Long-lived particle searches in ATLAS and CMS

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On behalf of ATLAS and CMS Collaboration

The EAGLE Project
Long-Lived Particle at ATLAS and CMS

• Why Long-lived particle (LLP)?
  • DM should be stable and cold.
  • New particle could be a long-lived.
  • Most of new physics analysis target prompt decays from signal
  • Technical difficulty
    • A lot of uncovered phase space.

• Key technique for LLP: Special reconstruction
  • Large Radius Tracking (LRT): LLP’s impact parameter ($d_0$) would be large
  • Displaced Vertex (DV): Vertex formed far from Primary Vertex (pp collision)
Long-Lived Particle

- **Small Coupling Case**
  - Small RPV coupling
  - Gravity (into gravitino)

- **Heavy intermediate**
  - 10 TeV squark → gluino
  - 100 TeV higgsino → wino/bino

- **Small ΔM**
  - pure wino LSP (ΔM~160 MeV)

- **Why they become LLP?**
  - Three reasons: coupling, heavy intermediate, small Δmass

- **How can we detect LLP?**
  - Detect LLP itself → Large dE/dx, disappearing track...
  - Detect SM particles from LLP decay → Displaced vertex, displaced late photon...
LLP's View in the Detector

- LLP's view in detector depends on how it produce/decay
- Many unique signatures

**Combination of**
- Track(s)
- Vertex
- Cluster
- Muon(s)

**Background**
- Random crossing
- SM LLP
- Fake track/vertex
LLP’s View in the Detector

- Disappearing or kinked tracks
- Emerging jets
- Quasi-stable charged particle
- Trackless, low-EMF jets
- Non-pointing photon
- Multitrack vertices in the muon spectrometer
- Displaced multitrack vertices
- Displaced leptons, lepton-jets
- Multitrack vertices in the muon spectrometer

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• LLP’s view in detector depends on how it produce/decay
• Many unique signatures
Displaced Vertices with Charged Leptons

- **LLP → ee/μμ/μμ**: simplified RPV SUSY or Z' toy model (model independent)
- Large radius tracking (LRT) is used to identify displaced vertices (DV)
- Muon or photon trigger: photon trigger is used for displaced electron pair

**Background**:
- Cosmic muon: reduce by selection and check cosmic muon CR

**Graph**

- ATLAS
- $\sqrt{s} = 13$ TeV, 32.8 fb$^{-1}$
- Cosmic rays control region
- Red bars: All dimuon pairs (scaled)
- Black line: DV matched dimuon pairs

`ΔR_{cos}`
Displaced Vertices with Charged Leptons

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- random crossing tracks: data-driven method event mixing and track flipping.

![Graph showing displaced vertices / 10 mm](image)

**ATLAS**

- Data / Estimate
- √s = 13 TeV, 32.8 fb⁻¹

- Track flipping

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**DM@LHC2020/Masahiro Morinaga**
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- **Background**:
  - Cosmic muon: reduce by selection and check cosmic muon CR
  - Random crossing tracks: data-driven method *event mixing* and *track flipping*.
- **Systematics**: LRT(DV): $K_s \rightarrow \pi \pi$ is used
- **Efficiency**: maximum (~40%) around 10-50mm
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**Efficiency**: maximum (~40%) around 10-50mm

**Results**: Expected $0.27 \pm 0.17$, 0 event observed.
- Model independent: Upper limit 0.09 fb for cross section (95%).
**Light Neutral LLP**

- **Light neutral LLP**: Benchmark FRVZ model
- **Signature**: ggF Higgs to, 4 fermions(DPJ), missing ET ($\gamma_d$ is LLP)
- **DPJ**: $\mu$DPJ or h(adronic)DPJ, using BDT
- **Signal Region**: two DPJ objects satisfying $\mu-\mu$, $\mu-h$, $h-h$
- **Background**: multi-jets using ABCD
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- **Signal Region**: two DPJ objects satisfying μ-μ, μ-h, h-h.
- **Background**: multi-jets using ABCD

\[
\begin{align*}
H & \rightarrow 2\gamma_d + X \\
m_H = 125 \text{ GeV} & \quad \sqrt{s} = 13 \text{ TeV} \\
m_{\gamma_d} = 400 \text{ MeV} & \\
\end{align*}
\]

- **μDPJ**: η, φ, z0, timing(MS)
- **μBDT**: 4 inputs variables
Light Neutral LLP

• **Light neutral LLP**: Benchmark FRVZ model
  - Signature: $ggF$ Higgs to, 4 fermions(DPJ), missing ET($\gamma_d$ is LLP)
  - **DPJ**: $\mu$DPJ or h(adronic)DPJ, using BDT

• **Signal Region**: two DPJ objects satisfying $\mu-\mu$, $\mu-h$, $h-h$

• **Background**: multi-jets using ABCD

• **Results**: No excess in the signal region.
Displaced Jets : Hidden Sector Mediator

• **LLP**: Hidden Sector (HS), mediator scalar $s$ is LLP
  
• **DV**: MSVx and IDVx
  
  • MSVx: DV at MS, MS track and chi2
  
  • IDVx: DV at ID, large radius track and chi2, material veto
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- **Background** : random crossing fake track $\rightarrow$ ABCD like data-driven estimation
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- **Background**: random crossing fake track → ABCD like data-driven estimation
- **Efficiency**: Strongly depends on scalar mass.

**Diagram**

- Long-lived particle decay \( R \) [mm]
  - \( R \) vs reco. efficiency
  - \( R \) vs Selection efficiency
  - Simulation ATLAS
  - No material veto, \( m_s = [125, 55] \) GeV
  - With material veto, \( m_s = [125, 25] \) GeV
  - \( m_s = [125, 8] \) GeV

**Plot**

- IDVx reconstruction efficiency
  - Simulation ATLAS
  - ATLAS Simulation
  - Standard and LRT
  - Only standard tracking
  - All vertices

**Graph**

- IDVx Selection Efficiency
  - ATLAS Simulation
  - \( m_s = [1000, 150] \) GeV

**Legend**

- Simulation ATLAS
- No material veto
- With material veto

**Equations**

\[ \text{Br}(85:5:8) \]

**Additional Information**

- **DM@LHC2020/Masahiro Morinaga**
Displaced Jets : Hidden Sector Mediator

- **LLP**: Hidden Sector (HS), mediator scalar $s$ is LLP
- **DV**: MSVx and IDVx
  - MSVx : DV at MS, MS track and chi2
  - IDVx : DV at ID, large radius track and chi2, material veto
- **Background**: random crossing fake track $\rightarrow$ ABCD like data-driven estimation
- **Efficiency**: Strongly depends on scalar mass.
- **Results**: agreed with background only expectation
**Displaced Jets**

- **LLP**: RPV/GMSB/split SUSY, Hidden Valley, Higgs,
- **GBDT**: 4 input variables
- **RM_Scluster**: #of tracks, $L_{xy}$ significance, $\kappa$ (sum of track IP significance).

- **Background**: QCD multi-jets,
- **MC prediction with seven CRs and three cross-checks regions.**

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**Several models**

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**Veto map**

**Veto efficiency**
Displaced Jets

- **LLP**: RPV/GMSB/split SUSY, Hidden Valley, Higgs,
- **GBDT**: 4 input variables
  - $R_{\text{MCluster}}$, #of tracks, $L_{xy}$ significance, $\kappa$(sum of track IP significance).
- **Background**: QCD multi-jets,
- MC prediction with seven CRs and three cross-checks regions.

4 inputs for BDT
Displaced Jets

$95.9 \text{ fb}^{-1}$ (13 TeV)

**CMS Preliminary**

- Observed events
- Background predictions
  - $m_X = 300 \text{ GeV, } \sigma_X = 3 \text{ mm}$
  - $m_X = 300 \text{ GeV, } \sigma_X = 30 \text{ mm}$
  - $m_X = 300 \text{ GeV, } \sigma_X = 300 \text{ mm}$

**signal region**

- **LLP**: RPV/GMSB/split SUSY, Hidden Valley, Higgs,
  - GBDT: 4 input variables
    - $R_{\text{MScluster}}$, #of tracks, $L_{xy}$ significance, $\kappa$(sum of track IP significance).
- **Background**: QCD multi-jets,
- **MC prediction** with seven CRs and three cross-checks regions.
- **Results**: Agreed with SM expectation

- **GBDT score**

- **Events**
  - $0.1 < g \leq 0.2$
  - $0.2 < g \leq 0.3$
  - $0.3 < g \leq 0.5$
  - $0.5 < g \leq 0.7$
  - $0.7 < g \leq 0.9$
  - $0.9 < g \leq 0.95$
  - $0.95 < g < 0.988$
  - $0.988 < g \leq 1$

- **Observed events**
- **Background predictions**

- CMS Preliminary 132 fb$^{-1}$ (13 TeV)

- **95% CL upper limits**
  - Observed
  - Median expected

- **Theory**
  - Expected = 1 $\sigma_{\text{expected}}$
  - CMS delayed jets

- **Observed = 1 $\sigma_{\text{observed}}$**

- **GMSB**: $\tilde{g} \to \tilde{g} \tilde{g}$
  - 95% NNLO approx NNLO exclusion

- **PP**: $pp \to \tilde{g} \tilde{g} \to g\tilde{g}$
  - CMS delayed jets

- **Cross section [fb]**
  - CMS Preliminary 132 fb$^{-1}$ (13 TeV)
  - 3500
  - 3000
  - 2500
  - 2000
  - 1500
  - 1000
  - $10^{-1}$
  - $10^{-2}$

- **Log$_{10}$ (cr$_0$/mm)**
  - 4
  - 3.5
  - 3
  - 2.5
  - 2.0
  - 1.5
  - 1.0
  - $10^{-1}$
Disappearing Track

- **LLP**: chargino is LLP decayed inside of the inner detector.
- If chargino is DM wino/higgsino < 1TeV/3TeV
- **Short track**: # of layer → 4, 5, ≧6, $E_{T\text{miss}} > 120$GeV (trigger)
- **Background**: lepton, spurious tracks
  - Using CR events with probability correction factors.
  - **HEM**: Hadronic calorimeter down for certain period of Run2.

\[
N_{\ell Bo}^{\ell} = \frac{N_{\text{ctrl}}^{\ell}}{\epsilon_{\text{trigger}}} \\
N_{\text{spurious}}^{\ell} = N_{\text{basic}}^{\ell} \cdot \mathcal{G}^{\text{raw spurious}}^{\text{spurious}}
\]

**PV**

- reconstructed 4 or 5 or more layers
Disappearing Track

- **LLP**: chargino is LLP decayed inside of the inner detector.
- If chargino is DM wino/higgsino < 1 TeV/3 TeV
- Short track: #of layer → 4, 5, ≥ 6, \( E_{\text{miss}} > 120 \text{GeV} \) (trigger)
- **Background**: lepton, spurious tracks
  - Using CR events with probability correction factors.
  - HEM: Hadronic calorimeter down for certain period of Run2
- **Results**: No significant excess → limit
  - Pure wino: Exclude 474 GeV, Higgsino: Exclude 175 GeV.

\[
N_{\text{est}} = \frac{N_{\text{ctrl}}}{c_{\ell}^{\text{trigger}}}
\]

\[
N_{\text{spurious}} = N_{\text{basic}} \cdot \frac{p_{\text{raw}}^{\text{spurious}}}{p_{\text{off}}^{\text{trig}}}
\]

Transfer factor

\( d_0 \) sideband
Disappearing Track

- **LLP**: Chargino is LLP decayed inside of the inner detector.
- If chargino is DM wino/higgsino < 1 TeV/3 TeV
- Short track: # of layer → 4, 5, ≥ 6, $E_T^{miss} > 120$ GeV (trigger)
- **Background**: Lepton, spurious tracks
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$$N_{est}^{\ell} = \frac{N_{ctrl}^{\ell}}{e^{\ell}_{trigger}}$$  
$$N_{est}^{spurious} = N_{basic}^{ctrl} \cdot \zeta^{P_{raw}^{spurious}}$$
**LLP Search Deep Neural Network**

- **DNN to identify jets from LLP**: split SUSY signal
  - Jet label: b, c, light quark, gluon
  - Training with seven $c\tau$ values
  - Categorize: (#of jets, #of tagged jets) and $H_T$
- **Background**: MC-based estimation
- **Results**: No significant excess
  - Improve longer lifetime region

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**CMS Simulation**

- **ROC**
  - $\sim 60\%$ efficiency at $1\%$ fake rate
Summary

- Long-live particle search at ATLAS and CMS become important as a dark matter candidate.
- Analysis technique to reconstruct LLP or its products is being mature.
- Machine learning become a key technique in LLP search.
- Lots of results are not updated by Run2 full data (~140/fb), will happen soon :)
“backup”