UiO : Department of Physics
University of Oslo

Recent searches for new phenomena with the ATLAS detector

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Eirik Gramstad

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Table of contents

ATLAS - A broad search strategy!

Talk	Speaker
Searches for **dark matter** with the ATLAS detector	A. W. Zeng
Searches for **rare top quark** production and decay processes with the ATLAS experiment	C. Wang
Searches for **new phenomena in final states with 3rd generation quarks** using the ATLAS detector	Meng-Ju Tsai
Searches for **additional Higgs bosons** in ATLAS	N. Cavalli
ATLAS searches for **supersymmetry with prompt particles**	S. Huang
ATLAS searches for **supersymmetry with long-lived particles**	K.K. Gan
ATLAS results on **exotic hadronic resonances**	I. Yeletskikh
Searches for **BSM physics using challenging and long-lived signatures** with the ATLAS detector	M. Didenko

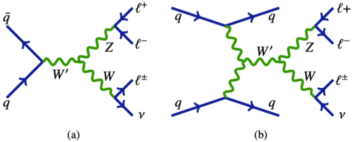
Poster	Presenter
Search for **new resonances** decaying into a Higgs boson and a generic new boson X in the XH -> qqbb final state with the ATLAS detector	E. Rossi
ATLAS searches for **Higgsinos with R-parity violating couplings** in events with leptons	O.A. Ducu
Search for direct production of **electroweak gauginos** in events with two same-sign or three leptons in 13 TeV pp collision data with the ATLAS detector	S. Huang
Search for **new physics in multi-body invariant masses in dijet events** with an isolated lepton in pp collisions at sqrt(s)=13 TeV with the ATLAS detector	W. Islam
Search for single production of a **vector-like** T **quark** decaying into a Higgs boson and top quark with fully hadronic final states using the ATLAS detector	J.H. Foo

In addition to **all** the interesting Standard Model precision measurements

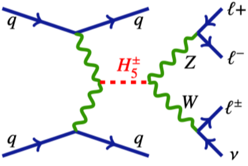
Overview

Search	Paper	Previous Results	Motivation
Search for resonant WZ in leptonic final states	arXiv	ATLAS@8TeV, CMS@8TeV, ATLAS@13TeV	Heavy Vetor Triplets (W'), extended Higgs Sector
Search for charged-lepton-flavor-violating decay $Z \to e\mu$	arXiv	LEP[1, 2, 3], ATLAS@8TeV	deviations from SM expectations sensitive to new physics
Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon	arXiv	ATLAS@8TeV, ATLAS@13TeV, CMS@8TeV, CMS@13TeV	Higgs Yukawa couplings (to 1^{st} and 2^{nd} gen.)

Search for resonant WZ in leptonic final states [arXiv:2207.03925]



1. search for new heavy vector triplet (HVT) resonances; *W*'
   - couples to the Higgs field (g_H) and longitudinally polarized SM gauge bosons (g_V)
   - no coupling of the heavy vector resonance to fermions (g_F)



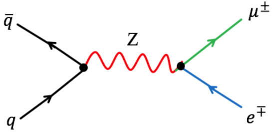
(c)

2. investigating tree-level couplings of charged Higgs bosons to vector bosons within the Georgi-Machacek (GM) model
   - extends the SM Higgs sector by including one real and one complex triplet

Search for charged-lepton-flavor-violating decay $Z \rightarrow e\mu$ [arXiv:2204.10783]

- lepton-flavour violation has been observed in the neutrino sector
- rate of charged-lepton-flavor violation is expected to be vanishingly small
- this analysis performs a search for $Z \rightarrow e\mu$ using the full LHC Run-2 data
  - indirect searches for $\mu \rightarrow e^+e^-e^+$ or $\mu \rightarrow e\gamma$ imply BR($Z \rightarrow e\mu$)$< 5 \times 10^{-13}$
    - these interpretations can be evaded
  - direct searches for two-body decays into $e\mu$ remains a vital part of the charged-lepton-flavor violation search

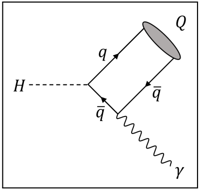
Measurement	Limit	Comment
$\mathcal{B}(Z \rightarrow e\mu)$	$< 7.5 \times 10^{-7}$	20.3fb^{-1}@8TeV
$\mathcal{B}(Z \rightarrow e\tau)$	$< 5.0 \times 10^{-5}$	full Run-2 data
$\mathcal{B}(Z \rightarrow \mu\tau)$	$< 6.5 \times 10^{-6}$	



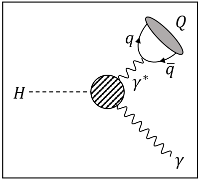
Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon [arXiv:2208.03122]

- a complete observation of higgs boson couplings to third generation charged fermions
- study of couplings of the 1st and 2nd generation quarks through $H \to q\bar{q}$ decays suffer from large multi-jet backgrounds
- radiative decays of the Higgs boson into a vector meson state ($\mathcal{Q}$) decaying to $\mu^+\mu^-$
  - $\mathcal{B}(H \to J/\psi\gamma) \sim 10^{-6}$
  - $\mathcal{B}(H \to \Upsilon(1S,2S,3S)\gamma) \sim 10^{-9}$ - 10^{-8}
  - $\mathcal{B}(H \to \psi(2S)\gamma) \sim 10^{-6}$
  - distinct experimental signature

direct



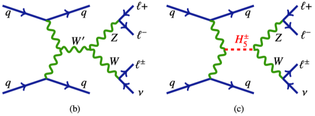
indirect



deviations of the quark Yukawa couplings from the SM expectations can lead to significant enhancements for the BR of radiative decays

Machine Learning in Event Selection I

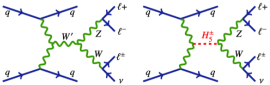
- the search for resonant WZ production in the VBF process uses an Artificial Neural Network (ANN) to select signal events



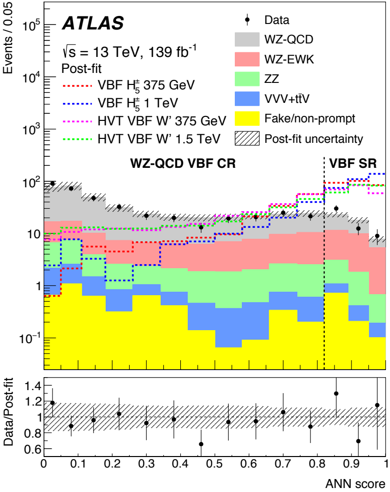
- binary classification (**VBF signal process** or **background**)
- trained on simulated $H_5^\pm$ events as signal against SM WZ production
- training sample reduced by requiring $\geq$ 2 jets with $m_{jj} > 100$ GeV

Training variable	Definition
m_{jj}	Invariant mass of the two leading-p_{T} jets
$\Delta\phi_{jj}$	Difference in ϕ of the two leading-p_{T} jets
η_W, η_Z	Pseudorapidities of the reconstructed gauge bosons
η_{j1}	Leading-p_{T} jet pseudorapidity
ζ_{Lep}	Event centrality
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum
H_{T}	Scalar p_{T} sum of the *VBF jets* and the leptons from the WZ decay

Machine Learning in Event Selection I

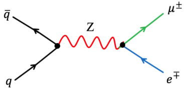


- network with two hidden layers and 45 neurons each
- the features were chosen based on their impact in training:
  - the loss in the expected significance when adding or replacing features were evaluated for each set of variables until an optimal set was found
- all mass samples (0.2-1 TeV) of simulated $H_5^\pm$ events used in training

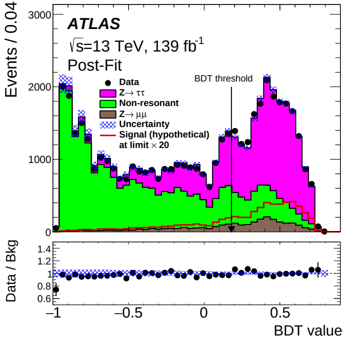


- training applied to both $H_5^\pm$ and HVT Model samples

Machine Learning in Event Selection II



- a Boosted Decision Tree (BDT) is used in the $Z \to e\mu$ search
- trained on simulated signal and background in the $85 < m_{\mu e} < 95$ GeV mass window
- the chosen threshold value of the BDT score maximizes $s/\sqrt{b}$
- same procedure used to define same-flavor control regions (CR)
- BDT trained on selected $e\mu$ events with $m_{\mu e}$ $\pm$20 GeV around the Z-mass

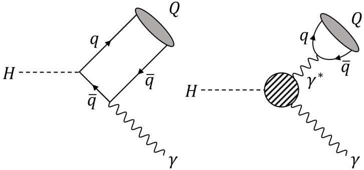


Features:

1. leading jet p_{T}
2. $E_{\mathrm{T}}^{\mathrm{miss}}$
3. $p_T^{e\mu}$ ($p_T^{ee}/p_T^{\mu\mu}$ used for $ee/\mu\mu$ CRs)

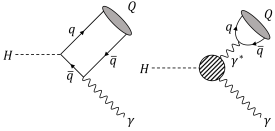
Classical Event Selection

- a cut and count procedure is used for the event selection in the the search for Higgs and Z boson decays into a vector quarkonium ($\mathcal{Q}$) state and a photon



Common Selection		
two muons with $p_T > 18/3$ GeV, $\|\eta\| < 2.5$ one photon with $p_T > 35$ GeV, $\|\eta\| < 2.37$	} forms a $\mathcal{Q} \rightarrow \mu^+\mu^- + \gamma$ candidate	
$\Delta\varphi(\mathcal{Q}, \gamma) > \pi/2$		
	$J/\psi - \psi(2S)$ **candidates** $2.4 < m_{\mu^+\mu^-} < 4.3$ GeV	Υ(**1S,2S,3S**)**candidates** $8.0 < m_{\mu^+\mu^-} < 12.0$ GeV
$m_{\mu^+\mu^-\gamma} \leq 91$ GeV	$p_T^{\mu^+\mu^-} > 40.0$ GeV	$p_T^{\mu^+\mu^-} > 34.0$ GeV
$m_{\mu^+\mu^-\gamma} \geq 140$ GeV	$p_T^{\mu^+\mu^-} > 54.4$ GeV	$p_T^{\mu^+\mu^-} > 52.7$ GeV
$91 > m_{\mu^+\mu^-\gamma} < 140$ GeV	$p_T^{\mu^+\mu^-}$ threshold varies linearly between the above cuts	
barrel (B) category	-	both muons $\|\eta\| < 1.05$
endcap (EC) category	-	at least one muon $\|\eta\| \geq 1.05$

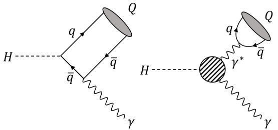
Background Estimations



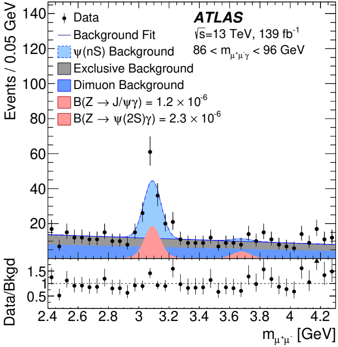
- **Exclusive background**: Drell-Yan production of muons with a highly energetic photon
  - shape of background estimated using simulations
  - normalization determined from a fit to the data in the signal region
- **Inclusive backgrounds**:
  1. inclusive multi-jet or γ+jet involving production of $\mathcal{Q}$ states with subsequent decays to $\mu^+\mu^-$
  2. non-resonant dimuon pairs with the γ-candidate being a mis-identified jet

  - estimated using data

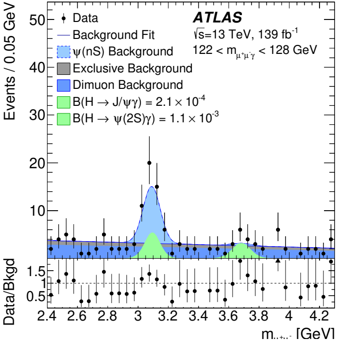
Results in J/ψ or $\psi(2S)+\gamma$



Z boson



Higgs

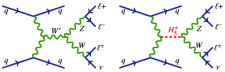


	95% CL_s upper limits					
	Branching fraction				$\sigma\times\mathcal{B}$	
Decay channel	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
	Expected	Observed	Expected	Observed	Observed	Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135

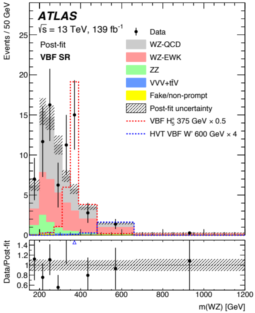
New Limits

Upper limits represent an improvement by a factor of ~ 2 relative to the previous results from ATLAS using $\sim 1/4$ of the data

Results for resonant WZ prod.

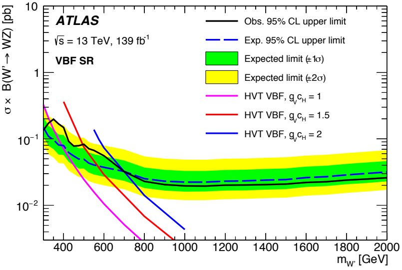


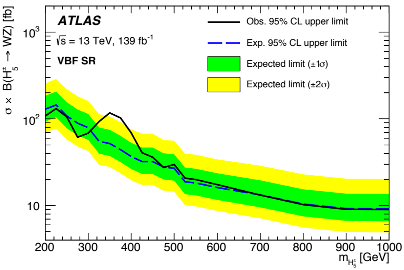
- local excess of events around mass of 375 GeV
  - 2.5σ and 2.8σ local significance in the W' and $H_5^{\pm}$ models (1.7σ and 1.6σ global)



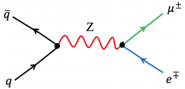
No significant excesses

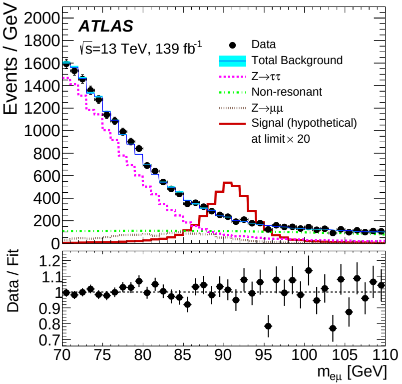
Limits on the BR times cross-section as a function of W' and $H_5^{\pm}$ have been set





Results for $Z \to e\mu$ search





no localized excess consistent with $Z \to e\mu$ decay is observed

$$N_{Z\to e\mu} = N_Z^{avg} (A \times \epsilon)_{Z\to e\mu} \times \mathcal{B}(Z \to e\mu)$$

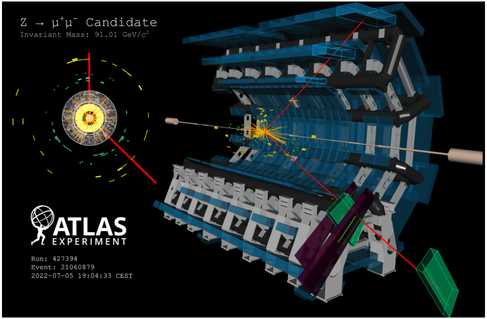
Quantity	Value
$A \times \varepsilon_{Z\to e\mu}$	$(10.3 \pm 0.3)\%$
N_Z^{avg}	$(7.87 \pm 0.19) \times 10^9$

The most stringent direct result yet reported!

$$\mathcal{B}(Z \to e\mu) < 2.62 \times 10^{-7}$$

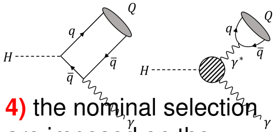
Conclusions and Outlook

- the ATLAS Experiment has a comprehensive set of searches for new phenomena exploiting the complete LHC Run-2 data set
- no significant evidences for any new physics yet reported
- LHC Run-3 has just started at an increased energy, $\sqrt{s} = 13.6$ TeV
  - a doubling of the current data set is expected in Run-3
  - several of the analysis presented here are limited by statistics
  - can expect improved limits (observations!?) in Run-3



BACKUP

Background Estimations

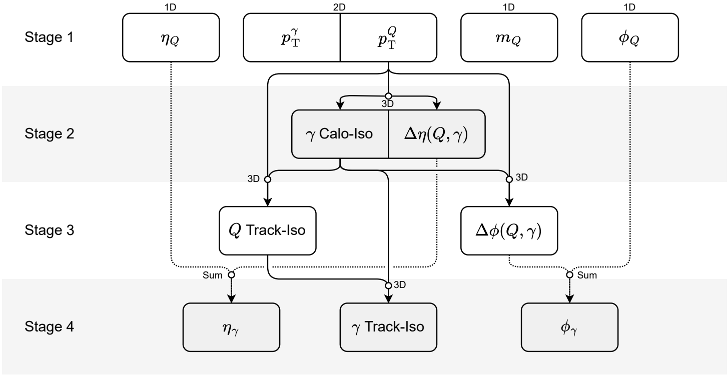


1) make a Generation Region of "soft" $\mathcal{Q} \to \mu^+\mu^-\gamma$-candidates

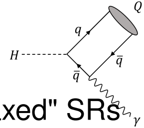
2) construct PDFs of the relevant kinematic and isolation variables, parameterised to respect the most important correlations

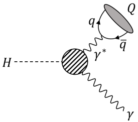
3) variables are drawn from different PDFs in a 4-stage procedure, where the PDFs used in each stage is based on the value from the previous stage

4) the nominal selection are imposed on the pseudo-candidate events and used to construct templates for the $m_{\mu^+\mu^-\gamma}$ distributions

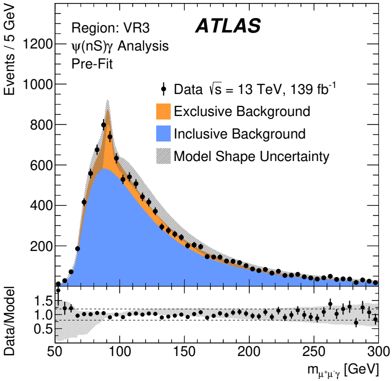


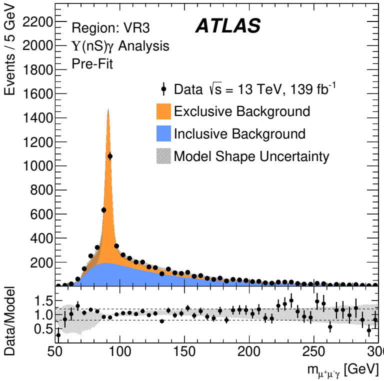
Background Estimations





Background estimations validated in different "relaxed" SRs

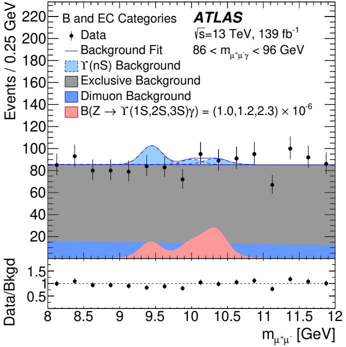




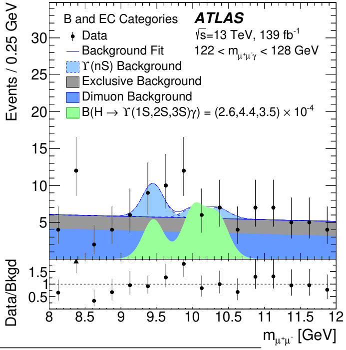
the grey band is estimated by allowing the shape of the background to vary around the nominal shape controlled by three variations: **1)** p_T^{γ}, **2)** $\Delta\varphi(\mathcal{Q},\gamma)$ and **3)** an overall "tilt" of the $m_{\mu^+\mu^-\gamma}$ distributions

Results in Υ(1S,2S,3S) $+ \gamma$

Z boson



Higgs

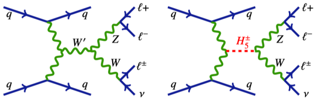


upper limits represent an improvement by a factor of $\sim$ 2 relative to the previous results from ATLAS using $\sim 1/4$ of the data

	95% CL_s upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
	Expected	Observed	Expected	Observed	Observed	Observed
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

Machine Learning in Event Selection I

- the search for resonant WZ production in the VBF process uses an Artificial Neural Network (ANN) to select signal events



- binary classification (**VBF signal process** or **background**)
- implemented using Keras on top of TensorFlow
- trained on simulated $H_5^{\pm}$ events as signal against SM WZ production

Pre-selection

$\geq$ **2 jets** [1]

$m_{jj} > 100$ GeV

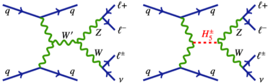
veto events with b-tagged jets

Features

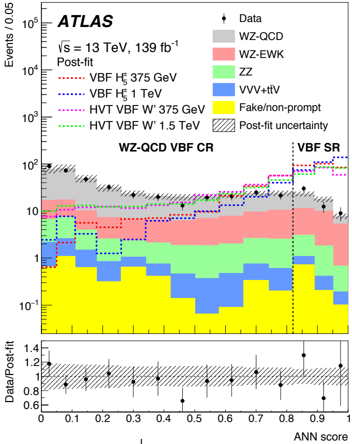
Training variable	Definition
m_{jj}	Invariant mass of the two leading-p_T jets
$\Delta\phi_{jj}$	Difference in ϕ of the two leading-p_T jets
η_W, η_Z	Pseudorapidities of the reconstructed gauge bosons
η_{j1}	Leading-p_T jet pseudorapidity
ζ_{Lep}	Event centrality
E_T^{miss}	Missing transverse momentum
H_T	Scalar p_T sum of the *VBF jets* and the leptons from the *WZ* decay

[1] with $\mathbf{p_T} > \mathbf{30}$ **GeV** and $|\eta| < \mathbf{4.5}$, **vetoing b-jets** and **removing jets likely to come from pileup**

Machine Learning in Event Selection I

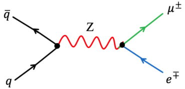


- a 4-fold cross-validation used when optimizing the network
- training performed with 100 epochs and two hidden layers w/ 45 neurons each
- the features were chosen based on their impact in training:
  - the loss in the expected significance when adding or replacing features were evaluated for each set of variables until an optimal set was found

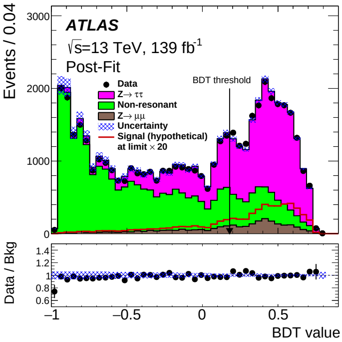


- all mass samples (0.2-1 TeV) of simulated $H_5^{\pm}$ events used in training
- training applied to both $H_5^{\pm}$ and HVT Model samples

Machine Learning in Event Selection II



- a Boosted Descision Tree (BDT) is used in the $Z \to e\mu$ search
- trained on simulated signal and background in the $85 < m_{\mu e} < 95$ GeV mass window
- the chosen threshold value of the BDT score maximizes $s/\sqrt{b}$
- same procedure used to define same-flavor control regions (CR)



Pre-selection

one electron and one oppositely charged muon

$70 < m_{\mu e} < 110$ GeV

$E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV

veto events containing a jet with $p_{\mathrm{T}} > 60$ GeV

veto events with b-tagged jets

Features

leading jet p_{T}

$E_{\mathrm{T}}^{\mathrm{miss}}$

$p_T^{e\mu}$ ($p_T^{ee}/p_T^{\mu\mu}$ used for $ee/\mu\mu$ CRs)

UiO : Department of Mathematics
University of Oslo

Eirik Gramstad

Recent searches for new phenomena with the ATLAS detector

XI International Conference on New Frontiers in Physics
Kolymbari, Crete, Greece, August 30 - September 11, 2022