



# Search for rare processes and lepton-flavor-violating decays of Higgs boson at the ATLAS experiment

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On behalf of **ATLAS** collaboration



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University of Liverpool, UK, Sept. 1<sup>st</sup> -6<sup>th</sup>

# Higgs Rare Decays

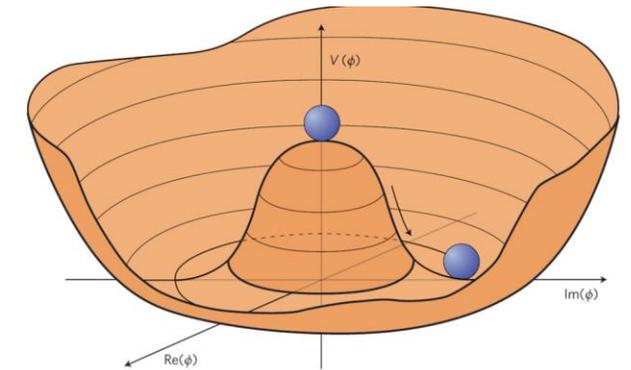
- Higgs boson plays a central role in the electroweak unification.
  - Mass for W, Z bosons via gauge symmetry
  - Mass for fermions via Yukawa coupling
- The main decay channels have been confirmed and no evidence for new physics.
  - Top, Bottom, Tau, W and Z bosons
- So we focus on **rare** decays of Higgs boson.
  - Higgs  $\rightarrow \mu\mu$ : rare due to small mass of muon
  - Higgs  $\rightarrow Z\gamma$  or  $l\gamma$ : rare due to loop diagrams
  - Higgs  $\rightarrow l\tau$ : forbidden in SM

❖ Precision tests of the SM

❖ Search for new physics Beyond SM.

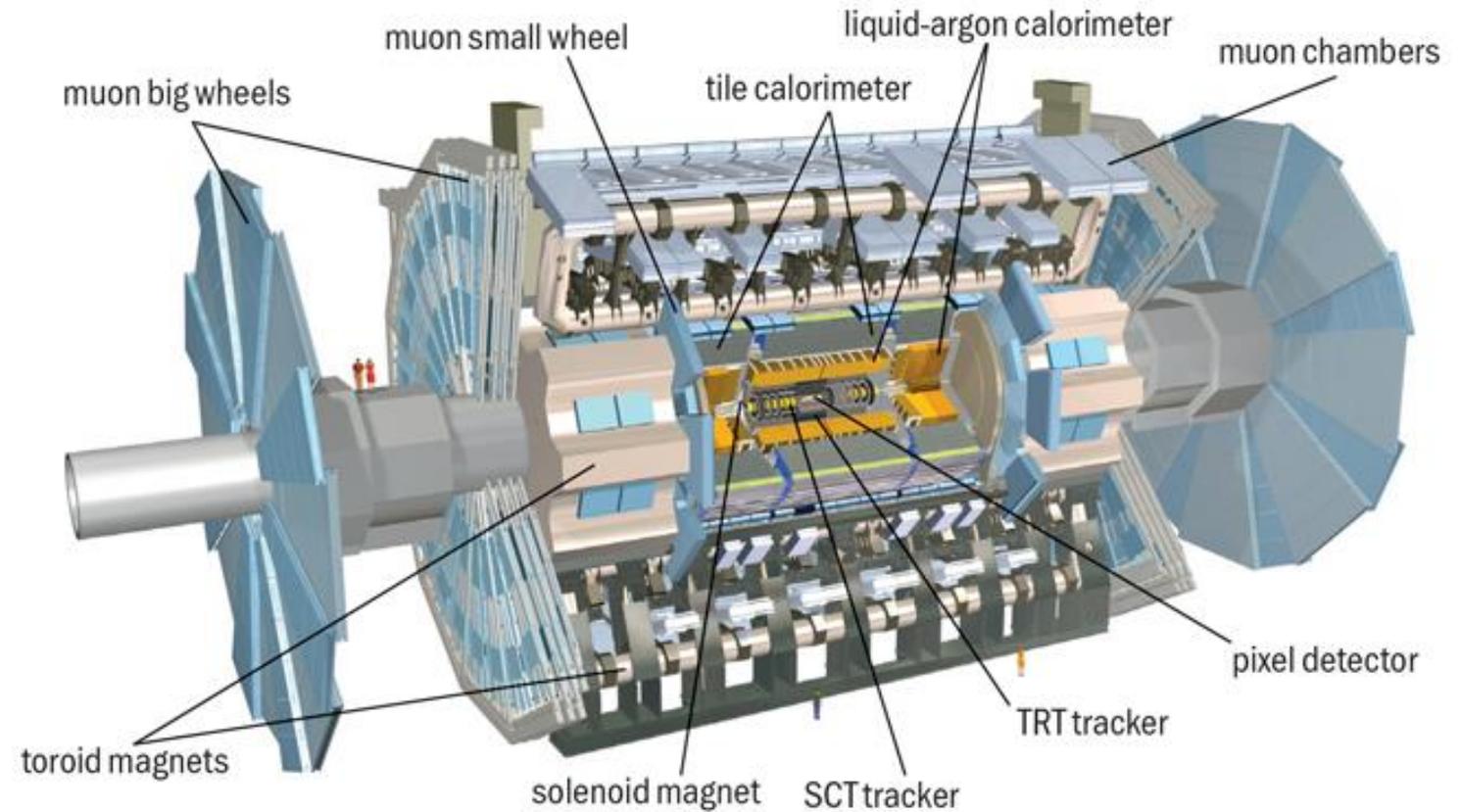
❖ Datasets:  $140 \text{ fb}^{-1}$  at 13TeV (Run2),  $165 \text{ fb}^{-1}$  at 13.6 TeV (Run3)

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$



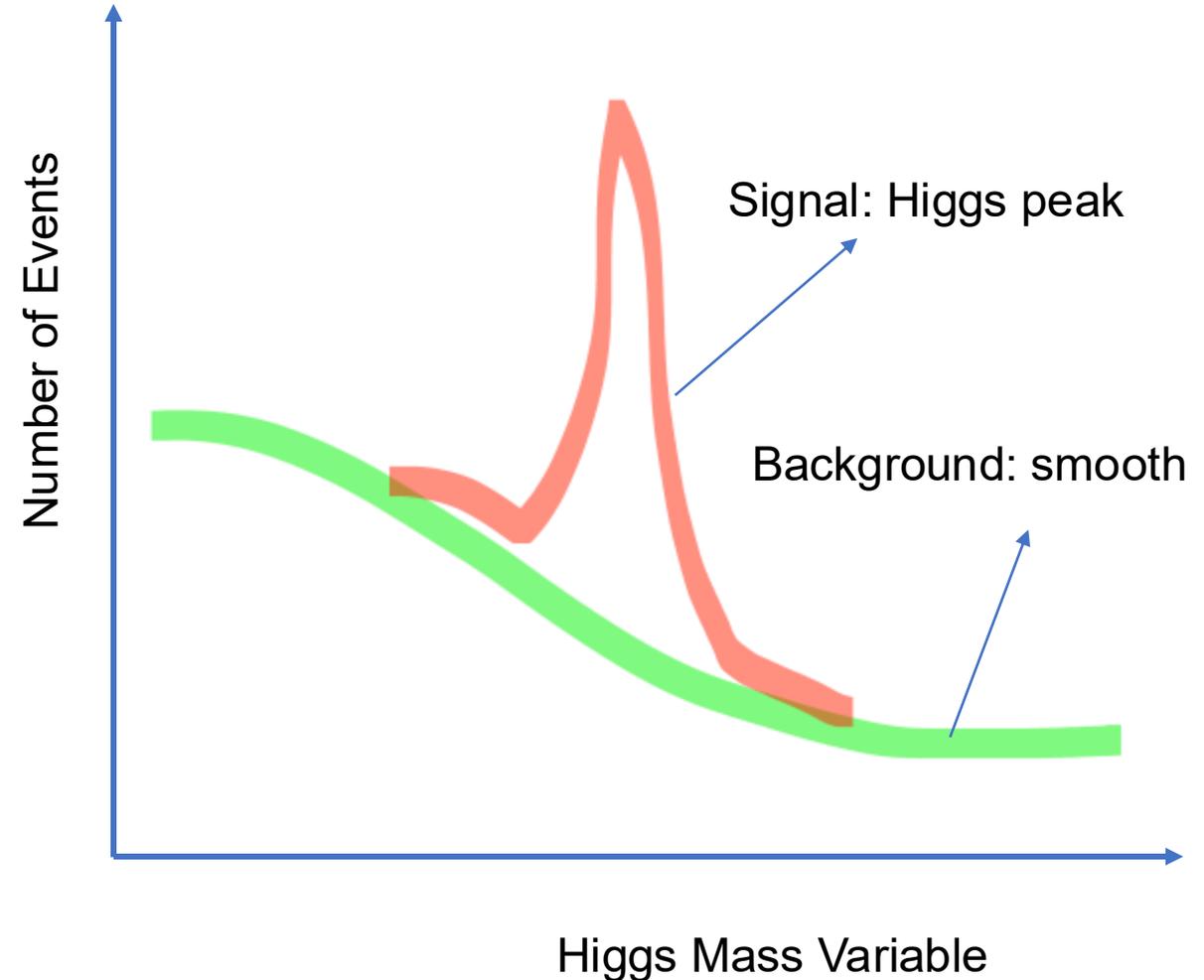
# ATLAS detector

- It is the largest general-purpose particle detector at LHC.
  - 46m long, 25m in diameter
- It has four major systems.
  - ❖ Inner Detector
    - Tracking/Momentum
  - ❖ Calorimeters
    - Jet/Photon
  - ❖ Muon Spectrometer
    - Muon
  - ❖ Magnet system
    - Solenoid magnets
    - Toroid magnets



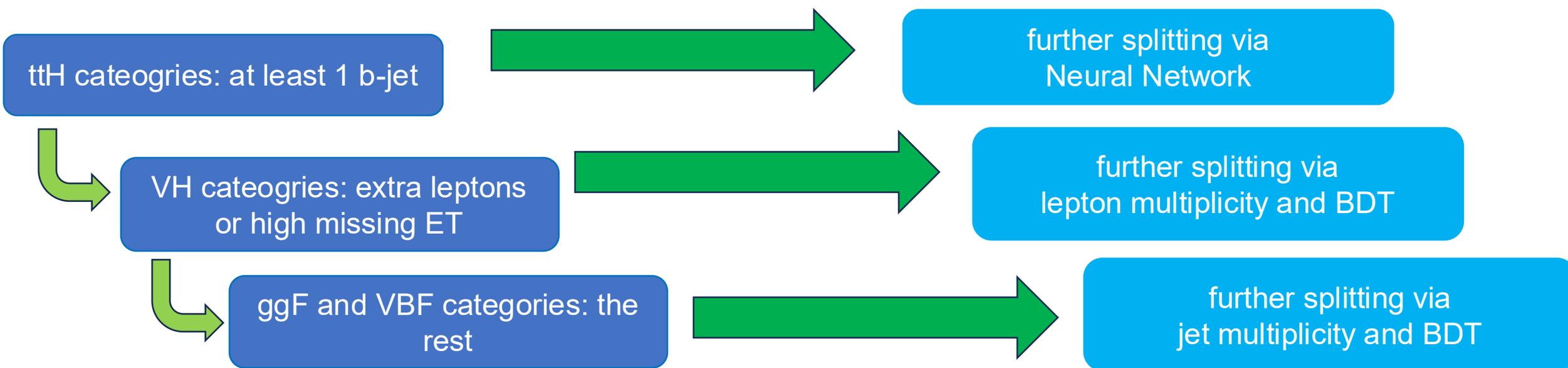
# Common Searching Strategy

- **Reconstruct the Higgs mass** from the final particles
- **Signal is a peak** around Higgs mass.
  - Modeled by analytic functions or MC simulation
- **Background is smooth.**
  - Modeled by analytic functions
    - Spurious signal test technique
  - Or MC simulation or Data-Driven



# Evidence for Higgs $\rightarrow \mu\mu$

- **Unique opportunity** to probe Higgs coupling to second-generation fermions
- SM predicts  $B(H \rightarrow \mu\mu) = 2.17 \cdot 10^{-4}$  due to the smallness of muon mass.
  - Enhancement in [conformal models with a dilaton](#) and [various flavour models](#).
- Datasets:  $140 \text{ fb}^{-1}$  at 13 TeV ([Run2](#)),  $165 \text{ fb}^{-1}$  at 13.6 TeV ([Run3](#))
- **Event selection**: at least a pair of opposite-charge muons
- **23 event categories** designed for different productions: ggF, VBF, VH and ttH

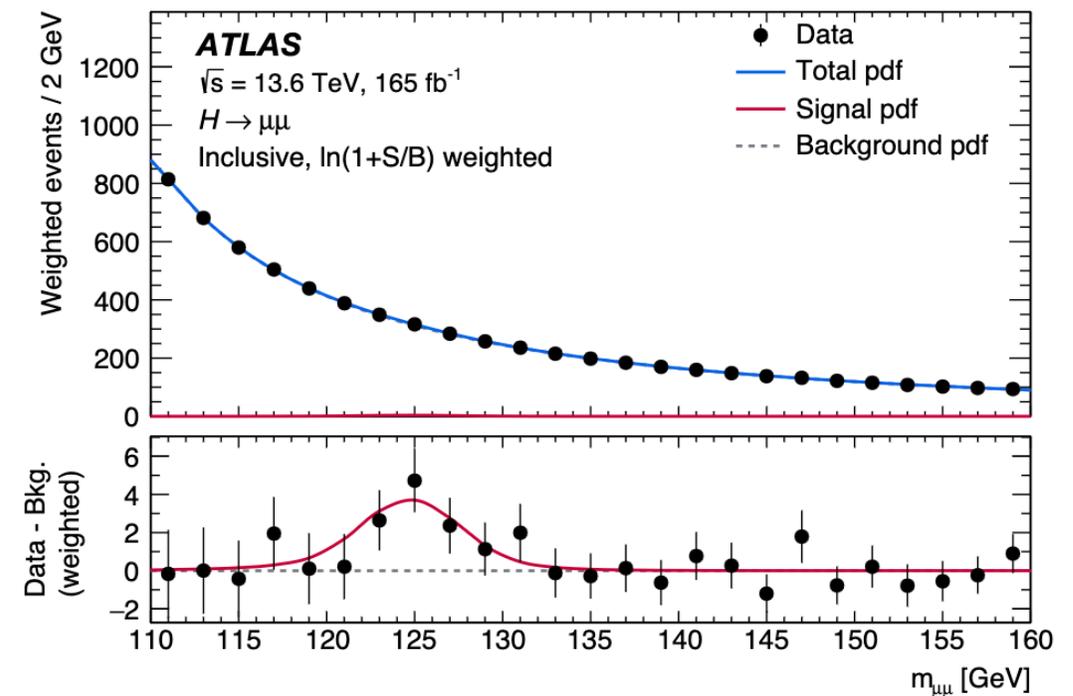
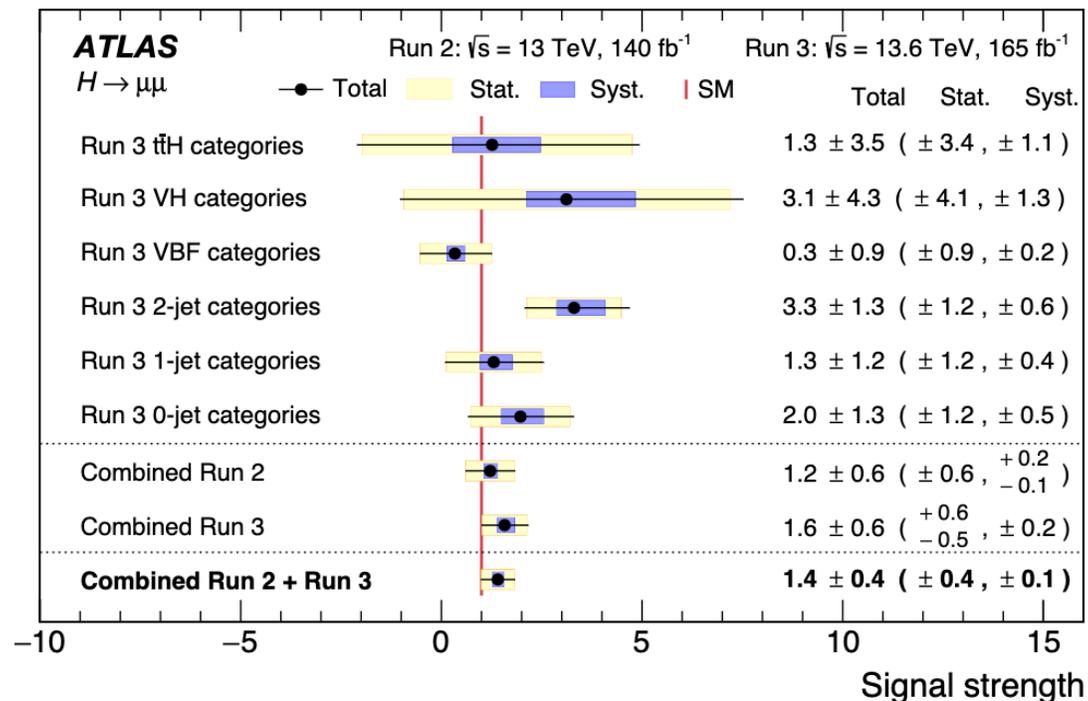


# Evidence for Higgs $\rightarrow \mu\mu$

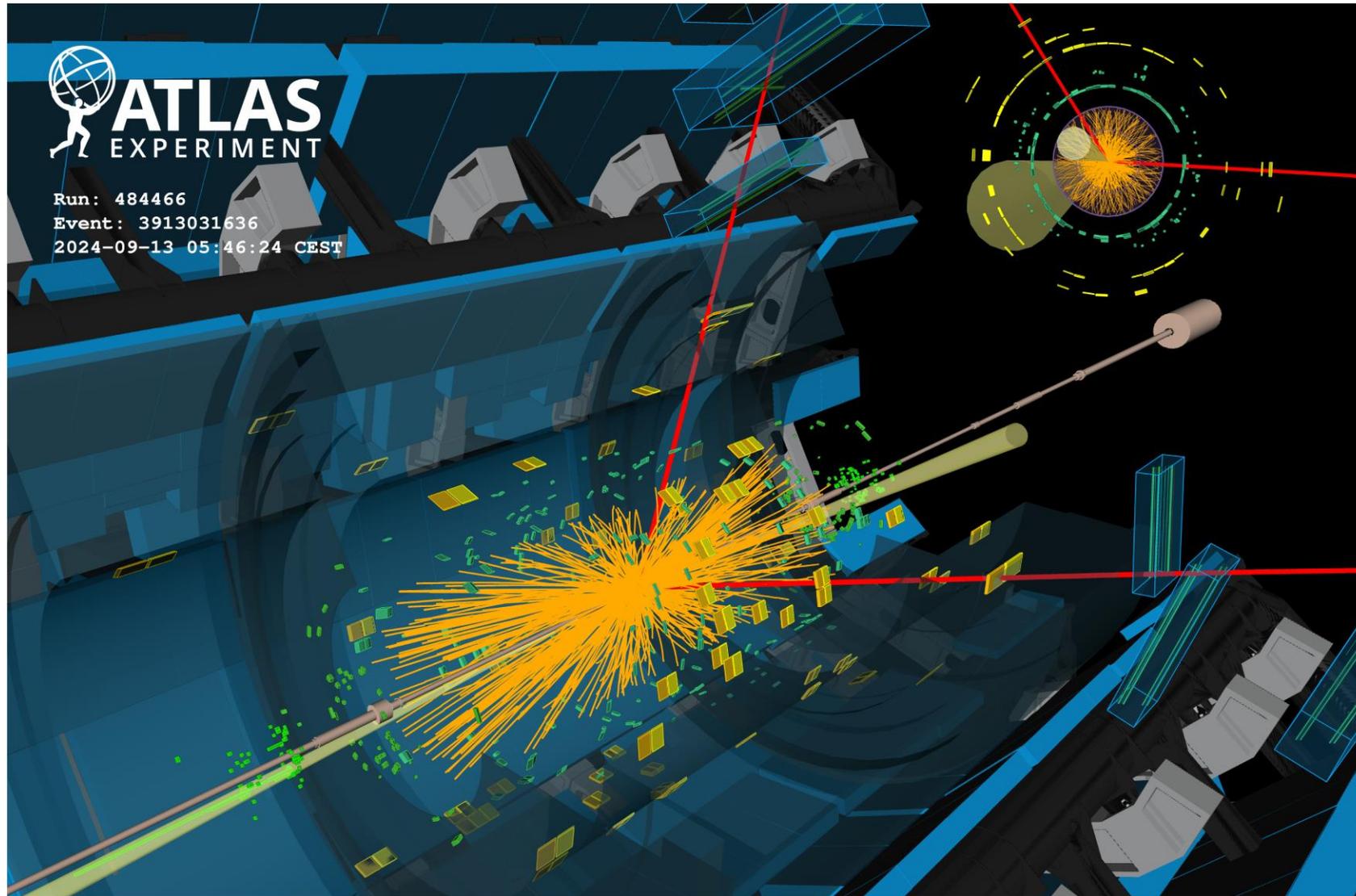
- **Unique opportunity** to probe Higgs coupling to second-generation fermions
- SM predicts  $B(H \rightarrow \mu\mu) = 2.17 \times 10^{-4}$  due to the smallness of muon mass.
- **Topology**: signal is a peak around Higgs mass while the background is smooth.
  - Both are modeled by analytic functions.
  - Background model selected through the Spurious Signal test
- **Dominant backgrounds**:
  - *Drell-Yan* process, *VV*, *top* background
- **Better signal sensitivity**:
  - Extensive Machine Learning techniques used: BDT(XGBoost, TMVA), NN (Keras and TensorFlow)
    - A penalty term to reduce the correlation between score and  $m(\mu\mu)$
  - Higgs vertex fit improves mass resolution by 2%
  - More produced modes: *ttH*(hadronic) and *VH*

# Evidence for Higgs $\rightarrow \mu\mu$

- **Unique opportunity** to probe Higgs coupling to second-generation fermions
- SM predicts  $B(H \rightarrow \mu\mu) = 2.17 \cdot 10^{-4}$  due to the smallness of muon mass.
- Run2:  $\mu = 1.2 \pm 0.6$ , Run3:  $1.6 \pm 0.6$ , Combination:  $1.4 \pm 0.4$  ( $3.4 \sigma$ )
- The search is still **dominated by statistical uncertainty** while syst. unc. is 25% of total.

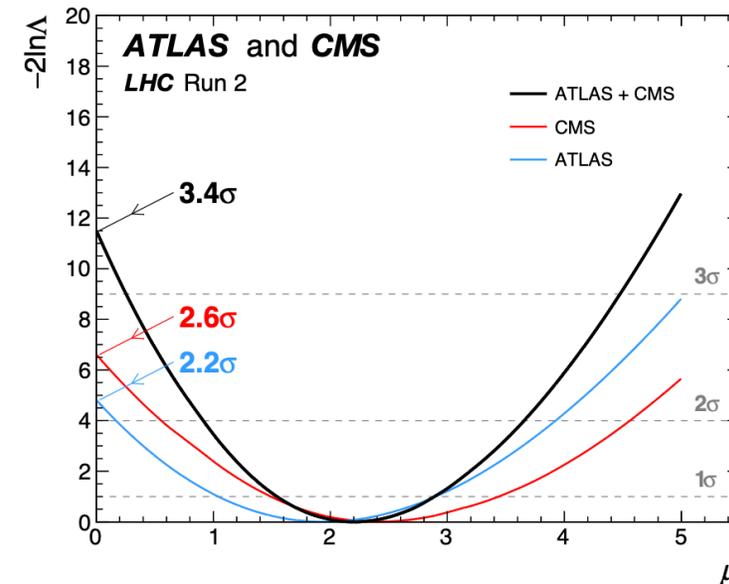
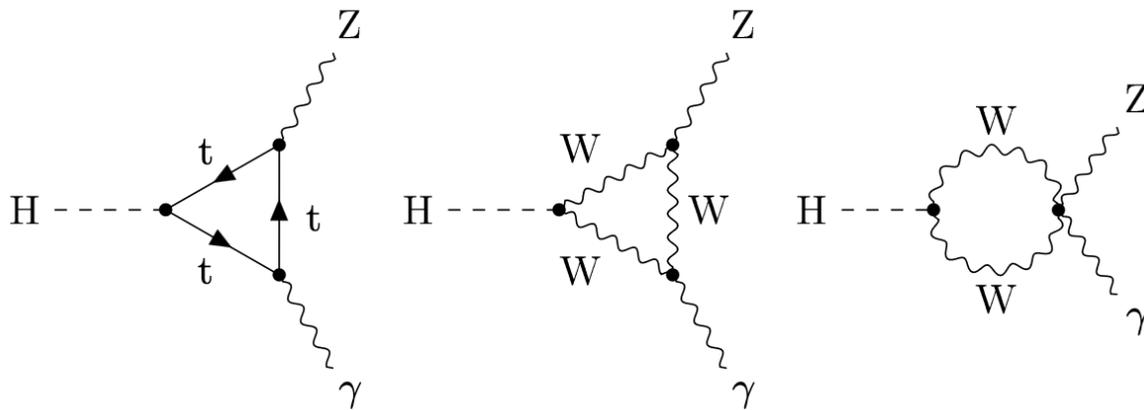


# Event display



# Search for $H \rightarrow Z\gamma$

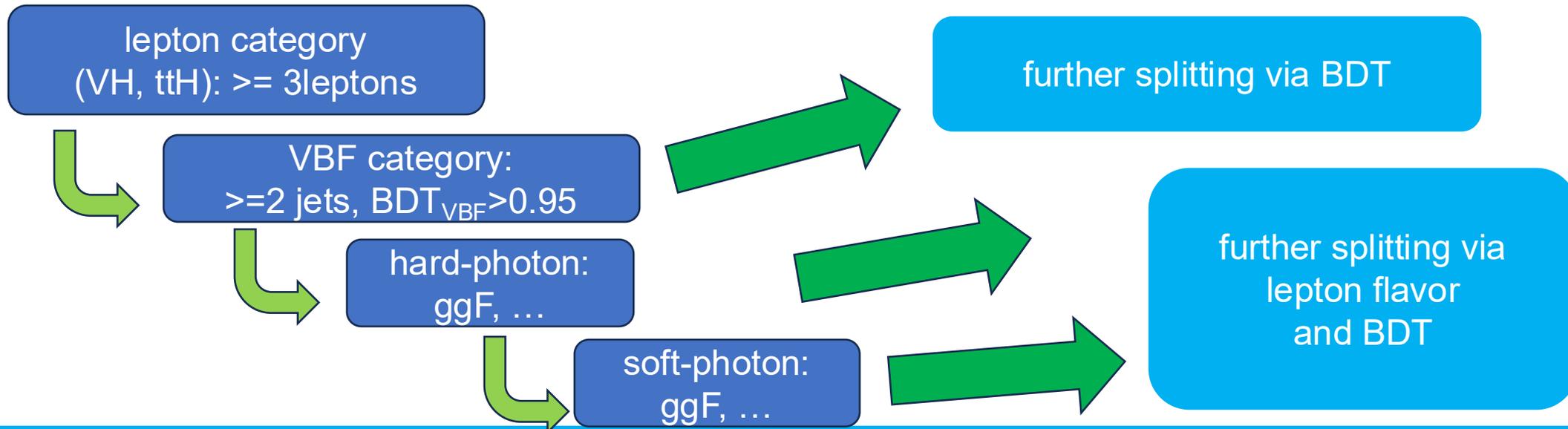
- The decay is driven by **loop-level diagrams**.
- SM predicts the branching fraction of  $B(H \rightarrow Z\gamma) = 1.54 \cdot 10^{-3}$ , similar to  $H \rightarrow \gamma\gamma$ .
- Beyond-SM models are sensitive to this measurement.
  - [Composite Higgs](#), [Higgs as a pseudo NG boson](#), [additional EW singlet scalar](#)
- [Run2 ATLAS+CMS](#) observes an excess,  $\mu = 2.2 \pm 0.7$  of  $3.4\sigma$  significance.
- Datasets:  $140 \text{ fb}^{-1}$  at 13TeV ([Run2](#)),  $165 \text{ fb}^{-1}$  at 13.6 TeV ([Run3](#))



[Phys. Rev. Lett.](#)  
[132\(2024\)021803](#)

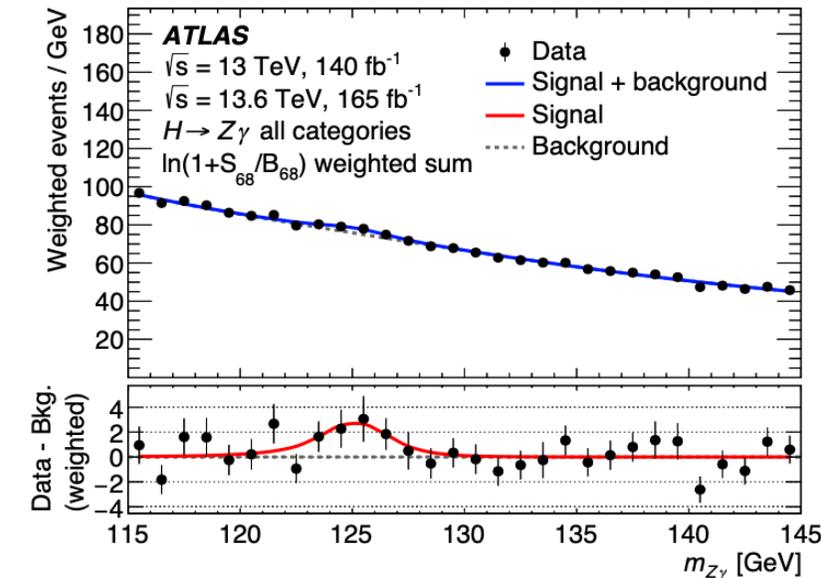
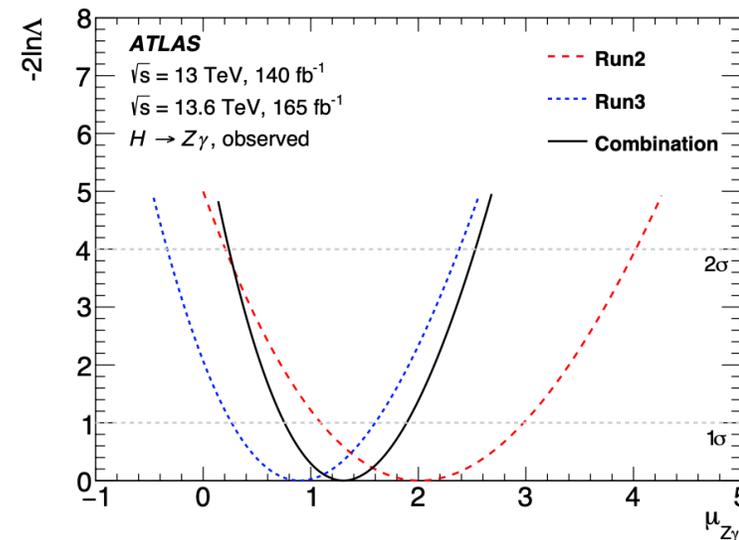
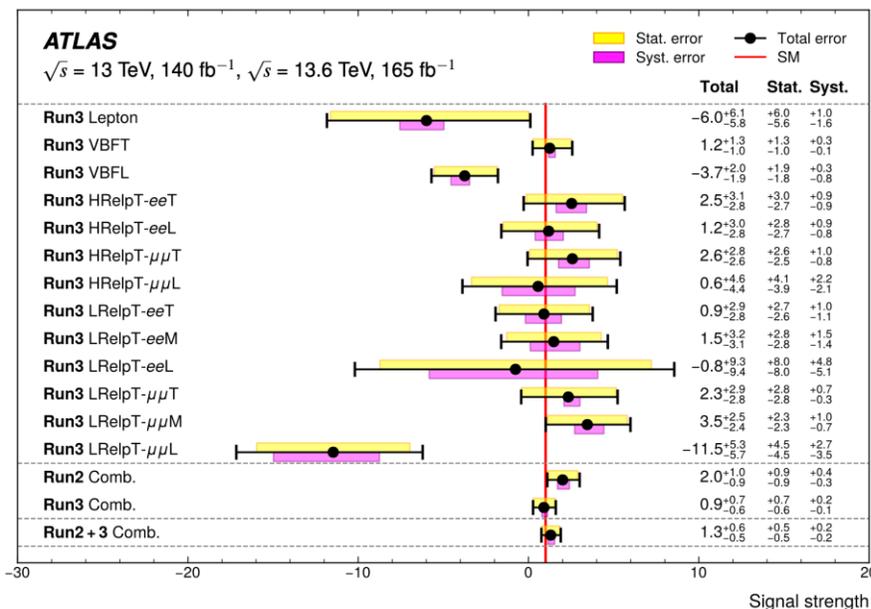
# Search for $H \rightarrow Z\gamma$

- **Event selection:** at least a pair of opposite-charge leptons ( $ee/\mu\mu$ ) + a photon
- **Dominant backgrounds:**
  - non-resonant lepton pair+a photon
  - Z+jets with a jet misidentified as a photon
  - Diboson (W,Z) background
- **13 exclusive categories** are design to maximize the sensitivity.
  - targeting different Higgs productions: VH/ttH, VBF, ggF

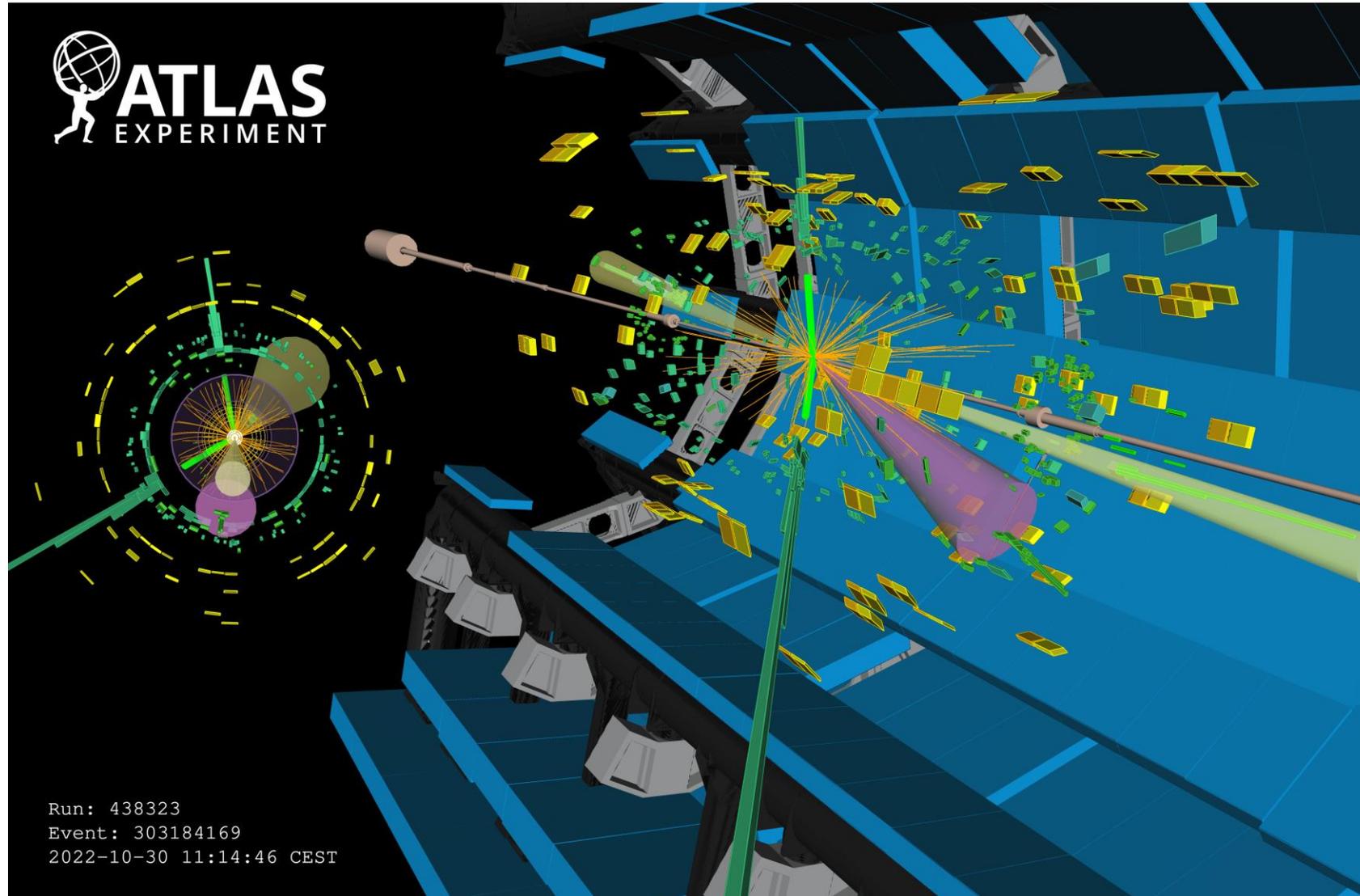


# Search for $H \rightarrow Z\gamma$

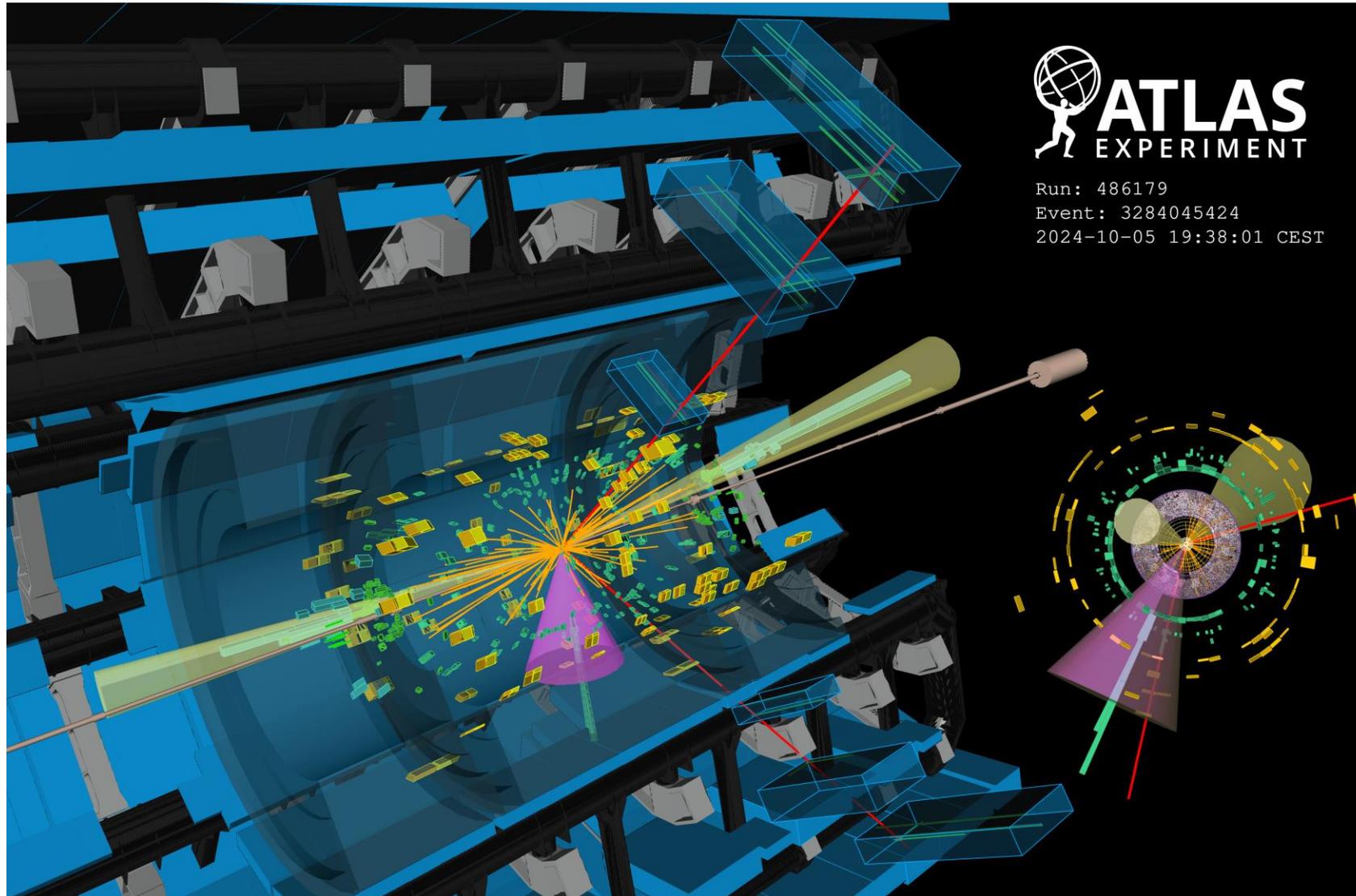
- The decay is driven by **loop-level diagrams**.
- SM predicts the branching fraction of  $B(H \rightarrow Z\gamma) = 1.54 \cdot 10^{-3}$ , similar to  $H \rightarrow \gamma\gamma$ .
- Run2:  $\mu = 2.0^{+1.0}_{-0.9}$ , Run3:  $0.9^{+0.7}_{-0.6}$ , Run2+Run3:  $1.3^{+0.6}_{-0.5}$
- Now it is consistent with SM.
- It is still **statistically dominated** with systematic uncertainty being 20% of total.



# Event display for $H \rightarrow Z\gamma$ in ee mode

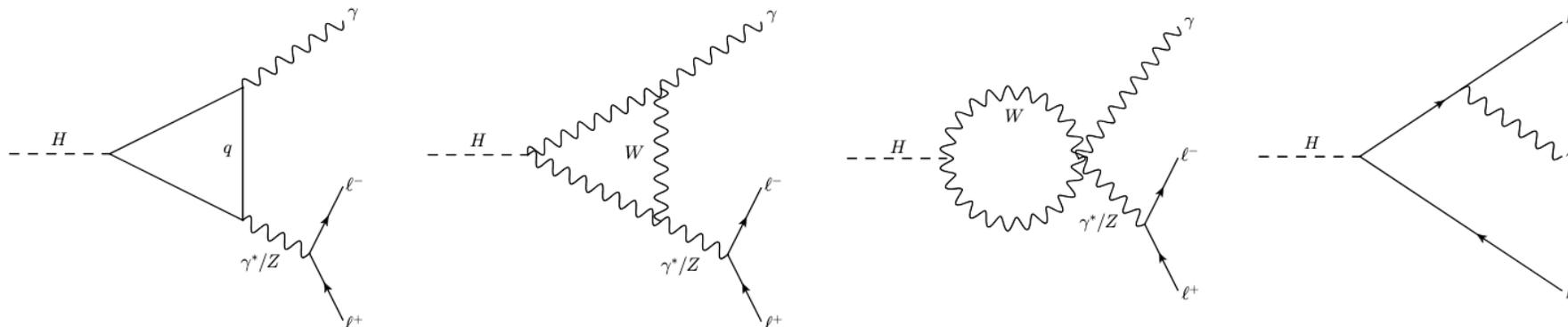


# Event display for $H \rightarrow Z\gamma$ in $\mu\mu$ mode



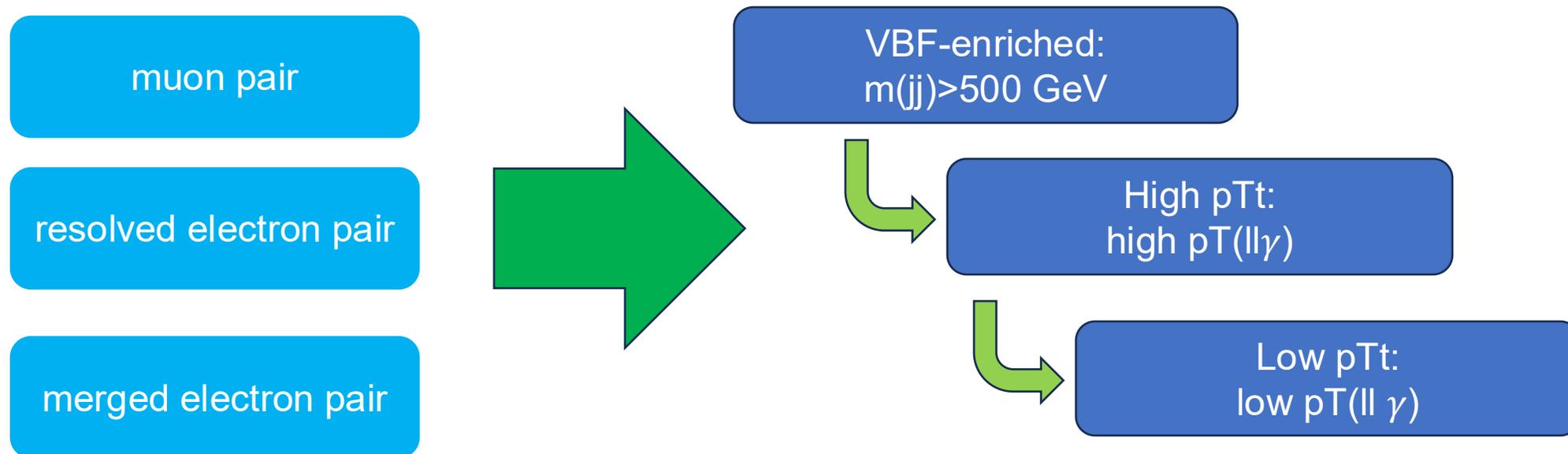
# Search for $H \rightarrow \text{low-mass } \ell\ell + \text{a photon}$

- This search focuses on a **low-mass dilepton system** with  $m(\ell\ell) < 30 \text{ GeV}$ .
  - coupling modification from [SM extensions](#)
  - probe CP-violation in the Higgs sector
- It is completely dominated by the process with a **off-shell photon**.
  - $H \rightarrow \gamma \gamma^*$  with a  $\gamma^* \rightarrow \ell\ell$  (Higgs Dalitz decay)
  - Other processes and interference are negligible
- SM predicts  $B(H \rightarrow ee\gamma) = 7.20 \cdot 10^{-5}$ ,  $B(H \rightarrow \mu\mu\gamma) = 3.42 \cdot 10^{-5}$ .
- Dataset:  $139 \text{ fb}^{-1}$  ([Run2](#))



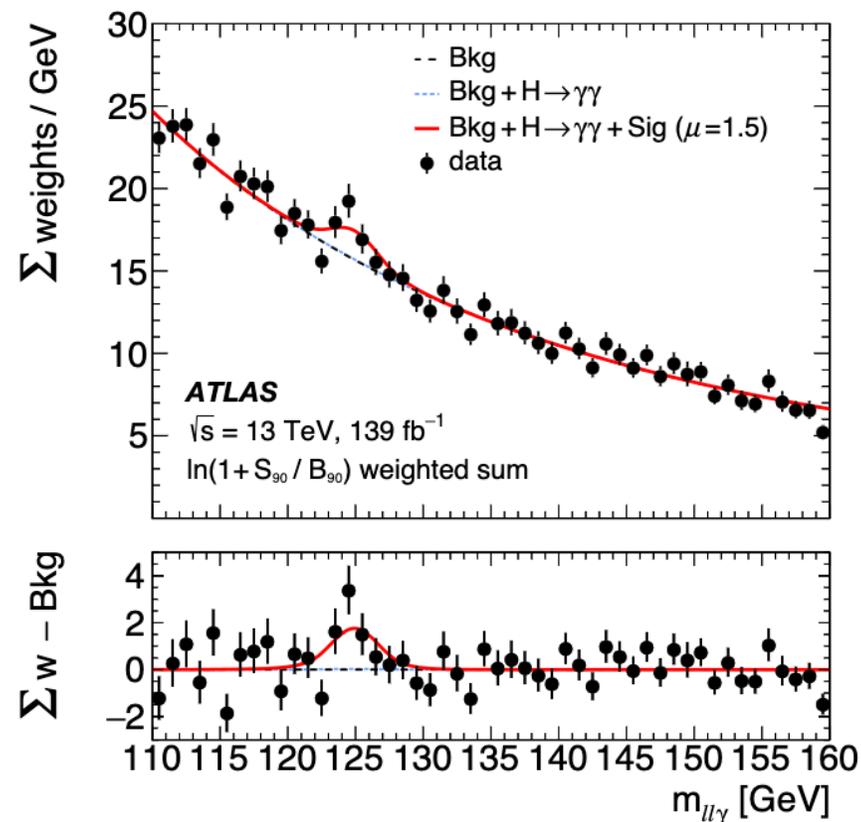
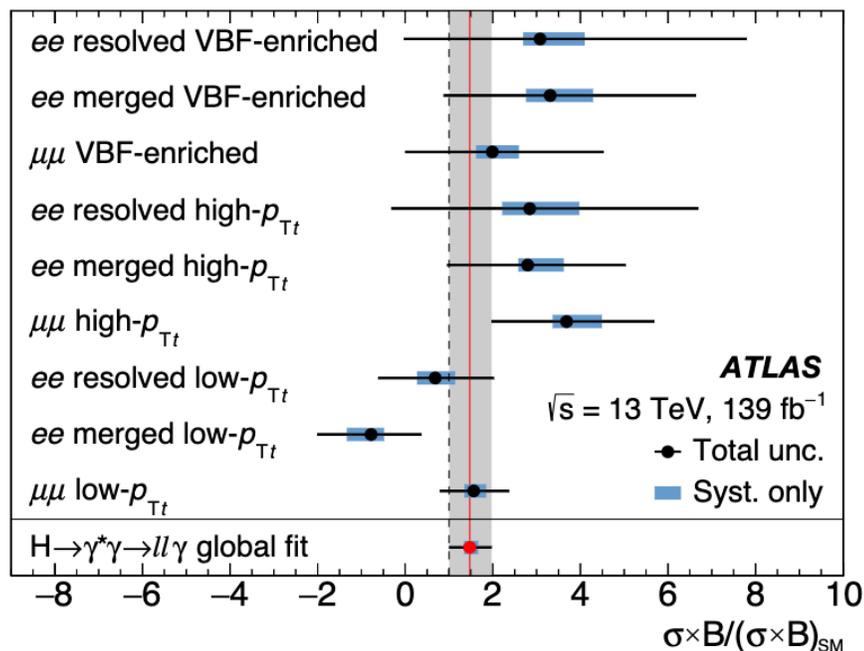
# Search for $H \rightarrow \text{low-mass } \ell\ell + \text{a photon}$

- Event selection:
  - at least one opposite-charge, same-flavour pair leptons
  - Or a *merged-ee* object
    - energy deposit of two electrons reconstructed as a single cluster due to boosted low-mass  $\ell\ell$  system.
  - lepton-pair mass  $< 30$  GeV with vetoing events in the  $J/\psi$  and  $\Upsilon(nS)$  mass windows
- **9 exclusive signal regions** defined depending on lepton type and event topology.



# Search for $H \rightarrow \text{low-mass } ll + \text{a photon}$

- This search focuses on a **low-mass dilepton system** with  $m(ll) < 30 \text{ GeV}$ .
- It is completely dominated by the process with a **off-shell photon**.
- The measurement gives  $\mu = 1.5 \pm 0.5$  consistent with the SM.
  - 3.2  $\sigma$  significance, first evidence for Dalitz decay  $H \rightarrow ll + \gamma$
  - Statistically dominated with syst. unc. 35% of stat. unc.



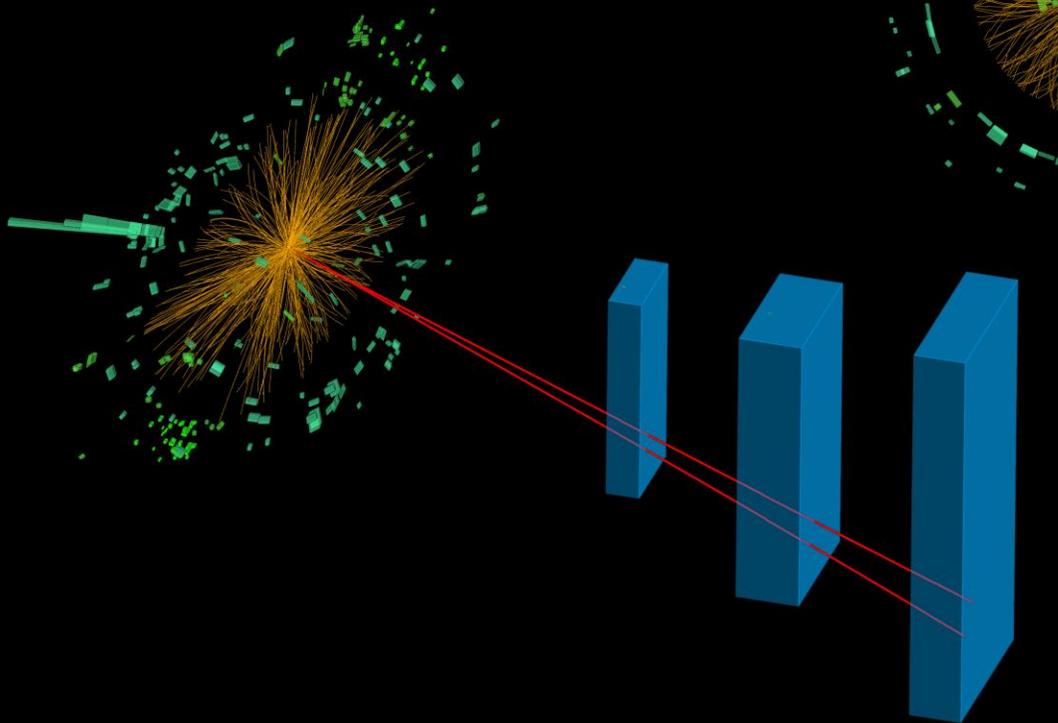
# Event display

$H \rightarrow e\bar{e}\gamma$

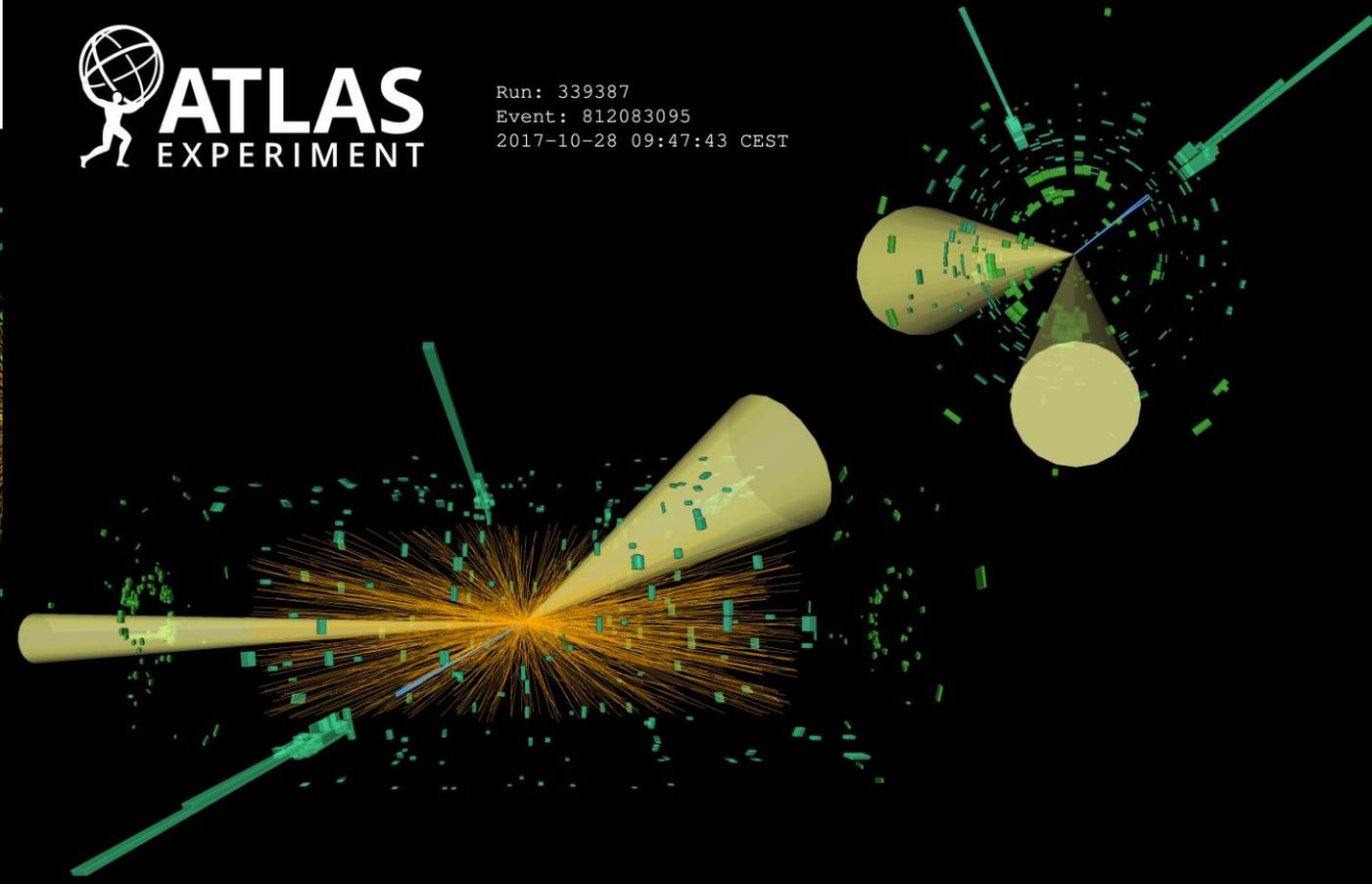
$H \rightarrow \mu\mu\gamma$



Run: 331951  
Event: 334662243  
2017-08-08 19:24:59 CEST



Run: 339387  
Event: 812083095  
2017-10-28 09:47:43 CEST



- The lepton-flavor violating Higgs decays are **forbidden in SM**.
- But they may arise from many Beyond-SM models.

- [more than one Higgs doublet](#)
- [composite Higgs models](#)
- [warped extra dimensions](#)

- Dataset:  $138 \text{ fb}^{-1}$  (Run 2)

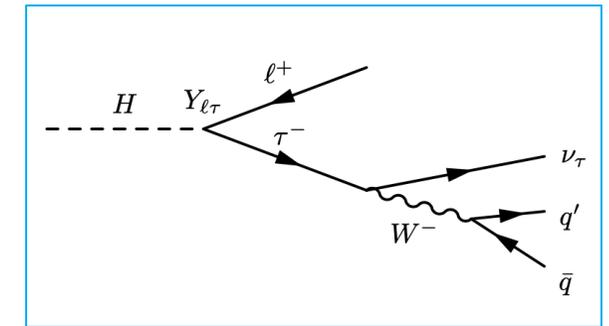
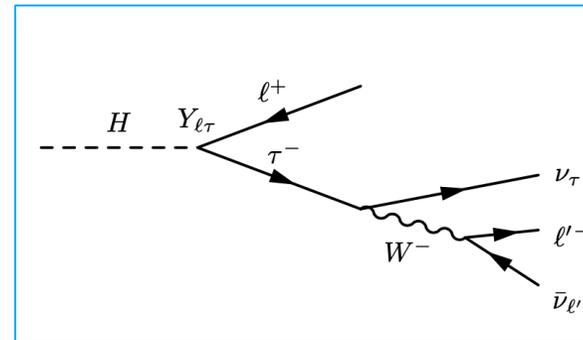
- Signal channels:  $e/\mu + \tau$

- [leptonically](#) or [hadronically](#) decaying [tau](#)

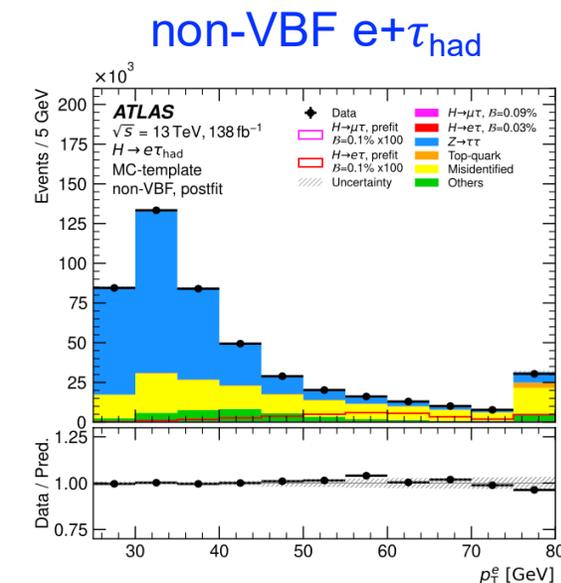
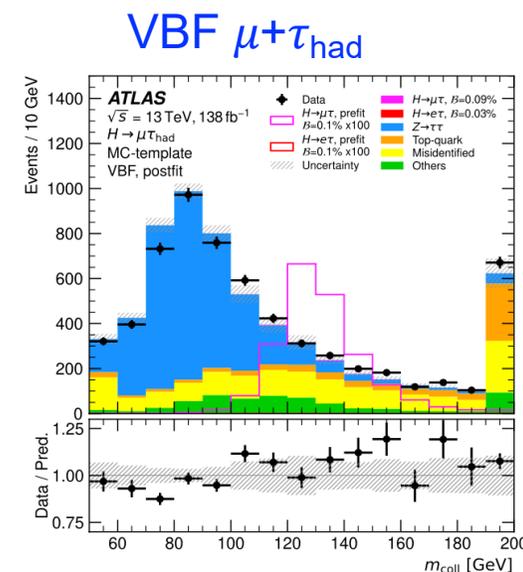
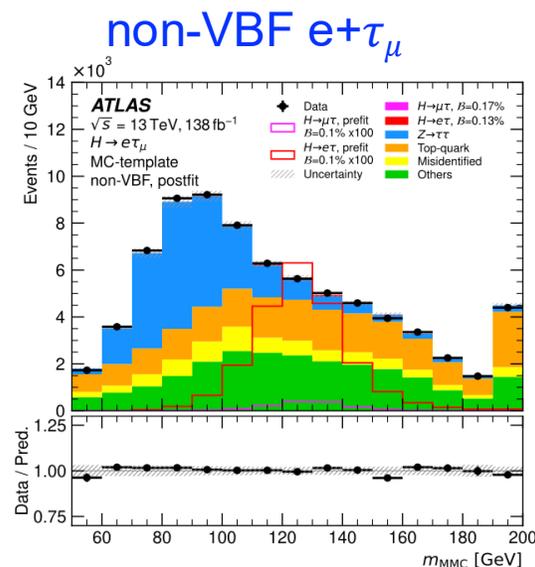
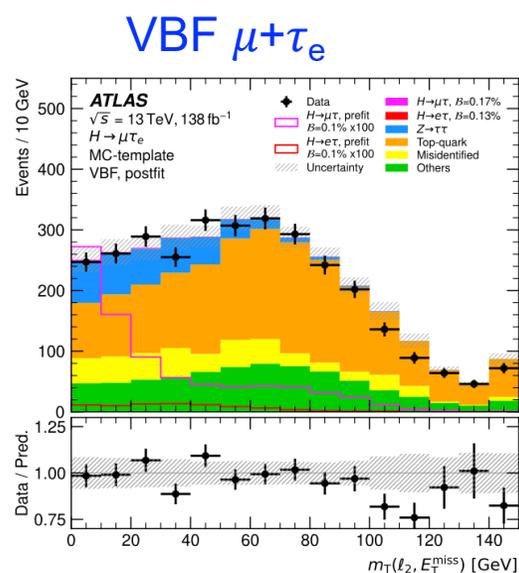
- exclude the same flavor signal for leptonically decaying tau due to huge Drell-Yan background

- Three statistical analyses performed.

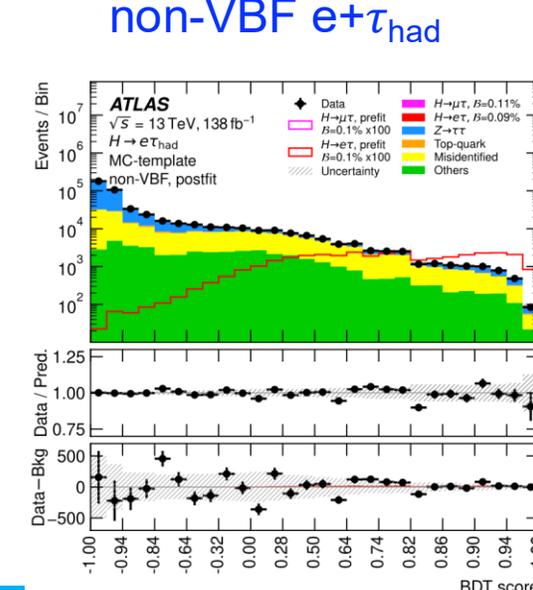
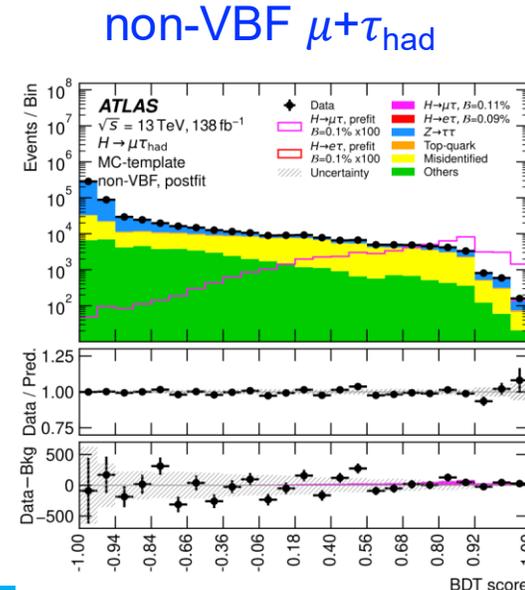
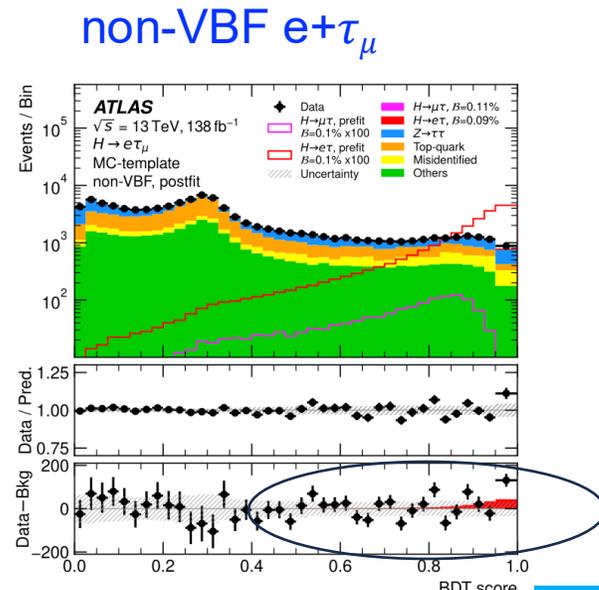
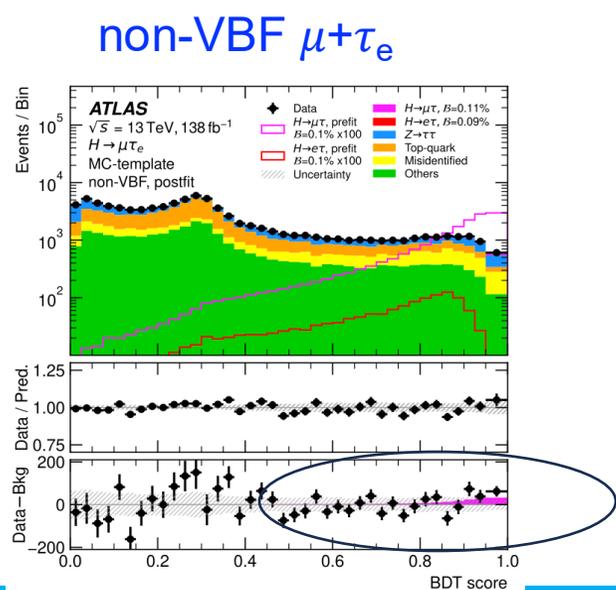
- independent search for  $H \rightarrow e + \tau$  assuming the other branching fraction is 0
- independent search for  $H \rightarrow \mu + \tau$  assuming the other branching fraction is 0
- simultaneous search for  $H \rightarrow e/\mu + \tau$



- Event selection
  - Baseline: a pair of opposite-charge, different-flavour lepton pair
  - Further split into **VBF** ( $m(jj) > 300 \text{ GeV}$ ,  $|\Delta\eta(jj)| > 3$ ) and **non-VBF** categories
  - **8 signal regions** in total to maximize the signal sensitivity
- Huge efforts to estimate various backgrounds
  - $Z \rightarrow \tau\tau$ , Top-quark processes, Diboson events for leptonically-decaying tau categories
  - $Z \rightarrow \tau\tau$  and fake tau backgrounds for hadronically-decaying tau categories



- Huge efforts to estimate various backgrounds
  - $Z \rightarrow \tau\tau$ , Top-quark processes, Diboson events for leptonically-decaying tau categories
  - $Z \rightarrow \tau\tau$  and fake tau backgrounds for hadronically-decaying tau categories
- **Multivariate Analysis strategy:**
  - Techniques: BDT, deep NN
  - Different techniques are used for non-VBF and VBF categories and choose the best one
  - Depending on the backgrounds, multiple ML classifiers are combined into a single score.

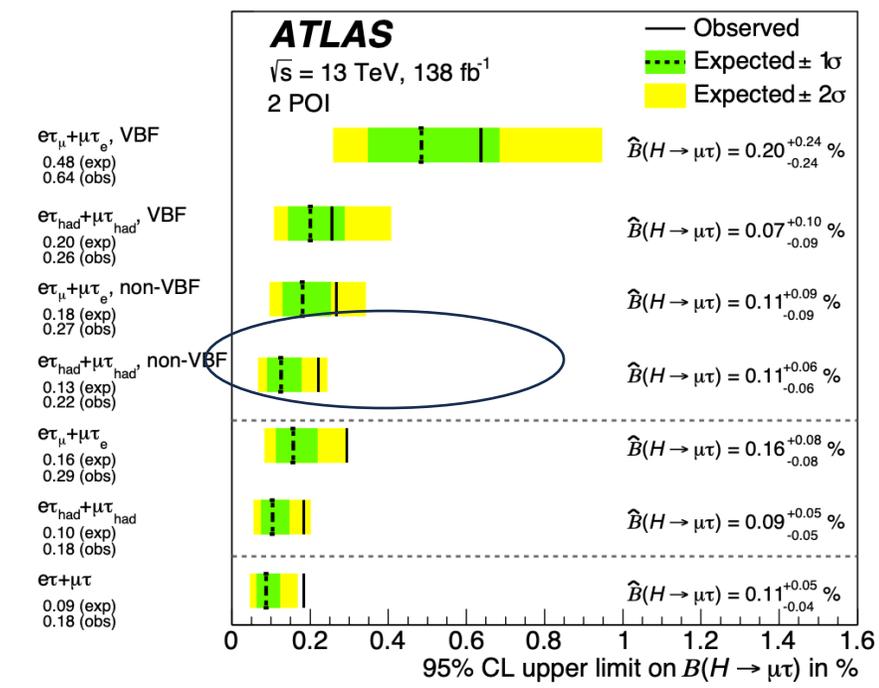
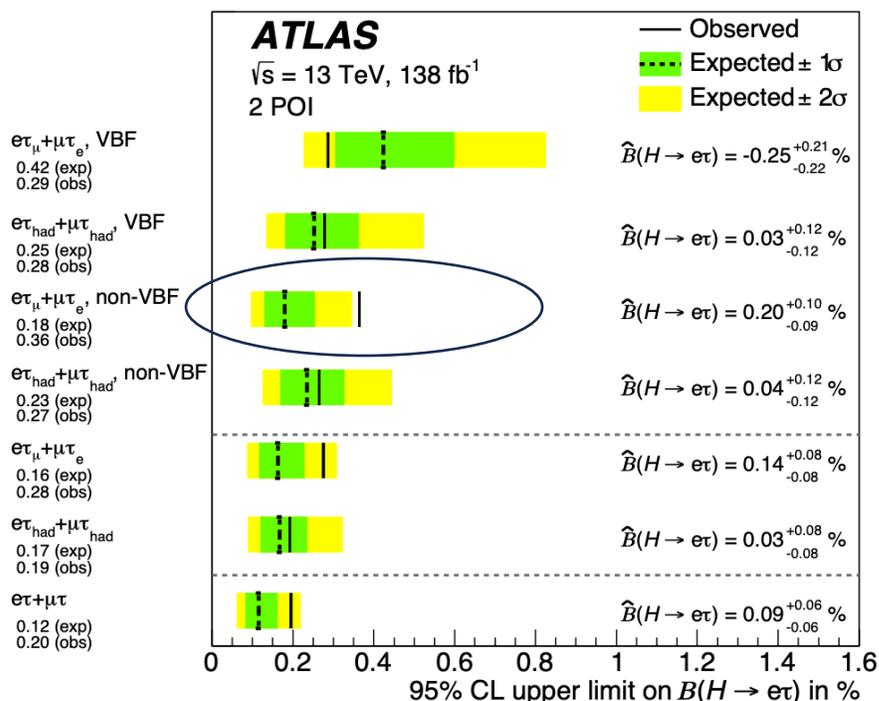


• Independent measurements:

- $B(H \rightarrow e + \tau) < 0.13\%$  at 95 C.L., observed with a significance of  $1.6\sigma$
- $B(H \rightarrow \mu + \tau) < 0.09\%$  at 95 C.L., observed with a significance of  $2.4\sigma$

$$\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0014$$

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0012.$$



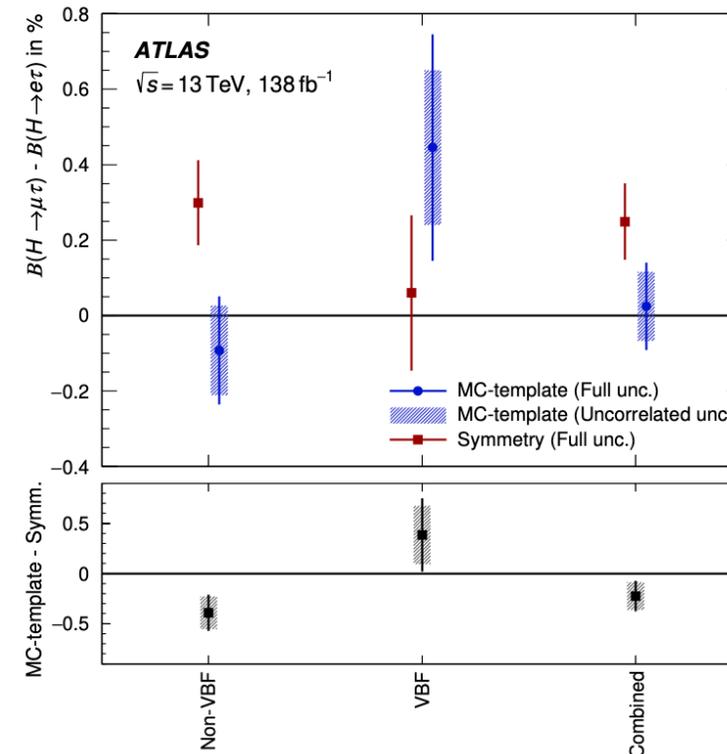
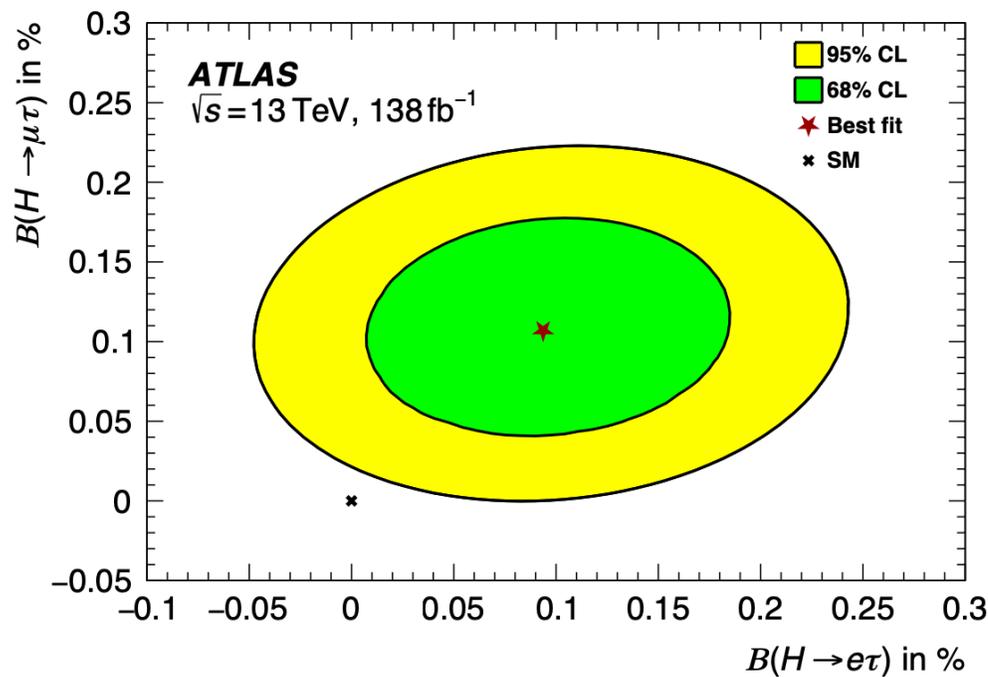
Natural Limits:

$$\frac{\sqrt{m_e m_\tau}}{v} \approx 1.2 \times 10^{-4}$$

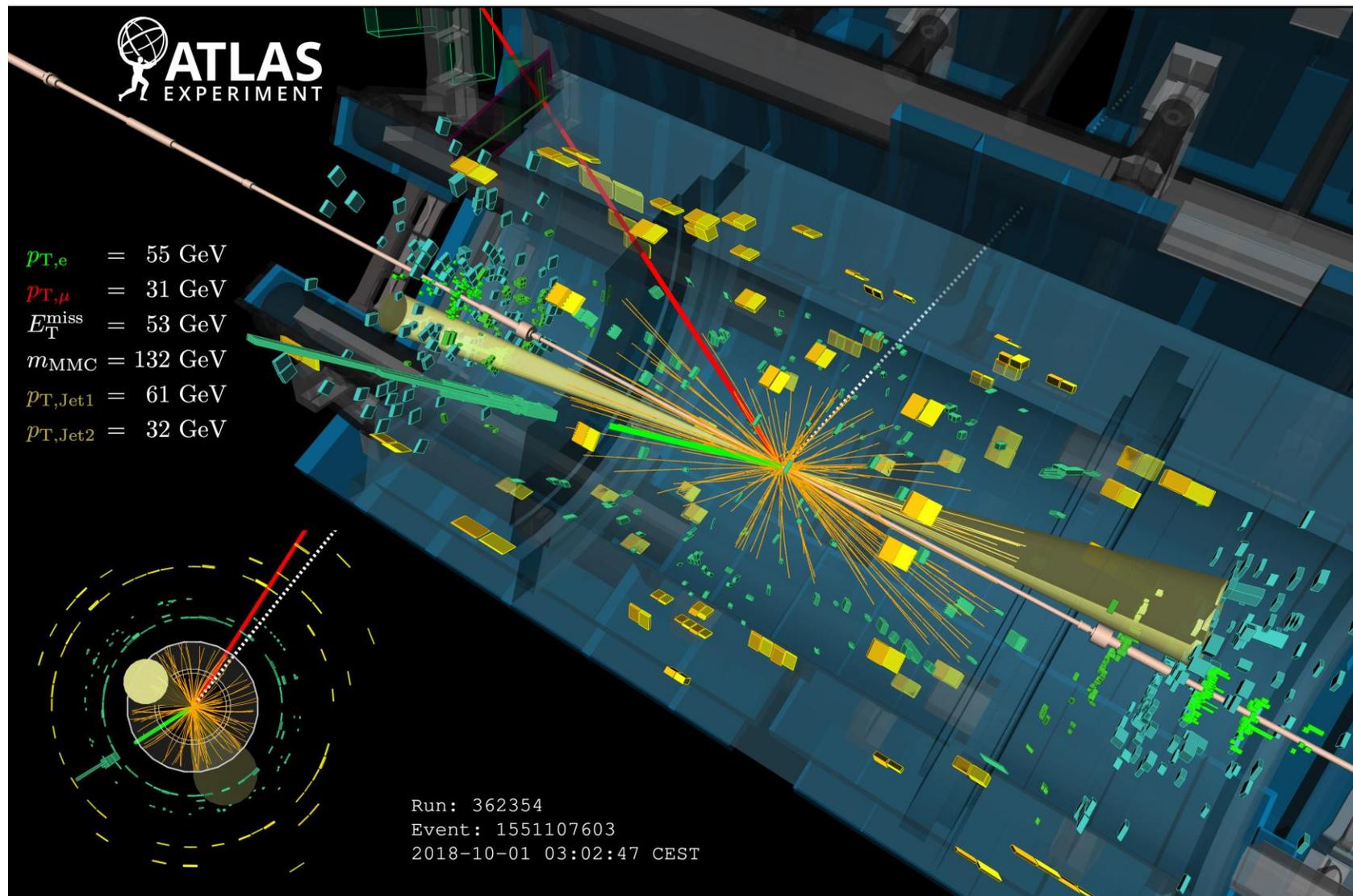
$$\frac{\sqrt{m_\mu m_\tau}}{v} \approx 1.7 \times 10^{-3}$$

The natural limit for mu-tau-Higgs coupling is excluded already!

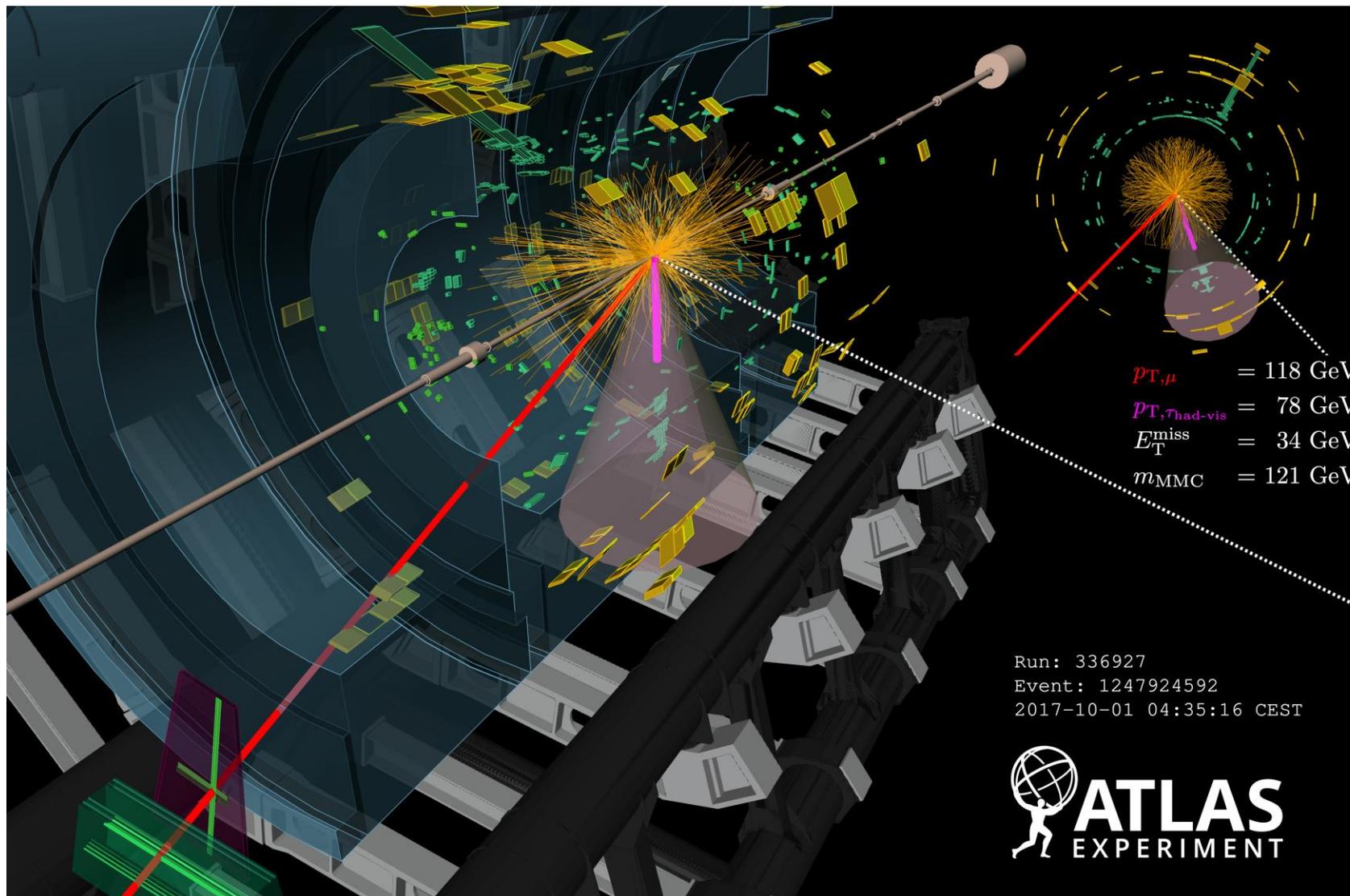
- Simultaneous measurement:
  - $B(H \rightarrow e + \tau) < 0.09\%$  at 95 C.L., observed with a significance of  $2.2\sigma$
  - $B(H \rightarrow \mu + \tau) < 0.11\%$  at 95 C.L., observed with a significance of  $1.9\sigma$
- The difference  $B(H \rightarrow \mu + \tau) - B(H \rightarrow e + \tau)$  is measured to be  $(0.02 \pm 0.12)\%$ .



# Event display for $H \rightarrow e + \tau(\mu)$



# Event display for $H \rightarrow \mu + \tau(\text{had})$



# Summary

- Based on **Run 2 (+ Run 3)** datasets, we have performed the searches for **rare** decays of Higgs boson.
  - Higgs  $\rightarrow \mu\mu$ : **3.4  $\sigma$**
  - Higgs  $\rightarrow Z\gamma$ : **2.5  $\sigma$**
  - Higgs  $\rightarrow$  low-mass  $ll+\gamma$ : **3.2  $\sigma$**
  - Higgs  $\rightarrow l\tau$ :  **$\sim 2 \sigma$**
- All measurements are **consistent with the SM** predictions.
- **No significant evidence for New Physics.**
- **But more and more** exciting experimental **results** expected with **full Run3** and in future **HL-LHC** era.

- BACK UP