Minimal Dark Matter and future colliders

Filippo Sala

IPhT, CEA/Saclay and CNRS

mainly based on Cirelli, S, Taoso 1407.7058

Universitat Autònoma de Barcelona, 27 October 2014

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Data: no answer so far, everything agrees with Standard Model

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1 The Fermi scale is "natural" [$\Rightarrow \Lambda_{\rm NP} \lesssim$ TeV]

A mechanism screens m_h from scales higher than M_{NP}, for any NP

Examples: Supersymmetry composite Higgs models

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"Standard" approach on Dark Matter:

it is a byproduct of theories that solve the HP, e.g. Neutralino in supersymmetry

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2 Short distance assumptions [$\Lambda_{\rm NP} =???$]

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2 and 3 open **new avenues for Dark Matter model building**

Can DM provide an indication for a NP scale?

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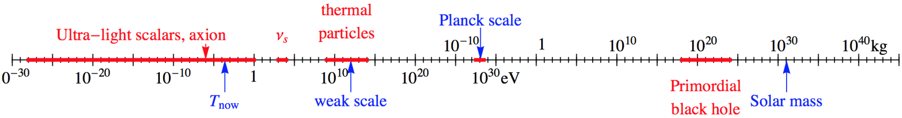
Not really



[courtesy of Marco Cirelli]

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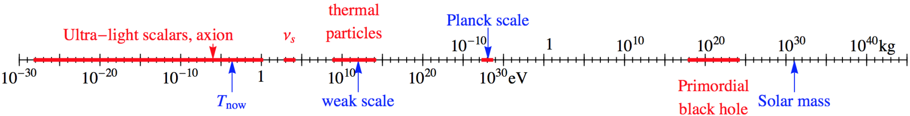
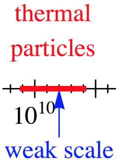


[courtesy of Marco Cirelli]

Less ambitiously:

how far can we probe the “thermal relic WIMP” paradigm?

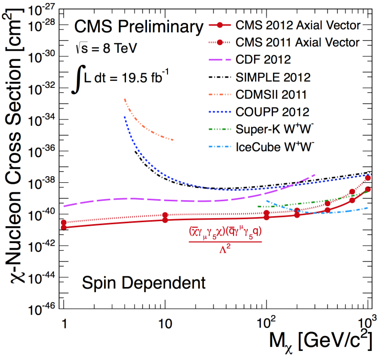


Unitarity bound: $M_{\rm DM} < 80 \div 120$ TeV Griest Kamionkowski PRL 1990

General strategy: effective field theories

EFT approach mostly used till now

- ☺ Model-independent
- ☺ easy comparison   collider - direct detection



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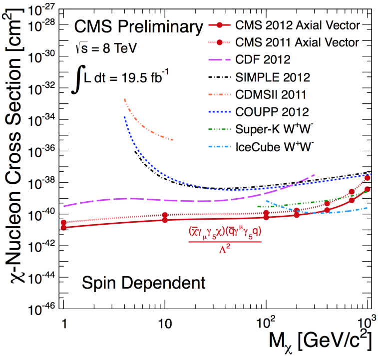
- ☺ Model-independent
- ☺ easy comparison collider - direct detection

☹ ∼ 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

Need to go to benchmark/simplified models!

Minimal Dark Matter

→ Modelling

→ Phenomenology

Minimal Dark Matter

→ Modelling

Minimal Dark Matter: intro

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

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM} + c\,\bar{\chi}(i\hat{D} - M_\chi)\chi} \qquad \left[+c\left(|D_\mu\chi|^2 - M_\chi^2|\chi|^2\right) \text{ if scalar, c} = 1 \text{ or } 1/2\right]$$

other terms forbidden by Lorentz + SM symmetries (fermions)/by hand (scalars)

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

[In "standard" SUSY many parameters obscure phenomenology]

Minimal Dark Matter: candidates

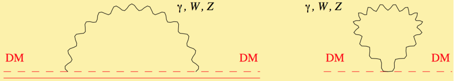
Allowed: χ neutral under g, γ, and almost under Z (direct detection)

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

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

$\Rightarrow$ first candidates are $n = 5$ fermion and $n = 7$ scalar

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



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

Ibe Matsumoto Sato 1212.5989

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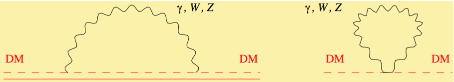

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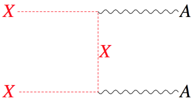
Avoid g_2 Landau pole before $M_{\rm Pl}$ $\Rightarrow$ n not too large

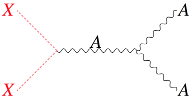
In practice: $n \leq 8$ for scalars, $n \leq 5$ for fermions

[issue from 2-loop? Nardecchia et al, work in progress]

Relic abundance

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





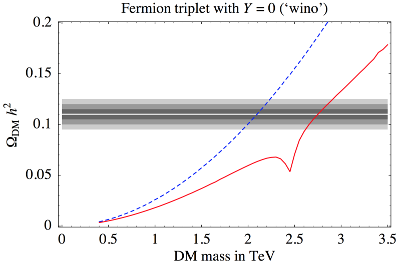
Important to include:

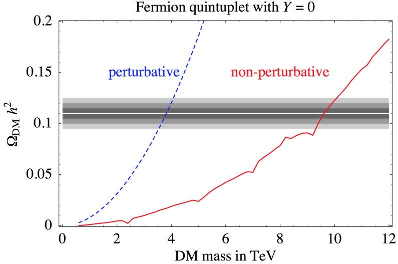
◇ Coannihilations

◇ Sommerfeld enhancement

? NLL corrections

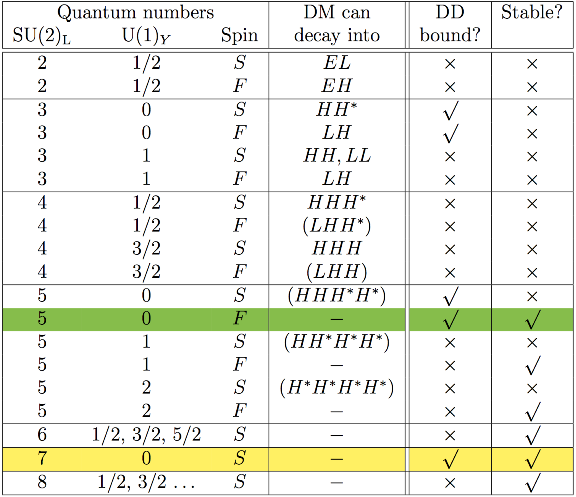
Cirelli Strumia Tamburini 0706.4071 →





Summary of candidates

Table from Cirelli Strumia 0903.3381



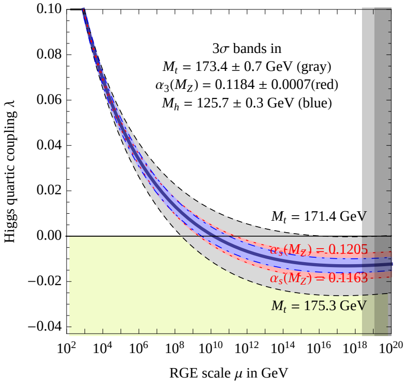
Quantum numbers			DM can	DD	Stable?
SU(2)$_\mathrm{L}$	U(1)$_Y$	Spin	decay into	bound?	
2	1/2	S	EL	×	×
2	1/2	F	EH	×	×
3	0	S	HH^*	√	×
3	0	F	LH	√	×
3	1	S	HH, LL	×	×
3	1	F	LH	×	×
4	1/2	S	HHH^*	×	×
4	1/2	F	(LHH^*)	×	×
4	3/2	S	HHH	×	×
4	3/2	F	(LHH)	×	×
5	0	S	(HHH^*H^*)	√	×
5	0	F	–	√	√
5	1	S	$(HH^*H^*H^*)$	×	×
5	1	F	–	×	√
5	2	S	$(H^*H^*H^*H^*)$	×	×
5	2	F	–	×	√
6	1/2, 3/2, 5/2	S	–	×	√
7	0	S	–	√	√
8	1/2, 3/2 …	S	–	×	√

Masses if χ thermal relic: $\boxed{M_3 \simeq 3\text{ TeV} \quad M_5 \simeq 10\text{ TeV} \quad M_7 \sim 25\text{ TeV}}$

MDM and vacuum stability

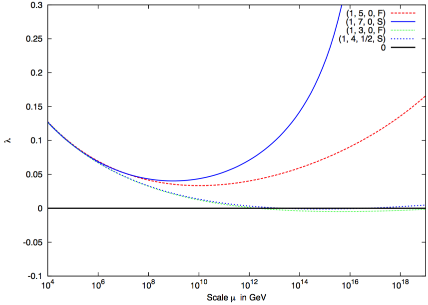
Standard Model vacuum is metastable

(*if* BICEP confirmed, NP *could* be necessary to correct λ running)



Buttazzo et al 1307.3536

Correction from MDM:



Chao Gonderinger Ramsey-Musolf 1210.0491

$\Big($right-handed neutrinos not relevant if $\boxed{M_{\nu_R} \lesssim 10^{13}\ \text{GeV}}$ $\quad \beta_\lambda \supset -y_\nu^4 \dfrac{\#}{16\pi^2} \quad m_\nu \sim \dfrac{y_\nu^2 v^2}{M_{\nu_R}}\Big)$

Why an EW fermion triplet?

Quantum numbers $\mathrm{SU}(2)_{\mathrm{L}}$	 $\mathrm{U}(1)_Y$	 Spin	DM can decay into	DD bound?	Stable?
3	0	F	LH	√	×

→ 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]

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→ 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]

→ Not a big issue for m_h ⇒ does not worsen fine-tuning

$$\delta m^2 = \frac{M^2}{(4\pi)^4}\,\frac{n(n^2-1)}{4}\,g_2^2\left(6\ln\frac{M^2}{\bar{\mu}^2}-1\right)$$

$M_\chi \lesssim 1.0\sqrt{\Delta}$ TeV to have less than $(100/\Delta)$ % fine-tuning

[5-plet $M_\chi \lesssim 0.4\sqrt{\Delta}$ TeV, 7-plet $M_\chi \lesssim 0.06\sqrt{\Delta}$ TeV]

Farina Pappadopulo Strumia 1303.7244

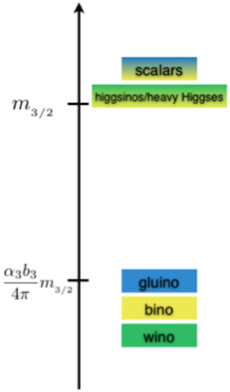
→ Helps with unification of gauge couplings

see e.g. "Split SUSY without SUSY" Frigerio Hambye 0912.1545

[Same running could put 5-plet in trouble, stay tuned with Nardecchia et al]

Why an EW fermion triplet?

→ 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)

- → 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
...
D'Eramo Hall Pappadopulo 1409.5123

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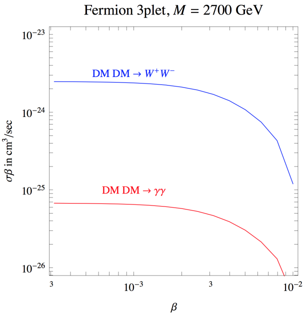
Indirect detection: ingredients

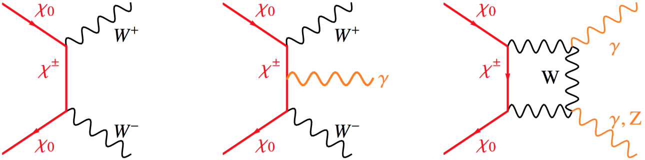
Sommerfeld enhancement

even more important than in abundance computation, since here

$$\boxed{v \sim 10^{-3} c}$$

Franceschini et al 0802.3378, WARNING: old →





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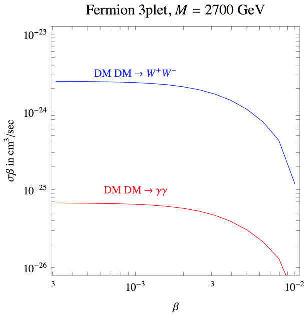
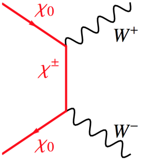
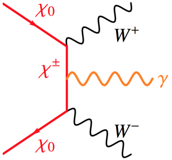
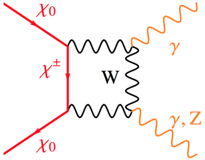






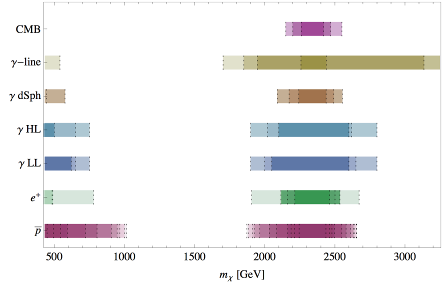


$\bar{p}$, e^+, ν, γ, ...

γ ray lines: smaller cross-sections

but features in γ spectrum enhance sensitivities

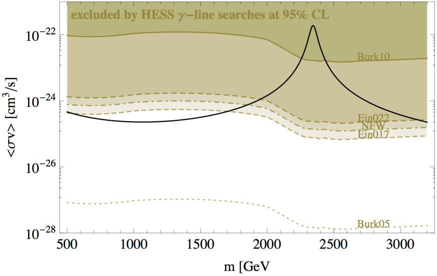
Indirect detection: constraints



Large astrophysical uncertainties

[shaded = different astro assumtpions]

Assume all DM made of EW triplet



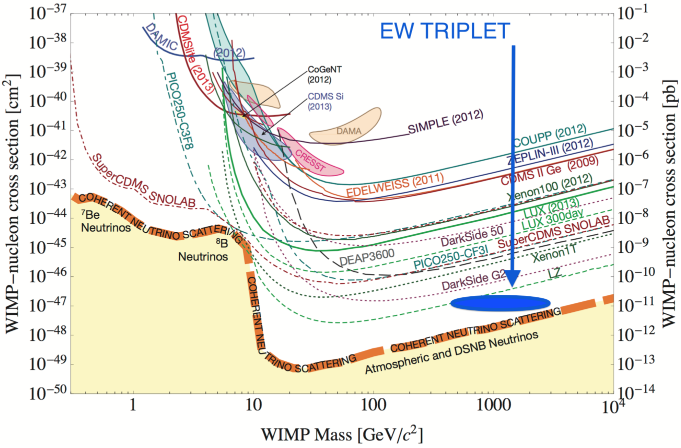
Will CTA improve substantially?

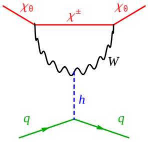
Currently unclear

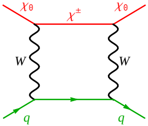
see e.g. Bertone et al. 1408.4131

Hryczuk Cholis Iengo Tavakoli Ullio 1401.6212

Direct Detection







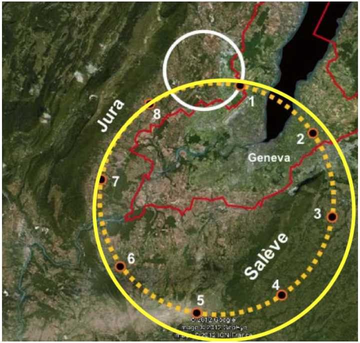
Hill Solon 1309.4092: $\boxed{\sigma_{\mathrm{SI}} = 1.3^{+1.3}_{-0.6} \times 10^{-47}\mathrm{cm}^2}$ valid at $O\left(m_W^2/M_\chi^2\right)$

Future colliders?

"The community needs studies of what could be probed at a 100 TeV machine and not elsewhere, and it needs them soon"

Michelangelo Mangano, 100 TeV kick-off meeting, Feb 2014, CERN

Currently unclear where particle physicists will put (EU? China? ???) money:



HL-LHC $\sqrt{s} = 14$ TeV, 3000 fb^{-1}, ~ 2025-2035

HE-LHC $\sqrt{s} = 33$ TeV, needs new technology

FCC-*pp* $\sqrt{s} \sim 100$ TeV, start ~ 2040(?),
needs ~ 100 km tunnel & new tech.

ILC $\sqrt{s} = 0.5 - 1$ TeV, maybe Japan soon

CLIC $\sqrt{s}$ up to 3 TeV, needs new tech.

TLEP $\sqrt{s}$ up to 500 GeV, higher luminosity,
needs ~ 100 km tunnel

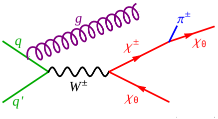
A pure Wino at colliders

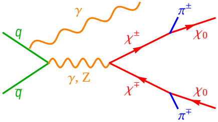
DM not detected in collider: look for missing transverse energy + SM radiation

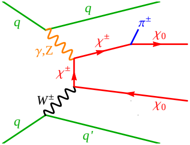
$$M_{\chi^\pm} - M_{\chi_0} = 165 \text{ MeV} > m_\pi \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors

$\Rightarrow$ $\chi^\pm$ add to the signal!







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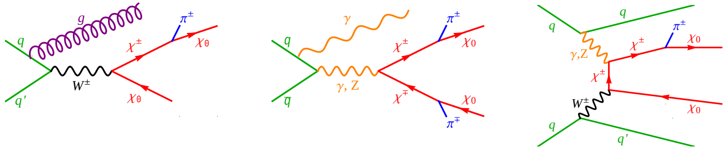

4 channels: Monojet Monophoton Vector boson fusion Disappearing tracks

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

For a recent study of Monojet and Disappearing Tracks see Low Wang 1404.0682

Monojets + missing energy

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

Cuts: inspired by rescaling of 8 TeV searches, optimized on a grid

$$\boxed{\text{Significance} = \frac{S}{\sqrt{B + \alpha^2 B^2 + \beta^2 S^2}}}$$

i.e. includes statistics + systematics

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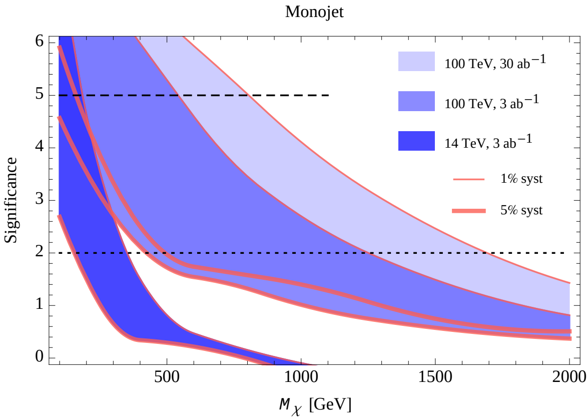

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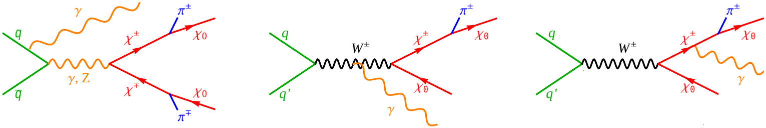
Qualitatively analogous to Monojet, but photons also from final state radiation!



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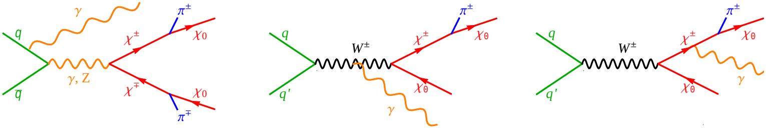
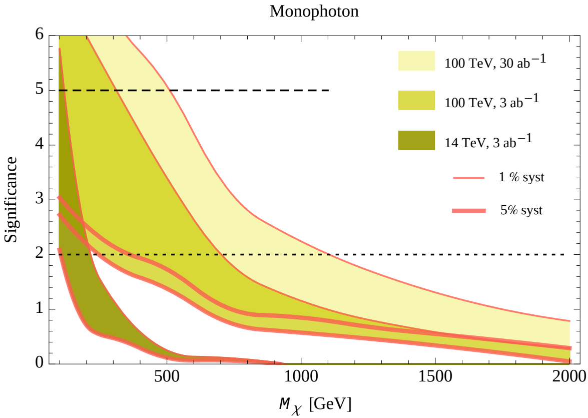
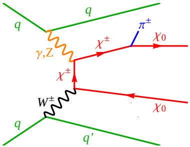
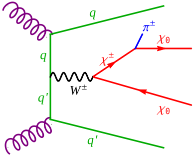




Forward dijets + missing energy (VBF)

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

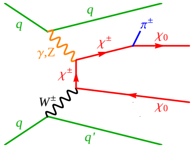


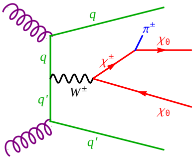


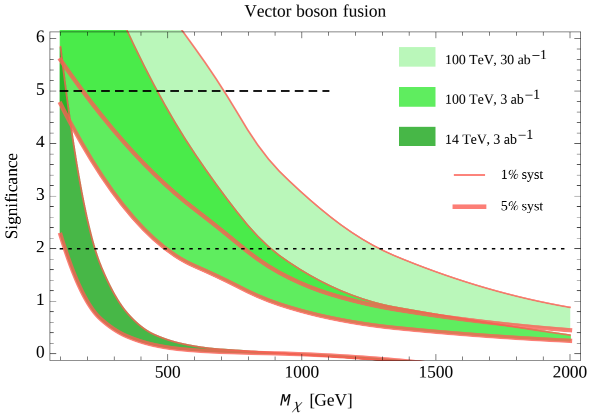
Delannoy et al. 1304.7779, studied VBF at 14 TeV and found sensitivity over 1 TeV!

Forward dijets + missing energy (VBF)

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







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...

Summary of missing energy + SM radiation

Tools used: Madgraph5_v2 + Pythia 6.4 + Delphes (CMS card)

Backgrounds: simulations validated with available 8 TeV CMS and ATLAS analyses

Cuts: 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

Take-home messages

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

→ Systematics understanding will be crucial, today we are at ∼ 5%, not 1%!

→ going from 14 to 100 TeV will increase mass reach by a factor $3 \div 4$

Disappearing Tracks - Introduction

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

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors

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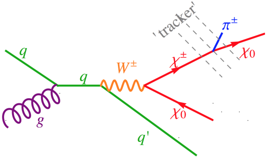

Feng Strassler 1994

Feng Moroi Randall Strassler Su 1999

...

Low Wang 1404.0682

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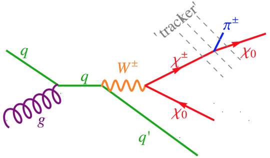

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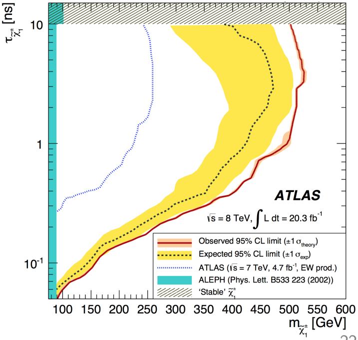
...

Low Wang 1404.0682

ATLAS performed this analysis at 8 TeV!

Current strongest limit on pure Wino

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



No background in the SM, but from detector:

- → interactions of charged hadrons in detector
- → unidentified leptons
- → mis-measured tracks, dominant at large p_T

Disappearing Tracks - Strategy

We mimic the ATLAS analysis [we cannot simulate backgrounds]

Disappearing Tracks - Strategy

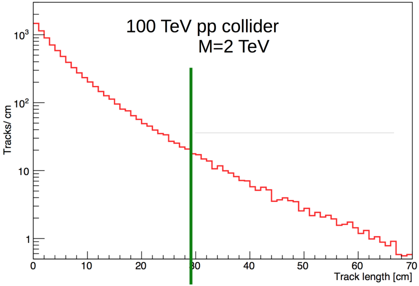
We mimic the ATLAS analysis [we cannot simulate backgrounds]

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

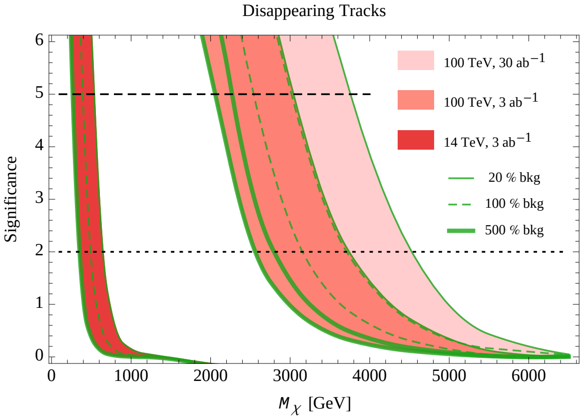


Assumptions for background:

- ◇ 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 $pp \to \nu\bar{\nu}jet$

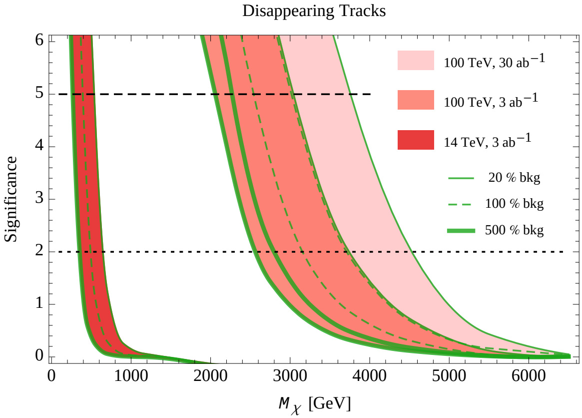
Then we quantify uncertainty on bkg with a factor of 5 up/down

Disappearing Tracks - Results



Potential to probe thermal Wino!

Disappearing Tracks - Results



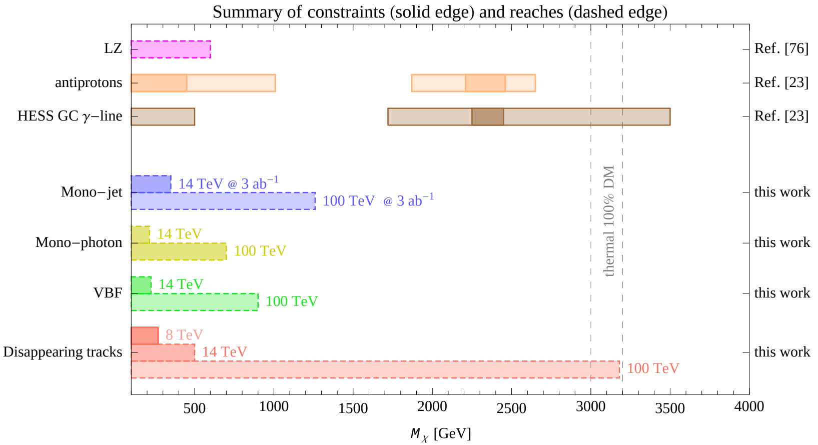
Potential to probe thermal Wino!

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

Summary of pure Wino phenomenology



Indirect detection good probe

but large astro uncertainties + assumes all DM = Wino

LHC14 poor reach, **100 TeV** could probe masses up to thermal (and beyond?)

Other electroweak multiplets?

A fermion quintuplet

Originally “the” Minimal Dark Matter candidate, cause automatically stable

$M_{\rm thermal} \simeq 10$ TeV

$\Delta M \simeq 165$ MeV

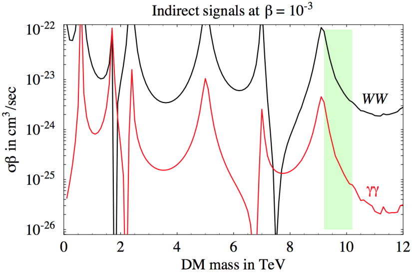
Direct Detection: poor prospects

100 TeV collider:

very unlikely to reach thermal mass

Indirect detection:

depends on position of Sommerfeld peaks, precise computation needed



OLD Cirelli Strumia Tamburini 0706.4071

A scalar triplet

Needs extra symmetry to be stabilised, e.g. Z_2

$M_{\rm thermal} \simeq 2.5$ TeV

$\Delta M \simeq 165$ MeV

emerges as "techni-pion" in scale-free models with strong interactions

Antipin Redi Strumia 1410.1817

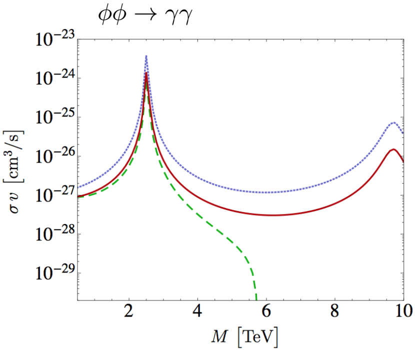
Direct Detection: poor prospects

100 TeV collider:

maybe disappearing tracks

Indirect detection:

precise computations available



Bauer Cohen Hill Solon 1409.7392

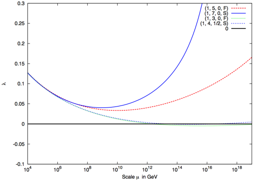
Conclusions

mainly based on Cirelli Sala Taoso 1407.7058

An EW fermion triplet to make Dark Matter

[needs non-standard attitude towards hierarchy problem]

- ✓ stable by $B - L$ (or discrete subgroup)
- ✓ not big contribution to m_h
- ✓ helps with unification of gauge couplings
- ✓ stabilizes EW vacuum
- ✓ mimics Wino LSP/provides benchmark



Phenomenology hard to see, need 100 TeV?

Outlook/in progress: other multiplets

ID prospects