Search for BSM physics using challenging signatures with ATLAS

19th LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

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Beyond Standard Model Searches in ATLAS

So far, no smoking gun of BSM physics at LHC → Observations in agreement with SM on very broad range of cross sections

LHC won’t increase centre of mass of collisions → Increase of integrated luminosity for Run3 (2021-2023) and Run4 (2026 and beyond) → Look for BSM in all corners of unexplored phase space
Unconventional Signatures

Long lived particles

Example: Charged pion lifetime:

\[
\frac{1}{\tau_{\pi^+}} = \frac{f_{\pi}^2}{256\pi m_{\pi}} \left[ \frac{g^2}{M_W^2} \frac{m_\mu}{m_{\pi}} \left( m_{\pi}^2 - m_\mu^2 \right) \right]^2
\]

Large decay lengths:

Small couplings → Hidden sectors
Large mediator mass → BSM mediators
Compressed spectra → Approximate symmetries

ATLAS detector have been designed primarily requiring high efficiency detection for “prompt” (or issued by b,c and \( \tau \) decays) particles

\[ \text{LLP Requires} \]

Modified algorithms for Long Lived Particles:

- Trigger selection
- Tracking and particle ID
- Background estimation
  - Non collision Background
    - (Beam Induced Background)
  - Material interactions
  - Cosmic Muons
Trigger selection

Design specific triggers for long lived particles
In ATLAS:
- L1 Trigger from Calorimeter and Muon Spectrometer (reduce rate down to 100kHz)
- High Level Trigger (HLT) from all detectors (from 100kHz to 1kHz)
Looking for decays outside ECal keeping small $E_T$ thresholds ($E_T > 30$ GeV)
Low-$E_T$ CalRatio uses L1Topo system to request
  → small deposit in ECal close to HCal L1 candidate
HLT selection: $\log(\text{HCal}/\text{ECal}) > 1.2$

arXiv:1902.03094
Large Radius Tracking

- Removes constraints on $d_0$, $z_0$ and number of hits → larger efficiency on tracks from large radius
- “Slow” tracking algorithms → Runs only on ~1% of hits (TRT, SCT and PIX)

Tracking efficiency recovered for tracks produced at large radius

Drawing from C. Ohm

ATL-PHYS-PUB-2017-014
Decays in Muon Spectrometer


drawing from E. Torro
Decays in Muon Spectrometer
Decays in Calorimeter

Drawing from E. Torro
Decays in Muon Spectrometer
Decays in Calorimeter
Decays in Inner Detector

Drawing from E. Torro
Decays in Muon Spectrometer
Decays in Calorimeter
Decays in Inner Detector
Highly Ionising Particle

Drawing from E. Torro
Decays in Muon Spectrometer

Drawing from E. Torro
Dark Photon Jets

Look for collimated leptons or light hadrons (DPJ) from decays in outer hadronic calorimeter or Muon Spectrometer (R>\sim1.5 \text{ m})

→ Interpreted as Dark Photon \gamma_d in FRVZ Model

DPJ can decay:

in MS (\gamma_d \rightarrow \mu\mu) \rightarrow 2 close-by muons in MS

in Calorimeter (\gamma_d \rightarrow ee/\pi\pi) \rightarrow Jet with large Had/EM Ratio

**Trigger strategy:**

- Three muons in MS (no ID matching) P_T>6 GeV
- Muon Narrow Scan → Single muon at L1. At HLT search around L1 candidate (R=0.5) at HLT muon with P_T> 6 (15) GeV
- CalRatio trigger single jet with E_T>60 GeV and log(HCal/ECal)>1.2

FRZV Model PRL 105 (2010)
241801
Dark Photon Jets

DPJ *per-jet* selection based on BDT:

- $\mu$BDT DPJ \rightarrow \text{discriminates muon DPJ signal – cosmic muon bkg}
- $h$BDT DPJ \rightarrow \text{discriminates e/\(\pi\) DPJ signal from multijet bkg}

Data driven background estimation using *Control Regions* with large background contributions
Dark Photon Jets

No excess observed
Limits on $c\tau$ vs $M\gamma_d$ translated in $\varepsilon$ (kinetic mixing parameter) vs $M\gamma_d$

<table>
<thead>
<tr>
<th>DPJ Types</th>
<th>Exp</th>
<th>Obs</th>
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<tbody>
<tr>
<td>$\mu$DPJ-$\mu$DPJ</td>
<td>128±26±3</td>
<td>113</td>
</tr>
<tr>
<td>$\mu$DPJ-hDPJ</td>
<td>177±86±4</td>
<td>179</td>
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<tr>
<td>hDPJ-hDPJ</td>
<td>97±48±2</td>
<td>69</td>
</tr>
</tbody>
</table>

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Decays in Calorimeter

Drawing from E. Torro
Displaced Jets (Calo)

Search for long lived $s$ bosons from $\Phi$ heavy boson. $\Phi$ could be SM Higgs or other heavier BSM mediator

Targeting decays in Calorimeter
Two trigger selections based on Hcal/ECal ratio
→ High-$E_T$, Low$E_T$ increase efficiency for smaller LLP momentum

Jet candidates are selected using a per-jet BDT → discriminates signal from multijet and beam induced background events

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ardXiv:1902.03094
Displaced Jets

*per-Jet* BDT and other event variables used in a *per-event* BDT
Estimated data driven background exploiting trackless jet information

Small $\sum \Delta R_{min}(\text{jet, tracks})$ for signal
Displaced Jets

No significant excess observed

<table>
<thead>
<tr>
<th>Main selections</th>
<th>Estim. A</th>
<th>Estim. A</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a priori)</td>
<td>(a posteriori)</td>
<td></td>
<td></td>
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<tr>
<td>High-$E_T$ selection</td>
<td>$6.7^{+3.2}_{-2.3}$</td>
<td>$8.5^{+2.3}_{-2.0}$</td>
<td>10</td>
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<tr>
<td>Low-$E_T$ selection</td>
<td>$2.5^{+2.5}_{-1.4}$</td>
<td>$5.3^{+2.1}_{-1.6}$</td>
<td>7</td>
</tr>
</tbody>
</table>

Combined fit on CRs and SR interpreted as limit in $\sigma(pp \rightarrow \Phi) \times BR(\Phi \rightarrow ss)$

Displaced Jets analysis increases sensitivity for $M_\Phi = 600$ GeV for small proper decay length of $s(\lesssim 2$ m) wrt analysis based on MS decays

Decays in Inner Detector

Drawing from E. Torro
Displaced Dileptons

Searches for $\ell^+\ell^-$ (ee, e\(\mu\) and \(\mu\mu\)) from Displaced Vertex in the Inner Detector (R<30 cm)

Use muon and photon triggers w/o ID requirement
Large Radius Tracking and \textit{ad-hoc} DV finding applied

→ No DV close to material or off pixel modules

$R_{xy} < 30$ cm and $|z|<30$ cm

$M_{\ell^+\ell^-} > 12$ GeV

Data Driven background:

- Cosmic Muons removed by $\Delta R_{\cos}<0.01$
  ($N_{bkg} \sim 0.25$)
- Random crossing tracks (<1 per mille)

\(\sqrt{s} = 13\) TeV, 32.8 fb\(^{-1}\)

\(\Delta R_{\cos}\)
Displaced Dileptons

No events observed in the Signal Region for ee, eμ and μμ candidates
→ Exclusion limits in RPV neutralino model

**ATLAS Simulation**

\[ \tilde{q} \rightarrow q[\tilde{\chi}_1^0 \rightarrow ee / e\mu] \]
\[ \sqrt{s} = 13 \text{ TeV} \]

**Upper limit on cross-section [fb]**

\[ \tilde{q} \rightarrow q[\tilde{\chi}_1^0 \rightarrow ee / e\mu] \]
\[ \sqrt{s} = 13 \text{ TeV}, 32.8 \text{ fb}^{-1} \]

All limits at 95% CL

\[ \sigma(pp \rightarrow \tilde{q}), m(\tilde{q}) = 1.6 \text{ TeV} \]
Highly Ionising Particle

Drawing from E. Torro
Monopoles

Monopoles proposed by Dirac in 1931

→ Some BSM extensions mass of monopoles accessible by LHC experiments

Monopole charge \( q_m = N g_D e c = N 68.5 e c \)

No spin or mass constrain

Interacts at least as Erbium fully ionized!

Peculiar signatures:

- Highly Ionizing Particles
- Stopping particles (no shower in ECal)

Trigger selection:

- Energy deposit in ECal \((E_T > 50 \text{ GeV})\) small energy in HCal
- Large fraction of High Level Threshold tubes in TRT \((f_{HT} > 0.5)\) around EM candidate

arXiv:1905.10130

23/08/2019

A. Sidoti

Phys. Rev. D 93 (2016) 052009
Monopoles

Event selection:

- Large fraction of High Threshold tubes in TRT ($f_{HT} > 0.7$)
- Large $(w_1 + w_2 + w_3)/3$ ($w_i = \text{fraction of energy in } i\text{-th section ECal}$) 
  $(w > 0.96) \rightarrow \text{Discriminates between signal and jet background}$

Background Data Driven estimation

→ Small contamination in signal region $\sim 0.2$ Events expected

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Conclusion

- No evidence of BSM physics in LHC data so far
- Going from theory motivated to signature based BSM direct searches
- LHC Integrated luminosity increase allows to look for BSM in unexplored phase spaces
- BSM physics could appear in unconventional signatures (long lived, heavy ionizing particles)
- ATLAS has developed specific trigger and reconstruction algorithms to select efficiently on unconventional (and challenging) signatures
- More severe collisions environment for Run3 and HL-LHC → improving selection techniques
- Work ongoing to fully exploit Run3 upgrades (accelerator and detector)
BackUp
# ATLAS Long-lived Particle Searches - 95% CL Exclusion

**Status:** July 2019

\[ \mathcal{L} dt = (18.4 - 36.1) \text{ fb}^{-1} \sqrt{s} = 8, 13 \text{ TeV} \]

**Model** | **Signature** | \([\mathcal{L} dt] \text{ [fb}^{-1}\text{]}\) | **Lifetime limit** |
---|---|---|---|
**RPV** | \(\chi_1^0 \rightarrow e e r / e u r / \mu r / \nu r\) | displaced lepton pair | 20.3 |
| GGM | \(\chi_1^0 \rightarrow Z \tilde{g}\) | displaced vtx + jets | 20.3 |
| GGM | \(\chi_1^0 \rightarrow Z \tilde{t}\) | displaced dimuon | 32.9 |
| GMSB | non-pointing or delayed \(\gamma\) | 20.3 |
| AMSB | \(pp \rightarrow \chi_1^0 \chi_1^0 \chi_1^0 \chi_1^0\) | disappearing track | 20.3 |
| AMSB | \(pp \rightarrow \chi_1^0 \chi_1^0 \chi_1^0 \chi_1^0\) | disappearing track | 36.1 |
| AMSB | \(pp \rightarrow \chi_1^0 \chi_1^0 \chi_1^0 \chi_1^0\) | large pixel \(dE/dx\) | 18.4 |
| Stealth SUSY | 2 MS vertices | 36.1 |
| Split SUSY | large pixel \(dE/dx\) | 36.1 |
| Split SUSY | displaced vtx + \(E_{\text{T}}^{\text{miss}}\) | 36.1 |
| Split SUSY | \(0 \ell, 2 - 6 \text{ jets} + E_{\text{T}}^{\text{miss}}\) | 36.1 |
| \(H \rightarrow s s\) | low-EMF trk-less jets, MS vtx | 36.1 |
| FRVZ | \(H \rightarrow 2\gamma + X\) | 2 \(e^-, \mu\)-jets | 20.3 |
| FRVZ | \(H \rightarrow 2\gamma + X\) | 2 \(e^-, \mu\)-jets, \(\pi\)-jets | 36.1 |
| FRVZ | \(H \rightarrow 4\gamma + X\) | 2 \(e^-, \mu\)-jets, \(\pi\)-jets | 36.1 |
| \(H \rightarrow Z\gamma Z\gamma\) | displaced dimuon | 32.9 | \(Z\gamma\) lifetime | 0.009-24.0 m |
| \(H \rightarrow ZZ\gamma\) | 2 \(e, \mu\) + low-EMF trackless jet | 36.1 | \(Z\gamma\) lifetime | 0.21-5.2 m |
| \(VH\) with \(H \rightarrow s s \rightarrow b b b b\) | 1 \(-2\ell + \text{multi-b-jets}\) | 36.1 | \(s\) lifetime | 0.18-120 m |
| Φ(200 GeV) \(\rightarrow s s\) | low-EMF trk-less jets, MS vtx | 36.1 | \(s\) lifetime | 0.18-120 m |
| Φ(600 GeV) \(\rightarrow s s\) | low-EMF trk-less jets, MS vtx | 36.1 | \(s\) lifetime | 0.18-120 m |
| Φ(1 TeV) \(\rightarrow s s\) | low-EMF trk-less jets, MS vtx | 36.1 | \(s\) lifetime | 0.18-120 m |
| HV \(Z(1 \text{ TeV}) \rightarrow q, q\nu\) | 2 ID/MS vertices | 20.3 | \(s\) lifetime | 0.1-49 m |
| HV \(Z(2 \text{ TeV}) \rightarrow q, q\nu\) | 2 ID/MS vertices | 20.3 | \(s\) lifetime | 0.1-49 m |

**Reference**

| ATLAS-CONF-2018-00 |

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*Only a selection of the available lifetime limits is shown.*
### ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

**Status:** May 2019

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
<th>Limit</th>
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</thead>
<tbody>
<tr>
<td>ADD ( g_{\text{KK}} + g/\psi )</td>
<td>0, ( e, \mu )</td>
<td>1 - 4</td>
<td>( j )</td>
<td>Yes</td>
<td>36.1</td>
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<tr>
<td>ADD Resonant ( \gamma \gamma )</td>
<td>2</td>
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<td>-</td>
<td>-</td>
<td>36.7</td>
</tr>
<tr>
<td>ADD HQB</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>37.0</td>
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<tr>
<td>ADD BH high ( \Sigma_{\text{ET}} )</td>
<td>1, e, ( \mu ), 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.2</td>
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<tr>
<td>ADD BH multijet</td>
<td>1, e, ( \mu ), 3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.6</td>
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<td>RS1 ( G_{\text{KK}} \rightarrow \gamma \gamma )</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
</tr>
<tr>
<td>Bulk RS ( G_{\text{KK}} \rightarrow WW/ZZ ) multi-channel</td>
<td>2, e, ( \mu )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
</tr>
<tr>
<td>Bulk RS ( G_{\text{KK}} \rightarrow WW \rightarrow qqqq )</td>
<td>0, e, ( \mu ), 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.6</td>
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<tr>
<td>2UED / RPP</td>
<td>1, e, ( \mu ), 2, 3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
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<tr>
<td>SSMS ( Z' \rightarrow \ell \ell )</td>
<td>2, e, ( \mu )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
</tr>
<tr>
<td>SSMS ( Z' \rightarrow \tau \tau )</td>
<td>2, ( \tau )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.6</td>
</tr>
<tr>
<td>Leptophobic ( Z' \rightarrow bb )</td>
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<td>b</td>
<td>b</td>
<td>b</td>
<td>36.6</td>
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<tr>
<td>Leptophobic ( Z' \rightarrow \tau \tau )</td>
<td>1, e, ( \mu ), ( \tau ), 2</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
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<tr>
<td>SSMS ( W' \rightarrow t \tau )</td>
<td>1, e, ( \mu )</td>
<td>-</td>
<td>-</td>
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<td>3.7 TeV</td>
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<tr>
<td>SSMS ( W' \rightarrow t \tau )</td>
<td>1, e, ( \mu )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
</tr>
</tbody>
</table>
| HVT \( V' \rightarrow W' 

### Gauge bosons

* Only a selection of the available mass limits on new states or phenomena is shown.

### Extra dimensions

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
<th>Limit</th>
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</thead>
<tbody>
<tr>
<td>CMS Dijet</td>
<td>2</td>
<td>e, ( \mu )</td>
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</table>

### DM

<table>
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<th>( \ell, \gamma )</th>
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<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
<th>Limit</th>
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<tbody>
<tr>
<td>Scalor ( L Q_{1} ) gen</td>
<td>2 ( \ell )</td>
<td>1, 2 ( j )</td>
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<tr>
<td>Scalor ( L Q_{3} ) gen</td>
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<td>1, 2 ( j )</td>
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<td>36.1</td>
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</table>

### Heavy quarks

<table>
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<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
<th>Limit</th>
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</thead>
<tbody>
<tr>
<td>VH ( g \rightarrow b )</td>
<td>2 ( j )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.3</td>
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### Excited fermions

<table>
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<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
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### Type II Seesaw

<table>
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<th>( \int \mathcal{L} , dt )</th>
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### Other

<table>
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<th>Jets</th>
<th>( E_{\text{T}}^{\text{miss}} )</th>
<th>( \int \mathcal{L} , dt )</th>
<th>Limit</th>
</tr>
</thead>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.

**Small-radius (large-radius) jets are denoted by the letter \( j \) (\( J \)).
ATLAS Inner Detector
Use Muon Spectrometer reconstructed tracklets to find displaced vertices outside hadronic calorimeter (R>4 m)
Dark Photon Jett Efficiencies
Displaced Jets in Calorimeter

![Graphs showing displaced jets in calorimeter.](image-url)
Displaced Jets in Calorimeter
Exclusion comparison with Run1
Monopole and High Charge BSM object exclusion limit
$\sqrt{s} = 8 \text{ TeV}, 7.0 \text{ fb}^{-1}$

- Data
- MC $W^\pm \rightarrow v_e^\pm$
- MC $\text{DY spin-}^{1/2} \ m=1000 \text{ GeV, } |g|=1.0g_D$
- MC $\text{DY spin-}^{1/2} \ m=1000 \text{ GeV, } |z|=40$
- MC $\text{DY} \rightarrow e^+e^-$
ATLAS
\sqrt{s} = 8 \text{ TeV}, 7.0 \text{ fb}^{-1}

- Data
- DY spin-$^{1/2}$ $m=1000 \text{ GeV}$, $|g|=1.0g_D$
- MC $W^\pm \rightarrow \nu e^\pm$
- DY spin-$^{1/2}$ $m=1000 \text{ GeV}$, $|z|=40$
- MC DY $\rightarrow e^+e^-$
Heavy Neutrino Lepton

Type1-SeeSaw mechanism predicts Heavy Neutrino Lepton (Dirac or Majorana)

Large lifetime HNL allowed by small couplings strengths $|U_l|$ and small HNL masses ($M_N$)

Looking for Majorana HNL both with Lepton Number Violation or Conservation

Two orthogonal selections:

- Prompt signature in $e^\pm e^\pm \mu^\mp$ or $\mu^\pm \mu^\pm e^\mp$ (Same Flavour Same Charge) to reduce SM background

- Displaced signature $\rightarrow$ prompt muon + DV ($e\mu$ or $\mu\mu$)

Sensitive to $U_\mu$ or $U_e$ couplings

Trigger selection using prompt single lepton or dilepton trigger

arXiv:1905.09787 A. Sidoti
HNL: Selection and Background

Prompt signature:
- Exactly three leptons (μμe or eeμ)
- 40<m(III)<90 GeV (Mee< 78 GeV in eeμ channel)
- B-jet veto
- Small E_{Tmiss} (E_{Tmiss} <60 GeV)
- W+jets and multijet data driven background
- tt background shape from MC, normalization from CR fit
- Other bkg from MC (diboson, single top, Z+jets)

Displaced Signature
- Large radius tracking and improved DV finding applied
- Exactly 2 tracks OS associated to DV
- M_{DV}>4 GeV
- SM background negligible from DV
- Multijet and W+jets data driven
- Cosmic muons and random particle crossings

23/08/2019 A. Sidoti
HNL: Exclusion Limits

Prompt search exclusion limit
Loose sensitivity for low $M_N$ and small $U_\mu$

Displaced search exclusion limit
Access lower $M_N$ and small $U_\mu$
Heavy Neutrino Lepton

Prompt search