Searches for New Physics that couple with third generation fermions

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In this presentation

- The Tau lepton
- The CMS experiment and trigger system
- New physics searches with τ at CMS during Run2
  - Focus on search for new physics in the τ lepton plus missing transverse momentum final state
- The Tau reconstruction at CMS
- The Tau identification and reconstruction at the CMS Trigger level
- Improvements on tau reconstruction at the High Level Trigger for new LHC data taking
- Conclusions

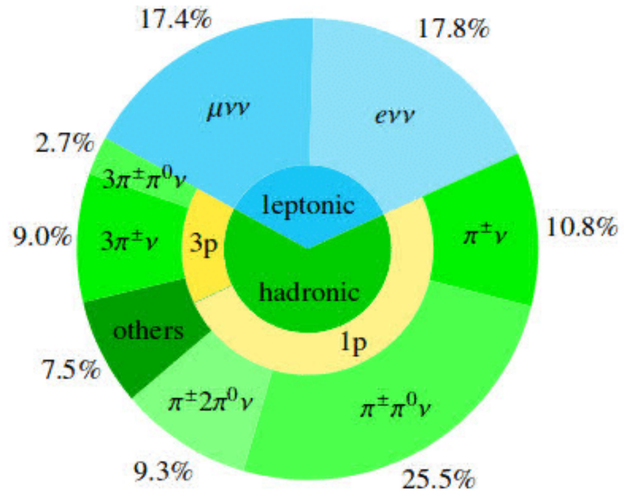
Who?

The τ lepton

- τ leptons (taus) are the heaviest leptons in the SM
- They can be used for several measurements with final states involving taus:
  - Standard Model tests
  - Higgs studies: Yukawa couplings of Higgs boson with fermions, CP properties of the Higgs
  - Tau polarization - in Z boson decays (see Abdollah's talk)
  - Searches for BSM physics: – Leptoquarks, SUSY, high mass resonances
  - Search for LFV with tau leptons in the final state (more in Luca's talk)

Name: Tau Lepton (τ)
Mass: 1776.86 MeV/c²
Av. lifetime: 2.9×10⁻¹³ s
Discovered: 1974 (SLAC)
Spin: 1/2 - Fermion
Family: 3rd lepton family
Features: **It is the only lepton that can decay to hadrons and has large Yukawa coupling with Higgs**

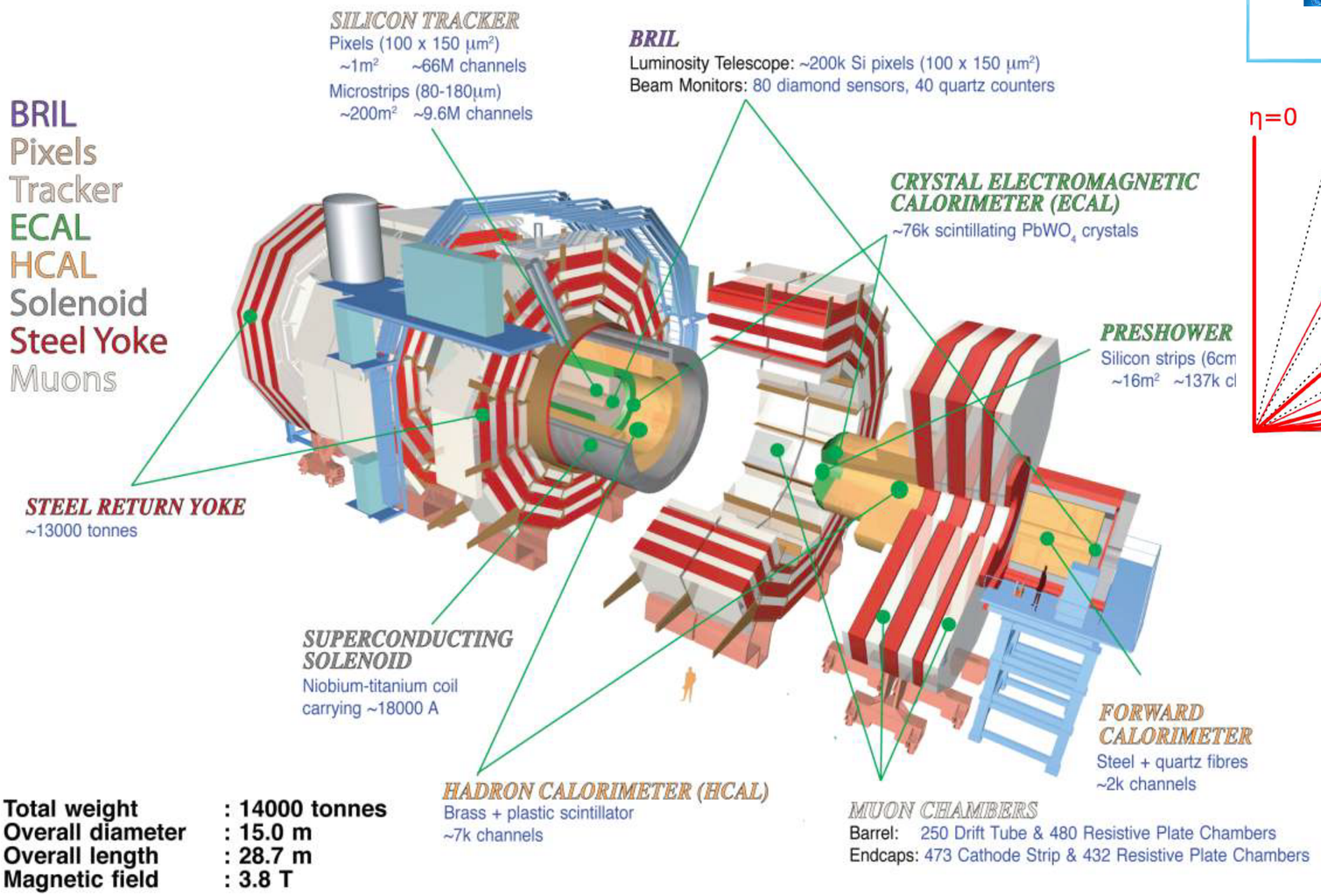
Tau decays involve charged particles, prongs



Where?

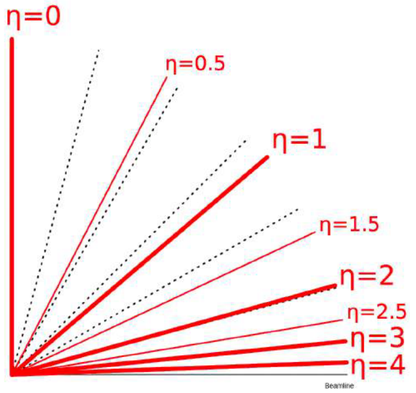
The CMS Detector

General purpose detector, "onion" structure



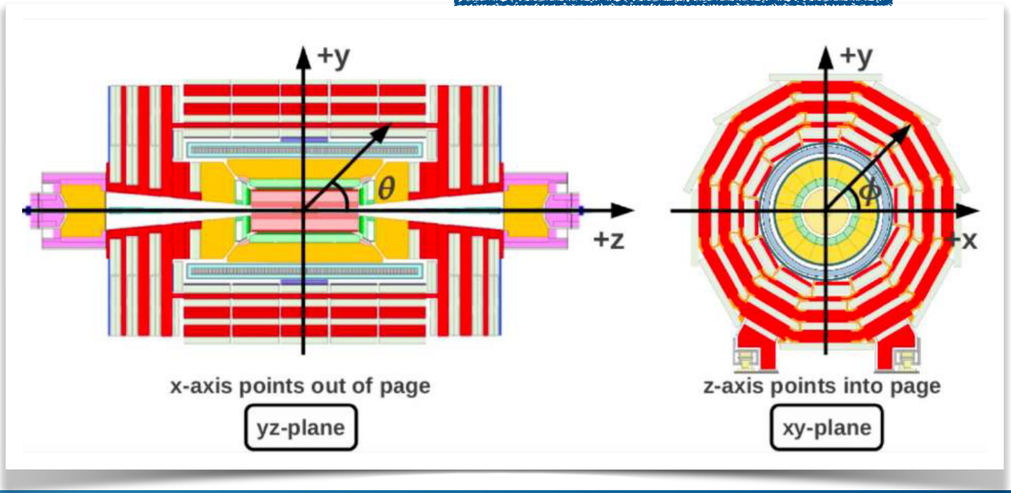
Useful definitions:

- Pseudorapidity: $\eta = -ln\left(\tan\left(\frac{\theta}{2}\right)\right)$, for HR particles it coincides with the rapidity
- Angular separation $\Delta R_{ij} = \sqrt{\left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2}$



Cartesian coordinate system:
origin - nominal collision
Y-axis - upward vertically
X-axis - radially inside the LHC ring
Z-axis - toward Jura mountains

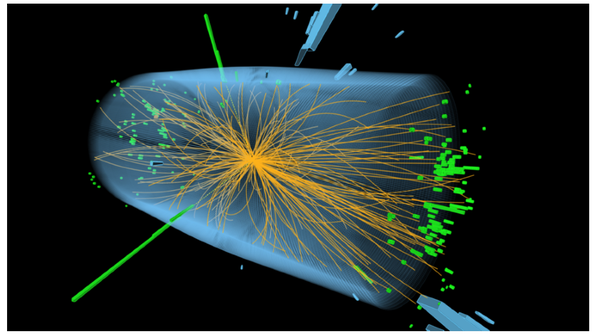
Cylindrical symmetry:
polar coordinate system is more convenient



Where?

The CMS Trigger system

Two Level Trigger system to select events of physics interest



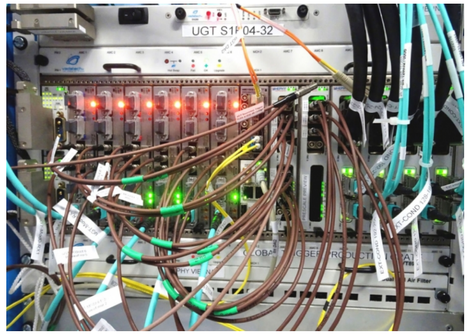
Collisions@LHC

Every 25 ns

Rate of 40 MHz

40 TB/s

Mostly not interesting events!



Level 1 (L1T)

Hardware based

Simplified readout with

Only muon/calo info

decision in < 3.8 μs

110 kHz max output rate

High Level (HLT)

Software based

Full event readout

All subdetector info

Decision in < 0.5 s

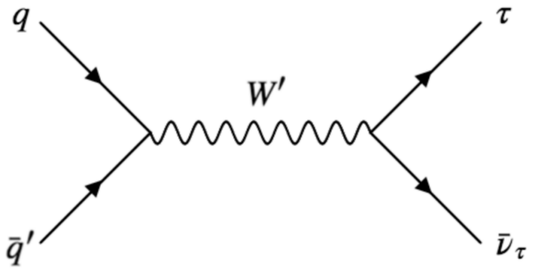
5 kHz, 15 GB/s output limit

What?

Search for new physics in the τ lepton plus missing transverse momentum final state

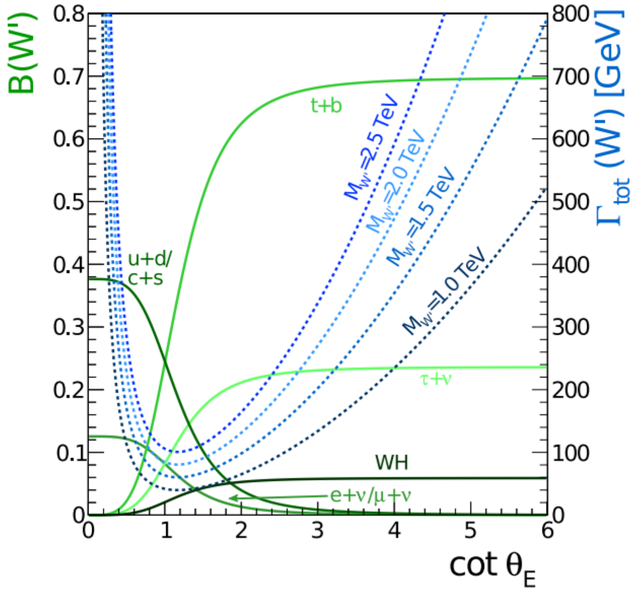
Different models:

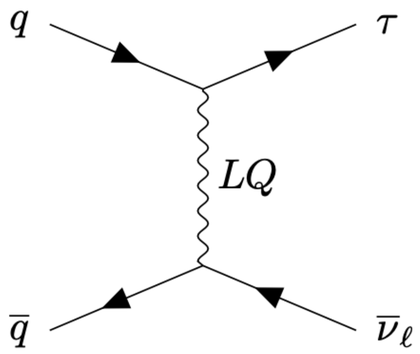
- Heavy charged vector boson (W') [1]
  - Parameters to scan:
    - Mass of the heavy charged vector boson
    - Coupling ratio $g_{W'}/g_W$ - impacts width and cross section
  - Included in Non-Universal Gauge Interaction Model
    - 2HDM model with additional SU(2) for heavy vector bosons, which mixes with SM SU(2) via angle ϑ_E
    - Width and cross section depends on relative coupling to τ lepton.
- Vector Leptoquark [2]
- Quantum Black Holes [3]
  - Extra spatial dimensions n = 4
  - Threshold mass
- Effective Field Theory [4]



Can use width dependent signal samples to interprete the limits for this model

Width and cross section depends on relative coupling to τ lepton





For reference, see [5] in Slide 21

What?

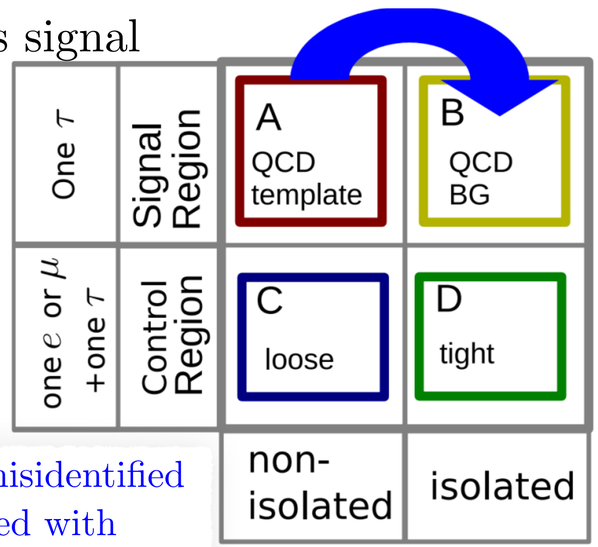
Search for new physics in the τ lepton plus missing transverse momentum final state

Signature: W' → $\tau\nu_\tau \Longrightarrow$ high p_T and MET

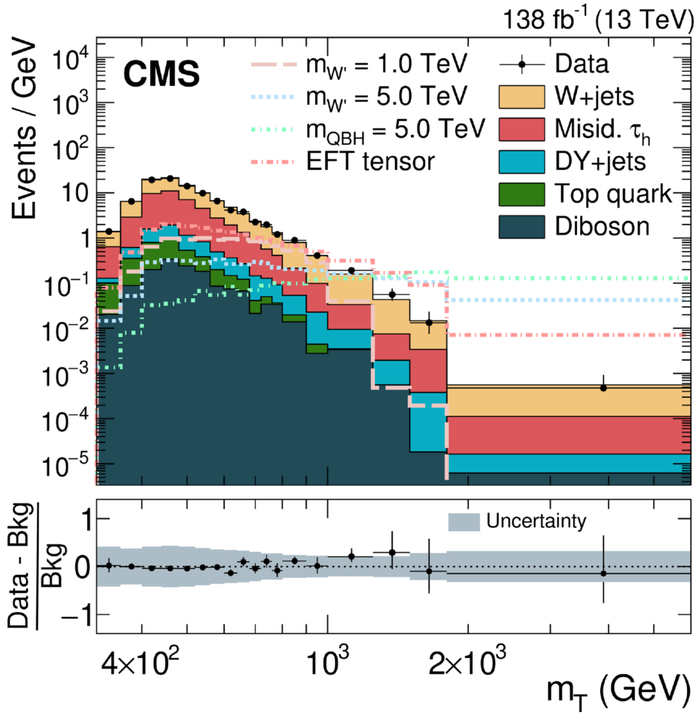
- Final state: one (hadronic) tau and missing transverse momentum
- Expect back-to-back kinematics and balanced in p_T
- Discriminant variable is transverse mass m_T

Main backgrounds:

- W+jets: dominant irreducible, same signature as signal
- Top-antitop production
- Single Top
- Z(ll)+jets
- Diboson (WW, WZ, ZZ)
- QCD multijet



Backgrounds from misidentified jets are calculated with datadriven method



$$Ratio == \frac{(N^{D}_{data} - N^{D,true\,\tau}_{MC})}{(N^{C}_{data} - N^{C,true\,\tau}_{MC})}$$

Apply this on an event basis to region A and normalise by removing true τ s from MC from this region

For reference, see [5] in Slide 21

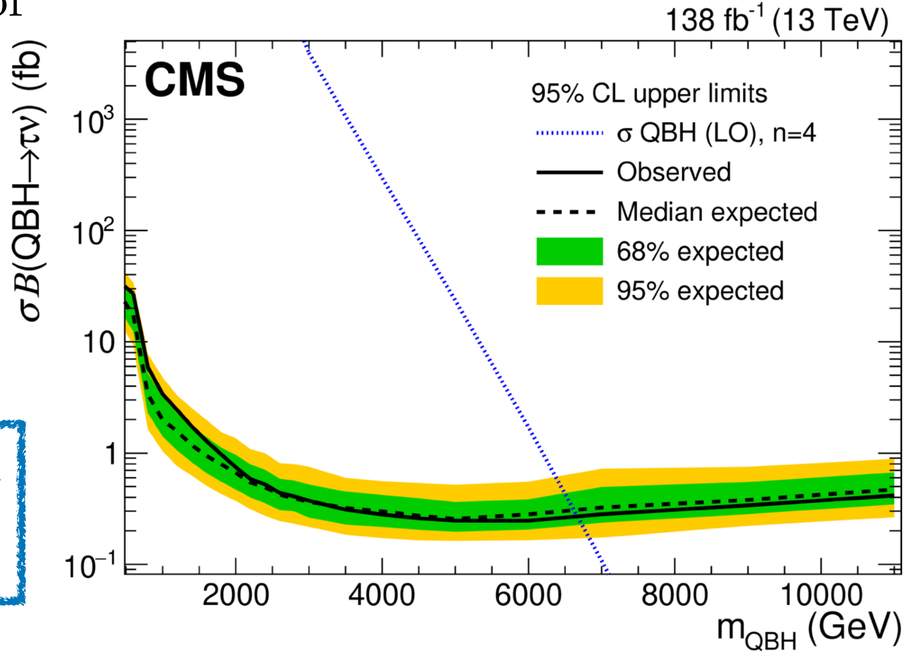
What?

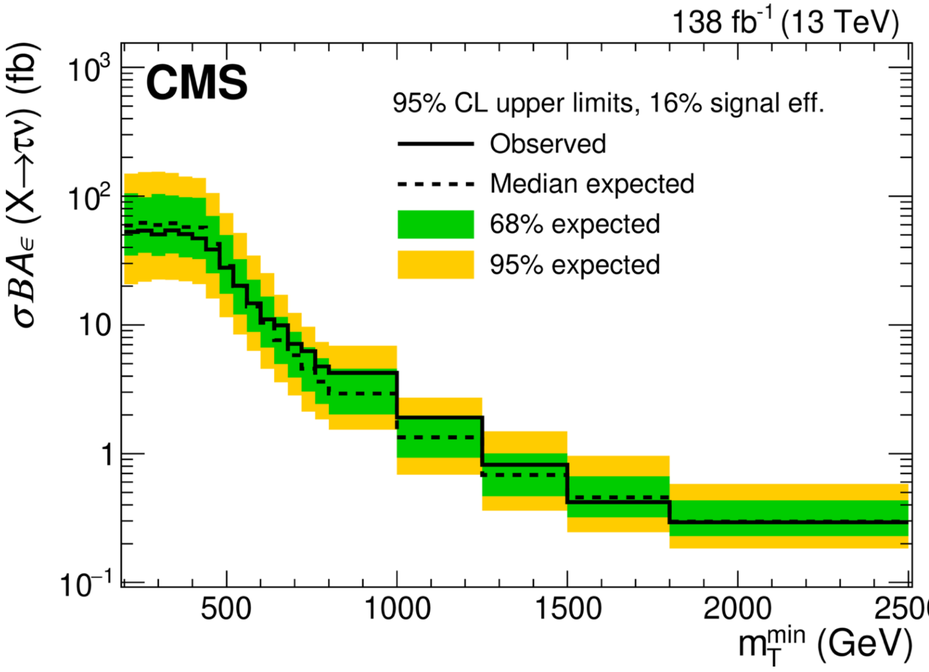
Search for new physics in the τ lepton plus missing transverse momentum final state

Results

- Model-independent upper limit on the product of signal cross section times branching fraction for the τ+ν decay for a back-to-back τ lepton + missing transverse momentum topology
- Bayesian upper exclusion limits at 95% CL on the product of the production cross section and branching fraction of a QBH

QBH model excluded for threshold masses of up to 6.6 TeV.





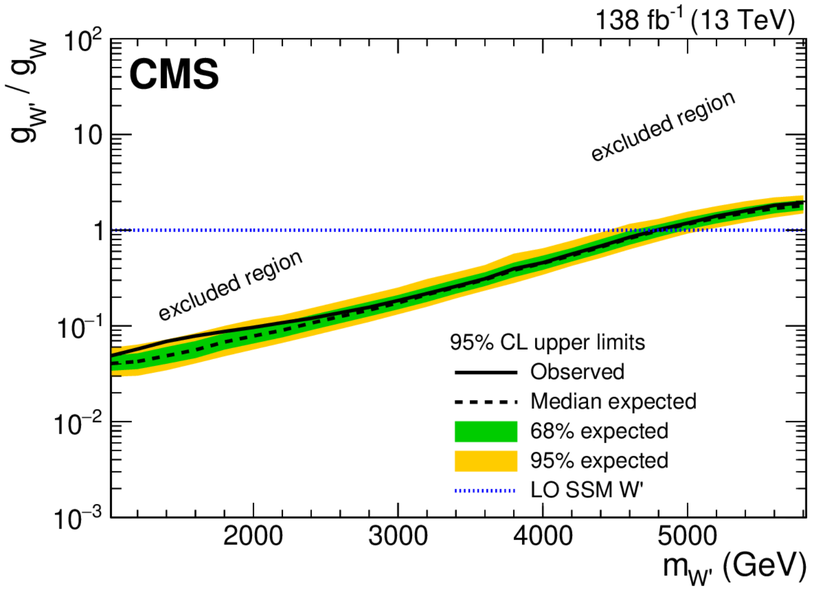
For reference, see [5] in Slide 21

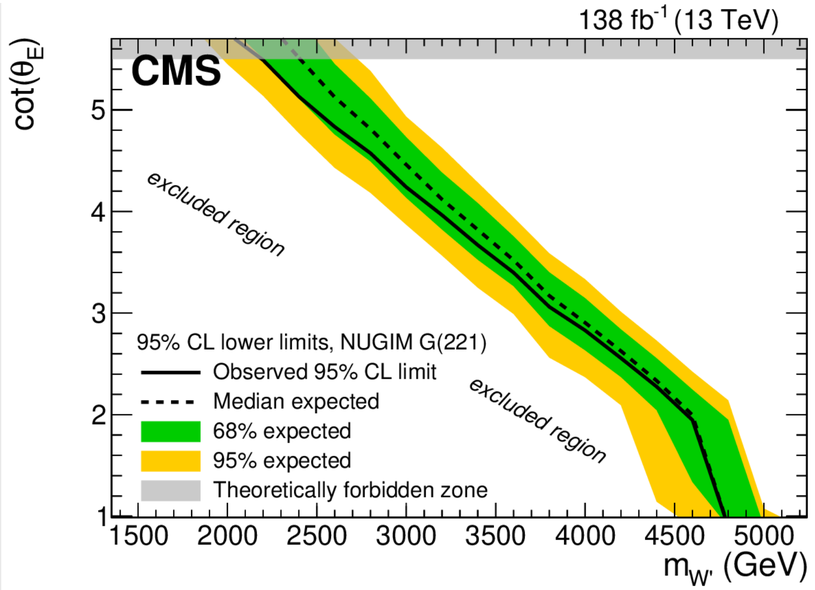
What?

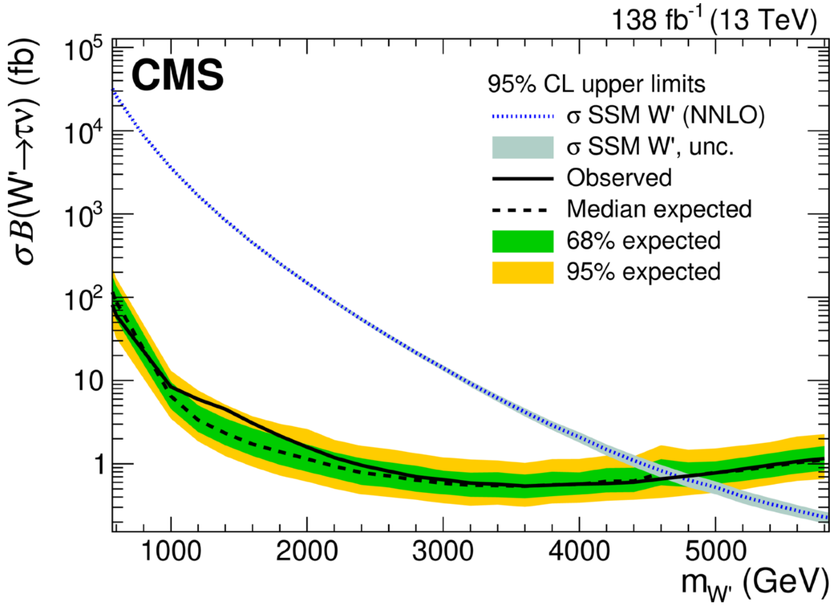
Search for new physics in the τ lepton plus missing transverse momentum final state

Results

- Bayesian upper exclusion limits at 95% CL on the product of the cross section times branching fraction of a W' boson decaying to a τ lepton and a neutrino in the SSM model
- Bayesian upper exclusion limitson the ratio gW′/gW for an SSM-like W' boson
- Lower exclusion limits on the NUGIM G(221) mixing angle $\cot\vartheta_E$







For values of $\cot(\vartheta_E)$=1, W' boson masses of up to 4.8 TeV can be excluded.

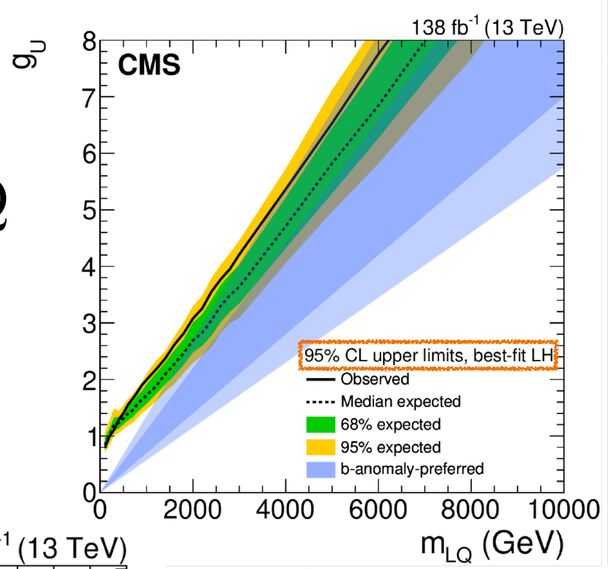
For reference, see [5] in Slide 21

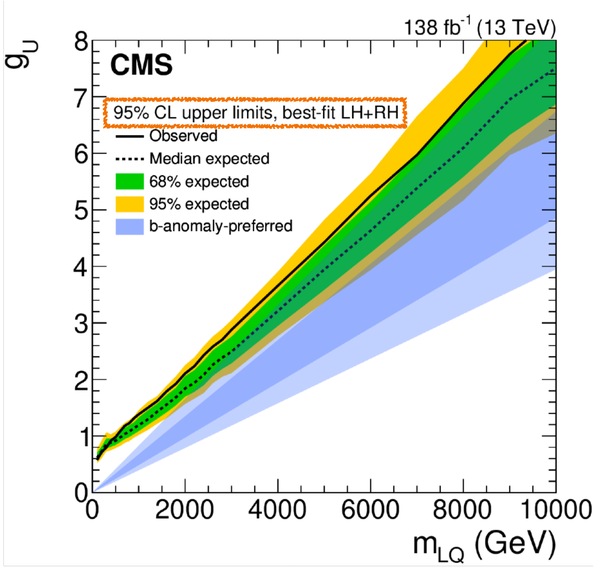
What?

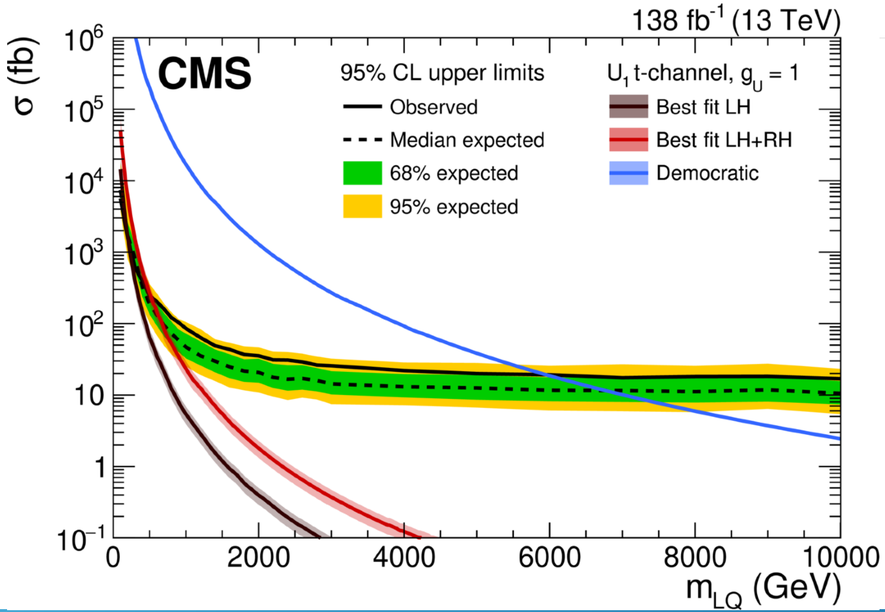
Search for new physics in the τ lepton plus missing transverse momentum final state

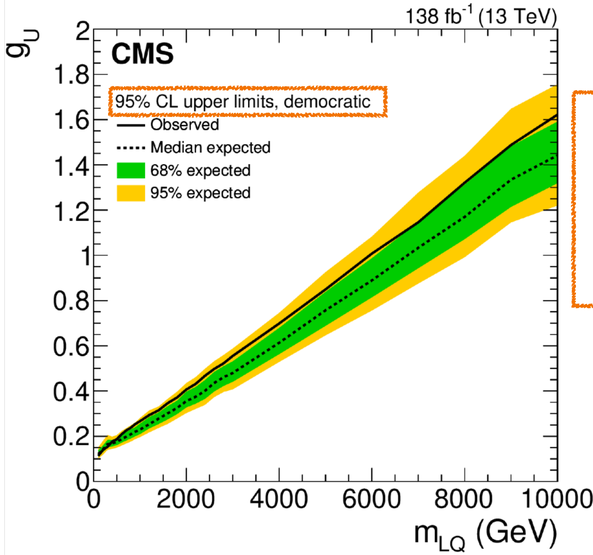
Results

- Expected and observed upper limits of the LQ coupling gU VS the LQ mass
- Bayesian upper limits at 95% CL on the xs of the process pp→τν mediated by LQ exchange in the t-channel









Masses up to 205/ 515 / 5900 GeV are excluded for the best-fit LH / best-fit LH+RH / democratic scenarios

Different scenarios: LH, LH+RH, democratic

For reference, see [5] in Slide 21

How?

The τ reconstruction at CMS - Run 2

L1 Tau reconstruction [6]

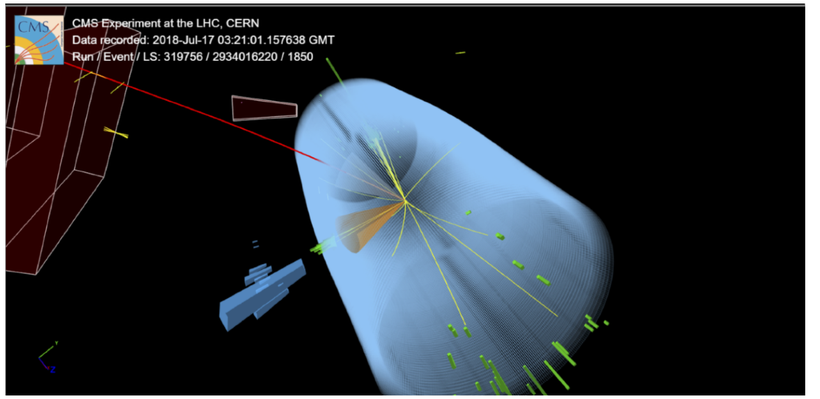
- Calibration of Trigger Towers to mimic true offline response
- Clustering is performed around a central seed
- Merging of clusters to form L1 Tau Objects

HLT Tau reconstruction [7-8]

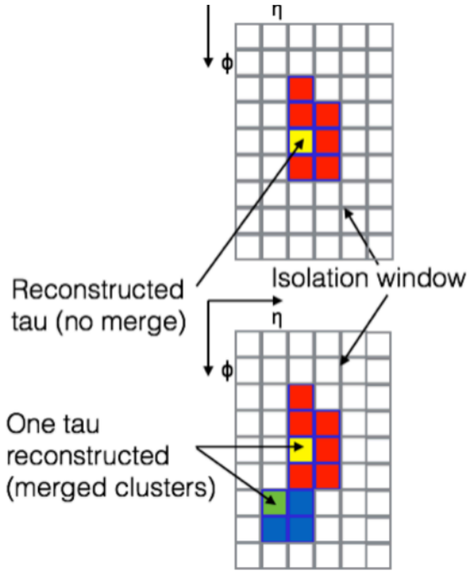
- L2: Calorimeter jets build around L1 seeds
- L2p5: Pixel track based isolation around L2 hadronic tau leptons (only di-τ_h triggers)
- Particle-Flow event reconstruction
- L3 tau reconstruction

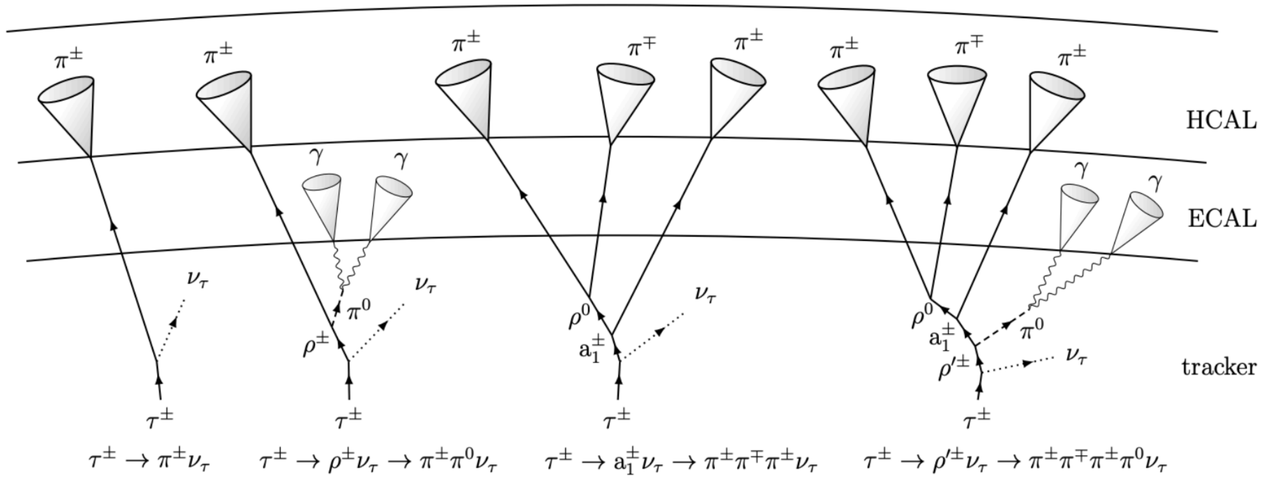
Offline reconstruction [9]

- AK4 jet (anti-k_T algorithm, $\Delta R = 0.4$) as seed
- Decay Mode reconstruction (charged tracks + calo clusters):
  - Hadron+Plus+Strips (HPS) algorithm
- Identification:
  - MVA algorithm
  - DeepTau



Higgs decaying to τμ (red track) τh with 3 charged hadrons which are indicated with the cone and the blue calorimeter cells





τ_h appear in the detector with 1 or 3 charged hadrons + one or more pions

When? The τ reconstruction at CMS - Run 2

L2

Jets built around **L1 seeds**. **Muon** and **calorimetric** info available

L2p5

Pixel track based isolation around L2 taus

Only di-τ_h triggers

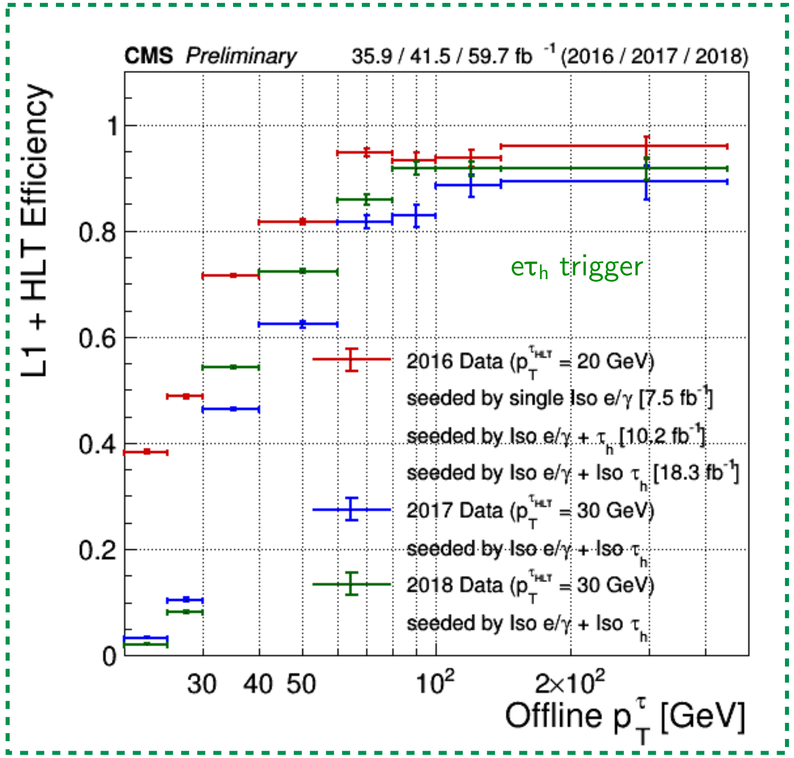
Particle Flow

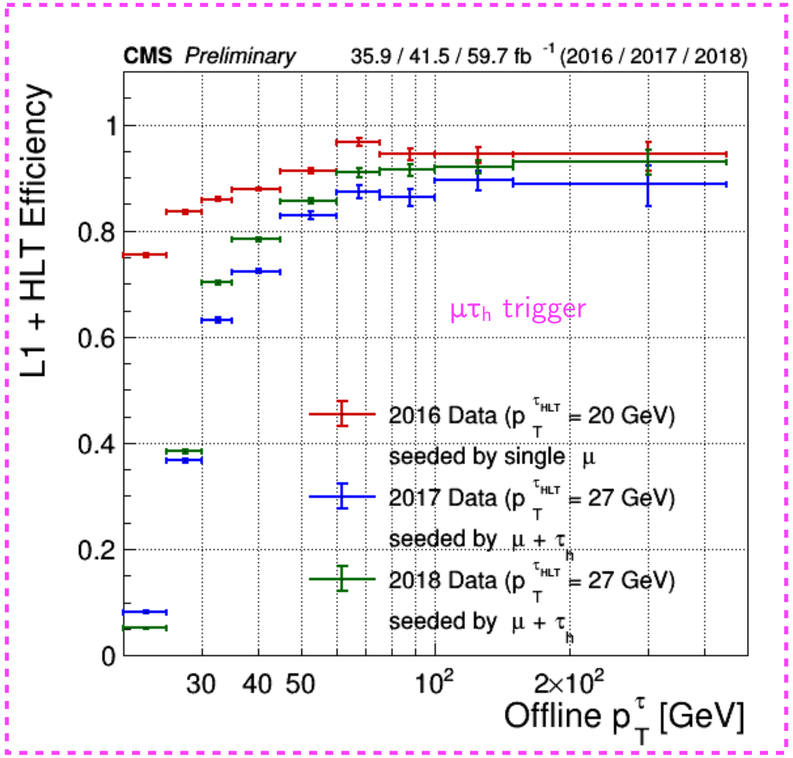
Complete Event reconstruction, **τ object** information available

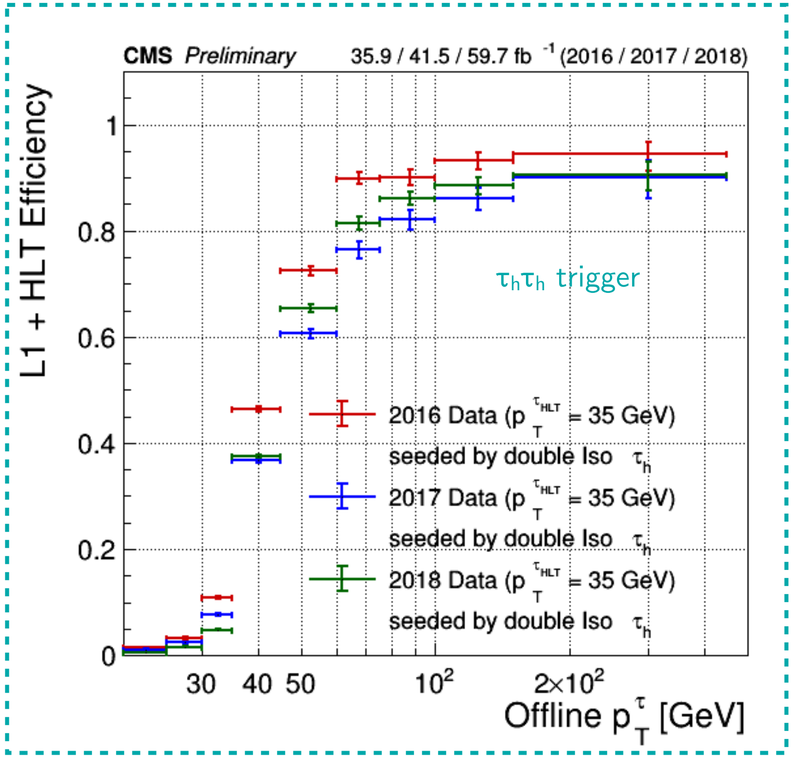
L3

From PF cand

- HPS / cone based algo
- Isolation criterion / deepTau







All plots are taken from the performance note: CMS-DP-2019-012

Great! But can we do better?

Great! But can we do better?

Of course!

Tau reconstruction
For Run 3

Many improvements for Run 3

New Machine learning based ID @ L1

DeepTau@ HLT

New offline DeepTau training (already available)

Improved systematics for data modeling (crucial for analyses!)

General: Update and uniform tools

Tau embedding

New triggers @HLT

Displaced τ reconstruction

Investigation of ParticleNet introduction for offline reconstruction & ID

New L2Tau identification with CNN L2TauNNTag

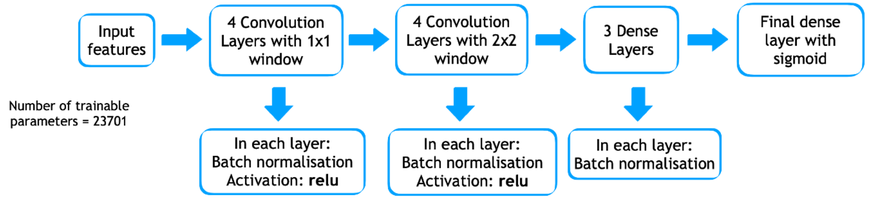
ParticleNet @HLT

Boosted τ identification

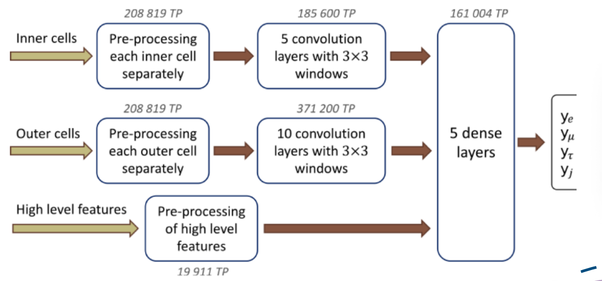
When? The τ reconstruction at HLT - Run 3

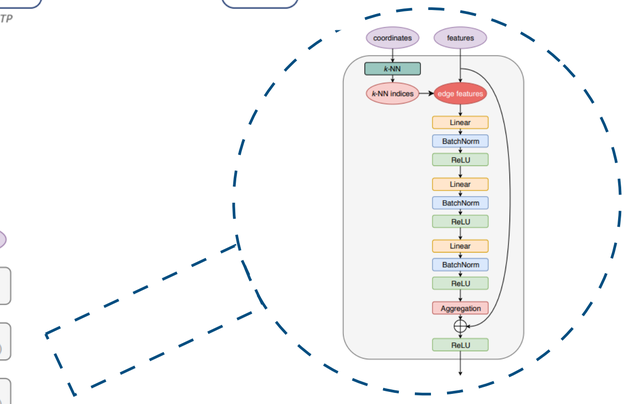
- Keep almost all Run2 triggers in the HLT menu, drop the unused ones
- Introduction of Machine Learning based techniques for τID at HLT
- New trigger paths:
  - <u>diTau + jets triggers</u>:
    - benefits boosted topologies (e.g. ggF + 1 jet), or final states with jets (HH→bb$\tau\tau$, ttH→$\tau\tau$...)
  - <u>Boosted diTau Trigger</u>:
    - Highly benefits all boosted searches with taus in the final state (HH→bb$\tau\tau$, H→$\tau\tau$..)
  - <u>Displaced Tau trigger</u>:
    - presence of displaced taus in several models considering neutral/charged BSM particles (SUSY, Heavy Neutral Leptons)
    - to improve the sensitivity for displaced di-τ final states in low pT/high displacement region
  - <u>DoubleTau, VBF+τ triggers</u> for VBF searches, can also be interesting for SUSY/ EXO
  - New <u>VBF diTau trigger</u>

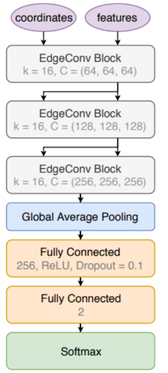
L2TauNNTag@HLT [10]



DeepTau@HLT [11,12]







ParticleNet@HLT [13,14]

When? The τ reconstruction at HLT - Run 3

L2 + L2p5

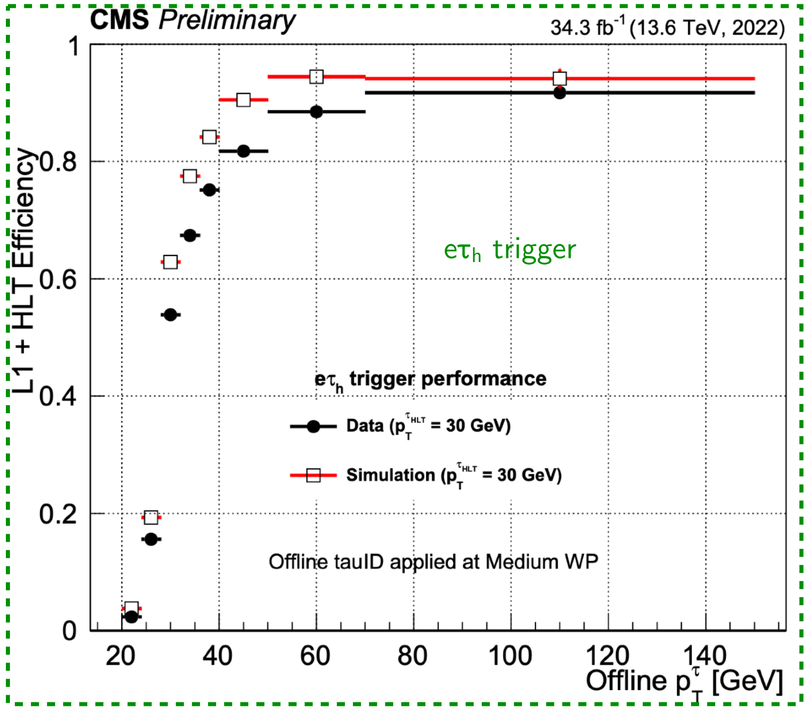
L2TauNNTag: Convolutional Neural Network (CNN) for τ_h tagging

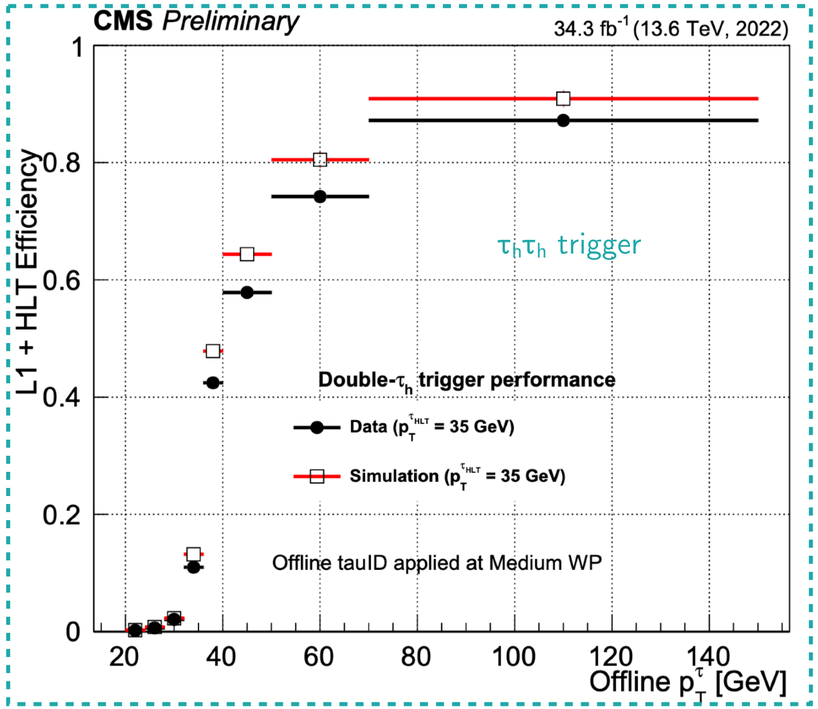
Particle Flow

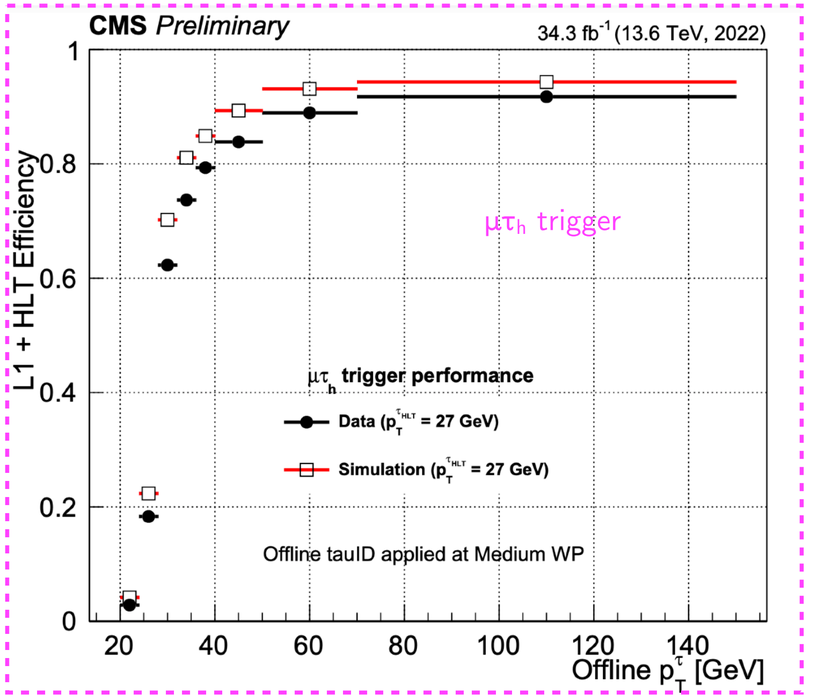
Complete Event reconstruction, **τ object** information available

L3
From PF cand

- HPS / cone based algo
- DeepTau@HLT/PNet@HLT





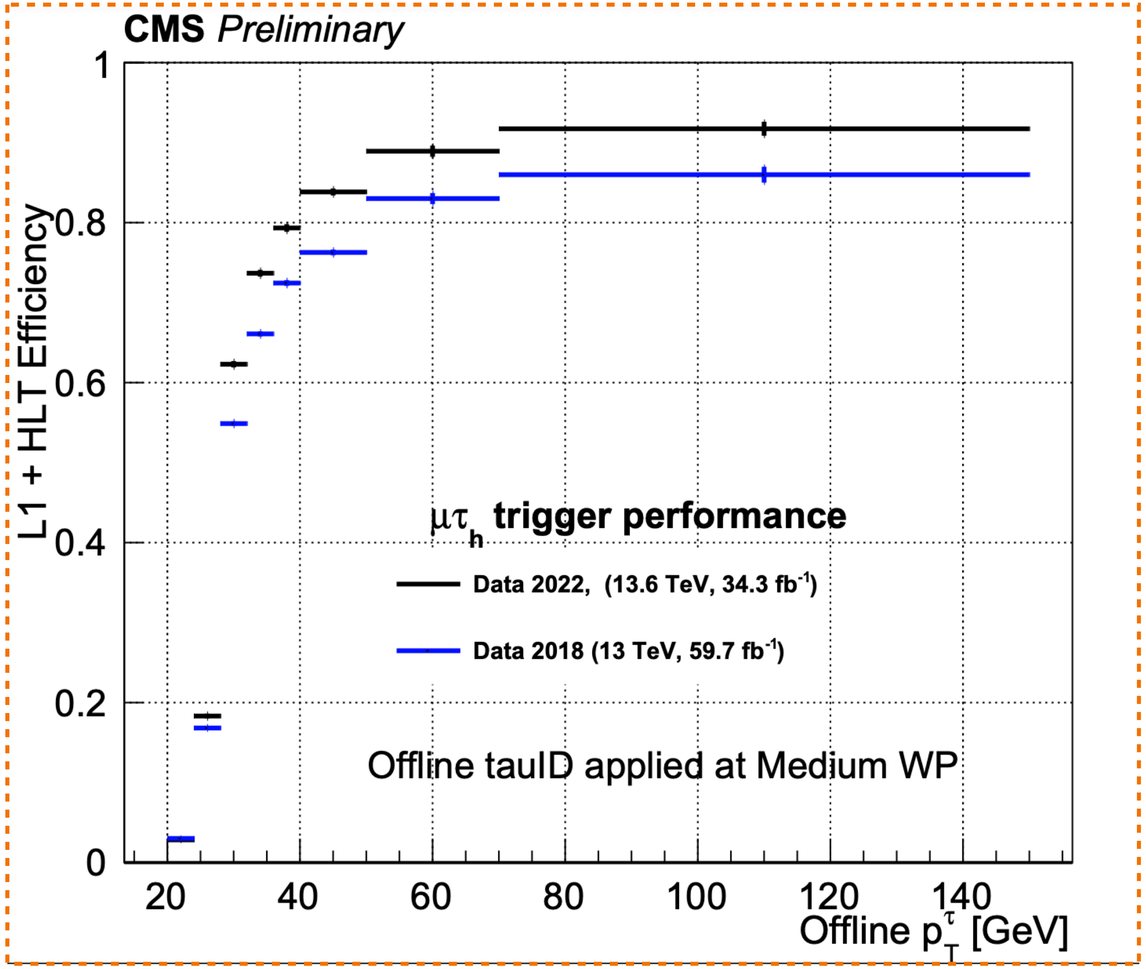


When?

The τ reconstruction at HLT Run 2 VS Run 3

Next steps:

- Evaluate performances for 2023 data taking (already in place, private plots)
- Introduce ParticleNet in HLT τ triggers and compare it with DeepTau: from preliminary studies PNet seems to overperform w.r.t. DeepTau
- Retrain L2TauNNTag
- Include boosted and displaced categories



In general: performance improvements in all τ p_T range!

For reference, see [15] in Slide 21

Conclusion and next steps

- Tau leptons are crucial to probe SM and to explore for BSM physics involving leptons
- Therefore, good performance in reconstruction and identification of the hadronic tau decays is crucial for many important physics analysis in CMS, both SM and BSM
- In order to correctly identify hadronic τ decays especially from jets coming from QCD multi-jet events, many strategies have been explored at CMS:
  - Offline reconstruction: HPS + deepTau
  - Online (trigger) reconstruction: L2NNTag + deepTau/ParticleNet
- Many improvements are foreseen/developed for Run3 and next LHC Runs in order to maximise efficiency while keeping an affordable budget rate
- We expect these improvement to have important impact on all analyses that include τ leptons

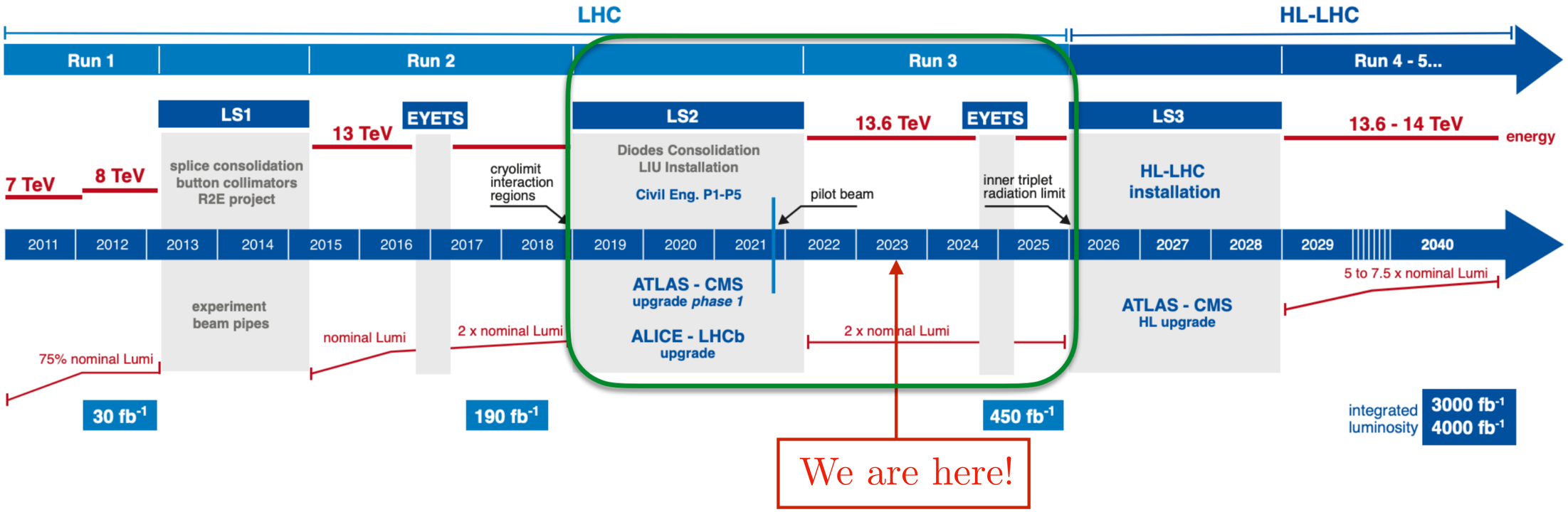
τhank you for the a$\tau\tau$enτion

References

1. arXiv:1408.0914
2. arXiv:2103.16558v2
3. arXiv:0912.0826
4. arXiv:1811.07920
5. Search for new physics in the τ lepton plus missing transverse momentum final state: arXiv:2212.12604v2
6. L1 τ algorithm for LHC Run2
7. Performances of reconstruction and identification of τ leptons during Run2 at CMS
8. CMS Tau Trigger
9. Tau reconstruction at CMS
10. L2TauNNTag at HLT
11. The deepTau algorithm: arXiv:2201.08458
12. DeepTau@HLT
13. ParticleNet: Jet tagging via Particle Clouds arXiv:1902.08570
14. ParticleNet@HLT
15. Performance of tau lepton reconstruction at High Level Trigger using 2022 data from the CMS experiment at CERN

BACKUP

LHC time schedule

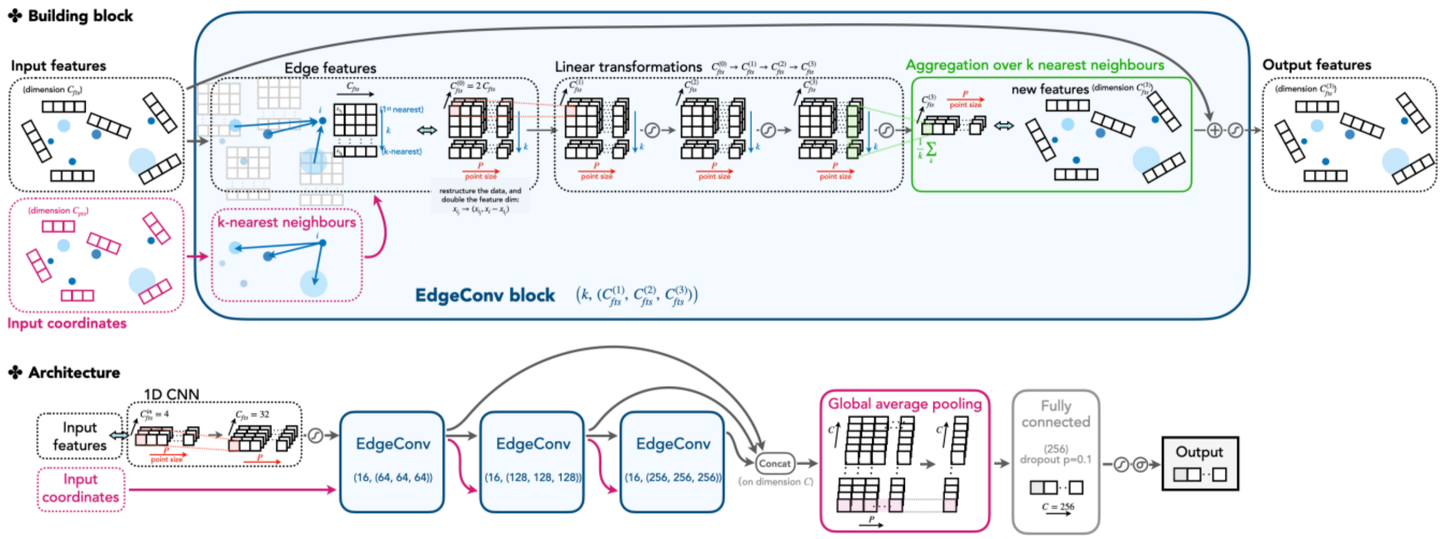


- After a very successful Run 2 of the Large Hadron Collider, we are now in Run 3 with LHC running at 13.6 TeV
- Run 3 will more than double the data delivered to the experiments

DeepTau@HLT

- DeepTau is a new multiclass tau identification algorithm based on a convolutional deep neural network (CNN)
- In order to achieve an optimal tau identification performance, DeepTau combines information from the high-level reconstructed tau features together with the low level information from the inner tracker, calorimeters and muon sub-detectors using particle flow candidates, electrons and muons reconstructed within the tau isolation cone
- In Run2 the DeepTau algorithm was used for offline τ identification
- DeepTau discriminator introduced* at HLT level in Run 3
  - DeepTau@HLT with same training as for offline taus, using HLT objects as inputs
- No re-training, but optimisation based on maximisation of algorithmic efficiency for signals while keeping the rate at the Run 2 budget
- HLT performance in Run 3 MC samples (signal efficiency) and Run 2 HLTPhysics data (background rate) used to optimised the deepTau threshold in different trigger paths

PaticleNet@HLT



ParticleNet: Dynamic Graph Neural Network based on particle cloud representation for jet tagging, wide use in CMS

CMS provides **offline and online (HLT) PNet training**.

With dedicated training the performances can further be improved.
The current results are stable w.r.t. the pile up.

First look at online tau ID and reconstruction with new ParticleNet@HLT training shows promising performance for both tau ID and tau reconstruction.

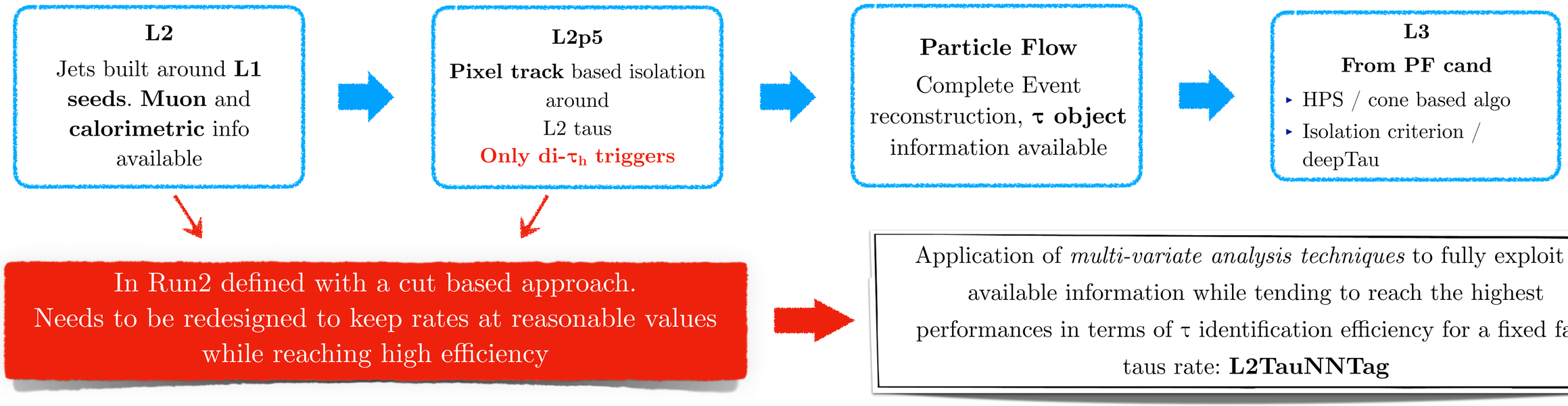
Output: Features of a jet, such as:

- $P_{h\tau+}$ probability that the jet originates from a positive hadronic τ
- $P_{h\tau-}$ probability that the jet originates from a negative hadronic τ
- $pNet_{p_T corr}$: correction for jet pT ($Jet_{p_T}^{corr} = Jet_{p_T} \cdot corr(pNet)$
- heavy flavour jet tagging, jet mass regression...

From the output features of ParticleNet..

- Hadronic tau probability: $P_{h\tau} = P_{h\tau_+} + P_{h\tau_-}$
- Charge confidence: $\tau_{c.c.} = |0.5 - \frac{P_{h\tau_+}}{P_{h\tau_+} + P_{h\tau_-}}|$

L2TauNNTag@HLT



- The L2TauNNTag is a Convolutional Neural Network (CNN) designed specifically for τ_h tagging
- Takes advantage of **new GPU based pixel tracks** in addition to the **calorimeter information**
- Training performed on **di-Tau MC samples** of Drell-Yan, TTbar and WJets samples for true taus, QCD events for fake taus
- L2TauNNTag threshold optimised to keep rate (measured from Run2 data) to an affordable budget with respect to cut based and to L1 rate
- Efficiency computed on VBF $H \to \tau\tau$ and $Z' \to \tau\tau$ MC samples