Lecture 4

Connection

with

Cosmology

Outline

- Cosmology 101.
- Cosmology connection with particle physics.
- The 3 allowed region of mSUGRA model and their phenomenology.
- UED model and the phenomenology of the LKP.
- Little Higgs model with T parity and phenomenology.

1. Cosmology 101

Cosmology is the scientific study of the large scale properties of the Universe as a whole, to understand the origin, evolution and ultimate fate of the entire Universe. The prevailing theory about the origin and evolution of our Universe is the so-called Big Bang theory

Success of Big Bang:

- Expansion of the universe
- Abundance of the light elements H, He, Li
- The cosmic microwave background (CMB) radiation

Limitations and extensions of the Big Bang theory:

- Structures in the universe
- Fluctuations in the cosmic microwave background (CMB) radiation
- The inflationary universe

Other puzzles of the Universe:

1. What types of matter and energy fill the universe? How much of each?
2. How rapidly is the universe expanding today?
3. How old is the universe today?
4. What is the overall shape of the universe? Open, flat, closed, or otherwise?
5. How is the expansion changing with time?
6. What is the ultimate fate of the universe?

Big Bang Cosmology

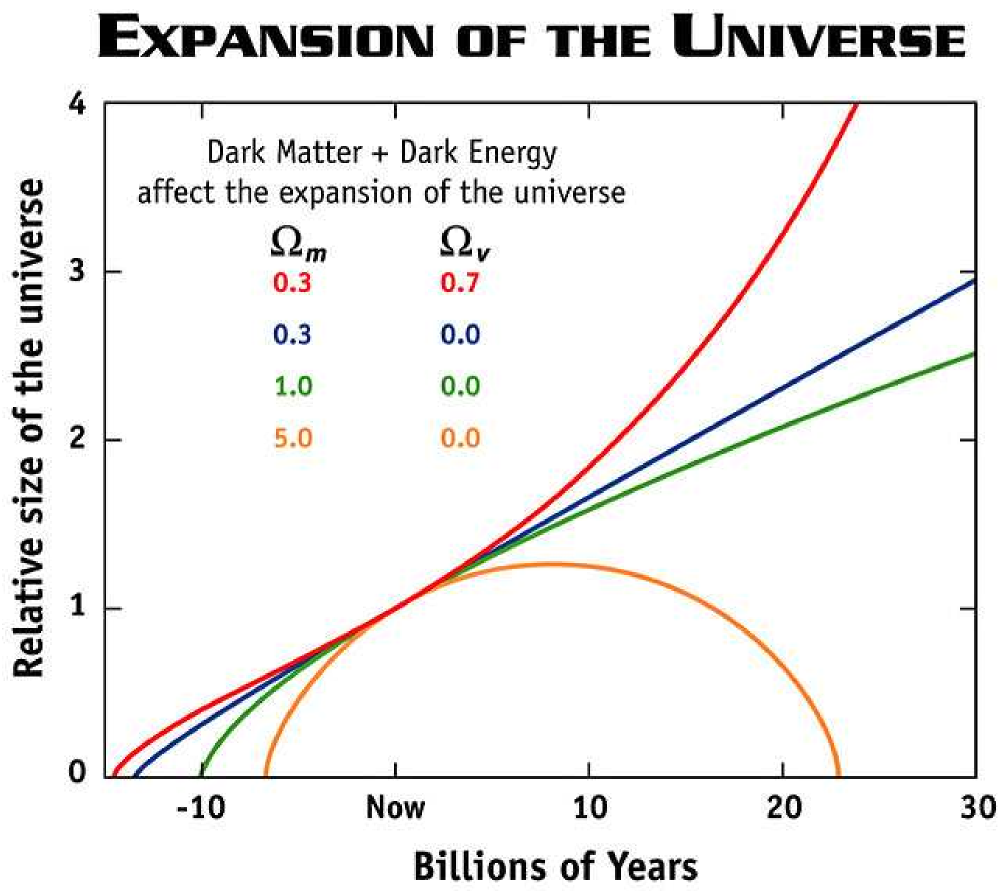
Big Bang Model rests on two theoretical pillars:

- General Relativity: gives the law of gravity.
- Cosmological Principle: the matter in the universe is homogeneous and isotropic when averaged over very large scales (a highly uniform CMB is a good indication.)

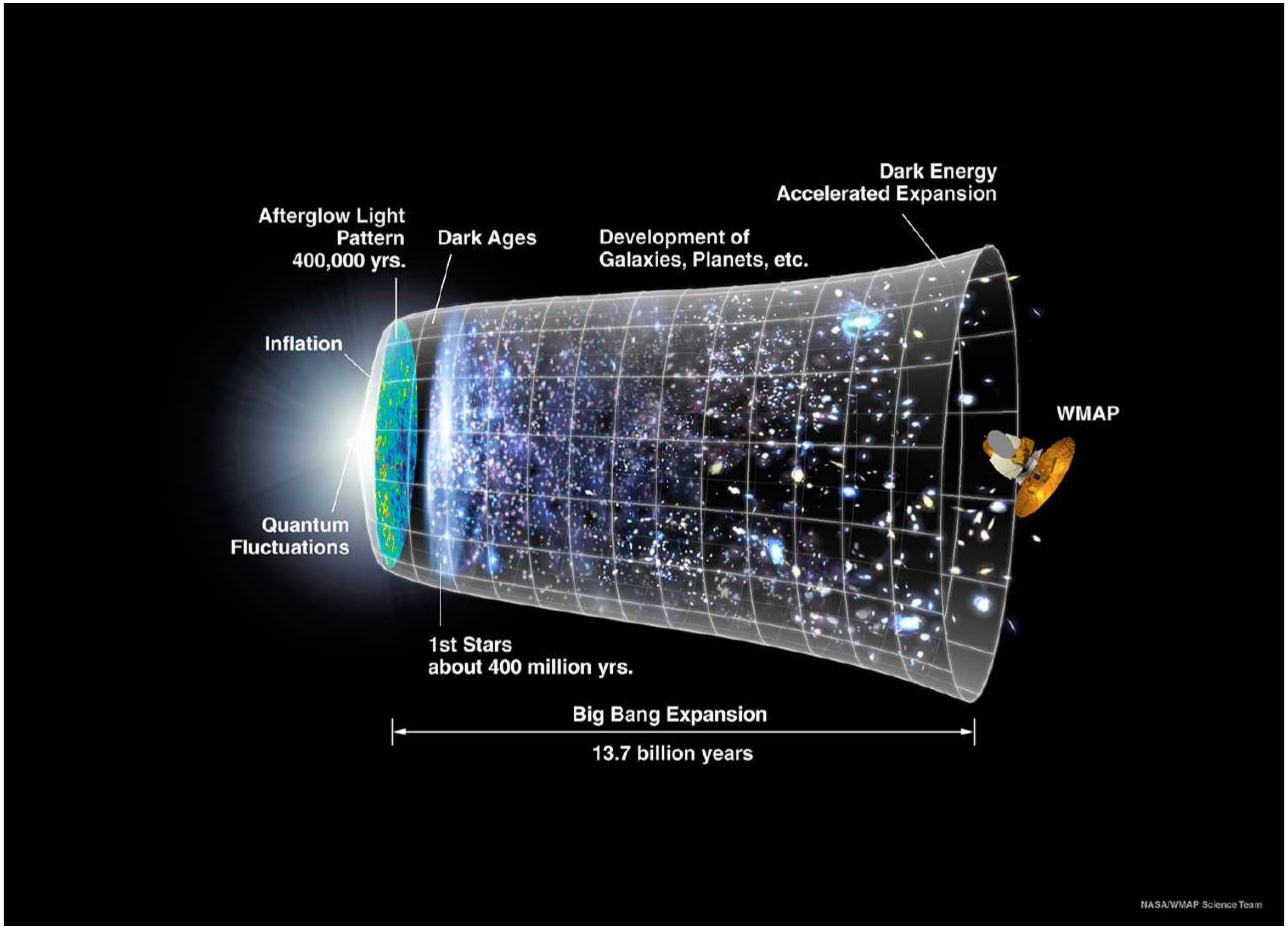
Matter plays a central role in cosmology. The average matter density uniquely determines the geometry of the universe, either close, open, or flat.

Given the law of gravity and distribution of matter, one can know the dynamics of the universe - how space and the matter in it evolves with time. It further depends on the nature (density, pressure) of the matter.

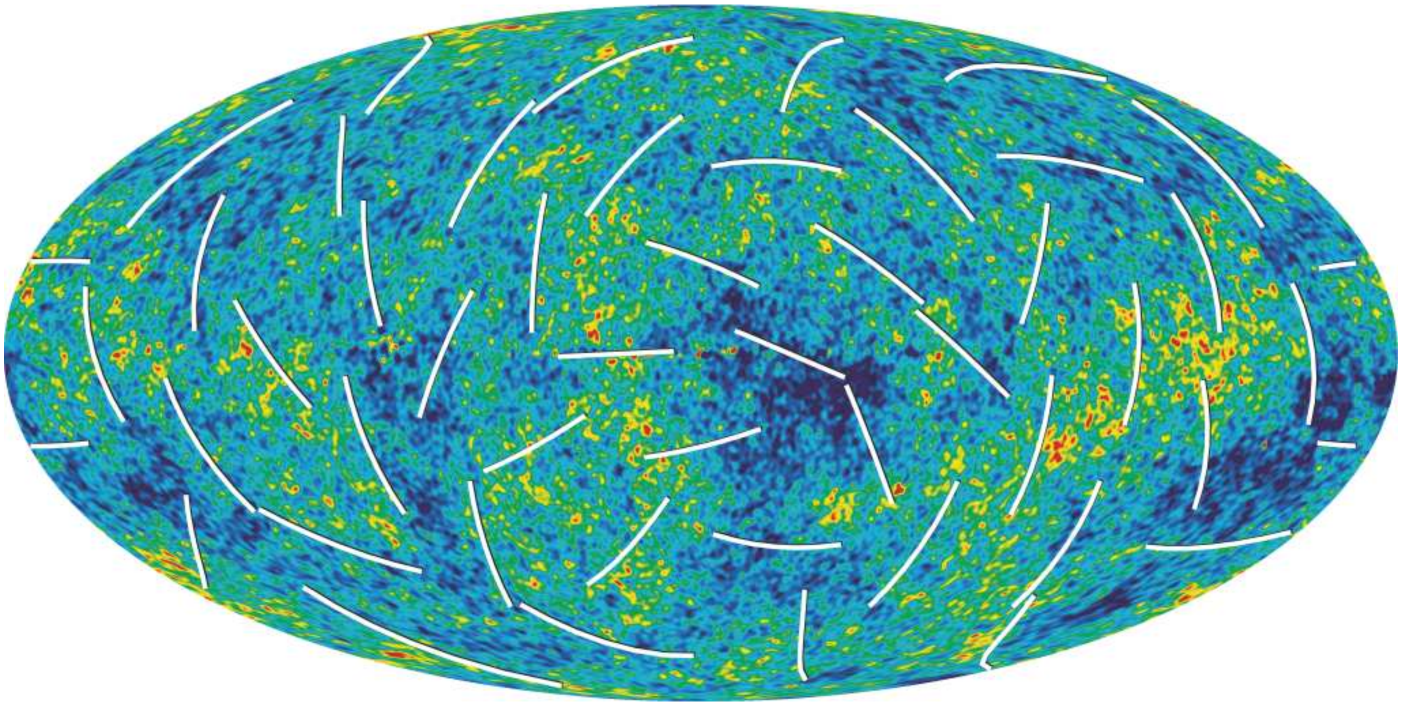
Expansion of the Universe



History of the Universe

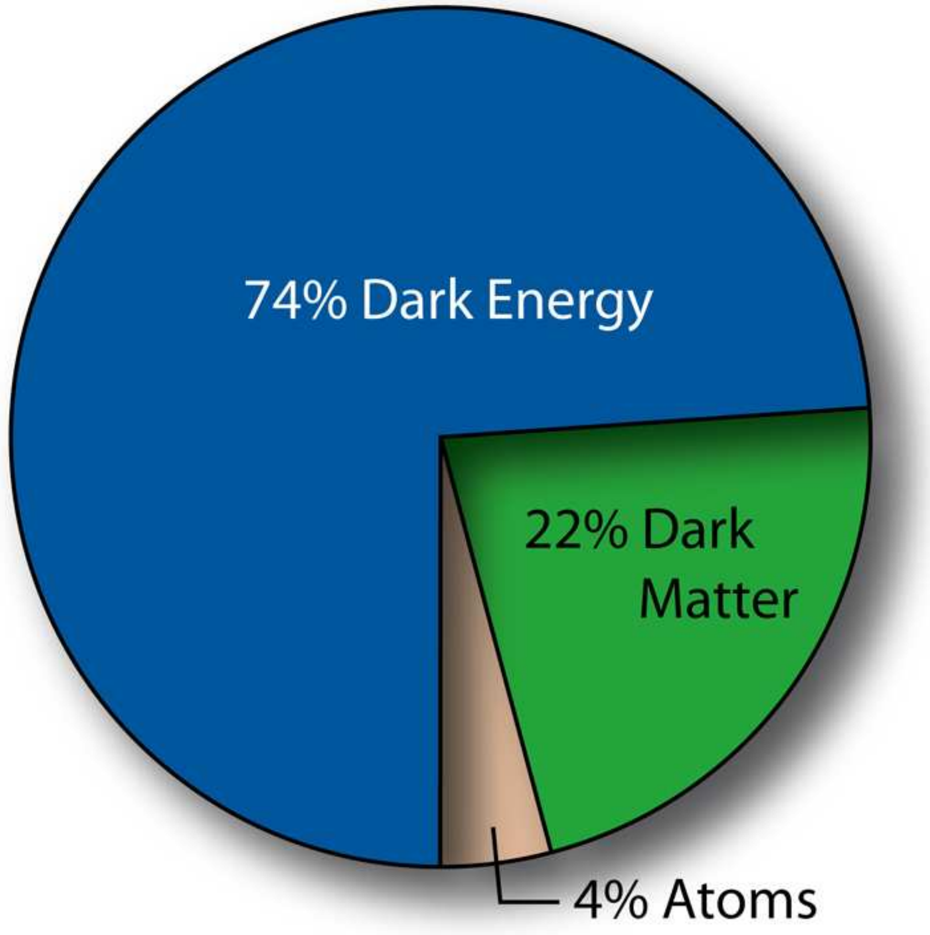


2006 WMAP Result

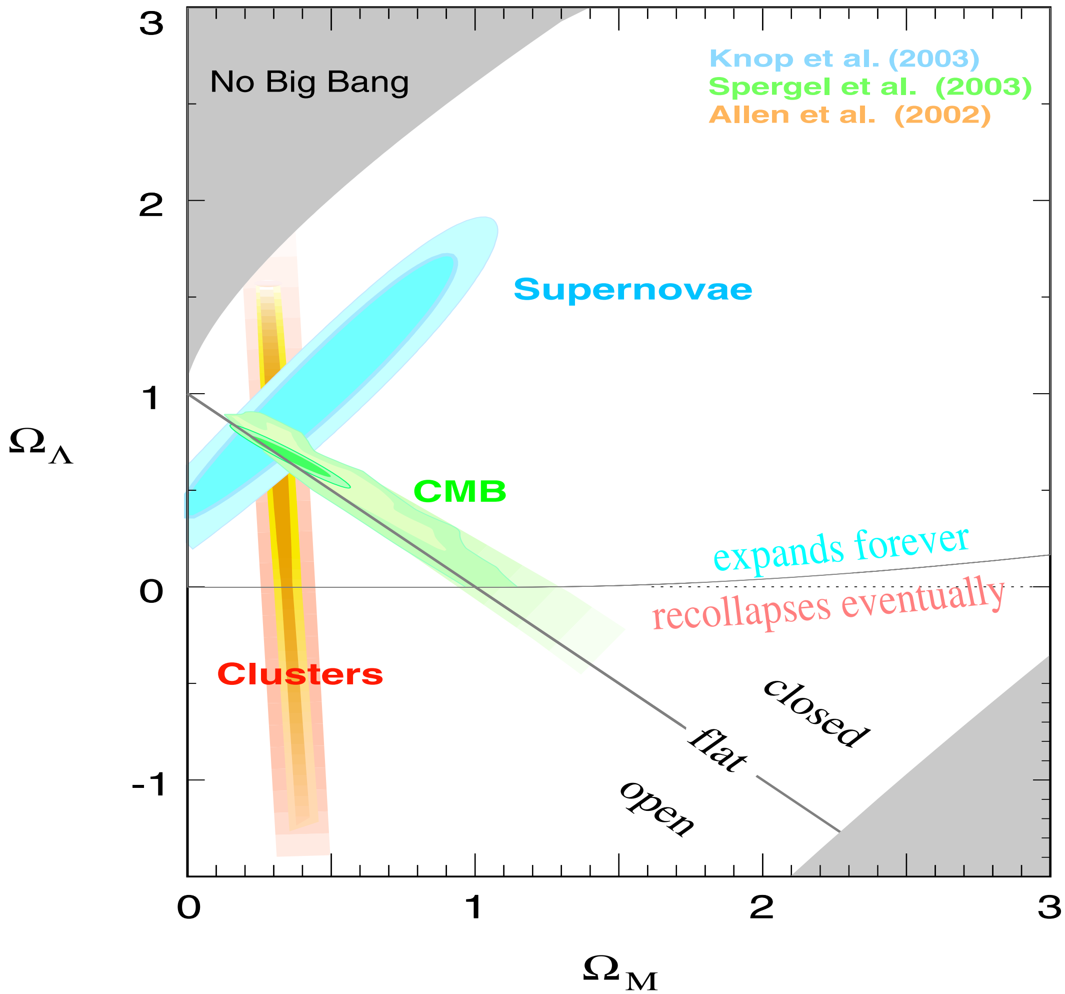


warmer (red), cooler (blue) spots, bars: polarization direction

What is the Universe Made Of?



A unified picture



Surprises in the Universe

- Dark matter is non-baryonic: $\Omega_m - \Omega_b$.
- WMAP data are consistent with a flat Universe in which the dark energy has an equation of state $w = -1$. All data of supernova, large-scale structure, and CMB reinforces the evidence of dark energy.
- Consistent with inflation.

$$\begin{aligned} h &= 0.732\,^{+0.018}_{-0.0062} \\ \Omega_m h^2 &= 0.1262\,^{+0.0045}_{-0.0062} \\ \Omega_b h^2 &= 0.00223\,^{+0.00066}_{-0.00083} \end{aligned}$$

Take the flat Universe one obtains

$$\Omega_\Lambda = 0.74, \qquad \Omega_{\rm DM} = 0.22, \qquad \Omega_b = 0.04$$

2. Cosmology Connection with Particle Physics

Cosmology needs new physics beyond the standard model (BSM):

- Often a scalar field is used as the inflaton, and to generate primordial fluctuations.
- Nature of the dark energy. Models for dark energy, such as quintessence, requires scalar fields.
- Dark matter is non-baryonic and requires physics BSM.
- Baryon asymmetry also requires physics BSM.

To understand the above problems which are in the astronomical scales require the fundamental understanding of the micro-physics involved – Synergy between the studies of the Universe on the smallest and the largest scales.

- Atomic physics is needed to understand the CMB signal at 379,000 years from Big Bang.
- Nuclear physics successfully predicts the BBN at $t \sim 1$ s.
- EW and TeV scale physics help us to understand the time before $t \sim 10^{-8}$ s.

The LHC will commence in 2007, which targets at TeV scale physics.

Relic density of a particle species

A particle species in the early Universe has to interact sufficently, otherwise it falls out of the thermal equilibrium. Roughly, when the interaction rate falls below the expansion rate ofthe Universe, the equilirium cannot be maintained and the particle decouples.

The evolution of the particle density is described by the Boltmann equation:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

where for massive particles in non-relativistic limit

$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^3 e^{-m/T}$$

We can expand

$$\langle \sigma v \rangle = a + b \langle v^2 \rangle \approx a + 6b/x^2$$

where $a(b)$ corresponds to $S(P)$-wave annihilation, and $x = m/T$.

Using the freeze-out condition, one can solve for $x_F = m/T_F$:

$$x_F = \ln \left[c(c+2)\sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{m M_{\rm pl}(a + 6b/x_F)}{g_*^{1/2} x_F^{1/2}} \right]$$

The relic density is given by

$$\Omega_X h^2 \simeq \frac{1.07 \times 10^9 \ {\rm GeV}^{-1}}{M_{\rm pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$$

Just for an order of magnitude estimate one can use:

$$\Omega_X h^2 \simeq \frac{3 \times 10^{-27} \ {\rm cm}^3 \ {\rm s}^{-1}}{\langle \sigma v \rangle}$$

Note that it is exactly the annihilation in the weak scale. That is why DM links closely with weak scale physics.

Dark matter and Collider studies

It is a coincidence that the required annihilation for weak scale dark matter is right at the weak scale interaction. Weakly-interacting massive particles (WIMP) is the leading candidate for the dark matter.

Most studied WIMPs are

- Lightest supersymmetric particle (LSP) of SUSY models.
- Lightest Kaluza-Klein (LKP) in universal extra dimenion models.
- Lightest T-odd particle (LTP) in little Higgs models with T parity.
- Branons in large extra dimension models.

These candidates offer immediate tests that can be readily carried out at colliders.

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Therefore, we focus on the neutralino DM in the following.

The lightest neutralino (LSP) of SUSY models

In SUSY models, neutralinos are linear combinations of the bino, neutral wino, and the two neutral Higgsinos.

In the basis $(\tilde{B}, \widetilde{W}^3, \tilde{H}_d, \tilde{H}_u)^T$,

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_z c_\beta s_W & m_z s_\beta s_W \\ 0 & M_2 & m_z c_\beta c_W & -m_z s_\beta c_W \\ -m_z c_\beta s_W & m_z c_\beta c_W & 0 & \mu \\ m_z s_\beta s_W & -m_z s_\beta c_W & \mu & 0 \end{pmatrix}$$

While $\mathcal{M}_N$ is diagonalized as

$$N^* \mathcal{M}_N N^\dagger = \text{diag}\left(m_{\widetilde{\chi}^0_1}, m_{\widetilde{\chi}^0_2}, m_{\widetilde{\chi}^0_3}, m_{\widetilde{\chi}^0_4} \right)$$

The LSP is then a combination of

$$\widetilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\widetilde{W}^3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

The LSP is stable because of the imposed R parity.

Neutralino Annihilations $\langle \sigma v \rangle$

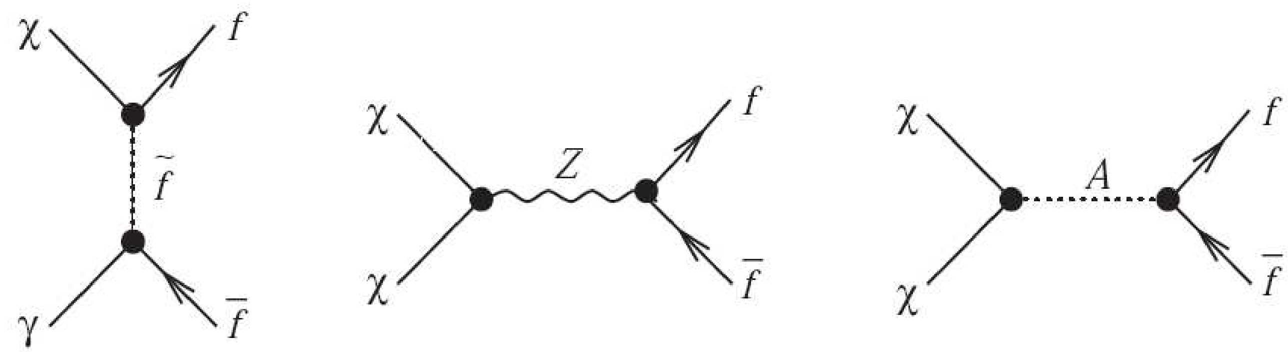
Gaugino and Higgsino fractions:

$$f_G = N_{11}^2 + N_{12}^2 \,, \qquad f_H = N_{13}^2 + N_{14}^2 \,.$$

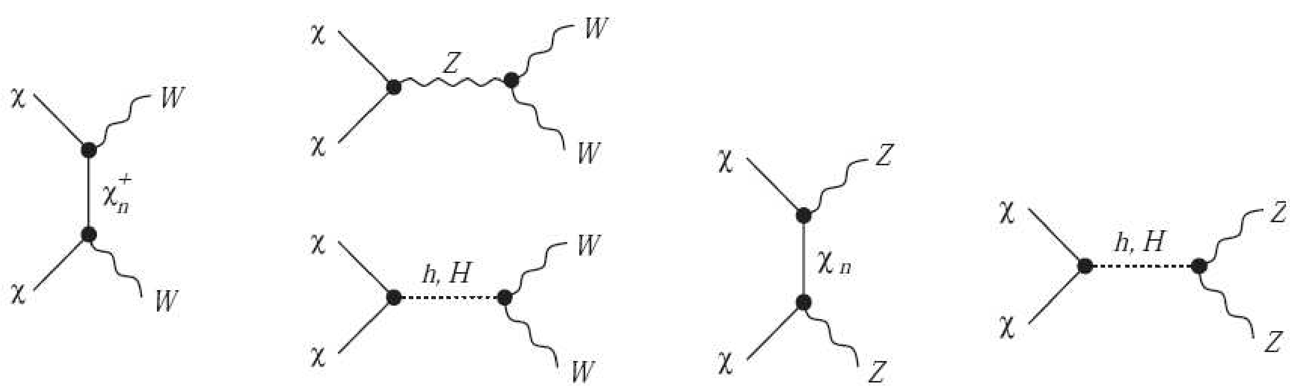
It determines the dominant mechanism in the neutralino annihilation.

- Bino-like: behaves like a photon, so weakly annihilate mainly through $\tilde{f}$ into $f\bar{f}$.
- Wino-like: behaves like W, Z, degenerates with charged winos, strong annihilation, annihilates strongly into WW, ZZ.
- Higgsino-like: behaves like the Higgs, degenerates with the charged Higgsinos, strong coannihilation.

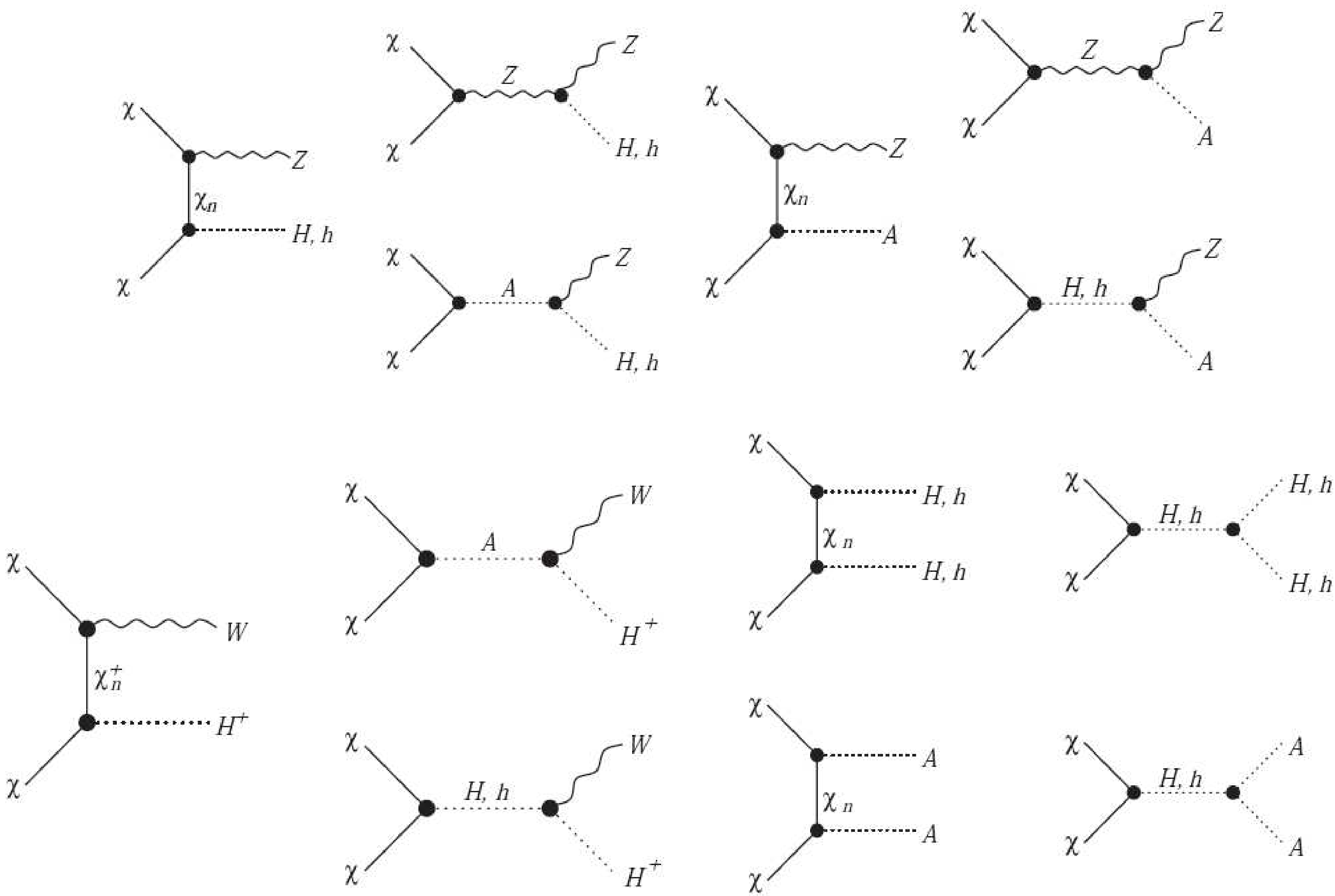
$\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to f \bar{f}$



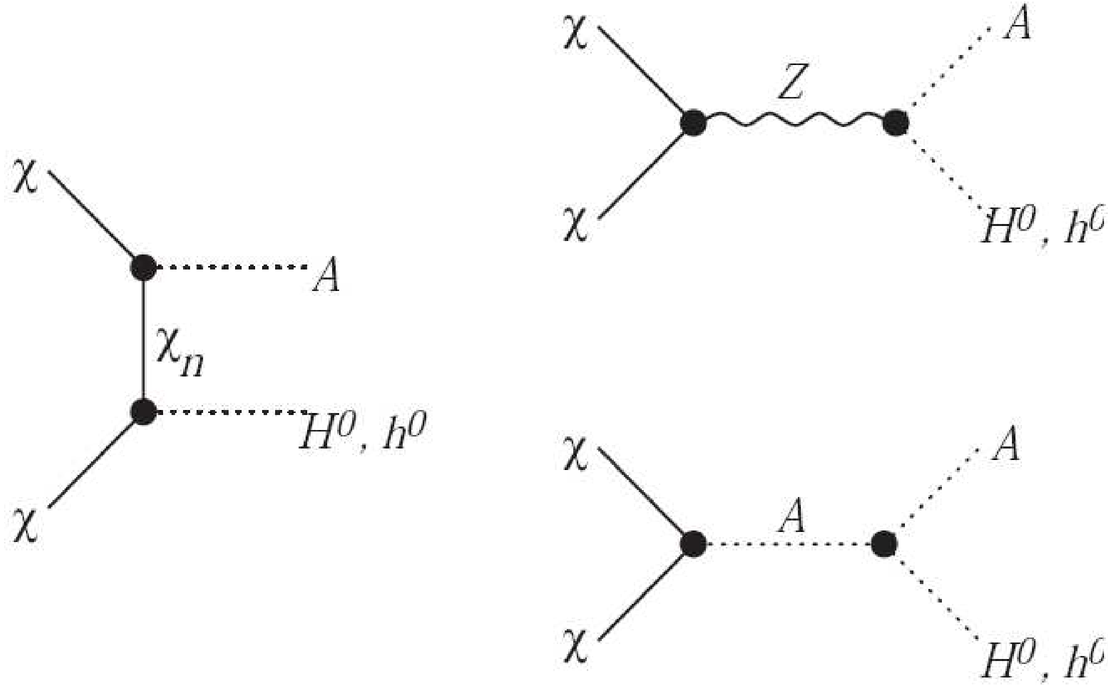
$\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to WW, ZZ$



$\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to ZH, ZA, AA, W^{\pm}H^{\mp},$



$\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to AH$



Coannihilations

If there are another particles with slightly larger mass in thermal equilibrium and thus a similar number density

$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

they help annihilating more neutralinos. The Boltzmann equation is modified to

$$\frac{dn}{dt} + 3Hn = - \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_{eq_i} n_{eq_i} \right)$$

where $n = \sum_i n_i$ (all other particles will decay into the LSP.)

$$\sigma_{ij} = \sum_X \sigma(X_i X_j \to Y)$$

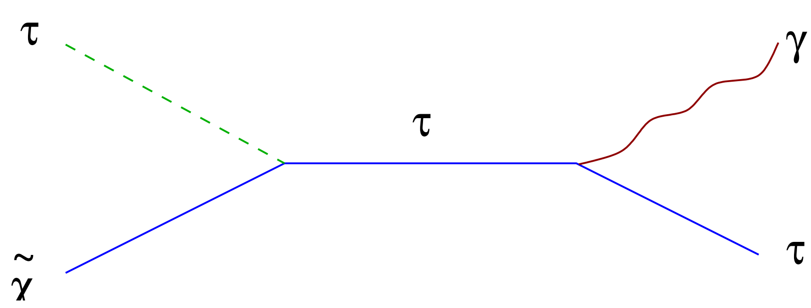
Effectively, the $\langle \sigma v \rangle$ increases due to coannihilation.

Coannihilations (cont...)

In the unconstrained MSSM, one can have any coannihilation particles, such as stop, gluino, stau, chargino, the next neutralino have been considered.

Most studied one is the stau in the framework of mSUGRA with universal boundary conditions. In fact, there are regions where the $m_{\tilde{\tau}_1} < m_{\widetilde{\chi}^0_1}$. Coannihilation region occurs where $m_{\tilde{\tau}_1} - m_{\widetilde{\chi}^0_1} < 5 - 15$ GeV, where the LSP is bino-like.

If without coannihilation, the bino annihilation is too slow so that $\Omega_{\widetilde{\chi}}$ is too large. Coannihilation can bring it down to the right value.

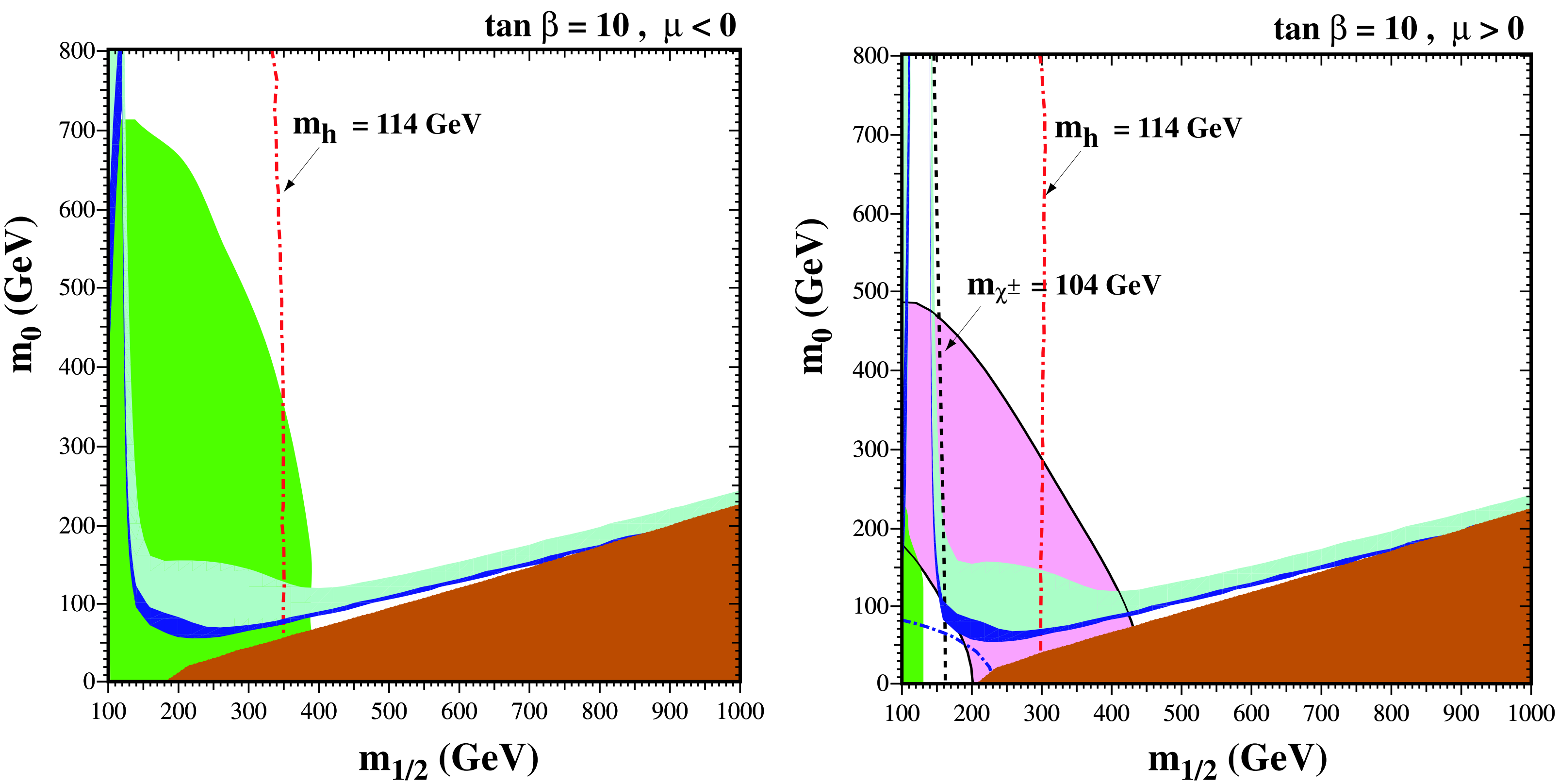


Fitted parameter space in mSUGRA

There are 3 regions still consistent with WMAP data in mSUGRA ($m_{1/2}$, m_0, A_0, $\tan\beta$, and sign(μ).)

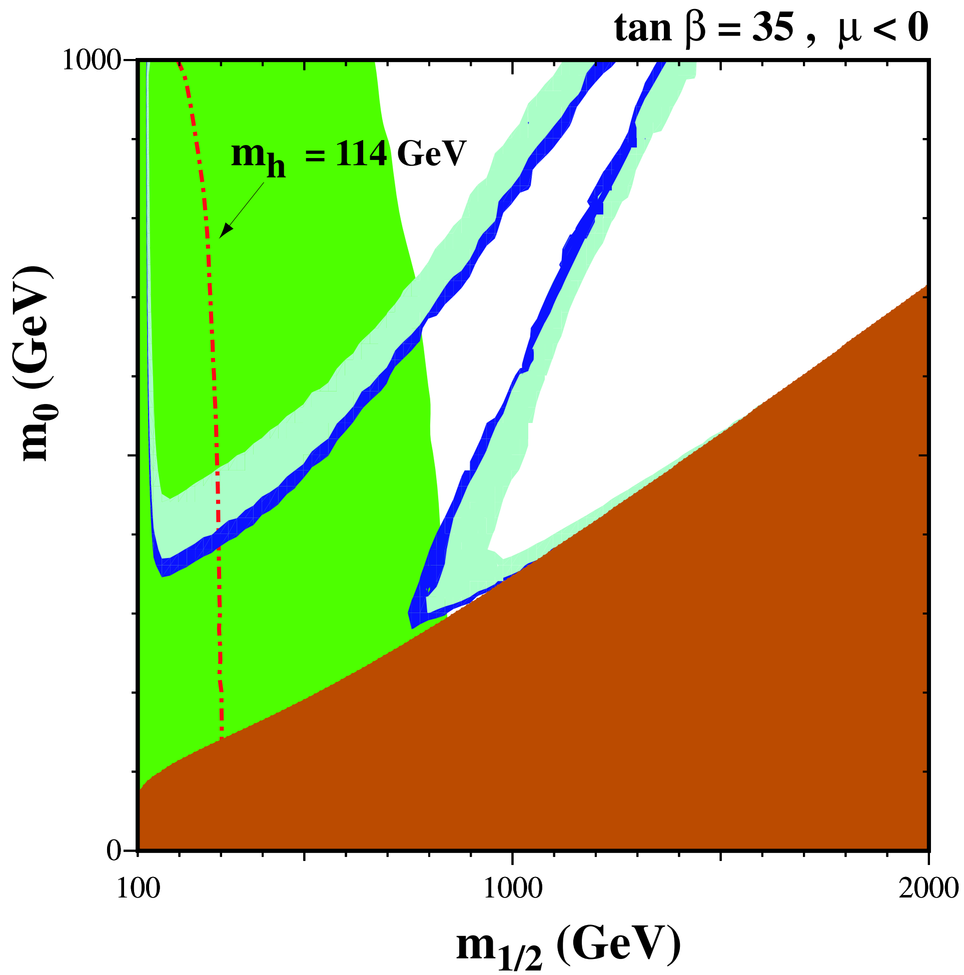
- Stau-neutralino coannihilation region.
- Higgs-funnel region where $m_{A,H} \simeq 2m_{\widetilde{\chi}_1^0}$.
- Focus point region where $\widetilde{\chi}_1^0$ has a large higgsino component.

Stau-neutralino coannihilation region



(Ellis, Olive, Santoso, Spanos 2003)

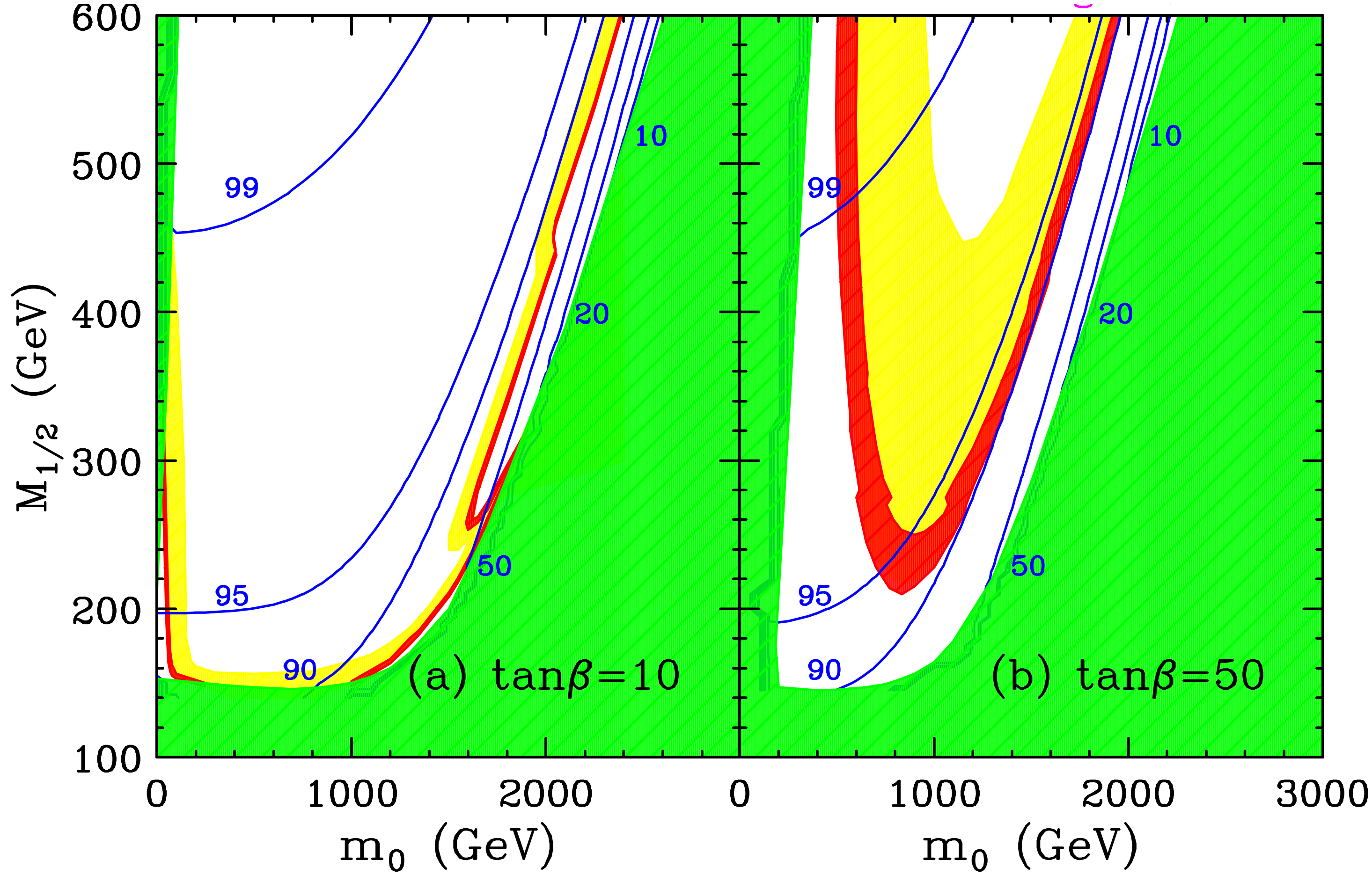
Higgs Funnel region



$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to A^{(*)} \to b\bar{b}, \tau^+\tau^-$

(Ellis, Olive, Santoso, Spanos 2003)

Focus point region



(Feng, Matchev, Wilczek 2000)

Collider signatures for the stau-neutralino coannihilation region

(Arnowitt, Dutta, Kamon + others, 2006, 2005, 2004)

Stau-neutralino coannihilation region

$$\Delta M \equiv m_{\tilde{\tau}_1} - m_{\widetilde{\chi}_1^0} = 5 - 15 \text{ GeV}$$

is characterized by soft tau leptons in the final state

$$\tilde{\tau}_1^- \to \tau^- \widetilde{\chi}_1^0$$

Decays of gauginos and staus into τ lepton are very frequent, but the τs are soft such that there are severe τ backgrounds.

Note: For studies at e^+e^- colliders, please see Baer et al. (hep-ph/0405058).

A LHC study

(Arnowitt, Dutta, Kamon + others, 2006, 2005, 2004)

The primary production is via strong interaction:

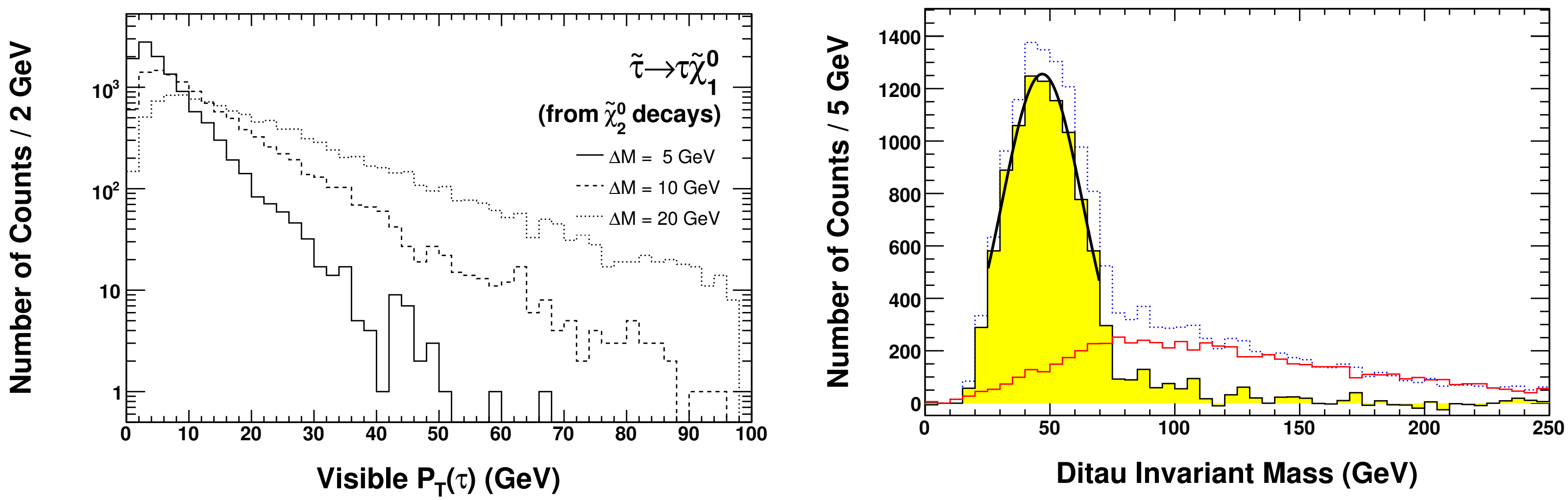
$$\begin{aligned} pp &\rightarrow \tilde{g}\tilde{g},\ \tilde{g}\tilde{q},\ \tilde{q}\tilde{q} \\ \text{followed by } \tilde{q} &\rightarrow q'\widetilde{\chi}_1^{\pm},\ q\widetilde{\chi}_2^0 \qquad \tilde{q}_R \rightarrow q\widetilde{\chi}_1^0 \\ \widetilde{g} &\rightarrow q\bar{q}'\widetilde{\chi}_1^{\pm},\ q\bar{q}\widetilde{\chi}_2^0,\ \bar{t}\tilde{t},\ \bar{b}\tilde{b} \end{aligned}$$

They result in $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$, $\widetilde{\chi}_2^0\widetilde{\chi}_2^0$ plus high p_T jets and large $\not{p}_T$.

Then

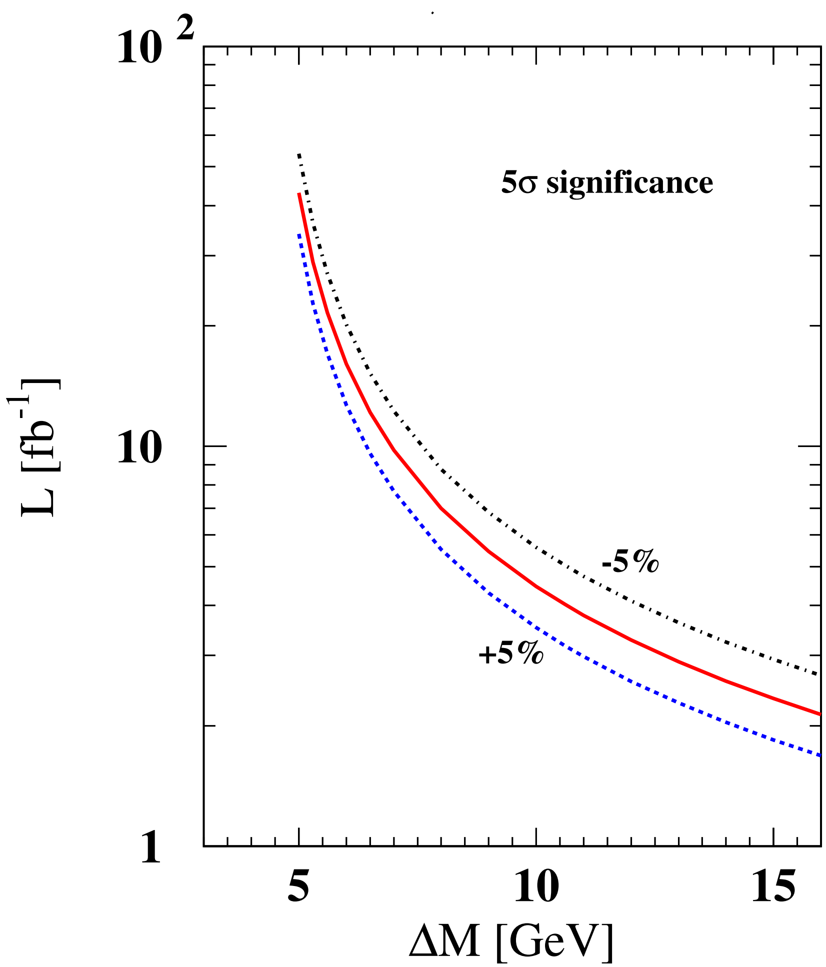
$$\begin{aligned} \widetilde{\chi}_2^0 &\rightarrow \tau^+\tilde{\tau} \rightarrow \tau^+\tau^-\widetilde{\chi}_1^0 \\ \widetilde{\chi}_1^{\pm} &\rightarrow \nu\tilde{\tau} \rightarrow \nu\tau\widetilde{\chi}_1^0 \end{aligned}$$

Final state includes at least 2 τ leptons, high p_T jets and large $\not{p}_T$.



The yellow peak is the $\tau^+\tau^-$ pair from $\widetilde{\chi}^0_2 \to \tau\tilde{\tau} \to \tau^+\tau^-\widetilde{\chi}^0_1$ decay.

blue: opposite sign, red: like sign



$\pm 5\%$ of the gluino mass (831 GeV)

Collider signatures for Focus point region

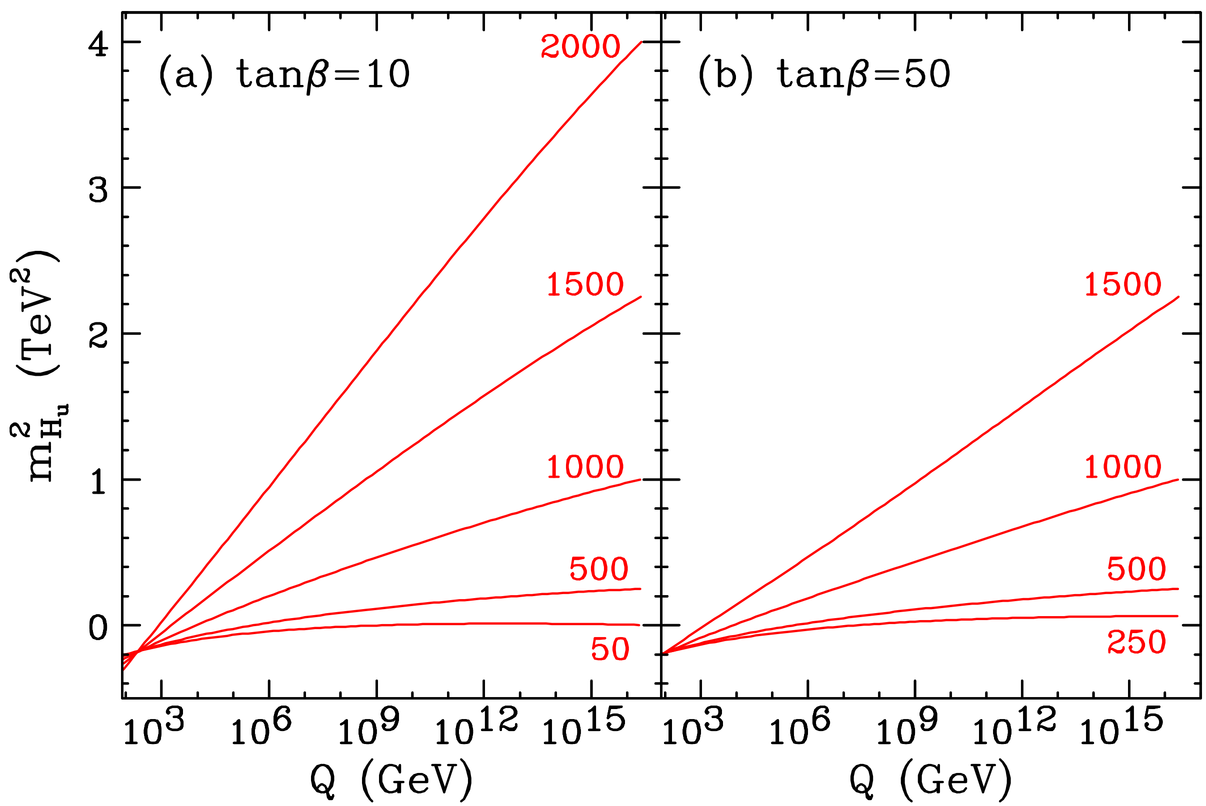
This region is characterized by very large m_0 without violating naturalness. This is possible because $m_{H_u}^2$ has a fixed-point behavior, i.e., one starts with a wide range of values and run to a similar negative value at low scale. EWSB needs no fine-tuning in the focus point region as long as $m_{1/2}$ is not too large. The tree-level EWSB condition:

$$\frac{m_Z^2}{2} \sim -m_{H_u}^2 - \mu^2$$

In focus-point region, $m_{H_u}^2$ stays small negative so that μ is also small, though m_0 is very large.

Thus, this region is characterized by large m_0, small μ, and $M_1 \sim \mu$ and thus the lightest neutralino contains a substantial higgsino component.

CP, FCNC, and dim-5 proton decay problems are alleviated.



The exact focus point is sensitive to the top mass
(Feng, Matchev, Morii 2000)

Higgsino-like DM Phenomenology

Since the $\widetilde{\chi}_1^0$ is a mixture of bino-higgsino, it has strong annihilation into WW, ZZ in addition to the usual bino annihilation into $f\bar{f}$ via $\tilde{f}$.

Larger $\langle \sigma v \rangle$ and effective coannihilation with $\widetilde{\chi}_1^\pm$ affords heavier LSP. In case of pure Higgsino:

$$\Omega h^2 \simeq 0.1 \left(\frac{M_{\rm LSP}}{1 \text{ TeV}} \right)^2$$

It also has strong scattering with nucleons via Higgs and squark exchanges, giving rise to σ^{SI}, which potentially can be observed in direct detection experiments (e.g. CDMS).

Due to higgsino nature, it also give strong annihilation into $WW, ZZ, \gamma\gamma, \nu\bar{\nu}$, which potentially be observed in the γ-ray experiments (e.g. GLAST), neutrino experiments (e.g. ICECUBE), positron-excess and $\bar{p}$-excess experiments (e.g., AMSII).

In particular for a pure Higgsino DM, mono-chromatic photon flux from the Galactic Center:

$$\sigma v(\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to \gamma\gamma) \simeq 1 \times 10^{-28}\,{\rm cm}^3\,{\rm s}^{-1}\,, \qquad \Phi_\gamma \simeq 1.5 \times 10^{-11}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$$

reachable at future ACT (HESS, GLAST).

Higgsino-like Collider Phenomenology

(Baer et al. hep-ph/0507282)

Since squarks and sleptons are multi-TeV, the detection at the LHC relies on gluino production and subsequent decays, ie., multi-jets, multi-leptons plus $\not{E}_T$.

Charginos and neutralinos are relatively light in FP region. So one can use the direct gaugino-pair production. In general,

$$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^0, \qquad \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0, \qquad \widetilde{\chi}_1^{+}\widetilde{\chi}_1^{-}$$

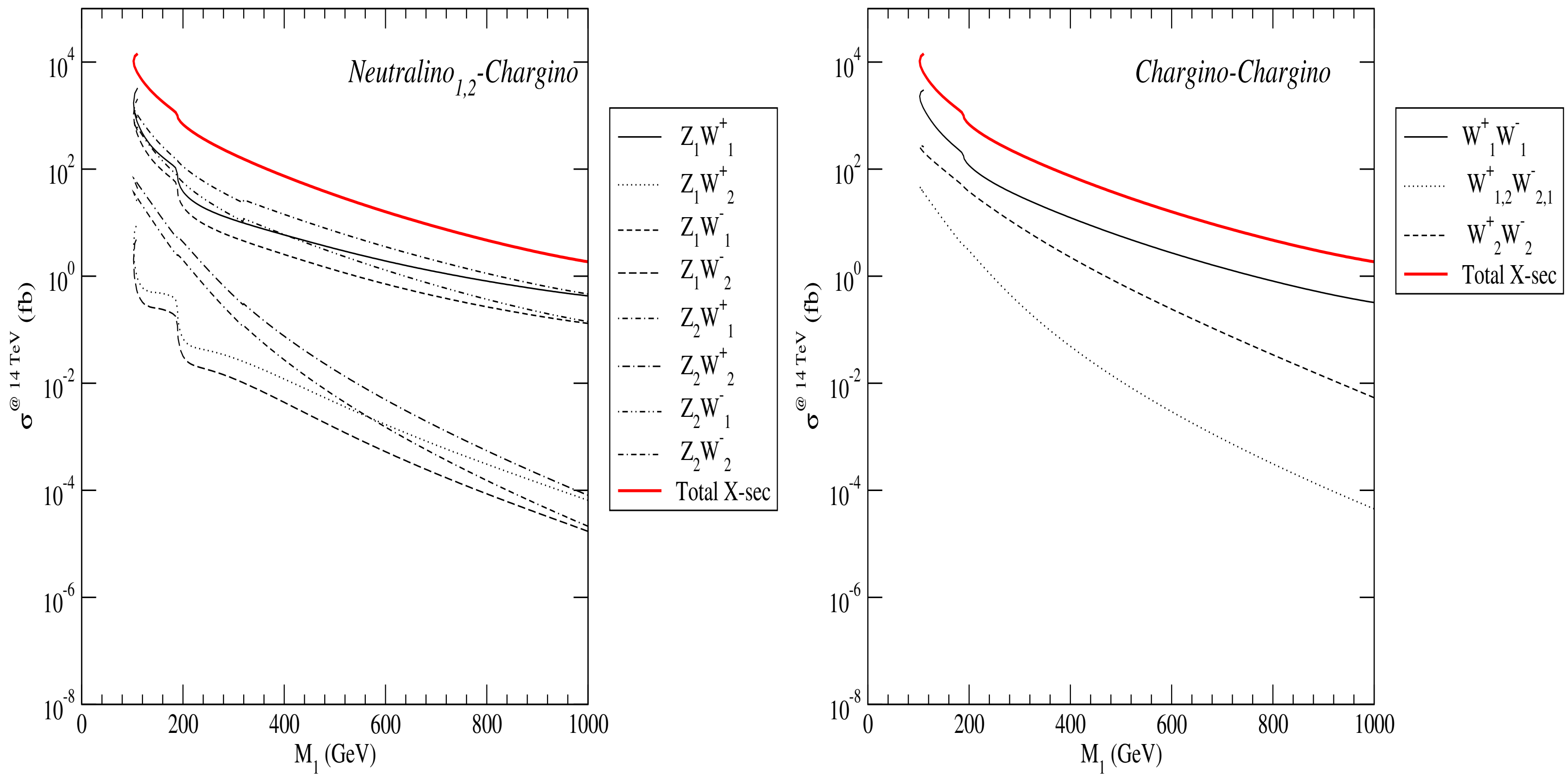
are the largest.

The mass splitting between them stays large:

$$\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 f \bar{f} \; , \qquad \widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0 f \bar{f}' \; ,$$

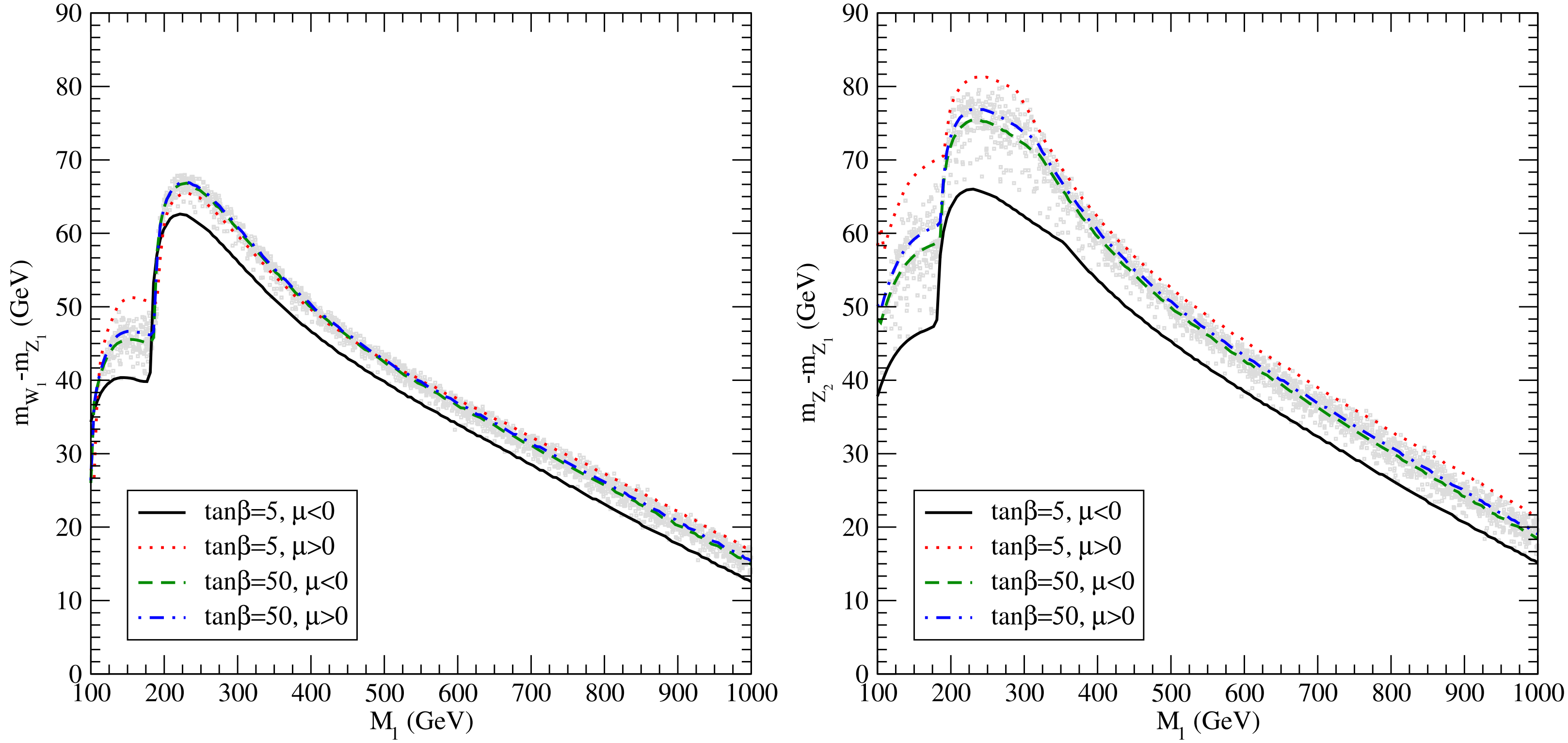
give hard enough lepton signals.

Gaugino-pair production



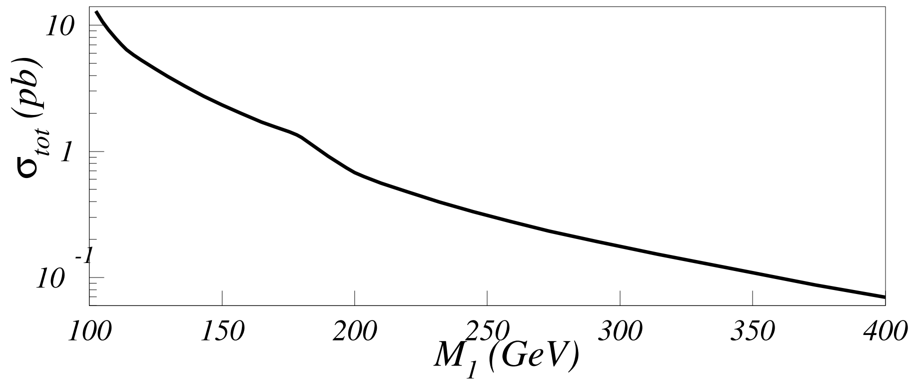
(Baer et al. hep-ph/0507282)

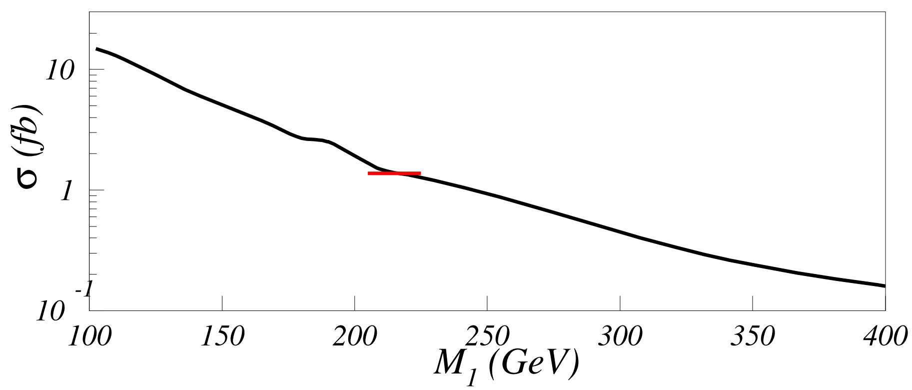
Mass differences



(Baer et al. hep-ph/0507282)

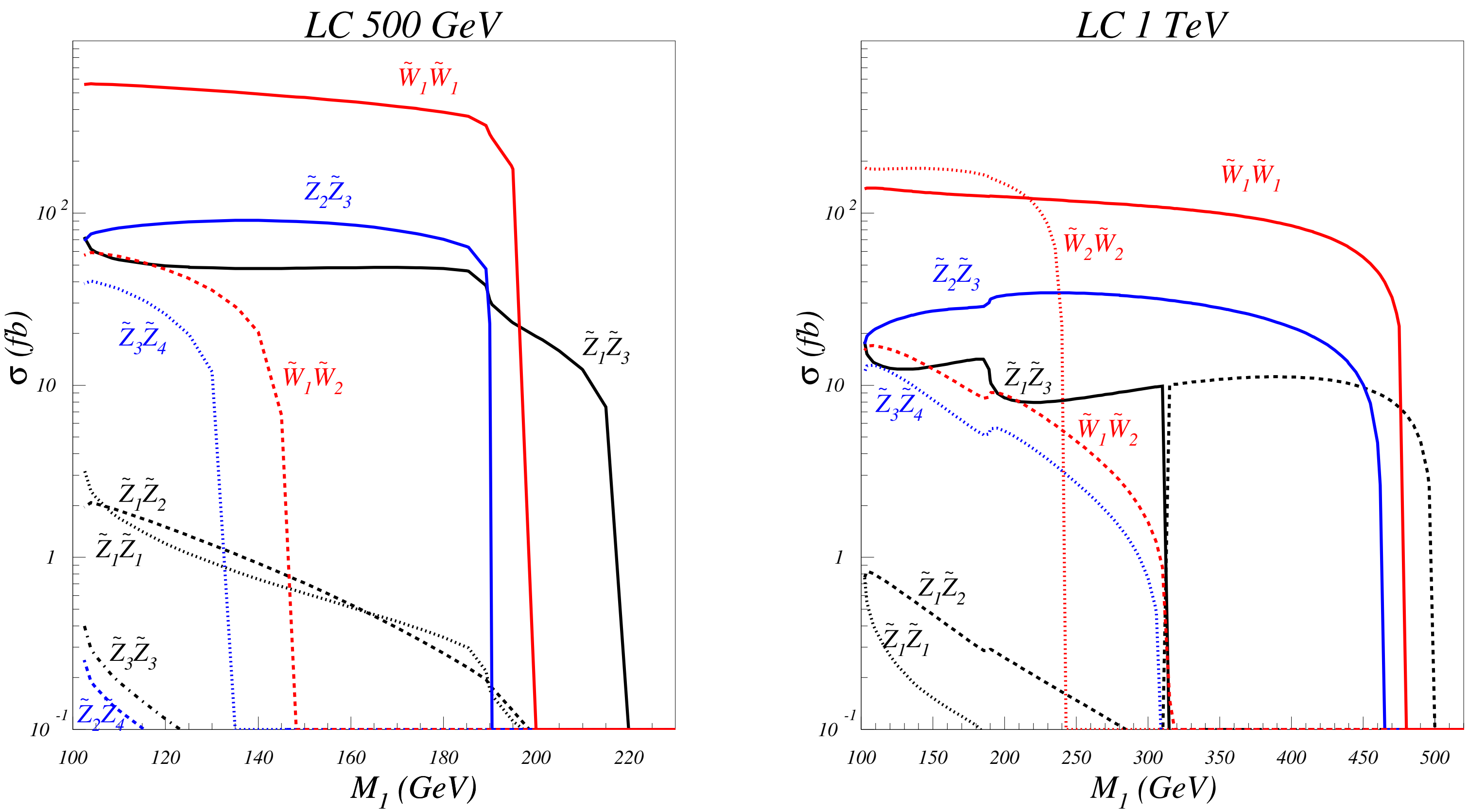
Tri-lepton signal from $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \to \ell^{\pm}\ell^{-}\ell^{-}\widetilde{\chi}_1^0\widetilde{\chi}_1^0$





The upper is $pp \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ cross sections. The lower is the clean trilepton cross section after the SC2 cuts. The red mark is the 5σ discovery limit for 100 fb^{-1}.

Gaugino-pair production at the ILC



Dominated by chargino-pair. One can use the di-lepton plus $\not{E}_T$ signal.

Other possible regions consistent with WMAP

- A-funnel: $m_A \simeq 2m_{\widetilde{\chi}_1^0}$. It is easier with large $\tan\beta$ to have this region. And in this region, the LSP has stronger gaugino-higgsino mixing, and thus strong $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 A$ coupling (see Djouadi, hep-ph/0602001).
- Higgs-pole region: $m_h \simeq 2m_{\widetilde{\chi}_1^0}$. (Djouadi, hep-ph/0504090). In the above 2 scenarios:

$$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to A, h \to b\bar{b},\ \tau^+\tau^-$$

- Stop coannihilation region: $m_{\tilde{t}_1} \simeq m_{\widetilde{\chi}_1^0}$.

$$\begin{pmatrix} m^2_{\tilde{t}_L} & m_t(A_t + \mu\cot\beta) \\ m_t(A_t + \mu\cot\beta) & m^2_{\tilde{t}_R} \end{pmatrix}$$

When A_t is large, the strong mixing pushes the lighter stop light enough. (Ellis et al., hep-ph/0112113).

4. Universal Extra Dimension (UED) and the LKP

All SM particles are free to move in the extra dimensions. It is natural in the sense why some are confined and some are not.

Translational invariance

$\Rightarrow$ Conservation of KK numbers (momentum)

Boundary breaks the momentum conservation down to a Z_2 parity,

Conservation of KK parity

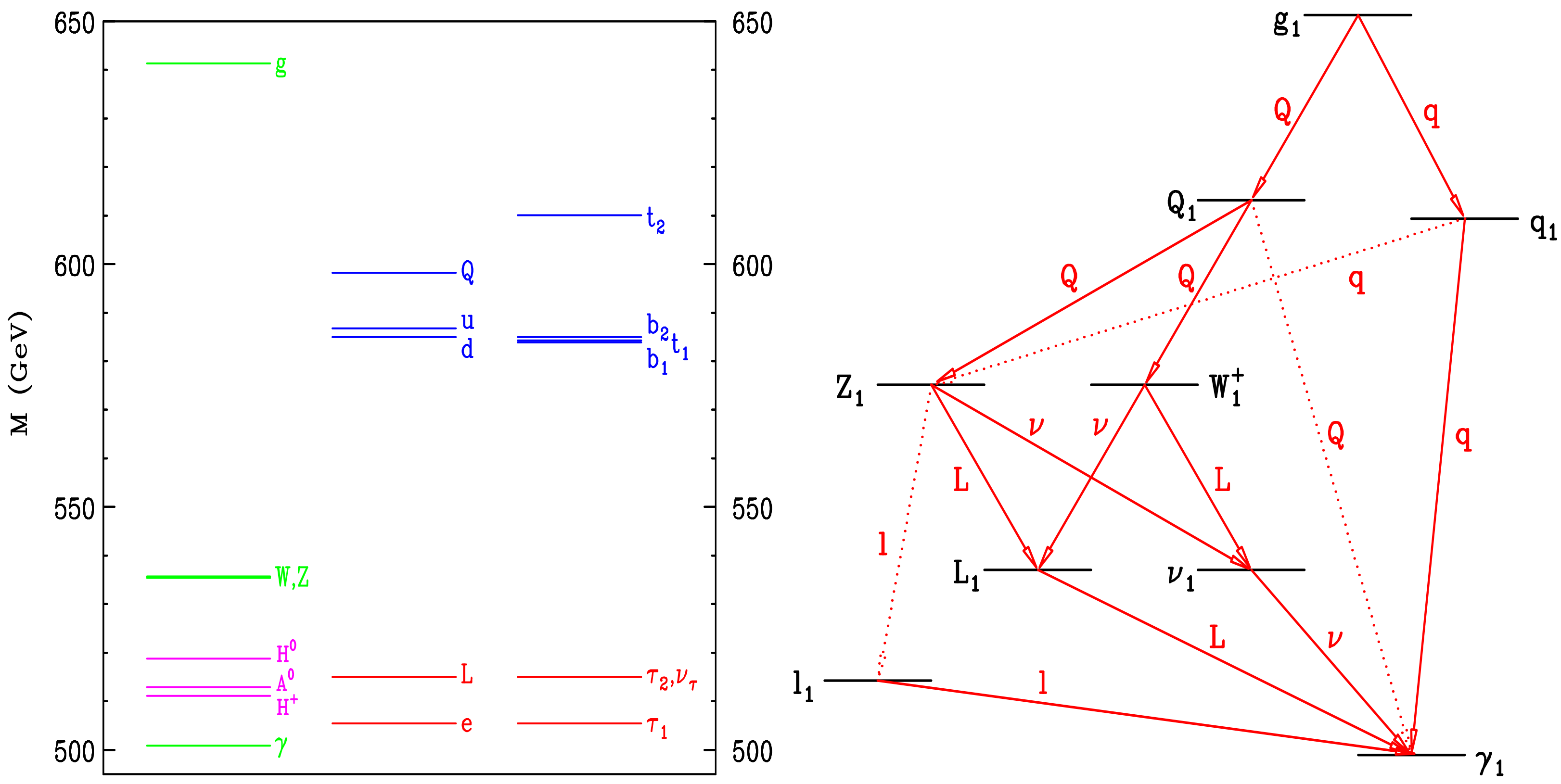
Radiation corrections and the boundart terms lift the mass degeneracy of KK states.

B^1, the first KK state of the hypercharge gauge boson, is the lightest KK particle (LKP)

The LKP with weak scale interaction could be a natural DM candidate.

Appelquist, Cheng, Dobrescu hep-ph/0012100

KK state spectrum



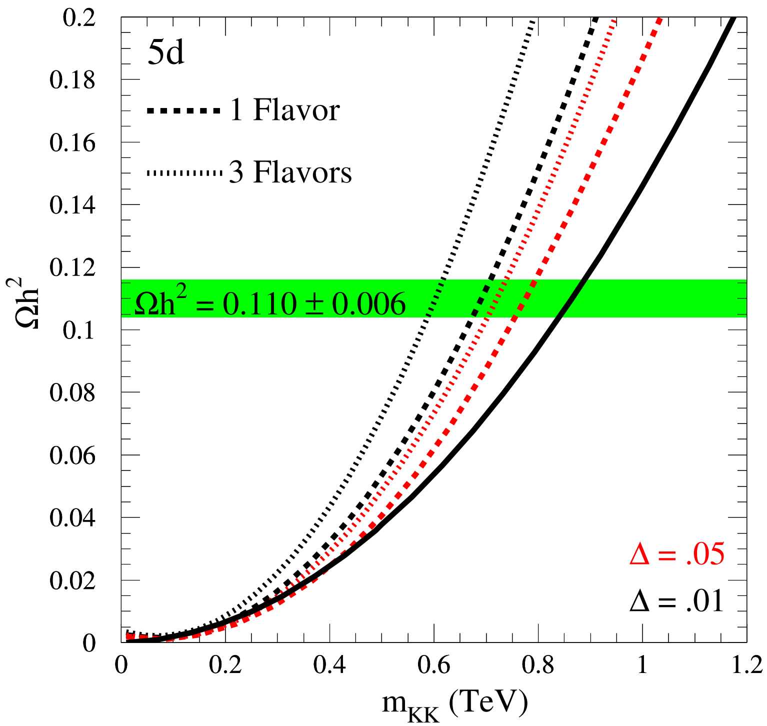
Cheng, Matchev, Schmaltz hep-ph/0204342

Lightest KK state as the Dark Matter

The calculation of the relic density of B^1 is rather standard. Consider the annihilation

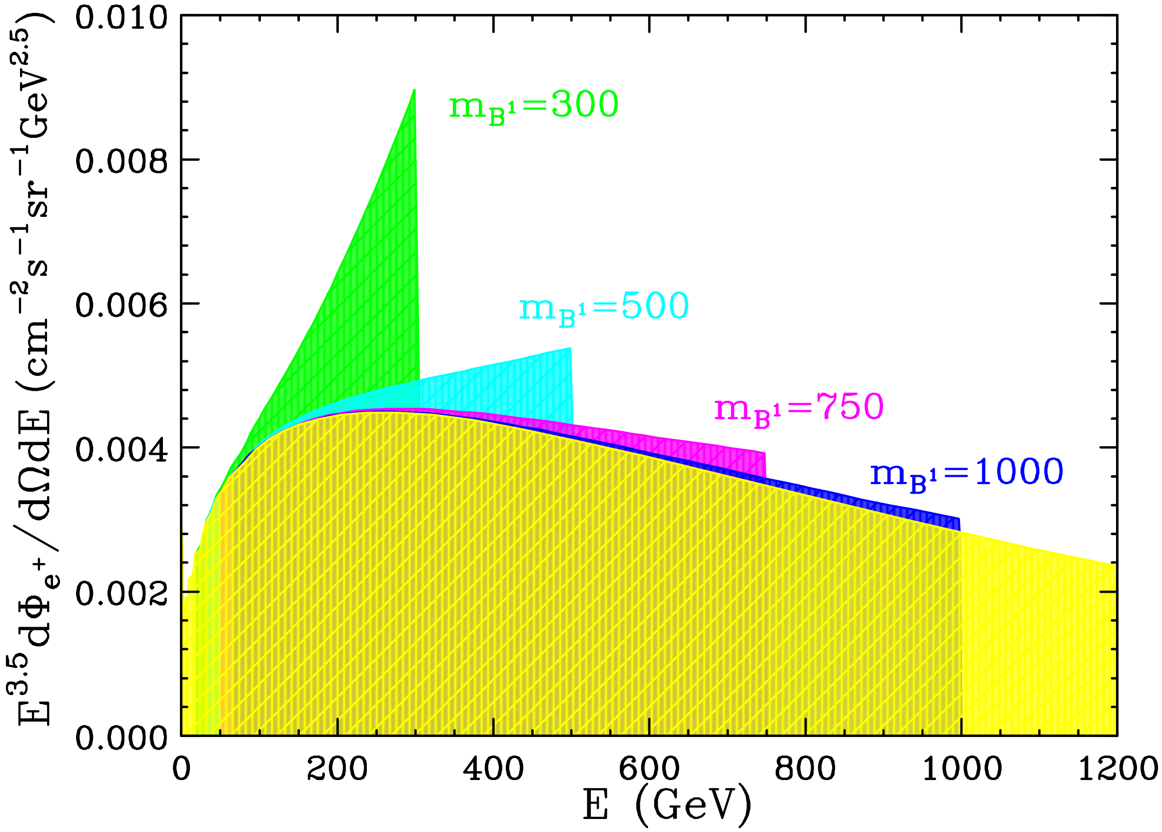
$$B^{(1)}B^{(1)} \to f\bar{f}$$

together with the possible coannihilation of $\ell_R^{(1)}$.



Servant and Tait hep-ph/0206071

Indirect positron signal $B^1 B^1 \to e^+ e^-$



Monoenergetic positron signal, but broadened during propagation.

Cheng, Feng, Matchev hep-ph/0207125

Collider Phenomenology

The largest production comes from KK quarks and KK gluons

$$\begin{aligned} qq' &\to q^{(1)} q'^{(1)} \\ q\bar{q} &\to q^{(1)} \bar{q}^{(1)} \\ gg &\to g^{(1)} g^{(1)} \\ gg, q\bar{q} &\to q'^{(1)} \bar{q}'^{(1)} \end{aligned}$$

Note that the mass of $q^{(1)}$ scale as $1/R$.

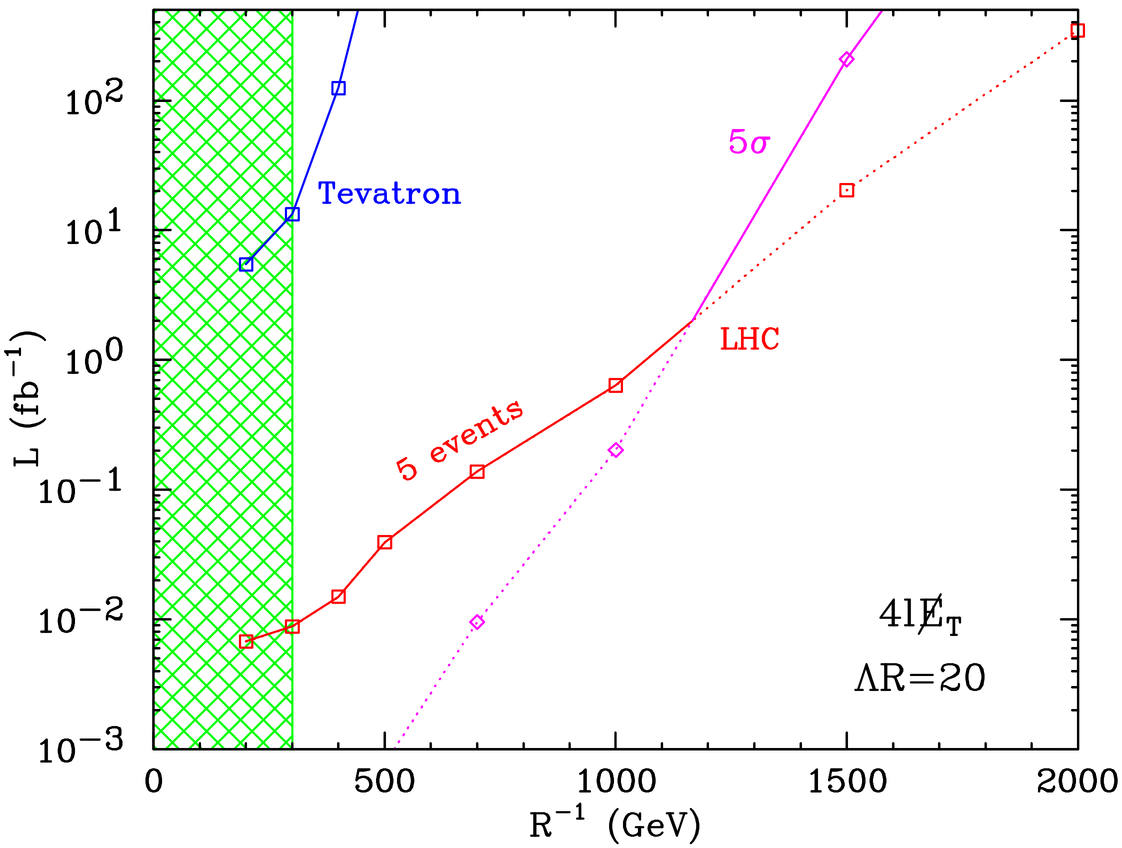
Each $q^{(1)}$ decays into jets and $B^{(1)}$ eventually

$\Rightarrow$ jets+ $\not{E}_T$

Each $q^{(1)}$ also decays $W^{(1)}, Z^{(1)}$, which decay into leptons and $B^{(1)}$

$\Rightarrow$ multi-leptons+ $\not{E}_T$

Sensitivity Reach



Cheng, Matchev, and Schmaltz hep-ph/0205314

Distinguish UED from SUSY

Datta, Kong, Matchev

Generic features of UED:

- For each SM particle, UED predicts an infinite tower of KK states.
- The spins and couplings of the SM particle and its KK states are the same.
- The lightest KK particle (LKP) is stable $\Rightarrow$ missing energy signal in colliders.

The last feature made UED similar to SUSY with the LSP. One is then forced to use

1. The presence of $n = 2$ KK states, or
2. The spin of the KK particles.

to distinguish UED from SUSY.

5. Little Higgs model with T parity

(Cheng, Low hep-ph/0308199, 0405243, 0409025)

The original "little Higgs" models propose the existence of TeV scale particles:

$$Z_H\,, W_H\,, A_H\,, \Phi, T_H\,, Q_H\,, L_H$$

which are the heavy partners of Z, W, A, t, q, ℓ, resp. They are introduced in a special way such that they cancel the loop correction to the Higgs boson mass. However, the early versions of LH models suffer from the constraints of precision measurements.

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T-parity was introduced

SM particles	$T = +$ parity
Heavy partners	$T = -$ parity

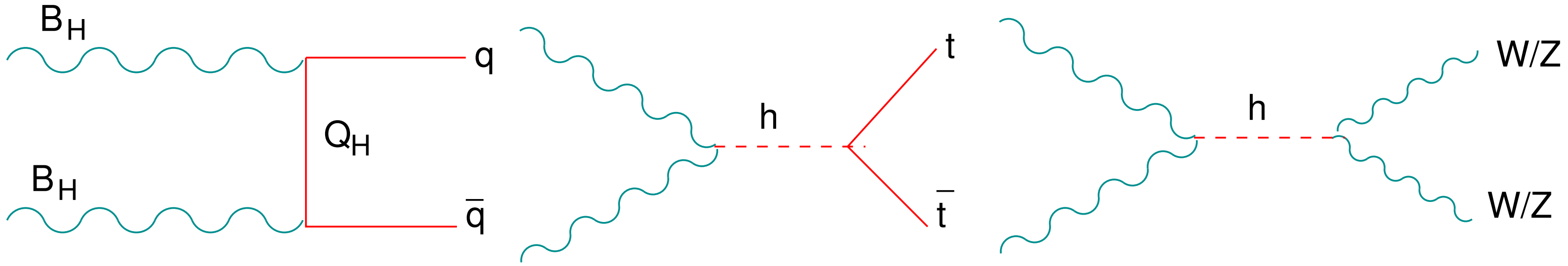
By doing that the vertex involving the heavy partners must occur in pairs, thus relieving the precision constraints.

The T parity also implies the lightest T-odd partner (LTP) is stable, thus can be a dark matter candidate. In general, the γ_H (B_H) is the LTP.

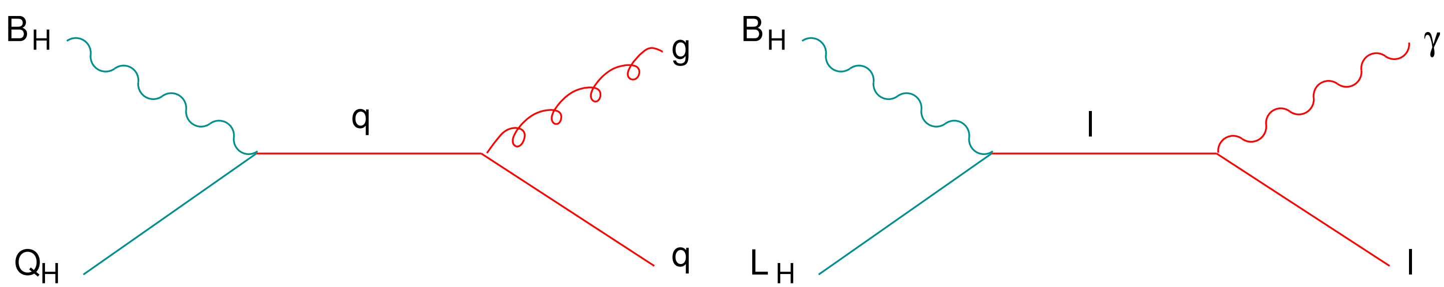
Relic density of A_H

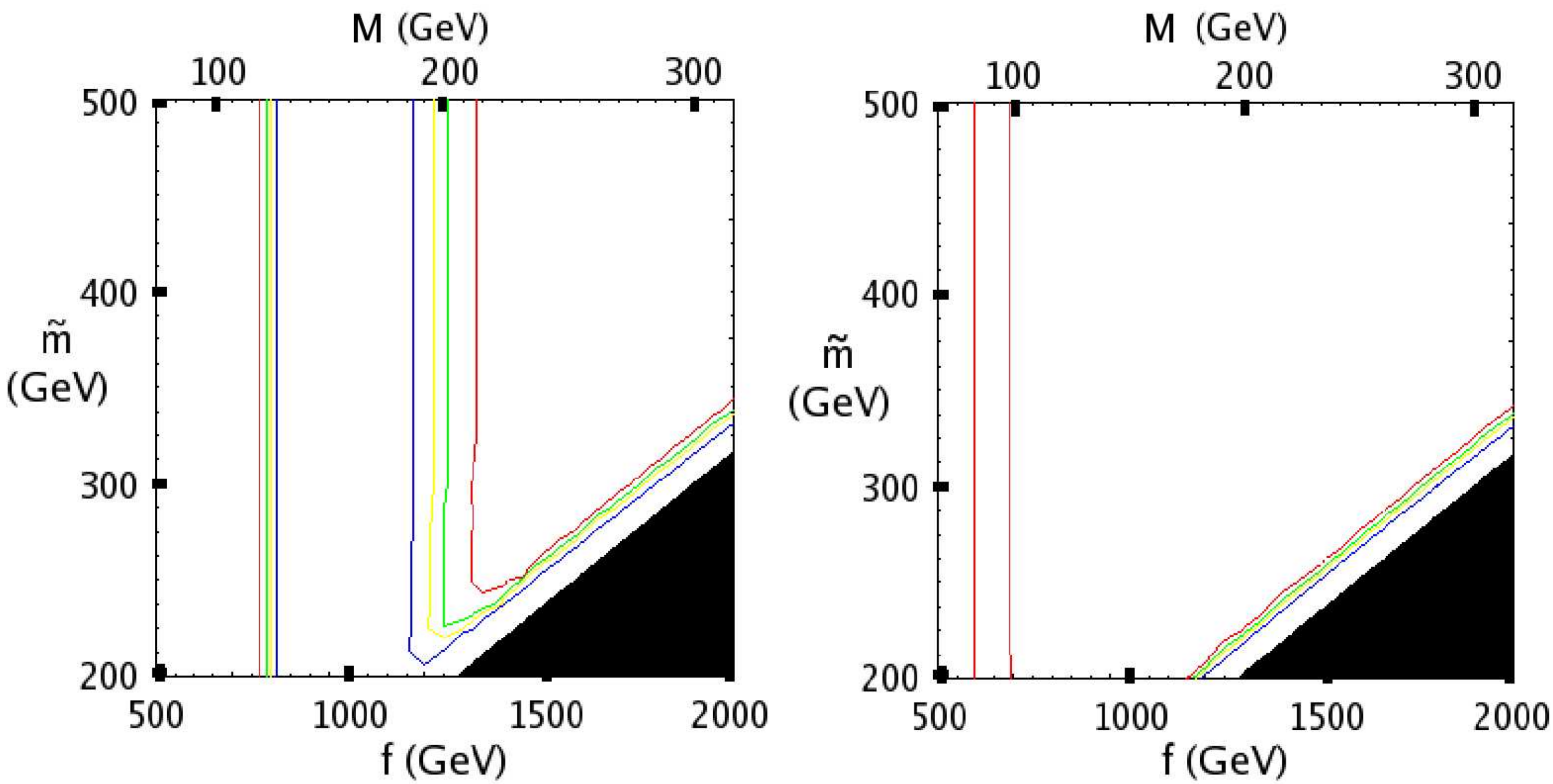
(Birkedal et al. hep-ph/0603077; Martin hep-ph/0602206)

The calculation is standard with the following annihilation:



There are also possibilities of coannihilation due to the heavy partners Q_H, L_H (γ_H, W_H are fixed at much higher mass):





$m_H = 300$ GeV (left), $m_H = 120$ GeV (right) (Birkedal et al. hep-ph/0603077).
0.93 (green) $< \Omega_{\rm DM} h^2 <$ 0.129 (red)

Collider Phenomenology

Without coannihilation:

The required mass for B_H is on both sides of the Higgs resonance:

$$M_{A_H} = \frac{m_h - 24}{2.38} \qquad \text{and} \qquad M_{A_H} = \frac{m_h + 24}{1.89} \qquad \text{(Birkedal et al.)}$$

With coannihilation:

The heavy Q_H needs to be slightly heavier than A_H to have efficient coannihilation:

$$M_{Q_H} - M_{A_H} \simeq 20 \text{ GeV}$$

One can test it using

$$\begin{aligned} pp &\to Q_H \bar{Q}_H ,\; Q_H A_H ,\; Q_H W_H ,\; Q_H Z_H , \\ pp &\to L_H \bar{L}_H ,\; L_H A_H ,\; L_H W_H ,\; L_H Z_H , \\ pp &\to W_H Z_H ,\; W_H W_H ,\; Z_H Z_H ,\; W_H A_H ,\; Z_H A_H \end{aligned}$$

Decay products of the heavy states include multi-jet and multi-leptons plus large missing enery.

Even the coannihilation Q_H and L_H have a fairly large mass difference from A_H, thus will give hard enough jets and leptons for detection.

Summary

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Summary

- LHC is an exciting era of discovery. SUSY, extra dimensions are just a small corner in the theory space. We may be puzzled by what we will observe.
- Cosmological observations in the largest scale require fundamental physics at the smallest scale. The LHC is going to test the yet smallest scale (at TeV).

Ready for surprises!!

References

Detector and Collider basics:

- CMS website
- "Collider Physics" , Barger and Phillips.

Supersymmetry phenomenology:

- "A Supersymmetry Primer", by S. Martin, hep-ph/9709356.
- " The search for supersymmetry: probing physics beyond the standard model", by Haber and Kane, Phys.Rept.117:75,1985.

Connection with Cosmology:

- "Particle dark matter: evidence, candidates and constraint", by Bertone, Hooper, and Silk, hep-ph/0404175.
- "ILC Cosmology", by J. Feng, hep-ph/0509309.

- “Supersymmetry and cosmology”, by J. Feng, hep-ph/0405215.

Extra dimension phenomenology:

- “Collider phenomenology for a few models of extra dimensions”, K.C., hep-ph/0409028.
- “Black holes in theories with large extra dimensions: a review”, by Kantihep-ph/0402168.
- “TASI lectures on extra dimensions and branes”, by C. Csaki, hep-ph/0404096.