Universal Extra Dimensions

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LHC is coming, what do we expect to see? Will we know what we discover if we see something at the LHC?

Hints we have for new physics @ 1 TeV:

- Electroweak symmetry breaking: New Physics @ TeV should explain the origin of the electroweak symmetry breaking, and/or the associated hierarchy problem. Possibilities include new interactions and new particles which cancel the quadratically divergent contributions to the Higgs masses squared from the Standard Model, or unitarize the WW scattering amplitude at high energies.

- Dark matter (best evidence for new physics beyond the Standard Model): If the dark matter is the thermal relic of a WIMP, its mass should be of the weak scale,

$$\Omega_{\rm wimp} \sim \left(\frac{1}{10^2\alpha}\right)^2 \left(\frac{m_{\rm wimp}}{1\ \rm TeV}\right)^2$$

⇨ A stable (electrically) neutral weakly interacting particle at or below 1 TeV. To be stable, it should be the lightest particle charged under a new symmetry.

- Electroweak precision measurements: There is no evidence of deviations of the EW observables from the SM predictions. (The little hierarchy problem)

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \|H^+ D_\mu H)\|^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

(Barbieri and Strumia '00)

New physics contributions to these EW observables should be suppressed. This is possible if new particles charged under a new symmetry under which SM is neutral. Then their contributions will be loop-suppressed.

A plausible scenario by taking these hints seriously:

New particles (vector bosons, fermions, scalars) at TeV are charged under a new symmetry (the simplest possibility is a Z_2 parity) and the lightest one (LPOP) is electrically neutral.

Collider phenomenology: Pair productions of these new particles. Their cascade decays down to LPOP give rise to missing energy plus jets and/or leptons.

What is the new physics if we see jets/leptons + missing energy at the colliders?

The standard answer: Supersymmetry (with R-parity)! For a long time, this is the only candidate.

From the above discussion, we see that any new physics satisfying the hints we have now may show up at the LHC with similar signals.

In the last few years, there have been several such SUSY-fakers proposed:

- Universal Extra Dimensions (UEDs) (this talk)
- Little Higgs theories with T-parity (M. Schmaltz's talk)

Universal Extra Dimensions

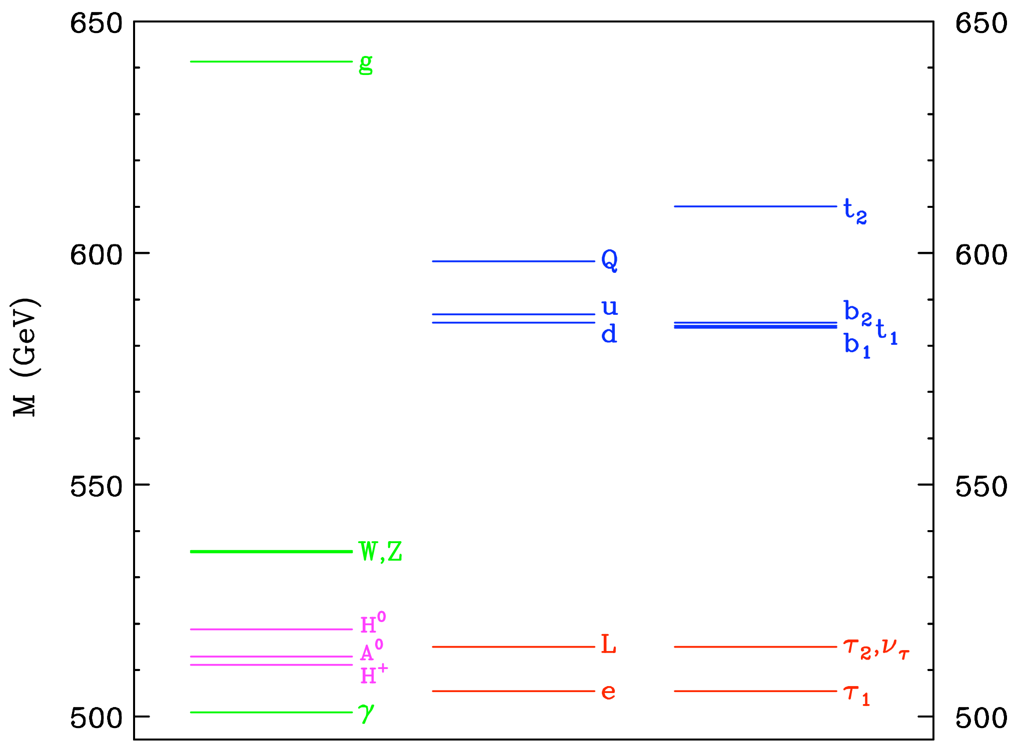
(Appelquist, HC, Dobrescu, hep-ph/0012100)

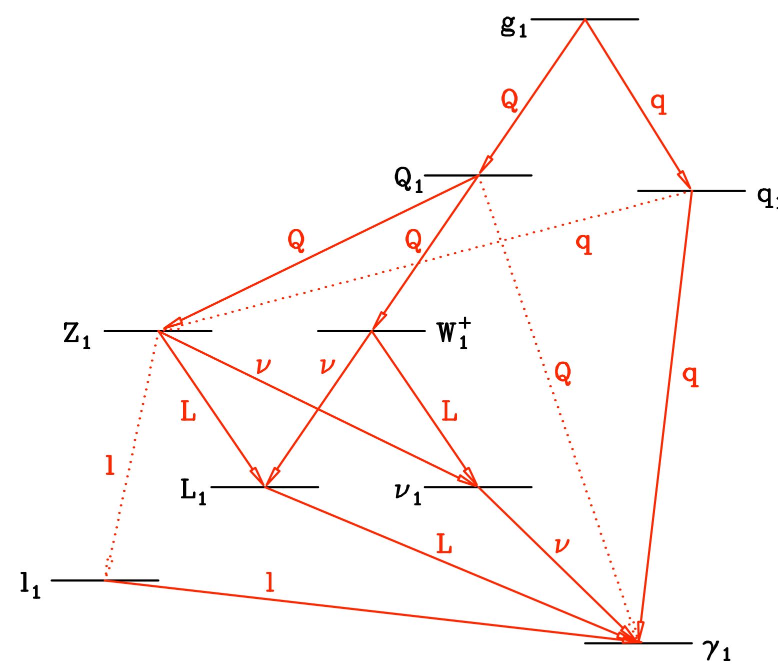
- All Standard Model fields propagate in the same extra dimensions.
- To have 4D chiral fermions, the extra dimensions should be compactified on an orbifold.
- From the 4D point of view, there are Kaluza-Klein (KK) towers of states for all SM particles, with masses governed by the inverse of the compactified radius.

Simplest possibility: one extra dimension on S^1/Z_2

- Masses of the KK states = n/R + corrections from boundary terms and finite nonlocal bulk contributions.
- Boundary terms receive divergent radiative corrections from the bulk interactions, so counter terms must be included.
- A KK-parity $(-1)^n$ is preserved by radiative corrections , so it can be consistently imposed.

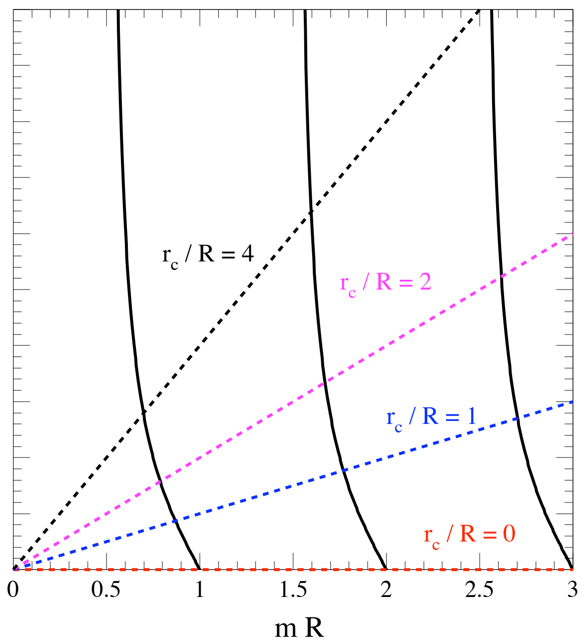
Minimal UEDs (boundary terms vanish at the cutoff)

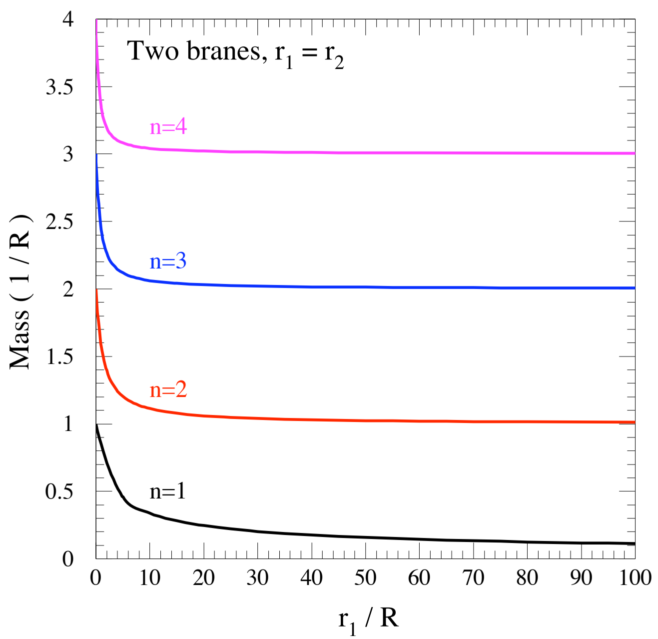




HC, Matchev, Schmaltz, hep-ph/0204342, 0205314

The approximate degeneracy at each KK level may be altered by large boundary terms, or more creative model-building.





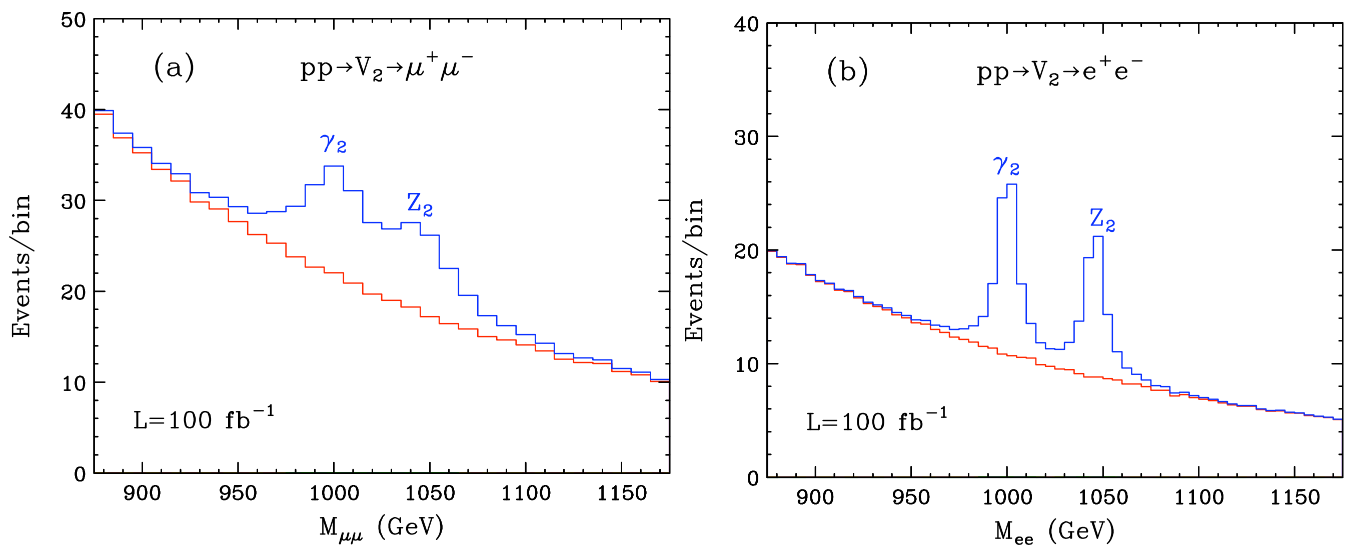
Carena, Tait, Wagner, hep-ph/0207056

There are two robust distinctions between UEDs and SUSY:

- KK excitations and superpartners have different spins.
- There are higher levels of KK excitations in UEDs.

Collider Searches for Level 2 KK Particles

Level 2 KK particles are even under KK-parity. They can be singly produced and decay back to SM particles (through boundary terms).

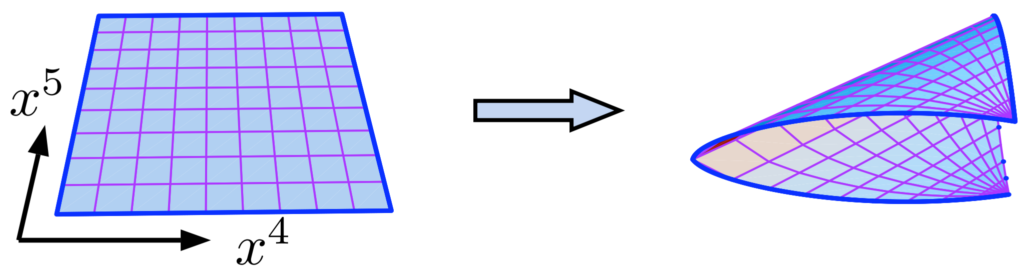


Level 2 gauge bosons, Datta, Kong, Matchev, hep-ph/0509246

Can it be SUSY + Z's?

The masses of the level 2 particles also depend on the number and the shape of extra dimensions.

E.g., 2 extra dimensions on a chiral square, T^2/Z_4
(Burdman, Dobrescu, Ponton, hep-ph/0506334, 0601186)



- Level 2 (1,1) mass: $M_{(1,1)} \sim \sqrt{2} M_{(1,0)}$

- Existence of "spinless adjoints" from extra components of the gauge fields, which decay predominately to top quarks.

Spin Measurements at LHC

- To distinguish SUSY from its fakers such as UED or T-parity, we need to measure the spins of the produced particles.
- It's quite a challenge at a hadron collider.
  - 2 missing particles, CM frame not known
  - Complicated decay chains, hard to identify subchains
- Need MC tools which keep spin correlations

Spin measurements at LHC

Tools available or being developed (as far as I know and see talks in this workshop):

Public:

SUSY with Herwig

SUSY with MadGraph (SMadGraph)

Private:

UEDs with CompHEP (Kong and Matchev)

UEDs+more with Herwig (Yavin)

T-parity with MadGraph (Hubisz, Meade, Reece)

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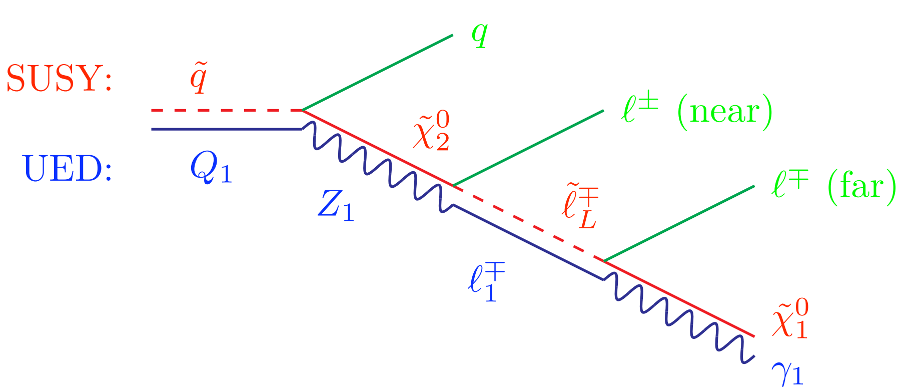
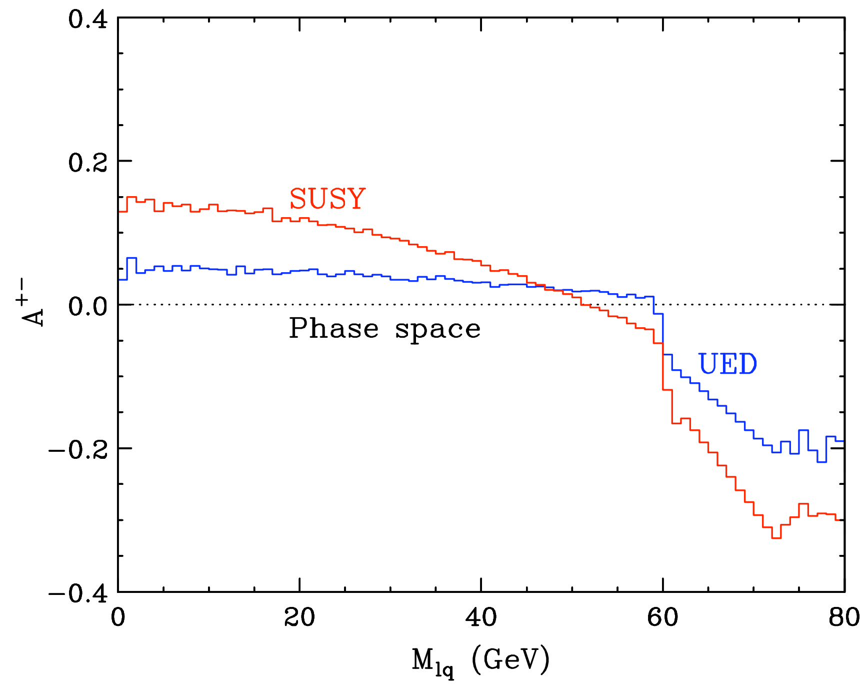
Spin Measurements at LHC

Some attempts

Barr hep-ph/0405052
Smille, Webber, hep-ph/0507170
Datta, Kong, Matchev, hep-ph/0509246





$$A^{+-} \equiv \left(\frac{dN(q\ell^+)}{dM_{ql}} - \frac{dN(q\ell^-)}{dM_{ql}}\right) \Big/ \left(\frac{dN(q\ell^+)}{dM_{ql}} + \frac{dN(q\ell^-)}{dM_{ql}}\right)$$

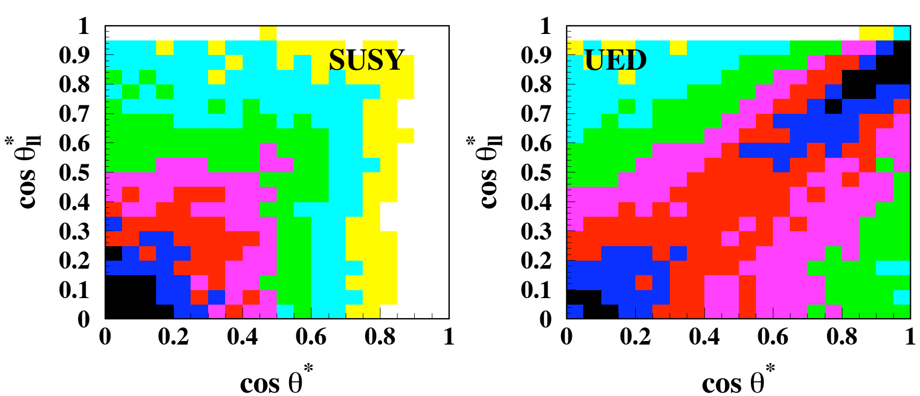
Spin Measurements at LHC

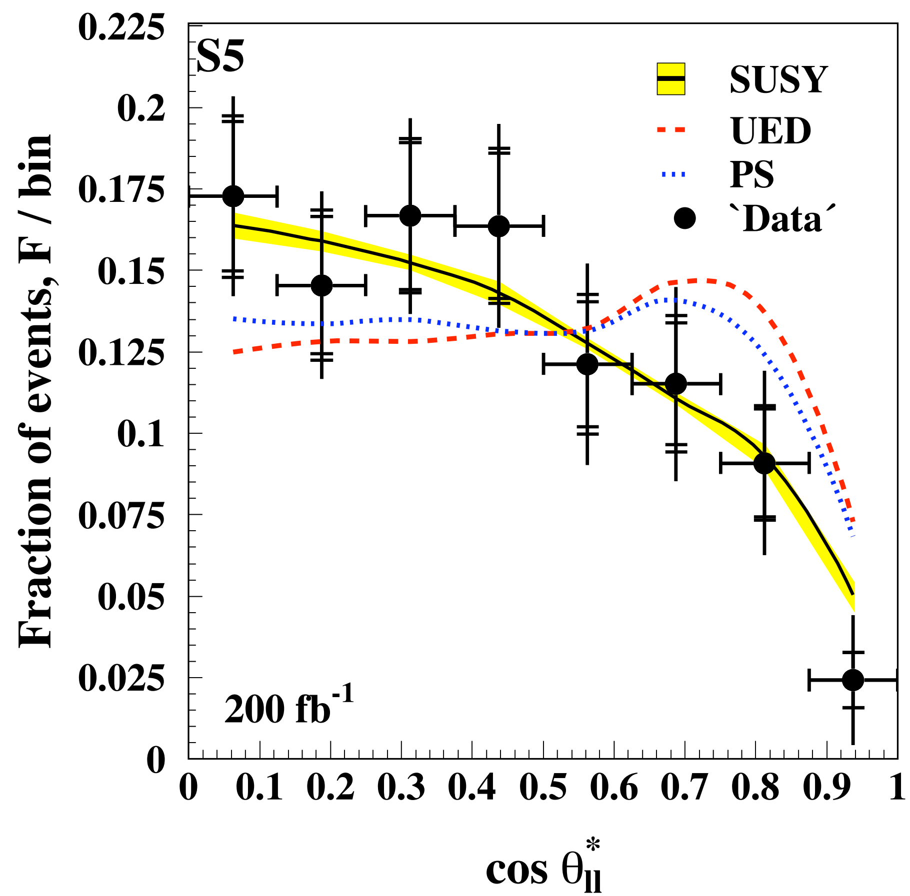
Barr, hep-ph/0511115

$$q\bar{q} \to Z^0/\gamma \to \tilde{\ell}^+\tilde{\ell}^- \to \tilde{\chi}_1^0\ell^+\ \tilde{\chi}_1^0\ell^-$$

vs

$$q\bar{q} \to Z^0/\gamma \to \ell_1^+\ell_1^- \to \gamma_1\ \ell^+\gamma_1\ \ell^-$$





$$\cos\theta^*_{ll} \equiv \cos\left(2\tan^{-1}\exp(\Delta\eta_{\ell^+\ell^-}/2)\right) = \tanh(\Delta\eta_{\ell^+\ell^-}/2)$$

Spin Measurements at LHC

Meade and Reece, hep-ph/0601124

$$g\,g,\ q\,\bar{q} \to t'\,\bar{t'}\ \left(\text{or } \tilde{t}\,\bar{\tilde{t}}\right) \to t\,\bar{t} + \not{E}_T$$

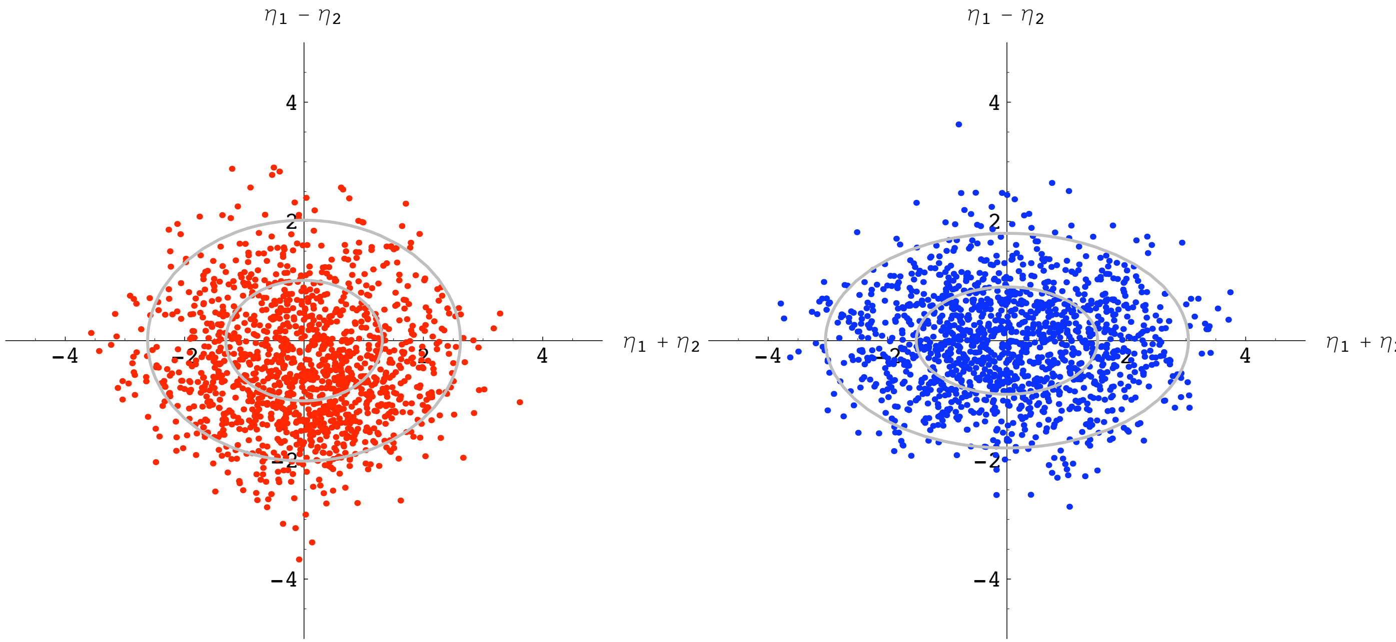


Figure 5: Distribution of events in the (η_+, η_-) plane for two points with similar cross-section and kinematics but different spins, with one and two sigma contours. At left: t' fermion, mass 700 GeV, N scalar, mass 400 GeV, $(\sigma_+, \sigma_-) = (1.31, 1.01)$; at right, t' scalar, mass 500 GeV, N fermion, mass 150 GeV, $(\sigma_+, \sigma_-) = (1.52, 0.90)$. In the lighter ($t'$ scalar) case, there is on average more boost, so the ellipse is stretched more along the η_+ axis.

Conclusions

- LHC is finally coming. Particle physics is entering an exciting new era.
- New physics beyond SM is expected to be discovered, but will we know what it is?
- Many candidates for new physics have similar signatures at LHC (e.g., SUSY, UEDs, T-parity).
- More complete MC tools are needed to study and distinguish various possibilities.
- A lot of work remains to be done!