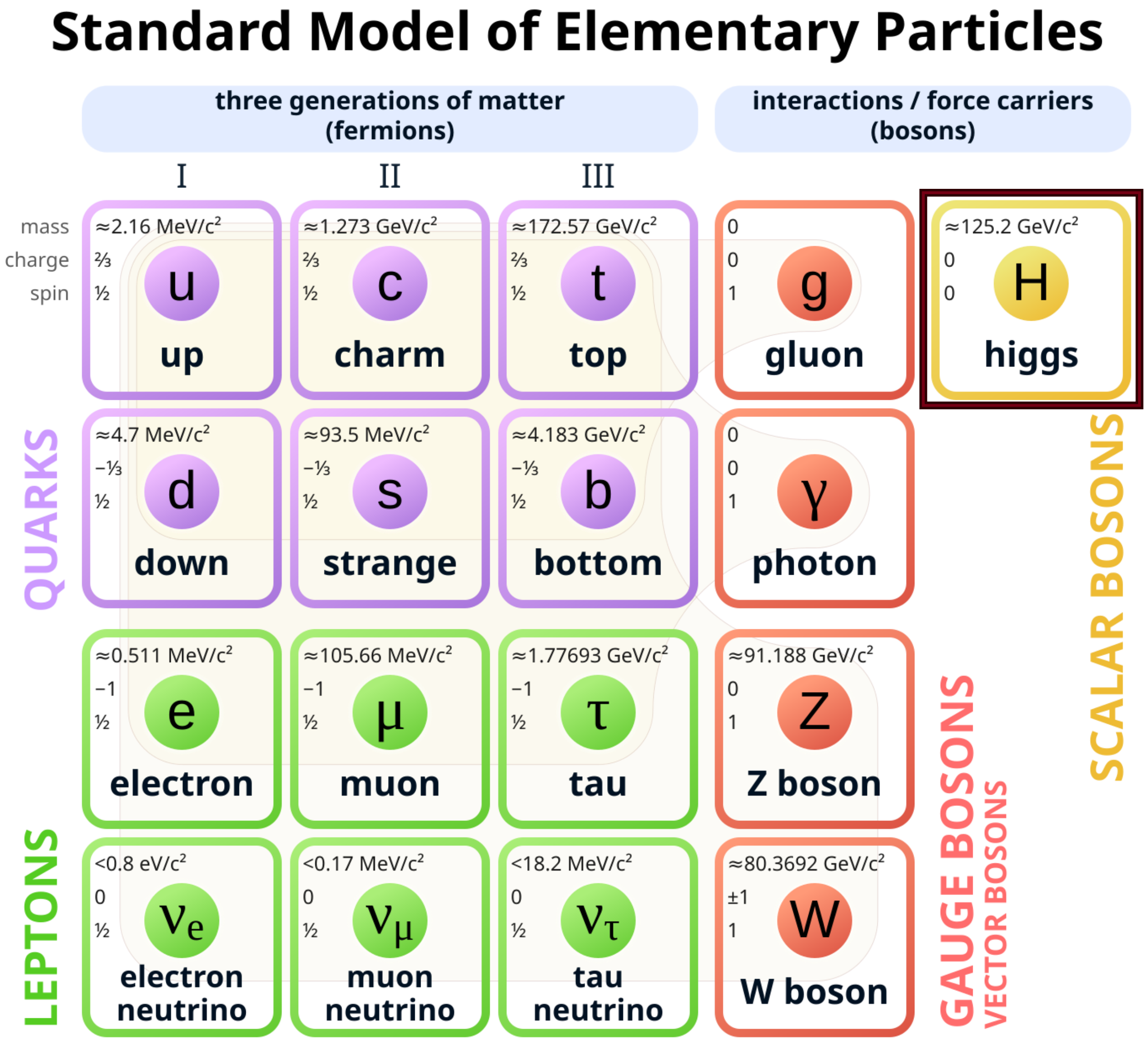
The Standard Model

- Describe particles and phenomenon in terms of interactions between fundamental fields.
- Success in explaining three of the four fundamental forces.
- The Higgs field plays a crucial role in the model, in that it allows for a mass-giving mechanism.

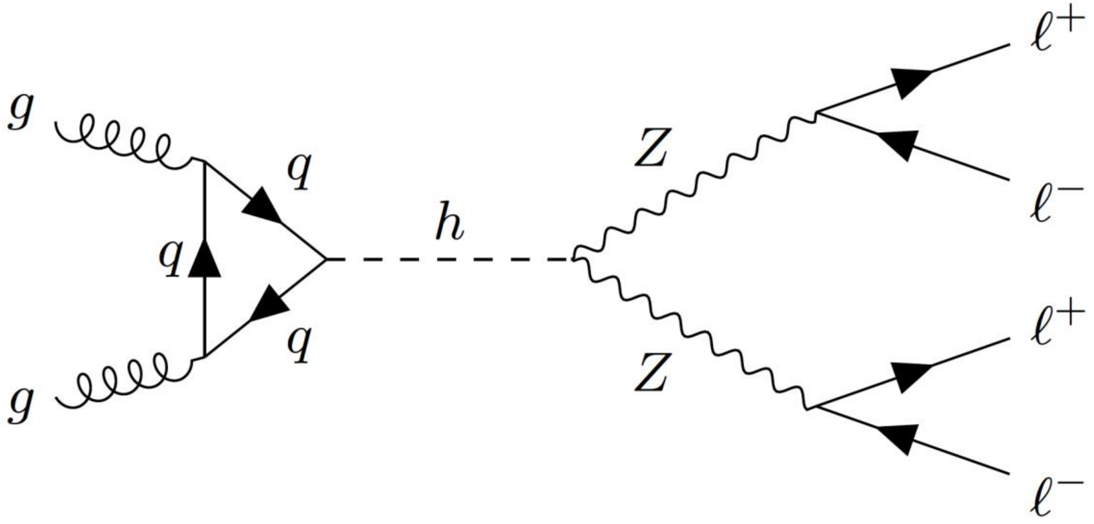


The Standard Model

- Describe particles and phenomenon in terms of interactions between fundamental fields.
- Success in explaining three of the four fundamental forces.
- The Higgs field plays a crucial role in the model, in that it allows for a mass-giving mechanism.
- Up to the 2000s, evidence for the Higgs boson was still missing.

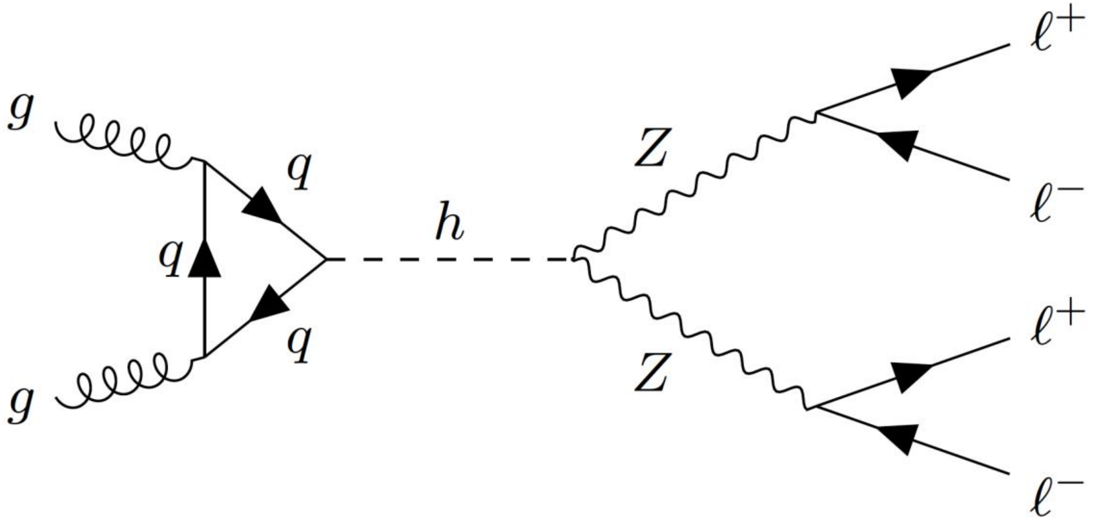


The four-lepton “golden” channel



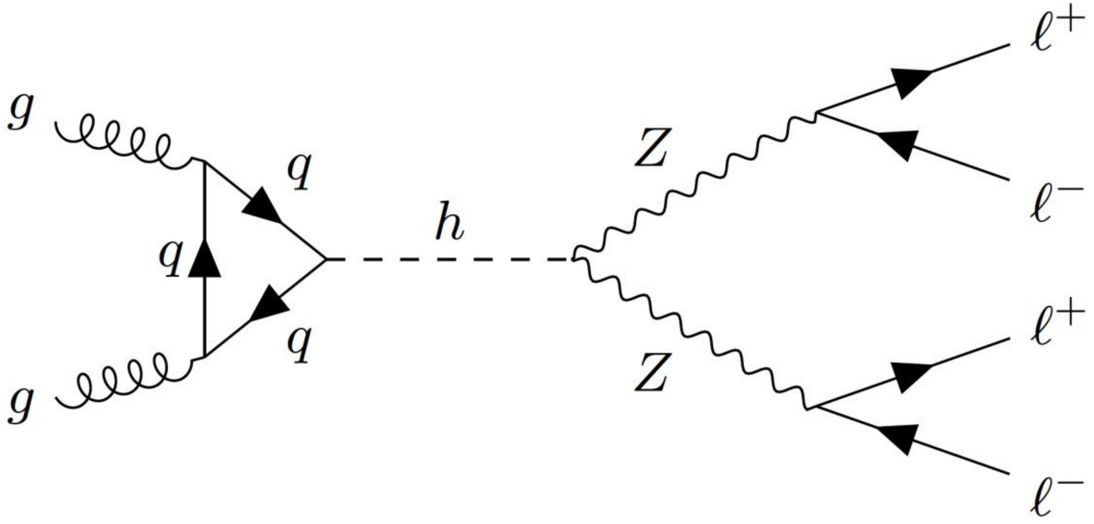
The four-lepton “golden” channel

- No neutrino → No missing energy and information loss.



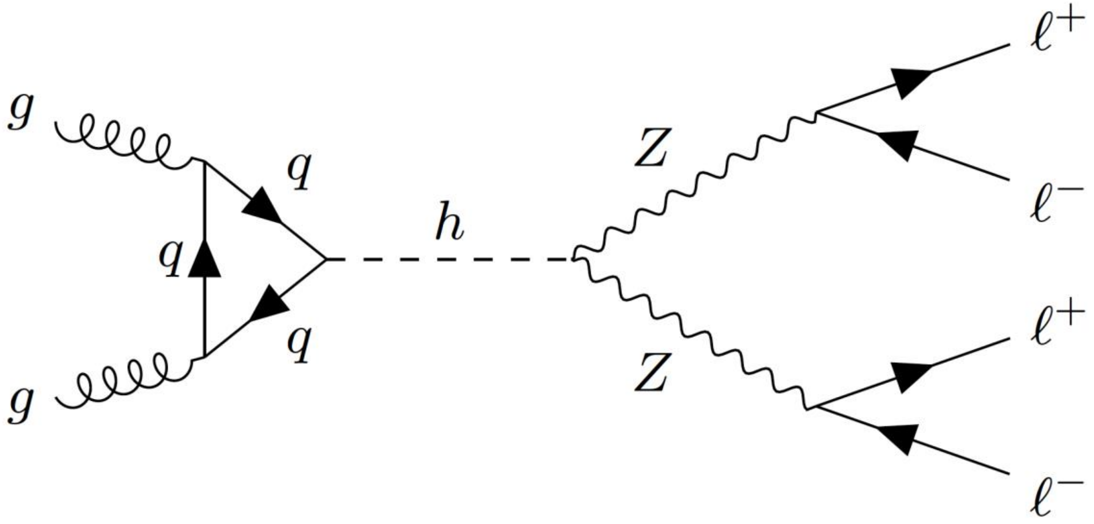
The four-lepton “golden” channel

- No neutrino → No missing energy and information loss.
- No hadron → Avoid complex modeling of hadron interactions and jets.



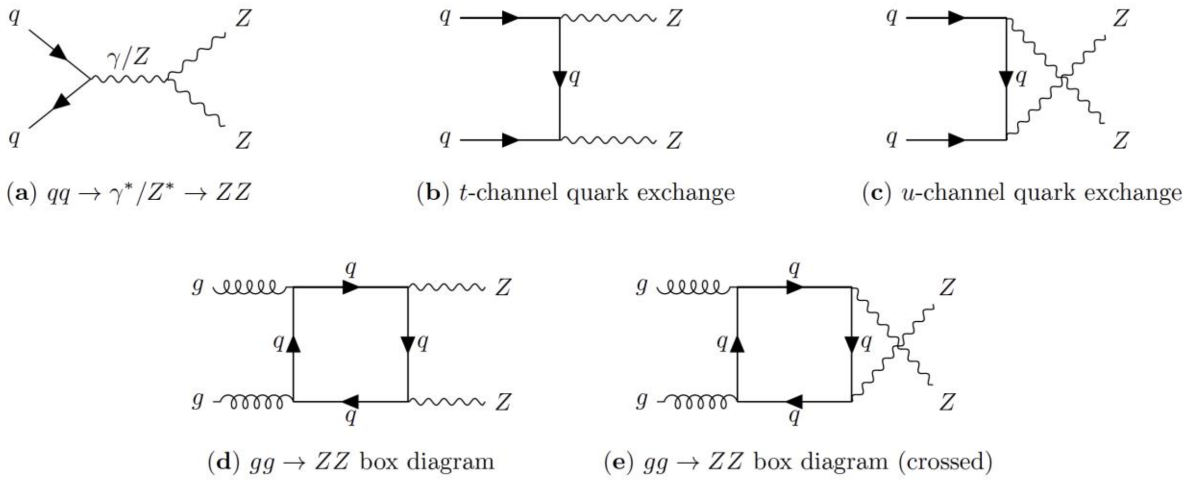
The four-lepton “golden” channel

- No neutrino → No missing energy and information loss.
- No hadron → Avoid complex modeling of hadron interactions and jets.
- Clear signature!



Four-lepton background

- Main source of events are the ZZ decays. These cannot be completely removed.

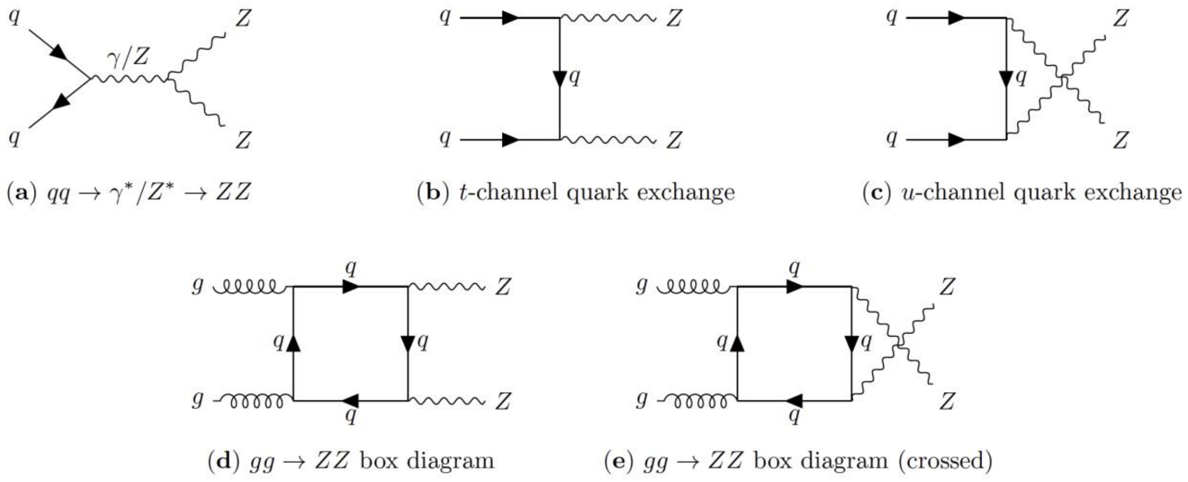


(a) $qq \rightarrow \gamma^*/Z^* \rightarrow ZZ$ (b) t-channel quark exchange (c) u-channel quark exchange

(d) $gg \rightarrow ZZ$ box diagram (e) $gg \rightarrow ZZ$ box diagram (crossed)

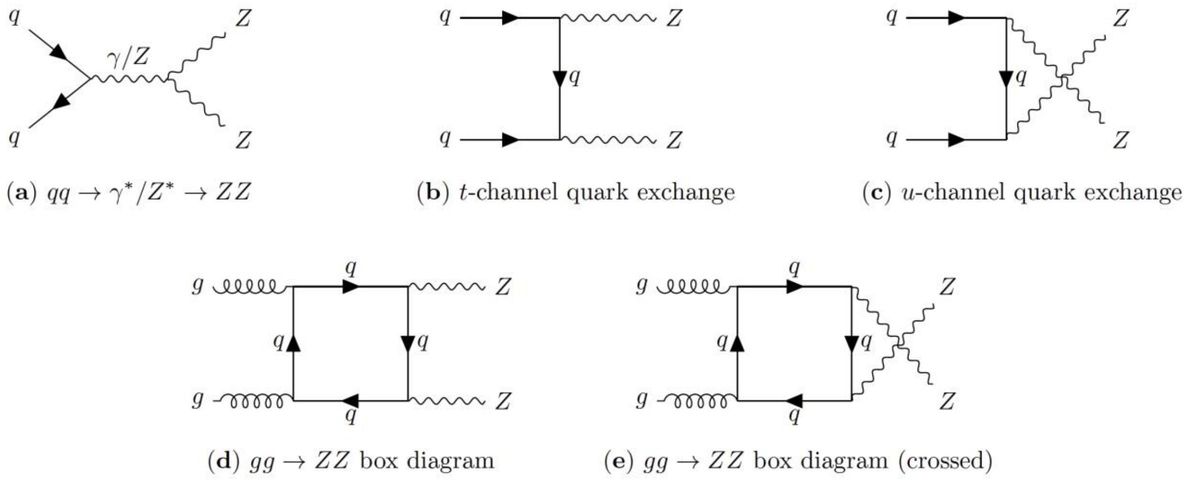
Four-lepton background

- Main source of events are the ZZ decays. These cannot be completely removed.
- Others include: Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$.



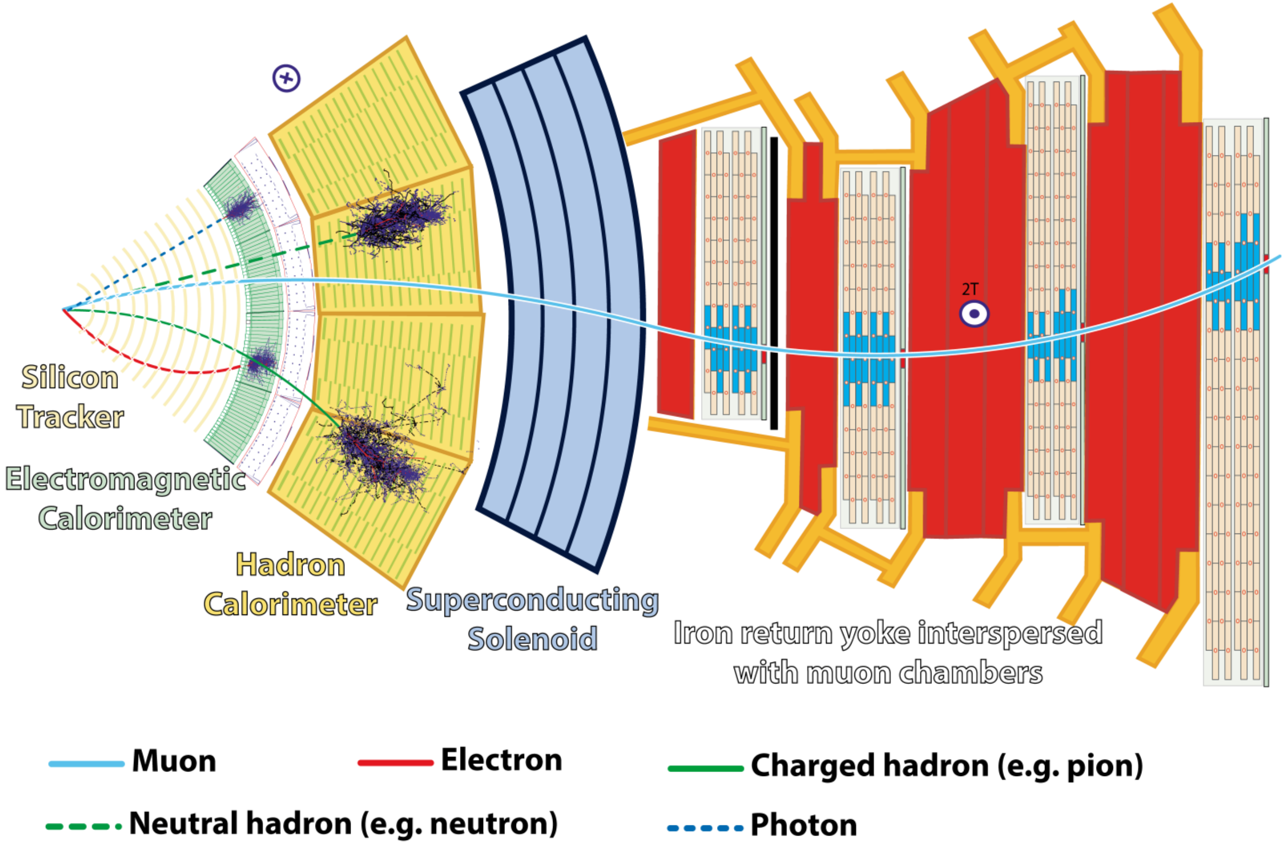
Four-lepton background

- Main source of events are the ZZ decays. These cannot be completely removed.
- Others include: Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$.
- These are reducible with careful event selection.



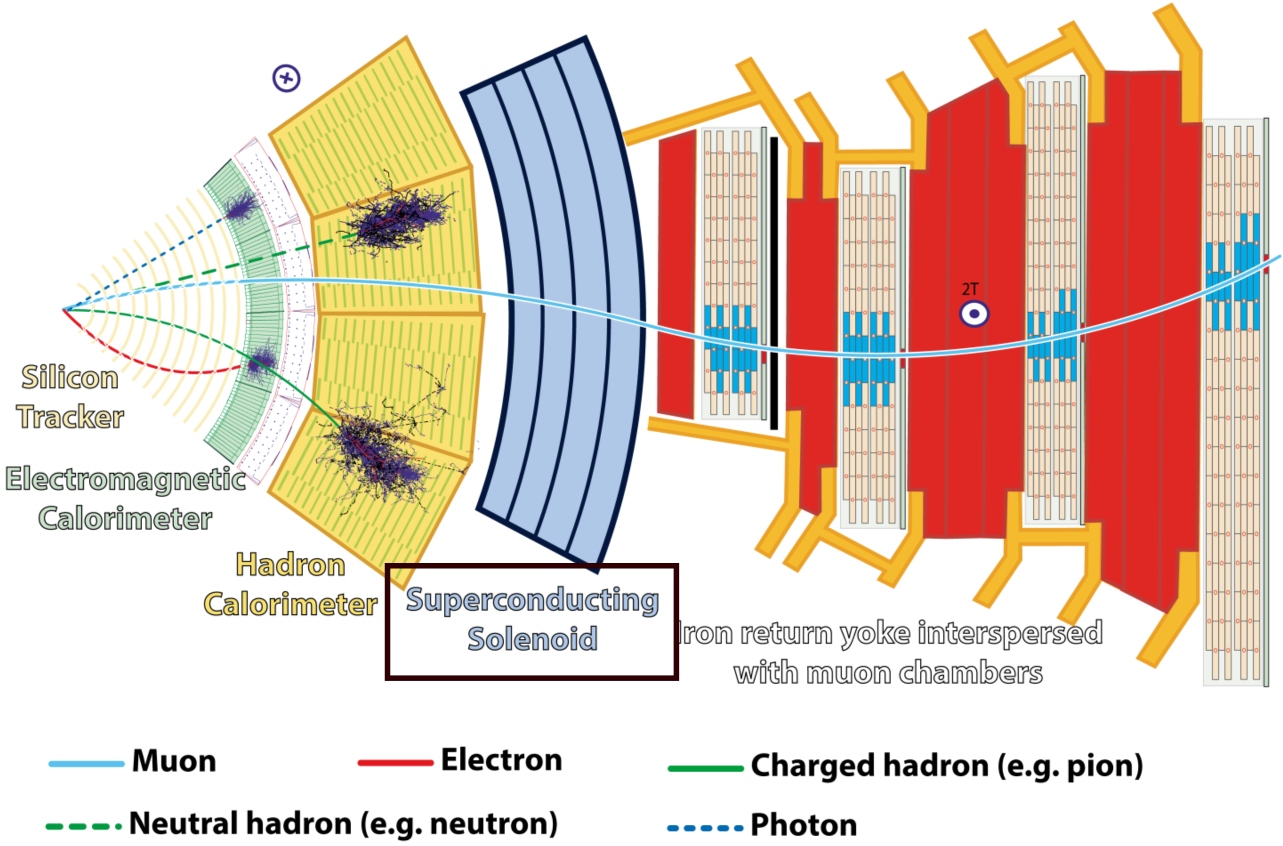
The CMS detector

- Compact Muon Solenoid



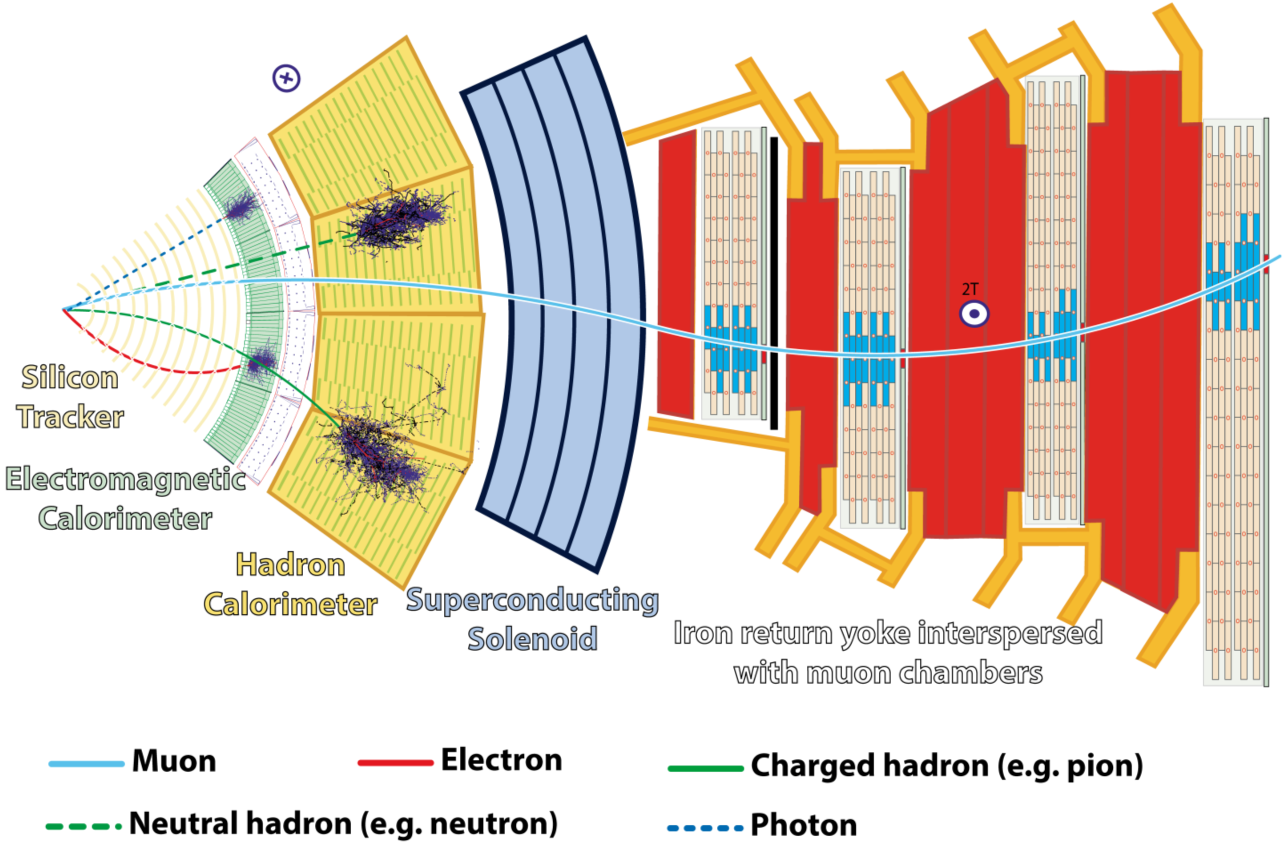
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.



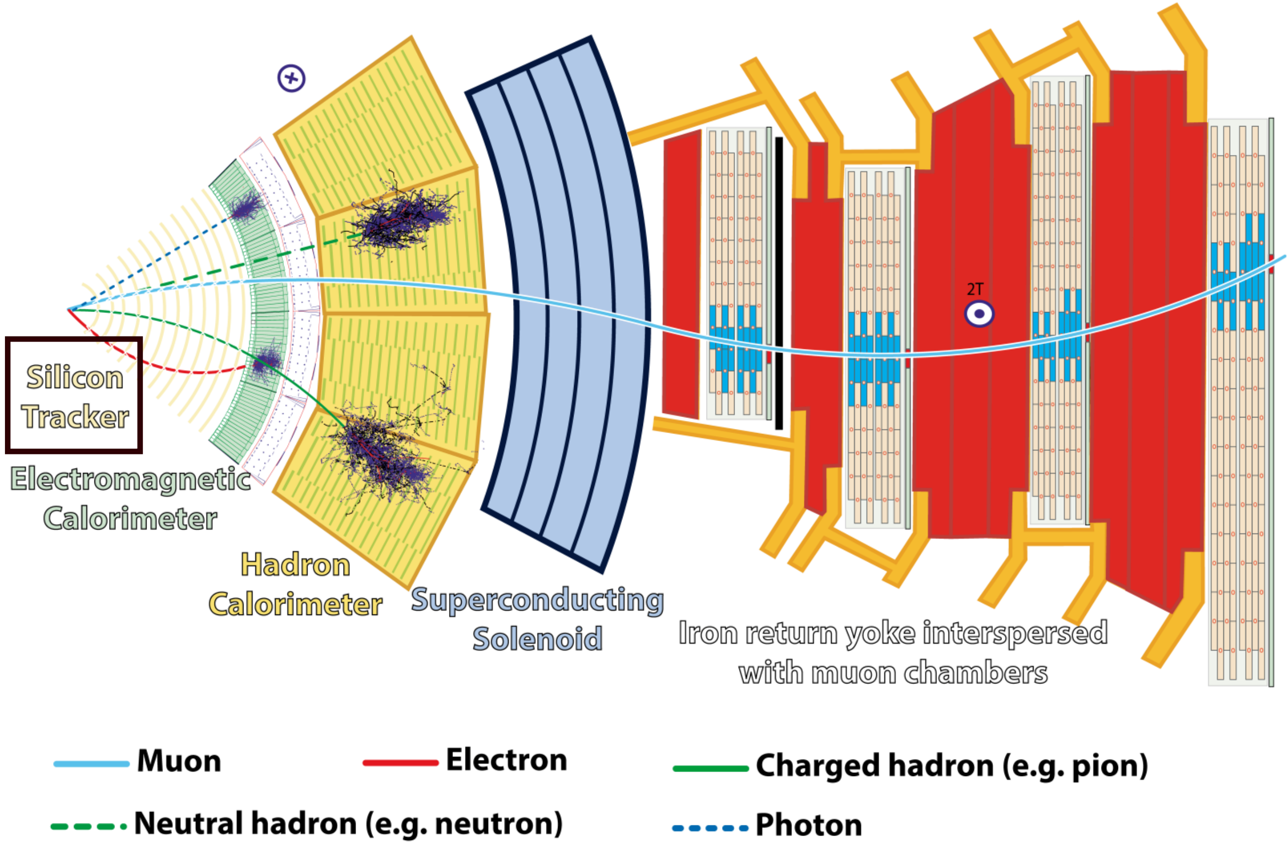
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.



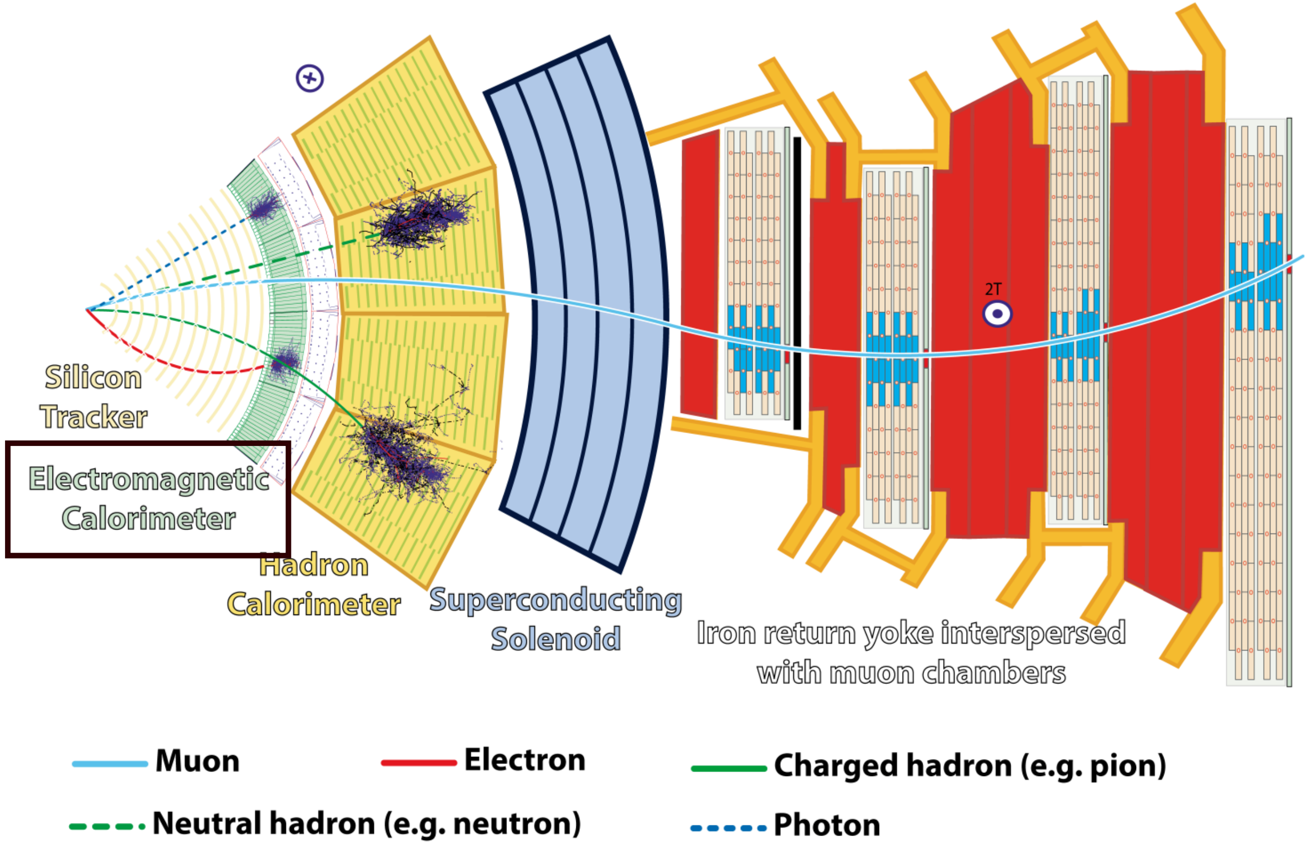
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.



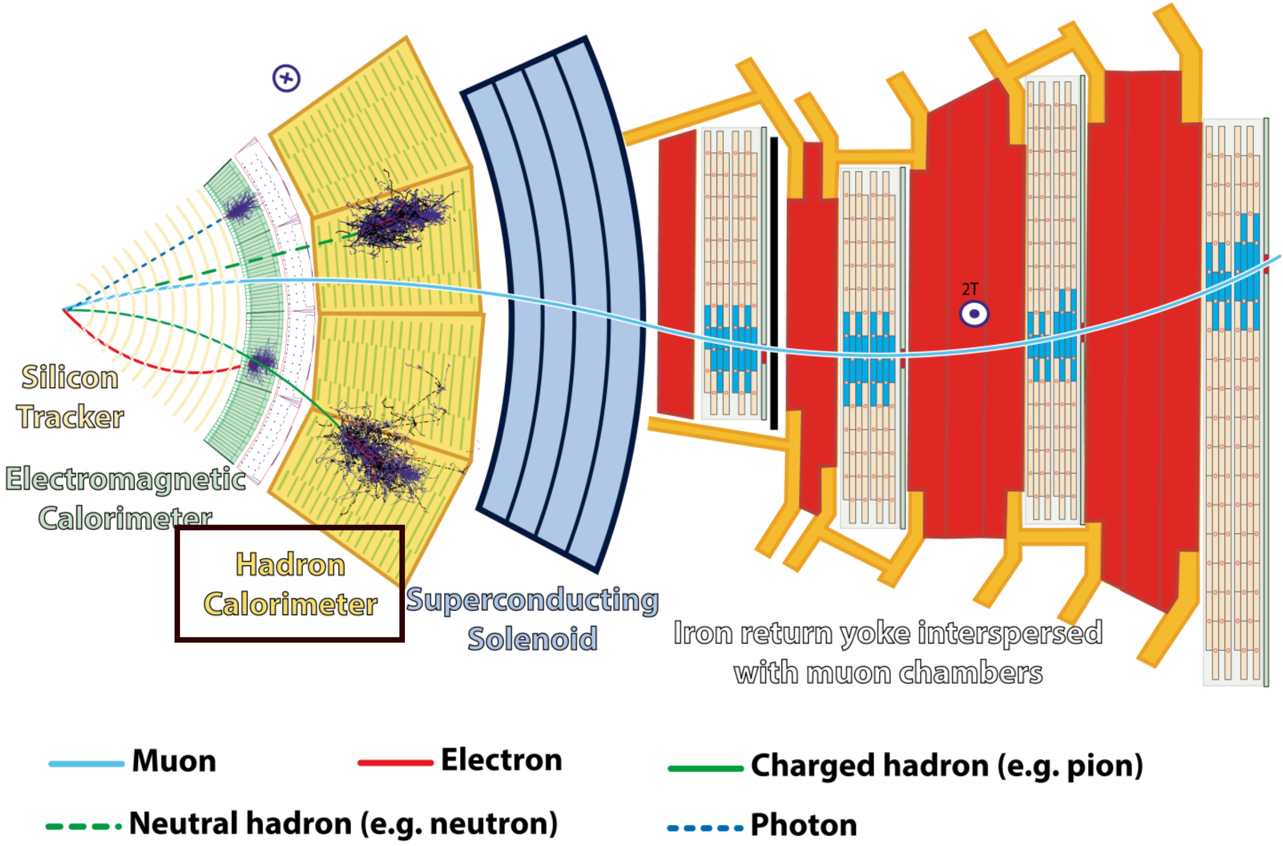
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.



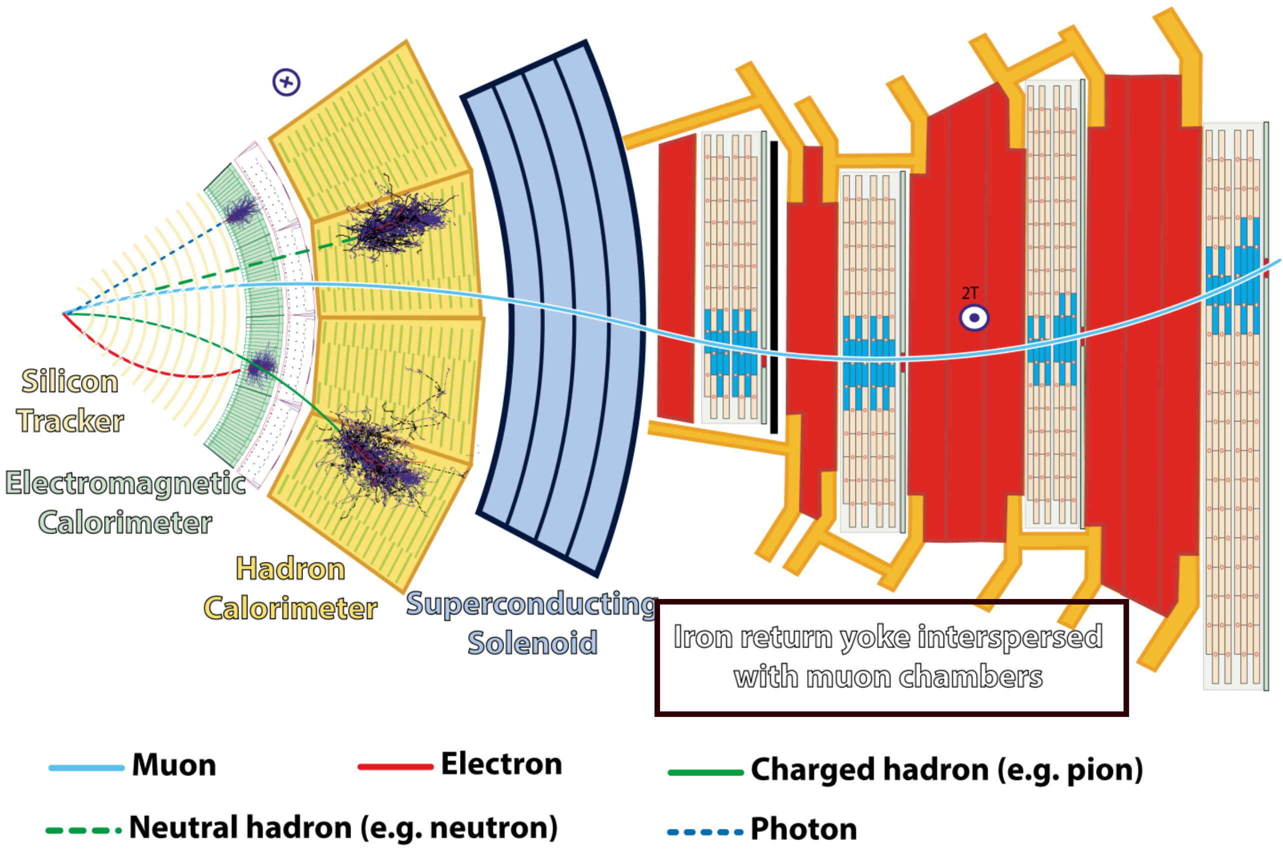
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.



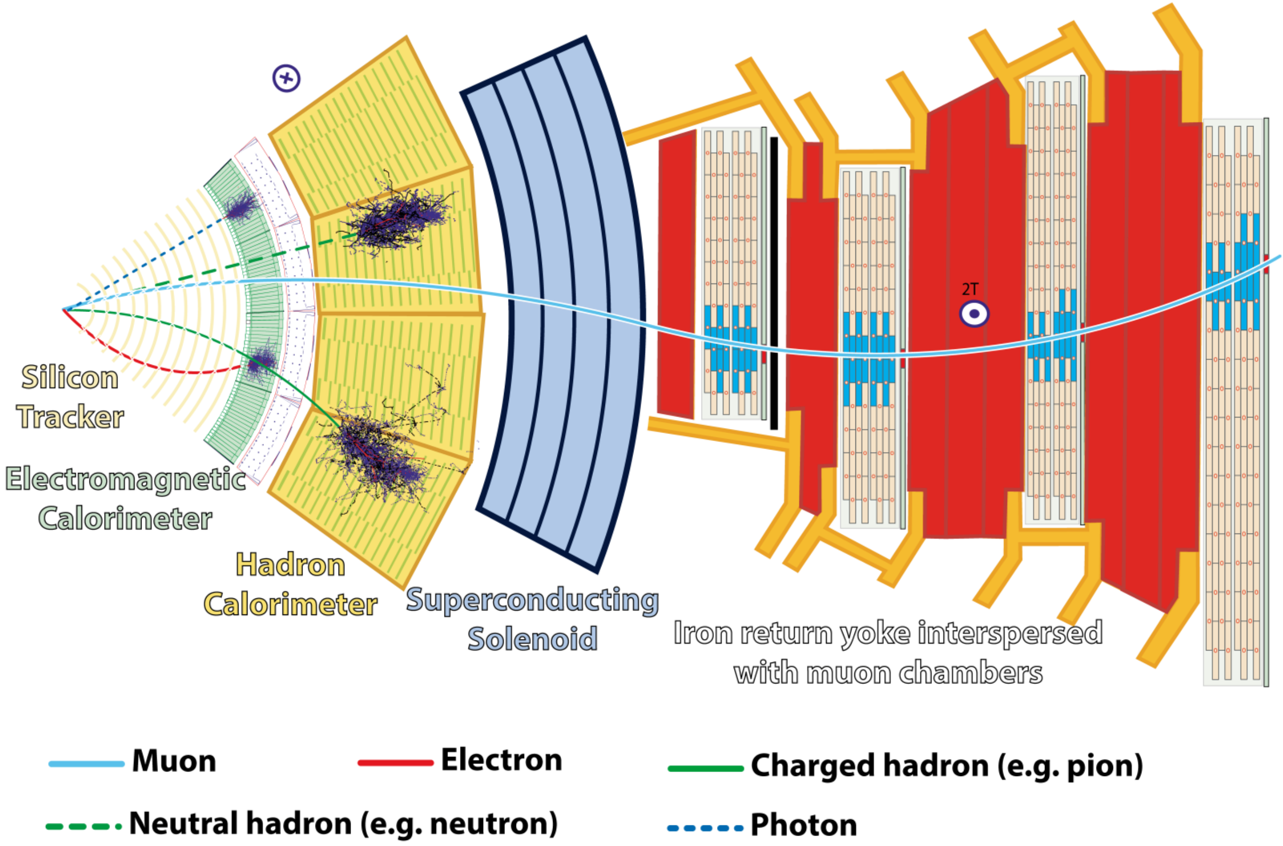
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.



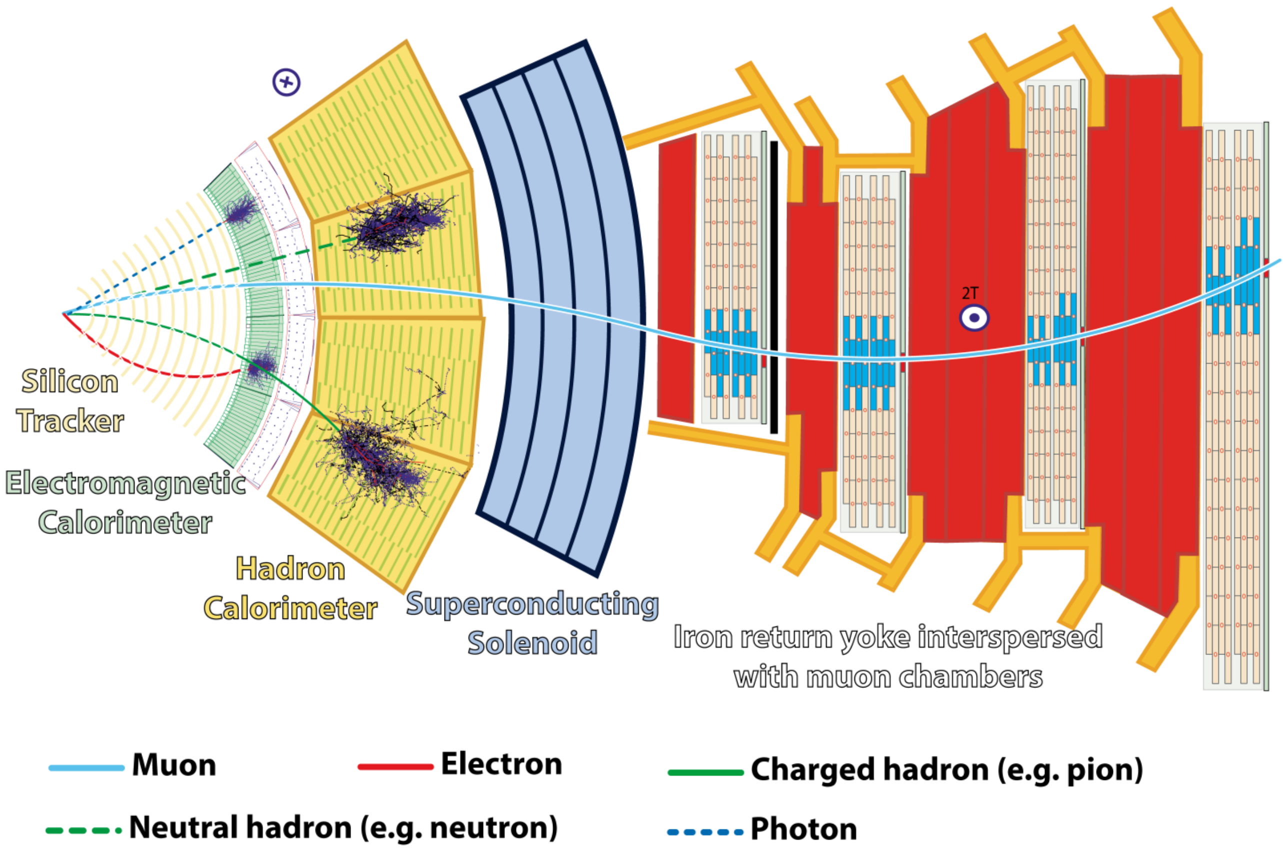
The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.
- Detector geometry is in terms of ϕ and $\eta = -\ln(\tan\theta/2)$.



The CMS detector

- Compact Muon Solenoid
- The detector center-piece: The superconducting solenoid, generating a $3.8\mathrm{T}$ magnetic field.
- Array of subdetectors measuring charge, momentum, and energy or particles.
- Detector geometry is in terms of ϕ and $\eta = -\ln(\tan\theta/2)$.
- $\eta_e \leq 2.5$, $\eta_{E/HCAL} \leq 3.0$, $\eta_\mu \leq 2.4$



Experimental data

- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.

Experimental data

- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.
- Monte Carlo simulations of events are generated to guide the analysis and event selections.

Experimental data

- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.
- Monte Carlo simulations of events are generated to guide the analysis and event selections.
- Four-lepton events requirements:
  - $|d_{xy}| < 0.5\ \mathrm{cm},\ |d_z| < 1.0\ \mathrm{cm}$

Experimental data

- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.
- Monte Carlo simulations of events are generated to guide the analysis and event selections.
- Four-lepton events requirements:
  - $|d_{xy}| < 0.5\ \mathrm{cm},\ |d_z| < 1.0\ \mathrm{cm}$
  - $\mathrm{SIP} = \frac{d_{3\mathrm{D}}}{\sigma_{d_{3\mathrm{D}}}} < 0.4$

Experimental data

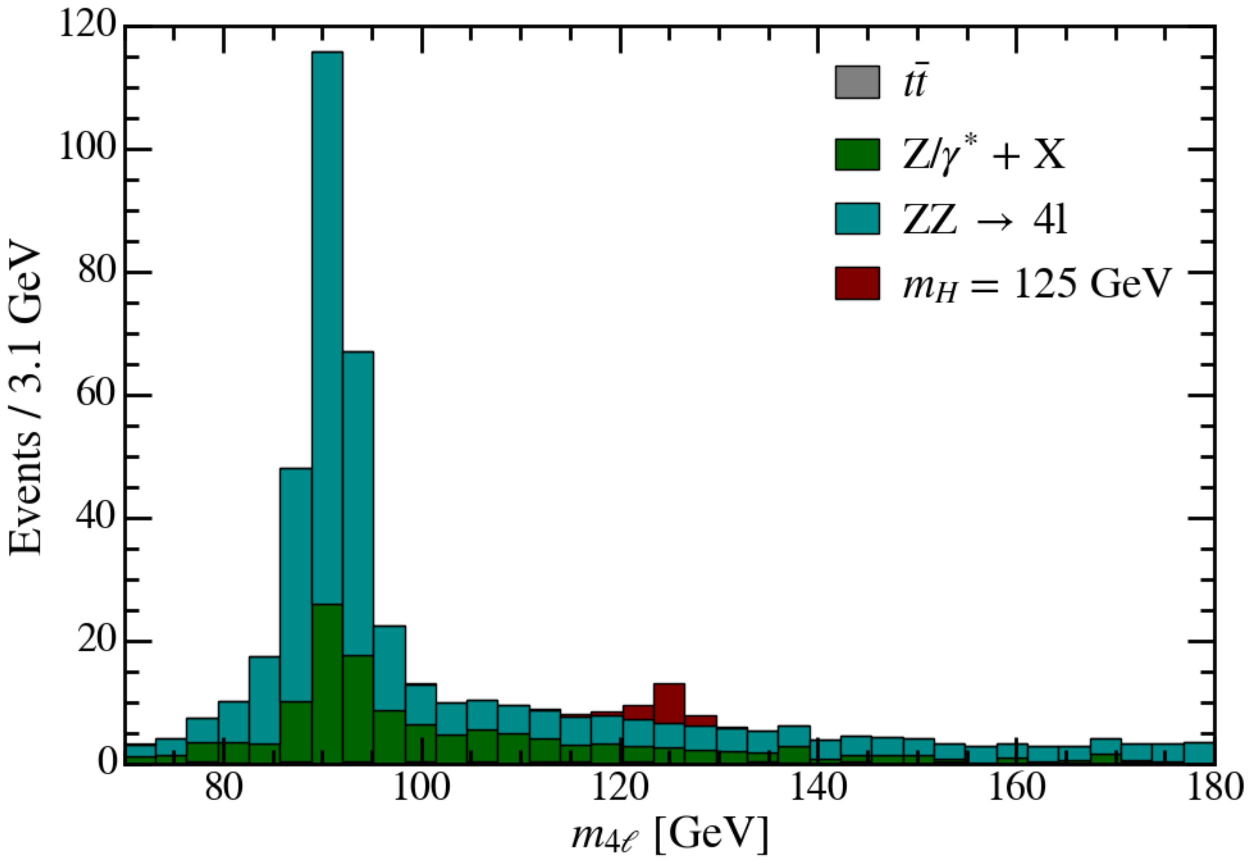
- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.
- Monte Carlo simulations of events are generated to guide the analysis and event selections.
- Four-lepton events requirements:
  - $|d_{xy}| < 0.5\ \mathrm{cm},\ |d_z| < 1.0\ \mathrm{cm}$
  - $\mathrm{SIP} = \frac{d_{3\mathrm{D}}}{\sigma_{d_{3\mathrm{D}}}} < 0.4$
  - $I_{rel} = \sum p_{\mathrm{T,i}} / p_{\mathrm{T},\ell} < 0.4$

$$\Delta R_i = \sqrt{\Delta\phi_{i,\ell}^2 + \Delta\eta_{i,\ell}^2} < 0.4$$

Experimental data

- Observations are from the CMS 2011-2012 runs with $\sqrt{s} = 7, 8\ \mathrm{TeV}$.
- Monte Carlo simulations of events are generated to guide the analysis and event selections.
- Four-lepton events requirements:
  - $|d_{xy}| < 0.5\ \mathrm{cm},\ |d_z| < 1.0\ \mathrm{cm}$
  - $\mathrm{SIP} = \frac{d_{3\mathrm{D}}}{\sigma_{d_{3\mathrm{D}}}} < 0.4$
  - $I_{rel} = \sum p_{\mathrm{T,i}} / p_{\mathrm{T},\ell} < 0.4$

  $\Delta R_i = \sqrt{\Delta\phi_{i,\ell}^2 + \Delta\eta_{i,\ell}^2} < 0.4$



Kinematics cuts

- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$

Kinematics cuts

- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Remove $90\text{-}95\%$ of Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$, $20\text{-}30\%$ of irreducible ZZ background. 95% of the signal still remain

Kinematics cuts

- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Remove 90-95% of Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$, 20-30% of irreducible ZZ background. 95% of the signal still remain
- Pair into lepton-antileptons pairs, each of these are assumed to be the product of Z decay.

Kinematics cuts

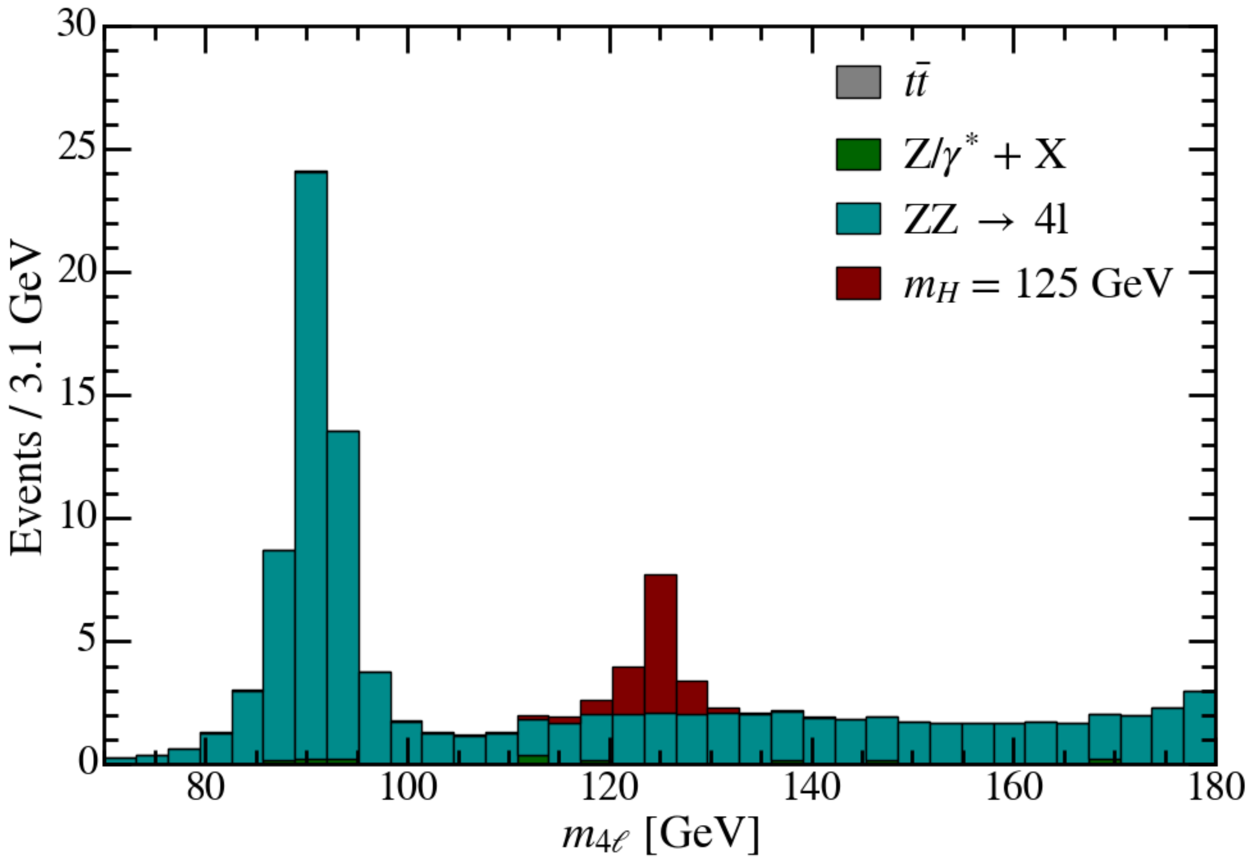
- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Remove 90-95% of Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$, 20-30% of irreducible ZZ background. 95% of the signal still remain
- Pair into lepton-antileptons pairs, each of these are assumed to be the product of Z decay.
- Require the invariant mass of the lighter Z boson to be within 12-$120\ \mathrm{GeV}$, and the heavier within 40-$120\ \mathrm{GeV}$.

Kinematics cuts

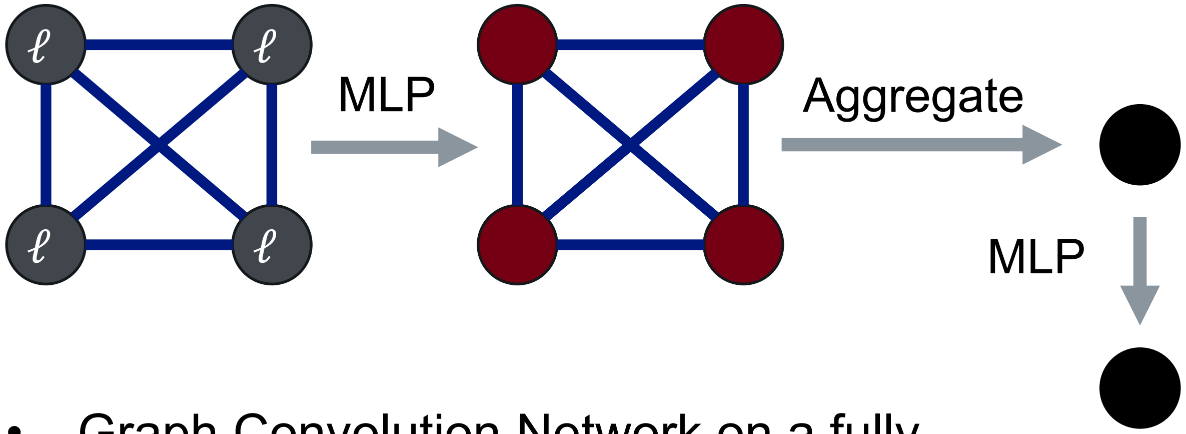
- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Remove 90-95% of Drell-Yahn ($Z/\gamma^* + X$) and $t\bar{t}$, 20-30% of irreducible ZZ background. 95% of the signal still remain
- Pair into lepton-antileptons pairs, each of these are assumed to be the product of Z decay.
- Require the invariant mass of the lighter Z boson to be within 12-$120\ \mathrm{GeV}$, and the heavier within 40-$120\ \mathrm{GeV}$.
- Remove extra 25% of ZZ background, while keeping 90% of the signal.

Kinematics cuts

- Charge conservation cut and transverse momentum cut: $\sum_i q_i = 0$, $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Remove $90\text{-}95\%$ of Drell-Yahn $(Z/\gamma^* + X)$ and $t\bar{t}$, $20\text{-}30\%$ of irreducible ZZ background. 95% of the signal still remain
- Pair into lepton-antileptons pairs, each of these are assumed to be the product of Z decay.
- Require the invariant mass of the lighter Z boson to be within $12\text{-}120\ \mathrm{GeV}$, and the heavier within $40\text{-}120\ \mathrm{GeV}$.
- Remove extra 25% of ZZ background, while keeping 90% of the signal.

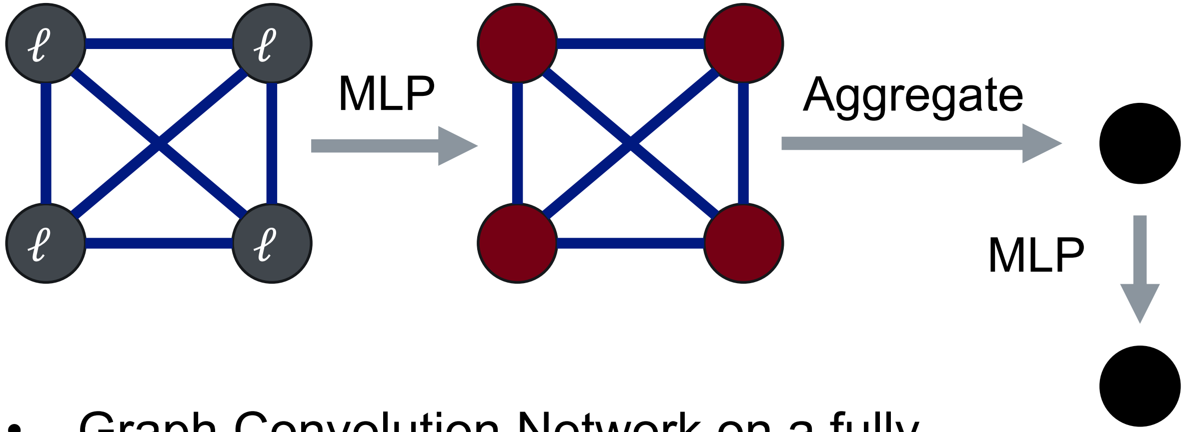


Machine learning cut



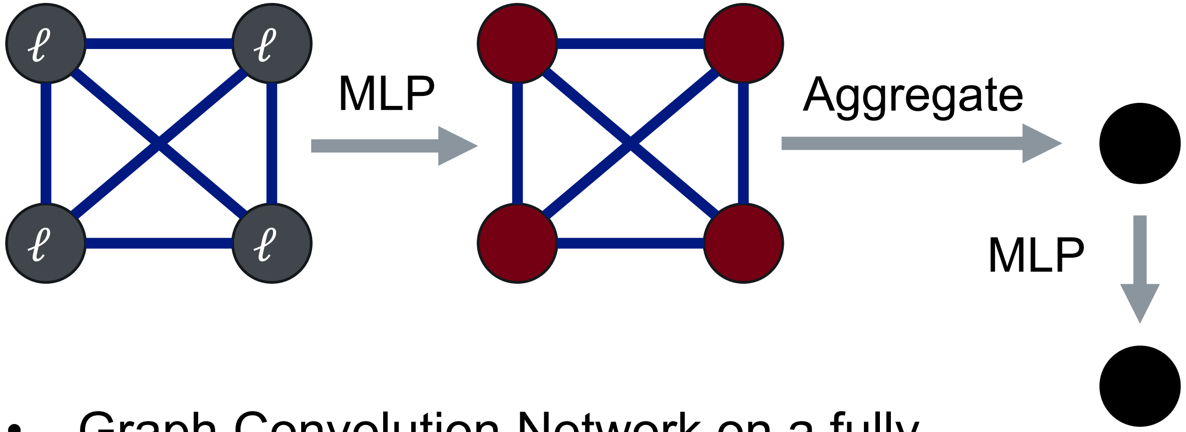
- Graph Convolution Network on a fully-connected graph. Each node represent a lepton.

Machine learning cut



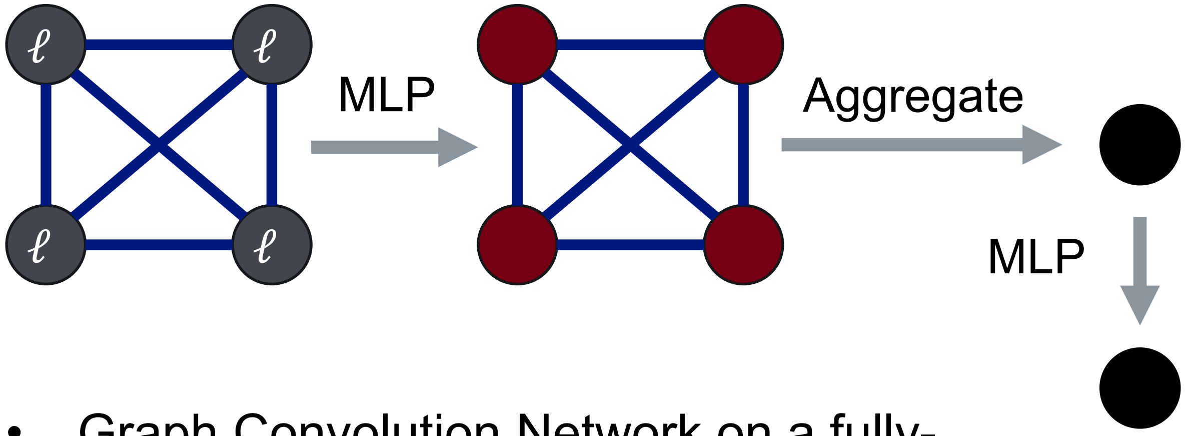
- Graph Convolution Network on a fully-connected graph. Each node represent a lepton.
- Features include particle ID (trainable encoded) and transverse momenta $p_{\mathrm{T},x}$, $p_{\mathrm{T},y}$.

Machine learning cut



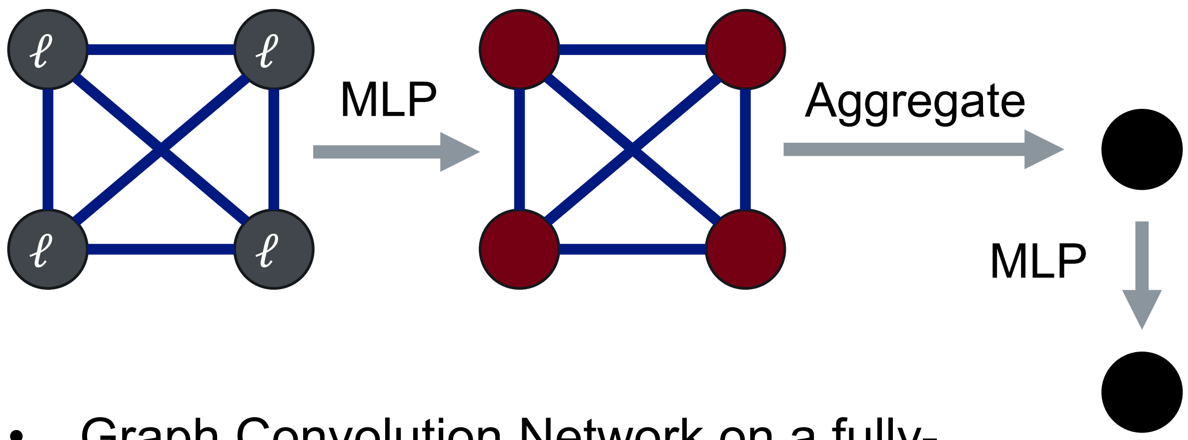
- Graph Convolution Network on a fully-connected graph. Each node represent a lepton.
- Features include particle ID (trainable encoded) and transverse momenta $p_{\mathrm{T},x}$, $p_{\mathrm{T},y}$.
- Train on events with four-lepton invariant mass of $m_{4\ell} \in [100; 160]\ \mathrm{GeV}$.

Machine learning cut

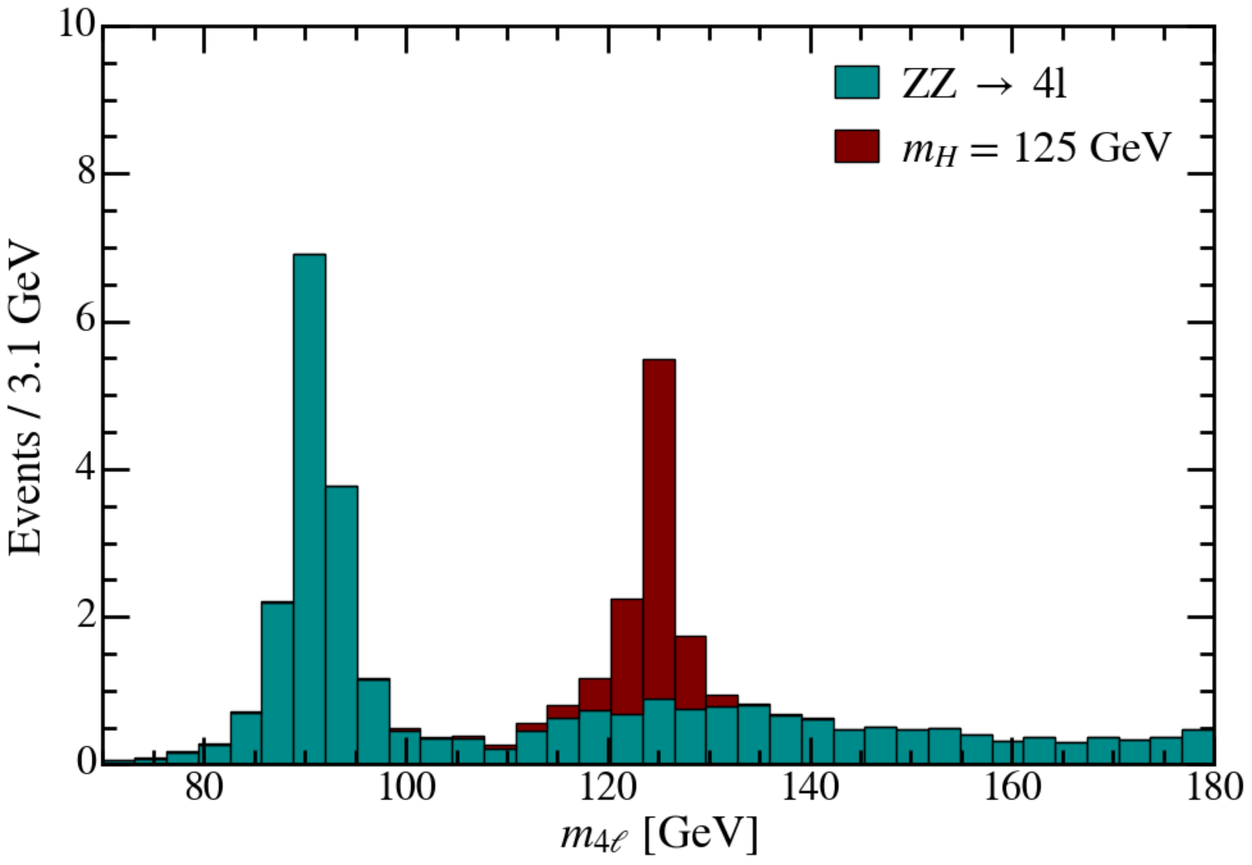


- Graph Convolution Network on a fully-connected graph. Each node represent a lepton.
- Features include particle ID (trainable encoded) and transverse momenta $p_{\mathrm{T},x}$, $p_{\mathrm{T},y}$.
- Train on events with four-lepton invariant mass of $m_{4\ell} \in [100; 160]\ \mathrm{GeV}$.
- $P_\mathrm{D} = 80\%$, $P_\mathrm{F} = 30\%$

Machine learning cut

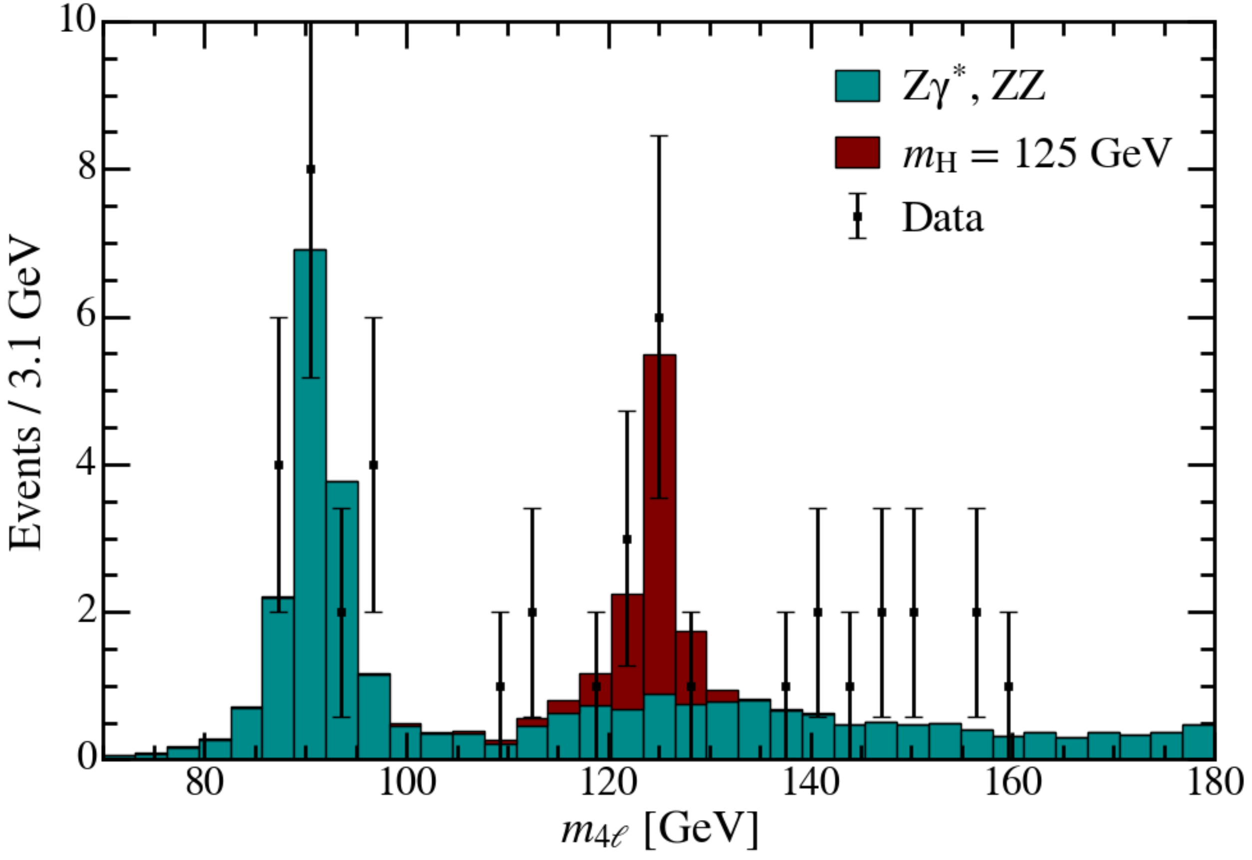


- Graph Convolution Network on a fully-connected graph. Each node represent a lepton.
- Features include particle ID (trainable encoded) and transverse momenta $p_{\mathrm{T},x}$, $p_{\mathrm{T},y}$.
- Train on events with four-lepton invariant mass of $m_{4\ell} \in [100; 160]\ \mathrm{GeV}$.
- $P_{\mathrm{D}} = 80\%$, $P_{\mathrm{F}} = 30\%$



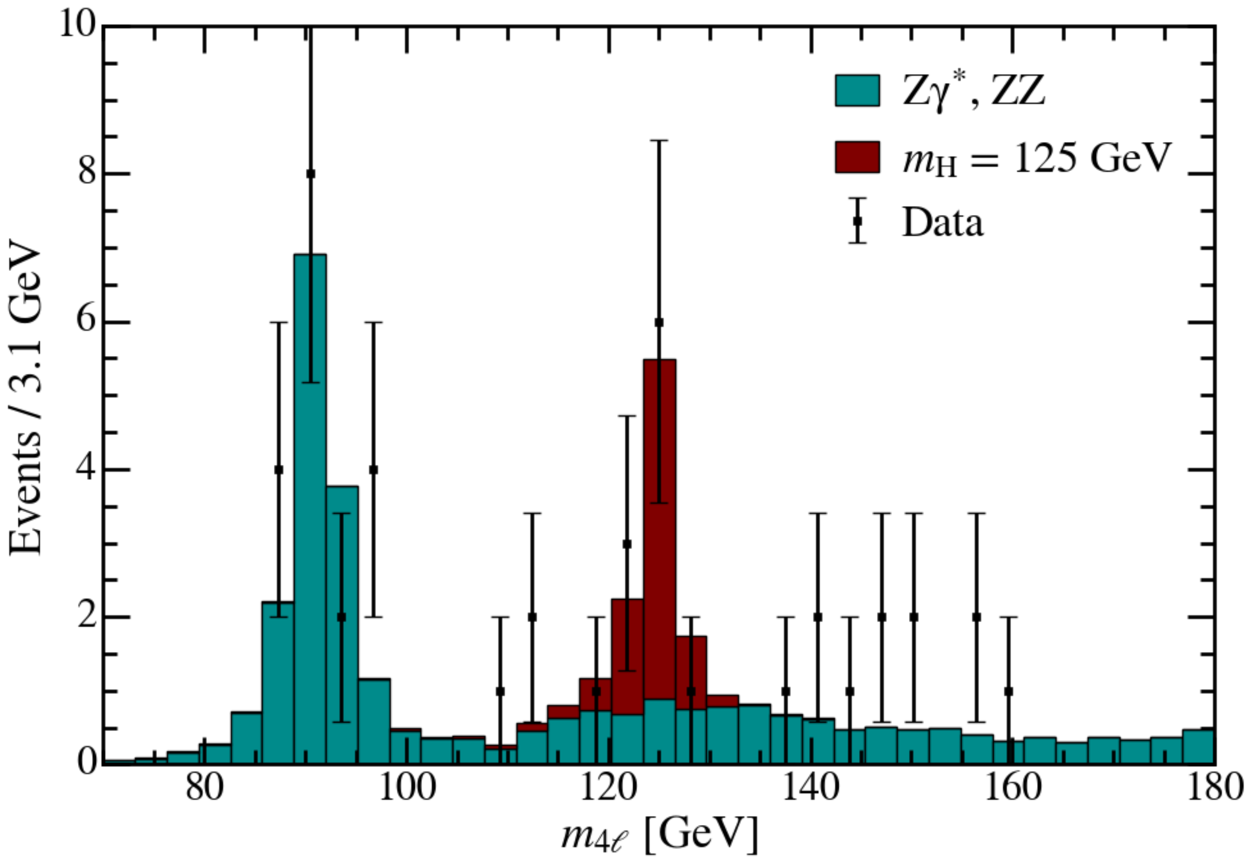
Unblind

- The observed event distribution agree well with the Monte Carlo (MC) prediction.



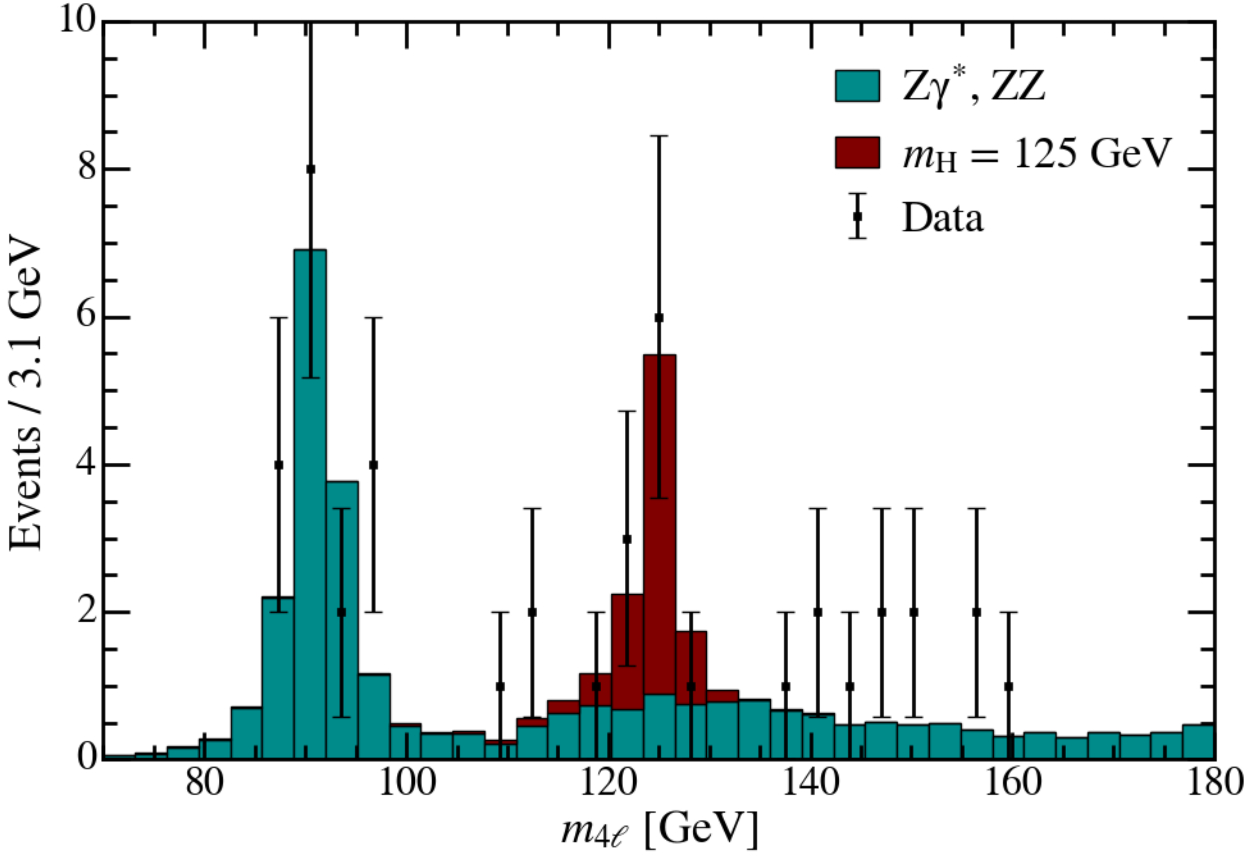
Unblind

- The observed event distribution agree well with the Monte Carlo (MC) prediction.
- Hypothesis testing:
    - Null hypothesis H_0: Only ZZ background, prior characterized by the MC prediction, scaled by a constant factor.



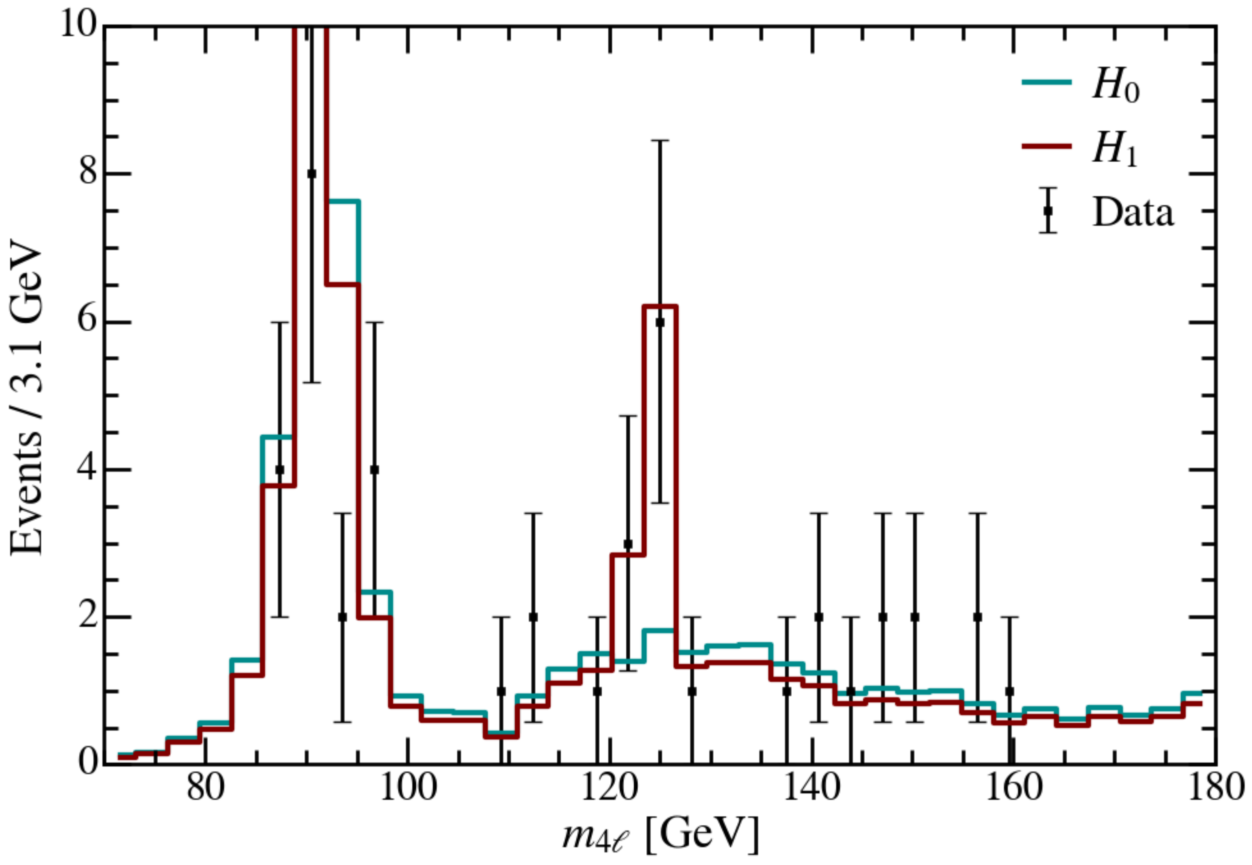
Unblind

- The observed event distribution agree well with the Monte Carlo (MC) prediction.
- Hypothesis testing:
  - Null hypothesis H_0: Only ZZ background, prior characterized by the MC prediction, scaled by a constant factor.
  - Alternative hypothesis H_1: Higgs signal + ZZ background, prior characterized by the background + a scaled gaussian peak at m_H, standard deviation σ_{m_H}.



Unblind

- The observed event distribution agree well with the Monte Carlo (MC) prediction.
- Hypothesis testing:
  - Null hypothesis H_0: Only ZZ background, prior characterized by the MC prediction, scaled by a constant factor.
  - Alternative hypothesis H_1: Higgs signal + ZZ background, prior characterized by the background + a scaled gaussian peak at m_H, standard deviation σ_{m_H}.



p-value

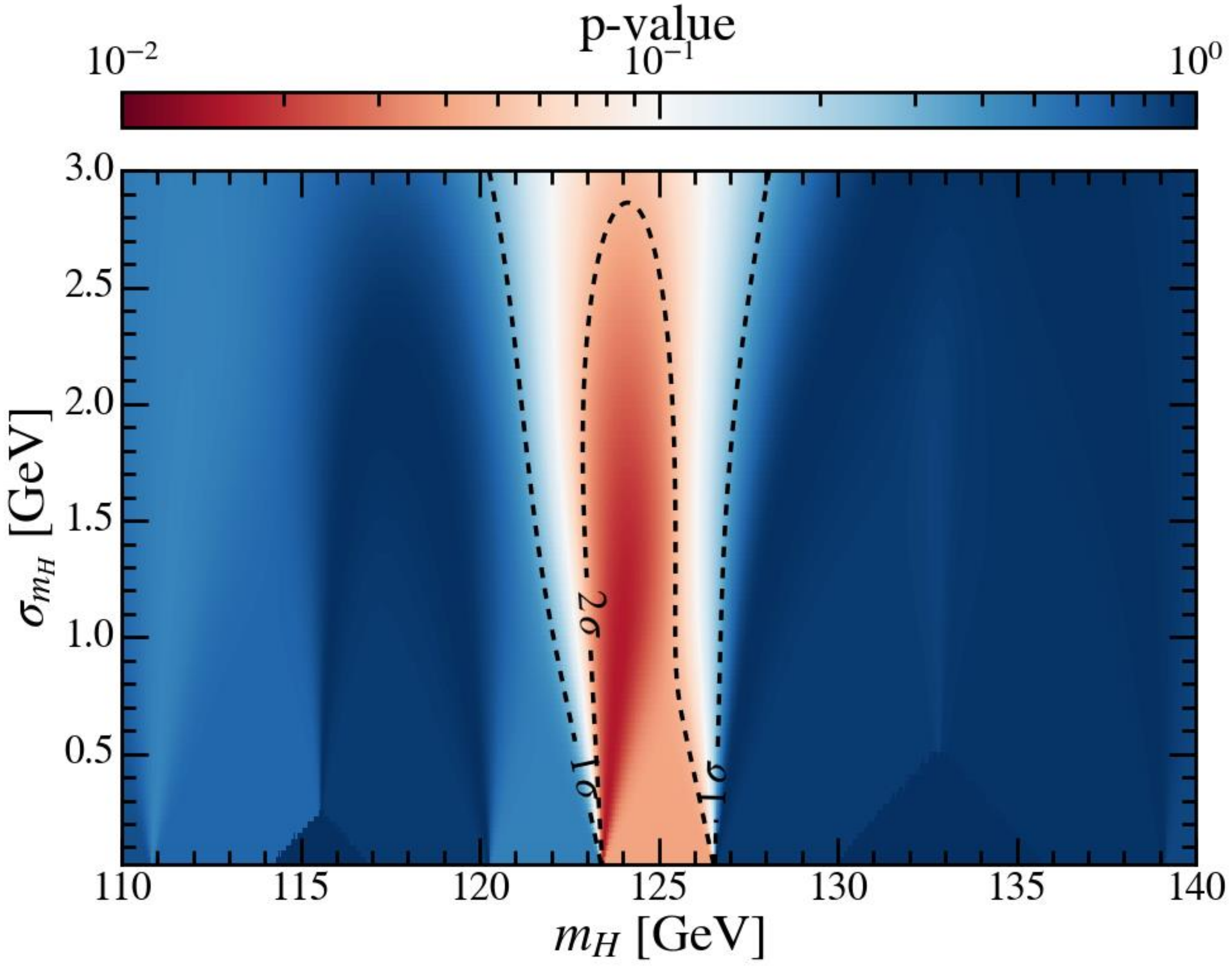
- Because of low event counts, we use Poisson-based likelihood fitting.

p-value

- Because of low event counts, we use Poisson-based likelihood fitting.
- For each m_H prior, we perform regression on fixed choices of σ_{m_H}. However, the p-value is calculated as if σ_{m_H} is a free parameter.

p-value

- Because of low event counts, we use Poisson-based likelihood fitting.
- For each m_H prior, we perform regression on fixed choices of σ_{m_H}. However, the p-value is calculated as if σ_{m_H} is a free parameter.
- Significance of 2.4σ at $m_H \simeq 123.8\,\mathrm{GeV}$.

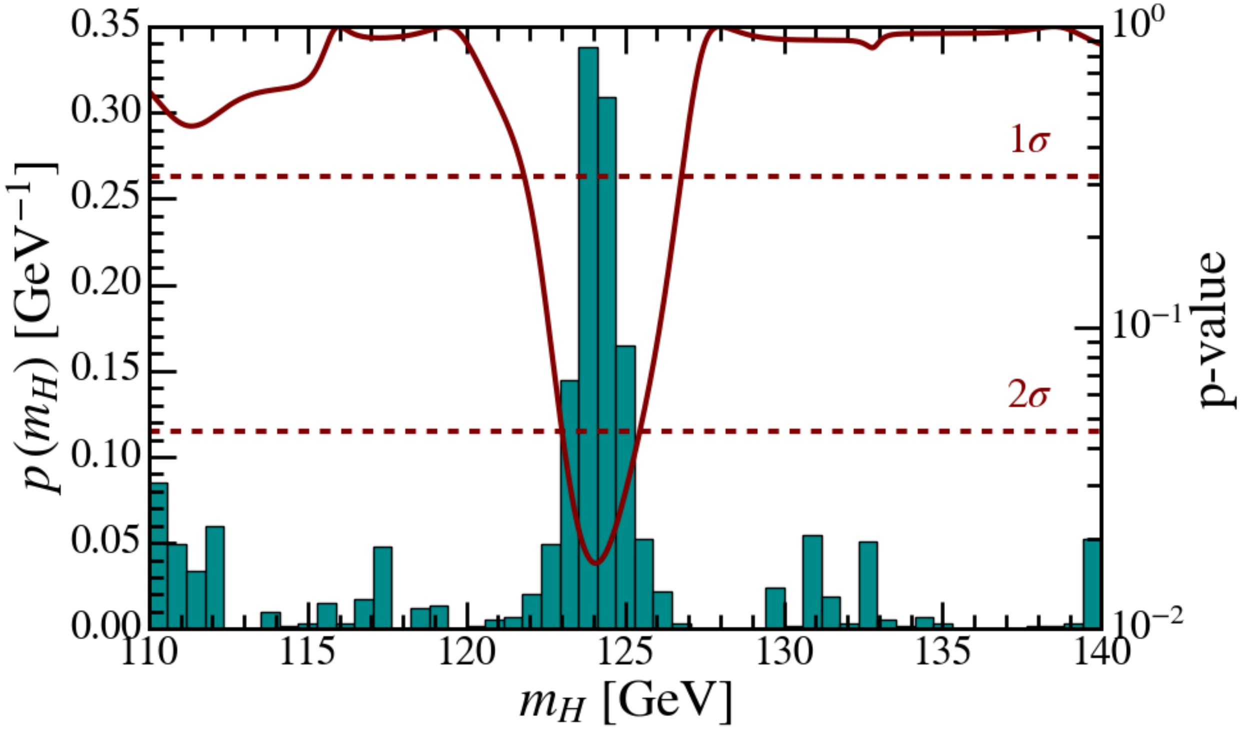


Bootstrapping

- Bootstrapping: Perturbing the observed data according to the uncertainties and repeat the analysis.

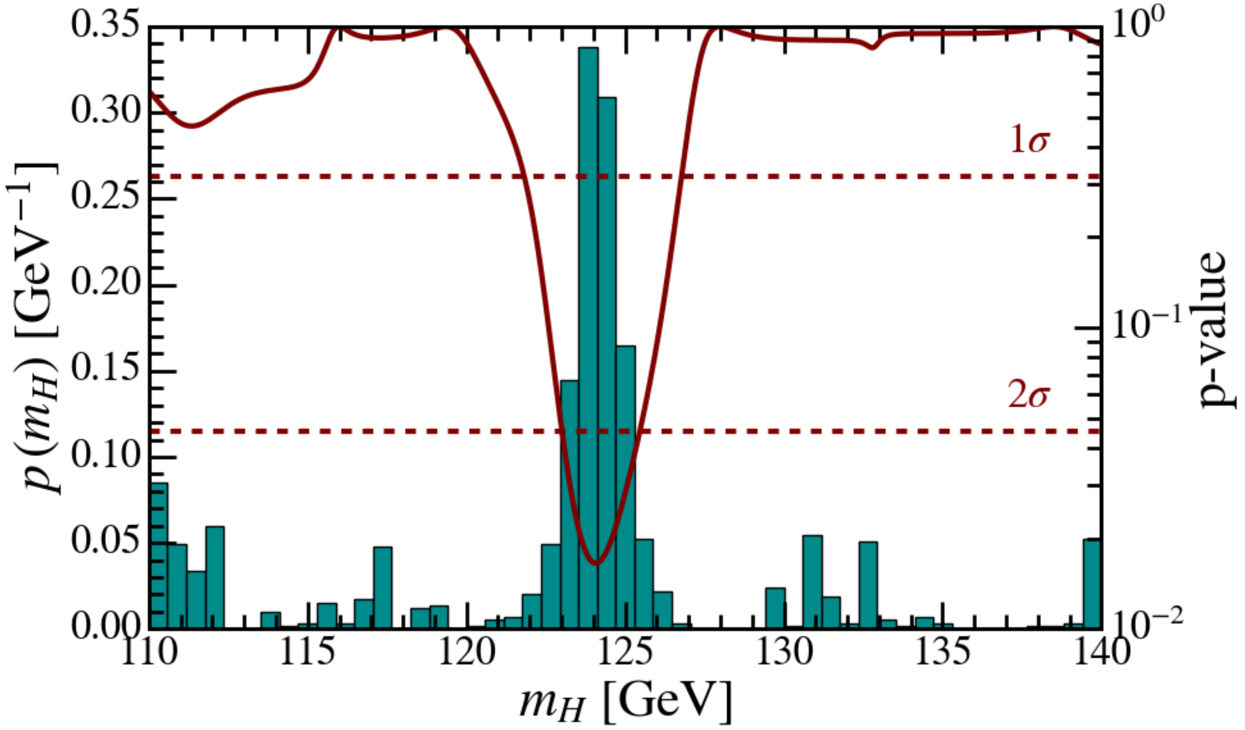
Bootstrapping

- Bootstrapping: Perturbing the observed data according to the uncertainties and repeat the analysis.



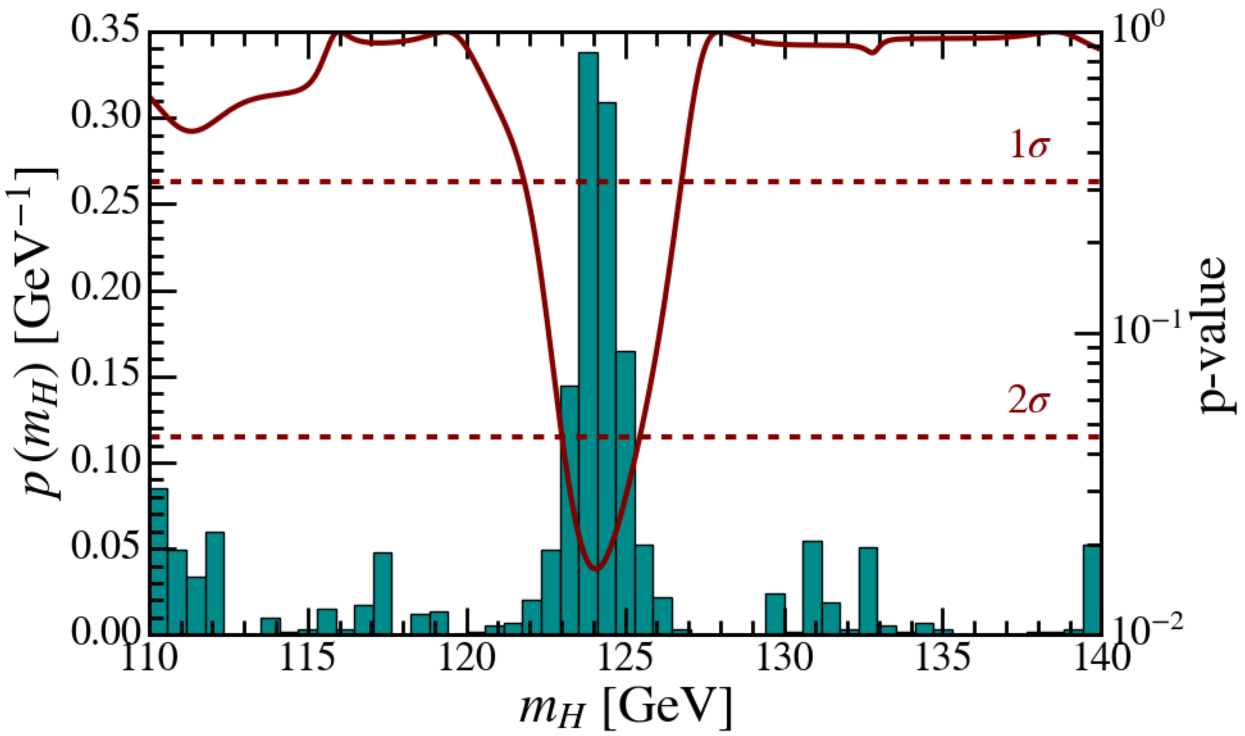
Bootstrapping

- Bootstrapping: Perturbing the observed data according to the uncertainties and repeat the analysis.
- The significances remain stable at 2.4σ.



Bootstrapping

- Bootstrapping: Perturbing the observed data according to the uncertainties and repeat the analysis.
- The significances remain stable at 2.4σ.
- Higgs mass: $m_H = 124.22 \pm 1.16\ \mathrm{GeV}$.



Conclusion

- A 2.4σ observation of Higgs boson through the four-lepton "golden" channel.
- Higgs mass of $m_H = 124.22 \pm 1.16\ \text{GeV}$. Consistent with the theoretical prediction of $m_H = 125\ \text{GeV}$!