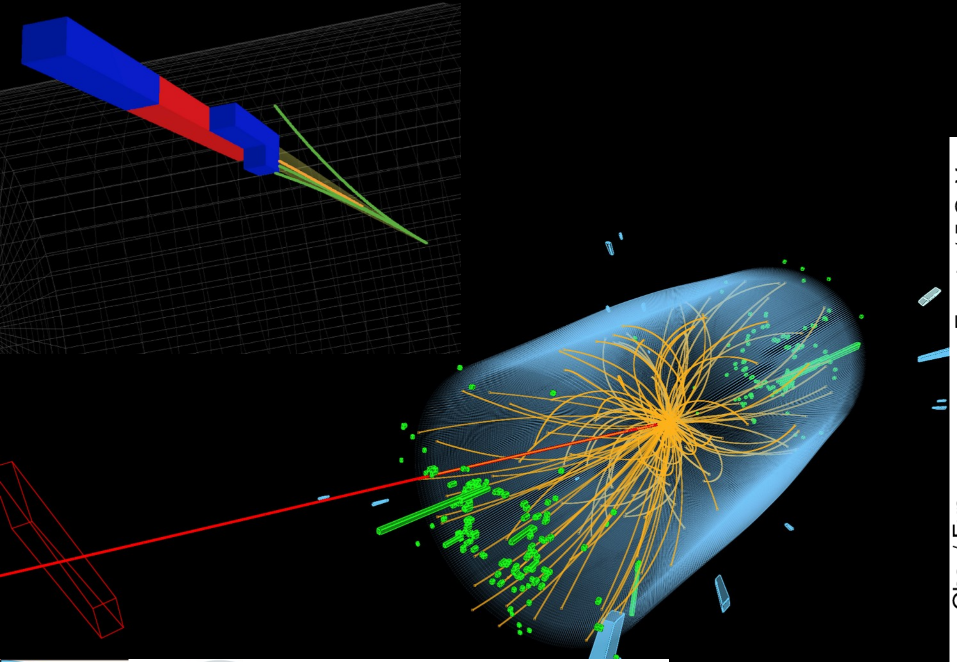
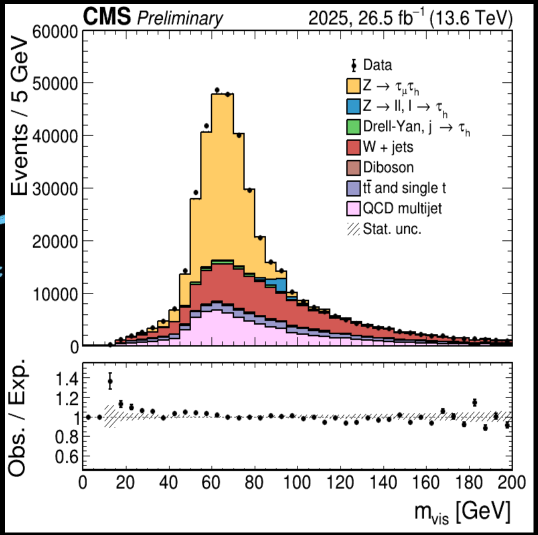
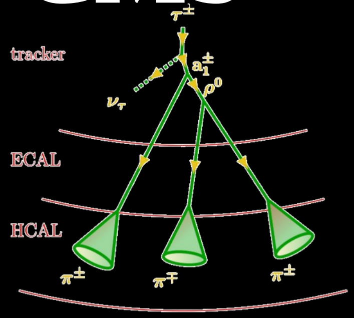
Investigating the Higgs and new physics at the LHC with the Tau Lepton:

Evolution and Latest Developments in CMS

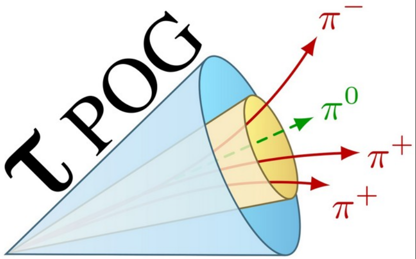


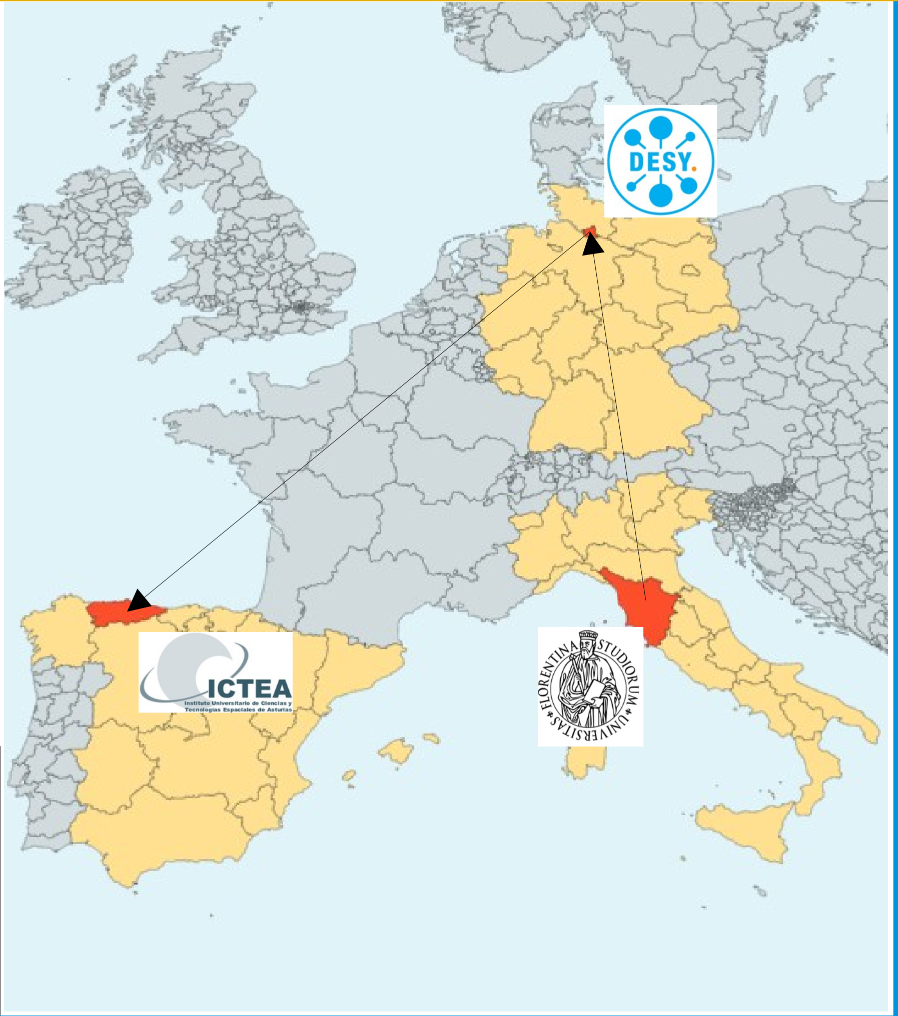




Andrea Cardini – ICTEA–Universidad de Oviedo, Spain

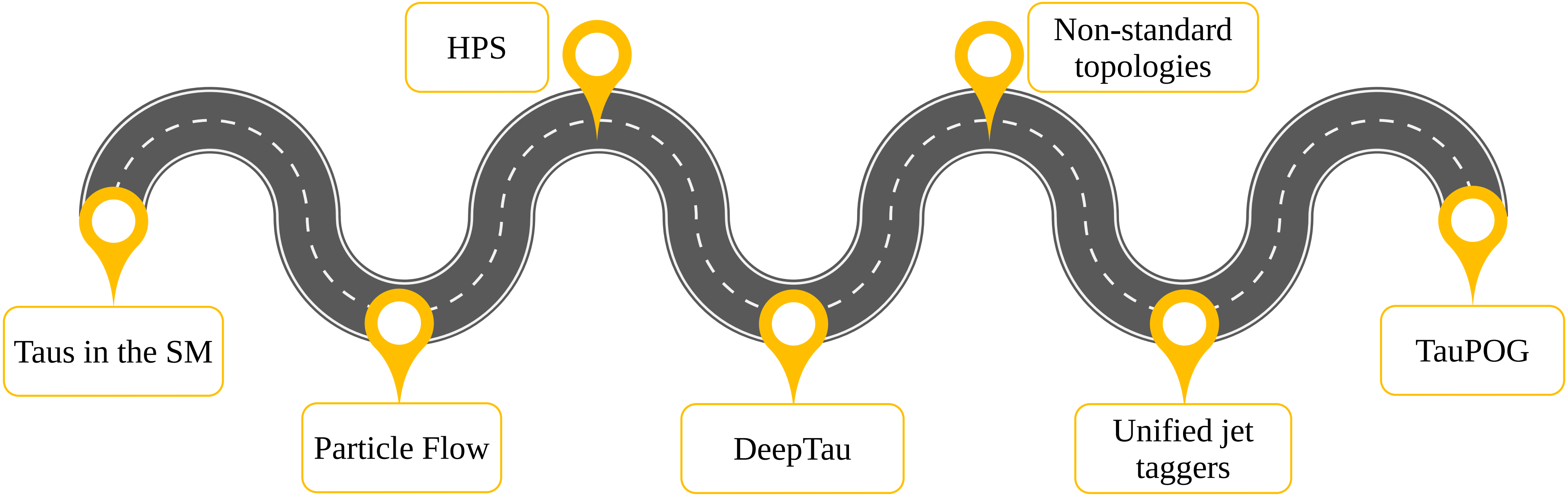
- Born in Firenze, Italy, in 1993, lived there till 2017
- Ph.D. in Particle Physics at DESY, Germany in 2021
- DESY Fellow between 2021–2024
- Since November 2024: Postdoc in Oviedo, Asturias
- Proud member of the CMS Collaboration since 2017
- Up to September last year: L2 coordinator of the CMS Tau Physics Object Group





Road of the talk

- The aim:
  - Historical overview of tau identification and reconstruction in CMS
  - Latest developments and what is *cooking* in our collaboration



Road of the talk

- The aim:
  - Historical overview of tau identification and reconstruction in CMS
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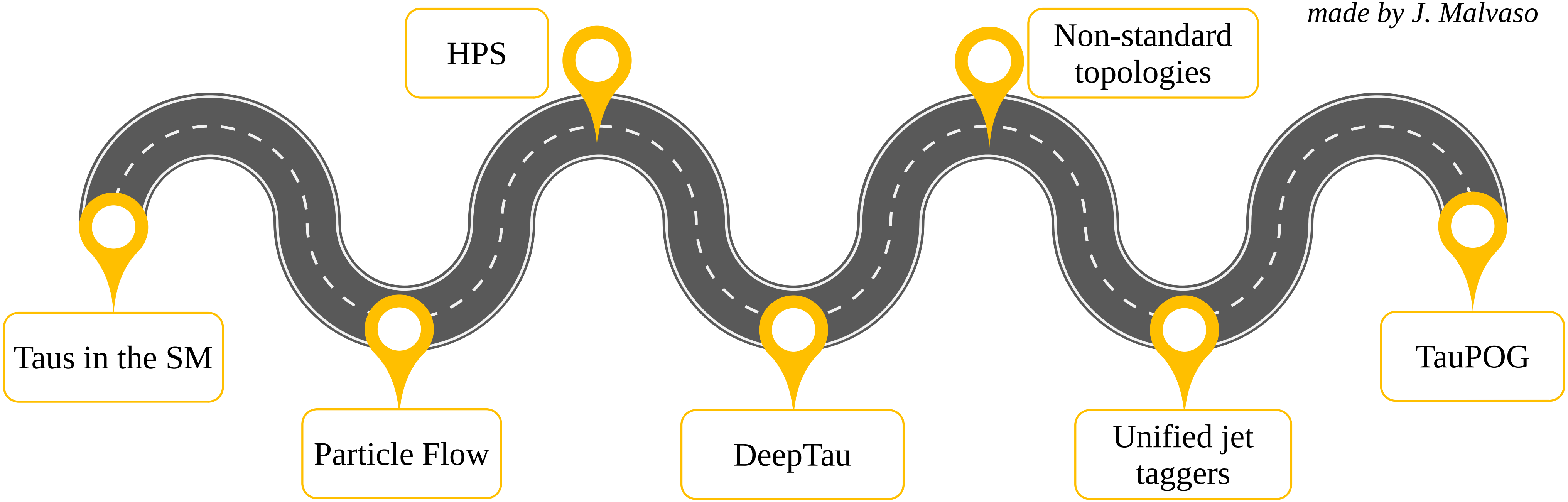
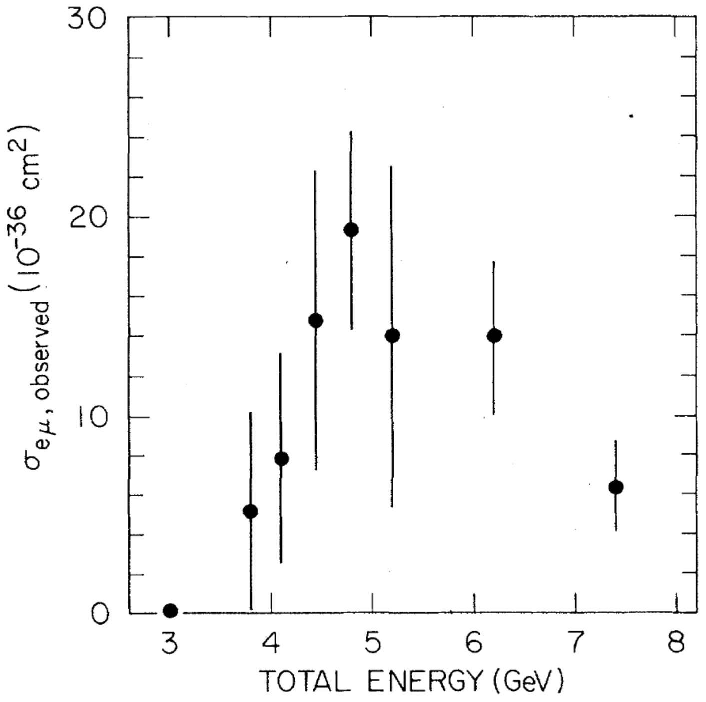
made by J. Malvaso



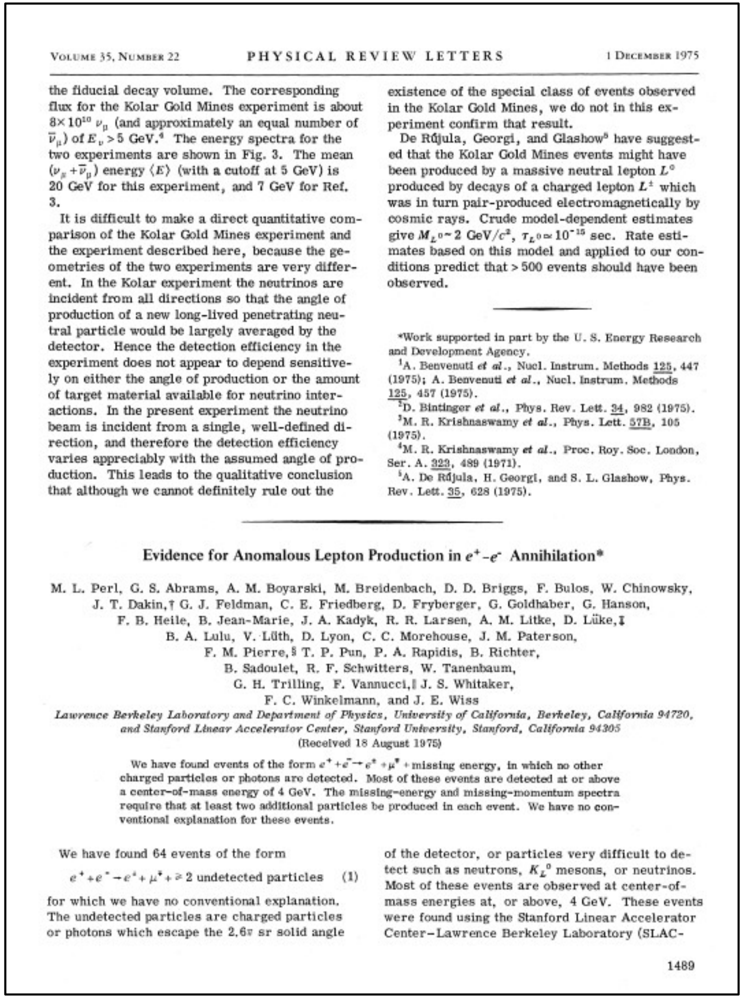
History of tau leptons

- Signatures of tau decays were initially predicted by Yung-Su Tsai in 1971, as a heavy lepton capable of decaying to hadrons
- The discovery came in 1975 with the observation at SLAC of 64 events for
  - $e^+e^- \rightarrow e^{\pm} + \mu^{\mp} + \geq 2$ undetected particles
- The existence of undetected particles (4) was inferred by the momentum conservation for the system
- Such events could not be explained by the decays of particles known at that time and agreed with the predictions made 4 years prior
- The particle was named tau as the first letter of the word *τρίτον* (*third* in Greek)
- Nowadays the tau lepton is an established particle of the SM and its neutrino has also been discovered



Phys. Rev. Lett. 35 (Dec, 1975) 1489–1492

50 years of tau leptons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the fiducial decay volume. The corresponding flux for the Kolar Gold Mines experiment is about 8×10^{10} ν_μ (and approximately an equal number of $\bar{\nu}_\mu$) of $E_\nu > 5$ GeV.[4] The energy spectra for the two experiments are shown in Fig. 3. The mean $(\nu_\mu + \bar{\nu}_\mu)$ energy $\langle E\rangle$ (with a cutoff at 5 GeV) is 20 GeV for this experiment, and 7 GeV for Ref. 3.

It is difficult to make a direct quantitative comparison of the Kolar Gold Mines experiment and the experiment described here, because the geometries of the two experiments are very different. In the Kolar experiment the neutrinos are incident from all directions so that the angle of production of a new long-lived penetrating neutral particle would be largely averaged by the detector. Hence the detection efficiency in the experiment does not appear to depend sensitively on either the angle of production or the amount of target material available for neutrino interactions. In the present experiment the neutrino beam is incident from a single, well-defined direction, and therefore the detection efficiency varies appreciably with the assumed angle of production. This leads to the qualitative conclusion that although we cannot definitely rule out the existence of the special class of events observed in the Kolar Gold Mines, we do not in this experiment confirm that result.

De Rújula, Georgi, and Glashow[5] have suggested that the Kolar Gold Mines events might have been produced by a massive neutral lepton L^0 produced by decays of a charged lepton $L^\pm$ which was in turn pair-produced electromagnetically by cosmic rays. Crude model-dependent estimates give $M_{L^0} \sim 2$ GeV/c^2, $\tau_{L^0} \simeq 10^{-15}$ sec. Rate estimates based on this model and applied to our conditions predict that > 500 events should have been observed.

*Work supported in part by the U. S. Energy Research and Development Agency.

[1] A. Benvenuti *et al.*, Nucl. Instrum. Methods 125, 447 (1975); A. Benvenuti *et al.*, Nucl. Instrum. Methods 125, 457 (1975).
[2] D. Bintinger *et al.*, Phys. Rev. Lett. 34, 982 (1975).
[3] M. R. Krishnaswamy *et al.*, Phys. Lett. 57B, 105 (1975).
[4] M. R. Krishnaswamy *et al.*, Proc. Roy. Soc. London, Ser. A. 323, 489 (1971).
[5] A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 35, 628 (1975).

Evidence for Anomalous Lepton Production in e^+–e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss
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(Received 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

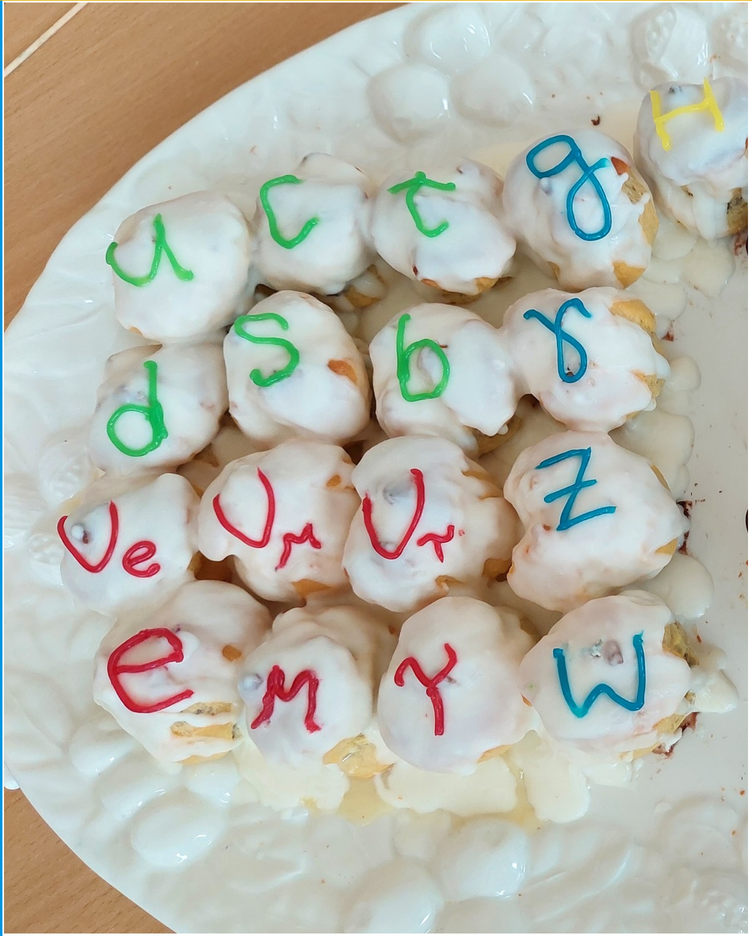
We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-

- The discovery of tau leptons was announced with an article on the 1st of December 1975
- We are now living in the 50th year after the discovery!
- Happy birthday tau lepton!

Taus in the Standard Model



made by A. Cardini and D. Leyva Pernia

- 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)

Leptonic decays: presence of 2 neutrinos which are mostly emitted collinearly

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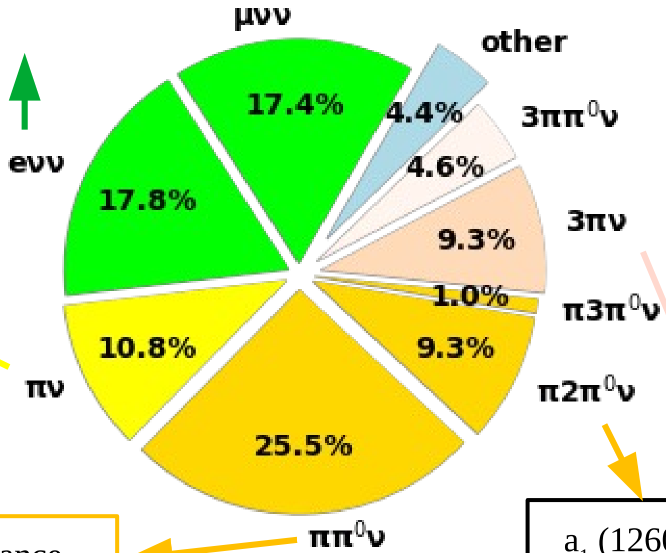
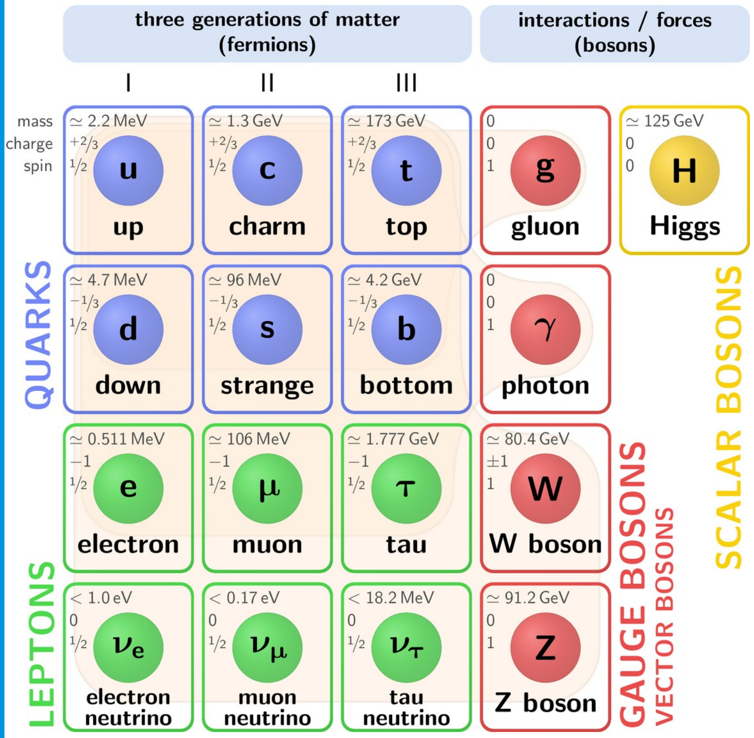


2-body decay

ρ (770) resonance

a_1 (1260) resonance

Taus in the Standard Model



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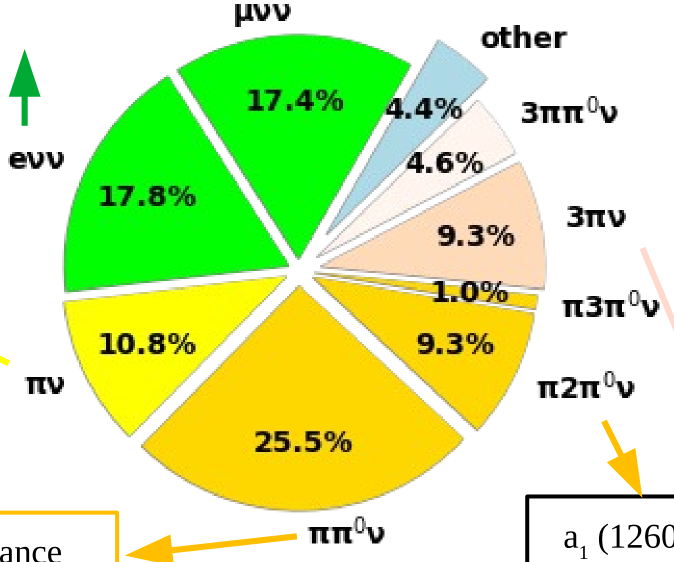

2-body decay

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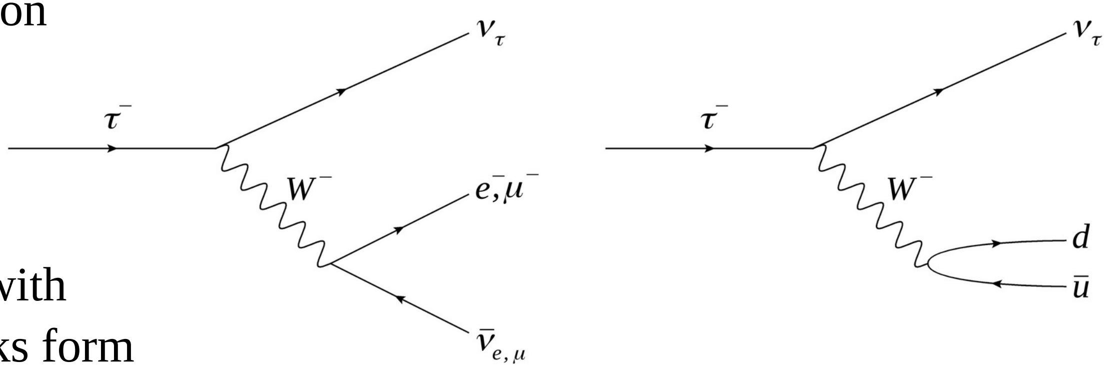
Taus as probe for EW physics

- Taus decay purely via electroweak interaction
- Its mass is ~50 times smaller than the W boson → the effective Fermi theory for weak interaction holds
- Tau leptons decay hadronically to mesons with small perturbative QCD effects as the quarks form a color-neutral bound state



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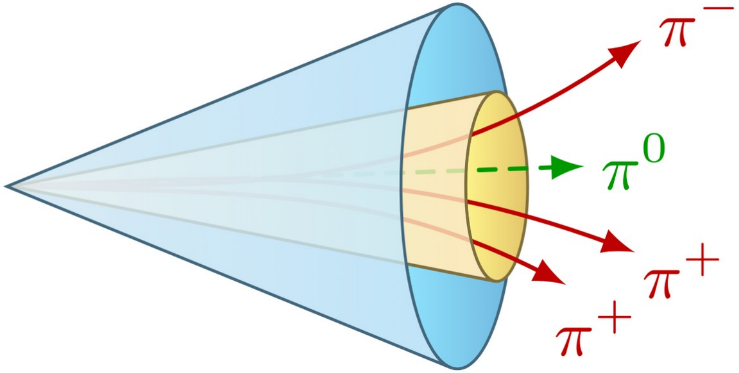
  - Hadronic decays can be *mostly* seen as a chain of 2-body decays with intermediate mesonic resonances
  - The mesons preserve memory of the tau spin → excellent probes for CP violation
  - Taus are also excellent probes for Lepton Flavor Universality tests
- Taus are also used in modern experiments to look for new physics
  - Forbidden decays: $\tau \to 3\mu$, $\tau \to \mu\gamma$, $\tau \to \mu ee$
  - Searches for BSM particles decaying to tau leptons: leptoquarks, super-partners of the tau, or extended Higgs sector

Taus in CMS: early days

- Taus have been studied in CMS since its inception
- As pure electroweak objects they are unaffected by infrared and collinear safety generally associated to the reconstruction algorithms used for QCD jets
- In the early days of the CMS experiment hadronically decaying taus (τ_h) were reconstructed directly from the tracks identified in the Tracker system and the energy deposits found in the calorimeters
  - Calorimeter Jets as seed → identify highest pT track
  - Define two cones around the track: a signal cone ($\Delta R \sim 0.15$) and an isolation cone ($\Delta R \sim 0.5$)
  - Gather tracks and electromagnetic deposits within signal cone as possible tau candidates + use isolation cone to reject quark/gluon jets



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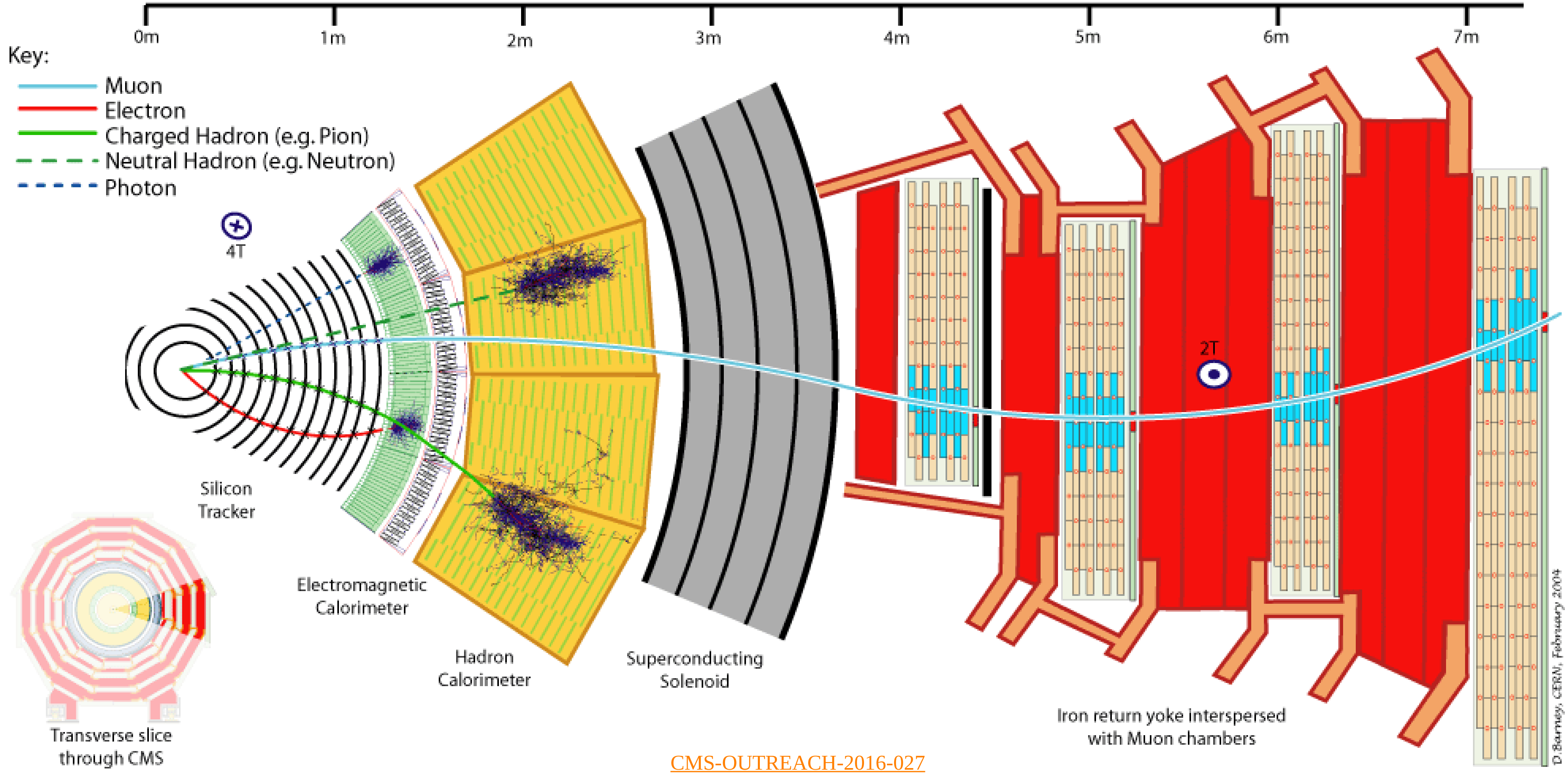
- It was one of the first cases used for the combination of particle properties across different detectors
  - Tau reconstruction was used as one of the first test cases for the Particle Flow algorithm
- The original group managing the reconstruction of τ_h was the PFT: Particle Flow and Tau

The Particle Flow algorithm



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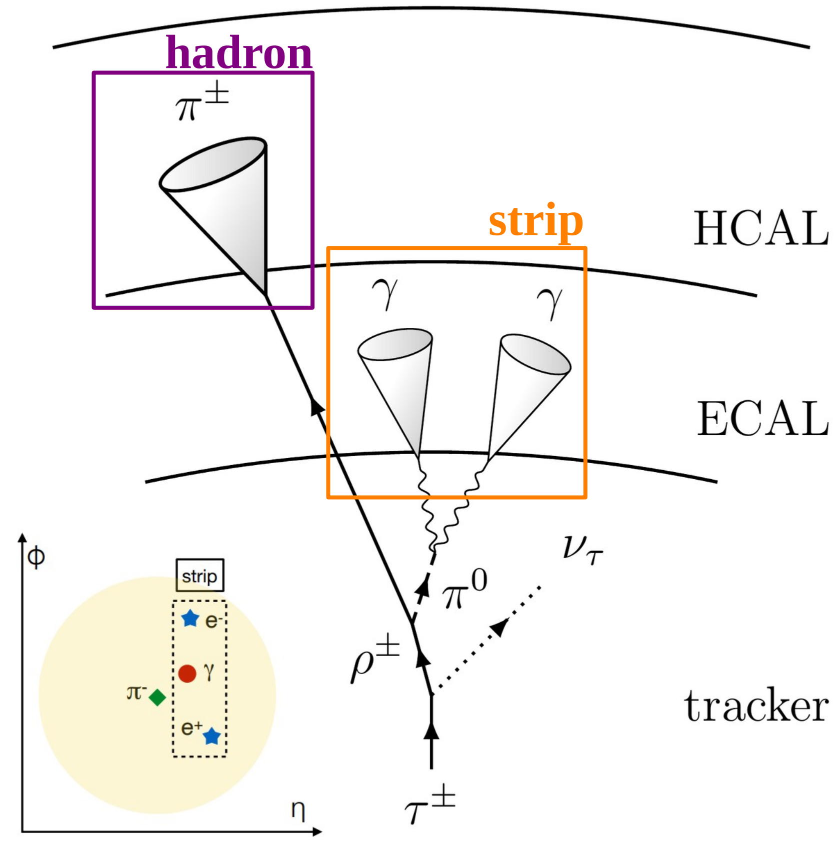


$\tau^{\pm} \to \rho^{\pm}\nu_\tau \to \pi^{\pm}\pi^0\nu_\tau$

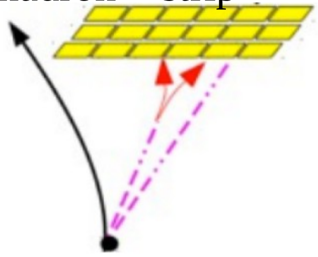
- The Hadron-plus-strip algorithm is used to reconstruct τ_h
- It combines information from the tracker and the electromagnetic and hadronic calorimeters
- Its first version identified 3 distinct decay channels (labeled DM=5×(n_{prong} – 1) + $n_{\pi 0}$)
  - DM identified:
    - 0) $\tau \to \pi$
    - 1) $\tau \to \pi+\pi^0$
    - 2) $\tau \to \pi+2\pi^0$
    - 10) $\tau \to 3\pi$

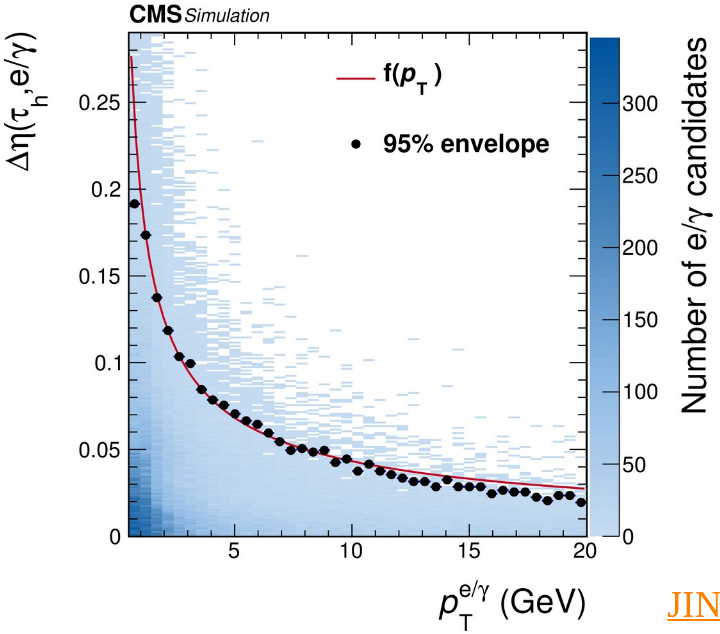
neutrinos are not written for simplicity

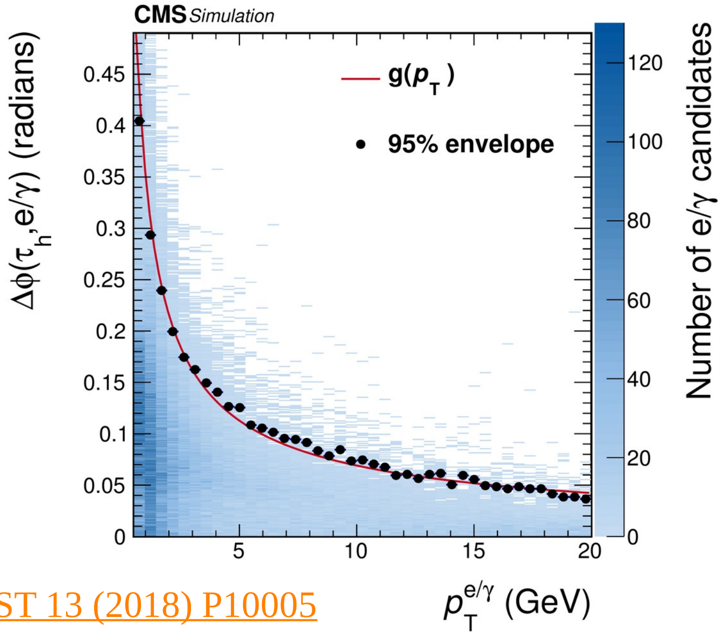
- Later versions introduced DM 11 and a recovery for 3 prong decays with one missing pion:
    - 11) $\tau \to 3\pi+\pi^0$
- A maximum of 6 tracks identified within $\Delta R<0.5$ from the jet direction of flight are evaluated as tau decay products

Neutral pion reconstruction

- Neutral pions are a crucial component in tau decays → their signature is a cluster of electrons, positrons and photons narrow in η and elongated in φ (magnetic drift for e+/e- pairs)
- Two versions of π^0 (strip) reconstruction have been used by CMS: labeled *fixed* and *dynamic*
- Starting from the jet seed direction of flight e+/e-/γ are added to the cluster if found within a certain window around the current center of the cluster







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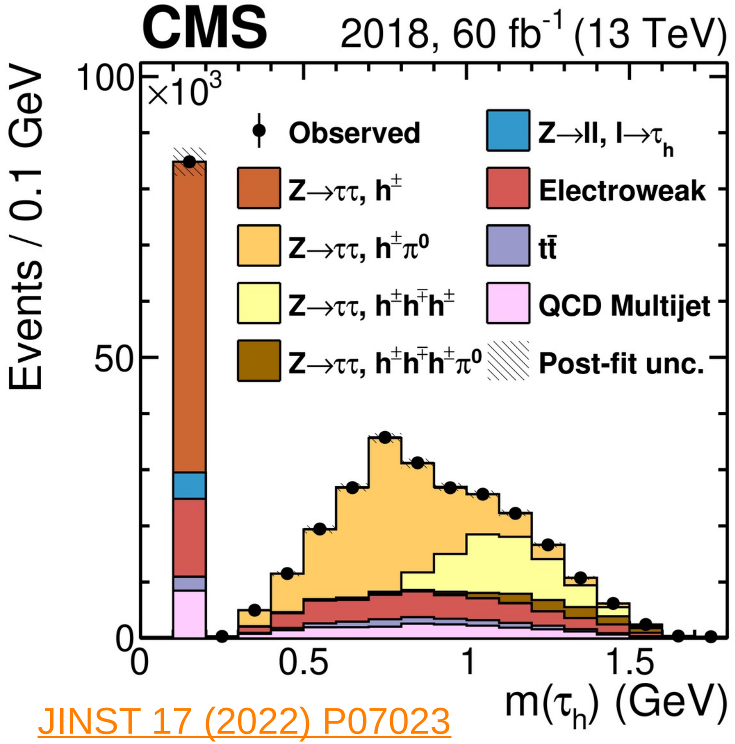
- The original algorithm had a fixed Δη-Δφ window
- The latest version uses a dynamic window size as function of pT
- The change maximized the efficiency in identifying π^0s at the cost of a reduced ability of counting them

The HPS algorithm

- Up to 6 tracks and 6 strip candidates are considered and compared to different tau decay hypotheses
- The combinations are ranked based on the invariant mass of the system, and track quality criteria
- Invariant mass of tau candidates are tested against the different decay channels

all values in GeV

  - $m_\tau < 1$ for **1 prong**
  - $0.3 < m_\tau < 1.3 \times \sqrt{(p_T/100)}$ for **1 prong + π^0**
  - $0.4 < m_\tau < 1.2 \times \sqrt{(pT/100)}$ for **1 prong + $2\pi^0$**
  - $0 < m_\tau < 1.2$ for **2 prong**
  - $0 < m_\tau < 1.2 \times \sqrt{(p_T/100)}$ for **2 prong + π^0**
  - $0.8 < m_\tau < 1.4$ for **3 prong**
  - $0.9 < m_\tau < 1.6$ for **3 prong + π^0**
- Decays with π^0s have the mass window widened based on the strip energy
- The 2 prong decays were introduced to account for cases where a third hadron was not properly reconstructed



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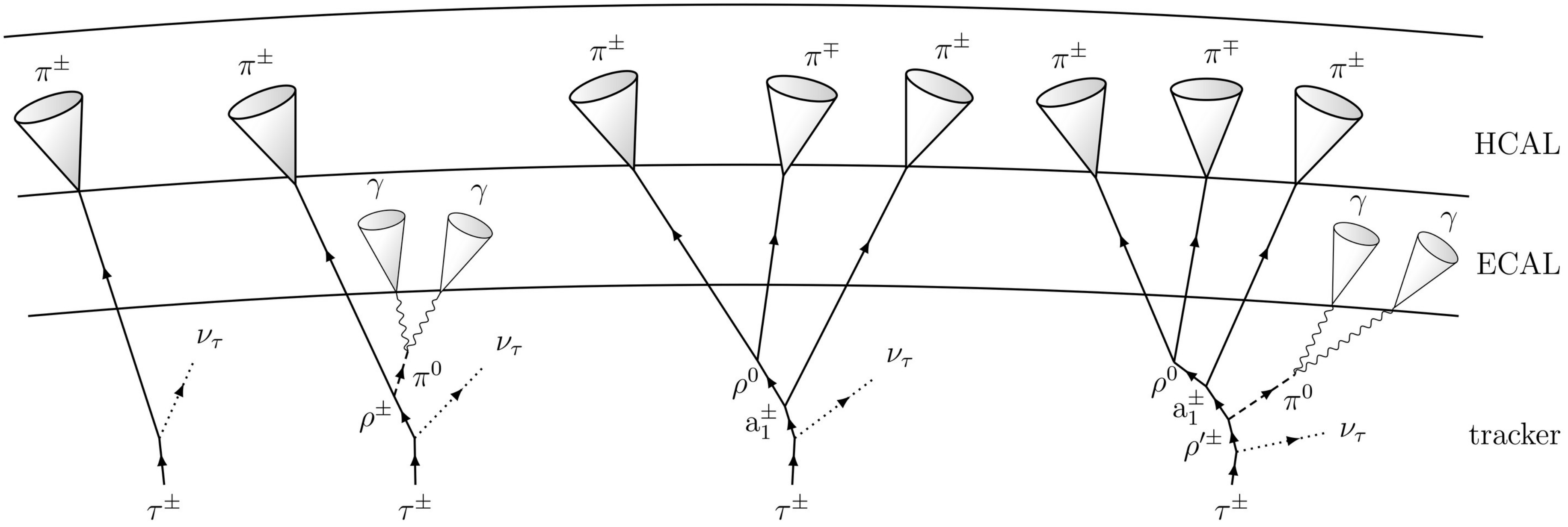
HPS decay channels

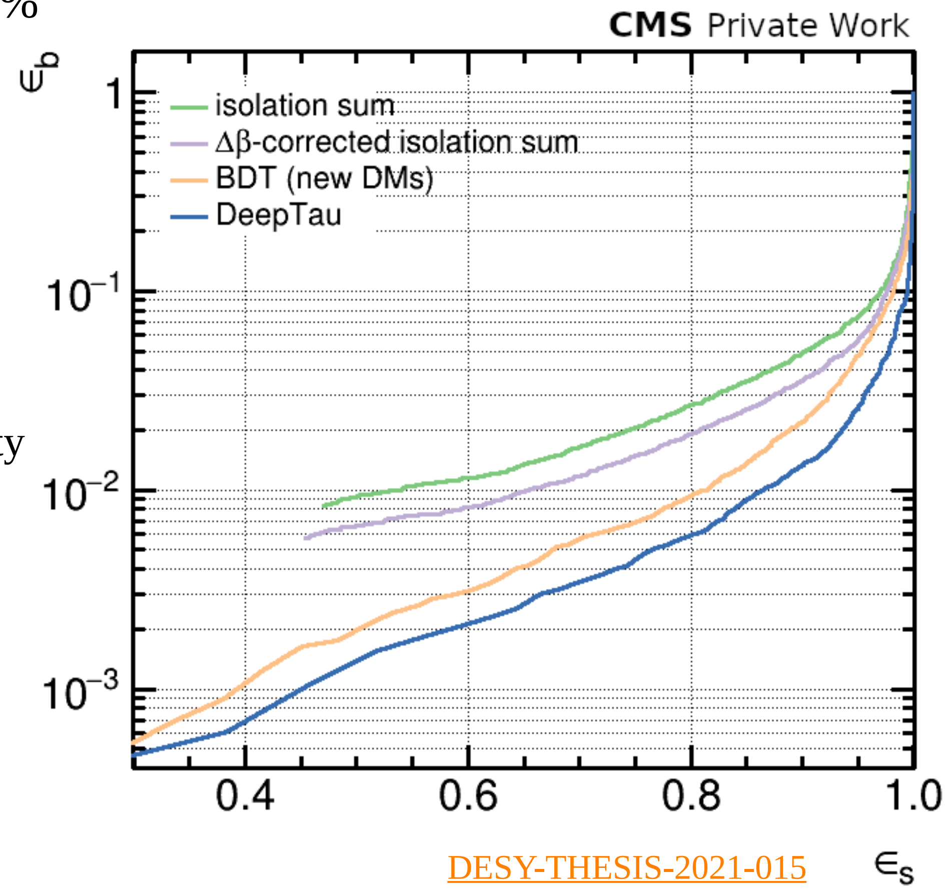


$\tau^\pm \to \pi^\pm \nu_\tau$ $\quad$ $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$ $\quad$ $\tau^\pm \to a_1^\pm \nu_\tau \to \pi^\pm \pi^\mp \pi^\pm \nu_\tau$ $\quad$ $\tau^\pm \to \rho'^\pm \nu_\tau \to \pi^\pm \pi^\mp \pi^\pm \pi^0 \nu_\tau$

- In practice 4 main decay modes are defined for HPS as the dynamic strip reconstructions causes a migration of events from DM 2 to 1, and the 2 prong channels are *generally* ignored due poorer charge resolution (~65%)
- Machine learning algorithms were found to be able to further refine the DM reconstruction done by HPS, particularly being able to count the number of neutral pions involved in the decay

Tau identification

- HPS is designed to prioritize efficiency over purity
- It reconstructs ~70% genuine taus while rejecting ~85% quark/gluon jets, ~90% electrons, and 99% muons
- More refined algorithms are needed to reject these misidentified objects
- The first iteration of tau identification was performed as an isolation variable:
  - Sum of the energy for charged and neutral objects found within 0.5 from the τ_h, later corrected by the energy density of the event
- ML-based models arose during Run 2 to further improve identification
- The first: a BDT-based ID to separate genuine taus from quark/gluon jets
  - It was accompanied by separate a BDT to reject electrons and a cut-based rejection against muons



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DeepTau – a CNN-based identification

- **DeepTau** was introduced during the LHC Run 2 as an alternative to the BDT-based algorithm used at the timed of Run 2
- Most distinctive features:
  - Simultaneous rejection of quark/gluon jets, electrons, and muons
  - Convolutional neural network architecture → features represented on a grid in η-φ centered around the τ_h direction of flight
  - Tau constituents (identified by HPS) and additional PF candidates found around the tau used for the classification
- DeepTau was trained and works with HPS candidates using their properties to improve the identification of genuine τ_h
- The first version of DeepTau used at analysis level in CMS was labeled v2.1 and it became the standard used for physics analyses after the end of Run 2

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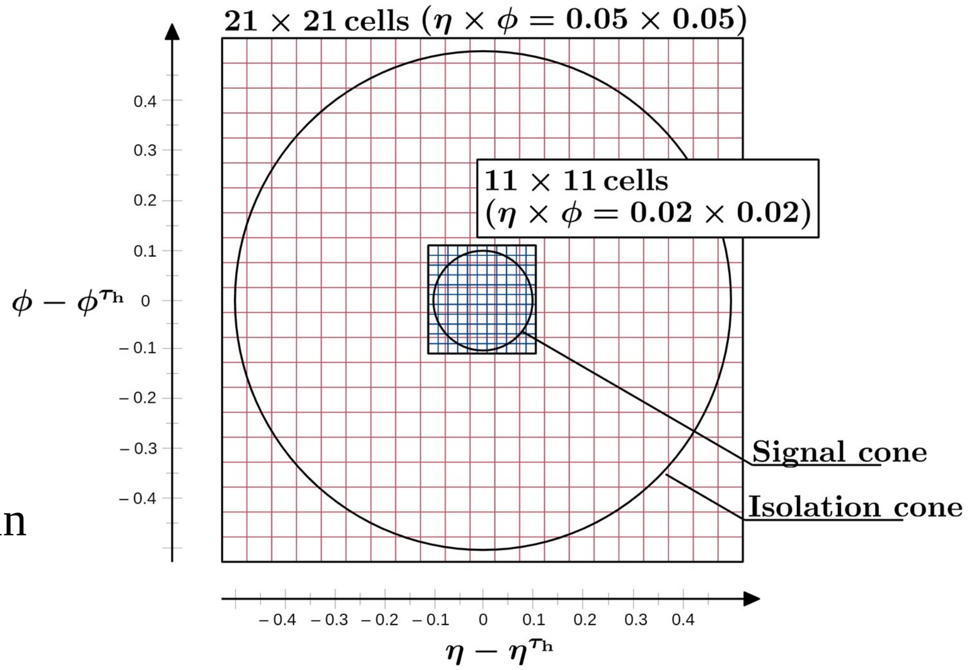

The DeepTau CNN algorithm

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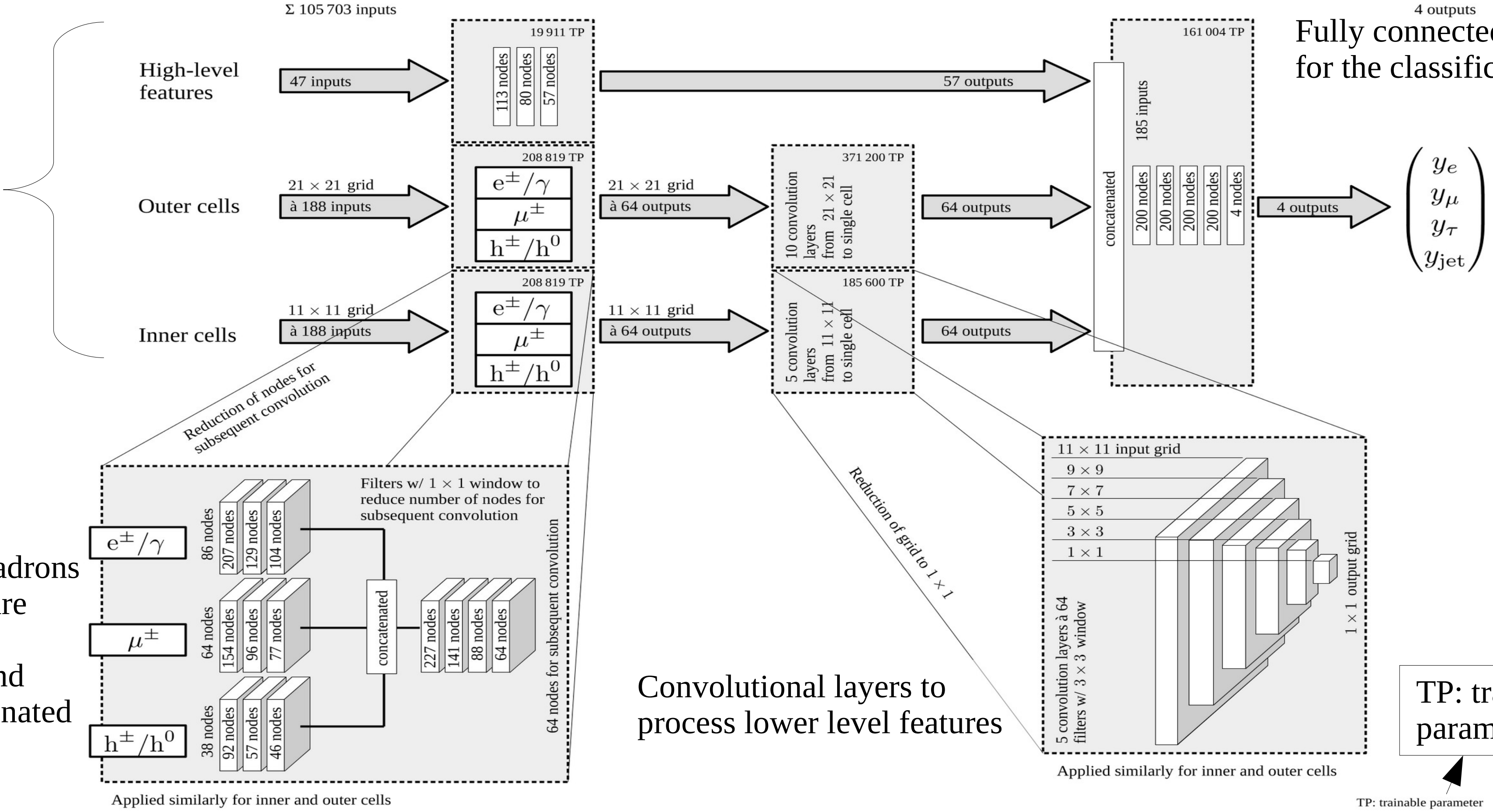
pre-processed separately

Fully connected layers for the classification



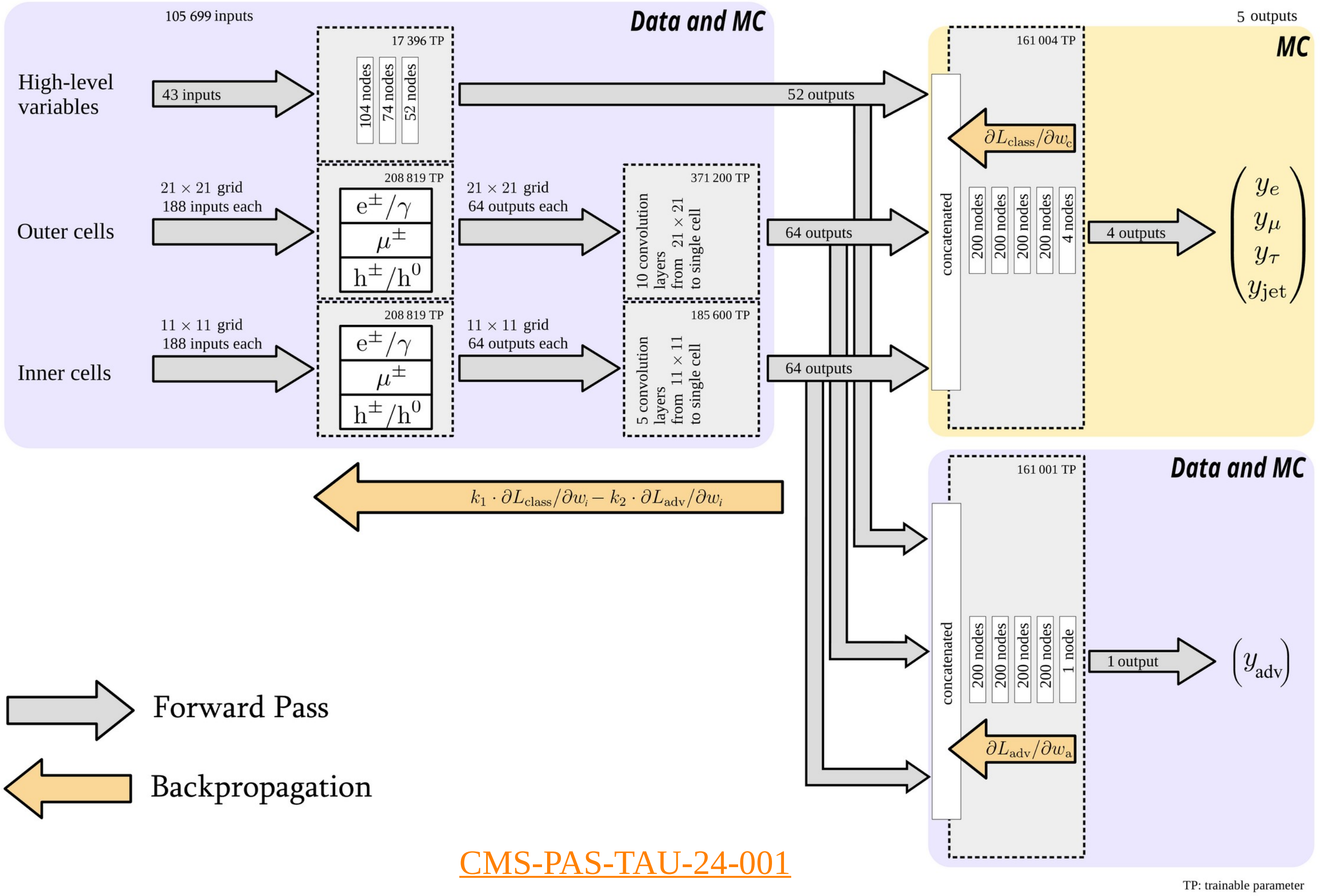
Electrons, hadrons and muons are processed separately and then concatenated

Convolutional layers to process lower level features

TP: trainable parameter

DeepTau for Run 3: version 2.5

- During the long shutdown CMS worked on improving upon DeepTau v2.1:
  - Improved dataset preparation and refinement of the training parameters
  - Introduction of domain adaptation techniques to reduce model sensibility to simulation mismodelling in training
- This new algorithm was deployed at the start of Run 3: **DeepTau v2.5**



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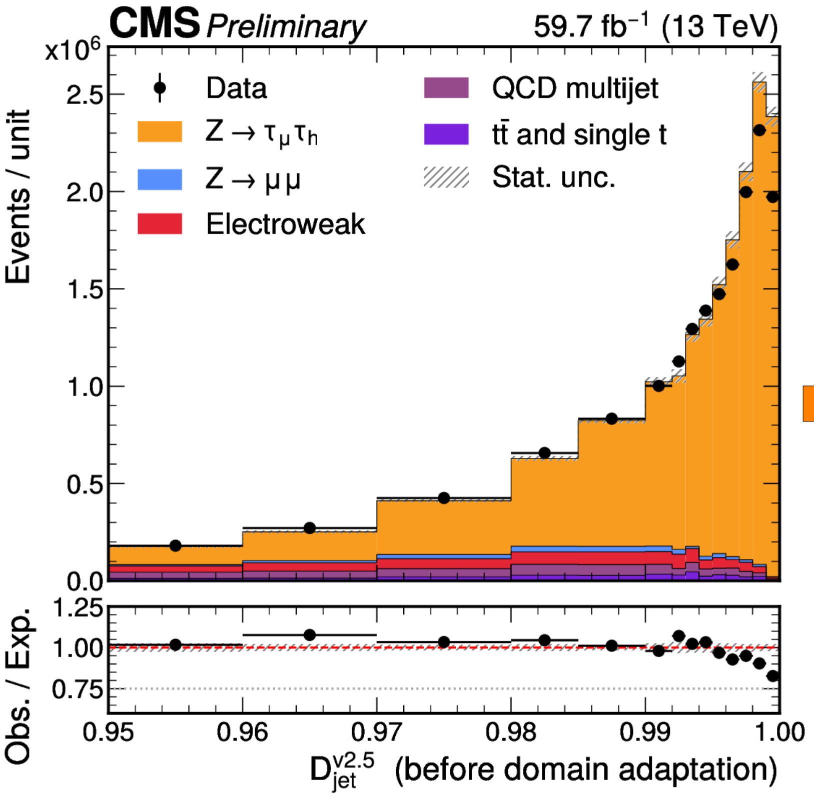
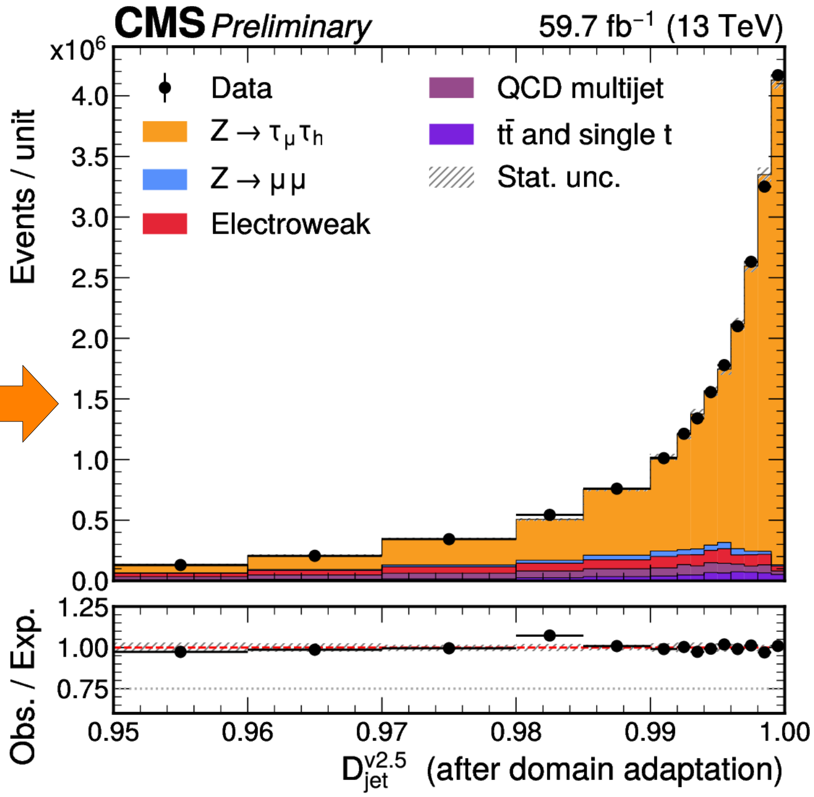
Domain adaptation

- A subnetwork is trained to separate data and MC reducing the weight of mismodelled events
- The effect is particularly relevant at the highest score for the classifiers
- The domain adaptation was performed for 2018 data but holds well also in Run 3





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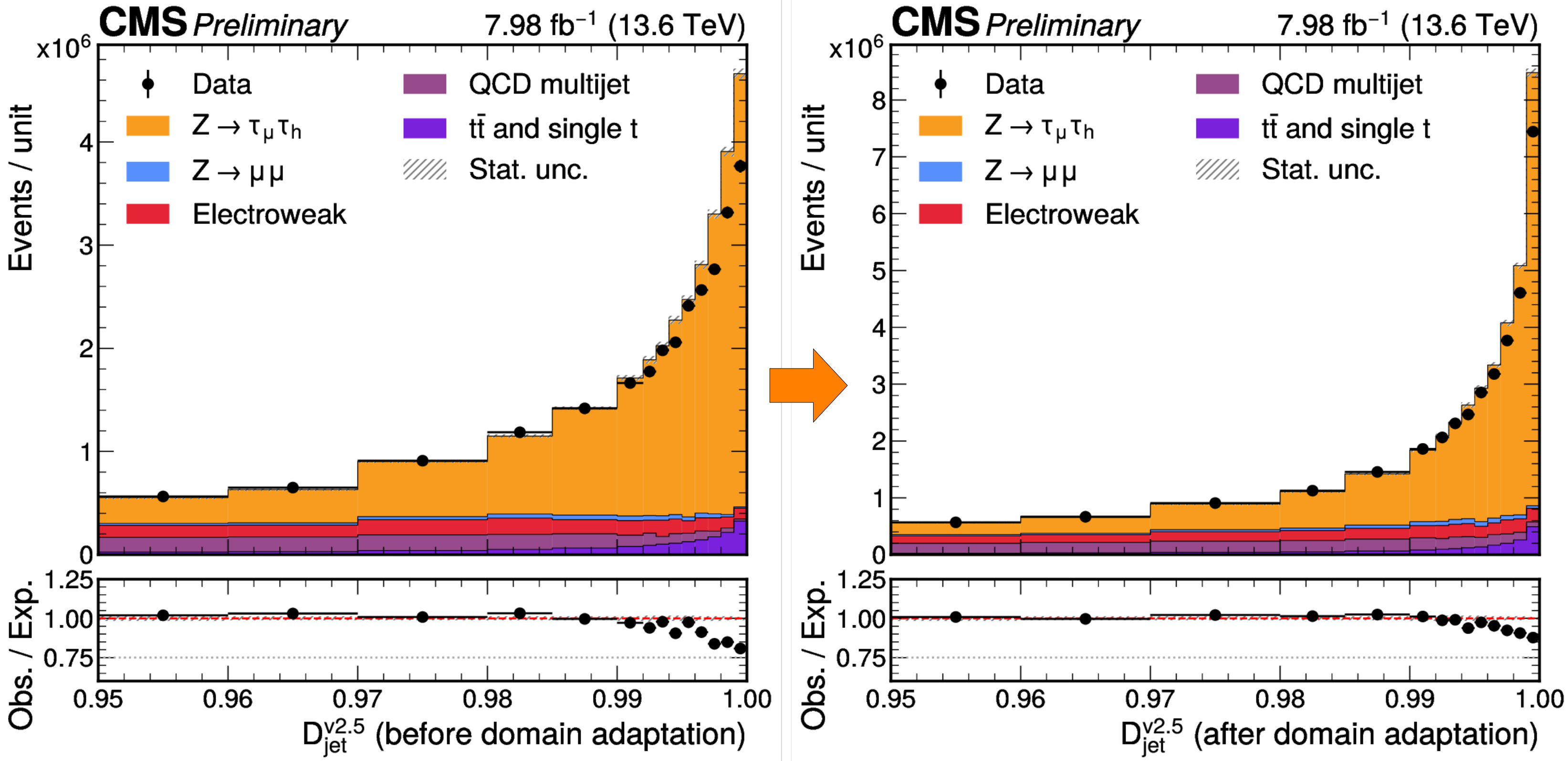

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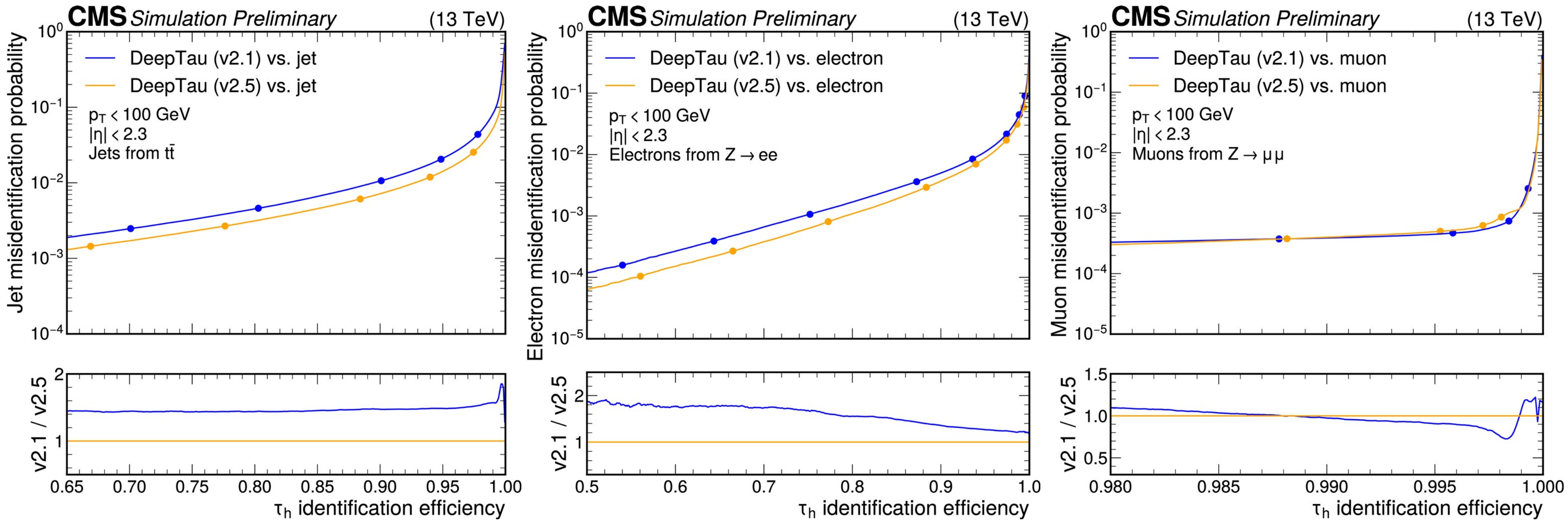
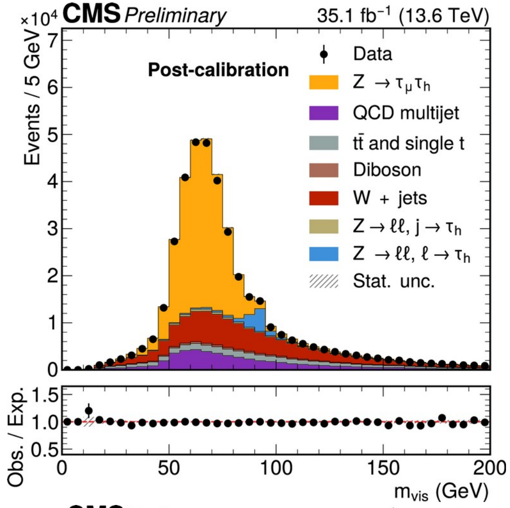
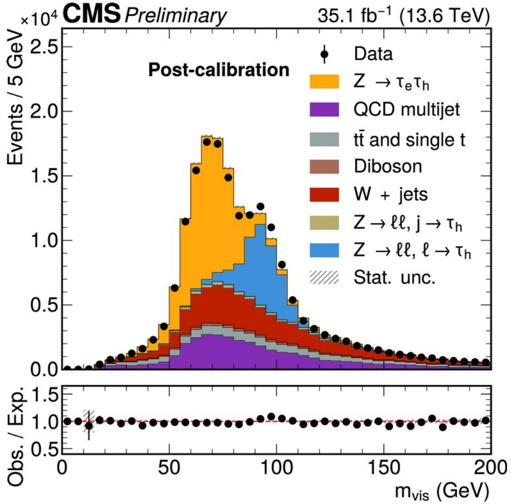


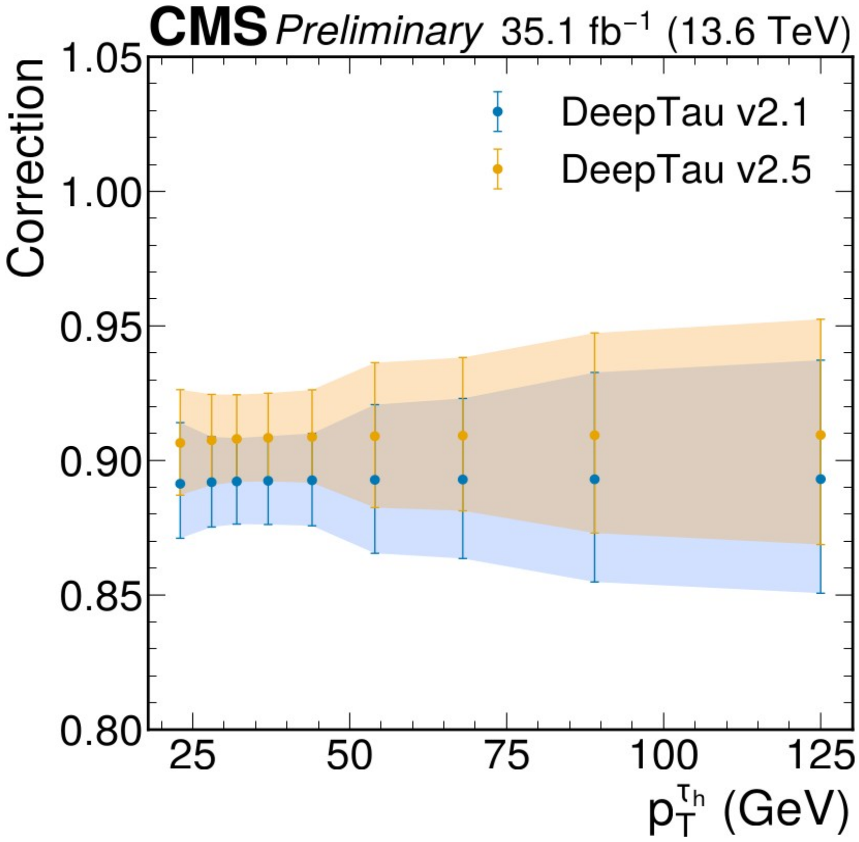
- Improvements for the new model focused on improving the identification of τ_h against both quark/gluon jets and electrons
- Performance was kept the same for muons while improving the modelling of the classifier scores across all classifiers

Performance during Run 3





- After calibrating for residual effects DeepTau v2.5 achieves excellent description of data and great rejection of both quark/gluon jets and leptons



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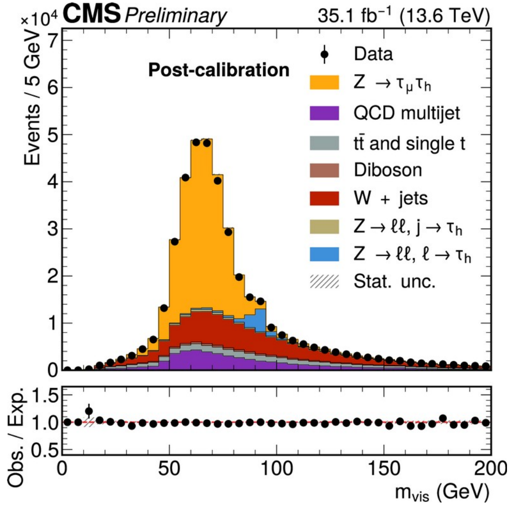

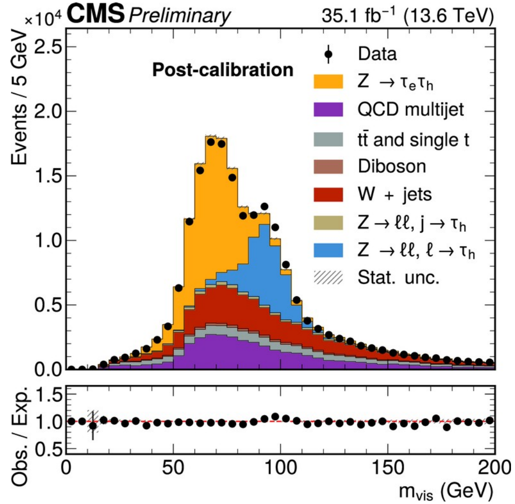

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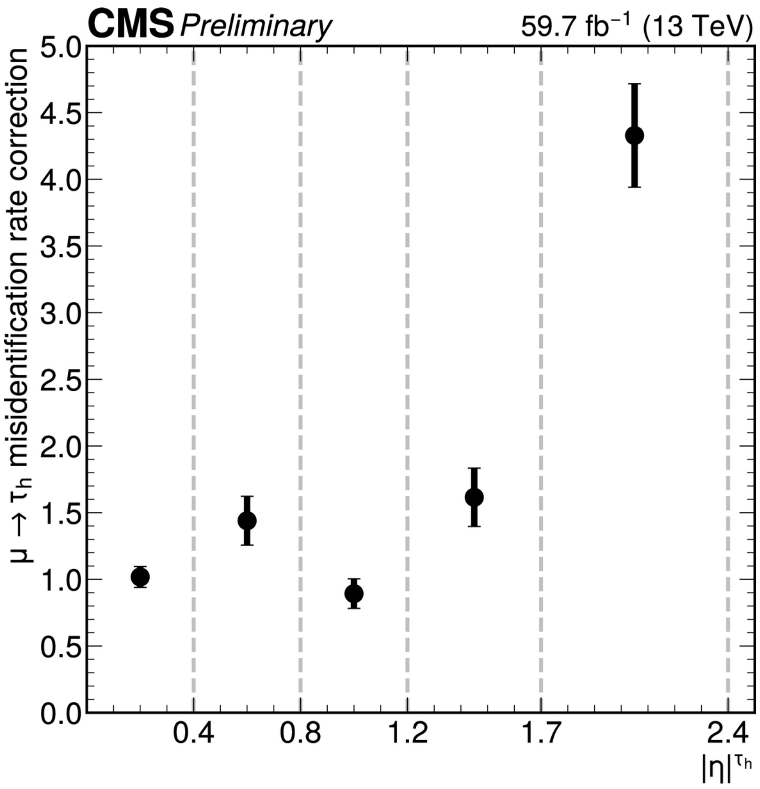
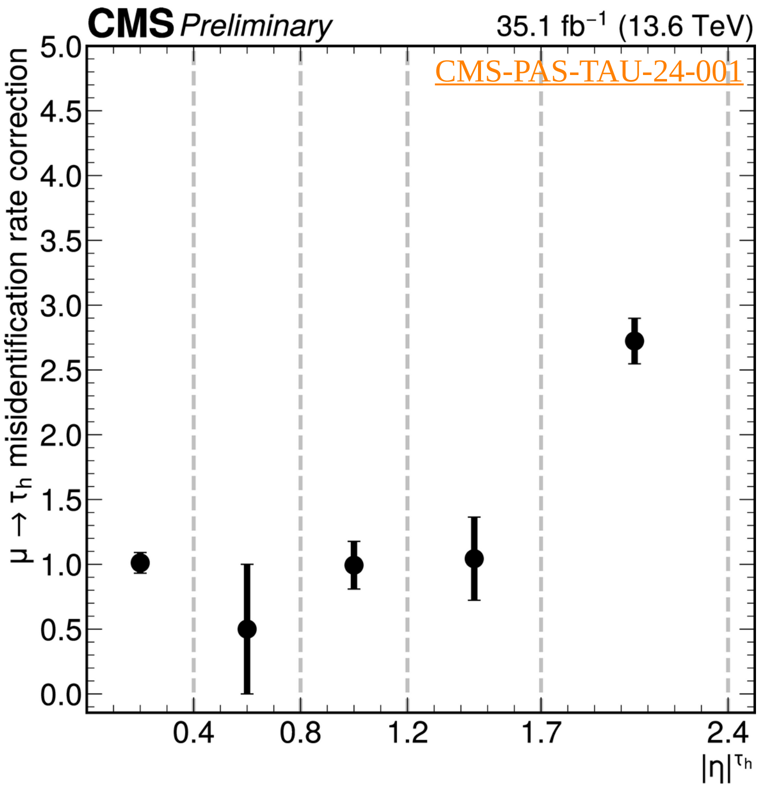
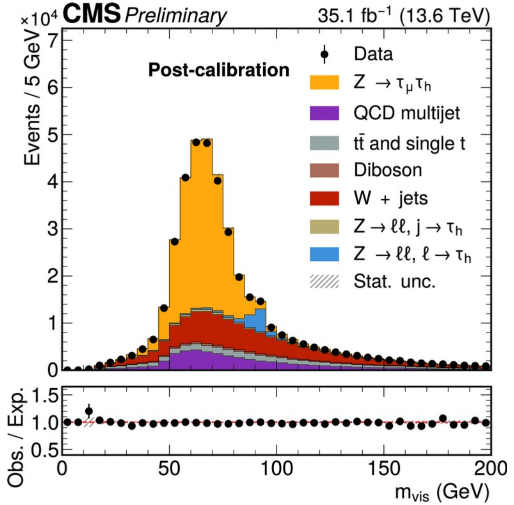
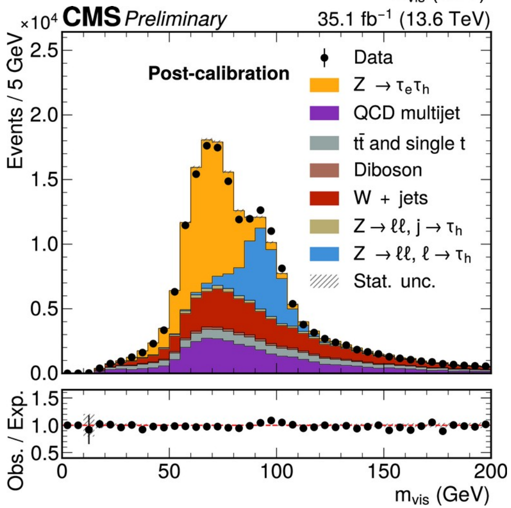


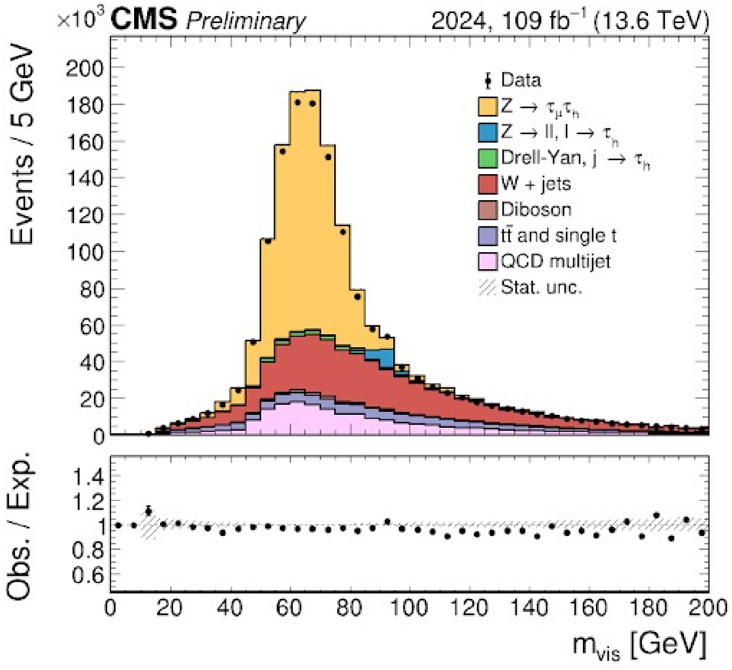


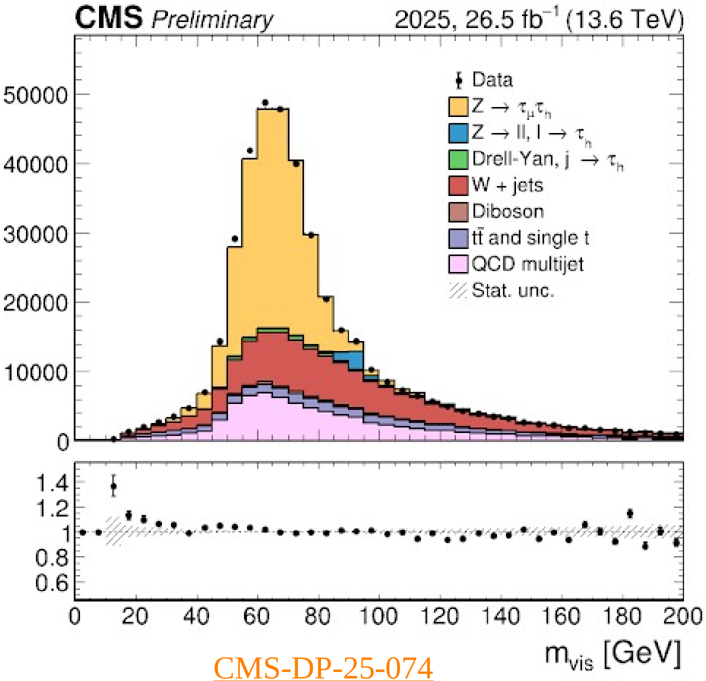
Performance during Run 3





- After calibrating for residual effects DeepTau v2.5 achieves excellent description of data and great rejection of both quark/gluon jets and leptons
- In October we also released a first look at the performance in 2024 and 2025





CMS-DP-25-074

Taus in non-standard topologies

- Up to now I focused on prompt taus coming from the primary vertex and isolated from other objects
  - This primarily covers taus from $Z/\gamma^* \rightarrow \tau\tau$ or $W^* \rightarrow \tau\nu$
- Some interesting processes to tackle do not fall into this category

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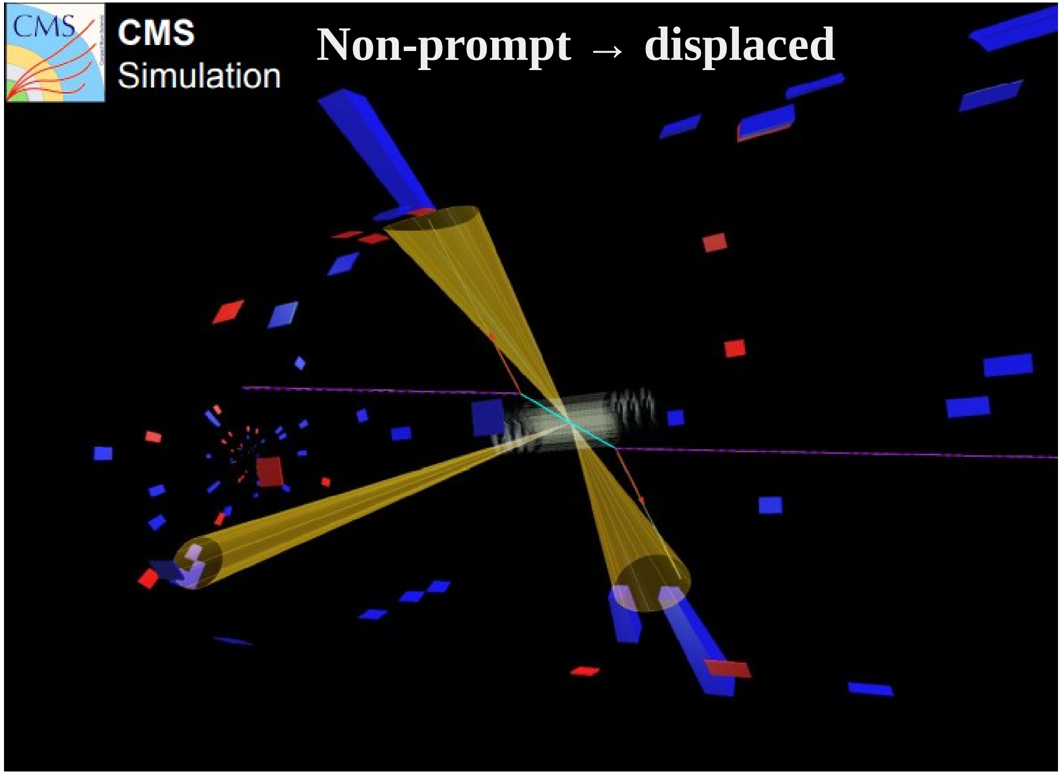

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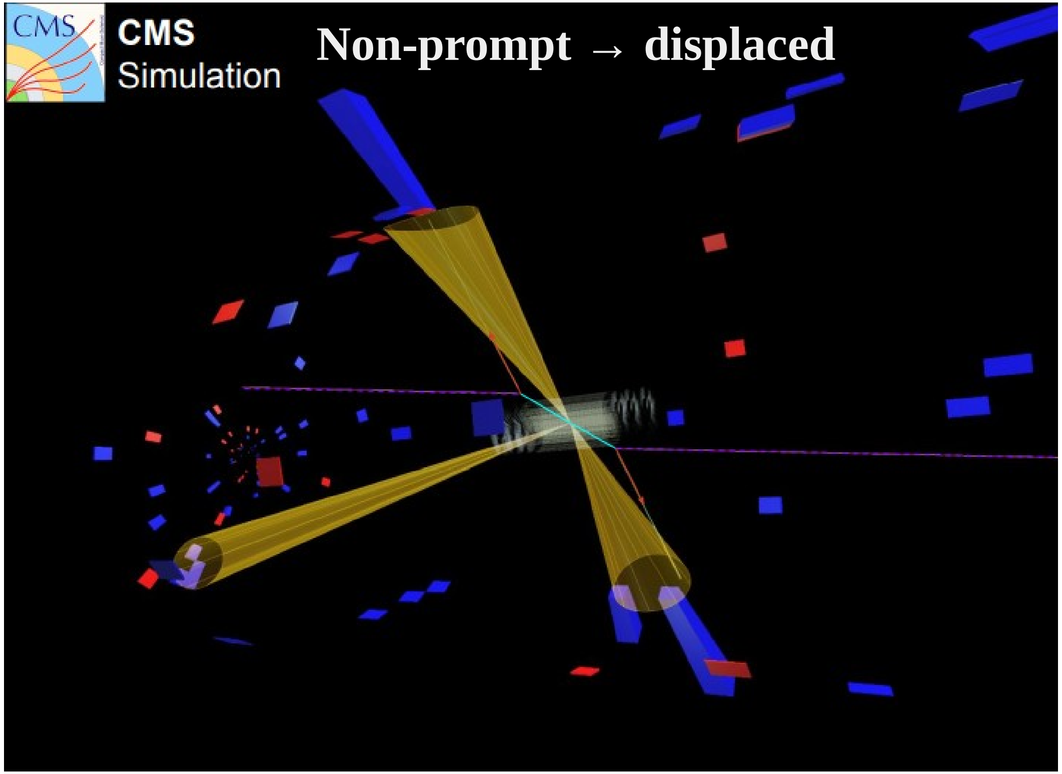

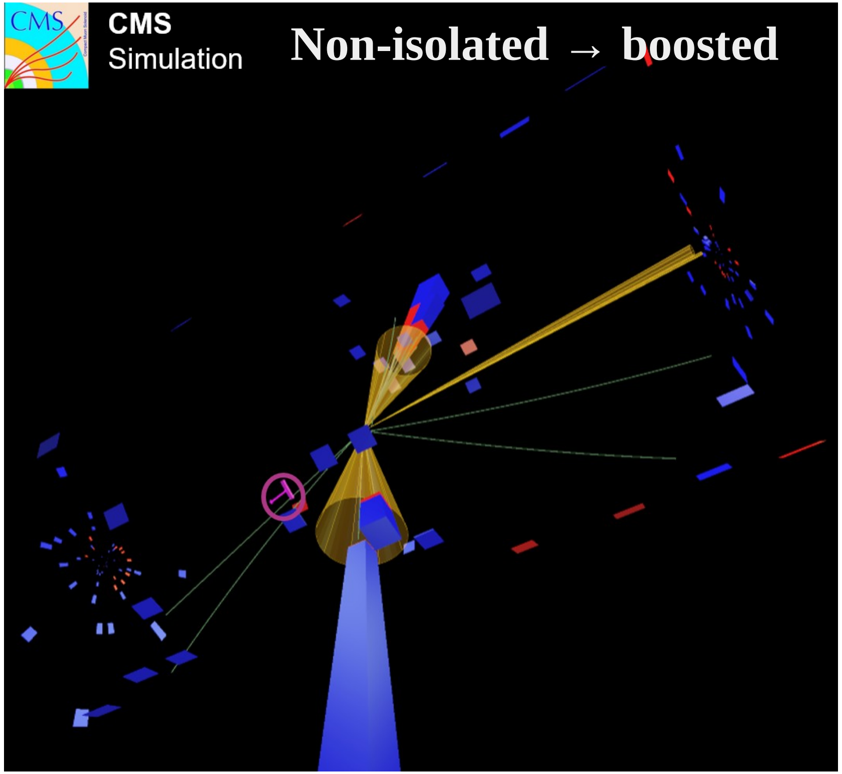

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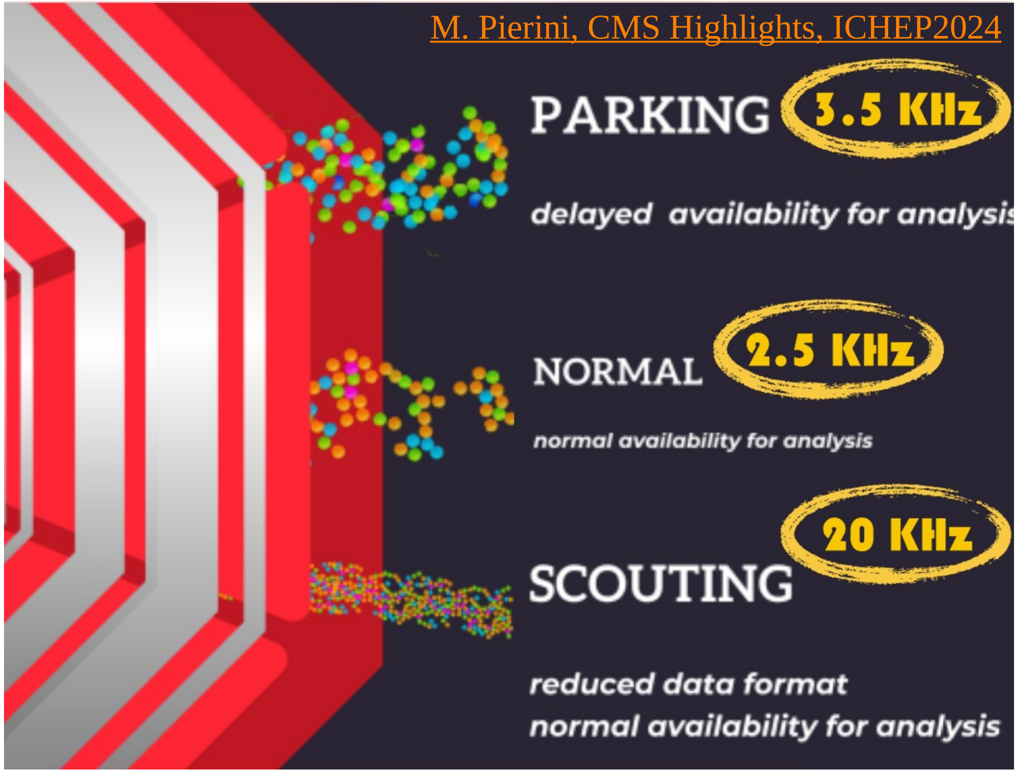
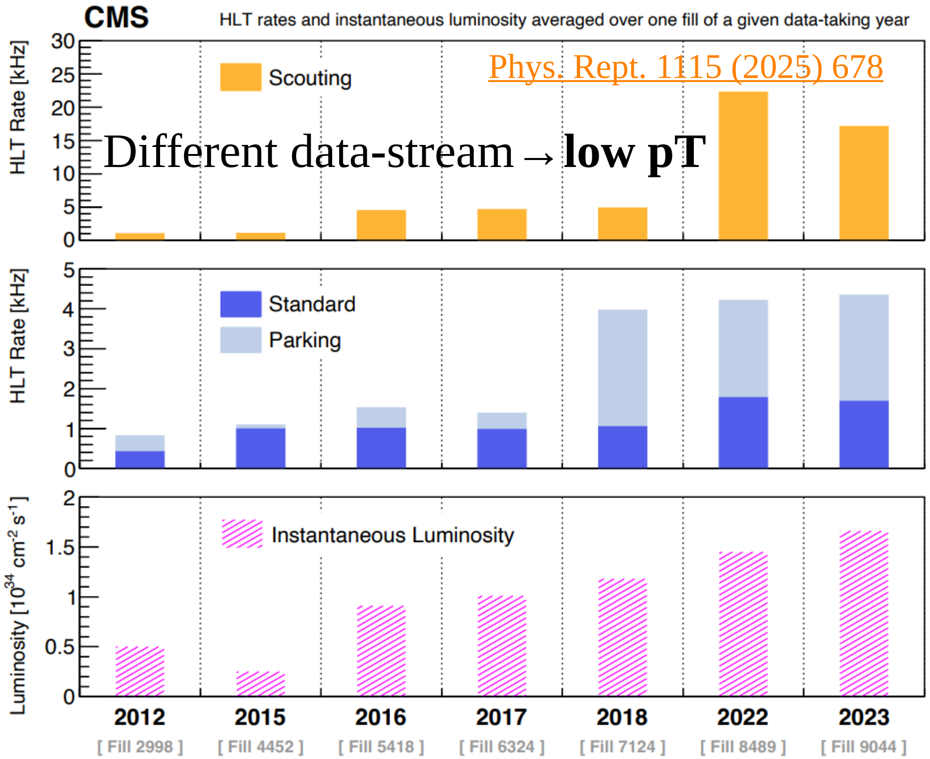
M. Pierini, CMS Highlights, ICHEP2024

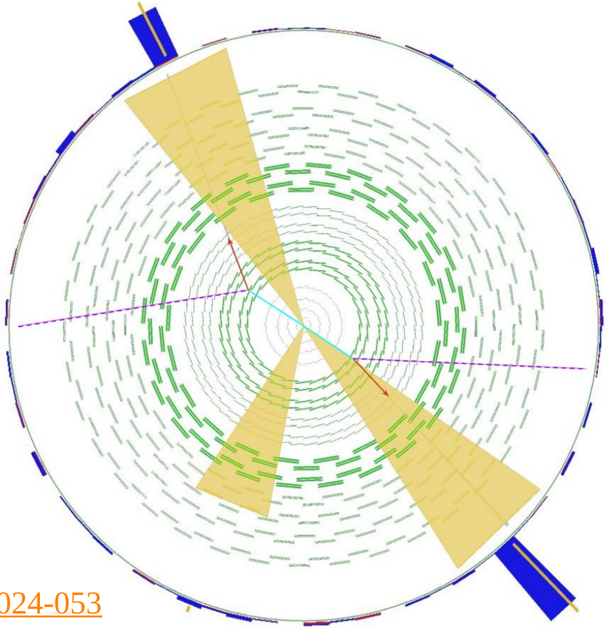


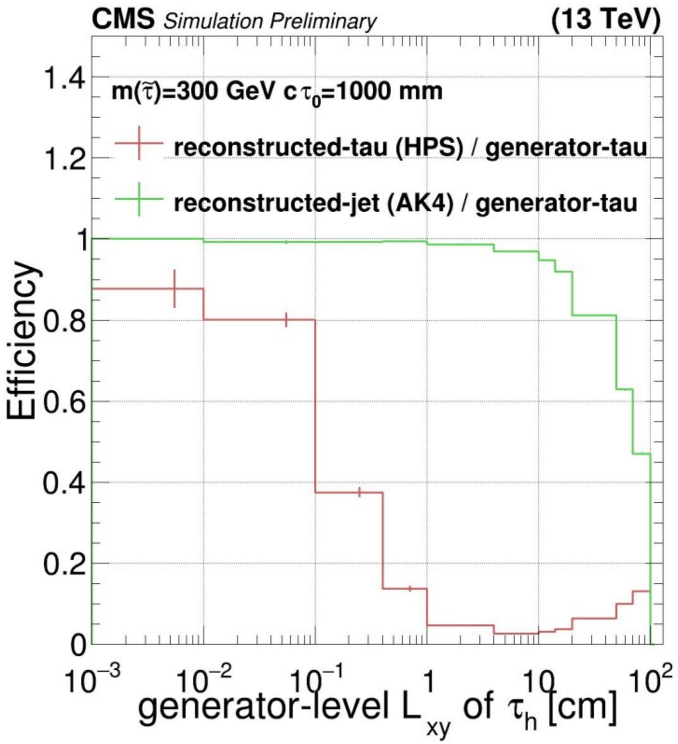
Phys. Rept. 1115 (2025) 678

Different data-stream → **low pT**



- Some particles predicted by theories beyond the standard model can have macroscopic* lifetimes
- Taus produced by these long-lived particles are reconstructed by HPS with vanishing efficiency as the track quality required used by HPS are failed by displaced tracks
- However PF jets reconstructed with the AK4 algorithm can still identify these taus
- An algorithm was created to tackle this topology
- It is a graph-neural-network based algorithm using a particle cloud representation for the inputs
  - > **DisTau**

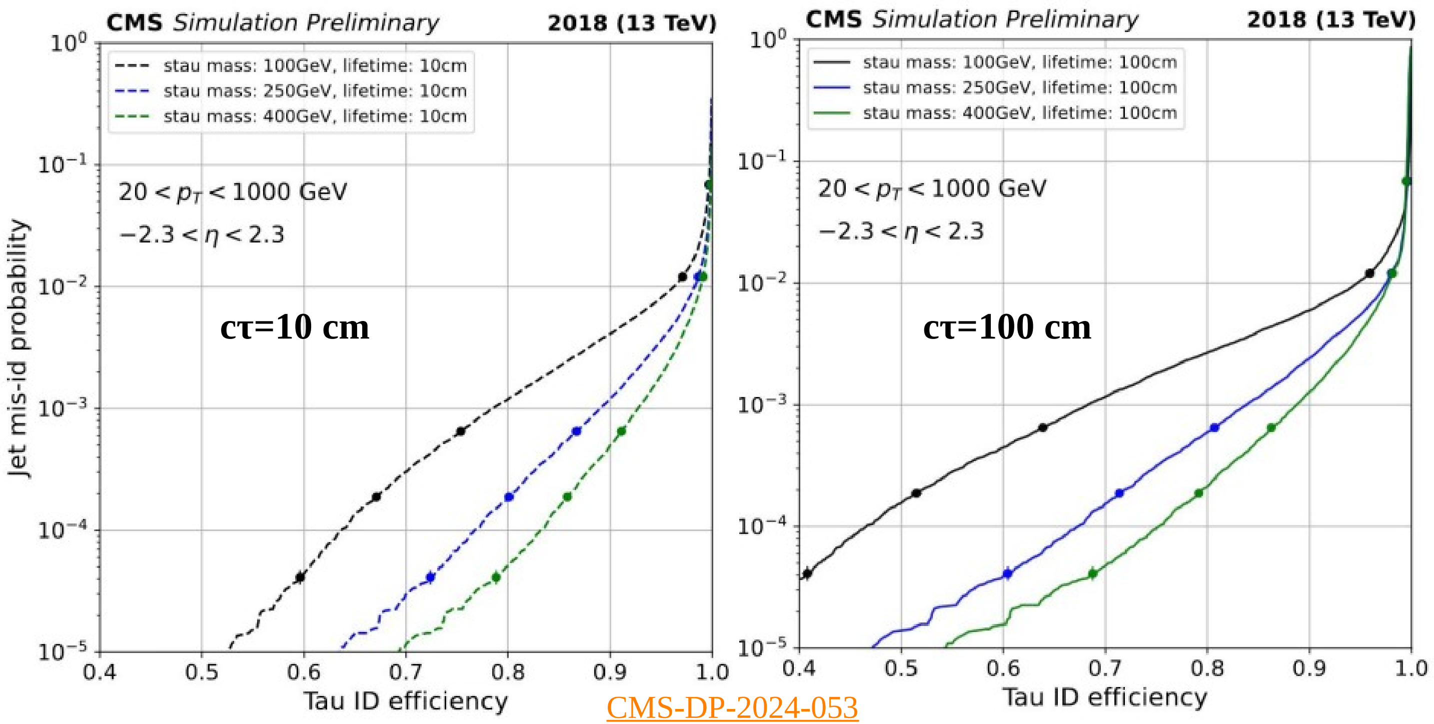




CMS-DP-2024-053

[*] Macroscopic on the scale of collider experiment = at energies on the GeV/TeV scale can decay in the detector medium

- DisTau was created to target taus produced by the decay of its super-symmetric partner in SUSY models, the stau → it targets topologies where a charged particle decays in the detector to a tau and a neutralino which escapes detection
- Efficiency varies with the mass of the stau and its decay length



CMS-DP-2024-053

DisTau performance

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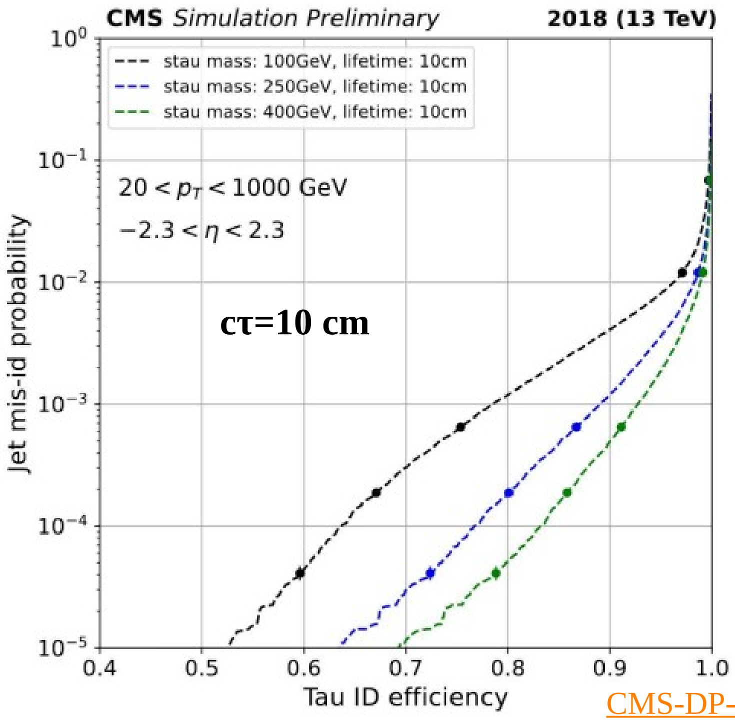
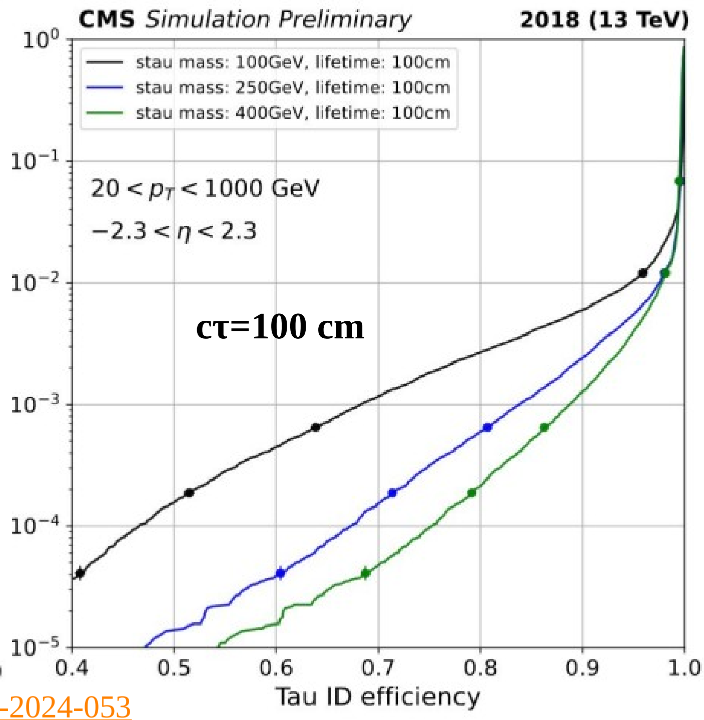
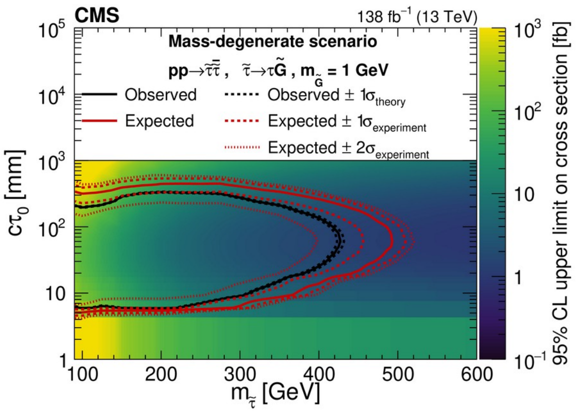




CMS-DP-2024-053

- The algorithm was trained for a Run 2 CMS analysis with submitted to JHEP: arXiv:2601.17576



Boosted taus

- Taus can be produced also non-isolated, e.g. as part of a boosted system with overlapping constituents
- This is particularly relevant for boosted neutral vector or scalar particles (Z’, Higgs boson, etc.) decaying to di-τ systems with decay products overlapping with each other
- Some studies require a precise identification of the tau constituents in this boosted topology → dedicated reconstruction

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1st step: re-clustering → **CA8 + HPS**

- Jets with large cone are selected and re-clustered to identify sub-jets using the Cambridge-Aachen algorithm with radius 0.8
- The re-clustered jets are cross-cleaned and used as input for a custom HPS reconstruction
- HPS is then run on the re-clustered tau candidates to identify τ_h

Already in Run 2

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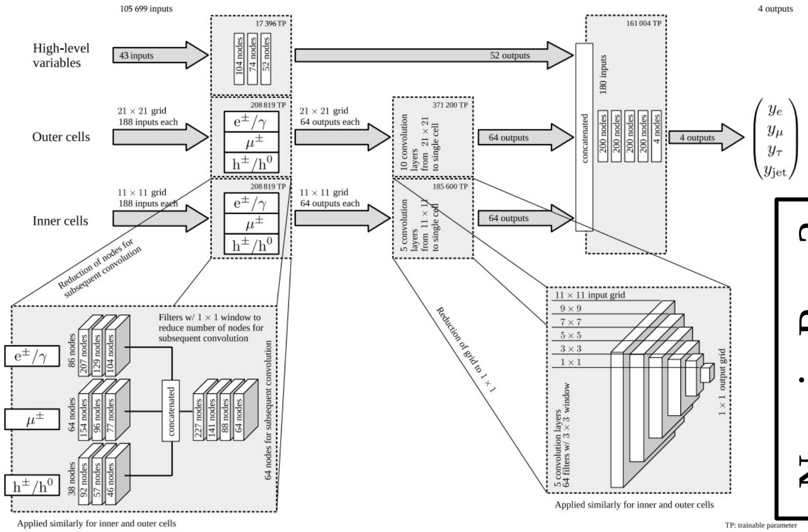
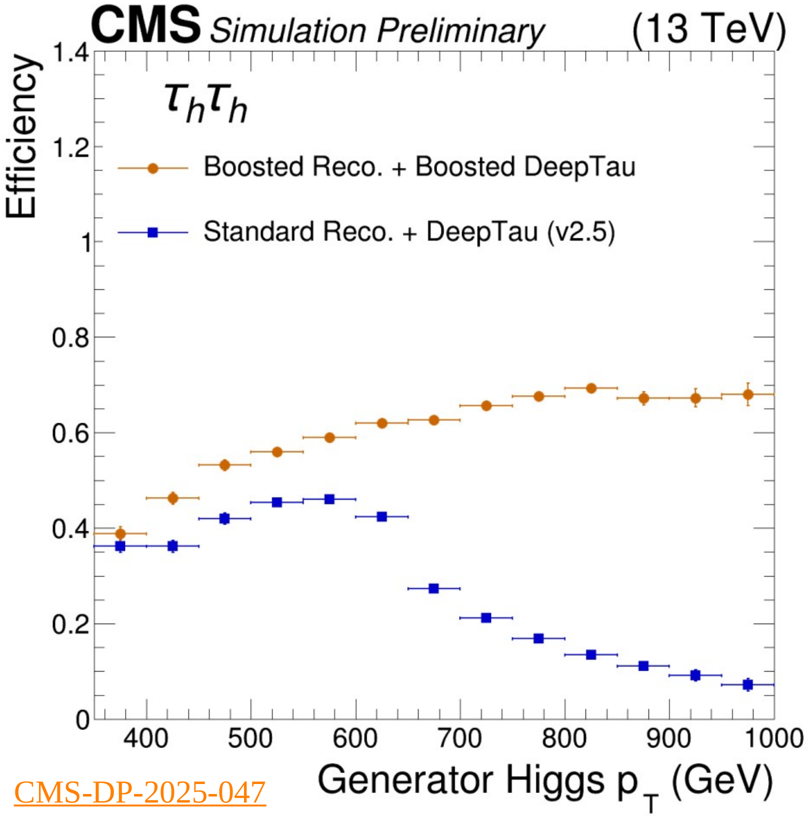
Already in Run 2

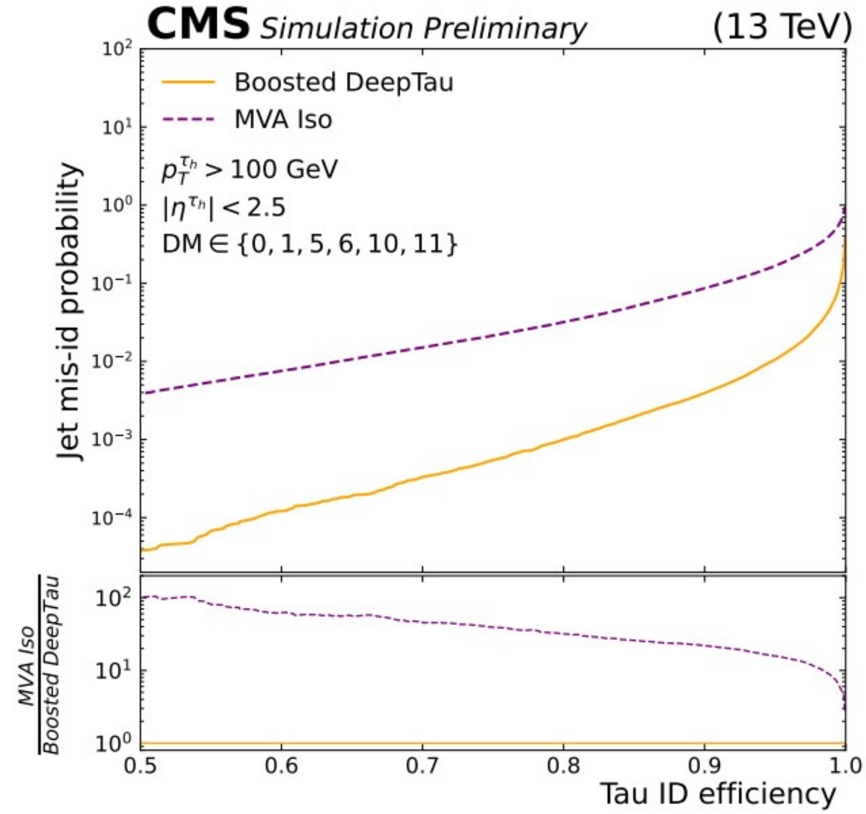
2nd step: identification → **Boosted DeepTau**



New in Run 3

- Boosted DeepTau uses the same architecture as DeepTau v2.5 without the domain adaptation
- The re-clustering allows to recover a good fraction of otherwise lost pairs of taus
- The refined identification performance also outperforms the previously used BDT-based ID





CMS-DP-2025-047

Taus at low p_T

- Taus at low pT are challenging to study: they suffer from a large QCD background leading to trigger rates which are not affordable
- CMS has tackled this problem with two strategies

Trigger on **mesonic resonances** decays to muons (J/ψ and $Y \rightarrow \mu\mu$)

- Used to study flavor physics already in Run 2
- Dedicated reconstruction targeting 3 prong decays found in proximity of low mass di-μ resonances
- Attention-based-cloud network (ABCNet) used to rank combinations of low pT pions to identify tau decays via $a_1 \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}$ resonance

CMS-DP-2020-039

Already in Run 2

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Not covered today

CMS-DP-2020-039

Already in Run 2

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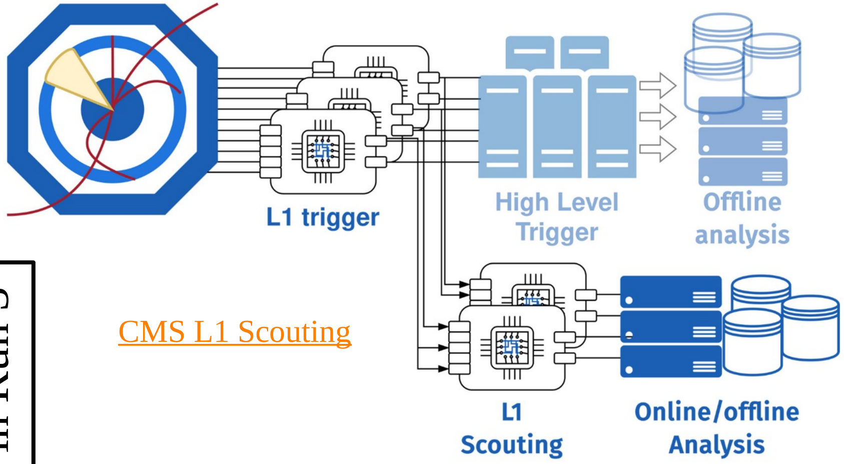
Not covered today

CMS-DP-2020-039

Already in Run 2

Use a separate data-stream: **scouting**

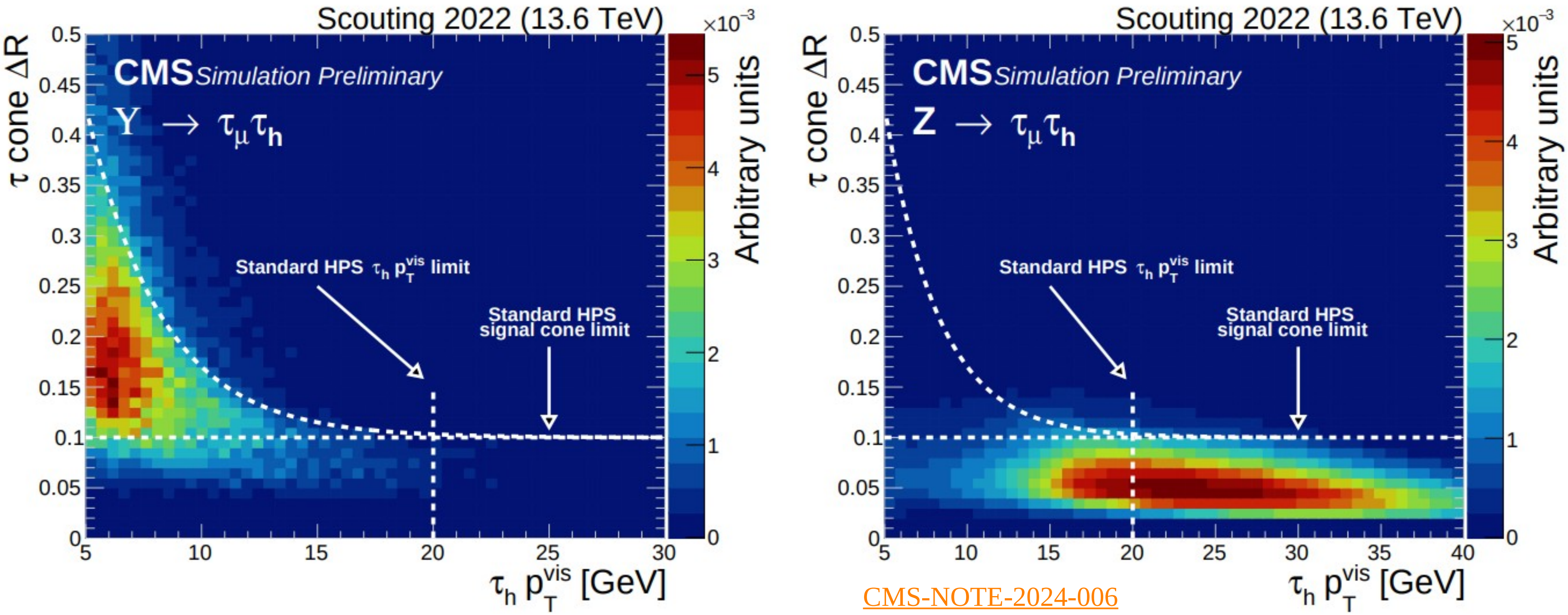


CMS L1 Scouting

~ New in Run 3

- Store data at higher rate but with reduced event information (trigger level event)

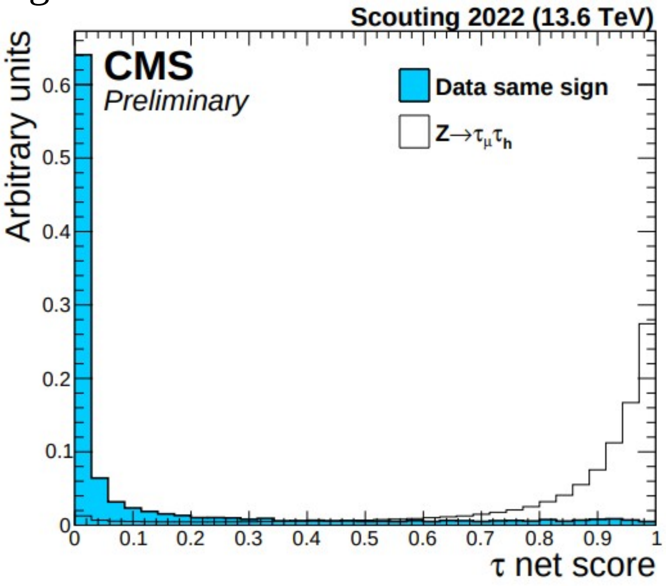
- Major differences with higher pT regime:
  - Tau decay products are more spread out → **New:** custom version of HPS to collect all decay products
  - Higher chance for a pilup hadron to be mis-assigned to the tau
- The scouting HPS uses a signal cone increasing in opening at lower pT ($\Delta R = 2.8^{-0.3 \times (pT-1.4)} + 0.1$) and adapted requirements on the m_τ, strip mass, etc.

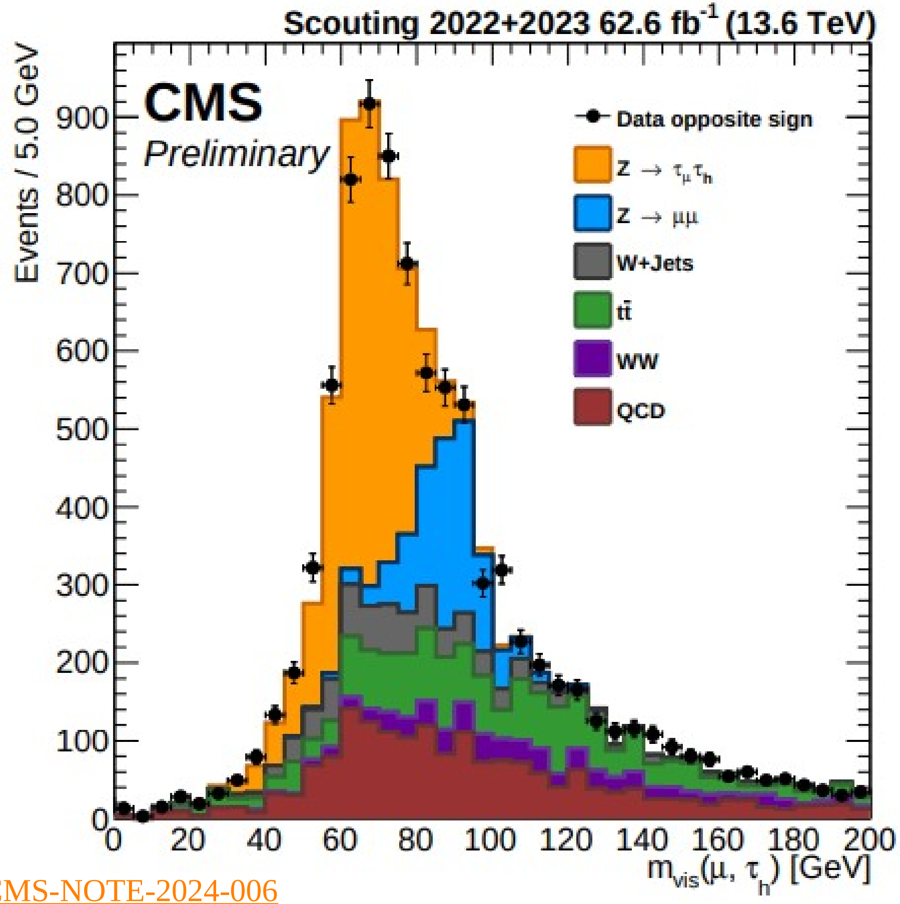


CMS-NOTE-2024-006

Identification for scouting taus

- A dedicated tau identification was defined to identify scouting taus against quark/gluon jets as that misidentification source takes center stage
- TauNet was developed to identify these scouting τ_h
  - Architecture: Energy Flow neural network (DeepSets)
  - Trained with genuine τ_h against $j \rightarrow \tau_h$ fakes from the same-sign region in data





CMS-NOTE-2024-006

A new idea: unified jet taggers

- Between the long shutdown 2 and Run 3 a new idea was developed for tau identification
  - > Simultaneous classification of jet type – treating the τ_h as a jet:
    - uds, gluon, c, b, τ_h, μ, e
  - > This idea comes with several advantages
    - Better modelling of correlation between different object identifications
    - Easier optimization of selection efficiency to prioritize rejection of specific fake types
    - Concentration of computing resources
  - > Being less specialized though means that some properties of taus might be overlooked in the process
    - Quark/gluon jets must be reconstructed with collinear/infrared safety in mind + the mesons and hadrons constituting the jets are created with an inherently stochastic element
    - Taus are pure electroweak objects → properties such as the angular distance and energy ratio between decay products carry physical meaning
- This leads to a tight balance CMS has threaded remarkably well

Tau identification with unified jet taggers

- Like for displaced taus the starting point is not HPS tau candidates but AK4 jets
- Tau constituents are not explicitly tagged
  - Tau DM cannot be obtained by counting the number of charged and neutral hadrons
  - The same is true for the τ_h charge
- The DM is instead assigned as a label and used as target for a classification task

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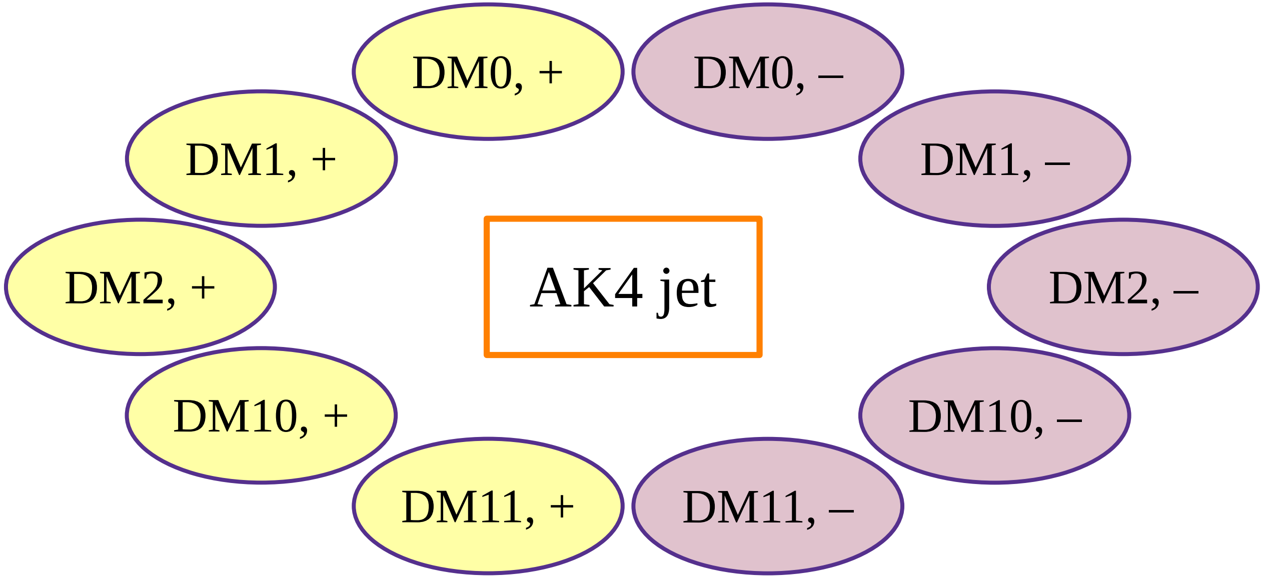
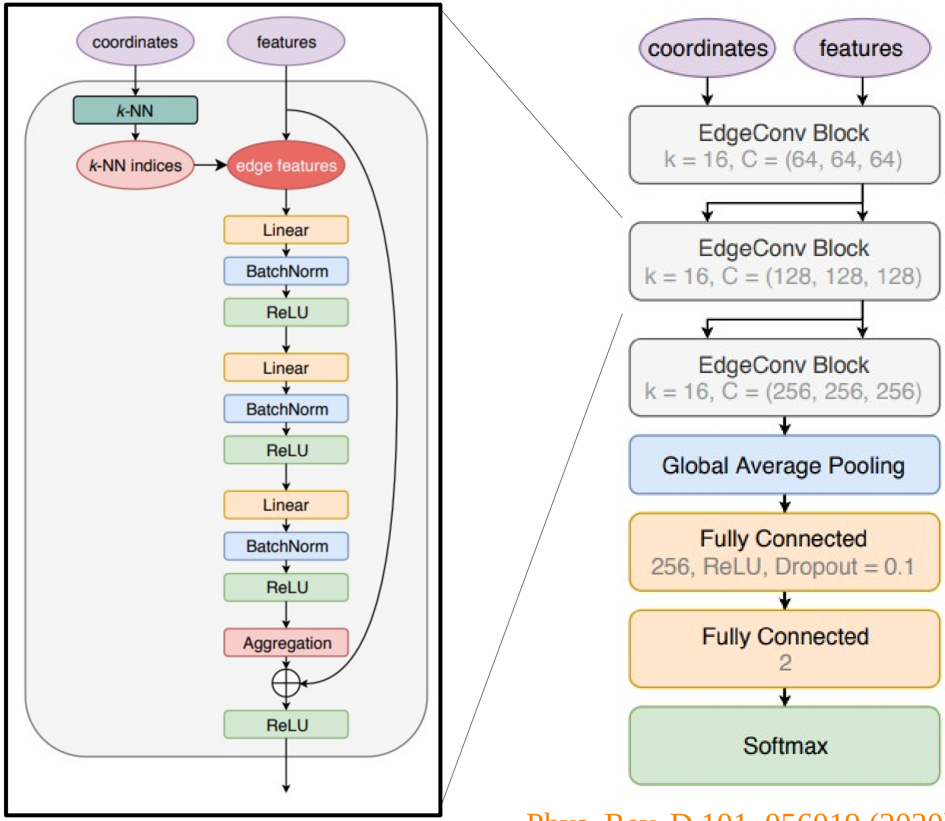


- Tau scores related to a specific DM are the sum of those for the different charge
- Charge identification score is obtained summing the scores across different DM
- The τ_h identification score against other object is the sum across charge and DM

ParticleNet

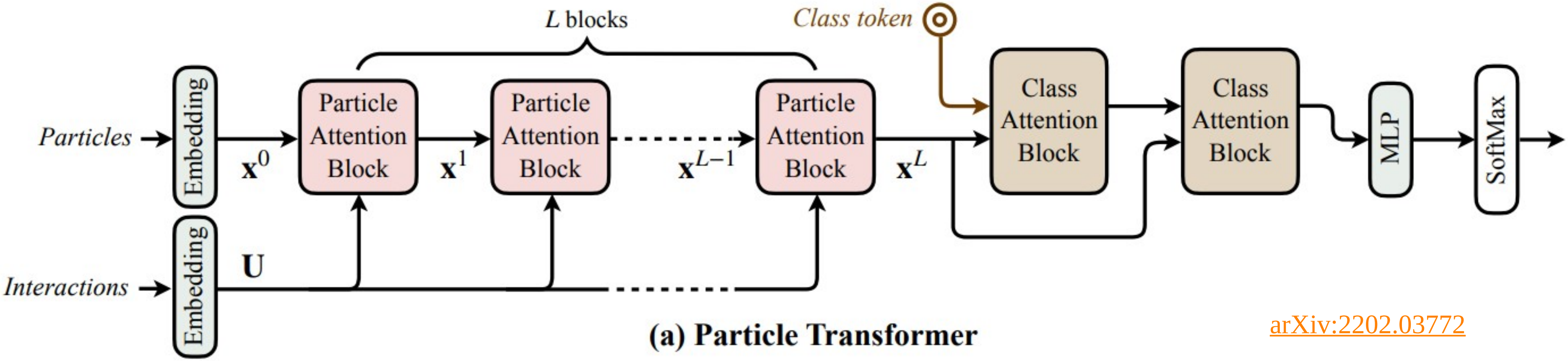
- The first unified jet *tagger* introduced in CMS was **ParticleNet** (or PNet)
- It is a graph neural network using a particle cloud representation for the jet constituents
- While originally devised as a heavy flavor jet tagger at the start of Run 3 it was later re-optimized to perform reliably also tau identification
- While the CNN architecture processes tau decays like an image in the detector the graph architecture sees particles as nodes in a graph, pair-wise features (distance, invariant mass, etc.) acting as edges



Phys. Rev. D 101, 056019 (2020)

UParT

- The Unified Particle Transformer (or UParT for short) was developed during Run 3 and deployed last year in 2024
- It uses a transformer architecture which relies on both self-attention and pair-wise attention to link particles in the jet as part of an unordered set



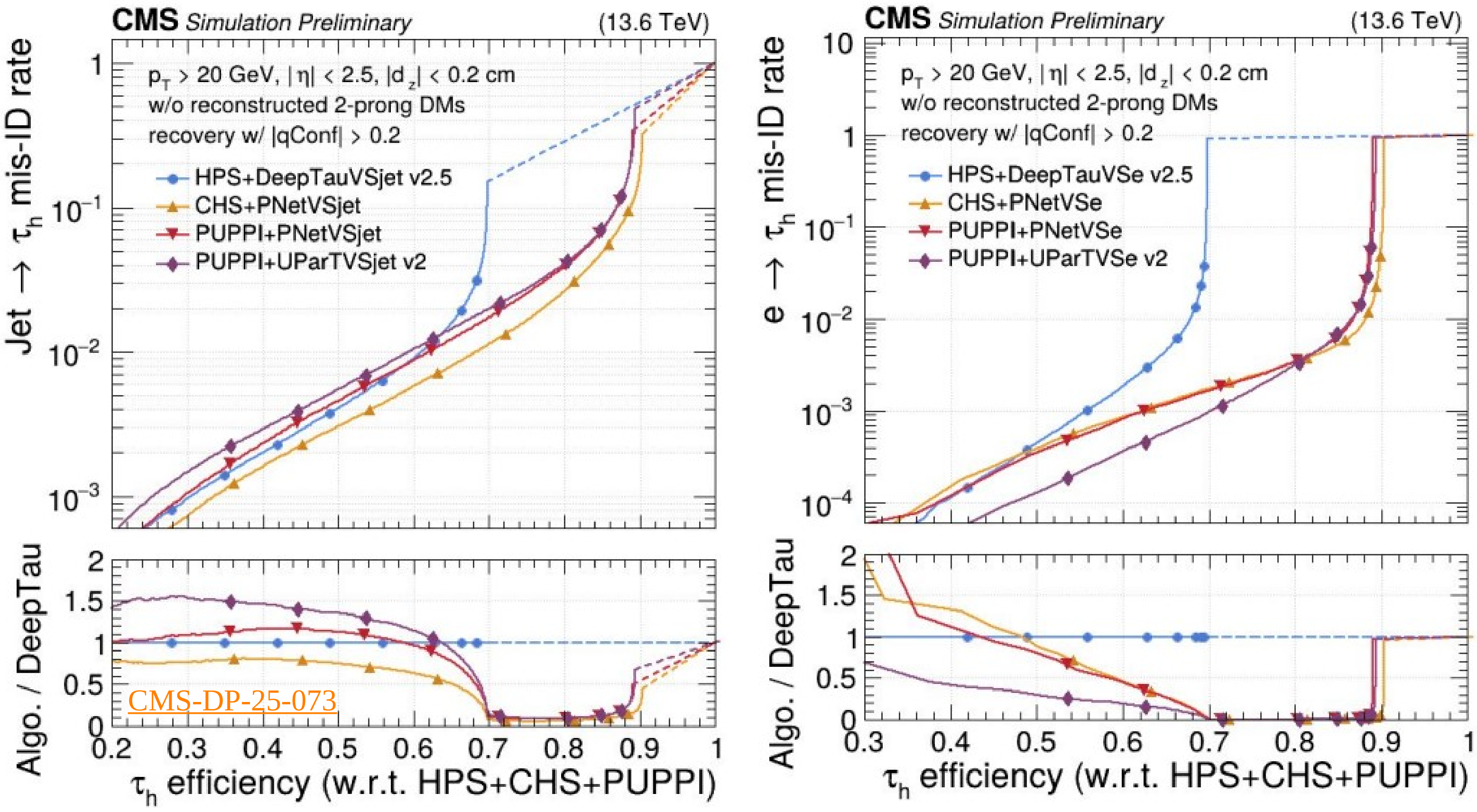
(a) Particle Transformer

arXiv:2202.03772

- The particle attention block focuses on the properties of jet constituents
- The class attention block focuses instead on different physics processes as the origin of the jet thus relying at an architectural level not only on the jet nature but how it was produced (decay of Higgs boson, top, Z, W, etc.)

Strength in unity

- A comprehensive study has recently been performed to evaluate and compare the performance of unified ID algorithms and DeepTau taking into account different reconstruction or pileup cleaning algorithms
- The comparison also looked at what objects are rejected by each algorithm

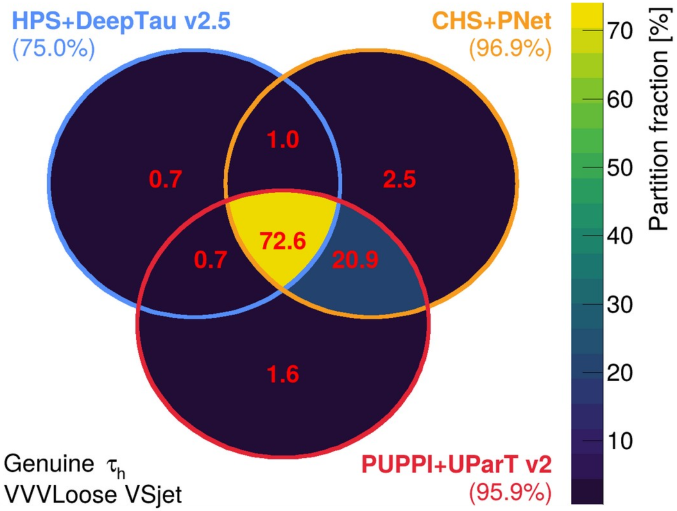


CMS-DP-25-073

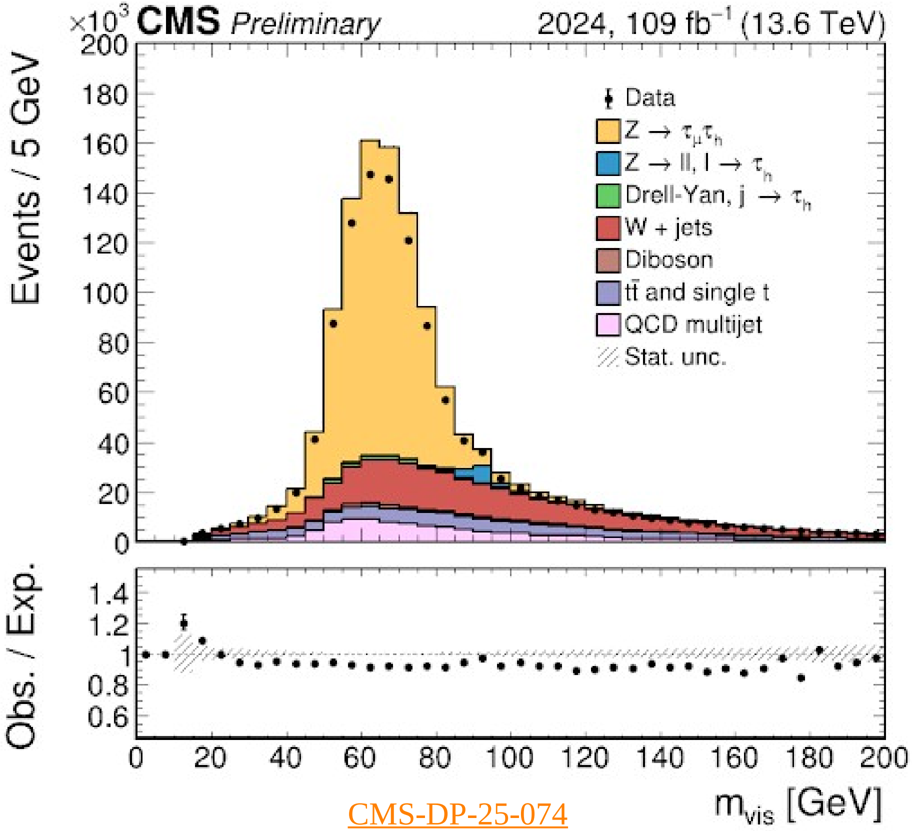
Strength in unity

- A comprehensive study has recently been performed to evaluate and compare the performance of unified ID algorithms and DeepTau taking into account different reconstruction or pileup cleaning algorithms

- The comparison also looked at what objects are rejected by each algorithm
- As the rejection power only partially overlaps the combination of different algorithms was also tested
- This yields the best selection to date



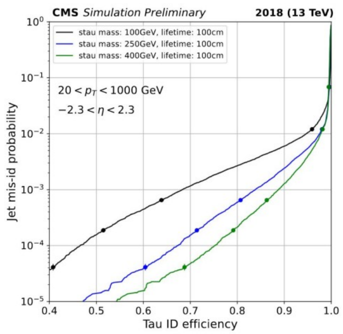
CMS-DP-25-073

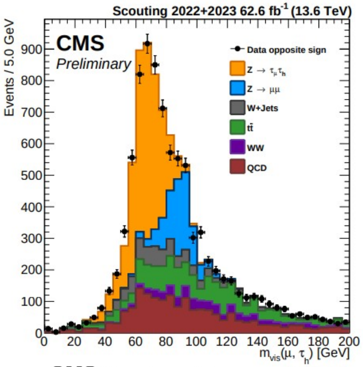


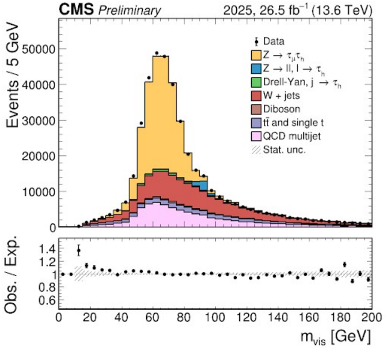
CMS-DP-25-074

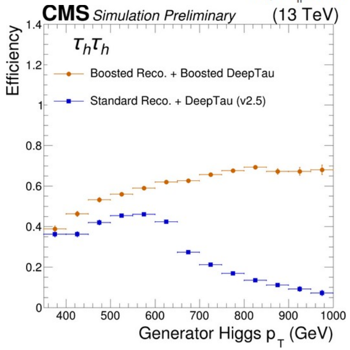
Conclusions

- CMS has a rich history of working with tau leptons and performing physics studies that thoroughly take advantage of their nature
- Plenty of physics analyses rely on precise reconstruction and identification of taus
- While I covered a lot of algorithms I barely scratched the surface
  - The entire treatment of taus at trigger level
  - Displaced tau ID from neutral lepton decays
  - Boosted di-tau ID with unified taggers starting from AK8 jets
  - The alternatives to HPS before the integration with Particle Flow
  - Algorithms designed to take advantage of new detectors in Phase 2
- Taus are reconstructed and identified on a wide phase-space
  - This was widened in Run 3 with the addition of several targeted algorithms
  - More will come for Phase 2 → stay tuned!





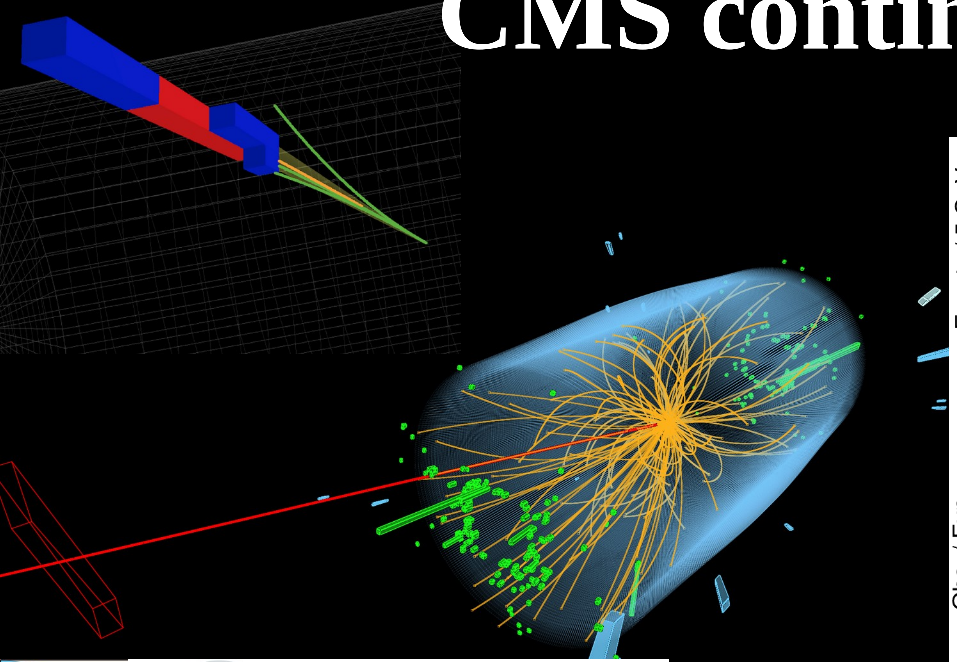


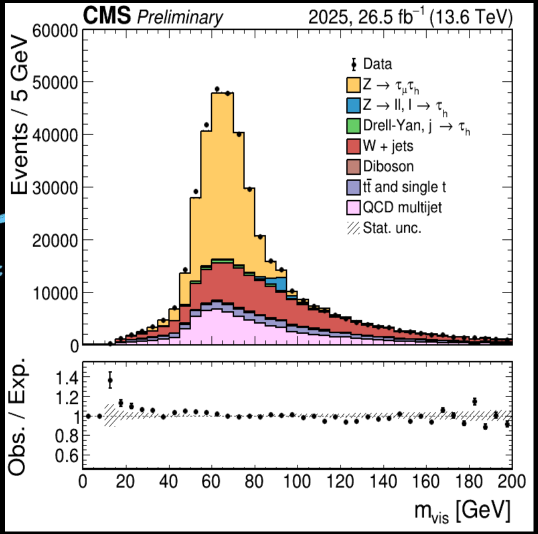


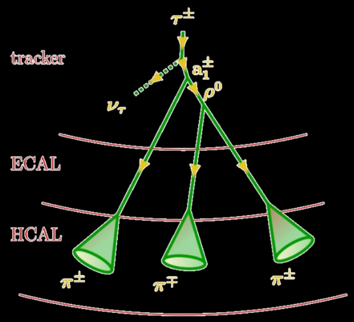
Continuing beyond Run 3

Investigating the Higgs and new physics at the LHC with the Tau Lepton:

CMS continues to improve!







Andrea Cardini – ICTEA–Universidad de Oviedo, Spain

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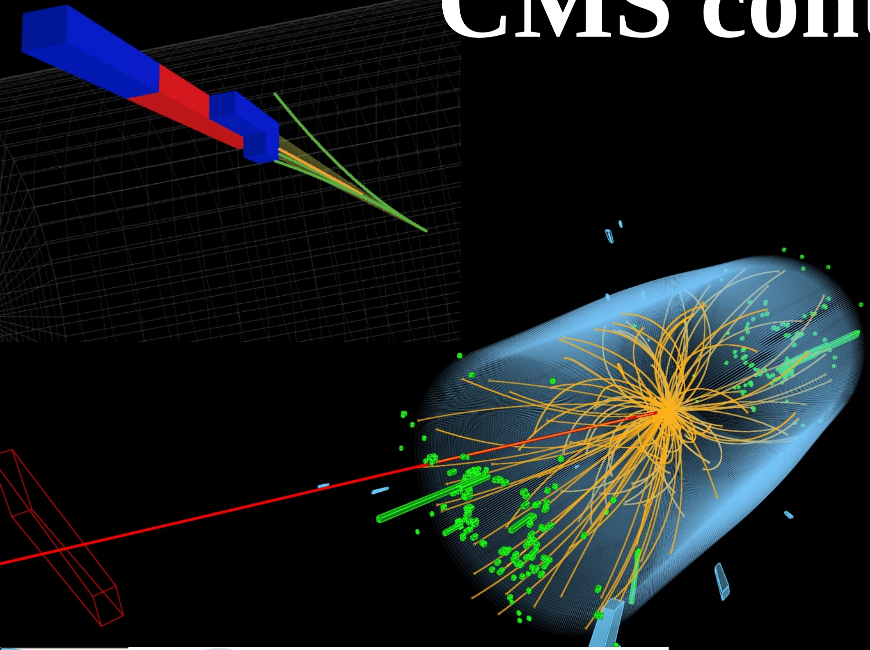

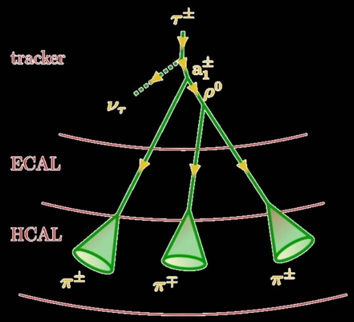

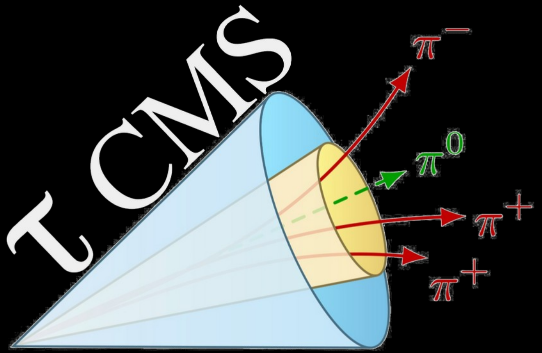

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