



Northern Illinois  
University

# Search for Charged Higgs Bosons in the $\tau + \ell$ Final State with $139\text{ fb}^{-1}$ of pp Collision Data at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS Experiment

Dissertation Defense

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October 13, 2022

Introduction

Theory

The Standard Model

Higgs Mechanism

BSM

Charged Higgs Bosons

Experimental Apparatus

LHC

ATLAS

Simulation

$$H^\pm \rightarrow \tau^\pm \nu_\tau$$

Fake Factors

Background Modeling

MVA

PNN HPO

Systematic Uncertainties

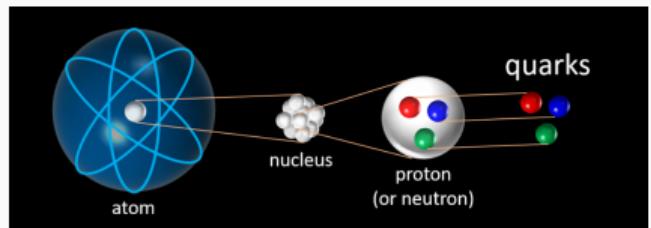
Results

Conclusion

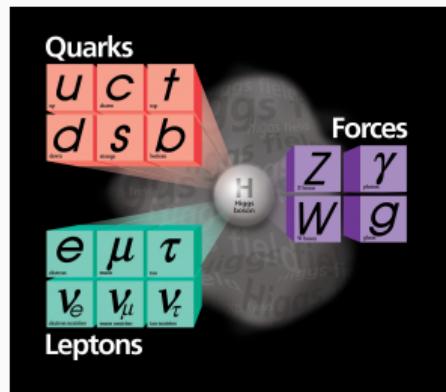
- This defense will take ~ 1 hour
  - I will walk you through the work that is contained in my PhD dissertation
  - After the presentation is complete, the committee and I will address comments privately
  - When we are done, I will return, the committee will discuss among themselves then return
- General Guidelines
  - Please remain muted unless you are speaking
  - There will be time at the end for questions, but feel free to interrupt if there is something urgent
- Thank you for attending!

# What are we made of?

- The scientific field of particle physics seeks to explain the building blocks of the universe
  - How many fundamental particles are there?
  - How do they interact with each other
- The Standard Model of Particle Physics (SM)
  - Matter is comprised of fermions
    - Quarks combine to create hadrons (protons, neutrons,  $\pi^{\pm, 0}$ , etc)
    - Anti-matter is identical to matter except for opposite electromagnetic charge
  - Forces are carried by an exchange of bosons
    - Gluon ( $g$ ) → Strong force
    - Photon ( $\gamma$ ) → Electromagnetism
    - $W^\pm, Z^0$  → Weak force



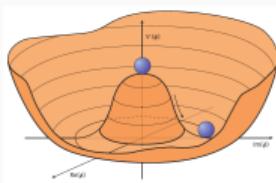
atom-to-quark SM-Diagram



# The Higgs Mechanism



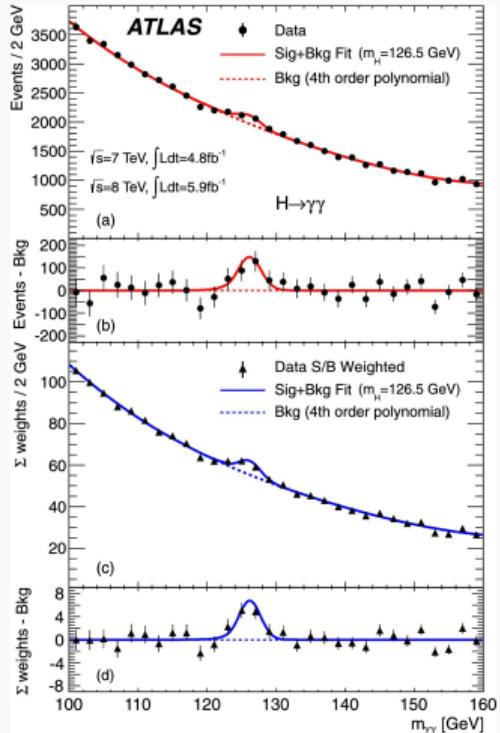
- Theorized by Higgs, Englert, and Brout in 1964
  - Complex scalar doublet ( $s = 0$ )
  - Non-zero vacuum expectation value
- Interactions with Higgs field give particles mass
- Discovered jointly by the ATLAS and CMS collaborations in 2012



Higgs potential **Higgs-phys**

Search for  $H^\pm \rightarrow \tau^\pm \nu_\tau$  with ATLAS

Theory Higgs Mechanism



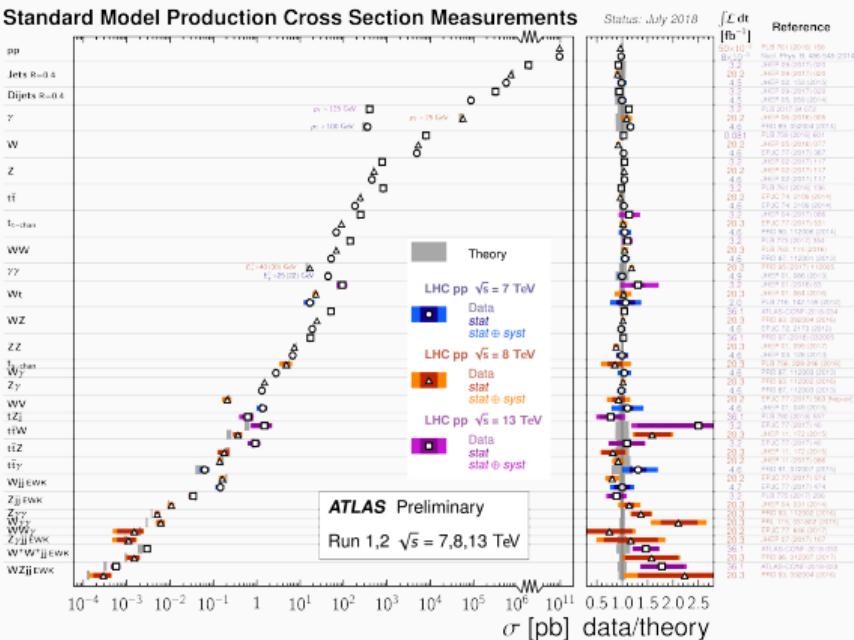
Higgs discovery **higgs-discovery-atlas**

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# The Standard Model

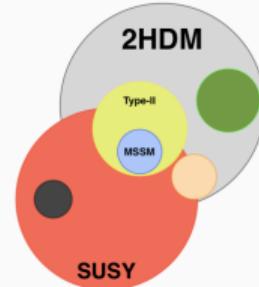
- Predicts the probabilities of particles decaying to others (among many other things)
  - Has been thoroughly tested
  - Measurements agree to a high degree of accuracy
- Not a complete theory
  - Gravity
  - Matter-antimatter asymmetry in the universe
  - Predicted neutrino masses are 0
    - Observed neutrino mixing says otherwise



# Beyond the Standard Model



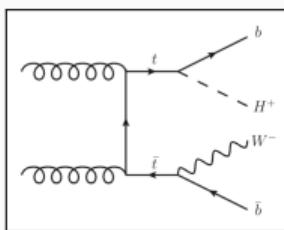
- Hierarchy problem, “unnaturalness”
  - Electroweak scale is  $\sim 100$  GeV
  - Planck scale is  $\sim 2.4 \times 10^{18}$  GeV
- 2 Higgs Doublet Models and Supersymmetry (SUSY) are large groups of theories
  - 2HDM have two complex doublet scalar fields  $2\text{HDM}$ 
    - Two relevant free parameters,  $\tan \beta$  and  $m_{H^\pm}$
    - $\tan \beta$  is the ratio of the vacuum expectation values of  $H^\pm$
  - SUSY proposes a symmetry between fermions and bosons
    - Many new possible particles
    - Minimal Supersymmetric Standard Model (MSSM) is the smallest SUSY extension to the SM



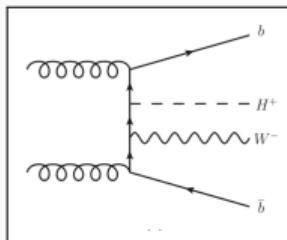
light neutral scalar	$h^0$
heavy neutral scalar	$H^0$
neutral pseudoscalar	$A^0$
two charged scalars	$H^\pm$

# Charged Higgs Bosons

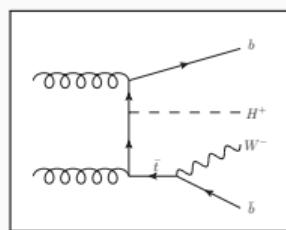
- At the LHC, theoretical production mode of  $m_{H^\pm}$  is mainly in top-quark decays or in association with a top-quark ( $t$ )
  - $H^\pm$  production mode is dependent on  $m_{H^\pm}$



$$m_{H^\pm} < m_t$$



$$m_{H^\pm} \simeq m_t$$



$$m_{H^\pm} > m_t$$

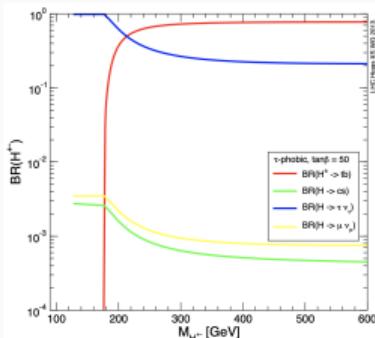
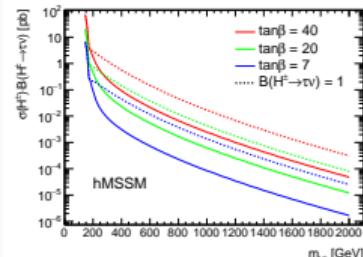
- $H^\pm \rightarrow \tau^\pm \nu_\tau$  decay channel remains significant for high  $\tan \beta$
- Two sub-channels based on the decay mode of associated  $t$

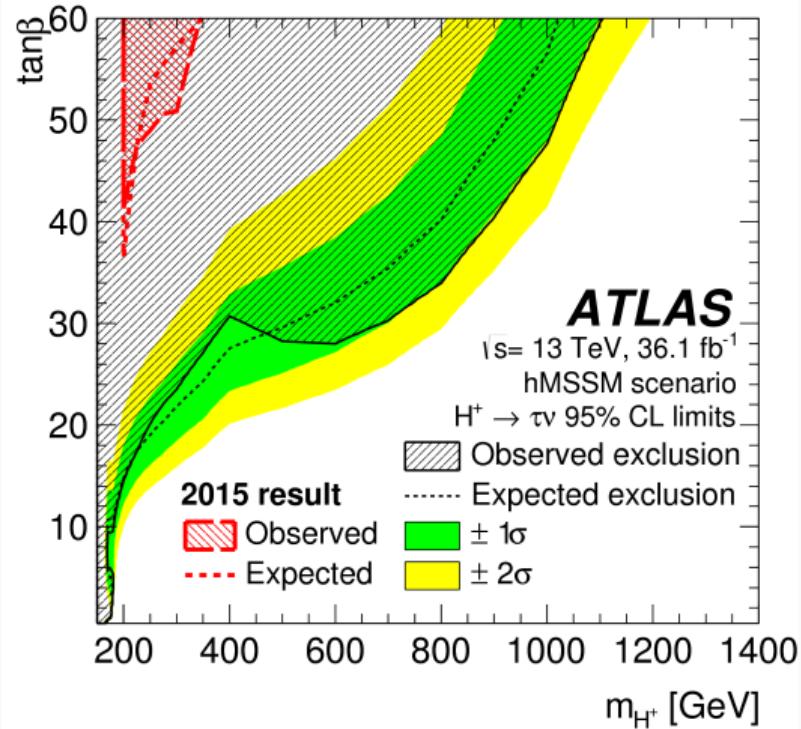
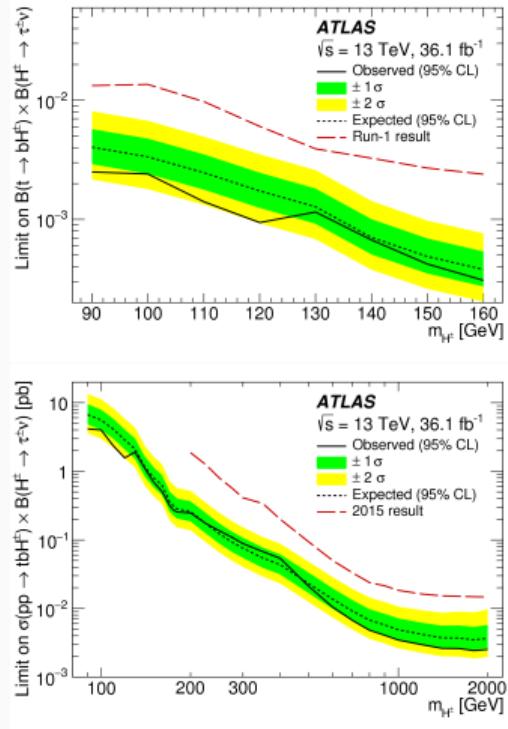
$t \rightarrow jets$

Sensitive at high mass due to higher  $W \rightarrow q\bar{q}$  BR

$t \rightarrow \ell$

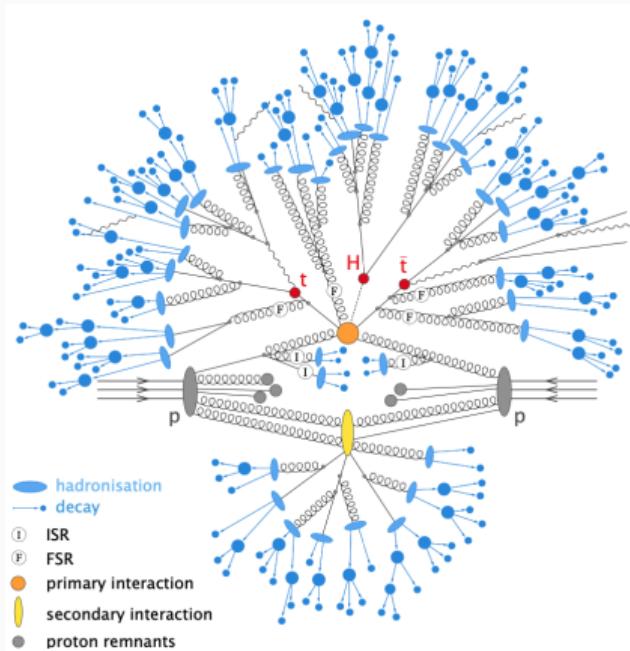
Sensitive at low mass due to easier triggering





# Particle Collisions

- Most particles we are interested in are not stable and do not exist in our environment
- Collide particles to study them and potentially new particles
  - $E^2 = m^2 c^4 + p^2 c^2$
- Hadronization
  - Quarks cannot exist on their own
  - Must combine to form bound states
  - Combine shower into a jet



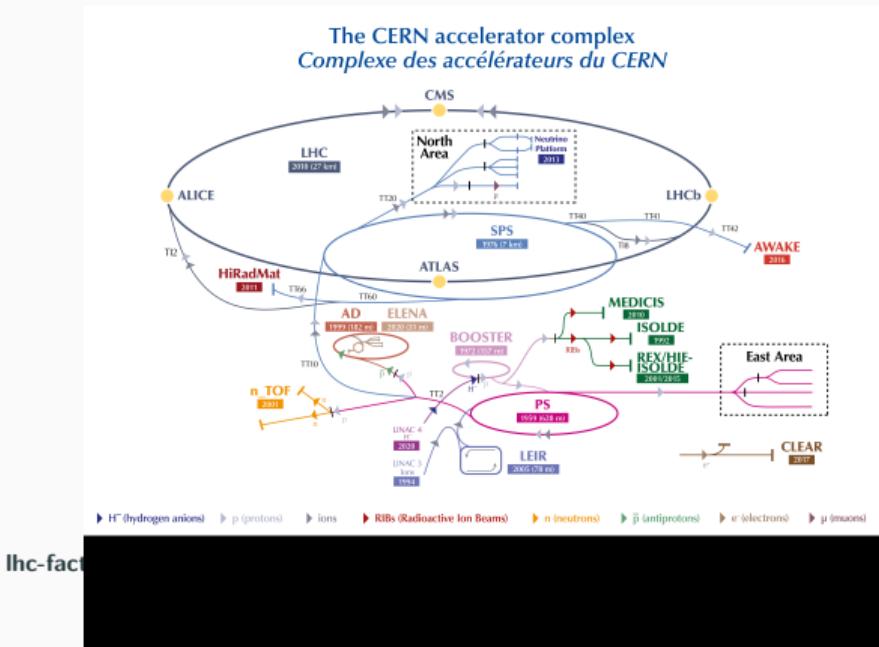
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# Large Hadron Collider



- Largest particle collider ever built
- Highest energy particle collider
- Located at CERN outside of Geneva, Switzerland
- Four main collision points
  - **ATLAS**, ALICE, CMS, LHCb

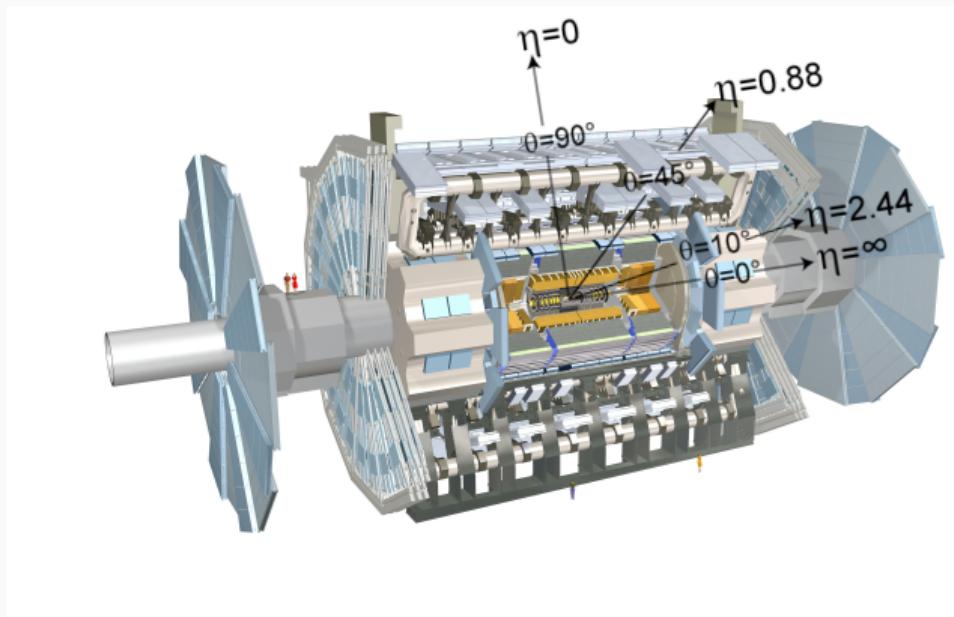
Circumference	26,659 m
Magnet operating temperature	1.9 K
Beam energy	6.5 TeV (13 CM TeV)
Protons per bunch	$1.2 \times 10^{11}$
Bunches per beam	2808
Speed of bunches	> 1,000,000,000 km/hr ( $\simeq 99.999\% c$ )



# The ATLAS Detector



- General purpose particle detector
  - Magnet System
  - Tracker
  - Calorimeters
  - Muon Spectrometer
- Coordinate system origin at interaction point
  - $r$  is radial distance
  - $\eta \equiv -\ln(\tan(\frac{\theta}{2}))$
  - $\phi$  is azimuthal angle
- Complex machine with  
 $\sim 3,000$  scientific authors

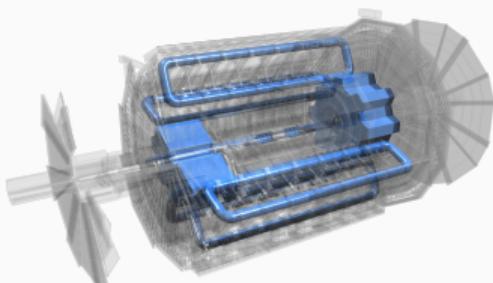


atlas-schematics pseudorapidity

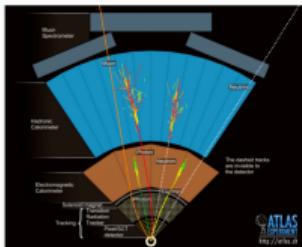
# Magnet System and Inner Detector



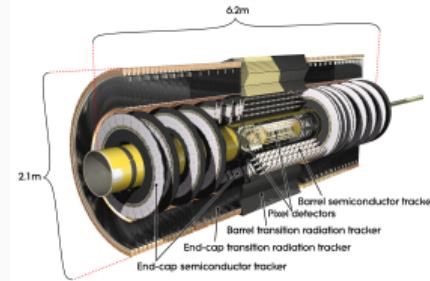
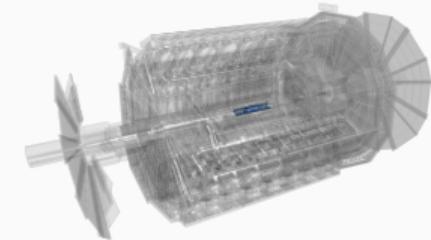
- Central solenoid
  - 2 T magnetic field
  - Bends charged particles in transverse plane
- Toroid system
  - 3.9 T magnetic field
  - Bends charged particles ( $\mu$ ) along beam axis



- Tracks trajectories of charged particles
  - Used to measure momentum in the transverse plane ( $p_T$ )

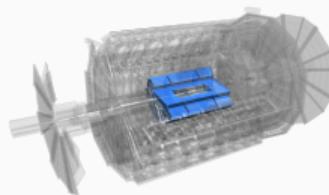
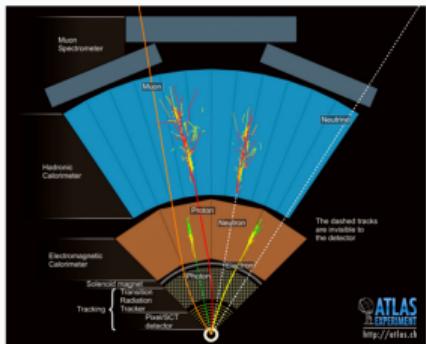


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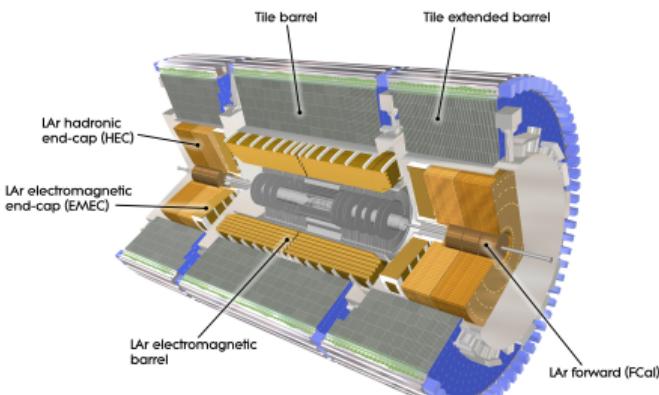


# Calorimeters

- Measures energy of charged particles
  - Fully absorb particles
  - Liquid argon electromagnetic calorimeter
  - Scintillating tile hadronic calorimeter



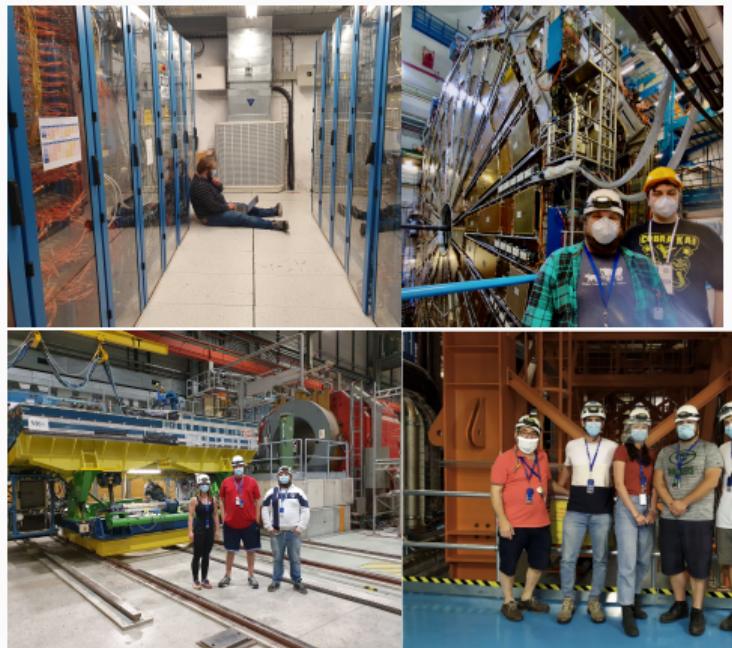
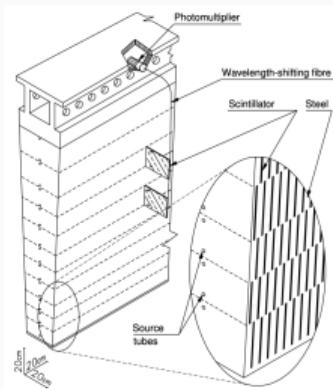
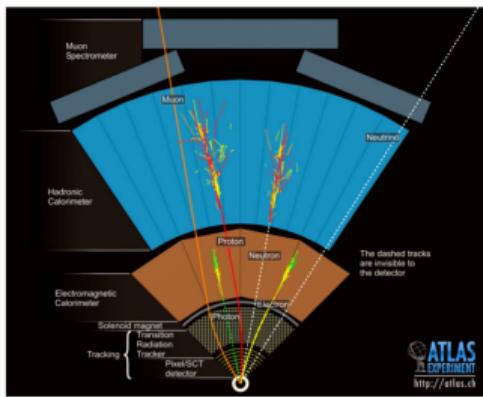
atlas-sc



# Tile Calorimeter



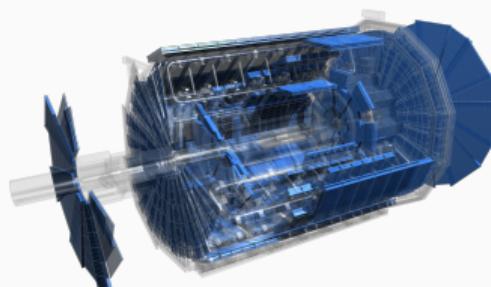
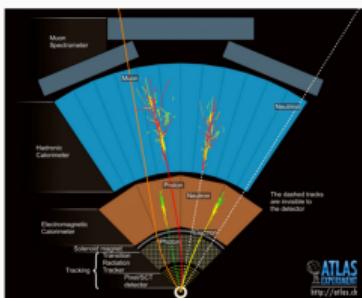
- Scintillating tile with steel absorber
- I served as Data Quality Co-Coordinator for several years
  - In Run-2 99.65% DQ efficiency **DQ-Run2**



# Muon System and Trigger



- Muon Spectrometers track trajectory of  $\mu$ 
  - Muons are minimally ionizing
  - $\mu$  reach the outermost region of the detector
- Information combined with inner detector to reconstruct  $\mu$

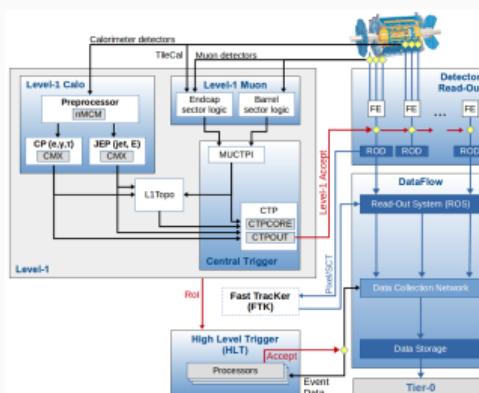


Search for  $H^\pm \rightarrow \tau^\pm \nu_\tau$  with ATLAS

Experimental Apparatus ATLAS

## Trigger System

- Need to quickly sort through data and decide if a collision is interesting or not
- Mix of hardware and software

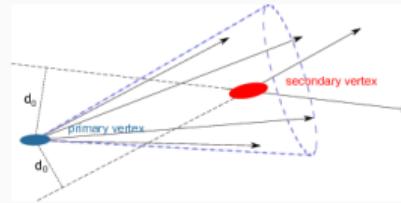


TDAQ Diagram

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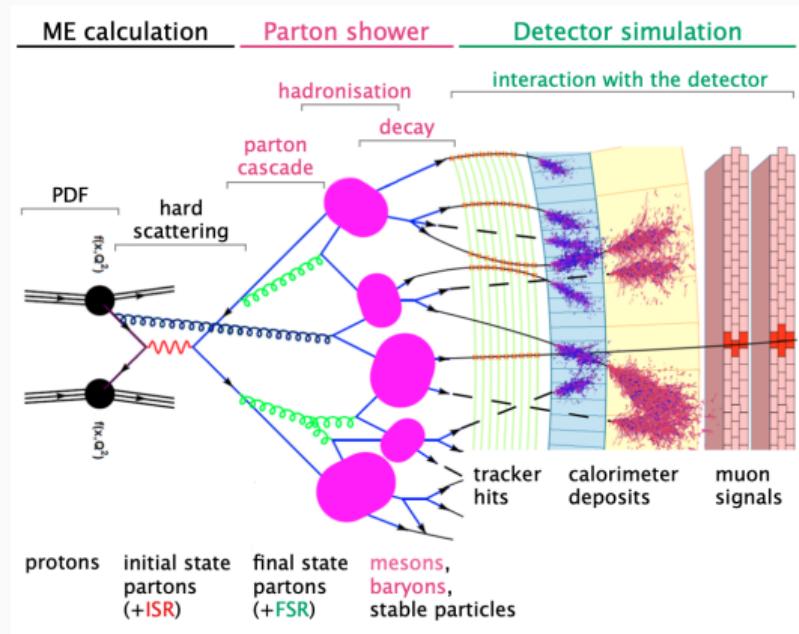
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- b quark initiated hadronic showers are identified by a displaced vertex
- Particles like  $\nu$  do not leave a signature within ATLAS



# Simulation

- Incredibly detailed simulations are used to create analysis strategy
  - Entire data flow from collision to detector readout is simulated
- Control regions are used to verify simulation agreement with data



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# Analysis Overview

- Search for singly charged  $H^\pm$  decaying to  $\tau^\pm \nu_\tau$  over a wide mass range
  - Low mass ( $m_{H^\pm} < m_t$ ):
  - Intermediate mass\* ( $m_{H^\pm} \simeq m_t$ )
  - High mass ( $m_{H^\pm} > m_t$ )

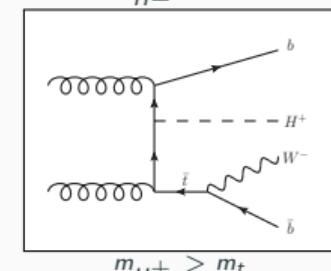
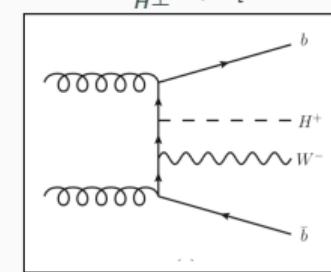
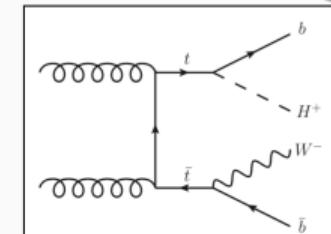
- Dominant backgrounds

Backgrounds w/ prompt hadronic $\tau$	Backgrounds w/ fake $\tau$
$t\bar{t}$ estimated with simulation	Fake $j \rightarrow \tau$ estimated with data driven fake factor method
$V + jets$ estimated with simulation	Fake $\ell \rightarrow \tau$ estimated with simulation, validated on $Z \rightarrow ee$
VV estimated with simulation	

- MVA score is used as the final discriminant

Sub-Channel							
$\tau + jets$ SR	$E_T^{\text{miss}}$ Trigger	1 hadronic $\tau$ $p_T^\tau > 40$ GeV	0 $\ell$ (e or $\mu$ ) $p_T^\ell > 20$ GeV	$\geq 3$ jets $p_T^j > 25$ GeV	$\geq 1$ b-jets $p_T^{\text{b-jet}} > 25$ GeV	$E_T^{\text{miss}} > 150$ GeV	$m_T(\tau, E_T^{\text{miss}}) > 50$ GeV
$\tau + \ell$ SR	Single Lepton Trigger	1 hadronic $\tau$ $p_T^\tau > 30$ GeV	1 $\ell$ (e or $\mu$ ) $p_T^\ell > 30$ GeV	$\geq 1$ jet $p_T^j > 25$ GeV	$\geq 1$ b-jets $p_T^{\text{b-jet}} > 25$ GeV	$E_T^{\text{miss}} > 50$ GeV	Opposite sign $\tau$ and $\ell$

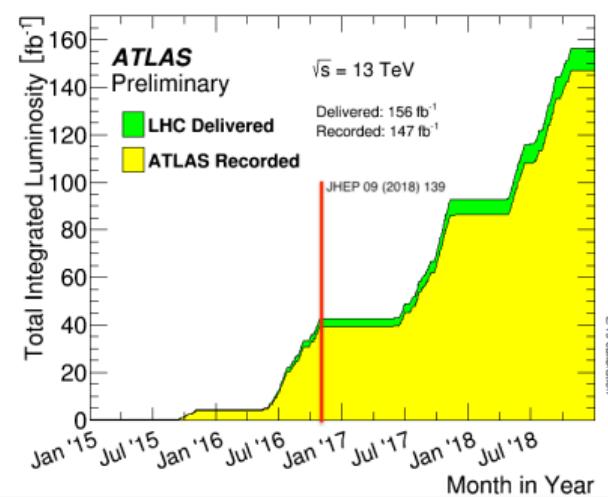
\*: First time probed experimentally JHEP 09(2018)139



# Updates to analysis since last publication



- Signal mass range extended
  - Previous:  $90 \leq m_{H^\pm} \leq 2000$  GeV
  - Current:  $80 \leq m_{H^\pm} \leq 3000$  GeV
- Signal filtering applied in order to effectively increase the statistics in the signal regions
- New analysis framework centered around using modern Machine Learning tools
- Investigated new multivariate analysis techniques
- Improved particle identification algorithms
- Almost 4× more data

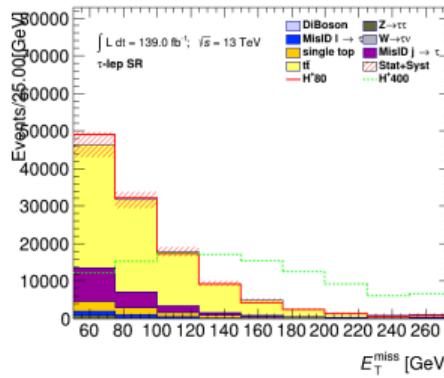
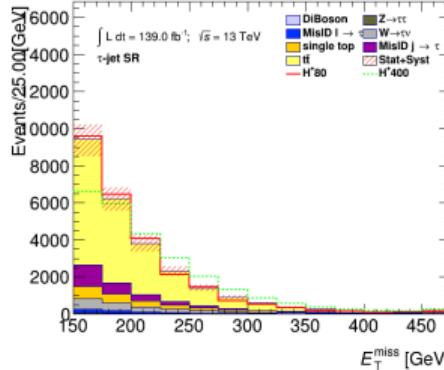


# Background Estimation

- Control regions defined to verify main sources of background

	$t\bar{t}$ CR	W+Jets CR	b-veto CR	b-veto $m_T > 100$ CR
Number of $\tau_{had-vis}$	1	1	0	0
$p_T^\tau$	$> 40$ GeV	$> 40$ GeV	$> 40$ GeV	$> 40$ GeV
Number of jets	$\geq 3$	$\geq 3$	$\geq 3$	$\geq 3$
$p_T^{jet}$	$\geq 25$ GeV	$\geq 25$ GeV	$\geq 25$ GeV	$\geq 25$ GeV
Number of b-jets	$\geq 2$	0	0	0
Number of $\ell$	0	0	0	0
$E_T^{\text{miss}}$	$> 150$ GeV	$> 150$ GeV	$> 150$ GeV	$> 150$ GeV
$m_T(\tau, E_T^{\text{miss}})$	$< 100$ GeV	$< 100$ GeV	$> 50$ GeV	$> 100$ GeV
Type of modeling	$t\bar{t}$	W+Jets	Close to SR	Fake $j \rightarrow \tau$ enriched

	Dilepton-btag CR	Zee CR	b-veto CR	Same Sign CR
Number of $\tau_{had-vis}$	0	1	0	0
$p_T^\tau$	$> 30$ GeV	$> 30$ GeV	$> 30$ GeV	$> 30$ GeV
Number of jets	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 1$
$p_T^{jet}$	$\geq 25$ GeV	$\geq 25$ GeV	$\geq 25$ GeV	$\geq 25$ GeV
Number of b-jets	$\geq 1$	0	0	$\geq 1$
Number of $\ell$	2 (1 e, 1 $\mu$ )	1 e	1 tight e ( $\mu$ )	1 tight e ( $\mu$ )
$E_T^{\text{miss}}$	$> 50$ GeV	$> 50$ GeV	$> 50$ GeV	$> 50$ GeV
mass( $\tau, e$ )	N/A	$> 40; < 140$ GeV	N/A	N/A
Type of modeling	$t\bar{t}$ and single-top	Fake $\ell \rightarrow \tau$ enriched	Close to SR	Fake $j \rightarrow \tau$ enriched



# Background Estimation: $j \rightarrow \tau$ Fakes

- Extract Fake-Factors  $FF = \frac{N_{\tau_{had-vis}}^{CR}}{N_{\bar{\tau}_{had-vis}}^{CR}}$  from two orthogonal control regions:

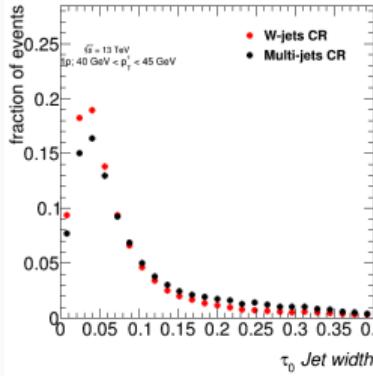
Multi-Jet (gluon enriched)	W+Jets (quark enriched)
$E_T^{\text{miss}}$ or Multi-Jet trigger	Single lepton triggers
$\geq 1\tau_{had}, p_T > 30 \text{ GeV}$	$\geq 1\tau_{had}, p_T > 30 \text{ GeV}$
$\geq 3 \text{ jets}$	$\geq 1 \text{ jet}$
0 b-jets	0 b-jets

- Combine the two Fake-Factors via the template fit method:
  - Find two separate templates for anti- $\tau$  in each CR
  - Fit both templates to the shape of the anti- $\tau$  in the SR
  - Lowest  $\chi^2$  of the fit defines  $\alpha_{MJ}$  value and the corresponding error

$$FF_i^{\text{comb}} = \alpha_i^{MJ} FF_i^{MJ} + [1 - \alpha_i^{MJ}] FF_i^{W+jets}$$

- Number of events with fake  $\tau$  in the signal region is given by:

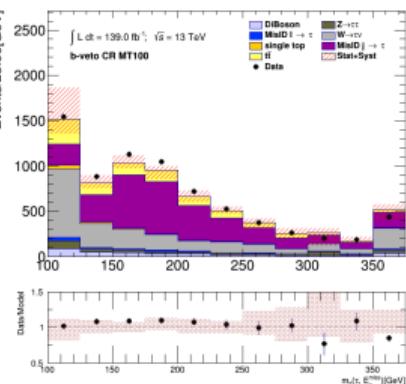
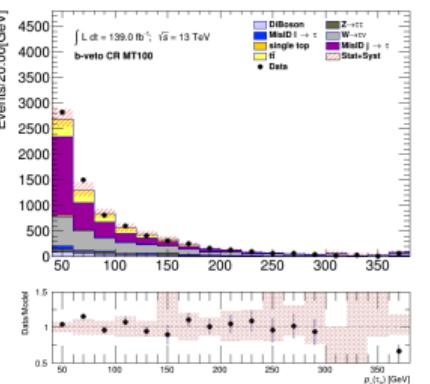
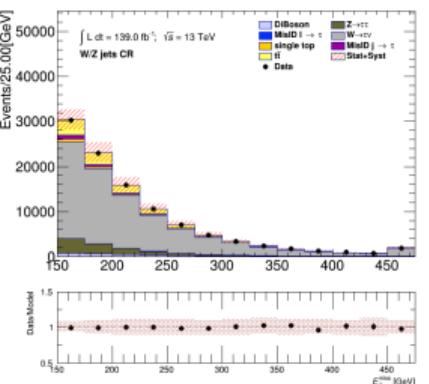
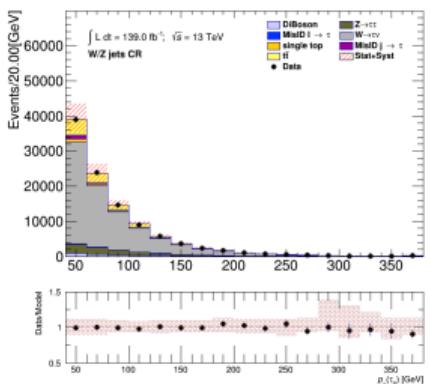
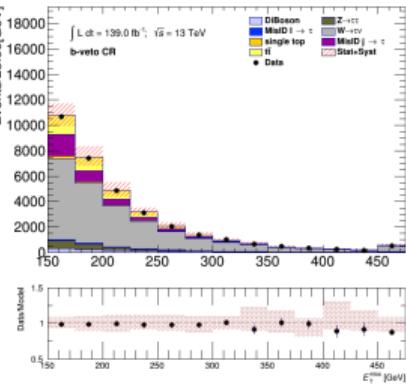
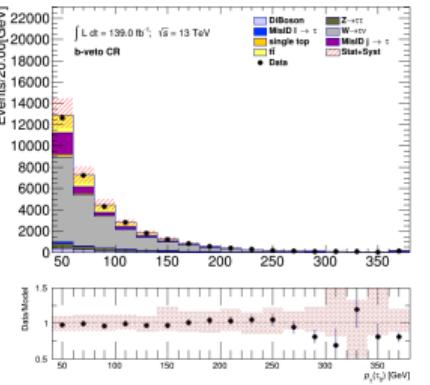
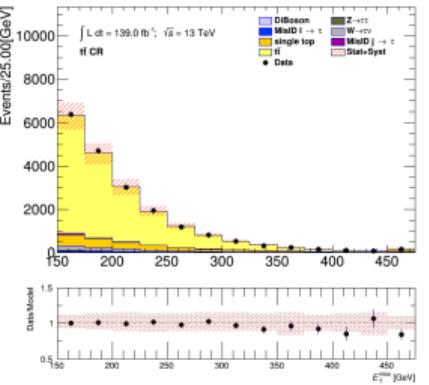
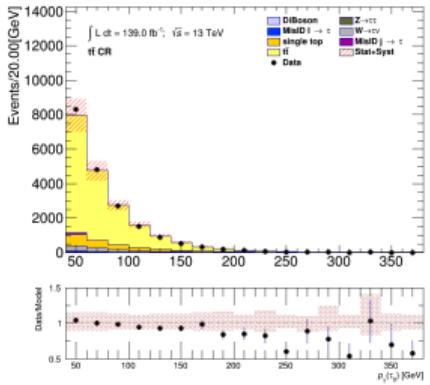
$$N_{\text{fakes}}^{Thad-vis} = \sum_i N_{\bar{\tau}_{had-vis}}^{SRi} FF_i$$



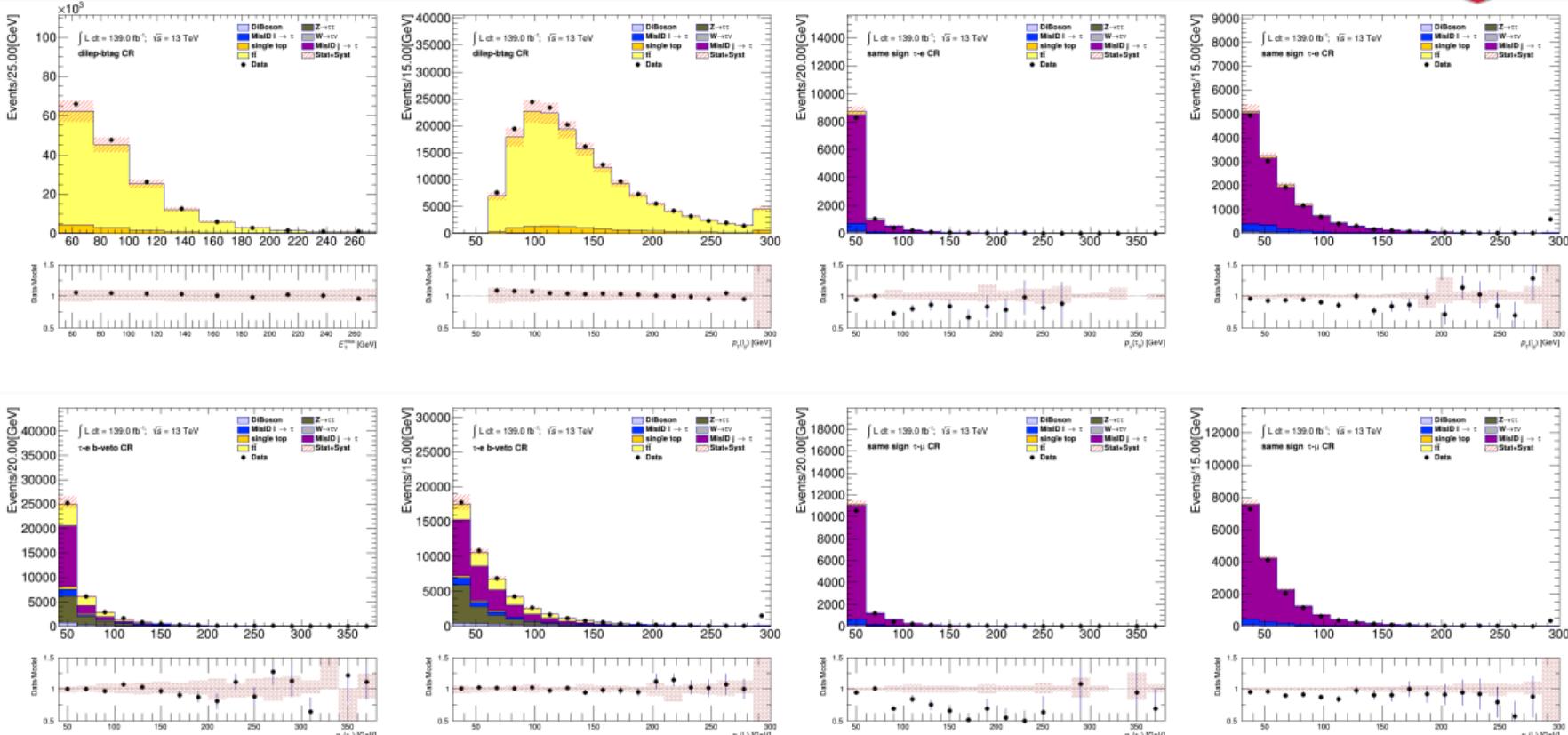
- $\bar{\tau}_0$  jet width used in  $\alpha$  fitting of 1-prong and 3-prong  $\bar{\tau}$

$\bar{\tau} ID$   
RNN Score > 0.01  
Not loose

# $\tau + \text{jets}$ Background Modeling



# $\tau + \ell$ Background Modeling

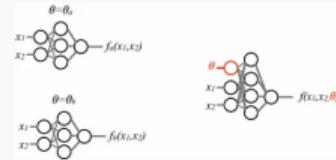


- Boosted Decision Tree (BDT)
  - Excel at exploiting linear correlations
  - Often combined into a random forest
- Neural Networks
  - Excel at exploiting non-linear correlations

# Parameterized Neural Networks



- Background modeling and classifier training kept statistically independent via the k-fold method
  - For this analysis  $k = 5$
- Trained using MC for backgrounds with true  $\tau$
- Data-driven  $j \rightarrow \tau$  fakes included for  $\geq 500$  GeV
- Parameterized Neural Networks (PNNs) can be trained and evaluated on an entire mass range
  - Detailed information here: [arXiv:1601.07913](https://arxiv.org/abs/1601.07913)
- Separate models trained on 1 prong and 3 prong  $\tau$
- $\tau + \ell$  channel is trained inclusive for  $\tau + e$  and  $\tau + \mu$



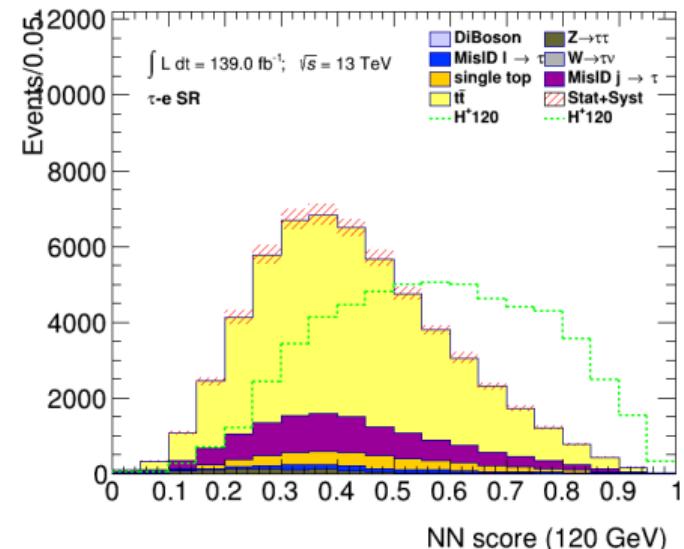
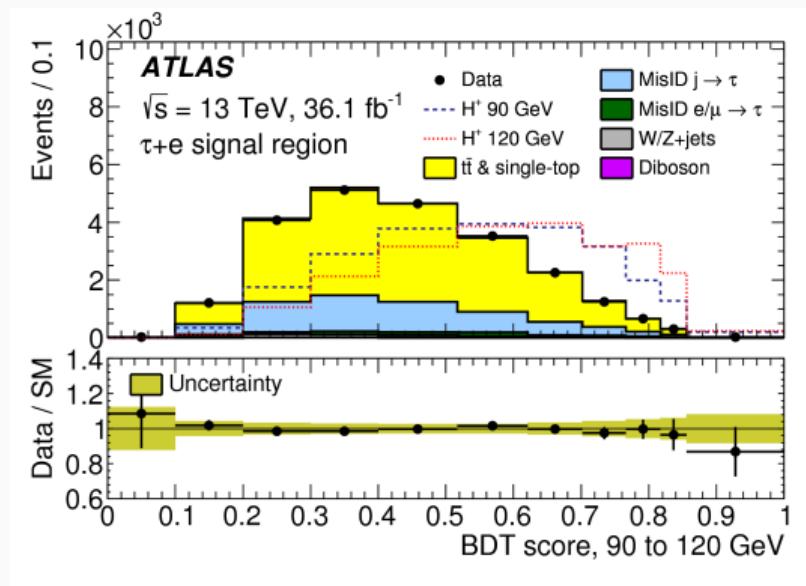
PNN

	Field 1	Field 2	Field 3	Field 4	Field 5	Background
Partition 1	Evaluation	Train	Evaluation	Train	Evaluation	Train
Partition 2	Train	Evaluation	Train	Evaluation	Train	Evaluation
Partition 3	Train	Evaluation	Train	Evaluation	Train	Evaluation
Partition 4	Train	Evaluation	Train	Evaluation	Train	Evaluation
Partition 5	Train	Evaluation	Train	Evaluation	Train	Evaluation

$\tau + \ell$ Input Variables		
$p_T^\tau$	$\eta^\tau$	$\phi^\tau$
$p_T^\ell$	$\eta^\ell$	$\phi^\ell$
$p_T^{j_0}$	$\eta^{j_0}$	$\phi^{j_0}$
$E_T^{\text{miss}}$	$\phi^{E_T^{\text{miss}}}$	$p_T^h$
$m_{Truth}^{H^\pm}$	$\Upsilon^\tau$	

$\tau + \text{jets}$ Input Variables		
$p_T^\tau$	$\eta^\tau$	$\phi^\tau$
$p_T^{j_0}$	$\eta^{j_0}$	$\phi^{j_0}$
$p_T^{j_1}$	$\eta^{j_1}$	$\phi^{j_1}$
$p_T^{j_2}$	$\eta^{j_2}$	$\phi^{j_2}$
$E_T^{\text{miss}}$	$\phi^{E_T^{\text{miss}}}$	$m_{Truth}^{H^\pm}$

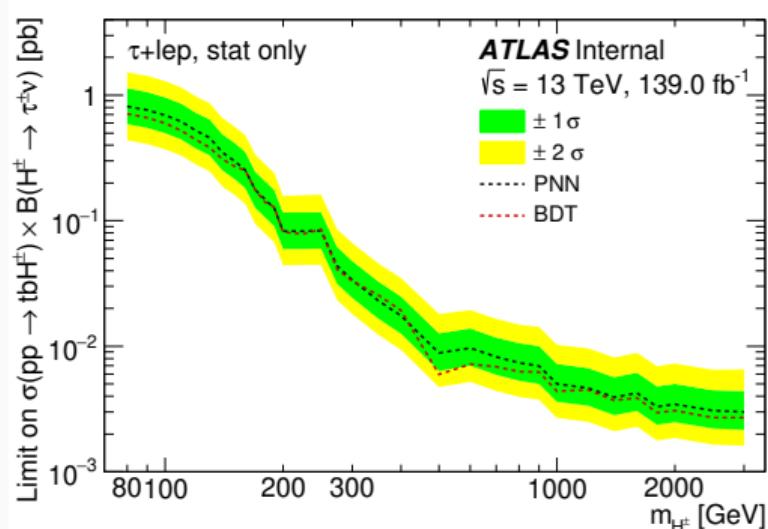
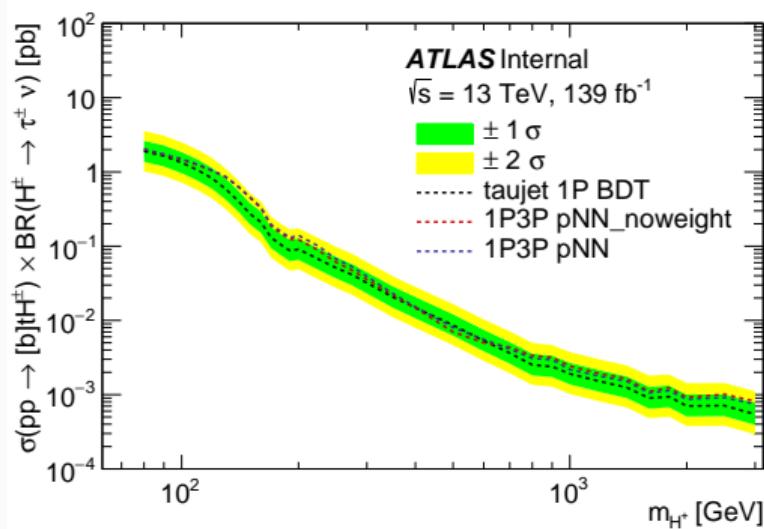
# Boosted Decision Tree vs Parameterized Neural Network



# Boosted Decision Tree vs Parameterized Neural Network



- One model for entire mass range makes analysis less computationally expensive
- PNN can be evaluated on mass points that are not simulated
- Limits are preliminary, many fixes and changes have been implemented since



# PNN Input Variable Selection



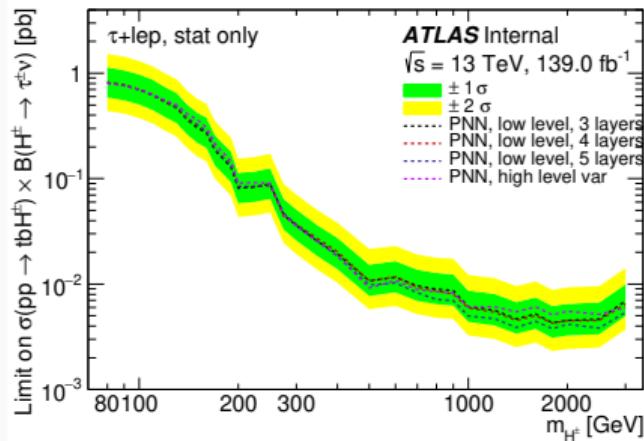
Low Level Input Variables

$p_T^\tau$	$\eta^\tau$	$\phi^\tau$
$p_T^\ell$	$\eta^\ell$	$\phi^\ell$
$p_T^{b-jet}$	$\eta^{b-jet}$	$\phi^{b-jet}$
$p_T^{jet}$	$\eta^{jet}$	$\phi^{jet}$
$E_T^{\text{miss}}$	$\phi_E^{\text{miss}}$	$p_T^h$
$\Upsilon$	$m_{H^\pm}^{\text{Truth}}$	

High Level Input Variables

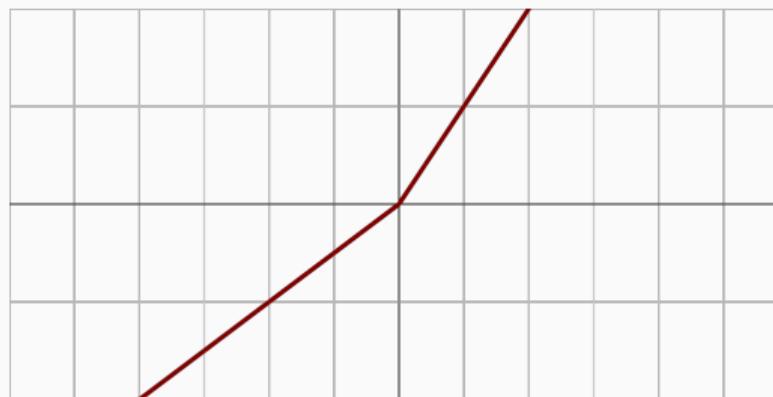
$p_T^\tau$	$p_T^{b-jet}$	$p_T^\ell$
$E_T^{\text{miss}}$	$\Delta\phi_{\tau, \text{miss}}$	$\Delta\phi_{b-jet, \text{miss}}$
$\Delta\phi_{\ell, \text{miss}}$	$\Delta R_{\tau, \ell}$	$\Delta R_{b-jet, \ell}$
$\Delta R_{b-jet, \tau}$	$\Delta\phi_{\tau, \text{miss}}/\Delta\phi_{jet, \text{miss}}$	$\Upsilon$
$m_{H^\pm}^{\text{Truth}}$		

- Comparison between raw input variables and engineered variables
- Expected limits in the  $\tau + \ell$  subchannel was used as figure of merit
- Low level variables best at high  $m_{H^\pm}$



- Performed in the  $\tau + \ell$  sub-channel
- Used area under curve (AUC) of scores as figure of merit
  - Averaged over 5 kfolds, standard deviation is taken from kfolds
- Used early stopping for training
  - $\Delta_{min} = 0.00001$  and a patience of 10
  - Best weights were kept
- To make hyperparameter optimization (HPO) go quicker, ran multiple small grids of hparams
  - Scan over activation functions and loss functions
  - Scan over dropout value
  - Scan over activation function
  - Scan over LeakyReLU  $\alpha$
  - Fixed alpha over more widths and depths
    - AUC from 80 GeV to 500 GeV to optimize for low mass

- LeakyReLU activation function has an  $\alpha$  parameter
- Slope of negative portion
  - Prevents neurons from "dying" by allowing negative weight values
- Standard relu is where  $\alpha = 0$



# PNN Hyperparameter Optimization



Parameter	softsign	relu	LeakyReLU
activation function	softsign	relu	LeakyReLU
loss function	binary crossentropy	mean squared error	mean absolute error
width	32		
depth	10		

Parameter	width	8	16	32
width	8	16	32	
depth	3	5	10	
dropout	0.1	0.3		
activation function	softsign			
loss function	binary crossentropy			

Parameter	width	32	64	128
width	32	64	128	
depth	2	3	4	
dropout	0.1			
activation function	softsign	relu	LeakyReLU	
batch size	1025			
loss function	binary crossentropy			

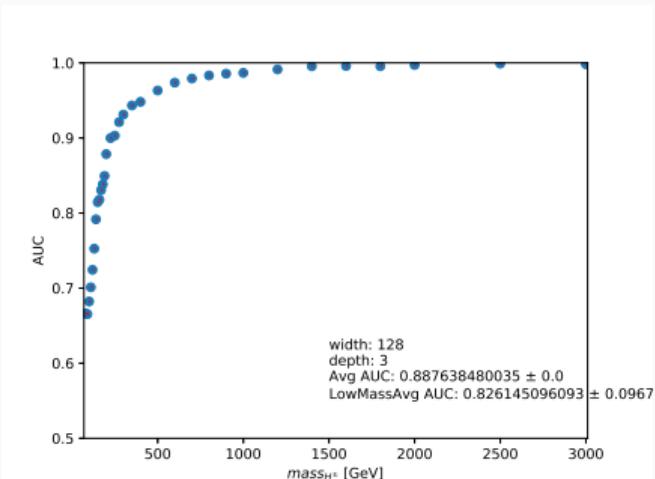
Parameter	32	64	128	
width	32	64	128	
depth	2	3	4	
$\alpha$	0.01	0.05	0.001	0.005
batch size	1024			
dropout	0.1			
activation function	LeakyReLU			
loss function	binary crossentropy			

Parameter	32	64	128	256
width	32	64	128	256
depth	2	3	4	5
batch size	1024			
dropout	0.1			
activation function	LeakyReLU			
$\alpha$	0.05			
loss function	binary crossentropy			

# Final PNN Model Performance



width	depth	Avg	LowMassAvg
128	3	$0.8876 \pm 0.0000$	$0.8261 \pm 0.0968$
128	5	$0.8861 \pm 0.0000$	$0.8235 \pm 0.1000$
128	4	$0.8858 \pm 0.0000$	$0.8232 \pm 0.0994$
128	2	$0.8857 \pm 0.0000$	$0.8231 \pm 0.1006$
64	4	$0.8857 \pm 0.0002$	$0.8230 \pm 0.0994$
64	2	$0.8855 \pm 0.0004$	$0.8228 \pm 0.0996$
64	5	$0.8853 \pm 0.0005$	$0.8224 \pm 0.0997$
64	3	$0.8853 \pm 0.0011$	$0.8223 \pm 0.0994$
256	5	$0.8844 \pm 0.0002$	$0.8213 \pm 0.1003$
256	4	$0.8823 \pm 0.0000$	$0.8181 \pm 0.1013$
32	3	$0.8798 \pm 0.0012$	$0.8139 \pm 0.1031$
32	4	$0.8799 \pm 0.0009$	$0.8139 \pm 0.1031$
32	2	$0.8796 \pm 0.0004$	$0.8135 \pm 0.1023$
32	5	$0.8792 \pm 0.0011$	$0.8128 \pm 0.1035$
256	2	$0.8781 \pm 0.0002$	$0.8120 \pm 0.1023$



# Fake-factor method uncertainties



Sources of systematic uncertainties associated with the FF method:

- Statistical uncertainties
- True  $\tau$  contamination in the anti- $\tau$  CR
- $\alpha_{MJ}$  fitting procedure uncertainty
- Smirnov transformation
- Tau RNN Identification SF variation
- Heavy flavor jet fraction

Source of uncertainty	$\tau + \text{jets}$		$\tau + \ell$	
	Effect on yield	Shape	Effect on yield	Shape
Fake factors: statistical uncertainties	3.9%	✗	3.2%	✗
Fake factors: True $\tau_{\text{had-vis}}$ in the anti- $\tau_{\text{had-vis}}$ CR	+3.4% -3.2%	✗	+4% -4.3%	✗
Fake factors: tau RNN Identification SF	2.7%	✓	2.7%	✓
Fake factors: $\alpha_{MJ}$ uncertainty	3.6%	✗	1.9%	✗
Fake factors: Smirnov transform	0%	✓	0%	✓
Fake factors: heavy flavor jet fraction	6%	✓	5.53%	✓

# Sources of Systematic Uncertainty



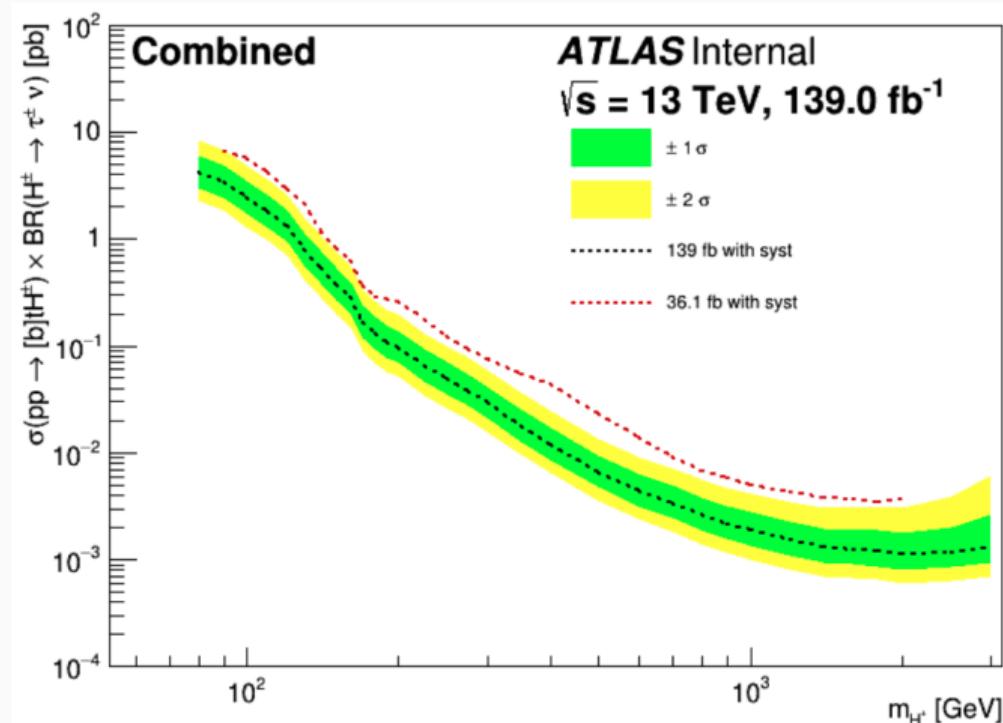
Table with sys



# Expected Yields



# $H^\pm \rightarrow \tau\nu$ Expected Limits



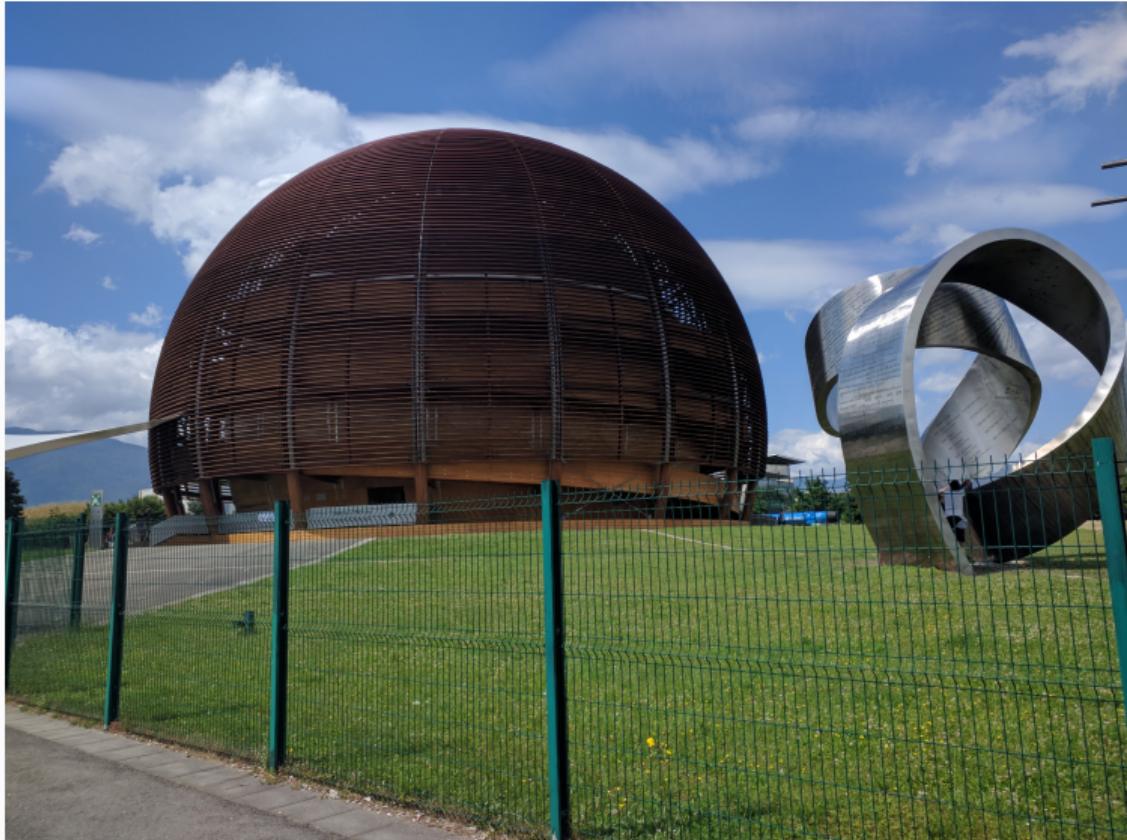
Combined

# Conclusions



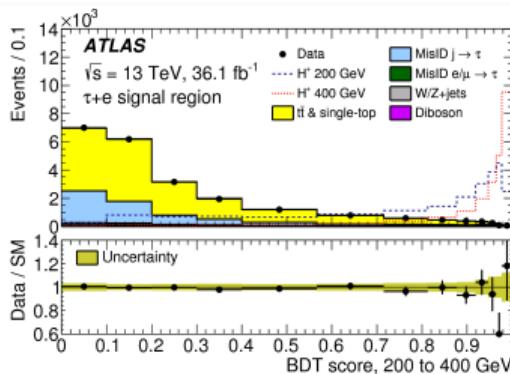
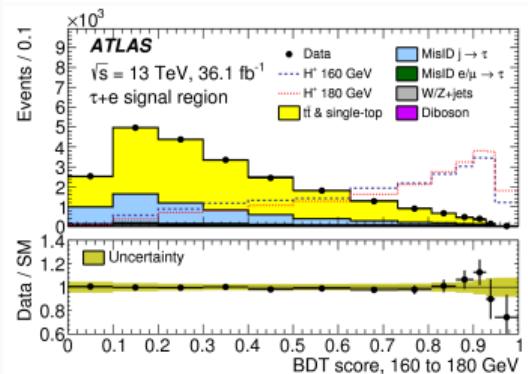
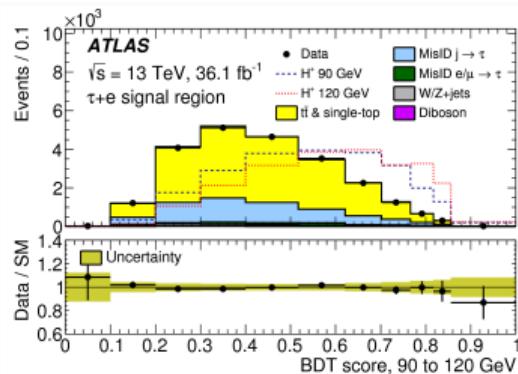
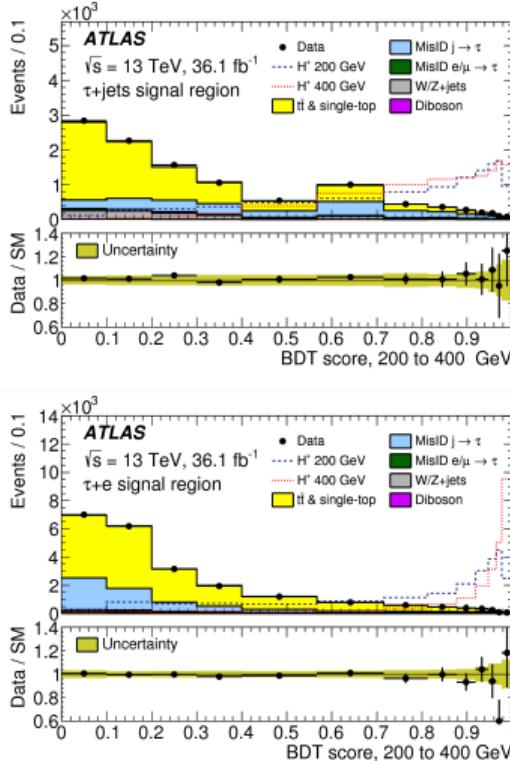
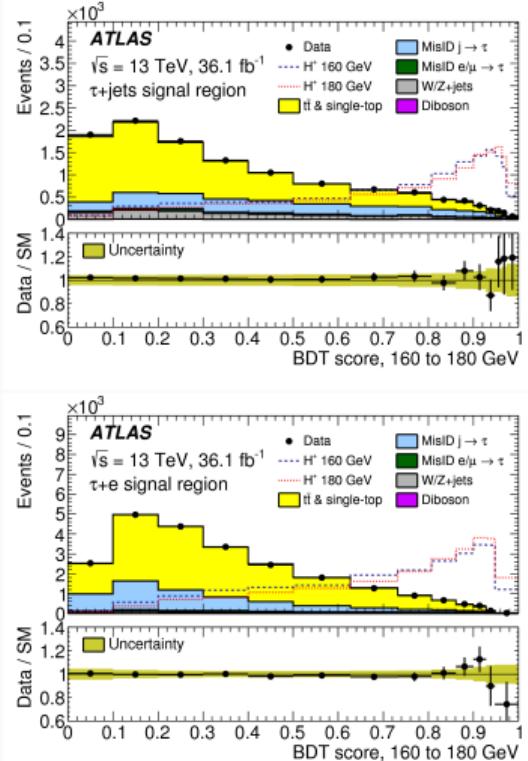
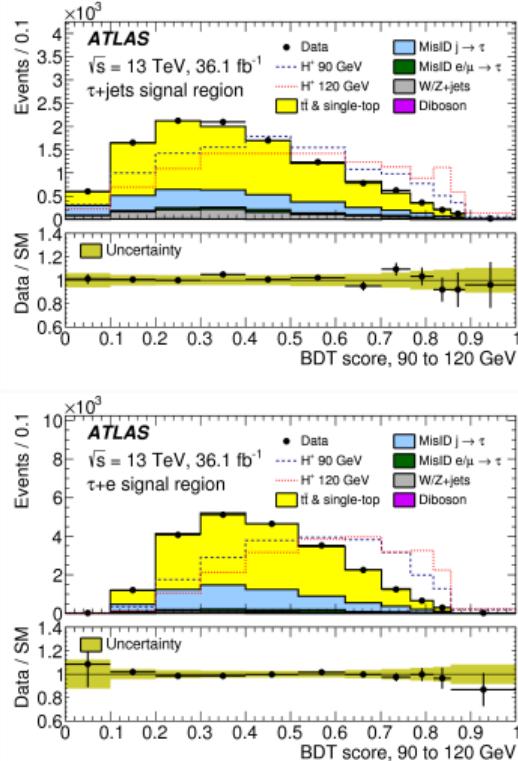
- New analysis strategy outperforms previous analysis by a factor of XX
- Analysis is still blinded
- Paper will be published soon

# Thank You

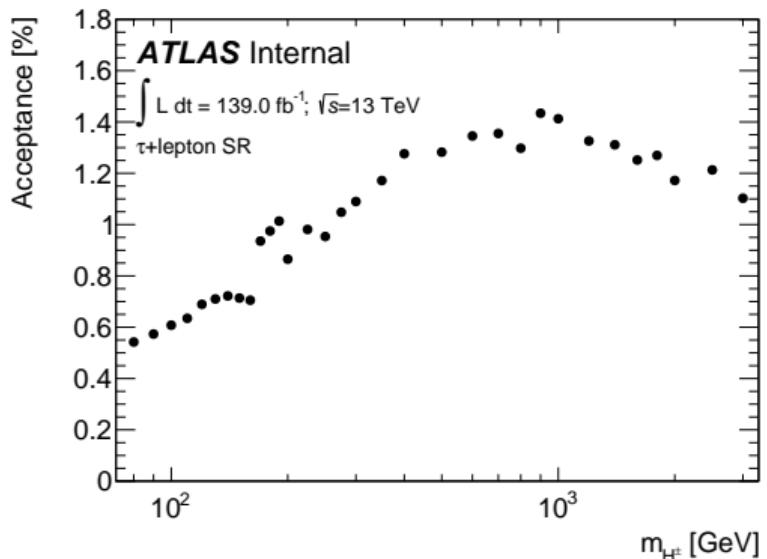
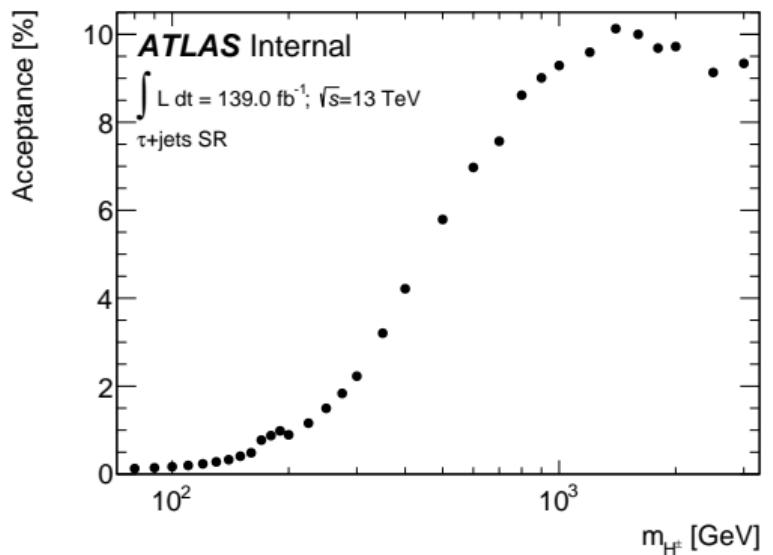


## References i

# JHEP 09(2018)139 BDT Scores in Signal Regions



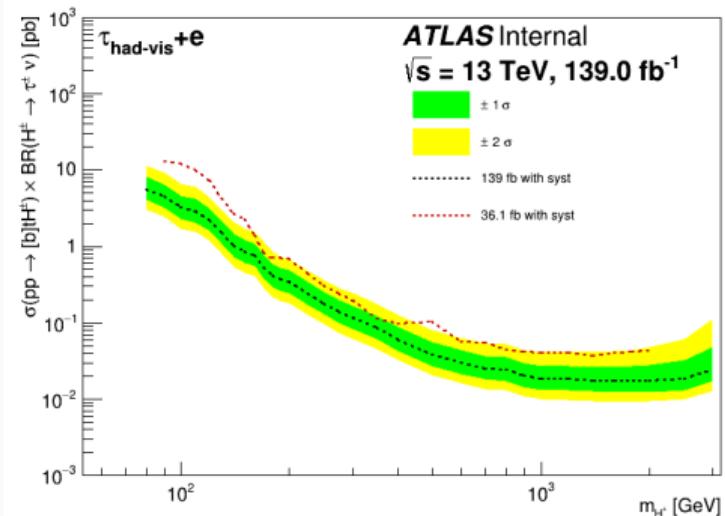
# Signal Acceptance



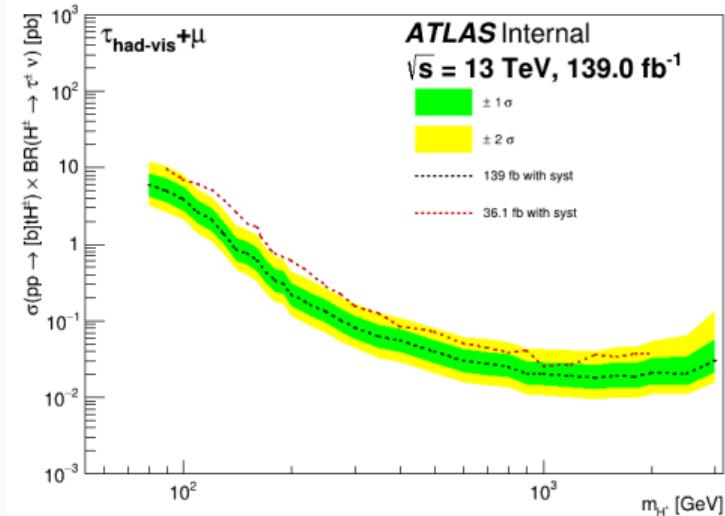
# PNN Hyperparameter Optimization Results

width	depth	80	150	250	500	Avg	LowMassAvg
128	3	$0.6661 \pm 0.0000$	$0.8145 \pm 0.0000$	$0.9031 \pm 0.0000$	$0.9633 \pm 0.0000$	$0.8876 \pm 0.0000$	$0.8261 \pm 0.0968$
128	5	$0.6492 \pm 0.0000$	$0.8043 \pm 0.0000$	$0.9078 \pm 0.0000$	$0.9628 \pm 0.0000$	$0.8861 \pm 0.0000$	$0.8235 \pm 0.1000$
128	4	$0.6593 \pm 0.0000$	$0.8117 \pm 0.0000$	$0.9012 \pm 0.0000$	$0.9638 \pm 0.0000$	$0.8858 \pm 0.0000$	$0.8232 \pm 0.0994$
128	2	$0.6444 \pm 0.0000$	$0.8070 \pm 0.0000$	$0.9075 \pm 0.0000$	$0.9631 \pm 0.0000$	$0.8857 \pm 0.0000$	$0.8231 \pm 0.1006$
64	4	$0.6576 \pm 0.0050$	$0.8080 \pm 0.0013$	$0.9052 \pm 0.0045$	$0.9656 \pm 0.0016$	$0.8857 \pm 0.0002$	$0.8230 \pm 0.0994$
64	2	$0.6528 \pm 0.0066$	$0.8052 \pm 0.0023$	$0.9057 \pm 0.0032$	$0.9651 \pm 0.0007$	$0.8855 \pm 0.0004$	$0.8228 \pm 0.0996$
64	5	$0.6538 \pm 0.0050$	$0.8044 \pm 0.0019$	$0.9058 \pm 0.0037$	$0.9653 \pm 0.0014$	$0.8853 \pm 0.0005$	$0.8224 \pm 0.0997$
64	3	$0.6520 \pm 0.0067$	$0.8051 \pm 0.0018$	$0.9042 \pm 0.0044$	$0.9649 \pm 0.0019$	$0.8853 \pm 0.0011$	$0.8223 \pm 0.0994$
256	5	$0.6536 \pm 0.0010$	$0.8044 \pm 0.0033$	$0.9036 \pm 0.0042$	$0.9644 \pm 0.0022$	$0.8844 \pm 0.0002$	$0.8213 \pm 0.1003$
256	4	$0.6434 \pm 0.0000$	$0.8018 \pm 0.0000$	$0.9017 \pm 0.0000$	$0.9619 \pm 0.0000$	$0.8823 \pm 0.0000$	$0.8181 \pm 0.1013$
32	3	$0.6369 \pm 0.0094$	$0.7950 \pm 0.0041$	$0.8977 \pm 0.0032$	$0.9635 \pm 0.0022$	$0.8798 \pm 0.0012$	$0.8139 \pm 0.1031$
32	4	$0.6384 \pm 0.0037$	$0.7935 \pm 0.0033$	$0.8986 \pm 0.0037$	$0.9636 \pm 0.0016$	$0.8799 \pm 0.0009$	$0.8139 \pm 0.1031$
32	2	$0.6399 \pm 0.0058$	$0.7924 \pm 0.0024$	$0.8983 \pm 0.0033$	$0.9629 \pm 0.0023$	$0.8796 \pm 0.0004$	$0.8135 \pm 0.1023$
32	5	$0.6350 \pm 0.0077$	$0.7931 \pm 0.0056$	$0.8981 \pm 0.0022$	$0.9625 \pm 0.0005$	$0.8792 \pm 0.0011$	$0.8128 \pm 0.1035$
256	2	$0.6320 \pm 0.0044$	$0.7971 \pm 0.0000$	$0.8939 \pm 0.0034$	$0.9587 \pm 0.0018$	$0.8781 \pm 0.0002$	$0.8120 \pm 0.1023$

# $H^\pm \rightarrow \tau\nu$ Expected Limits

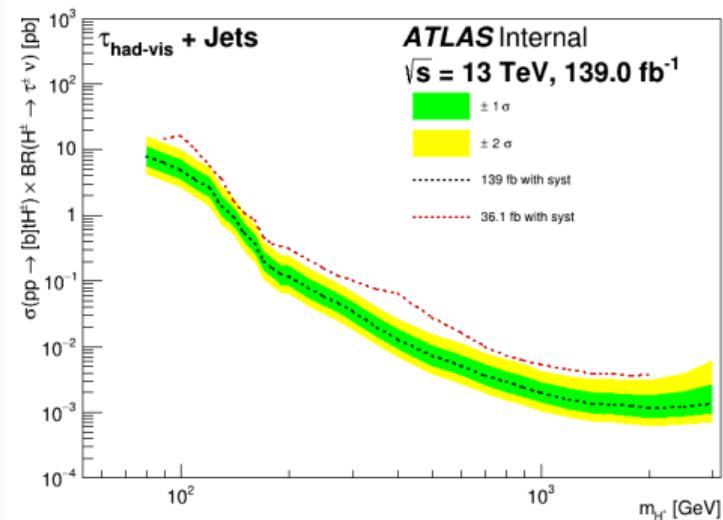


$\tau + e$

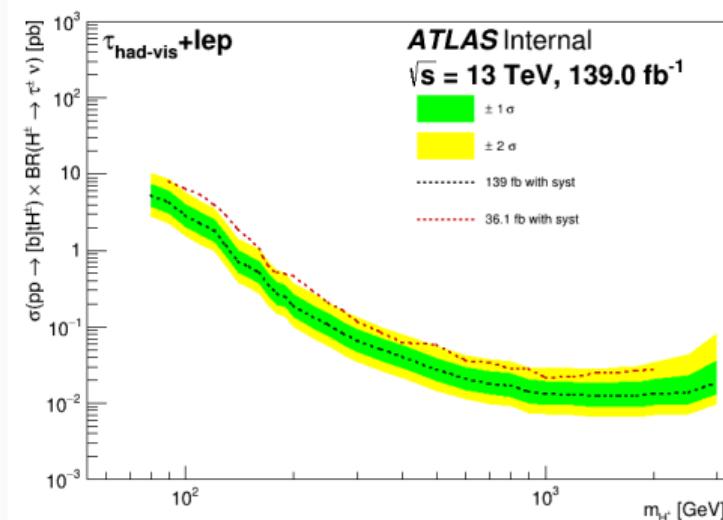


$\tau + \mu$

# $H^\pm \rightarrow \tau\nu$ Expected Limits



$\tau + jets$



$\tau + \ell$