Slepton Discovery and Measurement with a Z'

Work done with Can Kılıç, Thomas Hartman, and Lian-Tao Wang

Matthew Baumgart

Harvard University Department of Physics

Why a Z'?

Why a Z'?

- The idea for a Z' study arose after the second LHC olympics when we noticed that in a GMSB scenario, we were able to use the Z' to find the sleptons in the Harvard blackbox. This got us thinking about what all a Z' might be good for...

Why a Z'?

- The idea for a Z' study arose after the second LHC olympics when we noticed that in a GMSB scenario, we were able to use the Z' to find the sleptons in the Harvard blackbox. This got us thinking about what all a Z' might be good for...
- Why not a Z'? We have no $a\ priori$ reason for assuming that SUSY is implemented in the simplest possible way. Furthermore, extra $U(1)$ gauge groups abound in UV models such as GUTs and strings. We will focus most of our attention on $U(1)_{B-L}$. Gauging this group provides an explanation for the unique non-anomalous, accidental symmetry of the SM.

Why a Z'?

- The idea for a Z' study arose after the second LHC olympics when we noticed that in a GMSB scenario, we were able to use the Z' to find the sleptons in the Harvard blackbox. This got us thinking about what all a Z' might be good for...
- Why not a Z'? We have no $a\ priori$ reason for assuming that SUSY is implemented in the simplest possible way. Furthermore, extra $U(1)$ gauge groups abound in UV models such as GUTs and strings. We will focus most of our attention on $U(1)_{B-L}$. Gauging this group provides an explanation for the unique non-anomalous, accidental symmetry of the SM.
- As we try to develop more model independent methods for analyzing data, we should consider the effects of nonstandard scenarios. Studying a wider class of theories will give us a broader set of tools for looking at all models.

Why a Z'?

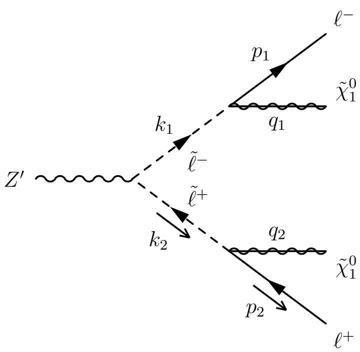
- The idea for a Z' study arose after the second LHC olympics when we noticed that in a GMSB scenario, we were able to use the Z' to find the sleptons in the Harvard blackbox. This got us thinking about what all a Z' might be good for...
- Why not a Z'? We have no $a\ priori$ reason for assuming that SUSY is implemented in the simplest possible way. Furthermore, extra $U(1)$ gauge groups abound in UV models such as GUTs and strings. We will focus most of our attention on $U(1)_{B-L}$. Gauging this group provides an explanation for the unique non-anomalous, accidental symmetry of the SM.
- As we try to develop more model independent methods for analyzing data, we should consider the effects of nonstandard scenarios. Studying a wider class of theories will give us a broader set of tools for looking at all models.
- Our experience with the Z' demonstrates this second point. To make measurements in this scenario, we developed a new technique that should apply to a generic set of decays with two invisible particles.

How is a Z' different?

How is a Z' different?

- Finding sleptons in an MSSM scenario depends on the vagaries of the spectrum. While one can arrange a cascade through sleptons (SPS1a), we cannot assume such points to be generic. Our best chance may thus lie with direct production.

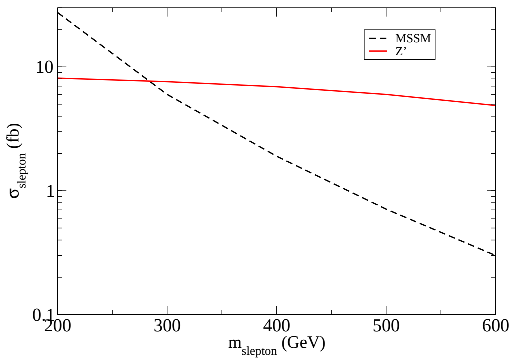
How is a Z' different?



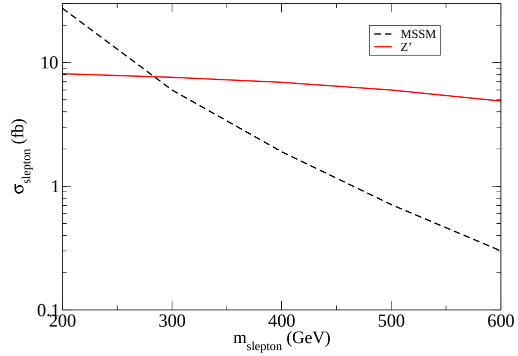
- Finding sleptons in an MSSM scenario depends on the vagaries of the spectrum. While one can arrange a cascade through sleptons (SPS1a), we cannot assume such points to be generic. Our best chance may thus lie with direct production.
- For both discovery and measurement, we consider the process $Z' \to \tilde{\ell}\tilde{\ell} \to \ell^+\ell^- + 2\ \mathrm{LSPs}$. We will consider the discovery reach as a function of $m_{Z'}$ and g_{B-L}, as well as several different candidates for LSP: bino, wino, and higgsino. Our benchmark point for measurement is $m_{Z'}$ = 2 TeV, g_{B-L} = 0.25, $m_{\tilde{\ell}}$ = 400 GeV, and m_{χ_1} = 100 GeV with bino LSP.

Discovery

Improvements over the MSSM

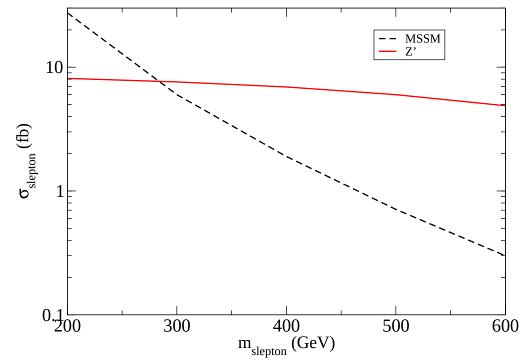


Improvements over the MSSM



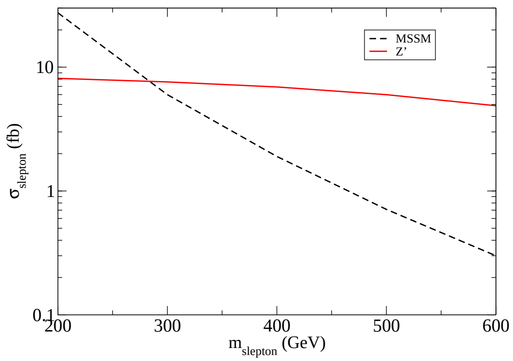
- For $m_{\tilde{\ell}>300}$ GeV, the Z' scenario has an increased cross section over the MSSM. It remains nearly constant up to $m_{Z'}/2$, while the MSSM falls as 1/s, and thus $m_{\tilde{\ell}}$. Our benchmark scenario has $m_{Z'}$ = 2 TeV and g_{B-L} = 0.25.

Improvements over the MSSM



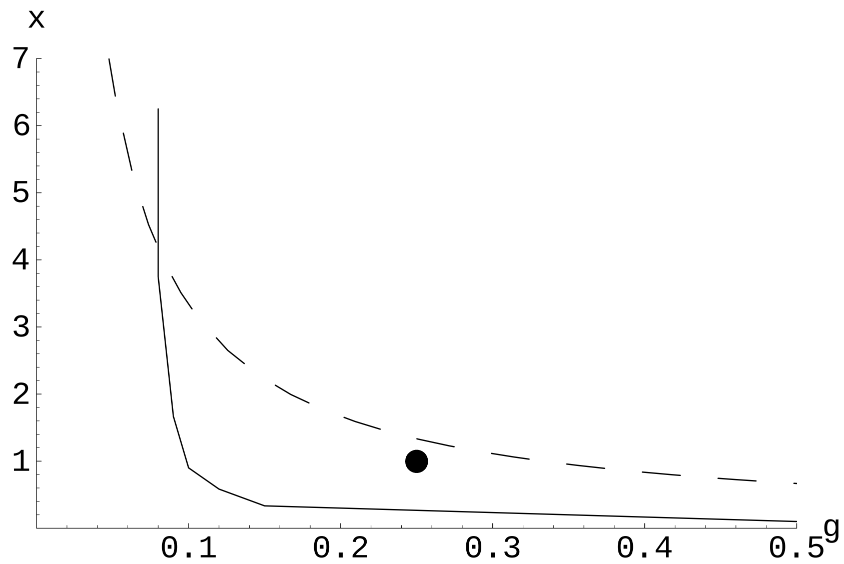
- For $m_{\tilde{\ell}>300}$ GeV, the Z' scenario has an increased cross section over the MSSM. It remains nearly constant up to $m_{Z'}/2$, while the MSSM falls as 1/s, and thus $m_{\tilde{\ell}}$. Our benchmark scenario has $m_{Z'}$ = 2 TeV and g_{B-L} = 0.25.
- We show the cross section for one flavor of charged slepton pair production as a function of slepton mass for Z' (red) and Z^*/γ^* (black) production modes.

Improvements over the MSSM



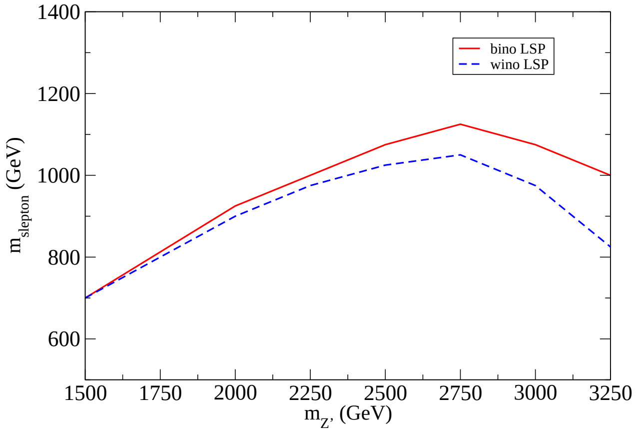
- For $m_{\tilde{\ell}>300}$ GeV, the Z' scenario has an increased cross section over the MSSM. It remains nearly constant up to $m_{Z'}/2$, while the MSSM falls as 1/s, and thus $m_{\tilde{\ell}}$. Our benchmark scenario has $m_{Z'}$ = 2 TeV and g_{B-L} = 0.25.
- We show the cross section for one flavor of charged slepton pair production as a function of slepton mass for Z' (red) and Z^*/γ^* (black) production modes.
- In this section we want to quantify the 5σ discovery reach at $100\ \mathrm{fb}^{-1}$ for sleptons as a function of $m_{Z'}$ and g_{B-xL}. We will also discuss how slepton signatures help us to identify the identity of the LSP.

Reach: Couplings

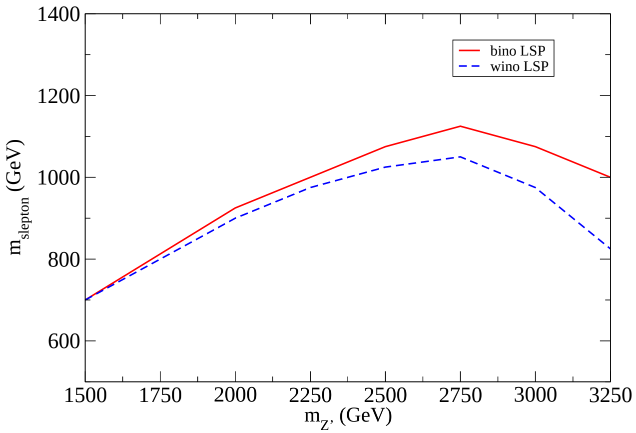


We can determine how the discovery reach changes with coupling for a general $U(1)_{B-xL}$ gauge group. Tevatron and LEP bounds force the constraint, $\frac{m_{Z'}}{g} \gtrsim x(6\ \mathrm{TeV})$. The sleptons are given $m_{\tilde{\ell}=400\ \mathrm{GeV}}$ and $m_{Z'} = 2\ \mathrm{TeV}$. Above and to the right of the dashed curve is excluded, while the upper right of the dashed curve is the 5σ disovery region at $100\ \mathrm{fb}^{-1}$. The benchmark scenario is indicated with a black dot. Increasing $m_{Z'}$ moves both curves to the upper right.

Reach: Masses

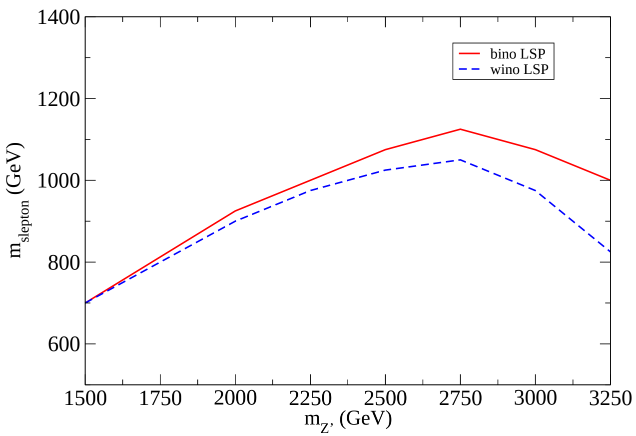


Reach: Masses



- In the MSSM, discovery bounds for the sleptons are $m_{\tilde{\ell} \leq 300}$ GeV for bino LSP and $m_{\tilde{\ell} \leq 175}$ GeV for wino. The Z' allows us to discover sleptons in a much larger range of slepton masses. Above, we show the discovery threshhold as a function of $m_{Z'}$ for bino (red) and wino (blue) LSP.

Reach: Masses



- In the MSSM, discovery bounds for the sleptons are $m_{\tilde{\ell} \leq 300}$ GeV for bino LSP and $m_{\tilde{\ell} \leq 175}$ GeV for wino. The Z' allows us to discover sleptons in a much larger range of slepton masses. Above, we show the discovery threshhold as a function of $m_{Z'}$ for bino (red) and wino (blue) LSP.
- The discovery analysis did include SM backgrounds (diboson and W + fake e). These were easily removed with appropriate lepton, $\not{E}_T$, and jet cuts. Measurements were thus done with signal only.

LSP Identity

LSP Identity

- Since leptons carry charge and flavor information, their presence in a SUSY scenario offers one of the best chances for determining the LSP identity. In the following scenarios, we consider the decay chain $Z' \to \tilde{\ell}\tilde{\ell} \to \ell^+\ell^- + 2\ \mathrm{LSPs}$.

LSP Identity

- Since leptons carry charge and flavor information, their presence in a SUSY scenario offers one of the best chances for determining the LSP identity. In the following scenarios, we consider the decay chain $Z' \to \tilde{\ell}\tilde{\ell} \to \ell^+\ell^- + 2\ \mathrm{LSPs}$.
- A charged slepton will always decay to bino LSP through a charge lepton, and single lepton events can only result from mismeasurement. In the wino LSP scenario, however, the nearly degenerate chargino allow for decay through a neutrino.

LSP Identity

- Since leptons carry charge and flavor information, their presence in a SUSY scenario offers one of the best chances for determining the LSP identity. In the following scenarios, we consider the decay chain $Z' \to \tilde{\ell}\tilde{\ell} \to \ell^+\ell^- + 2\ \mathrm{LSPs}$.
- A charged slepton will always decay to bino LSP through a charge lepton, and single lepton events can only result from mismeasurement. In the wino LSP scenario, however, the nearly degenerate chargino allow for decay through a neutrino.
- By comparing the ratios of dilepton to single lepton events we get a handle on the bino/wino component of the LSP. We find the ratio for higgsino LSP to lie somewhere in the middle.

	$R_{(\ell^+\ell^-)/(1\ell)}$
bino LSP	>100
wino LSP	1.4± 0.2
higgsino LSP	3.3± 0.6

Measurement

Introduction to the Minmax Approach

Introduction to the Minmax Approach

- In the hadronic collider environment with multiple sources of $\not{E}_T$, we lose information in every event that cannot be recovered. This forces us to work in terms of transverse variables.

Introduction to the Minmax Approach

- In the hadronic collider environment with multiple sources of $\not{E}_T$, we lose information in every event that cannot be recovered. This forces us to work in terms of transverse variables.
- Transverse variables cannot give us a measurement with a single event. However, for a generic decay scenario, one can construct an observable out of transverse quantities that is bounded above or below by the true values of the unknown variables. If one can populate a histogram with hundreds to thousands of such events, the endpoint of the distribution will give a measurement of the underlying quantity.

Introduction to the Minmax Approach

- In the hadronic collider environment with multiple sources of $\not\!\!E_T$, we lose information in every event that cannot be recovered. This forces us to work in terms of transverse variables.
- Transverse variables cannot give us a measurement with a single event. However, for a generic decay scenario, one can construct an observable out of transverse quantities that is bounded above or below by the true values of the unknown variables. If one can populate a histogram with hundreds to thousands of such events, the endpoint of the distribution will give a measurement of the underlying quantity.
- In multi-step decays with several unknown masses, one can use the output of one such minmax variable as the input to the next. In this way, complicated processes can be reduced to a very small number of free parameters.

Introduction to the Minmax Approach

- In the hadronic collider environment with multiple sources of $\not{E}_T$, we lose information in every event that cannot be recovered. This forces us to work in terms of transverse variables.
- Transverse variables cannot give us a measurement with a single event. However, for a generic decay scenario, one can construct an observable out of transverse quantities that is bounded above or below by the true values of the unknown variables. If one can populate a histogram with hundreds to thousands of such events, the endpoint of the distribution will give a measurement of the underlying quantity.
- In multi-step decays with several unknown masses, one can use the output of one such minmax variable as the input to the next. In this way, complicated processes can be reduced to a very small number of free parameters.
- For our benchmark scenario, we can easily measure $m_{Z'}$ through its leptonic decay, $Z' \to \ell^+ \ell^-$. Given the decay $Z' \to \tilde{\ell}^- \; \tilde{\ell}^+ \to \ell^- \; \ell^+ \; \chi_1^0 \; \chi_1^0$, a value for $m_{Z'}$, and two separate minmax variables, we can measure $m_{\tilde{\ell}}$ and m_{χ_1} to within 15 GeV.

m_{T2}: Theory

m_{T2}: Theory

- The classic example of a minmax variable is m_{T2}, developed by Lester et al. If we knew the missing p_T of the individual χ^0s and m_{χ^0} then we could calculate

$$m_T^2(\mathbf{p}_T^\ell, \mathbf{p}_T^{\chi^0}; m_{\chi 0}) \equiv m_{\chi^0}^2 + m_\ell^2 + 2(E_T^{\chi^0} E_T^\ell - \mathbf{p}_T^{\chi^0} \cdot \mathbf{p}_T^\ell)$$

for each branch and we would have

$$m_{\tilde{\ell}}^2 > \mathrm{Max}(\mathrm{m_T^2}(\mathbf{p}_\mathrm{T}^{\ell_1}, \mathbf{p}_\mathrm{T}^{\chi_1^0}; \mathrm{m}_{\chi 0}), \mathrm{m_T^2}(\mathbf{p}_\mathrm{T}^{\mathrm{l}_2}, \mathbf{p}_\mathrm{T}^{\chi_2^0}; \mathrm{m}_{\chi 0})).$$

m_{T2}: Theory

- The classic example of a minmax variable is m_{T2}, developed by Lester et al. If we knew the missing p_T of the individual χ^0s and m_{χ^0} then we could calculate

$$m_T^2(\mathbf{p}_T^{\ell}, \mathbf{p}_T^{\chi^0}; m_{\chi 0}) \equiv m_{\chi^0}^2 + m_\ell^2 + 2(E_T^{\chi^0} E_T^{\ell} - \mathbf{p}_T^{\chi^0} \cdot \mathbf{p}_T^{\ell})$$

for each branch and we would have

$$m_{\tilde{\ell}}^2 > \mathrm{Max}(\mathrm{m_T^2}(\mathbf{p}_\mathrm{T}^{\ell_1}, \mathbf{p}_\mathrm{T}^{\chi_1^0}; \mathrm{m}_{\chi 0}), \mathrm{m_T^2}(\mathbf{p}_\mathrm{T}^{\mathrm{l}_2}, \mathbf{p}_\mathrm{T}^{\chi_2^0}; \mathrm{m}_{\chi 0})).$$

- However, since we only know the total $\mathbf{p}_T$ the best we can do is to scan all possible values

$$m_{\tilde{\ell}}^2 > \mathrm{Min}_{\not{p}_\mathrm{T}^1 + \not{p}_\mathrm{T}^2 = \not{p}_\mathrm{T}}(\mathrm{Max}(\cdots)).$$

m_{T2}: Results

m_{T2}: Results

- Unfortunately, we usually do not know m_{χ^0}, and m_{T2} is defined as

$$m_{T2}^2(M) \equiv \mathrm{Min}_{\not{p}_{\mathrm{T}}^1+\not{p}_{\mathrm{T}}^2=\not{p}_{\mathrm{T}}}(\mathrm{Max}(\mathrm{m}_{\mathrm{T}}^2(\mathbf{p}_{\mathrm{T}}^{\ell_1},\mathbf{p}_{\mathrm{T}}^{\chi_1^0};\mathrm{M}),\mathrm{m}_{\mathrm{T}}^2(\mathbf{p}_{\mathrm{T}}^{\ell_2},\mathbf{p}_{\mathrm{T}}^{\chi_2^0};\mathrm{M}))).$$

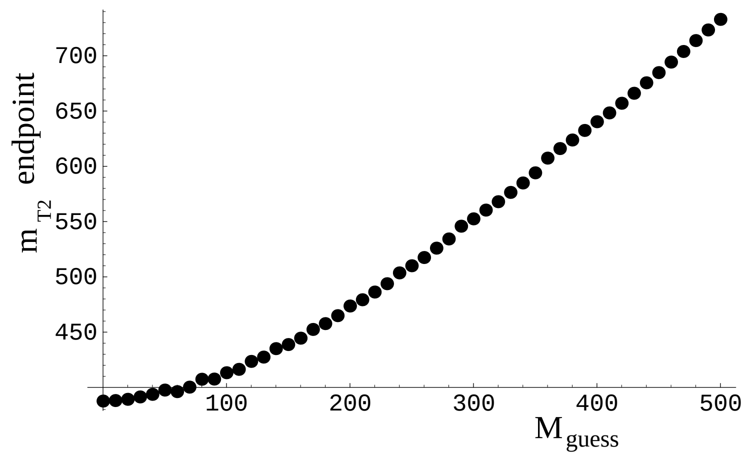
m_{T2}: Results

- Unfortunately, we usually do not know m_{χ^0}, and m_{T2} is defined as

$$m_{T2}^2(M) \equiv \mathrm{Min}_{\not{p}_T^1 + \not{p}_T^2 = \not{p}_T}(\mathrm{Max}(\mathrm{m}_\mathrm{T}^2(\mathbf{p}_\mathrm{T}^{\ell_1}, \mathbf{p}_\mathrm{T}^{\chi_1^0}; \mathrm{M}), \mathrm{m}_\mathrm{T}^2(\mathbf{p}_\mathrm{T}^{\ell_2}, \mathbf{p}_\mathrm{T}^{\chi_2^0}; \mathrm{M}))).$$

- It is not obvious however, how the extrapolated $m_{\tilde{\ell}}$ will depend on M.

m_{T2}: Results



- Unfortunately, we usually do not know m_{χ^0}, and m_{T2} is defined as

$$m_{T2}^2(M) \equiv \mathrm{Min}_{\not{p}_\mathrm{T}^1+\not{p}_\mathrm{T}^2=\not{p}_\mathrm{T}}(\mathrm{Max}(\mathrm{m}_\mathrm{T}^2(\mathbf{p}_\mathrm{T}^{\ell_1},\mathbf{p}_\mathrm{T}^{\chi_1^0};\mathrm{M}),\mathrm{m}_\mathrm{T}^2(\mathbf{p}_\mathrm{T}^{\ell_2},\mathbf{p}_\mathrm{T}^{\chi_2^0};\mathrm{M}))).$$

- It is not obvious however, how the extrapolated $m_{\tilde{\ell}}$ will depend on M.
- We plot $m_{\tilde{\ell}}$ vs. M; $m_{\tilde{\ell}}$ was obtained from the m_{T2} endpoint, with $m_{Z'} = 2\ \mathrm{TeV}$, $m_{\tilde{\ell}}^{true} = 400\ \mathrm{GeV}$ and $m_{\chi_1} = 100\ \mathrm{GeV}$ in the bino LSP scenario.

Can we do better?

Can we do better?

- We have succeded in reducing the $m_{\tilde{\ell}-m_{\chi_1}}$ plane to a one-dimensional curve. However, that would be the case if we did not have an on-shell Z' at the top of the decay chain. If we've measured $m_{Z'}$ in another channel, how can we turn that extra constraint into an additional measurement?
$8_{q_{1,2}} - 2_{\not{p}_T} - 1_{m_{\text{LSP}_1} = m_{\text{LSP}_2}} - 1_{m_{\tilde{\ell}_1} = m_{\tilde{\ell}_2}} - 1_{m_{Z'}} - 1_{m_{T2_{\text{endpoint}}}} = 2$ unknowns.

Can we do better?

- We have succeded in reducing the $m_{\tilde{\ell}-m_{\chi 1}}$ plane to a one-dimensional curve. However, that would be the case if we did not have an on-shell Z' at the top of the decay chain. If we've measured $m_{Z'}$ in another channel, how can we turn that extra constraint into an additional measurement?
$8_{q_{1,2}} - 2_{\not{p}_T} - 1_{m_{\mathrm{LSP}_1} = m_{\mathrm{LSP}_2}} - 1_{m_{\tilde{\ell}_1} = m_{\tilde{\ell}_2}} - 1_{m_{Z'}} - 1_{m_{T2_{\mathrm{endpoint}}}} = 2$ unknowns.
- Without the Z', we would have three unknowns, which we could take to be $q^{x,y}_{\chi 1}$ and $m_{\chi 1}$. We want to construct a minmax variable that takes in these three arguments and is bounded above by $m_{Z'}$. We hope that it will only give us the correct value of $m_{Z'}$ for the correct $m_{\chi 1}$.

Constructing an endpoint at $m_{Z'}$

Constructing an endpoint at $m_{Z'}$

- We begin by guessing the transverse momenta, $q_{\chi_1}^{x,y}$ for one of the LSPs, as well as the LSP mass.

Constructing an endpoint at $m_{Z'}$

- We begin by guessing the transverse momenta, $q_{\chi_1}^{x,y}$ for one of the LSPs, as well as the LSP mass.
- Using the measured $\not{p}_T$, we get the other neutralino's transverse momenta. m_{T2} gives us $m_{\tilde{\ell}}$ for the value of m_{χ_1} we have used as an input.

Constructing an endpoint at $m_{Z'}$

- We begin by guessing the transverse momenta, $q_{\chi 1}^{x,y}$ for one of the LSPs, as well as the LSP mass.
- Using the measured $\not{p}_T$, we get the other neutralino's transverse momenta. m_{T2} gives us $m_{\tilde{\ell}}$ for the value of $m_{\chi 1}$ we have used as an input.
- With the above inputs, we can solve for q^z of the two neutralinos and have a possible reconstruction for the entire event. We can thus construct $m_{Z'}$ for sensible inputs (those satisfying $m_T < m_{\tilde{\ell}}$) and minimize over our guesses for $q_{\chi 1}^{x,y}$. This will be bounded above by the Z' mass.

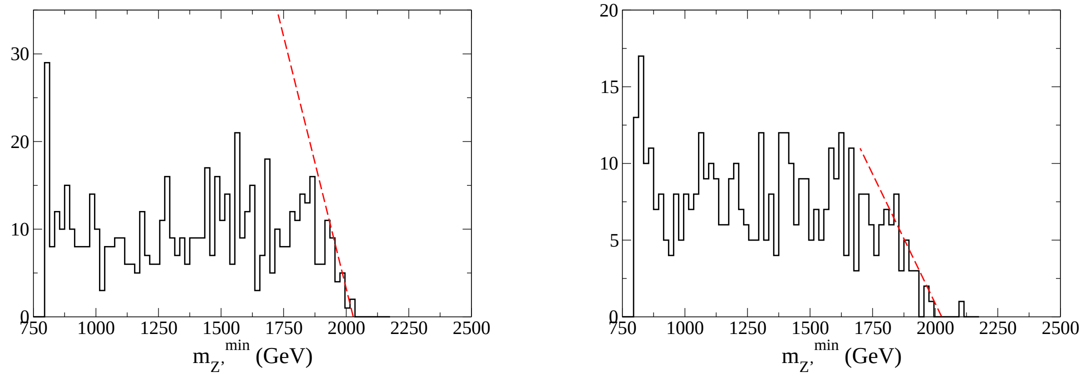
Constructing an endpoint at $m_{Z'}$

- We begin by guessing the transverse momenta, $q^{x,y}_{\chi 1}$ for one of the LSPs, as well as the LSP mass.
- Using the measured $\not{p}_T$, we get the other neutralino's transverse momenta. m_{T2} gives us $m_{\tilde{\ell}}$ for the value of $m_{\chi 1}$ we have used as an input.
- With the above inputs, we can solve for q^z of the two neutralinos and have a possible reconstruction for the entire event. We can thus construct $m_{Z'}$ for sensible inputs (those satisfying $m_T < m_{\tilde{\ell}}$) and minimize over our guesses for $q^{x,y}_{\chi 1}$. This will be bounded above by the Z' mass.
- There is one subtlety as the constraint equations that give us q^z are quadratic, and each have two roots. Thus, the reconstruction has a fourfold algebraic ambiguity. We simply minimize over it to avoid spoiling the upper bound given by $m_{Z'}$, arriving at the following quantity:

$$m^{\min}_{Z'} = \min_{q_1, q_2} [\min_{4 \text{ choices}} (m_{Z'}(q_1, q_2, m_{\chi 1}))]$$

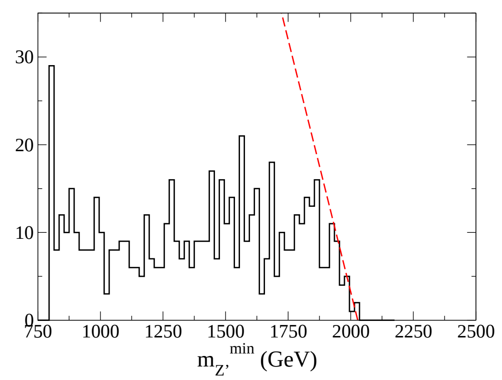
Results 1: $m_{Z'}$ endpoints

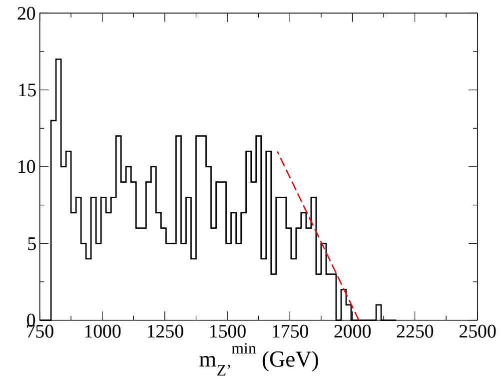
Results 1: $m_{Z'}$ endpoints



- Endpoints for $m_{Z'}^{min}$ with $m_{Z'} = 2$ TeV, $\Gamma_{Z'} = 27$ GeV, $m_{\tilde{\ell}} = 400$ GeV, and $m_{\chi 1} = 100$ GeV (L) or $m_{\chi 1} = 250$ GeV (R). Left endpoint is at 2.028 TeV. Right endpoint at 2.026 TeV. Results are for 130 fb^{-1} and have an uncertainty of 27 GeV from monte carlo and endpoint fitting.

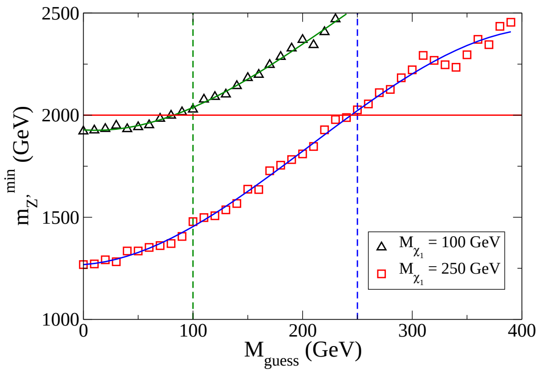
Results 1: $m_{Z'}$ endpoints





- Endpoints for $m_{Z'}^{min}$ with $m_{Z'} = 2$ TeV, $\Gamma_{Z'} = 27$ GeV, $m_{\tilde{\ell}} = 400$ GeV, and $m_{\chi_1} = 100$ GeV (L) or $m_{\chi_1} = 250$ GeV (R). Left endpoint is at 2.028 TeV. Right endpoint at 2.026 TeV. Results are for 130 fb^{-1} and have an uncertainty of 27 GeV from monte carlo and endpoint fitting.
- We should note that there is an additional uncertainty that we did not estimate. The endpoints of both plots are at $m_{Z'} + \Gamma_{Z'}$. We have no $a\ priori$ reason why this should be exact. Determination of this uncertainty may weaken our measurements, but we do not expect it to do so significantly.

Results 2: Bino and slepton masses



For both the 100 GeV bino (green) and 250 GeV (red) bino scenarios, we find the correct LSP mass to within ± 15. Plugging these values into m_{T2}, we measure $m_{\tilde{\ell}}$ as 405 ± 10 GeV and 407 ± 15 GeV, respectively. The true value is $m_{\tilde{\ell}} = 400$ GeV.

Once again, the uncertainties only include those of the monte carlo and $m_{Z'}^{min}$ endpoint-fitting.

Conclusions

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.
- We have shown that generically the presence of the vector particle greatly enhances the slepton discovery reach at the LHC.

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.
- We have shown that generically the presence of the vector particle greatly enhances the slepton discovery reach at the LHC.
- The increased visibility of sleptons gives us a handle on LSP identity

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.
- We have shown that generically the presence of the vector particle greatly enhances the slepton discovery reach at the LHC.
- The increased visibility of sleptons gives us a handle on LSP identity
- By using the extra constraint of an on-shell Z', we can use two minmax variables to measure the masses of its daughter particles.

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.
- We have shown that generically the presence of the vector particle greatly enhances the slepton discovery reach at the LHC.
- The increased visibility of sleptons gives us a handle on LSP identity
- By using the extra constraint of an on-shell Z', we can use two minmax variables to measure the masses of its daughter particles.
- The technique of using the output of one minmax variable as an input to the next will extend to generic scenarios with two invisible particles, reducing the number of parameters necessary to make a measurement.

Conclusions

- We have considered a non-minimal SUSY scenario by adding a vector particle that couples to baryons and leptons.
- We have shown that generically the presence of the vector particle greatly enhances the slepton discovery reach at the LHC.
- The increased visibility of sleptons gives us a handle on LSP identity
- By using the extra constraint of an on-shell Z', we can use two minmax variables to measure the masses of its daughter particles.
- The technique of using the output of one minmax variable as an input to the next will extend to generic scenarios with two invisible particles, reducing the number of parameters necessary to make a measurement.
- To read more, see hep-ph/0608172.