Vector Boson Productions Associated with New Physics

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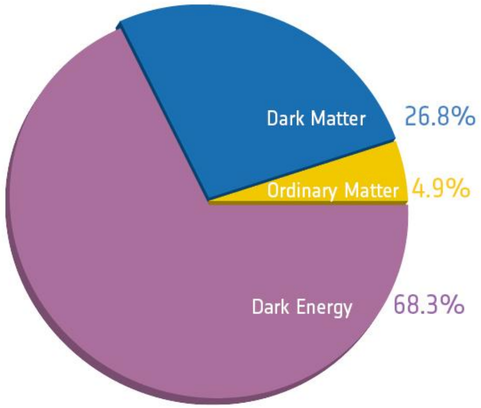
Next steps in the Energy Frontier - Hadron Colliders, FNAL, 2014

Big Picture

➔**We want to understand the next layer of matter - Dark Matter (DM)**



➔**DM content determination mostly depend on colorless particles, e.g., sleptons, staus, charginos, neutralinos, etc. and also depend on small mass gaps (ΔM) between lightest (LSP) and next to lightest particles (NLSP)**

➔**How do we produce these non-colored particles and the DM particle at colliders? Can we understand the origin of DM?**

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, smaller mass gaps

Wino, Higgsino➔ smaller ΔM is inevitable between NLSP & LSP
Bino➔May require smaller ΔM between NLSP &LSP for thermal DM
Can we establish these features at the LHC?

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)**

- $\tilde{e} / \tilde{\mu}$ **excluded between 110 and 280 GeV for a mass-less** $\tilde{\chi}_1^0$ **or for a mass difference >100 GeV, smaller ΔM is associated with smaller missing energy**
- $\tilde{\chi}_1^{\pm}$ **masses between 100 and 700 GeV are excluded for mass-less** $\tilde{\chi}_1^0$ **or for non-negligible mass difference**

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 ➔ Nonthermal scenarios/axions**
Higgsino DM has small ΔM

➔ **Can we establish this scenario?**

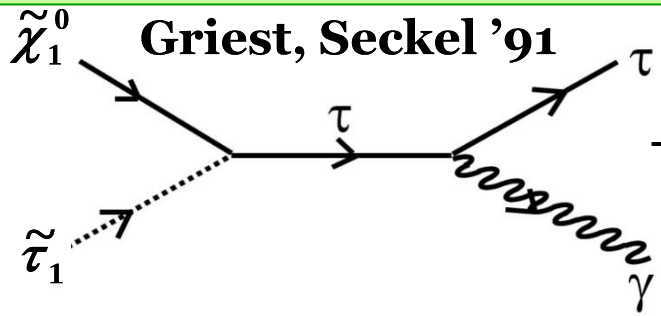
Small ΔM

Small mass gaps between LSP and NLSP➔ coannihilation➔increase the annihilation cross-section

Co-annihilation Process

Griest, Seckel '91

$$\Omega^{-1}_{CDM} \propto \left[\quad \right]^2 e^{-\Delta M / kT_f}$$

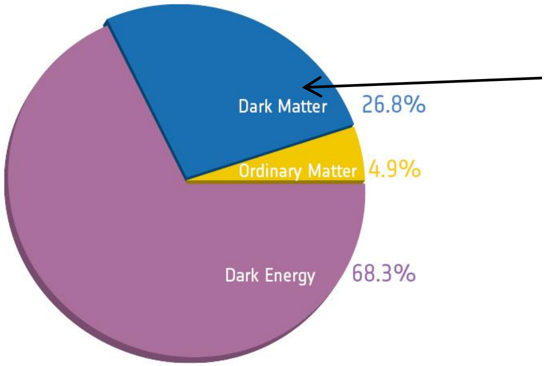


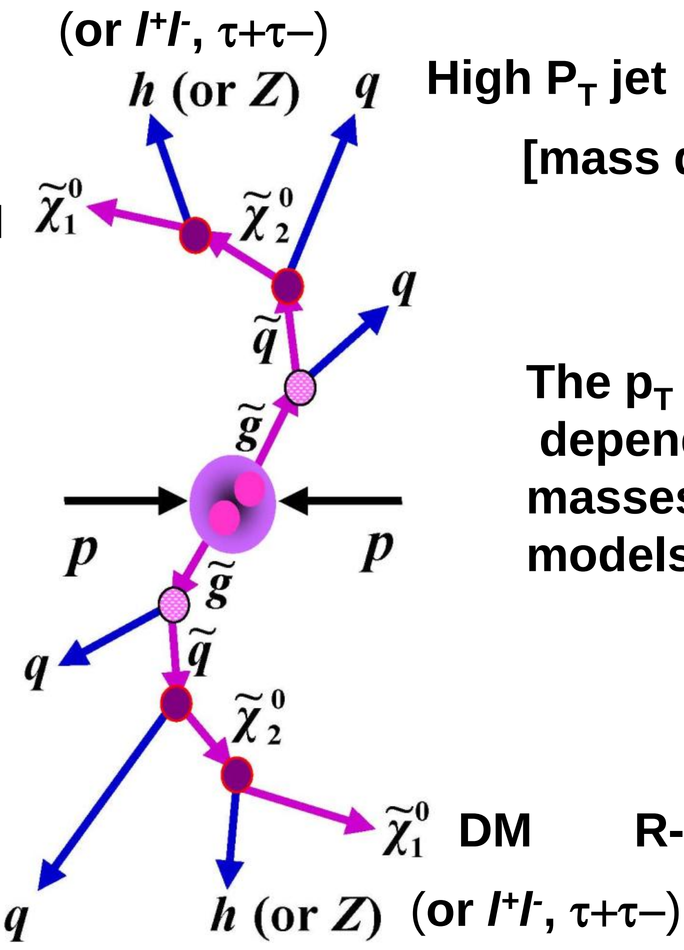
+ ....

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$$

Understanding small mass gaps is crucial for establishing dark matter models

Small ΔM via cascade





[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

R-parity conserving

The signal : jets + leptons+ t's +W's+Z's+H's + missing E_T

Difficult to identify small ΔM

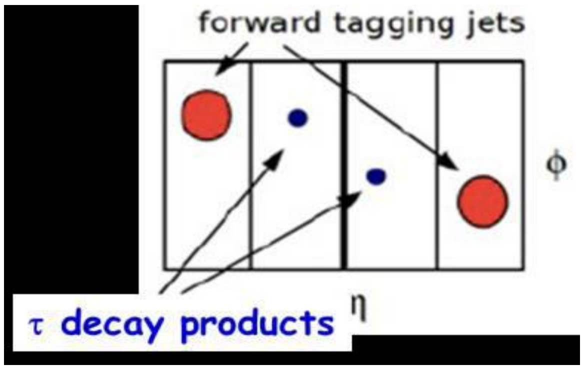
Dutta, Kamon, Krislock, Kolev'10,'11

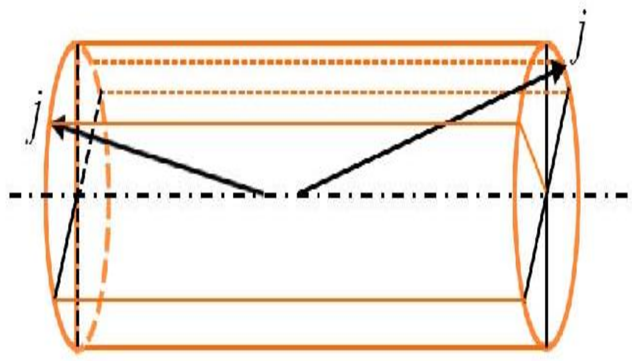
Small ΔM via VBF

Challenge:
How can we probe the colorless SUSY sector?

We will use VBF topology:

Tagging VBF jets





VBF tagged jets (2 energetic jets with large Δη separation: large M(jj)) in forward region, opposite hemispheres)

VBF production topology in transverse plane

Refs (For example):

A. Datta, P. Konar,
B. B. Mukhopadhyaya, PRL 88 (2002)
G. Giudice, T. Han, K. Wang, L.T. Wang, PRD 87 (2013) 035029

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

A.G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, E. Luiggi, A. Melo, P. Sheldon, K. Sinha, K. Wang, S. Wu, PRL 111 (2013) 061801

Compressed Sleptons Via VBF

Small mass gap measurements using VBF topology➔ Various Coannihilation regions:

$$\tilde{\mu}, \tilde{e} - \tilde{\chi}_1^0, \tilde{\tau} - \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0 - \tilde{\chi}_1^0, \tilde{t} - \tilde{\chi}_1^0, \hat{b} - \tilde{\chi}_1^0$$

Very little/no constraint from the current bound (future projections)

These scenarios need higher energy collider, e.g., 100 TeV Collider

Compressed Sleptons Via VBF

$pp \rightarrow \tilde{\mu}\tilde{\mu}jj$ **Signal:** $2j + 2\mu +$ **missing energy,**

$pp \rightarrow \tilde{\nu}\tilde{\mu}jj$ **Signal:** $2j + 1\mu +$ **missing energy,**

$$\Delta m = m_{\tilde{\mu}} - m_{\tilde{\chi}_1^0} = 15 GeV$$

Table I.1: [$2j + 2\mu + \not{E}_T$ study:] Summary of the effective cross section (fb) for the signal and main sources of background at LHC14 for the benchmark point $(m_{slep}, m_{neu1}) = (135, 120)$ GeV. All mass scales are in GeV.

Selection	(135, 120)	$VV + j$	$t\bar{t} + j$	$W + j$	$Z + j$
Initial	0.4910	1341.0000	702955.00	187575000.00	55570000.00
b-veto	0.4801	1231.0800	179234.00	186282000.00	52453900.00
2 j ($p_{T_j} > 30$)	0.2653	207.6700	33206.30	23814100.00	9614190.00
$\eta_{j_1}\eta_{j_2} < 0$	0.2473	157.7410	9784.39	3486260.00	1210970.00
$\geq 2\mu$	0.0761	7.3568	179.96	0.00	9428.27
2 μ	0.0761	6.8903	179.11		9428.27
OS charge	0.0761	5.4075	172.00		9428.27
veto e, τ	0.0746	4.4558	144.79		8725.97
Z-veto	0.0679	2.5496	123.92		307.54
Central μ selection	0.0514	1.9191	49.01		128.53
$\lvert\eta_{j_{1,2}}\rvert > 1.7$	0.0257	1.0654	6.65		9.18
$M_{j_1j_2} > 600$	0.0247	1.0264	4.10		0.00
$\Delta\phi_{j_1j_2} < 1.0$	0.0096	0.1288	0.85		
$\not{E}_T > 200$	0.0039	0.0184	0.00		
$H_T > 200$	0.0039	0.0153			
$p_{T_{\mu_1}} + p_{T_{\mu_2}} < 70$	0.0024	0.0020			
$p_{T_{\mu_2}} > 5$	0.0024	0.0020			
$p_{T_{\mu_1}} > 10$	0.0024	0.0020			
$p_{T_{\mu_2}} < 10$	0.0021	0.0020			

Combining $\tilde{\mu}\tilde{\mu}jj, \tilde{\mu}\tilde{\nu}jj$

LHC 14 TeV : **Signal:** $2j + \geq 1\mu +$ **missing energy,**

5 σ reach is 135 GeV with 10-15 GeV ΔM for 3000 fb^{-1}

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

Compressed Higgsino Via VBF

Lightest neutralino: Higgsino type→ Well Motivated

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

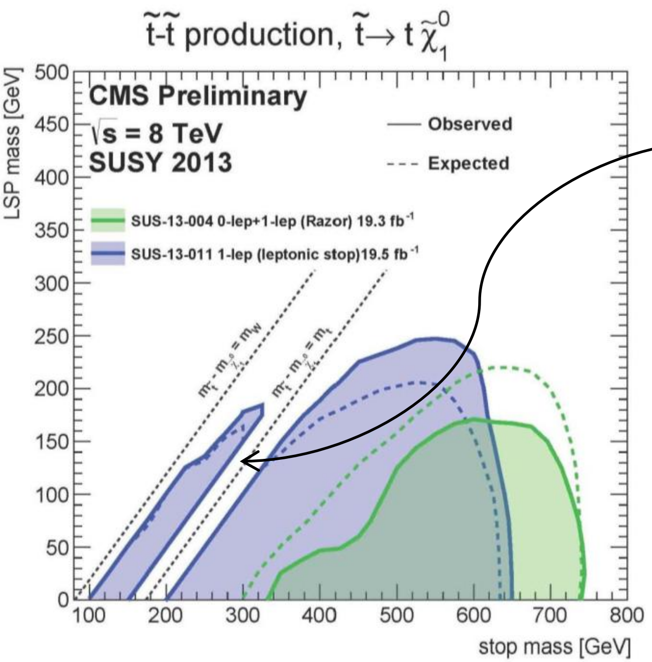
Can we probe 10 GeV mass difference?

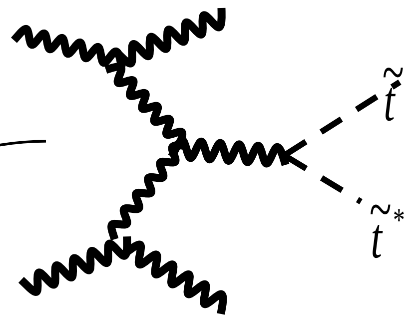
Signal: 2 j+ Met + 1 lepton for Direct Production

2 leading jets (j_1,j_2) : p_T (j_1,j_2) >(75,50) GeV ,
$|\Delta\eta(j_1, j_2)| > 3.5$ and $\eta_{j1}\eta_{j2} < 0$, $M_{j1j2} > 500$ GeV; MET is optimized
One isolated lepton ($p_T > 20$), two loose b jets ($p_T > 30$) : $\eta<2.5$

Work in Progress

Compressed Stop Via VBF





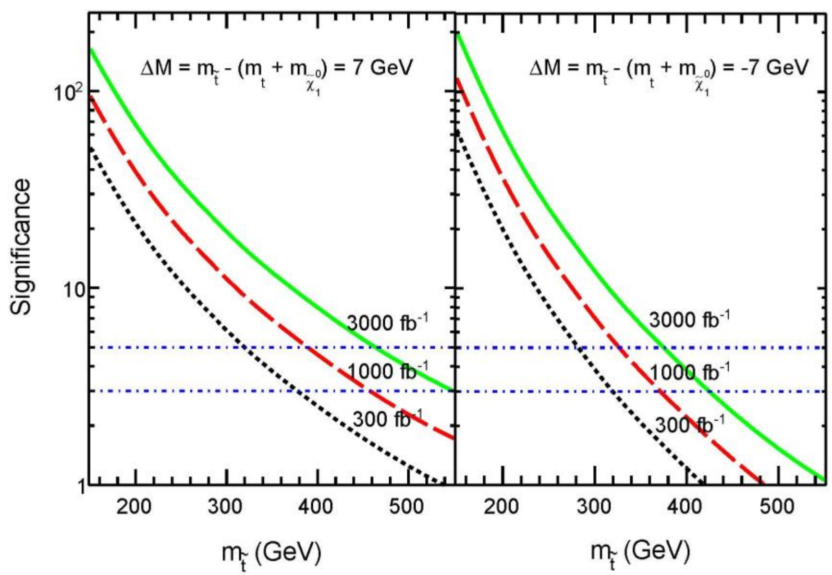
We investigated:

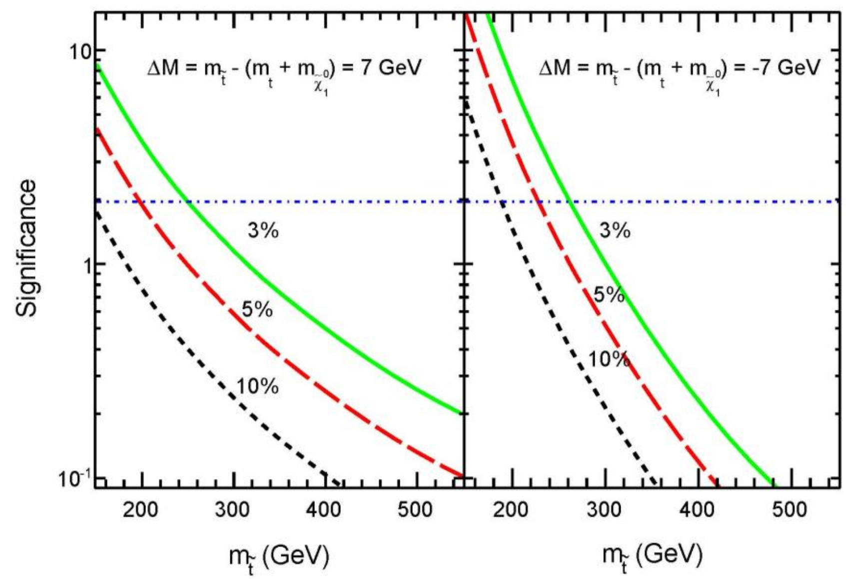
$$\Delta M \equiv m_{\tilde{t}} - (m_{\chi_1^0} + m_t) = \pm 7 GeV$$

Small ΔM: cosmological consequences

2 leading jets (j_1,j_2) : p_T (j_1,j_2) >(75,50) GeV , |Δη(j_1, j_2)| > 3.5 and $\eta_{j1}\eta_{j2}$ < 0, M_{j1j2} > 500 GeV; MET is optimized, one isolated lepton (p_T > 20), two loose b jets (p_T > 30) : η<2.5

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





Compressed Stop Via VBF

2 leading jets (j_1,j_2) : p_T (j_1,j_2) >(75,50) GeV ,
$|\Delta\eta(j_1, j_2)| > 3.5$ and $\eta_{j1}\eta_{j2} < 0$, $M_{j1j2} > 500$ GeV; MET is optimized
One isolated lepton ($p_T > 20$), two loose b jets ($p_T > 30$) : $\eta<2.5$

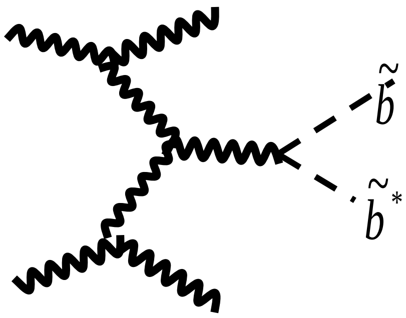
$$\Delta M > m_t : \tilde{t} \to t + \tilde{\chi}_1^0$$

$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$+jets
(200, 20) $\Delta M = 7$ GeV	Pre cut	5.5×10^4	6.9×10^5
	VBF	1.8×10^3	3.8×10^4
	1 lepton	390	8.1×10^3
	2 b-jets	170	4.5×10^3
	$\not{E}_T > 100$	44	990
	$100 < \not{E}_T < 200$	40	580
	$200 < \not{E}_T < 300$	3.2	83
(300, 120) $\Delta M = 7$ GeV	Pre cut	7.2×10^3	6.9×10^5
	VBF	250	3.8×10^4
	1 lepton	56	8.1×10^3
	2 b-jets	32	4.5×10^3
	$\not{E}_T > 100$	8.9	990
	$100 < \not{E}_T < 200$	7.3	580
	$200 < \not{E}_T < 300$	1.2	83
(400, 220) $\Delta M = 7$ GeV	Pre cut	1.6×10^3	6.9×10^5
	VBF	62	3.8×10^4
	1 lepton	14	8.1×10^3
	2 b-jets	8.4	4.5×10^3
	$\not{E}_T > 100$	4.8	990
	$100 < \not{E}_T < 200$	2.4	580
	$200 < \not{E}_T < 300$	0.66	83
(500, 320) $\Delta M = 7$ GeV	Pre cut	460	6.9×10^5
	VBF	19	3.8×10^4
	1 lepton	4.2	8.1×10^3
	2 b-jets	2.4	4.5×10^3
	$\not{E}_T > 150$	1.5	370
	$100 < \not{E}_T < 200$	0.64	580
	$200 < \not{E}_T < 300$	0.23	83

$$\Delta M < m_t : \tilde{t} \to b + W + \tilde{\chi}_1^0$$

$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$+jets
(200, 35) $\Delta M = -7$ GeV	Pre cut	5.6×10^4	6.9×10^5
	VBF	1.4×10^4	3.8×10^4
	1 lepton	270	8.1×10^3
	2 b-jets	79	4.5×10^3
	$\not{E}_T > 100$	29	990
	$100 < \not{E}_T < 200$	25	580
	$200 < \not{E}_T < 300$	4.1	83
(300, 135) $\Delta M = -7$	Pre cut	7.7×10^3	6.9×10^5
	VBF	220	3.8×10^4
	1 lepton	43	8.1×10^3
	2 b-jets	12	4.5×10^3
	$\not{E}_T > 100$	6.7	990
	$100 < \not{E}_T < 200$	4.5	580
	$200 < \not{E}_T < 300$	1.4	83
(400, 235) $\Delta M = -7$	Pre cut	1.6×10^3	6.9×10^5
	VBF	51	3.8×10^4
	1 lepton	10.	8.1×10^3
	2 b-jets	2.8	4.5×10^3
	$\not{E}_T > 200$	0.7	100
	$100 < \not{E}_T < 200$	1.7	580
	$200 < \not{E}_T < 300$	0.4	83

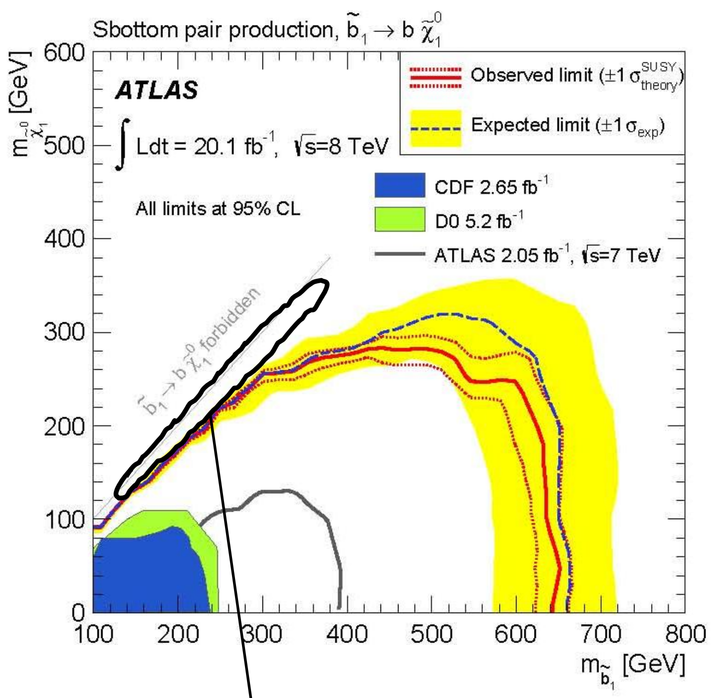
Compressed Sbottom Via VBF



Signal: 2 j + 1 b + missing energy

Compressed Region: $\Delta M \equiv m_{\tilde{b}} - m_{\chi_1^0} = 5GeV$

Dutta, Gurrola, Kamon, Sinha, S. Wu, Z. Wu; in progress



Comp. Spectra Via VBF at 100 TeV

We consider 5 spectra with small mass gaps:

1. $\tilde{e}_1, \tilde{\mu}_1$: 329, $\tilde{\nu}$: 319, $\tilde{\chi}_i^0$: 206,290,332,671, $\tilde{\chi}_i^\pm$: 208,337

2. $\tilde{e}_1, \tilde{\mu}_1$: 231, $\tilde{\nu}$: 218, $\tilde{\chi}_i^0$: 185,237,299,356, $\tilde{\chi}_i^\pm$: 229,354

3. $\tilde{\mu}_1, \tilde{e}_1$: 489, $\tilde{\nu}$: 483, $\tilde{\chi}_i^0$: 88,500,818,829, $\tilde{\chi}_i^\pm$: 500,829

4. $\tilde{\mu}_1, \tilde{e}_1$: 205, $\tilde{\nu}$: 190, $\tilde{\chi}_i^0$: 188,216,1019,1021, $\tilde{\chi}_i^\pm$: 216,1022

5. $\tilde{\mu}_1, \tilde{e}_1$: 496, $\tilde{\nu}$: 491, $\tilde{\chi}_i^0$: 481,501,1019,1027, $\tilde{\chi}_i^\pm$: 501,1026

1. $\tilde{\chi}_1^\pm \to l\nu\tilde{\chi}_1^0(0.3), qq'\tilde{\chi}_1^0(0.7); \tilde{\chi}_2^0 \to W\tilde{\chi}_1^\pm(0.5), Z\tilde{\chi}_1^0(0.5);$

2. $\tilde{\chi}_1^\pm \to l\tilde{\nu}; \tilde{\chi}_2^0 \to \nu\tilde{\nu}(0.8), l\tilde{l}(0.2); \tilde{\nu} \to \nu\tilde{\chi}_1^0, \tilde{l} \to l\tilde{\chi}_1^0$

3. $\tilde{\chi}_1^\pm \to l\tilde{\nu}; \tilde{\chi}_2^0 \to \nu\tilde{\nu}(0.85), l\tilde{l}(0.15); \tilde{\nu} \to \nu\tilde{\chi}_1^0, \tilde{l} \to l\tilde{\chi}_1^0$

4. $\tilde{\chi}_1^\pm \to l\tilde{\nu}; \tilde{\chi}_2^0 \to \nu\tilde{\nu}(0.85), l\tilde{l}(0.15); \tilde{\nu} \to \nu\tilde{\chi}_1^0, \tilde{l} \to l\tilde{\chi}_1^0$

5. $\tilde{\chi}_1^\pm \to l\tilde{\nu}; \tilde{\chi}_2^0 \to \nu\tilde{\nu}(0.8), l\tilde{l}(0.2); \tilde{\nu} \to \nu\tilde{\chi}_1^0, \tilde{l} \to l\tilde{\chi}_1^0$

BRs

Dutta,Ghosh, Padhi,work in progress

Conclusion

- **Small mass gap measurements are very important**

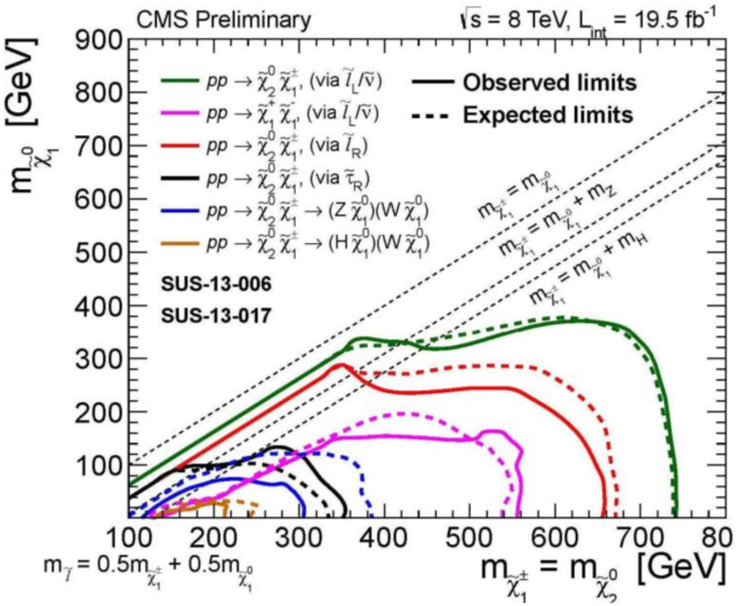
- **Small mass gaps between LSP and NLSP have cosmological consequences**

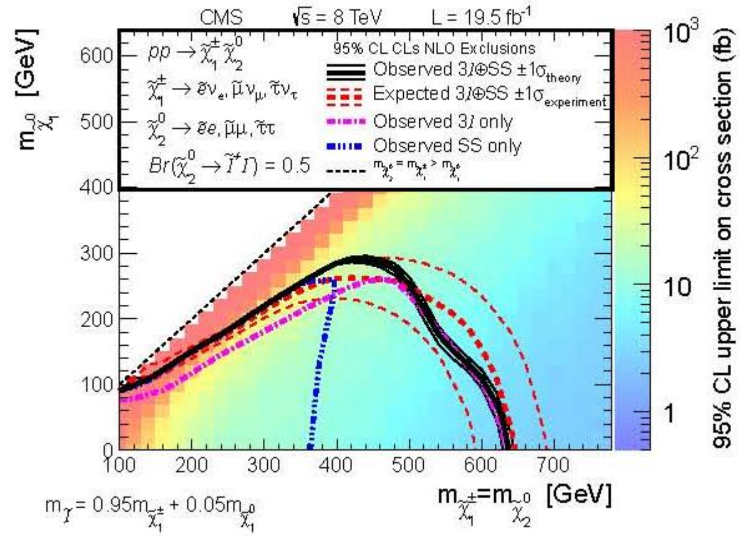
- **VBF topology is very helpful in establishing signals with small mass gaps**

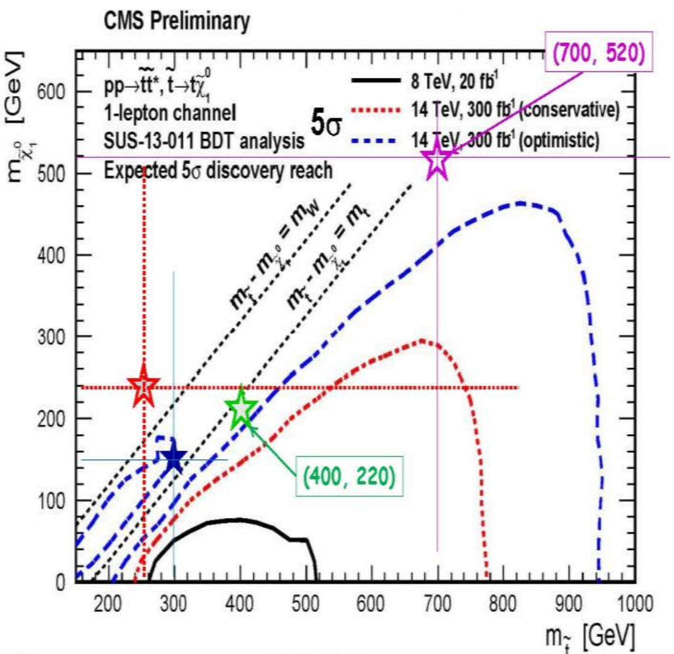
- **LHC reach is not large for sparticle spectrum with small mass gaps**

- **Higher energy collider will be important**

Back-up


CMS Preliminary
√s = 8 TeV, L_int = 19.5 fb^-1
Observed limits
Expected limits
SUS-13-006
SUS-13-017
m_l̃ = 0.5m_χ̃1± + 0.5m_χ̃1^0
m_χ̃1± = m_χ̃2^0 [GeV]
m_χ̃1^0 [GeV]


CMS √s = 8 TeV L = 19.5 fb^-1
95% CL CLs NLO Exclusions
Observed 3l⊕SS ±1σ_theory
Expected 3l⊕SS ±1σ_experiment
Observed 3l only
Observed SS only
m_l̃ = 0.95m_χ̃1± + 0.05m_χ̃1^0
m_χ̃1± = m_χ̃2^0 [GeV]
95% CL upper limit on cross section (fb)


CMS Preliminary
1-lepton channel
SUS-13-011 BDT analysis
Expected 5σ discovery reach
5σ
8 TeV, 20 fb^-1
14 TeV, 300 fb^-1 (conservative)
14 TeV, 300 fb^-1 (optimistic)
(700, 520)
(400, 220)
m_t̃ [GeV]
m_χ̃1^0 [GeV]