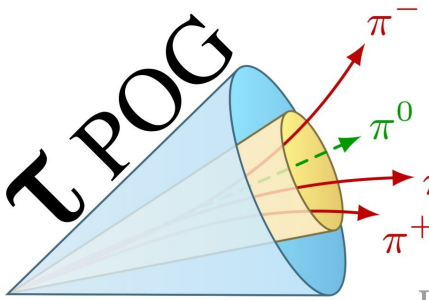
Tau Short Exercise

Andrea Cardini & Alexei Raspereza



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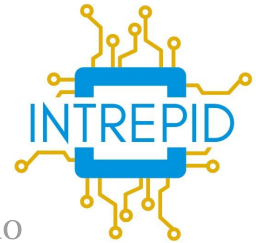
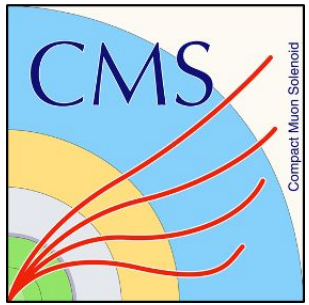
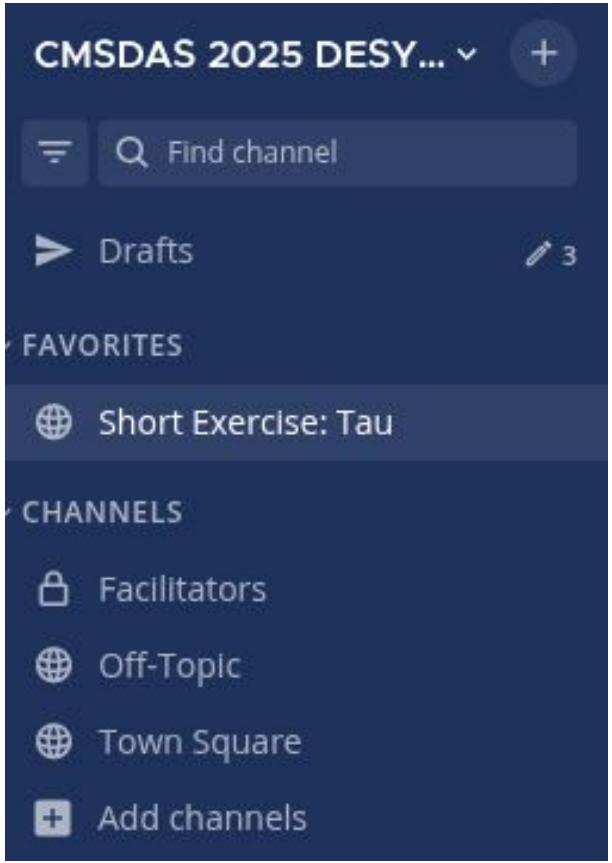




Communication channels



- Please join the mattermost channel
- If you're not already in the CMSDAS 2025 team on mattermost click on the link below: CMSDAS 2025 mattermost

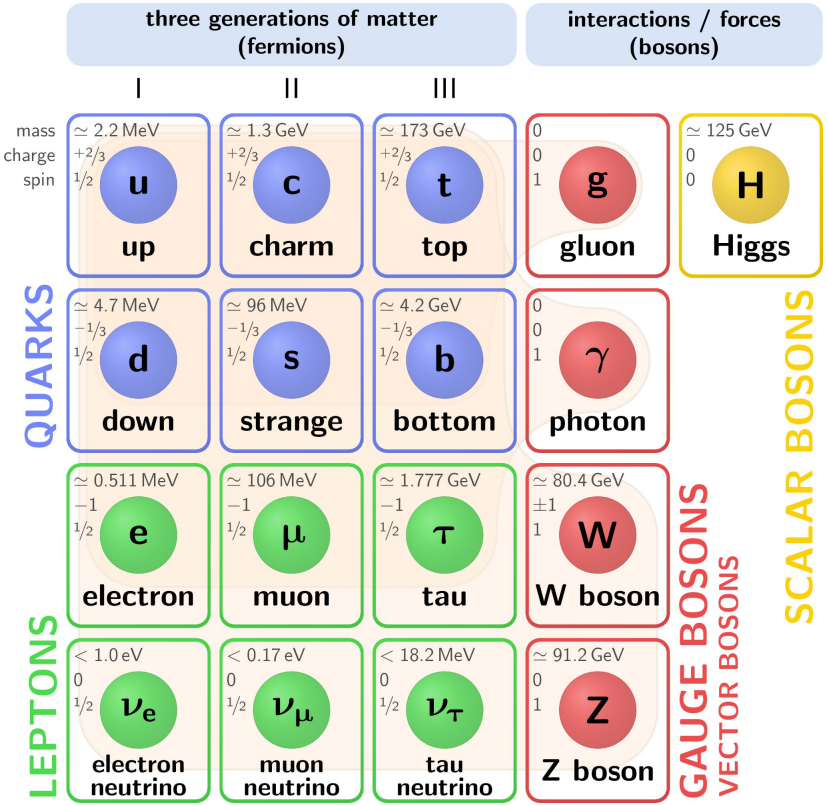
Greetings!

- It’s a pleasure for us that you decided to join the Tau exercise in this DAS!
- We’ll be your facilitator for the exercise

Andrea Cardini
Former Coordinator of the TauPOG in CMS

Alexei Raspereza
Current Coordinator of the TauCQM group in CMS

Taus in the SM

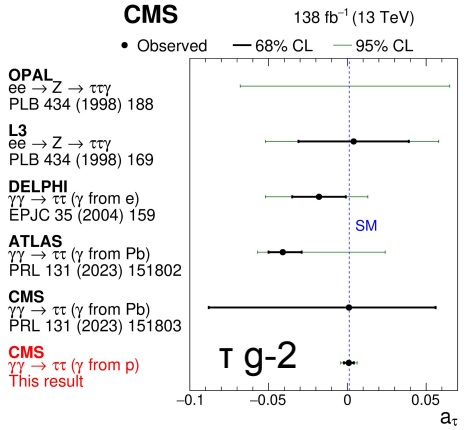


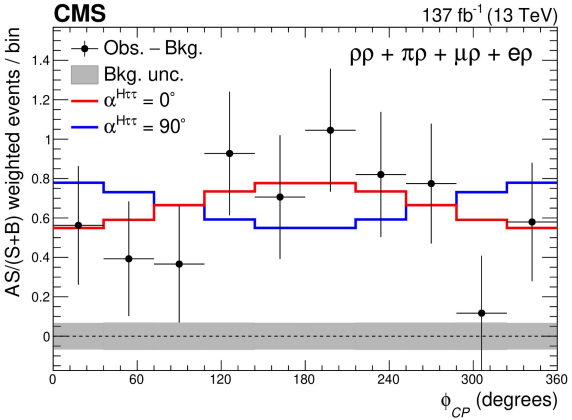
- Taus are the only leptons capable of decaying hadronically
  - mass ~1.777 GeV
  - average lifetime ~3 × 10-13 s ⟶ decay length of ~1.5 mm (with E ~30 GeV)
- They decay via pure electroweak interaction
  - Decay products preserve memory of tau spin -> excellent probes for CP violation
  - Strongest Yukawa coupling to Higgs among leptons
  - Used in a variety of searches for new physics: leptoquarks, extended higgs, LLP, etc.

Taus in CMS analyses

Tau lepton is a key object in many physics studies

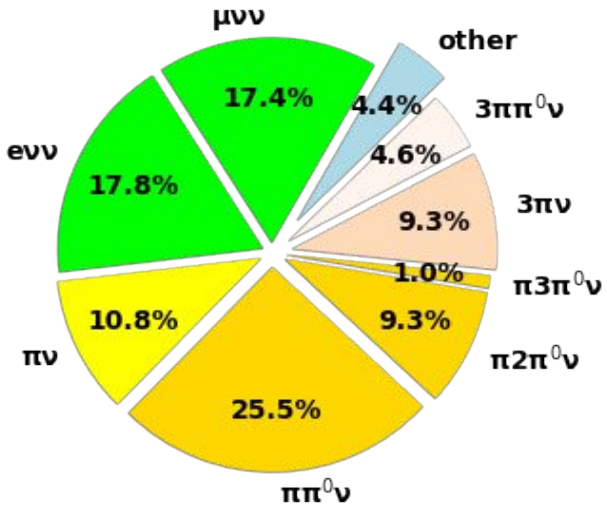
- Tests of the SM
  - lepton universality in semileptonic decays of heavy-flavour hadrons
  - precise measurements of τ g-2 and $\sin\theta_W$
- Studies of the Higgs boson properties
  - Production rates and differential cross sections with H⟶ττ
  - CP structure of the Hττ Yukawa coupling
  - Higgs self-coupling (HH⟶bbττ channel)
- Searches for BSM physics: additional neutral and charged Higgs bosons, Z' and W', leptoquarks; FCNC in B-meson decays

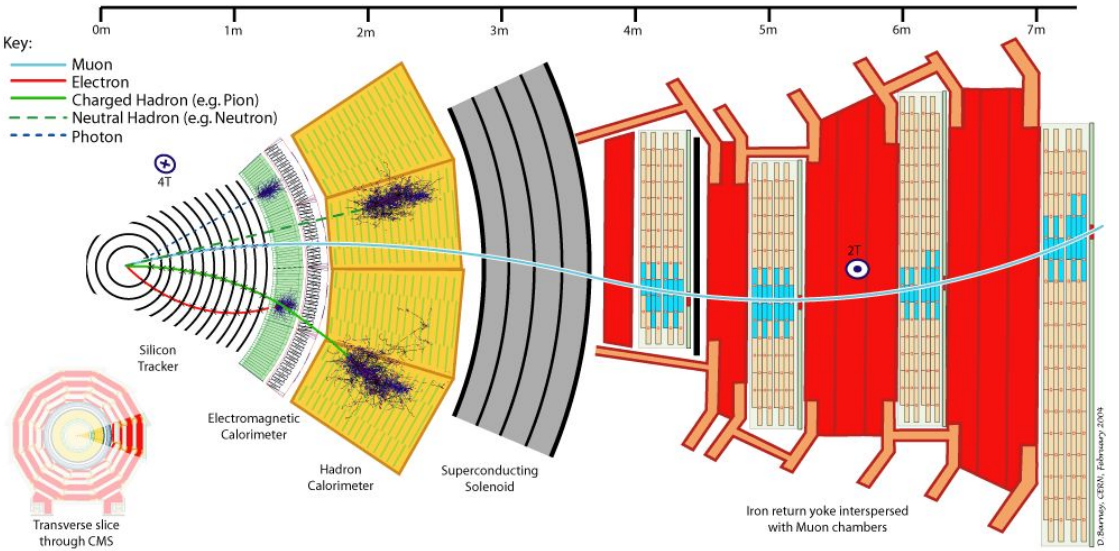




Taus in CMS

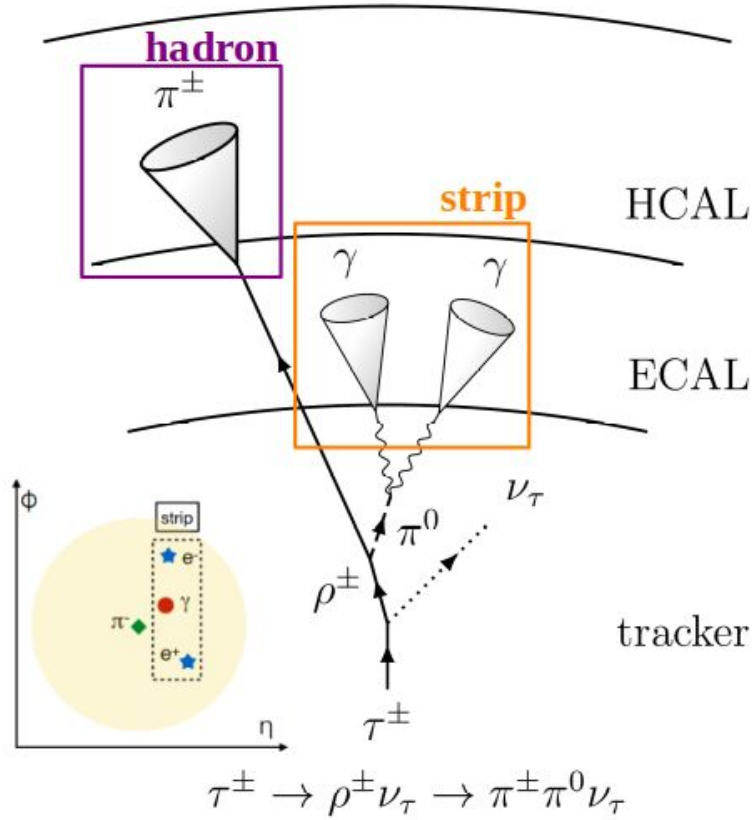
- Taus decay before reaching the inner layers of the CMS tracker detector-> they are reconstructed from their decay products
- Decays to muons and electrons use the standard CMS reconstruction for those objects
- The Tau Physics Object Group works on hardonically decaying tau leptons (τ_h)



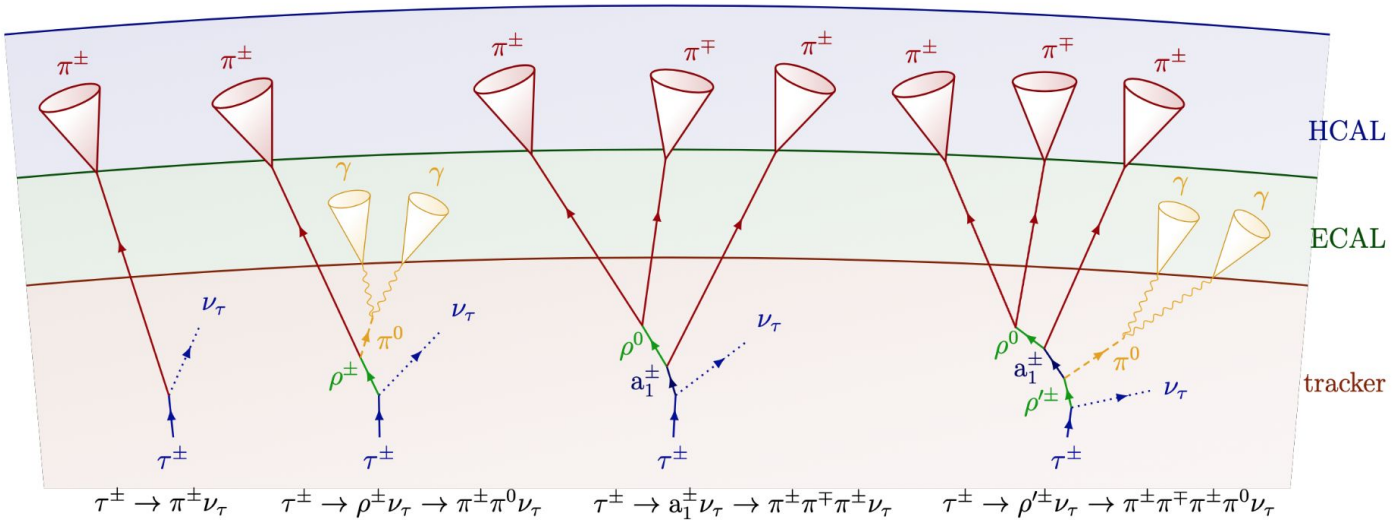


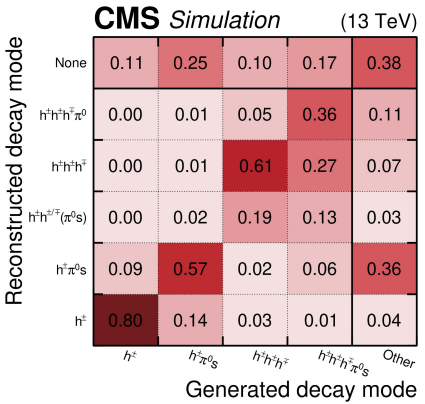
The Hadron-plus-strip algorithm

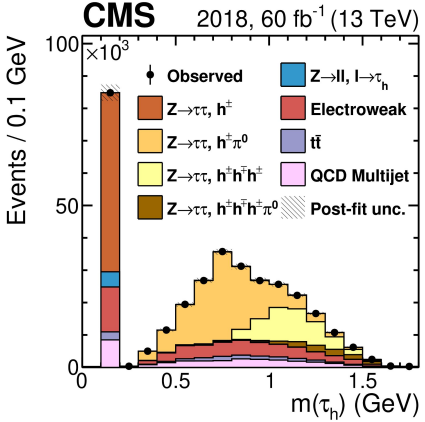
- Taus are reconstructed with the Hadron-plus-strip algorithm
  - Start from an AK4 jet
  - Select hadron candidates
  - Cluster e+/e-/γ as π^0 candidates (strip)
  - Test the combination against the hypotheses of tau decays
  - Identify the tau decay channel + the charge (count the charged/neutral hadrons) and measure the tau mass



HPS decay mode identification



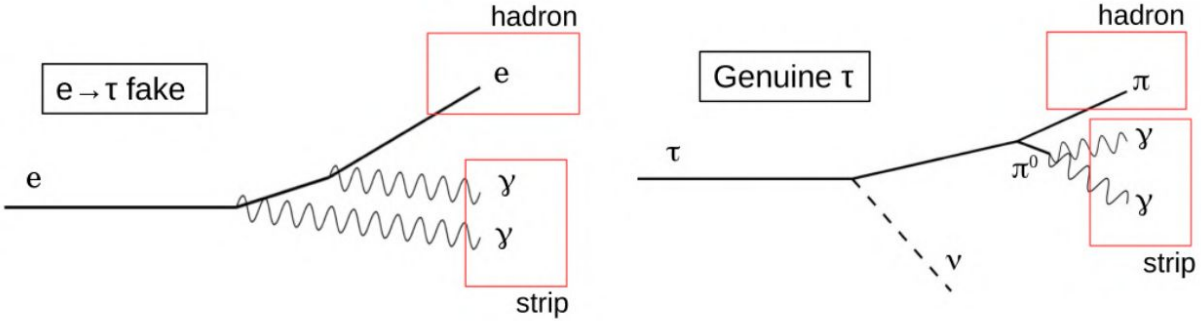


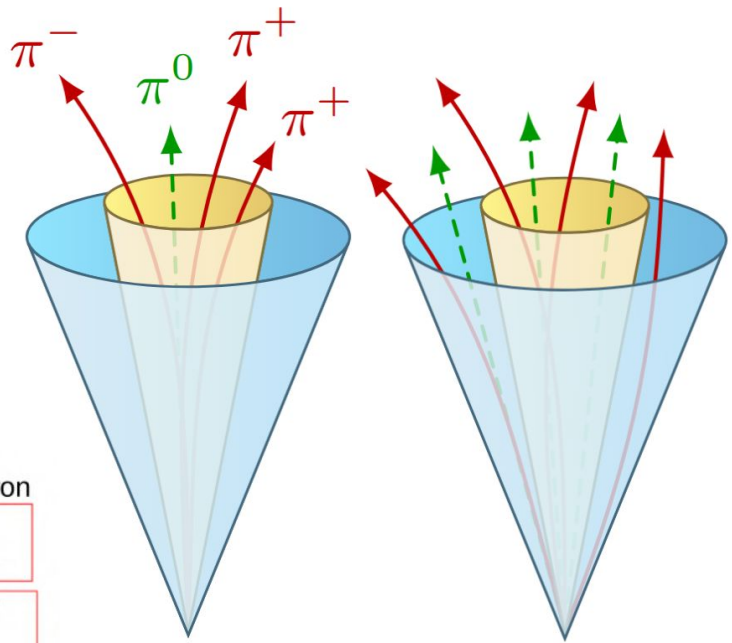


- HPS pattern defines four possible configurations (HPS decay modes)
- HPS algorithm does not differentiate between $\pi^\pm\pi^0$ and $\pi^\pm\pi^0\pi^0$ channels
- a more sophisticated tools are used to refine decay mode reconstruction, e.g. BDT was used in Run 2 CP H→ττ analysis, where discrimination between $\tau^\pm \to \rho^\pm(\pi^\pm\pi^0)\nu$ and $\tau^\pm \to a_1^\pm(\pi^\pm\pi^0\pi^0)\nu$ decays is crucial, **JHEP 06 (2022) 012**

Misidentified taus

- HPS focuses on efficiency at the expense of purity
- Some quark/gluon jets, electrons and muons can be misidentified as τ_h
  - Highly collimated jets
  - Electrons+bremsstrahlung radiation
  - Muons with low track quality

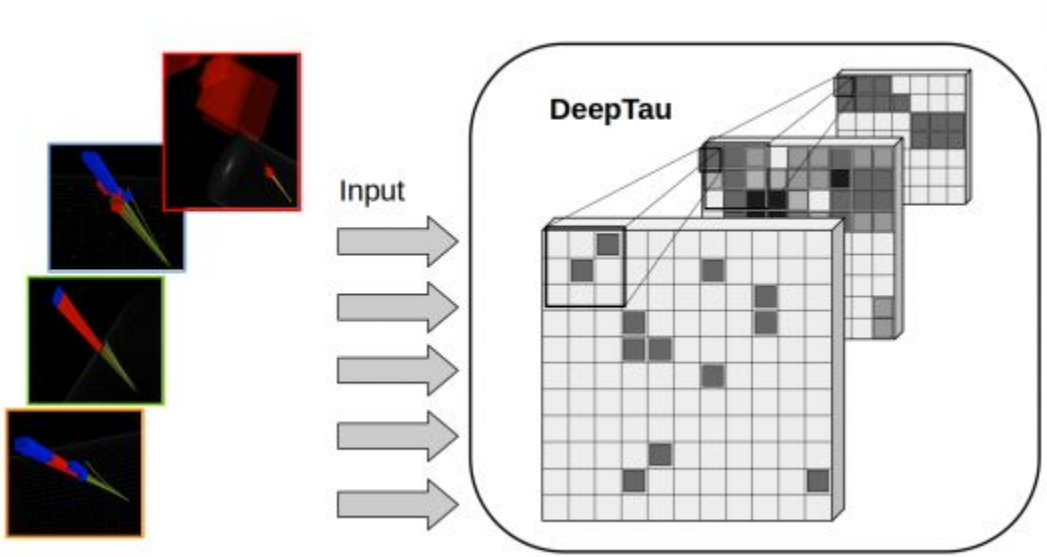




genuine τ_h j->τ_h fake

Tau identification with ML

- Starting with the end of Run 2 in CMS we use a Convolutional Neural network to identify genuine taus against misidentified jets and leptons: DeepTau
- Low and high level inputs are represented as an image which is then interpreted as a tau, quark/gluon jet, electron, or muon

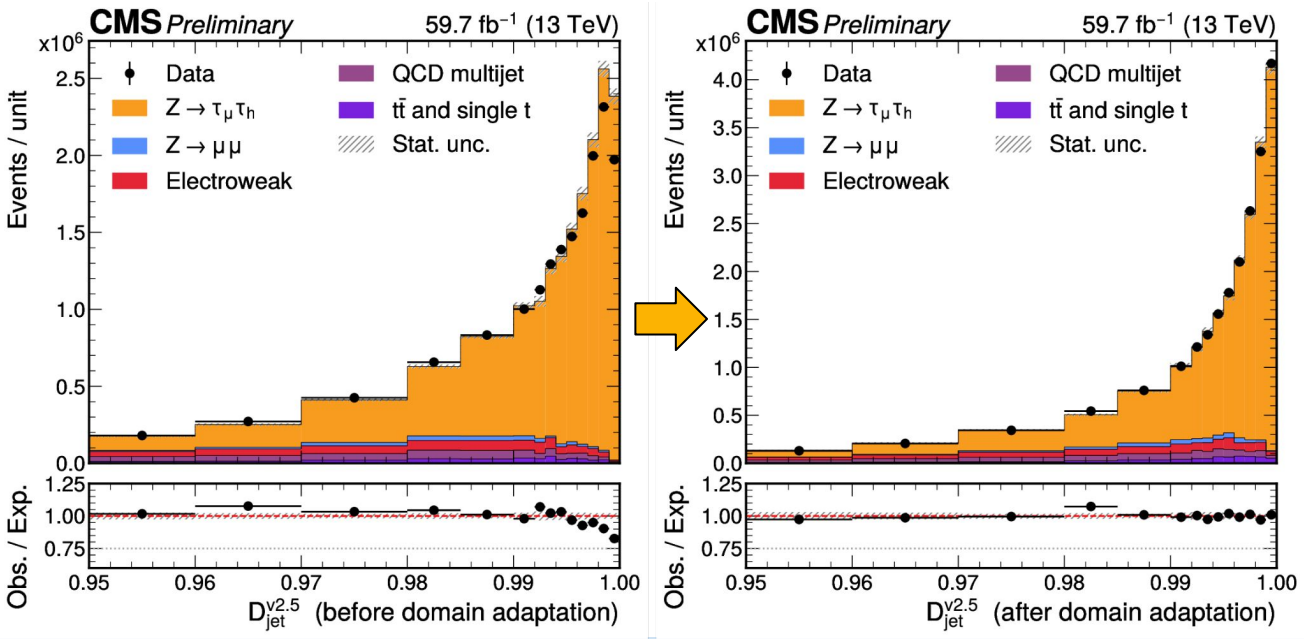


$$P_{\tau \text{ vs } obj.} = \frac{y_\tau}{y_\tau + y_{obj.}}$$

- The scores are then combined into classifiers to reject fakes

Latest updates

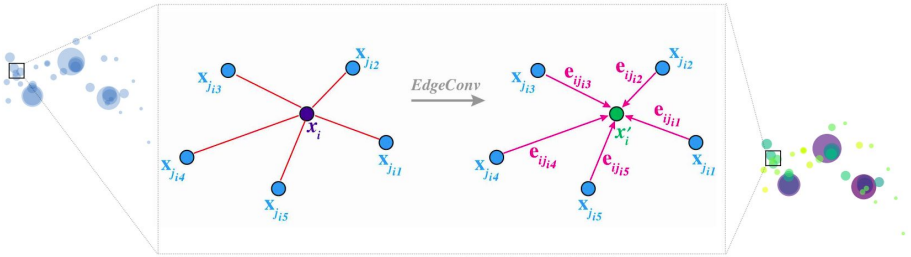
- Starting in the LHC Run 3 DeepTau has seen an upgrade
- We now include domain adaptation: an adversarial subnetwork to reduce effect of MC mismodelling in the output score



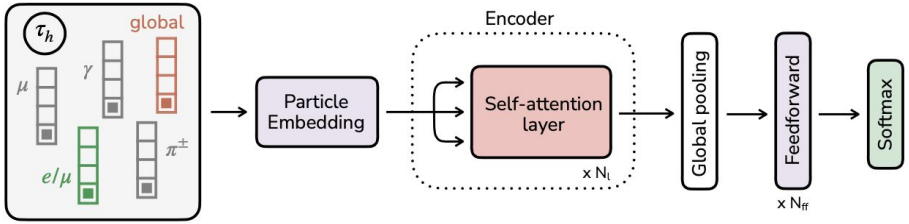
Alternative identification techniques

- During Run 3 in CMS new ideas of tau identification were proposed: unified jet taggers
- Unlike DeepTau+HPS they start directly from jets and identify them as jets, taus or light leptons (e/μ)
  - Decay channel, charge and other properties are regressed (rather than calculated based on the number of charged/neutral hadrons)
- Two algorithms have been introduced in CMS: ParticleNet (graph-based NNet) and UParT (transformer NNet with inter-feature self-attention mechanism)

ParticleNet

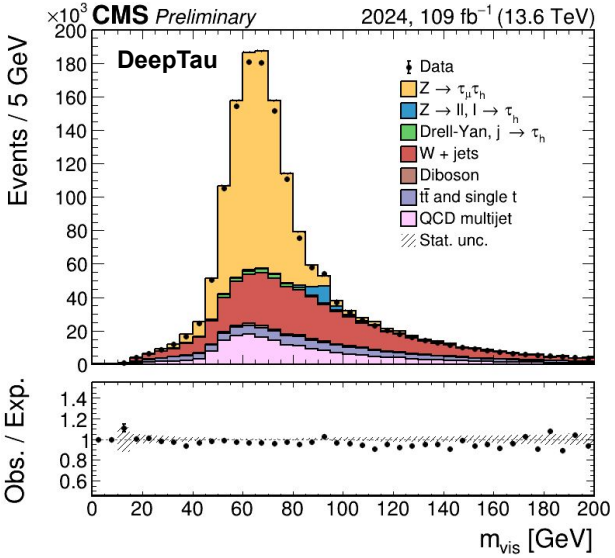


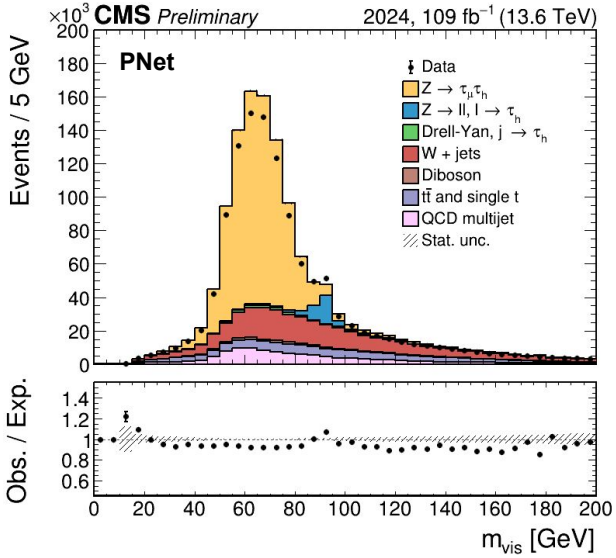
UParT

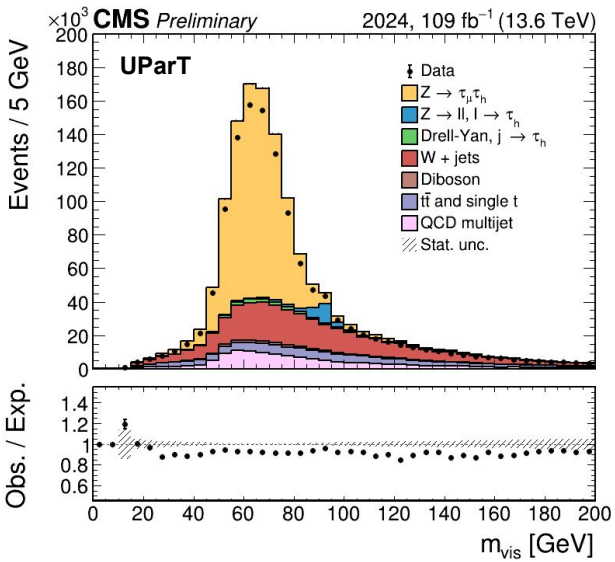


TauPOG activities

- In TauPOG we calibrate available ID algorithms and measure correction factors for genuine taus as well as lepton -> tau fakes

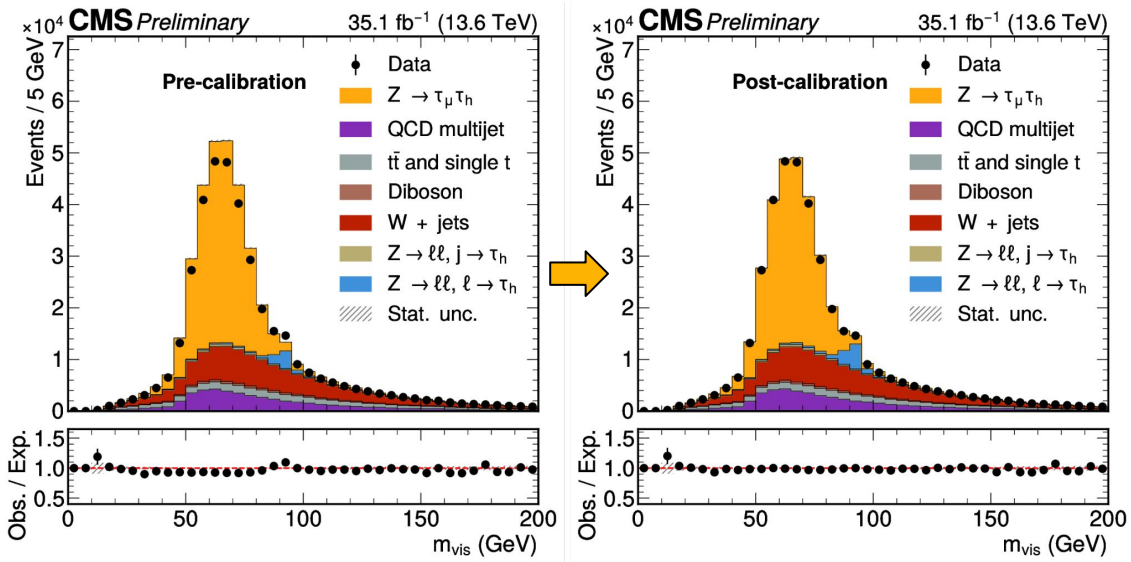


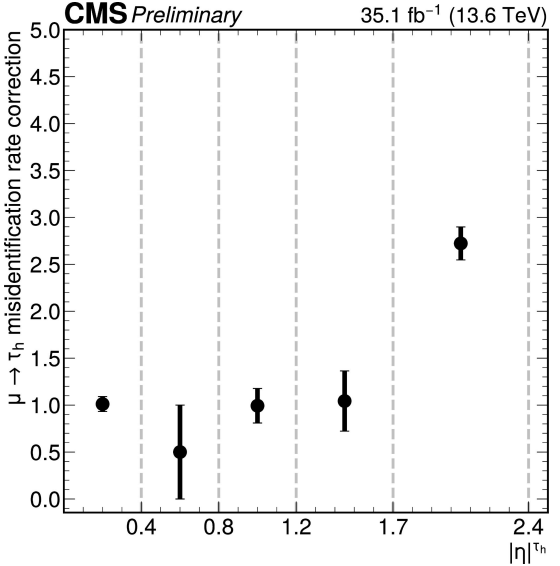




Corrections measured

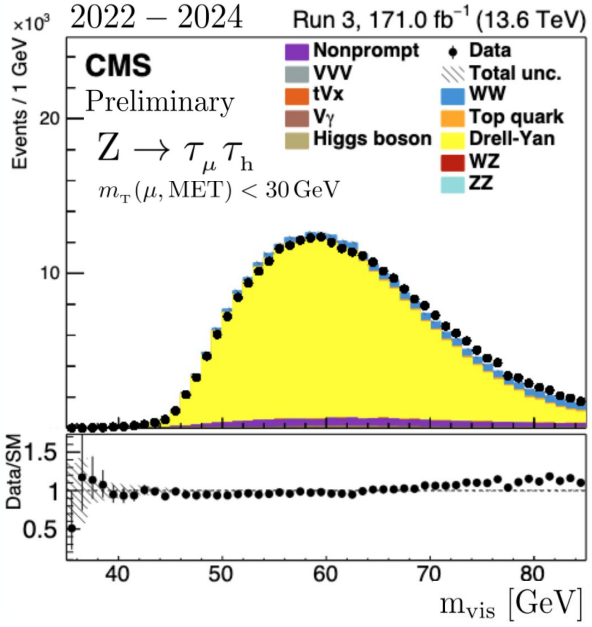
- We already released corrections for 2022 and 2023, with 2024 ones being completed soon before moving to 2025
- Several of our measurements are based on Tag&Probe analyses focusing in Z-enriched regions, at high pT we rely on W*-> τν events

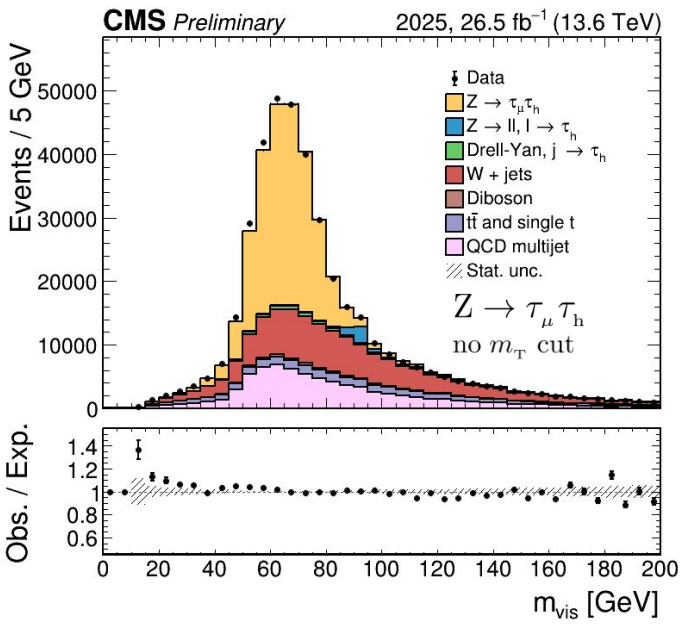


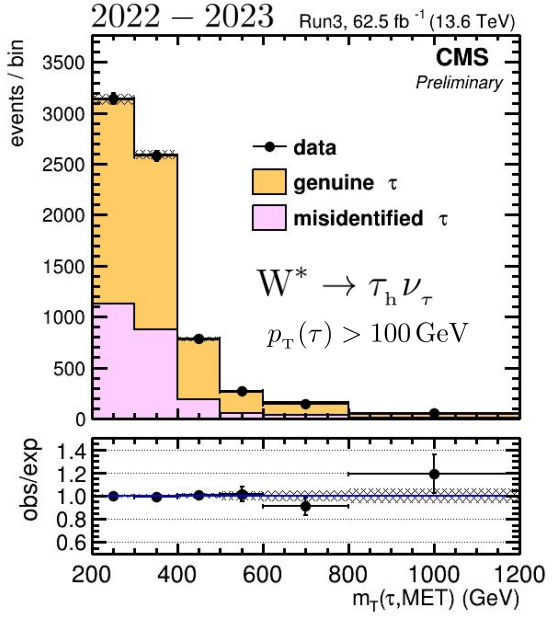


Performance of DeepTau tagger in Run 3

- A full scale campaign on determination of tau ID and energy scale corrections for Run 3 analyses is under way in the TAU POG of the CMS Collaboration.
- DeepTau v2.5 (baseline tagger) performs excellently in Run 3 over the wide range of τ p_T

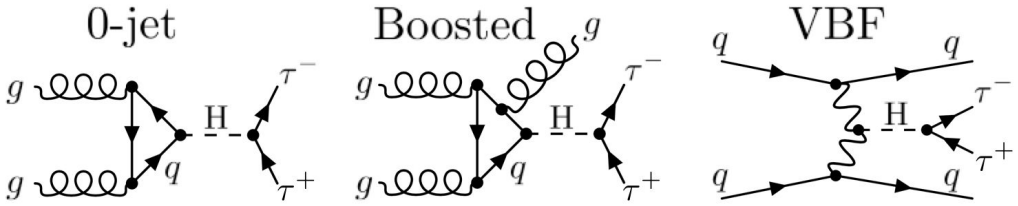


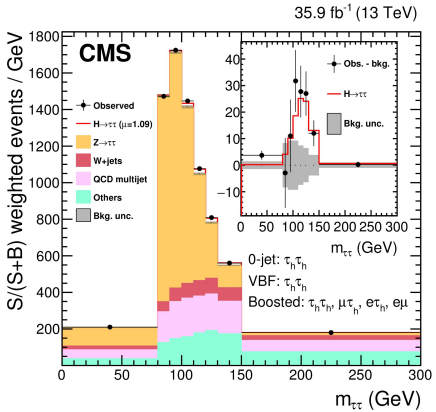


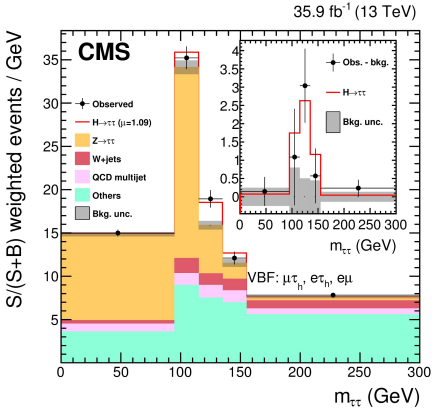


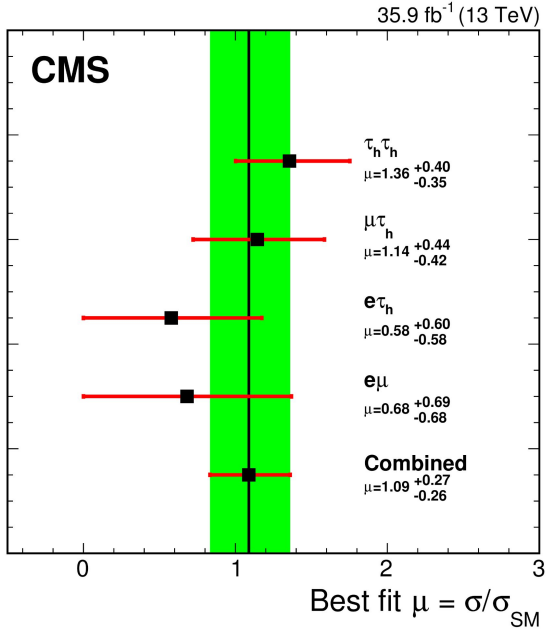
Discovery of H→ττ decay at CMS

- Run 1 (20 fb^{-1} at 8 TeV) + early Run 2 (36 fb^{-1} at 13 TeV) CMS data: **Phys. Lett. B 779 (2018) 283**
- Final states studied: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$ (94% of decay modes covered!)
- Dedicated categories and signal extraction strategies targeting specific production modes









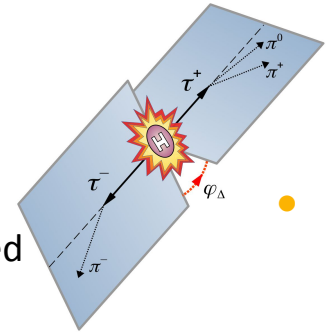
Higgs analyses with tau leptons: selected CMS results

- **CP structure of Hττ coupling** JHEP06 (2022) 012

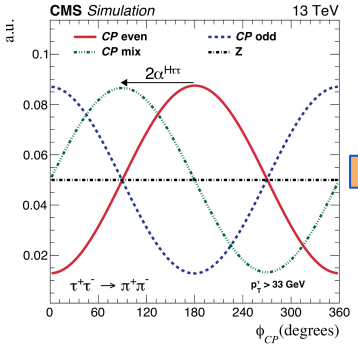
$$\mathcal{L}_Y = \frac{m_\tau}{v}\left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau\right) H$$

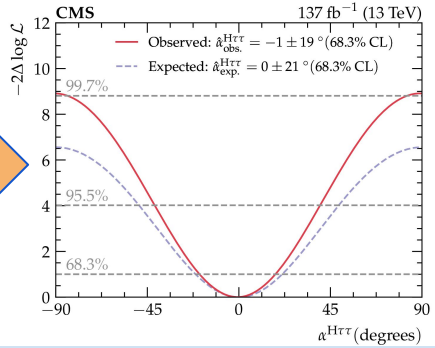
CP-even term — CP-odd term

CP-mixing angle : $\tan\left(\alpha^{H\tau\tau}\right) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$

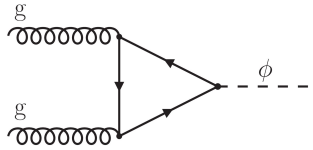


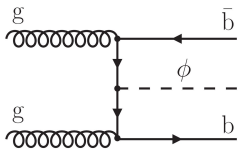
- CP structure of Hττ coupling is inferred from angle between τ decay planes
  - reconstructed using momenta and impact parameters of τ decay products



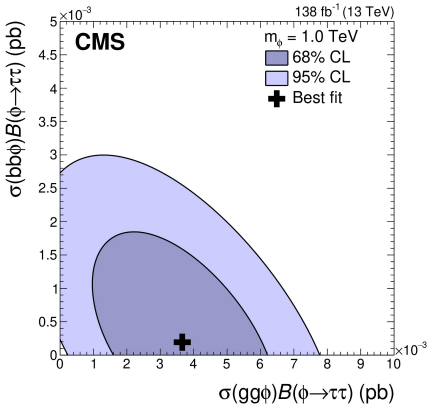


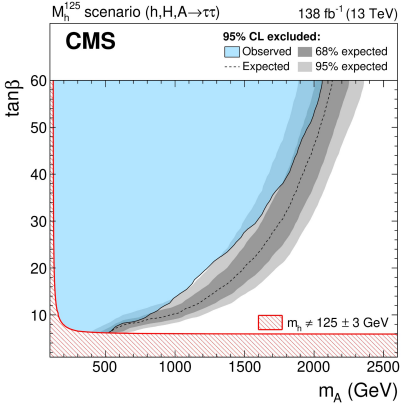
- **Search for BSM Φ→ττ (Φ=H/A)** JHEP07 (2023) 073





- Signal is extracted from the spectrum of transverse mass or fully reconstructed mass of H/A candidate
  - To explore a wide phase-space of SUSY parameters need good tau reconstruction on a wide pT range



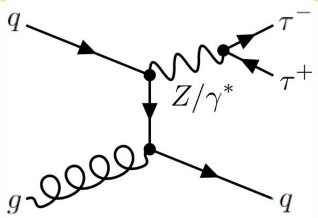


Backgrounds X→ττ analyses

Background with genuine τ pairs

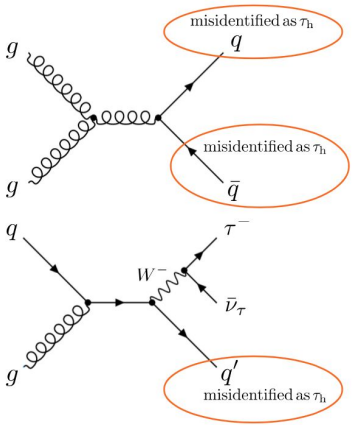
τ-embedding technique : replace $\mu^+\mu^-$ pairs selected in data by simulated τ decays

- Tau identification and energy scale is then calibrated



Background with τ candidates mimicked by hadronic jets

- extrapolated from sidebands with loosely identified τ candidates
- extrapolation factors (also referred to as fake factors) are derived in a dedicated control regions disjoint from the final selected sample of a specific analysis



Remaining background (5-10%) with genuine prompt e/μ or prompt e/μ misidentified as τ_h is estimated from simulation and corrected with correction factors from TauPOG

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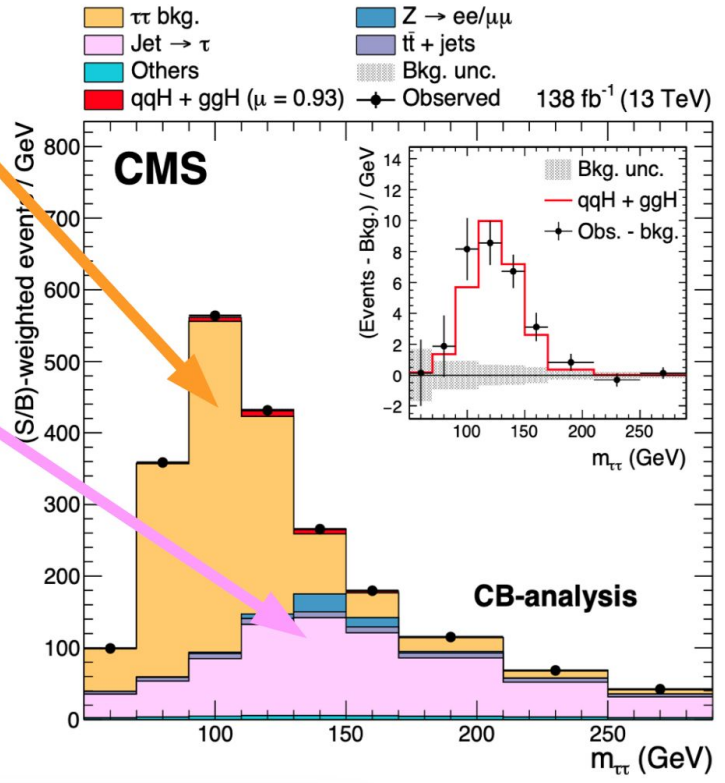


Tau Physics Object Group

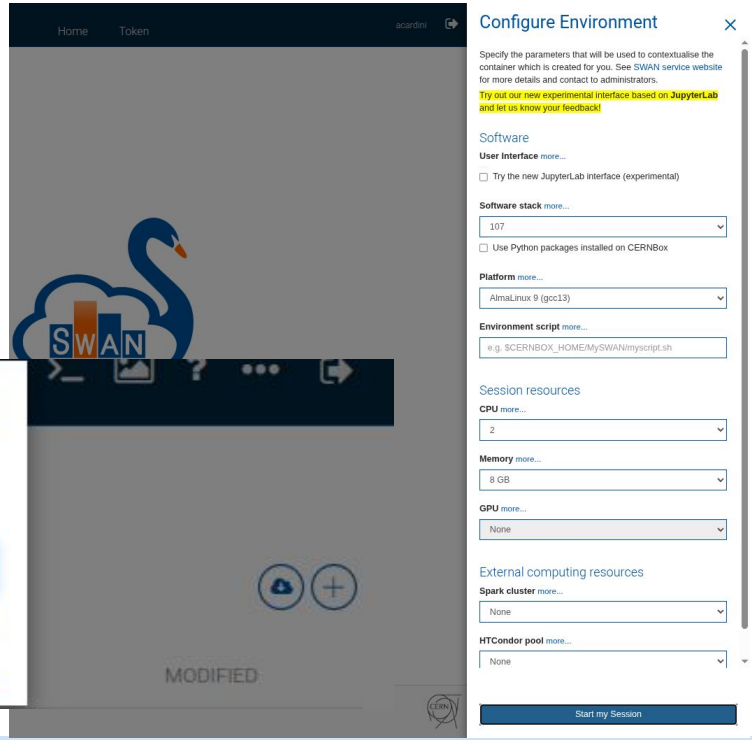
- TAU POG responsibilities
  - Development of tools for the reconstruction and identification of tau leptons
  - Timely delivery of simulation-to-data corrections for physics analyses
    - Tau ID efficiency and momentum scale corrections
    - e/μ→τ misID rate corrections
  - Calibration of the tau-related triggers
  - Review of CMS analyses with tau leptons
  - Work on algorithms for phase 2
- Come and join us!

Tau Website

(Sub-)group	Position	Convener/Contact
Tau Physics Object Group (TAU POG)	L2	Michał Bluj, Izaak Neutelings (all)
Tau Calibration-Quality-Monitoring (TAU CQM)	L3	Alexei Raspereza, Gourab Saha (all)
Tau Trigger (TAU TRIG)	L3	Braden Allmond, Botao Guo (all)
Tau Algorithms (TAU ALGO)	L3	Pritam Palit, Lucas Russell (all)
Validation (offline)	contact	Andreas Gruber
Validation (online)	contact	Gourab Saha
RECO/SW	contact	Pritam Palit, [looking for second!]
Phase II (upgrade)	contact	[Looking for trigger & offline contacts!]
MC	contact	Lucas Russell
Embedding	contact	Christian Winter

Now it's your turn

- Go to the GitLab page of the exercise and follow the instructions in the README
- Check you can access https://swan.cern.ch/ and download the exercise
- Download the exercise clicking on the + sign
- Enter the http url of the exercise
- You're ready to start learning how tau reconstruction and Identification works, and train with a bit of python



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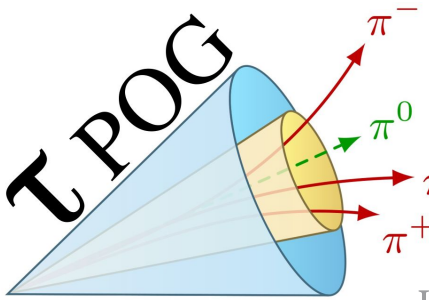

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