Measuring Masses and Spins of New Particles at Colliders!

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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

“Confusion scenario”

- What is new physics if we see jets/leptons + missing energy at the colliders?
- The standard answer: Supersymmetry with R-parity
  $\rightarrow$ 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?

Outline

- New physics beyond the SM is expected to be discovered at the LHC if it exists at TeV scale but will we know what it is?
  - How do you know if it is SUSY?
  - Example: Universal Extra Dimensions (5D)
- How to discriminate UED and SUSY
  - LHC/ILC/Dark matter
- Two Universal Extra Dimensions
  - LHC/ILC/Dark matter
- Measuring masses and spins is important to disentangle at the LHC
  - Improvement on bump hunting, edges in cascade decay, m_{T2}
- Summary

Universal Extra Dimensions

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

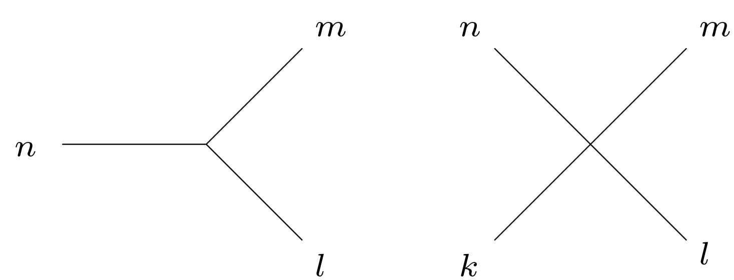
- Universal Extra Dimensions is an extra dimension theory with new bosonic coordinate y (spanning a circle of radius R):

$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \left(\phi^n(x^\mu) \cos\left(\frac{ny}{R}\right) + \chi^n(x^\mu) \sin\left(\frac{ny}{R}\right) \right)$$

- Each SM field ϕ (n=0) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with identical spins, identical couplings and unknown masses of order of n/R:

$$S = \int d^4x dy \mathcal{L}_{SM} = \int d^4x \mathcal{L}_{eff}, \qquad E^2 = \vec{p}^2 + p_5^2 = \vec{p}^2 + \left(\frac{n}{R}\right)^2$$

- Bulk interactions: conserve KK number $\Leftarrow p_y$ conservation

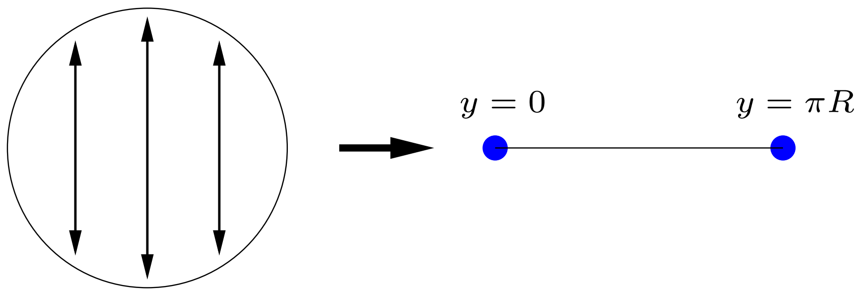


$n = m + l$ $\qquad$ $n + k = m + l$

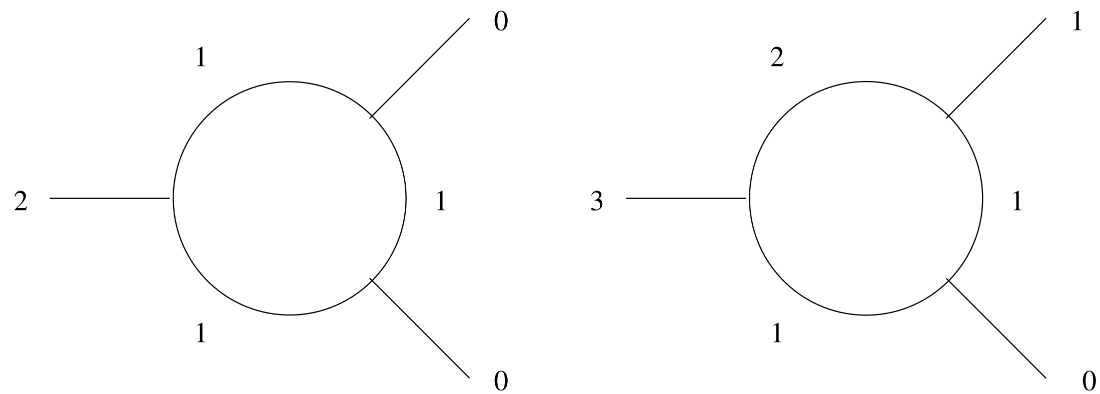
- Problem: chiral fermions?

KK number versus KK parity

- The ED is not really a circle, but orbifold S_1/Z_2:



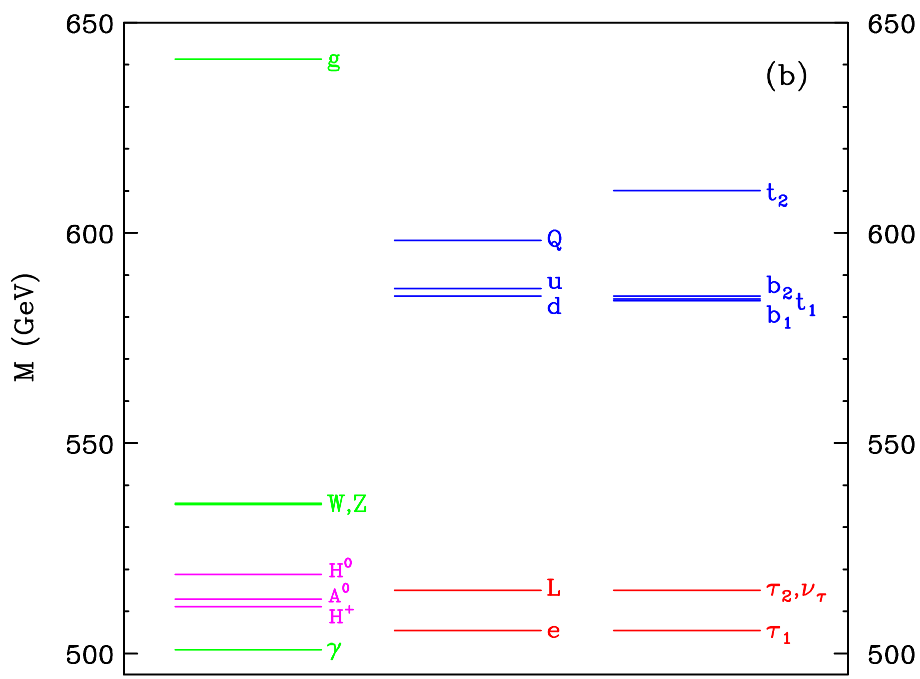
- Loop corrections generate boundary terms which break KK number n down to KK parity $(-1)^n$

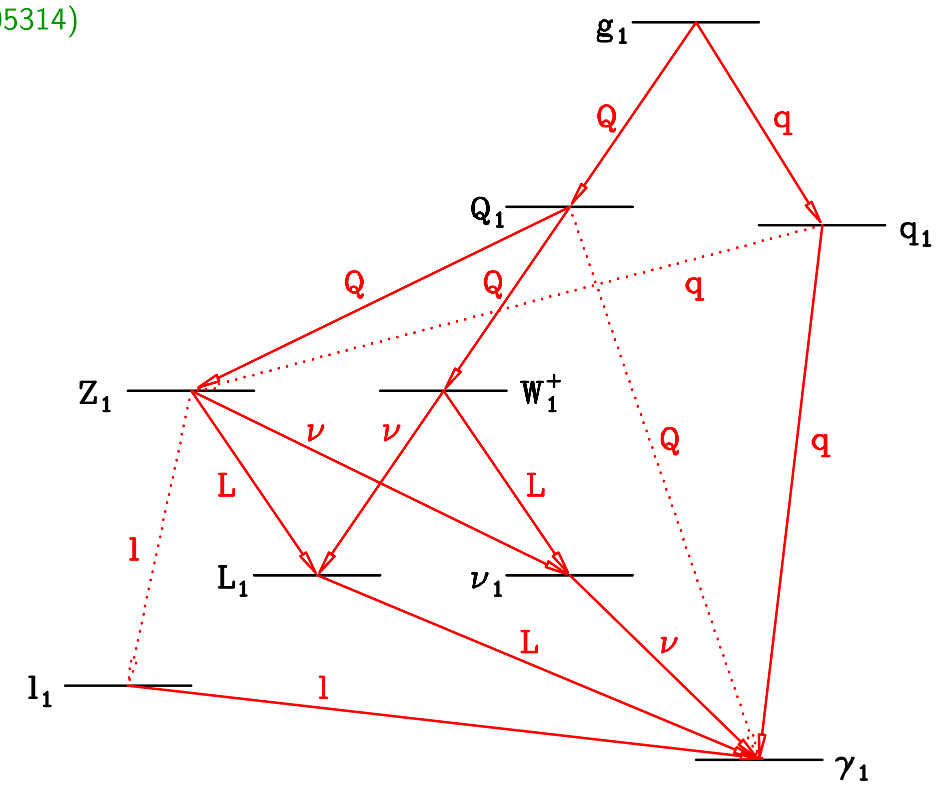


- Additional allowed decays: $2 \longrightarrow 00$, $3 \longrightarrow 10$, $\cdots$
- The lightest KK partner at level 1 (LKP) is stable $\Rightarrow$ DM ?
- No tree-level contributions to precision EW observables/need to pair-produce

UED phenomenology

- EW precision constraints: $R^{-1} \geq 300$ GeV (Appelquist, Cheng, Dobrescu,hep-ph/0012100)
- Current Tevatron limit: $R^{-1} > 280$ GeV in $3\ell + \not{E}_T$ channel at 95% C.L. (CDF)
- Region preferred by WMAP: $R^{-1} \sim 500 - 600$ GeV
  (Kong, Matchev, hep-ph/0509119, Burnell, Kribs, hep-ph/0509118, Servant, Tait, hep-ph/0206071)
- LHC reach: $R^{-1} \sim 1.5$ TeV in $4\ell + \not{E}_T$ channel
  (Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)





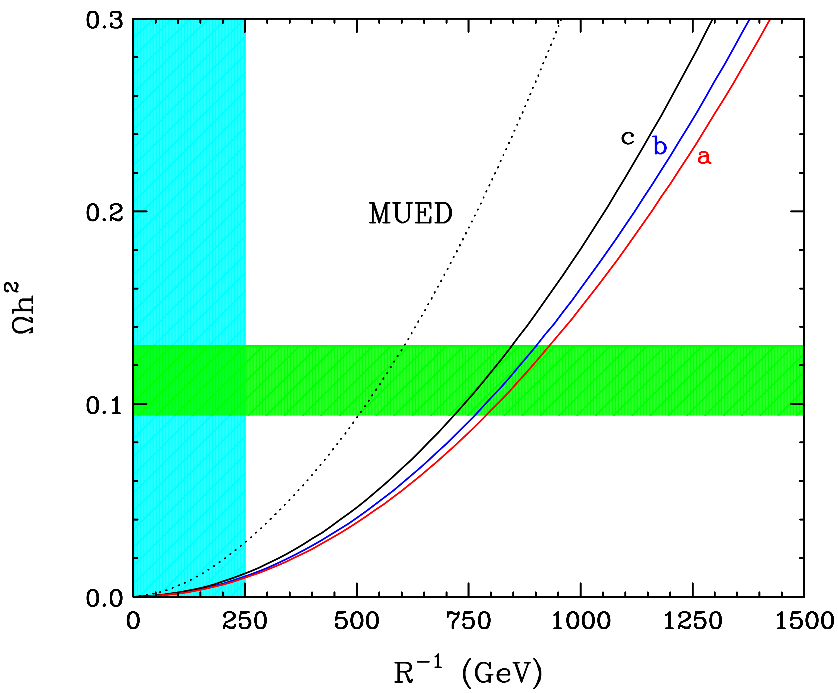
Relic Density Code

- 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 non-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 (ANL, 2002)
  - First code (γ_1 or ν_1 dark matter)
  - has cross sections in Mathematica, assuming same KK masses
  - use approximate non-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 non-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)

Relic density of KK dark matter

(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

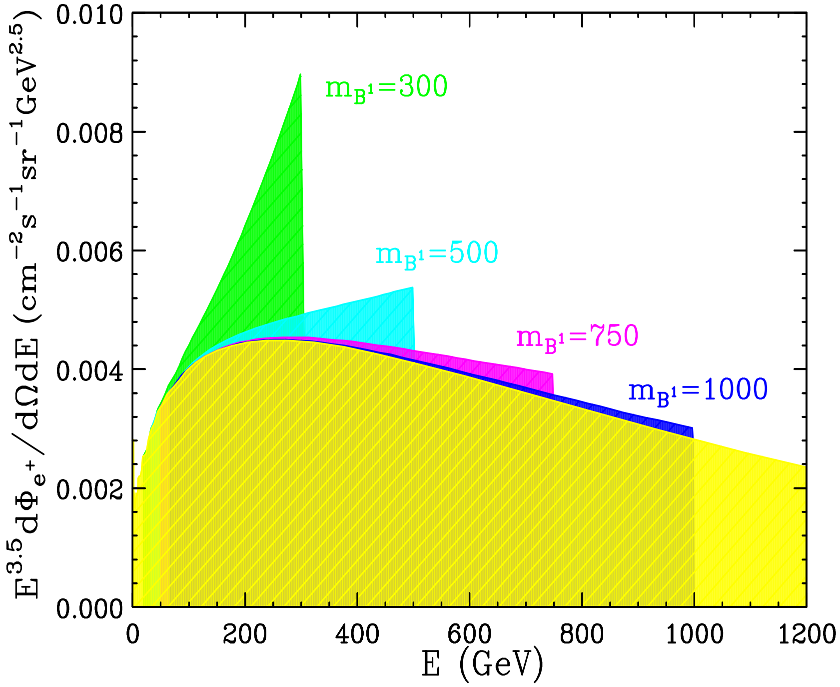


- a: $\gamma_1\gamma_1$ annihilation only (from hep-ph/0206071)
- b: repeats the same analysis but uses temperature dependent g_* and relativistic correction
- c: relaxes the assumption of KK mass degeneracy
- MUED: full calculation in MUED including all coannihilations with the proper choice of masses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

Dark matter as a Discriminator

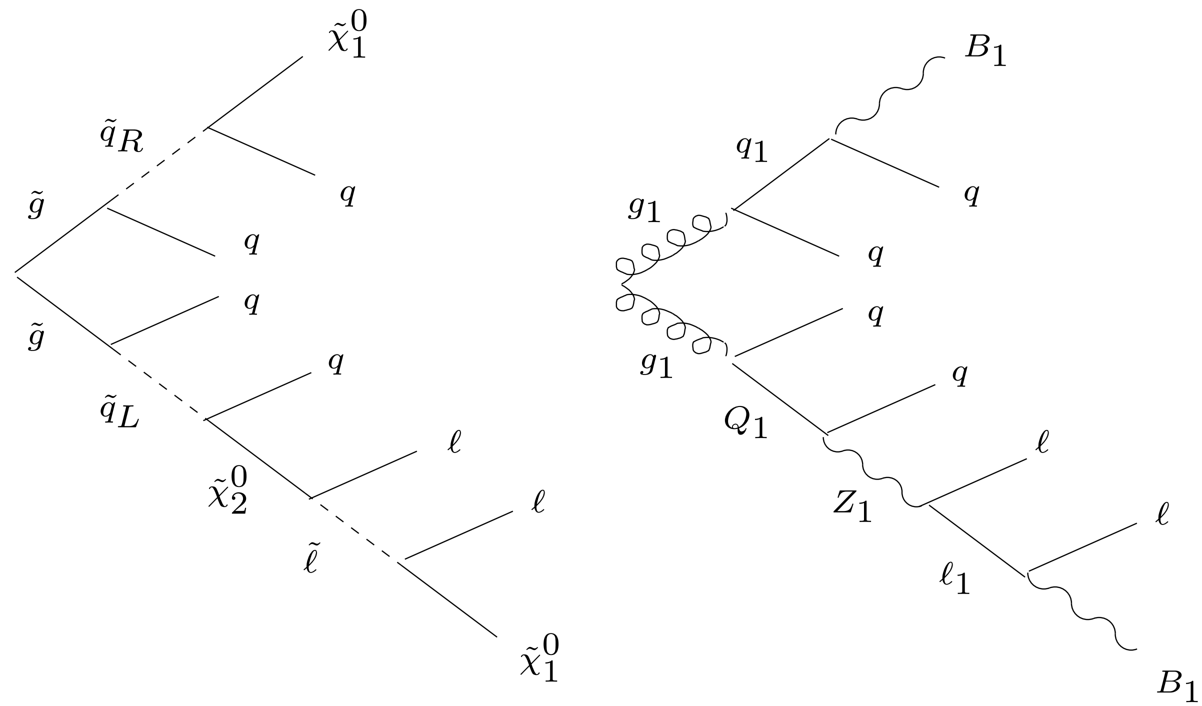
- Predicted positron signals

(Cheng, Feng, Matchev, hep-ph/0207125)



- SUSY: helicity-suppressed annihilation amplitudes
- A peak in the e^+ spectrum:
  - A smoking gun for γ_1 dark matter
  - can rule out neutralinos as the source

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)

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

– Spin measurements

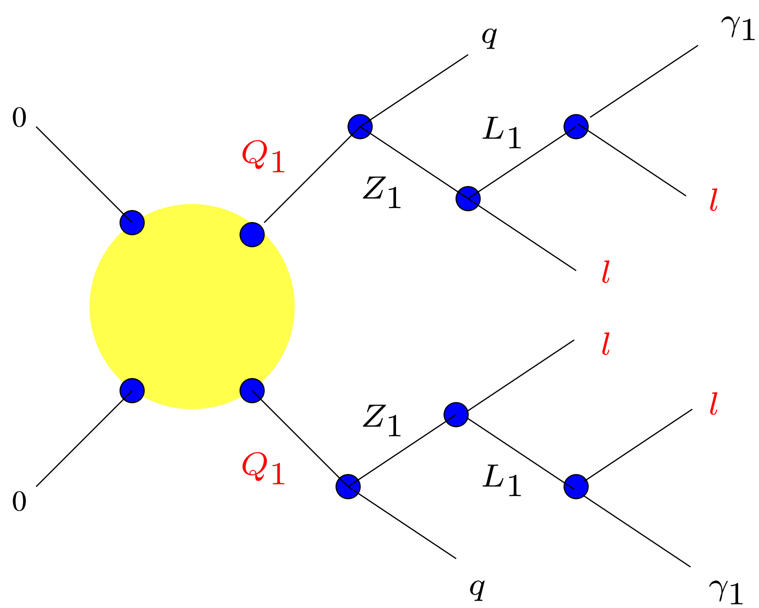
– Cross section: Datta, Kane, Toharia, hep-ph/0510204

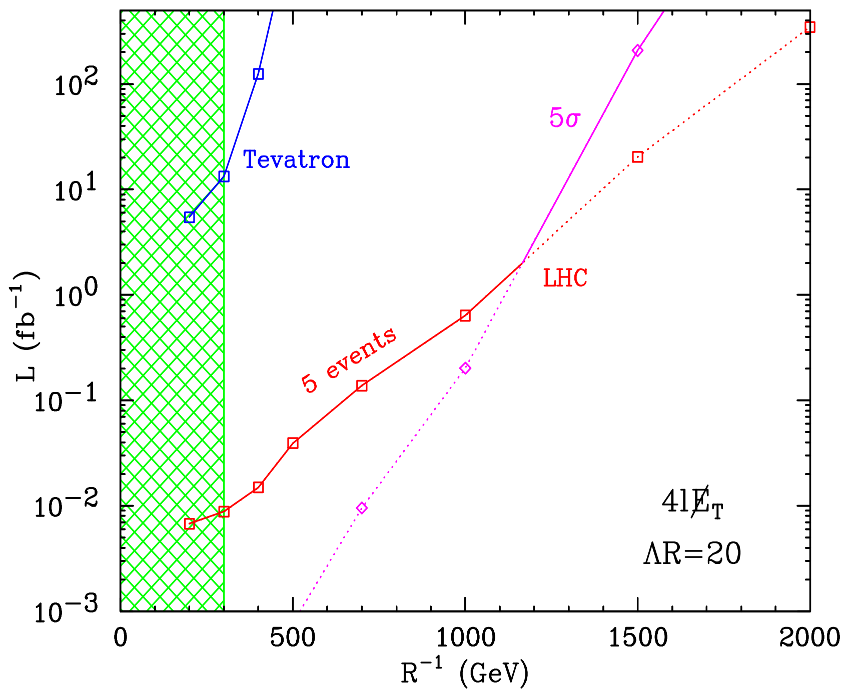
Implementation of UED in Event Generators

- 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)
  - Level 1 QCD and decays only in `MADGRAPH` (spin information!)
- Wang and Yavin (Harvard, 2006)
  - 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`

UED discovery reach at the Tevatron and LHC

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

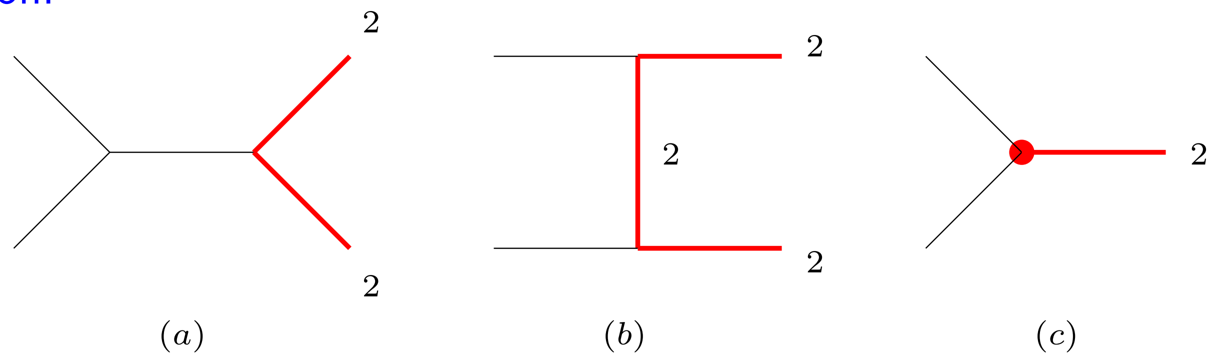




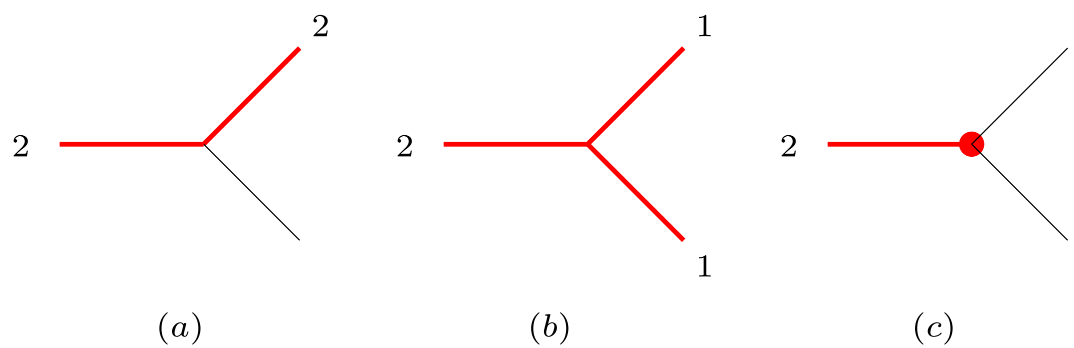
- Discovery reach in the $Q_1 Q_1 \to Z_1 Z_1 \to 4l + \not{E}_T$ channel

Looking for level 2 KK partners

- $n = 1$ ($M_1 = \frac{1}{R}$) is like MSSM and can be discovered: look for $n = 2$ ($M_2 = \frac{2}{R}$)
- Production:

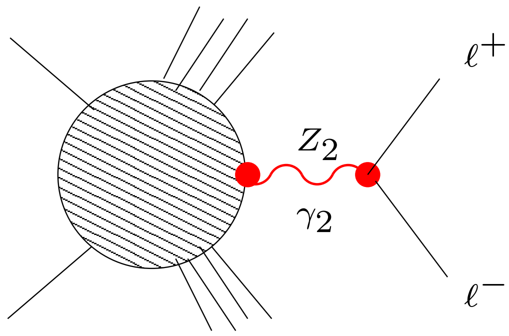


  - a, b: kinematically suppressed / c: suppressed couplings
  - only V_2 have KK number violating couplings to SM
  - Q_2 and L_2 : either forbidden or higher dimensional operator
- Decay:



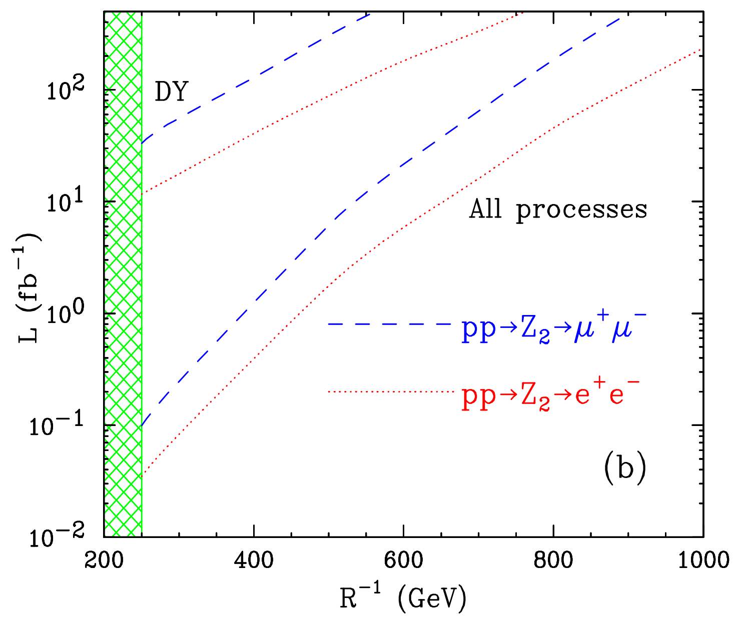
  - a: SM particle is soft / b: direct $n = 1$ production? / c: resonance

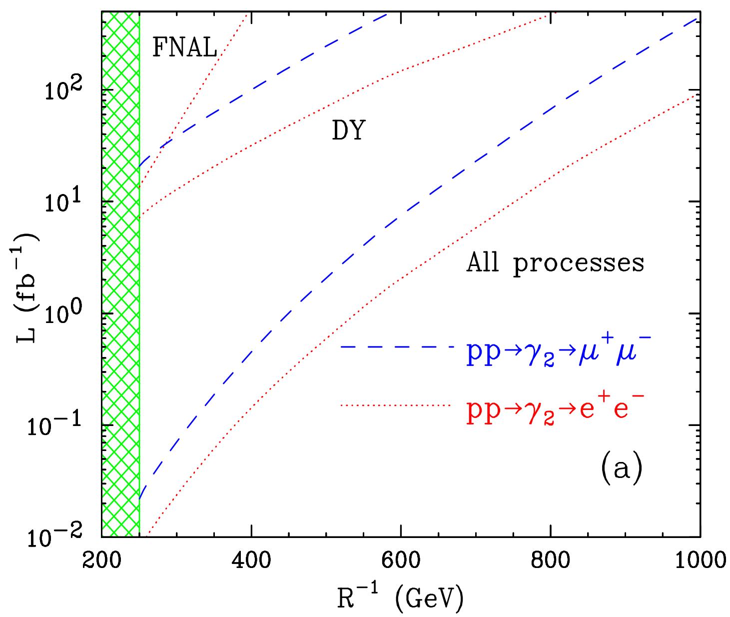
Discovery reach for MUED at LHC in inclusive dilepton channel

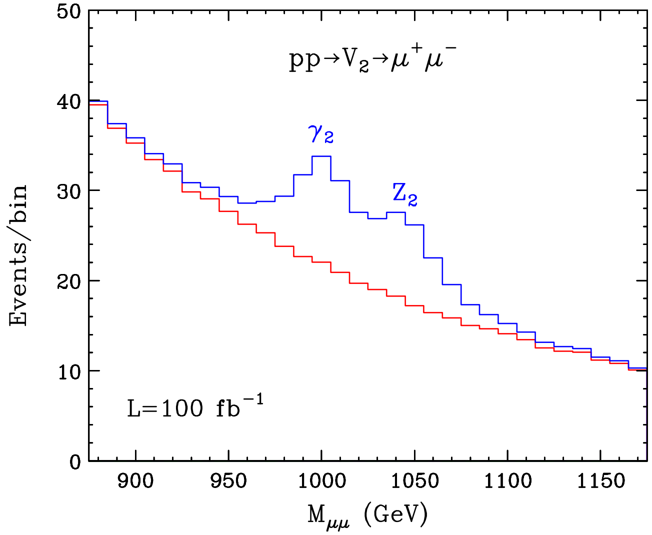


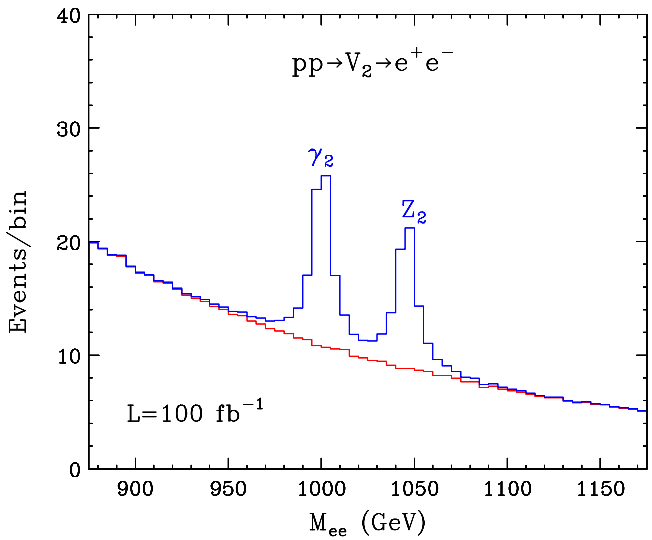
- $|p_t| > 20$ GeV, $|\eta| < 2.4$, $|M_{\ell^+\ell^-} - M_{V_2}| < 2\Delta M_{\ell^+\ell^-}$
- $\Delta M_{\ell^+\ell^-} = \sqrt{(\Gamma(V_2 \to \ell^+\ell^-))^2 + (\delta m)^2} \approx \delta m$
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV}\right)$ for $\mu^+\mu^-$
- Background with Pythia

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









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
    - $M_{V_2} \approx 2M_{V_1}$ and one single bump in dijet
    - Mass measurement of $W_2^{\pm}$ KK mode
- However in nonminimal UED models,

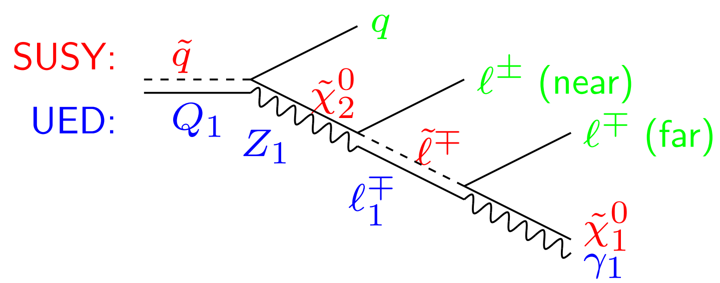
  degenerate spectrum is not required

  $\longrightarrow$ just like SUSY with a bunch of Z's

  $\longrightarrow$ need spins to discriminate

Spin measurement

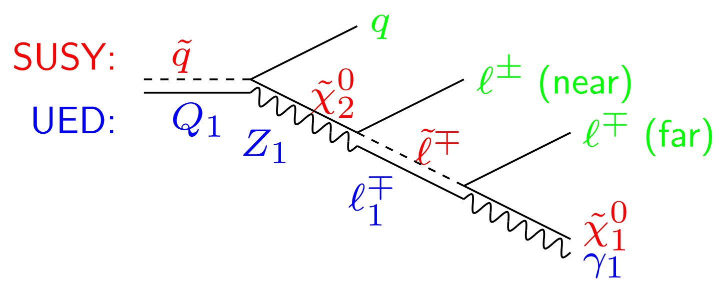
- spin measurement is difficult
  - LSP/LKP is neutral $\longrightarrow$ missing energy
  - There are two LSPs/LKPs $\Rightarrow$ cannot find CM frame
  - Decay chains are complicated $\longrightarrow$ cannot uniquely identify subchains
  - Look for something easy : look for 2 SFOS leptons,
    $\tilde{\chi}_2^0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



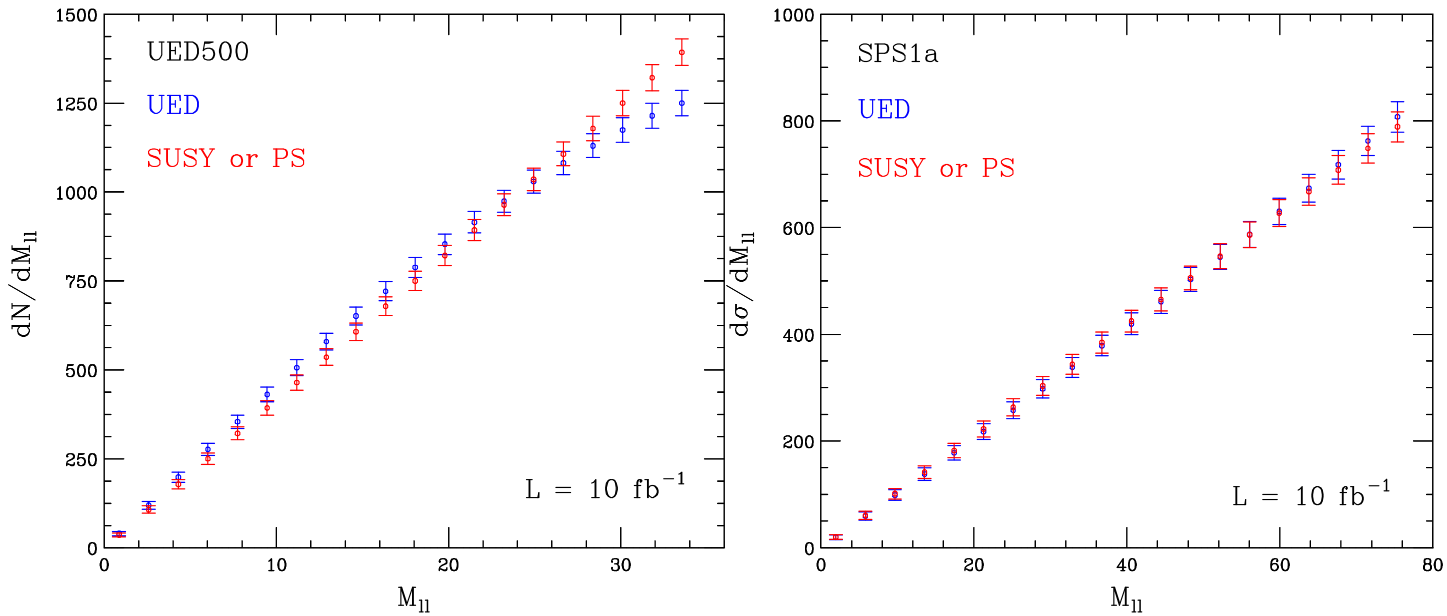
- Study this chain: Observable objects are q and $\ell^{\pm}$
- Can do: $M_{\ell^+\ell^-}$, $M_{q\ell^-}$ and $M_{q\ell^+}$ where $M_{ab}^2 = (p_a - p_b)^2$
- Which jet? Which lepton? Charge of jets (q and $\bar{q}$)?
  - $M_{\ell^+\ell^-}$, Asymmetry $= A^{+-} = \dfrac{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} - \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} + \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}$ (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)

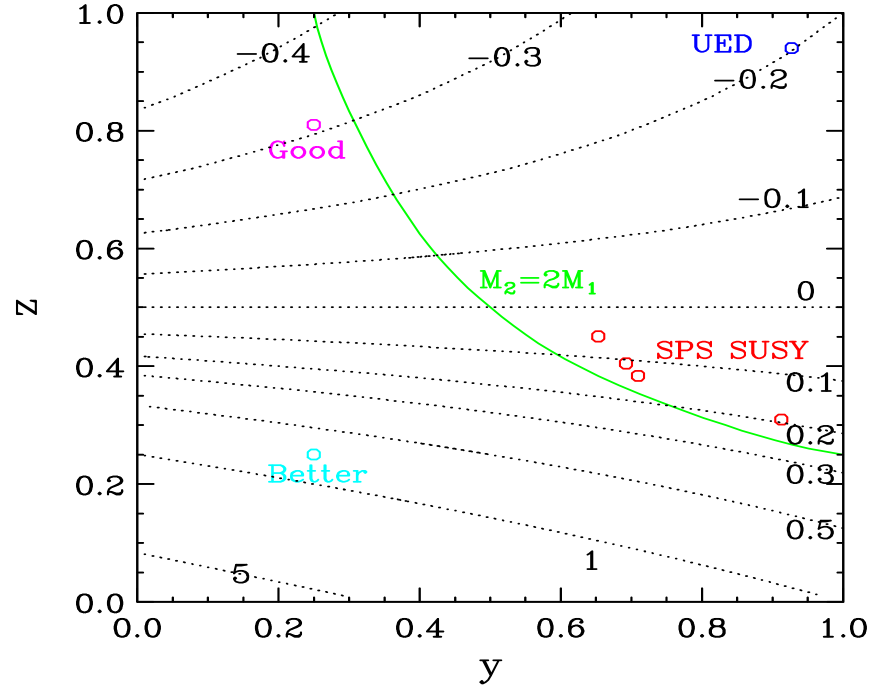
Phase Space : $\frac{dN}{d\hat{m}} = 2\hat{m}$

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

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

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

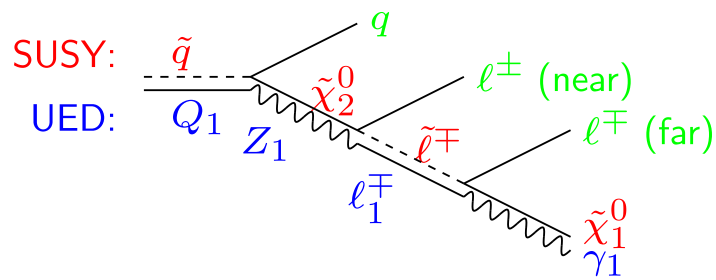
(Kong, Matchev Preliminary)



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

Spin measurement : Barr method



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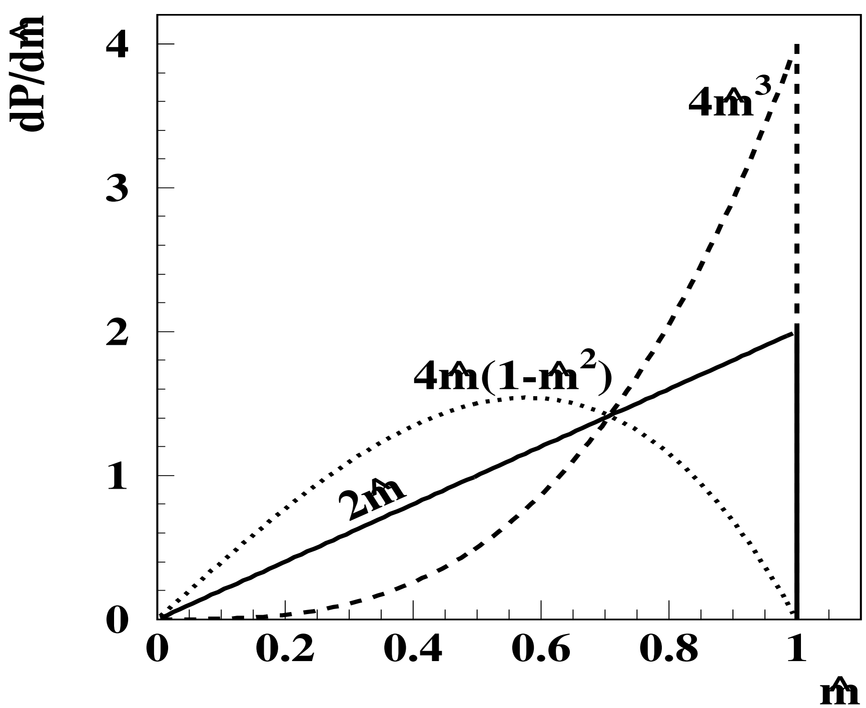
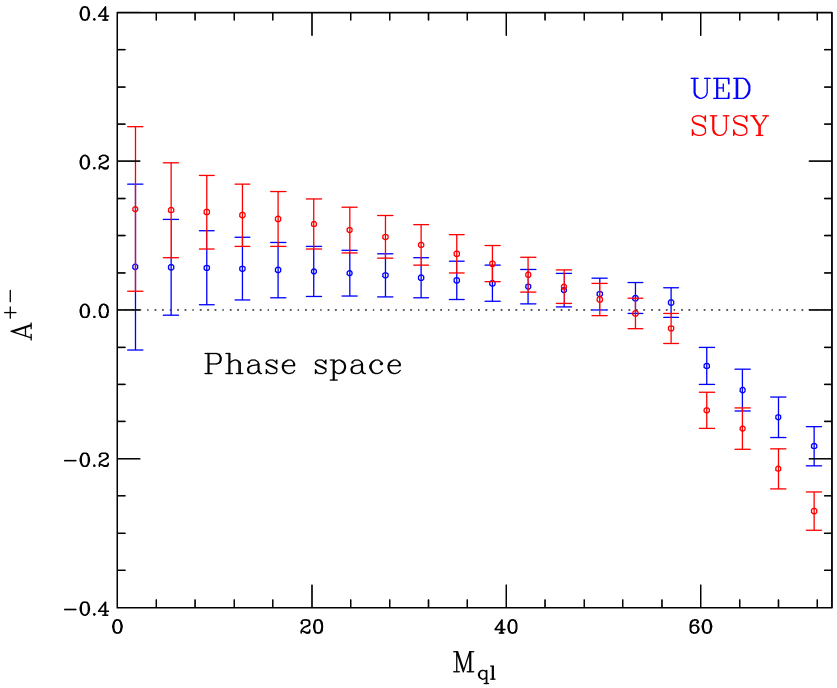


- Invariant mass distribution of q and ℓ (near)
  - $\frac{dP_{PS}}{d\hat{m}} = 2\hat{m}$ from phase space
  - $\frac{dP_1}{d\hat{m}} = 4\hat{m}^3$ for l^+q or $l^-\bar{q}$ in SUSY
  - $\frac{dP_2}{d\hat{m}} = 4\hat{m}(1-\hat{m}^2)$ for l^-q or $l^+\bar{q}$ in SUSY
  - $\hat{m} = \frac{m_{lq}^{near}}{\left(m_{lq}^{near}\right)_{max}}$
- Complications:
  - Which jet? Which lepton?
  - We don't distinguish q and $\bar{q}$
- Asymmetry:

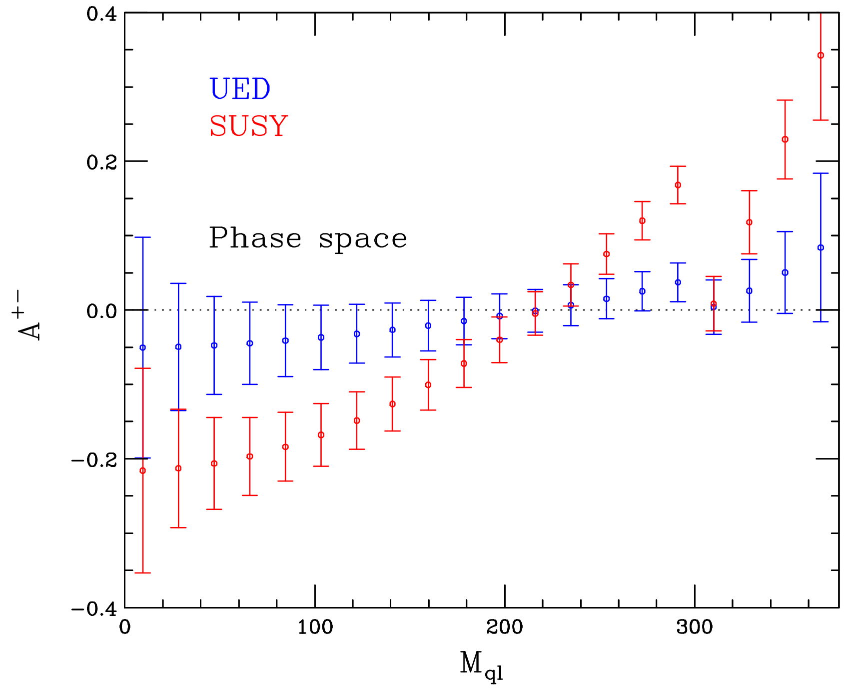
$$A^{+-} = \frac{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} - \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} + \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}$$

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)



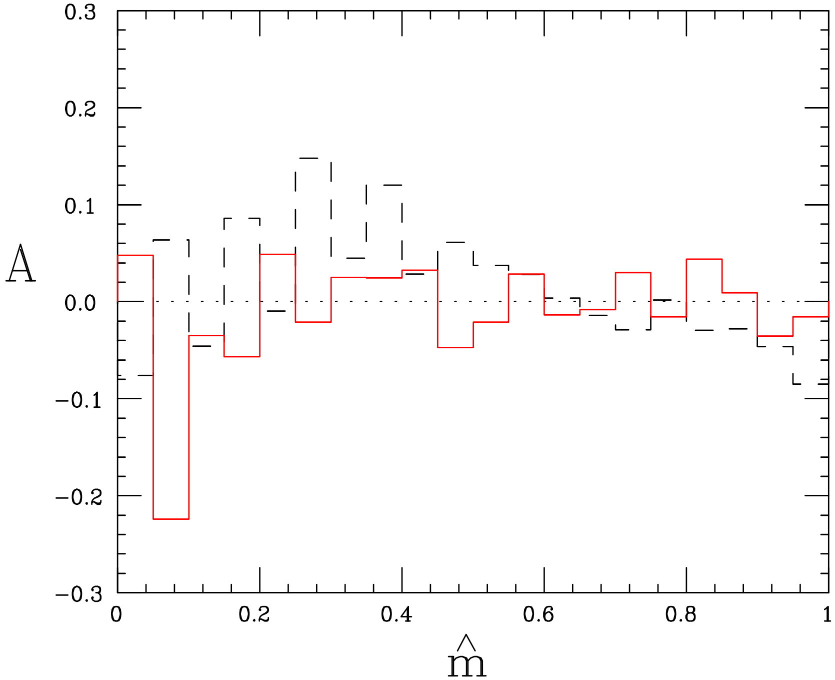
$$Z_1 \to \ell \ell_L^1 \to \ell^+ \ell^- \gamma_1 \qquad \text{Chirality} \qquad Z_1 \to \ell \ell_R^1 \to \ell^+ \ell^- \gamma_1$$

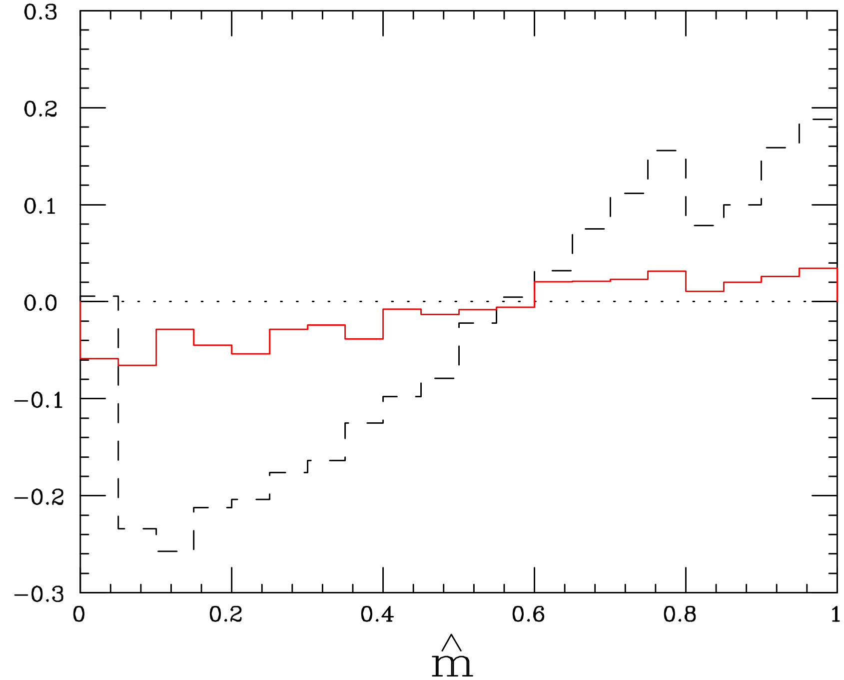
$$\tilde{\chi}_2^0 \to \ell \tilde{\ell}_L \to \ell^+ \ell^- \tilde{\chi}_1^0 \qquad \Longleftrightarrow \qquad \tilde{\chi}_2^0 \to \ell \tilde{\ell}_R \to \ell^+ \ell^- \tilde{\chi}_1^0$$

“Detector level” Asymmetry

(Smillie, Webber hep-ph/0507170)

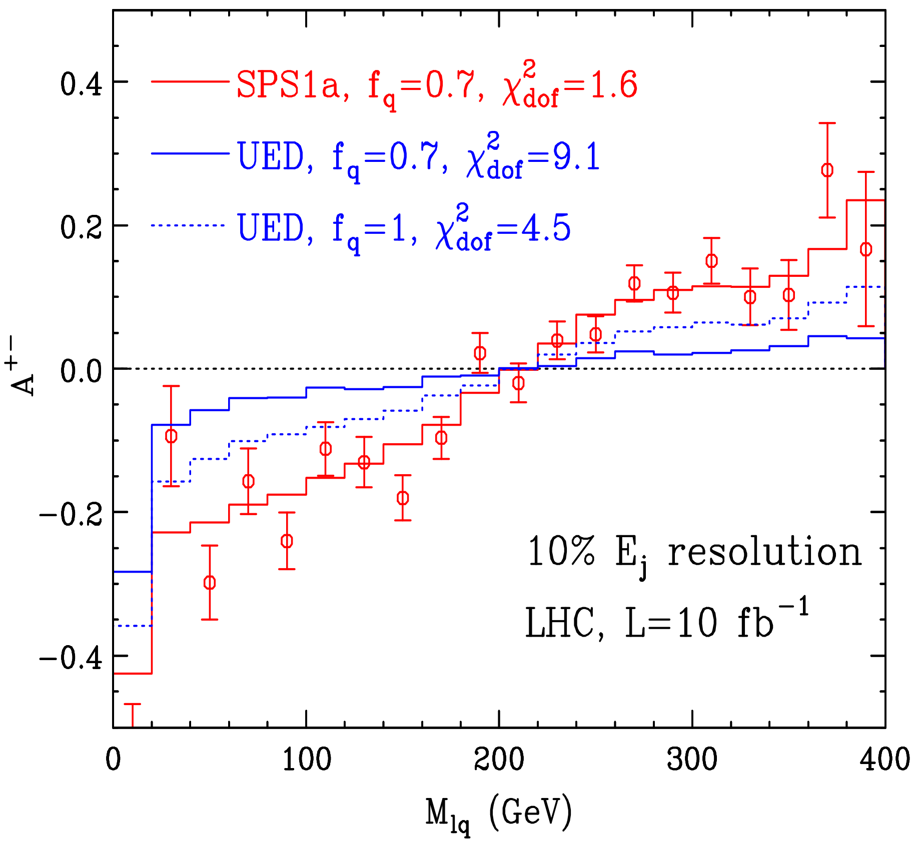
- UED500 mass spectrum: $(\mathcal{L} = 7\text{fb}^{-1})$
- SPS1a mass spectrum: $(\mathcal{L} = 131\text{fb}^{-1})$





SPS1a mSUGRA point

(Kong, Matchev Preliminary)

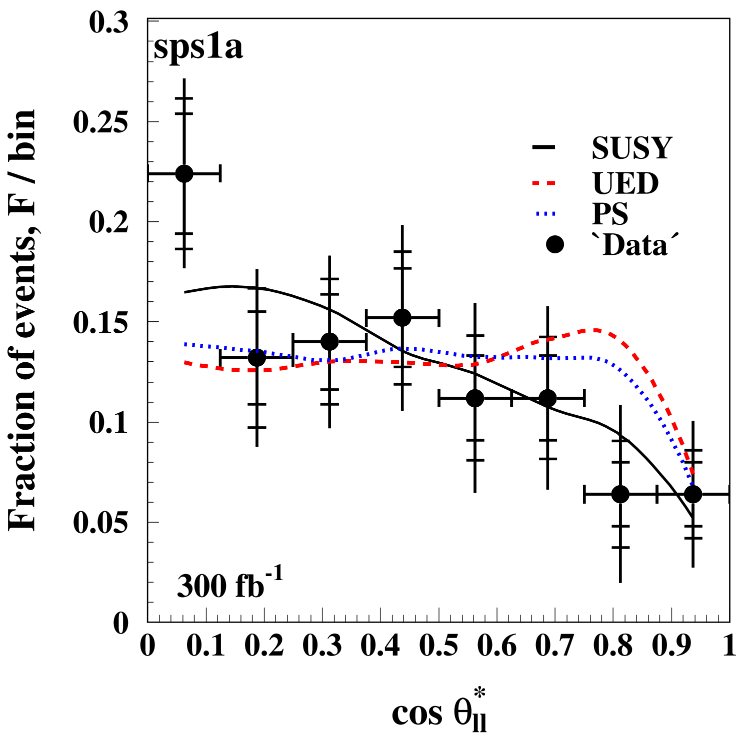


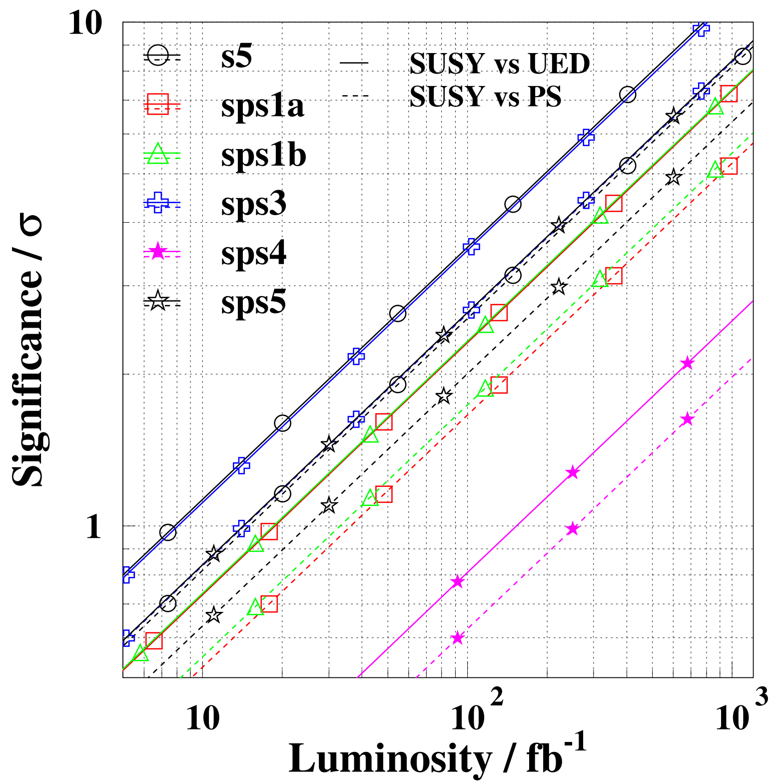
- How to fake SPS1a asymmetry
  - five parameters in asymmetry : f_q, x, y, z, $m_{\tilde{q}}$
  - three kinematic endpoints : m_{qll}, m_{ql} and m_{ll}
    - $m_{qll} = m_{\tilde{q}}\sqrt{(1-x)(1-yz)}$
    - $m_{ql} = m_{\tilde{q}}\sqrt{(1-x)(1-z)}$
    - $m_{ll} = m_{\tilde{q}}\sqrt{x(1-y)(1-z)}$
  - 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 $\longrightarrow \chi^2$ better but not enough to fake SPS1a in UED
- effect of wrong jets $\longrightarrow$ asymmetry smaller ? Flavor subtraction? (work in progress)

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

Other particles

- Gluino spin with three-body decays, arXiv:0707.0014, Csaki, Heinonen, Perelstein
- Gluino spin using Barr method, hep-ph/0605067, Alves, Eboli, Plehn
- Top partner, hep-ph/0601124, Meade, Reece
- Slepton spin, hep-ph/0511115, Barr
- . . .

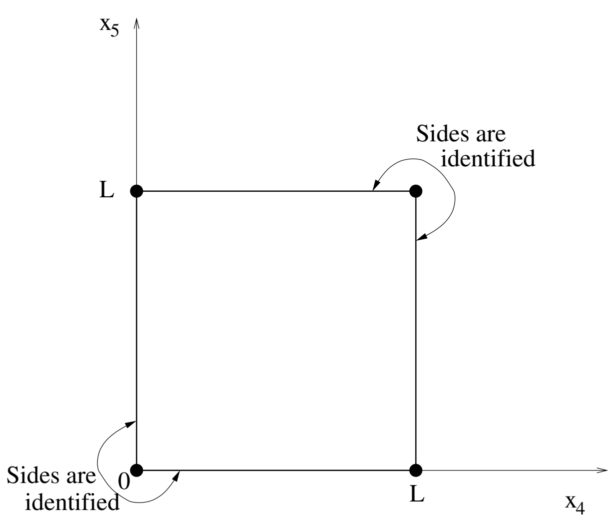


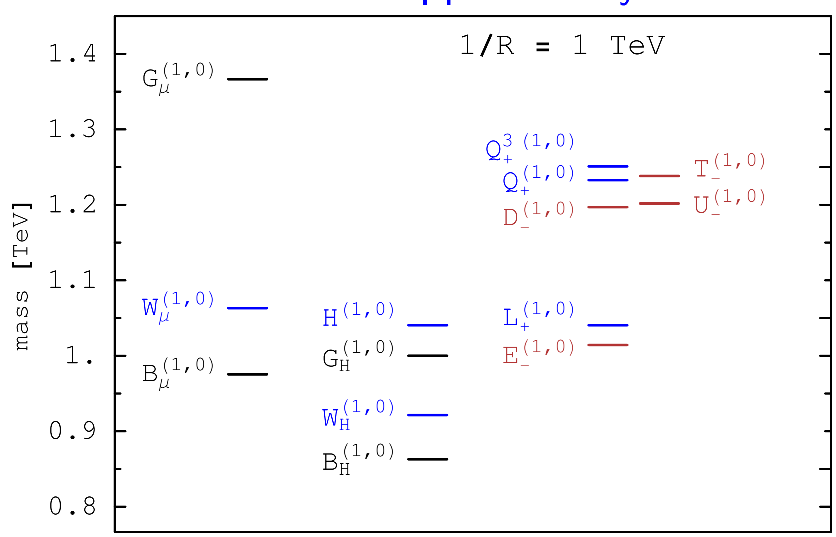


Two Universal Extra Dimensions on Chiral Square

- Motivation:
  - Possible to avoid proton decay (Appelquist, Dobrescu, Ponton hep-ph/0107056)
  - To cancel anomalies $\longrightarrow$ 3 generations (Dobrescu, Poppitz hep-ph/0102010)
- Chiral Square $\longrightarrow$ (n,m) KK-mode (Dobrescu, Ponton, hep-th/0401032)

  (Burdman, Dobrescu, Ponton, hep-ph/0506334) (Ponton, Wang, hep-ph/0512304)
- Different dark matter candidate: $B_H^{(1,0)}$ (Burdman, Dobrescu, Ponton, hep-ph/0601186)
  - $A_M^a = (A_\mu^a, A_5^a, A_6^a)$
  - $A_H^a \sim A_5^a - iA_6^a$ survives: a physical degree of freedom
  - $A_G^a \sim A_5^a + iA_6^a$ eaten: NGB
- $B_H^{(1,0)}$ self-annihilation: All fermion final states are suppressed by their mass

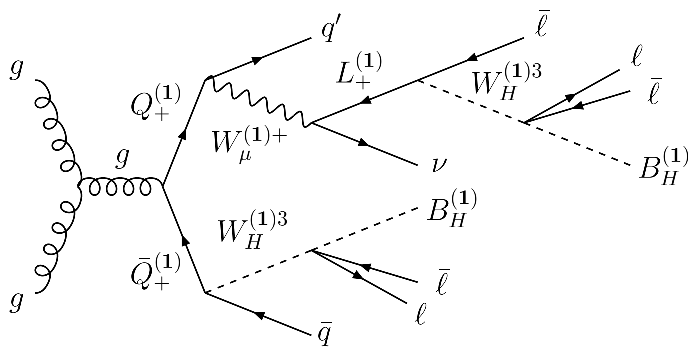


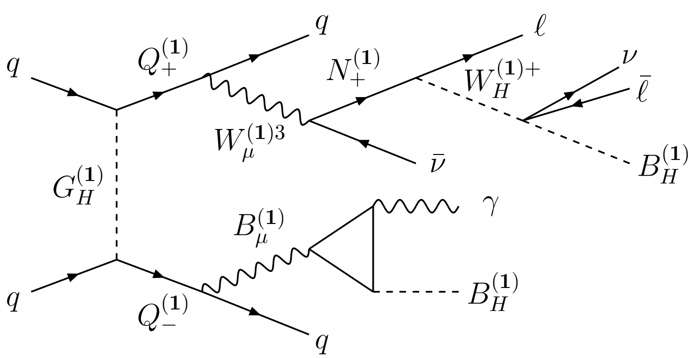


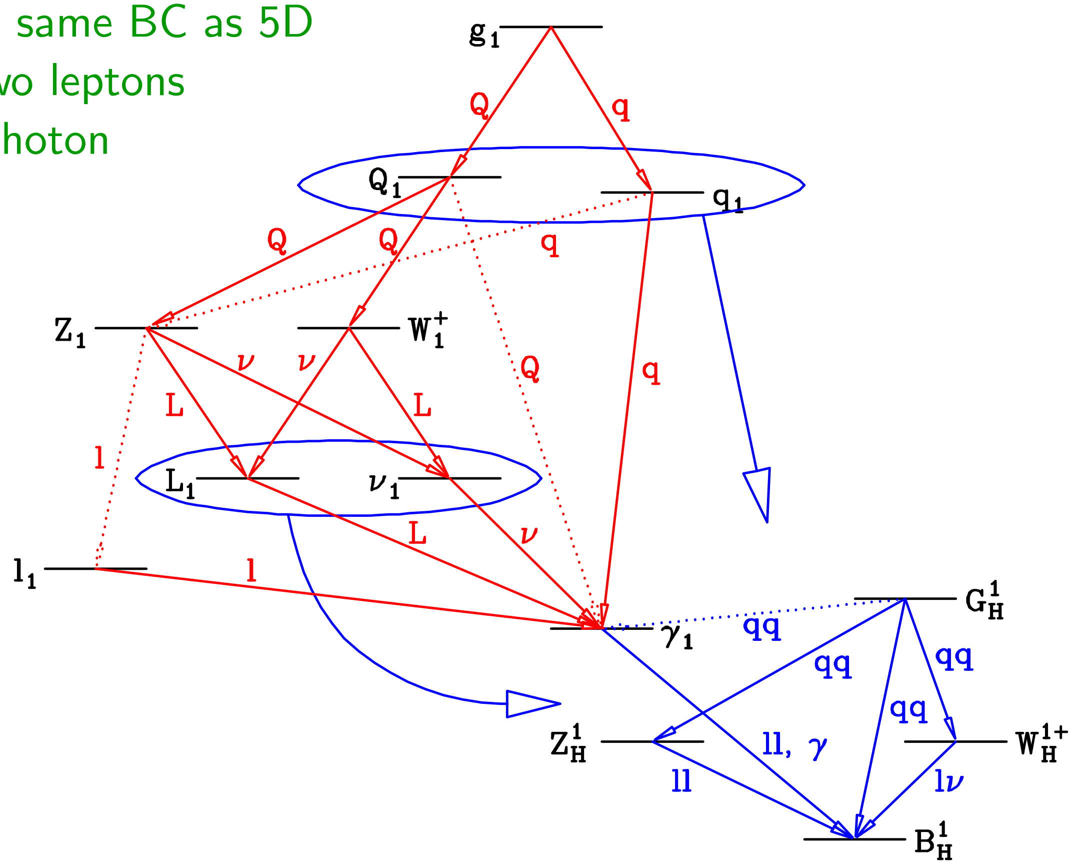
Longer cascade decays

(Dobrescu, Kong, Mahbubani, hep-ph/0703231)

- Explore different phenomenology: (1,0) mode with $M_{(1,0)} \sim \frac{1}{R}$
  - Spinless Adjoints: uneaten NGB, G_H, W_H and B_H
  - B_H: the lightest assuming the same BC as 5D
  - Tree-level 3-body decays $\longrightarrow$ two leptons
  - One-loop 2-body decay $\longrightarrow$ a photon
  - GMSB?

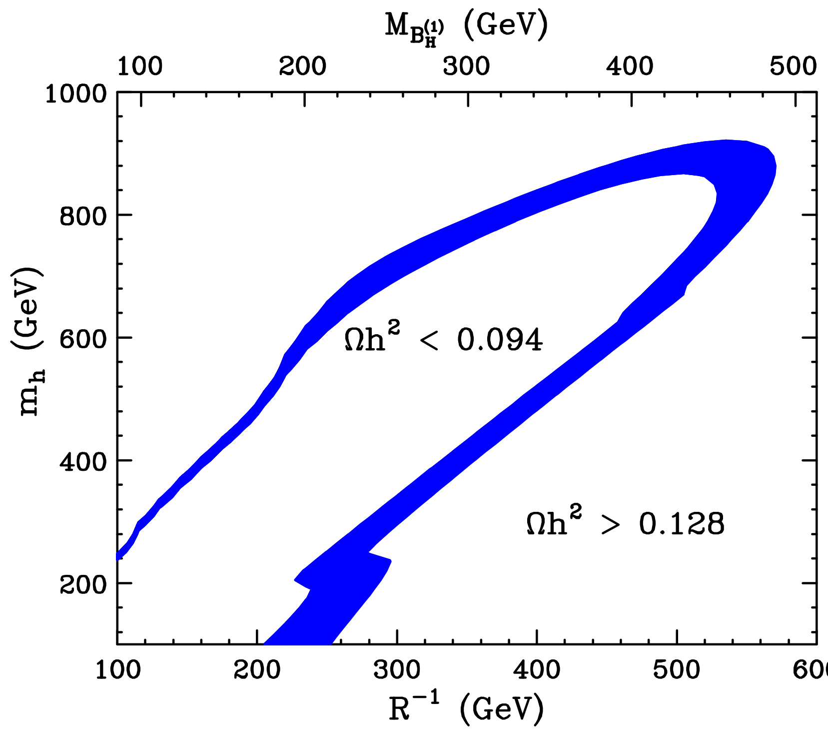


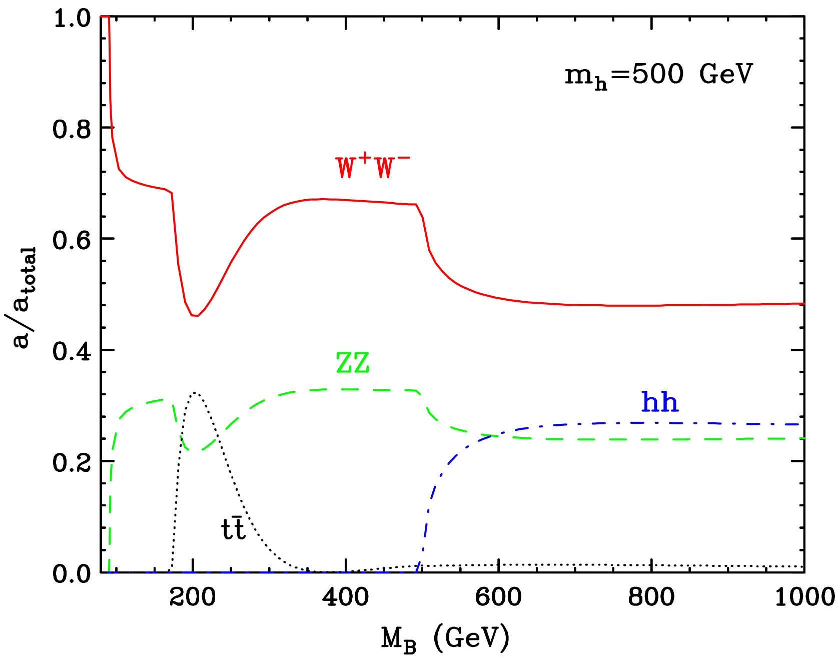




Two Universal Extra Dimensions on Chiral Square

(Dobrescu, Hooper, Kong, Mahbubani, arXiv:0706.3409)

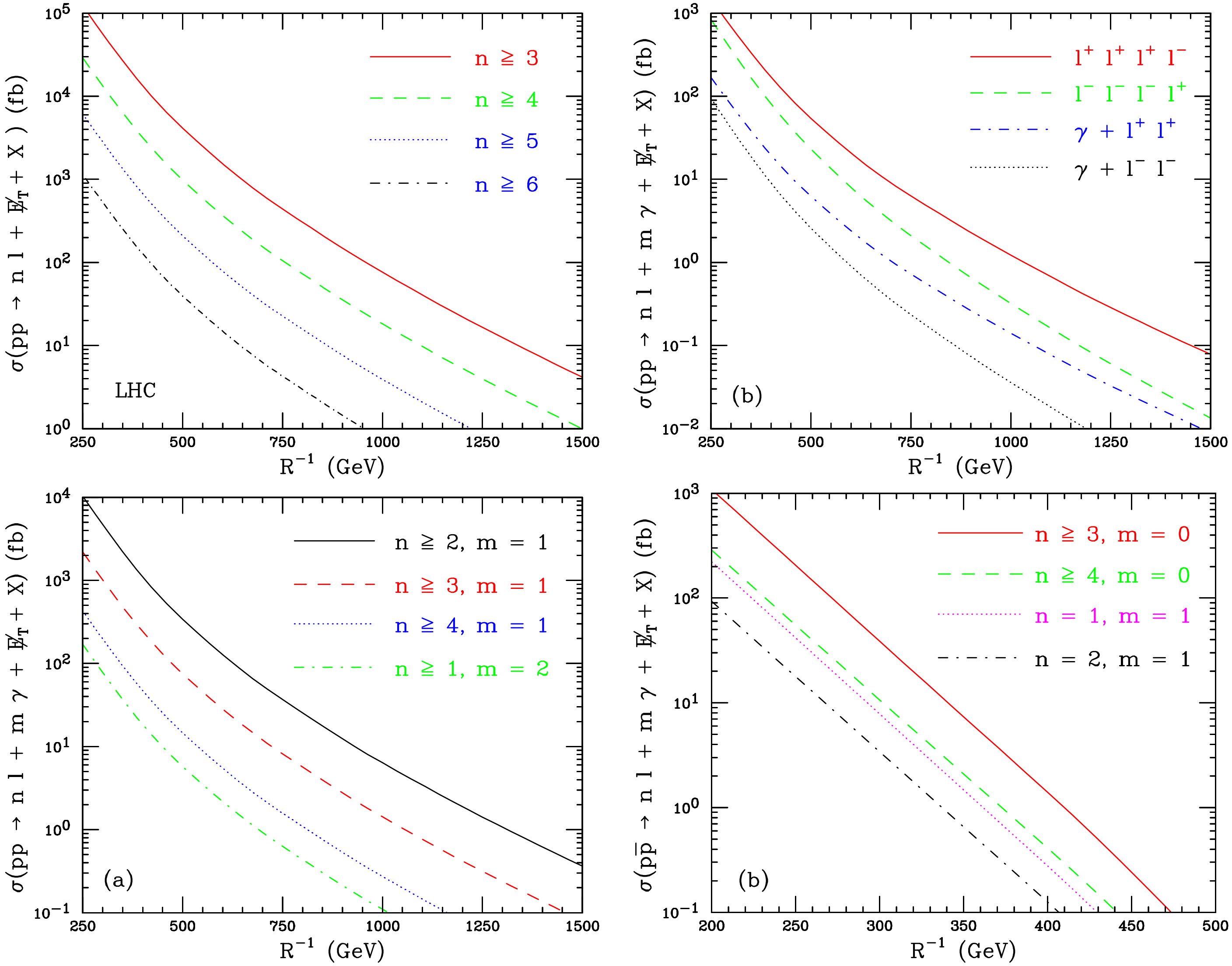




- $R^{-1} < 600$ GeV
- Light higgs requires light KK particles
  $\longrightarrow$ large production cross-sections at the LHC/Tevatron

Leptons/Photons in Two Universal Extra Dimensions

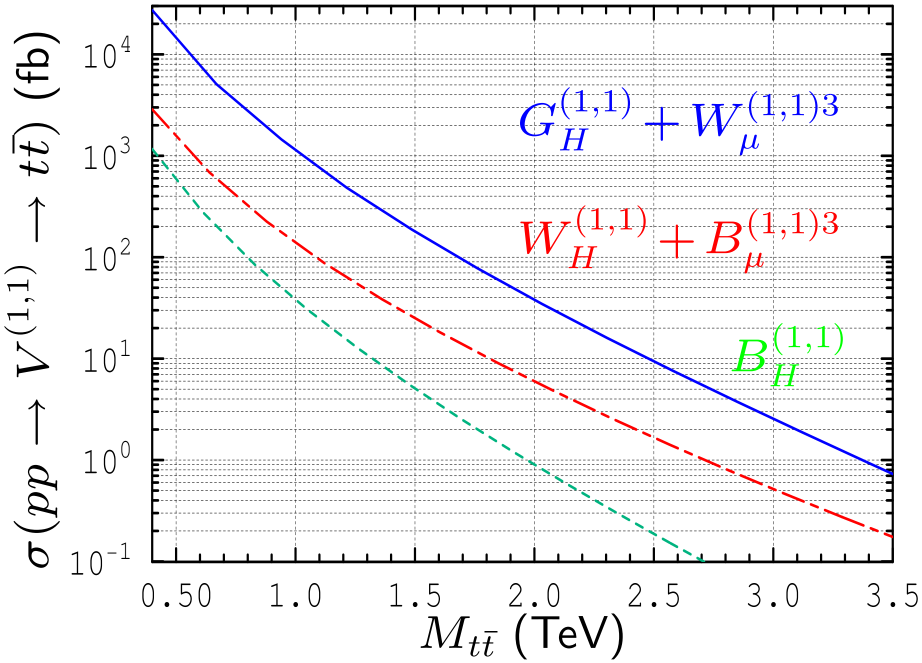
(Dobrescu, Kong, Mahbubani, hep-ph/0703231)



Resonances in Two Universal Extra Dimensions

(Burdman, Dobrescu, Ponton, hep-ph/0601186)

- (1,1) mode: $M_{(1,1)} \sim \frac{\sqrt{2}}{R}$
  - (1,1) mode is lighter than (2,0) mode
  - Three (neutral) gauge bosons: $G_\mu^{(1,1)}$, $W_\mu^{(1,1)}$, $B_\mu^{(1,1)}$
    - Loop-induced couplings $\longrightarrow$ lepto-phobic
    - $Br(W_\mu^{(1,1)},\, B_\mu^{(1,1)} \longrightarrow \ell^+\ell^-) \sim 1\%$
  - Three (neutral) spinless adjoints: $G_H^{(1,1)}$, $W_H^{(1,1)}$, $B_H^{(1,1)}$
    - Derivative coupling, $\bar{q}\gamma^\mu q \partial_\mu X_H^{(1,1)} \longrightarrow Br(X_H^{(1,1)} \longrightarrow t\bar{t}\,) = 1$
- 5 resonances in $t\bar{t}$: $(Br(G_\mu^{(1,1)} \longrightarrow t\bar{t}\,)$ is small)
  - But only 3 may be resolved:
    - $G_H^{(1,1)} + W_\mu^{(1,1)3} \sim 1.1\frac{\sqrt{2}}{R}$
    - $B_\mu^{(1,1)} + W_H^{(1,1)3} \sim 0.97\frac{\sqrt{2}}{R}$
    - $B_H^{(1,1)} \sim 0.86\frac{\sqrt{2}}{R}$
  - Top reconstruction?
  - Jet-energy resolution?
  - B-tagging?
  - A single bump with $\frac{\Gamma}{M} \sim 0.1$?



Discovering resonances: bump hunting

- Our first glimpse of new physics may be

  due to the production of a single new particle

- Z', W', vector-like quarks, $\cdots$

- Color octet spin-1 particles are present

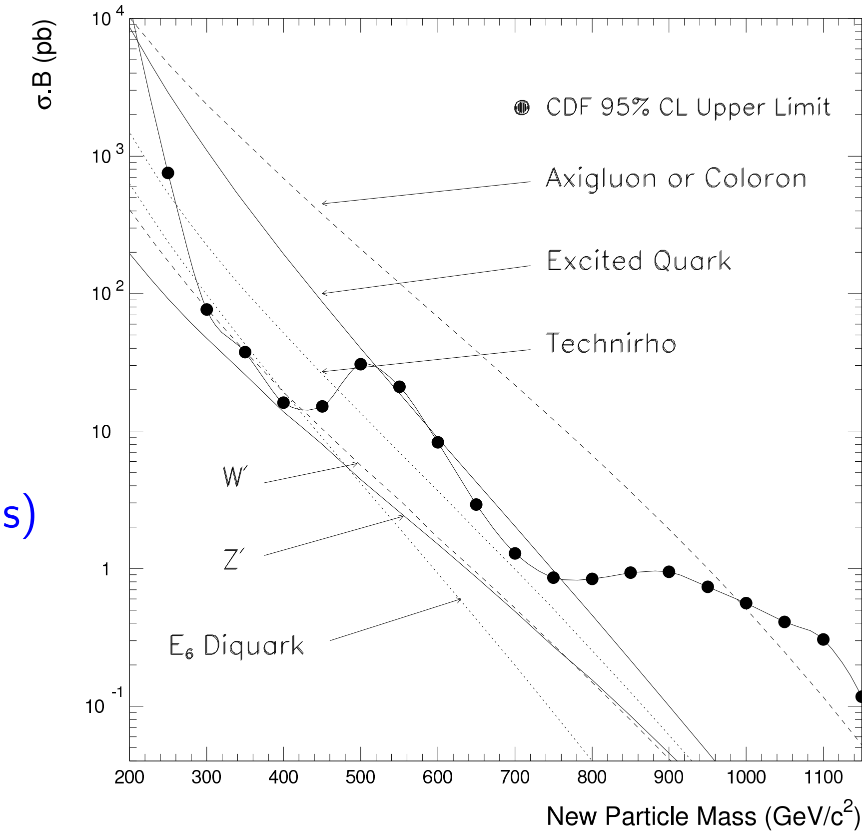
  in many models : G'_μ

  (techni-color, topcolor, extra dimensional models)

- Current Tevatron limit on dijet mass:

  $$M_G > 1 \text{ TeV}$$

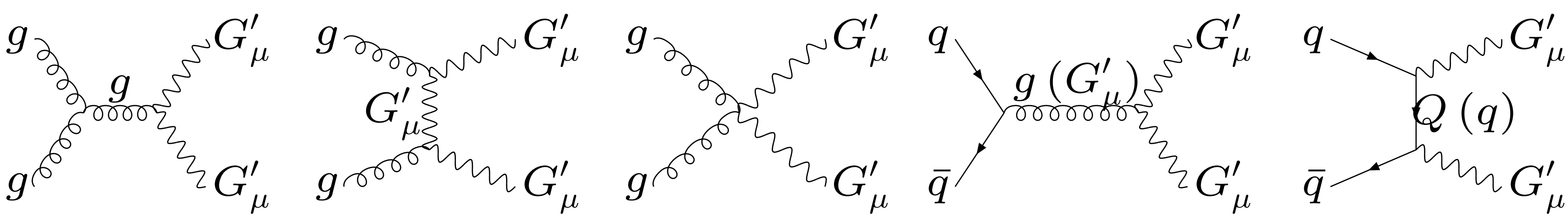
  (assuming same coupling as the gluon)



Massive color-octet bosons and pairs of resonances at hadron colliders

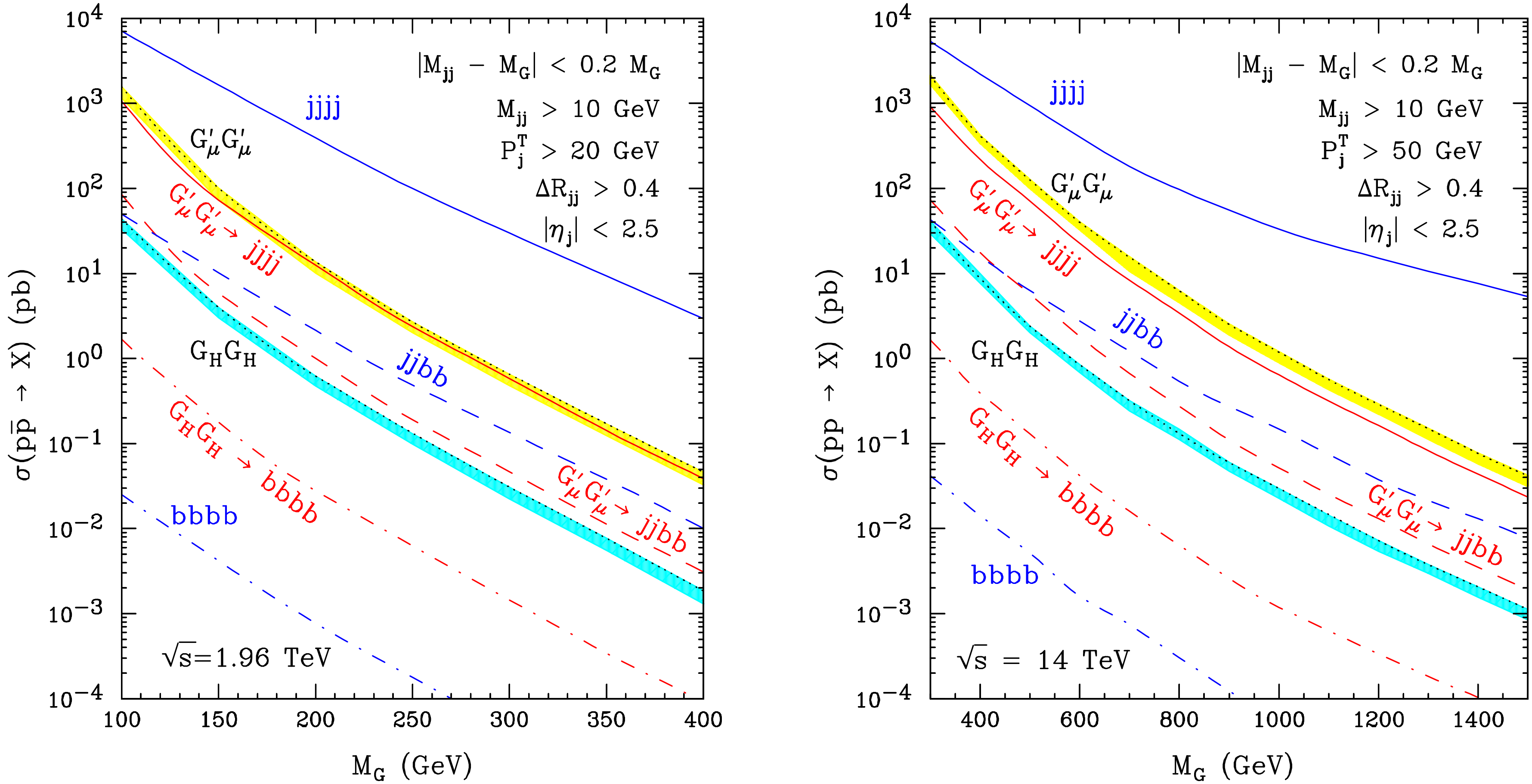
(Dobrescu, Kong, Mahbubani, arXiv:0709.2378)

- Motivation and idea:
  - Strong interaction at hadron colliders $\longrightarrow$ large cross section
  - Dijet search is model-dependent
  - A light coloron/axi-gluon is already ruled out
  - Is model-independent bump search possible?
- $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_c$ always contains heavy color octets that couple to the standard model gluon in pairs with the same strength as QCD
- Bump hunting is not always easy!
- Need dedicated search to find it!



Massive color-octet bosons and $\cdots$

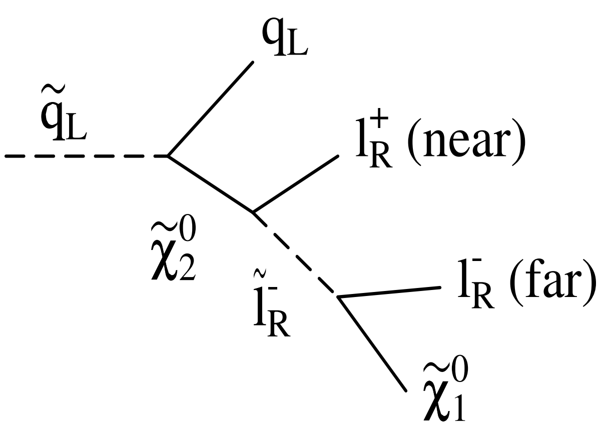
(Dobrescu, Kong, Mahbubani, arXiv:0709.2378)



- Lessons:
  - Di-jet resonance may not be seen in di-jet channel
  - Bump hunting may not be easy and need dedicated search to find it!

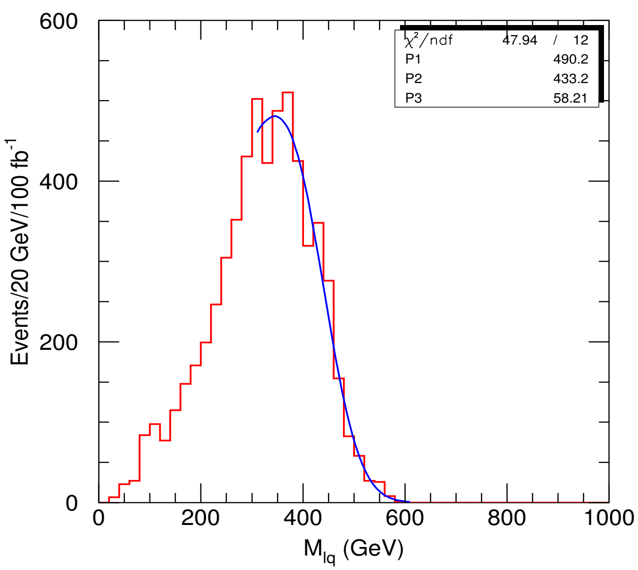
How do we measure masses?: cascade decays!

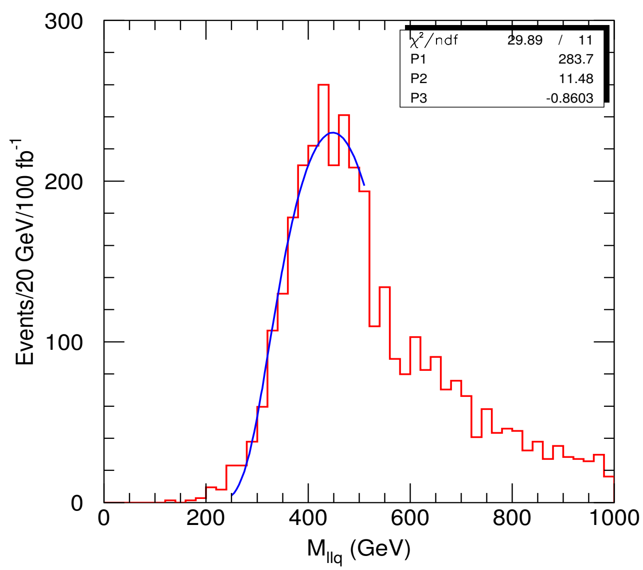
- Cascade decays! (Bachacou, Ian Hinchliffe, Paige, hep-ph/9907518)



$$M_{q\ell}^{max} = \sqrt{\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}_R}^2)}{M_{\tilde{\chi}_2^0}^2}}$$

$M_{\ell\ell q}^{\rm min}$ with $M_{\ell\ell} > M_{\ell\ell}^{max}/\sqrt{2}$, $M_{\ell\ell}^{max}$, $M_{q\ell\ell}^{max}$

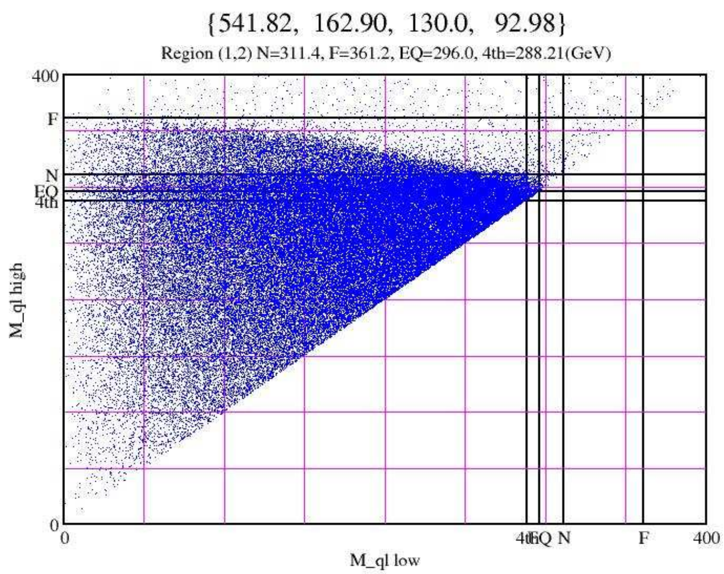


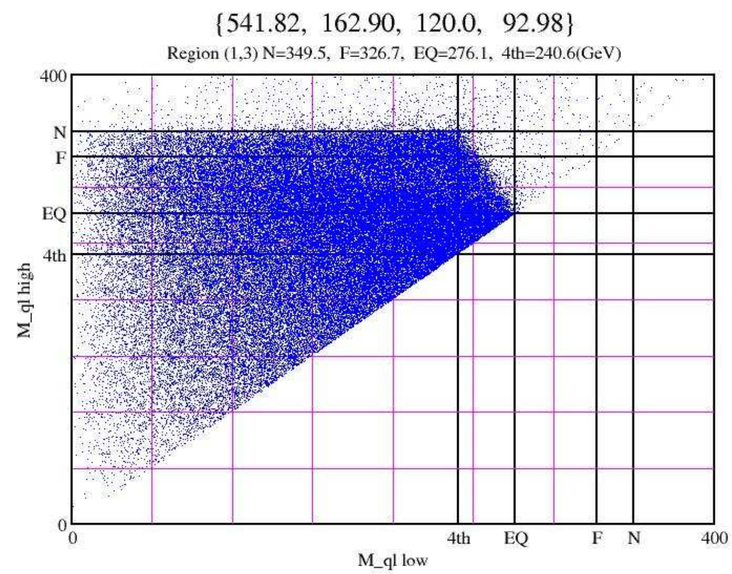


Myth of SPS1a

(Burns, Kong, Lee, Matchev, Park, Preliminary)

- 12 kinematic region, 3 incompatible solutions (Gjelsten, Miller, Osland, hep-ph/0410303)
- Inversion from observables to masses: 9 solutions
- SPS1a gives unique solution
- What if the nature is not SPS1a? $\longrightarrow$ keep the same on-shell decay chain but allow all possible masses $\longrightarrow$ unique solution 75% of the time but two solutions 25% of the time: (2,3)-(3,2), (2,3)-(3,1), (4,3)-(3,2), (4,3)-(3,1)
- Two-fold ambiguity can be resolved

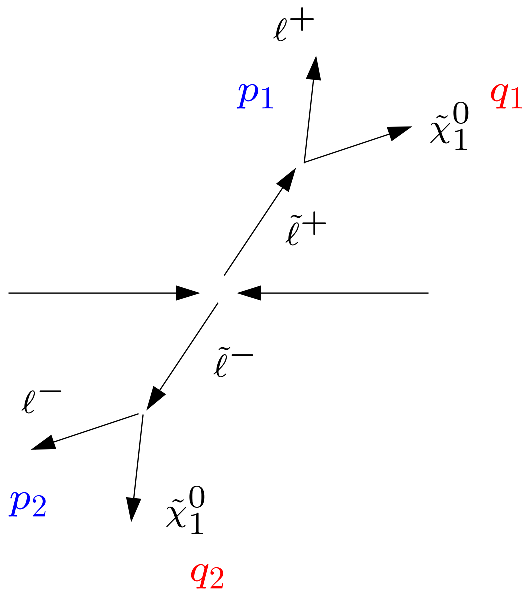




What if there are two missing particles?: m_{T2}

(Barr, Lester, Stephens, hep-ph/0304226, "m(T2): The Truth behind the glamour")

(Lester, Summers, hep-ph/9906349)



- $\not{E}_T = \vec{q}_1 + \vec{q}_2 = -(\vec{p}_1 + \vec{p}_2)$
- If $\vec{q}_1$ and $\vec{q}_2$ are obtainable,

$$m_{\tilde{\ell}}^2 \geq max\{\, m_T^2(\vec{p}_1, \vec{q}_1)\,, m_T^2(\vec{p}_2, \vec{q}_2)\,\}$$

- But $\not{E}_T = \vec{q}_1 + \vec{q}_2 \longrightarrow$ the best we can say is that

$$m_{\tilde{l}}^2 \geq m_{T2}^2 \equiv \min_{\not{q}_1 + \not{q}_2 = \not{E}_T} \left[\max\{m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2)\} \right]$$

What if there are two missing particles?: m_{T2}

(Barr, Lester, Stephens, hep-ph/0304226, "m(T2): The Truth behind the glamour")

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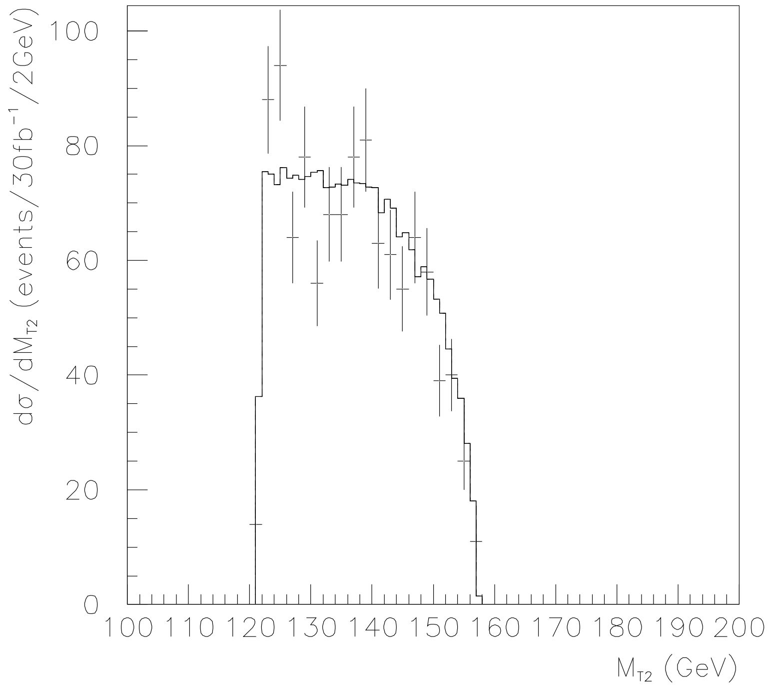
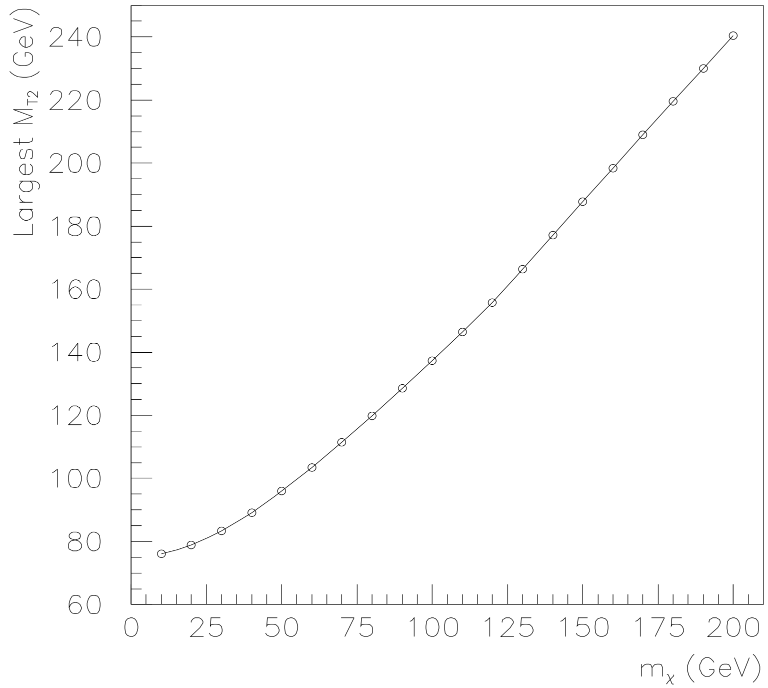


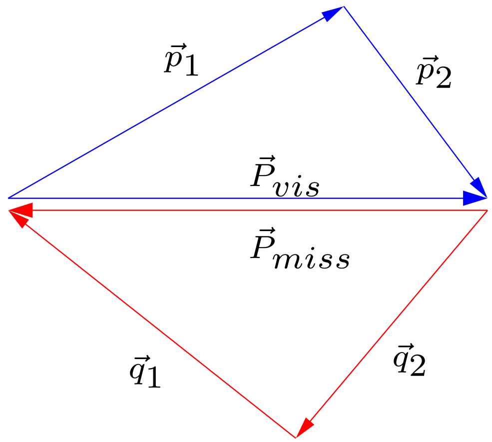


$$m_{\tilde{l}}^2 \geq m_{T2}^2 \equiv \min_{\not{q}_1 + \not{q}_2 = \not{E}_T} \left[\max \left\{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \right\} \right] \geq m_{\tilde{\chi}_1^0}^2$$

- Rely on momentum scan $\longrightarrow$ can be reduced to one dimensional parameter scan
  $\longrightarrow$ can not get analytic differential distribution
- Have to assume $m_{\tilde{\chi}_1^0}$ $\longrightarrow$ correlation between $m_{\tilde{l}}$ and $m_{\tilde{\chi}_1^0}$

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)



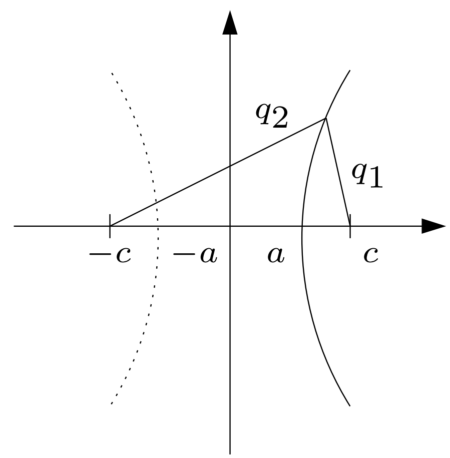
$$m_{T2}^2 \equiv \min_{\not{q}_1 + \not{q}_2 = \not{E}_T} \left[\max \{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \} \right]$$

Constraint: $m_T^2(\vec{p}_1, \vec{q}_1) = m_T^2(\vec{p}_2, \vec{q}_2)$

$$\rightarrow \sqrt{\vec{q}_2^2 + m^2} - \sqrt{\vec{q}_1^2 + m^2} = |\vec{p}_1| - |\vec{p}_2| > 0$$

- massless case ($m = 0$): WW production, $m_{\tilde{\chi}_1^0} << m_{\tilde{\ell}}$

$$2a \equiv p_1 - p_2 = q_2 - q_1$$
$$2c \equiv \not{E}_T$$
$$e = \frac{c}{a}$$



- Solution: $\vec{q}_1 = -\vec{p}_2$ and $\vec{q}_2 = -\vec{p}_1$
- Warning: $\vec{q}_1$ and $\vec{q}_2$ are NOT neutrino momenta

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)

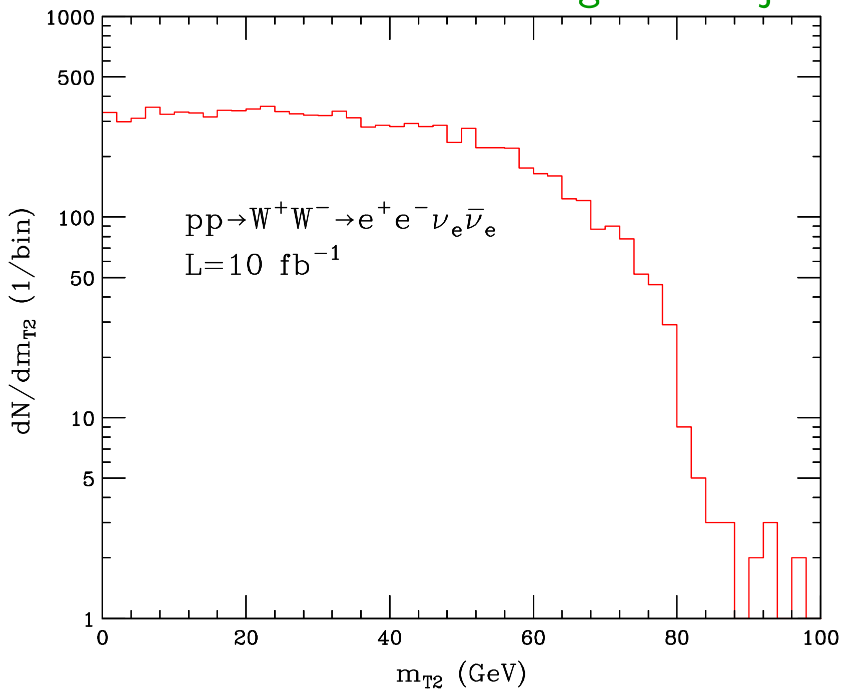
- massive case $(m \neq 0)$

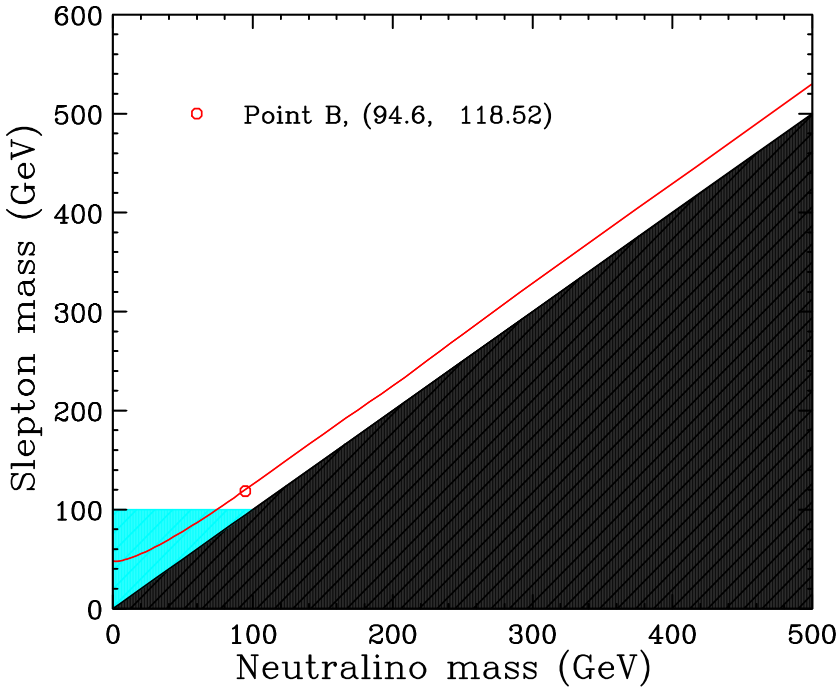
$$
\begin{aligned}
num &= 16\, e\, \left(1 + (-1 + e^2)\, \mu^2\right)^{\frac{3}{2}} (e + \cos(\phi))\, (1 + e\, \cos(\phi))\, \sin(\phi)^2 \\
&+ 4\, \left(1 + (-1 + e^2)\, \mu^2\right) \left(-2\, (1 + e^2 + e^4) - (-1 + e)\, (1 + e)\, (2 + e^4)\, \mu^2\right. \\
&- \left. 4\, e\, \left(1 + e^2 + (-1 + e^2)\, \mu^2\right)\, \cos(\phi) + e^2\, \left(-2 + (2 - 3\, e^2 + e^4)\, \mu^2\right)\, \cos(2\, \phi)\right) \sin(\phi)^2 \\
den &= -8\, (1 + 4\, e^2 + e^4) - 4\, (2 + e^2)\, (-2 - 5\, e^2 + 2\, e^4)\, \mu^2 + (-8 - 16\, e^2 - 12\, e^4 + 4\, e^6 - 3\, e^8)\, \mu^4 \\
&- 8\, e\, \left(4\, (-1 + \mu^2)^2 + 2\, e^2\, (2 - 3\, \mu^2 + \mu^4) + e^4\, (\mu^2 + \mu^4)\right)\, \cos(\phi) \\
&+ 4\, e^2\, \left(-4 + 2\, (6 + e^2 + e^4)\, \mu^2 + (-8 + 2\, e^2 - 2\, e^4 + e^6)\, \mu^4\right)\, \cos(2\, \phi) \\
&+ e^3\, \mu^2\, \left(8\, \left(2 + e^2 + (-2 + e^2)\, \mu^2\right)\, \cos(3\, \phi) + e\, \left(4 - (-2 + e^2)^2\, \mu^2\right)\, \cos(4\, \phi)\right)^4 \\
\sin^2\theta &= \frac{num}{den}
\end{aligned}
$$

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)

- Applications:
  - Mass correlation even if there are two missing particles:
    W and slepton pair production
  - Can be used for background rejection





- $N = \sigma \times BR \times \mathcal{L} \times \epsilon =$ fixed
  - $\sigma > \sigma_0(BR = 1) \to m < m_0$

Recent progress on m_{T_2}

- arXiv:0709.0288 by Cho, Choi, Kim, Park, Measuring superparticle masses at hadron collider using the transverse mass kink
- arXiv:0708.1028 by Lester, Barr, MTGEN: Mass scale measurements in pair-production at colliders
- arXiv:0709.2740 by Gripaios, Transverse observables and mass determination at hadron colliders.
- arXiv:0711.4008 by Barr, Gripaios, Lester, Weighing Wimps with Kinks at Colliders: Invisible Particle Mass Measurements from Endpoints.
- arXiv:0711.4526 by Cho, Choi, Kim, Park, Gluino Stransverse Mass
- $\cdots$

Summary and conclusion

- LHC is finally coming
- New physics beyond the SM is expected to be discovered but how do we know what we see is what we expect to see?
- Many candidates for new physics have similar signatures at the LHC (SUSY, UEDs, T-parity...).
- Crucial to know spin information of new particles.
  - Spin information has something to do with shapes
  - Good understanding of SM background
  - Important to know mass spectrum
- Need to develop new methods: m_{T2}...

Back up slides

Universal Extra Dimensions

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

- 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

UED vs. SUSY

	SUSY	UED
Field	$\Phi(x^\mu, \theta, \theta^*)$	$\Phi(x^\mu, y^i)$
Symmetry	Supersymmetry	5D Lorentz and gauge symmetry (broken by compactification and boundary interactions)
Component fields	**(SM, Superpartner)** Φ in terms of θ and θ^*	**(SM, KK partners)** Φ in terms of bases (exp(y), cos(y), sin(y))
Spins	**differ by** $\frac{1}{2}$	**same spins**
$\mathcal{L}_{eff}$	$\int d\theta d\theta^* S[\Phi(x, \theta, \theta^*)]$	$\int dy S[\Phi(x, y)]$
Discrete symmetry $\longrightarrow$ DM	R-parity	KK-parity $= (-1)^n$
$\#$ of parameters	many (soft terms) 5 in MSUGRA	many (boundary terms) 2 in MUED (R, Λ)
Gauge bosons	maybe	**KK partners of SM gauge bosons**
Renormalizability	Yes	No

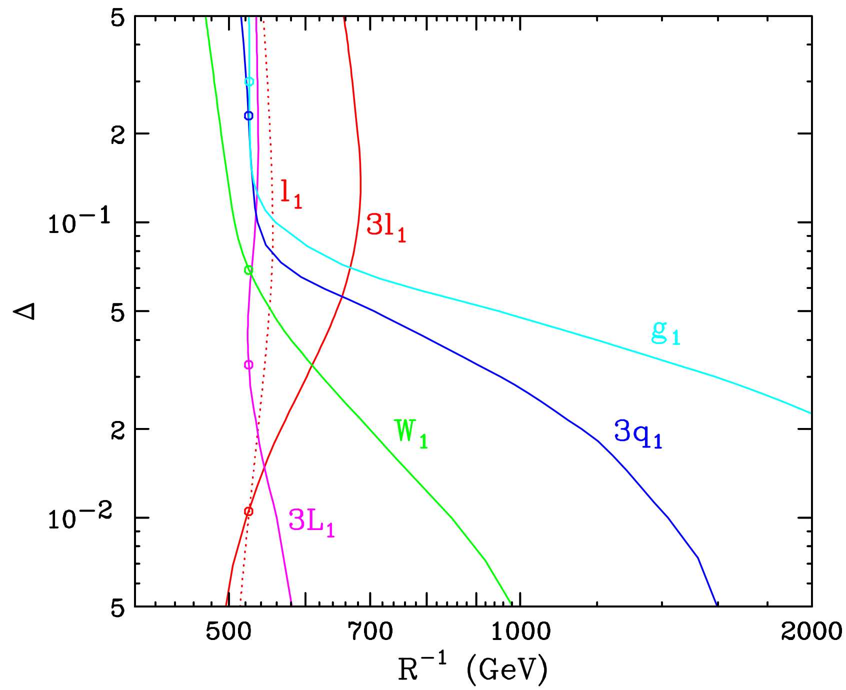
- Two theories look very similar - UED referred to as “Bosonic Supersymmetry”

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

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, $\Omega h^2 = 0.1$)

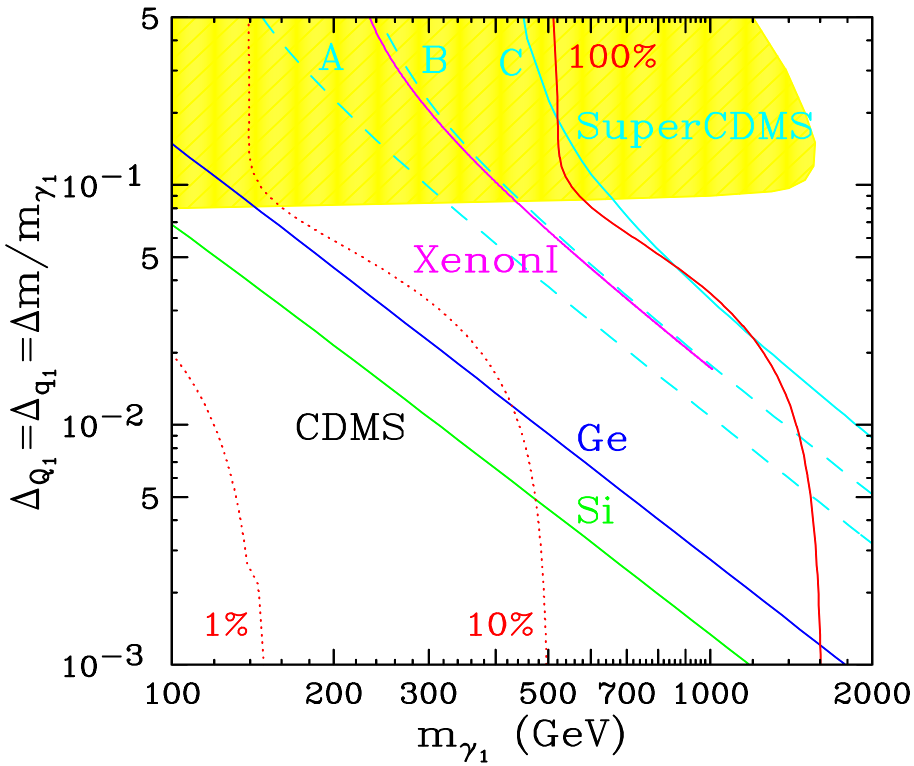
(Kong, Matchev, hep-ph/0509119)

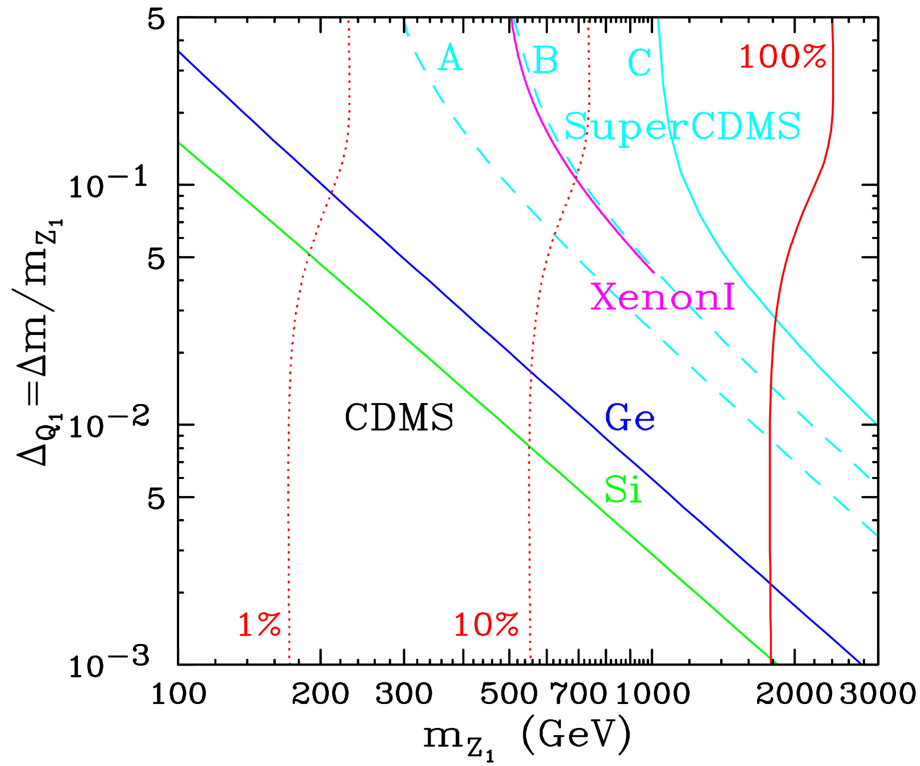


- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, m_{LKP} is large, UED escapes collider searches
    $\longrightarrow$ But, good news for dark matter searches

CDMS (Spin independent): B_1 and Z_1 LKP

(Baudis, Kong, Matchev, Preliminary)

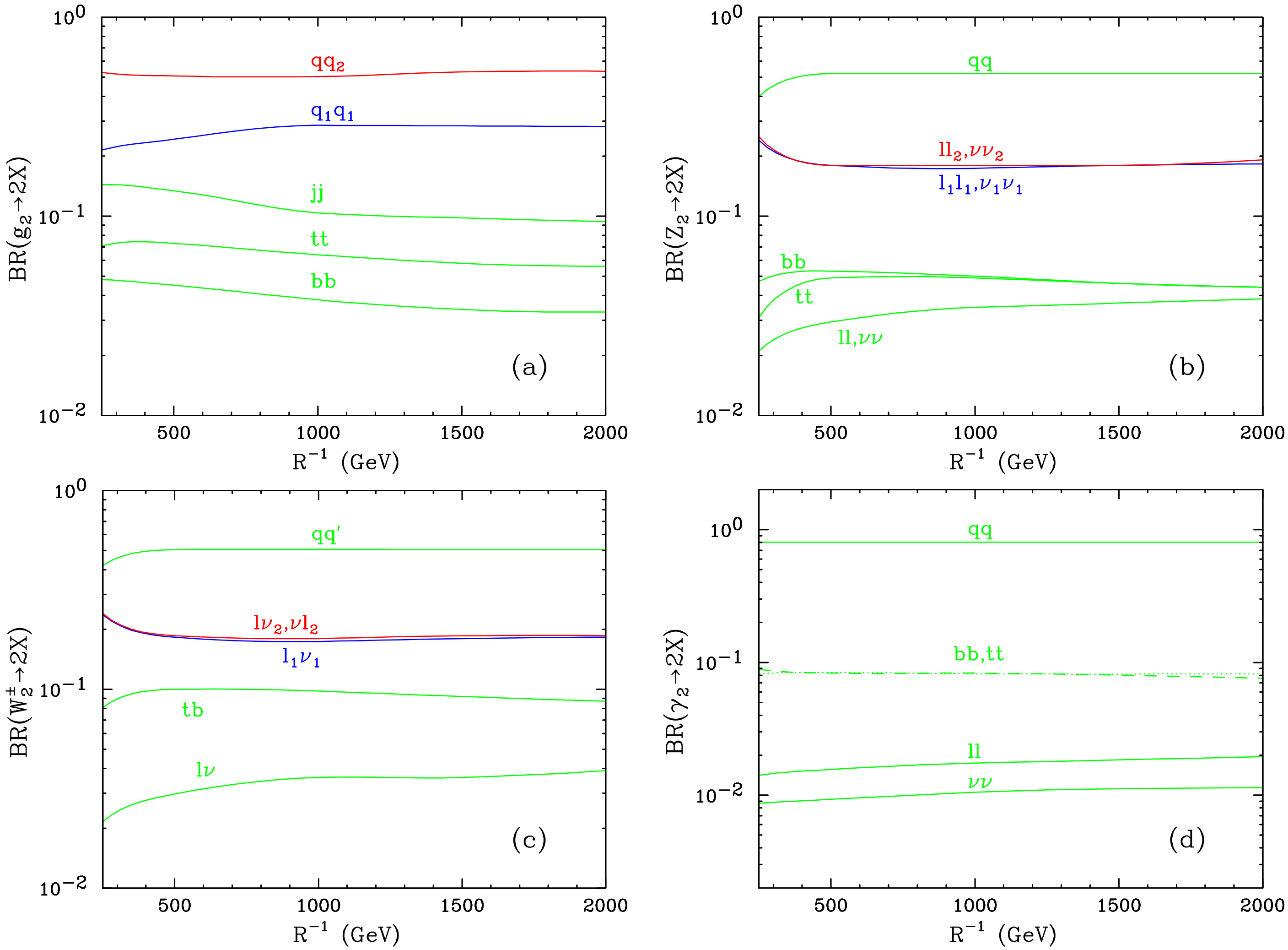




- SuperCDMS (projected)
  - A (25 kg), B (150 kg), C (1 ton)
- $\Delta_{q_1} = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$

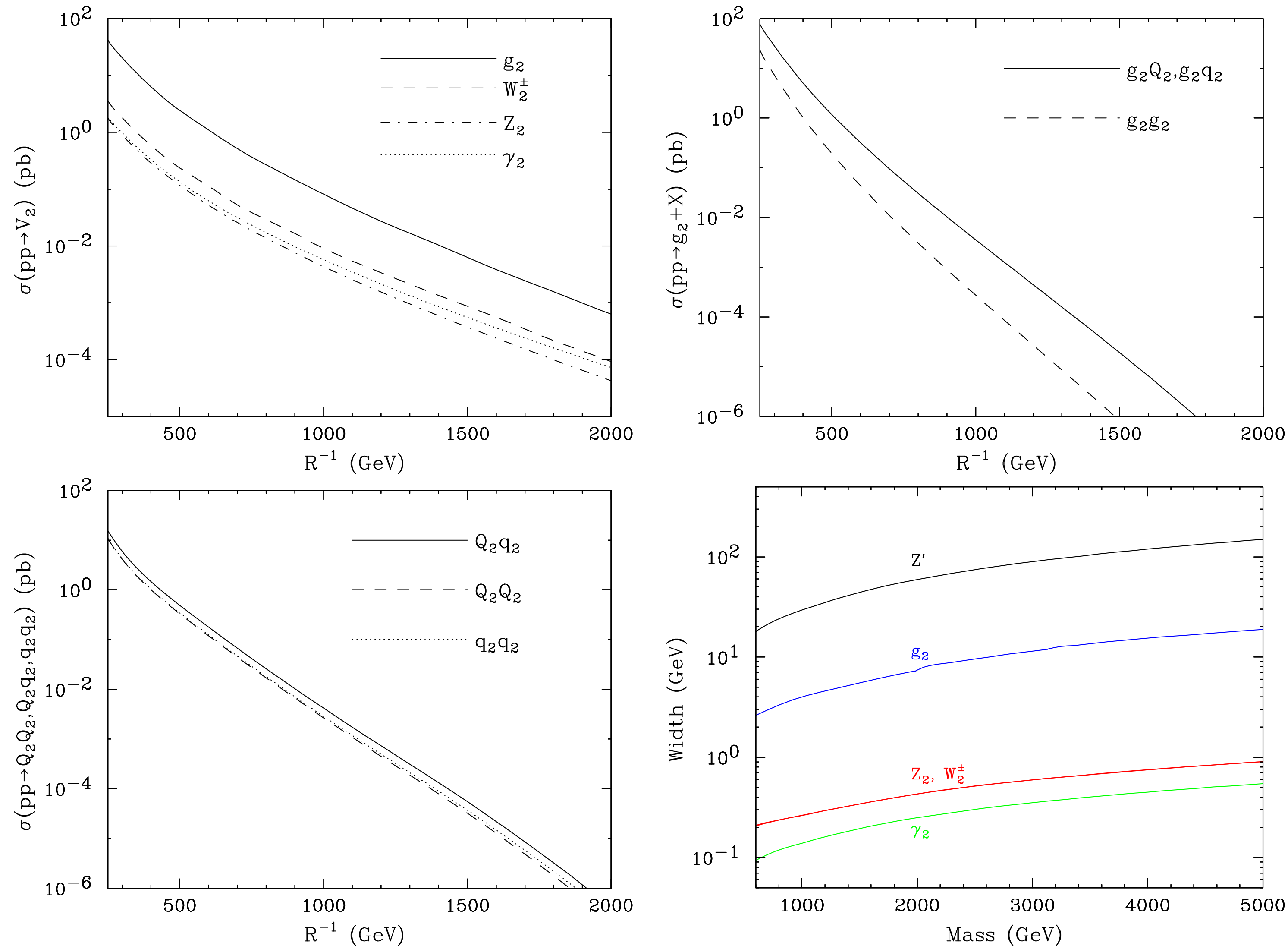
- Z_1 LKP in nonminimal UED:
  - $\Delta_{Q_1} = \frac{m_{Q_1} - m_{Z_1}}{m_{Z_1}}$
  - $\Delta_{g_1} = 0.2$
  - $\Delta_1 = 0.1$

Branching fractions of level 2 Gauge Bosons



- γ_2: almost Lepto-phobic
- $\gamma_2 + Z_2 + g_2 \longrightarrow$ one single bump in dijet

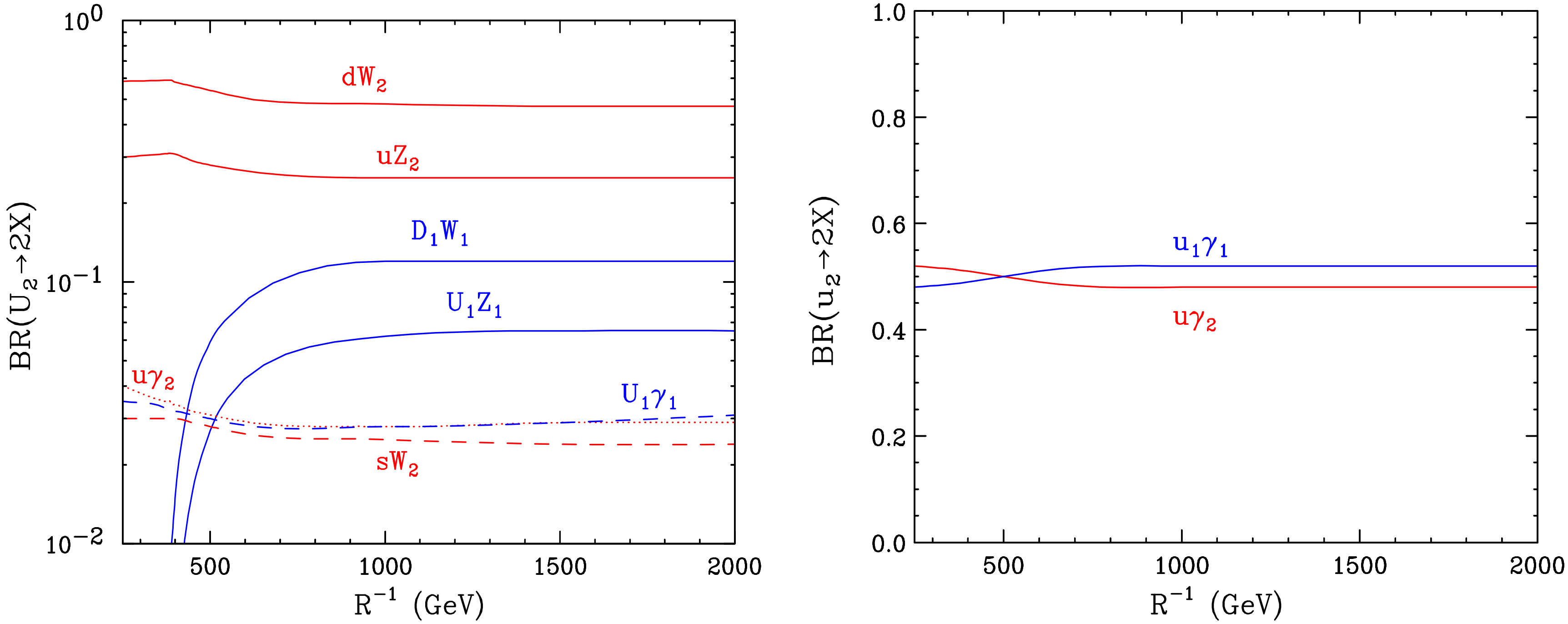
Production/Widths of level 2 Gauge Bosons



- Indirect production is important

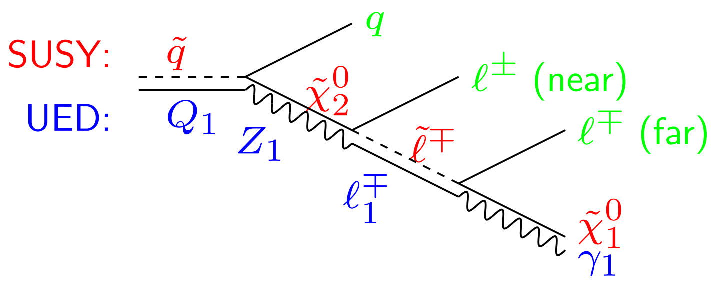
Branching Ratios of level 2 KK quarks

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



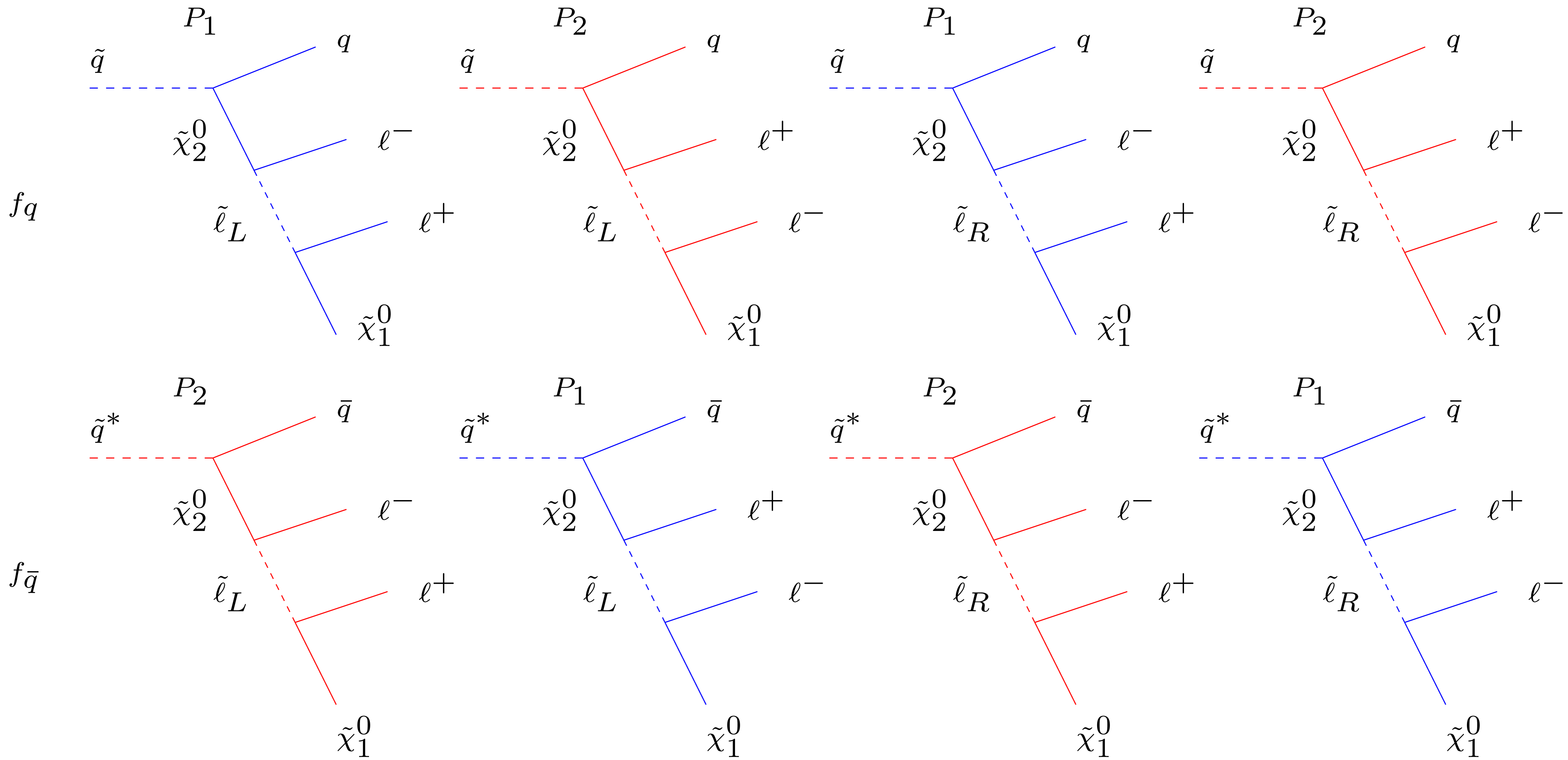
- Large Branching ratios into level 2 gauge bosons
  - $BR(Q_2 \longrightarrow Z_2Q_0) \geq 25\%$
  - $BR(Q_2 \longrightarrow \gamma_2Q_0) \geq 3\%$
  - $BR(q_2 \longrightarrow \gamma_2Q_0) \approx 50\%$
  - $BR(g_2 \longrightarrow Q_2Q_0 + q_2q_0) \approx 50\%$

Barr method



- Look at correlation between q and ℓ (Barr, hep-ph/0405052)
- Complications:
  - Which (quark) jet is the right one ?
    (Webber, hep-ph/0507170 "cheated", picked the right one)
    One never knows for sure. There can be clever cuts to increase the probability that we picked right one
    (work in progress)
  - Which lepton ? : "near" and "far" cannot be distinguished
    $\longrightarrow$ must add both contributions. Improvement on selection (work in progress)
  - Don't know q or $\bar{q}$
  - But more q than $\bar{q}$ at the LHC in t-channel production
- Can distinguish charge of leptons: look at $q\ell^+$ and $q\ell^-$ separately and compare

Barr method



- $f_q + f_{\bar{q}} = 1$

Barr method

(Datta, Kong, Matchev, hep-ph/0509246 and Smillie, Webber, hep-ph/0507170)

- Choose a study point : UED500 and SPS1a ($\mathcal{L} = 10 fb^{-1}$)
- Each $M_{q\ell}$ distribution contains 4 contributions

$$\left(\frac{d\sigma}{dm}\right)_{q\ell^+} = f_q \left(\frac{dP_2}{dm_n} + \frac{dP_1}{dm_f}\right) + f_{\bar{q}} \left(\frac{dP_1}{dm_n} + \frac{dP_2}{dm_f}\right)$$

$$\left(\frac{d\sigma}{dm}\right)_{q\ell^-} = f_q \left(\frac{dP_1}{dm_n} + \frac{dP_2}{dm_f}\right) + f_{\bar{q}} \left(\frac{dP_2}{dm_n} + \frac{dP_1}{dm_f}\right)$$

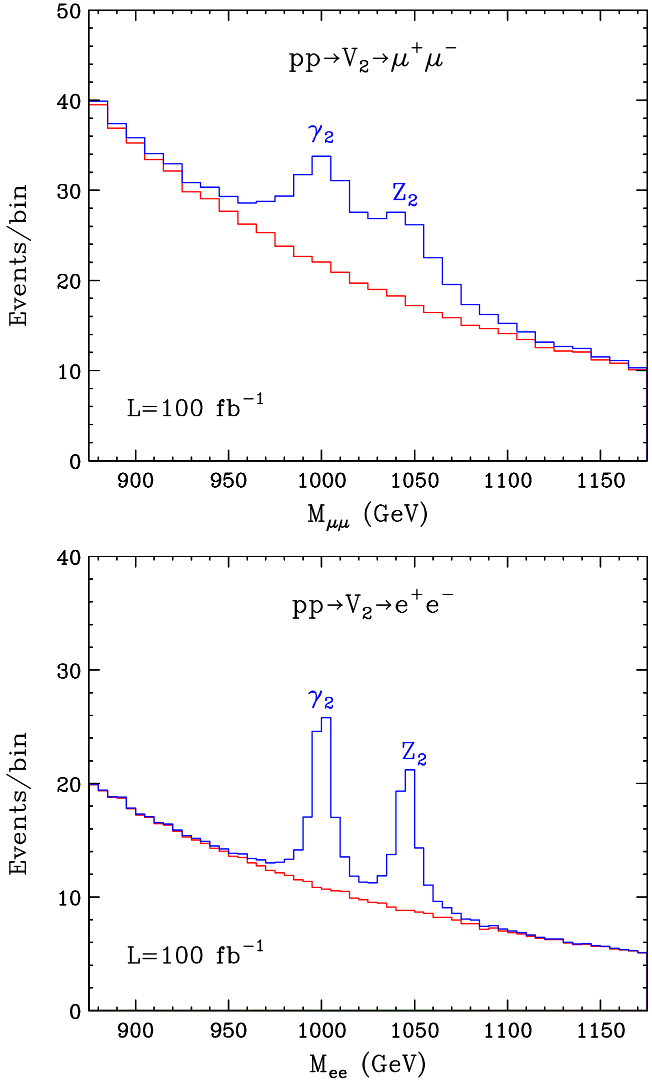
- Asymmetry:

$$A^{+-} = \frac{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} - \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} + \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}$$

- $f_q + f_{\bar{q}} = 1$
- If $f_q = f_{\bar{q}} = 0.5$, $A^{+-} = 0$ (for example, in the "focus point" region)

How do we measure masses?: bump hunting!

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

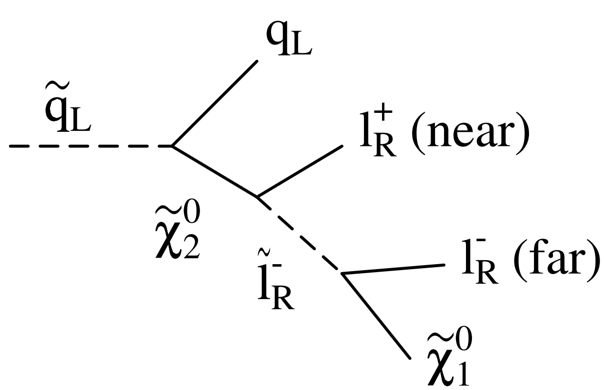


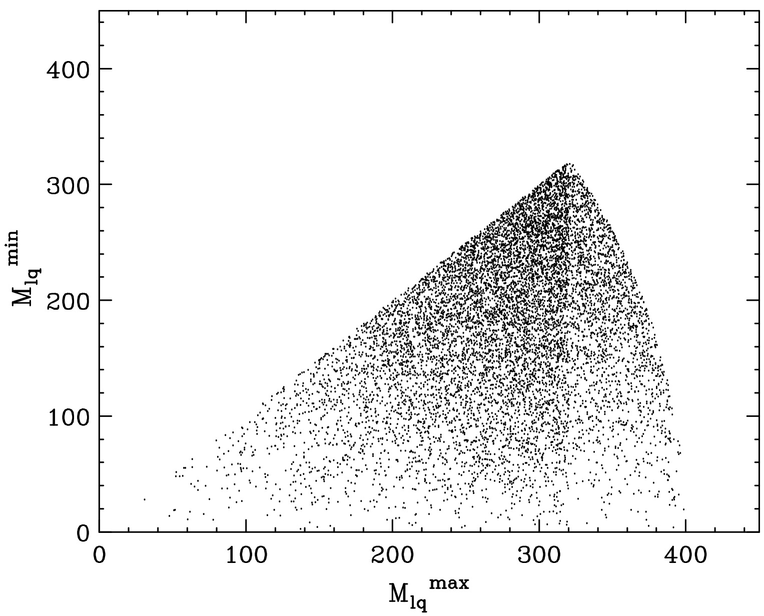
- Bump hunting!: ex. two resonances in UEDs
- Level 2 resonances can be seen at the LHC:
  - up to $R^{-1} \sim 1$ TeV for 100 fb^{-1}, $M_{ab}^2 = (p_a + p_b)^2$
  - covers dark matter region of MUED
- Mass resolution:
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV}\right)$ 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 $\longrightarrow$ just like SUSY with a bunch of Z's $\longrightarrow$ need spins to discriminate

Myth of SPS1a

(Burns, Kong, Lee, Matchev, Park, Preliminary)

- Can we distinguish near leptons from far leptons?





- Lose statistics
- Can we improve on spin measurement?

What if there are two missing particles?: m_{T2}

(Barr, Lester, Stephens, hep-ph/0304226, "m(T2): The Truth behind the glamour")

(Lester, Summers, hep-ph/9906349)

$$
\begin{aligned}
m_{\tilde{\ell}}^2 &= m_{\tilde{\chi}_1^0}^2 + 2\left[E_T^{\ell} E_T^{\tilde{\chi}_1^0} \cosh\left(\Delta\eta\right) - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\tilde{\chi}_1^0}\right] \\
E_T^{\ell} &= |p_T| \\
E_T^{\tilde{\chi}_1^0} &= \sqrt{\left(\vec{p}_T^{\,\tilde{\chi}_1^0}\right)^2 + m_{\tilde{\chi}_1^0}^2} \\
\eta &= \frac{1}{2}\log\left[\frac{E+p_z}{E-p_z}\right]
\end{aligned}
$$

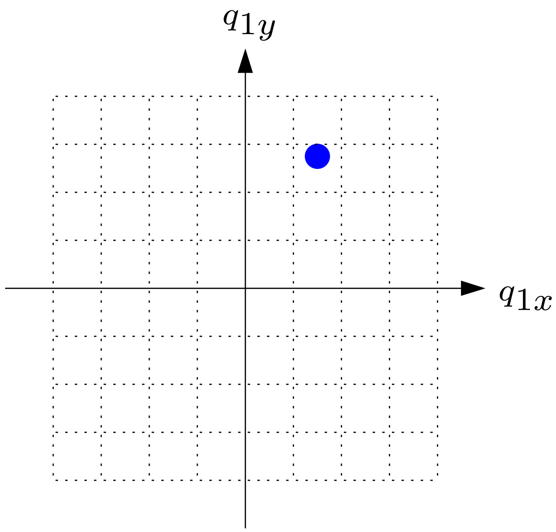
$(\tanh\eta = \frac{p_z}{E}, \sinh\eta = \frac{p_z}{E_T}$ and $\cosh\eta = \frac{E}{E_T})$

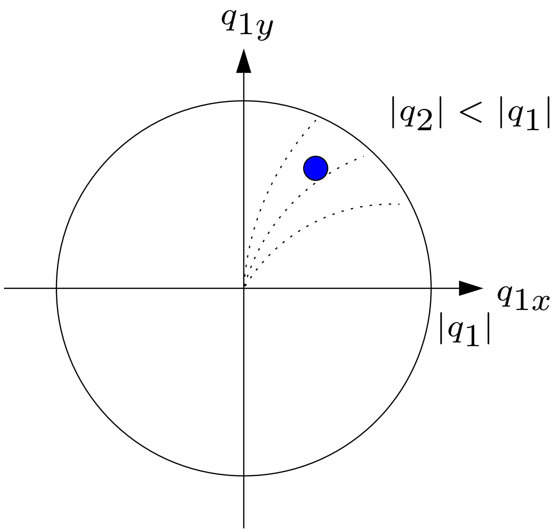
$$
\begin{aligned}
m_T^2(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^0}) &\equiv m_{\tilde{\chi}_1^0}^2 + 2\left(E_T^{\ell} E_T^{\tilde{\chi}_1^0} - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\tilde{\chi}_1}\right) \\
m_T &\leq m_{\tilde{\ell}}
\end{aligned}
$$

- We don't measure $\vec{p}_T^{\,\tilde{\chi}_1^0}$
- Most of new physics have at least two missing particles in the final state

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)





- good: uniform scan
- bad: how far should we scan?

  $0 \leq |q_{1x}|, |q_{1y}| \leq \#|p_1|$

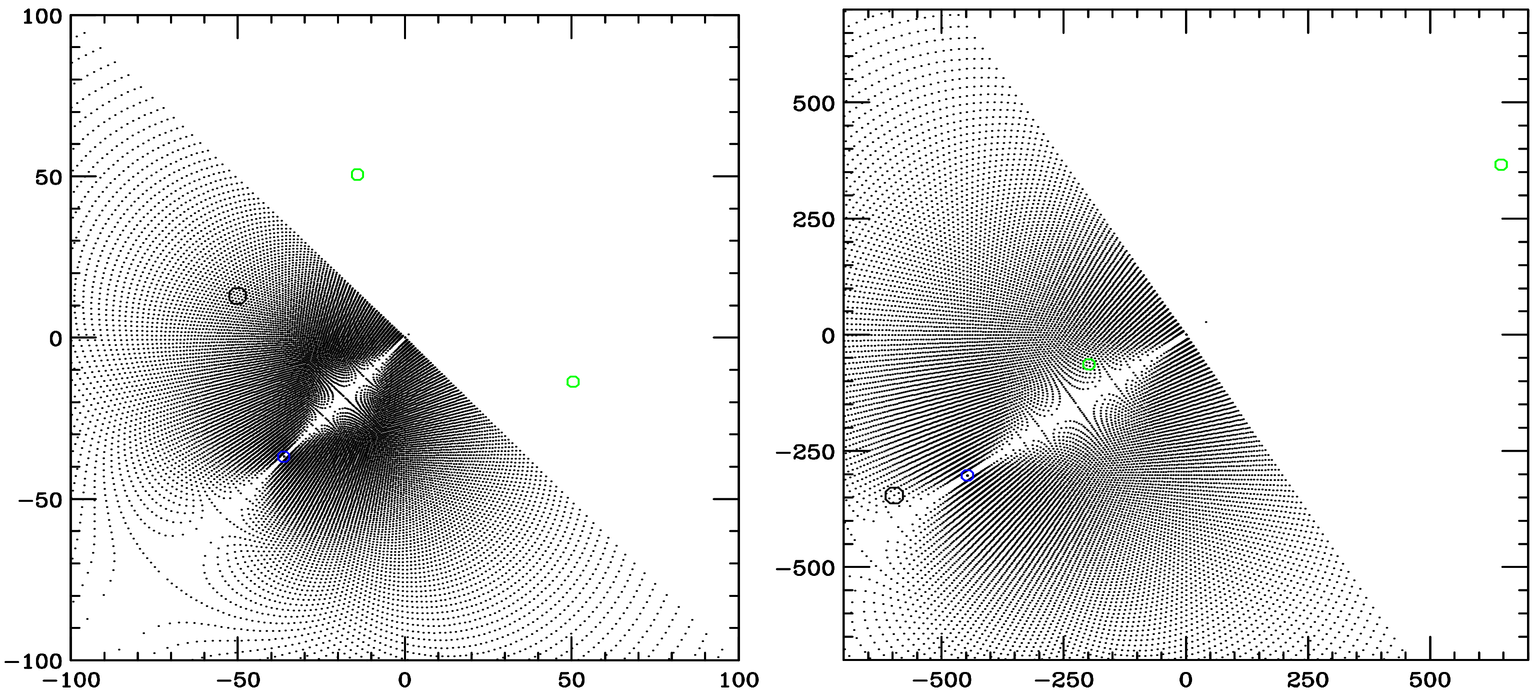
- bad: non-uniform scan
- good: compact scan

  $|q_2| \leq |q_1|,\ 0 \leq \theta_2 \leq 2\pi$

- $\vec{q}_1 + \vec{q}_2 = \vec{\not{E}}_T$

The Cambridge m_{T2} Variable Demystified

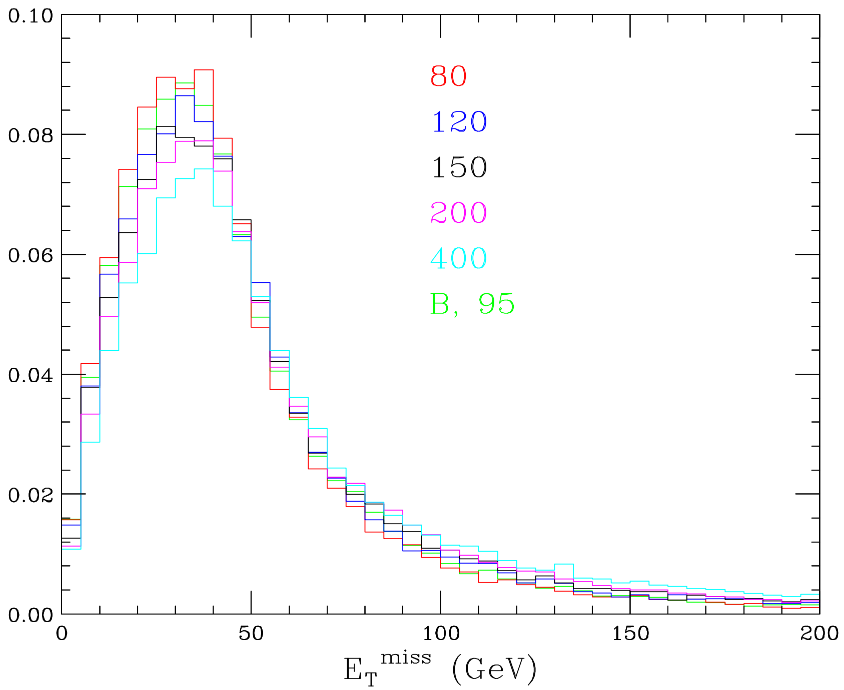
(Kong, Matchev, Preliminary)

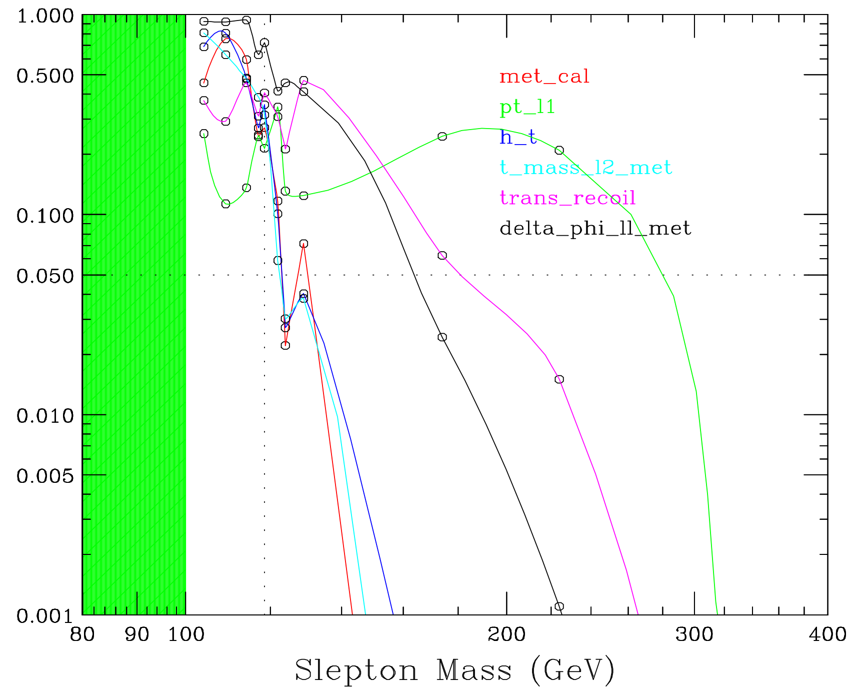


Kolmogorov-Smirnov Test

(Kong, Matchev, Preliminary)

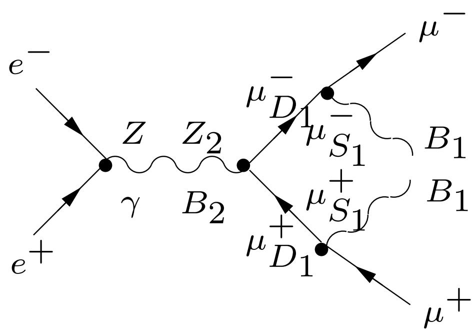
- Is there another mass measurement?
- KS test?

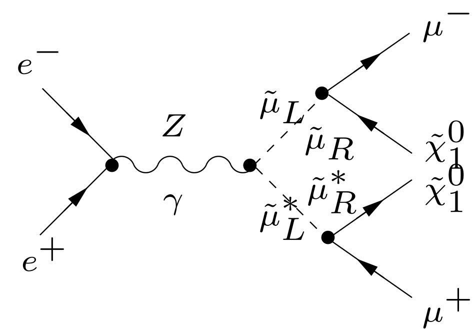




- Difficulties:
  - Not enough statistics
  - Cuts distort shapes of the distributions

SUSY vs UED at LC in $\mu^+\mu^- + \not{E}_T$ channel





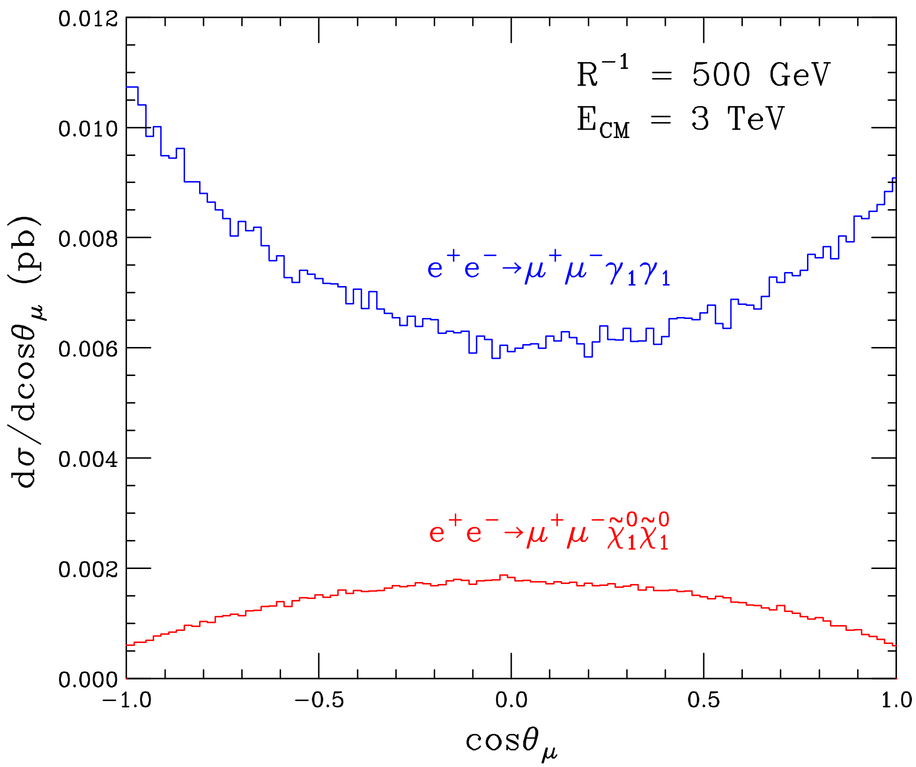
- Angular distribution

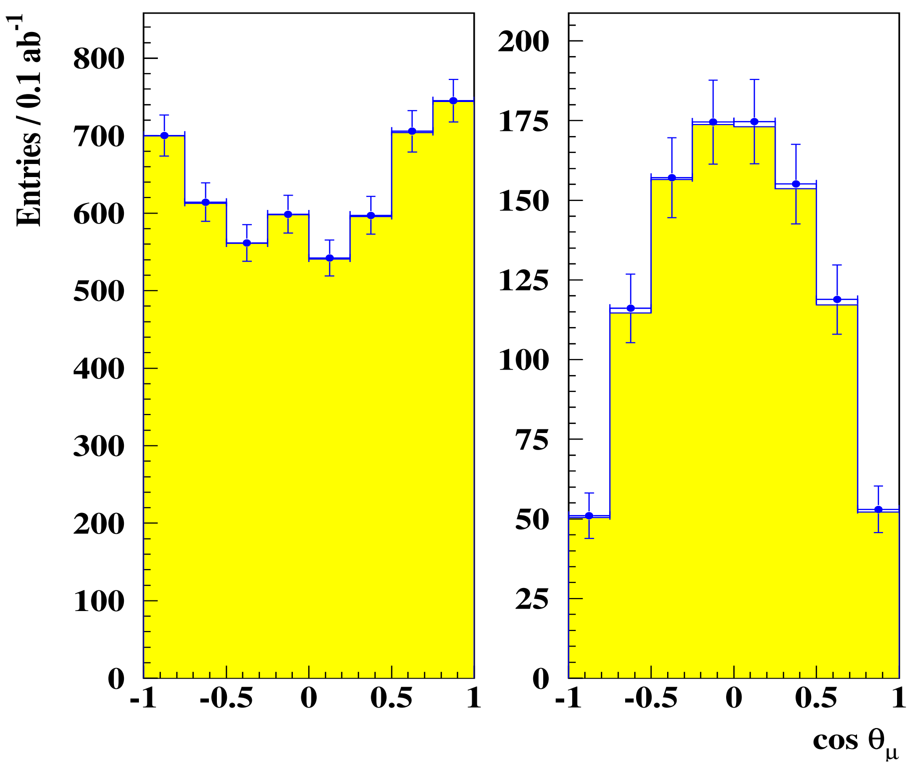
$$\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \frac{E^2_{\mu_1} - M^2_{\mu_1}}{E^2_{\mu_1} + M^2_{\mu_1}} \cos^2\theta \qquad \left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$$
$$\sim 1 + \cos^2\theta$$

- μ^- energy distribution
- Threshold scan
- Photon energy distribution

The Angular Distribution (LC)

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

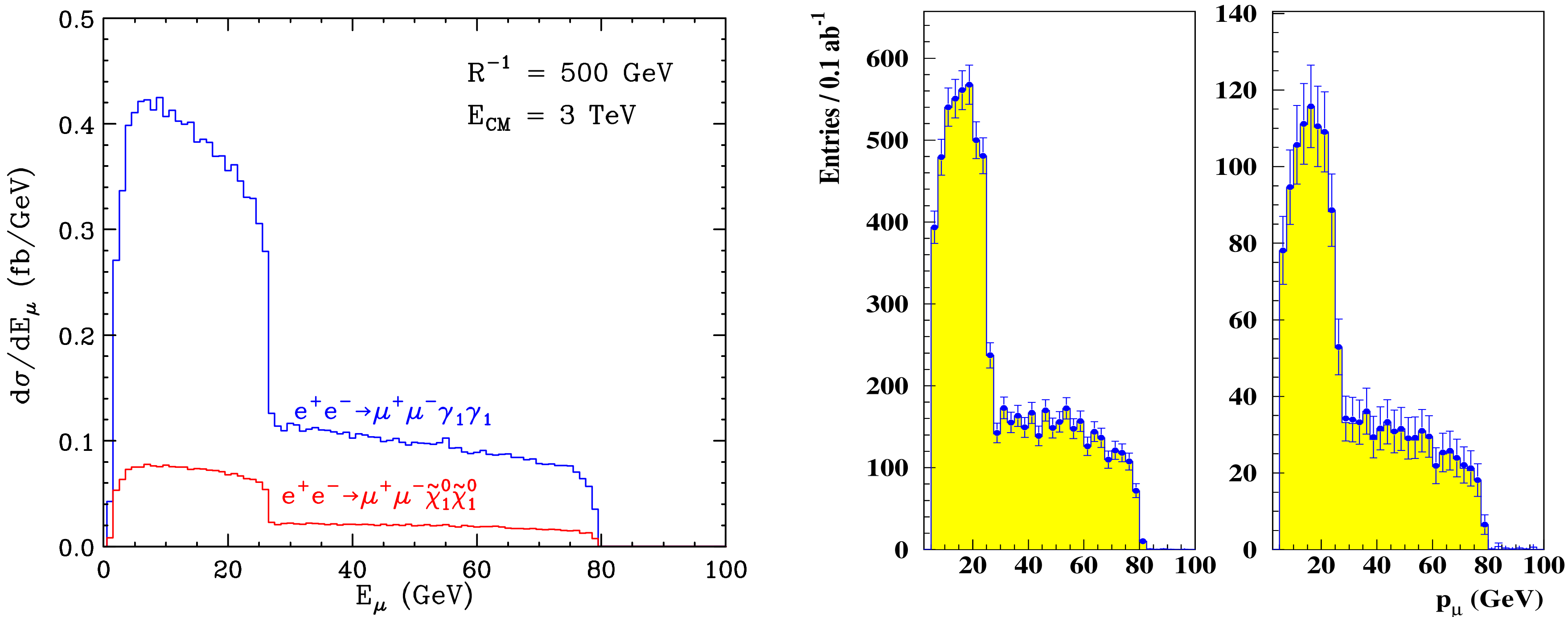




- $\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1+\cos^2\theta$
- $\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1-\cos^2\theta$

The μ Energy Distribution (LC)

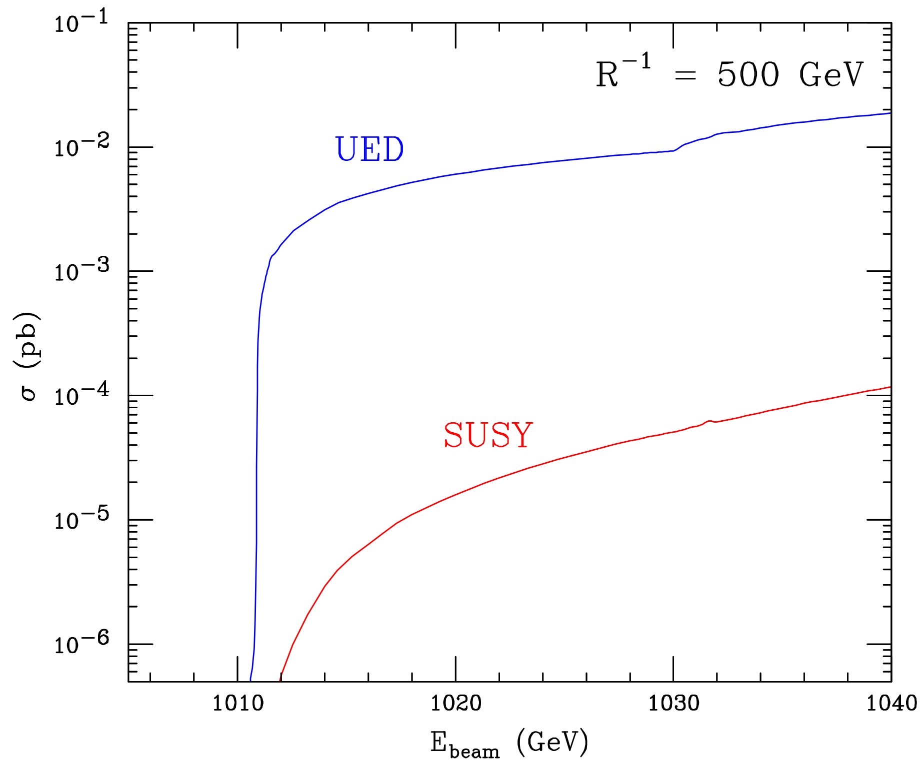
(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)



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

Threshold scans (LC)

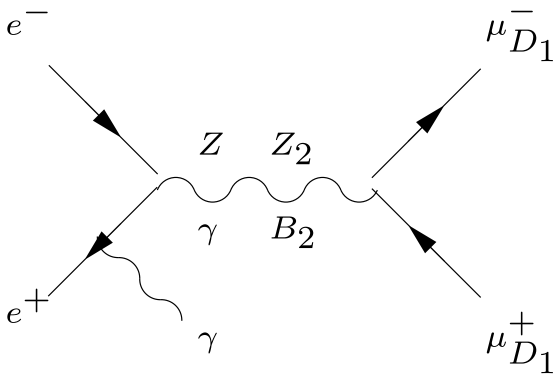
(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)

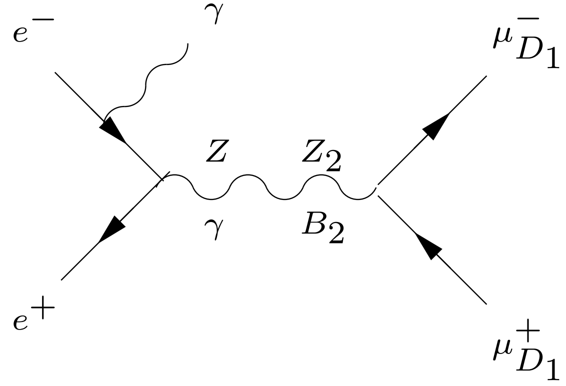


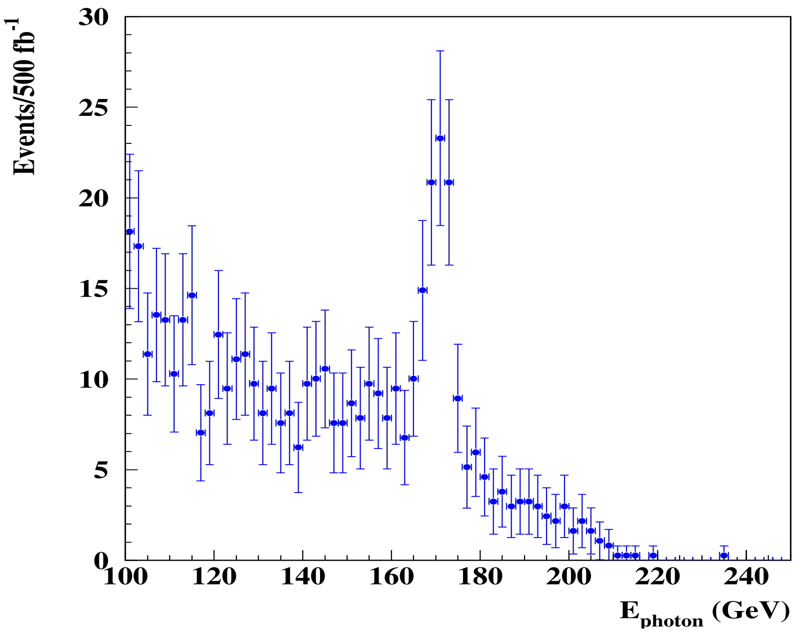
- Mass determination
- Cross section at threshold
  - in UED $\propto \beta$
  - in MSSM $\propto \beta^3 \left(\beta = \sqrt{1 - \frac{M^2}{E_{beam}^2}}\right)$

The Photon Energy Distribution (LC)

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



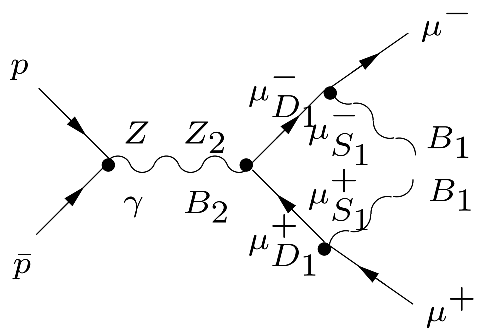


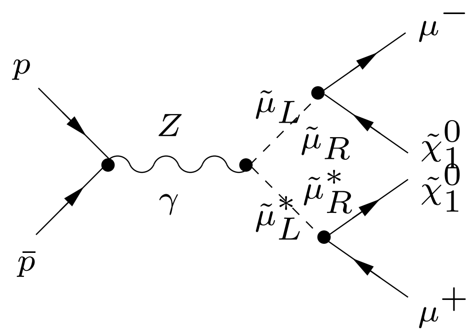


- Smuon production is mediated by γ and Z
- On-shell $Z_2 \to \mu_1 \bar{\mu}_1$ is allowed by phase space
- Radiative return due to Z_2 pole at

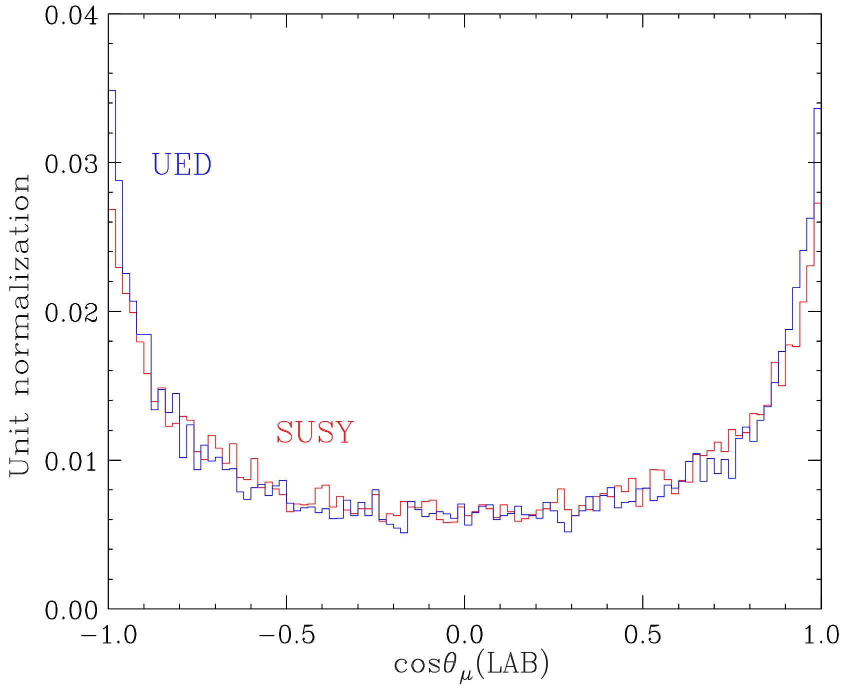
$$E_\gamma = \frac{s - M_{Z_2}^2}{2\sqrt{s}}$$

The Angular Distribution at the LHC





(Datta, Kong, Matchev, Preliminary)



- If we simply do the same trick as in linear collider, it doesn't work
- There is no fixed CM frame

Exact Beamstrahlung Function Required

- Analytic solutions are limited for small Υ only
  - Good agreement with simulation data
  - This is true for LC 500-1000
- Can't use same solution for large Υ
  - Need new approximation $\longrightarrow$ No analytic solution for large Υ in the case of high energy e^+e^- colliders such as CLIC
  - Solve rate equation numerically instead or
  - Use simulation data
- Caution : Implementation in event generators
  - Most event generators have one of these two parametrizations
  - Either numerically worse or has normalization problem
  - How to fix the event generator
    - Use old parametrizations and fake parameters
    - Use numerical solution/simulation data and import in the event generator
- A lot of soft photons at high energy e^+e^- colliders distort physical distributions, e.g. E_μ