Advancements in Tau Reconstruction and Identification at the CMS Detector

Pritam Palit

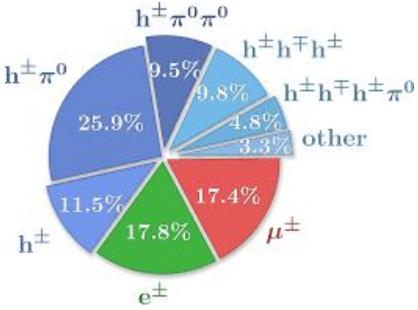
On behalf of the CMS collaboration

Lepton Photon 2025

Aug 28, 2025

Tau Lepton

- CMS uses the ParticleFlow (PF) algorithm to reconstruct individual (stable) particles
- τ lepton : heaviest lepton
  - lifetime 2.9×10^{-13} seconds! : reconstruction possible only through decay products
  - ~65% of the decay, one neutrino + a system of hadrons (hadronic taus, τ_h) : discussed in this talk.
  - τ_h decay (via weak interaction) : collimated, low-multiplicity jets.



- Dominant sources of background for tau misidentification :
  - Jets : highly collimated jet, similarity in structure
  - Electrons : bremsstrahlung photons, mimic the π^0 decay
  - Muons : energy deposits in the calorimeters, mimicking decay with only one charged particle
- Genuine τ_h identification : different state-of-the-art machine learning based algorithm
  - initiated in Run 2, improved in Run 3

Tau Reconstruction : Hadron-plus-strip (HPS) algorithm

1. Starts with AK4 jets seeded from PF

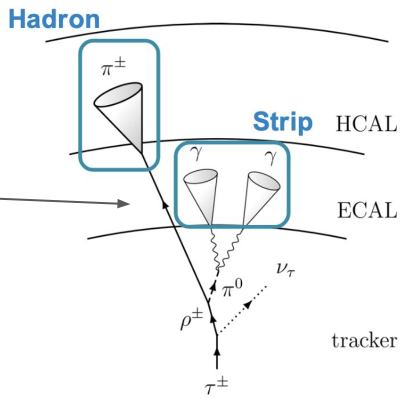
2. π^0 reconstruction from γ -> $e^+ e^-$

3. Charged hadrons ($\pi^\pm$) from PF

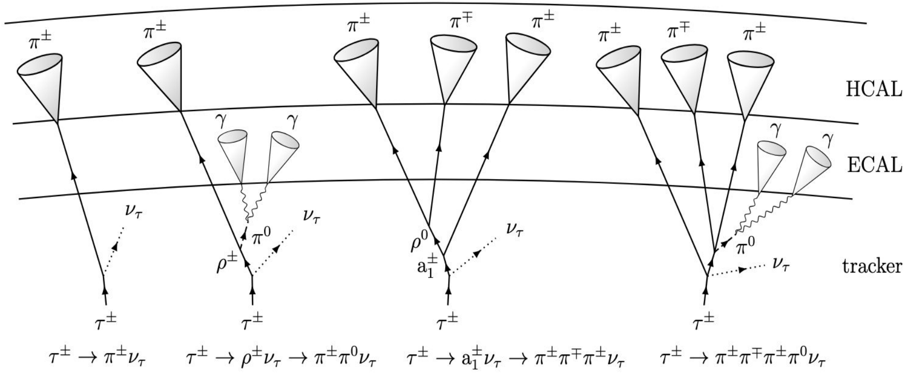
4. Build τ_h candidates in various decay mode (DM)s

5. Select highest p_T τ_h after constraints over mass, charge, signal cone size

Efficient reconstruction with excellent charge accuracy



[CMS-TAU-16-003](CMS-TAU-16-003)



Tau Identification Algorithms

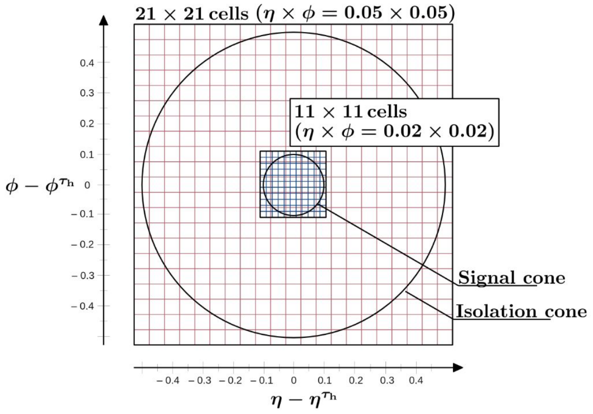
Deeptau v2.5

(CNN with domain adaptation)

DeepTau v2.5

CMS DP - 2024/063 CMS PAS TAU-24-001

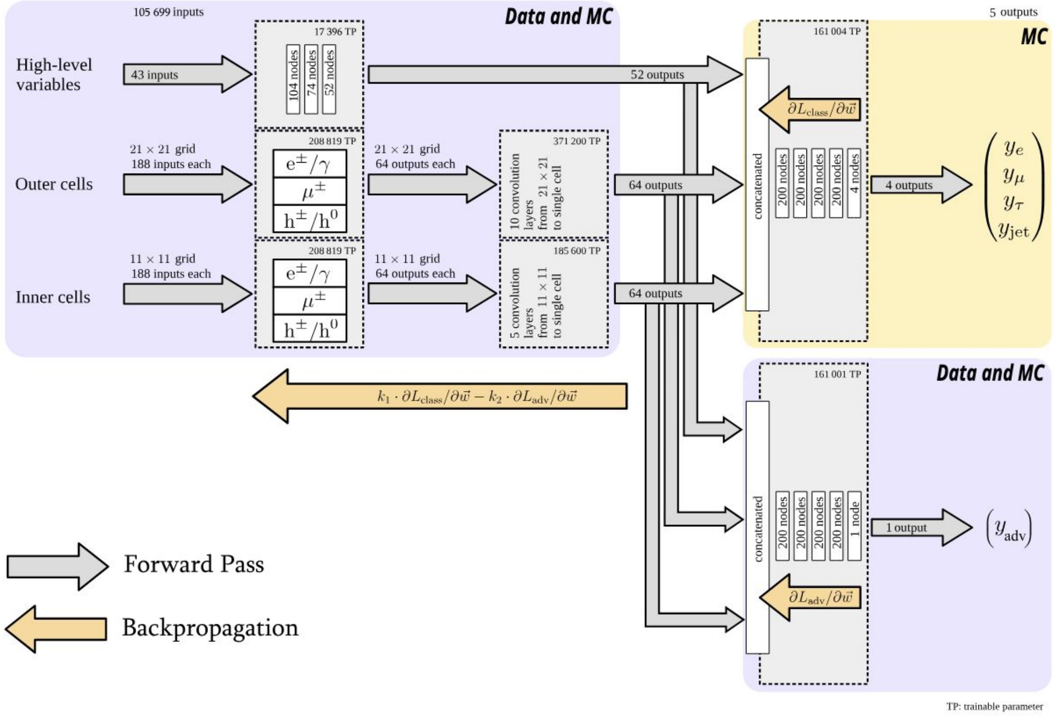
- DeepTau : multiclass tau identification algorithm based on a deep Convolutional Neural Network (CNN)
  - distinguish genuine hadronic tau from misidentified jets from quarks or gluons, electrons, and muons
- The latest version DeepTau v2.5 : enhanced iteration of its predecessor, v2.1 JINST 17 (2022) P07023
  - domain adaptation to mitigate the mismodelling effects in the simulated events used for training
  - Shuffle and Merge to balance events across different physics phase spaces
  - Trained on a new enhanced dataset with Hyperparameter Optimization



Input features represented on a grid in η-φ for PF candidates

reconstructed within $\Delta R<0.5$ around τ_h

DeepTau v2.5 Architecture



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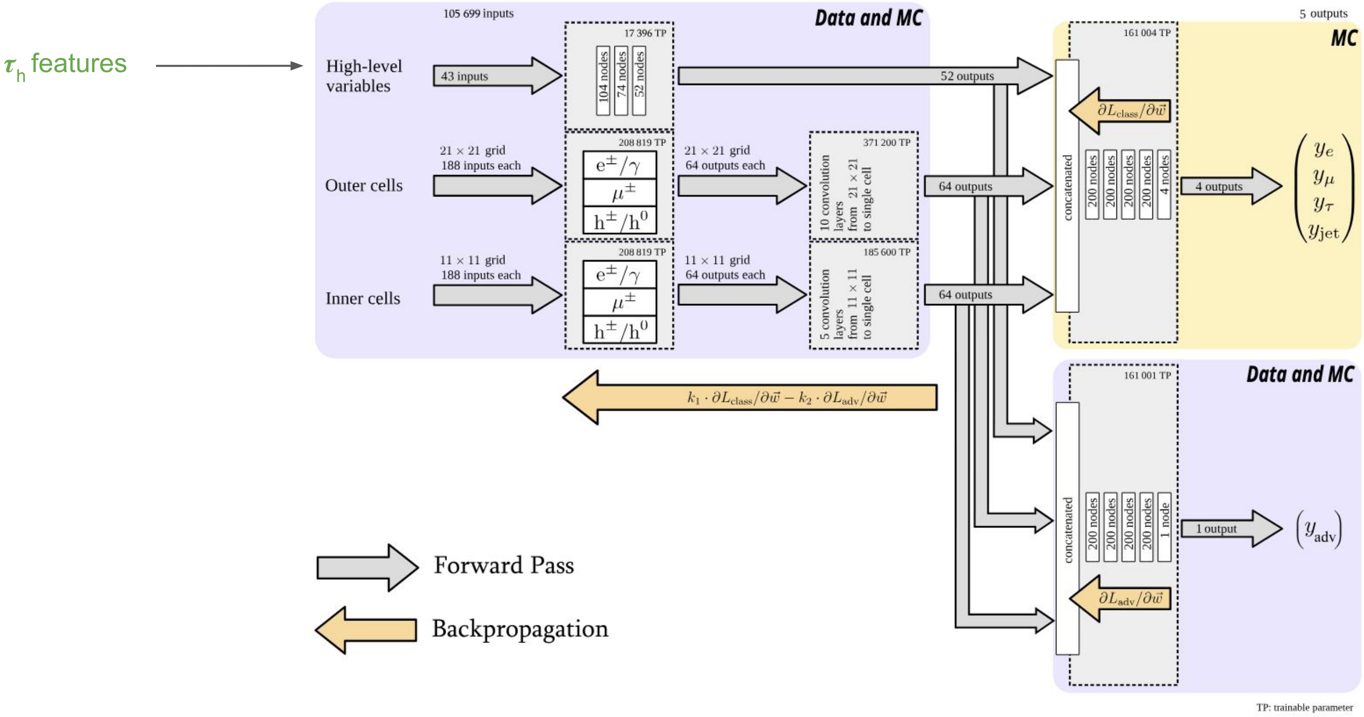
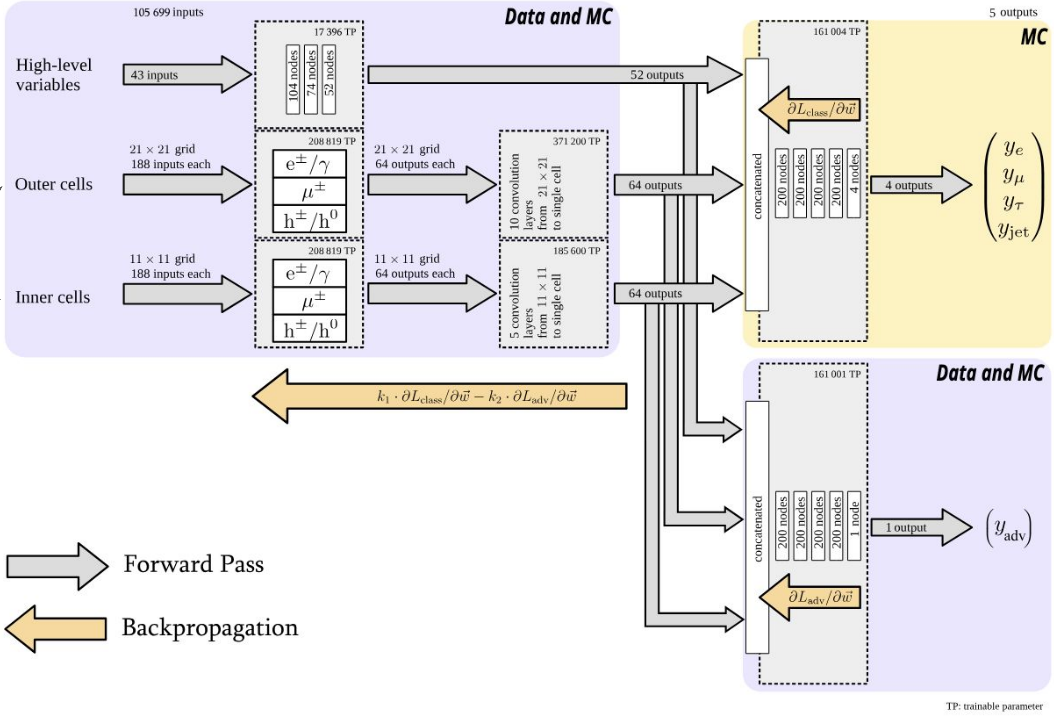


DeepTau v2.5 Architecture

τ_h features

Low level input variables : Grid info



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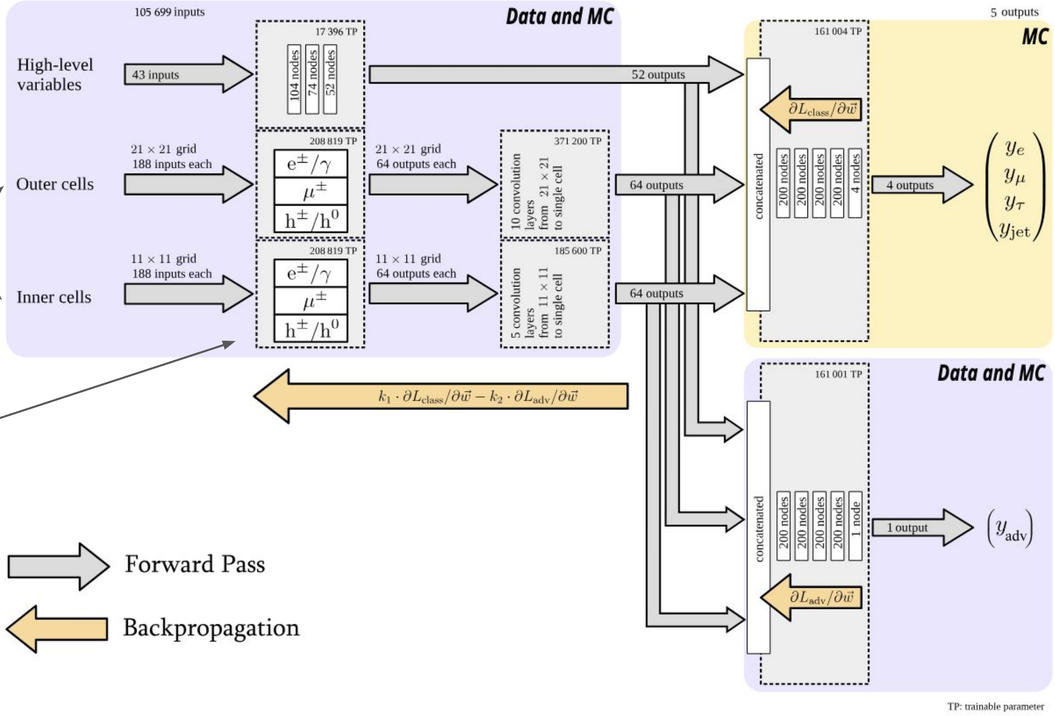

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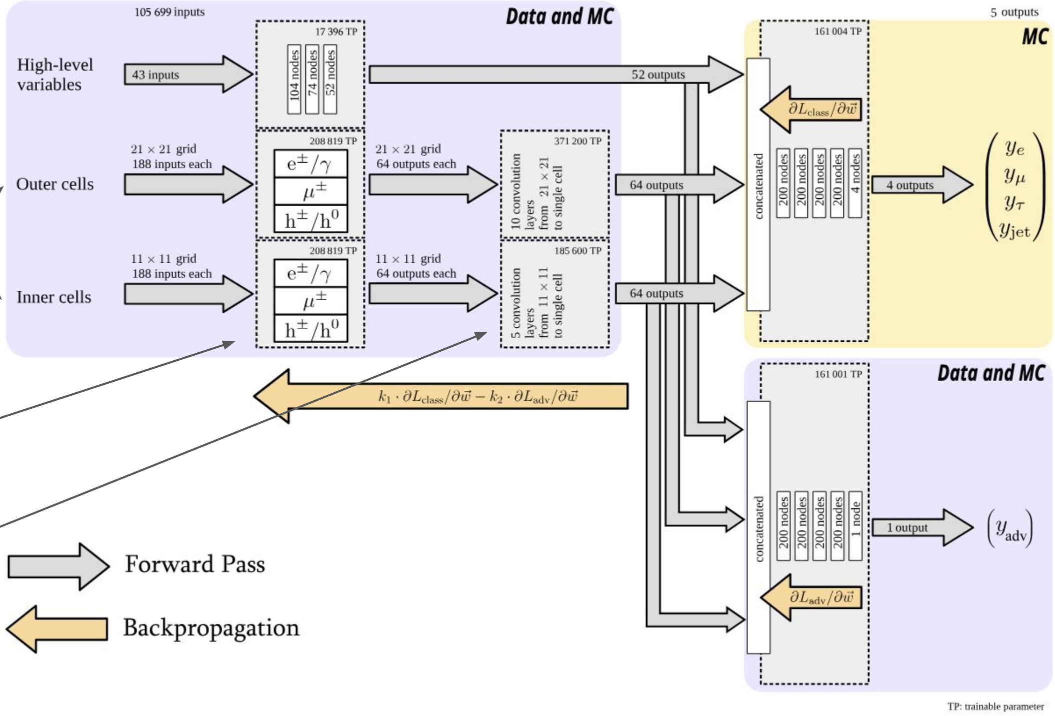

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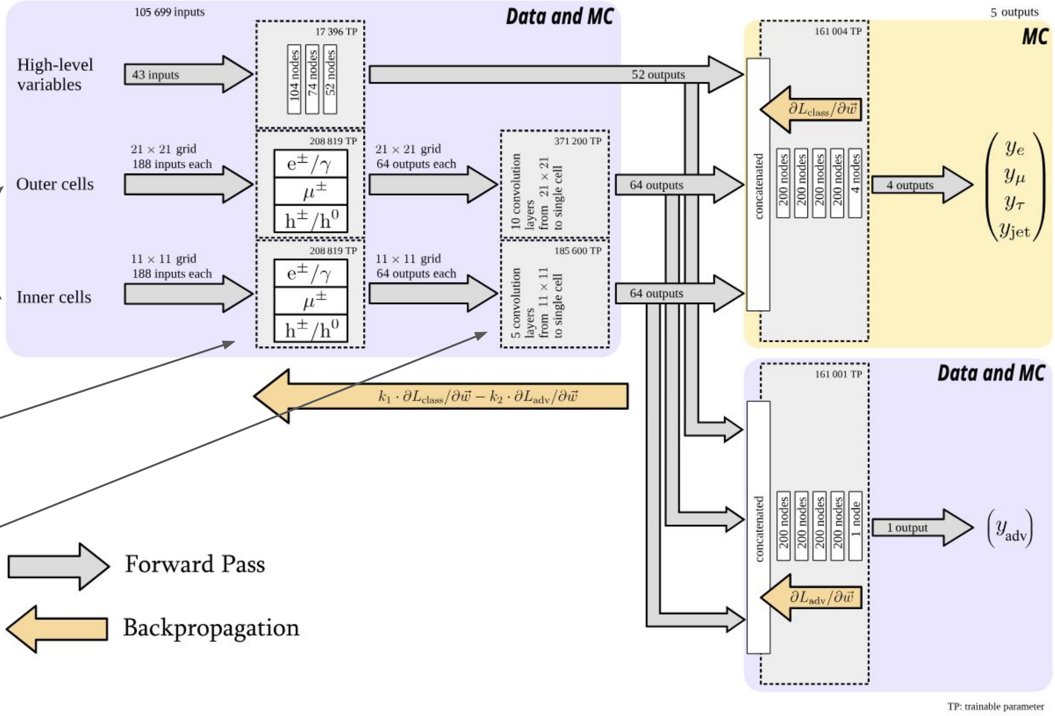

Final particle classification layers : genuine τ_h against misid jets/e/μ

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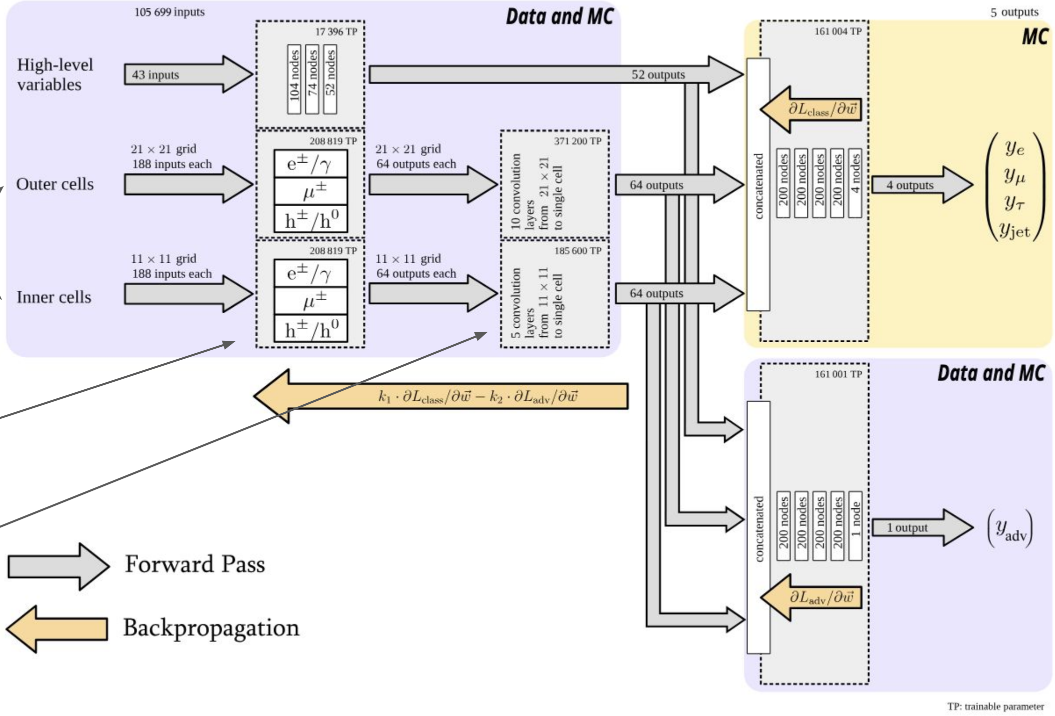

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Domain Adaptation layers

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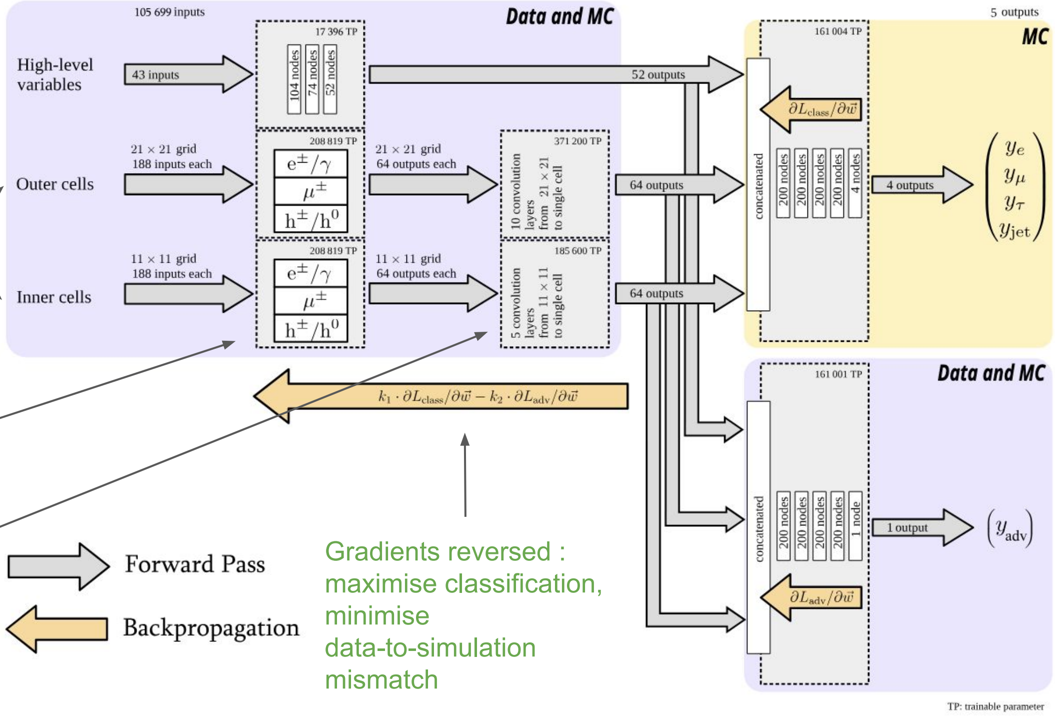


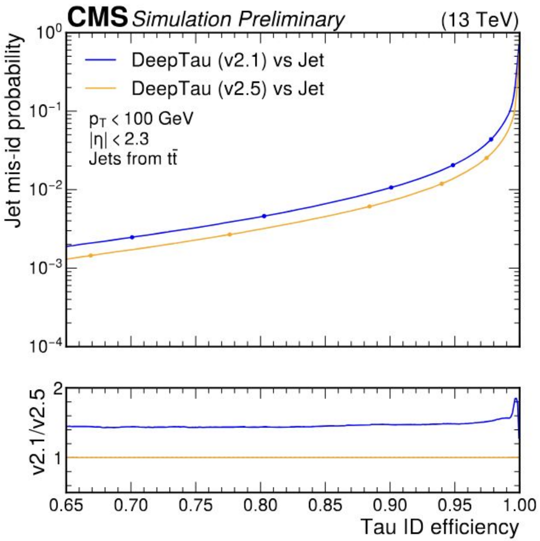
Gradients reversed : maximise classification, minimise data-to-simulation mismatch

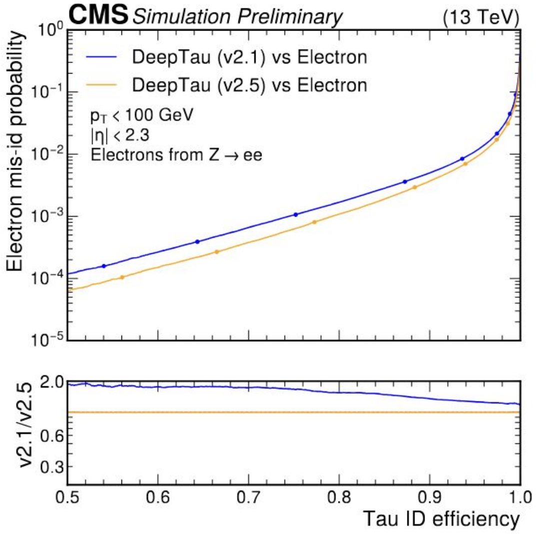
Final particle classification layers : genuine τ_h against misid jets/e/μ

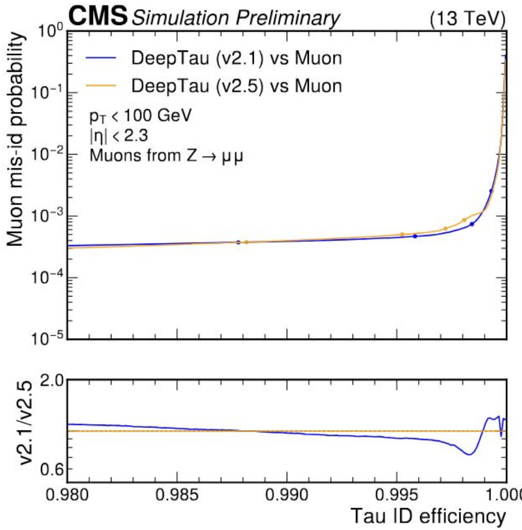
Domain Adaptation layers

Performance against jets, electrons and muons

Run 2







Jet misidentification probability : reduced by approximately 50%, across all defined working points

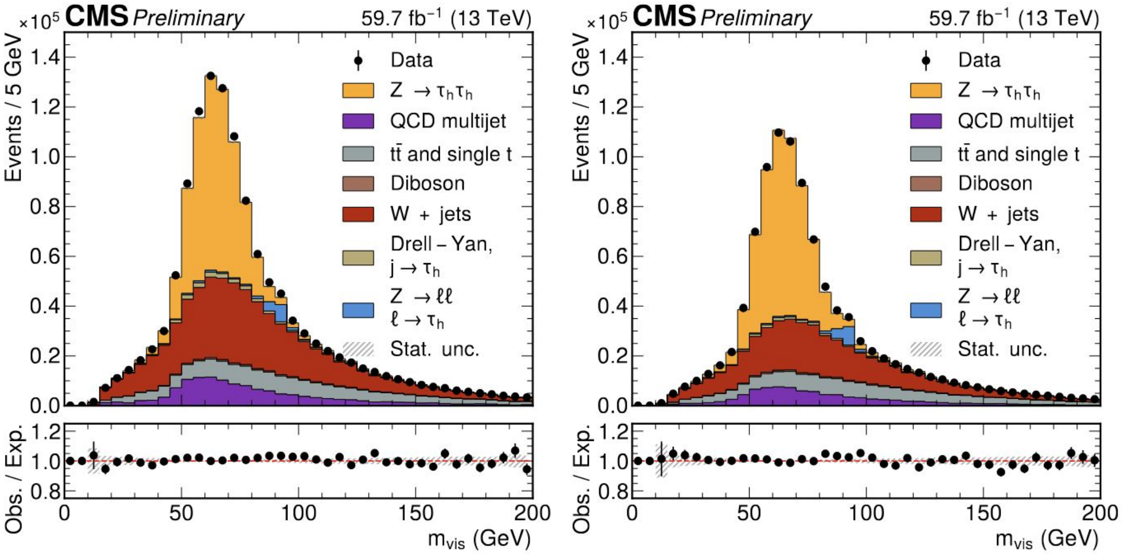
Electron misidentification : significant reduction in tighter working points

Muon misidentification : comparable between two versions

Background reduction

Run 2

Visible mass of $\mu\tau_h$ system, v2.1 (left), v2.5 (right)



A reduction in the background from jets by ~ 30%, especially for W + jets

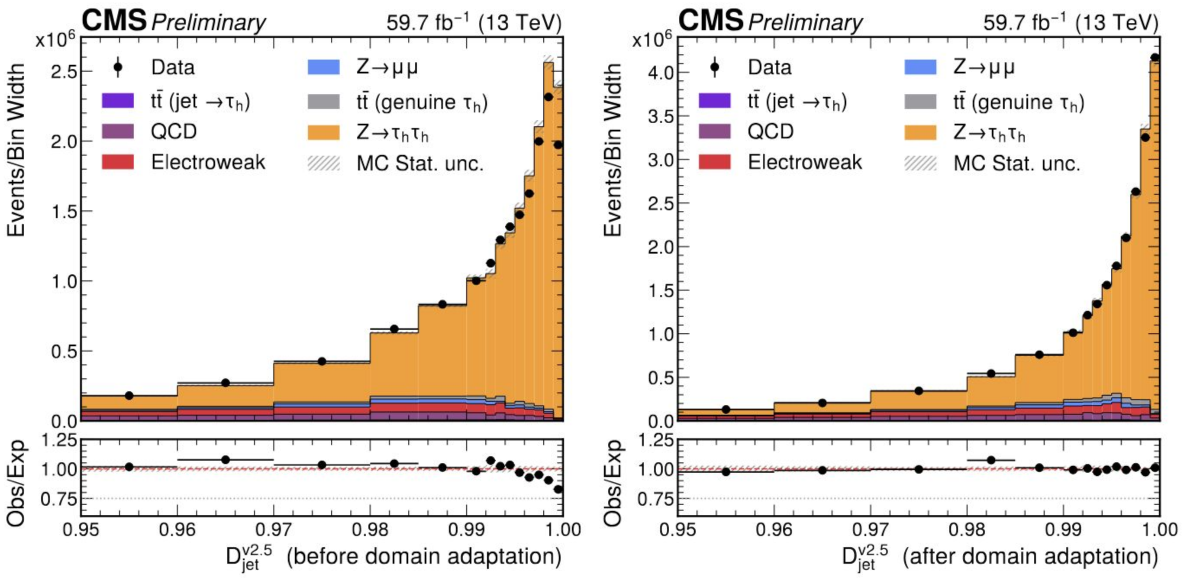
Simulation-to-data improvement by Domain Adaptation

Distribution of the DeepTau discriminator against jets

Run 2

Before

After



CMS PAS TAU-24-001

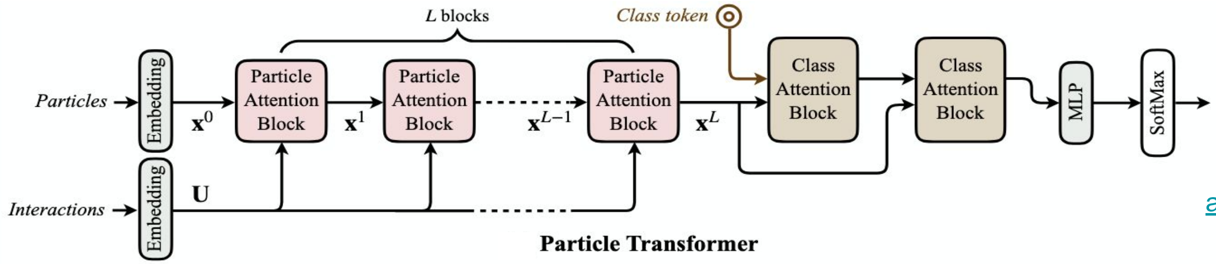
Significant improvement : Final bin (τ_h purity > 96%) disagreement reduced from 17.4% to 0.9%

Tau Identification Algorithms

Unified Jet Tagger (UParT and ParticleNet)

Unified particle transformer (UParT)

CMS DP - 2024/066



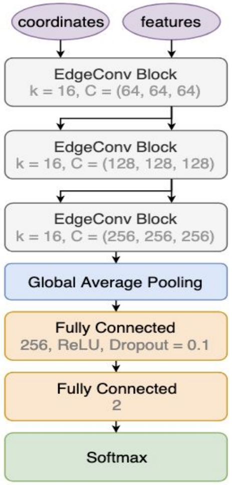
arXiv : 2202.03772

- Particle transformer (ParT) : Multi-Head “Attention”, pair-wise “interaction” features among jet constituents
- UParT : τ_h as unified objects with heavy flavor (b and c jets) and s jets, no identification of constituents
  - alternative strategy starting from jets, using ParT
  - τ_h DM and p_T are output nodes
  - simultaneous flavor aware jet energy regression and resolution estimation
  - Adversarial Training for better simulation-to-data agreement

arXiv : 2203.13890

- ParticleNet : Dynamic Graph CNN (DGCNN)
  - Edge Convolution blocks for particle clouds - unordered set of its constituent particles
  - learn relationships via nearest neighbors

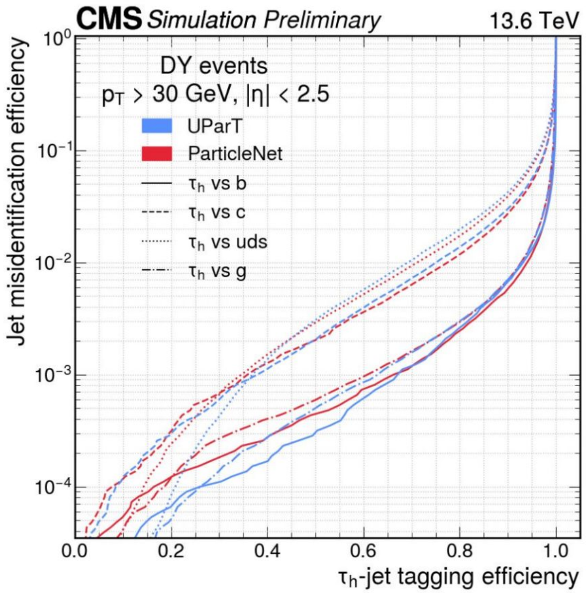
arXiv : 1902.08570

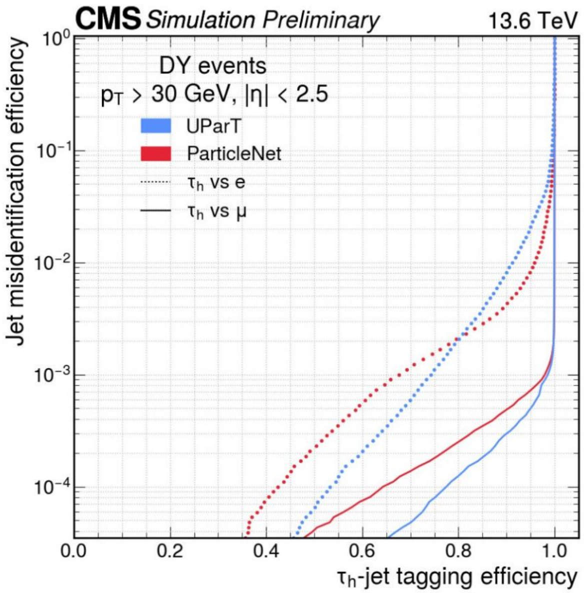


ParticleNet

Performance comparison

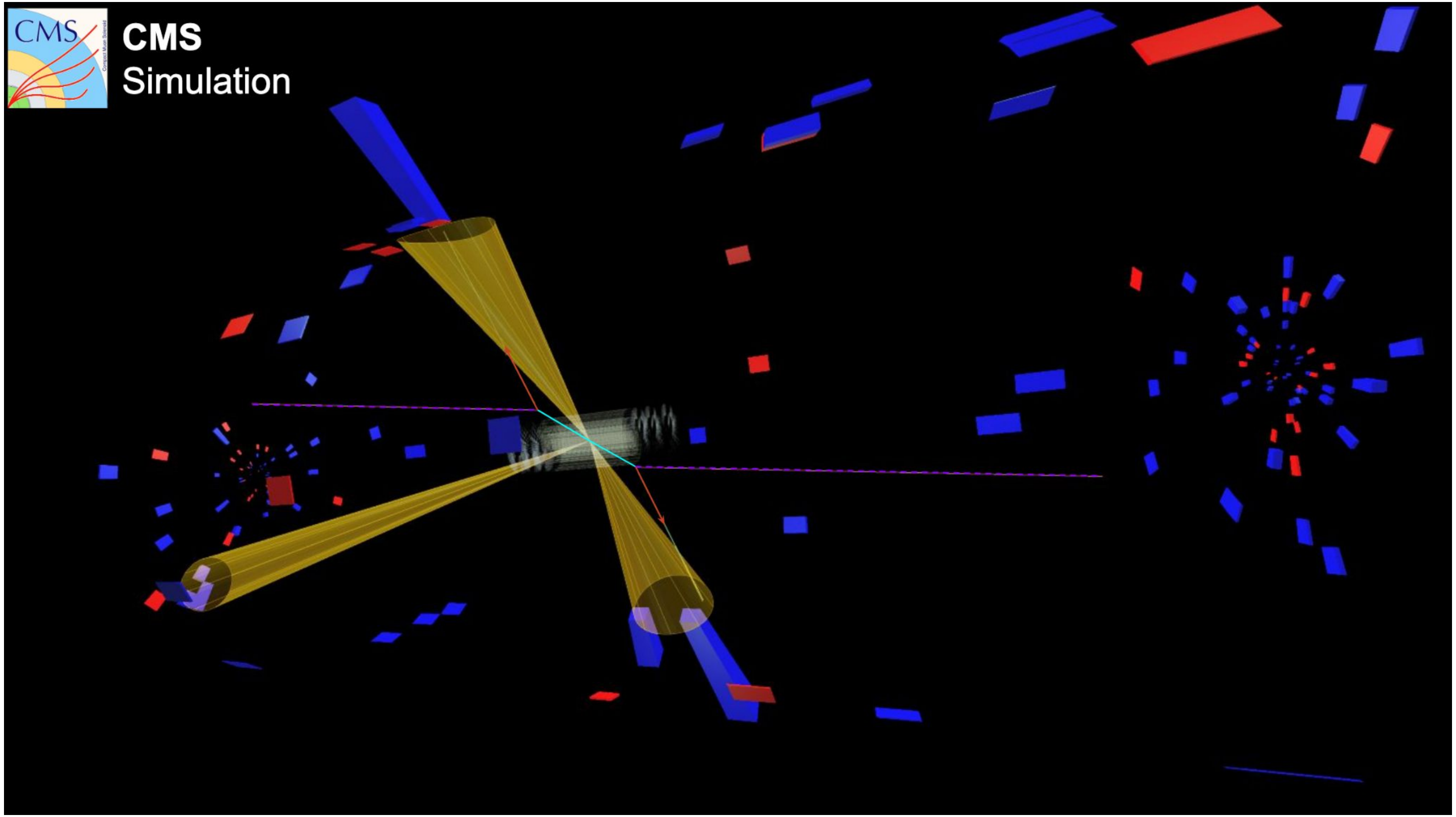
Run 3





$$\tau_h \text{ vs X} = \frac{prob(\tau_h)}{prob(\tau_h) + prob(X)}$$

Significant improvement using UParT at lower misidentification rate, while ParticleNet is better at high misidentification rate



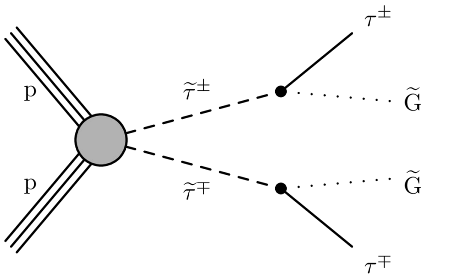
Dedicated Tau Identification Algorithm for specific physics object

Displaced Tau - DisTau (First time)

Displaced Tau and DisTau architecture

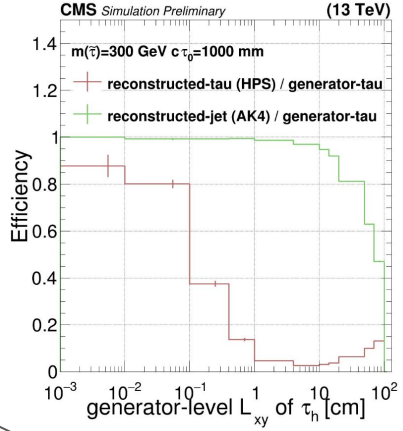
CMS DP-2024/053

- BSM models e.g. Gauge-Mediated SUSY Breaking models : supersymmetric partner of tau (staus) with macroscopic lifetime, $c\tau_0$ ~ 100 µm to 1m => displaced taus

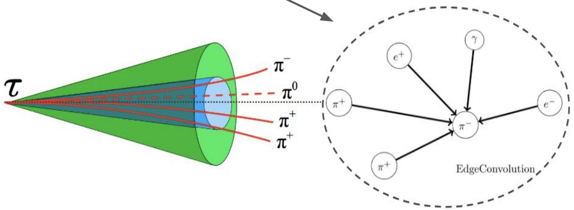


CMS EXO-24-020

- HPS not designed for displaced signatures
- AK4 jets efficiently reconstructed for tau with high displacement (L_{xy})



- DisTau : ParticleNet based algorithm with EdgeConv blocks
  - Use particle kinematics and distances in η and φ to identify genuine displaced taus against jets from light quarks and gluons



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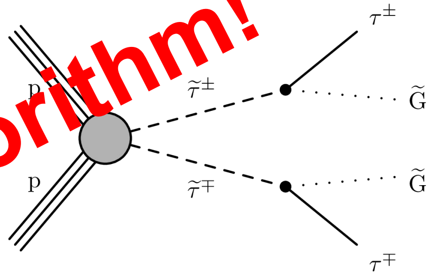
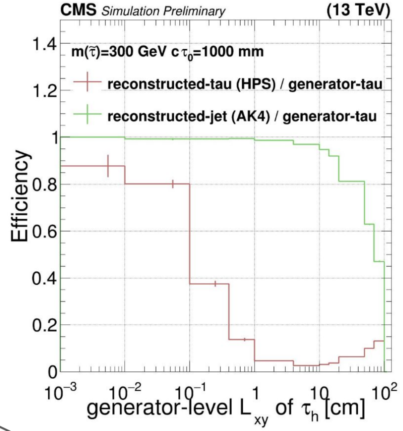
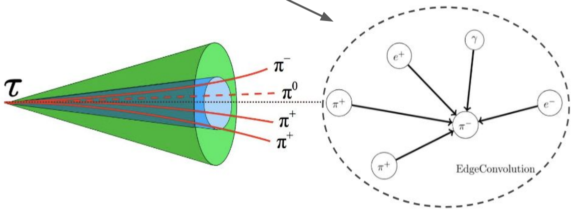
First effort of displaced tau ID algorithm!



[CMS-EXO-24-020]

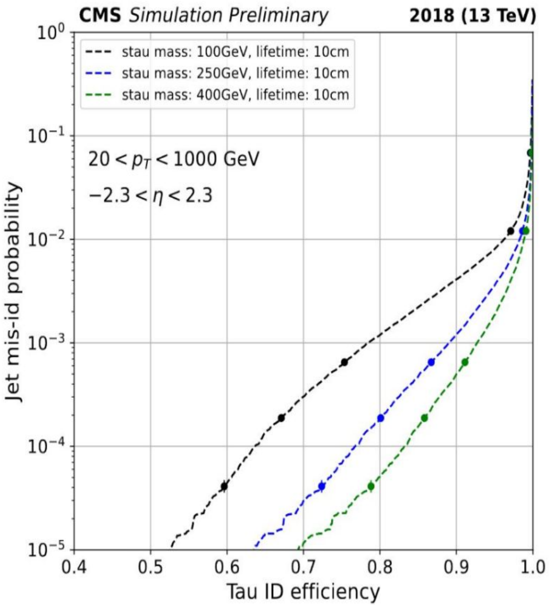




Performance

Jet misidentification probability : estimated from top-antitop simulated samples

$c\tau_0$= 10 cm



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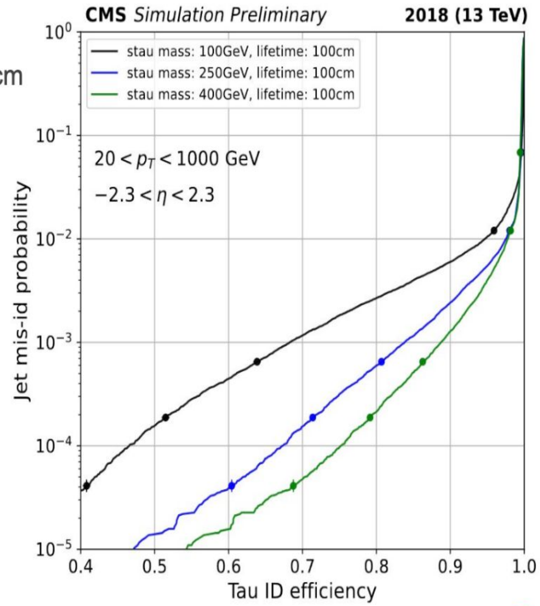
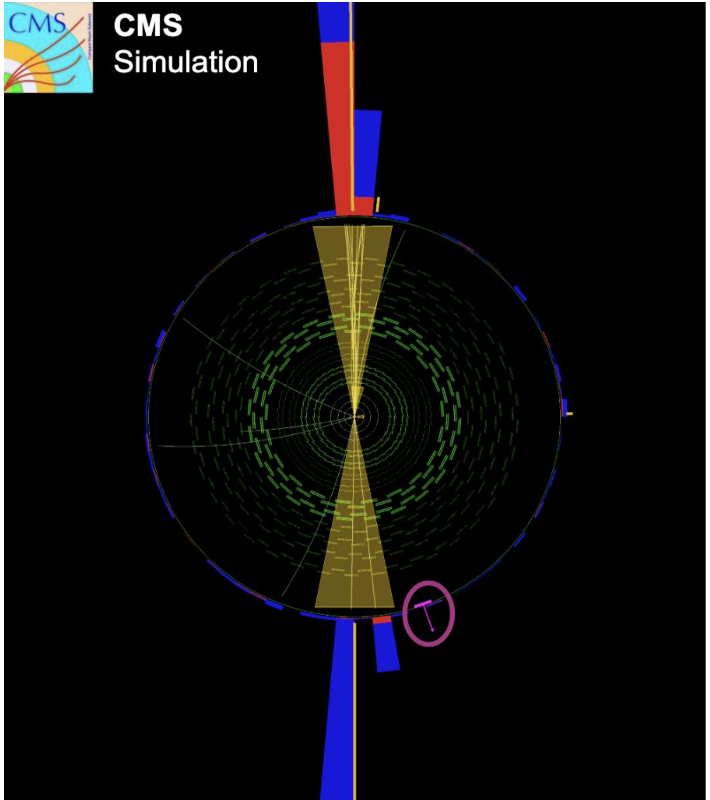


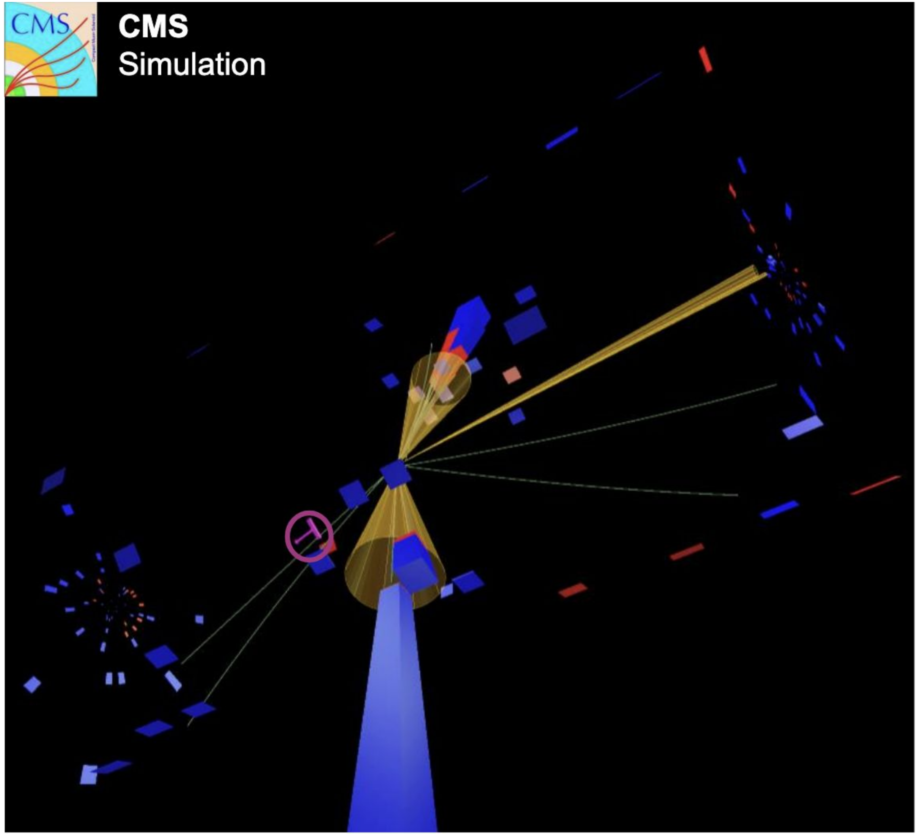
- Promising rejection efficiency of signal versus background.
- Validated with 13 TeV 2018 data => simulations agree well with data

Dedicated Tau Identification Algorithm for specific physics object

Boosted Tau - Boosted DeepTau (CNN)

Details covered by G. Parida

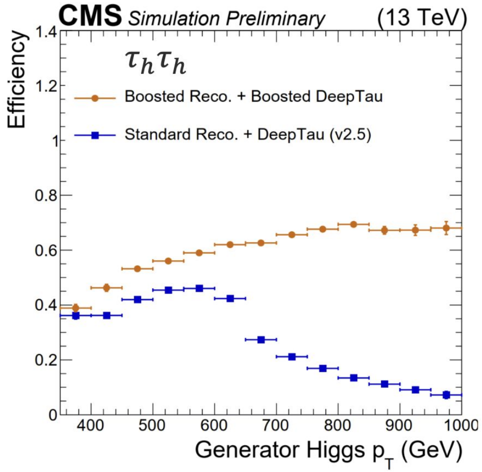




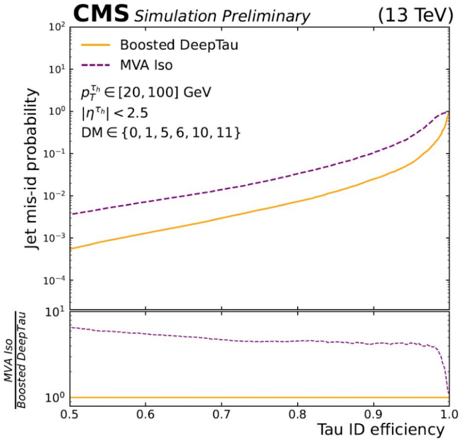
Boosted DeepTau

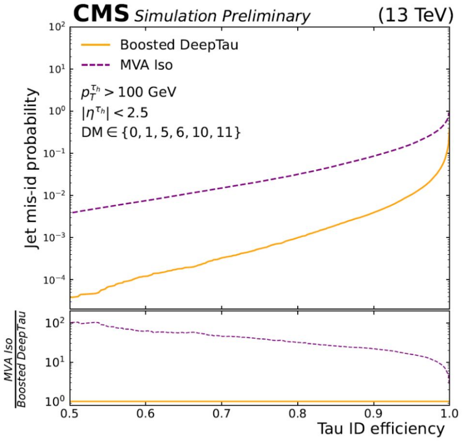
CMS DP-2025-047

- τ_h pairs from boosted bosons, e.g. X->HH->bb$\tau\tau$, m_X ~ O(TeV)
- Dedicated reconstruction : start from large cone jets (Cambridge-Aachen, R = 0.8) -> jet constituents are reclustered to identify subjets -> seed the HPS reconstruction for individual τ_h of boosted system
- Boosted DeepTau : DeepTau v2.5 (without domain adaptation) trained on boosted τ_h collections



Recovers efficiency at high Higgs p_T





Improvement of 2-4 (>10) for τ_h p_T < 100 GeV (> 100 GeV) than Run 2 BDT-based (MVA Iso) method

Conclusion

- Latest techniques of Hadronic Tau reconstruction and identification at the CMS detector for Run 2 and Run 3 are presented => more precise CMS physics analysis results.
- Latest DeepTau v2.5 => background rejection (~30%) along with improved data-to-simulation agreement.
- Unified approach of jet tagging UParT and ParticleNet => promising result for hadronic tau identification
- Dedicated displaced tau and boosted tau identification => good rejection efficiency of signal vs background for specific analysis purposes.
- CMS continues to improve the identification of tau leptons, including in particular topologies.

Backup

Adversarial Training : allowing the model to learn from input feature distortions and improve robustness against Monte-Carlo (MC) simulation mismodeling

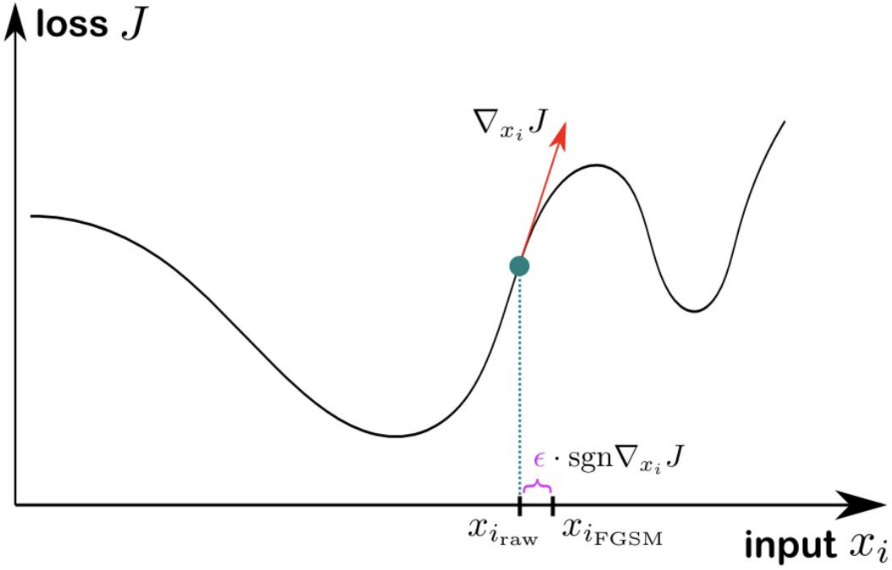
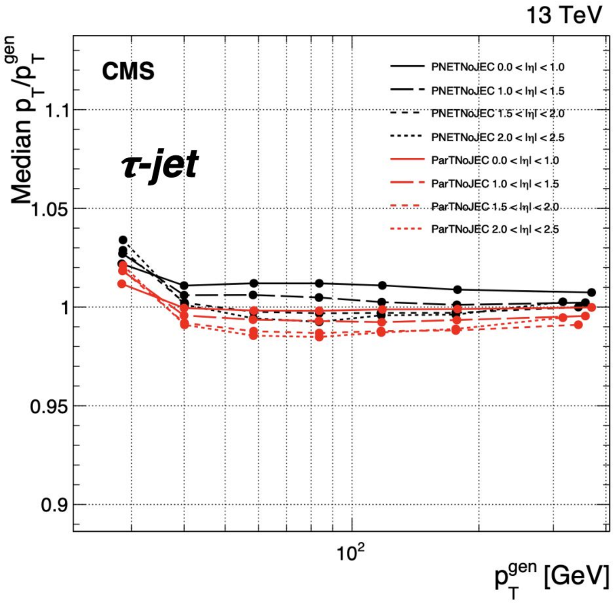


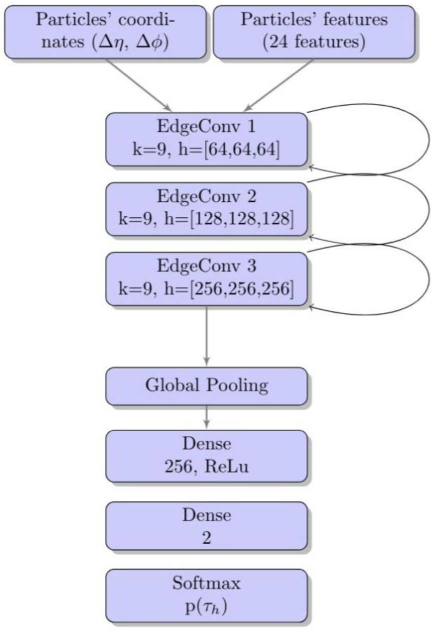
Illustration of an adversarial attack [1]

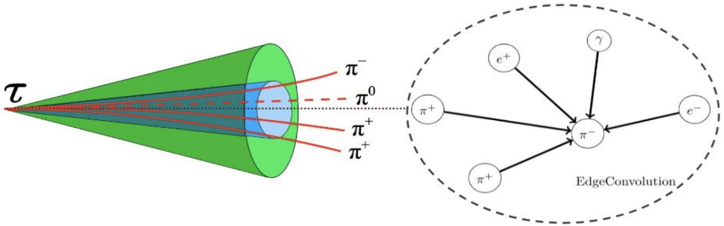
$$L = \overbrace{CatEntropy(x, x_{truth})}^{\textit{Classification}} + \overbrace{\gamma_{regr} \cdot log(cosh(y - y_{truth}))}^{\textit{Regression}} + \overbrace{\gamma_{quantile} \cdot [p_{0.16}(z - z_{truth}) + p_{0.84}(z - z_{truth})]}^{\textit{Quantile regression (resolution estimation)}}$$

pT response vs pT,GEN , ParT

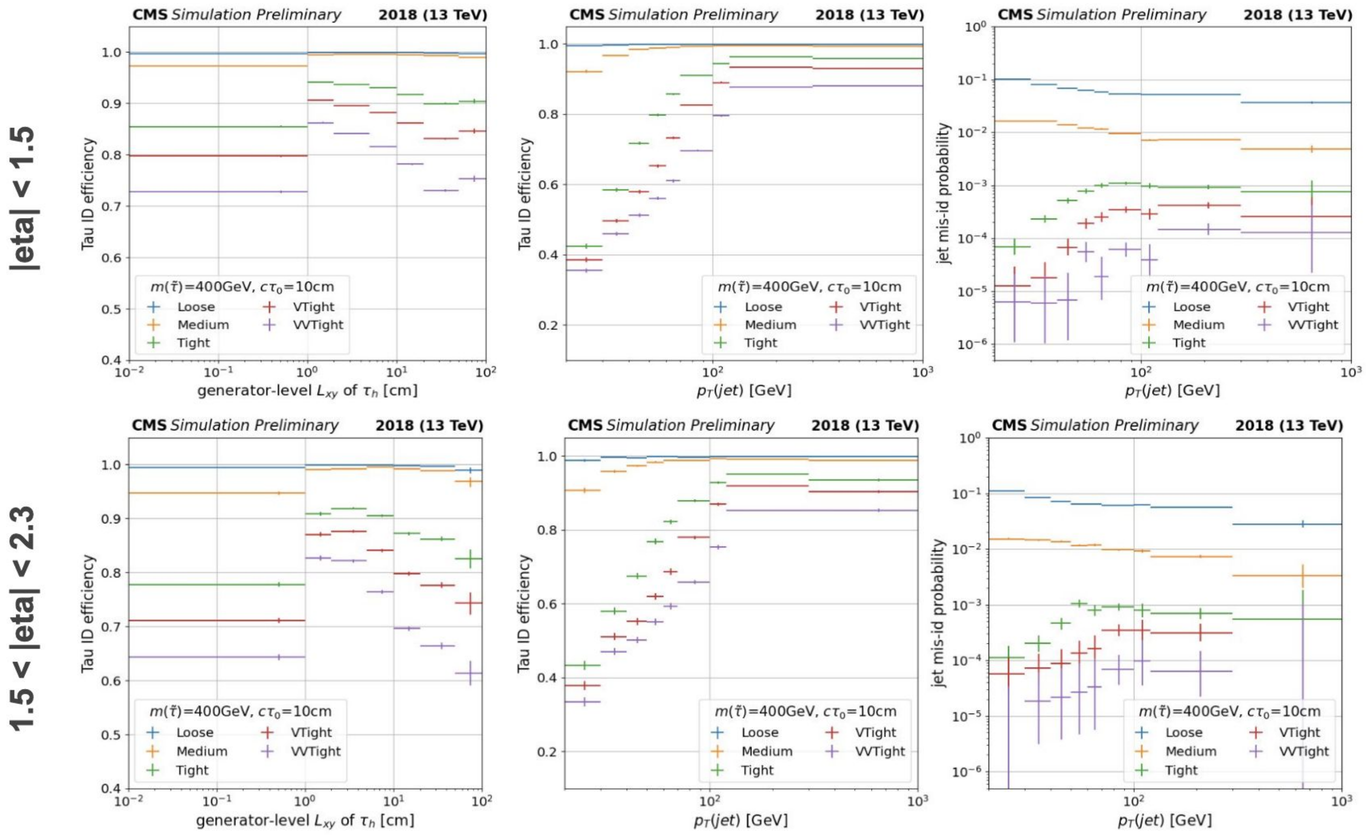


- genuine displaced τ_h vs jets from light quarks and gluons
- Use particle coordinates, $\Delta\eta = \eta_{jet} - \eta_{pf\text{-}candidate}$; $\Delta\varphi = \varphi_{jet} - \varphi_{pf\text{-}candidate}$ and 24 features like momentum, charge, impact parameter etc

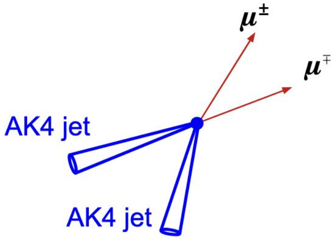


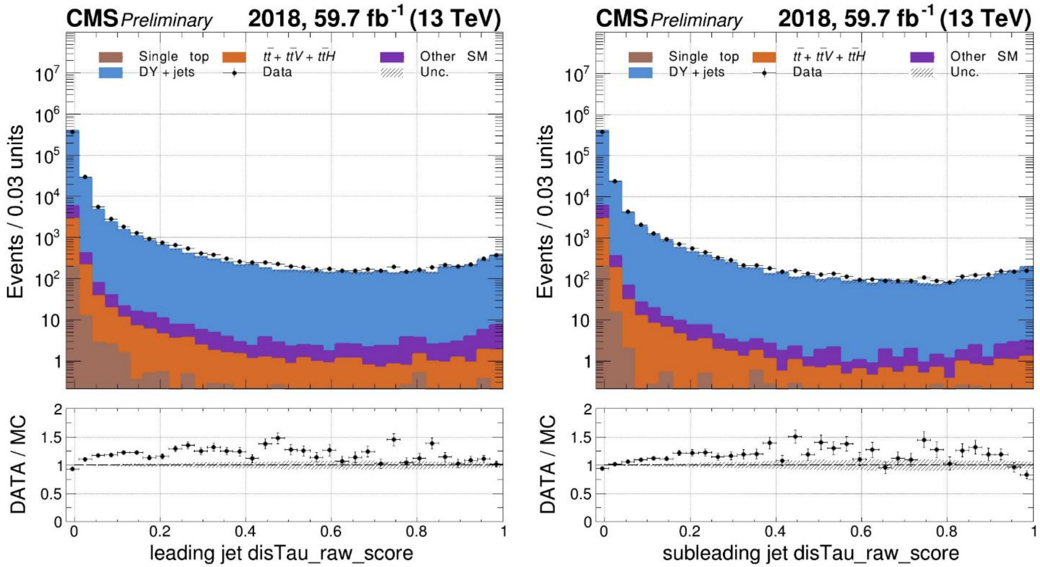


efficiency and misidentification rate of the DisTau algorithm for the different working points.



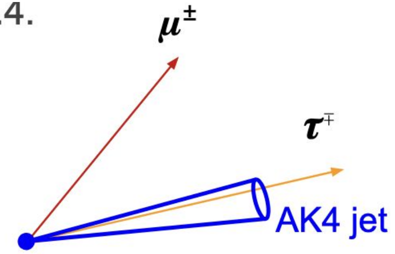
Tagger validation for background jets

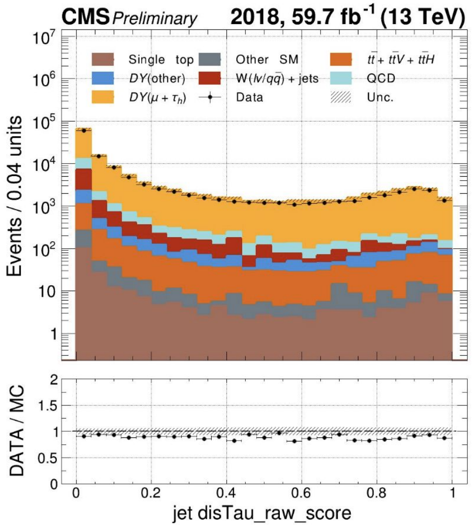




Tagger validation for genuine τ_h

< 0.4.

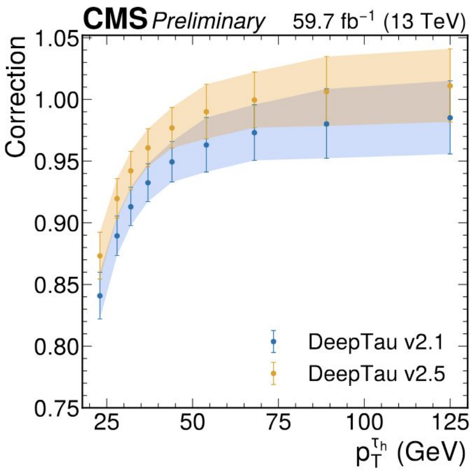




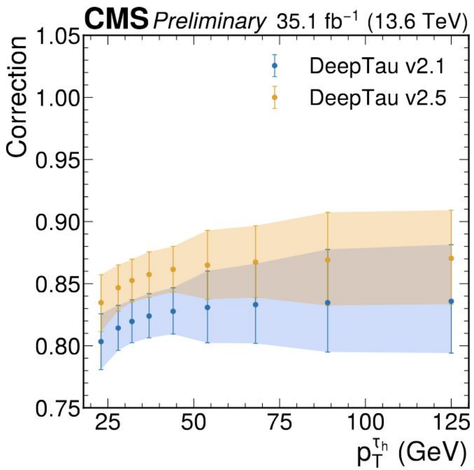
Data-to-simulation correction factors

τ_h Identification efficiency scale factors

Run 2



Run 3

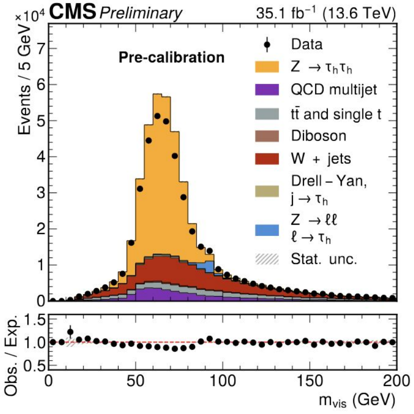


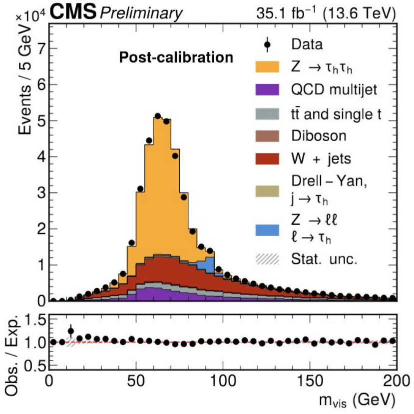
Results consistent with unity within 20% for Run 2

Improvement of ~ 5% for v2.5

$\mu\tau_h$ visible mass in Z -> $\tau_\mu \tau_h$ events :
Before and after scale factor application

Run 3





Data-to-simulation agreement is highly improved

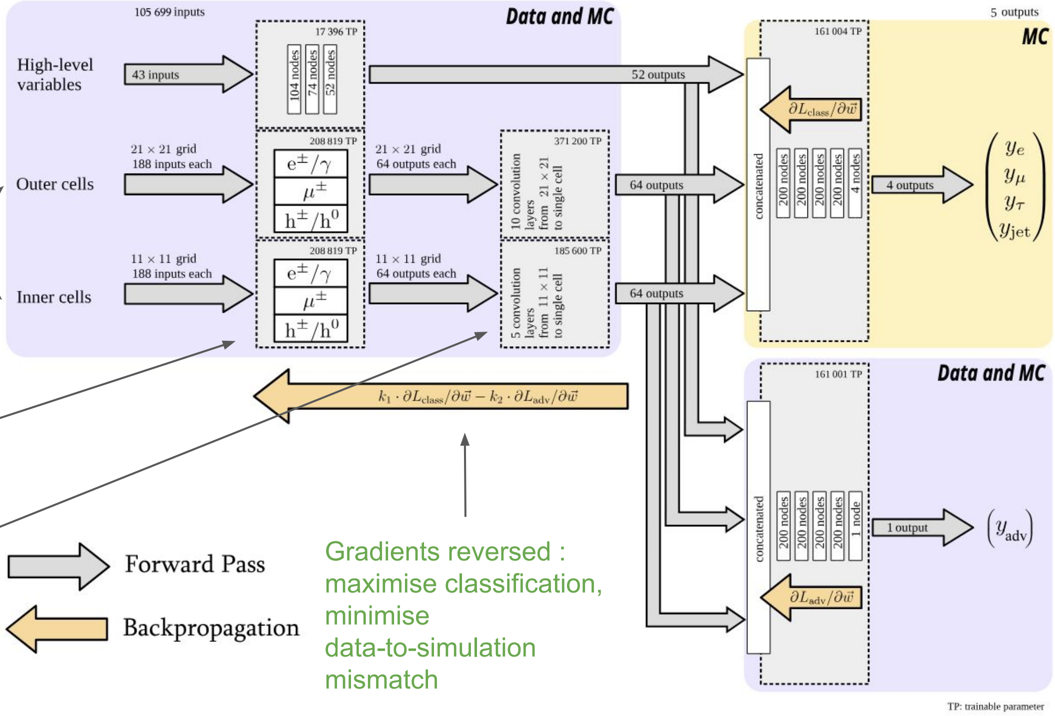
DeepTau v2.5 Architecture

τ_h features

Low level input variables : Grid info

Feature preprocessing : Fully connected layers to reduce dimensionality

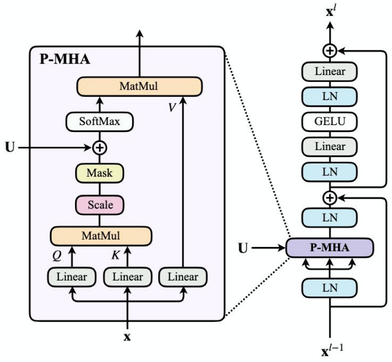
Feature extraction by convolutional layers



Gradients reversed : maximise classification, minimise data-to-simulation mismatch

Final particle classification layers : genuine τ_h against misid jets/e/μ

Domain Adaptation layers



(b) Particle Attention Block