Summary: Beyond the Standard Model WG

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on behalf of the BSM conveners:

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ILC Workshop, Snowmass CO, August 27 2005

The Charge for the Physics Working Groups

1. What are the most important measurements that the ILC should perform in the subject area of your working group?

2. What are the key measurements by which the ILC will add to what is already known from the LHC?

3. What are the processes and measurements new to the community in the past few years that further motivate the case for the ILC?

4. For each of these measurements, what criteria for the detectors are necessary to allow measurements to the appropriate precision?

5. Are there detector capabilities that are not strongly challenged by the list of processes in #1 and #2? Is this acceptable, or are there additional measurements that should be added to the list against which detectors will be evaluated?

Our subject: Non-SUSY models beyond the Standard model

Alternatives to SUSY models

There are many interesting models:

Model	Talk
Large extra dimension model (ADD)	**T. Han's talk**
Randall-Sundrum model (RS)	**T. Han's talk**
Universal Extra dimension model (UED)	**T. Han's talk**
Higgsless model	**T. Han's talk**
RS with matters in the bulk (RSMB)	**K. Agashe's talk**
Little Higgs model (LH)	**M. Schmaltz's talk**

Motivations of the models

Solving problems in the SM

fine-tuning problem: UV sensitivity of the Higgs mass

Origin of the EW symmetry breaking

Fermion mass hierarchy problem, etc.

no Dark Matter candidate in the SM

What is the scale of the new physics?

No fine-tuning: $\Delta m_H^2 \propto \Lambda_{new}^2$ → $\Lambda_{new} \sim 1\,\mathrm{TeV}$

Dark Matter: WMAP data → $\Omega h^2 = 0.112^{+0.0161}_{-0.0181}$

the most reasonable candidate is WIMP

whose mass scale is around O(100GeV – 1 TeV)

New Physics lies around TeV scale → accessible for LHC and ILC

General features of new physics models

1. **new particles with mass around 100GeV – TeV**
2. **characteristic couplings among SM matter and New Particles**

   → some new physics processes measurable at LHC and ILC

3. **Dark Matter candidate Yes/No**

   → if Yes, cosmology connections

   Relic density of DM highly depends on model parameters

   (mass and interactions)

What can we do with LHC and ILC

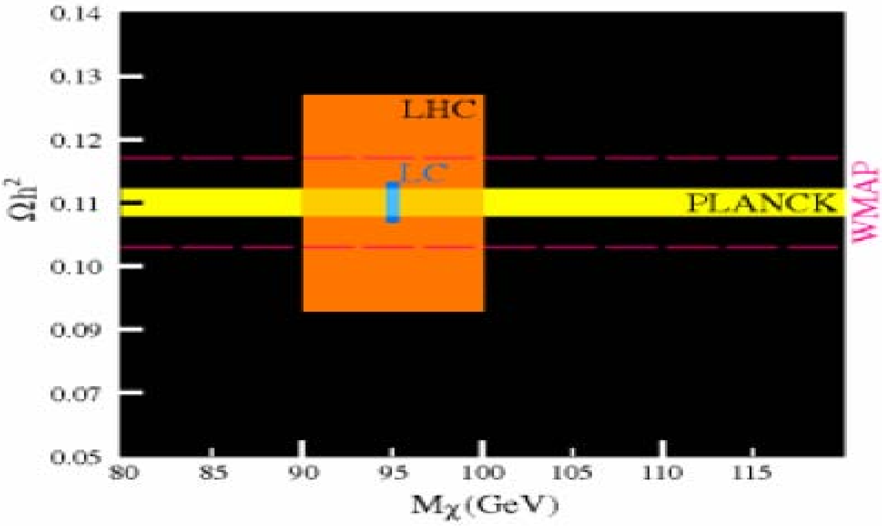
New Physics could be discovered @ LHC

Precision measurements of New Physics properties (mass, coupling constant, particle properties) @ ILC could discriminate the models

if DM candidate → cosmological connections

precision comparable to PLANCK

SUSY case



We can say the same thing for BSM models including DM candidate

Studies for each BSM models

1. ADD model

Arkani-Hamed-Dmopoulos-Dvali, PLB 429, 263, 1998

Brane World Scenario: 4+n dimensions

Low scale gravity: M = O(1 TeV)

Graviton Kaluza-Klein (KK) tower $\Delta m_{KK} = \frac{1}{R}$; $1/R = (M/M_P)^{2/n} M$

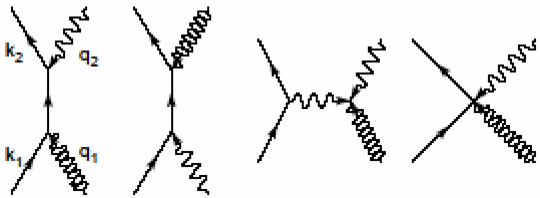
Universal couplings with SM particles $\mathcal{L}_{int} = -\frac{1}{M_P} G^{KK}_{\mu\nu} T^{\mu\nu}_{SM}$

Key processes @ILC:

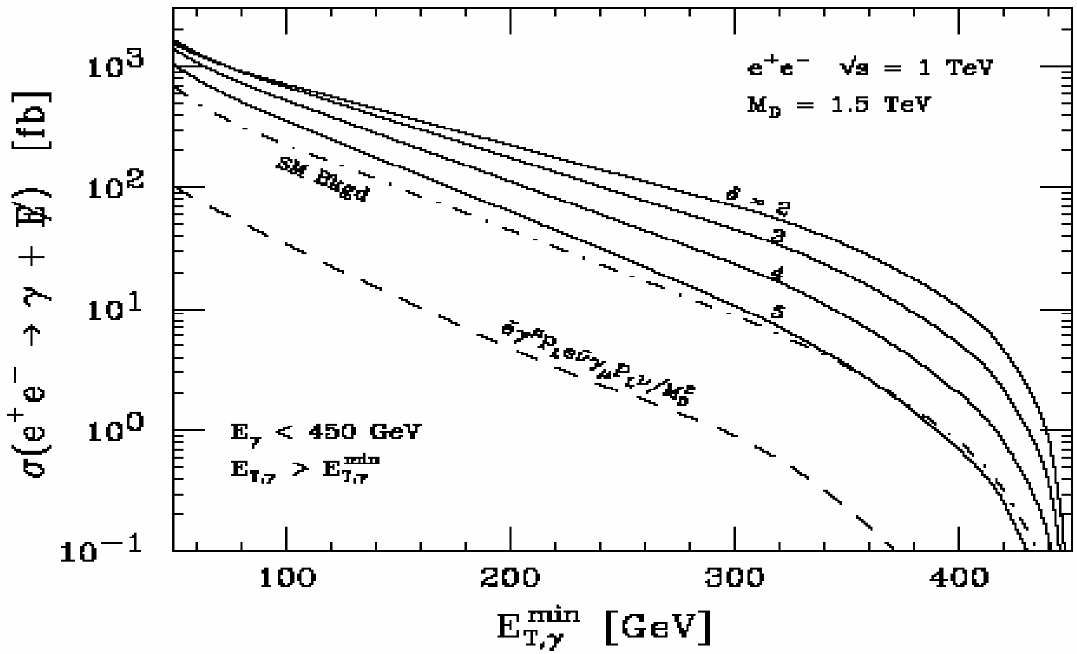
1. gamma + missing $e^+e^- \to \gamma + KK$

2. KK graviton mediated processes $e^+e^- \to f\bar{f}, VV, HH$

(1) gamma + missing



$$\sigma_{total} = \sum_{\vec{n}} \sigma^{(\vec{n})} \propto \frac{1}{M^2}\left(\frac{\sqrt{s}}{M}\right)^n$$



Guidice, Rattazzi & Wells,

NPB 544, 3, 1999

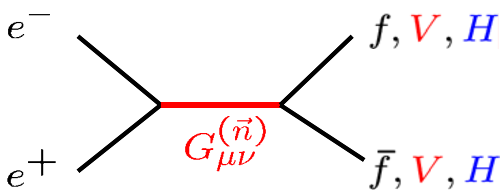
n-dim	LEP2	ILC(500 GeV)
4	M >730 GeV	M > 4.5 TeV
5	M > 520 GeV	M > 3.1 TeV

Guidice, Rattazi & Wells,

Mirabelli, Perelstein & Peskin,

Cheung & Keung, ..

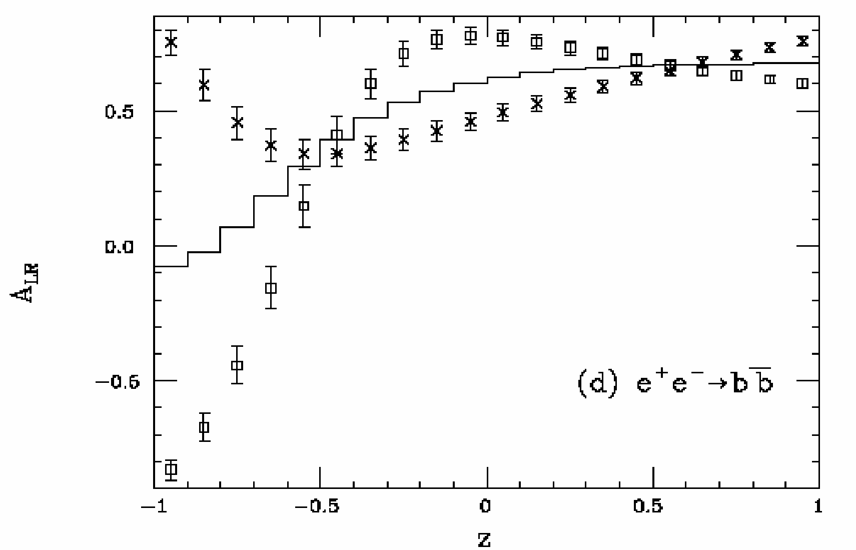
(2) KK graviton mediated process



$$\mathcal{M} = \pm \frac{4\pi}{M_S^4} T_{\mu\nu}(p_1, p_2) T^{\mu\nu}(p_3, p_4)$$

Measurement of Spin 2 nature of intermediate KK graviton

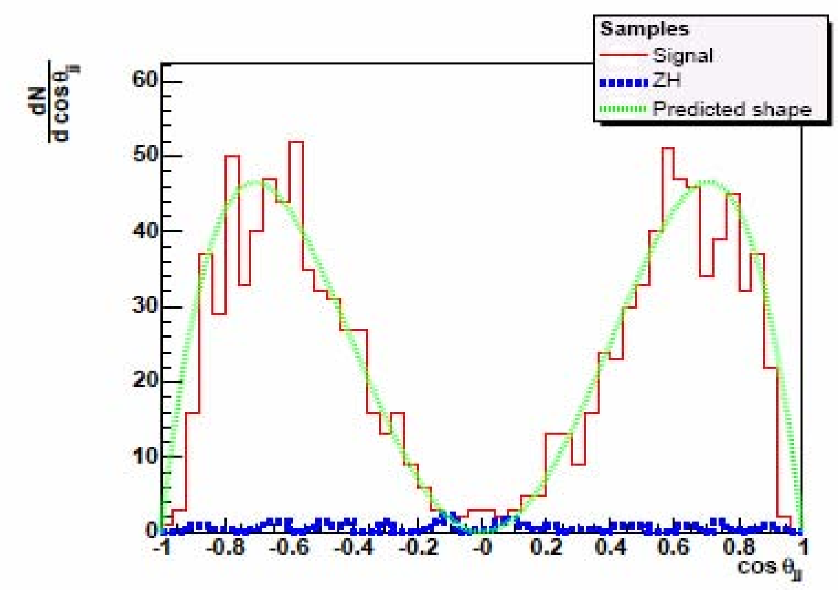
LR asymmetry



$$\sqrt{s} = 500\text{GeV};\ 75 fb^{-1}$$
$$M_S = 1.5\text{TeV}$$

J. Hewett, PRL 82, 4765 (1999)

MC simulations for HH



$$\sqrt{s} = 1\text{TeV};\ 500 fb^{-1}$$
$$M_S = 2\text{TeV}$$

Derelue, Fujii & N.O., PRD 70, 091701 (2004)

2. RS model

Randall & Sundrum, PRL 83, 3370 (1999)

Brane World Scenario: 4+1 dimensions

Warped geometry: M = O(1 TeV) $\sim M_P e^{-kr\pi}$

Graviton Kaluza-Klein (KK) tower

$m_{KK}^{(1)}$ **(model parameter),** $m_{KK}^{(2)} \simeq 1.8 m_{KK}^{(1)}, ..$

Couplings with SM matters

$$\mathcal{L}_{int} = -\frac{1}{M} G_{\mu\nu}^{(1)} T_{SM}^{\mu\nu}; \quad M = \frac{m_{KK}^{(1)}}{3.83} \frac{M_P}{k}$$

Key processes @ILC:

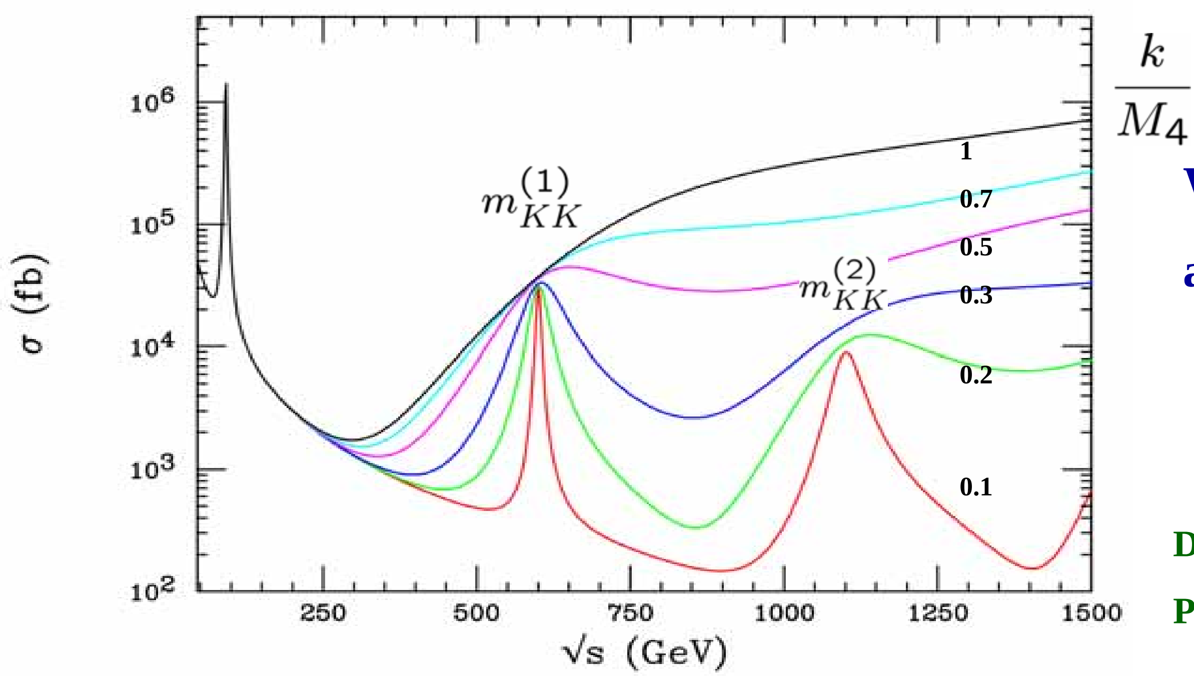
KK graviton resonance production, if $\sqrt{s} > m_{KK}^{(1)}$

Virtual KK graviton mediated process, if $\sqrt{s} < m_{KK}^{(1)}$

→ same as ADD with correspondence Ms ←→ M

1st KK graviton resonance production @ LC

$$e^+e^- \to g_{KK}^{(1)} \to \mu^+\mu^- \qquad \Gamma_1 = const. \times m_{KK}^{(1)} \frac{k}{M_P}$$



Width becomes large as k/Mp becomes large

$$m_{KK}^{(1)} = 600\text{GeV}$$

Davoudiasl, Hewett & Rizzo, PRL 84, 2080 (2000)

Check universality of KK graviton couplings: $\mathcal{L}_{int} = -\frac{1}{M} G_{\mu\nu}^{(1)} T_{SM}^{\mu\nu}$

Ratios of KK graviton partial decay width

$$\Gamma_{\gamma\gamma} : \Gamma_{gg} : \Gamma_{W^+W^-} : \Gamma_{ZZ} \simeq 1 : 8 : 2 : 1$$

$$\Gamma_{\ell\bar{\ell}} : \Gamma_{q\bar{q}} : \Gamma_{hh} \simeq 1 : 3 : 1/3$$

For $m_{final} \ll m_{KK}^{(1)}$

3. UED

Appelquist, Cheng & Dobrescu, PRD 64, 035002 (2001)

Extra dimension with SM particles in bulk

Only three model parameters: $1/R,\ \Lambda,\ m_h$

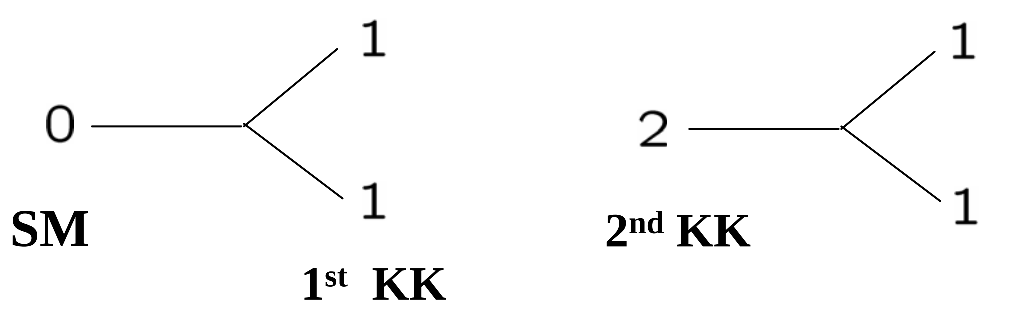
KK modes of SM particles: $m_{tree}^{(n)} = n/R;$ **1/R > 300 GeV by PEW**

→ mass splitting by EW corrections

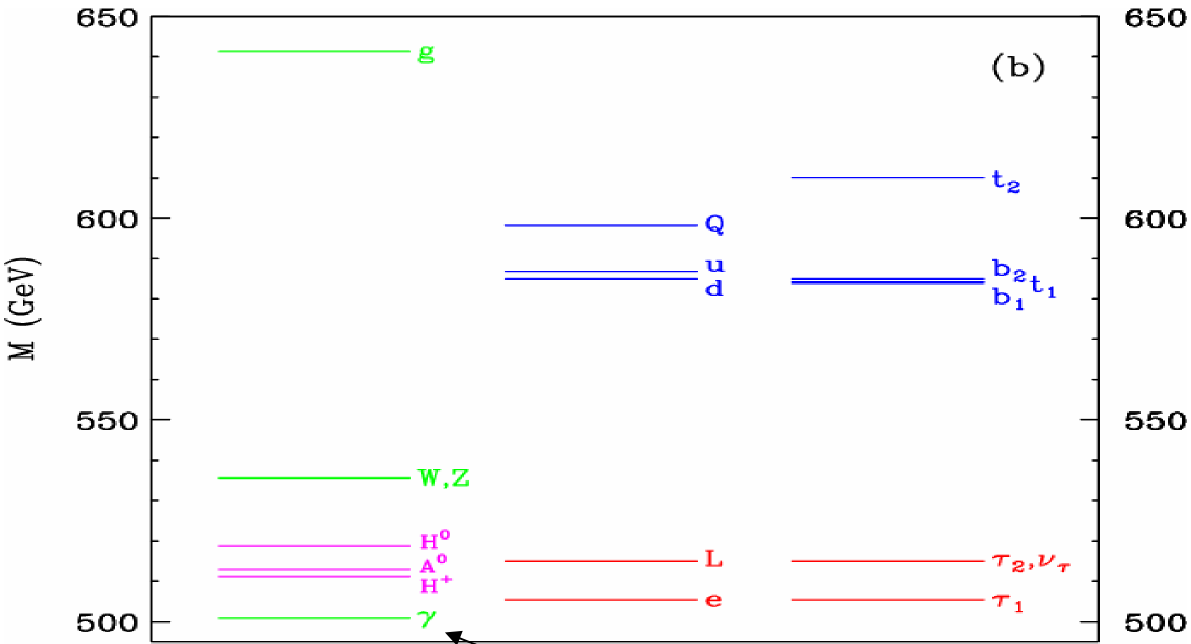
Special symmetry: KK parity → lightest KK particle (LKP) is stable

Dark Matter candidate

SM couplings with KK parity selection rule: total KK number should be even



1-loop corrected 1st KK mode mass spectrum



$$1/R = 500\mathrm{GeV}$$
$$\Lambda = 20 \times 1/R$$

Cheng, Matchev & Schmaltz, PRD 66, 056006 (2002)

DM candidate

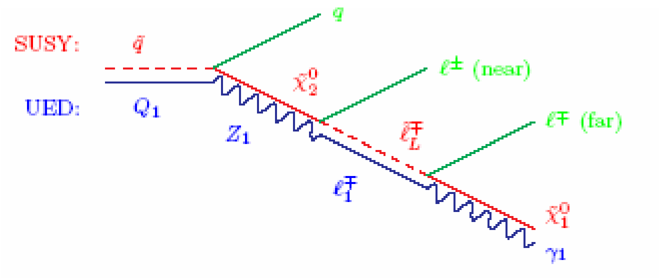
1st KK mode mass spectrum is very similar to MSSM

Sparticles ←→ 1st KK modes

$$\chi_0 \quad \longleftrightarrow \quad \gamma^{(1)}$$
$$\tilde{e} \quad \longleftrightarrow \quad e^{(1)}$$

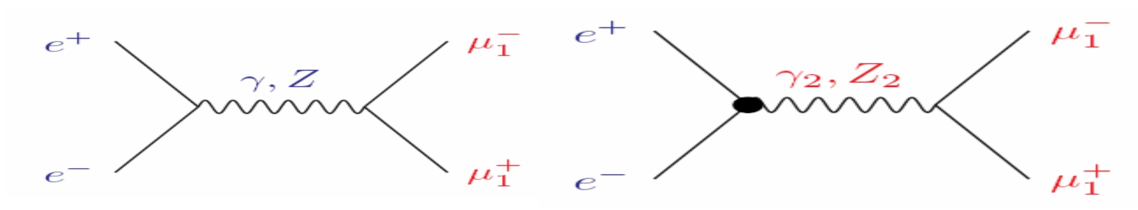
Spins of corresponding particles are different

Kinematics is similar → SUSY or UED? difficult @LHC



ILC → discriminate **SUSY or UED**

<u>Processes:</u>



Comparison of

$$e^+e^- \rightarrow \mu^{(1)+}\mu^{(1)-} \rightarrow \mu^+\mu^-\underline{\gamma^{(1)}\gamma^{(1)}} \text{ in UED}$$

with

Missing

$$e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \mu^+\mu^-\underline{\tilde{\chi}_1^0\tilde{\chi}_1^0} \text{ in SUSY}$$

Angular distribution

UED: $\mu^{(1)}$: Spin 1/2 $\quad \left(\frac{d\sigma}{d\cos\theta}\right) \propto 1+\cos^2\theta$

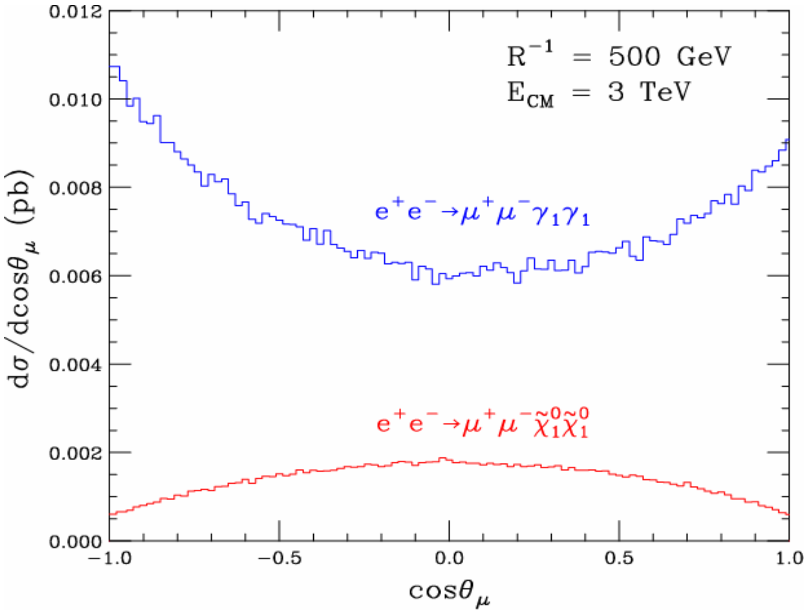
SUSY: $\tilde{\mu}$: Spin 0 $\quad \left(\frac{d\sigma}{d\cos\theta}\right) \propto 1-\cos^2\theta$

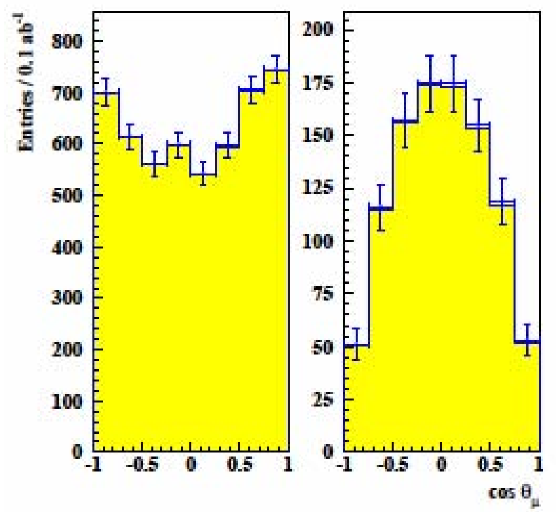
$\sigma(\mu^+\mu^-\gamma^{(1)}\gamma^{(1)}) = 14.4 \text{ fb}$

Factor ~ 5

$\sigma(\tilde{\mu}^+\tilde{\mu}^-\tilde{\chi}_1^0\tilde{\chi}_1^0) = 2.76 \text{ fb}$

at $\sqrt{s} = 3 \text{ TeV}$





: signal + background

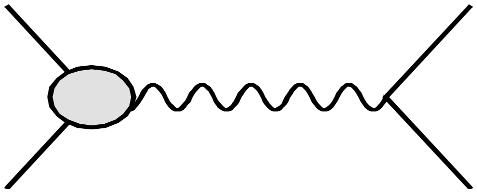
: signal

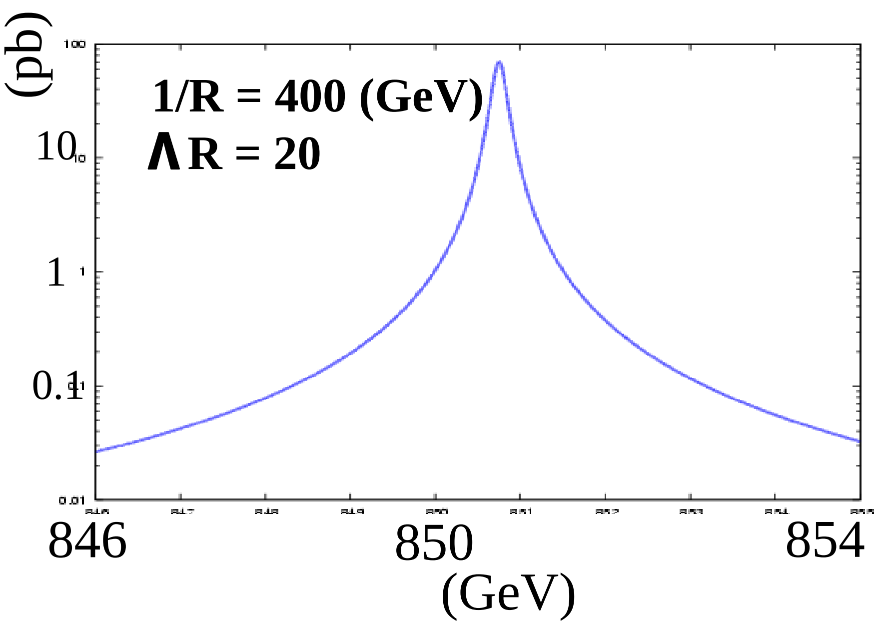
Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041

If 1/R =300 GeV or so → ILC with $\sqrt{s} = 1\text{TeV}$

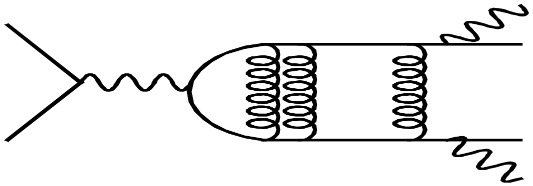
Resonance hunting

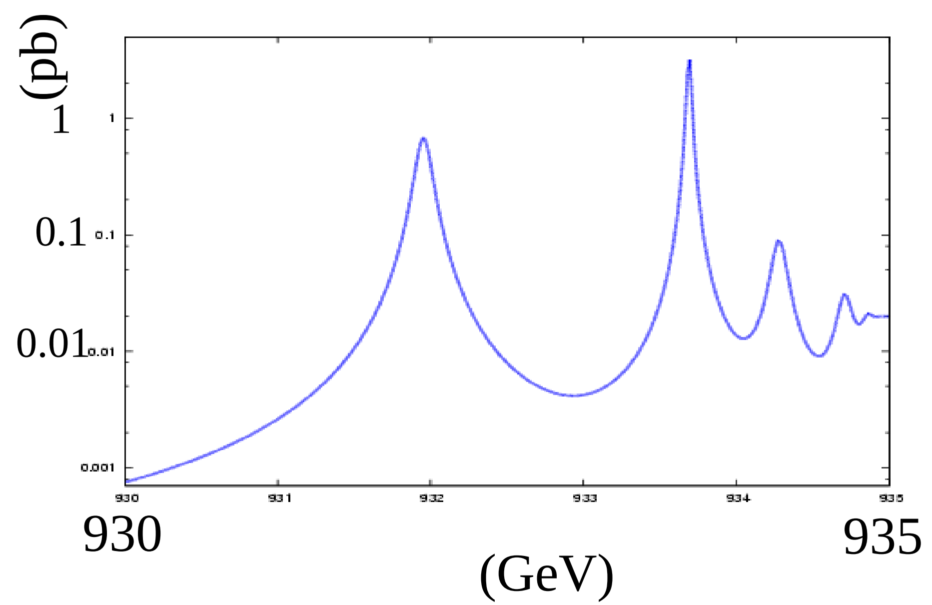
$e^+e^- \to Z^{(2)} \to \mu^+\mu^- + \text{missing}$





$e^+e^- \to b^{(1)}b^{(\bar{1})} \to b\bar{b} + \text{missing}$





Kakizaki, Matsumoto, N.O., Yamashita

Distinguish UED from MSSM by using resonances

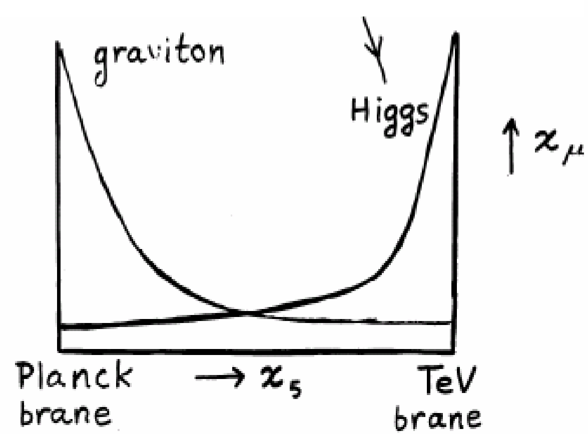
Determine model parameters: R and Λ

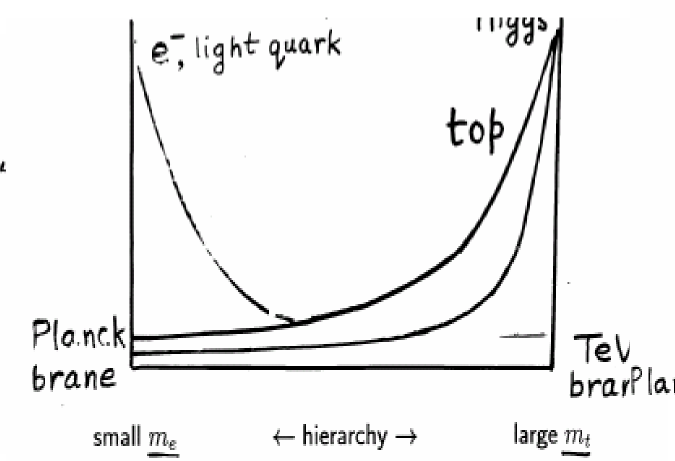
4. RSMB (K. Agashe's talk)

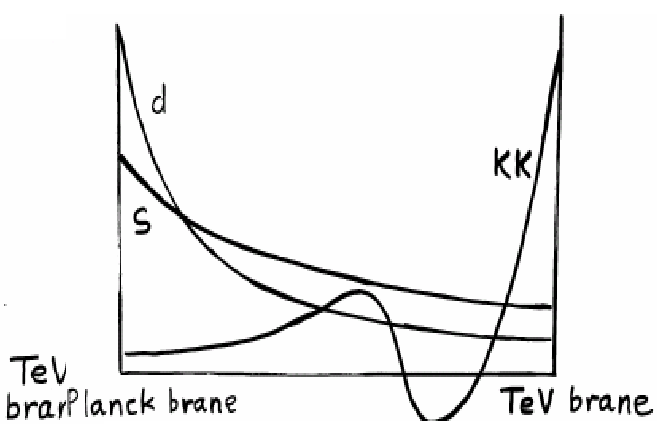
Agashe, Contino, Sundrum, Servant, Pomarol, …

RS model with Matter in the Bulk:

- Solution to the gauge hierarchy problem
- Grand Unification without SUSY
- non-trivial configuration
- couplings from wave function overlapping
- AdS/CFT duality → composite states in 4D theory







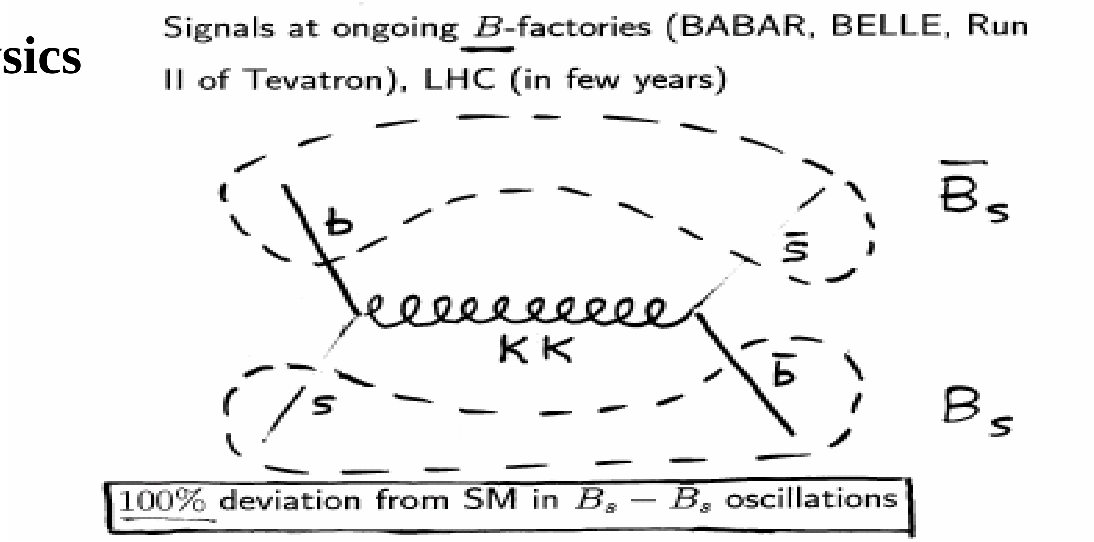
Weak gravity Composite Higgs

Fermion mass hierarchy

Coupling with KK gauge boson

Phenomenology

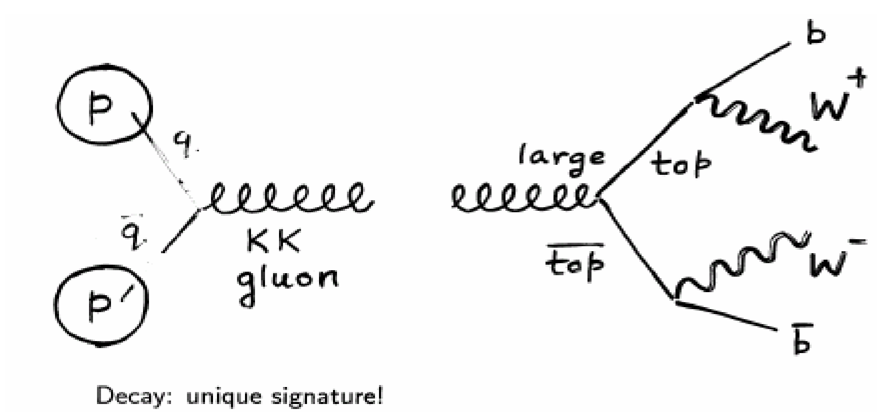
B physics



Agashe, Perez & Soni,

PRL 93, 201804 (2004)

LHC and ILC



KK gluon production @ LHC

10% shift in coupling to Z

← Measurement @ ILC

5. Little Higgs model

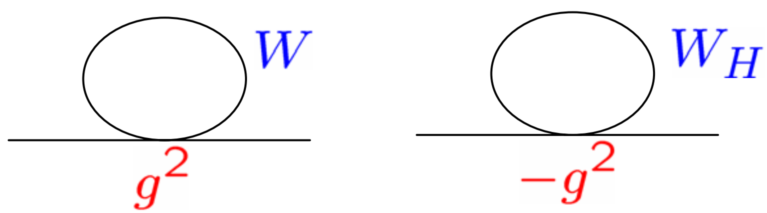
Arkani-Hamed, Cohen, Georgi, Katz, Nelson, Gregoire, Wacker, …

4D model , Higgs as (pseudo) Nambu-Goldstone particle

→ quadratic divergences at 1-loop are canceled out

by heavy particles with the same spin (LH mechanism)

New particles around 1 TeV: $A_H, Z_H, W_H\ T_H, \ldots$(LH partners)



Boson cancels boson

Parameters: f (> a few TeV) → scale of new particles

two new gauge couplings → interactions among SM and NP

If T-Parity → SM particles: T-parity even

Chang & Low

heavy gauge bosons: T-parity odd

→ lightest T-odd particle (LTP) is DM candidate

Processes: heavy gauge boson mediation $\begin{cases} \textbf{4 Fermi int.} & (\sqrt{s} < m_{heavy}) \\ \textbf{Resonances} & (\sqrt{s} > m_{heavy}) \end{cases}$

$$f\bar{f} \to f\bar{f}$$

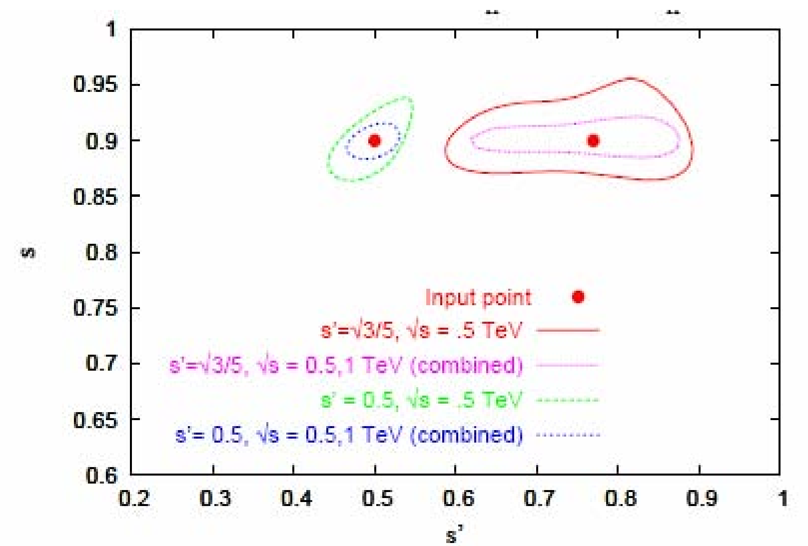
$$f\bar{f} \to Zh$$ ← **Important to verify LH mechanism**

Burdman, Perelstein & Pierce, PRL 90, 241802 (2003)

Coupling measurements

$$e^+e^- \to Z_H \to f\bar{f}$$

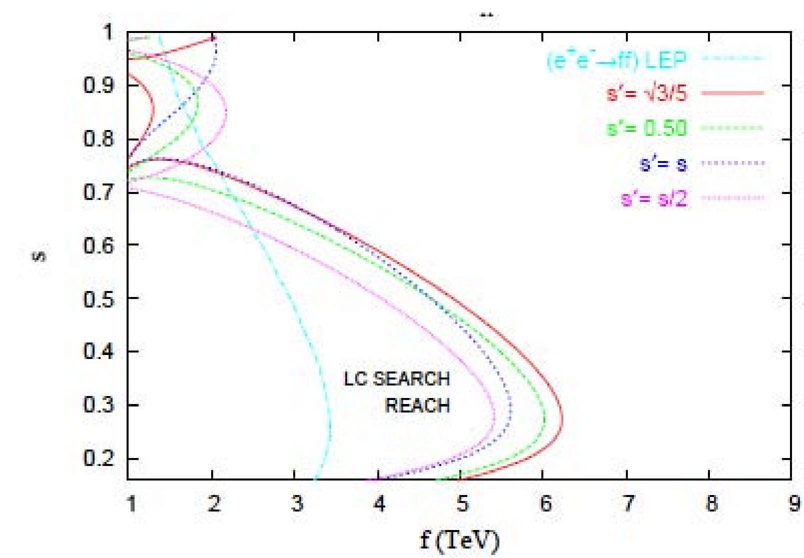
Sample fits for 95% CL



$$M_{Z_H} = 3.3\text{TeV},\ \mathcal{L} = 500 fb^{-1}$$

$$e^+e^- \to Z_H \to Zh$$

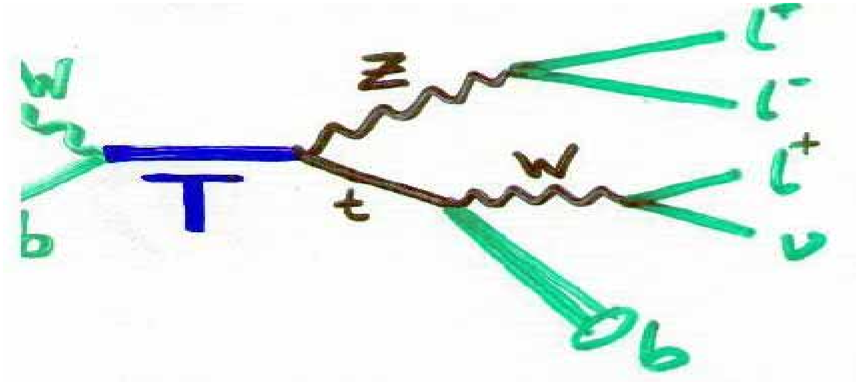
95% CL contours



$$M_{Z_H}^2 = m_W^2 \left(\frac{f^2}{s^2c^2v^2} - 1 - \frac{x_H s_w^2}{4s'^2c'^2c_w^2} \right)$$

Conley, Hewett & Le, hep-ph/0507198

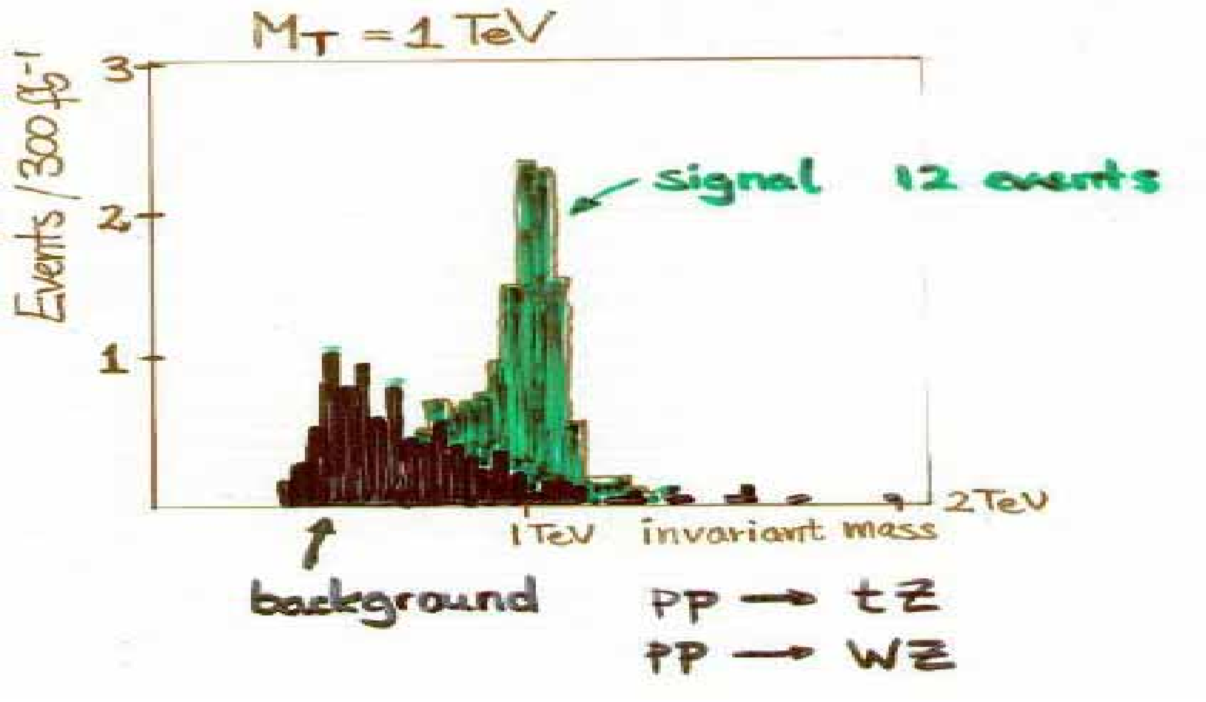
T (LH partner of top quark) resonances @ LHC (ATLAS study)



3 isolated leptons

Missing E > 100 GeV

One b-jet



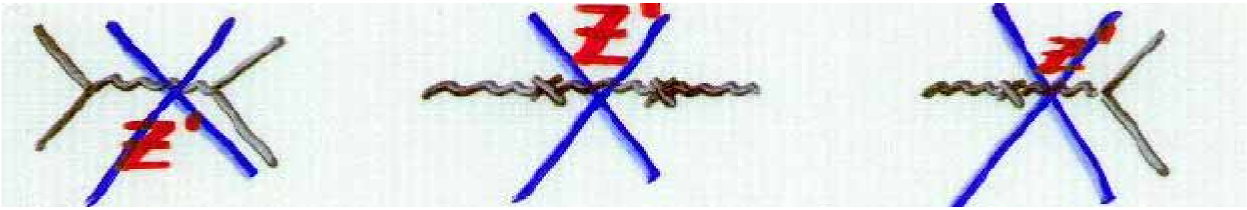
LH with T-parity

H.-C. Cheng & Low, JHEP 0309, 051 (2003)

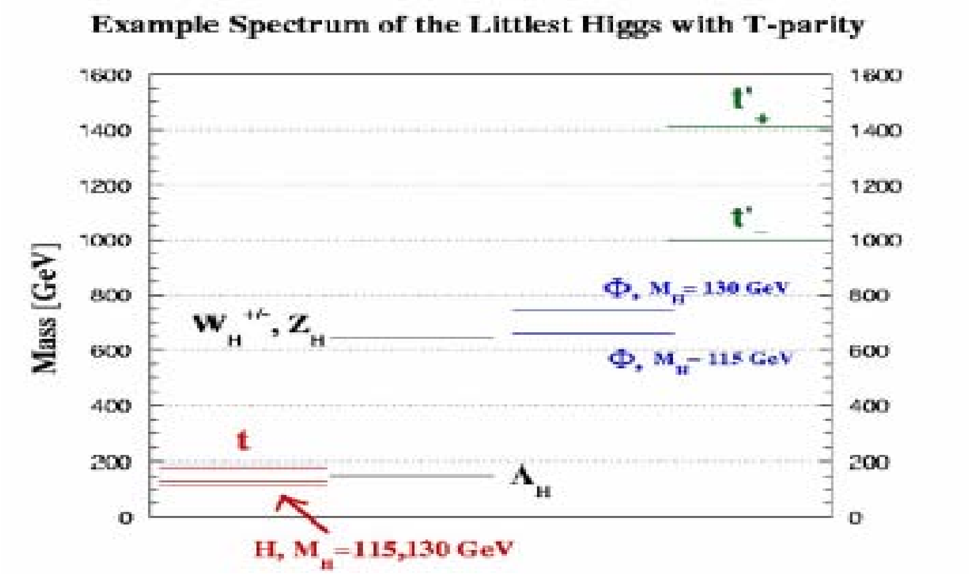
SM particles: T-even ⟷ **R-parity in MSSM**

Heavy gauge bosons: T-odd

T-parity kills tree level processes



PEW constraints are moderated → $M_{LHpartners} > 500\text{GeV}$



LTP is the DM candidate!

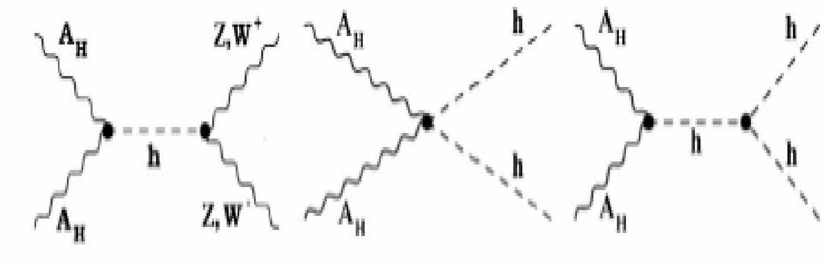
Hubisz & Meade,

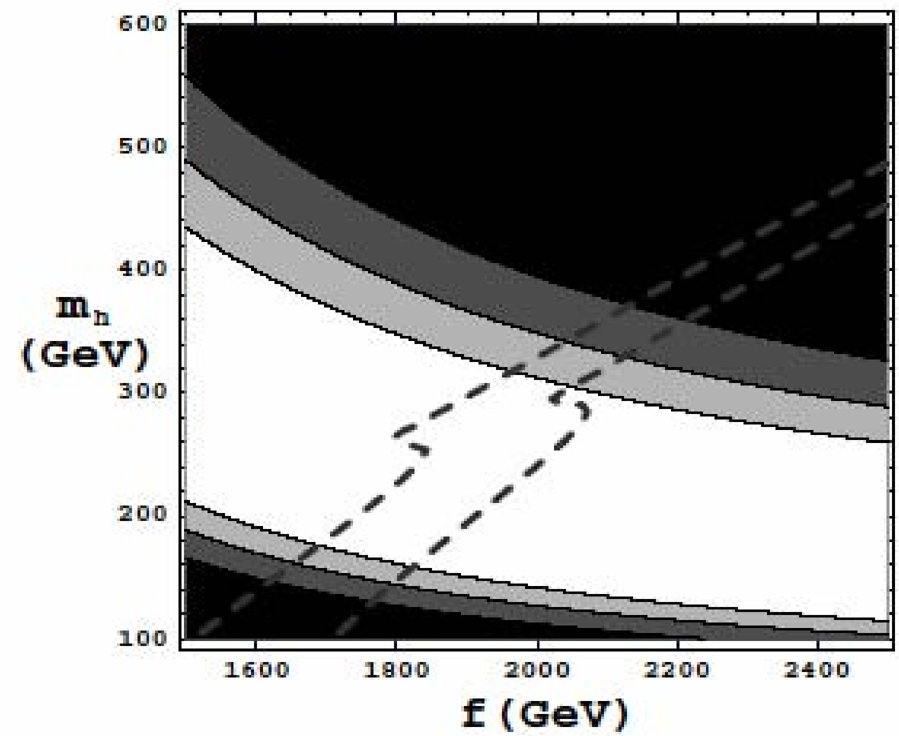
PRD 71, 035016 (2005)

PEW constraints & WMAP data

Hubisz, Meade, Noble & Perelstein, hep-ph/0506042

DM annihilation channels





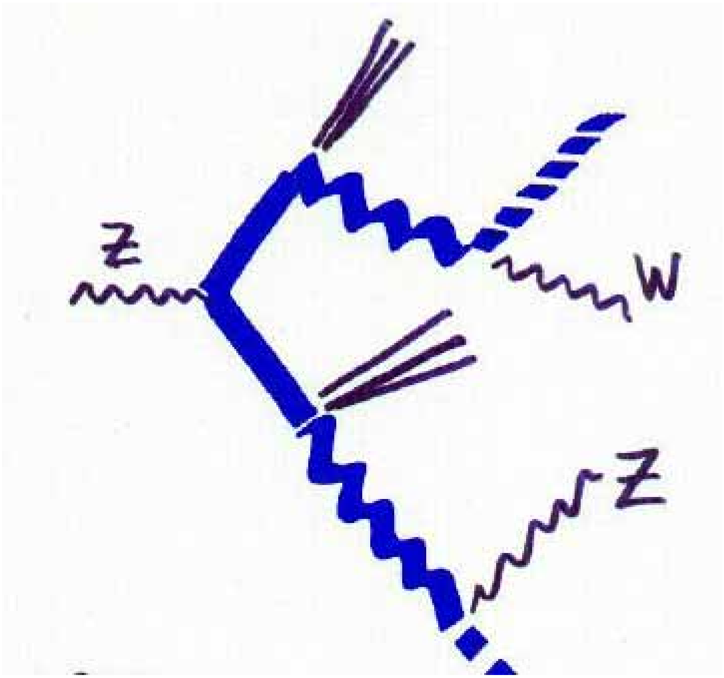
<u>Higgs can be heavy compare to the SM favored region</u>

Need ILC physics study for parameters in the allowed region

Collider phenomenology of LH with T-parity

- Pair produce new particles @ LHC and LC
- Cascade decay
- Missing energy signals due to LTP

→ Similar to SUSY model



How to discriminate models?

SUSY?

UED?

LH with T-parity

Distinguishing s-channel resonances @ILC (Talk by S. Godfrey)

There are lot of BSM models which predicts Z' (RS, LH, UED, E6 etc.)

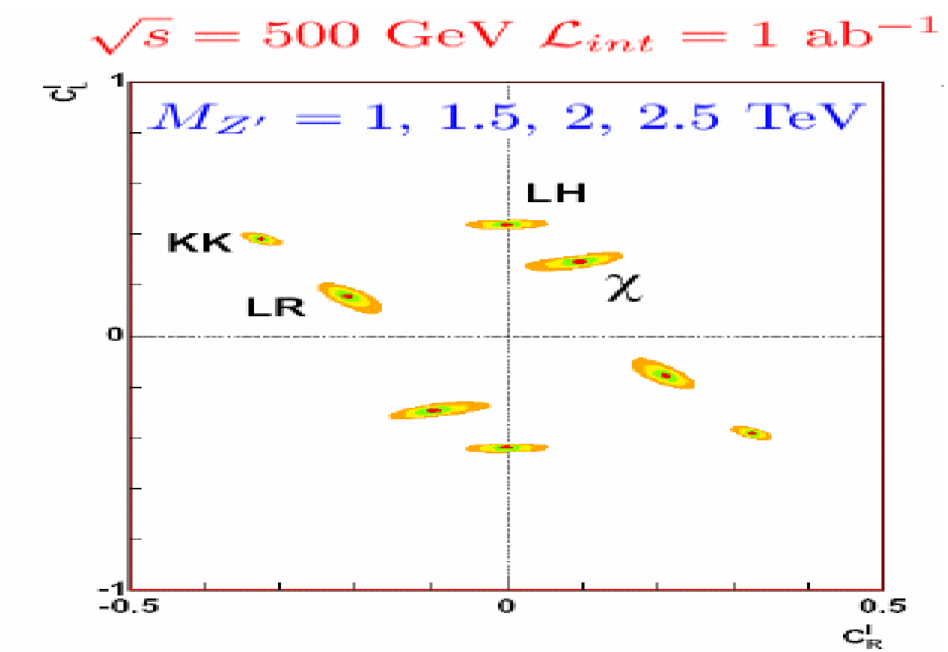
These models have new s-channel structure

→ How to distinguish the models?

Resonances can be found @ LHC

→Distinguish the models by precision measurement @ ILC

(cross section, FB asymmetry, LR asymmetry)



In some cases, positoron polarization is very effective to reduce back ground

Repository for BSM tools (Talk by P. Skands)

MCs of new BSM scenarios are important!

→ **BSM tool development**

collection of BSM tools

Web Repository in Durham (P. Richardson)

http://www.ippp.dur.ac.uk/montecarlo/BSM

You are invited to contribute

Conclusions

There are lots of well-motivated BSM models as alternatives to SUSY

These models predict New Particles with mass around 1 TeV, New Interactions, DM candidate, etc.

Some of New Particles would be discovered at LHC, but for some models it would be difficult to discriminate the models

Precision measurements (mass, couplings, spins etc.) at ILC could discriminate the models

Some models have been studied in detail, but some models recently proposed (LH with T-parity, RSMB etc.) have not and we need more studies

Collaborations among theorists and experimentalists are essential for ILC physics studies. Also, tool developments are very important

Let us bring progresses and information obtained at Snowmass back to your home institute and start and/or continue ILC studies for BSM

Acknowledgements

The BMS conveners would like to thank all the contributors!

I apologize that I can not mention all the contributions

Contributor List:

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More contributions are welcome!

See ``http://www.lns.cornell.edu/~maxim/snowmass'' for more information