Spin Measurements in Events with Missing Energy at the LHC

Zhenyu Han
Harvard University

With Hsin-Chia Cheng, Ian-Woo Kim, Lian-Tao Wang
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Outline

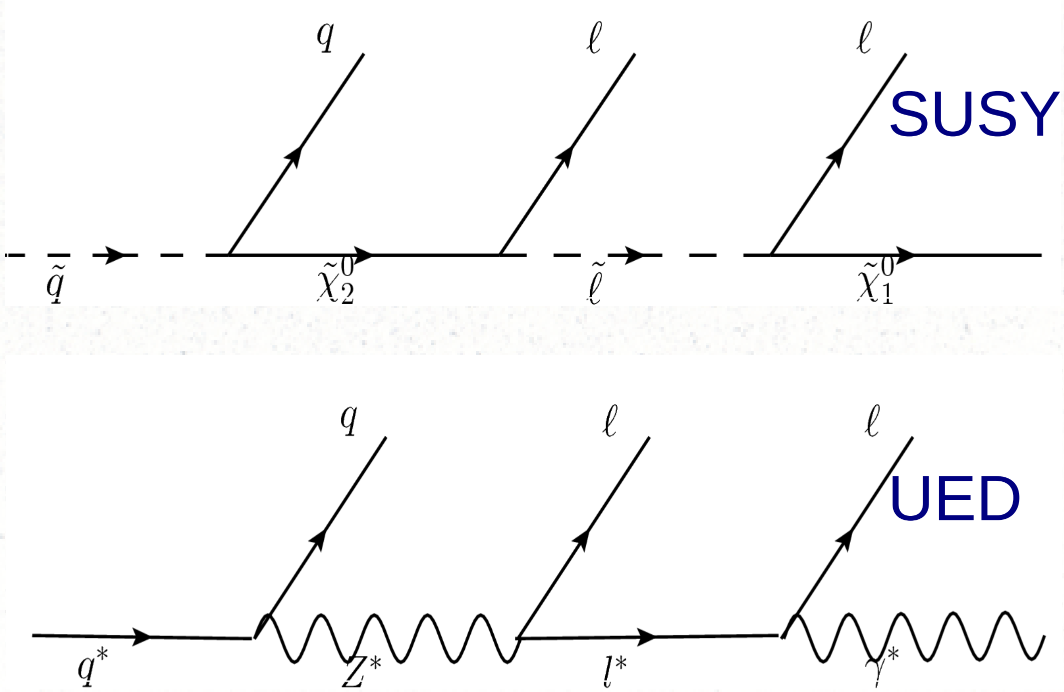
- Motivation
  - Spin determination important but difficult in events with missing energy
  - Existing methods have their limitations
- Obtaining spin correlation from event reconstruction
  - Single-chain case *vs* double-chain case
  - Under-constrained/solvable/over-constrained system
- Conclusion and outlook

Models with missing energy signature

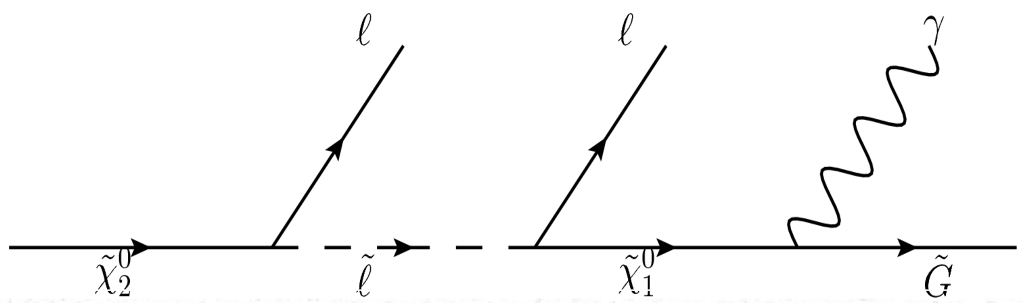
- SUSY (R-parity), UED (KK-parity), Little Higgs (T-parity)...

  Example process: $\widetilde{q} \to q\widetilde{\chi}_2^0 \to q\widetilde{\ell}\ell \to q\ell\bar{\ell}\widetilde{\chi}_1^0$

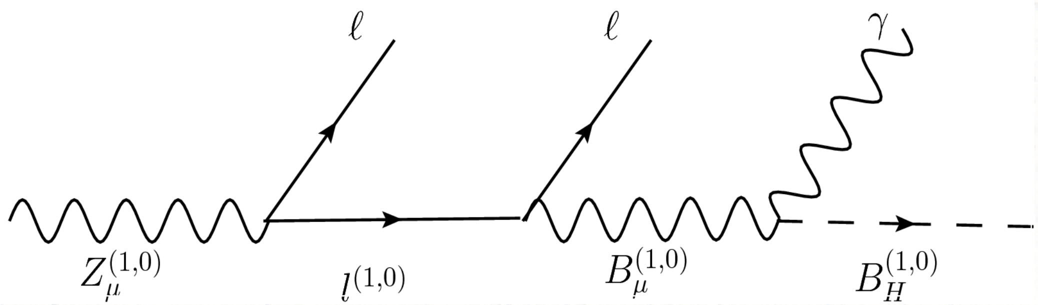
- Hard to reconstruct the kinematics due to two (or more) missing particles.



Another example



Gauge mediation



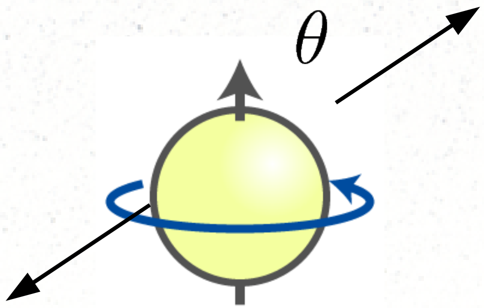
6D UED (*Burdman, Dobrescu, Ponton; Dobrescu, Kong, Mahbubani,*),
$B_H^{(1,0)}$: scalar “KK-photon”
Similar process in PQ-UED (*Csaki, Heinonen, Hubisz, Shirman*)

What's the theory?

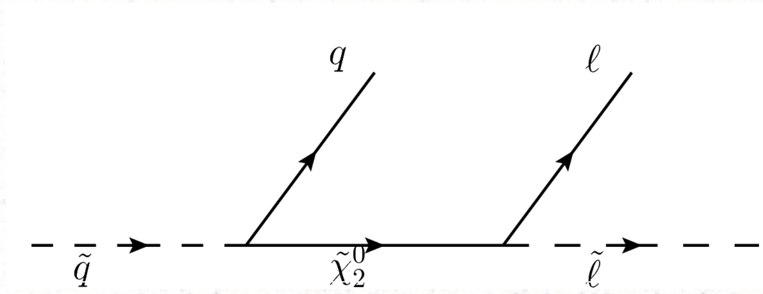
- Mass determination
- Spin determination
  - Cross-sections depend on spin
  - Kinematics: p_T
  - Invariant mass method
  - Event reconstruction method
    - Easier for e+e- machine (Buckley, Murayama, Klemm & Rentala)
    - Focus on LHC in this talk

Angular distribution of decay products

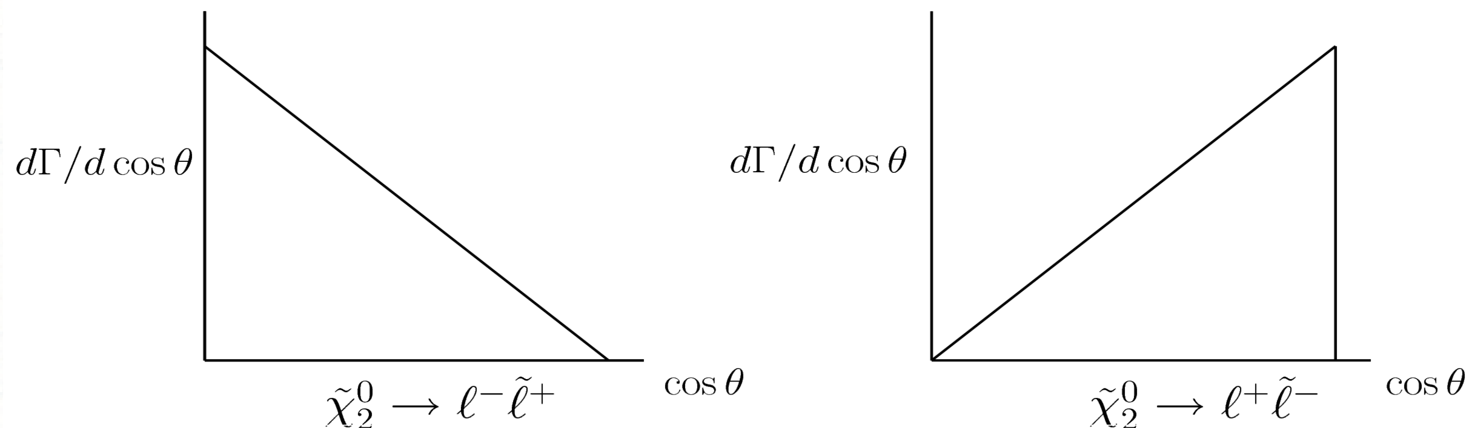
- Non-uniform angular distribution of decay product:
  - Polarized mother particle.
    - Helicity basis: reference direction is its own momentum
  - For fermions: chiral coupling for the decay.
- The angular distribution is a polynomial of $\cos\theta$ of order 2*Spin. θ: defined in the rest frame of mother particle



An example



$$\tilde{q} \to q_L \tilde{\chi}_2^0 \to q_L \ell_R \tilde{\ell}_R$$



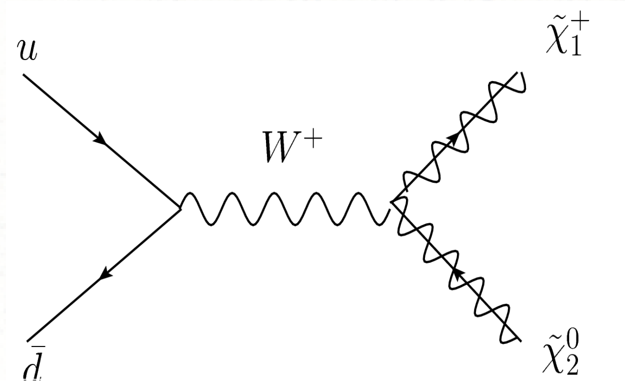
Equivalent to invariant mass distribution of quark-lepton.

- *Barr, 2004*
- *Smillie, Webber , 2005, 2006*
- *Kilic, Wang, Yavin, 2006, 2007*
- *Burns, Kong, Matchev, Park, 2008*
- *Ehrenfeld, Freitas, Landwehr, Wyler, 2009*

Limitation of inv. mass methods

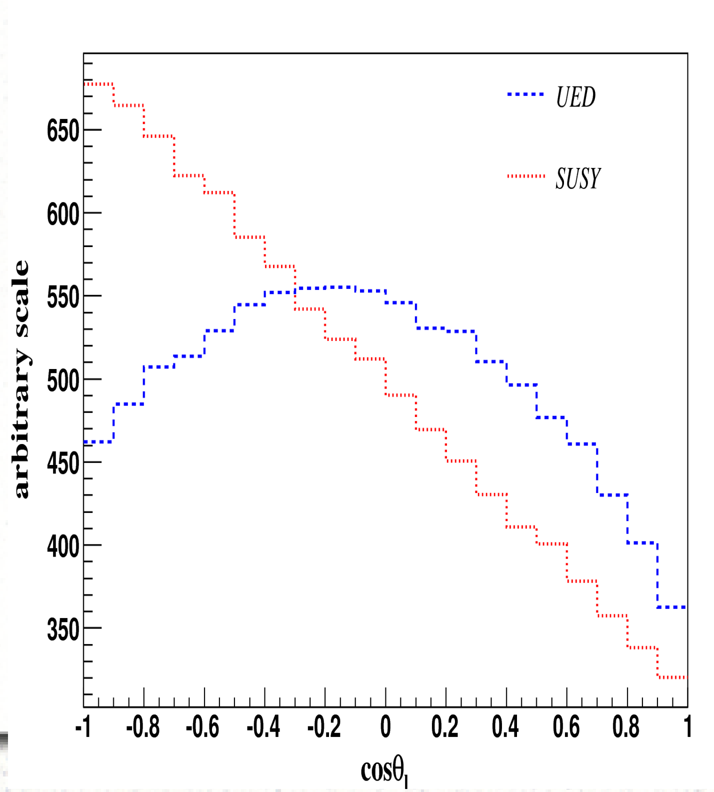
- The invariant mass distribution of two adjacent visible particles measures the spin of the particle in between.
- Can we measure the spin of the first particle in the decay chain?
  - It needs to be polarized
  - Need to reconstruct its momentum

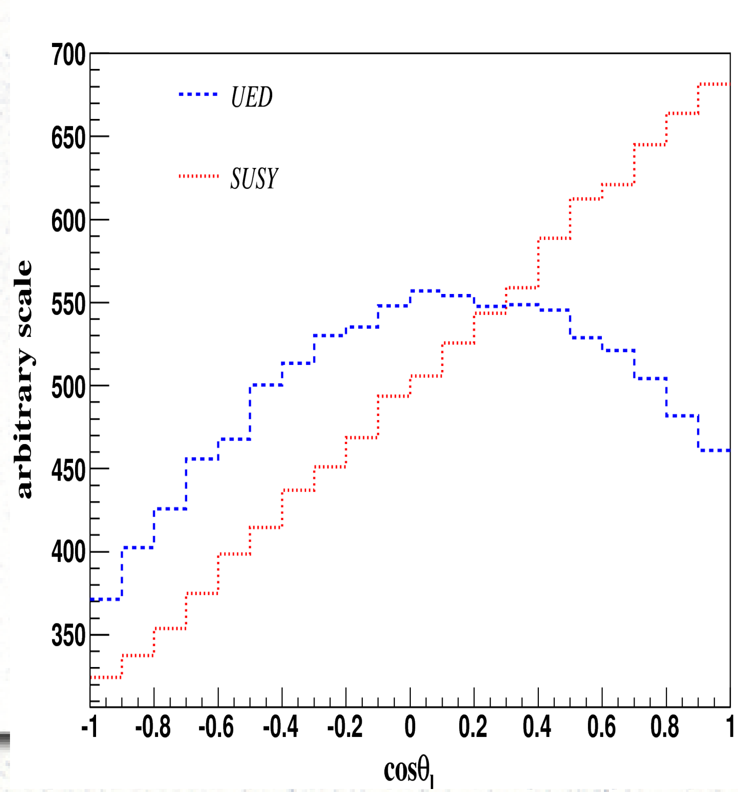
Chargino/neutralino production



- Similar for KK-Z/KK-W in UED
- Neutrlino 2 is polarized (in the lab frame)
- Need to reconstruct the momentum

$$\tilde{\chi}_2^0 \to \ell_R \tilde{\ell}_R$$

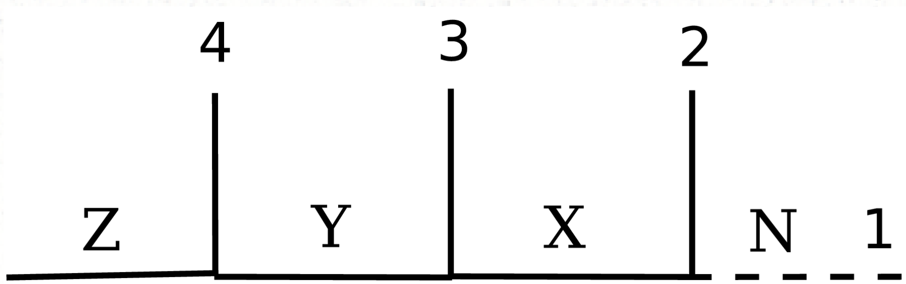




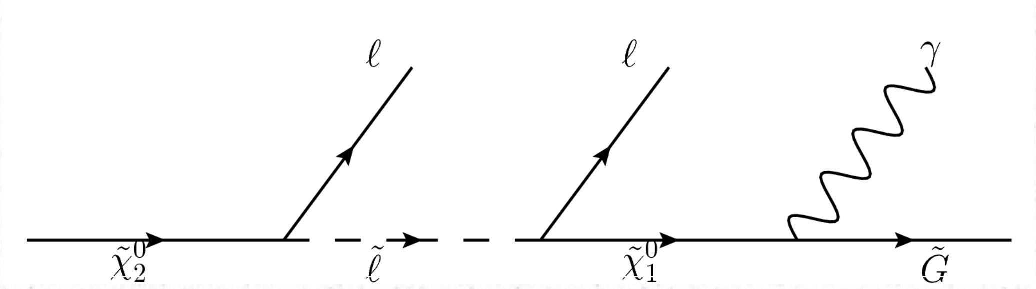
Reconstruct the missing particle's momentum --single decay chain case

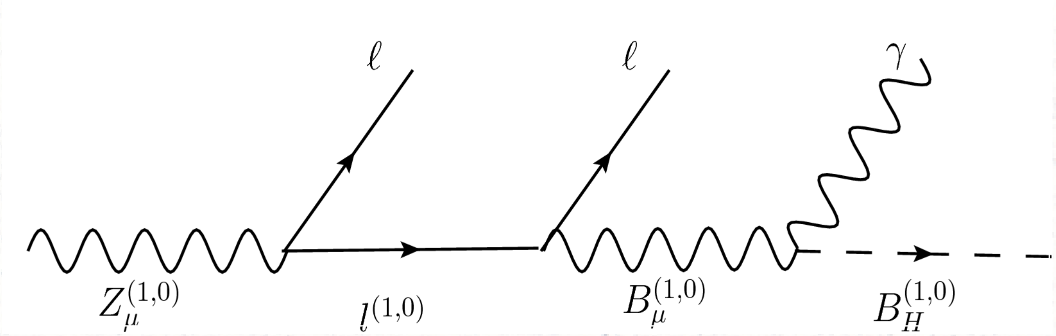
- Assuming masses are known.
- 4 unknowns: missing particle 4-momentum—need four equations.

$$p_1^2 = M_N^2$$
$$(p_1 + p_2)^2 = M_X^2$$
$$(p_1 + p_2 + p_3)^2 = M_Y^2$$
$$(p_1 + p_2 + p_3 + p_4)^2 = M_Z^2$$



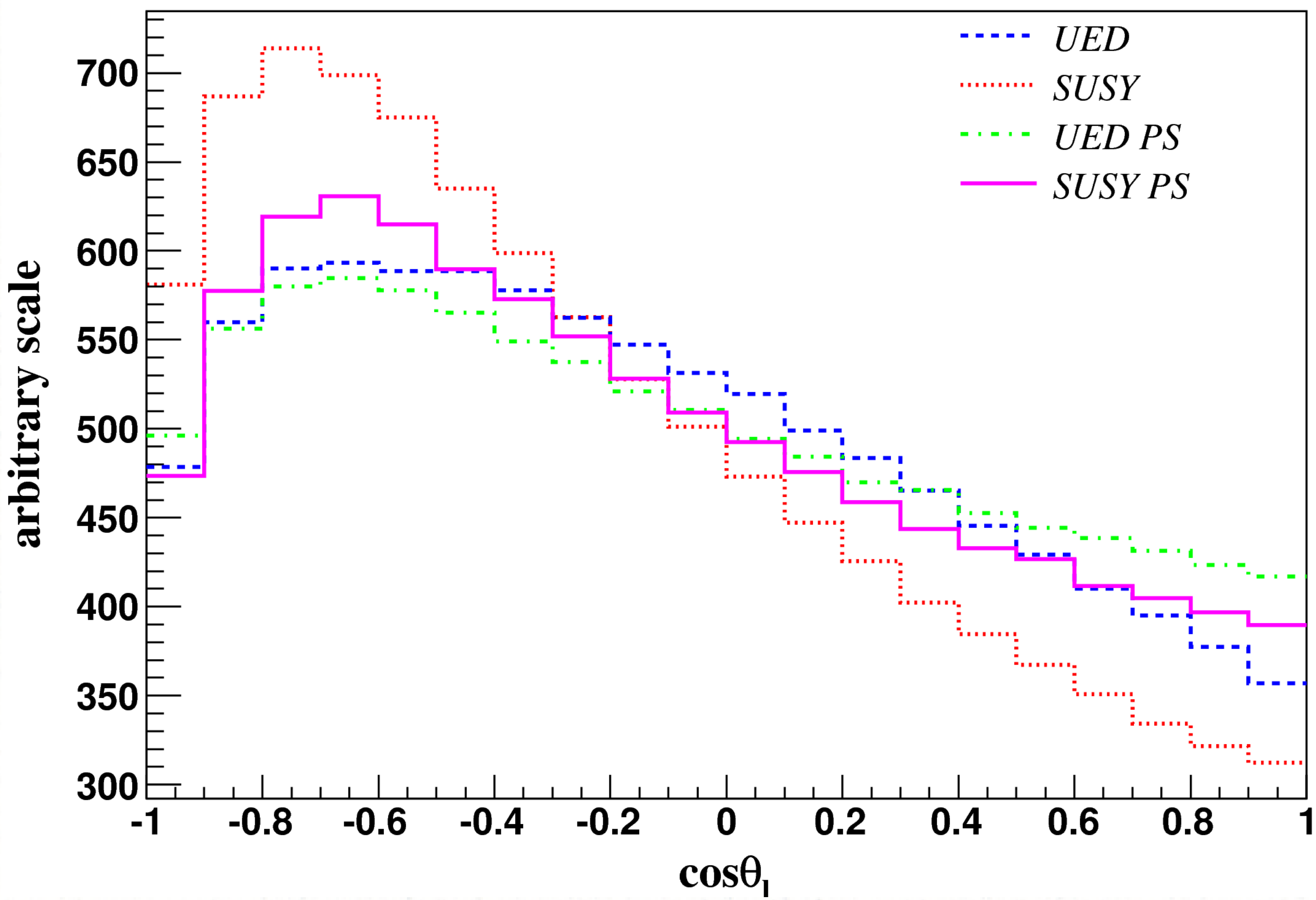
Chargino/neutralino in gauge mediation





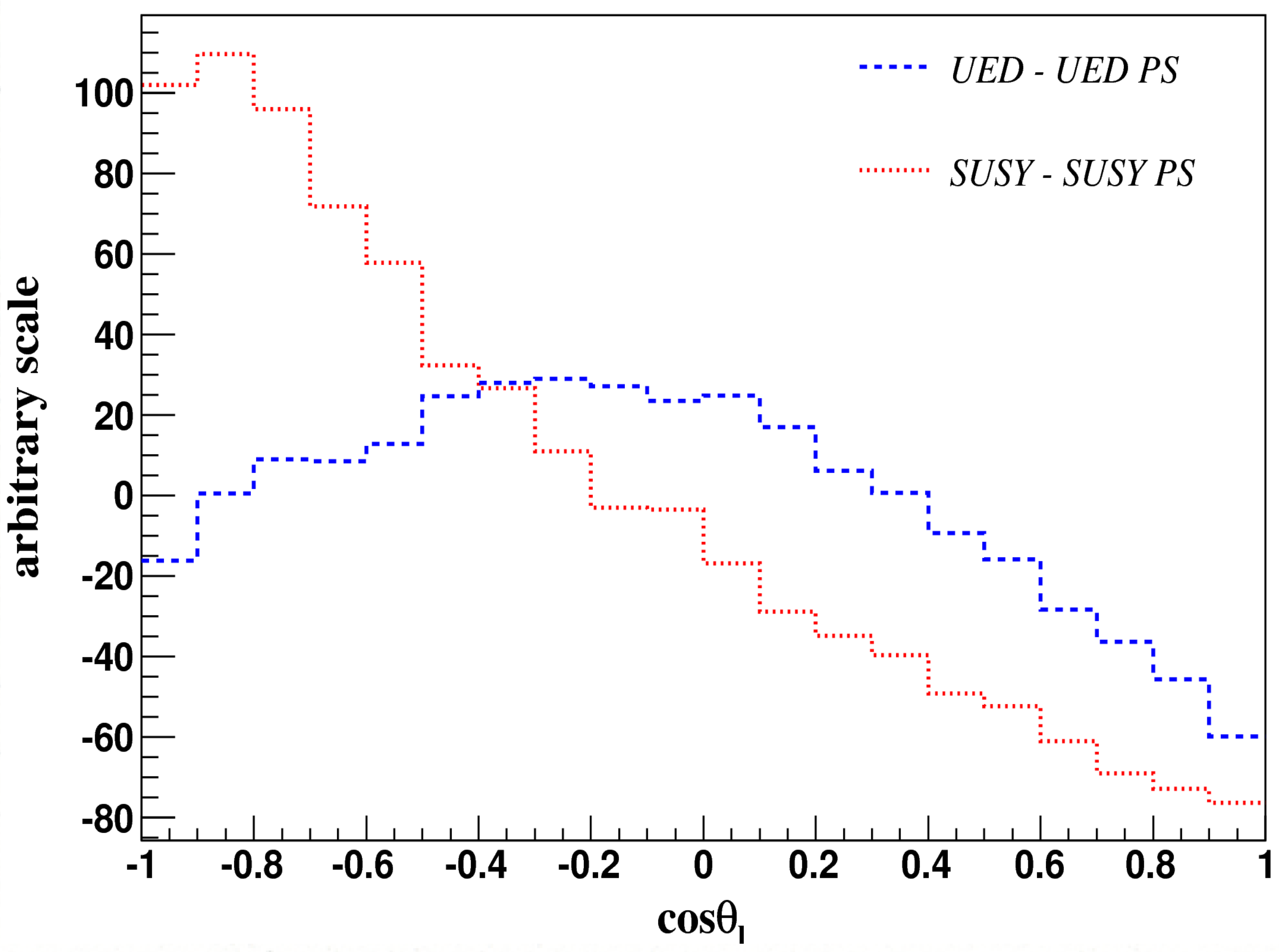
- 2 leptons not enough for reconstruction. Extra photon in gauge mediation. Similar for PQ/6D-UED

Reconstructed distributions

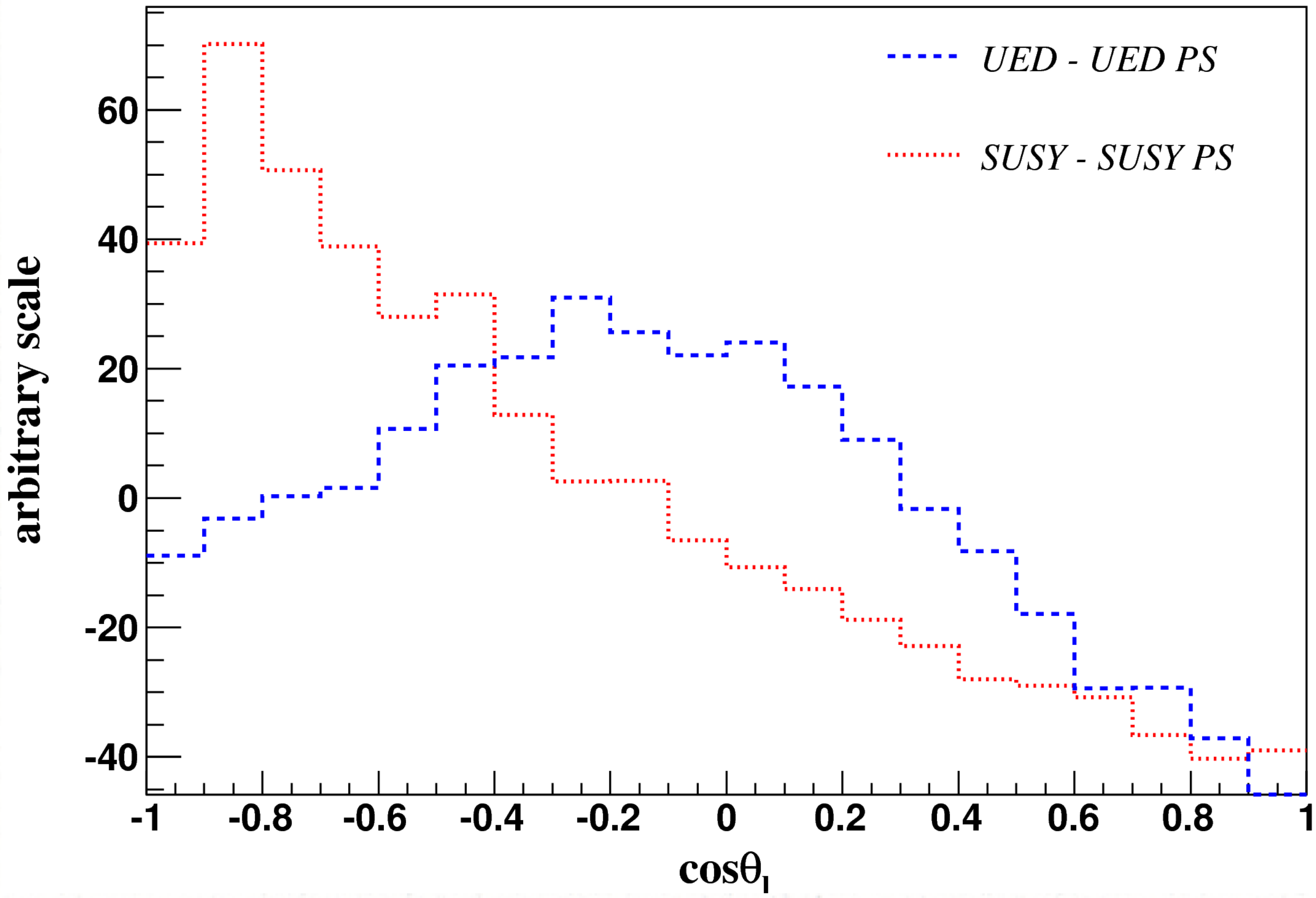


Distributions contaminated by wrong solutions, wrong combinations.

Subtracted from phase space distributions



Smeared distribution

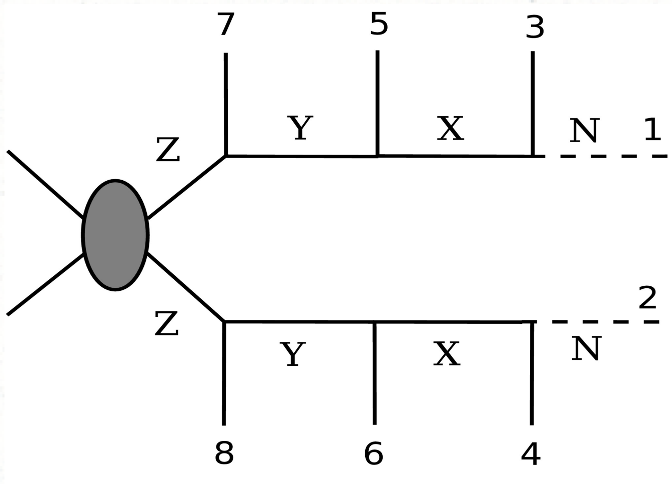


Experimental resolutions included

General counting of the constraints

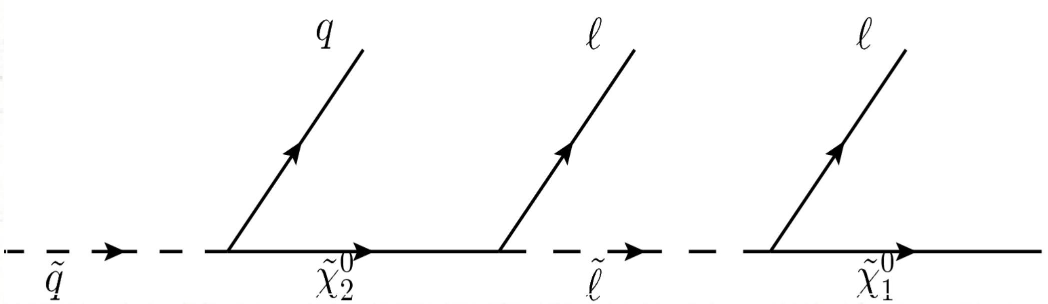
- One chain case: 4 unknowns, *i.e.*, 4-momentum of the missing particle
  - 4 on-shell particles, 3 visible particles: solvable
  - More than 4 on-shell particles: over-constrained
- Two chain case: 8 unknowns
  - 2 extra constrains from measured missing transverse momentum
  - 6 on-shell particles needed to solve, more than 6: over-constrained.

Over-constrained system



$$
\begin{aligned}
f_1 &= p_1^2 - m_N^2 \\
f_2 &= (p_1 + p_3)^2 - m_X^2 \\
\cdots \\
f_9 &= p_1^x + p_2^x - p_{miss}^x \\
f_{10} &= p_1^y + p_2^y - p_{miss}^y
\end{aligned}
$$

- $f_i = 0$ cannot be all satisfied (10 equations, 8 unknowns).



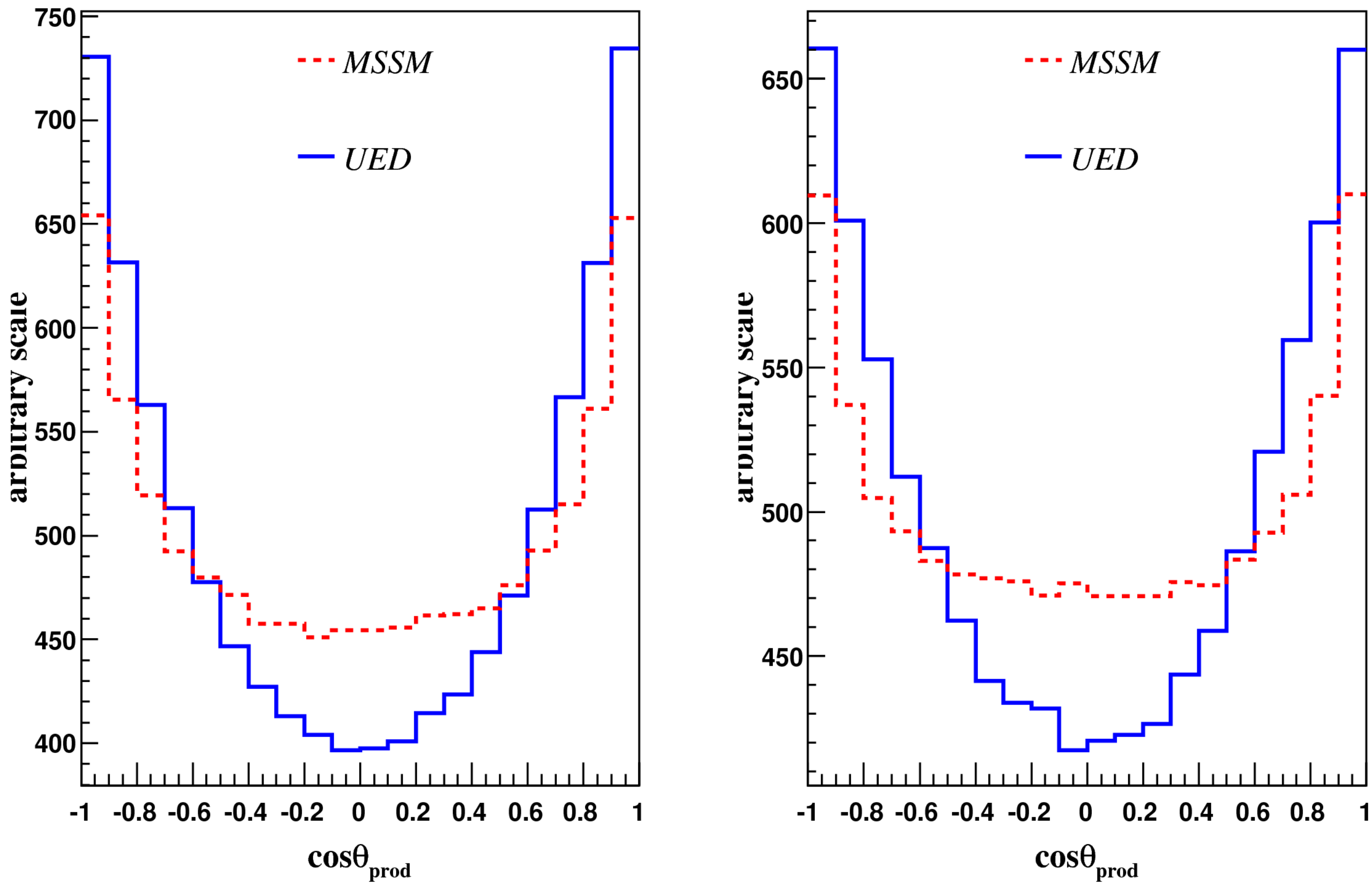
Likelihood fit

- A simplified version:

$$\chi^2 = \sum_i \left(\frac{f_i}{\delta f_i} \right)^2 , \quad \delta f_i^2 = \sum_{x = p_{vis}, m} \left(\frac{\partial f_i}{\partial x} \delta x \right)^2$$

- Find p_1 , p_2 that minimize χ^2
- We used a more complicated formalism where the correlations among the equations/measurements are taken into account.

Production angle depends on spin



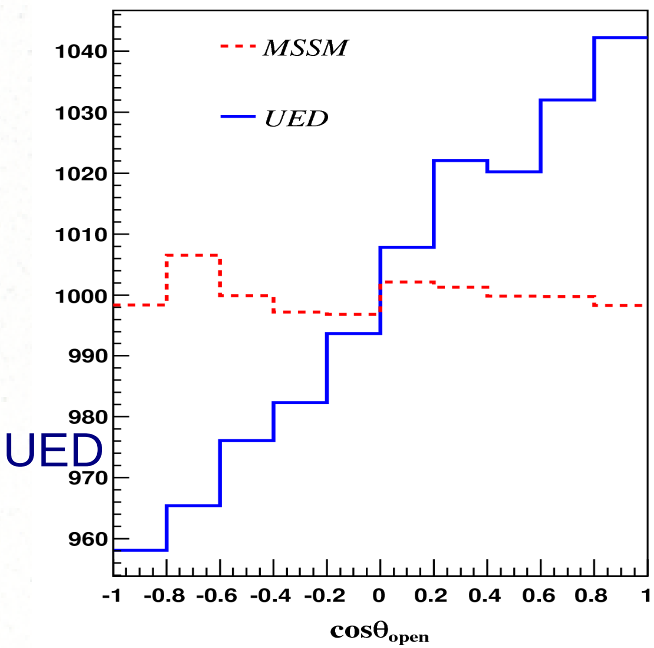
MC

Reconstructed

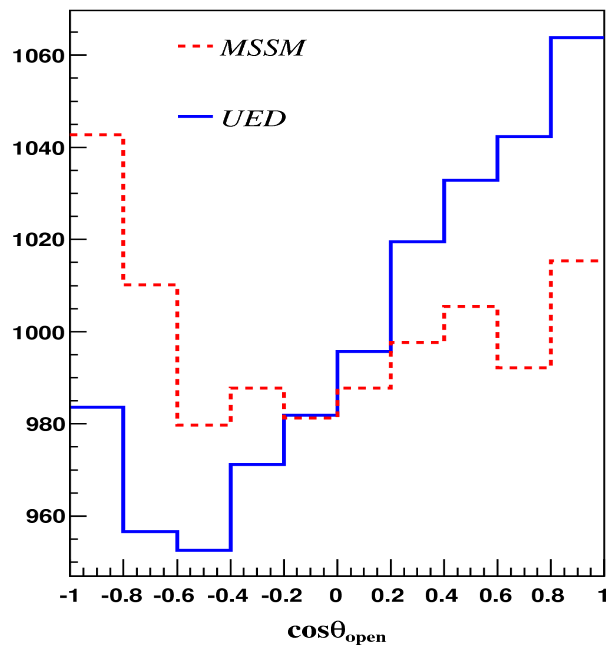
sbottom/KK-bottom production

Spin correlation between two chains

- Jet-jet opening angle (Boost the jets to their respective mother particle's rest frame, look at the angle between them.)



MC



Reconstructed

Conclusion

- It is often possible to reconstruct the missing particles' momenta if all masses are known—spin is determined in the same way as when all particles are visible.
- We obtain spin information that is only available after event reconstruction.
- Depending on whether the system is solvable or over-constrained, and whether we want to examine a single chain or both chains, apply different methods.