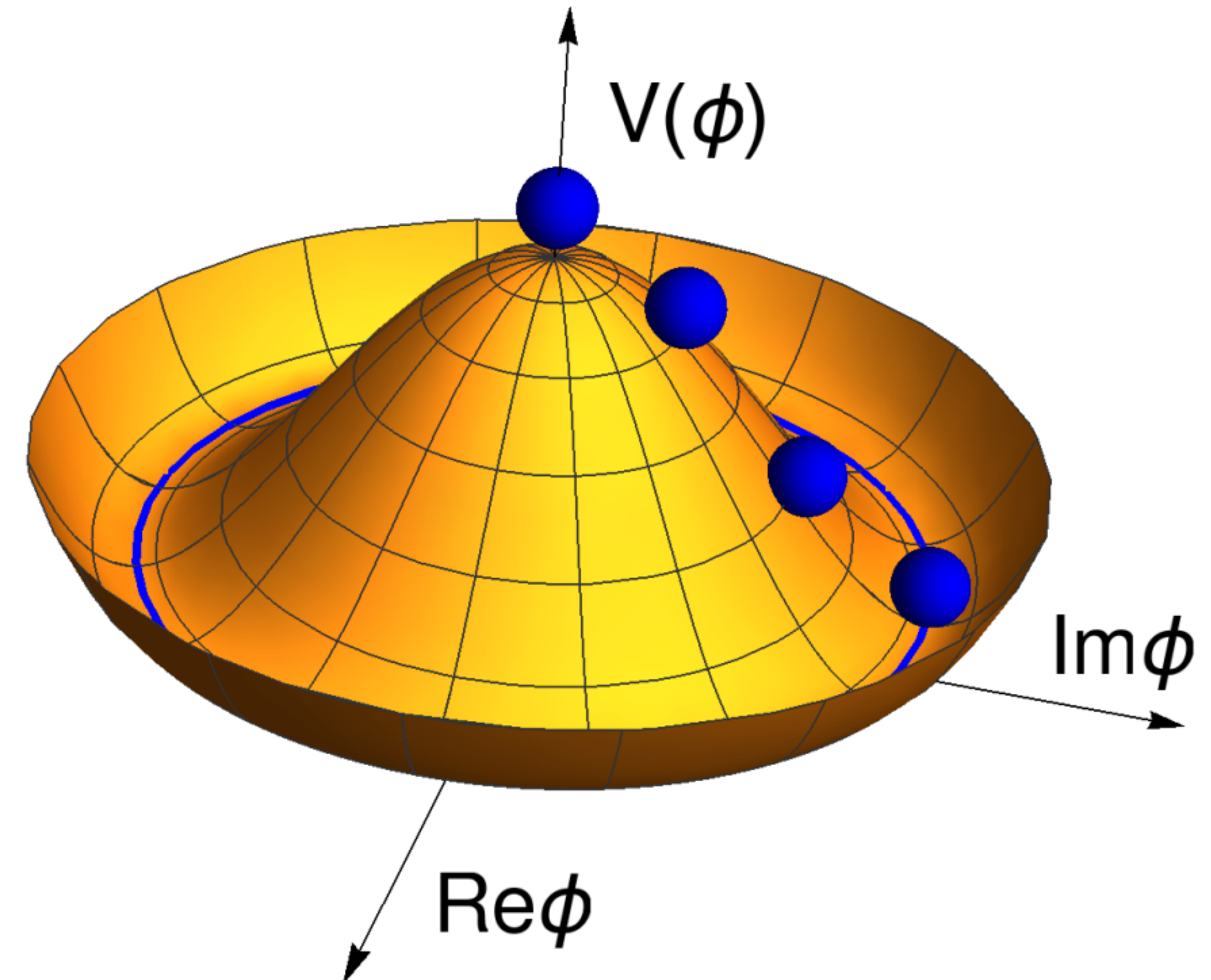


Search for Di-Higgs (HH) Production at the ATLAS Experiment at CERN

Baktash Amini, PhD Candidate

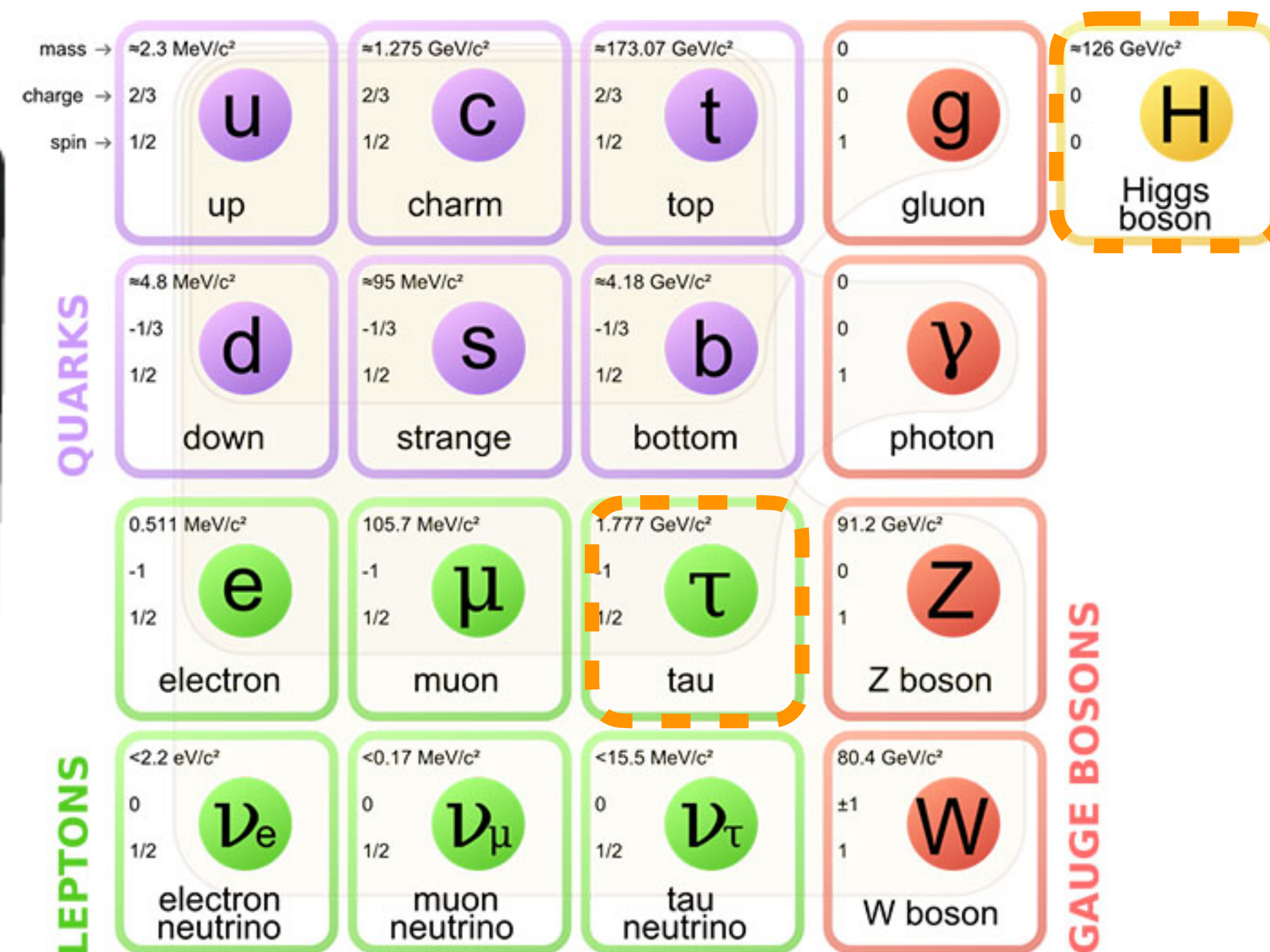
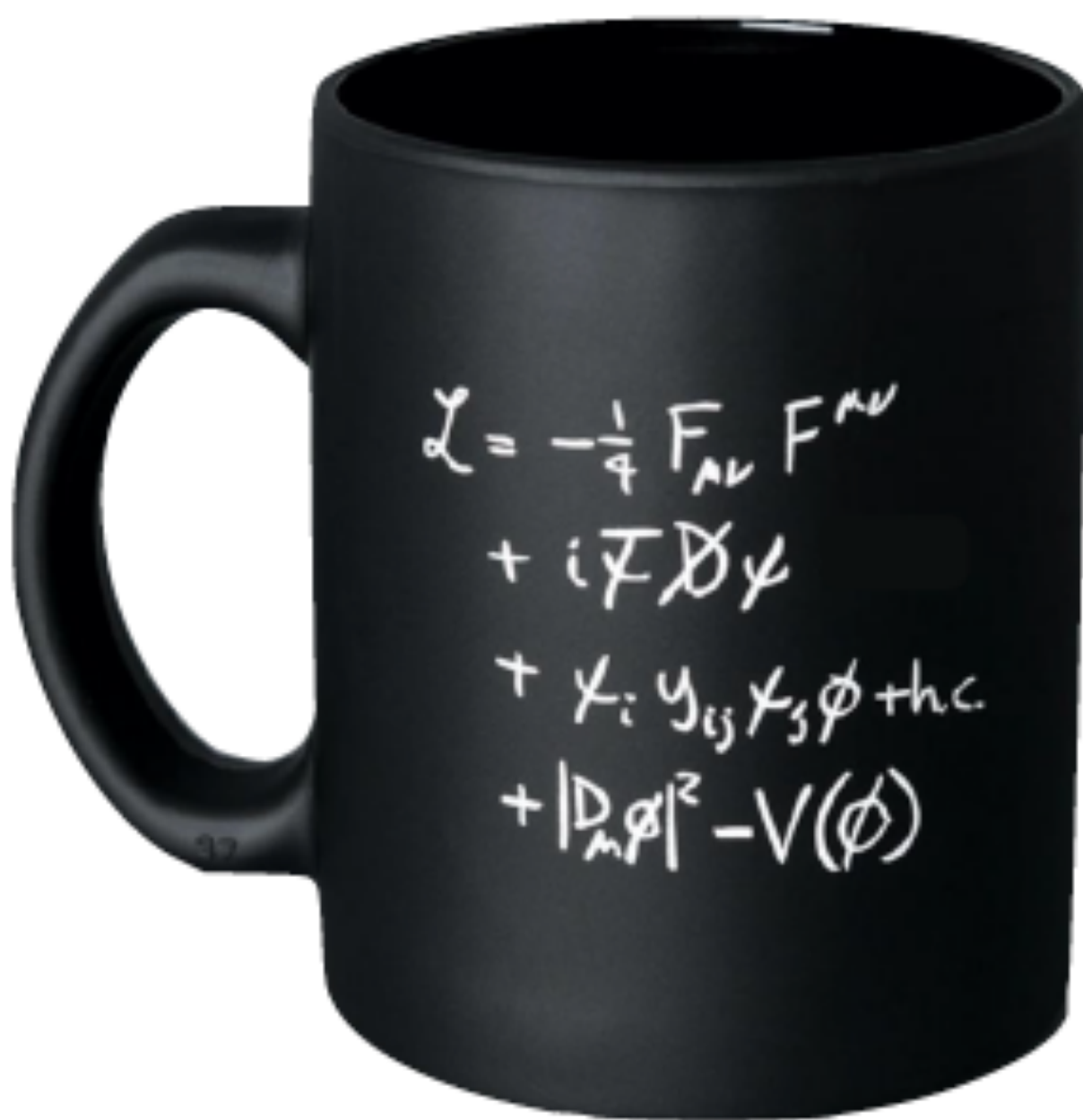
Afghan Physics Students Conference 2025

18, November 2025



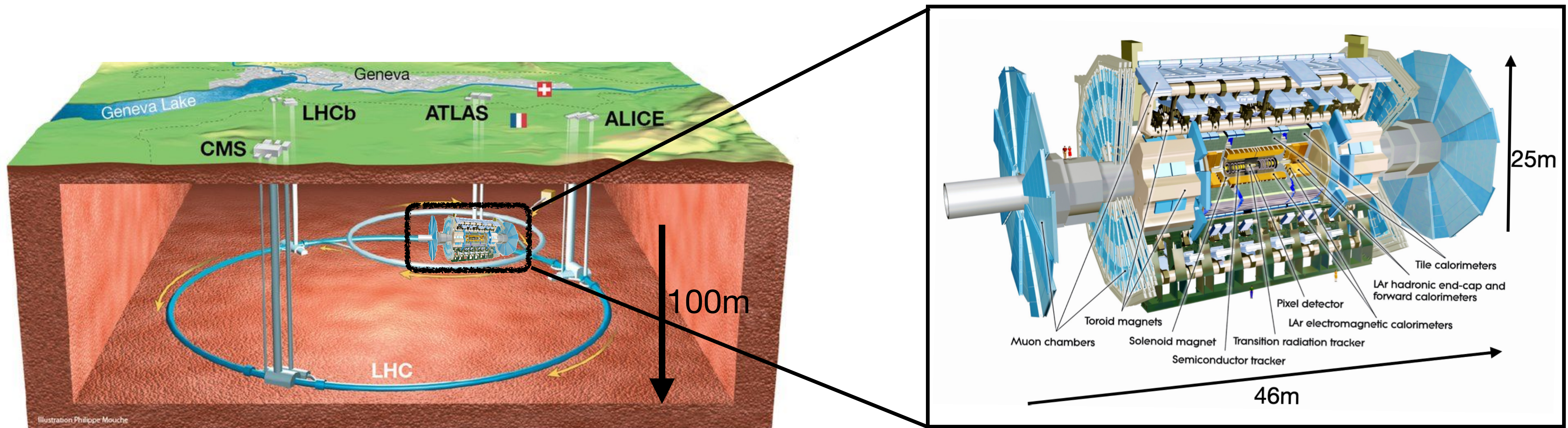
Standard Model of Particle Physics

Current state-of-the-art understanding of the fundamental particles of Nature and their interactions



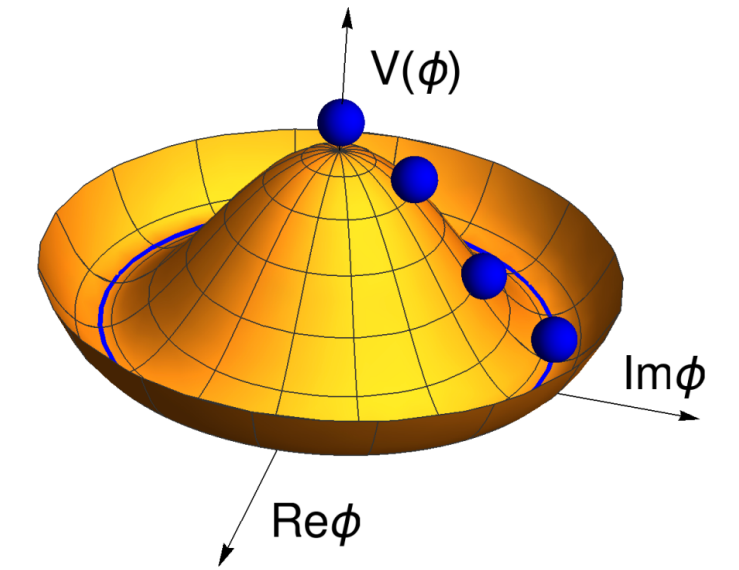
- Consistent with all observations made in laboratory experiments, except gravity.
- All particles predicted by the Standard Model (SM) have been observed since **the Higgs boson** was found at the CERN Large Hadron Collider (LHC) in 2012.
- Some crucial astronomical phenomena are not described (e.g. dark energy, dark matter, Baryon/Anti-Baryon asymmetry).

LHC & ATLAS Detector



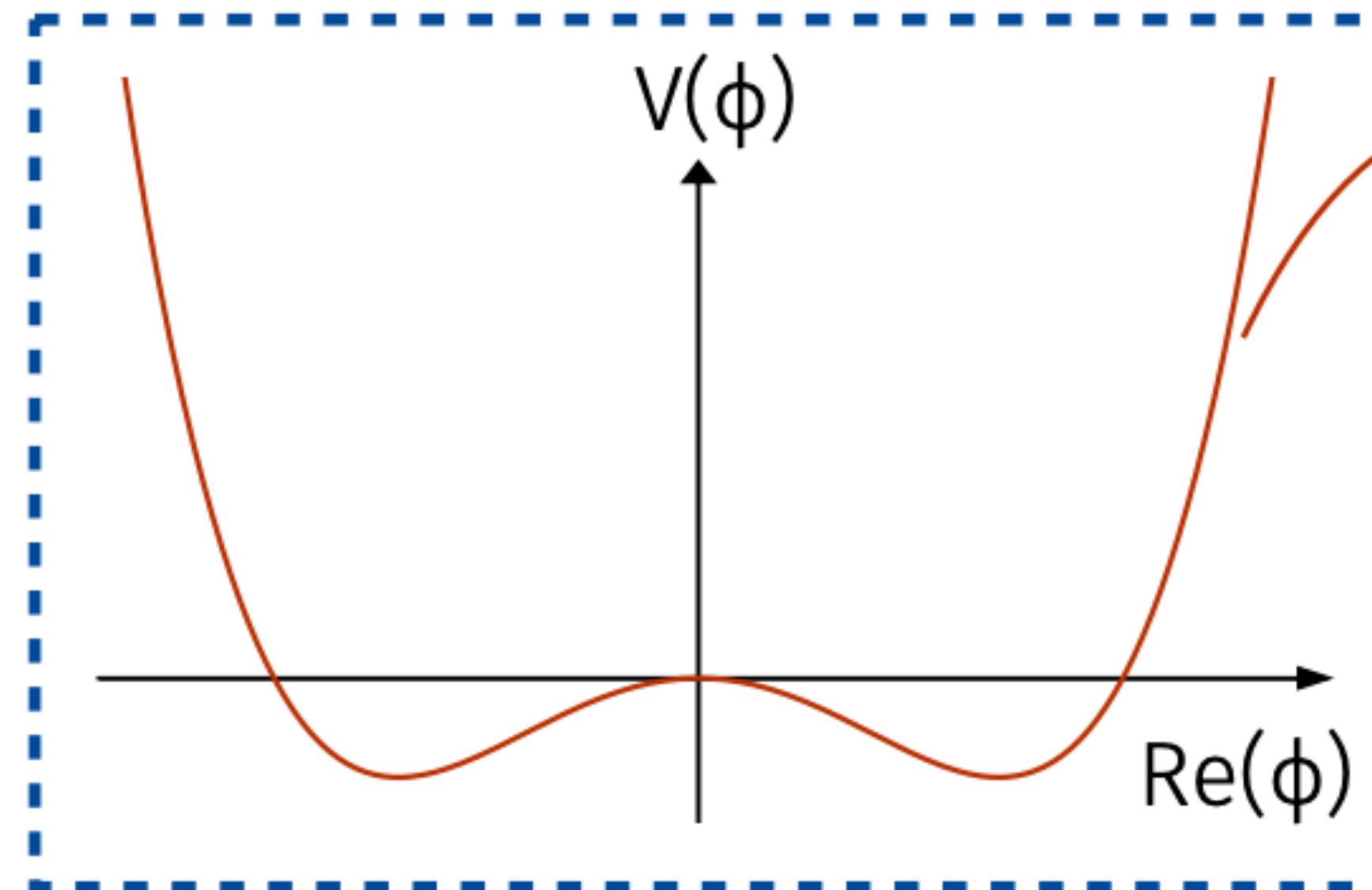
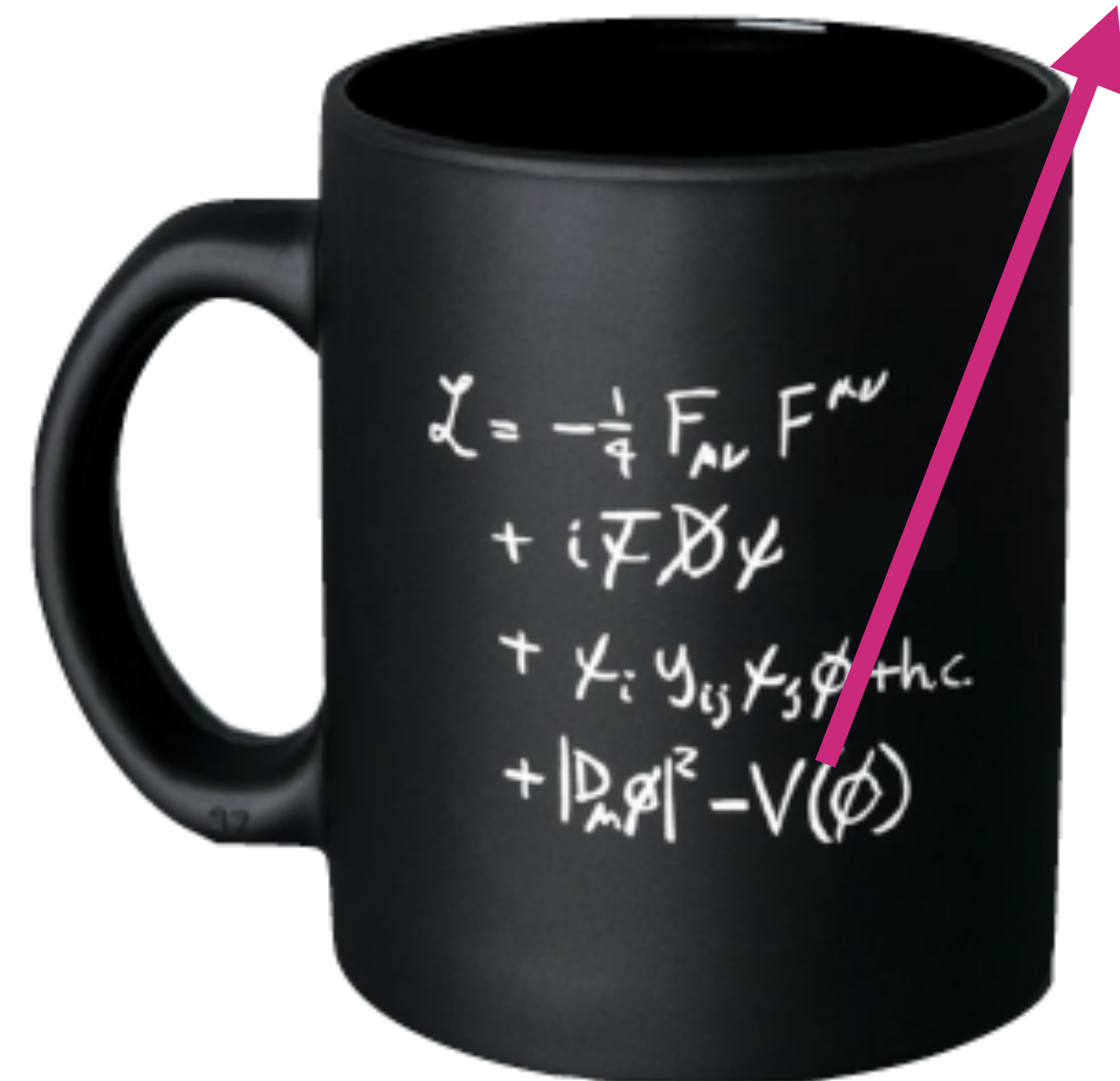
- World's largest and most powerful particle accelerator
- 27 km ring of superconducting magnets
- protons are accelerated and collided at **centre-of-mass energy** ($\sqrt{s}$) of 13 TeV in Run 2 (2015 - 2018).
- Weight: 7000 tonnes
- Detects individual particles (e.g. e , μ , γ and jets) created in the more than one billion proton-proton collisions per second.
- Records the trajectory, momentum and energy of particles

Setting the stage: The Higgs Potential



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

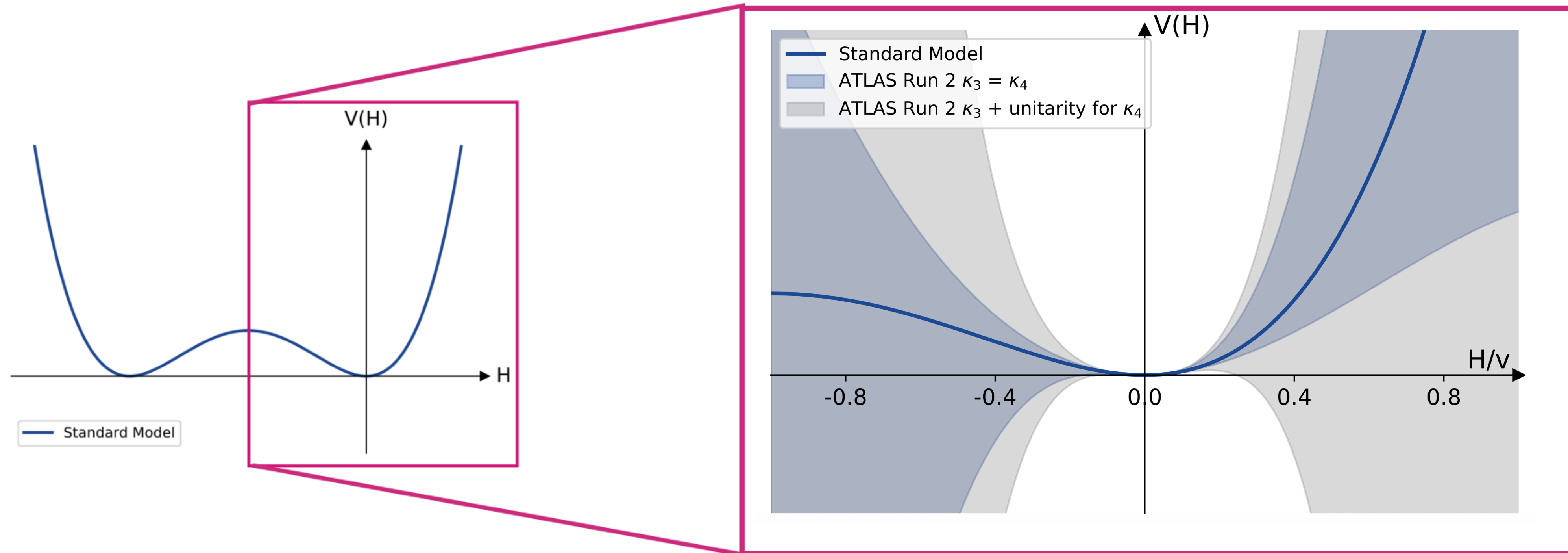
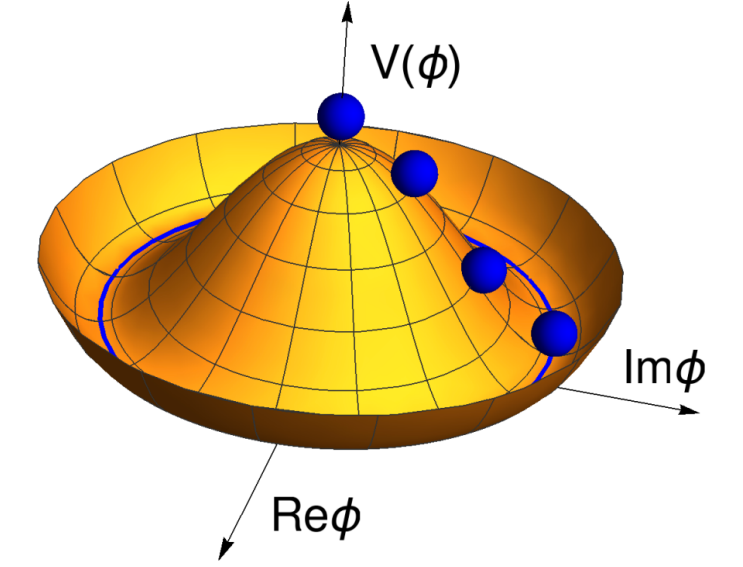
arbitrary >0



Where does this potential come from?

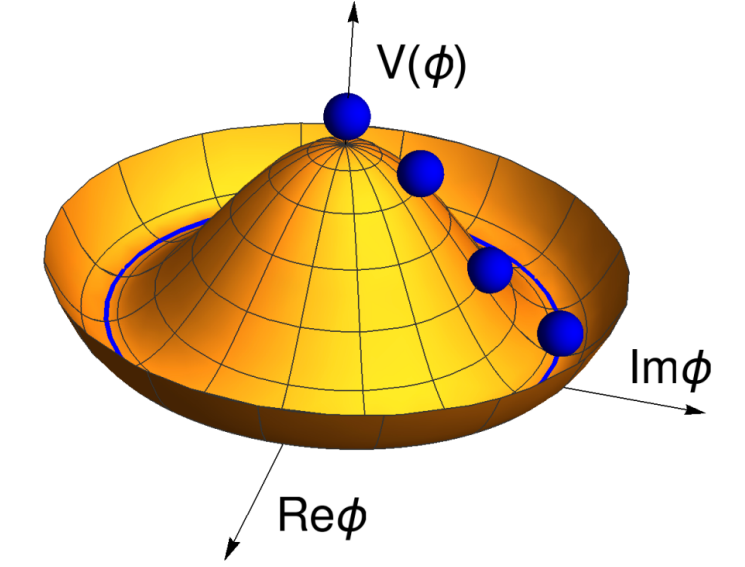
Why is it Mexican-hat shaped?

Setting the stage: The Higgs Potential



- The Higgs potential is introduced completely ad-hoc to the standard model of particle physics → no fundamental reason for its form (Mexican hat is an assumption)
- We need to measure the form of the potential in order to know it, experiment will have the final word.

Setting the stage: The Higgs Potential



Before

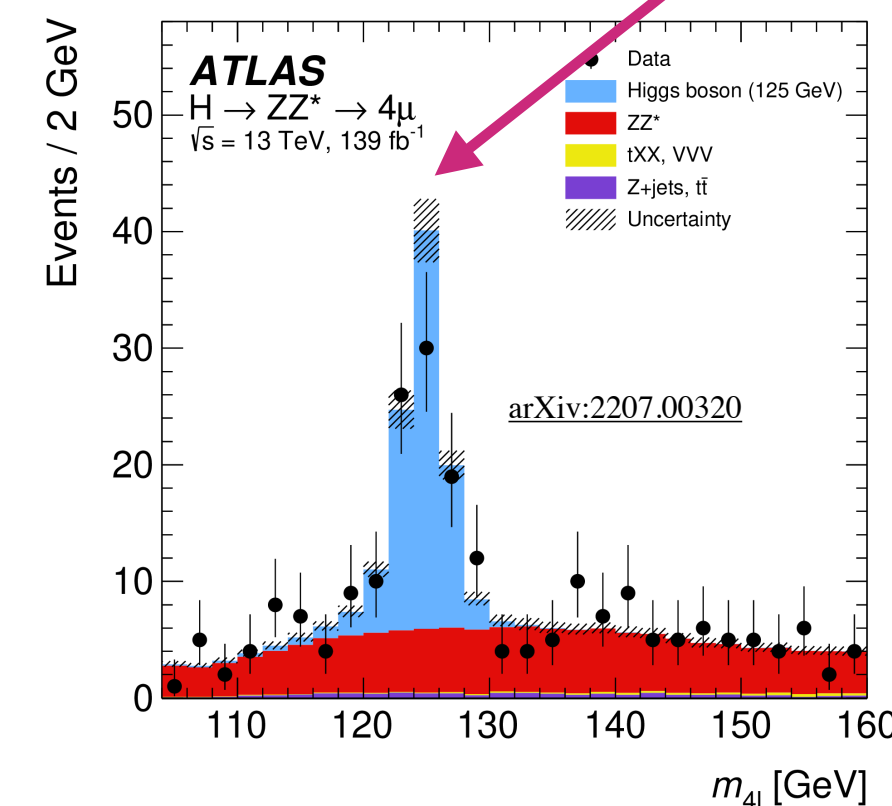
After

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

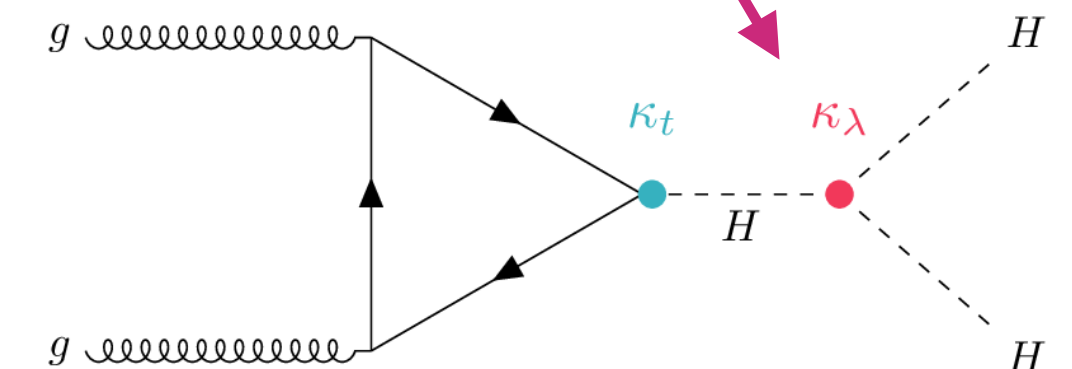
EWSB

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v_{\text{ev}} H^3$$

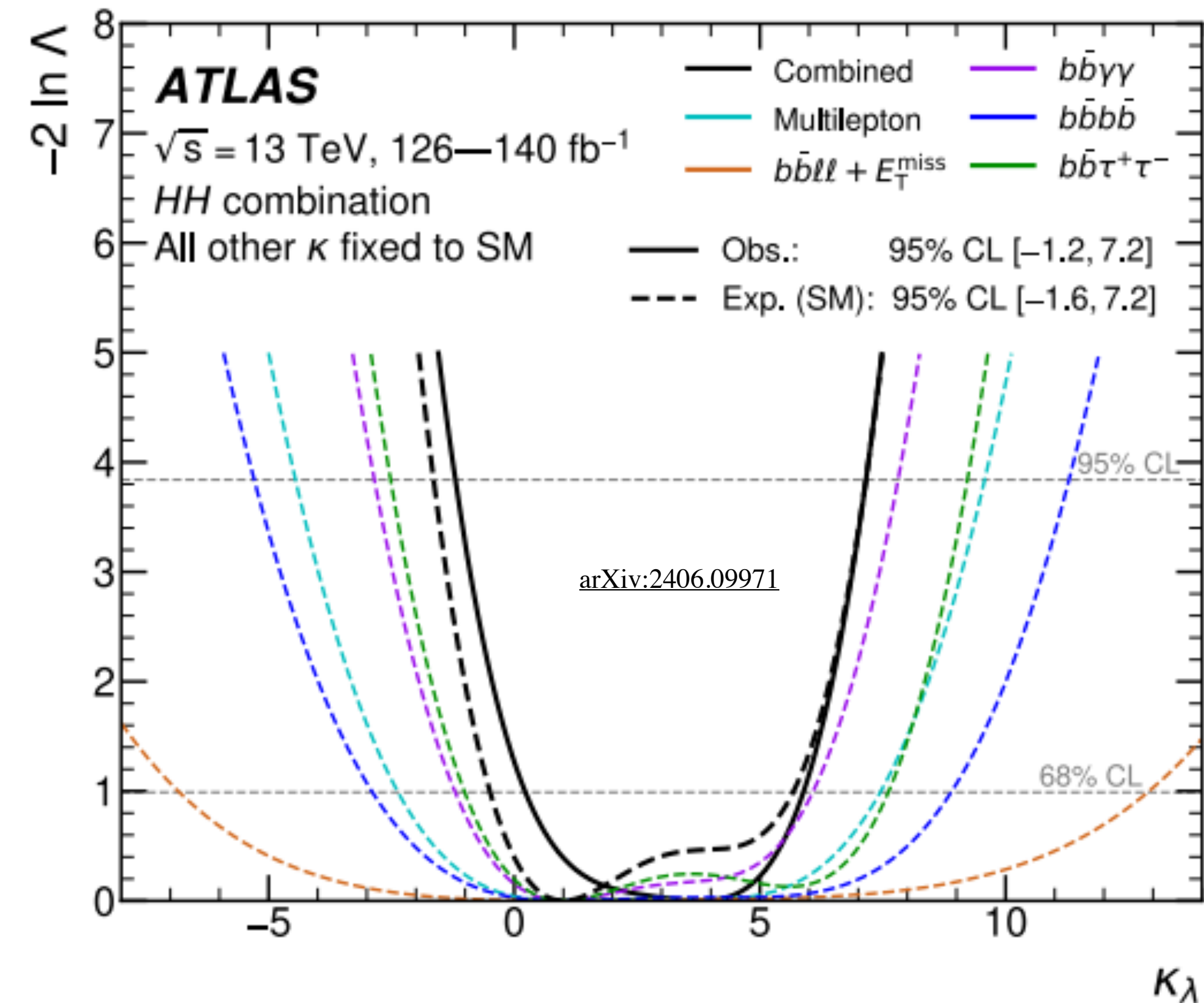
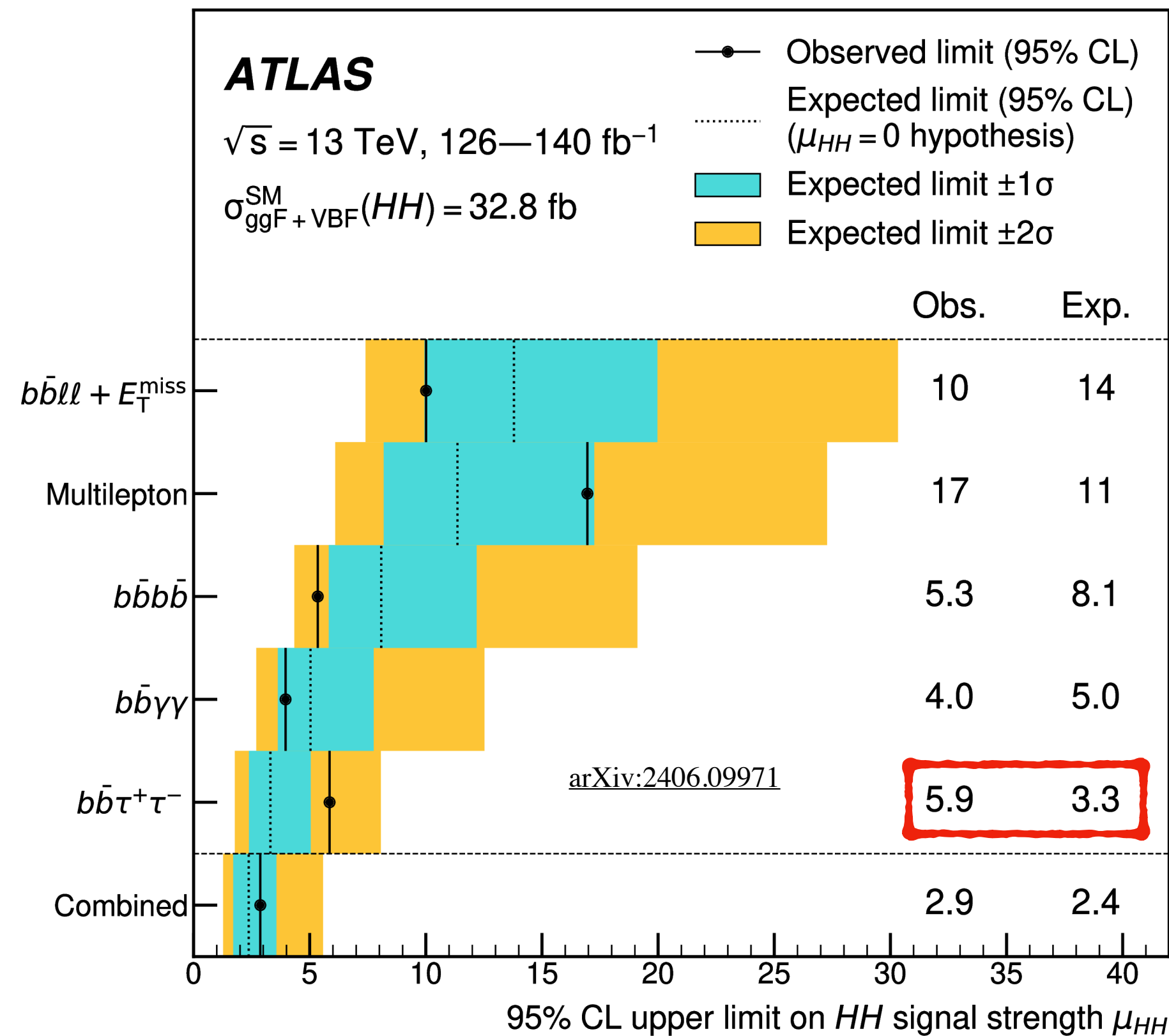
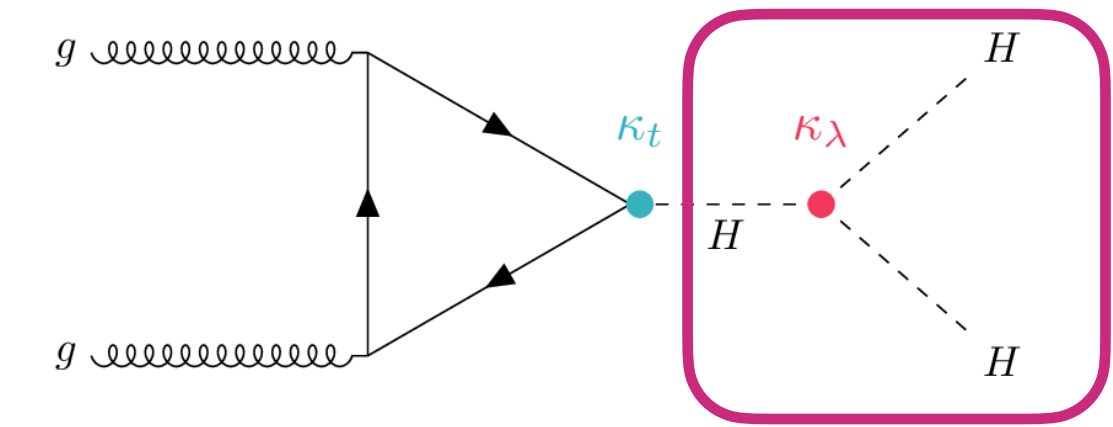
- We can experimentally measure the shape of the Higgs potential once we measure **the Higgs boson self-coupling (λ)**.
- Extensive experimental program at the LHC (ATLAS and CMS) to constrain/measure λ , mainly from Higgs boson pair production.
- Di-Higgs hasn't been experimentally observed yet.



$$\kappa_\lambda = \frac{\lambda_{\text{measured}}}{\lambda_{\text{SM}}}$$

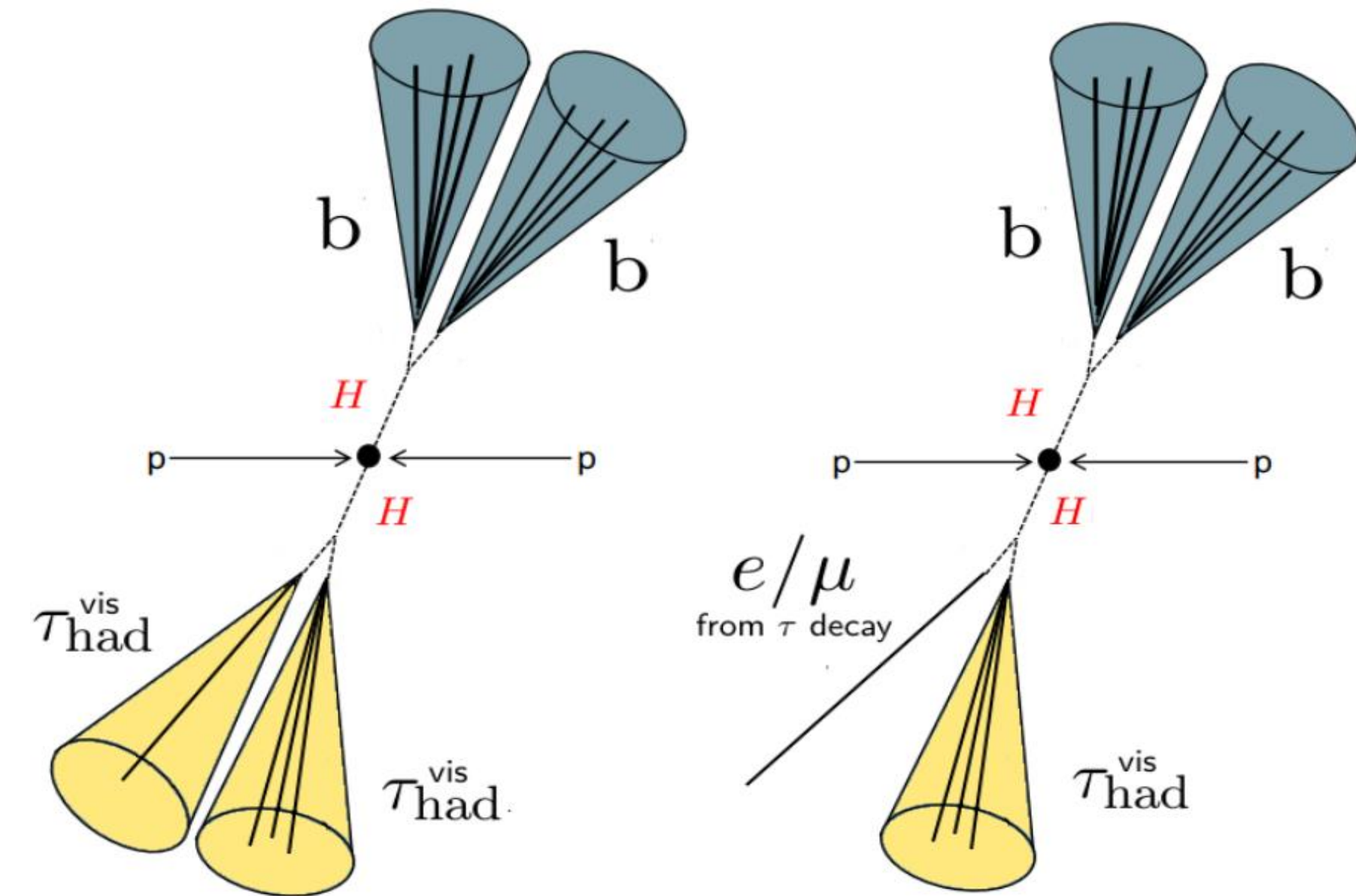
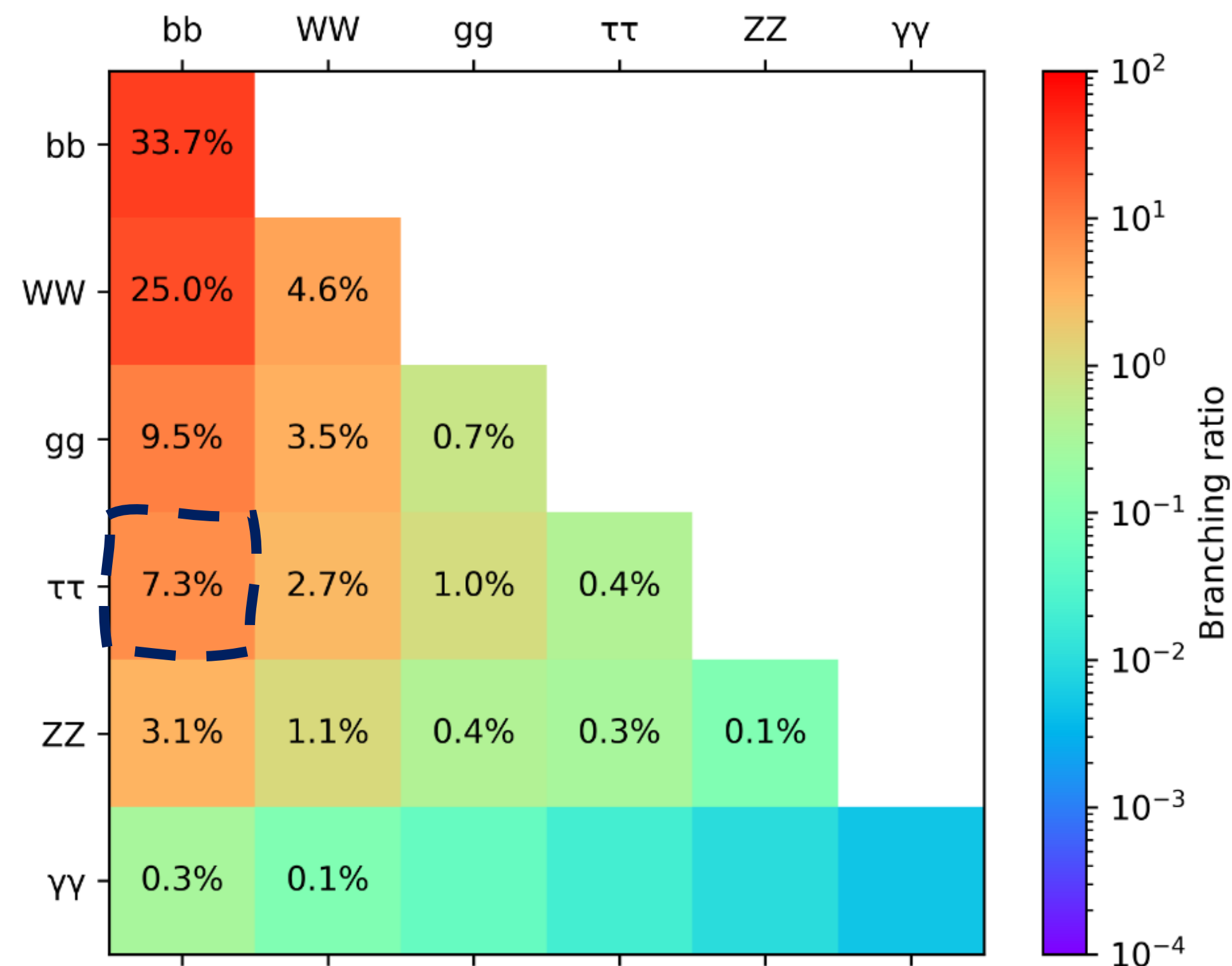


The Higgs Self-Coupling



- We need to measure the Higgs boson self-coupling (λ).
- Any deviations of the measured Higgs boson self-coupling from the standard model prediction would signal potential **new physics**.

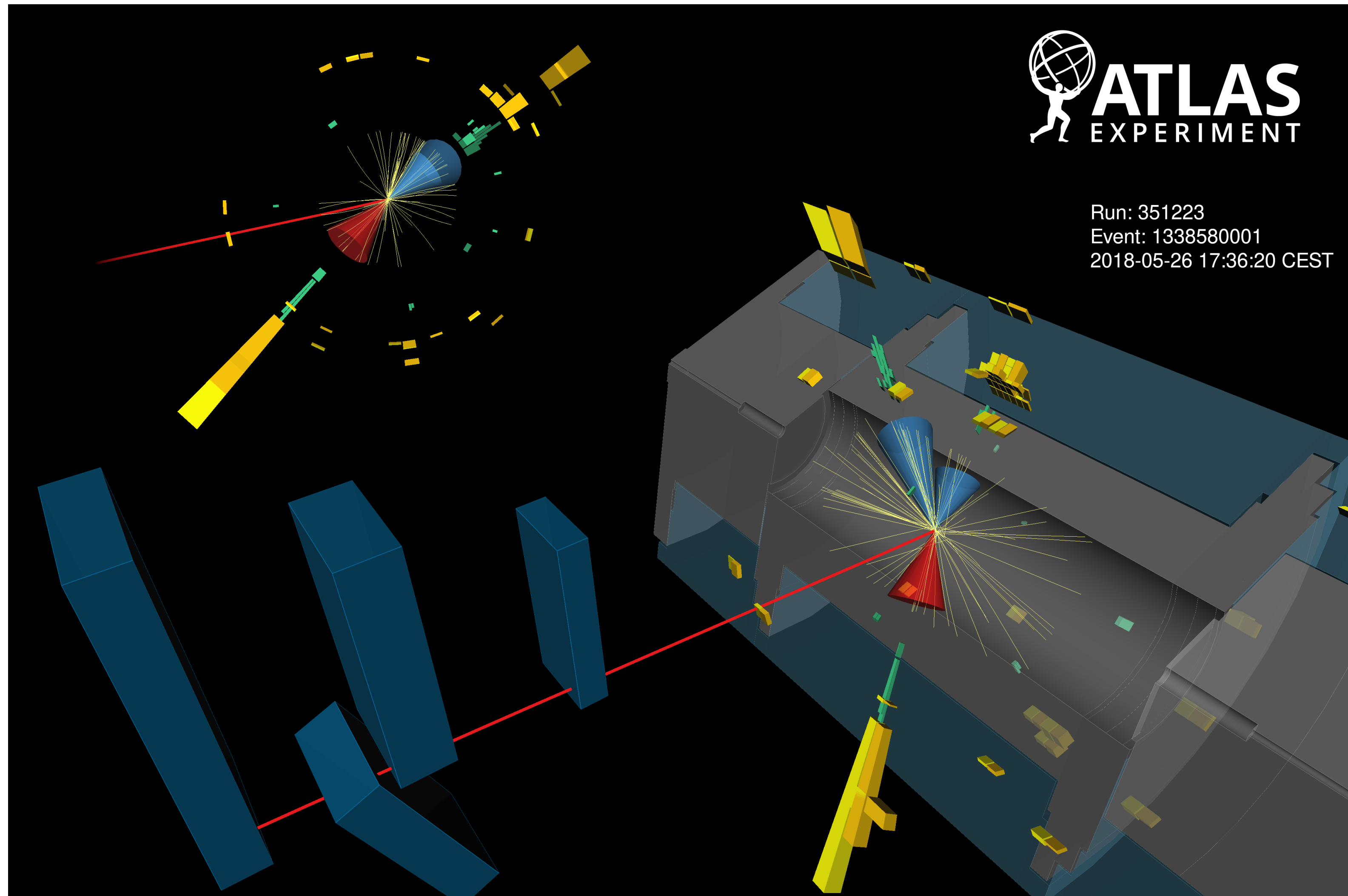
Di-Higgs to $bb\tau\tau$ Final State



- $HH \rightarrow bb\tau\tau$ provides a compromise between expected signal event yield and background contamination.
- This final state has a sensitivity similar to that of the $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$ decay modes.

Event Display of $HH \rightarrow bb\tau\tau$

Taken from [here](#).

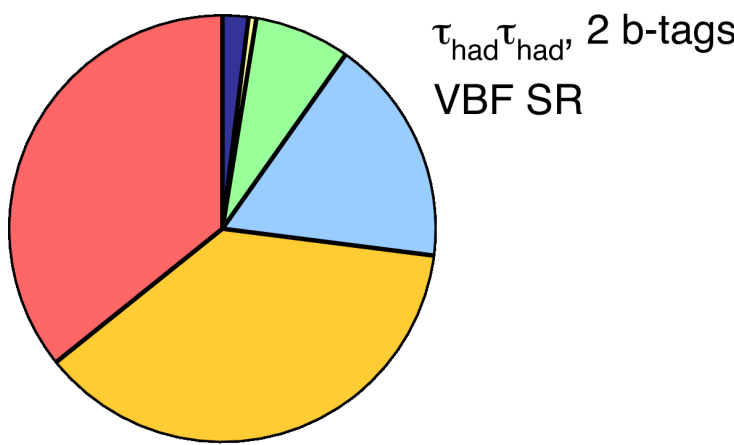
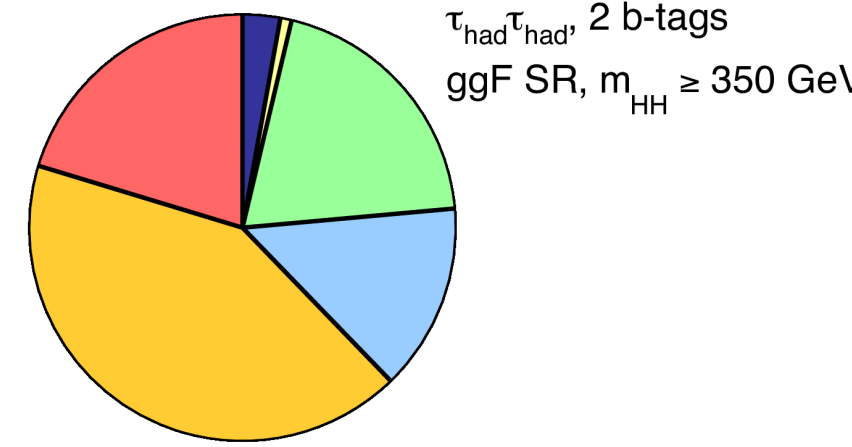
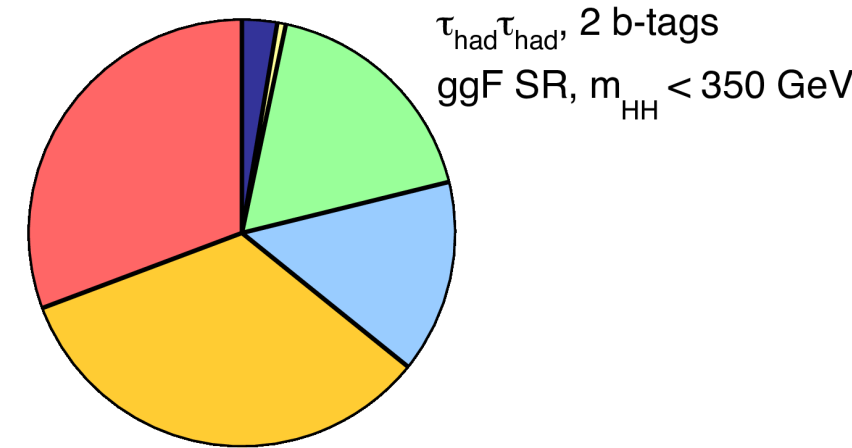


Event Composition

- $t\bar{t}$ fake $\tau_{\text{had-vis}}$ is the second largest background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel.
- My task is to estimate this background for the current analysis.

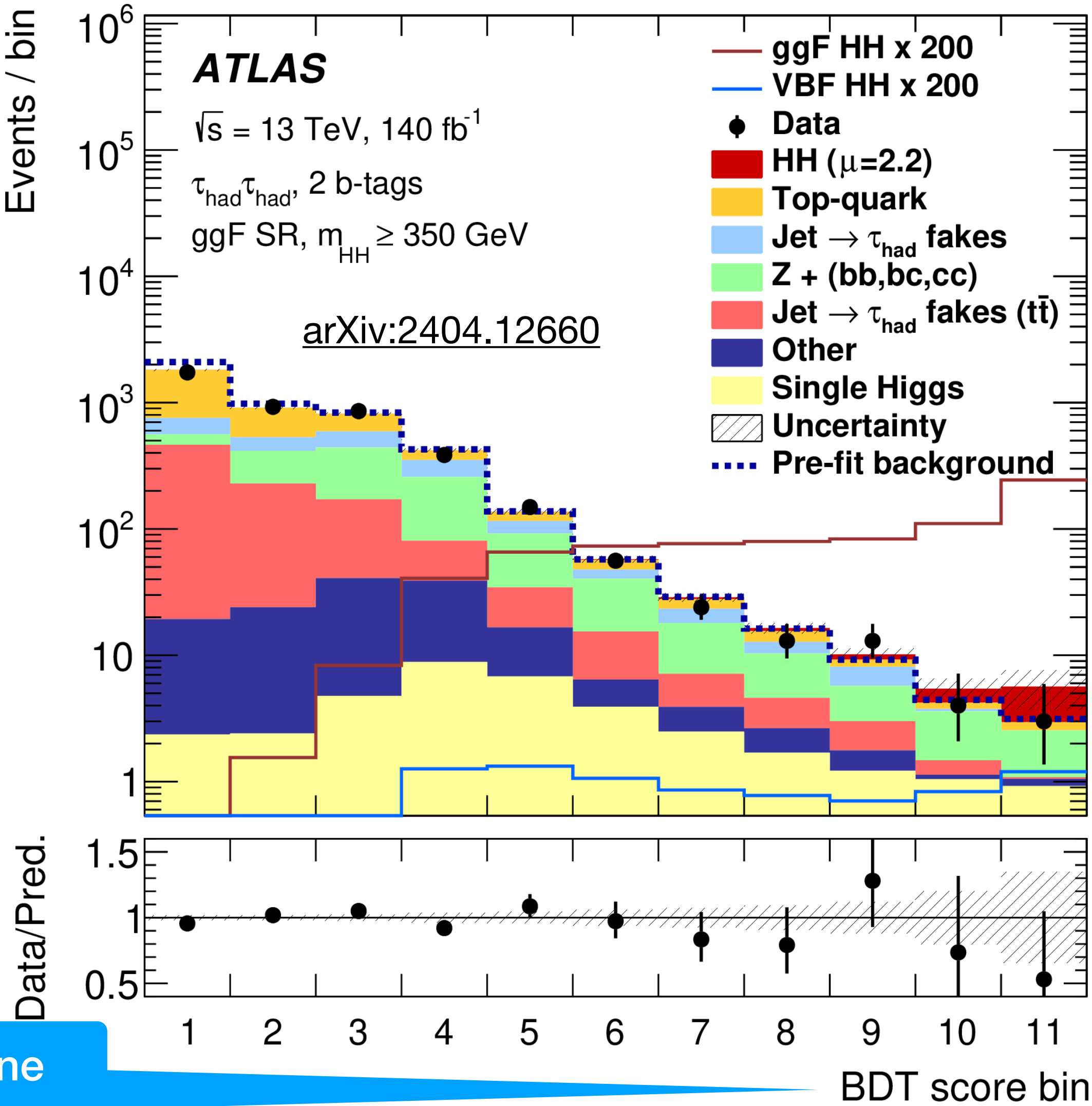
ATLAS

$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$



Top-quark
Jet $\rightarrow \tau_{\text{had}}$ fakes
Z + (bb, bc, cc)
Jet $\rightarrow \tau_{\text{had}}$ fakes ($t\bar{t}$)
Other
Single Higgs

[arXiv:2404.12660](#)

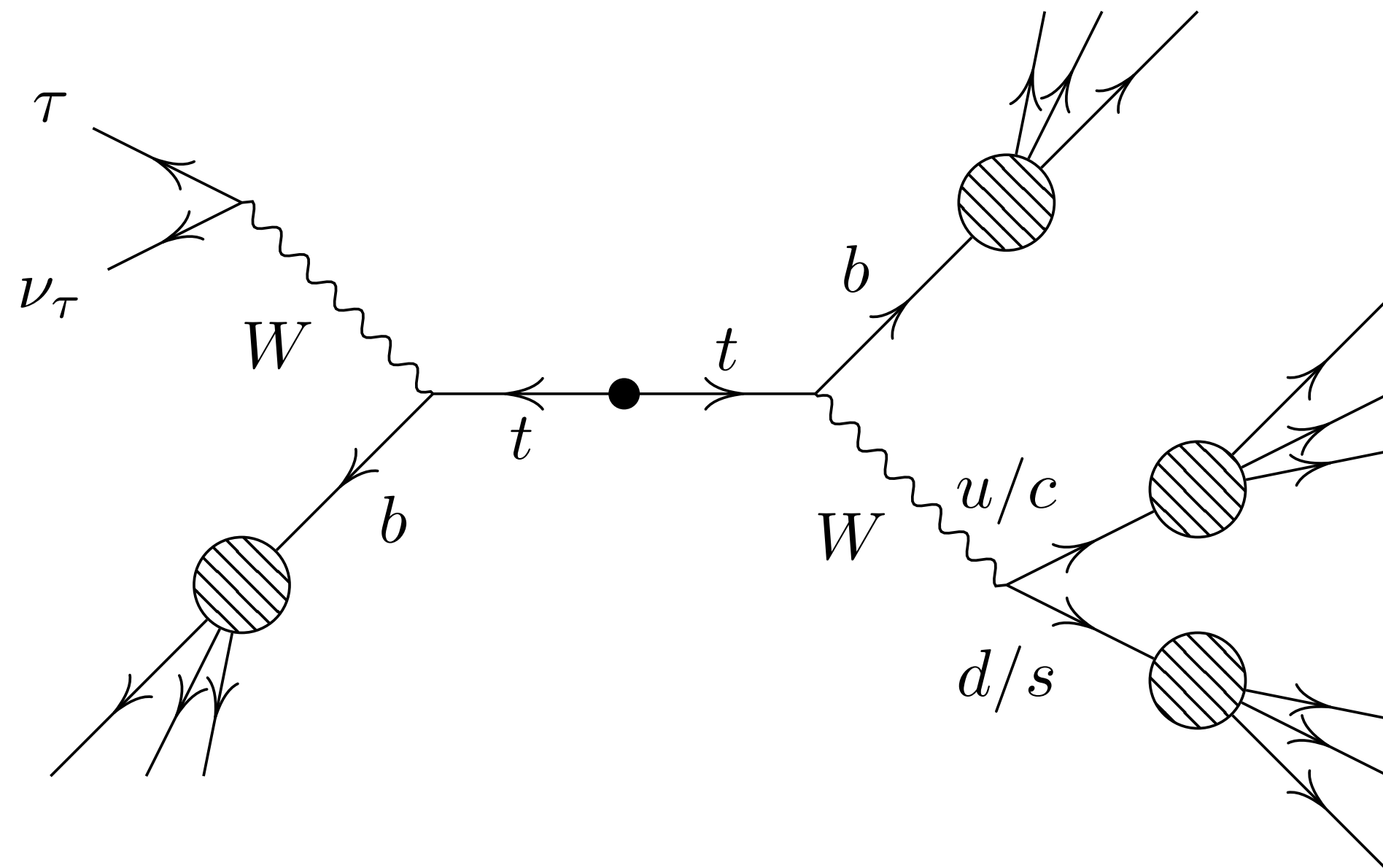


Boosted Decision Trees is a machine learning algorithm for classification.

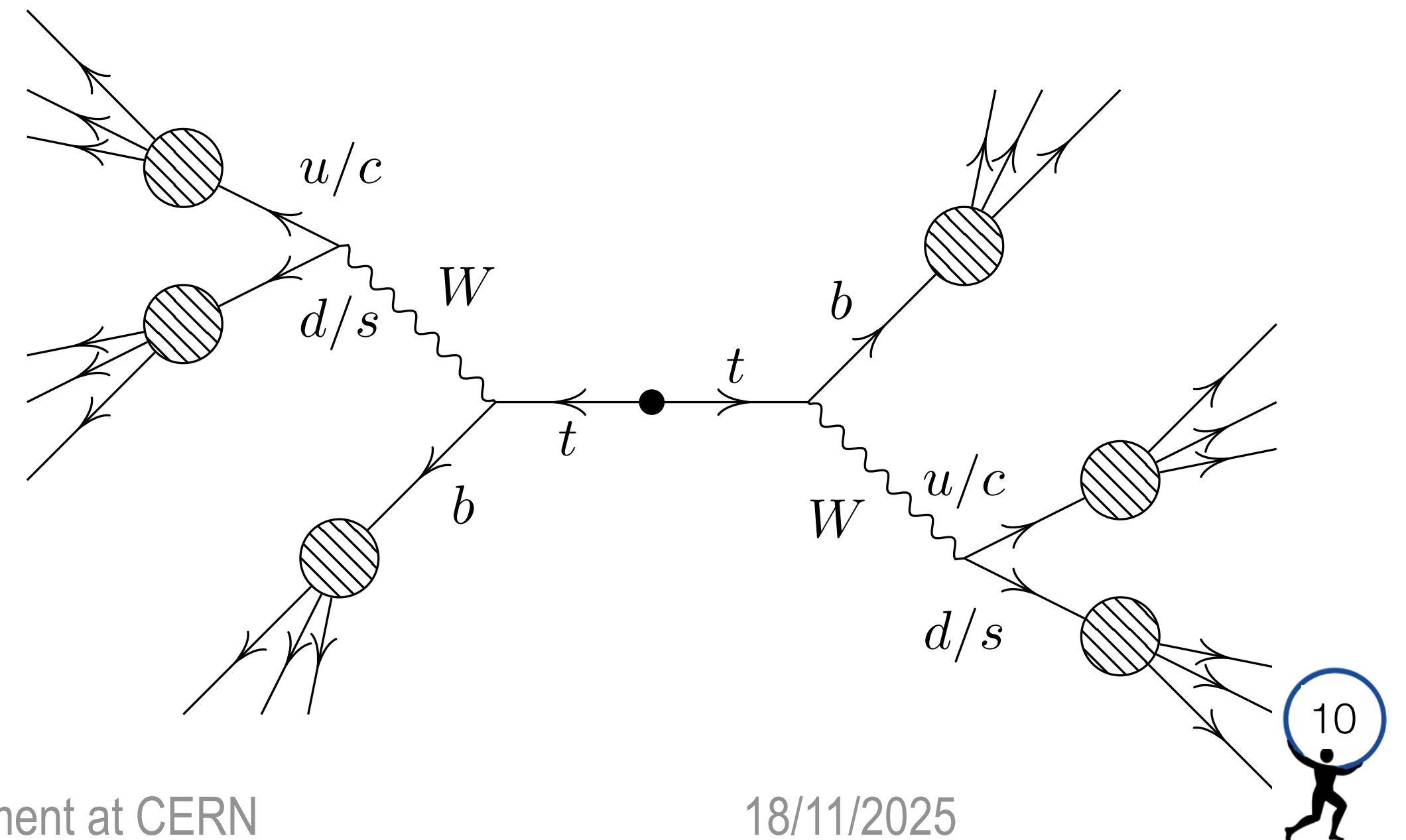
$t\bar{t}$ Fake $\tau_{\text{had-vis}}$ Background

- Top pair production ($t\bar{t}$) events in which at least one $\tau_{\text{had-vis}}$ candidate originates from a misidentified quark- or gluon-initiated.
- 85% of this background stems from semi-leptonic decay modes of $t\bar{t}$.
- 15% of this background stems from fully hadronically decay modes of $t\bar{t}$.

Semi-leptonic decay



Hadronic decay

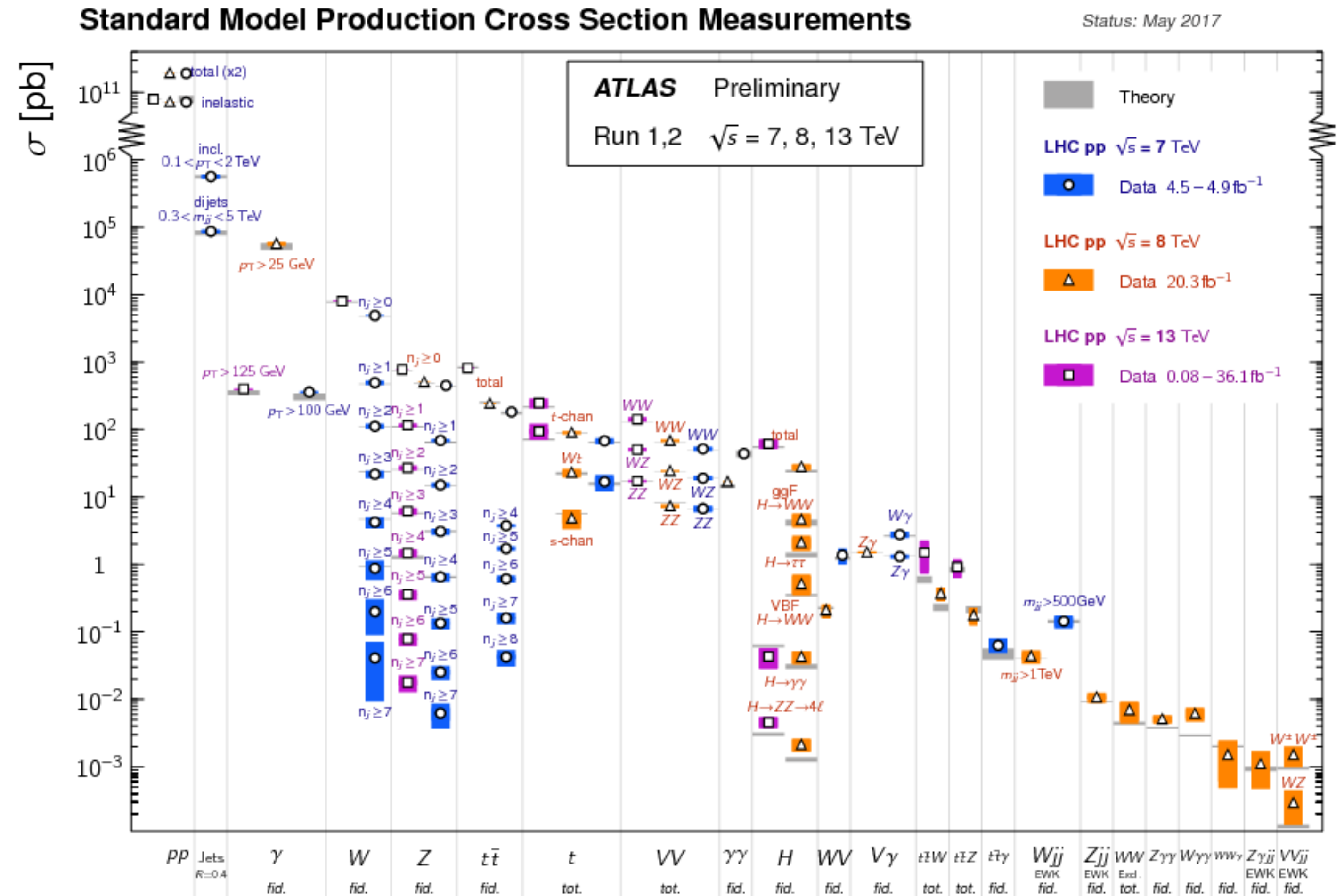


Estimation of the $t\bar{t}$ Fake $\tau_{\text{had-vis}}$ Background

- The $t\bar{t}$ fake- $\tau_{\text{had-vis}}$ background is estimated using Monte Carlo (MC) simulation.
- To correct any possible MC miss modelling for estimation of this background, we base our estimation on data.
- **Scale Factor method** is used to correct the estimated $t\bar{t}$ fake- $\tau_{\text{had-vis}}$ background.
 - We define a region which is mostly populated with the $t\bar{t}$ fake- $\tau_{\text{had-vis}}$ background events where we measure correction factors by correcting the estimation of this background based on data.
 - The correction/scale factors will be used to correct the MC estimation for this background.

Signal & Background Classification

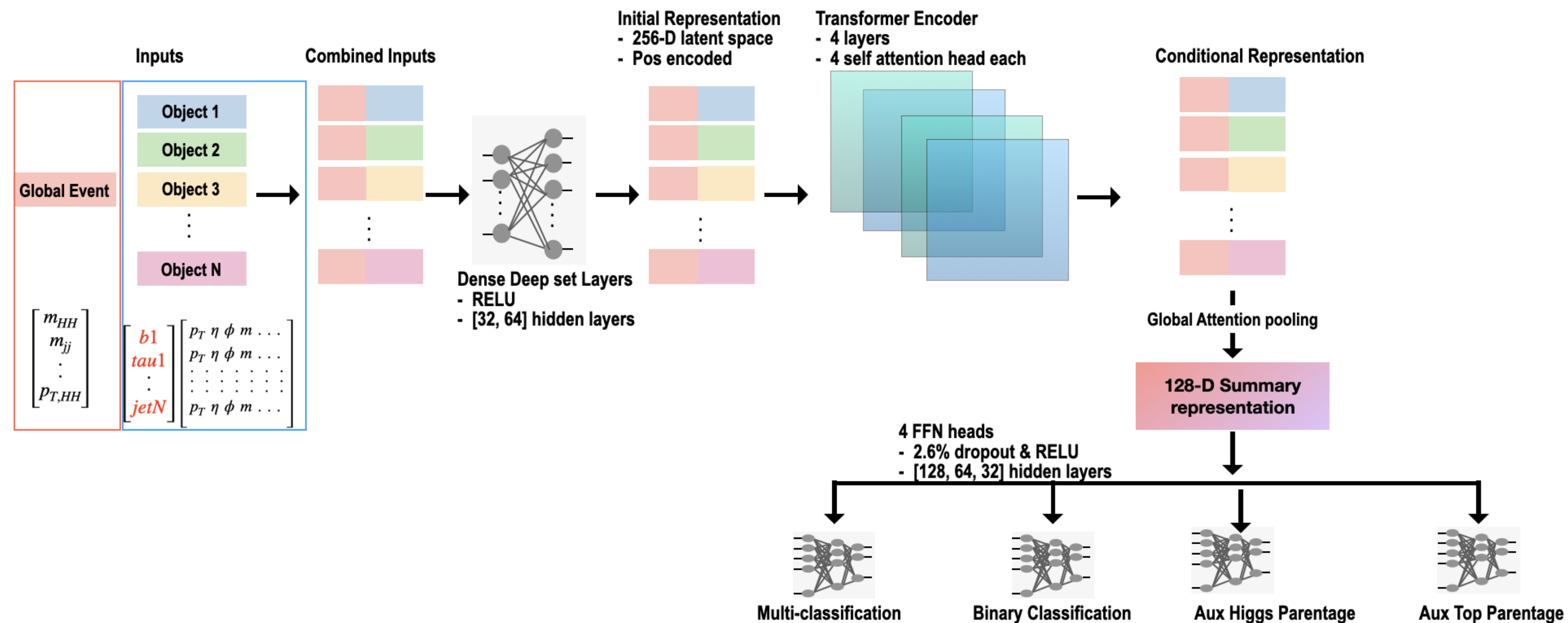
- Di-Higgs production has a very low cross-section; it's about three orders of magnitude smaller than the single Higgs production.
- In the analysis, the signal is very small compared to overwhelmingly larger background.
- We need sophisticated machine learning algorithms to separate backgrounds from signal.
 - In the previous analysis, **Boosted Decision Trees** were used.
 - We are exploiting a **Transformer** based machine learning architecture to perform classification.



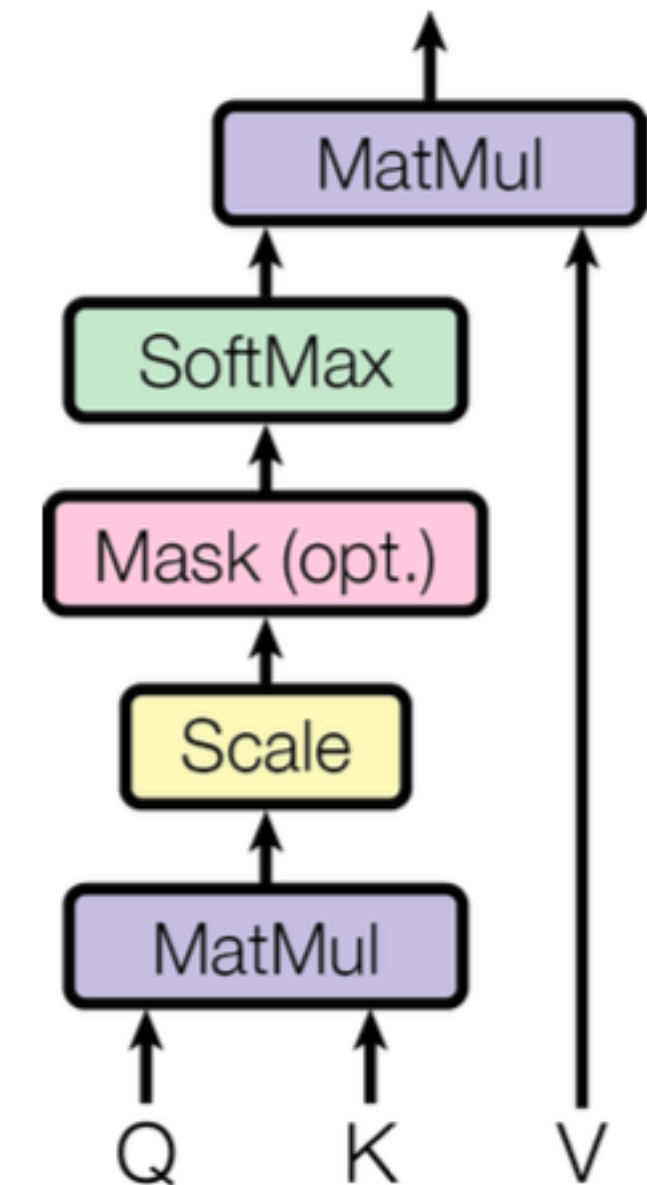
Taken from [here](#).



Transformer Based Classification



Scaled Dot-Product Attention



Taken from [here](#).

- My task is to optimise the hyper-parameters of the Transformer for the analysis.
- Transformers are the state-of-the-art architecture in modern machine learning.
- They are used in the Large Language Models (LLM), and **ChatGPT** is also based on Transformers.
- If you are interested in learning more about **Transformers**, I recommend watching the excellent videos by **3Blue1Brown** youtube channel.



Summary

- I hope I was able to convince you that searches for the Di-Higgs production are important for probing the shape of the Higgs potential.
- The $bb\tau\tau$ final state is the most sensitive channel for the observation of di-Higgs production.
- The scale factor approach is used to estimate one of the major backgrounds for the $HH \rightarrow bb\tau\tau$ analysis.
- We are exploring a Transformer based algorithm for signal & background classification in the $HH \rightarrow bb\tau\tau$ analysis.
- I am sorry that I am not allowed to show any of the current results related to the two tasks that I am responsible for in the analysis.