The impact of the 2019 CMS muon endcap upgrade with GEMs on the search for the $H \rightarrow \tau \tau \rightarrow \mu \mu$ final state

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Large Hadron Collider (LHC)

- Large: 27 KM in circumference
- Hadron: Accelerates protons and ions (Lead), which are hadrons
- Collider: Collides bunches of protons at 4 different interaction points!
CMS

- Compact: Heaviest detector @ 14000 tons!
- Muon: Chambers to detect muons
- Solenoid: Built around a huge solenoid magnet
- One of the two General purpose detectors
CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 µm) ~16m² ~66M channels
Microstrips (80x180 µm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
CMS GEM project

• Triple GEM detectors in $1.6 < |\eta| < 2.2$
• Redundancy in muon system for tracking and triggering
  – RPCs (Fast redundant detectors) end at 1.6, so only CSCs, no redundancy!
  – Must for High PU environment
2019 Geometry deals with GE1/1
Higgs Boson

• Higgs mechanism—combination of spontaneous symmetry breaking and local gauge invariance (soft-condensed matter physics)

• Production mechanism studied for this analysis: gluon fusion to Higgs (VBF, ttH excluded)

• Decay channel studied: Higgs→ττ→μμ
Monte-Carlo samples used for the analysis

• Signal:
  – Official samples (200K) with GEM geometry
    • Left with only 2K dimuon events (Branching ratio of 3 % for tau to mu)
    • Soln: Private samples (Forced decay of Taus to Muons )
  – Private Samples (200K) with GEM geometry
    • 40 K events after all pre-selection cuts (discussed later)

• Background:
  – Drell Yan to Tau (irreducible!)
    • Official samples (990K) with GEM geometry
      – Left with 2K events after pre-selection cuts!
    • Private samples (close to 200K): forced decay
      – Left with 20k events
  – Drell Yan to Mu
    • Official samples (990K) with GEM geometry
      – Left with 30 K events after pre-selection cuts!
<table>
<thead>
<tr>
<th>Physics process</th>
<th>COM energy (TeV)</th>
<th>Number of events</th>
<th>Pileup</th>
<th>GEMs used</th>
<th>Data Format</th>
<th>Private Official</th>
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<tbody>
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<td>200000</td>
<td>No</td>
<td>No</td>
<td>RECOSIM</td>
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<td>Drell Yan to Tau</td>
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<td>Drell Yan to Tau, Tau decaying to muons</td>
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<td>No</td>
<td>Yes</td>
<td>RECOSIM</td>
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</table>
Motivation

• Significant signals for the decay of observed boson (125 GeV) in the $\gamma\gamma$, ZZ and WW channels have been measured by CMS and ATLAS (July 4, 2012)
• Nature of interaction with fermions unclear (actively studied)
• Most promising channels $H\rightarrow b\bar{b}$ (57%) and $H\rightarrow \tau\tau$ (6%) (for a Higgs with $m_H = 125$ GeV)
• $H\rightarrow \tau\tau$ has Cleaner signature wrt $b\bar{b}$
• Challenging because of large backgrounds!
• Study involves dimuon final state
• Muons coming from $\tau$ decay have a soft $p_T$ spectrum, need to keep high trigger and reconstruction efficiency.

• 21% of the muons in the high eta region: Good channel for probing possible benefits from GEM inclusion in muon reconstruction!

• Increase of $p_T$ threshold from 15 to 30 GeV would cause a 50% event loss. Importance of keeping trigger thresholds low in Run-2 and Run-3.
Kinematic phase space for gluon fusion
H->tau tau->mu mu

Reco Muon ‖η‖ vs p_T

Reco Muon matched
With muon from tau Decay at gen level
In DR < 0.1

Muon from signal events have quite soft pt spectrum in the whole detector acceptance
Mean Values:

- w GEMs: -0.0003934
- w/o GEMs: 0.001862

Muon $p_T$ resolution in $1.5 < |\eta| < 2.2$

Without GEM

With GEM

Muon $p_T$ resolution in End cap region
• The improvement probably due to tracker upgrade and not end-cap upgrade
• Would be interesting to see the corresponding plots from the emu (or ee) channel
• With improvement in pT resolution, it would be insightful to look at the effect of lowering dimuon pT thresholds: **Acceptance plots**
Acceptance plots

• novel way of determining the correct dimuon $p_T$ trigger thresholds for the 2019 CMS run with the GEMs.

• Calculated by counting the number of events which have leading and sub-leading muon $p_T$ greater than the pair, and dividing it by the total number of (accepted) events.

• Only cuts used:
  – Dimuon event
  – $|\text{Eta}| < 2.4$
  – Global muon
The acceptance for dimuons in this channel can be improved over what we had in Run 1 by using the GE1/1 to lower trigger thresholds!
A clear improvement is seen with the Run-2 offline selection.
Towards a full-fledged analysis

• Pre-selection cuts:
  – the global muon must have at least one good hit in muon stations
  – the muon track must have more than 5 hits in the inner tracker and at least one pixel hit
  – $\chi^2$/ndof < 10 of the global muon track fit
  – Impact parameter in transverse plane $|d_0| < 0.04$ cm wrt primary vertex
  – Longitudinal impact parameter w.r.t. primary vertex $|d_z| < 0.1$ cm
Multivariate Analysis

- Low signal and high background cross-section!
- No single horizontal cut can differentiate the signal from the background
- Hence, the need to use Multivariate techniques
- Boosted Decision trees - out of the box method for weak classifiers!
Boosted Decision Trees

- **Software**: TMVA (Toolkit for Multivariate Analysis) interfaced with root
- Boost type: Adaptive boost
- Booked as:
  - `factory->BookMethod( TMVA::Types::kBDT, "BDT","!H:!V:NTrees=950:MinNodeSize=3.5%:MaxDepth=3:BoostType=AdaBoost:AdaBoostBeta=0.1:UseBaggedBoost:BaggedSampleFraction=0.5:SeparationType=GiniIndex:nCuts=20:DoBoostMonitor" );`
- Can be fine tuned extensively!
Discriminants

- The ratio of the transverse momentum of the dimuon system to the scalar sum of the positive and negative muon momenta, \( p_T (2\mu) / \Sigma p_T (\mu) \)
- The muon distance of closest approach (DCA) significance, DCASig(2\( \mu \)) of dxy and dz for both the leading and the subleading muon
- The pseudorapidity of the dimuon system, \( \eta(2\mu) \).
- MET
- The angle \( \omega^* \) between three-momentum of the positively charged muon and production plane of the dimuon system, assuming that the two muons originate directly from the Z boson decay.
- The azimuthal angle between direction of the positively charged muon three-momentum and the missing transverse energy, \( \Delta \Phi (\mu^+;\text{MET}) \)
\( d_{xy} \)
\( d_{xy} \)
$d_z$
Fine-tuning BDT parameters

• Separation power of BDTs can be enhanced by fine tuning the parameters (provided at the time of booking)
  – Number of trees (no effect!)
  – Tree Depth
  – Learning rate
  – Minimum number of events in leaf-node
  – Bagging

• A very useful parameter to optimize could be nCuts (however might make it time-consuming!)
Optimization seems to be a must!

Background rejection versus Signal efficiency
Background rejection versus Signal efficiency

MVA Method:

BDT
Can be optimized further!
Great for Drell yan, but not for signals!

<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
<th>ROC Integral value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$Z \rightarrow \mu\mu$</td>
<td>0.939</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$Z \rightarrow \tau\tau$</td>
<td>0.706</td>
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</table>
Conclusion

• Kinematic variables were studied
• Acceptance plots were used to quantify the improvement in dimuon trigger thresholds
• Decision trees were optimised and used to separate the signal from the background.
Acknowledgements

• Dr. Hohlmann: Thesis advisor
• Dr. Yumiceva (also helped in creating PAT tuples) and Dr. Welters: thesis committee
• Kerstin and Paolo: useful discussions on the upgrade physics topics
• Rosamaria: Bari skimmer
• Vallary: useful discussions on the MVAs (BDTs)
Backup!
Cross-sections

- [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV)
- Drell Yan to Tau: 6025 pb
- Drell Yan to Tau (less than 50 GeV): 18610 pb
$p_T$ distribution for leading and subleading muon in $1.5 < |\eta| < 2.2$ (no GEMs)

$p_T$ histograms for case 1:
- Leading muon $p_T$
- Subleading muon $p_T$

**hLeadMuon1**
- Entries: 4150
- Mean: 36.02
- RMS: 16.5
- Underflow: 0
- Overflow: 91
- Integral: 4059

**hSubLeadMuon1**
- Entries: 4150
- Mean: 18.27
- RMS: 10.62
- Underflow: 0
- Overflow: 4
- Integral: 4146
\( p_T \) distribution for leading muon in \( 1.5 < \eta < 2.2 \), subleading muon in \( \eta < 1.5 \) (no GEMs)

**hLeadMuon2**

- Entries: 15808
- Mean: 28.73
- RMS: 15.71
- Underflow: 0
- Overflow: 125
- Integral: 1.568e+04

**hSubLeadMuon2**

- Entries: 15808
- Mean: 13.28
- RMS: 8.606
- Underflow: 0
- Overflow: 4
- Integral: 1.58e+04

**Pt histograms for case 2**

- **leading muon Pt**
- **subleading muon pt**

**Reco Muon \( p_T \) in GeV/c**

**Number of muons/GeV**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
$p_T$ distribution for leading muon in $|\eta|<1.5$, subleading muon in $1.5<|\eta|<2.2$ (with GEMs)

$p_T$ histograms for case 3
- leading muon Pt
- subleading muon pt

<table>
<thead>
<tr>
<th>hLeadMuon3</th>
<th>hSubLeadMuon3</th>
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Impact parameter plot in $1.5 < |\eta| < 2.2$

<p>| | |</p>
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<tr>
<td>Integral</td>
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Events

$d_{xy}$ in cm
H→2τ→2µ: Kinematic acceptance for leading muon in 1.5<|η|<2.2, subleading muon in |η|<1.5 (with GEMs)

- \( p_T^{\text{lead}} \geq 13 \text{ GeV} \) and \( p_T^{\text{subl}} \geq 8 \text{ GeV} \) (\( \mathcal{L} = 3.7 \text{ fb}^{-1} \))
- \( p_T^{\text{lead}} \geq 17 \text{ GeV} \) and \( p_T^{\text{subl}} \geq 8 \text{ GeV} \) (\( \mathcal{L} = 19.1 \text{ fb}^{-1} \))

Offline selection
- \( p_T^{\text{lead}} \geq 20 \text{ GeV} \) and \( p_T^{\text{subl}} \geq 10 \text{ GeV} \)

Gradient direction

- 71%
- 62%
- 42%
H→2τ→2μ: Kinematic acceptance for leading Muon in |η|<1.5, subleading muon in 1.5<|η|<2.2 (with GEMs)

- $p_T^{\text{lead}} \geq 13 \text{ GeV}$ and $p_T^{\text{subl}} \geq 8 \text{ GeV}$ ($\mathcal{L} = 3.7 \text{ fb}^{-1}$)
- $p_T^{\text{lead}} \geq 17 \text{ GeV}$ and $p_T^{\text{subl}} \geq 8 \text{ GeV}$ ($\mathcal{L} = 19.1 \text{ fb}^{-1}$)

**Offline selection**
- $p_T^{\text{lead}} \geq 20 \text{ GeV}$ and $p_T^{\text{subl}} \geq 10 \text{ GeV}$

**Gradient direction**

- 71%
- 62%
- 41%
H→2τ→2µ: Kinematic acceptance for all the muons (with GEMs)

**HLT Paths (Run-1)**
- $p_T^{µ_{lead}} \geq 13 \text{ GeV and } p_T^{µ_{subl}} \geq 8 \text{ GeV (} \mathcal{L} = 3.7 \text{ fb}^{-1})$
- $p_T^{µ_{lead}} \geq 17 \text{ GeV and } p_T^{µ_{subl}} \geq 8 \text{ GeV (} \mathcal{L} = 19.1 \text{ fb}^{-1})$

**Offline selection**
- $p_T^{µ_{lead}} \geq 20 \text{ GeV and } p_T^{µ_{subl}} \geq 10 \text{ GeV}$

Gradient direction

Reco. leading muon $p_T$ in GeV vs. Reco. subleading muon $p_T$ in GeV

Kinematic acceptance in %

- 71%
- 63%
- 43%
Cluster (highlights)!

- Significant efforts were made to fix the cluster (not in a very healthy state back in 2014)! – system admin for 2 years
- Upgraded the cluster from CENT OS 5 to 6 (almost a semester)
- Fixed CERN SAM CE and SE tests
- Fixed Phedex (took a year!)
- Installed NAS-2 (new storage unit) with Curtis
- Figured out NAS-1 (main storage unit) issues, (convinced LSI support team! 😊)