Searches for New Physics at the LHC

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On behalf of the ATLAS, CMS and LHCb collaborations

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Large Hadron Collider

Excellent performance in 2018 for Vs=13 TeV proton-proton collisions

- Peak luminosity 2.1x10³⁴ cm⁻² s⁻¹ is double design
- First physics results this year with 140 fb⁻¹ from Run 2

Future Run 3 from 2021-2023 at Vs=14 TeV

• Goal: deliver 150 fb⁻¹

Extensive upgrades for High Luminosity LHC Run 2026-2035

- Peak luminosity 7.5x10³⁴ cm⁻² s⁻¹
- Goal: deliver over 3000 fb⁻¹





Standard Model

- Production cross section measurements in good agreement with theoretical predictions at Vs=13 TeV
- Measured diboson
 - WW
 - WZ
- Measured ttbar+boson
 - ttH
 - ttW
 - ttZ
- Measured triboson
 - WWW
 - WWZ

Standard Model Total Production Cross Section Measurements Status: March 2019

ATLAS ATL-PHYS-PUB-2019-010

CMS SM



<u>Overview</u>

Introduction

Emphasis on searches with 140/fb and on searches for new signatures

Exotics Searches

- High Mass Resonances
- Low Mass Resonances

Searches for Supersymmetry

- Electroweak production
- Strong production

Unconventional Signatures* Dark Matter and Dark Energy Summary

*Magnetic monopoles in Vasiliki Mitsou's talk on Thursday

Highest invariant mass (4.06 TeV) di-electron

• E_{T} of 2.01 TeV and 1.92 TeV



<u>Dilepton</u>

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ATLAS 139/fb arXiv:1903.06248 CMS 36/fb JHEP 06 (2018) 120

Direct production of high mass Z'

- Improved reconstruction for e and μ
- Mass resolution for electron channel < 2%, muon channel increases from 3% at 200 GeV to 15% at 3000 GeV
- Functional form fit for background
 No significant excess, report limits @ 95% CL

	Lower limits on $m_{Z'}$ [TeV]											
Model	e	e	$\mid \mu$	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						





- High mass W' decaying to lepton and neutrino (MET)
- No significant excess

	m(W') lower limit [TeV]			
Decay	Observed	Expected		
$W' \to ev$	6.0	5.7		
$W' \to \mu \nu$	5.1	5.1		
$W' \to \ell \nu$	6.0	5.8		



<u>Dijet</u>

- High mass resonance decaying to jets
 - Huge background from QCD dijets
 - Lowest single jet trigger p_T >420 GeV
 - Fully efficient for dijet masses above 1.1 TeV
- Background from functional form fit
- Benchmark model: excited quark > 6.7 TeV





ATLAS 139/fb ATLAS-CONF-2019-007

Highest invariant mass dijet event from ATLAS



Two central jets each with high p_T of 3.74 TeV

Invariant mass is 8.02 TeV

Diboson resonances

- High mass resonance decay to WW, WZ, ZZ
 - Boson hadronic decay products highly collimated
 - Not resolvable as separate jets
 - Large jets with two-prong substructure allow to differentiate from huge QCD multi-jet background





Combination

- Combine diboson searches for WW, WZ, ZZ, WH, ZH with 36/fb
 - Improve limits by up to 700 GeV for HVT model B with mass-degenerate heavy vector triplet
- Combine complementary diboson and dilepton channels
 - Dibosons sensitive for large boson couplings
 - Dileptons sensitive for large fermion couplings



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Combination

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CMS 36/fb arXiv:1906.00057 ATLAS 36/fb PRD 98 (2018) 052008

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LHCb Rare Decays

- Hadron collider high statistics B physics program can investigate rare decays
- $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K^{*0} \ell^+ \ell^-$
 - SM branching fractions small
 - Even small contribution from new physics can be detected
- Test lepton universality by measuring ratio of decays to muons to decays to electrons
- Ratio from 2014 was unexpectedly low
- Updated with 2x data in 2019, compatibility with SM unchanged at 2.5σ
- Lepton Flavor Universality breaking not confirmed or ruled out

LHCb Run 1 $R_K = 0.745 \substack{+0.090 \\ -0.074}$ (stat) ± 0.036 (syst) <u>PRL 113 (2014) 1</u>

 $+2015 + 2016 R_{K} = 0.846 \frac{+0.060}{-0.054} (stat) \frac{+0.016}{-0.014} (syst)$





LHCb

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- Doubled statistics for B⁺ with 2015-16 data added to Run 1 and improved reconstruction
- Total systematic uncertainty reduced from 4.8% to 1.7%

What's next?

- Update B⁰ result and angular analysis
- Future result will have double statistics again with 2017-18 data
- 2021-23 Run 3 will have upgraded LHCb detector with even better performance



LHCb search for lepton flavor violating decays

• Search for $B^0 \rightarrow \tau^- \mu^+$

- SM branching fraction 10⁻⁵⁴
- Indirect production of Z', leptoquarks, Pati-Salam as large as 10⁻⁴
- Results with 3/fb from 2011-2012
- Reconstruct τ⁻→π⁻π⁺π⁻ν_τ decays through two intermediate resonances a₁(1260)⁻ and ρ(770)⁰
- Normalize with $B^- \rightarrow D^-(K^+ \pi^- \pi^-)\pi^+$
- First limits on B_s and improve by x2 limits on B^0

Mode	Limit	$90\%~{\rm CL}$	$95\%~{ m CL}$
$B_s^0 \to \tau^{\pm} \mu^{\mp}$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	$3.9 imes 10^{-5}$	$4.7 imes 10^{-5}$
$B^0 \rightarrow \tau^{\pm} \mu^{\mp}$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	$1.9 imes 10^{-5}$



Search for 4 muons

- Low mass Z' from U(1) based on L_{μ} -L_{τ}
 - Z' only couples to muons and taus
- Radiate Z' from muons

- Exploit SM $Z \rightarrow \mu^+ \mu^-$ to produce muons
- Explore part of interesting parameter space





"Dijet" with ISR photon

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<u>CMS 36/fb arXiv:1905.10331</u> submitted to PRL ATLAS 80/fb Phys. Lett. B 795 (2019) 56 ATLAS 80/fb ATLAS-CONF-2018-052

- First limits below 50 GeV at a hadron collider for low mass resonances decaying to "dijets"
- Trigger on ISR photon p_T>200 GeV, large boost of low mass resonance collimates decay products into single large radius jet with two-prong substructure
- Data-driven background estimate for <u>non-resonant</u> and resonant (Z+γ,W+ γ,ttbar)



<u>Supersymmetry</u>

Significant progress in challenging SUSY signatures

- Many natural models have small mass differences, for example Higgsino triplet differences of 100's MeV
 - Cascade decays give visible particles with low p_{τ} , difficult to trigger and reconstruct

Compressed searches

- Non-prompt decays give unconventional signatures
 - Long-lived charged particle disappears after its decay to soft charged pion and neutral LSP
 - Searches for disappearing or short tracks
 - Long-lived neutral particle appears after its decay
 - Searches for emerging jets, displaced vertices
- First results at a hadron collider for SUSY partner to tau lepton "stau"







- LHC first results since LEP!!!
- Decay to di-tau and 2 LSPs
 - Large MET
 - Veto b-jets (ttbar)
 - Veto Z and H decays to taus
- Limits up to 390 GeV for mass-degenerate staus
- Limits up to 300 GeV for only "LH" staus



 $\tilde{\tau}^{*}_{\mathsf{R},\mathsf{L}}\tilde{\tilde{\tau}^{*}_{\mathsf{R},\mathsf{L}}} \rightarrow \mathbf{2} \times \tau \tilde{\chi}^{\mathbf{0}}_{\mathbf{1}}$

ATLAS Preliminary

√s=13 TeV, 139 fb⁻¹

All limits at 95% CL

SR-combined

Expected Limit ($\pm 1 \sigma_{exp}$)

Observed Limit ($\pm 1 \sigma_{\text{theory}}^{\text{SUSY}}$)

300

250

200

50

100

150

200

250

300

350

400

450

m(τ) [GeV]

500

 τ

 $m(\widetilde{\chi}_1^0)$ [GeV]



Chargino-Neutralino Production

- Compressed region: small mass differences between $ilde{\chi}^\pm_1$, $ilde{\chi}^0_2$, $ilde{\chi}^0_1$
- W and Z bosons off-shell, giving low p_T leptons

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Improved low p_T lepton reconstruction, added low p_T tracks



ATLAS 139/fb ATLAS-CONF-2019-014 CMS 36/fb Phys. Lett. B 782 (2018) 440 CMS 36/fb JHEP 03 (2018) 160



Chargino-Neutralino Production

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ATLAS 139/fb ATLAS-CONF-2019-014

CMS 36/fb Phys. Lett. B 782 (2018) 440



Inclusive searches: M_{T2} with disappearing tracks

CMS 137/fb SUS-19-005

- Strong pair production of gluinos or squarks
- Compressed: chargino and LSP almost mass degenerate, chargino decay to LSP and soft pion
- Look for disappearing track from chargino
 - Several categories optimized for various track lengths
 - Up to 700 GeV improvement over inclusive search alone!



Shorter-lived chargino with $c\tau=10 \text{ cm}$ Strongest limits when large mass splitting between gluino and chargino, $\vec{E}^{\tilde{R}}$ since large boost increases chance of chargino decay in tracking volume

Long-lived chargino with cτ=200 cm Strongest limits when small mass splitting between gluino and chargino, since small boost increases chance of chargino decay in tracking volume



Inclusive searches with 2 or 3 leptons

CMS 137/fb SUS-19-008 ATLAS 139/fb CONF-2019-015

 Strong pair production of gluinos or stops or sbottoms

- SM backgrounds very small for samesign leptons and 3 leptons
- Interpret for several possible decays, including compressed and RPV







Stop RPC

New result filling in gaps for <175 GeV mass difference between stop and LSP

 $\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ May 2018 800 m(x̃_) [GeV] ATLAS Preliminary Vs=13 TeV, 36.1 fb⁻¹ $\widetilde{t}_{t} \rightarrow t \widetilde{\chi}_{t}^{0} / \widetilde{t}_{t} \rightarrow W b \widetilde{\chi}_{t}^{0}$ 0L [1709.04183] 700 $/\tilde{t} \rightarrow W b \tilde{\chi}' / \tilde{t} \rightarrow b$ 1L [1711.11520] 2L [1708.03247] '́/τ̃,→Wbữ,'́/τ̃,→bf [1711.03301] Monojet /ĩ.→bff'ĩ 600 c0L [1805.01649] vs=8 TeV, 20 fb Run 1 [1506.08616] Observed limits ---- Expected limits All limits at 95% CL 500 400 300 200 100 0 400 500 600 700 800 900 1000 200 300 m(t̃_i) [GeV]



ATLAS Summary Plots SUSY

CMS Summary Plots SUSY

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.



Long-lived particles & Unconventional signatures

• LHC Long-lived particle forum

<u>arXiv:1903.04497</u>

- Lots of development of new techniques to search for particles decaying in detector
- Don't want to miss new physics because of missing trigger or reconstruction...
- Highlighting several new searches with new techniques in this talk



Long-lived particles: closing the gaps

ATLAS Summary Plots SUSY CMS Summary Plots SUSY

• Gluino (R-hadron)

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• Chargino (wino-type)



Long-lived gluino

- GMSB with gluino displaced decay to a jet & gravitino
- Emerging jets with timing in CMS EM Calorimeter 137 fb⁻¹ (13 TeV)







Long-lived stop

- RPV SUSY, long-lived stop decay
- Displaced vertex (≥3 tracks) and displaced muon
- Large Radius Tracking

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Events

Exclude 1.3 TeV stop with life-time in range 0.01 – 30 ns

ATLAS Preliminary - Data Heavy Flavor √s=13 TeV, 136 fb⁻¹ Fakes Cosmics $(m_{z},\tau_{z})=(1.7 \text{ TeV}, 0.01 \text{ ns})$ E_{T}^{miss} Trigger Selection - $(m_{\tau_{\tau}}) = (1.7 \text{ TeV}, 0.1 \text{ ns})$ 6 Full Muon Selection ---- (m,τ_γ)=(1.7 TeV, 1 ns) Preselected DVs Highest mass DV w/ ≥3 Tracks 10² 10³ 10^{4} 10 m_{DV} [GeV]



Where is dark matter?

Interpret searches for dark matter results in terms of a heavy mediator Z' model.

 $\gamma/V/g$ \bar{q} χ $Z'_{\rm V/A}$ Classic mono-jet signature!

Dijet and dilepton resonances contribute if sizable Z' coupling to quarks or leptons





Dark Matter

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- Z' mediator must have coupling to quarks to be produced at LHC!
- If g_α large, decay of Z' to dijets gives best sensitivity regardless of dark \bar{q} matter mass
- If g₁ not zero, decay of Z' to dileptons $Z'_{\rm V/A}$ gives best sensitivity regardless of dark matter mass

CMS Summary Plots

 $\gamma/V/g$

 $Z'_{
m V/A}$

- If g_{α} smaller, decay of Z' to dark matter still gives good sensitivity if kinematically allowed (Z' mass double dark matter mass), rely on visible ISR and large MET from $_{\bar{a}}$ $\gamma/V/g$ invisible dark matter
- Benchmark model:
 - Axial -Vector mediator
 - Dirac DM



Dark Matter

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 Comparison of ATLAS searches at 95% CL with direct detection searches at 90% CL

CMS Summary Plots

- Spin-dependent WIMP-proton scattering for vector mediator leptophobic model (large g_{α})
- Spin-independent WIMP-nucleon scattering for axial-vector leptophilic model



³⁸ Scalar Dark Energy

ATLAS 36/fb JHEP 05 (2019) 142

- Effective Field Theory implementation of Horndeski scalar dark energy theories
- Place first constraints on dark energy from Vs=13 TeV data
- L₁ operator proportional to mass of fermions, ttbar+MET most sensitive
 - Exclude suppression scale M_1 up to 200 GeV for $g_*=\pi^2$
- L₂ operator proportional to momenta, mono-jet most sensitive
 - Exclude suppression scale M_2 up to 1200 GeV for $g_*=\pi$





Summary

Kelpies Forth & Clyde Canal

First results from 2015-2018 data with 140/fb now available Many new results in progress for EPS and Lepton-Photon 2019 Many new developments for unconventional signatures in progress

ATLAS & CMS SUSY summary plots

ATLAS SUSY Searches* - 95% CL Lower Limits ATI								ATLAS Preliminary $\sqrt{s} = 13$ TeV						
	Model	S	ignatur	e∫	£ dt [fb⁻	1		Ma	ss limit					Reference
S	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0}$	0 e, µ mono-jet	2-6 jets 1-3 jets	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 36.1	<i>q</i> [2×, <i>q</i> [1×,	8x Degen.] 8x Degen.]		0.43	0.9 0.71	1	.55	m($ar{\chi}_{1}^{0})$ <100 GeV m($ar{q}$)·m($ar{\chi}_{1}^{0}$)=5 GeV	1712.02332 1711.03301
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0 <i>e</i> , <i>µ</i>	2-6 jets	E_T^{miss}	36.1	ğ ğ				Forbidden	0.95	2.0 5-1.6	$m(\tilde{\chi}_{1}^{0})$ <200 GeV $m(\tilde{\chi}_{1}^{0})$ =900 GeV	1712.02332 1712.02332
e Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell \ell)\tilde{\chi}_{1}^{0}$	3 e, μ ee, μμ	4 jets 2 jets	E_T^{miss}	36.1 36.1	ig ig					1.2	1.85	m(t̃10)<800 GeV m(g)-m(t̃10)=50 GeV	1706.03731 1805.11381
clusiv	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 e,μ 3 e,μ	7-11 jets 4 jets	E_T^{miss}	36.1 36.1	ğ ğ				0.98		1.8	m($\tilde{\chi}_1^0$) <400 GeV m($\tilde{\chi}_1^0$)-m($\tilde{\chi}_1^0$)=200 GeV	1708.02794 1706.03731
5	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\ell}_1^0$	0-1 e,μ 3 e,μ	3 b 4 jets	$E_T^{\rm miss}$	79.8 36.1	ğ ğ					1.25	2.2	5 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1706.03731
	$\tilde{b}_1\tilde{b}_1,\tilde{b}_1{\rightarrow}b\tilde{\chi}_1^0/\iota\tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{c} eta_1 \ ebee_1 \ ebeee_1 \ ebee_1 \ ebeee_1 \ ebeee_1 \ ebeeee_1 \ ebeee_1 \ ebeee$	F	orbidden	Forbidden Forbidden	0.9 0.58-0.82 0.7		$m(\tilde{\ell}_1^0)$	$m(\tilde{\chi}_1^0)=300 \text{ GeV}, BR(h\tilde{\chi}_1^0)=1$ $m(\tilde{\chi}_1^0)=300 \text{ GeV}, BR(h\tilde{\chi}_1^0)=BR(h\tilde{\chi}_1^+)=0.5$ $=200 \text{ GeV}, m(\tilde{\chi}_1^+)=300 \text{ GeV}, BR(h\tilde{\chi}_1^+)=1$	1708.09266, 1711.03301 1708.09266 1706.03731
ction	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}^0_2 \rightarrow b h \tilde{\chi}^0_1$	$0 e, \mu$	6 b	$E_T^{\rm miss}$	139	${ar b_1 \ ilde b_1}$	Forbidde	1	0.23-0.48		0.23-1.35		$\begin{array}{l} \Delta m(\tilde{k}_{2}^{0},\tilde{k}_{1}^{0}) {=} 130 \ \mathrm{GeV}, \ m(\tilde{k}_{1}^{0}) {=} 100 \ \mathrm{GeV} \\ \Delta m(\tilde{k}_{2}^{0},\tilde{k}_{1}^{0}) {=} 130 \ \mathrm{GeV}, \ m(\tilde{k}_{1}^{0}) {=} 0 \ \mathrm{GeV} \end{array}$	SUSY-2018-31 SUSY-2018-31
t produ	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP	0-2 e, µ	0-2 jets/1-2 Multiple	$b E_T^{miss}$	36.1 36.1	\tilde{t}_1 \tilde{t}_1				0.48-0.84	6	$m(\tilde{\ell}_1^0)$	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ =150 GeV, $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$, $\tilde{r}_{1} \approx \tilde{r}_{L}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520
direc	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{V}_1^0 / \tilde{z}_2, \tilde{z}_1 \rightarrow c \tilde{V}_1^0$	1 τ + 1 e,µ,τ 0 e, µ	2 jets/1 b	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{t}_1 \tilde{c}				0.85	1.16		m(ž ₁)=800 GeV	1803.10178 1805.01649
	111,11-01700,0001	0 e, µ	mono-jet	E_T^{miss}	36.1				0.46 0.43	0.000			$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$ $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1805.01649 1711.03301
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 <i>b</i>	$E_T^{\rm miss}$	36.1	ĩ2				0.32-0.88			$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=180$ GeV	1706.03986
	${\tilde \chi}_1^\pm {\tilde \chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} E_T^{miss}	36.1 36.1	$\begin{array}{c} \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \\ \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \end{array}$	0.17			0.6			$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{+})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	1403.5294, 1806.02293 1712.08119
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via WW	2 e, µ		E_T^{miss}	139	$\tilde{\chi}_{1}^{\pm}$			0.42				$m(\tilde{\chi}_{1}^{0})=0$	ATLAS-CONF-2019-008
*	$\tilde{\chi}_1^+ \tilde{\chi}_2^-$ via Wh $\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via $\tilde{\ell}_1 / \tilde{\nu}$	2 e. µ	20	E_T E_T^{miss}	36.1 139	$\frac{\chi_{1}^{-}/\chi_{2}}{\tilde{\chi}_{1}^{\pm}}$				0.68			$m(\tilde{\ell}, \tilde{v})=0.5(m(\tilde{\ell}^{\pm}_{1})+m(\tilde{\ell}^{0}_{1}))$	1812.09432 ATLAS-CONF-2019-008
direc	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}_1 \nu(\tau \tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu})$	2 τ		E_T^{miss}	36.1	$\begin{array}{c} \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \\ \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \end{array}$	0.22			0.76		$m(\tilde{\ell}_1^{\pm})-m(\tilde{\ell}$	$m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{+})+m(\tilde{\chi}_{1}^{0}))$ =100 GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{+})+m(\tilde{\chi}_{1}^{0}))$	1708.07875 1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} {\rightarrow} \ell \tilde{\chi}_1^0$	2 e, μ 2 e, μ	0 jets ≥ 1	$E_T^{\rm miss}$ $E_T^{\rm miss}$	139 36.1	ĩ ĩ	0.18			0.7			$m(\tilde{\ell}_{1}^{0})=0$ $m(\tilde{\ell})\cdot m(\tilde{\ell}_{1}^{0})=5 \text{ GeV}$	ATLAS-CONF-2019-008 1712.08119
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 36.1	ΪΙ Ĥ	0.13-0.2	3 0.3		0.29-0.88			$BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_{1}^{0} \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
cles	$\operatorname{Direct} \tilde{\chi}_1^{\dagger} \tilde{\chi}_1^{-} \operatorname{prod.},$ long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} = 0 $.15		0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
parti	Stable ğ R-hadron Metastable ğ R-hadron, ğ→qqΫ1		Multiple Multiple		36.1 36.1	ğ ğ [τ(ğ) =10 ns, 0.2 ns]					2.0 2.05	2.4 m($\bar{\chi}_1^0$)=100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
	LFV $pp \rightarrow \tilde{v}_{\tau} + X$, $\tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_{\tau}$						1.9	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07	1607.08079
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	$[\lambda_{i33} \neq 0, \lambda_{12k} \neq$	0]		0.82	1.33		$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1804.03602
>	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$	4	 5 large-R je Multiple 	ets	36.1 36.1	ĝ [m() ĝ [𝑋']	()=200 GeV, 110 =2e-4, 2e-5]	0 GeV]		1.0	1.3	1.9 2.0	Large \mathcal{X}_{112}^{0} m $(\overline{\mathcal{X}}_{1}^{0})$ =200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
ЧH	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	$\tilde{g} = [\lambda''_{32}]$	=2e·4, 1e·2]		0.	55 1.0	5		m(\tilde{t}_1^0)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1 = [qq]$	bs]		0.42	0.61		-		1710.07171
	$f_1 f_1, f_1 \rightarrow q\ell$	2 e,μ 1 μ	2 b DV		36.1 136	τ ₁ τ ₁ [1e	10< X'<1e-8, 3	3e-10< X'	<3e-9]	1.0	0.4-1.4	1.6	$\frac{BR(\tilde{r}_1 \rightarrow be/b\mu) > 20\%}{BR(\tilde{r}_1 \rightarrow q\mu) = 100\%, \cos\theta_i = 1}$	1710.05544 ATLAS-CONF-2019-006
Only i	a selection of the available mas	s limits on i	new state	s or	1	0-1					1		Mass scale [TeV]	,
ohen simp	omena is shown. Many of the li lified models, c.f. refs. for the as	mits are ba ssumptions	sed on 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.

ATLAS & CMS Exotics summary plots

ATLAS Preliminary

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

						L dt	= (3.2 – 139) fb ⁻¹	$\sqrt{s} = 8, 13 \text{ lev}$
	Model	<i>ℓ</i> , γ	Jets†	$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fb	I) Limit		Reference
Extra dimensions	$\begin{array}{l} \text{ADD } G_{KK} + g/q \\ \text{ADD non-resonant} \gamma\gamma \\ \text{ADD QBH} \\ \text{ADD QBH} \\ \text{ADD BH high } \sum p_T \\ \text{ADD BH multijet} \\ \text{RS1 } G_{KK} \rightarrow \gamma\gamma \\ \text{Bulk RS } G_{KK} \rightarrow WW/ZZ \\ \text{Bulk RS } G_{KK} \rightarrow WW \rightarrow qqqq \\ \text{Bulk RS } g_{KK} \rightarrow tW \rightarrow qqqq \\ \text{Bulk RS } g_{KK} \rightarrow tt \end{array}$	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ \hline \\ multi-channel \\ 0 \ e, \mu \\ 1 \ e, \mu \\ \hline \\ 1 \ e, \mu \end{array}$	1 - 4j -2j $\ge 2j$ $\ge 3j$ -2J $=1b, \ge 1J$ $\ge 2b, \ge 3$	Yes - 2j Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1 36.1	Mo 7.7 TeV Ma 6.5 Te Ma 6.9 Tr Ma 6.9 Tr Ma 8.2 TeV Gar mass 4.1 TeV Gar mass 4.1 TeV Gar mass 2.3 TeV Gar mass 1.6 TeV Gar mass 1.8 TeV	$\begin{array}{l} n=2 \\ n=3 \ \text{H.Z.NLO} \\ \forall n=6 \\ m=6, M_D=3 \ \text{TeV}, \text{rol BH} \\ \forall k \widetilde{M}_{Pl} = 0.3 \ \text{TeV}, \text{rol BH} \\ k \widetilde{M}_{Pl} = 0.3 \ \text{TeV}, \text{rol BH} \\ k \widetilde{M}_{Pl} = 1.0 \\ f m=1.0 \\ \text{Tref}, (1,1), \mathcal{B}(^{1(1,1)}) \rightarrow tt) = 1 \end{array}$	1711.03301 1707.04147 1703.09127 1806.02265 1512.02586 1707.04147 1808.02380 ATLAS-CONF-2019-003 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \text{SSM } Z' \rightarrow \ell\ell \\ \text{SSM } Z' \rightarrow \tau\tau \\ \text{Leptophobic } Z' \rightarrow tb \\ \text{Leptophobic } Z' \rightarrow tt \\ \text{SSM } W' \rightarrow t\nu \\ \text{SSM } W' \rightarrow t\nu \\ \text{SSM } W' \rightarrow t\nu \\ \text{HVT } V' \rightarrow WZ \rightarrow qqqq \model \\ \text{HVT } V' \rightarrow WH/ZH \model B \\ \text{LRSM } W_R \rightarrow tb \\ \text{LRSM } W_R \rightarrow \mu N_R \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array} \\ B \ 0 \ e, \mu \\ multi-channel \\ 2 \ \mu \end{array}$	- 2 b 1 b, ≥ 1J - 2 J 1 J	- 2j Yes Yes - -	139 36.1 36.1 139 36.1 139 36.1 36.1 36.1 80	27 mass 5.1 TeV 27 mass 2.42 TeV 27 mass 2.1 TeV 27 mass 3.0 TeV 27 mass 3.0 TeV W mass 6.0 TeV W mass 3.7 TeV W mass 3.8 TeV V mass 3.8 TeV W mass 3.8 TeV W mass 3.2 SteV We mass 5.0 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$ $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$	1903.06248 1709.07242 1805.09299 1804.10823 CERN-EP-2019-100 1801.06992 ATLAS-CONF-2019-003 1712.06518 1807.10473 1904.12679
CI	Cl qqqq Cl ℓℓqq Cl tttt	_ 2 e,μ ≥1 e,μ	2 j 	– – j Yes	37.0 36.1 36.1	Λ Λ Λ 2.57 TeV	21.8 TeV η_{LL}^{-} 40.0 TeV η_{LL}^{-} $ C_{4t} = 4\pi$	1703.09127 1707.02424 1811.02305
MQ	Axial-vector mediator (Dirac DM) Colored scalar mediator (Dirac D $VV_{\chi\chi}$ EFT (Dirac DM) Scalar reson. $\phi \rightarrow t_{\chi}$ (Dirac DM)	0 e, μ M) 0 e, μ 0 e, μ) 0-1 e, μ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \\ 1 \ b, 0\text{-}1 \ J \end{array}$	Yes Yes Yes Yes	36.1 36.1 3.2 36.1	mmed 1.55 TeV mmed 1.67 TeV M, 700 GeV my 3.4 TeV	$\begin{split} g_q = 0.25, g_\chi = 1.0, m(\chi) &= 1 \text{ GeV} \\ g = 1.0, m(\chi) &= 1 \text{ GeV} \\ m(\chi) &< 150 \text{ GeV} \\ y &= 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV} \end{split}$	1711.03301 1711.03301 1608.02372 1812.09743
70	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	1,2 e 1,2 μ 2 τ 0-1 e, μ	≥ 2 j ≥ 2 j 2 b 2 b	Yes Yes - Yes	36.1 36.1 36.1 36.1	LO mass 1.4 TeV LO mass 1.56 TeV LO2 mass 1.00 TeV LO2 mass 970 GeV	$\begin{split} \beta &= 1 \\ \beta &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^{\nu} \to b\tau) &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^{\ell} \to t\tau) &= 0 \end{split}$	1902.00377 1902.00377 1902.08103 1902.08103
Heavy quarks	$ \begin{array}{l} VLQ\;TT \to Ht/Zt/Wb + X \\ VLQ\;BB \to Wt/Zb + X \\ VLQ\;F_{5/3}\;T_{5/3} T_{5/3} \to Wt + X \\ VLQ\;Y \to Wb + X \\ VLQ\;Y \to Wb + X \\ VLQ\;B \to Hb + X \\ VLQ\;QQ \to WqWq \end{array} $	multi-channel multi-channel $2(SS)/\geq 3 e,\mu$ $1 e, \mu$ $0 e,\mu, 2 \gamma$ $1 e, \mu$	$\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 4 \text{ j}$	j Yes j Yes j Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass 1.37 TeV B mass 1.34 TeV Y mass 1.34 TeV Y mass 1.85 TeV B mass 1.21 TeV Q mass 690 GeV	$\begin{array}{l} {\rm SU(2) \ doublet} \\ {\rm SU(2) \ doublet} \\ {\mathcal B}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3} Wt) = 1 \\ {\mathcal B}(Y \rightarrow Wb) = 1, \ c_R (Wb) = 1 \\ \kappa_B = 0.5 \end{array}$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261
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	2j 1j 1b,1j -		139 36.7 36.1 20.3 20.3	e'mas 6,7 TeV e'mas 5,3 TeV o'mas 2.6 TeV e'mas 3.0 TeV e'mas 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-007 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{s\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$	$ \begin{array}{c} 1 \ e, \mu \\ 2 \mu \\ 2,3,4 \ e, \mu (SS) \\ 3 \ e, \mu, \tau \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ -$	≥ 2 j 2 j) - - - - - - - - full d	Yes 3 TeV ata	79.8 36.1 36.1 20.3 36.1 34.4	N ^a mass 560 GeV Na mass 570 GeV H ^a mass 870 GeV H ^a mass 1.22 TeV monopole mass 2.37 TeV 10 ⁻¹ 1	$ \begin{split} m(W_R) &= 4.1 \text{ TeV}, g_L = g_R \\ \text{DY production} \\ \text{DY production}, g(H_L^{aa} \to (\tau) = 1 \\ \text{DY production}, [g] &= 5e \\ \text{DY production}, [g] &= 1g_D, \text{spin } 1/2 \\ 10 \\ \text{Mass scale [TeV]} \end{split} $	ATLAS-CONF-2018-020 1809.11105 1710.09748 1411.2921 1812.08673 1905.10130

†Small-radius (large-radius) jets are denoted by the letter i (J).

Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Backup topics

- Vector-like leptons
- Vector-like quarks
- Leptoquarks
- Type III Seesaw

Vector-like means identical left-handed and right-handed interactions in SU(2)xU(1). Can't obtain mass from Higgs Yukawa coupling, so not bounded by constraints from Higgs production. Can cancel quadratic divergences to Higgs boson mass. Little Higgs and Composite Higgs models





Vector-like Leptons

- SU(2) doublet of non-chiral tau leptons
- Pair production of $\tau'\tau'$ and $\tau'v_{\tau}'$ and $v_{\tau}'v_{\tau}'$
- au' decay to $Z\tau$ or $H\tau$
- $v_{ au}'$ decay to W au



- Signal regions with 4 leptons, 3 leptons, 2 leptons & 1 tau lepton (L_T is scalar p_T sum of leptons)
- Exclude mass degenerate 3rd gen VLL in range 120-790 @ 95% CL



Vector-like Quarks

 CMS inclusive search for all decays using boosted event shape classifier for six types of jets (from top, H, Z, W, b, and quark/gluon) ATLAS 36/fb PRL 121 (2018) 211801 CMS 36/fb B2G-18-005

- ATLAS combination of searches
- Exclude T < 1.31 TeV and B < 1.03 TeV for any branching ratio





Leptoquarks

CMS 36/fb PRD 98 (2018) 032005 CMS 36/fb JHEP 03 (2019) 170 $b\tau$

 $B(LQ_3^U)$

↑ 0.9È

0.8

0.6

0.5F

0.4F

0.3E

ATLAS

---- observed

 $-tt + E_{T}^{miss} - 0\ell$

 $-\tau \tau b + E_{\tau}^{mit}$

 $-tt + E_{T}^{miss} - 1t$

s = 13 TeV, 36.1fb

ATLAS 36/fb arXiv:1902.08103

- Candidates to explain B meson anomalies, 3rd generation especially interesting here
- Limits from dedicated searches and reinterpretations of SUSY searches



Type III Seesaw

CMS 137/fb EXO-19-002

Ne

Even

- 3 or more leptons: scalar p_T sum of leptons & MET
- Seesaw model mass degenerate SU(2) triplet of Dirac charged leptons and Majorana neutral lepton
- Exclude heavy fermions with masses below 800 GeV for lepton flavor democratic scenario





Scalar (pseudoscalar) boson

- 3 or more leptons: dilepton resonance
- First search for this signature

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 Exclusions in 15-75 GeV and 108-340 GeV for branching ratios to dielectrons and dimuons above 0.003 (0.03) and 0.004 (0.04) for scalar(pseudoscalar)









Dielectron MOSSE (GeV