Search for Higgs boson decays to leptons at ATLAS

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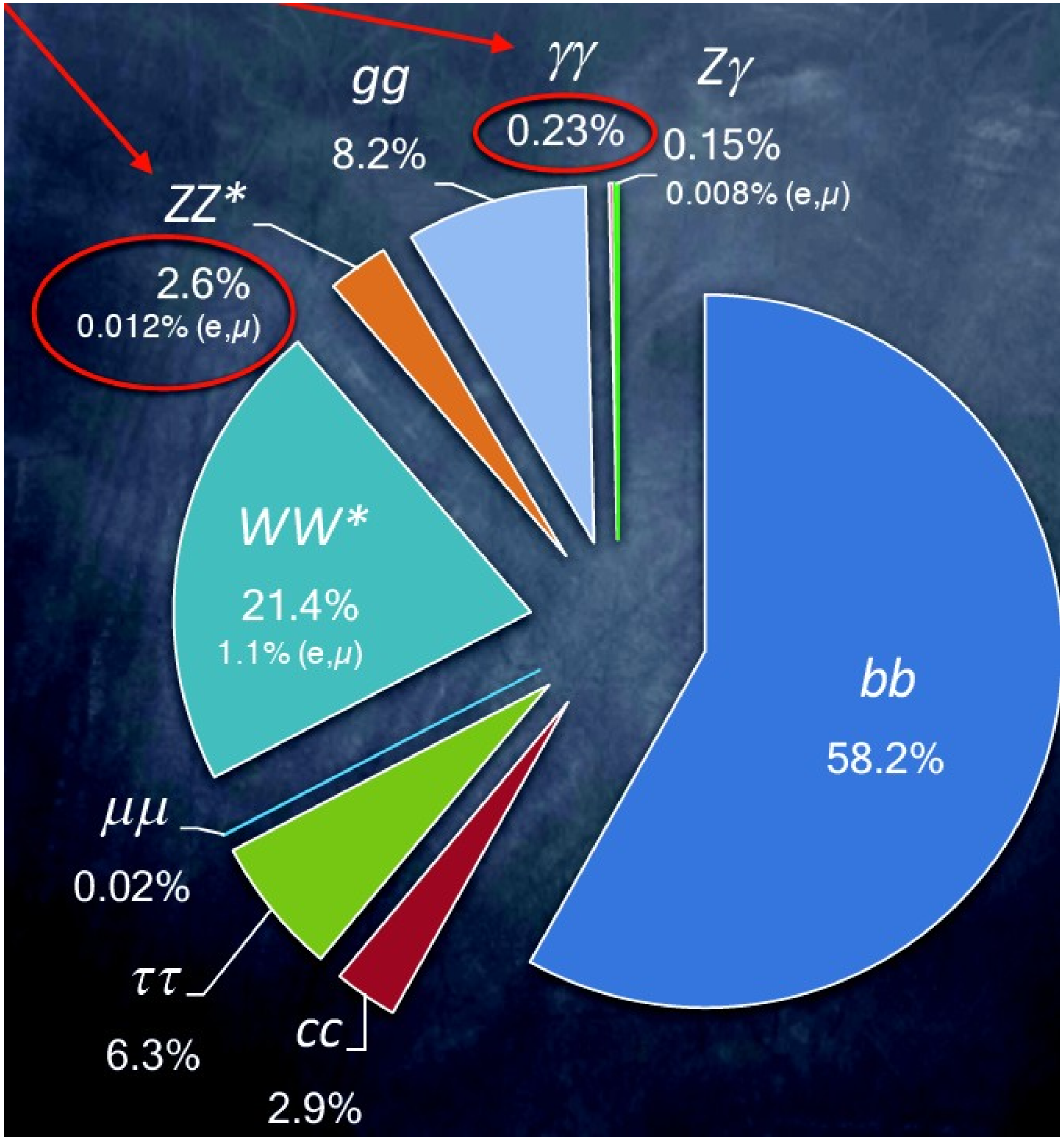
15.4.2019

Introduction (1)

- The Higgs coupling to fermions is proportional to the fermion mass, thus $\Gamma(H \to f\bar{f}) \sim m_f^2$
- Therefore:
  - $H \to e^+e^-$ is basically hopeless
  - $H \to \mu^+\mu^-$ has very small BR, but search is ongoing
  - $H \to \tau^+\tau^-$ observed with a significance > 5σ independently by ATLAS and CMS experiments

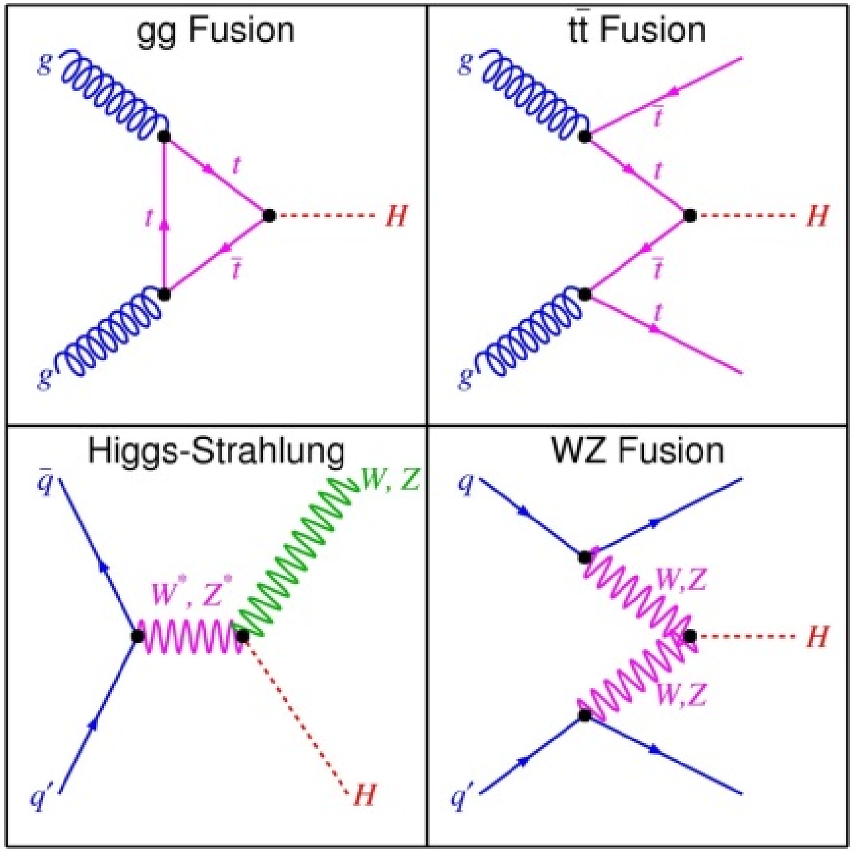
Higgs decay modes (m(H) = 125 GeV)



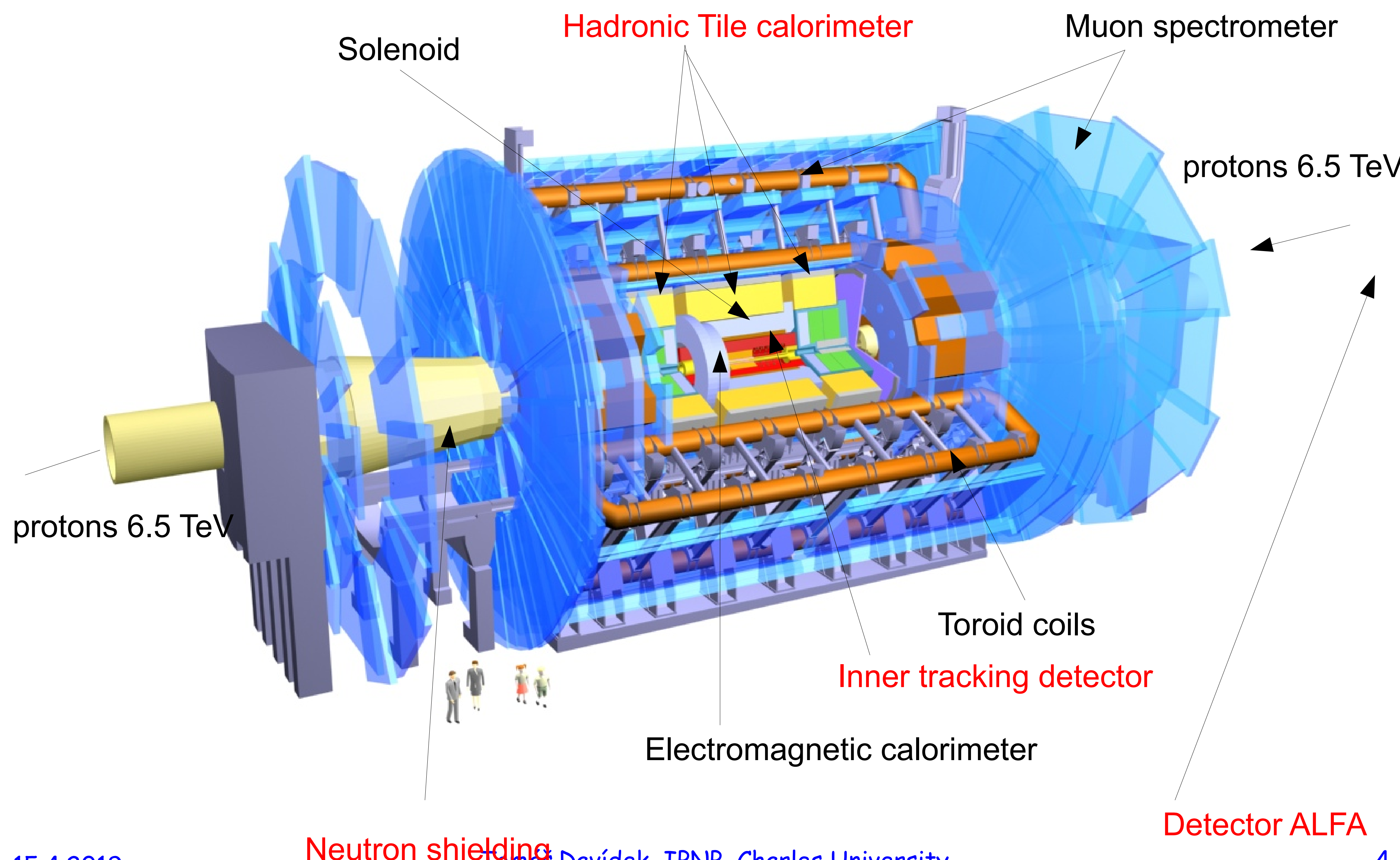
Introduction (2)

- Searches for non-Standard model final states are also ongoing, for instance
  - lepton flavour violating leptonic decays $H \to e\tau$, $H \to \mu\tau$
  - $H \to$ invisible (dark matter particles, neutrinos, …)

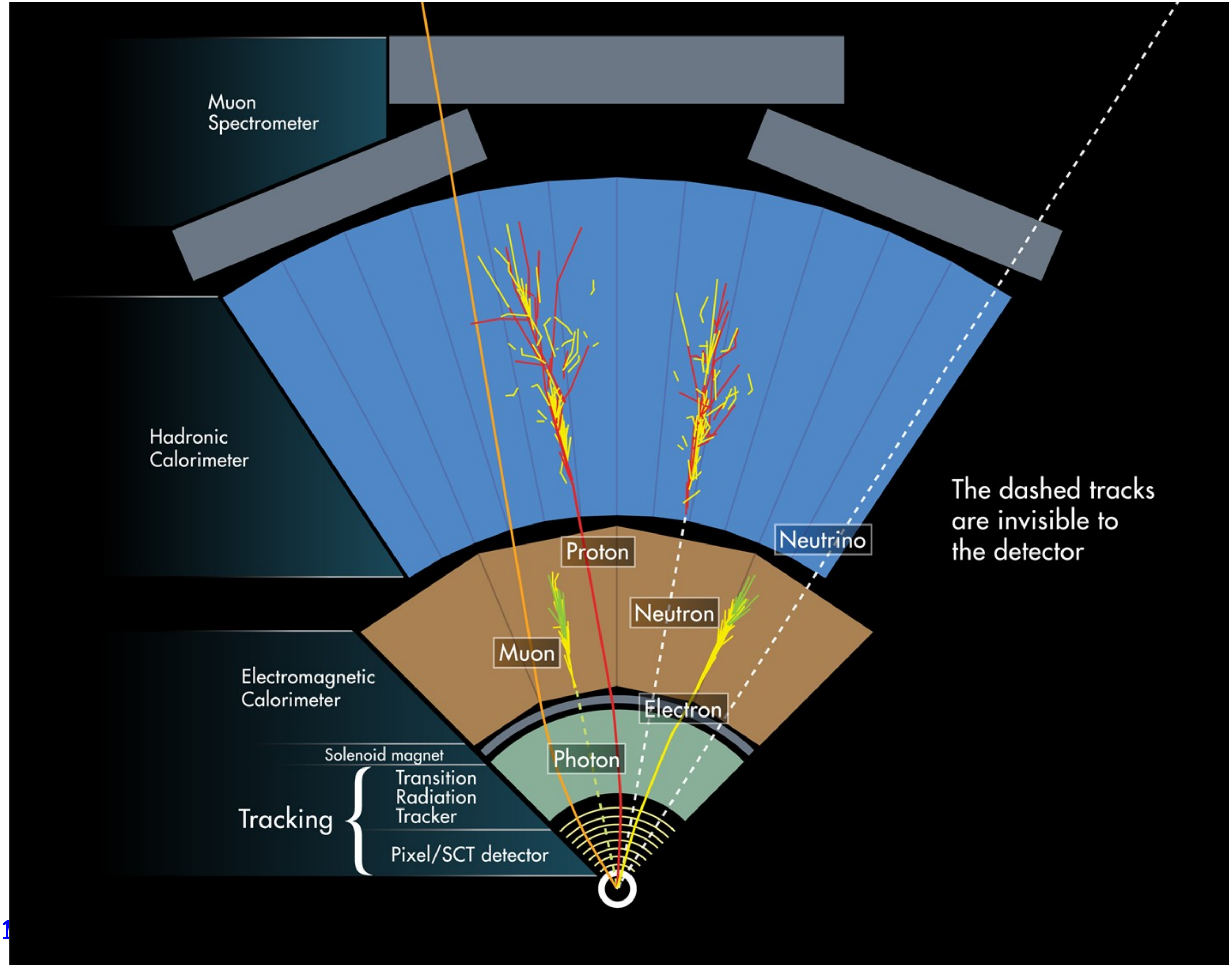
- Higgs boson production at LHC



ATLAS experiment



Principles of particle measurements



$H \rightarrow \mu^+\mu^-$ (1)

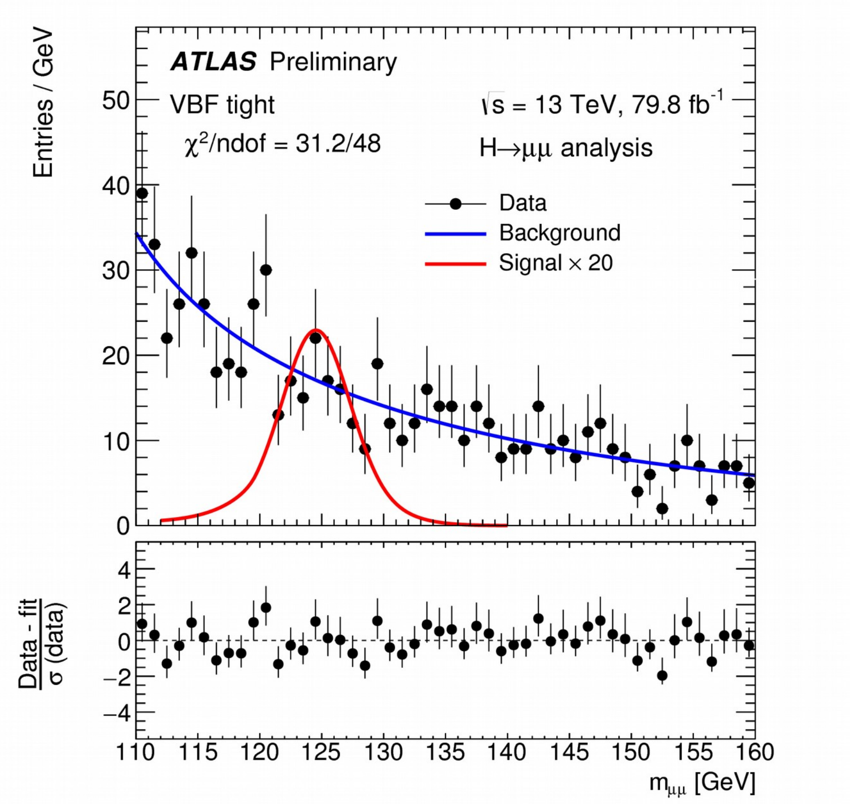
- Very clean final state, since muons can be reconstructed in both inner detector and muon spectrometer
  - select two isolated muons of opposite charge, $p_T > 15$ GeV
  - require low missing transverse energy (i.e. no neutrinos or other undetected particles in the final state) and b-veto
  - target the Higgs boson production via VBF as well as ggF (several categories defined based on $p_T(\mu\mu)$, η_μ
- Can measure the Higgs boson mass, reconstructed as the invariant mass of the muon pair
  - neglecting the mass of muon

$$E = E_1 + E_2, \quad \vec{p} = \vec{p}_1 + \vec{p}_2$$

$$M = \sqrt{E^2 - \vec{p}^2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} = \sqrt{2 E_1 E_2 (1 - \cos\theta)}$$

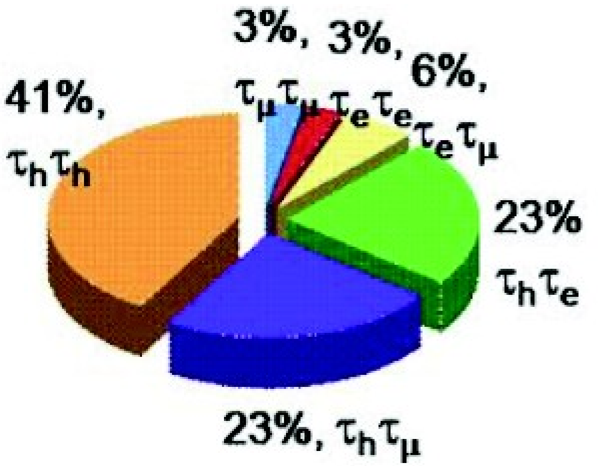
$H \to \mu^+\mu^-$ (2)

- ATLAS latest results (ATLAS-CONF-2018-026)
  - No signal observed yet, setting the upper limits on the production cross-section x BR @ 95% CL: 2.1 x SM



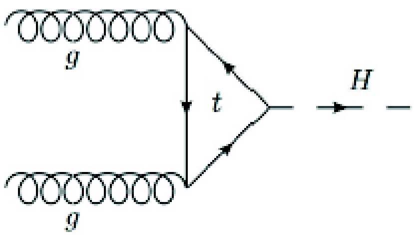
$H \rightarrow \tau\,\tau$ (1)

- The final state depends on the tau-lepton decay mode
  - di-lepton channel: $H \rightarrow \tau\,\tau \rightarrow 2\ell\ 4\nu$
  - semi-lepton channel: $H \rightarrow \tau\,\tau \rightarrow \ell\ n\pi\ 3\nu$ (n=1 - 3)
  - hadronic channel: $H \rightarrow \tau\,\tau \rightarrow n\pi\ 2\nu$

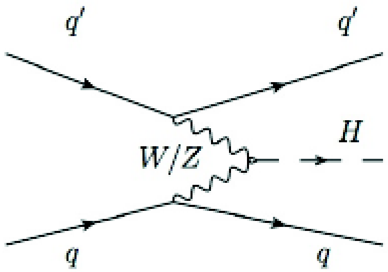


- Signatures in the detector
  - isolated electron(s) and/or muon(s)
  - missing transverse energy
  - reconstructed hadronic τ
  - accompanying jets (reflect the production mechanism)

gluon-gluon fusion (dominant production mode)



VBF (subdominant, ~10 weaker)



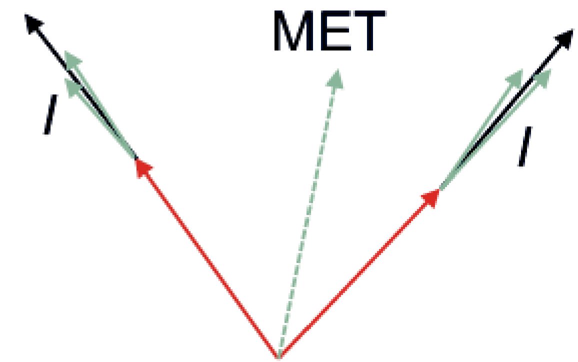
- Dominant background comes from $Z \rightarrow \tau\,\tau$, also top, $Z \rightarrow \ell\ell$ and fakes contribute

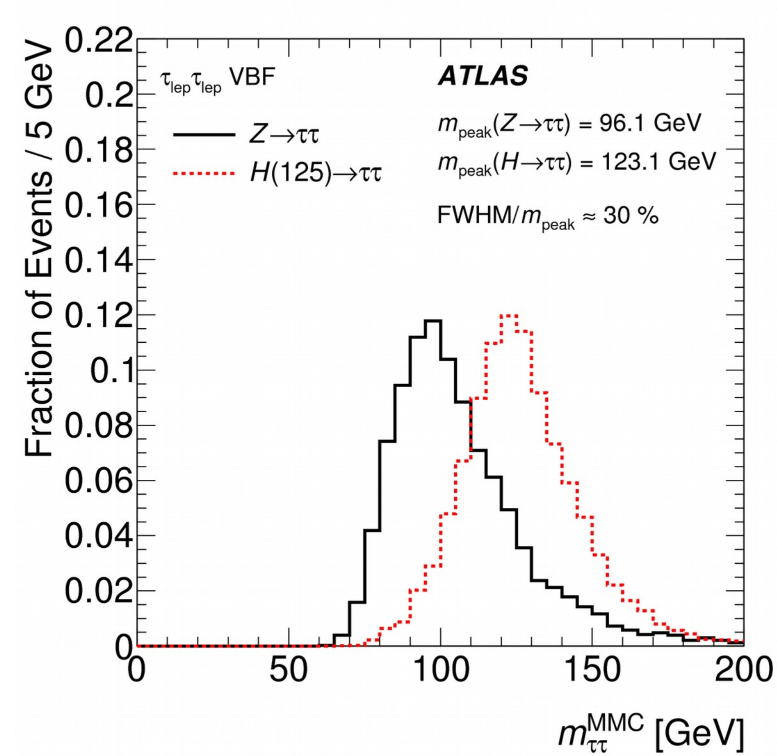
H → τ τ (2)

- Higgs boson mass reconstruction
  - invariant mass cannot be properly reconstructed due to 2-4 neutrinos
  - **collinear mass approximation**
    - assumes all τ-decay products are collinear

$$\vec{p}^{miss} = k_1 \vec{p}_{vis1} + k_2 \vec{p}_{vis2}$$

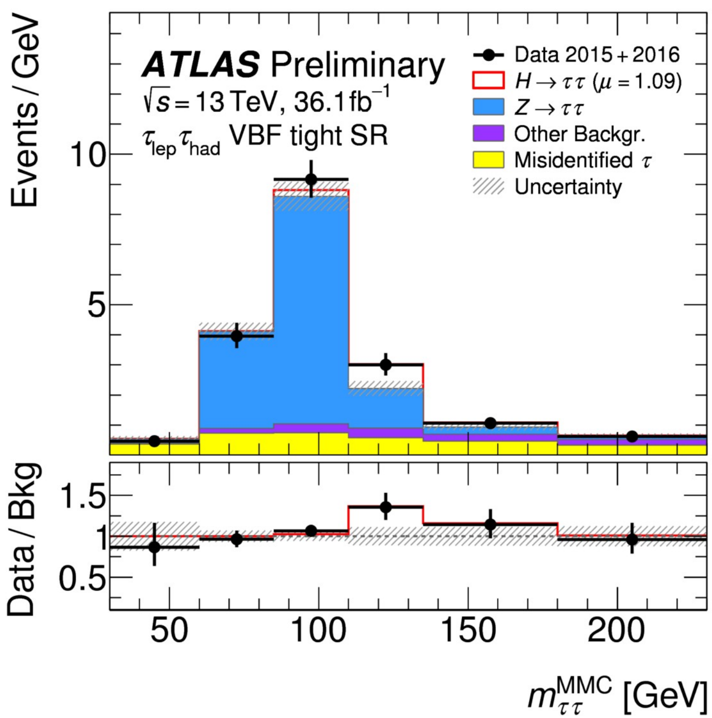
  - **Missing Mass Calculator**
    - takes into account the probability of the angular distribution between the τ-decay products
    - better resolution than collinear mass, critically depends on the MET resolution knowledge





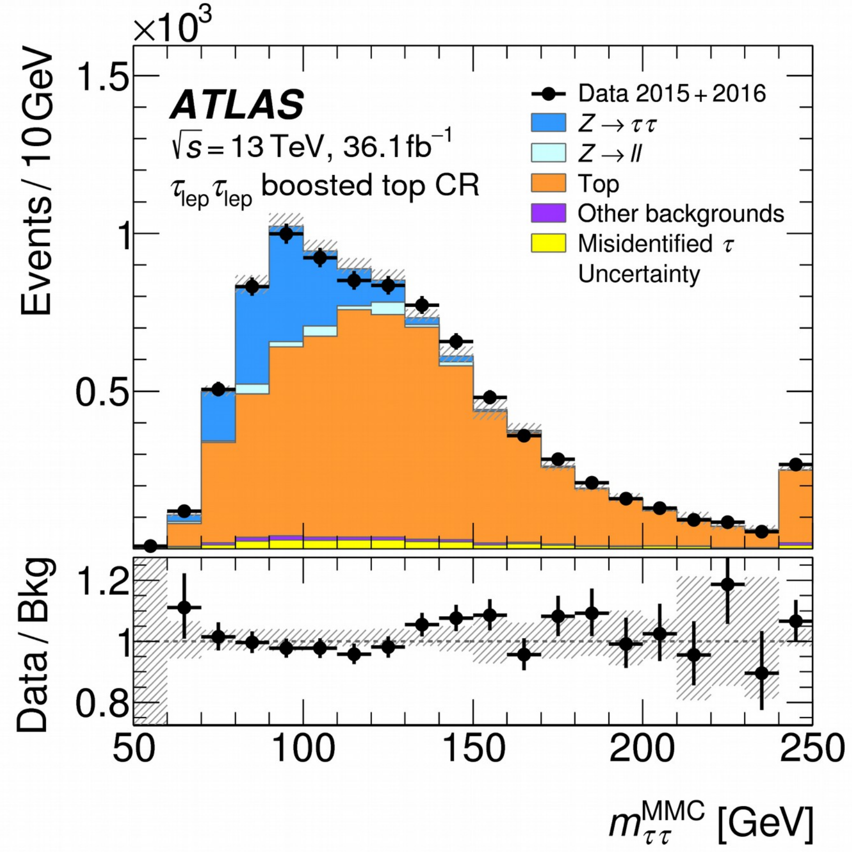
$H \rightarrow \tau\,\tau$ (3)

- Baseline selection depends on the channel, e.g. lep-lep requires two opposite-charge isolated leptons (e, μ) with large missing transverse energy
- Each channel is split into two basic categories targetting the corresponding production mechanism
  - VBF: require two forward jets (at least 2 jets, large m_{jj}, large $|\Delta\eta|$)
  - Boosted: $p_T(\tau\,\tau) > 100$ GeV with at least 1 jet
- Categories are further split into „Loose" and „Tight", to further increase the significance



$H \to \tau\,\tau$ (4)

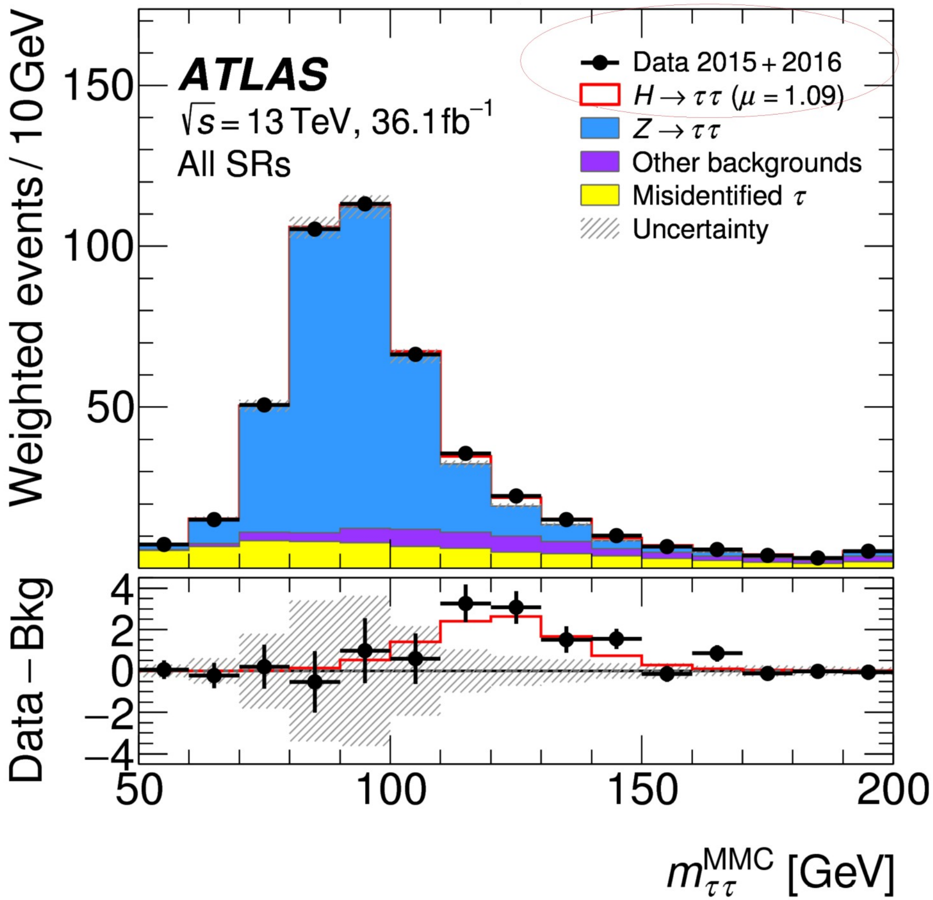
- Main background components are checked in specific control regions, which are enriched with the corresponding component (top in lep-lep and lep-had, $Z\ell\ell$ in lep-lep)

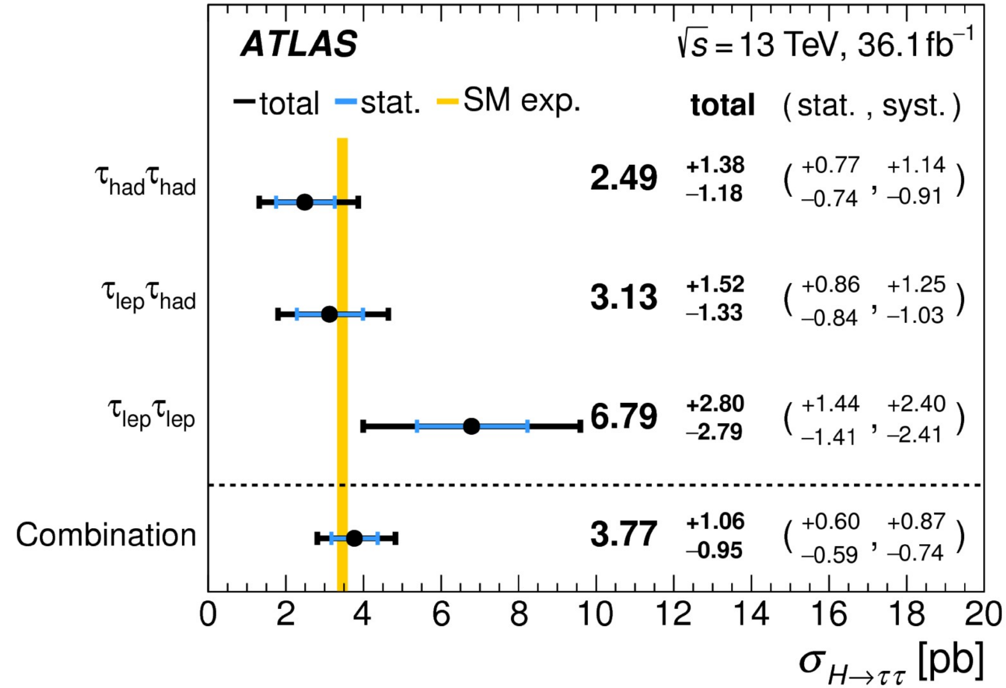


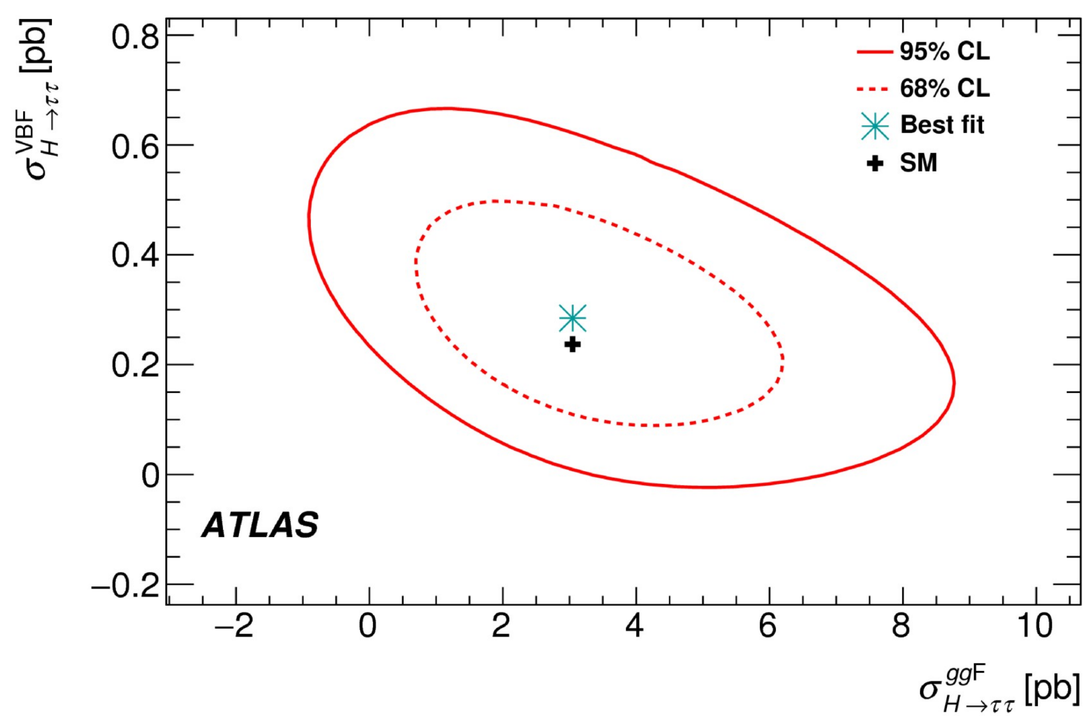
- Finally, the global fit is performed combining all (sub)categories across all 3 channels
  - fitting MMC spectra in individual signal regions
  - taking into account the background normalization in the control regions

$H \rightarrow \tau\,\tau$ (5)

- Results after the fit:





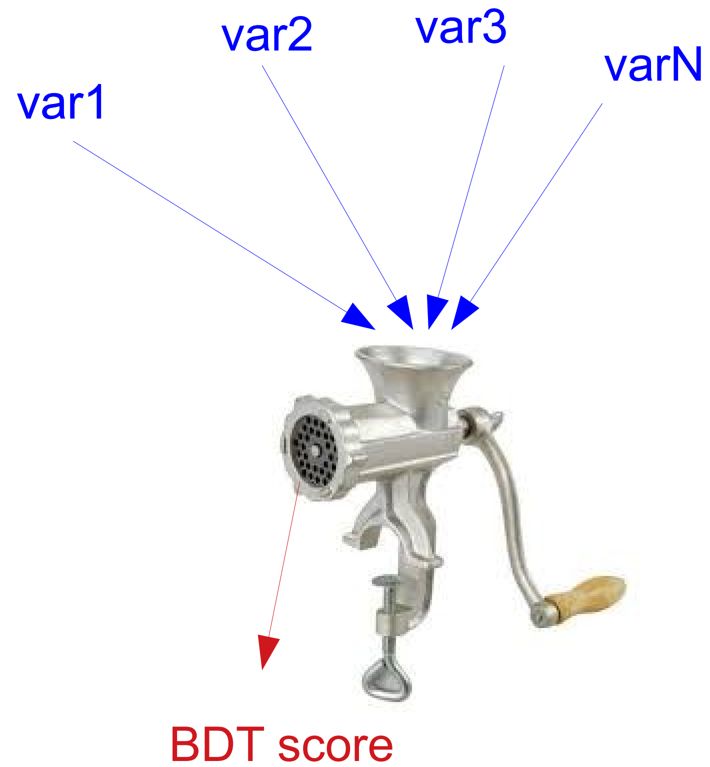


$H \rightarrow e\tau$, $H \rightarrow \mu\tau$ (1)

- This decay violates the lepton flavour conservation, it should not exist in nature. If a non-zero BR is measured, it would be a sign of new physics beyond the Standard model.
- Signatures in the detector depend on the τ decay mode:
  - leptonic decay → 2 light opposite-charge leptons and two neutrinos (MET) in the final state. Only different flavour combinations ($e\mu$, μe) are considered in order to reduce the background as much as possible
  - hadronic decay → one light lepton (e or μ), a „τ-jet" and 1 neutrino (MET) in the final state.
- As in the SM analysis $H \rightarrow \tau\tau$, both lep-lep and lep-had channels are further split into VBF and non-VBF categories
- The main background processes are similar as in $H \rightarrow \tau\tau$ measurement:
  - $Z \rightarrow \tau\,\tau$, top production, fakes
  - Standard model $H \rightarrow \tau\,\tau$ and $H \rightarrow WW$ also considered as background

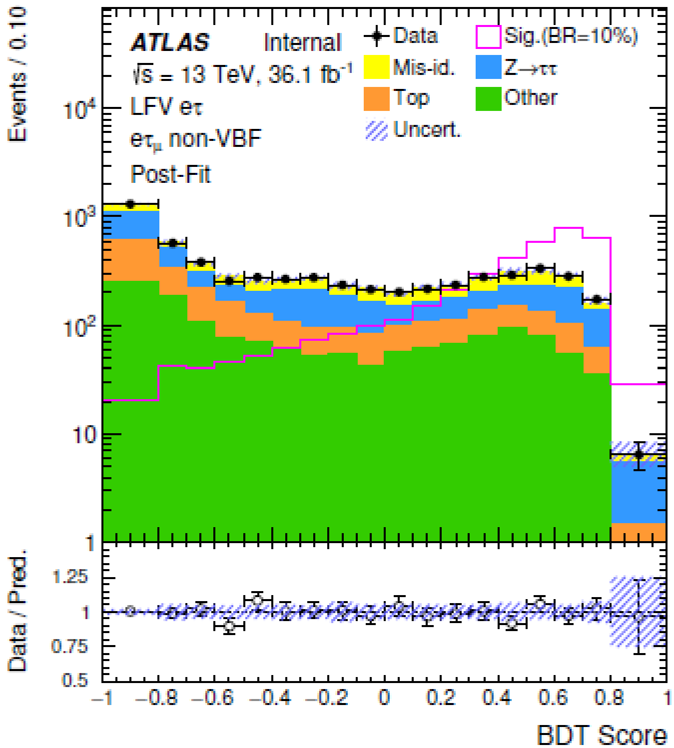
$H \to e\tau$, $H \to \mu\tau$ (2)

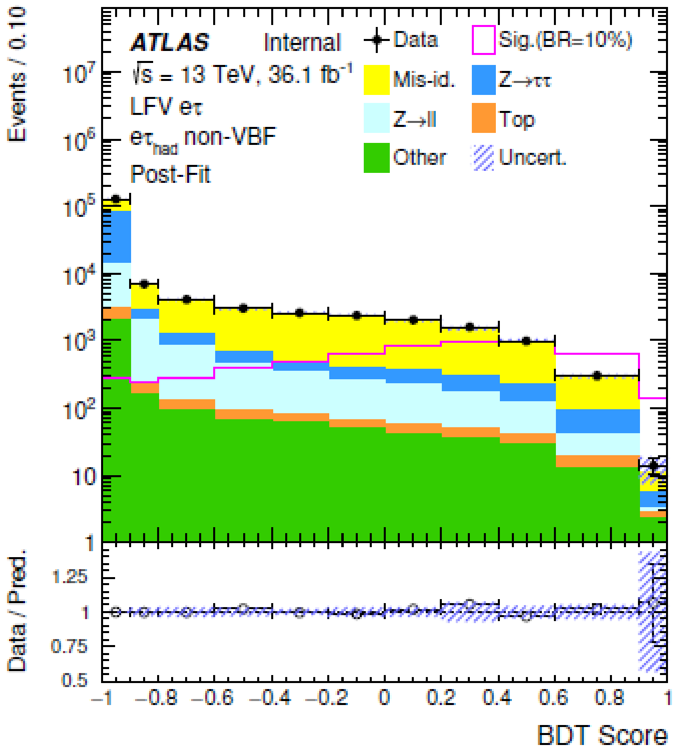
- The Higgs mass could be reconstructed via MMC or collinear approximation. Nevertheless, multi-variate approach (MVA) is used to further increase the search significance.
- MVA – uses of Boosted Decision Trees (simplest case of neural net)
  - choose several variables with large „separation power" (signal vs background), e.g. MMC/collinear mass, p_T(lepton), m_{jj}, ...
  - let the machine „learn" on MC how to separate signal from background (training sample) using the BDT discriminant
  - single number ranging from -1 (pure bckg) to +1 (pure signal)
- apply to data and MC (analysis sample) and evaluate the (non-)existence of the effect and its significance



H → eτ, H → μτ (3)

- Examples of the BDT score distributions in H → eτ channel



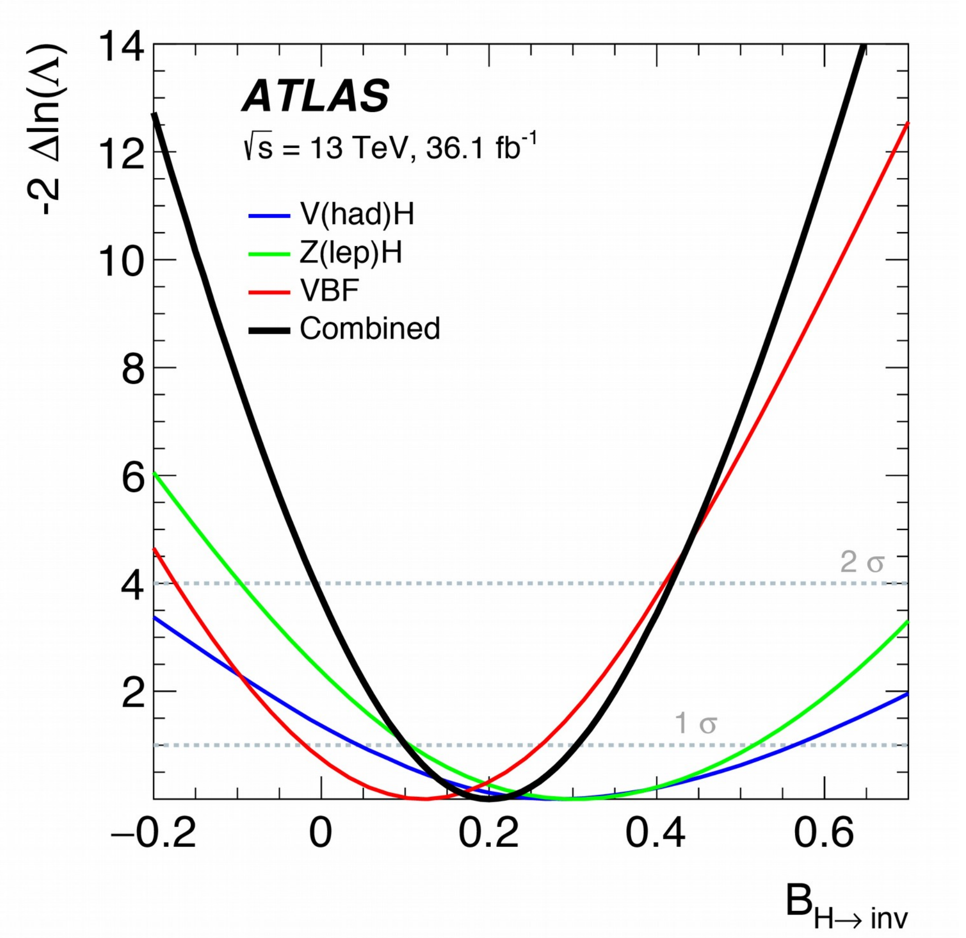


- Preliminary results: data are compatible with background (within uncertainties), upper limits on LFV Higgs decays set
  - 0.47% for H → eτ, 0.28% for H → μτ

$H \rightarrow$ invisible

- Searches are carried out in two production modes
  - VBF production (2 associated forward jets)
  - associated production: W(had)H, Z(had)H, Z(ℓℓ)H

- Results: observed upper limit 0.26 (arXiv: 1904.05105)



Conclusions

- Searches for Higgs boson decays to leptons ongoing
- $H \rightarrow \tau\tau$ decay is well established, observed by both ATLAS and CMS experiments, first measurements on the cross-sections exist
- $H \rightarrow \mu\mu$ is difficult to measure due to very small BR, but the results are already approaching the SM limit
- Searches for many non-SM Higgs decays are ongoing, no sign of new physics in the Higgs sector yet

BACKUP