IPhT CEA-Saclay

Marco Taoso

Minimal Dark Matter and future colliders

Effective Theories and Dark Matter

MITP, Mainz

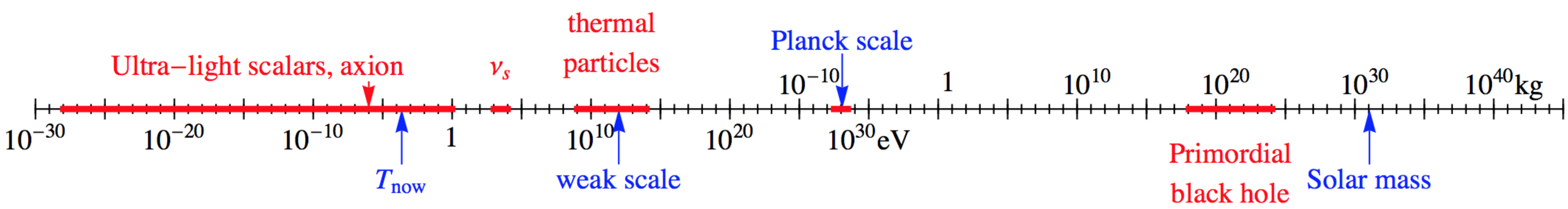
19-03- 2015

DE LA RECHERCHE À L'INDUSTRIE

NewDark

What do we know about DM?

Mass and cross sections largely unconstrained



Courtesy of M.Cirelli

WIMPs paradigm

Thermal relic from the early Universe

Connection with BSM at the Terascale

Multiple way to test the scenario: collider, direct detection, indirect searches

Minimal Dark Matter

Minimalistic approach: add to SM an extra gauge multiplet and search for assignments giving a viable DM candidate

$$\mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin } 1/2 \text{ fermionic multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin 0 bosonic multiplet} \end{cases}$$

Requirements for DM: stable, neutral and allowed by DM searches

The only free parameter is the DM mass, fixed by the thermal relic density

Cirelli, Fornengo, Strumia hep-ph/0512090

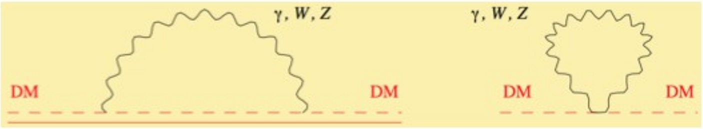
Minimal Dark Matter

Stability: for large enough representation , 5 (7) for fermions (scalars), renormalizable and dim 5 operators do not lead fast decays

Constraints from DM searches: no colored, Y=0 to avoid large Z-mediated SI scattering cross section with nuclei. Pure SU(2) multiplets

Lightest component is **neutral**

$$M_Q - M_{Q=0} \simeq Q(Q + \frac{2Y}{c\theta_w})\Delta M$$



g2 Landau pole: pushed above M_{PL} for reprs. n ≤ 5 for fermions and n ≤ 8 for scalars

Minimal Dark Matter

From Cirelli, Strumia 0903.3381

Quantum numbers			DM can	DD	Stable?
$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	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	–	×	√

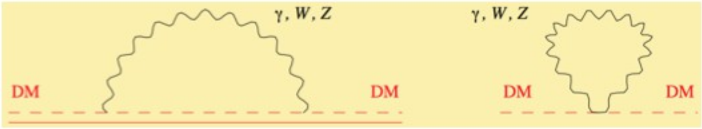
DM mass fixed for a thermal relic to match measured DM abundance.
Mass in the multi-TeV range (10 TeV for 5-plet and 25 TeV for 7-plet)

Triplet DM candidate

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DD bound?	Stable?
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	×	×

Fermionic triplet **stable** if L or B-L is respected (or at least matter parity)

Lightest component is **neutral**
Mass splitting at 2 loop $\Delta M = 164.5 \pm 0.5$ MeV

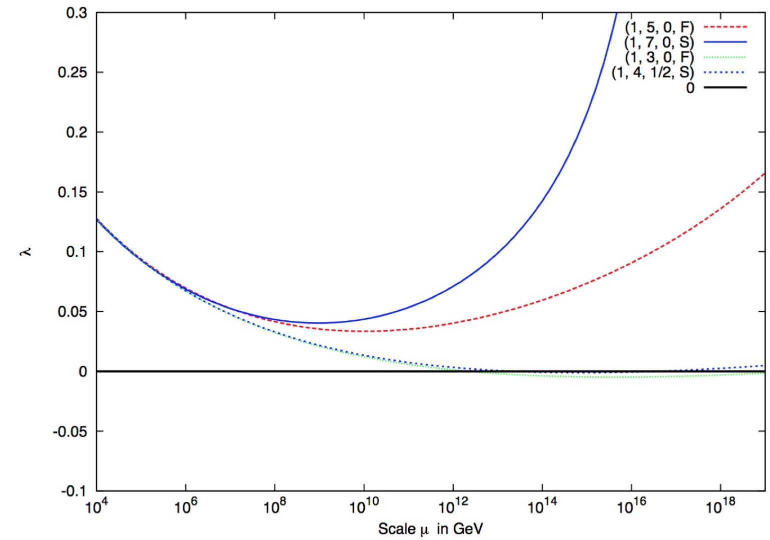


Ibe et al. 1212.5989

Capture low-energy pheno of SUSY models with **WINO LSP** and heavy scalars

Other remarks on the EW multiplets

Chao Gonderinger Ramsey-Musolf 1210.0491



- It correct the running of Higgs quartic coupling stabilizing the EW vacuum

- Helps with gauge-coupling unification

Frigerio, Hambye 0912.1545 "Dark Matter stability and unification without supersymmetry"

- Do not worsen fine-tuning of Higgs mass

Farina, Pappadopulo, Strumia 1303.7244

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

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

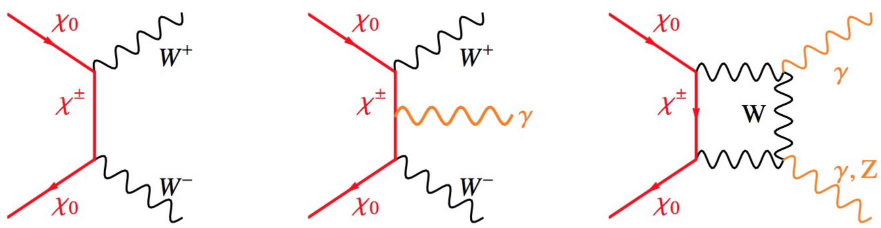
[5-plet $M_\chi \lesssim 0.4\sqrt{\Delta}$ TeV, 7-plet $M_\chi \lesssim 0.06\sqrt{\Delta}$ TeV]

Relic abundance

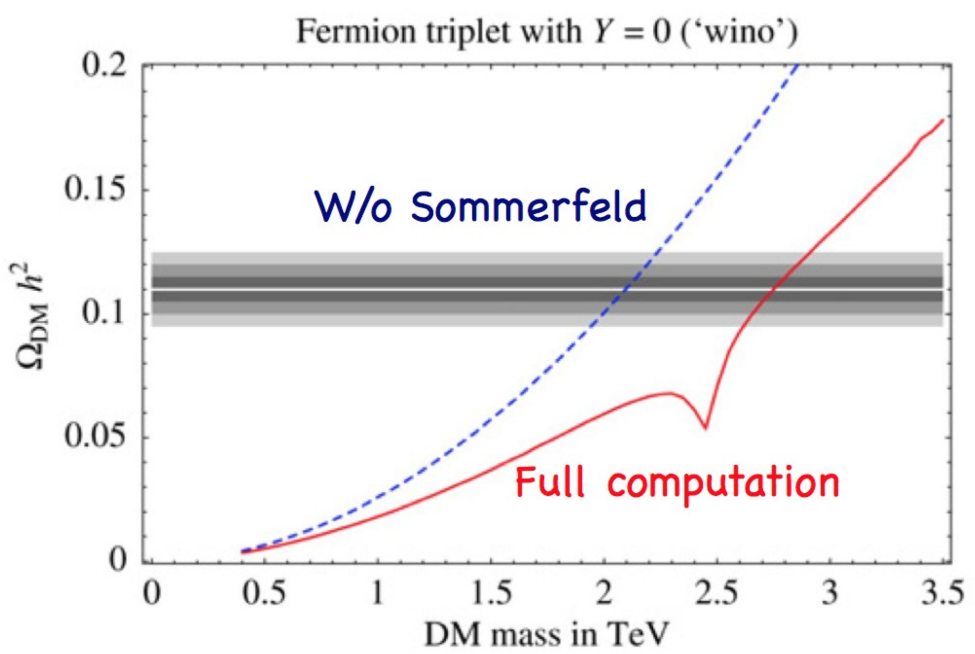
Dominant annihilation channel is WW
Relic abundance calculation should include:

Coannihilations with charged state in the multiplet

Sommerfeld corrections



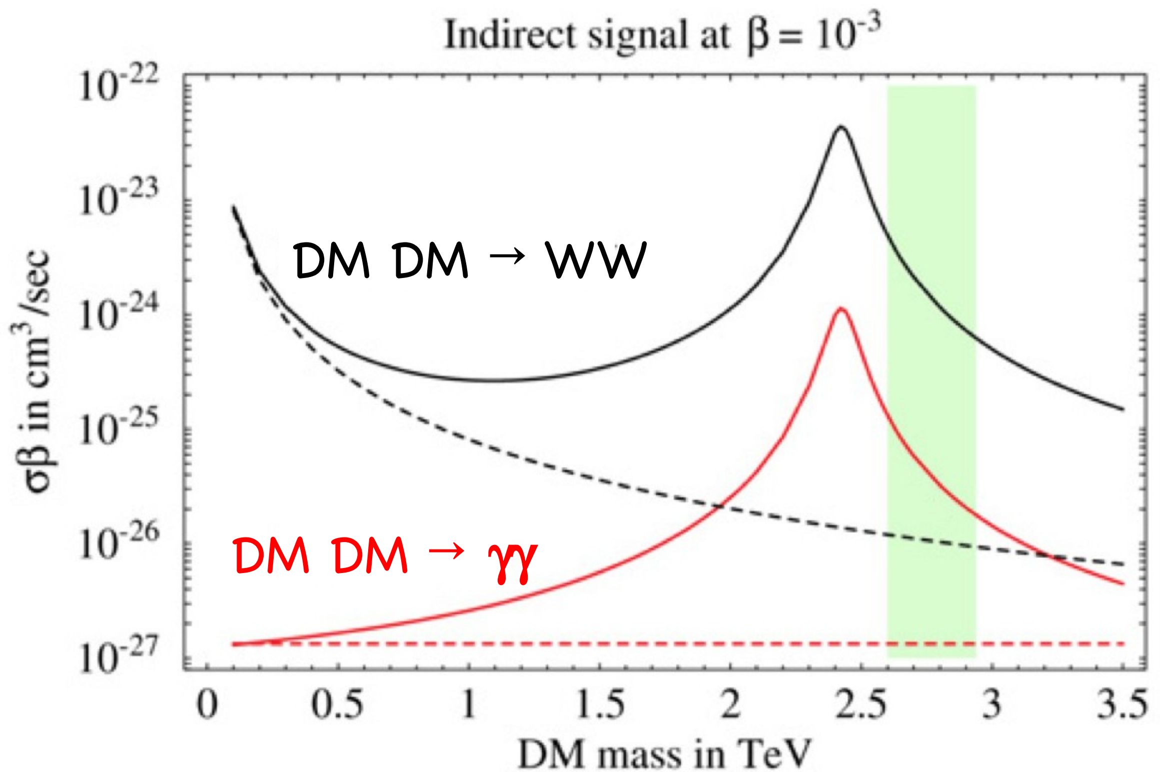
Cirelli, Strumia, Tamburini 0706.4071



Correct abundance for M around 3 TeV.
Under-abundant (over-abundant) for a lighter (heavier) triplet
Other masses possible for non-thermal production &/or non standard cosmology

Indirect searches

Sommerfeld effect enhances annihilation cross-section at low velocities, i.e. relevant for DM at present epoch inside galaxies

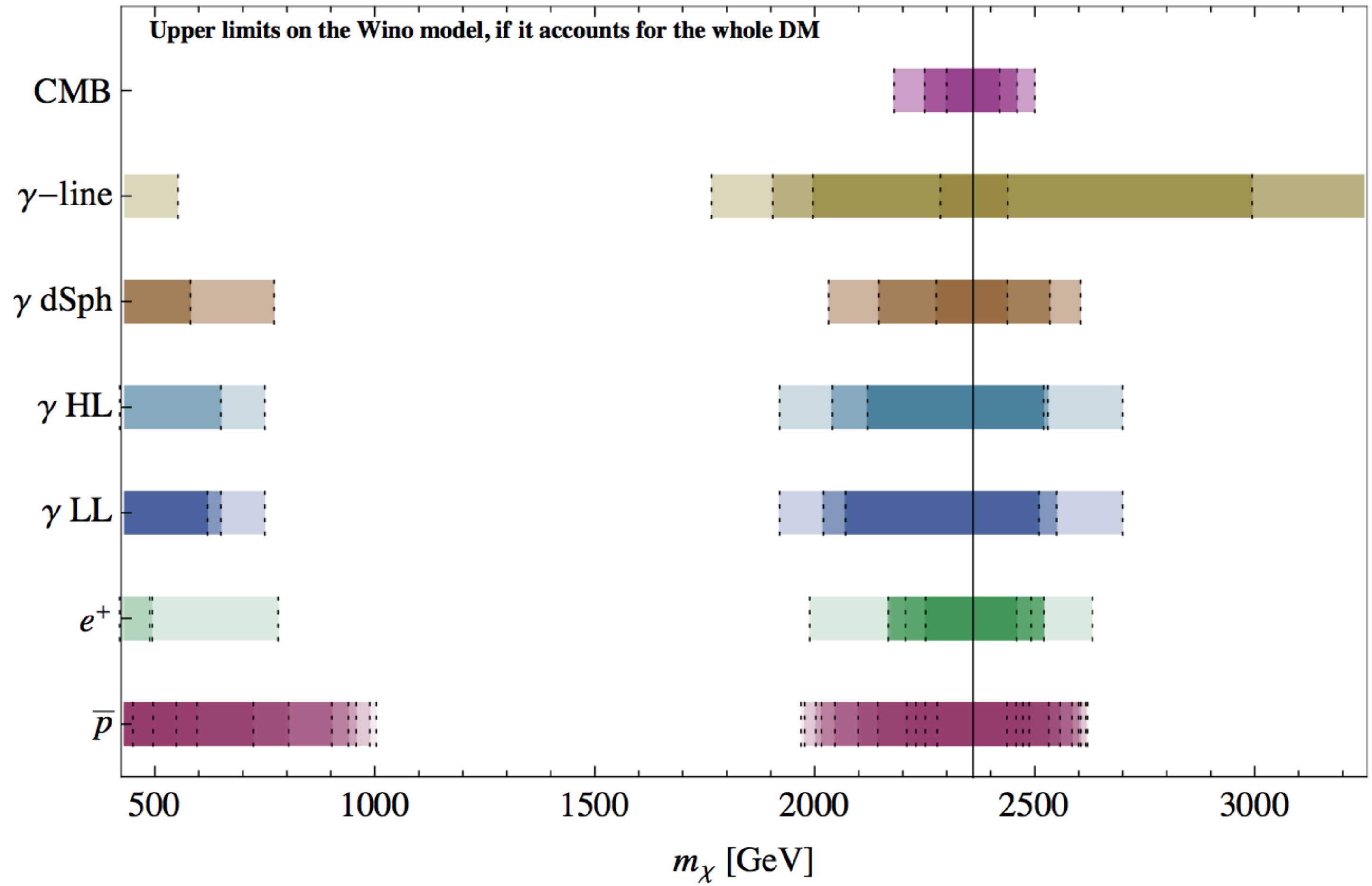


For accurate calculations of cross-sections see Hryczuk and Iengo 1111.2916

Recent works on resummation of EW Sudakov logs: Ovaneysian, Slatyer, Stewart 1409.8294, Bauer, Cohen, Hill, Solon 1409.7392, Baumgart, Rothstein, Vaidya 1412.8698

Indirect detection bounds

Bounds depend on astrophysical assumptions like DM density profiles, cosmic-rays propagation... Shading corresponds to different choices



From Hryczuk, Cholis, Iengo, Takavoli, Ullio 1401.6210

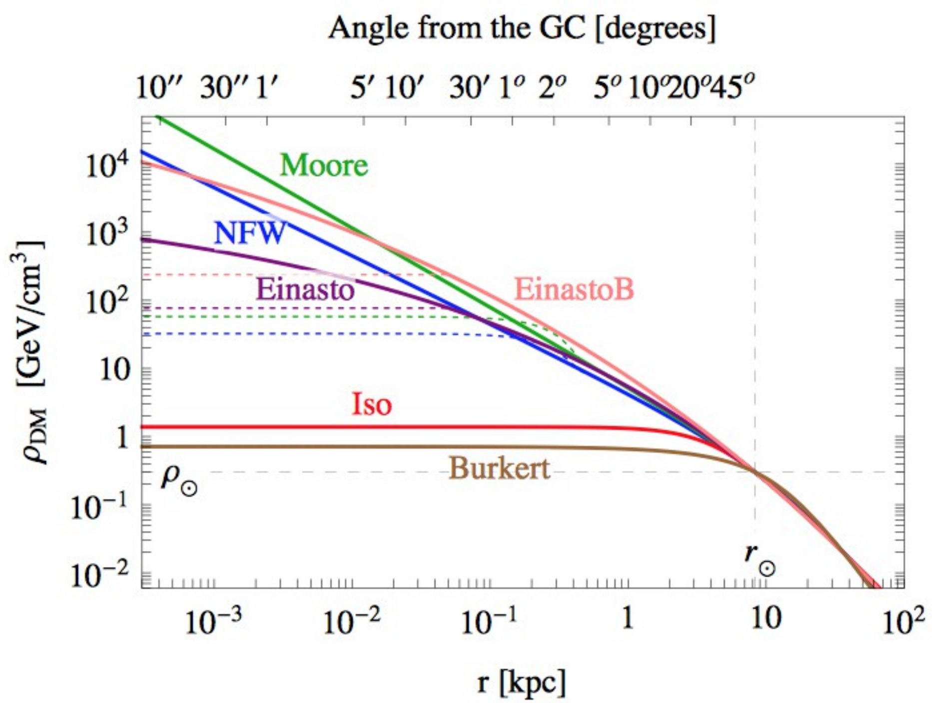
See also Cohen et al. 1307.4082 Fan, Reece 1307.4400

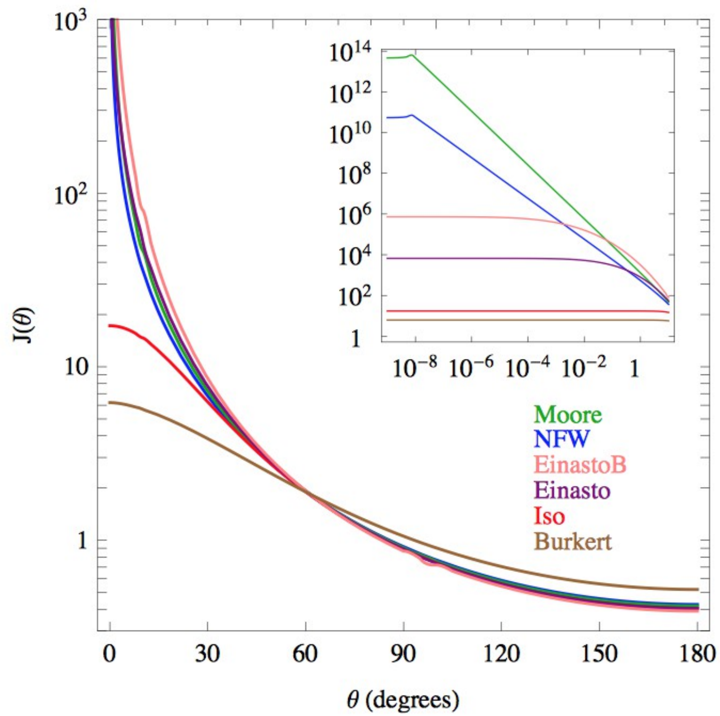
Constraints from gamma lines

"Search for photon line-like signatures from Dark Matter annihilations with H.E.S.S."

Hess collaboration 1301.1173

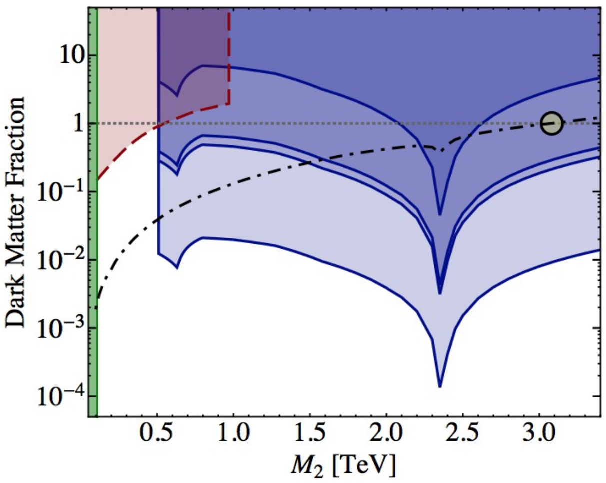
Region of observation: 1 deg around Galactic Center |b|>0.3 deg



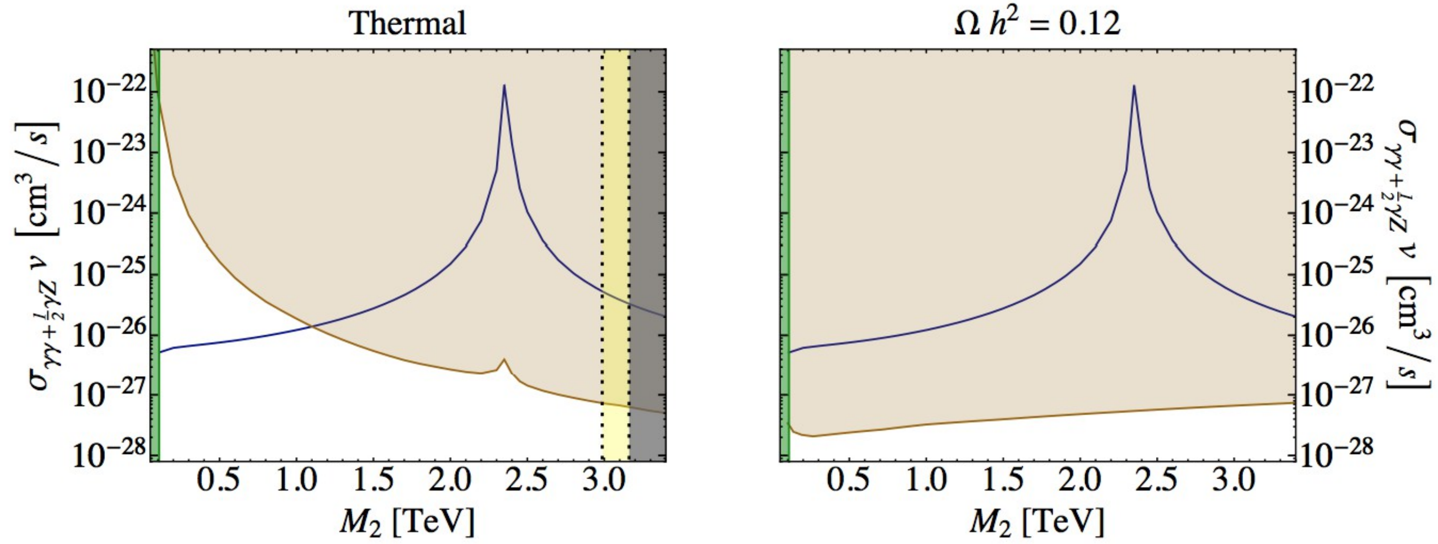


Indirect detection bounds

Thermal WINO: current bounds
Shading different profiles
Dod-dashed: cross section for thermal WINO



Prospects for CTA

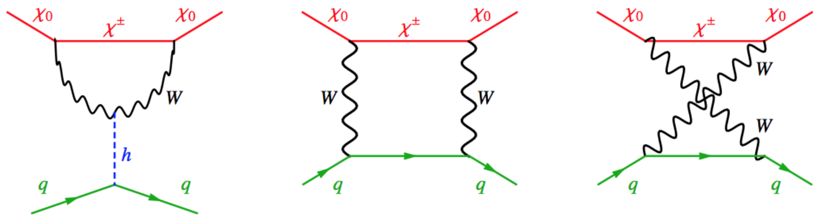


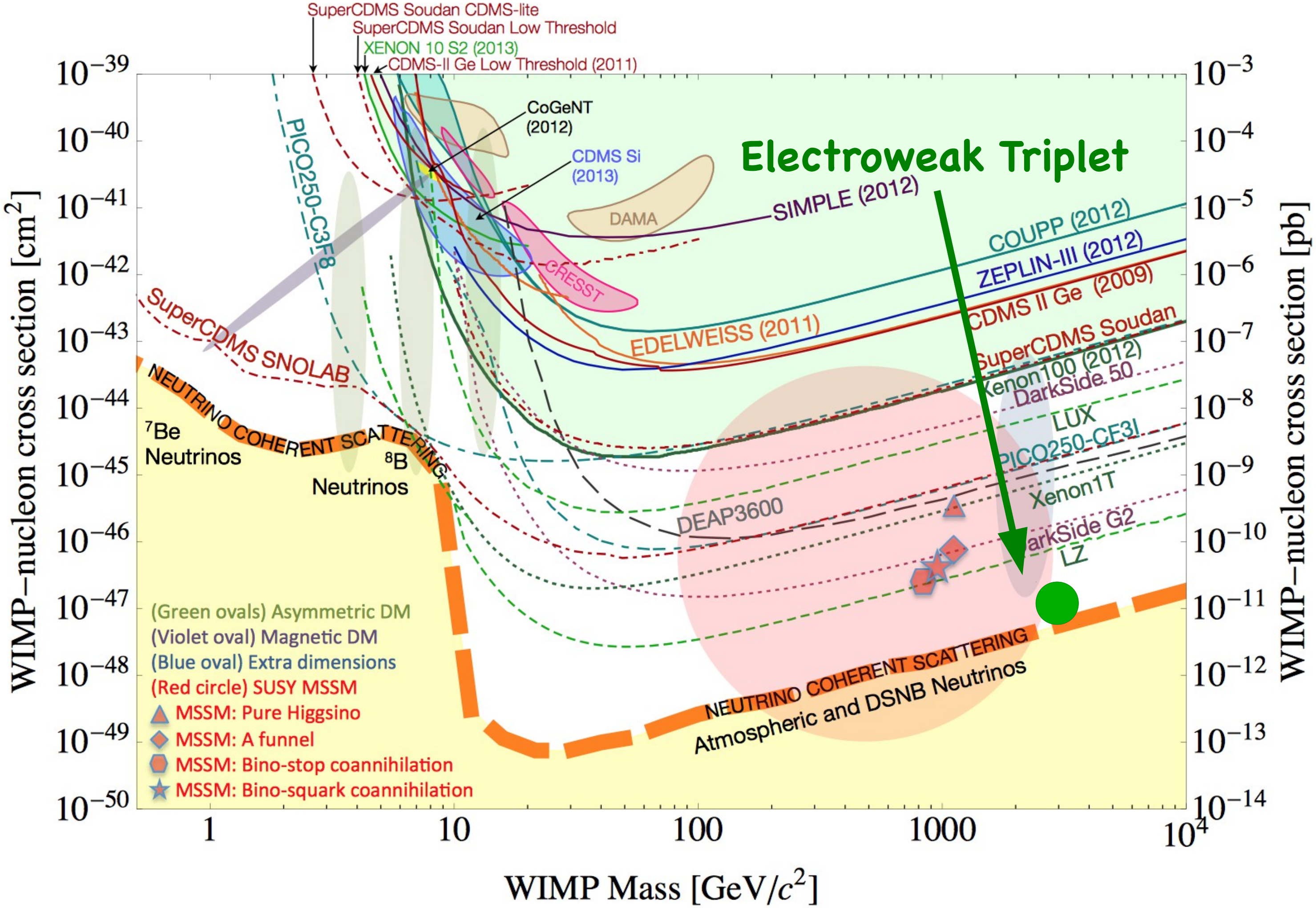
From Cohen et al. 1307.4082

Direct detection

Precise calculation of SI σ in

Hill, Solon 1309.4092

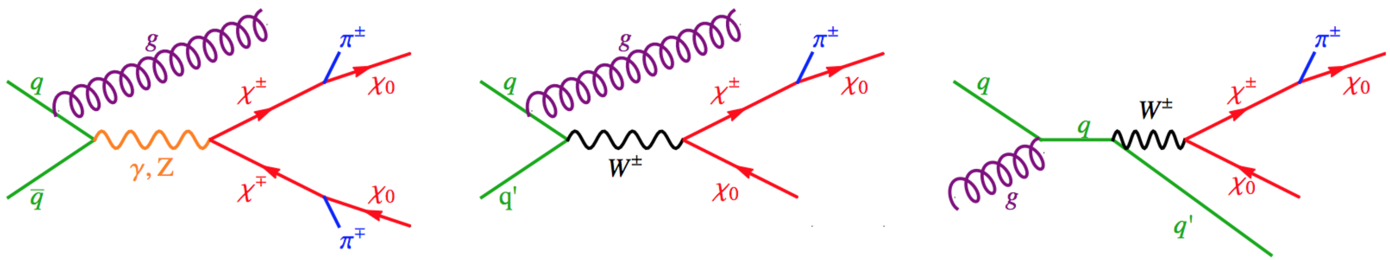




Triplet at Hadron Collider

Mass splitting between charged and neutral components around 165 MeV

Charged state decays into DM + soft pions



Channels: mono-jet, mono-photon, Vector Boson Fusion, disappearing tracks

Focus on **LHC 14 TeV** with L=3000 fb^{-1} and future **100 TeV pp collider** with L=3000 fb^{-1}

Results based on **Cirelli, Sala, Taoso 1407.7058**

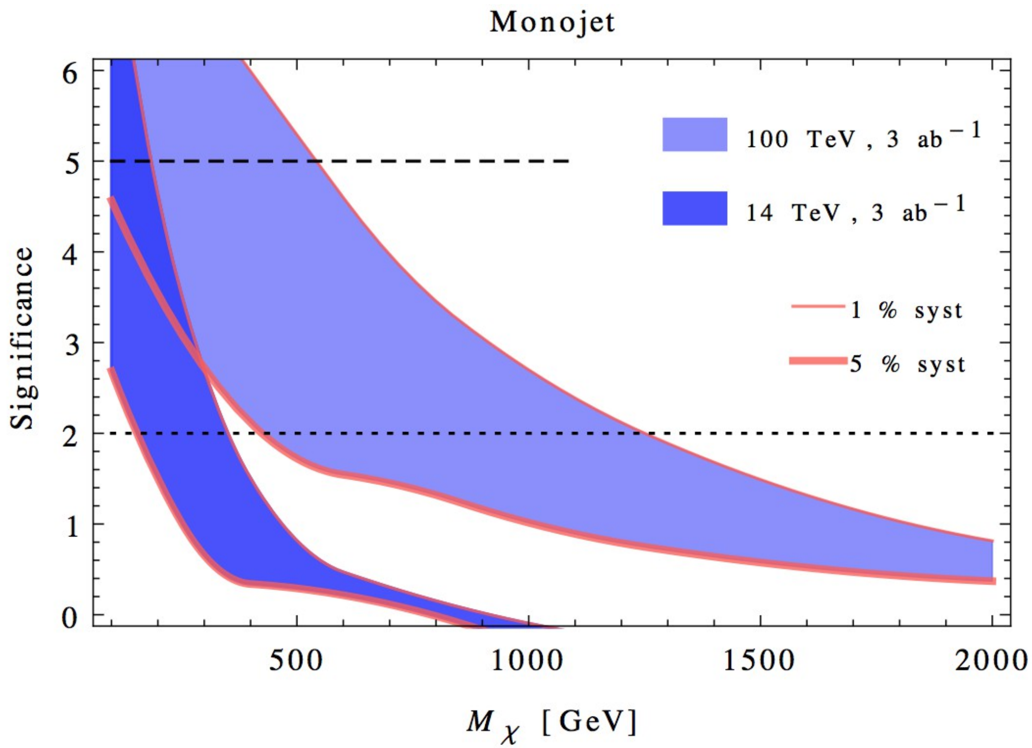
For a recent analysis with mono-jet and disappearing tracks see also

Low, Wang 1404.0682, Berlin Lin Low Wang 1502.05044

Monojet

Background: mainly Z(nu nu)+jets and W(l nu)+jets
Cuts on jets, MET, leptons similar to ATLAS-CMS mono-jet analysis rescaled to optimize sensitivity

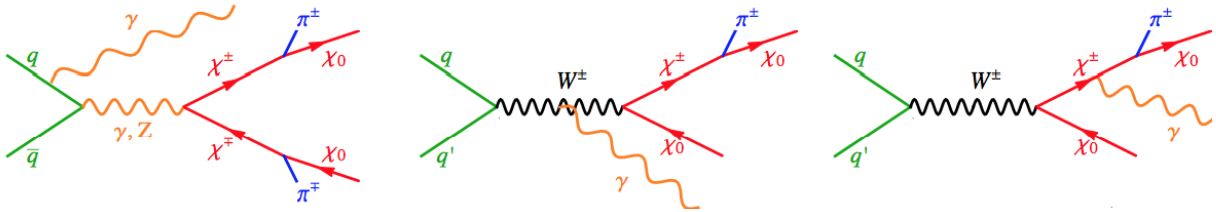
Madgraph5 + Pythia + Delphes



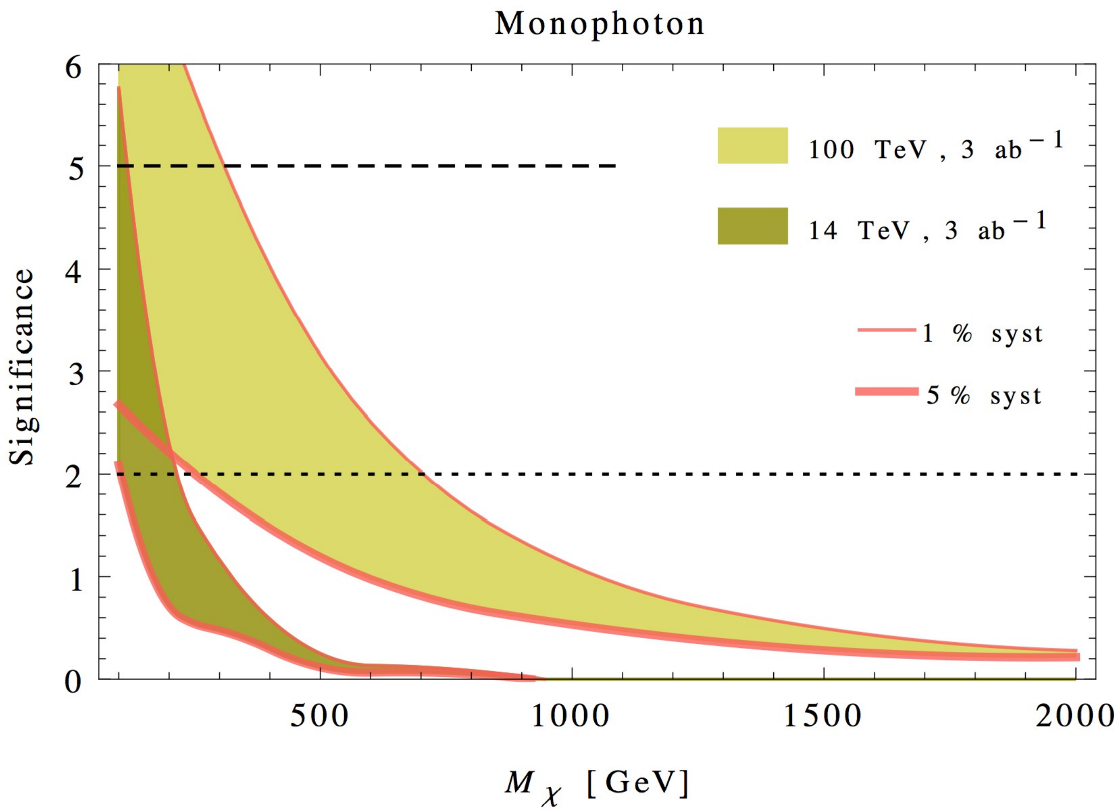
Sum in quadrature statistic and systematic errors

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

Mono-photon



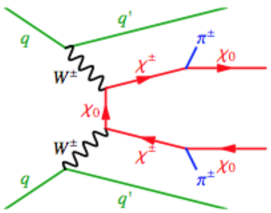
Qualitatively the same: systematics are crucial. 100 TeV increase the reach of a factor 3-4



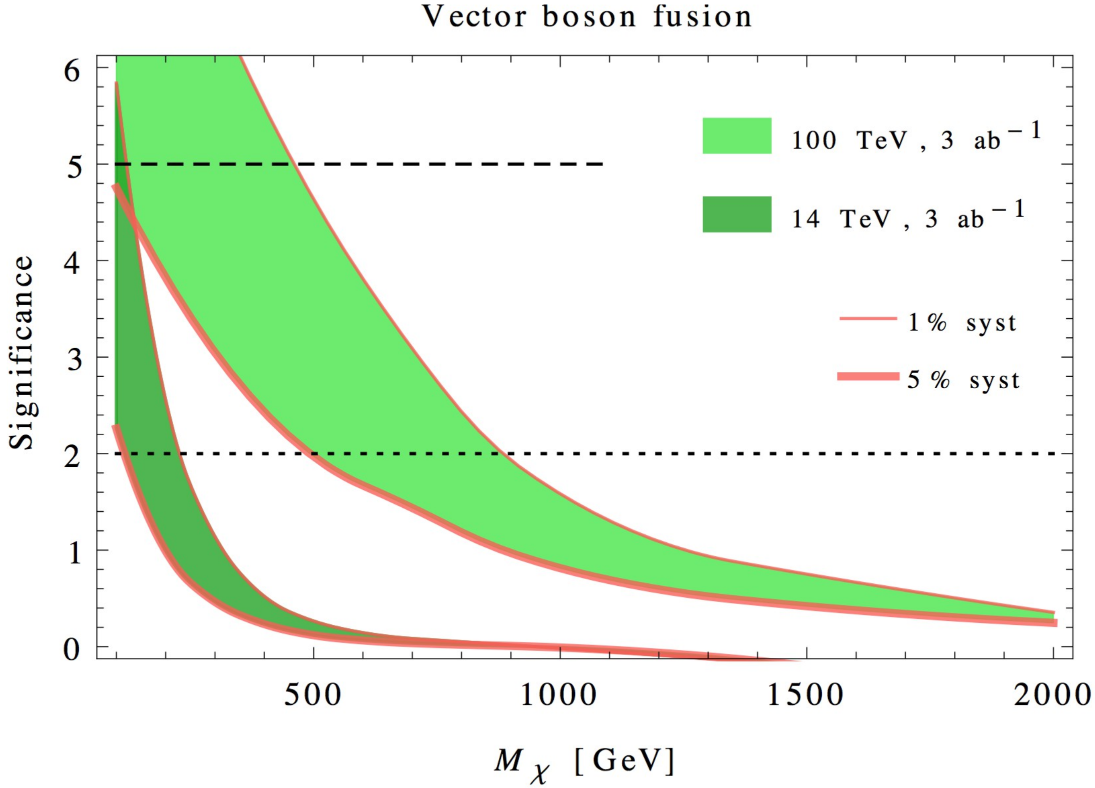
Dijet channel

VBF processes characterized by 2 forward jets

Apply cuts on rapidity, invariant mass and pT to reduce QCD background



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

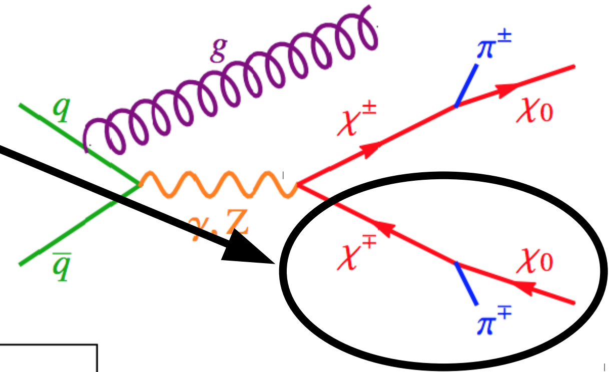


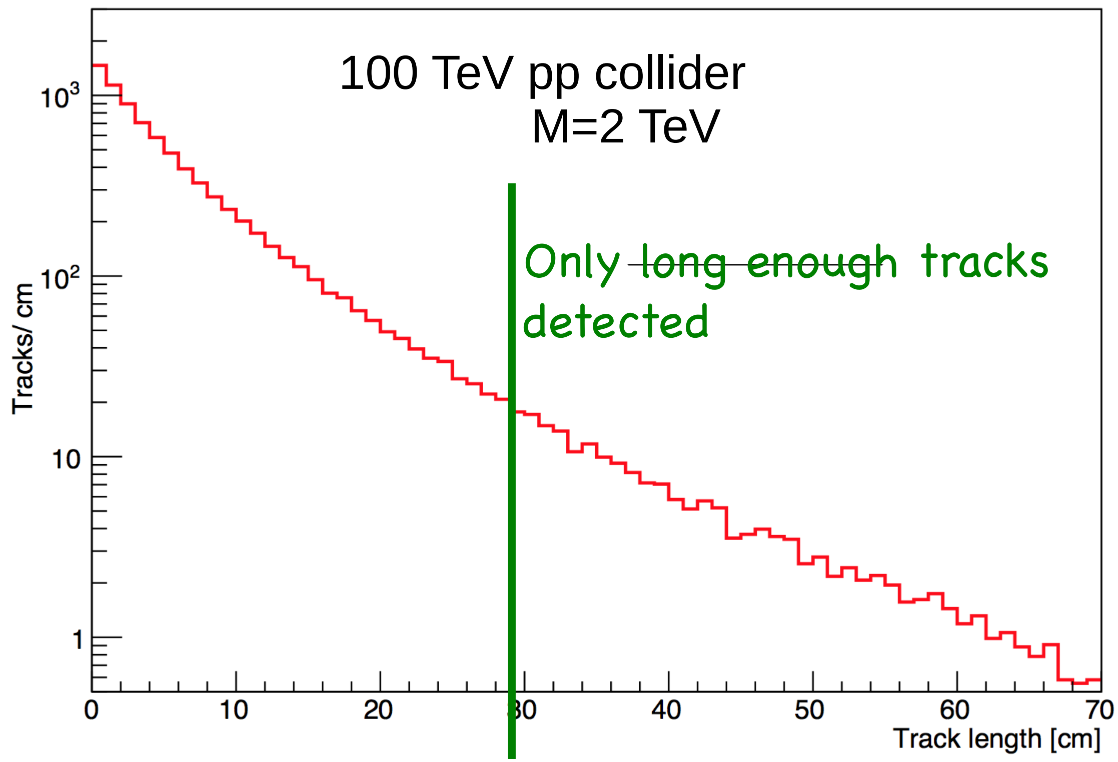
Smaller sensitivities than mono-j

Disappearing tracks

Lifetime of charged particle around 0.2 ns
Charged tracks of ~ 10 cm

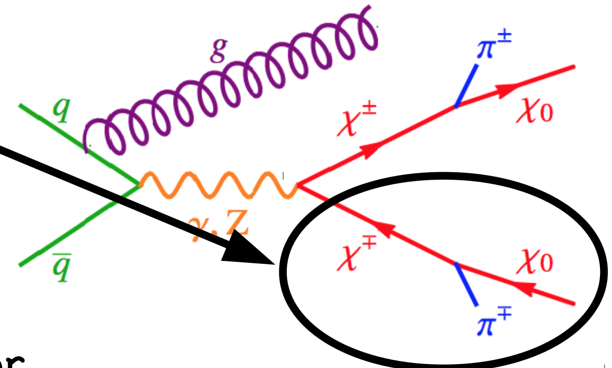
At 100 TeV larger production + boost





Disappearing tracks

Lifetime of charged particle around 0.2 ns
Charged tracks of ~ 10 cm



Backgrounds:

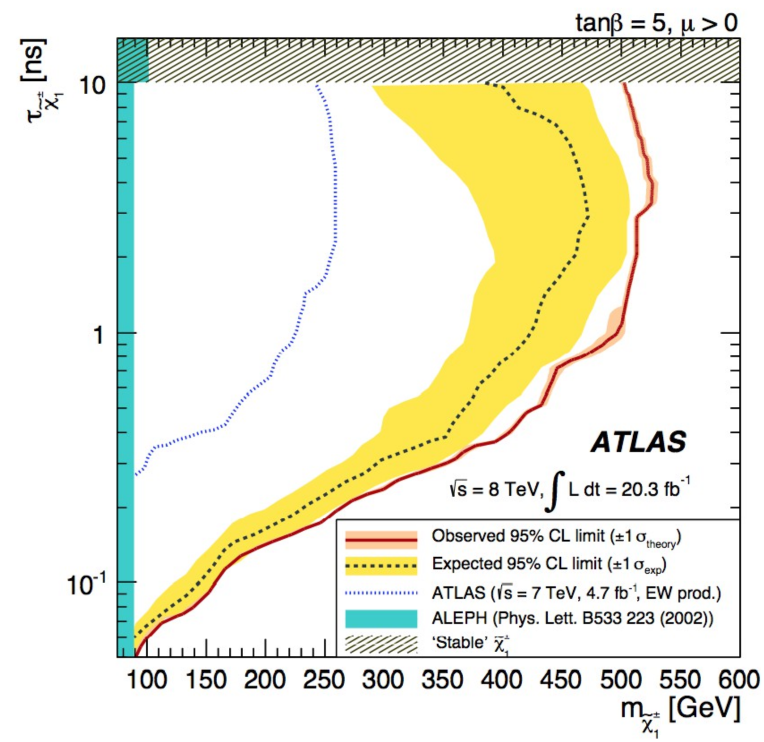
- interactions of charged hadrons in the detector

- unidentified leptons

- pT mis-measured tracks
  (dominant at large pT)

ATLAS 8 TEV with 20 fb^{-1}

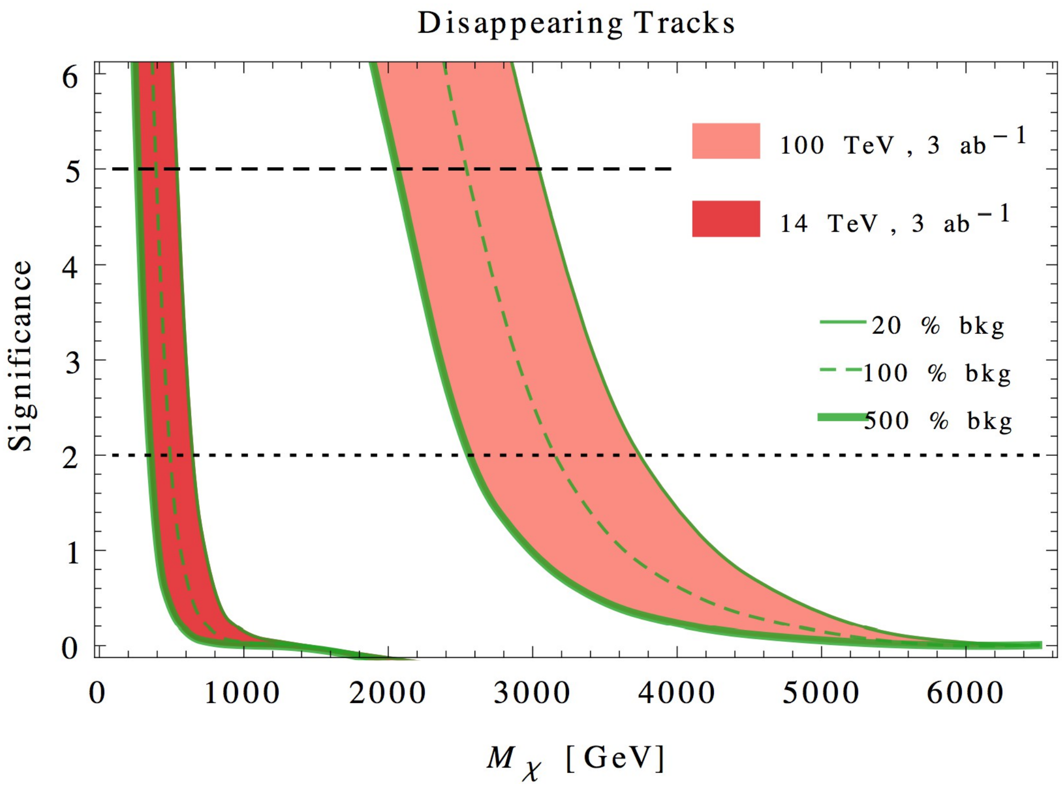
Bound M>270 GeV (95% CL)



Disappearing tracks

Estimate the sensitivity extrapolating the 8-TeV background rescaling with the jets+MET events cross-sections

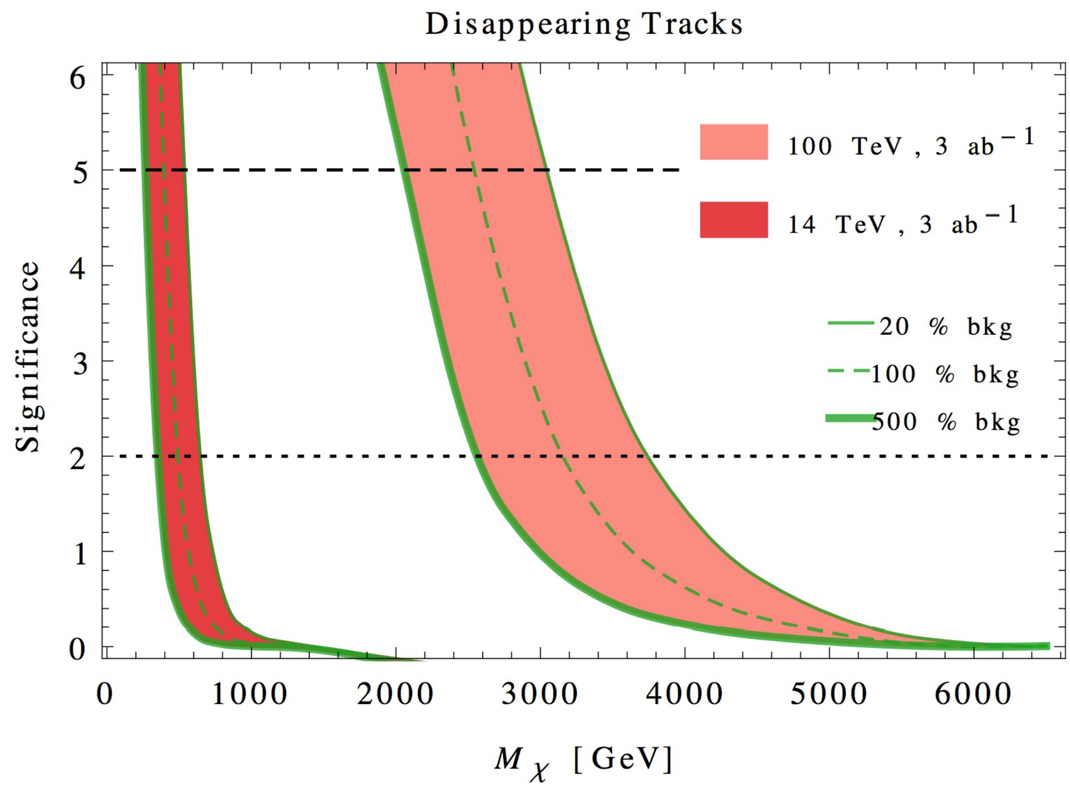
Band: bkg multiplied/divided by factor 5



Disappearing tracks

Estimate the sensitivity extrapolating the 8-TeV background rescaling with the jets+MET events cross-sections

Band: bkg multiplied/divided by factor 5

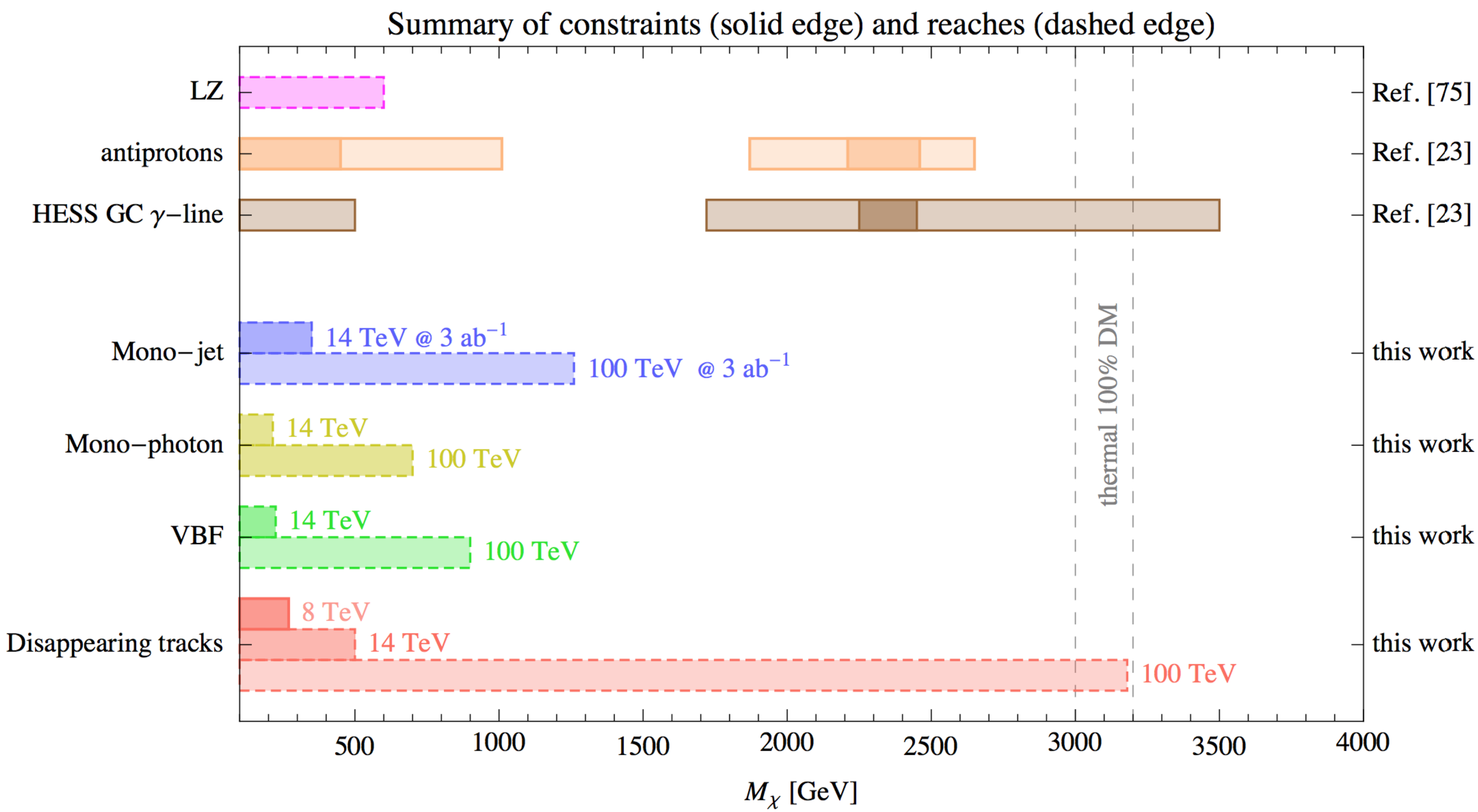


Mass splitting modified by operators >= 7. E g.

$$\chi^a \chi^b (H^\dagger \sigma^a H)(H^\dagger \sigma^b H) \qquad \Delta M \simeq \frac{1}{4}\frac{v^4}{\Lambda^3} < 10 \text{ MeV for } \Lambda > 5 \text{ TeV}$$

Summary

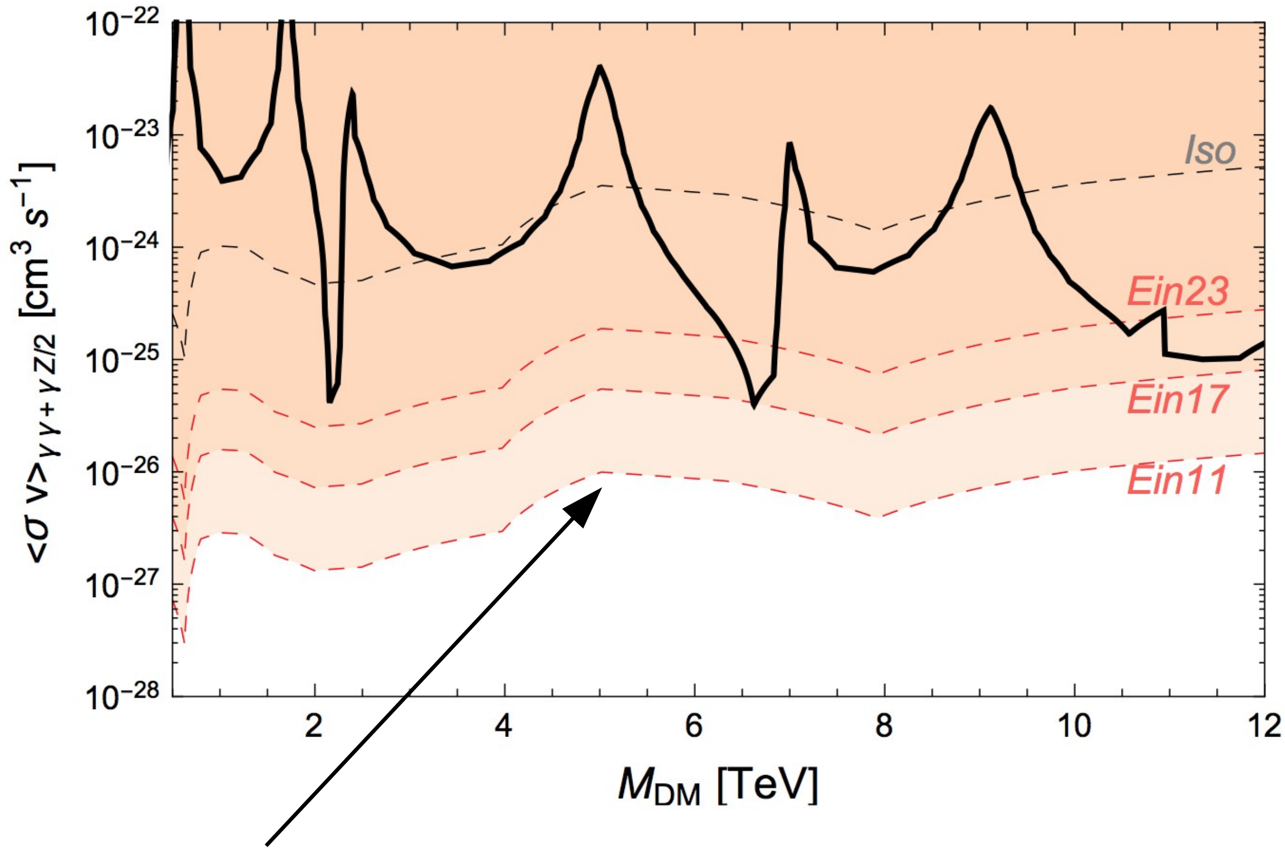
Indirect searches good probe of EW triplet DM BUT still large astro-uncertainties
LHC-14 covers part of non-thermal DM scenario / DM under-abundanant
100 TeV collider could potentially test thermal WINO.



Fermionic Quintuplet

The Minimal Dark Matter candidate, automatically stable
Thermal relic for M = 10 TeV

Cirelli, Hambye, Panci, Sala, Taoso. In progress

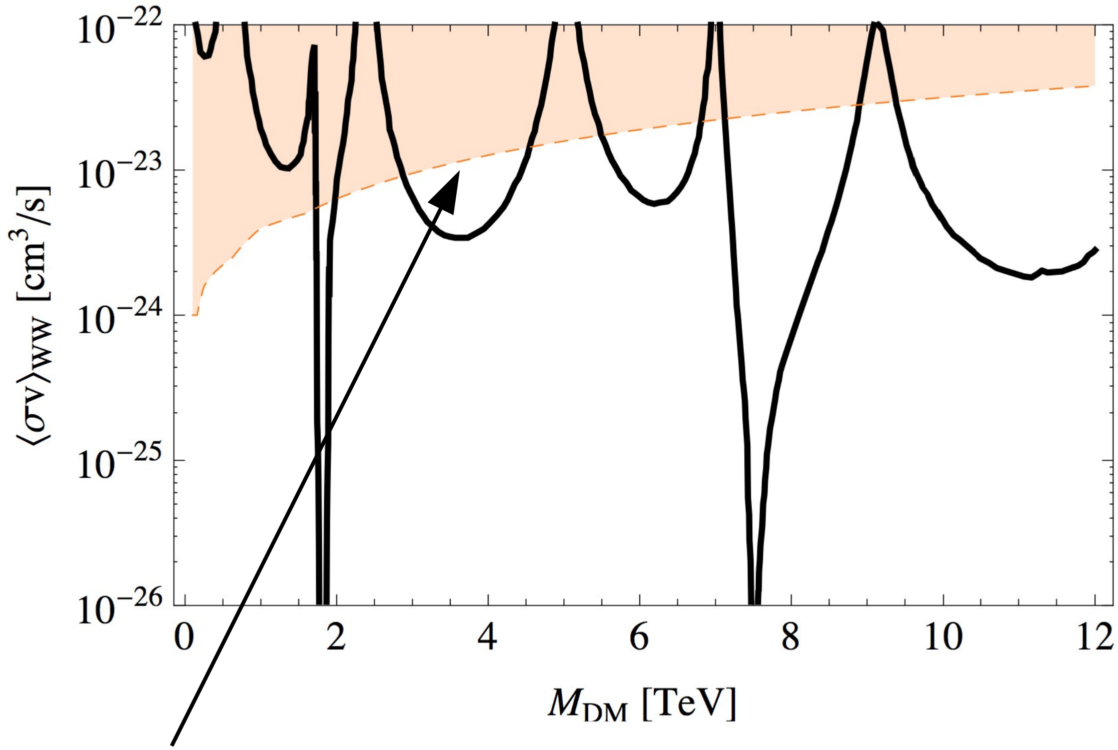


Limits on gamma-ray lines from HESS

Fermionic Quintuplet

The Minimal Dark Matter candidate, automatically stable
Thermal relic for M = 10 TeV

Cirelli, Hambye, Panci, Sala, Taoso. In progress



Limit on WW annihilations from FERMI (prompt +IC).

Direct detection : poor prospects
100 TeV collider: thermal mass beyond the reach

THANKS