Phenomenology of Universal Extra Dimensions

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Outline

- Universal Extra Dimensions (UEDs)
- Astrophysical Implications
  - Relic Density of KK Dark Matter
  - Direct Detection Limit
- Collider Phenomenology of UEDs
  - Level 2 search at the LHC
  - Spin determinations (at the LHC and a linear collider)
- Summary

Hints for New Physics Beyond the Standard Model

- Dark Matter: 23% of the unknown in the universe
  - 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

$$\Omega_{WIMP} \sim \left(\frac{1}{10^2\alpha}\right)^2 \left(\frac{M_{WIMP}}{1\ TeV}\right)^2$$

  - Requires a stable (electrically) neutral weakly interacting particle at $\mathcal{O}(1)$ 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
  - New physics contributions to the EW observables should be suppressed
  - Possible if new particles are charged under a new symmetry under which SM is neutral
  - Their contributions will be loop-suppressed and the lightest particle is stable

$\Rightarrow$ Collider implications:

  - Pair production of new particles
  - Cascade decays down to the lightest particle give rise to missing energy plus jets/leptons
  - KK-parity in UED

“Confusion scenario”

- What is new physics if we see jets/leptons + missing energy at the colliders?
- The standard answer: Supersymmetry with R-parity
  $\longrightarrow$ for a long time, this was the only candidate
- From the above discussion, we see that any new physics satisfying hints we have may show up at the LHC with similar signals
- Michael Peskin’s name for different kinds of new heavy particles whose decay chains result in the same final state
- How can we discriminate SUSY from confusion scenarios?
- How do we know new physics is SUSY?
- UEDs, Little Higgs $\cdots$

Universal Extra Dimensions

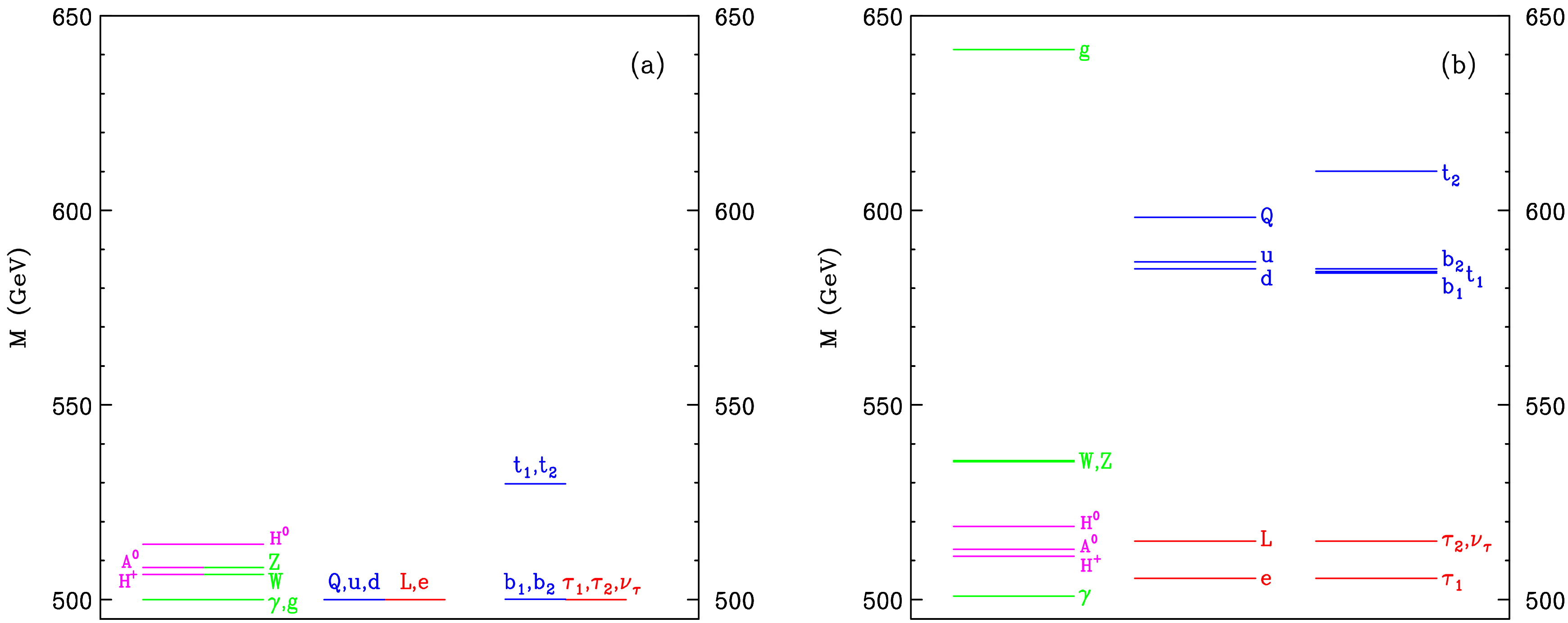
- Each SM particle has an infinite number of KK partners
  - The number of KK states $= \Lambda R$ (Λ is a cut-off)
- KK particle has the same spin as SM particle with a mass, $\sqrt{\frac{n^2}{R^2} + m^2}$
  - SM particles became massive through electroweak symmetry breaking
  - KK gauge bosons get masses by eating 5th components of gauge fields (Nambu-Goldstone bosons) and EWSB shifts those masses
- All vertices at tree level satisfy KK number conservation

$$|m \pm n \pm k| = 0 \text{ or } |m \pm n \pm k \pm l| = 0$$

- KK number conservation is broken down to KK-parity, $(-1)^n$, at the loop level
  - The lightest KK partner at level 1 (LKP) is stable $\Rightarrow$ DM ?
  - KK particles at level 1 are pair-produced
  - KK particles at level 2 can be singly produced
  - Additional allowed decays: $2 \to 00$, $3 \to 10$, $\cdots$
  - No tree-level contributions to precision EW observables
- New vertices are the same as SM interactions
  - Couplings between SM and KK particles are the same as SM couplings
  - Couplings among KK particles have different normalization factors
- There are two Dirac (KK) partners at each level n for one Dirac fermion in SM
- For two UEDs, see Burdman's talk

Mass Spectrum :
Tree level and radiative corrections

(Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)



- Tree level mass $m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2}$, e_1 is stable $\cdots$
- Radiative corrections are important !
- All but LKP decay promptly $\longrightarrow$ missing energy signals

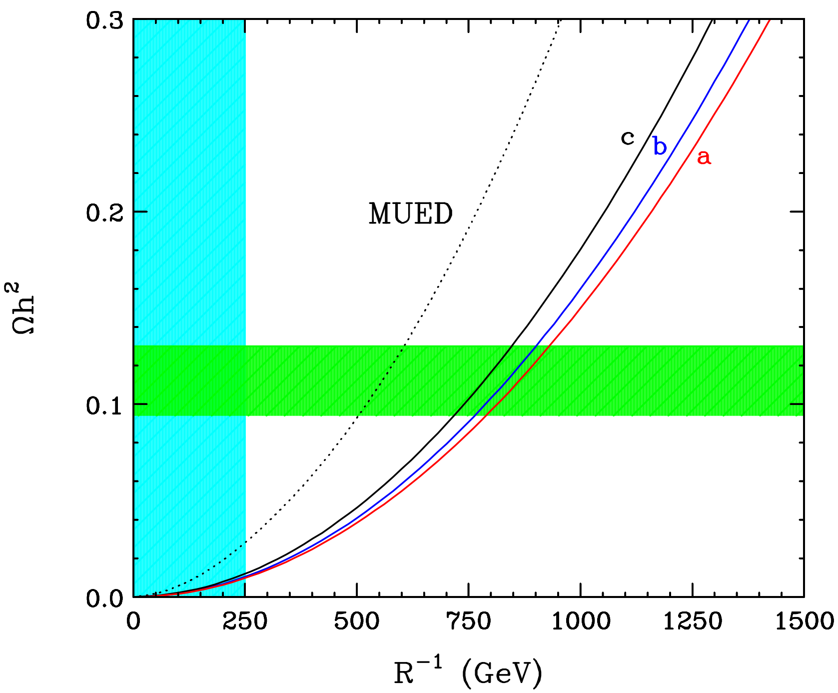
Relic Density Code

- Kong and Matchev (UF, 2005)
  - Fortran
  - Includes *all* level 1 KK particles
  - has a general KK mass spectra (all KK masses are, in principle, different)
  - can deal with different types of KK dark matter (γ_1, Z_1, $\nu_1 \cdots$)
  - improved numerical precision
    - use correct relativistic velocity expansion ($\langle \sigma v \rangle = a + b \langle v^2 \rangle$)
    - use temperature dependent degrees of freedom ($g_* = g_*(T_F)$)
- Servant and Tait (Annecy/ANL, 2002)
  - First code (γ_1 or ν_1 dark matter)
  - has cross sections in Mathematica, assuming same KK masses
  - use approximate relativistic velocity expansion
  - use approximate degrees of freedom ($g_* = 92.25$)
- Kribs and Burnell (Oregon/Princeton, 2005)
  - has cross sections in Maple, assuming same KK masses (γ_1 dark matter)
  - do not use relativistic velocity expansion
  - deal with coannihilations with all level 1 KK
- Kakizaki, Matsumoto and Senami (Bonn/KEK/Tokyo, 2006)
  - interested in resonance effects (γ_1 dark matter) $\longrightarrow$ See Senami's talk

Improved result

(Kong, Matchev, hep-ph/0509119)

- Improvements in our calculation:
  - Include all coannihilations: many processes (51×51 initial states)
  - Keep KK masses different in the cross sections:
  - Use temperature dependent g_*
  - Use relativistic correction in the b-term

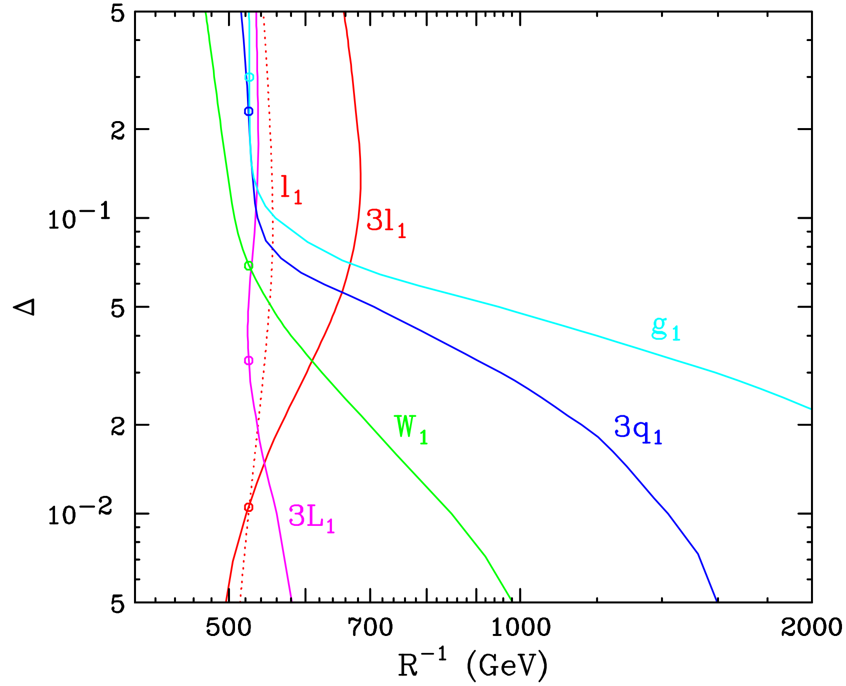


- a: $\gamma_1\gamma_1$ annihilation only (from hep-ph/0206071)
- b: repeats the same analysis but uses temperature dependent g_* and relativistic correction
- c: relaxes the assumption of KK mass degeneracy
- MUED: full calculation in MUED including all coannihilations with the proper choice of masses
- Preferred mass range: $500 - 600$ GeV for $0.094 < \Omega_{CDM}h^2 < 0.129$ $\longrightarrow$See Senami's talk for resonances

Dark matter in nonminimal UED

- The change in the cosmologically preferred value for R^{-1} as a result of varying the different KK masses away from their nominal MUED values (along each line, $\Omega h^2 = 0.1$)

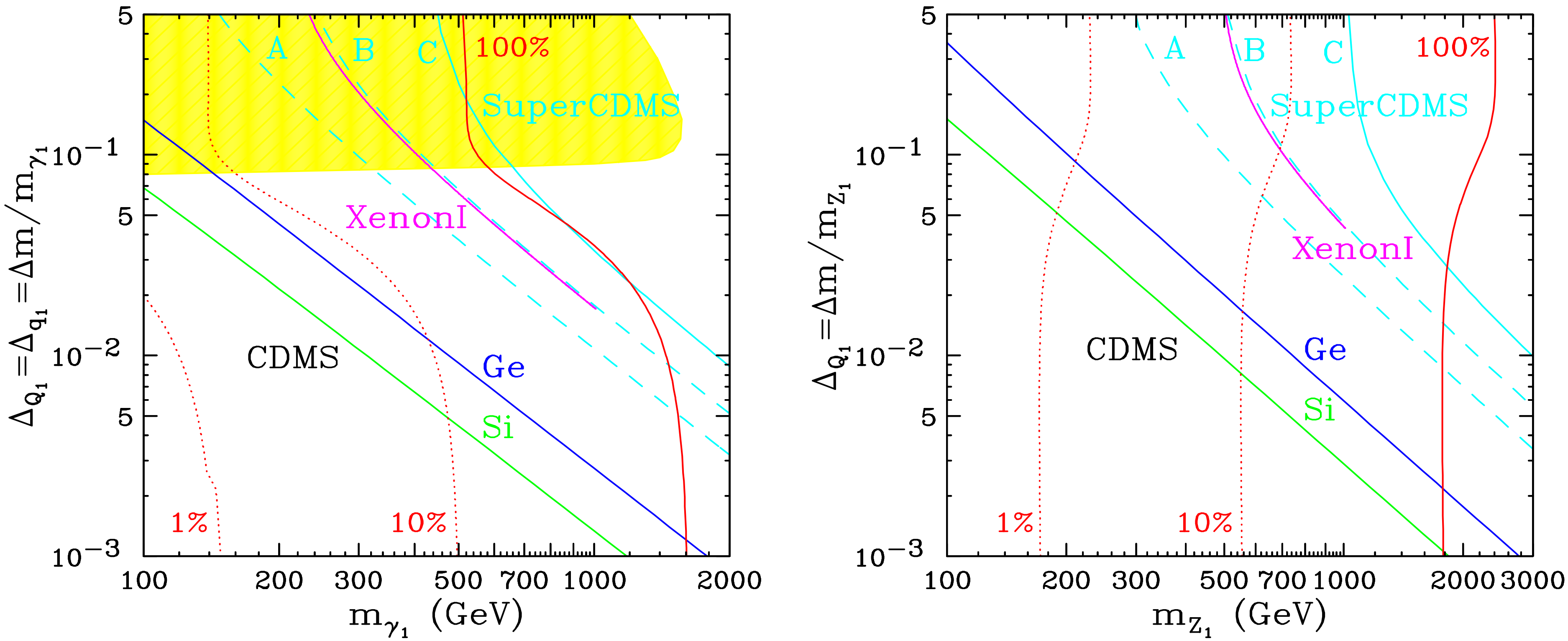
(Kong, Matchev, hep-ph/0509119)



- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, m_{LKP} is large, UED escapes collider searches
    $\longrightarrow$ But, good news for dark matter searches

CDMS (Spin independent): B_1 and Z_1 LKP

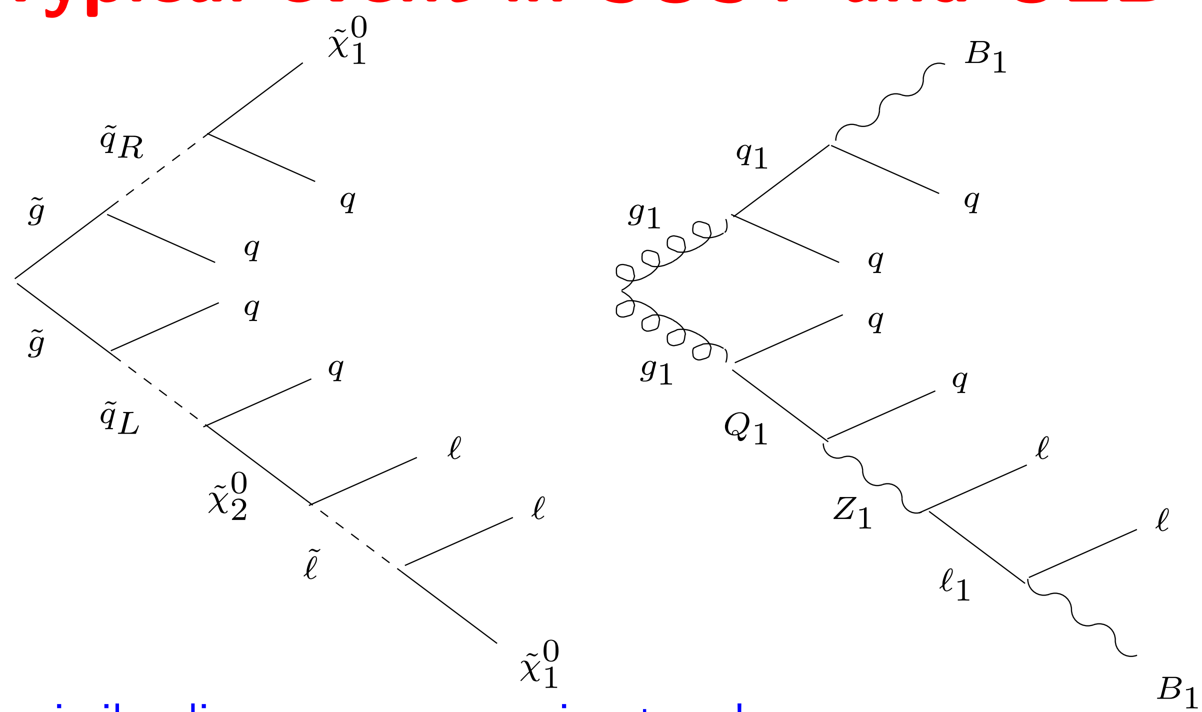
(Baudis, Kong, Matchev, Preliminary)



- SuperCDMS (projected)
  - A (25 kg), B (150 kg), C (1 ton)
- $\Delta_{q_1} = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$

- Z1 LKP in nonminimal UED:
  - $\Delta_{Q_1} = \frac{m_{Q_1} - m_{Z_1}}{m_{Z_1}}$
  - $\Delta_{g_1} = 0.2$
  - $\Delta_1 = 0.1$

Typical event in SUSY and UED



- Both have similar diagrams $\longrightarrow$ same signatures!
  - At first sight, it is not clear which model we are considering
- The decay chain is complicated
- A lot of jets $\longrightarrow$ correct jet identification is difficult $\longrightarrow$ ISR/FSR add more confusion
- UED discovery reach at the Tevatron and LHC: (Cheng, Matchev, Schmaltz, hep-ph/0205314)
  - Reach at the LHC: $R^{-1} \sim 1.5$ TeV with 100 fb^{-1} in $4l + \not{E}_T$ channel
  - UED search by CMS group (full detector simulation)
  - See Dannheim's talk for ATLAS study

How to discriminate:

- Level 1 just looks like MSSM with LSP dark matter:

  (Cheng, Matchev, Schmaltz, hep-ph/0205314)

- Can we discriminate SUSY from UED ?

	SUSY	UED
How many new particles	1^*	KK tower
Spin of new particles	differ by $\frac{1}{2}$	same spins
Couplings of new particles	same as SM	same** as SM
Masses	SUSY breaking	boundary terms
Discrete symmetry	R-parity	KK-parity $= (-1)^n$
Dark matter	LSP $(\tilde{\chi}_1^0)$	LKP (γ_1)
Generic signature***	$\not\!\!E_T$	$\not\!\!E_T$

* $N = 1$ SUSY

** Couplings among some KK particles may have factors of $\sqrt{2}$, $\sqrt{3}$, $\cdots$

*** with dark matter candidates

- Finding KK tower: Datta, Kong, Matchev, hep-ph/0509246
- Spin measurements: Barr, hep-ph/0405052

  Smillie, Webber hep-ph/0507170

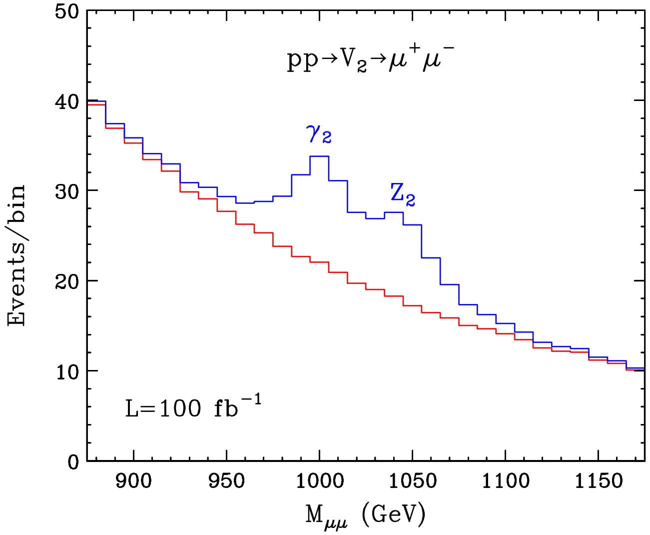
  Datta, Kong, Matchev, hep-ph/0509246 $\longrightarrow$see Plehn and Wang's talks
- Cross section: Datta, Kane, Toharia, hep-ph/0510204

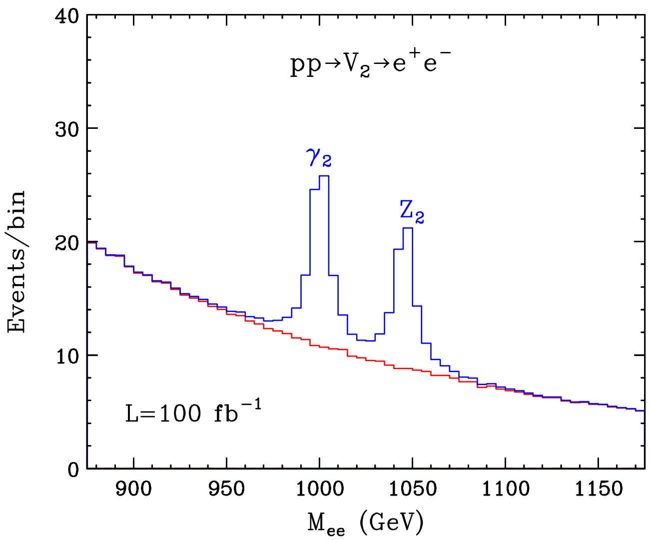
Implementation of UED in Event Generators

- Datta, Kong and Matchev (UF, 2004)
  - Full implementation of level 1 and level 2 in `CompHEP/CalcHEP` (spin information)
  - Provided for implementation in `PYTHIA`
  - Two different mass spectrum possible:
    * A general mass spectrum in Nonminimal UED
    * All masses/widths calculated automatically in Minimal UED
  - Used for dark matter study/collider studies
  - Used for ATLAS and CMS $(4\ell + \not{E}_T,\, nj + m\ell + \not{E}_T \cdots)$
- Alexandre Alves, Oscar Eboli, Tilman Plehn (2006) $\longrightarrow$ see Plehn's talk
  - Level 1 QCD and decays only in `MADGRAPH` (spin information!)
- Wang and Yavin (Harvard, 2006) $\longrightarrow$ see Wang's talk
  - Level 1 QCD and decays only in `HERWIG` (full spin information)
- Smillie and Webber (Cambridge, 2005)
  - Level 1 QCD and decays only in `HERWIG` (full spin information)
- Peskin (Stanford, in progress)
  - Level 1 QCD and decays only in `PANDORA` (full spin information)
- El Kacimi, Goujdami and Przysiezniak (2005)
  - Level 1 QCD and decays only in `PYTHIA` (spin information is lost)
  - Matrix elements from `CompHEP/CalcHEP`

Two resonances

(Datta, Kong, Matchev, hep-ph/0509246)

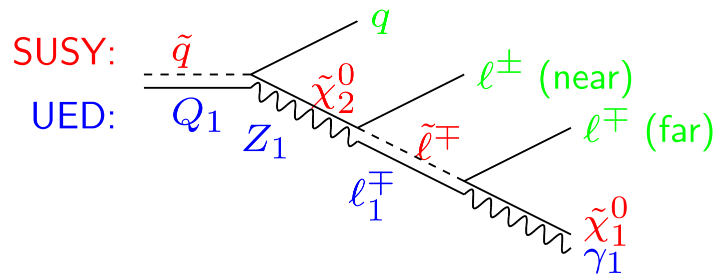




- Level 2 resonances can be seen at the LHC:
  - up to $R^{-1} \sim 1$ TeV for 100 fb^{-1}, $M_{ab}^2 = (p_a + p_b)^2$
  - covers dark matter region of MUED
- Mass resolution:
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV} \right)$ for $\mu^+\mu^-$
- Narrow peaks are smeared due to the mass resolution
- Two resonances can be better resolved in e^+e^- channel
- Is this a proof of UED ?
  - Not quite : resonances could still be interpreted as Z's
  - Smoking guns :
    * Their close degeneracy
    * $M_{V_2} \approx 2 M_{V_1}$
    * Mass measurement of $W_2^{\pm}$ KK mode
- However in nonminimal UED models,
  degenerate spectrum is not required
  → just like SUSY with a bunch of Z's
  → need spins to discriminate

Spin measurement

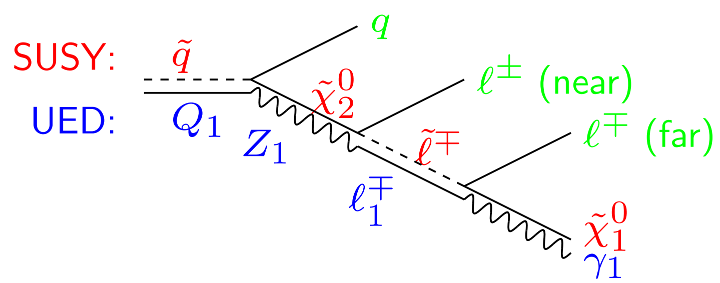
- spin measurement is difficult
  - LSP/LKP is neutral $\longrightarrow$ missing energy
  - There are two LSPs/LKPs $\Rightarrow$ cannot find CM frame
  - Decay chains are complicated $\longrightarrow$ cannot uniquely identify subchains
  - Look for something easy : look for 2 SFOS leptons, $\tilde{\chi}_2^0 \longrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \longrightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ or $Z_1 \longrightarrow \ell\ell_L^1 \longrightarrow \ell^+\ell^-\gamma_1$
  - Dominant source of $\tilde{\chi}_2^0/Z_1$: squark/KK-quark decay $\tilde{q} \longrightarrow q\tilde{\chi}_2^0 \longrightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \longrightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ or $Q_1 \longrightarrow qZ_1 \longrightarrow \ell\ell_L^1 \longrightarrow \ell^+\ell^-\gamma_1$:



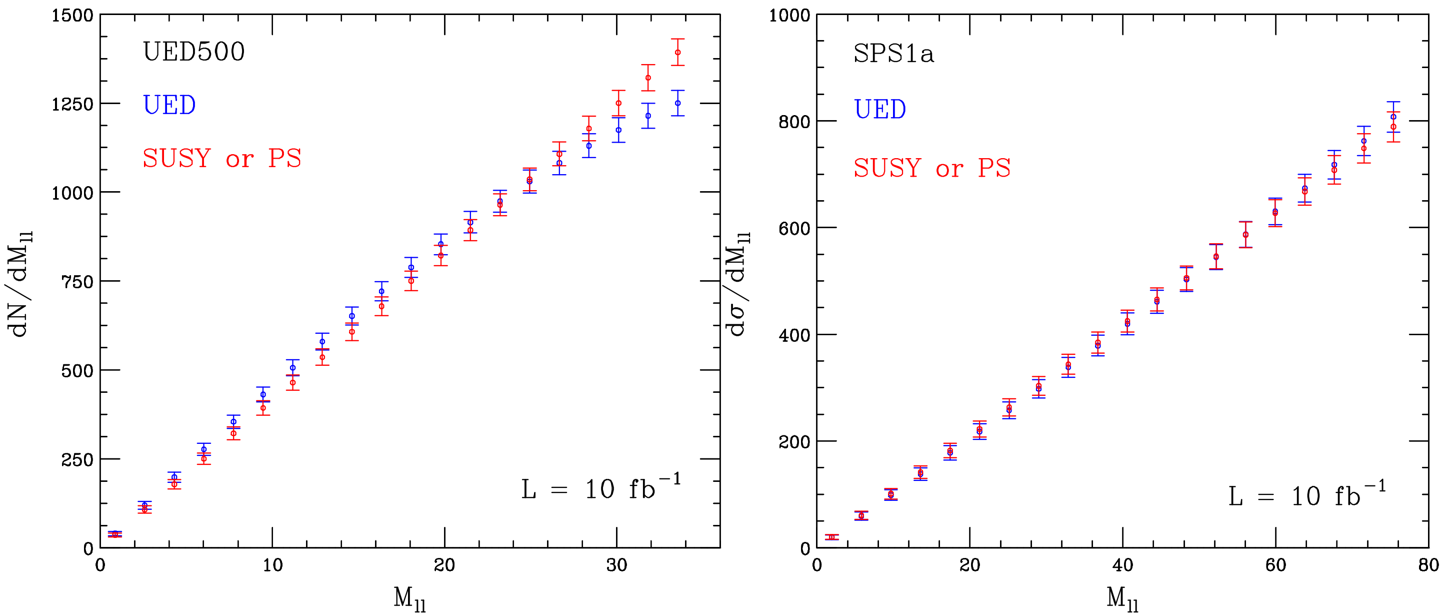
- Study this chain: Observable objects are q and $\ell^{\pm}$
- Can do: $M_{\ell^+\ell^-}$, $M_{q\ell^-}$ and $M_{q\ell^+}$ where $M_{ab}^2 = (p_a - p_b)^2$
- Which jet? Which lepton? Charge of jets (q and $\bar{q}$)?
  - $M_{\ell^+\ell^-}$, Asymmetry $= A^{+-} = \dfrac{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} - \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} + \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}$ (Barr,Phys.Lett.B596:205-212,2004)
- Masses don't discriminate

Dilepton distribution

- Look for spin correlations in $M_{\ell^+\ell^-}$
- Choose a study point in one model and fake mass spectrum in the other model



(Kong, Matchev Preliminary and Smillie, Webber hep-ph/0507170)



- Why are they the same ?

Dilepton distribution

- How do we fake the $M_{\ell^+\ell^-}$ distribution ?

(Smillie, Webber hep-ph/0507170)

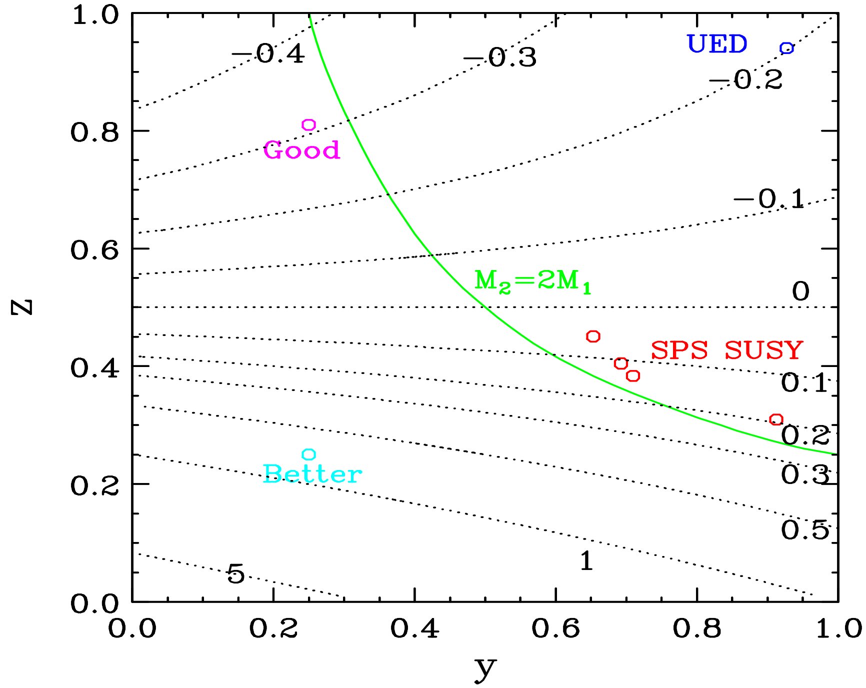
Phase Space : $\frac{dN}{d\hat{m}} = 2\hat{m}$

SUSY : $\frac{dN}{d\hat{m}} = 2\hat{m}$

UED : $\frac{dN}{d\hat{m}} = \frac{4(y+4z)}{(1+2z)(2+y)} \left(\hat{m} + r\,\hat{m}^3\right)$

$$r = \frac{(2-y)(1-2z)}{y+4z}$$

(Kong, Matchev Preliminary)



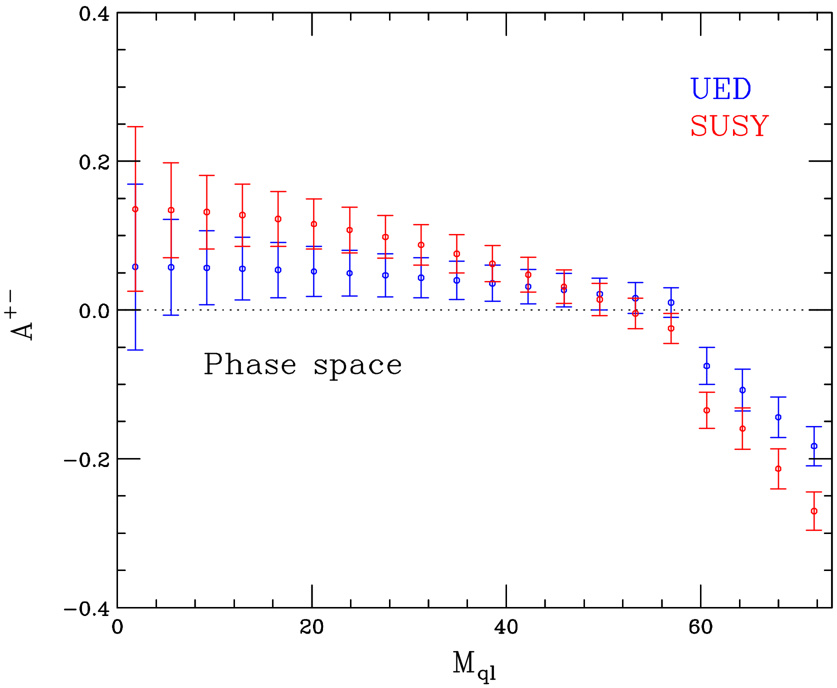
where $\hat{m} = \frac{m_{\ell\ell}}{m_{\ell\ell}^{max}}$, $y = \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2$ and $z = \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2$

- $|r| \leq 0.4$ in mSUGRA

Asymmetry

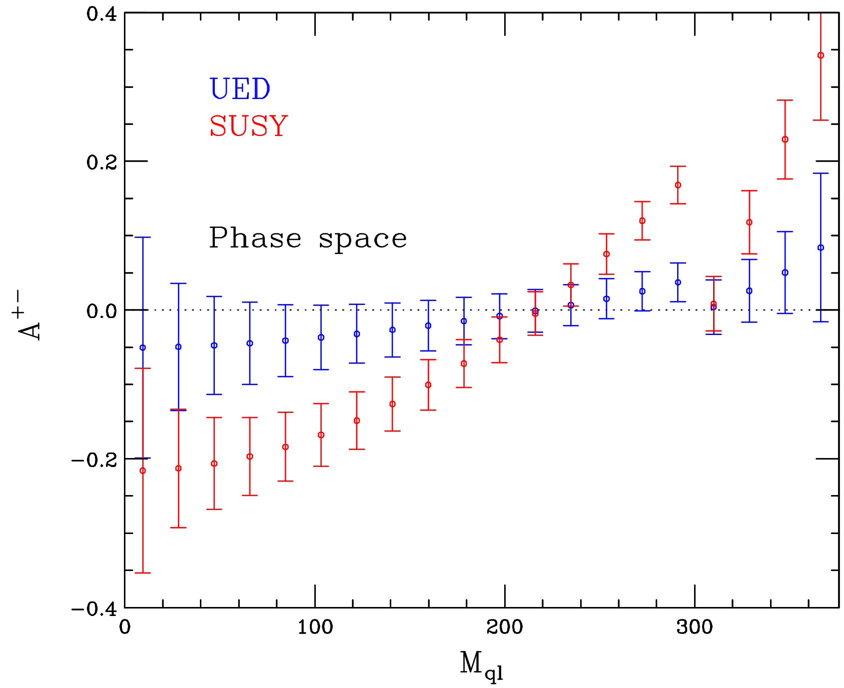
- Asymmetry with UED500 mass spectrum $(\mathcal{L} = 10\text{fb}^{-1})$

(Datta, Kong, Matchev, hep-ph/0509246)



- Asymmetry with SPS1a mass spectrum $(\mathcal{L} = 10\text{fb}^{-1})$

(Kong, Matchev Preliminary)

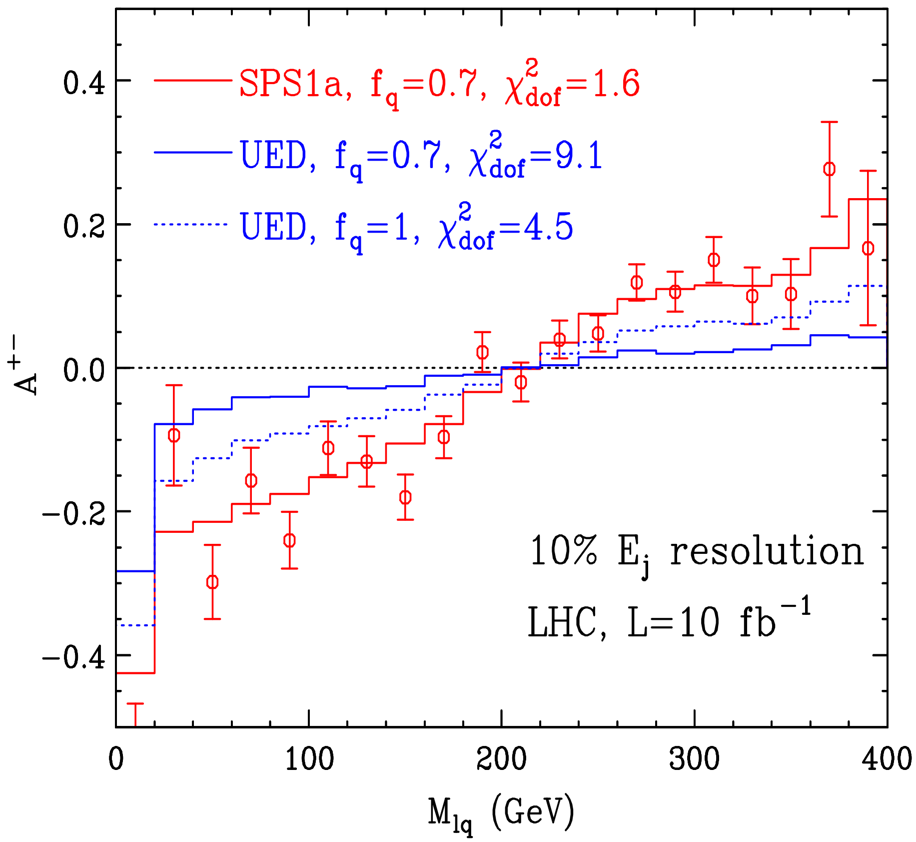


$$Z_1 \to \ell \ell_L^1 \to \ell^+ \ell^- \gamma_1 \qquad \text{Chirality} \qquad Z_1 \to \ell \ell_R^1 \to \ell^+ \ell^- \gamma_1$$

$$\tilde{\chi}_2^0 \to \ell \tilde{\ell}_L \to \ell^+ \ell^- \tilde{\chi}_1^0 \qquad \Longleftrightarrow \qquad \tilde{\chi}_2^0 \to \ell \tilde{\ell}_R \to \ell^+ \ell^- \tilde{\chi}_1^0$$

SPS1a mSUGRA point

(Kong, Matchev Preliminary)



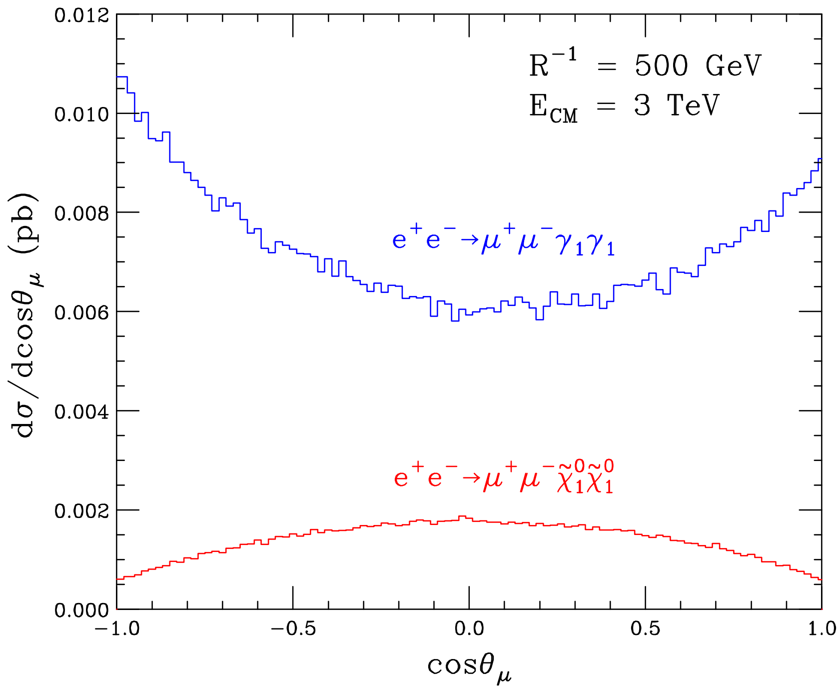
- How to fake SPS1a asymmetry
  - five parameters in asymmetry : f_q, x, y, z, $m_{\tilde{q}}$
  - three kinematic endpoints : m_{qll}, m_{ql} and m_{ll}
    - $m_{qll} = m_{\tilde{q}}\sqrt{(1-x)(1-yz)}$
    - $m_{ql} = m_{\tilde{q}}\sqrt{(1-x)(1-z)}$
    - $m_{ll} = m_{\tilde{q}}\sqrt{x(1-y)(1-z)}$
  - two parameters left : f_q, x
  - minimize χ^2 in the $(x,\ f_q)$ parameter space
  - minimum χ^2 when UED and SUSY masses are the same and $f_q \approx 1$
- 10% jet energy resolution + statistical error $\rightarrow \chi^2$ better but not enough to fake SPS1a in UED
- effect of wrong jets $\longrightarrow$ asymmetry smaller ? (work in progress)

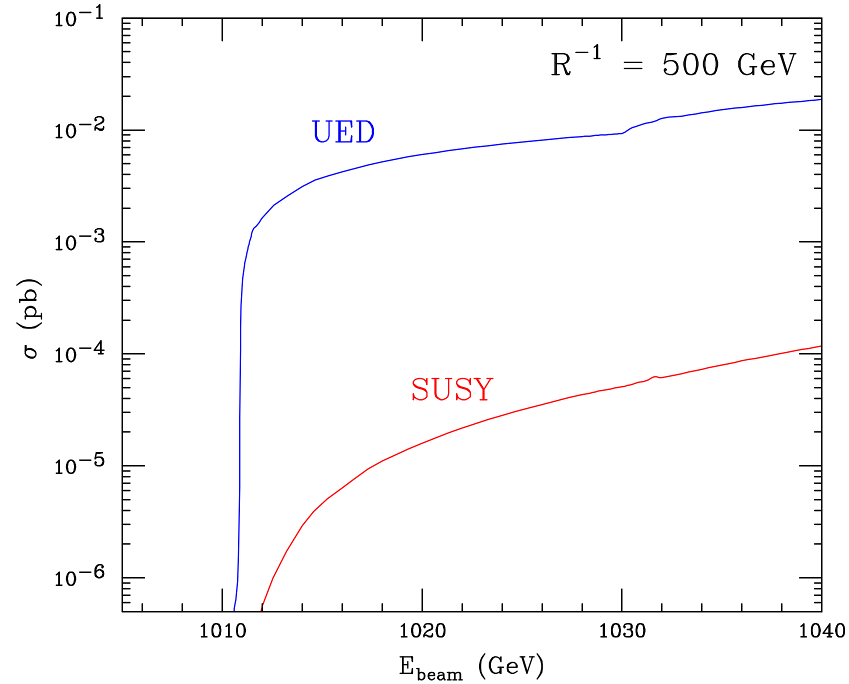
$$x = \left(\frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{q}}}\right)^2,\ y = \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2,\ z = \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2,\ f_q = \frac{N_q}{N_q+N_{\bar{q}}},\ f_{\bar{q}} = \frac{N_{\bar{q}}}{N_q+N_{\bar{q}}},\ f_q+f_{\bar{q}} = 1$$

- see Plehn and Wang's talks for spins/ Nojiri, Gjelsten and Miller's talks for masses

The Angular Distribution and Threshold Scans

(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)



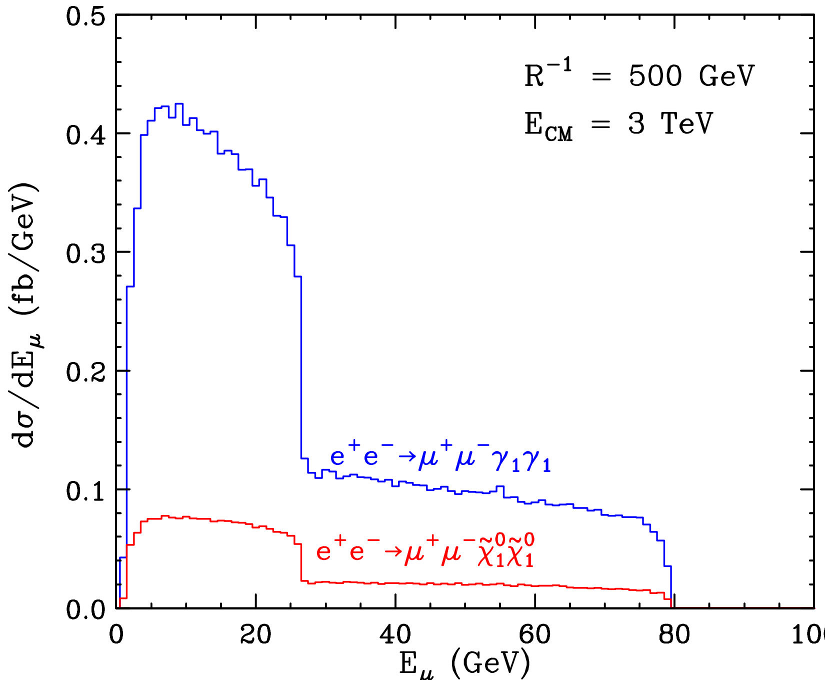


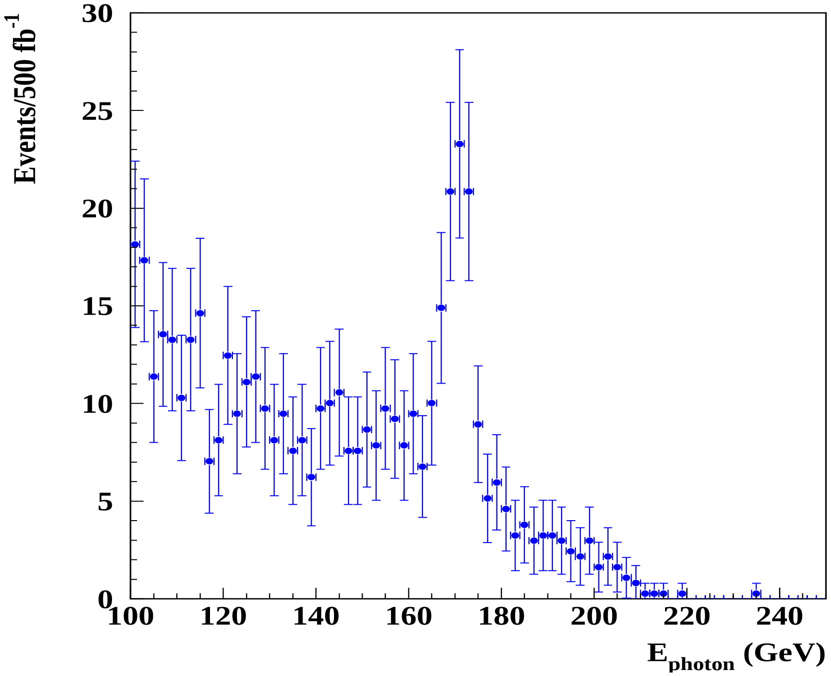
- $\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \cos^2\theta$
- $\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$
- $\mu^+\mu^- + \not{E}_T$ channel

- Mass determination
- Cross section at threshold
  - in UED $\propto \beta$
  - in MSSM $\propto \beta^3$ $\left(\beta = \sqrt{1 - \frac{M^2}{E_{beam}^2}}\right)$

The μ Energy Distribution and Photon Energy Distribution

(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)





- $E_{max/min} = \frac{1}{2} M_{\mu^*} \left(1 - \frac{M_N^2}{M_{\mu^*}^2}\right) \gamma(1 \pm \beta)$
  - M_{μ^*} : mass of smuon or KK muon
  - M_N : LSP or LKP mass
  - $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ with $\beta = \sqrt{1 - \frac{M_{\mu^*}^2}{E_{beam}^2}}$ (μ^* boost)

- Smuon production is mediated by γ and Z
- On-shell $Z_2 \longrightarrow \mu_1\bar{\mu}_1$ is allowed by phase space
- Radiative return due to Z_2 pole at

$$E_\gamma = \frac{s - M_{Z_2}^2}{2\sqrt{s}}$$

Summary

- LHC is finally coming
- New physics beyond the SM is expected to be discovered but will we know what it is?
- Many candidates for new physics have similar signatures at the LHC (SUSY, UEDs, T-parity).
- Universal Extra Dimensions
  - provide very interesting collider and dark matter phenomenology
  - Analogy to supersymmetry makes UEDs more interesting
  - Spin measurements at the LHC

Recent papers on UED

- Spin Measurements in Cascade Decays at the LHC, hep-ph/0605296, Wang, Yavin
- Distinguishing Spins in Decay Chains at the Large Hadron Collider, hep-ph/0605286, Athanasiou, Lester, Smillie, Webber
- Relic Abundance of dark matter in the minimal universal extra dimension model, hep-ph/0605280, Kakizaki, Matsumoto, Senami
- Precision electroweak constraints on Universal Extra Dimensions revisited, hep-ph/0605207, Gogoladze, Macesanu
- It's a Gluino, hep-ph/0605118, Alves, Eboli, Plehn
- Dark matter in universal extra dimension models: gamma(KK) versus nu(R,KK), hep-ph/0604154, Hsieh, Mohapatra, Nasri
- Resonances from two universal extra dimensions, hep-ph/0601186, Burdman, Dobrescu, Ponton
- Measuring slepton spin at the LHC,hep-ph/0511115, Barr
- Is it SUSY?, hep-ph/0510204, Datta, Kane, Toharia ....
- SUSY can fit any signal excess and for every single process in SUSY, there is corresponding diagram in UED!
- In principle, SUSY and UED are different. Can we distinguish two models at the LHC?