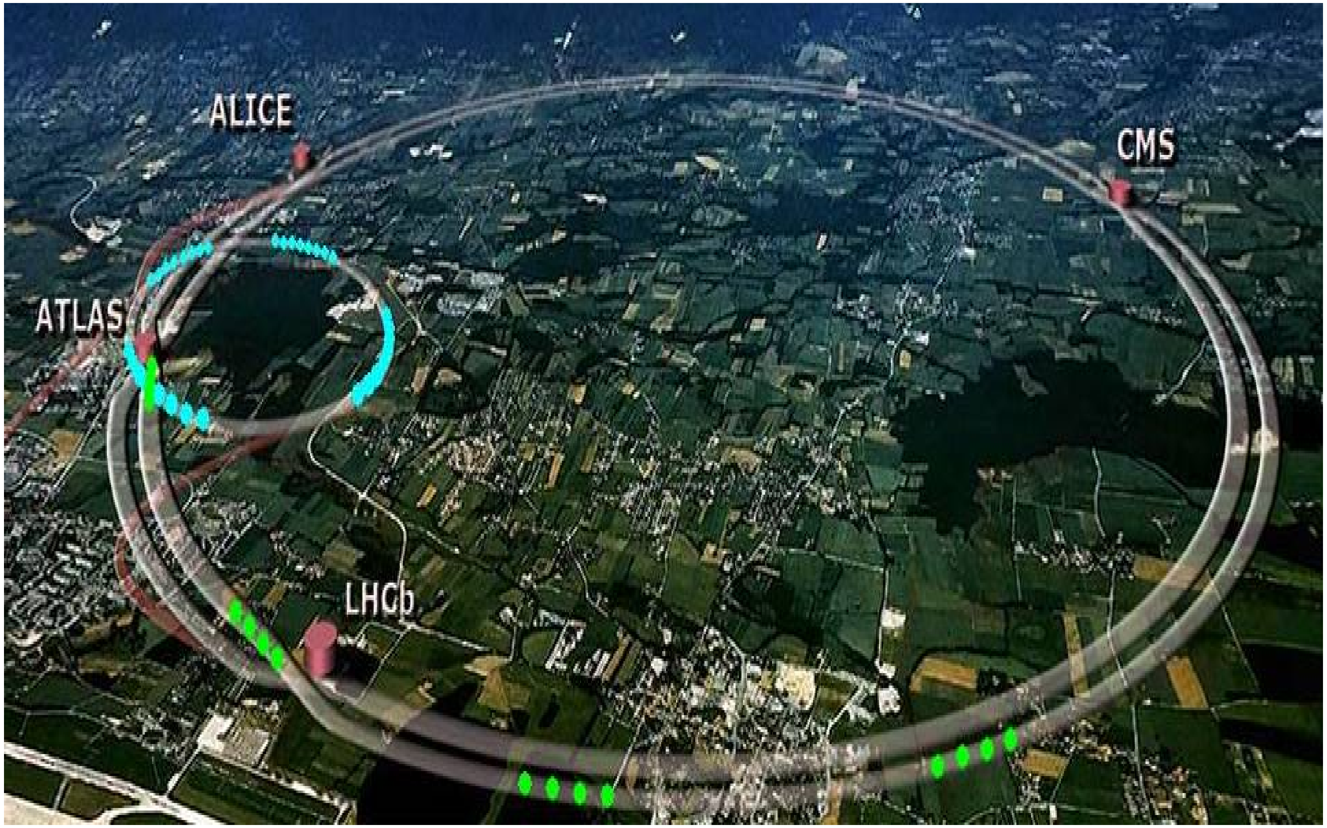
DM at the LHC



Bhaskar Dutta

Texas A&M University

WIN 2017, 19-24 June 2017

LHC DM Goal

Discover dark matter candidate!

What are the associated new particles?

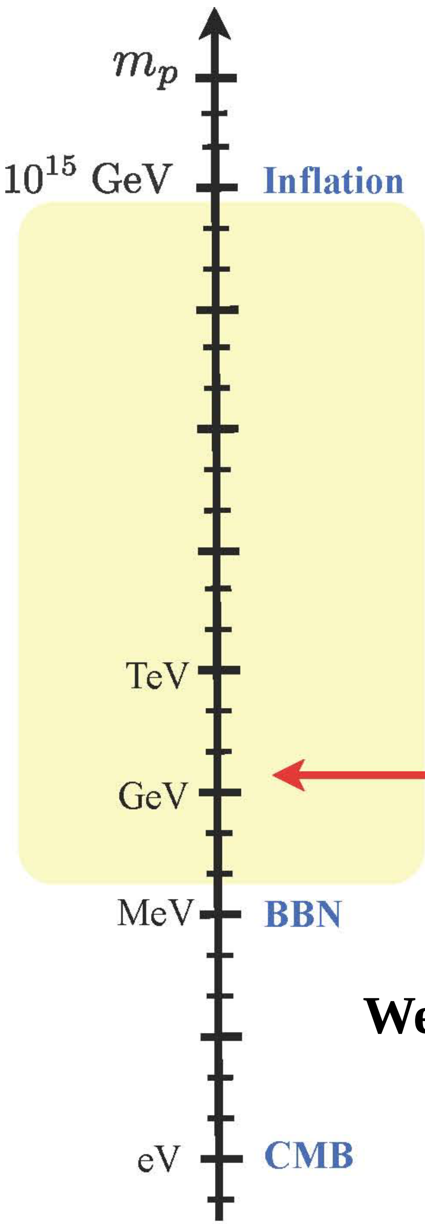
Can we find consistency with direct/indirect detection experiments?

Status of particle physics model(s)?

What could be the nature of DM?

What is the associated cosmology-standard/nonstandard etc.?

Thermal Dark Matter

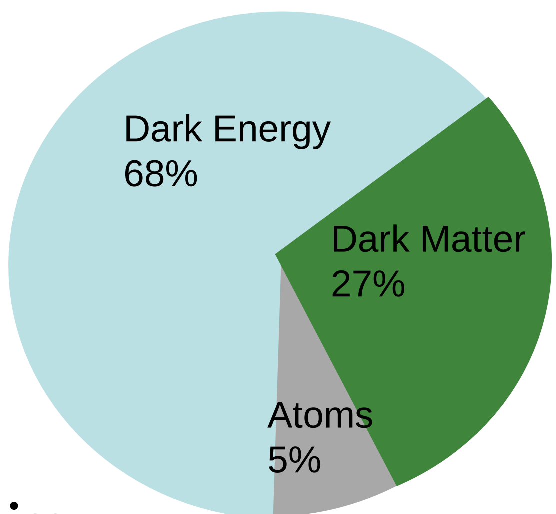


WIMP

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

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

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



➔ $\langle \sigma v \rangle \sim 2 \times 10^{-26} \dfrac{cm^3}{\sec}$

Weak scale physics :

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

This is not the only way to achieve the correct abundance of DM!

Dark Matter: Non-standard

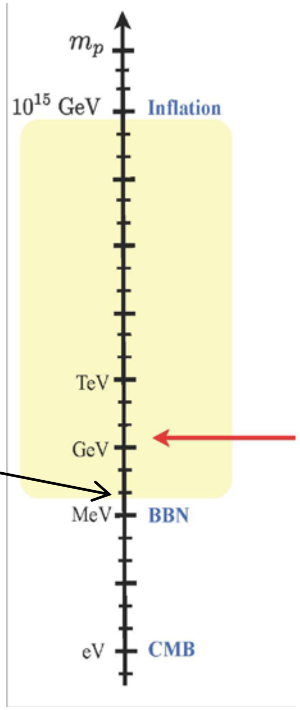
1. DM from the decay of heavy scalar Field (ϕ), e.g., Moduli decay

Moroi, Randall'99; Acharya, Kane, Watson'08, Randall; Kitano, Murayama, Ratz'08; Dutta, Leblond, Sinha'09; Allahverdi, Cicoli, Dutta, Sinha,'13

[Moduli : heavy scalar fields gravitationally coupled to matter]

Decay of moduli/heavy field occurs at:

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

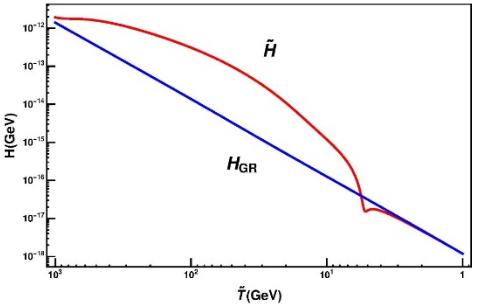


For $T_r<T_f$: Non-thermal dark matter

✓ Can accommodate large and small $\langle\sigma v\rangle$

Expansion rate can be different: scalar tensor theories

Catena Fornengo, Masiero, Pitroni, Rosati,'04
Meehan, Whittingham, '15
Gelmini, Huh, Rehagen,'13,
Dutta, Esteban, Zavala'16



✓ Can accommodate large and small $\langle\sigma v\rangle$

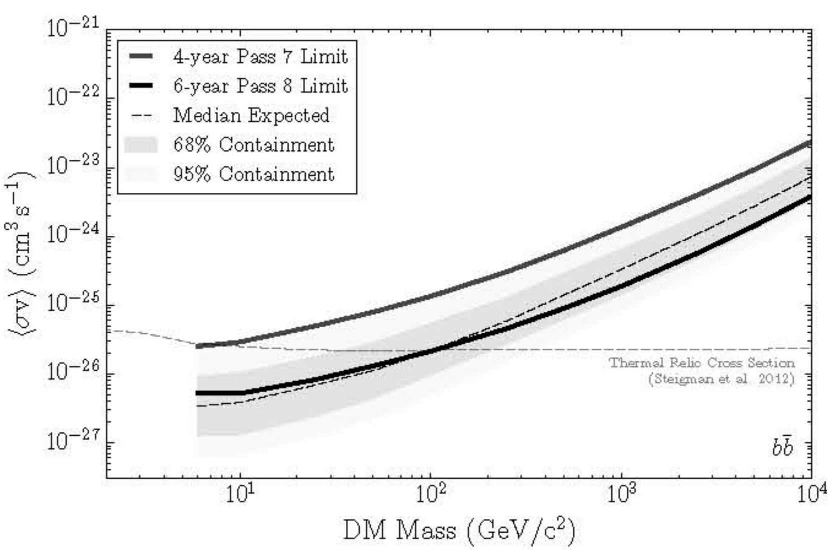
Larger or smaller <σv>

Prior to BBN: History of the Universe is not constrained

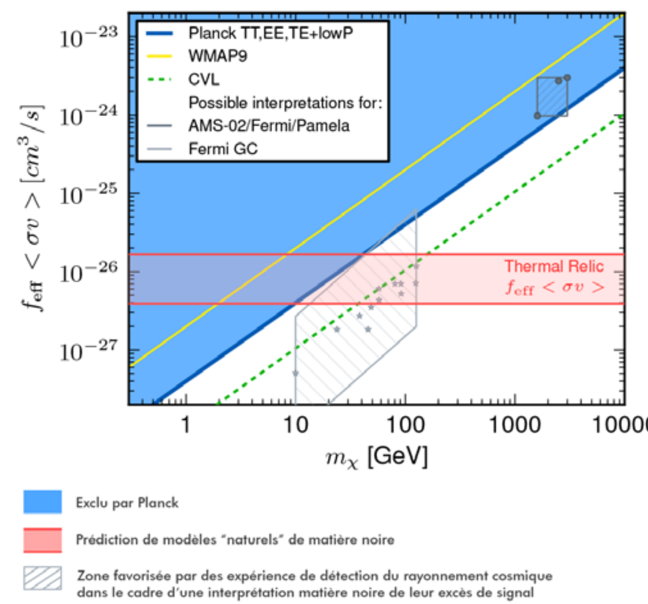
Larger/ smaller <σv> : Non thermal dark matter, e.g., due to moduli decay
Prior to BBN
Non standard cosmology: Expansion rate is different
[Dark Matter is thermal]

Experimental constraints:

Gamma-rays constraints: Dwarf spheroidals



CMB constraint



$\langle \sigma v \rangle$ constant or with velocity enhancement gets constrained

LHC status…

Supersymmetry

➔ $m_{\tilde{q}}$ (1st gen.) ~ $m_{\tilde{g}} \geq$ 1.9 TeV

➔ $\tilde{t}_1$ produced directly, $m_{\tilde{t}_1}$ ≥ 1000 GeV

➔ $\tilde{e}\,/\,\tilde{\mu}$ excluded between 100 and 500 GeV for a mass-less $\tilde{\chi}_1^0$ or for a mass difference >60 GeV, small ΔM is associated with small missing energy

➔ $\tilde{\chi}_1^\pm$ masses between 100 and 750 (1000) GeV are excluded for mass-less $\tilde{\chi}_1^0$ or for a mass difference > 100 GeV decaying into e/μ from $\tilde{\chi}_1^\pm$ pair production (from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair production)

DM at the LHC

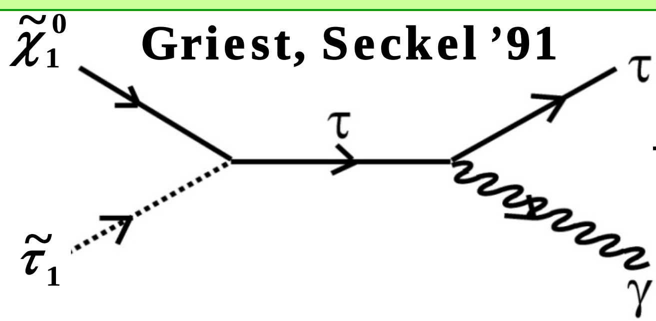
Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc.

In addition: Small mass gaps between LSP and NLSP ➔ coannihilation ➔ modify the annihilation cross-section

LHC

Co-annihilation (CA) Process

Griest, Seckel '91



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

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

Establishing DM at the LHC

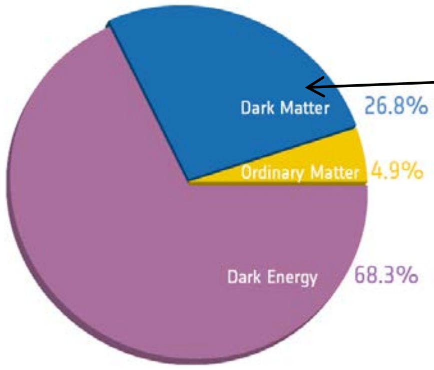
Annihilation of lightest neutralinos ➔ SM particles

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

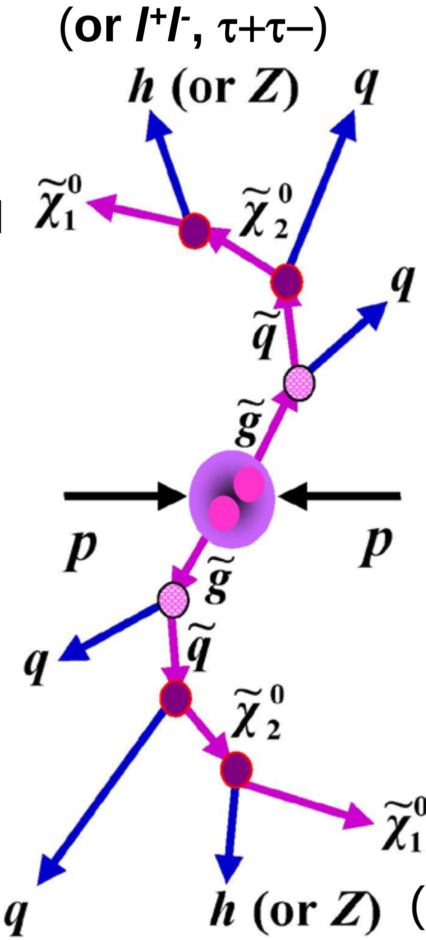
How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section $< \sigma_{ann} v >$?

1. **Cascade decays of squarks and gluinos**
2. **Via stop squark**
3. **Jet(s) + Missing energy (+ e, μ, τ, W, Z, H, γ, t, b etc.) [monojet, dijets, VBF : sleptons, Higgsinos, sbottoms, staus etc.]**

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

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

High P_T jet

The signal :

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

But squarks, gluinos are not found yet (>1.8 TeV)

Small ΔM via cascade and DM

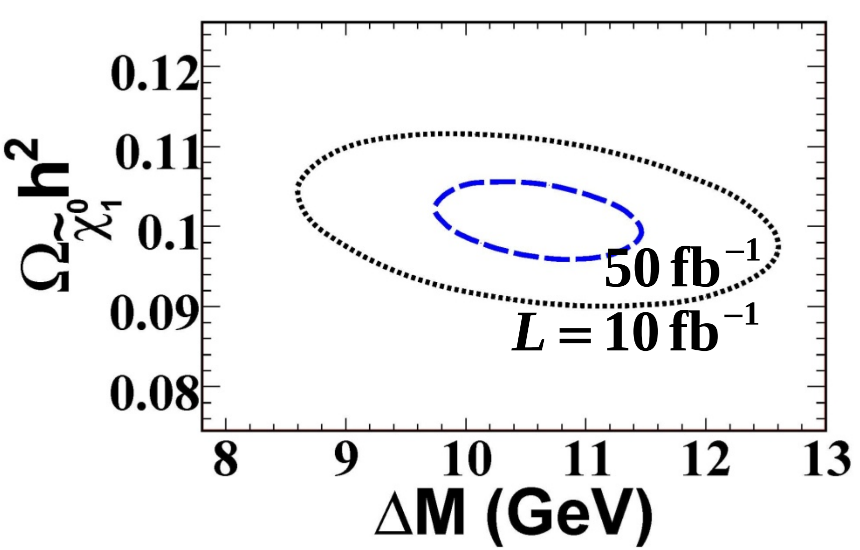
✓Solved by inverting the following functions:

$$M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)$$
$$M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{(b)\,\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

10 fb^{-1}

$$\begin{cases} m_0 = 210 \pm 5 \\ m_{1/2} = 350 \pm 4 \\ A_0 = 0 \pm 16 \\ \tan\beta = 40 \pm 1 \end{cases}$$

$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2} \tan\beta, A_0)$$



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 = 6.2\%\ (30\ \text{fb}^{-1})$$
$$= 4.1\%\ (70\ \text{fb}^{-1})$$

2. DM via Stop at the 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

(i) Small $\Delta m = m_{\tilde{t}} - m_t$ **: VBF, Monojet**

Dutta, Flanagan, Gurrola, Kamon, Sheldon,Sinha, Wang, Wu, 14; An, Wang, '15

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

Topness variable to identify stops

Grasser, Shelton, '13

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

For lighter sleptons

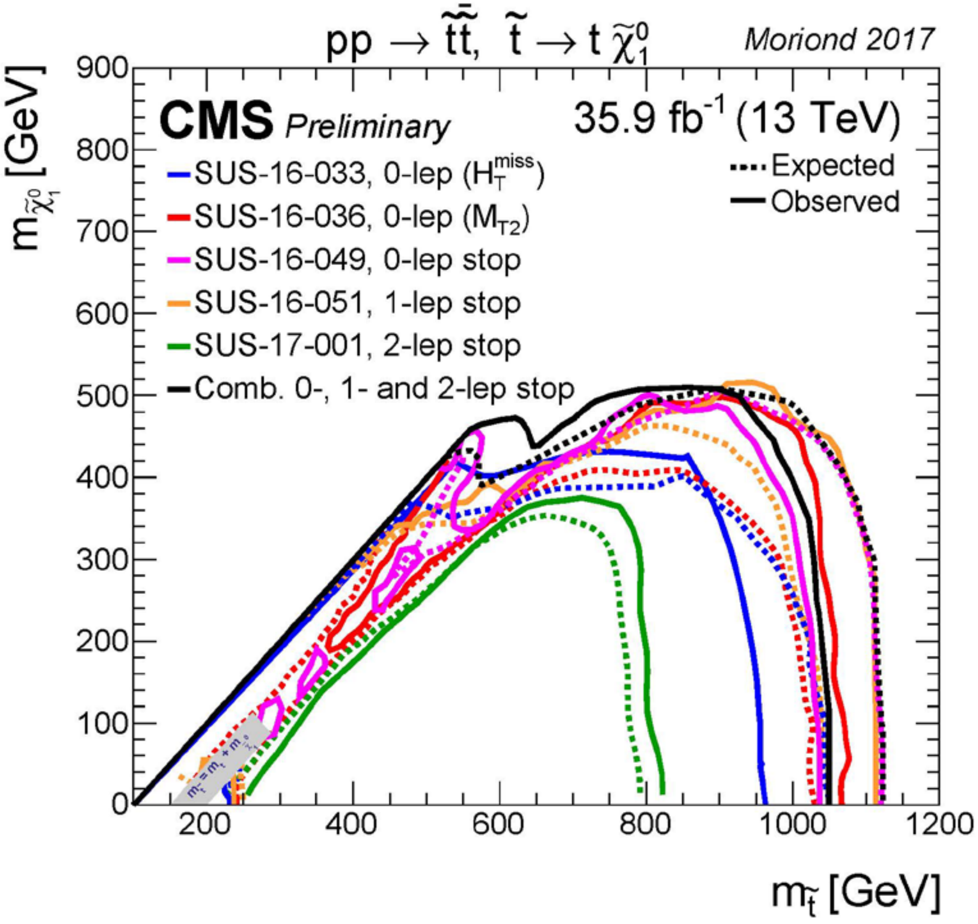
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_2^0 \rightarrow t + l + \tilde{l}^* \rightarrow t + l + \bar{l} + \tilde{\chi}_1^0,$$
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm \rightarrow t + \nu + \tilde{l} \rightarrow t + l + \nu + \tilde{\chi}_1^0$$
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

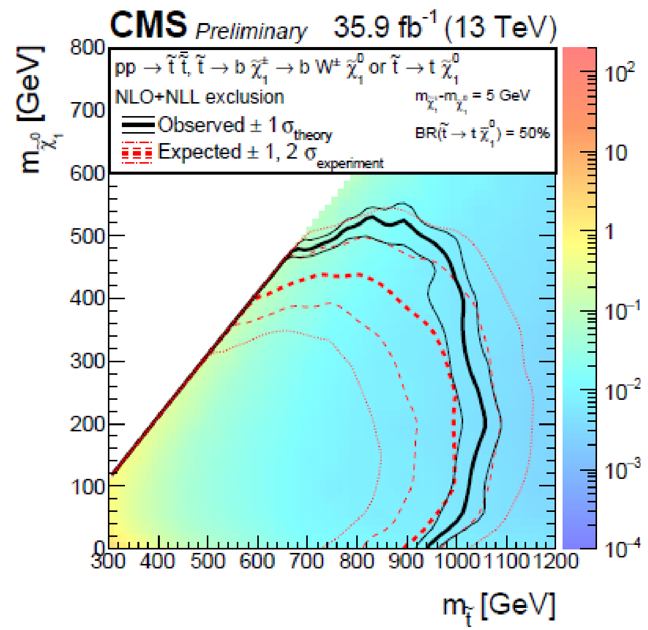
2 jets+ 2 leptons (OSSF-OSDF) +missing energy

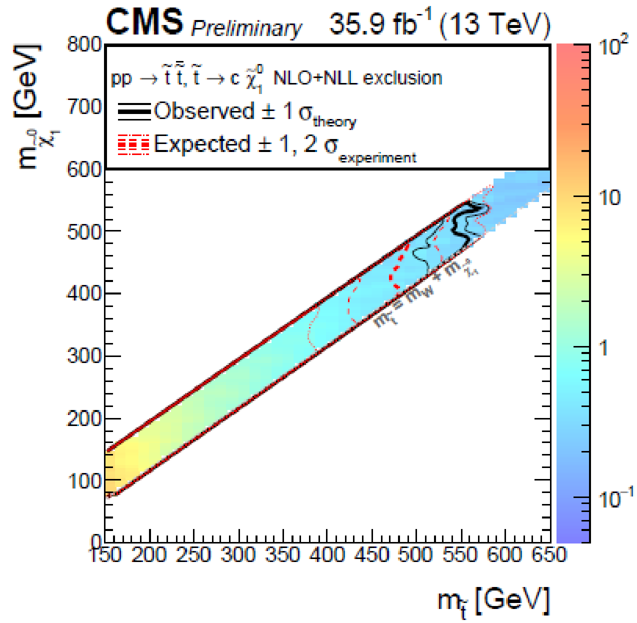
Dutta, Kamon, Kolev,Wang, Wu, '13

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

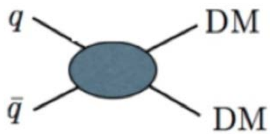
Stop at the LHC





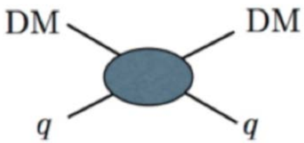


3. Jet(s) + Missing energy +…



: **Collider Searches**

Correlated to:



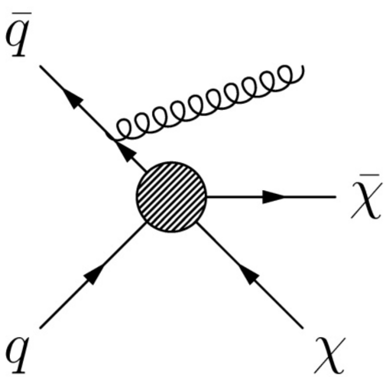
Direct detection

Effective Operators, e.g.,

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

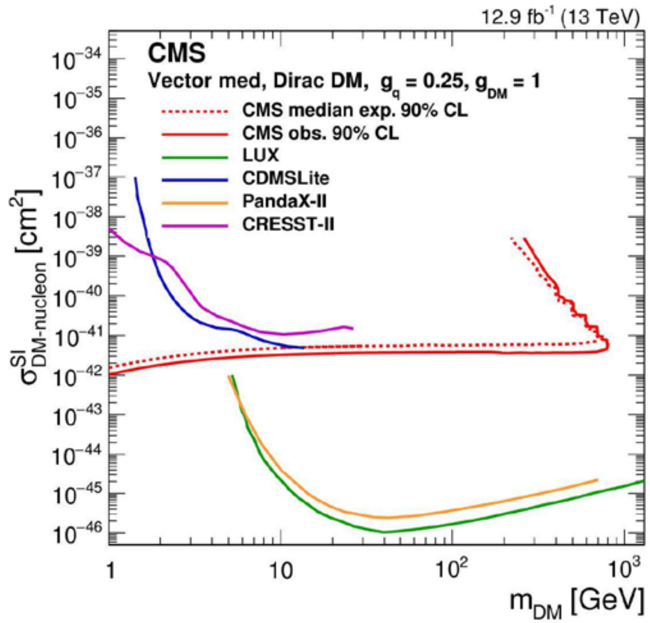
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

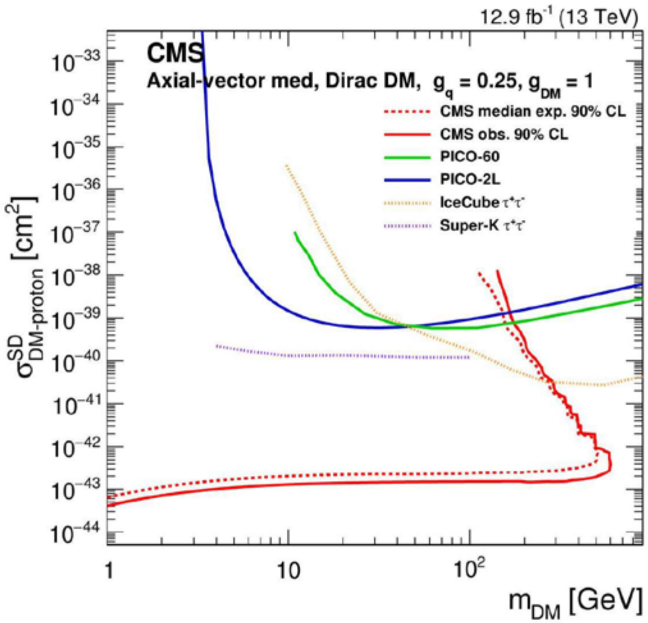
Dark Matter production ➔missing energy
Jets from a gluon radiated from quarks➔
Monojet + MET (similarly monophoton+MET)

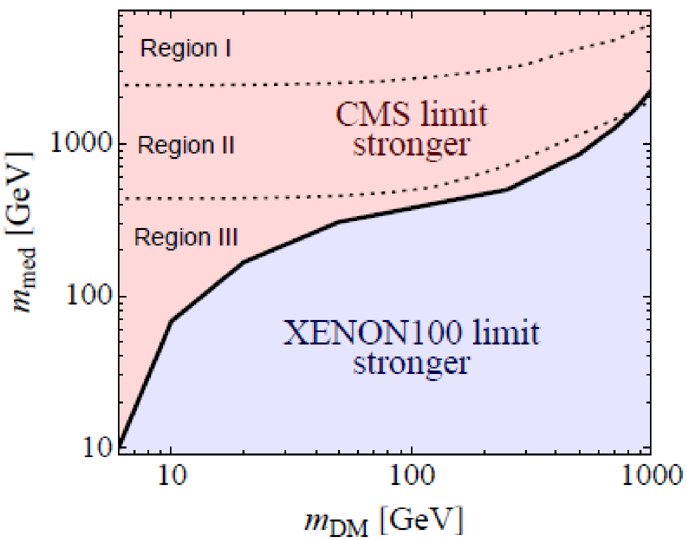


[**Bai,Fox and Harnik,JHEP 1012:048 (2010)]; Goodman, Ibe,Rajaraman, Shepherd,Tait,Yu, Phys.Rev.D82:116010 (2010)**]

Monojet Searches







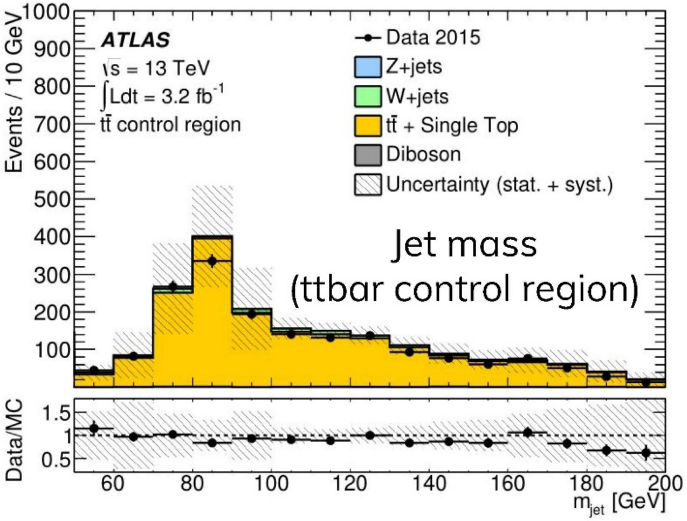
"Comparing only the EFT limit with direct searches is misleading and can lead to incorrect conclusions about the relative sensitivity of the two search approaches."

Buechmueller, Dolan, Mccabe, '13

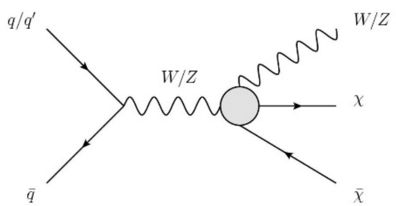
Mono-W

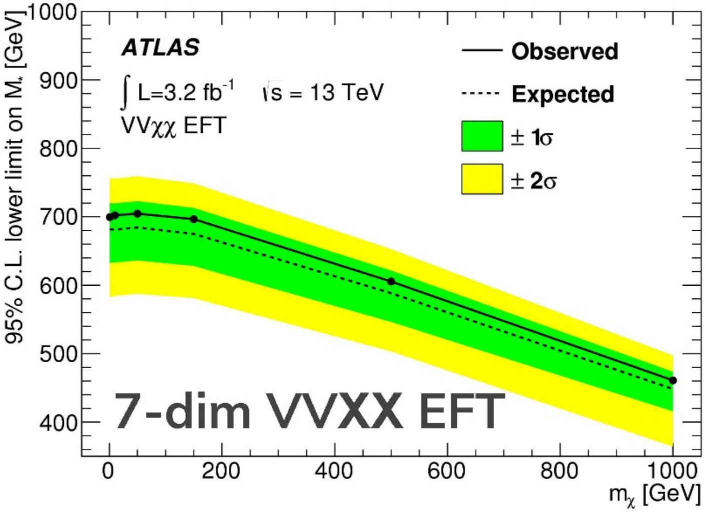
Mono-W/Z (hadronic)

Vector boson tagging using jet mass and substructure information is a key tool here.



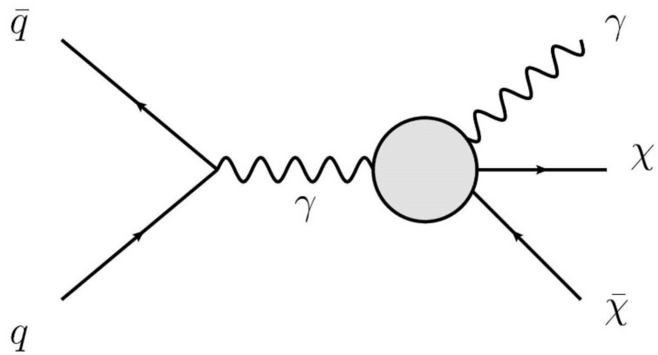
The **tagging efficiency is a major source of uncertainty** with 5-15% effect on signal yield.

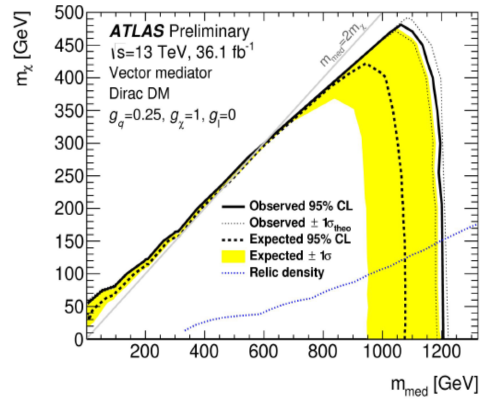


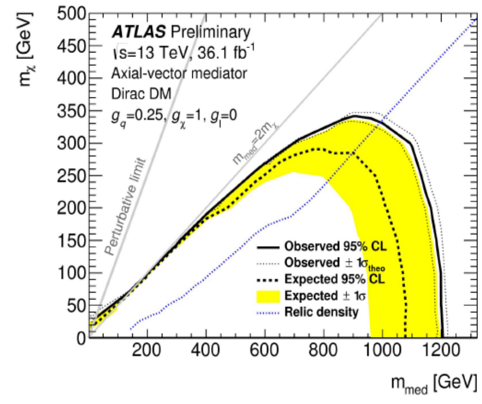


Uniquely, this channel allows us to probe for a **VVXX contact interaction.**

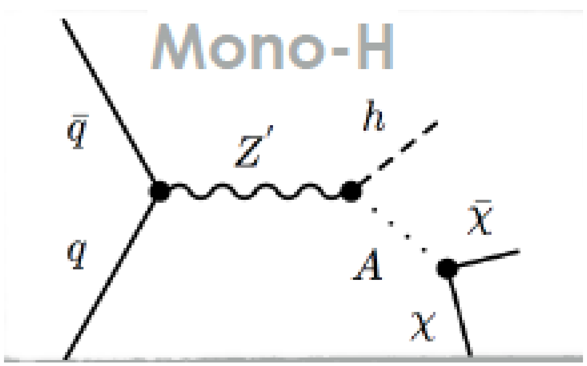
Mono-photon

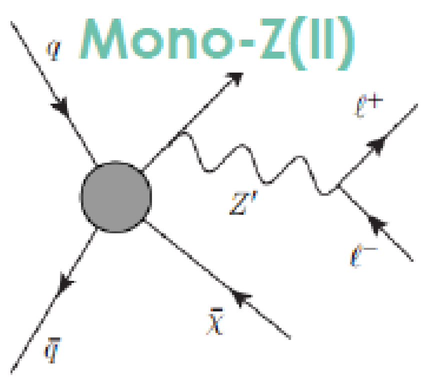


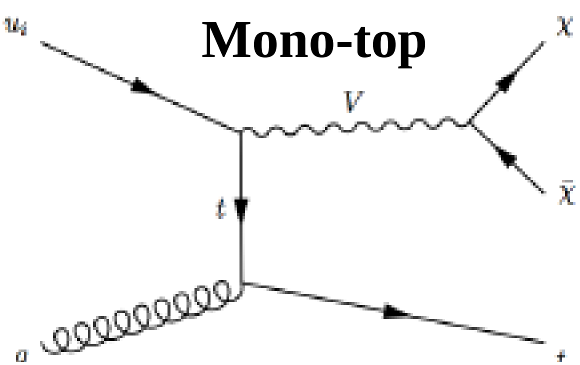




Various mono-X searches







Jets + missing energy

Realistic model: jets plus more final states

New Particles: Heavy colored states: $X, \overline{X}$

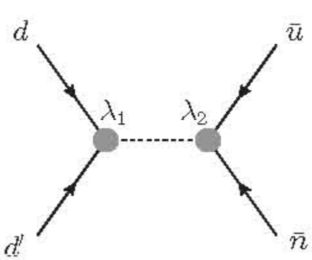
SM Singlet: N

$$L_{new} = \lambda_{1ij} X_{\alpha} d_i^c d_j^c + \lambda_{2ai} X_{\alpha}^{*} N u_i^c + m_{\alpha}^2 |X_{\alpha}|^2 + \frac{m_N}{2} NN + \text{h.c.} + \text{kinetic terms}$$

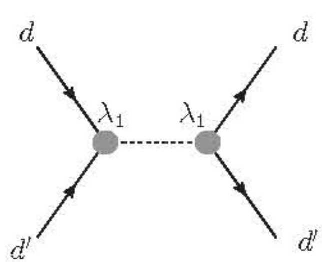
Explain Baryon and Dark Matter abundances and mini coincidence puzzle

If N is the DM candidate, i.e., $m_N \sim m_p$

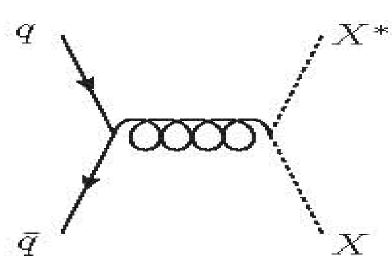
Allahverdi, Dutta, Mohapatra, '13;
Allahverdi, Dutta, '13;



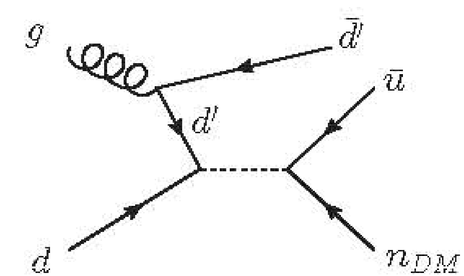
Monojet



Dijet



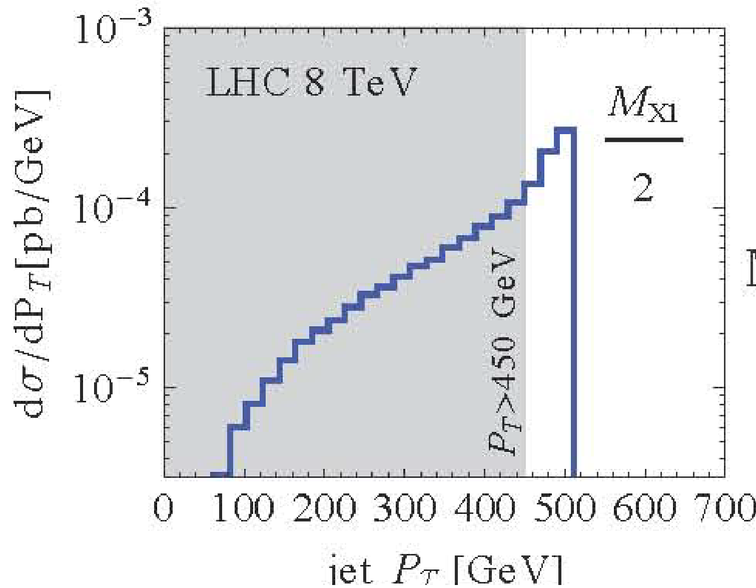
Dijet pair



Dijet + Missing Energy

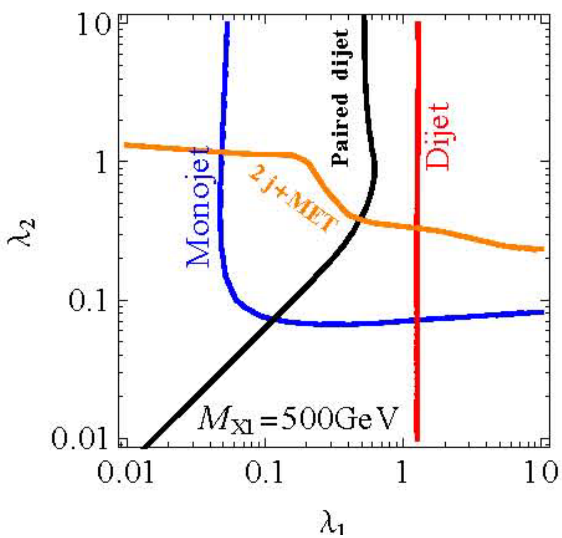
Dutta, Gao and Kamon'13

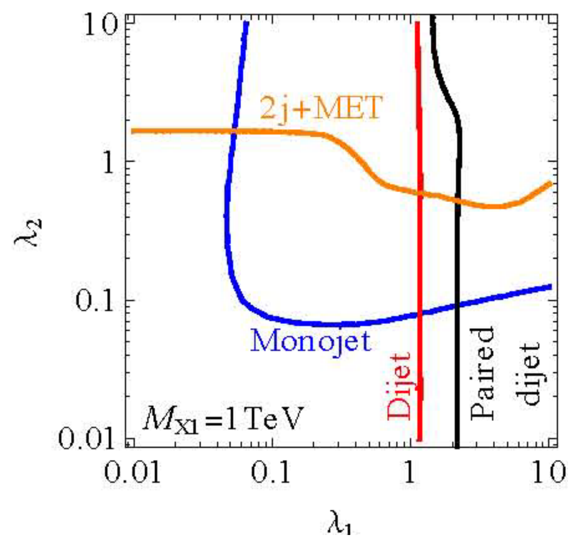
DM via Jets +missing energy

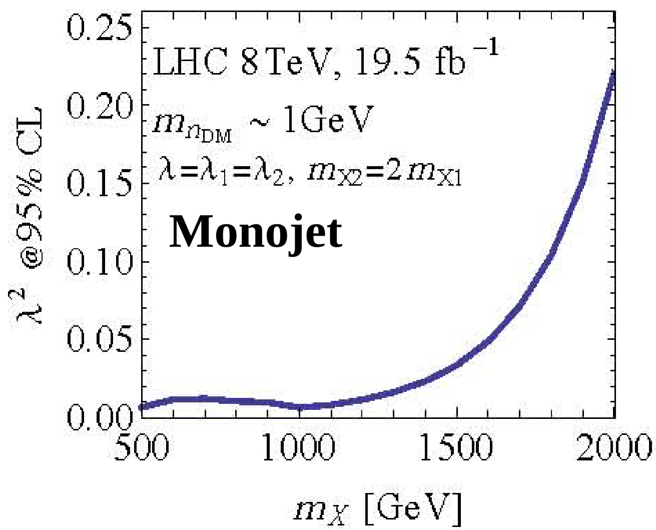


Monojet p_T distribution for M_{X1}=1 TeV

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





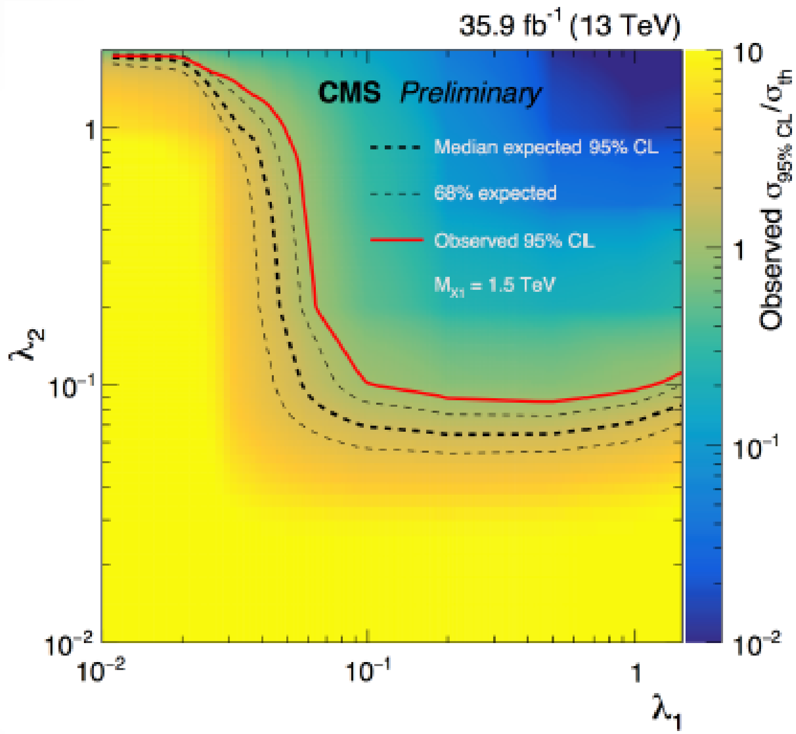


Combining various observables, we can probe <σv>

DM via Jets +missing energy

Non-thermal DM Interpretation

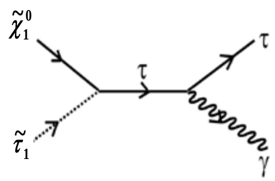
$L_{new} = \lambda_{1ij} X_\alpha d_i^c d_j^c + \lambda_{2ai} X_\alpha^* N u_i^c + m_\alpha^2 |X_\alpha|^2 + \frac{m_N}{2} NN +$ h.c. + kinetic terms



CMS PAS EXO-16-048

95% CL expected (black dashed line) and observed (red solid line) upper limits on $\mu = \sigma/\sigma_{\rm th}$ for a nonthermal DM particle for mediator mass M_{X1}=1.5 TeV, in the $\lambda_1 - \lambda_2$ plane.

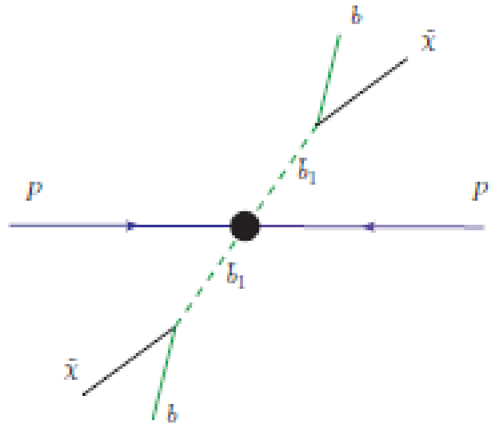
Small ΔM

$\Omega_{CDM}^{-1} \propto \Big[$  $\Big]^2 + \ldots\ e^{-\Delta M / kT_f}$

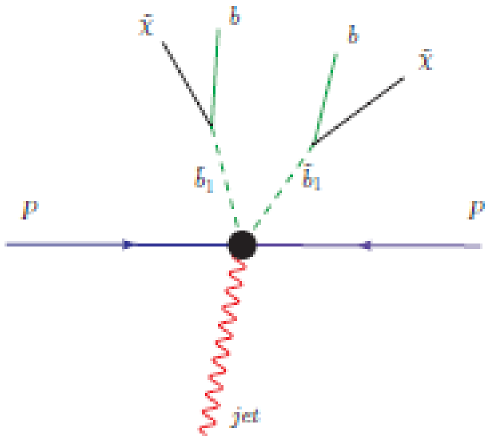
$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$$

Direct production:

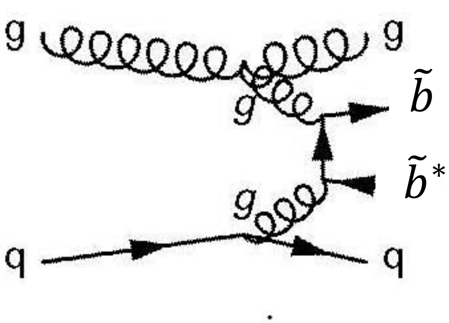
Small mass gaps➔ no missing energy

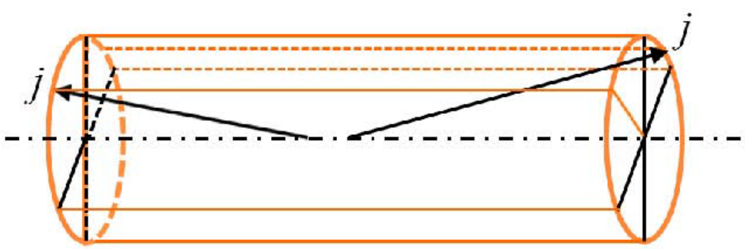


1. Direct production +jet:

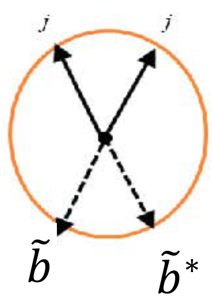


2. Direct production + 2 jets with VBF topology:





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

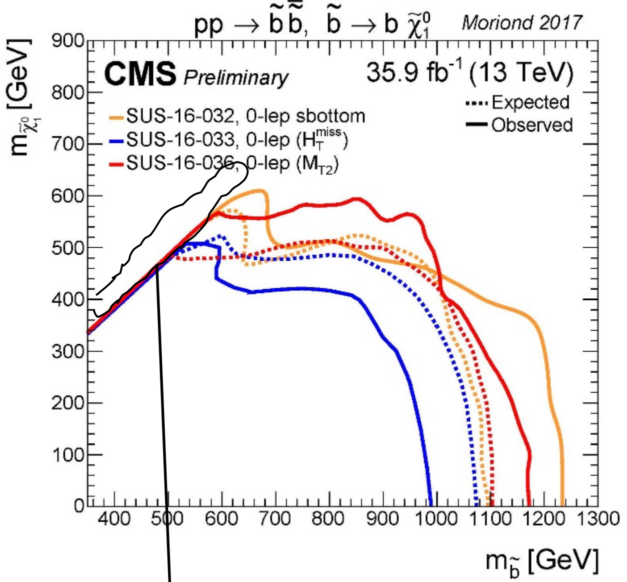


VBF production topology in transverse plane

Backgrounds are different for these two final states

Monojet, VBF: sbottoms

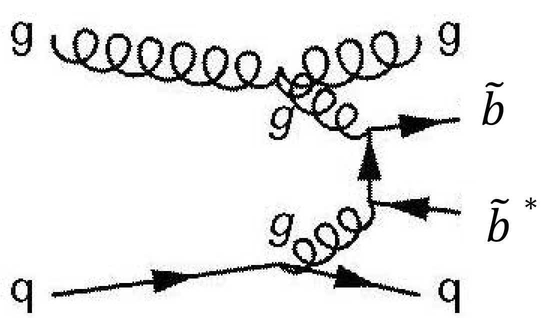
Sbottom



Cosmologically interesting

VBF cuts

Missing E_T > 50 GeV,
2 leading jets (j_1,j_2) :p_T (j_1),p_T(j_2) >50 GeV ,
$|\Delta\eta(j_1, j_2)|$ > 4.2 and $\eta_{j1}\eta_{j2}$ < 0.
M_{j1j2} > 1500 GeV; p_T(b)<80 GeV
Veto Leptons, $\Delta\phi_{jj}$<1.8



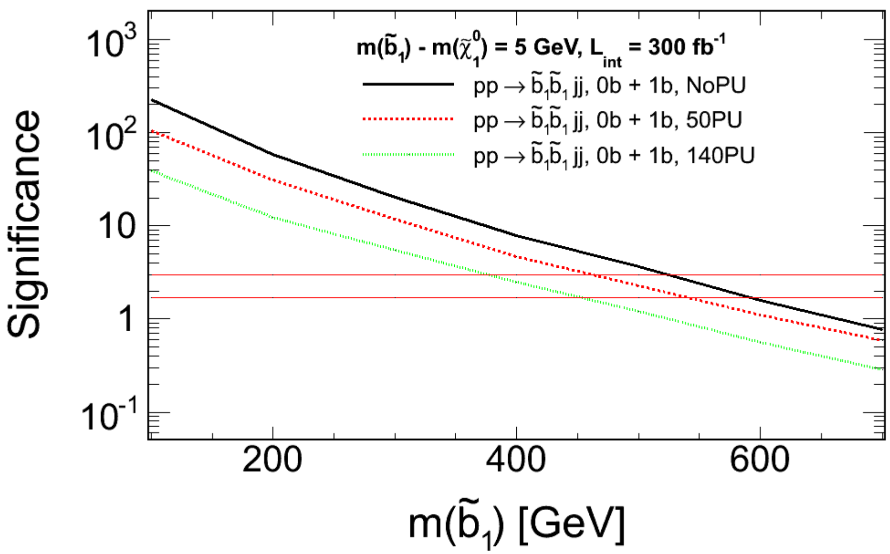
ISR jet+ missing E_T + b

Missing E_T > 400 GeV, p_T(b)<100 GeV
Veto Leptons, $\Delta\phi$(p_T(b), Missing energy)<1.8

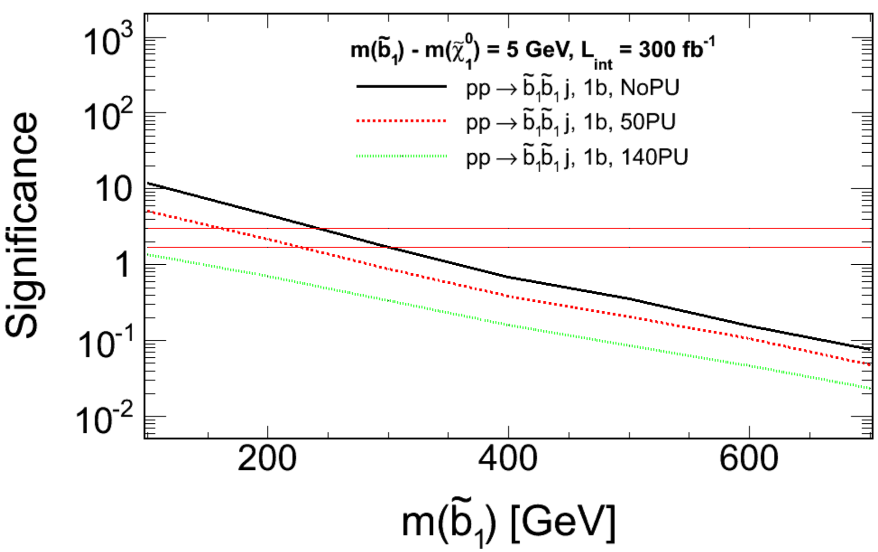
Dutta, Gurrola, Kamon, Wu etal
Phys.Rev. D92 (2015) 095009

Monojet, VBF: sbottoms

Signal: 2 j + 1 b + missing E_T



Signal: ISR jet + 1 b + missing E_T



Reach is better for VBF topology compared to ISR j+1b+ missing E_T

Monjet, VBF: $\tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{\chi}_i^{\pm}, \tilde{\chi}_i^0$

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

- **The weak Bosons from protons can produce them**

  ➔VBF (2 high E_T jets, $|\Delta\eta(j_1, j_2)| > 4.2$ and $\eta_{j1}\eta_{j2} < 0$)

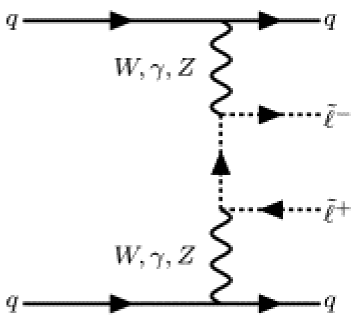
- **Monojet + e, μ, τ final states**

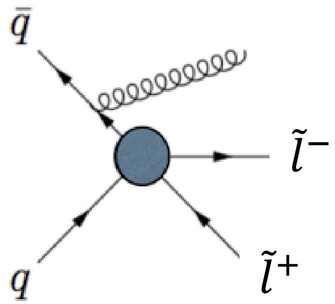
Compressed $\tilde{e}, \tilde{\mu}$

Small mass gap measurements using VBF topology, monojet+leptons➔Various Coannihilation regions:

$$\tilde{\mu}, \tilde{e} - \tilde{\chi}_1^0$$

VBF





Monojet+leptons

Dutta, Ghosh, Gurrola, Kamon, Sinha, Wang, Wu; '14;

Han, Liu '15

$pp \to \tilde{\mu}\tilde{\mu}j(j)$ **Signal:** $2(1)\,j + 2\mu +$ **missing energy,**

$pp \to \tilde{\nu}\,\tilde{\mu}j(j)$ **Signal:** $2(1)\,j + 1\mu +$ **missing energy,**

$$\Delta m = m_{\tilde{\mu},\tilde{e}} - m_{\tilde{\chi}_1^0} \leq 60 GeV$$

Monojet+Leptons: $\tilde{e}, \tilde{\mu}$

$\Delta\phi(l_1, l_2), \Delta\phi(l_{1,2}$, missing-$E_T), \Delta\phi(j$, missing–ET) are very useful

Selection	$t\bar{t}jj$	$ZZjj$	$WZjj$	$WWjj$	S^{110}_{10}	S^{110}_{20}	S^{110}_{30}	S^{110}_{40}	S^{110}_{50}	S^{110}_{60}
Small Mass Gap Optimization										
$1.0 < P_T^j \div \not{E}_T < 1.3$	4.5×10^{-1}	2.7×10^{-3}	6.2×10^{-2}	6.6×10^{-1}	$\mathbf{4.2 \times 10^{-1}}$	$\mathbf{3.0 \times 10^{-1}}$	2.4×10^{-1}	1.8×10^{-1}	1.6×10^{-1}	1.4×10^{-1}
$\Delta\phi(\not{E}_T, j) \div \pi > 0.95$	1.8×10^{-1}	2.2×10^{-3}	2.7×10^{-2}	3.8×10^{-1}	$\mathbf{4.0 \times 10^{-1}}$	$\mathbf{2.3 \times 10^{-1}}$	1.7×10^{-1}	9.6×10^{-2}	7.7×10^{-2}	6.2×10^{-2}
Events at $\mathcal{L} = 300$ fb^{-1}	52.7	0.7	8.1	113.6	**120.0**	**69.0**	51.0	28.8	23.1	18.6
$S \div (1 + B)$	-	-	-	-	**0.68**	**0.39**	0.29	0.16	0.13	0.11
$S \div \sqrt{1 + B}$	-	-	-	-	**9.0**	**5.2**	3.8	2.2	1.7	1.4
Intermediate Mass Gap Optimization										
$\Delta\phi(\ell_1, \ell_2) \div \pi > 0.5$	1.1×10^{0}	7.7×10^{-3}	1.2×10^{-1}	1.3×10^{0}	4.0×10^{-1}	4.0×10^{-1}	$\mathbf{4.4 \times 10^{-1}}$	$\mathbf{4.1 \times 10^{-1}}$	3.7×10^{-1}	3.9×10^{-1}
$\Delta\phi(\not{E}_T, \ell_1) \div \pi < 0.6$	4.8×10^{-1}	5.5×10^{-3}	7.9×10^{-2}	9.0×10^{-1}	3.7×10^{-1}	3.3×10^{-1}	$\mathbf{3.3 \times 10^{-1}}$	$\mathbf{3.0 \times 10^{-1}}$	2.4×10^{-1}	2.1×10^{-1}
$\Delta\phi(\not{E}_T, \ell_2) \div \pi < 0.6$	1.8×10^{-1}	4.4×10^{-3}	4.8×10^{-2}	5.1×10^{-1}	2.7×10^{-1}	2.3×10^{-1}	$\mathbf{2.2 \times 10^{-1}}$	$\mathbf{2.0 \times 10^{-1}}$	1.6×10^{-1}	1.4×10^{-1}
Events at $\mathcal{L} = 300$ fb^{-1}	52.8	1.3	14.5	151.7	81.0	69.0	**66.0**	**60.0**	48.0	42.0
$S \div (1 + B)$	-	-	-	-	0.37	0.31	**0.30**	**0.27**	0.22	0.19
$S \div \sqrt{1 + B}$	-	-	-	-	5.4	4.6	**4.4**	**4.0**	3.2	2.8
Large Mass Gap Optimization										
$\Delta\phi(\not{E}_T, \ell_1) \div \pi > 0.25$	8.5×10^{-1}	6.6×10^{-3}	1.0×10^{-1}	9.5×10^{-1}	2.4×10^{-1}	2.7×10^{-1}	3.3×10^{-1}	2.9×10^{-1}	$\mathbf{3.0 \times 10^{-1}}$	$\mathbf{3.3 \times 10^{-1}}$
$P_T^{\ell 2} > 40$ GeV	3.4×10^{-1}	5.6×10^{-4}	3.7×10^{-2}	4.1×10^{-1}	1.1×10^{-2}	7.3×10^{-2}	1.4×10^{-1}	1.5×10^{-1}	$\mathbf{2.1 \times 10^{-1}}$	$\mathbf{2.4 \times 10^{-1}}$
Events at $\mathcal{L} = 300$ fb^{-1}	102.2	0.2	11.0	124.3	3.3	21.9	42.0	45.0	**63.0**	**72.0**
$S \div (1 + B)$	-	-	-	-	0.01	0.09	0.18	0.19	**0.26**	**0.30**
$S \div \sqrt{1 + B}$	-	-	-	-	0.2	1.4	2.7	2.9	**4.1**	**4.7**

Dutta, Fantahun, Fernando, Ghosh, Kumar, Sandick, Stengel, Walker, arXiv:1706.05339

Monojet+Leptons: $\tilde{e}, \tilde{\mu}$

Benchmark	S_{10}^{160}	S_{20}^{160}	S_{30}^{160}	S_{40}^{160}	S_{50}^{160}	S_{60}^{160}
Events at $\mathcal{L} = 300$ fb^{-1}	43.4	39.8	24.5	27.5	29.5	28.3
$S \div (1 + B)$	0.24	0.22	0.11	0.12	0.12	0.12
$S \div \sqrt{1 + B}$	3.3	3.0	1.7	1.8	1.9	1.8
Benchmark	S_{10}^{200}	S_{20}^{200}	S_{30}^{200}	S_{40}^{200}	S_{50}^{200}	S_{60}^{200}
Events at $\mathcal{L} = 1000$ fb^{-1}	72.1	67.3	41.8	45.8	52.9	63.6
$S \div (1 + B)$	0.12	0.11	0.06	0.06	0.07	0.08
$S \div \sqrt{1 + B}$	3.0	2.8	1.5	1.7	1.9	2.3
Benchmark	S_{10}^{300}	S_{20}^{300}	S_{30}^{300}	S_{40}^{300}	S_{50}^{300}	S_{60}^{300}
Events at $\mathcal{L} = 3000$ fb^{-1}	48.7	55.4	31.7	33.8	46.8	60.7
$S \div (1 + B)$	0.03	0.03	0.01	0.02	0.02	0.03
$S \div \sqrt{1 + B}$	1.2	1.3	0.7	0.7	1.0	1.2

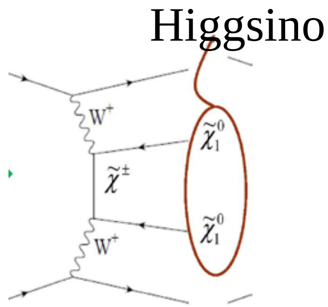
1.5-3 σ exclusion for $m_{\tilde{\mu}}$= 200 GeV with $\Delta m \leq 60$GeV at 1000 fb^{-1}!

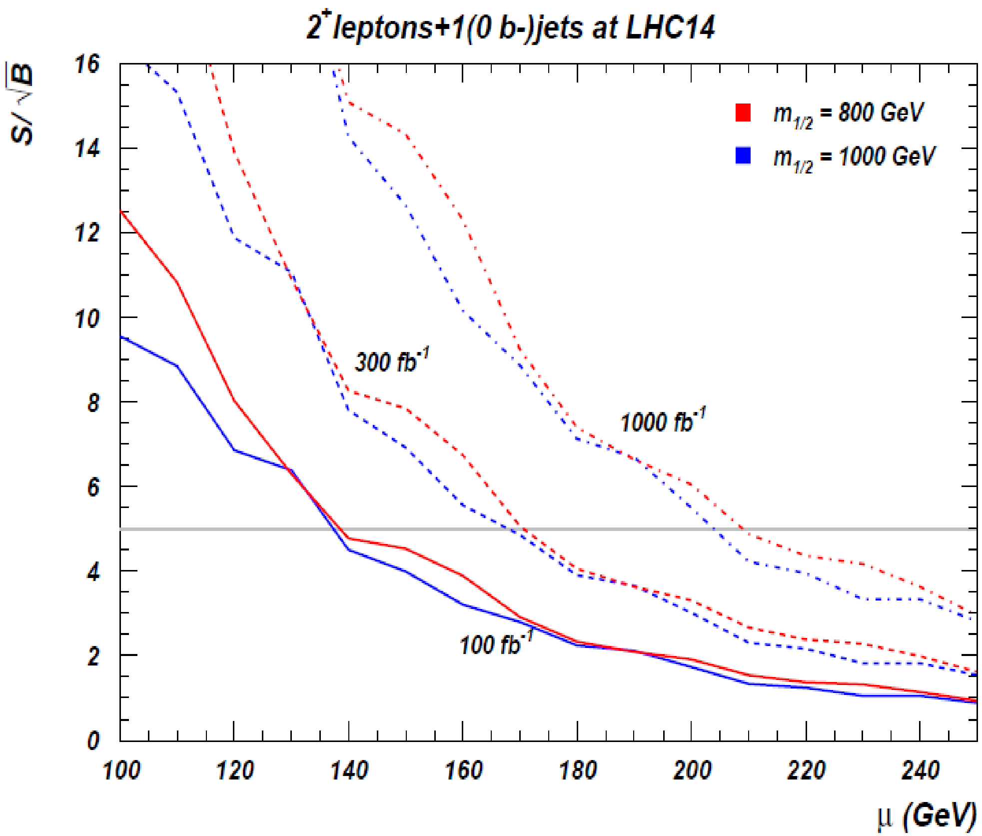
Monojet+Leptons: Higgsinos

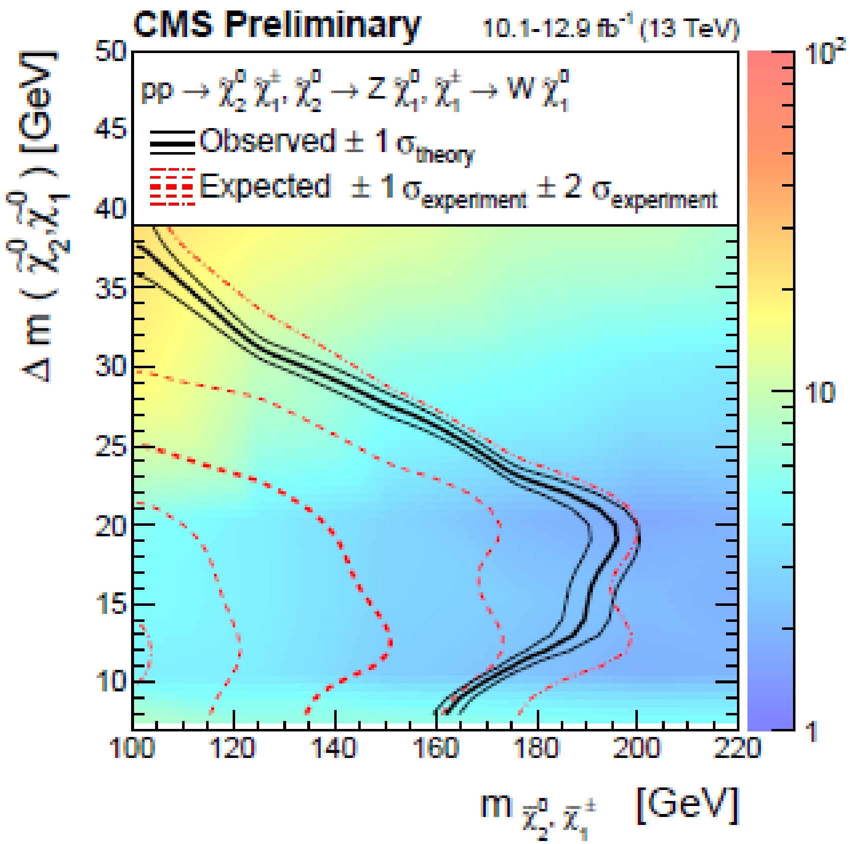
Higgsino type $\chi^0_{1,2}$ (cosmologically interesting):

The mass difference between χ^0_1 and χ^0_2, $\chi^\pm_1$: 10 GeV

ISR+missing E_T+Leptons







Baer, Mustafayev, Tata, Phys.Rev. D90 (2014), 115007

Compressed $\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^0$ Via VBF

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

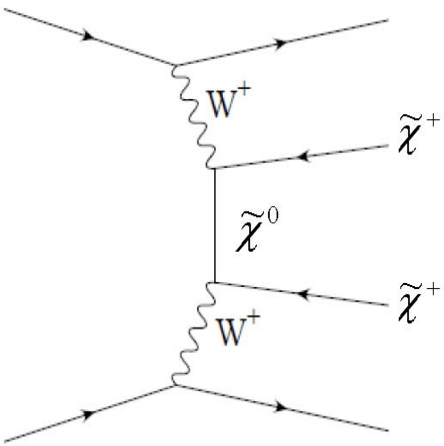
For : $m_{\chi_1^{\pm}}, m_{\chi_2^0} > m_{\tilde{l}} > m_{\chi_1^0}$

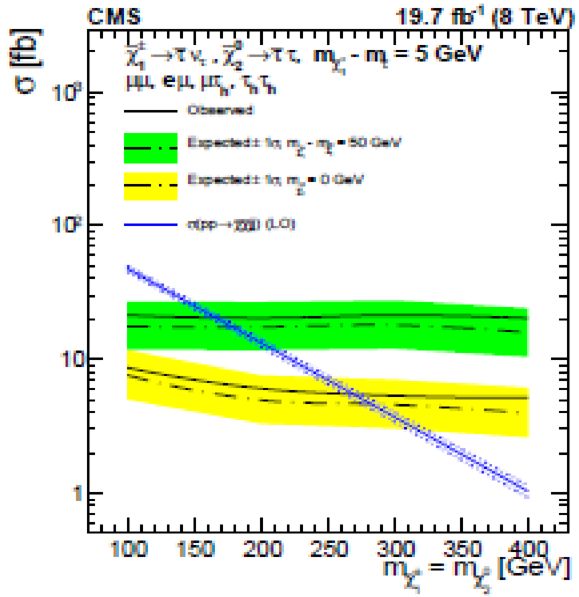
$\tilde{\chi}_1^{\pm}$ **masses between 100 and 400 GeV are excluded for mass-less $\tilde{\chi}_1^0$ or for a mass difference > 200 GeV (from $\tilde{\chi}_1^{\pm}$ pair production) with** $m_{\tilde{\tau}} = m_{\tilde{\nu}_\tau} = 0.5\,(m_{\tilde{\chi}_1^{\pm}} + m_{\tilde{\chi}_1^0})$

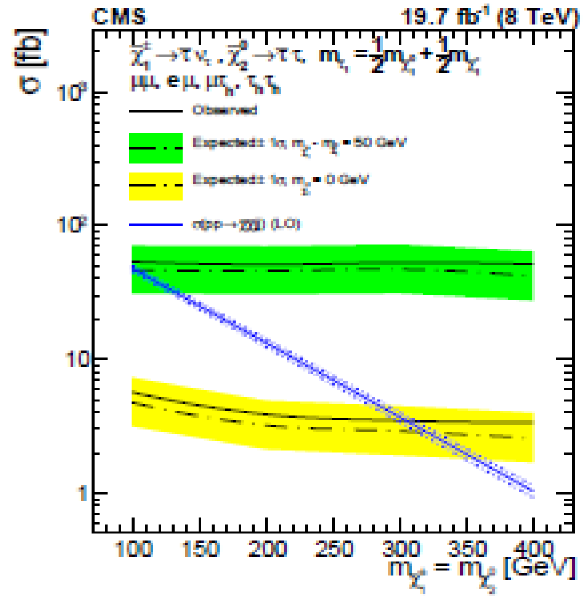
Signal: $\geq 2j + 2\tau +$ **missing energy,** $\geq 2j + 2\mu +$ **missing energy**

➔ **Probe small mass (Δm) difference between chargino and neutralino**

Dutta, Gurrola, Kamon, John, Sinha, Shledon; '13







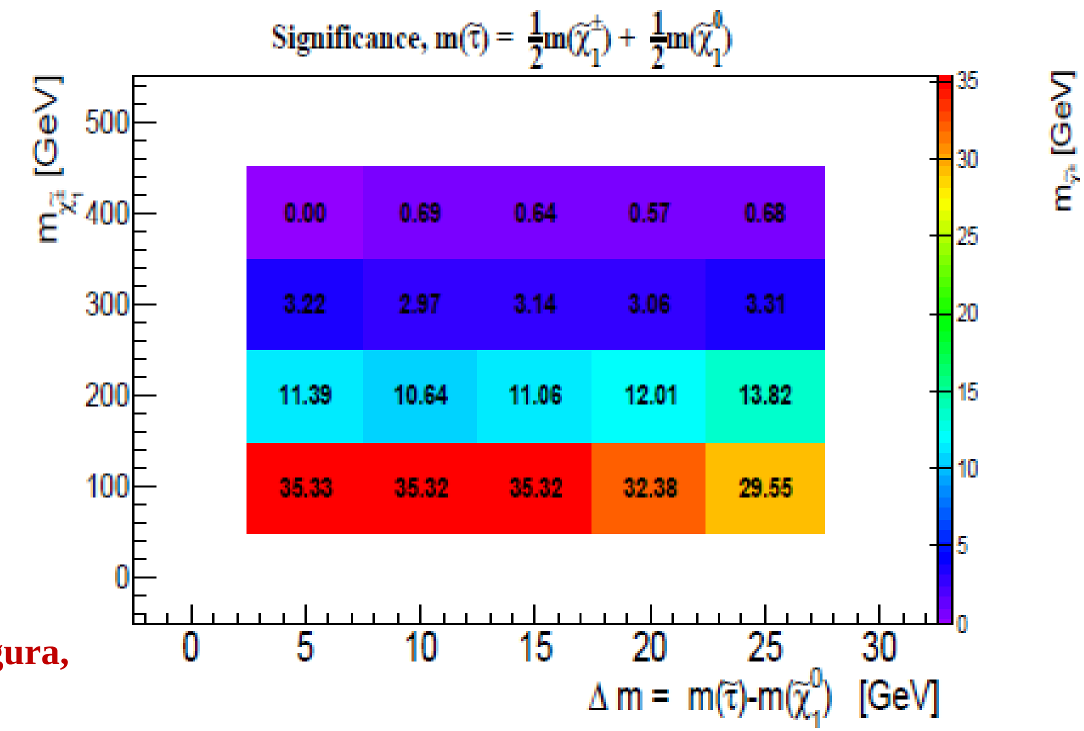
$\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^{0}$: jet+tau+missing energy

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \to \tilde{\tau}\tilde{\tau}\nu_\tau\nu_\tau, \tilde{\chi}_2^{0}\tilde{\chi}_2^{0} \to \tilde{\tau}\tilde{\tau}\tau\tau,$$

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0} \to \tilde{\tau}\tilde{\tau}\nu_\tau\tau \qquad \tilde{\tau} \to \tau\ \tilde{\chi}_1^{0}$$

$\Delta m = m(\tilde{\tau}) - m(\tilde{\chi}_1^{0})$ **is small ➔ One hard Jet+ missing energy +soft τ_h**

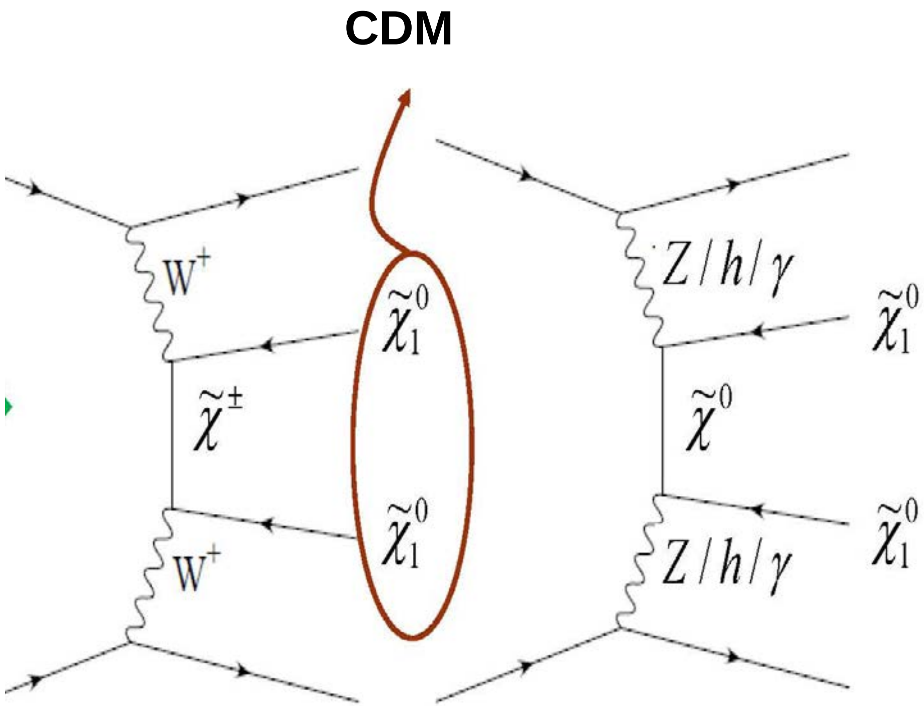
Criterion	Selection
$N(e/\mu)$	0
$N(\tau_h)$	1
$\lvert\eta(\tau_h)\rvert$	< 2.3
N(b-jets)	0
$p_T^{lead}(jet)$	100 GeV
$\Delta R(\tau_h, jet)$	> 0.4
$\lvert\eta(jet)\rvert$	< 2.5
$p_T(\tau_h)$	> 15 GeV & < 35 GeV
p_T^{miss}	> 230 GeV

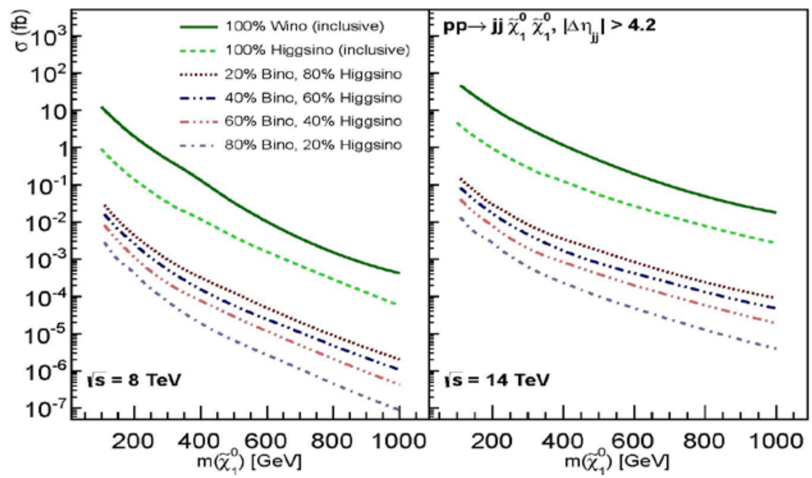


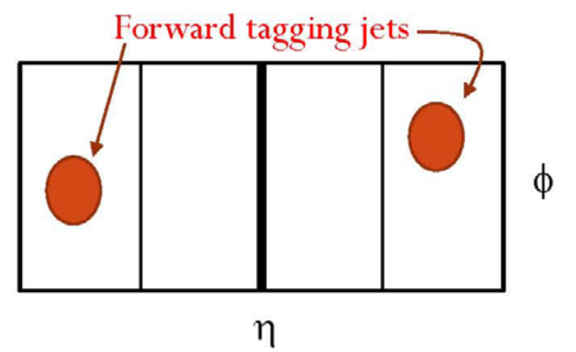
Flórez, Bravo, Gurrola, Ávila, Segura, Sheldon, Johns, '16

Compressed DM Via VBF

$$pp \rightarrow \tilde{\chi}_1^{\,0}\tilde{\chi}_1^{\,0}\, jj$$





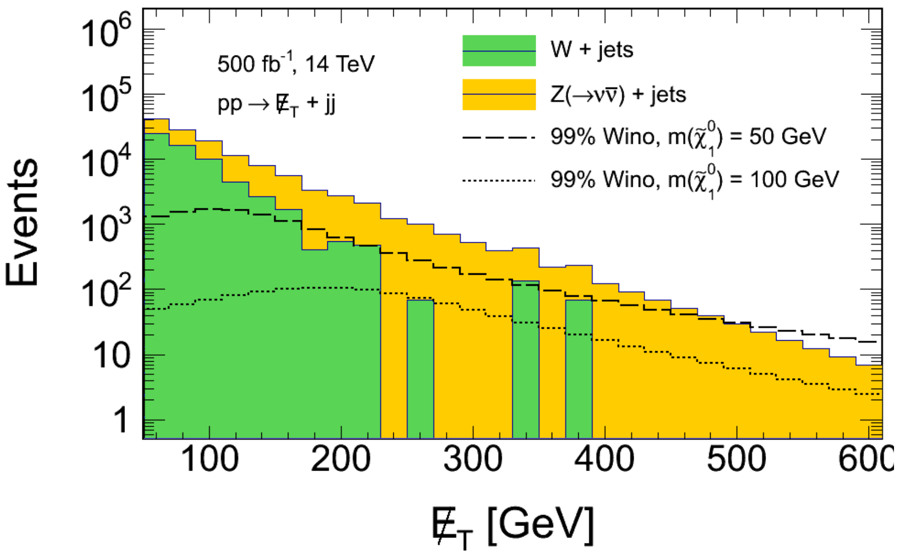


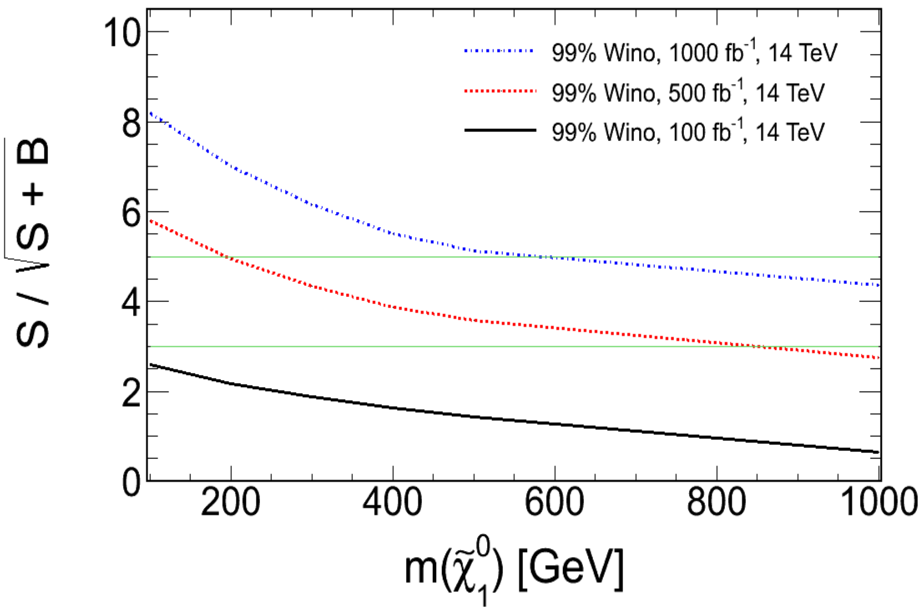
Delannoy, Dutta, Kamon, Sinha, Wang, Wu et al; '13

Cirelli, Sala ,Taoso, '14

Compressed DM 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 , $|\Delta\eta(j_1, j_2)| > 4.2$ and $\eta_{j1}\eta_{j2} < 0$.
Optimization: Tagged jets : p_T > 50 GeV, M_{j1j2} > 1500 GeV;
Events with leptons($l = e; \mu ; \tau_h$) and b-quark jets: rejected.
Missing E_T : optimized for different value of the LSP mass.



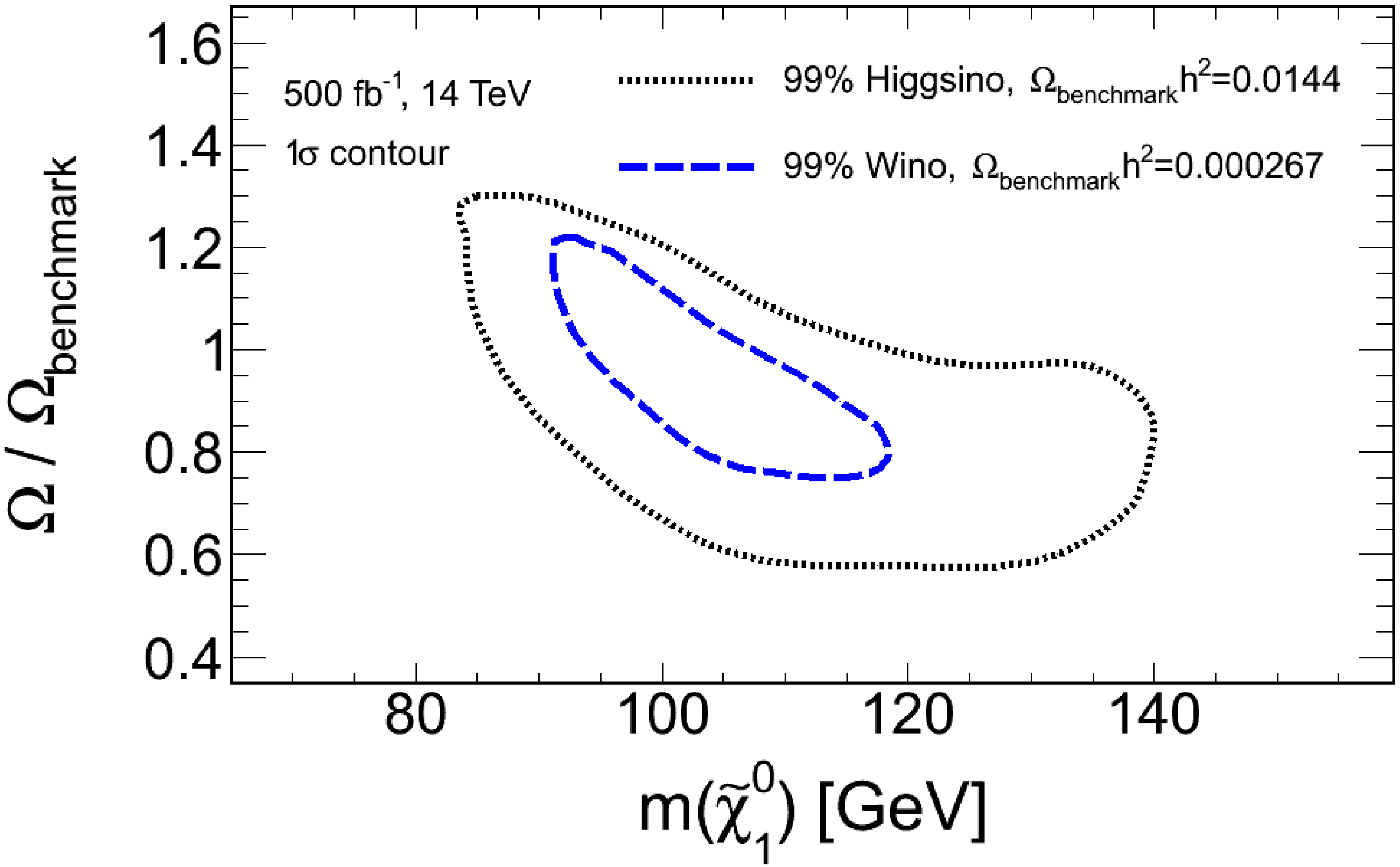


Jet energy scale uncertainty ~20% change the significance by 4%

Delannoy, Dutta, Kamon, Sinha, Wang, Wu et al; '13

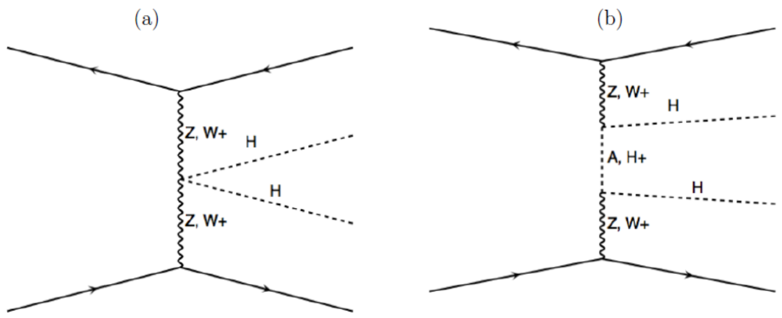
Compressed DM Via VBF

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



VBF DM: Inert Doublet model

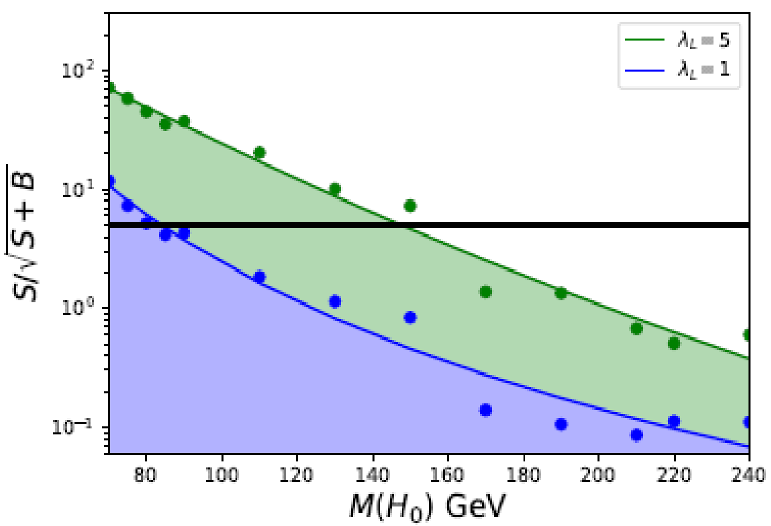
Scalar Dark Matter

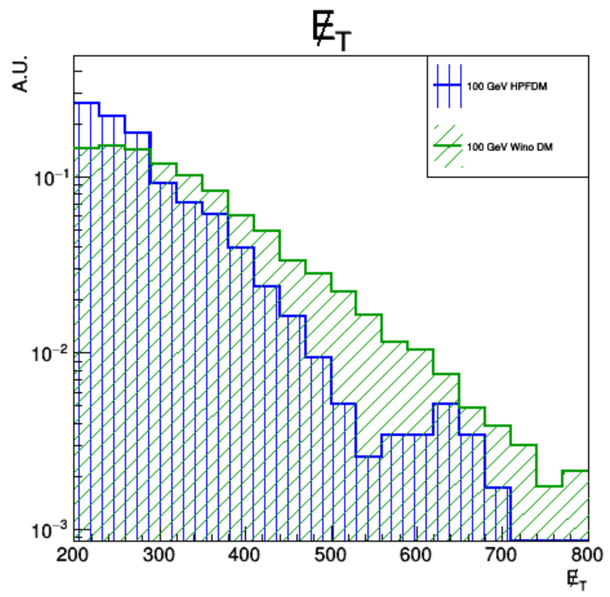


$$V(\Phi) = \mu_1^2 H^\dagger H + \mu_2^2 \Phi^\dagger \Phi + \lambda_2 (\Phi^\dagger \Phi)^2 + \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \Phi)(\Phi^\dagger H) + \frac{\lambda_5}{2}\left[(\Phi^\dagger H)^2 + h.c.\right],$$

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}h^+ \\ h_1 + i h_2 \end{pmatrix}$$

Compare wino-DM with scalar-DM





Alvarez, Cardenas, Dutta, Restrepo (to appear)

Outlook

- **Direct and Indirect detection experiments and collider searches are complimentary in searching for dark matter**

- **The origin of DM content is a big puzzle**
  We will be able to understand the history of the early universe

- **Search for non-colored particle, smaller mass gaps are crucial to tie DM explanations with models at the LHC. However, the reach is not very good**

- **1.5-3 σ exclusion for $m_{\tilde{\mu}}$= 200 GeV with $\Delta m \leq 60$GeV at 1000 fb^{-1}**