WIMP Dark Matter: colliders vs sky

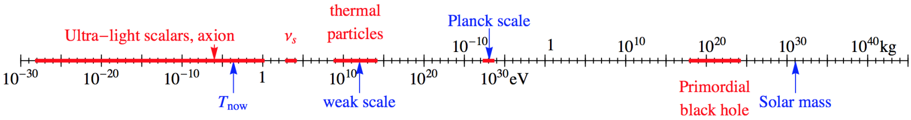
Filippo Sala

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?



[courtesy of Marco Cirelli]

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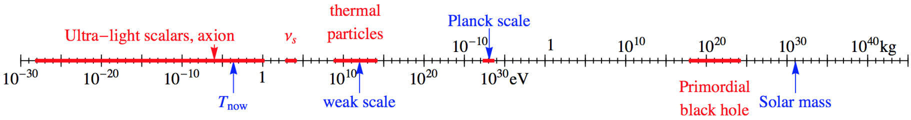

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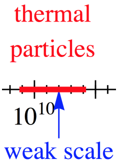


How to probe the "thermal relic WIMP" paradigm?

[Unitarity bound: $M_{\rm DM} < 80 \div 120$ TeV Griest Kamionkowski 1990,

...

Cahill-Rowley et al. 1501.03153]

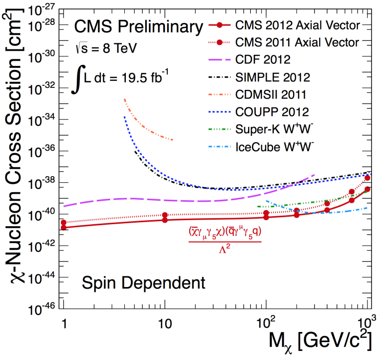
[Remark: WIMP paradigm is independent of hierarchy problem of the Fermi scale!]

General strategy: effective field theories?

The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection



General strategy: effective field theories?

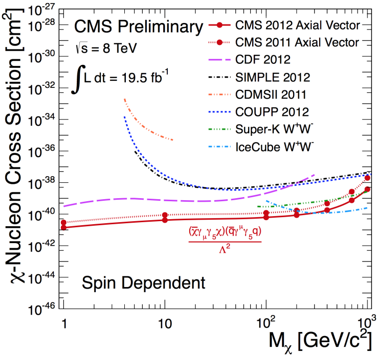
The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection

☹ $\sim$ wrong for LHC (especially 14 TeV) !!

often | momentum transfer $>$ suppression scale Λ |



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!

Quantum numbers		
$SU(2)_L$	$U(1)_Y$	Spin
3	0	F
5	0	F

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 χ?

- ☺ **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 χ
  and determine its "good" quantum numbers

  "good" = i) stable ii) lightest component neutral iii) allowed

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Phenomenology:

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

M_χ is the only one free parameter, fixed if we impose thermal relic abundance!

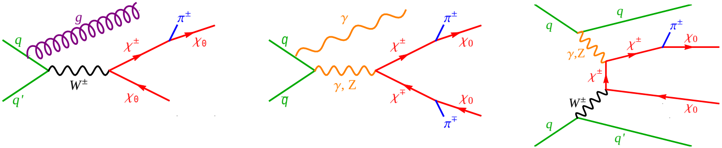
$$M_{\rm thermal}^{\rm 3plet} \simeq 3 \text{ TeV}$$

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 $> m_\pi \quad \Rightarrow \quad$ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

$\Rightarrow$ almost all $\chi^{\pm}$s decay to χ_0 + soft pions before reaching detectors



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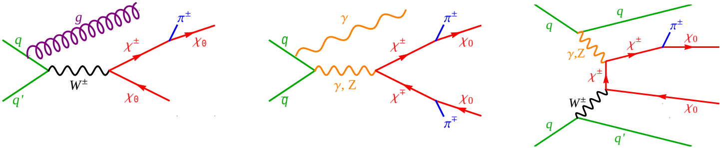
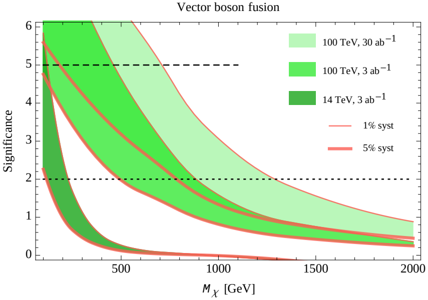


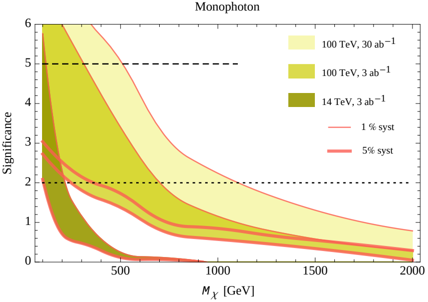
4 channels: Monojet Monophoton Vector boson fusion Disappearing tracks

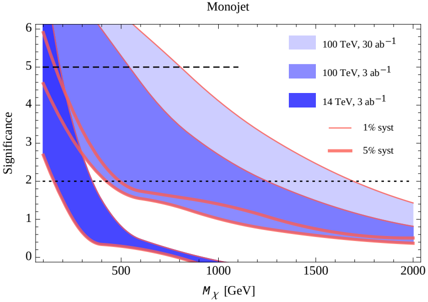
at **LHC14** with $L = 3\,\text{ab}^{-1}$, and at a **100 TeV** $p-p$ collider, for $L = 3, 30\,\text{ab}^{-1}$

see also Low Wang 1404.0682, Berlin Lin Low Wang 1502.05044

Missing Energy + SM radiation







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 $3 \div 4$

Disappearing Tracks

$M_{\chi^\pm} - M_{\chi_0} = 165$ MeV $> m_\pi \quad \Rightarrow \quad$ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

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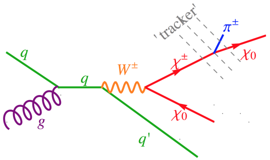
Feng Strassler 1994, ...



ATLAS performed this analysis!

Current strongest limit on pure Wino

$M_{\chi_0} > 270$ GeV

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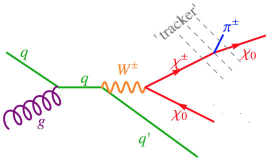

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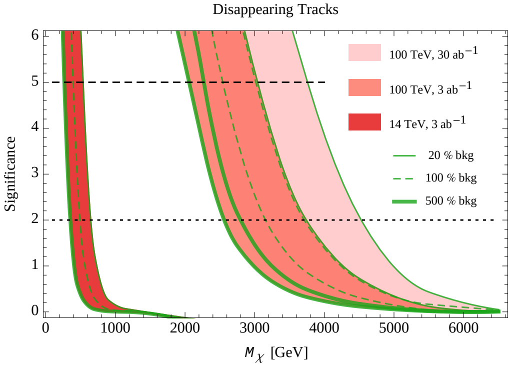
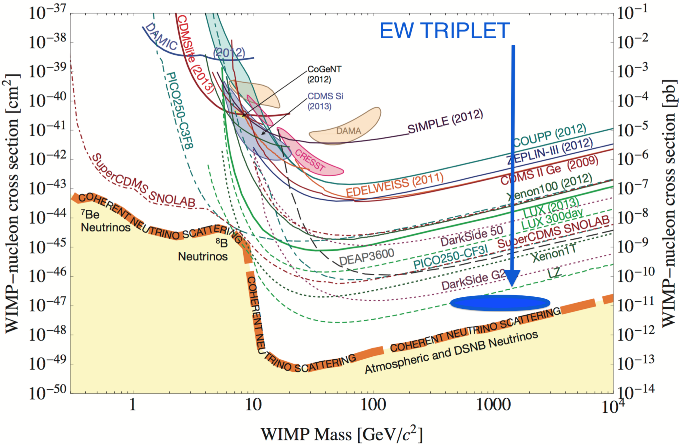
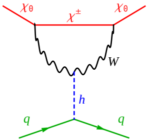
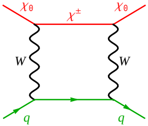


Potential to probe thermal Wino!

Direct Detection







Hisano et al. 1504.00915: $\sigma_{SI}^{3plet} = 2.3 \times 10^{-47} \mathrm{cm}^2$

full NLO in α_S, $O(50\%)$ uncertainties [largest error from charm content of nucleon]

An EW triplet in the (γ) sky

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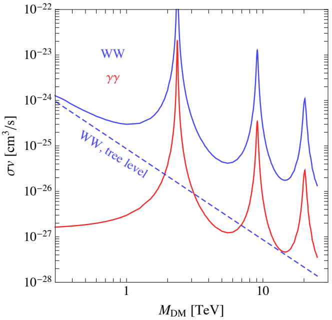
Sommerfeld enhancement

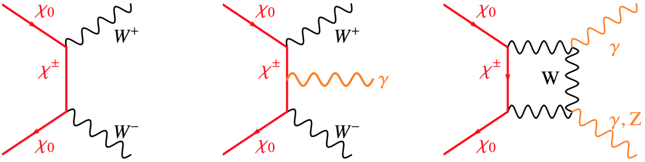
at low velocities non-rel. attractive potential

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

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

$\chi_0 \chi_0 \to WW, \gamma\gamma$ $\quad \sigma v$ saturates at $v \lesssim 10^{-2} \;\to$





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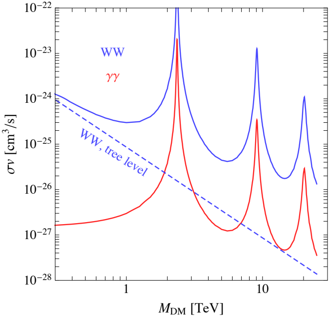

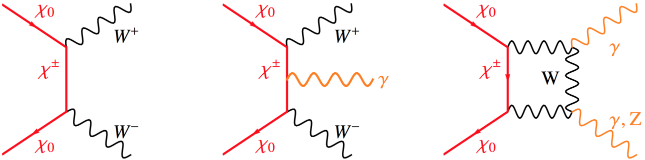

$\bar{p},\ e^+,\ \nu,\ \gamma, \ldots$

γ ray lines: smaller cross-sections

but features in γ spectrum enhance sensitivities

γ continuum from dwarf spheroidal galaxies

A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects $\rightarrow$ this is why they are good targets!
- often "trackers" are just a few $\rightarrow$ big uncertainties on DM properties

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

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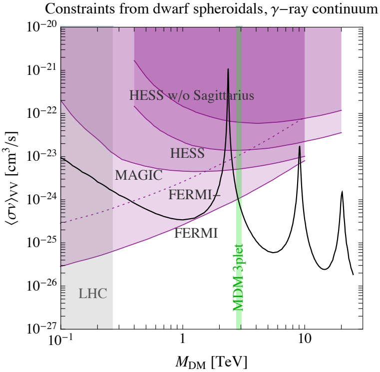

FERMI: 15 dwarves, assumes $\Delta J < 40\%$

HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

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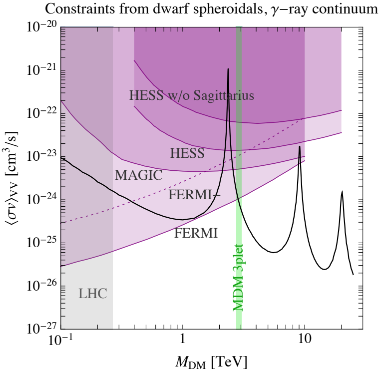

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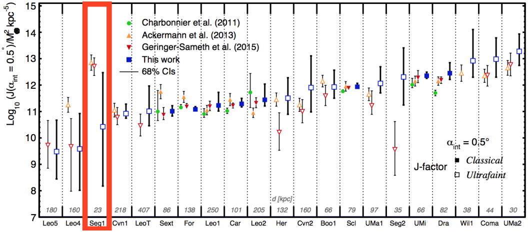
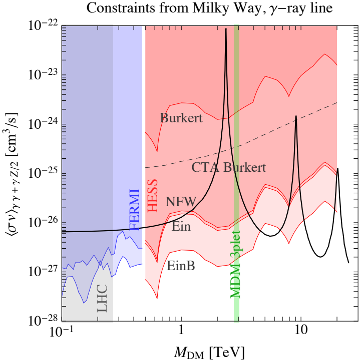
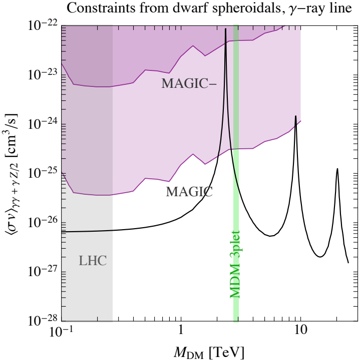


Bonnivard et al 1504.02048

γ 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!

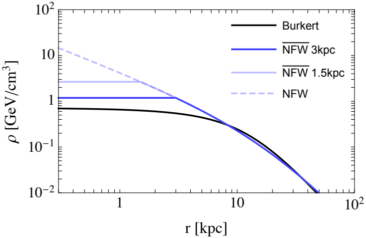
$\rightarrow$ Look at the same (other) dwarves with other (the same) experiments

$\rightarrow$ 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?



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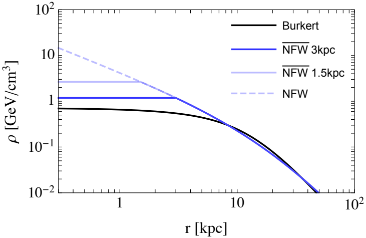

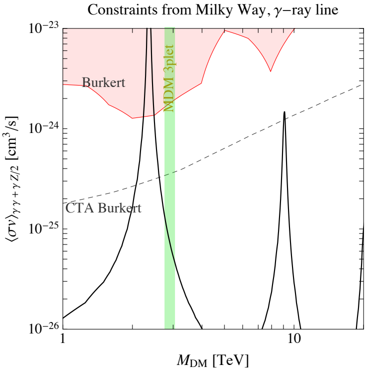

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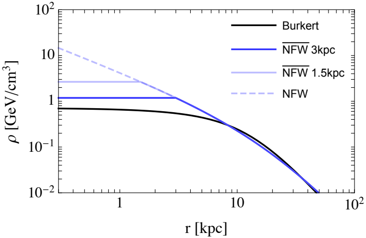

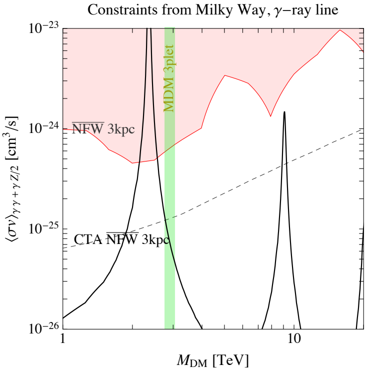

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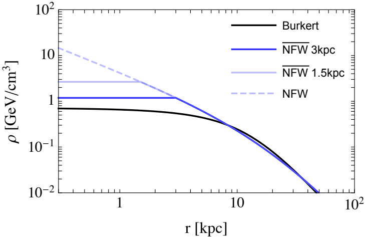

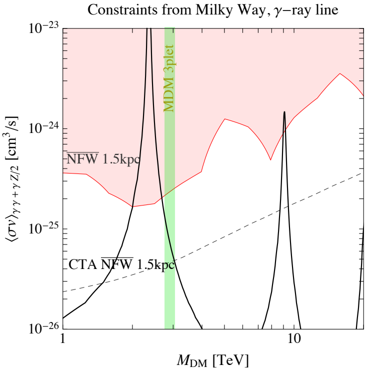

An EW fermion 3plet: summary

Why interesting?

Simple benchmark of a WIMP, and moreover

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

Minimal Dark Matter

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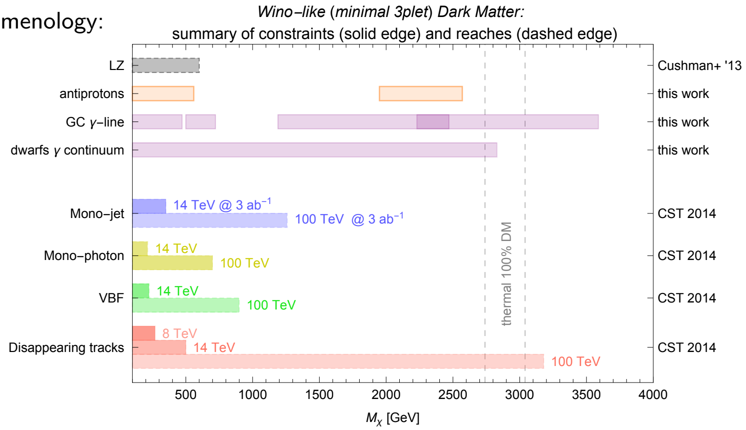
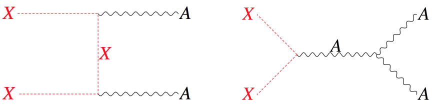
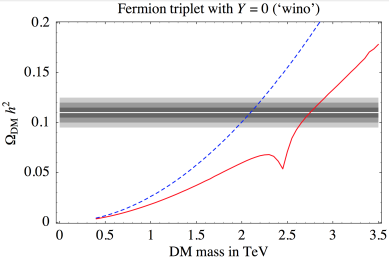
Phenomenology:



Back up Dark Matter

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

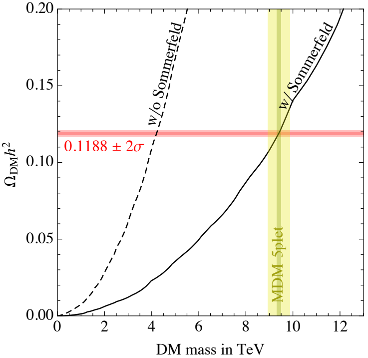




Important to include:

- ◇ Coannihilations
- ◇ Sommerfeld enhancement
- ? Corrections from higher orders

5plet from Cirelli et al 1507.05519 →



Minimal Dark Matter: candidates

Allowed: χ neutral under g, γ, and almost under Z (direct detection)

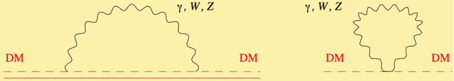
$$\Rightarrow \boxed{\chi = n\text{-tuplet of } SU(2)_L \qquad Y = 0}$$

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: $M_Q - M_{Q=0} \simeq Q(Q + \frac{2Y}{c_{\theta_W}})\Delta M$



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

Ibe Matsumoto Sato 1212.5989

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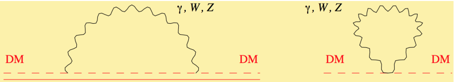

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Avoid g_2 Landau pole before M_{Pl} $\Rightarrow$ n not too large

In practice: $n \leq 8$ for scalars, $n \leq 5$ for fermions

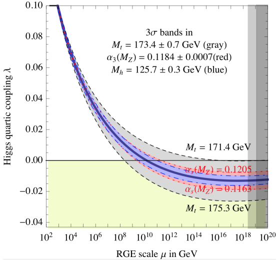
Why an EW fermion triplet?

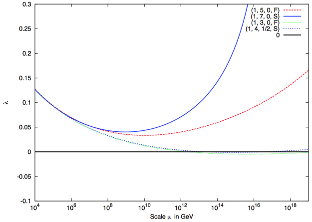
→ Stable if one imposes L or $B - L$ or discrete subgroup (already in the SM!)

[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]



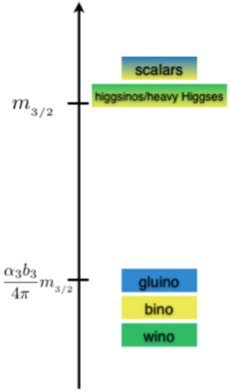


→ Not big contribution to m_h ⇒ does not worsen fine-tuning

→ Helps with unification of gauge couplings

Why an EW fermion triplet?

$\rightarrow$ Connection with SUSY with heavy scalars James Wells hep-ph/0306127



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

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

- $\rightarrow$ All other scalars are heavier
- $\rightarrow$ Higgsinos also heavier if $\mu \sim m_{3/2}$
- $\rightarrow$ 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
...
D'Eramo Hall Pappadopulo 1409.5123

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_v2 + Pythia 6.4 + Delphes (CMS card)

Backgrounds: mainly $Z \to \nu\bar{\nu}$, $W \to \ell\nu$ (+ 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:

Cuts	14 TeV	100 TeV 3 ab^{-1}	100 TeV 30 ab^{-1}
$\not{E}_T$[TeV]	$0.4 - 0.7$	$1.5 - 5.5$	$1.5 - 5.5$
$p_T(j_{12})$ [GeV]	40 (1%), 60 (5%)	150	200
M_{jj} [TeV]	1.5 (1%), 1.6 (5%)	6 (1%), 7 (5%)	7
$\Delta\eta_{12}$	3.6	3.6	3.6 (1%), 4 (5%)
$\Delta\phi$	$1.5 - 3$	$1.5 - 3$	$1.5 - 3$
$p_T(j_3)$ [GeV]	25	60	60
$p_T(\ell)$ [GeV]	20	20	20
$p_T(\tau)$ [GeV]	30	40	40

More on collider studies - II

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 $\Delta M^{\rm dim7} \simeq \frac{1}{4}\frac{v^4}{\Lambda^3} \lesssim 10\ {\rm MeV}$ for $\Lambda \gtrsim 3$ TeV

Disappearing Tracks - Strategy

We mimic the ATLAS analysis   [we cannot simulate backgrounds]

Disappearing Tracks - Strategy

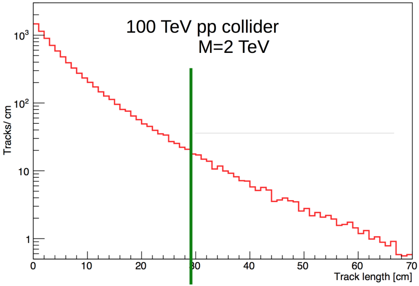
We mimic the ATLAS analysis [we cannot simulate backgrounds]

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 $pp \to \nu\bar{\nu}jet$

Then we quantify uncertainty on bkg with a factor of 5 up/down

γ continuum with FERMI - I

$\rightarrow$ FERMI measures γ flux from all sky

$\rightarrow$ We "conservatively" model astrophysical backgrounds

$\rightarrow$ We divide the sky into regions, and extract bounds from each one

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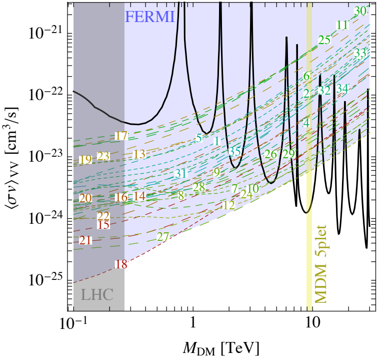
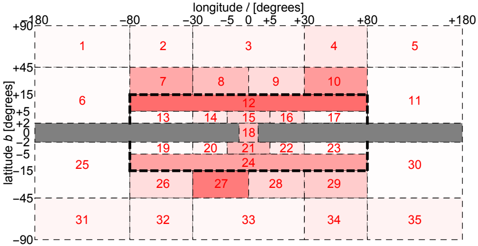
NFW profile, including background



NFW profile, bounds including background



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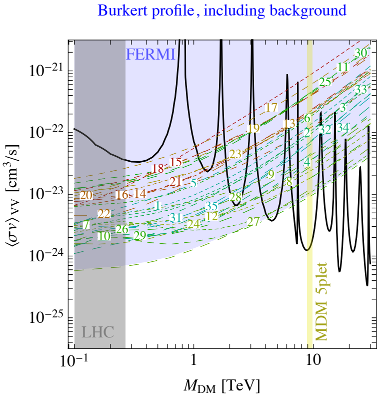
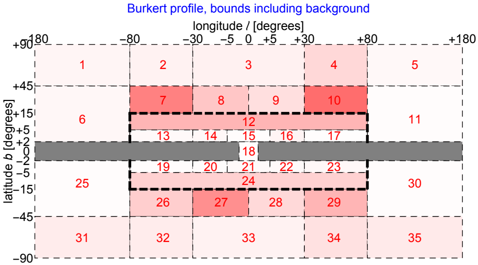
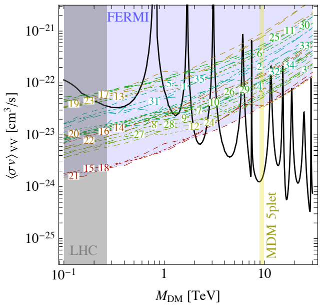




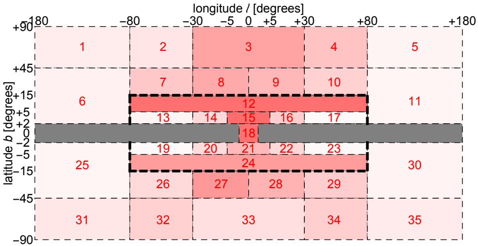
◇ Galactic bounds depend on DM profile

◇ All bounds assume 5plet = 100% of DM

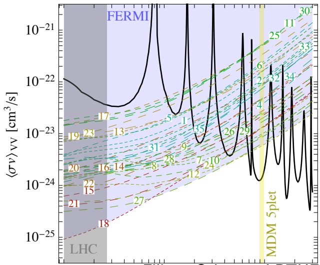
NFW profile, conservative bound



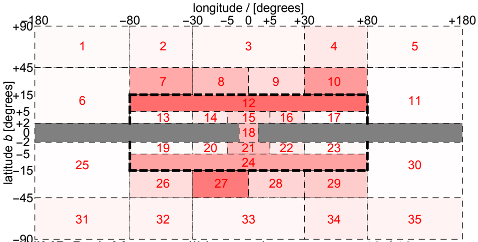
NFW profile, conservative bounds



NFW profile, including background

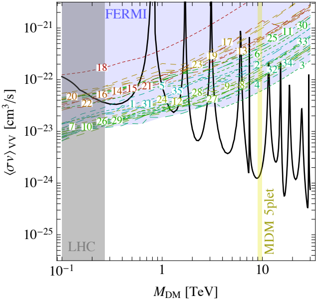


NFW profile, bounds including background

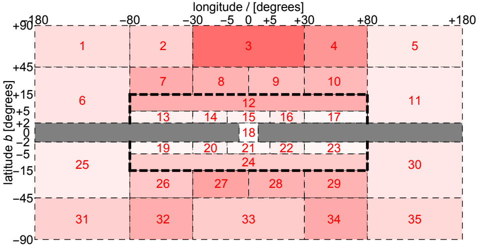


γ continuum with FERMI - II

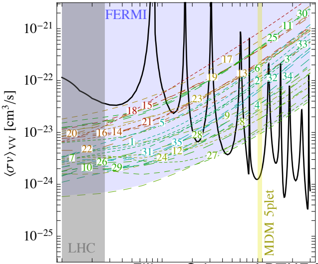
Burkert profile, conservative bound



Burkert profile, conservative bounds



Burkert profile, including background



Burkert profile, bounds including background