ATLAS @ NBI

C.

Stefania Xella On behalf of the ATLAS NBI team

CMS

LHC



ATLAS

LHC and ATLAS

Luminosity \mathcal{L} = how many particles we're able to squeeze through a given space in a given time $\mathcal{L} \cdot \sigma$ = collision rate

Two successful LHC Runs so far :

- 2008-2012, pp collision cms energy 7-8 TeV , \mathcal{L} peak 0.75 10 ³⁴ cm⁻² s⁻¹
- 2015-2018, pp collision cms energy 13 TeV , *L* peak 1.7 10 ³⁴ cm⁻² s⁻¹

ATLAS is a multi-purpose experiment at the LHC (the other is CMS). Some of the successes (imo):

- Observed the Standard Model (SM) Higgs decaying in Z, W, γ , τ , b, μ particles and produced in gluon-gluon or Vector Boson fusion processes, or associated with a W or Z or top particle.
- Measured several rare SM processes, uncharted before: 1-3 bosons, 1-4 top quarks,... This is important for searches for rare new phenomena, beyond the SM.
- Excluded most obvious (=less likely?) BSM scenarios (in supersymmetry or other exotic theories). new particles minimum 1-3 TeV or super-weakly interacting with SM particles
- Showed complementarity with direct and indirect dark matter search experiments. collider experiments important role in the quest for dark matter.
- Sensitivity to lepton flavour/lepton number/lepton universality violation. In some cases doing better than LEP experiments

Higgs properties [H]

Higgs production modes



Higgs decay modes



No indication of deviations from SM or additional Higgs particles yet Statistical and systematic errors are comparable -> room for improvements

Higgs decay modes [<u>htt</u>, <u>hzz</u>]

- Developed tau trigger algorithms and tau reconstruction and identification algorithms in Run 1, instrumental for the observation of the Higgs decay to tau leptons with Run 1 data, before CMS.
- Developed the parity and spin analysis of the Higgs boson, and excluded the spin-2 hypothesis, as well as other BSM spin-0 hyptheses, already with Run 1 data alone.







NBI

Rare standard Model processes [sm]



NBI

Performed the Run 1 ZZ measurements and set the first limits on anomalous gauge couplings with LHC data

Dark matter







Simplified model for DM :

One new force and one new particle, DM and SM particles interact

Complementarity of colliders and direct searches (eg LUX, Xenon1T) for dark matter

LFV Z decays to $\ell + \tau$ [<u>lfvz1</u>, <u>lfvz2</u>]

e.g. tau hadronic decays





	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell \tau)$ [×10 ⁻			
Final state, polarization assumption	ετ	μτ		
$\ell \tau_{\rm had}$ Run 1 + Run 2, unpolarised τ [10]	8.1 (8.1)	9.5 (6.1)		
$\ell \tau_{had}$ Run 2, left-handed τ [10]	8.2 (8.6)	9.5 (6.7)		
$\ell \tau_{had}$ Run 2, right-handed τ [10]	7.8 (7.6)	10 (5.8)		
$\ell \tau_{\ell'}$ Run 2, unpolarised τ	7.0 (8.9)	7.2 (10)		
$\ell \tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)		
$\ell \tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)		
Combined $\ell \tau$ Run 1 + Run 2, unpolarised τ	5.0 (6.0)	6.5 (5.3)		
Combined $\ell \tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)		
Combined $\ell \tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)		
EP OPAL, unpolarised τ [10]	9.8	17		
LEP DELPHI, unpolarised τ [11]	22	12		

Measurement still statistically limited

ATLAS sets the world best limit

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Combined NN output

NBI



Heavy Neutral Leptons [hnl1, hnl2]



"Realistic" multi-flavour mixing models consistent with neutrino oscillations data

- Introduce 3 right-handed states, and use seesaw mechanism to explain low mass for weakinteraction neutrinos (and dark matter and baryon asymmetry).
- ATLAS has demonstrated sensitivity to e-N and µ-N mixing at the same level as LEP experiments. Has also published a realistic interpretation of data for full Run 2 data analysis
- Investigate now the Run 2 data sensitivity for tau-N mixing and understand how to improve before Run 3 starts (new triggers)

Total elastic cross section [alfa, tot]

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t}\Big|_{t=0}, \qquad \rho = \frac{\operatorname{Re}\left[F_{\text{el}}(t)\right]}{\operatorname{Im}\left[F_{\text{el}}(t)\right]},$$

t=4-momentum transfer between protons

- ATLAS ALFA AFP beam line p jet beam line AFP ALFA p jet large distance large distance
- measurement of the differential cross section down to small angles gives not only the elastic cross section by integration, but also the total cross section from which the inelastic cross section can be deduced.
- Dedicated runs with low pileup and high β^* (low t), with ALFA detector, allow to measure unfolded differential elastic Xsection, and then fit it with otot as free parameters (ρ from models).
- Done measurement at 8 TeV. Working on measurement at 13 TeV.
- A final data taking with ALFA is planned in run 3 with very high-β * optics for a measurement of elastic scattering and associated parameters σtot, ρ and slope. Worth only if cms energy > 13.5 TeV





Run 3 (2022-2025)

- A new run starts in May, pp collision cms energy 13.5 TeV and \mathcal{L} peak 2 10³⁴ cm⁻² s⁻¹
- Run 3 will not add a lot of data, but will be used strategically to focus on new type of searches : eg
 - long lived particles, super-weakly interacting particles (continue from Run2)
 - dijet resonances, etc..
 - B physics
 - Rare Higgs decays
- Run 3 will also test completely new software and hardware, which will stay with ATLAS until the end of HL-LHC
 - New L1 trigger hardware and Central Trigger Processor
 - New multi threaded software (eg. tracking) and extensive use + establishment of machine learning for data analysis



Transition Radiation Tracker (TRT)





NBI contributes to TRT operations and maintenance from start Run 1 until end of Run 3

TRT provides half the momentum resolution and significant e/π rejection, capabilities which are crucial for several analyses

Challenges in Run 3 : deal with leaks – partly radiation induced – of both the cooling gas (a potent greenhouse gas) and the active Xenon gas (important for the electron identification, but at present very expensive). The effects of closing modules and switching other modules to Argon will be mitigated by improvements in software.

NBI

Bphysics



 $R_{K} = \frac{\mathcal{B}(B^{+} \to K^{+} \mu^{+} \mu^{-})}{\mathcal{B}(B^{+} \to J/\psi \, (\to \mu^{+} \mu^{-}) K^{+})} \Big/ \frac{\mathcal{B}(B^{+} \to K^{+} e^{+} e^{-})}{\mathcal{B}(B^{+} \to J/\psi \, (\to e^{+} e^{-}) K^{+})} \,.$

K could be other hadrons, eg K^{*0} B+ could be other B hadron, eg B^0 , B^0_s

- This is a rare decay, and the low electron momentum is a trigger challenge for ATLAS.
- Dedicated triggers were included in the last part of Run 2 data taking.
- New triggers are studied for Run 3, and improved data acquisition and rate allocation should allow to make ATLAS competitive.
- In Run 2 we collected enough events with $\ell = e, \mu$ to do a first measurement of R_{K^*}
- The analysis strategy is to select events (with ML) independently of the invariant masses, and fit the reconstructed B mass to estimate signal size and separate non-resonant (signal) from resonant (J/ψ control) contributions.

Photon / electron energy reconstruction NBI

- The photon energy resolution $\sigma(E\gamma)$ is the **dominant** performance parameter for the H → γγ
- Our team wishes to improve this resolution in ATLAS.
- Consider the cell energies in the LAr calorimeter as pixels in four images (one for each layer), and train a Convolutional Neural Network (CNN) to estimate the energy of electron/photon candidates.





Measured the improvement in data, using electrons (we have billions of Z→ee)

Expected improvement on photons E resolution of 20%

Rare Higgs decays : Z γ

- Current result, no optimized photon energy resolution yet (see right)
- The observed 95% CL upper limit on the $\sigma(pp \rightarrow H) \cdot B(H \rightarrow Z\gamma)$ is 3.6 times the SM prediction for a Higgs boson mass of 125.09 GeV [zg].
- Main background : non resonant Z production in association with a photon
- With expected improvement in photon energy resolution just shown, one can be sure to have a clear observation of thiis H decay within Run 3 end



Beyond Run 3: High Luminosity LHC



Big game changer for improving the SM and beyond SM physics measurements shown earlier. The high luminosity LHC which will bring 10 times more data, and additionally the ATLAS tracker will have a significant increase in angular acceptance.

New tracking trigger

- At HL-LHC the collision data rate will increase by a factor 10
- the ATLAS real-time data selection (trigger) is challenged : speed and efficiency are the critical parameters. layer
- charged particle track reconstruction is the bottleneck



Particles Xing ITK Tracking detector

Image in Graph neural network

New pattern recognition algorithms development

Focus on choice of

- Hardware implementation (optimal combination of CPU/GPU and possibly FPGAs)
- Algorithm type (neural networks is the option studied now, CNN vs GNN)



particle tracks

ITK DC-DC converter

DC-DC Converter is part of the End-of-Substructure communication module , and provides power for this.

- Converting in two steps from input voltage of 11 V first to 2.5 V used for optical chips and further to 1.2 V for electronics
- PCBs (panels of 10 each) by GS Swiss PCB AG, CH
- Automatized component mounting at Danchell A/S, DK
- Functionality testing and burn-in in NBI electronics lab





NBI

ITK endcap strip modules

- 600 modules will be produced [~10%] in Scandinavia (in two different geometries)
- Production will run from 2022 to 2025
- NBI responsible for all module
 Quality Control & Assurance
 - visual inspection
 - electrical testing
 - metrology
 - thermal cycling



ITK endcap strip modules



Who are we?

Name	Position	Interests
Peter Hansen	Prof. Emeritus	TRT calibration
Mogens Dam	Ass. Prof.	ITK HL-LHC : DC-DC converters , design & production in Denmark
Stefania Xella	Ass.Prof.	Trigger HL-LHC : optimal algorithms for tracking, design of final Trigger system Tau leptons reconstruction Lepton flavour/number. Lepton universality violation
Jørgen Beck Hansen	Ass.Prof.	Total cross section measurement
Troels Petersen	Ass.Prof.	Photon/electron reconstruction Lepton universality violation Higgs rare decays
Oleg Ruchayskyi	Ass. Prof.	Lepton flavour/number violation (STA)
Craig Wiglesworth	Assist. Prof.	ITK HL-LHC: module production & quality control
Alessandra Camplani	Assist. Prof.	Trigger HL-LHC: optimal algorithms for tracking, optimal hardware for tracking
Jimmy Hansen	technician	ITK HL-LHC : DC-DC converters, technical help in testing
	Master students	Lepton flavour violation, photon energy reconstruction, lepton universality violation

Summary

- LHC and ATLAS are an excellent machine and experiment for investigating fundamental new particle and forces at the energy frontier.
- The performance is exceeding what expected for this stage of the physics program thanks to the excellent accelerator team, the inventive of the experimental physicists (new software or hardware, new analysis methods) and the tight collaboration of the theoretical and experimental physicists
 - We are zooming in on the Higgs particle
 - We are testing theory extensions of the SM, looking for the reasons for neutrino mass, dark matter, fine tuning of the SM
- The ATLAS NBI team contributes strongly to these achievements

Back up

Which responsibilities did/do we have?

- Stefania : ATLAS NBI team leader, representant in TDAQ IB
 - Exotics subgroup convenor for searches for new physics with leptons + X 2020-2022
 - Trigger coordinator 2017-2019
 - Tau Trigger & Tau identification coordinator during Run 1 (<2015)
- Mogens : ATLAS NBI deputy team leader, representant in ITK IB
 - Responsible for DC-DC converters for the whole endcap strips detector, HL-LHC, ITK
- Alessandra : ATLAS representant in TDAQ IB
 - Firmware coordinator, HL-LHC, Trigger (EF)
- Peter :
 - TRT project leader 2019-2021
- Craig :
 - Trigger Calorimeter reconstruction coordinator 2014-2016
 - Overall coordinator for Quality control & assurance procedures, and responsible for scandinavian endcap strip modules. HL-LHC, ITK
- Jørgen:
 - Total cross section pp , 8 & 13 TeV , analysis coordinator

supersymmetry

ATLAS SUSY Searches* - 95% CL Lower Limits

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

	Model	Signature	∫ <i>L dt</i> [fb ⁻	¹] Mass limit		Reference
ş	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_{1}^{0}$	0 e, μ 2-6 jets E mono-jet 1-3 jets E	T_T^{miss} 139 T_T^{miss} 139	$ \vec{q} $ [1×, 8× Degen.] 7 7	.0 1.85 m($\tilde{\lambda}_1^0$)<400 GeV m(\tilde{q})-m($\tilde{\lambda}_1^0$)=5 GeV	2010.14293 2102.10874
nclusive Searche	$\tilde{g}\tilde{g}, \; \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i> 2-6 jets <i>E</i>	^{miss} 139	₿ ₿ Forbidd	2.3 m(\tilde{k}_{1}^{0})=0 GeV m(\tilde{k}_{1}^{0})=1000 GeV	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} W \tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} (\ell \ell) \tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (\ell \ell) \tilde{\chi}_1^0$	1 e, μ 2-6 jets $ee, \mu\mu$ 2 jets E 0 e, μ 7-11 jets F	139 miss 139 miss 139	ing and the second seco	2.2 m(k ₁ ⁰)<600 GeV 2.2 m(k ₁ ⁰)<700 GeV 1 97 m(t ⁰)<500 GeV	2101.01629 CERN-EP-2022-014 2008.06032
	$gg, g \rightarrow qq w z \lambda_1$	SS e, μ 6 jets	^T 139	6 if 6	1.15 m(x) (000 GeV m(x)=200 GeV	1909.08457
-	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^o$	$\begin{array}{cccc} 0-1 \ e, \mu & 3 \ b & E \\ SS \ e, \mu & 6 \ \text{jets} \end{array}$	79.8 T 139	50. 765	2.25 m(t_1^2)<200 GeV	ATLAS-CONF-2018-041 1909.08457
urks tion	$\tilde{b}_1 \tilde{b}_1$	0 e, µ 2 b E	^{miss} 139		1.255 $m(\tilde{k}_1^0) < 400 \text{ GeV}$ 10 GeV< $\Delta m(\tilde{b}_1, \tilde{k}_1^0) < 20 \text{ GeV}$	2101.12527 2101.12527
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}^0_2 \rightarrow b h \tilde{\chi}^0_1$	$\begin{array}{cccc} 0 \ e, \mu & 6 \ b & E \\ 2 \ \tau & 2 \ b & E \end{array}$	miss 139 miss 139 T 139	δ ₁ Forbidden 0.13-0.85	$\begin{array}{c} \textbf{0.23-1.35} \\ \Delta m(\tilde{\chi}_{2}^{0},\tilde{\chi}_{1}^{0}) \!=\! 130 \; \text{GeV}, \; m(\tilde{\chi}_{1}^{0}) \!=\! 100 \; \text{GeV} \\ \Delta m(\tilde{\chi}_{2}^{0},\tilde{\chi}_{1}^{0}) \!=\! 130 \; \text{GeV}, \; m(\tilde{\chi}_{1}^{0}) \!=\! 0 \; \text{GeV} \end{array}$	1908.03122 2103.08189
squa	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	$0-1 e, \mu \ge 1$ jet E	miss 139 miss 130	Ĩ, Ĩ	1.25 $m(\tilde{x}_1^0) = 1 \text{ GeV}$	2004.14060,2012.03799
ten.	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \chi_1$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1-2 τ 2 jets/1 b E	T 139 miss 139	Ti Forbidden 0.03 Ti Forbidden Forbidden	1.4 m(t_1)=500 GeV	2108.07665
3 rd g direc	$\tilde{t}_1\tilde{t}_1,\tilde{t}_1{\rightarrow}c\tilde{\chi}_1^0/\tilde{c}\tilde{c},\tilde{c}{\rightarrow}c\tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & & 2 \ c & E \\ 0 \ e, \mu & & \text{mono-jet} & E \end{array}$	T_{miss} 36.1 T_{miss} 139	č 0.85 7 ₁ 0.55	$m(\tilde{t}_{1}^{0})=0$ GeV $m(\tilde{t}_{1},\tilde{c})-m(\tilde{t}_{1}^{1})=5$ GeV	1805.01649 2102.10874
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	1-2 e, μ 1-4 b E 3 e, μ 1 b E	miss 139 miss 139 T 139	ī ₁ 0.0 0.1 ī ₂ Forbidden 0.86	57-1.18 $m(\tilde{\chi}_2^0)=500 \text{ GeV}$ $m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{\chi}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$	2006.05880 2006.05880
	${\tilde \chi}_1^\pm {\tilde \chi}_2^0$ via WZ	$\begin{array}{ccc} \text{Multiple } \ell/\text{jets} & E \\ ee, \mu\mu & \geq 1 \text{ jet} & E \end{array}$	miss Tmiss T 139	$\frac{\tilde{\chi}_{+}^{*}/\tilde{\chi}_{0}^{0}}{\tilde{\chi}_{+}^{*}/\tilde{\chi}_{2}^{0}}$ 0.205 0.9	$ \begin{array}{c} \mathbf{m}(\tilde{x}_{1}^{0})=0, \text{ wino-bino} \\ \mathbf{m}(\tilde{x}_{1}^{*})=\mathbf{m}(\tilde{x}_{1}^{0})=5 \text{ GeV}, \text{ wino-bino} \end{array} $	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW	2 e, µ E	miss 139	<i>x</i> [±] 0.42	$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	Multiple l/jets E	miss 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}$ Forbidden	$m(\tilde{\chi}_1^0)=70 \text{ GeV}, \text{ wino-bino}$	2004.10894, 2108.07586
Wect	$\chi_1 \chi_1$ via $\ell_L / \tilde{\nu}$	2 e,μ E 2 τ E	miss 139 miss 139	\tilde{x}_{1} $\tilde{x}_{1}, \tilde{x}_{P,1}$ 0 16-0 3 0 12-0 39	.0 $m(\ell, \tilde{v})=0.5(m(\ell_1^-)+m(\ell_1^-))$ $m(\tilde{v}_1^0)=0$	1908.08215
Шŝ	$\tilde{\ell}_{\mathrm{L,R}} \tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	$2 e, \mu$ 0 jets E $ee, \mu\mu \ge 1$ jet E	miss 139 miss 139 T 139	ζ 0.256 0.7	$m(\tilde{\xi}_1^0)=0$ $m(\tilde{\xi}_1^0)=10 \text{ GeV}$	1908.08215 1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$0 e, \mu \ge 3 b E$	miss 36.1	<i>H</i> 0.13-0.23 0.29-0.88	$BR(\tilde{\chi}^0_d \rightarrow h\tilde{G})=1$	1806.04030
		$4 \ e, \mu$ 0 jets E 0 $e, \mu \ge 2$ large jets E	miss 139 miss 139 T 139	H 0.55 Ĥ 0.45-0.93	$\begin{array}{c} BR(\mathcal{X}_1^\circ \to ZG) = 1\\ BR(\tilde{\mathcal{X}}_1^0 \to Z\tilde{G}) = 1 \end{array}$	2103.11684 2108.07586
σ.	$Direct \tilde{\chi}_1^{+} \tilde{\chi}_1^{-} \text{ prod., long-lived } \tilde{\chi}_1^{\pm}$	Disapp. trk 1 jet E	^{miss} 139	$\hat{\chi}^{\pm}_{1}$ 0.66 $\hat{\chi}^{\pm}_{1}$ 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472
live	Stable g R-hadron	pixel dE/dx E	miss 139	ĝ	2.05	CERN-EP-2022-029
ng-	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	pixel dE/dx E	miss 139	\tilde{g} [$\tau(\tilde{g})$ =10 ns]	2.2 $m(\tilde{\chi}_1^0)=100 \text{ GeV}$	CERN-EP-2022-029
Lo. Dig	$tt, t \rightarrow tG$	Dispit lep E	T 139	τ, μ 0.7 τ 0.34	$\tau(\ell) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$	2011.07812 2011.07812
		pixel dE/dx E	T 139	τ̃ 0.36	$\tau(\ell) = 10 \text{ ns}$	CERN-EP-2022-029
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 e,µ	139	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625	.05 Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ 0 jets E	T 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] $ 0.99	1.55 $m(\tilde{x}_1^0)=200 \text{ GeV}$	2103.11684
	$gg, g \rightarrow qq\chi_1, \chi_1 \rightarrow qqq$ $\tilde{t}, \tilde{t} \rightarrow t\tilde{V}^0, \tilde{V}^0 \rightarrow ths$	4-5 large jets Multiple	36.1	$\begin{bmatrix} g & [m(\mathcal{X}_1)=200 \text{ GeV}, 1100 \text{ GeV}] \\ \tilde{\mathcal{I}} & [\mathcal{X}'_{1,1}=2e-4, 1e-2] \\ \end{bmatrix} $ 0.55	.05 m(\hat{x}_{1}^{0})=200 GeV bino-like	ATLAS-CONF-2018-003
P	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\dagger}, \tilde{\chi}_{1}^{\dagger} \rightarrow bbs$	$\geq 4b$	139	ĩ Forbidden 0.9	5 m($\tilde{\chi}_1^+$)=500 GeV	2010.01015
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	36.7	$\tilde{t}_1 = [qq, bs]$ 0.42 0.61		1710.07171
	$t_1t_1, t_1 \rightarrow q\ell$	$2 e, \mu = 2 b$ $1 \mu = DV$	36.1 136	$\frac{t_1}{\tilde{t}_1}$ [1e-10< λ'_{21k} <1e-8, 3e-10< λ'_{21k} <3e-9]	.0 1.6 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ BR($\tilde{t}_1 \rightarrow q\mu$)=100%, $\cos\theta_t = 1$	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	<i>x</i> ₁ ^θ 0.2-0.32	Pure higgsino	2106.09609
*Only phen	a selection of the available ma omena is shown. Many of the	ss limits on new states o limits are based on	or 1	0 ⁻¹	1 Mass scale [TeV])
simp	lified models, c.f. refs. for the a	assumptions made.				

exotics

A	TLAS Exotics	Search	nes* -	95%	6 CL	Upper Exclusion	on Limits		ATLA	S Preliminary
Sta	atus: March 2021							$\int \mathcal{L} dt = (3$	3.6 – 139) fb ⁻¹	$\sqrt{s} = 8, 13 \text{ TeV}$
	Model	l,y	Jets†	E ^{miss} T	∫£ 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 $G_{KK} \rightarrow WW \rightarrow t \gamma qq$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	0 e, μ, τ, γ 2 γ - 2 γ multi-chann 1 e, μ 1 e, μ 1 e, μ	1-4j 2j $\geq 3j$ el 2j/1J $\geq 1b, \geq 1J/$ $\geq 2b, \geq 3$	Yes - - Yes 2j Yes j Yes	139 36.7 37.0 3.6 139 36.1 139 36.1 36.1	Mo Ma Ma Ma Grac máss Grac máss Grac máss Bor máss Kir máss Kir máss	4.5 T 2.3 TeV 2.0 TeV 3.8 TeV 1.8 TeV	11.2 Te 8.6 TeV 8.9 TeV 9.55 TeV eV		2102.10874 1707.04147 1703.09127 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to t\nu \\ \operatorname{HVT} W' \to ZH \mod B \\ \operatorname{HVT} Z' \to ZH \mod B \\ \operatorname{HVT} W' \to WH \mod B \\ \operatorname{LRSM} W_R \to tb \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 0 \ e, \mu \\ 1 \ e, \mu \\ el \ B \\ 1 \ e, \mu \\ 0.2 \ e, \mu \\ 0 \ e, \mu \\ multi-chann \\ 2 \ \mu \end{array}$	- 2 b ≥ 1 b, ≥ 2, - 2 j / 1 J 1-2 b ≥ 1 b, ≥ 2, iel 1 J	– – Yes Yes Yes Yes J	139 36.1 36.1 139 36.1 139 36.1 139 139 36.1 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass W' mass W' mass W' mass W' mass	5.1 2.42 TeV 2.1 TeV 4.1 TeV 3.7 TeV 4.3 TeV 3.2 TeV 3.2 TeV 3.2 TeV 3.25 TeV 5.0	1 TeV 6.0 TeV 9V 1 TeV	$\label{eq:gv} \begin{split} &\Gamma/m = 1.2\% \\ &g_V = 3 \\ &g_V = 3 \\ &g_V = 3 \\ &m(N_R) = 0.5 \text{ TeV}, g_L = g_R \end{split}$	1903.06248 1709.07242 1805.09299 2005.05138 1906.06609 1801.06992 2004.14636 ATLAS-COMF-2020-043 2007.05283 1807.10473 1904.12679
C	Cl qqqq Cl ℓℓqq Cl eebs Cl μμbs Cl tttt	2 e,µ 2 e 2 µ ≥1 e,µ	2j - 1b 1b ≥1b,≥1j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ	1.8 TeV 2.0 TeV 2.57 TeV		21.8 TeV η_{LL}^{-} 35.8 TeV η_{LL}^{-} $g_{*} = 1$ $ G_{tc} = 4\pi$	1703.09127 2006.12946 ATLAS-CONF-2021-012 ATLAS-CONF-2021-012 1811.02305
MQ	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DN) Vector med. Z'-2HDM (Dirac Pseudo-scalar med. 2HDM+a Scalar reson. $\phi \rightarrow t\chi$ (Dirac D	0 e, μ, τ, γ Λ) 0 e, μ, τ, γ DM) 0 e, μ 0 e, μ M) 0-1 e, μ	1 - 4 j 1 - 4 j 2 b 2 b 1 b, 0-1 J	Yes Yes Yes Yes Yes	139 139 139 139 36.1	m _{med} m _{reed} 376 0 m _{reed} m _p	2.1 TeV 3.1 TeV 520 GeV 3.4 TeV		$\begin{array}{l} g_{q} = 0.25, \ g_{\chi} = 1, \ m(\chi) = 1 \ {\rm GeV} \\ g_{q} = 1, \ g_{\chi} = 1, \ m(\chi) = 1 \ {\rm GeV} \\ \tan\beta = 1, \ g_{\chi} = 0.8, \ m(\chi) = 100 \ {\rm GeV} \\ \tan\beta = 1, \ g_{\chi} = 1, \ m(\chi) = 10 \ {\rm GeV} \\ y = 0.4, \ \lambda = 0.2, \ m(\chi) = 10 \ {\rm GeV} \end{array}$	2102.10874 2102.10874 ATLAS-CONF-2021-006 ATLAS-CONF-2021-006 1812.09743
ΓO	Scalar LQ 1 st gen Scalar LQ 2 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	2 e 2μ 1τ $0 e, \mu$ $\ge 2e, \mu, \ge 1$ $0 e, \mu, \ge 1$	$\geq 2j$ $\geq 2j$ $\geq 2b$ $\geq 2j, \geq 2b$ $l_T \geq 1j, \geq 1b$ $\tau 0 - 2j, 2b$	Yes Yes Yes Yes Yes Yes	139 139 139 139 139 139	LQ mass LQ mass LQ ⁴ mass LQ ³ mass LQ ³ mass LQ ³ mass	1.8 TeV 1.7 TeV 1.2 TeV 1.24 TeV 1.24 TeV 1.24 TeV 1.26 TeV		$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \mathcal{B}(LQ_{3}^{u} \to b\tau) = 1 \\ \mathcal{B}(LQ_{3}^{u} \to t\nu) = 1 \\ \mathcal{B}(LQ_{3}^{d} \to t\nu) = 1 \\ \mathcal{B}(LQ_{3}^{d} \to b\nu) = 1 \end{array}$	2006.05872 2006.05872 ATLAS-CONF-2021-008 2004.14060 2101.11582 2101.12527
Heavy quarks	$ \begin{array}{l} VLQ\;TT \rightarrow Ht/Zt/Wb + X \\ VLQ\;BB \rightarrow Wt/Zb + X \\ VLQ\;T_{5/3}\;T_{5/3} \rightarrow Wt + \mathcal{X} \\ VLQ\;Y \rightarrow Wb + X \\ VLQ\;Y \rightarrow Hb + X \\ VLQ\;QQ \rightarrow WqWq \end{array} $	multi-chann multi-chann X 2(SS)/≥3 e, 1 e, µ 0 e,µ 1 e, µ	el ⊎el ⇒1 b, ≥1 j ≥1 b, ≥1 j ≥2 b, ≥1 j ≥4 j	Yes Yes Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass B mass T _{5/5} mass Y mass B mass Q mass	1.37 TeV 1.34 TeV 1.64 TeV 1.85 TeV 1.21 TeV 690 GeV		$\begin{array}{l} & \mathrm{SU}(2) \text{ doublet} \\ & \mathrm{SU}(2) \text{ doublet} \\ & \mathcal{B}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3}Wt) = 1 \\ & \mathcal{B}(Y \rightarrow Wb) = 1, \ c_R(Wb) = 1 \\ & \mathrm{singlet}, \ \kappa_B = 0.5 \end{array}$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261
Excited	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	1 у 3 е, µ 3 е, µ, т	2j 1j 1b,1j -		139 36.7 36.1 20.3 20.3	q* mass q* mass b* mass /* mass v* mass	5. 2.6 TeV 3.0 TeV 1.6 TeV	6.7 TeV 3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0$ TeV $\Lambda = 1.6$ TeV	1910.08447 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles	1 e,μ 2 μ 2,3,4 e,μ (S 3 e,μ,τ _	≥ 2 j 2 j S) – – –	Yes - - -	139 36.1 36.1 20.3 36.1 34.4	№ mass № mass H ^{±±} mass H ^{±±} mass Multi-charged particle mass monopole mass	790 GeV 3.2 TeV 870 GeV 1.22 TeV 2.37 TeV		$\begin{split} m(W_R) &= 4.1 \text{ TeV}, g_L = g_R \\ \text{DY production} \\ \text{DY production}, \mathcal{B}(H_L^{++} \to \ell \tau) = 1 \\ \text{DY production}, q &= 5e \\ \text{DY production}, g &= 1g_D, \text{ spin } 1/2 \end{split}$	20008.07949 1809.11105 1710.09748 1411.2921 1812.03673 1905.10130
	√s = 8 TeV	√s = 13 TeV partial data	√s = 13 full d	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).

B anomalies



LHCb Run 1, 3 fb-1 [lhcb1]

LHCb Run 2, 9 fb-1 [lhcb2]



LHCb Run 2, 9 fb-1 [lhcb3]

$$R_{K_{\rm S}^0} = 0.66^{+0.20}_{-0.14} \,(\text{stat.})^{+0.02}_{-0.04} \,(\text{syst.}) \,,$$
$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13} \,(\text{stat.})^{+0.03}_{-0.04} \,(\text{syst.}) \,.$$

Heavy neutral leptons



Heavy neutral leptons

