Dark Matter Searches at Accelerator Facilities

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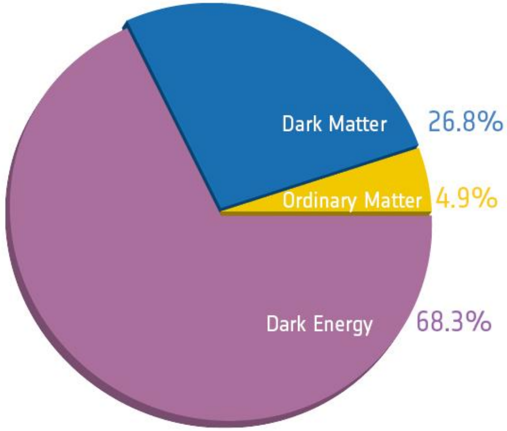
Questions

What kind of particle? What is the mass? What is the spin? What is the associated Model?



Can it be observed at the Colliders? Can we establish the dark matter content from the LHC data?

Do we have more components of dark matter? Is it thermal or non-thermal in nature?

What have we learnt so far from the LHC, Direct and Indirect Detection experiments? What is the current status of DM explanations?

Outline

(i) Thermal/Non-thermal/multi-component dark matter

(ii) LHC status of new physics

(iii) LHC and Dark Matter

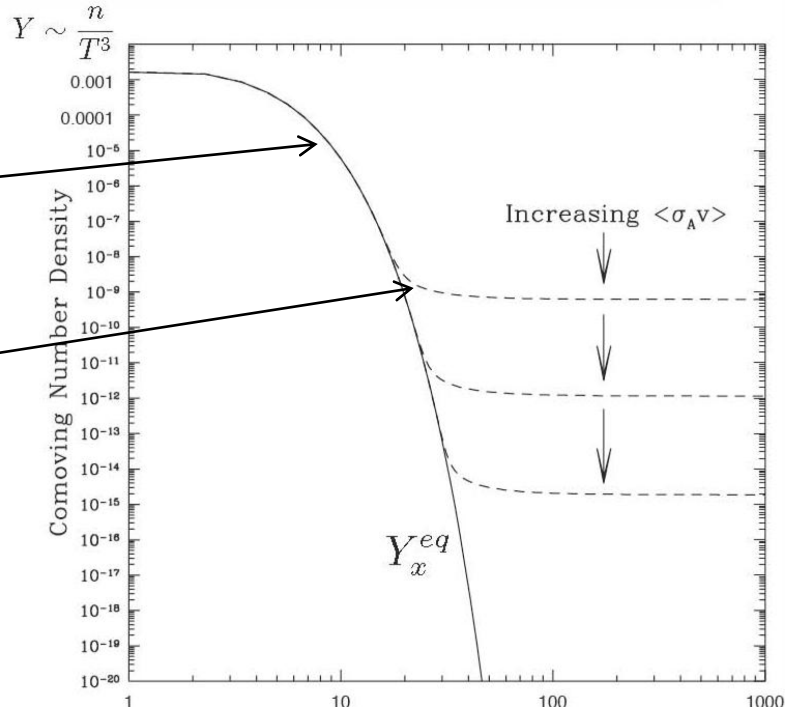
(iv) Conclusion

Dark Matter: Thermal

Production of thermal non-relativistic DM:

$$DM + DM \Leftrightarrow f + \bar{f}$$

Non-relativistic



m/T ⟶

Freeze-Out: Hubble expansion dominates over the interaction rate

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

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

➔ $\langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$

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

α_χ~O(10^{-2}) with m_χ ~ 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

Dark Matter: Non-Thermal

$< \sigma_{ann} v >$: **different from thermal average,** $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$ **is not 26%**

<u>Non-thermal DM can be a solution</u>

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:

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

T_r **~ MeV : Not allowed by BBN**

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

Abundance of decay products $Y_\phi \equiv \frac{3T_r}{4m_\phi}$

DM content: also need to consider the DM annihilation.

Inflation

↓

Radiation domination

↓

moduli domination

Decay of moduli → ↓

radiation domination

↓

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 $\Omega \rightarrow 26\%$

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

Outcome:

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

Since $\phi \rightarrow DM +$other particles, abundance (for $T_r \ll T_f$): 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** $< \sigma_{ann} v >$

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

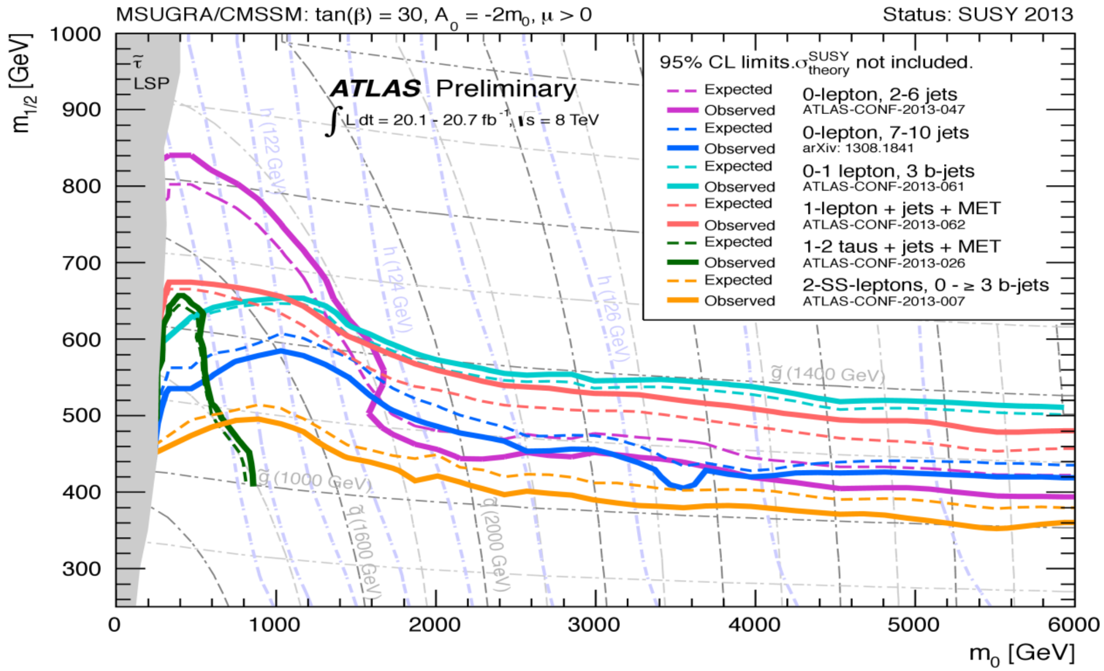
    Annihilation into photons: Fermi, H.E.S.S.

    Annihilation into neutrinos: IceCube

    Annihilation into electron-positrons: AMS

LHC status

Begin with the simplest model: mSUGRA/CMSSM



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

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)

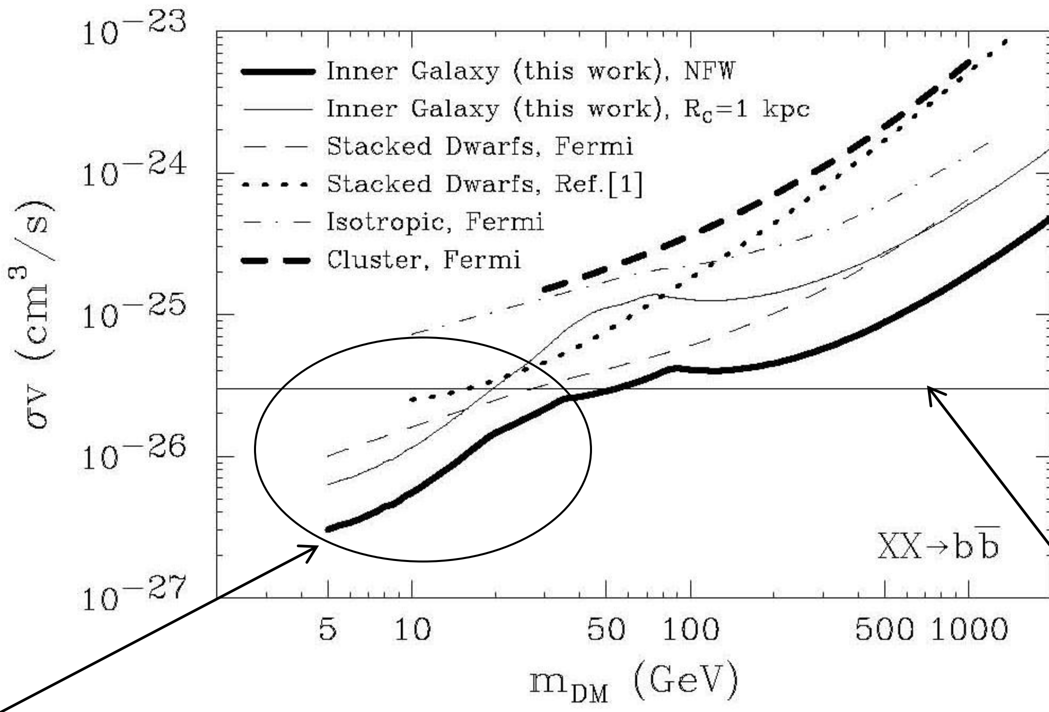
Indirect Detection

The current rate of annihilation of DM particles: $<\sigma_{ann}v>_o$

DM content: $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$ $<\sigma_{ann}v>_o$ **: 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%

$<\sigma_{ann}v>_o$ **: smaller than the thermal value**

Large cross-section is constrained

Establishing DM at the LHC

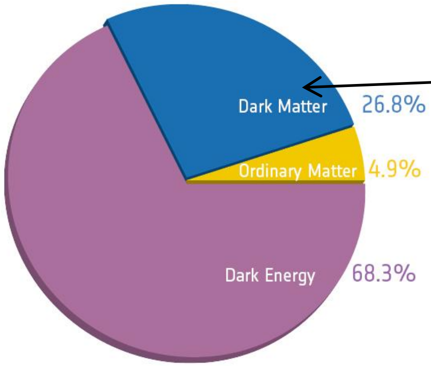
Annihilation of lightest neutralinos ➔ SM particles

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

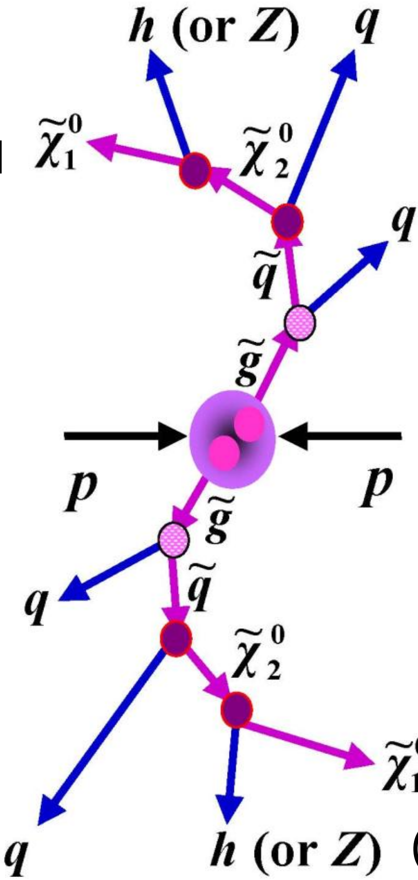
How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section $< \sigma_{ann} v >$?

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

1. Via Cascade decays at the LHC



DM



(or l^+l^-, τ+τ−)

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^-, τ+τ−)

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

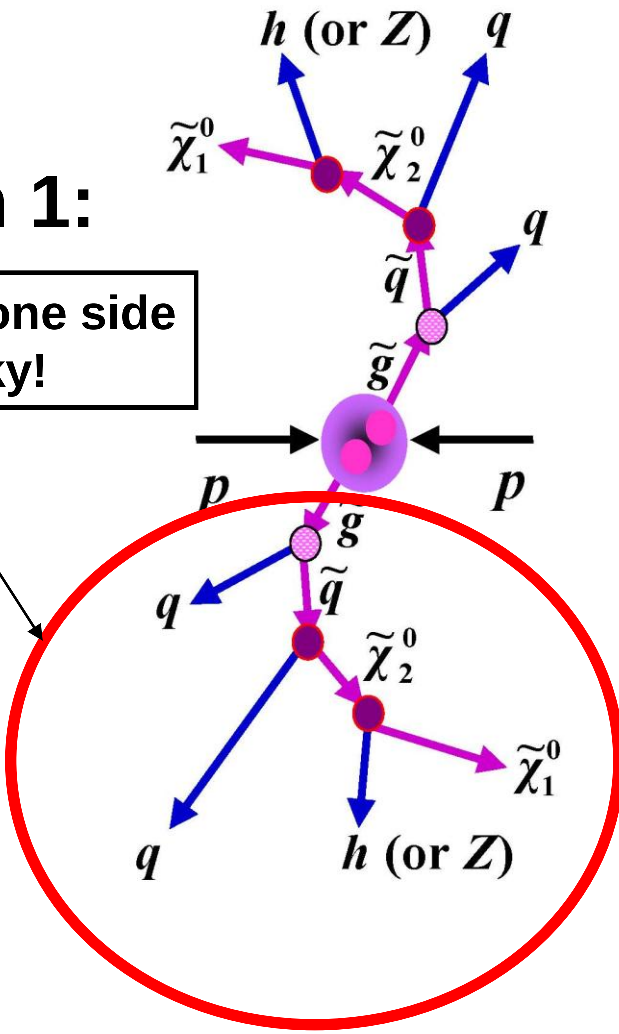
$$\tilde{Q} \to q + l + \tilde{\chi}_1^0 \quad \tilde{L} \to l + \tilde{\chi}_1^0$$

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

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

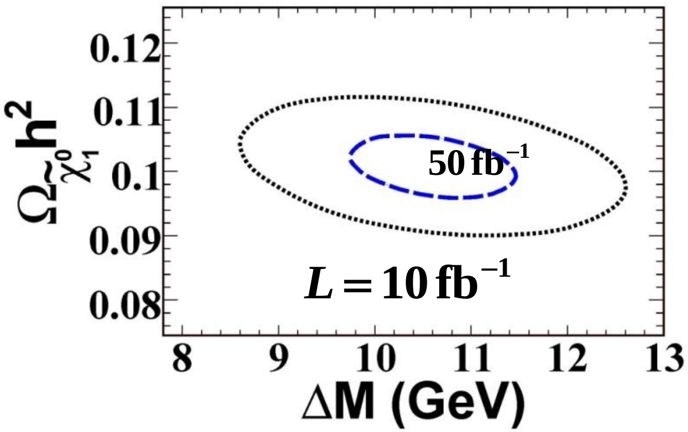
Problem 2:

Not all the sparticles appear in cascade decays

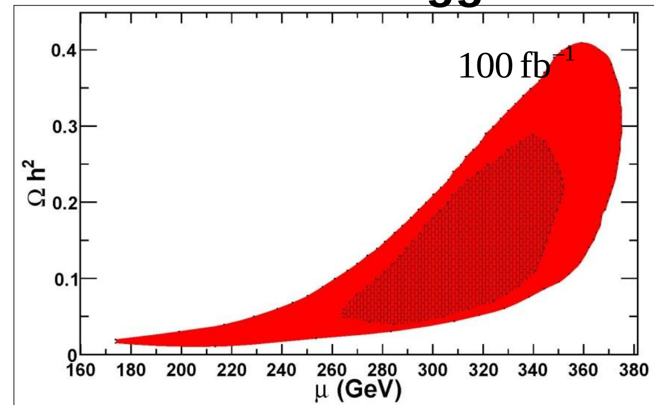
→ Solving for the MSSM : Very difficult

1. Via Cascade decays at the LHC

mSUGRA



Non Universal Higgs Model



$\mathcal{L}$ (fb^{-1})	$m_{1/2}$ (GeV)	m_H (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ (GeV)	$\Omega_{\tilde{\chi}^0_1} h^2$
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

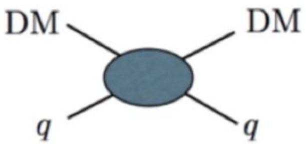
Particle	Mass	Stat.
$\tilde{t}$	690	$\pm$ 6
$\tilde{b}$	1002	$\pm$ 126
$\tilde{\tau}$	717	$\pm$ 10
$\tilde{q}$	1133	$-132, +167$

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

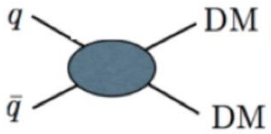
@ 200 fb^{-1}

Determine DM content at 14 TeV LHC with high luminosity

2. Monojet Searches



: Direct detection (t- channel)



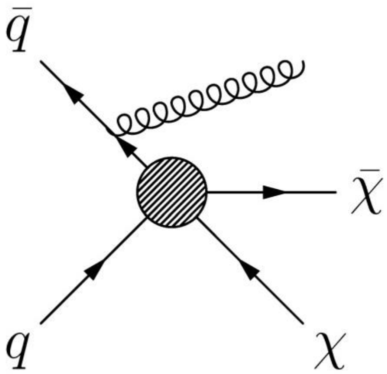
: Collider Searches (s- channel)

Effective Operators, e.g.,

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

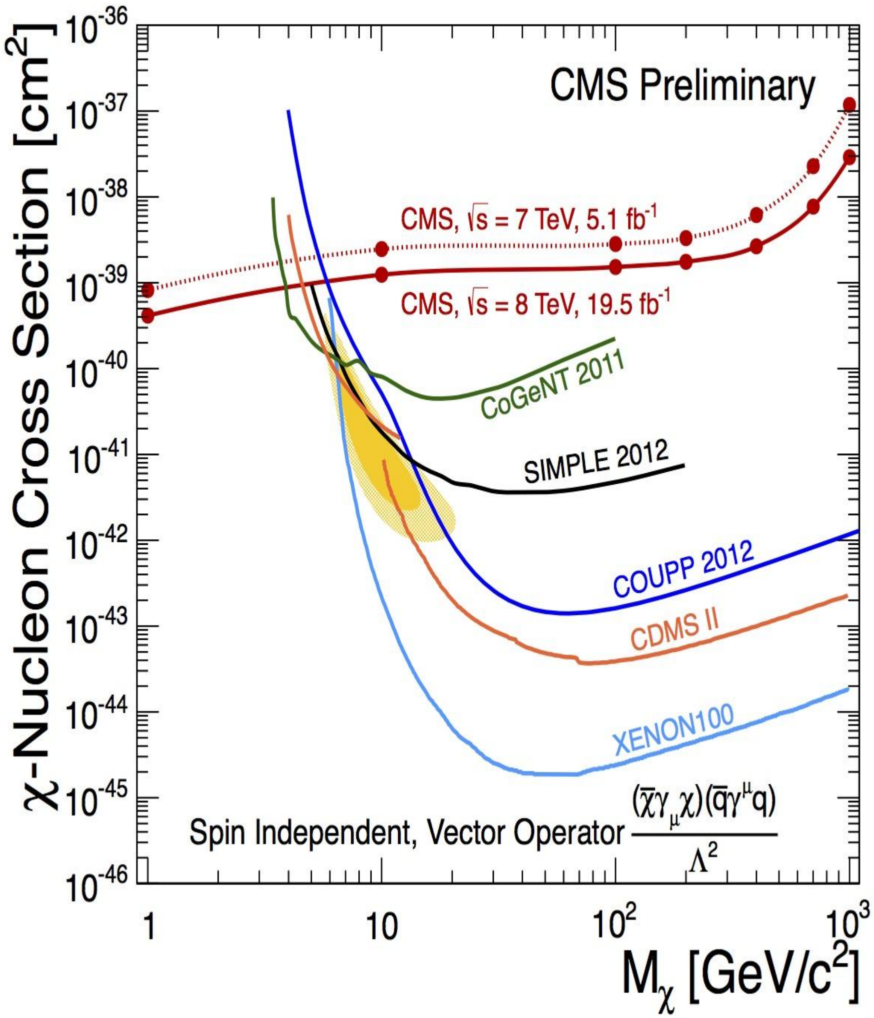
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

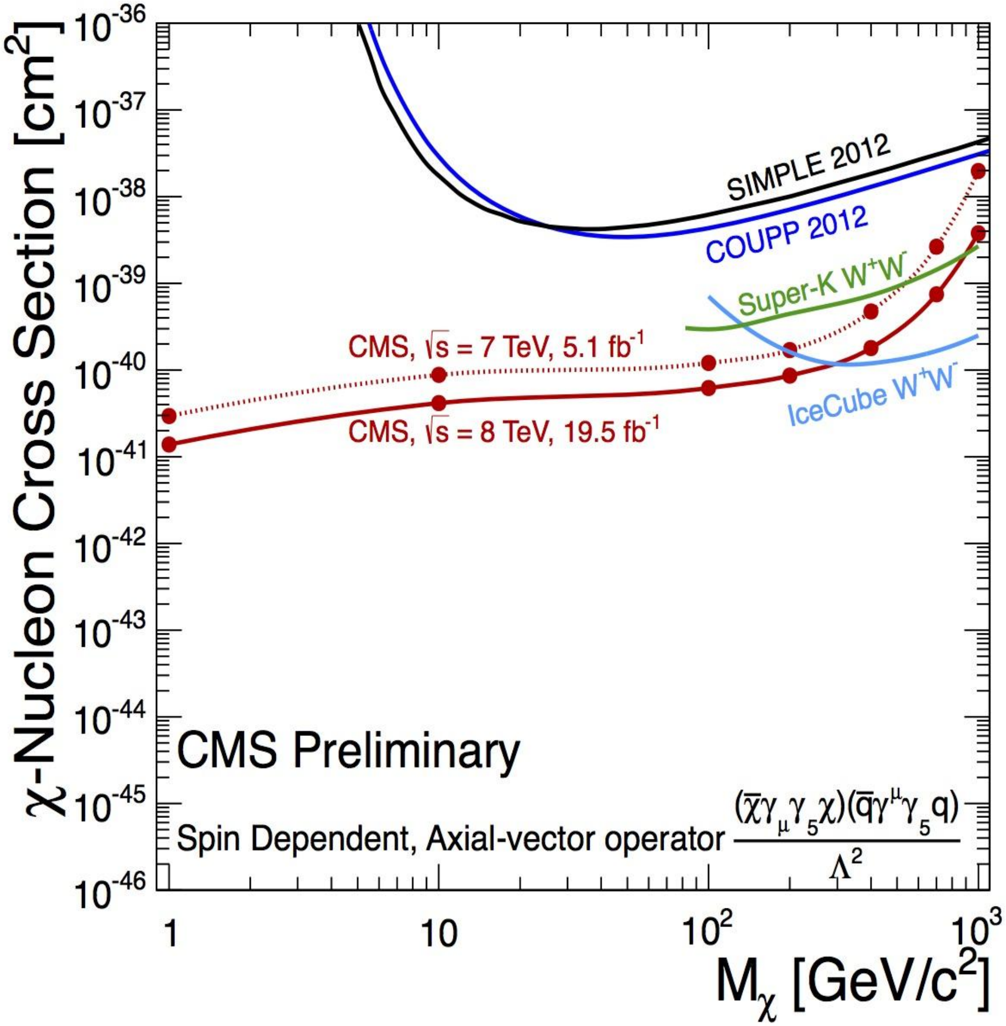
Dark Matter production ➔missing energy
Jets from a gluon radiated from quarks➔
Monojet plusMET (similarly monophoton+MET)



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

2. Monojet Searches





3. 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

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

Topness variable to identify stops

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

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, Phys. Rev. D 87, 095007 (2013)

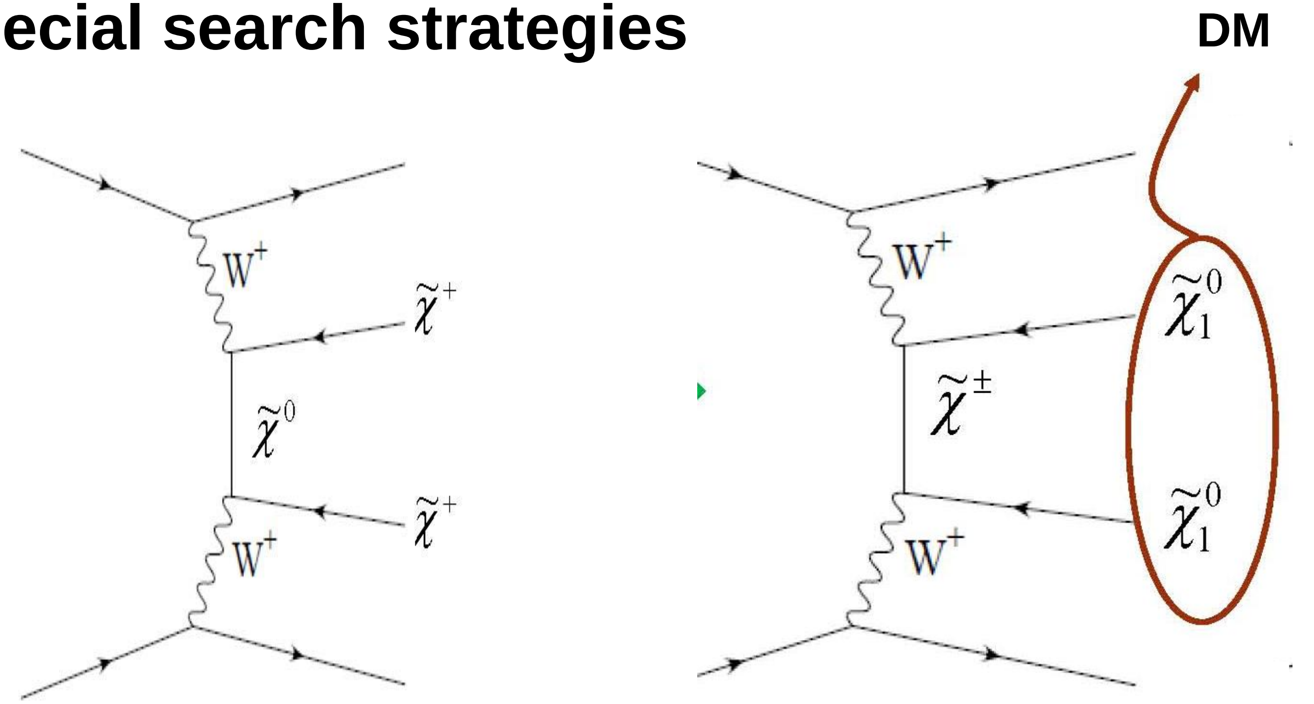
➔ Existence and type of DM particle, hard to calculate the DM content

4. DM at the LHC Via VBF

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

- **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

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

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

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

LHC 8 TeV data (expected): 260 GeV $[2j + 2\mu +$ **missing energy]**

180 GeV $[2j + 2\tau +$ **missing energy]**

Small mass difference between chargino and neutralino can be accessed!

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

$$pp \to \tilde{\mu}\tilde{\mu} jj$$

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

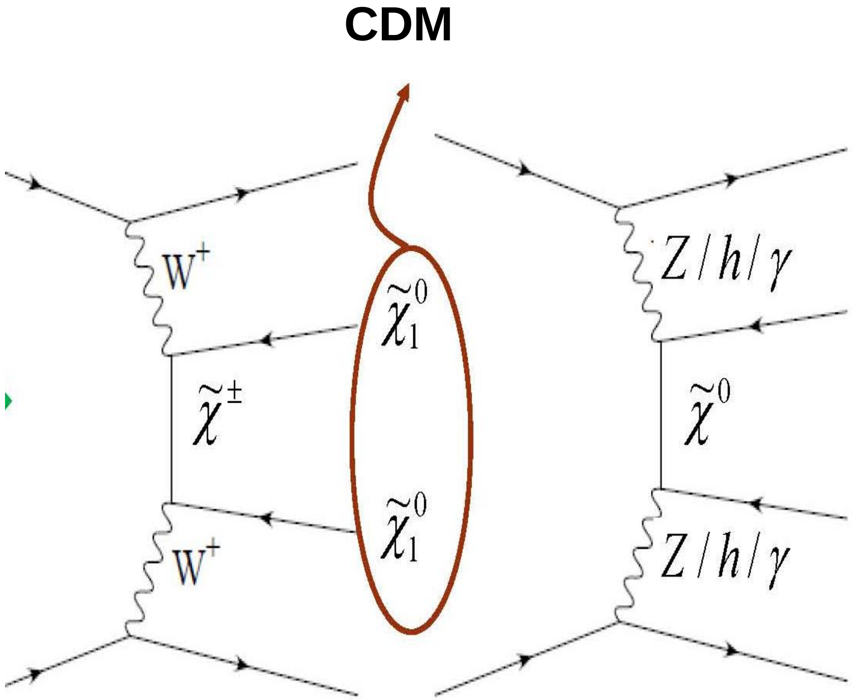
LHC 14 TeV data (expected): 160 GeV (3000 fb^{-1}), for

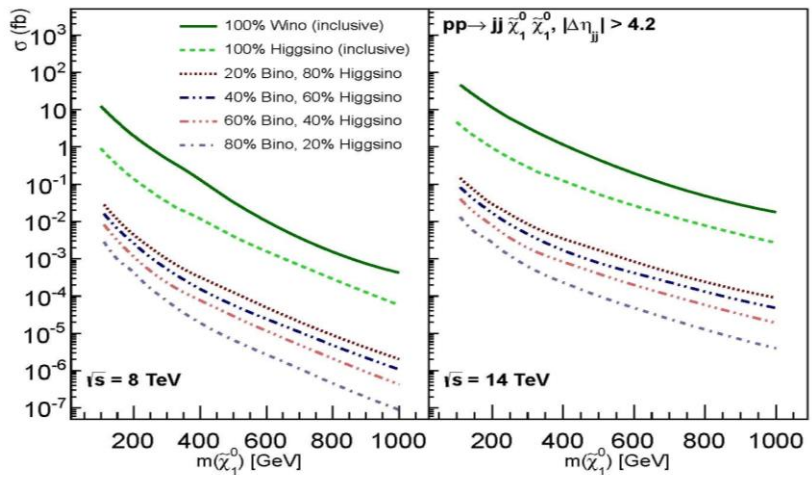
$$\Delta m = m_{\tilde{\mu}} - m_{\tilde{\chi}_1^0} = 10 GeV$$

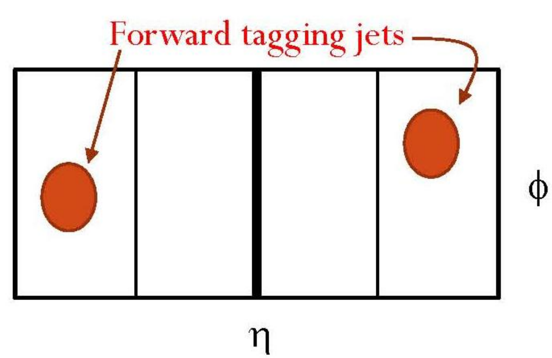
Dutta, Ghosh, Gurrola, Kamon, Sinha, Wang, Wu; to appear

4. DM at the LHC Via VBF

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







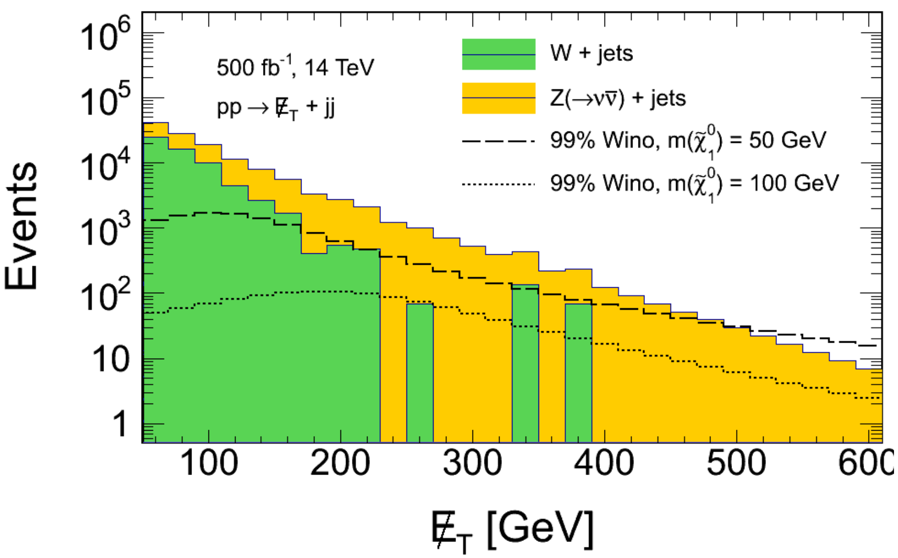
4. DM at the LHC Via VBF

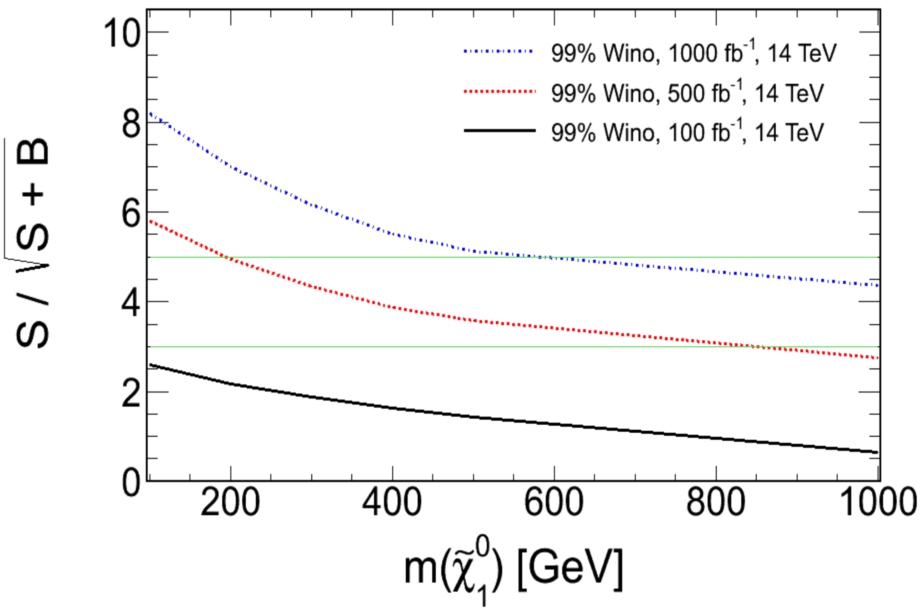
Preselection: missing E_T > 50 GeV, 2 leading jets (j_1,j_2) :$p_T(j_1),p_T(j_2)$ >30 GeV , $|\Delta\eta(j_1, j_2)| > 4.2$ and $\eta_{j1}\eta_{j2} < 0$.

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.



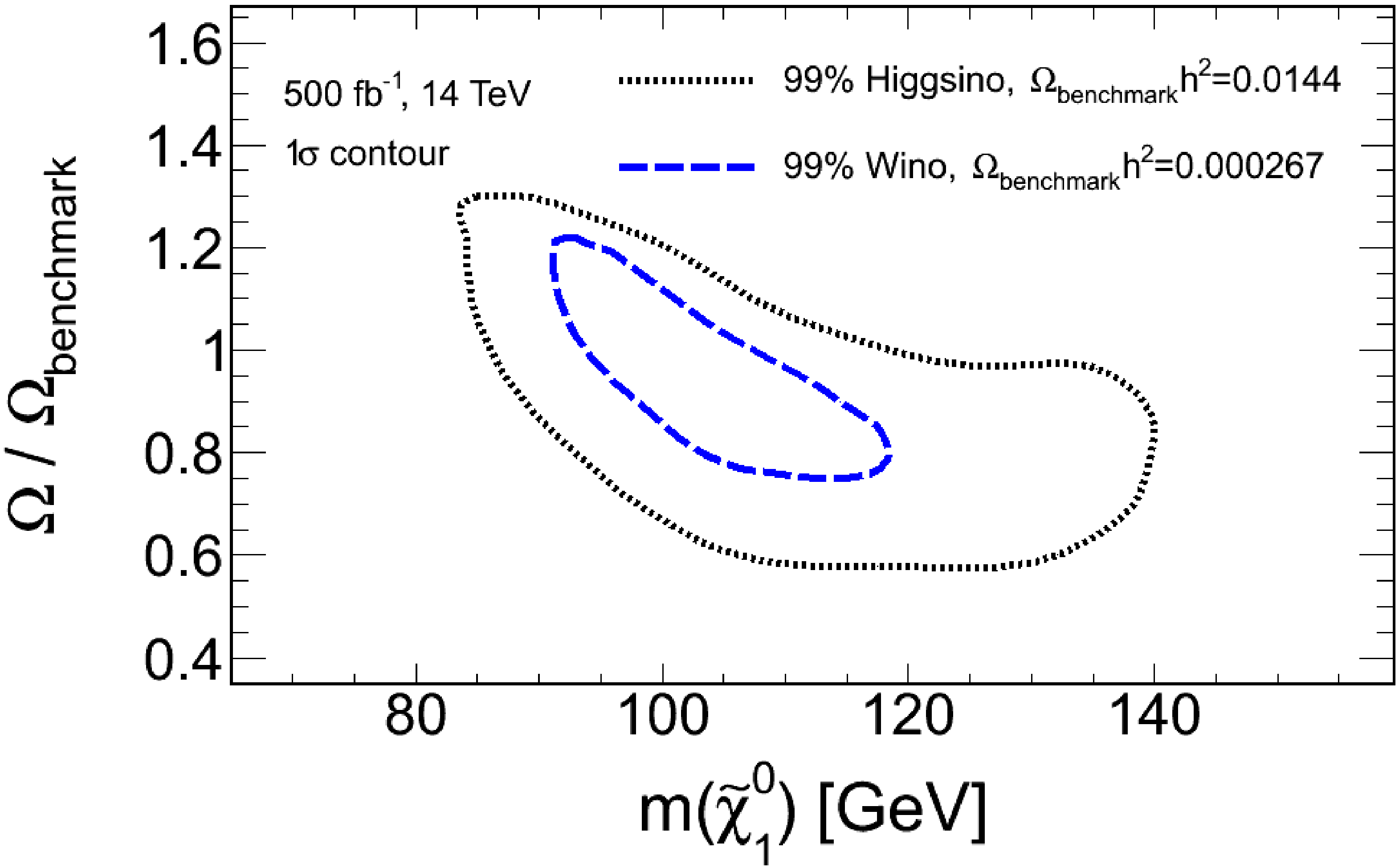


Jet energy scale uncertainty ~20% change the significance by 4%

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

4. DM at the LHC Via VBF

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



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 $<\sigma_{ann} v>$

- $<\sigma_{ann} v>$: LHC and Indirect Detections

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