Mass and Spin Measurements in Events with Missing Energy

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arXiv:0802.4290, 0905.1344
H. Cheng, ZH, I. Kim, L. Wang, in progress

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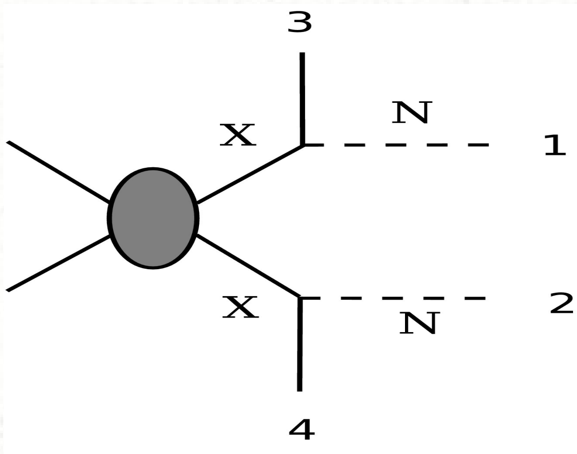
Outline

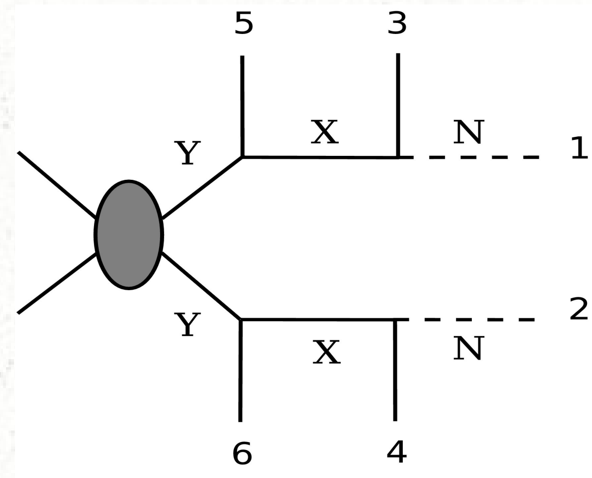
- Motivation
- Mass and spin determination using kinematic constraints
  - An example: decay chains with 3 visible particles
- Conclusion

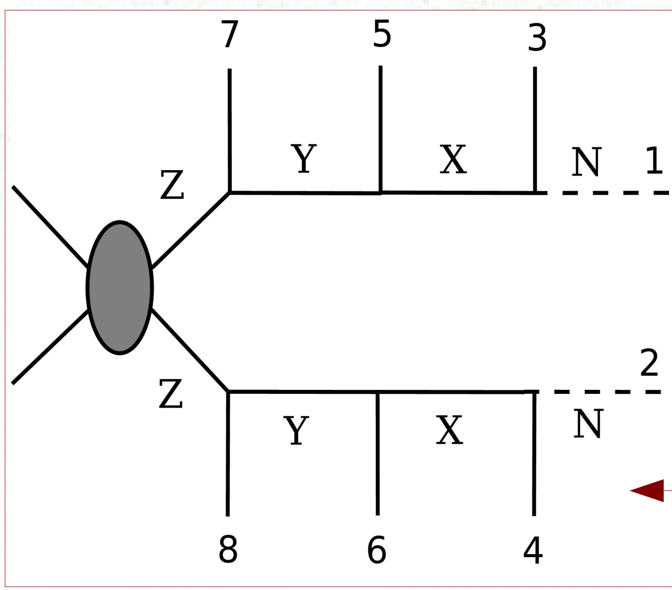
Motivation

- TeV scale theories often contain missing particles: SUSY, UED, little Higgs with T parity...
- Missing particles produced in pairs, difficult to reconstruct the kinematics and determine the masses and spins at the LHC
- Traditional edge/endpoint methods require a large amount of data—only use information from one decay chain.
- New techniques are needed.
    - Kinematic constraints
    - Double chain techniques

Different "topologies"



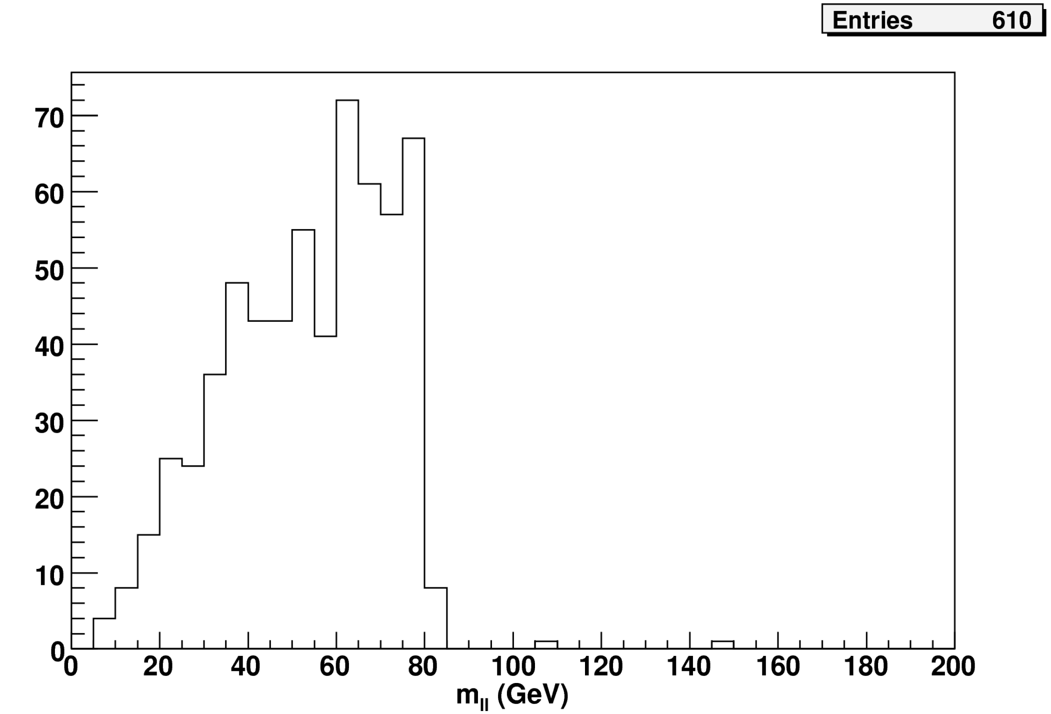




What are the masses of
Z, Y, X, N...?
What are their spins?

This talk

Identify the events-the dilepton edge

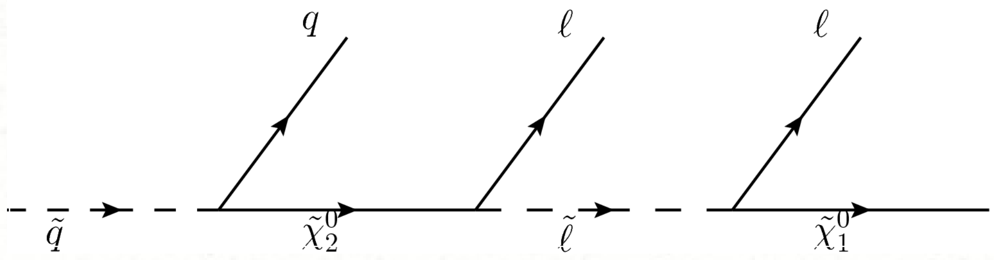


$$\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \ell\bar{\ell}\tilde{\chi}_1^0$$

$$m_{\ell\ell}^2|_{\rm edge} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\ell}}^2}$$

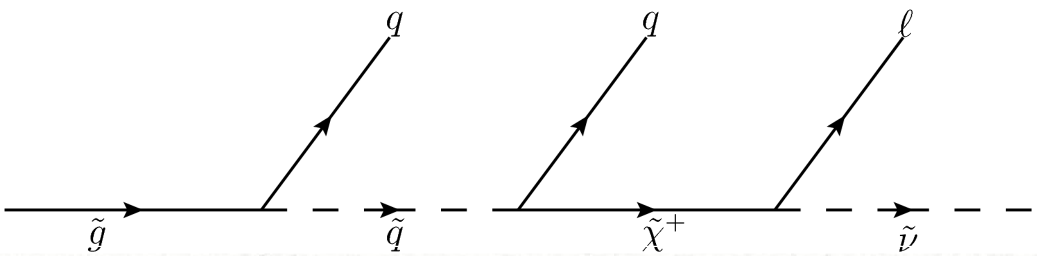
More observations

- Large cross-section
- High PT jets
- Large missing PT
- squark/KK-quark production
  $\widetilde{q} \to q\widetilde{\chi}_2^0 \to q\widetilde{\ell}\ell \to q\ell\bar{\ell}\widetilde{\chi}_1^0$

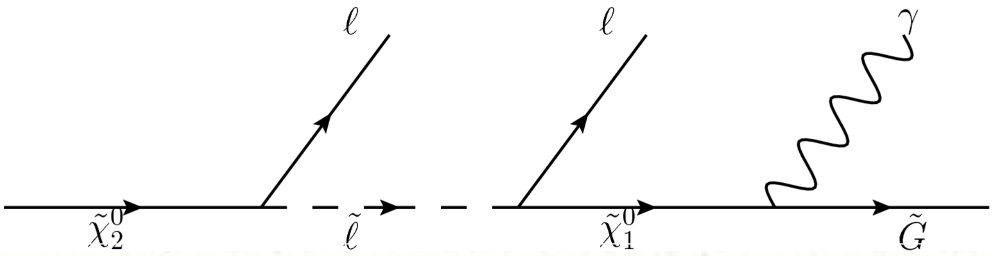


Other examples

- $\tilde{g} \to \tilde{q}q \to qq\tilde{\chi}^{+} \to qq\ell\tilde{\nu}$

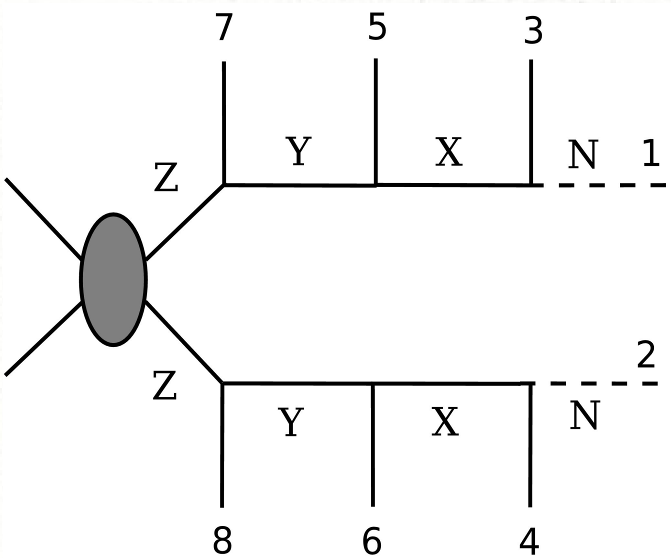


- Gauge mediation models (or PQ-UED, Jay's talk)



Two identical chains

$$\tilde{q} \to q\tilde{\chi}_2^0 \to ql\tilde{l} \to qll\tilde{\chi}_1^0$$



How many such events? Depending on the branching ratios.

Example: SPS1a: 565 GeV squark, 604 GeV gluino

For 10 inverse fb:

- ~7.4 K events if including stau's
- ~120 excluding stau's.

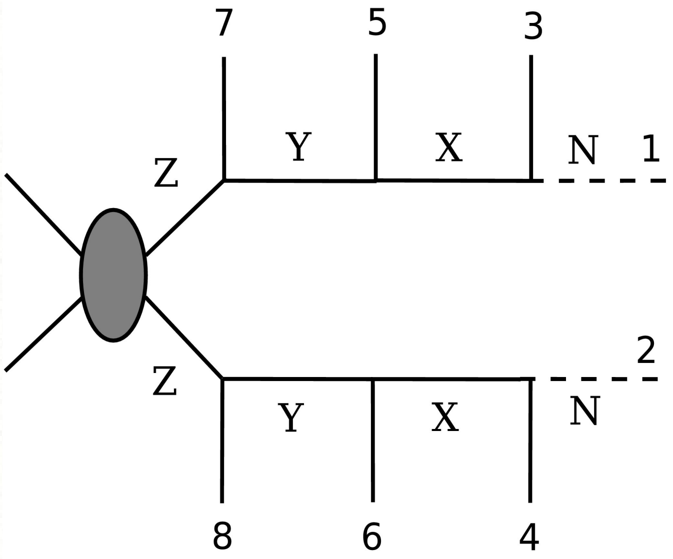
(neutralino 2 to stau branching ratio 14 times smuon/selectron)

- ~3k if assuming flavor universality.

Mass determination using kinematic constraints

(with Cheng, Engelhardt, Gunion, McElath)

$$\tilde{q} \to q\tilde{\chi}_2^0 \to ql\tilde{l} \to qll\tilde{\chi}_1^0$$



- 8 unknowns: p1, p2
- 6 equations: 4 mass shell constraints, 2 transverse momentum constraints

$$p_1^2 = p_2^2$$
$$(p_1 + p_3)^2 = (p_2 + p_4)^2$$
$$(p_1 + p_3 + p_5)^2 = (p_2 + p_4 + p_6)^2$$
$$(p_1 + p_3 + p_5 + p_7)^2 = (p_2 + p_4 + p_6 + p_8)^2$$
$$p_1^x + p_2^x = p_{miss}^x, \quad p_1^y + p_2^y = p_{miss}^y$$

Combining two events

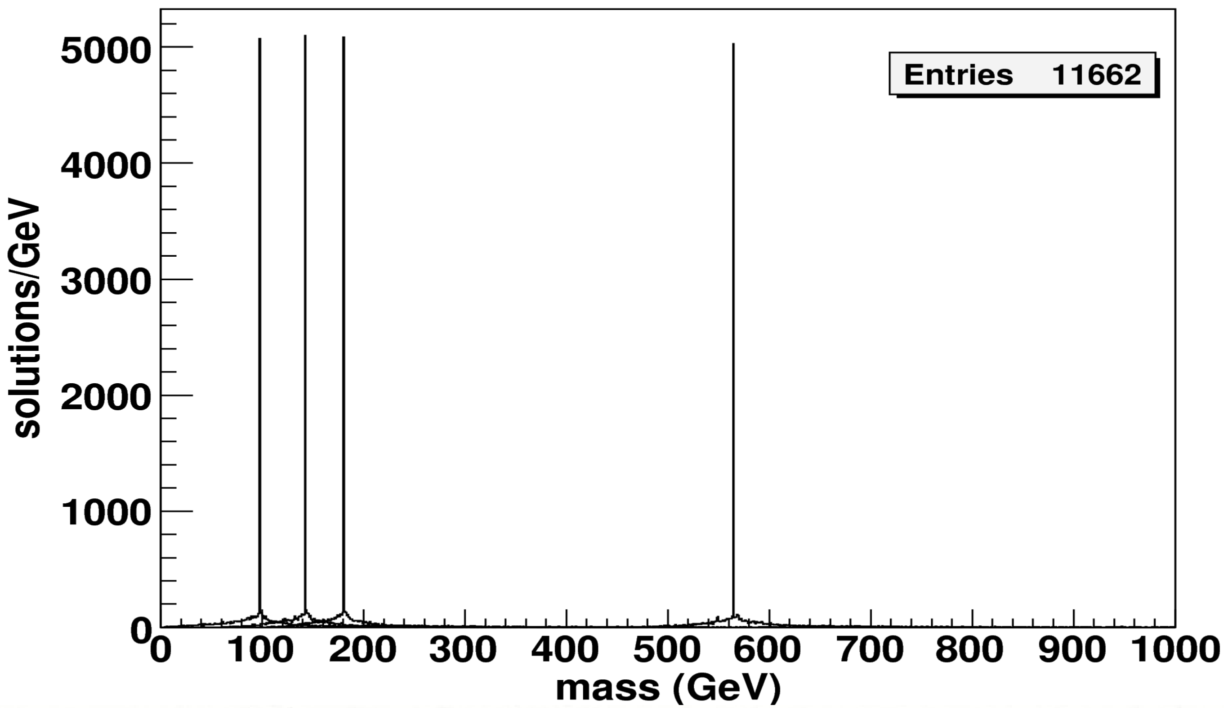
- Add one events, add 8 unknowns: q1, q2, but 10 equations

$$q_1^2 = q_2^2 = p_1^2$$
$$(q_1 + q_3)^2 = (q_2 + q_4)^2 = (p_2 + p_4)^2$$
$$(q_1 + q_3 + q_5)^2 = (q_2 + q_4 + q_6)^2 = (p_1 + p_3 + p_5)^2$$
$$(q_1 + q_3 + q_5 + q_7)^2 = (q_2 + q_4 + q_6 + q_8)^2 = (p_1 + p_3 + p_5 + p_7)^2$$
$$q_1^x + q_2^x = q_{miss}^x, \quad q_1^y + q_2^y = q_{miss}^y$$

16 equations and 16 unknowns
we can solve the system!

Ideal case

- No smearing, no wrong combinations
- SPS1a, (97.4, 142.5, 180.3, 564.8) GeV

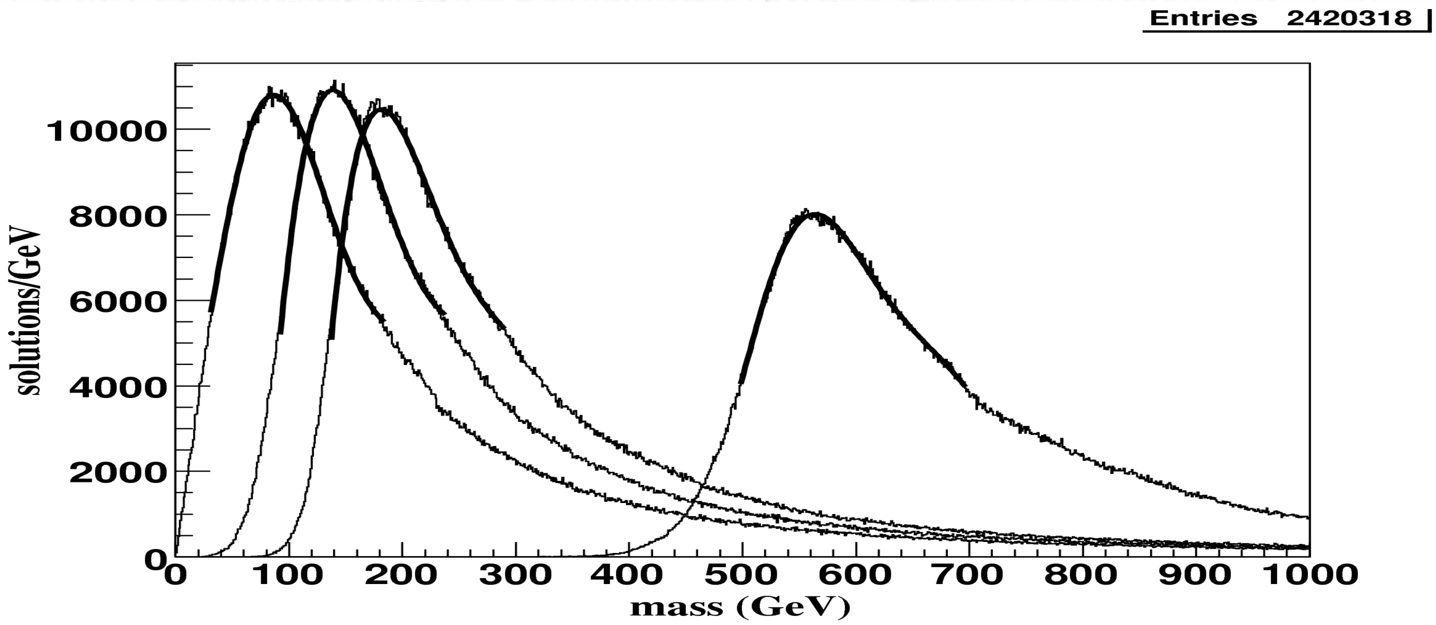


Realistic case

- Wrong combinations: one event, 8 combinations for 2mu+2e channel, 16 for 4mu/4e channel. A pair of events, 64, 128 or 256 combinations
- Finite width: 5 GeV, 20 MeV, 200 MeV for squark, neutralino 2, slepton.
- Flavor splitting between up-type and down-type squarks: ~6GeV
- initial/final state radiation
- Extra jet from gluino decay
- Experimental resolutions: simulated with PGS
- Background events: staus

Realistic case

About 600 events after kinematic cuts (~ 430 signals), detector simulation included, all pairs, all combinations.



Error estimate: fit to a Gaussian+quadratic polynomial, read the maximum, repeat over 20 different data sets. Small statistic errors, significant systematic errors.

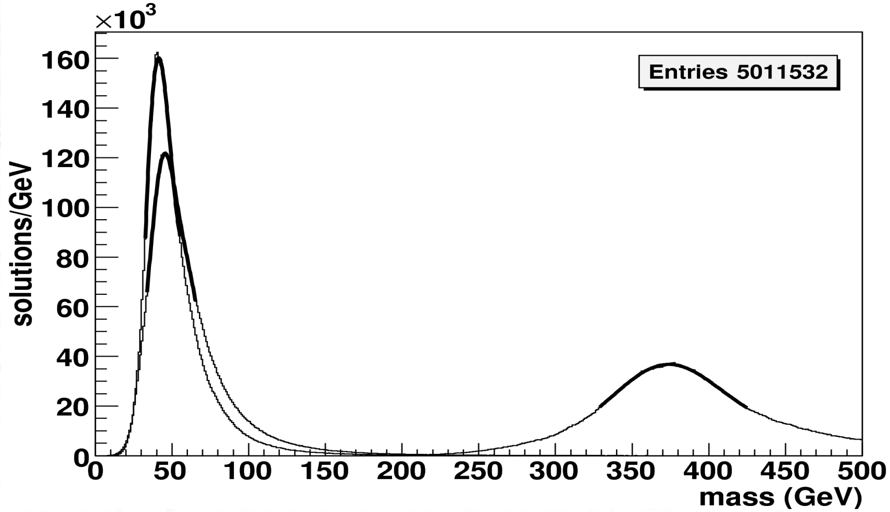
$$76.7 \pm 2.0, \quad 134.6 \pm 2.2, \quad 178.9 \pm 3.8, \quad 561.6 \pm 5.4 \mathrm{GeV}$$

Reduce the systematic errors

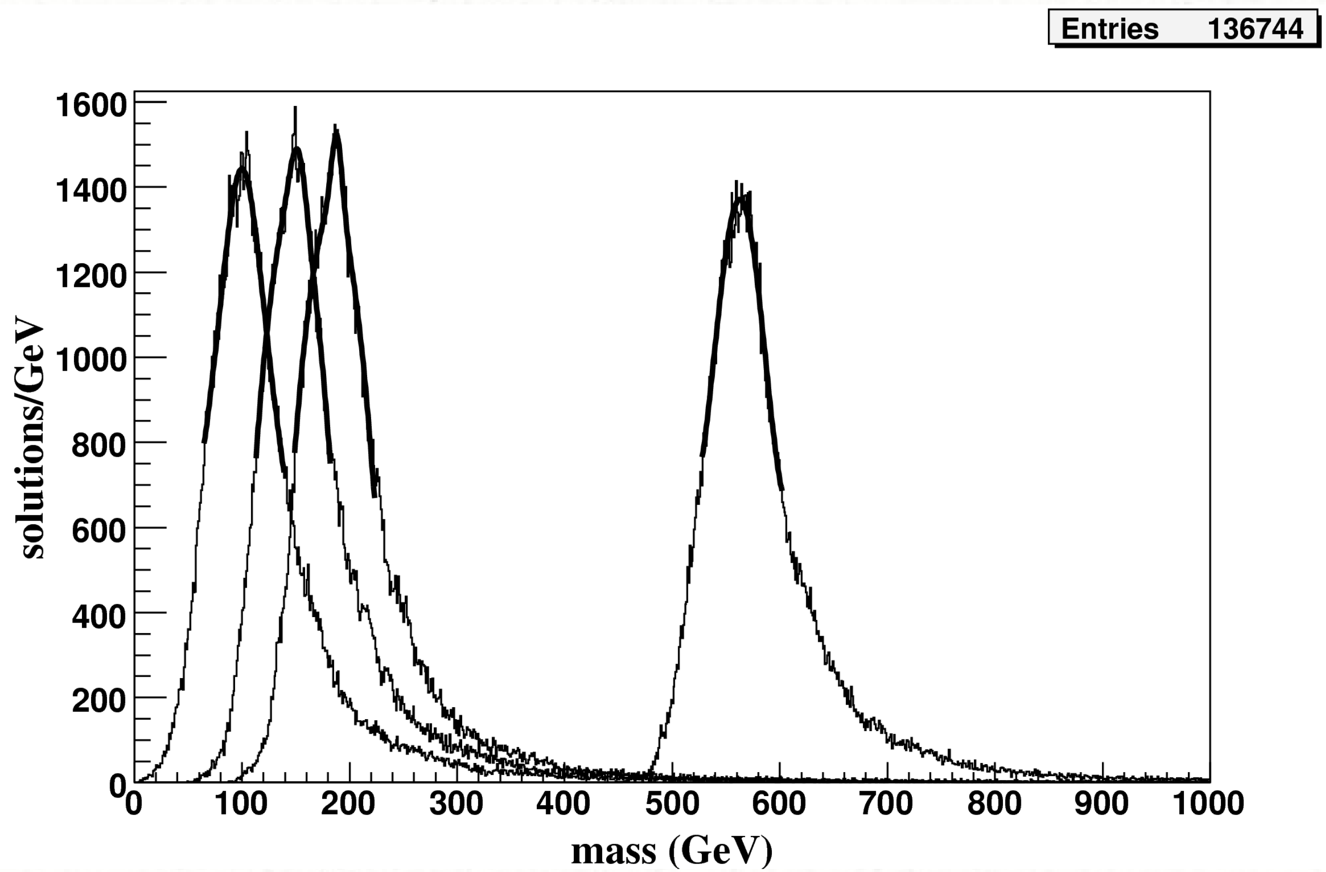
- Use the dilepton edge position as a cut

$$\left|\sqrt{(m_Y^2 - m_X^2)(m_X^2 - m_N^2)/m_X^2} - m_{\ell^+\ell^-}^{\text{edge}}\right| < 20\text{GeV}$$

- Eliminate “bad” combinations, (which do not pair with many events)
- Number of solutions weighting: weight solutions by 1/nsolutions (each pair is treated equally)
- Determine the mass differences first, use as a cut (include correlations)



Reduce the systematic errors

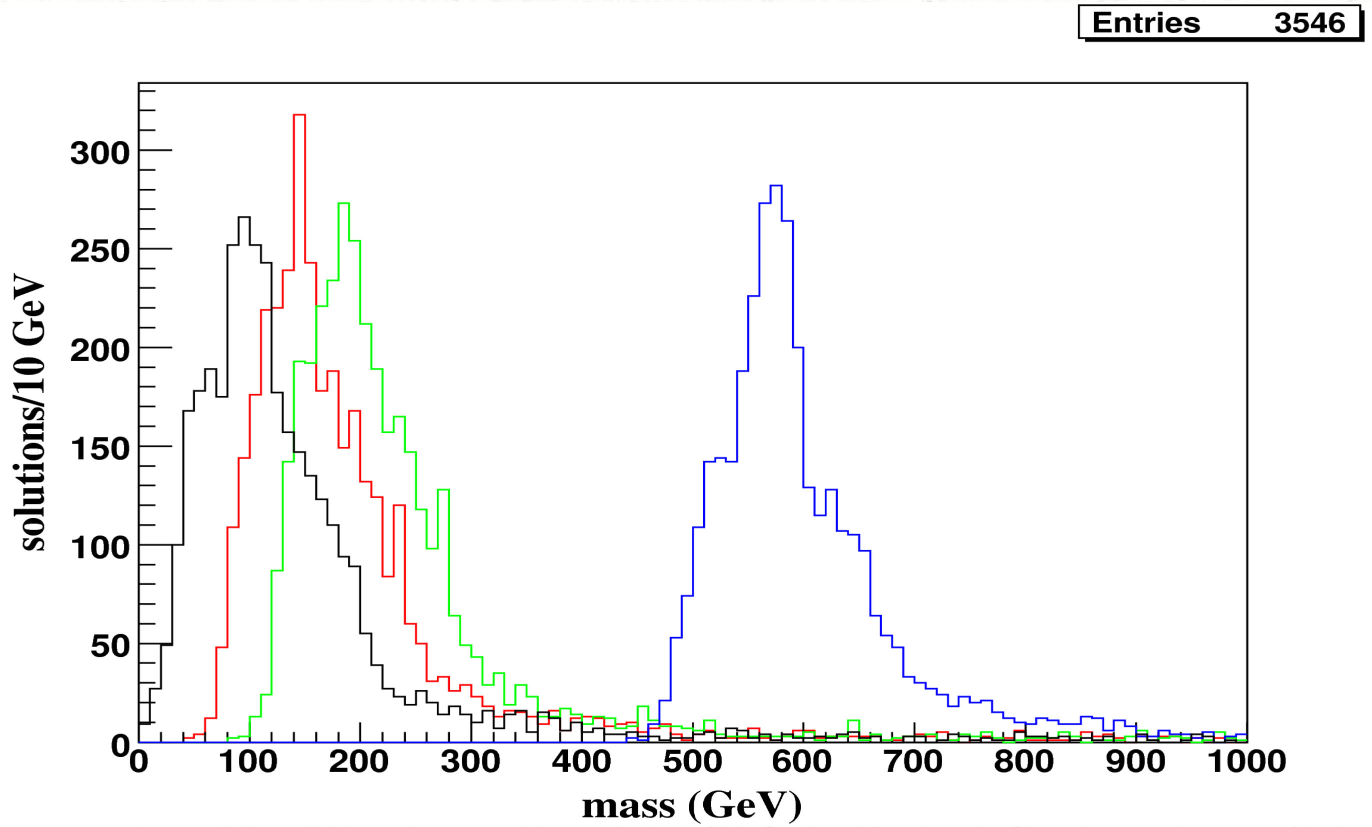


$$96.1 \pm 3.9, \quad 141.4 \pm 4.6, \quad 178.8 \pm 4.6, \quad 559.9 \pm 4.5 \text{GeV}$$

Compare inputs: 97.4, 142.5, 180.3, 564.8/570.8 GeV

Less events?

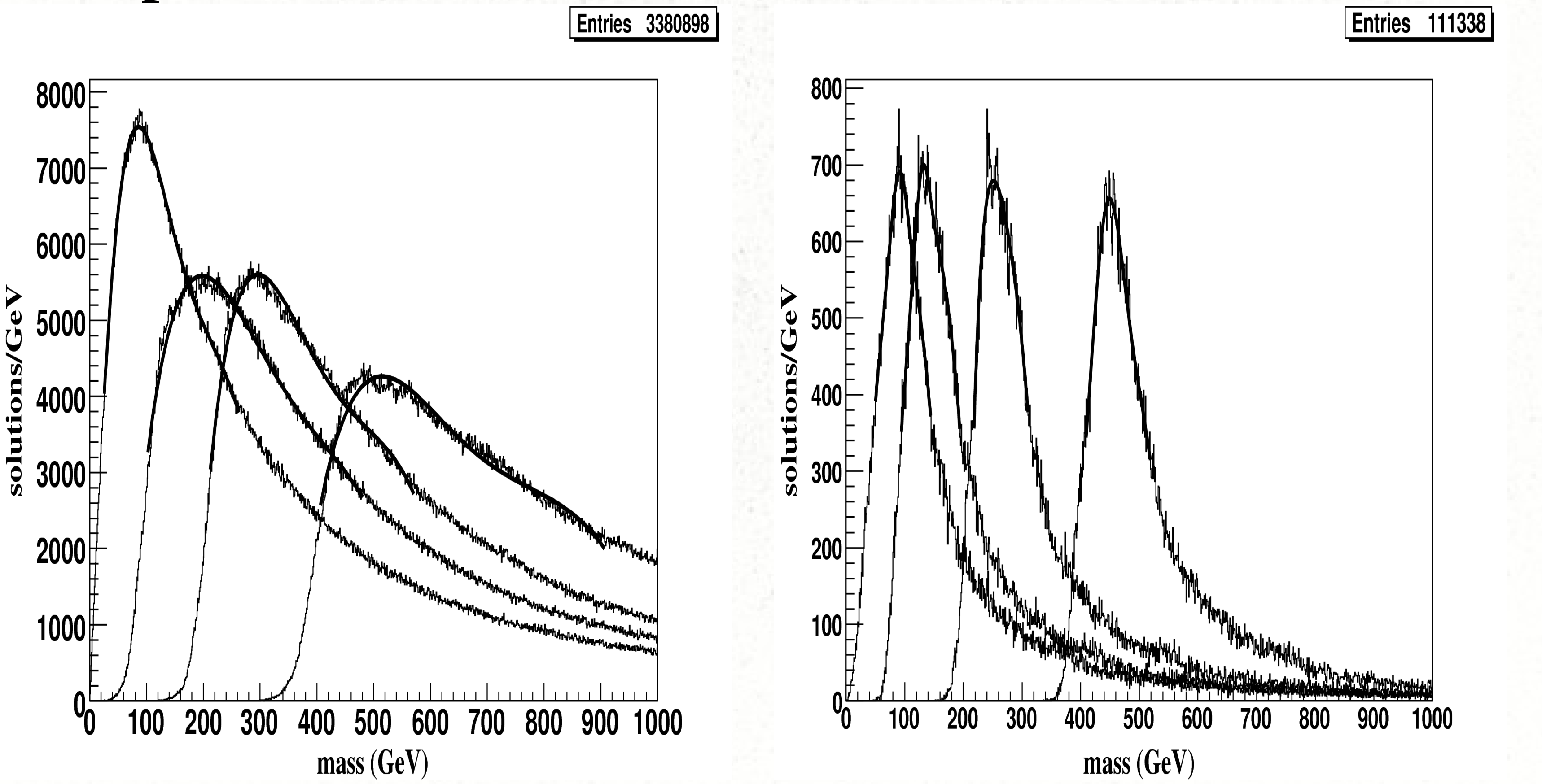
- 50 events, around 20 GeV errors for mN



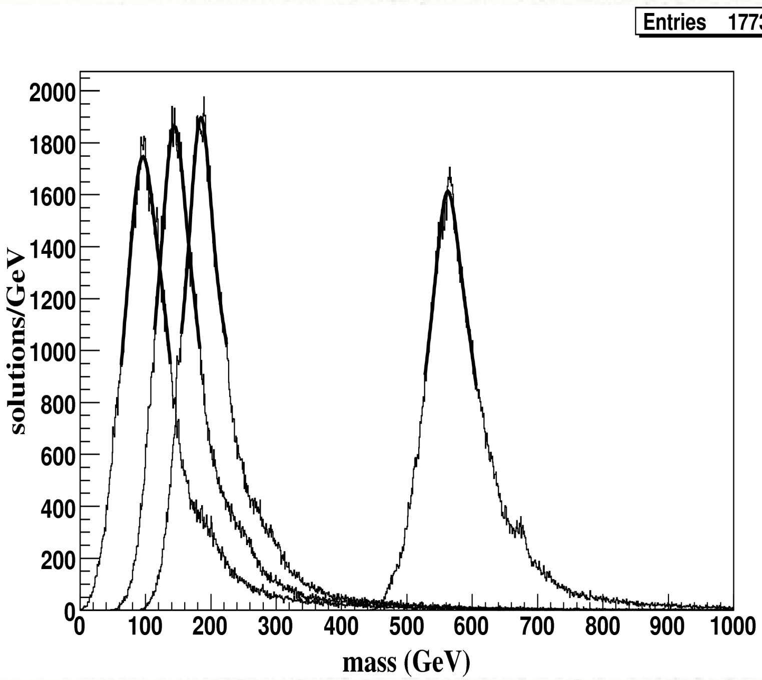
Without the dilepton edge cut

Another model point

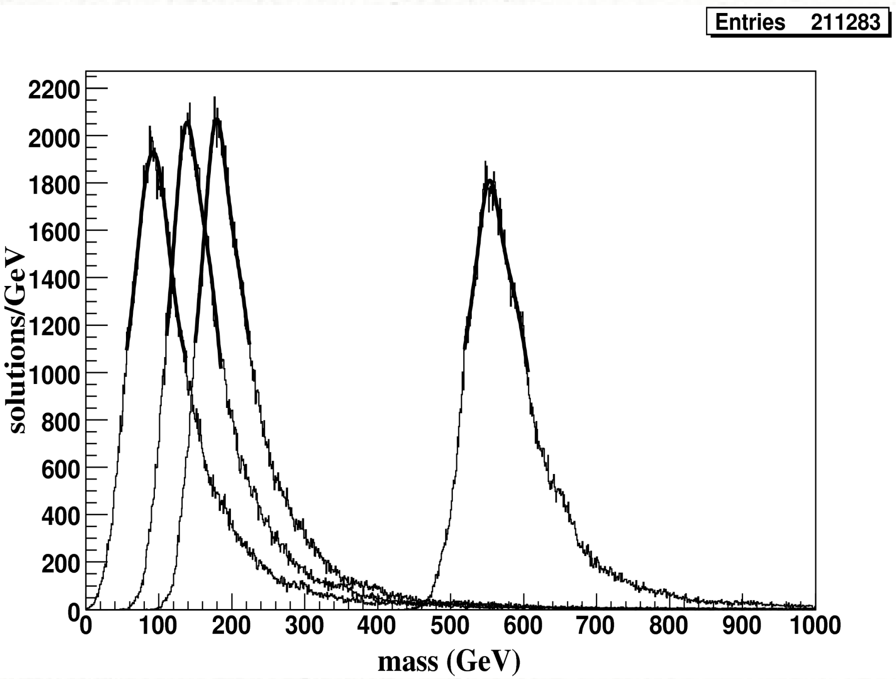
- Input masses: 85.3, 128.4, 246.6, 431.1/439.6



Model (spin) dependence?



SUSY

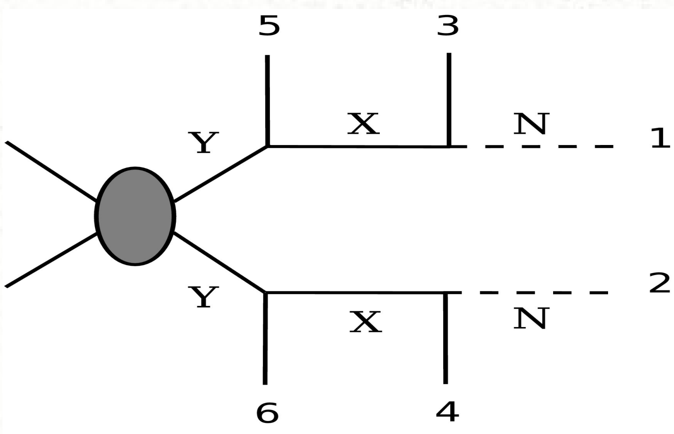


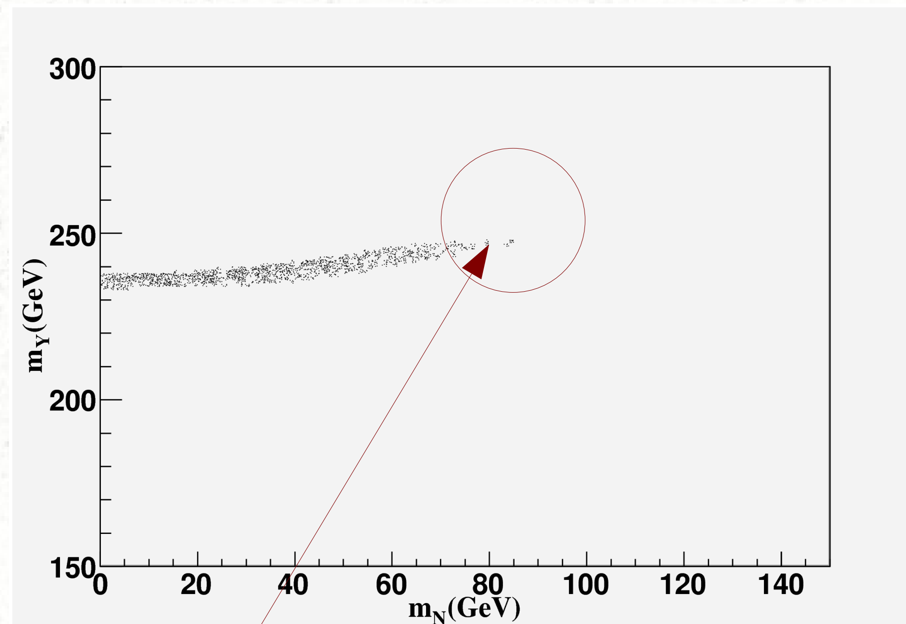
UED

Events generated with Herwig++, identical masses, spin correlation included
Can compare with Monte Carlo before knowing the model.

Other topologies

- Long decay chain: discrete solutions for the masses
- Shorter chains: constrain the mass space

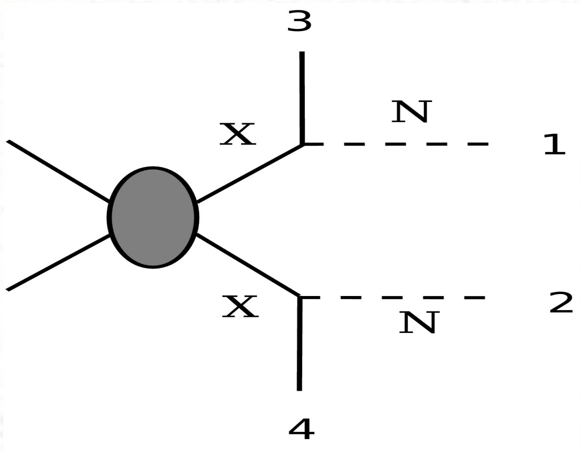


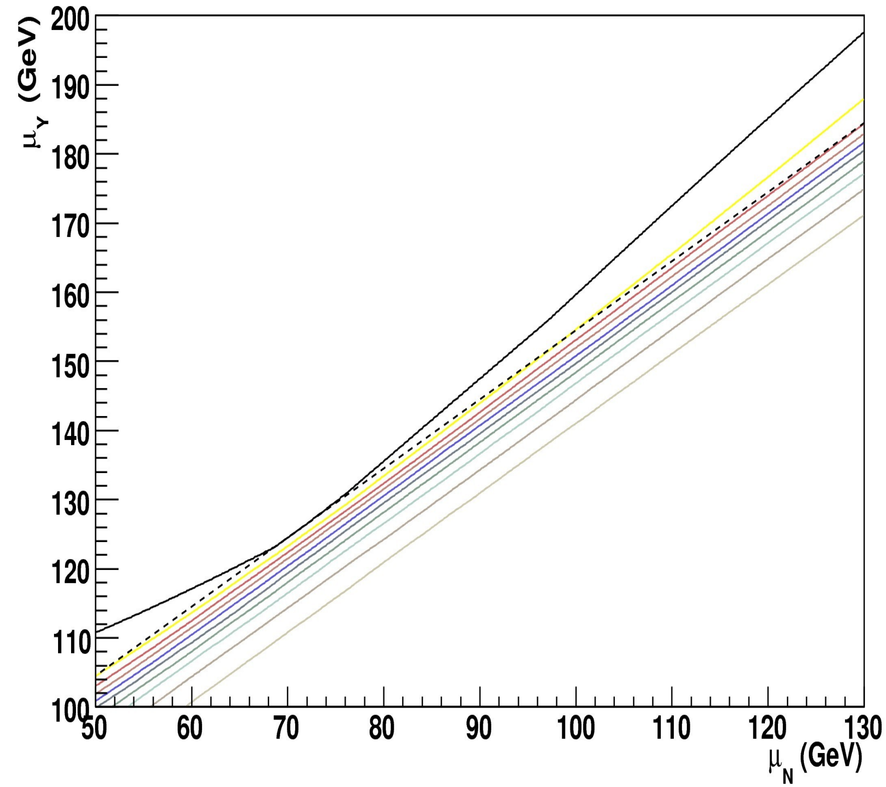


Bounded region, masses at the "tip" (Ref. 0707.0030)

Correct masses

Other topologies





Unbounded region,
mass at the “kink”
(MT2 kink)
(ref: 0810.5178)

Code

- Code available at

  http://particle.physics.ucdavis.edu/hefti/projects/doku.php?id=wimpmass

- Including all three topologies mentioned above

Spin measurements-the strategy

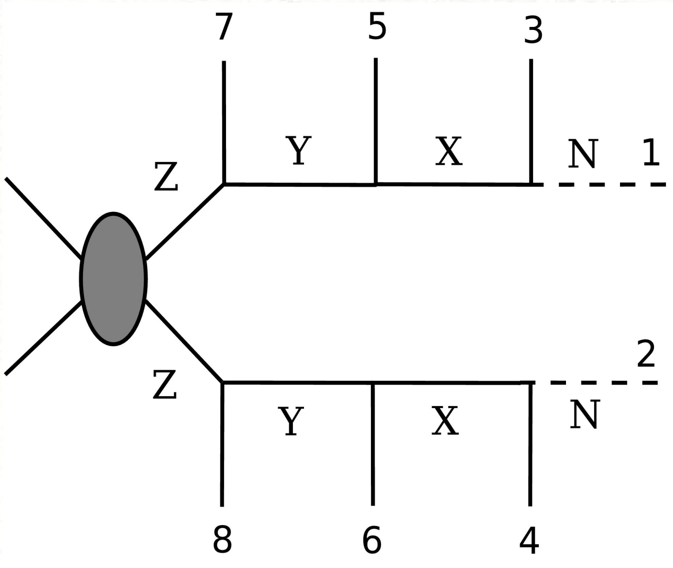
with H. Cheng, I. Kim and L. Wang

- Reconstruct the events—enough constraints
- Boost the particles to desired frame
- Look at the angular distributions

  --as if there are no missing particles.

Event reconstruction

- Assuming the masses are known, over-constrained system.
- chi square fit using experimental errors (under development)
- Simpler solution: first solve for p1, p2 using subsystem: particles 1-6 (leptons+missing Pt), then use 7 and 8 to select the "best" (closest to MZ) combination and solution. (~20-40% times get the correct combination).



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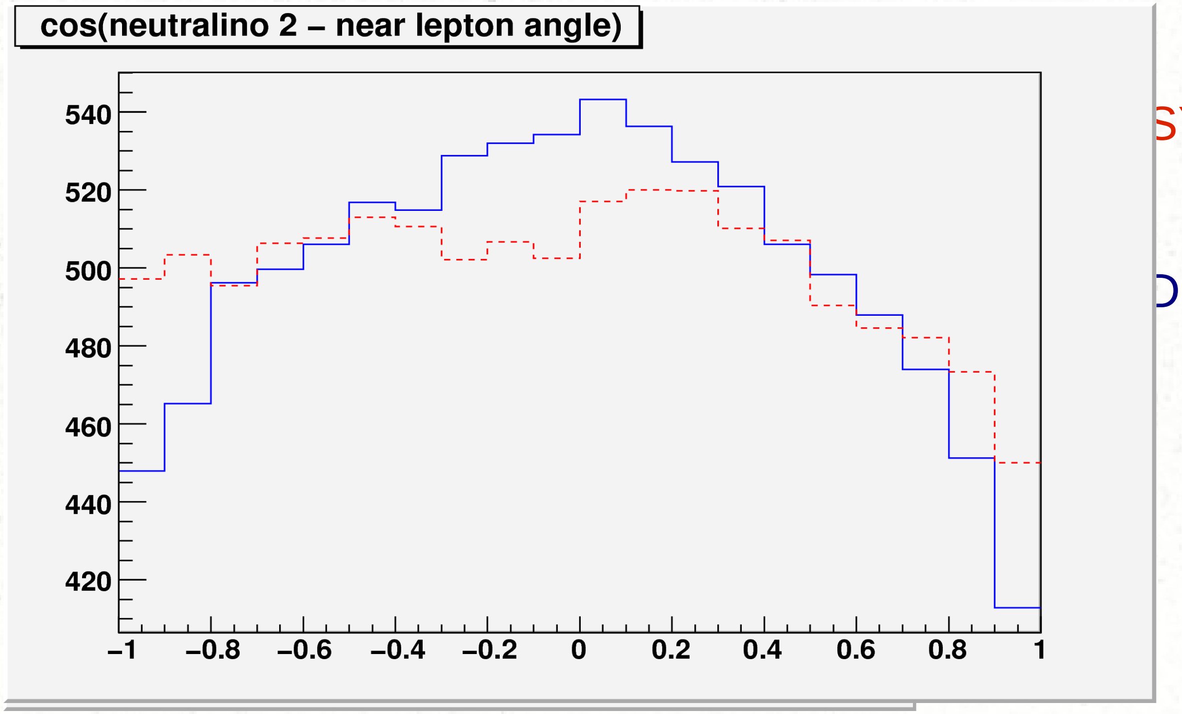
$$(p_1 + p_3 + p_5)^2 = (p_2 + p_4 + p_6)^2 = m_Y^2$$
$$(p_1 + p_3 + p_5 + p_7)^2 = (p_2 + p_4 + p_6 + p_8)^2 = m_Z^2$$
$$p_1^x + p_2^x = p_{miss}^x, \quad p_1^y + p_2^y = p_{miss}^y$$

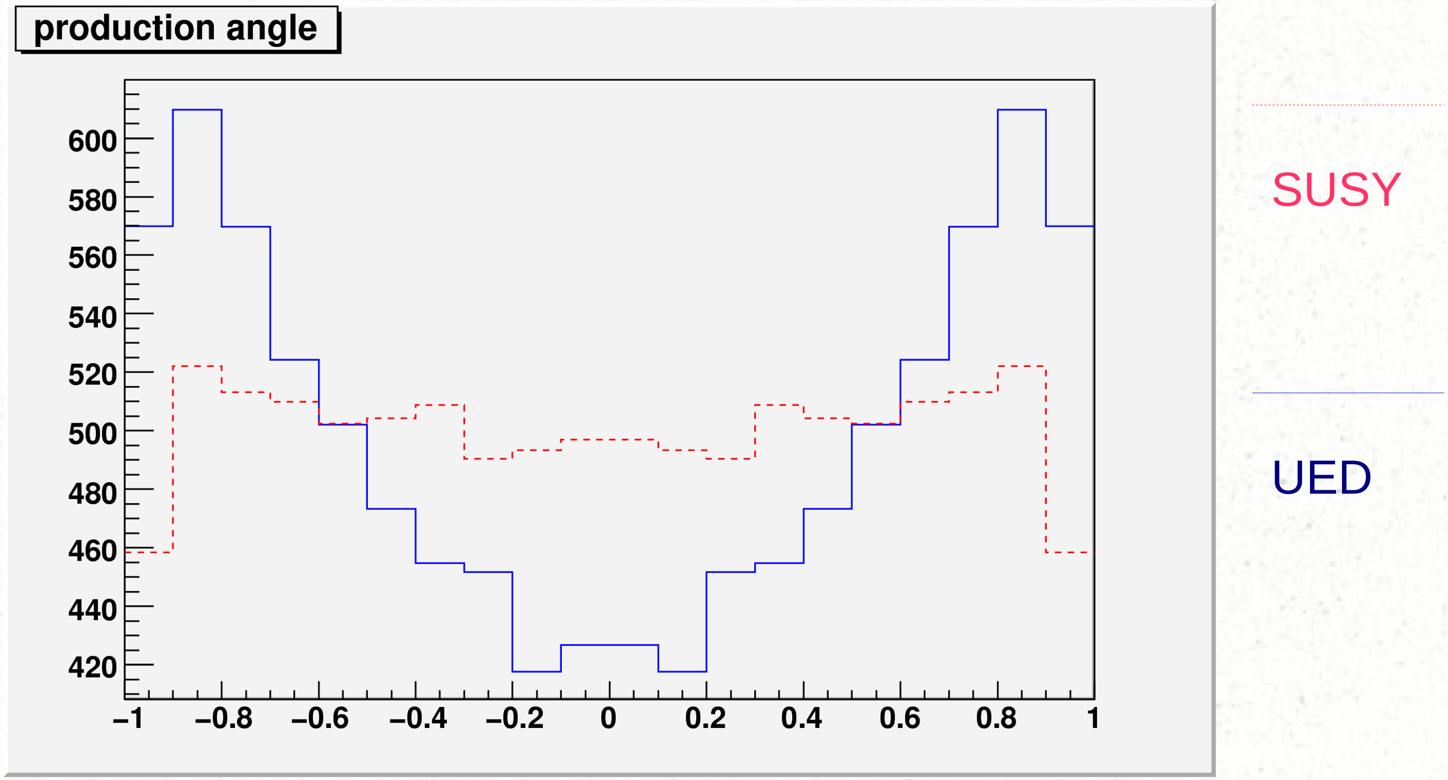
Compare UED and SUSY
after event reconstruction

- Daughter particle's angular distribution in the rest frame of the mother particle, with respect to the direction of the mother particle.



Also available in one decay chain case (invariant mass of ql)
What do we get from event reconstruction?

Production angle



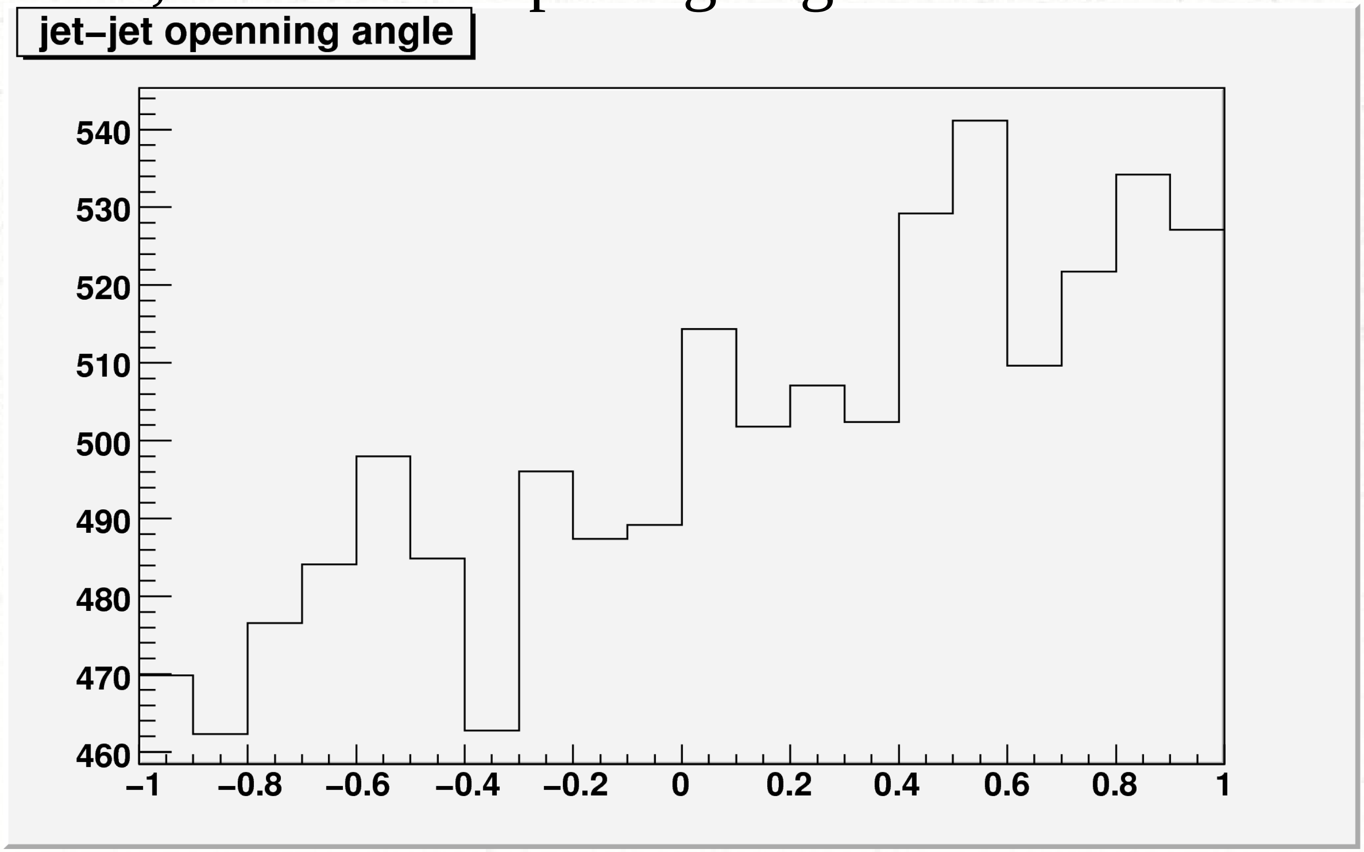
Sbottom/KK-bottom production

Spin correlation between the two chains

- The spins of the two KK-quarks are correlated, look at angular distribution correlations in the decay products—analogous to ttbar production
- Harder than ttbar: contributions from uubar/ddbar offset from gg
- Charge unknown
- Under study

Jet-jet opening angle

- Boost the jets to their respective mother particles' rest frames, look at the opening angle between them



Questions unanswered

- What other variables should we look at?
- What are the optimal cuts?
- How many events needed to distinguish different spins?

Conclusion

- Kinematic constraints are powerful for determining the masses at the LHC, do not need many events to obtain good precision
- Event reconstruction is possible for long enough decay chains, useful for spin determination
- More work needs to be done (asymmetric decay chains, likelihood fit, matrix element methods)