Karlsruhe Institute of Technology

# Experimental Physics at Hadron Colliders

## CERN Summer Students Lectures, July 24-26, 2024 - Lecture 3/4

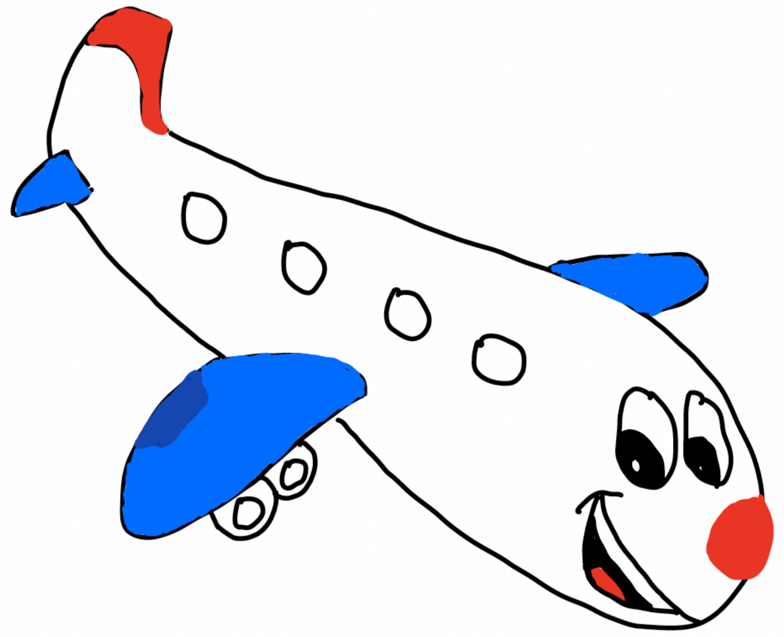
Markus KLUTE (markus.klute@kit.edu)
Institute of Experimental Particle Physics (ETP)

# Work Plans

- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

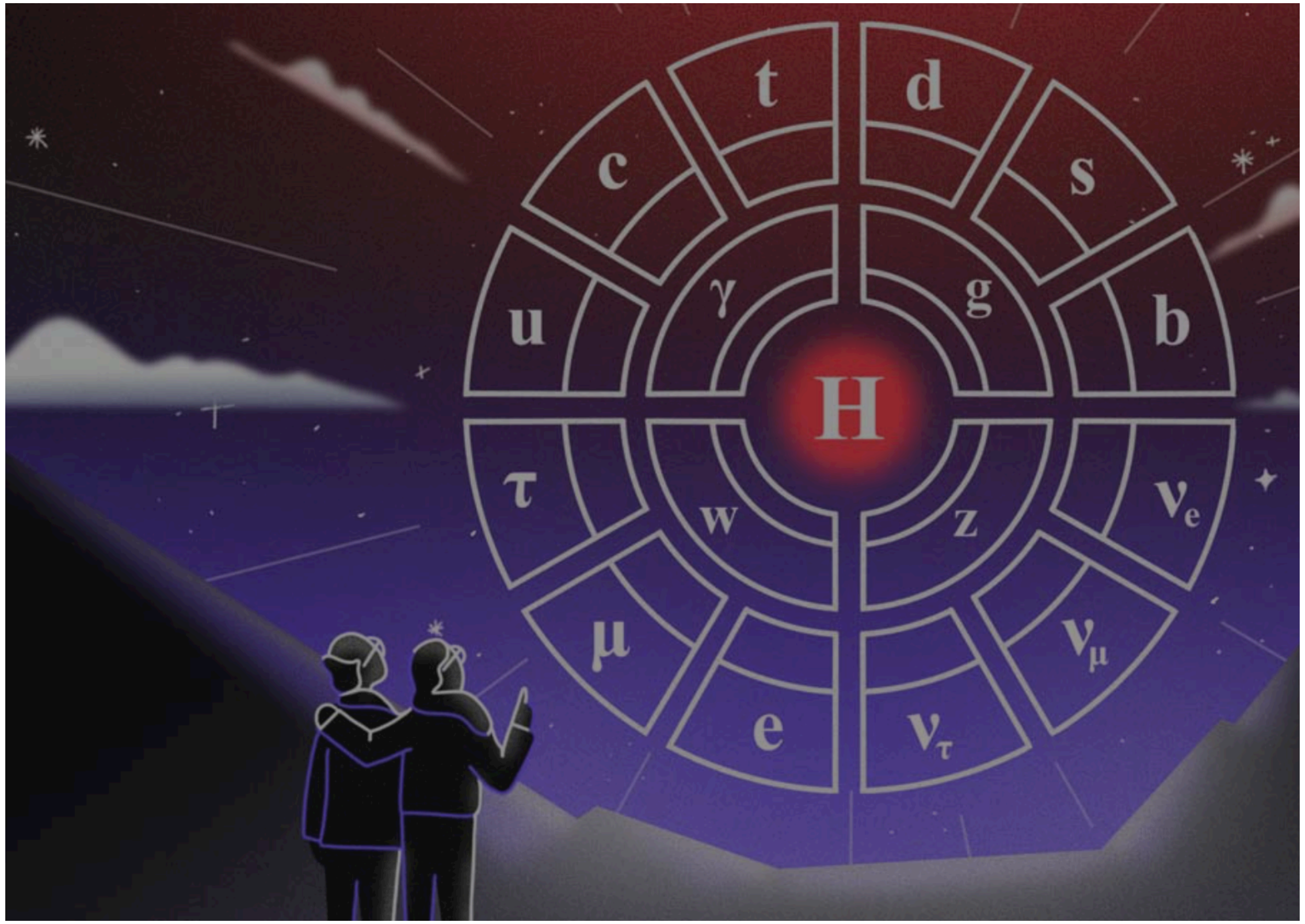
# Higgs Physics

- July 4th, 2012

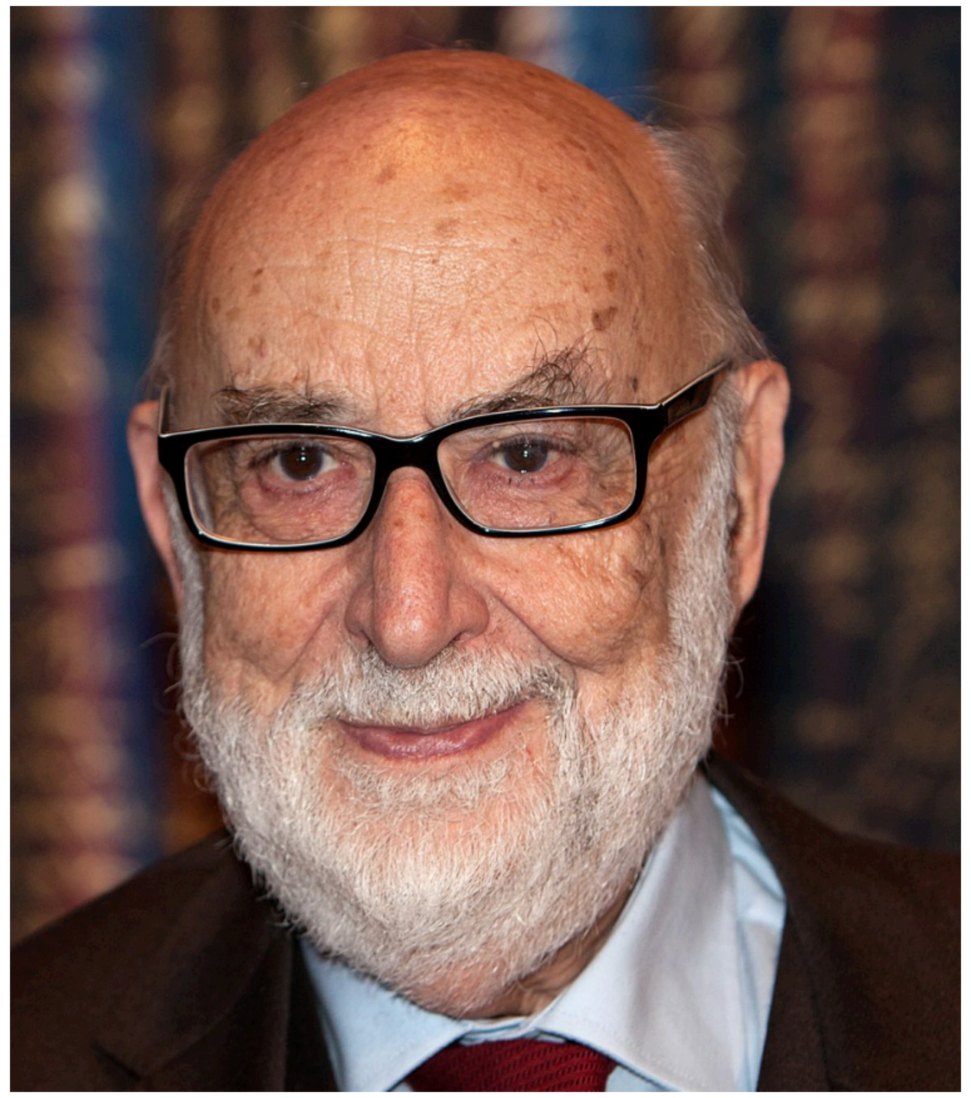


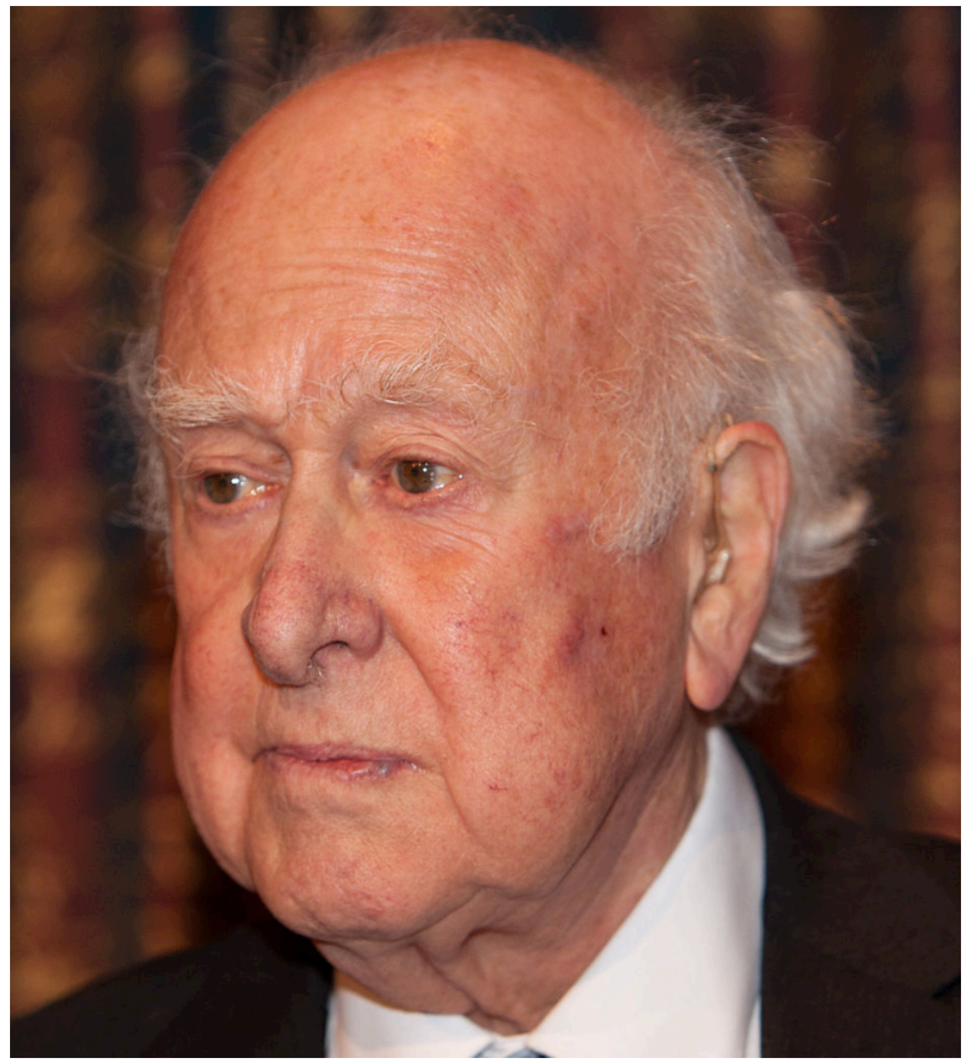
# Higgs Physics

- 2013




Source: BMBF-FSP-LHC

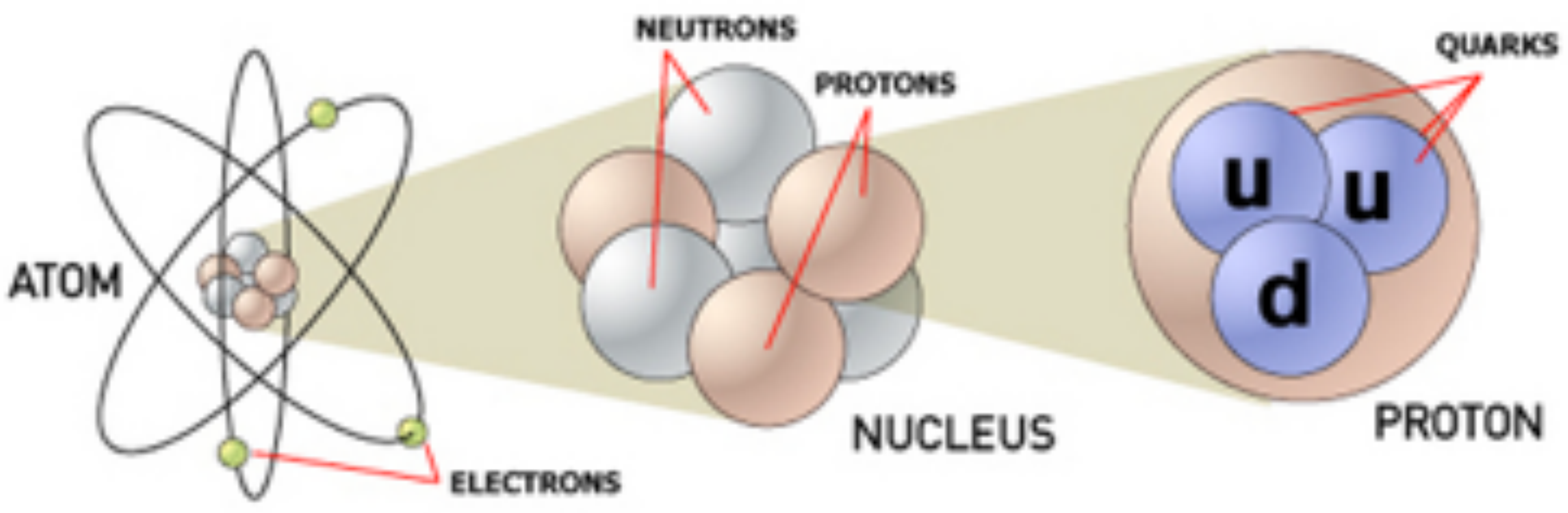


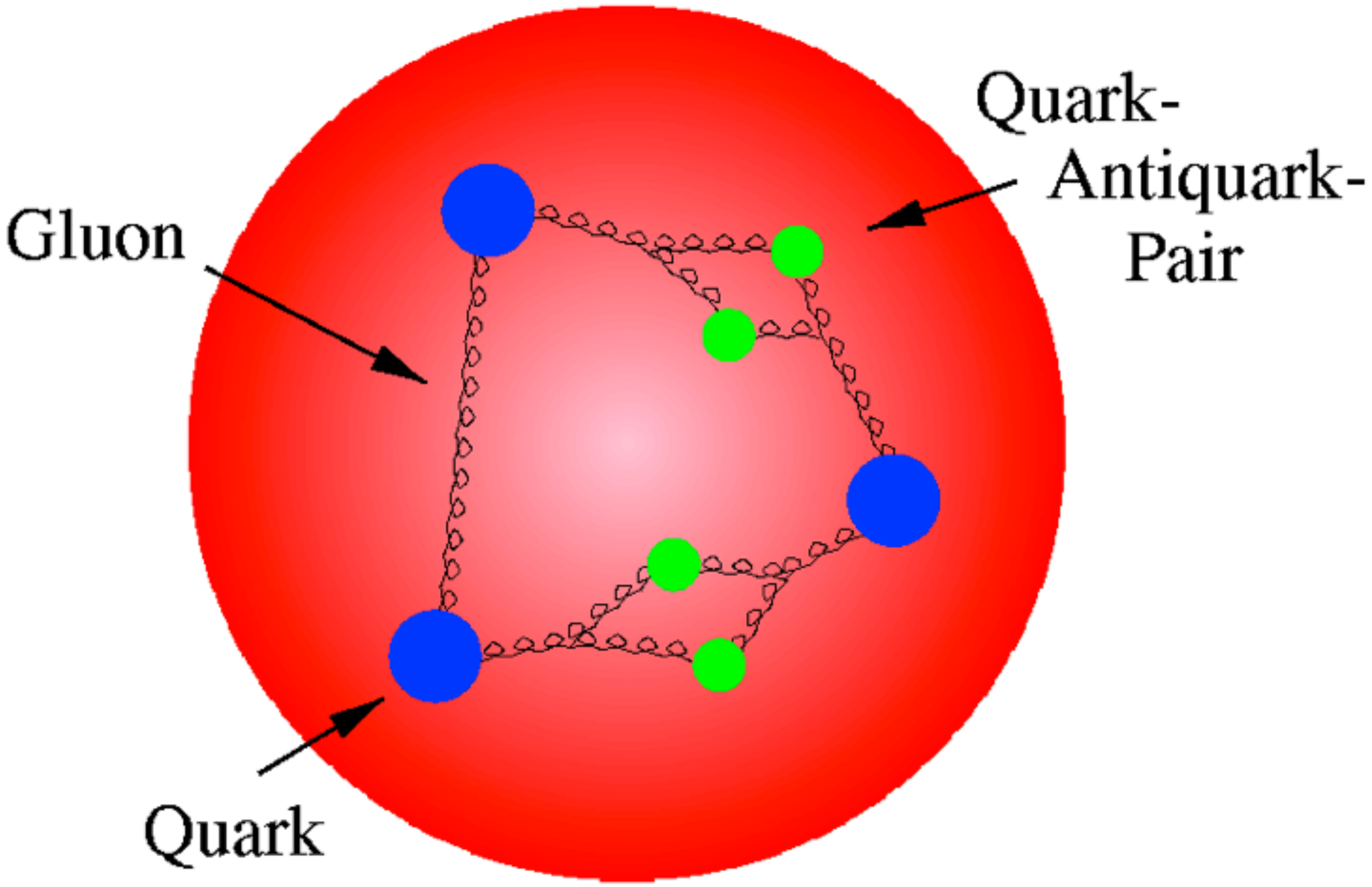


# Pingo

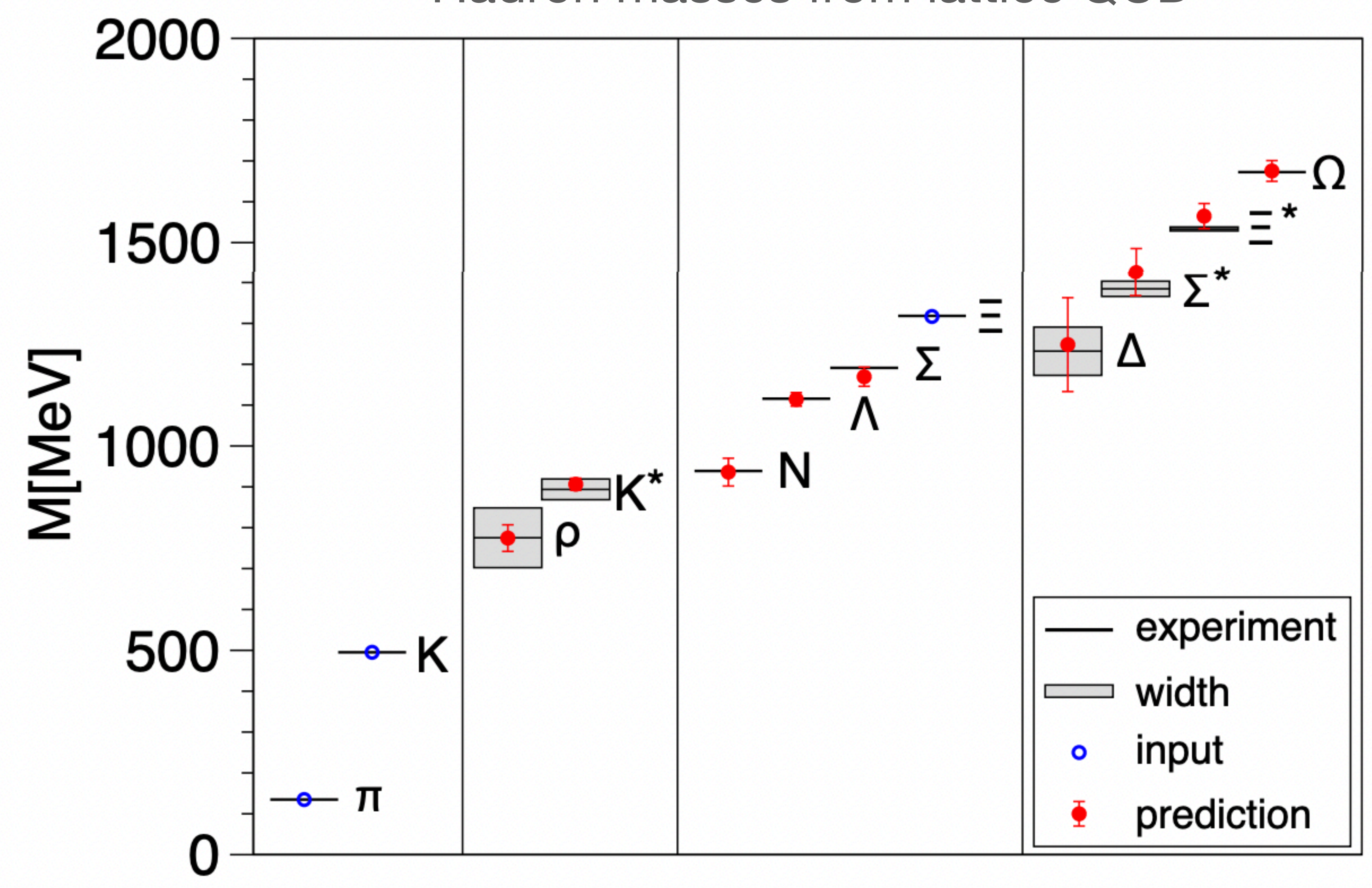
- What does “observation of a new particle” mean?
  - 1) the background plus signal hypothesis agrees with the data better than the hypothesis without new particle (background only)
  - 2) the background only hypothesis does not agree with the data
  - 3) the background plus signal hypothesis agrees with the data

# Understanding mass and matter




Hadron masses from lattice QCD




arXiv:1203.4789

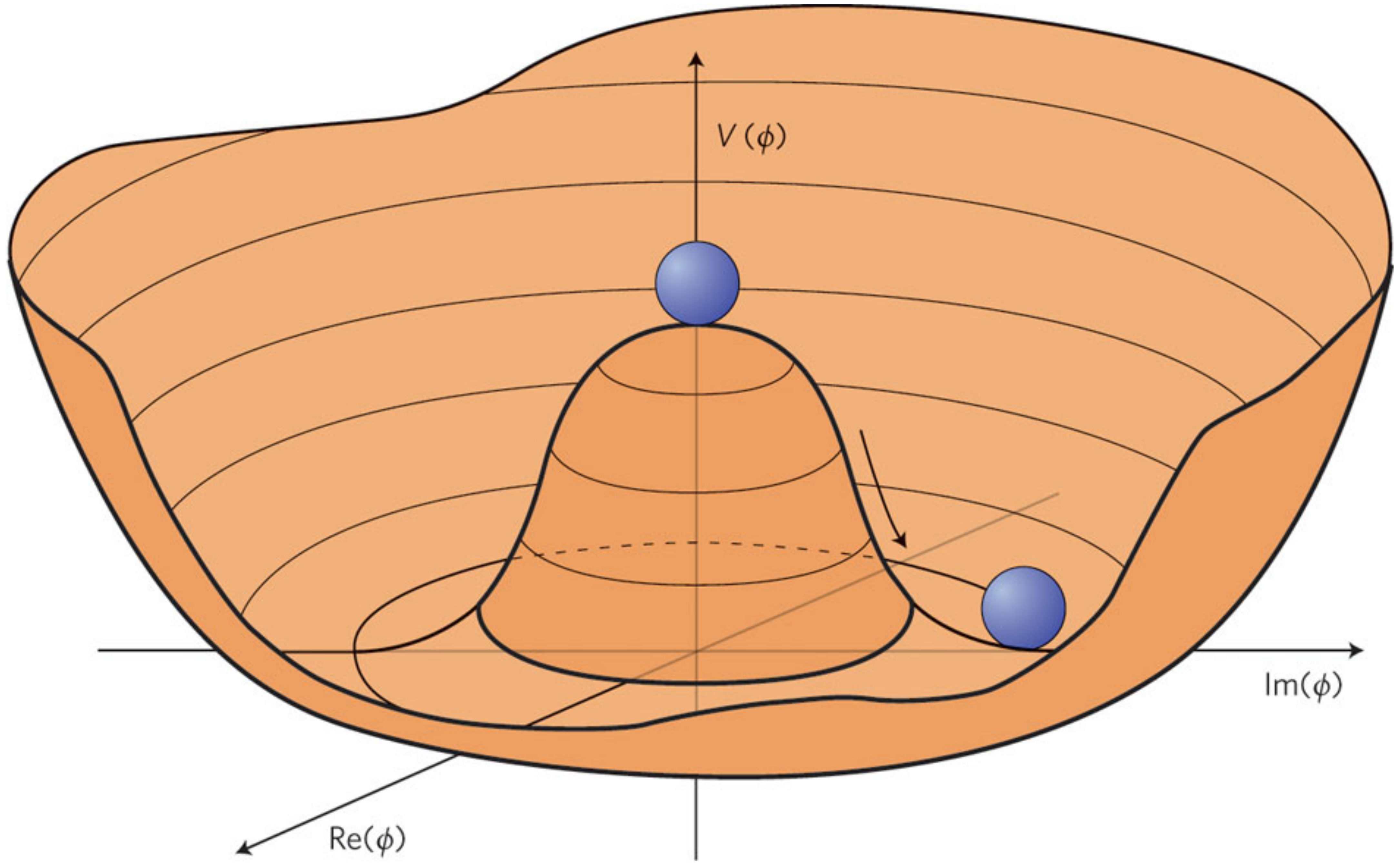
**Proton mass**
$m_P$ = 938 MeV

**Quark masses**
$m_u$ = 1.5-4.5 MeV
$m_d$ = 5.0-8.5 MeV

**Inertial mass**
mostly QCD effects

# Higgs Mechanism

- SM based on "local gauge invariance" of $SU(2)_L xU(1)xSU(3)$
- **Problem**: weak bosons are massive and a mass term can not be added "by hand" as gauge symmetry would be destroyed
- **Solution**: Higgs mechanism, i.e. introduction of a scalar, complex field with ground state breaking the gauge symmetry



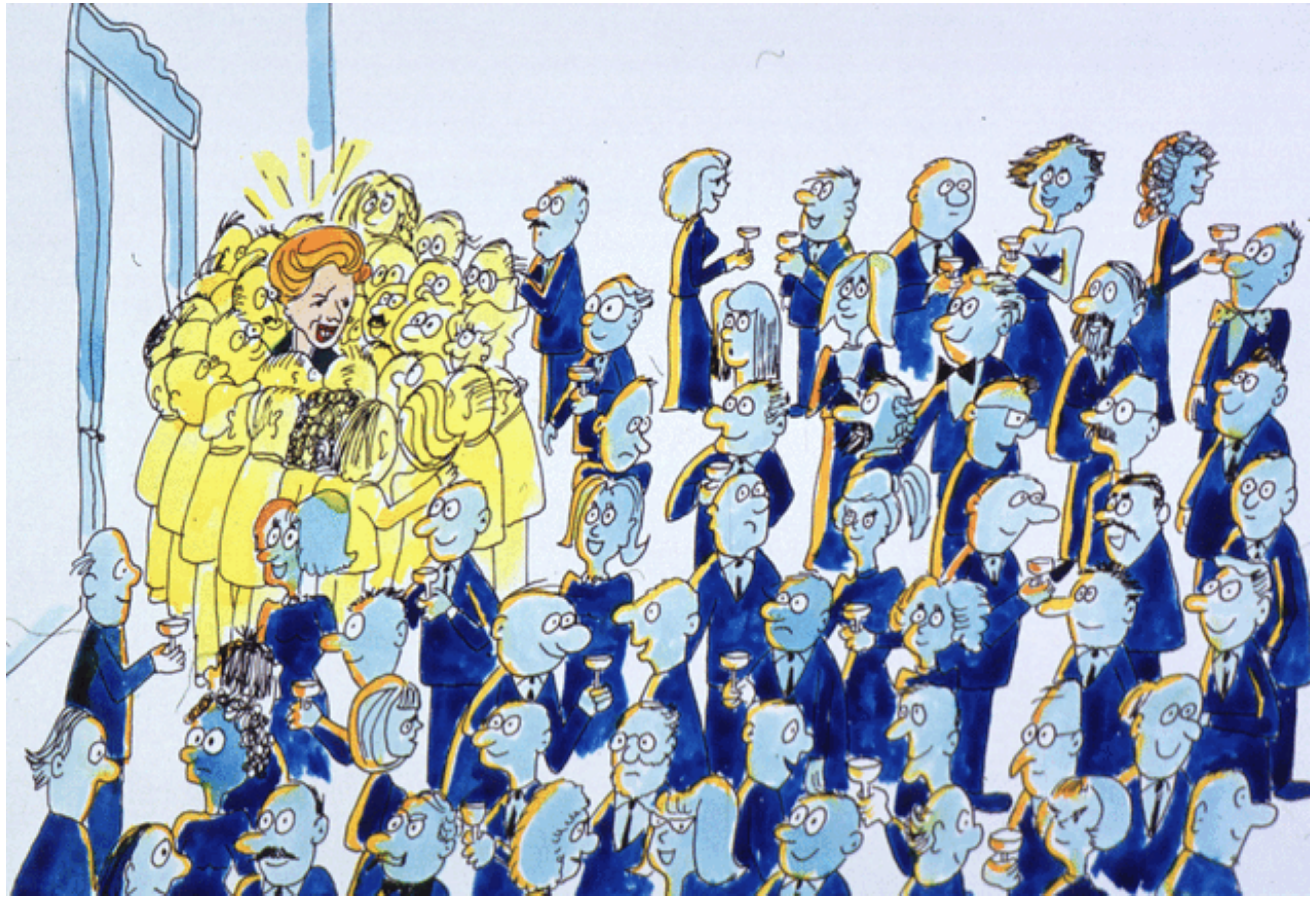

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V(\Phi) = \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \mu^2\left(\Phi^\dagger\Phi\right), \quad \lambda > 0$$

$$\mu^2 < 0$$

# Higgs Mechanism

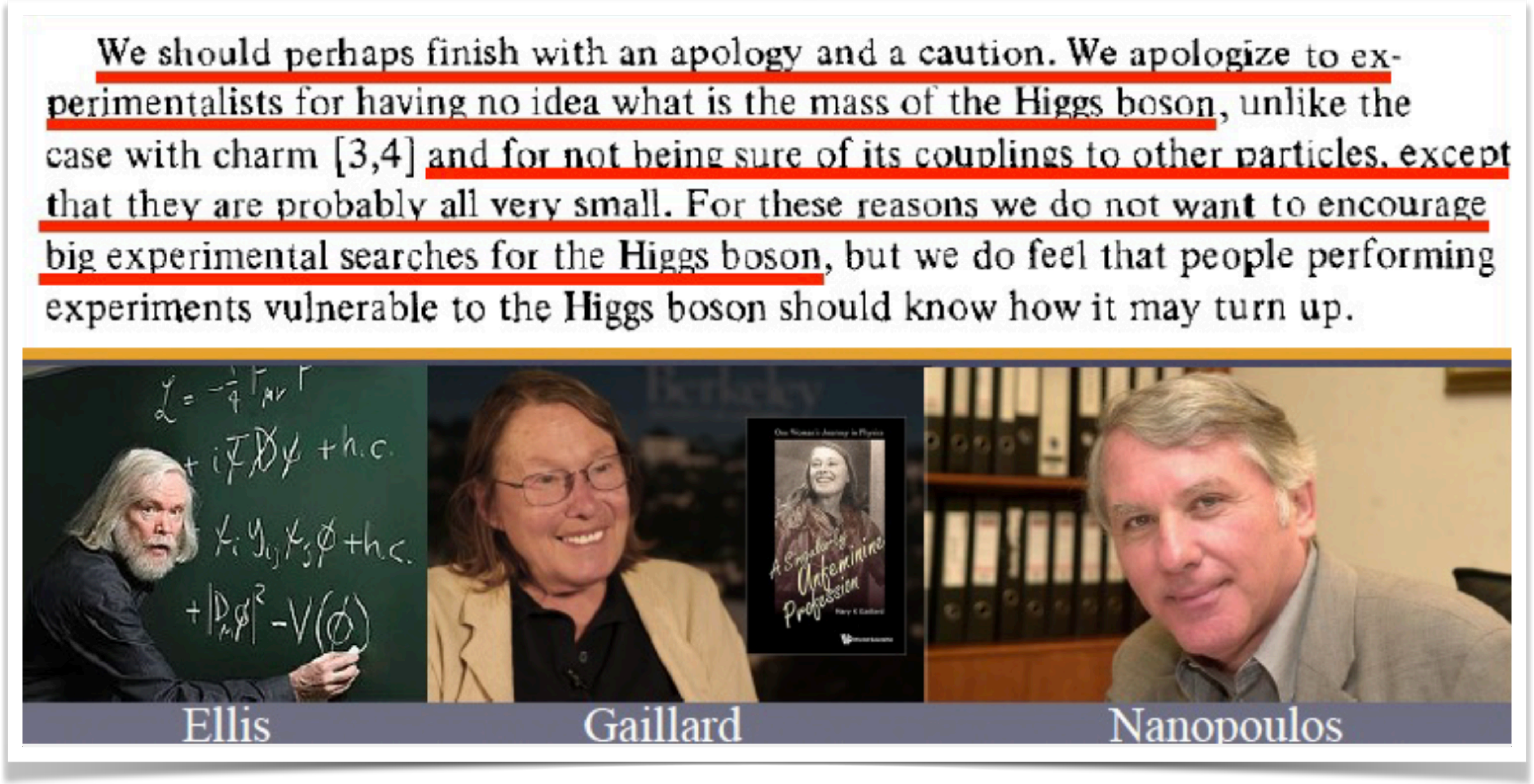
- Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field
- Higgs boson: field quantum of the Higgs field
- Complex scalar SU(2) doublet → 4 degrees of freedom
  - 3 components of the Higgs doublet → longitudinal components of the $W^+$, $W^-$, and Z bosons
  - 4th component: H the Higgs boson
- Models with two Higgs doublets (e.g. MSSM) => prediction: 5 physical Higgs bosons



Von David Miller (UCL) for Mr. Waldegrave, Quelle: CERN

# Higgs Boson History

- 1964 R. Brout, F. Englert, and, independently, P. Higgs "theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles"
- 1989 the search for the Higgs Boson started to gain momentum at LEP
- 2001 the Tevatron at Fermilab continued the search
- 2010 the LHC entered the game

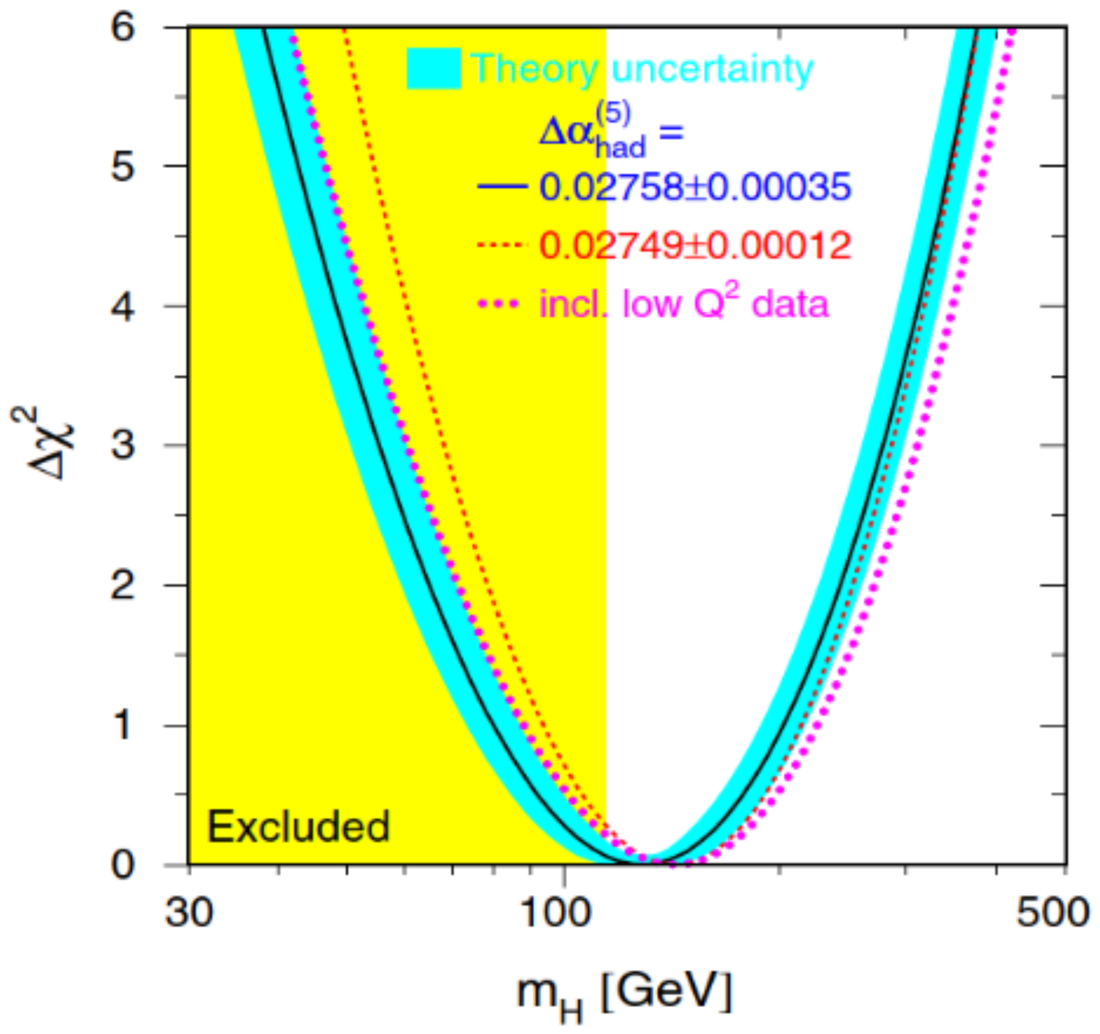


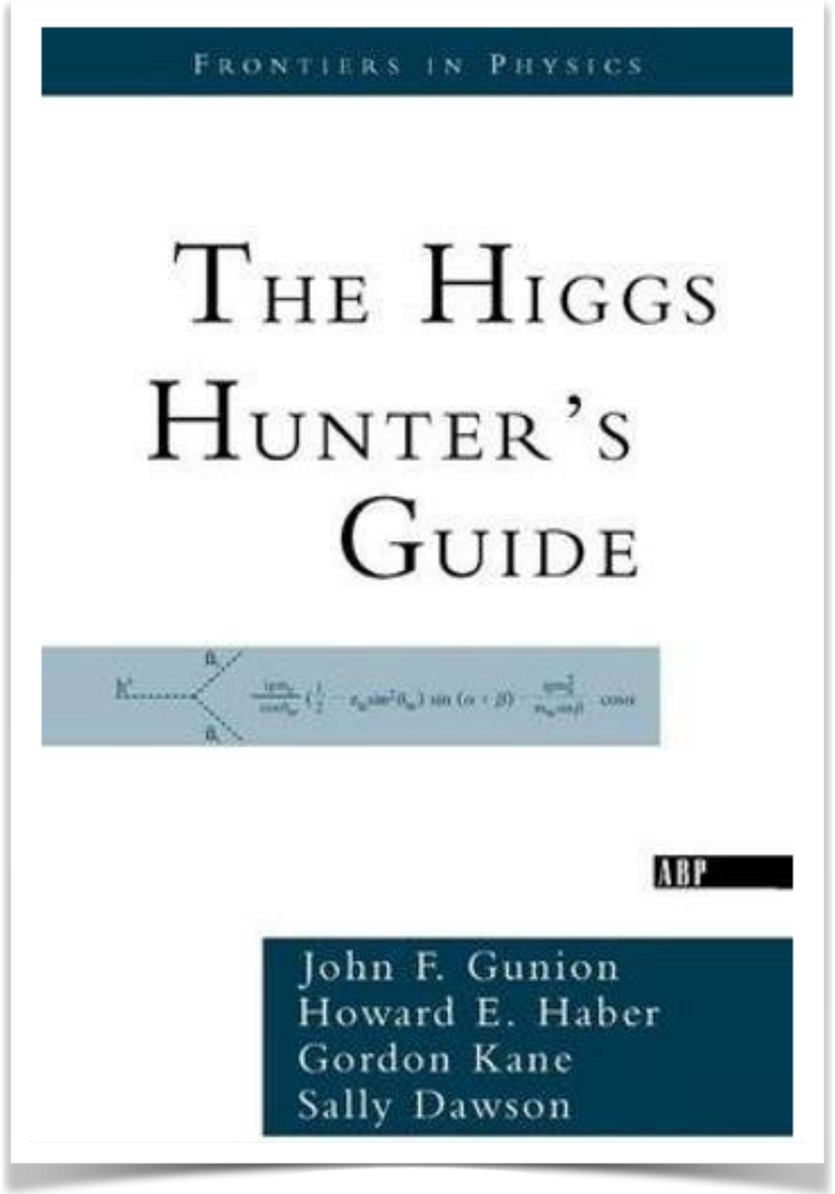
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



1976

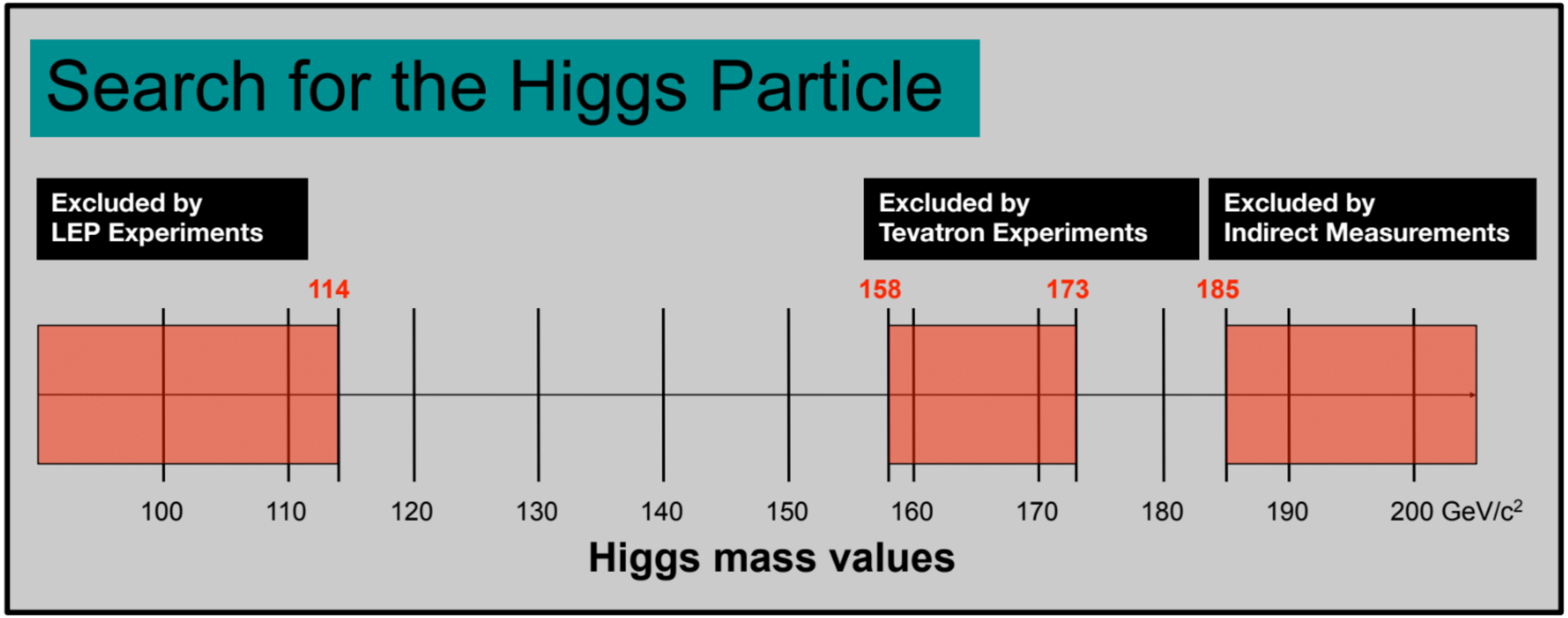
Source: Sally Dawson



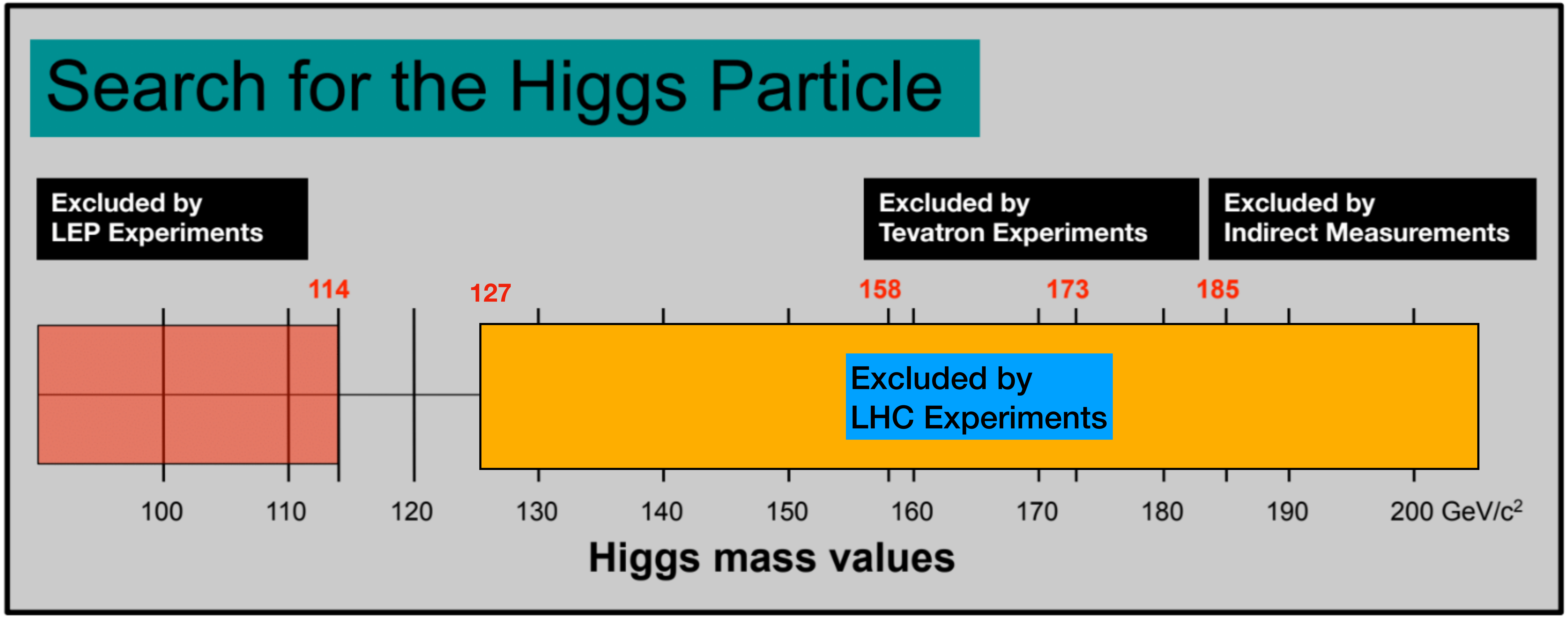

1990

# Road to Discovery



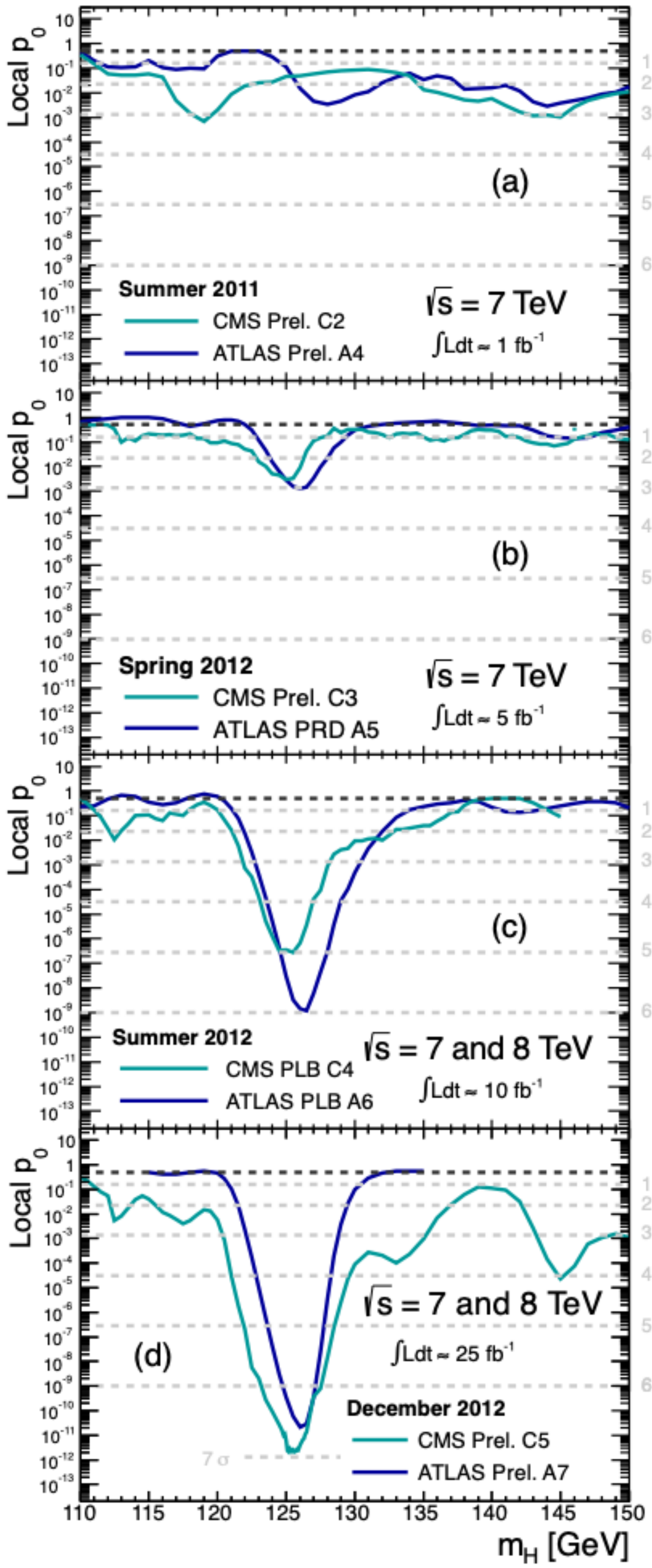

Status of the search in end of 2010

# Road to Discovery




Status of the search in end of 2011

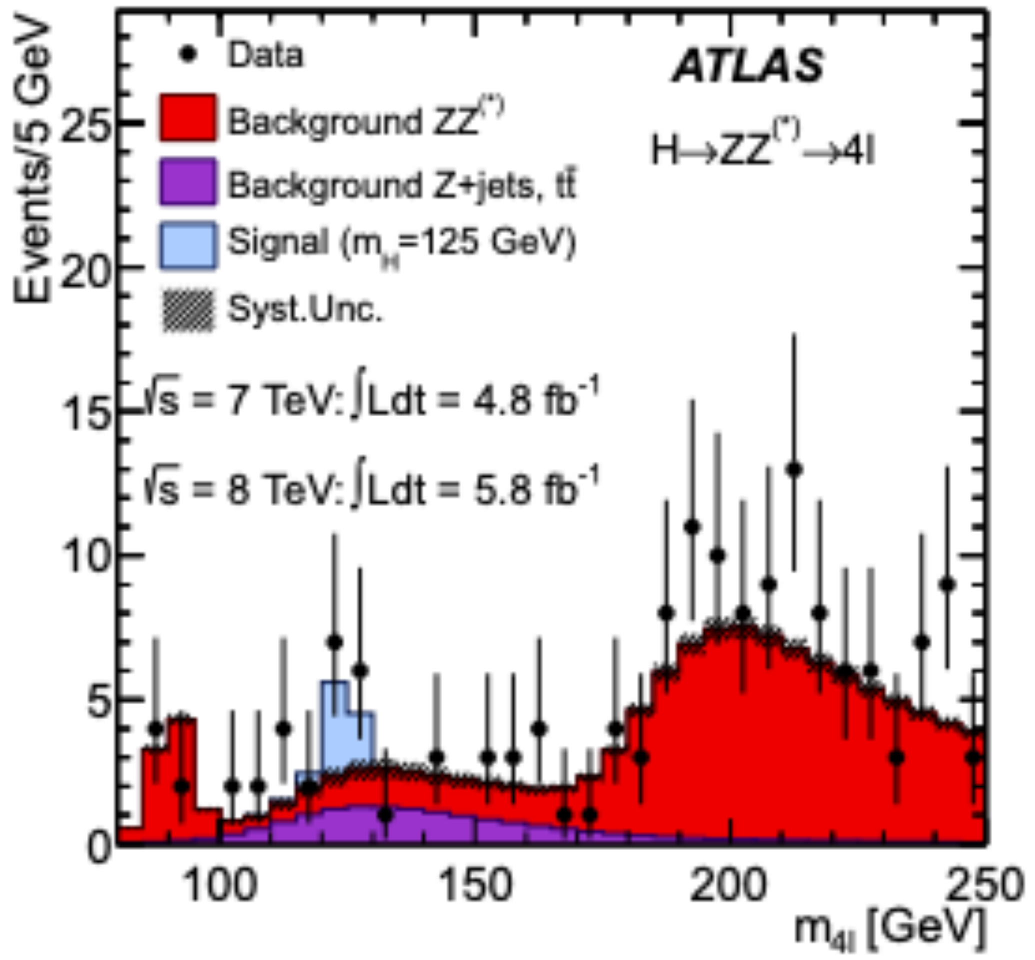
# Higgs Boson Discovery

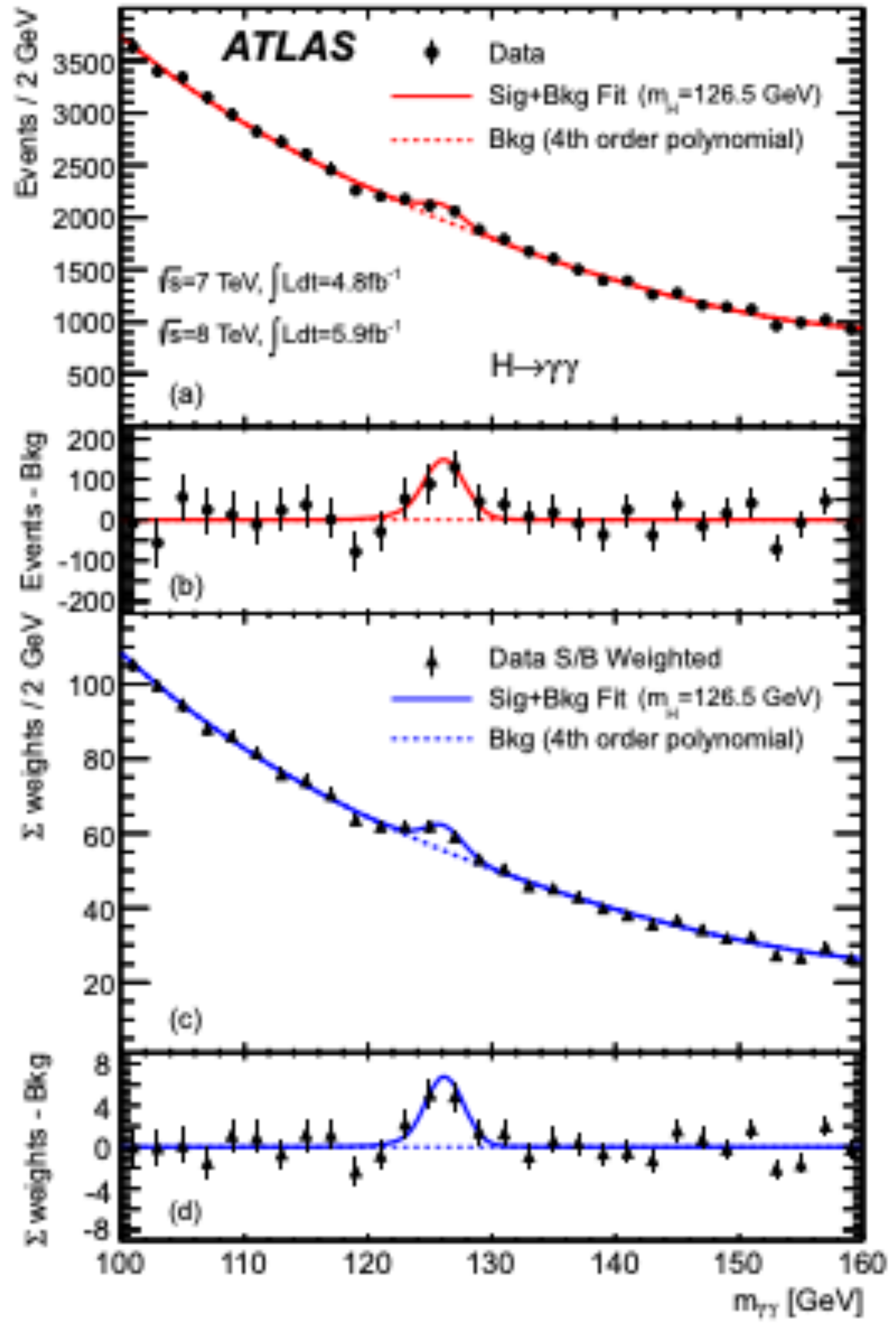



Textbook discovery!

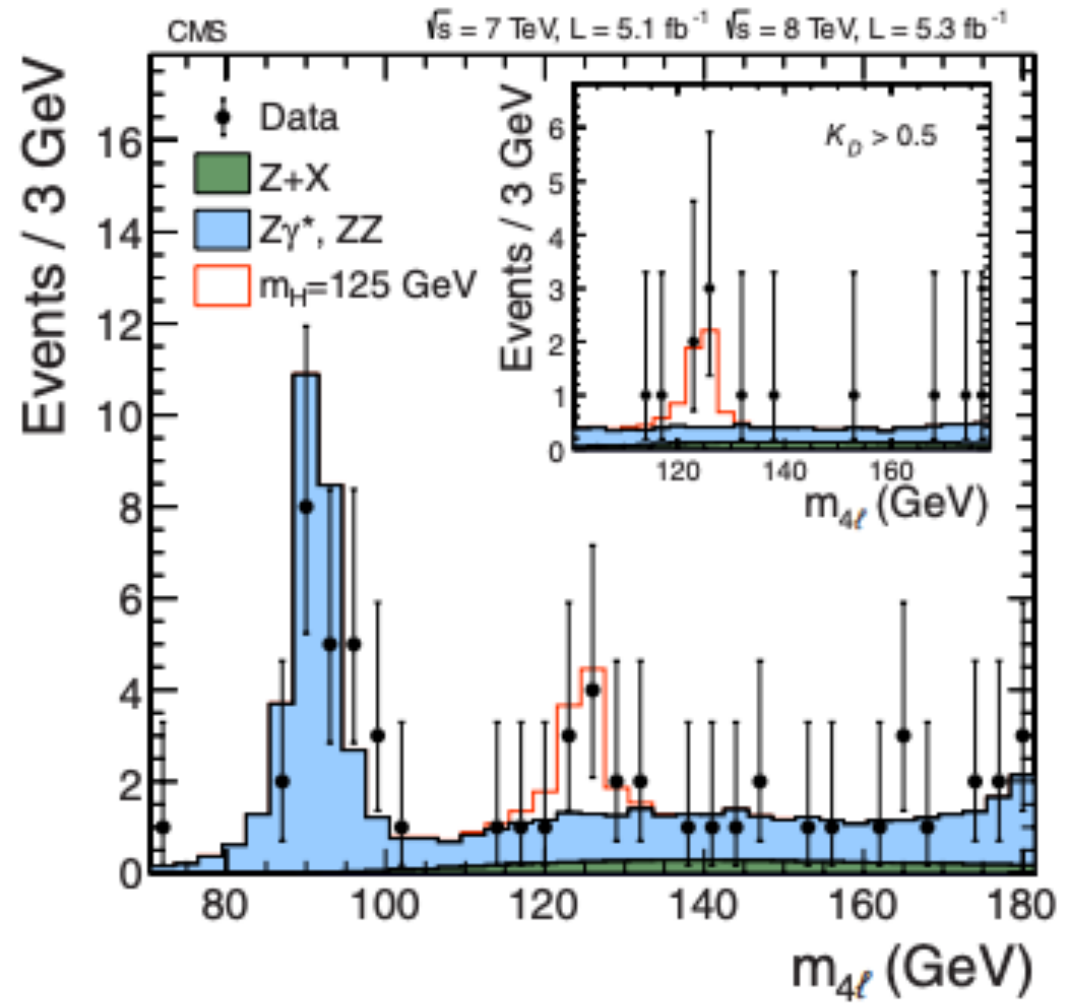
- two independent experiments
- two experimental signatures each
- overall consistent picture

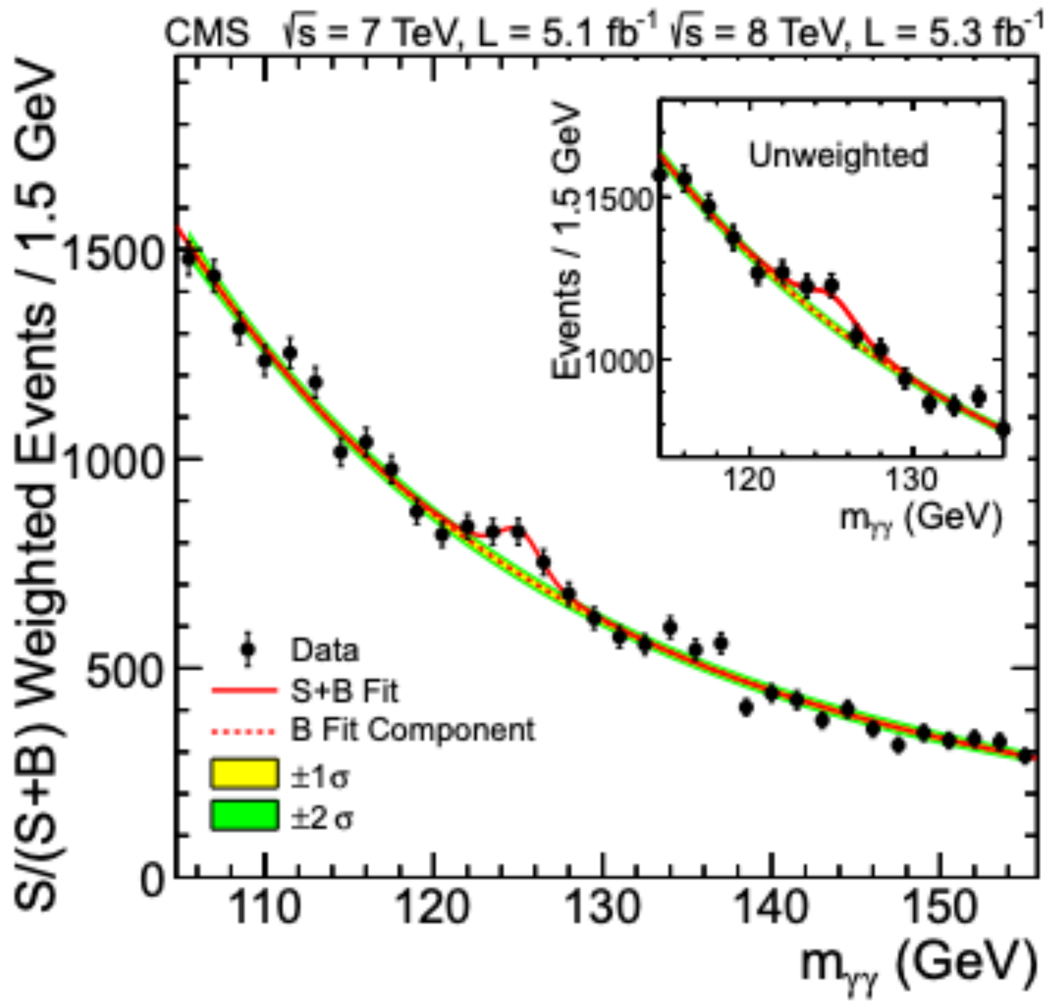
ATLAS



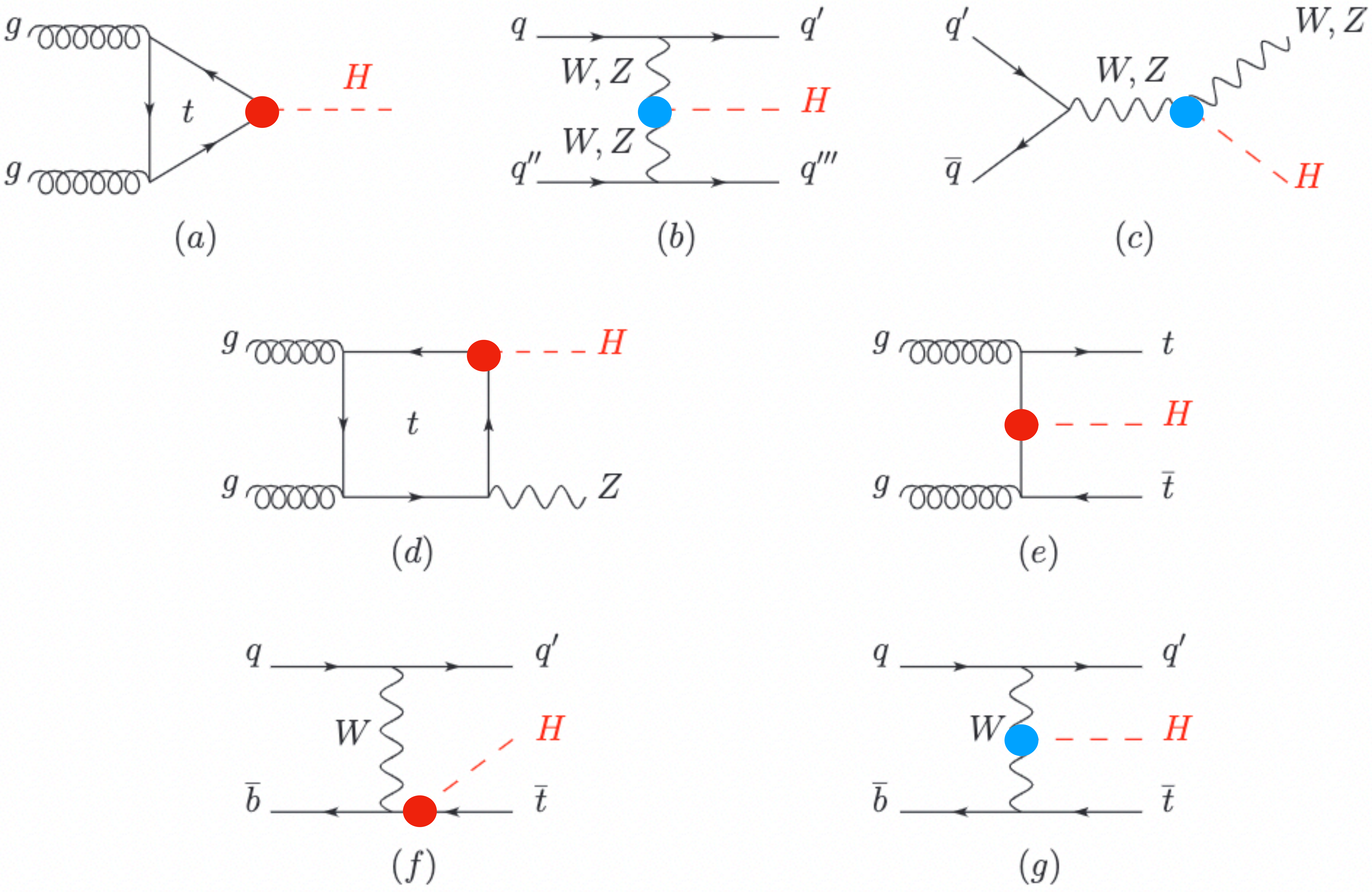




CMS

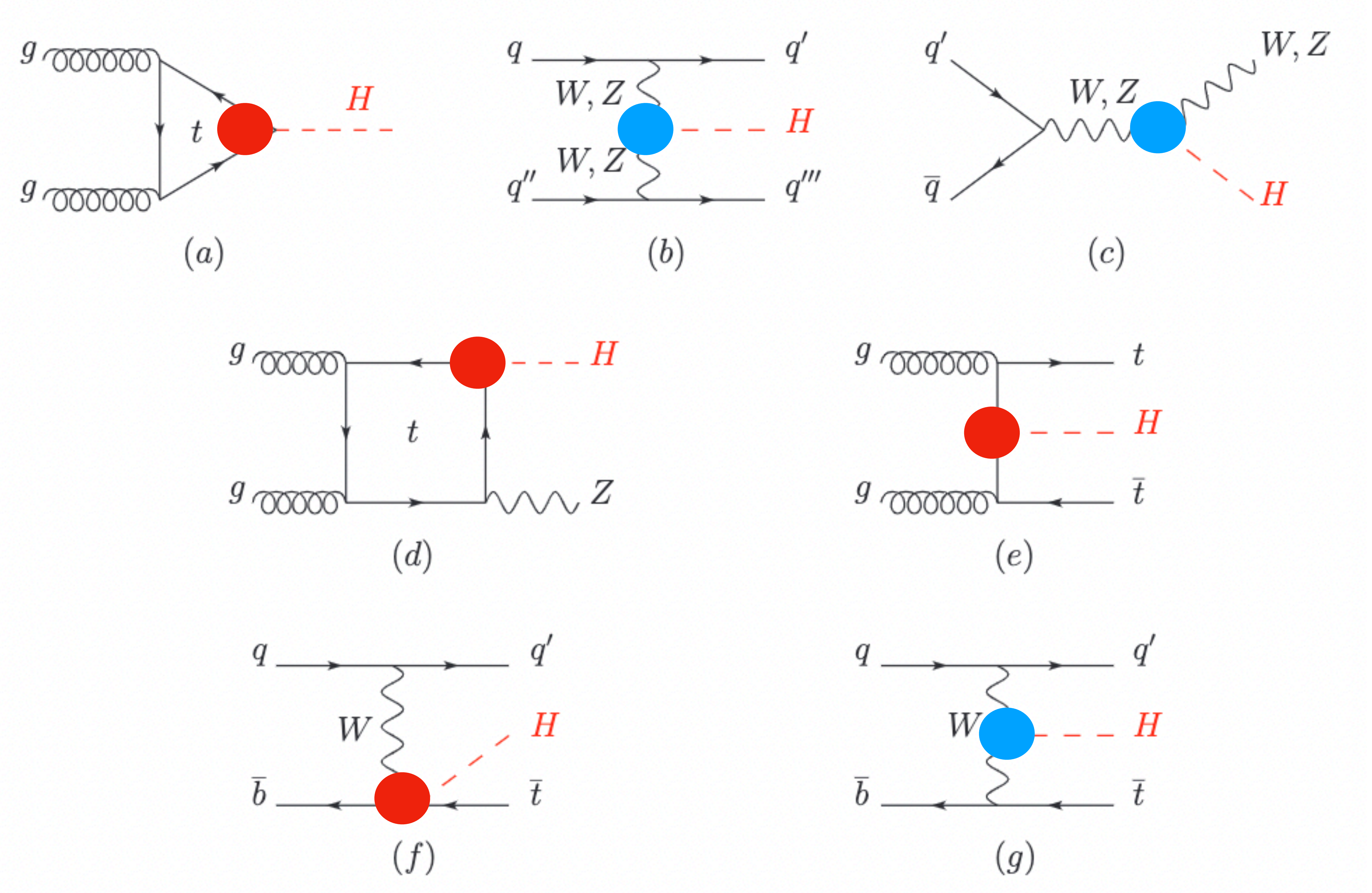


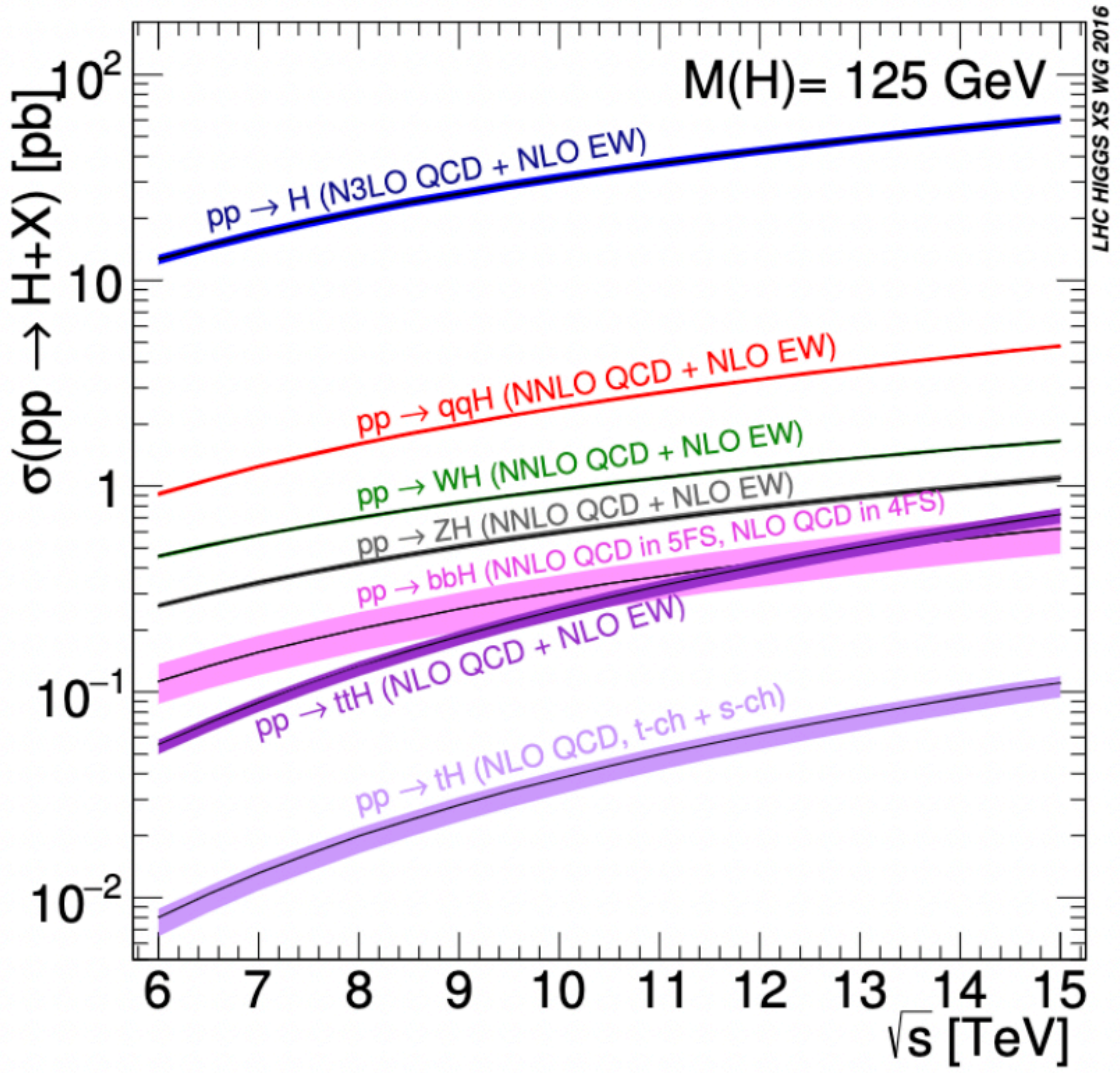



# Higgs Boson Production



# Higgs Boson Production and Decays

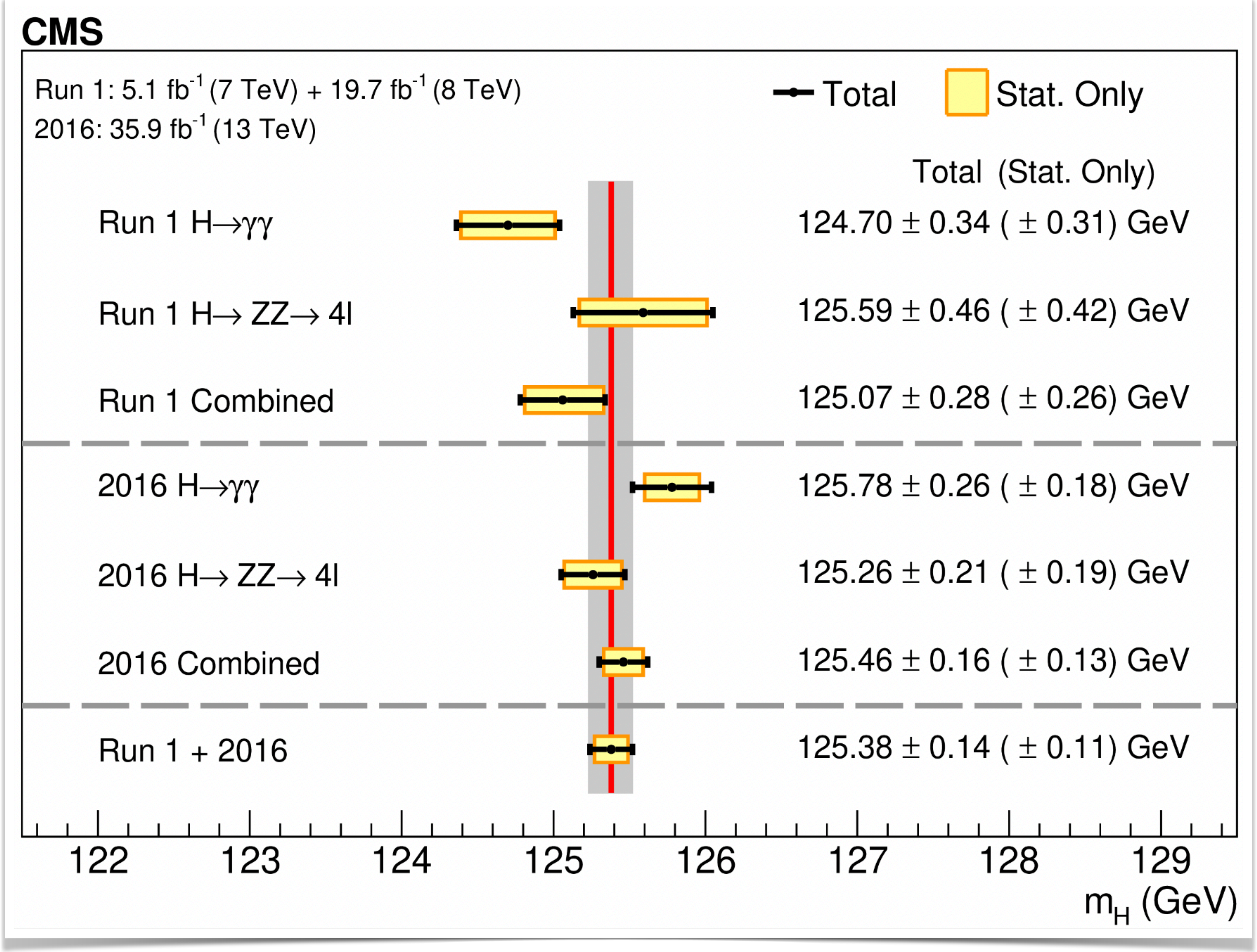


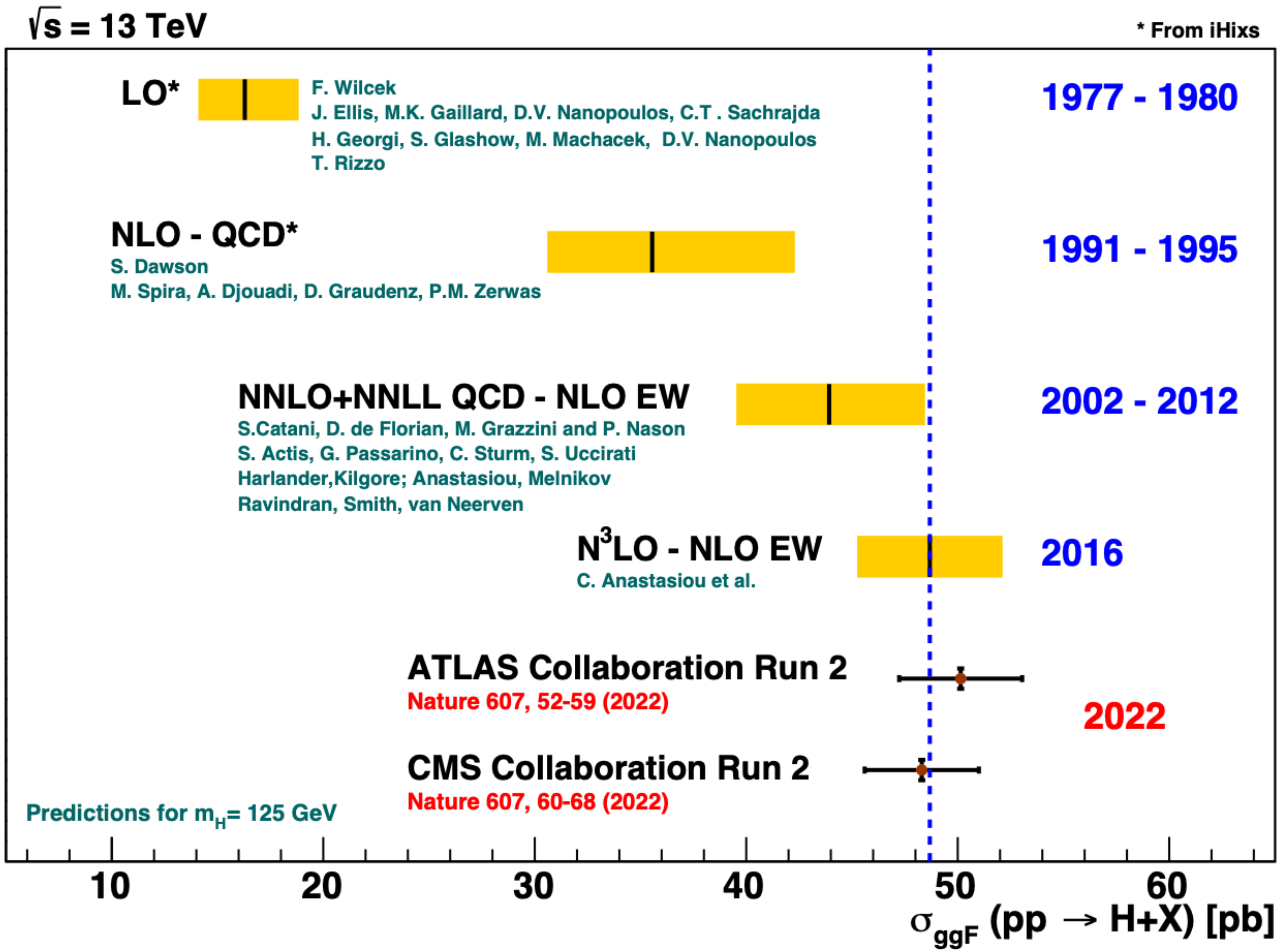

| Decay | BR [%] |
|---|---|
| bb | 57.7 |
| ττ | 6.32 |
| cc | 2.91 |
| μμ | 0.022 |
| WW | 21.5 |
| gg | 8.57 |
| ZZ | 2.64 |
| γγ | 0.23 |
| Zγ | 0.15 |
| ΓH [MeV] | 4.15 |

# Higgs Boson Mass

- Precision measurement $\Delta m_H/m_H = 0.1\%$
- Measurement performed in $H\rightarrow\gamma\gamma$ and $H\rightarrow 4l$ channels
- As $m_H$ is the only free parameter, all other observables can be predicted and tested



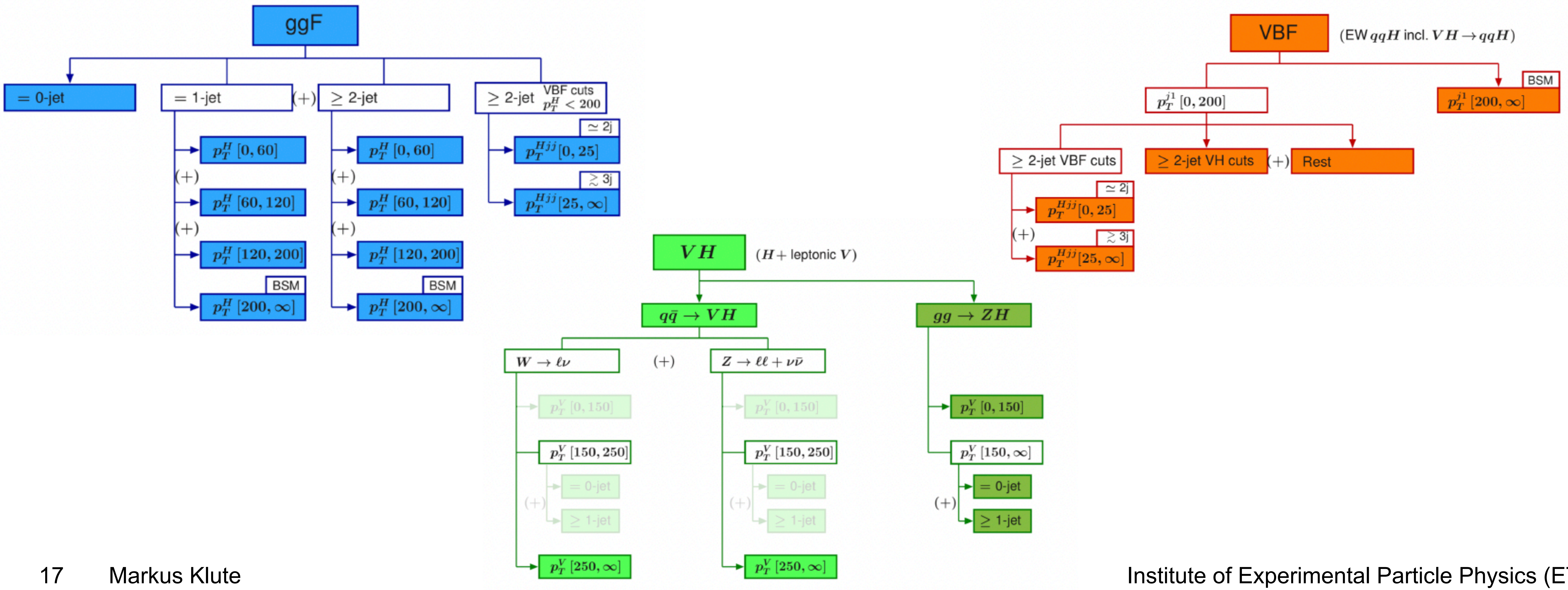
# Higgs Boson Cross Section



# Fiducial Cross Section

- Various production and decay channels are combined using a broad set of analysis techniques in a single inclusive cross section

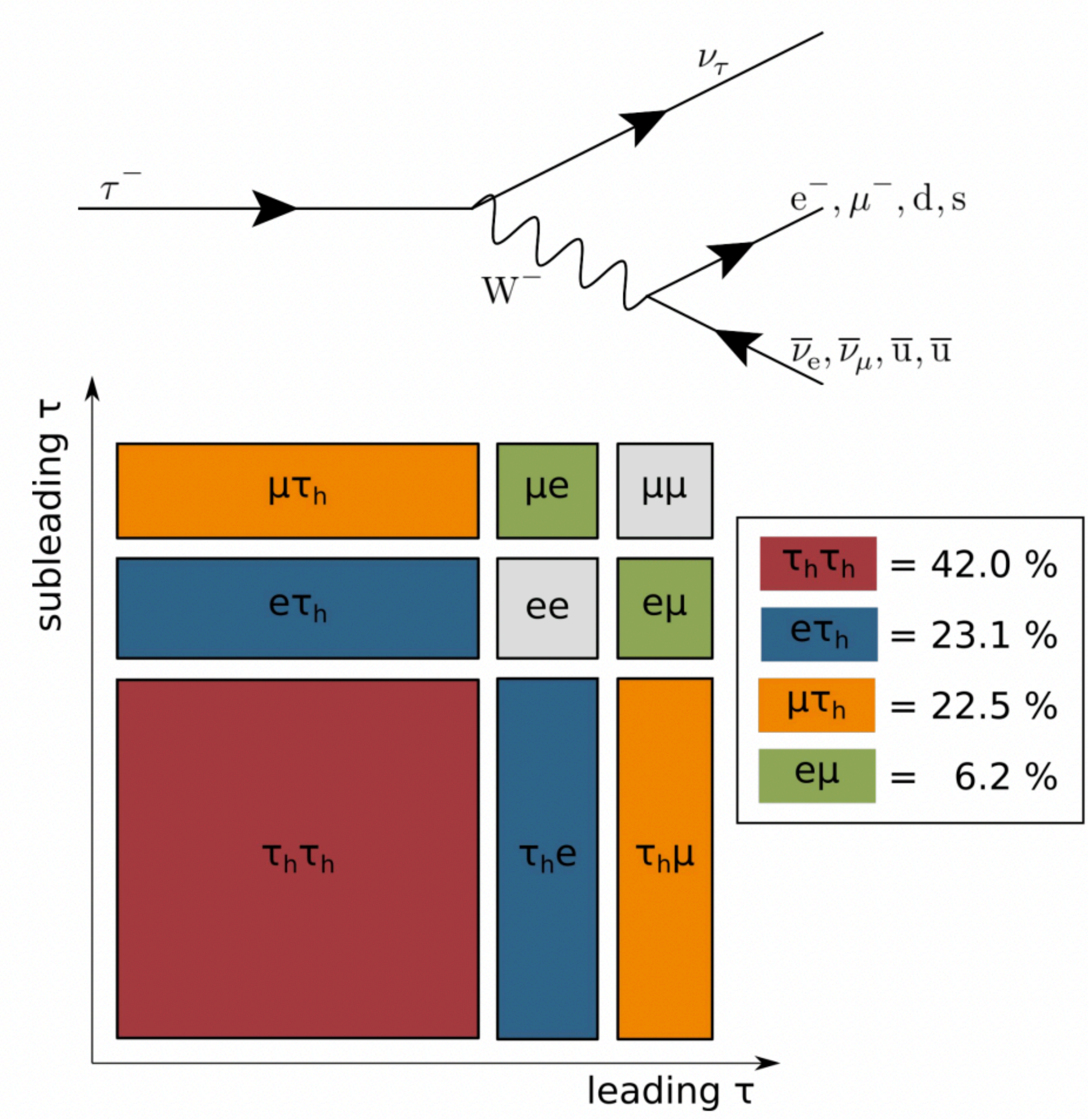
- Deployed approach with simplified fiducial template cross sections

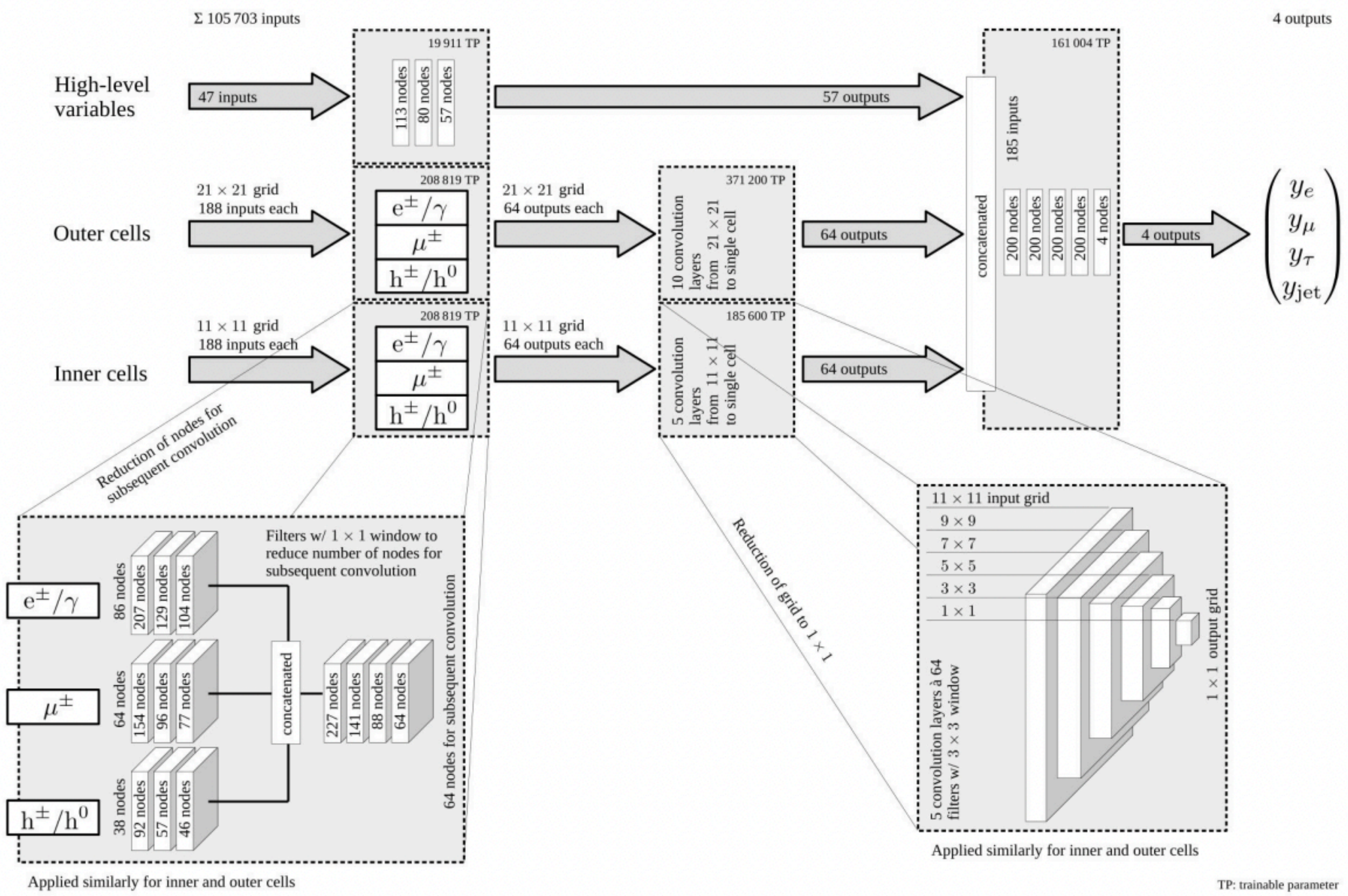


# Exploring (Testing) the Higgs Boson

- Higgs to Tau decays
  - Tau decay via the weak interaction to e, μ, or hadrons always including at least one ν
  - Tau identification using DNN (DeepTau)

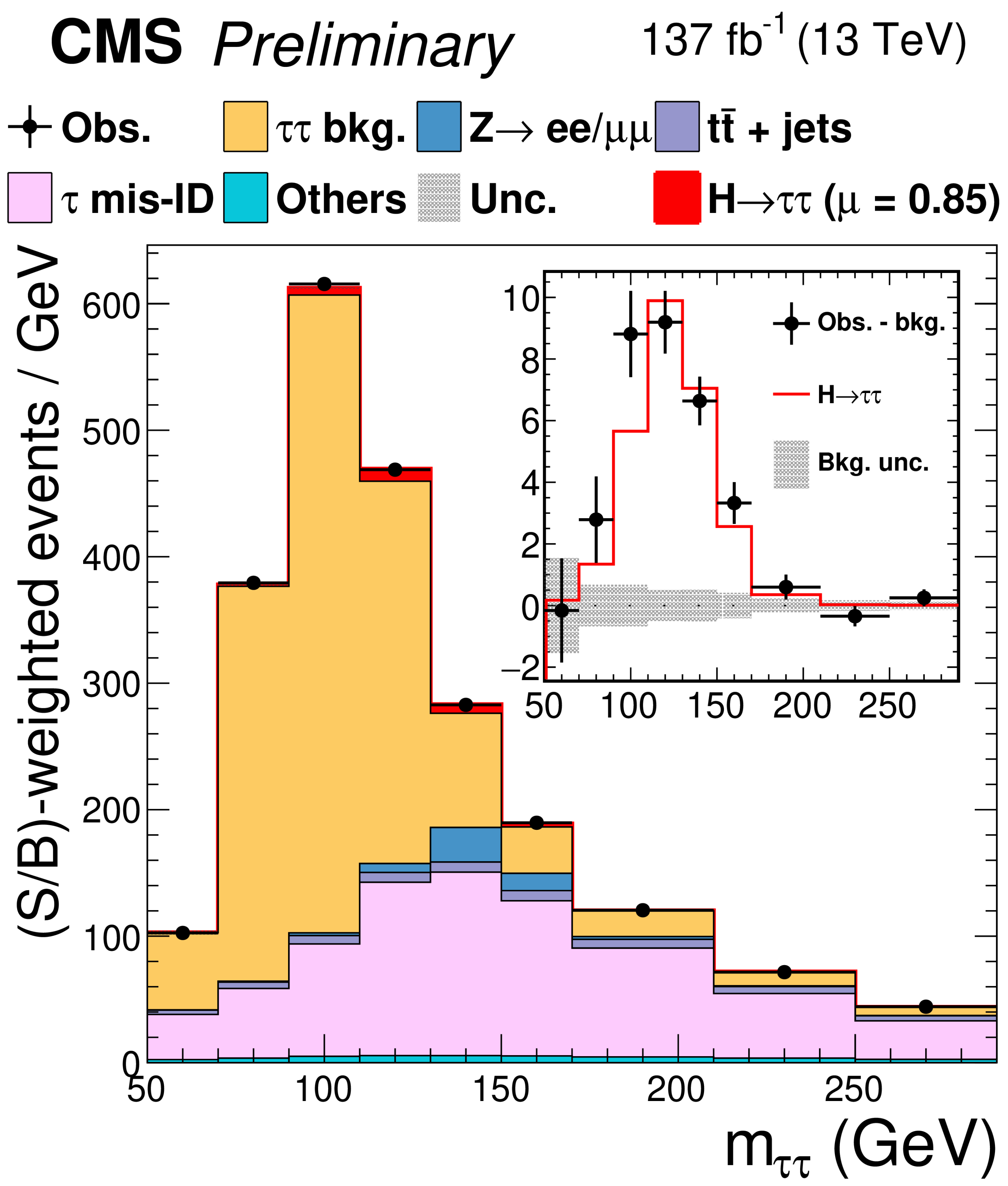
arXiv:2201.08458

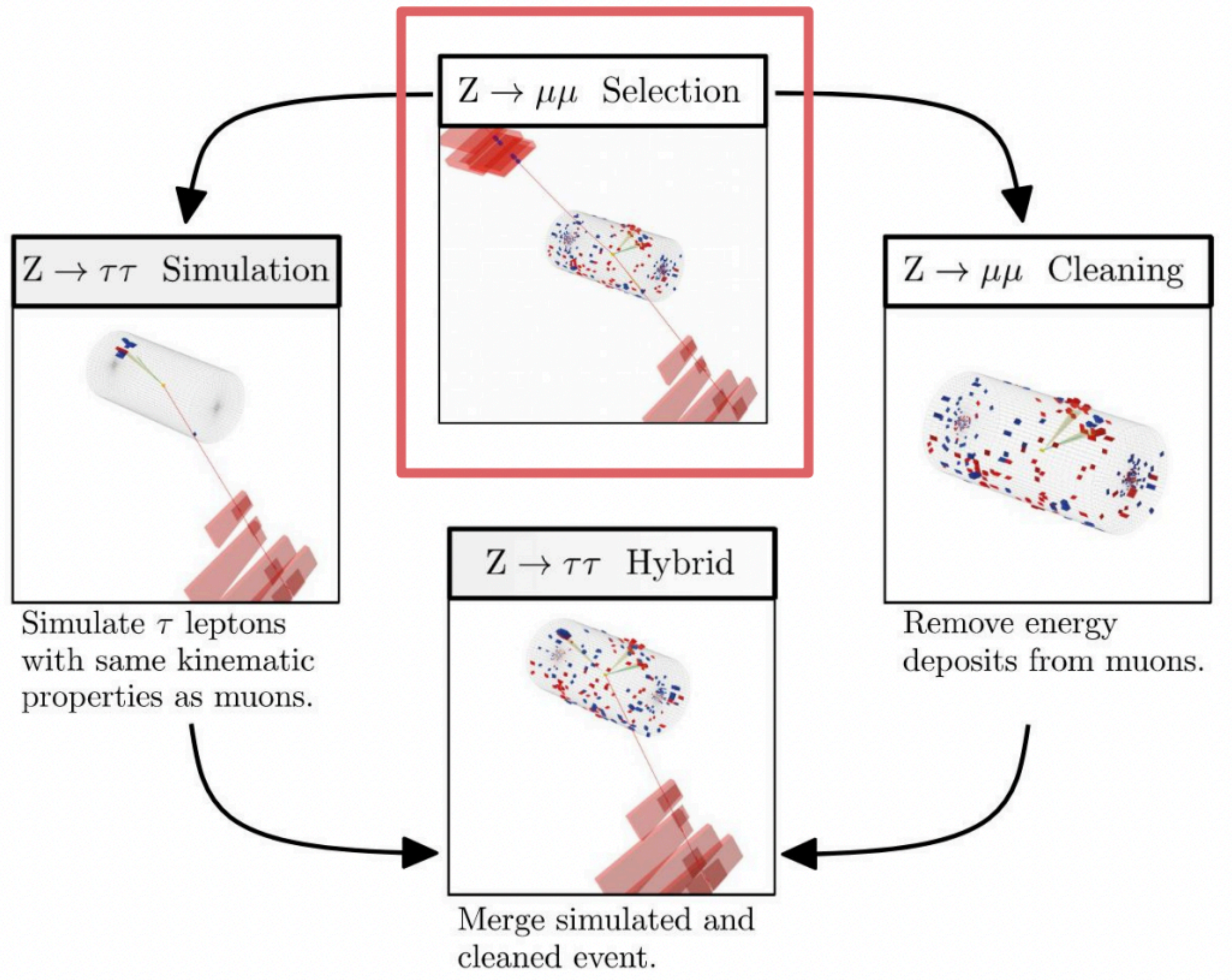


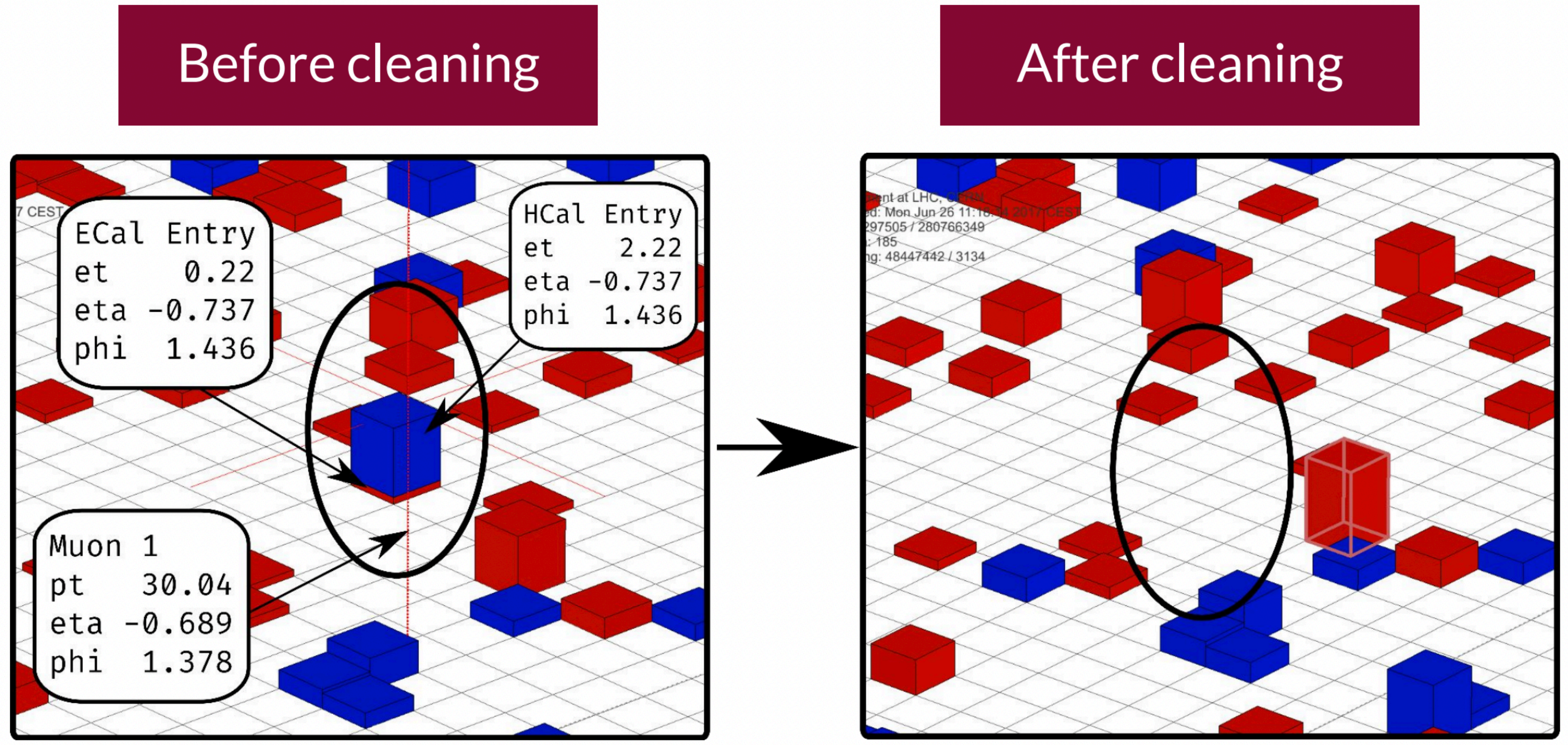



# Exploring (Testing) the Higgs Boson

- Higgs to Tau decays
  - Leading background Z→ττ
  - Using Z →μμ events, replay one μ with simulated τ

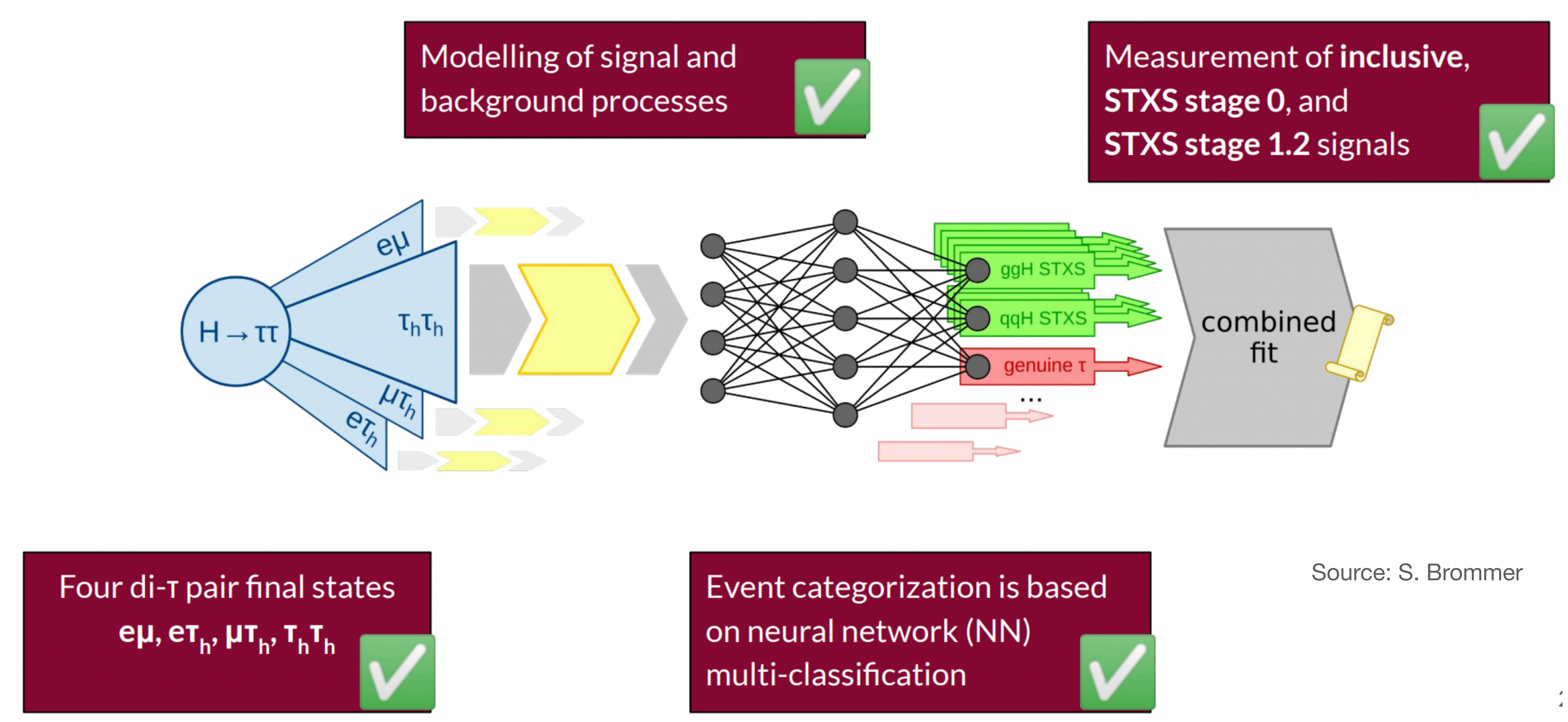


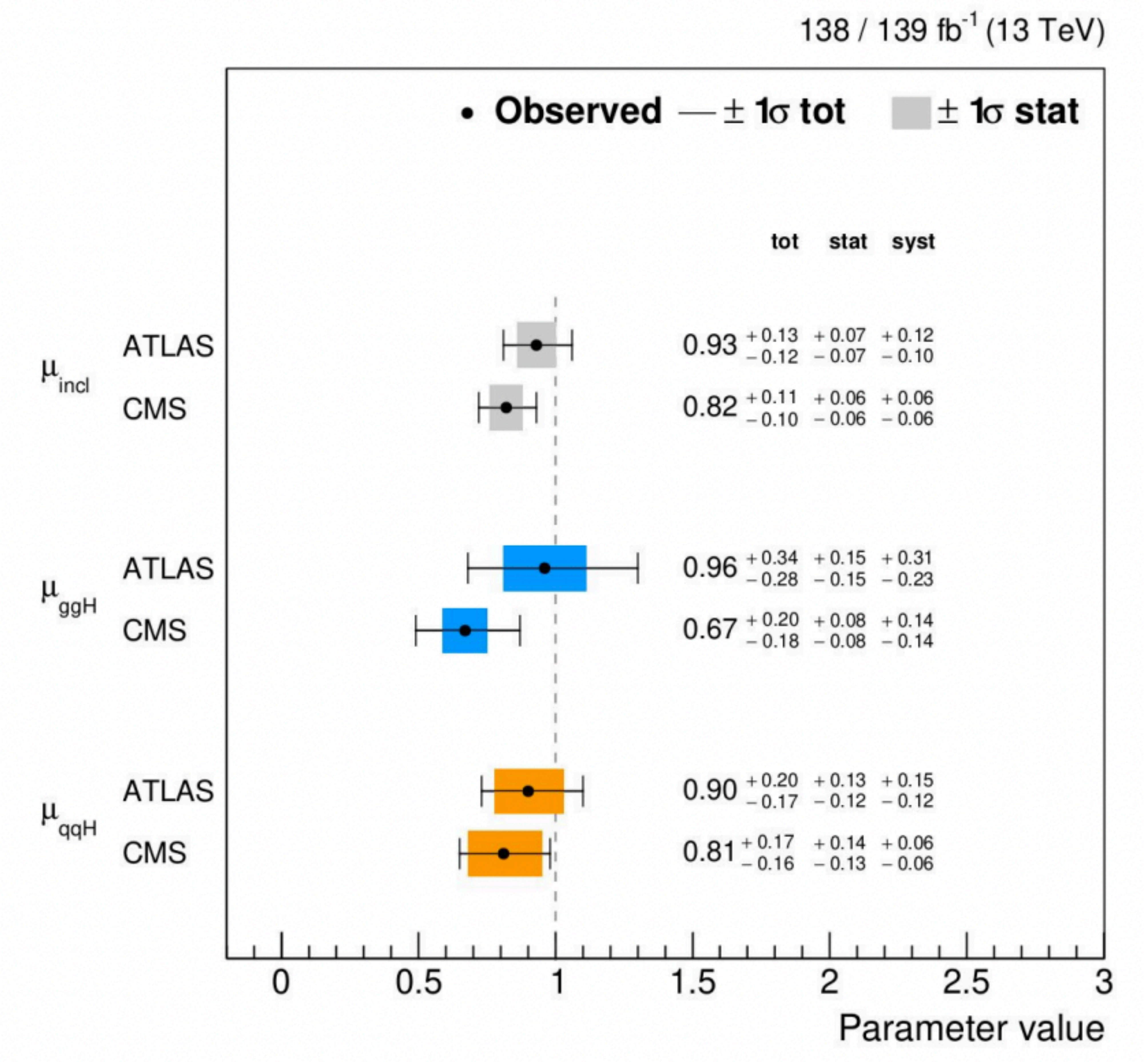



# Exploring (Testing) the Higgs Boson

- Higgs to Tau decays



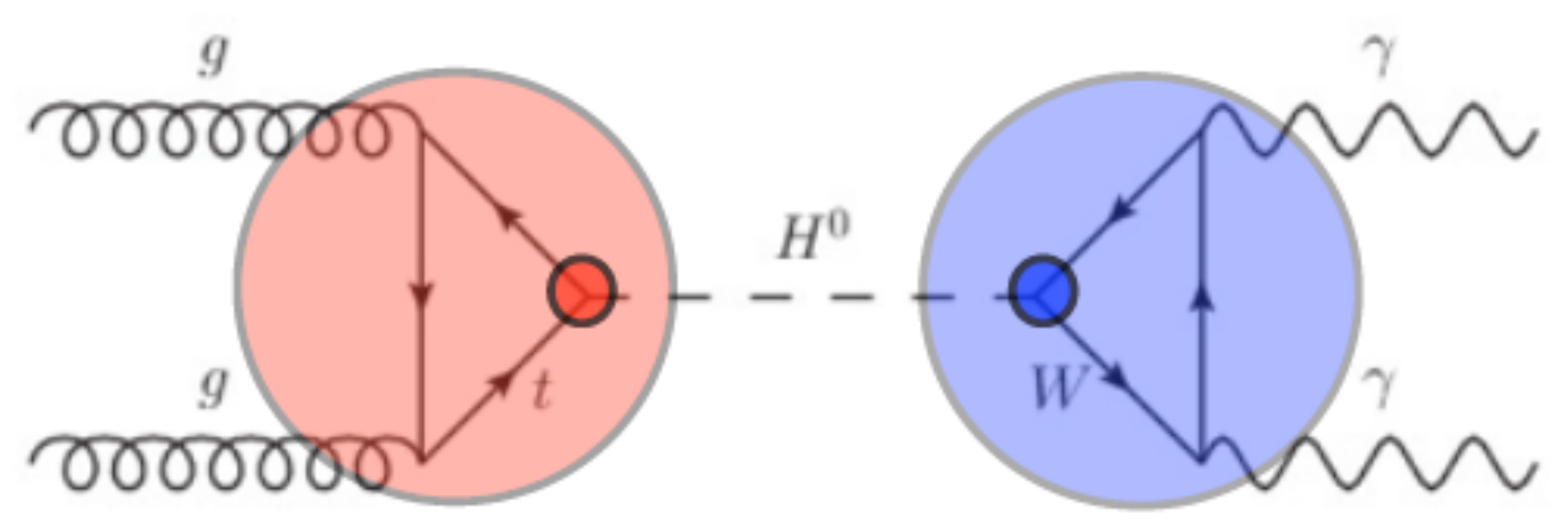
# Pingo

- Does the Higgs boson couple to photons?
  - 1) Yes, the Higgs boson couples directly to all gauge bosons
  - 2) Yes, but only through quantum loops including charged particles
  - 3) No, photons are massless and do not couple to Higgs bosons

# Exploring (Testing) the Higgs Boson

- Coupling Measurements
- Strategy: narrow width approximation
- Measurement: parametrize deviations wrt SM in production and decay
  - Implies precise knowledge of SM prediction
  - BSM acceptance effects are not considered

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

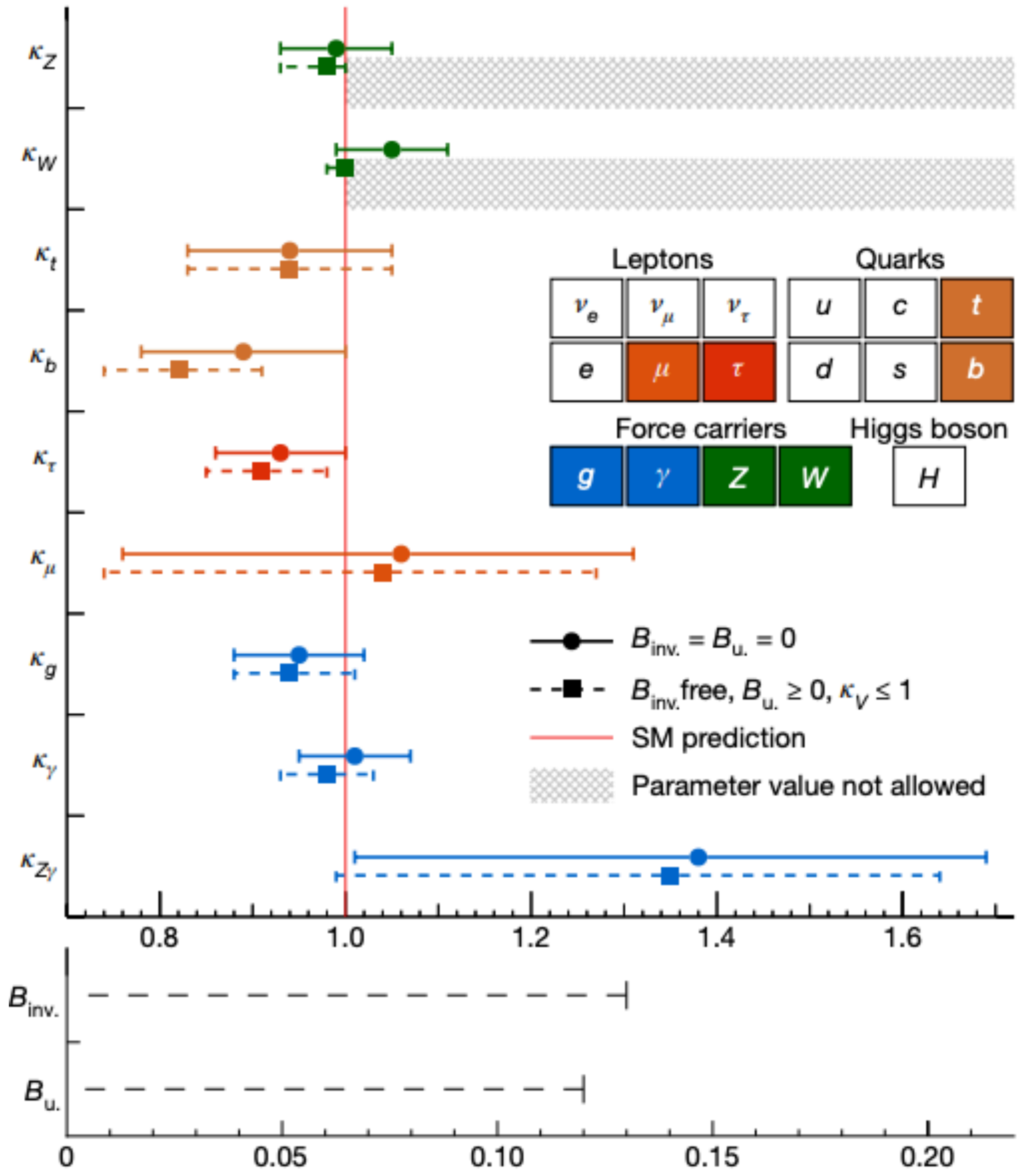



$$(\sigma \cdot \mathrm{BR})\,(gg \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

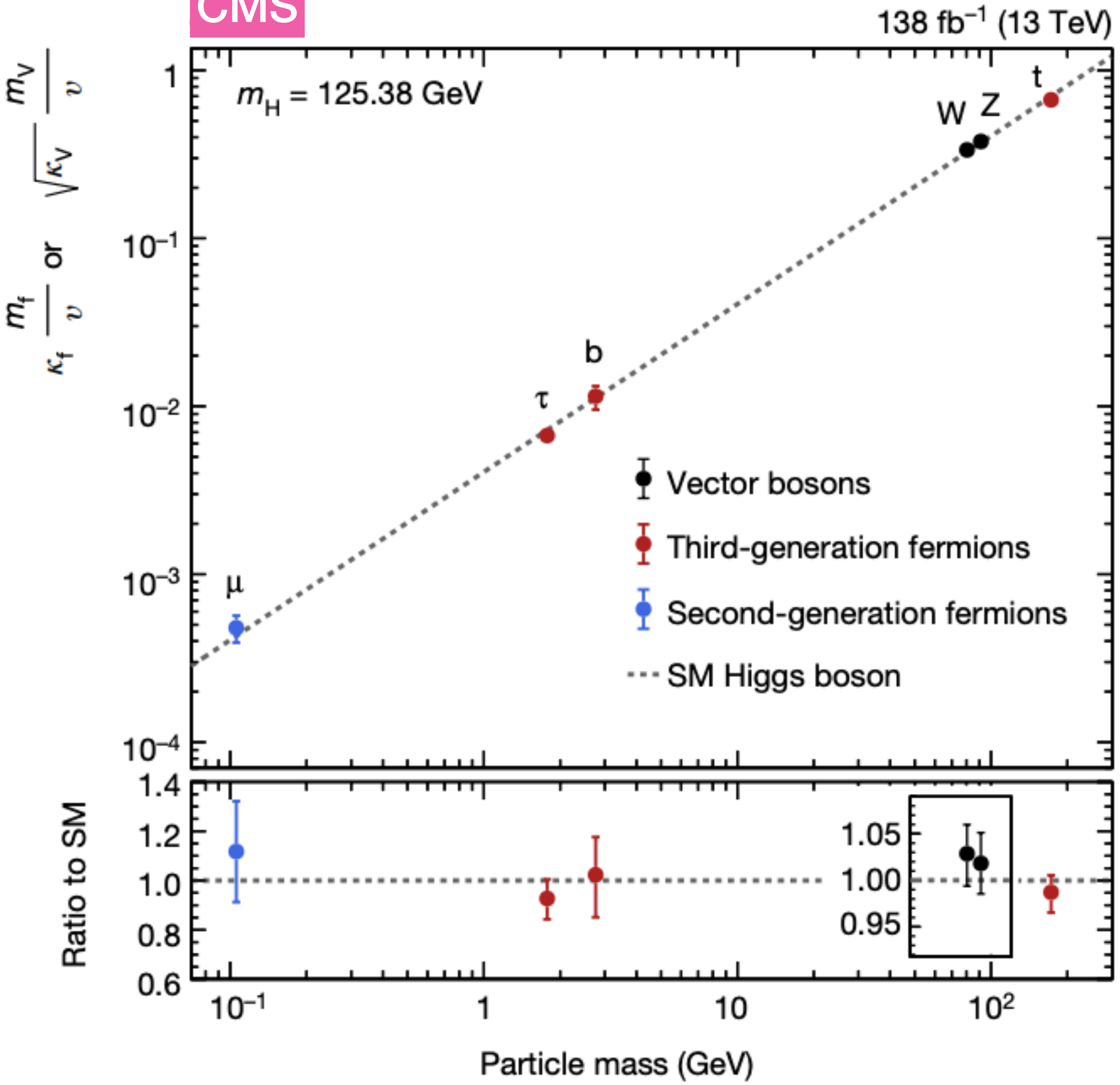
# Exploring (Testing) the Higgs Boson

- Coupling Measurements

ATLAS



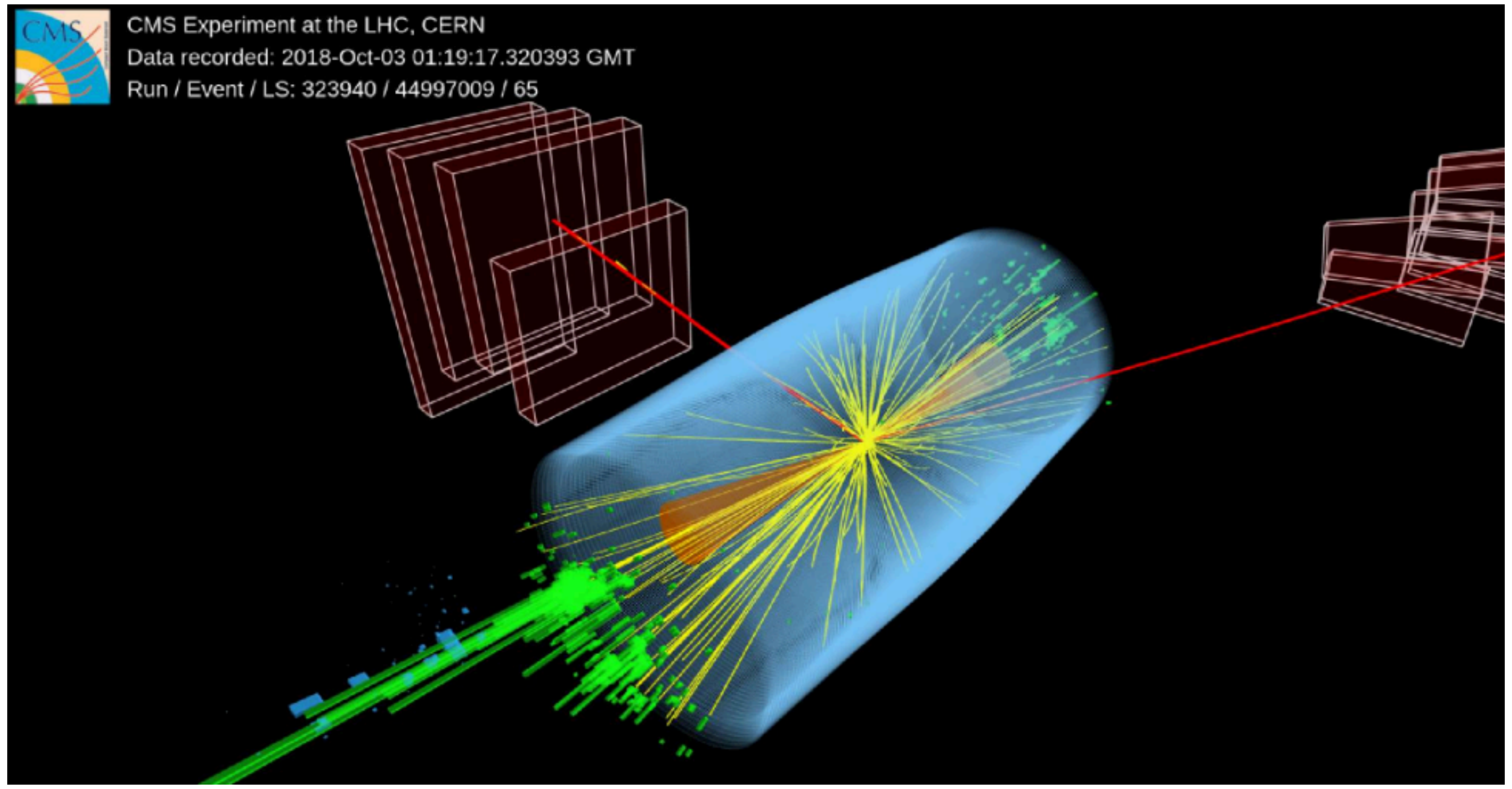

CMS

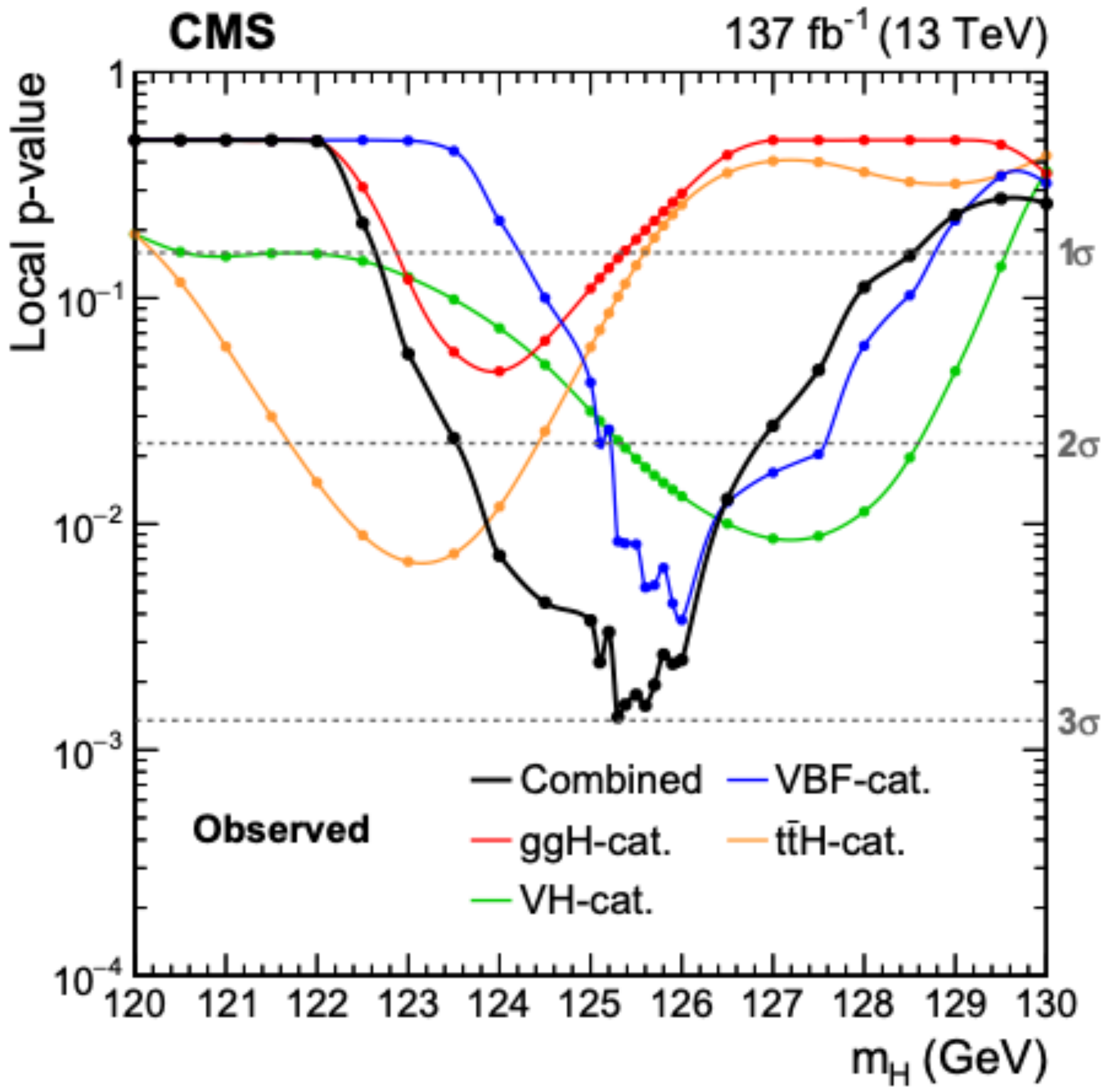


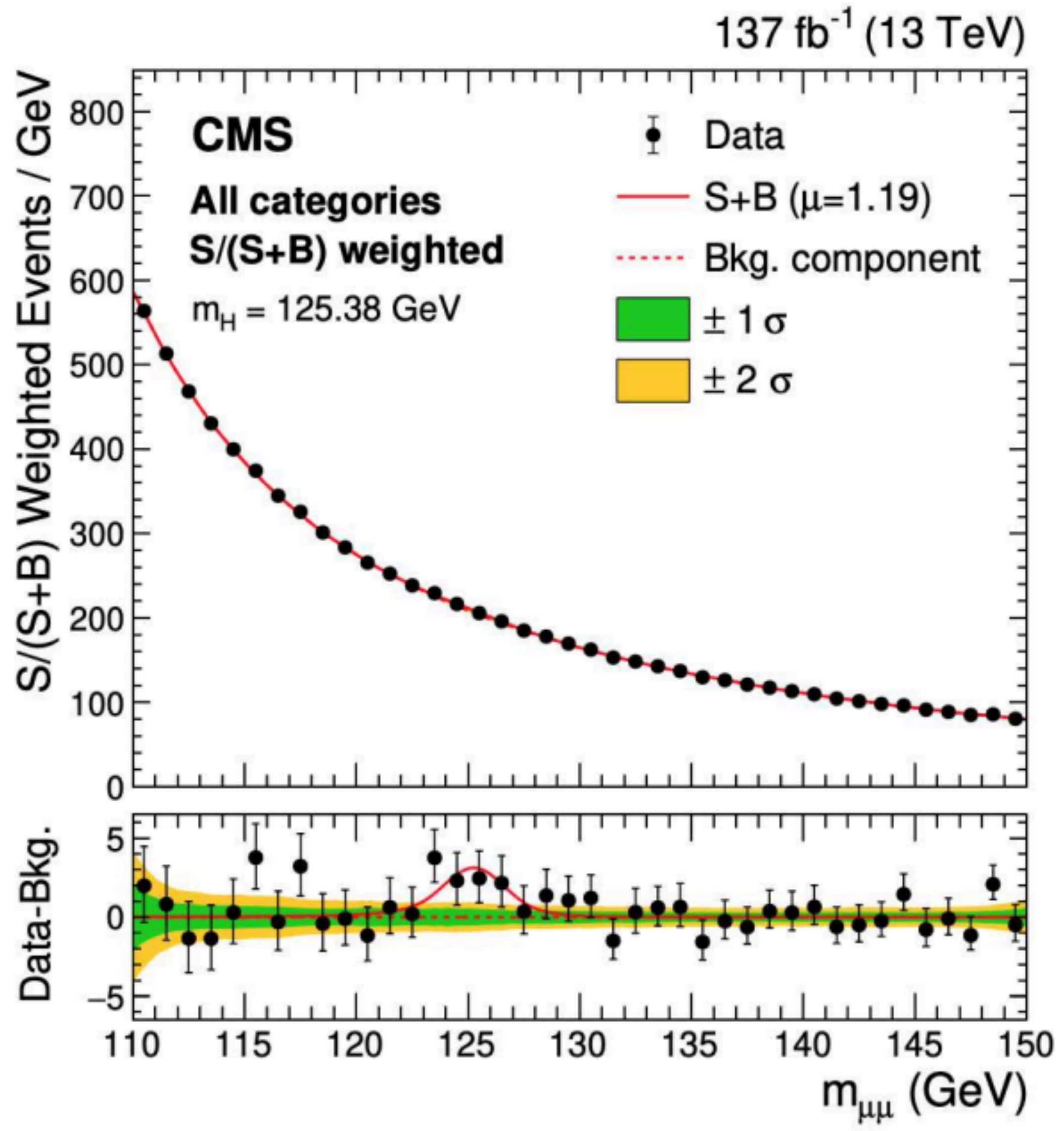
# Exploring (Testing) the Higgs Boson

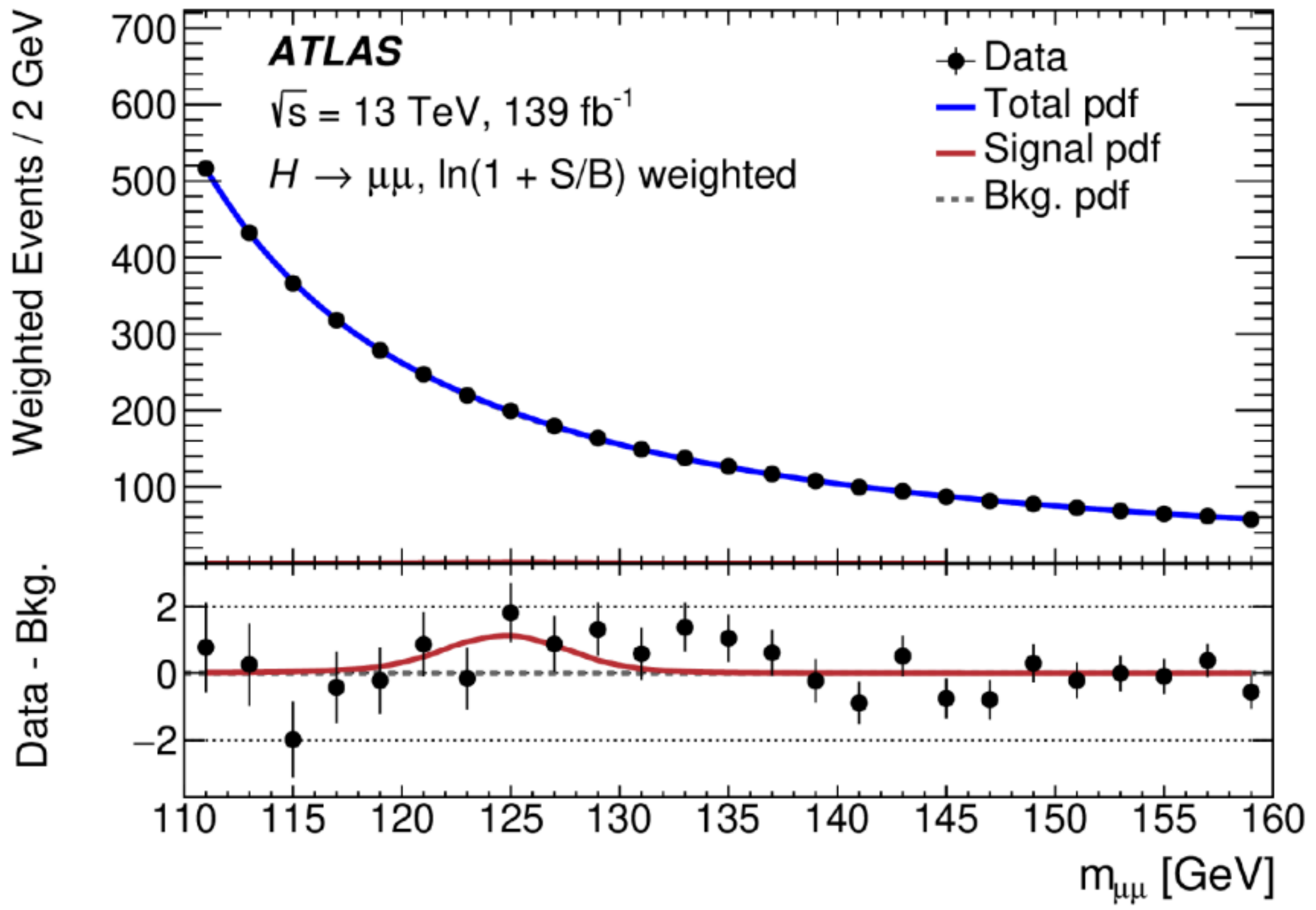
Mission Impossible

- Higgs to Muon Decays
  - Very small signal-to-noise ratio
  - Requires accurate description of backgrounds
  - Results dominated by statistical uncertainties



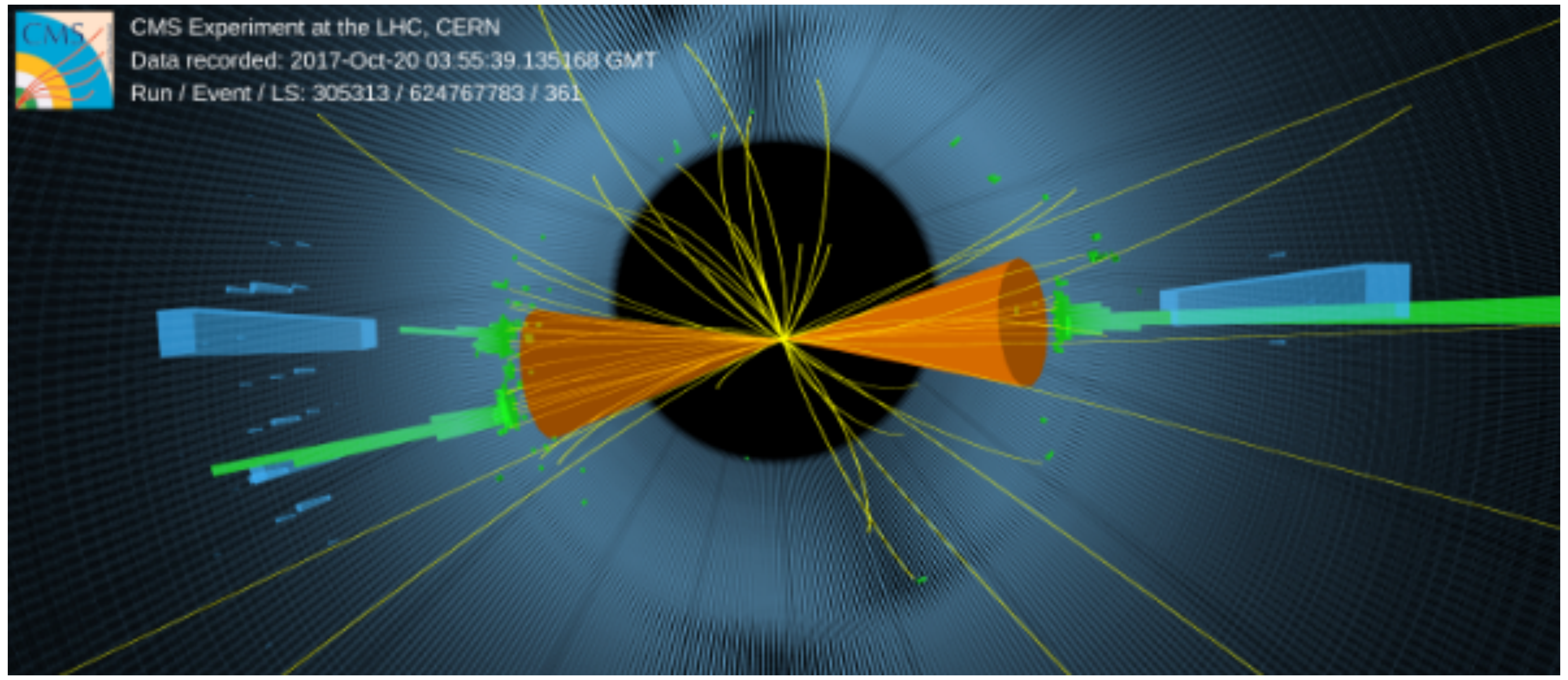



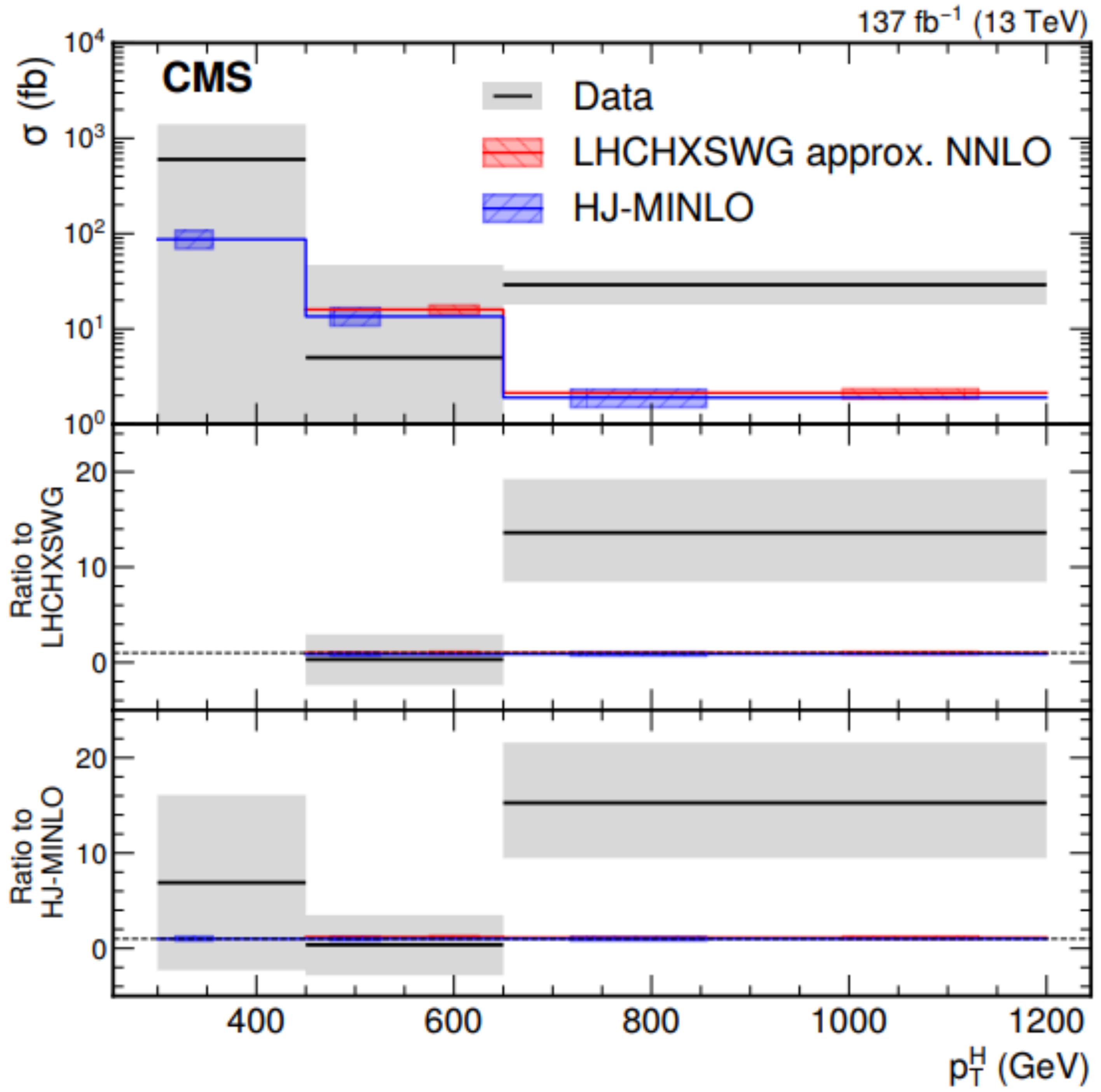



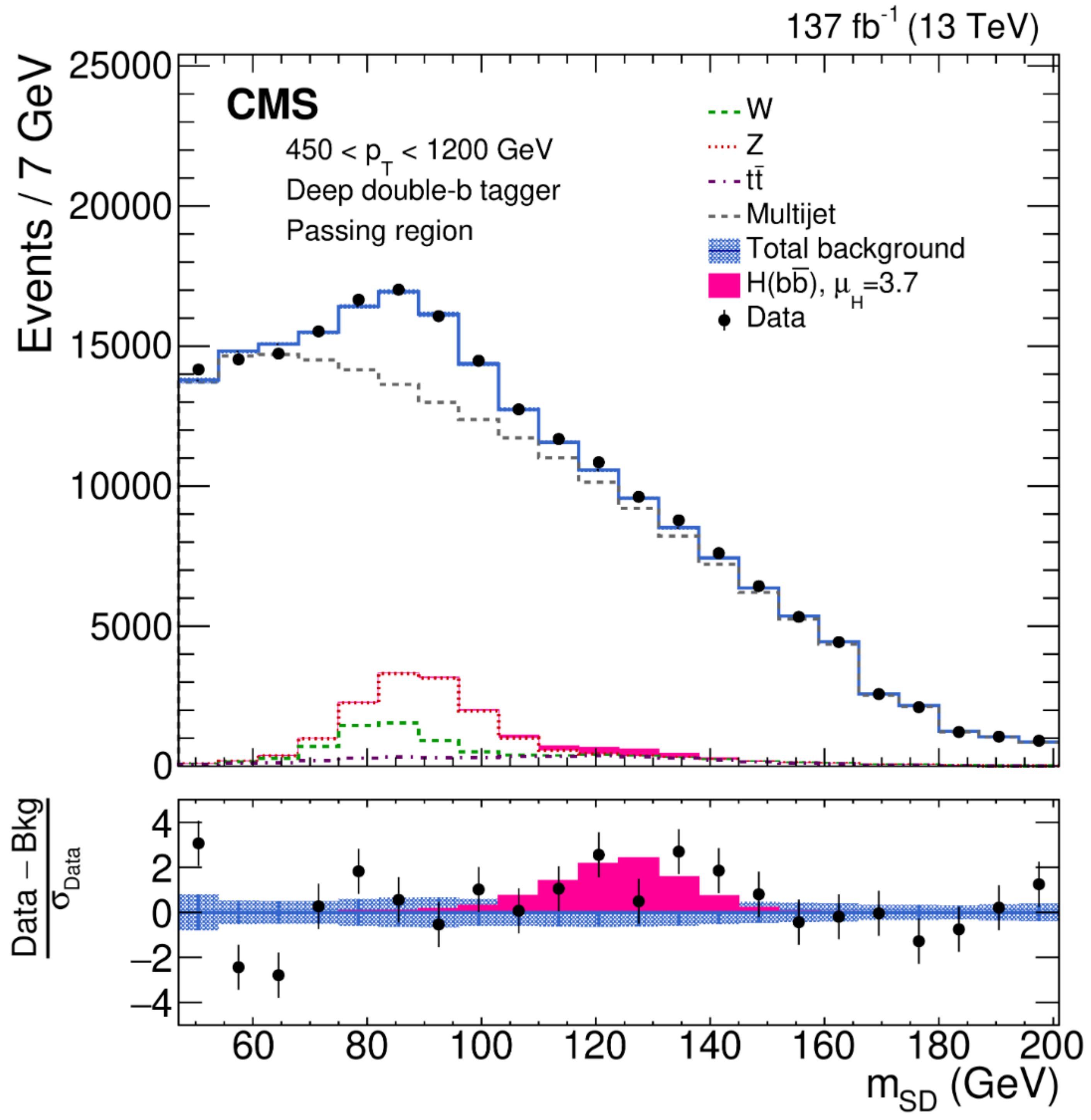
# Exploring (Testing) the Higgs Boson

Mission Impossible

- Higgs to b quark decays in gluon fusion prod.
  - Large cross section and branching fraction
  - Very small signal to noise
  - Requires accurate description of backgrounds
  - Exploiting high pT Higgs bosons and jet-substructure



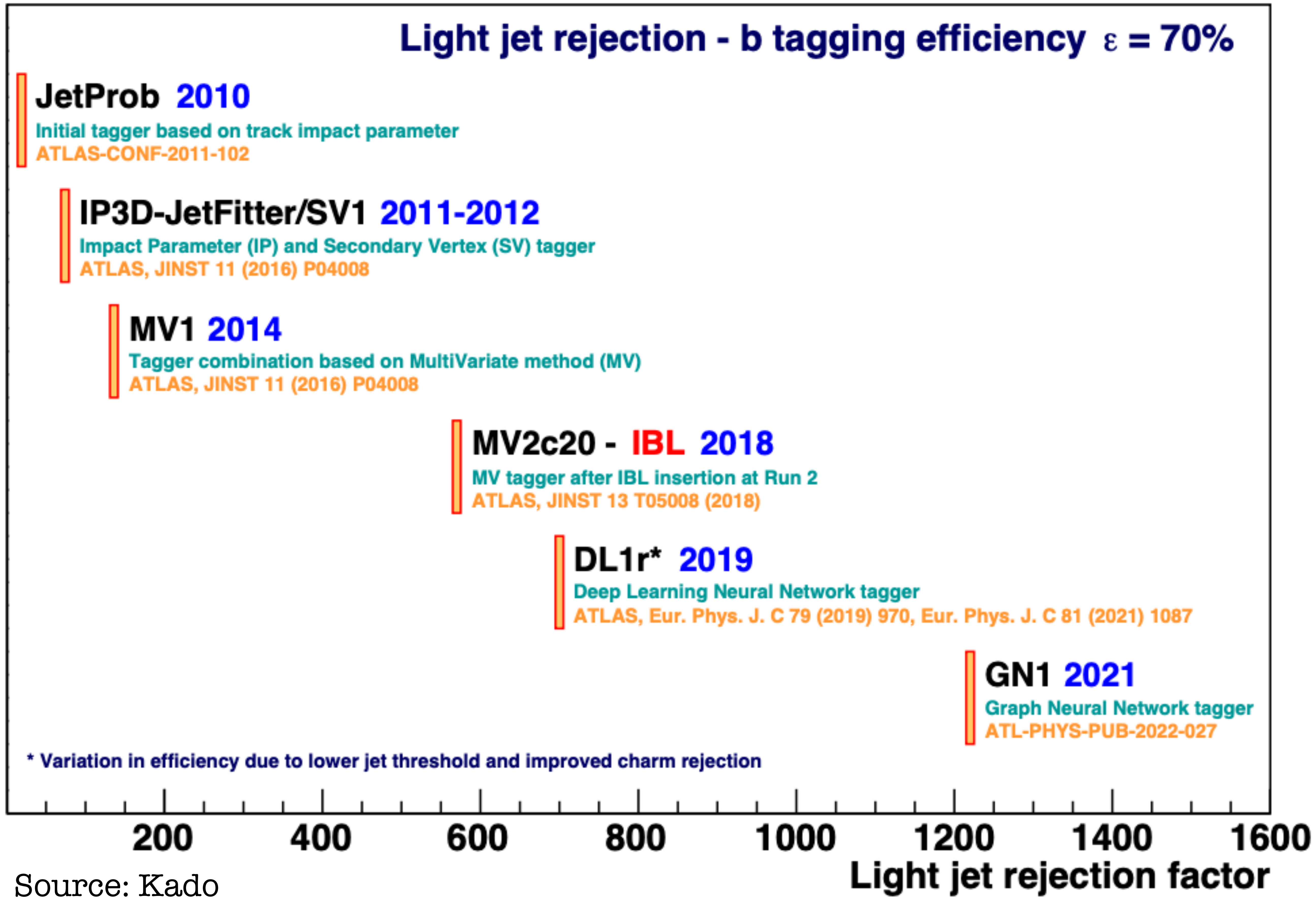



# Exploring (Testing) the Higgs Boson

Mission Impossible

- Jet tagging

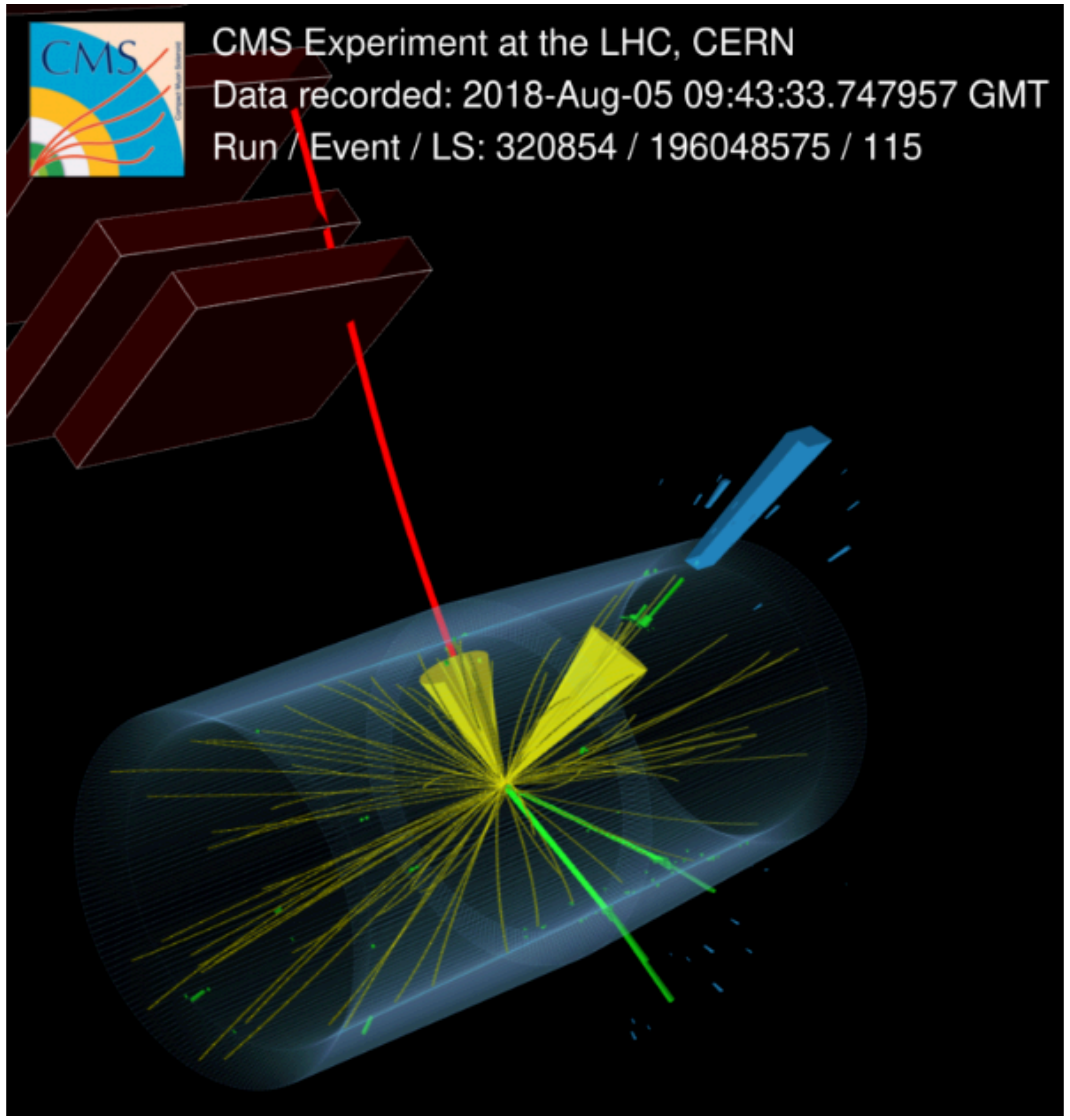


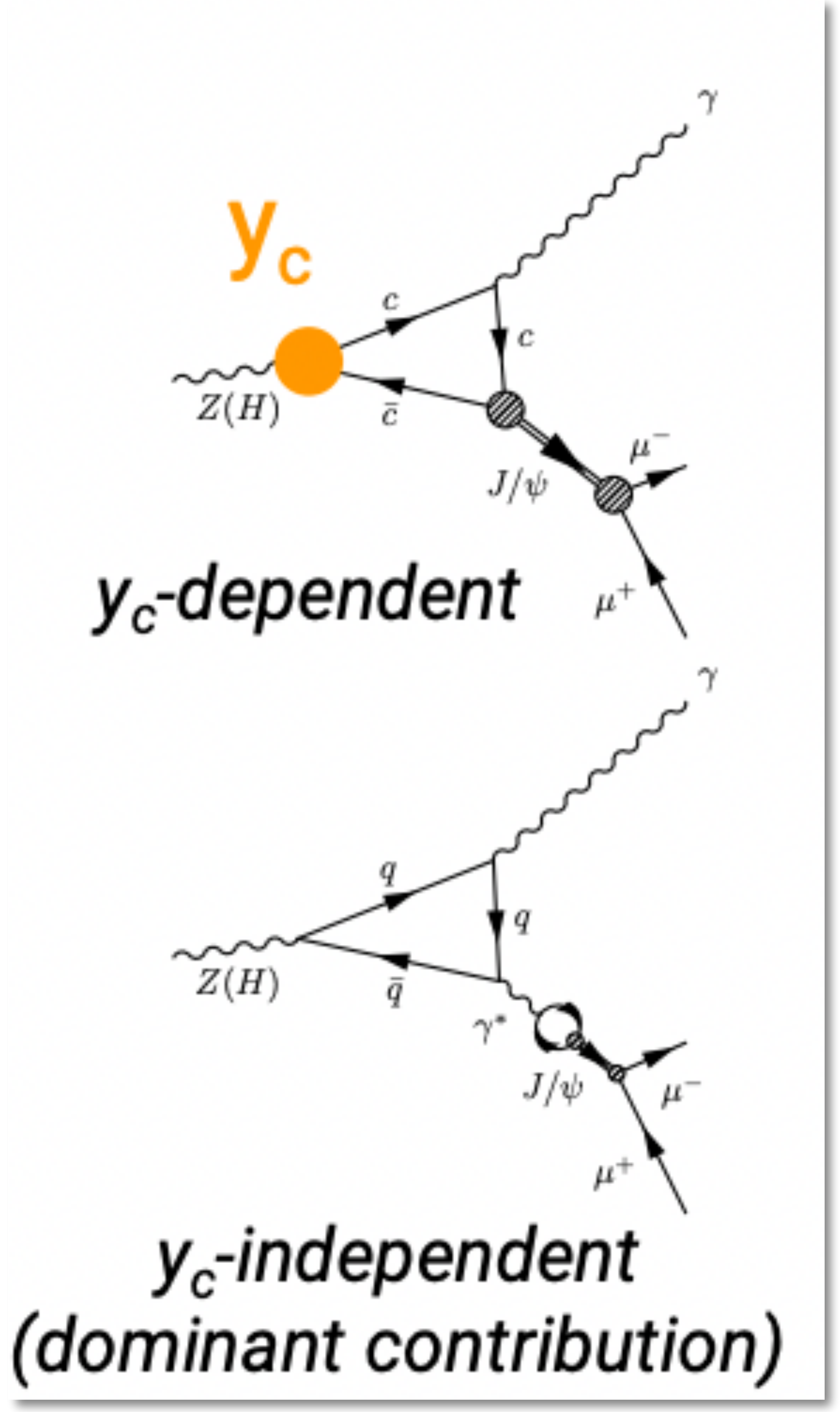

Source: Kado

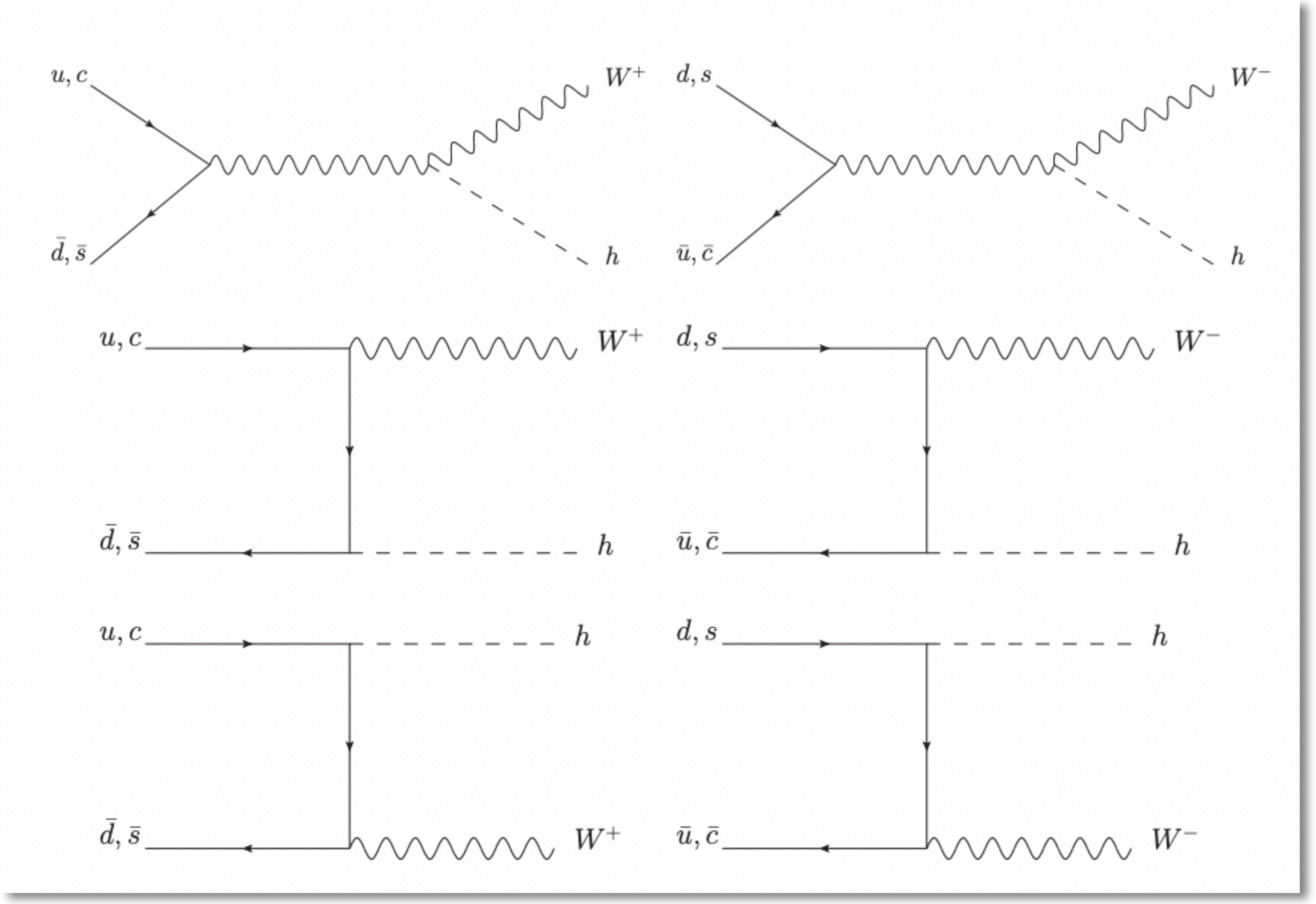
# Exploring (Testing) the Higgs Boson

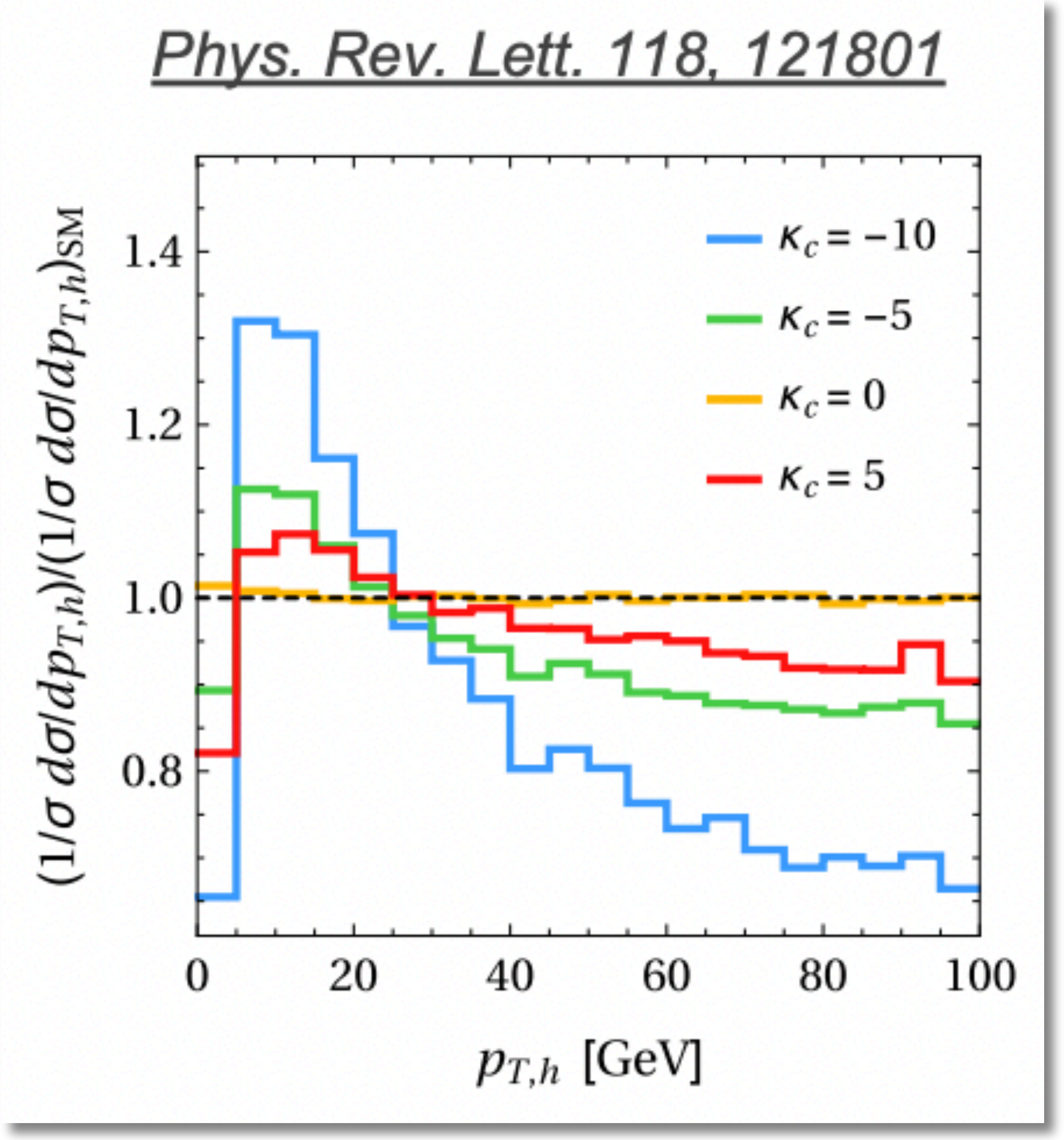
Mission Impossible

- Higgs to charm quark decays
  - Several methods to explore light quark decays



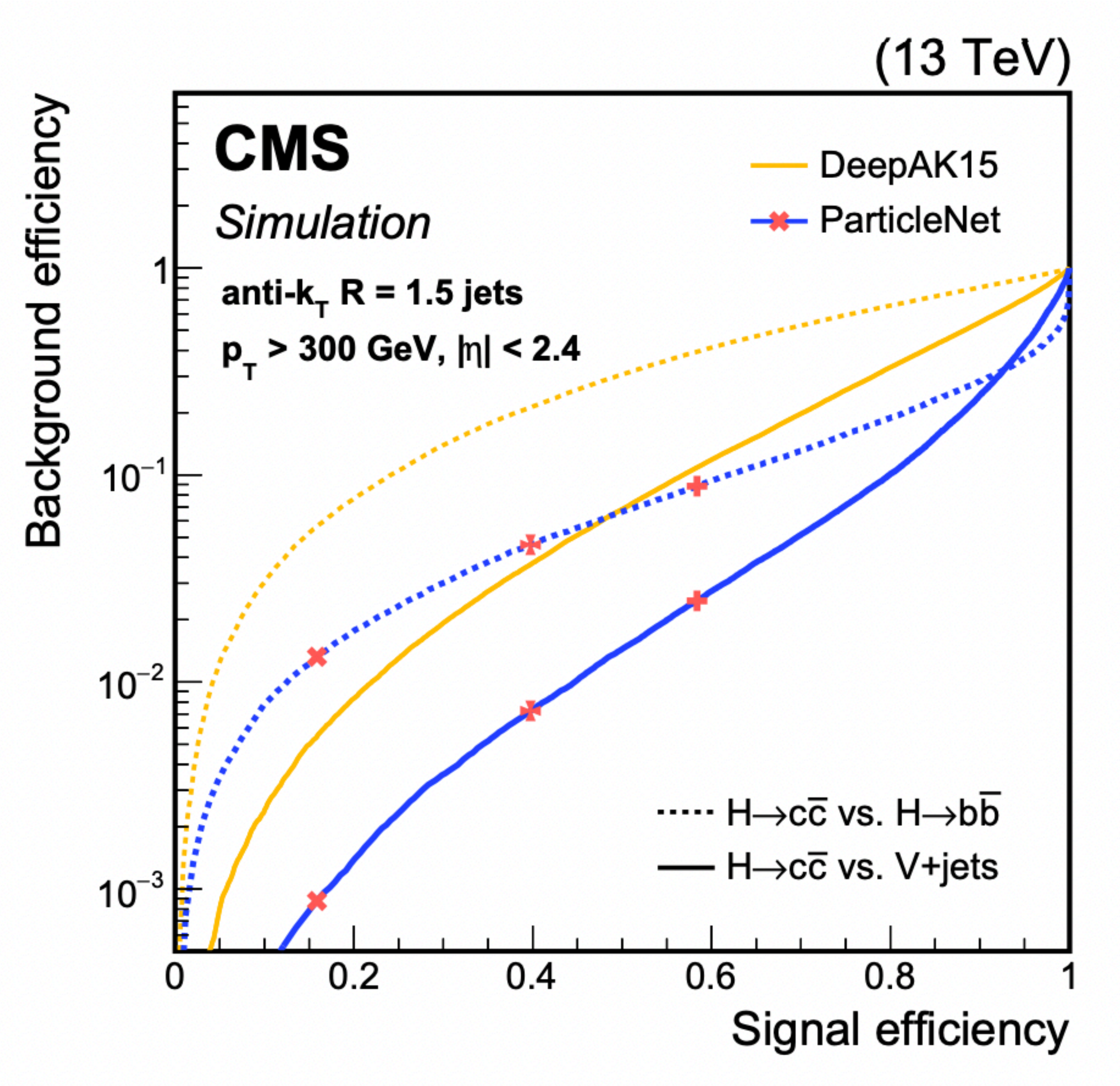



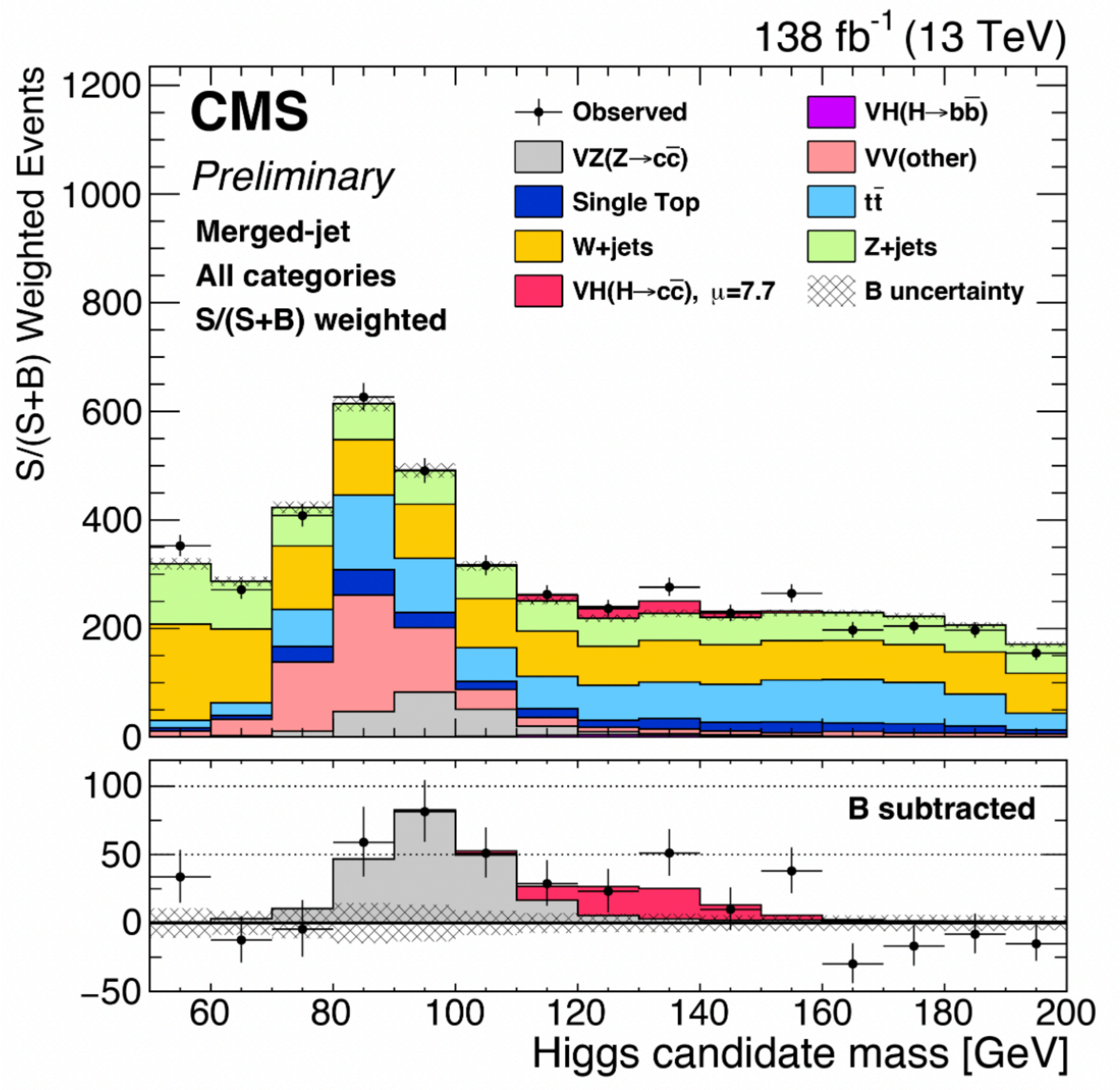


# Exploring (Testing) the Higgs Boson

Mission Impossible

- Higgs to charm quark decays
  - Very encouraging results
  - Signal strength < 14 SM

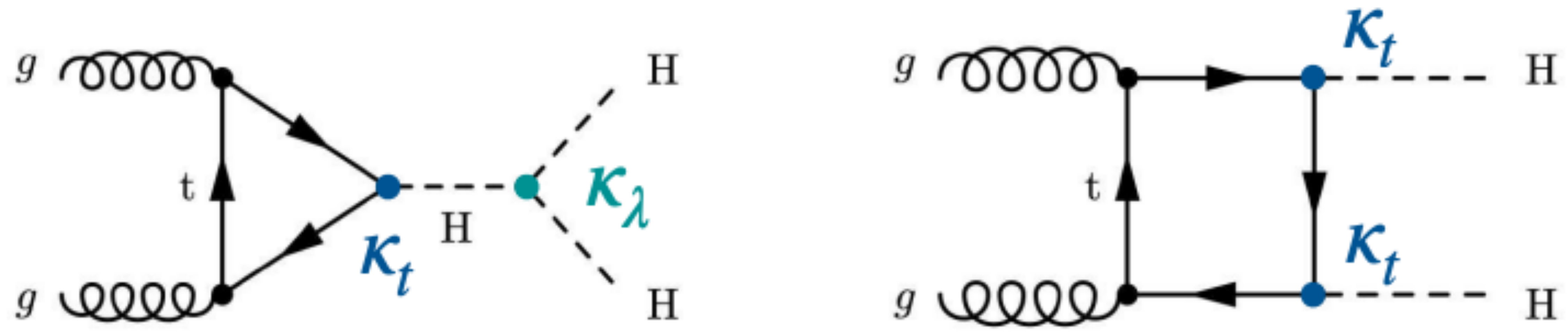


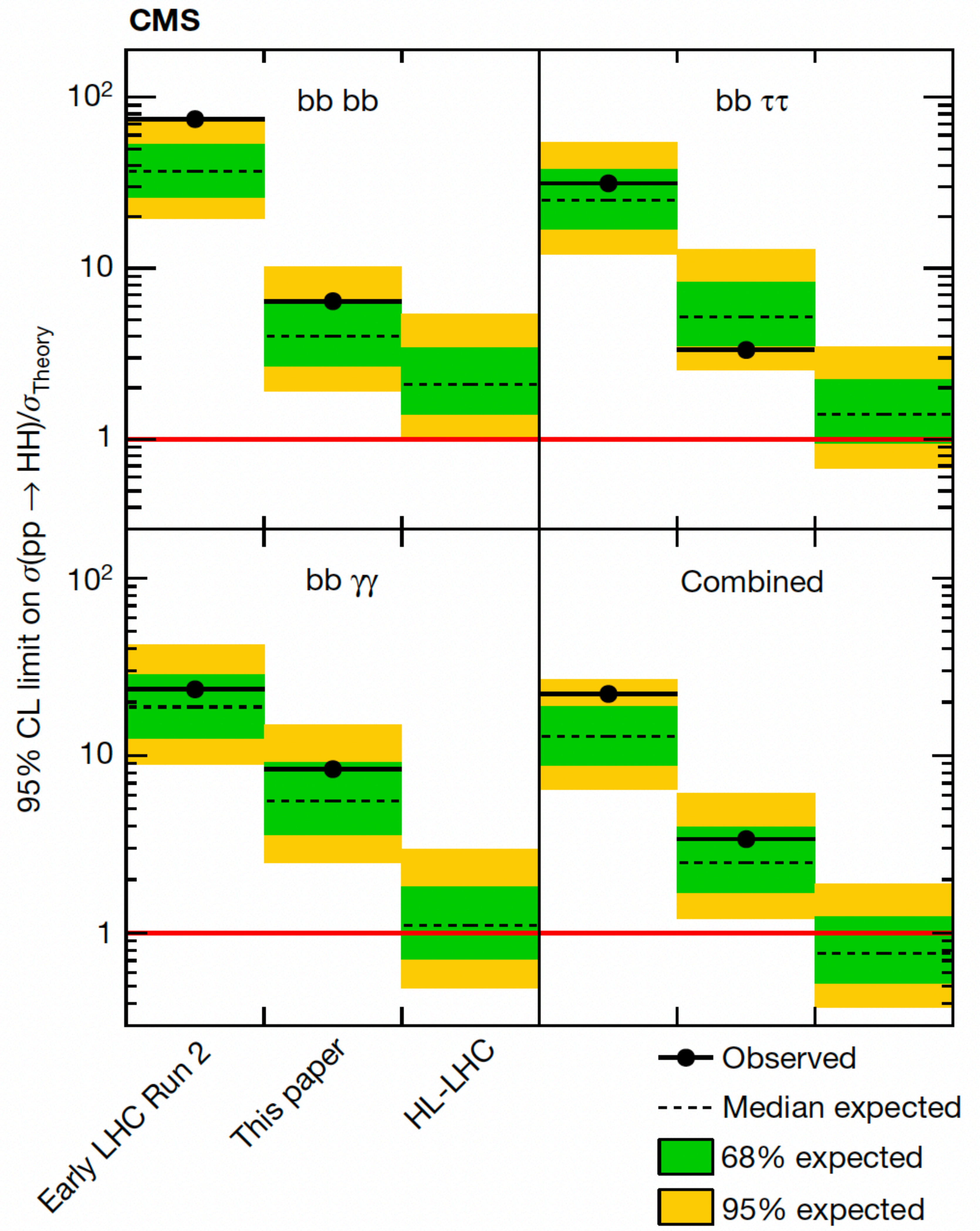



# Exploring (Testing) the Higgs Boson

Mission Impossible

- Higgs to Higgs Higgs




  - Higgs Boson pair production probes directly the Higgs self-interaction and, ultimately, the shape of the Higgs potential and the structure of the vacuum.
  - Higgs Boson pair production cross section ~1000 times smaller than single-Higgs production
  - Both, ATLAS and CMS investigate multiple channels with Higgs decays to bb, γγ, ττ, WW, ZZ - all complex topologies
  - Significant improvements in reconstruction and analysis techniques

# Higgs as Portal to New Physics

Warning! You are leaving the Standard Model

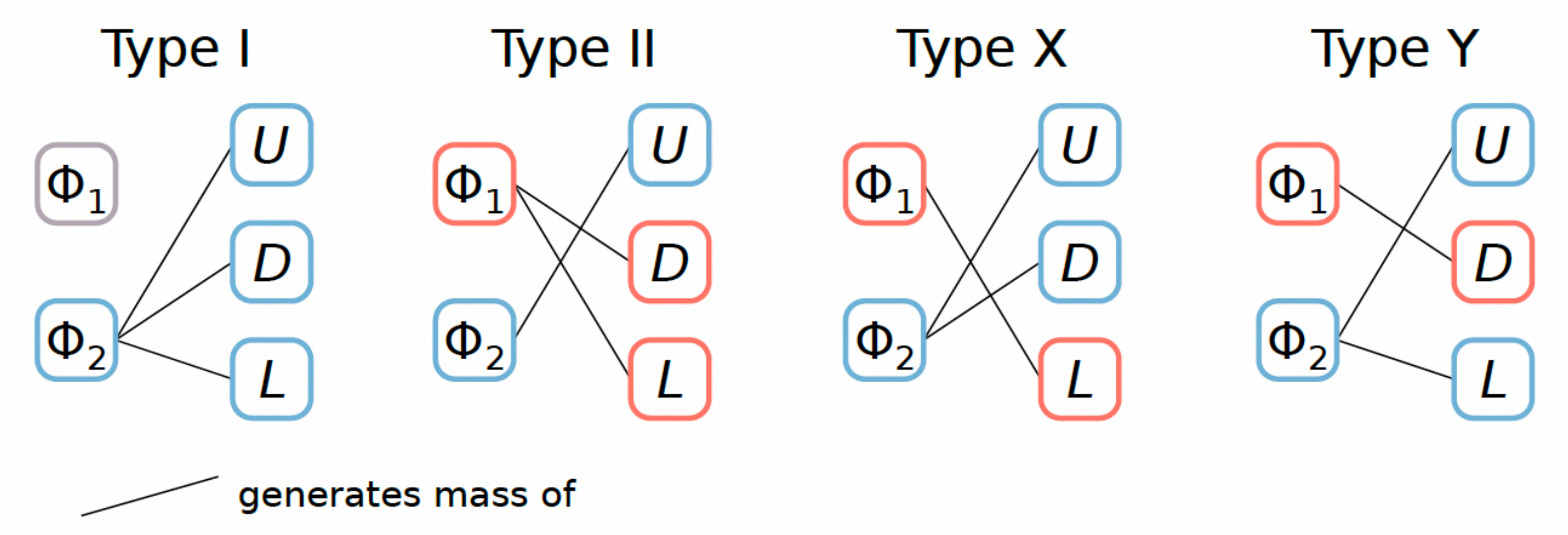
Many extended Higgs theories have over parts of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

- Beyond measuring Higgs properties with precision, we can look for
  - Additional Higgs bosons
  - Higgs boson decays to new particles
  - …

# Higgs as Portal to New Physics

Warning! You are leaving the Standard Model

- All SUSY models have extended Higgs sector
- In the minimal model (MSSM) as second Higgs doublet is introduced
  - New particles: h, H, A, $H^+$, $H^-$
  - At leading order, two parameter covern the Higgs sector, e.g. $m_A$ and tanβ (ratio of the two vacuum expectation value)
  - For large values of $m_A$ the h can very much look like the SM Higgs boson



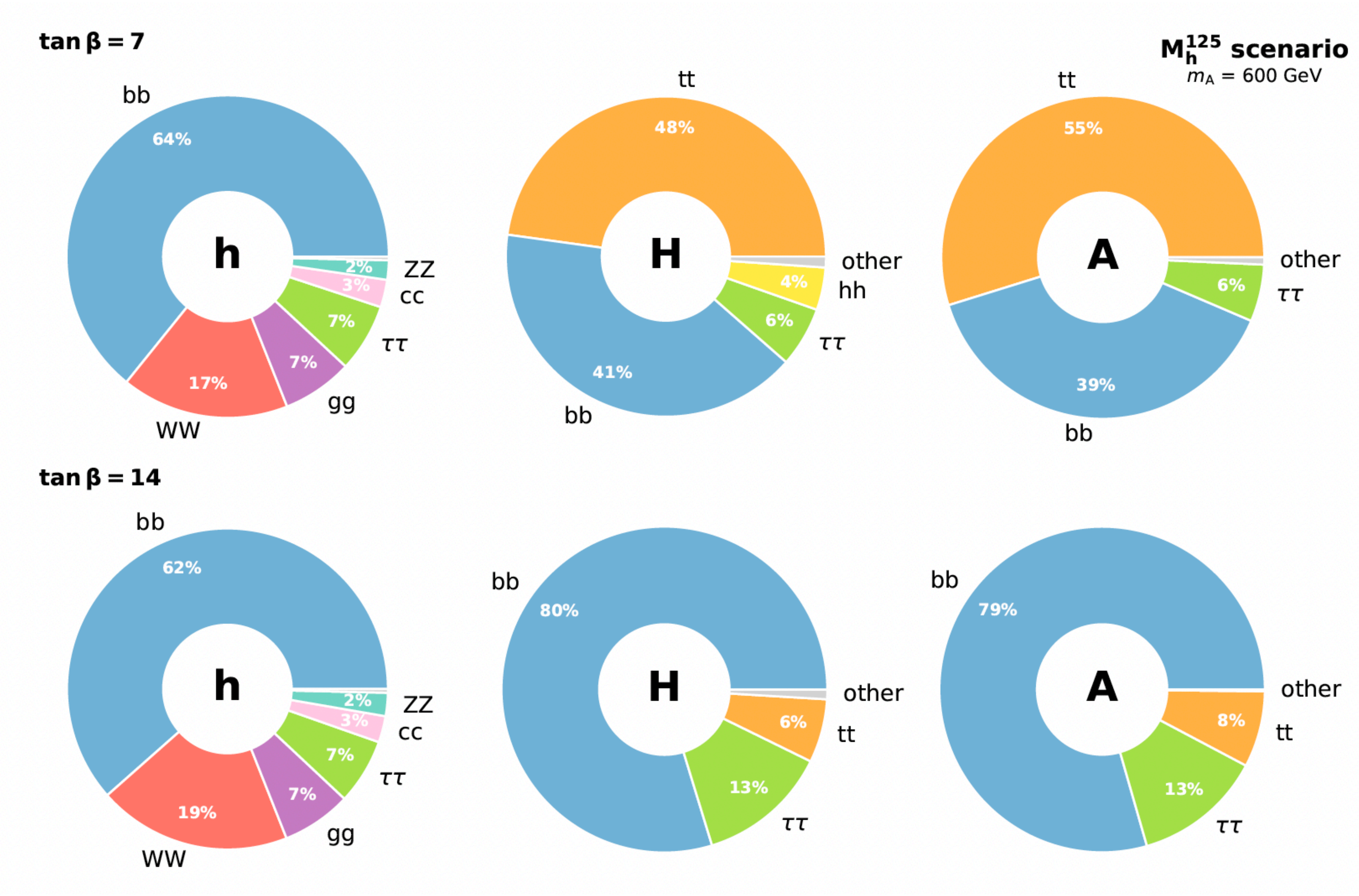

Source: M. Burkhardt

| | h | | | H | | | A | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\bar{U}U$ | $\bar{D}D$ | $\bar{L}L$ | $\bar{U}U$ | $\bar{D}D$ | $\bar{L}L$ | $\bar{U}U$ | $\bar{D}D$ | $\bar{L}L$ |
| Type I | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $-\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| Type II | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $-\cot\beta$ | $-\tan\beta$ | $-\tan\beta$ |
| Type X | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $-\cot\beta$ | $\cot\beta$ | $-\tan\beta$ |
| Type Y | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $-\cot\beta$ | $-\tan\beta$ | $\cot\beta$ |

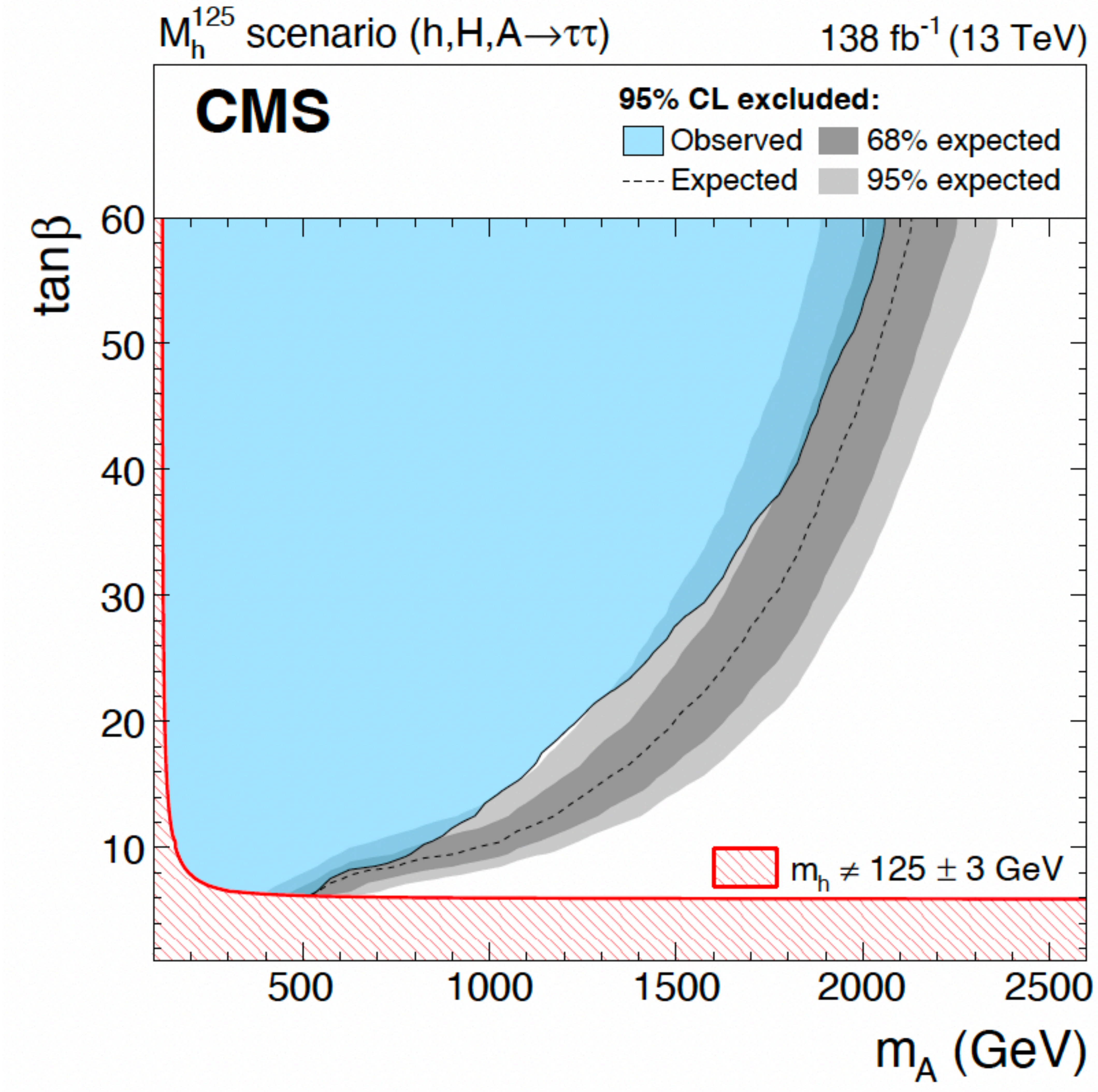
# Higgs as Portal to New Physics

Warning! You are leaving the Standard Model

- Higgs to tau decays excellent probes



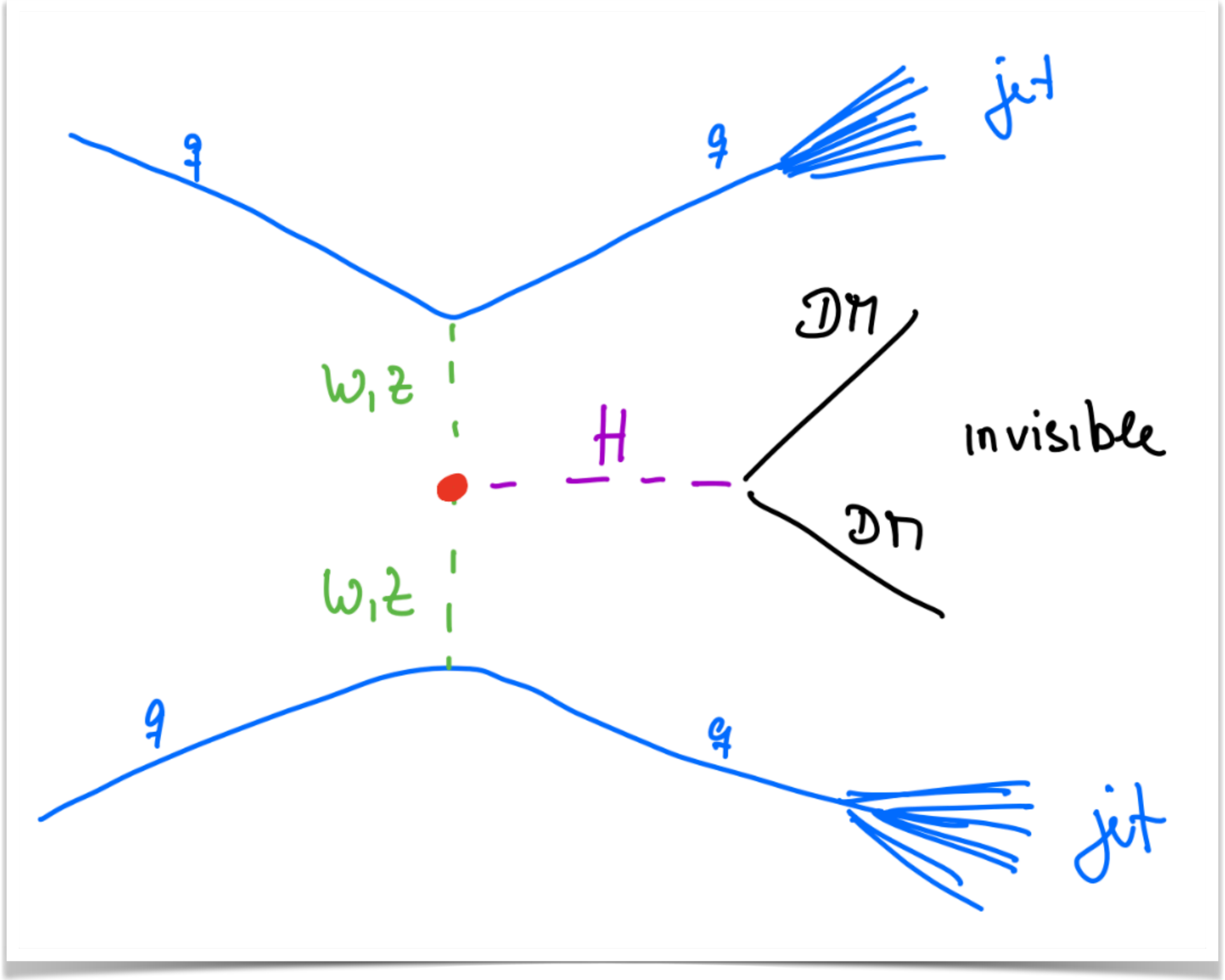

Source: M. Burkhardt

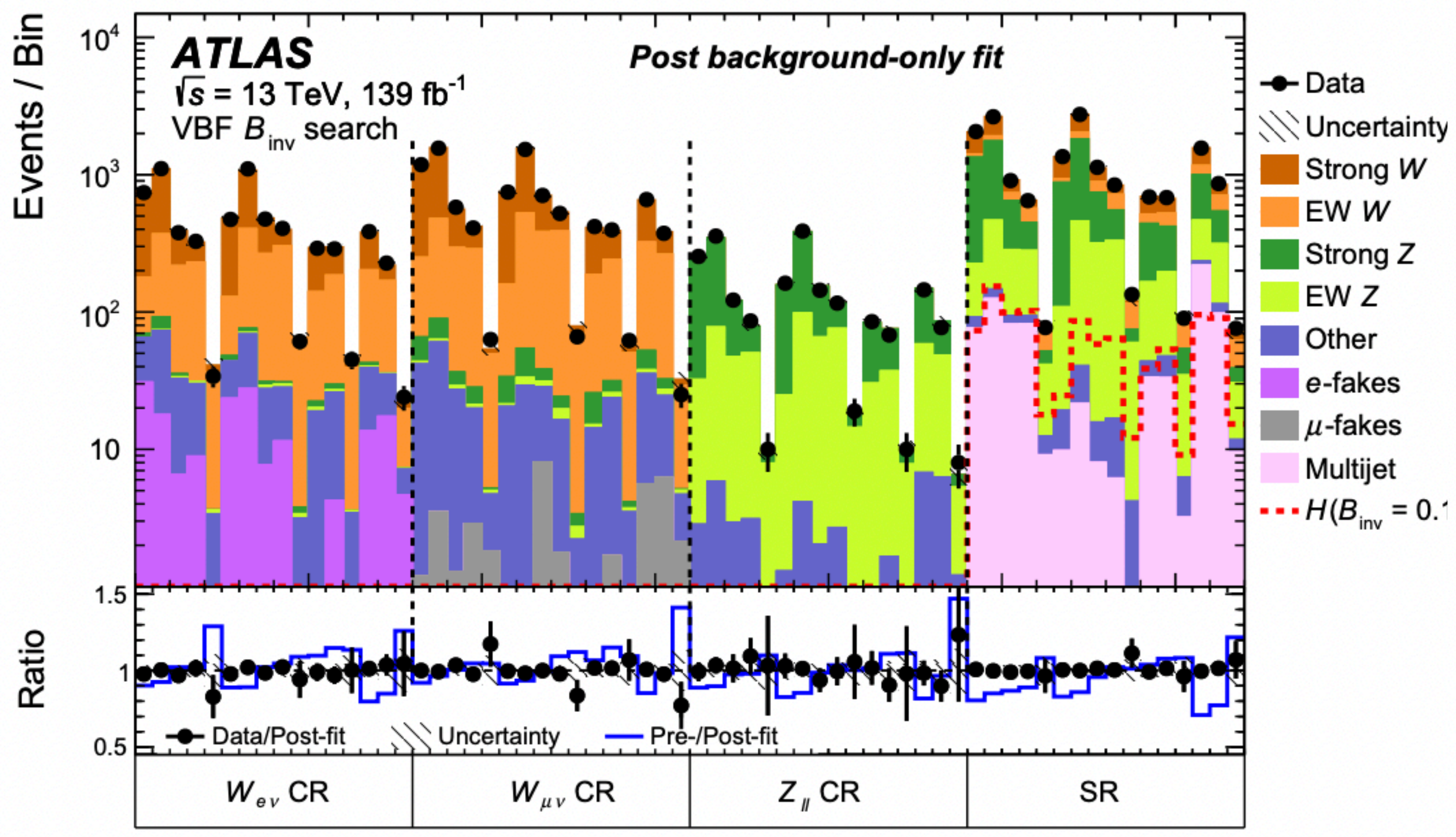


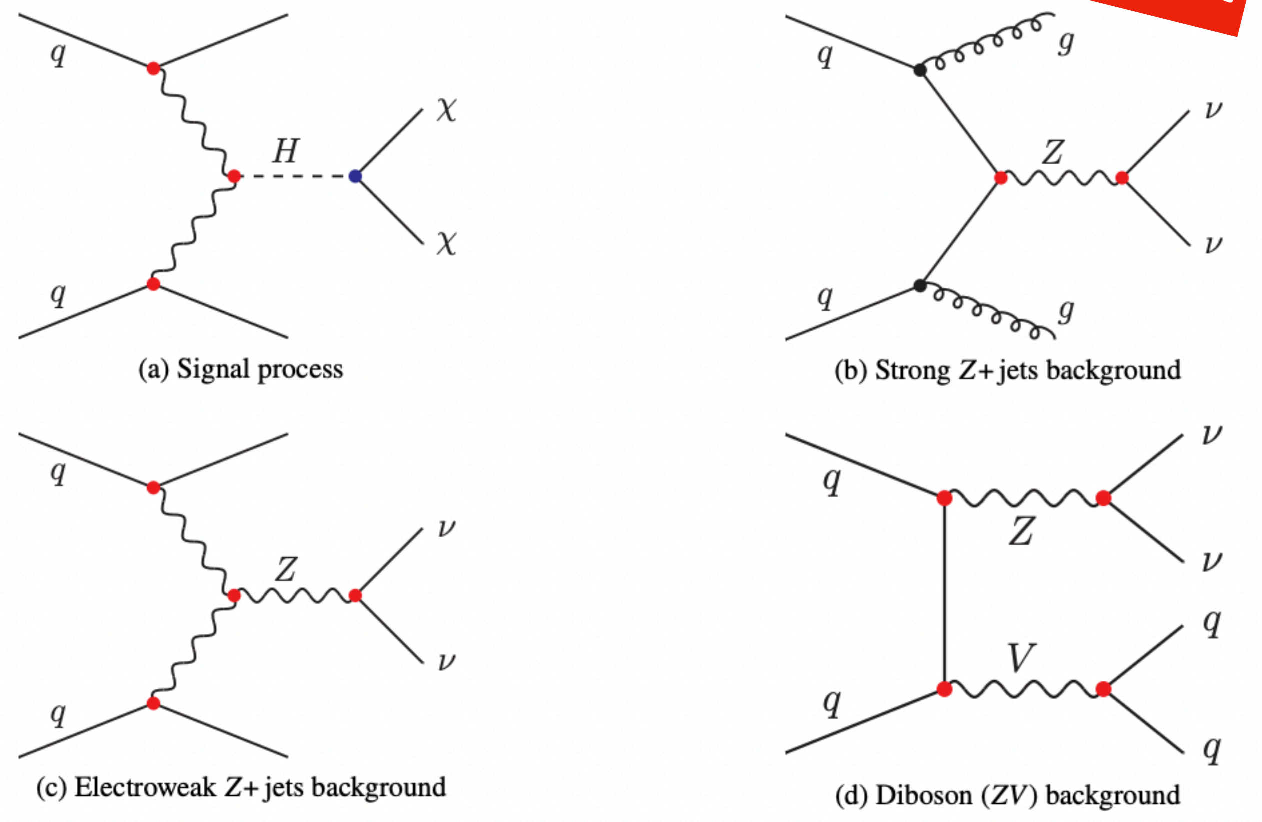
# Higgs as Portal to New Physics

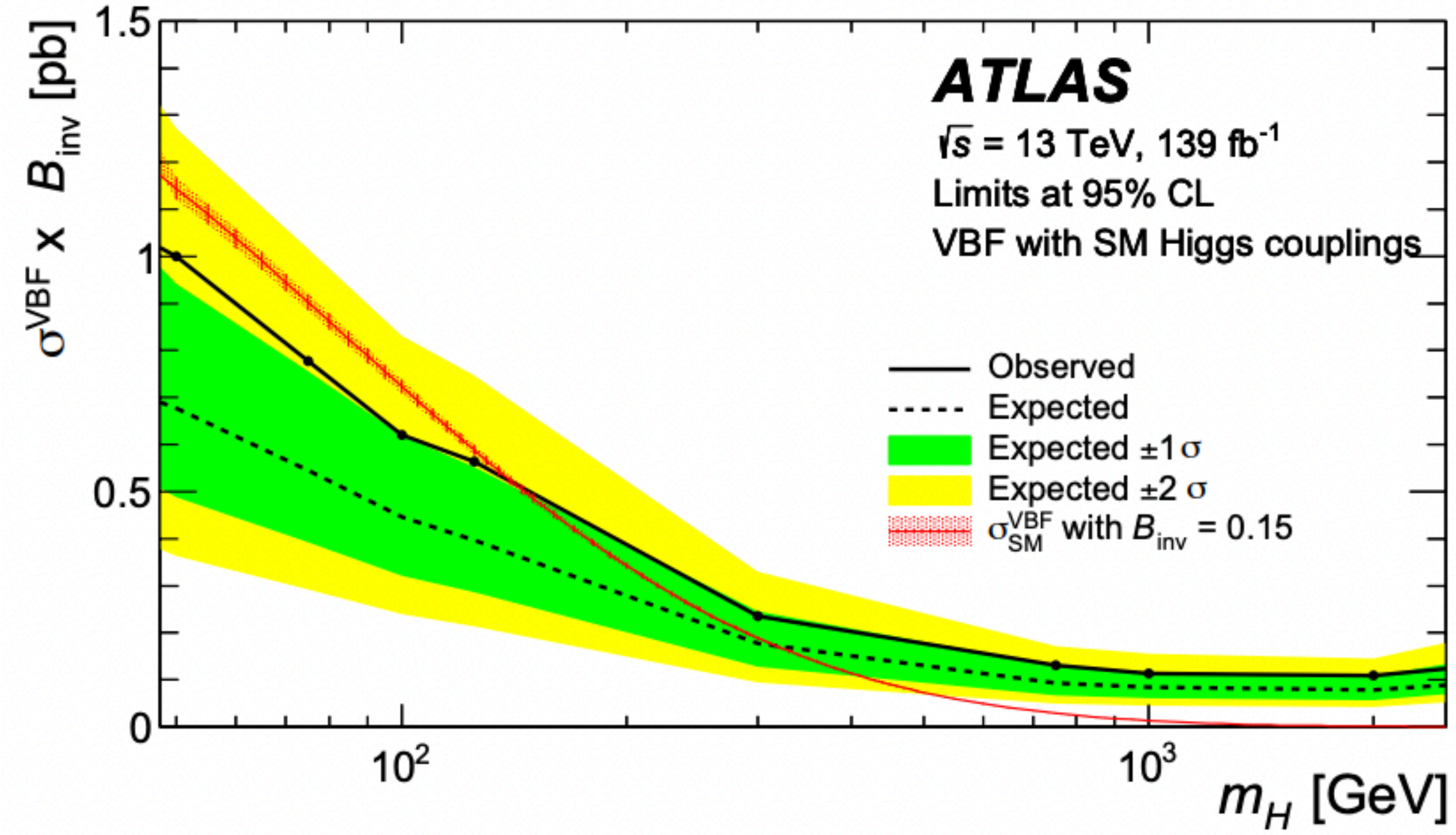
Warning! You are leaving the Standard Model

- Higgs to Dark Matter decays



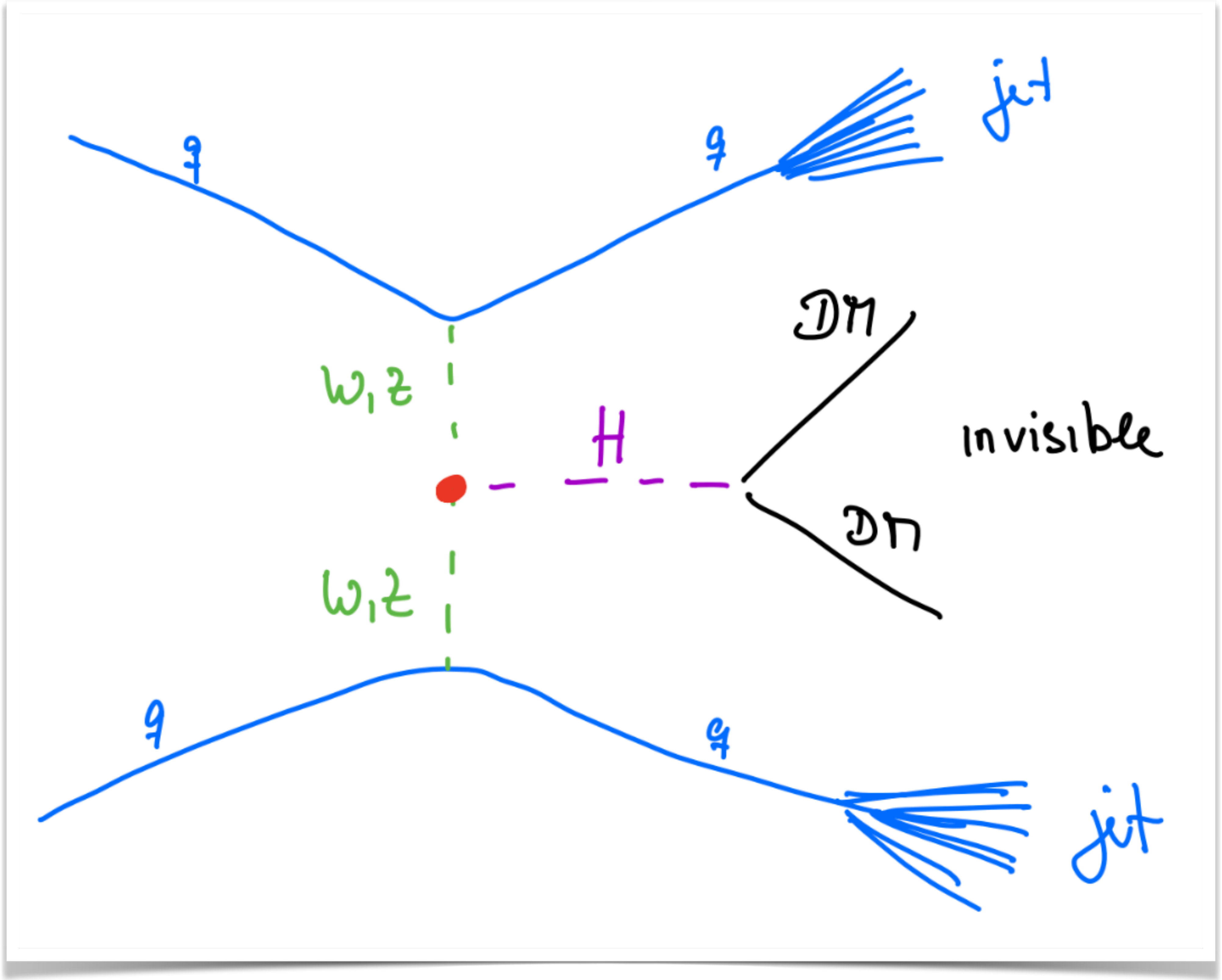



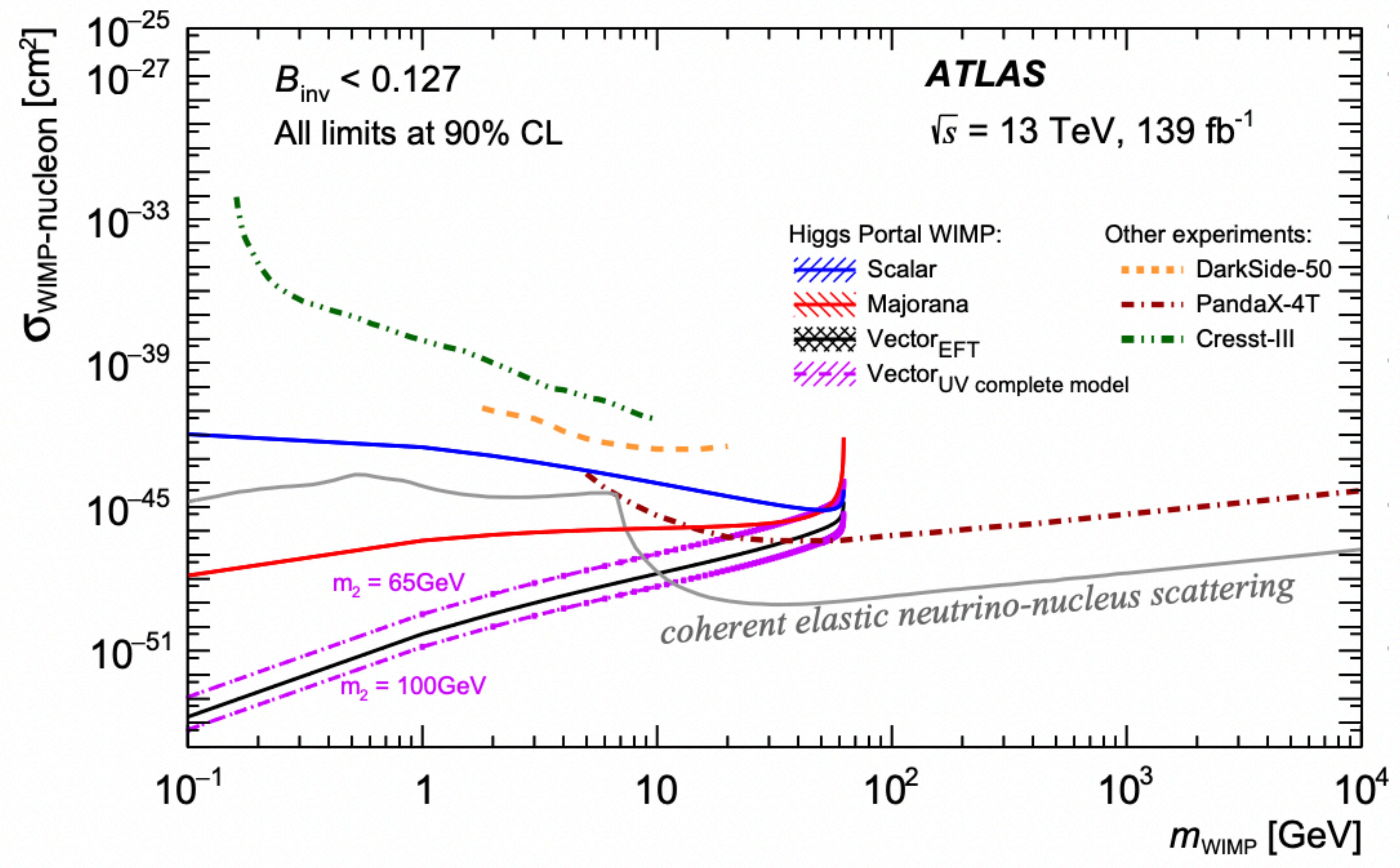



# Higgs as Portal to New Physics

Warning! You are leaving the Standard Model

- Higgs to Dark Matter decays



# Quiz

- Why was the LHC bound to make a discovery?
- What were the key channels used to discover the Higgs Boson?
- Which channels are used to measure the Higgs Boson mass? Why not other channels?
- How do the tau leptons decay?
- What are simplified fiducial cross sections?
- The statistical significance of a measurement usually scales with $\sqrt{L}$. How can we beat this?
- How do you extract limits on DM-nucleon cross section from a limit on the Higgs BR to DM?

# References and further reading

- Textbooks
  - Modern Particle Physics by Mark Thomson
  - QCD at Colliders by Ellis, Stirling, and Weber
- Pictures
  - CERN Document Server
  - Wikipedia
  - Or reference on page
- References
  - Previous CERN Summer Lectures - https://indico.cern.ch/category/97/
  - MIT's OCW 8.701 and 8.811
  - KIT's Particle Physics master courses (you can contact me)
  - Public results from ATLAS, CMS, and LHC combination groups
  - Or reference on page