Axion DM Search with Vector Boson Fusion

A. Gurrola[1], **E. Sheridan**[1], B. Soubasis[1]

Vanderbilt University[1]

May 19, 2020

Table of Contents

Motivating Axions

Theoretical Origins

- The structure of quantum chromodynamics permits a violation of the combined charge conjugation-parity symmetry, but experimental constraints (stemming from symmetry breaking repercussions on the neutron electric dipole moment) require this violation to be small
- It is unclear why this symmetry violation should simultaneously exist and be so small: this is the **strong CP problem**
- Roberto Peccei and Helen Quinn addressed this conundrum in 1977 by promoting the CP violation phase $\overline{\Theta}$—previously a Standard Model input requiring experimental measurement–to a scalar field which spontaneously breaks a new global symmetry (a Peccei–Quinn symmetry)
- The quanta (or boson) of this new scalar field is the **axion**

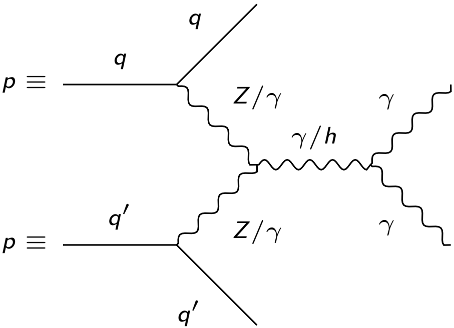
Axion Properties

- The axion is a neutral spin-0 boson, and different models permit widely varied mass values
- If the axion is sufficiently light, it presents itself as a dark matter candidate particle
- Axion theories require minor modifications to classical electrodynamics, as the presence of the axion serves to "rotate" the electric and magnetic fields into each other to an extent proportional to axion coupling and field strength

Axion Literature

- Astrophysics/cosmological experiments place bounds on axions and axion-like particles (ALPs) masses in some models, requiring them to be eV scale or lighter
- However, there still exist models which enable axions and ALPs to have masses in the MeV and GeV scales
- "Heavy axions" have been studied at the LHC, but primarily at higher mass scales due to sensitivity limitations

Motivating the Vector Boson Fusion Approach



Description

- Vector boson fusion processes (VBF; exhibited above) are experimentally important due to their distinctiveness at the LHC
- In particular, the so-called "tagged jets" (the outgoing quarks in the above diagram) carry tell-tale high pseudorapidities
- This VBF kinematic signature suppresses many background channels, including those with and without QCD vertices
- VBF cross sections typically surpass those of other topologies (Drell-Yan, etc) in new-physics processes with heavy new particles

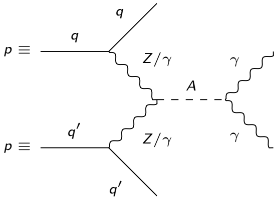
Signal Generation

Process

- Signal generated using **MadGraph** (version **2.6.5**) with the following command

```
import model ALP_chiral_UFO
generate p p > ax j j QCD=0, ax > a a
```

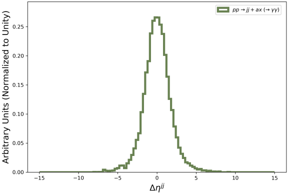
- We choose to consider an axion mass of **1 MeV**
- Only default MadGraph cuts employed: e.g., $p_T^j > 20$ GeV, $p_T^\gamma > 10$ GeV

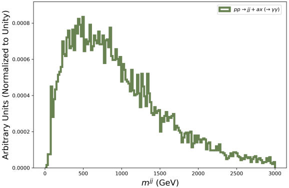


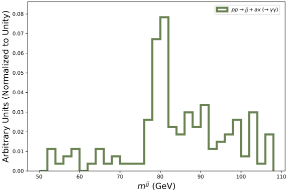
Comments

- `QCD = 0` selected due to our interest in axions with **negligible strong force couplings**
- `ax > a a` channel selected due to our emphasis on **lighter axions** (photons dominating heavier bosons)
- The significance of our studies arises in part from small axion mass scales probed

Initial Kinematics







Comments

- VBF processes are characterized by high $|\Delta\eta^{jj}|$, so a peak at 0 indicates that other processes dominate
- An m^{jj} peak at approx. 80-90 GeV indicates dominating `Z/W+/W- > j j` processes
- Total cross section for signal is 0.786 ± 0.001 pb

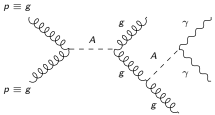
Channel	Cross-Section (pb)
`g g > ax g g`	$0.731 \pm$ 1e-3
`u d > ax u d`	$0.02414 \pm$ 2e-4
`u u > ax u u`	$0.01549 \pm$ 6e-5

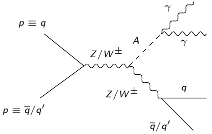
- Channel with next highest cross section on order of 1 fb.
- `q q > ax q q` processes can take on a VBF topology, but the
  `g g > ax g g` channel does not
- Despite the higher cross section, we avoid gluon-gluon processes due to their extensive prior analysis in the axion conext
- Additionally, gluon-gluon approaches are insensitive to light axions

Increasing VBF Purity in Signal

Objective

- Want to generate signal events in a phase space region which emphasizes our eventual optimization (ensuring sufficient statistics)
- Equivalently, want to generate signal events primarily with the particular topologies (VBF) we will later select
- Thus before comparing with background, want to impose **MadGraph-level cuts** on signal events
- We select two topologies to try and minimize with such cuts: `g g > ax g g` and `Z > j j`





Final Approach

- Choose to generate 1000000 signal events with all of the previous commands/setting, along with the following additional MadGraph selections.

  $|\Delta\eta^{jj}| > 2.4$, $m^{jj} > 120$ GeV

  - The gluon-gluon channel exhibits predominately low $|\Delta\eta^{jj}|$, so we apply a cut with the hopes of reducing its cross section
  - The vector boson resonance channel satisfies $m^{jj} \approx 80$ GeV, so we apply an m^{jj} cut with the hopes of also reducing that cross section
- The cross section for this signal is $0.10235 \pm 2.82\text{e-}5$ pb

Channel	Cross-Section (pb)
`g g > ax g g`	$0.06911 \pm 2.28\text{e-}5$
VBF channel	$0.03324 \pm 5.1\text{e-}5$

- While the gluon-gluon channel still dominates, we've achieved a VBF signal purity sufficient to achieve the necessary statistics during optimization

Background Generation

Process

We're interested in comparing our signal with **two** background processes.

- First, a general dijet, diphoton channel which we generate as follows.

  `generate p p > j j a a`

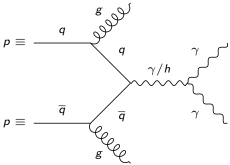
- Second, a more specific, VBF-oriented background with no QCD vertices, mimicking our signal generation.

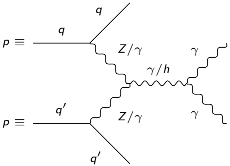
  `generate p p > j j a a QCD=0`

- Recognizing our eventual selection of high jet momentum events (heavy vector boson production boosting VBF jets), for both background processes we generate events in H_T bins
- In particular, we sought to simulate 1000000 events per background process per each of the following bins (all values given in GeV).

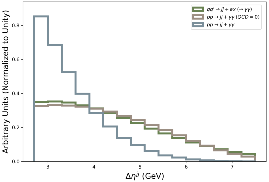
  $[0, 100], [100, 200], [200, 400], [400, 600], [600, 800], [800, 1200], [1200, 1600], [1600, \infty)$

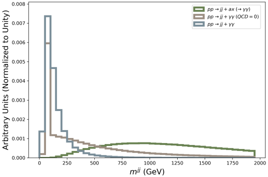
  - We note that MadGraph was unable to produce the full million events for higher H_T bins (likely due to diagram complexity)
  - However, the number of events generated was sufficient to reach desired optimization statistics
- Prototypical Feynman diagrams are given for the general (left) and QCD $= 0$ (right) cases.

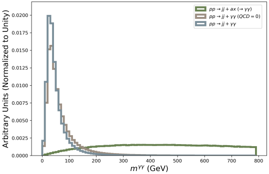


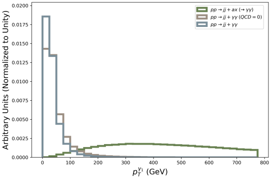


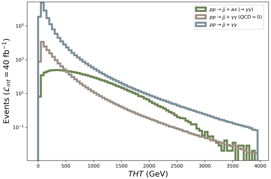
Kinematics with MG-Level Cuts











Comments

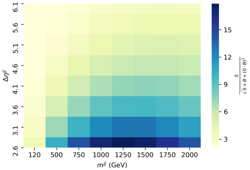
- The first four kinematic plots exhibit high signal-background discriminating power in the variables $\Delta\eta^{jj}$, m^{jj}, $m^{\gamma\gamma}$, p_T^{γ}, motivating our upcoming optimization procedure
  - This is a little less obvious in the $\Delta\eta^{jj}$ case: only the VBF subset of our signal has high $\Delta\eta^{jj}$, so disc. power appears only when omitting gluon-gluon signal events (achieved by removing g from the MadGraph proton definition)
- The final kinematic plot demonstrates how our H_T-binned background samples are "stiched" together smoothly (noise occurring only at the higher end of our final H_T bin).

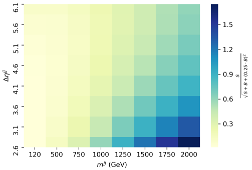
Jet Variable Selection Optimization ($\Delta\eta^{jj}$, m^{jj})

Process

- Optimized $\Delta\eta^{jj}$ and m^{jj} selections simultaneously (to account for correlations)
- Performed a gridsearch on pairs of selections $|\Delta\eta^{jj}| > \eta_0$, $m^{jj} > m_0^j$ for the following values (m^{jj} given in GeV)

  $(\eta_0, m_0^j) \in \{2.6, 3.1, 3.6, 4.1, 4.6, 5.1, 5.6, 6.1\} \times \{120, 500, 750, 1000, 1250, 1500, 1750, 2000\}$
- Significance computed twice on each of $8 \cdot 8 = 64$ scenarios: without (left) and with (right) systematic uncertainty
  - To avoid misleadingly high significance with insufficient signal statistics, changed base form $\frac{S}{B}$ to $\frac{S}{\sqrt{S+B}}$
  - Systematic uncertainty approximation implemented via denominator term $(r \cdot B)^2$ for $r \in [0, 1]$





Conclusions

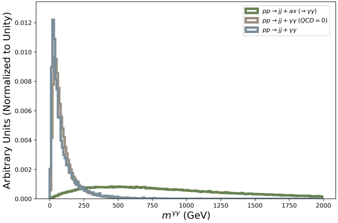
Experimental constraints motivate prioritizing higher $\Delta\eta^{jj}$ cuts, and our sys. uncert. approximation fails at higher m^{jj} cuts, so we invoke the non-sys. uncert. results and pursue two selection pairs:

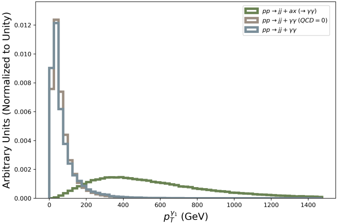
- A tight (lower significance/more experimental feasibility) cut $(\eta_0, m_0^j) = (3.6, 1250)$
- A loose (higher significance/less experimental feasibility) cut $(\eta_0, m_0^j) = (2.6, 1250)$

Checking Photon Discriminating Power

Confirmation

Before proceeding to the optimization for the other two variables—$m^{\gamma\gamma}$, p_T^{γ}—check that our tight/loose $\Delta\eta^{jj}$, m^{jj} cuts haven't reduced discriminating power: in particular, considering kinematic plots in the tight cuts scenario.





Conclusions

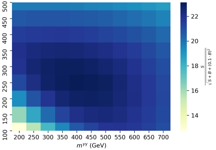
Discriminating power has been preserved (these plots behave similarly in the loose cuts scenario), allowing continuation onto a photon kinematics optimization routine.

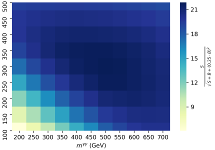
Photon Variable Selection Optimization ($m^{\gamma\gamma}$, p_T^{γ})

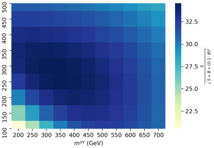
Process

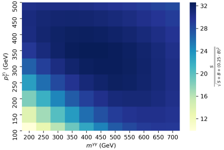
- Optimized $m^{\gamma\gamma}$ and p_T^{γ} selections simultaneously, performing a gridsearch on pairs of selections $m^{\gamma\gamma} > m_0^{\gamma}$, $p_T^{\gamma} > \gamma_0$ on the following values (both variables in GeV)

  $(m_0^{\gamma}, \gamma_0) \in \{200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700\} \times \{100, 150, 200, 250, 300, 350, 400, 450, 500\}$
- Computed significance in two ways on each of the $11 \cdot 9 = 99$ scenarios–in particular, using different systematic uncertainty coefficients–for both the tight (left plots) and loose (right plots) selections.









Conclusions

Each heatmap provides us with a slightly different local maxima for significance: we therefore decide to pursue four (m_0^{γ}, γ_0) selections (ordering coinciding with the heatmap ordering).

$$(m_0^{\gamma}, \gamma_0) \in \{(400, 250), (500, 300), (350, 250), (400, 350)\}$$

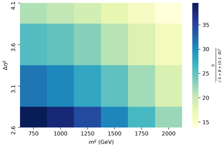
Jet Variable Selection Optimization, Again ($\Delta\eta^{jj}$, m^{jj})

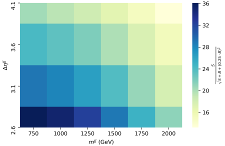
Process

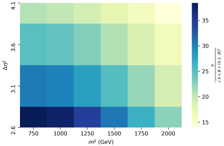
- Returned to the jet variables to study significance in $\Delta\eta^{jj}$, m^{jj} phase space for each of our four pairs of $m^{\gamma\gamma}$, p_T^{γ} cuts
- Performed smaller gridsearch, with selection pairs $|\Delta\eta^{jj}| > \eta_0$, $m^{jj} > m_0^j$ in the following values (m^{jj} again GeV)

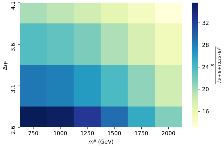
  $(\eta_1, m_1^j) \in \{2.6, 3.1, 3.6, 4.1\} \times \{750, 1000, 1250, 1500, 1750, 2000\}$
- Computed significance just once on each of these $4 \cdot 6 = 24$ scenarios, using the systematic uncertainty coefficient which led to the choice of that particular $m^{\gamma\gamma}$, p_T^{γ} selection; plots are ordered as follows

  $(m_0^{\gamma}, \gamma_0) = (400, 250), (m_0^{\gamma}, \gamma_0) = (500, 300), (m_0^{\gamma}, \gamma_0) = (350, 250), (m_0^{\gamma}, \gamma_0) = (400, 350)$









Conclusions

- Our four scenarios exhibit an approximately uniform shape, with a maximum near $(\eta_1, m_1^j) = (2.6, 750)$
  - Once again, we consider high $\Delta\eta^{jj}$ selections to be more experimentally feasible
  - We also seek to incorporate a realistically high systematic uncertainty
- These priorities motivate the following selections

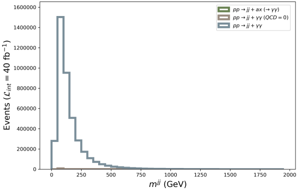
$$|\Delta\eta^{jj}| > 3.6,\ m^{jj} > 750,\ m^{\gamma\gamma} > 500,\ p_T^{\gamma} > 300$$

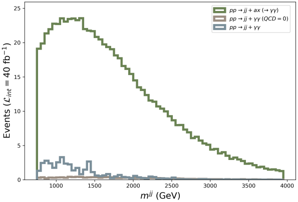
Selection Significance

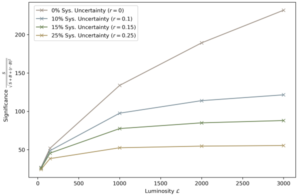
Objective

Given our new parameter selections, we quickly summarize our progress.

- Compare signal-background kinematic plots normalized to cross section between before (left) and after (center) selections are made
- Examine how significance scales with luminosity for different significance metrics (right)







Conclusions

We've selected a region of phase space where our new physics processes dominate and discovery potential is high.

Final Thoughts

Summary

- Introduced the theory of our particular BSM interest–the axion–and the collider topology we plan to use to study it, vector boson fusion (VBF)
- Discussed our generation of signal events, including imposed MadGraph-level selections to increase VBF purity
- Examined our generation of background events, including the choice of two distinct background channels and our H_T binning process
- Analyzed kinematic variables and elaborated on our three-step selection optimization process on $\Delta\eta^{jj}$, m^{jj}, $m^{\gamma\gamma}$, p_T^j, eventually arriving at an experimentally and statistically motivated selection for each of these variable
- Investigated signal versus background yield and the significance associated with our four final selections

Next Steps

- Resolve technical issues (potentially relating to `ax > a a` decay) and study how our findings vary with axions of different masses
- Investigate why virtual axion processes dominate (thoughts?)
- Anything else?