Overview on the energy frontier of particle physics beyond the standard model

22nd edition PANIC Lisbon Portugal Particles and Nuclei International Conference

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Topics from Parallel Sessions (Sunday)

- BSM vision, Elina Fuchs
- Prospects for BSM at LHC (experimental vision), Livia Soffi
- Tiesheng Dai
- EW SUSY production at the LHC, Holly Pacey
- Strong SUSY and third generation SUSY, Joshua Hiltbrand
- Probing dark matter with ILC, Aleksander Filip Zarnecki
- Search for dark matter at the LHC, Janna Katharina Behr
- Probing Higgs-portal dark matter with vector-boson fusion, Eric Madge

BSM Higgs physics at LHC (Direct and indirect from Higgs couplings),

New physics searches with the ILD detector at ILC, Mikael Berggren



Topics from Parallel Sessions (Wednesday)

- SM anomalies and BSM interpretations, Claudia Cornelia
- Constraints on colored scalars from global fits, Victor Miralles
- BSM with axions, Andrea Thamm
- Searches for Axion-Like particles, Adrian Casais Vidal
- Searches for long-lived particles at CMS, Malgorzata Kazana
- Prospects for searches of new physics at future facilities beyond HL-LHC, **Clement Helsens**
- Sreemanti Chakraborti
- Search for heavy resonances at LHC (ED, HVB, etc...), Dominik Duda
- Cosmological approaches to the Higgs hierarchy problem, Daniele Teresi

Leptoquarks and HVB (in scenarios of LFU anomaly), Arne Christoph Reimers

Long-lived particles and unconventional signatures at LHC, Monica Verducci

Search prospects for extremely weekly-interacting particles in gamma factory,



THE STANDARD MODEL OF PARTICLE PHYSICS

All particle foreseen by the Standard Model have been observed



+ anti-particles (i.e. copies of opposite charge)

(after a 40-year search)

JHEP01(2021)148



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EVIDENCE FOR BEYOND STANDARD MODEL PHYSICS

Higgs mass Hierarchy problem Planck scale: 10¹⁸ GeV Higgs mass: 10² GeV

Higgs field became active

Big Bang

Matter and antimatter are in equilibrium

Particles are massless



Higgs Boson potential

Electroweak phase transition





Dark Energy 68%

Baryon Asymmetry

There is matter, but not anti-matter



Particles have mass

Higgs Boson potential



Are there more forces? particles? symmetries?

What is the right description of gravity, and where does it become relevant for particle physics?

Is there unification of all forces? What breaks it?

Explain mass and relative strengths of the fundamental forces

What breaks electroweak symmetry? What is the origin of mass?

Are there extra dimensions? What is the structure of spacetime?

What is the physics beyond the SM? New particles? New interactions?

Flavor puzzles: Can we understand the masses, and fermions mixing?Why 3 families? Where does CP violation come from?

Can we explain the universe? Is it matter dominated? Cosmological constant? What is dark-matter?

What is the structure and fate of the Universe?

Adapted from: Maury Tigner; Physics Today 54, 36-40 (2001) — Originally from Persis Drell

pp collider 100 TeV

Muon collider

e⁺e⁻ collider multi-TeV

pp collider LHC 14 TeV

> e⁺e⁻ collider Higgs factory

Neutrino factory

> **B**, τ, charm factories

Particle astrophysics











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THE LARGE HADRON COLLIDER





Largest energy collider in the world \rightarrow our current tool

$L = ~140 \text{ fb}^{-1}$

SUPERSYMMETRY (SUSY)

• A favorite, ideal, long-time candidate to explain most of questions raised

- unification of forces, no fine-tuning required for Higgs mass
- Unfortunately, no evidence for SUSY found yet

Strong SUSY production

Large cross section



Symmetry between bosons and fermions, provides dark matter candidate, provides

Mass gluino > 1-2 TeV (depending on models)



ELECTROWEAK SUPERSYMMETRY



Wino, Higgsino, sleptons

Rare signatures, less constrained than Strong SUSY

Several decay modes



Lightest SUSY Particle

Missing Energy

ELECTROWEAK SUPERSYMMETRY

Excluded gaugino phase space for several final states (95% CL limits up to 1-1.3 TeV)



ATLAS Summary Plots

See talk by Holly Pacey

All limits at 95% CL

- Expected limits
 - **Observed** limits

WZ 0I, 2I, 3I arXiv:1806.02293 arXiv:1911.12606 arXiv:2106.01676 ATLAS-CONF-2021-022 Wh lbb, 01

arXiv:1909.09226

WW 01, 21

arXiv:1403.5294 arXiv:1908.08215

ATLAS-CONF-2021-022



CMS Summary Plots





STANDARD ATLAS SUSY SEARCHES SUMMARY

at 95% limits exclusion oserved \mathbf{O}

Α Jι	TLAS SUSY Sea	rches* - 959	% CL	Lov	ver Limits		ATLAS Preliminary $\sqrt{s} = 13$ TeV
	Model	Signatu	r e ∫.	<i>L dt</i> [fb ⁻	Mass limit		Reference
(0	$\tilde{q}\tilde{q}, \tilde{q} { ightarrow} q \tilde{\chi}_1^0$	0 e, μ 2-6 jets mono-jet 1-3 jets	$E_T^{ m miss} \ E_T^{ m miss}$	139 36.1		0 1.85 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874
arches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 <i>e</i> ,μ 2-6 jets	E_T^{miss}	139	<i>ğ ğ ğ Forbida</i>	2.3 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ m($\tilde{\chi}_1^0)=1000 \text{ GeV}$	2010.14293 2010.14293
lusive Sea	$\begin{split} \tilde{g}\tilde{g}, \ \tilde{g} \to q\bar{q}W\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \ \tilde{g} \to q\bar{q}(\ell\ell)\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \ \tilde{g} \to qqWZ\tilde{\chi}_{1}^{0} \end{split}$	1 e, μ 2-6 jets $ee, \mu\mu$ 2 jets 0 e, μ 7-11 jets SS e, μ 6 jets	$E_T^{ m miss}$ $E_T^{ m miss}$	139 36.1 139 139	ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ ເ	2.2 $m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ 1.2 $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ 1.97 $m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ m ($\tilde{\chi}_1^0$) = 200 GeV	2101.01629 1805.11381 2008.06032 1909.08457
Inc	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	$\begin{array}{ccc} \text{0-1} & e, \mu & & \text{3} & b \\ \text{SS} & e, \mu & & \text{6} & \text{jets} \end{array}$	$E_T^{ m miss}$	79.8 139	۲۵۵ ۲۵۵ ۲۵۵	2.25 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ 1.25 $m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1909.08457
	$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i> 2 <i>b</i>	$E_T^{ m miss}$	139		1.255 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 \text{ GeV}$	2101.12527 2101.12527
arks tion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$ \begin{array}{ccc} 0 \ e, \mu & 6 \ b \\ 2 \ \tau & 2 \ b \end{array} $	$E_T^{ m miss} \ E_T^{ m miss}$	139 139	$ \begin{array}{c c} \tilde{b}_1 & Forbidden \\ \tilde{b}_1 & 0.13-0.85 \end{array} $	2.23-1.35 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV} \\ \Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$	1908.03122 ATLAS-CONF-2020-031
3 rd gen. squa direct produc	$\begin{split} \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow t \tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow Wb \tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{\tau}_{1}b\nu, \tilde{\tau}_{1} \rightarrow \tau \tilde{G} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow c \tilde{\chi}_{1}^{0} / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_{1}^{0} \end{split}$	0-1 $e, \mu \ge 1$ jet 1 e, μ 3 jets/1 b 1-2 τ 2 jets/1 b 0 e, μ 2 c 0 e, μ monovid	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139 36.1	\tilde{t}_1 Forbidden0.65 \tilde{t}_1 ForbiddenForbidden \tilde{c} 0.85	1.25 $m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=500 \text{ GeV}$ $m(\tilde{\tau}_{1})=800 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$	2004.14060,2012.03799 2012.03799 ATLAS-CONF-2021-008 1805.01649
	$ \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 \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	$0 e, \mu$ mono-jen $1-2 e, \mu$ $1-4 b$ $3 e, \mu$ $1 b$	E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139	t1 0.55	$m(\tilde{t}_{1},\tilde{c})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$ $m(\tilde{\chi}_{2}^{0})=500 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=360 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=40 \text{ GeV}$	2102.10874 2006.05880 2006.05880
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{\mp}$ via WW	Multiple ℓ /jets $ee, \mu\mu \ge 1$ jet $2e \mu$	$E_T^{ m miss} \ E_T^{ m miss} \ E_T^{ m miss}$	139 139 139	$ \begin{array}{ccc} \tilde{\chi}_{1}^{\pm} / \tilde{\chi}_{2}^{0} & & 0.9 \\ \tilde{\chi}_{1}^{\pm} / \tilde{\chi}_{2}^{0} & & 0.205 \end{array} $	$m(\tilde{\chi}_1^0)=0$, wino-bino $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5$ GeV, wino-bino $m(\tilde{\chi}_1^0)=0$, wino-bino	2106.01676, ATLAS-CONF-2021-022 1911.12606 1908.08215
EW direct	$ \begin{aligned} &\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \text{ via } Wh \\ &\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp} \text{ via } \tilde{\ell}_{L}/\tilde{\nu} \\ &\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0} \\ &\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \end{aligned} $	Multiple ℓ /jets 2 e, μ 2 τ 2 e, μ 0 jets	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139 139 139	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$m(\tilde{\chi}_{1}^{0})=70 \text{ GeV, wino-bino}$ $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ $m(\tilde{\ell}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=0$	2004.10894, ATLAS-CONF-2021-022 1908.08215 1911.06660 1908.08215
	$ ilde{H} ilde{H}, ilde{H}\! ightarrow \!h ilde{G}/Z ilde{G}$	$ee, \mu\mu \ge 1$ jet $0 e, \mu \ge 3 b$ $4 e, \mu \qquad 0$ jets $0 e, \mu \ge 2$ large je	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss} ets E_T^{miss}	139 36.1 139 139	 <i>ℓ</i> 0.256 <i>H</i> 0.13-0.23 <i>Ω</i> 0.55 <i>Ω</i> 0.45-0.93 <i>Ω</i> 0.45-0.93 <i>Ω Ω</i>	$ \begin{split} m(\tilde{\ell})\text{-}m(\tilde{\chi}_1^0) &= 10 \text{ GeV} \\ BR(\tilde{\chi}_1^0 \to h\tilde{G}) &= 1 \\ BR(\tilde{\chi}_1^0 \to Z\tilde{G}) &= 1 \\ BR(\tilde{\chi}_1^0 \to Z\tilde{G}) &= 1 \end{split} $	1911.12606 1806.04030 2103.11684 ATLAS-CONF-2021-022
RPV	$\begin{split} \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{1}^{0} , \tilde{\chi}_{1}^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell \\ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{2}^{0} \rightarrow WW / Z\ell\ell\ell\ell\nu\nu \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq \\ \tilde{t}\tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs \\ \tilde{t}\tilde{t}, \tilde{t} \rightarrow b \tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{1}^{\pm} \rightarrow bbs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow bs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow s \end{split}$	$3 e, \mu$ $4 e, \mu$ 0 jets 4-5 large je Multiple $\ge 4b$ 2 jets + 2	$E_T^{ m miss}$ ets	139 139 36.1 36.1 139 36.7	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$.05 Pure Wino 1.55 $m(\tilde{\chi}_1^0)=200 \text{ GeV}$ 1.3 1.9 .05 $m(\tilde{\chi}_1^0)=200 \text{ GeV}$, bino-like $m(\tilde{\chi}_1^0)=200 \text{ GeV}$, bino-like $m(\tilde{\chi}_1^{\pm})=500 \text{ GeV}$	2011.10543 2103.11684 1804.03568 ATLAS-CONF-2018-003 2010.01015 1710.07171
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^{\pm} \rightarrow bbs$	$ \begin{array}{cccc} 1 & & & 2 & 0 \\ 1 & & & DV \\ 1-2 & e, \mu & \geq 6 \text{ jets} \end{array} $		136 139	$\tilde{t}_{1}^{0} \qquad [1e-10 < \lambda'_{23k} < 1e-8, 3e-10 < \lambda'_{23k} < 3e-9]$ $\tilde{\chi}_{1}^{0} \qquad 0.2-0.32$	0 1.6 $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1$ Pure higgsino	2003.11956 ATLAS-CONF-2021-007
*Only phen simp	a selection of the available ma omena is shown. Many of the lified models, c.f. refs. for the	ass limits on new state limits are based on assumptions made.	es or	1) ⁻¹	Mass scale [TeV]	

EXTRA DIMENSIONS

Hierachy problem solved by bringing down Planck scale

- n extra dimensions, compactified at radius R
- SM confined to brane in a higher dimensional space
- Only gravity can access extra dimensions















DIRECT NEW PHYSICS SEARCHES FROM LHC

Overview of CMS EXO results

Excited

Heavy ermion



		36-140 fb ⁻¹ (13 TeV)
1911.04968 (3ℓ, ≥ 4ℓ)	0.5-8.1 1911.03 0.35-4 1712.03143 (2µ + 1γ; 2e + 1γ; 2 0.72-3.25 1808.01257 (1j + 1γ) 0.5-3.7 1911.03947 (2j) 0.5-7.5 1911.039	3947 (2j) - 1 γ) - ⁷ (2j)	137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹
	0.2-5.6 2001.04521 (2e + 2j) 0.2-5.7 2001.04521 (2μ + 2)	<12.8 1803.0803 (2j) <20 1812.10443 (2 <i>l</i>) <17.5 1803.0803 (2j) <32 1812.10443 (2 <i>l</i>)	36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 77 fb ⁻¹ 77 fb ⁻¹
01.01553 (0 , $1l + ≥ 3j + E_T^{miss}$) 001.01553 (0 , $1l + ≥ 3j + E_T^{miss}$) 0.35–0.7 1911.0376 0.3–0.6 1811.10151 (1 µ	<pre><1.8 1712.02345 (\geq 1j + E^{miss}) 0.5-2.8 1911.03947 (2j)</pre> <1.4 1712.02345 (\geq 1j + E ^{miss}) <1.54 1810.10069 (4j) <1.9 1908.01713 (h + E ^{miss}) 0.5-3.2 1908.01713 (h + E ^{miss}) (\geq 3j) + 1j + E ^{miss})		36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 18 fb ⁻¹ 77 fb ⁻¹
0.08-0.52 1808.03124 (2j; 4j) 0.1-0.72 1806.010	58 (2j) 0.1–1.41 1806.01058 (2j) <1.5 1810.10092 (6j)		36 fb ⁻¹ 38 fb ⁻¹ 38 fb ⁻¹ 36 fb ⁻¹
	<9.3 1 <9.9 <8.2 1803.0 <5.6 1802.01122 (eμ) <4.1 1809.00327 (2γ) <5.9 1803.0803 (2j) <3.6 1802.01122 (eμ) <9.7 0.4-2.9 1803.11133 (ℓ + E ^{miss}) 0.5-2.6 1911.03947 (2j)	<pre><12 1803.0803 (2j) 12.10443 (2γ, 2ℓ) 1712.02345 (≥ 1j + E^{miss}) 803 (2j) 805.06013 (≥ 7j(ℓ, γ))</pre>	36 fb ⁻¹ 36 fb ⁻¹
	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
<0.88 19 0.12-0.79 1905.	.001-1.431802.02965; 1806.10905 ($3\ell(\mu, e)$; ≥ $1j + 2\ell(\mu, e)$)0.02-1.61806.10905 (≥ $1j + \mu + e$)1.04968 (3ℓ , ≥ 4ℓ)853 (3ℓ , ≥ 4ℓ , ≥ $1\tau + 2\ell$)		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 77 fb ⁻¹
<1.02 <0.74 1806.03	<1.44		36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 77 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
ı) 0.45 1909.04114 (2 j)	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 140 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹
1	e as v cale [TeV]	Moriond 20	-)21

NEW INTERESTING ANOMALIES

- Flavor: B, K and D meson sector
- Muon magnetic moment from g-2 (expect updated results soon) Dark Matter (AMS, Fermi-LAT, Xenon1T)
- Neutrinos
 - MiniBoone, LSND: $v_{\mu} \rightarrow \overline{v_e}$ excess
 - Gallium, Reactors: V_e, V_e disappearance

No convincing discoveries yet, but intriguing tensions



MUON ANOMALOUS MAGNETIC MOMENT COMPATIBILITY WITH SUSY



(arXiv:2104.03281)



NO NEW PHYSICS OBSERVED → LOOK FURTHER/DEEPER

Explore new tools and techniques



Long-lived particles (LLPs)

Long-lived particles (LLPs) are common in BSM

- Small phase space for decay (e.g. Split SUSY)
- Small couplings to SM particles
 - Suppressed (e.g. Higgs/gauge portal to Dark Sector)
 - Forbidden by symmetry (SUSY R-parity)

Could have escaped observation so far

Challenges:

- Often requires new triggers
- Exotic detector signatures (requiring new tools)
- Non-standard backgrounds

see talk by Małgorzata Kazana and Monica Verducci







Displaced leptons

Disappearing track

Large pixel dE/dx

Track-less jets

Displaced vertices

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Lifetime limit

.

Status: July 2021

	Model	Signature	∫£ dt [fb	⁻¹]
	RPV ${ ilde t} o \mu q$	displaced vtx + muon	136	ĩ li
	$RPV\chi_1^0 o eev/e\mu v/\mu\mu v$	[,] displaced lepton pair	32.8	χ_1^0
	$\operatorname{GGM} \chi_1^0 \to Z \tilde{G}$	displaced dimuon	32.9	χ_1^0
	GMSB	non-pointing or delayed γ	[/] 20.3	χ_1^0
	GMSB $\tilde{\ell} \to \ell \tilde{G}$	displaced lepton	139	$ ilde{\ell}$ i
X	GMSB $\tilde{\tau} \rightarrow \tau \tilde{G}$	displaced lepton	139	ĩΙ
SUS	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^{\pm} \chi_2^0$	$\frac{1}{1}$ disappearing track	136	χ_1^{\pm}
	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^{\pm} \chi_2^0$	$\frac{1}{1}$ large pixel dE/dx	18.4	χ_1^{\pm}
	Stealth SUSY	2 MS vertices	36.1	Ŝ١
	Split SUSY	large pixel dE/dx	36.1	ĝ١
	Split SUSY	displaced vtx + E_{T}^{miss}	32.8	ĝ١
	Split SUSY	0 ℓ , 2 – 6 jets + E_{T}^{miss}	36.1	ĝ
	$H \rightarrow s s$	ID/MS vtx, low EMF/trk jet	s 36.1	sl
	VH with $H \rightarrow ss \rightarrow bbb$	$b 2\ell + 2$ displaced vertices	139	s li
10%	FRVZ $H \rightarrow 2\gamma_d + X$	2 $e^{-,\mu-jets}$	20.3	γd
H =	FRVZ $H ightarrow 2\gamma_d + X$	2 μ –jets	36.1	γd
jgs B	FRVZ $H ightarrow 4 \gamma_d + X$	2 μ –jets	36.1	γd
Hiç	$H \rightarrow Z_d Z_d$	displaced dimuon	32.9	Zd
	$H \rightarrow ZZ_d$	2 e, μ + low-EMF trackless	jet 36.1	Zd
	$\Phi(200 \text{ GeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/tx 36.1	s li
alar	$\Phi(600 \text{ GeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/tx 36.1	s li
Sc	$\Phi(1 \text{ TeV}) \rightarrow s s$	low-EMF trk-less jets, MS v	/t× 36.1	s li
	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) +	μ 36.1	N
HNL	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) +	μ 36.1	Ν
		$\sqrt{s} = 13$ ToV		

*Only a selection of the available lifetime limits is shown.

partial data

full data

/s=8 iev

 $\int \mathcal{L} dt = (18.4 - 139) \text{ fb}^{-1}$



 $m(\tilde{t}) = 1.4 \text{ TeV}$ 0.003-6.0 m



ATLAS Preliminary $\sqrt{s} = 8, 13 \text{ TeV}$

- Reference
 - 2003.11956
 - 1907.10037
 - 1808.03057
 - 1409.5542
- 2011.07812
- 2011.07812
- ATLAS-CONF-2021-015
 - 1506.05332
 - 1811.07370
 - 1808.04095
 - 1710.04901
- ATLAS-CONF-2018-003
 - 1911.12575
 - 2107.06092
 - 1511.05542
 - 1909.01246
 - 1909.01246
 - 1808.03057
 - 1811.02542
 - 1902.03094
 - 1902.03094
 - 1902.03094
 - 1905.09787
 - 1905.09787

NO NEW PHYSICS OBSERVED \rightarrow LOOK FURTHER/DEEPER

Explore new tools and techniques

The highest energy possible

As low backgrounds as possible

The highest luminosity possible



THE LARGE HADRON COLLIDER

LHC and experiments being upgraded

Restart in 2022 with slightly higher energy (13 TeV → 13.6/14 TeV)

 $L = ~140 \text{ fb}^{-1}$



HL-LHC: 3000-4000 fb⁻¹





Next run: 300 fb⁻¹ (15 million Higgs particles)



New high-energy collider projects







Hadron versus lepton colliders





S/B ~ 10-10

1. Proton are compound objects

- Initial state unknown (particle and momentum)
- Limits achievable precision
- 2. High rates of QCD background
 - Complex triggers
 - High levels of radiation
 - Detector design focus on radiation hardness of many sub-detectors

3. Very high-energy circular colliders feasible



- **1. Electrons are point-like particles**
 - Initial state well-defined (particle, energy, polarization?)
 - High-precision measurements
- 2. Clean experimental environment
 - No (less) need for triggers
 - Lower levels of radiation

3. Very high-energies require linear colliders



European Strategy for Particle Physics, 2020

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting- edge technology:

• the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

 Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

https://cds.cern.ch/record/2720131?ln=en













What we know about the Higgs

- Gives mass to the W and Z bosons
- Gives mass to 3rd generation fermions via Yukawa interaction
- Evidence it couples to the 2nd generation fermions as expected
- Has spin 0
- Not composite (down to 10⁻¹⁹ m)







Higgs as a special probe

- Measure Higgs properties with highest precision
 - **Couplings fixed by masses, yukawa hierarchy?**
 - **Does it couple to the lighter fermions?**
 - λ determines shape and evolution of the Higgs potential \rightarrow cosmological implications
 - Is it a pure scalar or does it have a CP structure? \bullet
 - What stabilizes its mass much below the Planck scale? \bullet
 - New dark states? \rightarrow Portal to new physics beyond SM
 - Search for rare processes, through high-accuracy studies of SM cross sections

 $\mathscr{L}_{Higgs} = (D_{\mu}\phi)^{\dagger}(D^{\mu}\phi) - V(\phi^{\dagger}\phi) - \overline{\psi}_{L}\Gamma\psi_{R}\phi - \overline{\psi}_{R}\Gamma^{\dagger}\psi_{L}\phi^{\dagger}$ $V(\phi^{\dagger}\phi) = -\frac{m_H^2}{2}\phi^{\dagger}\phi + \frac{1}{2}\lambda(\phi^{\dagger}\phi)^2$ $\lambda = \frac{m_H^2}{2\nu^2}$

e⁺e⁻ colliders offer advantages due to the potentially high accuracy of measurements ₂₇





Higgs coupling measurement at future colliders





BSM Physics through Exotic Higgs Decays

General search for BSM

e⁺e⁻ collider better than HL-LHC for **MET+hadronic activity final states**





95% C.L. upper limit on selected Higgs Exotic Decay BR

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 $TT+ME_T$ (bb)(bb) (cc)(cc) (bb)(TT) (77)(77) $(jj)(\gamma\gamma)$ (YY)(YY)(jj)(jj)

Z. Liu, H. Zhang, LT Wang, 1612.09284







Higgs Self Coupling - λ_{HHH}



Requires full	HL-	LH
reach	SM	se

Need to combine all channels

Expected precision: 50%

ΗH	Branching ratio	Total yield (3000 fb ⁻¹)
bb + bb	33%	40,000
bb+WW	25%	31,000
bb + ττ	7.3%	8,900
ZZ + bb	3.1%	3,800
WW + ττ	2.7%	3,300
ZZ+WW	1.1%	1,300
γγ + bb	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

A major goal of HL-LHC: Measurements of Higgs pairs production f mm g mm

Extremely small cross section at LHC: $\sigma \sim 41$ fb ± 11%

- **C** luminosity to nsitivity





Higgs self-coupling at lepton colliders

Global effective-field-theory analysis can assess Higgs trilinear self-coupling







A DARK OR HIDDEN SECTOR AS A POSSIBLE SOLUTION

Dark Sector in particle physics has recently become very attractive

Can solve Dark Matter and Electroweak Phase Transition problems

Dark Sector particles interact very weakly with the SM particles and hence could have evaded discovery so far

Higgs boson can play "portal" role mediating the interactions between the two worlds Other SM "portal mediators": Dark Photon, Aµ, Z_D, Axion, a, Sterile Neutrino, N

mixing of the hidden-sector field with other SM "portal" mediators





Scalar or Higgs portal

New scalar can:

- Generate the baryon asymmetry of the Universe
- Mediate between SM particles and light DM
- Address the Higgs fine-tuning problem



e Universe ht DM

HL-LHC



Axion-Like Particles

QCD axions are a central idea in particle physics to solve the strong CP problem ALPs: can act as mediators between light DM and SM particles



Circular collider at Z pole



Dark Matter



	90% CL Direct Detection Pro	jection
	Indirect Detection	
	FCC-hh	
	LE-FCC	
	FCC-eh	
	HE-LHC	
	HL-LHC	
	CLIC ₃₀₀₀	
	CLIC ₁₅₀₀	
	ILC	
	CLIC ₃₈₀	
	FCC-ee	
	CEPC	Т
0	0.1 0.5	

FCC-hh (Dijet)			1		HE-LHC	
HL-LHC (Dijet)			Dijet	g _Q =1/4	HL-LHC	
FCC-hh					FCC-hh	
LE-FCC					LE-FCC	
HE-LHC			Monojet	t .	HE-LHC	
HL-LHC			<i>g</i> dn	1=1, g _Q =1/4	HL-LHC	
CLIC3000			g	_{рм×g_E=1/4}	CLIC3000	
CLIC ₃₈₀					CLIC ₃₈₀	
ILC		Monophoton			ILC	
FCC-ee		\sim			FCC-ee	
CEPC		European Strategy	Axial-	Vector	CEPC	
0.1 0.5	1		5 10)	0.1	0.5
	$M_{ m Media}$	tor [TeV]				1





Higgsino and Wino DM

FCC-hh can conclusively test the hypothesis of thermal DM for both scenarios

Simplified DM Models

DM particle + mediator

strongly dependent on the choice of couplings



After the Higgs boson discovery, no other new physics found Need to also pursue outstanding precision

- PRECISION physics can play a key role -





Top Mass Prediction from Precision Electroweak data



Top discovery at Tevatron

$M_{top} = 175 -> 173 \text{ GeV}$

World average: $m_{top} = 173.1 \pm 0.6 \text{ GeV}$ (0.35%)





July 21-27

Updated with EPS'01 results

Overnight update

Combination of electroweak measurements

Precision of theory predictions needs to improve for full sensitivity to new physics
 * higher order calculations needed
 Mogens Dam, HK2019

Effect of BSM physics

Modify EW observables through quantum effects (*cf* top & H @ LEP)

Blue (direct) & red (Z pole) ellipses may not overlap

Standard Model may not fit

FCC-ee provides improvement from all fronts...

e.g. m_z, α_{QED}, m_{top}, ...

...maximizing sensitivity to BSM physics

Final remarks

LHC to provide still 20-30x more data Hence, small discrepancies can still turn into discoveries

Higgs self coupling measurement at HL-LHC is a major milestone

Expect new exciting sensitivity for BSM physics and potential discoveries Higgs will continue to play an essential role

Both a future electron and hadron collider could play a significant role

The standard Model is well established but many questions remain answered

Planning for the next future accelerators has started

Extra Slides

ATLAS Diboson Searches - 95% CL Exclusion Limits

Status: June 2021

	Model	Channel [†]	Strategy*	
	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R ightarrow WW, ZZ ightarrow vvqq, \ell vqq, \ell \ell qq$	resolved, boosted	
	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	R ightarrow WW , $ZZ ightarrow qqqq$	boosted	
S	RS1 ($k/\overline{M}_{Pl}=0.01$)	$G_{KK} ightarrow \gamma\gamma$	resolved	
sion	RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} ightarrow \gamma\gamma$	resolved	
าคาร	RS1 ($k/\overline{M}_{Pl}=0.1$)	$G_{KK} ightarrow \gamma\gamma$	resolved	
a din	Bulk RS ($k/\overline{M}_{Pl} = 0.5$)	$G_{KK} ightarrow WW ightarrow ev\mu v$	resolved	
Extra	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} ightarrow ZZ ightarrow \ell \ell \ell \ell' \ell'$, $v v \ell \ell$	resolved	
E	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \rightarrow WW \rightarrow e \nu \mu \nu$	resolved	
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \rightarrow WW, ZZ \rightarrow \nu \nu q q, \ell \nu q q, \ell \ell q q$	resolved, boosted	
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} ightarrow WW$, $ZZ ightarrow qqqq$	boosted	
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WZ \to \ell \nu \ell' \ell'$	resolved	
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' ightarrow WZ ightarrow vvqq, \ell vqq, \ell \ell qq$	resolved, boosted	
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WH \to \ell \nu bb$	resolved, boosted	
	HVT ($g_F = -0.55, g_H = -0.56$)	W' ightarrow WZ ightarrow qqqq	boosted	
	HVT ($g_F = -0.55, g_H = -0.56$)	W' ightarrow WH ightarrow qqbb	boosted	
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' ightarrow WW ightarrow e u \mu u$	resolved	
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' o WW o \ell \nu q q$	resolved, boosted	
6	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \rightarrow ZH \rightarrow \nu \nu bb, \ell \ell bb$	resolved, boosted	
sons	HVT ($g_F = -0.55, g_H = -0.56$)	Z' ightarrow WW ightarrow qqqq	boosted	
oq é	HVT ($g_F = -0.55, g_H = -0.56$)	Z' ightarrow ZH ightarrow qqbb	boosted	
aug∈	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WZ \to \ell \nu \ell' \ell'$	resolved	
Ğ	HVT ($g_F = 0.14, g_H = -2.9$)	$W' ightarrow WZ ightarrow vvqq, \ell vqq, \ell \ell qq$	resolved, boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' ightarrow WH ightarrow \ell u bb$	resolved, boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	W' ightarrow WZ ightarrow qqqq	boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	W' ightarrow WH ightarrow qqbb	boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \to WW \to \ell \nu q q$	resolved, boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \rightarrow ZH \rightarrow \nu \nu bb, \ell \ell bb$	resolved, boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	Z' ightarrow WW ightarrow qqqq	boosted	
	HVT ($g_F = 0.14, g_H = -2.9$)	Z' ightarrow ZH ightarrow qqbb	boosted	
				0.2

 $\mathcal{L} = (36.1 - 139) \text{ fb}^{-1}$

ATLAS Preliminary

 \sqrt{s} = 13 TeV

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

	Model	<i>ℓ</i> ,γ	Jets†	E_{T}^{miss}	∫£ dt[fb	⁻¹] Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \ \gamma \\ - \\ 2 \ \gamma \\ multi-channe \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 - 4j - 2j $\geq 3j$ - 2j / 1J $\geq 1 b, \geq 1J/2$ $\geq 2 b, \geq 3 j$	Yes – – – – Yes Yes Yes	139 36.7 37.0 3.6 139 36.1 139 36.1 36.1	M _D M _S M _{th} M _{th} G _{KK} mass G _{KK} mass G _{KK} mass G _{KK} mass KK mass KK mass	11.2 Te 8.6 TeV 8.9 TeV 9.55 TeV 2.3 TeV 2.0 TeV 3.8 TeV 1.8 TeV	N $n = 2$ n = 3 HLZ NLO n = 6 $n = 6, M_D = 3$ TeV, rot BH $k/\overline{M}_{Pl} = 0.1$ $k/\overline{M}_{Pl} = 1.0$ $K/\overline{M}_{Pl} = 1.0$ $\Gamma/m = 15\%$ Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	2102.10874 1707.04147 1703.09127 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to t\nu \\ \operatorname{SSM} W' \to tb \\ \operatorname{HVT} W' \to WZ \to \ell\nu qq \ \mathrm{mod} \\ \operatorname{HVT} Z' \to ZH \ \mathrm{model} \ \mathrm{B} \\ \operatorname{HVT} W' \to WH \ \mathrm{model} \ \mathrm{B} \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	2 e, μ 2 τ - 0 e, μ 1 e, μ 1 τ - el B 1 e, μ 0-2 e, μ 0 e, μ 2 μ	$\begin{array}{c} - \\ 2 b \\ \geq 1 b, \geq 2 \\ - \\ 2 j / 1 J \\ 1 - 2 b \\ \geq 1 b, \geq 2 \\ 1 J \end{array}$	– – Yes Yes Yes J – Yes Yes	139 36.1 36.1 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass Z' mass W' mass Z' mass	5.1 TeV 2.42 TeV 2.1 TeV 4.1 TeV 6.0 TeV 5.0 TeV 4.4 TeV 4.3 TeV 3.2 TeV 3.2 TeV 5.0 TeV	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V = 3$ $g_V = 3$ $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 ATLAS-CONF-2021-025 ATLAS-CONF-2021-043 2004.14636 ATLAS-CONF-2020-043 2007.05293 1904.12679
CI	CI qqqq CI ℓℓqq CI eebs CI μμbs CI tttt	_ 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ Λ	1.8 TeV 2.0 TeV 2.57 TeV	$\begin{array}{c c} \textbf{21.8 TeV} & \eta_{LL}^- \\ \textbf{35.8 TeV} & \eta_{LL}^- \\ \textbf{g}_* = 1 \\ \textbf{g}_* = 1 \\ C_{4t} = 4\pi \end{array}$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
MQ	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DM) Vector med. Z'-2HDM (Dirac Pseudo-scalar med. 2HDM+a Scalar reson. $\phi \rightarrow t\chi$ (Dirac D	0 e, μ, τ, γ Μ) 0 e, μ, τ, γ DM) 0 e, μ multi-channe M) 0-1 e, μ	1 – 4 j 1 – 4 j 2 b 1 b, 0-1 J	Yes Yes Yes Yes	139 139 139 139 36.1	m _{med} 376 GeV m _{med} 376 GeV m _{med} 560 GeV m _{\phi} 560 GeV	2.1 TeV 3.1 TeV 3.4 TeV	g_q =0.25, g_{χ} =1, $m(\chi)$ =1 GeV g_q =1, g_{χ} =1, $m(\chi)$ =1 GeV tan β =1, g_Z =0.8, $m(\chi)$ =100 GeV tan β =1, g_{χ} =1, $m(\chi)$ =10 GeV y =0.4, λ =0.2, $m(\chi)$ =10 GeV	2102.10874 2102.10874 ATLAS-CONF-2021-006 ATLAS-CONF-2021-036 1812.09743
ГØ	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	$\begin{array}{c} 2 \ e \\ 2 \ \mu \\ 1 \ \tau \\ 0 \ e, \mu \\ \geq 2 \ e, \mu, \geq 1 \ \tau \\ 0 \ e, \mu, \geq 1 \ \tau \end{array}$	$ \begin{array}{c} \geq 2 \ j \\ \geq 2 \ j \\ 2 \ b \\ \geq 2 \ j, \geq 2 \ b \\ \geq 2 \ j, \geq 2 \ b \\ \geq 1 \ j, \geq 1 \ b \\ 0 - 2 \ j, 2 \ b \end{array} $	Yes Yes Yes Yes – Ves	139 139 139 139 139 139	LQ mass LQ mass LQ ^u mass LQ ^u mass LQ ^d mass LQ ^d mass 1	1.8 TeV 1.7 TeV 1.2 TeV 1.24 TeV 1.43 TeV 1.26 TeV	$egin{aligned} eta &= 1 \ eta &= 1 \ \mathcal{B}(\mathrm{LQ}_3^u o b au) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^u o t u) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^d o t u) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^d o t u) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^d o b u) &= 1 \end{aligned}$	2006.05872 2006.05872 ATLAS-CONF-2021-008 2004.14060 2101.11582 2101.12527
Heavy quarks	$\begin{array}{l} VLQ \ TT \rightarrow Zt + X \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + Z \\ VLQ \ T \rightarrow Ht/Zt \\ VLQ \ T \rightarrow Wb \\ VLQ \ B \rightarrow Hb \end{array}$	2 <i>e</i> /2µ/≥3e,µ multi-channe X 2(SS)/≥3 e,µ 1 e, µ 1 e, µ 0 e,µ ⊇	$u \ge 1 b, \ge 1 j$ $u \ge 1 b, \ge 1 j$ $u \ge 1 b, \ge 3 j$ $\ge 1 b, \ge 3 j$ $\ge 2 b, \ge 1 j, \ge 1$	– Yes Yes 1J –	139 36.1 36.1 139 36.1 139	T mass B mass T _{5/3} mass T mass Y mass B mass	1.4 TeV 1.34 TeV 1.64 TeV 1.8 TeV 1.85 TeV 2.0 TeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ SU(2) singlet, $\kappa_T = 0.5$ $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-024 1808.02343 1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	_ 1 γ _ 3 e, μ 3 e, μ, τ	2 j 1 j 1 b, 1 j –	_ _ _ _	139 36.7 36.1 20.3 20.3	q* massq* massb* massℓ* massν* mass	6.7 TeV 5.3 TeV 2.6 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1910.08447 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Multi-charged particles Magnetic monopoles	$2,3,4 e, \mu$ 2μ $2,3,4 e, \mu (SS)$ $2,3,4 e, \mu (SS)$ $3 e, \mu, \tau$ -	≥2 j 2 j 3) various 3) – – –	Yes Yes _ _ _ _	139 36.1 139 36.1 20.3 36.1 34.4	N ⁰ mass 910 Ge N _R mass H ^{±±} mass 350 GeV H ^{±±} mass 350 GeV 870 Ge H ^{±±} mass 400 GeV 1 multi-charged particle mass 1 monopole mass 1	eV 3.2 TeV V .22 TeV 2.37 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ DY production DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2	ATLAS-CONF-2021-023 1809.11105 2101.11961 1710.09748 1411.2921 1812.03673 1905.10130
	√s = 8 TeV	$\sqrt{s} = 13 \text{ TeV}$ partial data	$\sqrt{s} = 13$ full d	3 TeV ata		10 ⁻¹	1 1	⁰ Mass scale [TeV]	

*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 Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

 \sqrt{s} = 8, 13 TeV

Overview of CMS long-lived particle searches

0.0006-0.09 m

0.00035-0.08 m

0.003–1 m

CMS Preliminary

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.

SUSY RPV

SUSY RPC

Other

ced j	ets)	0.002–1.32 m				13
	<0.031 m					36
	0.0005	-0.4 m				3
Displa	aced jets) 0.005–0.2	4 m				13
Disp	laced jets) 0.00	6–0.55 m				13
	1906.06441 (Delayed jet +	MET)	0.32–34 m			13
		<1 m				36
		CMS-PAS-EXO-	-16-036 (dE/dx)		>0.7 m	13
			CMS-PAS-EXO-16-036 (dE/dx	(+ TOF)	>7.5 m	13
		1801.00359	(Delayed jet)		60–1.5e+13 m	39
		1801.00359 ((Delayed jet)		50-3e+13 m	39
			1801.00359 (Delayed μμ)		600-3.3e+12 m	39
	2004.05153 (Disappea	ring track)	0.7–30 m			14
	1909.06166 (Delayed γ(γ)) 0.2–6 m				77
77 (D i	isplaced dielectron)	0.000	12–25 m			20
77 (D	isplaced dimuon)		0.00012–100 m			20
ets)	0.003	1–0.53 m				13
jet +	jet) 0.0022-	0.3 m				16
10	-3 10-	-1	10 ¹	10 ³		
		-				

cτ [m]

Moriond 2021

140 fb⁻¹ (13 TeV) 132 fb⁻¹ (13 TeV) 140 fb⁻¹ (13 TeV) 132 fb⁻¹ (13 TeV) 36 fb⁻¹ (13 TeV) 3 fb⁻¹ (13 TeV) 132 fb⁻¹ (13 TeV)

L32 fb⁻¹ (13 TeV) L37 fb⁻¹ (13 TeV) B6 fb⁻¹ (13 TeV) L3 fb⁻¹ (13 TeV) L3 fb⁻¹ (13 TeV) B9 fb⁻¹ (13 TeV) B9 fb⁻¹ (13 TeV) L40 fb⁻¹ (13 TeV) Z7 fb⁻¹ (13 TeV)

0 fb⁻¹ (8 TeV) 0 fb⁻¹ (8 TeV) 32 fb⁻¹ (13 TeV) 6 fb⁻¹ (13 TeV)

ALPS LIMITS FROM HL-LHC

KSVZ ALP

