Searching for Uncovered and Unexpected New Physics Signatures at the Energy Frontier

Julia Gonski

15 November 2022
SLAC FPD Seminar
Introduction to high energy collider physics

1. The ATLAS Experiment & the HL-LHC upgrade
   - LAr calorimeter readout electronics

2. Analysis innovation for new physics searches
   - Long-lived particles
   - Anomaly detection

3. Future outlook & experiments
Outline

• Introduction to high energy collider physics

1. The ATLAS Experiment & the HL-LHC upgrade
   - LAr calorimeter readout electronics

2. Analysis innovation for new physics searches
   - Long-lived particles
   - Anomaly detection

3. Future outlook & experiments
Collider Experiment Strategy

High Energy Accelerator
High Energy Accelerator:

- Collider Experiment Strategy

Physics Results:

- Higgs → γγ Observation
- ATLAS
- Events / 2 GeV
- Data
- Sig+Bkg Fit (m_H=126.5 GeV)
- Bkg (4th order polynomial)

5.6. Systematic uncertainties:

- The dominant contribution is due to the modelling of the Higgs boson kinematics.
- Uncertainties due to the modelling of the underlying event are estimated with data using electrons from Z → e+e- and Z → μ+μ- events.
- The uncertainty on the expected fractions of signal and background is determined from the fit to the data histogram.
- The uncertainty from pile-up is estimated from the data using Z → e+e- and Z → μ+μ- events.

Higgs → γγ Observation:

- The dominant contribution is due to the modelling of the Higgs boson kinematics.
- Uncertainties due to the modelling of the underlying event are estimated with data using electrons from Z → e+e- and Z → μ+μ- events.
- The uncertainty on the expected fractions of signal and background is determined from the fit to the data histogram.
- The uncertainty from pile-up is estimated from the data using Z → e+e- and Z → μ+μ- events.
Collider Experiment Strategy

High Energy Accelerator

Physics Results

Higgs → γγ Observation

Gravity

Neutrino Masses

Dark Matter
Collider Experiment Strategy

Maximize chances to discover new physics!
The Higgs Boson Discovery

• **Standard Model of particle physics**: quantum field theory describing all known fundamental particles & their interactions

• Confirmed to great precision over decades of accelerator experiments

• Discovery of the Higgs boson with the LHC in 2012 “completes” the SM

1964-2013

**PHYSICAL REVIEW LETTERS**

**BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS**

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)
Hierarchy problem → motivates BSM models such as supersymmetry that stabilize Higgs mass

Higgs coupling to mass → probe unexplored multi-TeV mass scale for new particles, portal to heavy BSM physics

Precision measurement of Higgs decays → constrain Higgs to BSM branching ratio, for example to dark matter

→ Higgs coupling to mass: general portal to new physics above TeV scale

→ Higgs to invisible: limit on BR at 11% leaves lots of room for BSM decays (0.1% in SM)
## How To Look For New Physics?

~TeV scale exclusions across many final states?

### ATLAS SUSY Searches

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\ell\ell$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow q\bar{q}t\bar{t}$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>mono-jet</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tilde{b}_R \rightarrow q\bar{q}b$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2 jets</td>
<td>-</td>
<td>1.15</td>
</tr>
<tr>
<td>$\tilde{b}_L \rightarrow q\bar{q}b$</td>
<td>1, 2 jets</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow q\bar{q}t\bar{t}$</td>
<td>2, 4 jets</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>$\tilde{t}_R \rightarrow q\bar{q}t\bar{t}$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>1 jet</td>
<td>-</td>
<td>0.85</td>
</tr>
<tr>
<td>$\tilde{t}_L \rightarrow q\bar{q}t\bar{t}$</td>
<td>1, 2 jets</td>
<td>-</td>
<td>1.75</td>
</tr>
<tr>
<td>$\tilde{t}_R \rightarrow q\bar{q}t\bar{t}$</td>
<td>1 jet</td>
<td>-</td>
<td>0.85</td>
</tr>
</tbody>
</table>

### ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV} \)

### EW direct

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\ell\ell$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow WW$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$h \rightarrow ZZ$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>$h \rightarrow Z\gamma$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$h \rightarrow Z\gamma$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$h \rightarrow ZZ$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Long-lived particles

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\ell\ell$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable ( j )-R-hadron</td>
<td>Multiple</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Inflaton</td>
<td>Multiple</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### R-parity

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\ell\ell$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{f}_L \rightarrow f\bar{f}$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>$\tilde{f}_R \rightarrow f\bar{f}$</td>
<td>0, 2 jets</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

**Mass scale [TeV]**

---

15 November 2022

J. Gonski
How To Look For New Physics?

~TeV scale exclusions across many final states?

Two important things missing at first glance:

1. The majority of these exclusions are for prompt BSM particles
2. 95% CL exclusions are highly model dependent

These are blind spots!

Mass scale [TeV]
Search Topics for Today

→ Focus on uncovered/challenging signatures that use Higgs boson

1. **Long lived particles (LLPs)**: displaced + delayed photons

2. **Heavy resonances**: boosted jet final states

3. Anything that is different/unexpected: anomaly detection
Outline

• Introduction to high energy collider physics

1. The ATLAS Experiment & the HL-LHC upgrade
   - LAr calorimeter readout electronics

2. Analysis innovation for new physics searches
   - Long-lived particles
   - Anomaly detection

3. Future outlook & experiments
Status of the Large Hadron Collider

• 27 km synchrotron at CERN colliding protons at $\sqrt{s} = 13$ TeV
• High Luminosity LHC (HL-LHC) in ~2029: up to 200 simultaneous pp collisions to give better handle on very rare new physics processes
• ATLAS Detectors: many subsystems that must be upgraded for high lumi
ATLAS LAr Calorimeter

- Sampling calorimeter with accordion geometry of active (LAr) and absorber (lead) and three layers in barrel
- Readout electronics system samples calo cells at LHC frequency of 40 MHz and sends a digitized pulse off the detector

➡ HL-LHC Upgrade: completely new readout to ensure fast and rad-hard electronics
  - Read out *entire LAr calorimeter* with full granularity & precision: data volume = 16 bits x 2 gains x 128 chans x 40 MHz x 1524 boards = **250 Tb/s!**
HL-LHC LAr Front End Readout

- Columbia responsible for the custom analog-digital converter (ADC) ASIC in the readout chain and the integration of all custom chips (on-detector Front-End Board 2)
  - ✓ High dynamic range (16 bits): cover full energy range expected in a single cell (~50 MeV electronic noise to ~3 TeV from heavy Z$'$→ee)
  - ✓ Two gain scales: mitigate effects of systematic due to gain intercalibration (H→γγ)
  - ✓ Per-mille linearity at EWK scale
  - ✓ Rad-hard to full 10 years of HL-LHC/4000 fb$^{-1}$ dose: TID (12.9 x 10$^2$ Gy), NIEL (4.3 x 10$^{13}$ n$_{eq}$/cm$^2$), SEE (10.5 x 10$^{12}$ h/cm$^2$)
ADC Characterization

- COLUTA ADC ASIC: full custom 40 MSPS in 65nm CMOS with 8 channels
  - > 14 bit dynamic range with > 11 bit ENOB
  - Radiation tolerance: irradiate chip & measure SEUs, TID, NIEL (full HL-LHC dose in ~few hours)

→ Takeaways: custom ASICs are key for unique HEP DAQ needs
- Final Design Review in October to start pre-production (need 80k chips total produced & tested)
Slice Testboard

- **Slice Testboard** = pre-prototype of FEB2 (32 of 128 channels)
- Characterize performance of 3 custom ASICs in full readout chain (PA/S, ADC, lpGBT)
- For large pulses, energy resolution < 0.02% (cf. spec 0.25%), timing resolution ~50 ps (dominated by system jitter)

⇒ Takeaways: front end design is as crucial to experimental success as detector itself
  - Preliminary Design Review in December: full 128-channel FEB2 prototype + system tests
Outline

• Introduction to high energy collider physics

1. The ATLAS Experiment & the HL-LHC upgrade
   - LAr calorimeter readout electronics

2. Analysis innovation for new physics searches
   - Long-lived particles
   - Anomaly detection

3. Future outlook & experiments
I. Long-Lived Particles

- **Well-motivated searches**: particles in the SM have a range of lifetimes, so why not BSM?
- But challenging: often fail standard reconstruction criteria
  - Create displaced objects (eg. far from beam line) or out-of-time signals

▶ **Tactic: carefully understand detector signals & exploit them in custom ways**
- Example: Higgs production of delayed and non-pointing photons (NPPs) detected with LAr calorimeter

1. [2209.01029, prep. for submission to PRD]
2. [ATLAS-CONF-2022-051, prep. for submission to PRD]
LLP Decays in the LAr Calorimeter

- **Timing**: ATLAS LAr calorimeter provides timing measurement from ECAL cells with ~200 ps resolution (dominated by beamspread)
  - Photons from the decay of an LLP will be *late* with respect to the bunch crossing time
- **Spatial**: LAr calo segmented into multiple layers, which allow us to get photon’s direction of flight
  - **New**! For sensitivity to displaced di-e/γ vertices, combine directional info of 2 paths to localize vertex position in 2D ($V_r$, $V_z$)

---

**Di-e/γ Vertex Displacement**

---

---

---
Delayed Photon ATLAS Searches

• Delayed and non-pointing photons (NPPs) are a common signature in many BSM models (eg. exotic Higgs decays, GMSB SUSY)

• Exploited & calibrated sensitive LAr info for full Run 2 sensitive to single & vertexed NPPs
  1. Constrained Higgs→BSM branching ratio down to 1%
  2. Excluded phase space for ~100 GeV neutral particles & τ in 0.1-1000 ns range

→ Takeaway: LLP to e/γ tools validated & primed for use in future searches (eg. Run 3 displaced leptons with large-radius tracking)

![Diagram of Standard ID track and LRT track formed from unassociated hits](Image)
II. Heavy Resonance Searches

- Generic need for new physics at TeV-scale + high mass limits from Run 2 searches
- Heavy A gives momentum to B and C: decay products overlap in detector, so reconstruct each daughter as *single large-radius jet with N-prong substructure*
- General signatures: we cannot rely on having a full analysis for every possible topology

Tactic: model-independent tagging of anomalous jets

J. Collins, K. Howe, BPN
PRL 121 (2018) 241803
J. Collins, K. Howe, BPN
PRD 99 (2019) 014038

Columbia University
IN THE CITY OF NEW YORK

J. Gonski
Intro to Anomaly Detection

- **Anomaly detection (AD)** = identify features of the data that are inconsistent with a background-only model

- **Strategy**: train an ML architecture to reconstruct its input
  - Unsupervised: train over unlabeled events (data)
  - Rarer events with unusual features will be poorly reconstructed → reconstruction accuracy is a good discriminant
Autoencoders for Anomalous Jet Tagging

- Unsupervised training over jets in data modeled as sequence of kt-ordered constituent 4-vectors: no signal model!
Autoencoders for Anomalous Jet Tagging

- Unsupervised training over jets in data modeled as sequence of kt-ordered constituent 4-vectors: no signal model!
- Variational recurrent neural net: variational autoencoder embedded in recurrent architecture
  - *Encodes* variable-length, sequential input in lower-dimensional latent space, *decodes* from latent space, and checks reconstruction error
  - Define anomaly score per jet as a function of VRNN loss
Anomaly Detection in ATLAS $Y \rightarrow XH$ Search

- Search for heavy new resonance $Y$ (~1 TeV) decaying to an SM Higgs boson ($\rightarrow b\bar{b}$) and a new particle $X$ (~100s GeV) that decays hadronically.

![Feynman Diagram of the target signal process](image)
Anomaly Detection in ATLAS $Y \rightarrow XH$ Search

- Search for heavy new resonance $Y$ ($\sim 1$ TeV) decaying to an SM Higgs boson ($\rightarrow b\bar{b}$) and a new particle $X$ ($\sim 100$ GeV) that decays hadronically.

- Machine learning highlights:
  - Unsupervised machine learning via a variational recurrent neural network used to produce a per-jet anomaly score after training on Run 2 dataset.
  - Neural net-based tagging of boosted $H \rightarrow b\bar{b}$ topology.
  - DNN-based reweighting procedure for data-driven background estimation.

**Resonant mass (bump hunt)**

**Neural Net-based Boosted Higgs Tagging**

**Anomaly Score**
Anomalous X Tagging

- In Y→XH resonance search, train over full Run 2 dataset of large-R jets and use AS selection on new particle X decay for substructure-general SR definition
  - Test model-independence by studying AS discrimination performance on 4 jet topologies: 2-prong, 3-prong, heavy flavor (displaced vertices), and dark jets (pattern of missing and visible energy)

AR is competitive with supervised tagging (eg. D2) on 2-prong signals & better sensitivity for alternative signals
Neural Net H→b¯b Tagging

• Neural net-based double b-tag algorithm to select Higgs vs. dijet or top backgrounds [ATL-PHYS-PUB-2020-019]
  - Train over large-R jet p_T/|η| and up to 3 subjet b-tagging scores
  - Outputs: three class probabilities → discriminant D_{Hbb}

  ➤ Tag Higgs boson using 60% WP and f_{top}=0.25 as per central FTag recommendation

\[ D_{Xbb} = \ln \frac{p_H}{f_{top} \cdot p_t + (1 - f_{top}) \cdot p_{QCD}} \]
Analysis Flow

1. **Large-R jet trigger**: \( J_1(p_T) > 500 \text{ GeV} \) and \( m_{JJ} > 1.3 \text{ TeV} \)

2. **Ambiguity resolution**: jet with highest \( D_{Hbb} \) score is Higgs candidate

3. **X-tagging**: AS of X candidate > 0.5 (plus 2-prong regions)

4. **Higgs tagging**: \( D_{Hbb} \) of H candidate > 2.44

- **SR selection**: \( 75 < m_H < 145 \text{ GeV} \)
- **Background estimation**: DNN-derived reweights for untagged high sideband (HSB0 \( \rightarrow \) HSB1)
- **Validation**: low sideband (LSB)
Y→XH Results

• Fit invariant mass of X and H for excesses in overlapping windows of m_X
• Results: no significant deviations in anomaly region across m_X bins
  - Interpret in nominal X→qq, sensitive up to 6 TeV resonance mass

→ First application of fully unsupervised machine learning to an ATLAS analysis
→ Takeaway: anomaly detection analyses are the future!

Y→XH→qqbb Cross Section Limit

= previous 36 fb-1 coverage
Outline

• Introduction to high energy collider physics

1. The ATLAS Experiment & the HL-LHC upgrade
   - LAr calorimeter readout electronics

2. Analysis innovation for new physics searches
   - Long-lived particles
   - Anomaly detection

3. Future outlook & experiments
The LHC Timeline

2022: Snowmass Community Planning Process

2026: Upgrade for High Lumi LHC

2029: HL-LHC Data Taking

→ As of now, we've only recorded ~5% of anticipated total lumi!

Exciting & thorough physics plan for the coming runs

15 November 2022

J. Gonski

34
Beyond the LHC & Snowmass 2022

- **Snowmass**: decadal US HEP community planning process to discuss long term physics goals & inform next international experimental plan
  - Current DPF Executive Committee Early Career member & leader of Snowmass Early Career
  - Community summer study held in July 2022 at University of Washington, Seattle
Personal Snowmass Highlights

[2108.13451, 2204.00098]

- **Future of anomaly detection**: apply CWoLa weakly supervised method with high- and variable-dimensional inputs to radiative return e+e- events
  
  - **Future of calorimeter readout**: develop & deploy novel ML/AD algorithms on-chip
    
    - Fast ML for compression, classification, reconstruction in LHC readout

The concept:

**ROC: X=700 GeV vs. bkg**

- Feynman diagrams of the background (a) and signal (b) processes considered.

**Simulated Samples & Processing**

We consider e+e- collisions at a nominal centre-of-mass (CoM) energy of 1 TeV that produce final states with jets and a photon from initial-state-radiation (ISR). The signal process studied is the production of a BSM heavy scalar \( X \) that decays into a pair of scalars \( a \), each decaying to two \( b \)-quarks, in association with an ISR photon:

\[
e^+e^+ \rightarrow X \rightarrow aa \rightarrow b\bar{b}b\bar{b}
\]

Two sets of values of the invariant masses of particles \( X \) and \( a \) are examined:

- \( m_X, m_a = 350, 40 \) GeV
- \( 700, 100 \) GeV

The background originates from di-jet production in association with an ISR photon, with a cross-section that is dominated by the Drell-Yan \( \gamma^* \) production and extends to close to the nominal 1 TeV CoM. Feynman diagrams of the signal and background processes are shown in Figure 1.

The generation of background and signal events is done by MadGraph5_aMC@NLO \( X.X.X \) [4] with parton showering and hadronization performed by Pythia8 [5]. A minimum \( E_T \) threshold of 10 GeV is placed on the photon, with a pseudo-rapidity that extends to \( \pm 5 \).

The detector simulation is parameterized with Delphes \( X.X.X \), using a card for a generic ILC detector \([\] \). A particle flow algorithm is used to combine tracking and calorimeter information and define the final reconstructed objects. Photons are built from energy deposits in the electromagnetic calorimeter that are not matched to any track, using the central and forward calorimeter systems with pseudo-rapidity coverages of \( |\eta| < 3.0 \) and \( 3.0 < |\eta| < 4.0 \), respectively. Jets are built from particle flow objects (except isolated muons, electrons and photons) measured in the tracker (with an acceptance of up to \( |\eta| < 3.0 \), electromagnetic and hadronic calorimeters (central system up to 2.8 and forward system up to 3.8 in absolute pseudo-rapidity). The jet clustering is performed with the anti-\( k_t \) \[6] algorithm with a radius \( R=1.0 \) implemented in FastJet \[7].

Events are selected for analysis if they contain at least two jets with a minimum \( p_T \) of \( X \) GeV. An effective CoM energy can be calculated for all events based on the effective CoM energy \( \hat{p}_s \) is shown in Figure 2 for all generated samples, calculated with truth-level quantities. Distributions of the photon transverse energy and pseudo-rapidity are shown on Figure 4 for the background and signal processes considered.

The unpolarized cross-section for the background process is of the order of 1 pb, corresponding to approximately \( X \) events above the \( Z \) peak. This amount of statistics would

---

**CMS HGCal data compression**

<table>
<thead>
<tr>
<th>Trigger path stage</th>
<th>Number channels</th>
<th>bits/channel</th>
<th>Average Compression factor</th>
<th>Data rate*</th>
<th># links* (10.24 Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw data</td>
<td>6M</td>
<td>20</td>
<td>1</td>
<td>5 Pb/s</td>
<td>1M</td>
</tr>
<tr>
<td>Hardware reduction</td>
<td>1M</td>
<td>7</td>
<td>1</td>
<td>300 Tb/s</td>
<td>60k</td>
</tr>
<tr>
<td>Threshold selection</td>
<td>1M</td>
<td>7</td>
<td>3</td>
<td>40 Tb/s</td>
<td>9k</td>
</tr>
</tbody>
</table>

---

**The task:**

**The concept:**

[2108.13451, 2204.00098]

https://arxiv.org/abs/2105.01683

N. Tran \[2108.13451, 2204.00098\]
Conclusions

• The LHC provides an excellent handle for the pursuit of BSM/precision particle physics
  - Run 3 underway: focus on novel long-lived particle triggers & reconstruction
  - Higher lumi datasets also bode well for training of innovative ML methods & anomaly detection
  - ATLAS upgrade for the HL-LHC is well underway, and even more physics to be done with 3000 fb\(^{-1}\)

• International collider research provides unique reach towards BSM prospects
  - Long-term planning for future experimental program must start now

Prospects for discovery of physics beyond the SM remain bright!
Backup
HL-LHC Upgrade: Physics

• Key physics drivers motivate precision reconstruction of electron/photon energy & time

1. High expected dynamic range (eg. massive \(Z'\rightarrow ee\) with high E electrons)
2. Precise mass resolution for measurements of key SM processes (eg. di-Higgs: small, narrow \(m_{\gamma\gamma}\) peak on top of large irreducible background)
3. Ensure that photons from \(H\rightarrow \gamma\gamma\) are mostly digitized on high gain and minimize gain intercalibration systematic → new 2 gain scheme

<table>
<thead>
<tr>
<th>Resolutions [GeV]</th>
<th>ggF</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pessimistic</td>
<td>2.64</td>
<td>2.06</td>
</tr>
<tr>
<td>Optimistic</td>
<td>1.99</td>
<td>1.62</td>
</tr>
</tbody>
</table>

\(Z'\rightarrow ee\) Invariant Mass

\(Z'(5\text{ TeV})\rightarrow ee, \sqrt{s} = 14\text{ TeV}, 3000\text{ fb}^{-1}, <\mu> = 200\)

**ATLAS** Simulation

**Di-Higgs Signal** \(m_{\gamma\gamma}\)

\(ATLAS\) Simulation

Baseline \(\sqrt{s} = 14\text{ TeV}, 3000\text{ fb}^{-1}\)

\(\text{Stat. Unc.} \quad \text{HH}\rightarrow bb\gamma\gamma\)
HL-LHC Upgrade: Triggering

- New trigger/DAQ requirements: rate will be increased 10x to 1 MHz, latency 5-10x to 10 µs
- Motivates a new LAr readout architecture → free-running all digital design with no on-detector pipeline
  - Already installed (“Phase-I”): Super Cells to provide finer granularity to trigger
- For HL-LHC: Read out entire LAr calorimeter with full precision at 40 MHz LHC bunch crossing frequency
  - Data rate = 40 MHz x 16 bits x 2 gains x 128 chans x 1524 boards = \(~350\) Tbps
  - Results in lower trigger turn-on curves
  - Maintain ability to trigger on low-\(p_T\) objects

\[\text{HL-LHC } E_{\text{T} \text{miss}} \text{ Trigger Turn On}\]

\[\text{HL-LHC Simulation \ for } ZH \rightarrow \nu \nu\]

\[\text{HL-LHC, } <\mu> = 200\]

\[\text{Phase 1 Super Cells}\]

\[\text{Run 2 Offline Algorithm}\]

[ATLAS-TDR-027]
HL-LHC Readout

- **Phase-I:** installed 2019-2022 & commissioning now!

**HL-LHC:**

- Cover full energy range expected in a single cell (~50 MeV electronic noise to ~3 TeV)
- 16-bit DR with 11-bit precision (implemented in 2 overlapping 14-bit gain scales)
- Nonlinearity < 0.1% up to ~300 GeV
- Electronics noise < minimum ionizing particle (MIP) energy / intrinsic LAr resolution
- Radiation tolerance: full HL-LHC dose, eg. max TID 1400 Gy (1.5), NIEL < $4.1 \times 10^{13}$ n$_{eq}$/cm$^2$ (2)

<table>
<thead>
<tr>
<th>TID [Gy]</th>
<th>NIEL [n$_{eq}$/cm$^2$]</th>
<th>SEE [b$&gt;20$ MeV/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEC (barrel)</td>
<td>1400 (1.5)</td>
<td>$4.1 \times 10^{13}$ (2)</td>
</tr>
<tr>
<td>FEC (endcap)</td>
<td>210 (1.5)</td>
<td>$6.0 \times 10^{12}$ (2)</td>
</tr>
<tr>
<td>LVPS between TileCal fingers (barrel)</td>
<td>430 (1.5)</td>
<td>$1.1 \times 10^{12}$ (2)</td>
</tr>
<tr>
<td>HEC and FEC LVPS (endcap)</td>
<td>81 (1.5)</td>
<td>$2.0 \times 10^{11}$ (2)</td>
</tr>
<tr>
<td>LVPS new position (barrel)</td>
<td>18 (1.5)</td>
<td>$5.1 \times 10^{10}$ (2)</td>
</tr>
<tr>
<td>LVPS new position (endcap)</td>
<td>33 (1.5)</td>
<td>$5.2 \times 10^{10}$ (2)</td>
</tr>
</tbody>
</table>
LAr Pulse Analysis

AWG sends a pulse train of known amplitude to ADC chip, sampled at different phases

Pulse train is interleaved to reconstruct fine pulse for each amp. Check that maxima and zero point match across amplitudes

Samples from one phase (containing peak) and derivatives are used to calculate OFCs, then used to find energy and timing of each pulse

Optimal Filtering Coefficients

\[ A = \sum_{i} a_i S_i, \]

\[ \tau = \frac{1}{A} \sum_{i} b_i S_i \]
Offline LAr Timing Calibration

• Times are calibrated offline via a series of passes to synchronize cells and improve resolutions for analysis use
  - Uses electrons from Wev data to calibrate, Zee data to validate
  - Studies have shown (as expected from MC) that electrons and photons behave similarly for timing purposes

• Corrections obtained per gain and per IOV (interval of validity for OFCs) for cells
  • ~10 channels (of ~46K) per year are flagged as “bad” for time variations within an IOV

• Calibration achieved via a series of passes to empirically remove averaged/fitted variations
  ‣ Pass 0: time-of-flight (TOF) from PV to cell
  ‣ Pass 1: average time per FEB
  ‣ Pass 2: average time per channel
  ‣ Pass 3: energy-dependence (by slot)
  ‣ Pass 4: middle-layer cross-talk (by slot, based on δη, δφ)
  ‣ Pass 5: inter-layer cross-talk (by slot, based on f₁, f₃)
  ‣ Pass 6: average time per channel (pass 2 repeated)
    • Added because patterns re-emerged after applying other passes (passes are actually subtly correlated with each other)
LLPs in LAr: Timing

- Calculated from calorimeter samples using LAr optimal filtering coefficients (OFCs)
  - Determined by middle layer maximum energy deposit (\(\text{maxE}_{\text{cell}}\))
  - Online \(\sim 1\) ns resolution, calibrate offline with \(W \rightarrow \text{ev/Z}\rightarrow \text{ee}\) to reach \(\sim 200\) ps (dominated by beamspread)

- Photons from the decay of an LLP will be \textit{late} with respect to the bunch crossing time: timing is highly discriminating for LLPs with lifetimes \(O(\text{ns})\)

### Timing Resolution vs. E

**ATLAS Internal**

\[
\int L = 26.1 \text{ fb}^{-1}, \int \mathcal{L} = 13 \text{ TeV}
\]

\[
\sigma(t) = \frac{\rho_0}{E} + \rho_1
\]

### Timing in SUSY LLP Signals

**ATLAS Preliminary**

\(f_S = 13 \text{ TeV}, 139 \text{ fb}^{-1}\)

- Data, CR Template
- \(\tilde{\chi}_1^0(135 \text{ GeV, 2 ns}) \rightarrow H\tilde{\chi}_1^0\)
- \(\tilde{\chi}_1^0(135 \text{ GeV, 2 ns}) \rightarrow Z\tilde{\chi}_1^0\)
- \(\tilde{\chi}_1^0(135 \text{ GeV, 10 ns}) \rightarrow H\tilde{\chi}_1^0\)
- \(\tilde{\chi}_1^0(135 \text{ GeV, 10 ns}) \rightarrow Z\tilde{\chi}_1^0\)
- \(\tilde{\chi}_1^0(325 \text{ GeV, 2 ns}) \rightarrow H\tilde{\chi}_1^0\)
- \(\tilde{\chi}_1^0(325 \text{ GeV, 2 ns}) \rightarrow Z\tilde{\chi}_1^0\)

15 November 2022
Displaced Diphoton Vertices

\[ m_{\gamma\gamma} \text{[GeV]} \]

**CR**
- \( E_{T}^{\text{miss}} < 20 \text{ GeV} \)
- \( m_{\gamma\gamma} > 135 \text{ GeV} \)

**VR(\( E_{T}^{\text{miss}} \)) t < 0**
- \( 20 < E_{T}^{\text{miss}} < 30 \text{ GeV} \)
- \( m_{\gamma\gamma} > 135 \text{ GeV} \)

**VR(\( E_{T}^{\text{miss}} \)) t > 0**
- \( E_{T}^{\text{miss}} > 30 \text{ GeV} \)
- \( 60 < m_{\gamma\gamma} < 135 \text{ GeV} \)
- \( p_{T\gamma\gamma} > 70 \text{ GeV} \)
- \( \Delta\phi_{\gamma\gamma} < 2.4 \)
- \( t_{\gamma_1}, t_{\gamma_2} < 0 \)

**SR**
- \( E_{T}^{\text{miss}} > 30 \text{ GeV} \)
- \( 60 < m_{\gamma\gamma} < 135 \text{ GeV} \)
- \( p_{T\gamma\gamma} > 70 \text{ GeV} \)
- \( \Delta\phi_{\gamma\gamma} < 2.4 \)
- \( t_{\gamma_1}, t_{\gamma_2} > 0 \)

**VR(t)**
- \( E_{T}^{\text{miss}} > 30 \text{ GeV} \)
- \( 60 < m_{\gamma\gamma} < 135 \text{ GeV} \)
- \( t_{\gamma_1}, t_{\gamma_2} < 0 \)

*figure QR*

Illustrative definitions of the analysis regions after preselection

- The SR focuses on phase space with high \( E_{T}^{\text{miss}} \) low \( m_{\gamma\gamma} \)
- The CR contains events with low \( E_{T}^{\text{miss}} \) and high \( m_{\gamma\gamma} \)
- Three orthogonal VRs are defined to validate the extrapolation of the background estimation over \( E_{T}^{\text{miss}} \) and the sign of the times of both photons

*figure QS*

Observed and expected YUE CL limits on the cross-section for pair production of long-lived \( \tilde{j} \) particles as a function of \( m_{\tilde{j}} \) and for a \( \tilde{j} \) lifetime equal to \( R \) ns

- Straight lines are drawn between the results for the discrete signal models simulated
- The plot on the left (right) corresponds to the results for the final state under the assumption that \( B(\tilde{j} \rightarrow H + \tilde{\gamma}) = 1 \)

*figure QT*

Columbia University
Run 2 Highlights
- LLPs → e/γ objects
- Displaced (high d_0) leptons: exclude pair-produced slepton decays up to ~500 GeV for ~0.1 ns lifetimes (flavor dependent) using extended tracking out to 30cm

New for Run 3:
- Large radius tracking: additional ID tracking pass run after standard tracking on leftover hits with relaxed tracking cuts
- Displaced lepton triggers: considerable expansion of trigger acceptance d_0 and lower p_T threshold by including LRT

Run 2 Displaced Leptons

<table>
<thead>
<tr>
<th>Topology</th>
<th>Trigger *</th>
</tr>
</thead>
<tbody>
<tr>
<td>if ≥ e, p_T &gt; 160 GeV</td>
<td>HLT_g140_loose</td>
</tr>
<tr>
<td>else if ≥ 2e, p_T &gt; 60 GeV</td>
<td>HLT_2g50_loose</td>
</tr>
<tr>
<td>else if ≥ 1μ, p_T &gt; 60 GeV,</td>
<td>HLT_mu60_0eta105_msonly</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Some History and a Goal

Goal: trigger directly on displaced leptons for Run 3.
Variational Recurrent Neural Network

- **Variational RNN**: recurrent neural network (RNN) that updates a VAE latent space at each time step; accommodates variable-length input sequences.

- Define **anomaly score** per jet as a function of the KL divergence loss term: $AS = 1 - e^{-D_{KL}}$

\[ L(t) = |y(t) - x(t)|^2 + \lambda D_{KL}(z||z_t) \]

**Loss**
- Mean-squared reconstruction error
- Kullback-Leibler Divergence
VRNN in Action

- VRNN for anomalous jet tagging developed in simulation via the LHC Olympics community anomaly detection challenge [2101.08320]

- Achieve sensitivity with resulting jet-level anomaly score to both 2- and 3-particle decays over QCD/multijet

- VRNN paper published using this dataset [2105.09274]

**m_{JJ}, QCD + signal**

**No Selection**

![Graph showing m_{JJ} distributions for QCD and signal events](image)

Cut on VRNN anomaly score
Background Estimation

- Fully data-driven background estimation (~97% multijet processes)
- Derived from data template in high Higgs mass sideband that fails H tagger score, reweighted to shape in H-tagged region
- Build DNN to provide a reweight for each event
  - 3 fully-connected inner layers, 20 neurons each
  - Train inclusively in X-tagging over variables associated to the Higgs large-R jet (4 vector, 4-vectors of leading & subleading track jets associated to Higgs, # tracks)
  - Minimized on log-likelihood ratio of tagged to untagged regions'
- Systematics on DNN training region, statistical power of training sample, LSB non-closure

LSB Validation

![Graphs showing background estimation and validation](image-url)
Y→XH Statistical Analysis

- Fit $m_Y$ across overlapping categories of $m_X$
  - Bins chosen based on signal mass resolution

- Use BumpHunter as signal model-independent “excess finder” \[1101.0390\]
  - No significant (p-val < 0.01) excess across $m_X$ bins in the LSB VR

- No interpretation in anomaly region (no signal systematics)

**Post-fit LSB**

**$m_X$ Windows**
Y→XH Systematic Uncertainties

**Background**

- Determined inclusively in $m_x$, and then applied to each exclusive $m_x$ bin

1. DNN Source Systematic
   - Difference in resulting mJJ distribution due to the choice of training region
   - $O(1-10)\%$ effect across mJJ

2. DNN Bootstrap Systematic
   - Statistical error from neural network performance determined via the bootstrap procedure
   - $O(1)\%$ effect across mJJ

3. Non-Closure Systematic
   - Determined in the LSB as the difference between reweighted LSB0 and LSB1 data, with smoothing
   - Characterizes additional mis-estimation of data in the VR after determining weighting parameters from the HSB
   - Negligible for low mJJ, $O(10)\%$ effect in the tails

**Signal**

- Flat luminosity uncertainty of $1.7\%$ (as measured with LUCID)

- Jet uncertainties implemented with standard variations from jet/$E_T$ CP group
  - Included for both large-R (merged and resolved) and small-R (resolved only) jets
  - Rtrk Baseline, Modeling, Tracking, TotalStat, Closure uncertainties
  - JER Mass and $p_T$ variations

- PDF variation uncertainties
  - ISR/FSR included as flat $3\%$ uncertainty

- XbbSF uncertainties
Y→XH→qqbb Results

- Results for Y→XH→qqbb given as upper limit at 95% CL on production cross section across signal grid
- With respect to previous result:
  - Improved limit in highly boosted regime by ~10x
  - Increased upper resonance mass sensitivity from 4 to 6 TeV
  - Added coverage of unexplored resolved X decay phase space

= previous analysis coverage
VRNN Architecture

- Train directly on data (avoid data/MC discrepancies in QCD)
- Merge sequence modeling nature of RNN with variational inference capability of VAE

\[ L(t) = |y(t) - x(t)|^2 + \lambda D_{KL}(z||z_t) \]

Mean-squared reconstruction error

Kullback-Leibler Divergence

**Input**
(constituent 4-vectors)

**Hidden State** = long-term representation of info over sequence

**Latent Space** (Gaussian)

**Output**
(constituent 4-vectors)

**Feature extracting layers**

\[ h(t) = f(\phi_x, \phi_z, h(t - 1)) \]
VRNN Anomaly Score

- Preprocessing (right)
- Sequence Ordering: decreasing kt distance from hardest constituent
- Training: 16 neurons per intermediate layer, 500 epochs
- Results: sensitive to 2 and 3 prong signals, while less mass correlated than typical high-level substructure variables

Algorithm 1: Jet Boosting

Start
Boost jet in z direction until $\eta_{jet} = 0$
Rotate jet about z axis until $\phi_{jet} = 0$
Rescale jet mass to 0.25GeV
Boost jet along its axis until $E_{jet} = 1$GeV
Rotate jet about x axis until hardest constituent has $\eta_1 = 0$, $\phi_1 > 0$
if Any constituents have $\Delta R > 1$ then
  | Remove all constituents with $\Delta R > 1$
  | Rebuild jet with remaining constituents
  | Repeat from start
else
  continue
end
if Number of constituents > 20 then
  Keep up-to the first 20 constituents, ordered in $p_T$
  Rebuild jet with remaining constituents
  Repeat from start
else
  continue
end
Reflect constituents about $\phi$ axis such that the second hardest constituent has $\eta_2 > 0$

Two Prong Jets

Three Prong Jets
AS Comparison to D2

• Dataset = 2-prong % contaminated
  - Selections: D2 < 1.4 / AS > 0.65 (equivalent background rejection)
  - AS creates less mass sculpting than substructure variables
• In Y→XH→qqbb, cut on D2_{trk} < 1.2 (merged) or > 1.2 (resolved)
Towards Signal Model Independence

- Even restricting to the heavy resonance bump hunt, many signatures to search for!
- We cannot rely on having a full analysis for every possible topology

<table>
<thead>
<tr>
<th>A → BC</th>
<th>B = SM</th>
<th>B = BSM → SM1 × SM1</th>
<th>B = BSM → SM1 × SM2</th>
<th>B = BSM → complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>e μ τ</td>
<td>Z/γ</td>
<td>e μ τ</td>
<td>Z/γ</td>
<td>e μ τ</td>
</tr>
<tr>
<td>q/g b t</td>
<td>Z/γ</td>
<td>q/g b t</td>
<td>Z/γ</td>
<td>q/g b t</td>
</tr>
<tr>
<td>Z/γ</td>
<td>H</td>
<td>Z/γ</td>
<td>H</td>
<td>Z/γ</td>
</tr>
</tbody>
</table>

Group I (Table 1)

Group II (Table 2)

Group III (Table 3)

Group IV (Table 4)

<table>
<thead>
<tr>
<th>A → BC</th>
<th>B = BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → H'</td>
<td></td>
</tr>
<tr>
<td>H'' → H'</td>
<td></td>
</tr>
</tbody>
</table>

Group V (Table 5)

Group VI (Table 6)

Group VII (Table 7)

Group VIII (Table 8)

Group IX (Table 9)

<table>
<thead>
<tr>
<th>A → BC</th>
<th>B = BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>N → jjf, ¯q(→ jjf), or W±/0(→ jjf)</td>
<td></td>
</tr>
<tr>
<td>Q'(→ jjj), H+/(0→ jjj), or ¯q(→ jjj)</td>
<td></td>
</tr>
<tr>
<td>LQ(→ fj), qf(→ fj), or q(→ jj)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A → BC</th>
<th>B = BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>t'</td>
<td>L' → τ'</td>
</tr>
<tr>
<td>j(b, t, q)</td>
<td>W' → τN</td>
</tr>
<tr>
<td>i, t'</td>
<td>LQ → i, qf(→ f)</td>
</tr>
<tr>
<td>L' → qLQ</td>
<td></td>
</tr>
<tr>
<td>V(W, γ, Z)</td>
<td>L' → Wn</td>
</tr>
<tr>
<td>H</td>
<td>N → Hn</td>
</tr>
<tr>
<td>LQ' → H LQ</td>
<td></td>
</tr>
</tbody>
</table>

Group X (Table 10 and 11)

<table>
<thead>
<tr>
<th>A → BC</th>
<th>B = BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ</td>
<td>LQ → τL</td>
</tr>
<tr>
<td>j(b, t, q)</td>
<td>W' → bL</td>
</tr>
<tr>
<td>Z' → τ'</td>
<td></td>
</tr>
<tr>
<td>LQ → jL</td>
<td></td>
</tr>
<tr>
<td>N → τW', N → τH'</td>
<td></td>
</tr>
<tr>
<td>B' → τW', B' → τH'</td>
<td></td>
</tr>
<tr>
<td>X5/3 → Wb', X5/3 → Wb'</td>
<td></td>
</tr>
<tr>
<td>V(W, γ, Z)</td>
<td>B' → Wp</td>
</tr>
<tr>
<td>X5/3 → Wb, X5/3 → Wb</td>
<td></td>
</tr>
<tr>
<td>H' → γW', Z' → Wb'</td>
<td></td>
</tr>
<tr>
<td>H'' → H LQ</td>
<td></td>
</tr>
</tbody>
</table>

J. Kim, K. Kong, B. Nachman, and D. Whiteson, 1907.06659
CWoLa Weakly Supervised Learning

- Classification without labels (CWoLa) [1708.02949]: NN trained in signal region vs. sideband is sensitive to signal vs. background characteristics
  - SR and SB defined in windows of m JJ, each region has different fraction of signal
  - NN input training features = two leading jet masses
- First application of weakly supervised learning from ATLAS! [PRL 125 131801]
- Outperforms inclusive search at high mass hypotheses

Features for training CWoLa classifier

1708.02949, 1805.02664
CWoLa in $e^+e^-$ Collisions

- **Radiative return**: “scan” new particle masses with ISR photons, à la dijet invariant mass bump hunts
- Apply CWoLa method with *high- and variable-dimensional inputs* with **Particle Flow Networks**: model an event as an unordered, variable-length set of jets
  - Up to 15 jets per event & 10 features per jet: 4 vector ($p_T$, $\eta$, $\phi$, $m$), b-tagging bit, 5 N-subjettiness variables
  - 150 input features per event

---

**Figure 1**: Feynman diagrams of the background (a) and signal (b) processes considered.

**Figure 2**: The effective CoM energy $p_\text{\hat{s}}$ is shown for all generated samples, calculated with truth-level quantities.

**Figure 4**: Distributions of the photon transverse energy and pseudo-rapidity are shown for the background and signal processes considered.

---

**e$^+$$e^-$ $\sqrt{s} = 1$ TeV**

- $350$ GeV $X$ $\sim 650$ GeV $\gamma$
- $700$ GeV $X$ $\sim 300$ GeV $\gamma$

[arXiv:2108.13451]
CWoLa in $e^+e^-$ Collisions

- Select signal and background in $\pm 25$ GeV windows in $\sqrt{s}$ around the resonance mass (SR = [675, 725]) with sideband in $\pm 50$ GeV windows on either side (SB = [625,675) U [725,775])
- Train with a variety of signal contaminations: $\sigma=0.0, 0.5, 1.0, 2.0, 3.0, 5.0,$ and $\infty$ (eg. all S vs. all B)
- Significance Improvement Characteristic (SIC): sensitivity proxy that gives multiplicative factor by which the NN can improve signal significance
  - Enhance sensitivity to signal contaminations down to 0.3% by a factor of ~3

[arXiv:2108.13451]