Massachusetts Institute of Technology

Signal for a Higgs-like Particle of 124.15 ± 1.16 GeV from $H \to ZZ \to 4l$ Search

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Standard Model of Particle Physics and the Missing Piece

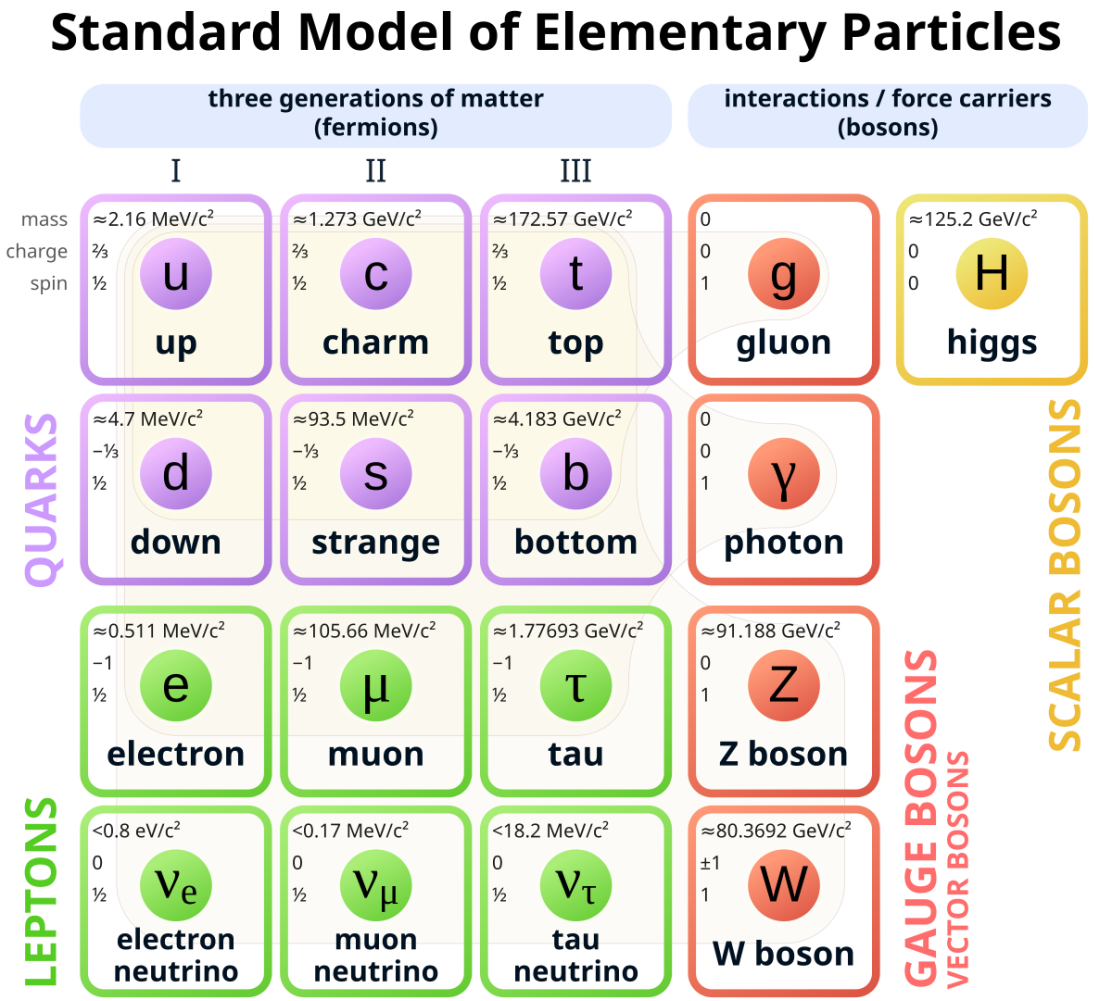


Image credit: Cush

Higgs Mechanism

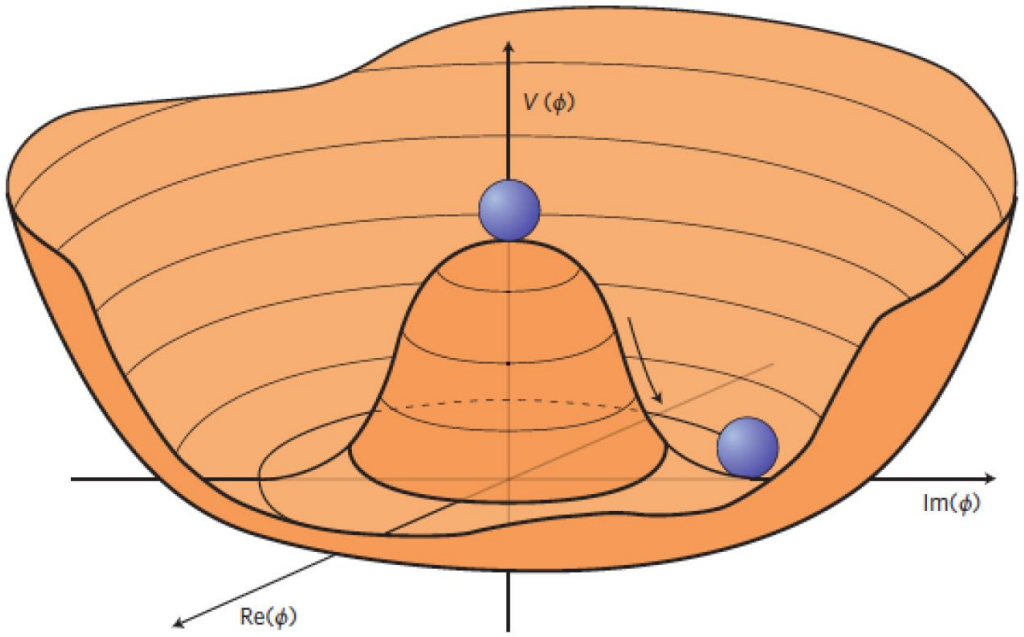


Image credit: CERN

The Possible Modes of Search for Higgs

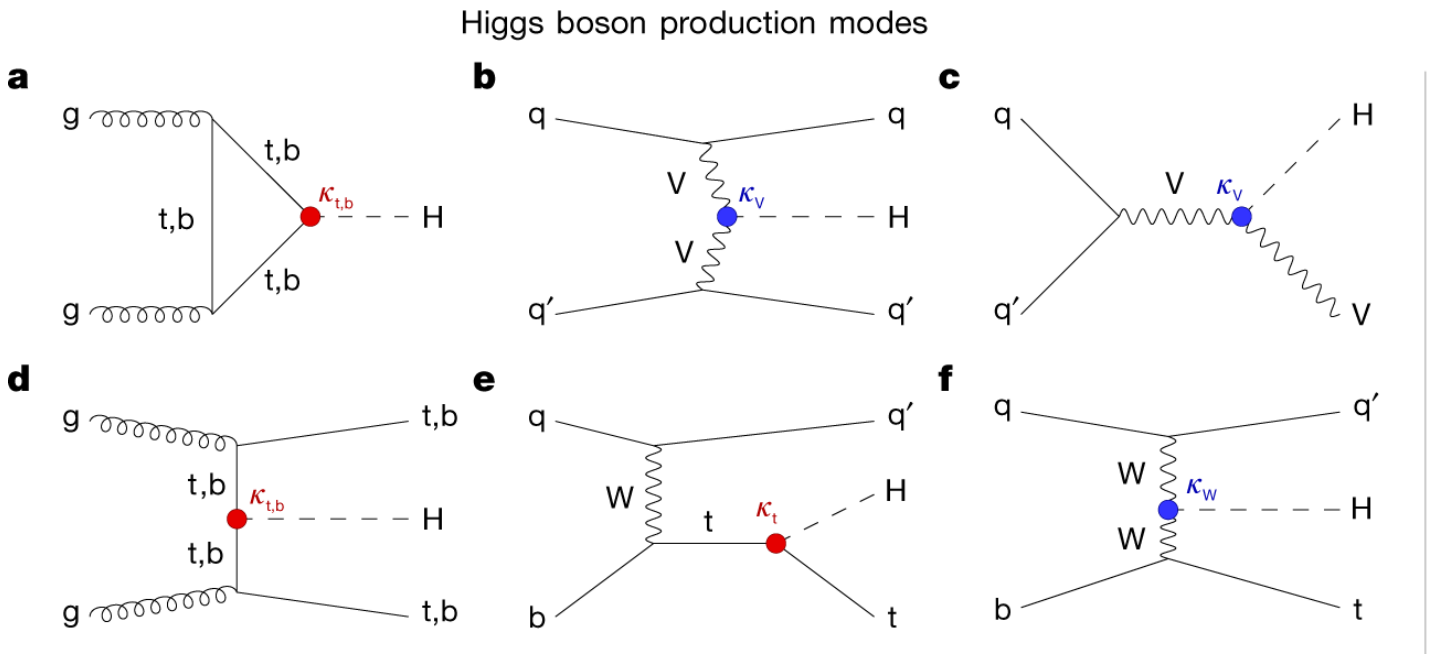
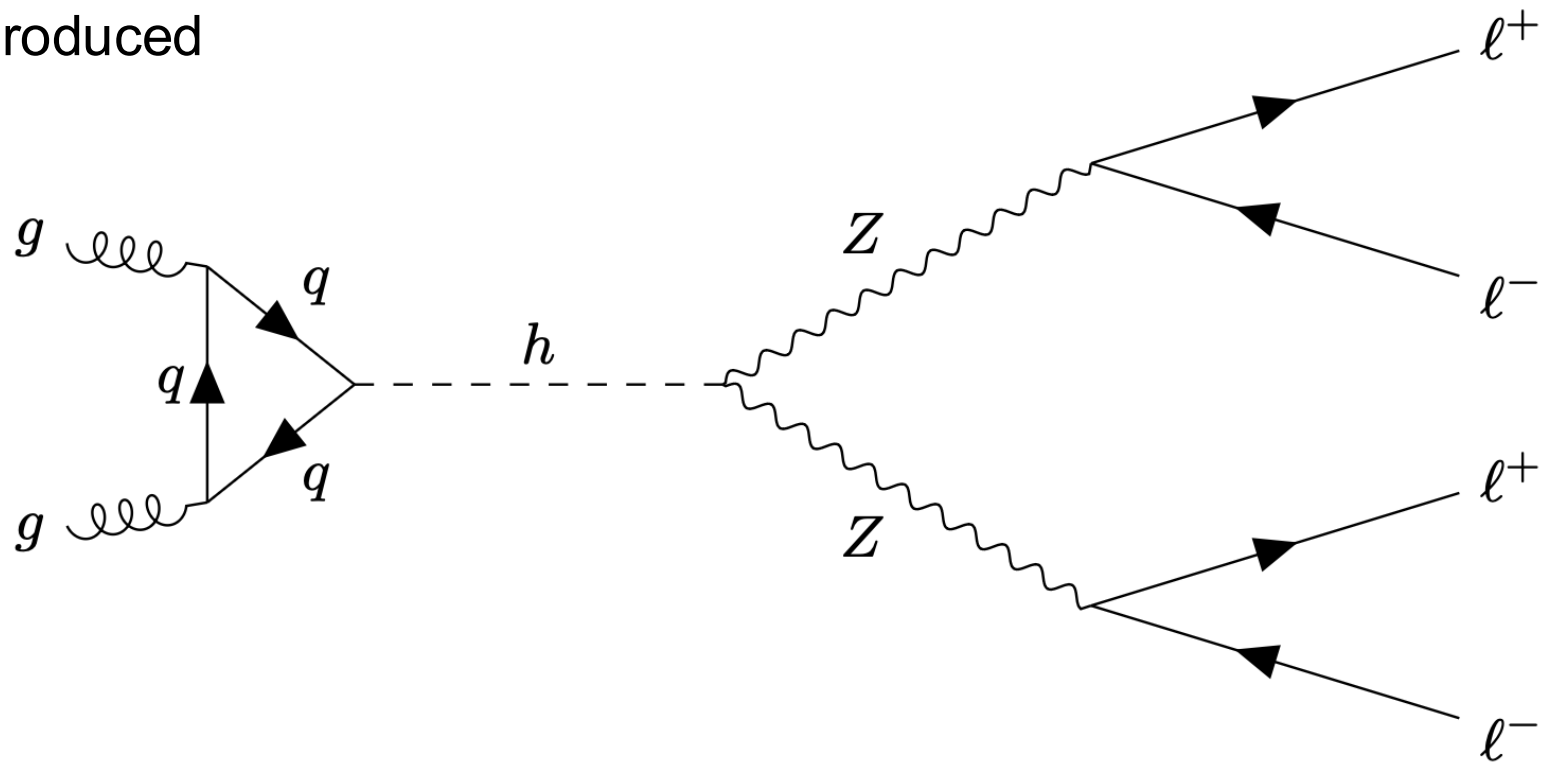


Image credit: CMS

$$H \to \gamma\gamma,\ H \to ZZ,\ H \to W^+W^-,\ H \to \tau^+\tau^-,\ H \to b\bar{b}$$

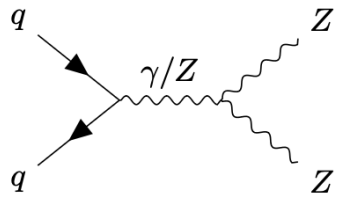
$H \rightarrow ZZ \rightarrow 4l$: "the Golden Channel"

- Non-hadronic
- No neutrino produced

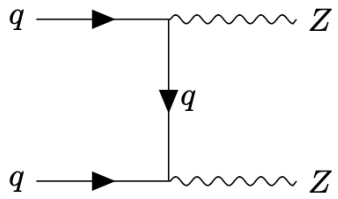


There are still some irreducible background that we need to differentiate

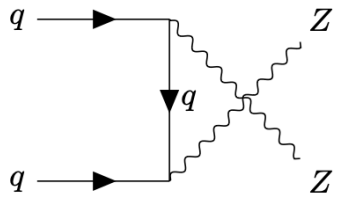
- Continuum ZZ* Production



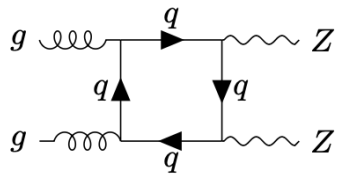
(a) $qq \to \gamma^*/Z^* \to ZZ$



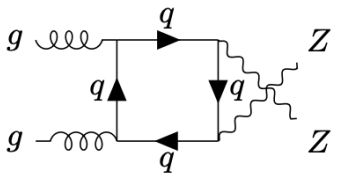
(b) t-channel quark exchange



(c) u-channel quark exchange



(d) $gg \to ZZ$ box diagram



(e) $gg \to ZZ$ box diagram (crossed)

- $Z/\gamma + X$ production (only a pair of leptons)
- $t\bar{t}$ pair production

LHC and CMS Detector

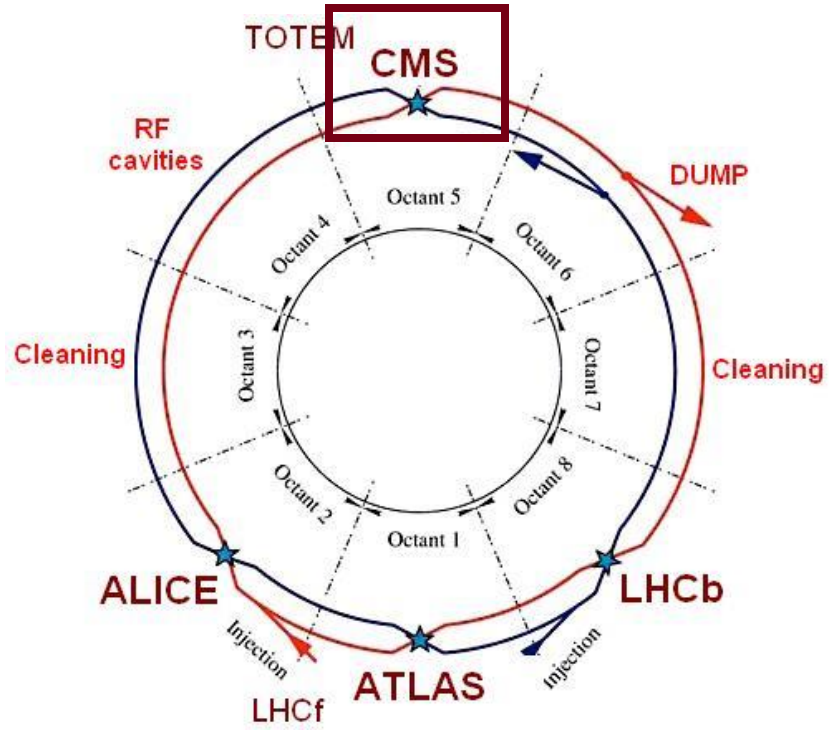


Image credit: Xabier Cid Vidal & Ramon Cid

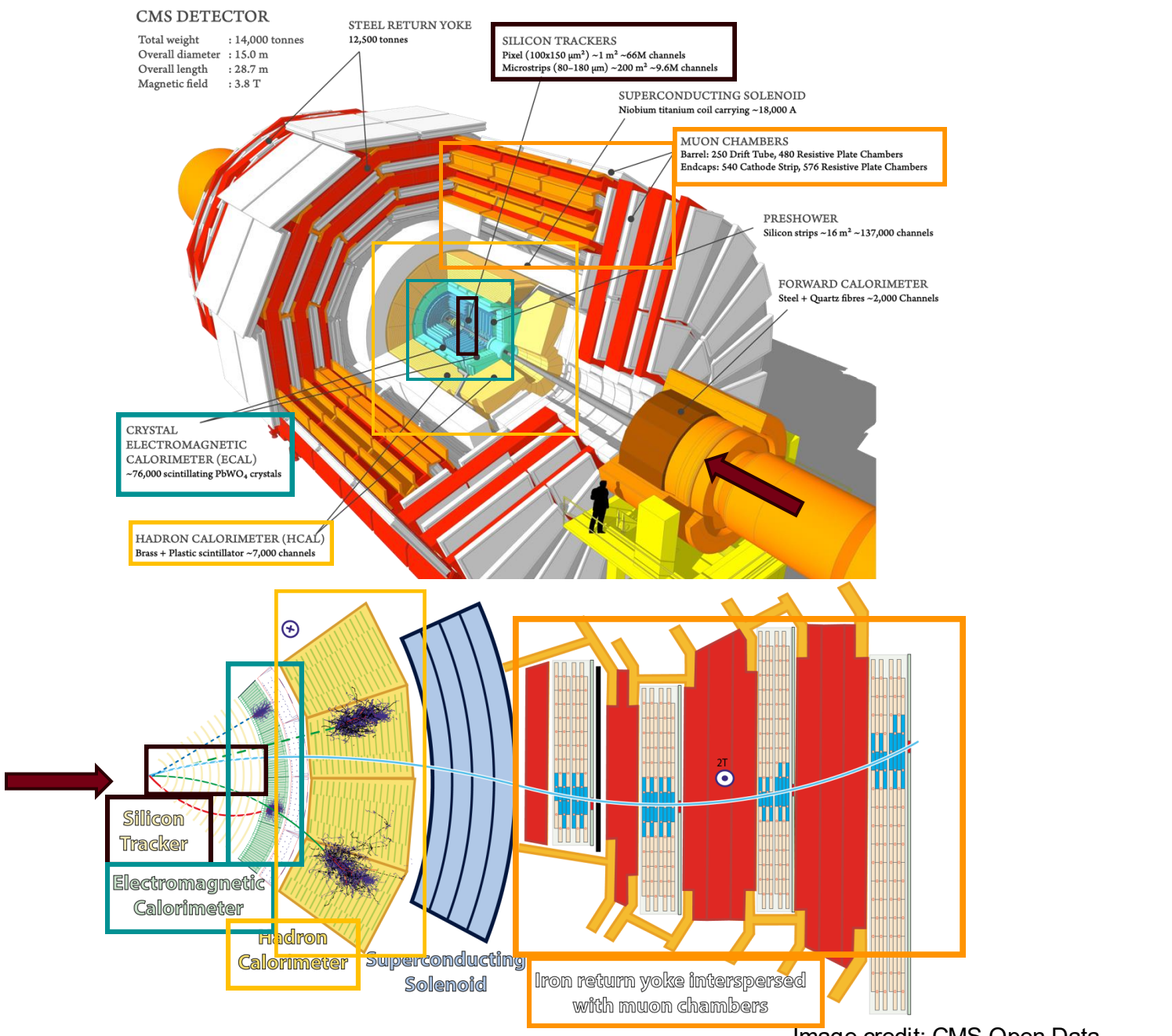
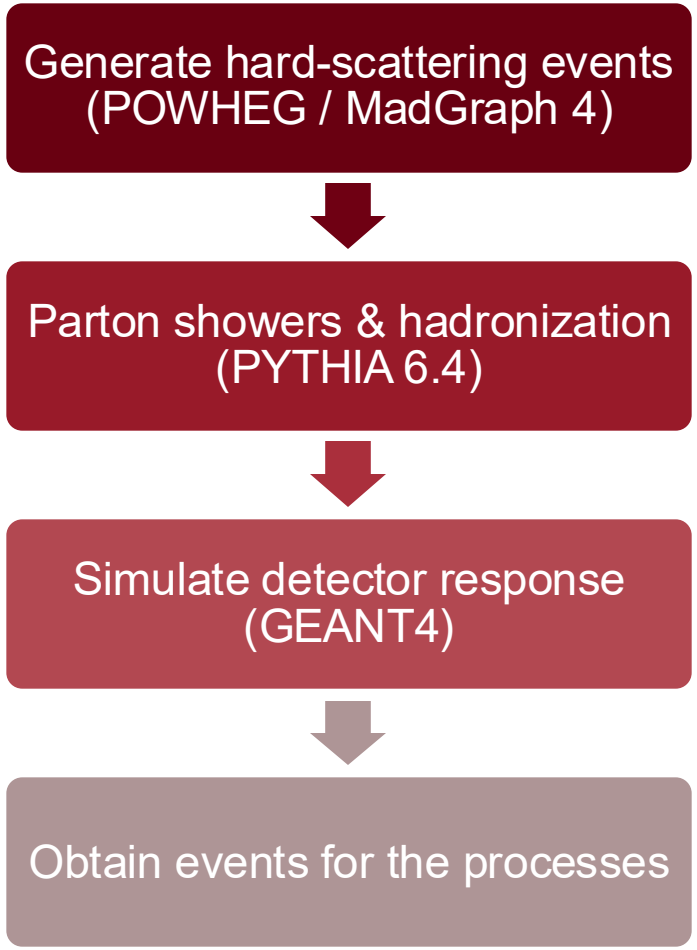


Image credit: CMS Open Data

Monte Carlo Simulation for Background and Signal Processes

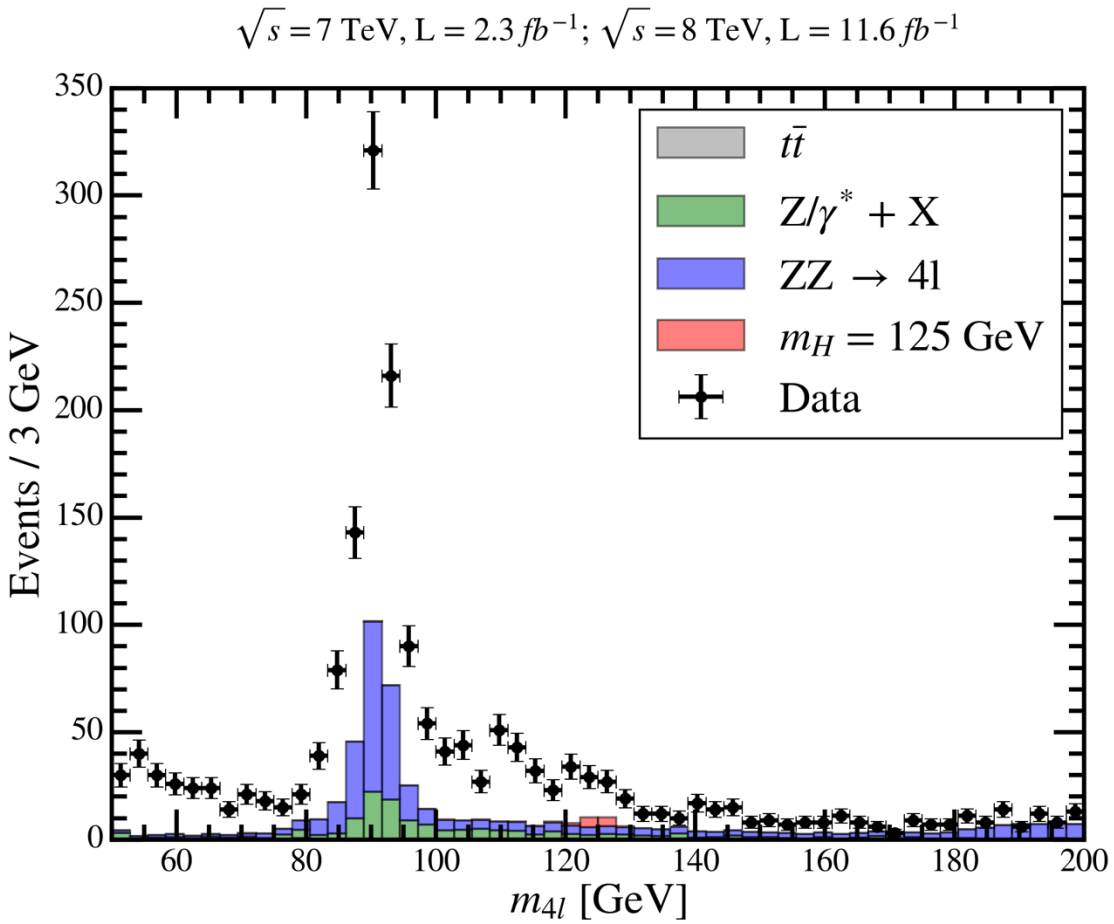


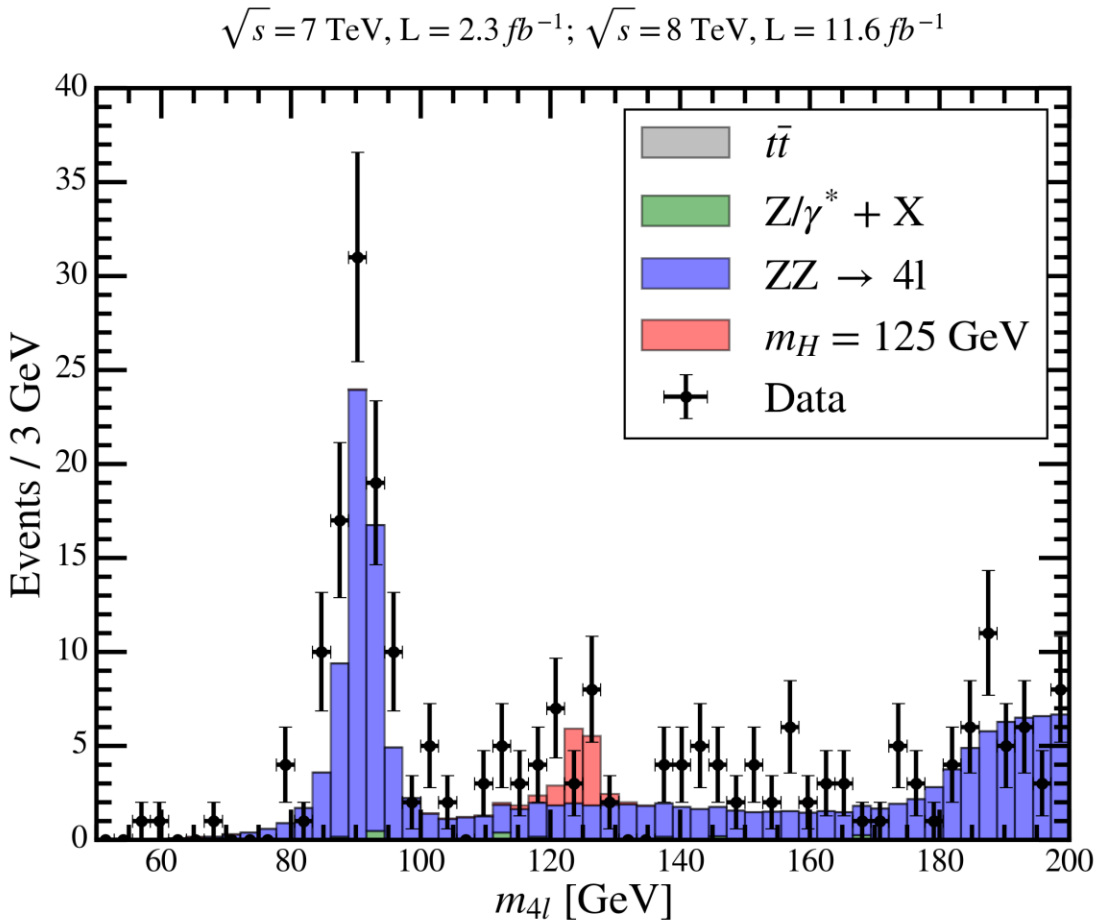
- Used official Parton Distribution Function (PDF) sets recommended by PDF4LHC Working Group.
- MC simulation obtained from CMS Open Data

Preliminary Cuts to Process Data

- Four-lepton final state, two pairs of same-flavor, opposite-charged leptons
- Transverse and longitudinal impact parameter: $|d_{xy}| < 0.5\ \mathrm{cm}$, $|d_z| < 1.0\ \mathrm{cm}$
- 3D impact parameter significance: $\mathrm{SIP} = \frac{d_{3D}}{\sigma_{d_{3D}}} < 4$
- Isolation cut of leptons: $I_{rel} = \sum p_{\mathrm{T,i}}/p_{\mathrm{T},\ell} < 0.4$ with $\Delta R_i = \sqrt{\Delta\phi_{i,\ell}^2 + \Delta\eta_{i,\ell}^2} < 0.4$
- Pseudorapidity (angle) cut for leptons: $|\eta_e| < 2.5, |\eta_\mu| < 2.4$
- Transverse momentum cut for leptons: $p_{\mathrm{T},e} > 7\ \mathrm{GeV}$, $p_{\mathrm{T},\mu} > 5\ \mathrm{GeV}$
- Invariant mass cuts of lepton pairs: leading pair $40\text{-}120\ \mathrm{GeV}$, the other pair $12\text{-}120\ \mathrm{GeV}$.

Preliminary Cuts Processed Data





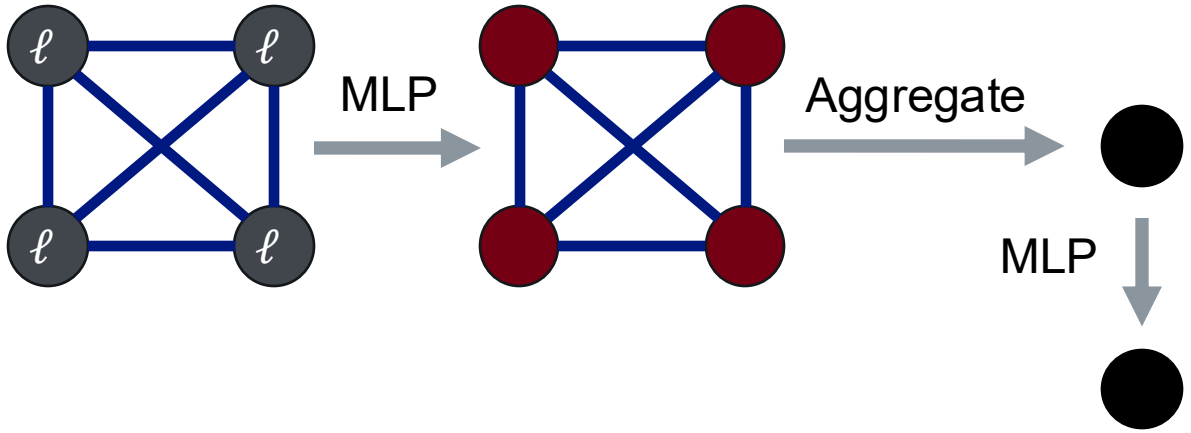
Neural Network: Graph Convolution Network to Further Differentiate Signal from Background

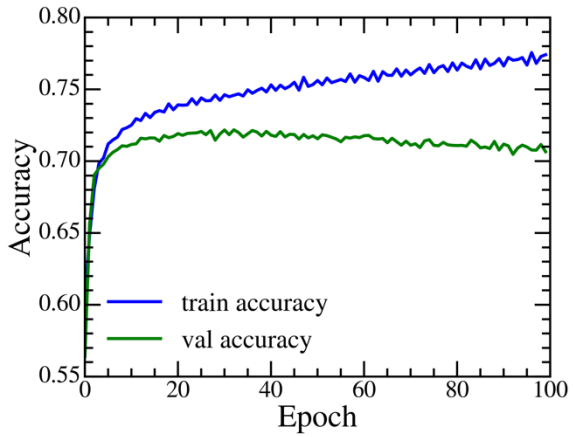
Pre-process events and feed in p_x, p_y, particle type

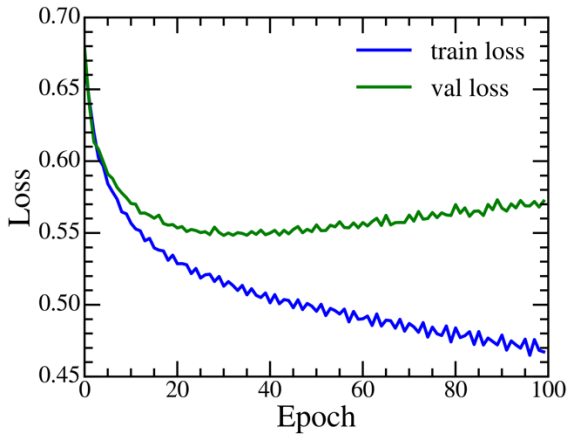
Feed-forward MLP per lepton (3 layers)

Combine all 4 leptons (4 layers)

Binary output (signal/background)

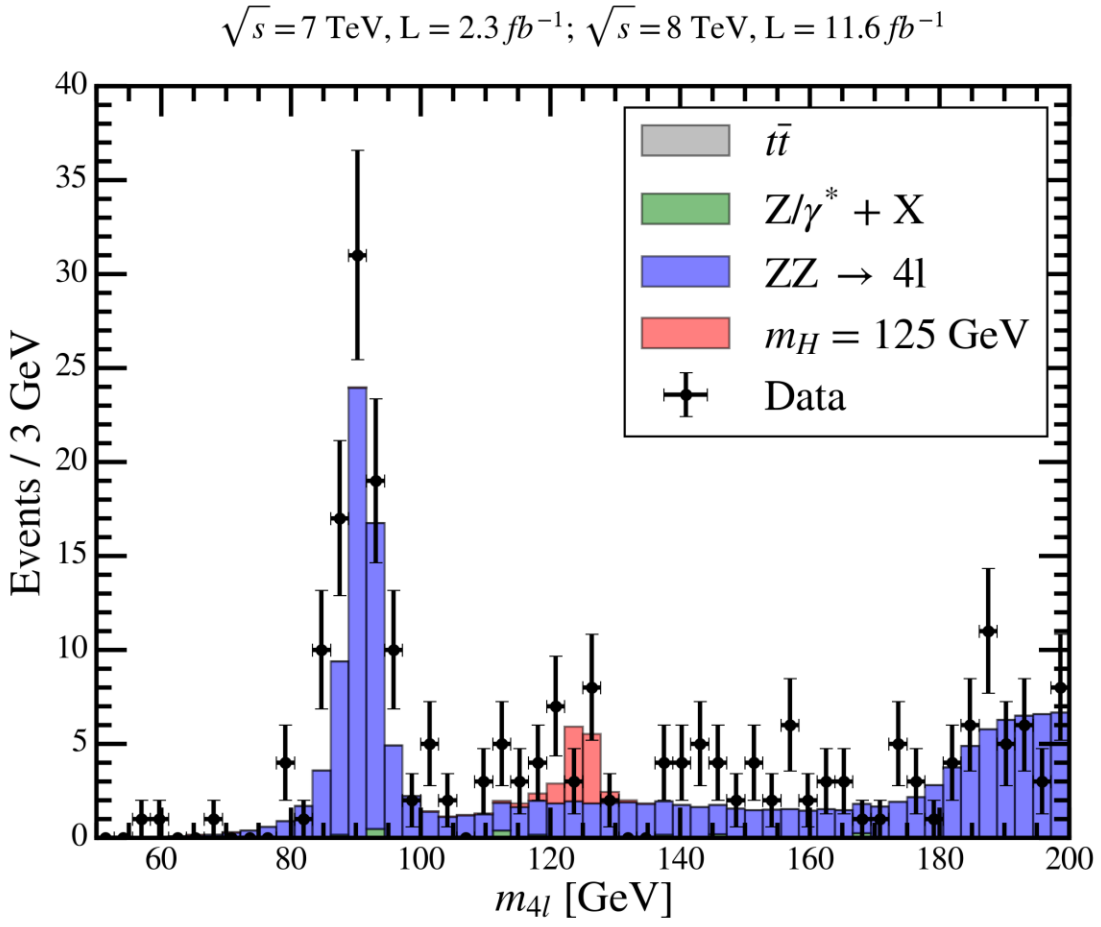


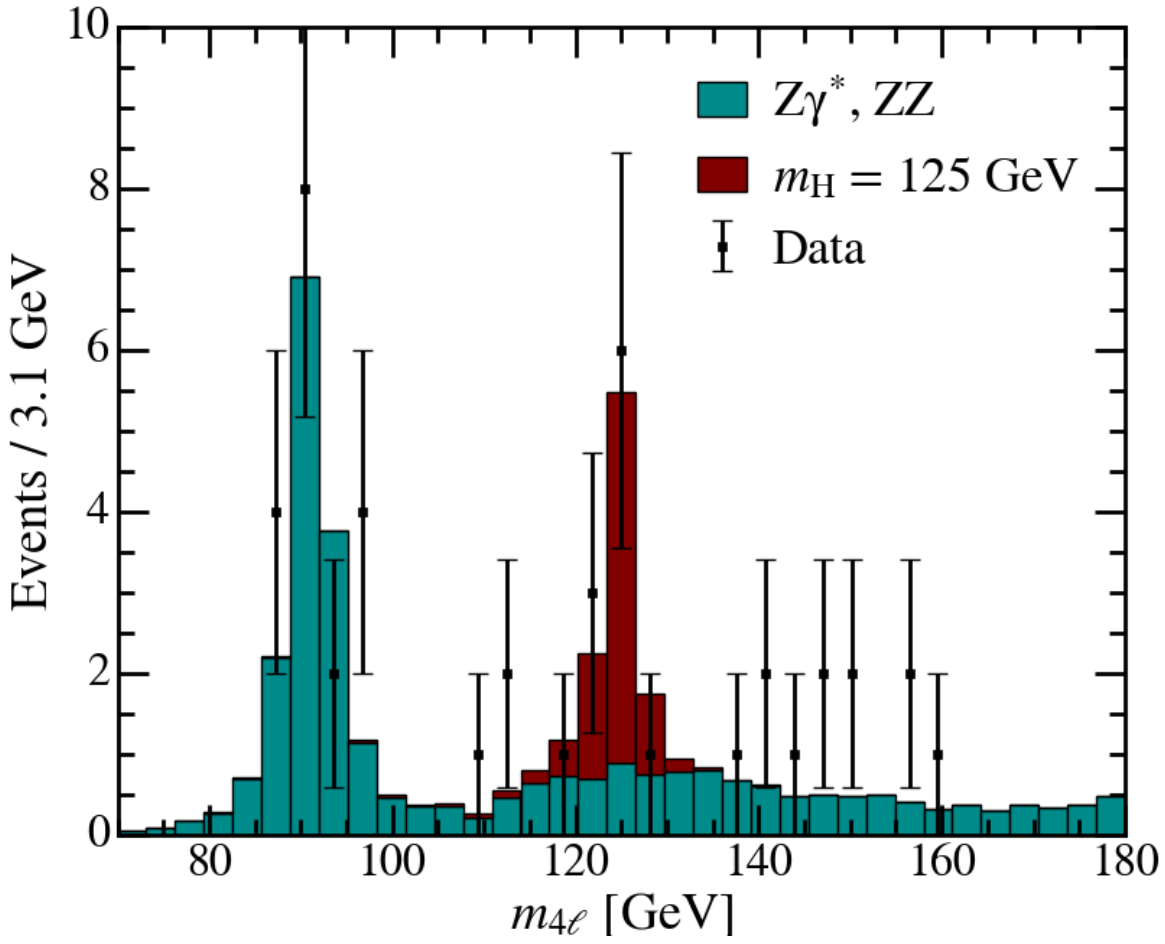




Training: Adam optimizer, binary cross entropy loss function, 100 epoch, 72% training, 18% validation, 10% testing

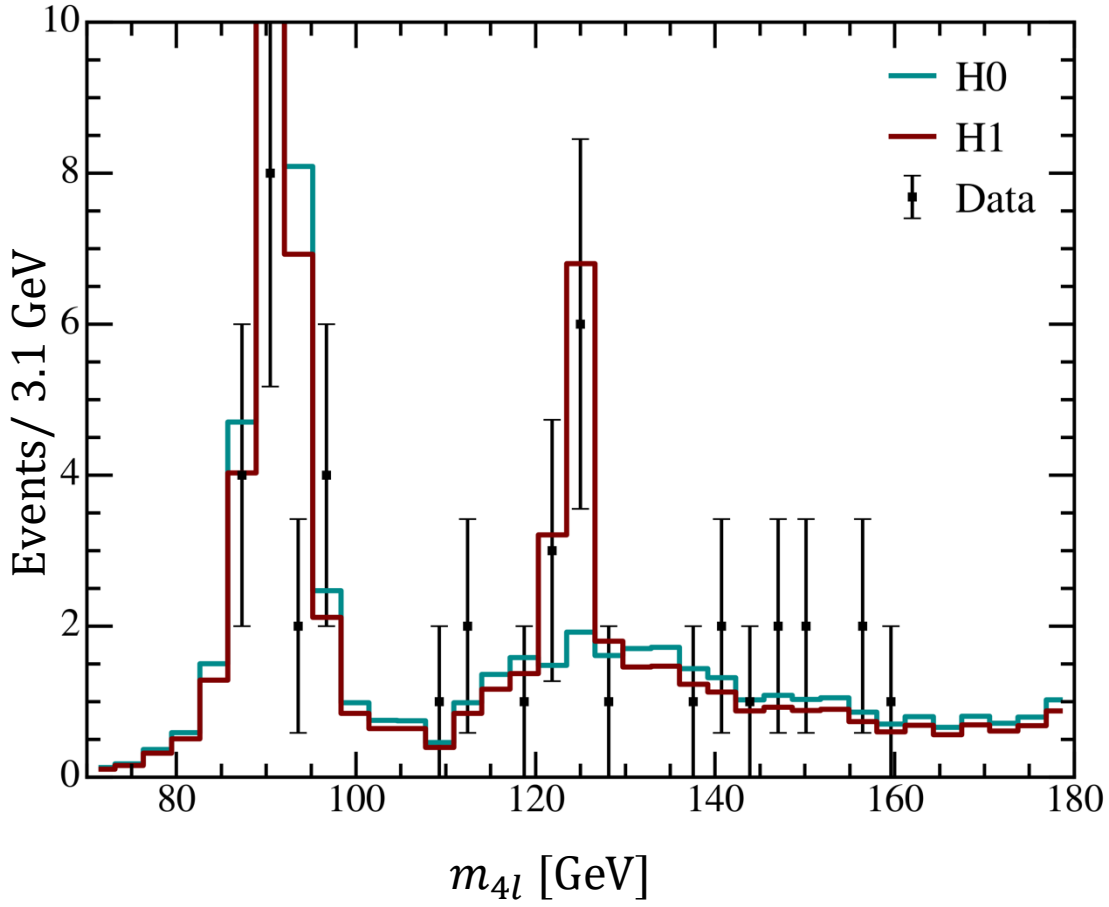
Background Gets Cut Significantly after Neural Network

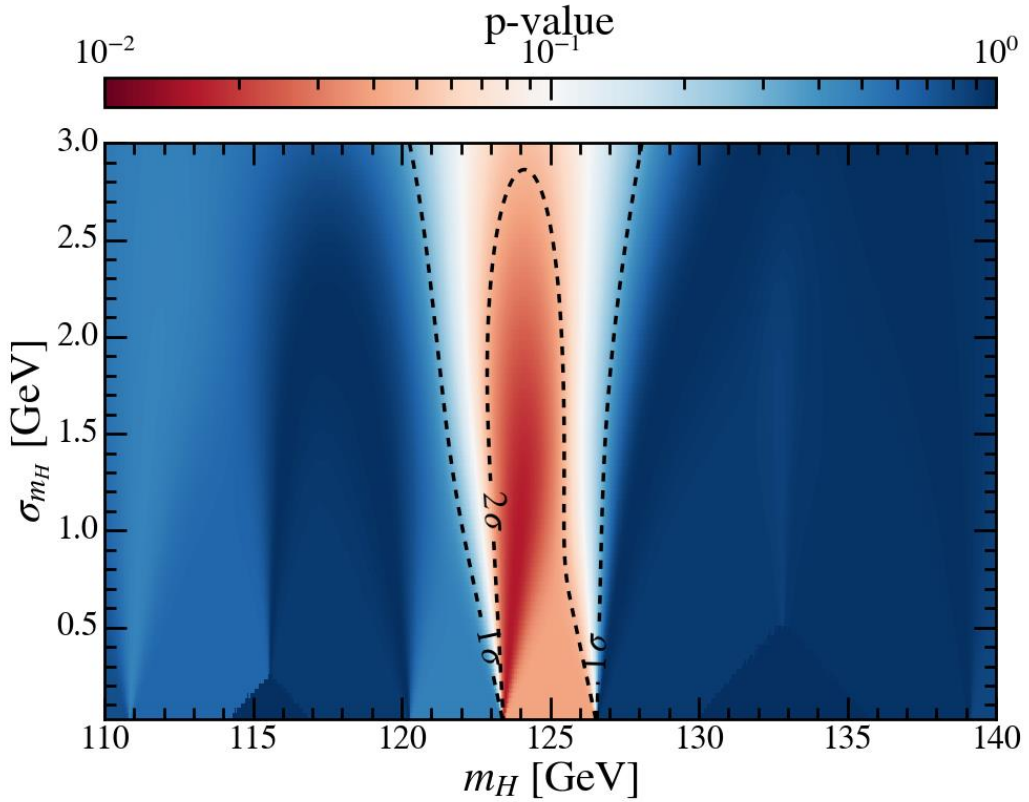




Likelihood Test determines the Excess of Signal as $2.4\,\sigma$

Estimate the signal as a Gaussian function → H0: background; H1: background+Signal → Calculating $\Delta\chi_r^2$ → Convert to p-value and Z-score





$2.4\,\sigma$ excess at $m_H \simeq 123.8$ GeV

Uncertainty Dominated by Limited Size of Event and PDF

- Statistics Uncertainty
  - Limited size of events recorded
  - Can be improved with higher combined luminosity (LHC Run 2)

- Systematic Uncertainty
  - Parton Distribution Function (PDF4LHC): $\sim 5 - 8\%$

S. Alekhin et al. The PDF4LHC Working Group Interim Report. 2011.
R. D. Ball and others (NNPDF Collaboration). Impact of Heavy Quark Masses on Parton Distributions and LHC Phenomenology. Nucl. Phys. B, 849:296–363, 2011.
M. Botje et al. The PDF4LHC Working Group Interim Recommendations. 2011.
H.-L. Lai et al. New parton distributions for collider physics. Phys. Rev. D, 82:074024, 2010.

Conclusion: An Excess in Signals for Higgs Boson!

$2.4\,\sigma$ excess at $m_H \simeq 123.8\,\mathrm{GeV}$ in $H \to ZZ \to 4l$ channel

Bootstrapping gives us $m_H \simeq 124.15 \pm 1.16\,\mathrm{GeV}$

Combined with other channels gives us $5\,\sigma$ requirement for discovery!