Dark Matter: Theory and Phenomenology

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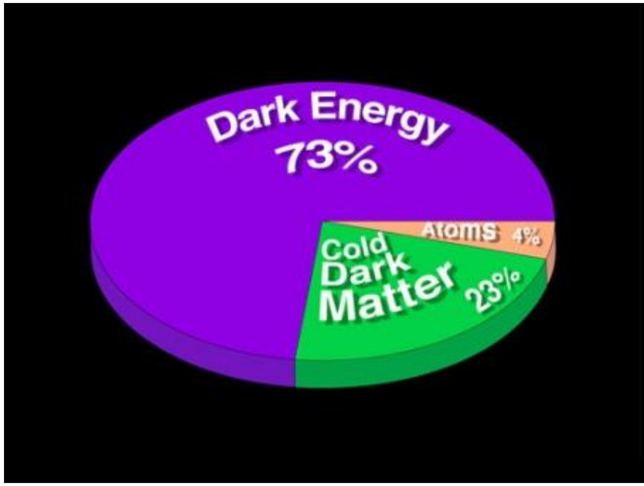
Aspen Winter Workshop: Closing In On Dark Matter 2013

Questions

➔What kind of particle?



What is the mass? What is the spin?
What is the associated Model

Can it be observed at the Colliders?
How about direct and
Indirect detection experiments?

➔ Do we have more components?

➔ Is it thermal or non-thermal in nature?

➔ Is there a correlation between the DM content and Baryon content? --- Coincidence problem

Now

Current Status

We have results from the LHC, Direct and Indirect detection experiments

➔ What have we learnt? What is the current status of the DM explanations?

➔How much more do we expect in the near future at the 8 TeV LHC, Direct and Indirect detection?

Are we closing in?

Outline

(i) Thermal dark matter and SUSY

(ii) LHC status of SUSY

(iii) Models with larger annihilation cross-section➔
Under-abundance: Motivated? Non-thermal DM?

(iv) Non-thermal DM and benefits

(v) 8 TeV LHC and DM

(vi) Conclusion

(i) Thermal Dark Matter

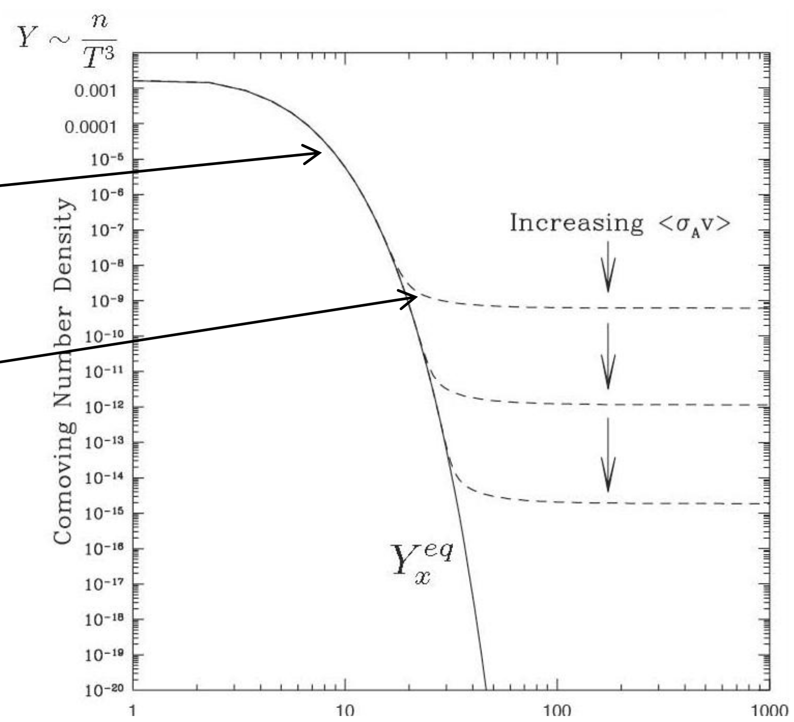
Production of thermal DM:

Non-relativistic

Thermal Models:
Hubble expansion dominates over the interaction rate:

➔ $$\langle \sigma v \rangle = 3\times10^{-26}\,\frac{cm^3}{s}$$

freeze out ➔ $$T_f \sim \frac{m_{DM}}{20}$$



Dark Matter content: $$\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$$

Assuming : $$\langle \sigma v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$$

$\alpha_\chi \sim O(10^{-2})$ with $m_\chi \sim O(100)$ GeV leads to the correct relic abundance

Thermal Dark Matter

Suitable DM candidate:
Weakly Interacting Massive Particle (WIMP)

Typical in physics beyond the SM (LSP, LKP, …)

Most Common: Neutralino (SUSY Models)

smaller annihilation cross-section

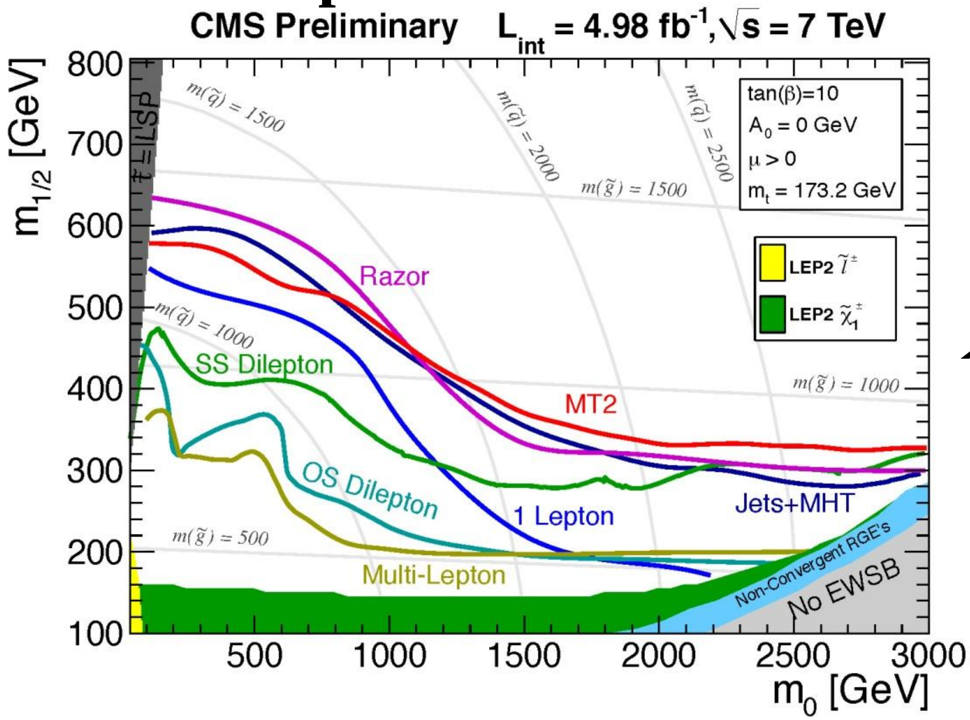
Neutralino is a mixture of Wino, Higgsino and Bino

Larger annihilation cross-section

% of various components of Neutralinos: Model details

(ii) LHC status

Begin with the simplest model: mSUGRA/CMSSM



$$\tilde{\chi}_1^0 \sim 0.4 m_{1/2}$$

Searches for new physics with Missing Energy

a_μ of muon, Br(B_s → μμ), dark matter relic density, squark mass constraint+ Higgs mass constraint

Is there any parameter space left? First casualty in the SUSY family?

LHC status...

➔ Recent Higgs search results from Atlas and CMS indicate that m_h (if it is Higgs) ~125 GeV

- in the tight MSSM window: 115-135 GeV

➔ $m_{\tilde{q}}$ (1st gen.) ~ $m_{\tilde{g}}$ ≥ 1.4TeV

➔ For heavy $m_{\tilde{q}}$, $m_{\tilde{g}}$ ≥ 1 TeV

➔ $\tilde{t}_1$ produced from $\tilde{g}$, $m_{\tilde{t}_1}$ ≥ 700 GeV

➔ $\tilde{t}_1$ produced directly, $m_{\tilde{t}_1}$ ≥ 550 GeV (special case)

➔ $\tilde{e}$ / $\tilde{\mu}$ between 85 and 195 GeV for a 20 GeV $\tilde{\chi}_1^0$ are excluded at 95% confidence

➔ $\tilde{\chi}_1^{\pm}$ masses between 110 and 340 GeV are excluded at 95% CL for a $\tilde{\chi}_1^0$ of 10 GeV for $\tilde{\chi}_1^{\pm}$ decaying into e/μ

(iii) Higgsino Dark Matter

LHC constraints on first generation squark mass + Higgs mass:

Natural SUSY and dark matter [Baer, Barger, Huang, Mickelson, Mustafayev and Tata'12; Gogoladze, Nasir, Shafi'12, Hall, Pinner, Ruderman,'11; Papucchi, Ruderman, Weiler'11],
Higgs mass 125 GeV & Cosmological gravitino solution [Allahverdi, Dutta, Sinha'12]

➔ **Higgsino dark matter**

Higgsino dark matter has larger annihilation cross-section
Typically > 3 x 10^{-26}cm^3/sec for sub-TeV mass

Thermal underproduction of sub-TeV Higgsino

- **Unnatural SUSY: Wino DM- Larger annihilation cross-section**

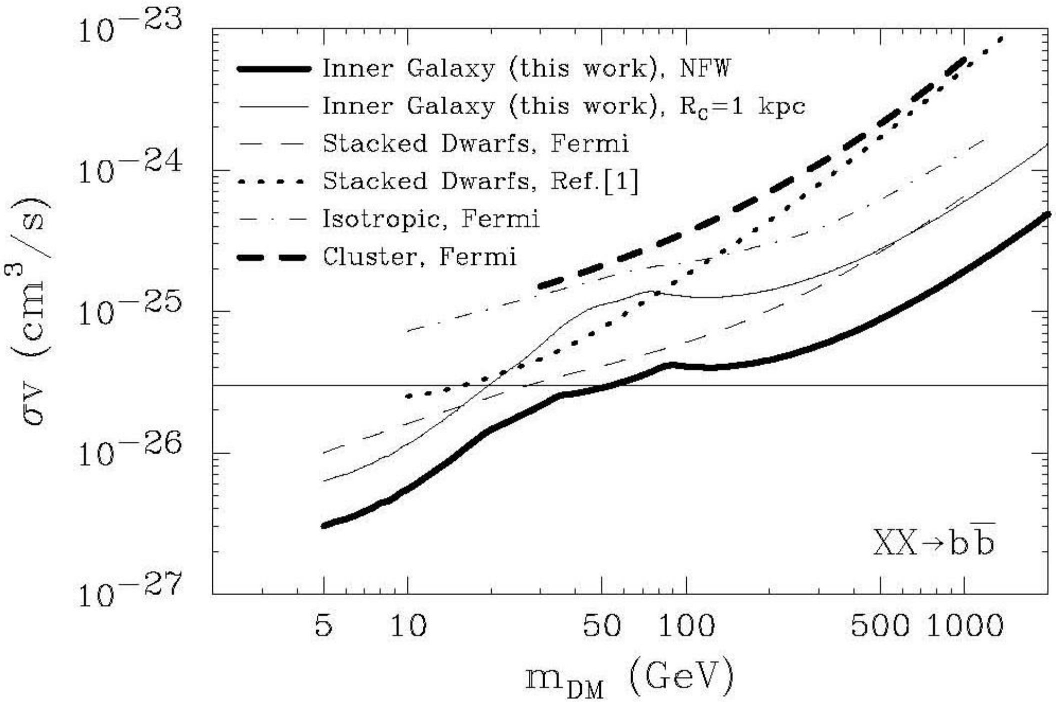
Arkani-Hamid, Gupta, Kapla, Weiner, Zorawsky'12 **(for smaller wino mass)**

Higgsino DM

$< \sigma_{ann} v >_o$ **is constrained by Fermi constraint**

Gamma-rays constraints: Dwarf spheroidals, Galactic center

Hooper, Kelso, Queiroz, arXiv:1209.3015



Problem of large DM annihilation cross-section:

Large Cross-section/under production is constrained

Need for Non-Thermal DM

Question: How to obtain the correct relic abundance?
➔Non-thermal dark matter, additional DM candidate

- **Two component DM: Strong CP problem solved by the Peccei-Quinn mechanism in a SUSY context**
  In this case, dark matter may be consisting of two particles: Axion, Higgsino

Baer, Kraml, Lessa, Sekmen, 2010
Baer, Barger, Huang, Mickelson, Mustafayev andTata, '12

- **Decay of heavy scalar field (Moduli/Visible sector scalar):**
  Non-Thermal DM➔Many Interesting Prospects

Moroi, Randall,'99,
Allahverdi, Dutta, Sinha,' 10,'11,'12
Kane, Watson, et al, '10, '11

Non-Thermal DM

Dark Matter from Moduli decay:

Moduli are heavy scalar fields that acquire mass after SUSY breaking and are gravitationally coupled to matter

The moduli decay width: $\Gamma_\tau = \frac{c}{2\pi}\frac{m_\tau^3}{M_p^2}$

- **start oscillating when $H < m_\tau$**
- **dominate the Universe before decaying and reheating it**

$$T_r \sim c^{1/2}\left(\frac{m_\tau}{100\,\mathrm{TeV}}\right)^{3/2}(5\,\mathrm{MeV})$$

$T_r \sim$ MeV : not allowed by BBN

Inflation
↓
Radiation domination
↓
moduli domination
Decay of moduli → ↓
radiation domination
↓
.
.
.

Dark Matter from Moduli

Moduli decay produces dilution in the yield of the decay products

- **The dilution factor even from a 100 TeV moduli is huge!**

$$Y_\tau = \frac{n_\tau}{s} = \frac{3T_r}{4m_\tau} \sim c^{1/2}\left(\frac{m_\tau}{100\mathrm{TeV}}\right)^{1/2}(5\times10^{-8})$$

Any previously produced DM abundance and baryon asymmetry are also diluted away

Interesting:
baryon abundance ~ 10^{-10},
dark matter abundance 10^{-11} (50 GeV DM particle)

Dark Matter from Moduli

The dark matter abundance from the moduli decay

Moduli Decay to DM particles

$$\frac{n_\chi}{s} = \min.\left[\left(\frac{n_\chi}{s}\right)_{th}\frac{T_f}{T_r}, Y_\tau Br_\chi\right]$$

Moroi, Randall'99

entropy density

Moduli Decay + DM annihilation

$$\Omega = \frac{\rho}{\rho_c}, \rho = mn$$

Br_χ = Branching ratio for producing R-parity odd particles

Moduli Decay + DM annihilation: Larger annihilation cross-section

Moduli Decay to DM particles: Independent of Cross-section (unless it is very large)

Baryogenesis from moduli decay

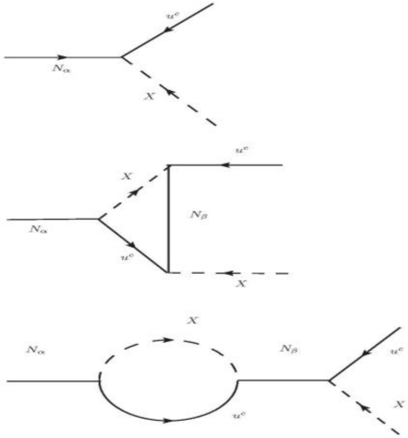
Need to produce baryon asymmetry from moduli decay

$$W_{extra} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \bar{X}_\alpha + M_\alpha X_\alpha \bar{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta$$

N : **SM singlet;** $X, \bar{X}$: **Color triplet, hypercharge +4/3**

R= +1: *N* fermions and *X* scalars

➔ R parity conserved



Baryogenesis :

From decays of $X, \bar{X}$ **(if** $M_\alpha > M_\beta$ **)**

Or

decays of N **(if** $M_\alpha < M_\beta$ **)**

$$\varepsilon_\alpha = \frac{1}{24\pi} \frac{\mathrm{Im}[(\lambda^+\lambda)_{\alpha\beta}]^2}{(\lambda^+\lambda)_{\alpha\alpha}} [3F_s(x) + F_V(x)]$$

$$\lambda \sim O(1),$$

Allahverdi, Dutta, Sinha: Phys.Rev. D82 (2010) 035004

➔ $\varepsilon_\alpha \sim O(0.1)$

(iv) Benefit of Non-Thermal DM

Coincidence Problem: ***Cladogenesis*** **→ Both DM abundance and Baryon asymmetry are produced from the same source**

$Y_\tau \sim 10^{-7} - 10^{-9}$

DM abundance in this model: $$\frac{n_\chi}{s} = Y_\tau Br_\chi$$

Br_χ : branching ratio of moduli decay to χ

$\frac{n_B}{s} = Y_\tau \varepsilon Br_N$ **: $\varepsilon Br_N \sim 10^{-3}$ easy to satisfy for baryogenesis**

$$\frac{\Omega_b}{\Omega_\chi} = \frac{1}{m_\chi}\frac{\varepsilon BR_N}{BR_\chi} \quad \Rightarrow \quad 5\text{GeV} \le m_\chi \le 500\text{GeV}$$

$Br_\chi \ge 10^{-3}$ Lower limit from the branching ratio into gauginos

No annihilation cross-section involves

Allahverdi, Dutta, Sinha: Phys.Rev. D83 (2011) 083502

(v) Dark Matter at the LHC (8 TeV)

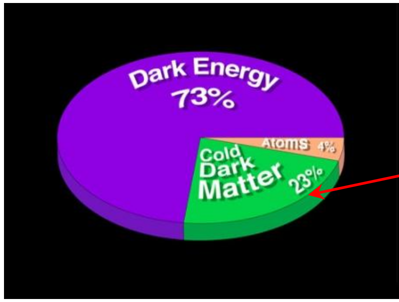
Annihilation of lightest neutralinos → SM particles

Annihilation diagrams: mostly non-colored particles,
e.g., sleptons, staus, charginos, neutralinos, etc.

How to produce these non-colored particles at the LHC?

1. **Cascade decays of squarks and gluinos**
2. **Via stop squark @ 8 TeV LHC**
3. **Vector Boson fusion @ 8 TeV LHC**

1. Via Cascade decays at the LHC

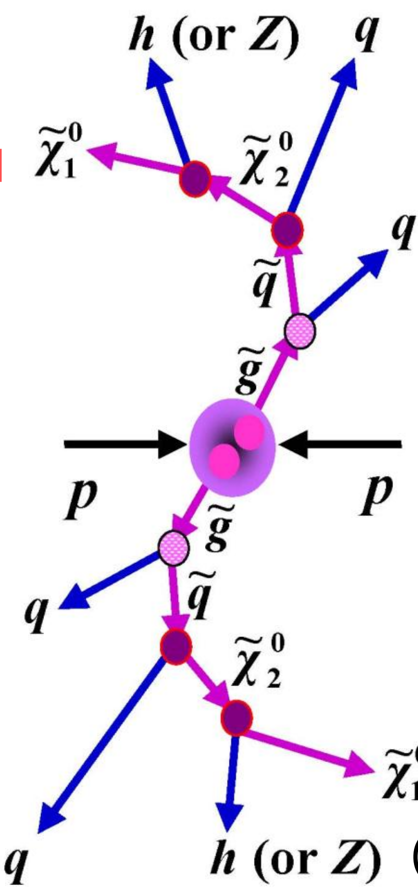


DM

(or l^+l^-, $\tau+\tau-$)

High P_T jet

[mass difference is large]



The p_T of jets and leptons depend on the sparticle masses which are given by models

Colored particles are produced and they decay finally into the weakly interacting stable particle

DM

R-parity conserving

High P_T jet

(or l^+l^-, $\tau+\tau-$)

The signal :

jets + leptons+ t's +W's+Z's+H's + missing E_T

DM at the LHC

Ambitious Goal:

Final states → Masses → Model Parameters
→ Calculate dark matter density

$$\tilde{Q} \to q + l + \tilde{\chi}_1^0 \quad \tilde{L} \to l + \tilde{\chi}_1^0$$

$$\tilde{\chi}_{2,3,4}^0 \to Z, h, \bar{l}l + \tilde{\chi}_1^0$$ **etc.**

We may not be able to solve for masses of all the sparticles in a model

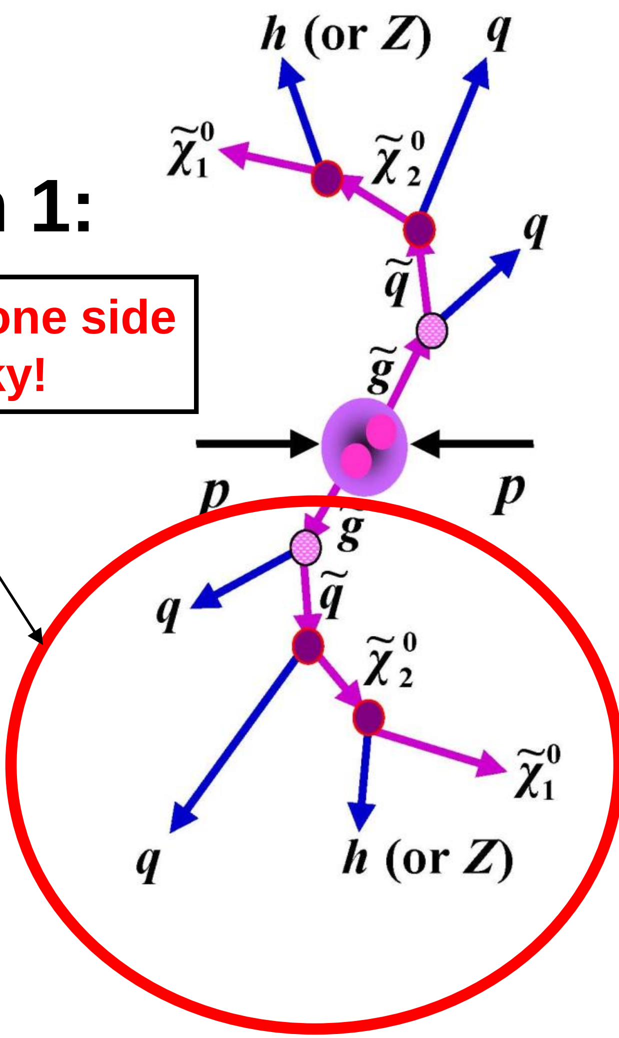
Problem 2:

Not all the sparticles appear in cascade decays

Problem 1:

Identifying one side is very tricky!

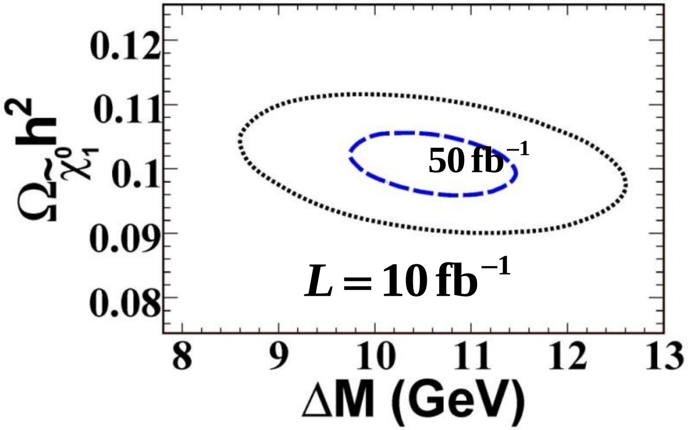
Apply :
Bi-Event Subtraction Technique (BEST)
Dutta, Kamon, Krislock, '12



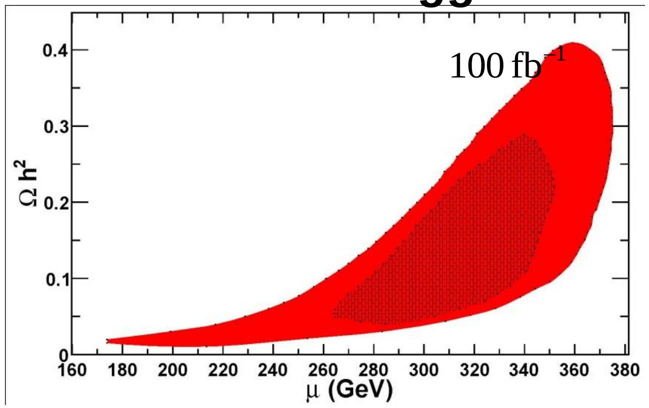
→ Solving for the MSSM : Very difficult

Determining Dark Matter Content

mSUGRA



Non Universal Higgs Model



$\mathcal{L}$ (fb^{-1})	$m_{1/2}$ (GeV)	m_H (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ (GeV)	$\Omega_{\tilde{\chi}_1^0} h^2$
1000	500 ± 3	727 ± 10	366 ± 26	3 ± 34	39.5 ± 3.8	321 ± 25	$0.094^{+0.107}_{-0.038}$
100	500 ± 9	727 ± 13	367 ± 57	0 ± 73	39.5 ± 4.6	331 ± 48	$0.088^{+0.168}_{-0.072}$
Syst.	± 10	± 15	± 56	± 66	± 4.5	± 48	${}^{+0.175}_{-0.072}$

Mirage Mediation Model

Particle	Mass	Stat.
$\tilde{t}$	690	± 6
$\tilde{b}$	1002	± 126
$\tilde{\tau}$	717	± 10
$\tilde{q}$	1133	$-132, +167$

@ 200 fb^{-1}

$$\Omega h^2 = 0.23 \pm 0.13.$$

Determine DM content at 14 TeV LHC with high luminosity

2. DM via Stop at 8 TeV LHC

LHC Stop pair productions up to ~ 600 GeV @ 8 TeV LHC
Utilize Stop decay modes to search charginos, sleptons, neutralinos

Ex. 1 χ_1^0 is mostly bino and χ_2^0 is wino

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

Stop can identified via fully hadronic or 1 lepton plus multijet final states

[Yang Bai, Cheng, Gallichio, Gu, 1203.4813;Han, Katz, Krohn, Reece, 1205.5808;Plehn, Spannowsky, Takeuchi, 1205.2696;Kaplan, Rehermann, Stolarski, 1205.5816; Dutta, Kamon, Kolev, Sinha, Wang, 1207.1893]

Ex. 2 $\chi_{1,2}^0$ are mostly Higgsino

Topness variable to identify stops

Grasser, Shelton, 2012

Ex. 3 χ_1^0 is mostly Bino-Higgsino
Correct relic density

For lighter sleptons

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_2^0 \rightarrow t + l + \tilde{l}^* \rightarrow t + l + \bar{l} + \tilde{\chi}_1^0,$$
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm \rightarrow t + \nu + \tilde{l} \rightarrow t + l + \nu + \tilde{\chi}_1^0$$
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

Dutta, Kamon, Wang, Wu, In prep

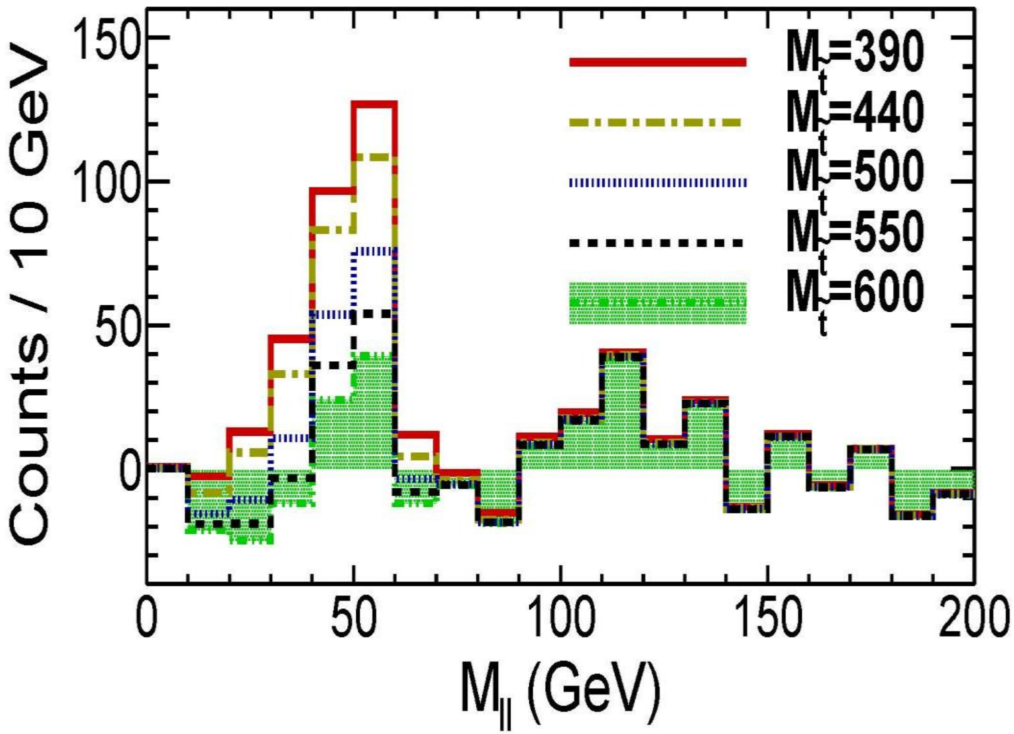
2 jets+ 2 leptons (OSSF-OSDF) +missing energy

➔ Existence and type of DM particle, hard to calculate the DM content

2. DM via Stop at 8 TeV LHC

Bino-Higgsino dark matter

Dilepton end-point after OSSF-OSDF including background



$$m_{\chi_1^0} \approx 110\text{GeV}$$

$$m_{\chi_2^0} - m_{\chi_1^0} \approx 65\text{GeV}$$

➔ **Correct dark matter content**

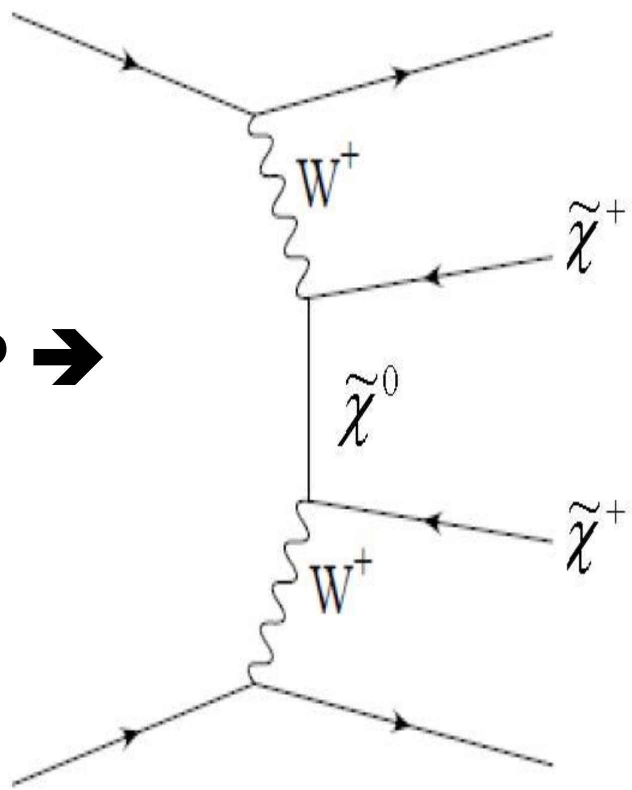
Dutta, Kamon, Wang, Wu, In prep

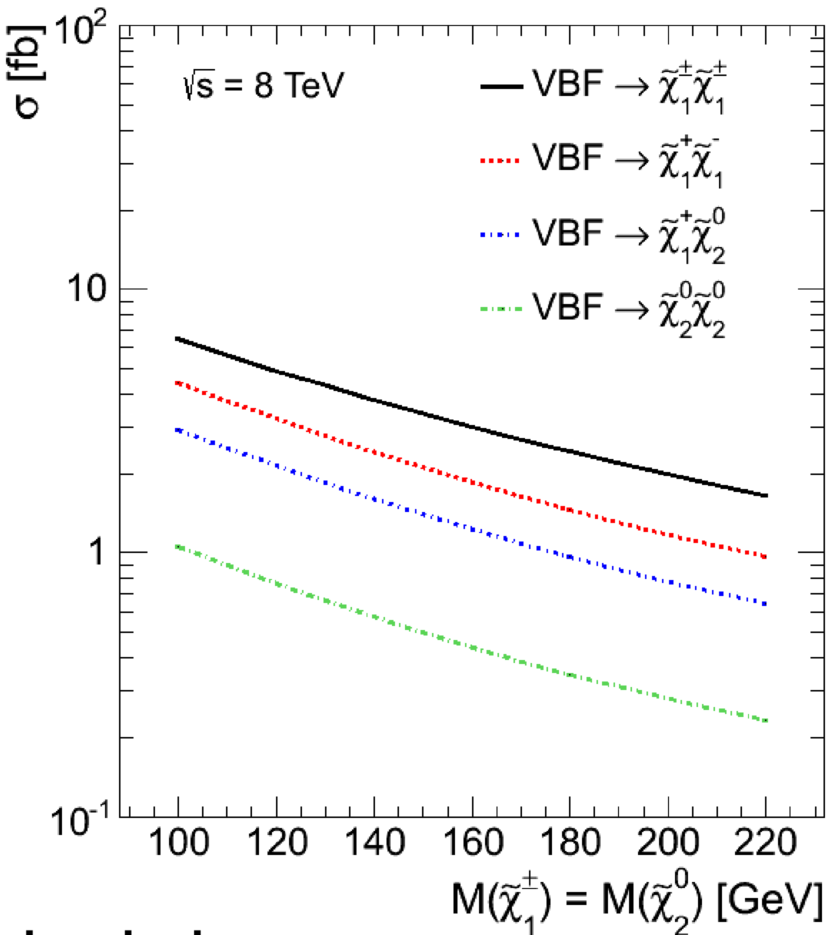
5σ (s/√(s+B)) : for lightest stop mass ~ 600 GeV at 30 fb^{-1}

3. DM at the LHC Via VBF

Direct probes of charginos, neutralinos and sleptons

P + P ➔





Two high E_T forward jets in opposite hemispheres with large dijet invariant mass

Dutta, Gurrola, John, Kamon, Sheldon, Sinha, arXiv:1210.0964

Signal: ≥ 2j+2μ, 2τ+miss. energy

2 jets each with p_T>50 GeV, leading p_T>75 GeV
$|\Delta\eta(j_1,j_2)|$>4.2, $\eta_{j1}\eta_{j2}$<0, M_{j1j2}>650 GeV } **VBF cuts**

$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV}, \quad \sqrt{s} = 8$ **TeV, Lum: 25 fb^{-1}**

(a) Signal : $\geq 2j + 2\mu +$ **missing energy** **(b) Signal:** $\geq 2j + 2\tau +$ **missing energy**

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	0.97×10^2	19.0
$\not{E}_T > 75$	4.33	0.27	5.29×10^2	17.6	3.45
2μ, inclusive	1.83	0.15	0	0.12	0.19
$(S/\sqrt{B})$			13.5		
$\mu^\pm\mu^\pm$	0.87	0	0	0.03	0.05
$(S/\sqrt{B})$			15.4		
$\mu^\pm\mu^\mp$	0.96	0.15	0	0.09	0.14
$(S/\sqrt{B})$			7.80		

2.7σ (s/√(s+B)) : $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 260\text{GeV}$

2.4σ : $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV}$

➔Can answer many questions:
Is there coannihilation?
What kind of Neutralino?
Mass difference between neutralinos?

VBF analysis for both 8 TeV and 14 TeV are important!

Conclusion

- **Understanding the origin of DM requires a connection between the particle physics and cosmology**
- **Models with larger annihilation cross-sections seem to have preference.**

- **Non-thermal scenarios can accommodate both over and under abundance scenarios and can accommodate baryon abundance**

Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc.
[not much constraints on their masses]

➔Investigate sleptons, charginos, neutralinos etc. at the LHC

- **Via Vector Boson Fusion**
- **Stop decay**