NP searches Summary & Highlights

Yang Liu on behalf of many Sun Yat-sen University (SYSU) <u>yang.l@cern.ch</u>



Why new physics:

Today



Why new physics:



2009 COC 84 6420

SM landscape

60581N - 9522

Why new physics:



Golden age for revolutionary discovery!

Overview of NP searches @ LHC:

- LHC is world's most powerful facilities to push the limits of our understanding of the universe at high energy frontier
- Searches covering most appealing directions of the new physics:
 - HBSM: see talk from Jin Wang
 - Exotics: see more details from 昊许, TianaoWang, 齐斌刘, 桐彬赵, YifanYang, 丹宁刘, 睿袁
 - <u>SUSY</u>: see more details from 诗怡梁, 家荣袁



Exostic searches

Exotic summary:

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits ATLAS Preliminary **Overview of CMS EXO results** CMS Prelimin Status: March 2023 $\int f dt = (3.6 - 139) \, \text{fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$ 0.72-0.25 1000.01257 (1) + 1y ℓ, γ Jets + E_{τ}^{miss} ($\mathcal{L} dt [fb^{-1}]$ Model Reference Limit ADD $G_{KK} + g/q$ 0 e, μ, τ, γ 1 – 4 i Yes 139 11.2 Te n = 2 8.6 TeV n = 3 HLZ NLO 2102 10874 is a memory solar targing in all a statistical in a 3 0010 800 EXCLUSION OF AN ADDRESS OF ADDRES f + φ, pseudoscelar (scalar), σ² + 58(φ+eebac) = -0.03(0.84 ADD non-resonant yy 2γ 36.7 1707.04147 2 i ADD OBH 139 3.6 9.4 TeV n = 6 1010 08447 0.0243 0 ADD BH multiet 9.55 TeV ■n = 6, M_D = 3 TeV. rot BH ≥3j 1512.02586 0.0260 2113.02710 (2/) 4.5 TeV BS1 Gev → YY 2γ 139 $k/\overline{M}_{ct} = 0.1$ 2102 13405 02-5.5 2001-04521 (2e + 2) 02-5.7 2001-04521 (2e + 2) Bulk RS GKK → WW/ZZ 2.3 TeV multi-channel 36.1 $k/\overline{M}_{P1} = 1.0$ 1808 02380 Bulk RS $g_{KK} \rightarrow tt$ 1 e, µ ≥1 b, ≥1J/2j Yes 3.8 TeV 36.1 $\Gamma/m = 15\%$ 1804.10823 whether modulater (ag), $p_{0}=0.25, p_{00}=1.1, m_{1}=1.6m^{2}$ whether modulater (ii), $p_{0}=0.2, p_{00}=1, p_{0}=0.11, m_{1}>1.5m^{2}$ (initial) here ther modulater (iii), $p_{0}=0.25, p_{00}=1.2m_{1}=1.0m^{2}$ (see) initial-modulater modulater (iii), $p_{0}=0.25, p_{00}=1.2m_{1}=1.0m^{2}$ (initial-modulater (iii)), $p_{0}=0.2m_{1}=1.0m^{2}$ (initial-modulater (iii)), $p_{0}=0.2m_{1}=1.0m^{2}$ (iii) and modulater (iii)), $p_{0}=0.2m_{1}=1.0m^{2}$ (iii) and indicates (iii), $p_{0}=0.2m_{1}=1.0m^{2}$ ≥2 b, ≥3 j Yes Tier (1,1), $S(A^{(1,1)} \rightarrow tt) = 1$ 2UED / RPP 1 e, µ 1.8 TeV 1803.09678 36.1 0.2-1.92 2103.02708 (2x, 2p $\operatorname{SSM} Z' \to \ell \ell$ 2 e, µ 1903.06248 0.5-3 # 1911.03947/ 0.0-1.95 2107.13021 (# 21+p) 139 5.1 TeV SSM $Z' \rightarrow \tau \tau$ 21 36.1 2.42 TeV 1709.07242 0.0-0.29 1901.01551 (0.1r + a 2i + a) Leptophobic $Z' \rightarrow bb$ 2 b 36.1 2.1 TeV 1805.09299 0092 (0, 1/ + a 2j + p)" mass Leptophobic $Z' \rightarrow tt$ 0 e, µ ≥1 b, ≥2 J Yes 139 4.1 TeV $\Gamma/m = 1.2\%$ 2005 05138 0.0-0.47 2107.13021 (x 1)+p(**) mass SSM $W' \rightarrow \ell v$ 1 e, µ Yes 139 mass 6.0 TeV 1006 05600 $\begin{array}{l} \text{pseudocciair mobility} \left(+ 50; \mu_{1} = 1, \mu_{2} = 1, \mu_{1} = 1, \text{GeV} \\ \text{pseudocciair mobility} \left(+ 15; \mu_{1} = 1, \mu_{2} = 1, \mu_{1} = 1, \text{GeV} \\ \text{complex } x_{1} = 0, \text{Start} \left(- 20; \mu_{1} = -3, \text{GeV} \right), \mu_{2} = -3, \text{Start} \\ \text{Starting} \left(x_{1} = 0, x_{2} \right), \mu_{2} = 1, \lambda_{2} = 1, \text{GeV} \\ \text{Starting} \left(x_{2} = 0, x_{3} \right), \mu_{2} = 1, \lambda_{2} = 1, 1, 0 \in \mathbb{N} \\ \text{Starting} \left(x_{2} = 0, x_{3} \right), \mu_{2} = 1, \lambda_{2} = 1, 1, 0 \in \mathbb{N} \\ \text{Starting} \left(x_{2} = 0, x_{3} \right), \mu_{2} = 1, \lambda_{2} = 1, 1, \lambda_{2} = 0, 1, 0 \in \mathbb{N} \\ \text{Start} \left(x_{2} = 0, x_{3} \right), \mu_{2} = 1, \lambda_{2} = 1, \lambda_{2} = 1, \lambda_{2} = 0, \lambda_{3} = 0, \lambda_{3}$ 0.05-0.42 2187.10982 (8, 3/ + 3/2) + p SSM $W' \rightarrow \tau r$ 1 7 Yes 139 5.0 TeV ATLAS-CONF-2021-025 >1 h >1. 1016 1908.00712 (b + p(**) SSM $W' \rightarrow tb$ 139 44 TeV ATLAS-CONF-2021-043 0-2 e, µ $g_V = 3$ HVT $W' \rightarrow WZ$ model E 21/1.1 Yes 139 V' mass 4.3 TeV 2004 14636 8306 10111111 (3p+3)+p(**) 0528 0454550021-011 (pp 2 i (VBF) $HVT W' \rightarrow WZ \rightarrow \ell_Y \ell' \ell' model$ 3 e.u Yes 139 139 / mass 340 GeV $g_V c_H = 1, g_f = 0$ 2207.03925 HVT $Z' \rightarrow WW$ model B 2i/1J Yes 3.9 TeV $g_V = 3$ $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 2004 14636 1 e.u LRSM $W_R \rightarrow \mu N_R$ 2 /1 5.0 TeV 1 J 80 1904 12679 11649 (2 displaced µ + p)" 2 j 37.0 21.8 TeV 11 1703.09127 CI qqqq 0.08-0.52 1099.03124 (2 RPV stap to 4 quark Clllgg 2 e, µ 139 35.8 TeV 2006.12946 η_L 0 CI eebs 1 b 139 1.8 TeV $g_{*} = 1$ 2105.13847 2 e 0.07-0.075 6 E095-0.185 CHS-PAS-EX0 Cl µµbs 2μ 1 b 139 2.0 TeV $g_1 = 1$ 2105.13847 $\begin{array}{c} 0.01 \ (\beta + 12, r_{00} + 3 \\ 0.01 \ (\beta + 12, r_{00} + 3 \\ 0.01 \ (\beta + 12, r_{00} + 3 \\ 0.01 \ (\beta + 12, r_{00} + 3 \\ 0.00 \ (\beta + r_{00} + r_{00} + 3 \\ 0.00 \ (\beta + r_{00} + r_{00} + 3 \\ 0.00 \ (\beta + r_{00} + r_{00} + 3 \\ 0.00 \ (\beta + r_{00} + 1 \\ 0.01 \ (\beta + r_{00} +$ CI tttt ≥1 e,µ ≥1 b, ≥1 j Yes 36.1 2.57 TeV $|C_{4c}| = 4\pi$ 1811.02305 0-12/0 1003.00030 (20) 0.0-9.3 1812 10443 (2y, 20 Axial-vector med. (Dirac DM) 2j 1-4j 130 3.8 TeV ga=0.25, g,=1, m(x)=10 TeV 1.PHVS.PHB.2022.036 Pseudo-scalar med. (Dirac DM) 0 e. u. t. y ge=1, gt=1, m(x)=1 GeV Yes Yes 139 376 GeV 2102.10874 Vector med. Z'-2HDM (Dirac DM) 0 e. u 139 3.0 TeV $= \tan \beta = 1, g_{\chi} = 0.8, m(y) = 100 \text{ GeV}$ 2 b 2108 13391 Pseudo-scalar med. 2HDM+a multi-channel 139 800 GeV $\tan\beta=1, g_{1}=1, m(\chi)=10 \text{ GeV}$ TI AS-CONE-2021-036 Scalar LQ 1st gen $\beta = 1$ 2006.05872 2 e ≥2j Yes 139 1.8 TeV Scalar LQ 2nd gen 2μ ≥2j Yes 139 1.7 TeV $\beta = 1$ 2006.05872 1 7 2 b Yes 139 mas 1.49 TeV $\mathcal{B}(LQ_3^o \rightarrow b\tau) = 1$ 2303.01294 Scalar LQ 3rd gen Q Scalar LQ 3rd gen 0 e, µ ≥2 j, ≥2 b Yes 139 1.24 TeV $\mathcal{B}(LQ_3^u \rightarrow tv) = 1$ 2004.14060 2 0 4 3 2201 02140 (20 Scalar LQ 3rd gen $\geq 2 e, \mu, \geq 1 \tau \geq 1 j, \geq 1 b$ 139 1.8 TeV $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$ 2101.11582 02.06315 (X + p(*** Scalar LQ 3rd gen 0 e, µ, ≥1 τ 0 - 2 j, 2 b Yes 139 mass 1.26 TeV $\mathcal{B}(LQ_2^d \rightarrow bv) = 1$ 2101 12527 excited light quark logi, A = m 1040 1911.0947 (2) 2.0 TeV Vector I O mix gen multi-channel ≥1 j, ≥1 b Yes 139 $\mathcal{B}(\tilde{U}_1 \rightarrow t\mu) = 1$, Y-M coupl. ATLAS.CONE.2022.052 LB-2.2 2385.07990 (y+j) Vector LQ 3rd gen 2 e, μ, τ ≥1 b Yes 139 1.96 TeV $\mathcal{B}(LO_{Y}^{Y} \rightarrow br) = 1$. Y-M coupl 2303.01294 0.25-3.9 1011.03052 (y + 2e) 0.25-3.9 1011.03052 (y + 2e) 0.25-3.8 1011.03052 (y + 2e) SU(2) doublet VLQ $TT \rightarrow Zt + X$ 2e/2µ/≥3e_µ ≥1 b, ≥1 j 139 1.46 TeV 2210.15413 $\begin{array}{l} \mathsf{MS24}, ||V_{eff}|^2 = 1.0, \; ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, ||V_{eff}|^2 = 1.0, \; ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, ||V_{eff}V_{eff}|^2 = ||V_{eff}|^2 + ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, \; ||V_{eff}V_{eff}|^2 + ||V_{eff}|^2 + ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, \; ||V_{eff}V_{eff}|^2 + ||V_{eff}|^2 + ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, \; ||V_{eff}V_{eff}|^2 + ||V_{eff}|^2 + ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, \; ||V_{eff}V_{eff}|^2 + ||V_{eff}|^2 + ||V_{eff}|^2 + ||V_{eff}|^2 = 1.0 \\ \mathsf{MS24}, \; ||V_{eff}V_{eff}|^2 + ||V_{eff}|^2 +$ VLQ $BB \rightarrow Wt/Zb + X$ SU(2) doublet 1808.02343 multi-channel 36.1 1.34 TeV 1.64 TeV $\begin{array}{c} \text{MUID-Channel}\\ 2(SS)/\geq 3 \ e,\mu\geq 1 \ b,\geq 1 \ j \quad \text{Yes}\\ 1 \ e,\mu \quad \geq 1 \ b,\geq 3 \ j \quad \text{Yes} \end{array}$ $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) =$ VLQ $T_{5/3}T_{5/3}|T_{5/3} \rightarrow Wt$ 36.1 1807.11883 0.05218 1006 1005 (x 1) + µ + el 8 L 0 90 2000 0007 (0), ex, ty+ 24, 2y+ 40, 2y+ 24, 2y+ 41, 2y+ 24, 2y+ 41, VLQ $T \rightarrow Ht/Zt$ 139 1.8 TeV SU(2) singlet, ky = 0.5 TLAS-CONF-2021-040 mass $VLQ Y \rightarrow Wb$ 1 e, μ ≥1 b, ≥1 j Yes 0 e,μ ≥2b, ≥1i, ≥1J -36.1 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ 1812.07343 $$\label{eq:constraint} \begin{split} & \text{Watch is into, Support} \\ & \text{Support} = \text{Support} (x_i^2 + y_i^2)^2 \, \text{Supp} (x_i^2 + y_i^2)^2 \, \text{Supp} (x_i^2 + y_i^2)^2 \, \text{Supp} (x_i^2 + y_i^2 +$$ $VLQ B \rightarrow Hb$ 139 2.0 TeV SU(2) doublet, KR= 0.3 ATLAS-CONF-2021-018 mass 15-0.075 1902.04776 (2a) VLL $\tau' \rightarrow Z \tau / H \tau$ multi-channel ≥1 j Yes 139 898 GeV SI I(2) doublet 2303.05441 1142 1112 MITC/N Excited quark $q^* \rightarrow qg$ 2 j 6 7 TeV only u^* and $d^* \Lambda = m(a^*)$ 130 1910 08447 5 15 2003 82208 (24 Excited quark a* -> m 1γ 36.7 5.3 TeV only u' and d', $\Lambda = m(a^*)$ 1700 10440 1 b, 1 j ≥2 j 125 1905 10031 (IL by Excited quark b* → bg 3.2 TeV 1910.08443 139 0 2 4 5 2103.02708 (2+, 2 -4 6 ToV A - 4.6 TeV Excited lepton T 139 2303 09444 8.2-5.0 2205.06709 (eg Type III Seesaw 2,3,4 e, µ ≥2j 8.2-6.1 2205.06709 (pr Yes 139 910 GeV 2202.02039 6.4.5.7 2202. LRSM Majorana v 2μ 21 36.1 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 1809.11105 mass Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ 2.3.4 e, µ (SS) various (2) C+20 1811 02947 (2) Yes 139 350 GeV DY production 2101.11961 an mass 0.550 2117.0049 (2p + 2) 0.548 2212.0004 (7 + p)⁽¹⁾ 0.548 2212.0004 (7 + p)⁽¹⁾ 0.542 212.0004 (2 + 2) 0.3522 2007.01708 (2 + p + 3 30) 0.935 1011.00006 (2 + 2) Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 e, µ (SS) 139 1.08 TeV DY production 2211.07505 Multi-charged particles 139 rulti-charged particle mas 59 TeV DY production, Ial = 5e TLAS-CONF-2022-034 Magnetic monopoles 34.4 2.37 TeV DY production, $|g| = 1g_D$, spin 1/2 1905.10130 √s = 13 TeV √s = 13 TeV partial data full data 10^{-1} 10 Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included) Mass Scale [TeV] Mass scale [TeV]

August 2023

137 fb⁻¹ 36 fb⁻¹ 137 fb⁻¹ 137 fb⁻¹ 137 fb⁻¹ 137 fb⁻¹ 138 fb⁻¹ 138 fb⁻¹ 138 fb⁻¹ 138 fb⁻¹

a 140 fb⁻¹ 140 fb⁻¹ 77 fb⁻¹ 77 fb⁻¹

> 18 m⁻¹ 140 h⁻¹ 137 h⁻¹ 140 h⁻¹ 140 h⁻¹ 140 h⁻¹ 137 h⁻¹ 101 h⁻¹ 137 h⁻¹ 137 h⁻¹ 137 h⁻¹ 138 h⁻¹ 1

36 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 128 fb⁻¹ 128 fb⁻¹

36 fb⁻¹ 36 fb⁻¹ 36 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 36 fb⁻¹ 36 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹ 38 fb⁻¹

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137 fb⁻¹ 137 fb⁻¹ 137 fb⁻¹ 140 fb⁻¹ 137 fb⁻¹ 137 fb⁻¹ 138 fb⁻¹

*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).

Exotic summary:



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

Compositeness searches:

• Explain if the current quarks or leptons are elementary or compositeness

Ele VS Comp

- Search for excited states of quarks (q*) and leptons (l*)
- Excited states could be produced by Gauge Interactions (GI) or contact interaction (CI)



Additional vector boson searches:

- Motivated by many BSM theories:
 - Sequential Standard Model (SSM), GUT, topcolour-assisted-technicolour (TC2), heavy vector triplet (HVT)
- Rich phenomena behind according to different models
- LHC search for them by using resonant & excesses in the tails
 - \circ ~ Two-body final states with quarks or leptons: dijet, II, Iv, and with τ
 - Diboson final states: VV, VH in FullHad, Lep+Jets
 - \circ ~ Final states with heavy quarks: Z' to tt, W' to tb, and ttZ' to tttt
 - CI: bsll final state

resonant

V'	Analysis final state	Observed lower limit on $m_{V'}$ [TeV]
Z' _{SSM}	bb	2.7
	$ee + \mu\mu$	5.1
W' _{SSM}	qq	4.0
	$ev + \mu v$	6.0
	$\tau \nu$	5.0
Z'_{ψ}	$ee + \mu\mu$	4.5
Z' _{TC2}	tī	3.9
Z' _{LUV}	$b\bar{b}b\bar{b}$	1.45
$W_R^\prime(g^\prime/g=1.0)$	tb	4.6
$W'_{\rm HVT}$ (model A)	$WZ \rightarrow XXqq$	3.9
$W'_{\rm HVT}$ (model B)	$WZ \rightarrow XXqq$	4.3
$W'_{\rm HVT}$ (model C)	$WZ \rightarrow \ell \nu \ell \ell$	3.4
Z' _{HVT} (model A)	$WW \rightarrow \ell \nu q q$	3.5
$Z'_{\rm HVT}$ (model B)	$WW \rightarrow \ell \nu q q$	3.9



Unification

Hierarchy





Additional lepton searches:



Neutrino oscillation

Vector-like lepton and quarks:

Large gap between EW & Planck scales

- VLQ: motivated from many composite Higgs models
- VLL: motivated from string theory, large extra D ...





Hierarchy

Search	Production mode	Decay channel
Hadronic T search [136]	Single	$T \rightarrow Ht$
Hadronic B search [135]	Single	$B \rightarrow Hb$
Multilepton (single) [137]	Single	$T \rightarrow Zt$
Multilepton (pair) [138]	Pair	$TT \rightarrow ZtVt, BB \rightarrow ZbVb, V = W, Z, H$
High $E_{\rm T}^{\rm miss}$ [139]	Pair	$T \to Vt \text{ or } B \to Vb, V = W, Z, H$
Lepton and jets [140]	Single	$T \to Ht, T \to Zt$



Leptoquarks:

- Could explain the similarity of the lepton and quark structure
- Motivated by many BSM:
 - GUT, composite fermions, and SUSY \bigcirc
 - Explain the B anomalies and mu g-2 Ο
- Up and down type LQ searches separately





Single + Non-res. (Obs.limit ± 1a)

----- Single + Non-res. (Exp.limit ± 1a)

Preferred by B anomalies

Total (Obs.limit ± 1a)

Total (Exp.limit ± 10)

Excluded region

2500

3000

m_{u™} [GeV]

ATLAS

95% CL

3.5 Vs=13 TeV, 139 fb⁻¹

1000

1500

2000

U^{MIN} model, High b-jet p₊ only

Interference with SM neglected

Coupling **\lambda**

0.5

Unification

Lepton Flavour Violation:

- Measuring the LFV precisely can probe the BSM (N and Z')
- Z/Z'->LFV (HLFV will be covered by another talk)
 - $\circ~$ Z to emu, Z to etau, and Z to mutau with τ_had and τ_lep

ZLFV	
Channel	Upper limit on $\mathcal{B}(Z \to \ell \ell')$
еµ	2.62×10^{-7}
$e\tau$ (τ_{had} and $\tau_{\ell'}$ channels combined)	5.0×10^{-6}
$\mu \tau$ (τ_{had} and $\tau_{\ell'}$ channels combined)	6.5×10^{-6}



Neutrino oscillation

Hidden(dark) sector searches:



- Predicted by many BSM theories
- Particles in hidden sectors can only interact with SM particles via a mediator:
 - Could be Higgs, new scalar, pseudoscalar, vector or axial-vector particle
 - With small couplings leading to LLPs giving **DPJ**, **muDPJ**, **caloDPJ**, **DV**, and **muDV**



Dark matter searches:

- WIMP mass close to the electroweak scale and an interaction strength with SM particles of the order of the weak interaction's strength
- Can be produced at LHC
- Simplified DM models are used:
 - Through a vector, axial vector, pseudoscalar or Higgs portal
 - \circ \quad Composite stable particles coupled with hidden sector

Vector or Axial vector portal











Dark Matter

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Dark matter searches:

WIMP mass close to the electroweak scale and an interaction strength with SM particles of the order of the weak interaction's strength

Dark Matter

¹⁵+h(bb), 139 fb⁻

^{iss}+h(bb), 139 fb

E^{miss}+h(γγ), 139 fb'

E^{miss}_T+Z(II), 139 fb⁻

E_+ +Z(qq), 36.1 fb

PLB 829 (2022) 132066

JHEP 10 (2018) 180

E_+Wt, 139 fb arXiv:2211.13138

Er +j, 139 fb⁻¹ PRD 103 (2021) 11200 tbHⁱ(tb), 139 fb⁻¹ JHEP 06 (2021) 145 Combination E^{miss}+h(bb), E^{miss}+Z(II), tbH¹(tb)

JHEP 11 (2021) 209

JHEP 10 (2021) 13

JHEP 11 (2021) 209

- Er +Z(II), 139 fb

tbH1(tb), 139 fb

JHEP 06 (2021) 145

- tttt. 139 fb⁻¹ arXiv:2211.01136

- Combination E_{τ}^{miss} +h(bb), E_{τ}^{miss} +Z(II), tbH²(tb)

PLB 829 (2022) 137066 Erniss+tW, 139 fb arXiv:2211 13138

2HDM+a, Dirac DM, sin0 = 0.35, m, = 10 GeV, g, = 1, m, = m, = m, m = 250 GeV

ATLAS

 $\Gamma/m > 203$

1500

2HDM+a, Dirac DM

m, = 10 GeV, g, = 1

m_A = m_H = m_H = 600 GeV

07 0.8 sin0

(2)

m, = 200 GeV

 $\tan \beta = 1$

m, [GeV]

Vs = 13 TeV. 139 fb⁻¹

Limits at 95% CL Observed Expected

~

an

- Can be produced at LHC
- Simplified DM models are used:
 - Through a vector, axial vector, pseudoscalar or Higgs portal 0
 - Composite stable particles coupled with hidden sector 0



Charged LLPs:

- Motivated from many BSM theories
- Can have varied charge multiplicity |z|:
 - Multi-charged particles (MCPs): 2<|z|<7:
 - Two doubly charged fermions, table multi-charged technibaryons, long-lived doubly charged Higgs bosons
 - Like heavy muons with a higher specific energy loss dE/dx in the pixel, TRT and MDT
 - Highly ionizing particles (HIPs): 20<|z|<100
 - Strange matter, Q-ball, Dirac magnetic monopoles
 - HI hit in TRT and custom HIP trigger together with specific reco alg



- For MCP:
 - Models with 500 GeV masses are strongly excluded
 - At 2 TeV, none of the MCP models are excluded

Gravitons:

small gravity

- Motivated from extra dimensions:
 - Arkani-Hamed, Dimopoulos and Dvali (ADD) model
 - Randall–Sundrum (RS) model
- If produced in the pp collisions, the KK graviton (GKK) escapes into the EDs



ADD GKK

	NC 1.1	1 / 7 4	
Analysis final state	Model	k/M_{Planck}	Excluded mass range for $m_{G_{\rm KK}}$ [TeV]
bb	RS1	0.2	< 2.8
γγ	RS1	0.1	< 4.5
Semileptonic $t\bar{t}$ (36.1 fb ⁻¹)	bulk RS	1.0	0.45–0.65
$HH \rightarrow bbbb$	bulk RS	1.0	0.298–1.46
$WW/ZZ \rightarrow qqqq$	bulk RS	1.0	1.3–1.8
$WW \to \ell \nu q q + ZZ \to \ell \ell q q$			
ggF production	bulk RS	1.0	< 2.0
VBF production	bulk RS	1.0	< 0.76
$ZZ \to \ell\ell\ell\ell + ZZ \to \ell\ell\nu\nu$	bulk RS	1.0	< 1.83

RS GKK

Quantum black hole:

small gravity

- Motivated from extra dimensions:
 - Arkani-Hamed, Dimopoulos and Dvali (ADD) model
 - Randall–Sundrum (RS) model
- QBH could potentially be produced at the LHC if the energy is above the fundamental Planck scale *MD*, decay into two-particle final states



SUSY searches

Why SUSY:

- "SUSY is the most <u>complete</u> microscopic theory conceived so far to go beyond the SM":
 - Can be used to compute any* observable quantity
 - Contains the ingredients to deal with all/most issues that the SM cannot address
 - "Supersymmetric models are extremely compelling theoretically"
- "SUSY is the most <u>complete</u> "LHC" of experimental signals conceived so far to go beyond the SM":
 - Hard to find an experimental signature that can be attained in another model and cannot be attained in SUSY
 - Comes with "some" way to judge how likely it is the particular signal at hand
 - Allows to derive the experimental implications of observing such signal
- Being "<u>complete</u>" in the theory and experimental sense:
 - Can use it to stress-test the capability of your present (or future) accelerator+experiment
 - Create a solid ground for exchange about **reinterpretation/preservation** of the searches

SUSY summary:

ATLAS SUSY Searches* - 95% CL Lower Limits

JL	July 2024								
	Model	S	ignatur	e ∫£	dt [fb ⁻	Mass limit			Reference
s	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\ell}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	140 140	[1x, 8x Degen.] [8x Degen.]	1.0 0.9	1.85 m(k ⁰)<400 GeV m(∂)-m(k ⁰)=5 GeV	2010.14293 2102.10874
sive Searche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_1^0$	0 e.µ	2-6 jets	$E_T^{\rm miss}$	140	iê B	Forbidden 1.	2.3 m(t ²) =0 GeV 15-1.95 m(t ²) =1000 GeV	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_{1}^{0}$	1 e, µ	2-6 jets		140	8		2 m(\hat{x}_1^0)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{0}$	ee, µµ	2 jets 7 11 jets	Emiss	140	8		2 m(X ₁ ⁰)<700 GeV	2204.13072
shis	$gg, g \rightarrow qq WZ t_1$	SS e, µ	6 jets	- T	140	r R	1.15	m(x) <600 GeV m(g)-m(x)=200 GeV	2307.01094
ç	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow tD\tilde{\ell}_{1}^{0}$	0-1 e,μ SS e,μ	3 b 6 jets	E_T^{miss}	140 140	iê ie	1.25	2.45 m(² ₁)<500 GeV m(² ₂)−m(² ₁)=300 GeV	2211.08028 1909.08457
arks stion	$b_1 b_1$	0 e, µ	2 b	E_T^{miss}	140	δ ₁ δ ₁	0.68	m(\tilde{k}_{1}^{0})<400 GeV 10 GeV<∆m($\tilde{b}_{1}, \tilde{k}_{1}^{0}$)<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}	140 140	bi Forbidden bi	0.23-1.35	$ \Delta m(\tilde{k}_{2}^{0}, \tilde{k}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{k}_{1}^{0}) = 100 \text{ GeV} \\ \Delta m(\tilde{k}_{2}^{0}, \tilde{k}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{k}_{1}^{0}) = 0 \text{ GeV} $	1908.03122 2103.08189
nbs	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{t}_1^0$	0-1 e, µ	≥ 1 jet 2 lots/1 /s	E_T^{miss}	140	It Participant	1.25	m(t ² ₁)=1 GeV	2004.14060, 2012.03799
en.	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{w} b \tilde{v}_1$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b r, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1-2 T	2 jets/1 b	Emiss	140	i Porbidden	Forbidden 1.4	m(t ₁)=500 GeV m(t ₁)=800 GeV	2108.07665
fired	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 e. µ	20	ETitis	36.1	2	0.85	$m(\hat{\epsilon}^0_A)=0$ GeV	1805.01649
e. 0	55 5 50 50 . au 50	1.2 e u	1.4.6	Fmiss	140	7. 0.3	0.067. 19	m(r ₁ ,z)·m(t ² ₁)=5 GeV	2102.10874
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t} \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e. µ	1 b	E_T^{miss}	140	ia Forbidden	0.86	$m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$	2006.05880
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jet ce, μμ	s ≥1jet	E_T^{miss} E_T^{miss}	140 140	$\frac{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}} = 0.205$	0.96	$m(\tilde{\xi}_1^0)=0$, wino-bino $m(\tilde{\xi}_1^1)-m(\tilde{\xi}_1^0)=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW	2 e, µ		E_T^{miss}	140	x [±] 0.42	E	$m(\tilde{k}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	Multiple <i>l</i> /jet	8	ET	140	$\hat{X}_{1}^{*}/\hat{X}_{2}^{*}$ Forbidden	1.06	m($\tilde{\ell}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
st <	$\chi_1^*\chi_1$ via ℓ_L/\hat{v} $\hat{\tau}_1$ $\hat{\tau}_{-\rightarrow}$ $\hat{\chi}_1^0$	2 e.µ		Emiss	140	7 1 [TeTe] 0.35 0.5	1.0	$m(\ell, \bar{\nu})=0.5(m(\ell_1^-)+m(\ell_1^-))$ $m(\ell_1^+)=0$	1908.08215 2402.00603
die	$\tilde{\ell}_{1,R}\tilde{\ell}_{1,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0 jets	Emiss	140	1	0.7	m(x ²)=0	1908.08215
	00 0 .LČ17Č	0 e u	> 1 jet	Emiss	140	0.26	0.94	m(l)-m(ki)=10 GeV	1911.12606
	111,11-40/20	4 e, µ	0 jets	Ethiss	140	H 0.5	5	$BR(\tilde{\xi}_{1}^{0} \rightarrow Z\tilde{G})=1$	2103.11684
		2 e. µ	2 large jet 2 iets	Emiss	140	H II	0.45-0.93	$BR(\tilde{k}_1^n \rightarrow ZG)=1$ $BR(\tilde{k}_1^n \rightarrow ZG)=RR(\tilde{k}_1^n \rightarrow KG)=0.5$	2108.07586 2204.13072
_			,	-1				maint - rolenatel - advera	
ο	Direct $\chi_1^* \chi_1^*$ prod., long-lived χ_1^*	Disapp. trk	1 jet	E_T^{anas}	140	$\frac{\chi_1^+}{\chi_1^+}$ 0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472
-live cles	Stable § R-hadron	pixel dE/dx		E_T^{miss}	140	ž.		2.05	2205.06013
artie	Metastable \hat{g} R-hadron, $\hat{g} \rightarrow qq \hat{\chi}_1^{-1}$ $\hat{I}\hat{f} \rightarrow I\hat{G}$	Disol, leo		Fmis	140	g [r(g)=10 ns] e.u	0.74	2.2 m(Y)=100 GeV	2205.05013 ATLAS.CONF.2024.011
DIG	are so	nivel dE ldu		rmiss	440	Ť 0.36		$\tau(\tilde{\ell}) = 0.1 \text{ ns}$	ATLAS-CONF-2024-011
_		pixerumox		~r	140	0.36		$\tau(t) = 10$ hs	2205.06013
	$\hat{\chi}_{1}^{\pm} \hat{\chi}_{1}^{\mp} / \hat{\chi}_{1}^{0}$, $\hat{\chi}_{1}^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 e, µ	0 inte	rmiss	140	$\tilde{X}_{1}^{\mp}/\tilde{X}_{1}^{0}$ [BR(Z _T)=1, BR(Z _e)=1]	0.625 1.05	Pure Wino	2011.10543
	$\chi_1 \chi_1 / \chi_2 \rightarrow W W/Z UUUVV$ $\tilde{x} \tilde{y} \rightarrow a a \tilde{Y}^0 \tilde{y}^0 \rightarrow a m a$	4 e, µ	≥8 iets	LT.	140	[X ₁ /X ₂ = [X ₁₀ ≠ 9, X _{12k} ≠ 0] ≥ [m(X ²)=50 GeV 1250 GeV]	0.95 - 1.95	6 2.34 Large X	2401.16333
>	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	7 [X''_3=2e-4, 1e-2] 0.5	5 1.05	m(X ⁰ ₁)=200 GeV, bino-like	ATLAS-CONF-2018-003
B	$\overline{tt}, \overline{t} \rightarrow b \widehat{\chi}_{1}^{\pi}, \widehat{\chi}_{1}^{\pi} \rightarrow b b s$		2 46		140	i Forbidden	0.95	m(k̃1)=500 GeV	2010.01015
	$\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow q\ell$	2 e.µ	26		140	1 (09,00) 0.42	0.01	-1.85 BR(i₁→be/bµ)>20%	2406.18367
	** -9 -9 - 0 **	1μ	DV		136	[<i>t</i> ₁ [1e-10 < <i>λ</i> ' ₂₁₄ <1e-8, 3e-10 < <i>λ</i> ' ₂₃₄ <3e-9]	1.0 📕 1.	6 BR(i₁→qµ)=100%, cosθ,=1	2003.11956
	$\chi_1^*/\chi_2^*/\chi_1^*, \chi_{1,2}^{*} \rightarrow tbs, \chi_1^* \rightarrow bbs$	1-2 e, µ	≥6 jets		140	x" 0.2-0.32		Pure higgsino	2106.09609
*Only a selection of the available mass limits on new states or 10 ⁻¹ 1 Mass scale [TeV]									
pner	phenomena is shown. Many of the limits are based on								

ATLAS Preliminary



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary spaticle and the LSP, and the difference between the intermediate spaticle and the LSP relative to ΔM , respectively, unless indicated otherwise.



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simplified models, c.f. refs. for the assumptions made



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM , respectively, unless indicated otherwise.

CMS Preliminary

June 2023

Strongly produced SUSY:













EWKly produced SUSY:





RPV case: (prompt)



RPC-RPV:

- Using published results to fill the gap between the RPC and RPV scenarios
- Stau+EWKinos LLE case got published: ATL-PHYS-PUB-2024-007
- Gluino & Squarks with LQD and UDD are ongoing



Published results can also be used to fill the gap between Long-Lived with prompt









Long-Lived SUSY:



Beyond simplified model:

- pMSSM-19 scannings
- GMSB scannings
- Plenty of information can be extracted from the scanning:
 - Presented in function of mass(EWKino), DM related observables
 - Complementary constraints from collider and non-collider measurements
 - Z/h 'funnel regions' got completed exclusion



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Summary & Outlook:

• Summary:

- The Run 2 data have offered an unprecedented opportunity to search for answers to many of the fundamental questions still open today in high-energy physics
- No significant excess of events in data observed
- Putting more stringent constraints on the phase space of models with applications of most cutting edge techs and methods
- "Theorists are happy with our current search strategies"
 - Targeting at specific final states and interpreting as wider as we can

• Outlook:

- "Leave no stone unturned"
- Followed the "tiny trace" we saw
- Go beyond simplified models
- Reinterpretation & Preservation are the keys to the future:
 - Build a bridge between experimentalists and theorists
 - Necessary step for (Q)AI4Science
 - A tool might change the search pattern for the future