Highlights from Long-Lived Particle Searches at ATLAS

Julia Gonski

Moriond QCD
23 March 2022
ATLAS Search Program

- Supersymmetry
- Multiple Higgses
- Heavy Resonances
- Flavor Anomalies
- Hidden Sector
- Dark Matter
ATLAS Search Program

- **Supersymmetry**
- **Multiple Higgses**
- **Heavy Resonances**
- **Flavor Anomalies**
- **Hidden Sector**
- **Dark Matter**

**Long-Lived Particles (LLPs)**
- Lifetime from nearly degenerate mass spectra or small couplings
- Existing exclusions often invalid/considerably weaker for non-prompt particles
- Rely on custom use of detector info
Analyses Covered Today

**LLP Signature Subsystem**

**Inner Detector:**
1. Displaced Heavy Neutral Leptons
2. Pixel dE/dx

**Calorimeters:**
3. Non-pointing & delayed photons
4. Hidden Sector displaced jets

**Muon spectrometer:**
5. Dark photons (plus cal)

\( c \tau \sim 1 \text{m} \)
\( c \tau \sim 4 \text{m} \)
\( c \tau \sim 11 \text{m} \)
Analyses Covered Today

**LLP Signature Subsystem**

![New for Moriond/La Thuile](image)

**Inner Detector:**
1. Displaced Heavy Neutral Leptons
2. Pixel dE/dx

**Calorimeters:**
3. Non-pointing & delayed photons
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$c_\tau \approx 1m$
$c_\tau \approx 4m$
$c_\tau \approx 11m$
Displaced Heavy Neutral Leptons

**Signature**: prompt lepton + opposite sign dilepton displaced vertex from decay of light long-lived HNL
- **Sensitivity**: $m = O(3-20)$ GeV, $c\tau \sim 1-100$ mm
- Interpret in weak-like dimensionless mixing angles ($|U_\alpha|^2$)

**Strategy**: novel reconstruction of HNL mass using energy-momentum conservation
- Separate channels by lepton flavor ($e/\mu$)
- Large radius tracking for sensitivity to displaced leptons
- Background dominated by random track crossings; data-driven estimate with toys

**Diagram**
- Standard ID track
- LRT track formed from unassociated hits

**Formula**
$$m_{HNL}^2 = (P_{l_\beta} + P_{l_\gamma} + P_{\nu_\gamma})^2$$

**Figure**
- ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- $\mu$-e, $c\tau = 10$ mm
- SR:CR

**Background**
- Data
- HNL (5 GeV)
- HNL (10 GeV)
- HNL (15 GeV)
dHNL Result

- Interpret in both Dirac-like (lepton number conserving) Majorana-like (add lepton number violating)
- New & improved limits on single-flavor (1SFH) $|U_{\mu}|^2$
- First ATLAS limits on 1SFH $|U_{e}|^2$
- First two quasi-degenerate HNL (2QDH) multi-flavor mixing scenarios motivated by neutrino-flavor oscillations (normal & inverted hierarchy)

![Graphs showing experimental and expected limits for different scenarios](attachment:image.png)
**Pixel dE/dx**

- **Signature:** anomalously high dE/dx due to heavy non-relativistic particle in ID
  - *Sensitivity:* aim for model independence; charged, m = O(100s-1000s) GeV, τ ~ 0.1-100 ns

- **Strategy:** parameterize Bethe-Bloch to turn dE/dx measurement into mass
  - dE/dx_{trunc}: remove highest energy clusters (mitigate effect of Landau tail)
  - Calibrate dE/dx-βγ relation with SM particles in low pileup runs
  \[ m_{dE/dx} \equiv \frac{p_{\text{reco}}}{\beta \gamma (\langle dE/dx \rangle_{\text{corr}})} \]

- **dE/dx-βγ Calibration**

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Pixel dE/dx Analysis Strategy

- **SR = \( E^{\text{miss \ trigger}} > 170 \text{ GeV} \) + central (\(|\eta| < 1.8\)) isolated tracks with high pT (> 120 GeV) and large specific ionization (dE/dx > 1.8)
  - Two inclusive SRs for discovery, in bins of dE/dx
  - Six exclusion SRs, in bins of dE/dx, matching to a muon, or IBL overflow hits
- Fully data-driven background estimation using toys from orthogonal track mass templates (CR-kin, CR-dEdx)
- Validated in low track pT ([50, 110] GeV) and high track \( \eta \) ([1.8, 2.5])

Select a \( (1/pt, \eta) \)

Select a dE/dx value according to \( \eta \)

Calculate mass = \( p/\beta \gamma \)
**Pixel dE/dx Result**

- **Excess (3.6σ local, 3.3σ global)** in high dE/dx SR (> 2.4) with for target mass hypothesis of 1.4 TeV
  - Cross check of candidate tracks with TileCal and MS time-of-flight variables was consistent with β = 1, therefore **not consistent with LLP hypothesis**

- Set limits on gluino, chargino, stau hypotheses
  - Max sensitivity for τ ∼ 10-30 ns
  - Gluino R-hadrons with mass < 2.27 TeV excluded with τ = 20 ns and LSP mass = 100 GeV
Non-Pointing/Delayed Photons

- **Signature:** photons from the decay of a heavy LLP that are late w.r.t bunch crossing and non-pointing (NPPs)
  - Sensitivity: \( m = 30-60 \text{ GeV}, \tau \sim 0.25-100 \text{ ns} \)
  - Interpret as Higgs to BSM signal with GMSB decay

- **Strategy:** precise LAr calorimeter pointing and timing
  - Signal region = high \( E_{T}^{\text{miss}} \), high timing, high pointing, optimized separately for low- and high- (NLSP, LSP) mass splitting kinematics
  - Fully data-driven background estimate due to non-Gaussian tails of sensitive variables, from real photon- and fake photon-enriched templates

LAr Calo Pointing \((z_{\gamma})\)

LAr Calo Timing \(t_{\gamma}\)

23 March 2022
NPP Result

- Simultaneously fit photon timing data templates across 5 categories of photon pointing, separately for low- and high-mass splitting regions

**Result:** set exclusions on Higgs $\rightarrow$ 2 NLSP BR
- As low as 1% for $\tau \sim 1$ ns and high (NLSP,LSP) mass splittings of $\sim 40$ GeV

- First full Run 2 sensitivity to this signature (no CMS analogy)
Hidden Sector Displaced Jets

• Signature: displaced jets from exotic scalar to LLP
  - Sensitivity: \( m = O(100\text{s}-1000) \) GeV, \( c\tau \sim 2 \text{ cm} - 1 \text{ m} \)

• Strategy: select “CalRatio” jets with anomalously low ratio of ECAL to HCAL energy (also narrow & trackless)
  - Backgrounds: cosmics, beam-induced background (BIB), QCD
  - Jet-level NN to distinguish BIB, using low-level inputs + adversarial NN to remove mismodeling from simulation
  - Event-level BDT trained on jet NN output + other event vars

• Result:
  - Limits for mediator masses between [60 GeV, 1 TeV] and LL scalar masses between [5, 475] GeV
  - Constrain also SM Higgs BR < 10% for proper decay lengths between [2, 10] cm
Dark Photon (Lepton Jets)

• **Signature:** displaced collimated SM fermions from decay of light neutral LLP (dark photon)
  - *Sensitivity:* $m = O(\text{MeV-GeV})$, $c\tau \sim 10-250$ mm
  - Target dark photons with small kinematic mixing to SM in decay of ggF or associated W Higgs

• **Strategy:** separate channels by dark photon jet (DPJ) flavor
  - *Muonic DPJs:*
    - reco by CA-clustering MS only tracks
    - Deep NN to distinguish from cosmic ray background using impact parameter/timing/angular info
  - *Calorimeter DPJs*
    - select low EM fraction jets
    - Distinguish from QCD & BIB background with convolutional NN event level tagger trained over $(\eta,\Phi)$ map
  - Data-driven background estimate with ABCD method (QCD tagger score, $\Delta\Phi$ DPJs)

• **Result:**
  - First ATLAS exclusion for electron channels
  - First ATLAS exclusion for $m_{\gamma_d} < 0.1$ GeV
  - Higgs BR to $\gamma_d$ down to 0.1% (~SM value)
Summary & Conclusions
Hidden Sector

Displaced CalRatio Jets

ATLAS Preliminary (March 2022) 13 TeV, 36-139 fb⁻¹

Hidden Sector, mₜ = 125 GeV
Selected ATLAS results
95% CL observed limits

Searches:
- Muon System (2 Vtx Only), 139 fb⁻¹
- Muon System (1 Vtx + 2 Vtx), 36 fb⁻¹
- Calorimeter, 139 fb⁻¹
- Tracker-Muon System, 36 fb⁻¹
- Tracker (LRT), 139 fb⁻¹
  JHEP 11 (2021) 229
  - Tracker (b-tag), 36 fb⁻¹
  JHEP 10 (2018) 031
  - Monojet, 139 fb⁻¹
  ATL-PHYS-PUB-2021-020
  - H→inv, 7-8-13 TeV combination
  ATLAS-CONF-2020-052

LLP masses:
- 5-8 GeV
- 15-20 GeV
- 25-35 GeV
- 40 GeV
- 45-60 GeV
- Any

ATLAS Preliminary (March 2022) 13 TeV, 11-139 fb⁻¹

Hidden Sector, mₜ = 125 GeV
B(H→ss) = 10%
95% CL observed limits

Searches:
- Muon System (2 Vtx Only), 139 fb⁻¹
- Muon System (1 Vtx + 2 Vtx), 36 fb⁻¹
- Calorimeter, 139 fb⁻¹
- Calorimeter, 11 fb⁻¹
- Tracker-Muon System, 36 fb⁻¹
- Tracker (LRT), 139 fb⁻¹
  JHEP 11 (2021) 229
Supersymmetry

**Pixel dE/dx**

- **Gluino**
  - RPC OL 2-6 jets arXiv:1712.02332 (Fσ=13 TeV, 36 fb⁻¹)
  - ATLAS Preliminary
  - Disappearing track arXiv:1710.04301 (Fσ=13 TeV, 33 fb⁻¹)
  - Pixel dE/dx CERN-EP-2022-029 (Fσ=13 TeV, 139 fb⁻¹)
  - Stable charged arXiv:1902.01636 (Fσ=13 TeV, 36 fb⁻¹)
  - Stopped gluino arXiv:2104.03050 (Fσ=13 TeV, 103 fb⁻¹)

- **Chargino**
  - 136 fb⁻¹, Fσ=13 TeV
  - ATLAS Preliminary
  - Disappearing track arXiv:1902.01636

**Lifetime**

- ATLAS Preliminary
- Expected limits
- Observed limits
- 95% CL limits
- SUSY theory not included
Conclusions

- Many searches I didn’t get to cover: heavy particles (e.g. leptoquarks), prompt (SUSY, Exotics, Higgs & Diboson)
  
  - See latest ATLAS Public Results

- New LLP data-taking features as of 2022: large radius tracking integrated into ATLAS HLT chain & default reco → new displaced lepton triggers
  
  ➡ Run 3 will be exciting for the ATLAS search program!
Backup
HNL Extras

HNL Mass Reconstruction

\[ m_{\text{HNL}}^2 = (P_{l_\beta} + P_{l_\gamma} + P_{\nu_\gamma})^2 \]

\[ m_{\text{HNL}}^2 = m_{23}^2 + 2p'_\nu \cdot p'_\nu = 2E'_{23}\sqrt{q_{\perp}^2 + \alpha^2} + 2q_{\perp}^2 - 2q_z \alpha \]

- Four-momentum conservation in the \( W \) and N decays: use of charged lepton kinematics, known \( W \) mass, approximation of massless leptons/neutrino, flight direction of the N (vector connecting the PV and DV)
- In 1SFH scenarios, the analysis is sensitive to the squared mixing parameter \(|U_\mu|^2\) via the final states \( \mu - \mu \mu, \mu - e \mu, \) and \( \mu - e e, \) while \(|U_\mu|^2\) is accessible via \( e - e e, e - e \mu, \) and \( e - \mu \mu \) "\( \ell_\alpha - \ell_\beta \ell_\gamma \)"
- Accidental track crossings are only background that equally produce OS and SS DVs
- Background estimation = ratio of "shuffled" events in SR and CR (OS DV in VR event with prompt lepton from non-VR event that contains SS DV)
- Systematic from comparing mHNL shapes across SS and OS DVs (5-79%)

Validation in prompt lepton veto region

**ATLAS**

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

- **Opposite-sign (OS)**
- **Same-sign (SS)**
ATLAS Pixel Detector

- Barrel only, $\eta < 1.8$: MIP energy in pixel sensor = $20000 \text{ e-}$; charge threshold = $3500 \pm 40 \text{ e-}$
  - No overflow: hits exceeding this are lost
  - ToT digitized to 8 bits
- IBL: smaller-area pixels, thinner (200 vs. 250 $\mu$m), faster electronics, low resolution/dynamic range
  - IBL OverFlow bit is set if charge exceeds 30k e-
  - ToT digitized to 4 bits

- Measurements:
  - 4 precision measurements from 3.4 cm to 13 cm radially
  - Connected component analysis forms clusters of hits (charge = sum of pixels after calibration)

- Calibration: occupancy (exclude modules), threshold tuning per pixel, ToT tuning, bump analysis (check bonds)

![Image of ATLAS Pixel Detector](image-url)
**Pixel dE/dx Measurement**

- **dE/dx** for a track = average of the ionization measurement (charge in cluster per unit track length in sensor) across clusters
- **dE/dx_{trunc}**: remove highest dE/dx cluster, or 2 highest if track has > 4 clusters, but minimum of 2 (excluding IBL overflow clusters)
  - Avg # clusters per track in dE/dx_{trunc} = 2.7
  - |η| and detector conditions dependent (eg. different fluence), so each measurement is calibrated as a function of run number and |η| to be flat (normalize dE/dx_{trunc} peak to MPV of reference run)
- **dE/dx_{corr}** normalised for MIP-like tracks to peak at ~1 MeV g⁻¹cm⁻¹ (value for unirradiated silicon of ~200um pixel thickness)
- Mapping of βγ to dE/dx_{corr} is extracted in low-mu runs (track pT down to 100 GeV)

\[
\text{MPV}_{\text{dE/dx}}(\beta\gamma) = \frac{1 + (\beta\gamma)^2}{(\beta\gamma)^2} \left( c_0 + c_1 \log_{10}(\beta\gamma) + c_2 \left[ \log_{10}(\beta\gamma) \right]^2 \right)
\]

**Figure**: MPV of dE/dx as a function of the delivered integrated luminosity in Run 2, divided by 20 fb⁻¹ per year. The drift of MIP-MPV (value for unirradiated silicon) is due to the contribution of the IBL clusters which are restricted to be flat (normalize dE/dx_{trunc} peak to MPV of reference run). The lower mass of the particle associated with the track can be calculated as

\[
\text{mass} \sim \frac{\text{dE/dx}}{\text{det}} \times l_{\text{track}}
\]

Even after the equalisation of the MPV over the full range of run conditions, the drift of MIP-MPV is not uniform over |η|, but a substantial fraction of tracks with smaller |η| is still biased. This momentum bias was derived using the same low-mu data and is referred to as DSCB. Combined with the momentum measurement, the reconstructed momentum is unbiased for charged pions.

**Change in pixel charge calibration scheme**

**ATLAS Preliminary**

- **p > 10 GeV, OF0**
- **1.4 < |η| < 1.6**
- **1.8 < |η| < 2.0**

**Small jumps = changes to charge/threshold calibrations (eg. TS)**
Pixel \( \text{dE/dx} \) Regions

### Preselection

<table>
<thead>
<tr>
<th>Category</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event topology</td>
<td>Trigger</td>
<td>Unprescaled lowest-threshold ( E_T^{\text{miss}} ) trigger</td>
</tr>
<tr>
<td></td>
<td>( E_T^{\text{miss}} )</td>
<td>( E_T^{\text{miss}} &gt; 170 ) GeV</td>
</tr>
<tr>
<td></td>
<td>Primary vertex</td>
<td>The hard-scatter vertex must have at least two tracks (p_T &gt; 500 MeV)</td>
</tr>
<tr>
<td>Events are required to have at least one track fulfilling all criteria listed below; tracks sorted in ( p_T ) descending order</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Track kinematics | Momentum | \( p_T > 120 \) GeV |
| | Pseudorapidity | \( |\eta| < 1.8 \) |
| | \( W^a \rightarrow \ell^+\nu \) veto | \( \eta(\text{track}, \vec{E}_T^{\text{miss}}) > 130 \) GeV |

| Track quality | Impact parameters | Track matched to the hard-scatter vertex; \( |d_0| < 2 \) mm and \( |\Delta\eta\sin\theta| < 3 \) mm |
| | Rel. momentum resolution | \( \sigma_{p_T} < \max\left( 0.1, -1.0 \times \frac{|\eta|}{10.0}, 0.2 \right) \) |
| | Cluster requirement (1) | At least two clusters used for the \( (\text{dE/dx})_{\text{track}} \) calculation |
| | Cluster requirement (2) | Must have a cluster in the IBL (if this is expected), or |
| | Cluster requirement (3) | a cluster in the next-to-innermost pixel layer |
| | Cluster requirement (4) | (if this is expected while a cluster is not expected in IBL) |
| | No shared pixel clusters and no split pixel clusters |
| | Number of SCT clusters > 5 |

| Isolation | \( \sum_{\text{track}} p_T^i < 5 \) GeV (cone size \( \Delta R = 0.3 \) |
| Electron veto | EM fraction < 0.95 |
| Hadron and \( \tau \)-lepton veto | \( F_{\text{had}}/F_{\text{track}} < 1 \) |
| Muon requirement | SR-\( \text{Trk} \): MS track matched to ID track; SR-\( \text{Trk} \): otherwise |

### Signal Regions

#### SR For Discovery

- SR-Inclusive_Low
- SR-Inclusive_High

#### SR For Exclusion

- SR-Mu-IBL0_Low
- SR-Mu-IBL0_High
- SR-Mu-IBL1
- SR-Trk-IBL0_Low
- SR-Trk-IBL0_High
- SR-Trk-IBL1

- When we going for exclusion limits the events are categorized according to the selected track properties:
  - Matched to a Muon (\( \mu \)) or Not (\( \ell \))
  - \( \text{dE/dx} \) in \((1.8, 2.4]\) (Low) or \((2.4, \infty]\) (High)
  - Has a hit with an IBL Overflow (IBL1) \( \text{dE/dx} > 1.8 \)

- \( 2 \) exclusive signal regions that are used for searching for new physics.
  - \( \text{dE/dx} \) in \((1.8, 2.4]\) (Low)
  - \( \text{dE/dx} \) in \((2.4, \infty]\) (High)

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I. Siral, La Thuile

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23 March 2022

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J. Gonski

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Columbia University

IN THE CITY OF NEW YORK
Validation of the Background Method

Entries / 100 GeV

Data / Pred.

Entries / 30 GeV

Pixel dE/dx Background Estimation Validation

• Validation regions: each have exclusive kinematic and dE/dx templates and unique background estimation is derived
  - Low-Pt: 50 < track pT < 110 GeV
  - High-Eta: 1.8 < |η| < 1.5 and pT > 50 GeV

• VR-LowPt-Trk-IBL0_Low: observed yield is approximately 35% lower than the prediction

<table>
<thead>
<tr>
<th>Region</th>
<th>Category</th>
<th>Bin</th>
<th>Expected</th>
<th>Observed</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Trk</td>
<td>IBL0_Low</td>
<td>65.6 ± 18.3</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBL0_High</td>
<td>6.8 ± 2.2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBL1</td>
<td>3.8 ± 1.5</td>
<td>4</td>
</tr>
<tr>
<td>VR-LowPt</td>
<td>Mu</td>
<td>IBL0_Low</td>
<td>292 ± 17</td>
<td>300</td>
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<tr>
<td></td>
<td></td>
<td>IBL0_High</td>
<td>24.8 ± 3.6</td>
<td>32</td>
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<tr>
<td></td>
<td></td>
<td>IBL1</td>
<td>20.4 ± 3.7</td>
<td>19</td>
</tr>
<tr>
<td>Inclusive</td>
<td>Low</td>
<td></td>
<td>391 ± 24</td>
<td>361</td>
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<tr>
<td></td>
<td>High</td>
<td></td>
<td>37.2 ± 4.4</td>
<td>43</td>
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<tr>
<td>VR-HiEta</td>
<td>Trk</td>
<td>IBL0</td>
<td>26.6 ± 7.3</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBL1</td>
<td>8.0 ± 2.6</td>
<td>5</td>
</tr>
<tr>
<td>Mu</td>
<td>IBL0</td>
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<td>56.4 ± 2.5</td>
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<tr>
<td></td>
<td>IBL1</td>
<td></td>
<td>15.1 ± 1.5</td>
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<tr>
<td>Inclusive</td>
<td>—</td>
<td></td>
<td>101 ± 6</td>
<td>97</td>
</tr>
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</table>
Pixel dE/dx Systematics

• "Template correlation": estimated by different of estimate to data in high dE/dx CR-dE/dx (leading >1 TeV)
• "eta-slicing": repeat background estimation with alternate set of eta bins
• "dE/dx scale": empirical scale uncertainty on VR-LowPt-Trk-IBL0_Low; 27% (3%) for Trk (Mu) categories, pileup dependent (dominant in Trk < 1 TeV)
• "Stat": alternate shape from Poissonian fluctuations on templates & regenerate mass distro
• "dE/dx tail": alternate shape from fitting Landau tails to template instead of data shape
• "MET trig": alternate shape with/without reweighting of low-MET below threshold CR-dE/dx
• "Norm": stat uncertainty in normalization factor of background prediction
Pixel dE/dx Unblinded Distributions

SR-Inclusive-Low

SR-Inclusive-High
Pixel dE/dx Background p-values

- Min $p_0$-value of $1.46 \times 10^{-4}$ in mass window $= [1100, 2800]$ GeV (target mass of 1400 GeV in long lifetime regime)
Pixel dE/dx Excess Characterization

ATLAS Preliminary

SR-Inclusive (Low+High)

Excess Events in the Inclusive High Category that are at the high mass tail.

- Excess events: 4 have matched muon, 2 are non-muon (Trk) with IBL overflow, 1 is Trk with IBL overflow
- Overall these events have a counter-balance topology (6/7 have a jet, 1 has ETmiss); common in CR-kin
- Cross-checks with other subsystems: consistent with a particle of $\beta \sim 1$
  - TileCal: ToF weighted by the timing resolution of the cells associated to track
  - MS: fit muon tracks with $\beta$ as a free parameter
**LAr Timing**

- 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 $\delta\eta$, $\delta\varphi$)
  - Pass 5: inter-layer cross-talk (by slot, based on $f_1$, $f_3$)
  - 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)

- 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
**CalRatio Extras**

- **Jet-level NN** is trained to separate signal from BIB and QCD background (CNN fed into LSTM)
  - analysis split into 2 channels: low- and high-mass models
  - Variables with low level input: 10 track var., 10 jet constituents var., 6 muon segment var., and 3 jet var.
Dark Photon Extras

**SR Selections**

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>SR$_{\mu}$</th>
<th>SR$_{2\mu}$</th>
<th>SR$_{c+\mu}$</th>
</tr>
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<tbody>
<tr>
<td>Number of $\mu$DPIs</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Number of caloDPIs</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Tri-muon MS-only trigger</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Muon narrow-scan trigger</td>
<td>yes</td>
<td>-</td>
<td>yes</td>
</tr>
<tr>
<td>CalRatio trigger</td>
<td>-</td>
<td>yes</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>\Delta t_{\text{caloDPIs}}</td>
<td>$ [ns]</td>
<td>-</td>
</tr>
<tr>
<td>caloDPI JVT</td>
<td>-</td>
<td>&lt; 0.4</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta\phi_{\text{DPJ}}$</td>
<td>$&gt; \pi/5$</td>
<td>$&gt; \pi/5$</td>
<td>$&gt; \pi/5$</td>
</tr>
<tr>
<td>BIB tagger score</td>
<td>-</td>
<td>$&gt; 0.2$</td>
<td>$&gt; 0.2$</td>
</tr>
<tr>
<td>max($\Sigma p_T$) [GeV]</td>
<td>&lt; 4.5</td>
<td>&lt; 4.5</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>$\prod QCD$ tagger</td>
<td>-</td>
<td>$&gt; 0.95$</td>
<td>&gt; 0.9</td>
</tr>
</tbody>
</table>

**ABCD Background Estimation (ggF)**

ATLAS Preliminary

+L1Calo “CalRatio” trigger (ggF) OR single lepton (WH)
Dark Matter + $t\bar{t}$

- **Signature**: WIMP DM particle ($E_{miss}$) with associated top(s)
  - Sensitivity: $m = O(10-100)$ GeV, $\tau \sim$ stable

- **Strategy**: statistical combination of existing and orthogonal 0L [2004.14060], 1L [2012.03799], 2L [2102.01444] searches

- **Result**: improves the expected coupling exclusion reach by 14% (24%) for a scalar (pseudoscalar) mediator of 10 GeV

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**Scalar $\phi$**

**Pseudoscalar $a$**

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*ATLAS Preliminary*

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

All limits at 95% CL

Scalar $\phi$, $\phi \rightarrow \chi \bar{\chi}$

$g_{#chi} = g_{#chi} = 1$

Dirac DM, $m_{#chi} = 1$ GeV

DM+t and DM+tt

*ATLAS Preliminary*

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

All limits at 95% CL

Pseudoscalar $a$, $a \rightarrow \chi \bar{\chi}$

$g_{#chi} = g_{#chi} = 1$

Dirac DM, $m_{#chi} = 1$ GeV

DM+t and DM+tt