Dark matter and its implications at the LHC

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Work in progress

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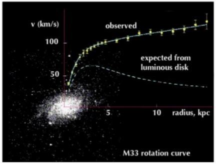
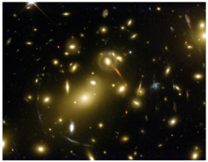
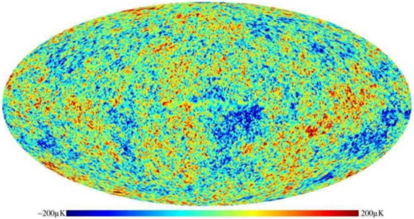
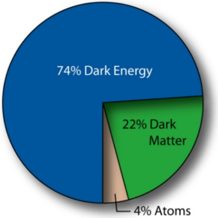
Dark matter (DM) in the universe







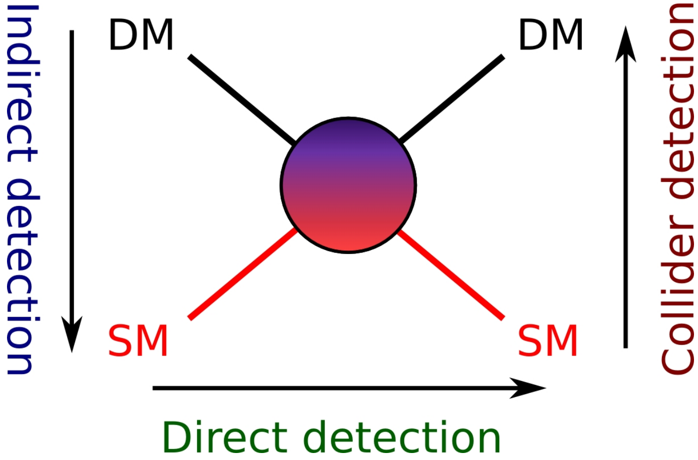


Dark matter exists at various scales in the universe.

(galaxies, clusters, large scale struture, cosmological scale)

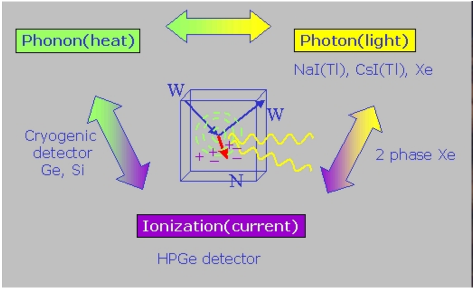
However, we hardly know its property.

Different kinds of DM detection

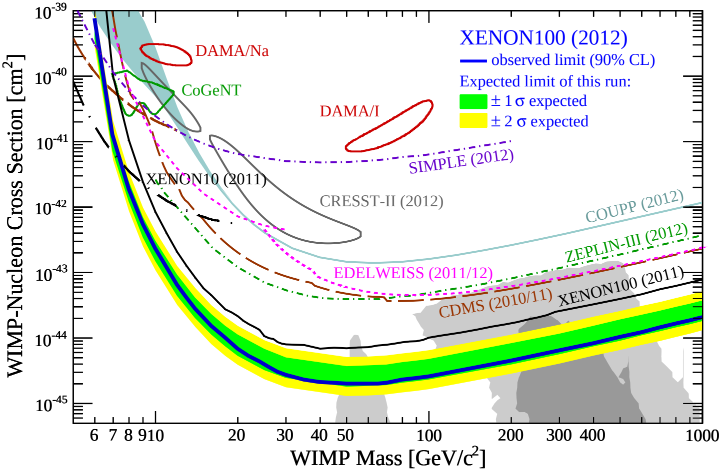


DM direct detection

Detect recoil signals of nuclei scattered by DM particles
(phonons, photons, ionization)
Work underground to reduce cosmic ray background



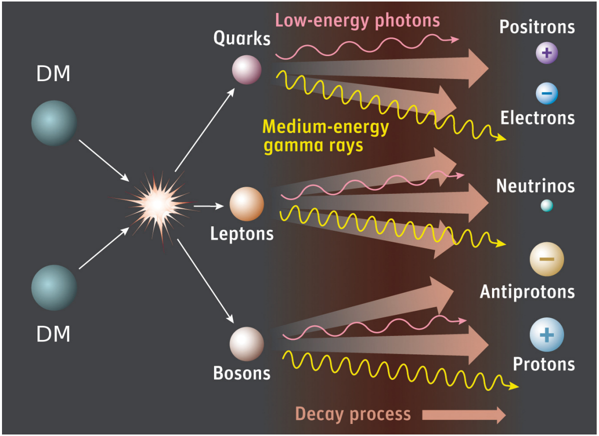
DM direct detection results



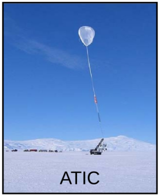
[arXiv:1207.5988]

DM indirect detection

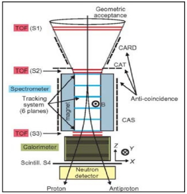
Detect products from dark mater annihilation or decay

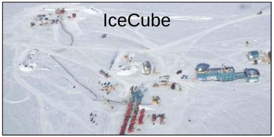


DM indirect detection experiments

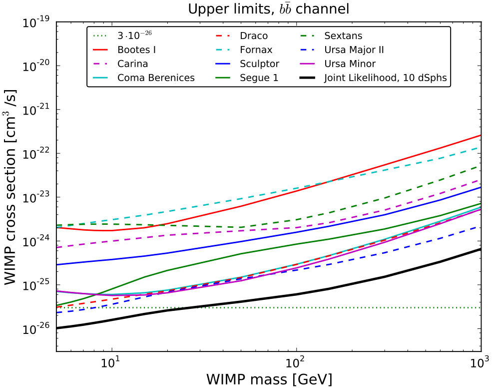


PAMELA





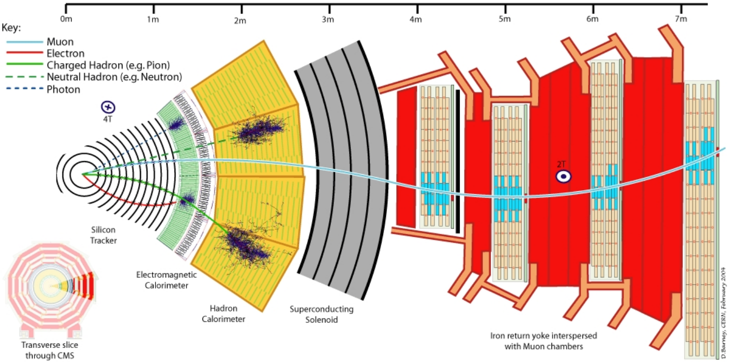
DM indirect detection results



Fermi-LAT γ-ray observation on 10 dwarf galaxies [PRL 107 241302 (2001)]

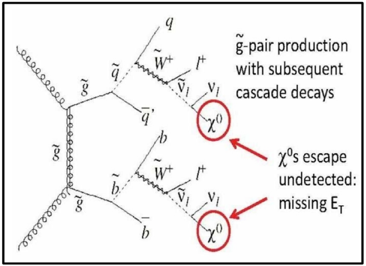
Reach the most generic annihilation cross section of thermal produced dark matter ($\sim 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$).

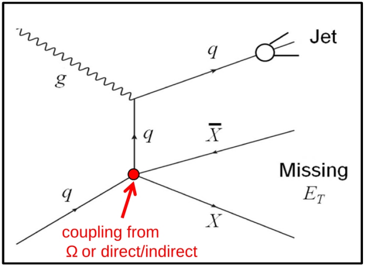
DM in collider detectors



How about DM particles? **Missing!** ($\to \not{E}_{\mathrm{T}}$)

DM signature at the LHC





Social DM

Accompanied by many other new particles

Complicated decay chain

Various kinds of signal

Maverick DM

DM particle is the only new particle

Monojet signal

Hard process

⇑

MadGraph 5

(Matrix element calculation & parton-level event generation)

Parton shower

⇑

Pythia 6.4

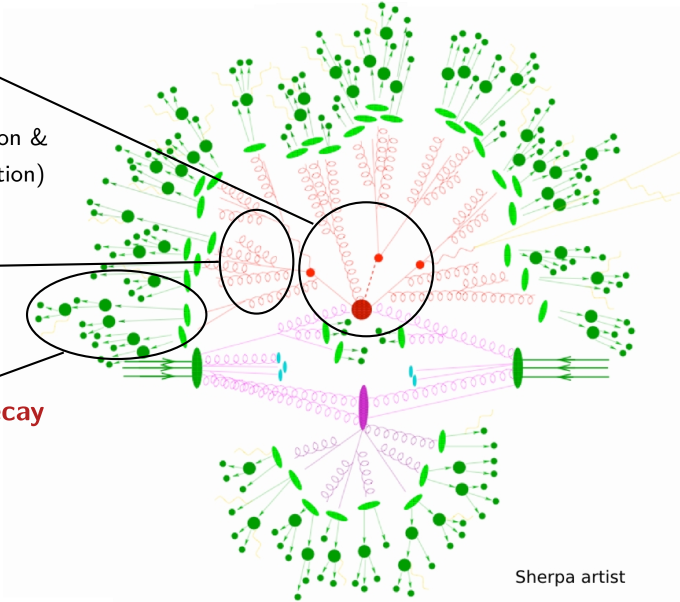
⇓

Hadronization & decay

PGS 4

⇓

Detector simulation



Supersymmetry (SUSY)

A symmetry between fermions and bosons

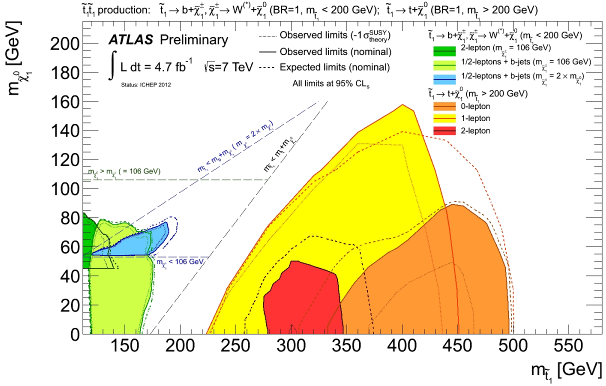
$e,\ \mu,\ \tau$	leptons $\longleftrightarrow$ sleptons	$\tilde{e},\ \tilde{\mu},\ \tilde{\tau}$
$\nu_e,\ \nu_\mu,\ \nu_\tau$	neutrinos $\longleftrightarrow$ sneutrinos	$\tilde{\nu}_e,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$
$d,\ u,\ s,\ c,\ b,\ t$	quarks $\longleftrightarrow$ squarks	$\tilde{d},\ \tilde{u},\ \tilde{s},\ \tilde{c},\ \tilde{b},\ \tilde{t}$
g	gluon $\longleftrightarrow$ gluino	$\tilde{g}$
$W^\pm,\ H^\pm$	charged bosons $\longleftrightarrow$ charginos	$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$
$B,\ W^3,\ H_1^0,\ H_2^0$	neutral bosons $\longleftrightarrow$ neutralinos	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$

Most probably the lightest neutralino $\tilde{\chi}_1^0$ is the lightest SUSY particle (LSP) and can be a well-motivated **DM candidate**.

In order to solve the hierarchy problem of standard model, the stops $\tilde{t}_{1,2}$ need to be light enough. Thus $\tilde{t}_1$ is probably reachable in early LHC searches. In the following work, the direct production of $\tilde{t}_1\tilde{t}_1^*$ pairs at the LHC is considered:

$$pp \to \tilde{t}_1\tilde{t}_1^* + \text{jets}$$

Current stop direct searches



Assuming some simplified models in which stops can be easily detected

Excluding stops up to $\sim 500\,\mathrm{GeV}$

"If you cover the white then Weak scale SUSY is probably dead" R. Barbieri (ICHEP2012)

Dark matter (DM) Relic density

ΛCDM model fitted by 7-year WMAP data: [Ap. J. Suppl. **192**, 16 (2011)]

$$\Omega_{\text{CDM}}h^2 = 0.1109,\ \Omega_{\text{baryon}}h^2 = 0.02258,\ \Omega_\Lambda = 0.734$$

(Cold DM $\sim$ 21.1%, baryons $\sim$ 4.3%, dark energy $\sim$ 74.6%)

For thermal produced DM, $\Omega_{\text{CDM}} \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$.

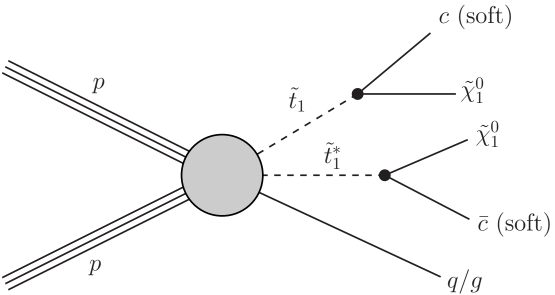
However, in SUSY models, the self-annihilation cross section σ_{ann} of the LSP neutralino $\tilde{\chi}_1^0$ is generally **not large enough** to yield the observed relic density Ω_{CDM}.

A way out: the next-to-lightest SUSY particle (NLSP) **coannihilates** with the LSP.

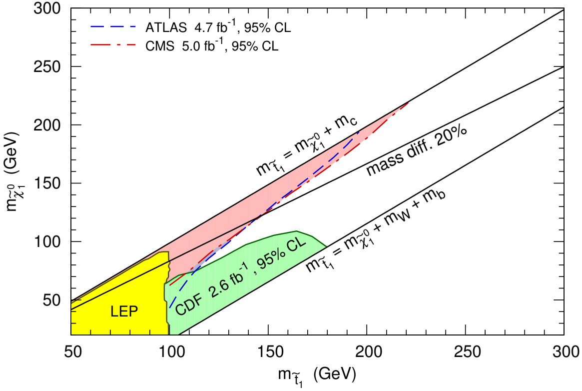
Need: $$\frac{m_{\text{NLSP}} - m_{\text{LSP}}}{m_{\text{LSP}}} \lesssim 20\%$$

Coannihilation scenario 1 (NLSP $\tilde{t}_1$)

The lighter stop $\tilde{t}_1$ is the NLSP: $m_{\tilde{\chi}_1^0} \lesssim m_{\tilde{t}_1}$
Possible decay channels: $\tilde{t}_1 \to t\tilde{\chi}_1^0,\ bW\tilde{\chi}_1^0,\ c\tilde{\chi}_1^0,\ ff'b\tilde{\chi}_1^0$
For $m_{\tilde{\chi}_1^0} + m_c < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_b + m_W$, assume $\tilde{t}_1 \to c\tilde{\chi}_1^0$ (100%).
LHC signature: monojet + $\not{E}_{\mathrm{T}}$



Scenario 1 (NLSP $\tilde{t}_1$): $\tilde{t}_1 \to c\tilde{\chi}_1^0$



Exclude $m_{\tilde{t}_1} \lesssim 220\,\text{GeV}$ for $m_{\tilde{t}_1} \simeq m_{\tilde{\chi}_1^0} + m_c$

ATLAS $\sqrt{s} = 7\,\text{TeV}$, $4.7\,\text{fb}^{-1}$, monojet + $\not{E}_T$ [ATLAS-CONF-2012-084]

CMS $\sqrt{s} = 7\,\text{TeV}$, $5.0\,\text{fb}^{-1}$, monojet + $\not{E}_T$ [arXiv:1206.5663]

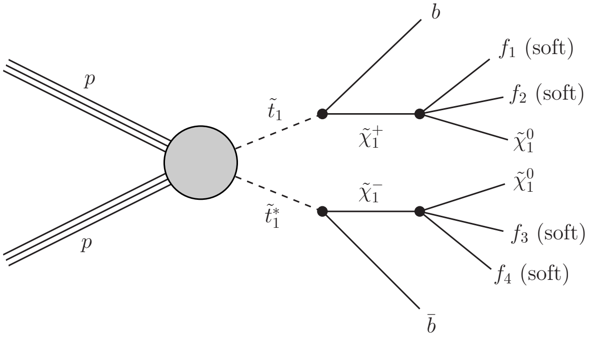
Coannihilation scenario 2 (NLSP $\tilde{\chi}_1^\pm$)

The lighter chargino $\tilde{\chi}_1^\pm$ is the NLSP: $m_{\tilde{\chi}_1^0} \lesssim m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$

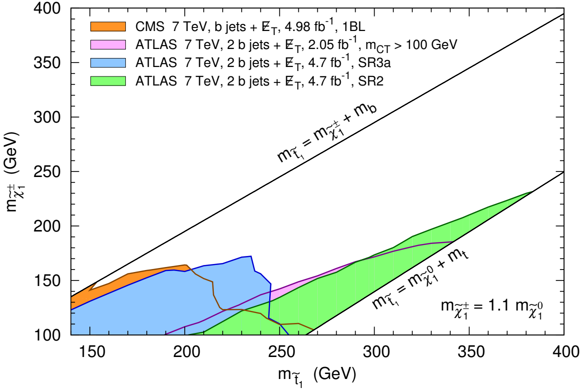
Fixing $(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} = 10\%$, for $m_b + m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$,

assume $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (100%) and $\tilde{\chi}_1^\pm \to f f' \tilde{\chi}_1^0$ (100%).

LHC signature: 1-2 b-jets + $\not{E}_\mathrm{T}$



Scenario 2 (NLSP $\tilde{\chi}_1^\pm$): $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to f f' \tilde{\chi}_1^0$



Sensitive to $m_{\tilde{\chi}_1^\pm} \lesssim 150\,\text{GeV}$

Excluding the scenario up to $m_{\tilde{t}_1} \simeq 380\,\text{GeV}$

CMS $\sqrt{s} = 7\,\text{TeV}$, $4.98\,\text{fb}^{-1}$, b-jets + $\not{E}_T$ [CMS PAS SUS-12-003]
ATLAS $\sqrt{s} = 7\,\text{TeV}$, $4.7\,\text{fb}^{-1}$, 2b-jets + $\not{E}_T$ [ATLAS-CONF-2012-106]
ATLAS $\sqrt{s} = 7\,\text{TeV}$, $2.05\,\text{fb}^{-1}$, 2b-jets + $\not{E}_T$ [PRL 108, 181802]

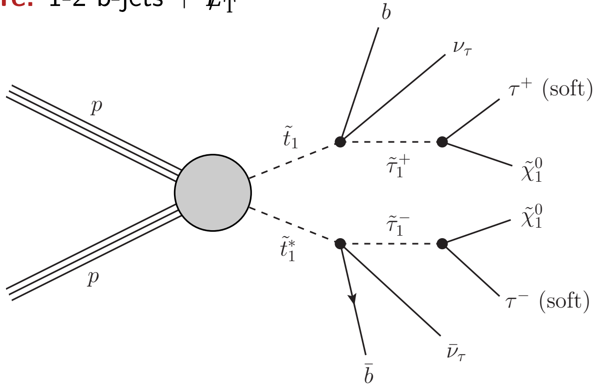
Coannihilation scenario 3 (NLSP $\tilde{\tau}_1^{\pm}$)

The lighter stau $\tilde{\tau}_1^{\pm}$ is the NLSP: $m_{\tilde{\chi}_1^0} \lesssim m_{\tilde{\tau}_1} < m_{\tilde{t}_1}$

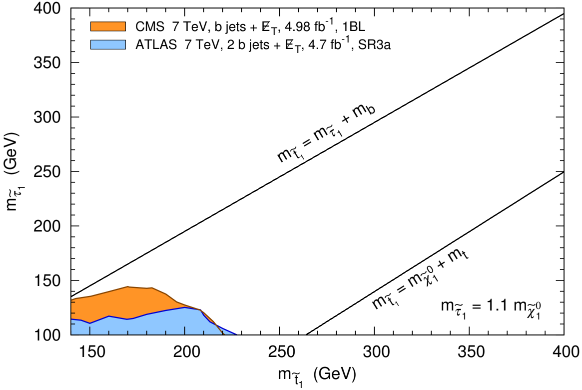
Fixing $(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} = 10\%$, for $m_b + m_{\tilde{\tau}_1} < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$,

assume $\tilde{t}_1 \to b\tilde{\tau}_1^+ \nu_\tau$ (100%) and $\tilde{\tau}_1^{\pm} \to \tau^{\pm}\tilde{\chi}_1^0$ (100%).

LHC signature: 1-2 b-jets + $\not{E}_T$



Scenario 3 (NLSP $\tilde{\tau}_1^\pm$): $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$, $\tilde{\tau}_1^\pm \to \tau^\pm\tilde{\chi}_1^0$



The neutrinos $\nu_\tau(\bar{\nu}_\tau)$ take away some energy so that b-jets become soft.

Sensitive to $m_{\tilde{\chi}_1^\pm} \lesssim 150\,\text{GeV}$ for $m_{\tilde{t}_1} \simeq 200\,\text{GeV}$

Excluding the scenario up to $m_{\tilde{t}_1} \simeq 230\,\text{GeV}$

CMS $\sqrt{s} = 7\,\text{TeV}$, $4.98\,\text{fb}^{-1}$, b-jets + $\not{E}_T$ [CMS PAS SUS-12-003]
ATLAS $\sqrt{s} = 7\,\text{TeV}$, $4.7\,\text{fb}^{-1}$, 2b-jets + $\not{E}_T$ [ATLAS-CONF-2012-106]

Conclusions and discussions

1. Collider detection is an important DM detection method complementary to direct and indirect detection.
2. Current LHC data give constraints on light stop in our coannihilation scenarios.
    - Scenarios 1 (NLSP $\tilde{t}_1$): up to $m_{\tilde{t}_1} \sim 220\,\mathrm{GeV}$
    - Scenarios 2 (NLSP $\tilde{\chi}_1^\pm$): up to $m_{\tilde{t}_1} \sim 380\,\mathrm{GeV}$
    - Scenarios 3 (NLSP $\tilde{\tau}_1^\pm$): up to $m_{\tilde{t}_1} \sim 230\,\mathrm{GeV}$
3. After taking care of DM relic density, the constraints on light stop are **much weaker** than those in the simplified models considered by experimentalists (up to $\sim 500\,\mathrm{GeV}$)
4. In these scenarios, there is still lots of parameter space where SUSY can live in, and there may be plenty of modified SUSY scenarios we never considered. **Weak scale SUSY is far from death.**