SEARCH FOR A DARK Z BOSON WITH MACHINE LEARNING AT ATLAS

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Dark Sector at the LHC

- Many BSM theories introduce a dark sector through an additional $U(1)_d$ gauge symmetry
- Can use different portals to search for this sector at LHC: vector, neutrino, photon, Higgs

Higgs Portal

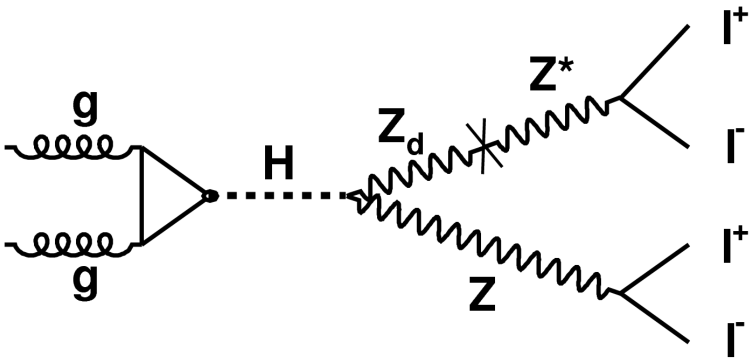
- Higgs portal introduces:

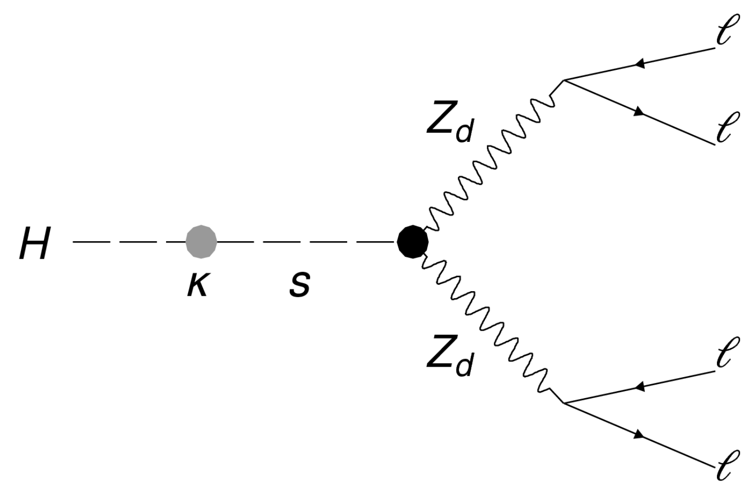
1. New gauge field with kinetic mixing ε with hypercharge gauge boson
2. In the case of broken $U(1)_d$ symmetry, a new Higgs with mass mixing κ with SM Higgs, leading to new Higgs doublet and mass mixing δ between SM Z and dark sector

- In the $\varepsilon >> \kappa$ case, kinetic mixing dominates, mass of new particle is higher, interpreted as a dark Z (Z_d) that couples to the dark charge

Higgs Portal at ATLAS

- Can infer the existence of Z_d through:
  1. Deviations of SM predicted Drell-Yan rates
  2. Higgs decays through exotic intermediate states
- In particular, allows for new processes with 4l final states: $H \to ZZ_d \to 4l$ and $H \to Z_d Z_d \to 4l$
- Not ruled out by electroweak constraints on ε





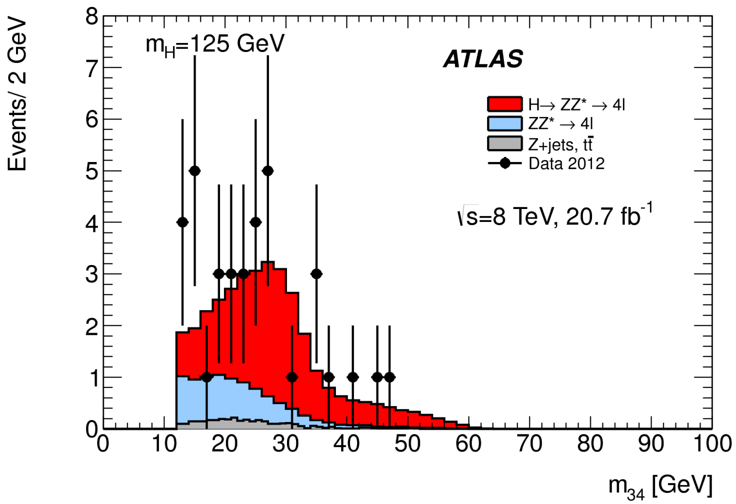
Analysis Strategy

- Apply event selection:
  - Run 1: Same event selection as $H \to ZZ^* \to 4l$ analysis
  - Run 2: Selection will be further optimized for ZZ_d analysis
- Look at m_{34} spectrum, apply LH fit to search for narrow peak about featureless SM background

$$L(\rho,\mu_h,\nu) = \prod_{i=1}^{Nbins} P(n_i^{obs} \mid n_i^{\exp}) = \prod_{i=1}^{Nbins} P(n_i^{obs} \mid \mu_h \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu))$$

- In absence of excess, set limits

on $$R_b = \frac{BR(H \to ZZ_d \to 4l)}{BR(H \to 4l)}$$



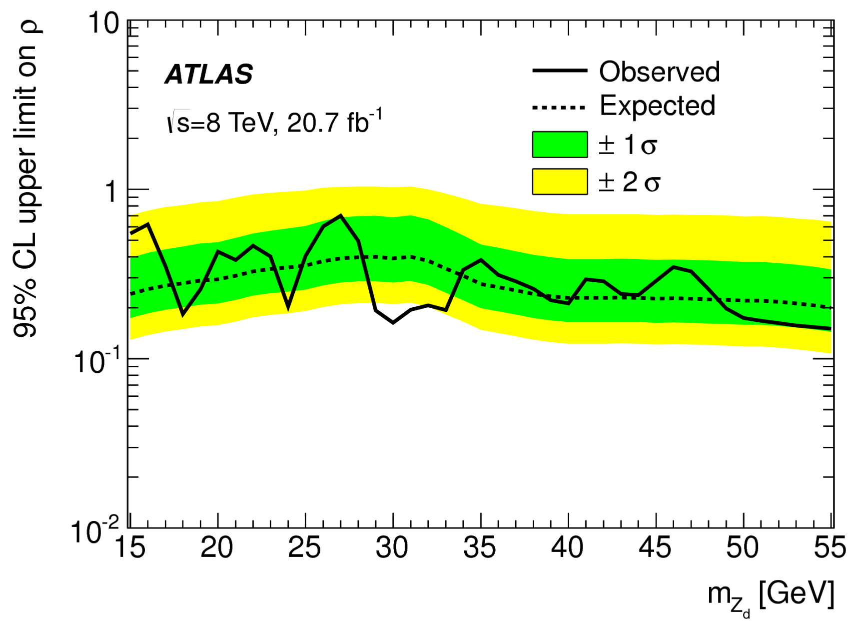
Run 1 Analysis

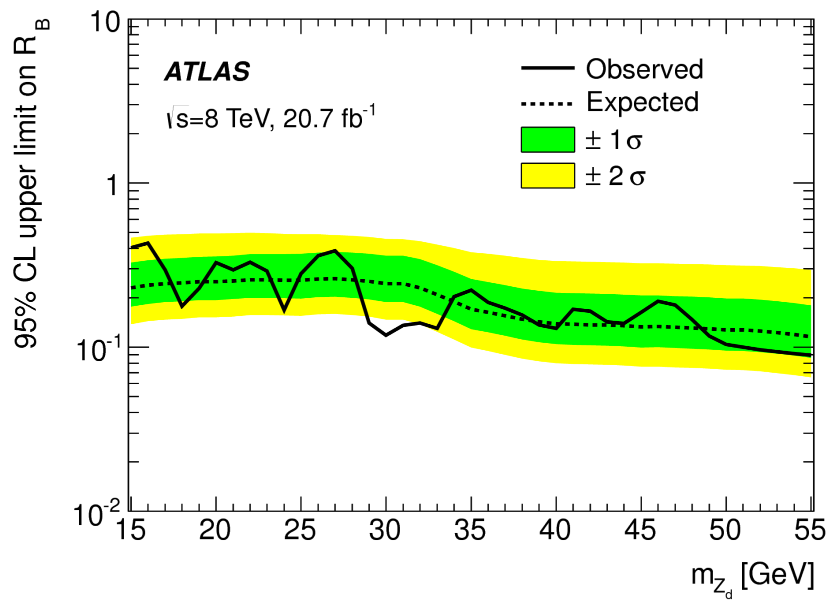
- Simulated signal with m_{Z_d} 15-55 GeV in 5 GeV steps (interpolated between steps) from ggF H using Hidden Abelian Higgs Model (Z_d is on shell)
- Relevant backgrounds ($H \rightarrow ZZ^* \rightarrow 4l, ZZ^* \rightarrow 4l, Z + jets, ttbar$) simulated and normalized to data (or SM cross section)
- Dominant uncertainties from lepton ID, background normalizations

Channel	ZZ^*	$t\bar{t}$ + Z+jets	Sum	Observed	$H \rightarrow 4\ell$
4μ	$3.1 \pm 0.02 \pm 0.4$	$0.6 \pm 0.04 \pm 0.2$	$3.7 \pm 0.04 \pm 0.6$	12	$8.3 \pm 0.04 \pm 0.6$
4e	$1.3 \pm 0.02 \pm 0.5$	$0.8 \pm 0.07 \pm 0.4$	$2.1 \pm 0.07 \pm 0.9$	9	$6.9 \pm 0.07 \pm 0.9$
2μ2e	$1.4 \pm 0.01 \pm 0.3$	$1.2 \pm 0.10 \pm 0.4$	$2.6 \pm 0.10 \pm 0.6$	7	$4.4 \pm 0.10 \pm 0.6$
2e2μ	$2.1 \pm 0.02 \pm 0.3$	$0.6 \pm 0.04 \pm 0.2$	$2.7 \pm 0.10 \pm 0.5$	8	$5.3 \pm 0.04 \pm 0.5$
all	$7.8 \pm 0.04 \pm 1.2$	$3.2 \pm 0.1 \pm 1.0$	$11.1 \pm 0.1 \pm 1.8$	36	$24.9 \pm 0.1 \pm 1.8$

Run 1 Results

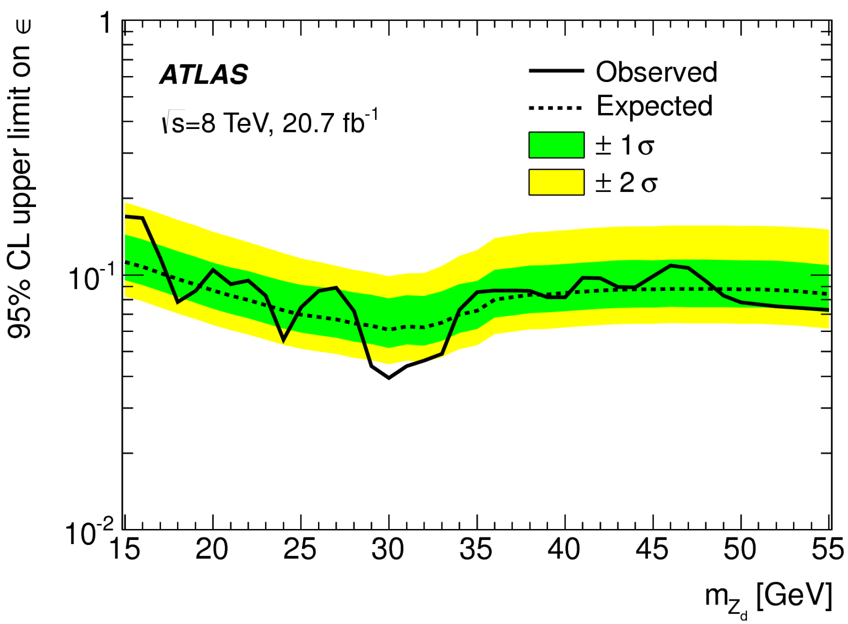
- No significant deviations from SM expectations ☹
- Can extract limits on ρ from LH fits
- Using $R_B = \dfrac{\rho}{\rho + C}$ can extract limits on R_B

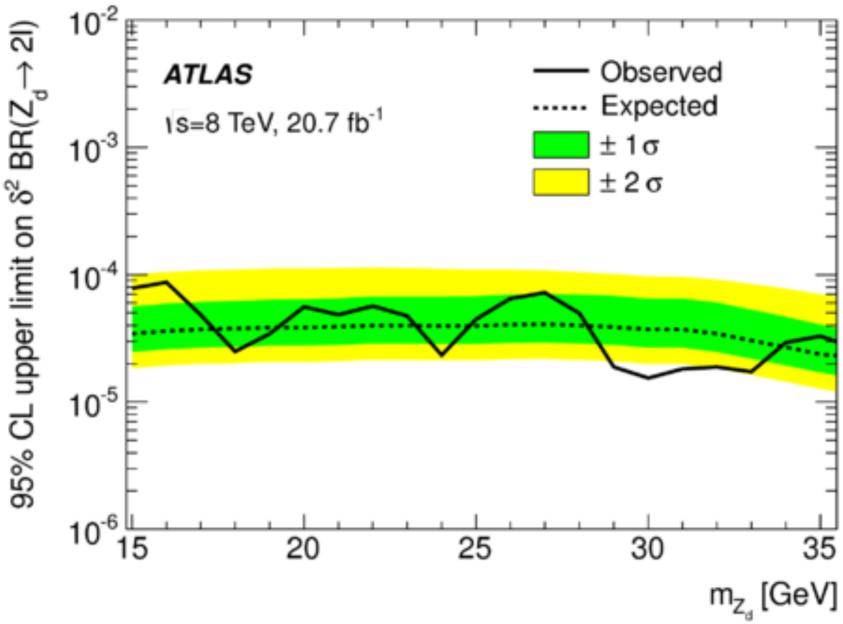




Run 1 Results

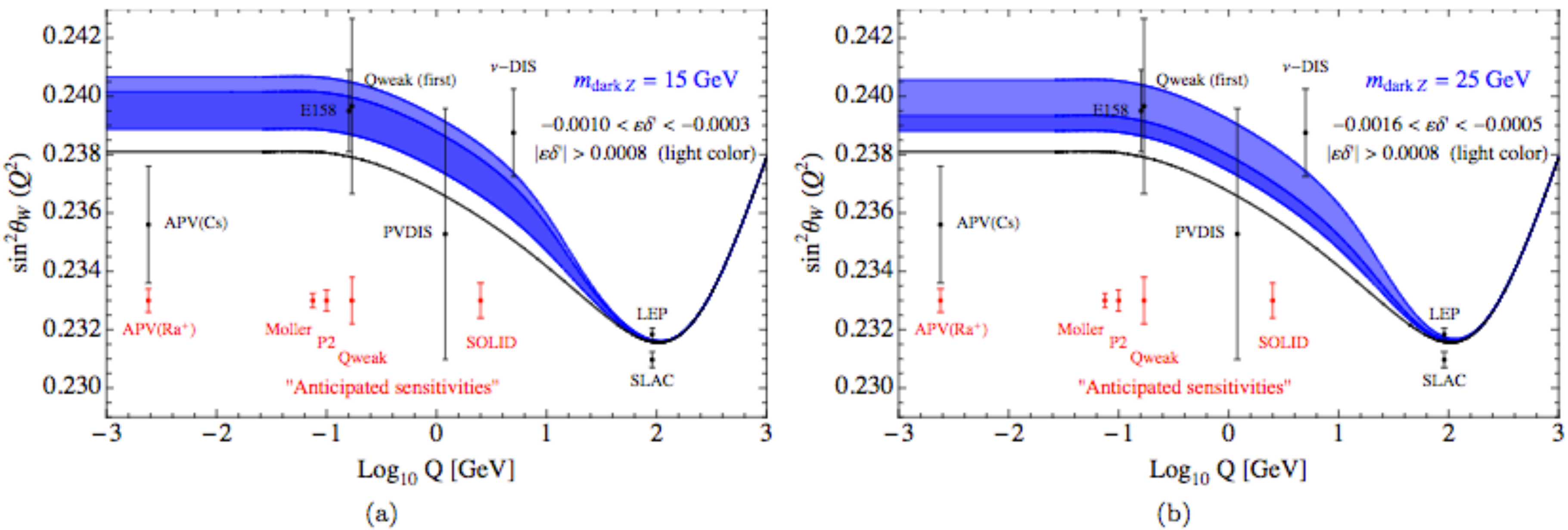
- By assuming SM cross section of $H \to ZZ^* \to 4l$, can extract limits on ε
- By approximating $BR(Z_d \to 2l)$ can extract limits on δ





Applications

- SM predictions for the running of weak mixing angle with Q^2 does not match data
- Z_d with mass in our search range could improve agreement



Run 2 Improvements

- Optimize the Higgs mass window for ZZ_d decays (in progress)
- Consider lifetime of Z_d (possible displaced vertices)
- Consider lower m_{Z_d} (in progress)
  - Aided by lowering lepton ID threshold
- Improve event selection and signal yield using machine learning

Machine Learning

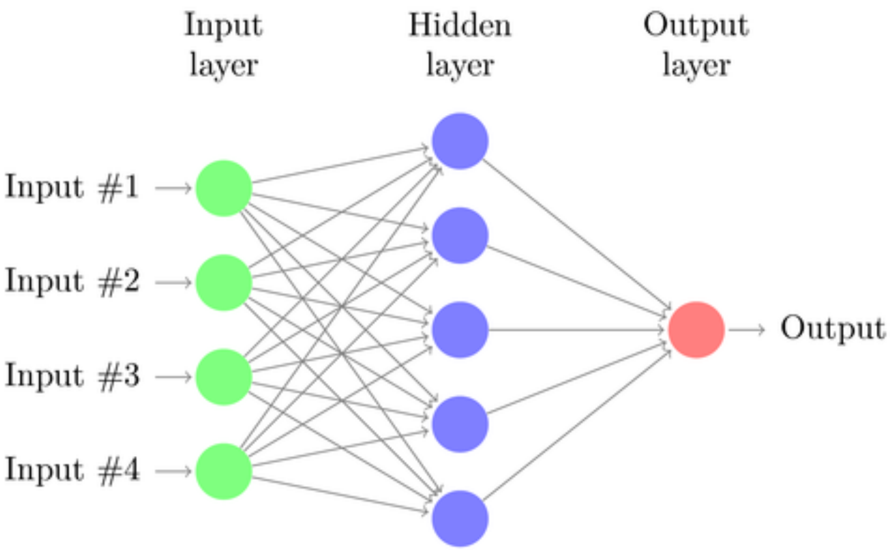
- Machine Learning allows algorithms to ‘learn’ parameters without being explicitly programed
- Can be used for classification, dataset generation, high level vector space transformations, unsupervised grouping, taking over the world…
- Already used in a few LHC analyses, triggers, reconstructions, and IDs
  - Usually relatively simple algorithms: LHs and BDTs

Deep Neural Networks

- Layered graph of multi-dimensional linear transformations
- Classification error is back-propagated using gradient descent based on cost function

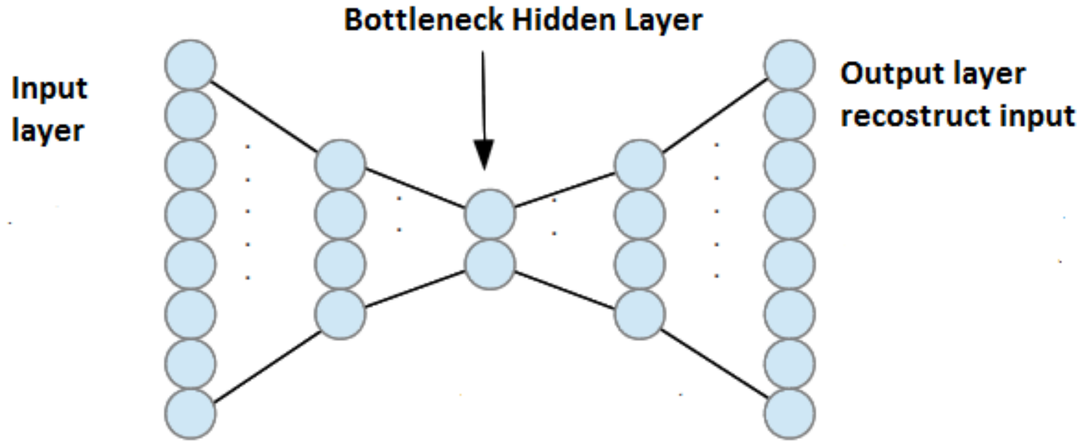
$$L(X,\theta) = \frac{1}{2n}\sum_{i=1}^{n}\left\|x_i - \rho_\theta(x_i)\right\|^2 + \lambda\left\|W\right\|^2$$

- Able to learn highly abstracted representations of data and extract high level patterns



Deep Neural Networks with Autoencoders

- NN performance is highly hyperparameter dependent
- One way to mitigate this is unsupervised pre-training
- Autoencoders create a “bottleneck of dimensionality”
- Goal is to accurately encode and decode information at each layer according to $\phi(x) = f(W_1 x + b_1)$ and $\psi(x) = g(W_2 \phi(x) + b_2)$
- Encoder weights are used as preliminary NN weights



Machine Learning for Z_d Search

- Two options for applying ML to this analysis:
  1. Use ML to optimize the $H \to ZZ^* \to 4l$ event selection
     - Goal to increase statistics in m_{34} distribution
  2. Use $H \to ZZ_d \to 4l$ trained algorithm *after/instead of* $H \to ZZ^* \to 4l$ event selection
     - Goal to resolve peak in m_{34} distribution
     - Would help remove remaining non-resonant ZZ* background and $H \to ZZ^* \to 4l$ background outside of Z_d mass range
     - More difficult because processes have identical kinematics in $m_{Z^*} = m_{Z_d}$ range.
  3. Can combine both techniques
- Option 1 currently being studied with pre-trained DNNs, have demonstrated clear improved event selection efficiency (for Run 1 data)

Conclusions

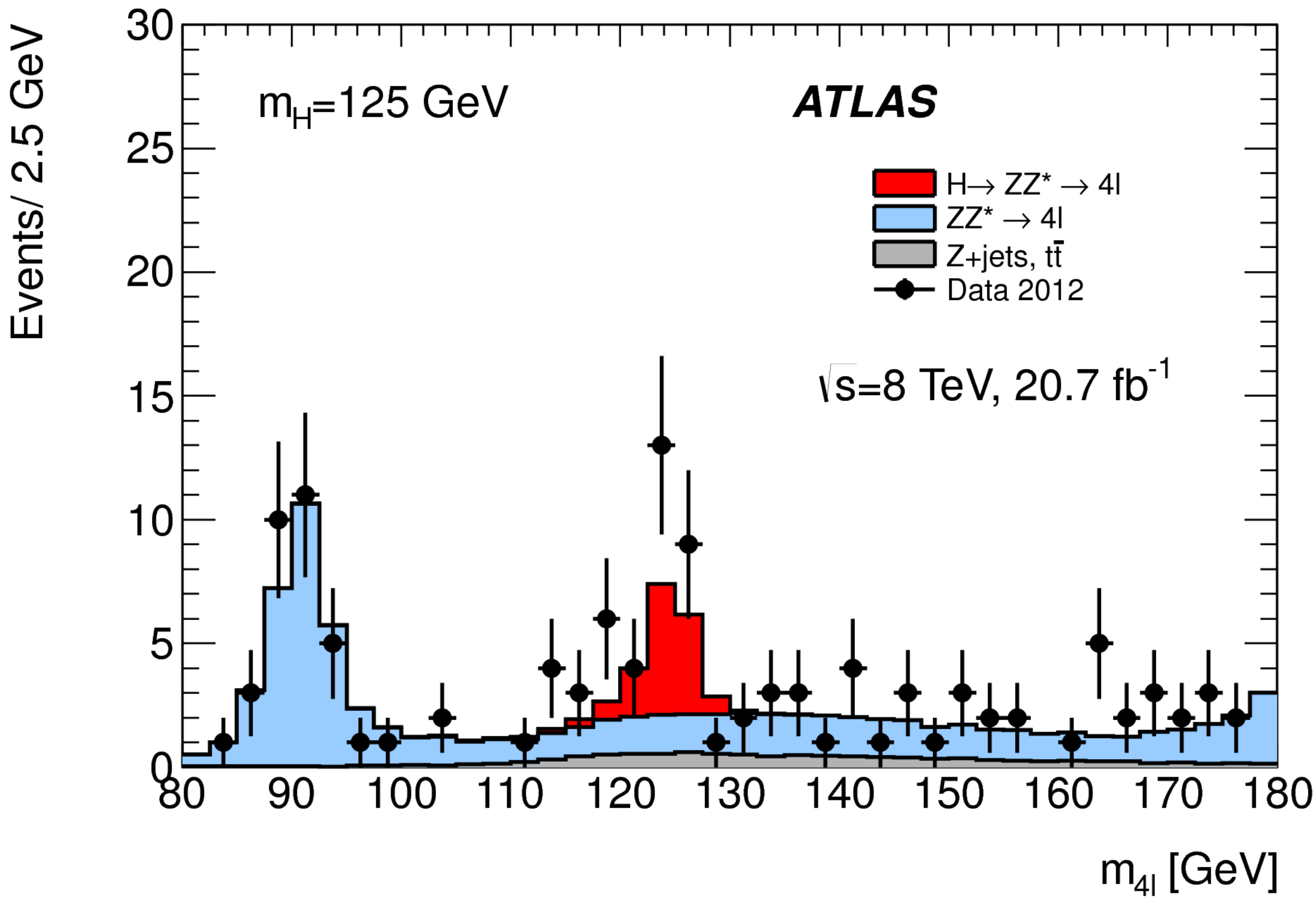
- Search for a dark sector vector boson in the intermediate mass range where kinetic mixing dominates is well motivated and accessible at the LHC
- Run 1 found no significant excess in Z* spectrum, set improved limits on R_B and mixing parameters
- Machine learning is a promising way to increase search sensitivity in Run 2
- Many thanks to Daniela, Keith, Luke de Olivera
- This work is supported by the National Science Foundation Graduate Research Fellowship

Backup

Higgs to 4l Standard Event Selection

Leptons and Jets requirements	
Electrons	
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\|\eta\| < 2.47$	
Muons	
Loose identification $\|\eta\| < 2.7$	
Calo-tagged muons with $p_T > 15$ GeV and $\|\eta\| < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV	
Jets	
anti-k_t jets with $p_T > 30$ GeV, $\|\eta\| < 4.5$ and passing pile-up jet rejection requirements	
Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: 50 GeV $< m_{12} <$ 106 GeV Sub-leading dilepton mass requirement: $12 < m_{34} < 115$ GeV Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T / p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_T / E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T / E_T < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\|d_0/\sigma_{d_0}\| < 5$ For muons : $\|d_0/\sigma_{d_0}\| < 3$
Vertex Selection	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

M4l Distribution Run 1



Deriving Limit Setting Equations

$$R_B = \frac{\rho \times \mu_H \times n(H \to 4\ell)}{\rho \times \mu_H \times n(H \to 4\ell) + C \times \mu_H \times n(H \to 4\ell)} = \frac{\rho}{\rho + C}, \tag{4}$$

where C is the ratio of the products of the acceptances and reconstruction efficiencies in $H \to ZZ_d \to 4\ell$ and $H \to ZZ^* \to 4\ell$ events:

$$C = \frac{\mathcal{A}_{ZZ_d} \times \varepsilon_{ZZ_d}}{\mathcal{A}_{ZZ^*} \times \varepsilon_{ZZ^*}}. \tag{5}$$

Setting R_B limits from LH parameters

From Eq. (2) and for $m_{Z_d} < (m_H - m_Z)$

$$\frac{\mathrm{BR}(H \to ZZ_d \to 4\ell)}{\mathrm{BR}(H \to ZZ^* \to 4\ell)} = \frac{R_B}{(1 - R_B)}, \simeq \frac{\Gamma(H \to ZZ_d)}{\Gamma_{\mathrm{SM}}} \times \frac{\mathrm{BR}(Z^* \to 2\ell) \times \mathrm{BR}(Z_d \to 2\ell)}{\mathrm{BR}(H \to ZZ^* \to 4\ell)}, \tag{6}$$

where Γ_{SM} is the total width of the SM Higgs boson and $\Gamma(H \to ZZ_d) \ll \Gamma_{\mathrm{SM}}$. From Eqs. (4), (A.3) and (A.4) of Ref. [7], $\Gamma(H \to ZZ_d) \sim \delta^2$. It therefore follows from Eq. (6), with the further assumption $m_{Z_d}^2 \ll (m_H^2 - m_Z^2)$ that

$$\frac{R_B}{(1 - R_B)} \simeq \delta^2 \times \mathrm{BR}(Z_d \to 2\ell) \times \frac{\mathrm{BR}(Z^* \to 2\ell)}{\mathrm{BR}(H \to ZZ^* \to 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{\mathrm{SM}}},$$

$$f(m_{Z_d}) = \frac{1}{16\pi} \frac{(m_H^2 - m_Z^2)^3}{v^2 m_H^3}, \tag{7}$$

Deriving limits on mass mixing from R_B

M_{34} Spectrum from Run 2