Probing Dark Photons in Top-Associated production at the LHC

70th SAIP Annual Conference 2026

Thabo James Lepota* Mukesh Kumar Rachid Mazini

[1]School of Physics and Institute for Collider Particle Physics,
University of the Witwatersrand, Johannesburg, South Africa

*thabo.james.lepota@cern.ch

70^{th} SAIP Annual Conference, University of Western Cape, 6-11 July 2026

Outline

Motivation

Why dark photons?
Why the top quark?

Theory

Lagrangian
Coupling benchmark

Analysis strategy

Signal process
Backgrounds
Selection cuts

Progress

Current status
Validation
Next steps

Motivation: Dark Photons in Top-Associated Production

SM (QCD)
$gg \to t\bar{t}$

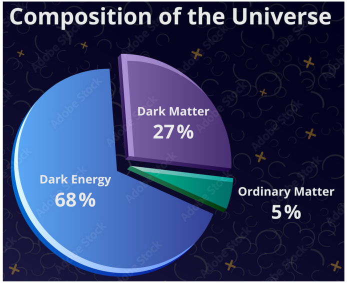
→

$t\bar{t}Z_D$
Mediator / Portal

→

BSM
$U(1)_D$ / Z_D

-
- **Dark photons (Z_D)** arise from $U(1)$ extensions of the SM
  - Kinetic mixing: $\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F_{D\mu\nu}$
  - Direct couplings: $\sum_f \bar{f}\gamma^\mu(g_V - g_A\gamma^5) f Z_{D\mu}$
- **Top quark as probe:**
  - Heaviest SM fermion → enhanced coupling sensitivity
  - $t\bar{t}Z_D$: $gg \to t\bar{t}Z_D$ (82.7%), $q\bar{q} \to t\bar{t}Z_D$ (17.3%)
  - Clean signature: $3\ell + \text{MET} + 4j + 2b$



Theoretical Framework

Lagrangian

$$\mathcal{L}_{\text{int}} = \frac{g_w}{2\cos\theta_W} \sum_f \bar{f}\gamma^\mu(g_V - g_A\gamma^5) f Z_{D\mu}$$

where g_V and g_A are the vector and axial couplings.

Coupling Parameterisation

$$g_V^{\text{phys}} = g_V, \qquad g_A^{\text{phys}} = g_A\sqrt{1 - g_V^2}$$

Guarantees: $g_V^2 + g_A^2(1 - g_V^2) \leq 1$

Total Coupling: $g = \sqrt{g_V^2 + g_A^2}$

Model Features

- New $U(1)_D$ gauge boson (dark photon)
- Flavour-universal couplings to all SM fermions
- Z_D width computed dynamically from all kinematically accessible decays

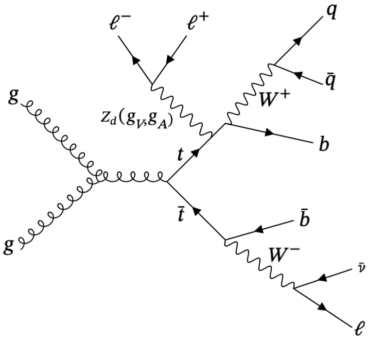
Signal and Background Processes

Signal Model

- Simplified Dark Photon (Z_D) model
- Production: $pp \to t\bar{t}Z_D$
- Mass range: $m_{Z_D} = 50\text{–}2500\ \mathrm{GeV}$
- Decay: $Z_D \to \ell^+\ell^-$ $(\ell = e, \mu)$
- Benchmark: $(g_V, g_A) = (0.7, 0.3)$

Background Processes

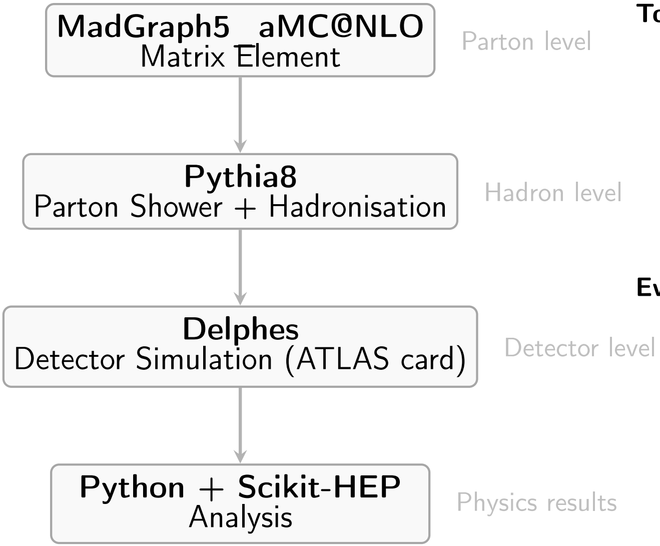
- $t\bar{t}Z$ (irreducible, same final state)
- $t\bar{t}W$ (3 prompt leptons)
- $t\bar{t}\ell^+\ell^-$ $(Z/\gamma^*$ contribution)
- WZ (diboson, rejected by jet cuts)



- Semileptonic channel: one $W \to q\bar{q}$, one $W \to \ell\nu$
- Final state: $3\ell + \text{MET} + 4j + 2b$ (signature interest)

HL-LHC: $\sqrt{s} = 14$ TeV, $\mathcal{L} = 3000\ \text{fb}^{-1}$

Simulation Workflow



Tools Summary

- **Matrix Element:** MadGraph5_aMC@NLO
- **Shower:** Pythia8
- **Detector:** Delphes (ATLAS card)
- **Analysis:** Python + Scikit-HEP

Event Statistics

- Signal: 10,000 events per mass point
- Backgrounds: 10,000–200,000 events per sample

Analysis Strategy

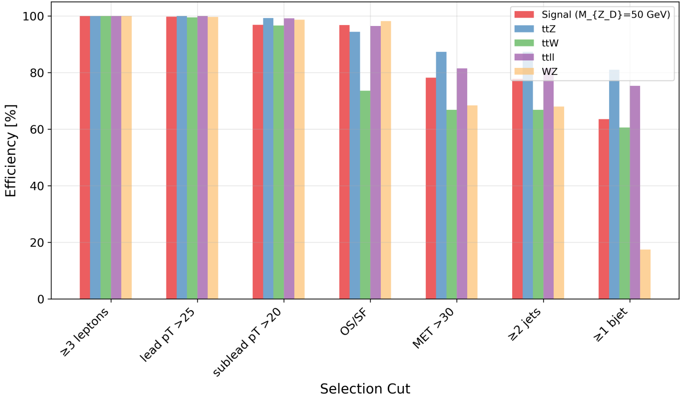
Object Definitions

Object	Requirement
Electrons	$p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$
Muons	$p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$
Jets	anti-k_T, $R = 0.4$, $p_T > 20$ GeV
b-tagging	70% efficiency
MET	p_T^{miss}

Event Selection

Cut	Value
≥ 3 leptons	-
lead p_T	> 25 GeV
sublead p_T	> 20 GeV
3^{rd} lepton p_T	> 10 GeV
OS/SF pair	-
MET	> 30 GeV
≥ 2 jets	-
≥ 1 b-jet	-

Cutflow Efficiency (Preliminary)



Observations

- Signal efficiency: 11.84% after full selection
- WZ killed by b-jet requirement
- $t\bar{t}\ell\ell$ similar to signal

Status

- Framework validated for 50 GeV
- Background statistics being improved
- Systematics under study

Cutflow Table (Unweighted) -Preliminary

Table: Cumulative efficiency [%] after each selection cut.

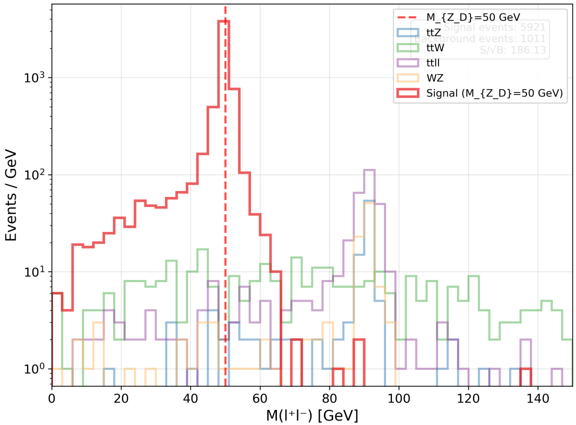
Cut	Signal (50 GeV)	ttZ	ttW	ttll	WZ
$\geq$ 3 leptons	18.64	0.88	0.33	14.01	0.34
lead $p_T > 25$	18.59	0.88	0.33	14.01	0.34
sublead $p_T > 20$	18.06	0.87	0.32	13.90	0.33
OS/SF	18.05	0.83	0.24	13.52	0.33
MET > 30	14.57	0.77	0.22	11.42	0.23
$\geq$ 2 jets	14.50	0.77	0.22	11.42	0.23
$\geq$ 1 b-jet	11.84	0.71	0.20	10.56	0.06

Key Observations

- **Signal:** 11.84% total efficiency
- **b-jet cut:** Reduces WZ (0.23% $\rightarrow$ 0.06%)
- **ttll:** High efficiency (same final state)
- **ttZ/ttW:** Suppressed by jet/b-jet cuts

Note: Unweighted event counts. Efficiencies relative to generated events.

Dilepton Mass: Signal vs Background (Unweighted)



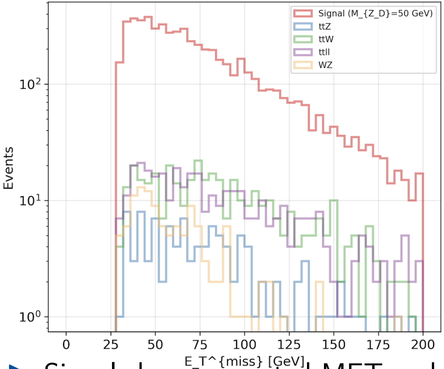
Preliminary observations

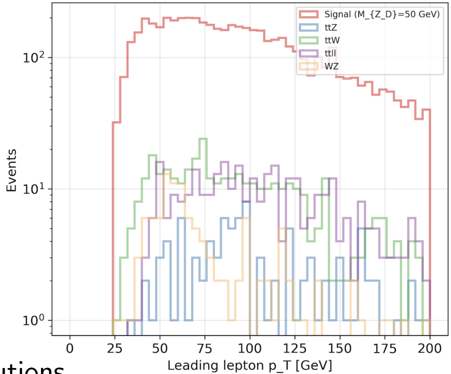
- Signal peak observed at $m_{Z_D} = 50$ GeV
- Background: Smooth continuum
- **Note:** Unweighted event counts

Validation in progress

- Cross-check with $Z \to \ell^+\ell^-$ peak
- Comparing with SM predictions
- More statistics needed for higher masses

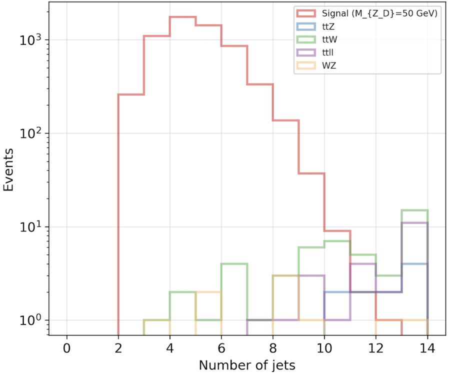
Kinematic Distributions (Unweighted)

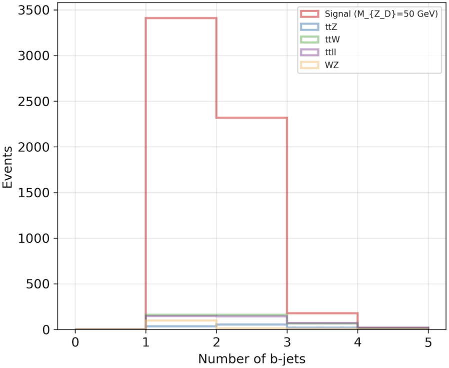




- Signal shows expected MET and p_T distributions
- Background shapes consistent with SM expectations
- PDF and scale uncertainties being evaluated
- Unweighted distributions — show relative shapes

Jet and *b*-jet Multiplicities (Unweighted)





b-jet multiplicity distribution

- Signal shows ≥ 4 jet requirement for hadronic W decay
- ≥ 2 *b*-jets consistent with top quark decays
- **Validation in progress:** b-tagging efficiency being validated

Selection Summary (Unweighted)

Table: Surviving events after full selection ($M_{Z_D} = 50$ GeV).

Sample	Events after cuts	Efficiency [%]	Generated Events
Signal (50 GeV)	**5,921**	**11.84**	50,000
$t\bar{t}Z$	115	0.71	16,195
$t\bar{t}W$	396	0.20	197,099
$t\bar{t}\ell\ell$	382	10.56	3,618
WZ	118	0.06	200,000
Total background	**1,011**	-	-
S/B		**5.86**	
S/$\sqrt{B}$ (stat. only)		**186.2**	

Notes:

- Unweighted event counts
- Statistical uncertainties only
- Different generated event counts due to sample statistics

Progress Summary & Next Steps

Completed	In Progress	Next Steps
Signal generation (50, 100 GeV)	Mass scan (60, 70, 80, 90, 200 GeV)	Generate remaining masses
Background samples	Systematic uncertainties	Validate against SM
Delphes simulation	Coupling limit calculation	Set exclusion limits
Analysis framework	ML optimisation	HL-LHC projections
Cutflow optimisation	Full background evaluation	Publication preparation
Mass peak observed		

Current status: Analysis framework validated with signal $M_{Z_D} = 50$ GeV
Work in progress — more investigation and validation being carried out

Outlook

- Complete mass scan (60, 70, 80, 90, 200 GeV) and measure σ vs m_{Z_D}
- Evaluate systematic uncertainties: PDF, scale, detector effects
- Optimise cuts using ML to improve signal/background discrimination
- Derive HL-LHC exclusion limits in (m_{Z_D}, g_V, g_A) space
- Study angular observables: helicity angles and spin correlations

Acknowledgements

Thank You

National Research Foundation (NRF) iThemba Labs
South African CERN Programme
ICPP
Nithecs

Questions?

thabo.james.lepota@cern.ch

Backup: Significance Context

- **S**/$\sqrt{B}$ = **186.2** is a **statistical figure of merit**
- **Not a realistic HL-LHC significance**
- **Why it's high:**
  - No systematic uncertainties
  - No pile-up
  - Generator-level + Delphes only
  - Raw event counts (not cross-section weighted)
- **Next steps:**
  - Include PDF and scale uncertainties
  - Add detector systematics
  - Include pile-up
  - Recalculate realistic significance