Parity violating observables for LHC searches for new physics

Candidate Number: 8291T
Supervisor: Christopher Lester

Abstract

General properties of parity-odd observables are investigated, and used to discuss whether these observables might be employed to search for new parity-violating processes at the LHC, and what limitations exist on this method. We find that the only local Lorentz invariant processes that will produce an asymmetry in these observables are those which violate CP. The fact that the LHC initial state is an eigenstate of parity ensures that asymmetries in distributions of parity-odd observables are a signature of parity-violating processes.

Asymmetries in $\cos\theta$ are discussed as a model-dependent indication of parity-violation for spin-1 s-channel processes.

The parity-violating "screw model" is examined using a purpose-built event generator. It produces large asymmetries in a parity-odd observable, and has enough free parameters for invariant mass distributions to be fixed so that it can be hidden in Standard Model backgrounds.

1 Introduction

Parity-violation has been known to be a feature of the Standard Model since Lee and Yang's proposal of parity-violating weak interactions [1] was experimentally confirmed by Wu et al. in 1957 [2]. Parity reverses the sign of all spatial components of a four-vector, but does not affect any component of an axial vector. Parity on a process thus reverses the direction of all particle momenta while leaving spins unchanged; parity is violated if the cross-section for this mirror process is different to the cross-section for the original process. No standard model interactions apart from weak interactions have been found to violate parity.

In this project we investigate the possibility of using parity-violation to search for new physics at the LHC. The parity-violation in the Standard Model is well known and can be very small for certain final states, so looking for an excess of parity-violation could be an easy and model-independent indication that something new is going on.

We begin in section 2 with a discussion of parity-odd observables, their use and limitations. Section 3 discusses asymmetries in $\cos\theta$ and how they are used as model-dependent indications of parity-violating interactions. The consequences of a parity-violating model are set out in section 4, and a summary of conclusions drawn is given in section 5.

2 Parity-odd observables

2.1 Possible parity-odd observables and why they work

Parity-odd observables change sign under parity. A number of candidate observables for collider experiments have been proposed in the literature [1] [3] [4].

Examples of these are:

$$\boldsymbol{p}_1 - \boldsymbol{p}_2$$
$$\boldsymbol{p}_1 \cdot (\boldsymbol{p}_2 \times \boldsymbol{p}_3)$$
$$(\boldsymbol{p}_1 \times \boldsymbol{p}_2) \cdot (\boldsymbol{p}_3 - \boldsymbol{p}_4)$$

where $\boldsymbol{p}_1, \boldsymbol{p}_2, ...$ are three-momenta of relevant final-state particles in the event. These are all parity odd since $\boldsymbol{p_i} \to -\boldsymbol{p_i}$ under parity ($i = 1, 2, 3$). An asymmetry in any one of these observables O_P is defined as

$$A = \frac{N(O_P > 0) - N(O_P < 0)}{N(O_P > 0) + N(O_P < 0)}$$

Parity-violating processes have a squared matrix element of the form

$$|M|^2 = A[\text{Parity-even bit}] + B[\text{Parity-odd bit}],$$

where A and B are real coefficients, and A>B. This means that the squared matrix element of the parity-conjugate process is

$$|M_P|^2 = A[\text{Parity-even bit}] - B[\text{Parity-odd bit}],$$

and thus the cross-sections are different for the two processes. So the distribution of a parity-odd observable $O(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)$ will be asymmetric about zero if the process we're looking at violates parity, because:

$$Probability[O(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)] \propto |M|^2(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)$$

and

$$Probability[O(-\boldsymbol{p}_1, -\boldsymbol{p}_2, ...)] \propto |M|^2(-\boldsymbol{p}_1, -\boldsymbol{p}_2, ...) = |M_P|^2(\boldsymbol{p}_1, \boldsymbol{p}_2, ...) \neq |M|^2(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)$$

So the number of events with $O(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)$ is not equal to the number of events with $O(-\boldsymbol{p}_1, -\boldsymbol{p}_2, ...)$ = $-O(\boldsymbol{p}_1, \boldsymbol{p}_2, ...)$. By contrast for a parity-conserving process, $|M_P|^2 = |M|^2$, so the distribution of O will be symmetric.

Candidate observables should be invariant under other symmetries, for example rotational symmetry, to ensure that they are only testing for parity violation and not for any other violated symmetries.

2.2 Lorentz invariance and CP violation

At the LHC the beams are unpolarised and it is not possible to measure particle spins directly; we measure only particle energy and momentum. The cross-section is measured after a spin-average has been taken, so the squared matrix element can only depend on particle four-momenta. The only possible parity-odd term in a Lorentz-invarant matrix element is one involving the four-dimensional epsilon tensor, $\epsilon_{\mu\nu\rho\sigma}$. And the term $\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$ is odd under time reversal because one of the momentum components will change sign.

The squared matrix element for a process which contains one of these parity-odd epsilon terms can be written

$$|M_{if}|^2 = A[\text{Parity-even bit}] + B\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma,$$

and the squared matrix element for the time-reversed process is

$$|M_{fi}|^2 = A[\text{Parity-even bit}] - B\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma.$$

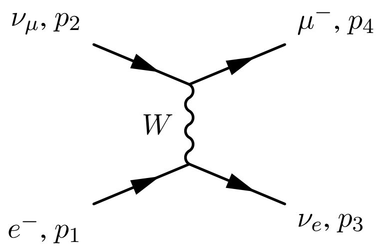


Figure 1: t-channel scattering process exchanging a W^- boson.

Since these are unequal, the process violates time-reversal symmetry T. According to the CPT theorem [6], any local Lorentz invariant quantum field theory must be invariant under the combined symmetries of C, P and T. This means that T violation is equivalent to CP violation in these theories, which include the Standard Model and all supersymmetric theories. Therefore the only local, Lorentz invariant processes that will show an asymmetry in a parity-odd observable at the LHC (or indeed at any collider which collides unpolarised beams and whose detectors are insensitive to particle spins) will be those that violate CP. To illustrate this point, a process involving the exchange of a single W or Z boson, though parity violating, will show no asymmetry in any parity-odd observable. The squared matrix element for a scattering process involving a W boson, for which the Feynman diagram is shown in figure 1, has the form

$$|M|^2 \propto (p_1 \cdot p_4)(p_2 \cdot p_3)$$

which is symmetric under parity, so cannot produce an asymmetry in the distribution of a parity-odd observable.

Measurements of electric dipole moments (for example of the neutron) are putting strong constraints on the maximum amount of CP violation that theories beyond the Standard Model (BSM) could have [7][8]. On the other hand a larger amount of CP violation than in the Standard Model is a desirable feature in a BSM theory because it could help explain the matter-antimatter asymmetry in the universe, so there is motivation for searching for these models through their CP violation. In fact, observables suggested in the literature to search for CP violation have exactly the same triple-product form as some of the parity-odd observables suggested [4][5][9].

2.3 Initial state

The parity operator, P, has two eigenstates, with eigenvalues ± 1:

$$P\,|\phi\rangle \to +\,|\phi\rangle$$

$$P\,|\psi\rangle \to -\,|\psi\rangle$$

Then any general state can be written as a linear superposition of these eigenstates,

$$|state\rangle = \alpha\,|\phi\rangle + \beta\,|\psi\rangle\,.$$

Without parity-violating interactions, the state will forever remain as this mixture, and the magnitudes of α and β will not change because there can be no mixing between the two eigenstates. So a state or collection of states that gives a symmetric distribution in a parity-odd observable before it undergoes some interaction will produce a symmetric distribution after the interaction, as long as the interaction is parity-conserving.

If the signature for parity-violating interactions is supposed to be an asymmetry in a distribution of a parity-odd observable, we had better be sure that the initial state will produce a symmetric distribution before any interactions have occurred.

There are three ways to produce a symmetric distribution in a parity-odd observable.

- The first is to take a parity eigenstate.

  In order for parity-eigenstates to look the same under parity (as they must), for each three-momentum $\boldsymbol{p}_1$ in the event there must also be another momentum $\boldsymbol{p}_2 = -\boldsymbol{p}_1$ carried by an identical particle, so that under parity these two momenta transform into each other. I will call p_1 and p_2 "mirror momenta". This means that under parity, $p_1^\mu \;\to\; p_2^\mu$.

  Since the mirror pairs have the same magnitudes for each component of their momenta, any parity-odd observable must either be unchanged or change sign under exchange of a particle with its mirror partner. But swapping the mirror partners has the same effect on the state as parity, so if the observable is unchanged under this exchange it implies that it is both odd and even under parity, so it must be zero. If the observable changes sign, then since the mirror momenta belong to identical particles, the observable is equally likely to contain a momentum as its mirror momentum (or, equally likely to contain them both in either order), so the frequency of a certain value of the observable will equal the frequency of the negative value. In both cases, therefore, we obtain a symmetric distribution in any parity-odd observable.

- Secondly, if a state can be transformed into its mirror image by rotation, it will also give a symmetric distribution in a parity-odd observable. A parity-odd observable designed to prove parity-violation should be rotationally symmetric, which means that rotating the state should not affect the value of the observable. But under parity the observable changes sign. So if these two operations are equivalent on some state, then the value of the observable, if it is computed using all particle momenta in the event, must be zero.

  The state might contain identical particles which can be rotated into each other to give the mirror-image state, and the parity-odd observable might be computed using only one of these particle momenta. But the observable is equally likely to contain the momentum of either of two identical particles, and seeing as these particles can be transformed into each other by parity+rotation, you must get equal numbers of a certain value for the observable as of its negative. So here you also get a symmetric distribution.

- Finally, you can produce a symmetric distribution in a parity-odd observable by taking equal numbers of a state and its parity-mirrored state. That is, if

  $$P\,|state\ 1\rangle \;\to\; |state\ 2\rangle$$

  then the experiment must be run on both $|state\ 1\rangle$ and $|state\ 2\rangle$ in equal numbers. Then $|state\ 1\rangle$ will produce some non-zero value of the observable, while $|state\ 2\rangle$ will produce the same value but with the opposite sign (or both states might produce more than one value if there are more momenta in the event than are involved in calculating the observable, but the states will still produce equal numbers of oppositely signed values). So a symmetric distribution of the parity-odd observable is again produced.

Thus asymmetries in parity-odd observables can be used to search for parity-violation at the LHC, since its initial state is its own mirror image so will produce a symmetric distribution in these observables. And since the Tevatron can be rotated into its own mirror image, here also these observables can be used.

2.4 Charge-conjugation and distinguishable particles

All that remains is to ensure that we choose the right particles to calculate the observables with. There will usually be several possible choices in each event, but since the observables will be calculated on an event-by-event basis, the particles must be chosen carefully to ensure that asymmetries do not cancel between events of different types.

Observables derived simply from the epsilon tensor, ie. of the form

$$\epsilon_{\mu\nu\rho\sigma}p_1^{\mu}p_2^{\nu}p_3^{\rho}p_4^{\sigma}$$

or a triple product

$$\boldsymbol{p}_1 \cdot (\boldsymbol{p}_2 \times \boldsymbol{p}_3)$$

are odd under the exchange of any two particles. For these observables, indistinguishable particles and charge-conjugation can cause problems if not treated properly. This is because if there are two indistinguishable particles in an event, and the momenta of both are used to calculate the observable, the observable will change sign depending on how you label the particles. Also, if there are two particles that can be transformed into each other by charge-conjugation, for example an e^+e^- pair, then if charge-conjugation is a symmetry of the underlying Lagrangian, the charge-conjugate process will produce an opposing effect in these observables.

This can be solved by using observables such as

$$((\boldsymbol{p}_1 \times \boldsymbol{p}_2) \cdot \hat{\boldsymbol{z}})((\boldsymbol{p}_1 - \boldsymbol{p}_2) \cdot \hat{\boldsymbol{z}}),$$

which are odd under parity but even under exchange of particles. If we take the $\hat{\boldsymbol{z}}$ vector to be along the beam axis at the LHC, we then only need to choose two particles in an event to construct this parity-odd observable. We can say $\hat{\boldsymbol{z}} = \boldsymbol{b} - \bar{\boldsymbol{b}}$, where $\boldsymbol{b}$ is the momentum direction of one of the beams and $\bar{\boldsymbol{b}}$ is the momentum direction of the other to ensure that the observable is even under $\boldsymbol{b} \rightarrow \bar{\boldsymbol{b}}$, as it should be because the LHC initial state is invariant under exchange of the beams.

Another possible parity-odd observable that is invariant under particle exchange is $\Delta\eta\Delta\phi$, where $\Delta\eta$ is the difference in pseudorapidity of the two particles and $\Delta\phi$ is the difference in their ϕ angle (that is, the angle perpendicular to the beam axis). This observable will be used in section 4 to investigate the parity-violating properties of the screw model.

3 Forward-backward asymmetries and charge asymmetries

Observables which are even under parity can never be used to *prove* that a process has violated parity. However, it is possible to use asymmetries in $\cos\theta$ to find parity violation in spin-one boson couplings in a quantum field theory.

A spin-one boson can have two possible types of term in its vertex factor: γ^{μ} (vector), and $\gamma^{\mu}\gamma^5$ (axial vector) [10]. Purely vector or purely axial vector couplings are parity-conserving because they couple to particles and anti-particles of both chiralities equally. Once you have a mixture of vector and axial vector couplings, the boson couples preferentially to left-handed particles and right-handed antiparticles (if c_V and c_A have opposite signs), or to right-handed particles and left-handed antiparticles (if c_V and c_A have the same sign). Under parity, momenta change direction but spins are left unchanged – so left-handed particles change to right-handed particles and vice versa. For a mixture of vector and axial vector couplings, therefore, the squared matrix element is not invariant under parity, so parity is violated. For a two-to-two s-channel process involving the exchange of a spin-1 boson, we will show that an asymmetry in $\cos\theta$ (as shown in figure 2) means that the boson must have parity-violating couplings.

An s-channel scattering event is shown in figure 3*(a)*, with momenta labelled. For a spin-one particle, the vertex factor must be generally of the form $\gamma^{\mu}(c_{V1} + c_{A1}\gamma^5)$ at one of the two vertices, and $\gamma^{\mu}(c_{V2} + c_{A2}\gamma^5)$ at the other [10]. When the matrix element is calculated, there are

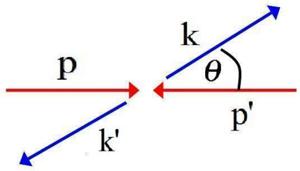
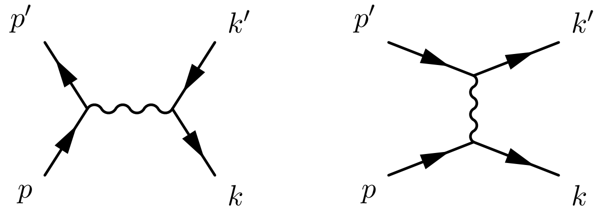


Figure 2: Diagram to show how $\cos\theta$ is defined in a scattering process.



(a) s-channel scattering process exchanging a spin one boson.

(b) t-channel scattering process exchanging a spin one boson.

Figure 3: Feynman diagrams for scattering processes exchanging a spin one boson (time goes left to right horizontally).

then two traces that must be multiplied together, one from each half of the diagram (and assuming that we are in the massless limit):

$$\text{Trace1} = 4a_1(p^\mu p'^\nu + p^\nu p'^\mu - g^{\mu\nu} p \cdot p') - 4ib_1\epsilon^{\alpha\mu\beta\nu} p'^\alpha p^\beta$$

$$\text{Trace2} = 4a_2(k^\mu k'^\nu + k^\nu k'^\mu - g^{\mu\nu} k \cdot k') - 4ib_1\epsilon^{\alpha\mu\beta\nu} k'^\alpha k^\beta$$

where $a_1 = c_{V1}^2 + c_{A1}^2$, $b_1 = 2c_{V1}c_{A1}$ and similar expressions for a_2 and b_2. When these traces are dotted together, this gives:

$$|M|^2 \propto (p' \cdot k)(p \cdot k')[a_1a_2 + b_1b_2] + (p' \cdot k')(p \cdot k)[a_1a_2 - b_1b_2]$$

With θ defined as in the diagram above, this can be written

$$|M|^2 \propto (1 + \cos\theta)^2[a_1a_2 + b_1b_2] + (1 - \cos\theta)^2[a_1a_2 - b_1b_2]$$

And $\frac{d\sigma}{d\Omega} \propto |M|^2$. For purely vector or purely axial-vector couplings at either vertex, there are only even powers of $\cos\theta$ in $|M|^2$ so the differential cross-section is symmetric in $\cos\theta$.

If there is some mixture of vector and axial-vector couplings, there will be odd powers of $\cos\theta$ as well as even powers in the differential cross-section, so the distribution will be asymmetric. The asymmetry will be greatest for maximal parity violation, when $c_V = \pm c_A$.

The situation is different for t-channel exchange, figure 3*(b)*. The squared matrix element for the t-channel exchange of a spin-1 boson can be written in the general form

$$|M|^2 \propto (1 + \cos\theta)^2[a_1a_2 + b_1b_2] + 2[a_1a_2 - b_1b_2]$$

(where θ is the same angle as in the s-channel case, as shown in figure 2 above). So even for purely parity-conserving couplings, the differential cross-section distribution is not symmetric in $\cos\theta$.

Asymmetries in $\cos\theta$ can thus be used to measure parity violation in the couplings of a spin-one boson, but only if you know that the process is going through the s-channel rather than the t-channel. On a resonance, particles are being produced mostly via the s-channel, and you can then use this $\cos\theta$ asymmetry to work out the amount of parity violation in the couplings of the resonant boson. For an e^+e^- collider such as LEP, a $\cos\theta$ asymmetry translates to a simple forward-backward asymmetry.

The actual asymmetry between the two terms in the s-channel squared matrix element, ie. the difference in the coefficients of the $(1 + cos\theta)$ and $(1 - cos\theta)$ terms divided by their sum, is

$$A = \frac{b_1 b_2}{a_1 a_2} = A_1 A_2$$

where

$$A_1 = \frac{2c_{V1}c_{A1}}{c_{V1}^2 + c_{A1}^2}$$

and similarly for A_2. Whereas the forward-backward asymmetry, defined as

$$A_{FB} = \frac{N(\eta_l > 0) - N(\eta_l < 0)}{N(\eta_l > 0) + N(\eta_l < 0)}$$

(where l is the produced lepton) works out as $A_{FB} = \frac{3}{4}A_1 A_2 = \frac{3}{4}A$ [11]. So the ratio of vector to axial-vector couplings can be deduced from the forward-backward asymmetry. This was the method used by the LEP experiments to calculate the couplings of the Z boson [12].

At the LHC, it isn't possible to use forward-backward asymmetry in this way because the two beams are identical, so there is no definite "forward" direction. However there is another observable that can be used to see these effects at the LHC - the asymmetry in $\Delta|y|$, the difference between the absolute rapidities of the pair of particles produced [13].

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

This is being used in the ATLAS experiment to investigate the $t\bar{t}$ asymmetry that the Tevatron experiments (which have distinguishable beams) use forward-backward asymmetries to measure.

For this observable, the forward direction is defined by the direction of the incoming quark in a quark-antiquark collision. In a proton there are three "valence" quarks, as well as a "sea" of quark-antiquark pairs. A valence quark will carry more of the momentum of the proton than a quark or antiquark from the sea. Hence quarks tend to have a higher proportion of the proton's momentum than antiquarks.The result of this is that the centre-of-mass frame tends to be boosted relative to the lab frame in the direction of the incoming quark. (This effect will be diluted by quark fusion events or events where the incoming quark is a sea quark.) So the forward direction can be defined, on average, as the direction of the boost of the final state particles.

So this method can be used at the LHC to find out whether a process producing a resonant spin-one boson is parity-violating. It is unlikely to be useful for discovering new physics, however, because in order to be sure that particles were being produced mostly in the s-channel, it would be necessary to look for resonances in invariant mass distributions. These resonances would already be an indication of new physics in themselves.

4 The screw model

4.1 Idea

A parity-violating model has been proposed [14] based on a screw. The model is that of a process that produces two particles - let's call them "spoons" - in such a way that the difference in ϕ between the two spoons is proportional to the difference in η between them. Thus the two spoons lie on a screwthread as shown in figure 4, and the amount that one spoon is "wound" around the thread compared to the other is proportional to their η difference.

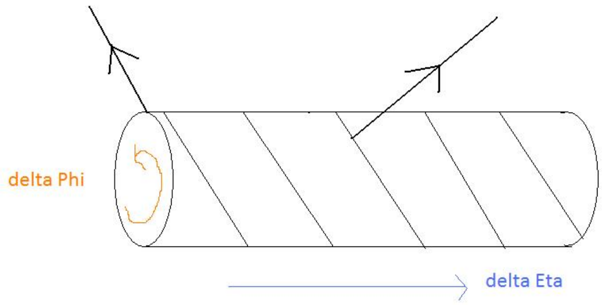


Figure 4: The screw model

At least one other particle must be produced in the event (call it a “fork”) to balance energy and momentum. The spoons and forks can be any particles - the important thing is that it is a parity-violating process; a right-handed screw is the mirror image of a left-handed screw, and they cannot be transformed into each other by any rotation. The screw model is not based on any quantum field theory, ie. there is no Lorentz-invariant Lagrangian to describe the interaction, so the model does not need to obey the CPT theorem. This means that the arguments given above in section 2.2, which show that a local Lorentz-invariant quantum field theory can only show an asymmetry in parity-odd observables at the LHC if there is CP violation in the theory, are not relevant here.

4.2 Event Generator

A Monte Carlo generator was written for the screw model, which produces two spoons and a fork with the required properties, and then uses the Les Houches Accord [15] to put the events through Pythia [16]. Pythia showers the particles and calculates what happens to the rest of the proton remnants in the events. Although the screw model places no restrictions on the species of the spoons and forks, Pythia needs to know what kind of particle it is being given so the spoons were chosen to be an electron-positron pair, and the fork a neutrino.

A Rivet [17] analysis was written to analyse the events once they had been through Pythia. Figure 5 shows that the screwthread can be seen clearly in the $\Delta\eta$-$\Delta\phi$ plane, where $\Delta\eta$ is the difference of the pseudo-rapidities of the two spoons, and $\Delta\phi$ is the difference in their ϕ angles. The generator allows the pitch of the screwthread to be chosen, so there can be more or fewer turns of the screw in a given η range.

The parity-odd observable $\Delta\eta\Delta\phi$ (see section 2.4) shows an asymmetry for the screw model, figure 6, and it is also seen that this observable is indeed odd under parity.

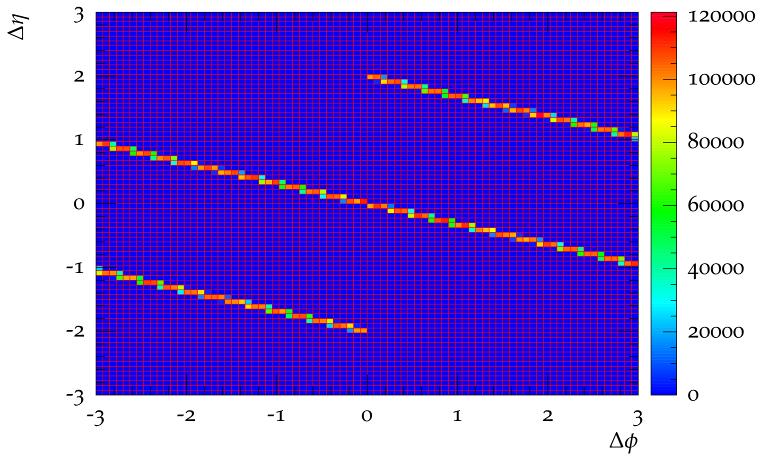
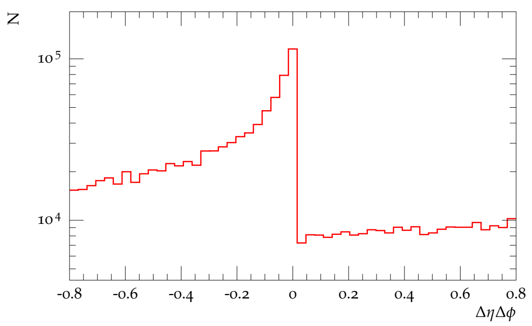
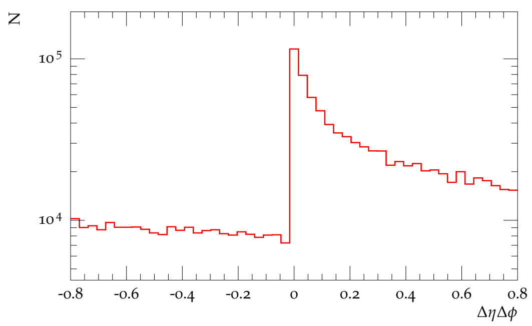


Figure 5: A 2D histogram of $\Delta\eta$ against $\Delta\phi$ of the two spoons for 1×10^5 screw model events. The frequencies shown in the key indicate number of events in the bin divided by the bin size.



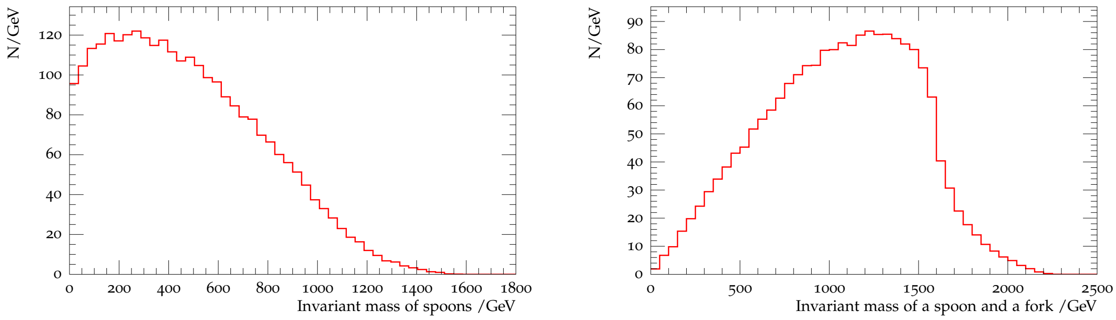
(a) Distribution of $\Delta\eta\Delta\phi$ of the spoons for the generated screw model events



(b) Distribution of $\Delta\eta\Delta\phi$ of the spoons for the generated screw model events after they have been acted on by parity

Figure 6: Distribution of $\Delta\eta\Delta\phi$ of the spoons in the screw model events and for the parity-mirrored screw model events (1×10^5 events). N on the vertical axis means number of events in each bin divided by bin size.

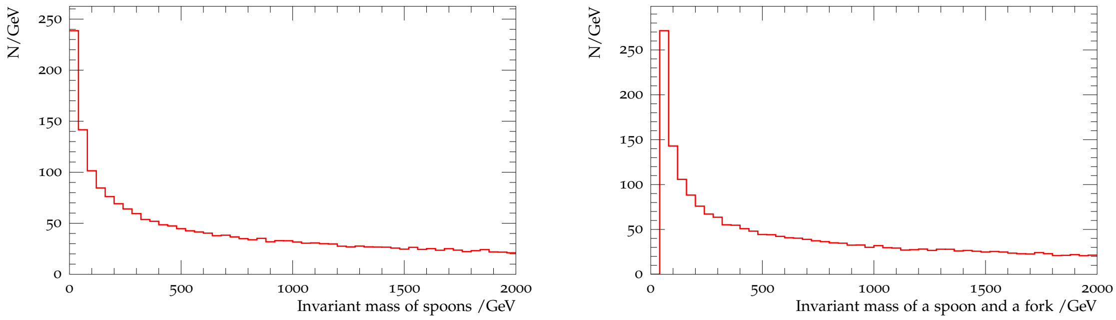
Generating the spoon momenta uniformly in η ($0 < \eta < 1$) and $\Delta\eta$ ($0 < \Delta\eta < 1$) and with energy in the range $0 - 800\,\mathrm{GeV}$ gives invariant mass distributions of the two spoons and of the fork and a spoon as shown in figure 7. There is a bump in both these distributions - so in this case a search for the screw model would not need to involve parity-odd observables at all since (depending on backgrounds and number of screw events), it could be detected in invariant mass distributions. So in the interests of creating a model which might realistically have gone undetected until now (given that invariant mass searches are common) - the invariant mass distributions need to be fixed in such a way that they appear background-like. As it turns out, there is easily enough freedom in the screw model to fix two independent invariant mass distributions (eg. that of the two spoons, and that of a spoon and the fork) to required shapes. This is because there are 6 degrees of freedom for the two spoons, and the screw model only constrains one of these by forcing $\Delta\eta$ to be proportional to $\Delta\phi$. Fixing two invariant mass distributions only involves constraining two additional degrees of freedom. This was done by solving simultaneous equations for the magnitudes of the momenta of the two spoons once the two invariant masses



(a) Invariant mass distribution of the two spoons

(b) Invariant mass distribution of the fork and a spoon

Figure 7: Invariant mass distributions in the screw model (with $1 \times 10^5 events$).



(a) Invariant mass distribution of the two spoons

(b) Invariant mass distribution of the fork and a spoon

Figure 8: Invariant mass distributions made to look background-like (1×10^5 events).

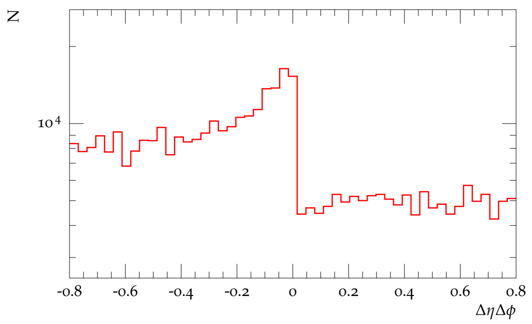
have been chosen from the specified cumulative distributions using a random number generator. Sometimes the two chosen masses produce no solutions for the momentum magnitudes for given positions on the screwthread. This can lead to distorted distributions because invariant masses which are more likely to give no solutions have fewer events. This problem is solved by picking the screw parameters (η, $\Delta\eta$, $\Delta\phi$) after the invariant masses have been chosen, and iterating over different randomly-chosen screw parameters until a solution is found. (If two invariant mass distributions are specified which contain points for which a solution can never be found, the event generator will print an error message and the distributions must be changed).

4.3 Hiding the screw model

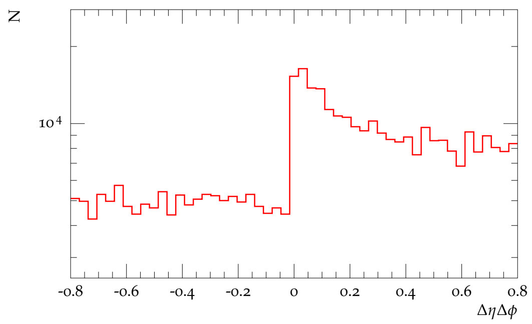
In figure 8 both the invariant mass distributions have been fixed simultaneously to go as $N \propto M^{-\frac{1}{2}} + c$ ($c = 0$ for the invariant mass of the spoons, and $c = 50$ for the invariant mass of the fork and a spoon).

After these constraints, there is still a large asymmetry in the observable $\Delta\eta\Delta\phi$ which can be seen in figure 9. Also, as figure 10 shows, the events all still lie on the screwthread although they are no longer spread uniformly along it. So if the (unknown) mechanism behind the screw model happened to produce these kind of invariant mass distributions, you might not be able to detect the screw model in the invariant mass distributions, and you would have to look at a parity-odd observable to get a clear indication that something new was going on.

In order to work out how large the cross-section of a version of the screw model needs to be before it can be detected in a parity-odd observable, a χ^2 test was done on events with an



(a) Distribution of $\Delta\eta\Delta\phi$ of the spoons for the generated screw model events



(b) Distribution of $\Delta\eta\Delta\phi$ of the spoons for the generated screw model events after they have been acted on by parity

Figure 9: Distribution of $\Delta\eta\Delta\phi$ of the spoons for the screw model events and for the parity-mirrored screw model events (1×10^5 events). N on vertical axes means number of events in a bin divided by bin size.

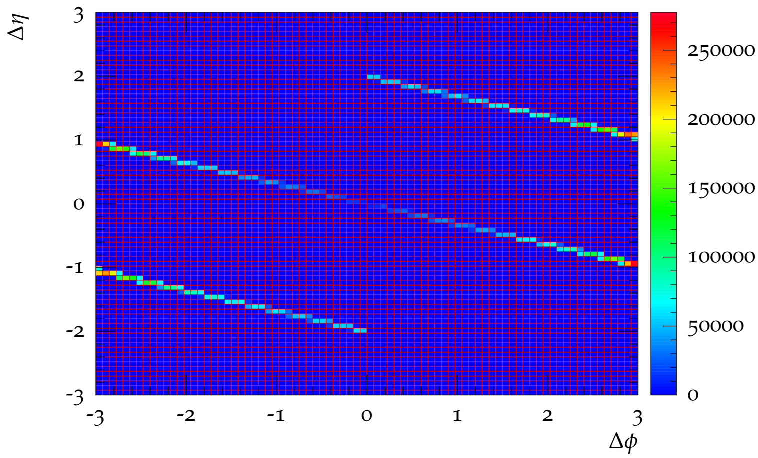
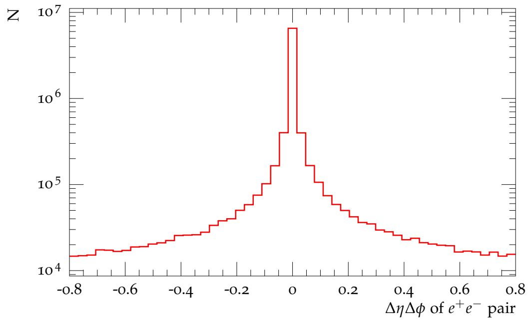
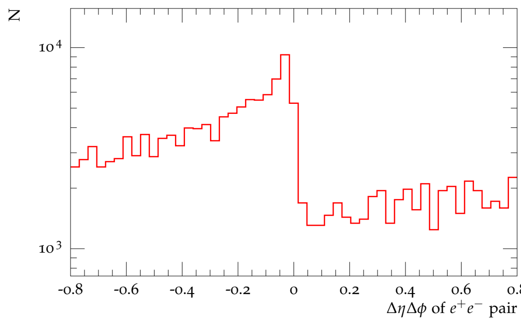


Figure 10: A 2D histogram of $\Delta\eta$ against $\Delta\phi$ for the spoons in the screw model events when the invariant mass distributions are being constrained to look background-like (1×10^5 events.

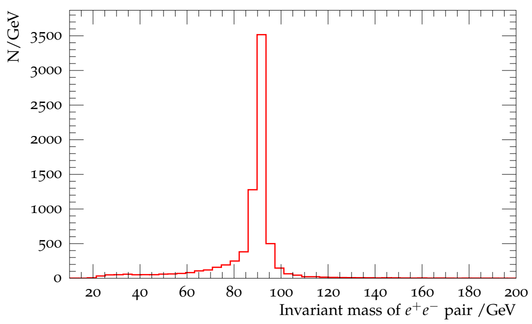


(a) $\Delta\eta\Delta\phi$ distribution for the Standard Model e^+e^- pairs (2.8813×10^4 events)

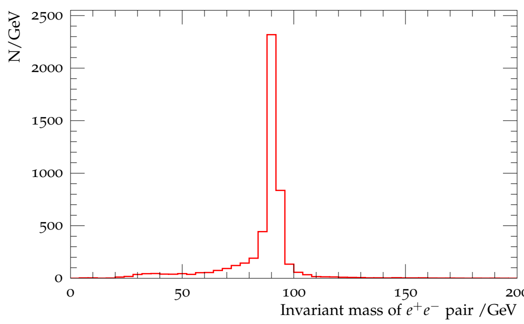


(b) $\Delta\eta\Delta\phi$ distribution for the screw model e^+e^- pairs (2×10^4 events)

Figure 11: Distribution of $\Delta\eta\Delta\phi$ of the e^+e^- pairs for the screw model events and for the Standard Model events. The frequencies shown in the key indicate number of events in the bin divided by the bin size.



(a) Invariant mass of the e^+e^-pair from the Pythia Z/γ events (2.8813×10^4 events)



(b) Invariant mass of the e^+e^- pair from the screw model events (2×10^4 events)

Figure 12: Invariant mass distributions from both the Standard Model events and the screw model events

e^+e^- pair in the final state. Standard Model events involving photons or Z bosons as intermediate states, with final state particles having $p_T > 30\,\text{GeV}$, were obtained from Pythia [18]. The γ/Z processes were chosen because they are the dominant processes for producing an e^+e^- pair in the Standard Model. The screw model generator was run with the spoons specified to be an e^+e^- pair and each having energy within the range $0\,\text{GeV}$ and $1000\,\text{GeV}$. Both generators assumed LHC beams with $14\,\text{TeV}$ centre-of-mass energy. Then the two sets of events were analysed with a Rivet [17] analysis - which took the highest energy electron and positron in the event as the spoons, and vetoed any events which did not include these two particles. However this analysis did not require the existence of a fork in the final state (ie. a neutrino in the current set-up) - a fork was not necessary since we only wanted to compare e^+e^- invariant mass distributions, and requiring one would have reduced the number of Standard Model events found.

The Pythia Standard Model events give e^+e^- pairs with an invariant mass distribution as shown in figure 12(a), which has a clear resonance peak at the Z mass. So the invariant mass of the e^+e^- pairs in the screw model events was constrained to fit the same distribution (figure 12(b)), meaning that this screw model should in theory never be able to be detected by looking at the invariant mass distribution, as long as the test is not done on absolute numbers, but on the shape of the distribution. That is, for example, if the χ^2 variable used for a χ^2 test is of the form

$$\chi^2 = \sum_{i=1}^{N} \frac{(O_i - \lambda E_i)^2}{\sigma_i^2}$$

where N is the number of degrees of freedom in the sample, O_i is the number of observed events in a bin, E_i is the number of events expected from the Standard Model alone, σ_i is the error in the Standard Model prediction, and λ is a (single) free parameter to be minimised. The λ parameter allows an excess of events over the Standard Model contribution to be undetectable as long as these events follow the same distribution as the Standard Model.

It can be seen in figure 11 that with these constraints on the invariant mass, the screw model still produces a large asymmetry in the $\Delta\eta\Delta\phi$ observable. The Standard Model events are approximately symmetric in this observable.

A χ^2 test on the parity-odd observable $\Delta\eta\Delta\phi$ showed that the screw model becomes detectable in the $\Delta\eta\Delta\phi$ observable at the 95% confidence level when there are 1200 screw model events (to the nearest hundred) to 1 million γ/Z events. Of these 1 million events, 2.8813×10^4 events contained e^+e^- pairs and were used in the test. The test was done with the distribution of the invariant mass of the spoons as shown in figure 12, and with χ^2 as defined above.

Pythia gives the cross-section of its simulated events as 3.207×10^{-5}mb for all the γ/Z processes together, meaning that the cross-section of the screw model events when they reach the point where they can be detected to a 95% confidence level is 3.848×10^{-8}mb. So the integrated luminosity needed to produce this number of screw model events is

$$\int \mathcal{L}\,\mathrm{d}t = \frac{N}{\sigma} = 3.12 \times 10^{-2} fb^{-1}.$$

Since the LHC experiments have so far taken several inverse femtobarns of data [19], it is likely that this particular implementation of the screw model would be able to be excluded with the current data by looking in $\Delta\eta\Delta\phi$ distributions.

5 Conclusions

As the LHC continues to gather more data, it becomes more and more important to think of new and model-independent methods of searching for new physics in the data, and especially to ensure that we are not missing anything by looking in the wrong observables. Parity-odd observables are a simple way to prove parity-violation in a process and are therefore a model-independent way to check for deviations from the Standard Model.

Parity-odd observables can be used at the LHC. The fact that the initial state of the LHC is a parity eigenstate allows asymmetries in parity-odd observables to be used as a signature of parity-violation. For Lorentz invariant quantum field theories, however, you will end up detecting CP violation instead of parity violation because Lorentz invariance ensures that only CP-violating matrix elements contain a parity-odd term.

Asymmetries in $\cos\theta$ cannot be used to prove parity violation since $\cos\theta$ is even under parity. However we have shown that for the s-channel exchange of any spin-one boson, asymmetries in $\cos\theta$ imply parity violation. This is unlikely to be useful as a search for new physics, however, since in order to know that most processes are going through the s-channel you would need to find a resonance peak in an invariant mass distribution, which would be enough to show that a new boson exists without the need to look for any excess parity violation.

The consequences of the parity-violating screw model have been investigated. It shows large asymmetries in distributions of a parity-odd observable, and has enough free parameters for the invariant mass distributions to be specified. Comparing the distibution of $\Delta\eta\Delta\phi$ in the screw model to that in a Standard Model process has shown that the screw model is likely to be easily detectable with this observable.

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