Axion DM Search with Vector Boson Fusion

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Table of Contents

Motivating Axions

Theoretical Origins

- The structure of quantum chromodynamics permits a CP (charge conjugation-parity) symmetry violation, but experimental constraints 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**
- In 1977, Roberto Peccei and Helen Quinn addressed this conundrum 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**

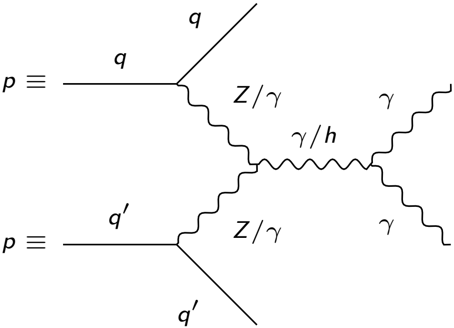
Axion Properties

- The axion is a neutral spin-0 boson, and different models permit widely varied mass values
- Sufficiently light axions are compatible with current dark matter relic density calculations, making these light axions dark matter candidates
- Axion theories modify classical electrodynamics: the axion "rotates" the electric and magnetic fields into each other by an amount 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 ($\sim$ 100 GeV) due to sensitivity limitations

Motivating the Vector Boson Fusion Approach



Description

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

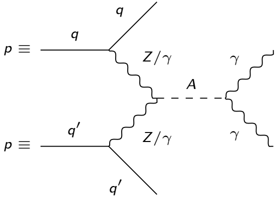
Signal Generation

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
```

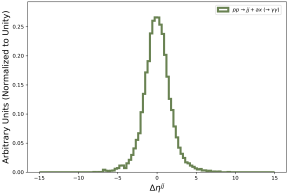
- Our studies focus on an axion mass of **1 MeV**
- Only default MadGraph cuts employed: e.g., $p_T^j > 20$ GeV, $p_T^\gamma > 10$ GeV

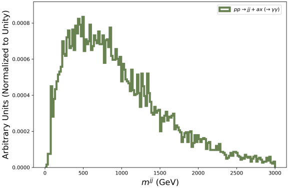


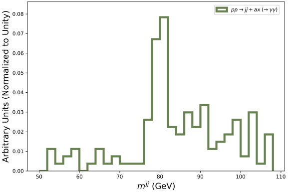
Comments

- `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

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- VBF processes are characterized by high $|\Delta\eta^{jj}|$, so a peak at 0 indicates the dominance of other processes
- The m^{jj} peak at approx. 80-90 GeV points to contributions from `Z/W+/W- > j j` processes
- Total cross section for signal is 0.786 $\pm$ 0.001 pb

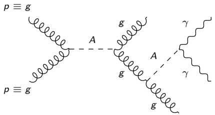
Channel	Cross-Section (pb)
`g g > ax g g`	0.731 $\pm$ 1e-3
`u d > ax u d`	0.02414 $\pm$ 2e-4
`u u > ax u u`	0.01549 $\pm$ 6e-5

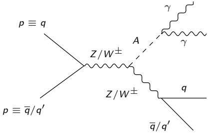
- Channel with next highest cross section on order of 1 fb.
- `q q > ax q q` processes can take on a VBF topology, but the `g g > ax g g` channel does not
- Despite the higher cross section, we avoid gluon-gluon processes for two reasons
  - The gluon-gluon topology has been extensively studied in previous axion research
  - Gluon-gluon approaches have been shown to be largely 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 with the particular topologies (VBF) we will later select
- Thus before comparing with background, want to impose **MadGraph-level cuts** on signal events
- Two topologies being targeted by our cuts: `g g > ax g g` and `Z/W > 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 there to reduce its cross section
  - As noted, the vector boson resonance channel satisfies $m^{jj} \approx 80$ GeV, so we apply an m^{jj} cut to reducing that cross section as well

- 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 generated as follows.

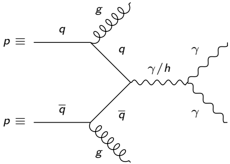
  `generate p p > j j a a`

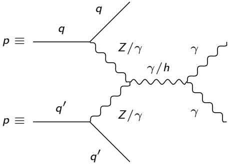
- Second, a more specific, VBF-oriented background with no QCD vertices, mimicking our signal generation.

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

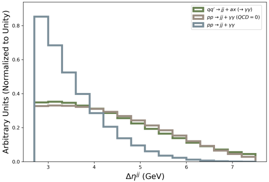
- Recognizing our eventual selection of high jet momentum events (VBF jets being boosted by heavy vector boson production), we generate background events in H_T bins
  - In particular, we sought to simulate 1000000 events per background process per each of the following bins (all values given in GeV).

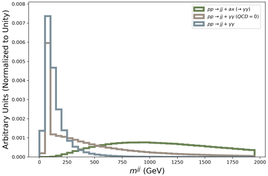
    $[0, 100], [100, 200], [200, 400], [400, 600], [600, 800], [800, 1200], [1200, 1600], [1600, \infty)$
  - MadGraph was unable to produce the full million events for higher H_T bins (likely due to diagram complexity)
  - However, the number of events generated was sufficient to reach desired optimization statistics
- Prototypical Feynman diagrams are given for the general (left) and QCD $= 0$ (right) cases.

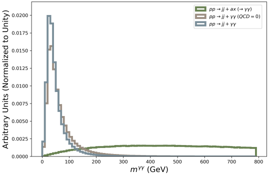


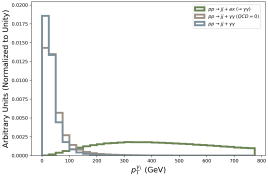


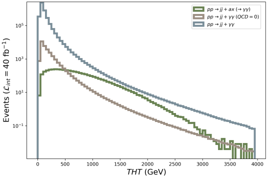
Kinematics with MG-Level Cuts











Comments

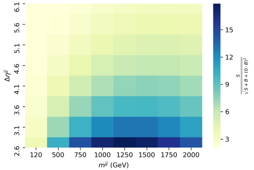
- First four kinematic plots exhibit high signal-background discriminating power in the variables $\Delta\eta^{jj}$, m^{jj}, $m^{\gamma\gamma}$, p_T^{γ}, motivating our upcoming optimization procedure
    - More subtle in the $\Delta\eta^{jj}$ case: only the VBF subset of the signal has high $\Delta\eta^{jj}$, so disc. power appears only when omitting gluon-gluon signal events (removing g from the MadGraph proton definition)
- The final kinematic plot demonstrates how our H_T-binned background samples are “stiched” together smoothly when normalized to cross section (noise occurring only at the higher end of our final H_T bin).

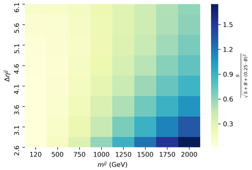
Jet Variable Selection Optimization ($\Delta\eta^{jj}$, m^{jj})

Process

- Optimized $\Delta\eta^{jj}$ and m^{jj} selections simultaneously (to account for correlations)
- Performed a gridsearch on pairs of selections $|\Delta\eta^{jj}| > \eta_0$, $m^{jj} > m^j_0$ for the following values (m^j_0 given in GeV)

  $(\eta_0, m^j_0) \in \{2.6, 3.1, 3.6, 4.1, 4.6, 5.1, 5.6, 6.1\} \times \{120, 500, 750, 1000, 1250, 1500, 1750, 2000\}$
- Significance computed twice on each of $8 \cdot 8 = 64$ scenarios: without (left) and with (right) systematic uncertainty
  - To avoid misleadingly high significance for insufficient signal statistics, we chose $\frac{S}{\sqrt{S+B}}$ over $\frac{S}{B}$
  - Systematic uncertainty approximation then implemented via denominator term $(r \cdot B)^2$ for $r \in [0, 1]$





Conclusions

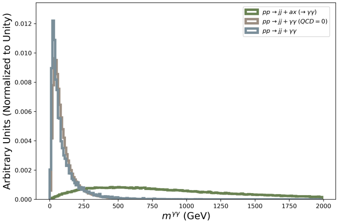
Experimental constraints motivate prioritizing higher $\Delta\eta^{jj}$ cuts, and our sys. uncert. approximation fails at higher m^{jj} cuts, so we invoke the non-sys. uncert. results and pursue two selection pairs:

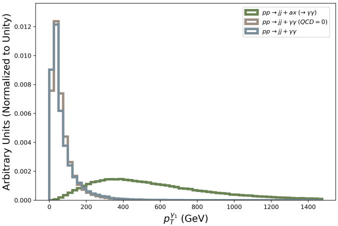
- A tight (lower significance/more experimental feasibility) cut $(\eta_0, m^j_0) = (3.6, 1250)$
- A loose (higher significance/less experimental feasibility) cut $(\eta_0, m^j_0) = (2.6, 1250)$

Checking Photon Discriminating Power

Objective

Before proceeding to the optimization for the other two variables—$m^{\gamma\gamma}$, p_T^{γ}—we check that our tight/loose $\Delta\eta^{jj}$, m^{jj} cuts haven't lost discriminating power.





Conclusions

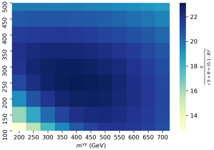
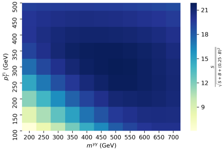
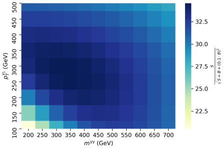
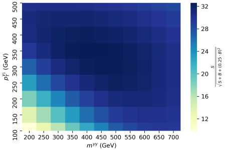
These are "tight cut" plots, but they behave similarly in the loose cuts scenario. Discriminating power has therefore been preserved, allowing continuation onto a photon kinematics optimization routine.

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).

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

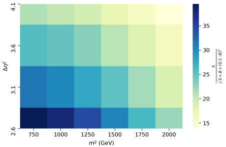
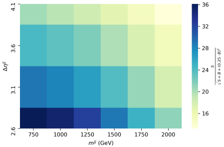
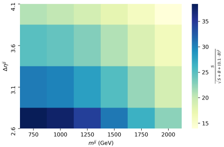
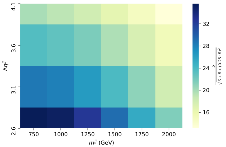
Jet Variable Selection Optimization, Again ($\Delta\eta^{jj}$, m^{jj})

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 $|\Delta\eta^{jj}| > \eta_0$, $m^{jj} > m_1^j$ in the following values (m_1^j also in 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

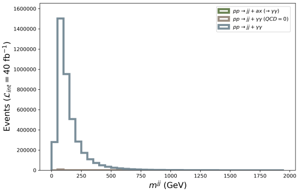
- Our four scenarios exhibit an approximately uniform shape, with a maximum near $(\eta_1, m_1^j) = (2.6, 750)$
  - Once again, we consider high $\Delta\eta^{jj}$ selections to be more experimentally feasible
  - We also seek to incorporate a realistically high systematic uncertainty
- These priorities motivate the following selections: $|\Delta\eta^{jj}| > 3.6$, $m^{jj} > 750$, $m^{\gamma\gamma} > 500$, $p_T^{\gamma} > 300$

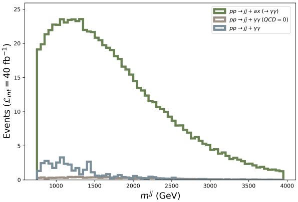
Selection Significance

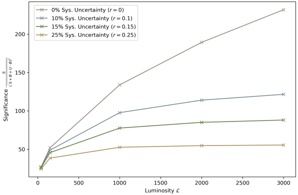
Objective

We seek to quickly evaluate our new parameter selections.

- Want to compare signal-background kinematic plots normalized to cross section between before (left) and after (center) selections are made
- Want to 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
- Begin formalizing our results and writing a paper