ATLAS Liverpool activities: Physics during lockdown

Monica on behalf of the Liverpool ATLAS Team 28/4/2021

Run: 308084 Event: 2658892674 2016-09-1<u>0 04:14:14 CEST</u>



Overview

The past year+ has been quite challenging for everybody...

Nonetheless, the team maintained a good spirit and produced fantastic results :) We meet every week, with students reports and regular discussions



Team and achievements in a nutshell

During this challenging year, the team:

- congratulated two new doctors: Hannah and Matt (now a PDRA at Liverpool still in ATLAS)
- welcomed three new PhD students: Ting, Sam and Conor
- complemented our activities with a grant on Machine Learning and explainable AI (MD, Cristiano, based also upon Hamish work) and of course contributed to the CG
- got new leadership roles within ATLAS, ATLAS UK and key HEPwide panels
 - Carl: ATLAS UK Physics Coordinator (was Exotics convenor till 2020)
 - Jan: ATLAS PMG Convener (was also PubCom member)
 - Nikos: LHC-wide convener of Extended Higgs sectors
 - Cristiano: SCT software coordinator
 - Uta: Z-counting Luminosity group leader
 - Monica: PPAP member
 - Max: UK ECFA chair, rECFA and PPTAP member (was CB ATLAS chair for 2017-2020)
- had members on editorial boards responsible for ATLAS publications
- presented at key conferences (ICHEP, LHCP, Moriond...)



Group members developed and led data analyses for more than 10 papers published in the past year and contributed to several general tasks (also in ATLAS upgrade, see Helens talk)

 \rightarrow in this talk, a brief summary is given with studies in progress

Physics activities

Liverpool leads key areas of the ATLAS physics programme, pursuing different routes to uncover NP through:

- Higgs boson studies (SM and BSM) and searches for di-Higgs production;
- Searches for SUSY, DM and Hidden Sectors;
- Searches for Z', W', leptoquarks but also LFV dedicated studies;
- Precise measurements such as W-mass and Drell-Yan cross sections.

We also contribute to the operation of the experiment, in particular:

- SCT operations and software
- Monte Carlo generators development
- Analysis software
- heavy flavour tagging, reconstruction of key physics objects and estimate of luminosity

SM HIGGS BOSON PHYSICS

Since the Higgs discovery in 2012, studies of its properties are at the core of our programme

Recent (2020) results include searches for the rare $h \rightarrow \mu\mu$ decays and for the even rarer $h \rightarrow ee$ or the exotic LFV $h \rightarrow e\mu$ decays

Andy, Jan, Hanna PhD





For $h \rightarrow$ leptons, more work is in progress on

- Run 2 $h \rightarrow e\tau/\mu\tau$ Carl, Uta (Joseph)
- Run 3 $h \rightarrow \mu \mu$ Andy, Jan

For higgs decaying into quarks, studies are on-going / planned to:

- measure differential cross sections of
 h→bb in Vh production Andy, Ting PhD
- search for rare h→cc decays Andy using Run 2 and Run 3 data

In all cases, exploit Liv expertise on leptons reconstruction and b/c-tagging

Monica, ATLAS Liverpool

SM HIGGS BOSON PHYSICS: DI-HIGGS

- Di-Higgs provides only direct measurement of λ_{HHH} → crucial test of higgs potential and EWSB
 - bbtt channel offers good balance of BR vs background
 - Liverpool led previous result with 36/fb, giving world best result at that time

Carl, Nikos, Jordan PhD, and Matt - now joining the effort as PDRA

- Currently focusing on full run-2 result in τ_{lep}τ_{had} channel
 - Many improvements: Better b-tagging and τ ID; Improved systematic treatment; Improved MVA techniques, ...
- Aiming for public x-sec results for EPS 2021
 - See also <u>Jordan's IoP talk</u>
- Followed by second non-res paper focusing on λ_{HHH} scan with EFT constraints & HH combination paper (Matt joining)
 - Should get close to ~2x SM





BSM HIGGS BOSON PHYSICS

Heavier Higgs bosons are predicted by several New Physics models (SUSY MSSM but also extended Higgs sectors, 2HDM models etc).

At Liverpool, we searched for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the *ll*bb and *ll*WW final states

Nikos, Alan PhD GeV Data - A \rightarrow ZH \rightarrow llbb 13 TeV. 139 fb Z+(bb,bc,cc,bl) Z+(cl,l) 670 GeV, m. = 500 Ge Top quark uon-aluon fusion produced A ttV W+iets. VV. Vh Uncertaintv A 10- 10^{-2} arXiv:2011.05639 Data/Pred 600 850 m_{llbb} [GeV]

More decay modes under studies (Nikos)

YSICS Exotics decays of the Higgs boson are also predicted in several SM extensions. Here, we search for Higgs decaying into axion-like particles (ALPs)



- Results expected for Autumn 2021 (see IoP talk).
- Plan to extended to long-lived axions

\rightarrow displaced photons

Higgs, dark matter and dark sectors

The higgs boson could be a 'portal' to DM, if $\,M_{
m DM}\,<\,M_{H}/2\,\simeq\,62.5{
m GeV}$

being the only particle that interacts with that



@Liverpool, we are currently finalizing studies of Z+higgs associated production, with the higgs decaying invisibly

- use dilepton+E_T^{miss} signature
- Exploit BDT to maximize sensitivity and data in control regions to estimate at best SM background
- Paper expected for June
- Also sensitive to several dark matter simplified models
 Andy, Matt, Monica, Eloisa PhD

See also Eloisa's talk at this meeting

Higgs, dark ma

The Higgs could be the only We study also higgs decays i

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very unconventional topology: two collimated structures of leptons or light hadrons: Dark Photon Jets (DPJ)

full Run-II analysis (2015-18 dataset):

DPJ tagger for QCD rejection

- From each jet three 3D images are produced
- ⁹ 3D images are η-φ-Calo_layer maps (around the jet axis) of caloclusters associated to the jet
- images and jet JVT are inputs of a CNN
- network trained using agE signal and multi-jet

'k sectors

ng

Searches for SUSY and dark matter

Dark matter candidates are of course predicted by SUSY models

We study that looking at both strong sectors (third generation squarks like sbottom) and EWK sector (chargino and neutralinos decaying in higgs, lepton and missing transverse momentum) Monica, Hamish PhD

Search in bb+Missing ET final states

m_{x̃}, [GeV]

Use specialized BDT techniques to target difficult-to-reach scenarios for DM and SUSY

Other decay modes involving higgs bosons published earlier this year JHEP 12 (2019) 060

Search for EWK SUSY in W+higgs final states

In progress: use AI techniques to target semi-compressed models (very relevant for models which can also explain g-2 results)

Searches for SUSY and dark

Dark matter candidates are of course predicted by SUSY models: in case of ν hierarchy, sparticles might be long-lived

- In this case, chargino decays in O(0.1 \rightarrow 1) ns (c τ =cm) to stable neutralino $i\frac{\pi}{2}$
- Detector signature is a short track in the pixel detector, leading to soft or ur

 \rightarrow a "Disappearing Track" or "Tracklet"

ATLAS-CONF-2021-15 Paper in preparation

Helen, Monica, James PhD

This signature is very sensitive to several DM models and is one of the main benchmark model considered for future colliders. For Run 2, James will focus on improved reconstruction for short lifetimes

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See also James's talk at this meeting

Searches for SUSY and dark matter

NEW PHYSICS IN RESONANT AND NON-RESONANT DECAYS: LEPTOQUARKS

Leptoquark searches came back to fashion as LQ could explain LHCb anomalies In the past, third generation LQ results had been obtained with reinterpretations (Carl, Monica)

This year, we have searched directly for LQ decaying into electron/muon + jets, including charm and b-jets. <u>JHEP 10 (2020) 112</u>

Andy, Monica, Adam J PhD

First time charm-tagging is directly used for these searches. Constraints up to 1.8 TeV (world-best limits)

NEW PHYSICS IN RESONANT AND NON-RESONANT DECAYS: W, Z PRIME AND MORE

Searches for heavy gauge vector bosons in different **leptonic final states** has been the focus of Liv team members for several years – one of the work-horses analyses to search for NP

- Previous result on W and Z prime published Uta, Michael PhD
- Non-resonant dilepton search published Jan, Uta, Ricardo PhD

See also Ricardo's talk at this meeting

Currently working on (1) EFT interpretation (2) on precision measurements of high mass DY Jan, Uta, Sam PhD.

In addition, a search for new phenomena in final states with two leptons and one or no b-tagged jets has been finalised (Uta), showing intriguing excess in electron channel

NEW PHYSICS IN RESONANT AND NON-RESONANT DECAYS: LFV

New efforts on LFV now on-going, motivated by recent experimental tensions in R(K) measurement @ LHCb and g-2 @ Fermilab hint of BSM physics. In addition to the already mentioned higgs in LFV decays:

Carl, Jan, Matt, Conor PhD working on $\tau \rightarrow \mu \mu \mu$

- SM BR of 10⁻⁵⁵ 10⁻⁵⁶ through neutrino oscillation. BR can be enhanced by BSM physics: Z', leptoquarks, SUSY.
 - Current best limit from Belle: 2.1x10⁻⁸
 - CMS Run-2 result (2015-2016 data): ~1.1x10⁻⁷
- Analysis status:
 - First ATLAS Run-2 result led by Liverpool.
 - Use ML classifier to separate signal events from m(μμμ) sideband data and fit m(μμμ) spectrum to extract limit.
 - Finalising ML training and fitting strategy, with initial expected results showing sensitivity similar to CMS.

Publication of result in 2022.

STANDARD MODEL MEASUREMENTS

Drell-Yan production of *W* and *Z* bosons and the W mass measurement provide crucial tests of the SM QCD and EW sectors.

 Working on W mass measurement using Run 2 data, aiming to reduce the uncertainty by a factor of 2 once Run 1 and 2 results are combined (Jan, Max, Uta, Harry PhD)

 $Z \rightarrow ee/\mu\mu$ data can also be used to estimate precisely the integrated luminosity: **Z-counting** $\mathcal{L}_Z =$

Month / Year

Software and detector maintenance

- Z-counting for precision luminosity measurement is only one of the tasks relevant for the whole ATLAS analysis programme carried out by Liverpool members. Among others:
 - SCT software (Cristiano)
 - Study of b- and charm-jets Andy, Carl, Nikos, Jordan PhD

FTAG-2021-001

- Electron identification algorithm improvements and calibration (Eloisa PhD)
- Tau reconstruction through a novel method to identify tau-leptons using calorimeterbased images of jets as inputs to a convolutional neural network (Matt).
- Now and for future: work to improve MC generator performance (Jan, Monica) and software (Carl) also for HL-LHC (collaboration within SWIFT-HEP)

Conclusions

- Despite the challenges, it has been a very productive 1+1/2 year
- Congratulations to students, postdocs and academics for their successes as well as their dedication
 - Also, for work on ATLAS upgrade, from students qualified/qualifying as ATLAS authors (Hamish, Alessandro, Ricardo, James, Conor, Ting) to academics actively working on tasks (e.g. Carl, Sergey)
- Our physics programme has expanded, also responding to intriguing signs of new physics elsewhere
- Run 2 data has still a lot to say, and we are certainly well placed to take the most out of them and prepare well for Run 3 and beyond