Searches for New Physics at the LHC

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Physics & Astronomy Colloquium

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Structure of Matter

Three phases of matter and light
Democritus 5th century BC

Discovery of electron
Thomson 1897

Nuclear atom
Rutherford 1911

Periodic Table of Elements Mendeleev 1869

Discovery of neutron
Chadwick 1932
Standard Model Particles & Forces

- Electron: 1897
- Top quark: 1995
- W, Z: 1983
- Higgs: 2012

SU(3) x SU(2)_L x U(1)_Y
Standard Model Forces

Successful Quantum Field Theory $SU(3) \times SU(2)_L \times U(1)_Y$

- Electromagnetism (QED) carried by mass-less photon
- Strong force (QCD) carried by mass-less gluon
- Electroweak force carried by photon and massive $W^+, W^-, Z^0$
- Higgs field breaks Electroweak symmetry and provides mass to W and Z, and to all elementary particles
  - Right-handed neutrinos do not have a weak interaction

Gravitational force is not included

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**Electromagnetism**

$$e^- \rightarrow e^- \gamma$$

All charged particles
Never changes flavour

$$\alpha \approx 1/137$$

---

**Strong interaction**

$$q \rightarrow q g_s$$

Only quarks
Never changes flavour

$$\alpha_s = 1$$

---

**Weak interaction**

$$e^- \rightarrow \nu_e g_W$$

All fermions
Always changes flavour

$$\alpha_{W/Z} \approx 1/30$$

---

**Gravity is not included**

*Figure credit: Mark Thomson*
Standard Model

- Production cross section measurements in good agreement with theoretical predictions at $\sqrt{s}=13$ TeV
  - Measured diboson
    - $WW$
    - $WZ$
  - Measured $tt\bar{b}+\text{boson}$
    - $ttH$
    - $ttW$
    - $ttZ$
  - Measured triboson
    - $WWW$
    - $WWZ$
Quantum corrections to the W boson mass

- Quite astonishing that virtual particles have real effects on measured mass!

- Direct measurements of top quark mass and W boson mass in blue

- Prediction of Standard Model in grey from fit to all Electroweak measurements without W mass and top mass measurements
Quantum corrections to the Higgs boson mass

The Higgs boson itself is an enigma

• Quantum Mechanics tends to make the Higgs very heavy ($10^{16}$ GeV), but it is only 125 GeV

This effect should change the Higgs mass to be a very large number

• Solve by a new symmetry: supersymmetry gives every standard model particle a partner with different spin

The effect from the supersymmetric partner should provide cancellation
Unification of forces
Dark matter

Gravity of stars in the middle of a galaxy pulls on stars at the edges to keep them moving in a circle

But there aren’t enough stars! Nor enough plasma

Need something extra, need something invisible= dark matter
Dark matter

Gravity of stars in the middle of a galaxy pulls on stars at the edges to keep them moving in a circle

But there aren’t enough stars! Nor enough plasma

Need something extra, need something invisible = dark matter
Dark matter

What is it?

• SUSY neutralino?
• Gravitino?
• Axion?

Searches at LHC complementary to direct searches
Proton Collisions at the Large Hadron Collider (LHC)

Need many collisions of high energy protons to discover new rare massive particles.

Collide protons at center of detectors at 40 MHz

Keep only 1000 Hz most interesting collisions!

High energy protons moving close to the speed of light around ring

\[ \gamma = \frac{E}{m} = \frac{6500 \text{ GeV}}{0.938 \text{ GeV}} \]
Why so high energy? Colliding proton components

Three static quarks

\[ E = (x_1 + x_2) E_{\text{proton}} \]
\[ p_z = (x_1 - x_2) p_{\text{proton}} \]
\[ p_x = 0 + 0 \]
\[ p_y = 0 + 0 \]
\[ \sqrt{s} = \sqrt{E^2 - p^2} \]

In total, gluons carry \( \frac{1}{2} \) of proton’s momentum!

Gluons produce virtual quark & anti-quark pairs

Three interacting quarks

\[ p_z = x_1 - x_2 \]
\[ p_x = 0 + 0 \]
\[ p_y = 0 + 0 \]
\[ s = E^2 - p^2 \]
Brightness of the beams

Increase collision rate by shrinking beam size from 200 to 16 microns with strong quadrupole magnets next to detectors

**Instantaneous luminosity** $L = N^2 f / \text{area}$
- $N = 115$ billion protons per bunch
- $f = 40$ MHz bunch crossing rate
- Area = $4\pi (16 \text{ microns})^2$
- Peak luminosity $L = 20 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$

**Integrated luminosity** \[ \mathcal{L} = \int L dt \]
- In a week, collect $5 \times 10^{39} \text{ cm}^{-2} = 5 \text{ fb}^{-1}$ record-setting performance

ATLAS Online Luminosity
- LHC Delivered All
- LHC Delivered Stable
- ATLAS Ready Recorded

31\textsuperscript{st} August through 7\textsuperscript{th} September 2018
Large Hadron Collider

Excellent performance in 2018 for $\sqrt{s}=13$ TeV proton-proton collisions

- **Peak luminosity** $21 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ is double design
- Physics results with 140 fb$^{-1}$ from Run 2

Future Run 3 from 2021-2024 at $\sqrt{s}=14$ TeV

- Goal: deliver 300 fb$^{-1}$

Extensive upgrades for High Luminosity LHC Run 2026-2035

- Peak luminosity $75 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
- Goal: deliver over 3000 fb$^{-1}$
LHC components

Accelerate protons to high energy with electric fields
• Takes 20 minutes to increase energy from 450 GeV to 6500 GeV
• Superconducting radio-frequency cavities
• Gain energy $qV$ on each lap

Bend protons around ring with magnetic fields
• 1232 superconducting dipole magnets at 1.9 K
• Need to increase $B$ as momentum increases $B=p/qR$
• Maximum 7.7 T sets maximum beam energy of 6500 GeV

Focus protons with magnetic fields
• Quadrupoles, sextupoles, octupoles, decapoles

Protection against beam losses, magnet quenches
• Each beam has 2500 bunches with 115 billion protons
• Energy in each beam 300 MegaJoules (140 lbs of dynamite!)
• Only takes milliJoules to quench a magnet (8 MegaJoules of stored energy)
ATLAS Detector

Measure energy of **Electrons & Photons** in EM calorimeter (Lead/Liquid Argon)
Energy resolution 9%/√E

Measure energy of **Jets** in EM & Hadronic (Iron/Scintillator) Calorimeters
Energy resolution 45%/√E

Measure momentum of **Muons** from deflection in strong magnetic fields
Momentum resolution 5% at 500 GeV

Measure momentum of charged particles from deflection in strong magnetic fields
ATLAS Inner Detector 2009-2024

Penn readout electronics experts for Transition Radiation Tracker
Straw radius 2 mm, gas Xenon/CO₂
Position resolution 130 microns
350,000 channels with high occupancy 40-60%

Penn electronics each chip handles 8 TRT straws

Expect similar conditions for Run 3 2021-24
Simulation of pileup (Z boson decay to 2 muons)
ATLAS Upgrade Inner Tracker: High-Luminosity LHC 2026-35

Penn leading design of readout electronics of new silicon strip tracker in much harsher radiation environment (66 Mrad)
76 micron pitch, 2.4 or 4.8 cm long in barrel
Position resolution below 20 microns
60 million channels, occupancy below 1%
165 square meters of silicon strips

Prototype for strips barrel stave (2019)
1.4 m long, 14 modules on each side
US will build 196 staves at Brookhaven
Penn will test electronics in DRL
Upgrade prototype modules

Long Strip barrel module (RAL, UK)
97 mm x 97 mm
2560 channels to single HCCStar

Endcap R0 module (Freiburg, Germany)
Upgrade testing at Penn

Wafer probe station in clean room at Penn

2020: test 12 wafers for preproduction prototypes

2021: test 50 wafers to build detector
25,536 HCCStar
17,888 AMAC

Prototype chips on 8 inch wafer

Probe card to test each chip
Overview

Introduction

Emphasis on searches with 140/fb and on searches for new signatures

Summary

Unconventional Signatures

Exotics Searches

High Mass Resonances

Low Mass Resonances

Dark Matter

Searches for Supersymmetry

Strong production

Electroweak production

Highest invariant mass (4.06 TeV) di-electron

Electron $E_T$, 2.01 TeV and 1.92 TeV
Dilepton

Signature of many new particles: spin-0 high mass Higgs, spin-1 $Z'$ from new U(1) or heavy vector triplet, spin-2 graviton.

- Electron $E_T > 30$ GeV, muon $p_T > 30$ GeV
- Mass $> 225$ GeV, resolution $< 2\%$ for electrons, $3\%$ to $15\%$ for muons from 225 to 3000 GeV
- Data fit to a background-only function with 5 free parameters, minimize spurious signal

No significant excess, report limits @ 95\% CL

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</tr>
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<td>4.6</td>
</tr>
<tr>
<td>$Z'_{SSM}$</td>
<td>4.9</td>
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ATLAS 139/fb arXiv:1903.06248
CMS 140/fb EXO-19-019
Dilepton

Electrons

CMS Preliminary

Obs. 95% CL limit
Exp. 95% CL limit, median
Exp. (68%)
Exp. (95%)

Electrons

137 fb\(^{-1}\) (13 TeV, ee)

Z'\(_{SSM}\)

Z'\(_{\psi}\)

Muons

CMS Preliminary

Obs. 95% CL limit
Exp. 95% CL limit, median
Exp. (68%)
Exp. (95%)

Muons

140 fb\(^{-1}\) (13 TeV, \(\mu\mu\))
**Z’ with low mass**

- Low mass Z’ from U(1) based on $L_\mu - L_\tau$
  - Z’ only couples to muons and taus
- Radiate Z’ from muons
  - Exploit SM $Z \rightarrow \mu^+\mu^-$ to produce muons
- Exploring part of interesting parameter space
Dijet

Wide Jet 1,
pt = 4.30 TeV
eta = -0.32
phi = 0.44

Wide Jet 2,
pt = 3.93 TeV
eta = 0.07
phi = -2.72

Dijet Mass = 8.4 TeV
Dijet

- New background estimate using control region with widely separated jets in $\eta$
  - QCD background from t-channel
  - Signal from s-channel
- Improved sensitivity by a factor of 2 for broad resonances

ATLAS 139/fb JHEP 03 (2020) 145
CMS 137/fb EXO-19-012
Dijet with low mass

- First limits below 50 GeV at a hadron collider for low mass resonances decaying to “dijets”
- Trigger on ISR photon $p_T > 200$ GeV, large boost of low mass resonance collimates decay products into single large radius jet with two-prong substructure
- Data-driven background estimate
Where is dark matter?

Interpret searches for dark matter results in terms of a heavy mediator Z’ model.

\[
\begin{align*}
\bar{q} & \quad \gamma/V/g \quad \chi \\
q & \quad Z'_{V/A} \quad \bar{\chi}
\end{align*}
\]

Classic mono-jet signature!

Dijet and dilepton resonances contribute if sizable Z’ coupling to quarks or leptons.

Monojet $p_T$ 1.7 TeV
MET 1.7 TeV
No other jets with $p_T > 30$ GeV
Dark Matter

- Z’ mediator must have coupling to quarks to be produced at LHC
- If $g_q$ large, decay of Z’ to dijets gives best sensitivity regardless of dark matter mass
- If $g_l$ not zero, decay of Z’ to dileptons also sensitive
- If $g_q$ smaller, decay of Z’ to dark matter gives best sensitivity if kinematically allowed (Z’ mass double dark matter mass), rely on visible ISR and large MET from invisible dark matter
- Benchmark model:
  - Vector mediator
  - Dirac DM
Search for Higgs boson decay to dark matter

Best sensitivity in Vector Boson Fusion channel

Dominant backgrounds: Z+jets with Z decay to neutrinos, W+jets with W decay to $\ell\nu$ (miss lepton)

Dijet mass $>$ 0.8 TeV

$|\Delta \eta| > 3.8$

MET $>$ 200 GeV

(a) Signal process

(b) Example diagram for the strong Z+jets background process

(c) Example diagram for the electroweak VBF Z+jets background process

(d) Example diagram for the electroweak diboson process
Search for Higgs boson decay to dark matter

Background estimation critical for sensitivity

11 signal regions (SR)

Exclude 0.13 branching fraction at 95% CL
Search for Higgs boson decay to dark matter

Invisible Higgs decay branching fraction $< 0.13$ (0.13) @ 95% CL

Previous VBF result $< 0.37$ (0.28) obs (exp)

Interpretation in Higgs portal model
Supersymmetry

Strong production
- Gluinos
- Top squarks

Rarer Electroweak production
- Charginos and neutralinos
  - WZ+MET Signature if bino LSP
  - Disappearing/appearing track signature if wino or higgsino LSP
- Stau

SU(3) x SU(2)\_L x U(1)\_Y

\[ h, H^0, H^+, H^-, A \]

Gluinos: 3 winos, 1 bino, 4 higgsinos

bino, winos, higgsinos mix to form
neutralinos \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \)
charginos \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm \)

Lightest supersymmetric particle (LSP) is \( \tilde{\chi}_1^0 \)
Ninjalinos
Gluinos

Direct decays

Inclusive search in regions with 2-10 jets 0-4 b-tagged jets

Discrimination with scalar sum of jet $p_T (H_T)$ and $M_{T2}$ for two invisible particles

One-step decays

ATLAS 139/fb CONF-2020-002
Gluinos

High $H_T$

signal regions

2-10 jets

0-4 b-jets

binned in $M_{T2}$
For decay to quarks, exclude gluino up to 1970 GeV with light LSP.
For decay to top quarks, exclude gluino up to 2250 GeV with light LSP
Searches for Stop

Signature depends on mass splitting between stop and LSP

Advanced techniques improve sensitivity
Results for stop

Improvement from previous results for 4-body and 3-body regions

Extend reach by over 200 GeV at high stop mass
\( \Delta m(\text{stop, LSP}) \gg \text{top quark mass} \)

- Reject large background from dilepton ttbar using multivariate technique
- Multi-bin search in MET and \( M_T \)

\( \Delta m(\text{stop, LSP}) \approx \text{top quark mass} \)

- Difficult region since looks like ttbar
- ISR jet \( p_T > 400 \) GeV to boost system, thus increasing MET from LSPs
Stop 3-body

\[ \Delta m(\text{stop, LSP}) \] between W boson mass (80 GeV) and top quark mass (173 GeV)

- Dominant background from dilepton ttbar with one lepton not identified
- Recurrent neural network with jet 4-vectors as input, handles wide range of jet multiplicity
- Shallow neural network with RNN outputs, lepton, MET, and leading b-jet kinematics
\( \Delta m(\text{stop}, \text{LSP}) < 80 \text{ GeV} \) gives very soft leptons and b-jets

- Require ISR jet with \( p_T > 200 \text{ GeV} \) to boost system
- Soft lepton \( p_T > 4(4.5) \text{ GeV} \) for electron (muon)
- New soft b-tagging algorithm using secondary vertices gives sensitivity for \( \Delta m(\text{stop}, \text{LSP}) < 40 \text{ GeV} \)
- Excellent discrimination with lepton \( p_T / \text{MET} \)
Supersymmetry

**Strong production**
- Gluinos
- Top squarks

**Rarer Electroweak production**
- Charginos and neutralinos
  - WZ+MET Signature if bino LSP
  - Disappearing/appearing track signature if wino or higgsino LSP
- Stau

\[
\text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y
\]

\[h, H^0, H^+, H^-, A\]

Gluinos \(3\) winos \(1\) bino \(4\) higgsinos

Lightest supersymmetric particle (LSP) is \(\tilde{\chi}_1^0\)

bino, winos, higgsinos mix to form neutralinos \(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\)

charginos \(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm\)
Electroweakinos

Compressed region
Off-shell W and Z bosons:
Soft lepton, ISR jet to boost system

On-shell W and Z bosons
Exclude wino-type NLSPs below 600 GeV for LSP below 100 GeV
Chargino-Neutralino Production

Compressed region: small mass differences between $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$

- W and Z bosons off-shell, giving low $p_T$ leptons
- New! electron $p_T > 4.5$ GeV, muon $p_T > 3$ GeV
- New! track $p_T > 1$ GeV

ISR jet $p_T > 100$ GeV boosts system, increases lepton $p_T$ and MET

Dilepton mass endpoint at mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$
Compressed Electroweakinos

Limit on Higgsinos with mass splitting below 2 GeV

Run 3 and HL-LHC will explore further

Even lower mass splittings give long-lived chargino decaying in detector

ATLAS Preliminary

$\sqrt{s} = 13$ TeV

$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ (Higgsino)

All limits at 95% CL

- Observed limits
- Expected limits

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]

$m(\tilde{\chi}_1^\pm)$ [GeV]
Really Really Compressed Electroweakinos

100-350 MeV mass splittings: long-lived chargino decays to very soft pion and LSP in detector, giving disappearing track signature

- ATLAS new pixel layer in 2015-18 data at \( r = 3.3 \) cm, CMS new pixel layer in 2017-18 data at \( r = 2.9 \) cm improves reach for short tracks, especially important for Higgsino

Assuming production cross-section for

- Higgsino exclude below 750 (175) GeV for a lifetime of 3 (0.05) ns
- Wino exclude below 884 (474) GeV for a lifetime of 3 (0.2) ns.
SUSY and R-Parity = \((-1)^{3(B-L)+2s}\)

Question assumptions! Do you prevent proton decay by

• Conserving a new quantum number called R-Parity? \(\text{RPC & LSP stable}\)
• Adding a new gauge symmetry \(U(1)\) with B-L charge? \(\text{RPV & LSP decays}\)
Add right-handed neutrinos to standard model
Start from Superstring/M-theory with gravity

\[ \rightarrow \text{SU}(3) \times \text{SU}(2)_L \times U(1)_Y \times U(1)_{B-L} \]

\[ \rightarrow \text{Right-handed neutrino’s supersymmetric partner spontaneously breaks } U(1)_{B-L} \]

\[ \rightarrow \text{Baryon number conserved (proton is safe!)} \]

\[ \rightarrow \text{Lepton number violation allowed} \]

\[ \text{SU}(3) \times \text{SU}(2)_L \times U(1)_Y \times U(1)_{B-L} \]

h, H^0, H^+, H^-, A

gluinos

3 winos

1 blino

1 rino

4 higgsinos

RPV allows mixing with leptons too

9 neutralinos \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \ldots \)

5 charginos \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \ldots \)

Lightest supersymmetric particle (LSP) has RPV decay
RPV trilepton resonance

MSSM with U(1) B-L charge, broken by RH sneutrino
Tiny RPV couplings since related to neutrino masses

ATLAS 139/fb ATLAS-CONF-2020-009

≥3 leptons, ≥1 leptonic Z candidate
No Hadronic boson or second leptonic Z candidate
Yes

If ≥2 additional boson candidates, choose that closest to expected boson mass
RPV trilepton resonance

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

All limits at 95% CL
\( \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \) production
\( \tilde{\chi}_1^0 \to Z\ell^\pm, H\ell^\pm, W^\pm\ell^- \)
\( \ell = (e, \mu, \tau) \)

- Expected Limit (\( \pm 1 \sigma_{\text{exp}} \))
- Observed Limit (\( \pm 1 \sigma_{\text{SUSY}} \))
- Observed Exclusion Region

\[ m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) \text{ [GeV]} \]
Long-lived particles & Unconventional signatures

- LHC Long-lived particle forum
  arXiv:1903.04497
- Lots of development of new techniques to search for particles decaying in detector
- Don’t want to miss new physics because of missing trigger or reconstruction...
Useful Links

• [ATLAS Physics Public Results](#) and [Physics Briefings](#)
• [CMS Physics Public Results](#) and [Physics Briefings](#)
• [CERN LHC Seminars](#) (recorded)
• [Penn ATLAS group](#)
Graduate Students in Penn ATLAS group

Exceptionally collaborative group of faculty & postdocs

24 PhD theses so far from Penn ATLAS
- 2020 Rachael Creager
- 2018 Bill Balunas, Rob Fletcher
- 2016 Kurt Brendlinger
- 2015 Elizabeth Hines, Brett Jackson, Chris Lester, Alex Tuna, Rami Vanguri
- 2014 Jamie Saxon, Doug Schaefer, Jon Stahlman
- 2013 Josh Kunkle, Ryan Reece
- 2012 John Alison, Dominick Olivito
- 2011 Mike Hance

Current graduate students
- Avi Kahn
- Luis Gutierrez Zagazeta, Sicong Lu, Riley Xu
- James Heinlein
- Ben Rosser, Joe Mullin
- Ian Dyckes, Lucas Flores

Incoming class!
- Gwen Gardner, Thomas Gossart, Bobby McGovern, Lauren Osojnak, Andie Wall

6 Outstanding ATLAS thesis awards
4 Springer Thesis Awards
ATLAS & CMS have giant numbers of searches with results & in progress
Sophisticated techniques & unconventional signatures
Future is bright!
• Run 3 expect 300/fb
• High Luminosity LHC expect 3000/fb
Signature of many new particles: spin-0 high mass Higgs, spin-1 $Z'$ from new U(1) or heavy vector triplet, spin-2 graviton.

- Electron $E_T > 35$ GeV, one central $|\eta| < 1.44$
- Muon $p_T > 53$ GeV
- Background estimate from simulation fit to a function with 2x5 parameters, normalized around Z peak 60-120 GeV

No significant excess, report limits @ 95% CL

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From dijets to dibosons

Wide Jet 1:
pt = 3.5 TeV
Mass = 1.8 TeV

Wide Jet 2:
pt = 3.4 TeV
Mass = 1.8 TeV

PF Jet 1,
pt = 2.19 TeV
eta = 0.27
phi = 1.47

PF Jet 3,
pt = 1.71 TeV
eta = 0.21
phi = 2.45

PF Jet 4,
pt = 1.40 TeV
eta = -0.74
phi = -1.17
Diboson resonances

- High mass resonance decay to WW, WZ, ZZ
  - Boson hadronic decay products highly collimated
  - Not resolvable as separate jets
  - Large jets with two-prong substructure allow to differentiate from huge QCD multi-jet background
Vector-like Quarks

Pair-produce new heavy spin-1/2 top quark T with vector-like coupling, motivated by “Little Higgs”

• $T \rightarrow bW$ looks like a heavy top quark
• $T \rightarrow tH, \ T \rightarrow tZ$ more complicated to reconstruct

Select all-hadronic decays with 4 wide AK8 jets

For each jet, calculate boosted event shapes for each mass hypothesis $\rightarrow$ inputs to Machine Learning Dense Neural Network

• 59 inputs
• 3 hidden layers with 40 nodes
• 6 outputs to classify each wide AK8 jet as top, H, Z, W, b, q/g

Observed limit for 100% decay to $tZ$

Observed limit for 100% decay to $tH$
Stop: 2-body and 4-body signal regions

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**ATLAS** Preliminary

**VR Events**

**Validation Regions**
- Data
- Total SM
- $t\bar{t}$
- $W$+jets
- $t\bar{t}V$
- Multiboson
- Single top
- Other

**Signal Regions**

**Significance**

**SR Events**
Stau

- LHC has first results since LEP!!!
- Decay to di-tau and 2 LSPs
  - Large MET
  - Veto b-jets (ttbar)
  - Veto Z and H decays to taus
- Limits up to 390 GeV for mass-degenerate staus
- Limits up to 300 GeV for only “LH” staus
Long-lived particles: closing the gaps

- **Gluino** (R-hadron)
- **Chargino** (wino-type)
Long-lived gluino

- GMSB with gluino displaced decay to a jet & gravitino
- Emerging jets with timing in CMS EM Calorimeter
Heavy Neutral Lepton

Cover 4.5-50 GeV mass range using leptonic W boson decays

New LHC signature of prompt muon & displaced vertex of two leptons extends previous prompt searches to
- lower masses (longer lifetimes)
- lower couplings
- lepton number conserving processes (LNC)

Large Radius Tracking on dimuon sample

Displaced vertex radius 4-300 mm
two opposite-charge leptons
mass > 4 GeV

1 prompt muon
displaced vertex

3 prompt leptons
same-flavor same-charge pair