Searches for New Physics that couple with third generation fermions

Valeria D’Amante\textsuperscript{1,2} on behalf of the CMS collaboration

The 17th International Workshop on Tau Lepton Physics (TAU2023)

06/12/2023

\textsuperscript{1}Università di Siena, \textsuperscript{2}INFN Sezione di Pisa
The Tau lepton

The CMS experiment and trigger system

New physics searches with $\tau$ at CMS during Run2

Focus on search for new physics in the $\tau$ 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
The $\tau$ lepton

$\tau$ 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)

<table>
<thead>
<tr>
<th>Name:</th>
<th>Tau Lepton ($\tau$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass:</td>
<td>1776.86 MeV/c$^2$</td>
</tr>
<tr>
<td>Av. lifetime:</td>
<td>$2.9 \times 10^{-13}$ s</td>
</tr>
<tr>
<td>Discovered:</td>
<td>1974 (SLAC)</td>
</tr>
<tr>
<td>Spin:</td>
<td>$1/2$ - Fermion</td>
</tr>
<tr>
<td>Family:</td>
<td>3rd lepton family</td>
</tr>
</tbody>
</table>

Features: It is the only lepton that can decay to hadrons and has large Yukawa coupling with Higgs.

Tau decays involve charged particles, prongs.
General purpose detector, “onion” structure

Useful definitions:

1. Pseudorapidity: \( \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \) for HR particles it coincides with the rapidity

2. Angular separation \( \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \)

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 $< 3.8 \mu s$
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
Search for new physics in the $\tau$ 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 $\theta_E$
    - Width and cross section depends on relative coupling to $\tau$ lepton.

- **Vector Leptoquark [2]**

- **Quantum Black Holes [3]**
  - Extra spatial dimensions $n = 4$
  - Threshold mass

- **Effective Field Theory [4]**

What?

Search for new physics in the $\tau$ lepton plus missing transverse momentum final state

Signature: $W' \rightarrow \tau \nu \rightarrow \text{high } p_T \text{ and MET}$

- 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
- $Z(\ell\ell)+jets$
- Diboson ($WW$, $WZ$, $ZZ$)
- QCD multijet

Results

- Model-independent upper limit on the product of signal cross section times branching fraction for the $\tau + \nu$ decay for a back-to-back $\tau$ 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.
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 limits on the ratio $g_{W'}/g_W$ for an SSM-like W' boson.
- Lower exclusion limits on the NUGIM G(221) mixing angle cot$\theta_E$.

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

Search for new physics in the $\tau$ lepton plus missing transverse momentum final state

Results

- Expected and observed upper limits of the LQ coupling $g_U$ VS the LQ mass
- Bayesian upper limits at 95% CL on the $\sigma$ of the process $pp \rightarrow \tau\nu$ 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

For reference, see [5] in Slide 21
How? The $\tau$ 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-$\tau_h$ 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 $\tau\mu$ (red track) $\tau_h$ with 3 charged hadrons which are indicated with the cone and the blue calorimeter cells.

$\tau_h$ appear in the detector with 1 or 3 charged hadrons + one or more pions.
The \( \tau \) 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-\( \tau_h \) triggers

**Particle Flow**
Complete Event reconstruction, \( \tau \) 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 \( \tau \) reconstruction
- Investigation of ParticleNet introduction for offline reconstruction & ID
- New L2Tau identification with CNN L2TauNNTag
- ParticleNet @HLT
- Boosted \( \tau \) identification

06/12/2023
Valeria D’Amante
The 17th International Workshop on Tau Lepton Physics (TAU2023)
Keep almost all Run2 triggers in the HLT menu, drop the unused ones

Introduction of Machine Learning based techniques for $\tau$ID at HLT

New trigger paths:

- **diTau + jets triggers:**
  - benefits boosted topologies (e.g. $ggF + 1$ jet), or final states with jets ($HH \rightarrow bb\tau\tau$, $ttH \rightarrow \tau\tau...$)

- **Boosted diTau Trigger:**
  - Highly benefits all boosted searches with taus in the final state ($HH \rightarrow bb\tau\tau$, $H \rightarrow \tau\tau..$)

- **Displaced Tau trigger:**
  - presence of displaced taus in several models considering neutral/charged BSM particles (SUSY, Heavy Neutral Leptons)
  - to improve the sensitivity for displaced di-$\tau$ final states in low $p_T$/high displacement region

- **DoubleTau, VBF+$\tau$ triggers** for VBF searches, can also be interesting for SUSY/EXO

- **New VBF diTau trigger**
When? The $\tau$ reconstruction at HLT - Run 3

**L2 + L2p5**

L2TauNNTag: Convolutional Neural Network (CNN) for $\tau_h$ tagging

**Particle Flow**

Complete Event reconstruction, $\tau$ object information available

**L3**

From PF cand

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

---

06/12/2023

Valeria D’Amante

The 17th International Workshop on Tau Lepton Physics (TAU2023)
In general: performance improvements in all $\tau$ $p_T$ range!

Next steps:

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

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

Thank you for the attention
1. arXiv:1408.0914
2. arXiv:2103.16558v2
3. arXiv:0912.0826
5. Search for new physics in the $\tau$ lepton plus missing transverse momentum final state: arXiv:2212.12604v2
6. L1 $\tau$ algorithm for LHC Run2
7. Performances of reconstruction and identification of $\tau$ leptons during Run2 at CMS
8. CMS Tau Trigger
9. Tau reconstruction at CMS
10. L2TauNNTag at HLT
12. DeepTau@HLT
14. ParticleNet@HLT
15. Performance of tau lepton reconstruction at High Level Trigger using 2022 data from the CMS experiment at CERN
BACKUP
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.
Output: Features of a jet, such as:

- $P_{h\tau^+}$ probability that the jet originates from a positive hadronic $\tau$
- $P_{h\tau^-}$ probability that the jet originates from a negative hadronic $\tau$
- $pNet_{pTcorr}$: correction for jet $pT$ ($Jet_{pT}^{corr} = Jet_{pT} \cdot corr(pNet)$)
- 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 \( \tau \) 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 \( H \rightarrow \tau \tau \) and \( Z' \rightarrow \tau \tau \) MC samples.

---

In Run2 defined with a cut based approach. Needs to be redesigned to keep rates at reasonable values while reaching high efficiency.

Application of **multi-variate analysis techniques** to fully exploit all available information while tending to reach the highest performances in terms of \( \tau \) identification efficiency for a fixed fake taus rate: **L2TauNNTag**.