Lecture 3: Dark Matter Searches at Hadron Colliders

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Frontiers in Dark Matter, Neutrinos, and Particle Physics
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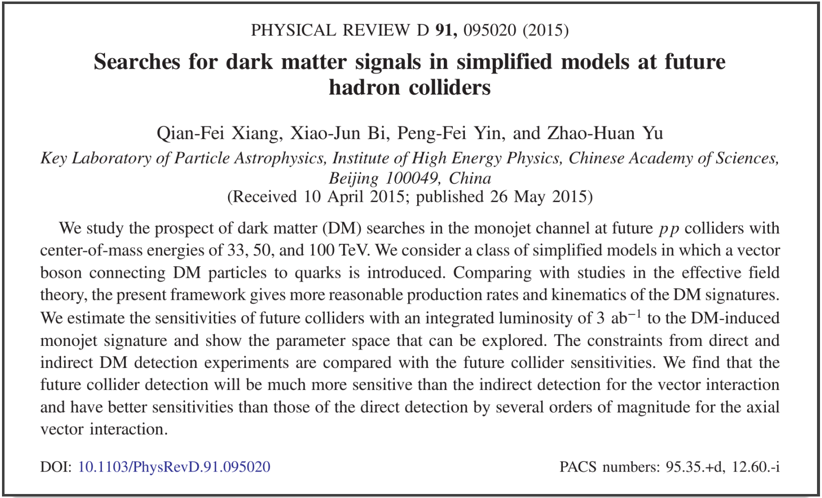
Monojet Searches and Z'-portal Simplified DM Models



PHYSICAL REVIEW D **91,** 095020 (2015)

Searches for dark matter signals in simplified models at future hadron colliders

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We study the prospect of dark matter (DM) searches in the monojet channel at future pp colliders with center-of-mass energies of 33, 50, and 100 TeV. We consider a class of simplified models in which a vector boson connecting DM particles to quarks is introduced. Comparing with studies in the effective field theory, the present framework gives more reasonable production rates and kinematics of the DM signatures. We estimate the sensitivities of future colliders with an integrated luminosity of 3 ab^{-1} to the DM-induced monojet signature and show the parameter space that can be explored. The constraints from direct and indirect DM detection experiments are compared with the future collider sensitivities. We find that the future collider detection will be much more sensitive than the indirect detection for the vector interaction and have better sensitivities than those of the direct detection by several orders of magnitude for the axial vector interaction.

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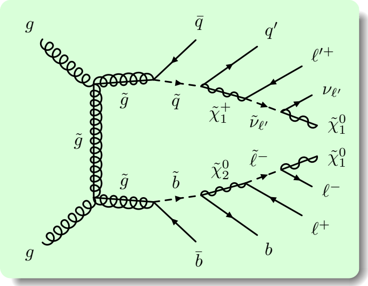
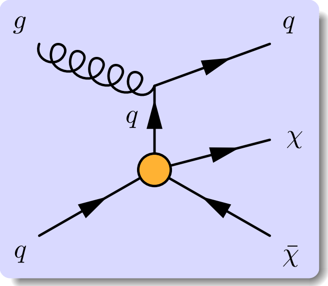
[arXiv:1503.02931, PRD]

DM Production





Social dark matter

Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

(jets + leptons + $\not{E}$, ...)

Maverick dark matter

DM particle is the only new particle reachable at the collision energy

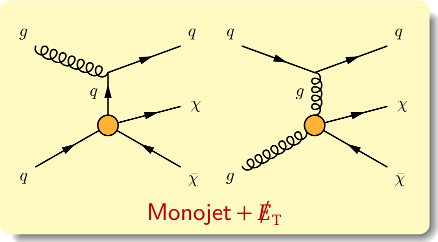
Direct production

Mono-X + $\not{E}$ final states

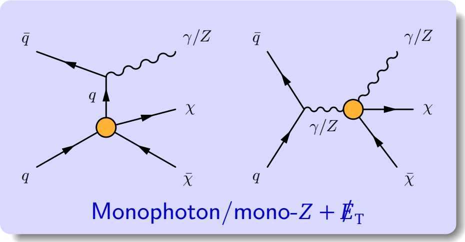
(monojet, mono-γ, mono-W/Z, ...)

[From Rocky Kolb's talk]

DM Direct Production at Hadron Colliders



Monojet + $\not{E}_{\mathrm{T}}$



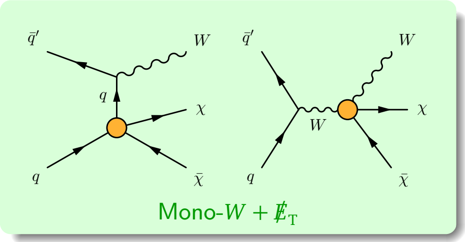
Monophoton / mono-Z + $\not{E}_{\mathrm{T}}$

Sensitive to the DM couplings to

quarks, gluons

photons, Z bosons

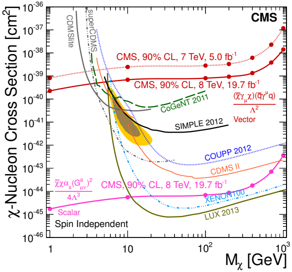
$W^{\pm}$ bosons

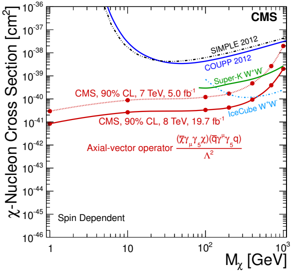


Mono-W + $\not{E}_{\mathrm{T}}$

Monojet + $\not{E}_\mathrm{T}$ Channel at the LHC

- In the context of effective field theory, **effective operators** can be used to describe interactions between DM and quarks, which could induce the **monojet + $\not{E}_\mathrm{T}$ signal** at the LHC, as well as **DM-nucleus scattering signals** in DM direct detection experiments
- $\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$ **operators: upper right plot**
  The 8 TeV LHC sensitivity is better than direct detection only when $m_\chi \lesssim 3$ GeV
- $\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$ **operators: lower right plot**
  The 8 TeV LHC sensitivity is much better than direct detection

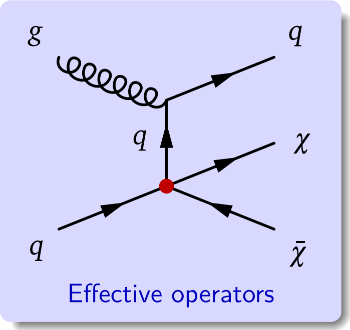




[CMS coll., arXiv:1408.3583]

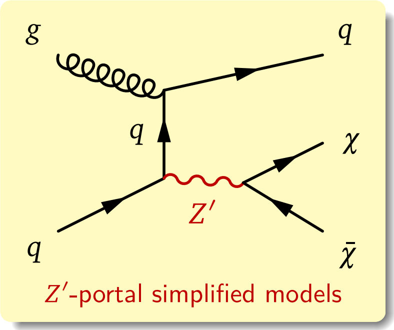
A Little Further than Effective Operators

- The **valid range** of effective field theory is limited: if the **momentum transfer** in scattering is **sufficient large** (comparable to or even larger than the mediator mass), the effective operator approach would **break down**
- In this case, **simplified models** involving **only renormalizable operators** would give a more reasonable description



Effective operators

$\Rightarrow$



Z'-portal simplified models

Z'-portal DM Simplified Models

We discussed a class of **Z'-portal simplified models**, where the mediator Z' is a vector boson

- **FV model: Dirac fermion χ, vector current interactions**

$$\mathcal{L}_{\mathrm{FV}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

- **FA model: Dirac fermion χ, axial vector current interactions**

$$\mathcal{L}_{\mathrm{FA}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

- **SV model: complex scalar χ, vector current interactions**

$$\mathcal{L}_{\mathrm{SV}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + i g_\chi Z'_\mu [\chi^* \partial^\mu \chi - (\partial^\mu \chi^*)\chi]$$

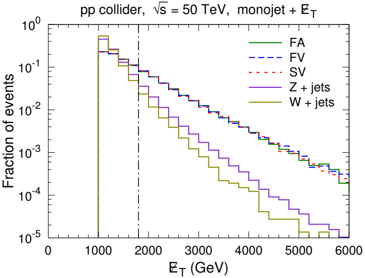
We would like to investigate the sensitivity of the monojet $+ \not{E}_{\mathrm{T}}$ channel at future hadron colliders with $\sqrt{s} = 33$ TeV (VHE-LHC), 50 TeV (SPPC), and 100 TeV (FCC-hh)

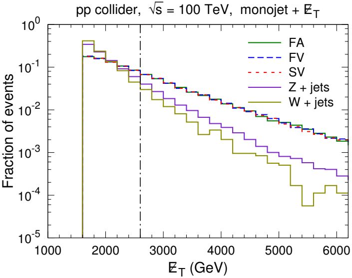
Event Selection in the monojet $+ \not{E}_\mathrm{T}$ Channel

DM production signal: $pp \to Z'^{(*)}(\to \chi\bar{\chi}/\chi\chi^*) + \text{jets}$

Main SM backgrounds: $pp \to Z(\to \nu\bar{\nu}) + \text{jets}$, $pp \to W(\to l\nu) + \text{jets}$

- $\not{E}_\mathrm{T} > 1.6/1.8/2.6$ TeV; Jet number $n_\mathrm{jet} \geq 1$; the leading jet j_1 satisfies $|\eta(j_1)| < 2.4$ and $p_\mathrm{T}(j_1) > 1.6/1.8/2.6$ TeV for $\sqrt{s} = 33/50/100$ TeV
- Reject events containing > 2 jets with $p_\mathrm{T} > 100$ GeV and $|\eta| < 4$; a second jet is allow if it satisfies $\Delta\phi(j_1, j_2) < 2.5$ for suppressing the QCD multi-jet background
- Reject events containing isolated electrons, muons, τ-jets, and photons with $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.5$





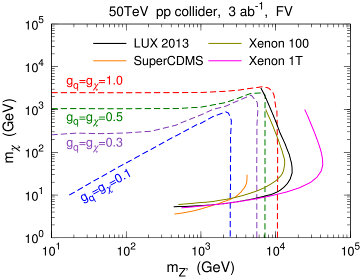
Signal benchmark point:

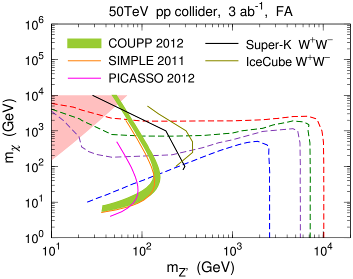
$m_\chi = 1$ TeV

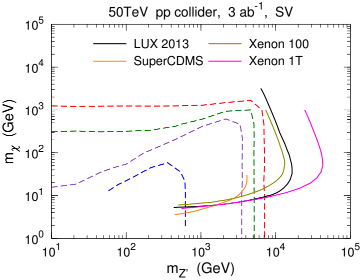
$m_{Z'} = 5$ TeV

$g_q = g_\chi = 0.1$

SPPC vs. DM Direct Detection







Dashed lines: 90% CL expected exclusion limits at the SPPC

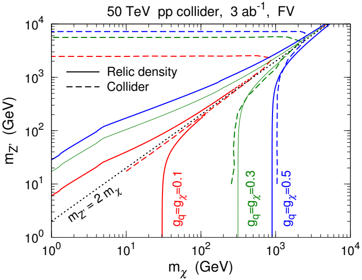
Solid lines: 90% CL exclusion limits from direct detection for

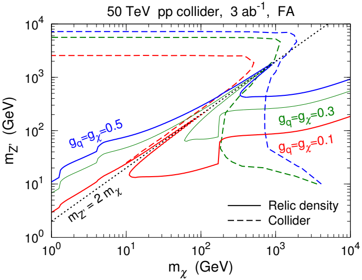
$$g_q = g_\chi = 0.5$$

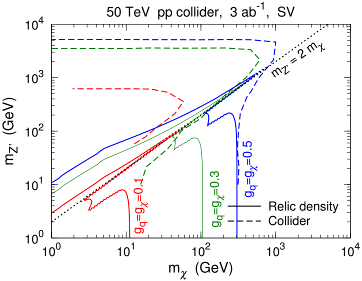
Light red region: unitarity violation for

$$g_q = g_\chi = 1$$

SPPC vs. DM Relic Density


50 TeV pp collider, 3 ab^{-1}, FV

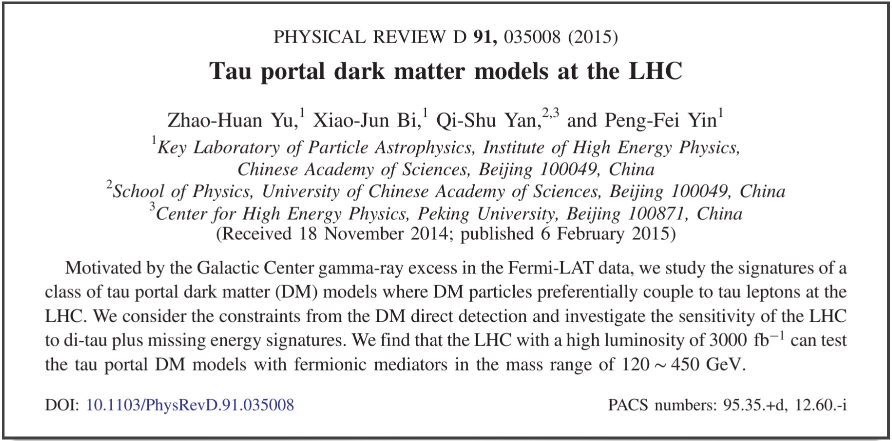

50 TeV pp collider, 3 ab^{-1}, FA


50 TeV pp collider, 3 ab^{-1}, SV

Dashed lines: 90% CL expected exclusion limits at the SPPC

Solid lines: observed value of the DM relic density

LHC Searches for τ-portal DM Models



PHYSICAL REVIEW D **91,** 035008 (2015)

Tau portal dark matter models at the LHC

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Motivated by the Galactic Center gamma-ray excess in the Fermi-LAT data, we study the signatures of a class of tau portal dark matter (DM) models where DM particles preferentially couple to tau leptons at the LHC. We consider the constraints from the DM direct detection and investigate the sensitivity of the LHC to di-tau plus missing energy signatures. We find that the LHC with a high luminosity of 3000 fb^{-1} can test the tau portal DM models with fermionic mediators in the mass range of $120 \sim 450$ GeV.

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[arXiv:1410.3347, PRD]

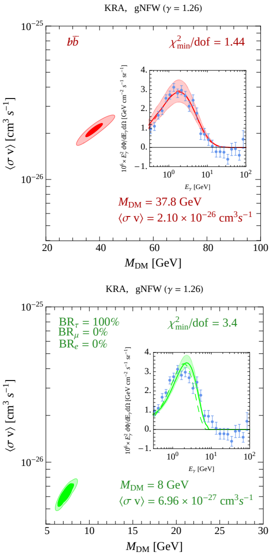
Excess of GeV Continuous Spectrum γ-rays

- Since 2009, several groups reported an **excess of continuous spectrum γ-rays** in the **Galactic Center (GC)** region, peaking at a few GeV after subtracting well-known astrophysical backgrounds in the **Fermi-LAT data**
- Interpretation with **DM annihilation into $b\bar{b}$**:

$$m_\chi \simeq 30-40\ \text{GeV}$$
$$\langle\sigma_{\text{ann}}v\rangle \sim 10^{-26}\ \text{cm}^3\ \text{s}^{-1}$$

- Interpretation with **DM annihilation into $\tau^+\tau^-$**:

$$m_\chi \sim 9\ \text{GeV}$$
$$\langle\sigma_{\text{ann}}v\rangle \sim 5\times10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$



[Cirelli *et al.*, arXiv:1407.2173]

τ-portal Simplified DM Models

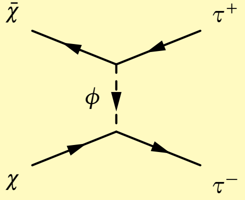
- We studied four **τ-portal simplified models** involving a mediator with **additive quantum numbers identical to the right-handed τ^-**
- We interpreted the GC GeV excess signal as DM annihilation into $\tau^+\tau^-$, and discussed **how to test this interpretation at the LHC**
- **Spin-1/2 fermion χ, spin-0 mediator ϕ**:

$$\mathcal{L}_\phi = \lambda\phi\bar{\tau}_R\chi_L + \text{h.c.}$$

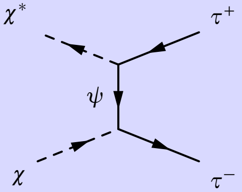
  - **DFDM model:** χ is a Dirac fermion
  - **MFDM model:** χ is a Majorana fermion
- **Spin-0 scalar χ, spin-1/2 mediator ψ**:

$$\mathcal{L}_\psi = \kappa\chi\bar{\tau}_R\psi_L + \text{h.c.}$$

  - **CSDM model:** χ is a complex scalar
  - **RSDM model:** χ is a real scalar



DFDM: annihilation



CSDM: annihilation

DM Annihilation into $\tau^+\tau^-$ in the Low Velocity Limit

DFDM model:

$$\frac{1}{2}\langle\sigma_{\text{ann}}v\rangle = \frac{\lambda^4\, m_\chi^2\, \beta_\tau}{64\pi(m_\phi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{m_\chi}{9.4\ \text{GeV}}\right)^2\left(\frac{\lambda}{m_\phi/179\ \text{GeV}}\right)^4$$

MFDM model:

$$\langle\sigma_{\text{ann}}v\rangle = \frac{\lambda^4\, m_\tau^2\, \beta_\tau}{32\pi(m_\phi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\lambda}{m_\phi/93\ \text{GeV}}\right)^4$$

CSDM model:

$$\frac{1}{2}\langle\sigma_{\text{ann}}v\rangle = \frac{\kappa^4\, m_\tau^2\, \beta_\tau^3}{32\pi(m_\psi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\kappa}{m_\psi/93\ \text{GeV}}\right)^4$$

RSDM model:

$$\langle\sigma_{\text{ann}}v\rangle = \frac{\kappa^4\, m_\tau^2\, \beta_\tau^3}{4\pi(m_\psi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\kappa}{m_\psi/156\ \text{GeV}}\right)^4$$

$$\left(\beta_\tau \equiv \sqrt{1 - m_\tau^2/m_\chi^2};\ \ m_\tau \ll m_\chi \ll m_\phi, m_\psi\ \text{approximation}\right)$$

DM Annihilation into $\tau^+\tau^-$ in the Low Velocity Limit

DFDM model:

$$\frac{1}{2}\langle\sigma_{\text{ann}}v\rangle = \frac{\lambda^4\, m_\chi^2\, \beta_\tau}{64\pi(m_\phi^2+m_\chi^2-m_\tau^2)^2} \simeq 5\times10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{m_\chi}{9.4\ \text{GeV}}\right)^2\left(\frac{\lambda}{m_\phi/179\ \text{GeV}}\right)^4$$

MFDM model:

Helicity suppression

$$\langle\sigma_{\text{ann}}v\rangle = \frac{\lambda^4 \boxed{m_\tau^2}\beta_\tau}{32\pi(m_\phi^2+m_\chi^2-m_\tau^2)^2} \simeq 5\times10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\lambda}{m_\phi/93\ \text{GeV}}\right)^4$$

CSDM model:

Helicity suppression

$$\frac{1}{2}\langle\sigma_{\text{ann}}v\rangle = \frac{\kappa^4 \boxed{m_\tau^2}\beta_\tau^3}{32\pi(m_\psi^2+m_\chi^2-m_\tau^2)^2} \simeq 5\times10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\kappa}{m_\psi/93\ \text{GeV}}\right)^4$$

RSDM model:

Helicity suppression

$$\langle\sigma_{\text{ann}}v\rangle = \frac{\kappa^4 \boxed{m_\tau^2}\beta_\tau^3}{4\pi(m_\psi^2+m_\chi^2-m_\tau^2)^2} \simeq 5\times10^{-27}\ \text{cm}^3\ \text{s}^{-1}\left(\frac{\kappa}{m_\psi/156\ \text{GeV}}\right)^4$$

$$\left(\beta_\tau \equiv \sqrt{1-m_\tau^2/m_\chi^2};\quad m_\tau \ll m_\chi \ll m_\phi, m_\psi\ \text{approximation}\right)$$

Direct Detection

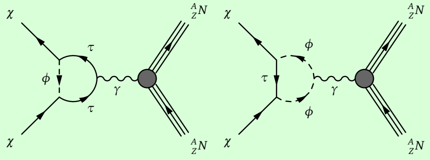
- SI DM-nucleus scattering cross sections in the **DFDM** and **CSDM** models:

$$\sigma_{\chi N}^{\mathrm{DFDM}} = \frac{Z^2 e^2 B^2 \mu_{\chi N}^2}{\pi A^2}, \quad \sigma_{\chi N}^{\mathrm{CSDM}} = \frac{Z^2 e^2 C^2 \mu_{\chi N}^2}{8\pi A^2}, \quad \mu_{\chi N} \equiv \frac{m_\chi m_N}{m_\chi + m_N}$$

Form factor $B \simeq -\frac{\lambda^2 e}{64\pi^2 m_\phi^2}\left[\frac{1}{2} + \frac{2}{3}\ln\left(\frac{m_\tau^2}{m_\phi^2}\right)\right]$ matches $[\bar\chi\gamma^\mu(1-\gamma_5)\partial^\nu\chi + \mathrm{h.c.}]F_{\mu\nu}$

Form factor $C \simeq -\frac{\kappa^2 e}{16\pi^2 m_\psi^2}\left[1 + \frac{2}{3}\ln\left(\frac{m_\tau^2}{m_\psi^2}\right)\right]$ matches $(\partial^\mu\chi)(\partial^\nu\chi^*)F_{\mu\nu}$

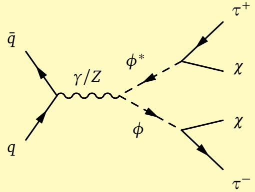
- **Unconstrained by experiments:**
  - **MFDM:** the leading contribution comes from an anapole moment operator $[-\bar\chi\gamma^\mu\gamma_5\partial^\nu\chi + \mathrm{h.c.}]F_{\mu\nu}$
  - **RSDM:** the leading contribution comes from two-loop diagrams via exchanging two photons



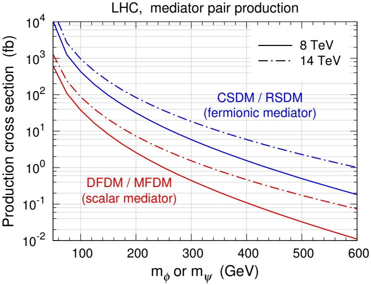
DM-nucleus scattering for DFDM
($\phi \leftrightarrow \psi$: DM-nucleus scattering for **CSDM**)

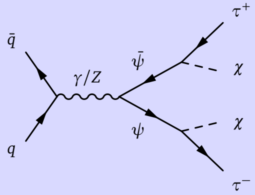
Mediator Pair Production at the LHC

- As the mediators ϕ and ψ carry $Q = Y = -1$, they could be produced at the LHC through **Drell-Yan processes** exchanging s-channel γ or Z, and then decay into $\tau^\pm$ and χ
- We found that the **8 TeV LHC data cannot explore the interesting regions** in these models, and went further to investigate the LHC sensitivity at $\sqrt{s} = 14$ TeV with **tight τ_h-tagging** techniques



DFDM or MFDM

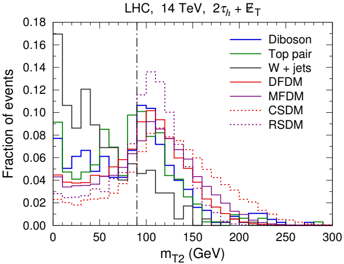




CSDM or RSDM

14 TeV LHC Searches for $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

$2\tau_\mathrm{h} + \not{E}_\mathrm{T}$ channel: two opposite-sign tau-jet (τ_h); without any other particle; $m_{\mathrm{T2}} > 90$ GeV



Signals:

DFDM model

$m_\phi = 225$ GeV

MFDM model

$m_\phi = 250$ GeV

CSDM model

$m_\psi = 300$ GeV

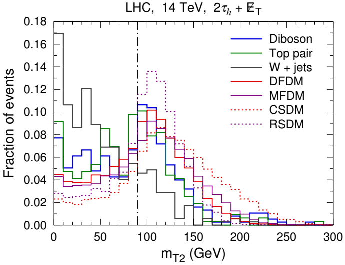
RSDM model

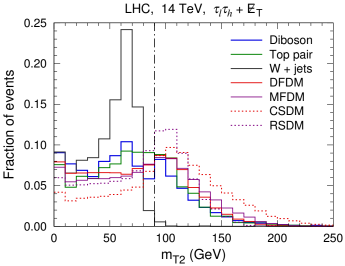
$m_\psi = 200$ GeV

14 TeV LHC Searches for $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

$2\tau_h + \not{E}_T$ channel: two opposite-sign tau-jet (τ_h); without any other particle; $m_{T2} > 90$ GeV

$\tau_\ell\tau_h + \not{E}_T$ channel: one τ_h and one light lepton ($\ell = \mu, e$) with opposite signs; without any other particle; $m_{T2} > 90$ GeV





Signals:

DFDM model

$m_\phi = 225$ GeV

MFDM model

$m_\phi = 250$ GeV

CSDM model

$m_\psi = 300$ GeV

RSDM model

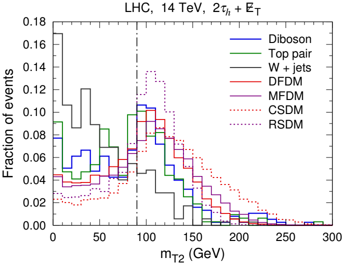
$m_\psi = 200$ GeV

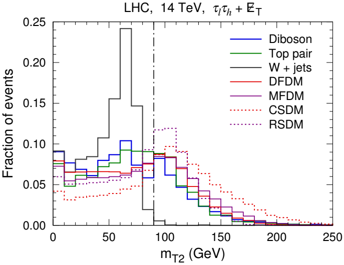
14 TeV LHC Searches for $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

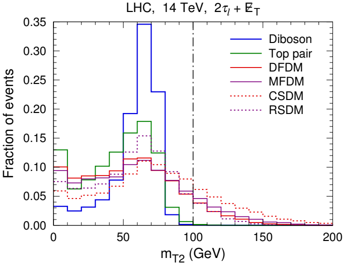
$2\tau_\mathrm{h} + \not{E}_\mathrm{T}$ channel: two opposite-sign tau-jet (τ_h); without any other particle; $m_{\mathrm{T2}} > 90$ GeV

$\tau_\ell\tau_\mathrm{h} + \not{E}_\mathrm{T}$ channel: one τ_h and one light lepton ($\ell = \mu, e$) with opposite signs; without any other particle; $m_{\mathrm{T2}} > 90$ GeV

$2\tau_\ell + \not{E}_\mathrm{T}$ channel: two opposite-sign light leptons; $|m_{\ell\ell} - m_Z| > 10$ GeV for the same-favor case; without any other particle; $m_{\mathrm{T2}} > 100$ GeV



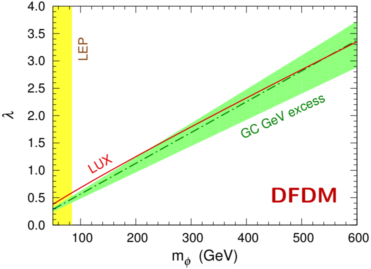




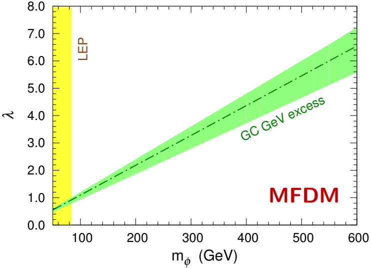
Signals:
DFDM model
$m_\phi = 225$ GeV
MFDM model
$m_\phi = 250$ GeV
CSDM model
$m_\psi = 300$ GeV
RSDM model
$m_\psi = 200$ GeV

Results

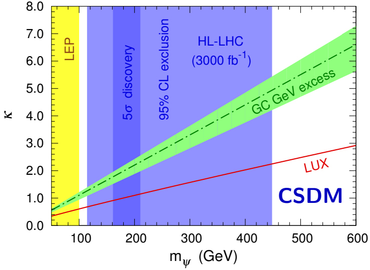
Dirac fermionic DM, scalar mediator



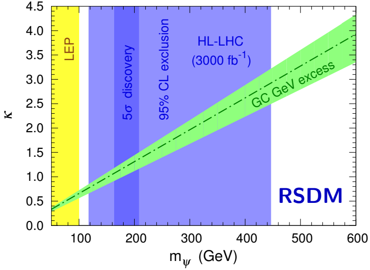
Majorana fermionic DM, scalar mediator



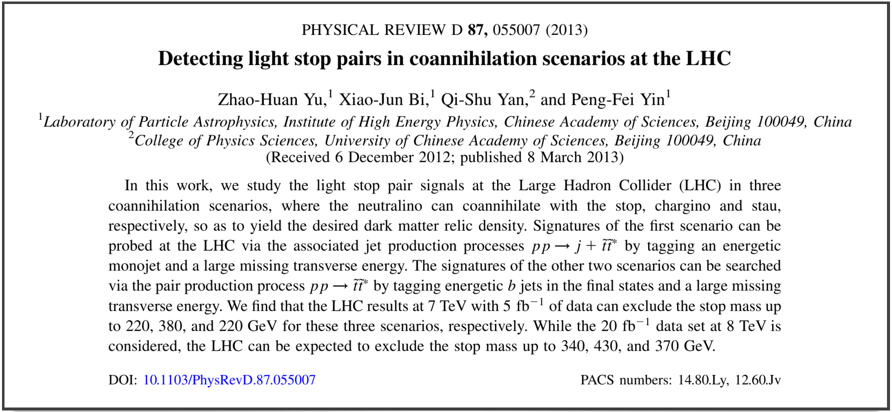
Complex scalar DM, fermionic mediator



Real scalar DM, fermionic mediator



Stop Searches and DM Coannihilation



PHYSICAL REVIEW D **87,** 055007 (2013)

Detecting light stop pairs in coannihilation scenarios at the LHC

Zhao-Huan Yu,[1] Xiao-Jun Bi,[1] Qi-Shu Yan,[2] and Peng-Fei Yin[1]
[1]*Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
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(Received 6 December 2012; published 8 March 2013)

In this work, we study the light stop pair signals at the Large Hadron Collider (LHC) in three coannihilation scenarios, where the neutralino can coannihilate with the stop, chargino and stau, respectively, so as to yield the desired dark matter relic density. Signatures of the first scenario can be probed at the LHC via the associated jet production processes $pp \to j + \tilde{t}\tilde{t}^*$ by tagging an energetic monojet and a large missing transverse energy. The signatures of the other two scenarios can be searched via the pair production process $pp \to \tilde{t}\tilde{t}^*$ by tagging energetic b jets in the final states and a large missing transverse energy. We find that the LHC results at 7 TeV with 5 fb^{-1} of data can exclude the stop mass up to 220, 380, and 220 GeV for these three scenarios, respectively. While the 20 fb^{-1} data set at 8 TeV is considered, the LHC can be expected to exclude the stop mass up to 340, 430, and 370 GeV.

DOI: 10.1103/PhysRevD.87.055007

PACS numbers: 14.80.Ly, 12.60.Jv

[arXiv:1211.2997, PRD]

Problem of the Standard Model (SM)

A ∼125 GeV SM-like Higgs boson has been discovered

The quantum correction of SM Higgs boson mass Δm_H^2 suffers from quadratic divergence

$\Downarrow$

Hierarchy problem

$\Downarrow$

New physics at TeV scale

(supersymmetry, extra dimension, little Higgs, ...)

Stops in Supersymmetric (SUSY) Models

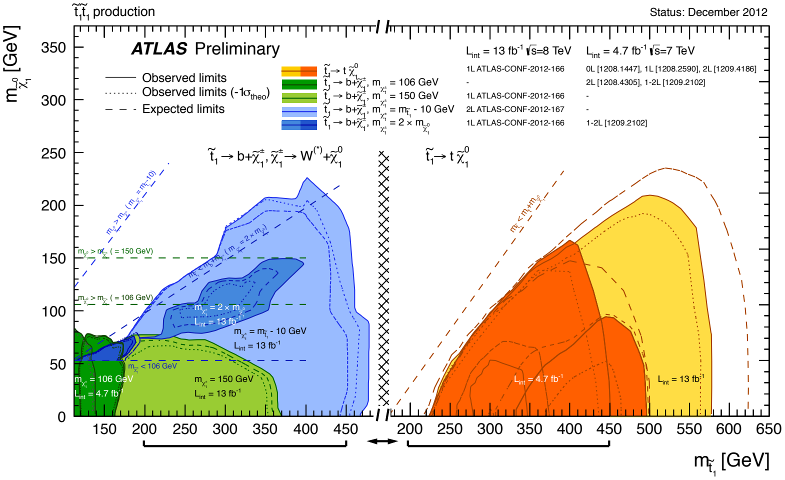
The lighter stop $\tilde{t}_1$ is probably reachable in early LHC searches.

- In order to cancel the large radiative corrections to m_H from the top quark loop without fine tuning, the stops $\tilde{t}_{1,2}$ need to be light enough.
- $\tilde{t}_1$ can be the lightest colored supersymmetric particle due to the large top Yukawa coupling and large mass splitting terms in many SUSY models.

In the following work, the direct production of $\tilde{t}_1\tilde{t}_1^*$ pairs at the LHC is considered: $pp \to \tilde{t}_1\tilde{t}_1^* + \text{jets}$

$m_{\tilde{t}_1}$ [GeV]	200	400	600
7 TeV, σ_{NLO} [fb]	11837	205	12
8 TeV, σ_{NLO} [fb]	17296	342	23

Stop Direct Searches



Assuming some simplified models in which stops can be easily detected
Excluding stops up to ~ 580 GeV

Dark Matter (DM)

Not to violate baryon number B or lepton number L

(proton decay, flavor physics constraints)

$\Downarrow$

R-parity conserved SUSY $[P_R = (-1)^{3(B-L)+2s}]$

$\Downarrow$

The **lightest SUSY particle (LSP)** is stable.

$\Downarrow$

If the LSP is electrically neutral, such as $\tilde{\chi}_1^0$, it would be an attractive candidate for **non-baryonic 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 ∼ 21.1%, baryons ∼ 4.3%, dark energy ∼ 74.6%)

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

In many SUSY models, most likely the lightest neutralino $\tilde{\chi}_1^0$ is the LSP.

However, the sfermion exchange process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to f\bar{f}$ has the helicity suppression issue. The self-annihilation cross section σ_{ann} of $\tilde{\chi}_1^0$ is generally **not large enough** to yield the observed relic density Ω_{CDM}.

Additional mechanisms are needed (resonance, coannihilation, ...).

CMSSM Case

① Higgs funnel region

$2m_{\tilde{\chi}_1^0} \simeq m_{A^0}$ or m_{h^0} or m_{H^0}

$\tilde{\chi}_1^0$ annihilates via a resonance

② Focus point region

$\tilde{\chi}_1^0$ is a bino-higgsino or bino-wino mixture

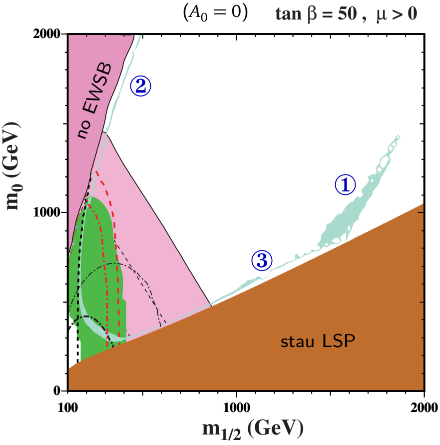
$m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm}$ or $m_{\tilde{\chi}_2^0}$

$\tilde{\chi}_1^0$ coannihilates with $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$

③ Sfermion coannihilation region

$m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1}$ or $m_{\tilde{t}_1}$

$\tilde{\chi}_1^0$ coannihilates with $\tilde{\tau}_1$ or $\tilde{t}_1$



[Ellis, Olive, Sandick, arXiv:0704.3446]

Coannilation Scenarios

In general, in order to yield the desired dark matter relic density by coannihilation mechanism, the mass of the next-to-lightest SUSY particle (NLSP) m_{NLSP} should satisfies

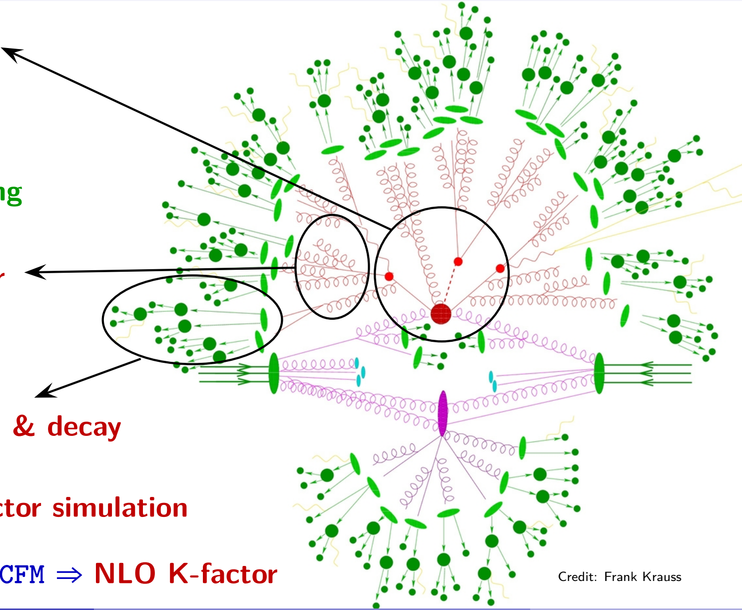
$$\frac{m_{\mathrm{NLSP}} - m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}} \lesssim 20\%.$$

[Profumo, Yaguna, arXiv:hep-ph/0407036]

In this work, we study 3 coannihilation scenarios with a light stop.

1. $\tilde{t}_1$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{t}_1}$
2. $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$
3. $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1} < m_{\tilde{t}_1}$

MC Simulation



Hard process

⇑

`MadGraph5`

⇕

MLM matching

⇕

Parton shower

⇑

`Pythia 6.4`

⇓

Hadronization & decay

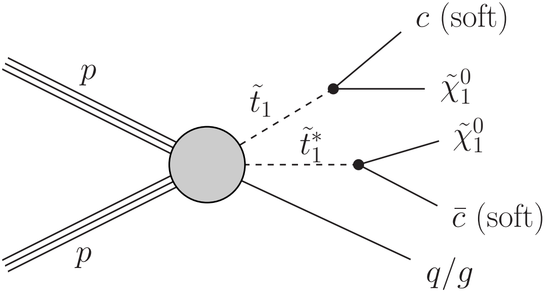
`PGS4` ⇒ **Detector simulation**

`Prospino2, MCFM` ⇒ **NLO K-factor**

Credit: Frank Krauss

Scenario 1: $\tilde{t}_1$-$\tilde{\chi}_1^0$ Coannihilation

The lighter stop $\tilde{t}_1$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{t}_1}$
$\tilde{t}_1$ 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 searching channel: monojet + $\not{E}_{\mathrm{T}}$
SM backgrounds: $Z(\to \nu\bar{\nu})$ + jets, $W(\to \ell\nu)$ + jets, ...

$\tilde{t}_1$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

Analysis instance:

(ATLAS Signal Region 2)

Lepton veto

$\not{E}_\mathrm{T} > 220\mathrm{GeV}$

Jet 1: $p_\mathrm{T} > 220\mathrm{GeV}$, $|\eta| < 2$

Jet 3: $p_\mathrm{T} < 30\mathrm{GeV}$

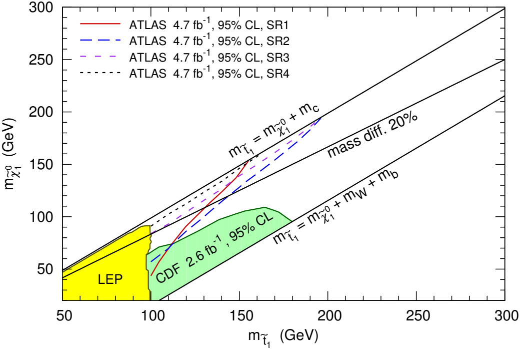
$\Delta\phi(j_2, \not{E}_\mathrm{T}) > 0.5$

$\Downarrow$

SM bkg: 8800 ± 400

Observed: 8631

$\sigma_\mathrm{vis}^\mathrm{BSM} < 170$ fb (95% CL)



ATLAS 7 TeV, 4.7fb^{-1}, monojet + $\not{E}_\mathrm{T}$

[arXiv:1210.4491]

($\sigma_\mathrm{vis} \equiv \sigma \cdot A \cdot \epsilon$ = production cross section × acceptance × efficiency)

$\tilde{t}_1$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to c\tilde{\chi}_1^0$

LHC 8 TeV, 20 fb^{-1}

Kinematic cuts:

Lepton veto

$\not{E}_\mathrm{T} > 300\text{GeV}$

Jet 1: $p_\mathrm{T} > 150\text{GeV}$,
$|\eta| < 2.4$

Jet 3: $p_\mathrm{T} < 50\text{GeV}$

$\Delta\phi(j_1, j_2) < 2.5$

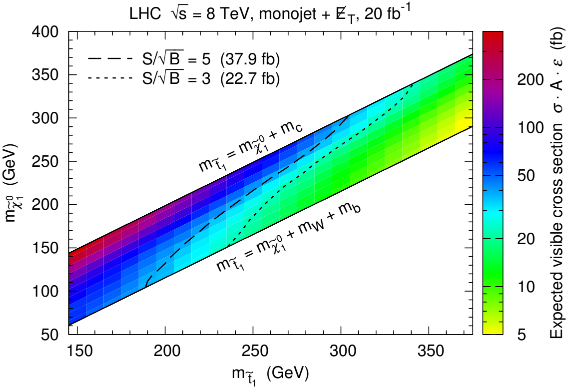
$\Downarrow$

SM bkg: 22944

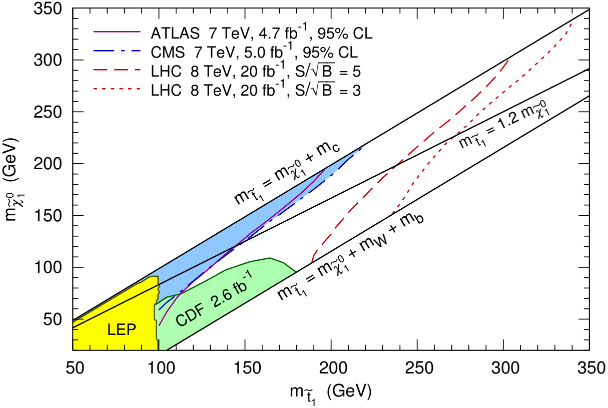
$(13939\ Z(\to \nu\bar{\nu}) + \text{jets},\ 9005\ W(\to \ell\nu) + \text{jets})$

$\Downarrow$

$\sigma_\mathrm{vis}^\mathrm{BSM} < 22.7\text{fb}$ for $S/\sqrt{B} < 3$, $\sigma_\mathrm{vis}^\mathrm{BSM} < 37.9\text{fb}$ for $S/\sqrt{B} < 5$



$\tilde{t}_1$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to c\tilde{\chi}_1^0$



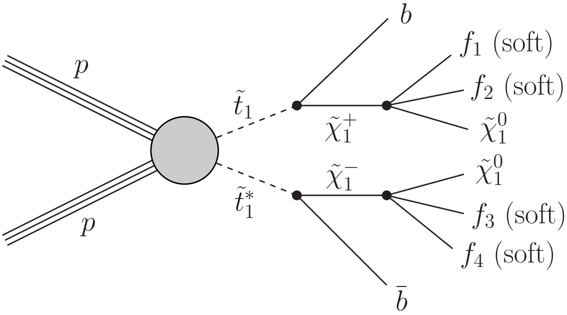
For "coannihilation region" ($m_{\tilde{t}_1} < 1.2 m_{\tilde{\chi}_1^0}$),

7 TeV, ~ 5 fb^{-1} → $m_{\tilde{t}_1} \gtrsim 150 - 220\,\text{GeV}$ (95% CL)

8 TeV, 20 fb^{-1} → $m_{\tilde{t}_1} \gtrsim 270 - 340\,\text{GeV}$ $(S/\sqrt{B} < 3)$

Scenario 2: $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ Coannihilation

The lighter chargino $\tilde{\chi}_1^\pm$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$
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 searching channel: 1-2 b-jets + $\not{E}_{\rm T}$
SM backgrounds: top pair, $Z/W+$heavy flavors, single top, ...

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

Analysis instance:

(ATLAS Signal Region 2)

Lepton veto

$\not{E}_\mathrm{T} > 200\mathrm{GeV}$

$n_\text{b-jet} = 2$ ($p_\mathrm{T} > 60\mathrm{GeV}$)

Jet 3: $p_\mathrm{T} < 50\mathrm{GeV}$

$\not{E}_\mathrm{T}/m_\mathrm{eff} > 0.25$

$m_\mathrm{CT} > 100\mathrm{GeV}$

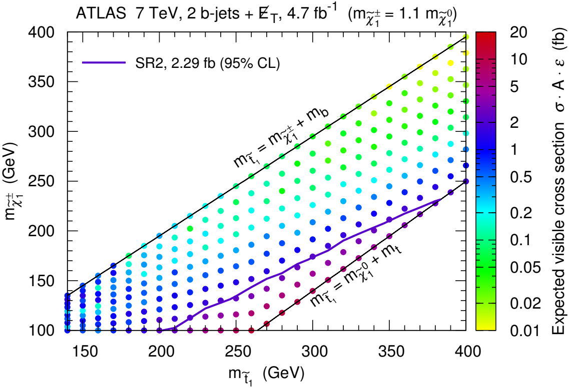
$\Delta\phi(j_{1,2}, \not{E}_\mathrm{T}) > 0.4$

$\Downarrow$

SM bkg: 27 ± 7

Observed: 20

$\sigma_\mathrm{vis}^\mathrm{BSM} < 2.29\mathrm{fb}$ (95% CL)



ATLAS 7 TeV, 4.7 fb^{-1}, 2b-jets + $\not{E}_\mathrm{T}$

[ATLAS-CONF-2012-106]

(The contransverse mass m_CT defined as $m_\mathrm{CT}^2 = (E_\mathrm{T}^{j_1} + E_\mathrm{T}^{j_2})^2 - (\mathbf{p}_\mathrm{T}^{j_1} - \mathbf{p}_\mathrm{T}^{j_2})^2$)

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to ff'\tilde{\chi}_1^0$

Analysis instance:

(CMS Signal Region 1BL)

Lepton veto

$\not{E}_T > 250\text{GeV}$

$H_T > 400\text{GeV}$

$n_{\text{jet}} \geq 3 \ (p_T > 50\text{GeV})$

$n_{\text{b-jet}} \geq 1 \ (p_T > 30\text{GeV})$

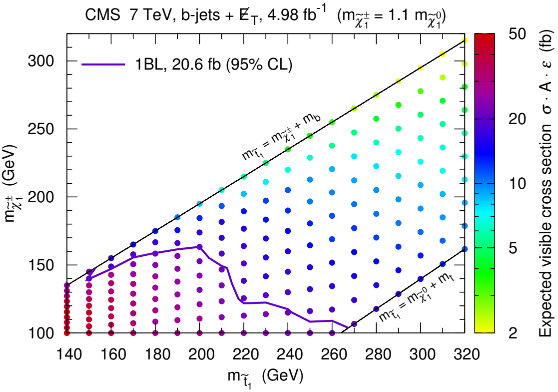
$\Delta\hat{\phi}_{\min} > 4.0$

$$\Downarrow$$

SM bkg: $477 \pm 26 \pm 38$

Observed: 478

$\sigma_{\text{vis}}^{\text{BSM}} < 20.6$ fb (95% CL)



CMS 7TeV, 4.98 fb^{-1}, b-jets + $\not{E}_T$

[arXiv:1208.4859]

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

LHC 8 TeV, 20 fb^{-1}

Kinematic cuts:

Lepton veto

$\not{E}_T > 200\text{GeV}$

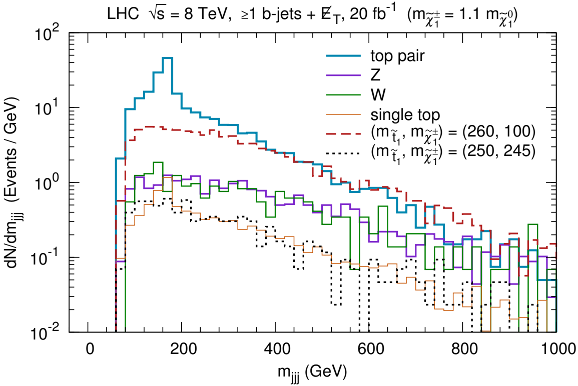
$H_T > 300\text{GeV}$

$n_{\text{jet}} \geq 3 \ (p_T > 60\text{GeV})$

$n_{\text{b-jet}} \geq 1 \ (p_T > 30\text{GeV})$

$\Delta\phi(j_{1,2,3}, \not{E}_T) > 0.4$

$m_{jjj} \notin (130, 200)\,\text{GeV}$

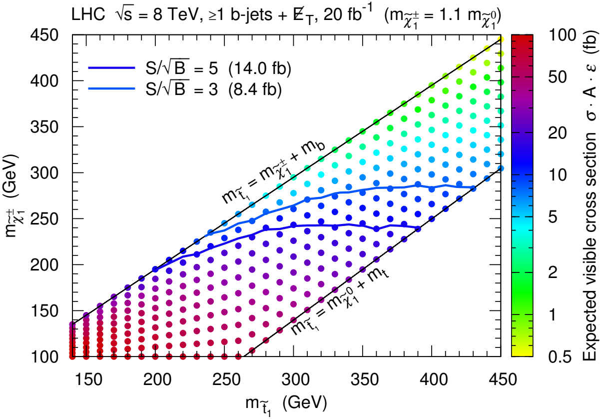


(Pick up a pair of jets with $m_{jj} > 60\,\text{GeV}$ and smallest ΔR, and m_{jjj} is the invariant mass of this pair of jets and a third jet which is closest to them.)

$m_{jjj} \notin (130, 200)\,\text{GeV}$ rejects 47% (31%) of top pair (single top) events, while only rejects 20% of stop events for $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}) = (260, 100)\,\text{GeV}$.

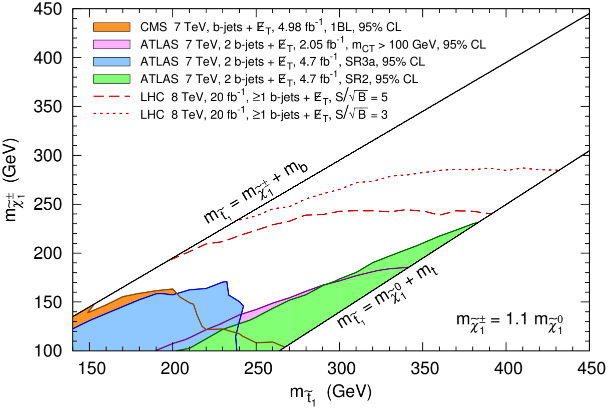
$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

SM bkg: 3132
(2269 top pair
390 Z + heavy flavor
353 W + heavy flavor
120 single top)



$$\sigma_{\text{vis}}^{\text{BSM}} < 8.4 \text{ fb for } S/\sqrt{B} < 3, \quad \sigma_{\text{vis}}^{\text{BSM}} < 14.0 \text{ fb for } S/\sqrt{B} < 5$$

$\tilde\chi_1^\pm$-$\tilde\chi_1^0$ Coannihilation: $\tilde t_1 \to b\tilde\chi_1^+$, $\tilde\chi_1^+ \to f f'\tilde\chi_1^0$

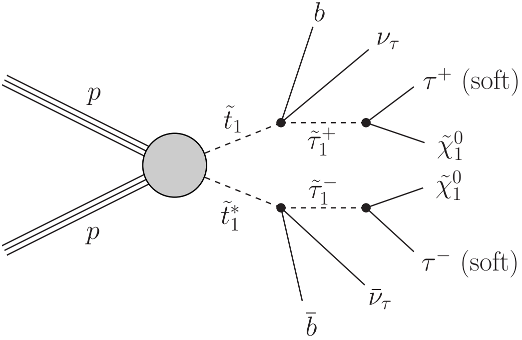


7 TeV, ~ 5 fb^{-1} → exclusion up to $m_{\tilde t_1} \simeq 380\,\mathrm{GeV}$ (95% CL)

8 TeV, 20 fb^{-1} → exclusion up to $m_{\tilde t_1} \simeq 430\,\mathrm{GeV}$ ($S/\sqrt{B} > 3$)

Scenario 3: $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ Coannihilation

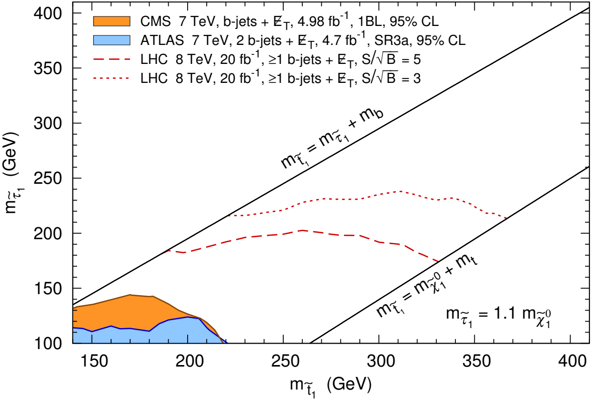
The lighter stau $\tilde{\tau}_1^\pm$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1} < m_{\tilde{t}_1}$
Fixing $(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} = 10\%$, for $m_b + m_{\tilde{\tau}_1} < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$,
assume $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$ (100%) and $\tilde{\tau}_1^\pm \to \tau^\pm\tilde{\chi}_1^0$ (100%).



LHC searching channel: 1-2 b-jets + $\not{E}_{\rm T}$

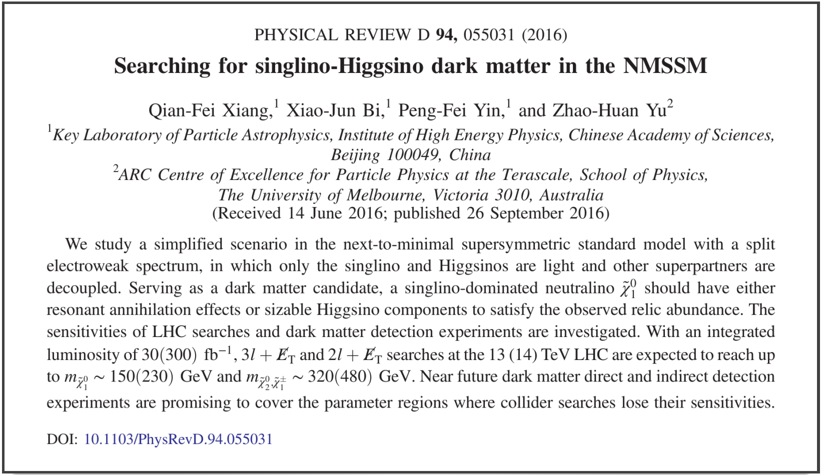
$\tilde{\tau}_1$-$\tilde{\chi}_1^0$ Coannihilation: $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$, $\tilde{\tau}_1^+ \to \tau^+\tilde{\chi}_1^0$

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



7 TeV, $\sim 5\ \text{fb}^{-1}$ → exclusion up to $m_{\tilde{t}_1} \simeq 220\,\text{GeV}$ (95% CL)
8 TeV, $20\ \text{fb}^{-1}$ → exclusion up to $m_{\tilde{t}_1} \simeq 370\,\text{GeV}$ ($S/\sqrt{B} > 3$)

LHC Searches for Singlino-Higgsino DM in the NMSSM



PHYSICAL REVIEW D **94,** 055031 (2016)

Searching for singlino-Higgsino dark matter in the NMSSM

Qian-Fei Xiang,[1] Xiao-Jun Bi,[1] Peng-Fei Yin,[1] and Zhao-Huan Yu[2]
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[2] *ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Melbourne, Victoria 3010, Australia*

(Received 14 June 2016; published 26 September 2016)

We study a simplified scenario in the next-to-minimal supersymmetric standard model with a split electroweak spectrum, in which only the singlino and Higgsinos are light and other superpartners are decoupled. Serving as a dark matter candidate, a singlino-dominated neutralino $\tilde{\chi}_1^0$ should have either resonant annihilation effects or sizable Higgsino components to satisfy the observed relic abundance. The sensitivities of LHC searches and dark matter detection experiments are investigated. With an integrated luminosity of 30(300) fb^{-1}, $3l + \not{E}_{\mathrm{T}}$ and $2l + \not{E}_{\mathrm{T}}$ searches at the 13 (14) TeV LHC are expected to reach up to $m_{\tilde{\chi}_1^0} \sim 150(230)$ GeV and $m_{\tilde{\chi}_2^0,\tilde{\chi}_1^\pm} \sim 320(480)$ GeV. Near future dark matter direct and indirect detection experiments are promising to cover the parameter regions where collider searches lose their sensitivities.

DOI: 10.1103/PhysRevD.94.055031

[arXiv:1606.02149, PRD]

Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term ⇒ **hierarchy problem**
- No cold **dark matter (DM)** candidate

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- Elegant solution to the hierarchy problem
- Lightest supersymmetric particle (LSP) ⇒ DM candidate

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No evidence of superpartners in LHC Run 1 data

- Push gluino and squark mass limits up to $\gtrsim \mathcal{O}(1)$ TeV

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No evidence of superpartners in LHC Run 1 data

- Push gluino and squark mass limits up to $\gtrsim \mathcal{O}(1)$ TeV
- Electroweak (EW) production rates are much lower; $m \sim \mathcal{O}(100)$ GeV **EW superpartners** could hide in Run 1 searches

LHC Run 2 and further searches are promising to directly probe **an** $\mathcal{O}(100)$ GeV-**scale neutralino-chargino sector**

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

No explanation for why μ **is of the same order of the SUSY breaking scale** in the Minimal Supersymmetric Standard Model (MSSM): μ-**problem**

$$\Downarrow$$

Introducing **a singlet chiral superfield** $\hat{S}$ in the NMSSM: $\mu_{\text{eff}} = \lambda v_s$

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Z_3-invariant (scale-invariant) superpotential: $W_{\text{MSSM}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \kappa\hat{S}^3/3$

Soft breaking terms in the Higgs sector:

$$V_{\text{soft}} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3/3 + \text{h.c.}\right)$$

Higgs and higgsino sectors are determined by $\{\lambda,\, \kappa,\, A_\lambda,\, A_\kappa,\, \mu_{\text{eff}},\, \tan\beta \equiv v_u/v_d\}$

Neutralino mass matrix for the gauge basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$:

$$M_{\text{N}} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_s \end{pmatrix}$$

Simplified Scenarios for the Neutralino-chargino Sector

Singlino-dominated LSP $\tilde{\chi}_1^0 \sim \tilde{S}$ $\Rightarrow$ different phenomenology from MSSM's

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  - Observed DM relic density $\Rightarrow$ $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ GeV
  - Very low production rates for $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ at the LHC

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- **Singlino-Higgsino Scenario** $(2\kappa v_s < \mu_{\text{eff}} \ll M_1, M_2)$: $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_{2,3}^0, \tilde{\chi}_1^\pm \sim \tilde{H}$
  - Higgsino components of $\tilde{\chi}_1^0$ help satisfy the observed relic density
  - Lower $\tilde{\chi}_{2,3}^0\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ rates compared with the singlino-wino scenario
  - Previous studies on this scenario focused on **LHC [Ellwanger, 1309.1665; Kim & Ray, 1405.3700] and IceCube [Enberg *et al.*, 1506.05714] searches**

Parameter Scan

For the singlino-higgsino scenario, we perform **a random parameter scan** upon

$$100\ \text{GeV} \le \mu_{\text{eff}} \le 600\ \text{GeV} \quad -1\ \text{TeV} \le A_\kappa \le 0 \quad 100\ \text{GeV} \le A_\lambda \le 10\ \text{TeV}$$

$$1 \le \tan\beta \le 50 \quad 0.05 \le \lambda \le 0.7 \quad 0.05 \le \kappa/\lambda \le 0.4$$

The condition $\kappa/\lambda \le 0.4$ is imposed for ensuring $\tilde{\chi}_1^0 \sim \tilde{S}$

Set $M_1 = M_2 = 2$ TeV and other dimensional parameters to be 5 TeV

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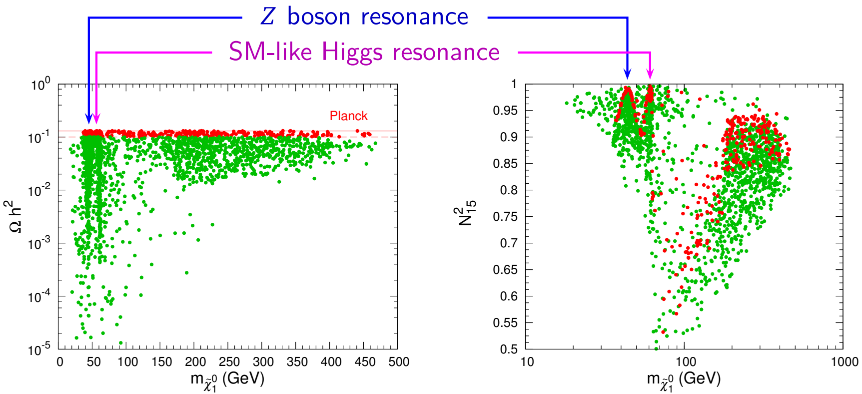
Set $M_1 = M_2 = 2$ TeV and other dimensional parameters to be 5 TeV

`NMSSMTools 4.6` and `micrOMEGAs 3` are employed for calculating mass spectra, relic density, and other observable. The following constraints are imposed.

- **DM relic density:** $\Omega_{\tilde{\chi}_1^0} h^2 < 0.131$
- **Higgs:** an SM-like Higgs with $m_h = 122 - 128$ GeV; current Higgs bounds
- **LEP bounds:** $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV; $\Gamma_Z^{\text{inv}} < 2$ MeV
- **Muon $g-2$:** within the 3σ deviation $-5.62 \times 10^{-11} < a_\mu^{\text{NMSSM}} < 5.54 \times 10^{-9}$
- **B physics bounds**: $1.7 \times 10^{-9} < \text{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$; $0.85 \times 10^{-4} < \text{BR}(B^+ \to \tau^+ \nu) < 2.89 \times 10^{-4}$; $2.99 \times 10^{-4} < \text{BR}(B_s \to X_s \gamma) < 3.87 \times 10^{-4}$

Relic Density $\Omega_{\tilde{\chi}_1^0}h^2$ and Singlino Component $|N_{15}|^2$

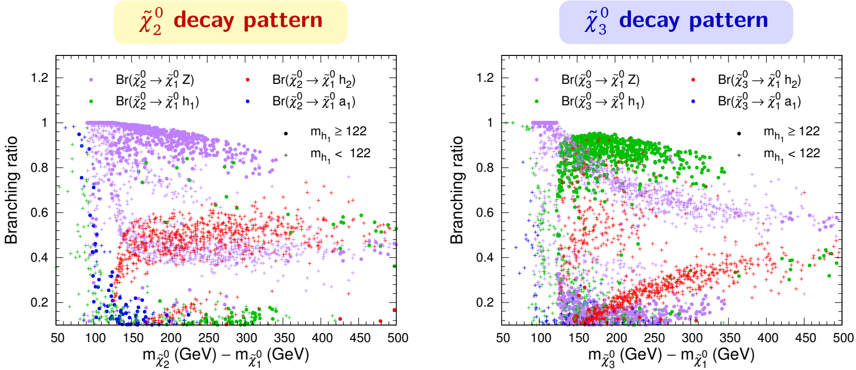


Z boson resonance

SM-like Higgs resonance

- All points pass the above constraints; red points for $0.107 < \Omega_{\tilde{\chi}_1^0}h^2 < 0.131$
- $m_{\tilde{\chi}_1^0} \sim 45$ GeV and ~ 60 GeV: resonance enhancements of the Z boson and the SM-like Higgs boson for $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation
- $m_{\tilde{\chi}_1^0} \gtrsim 70$ GeV: smaller $|N_{15}|^2$ and sizable Higgsino components

Decay Patterns of $\tilde\chi_2^0$ and $\tilde\chi_3^0$

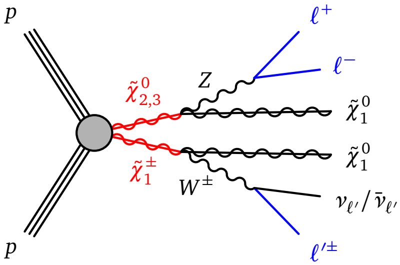


- $\tilde\chi_2^0$ **decay:** $\tilde\chi_2^0 \to \tilde\chi_1^0 Z$ is typically dominant
- $\tilde\chi_3^0$ **decay:** $\tilde\chi_3^0 \to \tilde\chi_1^0 Z$, $\tilde\chi_3^0 \to \tilde\chi_1^0 h_1$, and $\tilde\chi_3^0 \to \tilde\chi_1^0 h_2$ are significant

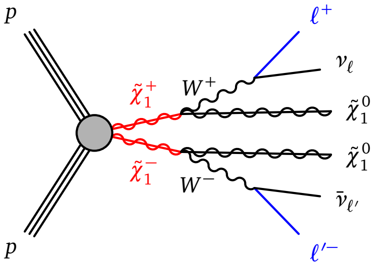
Benchmark Points

	BP1	BP2	BP3
λ, κ	0.091, 0.016	0.270, 0.100	0.368, 0.144
$\tan\beta$, μ_{eff} (GeV)	39.6, 163.3	35.1, 121.3	35.6, 121.0
A_κ (GeV), A_λ (TeV)	−35.9, 8.94	−173.4, 3.79	−8.77, 4.43
$m_{\tilde{\chi}_1^0}$ (GeV)	59.6	77.0	71.7
$m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_3^0}$, $m_{\tilde{\chi}_1^\pm}$ (GeV)	169, 173, 170	134, 146, 126	137, 160, 126
m_{h_1}, m_{h_2}, m_{a_1} (GeV)	46.0, 126, 55.8	23.0, 125, 153	95.3, 125, 38.7
$\|N_{13}\|^2+\|N_{14}\|^2$, $\|N_{15}\|^2$	1.3%, 98.7%	33.2%, 66.8%	43.5%, 56.4%
$\Omega_{\tilde{\chi}_1^0}h^2$	0.120	0.059	0.067
$\text{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 X)$	Z 98.7%	h_1 84.4%, $q\bar{q}$ 10.6% $\ell^+\ell^-$ 3%, $\nu_\ell\bar{\nu}_\ell$ 3%	a_1 98.6%
$\text{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 X)$	Z 97.1% a_1 2.7%	h_1 100%	a_1 73.2%, $q\bar{q}$ 14% $\ell^+\ell^-$ 2%, $\nu_\ell\bar{\nu}_\ell$ 4%
$\text{BR}(h_1/a_1 \to b\bar{b}/\tau^+\tau^-)$	/	$h_1 \to b\bar{b}$ 91.8% $h_1 \to \tau^+\tau^-$ 7.3%	$a_1 \to b\bar{b}$ 91.8% $a_1 \to \tau^+\tau^-$ 7.7%

LHC Searches



$3\ell + \not{E}_T$ signature



$2\ell + \not{E}_T$ signature

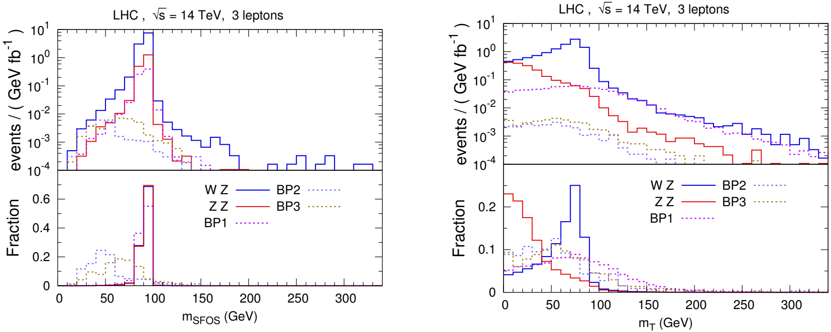
We consider $pp \to \tilde{\chi}^0_{2,3}\tilde{\chi}^\pm_1$ **and** $pp \to \tilde{\chi}^+_1\tilde{\chi}^-_1$ **production** at the LHC for the survived parameter points in the singlino-higgsino scenario

MC simulation: `MadGraph 5` + `PYTHIA 6` + `Delphes 3`

↘ ↙ ↓

MLM matching **ATLAS setup**

$3\ell + \not{E}_{\mathrm{T}}$ Channel

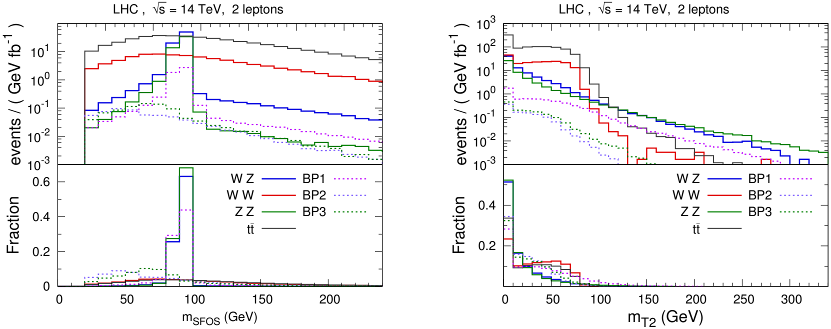


Main backgrounds: WZ + jets and ZZ + jets production

Selection cuts at $\sqrt{s} = 14$ TeV: exact 3 charged leptons ℓ ($\ell = e, \mu$) with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$; no b-jet with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.5$; $|m_{\mathrm{SFOS}} - m_Z| < 10$ GeV; $\not{E}_{\mathrm{T}} > 50$ or 100 GeV; $m_{\mathrm{T}} > 100$ GeV

(m_{SFOS} is the invariant mass of a same-flavor opposite-sign (SFOS) lepton pair. Transverse mass $m_{\mathrm{T}} \equiv \sqrt{2(p_{\mathrm{T}}^{\ell}\not{E}_{\mathrm{T}} - \mathbf{p}_{\mathrm{T}}^{\ell} \cdot \not{\mathbf{p}}_{\mathrm{T}})}$ with ℓ the one not forming the SFOS lepton pair.)

$2\ell + \not\!\!E_{\mathrm{T}}$ Channel



Main backgrounds: $t\bar{t}$ + jets, WW + jets, WZ + jets, and ZZ + jets production

Selection cuts at $\sqrt{s} = 14$ TeV: exact 2 opposite-sign charged leptons with $p_{\mathrm{T}}^{\ell_1} > 30$ GeV, $p_{\mathrm{T}}^{\ell_2} > 20$ GeV, and $|\eta| < 2.5$; $|m_{\mathrm{SFOS}} - m_Z| > 10$ GeV; no jet with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.5$; $m_{\mathrm{T2}} > 90$, 120, or 150 GeV

(Stransverse mass $m_{\mathrm{T2}} \equiv \min\limits_{\mathbf{p}_{\mathrm{T}}^1 + \mathbf{p}_{\mathrm{T}}^2 = \not{\mathbf{p}}_{\mathrm{T}}} \{\max[m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^1), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^2)]\}$.)

Cut Flows

$3\ell + \not{E}_{\mathrm{T}}$ channel at $\sqrt{s} = 14$ TeV

	WZ	ZZ	BP1		BP2		BP3	
	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Basic cuts	105	17.3	6.39	9.77	0.021	0.033	0.060	0.095
$\not{E}_{\mathrm{T}} > 50$ GeV	37.2	1.51	4.11	10.9	0.008	0.023	0.034	0.094
$m_{\mathrm{T}} > 100$ GeV	1.22	0.06	1.60	16.3	0.004	0.058	0.014	0.212

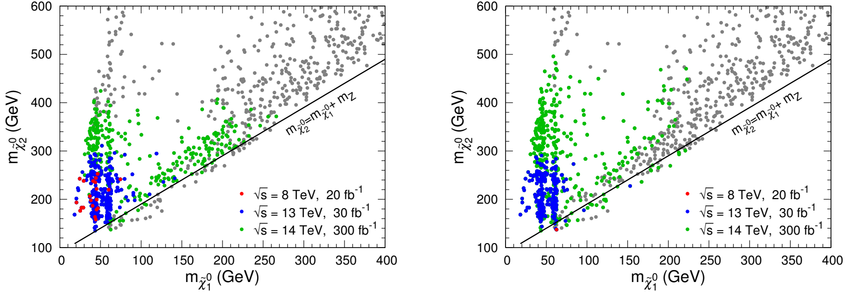
$2\ell + \not{E}_{\mathrm{T}}$ channel at $\sqrt{s} = 14$ TeV

	WZ	ZZ	WW	$t\bar{t}$	BP1		BP2		BP3	
	σ	σ	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Basic cuts	88.8	22.3	1798	8930	16.8	2.79	9.75	1.62	12.7	2.12
Jet veto	35.8	7.25	848	253	8.23	4.20	5.42	2.77	6.86	3.50
$m_{\mathrm{T2}} > 90$ GeV	0.24	0.32	0.48	0.98	0.58	6.21	0.05	0.61	0.13	1.48

(σ in fb; $\mathcal{S} \equiv S/\sqrt{B+S}$ calculated with an integrated luminosity of 300 fb^{-1})

(Expected) Exclusion at 95% CL

$3\ell + \not{E}_T$ channel **$2\ell + \not{E}_T$ channel**



Red/blue/green points: $\sqrt{s} = 8/13/14$ TeV with $20/30/300$ fb^{-1} data

8 TeV results are recasted from Run 1 analyses [ATLAS, 1402.7029, 1403.5294]

- $3\ell + \not{E}_T$ **channel** at 14 TeV: up to $m_{\tilde\chi_2^0,\tilde\chi_1^\pm} \sim 420$ GeV
- $2\ell + \not{E}_T$ **channel** at 14 TeV: up to $m_{\tilde\chi_2^0,\tilde\chi_1^\pm} \sim 500$ GeV
- Some points with $m_{\tilde\chi_2^0} - m_{\tilde\chi_1^0} \lesssim m_Z$ are hard to probe due to soft final states

Spin-Independent (SI) DM-Nucleus Scattering

In the singlino-higgsino scenario, the **SI** DM-nuclei scattering is mediated by h_1 **and** h_2

Resonance enhancement for freeze-out

⇓

Small higgsino components in $\tilde{\chi}_1^0$

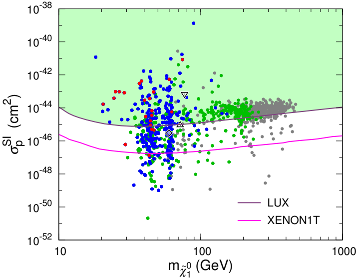
⇓

Small scattering cross section

90% CL exclusion limits: **LUX** [1310.8214], **XENON1T** expected for 2 t · yr [1512.07501]

Red/blue/green points: 8/13/14 TeV LHC

◇ BP1 ▽ BP2 △ BP3



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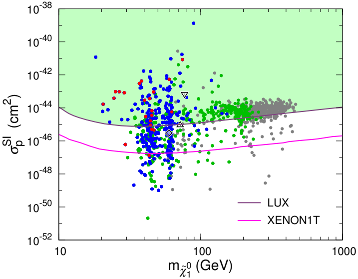
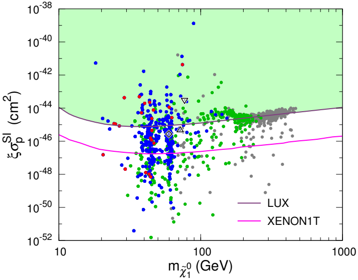
◇ BP1 ▽ BP2 △ BP3

Define $\xi = \min(1, \Omega_{\tilde{\chi}_1^0} h^2/0.107)$ to take into account the possibility that $\tilde{\chi}_1^0$ just contributes a fraction of dark matter ⟶





Spin-Dependent (SD) DM-nucleus Scattering

The ***Z*-mediated SD** DM-nuclei scattering cross section $\sigma^{\rm SD}$ is typically **larger** than $\sigma^{\rm SI}$ by $\sim 2-6$ orders of magnitude, but the experimental constraints are quite weak

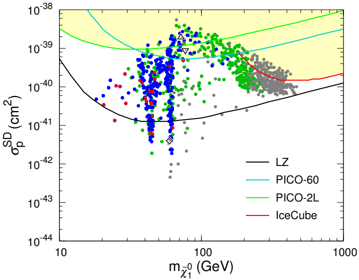
90% CL exclusion limits:

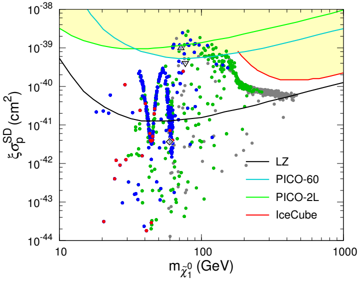
- **PICO** [1503.00008, 1510.07754]
- **LZ** expected for 5600 t · day [1509.02910]
- **IceCube** search for ν_μ from $\tilde\chi_1^0\tilde\chi_1^0 \to t\bar t$ in the center of the Sun [1601.00653]

Introducing ξ will weaken the constraints ⟶

Red/**blue**/**green** **points:** 8/13/14 TeV LHC

◇ BP1 ▽ BP2 △ BP3





DM Annihilation

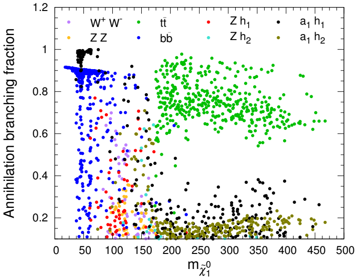
***p*-wave annihilation** is important at the freeze-out epoch, but becomes **negligible** for today's nonrelativistic DM relevant to indirect detection

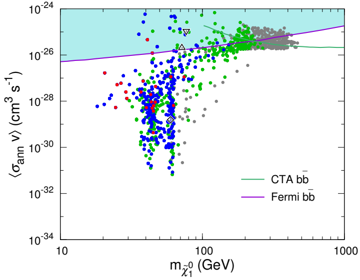
Nonrelativistic $\tilde\chi_1^0\tilde\chi_1^0$ annihilation

- $m_{\tilde\chi_1^0} \lesssim m_t$: $\tilde\chi_1^0\tilde\chi_1^0 \to b\bar b$ or $a_1 h_1$ dominant with $\langle\sigma_{\text{ann}}v\rangle \sim \mathcal{O}(10^{-31} - 10^{-27})$ cm^3/s
- $m_{\tilde\chi_1^0} \gtrsim m_t$: $\tilde\chi_1^0\tilde\chi_1^0 \to t\bar t$ dominant with canonical $\langle\sigma_{\text{ann}}v\rangle \sim \mathcal{O}(10^{-26})$ cm^3/s

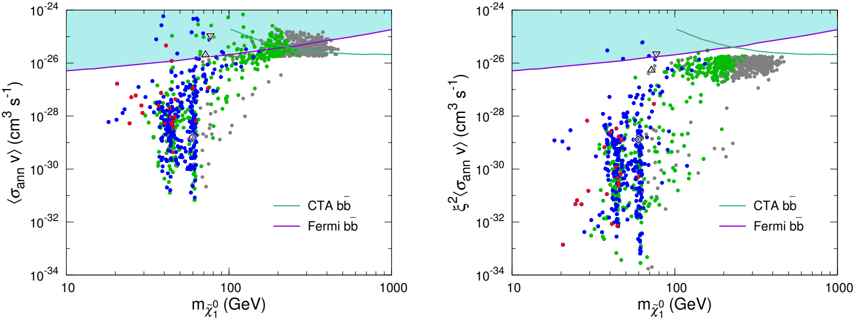
95% CL exclusion limits for $\tilde\chi_1^0\tilde\chi_1^0 \to b\bar b$: **Fermi-LAT** γ-ray observation of dwarf galaxies for 6 years [1503.02641], expected **CTA** γ-ray observation of GC vicinities for 100 h [1208.5356]

Red/**blue**/**green** **points:** 8/13/14 TeV LHC
◇ BP1 ▽ BP2 △ BP3





Indirect Detection: the ξ^2 Factor



Without the ξ^2 factor

With the ξ^2 factor

Red/blue/green points: 8/13/14 TeV LHC

◇ BP1 ▽ BP2 △ BP3

Homework

1. Calculate the Z' partial widths $\Gamma(Z' \to \bar{q}q)$ and $\Gamma(Z' \to \bar{\chi}\chi)$ for the Z'-portal Lagrangians in Page 7

   (Results can be found in arXiv:1503.02931)

2. Draw Feynman diagrams for DM annihilation into $\tau^+\tau^-$ in the MFDM and RSDM models described in Page 13

3. In the low velocity limit, derive the DM annihilation cross sections into $\tau^+\tau^-$, $\langle\sigma_{\text{ann}}v\rangle$, in Page 14 from the τ-portal Lagrangians in Page 13

4. Draw Feynman diagrams for stop decay processes $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $bW\tilde{\chi}_1^0$, $c\tilde{\chi}_1^0$, $ff'b\tilde{\chi}_1^0$, $b\tilde{\chi}_1^\pm$, and $b\tilde{\tau}_1^+\nu_\tau$

5. Derive the neutralino mass matrix M_N in Page 42 from the NMSSM superpotential and soft breaking terms