Filippo Sala

LPTHE Univ. Paris 6 and CNRS

based on Cirelli, S, Taoso 1407.7058,
  Cirelli, Hambye, Panci, S, Taoso 1507.05519
  and Cirelli, Panci, S, Taoso, work in progress

TeVPA 2015, Tokyo, 26 Oct 2015
Where is Dark Matter?

How to probe the "thermal relic WIMP" paradigm?

- Unitarity bound: $M_{DM} < 80 \div 120 \text{ TeV}$ (Griest Kamionkowski 1990, Cahill-Rowley et al. 1501.03153)

Remark: WIMP paradigm is independent of hierarchy problem of the Fermi scale!

[courtesy of Marco Cirelli]
Where is Dark Matter?

How to probe the “thermal relic WIMP” paradigm?

[Unitarity bound: $M_{DM} < 80 \div 120$ TeV  
Griest Kamionkowski 1990,  
Cahill-Rowley et al. 1501.03153]

[Remark: WIMP paradigm is independent of hierarchy problem of the Fermi scale!]

Filippo Sala  
LPTHE Paris  
WIMP Dark Matter: colliders vs sky  
1 / 13
General strategy: effective field theories?

The EFT approach:

😊 Model-independent
😊 easy comparison collider - direct detection
General strategy: effective field theories?

The EFT approach:

😊 Model-independent
😊 easy comparison collider - direct detection
😊 ~ wrong for LHC (especially 14 TeV) !!

often momentum transfer $>\text{suppression scale } \Lambda$

Lot of recent activity

Busoni et al 1307.2253 and 1402.1275,
Buchmuller et al 1308.6799,…
Abdallah et al 1409.2893,
Racco Wulzer Zwirner 1502.04701

Need to go to benchmark/simplified models!
An EW fermion multiplet

Possibly the “simplest” simplified model

This talk: a 3plet, see Panci on Thursday for a 5plet
Despite a simple benchmark, why an EW triplet $\chi$?

- **Supersymmetry**: EW triplet $\equiv$ pure Wino LSP! (Split SUSY, ...)

- **Minimal Dark Matter**
  
  Cirelli Fornengo Strumia hep-ph/0512090

  Philosophy: Focus on DM, and try to preserve SM successes (flavour & CP, ..) + DM stability, adding the least possible ingredients to the theory

  Approach: add to the SM extra particle $\chi$

  and determine its “good” quantum numbers

  “good” = i) stable ii) lightest component neutral iii) allowed
Despite a simple benchmark, why an EW triplet $\chi$? 

😊 **Supersymmetry**: EW triplet $\equiv$ pure Wino LSP! (Split SUSY, ...)

😊 **Minimal Dark Matter**  
Cirelli Fornengo Strumia hep-ph/0512090

Philosophy: Focus on DM, and try to preserve SM successes (flavour & CP, ..)  
+ DM stability, adding the least possible ingredients to the theory

Approach: add to the SM extra particle $\chi$

and determine its “good” quantum numbers

“good” = i) stable ii) lightest component neutral iii) allowed

Phenomenology:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \bar{\chi} (i\hat{D} - M_\chi) \chi$$

$M_\chi$ is the only one free parameter, fixed if we impose thermal relic abundance!

$M^{3\text{plet}}_{\text{thermal}} \simeq 3$ TeV
An EW triplet at colliders

DM not detected in collider: look for missing transverse energy + SM radiation

Pure Wino: $\chi^\pm$ add to the signal!

In fact: $M_{\chi^\pm} - M_{\chi^0} = 165$ MeV $\Rightarrow \tau \simeq 6$ cm $\simeq 0.2$ ns $\Rightarrow$ almost all $\chi^\pm$ s decay to $\chi^0 +$ soft pions before reaching detectors

4 channels: Monojet Monophoton Vector boson fusion Disappearing tracks at LHC14 with $L = 3 \text{ ab}^{-1}$, and at a 100 TeV $p-p$ collider, for $L = 3 \text{ ab}^{-1}$, $30 \text{ ab}^{-1}$ see also Low Wang 1404.0682, Berlin Lin Low Wang 1502.05044
DM not detected in collider: look for missing transverse energy + SM radiation

Pure Wino: $\chi^\pm$ add to the signal!

In fact: $M_{\chi^\pm} - M_{\chi_0} = 165$ MeV $> m_\pi \Rightarrow$ lifetime $\tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns}$

$\Rightarrow$ almost all $\chi^\pm$s decay to $\chi_0 +$ soft pions before reaching detectors
DM not detected in collider: look for missing transverse energy + SM radiation

Pure Wino: $\chi^\pm$ add to the signal!

In fact: $M_{\chi^\pm} - M_{\chi^0} = 165$ MeV $> m_\pi \Rightarrow$ lifetime $\tau \simeq 6$ cm $\simeq 0.2$ ns

$\Rightarrow$ almost all $\chi^\pm$s decay to $\chi^0 +$ soft pions before reaching detectors

4 channels: Monojet, Monophoton, Vector boson fusion, Disappearing tracks

at LHC14 with $L = 3$ ab$^{-1}$, and at a 100 TeV $p - p$ collider, for $L = 3, 30$ ab$^{-1}$
Take-home messages

→ **Complementary to Indirect Detection**, will not cover thermal relic mass

→ **Systematics** understanding will be crucial today we are at $\sim 5\%$, not 1%!

→ going from 14 to 100 TeV will increase mass reach by a factor $3 \div 4$
$M_{\chi^\pm} - M_{\chi^0} = 165 \text{ MeV} > m_{\pi} \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns}$

Almost all $\chi^\pm$s decay to $\chi^0 + \text{soft pions}$ before reaching detectors
\[ M_{\chi^\pm} - M_{\chi^0} = 165 \text{ MeV} > m_\pi \Rightarrow \text{ lifetime } \tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns} \]

Almost all \( \chi^\pm \)s decay to \( \chi^0 + \) soft pions before reaching detectors

Feng Strassler 1994, ...

ATLAS performed this analysis!

Current strongest limit on pure Wino

\[ M_{\chi^0} > 270 \text{ GeV} \]
$M_{\chi^\pm} - M_{\chi_0} = 165 \text{ MeV} > m_{\pi} \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6 \text{ cm} \simeq 0.2 \text{ ns}$

Almost all $\chi^\pm$s decay to $\chi_0 + \text{soft pions}$ before reaching detectors

Feng Strassler 1994, ...

ATLAS performed this analysis!

Current strongest limit on pure Wino

$M_{\chi_0} > 270 \text{ GeV}$

Potential to probe thermal Wino!
Hisano et al. 1504.00915:

$$\sigma_{3\text{plet}}^{SI} = 2.3 \times 10^{-47} \text{cm}^2$$

full NLO in $$\alpha_S$$, O(50%) uncertainties [largest error from charm content of nucleon]
Hisano et al. 1504.00915:  \[ \sigma_{SI}^{3\text{plet}} = 2.3 \times 10^{-47} \text{cm}^2 \]

full NLO in \( \alpha_S \), \( O(50\%) \) uncertainties  

[largest error from charm content of nucleon]

Filippo Sala  
LPTHE Paris  
WIMP Dark Matter: colliders vs sky
An EW triplet in the ($\gamma$) sky

Sommerfeld enhancement at low velocities non-rel. attractive potential

Milky Way $v \sim 10^{-3} c$

Dwarf spheroidals $v \sim 1 \div 5 \times 10^{-5} c$

$\chi_0 \chi_0 \rightarrow WW, \gamma\gamma \sigma_{\nu s} \text{saturates at } v \lesssim 10^{-2}$

bar \(p\), \(e^+\), \(\nu\), \(\gamma\) ray lines: smaller cross-sections but features in $\gamma$ spectrum enhance sensitivities
An EW triplet in the ($\gamma$) sky

**Sommerfeld enhancement**

at low velocities non-rel. attractive potential

- Milky Way $v \sim 10^{-3}c$
- Dwarf spheroidals $v \sim 1 \div 5 \times 10^{-5}c$

$\chi_0\chi_0 \rightarrow WW, \gamma\gamma$  
$s\nu$ saturates at $v \lesssim 10^{-2}$ 

![Diagrams](image)
An EW triplet in the (\(\gamma\)) sky

Sommerfeld enhancement

at low velocities non-rel. attractive potential

Milky Way \(v \sim 10^{-3}c\)

Dwarf spheroidals \(v \sim 1 \div 5 \times 10^{-5}c\)

\(\chi_0\chi_0 \rightarrow WW, \gamma\gamma\) \(\sigma v\) saturates at \(v \lesssim 10^{-2}\)

\(\bar{p}, e^+, \nu, \gamma, \ldots\)

\(\gamma\) ray lines: smaller cross-sections

but features in \(\gamma\) spectrum enhance sensitivities
A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- often “trackers” are just a few → big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]
continuum from dwarf spheroidal galaxies

A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- often “trackers” are just a few → big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]

FERMI: 15 dwarves, assumes $\Delta J < 40\%$
HESS: subset of 4, plus Sagittarius
MAGIC: only Segue1 (large uncertainties!)
continuum from dwarf spheroidal galaxies

A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- often “trackers” are just a few → big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]

FERMI: 15 dwarves, assumes $\Delta J < 40\%$

HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)
\[ \langle \sigma \langle p \rangle \rangle_{\gamma^+\gamma^0} \text{ [cm}^3\text{s]} \]

\[ M_{\text{DM}} \text{ [TeV]} \]

\[ 10^{-22} \quad 10^{-23} \quad 10^{-24} \quad 10^{-25} \quad 10^{-26} \quad 10^{-27} \quad 10^{-28} \]

\[ 10^{-1} \quad 1 \quad 10 \]

\[ \gamma \text{ lines: galactic center and dwarves} \]

[CTA prospects from Ovanesyan et al 1409.8294 and Bergstrom et al 1207.6773]

MAGIC = only one that looked for lines from dwarves - but just Segue1

Lot of progress conceivable with dwarf spheroidals!

→ Look at the same (other) dwarves with other (the same) experiments
→ measure better DM properties to reduce uncertainties
A question for astrophysicists and N-body simulators

DM density in the Milky Way:

up to which $r$ can it be flat?
A question for astrophysicists and N-body simulators

DM density in the Milky Way:

up to which \( r \) can it be flat?

![Graph showing DM density in the Milky Way](image-url)
DM density in the Milky Way:

up to which $r$ can it be flat?
DM density in the Milky Way:

up to which $r$ can it be flat?
An EW fermion 3plet: summary

Why interesting?

**Simple benchmark** of a WIMP, and moreover

**Supersymmetry** pure Wino LSP, typical of Split SUSY,...

**Minimal Dark Matter**
An EW fermion 3plet: summary

Why interesting?

**Simple benchmark** of a WIMP, and moreover

**Supersymmetry** pure Wino LSP, typical of Split SUSY,...

**Minimal Dark Matter**

Phenomenology:

*Wino–like (minimal 3plet) Dark Matter:*
summary of constraints (solid edge) and reaches (dashed edge)

- **LZ**
- **antiprotons**
- **GC γ–line**
- **dwarfs γ continuum**
- **Mono–jet**
- **Mono–photon**
- **VBF**
- **Disappearing tracks**

**Mχ [GeV]**

- 14 TeV @ 3 ab⁻¹
- 100 TeV @ 3 ab⁻¹
- 14 TeV
- 100 TeV
- 14 TeV
- 8 TeV
- 14 TeV
- 100 TeV

**Cushman+ ’13**
**this work**
**this work**
**this work**
**CST 2014**
**CST 2014**
**CST 2014**
**CST 2014**

Filippo Sala LPTHE Paris WIMP Dark Matter: colliders vs sky 13 / 13
Back up  Dark Matter
Relic abundances

Typical WIMP candidate $\rightarrow M_{DM} \sim \text{TeV}$

- Coannihilations
- Sommerfeld enhancement
- Corrections from higher orders

5plet from Cirelli et al 1507.05519 $\rightarrow$
Minimal Dark Matter: candidates

Allowed: $\chi$ neutral under $g, \gamma$, and almost under $Z$ (direct detection)

$$\Rightarrow \chi = n\text{-tuple of } SU(2)_L \quad Y = 0$$

Stable: No renormalizable nor dim-5 operators that lead to decay

$$\Rightarrow \text{first candidate is a } n = 5 \text{ fermion}$$

$(n = 7 \text{ scalar killed recently } \text{Di Luzio et al. } 1504.00359)$

Lightest component neutral: $M_Q - M_{Q=0} \simeq Q(Q + \frac{2Y}{c_\theta w})\Delta M$

$\Delta M^{2-\text{loop}} = 164.5 \pm 0.5 \text{ MeV}$

Ibe Matsumoto Sato 1212.5989
Minimal Dark Matter: candidates

Allowed: $\chi$ neutral under $g, \gamma$, and almost under $Z$ (direct detection)

$\Rightarrow \chi = n$-tuple of $SU(2)_L$ $\ Y = 0$

Stable: No renormalizable nor dim-5 operators that lead to decay

$\Rightarrow$ first candidate is a $n = 5$ fermion

$(n = 7$ scalar killed recently Di Luzio et al. 1504.00359$)$

Lightest component neutral: $M_Q - M_{Q=0} \sim Q(Q + \frac{2Y}{c_{\theta w}})\Delta M$

$\Delta M^{2\text{-loop}} = 164.5 \pm .5$ MeV

Ibe Matsumoto Sato 1212.5989

Avoid $g_2$ Landau pole before $M_{Pl} \Rightarrow n$ not too large

In practice: $n \leq 8$ for scalars, $n \leq 5$ for fermions
Why an EW fermion triplet?

→ **Stable** if one imposes $L$ or $B - L$ or discrete subgroup (already in the SM!)

[also kills all higher-dimensional operators that could make it decay]

→ **Stabilizes Standard Model vacuum**

without MDM [Buttazzo et al 1307.3536]

with MDM [Chao et al 1210.0491]

→ Not big contribution to $m_h$ ⇒ does not worsen fine-tuning

→ Helps with unification of gauge couplings
Why an EW fermion triplet?

Connection with SUSY with heavy scalars

Keep all good features of Supersymmetry
DM, unification of gauge couplings,...

And accept a tuned $m_h$ (e.g. anthropic)

All other scalars are heavier

Higgsinos also heavier if $\mu \sim m_{3/2}$

Wino LSP candidate for Dark Matter!

See also:
Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088
Arvanitaki Craig Dimopoulos Villadoro 1210.0555
...
More on collider studies - I

\[ \text{Significance} = \frac{S}{\sqrt{B + \alpha^2 B^2 + \beta^2 S^2}} \]

i.e. includes statistics + systematics

**Tools used:** Madgraph5-a2 + Pythia 6.4 + Delphes (CMS card)

**Backgrounds:** mainly \( Z \rightarrow \nu \bar{\nu}, \quad W \rightarrow \ell \nu \) (+ mistagged lepton)
simulations validated with available 8 TeV CMS and ATLAS analyses

**Cuts:** inspired by rescaling of 8 TeV searches
fixed values chosen on a pre scan, those with higher impact left free

For example VBF:

<table>
<thead>
<tr>
<th>Cuts</th>
<th>14 TeV</th>
<th>100 TeV 3 ab(^{-1})</th>
<th>100 TeV 30 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_T ) [TeV]</td>
<td>0.4 – 0.7</td>
<td>1.5 – 5.5</td>
<td>1.5 – 5.5</td>
</tr>
<tr>
<td>( p_T(j_{12}) ) [GeV]</td>
<td>40 (1%), 60 (5%)</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>( M_{jj} ) [TeV]</td>
<td>1.5 (1%), 1.6 (5%)</td>
<td>6 (1%), 7 (5%)</td>
<td>7</td>
</tr>
<tr>
<td>( \Delta \eta_{12} )</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6 (1%), 4 (5%)</td>
</tr>
<tr>
<td>( \Delta \phi )</td>
<td>1.5 – 3</td>
<td>1.5 – 3</td>
<td>1.5 – 3</td>
</tr>
<tr>
<td>( p_T(j_3) ) [GeV]</td>
<td>25</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>( p_T(\ell) ) [GeV]</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>( p_T(\tau) ) [GeV]</td>
<td>30</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
Delannoy et al. 1304.7779, studied VBF at 14 TeV and found sensitivity over 1 TeV! Discrepancy not solved, we find a higher background count at high MET cuts...

Disappearing tracks heavily rely on $M_{\chi^\pm} - M_{\chi^0} = 165$ MeV

OK, but isn’t mass splitting sensitive to higher energy scales?

Only mildly, first operators at dim 7, e.g. $\chi^a \chi^b (H^+ \sigma^a H)(H^+ \sigma^b H)$

they give $\Delta M^{\text{dim7}} \approx \frac{1}{4} \frac{v^4}{\Lambda^3} \lesssim 10$ MeV for $\Lambda \gtrsim 3$ TeV
We mimic the ATLAS analysis [we cannot simulate backgrounds]
We mimic the ATLAS analysis [we cannot simulate backgrounds]

We require: i) high-$p_T$ jet  ii) large missing energy  iii) track with high $p_T$

Track reconstruction becomes solid at $\sim 30$ cm from pipe

DISCLAIMER: of course we cannot foresee future detectors, but such a study useful also for their characterization

Assumptions for background:

- mis-measured tracks dominate
- their shape is the one fitted by ATLAS $\frac{d\sigma}{dp_T} \propto p_T^{-a}$
- their cross section scales as the one for $pp \rightarrow \nu\bar{\nu}jet$

Then we quantify uncertainty on bkg with a factor of 5 up/down
- FERMI measures $\gamma$ flux from all sky
- We “conservatively” model astrophysical backgrounds
- We divide the sky into regions, and extract bounds from each one
→ FERMI measures \( \gamma \) flux from all sky

→ We “conservatively” model astrophysical backgrounds

→ We divide the sky into regions, and extract bounds from each one

\[
\langle \sigma \langle v \rangle \rangle \quad \text{NFW profile, bounds including background}
\]

\[
M_{\text{DM}} \quad [\text{TeV}]
\]

\[
(\sigma \langle v \rangle)_{\text{VV}} \quad [\text{cm}^3/\text{s}]
\]

Galactic bounds depend on DM profile

All bounds assume 5plet = 100% of DM
→ FERMI measures γ flux from all sky
→ We “conservatively” model astrophysical backgrounds
→ We divide the sky into regions, and extract bounds from each one

Burkert profile, including background

Galactic bounds depend on DM profile
All bounds assume 5plet = 100% of DM
### NFW profile, conservative bound

![Graph showing NFW profile, conservative bound](image1)

### NFW profile, including background

![Graph showing NFW profile, including background](image2)