Search for heavy neutral leptons in multilepton final states in full Run II data

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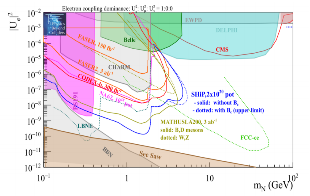
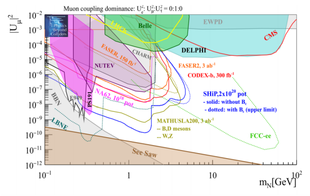
November 27, 2020

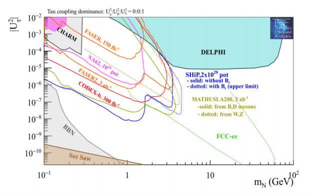
ULB*, UGent**, Wisconsin-Madison***

Heavy Neutral Leptons (HNL)

- Introduction of right-handed HNL can solve some of the problems of the SM:
  - Origin of the SM neutrino masses through Seesaw mechanism
  - Candidate for dark matter
  - matter-antimatter asymmetry
- No direct interactions with sterile HNL
- Interactions through mixing of HNL and SM ν
- Existing constraints from direct searches on the right
- Filled areas = excluded
- contours = projections

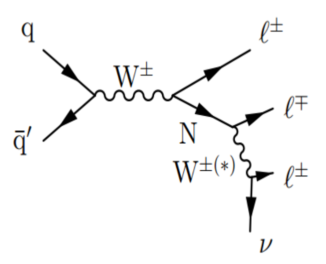


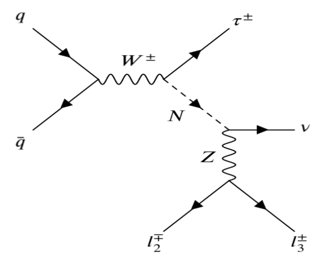




arxiv:1901.09966

Target Signal Topology





- HNL produced in W decay
- Decay of HNL to W or Z
- Three lepton final state
- small missing energy
- Large difference in kinematics depending on m_N:
  - Low HNL mass ($m_N < m_W$): W from HNL decay off-shell
  - High HNL mass ($m_N > m_W$): First W off-shell
- Lepton flavors depend on coupling V_{lN}
- In currently used models:
  - $V_{lN} \neq 0$ for one flavor
  - $V_{lN} = 0$ for other two flavors

CMS-EXO-17-012

Current analysis is a continuation of CMS-EXO-17-012:
Search for HNL in three light lepton final states in 2016 data

- **Trigger strategy:** an OR of all single/double/triple leptons unprescaled with the lowest p_T cuts available
- **Object Selection:** Light leptons only. Cut-based identification
- **Strategy:** Split between low mass and high mass HNL. Simultaneous fit to bins in discriminating variables:
  - Low mass region ($m_N < 80$ GeV) with categorization in $p_T(\text{leading})$, and min(M_{OS})
  - High mass region ($m_N > 80$ GeV) with categorization in M_{3l}, min(M_{OS}) and M_T^{other}
- Main changes in current analysis

Subject	Old approach	Possible improvement	Motivation
Light Lepton Selection	Isolation cone < 0.3 ($I_{rel} < 0.1$)	LeptonMVA	Main backgrounds: fake leptons leptonMVA can reduce these
τ_h Selection	No τ_h considered	DeepTau	Probe coupling between ν_τ and HNL
Signal extraction	Simultaneous fit to search region bins	BDT	Optimize discrimination

Goal of this analysis:
Update and extend CMS-EXO-17-012 to use full RunII data and add τ final states

Overview of analysis status

Collaboration:

- UGent-ULB group has been working on search for HNL in final states that can contain a τ_h
- Independently, a search for HNL in τ_h final states was being performed by Cecile Caillol

$\Rightarrow$ The two analyses have been merged into a collaborative effort!

- UGent-ULB will focus on $\nu_e - HNL$ and $\nu_\mu - HNL$ coupling as well as $\nu_\tau - HNL$ coupling for low mass HNL
- Wisconsin-Madison will focus on $\nu_\tau - HNL$ coupling for high mass HNL

Status:

Light lepton coupling and low m_N τ coupling

- Synchronization with CMS-EXO-17-012 ✓
- Gen level studies of kinematics ✓
- Trigger strategy ✓
- Trigger efficiencies ✗
- Object selection and optimization ✓
- Event selection and categorization ✓
- Private sample production
- Nonprompt background estimation
- Other backgrounds ✗
- Systematics ✗
- Signal extraction

High m_N τ coupling

- Trigger strategy ✓
- Trigger efficiencies ✗
- Object selection and optimization ✓
- Event selection and categorization ✓
- Preliminary expected limits ✓
- Nonprompt background estimation ✓
- Signal extraction
- Systematics ✓

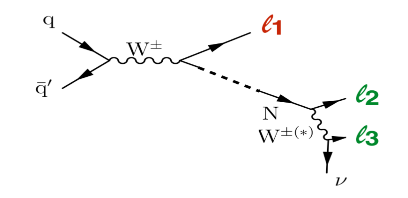
Status update

Categorization

	Categories			
	l1	l2	l3	Name
1	$\tau_h^\pm$	$\tau_h^\pm$	l	SSτ+l
2	$\tau_h^\pm$	$\tau_h^\mp$	l	OSτ+l
3	$\tau_h^\pm$	l	l	OS l $+ \tau$
4	$l^\pm$	$\tau_h^\mp$	$l^\pm$	SS l $+ \tau$
5	e	e	e	eee
6	μ	μ	μ	$\mu\mu\mu$
7	e	e	μ	$ee\mu$
	e	μ	e	
	μ	e	e	
8	e	μ	μ	$e\mu\mu$
	μ	e	μ	
	μ	μ	e	

high mass
+ low mass

high mass



- **1-4:** Probe coupling of HNL to ν_τ ($V_{\tau N}$)
  - 1: Majorana
  - 2, 3, 4: Dirac or Majorana
- **5-8:**
  - Probe coupling of HNL to ν_e (V_{eN}) and ν_μ ($V_{\mu N}$)
  - Interpret ν_τ coupling if no excess is seen

Object selection

Light Lepton Selection

leptonMVA TOP

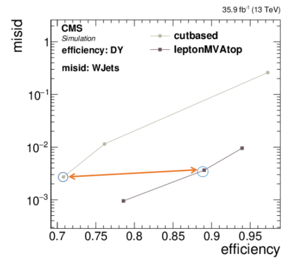
New MVA developed by Ghent CMS group

preselection

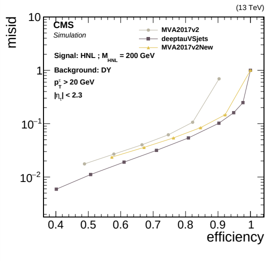
- p_T >10 GeV, $|\eta| < 2.5$
- $|d_{xy}|$ <0.05cm
- $|d_z|$ <0.1cm
- $I_{\mathrm{mini}} < 0.4$
- $IP_{3D}/\sigma(IP_{3D}) < 8$

e	μ
• 0 missing hits	• medium POG

- Largest background in CMS-EXO-17-012: Nonprompt leptons
- Optimized ID to use leptonMVA
- Increase in efficiency per lepton of 20%



τ_h selection (Low Mass)



- Medium DeepTauVsJets, Loose DeepTauVsE, Loose DeepTauVsMu
- Clean from light leptons
- $p_T > 20$ GeV, $|\eta| > 2.3$
- New Decay Mode Finding, veto on 2 prong

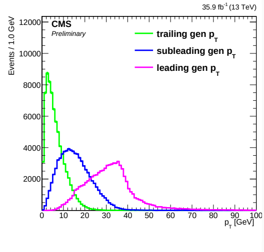
Search Strategy

Performed synchronization of the light lepton channels with CMS-EXO-17-012 as a baseline

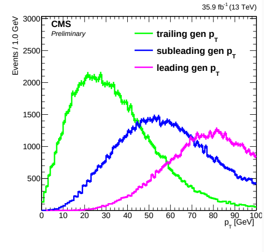
Triggers:

- Similar trigger strategy to CMS-EXO-17-012 studied and updated
- Signal kinematics are characterized by a soft lepton
- Use single lepton, dilepton and trilepton light lepton triggers to go as low as possible in p_T

$m_N = 20$ GeV



$m_N = 200$ GeV



Baseline selection

- 3 leptons
- No 4th FO lepton
- 1 OS
- No b-jet (Loose DeepFlavor)
- Trigger matching

Low mass

- No OSSF
- $p_T(l1) < 55$ GeV
- $p_T^{\mathrm{miss}} < 75$
- $M_{3l} < 80$ GeV

High mass

- $p_T(l1) < 55$ GeV
- OSSF off-Z
- $|M_{3l} - M_Z| < 15$ GeV

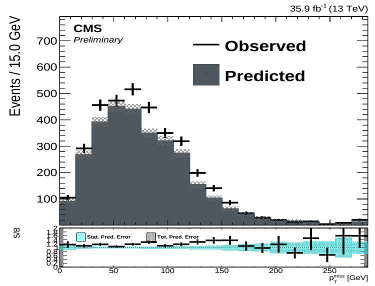
Signal Extraction:

- Due to different kinematics, adopt split in low mass and high mass category
- Initially same strategy as CMS-EXO-17-012: Bin events into discriminating variables and fit simultaneously
- Studies into using BDT techniques for improved signal extraction ongoing:
  - Preliminary BDT's trained for light lepton coupling
  - Plans are there to train BDT for tau coupling as well

Nonprompt background estimation

Nonprompt Light Leptons

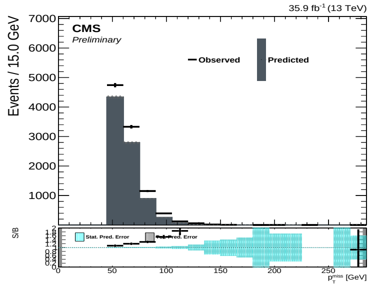
- Using tight-to-loose ratio method for measuring fake rate
- Measured in QCD region with 1 lepton + jet
- $\Delta R(l, jet) > 0.7$
- Measurement performed by Tu Thong Tran



Preliminary closure test for muon fakes in 2016 $t\bar{t}$ MC

Nonprompt Taus

- Using tight-to-loose ratio method for measuring fake rate
- Measured in DY+jets region
- OSSF light leptons with Z mass + τ_h



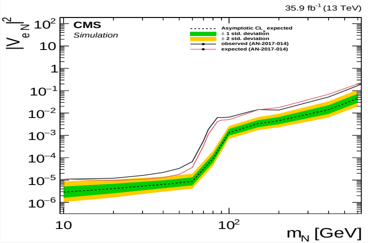
Preliminary closure test for tau fakes in 2016 DY MC

Work in progress

Light Lepton Final States

Search regions

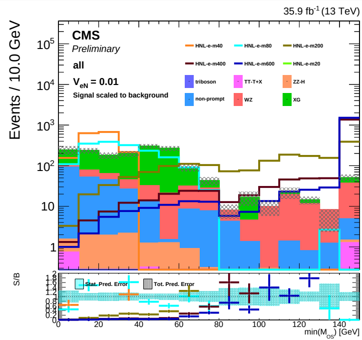
- Similar strategy to CMS-EXO-17-012
- Design search regions with following variables:
  - Low mass: p_T^{leading}, min $M_{2l(OS)}$
  - High mass: M_{3l}, M_T, min $M_{2l(OS)}$
- Used for synchonization and is a good baseline for comparison



Preliminary expected limits from simultaneous fit for e coupling in full Run II. Background from MC. Improvements from increased luminosity and improved object selection.

MVA

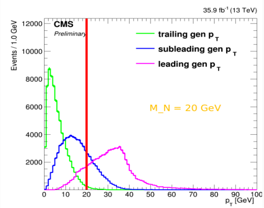
- Train MVA separately for $e - N$ coupling and $\mu - N$ coupling, for each year and split into low mass and high mass trainings
- Input variables:
  - $p_T(l1)$, $p_T(l2)$, $p_T(l3)$
  - $\eta(l1)$, $\eta(l2)$, $\eta(l3)$
  - $\phi(l1)$, $\phi(l2)$, $\phi(l3)$
  - M_{3l}
  - $\min(M_{2lOS})$
  - M_T^{other}
  - p_T^{miss}
  - L_T, H_T
  - $p_T(j1)$, $\eta(j1)$, $\phi(j1)$
  - $p_T(j2)$, $\eta(j2)$, $\phi(j2)$

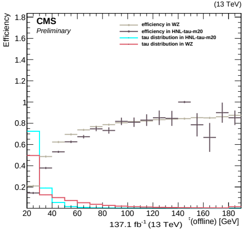


Tau Lepton Final States: Low Mass

Exploring similar strategies as for light lepton final states
Main bottleneck for these studies: Lack of statistics

Min $p_T(\tau)$ threshold: 20 GeV
Reco + lower ID efficiencies
$\Rightarrow$ Quite low acceptance for final states with hadronic tau



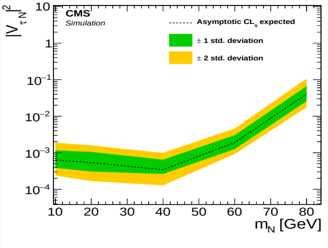


Search Regions:

- Low backgrounds but also nearly no signal events in τ_h final states
- Most of the sensitivity comes from leptonic tau decays

MVA:

- ML techniques can give interesting improvements for τ_h final states
- But Sensitive to large statistics
- Looking into ways to increase statistics



First expected limits for ν_τ coupling from simultaneous fit to all final states for all three years

Tau Lepton Final States: High Mass

Similar strategy/methods as SM WH→ $\tau\tau$ analysis (AN-20-089)
High mass tau final states search performed by Cecile Caillol

7 analysis categories

- $e\mu$ (OS+SS) + τ_h
- $\mu\mu$ (SS) + τ_h
- μ + OS$\tau_h\tau_h$
- μ + SS$\tau_h\tau_h$
- e + OS$\tau_h\tau_h$
- e + SS$\tau_h\tau_h$

Signal samples

Official samples for $|V_{\tau N}|^2 = 0.01$ with aMC@NLO in the final state L$\tau\tau$
Mass points: 100, 150, 200, 400, 600, 800 GeV

Triggers

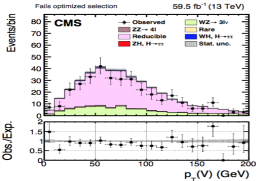
Single lepton triggers. No double lepton or cross triggers:
- Keep background rates lower (larger fake rates at low p_T)
- Simplicity of fake rate estimation method

Systematic uncertainties

Model in place. (More in backup)

Topology

- No b-jet (M deep CSV)
- No additional e/μ
- $\Delta R(l, \tau_h) > 0.5$
- $\Delta R(\tau_h, \tau_h) > 0.5$
- $\Delta R(l, l) > 0.3$
- $|\Sigma(q)| = 1$
- Trigger matching

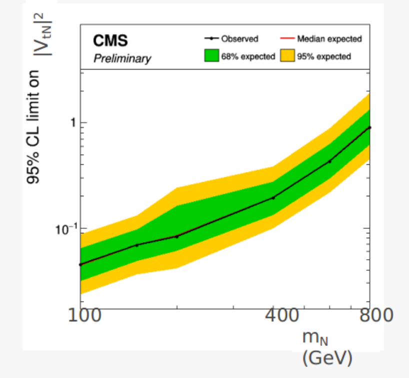


Reducible background

Mostly Z+jets, W+jets, and $t\bar{t}$ events
Estimated with a fake rate method, measured in DY+jet region.
← Control plots produced

Tau Lepton Final States: High Mass

- Simultaneous fit of distributions in the 7 categories for each year
- 2 observables for each category:
  - For $l\tau_h\tau_h$: Average $p_T(\tau_h)$
  - For $ll\tau_h$: $p_T(\tau_h)$
  - Low $p_T(\tau_h)$: separate based on $\min(M_{2lOS})$



First expected limits for high mass ν_τ coupling

Outlook

Aiming for pre-approval in May 2021

- End of 2020:
  - Tackle statistics issues
  - Nonprompt background estimation
  - Finalize signal extraction
- January-February 2021:
  - (If necessary) Finalize signal extraction
  - Estimation of other backgrounds
- March-April 2021:
  - Scale factors
  - Systematic uncertainties
  - Final touches

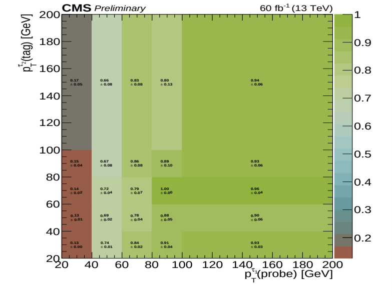
EPR

Tau POG

Factorization in ditau triggers

- τ leg is measured in $\mu\tau$ cross trigger
- If no correlation. SF can be applied to each τ independently
- In 2019 correlations were found
- Task: Measure conditional SF($\tau_2|\tau_1$) and determine preliminary correction factors
- Done using $\mu\tau\tau$ DY events for both MVA2017v2 and deepTau

$P(\tau_{probe}|\tau_{tag})$



DeepTau@HLT for Run3

- τ HLT currently use cut-based isolation for discrimination
- For Run 3, the use of deepTau for discrimination at the HLT is being studied
- Task: DeepTau@HLT integration into CMSSW
- Task: Apply DeepTau@HLT and perform studies

L3 HLT convener

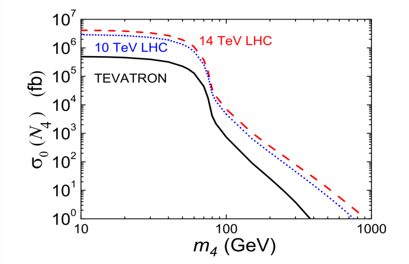
- Took up the position of Tau HLT convener on September 1st 2020

Conclusions

- Analysis to measure or set limits on couplings between SM neutrinos and 1 HNL using trilepton final states as a continuation of EXO-17-012 to extend to full Run II and include τ_h final states
- Collaborative effort between ULB-UGent-Wisconsin
- Current expected limits show factor 5 improvement in upper limits on coupling with ν_e and ν_μ
- First direct limits for coupling with ν_τ:
  Expected exclusion for $|V_{\nu_\tau}|^2 \sim 10^{-3}$ for low mass, between 10^{-2} and 1 for high mass
- These limits can be possibly improved by using machine learning techniques but currently statistics are too low
- Foundation has been laid with trigger strategy, object selection, event selection, signal extraction and start of background estimation

Backup

Mass dependency of the target signal



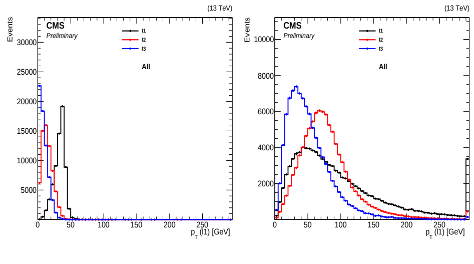
arxiv:0901.3589

$$\sigma(pp \to l_1^{\pm} l_2^{\pm} W^{\mp}) = (2 - \delta_{l_1 l_2}) \frac{|V_{l_1 N} V_{l_2 N}|^2}{\sum_{l=e}^{\tau} |V_{lN}|^2} \sigma_0(N)$$

- σ_0 depends mainly on W production cross section and phase space
- Large, flat cross section for $m_N < 80$ GeV
- Large drop-off when m_N nears W mass
- Steadily decreasing cross-section for $m_N > 80$ GeV

- **Low** m_N: Soft leptons from HNL decay
- $m_N \sim m_W$: Soft lepton from initial W decay
- **High** m_N: Relatively high p_T leptons

$m_N = 5$ GeV $\quad$ $m_N = 200$ GeV



$V_{\tau N} = 0.01$

Signal samples

Private Samples

A plethora of privately produced samples was used. Mass points available with V_{lN}=0.01 for all three years:

- $e - N$ coupling: 100000 events for masses of 10, 20, 30, 40, 50, 60, 80, 100, 130, 150, 200, 400, 600 GeV
- $\mu - N$ coupling: 60000 to 100000 events for masses of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 130, 150, 200, 400, 600 GeV
- $\tau - N$ coupling: 100000 to 150000 events for masses of 10, 20, 30, 40, 50, 60, 80, 90, 100, 120, 130, 150, 200, 400, 600, 800, 1000 GeV

Central Samples

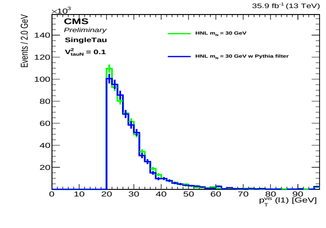
The following central samples are available

- $\tau - N$ coupling: 100000 to 300000 events for masses of 100, 150, 200, 400, 600, 800 GeV

Low acceptance

Low acceptance issue for low mass τ_h final states:

- Looking into using a pythia filter in signal sample generation
- Filter on visible genJets of generator level hadronically decaying tau's
- At least 1 tau above certain p_T^{vis} threshold
- Studying best threshold for this



We will probably miss Moriond deadline ⇒ We will need UL samples
Private samples can then no longer be used and we will need to request factor 2 larger