Collider searches for neutralino dark matter in relic-density-consistent SUSY models without gaugino mass universality

Eun-Kyung Park

Bonn University

in collaboration with

H. Baer(Florida State U.), A. Mustafayev (U. of Kansas), T. Krupovnickas (BNL), S. Profumo (UC Santa Cruz) and X. Tata (U. of Hawaii)

Focus week on LHC physics, IPMU, Japan

June 25, 2008

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Neutralino dark matter

- Dark Matter should be non-baryonic (no candidate in the SM), non-relativistic (cold), stable(or long-lived), weakly (or super-weakly) interacting matter
- From the WMAP results, the cold dark matter density of the universe is $\Omega_{CDM}h^2 = 0.111^{+0.011}_{-0.015}$: (upper bound is a tight constraint on SUSY models containing DM candidates : DM may consist of several components)
- In SUSY models with R-parity conservation
  $\Rightarrow$ the Lightest Supersymmetric Particle(LSP) is stable
  $\Rightarrow$ lightest neutralino $\tilde{Z}_1$ is the LSP in most of MSSM parameter space
  $\Longrightarrow$ $\tilde{Z}_1$ is good candidate for Cold Dark Matter (CDM)
  $\tilde{z}_1 = v_1^{(1)}\psi_{h_u^0} + v_2^{(1)}\psi_{h_d^0} + v_3^{(1)}\lambda_3 + v_4^{(1)}\lambda_0$
  Here, $R_{\tilde{w}} = |v_3^{(1)}|$, $R_{\tilde{B}} = |v_4^{(1)}|$ and $R_{\tilde{H}} = \sqrt{|v_1^{(1)}|^2 + |v_2^{(1)}|^2}$: W-ino, B-ino and Higgsino
- Number density is governed by Boltzmann equation,
  $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  $\Rightarrow$ requires evaluating many thousands Feynman diagrams
  $\Longrightarrow$ high (co-)annihilation cross section implies low relic abundance

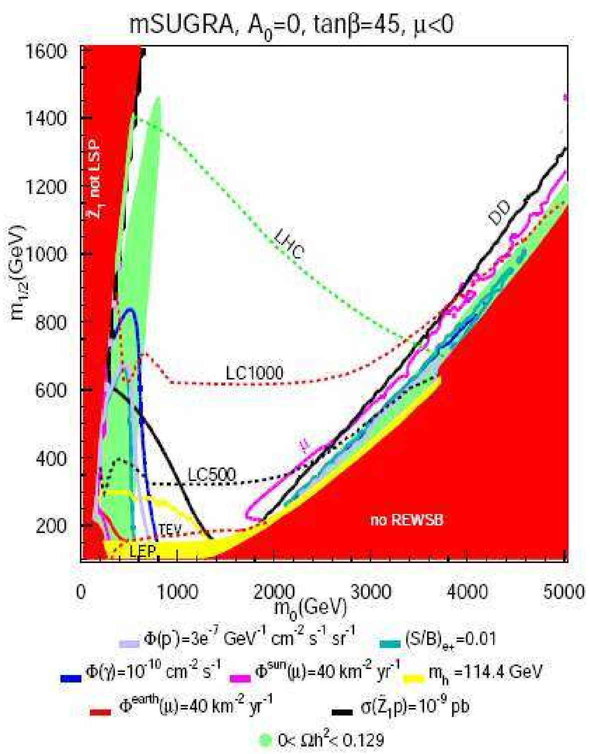
We assume,

- MSSM is an effective theory between the weak and GUT scale
- R-parity is conserved
- Neutralino LSP
- (near)degeneracy of first and second generation of SSB sfermions $\rightarrow$ FCNC suppressed
- CP-violating phases in SSB suppressed $\rightarrow$ CP contribution of SUSY is small

Review of mSUGRA

- **Parameter space : universal Soft Susy Breaking terms at $Q = M_{GUT}$**
  m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$

- **WMAP allowed Regions in m_0-$m_{1/2}$ space**
  1. $\tilde{\tau}$ co-annihilation region at low m_0, $m_{\tilde{\tau}_1} \sim m_{\tilde{Z}_1}$
  2. bulk region at low m_0 and $m_{1/2}$, light sleptons (LEP2 excluded)
  3. Higgs-funnel H, A resonance($2m_{\tilde{Z}_1} \simeq m_{A,H}$) at large $\tan\beta \sim 50$ or h-resonance at low $m_{1/2}$ ($2m_{\tilde{Z}_1} \simeq m_h$)
  4. FP/HB region at large m_0, low $\mu \to$ mixed higgsino dark matter (**MHDM**)
  ⋆ Region 1, 2, 3 → Bino-like LSP



H.Baer et al. JCAP0408 (2004) 005

Motivations for susy models without gaugino mass universality

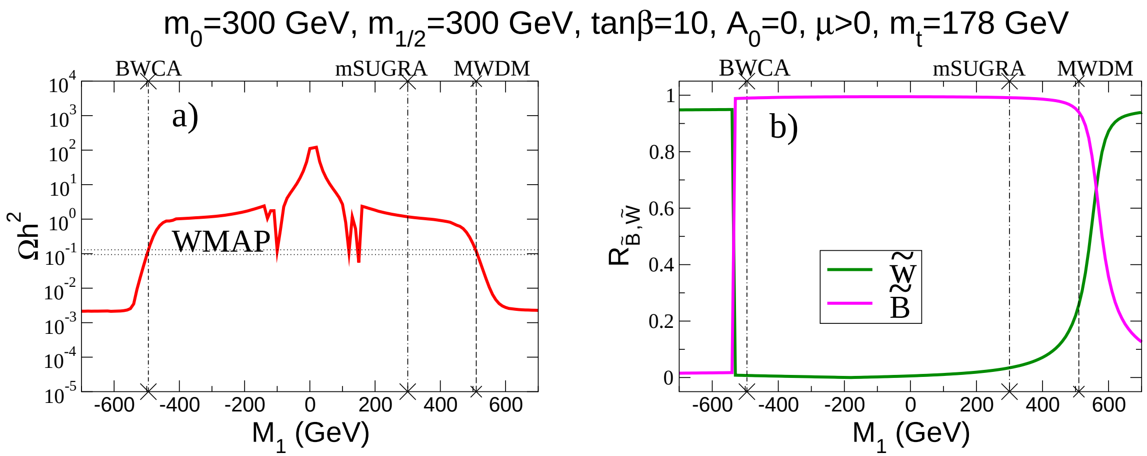
- **Limitation of mSUSGRA**
  - ⋆ all relic-density-consistent regions in mSUGRA are near the edges of theoretically (or LEP2 experiment) excluded regions
  - ⋆ need to examine how already drawn conclusions from the mSUGRA model are affected by relaxing the universality assumptions
  - ⋆ within R-parity conserved neutralino dark matter assumption, WMAP value provides a strong constraint reducing model parameter space by one unit

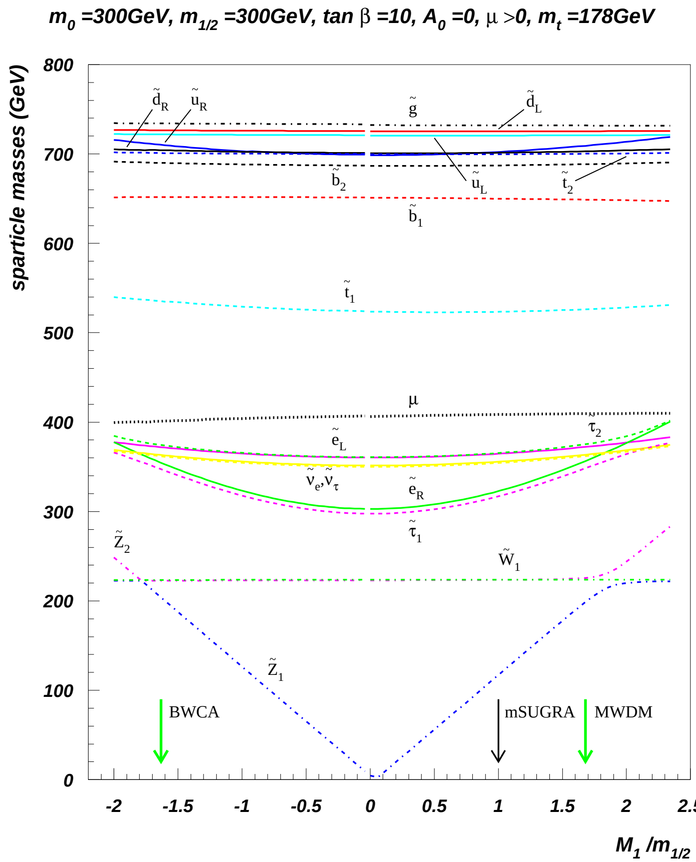
- **Motivation for non-universal gaugino mass models**
  - non-minimal f_{AB} in SUGRA models, e.g. $f_{AB} \ni 1, 24, 75, 200$ in $SU(5)$ SUSY GUTs
  - various string models, e.g. KKLT model
  - extra-dim SUSY GUTs with gaugino mediated SUSY breaking, e.g. Dermisek-Mafi $SO(10)$ model

Non-universal gaugino mass models

- Relic-density-consistent models obtained by adjusting
  - composition of neutralino (**WTN**: Well-Tempered Neutralino*)
  - masses of neutralino or other sparticles *:Arkani-Hamed et al. Nucl.Phys.B741, 108, 2006
- **mixed wino dark matter** (**MWDM1**, **MWDM2**):
  m_0, M_1(or M_2), $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by increasing the wino content of the LSP by reducing the ratio M_2/M_1
  - $M_1 \neq M_2 = M_3 = m_{1/2}$ or $M_2 \neq M_1 = M_3 = m_{1/2}$
- **bino-wino co-annihilation Scenario (BWCA1, BWCA2)**:
  same as MWDM but M_1 and M_2 are in opposite sign
  - by allowing co-annihilation between high bino-like and wino-like states
- **low $|M_3|$ dark matter: compressed SUSY** (**LM3DM**):
  m_0, M_3, $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by increasing the higgsino content of the LSP by decreasing the gluino mass
  - $M_3 \neq M_1 = M_2 = m_{1/2}$
- **high $|M_2|$ dark matter: left-right split SUSY** (**HM2DM**):
  m_0, M_2, $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by allowing large M_2 mass
  - $M_2 >> M_1 = M_3 = m_{1/2}$

NUGM Models - MWDM, BWCA





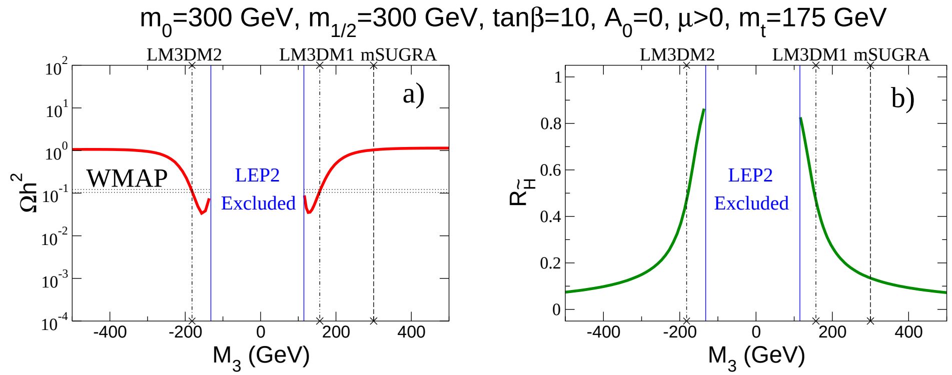
⋆ As $|M_1|(|M_2|)$ increases(decreases) past its mSUGRA value,

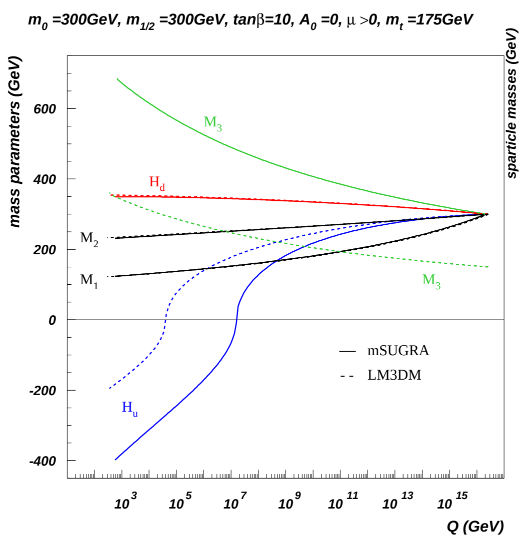
$\longrightarrow$ $\tilde{Z}_1$ becomes wino-like(MWDM) or bino-like but $m_{\tilde{Z}_1} \sim m_{\tilde{W}_1}$ (BWCA)

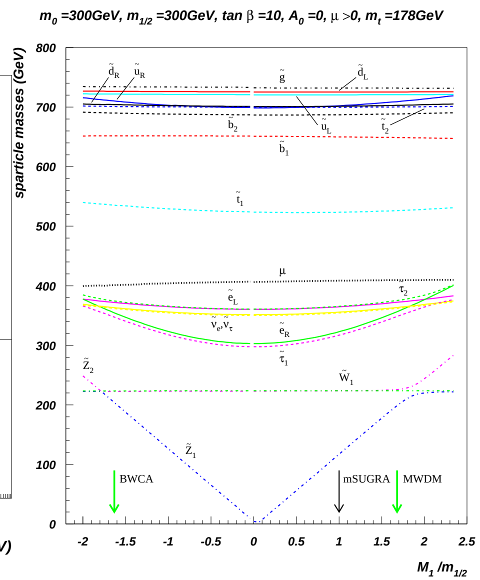
$\longrightarrow$ relic density decreases

$\longrightarrow$ WMAP $\Omega_{CDM}h^2$ value is reached

NUGM Models - LM3DM

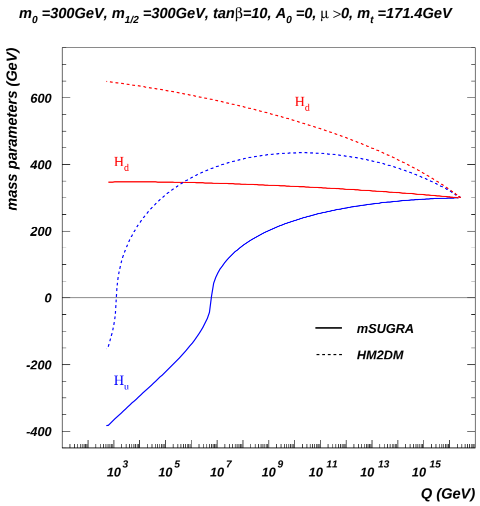


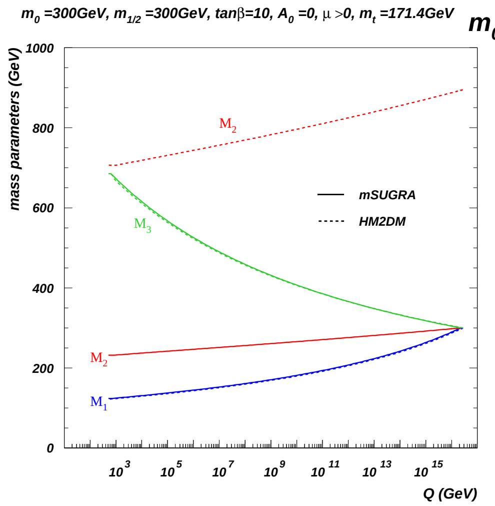


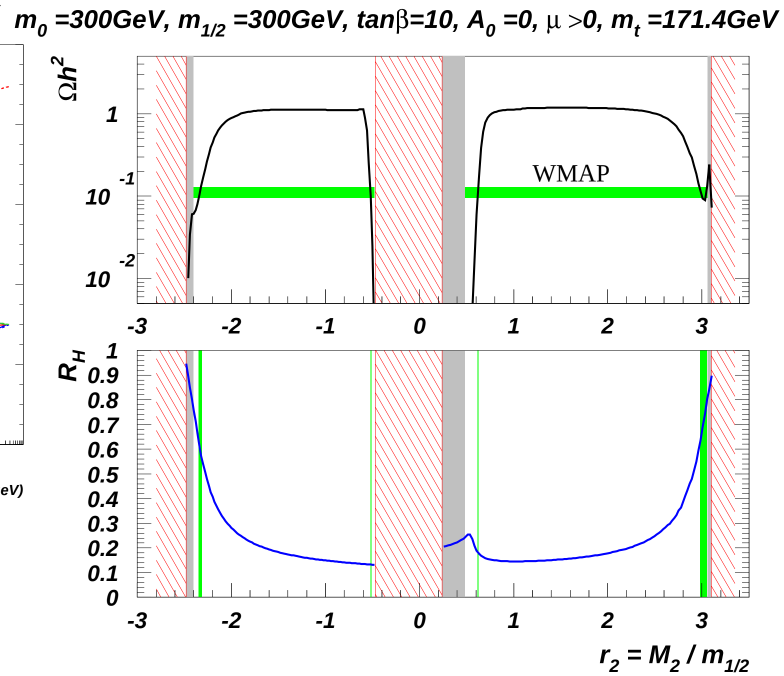


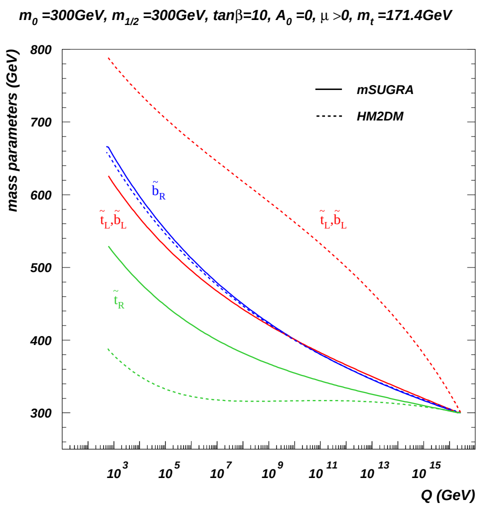
- Mild evolution of $m^2_{H_d}$ due to small Yukawa coupling f_b, f_τ
- Lighter squarks and gluinos $\rightarrow$ reduced effect of f_t on $m^2_{H_u}$ $\Rightarrow$ smaller μ
- $\frac{dm^2_{H_d}}{dt} \propto f^2_{b,\tau} X_{b,\tau}$, $\frac{dm^2_{H_u}}{dt} \propto f^2_t X_t$
- $\mu^2 = \frac{m^2_{H_d} - m^2_{H_u} tan\beta}{tan^2\beta - 1} - \frac{M^2_Z}{2} \simeq -m^2_{H_u}$

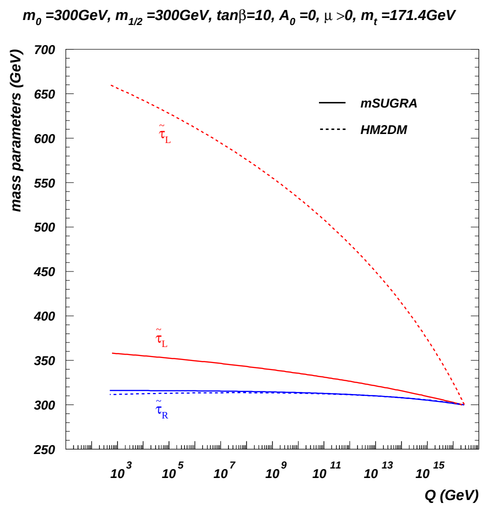
NUGM Models - HM2DM









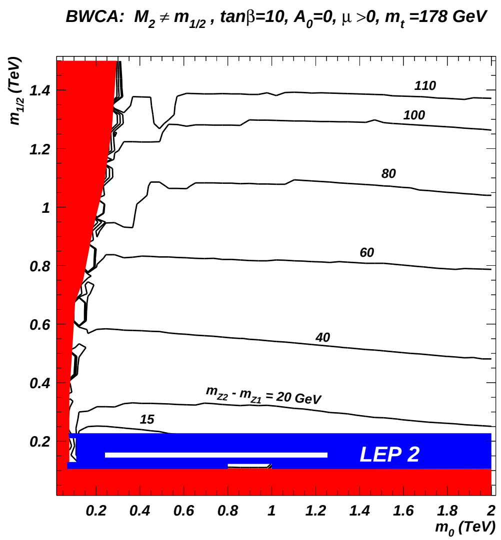


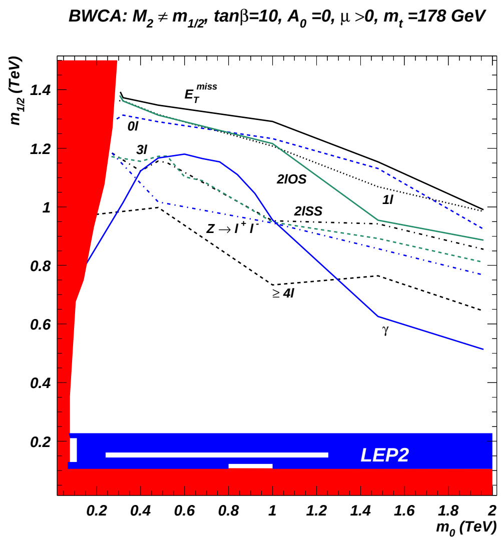
- large M_2 $\rightarrow$ reduced effect on $m^2_{H_u}$ at weak scale $\rightarrow$ smaller μ $\Rightarrow$ MHDM!
- large L-R splitting in squark and slepton sector

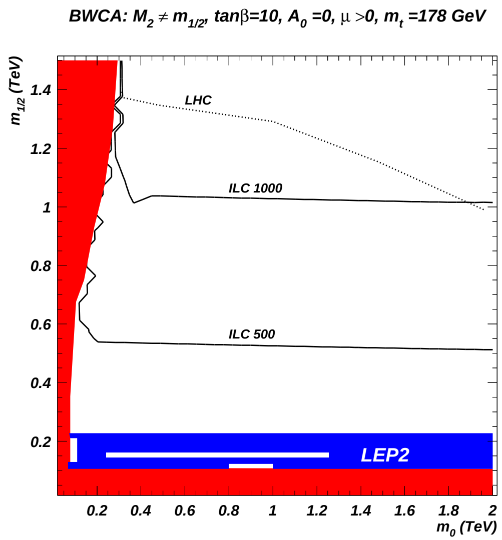
Benchmark Cases: m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$ = 300 GeV, 300 GeV, 0, 10, +1, m_t = 171.4 GeV

parameter	mSUGRA	MWDM	BWCA	LM3DM	HM2DM
special	—	$M_1(M_{GUT})$	$M_1(M_{GUT})$	$M_3(M_{GUT})$	$M_2(M_{GUT})$
value	—	490	-480	160	900
μ	385.1	385.9	376.6	185.3	134.8
$m_{\tilde{g}}$	729.7	729.9	731.7	420.2	736.4
$m_{\tilde{u}_L}$	720.8	721.2	722.0	496.9	901.8
$m_{\tilde{u}_R}$	702.7	708.9	709.9	467.0	696.3
$m_{\tilde{t}_1}$	523.4	526.5	536.3	312.2	394.3
$m_{\tilde{b}_1}$	656.8	656.0	658.9	443.2	686.4
$m_{\tilde{e}_L}$	364.5	371.5	371.4	366.1	669.3
$m_{\tilde{e}_R}$	322.3	353.3	352.2	322.6	321.3
$m_{\widetilde{W}_2}$	411.7	412.4	404.5	282.9	719.7
$m_{\widetilde{W}_1}$	220.7	220.8	220.0	152.5	136.5
$m_{\widetilde{Z}_2}$	220.6	223.2	219.2	163.6	142.3
$m_{\widetilde{Z}_1}$	119.2	194.6	201.7	105.5	94.8
m_A	520.3	525.9	518.6	398.3	670.7
m_{H^+}	529.8	535.3	528.1	408.7	679.8
m_h	110.1	110.2	109.8	106.0	111.9
$\Omega_{\widetilde{Z}_1}h^2$	1.1	0.10	0.10	0.10	0.10
$\sigma_{SI}(\widetilde{Z}_1 p)$	2.1×10^{-9} pb	1.5×10^{-8} pb	3.1×10^{-11} pb	7.2×10^{-8} pb	3.4×10^{-8} pb
$R_{\tilde{H}}$	0.15	0.25	0.16	0.50	0.67

Collider reaches in parameter space: BWCA





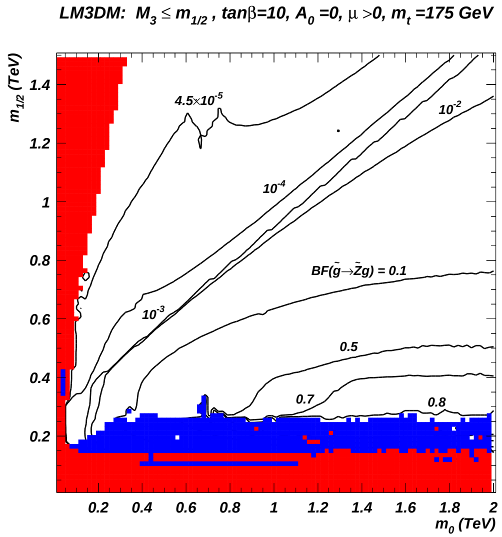


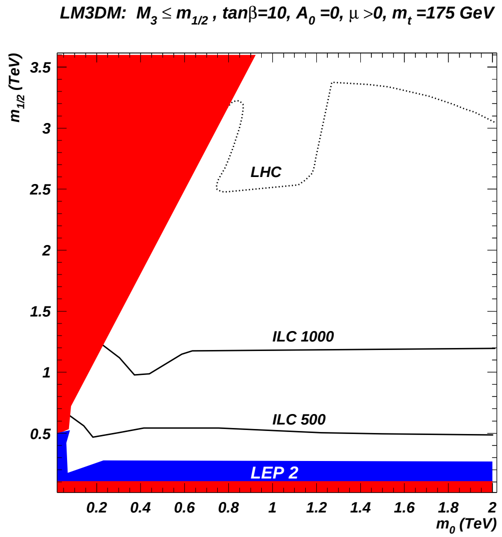
- $\tilde{Z}_2 - \tilde{Z}_1$ mass gap contour in $m_0 - m_{1/2}$ plane
- M_2 lowered at every point until $\Omega h^2 \to 0.11$
- Small $\tilde{Z}_2 - \tilde{Z}_1$ or $\tilde{W}_1 - \tilde{Z}_1$ mass gap $\Rightarrow \tilde{Z}_2 \to l\bar{l}\tilde{Z}_1 \Rightarrow m(l^+l^-)$ mass edges over all parameter space

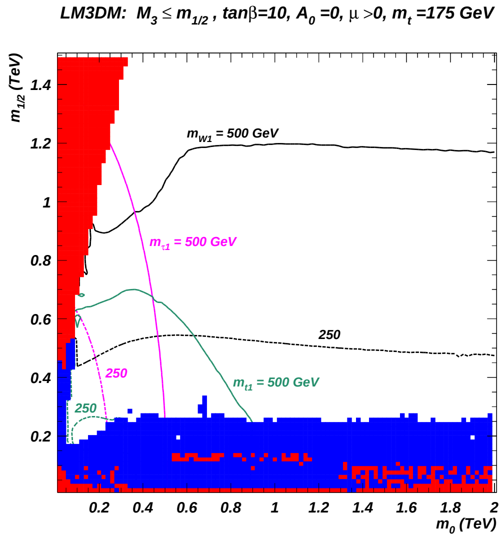
- **ISAJET** event generator
- multijet + isolated leptons + E_T^{miss} signals in $m_0 - m_{1/2}$ plane (5σ for $100 fb^{-1}$)
- $E_T^{miss} > 200GeV$, $p_T^{jet} > 40GeV$ ($n_{jet} > 2$), $p_T > 10GeV$ for muon $p_T > 20GeV$ for electron and photon, $|\eta| < 2.4$
- larger rate of isolated photon signal
  refer JHEP 0306 (2003) 054

- LHC reach depends on gluino and squark mass
- ILC reach determined by kinematical accessibility of reactions $e^+e^- \to \tilde{W}_1\tilde{W}_1$or $e^+e^- \to \tilde{l}^+\tilde{l}^-$
- $100 fb^{-1}$ for both LHC and ILC
- ILC reach for $\sqrt{s} = 500$ GeV and 1000 GeV

Collider reaches in parameter space: LM3DM





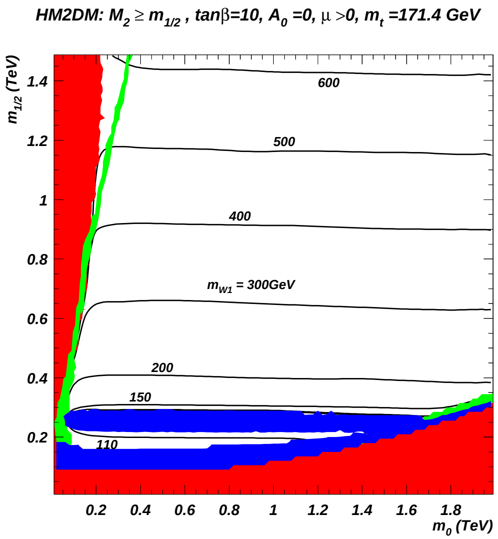


- Lighter gluinos expected in LM3DM $\longrightarrow$ larger pair production
- Heavy squarks at large m_0 and large higgsino component
- in lower right region, $\tilde{g} \to \tilde{Z}_i g$ are dominant

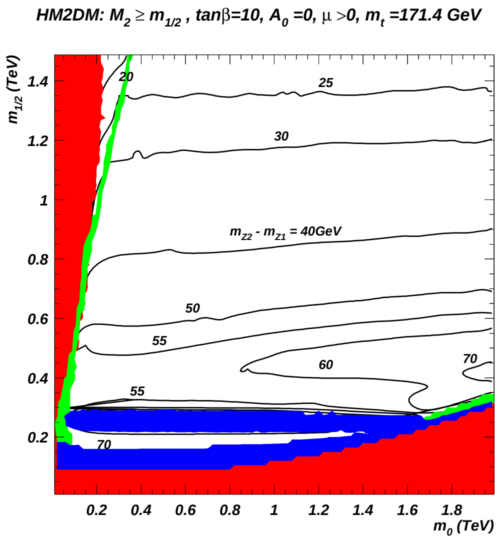
- Reduced squark and gluino masses $\Rightarrow$ enhanced reach
- Small $\tilde{Z}_2 - \tilde{Z}_1$ or $\tilde{W}_1 - \tilde{Z}_1$ mass gap $\Rightarrow$ $\tilde{Z}_2 \to l\bar{l}\tilde{Z}_1 \Rightarrow m(l^+l^-)$ mass edges over all parameter space

- Enhanced $\tilde{W}_1^+\tilde{W}_1^-$ production due to smaller μ
- Possible $\tilde{t}_1\bar{\tilde{t}}_1$ production
- All charginos and neutrlainos accessible
- $\tilde{q} \to \tilde{g}q$ kinematically allowed $\Rightarrow$ precise determination of $\tilde{q}$, $\tilde{g}$ masses

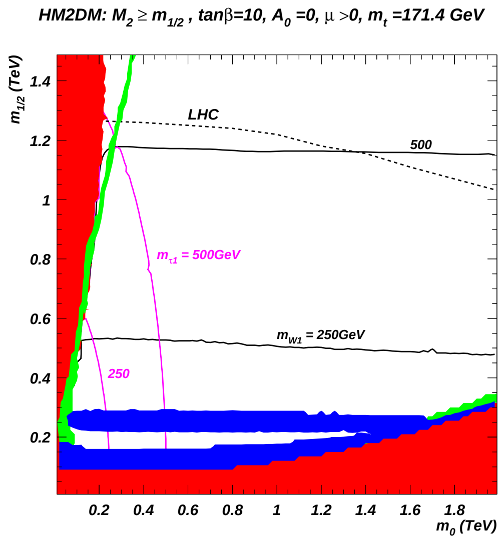
Collider reaches in parameter space: HM2DM



- $m_{\tilde{W}_1} \sim 1/2 m_{1/2}$, whereas $m_{\tilde{W}_1} \sim 3/2 m_{1/2}$ in mSUGRA
- relevant at ILC if $\tilde{W}_1 \tilde{W}_2$ production is possible



- mass gap is larger than 25 GeV and decreases with increasing $m_{1/2}$ $\rightarrow$ distinguishable from other models

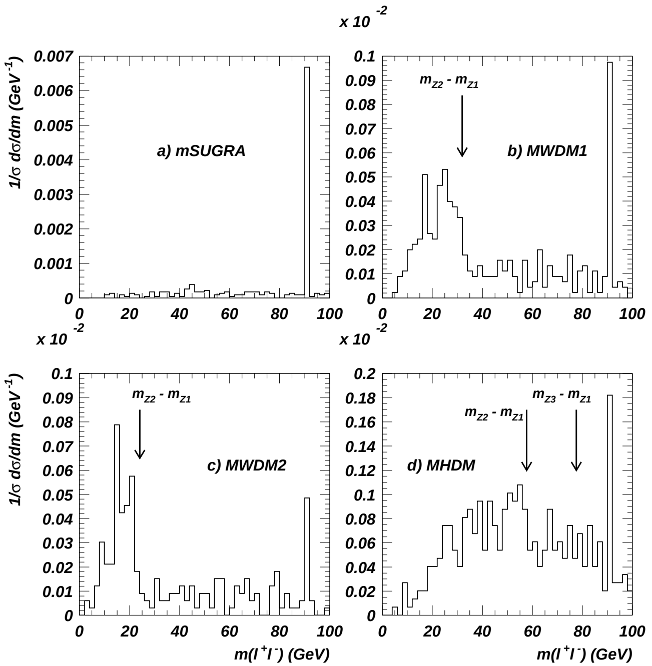


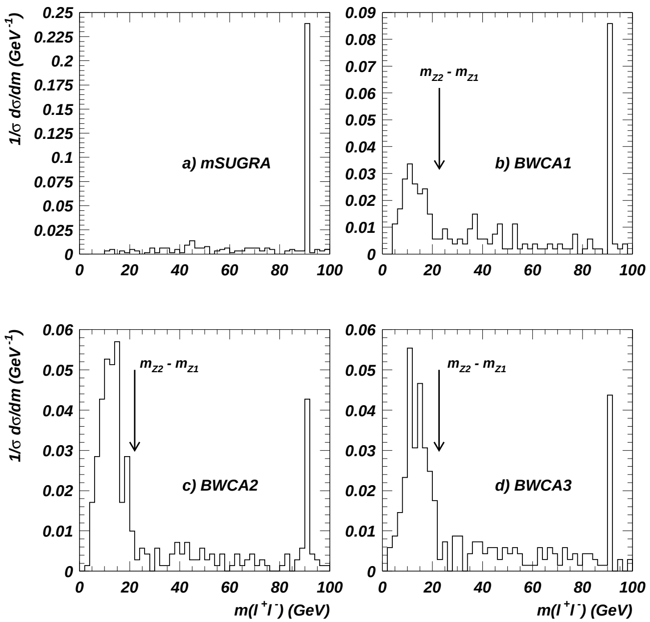
- LHC and ILC reaches in parameter space

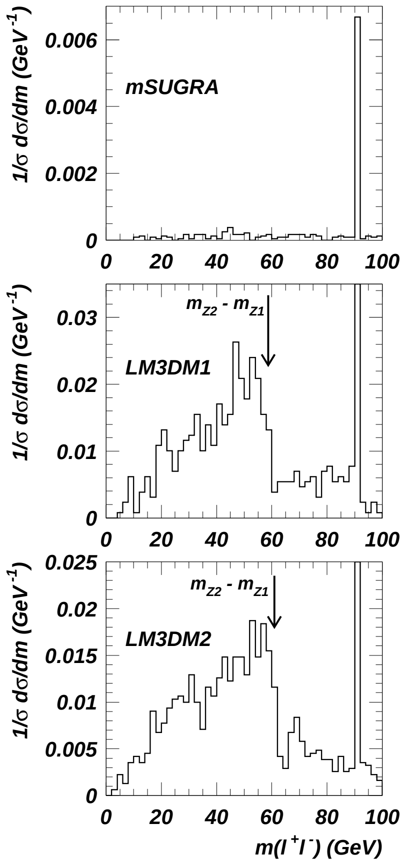
SUSY signals at Colliders without non-universal gaugino masses

- CERN LHC and Fermilab Tevatron
  - If $\tilde{Z}_2 \longrightarrow \tilde{l}\bar{l}, \bar{\tilde{l}}l \longrightarrow \tilde{Z}_1 l\bar{l}$ or $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 l\bar{l}$ are open ($l = e$ or μ)
    $\Longrightarrow$ good prospects for measuring the $\tilde{Z}_2$ - $\tilde{Z}_1$ mass gap at the CERN LHC and possibly at the Fermilab Tevatron
  - In the mSUGRA case, most of the parameter space has $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} > 90$ GeV, $\Longrightarrow$ $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 Z^0$ or $\tilde{Z}_1 h$ "spoiler" decays dominant
  - When the mass gap is much smaller
    * spoiler decays are closed, 3-body decays are open
    * $l\bar{l}$ mass edge always visible at LHC
- Linear e^+e^- collider(ILC)
  - $m_{\tilde{Z}_2}$, $m_{\tilde{W}_1}$ and $m_{\tilde{Z}_1}$ can be inferred from $\tilde{W}_1^+\tilde{W}_1^- \longrightarrow \bar{l}\nu_l\tilde{Z}_1 + q\bar{q}\tilde{Z}_1$ (dijet events)
  - $\tilde{W}_1^+\tilde{W}_1^-$, $\tilde{Z}_1\tilde{Z}_2$, $\tilde{Z}_2\tilde{Z}_2$ production cross sections can be measured as a function of beam polarization
- ISAJET program (H. Baer, F.E. Paige, S.D. Protopopescu, and X. Tata)

Dilepton Distribution at LHC

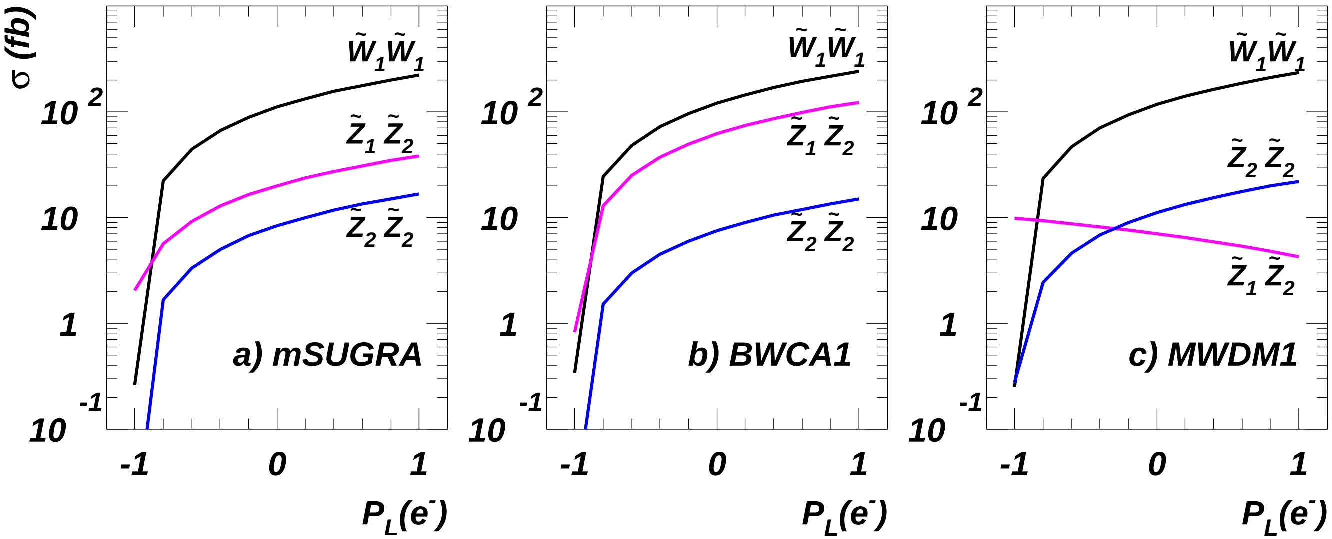


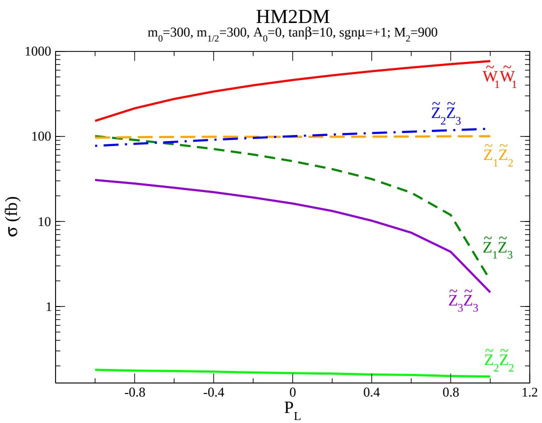




- **ISAJET** event generating program
- $E_T^{miss} > max(100GeV, M_{eff})$, $E_T > 50GeV$ ($n_{jet} >= 4$, hardest jet has $E_T > 100GeV$), $S_T > 0.2$, $M_{eff} > 800GeV$ LHC Point 5 from PRD 55 (1997) 5520, PRD 60 (1999) 095002
- NUGM :
  Z^0 peak from $\tilde{Z}_3$, $\tilde{Z}_4$, $\tilde{W}_2$ decays + continuum distribution $m(l^+l^-) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$

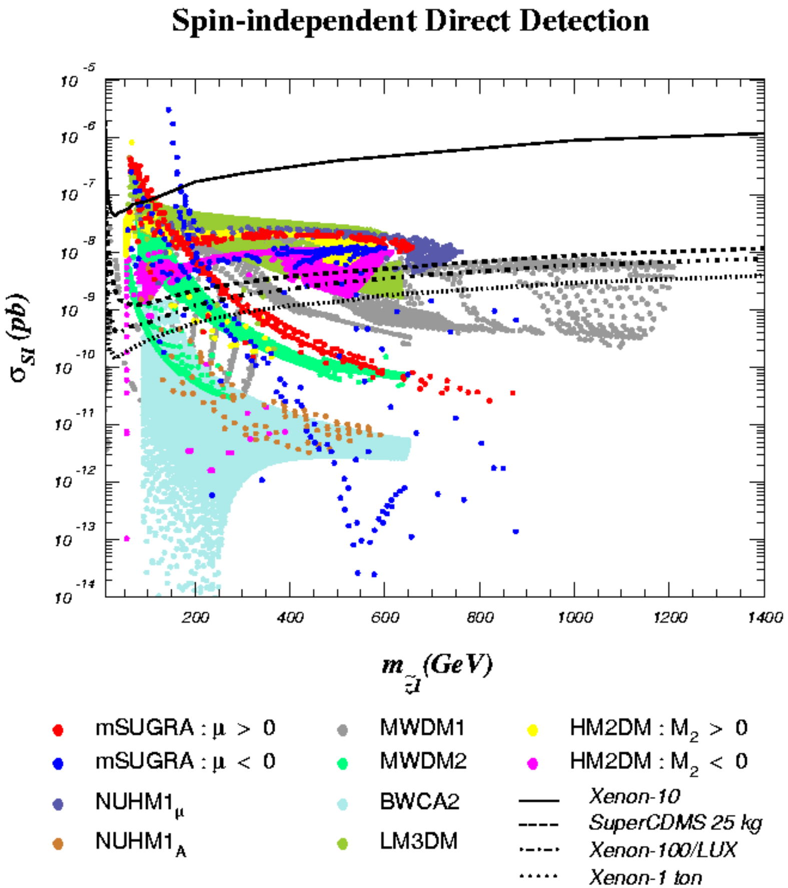
Cross Section for $\tilde{W}_1^+\tilde{W}_1^-$ and $\tilde{Z}_i\tilde{Z}_j$ Production at ILC





- $\tilde{W}_1$ and $\tilde{Z}_2$ are mainly wino-like
  $\longrightarrow \sigma(\tilde{W}_1\tilde{W}_1)$ and $\sigma(\tilde{Z}_2\tilde{Z}_2)$ are similar to one another
- $\tilde{Z}_1\tilde{Z}_2$ process are quite different

Implications for direct dark matter detection



- models with WTN within reach of next generation of detectors
- models adjusted masses to get WMAP value below sensitivities of detectors

Conclusions

- Most of mSUGRA parameter space is excluded by WMAP bound
- New perspectives open with gaugino mass non-universalities in SUGRA
- If DM in nature is indeed composed of SUSY models with non-universal gaugino masses (MWDM($M_1 \sim M_2$), BWCA DM($M_1 \sim -M_2$), LM3DM($|M_3| \ll M_1 \simeq M_2$) or HM2DM ($|M_2| \gg M_1 \simeq M_3$))
  - $\tilde{Z}_2 - \tilde{Z}_1$ and $\tilde{W}_1 - \tilde{Z}_1$ mass gaps are reduced compared to the case with gaugino mass universality
  - SUSY can be discovered at Tevatron via squarks and gluinos
  - CERN LHC should be able to measure $m_{\tilde{g}}$ and $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ mass gap from dilepton distribution from $\tilde{Z}_2 \longrightarrow l\bar{l}\tilde{Z}_1$ decay; $\tilde{Z}_2 \longrightarrow \tilde{Z}_1\gamma$ (spoiler 2-body decay closed)
  - At ILC, $\tilde{W}_1^+\tilde{W}_1^-$, $\tilde{Z}_1\tilde{Z}_2$, $\tilde{Z}_2\tilde{Z}_2$ production cross sections as a function of beam polarization should be able to measurable.
  - Direct and Indirect detection experiments may discriminate between these scenarios
- Where the neutralino composition is adjusted to give the WMAP value (WTN models),
  - neutralino is typically of the mixed bino-wino or mixed bino-higgsino states
  - enhanced neutralino annihilation rates $\rightarrow$ direct detection scattering rates enhanced

MSSM RGEs

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$\frac{dm_{H_d}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + 3f_b^2X_b + f_\tau^2X_\tau\right)$$

$$\frac{dm_{Q_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{1}{15}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{10}g_1^2S + f_t^2X_t + f_b^2X_b\right)$$

$$\frac{dm_{\tilde{t}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2f_t^2X_t\right)$$

$$\frac{dm_{\tilde{b}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{4}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{5}g_1^2S + 2f_b^2X_b\right)$$

$$\frac{dm_{L_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + f_\tau^2X_\tau\right)$$

$$\frac{dm_{\tilde{\tau}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{12}{5}g_1^2M_1^2 + \frac{3}{5}g_1^2S + 2f_\tau^2X_\tau\right)$$

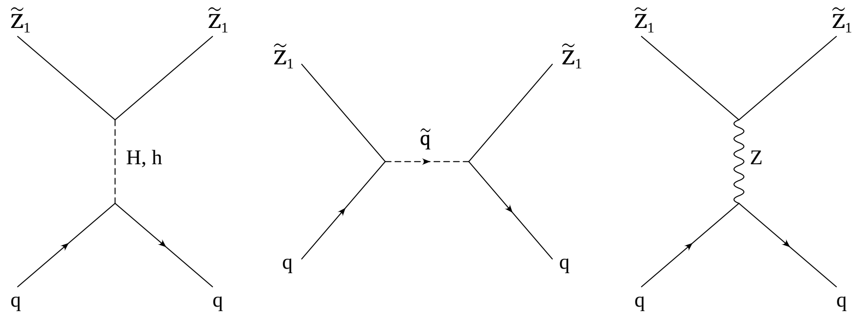
$$S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$$

where $t = \log(Q)$, $f_{t,b,\tau}$ are the t, b and τ Yukawa couplings, and

$$\begin{aligned} X_t &= m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A^2_t \\ X_b &= m^2_{Q_3} + m^2_{\tilde{b}_R} + m^2_{H_d} + A^2_b \\ X_\tau &= m^2_{L_3} + m^2_{\tilde{\tau}_R} + m^2_{H_d} + A^2_\tau \end{aligned}$$

Feynman Diagrams Contributing to Neutralino DM Detection

- Direct Detection



- Indirect Detection