Recovering Event Kinematics Using Constraints from Displaced Tracks

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Background/Motivation

- Early stages of LHC analysis – Look for deviations from Standard Model of any kind
  - Standard Model predicts rates for final states
  - Counting experiments generally most straightforward
  - Requires precise knowledge of SM backgrounds
  - Can claim new physics but cannot claim what new physics
- Specific discoveries need more detailed information
  - Mass spectra, spin structure, coupling strengths, etc... required to validate or invalidate specific models

Background/Motivation

- Reconstruction of mass resonance peaks
  - Non-interacting particles will pass through LHC undetected
  - Existence inferred by missing transverse momentum
  - Mass resonance reconstruction not possible
- Missing energy signatures are particularly challenging
  - Irrecoverable loss of information
- Missing energy signatures are fairly generic for BSM models
  - R-parity in SUSY, Extra Dimensions, “WIMP Miracle”, etc..

The Problem

- Many mass measurement techniques exist for MET events
  - Cleverly constructed variables reveal kinematic features
    - MT2, mass edges from on-shell cascades, etc..
- Most existing techniques require large number of events
  - Kinematic features only apparent in high stat, distributions
  - Difficult to use for early discovery level searches
- Is it possible, under any circumstances, to recover all kinematic quantities event-by-event from MET events?
- Presence of displaced vertices or tracks provides a handle

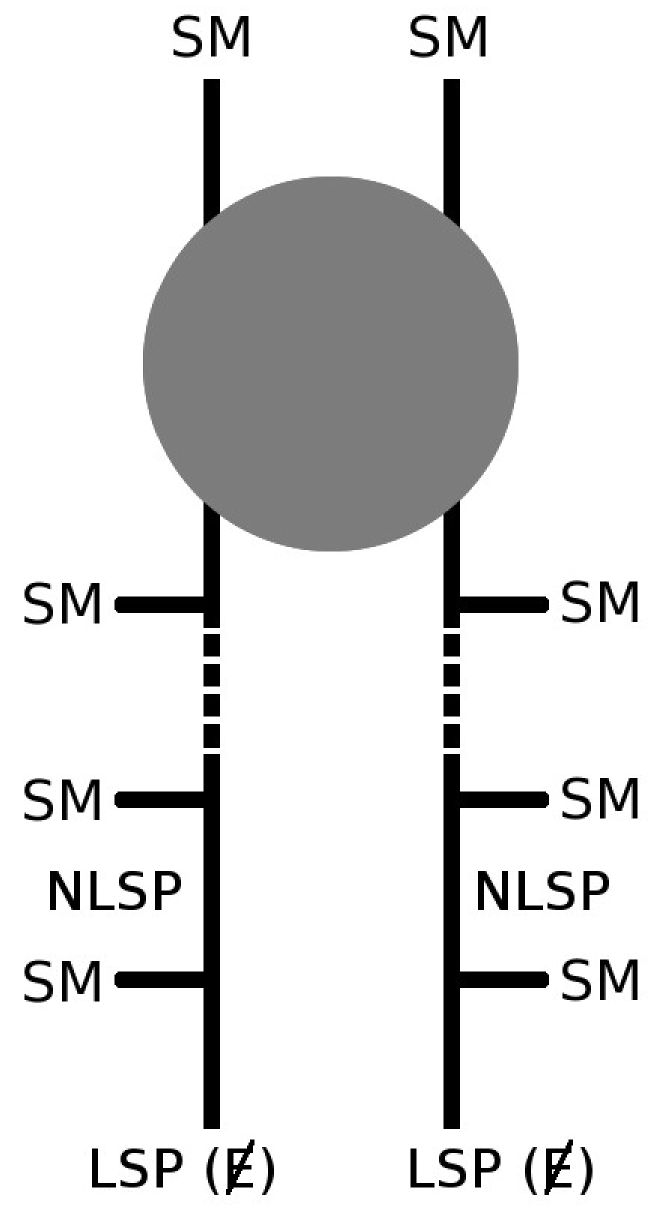
Quantifying the Unknowns

Unknowns	
LSP 4-momenta	8
Constraints	
Missing p_T	2
Constraint Equations	k
Total Number of Unknowns: 6-k	

- Constraints - Assume some symmetry between decay chains (Gunion, McElrath,...)

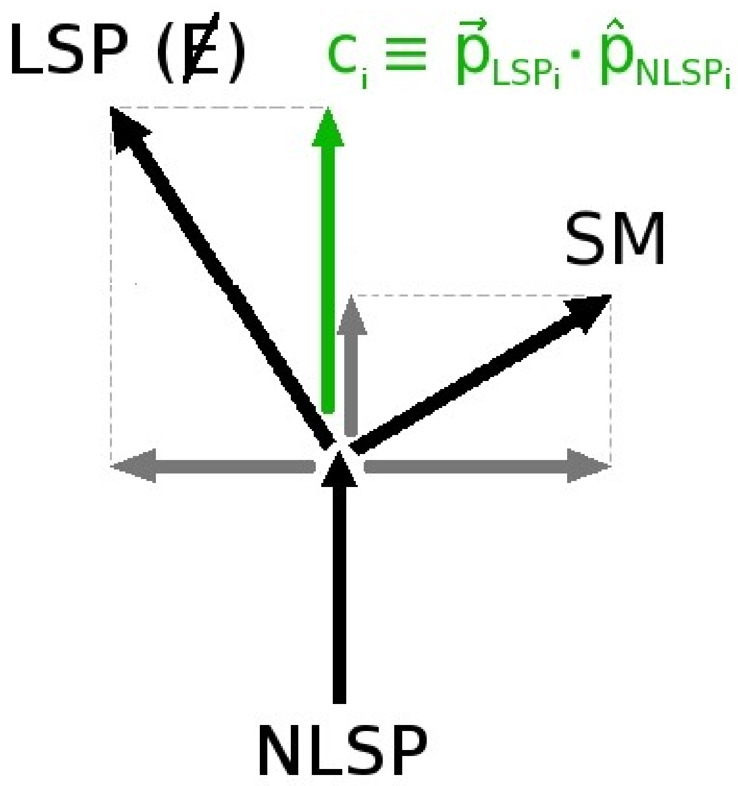
- Considering m events we must add to the above another (m-1)(6-2k) unknowns

- For m events: 6m-2km+k unknowns



Parameterizing the Unknowns

- Naively seems like the LSP momenta are lost – NOT TRUE!
- **The 3-momenta of the LSP's depend ONLY on the direction of the NLSP 3-momenta**



$$\vec{p}_{LSP_i}(c_i,\ \hat{p}_{NLSP_i})$$

Two constraints

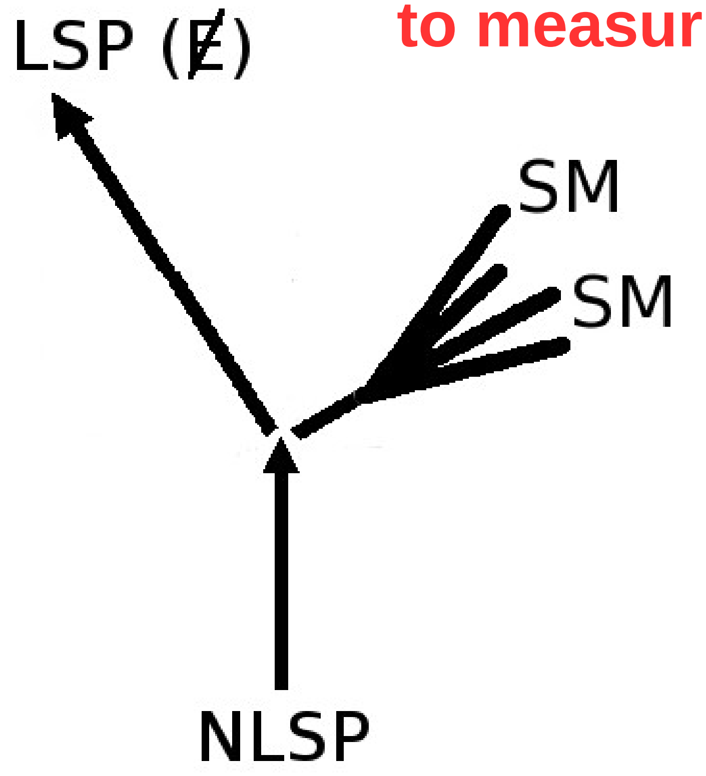
$$\vec{\not{p}} = \vec{p}_{LSP_1} + \vec{p}_{LSP_2}$$

Eliminate c_1 and c_2

$$\vec{p}_{LSP_i}(\hat{p}_{NLSP_1},\ \hat{p}_{NLSP_2})$$

Displaced Vertex Constraints

- Key Assumption: $c\tau\big|_{\text{NLSP}} \gg c\tau\big|_{\text{All Other Particles}}$
- Then direction of NLSP ~ location of the displaced vertex



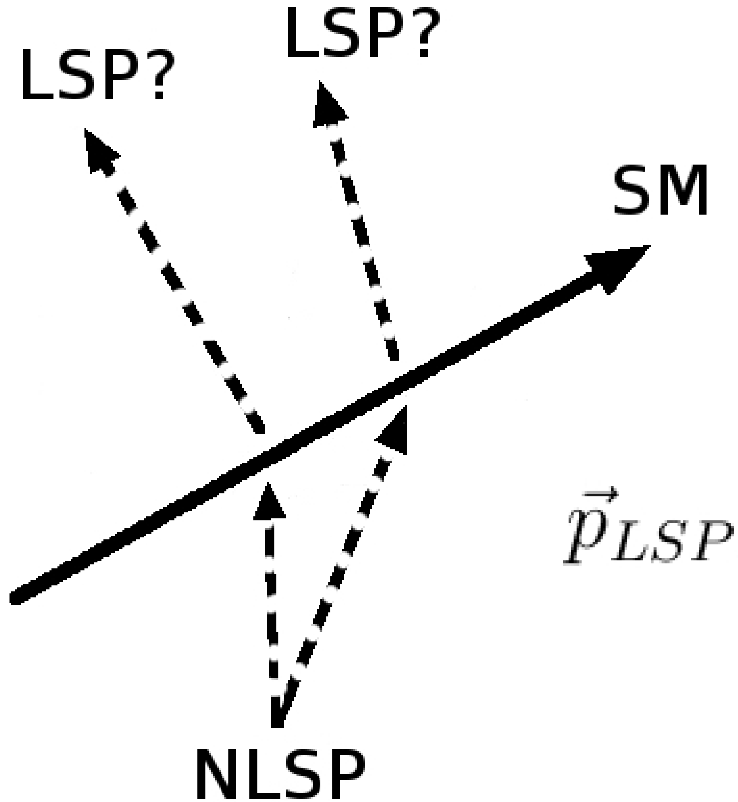
- **Measuring displaced vertices equivalent to measuring LSP 3-momenta**

$$\vec{p}_{LSP_i}(\vec{r}_1,\ \vec{r}_2)$$

- Difficulties with measurement
  - Prompt SM particle decays
  - Example of b-jet tagging

Displaced Track Constraints

- If final SM particle is stable, only displaced tracks appear
- Displaced vertex must lie somewhere along path of track



- Location of displaced vertex parameterized by one number
  - Location along beam axis

$$\vec{p}_{LSP_i}(\vec{r}_1,\ \vec{r}_2) \rightarrow \vec{p}_{LSP_i}(z_X,\ z_Y)$$

Examples from GMSB

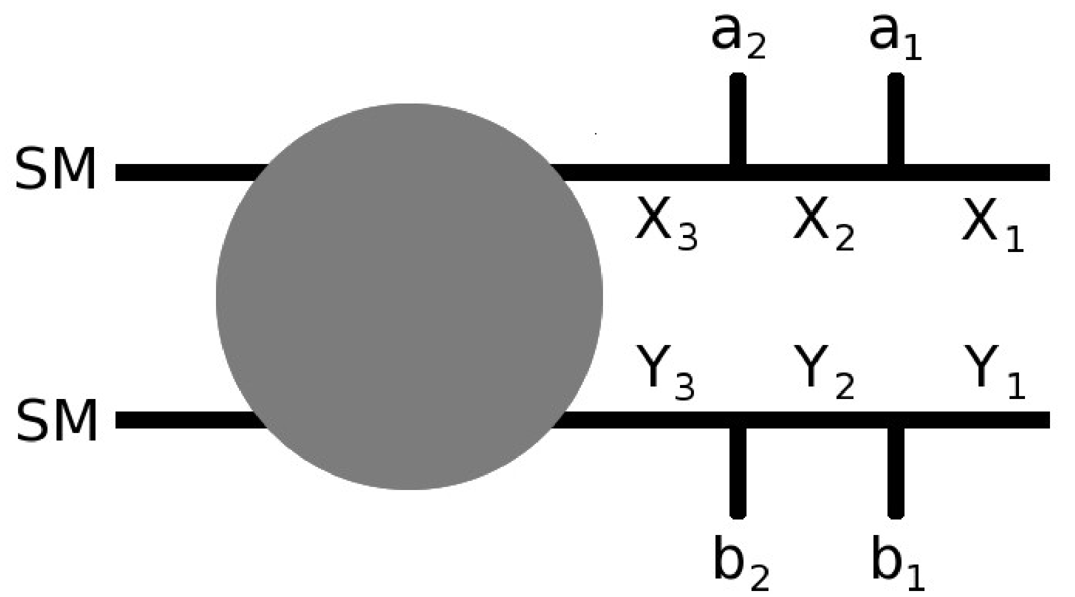
- Low scale SUSY breaking implies massless LSP
- Displaced vertices
  - Trivial (will not be discussed)
- Displaced tracks
  - Condition for recovery of all unknowns is 2m-2km+k=0

Particle	Symbol	Mass
Bino	$\tilde{B}$	199.30 GeV
Slepton	$\tilde{l}_R$	107.44 GeV
Gravitino	$\tilde{G}$	0 GeV

GMSB Example 1 (m=1, k=2)

k = 2 implies

- $m_{X_2} = m_{Y_2}$
- $m_{X_3} = m_{Y_3}$



- Two equations for two unknowns

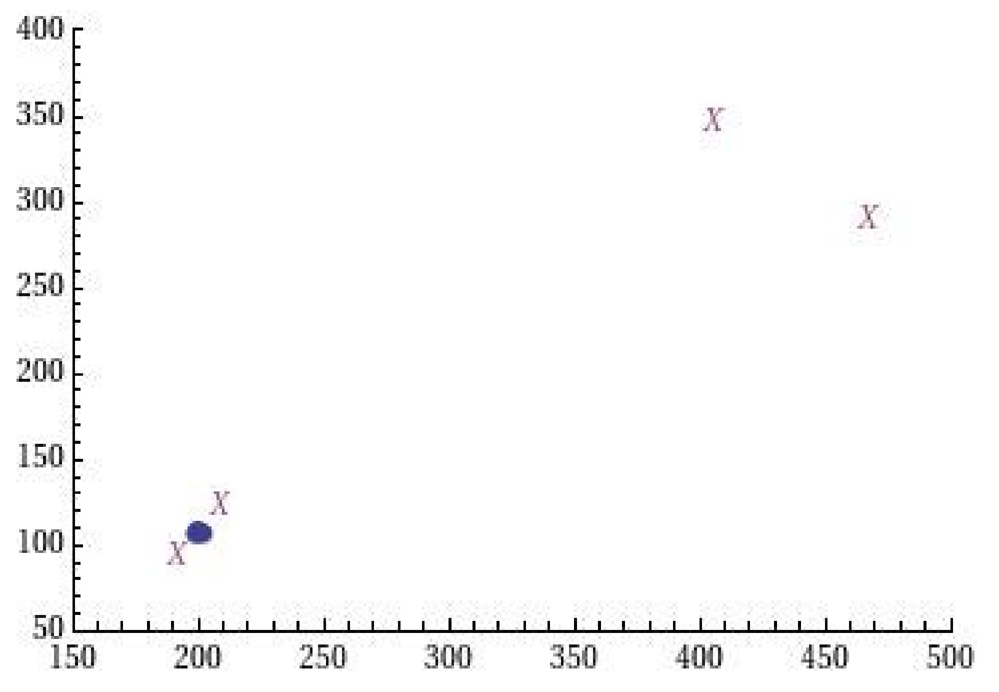
$$m_{X_2}^2 = (p_{X_2}^\mu(z_X, z_Y) + p_{a_1}^\mu)^2 = (p_{Y_1}^\mu(z_X, z_Y) + p_{b_1}^\mu)^2 = m_{Y_2}^2$$

$$m_{X_3}^2 = (p_{X_2}^\mu(z_X, z_Y) + p_{a_1}^\mu + p_{a_2}^\mu)^2 = (p_{Y_1}^\mu(z_X, z_Y) + p_{b_1}^\mu + p_{b_2}^\mu)^2 = m_{Y_3}^2$$

GMSB Example 1 (m=1, k=2)

- Highly nonlinear system of equations
  - Multiple solutions
- In practice, need few events to confirm mass spectrum measurement
- Plot of solutions using 4 Monte Carlo events

Particle	Symbol	Mass
Bino	$\tilde{B}$	199.30 GeV
Slepton	$\tilde{l}_R$	107.44 GeV
Gravitino	$\tilde{G}$	0 GeV



Can We Do Better?

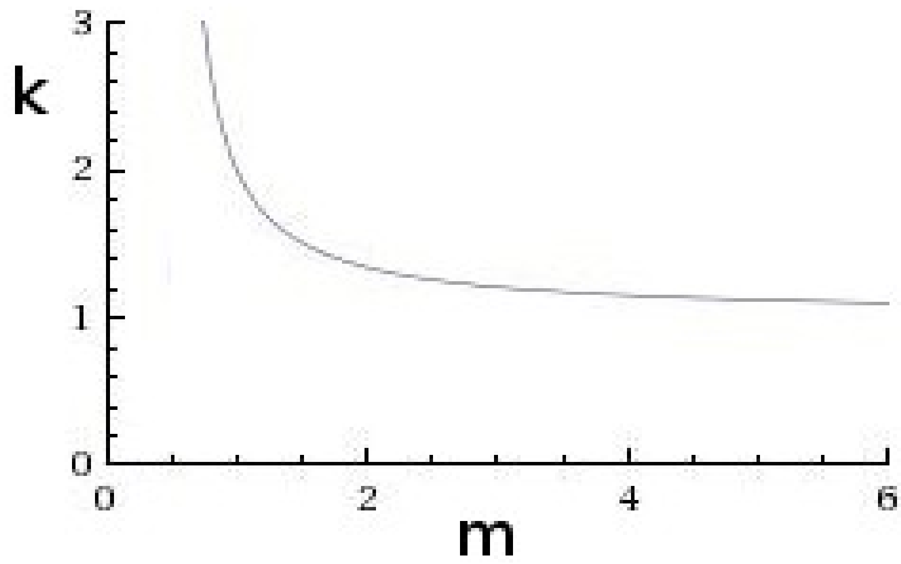
- Can we reduce dependence on constraint equations by analyzing more events?

- The condition for total kinematic recovery 2m-2km+k=0

$$k = \frac{2m}{2m-1} \text{ so as m } \to \infty, \text{ k } \to 1$$

- Possible to reconstruct masses with k=1?

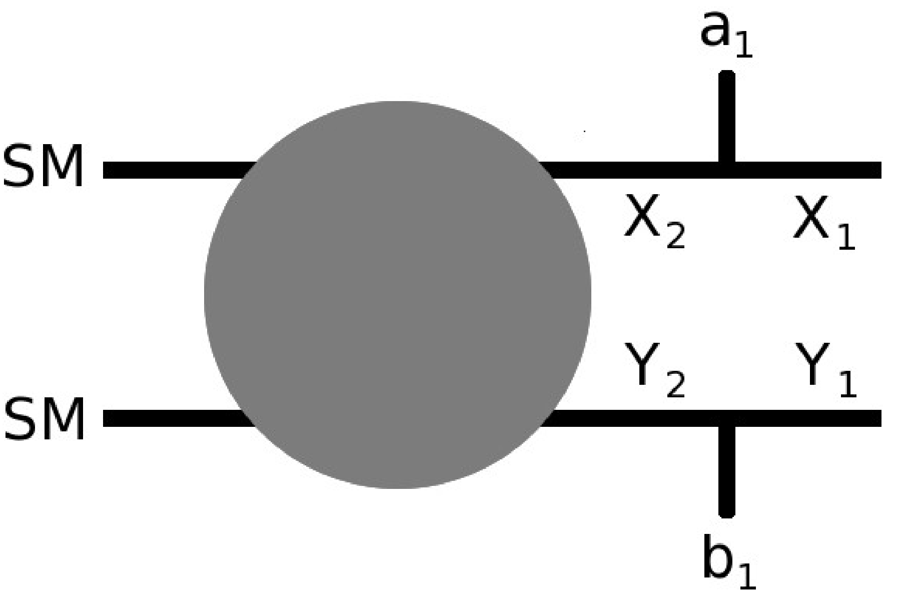
- Naïve answer: **NO**



GMSB Example 2 (k=1)

- Condition k=1 implies one equation with two unknowns

- Not enough constraints to specify unique solution



$$m^2_{X_2} = (p^\mu_{X_1}(z_X, z_Y) + p^\mu_{a_1})^2 = (p^\mu_{Y_1}(z_X, z_Y) + p^\mu_{b_1})^2 = m^2_{Y_2}$$

- Can reduce space of solutions to one-dimensional subspace

$$z_Y \to z_Y(z_X)$$

GMSB Example 2 (k=1)

- One-to-one map between particle mass and beam axis coordinate of a secondary vertex

$$m^2_{X_2}(z_X, z_Y) \to m^2_{X_2}(z_X)$$

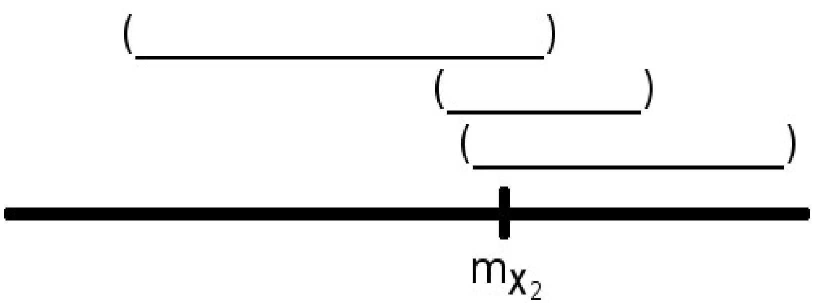
- **As z_X goes to infinity, the direction of the NLSP asymptotically approaches a fixed unit vector, hence m_{X_2} asymptotically approaches some fixed number**

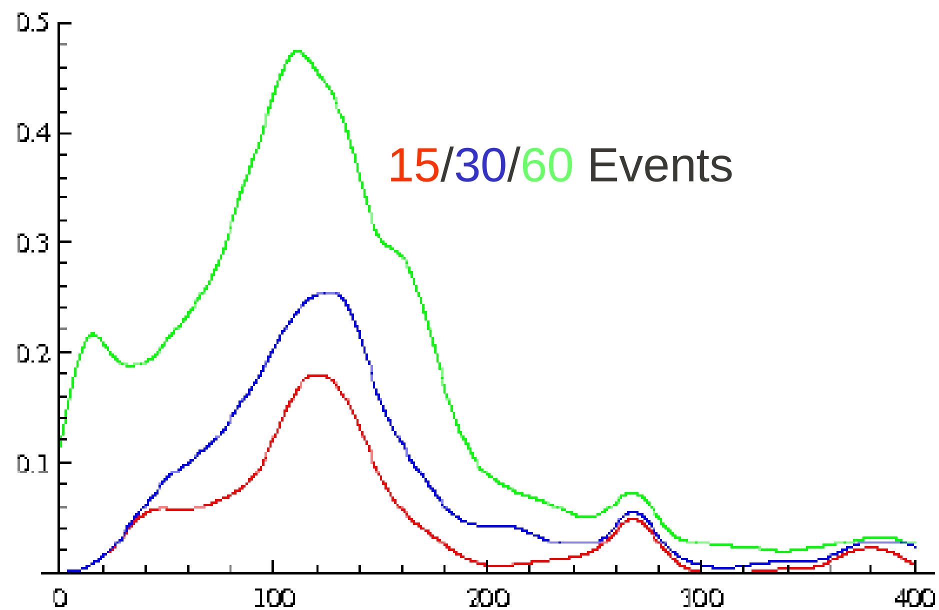
- Range of possible values for m_{X_2} form a finite set
  - Correct value is always an element of this set

GMSB Example 2 (k=1)

- Over a few events, plot entire range of possible solutions for particle mass

- Since correct mass is always inside the range, histogram will peak at correct solution



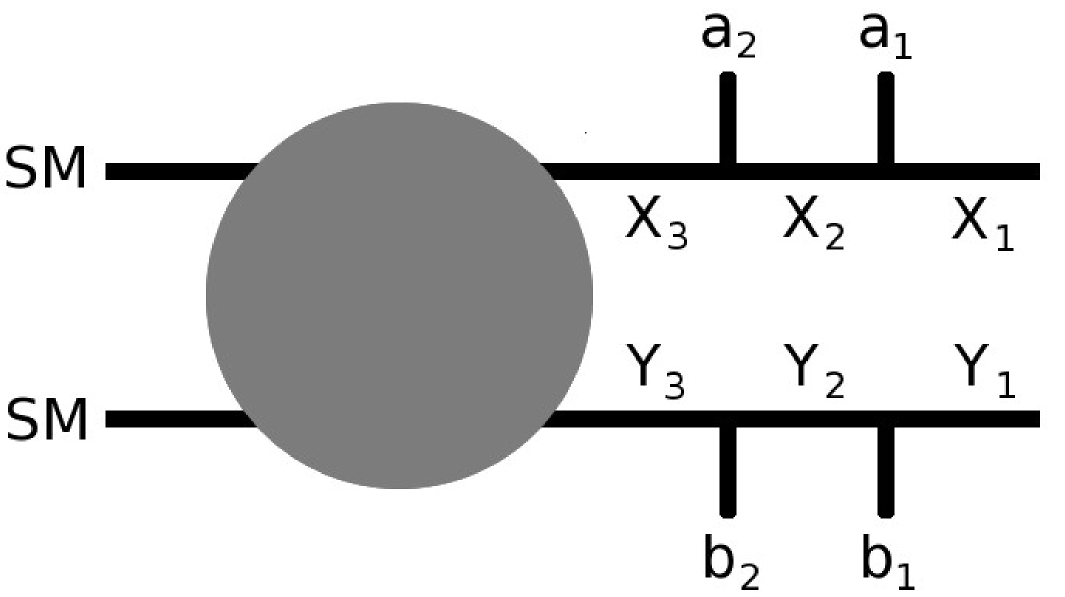


Particle	Symbol	Mass
Bino	$\tilde{B}$	199.30 GeV
Slepton	$\tilde{l}_R$	107.44 GeV
Gravitino	$\tilde{G}$	0 GeV

A Massive LSP (m=2, k=2)

- With displaced tracks and a massive LSP there are 3m-2km+k unknowns

$$m_{X_1} \neq 0$$
$$m_{Y_1} \neq 0$$
$$m_{X_1} = m_{Y_1}$$



- One possible solution to this condition has m=2, k=2

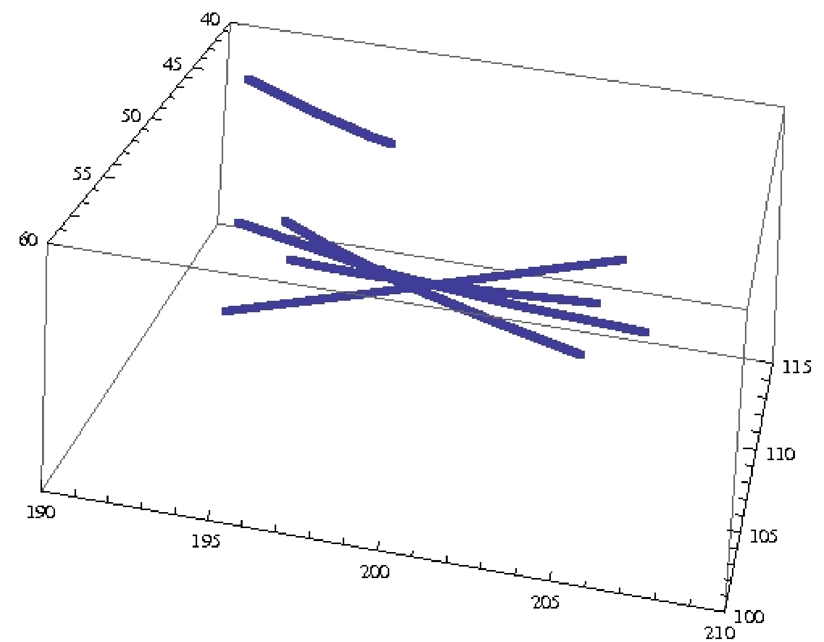
$$m^2_{X_2}(z_X, z_Y, m_{X_1}) = m^2_{Y_2}(z_X, z_Y, m_{X_1})$$
$$m^2_{X_3}(z_X, z_Y, m_{X_1}) = m^2_{Y_3}(z_X, z_Y, m_{X_1})$$

A Massive LSP (m=2, k=2)

- Two equations, three unknowns - solutions are lines in R^3
- Convenient to change variables to (m_{X_1}, m_{X_2} , m_{X_3})

$$m_{X_3} \to m_{X_3}(m_{X_1}, m_{X_2})$$

- Plotting solutions over 3 events yields:
- In the very narrow width limit, correct solution lies at intersection of the curves

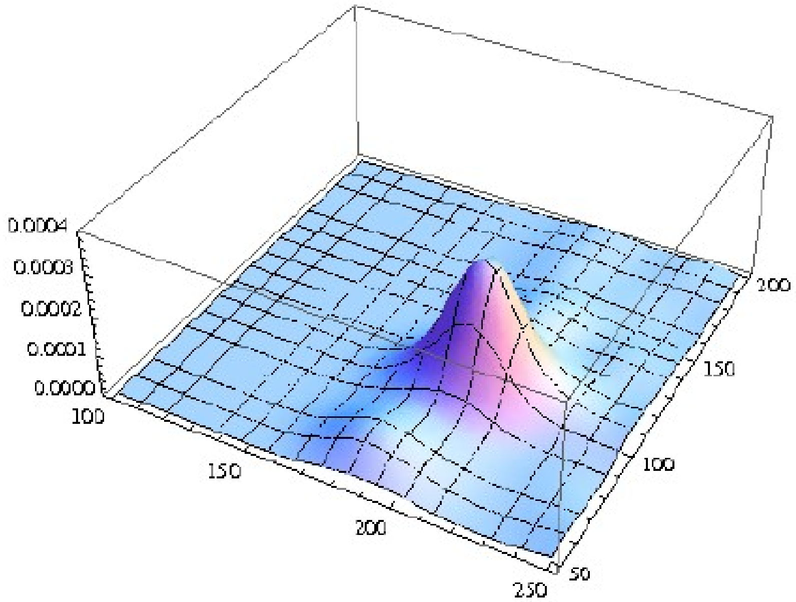


A Massive LSP (m=2, k=2)

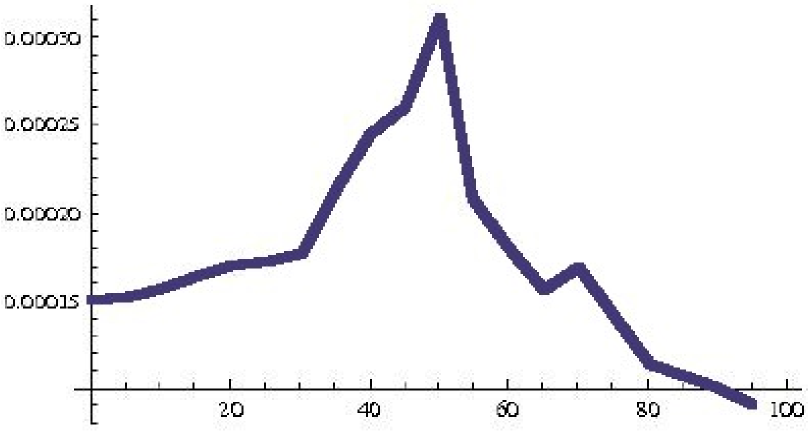
• Non-zero widths mean lines will not intersect perfectly

• Search for region with highest Gaussian density of lines

•Perform a likelihood fit using Gaussian template



Particle	Symbol	Mass
Bino	$\tilde{B}$	199.30 GeV
Slepton	$\tilde{l}_R$	107.44 GeV
Gravitino	$\tilde{G}$	50 GeV



Conclusions

- Early search strategy - Search under the lamp post
- If new physics manifests as dual displaced vertices or tracks then O(few) events could provide us with
  - Convincing evidence of this decay topology
  - The mass spectrum of new particle states
  - In supersymmetric theories, decay length of NLSP and an estimation of the SUSY breaking scale

$$c\tau \sim \frac{(\sqrt{F})^4}{m_{X_2}^5}$$