

# Search for extra MSSM Higgs bosons decaying to a $\tau$ lepton pair in the CMS experiment

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## 1 Theoretical context

- The standard model
- MSSM and 2HDM

## 2 Experimental context

- CMS (Compact Muon Solenoid)
- Reconstruction
- Machine learning in mass reconstruction

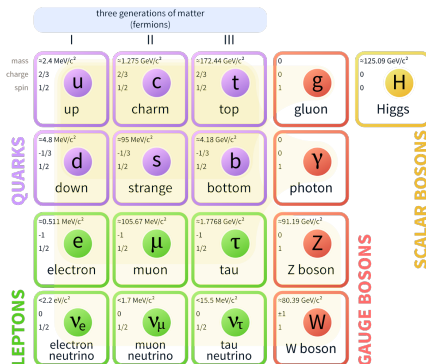
## 3 The analysis

- Backgrounds
- Discriminating variable

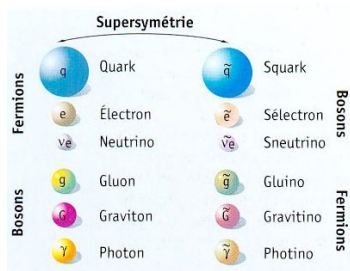
# The standard model

- SM *Higgs*  $\rightarrow \tau\tau$ 
  - Higgs Coupling to fermions  
 $\propto M_{\text{fermion}}$
  - $M_\tau \approx 1.777 \text{ GeV} \cdot c^{-2}$
- $\tau_\tau = 290.3 \pm 0.5 \times 10^{-15} \text{ s}$ 
  - $\Rightarrow c\tau = 87.03 \mu\text{m}$
  - detecting  $\tau$ 's decay products
  - $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$
  - $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$
  - $\tau^- \rightarrow h^- + \nu_\tau + \dots$
- final states :  $ee$  ,  $\mu\mu$  ,  $e\mu$  ,  $\tau_h e$  ,  $\tau_h \mu$  ,  $\tau_h \tau_h$

## Standard Model of Elementary Particles



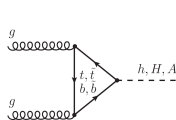
# The MSSM



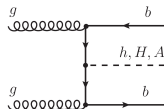
- MSSM adds a boson/fermion symmetry on top of the standard model
- 1 Higgsino  $\Rightarrow$  gauge anomaly! 2 Higgsino  $\Rightarrow$  OK.
- Furthermore in MSSM single Higgs field can't couple to both up-type and down-type fermions
- $\Rightarrow$  two scalar Higgs doublet

# The 2HDM

- MSSM (and 2HDM) Higgs sector consists of two Higgs Doublets  $\Rightarrow$  5 Physical Higgs bosons
  - Charged  $H^\pm$  pair
  - Three neutral bosons  $h, H, A$
  - Transparent look for extra boson called  $\phi$
- At tree level properties are described by 2 free parameters :  $m_A, \tan\beta$ 
  - $\tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$
- Enhanced couplings to fermions at large  $\tan\beta$  values :
  - Enhanced branching ratios of  $H \rightarrow \tau\tau$  and  $A \rightarrow \tau\tau$  with respect to SM  $h \rightarrow \tau\tau$  branching ratio
  - An additional important production mode - b associated production



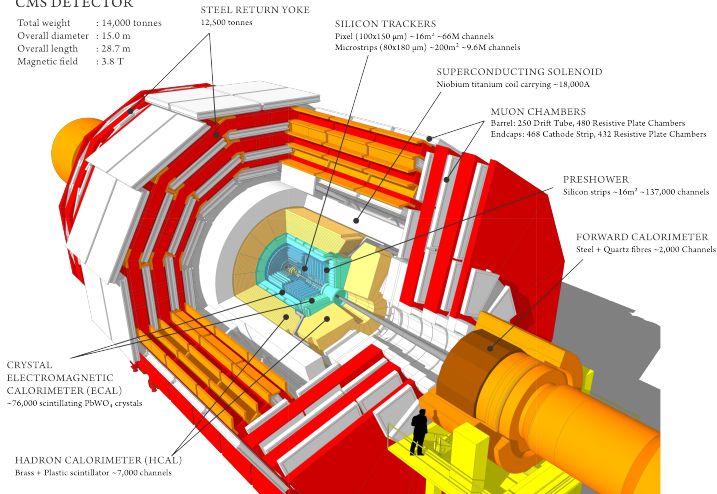
gluon fusion



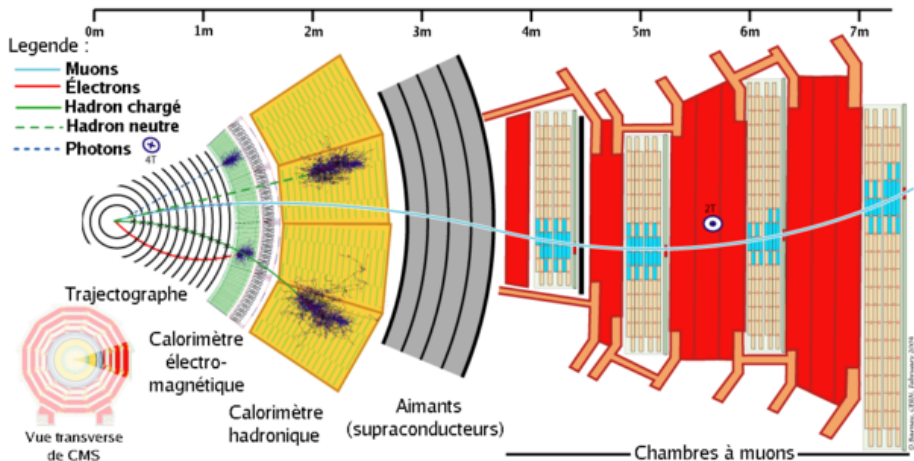
b-associated production

## CMS DETECTOR

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



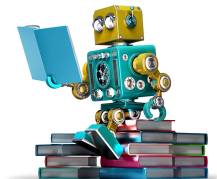
# Particle reconstruction



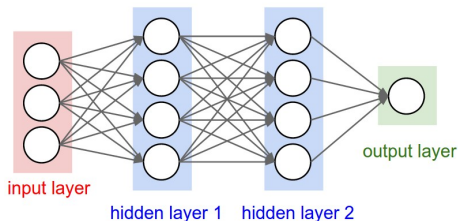
- Missing Energy!
  - $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$
  - $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$
  - $\tau^- \rightarrow h^- + \nu_\tau + \dots$
- Each  $H \rightarrow \tau\tau$  event has at least 2  $\nu$ 
  - MET helps partially
- Solutions :
  - Introduce new variable as final discriminant :  $m_T^{tot}$ 
    - $m_T^{tot} = \sqrt{m_T^2(l_1, MET) + m_T^2(l_2, MET) + m_T^2(l_1, l_2)}$
    - $m_T(x, y) = \sqrt{2 \times p_T^x \times p_T^y \times (1 - \cos(\Delta\Phi_{x,y}))}$
  - Fit event's variables to get the most likely mass value : SVFit
  - What about using ML (Machine Learning) to find the resonance mass?

# What is machine learning?

- $\Rightarrow$  Type of algorithm that uses a training sample as basis to learn how to do a given task, as regression or classification
- In the training sample, the result we expect as output from the algorithm needs to be known!
- A few examples :
  - BDT (Boosted Decision Trees)
  - Likelihood-based estimators
  - k-Nearest Neighbours
  - **(Deep) Neural Network**
  - ...



# Deep Neural Network (DNN)



- Training :
  - 1 Test what is the output for a given set of input
  - 2 How different is the output from what we wanted??
  - 3 Propagate this difference backwards into the network
  - 4 Adapt the state of each neuron in order to minimize the difference
  - 5 Start again!
- Perfect training  $\Rightarrow$  DNN uses optimally all the available information he is given to compute the desired output

# It works!

- SVFit Comparison :
  - Similar results
  - But computation time for SVFit  $\approx 1$ s per event
  - Evaluation of DNN's output quasi instantaneous
  - Though the training phase requires a lot of computational power, it only needs it once!

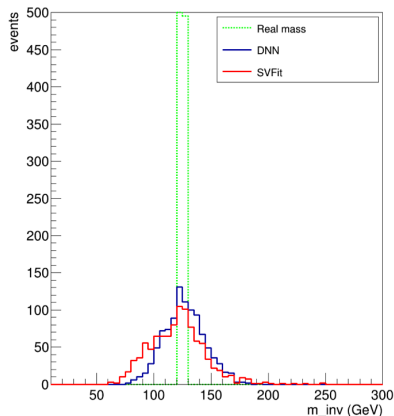
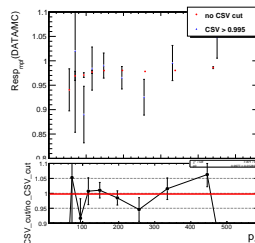
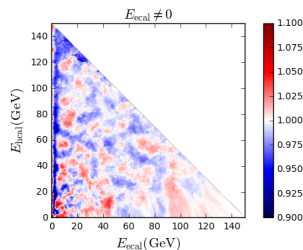


Figure 1: Preliminary study done by a CMS Summer Student (Clemens Lange)

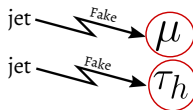
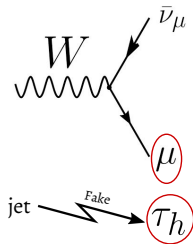
# Others development useful for the analysis (Services tasks)

- Asymmetric  $p_T$  threshold double  $\tau_h$  HLT study
  - Goal : get a better acceptance (greater number of signal events) while keeping the trigger rate low enough
  - No results to show yet...
- Hadron energy calibration in the Particle Flow (using kNN)
- Residual b-jet energy correction using  $\gamma + bjet$  analysis



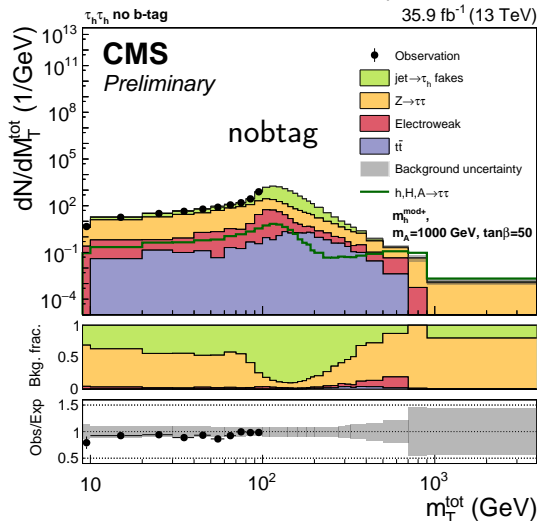
# Analysis backgrounds

- $Z \rightarrow \tau\tau$
- $t\bar{t}$
- Diboson
- QCD
- $W + jets$
- single top



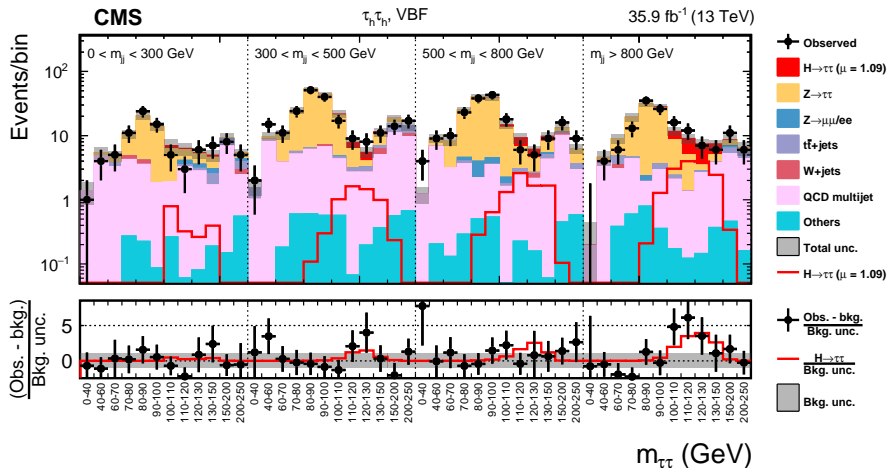
# Which variable to fit?

## Fitted distribution MSSM $H \rightarrow \tau\tau$ (CMS-HIG-17-020)



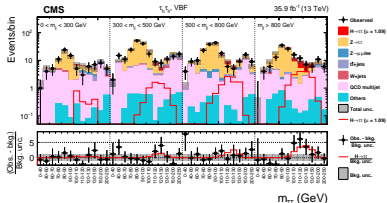
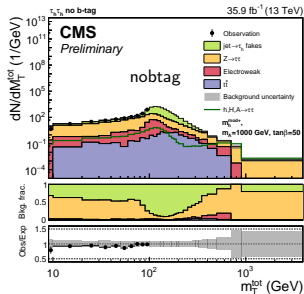
# Several variables to fit?

Fitted distribution SM  $H \rightarrow \tau\tau$  (CMS-HIG-16-043)

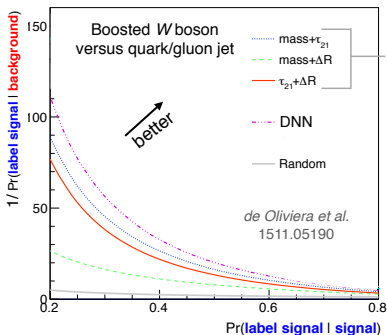


## Which variable(s)?

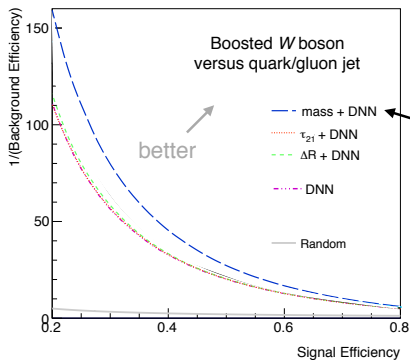
- Why not fit the output of a DNN trained to classify signal and background?
  - Perfect DNN  $\Rightarrow$  optimal use of the given informations allowing discrimination
  - New techniques could allow to train on data!



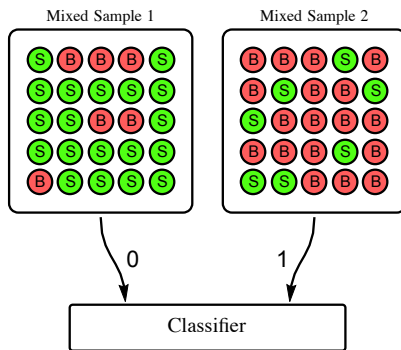
# Does DNNs learn as much as they can? jet discrimination example



$\text{mass}, \tau_{21}, \Delta R$   
are all simple  
functions of  
the image



# Train on data!



Solution: Train **directly on data** using mixed samples

# Conclusion

- My goal will be to find the evidence or reject the possibility of extra Higgs bosons from MSSM and 2HDM.
- New analysis using 2017 data.
- Studies around the analysis :
  - $p_T$ -asymmetric  $\tau\tau$  HLT
  - Calibration of analysis objects : PF-hadrons et bjets
- Introducing machine learning in the analysis
  - Resonance's mass determination
  - Classification Signal / Background
- Let's get to work!



Thank you for your attention!

