Closing the window on WIMP Dark Matter

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2107.09688, 2205.04486 in collaboration with
Bottaro, Costa, Franceschini, Panci, Redigolo, Vittorio

MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA
PRIN "The consequences of flavor"

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

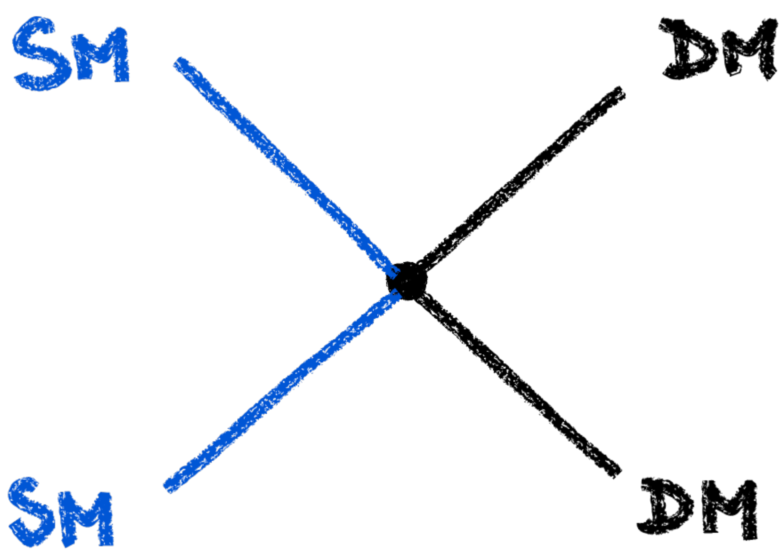
57th Rencontres de Moriond, EW session – La Thuile, 22.3.2023

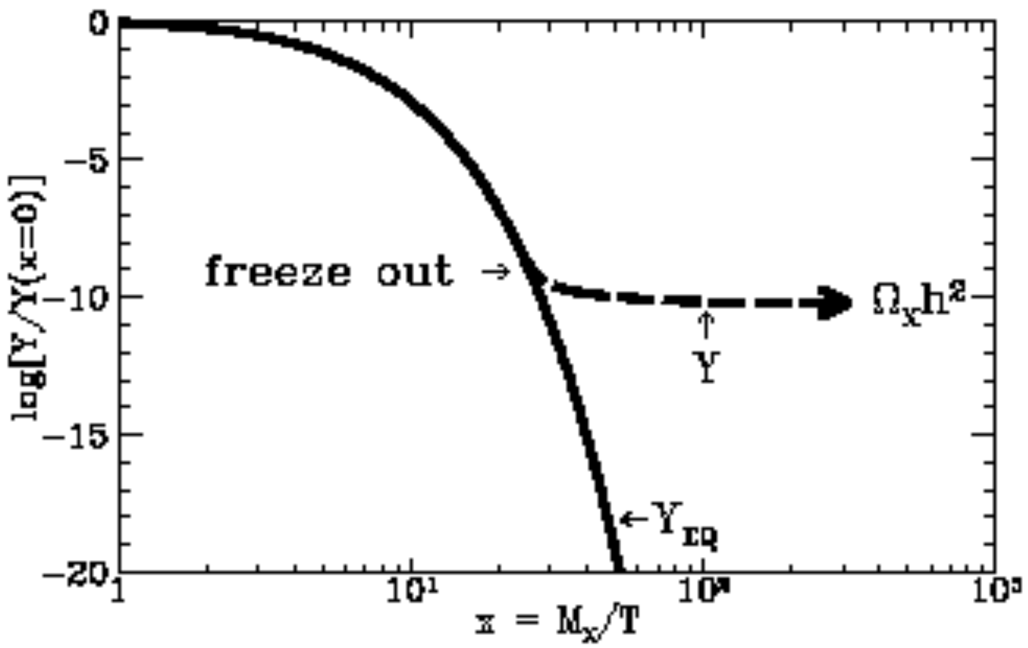
“Physicist searching for heavy WIMP Dark Matter on the mountains near La Thuile” according to StableDiffusion AI

thanks to C. Cesarotti for the idea!

The case for WIMPs

- Production in early Universe: thermal freeze-out of 2 → 2 scatterings





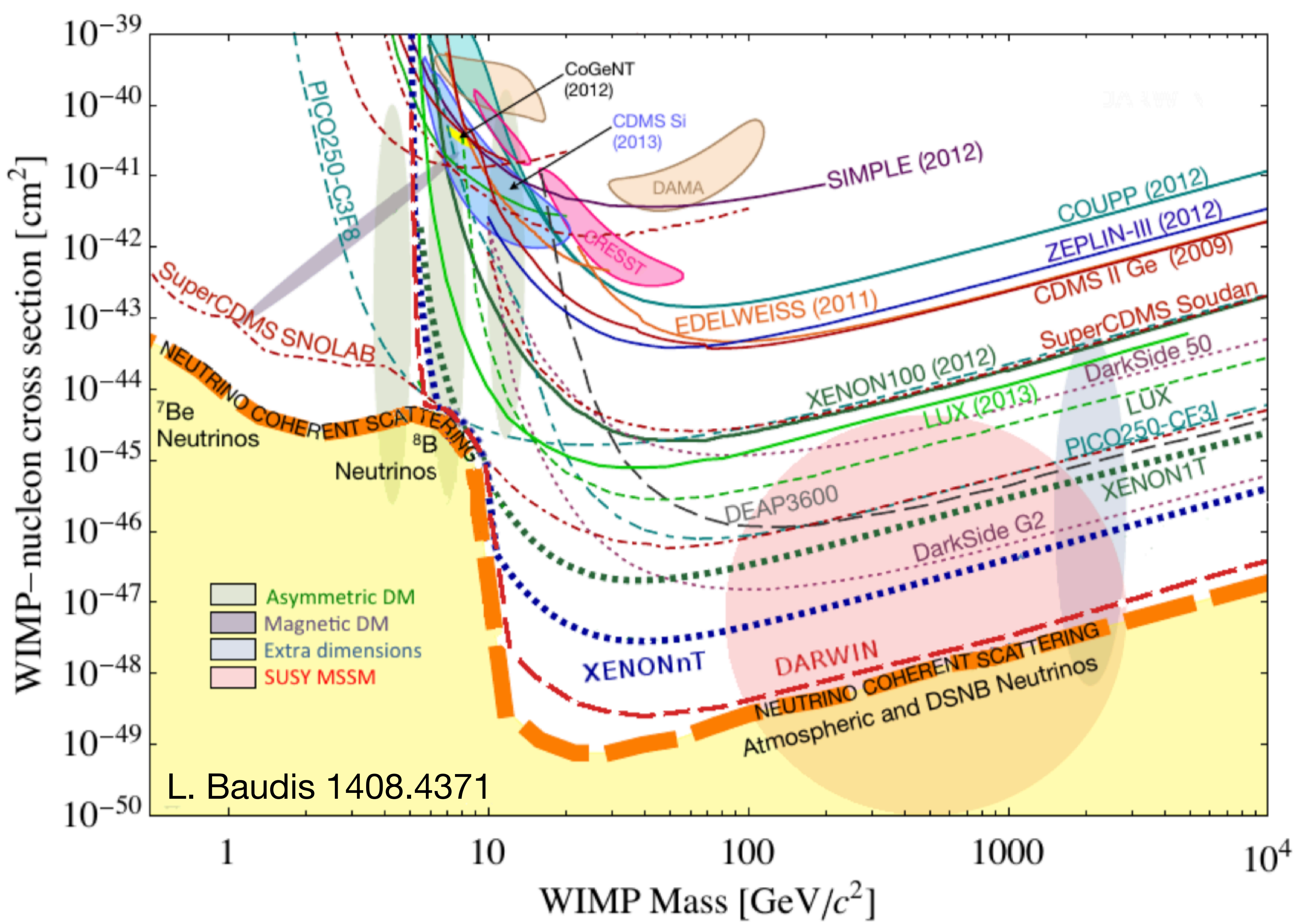
- For each value of the DM-SM coupling $g_\star$ the DM mass is predicted.

$$g_\star \sim g_{EW} \;\Rightarrow\; M_{DM} \sim \text{TeV}$$

- **WIMP miracle:** simple explanation for the observed Dark Matter abundance (Ω_{DM} ~ 0.26) and a connection to naturalness of EW scale.

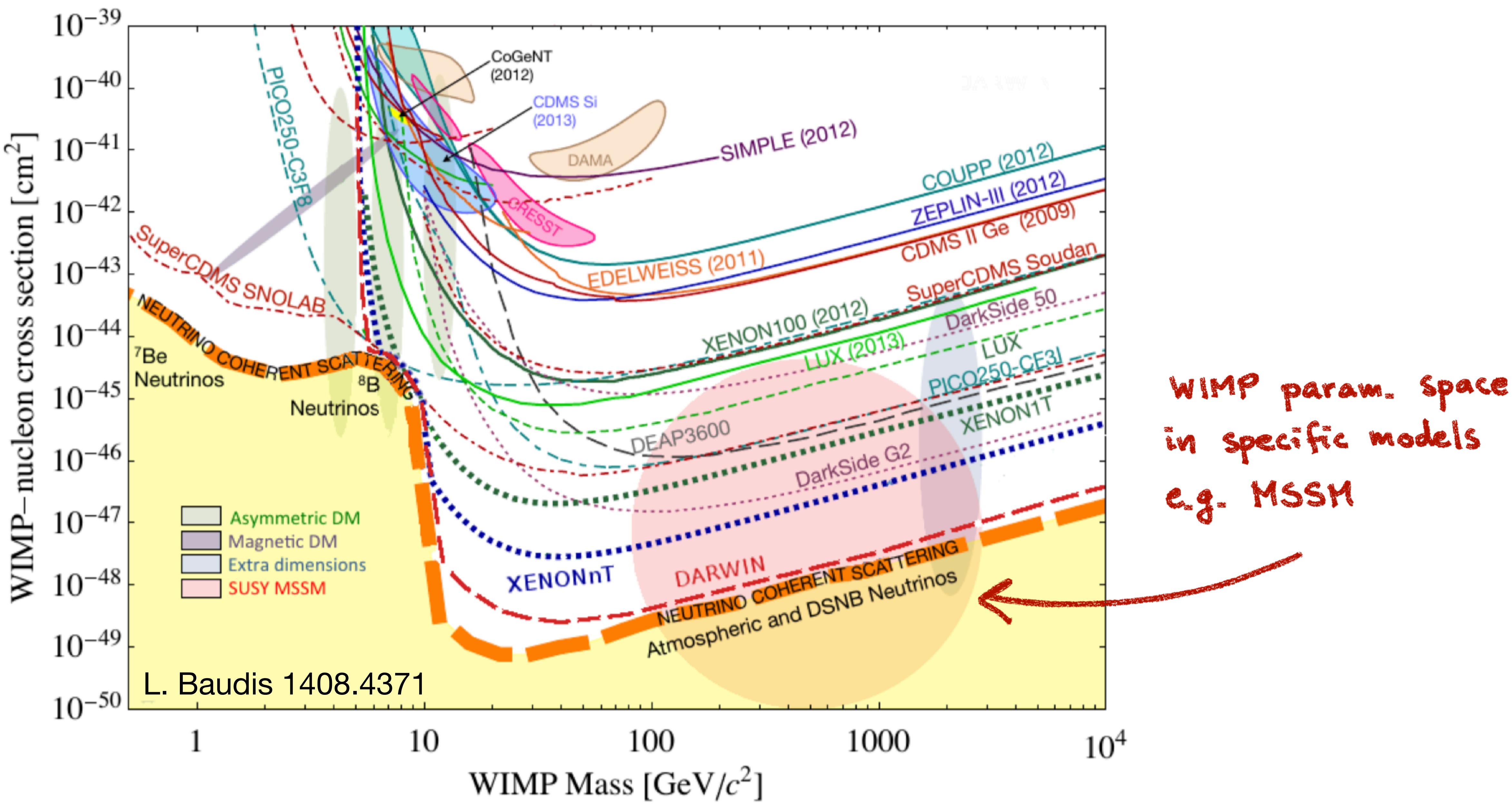
Ideal target for nuclear recoils & colliders!

Are WIMPs almost dead?



- Large fraction of the “standard” WIMP parameter space ruled out?

Are WIMPs almost dead?



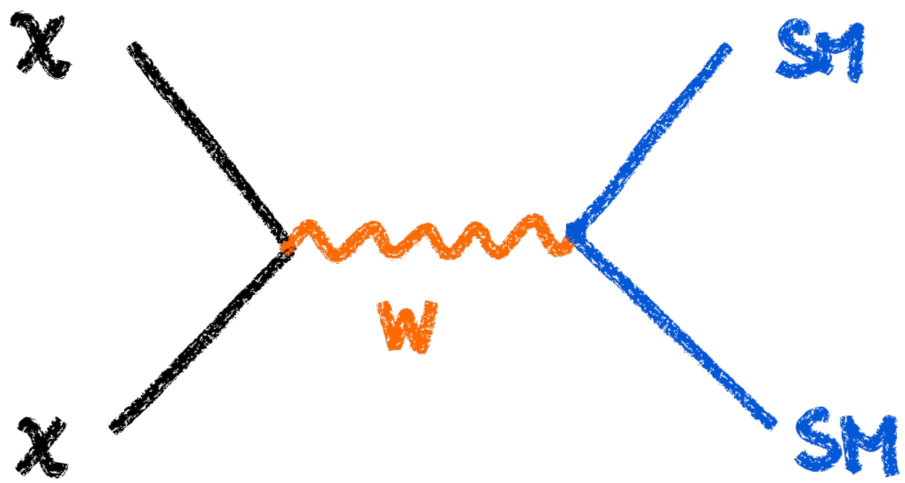
- Large fraction of the "standard" WIMP parameter space ruled out?

Not quite yet…

Which WIMP?

Consider generic EW multiplet: interacts w/ SM through W, Z

"Minimal Dark Matter": Cirelli, Fornengo, Strumia 2005



- DM is the neutral component

$$\chi_n = (\cdots, \chi^-, \chi^0, \chi^+, \cdots)$$

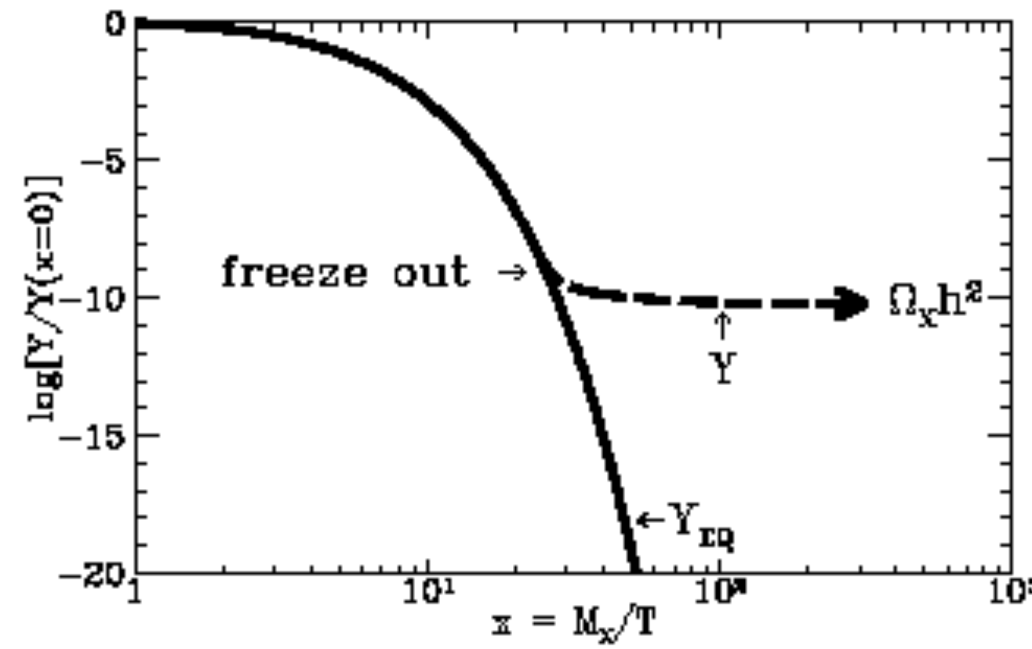
- DM needs to be stable: χ^0 lightest state
- Strong bounds from Direct Detection: no Z coupling @ tree-level
  - Real multiplet: Y = 0, *n* odd
  - Complex multiplet: Y ≠ 0,
    (mass splittings from higher-dimensional operators needed)
- Single parameter sets the DM abundance: mass M_{DM}

Which WIMP?

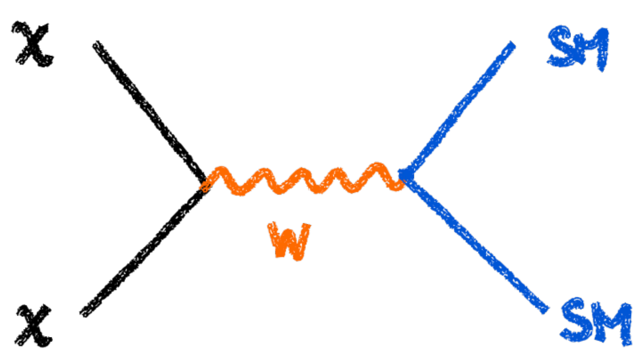
- Consider generic EW multiplet: interacts w/ SM through W, Z

$$\frac{dY}{dx} \propto \langle \sigma v \rangle (Y^2 - Y_{\rm eq}^2)$$

which cross-section?



- Tree-level EW cross-section…

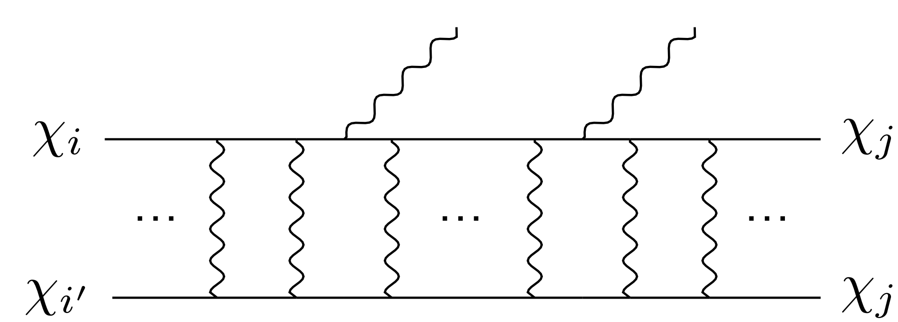


$$\langle \sigma v \rangle_0 = \frac{\pi \alpha_2^2 (2n^4 + 17n^2 - 19)}{16 g_\chi M_\chi^2}$$

… is inaccurate!

Large non-perturbative, non-relativistic effects

- Sommerfeld enhancement
- Bound state formation



Bound state formation

- Coupled Boltzmann eq. for DM and bound states:

$$z\frac{\mathrm{d}Y_{\mathrm{DM}}}{\mathrm{d}z} = -\frac{2s}{H}\langle\sigma_{\mathrm{ann}}v_{\mathrm{rel}}\rangle\left[Y_{\mathrm{DM}}^2 - (Y_{\mathrm{DM}}^{\mathrm{eq}})^2\right] - \frac{2s}{Hz}\sum_{B_I}\langle\sigma_{B_I}v_{\mathrm{rel}}\rangle\left[Y_{\mathrm{DM}}^2 - (Y_{\mathrm{DM}}^{\mathrm{eq}})^2\frac{Y_{B_I}}{Y_{B_I}^{\mathrm{eq}}}\right],$$

$$z\frac{\mathrm{d}Y_{B_I}}{\mathrm{d}z} = Y_{B_I}^{\mathrm{eq}}\left\{\frac{\langle\Gamma_{B_I,\mathrm{break}}\rangle}{H}\left[\frac{Y_{\mathrm{DM}}^2}{(Y_{\mathrm{DM}}^{\mathrm{eq}})^2} - \frac{Y_{B_I}}{Y_{B_I}^{\mathrm{eq}}}\right] + \frac{\langle\Gamma_{B_I,\mathrm{ann}}\rangle}{H}\left[1 - \frac{Y_{B_I}}{Y_{B_I}^{\mathrm{eq}}}\right] + \sum_{B_J}\frac{\langle\Gamma_{B_I\to B_J}\rangle}{H}\left[\frac{Y_{B_J}}{Y_{B_J}^{\mathrm{eq}}} - \frac{Y_{B_I}}{Y_{B_I}^{\mathrm{eq}}}\right]\right\}$$

BS breakup in thermal plasma (negligible for tight bound states)

annihilation

decay into other BS

Bound state formation

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- if BS decay/annihilate quickly

$$\frac{\mathrm{d}Y_{\mathrm{DM}}}{\mathrm{d}z} = -\frac{\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle s}{Hz}(Y_{\mathrm{DM}}^2 - Y_{\mathrm{DM}}^{\mathrm{eq},2})$$

$$\langle\sigma_{\mathrm{eff}}v_{\mathrm{rel}}\rangle \equiv S_{\mathrm{ann}}(z) + \sum_{B_J}S_{B_J}(z)$$

Bound state formation

- Coupled Boltzmann eq. for DM and bound states:

$$z\frac{\mathrm{d}Y_{\rm DM}}{\mathrm{d}z} = -\frac{2s}{H}\langle\sigma_{\rm ann}v_{\rm rel}\rangle\left[Y_{\rm DM}^2-(Y_{\rm DM}^{\rm eq})^2\right] - \frac{2s}{Hz}\sum_{B_I}\langle\sigma_{B_I}v_{\rm rel}\rangle\left[Y_{\rm DM}^2-(Y_{\rm DM}^{\rm eq})^2\frac{Y_{B_I}}{Y_{B_I}^{\rm eq}}\right],$$

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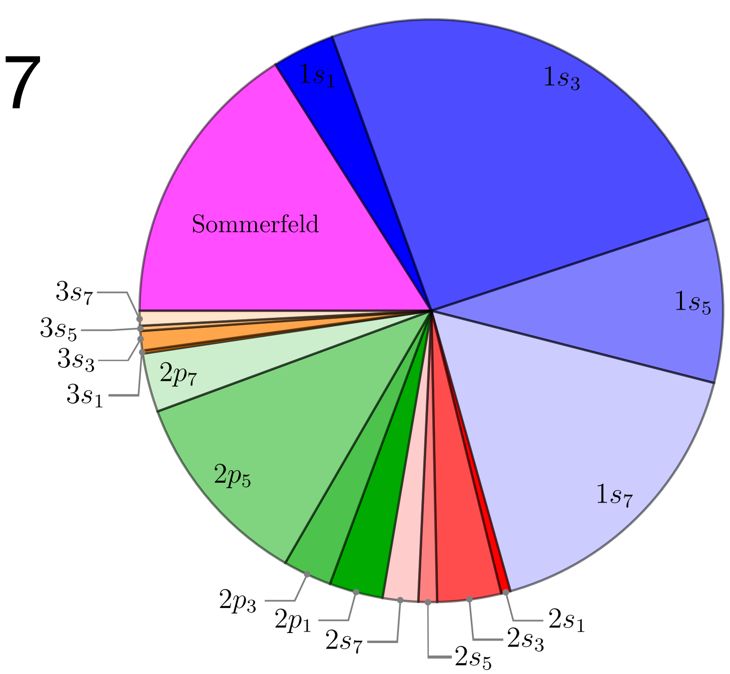
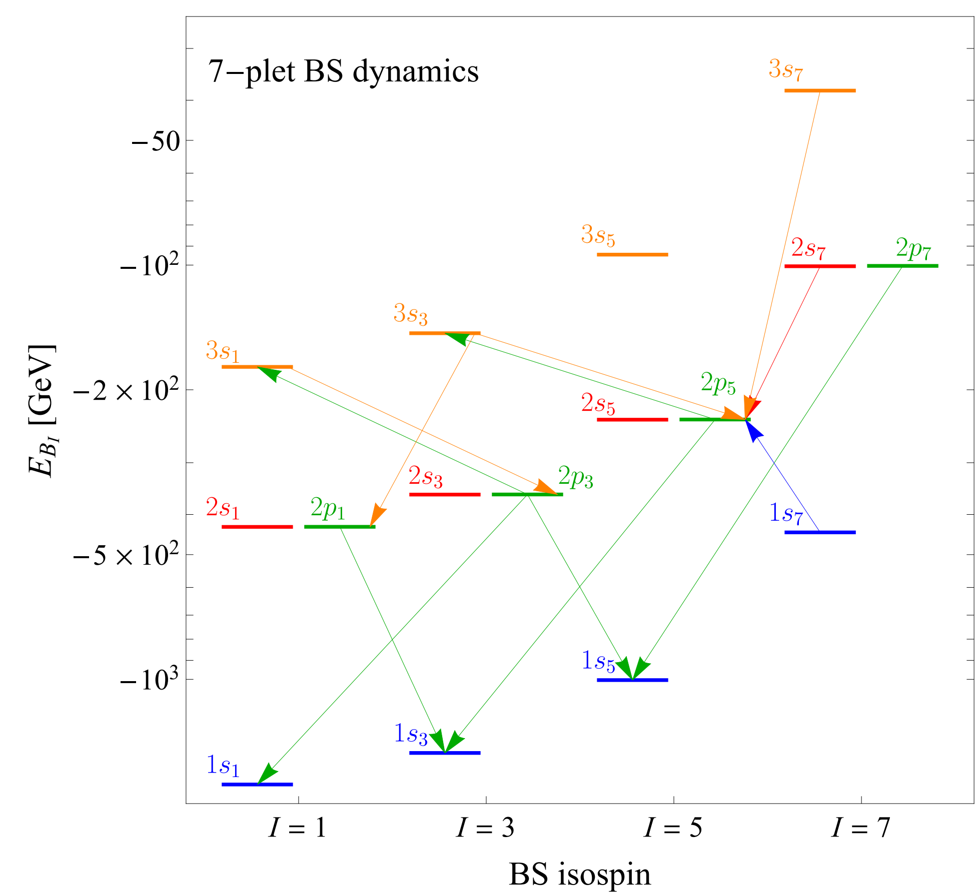
$$\langle\sigma_{\rm eff}v_{\rm rel}\rangle \equiv S_{\rm ann}(z)+\sum_{B_J}S_{B_J}(z)$$

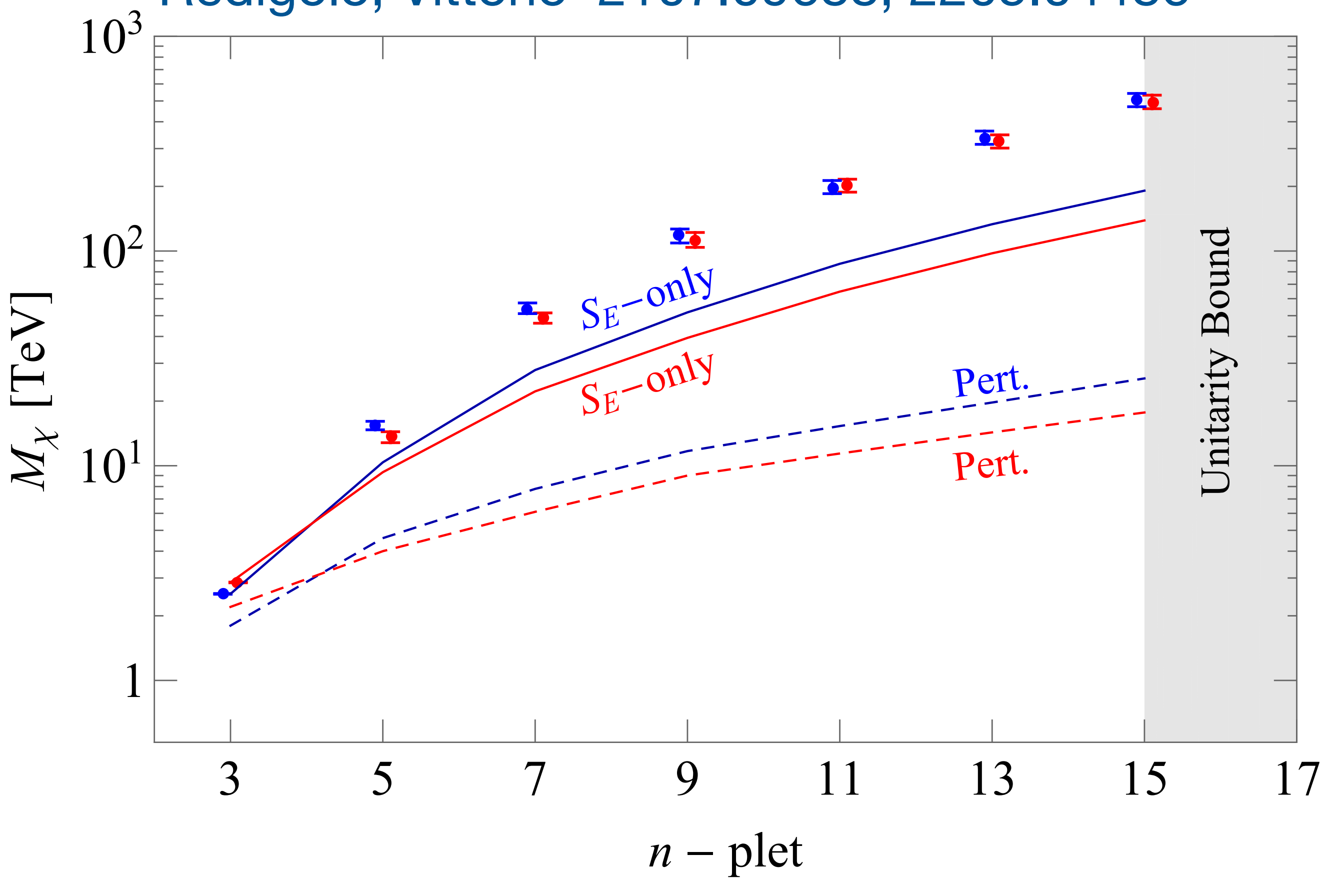
- Example: n = 7





Thermal freeze-out masses

Bottaro, DB, Costa, Franceschini, Panci, Redigolo, Vittorio 2107.09688, 2205.04486

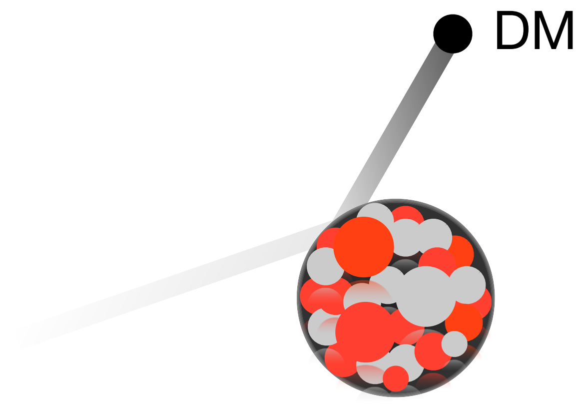


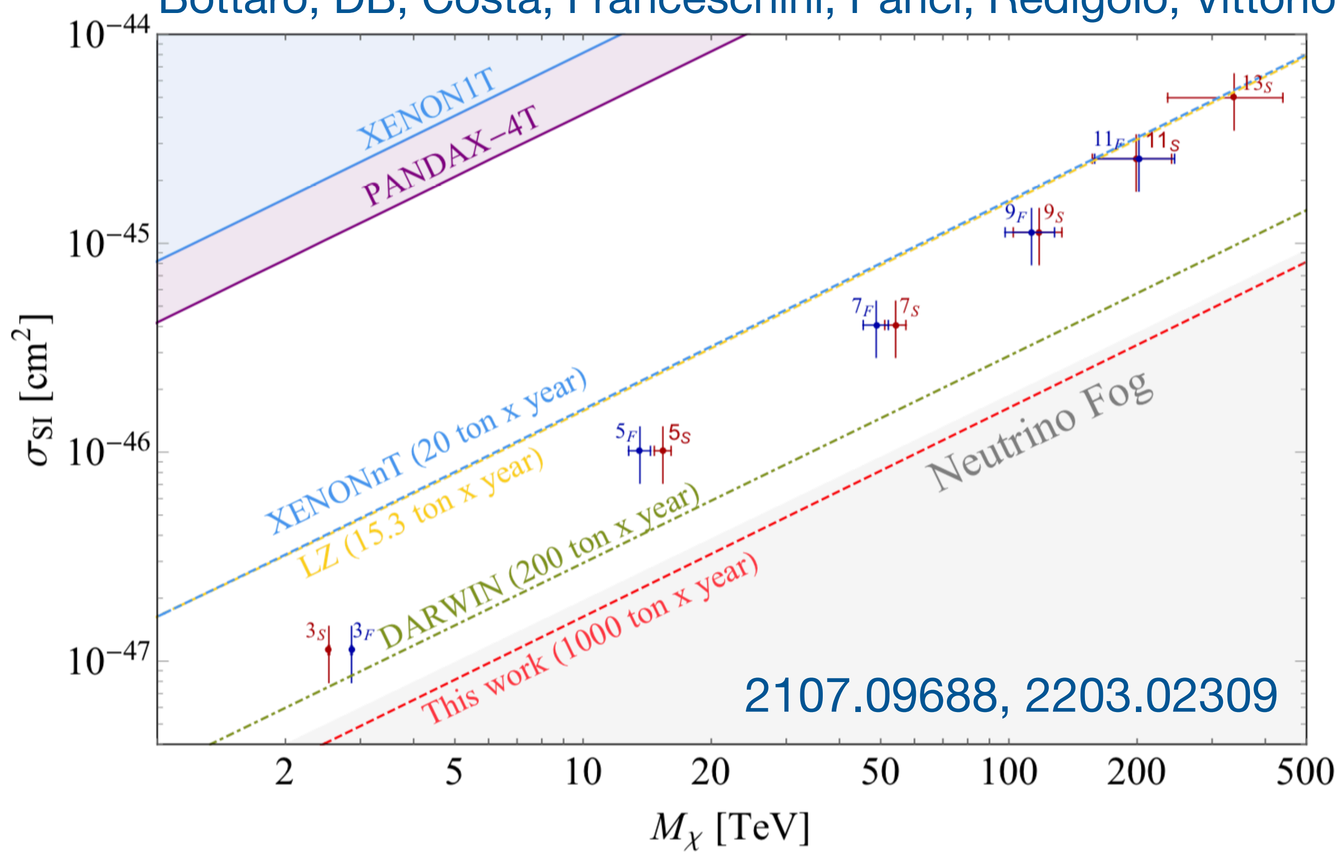
(and similar for scalars)

How do we probe these states?

	EW n-plet	Mass [TeV]
Majorana fermion	3_0	2.86
	5_0	13.6
	7_0	48.8
	9_0	113
	11_0	202
	13_0	324.6
Dirac fermion	$2_{1/2}$	1.08
	3_1	2.85
	$4_{1/2}$	4.8
	5_1	9.9
	$6_{1/2}$	31.8
	$8_{1/2}$	82
	$10_{1/2}$	158
	$12_{1/2}$	253

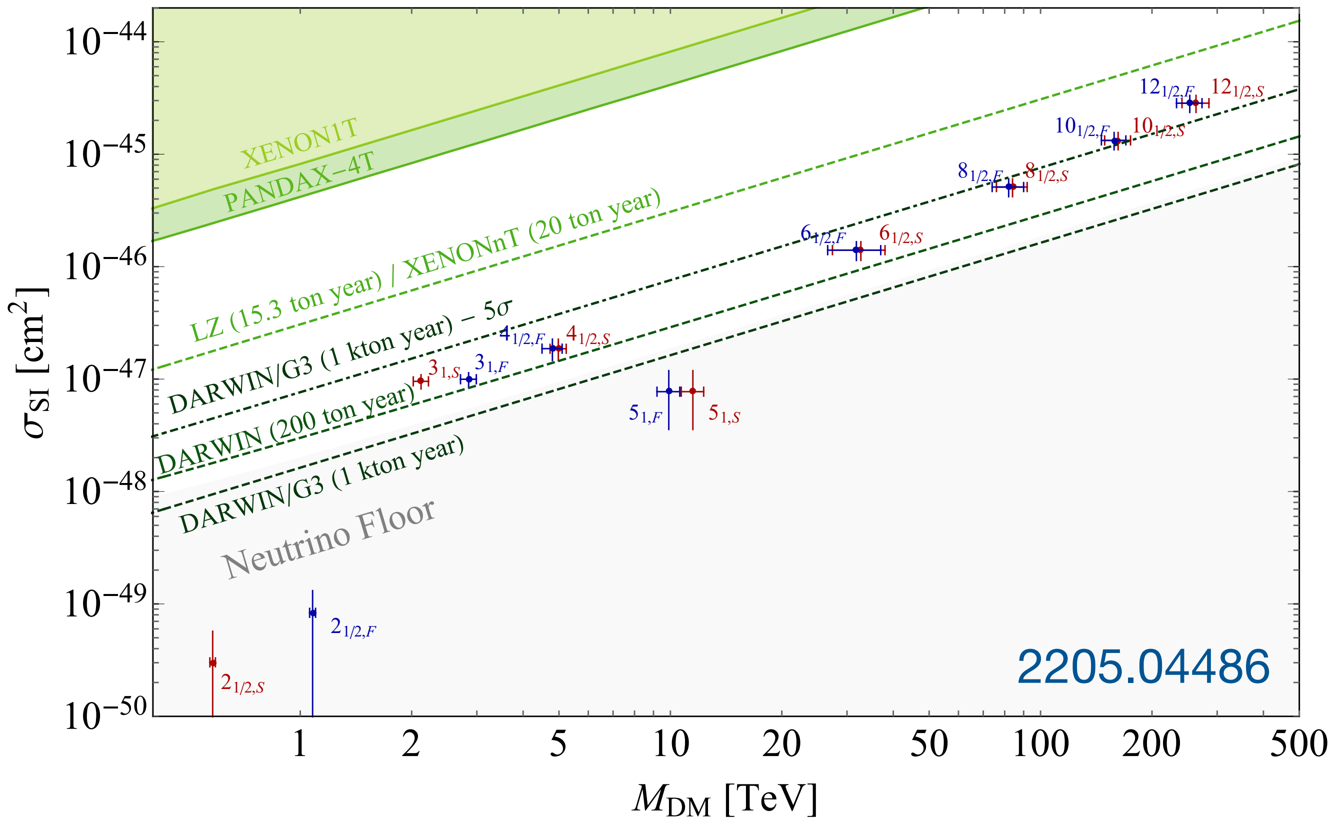
Direct detection





$$\mathscr{L}_{\text{eff}}^{\text{SI}} = \bar{\chi}\chi\left(f_q m_q \bar{q}q + f_G G^a_{\mu\nu}G^{\mu\nu,a}\right) + \frac{g_q}{M_\chi}\left(\bar{\chi}i\partial^\mu\gamma^\nu\chi\right)\mathcal{O}^q_{\mu\nu}$$

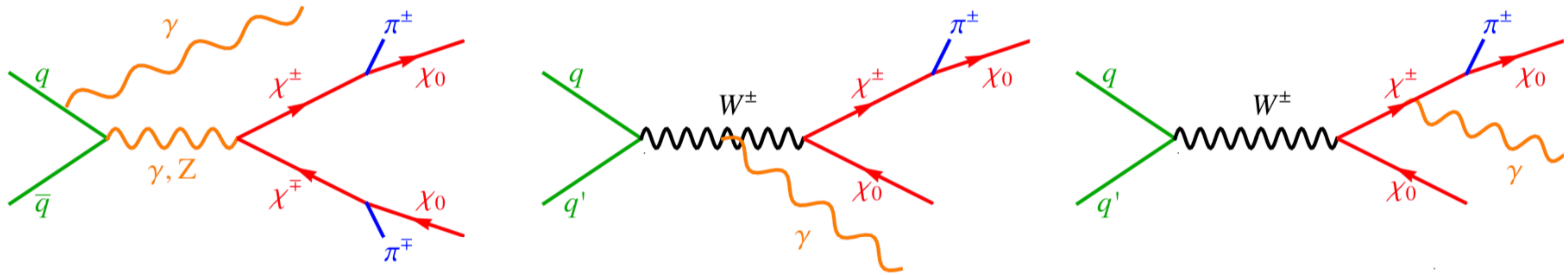
$$f_i \approx \frac{\alpha^2_{\text{EW}}}{m^3_{\text{EW}}}(n^2-1)$$



All WIMP candidates (except doublet!) above the neutrino floor, but need a very large exposure to be probed

Colliders: missing energy searches

- $2 \to 2$ production of invisible χ pair + event tag, e.g. monophoton



very difficult at hadron colliders: large backgrounds, and strong PDF suppression at high partonic c.o.m. energies (large invariant masses)

- LHC sensitive to DM masses ~ O(100 GeV)
- even at 100 TeV can't reach thermal freeze-out targets

Cirelli, Sala, Taoso 1407.7058

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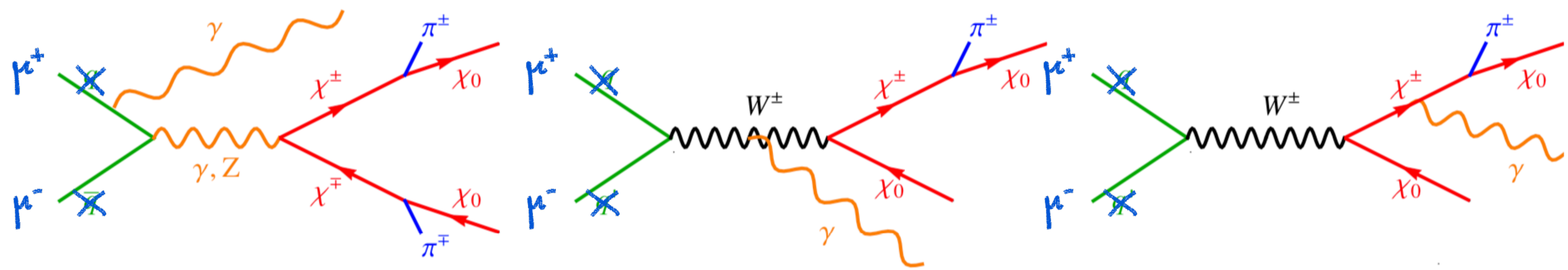

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Cirelli, Sala, Taoso 1407.7058

➠ **Try with a high-energy lepton collider!**

MUON COLLIDER

Missing mass searches at μ collider

Want to know more?

2303.08533
2210.02591
2209.01318
2203.07256
2203.07261
2103.14043
1901.06150

2203.07964
2203.08033
2203.07224

International
MUON Collider
Collaboration

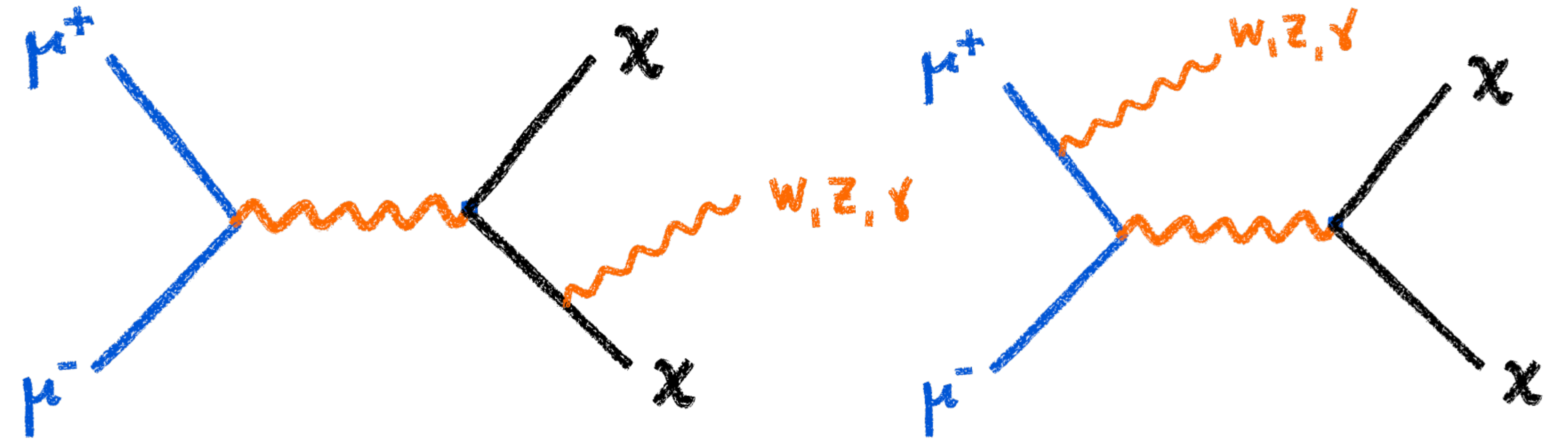
+ many more…

www.redbubble.com/people/muon-collider

Sudakov factor $\frac{\alpha}{4\pi}\log^2(E/m_W) \approx 1$ for E ~ 10 TeV

- mono-γ, mono-W, mono-Z are all similar!
- multiple gauge boson emission

Missing mass searches at μ collider



$2 \to 2$ production of χ pair

- ✦ Full energy available

  in the center of mass:

  ability to discover particles **up to kinematical threshold** $\sqrt{s}/2$

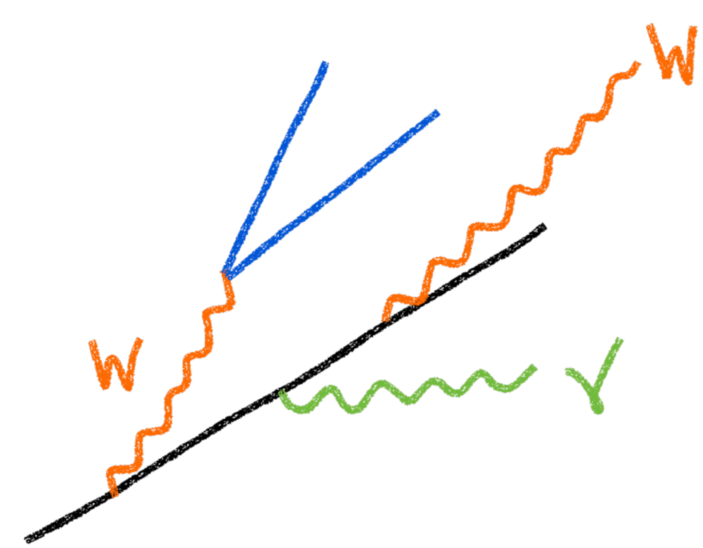
- ✦ Full event reconstruction: **missing invariant mass** (not just pT)

- ✦ No QCD backgrounds: ideal for EW physics

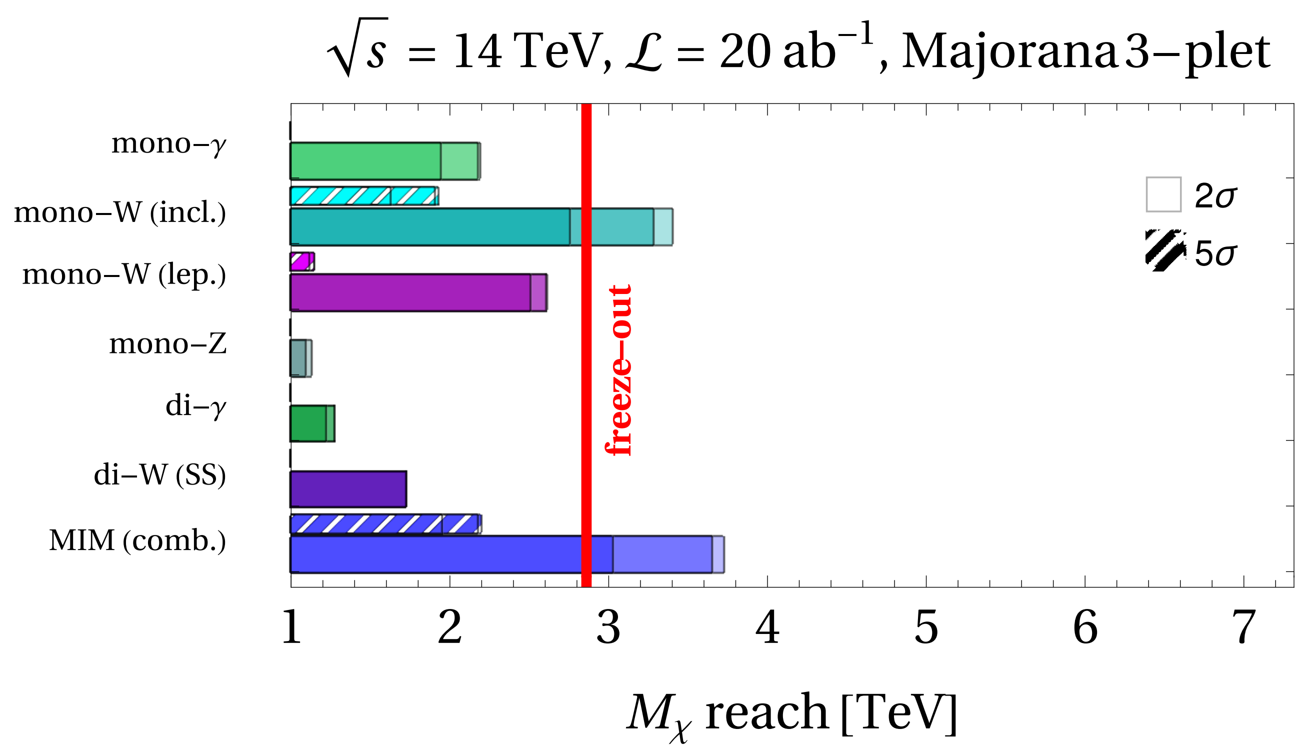
- ✦ **EW radiation** becomes important at multi-TeV energies!

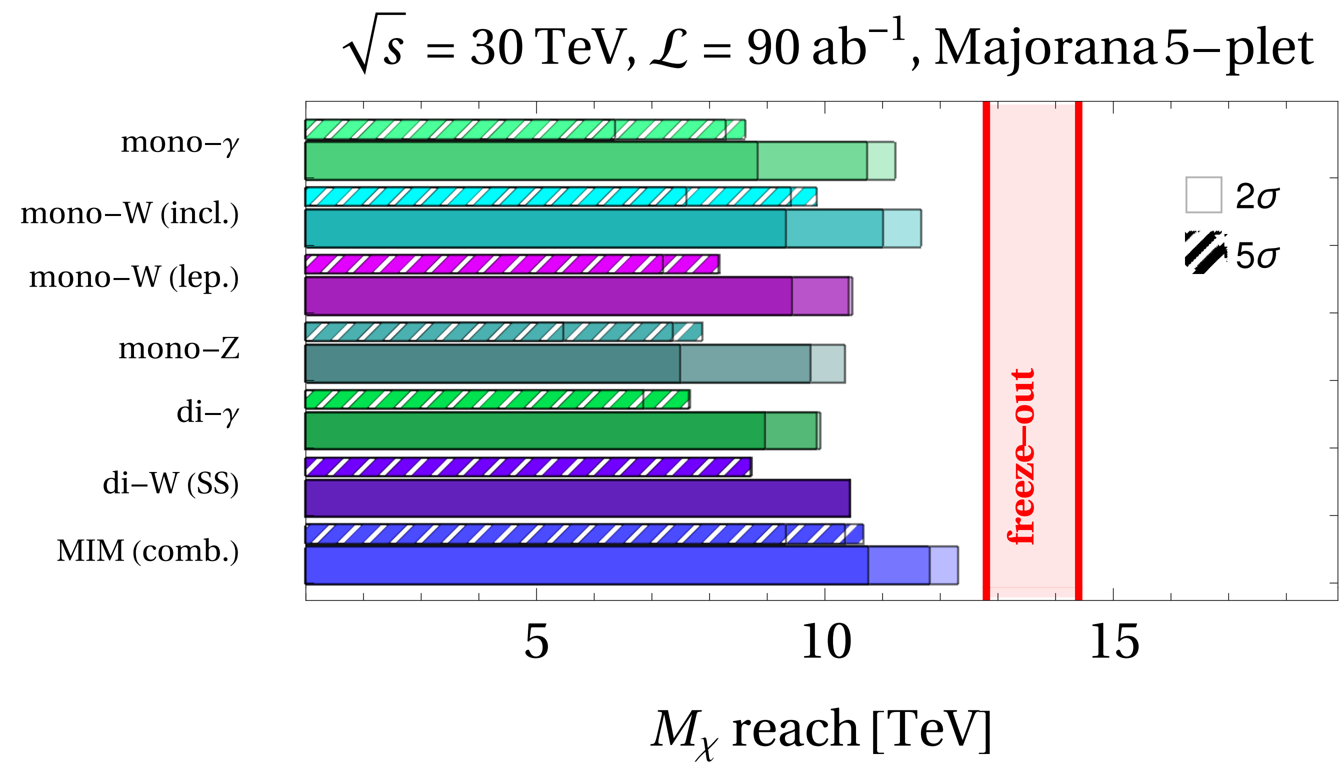
  Sudakov factor $\dfrac{\alpha}{4\pi}\log^2\left(E/m_W\right) \approx 1$ for E ~ 10 TeV

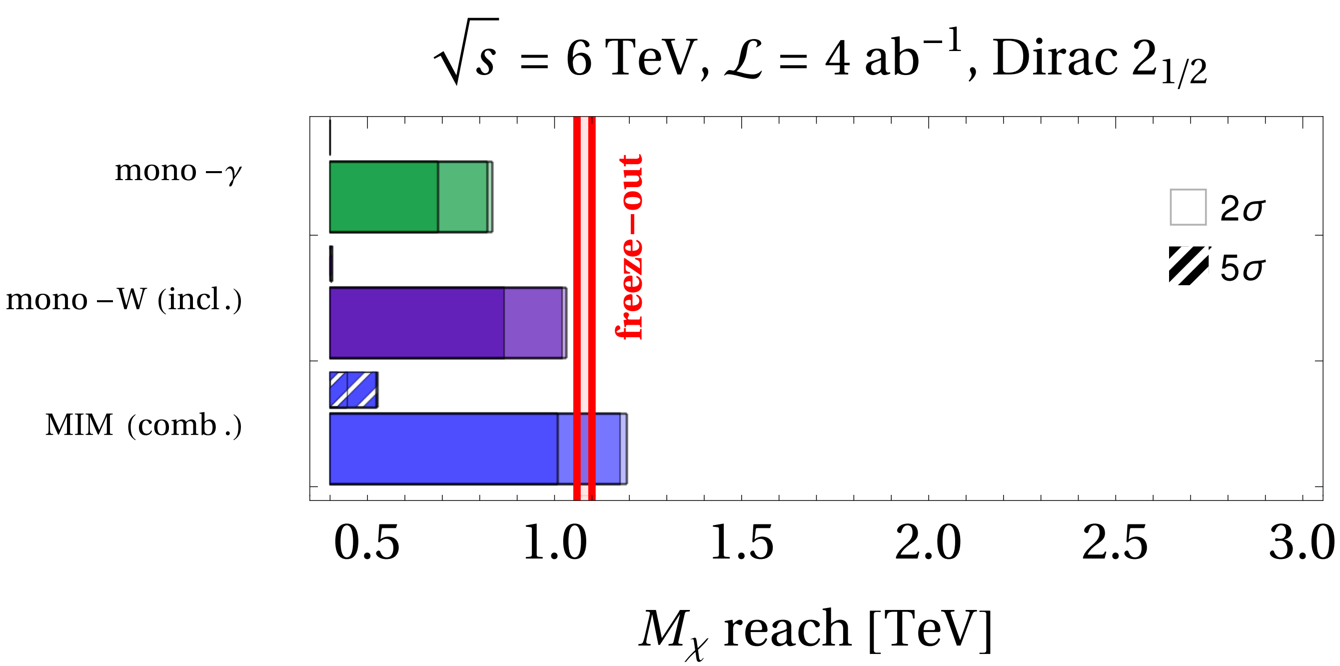
  - ‣ mono-γ, mono-W, mono-Z are all similar!
  - ‣ multiple gauge boson emission

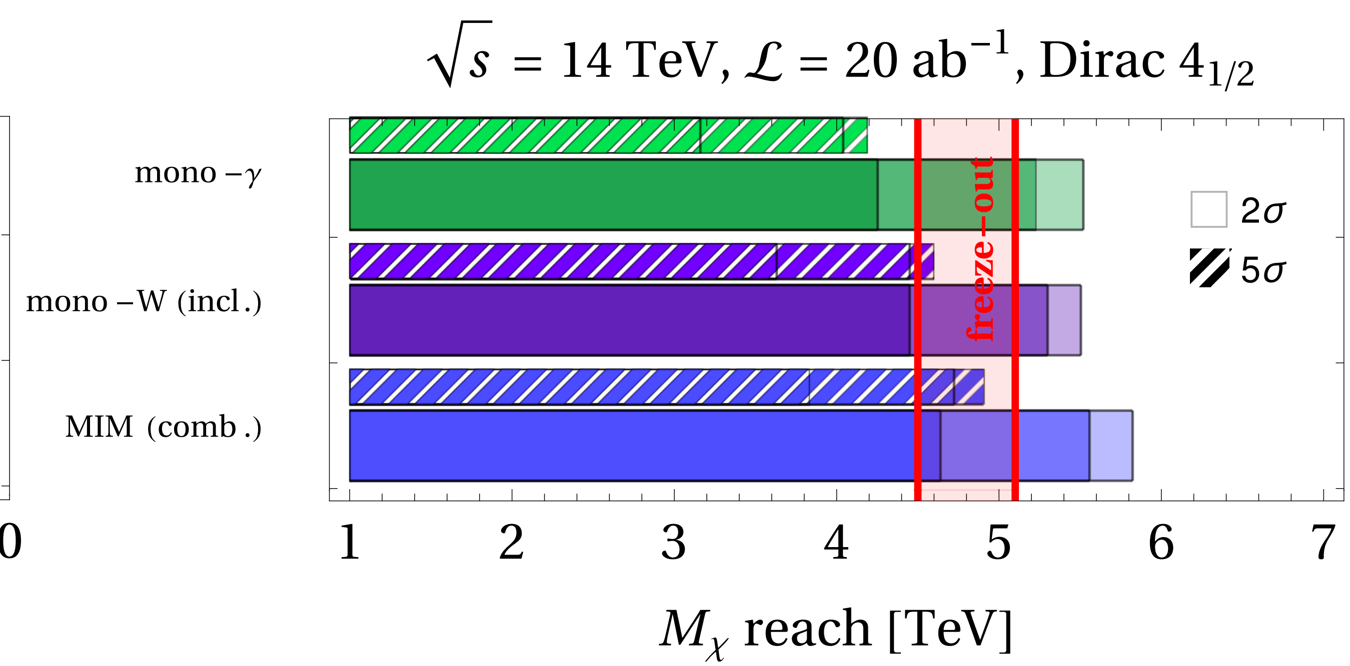


Missing mass searches at μ collider









* shadings = different assumptions about systematic errors
typically low signal/background ➔ requires good control of systematics

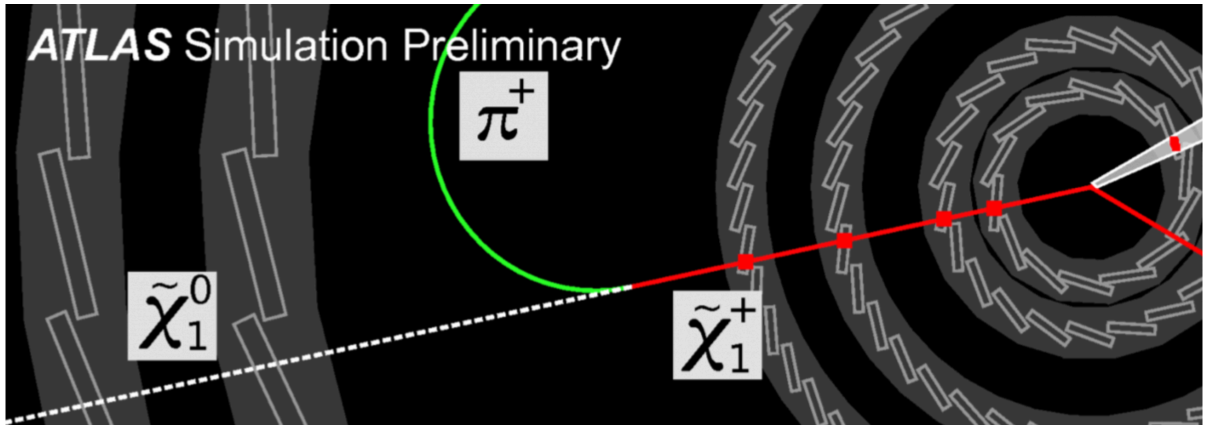
Mass splittings and disappearing tracks

- Dark Matter is part of a multiplet that includes also charged states

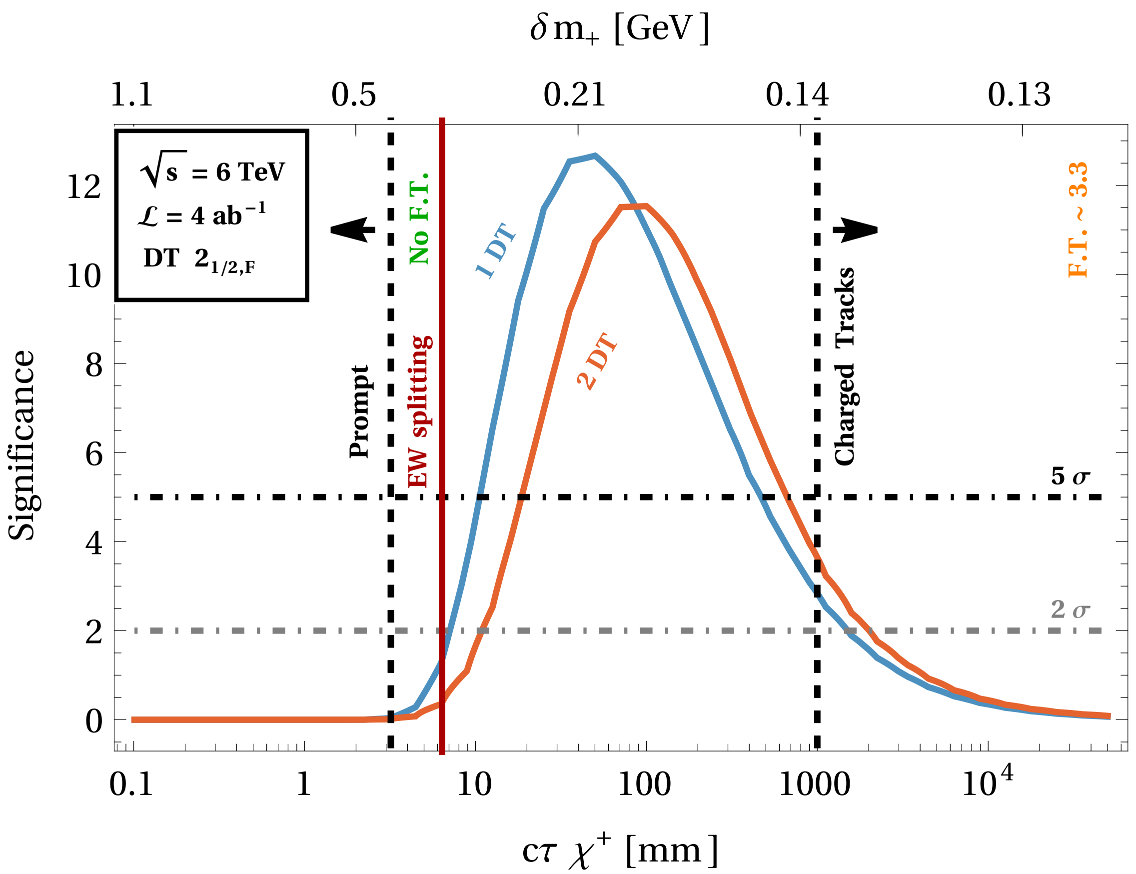
$$\chi_n = (\cdots, \chi^-, \chi^0, \chi^+, \cdots)$$

$\chi^\pm$ decays into DM inside the detector

- Look for the disappearing tracks of the charged particles to isolate the DM signal from the SM background (mainly neutrinos)



Capdevilla, Meloni, Simoniello, Zurita 2102.11292



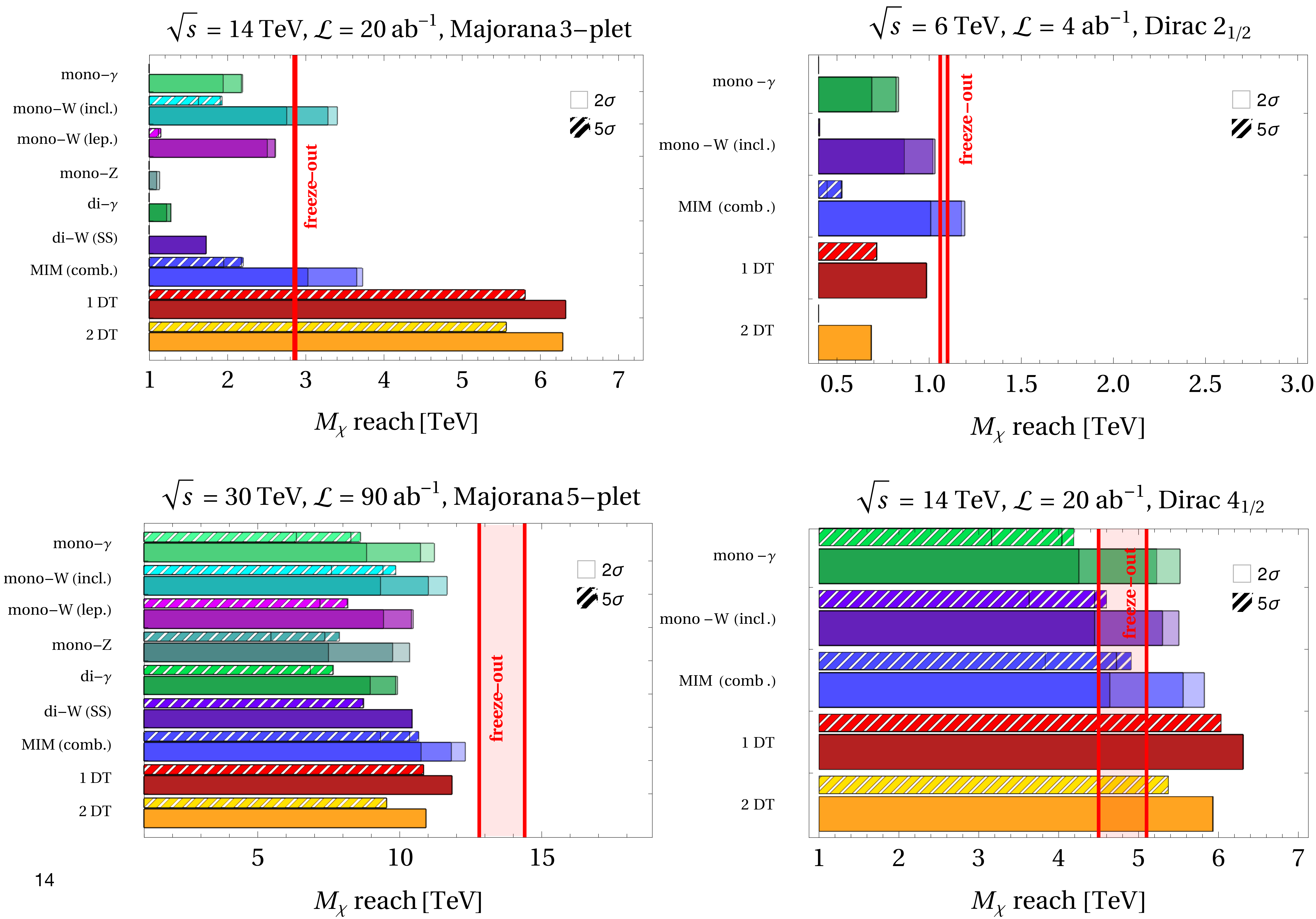
- Real WIMPs (Y = 0): mass splitting fixed by gauge interactions

$$M_Q - M_0 \approx Q^2 \alpha_{\rm em} m_W$$

$$c\tau_{\chi^\pm} \approx 50\,{\rm cm}/(n^2 - 1)$$

- Complex WIMps: additional splitting needed to make DM stable

Disappearing tracks at μ collider



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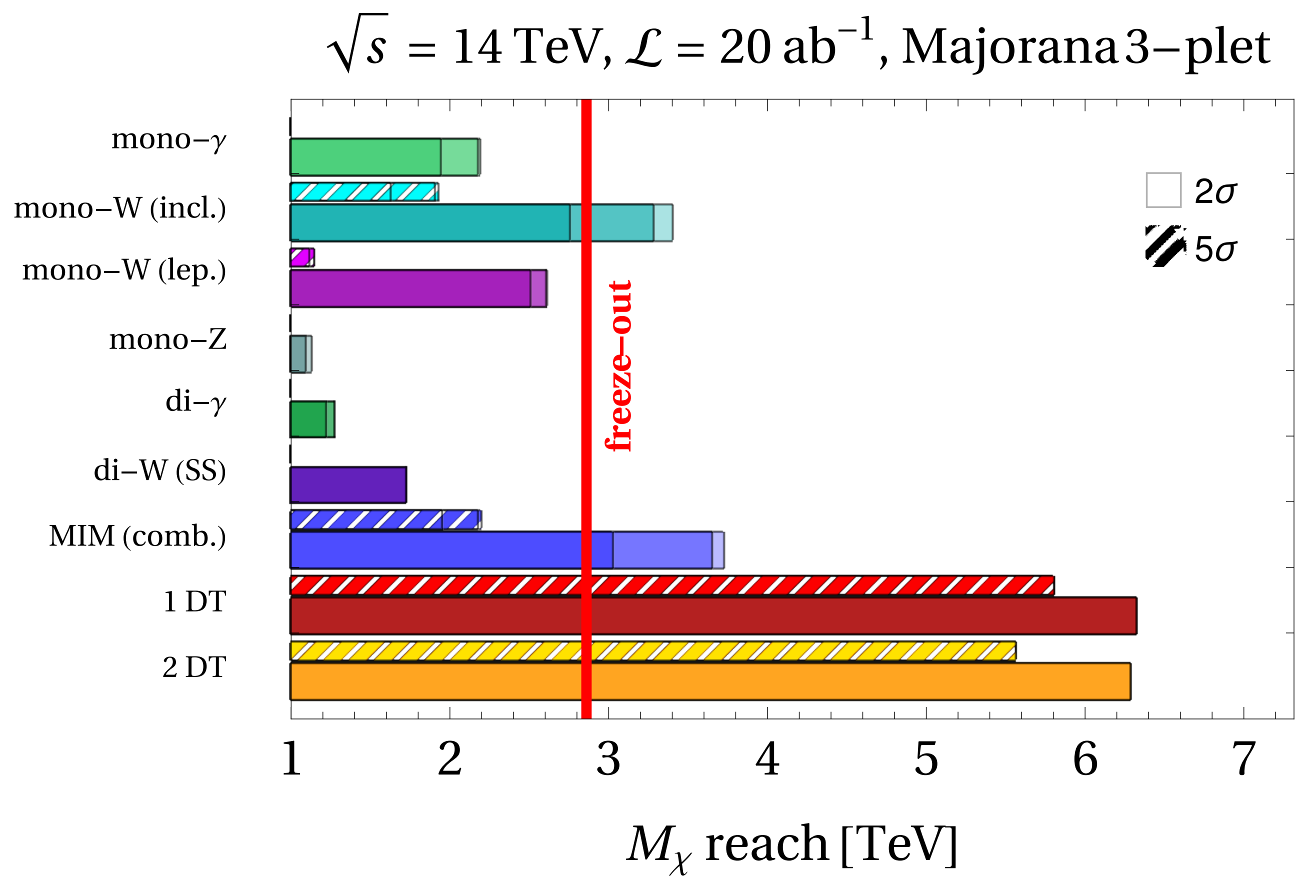
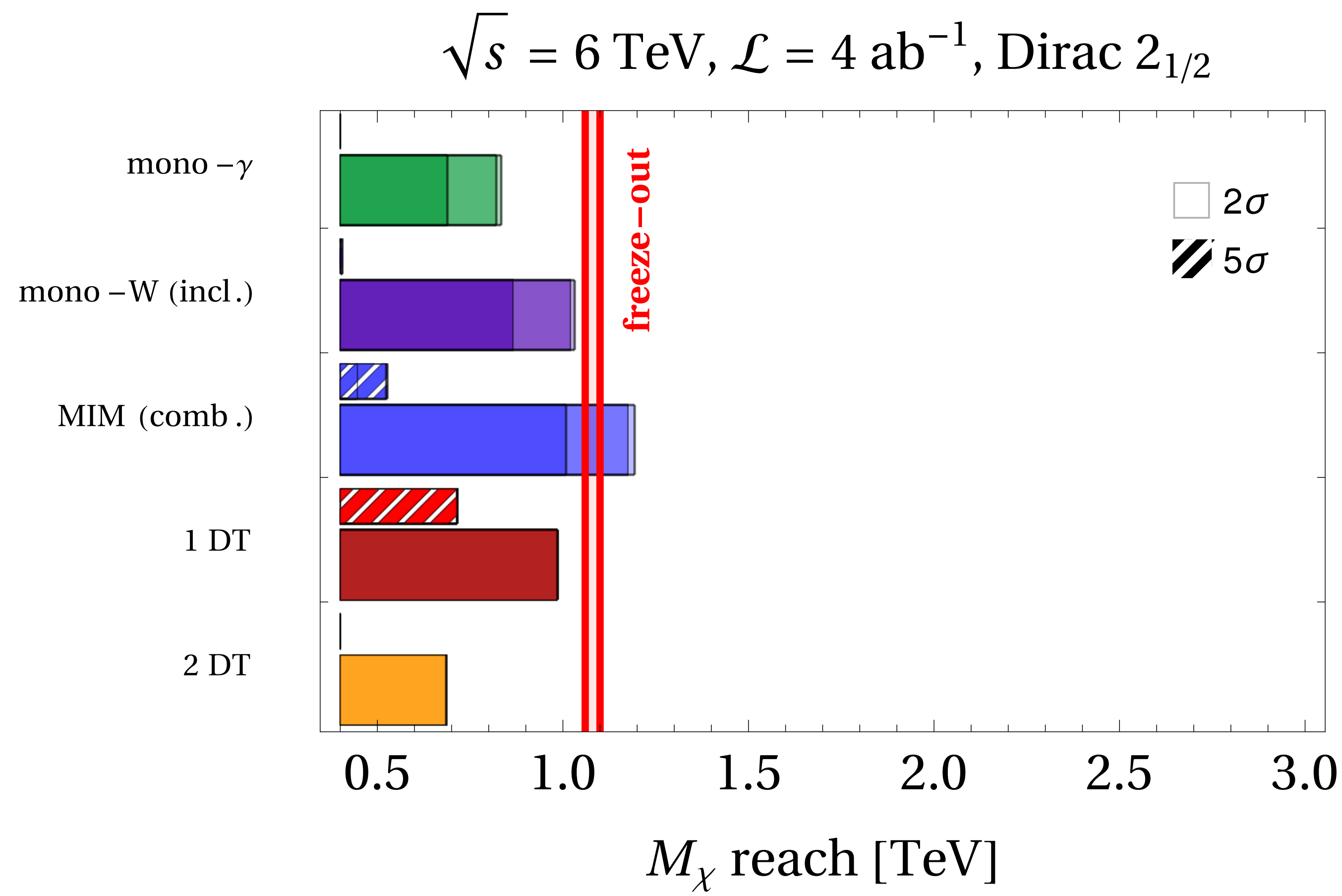
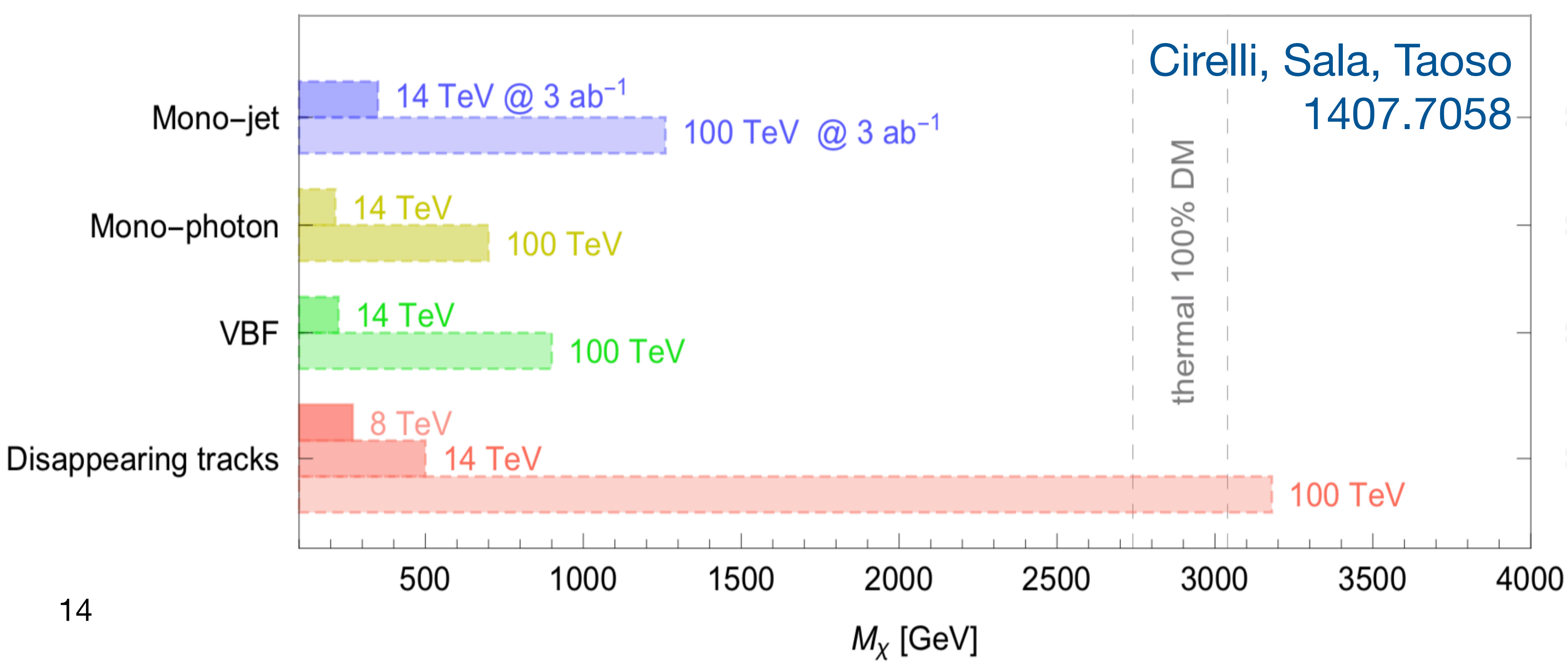




Majorana 3-plet at 100 TeV pp

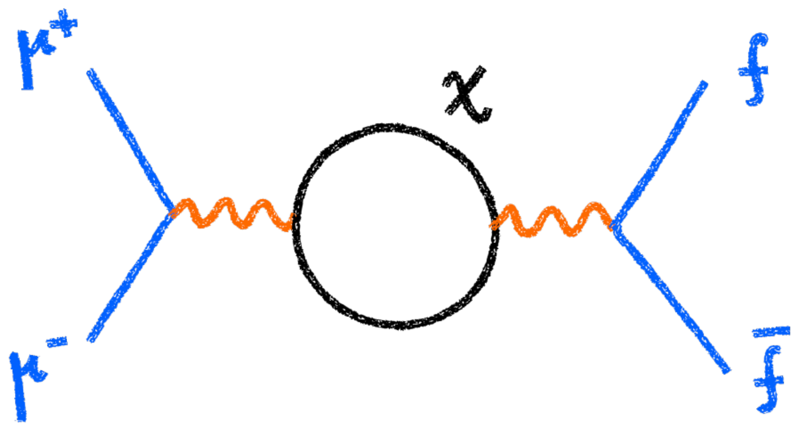


* disappearing tracks allow to probe the Wino also at FCC-hh

Indirect effects at colliders

- All EW multiplets contribute to high-energy $2 \to 2$ fermion scattering: effects that grow with energy, can be tested at μ collider or FCC-hh

Di Luzio, Gröber, Panico 1810.10993



$$\hat{W} \approx 10^{-7} \times \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{DM}}}\right)^2 n^3 \propto 1/n^2$$

$$\hat{Y} \approx 10^{-7} \times \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{DM}}}\right)^2 Y^2 n \propto 1/n^4$$

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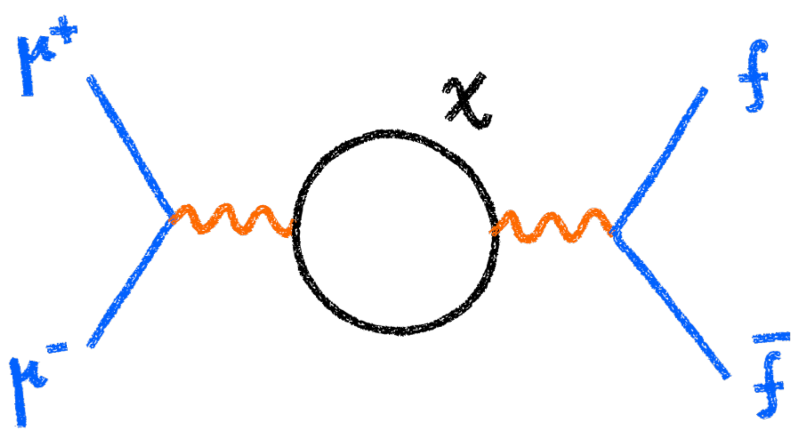
Di Luzio, Gröber, Panico 1810.10993



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- Complex multiplets need mass splittings from higher dim. operators
  - Charged-neutral splitting (to make DM stable): $\left(\bar{\chi} T^a \chi\right)\left(H^\dagger \sigma^a H\right)$
  - Inelastic splitting (suppress Z-induced scattering): $\left(\bar{\chi}(T^a)^{2Y} \chi^c\right)\left(H^{\dagger c} \sigma^a H\right)^{2Y}$

$$\hat{S} \approx 10^{-5} \times \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{DM}}}\right)\left(\frac{\delta M}{10\,\mathrm{GeV}}\right) n^3, \qquad \hat{T} \approx 10^{-5} \times \left(\frac{\delta M}{10\,\mathrm{GeV}}\right)^2 n^3$$

can be tested at FCC-ee

Di Luzio, Gröber, Kamenik, Nardecchia 1505.00359

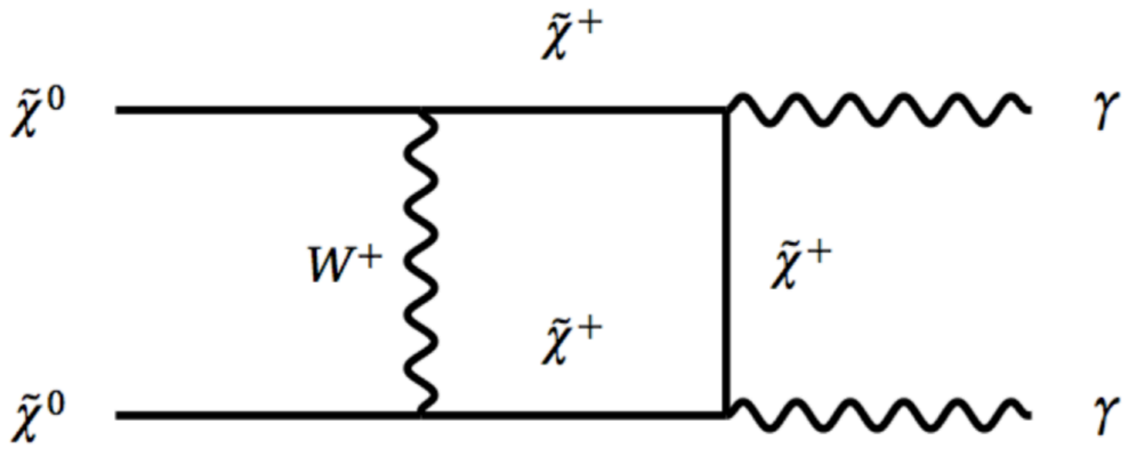
Indirect detection

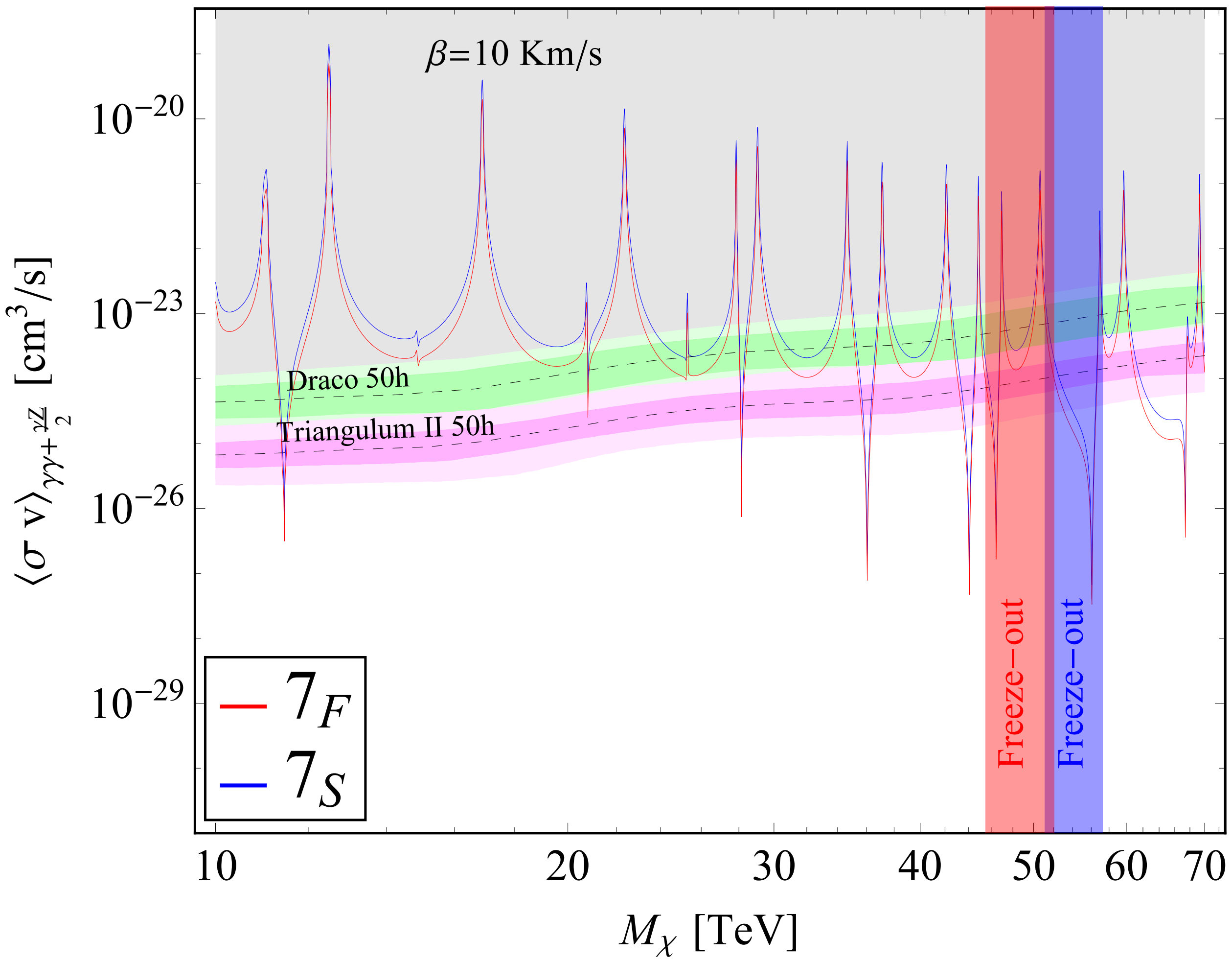
- Searches for high-energy gamma-ray lines with Cherenkov telescopes are a powerful constraint for high-mass WIMP DM

γ-ray line at $E_\gamma \approx M_\chi$

to be included:

- continuum
- bound-state contribution
- EW radiation





- Large multiplets are easily probed due to increased annihilation cross-section

- Thermal, weakly interacting Dark Matter generically points to multi-TeV mass scales. Not probed yet!
- Next-generation experiments needed to fully cover the parameter space:

large exposure
direct detection

high-energy
muon collider

indirect detection
gamma-ray lines

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large exposure
direct detection

high-energy
muon collider

indirect detection
gamma-ray lines

needs a
μ-collider!

Results: real WIMPs

DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	2.4×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	7×10^{36}	3×10^{24}
	7	54.2 ± 3.1	0.022	7.8×10^{16}	2×10^{24}
	9	117.8 ± 8.8	0.088	3×10^{4}	2×10^{24}
	11	199 ± 14	0.25	62	1×10^{24}
	13	338 ± 24	0.6	7.2	2×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	2.4×10^{37}	$2 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	5.5×10^{17}	3×10^{12}
	7	48.8 ± 2.7	0.019	1.2×10^{4}	1×10^{8}
	9	113 ± 9	0.07	41	1×10^{8}
	11	202 ± 14	0.2	6	1×10^{8}
	13	324.6 ± 23	0.5	2.6	1×10^{8}

$$\mathscr{L}_{\rm s} \supset \frac{C_1^{(s)}}{\Lambda_{\rm UV}^{n-4}}\chi(H^\dagger H)^{\frac{n-1}{2}} + \frac{C_2^{(s)}}{\Lambda_{\rm UV}^{n-4}}\chi W_{\mu\nu}W^{\mu\nu}(H^\dagger H)^{\frac{n-5}{2}} + \cdots + \frac{C_w^{(s)}}{\Lambda_{\rm UV}^{n-4}}\chi(W_{\mu\nu}W^{\mu\nu})^{\frac{n-1}{4}} + \frac{C_{3\chi}^{(s)}}{\Lambda_{\rm UV}}\chi^3 H^\dagger H,$$

$$\mathscr{L}_{\rm f} \supset \frac{C_1^{(f)}}{\Lambda_{\rm UV}^{n-3}}(\chi HL)(H^\dagger H)^{\frac{n-3}{2}} + \frac{C_2^{(f)}}{\Lambda_{\rm UV}^{n-3}}(\chi\sigma^{\mu\nu}HL)W_{\mu\nu}(H^\dagger H)^{\frac{n-5}{2}} + \cdots + \frac{C_w^{(f)}}{\Lambda_{\rm UV}^{n-3}}(\chi HL)(W_{\mu\nu}W^{\mu\nu})^{\frac{n-3}{4}} + \frac{C_{3\chi}^{(f)}}{\Lambda_{\rm UV}^{3}}\chi^3 HL,$$

Results: complex WIMPs

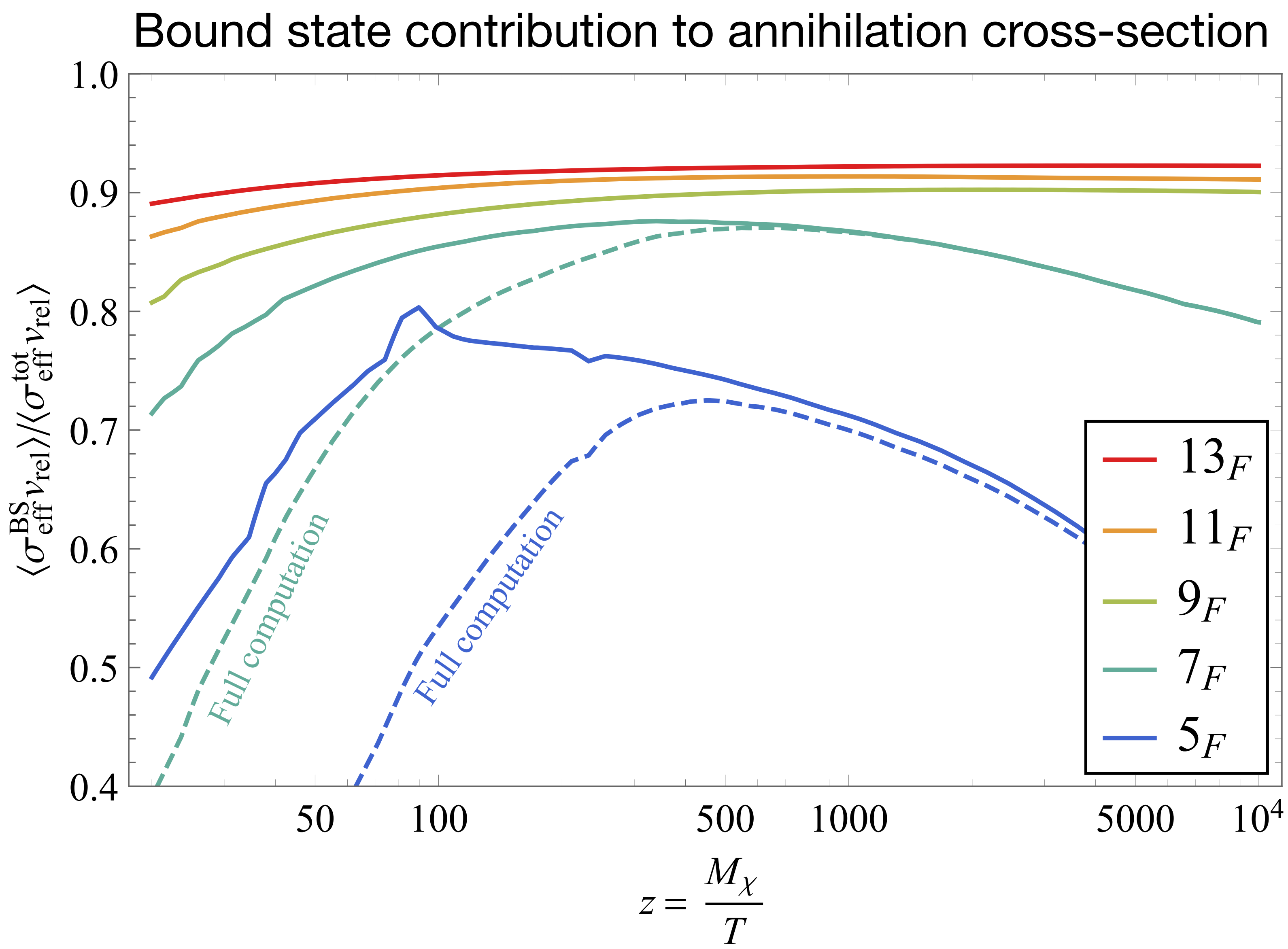
DM spin	n_Y	$M_{\rm DM}$ (TeV)	$\Lambda_{\rm Landau}/M_{\rm DM}$	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	δm_0 [MeV]	$\Lambda^{\rm max}_{\rm UV}/M_{\rm DM}$	δm_{Q_M} [MeV]
Dirac fermion	$2_{1/2}$	1.08 ± 0.02	$> M_{\rm Pl}$	-	0.22 - 2×10^4	10^7	4.8 - 10^4
	3_1	2.85 ± 0.14	$> M_{\rm Pl}$	-	0.22 - 40	60	312 - 1.6 $\times 10^4$
	$4_{1/2}$	4.8 ± 0.3	$\simeq M_{\rm Pl}$	0.001	0.21 - 3×10^4	5×10^6	20 - 1.9 $\times 10^4$
	5_1	9.9 ± 0.7	3×10^6	0.003	0.21 - 3	25	$10^3 - 2 \times 10^3$
	$6_{1/2}$	31.8 ± 5.2	2×10^4	0.01	0.5 - 2×10^4	4×10^5	100 - 2×10^4
	$8_{1/2}$	82 ± 8	15	0.05	0.84 - 10^4	10^5	440 - 10^4
	$10_{1/2}$	158 ± 12	3	0.16	1.2 - 8×10^3	6×10^4	1.1×10^3 - 9×10^3
	$12_{1/2}$	253 ± 20	2	0.45	1.6 - 6×10^3	4×10^4	2.3×10^3 - 7×10^3
Complex scalar	$2_{1/2}$	0.58 ± 0.01	$> M_{\rm Pl}$	-	4.9 - 1.4×10^4	-	4.2 - 7×10^3
	3_1	2.1 ± 0.1	$> M_{\rm Pl}$	-	3.7 - 500	120	75 - 1.3 $\times 10^4$
	$4_{1/2}$	4.98 ± 0.25	$> M_{\rm Pl}$	0.001	4.9 - 3×10^4	-	17 - 2 $\times 10^4$
	5_1	11.5 ± 0.8	$> M_{\rm Pl}$	0.004	3.7 - 10	20	650 - 3 $\times 10^3$
	$6_{1/2}$	32.7 ± 5.3	$\simeq 6 \times 10^{13}$	0.01	4.9 - 8×10^4	-	50 - 5×10^4
	$8_{1/2}$	84 ± 8	2×10^4	0.05	4.9 - 6 $\times 10^4$	-	150 - 6×10^4
	$10_{1/2}$	162 ± 13	20	0.16	4.9 - 4×10^4	-	430 - 4×10^4
	$12_{1/2}$	263 ± 22	4	0.4	4.9 - 3×10^4	-	10^3 - 3×10^4

$$\mathscr{L}_{\rm D} = \overline{\chi}\left(i\not{D} - M_\chi\right)\chi + \frac{y_0}{\Lambda_{\rm UV}^{4Y-1}}\mathcal{O}_0 + \frac{y_+}{\Lambda_{\rm UV}}\mathcal{O}_+ + {\rm h.c.}\ ,$$

$$\mathcal{O}_0 = \frac{1}{2(4Y)!}\left(\overline{\chi}(T^a)^{2Y}\chi^c\right)\left[(H^{c\dagger})\frac{\sigma^a}{2}H\right]^{2Y}\ ,$$

$$\mathcal{O}_+ = -\overline{\chi}T^a\chi H^\dagger\frac{\sigma^a}{2}H\ ,$$

Impact of bound state formation



Sommerfeld

$$S_{\rm ann} = \sum_I \left\langle \sigma^I_{\rm ann} v_{\rm rel} \frac{2\pi\alpha_{\rm eff}}{v_{\rm rel}} \right\rangle$$

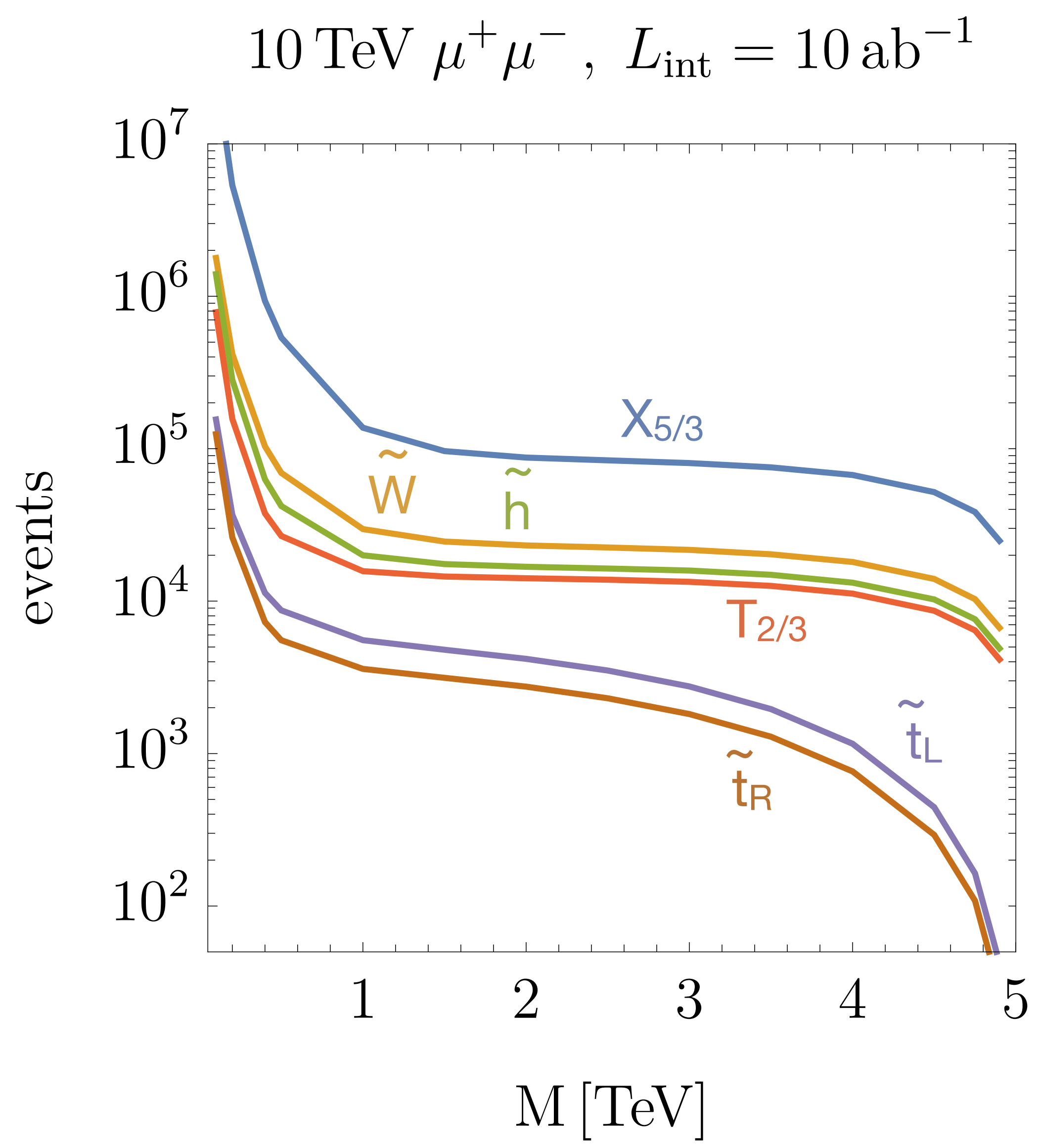
$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle \equiv S_{\rm ann}(z) + \sum_{B_J} S_{B_J}(z)$$

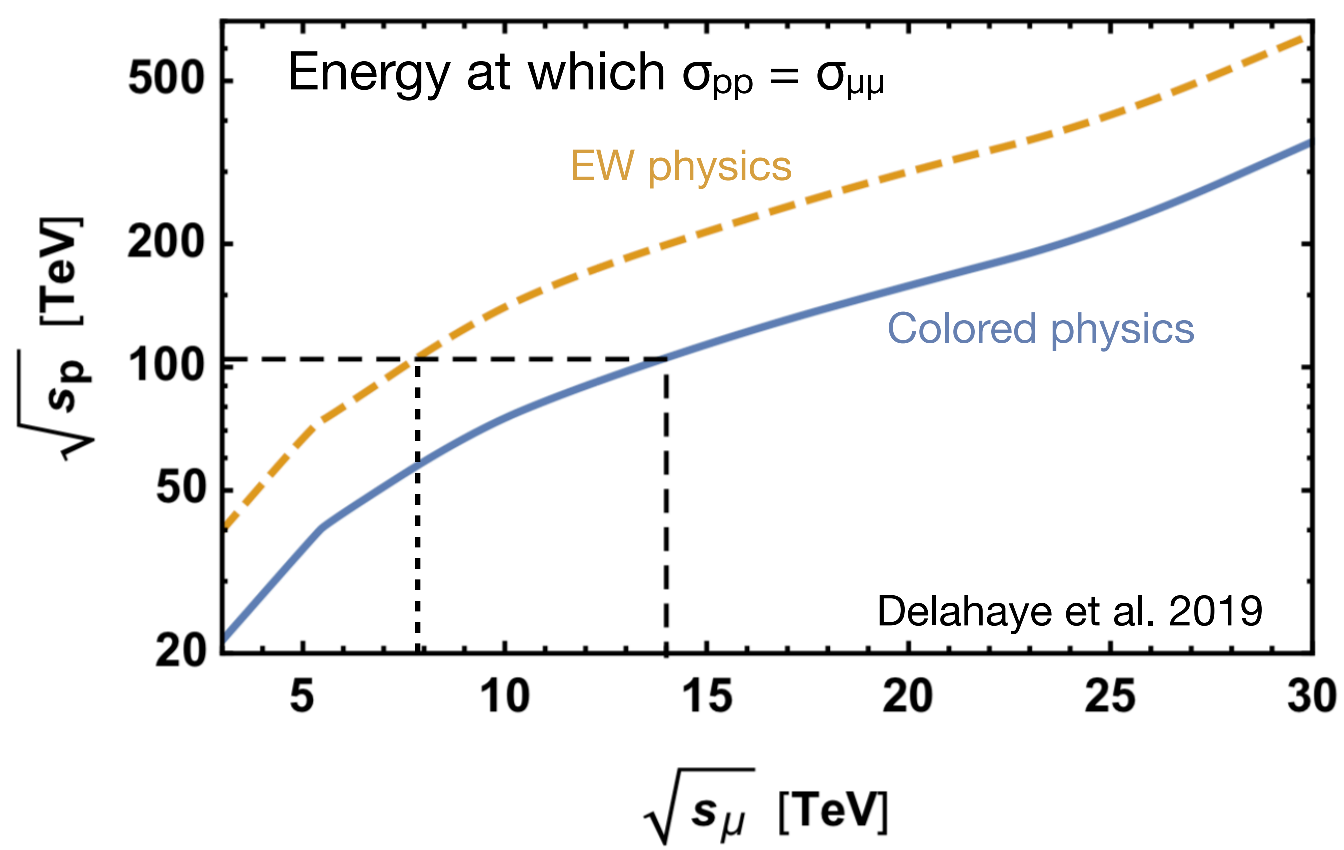
$$S_{B_J} = \sum_{I,l} \sigma^{I,l}_{B_J} \frac{2\pi\alpha_{\rm eff}}{v_{\rm rel}} R_J$$

branching ratio into SM

Muon collider physics: energy AND precision

- Pair-production of EW particles up to threshold

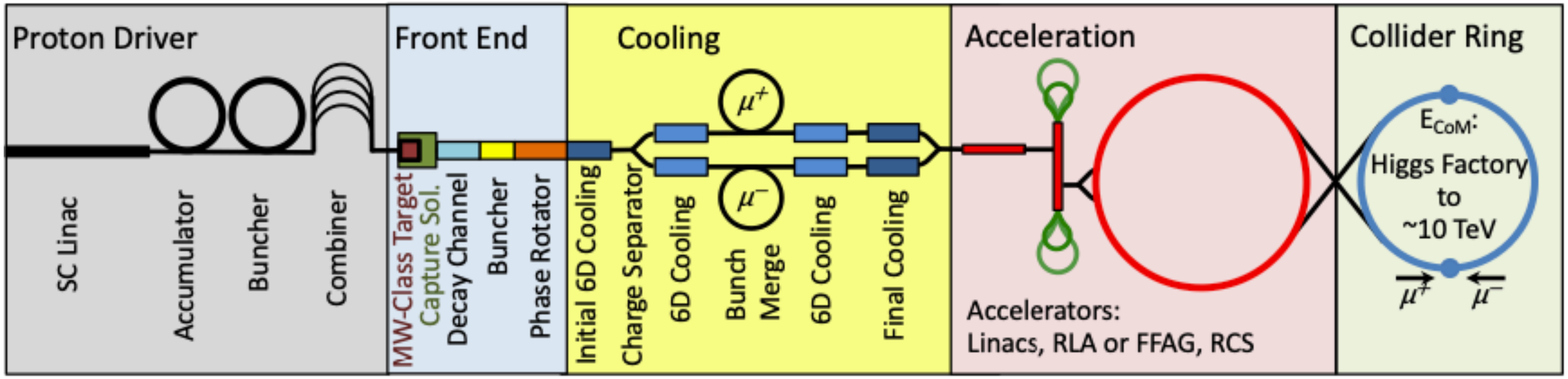


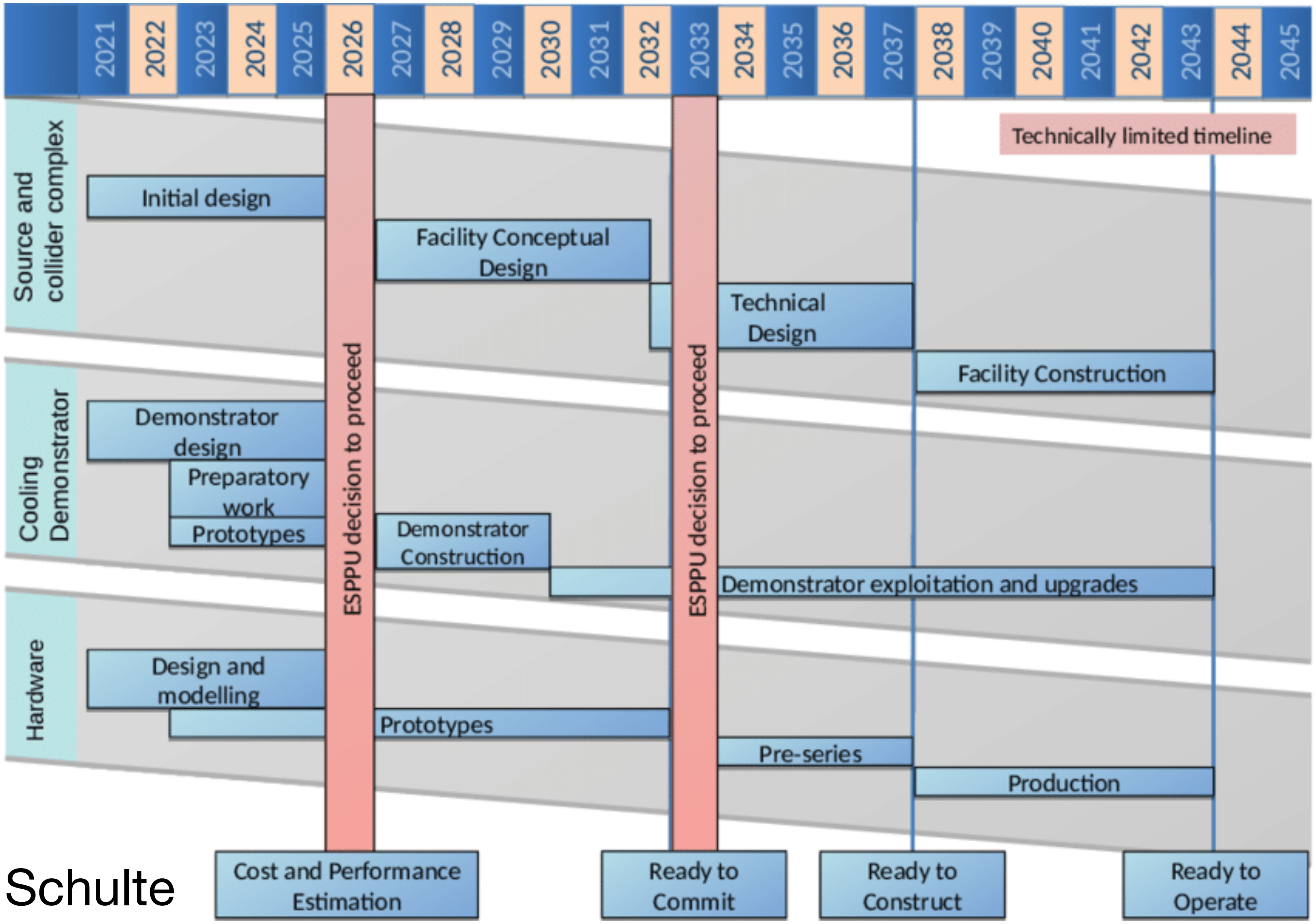


- Precision physics: Higgs boson physics comparable to Higgs factories

- High-energy probes: probe new physics at 100 TeV

Muon collider: possible timeline



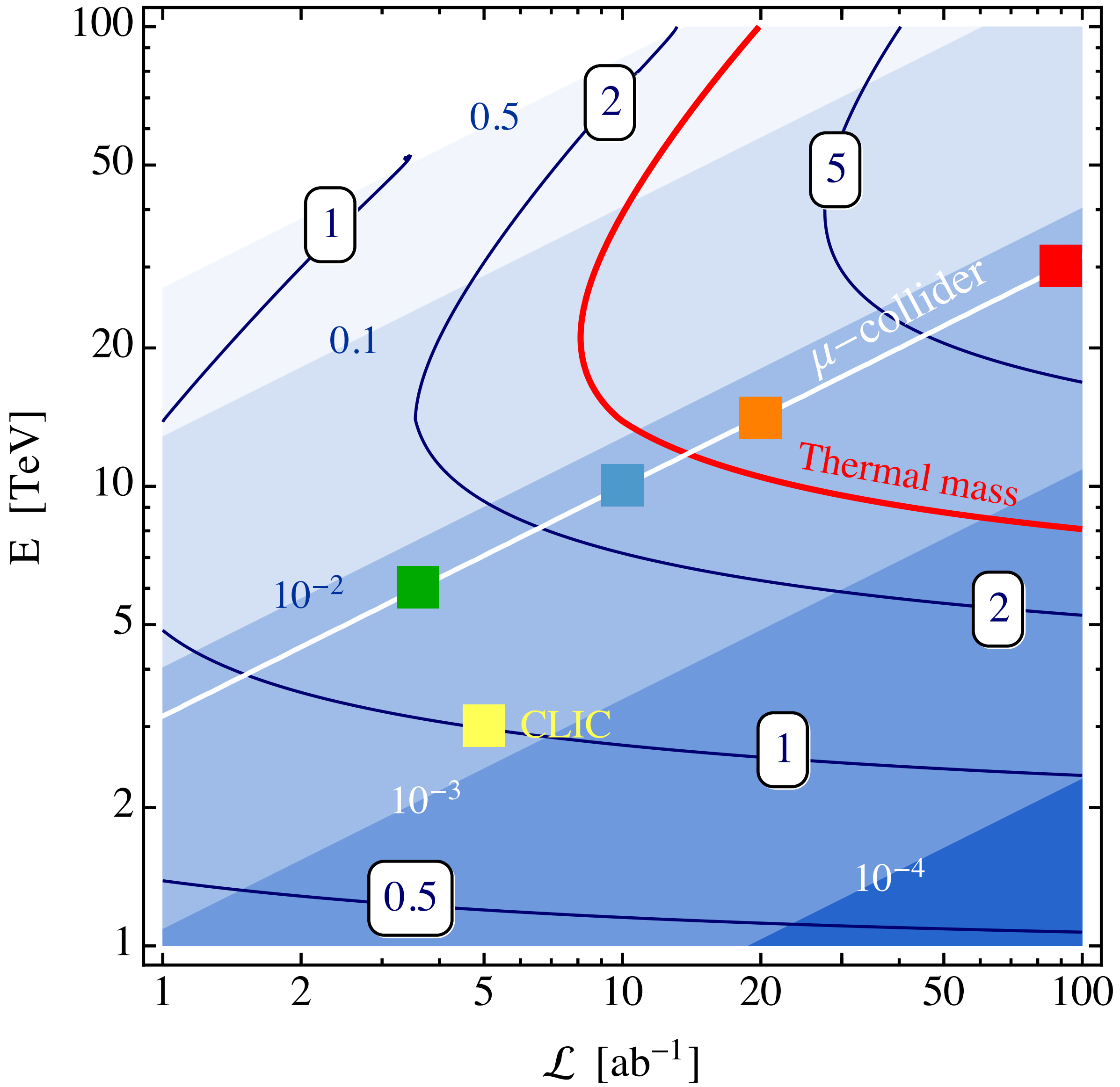


D. Schulte

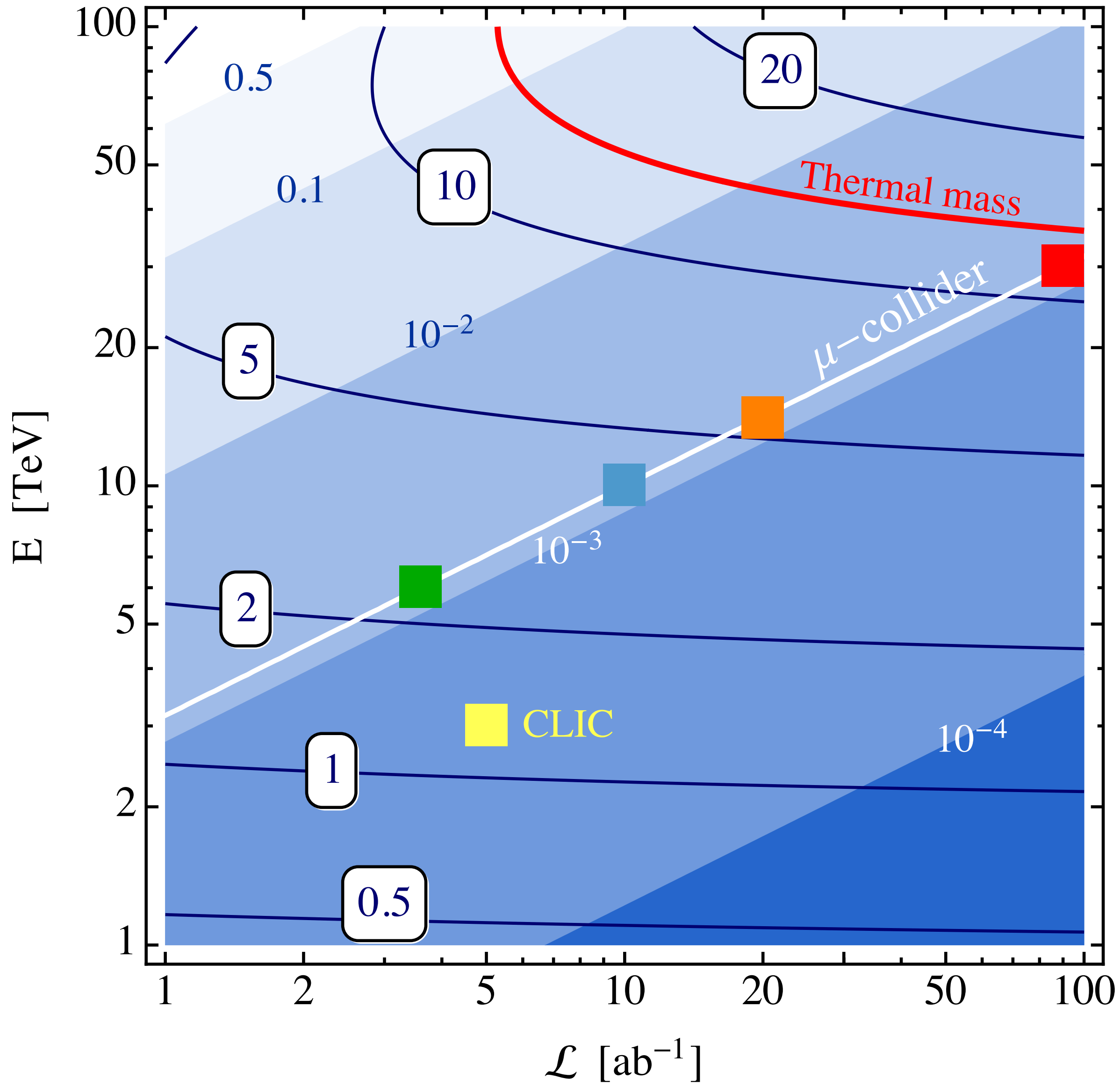
Reach at muon colliders

mono-W searches

Majorana 3-plet (Wino)

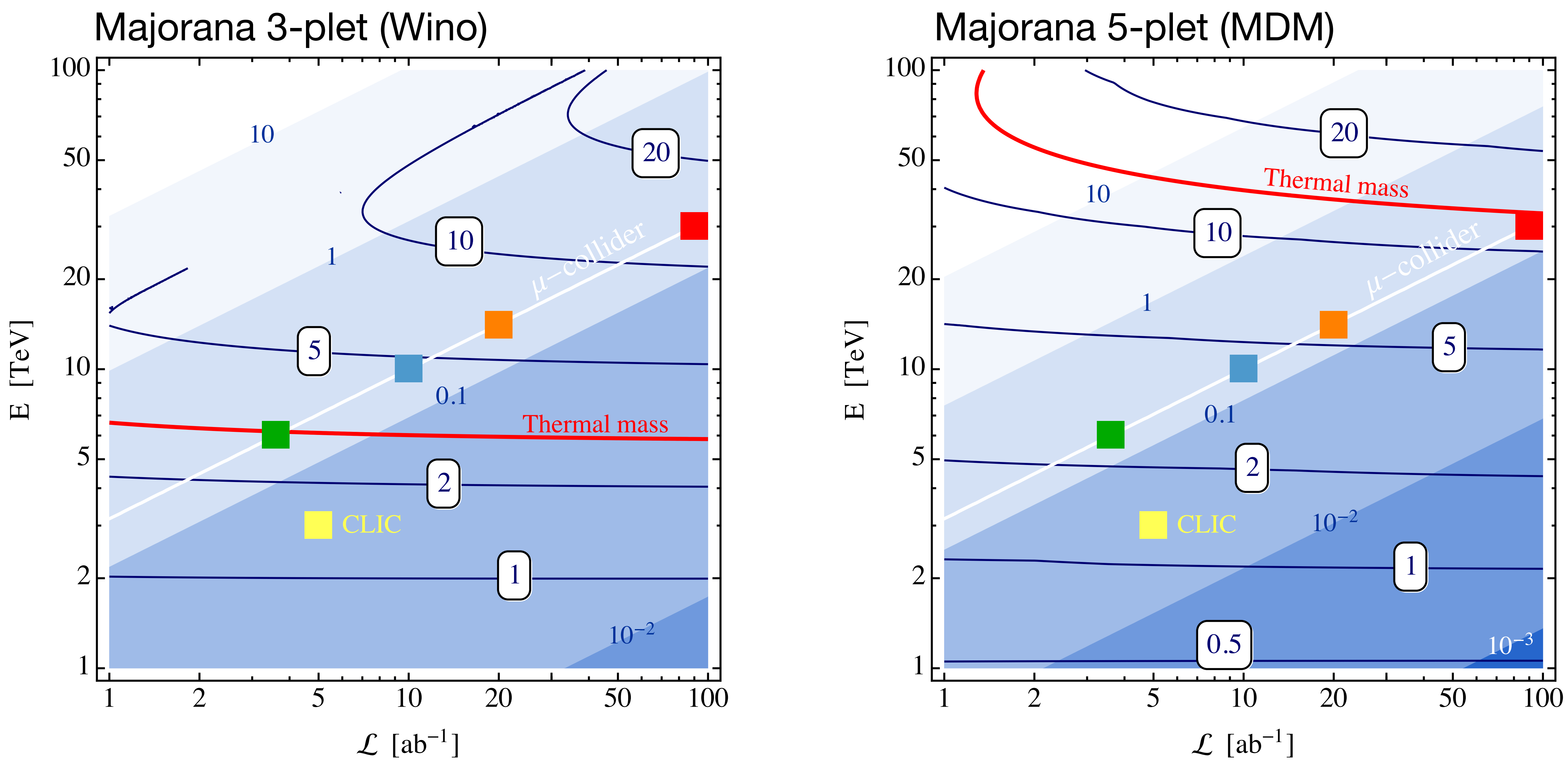


Majorana 5-plet (MDM)



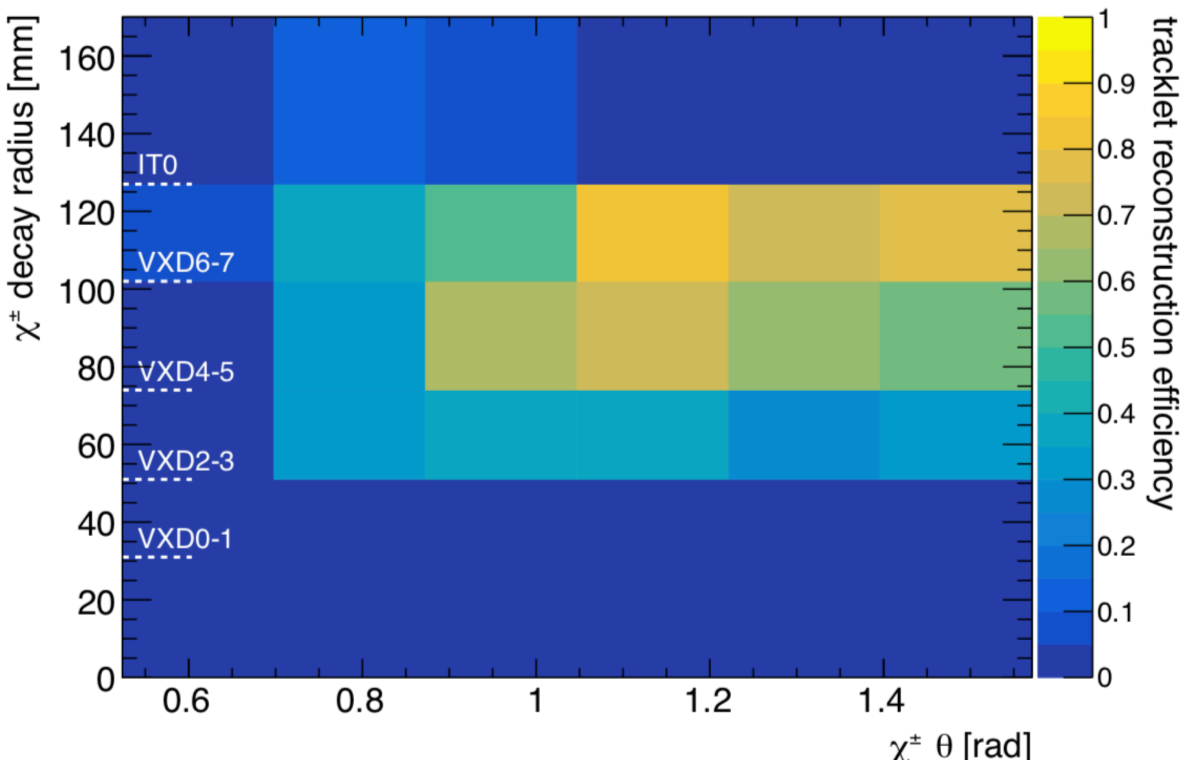
Reach at muon colliders

Disappearing track searches (mono-γ)

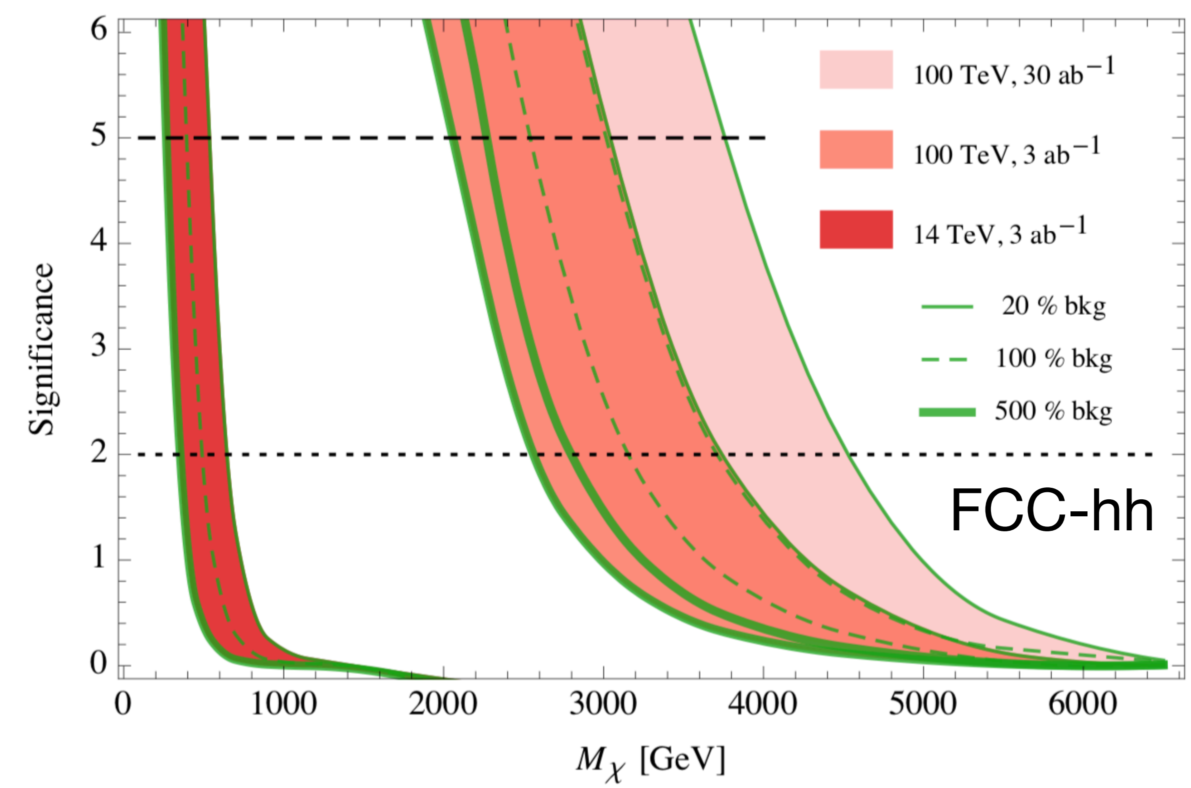


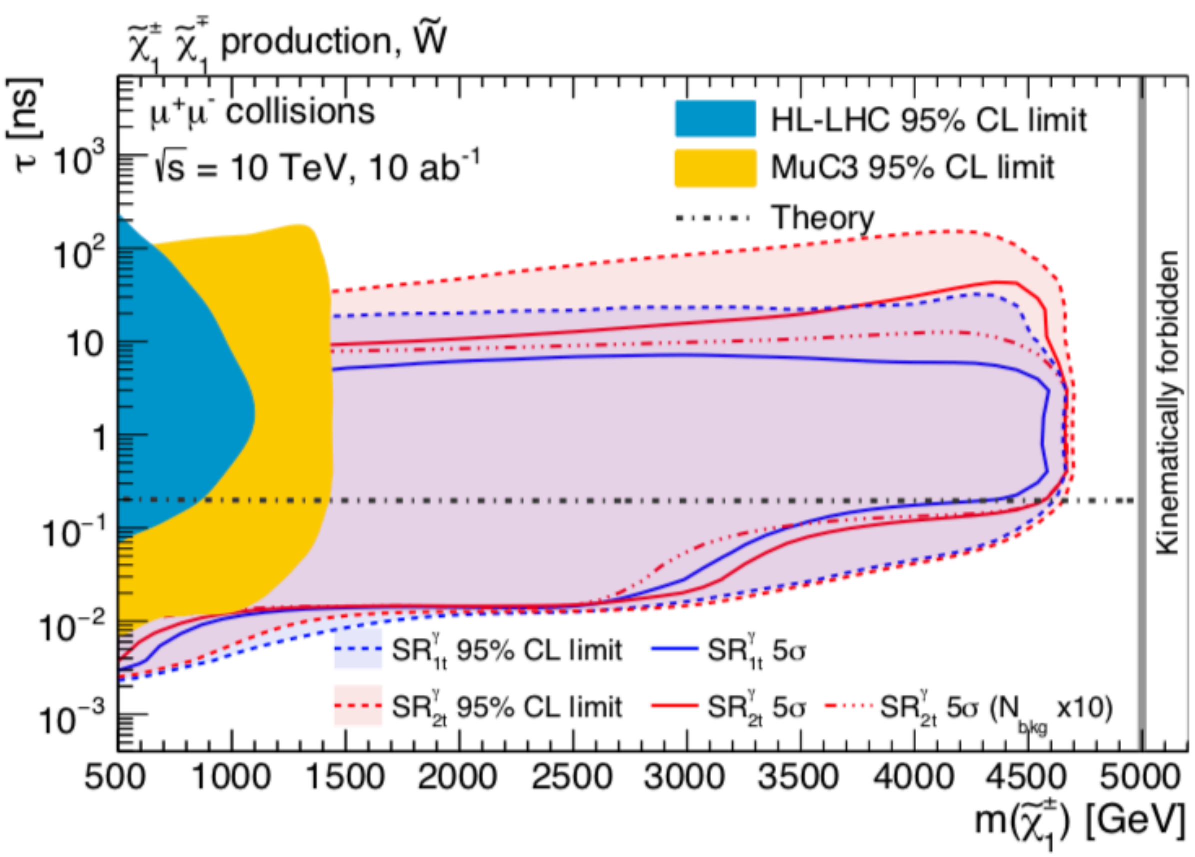
Disappearing tracks

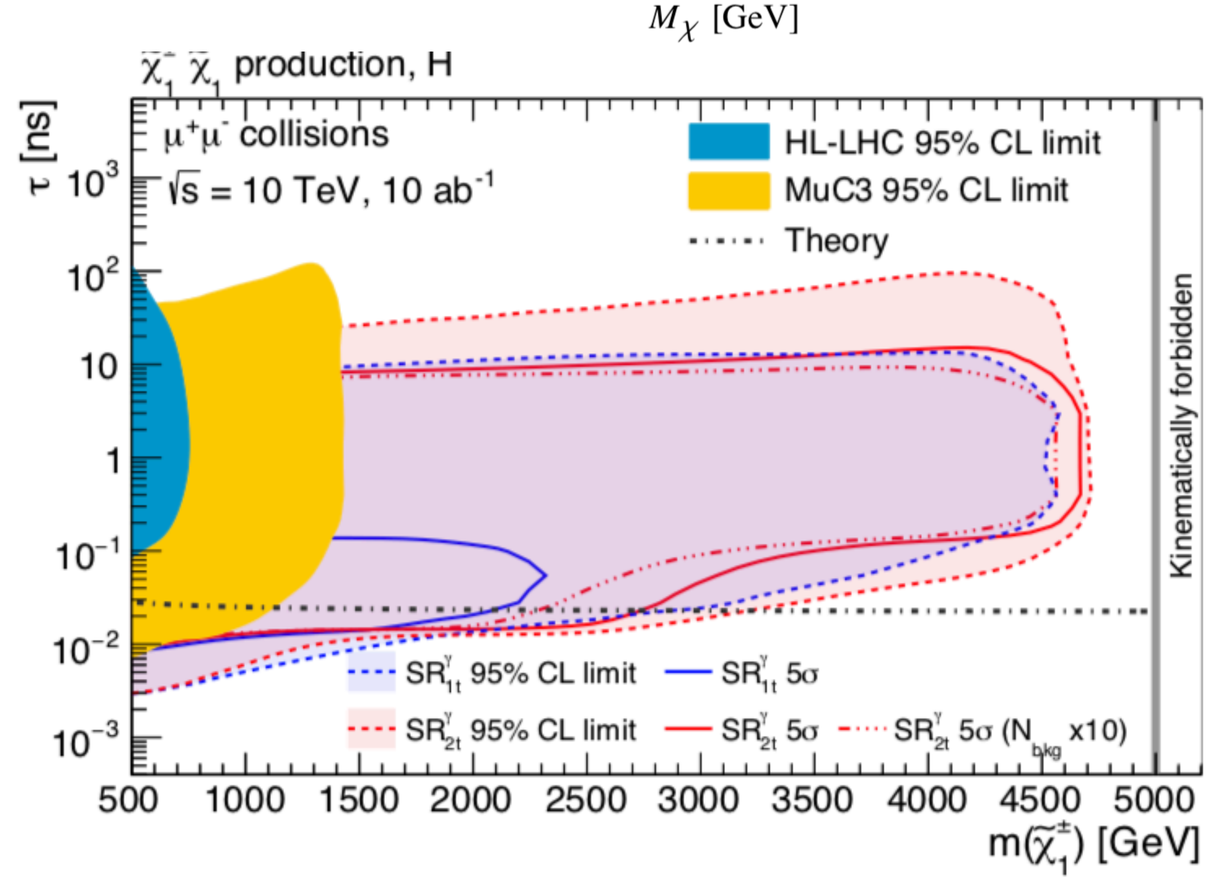
Capdevilla, Meloni, Simoniello, Zurita 2102.11292



Cirelli, Sala, Taoso 1407.7058

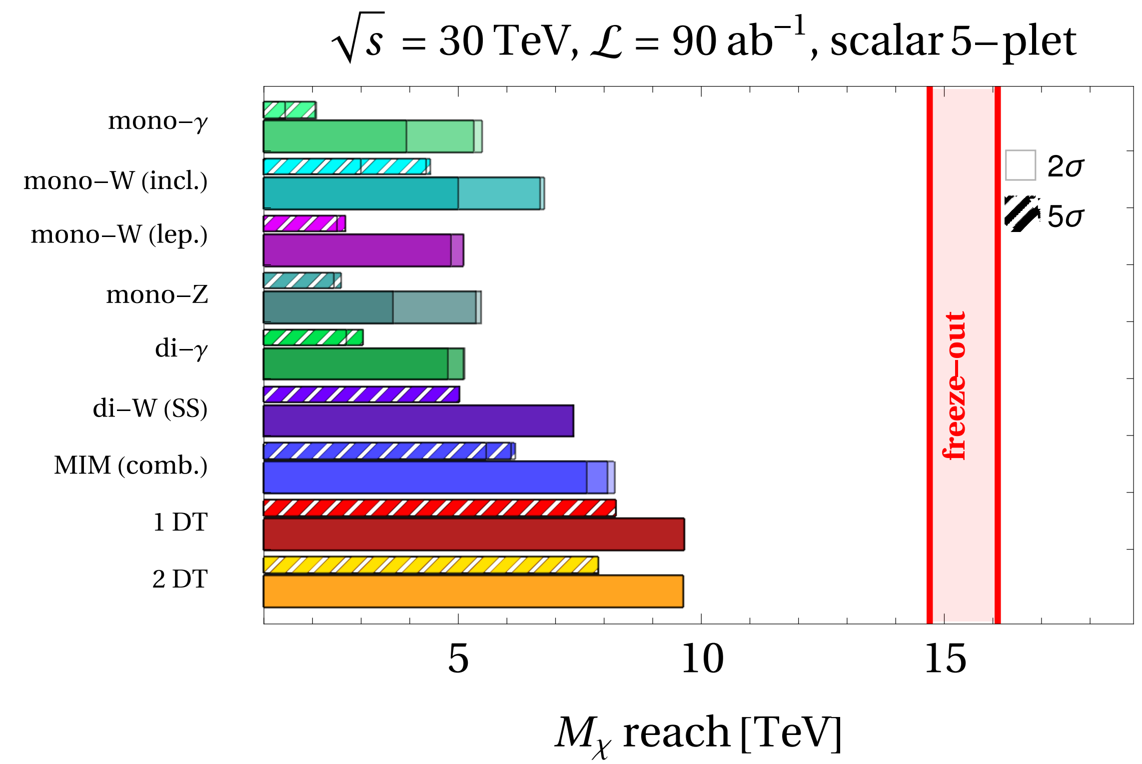


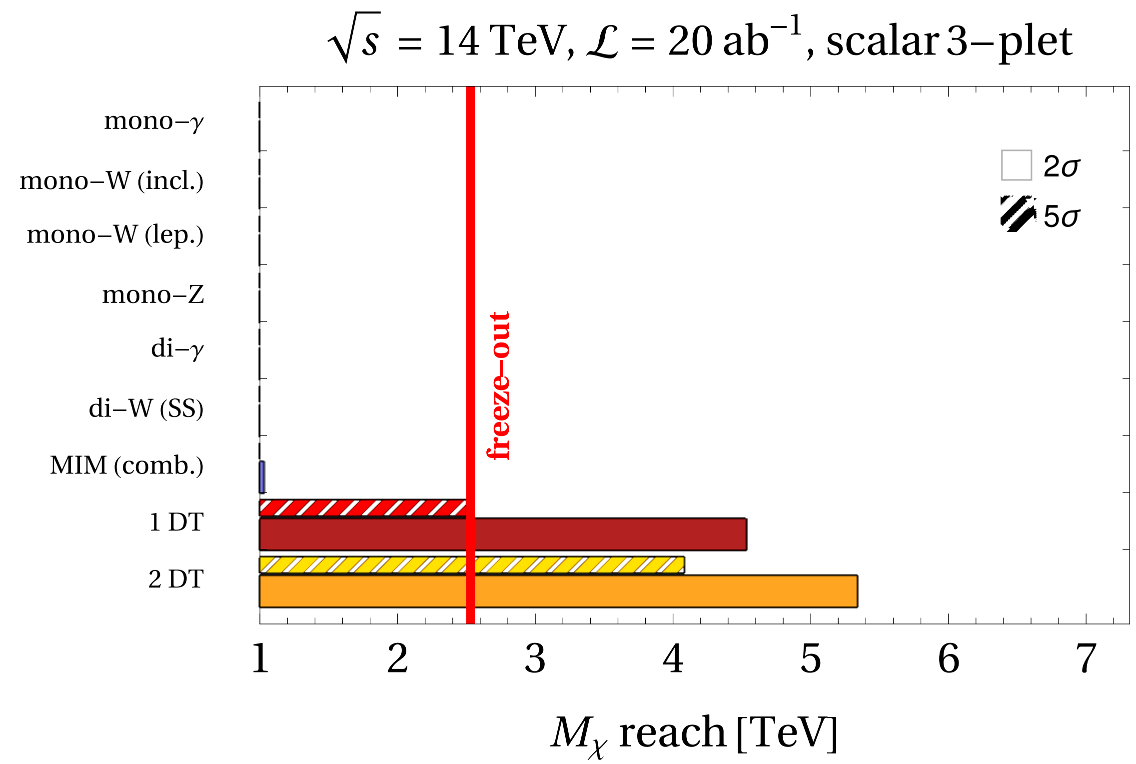




Scalar WIMPs

- Scalars have lower cross-sections





- Higgs portal coupling
  ➔ direct detection