



Searches for BSM physics at the LHC

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Setting the theme - BSM searches

- Dark matter and dark energy
- Abundance of matter over anti-matter
- Neutrino masses and origin
- Origin of EW symmetry breaking
- A more "natural" solution to the hierarchy problem
- Strong CP problem



"There is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee discoveries beyond the SM, and answers to the big questions of the field" (M.Mangano, 98th ECFA, November 2015)



Setting the theme - BSM searches at the LHC

- There is an overwhelmingly large collection of BSM models to choose from
 - Non exhausted list: SUSY, extra dimensions, vector-like quarks, lepto-quarks...
 - Also: simplified models, minimal models, and EFT
 - Gauge invariance, UV-completion, existing experimental results provide the best guidance
 - The constraint can be very loose: many caveats and work-around
- LHC searches are signature-driven as a first principle
 - Search for excesses in number of events in a plethora of kinematic regions and for resonances from new particles, exploring the highest mass range possible → main focus of this talk
 - Perform precision measurements of SM parameters to search for deviations \rightarrow not covered
- Challenges in interpreting LHC search results
 - There are numerous results with similar final states \rightarrow not trivial to correlate or compare
 - Many searches take advantage of machine learning algorithms \rightarrow non-trivial to interpret
 - \Rightarrow Present, and preserve, physics object efficiency/resolutions, and particle-level results

Run I+2 pp collision data

Link to ATLAS Lumi public plot CMS Integrated Luminosity, pp, $\sqrt{s} =$ 7, 8, 13 TeV 80 Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC Delivered Luminosity [fb⁻¹] 200 200 AS Online Luminosity Total Integrated Luminosity (${
m fb}^{-1}$) LHC Delivered: 192.29 fb^{-1} 70 2011 pp $\sqrt{s} = 7 \text{ TeV}$ CMS Recorded: 177.65 fb^{-1} √s = 8 TeV 2012 pp √s = 13 TeV 2015 pp 60 2016 pp vs = 13 TeV 150 150 2017 pp vs = 13 TeV 2018 pp √s = 13 TeV 50 **40** 100 100 30 20 50 50 2/19 calibration 10- Jan'18 Jan'12 Jan'16 0 Jan'11 Jan'13 Jan 14 Jan'15 0 Jan'17 0 Apr JUI Oct Jan Date Month in Year

• Many key analyses are based on full Run I+Run-2 data

ATLAS/CMS: 140 fb⁻¹ at $\sqrt{s} = 13$ TeV

• Expect more results: many analyses are still analysing this legendary dataset

Highlight of the search results

- General remarks on the LHC DM searches, embedded in many BSM searches
- Highlight of recent searches results in
 - High mass/pT regions
 - SUSY
 - Long-lived particles (LLP)
- Areas not covered
 - BSM searches in dedicated quark-flavour sector \rightarrow Eva Gersabeck's talk earlier
 - Dark sector scenarios \rightarrow Phil Ilten's talk next
 - BSM searches using Higgs boson → Kristin Lohwasser's talk tomorrow
- For detailed information, especially the "how", tune in the relevant parallel sessions
 - Also follow these experimental public webpages for complete list of results

ATLAS public results CMS public results

General remark on DM searches

- Dark matter represents one of the clear guidance for BSM physics
 - Embedded in many BSM models, e.g. R-parity conserving SUSY, dark sector...
 - LHC searches have gone much beyond the traditional MET+X regions



LHCDMWG: 1810.09420

DM searches - models and signatures*





Can search for these BSM particles (mediators) in visible decays as well!

In many cases, the visible decay dominate the sensitivity

* non-exclusive list, much more at arXiv:1507.00966 (LHCDMWG)

High pT/mass region

A summary of search results - mass scale (non-SUSY)

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits **ATLAS** Preliminary Status: March 2021 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8.13 \text{ TeV}$ E^{miss} $\int \mathcal{L} dt [fb^{-1}]$ Jets† Model ℓ, γ Limit Reference ADD $G_{KK} + g/q$ **11.2 TeV** n = 2 $0 e, \mu, \tau, \gamma$ 1 – 4 j Yes 139 Мг 2102.10874 ADD non-resonant $\gamma\gamma$ dimensio 2γ 36.7 Ms 8.6 TeV n = 3 HLZ NLO 1707.04147 ADD QBH 2 i Mth 1703.09127 37.0 8.9 TeV n = 6ADD BH multijet ≥ 3 j 3.6 Mth 9.55 TeV n = 6, $M_D = 3$ TeV, rot BH 1512.02586 RS1 $G_{KK} \rightarrow \gamma \gamma$ 2γ G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$ 139 2102.13405 Bulk RS $G_{KK} \rightarrow WW/ZZ$ multi-channel 36.1 GKK mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$ 1808.02380 Extra 1 e,μ 2 j / 1 J Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell v q q$ Yes GKK mass $k/\overline{M}_{Pl} = 1.0$ 2004.14636 139 2.0 TeV Bulk RS $g_{KK} \rightarrow tt$ $\geq 1 \text{ b}, \geq 1 \text{J/2j}$ Yes **g_{KK} mass** 36.1 $\Gamma/m = 15\%$ 1804.10823 1 e, μ 3.8 TeV 2UED / RPP 1 e,μ Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ $\geq 2 b_1 \geq 3 j$ 36.1 KK mass 1.8 TeV 1803.09678 Yes 2 e, µ 139 5.1 TeV SSM $Z' \rightarrow \ell \ell$ 7' mass 1903.06248 SSM $Z' \rightarrow \tau \tau$ 2τ 36.1 Z' mass 2.42 TeV 1709.07242 bosons Leptophobic $Z' \rightarrow bb$ 36.1 2.1 TeV 2 b Z' mass 1805.09299 Leptophobic $Z' \rightarrow tt$ 0 e,μ $\geq 1 \text{ b}, \geq 2 \text{ J}$ Yes 139 Z' mass 4.1 TeV $\Gamma/m = 1.2\%$ 2005.05138 SSM $W' \rightarrow \ell v$ 139 W' mass 1906.05609 1 e, µ Yes 6.0 Te SSM $W' \rightarrow \tau v$ Gauge 1τ Yes 36.1 W' mass 3.7 TeV 1801.06992 $\mathsf{HVT} \ W' \to WZ \to \ell \nu qq \text{ model } \mathsf{B}$ 1 e, µ 2j/1J Yes 139 W' mass 4.3 TeV $g_V = 3$ 2004.14636 0-2 e, μ 139 $g_V = 3$ HVT $Z' \rightarrow ZH$ model B 1-2 b Yes Z' mass 3.2 TeV ATLAS-CONF-2020-043 139 W' mass 3.2 TeV $g_V = 3$ HVT $W' \rightarrow WH$ model B 0 e,μ $\geq 1 \text{ b}, \geq 2 \text{ J}$ 2007.05293 LRSM $W_R \rightarrow tb$ W_P mass multi-channel 36.1 3.25 TeV 1807.10473 LRSM $W_R \rightarrow \mu N_R$ W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV}, g_I = g_R$ 1904.12679 2μ 1 J 80 2 j Cl qqqq 37.0 **21.8 TeV** η₁₁ 1703.09127 2 e, µ Cl llqq _ 139 35.8 TeV 2006.12946 _ η_{LL}^- 5 CI eebs 139 1.8 TeV $g_* = 1$ ATLAS-CONF-2021-012 2 e 1 b _ 2μ 139 $g_{*} = 1$ Cl µµbs 1 b 2.0 TeV ATLAS-CONF-2021-012 2.57 TeV $|C_{4t}| = 4\pi$ CI tttt ≥1 *e*,µ ≥1 b, ≥1 j Yes 36.1 1811.02305 Λ Axial-vector med. (Dirac DM) 2.1 TeV $g_q=0.25, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 0 e, μ, τ, γ 1 - 4Yes 139 **m**..... 2102 10874 Pseudo-scalar med. (Dirac DM) $g_{q}=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 0 e, μ, τ, γ 1 – 4 j Yes 139 m_{med} 376 GeV 2102.10874 M Vector med. Z'-2HDM (Dirac DM) 0 e,μ 2 b 139 m_{med} 3.1 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ ATLAS-CONF-2021-006 Yes 0 e,μ Pseudo-scalar med. 2HDM+a 139 m_{med} 520 GeV $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ 2 b Yes ATLAS-CONF-2021-006 Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM) 0-1 e,μ 1 b, 0-1 J Yes 36.1 m_φ 3.4 TeV y=0.4, λ=0.2, m(χ)=10 GeV 1812.09743 Scalar LQ 1st gen ≥ 2 j Yes 139 _Q mass 1.8 TeV $\beta = 1$ 2 e 2006.05872 Scalar LQ 2nd gen $\beta = 1$ ≥ 2 j 2μ Yes 139 LQ mass 1.7 TeV 2006.05872 Scalar LQ 3rd gen Ŋ 2 b Yes 139 _Q^u mass 1.2 TeV $\mathcal{B}(LQ_3^u \to b\tau) = 1$ ATLAS-CONF-2021-008 1τ LQⁱⁱ mass $\mathcal{B}(LQ_3^{\tilde{u}} \to t\nu) = 1$ Scalar LQ 3rd gen 0 e,μ $\geq 2 j, \geq 2 b$ 139 1.24 TeV 2004.14060 Yes $\mathcal{B}(LQ_3^d \to t\tau) = 1$ Scalar LQ 3rd gen $\geq 2e, \mu, \geq 1\tau \geq 1$ j, ≥ 1 b 139 LQ^a mass 1.43 TeV 2101 11582 LQ^d mass Scalar LQ 3rd den $0 e, \mu, \ge 1\tau \ 0 - 2j, 2b$ $\mathcal{B}(LQ_3^d \to bv) = 1$ Yes 139 1.26 TeV 2101.12527 multi-channel VLQ $TT \rightarrow Ht/Zt/Wb + X$ 1.37 TeV SU(2) doublet 36.1 T mass 1808.02343 VLQ $BB \rightarrow Wt/Zb + X$ multi-channel 36.1 **B** mass 1.34 TeV SU(2) doublet 1808.02343 VLQ $T_{5/3}T_{5/3}|T_{5/3} \rightarrow Wt + X$ 2(SS)/≥3 *e*,*µ* ≥1 b, ≥1 j 36.1 T_{5/3} mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 1807.11883 Yes $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ Ъ, VLQ $Y \rightarrow Wb + X$ 1 e,μ $\geq 1 \text{ b}, \geq 1 \text{ j}$ Yes 36.1 Y mass 1.85 TeV 1812.07343 VLQ $B \rightarrow Hb + X$ 0 e,µ \geq 2 b, \geq 1j Yes 79.8 1.21 TeV singlet, $\kappa_B = 0.5$ ATLAS-CONE-2018-024 B mass VLQ $QQ \rightarrow WqWq$ $1 e, \mu$ ≥4 j Yes 20.3 Q mas 690 GeV 1509.04261 2 j Excited quark $q^* \rightarrow qg$ 139 a* mass 6.7 eV only u^* and d^* , $\Lambda = m(q^*)$ 1910.08447 cited Excited quark $q^* \rightarrow q\gamma$ 1 j 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1γ _ 36.7 a* mass 1709.10440 Excited quark $b^* \rightarrow bg$ 1 b, 1 j 36.1 b* mass 2.6 TeV 1805.09299 _ ற் ந 3 e,µ Excited lepton ℓ^* _ 20.3 $\Lambda = 3.0 \text{ TeV}$ 1411.2921 l* mass 3.0 TeV 1.6 TeV Excited lepton v^* 3 e, μ, τ $\Lambda = 1.6 \text{ TeV}$ _ _ 20.3 ^{*} mass 1411.2921 Type III Seesaw $\geq 2i$ 20008.07949 1 e, µ Yes 139 N⁰ mass 790 GeV LRSM Majorana v 2μ 2 j 36.1 N_R mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 1809.11105 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ H^{±±} mass DY production 2,3,4 e, µ (SS) 870 GeV _ 36.1 1710.09748 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ DY production, $\mathcal{B}(H_l^{\pm\pm} \rightarrow \ell \tau) = 1$ 1411.2921 20.3 H^{±±} mas đ DY production, |q| = 5eMulti-charged particles multi-charged particle mass 1.22 TeV 1812.03673 36.1 2.37 TeV DY production, $|g| = 1g_D$, spin 1/2 Magnetic monopoles 34.4 1905.10130 monopole mass √s = 13 TeV <mark>√s</mark> = 13 TeV <u>√s = 8 TeV</u> 10^{-1} 10 partial data 1 full data 5 TeV 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).

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A summary of search results - mass scale (non-SUSY)

Overview of CMS EXO results



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CMS Exotica summary

Single lepton + E_T



Mono-jet + \mathcal{E}_T



Di-lepton searches



Phys. Lett. B 796 (2019) 68



Interpretation of search results



ATLAS

	Lower limits on $m_{Z'}$ [TeV]							
Model	e	ee	$\mid \mu$	μ –	$\ell\ell$			
	obs	\exp	obs	\exp	obs	\exp		
Z'_{ψ}	4.1	4.3	4.0	4.0	4.5	4.5		
Z'_{χ}	4.6	4.6	4.2	4.2	4.8	4.8		
$Z'_{\rm SSM}$	4.9	4.9	4.5	4.5	5.1	5.1		





Di-"jet" summary $X \rightarrow q\bar{q}/qg/gg/b\bar{b}/t\bar{t}$



Creative trigger strategy is a must → See Elena Villhauer's talk on how ATLAS can keep improving L1-jet trigger in Run-3

ATL-PHYS-PUB-2021-006

Two examples of di-"jet" searches

$pp \rightarrow X \rightarrow q\bar{q}/gg/qg$





Dilepton and Dijet implications on DM searches



LHC DM searches vs non-Collider approaches

Spin-dependent

Universal fermion coupling Lepotonphobic couplings 10^{-37} 10⁻³⁷ σ_{SI} (χ -nucleon) [cm²] σ_{SD} (χ -proton) [cm²] Dilepton Dijet ATLAS Preliminary S Preliminary PLB 796 (2019) 68 Dijet; JHEP 03 (2020) 145 10⁻³⁸ 10⁻³⁸ Dijet TLA; PRL 121 (2018) 081801 √s = 13 TeV, March 2021 s = 13 TeV. March 2021 Dijet Dijet+ISR; PLB 795 (2019) 56 Dijet; JHEP 03 (2020) 145 10⁻³⁹ Boosted dijet+ISR; PLB 788 (2019) 316 Dijet TLA; PRL 121 (2018) 081801 10^{-39} tt resonance Boosted di-b+ISR; ATLAS-CONF-2018-052 XENON1T MIGD bb resonance 10^{-40} E^{miss}+X – tī resonance JHEP 03 (2020) 145 EPJC 78 (2018) 565 10⁻⁴⁰ E_T^{miss}+X 10⁻⁴ bb resonance E^{miss}_τ+γ; arXiv:2011.05259 JHEP 03 (2020) 145 E_{T}^{miss} +jet; arXiv:2102.10874 bb resonance 10^{-4} 10⁻⁴² E^{miss}+X DarkSide-50 Dijet PICO-60 C₃F₈ E^{miss}₇+jet; arXiv:2102.10874 PRD 100 (2019) 022001 10⁻⁴³ E_{τ}^{miss} + γ ; arXiv:2011.05259 10⁻⁴² Dijet E^{miss}_T+V(had); JHEP 10 (2018) 180 E_T^{miss} +X E^{miss}_T+Z(II); PLB 776 (2017) 318 10⁻⁴⁴ 10^{-43} XENON1T bb 10⁻⁴⁵ PRL 121 (2018) 111302 10⁻⁴⁴ PandaX XENON1T 10^{-46} PRL 117 (2016) 121303 Dilepton DarkSide-50 Vector mediator, Dirac DM Axial-vector mediator, Dirac DM -45 10 10⁻⁴⁷ PRL 121 (2018) 081307 $g_{_{II}} = 0.25, g_{_{II}} = 0, g_{_{IV}} = 1$ = 0.1, g_i = 0.1, g_i = 1 XENON1T MIGD ATLAS limits at 95% CL, direct detection limits at 90% CL ATLAS limits at 95% CL, direct detection limits at 90% CL 10^{-48} PRL 123 (2019) 241803 10 10³ 10³ 10^{2} 10^{2} 10 10 m_γ [GeV] m_γ [GeV]

ATL-PHYS-PUB-2021-006/

Spin-independent

Lepto-quark searches

Productions at the LHC Potential contributions to anomalies $\Phi_{-5/3} \left(\Phi_{-1/3} \right)$ gLee ou LQ $l, e/\mu/\tau$ \overline{S} \overline{LQ} μ^{-} b 000600000 $t(t^c)$ LQ****LQ ℓ^+ 1612.06858 Two latest results focusing on third-generation fermion LQ $\mathscr{B}(LQ_S \rightarrow b\mu) = 100\%$ $tb\tau\nu + t\tau\nu(b)$ 137 fb⁻¹ (13 TeV) 10-1 $\sigma(pp \rightarrow LQLQ \rightarrow b\mu b\mu)$ [pb] Obs. 95% CL limit Obs. (95% CL) Exp. (95% CL) CMS Preferred by $- LQ_{v} \overline{LQ}_{v} + \tau LQ_{v} - - LQ_{v} \overline{LQ}_{v} + \tau LQ_{v}$ $- LQ_{v} \overline{LQ}_{v} - LQ_{v} \overline{LQ}_{v}$ 3.5 Exp. 95% CL limit **B** anomalies k = 1 (95% CL) 10⁻² Exp. $\pm 1\sigma$ $\cdots \tau LQ_{v}$ τLQ Exp. $\pm 2\sigma$ 2.5 $\sigma(pp \rightarrow LQLQ)$ theory 10^{-3} 2 1.5 10^{-4} ATLAS 0.5 \sqrt{s} =13 TeV, 139 fb⁻¹ $B(LQ \rightarrow b\mu)=1$ 10⁻⁵ 0 2 2.2 m_{LQ} [TeV] 1.2 1.6 1.4 0.6 0.8 1.8 2 1000 1200 1400 1800 2000 1600 600 800 m_{LQ} [GeV] $LQ_V(LQ_S) \rightarrow t\tau(t\nu) \qquad LQ_V(LQ_S) \rightarrow b\nu(b\tau)$ ATLAS JHEP 10 (2020) 112 2012.04178

Diboson searches



Model Unspecific Search in CMS (MUSiC)

Input: several hundred final states and multiple kinematic distributions



2010.02984

Supersymmetry

General remark on SUSY searches

- One of the long-term favourite of both theorists and experimentalists
 - Elegant solution to hierarchy problem, stabilising the Higgs boson mass
 - DM candidates in R-parity violation scenarios
 - Gauge coupling unifications
- No SUSY particles seen yet at the LHC \Rightarrow a blow to the much hoped favoured "natural" region
 - SUSY breaking varies \rightarrow wide range of predictions on signal parameters at EWK
 - There is no rigours definition of naturalness ⇒ SUSY searches continue, and more creatively!

Typical spectrum for low Δ_{EW} models





LHC SUSY Cross-section Working group

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A snapshot of search summary

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary $\sqrt{s} = 13$ TeV

March 2021

	Model	Signature	$\int \mathcal{L} dt [\mathrm{fb}^{-1}]$	Mass limit		Reference
	$ ilde q ilde q, ilde q ightarrow q ilde \chi_1^0$	0 e, μ 2-6 jets E_{Tis}^{miss} mono-jet 1-3 jets E_{T}^{miss}	s 139 s 36.1	\tilde{q} [1×, 8× Degen.]	1.85 m($\tilde{\chi}_1^0$)<400 GeV m(\tilde{q})-m($\tilde{\chi}_1^0$)=5 GeV	2010.14293 2102.10874
arches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	$0 e, \mu$ 2-6 jets E_T^{miss}	^s 139	ğ ğ Forbidden	2.3 m($\tilde{\chi}_1^0)$ =0 GeV 1.15-1.95 m($\tilde{\chi}_1^0)$ =1000 GeV	2010.14293 2010.14293
Seé	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ Inclusive/	1 <i>e</i> , <i>µ</i> 2-6 jets	139	ĝ	2.2 $m(\tilde{\chi}_1^0)$ <600 GeV	2101.01629
Ve	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}(\ell\ell)\tilde{\chi}$ strong	$ee, \mu\mu$ 2 jets E_T^{miss}	^s 36.1	<i>ỹ</i>	1.2 $m(\tilde{g})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$	1805.11381
clusi	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{X}$	$\begin{array}{ccc} 0 \ e, \mu & \text{7-11 jets} & E_T^{\text{miss}} \\ \text{SS} \ e, \mu & \text{6 jets} \end{array}$	° 139 139	ξ ğ	1.97 $m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ 15 $m(\tilde{g})$ - $m(\tilde{\chi}_1^0)$ =200 GeV	2008.06032 1909.08457
4	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_1^0$	$\begin{array}{ccc} \text{0-1 } e, \mu & \text{3 } b & E_T^{\text{miss}} \\ \text{SS } e, \mu & \text{6 jets} \end{array}$	^s 79.8 139	ig ig	2.25 $m(\tilde{\chi}_{1}^{0})$ <200 GeV 1.25 $m(\tilde{g})$ - $m(\tilde{\chi}_{1}^{0})$ =300 GeV	ATLAS-CONF-2018-041 1909.08457
	$ ilde{b}_1 ilde{b}_1$	$0 e, \mu$ $2 b$ E_T^{miss}	° 139	$ \tilde{b}_1 \\ \tilde{b}_1 $ 0.68	1.255 $m(\tilde{\lambda}_1^0) \!$	2101.12527 2101.12527
arks tion	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh$ 3rd	$\begin{array}{ccc} 0 \ e, \mu & 6 \ b & E_T^{\text{mis}} \\ 2 \ \tau & 2 \ b & E_T^{\text{mis}} \end{array}$	§ 139 § 139	\$\tilde{b}_1\$ Forbidden 0 \$\tilde{b}_1\$ 0.13-0.85 0	$\begin{array}{c} \textbf{23-1.35} \\ \Delta m(\tilde{\chi}_{2}^{0},\tilde{\chi}_{1}^{0}) {=} \textbf{130} \text{GeV}, m(\tilde{\chi}_{1}^{0}) {=} \textbf{100} \text{GeV} \\ \Delta m(\tilde{\chi}_{2}^{0},\tilde{\chi}_{1}^{0}) {=} \textbf{130} \text{GeV}, m(\tilde{\chi}_{1}^{0}) {=} \textbf{0} \text{GeV} \end{array}$	1908.03122 ATLAS-CONF-2020-031
onp	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ Gen	0-1 $e, \mu \ge 1$ jet E_T^{miss}	^s 139	\tilde{t}_1	1.25 $m(\tilde{\chi}_1^0)=1 \text{ GeV}$	2004.14060,2012.03799
n. s pro	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ 3 jets/1 b E_T^{miss}	° 139	<i>ĩ</i> ₁ Forbidden 0.65	$m(\tilde{\chi}_1^0)=500 \text{ GeV}$	2012.03799
gei	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1-2 τ 2 jets/1 b E_T^{miss}	° 139	ĩ ₁ Forbidden	1.4 m($\tilde{\tau}_1$)=800 GeV	ATLAS-CONF-2021-008
3 rd dire	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 2 \ c & E_T^{\text{miss}} \\ 0 \ e, \mu & \text{mono-jet} & E_T^{\text{miss}} \end{array}$	\$36.1 \$139	$\tilde{i}_{1} = 0.85$	m(∛))=0 GeV m(ī₁,ī)-m(∛₁)=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}	^s 139	ĩ ₁ 0.067-	.18 $m(\tilde{\chi}_2^0)=500 \text{GeV}$	2006.05880
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu$ $1 b E_T^{\text{miss}}$	° 139	<i>ĩ</i> ₂ Forbidden 0.86	$m(\tilde{\chi}^0_1)$ =360 GeV, $m(\tilde{\imath}_1)$ - $m(\tilde{\chi}^0_1)$ = 40 GeV	2006.05880
	${ ilde \chi}_1^{\pm} { ilde \chi}_2^0$ via WZ	$\begin{array}{ccc} 3 \ e, \mu & E_T^{\text{mis.}} \\ ee, \mu \mu & \geq 1 \ \text{jet} & E_T^{\text{mis.}} \end{array}$	5 139 5 139	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.64 $ $ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.205 $	$m(ilde{\chi}_1^0)=0$ $m(ilde{\chi}_1^1)-m(ilde{\chi}_1^0)=5~GeV$	ATLAS-CONF-2020-015 1911.12606
	$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW	$2 e, \mu \qquad E_T^{\text{miss}}$	^s 139	$ ilde{\chi}_1^{\pm}$ 0.42	$m(\tilde{\chi}_1^0)=0$	1908.08215
t.	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via <i>Wh</i> FWK	$0-1 \ e, \mu \qquad 2 \ b/2 \ \gamma \qquad E_T^{\text{miss}}$	^s 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden 0.74	$m(ilde{\chi}_1^0)$ =70 GeV	2004.10894, 1909.09226
N Sec	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{+}$ via $\tilde{\ell}_L/\tilde{\nu}$	$2 e, \mu \qquad E_T^{\text{miss}}$	° 139	$\tilde{\chi}_1^x$ 1.0	$m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	1908.08215
Ш i	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2τ E_T^{miss}	§ 139	τ̃ [τ̃ _L , τ̃ _{R,L}] 0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0)=0$	1911.06660
	$\ell_{\mathrm{L,R}}\ell_{\mathrm{L,R}}, \ell \rightarrow \ell \chi_1^\circ$	$2 e, \mu$ 0 jets E_T^{miss} $ee, \mu\mu$ ≥ 1 jet E_T^{miss}	° 139 ° 139	<i>ϵ</i> 0.7 <i>ϵ</i> 0.256	$m({ ilde \chi}^0_1)=0 \ m({ ilde \ell})=10 \ { m GeV}$	1908.08215 1911.12606
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	$\begin{array}{lll} 0 \ e, \mu & \geq 3 \ b & E_T^{\text{miss}} \\ 4 \ e, \mu & 0 \ \text{jets} & E_T^{\text{miss}} \end{array}$	s 36.1 s 139	Ĥ 0.13-0.23 0.29-0.88 Ĥ 0.55	$\begin{array}{l} BR(\tilde{\chi}^0_1 \to h\tilde{G}){=}1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}){=}1 \end{array}$	1806.04030 2103.11684
pé s	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet E_T^{miss}	^s 139	$ \tilde{\chi}_{1}^{\pm} 0.66 $	Pure Wino Pure higgsino	ATLAS-CONF-2021-015 ATLAS-CONF-2021-015
cle	Stable \tilde{g} R-hadro	Multiple	36.1	ğ	2.0	1902.01636,1808.04095
ng- arti	Metastable g R-h	Multiple	36.1	$\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}]$	2.05 2.4 $m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1710.04901,1808.04095
Lo. Pä	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep E_T^{miss}	^s 139	<i>ẽ</i> , μ̃ 0.7 τ̃ 0.34	$\begin{split} \tau(\tilde{\ell}) &= 0.1 \text{ ns} \\ \tau(\tilde{\ell}) &= 0.1 \text{ ns} \end{split}$	2011.07812 2011.07812
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0},\tilde{\chi}_{1}^{\pm}\rightarrow Z\ell\rightarrow\ell\ell\ell$	3 <i>e</i> , <i>µ</i>	139	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.0	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ 0 jets E_T^{miss}	^s 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$ 0.95	1.55 $m(\tilde{\chi}_1^0)=200 \text{ GeV}$	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q$	4-5 large-R jets	36.1	$\tilde{g} [m(\tilde{\chi}_1^0)=200 \text{ GeV}, 1100 \text{ GeV}]$	1.3 1.9 Large $\lambda_{112}^{\prime\prime}$	1804.03568
>	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$ KPV	Multiple	36.1	$t [\lambda'_{323}=2e-4, 1e-2]$ 0.55 1.09	$m(\tilde{\chi}_1^0)=200 \text{ GeV, bino-like}$	ATLAS-CONF-2018-003
RF	$tt, t \to b \chi_1^+, \chi_1^+ \to b b s$	$\geq 4b$	139	t Forbidden 0.95	$m(\bar{\chi}_1^{\pm})=500 \text{ GeV}$	2010.01015
	$\begin{array}{c} t_1 t_1, t_1 \rightarrow bs \\ \tilde{z}, \tilde{z}, \tilde{z}, \tilde{z} \rightarrow c\ell \end{array}$	2 jets + 2 b	36.7	$t_1 \ [qq, bs]$ 0.42 0.61		1710.07171
	$t_1 t_1, t_1 \rightarrow q t$	$2 e, \mu$ $2 b$ 1μ DV	36.1 136	t_1 \tilde{t}_1 [1e-10< λ'_{au} <1e-8, 3e-10< λ'_{au} <3e-9] 1.0	U.4-1.45 BR($t_1 \rightarrow be/b\mu$)>20% 1.6 BR($\tilde{t}_1 \rightarrow a\mu$)=100%. cos $\theta_{r=1}$	1710.05544 2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	$1-2 \ e, \mu \ge 6 \ jets$	139	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007
*Only a	a selection of the available mass	limits on new states or	1) ⁻¹	Mass scale [TeV]	

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

A snapshot of search summary

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary

 $\sqrt{s} = 13 \text{ TeV}$

	Model	S					Mass lim	it				Reference
				• -	<u> </u>							1908.03122 ATLAS-CONF-2020-031
		increasing efforts on									2004.14060,2012.03799	
												2012.03799 ATLAS-CONF-2021-008 1805.01649
		• statistically limited final states, e.g. EWK sector										
		• unconventionally experimental signatures e.g. LLP										
			COII	V CI		nany chp		iitai si	gna	tures, e.g	. 661	1911.12606
		 challenging kinematic regions, e.g. compressed region R-parity violation and stealth SUSY 										1908.08215 2004.10894, 1909.09226 1908.08215 1911.06660 1908.08215 1911.12606
		0 e,μ 4 e,μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 139	<i>́</i> <i>Ĥ</i> 0.13-0.23 <i>Ĥ</i>		0.29-	-0.88		$ \begin{array}{c} BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1 \end{array} $	1806.04030 2103.11684

*Only a selection of the available mass limits on new states of phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

General remarks on SUSY results

- Typical result: exclusion limits as functions of two masses
 - Strong assumptions on the remaining signal parameters
 - Extra information, e.g. efficiencies in signal regions, are provided to allow for re-interpretation
- Interpretations in many different signal models, even beyond SUSY



Compressed Region - \tilde{t} in the top corridor



\tilde{t} in the compressed "top corridor"

Multivariate analysis: II input variables 7 hidden layer DNN



 $b\bar{b} + \mathcal{E}_T$











100

ATLAS: JHEP 06 (2020) 46

Tackling rare final states $4\ell + E_T$



31

ATLAS: arXiv:2103.11684

Long-lived particles



A summary of search results - CT

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

Status: March 2021



ATL-PHYS-PUB-2021-009/

ATLAS Preliminary

A summary of search results - $c\tau$





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.

RPV UDD, $\tilde{g} \rightarrow tbs$, $m_{\tilde{g}} = 2500 \text{ GeV}$

RPV UDD, $\tilde{g} \rightarrow tbs$, $m_{\tilde{g}} = 2500 \text{ GeV}$

RPV UDD, $\tilde{t} \rightarrow \overline{dd}$, $m_{\tilde{t}} = 1600 \text{ GeV}$

RPV UDD. $\tilde{t} \rightarrow \overline{dd}$. $m_{\tilde{t}} = 1600 \text{ GeV}$

RPV LQD, $\tilde{t} \rightarrow bI$, $m_{\tilde{t}} = 600 \text{ GeV}$

RPV LQD, $\tilde{t} \rightarrow bI$, $m_{\tilde{t}} = 600 \text{ GeV}$

RPV LQD, $\tilde{t} \rightarrow bI$, $m_{\tilde{t}} = 1600 \text{ GeV}$

GMSB, $\tilde{g} \rightarrow g\tilde{G}$, $m_{\tilde{a}} = 2450 \text{ GeV}$

GMSB, $\tilde{g} \rightarrow g\tilde{G}$, $m_{\tilde{g}} = 2100 \text{ GeV}$

Stopped $\tilde{t}, \tilde{t} \rightarrow t \chi_1^0, m_{\tilde{t}} = 700 \text{ GeV}$

AMSB, $\chi^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$, $m_{\chi^{\pm}} = 700 \text{ GeV}$

GMSB SPS8, $\chi_1^0 \rightarrow \gamma \tilde{G}$, $m_{\chi_1^0} = 400 \text{ GeV}$

dark QCD, $m_{\pi_{DV}} = 5 \text{ GeV}$, $m_{X_{DV}} = 1200 \text{ GeV}$

Split SUSY, $\tilde{g} \rightarrow q\bar{q}\chi_1^0$, $m_{\tilde{g}} = 1300 \text{ GeV}$

SUSY RPV

SUSY RPC

Other

34

Displaced signatures in high pT/mass region



Stopped LLP in bunch crossings with no collision



Summary

- A vast programme of BSM physics searches has been carried out based on the successful LHC Run I+2 data-taking
- ATLAS and CMS explored a huge chunk of the phase-space at multi- TeV scale
 - More efforts are now devoted to challenging kinematic regions and theoretical phase-space
 - Closing up the gaps!
 - Presenting and preserving this legendary dataset are also becoming mainstream
- Several intriguing anomalies in the flavour sector, led by the LHCb experiment, may just be what we need to go behind the SM
 - Muons appear to be "acting up" in several places, and will surely shake/shape the LHC BSM physics programme
- This is really just the beginning ...





A historical perspective



Backup slides

LHC schedule





Shutdown/Technical stop Protons physics Ions Commissioning with beam

Hardware commissioning/magnet training

ATLAS SUSY summary results



ATL-PHYS-PUB-2021-007

Third-generation $\tilde{t}\tilde{t}$



Dilepton and Dijet implications on DM mediators



CMS EXO Summary

BSM searches in *b*-decays

Dedicated quark-flavour results in Eva Gersabeck's talk earlier

$B_s \to \mu^+ \mu^-$

• Very rare and experimentally clean final states, particularly sensitive to NP





 $\mathscr{B}(B_s^0 \to \mu^+ \mu^-)_{\rm SM} = 3.66 \pm 0.14 \times 10^{-9}$





Angular anomaly in $B \to K^* \mu^+ \mu^- (P'_5)$



 $\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2 \,\mathrm{d}\vec{\Omega}} \Big|_{\mathrm{P}} = \frac{9}{32\pi} \Big[\frac{3}{4} (1-F_{\mathrm{L}}) \sin^2 \theta_K + F_{\mathrm{L}} \cos^2 \theta_K + \frac{1}{4} (1-F_{\mathrm{L}}) \sin^2 \theta_K \cos 2\theta_l + \frac{1}{4} (1-F_{\mathrm{L}}) \sin^2 \theta_K \cos 2\theta_l + \frac{1}{4} (1-F_{\mathrm{L}}) \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos 2\phi + S_4 \sin 2\theta_L \cos 2\phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{\mathrm{FB}} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \Big]$



Test of lepton flavour universality R_{K}

- Many experiments are testing LFU \rightarrow 2 dedicated sessions in Parallel Stream 2
 - In particular LHCb has revealed a range of anomalies known as $R_K, R_{K^*}, R_{D^*}^{\tau,\ell}$



$$R_{\mathcal{K}} = \frac{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to \mathcal{K}^+ \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to \mathcal{K}^+ e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

Double-ratio approach → cancel out most systematic uncertainties

$$R_{K} = \frac{\mathcal{B}(B^{+} \to K^{+} \mu^{+} \mu^{-})}{\mathcal{B}(B^{+} \to K^{+} J/\psi(\mu^{+} \mu^{-}))} \left/ \frac{\mathcal{B}(B^{+} \to K^{+} e^{+} e^{-})}{\mathcal{B}(B^{+} \to K^{+} J/\psi(e^{+} e^{-}))} = \frac{N_{\mu^{+}\mu^{-}}^{\mathrm{rare}} \varepsilon_{\mu^{+}\mu^{-}}^{J/\psi}}{N_{\mu^{+}\mu^{-}}^{J/\psi} \varepsilon_{\mu^{+}\mu^{-}}^{\mathrm{rare}}} \times \frac{N_{e^{+}e^{-}}^{J/\psi} \varepsilon_{e^{+}e^{-}}^{\mathrm{rare}}}{N_{e^{+}e^{-}}^{I/\psi} \varepsilon_{e^{+}e^{-}}^{\mathrm{rare}}}$$

LHCb-PAPER-2021-004

More in Razvan-Daniel Moise's talk in PS

Test of lepton flavour universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$



• What does this mean for BSM searches?

- Dedicated resonance searches (e.g. LQ, Z' at ATLAS CMS)
- Global fit EFT Lagrangian for $b \to s\ell\ell$: $\mathcal{L}_{eff} \propto \frac{4G_F}{\sqrt{2}} \sum_k C_k(\mu) \mathcal{O}_k(\mu)$

<u>I. Kriewald, Moriond 2021</u>

Input to the global fit on $b \to s\ell\ell$

Results: V_1 leptoquark & non-unitary mixing from VL leptons

 ~ 350 Observables taken into account:

Lepton Flavour Violation: $(\mu - e)$ -conversion, $\ell \to \ell' \gamma$, $\ell \to \ell' \ell' \ell'$, $\tau \to (\rho, \phi) \ell$, $B_{d,s} \to \ell^{\pm} \ell'^{\mp}$, $K_L \to \mu^{\pm} e^{\mp}$, $B \to (K, K^*, \pi) \ell^{\pm} \ell'^{\mp}$, $K \to \pi \ell^{\pm} \ell'^{\mp}$, $(B \to K \nu \bar{\nu}, K \to \pi \nu \bar{\nu})$

EW Precision Observables: g_V^ℓ , g_A^ℓ , Γ_Z^ℓ , $Z \to \ell \ell^{(\prime)}$

Semi-leptonic decays: $B_{d,s} \to \mu\mu$, $B_s \to \phi\mu\mu$, $B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B \to D^{(*)}\tau\nu$, $D_{(s)} \to \ell\nu$, $D \to \pi\ell\nu$, $D \to K\ell\nu$, $K \to \ell\nu$, $\tau \to (K,\pi)\nu$, $B \to \ell\nu$, $B \to \pi\ell\nu$

LFU Violation: $R_{K^{(*)}}$, $R_{D^{(*)}}$, angular observables and asymmetries in $b \to s\ell\ell$ à la P'_5

Direct searches (colliders): $m_{V_1} \gtrsim 1.5 \text{ TeV}$

Global EFT fit for $b \rightarrow s\ell\ell$



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