Dark Matter at Colliders

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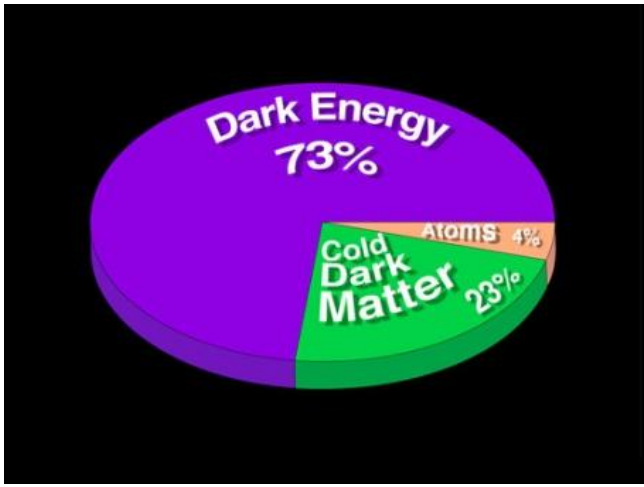
PPC 2014, Leon, Mexico

LHC and Dark Matter

➔**LHC is very efficient in producing colored particles**



➔**Annihilation cross-section of dark matter particles generates dark matter content of the universe**

➔**Annihilation cross-section strength mostly depend on the colorless particles, e.g., sleptons, staus, charginos, neutralinos, etc.**

How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section?

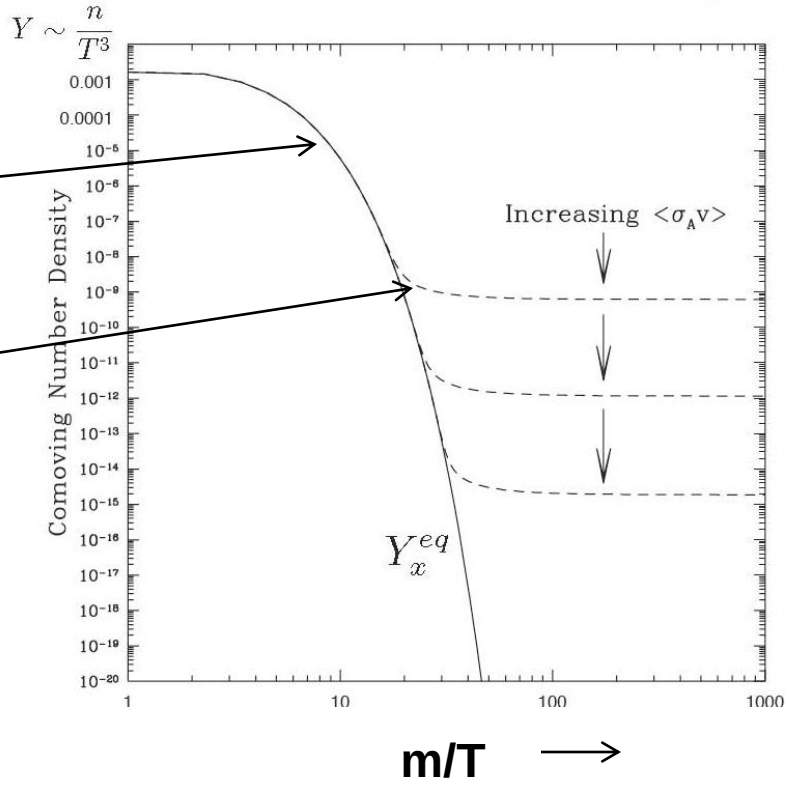
1. **Cascade decays of squarks and gluinos (mSUGRA, NUSUGRA, Mirage Mediation Models)**
2. **Monojet searches**
3. **Via stop squark**
4. **Vector Boson fusion/related topologies**

Dark Matter: Thermal

Production of thermal non-relativistic DM:

$$DM \quad DM \square \quad f \quad \bar{f}$$

Non-relativistic



Freeze-Out: Hubble expansion dominates over the interaction rate

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

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

➔ $\langle v \rangle \quad 3 \square 10^{\,26} \frac{cm^3}{s}$ ^{2}

Assuming : $\langle v \rangle_f \sim \frac{}{m^2}$

~O(10^{-2}) with m ~ O(100) GeV leads to the correct relic abundance

Dark Matter: Thermal

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: Mixture of Wino, Higgsino and Bino

Larger annihilation cross-section

Larger/Smaller Annihilation ➔ Non-thermal Models
Can we establish these features at the LHC?

Dark Matter: Non-Thermal

$_{ann}v$: different from thermal average, $_{DM} \sim \frac{1}{\langle v \rangle}$ is not 26%

Non-thermal DM can be a solution

DM from the decay of heavy scalar field, e.g., Moduli decay

[Moduli : heavy scalar fields gravitationally coupled to matter]

Decay of moduli/heavy field occurs at:

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

Inflation

↓

Radiation domination

↓

moduli domination

Decay of moduli → ↓

radiation domination

↓

T_r ~ MeV : Not allowed by BBN

For $T_r < T_f$: Non-thermal dark matter

Abundance of decay products $Y_{\square} \quad \frac{3T_r}{4m_{\square}}$

DM content: also need to consider the DM annihilation.

Dark Matter: Non-thermal

- **For $T_r < T_f$, larger annihilation cross-section $\langle \sigma_{ann} v \rangle_f$ $\langle \sigma_{ann} v \rangle_f^{th} \frac{T_f}{T_r}$ is needed for** 26%

- **For $T_r << T_f$, Yield $Y_{\chi} \frac{3T_r}{4m_{\chi}}$ is small enough (10^{-10})**
  DM will be produced without any need of annihilation
  [Note: For m_{DM}~10 GeV, Y_{χ} ~10^{-10} to satisfy the DM content]

Outcome:

Rouzbeh Allahverdi's talk' PPC14

- **Large and small annihilation cross-section from models are okay**
- **We may not need any annihilation**

Since χ DM other particles, abundance (for $T_r << T_f$): 10^{-10}

- **The Baryon and the DM abundance are correlated ~ 10^{-10}**

Barrow, '82; Kamionkowski ,Turner, '90; Gelmini, Gondolo, Soldatenko, Yaguna, '07
Allahverdi, Dutta, Sinha,'09,'10,'11,'12,'13; Acharya,Kane, Kumar,Watson, '09,'10

Thermal, Non-thermal

Measurement of DM annihilation cross-section is crucial
Large : multicomponent/non-thermal; Small: Non-thermal

- **LHC: Determine the model then calculate** $_{ann}\nu$

- **DM annihilation from galaxy, extragalactic sources**

  Annihilation into photons: Fermi, HAWC, H.E.S.S.

  Annihilation into neutrinos: IceCube

  Annihilation into electron-positrons: AMS

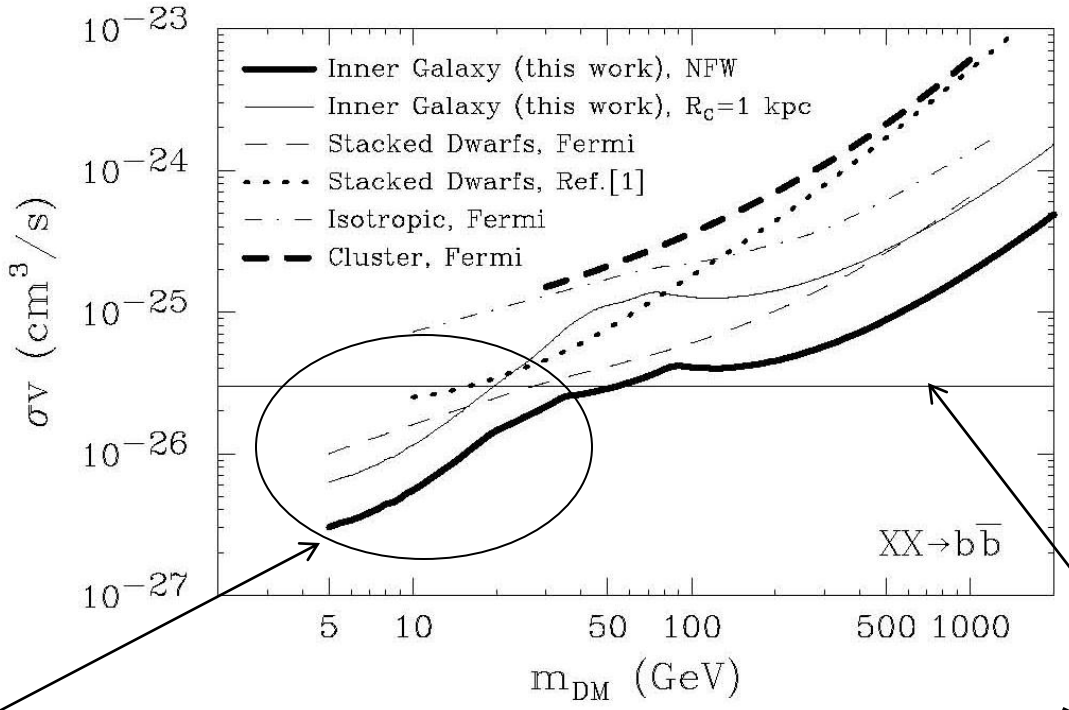
Indirect Detection

The current rate of annihilation of DM particles: $_{ann}\nu \quad _{o}$

DM content: $_{DM} \sim \frac{1}{\langle \nu \rangle}$ $_{ann}\nu \quad _{o}$ **: constrained by Fermi**

Gamma-rays constraints: Dwarf spheroidals, Galactic center

Geringer-Sameth, Koushiappas, Phys. Rev. Lett. 107, 241303 (2011)
Hooper, Kelso, Queiroz, Astropart.Phys. 46 (2013) 55



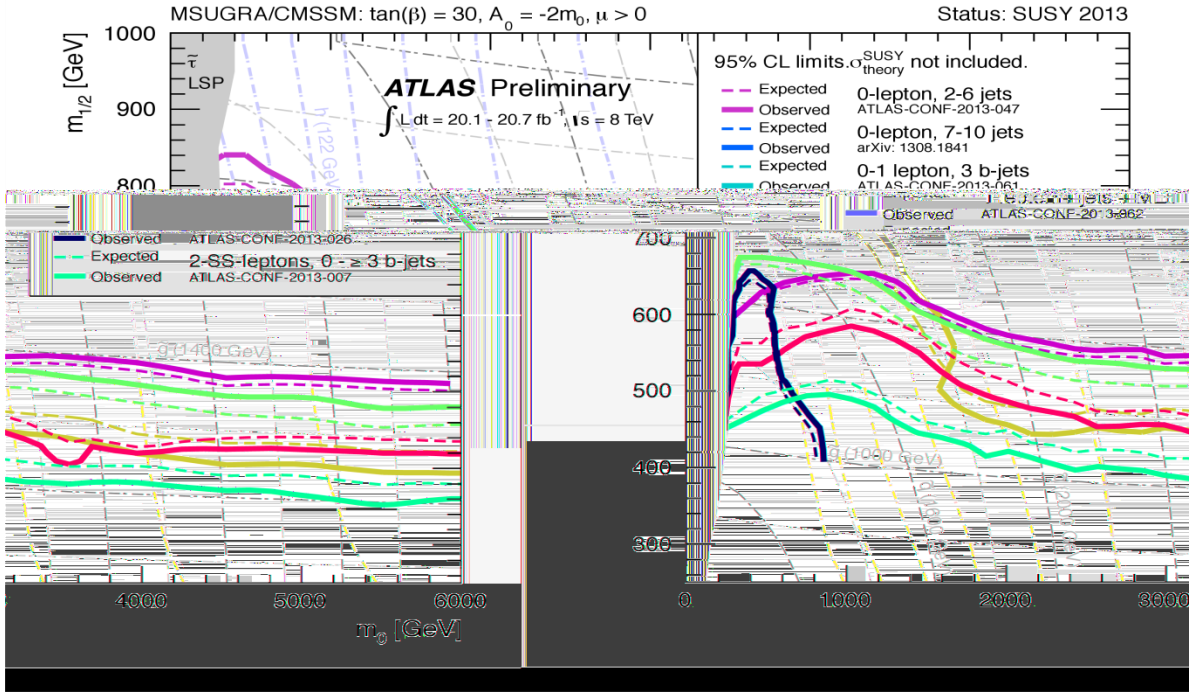
Thermal DM: 27%

$_{ann}\nu \quad _{o}$ **: smaller than the thermal value**

Large cross-section is constrained

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

Is there any parameter space left?

LHC status…

- **Recent Higgs search results from Atlas and CMS indicate that m_h ~126 GeV**
  - **in the tight MSSM window <135 GeV**
- $m_{\tilde{q}}$ **(1st gen.) ~** $m_{\tilde{g}}$ **≥ 1.7 TeV**
- **For heavy** $m_{\tilde{q}}$, $m_{\tilde{g}}$ **≥ 1.3 TeV**
- $\tilde{t}_1$ **produced from** $\tilde{g}$, $m_{\tilde{t}_1}$ **≥ 700 GeV**
- $\tilde{t}_1$ **produced directly,** $m_{\tilde{t}_1}$ **≥ 660 GeV (special case)**

- $\tilde{e}$ / $\tilde{}$ **excluded between 110 and 280 GeV for a mass-less** $\tilde{}^0_1$ **or for a mass difference >100 GeV**
- $\tilde{}_1$ **masses between 100 and 600 GeV are excluded for mass-less** $\tilde{}^0_1$ **for** $\tilde{}_1$ **or for the mass difference >50 GeV decaying into e/**

LHC Constraints and DM

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)

Can we establish any of these scenarios at the LHC?

Establishing DM at the LHC

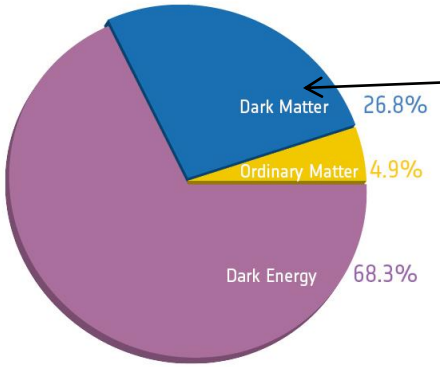
Annihilation of lightest neutralinos ➔ SM particles

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

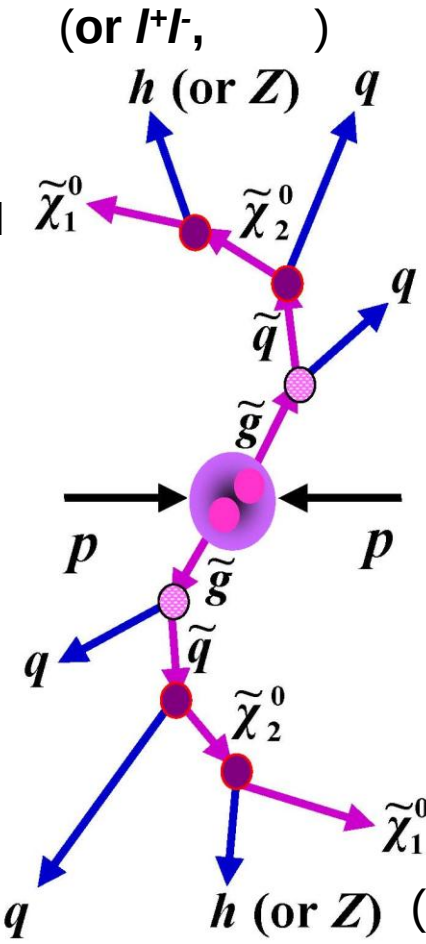
How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section $_{ann}v$ **?**

1. **Cascade decays of squarks and gluinos**
2. **Monojet searches**
3. **Via stop squark**
4. **Vector Boson fusion**

1. Via Cascade decays at the LHC



DM



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

The signal :

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

1. Via Cascade decays at the LHC

Ambitious Goal:

Final states → Masses → Model Parameters

→ Calculate dark matter density

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

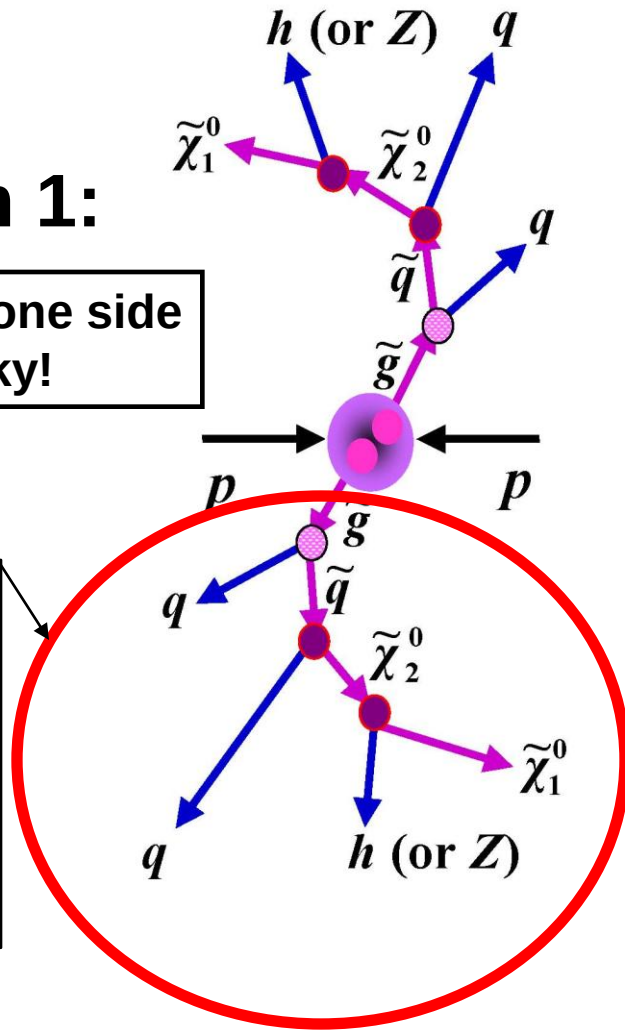
$\tilde{\chi}_{2,3,4}^0 \quad Z, h, \bar{l} l \quad \tilde{\chi}_1^0$ **etc.**

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

Problem 1:

Identifying one side is very tricky!

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



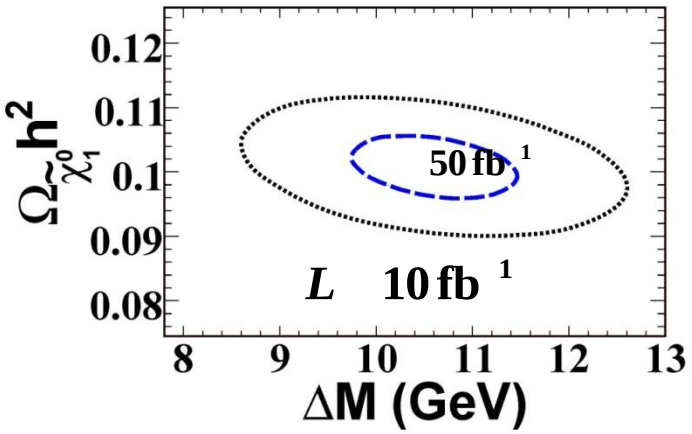
Problem 2:

Not all the sparticles appear in cascade decays

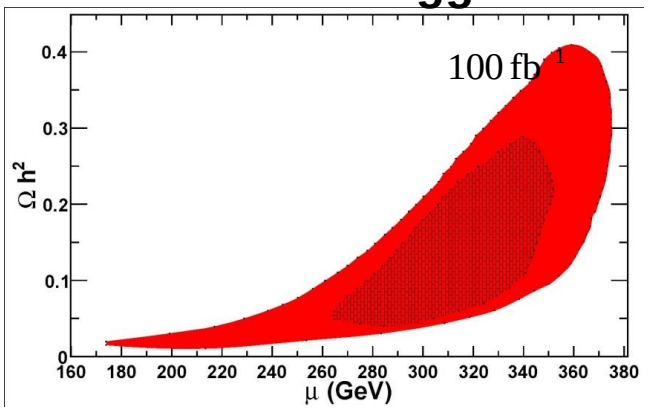
→ Solving for the MSSM : Very difficult

1. Via Cascade decays at the LHC

mSUGRA



Non Universal Higgs Model



Mirage Mediation Model

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

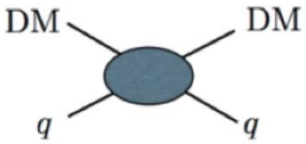
$\Omega h^2 = 0.23 \pm 0.13.$

@ 200 fb^{-1}

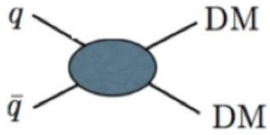
$\mathcal{L}$ (fb^{-1})	$m_{1/2}$ (GeV)	m_H (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ (GeV)	$\Omega_{\tilde{\chi}_1^0} h^2$
1000	500 ± 3	727 ± 10	366 ± 26	3 ± 34	39.5 ± 3.8	321 ± 25	$0.094^{+0.107}_{-0.038}$
100	500 ± 9	727 ± 13	367 ± 57	0 ± 73	39.5 ± 4.6	331 ± 48	$0.088^{+0.168}_{-0.072}$
Syst.	± 10	±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

Determine DM content at
14 TeV LHC with high luminosity

2. Monojet Searches



: Direct detection (t- channel)



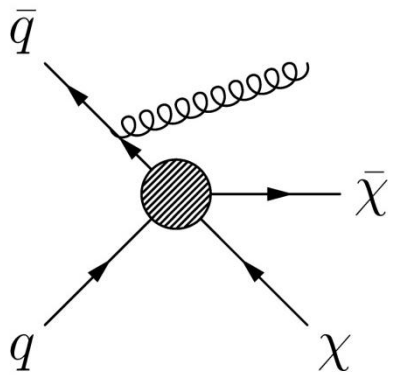
: Collider Searches (s- channel)

Effective Operators, e.g.,

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Dark Matter production ➔missing energy
Jets from a gluon radiated from quarks➔
Monojet plusMET (similarly monophoton+MET)



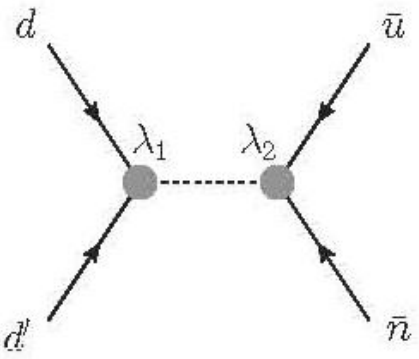
[Bai,Fox and Harnik,JHEP 1012:048 (2010)]; Goodman, Ibe,Rajaraman, Shepherd,Tait,Yu, Phys.Rev.D82:116010 (2010)]

2. DM via Monojet at LHC

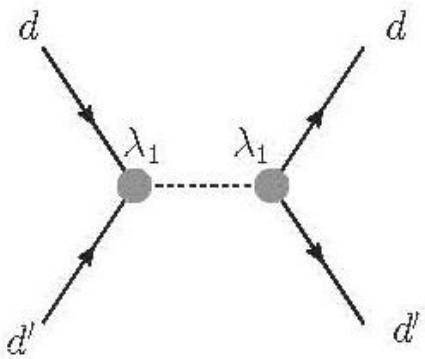
Models of Monojet can have other signals, e.g., dijet, dijet+missing energy etc

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm new} \\ \mathcal{L}_{\rm new} &= (\lambda^{1}_{\alpha i} X^*_\alpha N u^c_i + \lambda^{2}_{\alpha ij} X_\alpha d^c_i d^c_j + \frac{1}{2} m_N N N + \text{h.c.}) \\ &+ m^2_\alpha |X_\alpha|^2 + (\text{kinetic terms})\,. \qquad (1)\end{aligned}$$

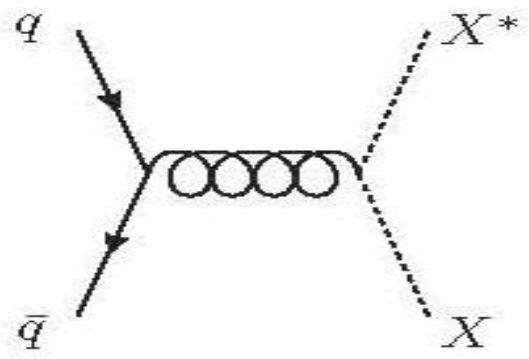
Allahverdi, Dutta: Phys.Rev. D88 (2013) 023525



Monojet



Dijet

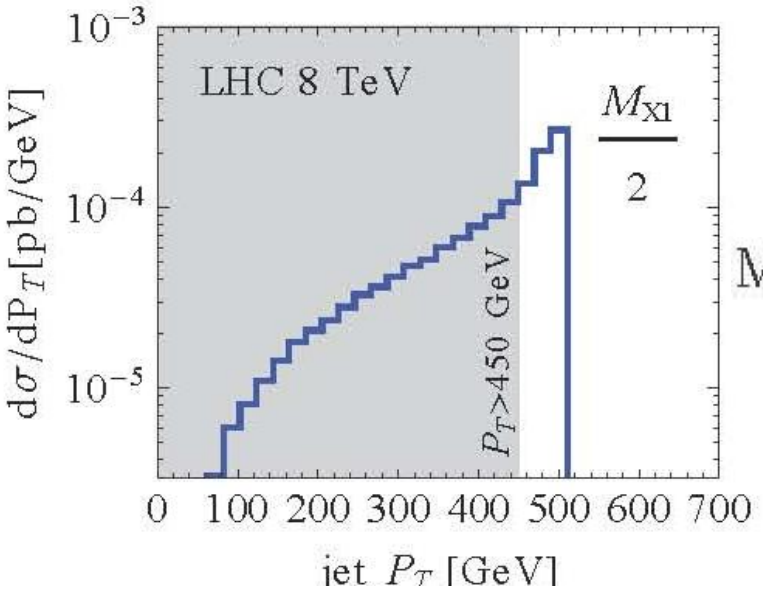


Dijet pair

Dutta, Gao, Kamon: Phys.Rev. D89 (2014) 096009

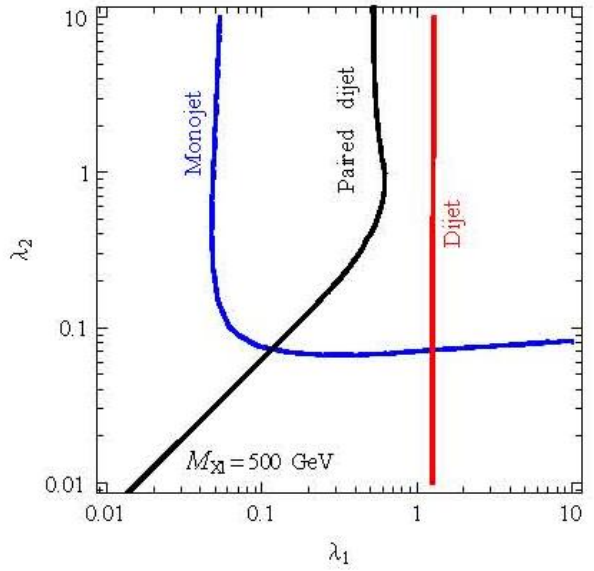
➔ **Existence and type of DM particle and associated model**

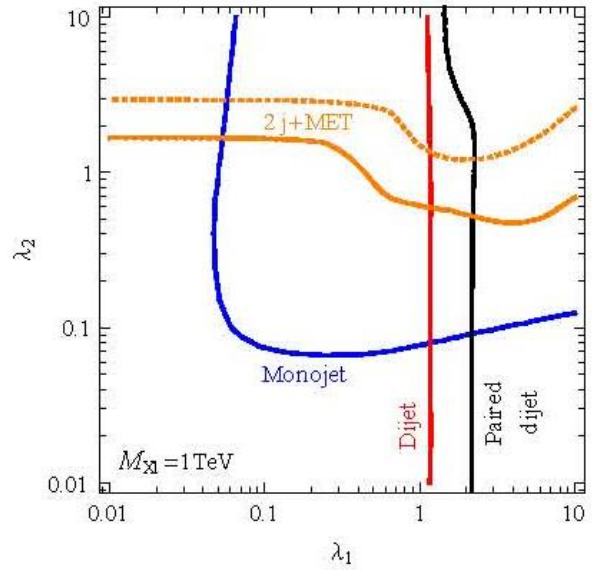
2. DM via Monojet at LHC



Monojet p_T distribution for M_{X1}=1 TeV

Also, Mono-top, di-tops in this model





Combining various observable, we can probe annihilation cross-section

3. DM via Stop at the LHC

Utilize Stop decay modes to search charginos, sleptons, neutralinos

Ex. 1 $\tilde{\chi}_1^0$ **is mostly bino and** $\tilde{\chi}_2^0$ **is wino**

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

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

[Bai, Cheng, Gallichio, Gu, JHEP 1207 (2012) 110 ;Han, Katz, Krohn, Reece, JHEP 1208 (2012) 083;Plehn, Spannowsky, Takeuchi, JHEP 1208 (2012) 091;Kaplan, Rehermann, Stolarski, JHEP 1207 (2012) 119; Dutta, Kamon, Kolev, Sinha, Wang, Phys.Rev. D86 (2012) 075004]

Ex. 2 $\tilde{\chi}_{1,2}^0$ **are mostly Higgsino**

Topness variable to identify stops

Grasser, Shelton, Phys.Rev.Lett. 111 (2013) 121802

Ex. 3 $\tilde{\chi}_1^0$ **is mostly Bino-Higgsino Correct relic density**

For lighter sleptons

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

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

Dutta, Kamon, Kolev,Wang, Wu, Phys. Rev. D 87, 095007 (2013)

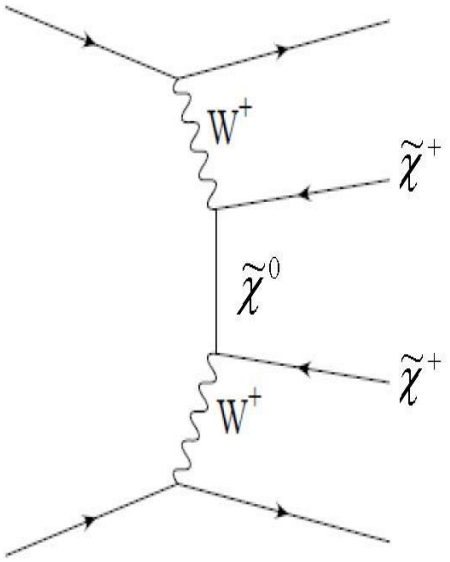
➔ Existence and type of DM particle, hard to calculate the DM content

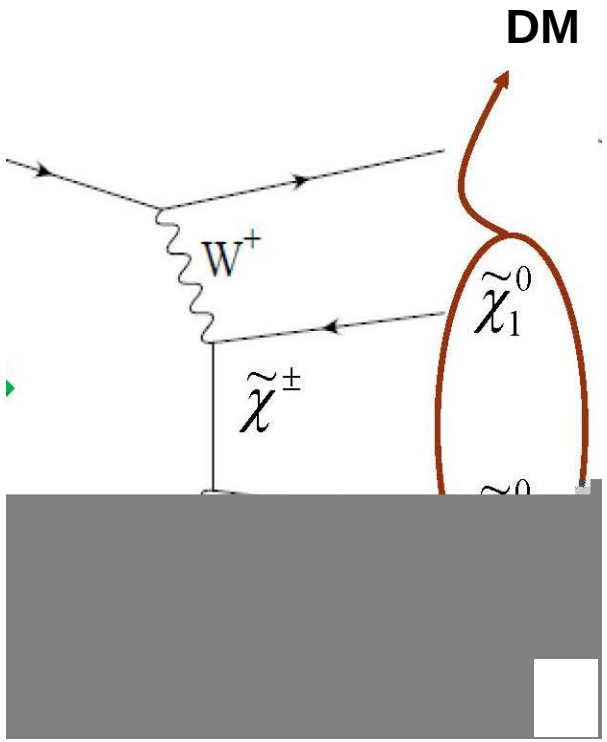
4. DM at the LHC Via VBF

- **Direct probes of charginos, neutralinos and sleptons: Do not have strong limits from the LHC (depends on Dm**

- **The weak Bosons from protons can produce them We need special search strategies**

P + P ➔





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

4. DM at the LHC Via VBF

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} jj,\ \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0} jj,\ \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0} jj,\ \tilde{\chi}_2^{0}\tilde{\chi}_2^{0} jj$$

For : $m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_2^{0}}$ $m_{\tilde{l}}$ $m_{\tilde{\chi}_1^{0}}$

Signal: $2j$ $\not{E}_T$ **missing energy,** $2j$ $\not{E}_T$ **missing energy**

➔ **Small mass (m) difference between chargino and neutralino**

Dutta, Gurrola, Kamon, John, Sinha, Shledon; Phys.Rev. D87 (2013) 035029

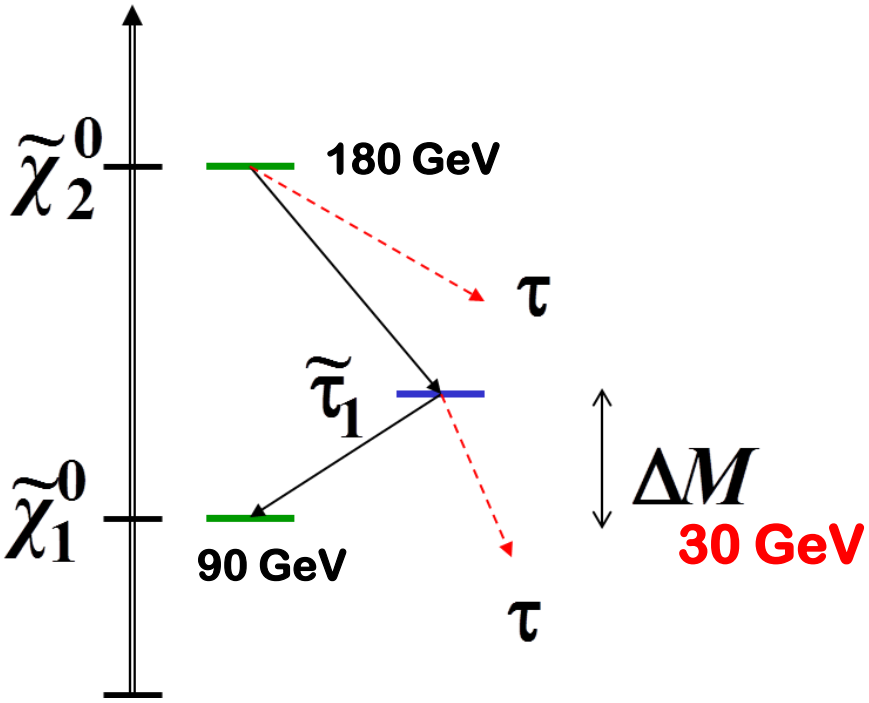
Charginos, Neutralinos via VBF

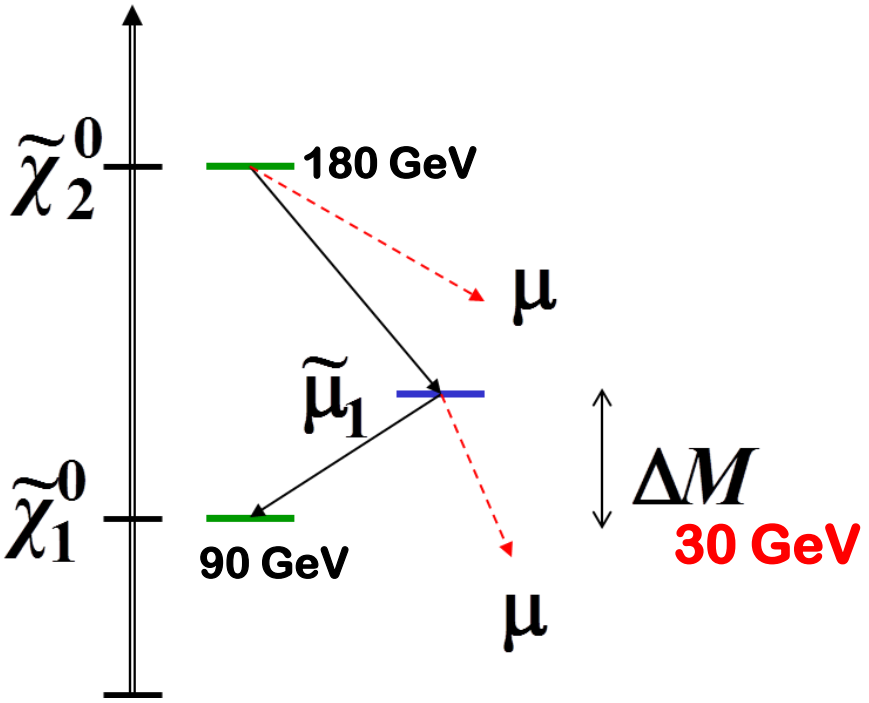
2 jets with $p_T(j)$ 50 GeV; $p_T(j_1)$ 75 GeV

$|\ |$ 4.2; $_1$ $_2$ 0

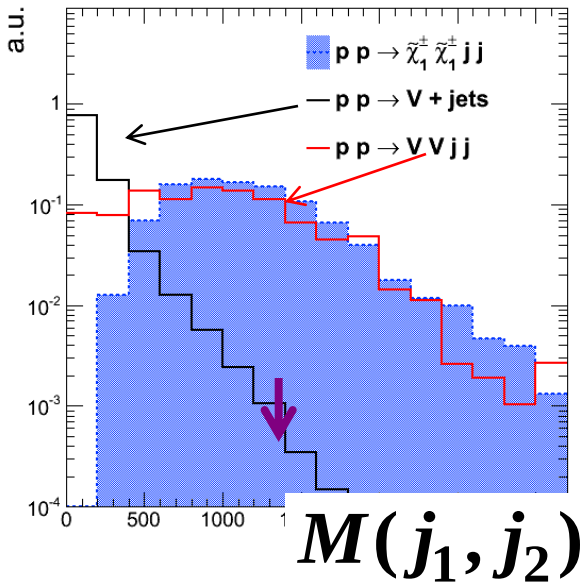
$M(j_1, j_2)$ 650 GeV; MET 75 GeV

2 Benchmark Scenarios

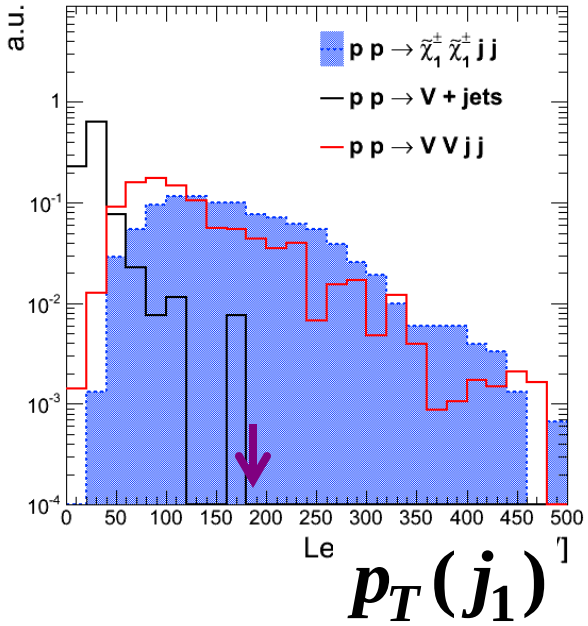




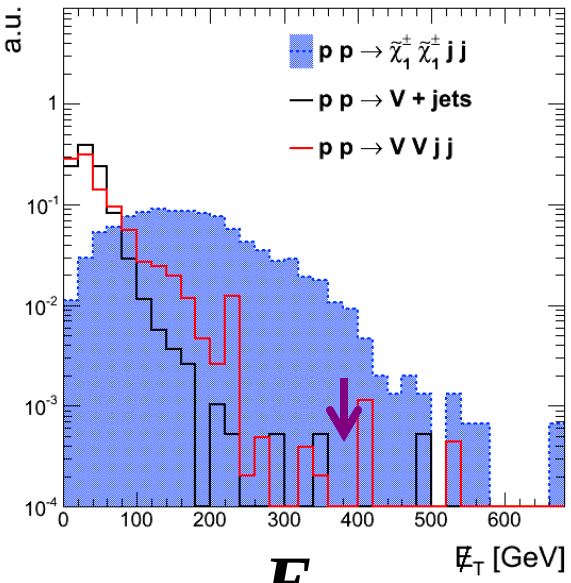
VBF Kinematics



$M(j_1, j_2)$



$p_T(j_1)$



E_T

$M(\tilde{\ }_1) \sim M(\tilde{\ }^0_2)$ 180 GeV

$M(\tilde{\ }^0_1)$ 90 GeV

$M(\tilde{\ }_1)$ $M(\tilde{\ }^0_1)$ 30 GeV

Signal Characteristics:
Large MET, large M_{jj}, large p_T jets

Phys. Rev. D 87, 035029 (2013)

Signal: ≥ 2j+2 +missing energy

2 jets each with p_T>50 GeV, leading p_T>75 GeV
(j_1,j_2)|>4.2, j1 j2<0, M_{j1j2}>650 GeV

Signal: $2j$ 2 **missing energy**

$m_{\tilde{1}} \sim m_{\tilde{0}_2}$ 180GeV,

$\sqrt{s}$ 8 **TeV**

Lum: 25 fb^{-1}

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	97.0	19.0
$\not{E}_T > 75$	4.33	0.27	5.29×10^2	17.6	3.45
2τ, inclusive	0.45	0.06	0.23	0.09	0.04
$(S/\sqrt{B})$			3.47		
$\tau^{\pm}\tau^{\pm}$	0.21	0	0.11	0.02	0.01
$(S/\sqrt{B})$			2.91		
$\tau^{\pm}\tau^{\mp}$	0.24	0.06	0.12	0.07	0.03
$(S/\sqrt{B})$			2.27		

Two 's with p_T >20 GeV in < 2.1, with R( ) > 0:3. All 's are hadronic
The ID efficiency is assumed to be 55% and the jet→ Mis-identification rate is taken to be 1%,

Signal: ≥ 2j+2 +missing energy

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

Signal: $2j\ \ 2$ **missing energy** $m_{\tilde{\ }_1} \sim m_{\tilde{\ }^0_2}\ \ 180\text{GeV},$

	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		

$\sqrt{s}\ \ 8$ **TeV**

Lum: 25 fb^{-1}

Two isolated 's with p_T >20 GeV in < 2.1

For 3 : $m_{\tilde{\ }_1} \sim m_{\tilde{\ }^0_2}\ \ 330\text{GeV}$

4. DM at the LHC Via VBF

Natural SUSY and dark matter :

Lightest neutralino: Higgsino ➔ $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ **similar masses**

10 GeV mass difference with final state: 2 j+ Met + 1 lepton [work in Progress]

This will probe:
thermal vs non-thermal, multicomponent dark matter

4. DM at the LHC Via VBF

Small mass gap measurement using VBF topology:
Various Coannihilation regions:

$\tilde{e}, \tilde{\ }, \tilde{\ }_1^0, \tilde{\ }, \tilde{\ }_1^0, \tilde{\ }_1, \tilde{\ }_2^0, \tilde{t}, \tilde{\ }_1^0, \hat{b}, \tilde{\ }_1^0$

$pp \quad \tilde{\ }\tilde{\ } jj$ **Signal:** $2j \quad 2$ **missing energy,**

$m \quad m_{\tilde{\ }} \quad m_{\tilde{\ }_1^0} \quad 10 GeV$

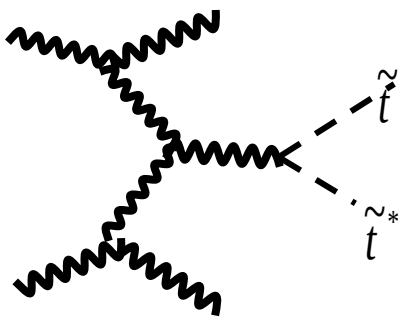
LHC 14 TeV data (expected): 150 GeV (3000 fb^{-1}), for

Dutta, Ghosh, Gurrola, Kamon, Sinha, Wang, Wu; to appear

Lightest neutralino: Higgsino ➔ $\tilde{\ }_1^0, \tilde{\ }_1, \tilde{\ }_2^0$ **similar masses**

10 GeV mass difference with final state: 2 j+ Met + 1 lepton [work in Progress]

4. DM at the LHC Via VBF



$pp \quad \tilde{t}\,\tilde{t}\,jj$ **Signal: 2 j + 2 b + 1 l + missing energy**

Compressed Region: $M \quad m_{\tilde{t}} \quad m_{\tilde{0}_1} \quad 180,165GeV$

$M \quad m_t : \tilde{t} \quad b \quad W \quad \tilde{0}_1$

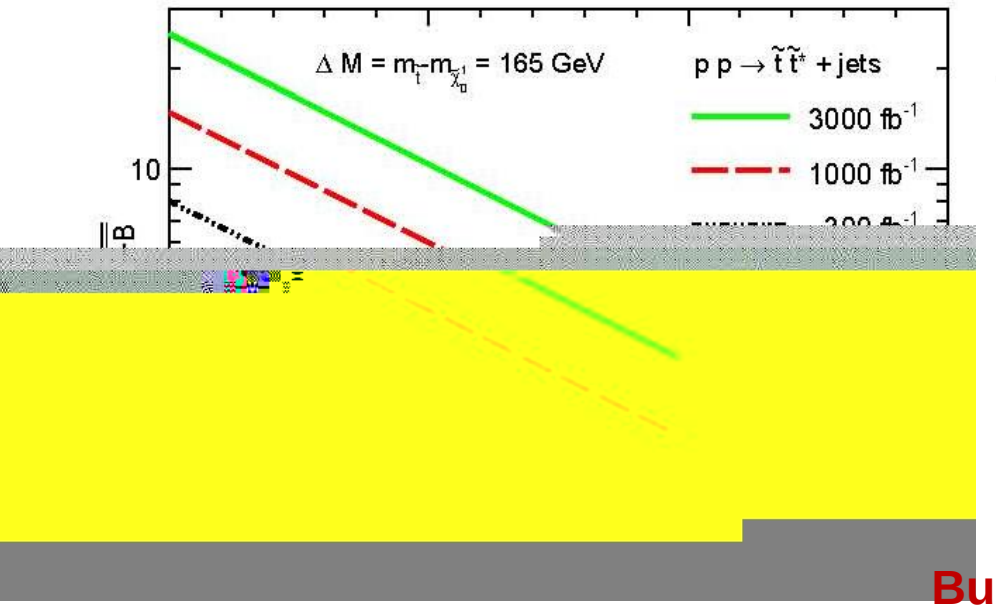
$M \quad m_t : \tilde{t} \quad t \quad \tilde{0}_1$

Cuts:

2 leading jets (j_1,j_2) : p_T (j_1,j_2) >(75,50) GeV ,

| (j_1, j_2)| > 4.2 and $_{j1\ j2}$ < 0, M_{j1j2} > 500 GeV; MET is optimized

One isolated lepton (p_T > 20), two loose b jets (p_T > 30) : <2.5



The significance reduces to 3 with 3% sys. For 200 GeV stop

Dutta, Flanagan, Gurrola, Kamon, Sheldon,Sinha, Wang, Wu; 1312.1348

VBF topology with angular correlation:

Buckley, Plehn, Ramsey-Musolf; 1403.2726

4. DM at the LHC Via VBF

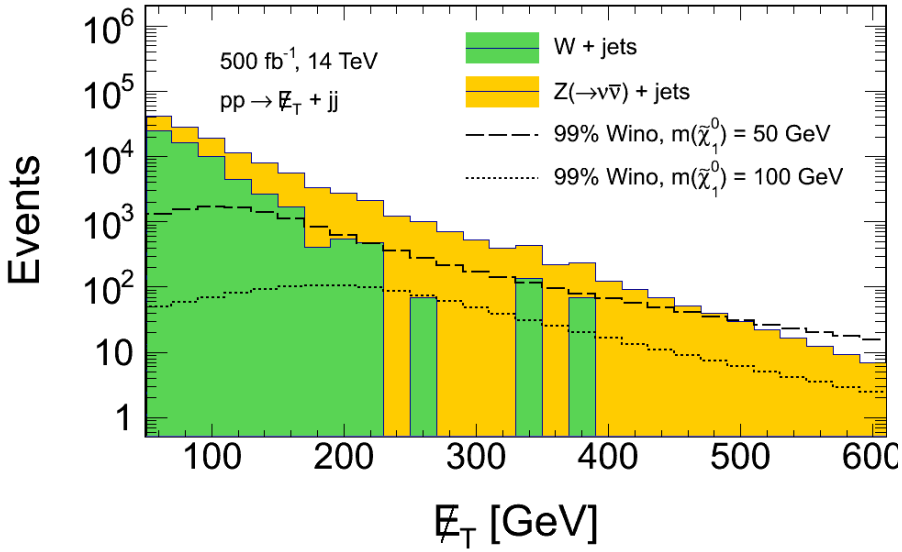
4. DM at the LHC Via VBF

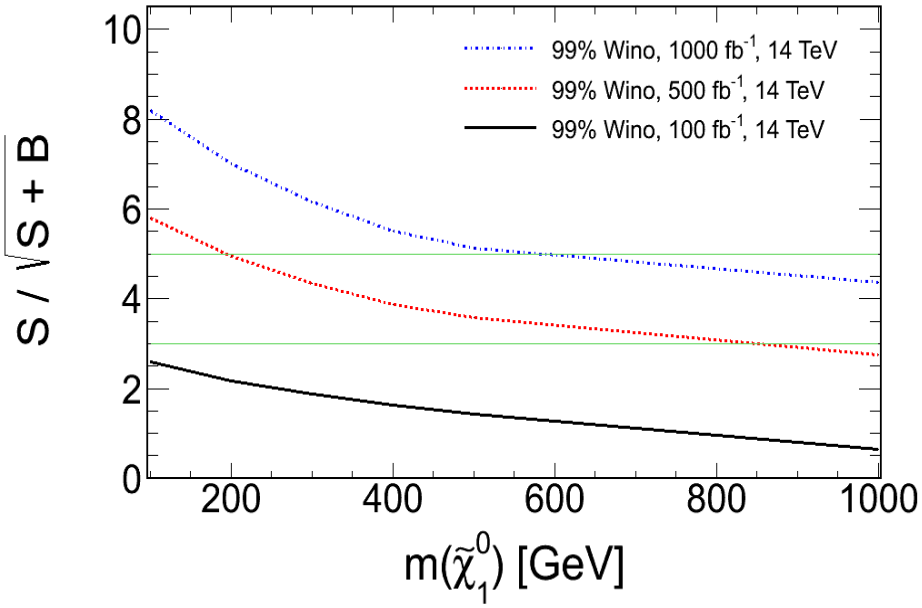
Preselection: missing E_T > 50 GeV, 2 leading jets (j_1,j_2) :p_T (j_1),p_T(j_2) >30 GeV , | (j_1, j_2)| > 4.2 and $_{j1\ j2}$ < 0.

Optimization: Tagged jets : p_T > 50 GeV, M_{j1j2} > 1500 GeV;

Events with leptons(l = e; ; $_h$) and b-quark jets: rejected.

Missing E_T : optimized for different value of the LSP mass.

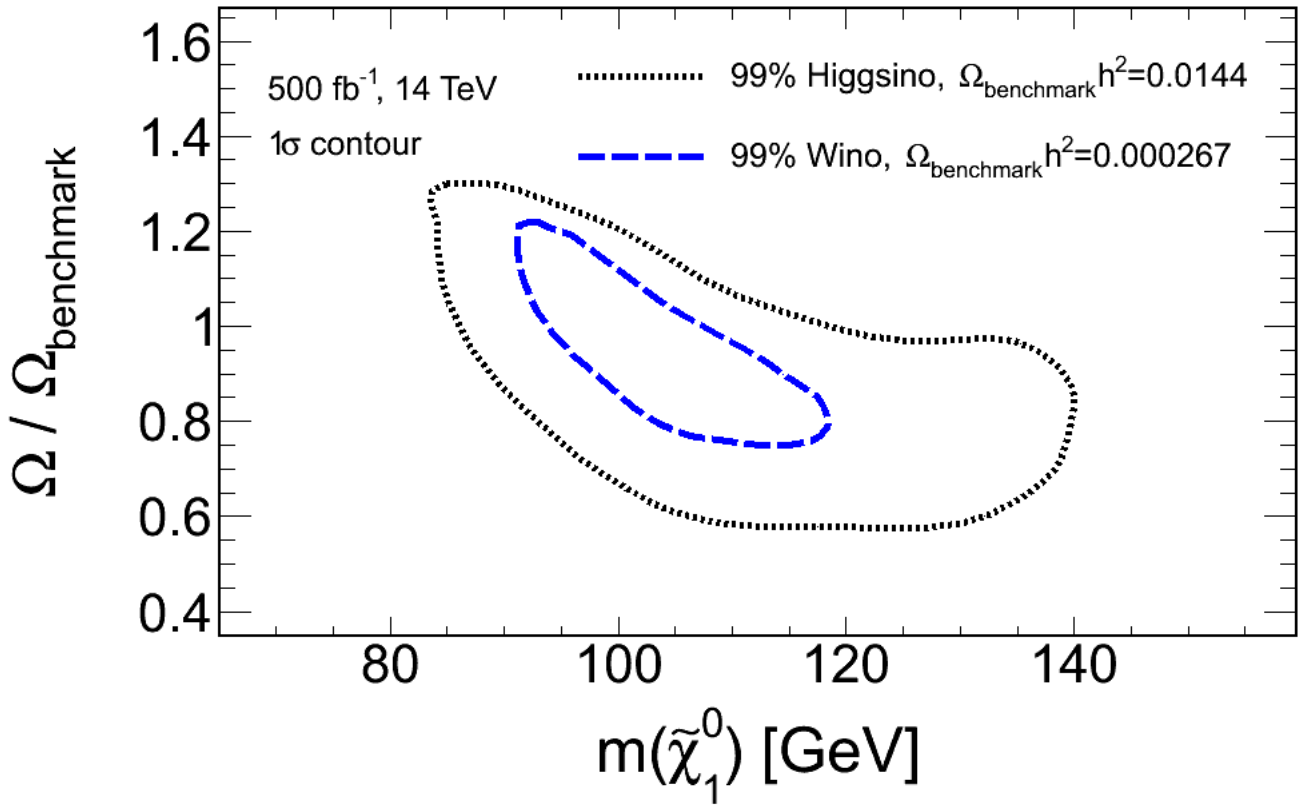




Delannoy, Dutta, Kamon, Sinha, Wang, Wu et al; Phys.Rev.Lett. 111 (2013) 061801

4. DM at the LHC Via VBF

Simultaneous fit of the observed rate, shape of missing energy distribution:



thermal vs non-thermal, multicomponent dark matter

Conclusion

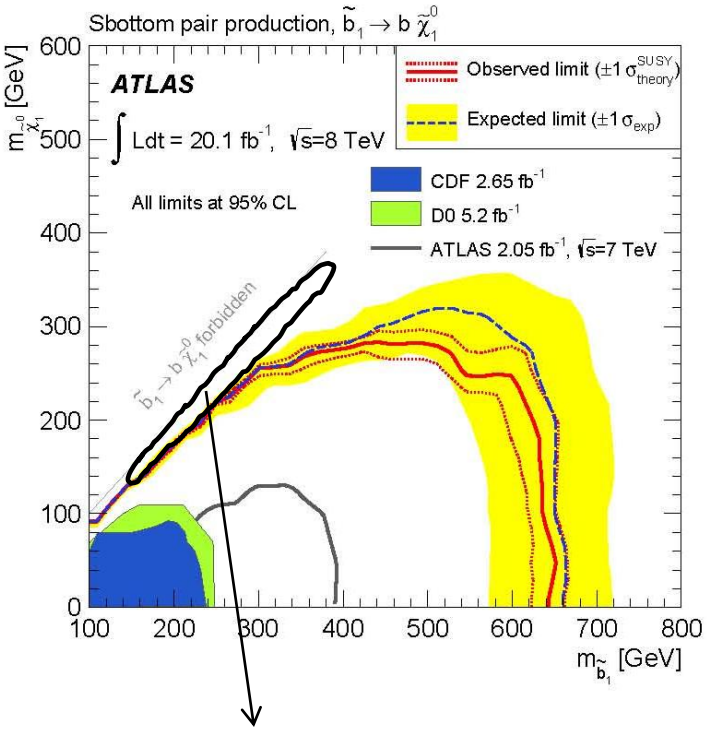
- **Understanding the origin of DM requires a connection between the particle physics and cosmology**

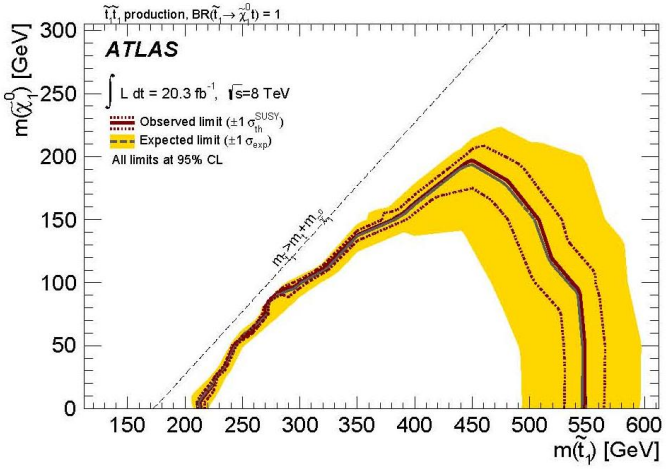
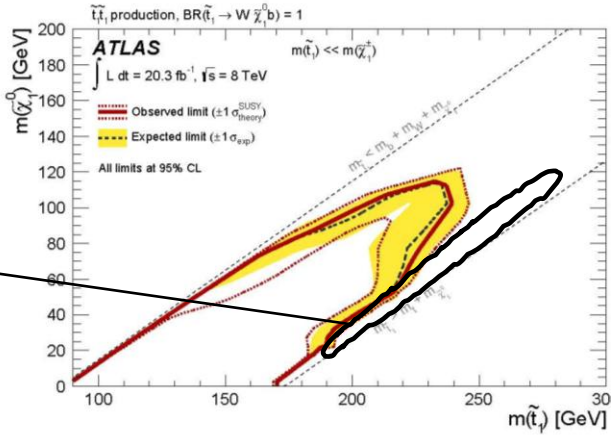
- **Origin of Dark Matter: Thermal, Non-Thermal or multicomponent? Need to measure** $_{ann}v$

- $_{ann}v$ **: LHC and Indirect Detections**

- **Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc. [not much constraints on their masses for small M]**
- **Need to Investigate sleptons, charginos, neutralinos etc. at the LHC**
- **VBF topology is very helpful in identifying regions with with small mass gap among the SUSY particles**

Back-up: Stop-Sbottom at the





We probe this region