Searches for Dark Matter and Long Lived Particles at the LHC

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Introduction

While the Standard Model is in excellent agreement with the LHC measurements, many questions still unanswered:

- The origin of Dark Matter remains a mystery
- The solution to the hierarchy problem

These questions lead to searches for physics beyond the Standard Model

This talk will focus on searches based on:

- Direct searches for Dark Matter (DM) production in the LHC
- Searches for novel long lived particles (LLPs)

Dark matter candidates also arise in SUSY models, see SUSY overview talk by Tommaso Lari

Results shown from the ATLAS, CMS and LHCb collaborations at the LHC, utilising (a part of) the 13 TeV run-2 dataset

CMS: Single top or a top pair + dark matter

Looking at models with a scalar or a pseudoscalar mediator particle and the mass of the mediator and DM particles are free parameters

Trigger: High MET or a high p_T lepton

Selection:

Split based on number b-tagged jets (1, 2, or more) and number of forward jets

Regions split based on number of leptons (*all hadronic* or *single-lepton*)

	Sir	ngle-lepton SRs		All-hadronic SRs				
	1 <i>l</i> , 1 b-tag, 0 FJ	1ℓ , 1 b-tag, 1FJ	1ℓ , 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag		
Forward jets	=0	≥ 1		= 0	≥1	—		
n _b	=1	=1	≥ 2	=1	=1	≥ 2		
n _{lep}	=1	=1	=1	= 0	=0	=0		
$p_{\rm T}(j_1)/H_{\rm T}$				— <0.5				
n _{jet}		≥ 2		≥ 3				
$p_{\rm T}^{\rm miss}$		>160 GeV		>250 GeV				
m _T		>160 GeV		—				
m_{T2}^W		>200 GeV		—				
$\min \Delta \phi(j_{1,2}, \vec{p}_{T}^{miss})$		>1.2 rad.		>1.0 rad.				
m ^b _T		>180 GeV		>180 GeV				

arXiv:1901.01553 ATLAS: arXiv:1812.09743, arXiv:1711.11520



CMS: Single top or a top pair + dark matter

The normalisation of the main backgrounds is established in specific control regions

- These include the tt, W and Z backgrounds
- Fit between data/MC performed in these enriched regions
- Normalisation determined as a function of p_{T}^{miss}



	Single-le	pton CRs	1	CRs	
	$CR t\bar{t}(2\ell)$	$CR W(\ell \nu)$	$\overline{\operatorname{CR} \operatorname{t}\overline{\operatorname{t}}(1\ell)}$	$CR W(\ell \nu)$	$\operatorname{CR} Z(\ell \ell)$
n _b	≥ 1	=0	≥ 1	=0	=0
$n_{\rm lep}$	=2	=1	=1	=1	=2
n _{jet}	≥ 2	≥ 2	≥ 3	≥ 3	≥ 3
$p_{\mathrm{T}}^{\mathrm{miss}}$	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m _T		>160 GeV	<160 GeV	<160 GeV	—
$\min \Delta \phi(\mathbf{j}_{1,2}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$			>1.0 rad.		—
$m_{\ell\ell}$			_		[60, 120] GeV

CMS: Single top or a top pair + dark matter

No excess above expected background observed

Exclusion of scalar and pseudoscalar at 95% confidence level for masses below 290 and 300 GeV respectively



arXiv:1901.01553 ATLAS: arXiv:1711.11520

(13 TeV

450

m, (GeV)

500

00000000

ATLAS: Single top + dark matter

Analysis using a similar strategy, targeting models:

- 1. Massive vector boson V decaying to two DM particles $\boldsymbol{\chi}$
- 2. Resonant production of a colored, charge $\frac{2}{3}$ scalar ϕ decaying into a spin $\frac{1}{2}$ DM particle χ and a top quark

Similar strategy to previous analysis, relying additionally on large radius jets and top tagging using substructure information.



arXiv:1903.01400 CMS: arXiv:1811.06562

ATLAS: Dark matter summary paper

2HDM + pseudo-scalar mediator model

A paper summarising the ATLAS limits on mediator-based Dark Matter models

- Considering Dirac fermions as WIMP DM particles (χ)
- Assumed to be pair produced in LHC collisions
- In certain models can decay back to SM particles

DM/SM interactions through mediator particle



						theo		F ATLA F√s = 1	S 3 TeV. 36.1 fb⁻¹	2HDM+a, Dirac DM	-	EPJC 78 (2018) 18
Short description	Acronym	Symbol	JCP	Charge	Signatures	0/۵			mits at 95% CL — Observed	$m_{\chi} = 10 \text{ GeV}, g_{\chi} = 1$ $m_{a} = 200 \text{ GeV}$	-	
Vector/axial-vector mediator	V/AV	Z_V'/Z_A'	1^{\pm}	-	$jet/\gamma/W/Z + E_{T}^{miss},$ di-fermion resonance		10		Expected	$m_{A} = m_{H} = m_{H^{\mp}} = 600 \text{ G}$ $tan\beta = 50: E_{T}^{miss} + b\overline{b}$ $tan\beta = 0.5: E_{T}^{miss} + t\overline{t}, t\overline{t}t\overline{t}$	ieV -	EPJC 78 (2018) 18 E ^{miss} +h(bb) PRL 119 (2017) 18180
Vector baryon-charged mediator	VBC	Z'_B	1 ⁺	baryon-number	$h + E_{\mathrm{T}}^{\mathrm{miss}}$					$\tan\beta = 1$: all others		-E ^{miss} +h(γγ) PRD 96 (2017) 112004
Scalar/pseudo-scalar mediator	S/PS	ϕ/a	0^{\pm}	-	$jet+E_{T}^{miss},\ tar{t}/bar{b}+E_{T}^{miss}$		1					-E ^{miss} +Z(II)
Scalar colour-charged mediator	$\mathrm{SCC}_{q/b}$	$\eta_{q/b}$	0^{+}	colour, 2/3 electric-charge	$ \begin{array}{l} \text{jet} + E_{\text{T}}^{\text{miss}}, \\ b + E_{\text{T}}^{\text{miss}} \end{array} $		'					PLB 776 (2017) 318
Two-Higgs-doublet plus vector mediator	2 HDM $+Z'_V$	Z'_V	1 ⁺	-	$h + E_{\mathrm{T}}^{\mathrm{miss}}$	_					-	— E _T ^{mag} +Z(qq) JHEP 10 (2018) 180
Two-Higgs-doublet plus pseudo-scalar mediator	2HDM $+a$	a	0-	-	$W/Z/h + E_{\rm T}^{\rm miss}, t\bar{t}/b\bar{b} + E_{\rm T}^{\rm miss}, h({\rm inv}) t\bar{t}t\bar{t}$		10 ⁻¹ C	.1 0.	2 0.3 0.4	0.5 0.6 0.7 0	.8 0.	
					<i>n</i> (mv), <i>nut</i>	1					sin0	

arXiv:1903.01400 CMS: arXiv:1811.06562

ATLAS: Dark matter summary paper

2HDM + pseudo-scalar mediator model



See also talk by Veronica Fabiani on Tuesday



m_a [GeV]

	Symbol	JCP	Charge	Signatures	0/0		Limits at 95% CL — Observed	$m_{\chi} = 10 \text{ GeV}, g_{\chi} = 1$ $m_{a} = 200 \text{ GeV}$	JHEP 06 (2018) 108 $-E_{T}^{miss}+b\overline{b}$
V/AV	Z_V'/Z_A'	1^{\pm}	-	$jet/\gamma/W/Z + E_{T}^{miss},$ di-fermion resonance	_	10	Expected	m _A = m _H = m _{H[±]} = 600 GeV tanβ = 50: E _T ^{miss} +bb tanβ = 0.5: E _T ^{miss} +tĨ, tĨtĨ	EFJC 78 (2016) 18 ET ET FT FT FT FT FT FT FT FT FT F
VBC	Z'_B	1 ⁺	baryon-number	$h + E_{\mathrm{T}}^{\mathrm{miss}}$	_			$\tan\beta = 1$: all others	— E ^{miss} +h(γγ) PRD 96 (2017) 112004
S/PS	ϕ/a	0^{\pm}	-	$jet + E_{T}^{miss}, t\bar{t}/b\bar{b} + E_{T}^{miss}$	_	1 =			E ^{miss} +Z(II)
$\mathrm{SCC}_{q/b}$	$\eta_{q/b}$	0^{+}	colour, 2/3 electric-charge	$ \begin{array}{l} \text{jet} + E_{\text{T}}^{\text{miss}}, \\ b + E_{\text{T}}^{\text{miss}} \end{array} $	_				PLB 776 (2017) 318
$2\text{HDM} + Z'_V$	Z'_V	1 ⁺	-	$h + E_{\mathrm{T}}^{\mathrm{miss}}$	_	-			- —E ^{mss} +Z(qq) JHEP 10 (2018) 180
2HDM+a	a	0-	-	$ \begin{array}{l} W/Z/h + E_{\rm T}^{\rm miss}, \\ t\bar{t}/b\bar{b} + E_{\rm T}^{\rm miss}, \\ h({\rm inv}), t\bar{t}t\bar{t} \end{array} $		10 ⁻¹ 0.1	0.2 0.3 0.4	0.5 0.6 0.7 0.8	
	$\overline{V/AV}$ \overline{VBC} $\overline{S/PS}$ $\overline{SCC}_{q/b}$ $2HDM+Z'_{V}$ $2HDM+a$	NATURAL Z_J mode V/AV Z'_V/Z'_A VBC Z'_B S/PS ϕ/a $SCC_{q/b}$ $\eta_{q/b}$ $2HDM+Z'_V$ Z'_V $2HDM+a$ a	NIME Z_{J} mode $U = 0$ V/AV Z'_V/Z'_A 1^{\pm} VBC Z'_B 1^+ S/PS ϕ/a 0^{\pm} $SCC_{q/b}$ $\eta_{q/b}$ 0^+ $2HDM+Z'_V$ Z'_V 1^+ $2HDM+a$ a 0^-	Interny III z_{f} inset $v \in 1$ $v \text{ intege}$ V/AV Z'_V/Z'_A 1^{\pm} - VBC Z'_B 1^+ baryon-number S/PS ϕ/a 0^{\pm} - $SCC_{q/b}$ $\eta_{q/b}$ 0^+ colour, 2/3 electric-charge $2HDM+Z'_V$ Z'_V 1^+ - $2HDM+a$ a 0^- -	$\begin{array}{cccccccc} V/AV & Z'_V/Z'_A & 1^{\pm} & - & \begin{array}{c} jet/\gamma/W/Z + E_{\rm T}^{\rm miss} \\ {\rm di-fermion} \\ resonance \\ \hline VBC & Z'_B & 1^{\pm} & \mbox{baryon-number} & h + E_{\rm T}^{\rm miss} \\ \hline S/PS & \phi/a & 0^{\pm} & - & \begin{array}{c} jet + E_{\rm T}^{\rm miss} \\ t\bar{t}/b\bar{b} + E_{\rm T}^{\rm miss} \\ \hline SCC_{q/b} & \eta_{q/b} & 0^{\pm} & \mbox{colour, 2/3} & \mbox{jet} + E_{\rm T}^{\rm miss} \\ electric-charge & b + E_{\rm T}^{\rm miss} \\ \hline 2HDM + Z'_V & Z'_V & 1^{\pm} & - & h + E_{\rm T}^{\rm miss} \\ \hline 2HDM + a & a & 0^{-} & - & \begin{array}{c} W/Z/h + E_{\rm T}^{\rm miss} \\ t\bar{t}/b\bar{b} + E_{\rm T}^{\rm miss} \\ h({\rm inv}), t\bar{t}t\bar{t} \end{array}$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$

10² ⊑ >

<u>arXiv:1903.01400</u> CMS: <u>arXiv:1811.06562</u>

ATLAS: Dark matter summary paper

(Axial-)vector mediator model

$\bar{q} \gamma/V/g$	$\overline{\langle}$	χ $ar{\chi}$	\bar{q}	$Z'_{V/A}$	$\overbrace{\bar{f}}^{f}$	m ₂ [TeV	1.4 ATL 1.2 1.2 0.8 0.6 0.4 0.2 0	AS 0.5 1	Dibjet	the second response of the second response o	diator, Dirac DM , $g_{\chi} = 1$ 3 3. $m_{Z_{\Lambda}}$ [Te ³]	Digit Digit $f = 13 \text{ TeV}, 37.0 \text{ b}^{-1}$ PRD 96.082004 (2017) Digit TLA $f = 13 \text{ TeV}, 29.3 \text{ b}^{-1}$ PRL 121 (2018) 0810016 Digit + ISR $f = 13 \text{ TeV}, 36.2 \text{ b}^{-1}$ Preliminary ATLAS-CONF-2016.0 It if resonance $f S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ EPJC 78 (2018) 985 Dibjet $f S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ PRD 96 (2018) 085 Dibjet $f S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ PRD 96 (2018) 085 E ur PRys.J. C77 (2017) 383 $E_{T}^{-1} \text{ evt} f G = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ Did = 13 TeV, 36.1 fb^{-1} PLD 576 (2017) 318 $E_{T}^{-1} \text{ evt} (2015) 135$ $E_{T}^{-1} \text{ evt} (2015) 136$
						l cleon) [cm²]	10^{-37} 10^{-38} 10^{-39}	TLAS				Dijet Dijet € = 13 TeV, 37.0 fb ⁻¹ PRD 96, 052004 (2017) Dijet TLA € = 13 TeV, 29.3 fb ⁻¹ PRI, 121 (2018) 0618016 Dijet 4, 156 € = 13 TeV, 155 fb ⁻¹
Short description	Acronym	\mathbf{Symbol}	JCP	Charge	Signatures	א-nu	10 ⁻⁴⁰	CRES	ST III		tt resonance	Preliminary ATLAS-CONF-2016-070
Vector/axial-vector mediator	V/AV	Z_V'/Z_A'	1^{\pm}	-	$jet/\gamma/W/Z + E_{T}^{miss}$, di-fermion resonance	σ _{si} (10 ⁻⁴¹			E _T +X	Dibjet et	(S = 13 TeV, 36.1 fb ⁻¹ EPJC 78 (2018) 565 ■ Dibjet (S = 13 TeV, 36.1 fb ⁻¹ PRD 98 (2018) 032016 ■ E _T miss + X
Vector baryon-charged mediator	VBC	Z'_B	1^{+}	baryon-number	$h + E_{\mathrm{T}}^{\mathrm{miss}}$	-	10 ⁻⁴³	Dain				$E_T^{miss} + \gamma fs = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ Eur. Phys. J. C 77 (2017) 393 $E_T^{miss} + \text{jet} fs = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
Scalar/pseudo-scalar mediator	S/PS	ϕ/a	0 [±]	-	$ \begin{array}{l} \text{jet} + E_{\text{T}}^{\text{miss}}, \\ t\bar{t}/b\bar{b} + E_{\text{T}}^{\text{miss}} \end{array} $	_	10 ⁻⁴⁴		`		PandaX LUX	JHEP 1801 (2018) 126 E _T ^{miss} +Z(II) √ s = 13 TeV, 36.1 fb ⁻¹ PLB 776 (2017) 318 E _T ^{miss} +V(had) √ s = 13 TeV, 36.1 fb ⁻¹
Scalar colour-charged mediator	$\mathrm{SCC}_{q/b}$	$\eta_{q/b}$	0^+	colour, 2/3 electric-charge	$ \substack{\text{jet}+E_{\text{T}}^{\text{miss}},\\ b+E_{\text{T}}^{\text{miss}}} $		10 ⁻⁴⁵			XENON		JHEP 10 (2018) 180 CRESST III arXiv:1711.07692
Two-Higgs-doublet plus vector mediator	2 HDM $+Z'_V$	Z'_V	1 ⁺	-	$h + E_{\rm T}^{\rm miss}$		10 ⁻⁴⁷	Vector mediator, Di g = 0.25, g = 0. g	rac DM			XENON1T arXiv:1805.12562 PandaX
Two-Higgs-doublet plus pseudo-scalar mediator	2HDM+a	a	0-	-	$ \begin{array}{l} W/Z/h + E_{\rm T}^{\rm miss}, \\ t\bar{t}/b\bar{b} + E_{\rm T}^{\rm miss}, \\ h({\rm inv}), t\bar{t}t\bar{t} \end{array} $	_	10 ⁻⁴⁸	ATLAS limits at 959	6 CL, direct d	etection limits at 90 10 ²	^{2% CL} 10 ³ m _x [GeV]	DarkSide-50 arXiv:1802.06994 UUX PRL 118.021303 (2017) Phys. Rev. Lett. 115, 161302 (2016)

ATLAS: DM in invisible Higgs decays

ATLAS-CONF-2018-054 CMS: arXiv:1809.05937

Combination of limits from multiple previous results:

VBF: VBF production (See talk by Andrey Popov)

VH: Higgstrahlung with vector boson (Z/W) decay into quarks

 ${\pmb Z} {\pmb H}$: Higgstrahlung with Z decay to e^+e^- or $\mu^+\mu^-$

Additionally combined with the run-1 result (see <u>arXiv:1903.01400</u>)

Input analyses orthogonal to each other and correlation between systematics considered.

Combination performed by maximising the binned likelihood ratio

The result is an upper limit on $B_{H \rightarrow inv} < 0.26$



LHCb: Dark Photons

Search for dark photons of mass m(A') with SM couplings suppressed by a factor ϵ .

Considering the A' $\rightarrow \mu^+ \mu^-$ decays, both promptly decaying and long-lived

Analysis performed via fit on $m(\mu^+ \mu^-)$ spectrum

- Prompt-lepton background estimated from data
- Mis-identified muon backgrounds estimated using same sign muons



LHCb: Dark Photons

90% CL upper limit on $n_{\rm ob}^{A'}[m(A'), \varepsilon^2] / n_{\rm ex}^{A'}[m(A'), \varepsilon^2]$ No excess above background observed and limits set. 10^{-8} long-lived excluded $\mathcal{C}_{(j)}$ LHCb Results for promptly decaying dark photons (below) most stringent above 10 GeV, competitive with current 10^{-9} best limits elsewhere! For long-lived dark photons (right) limits are set for the first time! 10^{-10} 250 300 350 m(A') [MeV] 90% CL exclusion regions on $[m(A'), \varepsilon^2]$ 10^{-3} ω^{2} LHCb 10^{-4} 10^{-5} 10^{-6} LHCb prompt-like BaBar 10⁻⁷ KLOE

1

10

m(A') [GeV

CMS: Jets and emerging jets

Investigating a model where a new heavy particle (X $_{\rm DK}$) with QCD dark-QCD couplings decays to a dark quark (Q $_{\rm DK}$)

- The dark quark will hadronise to a jet of dark pions
- Dark pions have long lifetime and decay to quarks
- Result in displaced vertices in an "emerging" jet
- For longer lifetimes can result in p_T^{miss} .

Models constructed in terms of mass of $X_{\rm DK}^{}$, lifetime and mass of the dark pions

Trigger: Selecting high-p_T jets

Selection: Selecting jets within |eta| < 2 where impact parameter resolution is best.

At least four jets are required, with two emerging jets, or one emerging jet and large p_{T}^{miss} .



arXiv:1810.10069

CMS: Jets and emerging jets

Backgrounds are estimated in a data-driven way starting from a sample of events with four jets but no identified emergent jets

- The probability of a jet being misidentified as an emergent jet is modeled
- Depends on the flavour of the initiating parton and track multiplicity

Misidentification probability estimated using independent control sample (single photon trigger)

• Flavour composition determined using a template fit to the b-tagging discriminator variable

The results are evaluated in dedicated analysis regions



CMS: Jets and emerging jets

No significant excess above the SM expectation observed.

Limits are placed on the considered models

Models with dark pion masses between 400 and 1250 GeV are excluded for decay lengths 5-225 mm

A larger range is excluded at low masses but with higher mass dependence



Sotnumbor	Expected	Obsorwad	Signal	Model parameters				
Set number	Expected	Observed	Signal	$m_{X_{DK}}$ [GeV]	$m_{\pi_{\rm DK}}$ [GeV]	$c au_{\pi_{ m DK}}$ [mm]		
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1		
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60		
3	$19.4 \pm ~7.0 \pm ~5.5$	20	15.6 ± 1.6	1250	1	150		
4	$22.5 \pm \ 2.5 \pm \ 1.5$	16	15.1 ± 2.0	1000	1	2		
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150		
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300		
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225		

ATLAS: Heavy charged long-lived particles

Looking for heavy charged particles produced in LHC in a SUSY context

- Gluinos/squarks (R-hadrons), staus or charginos
- Heavy with low velocity \rightarrow highly ionising

Primary observables:

- dE/dx measurement from charge in the Pixel detector
- TOF measurement in Tile, RPC and MDT detectors

Trigger: High-MET or isolated high-p_T muons

Selection: One or two candidate tracks with associated mass measurement

Split based on whether muon spectrometer is used and number of candidate tracks

Signal region	Trigger	Candidate	Candidates	Final requirements						
	(145) 3 (224) 17	selection	per event	$ \eta $	$p \; [\text{GeV}]$	eta_{ToF}	$(\beta\gamma)_{dE/dx}$	Mass		
SR-Rhad-MSagno	$E_{\mathrm{T}}^{\mathrm{miss}}$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx		
SR-Rhad-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	LOOSE	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.3	ToF & dE/dx		
SR-Rhad-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx		
SR-2Cand-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	LOOSE	=2	≤ 2.00	≥ 100	≤ 0.95		ToF		
SR-1Cand-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	TIGHT	=1	≤ 1.65	≥ 200	≤ 0.80	-	ToF		



From arXiv:1810.12602

ATLAS: Heavy charged long-lived particles

Background PDFs fully data-driven manner

- Invert the momentum requirements and obtain the PDFs for β_{TOF} , $(\beta\gamma)_{dE/dx}$. Vice-versa for the momentum PDF.
- Randomly sampling from these construct the m_{TOF} and m_{dE/dx}

PDFs normalised in control regions

- Control regions are defined based on side-bands to the SR requirements
- Normalisation derived from data and backgrounds scaled



ATLAS: Heavy charged long-lived particles

arXiv:1902.01636 CMS: arXiv:1609.08382

No significant excess above the expected background observed

Limits set on multiple different long-lived particles

- Gluinos: < 2000 GeV
- **Sbottom:** < 1250 GeV
- **Stop:** < 1340 GeV
- Staus: < 430 GeV
- Charginos: < 1090 GeV





ATLAS: Neutral Long-Lived Particles

Searching for production of a heavy neutral scalar particle decaying into two long-lived scalars.

Signature: Scalars decay into fermions in the calorimeter, but after EM calorimeter (Higgs-like couplings assumed)

Trigger: Jets with high ratio of energy in the hadronic calorimeter, low- E_{T} and high- E_{T} triggers

Selection: At least two jets with no associated tracks (jet formed after tracker)

Jet origin estimated with a neural network and a further BDT classifies jets as signal-like, multijet-like and beam background-like





arXiv:1902.03094 CMS: arXiv:1811.07991

ATLAS: Neutral Long-Lived Particles

Signal regions defined in terms of a event-level BDT as well as E_H/E_{ecal} , jet p_T and H_T^{miss} / H_T . The selection is split into high- and low- E_T .

Multijets is primary background following the selection.

The background is estimated in a data-driven manner using an ABCD method, splitting based on the BDT output and track-jet separation.







ATLAS: Neutral Long-Lived Particles

No excess above expected background observed and limits are set.

For mediator scalar compatible with Higgs boson limits on scalar masses between 5 - 55 GeV for proper decay lengths 5 cm - 5 m.

Results combined with search for displaced jets in the muon spectrometer (see <u>arXiv:1811.07370</u>) and $H \rightarrow aa \rightarrow bbbb$ (see <u>arXiv:1806.07355</u>).





CMS: Displaced vertices in multijet events

arXiv:1808.03078 ATLAS: arXiv:1710.04901

Looking for signals with multiple jets and two displaced vertices in a SUSY context

Trigger: Using H_{T} (sum of jet p_{T}) trigger

Selection: At least four jets and two significantly displaced vertices, $H_{T} > 1000$ GeV

The signal vertices are required to have at least five tracks

• Vertices with 3-4 tracks or only one signal vertex used to constrain backgrounds

Main discriminating variable is d_{VV} , the distance between the jets in the x-y plane.







CMS: Displaced vertices in multijet events

The background in this measurement arises from mis-reconstructed tracks overlapping with other tracks to form a vertex

- The input to the background estimation is sampled from the distribution of distance from the beamline (d_{BV}) for the single vertex with ≥ 5 tracks sample
- The angular distribution of the vertices is approximated based on a dijet opening angle in the 3-track single vertex sample
- Corrections are applied for merging of vertices as well as angular correlations arising from b-quark production

The procedure is validated in the 3 and 4 track vertex samples

38.5 fb⁻¹ (13 TeV) Events/0.1 mm 10³ CMS Data Multijet signals, m = 800 GeV, σ = 1 fb: $c\tau = 0.3 \text{ mm}$ $c\tau = 1.0 \text{ mm}$ $c\tau = 10 \text{ mm}$ 10 10 0 0.52.5 3 3.5 d_{BV} (mm) 38.5 fb⁻¹ (13 TeV 40 Events/0.1 mm CMS 35 4-track x 3-track 30 Data Background template 25 20 15 10 2 2.5 3 0.51.5 3.5 d_{vv} (mm)

arXiv:1808.03078

ATLAS: arXiv:1710.04901

CMS: Displaced vertices in multijet events

No significant excess above the expected background is observed.

Limits are set on the lifetime and mass of neutralinos/gluinos/squarks assuming a 100% branching ratio

Additionally limits are set on the branching ratio for a fixed lifetime or a fixed mass



arXiv:1808.03078 ATLAS: arXiv:1710.04901



Summary

Showed a selection of recent results from ATLAS, CMS and LHCb

- Cover many different models and final states
- Still only a fraction of the Run-2 data analysed, stay tuned!

These are analyses with novel final states

- Many different signatures to cover
- Diverse final states mean a lot of creativity goes into these analyses

For many of the analyses shown an extensive set of data is published for re-interpretations (HepData) in different models!

For a glimpse into the future see the talk by *Maximilian Emanuel Goblirsch-Kolb* tomorrow on prospects at the HL-LHC!

BACKUP SLIDES

Event display of events with emerging jets

