Exotics Searches and Long-Lived Particles

Sara Alderweireldt

on behalf of the ATLAS and CMS collaborations

La Thuile 2023 March 6th-10th, 2023







Beyond the Standard Model



Measured many SM parameters

- over a wide range of magnitude in cross section
- at multiple CoM energies

Despite great success of the SM still need to look beyond

- ▶ g 2
- flavour sector
- ..

Multiple avenues for searches at the LHC

Leptoquarks

Vector-Like Fermions

Resonances

Long-Lived Particles Unconventional Signatures Supersymmetry

BSM Hiaas

→ Aran's talk Dark Matter Fri, 17:20

> → Gabriel's talk ⊄ Fri, 16:30

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Exotics Searches and LLP (10/Mar 2023)



Leptoquarks

Leptoquarks offer a connection Between quark/lepton sectors through Yukawa interaction (λ)

- pair-, single-, or non-resonant production
- two scalar LQs or one vector LQ
- several free parameters \rightarrow grid scans (λ, β)
 - mass, charge, ...
 - β : BF into charged lepton ($\beta = 1$) or neutrino ($\beta = 0$)
 - κ : coupling to colour: nominal Yang-Mills ($\kappa = 0$)

or minimal ($\kappa = 1$)

- ► 🔬 LQ → $b\tau\tau$ (hh/lh)
- ► \bigotimes LQLQ → $b\tau b\tau$

NEW

NFW

- ► A LQLQ → tvbℓ / tℓbv
- ► 🔬 LQLQ → $t\ell t\ell$
- ► \bigotimes LQ / LQLQ \rightarrow $b\tau b\tau / b\tau \tau / \tau \tau$
- lacktriangleright hadronic $\tau + E_T$

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ATLAS-CONF-2022-037

🔊 Scalar Leptoquarks

$\tau \mathbf{L} \mathbf{Q}^{\tilde{S}_1} \rightarrow b \tau_{had} \tau_{had} \ / \ b \tau_{lep} \tau_{had}$

- Singly- and pair-produced scalar LQ → tau + b-hadron
 - $\hfill\square$ range of LQ ${\rightarrow}b\tau$ Yukawa coupling strength λ
- > \geq 1 b-jet, 2 τ , opposite-sign leptons, high b-jet p_T , high S_T selection
 - had-had and lep-had τ decays
 - $\hfill\square$ signal/background discrimination in S_{T}
 - $\hfill\square$ top background correction in function of S_{T}
- limited by statistics & top background modelling systematics
- m(LQ) excluded up to 0.89 (1.28) TeV for $\lambda = 1.0$ (2.5) for singly-produced LQ





Reproduced Leptoquarks $LQ_3^{d(u)}LQ_3^{d(u)} \rightarrow b\tau b\tau$

- **Pair-produced scalar or vector LQ** \rightarrow tau + b-hadron (3rd gen) interactions within the same family
- \blacktriangleright \geq 2 jet (\geq 1 b-jet), 2 τ , opposite-sign leptons, high S_T selection
 - had-had and lep-had τ decays
 - top background correction in function of S_T
- PNN multivariate discriminant, parametrised in LQ mass
 - using multiplicity, kinematic, and angular features
- m(LQ) excluded up to 1.49 TeV (scalar) and 1.69/1.96 TeV (min/YM vector)



Interpretation for scalar/vector(YM/min) LQ



arXiv:2303.01294 @@ NEW





3(LQ



\bigcirc Pair-produced Leptoquarks \rightarrow 1 lepton $LQ_{mix}^{d(u)}LQ_{mix}^{d(u)} \rightarrow t\nu b\ell/t\ell b\nu$

- Scalar or vector LQ \rightarrow 3rd gen guark + 1st/2nd gen lepton
- >4 jet, >1 b-jet, =1 lepton, E_T > 250 GeV selection • top background correction in function of $m_{\rm eff}$
- Dedicated NN (NeuroBayes) trained separately for scalar/vector LQ channels signal/background selection in NN, then simultaneous fit over all regions
- limited by statistics, top modelling systematics, and JES uncertainties
- m(LQ) excluded up to 1.46 TeV (scalar) and 1.71/1.98 TeV (min/YM vector)



SR NN output score

t, bLQ^u_{mix} pvLQ_{mi}, $\nu.\ell$ LQ_{mix}^{u} p $\mathrm{vLQ}_{\mathrm{mix}}$ t, b

arXiv:2210.04517

$\begin{array}{c} \widehat{\hbox{\rm Pair-produced Leptoquarks}} \rightarrow multilepton \\ {\hbox{\rm LQ}}^d_{{\rm mix}} {\hbox{\rm LQ}}^d_{{\rm mix}} \rightarrow t\ell t\ell \\ \end{array}$

- ▶ Pair-produced scalar/vector LQ \rightarrow top + multi-lep (2 ℓ SS; 3 ℓ , 4 ℓ)
- ► ≥ 2 jet (≥ 1 b-jet), $\geq 2\ell$ selection

■ signal/background discrimination in $m_{\text{eff}} = \sum_{j \in l, \ell} p_T + E_T$ and high $m_{\ell \ell}^{\min}$

- limited by statistics, lepton ID systematics
- ▶ m(LQ) excluded up to 1.6 TeV (scalar) and 1.7/2.0 TeV (min/YM vector)





Interpretation for scalar/vector(min/YM) LQ



ATLAS-CONF-2022-052



CMS-PAS-EX0-19-016 📓 🖻

3rd gen Leptoquarks $LQ_3 \rightarrow b\tau b\tau / b\tau \tau / \tau\tau$

- Single-, pair-, and non-resonant LQ production & scalar and vector LQ interpretation
- \geq 1 b-jet, \geq 1 τ (hh, lh, ll) selection
 - categorise by tau-decay channel
- Novel non-resonant production $\rightarrow \tau$ pair channel
 - exploit angular separation x between taus
- m(LQ) excluded up to 1.25 TeV (scalar) and up to 1.53/1.86 TeV (min/YM vector), for $\lambda = 1$
 - \Box excess at higher mass/ λ , most prominent in non-resonant production





CMS-PAS-EX0-19-016 📓 🖻

🎽 3rd gen Leptoquarks $LQ_3 \rightarrow b\tau b\tau / b\tau \tau / \tau\tau$

- Single-, pair-, and non-resonant LQ production & scalar and vector LQ interpretation
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137 fb⁻¹ (13 TeV) $\tau_h \tau_h$, $m_{vis} > 600 \text{ GeV}$ Events / 1 104 LQ. 2000 GeV. \u03c8=2.5 - Scalar nonree a = 63 10^{3} → τ. fake: rell-Yan with I -> 10 10-

 $\tau\tau$ SR angular separation



Vector LQ interpretation ($\lambda = 2.5, \kappa = 0$)

$m_{1,0} - \lambda$ plane 2D exclusion ($\kappa = 0, \beta = 1$)



Obs. / Bkg. 1.5

0.5



 $\sigma B(W \rightarrow \tau v)$ (fb)

10⁴

10³

102

10

1000

(Submitted to JHEP) arXiv:2212.12604 🖾 🖉 NEW

10000

138 fb⁻¹ (13 TeV) Events / GeV - Data n'_{ac} = 1.0 TeV \succ $\tau_h + \not\!\! E_T$ selection CMS m_w = 5.0 TeV W+iets 10 m_{OBH} = 5.0 TeV Misid. τ. • Search for BSM physics in $m_{T}(\tau, E_{T})$ variable 10 FFT tensor DY+iets Top quark-Multiple interpretations Diboson □ heavy charged W' boson \rightarrow exclusion up to 4.8 TeV 10-□ **guantum black hole** \rightarrow exclusion up to 6.6 TeV 10t-channel (non-resonant) LQ production 10 \rightarrow exclusion up to 0.2/0.5/5.9 TeV (LH/LH+RH/democratic, $\lambda = 1$) 10 Data - Bkg Bkg Uncertainty 2D interpretation ifo. coupling strengths model-independent and EFT limits 10^{3} 4×10² 2×10³ m₊ (GeV) Quantum black hole Non-resonant LQ production ($\lambda = 1$) Heavy charged boson 138 fb⁻¹ (13 TeV) 138 fb⁻¹ (13 TeV) 138 fb⁻¹ (13 TeV) (g (fb CMS CMS CMS 95% CL upper limits U, t-channel, g, = 95% CL upper limits 95% CL upper limits (ב ל ь 10 10⁵ - Observed σ SSM W' (NNLO) σ QBH (LO), n=4 Median expected Rost fit I H+RH σ SSM W', unc. Observed σB(QBH-68% expected Democrati Observed 104 Median expected 95% expected Median expected 10 68% expected 68% expected 10³ 95% expected 95% expected 10 10^{-1} 5000 2000 2000 8000 2000 3000 4000 4000 6000 8000 10000 0 4000 6000 m_{Mr} (GeV) mOBH (GeV) min (GeV)

🔝 🕎 Leptoquark Summary Plots

ATL-PHYS-PUB-2022-012

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- LQ3LQ3, all contours at 95% confidence lev

Vector-Like Fermions

Vector-Like Fermions are a BSM extension which

- allows to avoid Higgs Yukawa constraints \clubsuit the hierarchy problem \rightarrow composite models, \ldots
- has non-chiral new particles \rightarrow same L/R charges/isospin
- triplet/double/singlet vector-like quarks (VLQ): T, B, X, Y
- doublet/singlet vector-like leptons (VLL): charged E, neutral N
- Branching fractions depend on representation
- Often assume decays to 3rd generation

🕨 🔝 3rd gen VLL



- ▶ M VLQ TT/BB $\rightarrow 2/3\ell$
- ► A VLQ TT/BB $\rightarrow 1\ell + \textbf{\textit{E}}_T$
- Kale VLQ mono-top (backup)

3rd generation Vector-Like Leptons

- ► Consider SU(2) doublet $L' = (v'_{\tau}, \tau')$ VLL \rightarrow 3rd gen SM leptons
- Multi-lepton 2ℓ , 3ℓ , $\geq 4\ell$ ($\geq 0\tau_h$) selection
- BDT discrimination: 7 SRs for different lepton multiplicities
 - 7 training regions, 34 kinematic & topological features
 - $\hfill\square$ multiple VLL τ' signals in training
- limited by statistics
- m(VLL) excluded up to 900 GeV
 - similar to CMS-PAS-EXO-21-002 2 r

Background estimation & validation



BDT discrimination



7 signal regions by lepton multiplicity







arxiv:2303.05441 📾 🖉 NEW

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Exotics Searches and LLP (10/Mar 2023

M_[GeV]

Vector-Like Quark pair production (TT/BB)

arXiv:2210.15413 📾 🖻 arXiv:2212.05263 📾 🖻

$2/\geq 3$ leptons

- ▶ high p_T Z → ≥ 1 b-jet + OSSF ℓ + extra ℓ
- DNN for large-R jet tagging (W/Z/H/top)
 - multi-class boosted object tagger: MCBOT
 - 19 fit categories based on DNN tags and lepton & b multiplicity
 - binned likelihood fit

1 leptons + E_T

- ► Zt/Ht/Wb / Zb/Hb/Wt $\rightarrow \geq 4$ jets (≥ 1 b-jet) + 1 $\ell + E_T$
- ▶ 7 NNs (NeuroBayes) trained for different TT/BB BF mixes
 - □ preselection in m_T , $W \& m_T$, 2 (CR/SR)
 - top background reweighting ifo. N_i / m_{eff}
 - 13 input features
 - binned likelihood fit



Vector-Like Quark pair production (TT/BB)

arXiv:2210.15413 📾 🖻 arXiv:2212.05263 📾 🖻

$2/\geq 3 \text{ leptons}$

- Singlet/doublet/pure interpretations
 2/3ℓ combination
- Zt+X sensitivity bottom-left in mass/BF plane



1 leptons + ∉_T

- Singlet/doublet/pure interpretations
- ► largest sensitivity for T→Zt (bottom-left) and B→Wt (bottom-right in mass/BF plane)



Resonance searches



- heavy resonances in γ+jet
- Image: di-lepton resonances
- 🕨 🎇 low-mass μμ

- NEW
- ⁽¹⁾ 3/4 body masses in leptons+jets (backup)

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CMS

 $q^* \rightarrow q\gamma$

CMS-PAS-EX0-20-012 📓 🖻

Resonance search in m_{y+iet} spectrum

- interpretation for models with excited quarks (q*/b*) and quantum black holes (ADD/RS)
- □ q \leftrightarrow q^{*} via contact interaction at Λ scale $\gg \sqrt{s}$, or via gauge mediation $< \sqrt{s}$

Heavy resonances in γ +jet

- γ + jets selection
 - recluster wide jets (ΔR =1.1) including FSR to improve m_{v+iet} resolution (1-1.3%)
 - □ select back-to-back $\Delta R(\gamma, jet) > 1$
- Smooth parametrised fit over mytiet
- Resonance masses excluded up to 6.0 / 2.2 / 7.5 / 5.2 TeV for q^* / b^* / ADD QBH / RS QBH

cross-section: $QBH > q^* > b^*$

CMS Simulation Preliminary 107 ADD QBH (n=6) CMS Preliminary 10 RS1 QBH (n=1) 10 f=0.5 10 /ents/bin b* f=0.5 [qd] *H* × 10 $\times B$ (fb) Data b 10 10 Fit to data 10 10 10 10 Expected ± 2σ Excited quark (f=1 10 2000 7000 8000 Resonance mass [TeV] Mass (GeV) m_{v+jet} [TeV] Exotics Searches and LLP (10/Mar 2023)

Fit of $m_{\nu+iet}$ spectrum







CMS-PAS-EX0-21-018 🕎 🕫

Di-lepton resonances from decays of (pseudo-)scalar bosons

- Search for new, light, neutral, spin-0 boson ϕ , in associated production with W/Z/tt
 - consider scalar, pseudo-scalar, and higgs-like couplings
 - □ di-lepton decays with lepton number & charge conservation $\rightarrow 3/4\ell$ final states
- 7 distinct orthogonal channels of different τ/light lepton multiplicities
 - categorise in N_i, N_b, N_{OSSF} & define inv/transv. masses
 - □ further selection on S_T , $p_{T,3}$, m_ℓ , q_ℓ
- 12+12+13 ($ee/\mu\mu/\tau\tau$) = 37 SRs for 24 signal models





Interpretation for (pseudo)scalar/higgs-like ϕ in W/Z/tt ϕ



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Exotics Searches and LLP (10/Mar 2023)



- Search performed on dedicated scouting trigger stream (2017–2018)
 - record di-muon events with transverse momenta as low as 3 GeV
 - save only partial event information to reduce the high-level trigger rate

Search for narrow resonances in the low mass range

- bump hunt 1.1–2.6 and 4.2–7.9 GeV range in di-muon mass
- multivariate ID to reduce mis-ID muon contribution, and data-driven trigger & reco efficiency
- \Box J/ ψ (Y) training for low mass/boosted (higher mass) category
- background est.: O(4) Bernstein combinatorial + peaking from CRs, signal: double CB + gaussian
- □ largest excess $3.2(1.3)\sigma$ local (global) at m_{µµ} = 2.41 GeV
- Limits set on di-muon resonance production
 - □ interpretation in the context of a dark photon model, and a 2HDM+scalar model $\sim g - 2$
- ► Using the same trigger: observation of $\eta \rightarrow 4\mu$, CMS-PAS-BPH-22-003 🕎 @



Exotics Searches and LLP (10/Mar 2023)

 $\sin(\theta_{H})$

10



Long-Lived Particles & Unconventional Signatures

Consider charged/neutral LLPs and more unconventional signatures

- unusual energy deposits
- displaced vertices

Also with unconventional Backgrounds

- detector noise
- Machine-induced Background
- data-driven approaches

- Pixel dE/dx
- Multi-Charged Particles
- Fractionally Charged Particles
- Displaced Vertices + jets
- Displaced Heavy Neutral Leptons

- Kale (Vertexed) Displaced Photons
- Delayed Trackless Jets
- Displaced 'hadronic' jets (backup)
- Decays in the muon system (backup)

Ionisation in Trackers

Pixel dE/dx

Target massive charged LLPs

□ determine $m \sim$ Bethe-Bloch: m = $p / \beta \gamma$

• High E_T , high p_T isolated track, large ionisation selection

- □ calibrate dE/dx ~ $\beta\gamma$ in low mu runs
- fully data-driven background estimation
- Consistent with SM in all-but-one SR
 - □ 3.6 (3.3) σ local (global) excess ~ 1.4 TeV
 - □ not confirmed to be consistent with actual slow particles in additional ToF measurements ($\beta \sim 1$)
 - could still be consistent with e.g. boosted LLPs, or MCPs [ref]

Multi-Charged Particles

arXiv:2205.06013 @

ATLAS-CONF-2022-034

- Target heavy multi-charged particles (|q| = 2 7e)
 - $\ \ \, \square \ \ \, long-lifetime \rightarrow exploit \ \ muon-like \ \ signature$
 - anomalously high ionisation dE/dx in ID, TRT, and MDT
- Single/late muon + *E_T* preselection
 MDT dE/dx significance for final selection
- m(MCP) excluded between 500-1600 GeV
- Sensitivity insufficient to probe cross-sections relevant in pixel dE/dx excess context



CMS-PAS-EX0-19-006 🕎 🖻



Fractionally Charged particles

- Consider free-propagating particles with charges < 1e</p>
 - Dertal scenarios, hidden symmetries, fields weakly/non-connected to the SM
 - Previous results for |q| = 2/3 from 7 & 8 TeV analyses

▶ FCPs only ionise matter weakly \sim low charge \rightarrow analyse tracker dE/dx

- □ count 'low' dE/dx hits: background ≪ signal
- tracker layer dependent 'low' threshold
- almost background free SRs
- ▶ FCPs excluded for masses up to 636 GeV for charges 0.5-0.9e



Displaced vertices

Target LLP decays inside the inner tracker

Displaced Vertex + jets

- Search for LL particles decaying into hadrons
- 2-7 high p_T jet selection + ≥1 displaced vertex with ≥5 tracks and mass>10 GeV
 - □ additional dedicated SR for lower p_T jets
 - rely on large-radius tracking
- Interpretation for strong and EW production SUSY models
 - limits set in broad ps-ns range



Displaced Heavy Neutral Leptons

arXiv:2301.13866 @@ NEW arXiv:2204.11988 @@

- Displaced vertex from decay of LL HNL
- Prompt lepton + opposite-sign, displaced, di-lepton vertex selection
 - HNL mass reco through energy-momentum conservation
 - rely on large-radius tracking
- Interpretation both for LFC and LFV scenarios
 - first direct search results for two-quasi degenerate HNL models (2QDH)
 - $\hfill\square$ good agreement with SM \rightarrow limits set



(Vertexed) delayed displaced photons

arXiv:2209.01029 📾 🕫 ATLAS-CONF-2022-051 📾 🕫

Target photons from heavy LLP decays

- late w.r.t. bunch crossing + non-pointing
- exploit LAr calorimeter timing and pointing: \sim 0.2ns/10mm resolution \rightarrow derive pointing in z along the beam axis

Not vertexed

2γ from LL NLSPs + trigger on lepton leg

- photons from different decays
- Shape fit of timing distribution in $1\gamma \ge 2\gamma$ & pointing/timing categories
- Interpretation ~ GMSB model
 - □ scan BF(→NLSP pair) & NLSP-LSP mass splitting

Vertexed

2γ / 2e from H/Z decays

- photons from the same decay
- Shape fit of timing distribution in pointing/timing categories
- Interpretation ~ GMSB model
 - □ for both pure NLSP→Z/H + \tilde{G} , w.r.t. mass/lifetime



(Vertexed) delayed displaced photons

arXiv:2209.01029 🔬 🕫 ATLAS-CONF-2022-051 🔬 🕫

Target photons from heavy LLP decays

- late w.r.t. bunch crossing + non-pointing
- exploit LAr calorimeter timing and pointing: \sim 0.2ns/10mm resolution \rightarrow derive pointing in z along the beam axis

Not vertexed

2γ from LL NLSPs + trigger on lepton leg

- photons from different decays
- Shape fit of timing distribution in 1γ/ ≥ 2γ & pointing/timing categories
- ▶ Interpretation ~ GMSB model
 - □ scan BF(→NLSP pair) & NLSP-LSP mass splitting



Vertexed

2γ / 2e from H/Z decays

- photons from the same decay
- Shape fit of timing distribution in pointing/timing categories
- Interpretation ~ GMSB model
 - $\hfill\square$ for both pure NLSP ${\rightarrow}$ Z/H + $\tilde{G},$ w.r.t. mass/lifetime



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(Submitted to JHEP) EX0-21-014 🕎 🖉





- DNN based on trackless and out-of-time information
 - 22 track & ECAL features
 - jet time resolution 400-600ps
- 2D interpretation scanning $c\tau$ and m(NSLP)
 - m(NLSP) excluded up to 1.18 TeV
 - highest sensitivity around $c\tau \sim 0.5m$
 - \Box previous results based on tracks: smaller $c\tau < 0.2m$, or muon system: larger $c\tau > 1m$





Summary & Outlook

- Many new and improved results from both experiments on
 - Leptoquarks
 - Vector-Like Fermions
 - Resonance searches
 - Long-Lived Particles & Unconventional Signatures
- Various detailed summary plots available: see backup slides
- Stay tuned for more results as Run 3 data becomes available from ATLAS and CMS!



Exotics Searches and LLP (10/Mar 2023)

Additional material





Mono-top + invisible

- Target top-associated DM or VLQ (T)
- DNN top and b-tagging
- Top-tagged jet + lepton veto + high ∉_T selection
 □ categorise in Nb and min(Δφ(jet,∉_T))
- Extreme gradient BDT for sig/bkg discrimination
 - 3 versions: VLQ, resonant, and non-resonant DM
- Apply likelihood fit on yields and score
 - interpret ifo. resonanant / non-resonant DM production
 - □ in association with single *t* or single vector-like *T*







ATLAS-CONF-2022-036



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3/4 body masses in lepton+jets

- Heavy resonance search
- 2 jets (incl. b-jets), =1 lepton (e/μ) selection
- Fit 3/4-body invariant mass spectra w/ multiple interpretations
 - model-independent limits on generic resonances
 - assuming gaussian resonance peaks
 - dedicated interpreations
 - SSM W'->WZ' with small ΔM(W',Z'); excluded < 2.5 GeV
 - DM SM axial-vector Z' + SM W
 - W_{KK} with phi radion \rightarrow gg; excluded mphi < 1 TeV
 - composite lepton with Z'; excluded (500 GeV ℓ, <1.3 TeV Z')

Invariant mass distributions

Model-independent results

Model-specific results



arXiv:2211.08945 🗛🛛

Exotics Searches and LLP (10/Mar 2023)

Displaced "hadronic" jets

Targetting benchmarks in hidden sector models

CalRatio

- ► low/high *E*_T CalRatio selection
 - isolated calorimeter activity
 - dedicated CalRatio trigger (ratio had/EM deposits)
- Dedicated NN solutions for BIB/QCD background
 - Adversary Network to avoid using info not well-modelled in simulation
 - per-event BDT for beam-induced-background discrimination
- Limits set for
 - mediator masses 60 GeV-1 TeV, improved both above/below 200 GeV
 - LLP scalar masses 5–475 GeV



JHEP 06 (2022) 005, arXiv:2203.01009 @@ ATLAS-CONF-2022-038 @@

Semi-visible jets

- Semi-visible jets from partial decays back to SM particles
- Select on
 - back-to-back jet balance
- Limits set for mediator masses 1–5 TeV
 - exclusion in 2.4–2.7 TeV window
 - additional interpretation ifo. coupling strength



Decays in the muon system

DV from neutral LLPs

- Decays to hadronic jets in the muon spectrometer
 - two displaced decays in the muon system
 - veto on ID/calo activity
 - dedicated trigger
- Interpretation for scalar portal model
 - □ (scalar) $\Phi(125) \rightarrow ss$ (long-lived)
 - □ limits set ifo. lifetime and $BF(\Phi \rightarrow ss)$



Phys. Rev. D 106(2022)032005, arXiv:2203.00587 & arXiv:2206.12181 & &

Collimated pairs of leptons/light hadrons

- Displaced collimated SM fermions in calo/MS
 - two displaced decays in the muon system
 - veto on ID activity
- Interpretation for LL dark photons
 - limits set ifo. mass and lifetime, and kinetic mixing parameter SM-hidden sector



Summary Plots

ATI AS Preliminary

M	arch 2022	ouronoo								$\sqrt{s} = 13 \text{ TeV}$
	Model	s	Signatur	re ∫-	[dt [fb-	'] Ma	ss limit			Reference
s	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$	0 e, µ mono-jet	2-6 jets 1-3 jets	E_{T}^{miss} E_{T}^{miss}	139 139	<pre># [1×, 8× Degen.] # [8× Degen.]</pre>	1.0 0.9	1.85	m($\tilde{t}_1^0)$ <400 GeV m(\tilde{q})-m(\tilde{t}_1^0)=5 GeV	2010.14293 2102.10874
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{k}_{1}^{0}$	0 e, µ	2-6 jets	$E_T^{\rm miss}$	139	8	Forbidden	1.15-1.95	m(t ⁰)=0 GeV m(t ¹)=1000 GeV	2010.14293 2010.14293
Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W \tilde{\chi}_{1}^{0}$	1 e, µ	2-6 jets		139	8		2.2	m(t ⁰ ₁)<600 GeV	2101.01629
sive	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{0}$	ee, µµ	2 jets	E _T	139	8		2.2	m(x ⁰)<700 GeV	CERN-EP-2022-014
clus	$gg, g \rightarrow qqWZX_1$	SS e, µ	6 jets	L _T	139	8	1	.15	m(ž)-m(ž)=200 GeV	1909.08457
4	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{t}_1^0$	0-1 e.μ SS e.μ	3 b 6 jets	E_T^{dinse}	79.8 139	18 18		1.25	m(ž ⁿ ₁)<200 GeV m(ž)-m(ž ⁿ ₁)=300 GeV	ATLAS-CONF-2018-041 1909.08457
arks tion	$\tilde{b}_1 \tilde{b}_1$	0 e, µ	2 b	$E_T^{\rm miss}$	139	b ₁ b ₁	0.68	1.255	m(² ⁰ ₁)<400 GeV 10 GeV<Δm(² ₀₁ , ² ₁)<20 GeV	2101.12527 2101.12527
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b	E_T^{miss} E_T^{miss}	139 139	bi Forbidden bi	0.13-0.85	.23-1.35	$\operatorname{Am}(\tilde{t}_{2}^{0}, \tilde{t}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{t}_{1}^{0}) = 100 \text{ GeV}$ $\operatorname{Am}(\tilde{t}_{2}^{0}, \tilde{t}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{t}_{1}^{0}) = 0 \text{ GeV}$	1908.03122 2103.08189
squa	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e.µ	≥ 1 jet	E_T^{miss}	139	Ĩ1		1.25	m($\tilde{\ell}_{1}^{0}$)=1 GeV	2004.14060,2012.03799
Pro-	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W h \tilde{\chi}_1^{\prime}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_2 h \mu, R_1 \rightarrow \pi \tilde{C}$	1 e, µ	3 jets/1 b 2 jets/1 b	E_T^{minx}	139	11 7.	Forbidden 0.65	14	m(²)=500 GeV m(²)=800 GeV	2012.03799 2108.07865
3 ^N g	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow o \tilde{\ell}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow o \tilde{\ell}_1^0$	0 e. µ 0 e. µ	2 c mono-jet	E_{L}^{miss} E_{T}^{miss}	36.1 139	ě Î ₁	0.85		m(t ⁰)=0 GeV m(r,z)-m(t ⁰)=5 GeV	1805.01649 2102.10874
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0$	1-2 e,µ	1-4 b	E_T^{miss}	139	ĩ,	0.067-	1.18	m(x2)=500 GeV	2006.05880
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ	1 b	E_T^{miss}	139	Ĩ ₂	Forbidden 0.86		$n(\tilde{t}_1^0)=360 \text{ GeV}, m(\tilde{t}_1)=m(\tilde{t}_1^0)=40 \text{ GeV}$	2006.05880
	$\hat{\chi}_1^* \hat{\chi}_2^0$ via WZ	Multiple ℓ/je ee, µµ	ts ≥1 jet	E_T^{miss} E_T^{miss}	139 139	$\frac{\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}}$ 0.205	0.96		$\begin{array}{c} m(\tilde{\chi}_1^0){=}0, \text{wino-bino} \\ m(\tilde{\chi}_1^*){-}m(\tilde{\chi}_1^0){=}5 \text{ GeV, wino-bino} \end{array}$	2106.01678, 2108.07586 1911.12606
W. BCI	$\hat{\chi}_{1}^{*}\hat{\chi}_{1}^{*}$ via WW	2 e, µ		E_T^{miss}	139	\hat{X}_{1}^{\dagger}	0.42		m(x1)=0, wino-bino	1908.08215
	$\chi_1^*\chi_2^*$ via Wh $\chi^+\chi^+$ via Z (0)	Multiple //je	IS	E-miss	139	X ₁ /X ₂ Forbidden	1.0	5	m(X1)=70 GeV, wino-bino	2004.10804, 2108.07586
	$r_{1}r_{1}$ via r_{L}/r	21		Erniss	139	† [†L-†R.L] 0.16-0.3	0.12-0.39		$m(r,v)=0.5(m(v_1)+m(v_1))$ $m(\tilde{v}_1)=0$	1911.06660
- 18 19	$\tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e.μ ee.μμ	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	2 2 0.256	0.7		m($\tilde{\xi}_1^0$)=0 m($\tilde{\ell}$)-m($\tilde{\xi}_1^0$)=10 GeV	1908.08215 1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e. µ	$\geq 3 b$	ETims	36.1	Ĥ 0.13-0.23	0.29-0.88		$BR(\hat{t}_{j}^{0} \rightarrow h\bar{G})=1$	1806.04030
		0 e, µ	≥ 2 large je	E_T	139	H H	0.55		$BR(t_0^* \rightarrow ZG)=1$ $BR(t_0^* \rightarrow ZG)=1$	2108.07586
ъ.,	$\operatorname{Direct} \widehat{\chi}_1^* \widehat{\chi}_1^- \operatorname{prod., long-lived} \widehat{\chi}_1^*$	71 Disapp. tri	: 1 jet	$E_T^{\rm miss}$	139	$\frac{\tilde{\chi}_{1}^{\pm}}{\tilde{\chi}_{1}^{\pm}}$ 0.21	0.66		Pure Wino Pure higgsino	2201.02472 2201.02472
20S	Stable g R-hadron	pixel dE/dx		E_T^{miss}	139	ž.		2.05		CERN-EP-2022-029
ng.	Metastable § R-hadron, g→qq	R [®] pixel dE/dx Dirol loo		E ^{mass} E ^{miss}	139	g [r(g) =10 ns]	07	2.2	$m(\tilde{t}_{1}^{*})=100 \text{ GeV}$	CERN-EP-2022-029 2011 07812
20	<i>u</i> , <i>u</i> → <i>u</i>	Drapt. rep		**T	139	τ 0.	34		$\tau(l) = 0.1 \text{ ns}$	2011.07812
		pixel dE/dx		E_T^{men}	139	÷	0.36		$\tau(l) = 10 \text{ ns}$	CERN-EP-2022-029
	$\tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{*}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{*} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, µ			139	$\tilde{\chi}_{1}^{\pi}/\tilde{\chi}_{1}^{0}$ [BR(Zr)=1, BR(Ze)=1]	0.625 1.05		Pure Wino	2011.10543
	$\tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0 jets	E_T^{miss}	139	$\tilde{X}_{1}^{\pm} / \tilde{X}_{2}^{\pm} = [\lambda_{03} \neq 0, \lambda_{124} \neq 0]$	0.95	1.55	m(t ² 1)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq \chi_1, \chi_1 \rightarrow qqq$ $\tilde{g}, \tilde{g} \rightarrow qq \chi_1, \chi_1 \rightarrow qqq$		4-5 targe je Multiple	1.5	36.1	g [m(X ₁)=200 GeV, 1100 GeV]	0.55 1.05	1.3 1.9	mit ²⁰ 1-200 Gold bios Bio	ATLAS.CONF.2018.013
P 2	$ii_1 i \rightarrow ii_1 i_1 i_2 i_1 i_2 i_2 i_3 i_4 i_5 i_6 i_6 i_6 i_6 i_7 i_7 i_7 i_7 i_7 i_8 i_8 i_8 i_8 i_8 i_8 i_8 i_8 i_8 i_8$		$\geq 4b$		139	1	Forbidden 0.95		m(*;)=200 GeV, BH5-IM m(*;)=500 GeV	2010.01015
œ	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 /	, ,	36.7	$\tilde{t}_1 = [qq, bv]$	0.42 0.61			1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e. µ 1 µ	2 b DV		36.1 136	<i>l</i> ₁ <i>l</i> ₁ [1e-10< <i>X</i> ₁₁ <1e-8, 3e-10< <i>X</i> ₁₁	<39-9] 1.0	0.4-1.45	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow e\mu) = 100\%, cost = 1$	1710.05544 2003.11956
	$\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1,2}^{0} \rightarrow tbs, \tilde{\chi}_{1}^{+} \rightarrow bbs$	1-2 e,µ	≥6 jets	s 139		x ⁰ ₁ 0.2-0.3	2		Pure higgsino	2106.09609
										l
Only	a selection of the availabl	e mass limits on	new state	rs or	1	U	1		Mass scale [TeV]	

ATLAS SUSY Searches* - 95% CL Lower Limits

"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.

Exotics Searches and LLP (10/Mar 2023)

ATL-PHYS-PUB-2022-034

Summary Plots ATLAS

			and an					,		
Model	1.7	Jets	τ.	17 orlin .	1	Limit				Heterence
ADD G _{KK} + g/q ADD non-resonant yy ADD QBH ADD QBH multijet RS1 G _{KK} → tyy Buk RS G _{KK} → WW/ZZ Buk RS G _{KK} → WV → free	0 e.,µ, r, y 2 y 	1-4j 2j 33j	Yes - - -	129 36.7 129 2.6 129 36.1 129	Ma Ma Ma Sax mass Sax mass Sax mass		23TeV 4	11.2 Tel 8.6 Tel 9.4 Tel 9.55 Tel 5 Tel	x = 2 x = 3 HL2 NLO x = 6, Mb = 3 TeV, set EH $\frac{1}{2}(\frac{M_{H_{1}}}{M_{1}} = 0.1$ $\frac{1}{2}(\frac{M_{H_{2}}}{M_{1}} = 1.0)$	2102.10874 1707.04147 1910.08447 1910.08447 1912.02688 2102.13405 1908.02080 2004.1458
Bulk RS gex -> 11	14,4 21	1 6 213/2	Yes	26.1	Exx mass		2.87	eV.	f/m = 20%	1804.10823
$\begin{array}{c} \text{SSM} \ \mathcal{X}^* \rightarrow \ell\ell \\ \text{SSM} \ \mathcal{X}^* \rightarrow \ell\ell \\ \text{Lepsphole} \ \mathcal{X}^* \rightarrow \ell\epsilon \\ \text{Lepsphole} \ \mathcal{X}^* \rightarrow \epsilon\epsilon \\ \text{Lepsphole} \ \mathcal{X}^* \rightarrow \epsilon\epsilon \\ \text{SSM} \ \mathcal{W}^* \rightarrow \epsilon\epsilon \\ \text{SSM} \ \mathcal{W}^* \rightarrow \epsilon\epsilon \\ \text{SSM} \ \mathcal{W}^* \rightarrow \ell\epsilon \\ \text{SSM} \ \mathcal{W}^* \rightarrow \mathcal{W} \\ \text{SSM} \ \mathcal{W} \mathcal{W} \\ \text{SSM} \ \mathcal{W}^* \rightarrow \mathcal{W} \\ \text{SSM} \ \mathcal{W} \\ \ \mathcal{W} \mathcal{W}$	2 s.p 2 r 2 r 1 s.p 1 r 8 B 1 s.p 1 s 0 c 0 c 2 s.p 2 c 1 s 2 r 1 s 2 r 1 s 2 r 1 s 2 r 1 s 2 r 1 s 2 s 2 r 2 r 2 r 2 r 2 r 2 r 2 r 2 r 2 r 2 r	2b 1b, 22 J 2) (1a) 2) (1a) 2) (1a) 2b, 1-0 2b, 1-0 1 J	- Ves Ves Ves Ves Ves Ves	129 26.1 26.1 129 129 129 129 129 129 129 129 129 12	 Trans 	343 GeV	2.42 TeV 2.1 TeV 4.1 4.2 2.3 TeV 3.2 TeV	S.1 TeV S.0 TeV S.0 TeV S.0 TeV TeV TeV S.0 TeV	$Im (1/2, q/p^{-1} - q_{1}) = 1$ f/m = 1.2% $g_{1} = 1$ $g_{2} = 1$	10223874 1139230248 11392322 10253029 200531138 10062860 XFLAS CONF 2020- 20053402 20053402 200730220 20270220 20270220 10053029
Ci qaqaq Ci Adag Ci adaba Ci adaba Ci mmr	2.e.,µ 2.e 2.µ 21.e,µ 2	2j 1b 1b 1b,21j	- - Yes	27.0 129 129 129 26.1			1.8 TeV 2.0 TeV 2.57 TeV		$\begin{array}{c} 21.0 \text{ TeV} e_{11}^{\prime} \\ & 35.0 \text{ TeV} \\ z_{1}=1 \\ z_{1} =z_{1} \\ z_{1} =z_{2} \end{array}$	1703.09/27 2008.72948 2105.73947 2105.73947 1811.02205
Asial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac D/ Vector med. 21-2HDM (Dirac Pseudo-scalar med. 2HDM+a	0 e.,µ, r, y 8) 0 e.,µ, r, y DM) 0 e.,µ multi-channel	1-4 1-4 2b	Yes Yes Yes	129 129 129 129	E	275 GeV 560 Ge	2.1 TeV 2.1 TeV		$\begin{array}{l} g_{1}\!=\!0.26, \ g_{2}\!=\!1, \ m(g_{1})\!=\!1 \ \text{GeV} \\ g_{2}\!=\!1, \ g_{1}\!=\!1, \ m(g_{2})\!=\!1 \ \text{GeV} \\ \tan(l+1, \ g_{2}\!=\!0.8, \ m(g_{2})\!=\!1 \ \text{GeV} \\ \tan(l+1, \ g_{2}\!=\!0.8, \ m(g_{2})\!=\!1 \ \text{GeV} \end{array}$	2132.10874 2132.10874 2138.13091 #TLAS-CONF-2021
Scalar LO, 1 ^{er} gen Scalar LO, 2 ^{er} gen	2.0 2.µ 1.r 0.e.µ 2 2.e.µ,21r 2 0.e.µ,21r 0 1.r	222 b 2 1 2 1	Yes Yes Yes Yes Yes	129 129 129 129 129 129 129 129	0 mass 0 mass 0 mass 0 mass 0 mass 0 mass 0 mass 0 mass		1.0 TeV 5.7 TeV 5.2 TeV 1.20 TeV 1.20 TeV 1.40 TeV 1.26 TeV 5.27 TeV		$\begin{array}{l} \mu = 1 \\ \mu = 1 \\ \theta(LQ_1^* \to kr) = 1 \\ \theta(LQ_2^* \to ir) = 1 \\ \theta(LQ_2^* \to ir) = 1 \\ \theta(LQ_1^* \to ir) = 1 \\ \theta(LQ_1^* \to kr) = 1 \end{array}$	2008.05872 2008.05872 2108.07985 2004.14090 2101.11582 2101.02507 2108.07985
$\begin{array}{c} \text{VLQ } TT \rightarrow Zt + X\\ \text{WLQ } BH \rightarrow Wh (Zh + X)\\ \text{VLQ } T_{0:1}T_{0:1}T_{0:1} \rightarrow Wh t + .\\ \text{VLQ } T_{0:1}T_{0:1}T_{0:1} \rightarrow Wh t + .\\ \text{VLQ } Y \rightarrow Wh (Zt)\\ \text{VLQ } Y \rightarrow Wh (Zt$	2x/2µ/23xµ 2 muti-channel C 2(55)/23 xµ 2 1 xµ 2 1 xµ 2 0 xµ 22 muti-channel	21 b, 21 j 21 b, 21 j 21 b, 23 j 21 b, 23 j 21 b, 21 j 21 j 21 j	- Yes Yes Yes	129 36.1 35.1 129 36.1 129 129 129	E MARK E MARK E LA MARK E MARK E MARK E MARK I MARK		1.4 TeV 1.34 TeV 1.64 TeV 1.6 TeV 1.8 TeV 1.5 TeV 2.0 TeV 690 GeV		$\begin{array}{l} S3.32; doublet\\ S3.22; doublet\\ S3.22; doublet\\ S3.23; doublet, n = 1, e \{T_{4,1}, W0\} e \ 1\\ S3.23; doublet, n = 0, 5\\ S3.23; doublet, n = 0, 3\\ S3.23; doublet\\ S3.23; doublet\end{array}$	ATLAS-CONF-2021- 1808-22343 1807-11803 ATLAS-CONF-2021- 1812-07343 ATLAS-CONF-2021- ATLAS-CONF-2020- ATLAS-CONF-2020-
Excited quark q ² → qg Excited quark q ² → qg Excited quark d ² → bg Excited lepton t ² Excited lepton v ²	1y 26,4 26,47	2j 1j 1b,1j -		129 36.7 129 20.3 20.3	r mass r mass r mass r mass r mass		2.2 TeV 2.0 TeV 1.6 TeV	6.7 TeV 5.3 TeV	and u^* and u^* , $\Lambda = m(q^*)$ and u^* and u^* , $\Lambda = m(q^*)$ $\Lambda = 3.0$ TeV $\Lambda = 1.6$ TeV	1910-38647 1739-10663 1910-5667 1411-3921 1411-3921
Type III Seesaw LIGAN Majorana v Hoge triplet H ^{are} W ^{ar} W ^a Hoge triplet H ^{are} Lf Hoge triplet H ^{are} Lf Mulli-charged particles Magnetic monopoles	2,3,4 κ,μ 2,μ 2,3,4 κ,μ (55) 2,3,4 κ,μ (55) 3 κ,μ,τ	various	Yes Yes	129 36.1 129 129 20.3 129 34.4	V ^a mass. V _a mass. enr mass. e ⁿⁿ mass. e ⁿⁿ mass. mati-charged parties m noncycle-mass.	SSD GeV 400 GeV	910 GeV 3.2 TeV 1.09 TeV 1.59 TeV 2.37 TeV		$\begin{split} &m(W_{0})=4.1\text{TeV}_{1}\underline{e}_{1}=\underline{e}_{0}\\ &\text{DY production}\\ &\text{DY production}\\ &\text{DY production}, \mathcal{D}(H_{1}^{**}-r,r_{7})=1\\ &\text{DY production}, \underline{e} =5r\\ &\text{DY production}, \underline{e} =5r\\ &\text{DY production}, \underline{e} =1\underline{e}_{0}, \text{ spin }1/2 \end{split}$	2012-03038 1808-11105 2101-11841 ATLAS-CONF-0020 1411-2801 ATLAS-CONF-0020 1805-10130



+Small-radius (large-radius) jets are denoted by the letter j (J).

Summary Plots

ATL-PHYS-PUB-2022-007 (LLP) AR ATL-PHYS-PUB-2022-013 (SUSY) Reg arXiv:2204.11988 (HNL) @@

τ (ns)

16





Overview of CMS EXO results



S. Alderweireld

Exotics Searches and LLP (10/Mar 2023)





Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Moriond 2022

Summary Plots