Search for a Z’ at an e^+e^- Collider

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Many theories predict that another neutral gauge boson (Z’) may exist. In order to detect this Z’, I would use an e^+e^- linear collider at 5 TeV. I would focus on measuring the Forward-Backward Asymmetry of $e^+e^- \rightarrow \mu^+\mu^-$. This should allow detection of any Z’ particles with M < 25 TeV. The LHC will be running sooner, but should only be able to see Z’s with M < 6 TeV, and if one is found, an e^+e^- collider will be vital to exploring this particle. Although many systematic errors and backgrounds will be present in the data, it should be possible to get a 1-2% measurement of the Z’ mass if it is less than 5 TeV, and a discovery if it is less than 25 TeV.

Significance:

Many proposed Grand Unified Theories (GUTs) propose the existence of extra neutral gauge bosons (Z'). In particular, for a gauge group G, there must exist n neutral gauge bosons where n = rank[G]. The smallest G that currently describes the standard model is SU(5) with n = 4. Since we already have 4 neutral gauge bosons, there cannot be a Z' in the SU(5) theory. However, the SU(5) theory does not correctly describe the running of coupling constants without the addition of something like supersymmetry [1]. A different way to solve this problem would be to choose a different gauge group.

The next interesting gauge group is SO(10) with n=5. This theory would require one Z' particle and one extra fermion with the quantum numbers of a right-handed neutrino [1]. Since some theories about the mixing and mass hierarchy of neutrinos include right-handed neutrinos, this theory has a good chance of being correct. Nearly any extension of the SU(5) standard model (such as supersymmetry) should also work for an SO(10) model, making the detection of the Z’ or the extra fermion the only definitive way to discriminate between the two. Other gauge groups larger than SO(10) would predict more Z's and more fermions.

The new neutral gauge boson will have to couple to some (possibly unknown) charge. In its simplest form, this interaction would be U(1). Since the carrier of this force should have the same quantum numbers as the B and W_0, It should mix with them. This mixing will lead to 3 particles: the γ, the Z, and the Z'. Since the nature of the interaction is unknown, there is no way to predict the couplings between the Z' and the standard model fermions. However, in analogy to the Z, it is likely that similar particles from different generations should have the same coupling.

Current limits on this type of Z' particle come from LEP2 and the Tevatron. CDF measured $M_{Z'}$>595 GeV using p p-bar collisions at $\sqrt{s}$ = 1.8 TeV [2], while OPAL measured $M_{Z'}$ >781 GeV using a e^+e^- collisions at $\sqrt{s}$ = 207 GeV [3].

Another proposed Z' would be an exact copy of the standard model Z'. This particle would arise if the standard model Z is a composite particle or if there are multiple generations of bosons. With this model for the Z', all of the coupling constants are predicted, so it would be easier to find this particle. Using these assumptions, CDF measured $M_{Z'}$>690 GeV [2], OPAL measured $M_{Z'}$>1018 GeV [3], and Cheung calculated that $M_{Z'}$>1500 GeV using a global electroweak analysis [4].

Method:

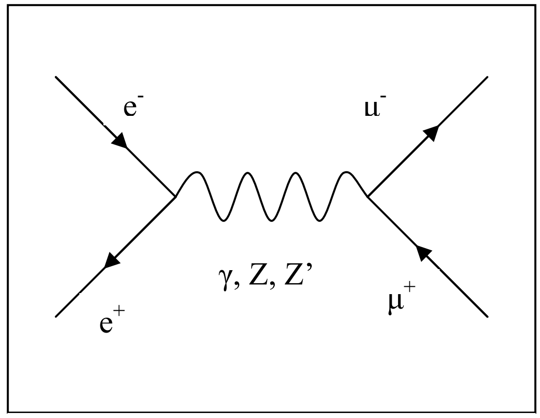

Fig. 1 The most important reaction for finding the Z' at an e^+e^- collider.

I would propose to look for look for a Z' at an e^+e^- linear collider. The reaction of interest would be $e^+e^- \rightarrow Z' \rightarrow f$ f-bar. In an electron collider, it would be easy to look for both muon pairs and jet pairs. However, the most accurate measurements will be done using muon pairs in the final state. This is because final-state electrons have contributions from other Feynman diagrams, while hadrons and taus all form jets, and are thus difficult to separate. Thus the best way to search for a Z' is to look at $e^+e^- \rightarrow \mu^+\mu^-$. When looking at this reaction, there are three major measurements that can be made as a function of center of mass energy: Cross-section, Forward-Backward Asymmetry, and Left-Right Asymmetry. Each of these measurements will be discussed in more detail later, but the main point is that each measurement will be compared with the Standard Model prediction for that measurement. Any significant deviations from the predictions (especially as a function of energy) would indicate the presence of a new particle.

The cross-section measurement is probably the easiest measurement to do. All that is required is that you measure the rate of $e^+e^- \rightarrow \mu^+\mu^-$ events over a range of energies (with good beam luminosity calibrations). It would be possible to do this measurement based solely on changing the incident beam energy, but if you can also reconstruct the invariant mass of the outgoing muons, you can make the measurement more accurate. This is because beam imperfections and beam-beam interactions like beamstrahlung create an energy spread in your "mono-energetic" beam of up to 5% of the beam energy [1]. By reconstructing the invariant mass of the event, you can try to correct for that spread.

The Z' signal in this measurement would be a Breit-Wigner resonance similar to the Z resonance found at LEP, although there may be interference with the Z that would distort the shape. Below the resonance, there should be a slight increase in cross-section due to virtual Z's. It could be possible to extract the Z' mass from that increase, although it would be much less definitive than a measurement of the Z' peak.

Other than Standard Model backgrounds, some of the major backgrounds would be errors in the standard model calculations, cosmic-ray muons, mis-reconstruced events, and backgrounds from new physics such as the Higgs. Errors in the standard model calculations could come from some of the approximations used to calculate the rates. Two of the worst approximations could be the leading-log approximation and the fact that you must use a Taylor expansion to renormalize the theory. These errors can be minimized by measuring the cross-section as a function of energy. Any errors should be slowly varying functions of energy, while the Z' resonance should be a sharp peak. Cosmic-ray muons can cause a background because 1 muon that flies close to the interaction region will look very similar to a $\mu^+\mu^-$ pair. High beam luminosities and cuts based on reconstructed position can minimize these background events. Mis-reconstruced events are always a problem, but cuts based on data quality should be able to reduce this source of error. The Higgs could be another source of error, but should not be a huge problem. First, measurements at the LHC should see the Higgs before it could be created at this collider, so it could be integrated into the Standard Model prediction. In addition, the Higgs should not couple to muons very strongly, so even that correction

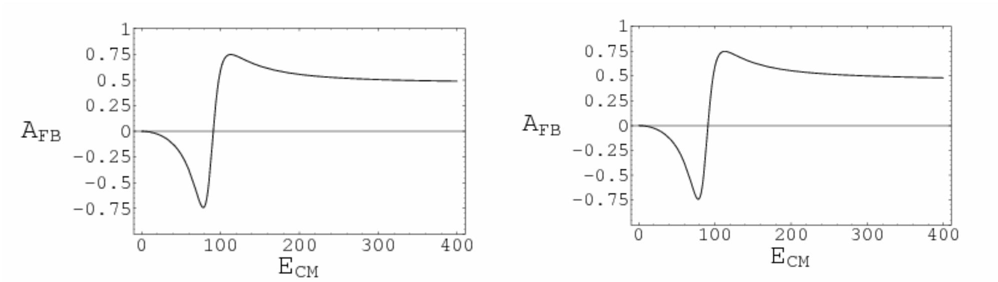

Fig 2. Forward Backward Asymmetry measurements near the Z-pole for:
(1) no Z'
(2) a Z' with M = 2TeV, Γ = 20 GeV, and G' = G_W / 1000

should be small. However, if a resonance is seen, you will need to verify that it is a Z' and not a Higgs by looking at the cross-section as a function of angle and by comparing the resonance with similar resonances in $e^+e^- \rightarrow$ heavy quarks.

The Forward-Backward Asymmetry is a slightly harder measurement to make, but it can be much more powerful that a cross-section measurement. This measurement requires that you tag the μ^+ and the μ^-, and know their direction relatively well. The measurement is to compare the rate of μ^+ going in the forward direction (F) $(0<\theta<\pi/2)$ to the rate of μ^+ going in the backward direction (B) $(\pi/2<\theta<\pi)$.

$$A_{FB} = (F-B) / (F+B)$$

This measurement relies on the fact that the photon, Z and Z' have different vector and axial-vector couplings. Because the Z and Z' have mass, their resonances produce a distinctive interference pattern in A_{FB}. In Figs. 2 and 3, I have plotted these resonance patterns for the standard model, and for the case when a Z' exists with M = 2TeV, Γ = 20 GeV, and G' = G_W / 1000, and couplings equal to those of the Z. In both cases, it was assumed that no Higgs appeared below 3TeV, and QED corrections were not included. The best thing about this measurement is that it is very sensitive to the Z'. While the cross-section measurement has to be within a few widths of the Z' mass, this measurement can detect a Z' at 1/3 to 1/5 of the Z' mass. Unfortunately, this can only measure a ratio of coupling to mass until the Z' mass is reached. Before then, a light Z' with

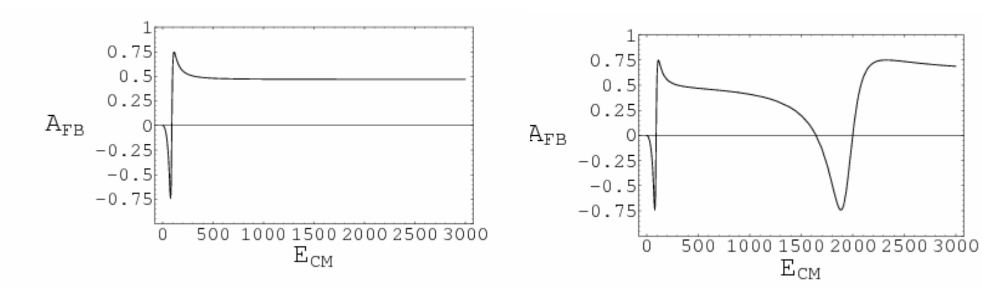

Fig 3. Forward Backward Asymmetry measurements near the Z'-pole for:
(1) no Z'
(2) a Z' with M = 2TeV, Γ = 20 GeV, and G' = G_W / 1000

relatively weak interaction strength looks the same as a heavy Z' with a relatively strong interaction. The asymmetry measurement is also much less dependent on the strength of the Z' interaction than the cross-section measurement.

For this measurement, the same problems with uncertainty in beam energy apply, although some of the backgrounds and systematic uncertainties become much smaller. For example, cosmic-ray muons should have no forward-backward asymmetry, so their presence would decrease the magnitude of the measured asymmetry, but would not change the shape. In addition, any errors in calculating the beam luminosity should also cancel out. However, new systematic uncertainties also enter this calculation. If the detector has different acceptances in the forward and backward directions, this asymmetry will be meaningless. Thus the detector must be designed to be the same in the forward and backward directions, and should be able to rotate 180° in order to calibrate out any detector asymmetries. Another problem comes if the particles consistently end up boosted in one direction. Although the e^+e^- beams should nominally be the same energy, beam effects may end up changing the center-of-mass rest frame. One good way to check this is to reconstruct the muons so that you can check for any boots, and possibly correct for this boost on every event. Problems with errors in theory, mis-reconstructed events, and non-Standard Model backgrounds are very similar to those in the cross-section measurement.

The Left-Right Asymmetry is the most complicated of the three measurements. It involves polarizing the electron beam (and also the positron beam for the 4 double-asymmetry measurements). You would then measure the cross-section (possibly as a function of angle) to get the cross-section for left-handed electrons (L) and right-handed electrons (R) (both are helicity measurements).

$$A_{RL} = (R-L) / (R+L)$$

This measurement again relies on the different vector and axial-vector couplings of photon and the Zs to create interference patterns.

This measurement has similar strengths to the Forward-Backward Asymmetry, but different weaknesses. Some of the main systematic uncertainties are how well the beams are polarized, and how the acceptance of the detector might interact with the different angular distributions of the right- and left-handed cross-sections. All of these systematic uncertainties can be overcome, but they require a bit more thought than those of the cross-section measurement and the Forward-Backward Asymmetry.

LHC Competition:

Since the LHC will be ready before this proposed e^+e^- collider, we need to consider what it will be able to do. Since the LHC collides hadrons, there will be a lot of background jets. Thus the best way to observe Z' events at the LHC is to look for $Z' \rightarrow \mu^+\mu^-$. There are 2 main ways to produce a Z' at the LHC: direct production, and indirect production. In direct production, a u u-bar or d d-bar pair annihilates into a Z'. The problem with this method is that the u-bar or d-bar quarks in the proton do not carry much of its momentum. Thus most reactions of this type will be boosted along the beam direction. These events will be hard to measure accurately because it is harder to place instruments near the beam and the background rate close to the beam direction will be very high. In indirect production, the main reaction is mediated by another force, and then a Z' is emitted along the way. It should be possible to measure the Z' mass from this, but there are problems with separating the Z' from the rest of the event and with the low event rate (must be a 3rd order or higher diagram). Also, these events will only let you measure the cross-section of events involving the Z', and only if the event energy is higher than the Z' mass. Since the proton is a composite particle, events at a hadron collider only have a fraction of their beam energy available for each interaction. Thus although the LHC should get up to E_{CM} = 14 TeV, it will probably only be able to find a Z' with a mass less than 6 TeV. In addition, the LHC machines have to rely on their momentum reconstruction in order to find the Z' mass. At CMS, they have a momentum resolution of $\Delta P_T/P_T = (4.5 \sqrt{P_T}\,(\text{TeV}))\%$, giving them a resolution of ~8% for 3TeV muons [5]. This is probably good enough to observe a Z' peak, but not measure its width accurately. In the end, the LHC will probably find the Z' if it is there, but will not be able to measure many of its properties. Then we would need an e^+e^- collider to measure them precisely. Also, because of the resolving power of the Asymmetries and the wasted energy in a hadron collider, an e^+e^- collider with E_{CM} = 1.5 TeV could still get a higher limit on the Z' mass.

Design Considerations:

The first design element of an e^+e^- collider must be its beam energy. Current designs for an International Linear Collider call for a 1.5TeV e^+e^- beam. Since this project would have unlimited funding, the beam energy could probably be boosted to 5 TeV without too much trouble. This should allow detection of any Z' with M < 25 TeV. The beams would have symmetric energies so that the muons would not be boosted. In addition, the beams would have polarization systems that would allow polarizations of probably 60% for electrons and 40% for positrons. These polarization systems would be turned off for the initial cross-section and A_{FB} measurements, but could be used later.

Once the beam is in place, we will need a detector. In order to do the muon measurement, we will need a tracking system with a magnet, followed by a veto system for photons, electrons, and jets, followed in the end by a muon tracking system. Although this is the minimal detector system, adding better Electromagnetic and Hardonic Calorimeters and a vertex tracker would be a small increase in cost, and would add enormously to the physics potential of the collider. For instance, if a Z' was using muons, it would then be possible to measure the coupling constants for all of the quarks and the charged leptons. This measurement is essentially impossible at a hadronic collider, and would increase our knowledge of the newfound Z' immensely. However, this would be impossible at a detector optimized just for muons.

With this in mind, I would propose the

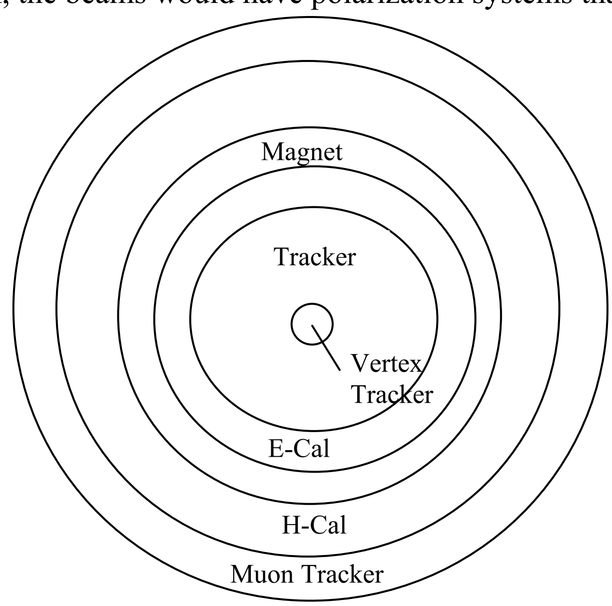

Fig 4. Detector sizes:

Vertex Tracker	5cm < r <10 cm
Tracker	20 cm < r < 2.5 m
E-Cal	2.5 m < r < 3 m
Magnet	3 m < r < 3.5 m
H- Cal	3.5 m < r < 5.5 m
Muon Tracker	5.5 m < r < 6 m

following standard beamline detector:

Vertex Tracker: ~ 5 layers of silicon pixel detectors close to the beamline. The vertex trackers are meant to find any vertices that are displaced from the beamline, thus showing that b-meson or τ decayed. The pixels ensure that the channel occupancy stays low even during messy jet events.

Tracker: This is the heart of the muon reconstruction system. I would propose ~15 layers of silicon strip detectors arrayed over a 2.5 m radius. This would be the same number of silicon layers as in the CMS detector, arrayed over 2.5 times more distance. Since momentum resolution is based on reconstructing the curvature of the track, the resolution goes as [6]:

$$\Delta P_T/P_T \ \alpha \ P_T \ \Delta x /(r^2 B)$$

where P_T is the transverse momentum, Δx is the spatial resolution of the detectors, r is the detecting radius, and B is the magnetic field. Since CMS has a resolution of 8% at 3 TeV, this detector should have a resolution of 1.2% at 3 TeV. This should give allow for detailed measurements of the Z' properties.

One possible problem with a silicon tracker is that particles may multiple-scatter off of the silicon. However, the silicon trackers are now made to be very thin, and can have thicknesses of .01 to .015 radiation lengths. With 20 layers of silicon, that comes to less than .3 radiation lengths. Since the particles have high momentum, and $\theta \ \alpha \ \sqrt{(x/x_0)} / P$, the muons should have very small multiple-scattering angles [6]. That said, the curvature measurement is also very small, so this could be a problem. However, CMS uses the same number of silicon layers and is not limited by multiple-scattering at high energies. This might be a larger problem at lower energies, but lower energy particles can be measured well with just a few layers of silicon, before they have a chance to scatter very much.

E-Cal: I would use a standard Lead-Glass or Lead-Tungstate electromagnetic calorimeter. In order to get ~25 radiation lengths, this would require at least 25 cm for Lead-Tungstate, and probably closer to 50 cm for Lead-Glass. These detectors should be able to measure electron and photon energies to within a few percent.

Magnet: I would propose a 3 m radius superconducting solenoid for the magnet. With such a magnet, it is possible to get 4 Tesla magnetic fields. This is very similar to the CMS magnet, and thus should be easy to produce. There will probably have to be an iron yoke at a larger radius to return the magnetic field, but I am not sure how much iron is needed, or exactly where it should go.

H-Cal: I would use a standard sampling hadronic calorimeter such as an iron-scintillator sandwich. Again, in order to achieve ~25 radiation lengths, this section would need to be a couple of meters thick. Since this is placed outside of the magnets, it can be whatever size it needs to be without interfering with anything else. Because it is placed outside of the magnets, there will be some degradation of the signal due to multiple scattering and energy loss. However, the jets are less important than the muons, and there will be some measurements of momentum and energy loss from the tracker and E-Cal. Thus although this system might only have ~5% resolution, that should be good enough.

Muon System: I would use an ATLAS-style drift tube system to tag and track the muons as they leave the detector. Because the muons will have traveled though the H-Cal and probably an iron yoke, they will have had many opportunities to multiple-scatter, thus making this point much less useful for calculating the momentum of the muons. However, this system does allow muons to be tagged, and then tracked back through the H-Cal and E-Cal to the Tracker, where their momentum can be measured well.

Conclusions:

Overall, an e+e- collider is the best way to look for Z' particles. The Forward-Backward Asymmetry measurement allows detection of a Z' that weighs more than 3 times the beam energy. If the Z' mass is actually reached, this detector will allow measurement of couplings to many of the standard model particles. The main systematics of this experiment are the energy resolution of the beam and tracking system, the detector acceptance uniformity for the Forward-Backward Asymmetry. The main backgrounds are cosmic-ray muons, theoretical errors, mis-reconstructed events, and non-Standard Model processes. All of these systematics and backgrounds are small enough that this experiment should be able to detect a Z' and measure its parameters very effectively.

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