A final word on minimal dark matter at future lepton colliders

S.Bottaro, D.Buttazzo, M.Costa, R.Franceschini, P.Panci, D.Redigolo, L.Vittorio

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD (Y=0)

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD (Y=0)

Also even n is possible, but requires mixing partners… (Y≠0)

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD (Y=0)

Also even n is possible, but requires mixing partners… (Y≠0)

Computability criterion: only n≤9(F),11(S) is possible (we need the mass of the DM << Landau poles)

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD (Y=0)

Also even n is possible, but requires mixing partners… ($Y \neq 0$)

Computability criterion: only $n \leq 9(F), 11(S)$ is possible (we need the mass of the DM << Landau poles)

→ *How can we probe/exclude it???*

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

⇒ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD ($Y=0$)

Also even n is possible, but requires mixing partners… ($Y\neq 0$)

Computability criterion: only $n\leq 9(F), 11(S)$ is possible (we need the mass of the DM << Landau poles)

⇒ *How can we probe/exclude it???*

1. high-energy collider
2. Direct Detection (DD)
3. Indirect Detection (ID)

A brief recap on Minimal Dark Matter (MDM)

Simplest (and minimal!!) set-up: Standard Model + EW n-plet of SU(2)

→ Dark Matter (DM) is the neutral component of the n-plet

In this talk: (real) odd n in order to avoid bounds from DD (Y=0)

Also even n is possible, but requires mixing partners… ($Y \neq 0$)

Computability criterion: only $n \leq 9(F), 11(S)$ is possible (we need the mass of the DM << Landau poles)

→ *How can we probe/exclude it???*

1. high-energy collider
2. Direct Detection (DD)
3. Indirect Detection (ID)

WIMPs @ high-energy lepton colliders

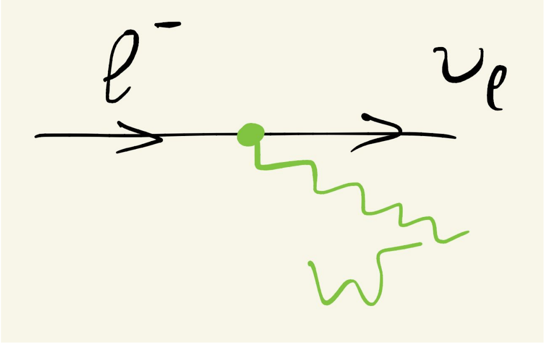
Why high energy lepton colliders?

- **EW nature of signal**
- **Full event reconstruction** (MIM, etcetc)

WIMPs @ high-energy lepton colliders

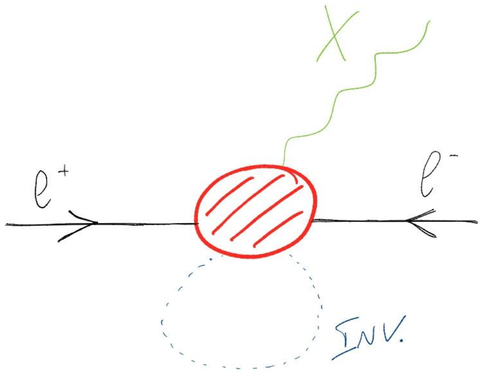
Why high energy lepton colliders?

- **EW nature of signal**
- **Full event reconstruction** (MIM, etcetc)



How to detect DM @ lepton colliders?

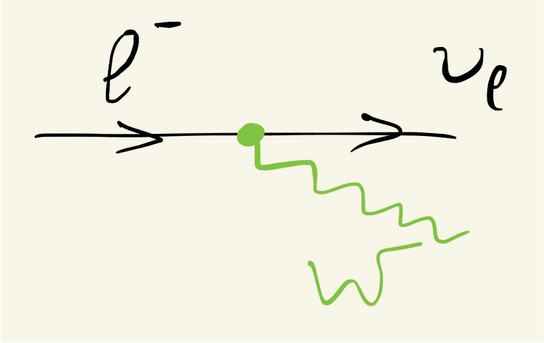
- **Tracks from the charged states** in the n-plet
- **Recoil** against an invisible object: mono-X/di-X signals



WIMPs @ high-energy lepton colliders

Why high energy lepton colliders?

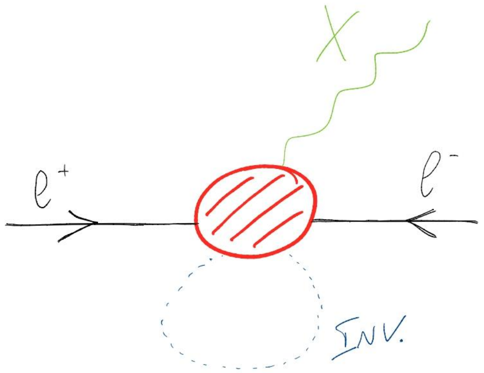
- **EW nature of signal**
- **Full event reconstruction** (MIM, etcetc)



How to detect DM @ lepton colliders?

- **Tracks from the charged states** in the n-plet
- **Recoil** against an invisible object: mono-X/di-X signals

$$\sqrt{s} = 3,\ 14,\ 30,\ 100\ \text{TeV}$$
$$\mathcal{L} = 1,\ 20,\ 90,\ 1000\ \text{ab}^{-1}$$



Mono-X channels

$$\ell^+\ell^- \to \chi^k\chi^{-k-p} + V + X^{(p)}$$

Mono-X channels

$$\ell^+\ell^- \rightarrow \boxed{\chi^k \chi^{-k-p}} + V + X^{(p)}$$

DM couple

Mono-X channels

$$\ell^+\ell^- \rightarrow \boxed{\chi^k\chi^{-k-p}} + \textcircled{V} + X^{(p)}$$

DM couple

EW gauge boson

Mono-X channels

any additional undetected particles

$$\ell^+\ell^- \rightarrow \boxed{\chi^k \chi^{-k-p}} + V + \boxed{X^{(p)}}$$

DM couple

EW gauge boson

Mono-X channels

any additional undetected particles

$$\ell^+\ell^- \rightarrow \boxed{\chi^k \chi^{-k-p}} + \textcircled{V} + \boxed{X^{(p)}}$$

DM couple

EW gauge boson

In our study we have considered three different mono-X cases:

- **Mono-photon**
- **Mono-Z**
- **Mono-W**

→ **sizable rates** due to large weak charge of DM and beams!

One detailed example: the mono-photon

One detailed example: the mono-photon

Signal events: $$\mu^-\mu^+ \to \gamma\chi^n\chi^{-n}$$

One detailed example: the mono-photon

Signal events: $\mu^- \mu^+ \to \gamma \chi^n \chi^{-n}$

Background (SM) events: $\mu^- \mu^+ \to \gamma \nu \bar{\nu}$

One detailed example: the mono-photon

Signal events: $\mu^-\mu^+ \to \gamma\chi^n\chi^{-n}$

Background (SM) events: $\mu^-\mu^+ \to \gamma\nu\bar{\nu}$

Reach computation? $$\frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}}$$

One detailed example: the mono-photon

Signal events: $\mu^-\mu^+ \to \gamma\chi^n\chi^{-n}$

Background (SM) events: $\mu^-\mu^+ \to \gamma\nu\bar{\nu}$

Reach computation? $$\frac{S}{\sqrt{S+B+(\epsilon_S S)^2+(\epsilon_B B)^2}}$$

Strategy to maximise the reach: set of cuts on kinematical variables!

$$\mathrm{MIM} > 2m_\chi\ , \quad |\eta_\gamma| < \eta_{\gamma\mathrm{cut}}\ , \quad \mathrm{MET} > \mathrm{MET}_{\mathrm{cut}}$$

One detailed example: the mono-photon

Signal events: $\mu^-\mu^+ \to \gamma\chi^n\chi^{-n}$

Background (SM) events: $\mu^-\mu^+ \to \gamma\nu\bar{\nu}$

Reach computation? $$\frac{S}{\sqrt{S+B+(\epsilon_S S)^2+(\epsilon_B B)^2}}$$

Strategy to maximise the reach: set of cuts on kinematical variables!

$$\boxed{\mathrm{MIM} > 2m_\chi}, \quad |\eta_\gamma| < \eta_{\gamma\mathrm{cut}}\ , \quad \mathrm{MET} > \mathrm{MET}_{\mathrm{cut}}$$

exploit the events kinematics

One detailed example: the mono-photon

Signal events: $$\mu^- \mu^+ \to \gamma \chi^n \chi^{-n}$$

Background (SM) events: $$\mu^- \mu^+ \to \gamma \nu \bar{\nu}$$

Reach computation? $$\frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}}$$

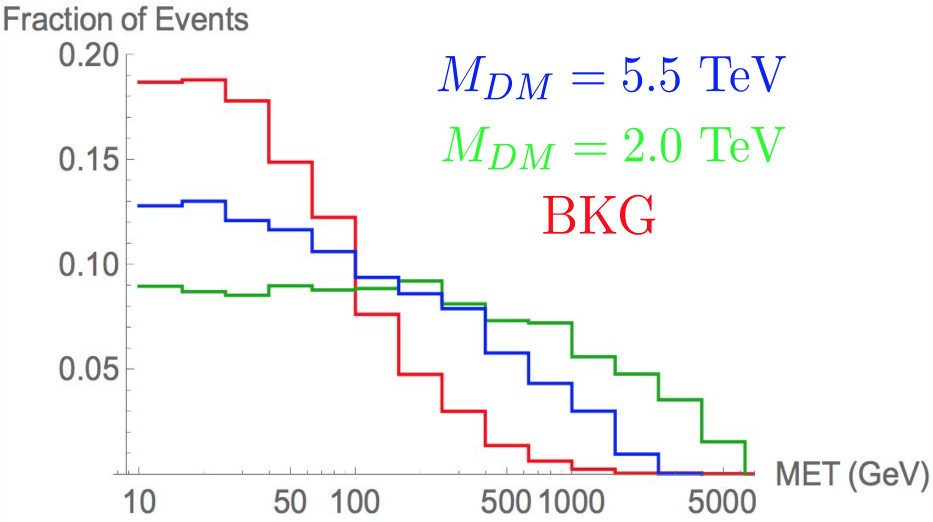
Strategy to maximise the reach: set of cuts on kinematical variables!

$$\boxed{\mathrm{MIM} > 2m_\chi}, \quad |\eta_\gamma| < \eta_{\gamma\mathrm{cut}}\ , \quad \mathrm{MET} > \mathrm{MET}_{\mathrm{cut}}$$

exploit the events kinematics

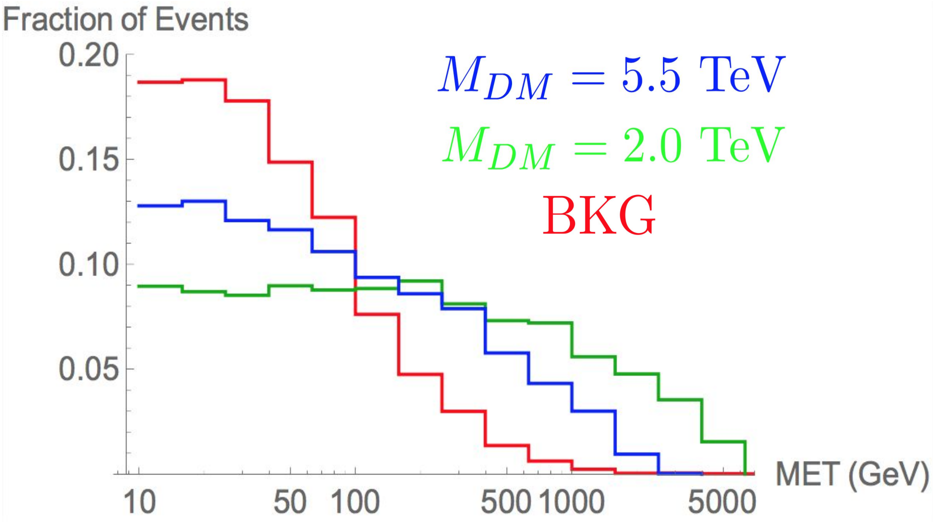
→ improvement of the signal-to-noise ratio S/B!

One detailed example: the mono-photon (7F)

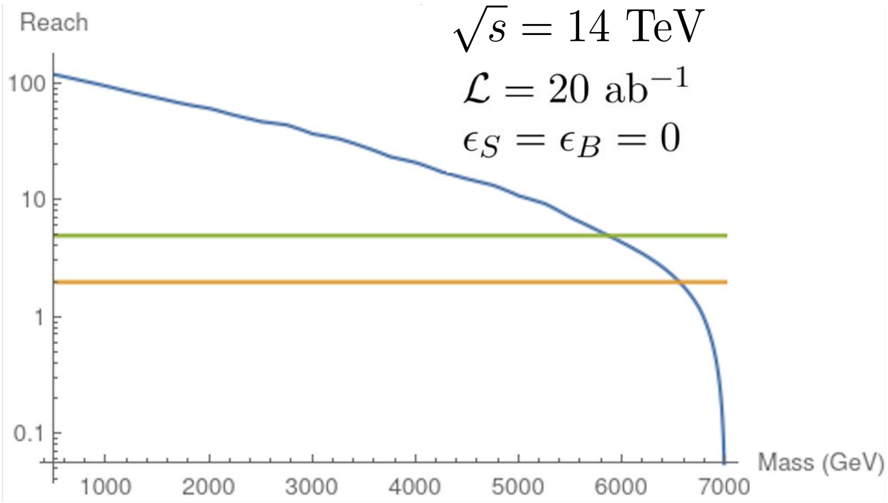


$\sqrt{s} = 14$ TeV

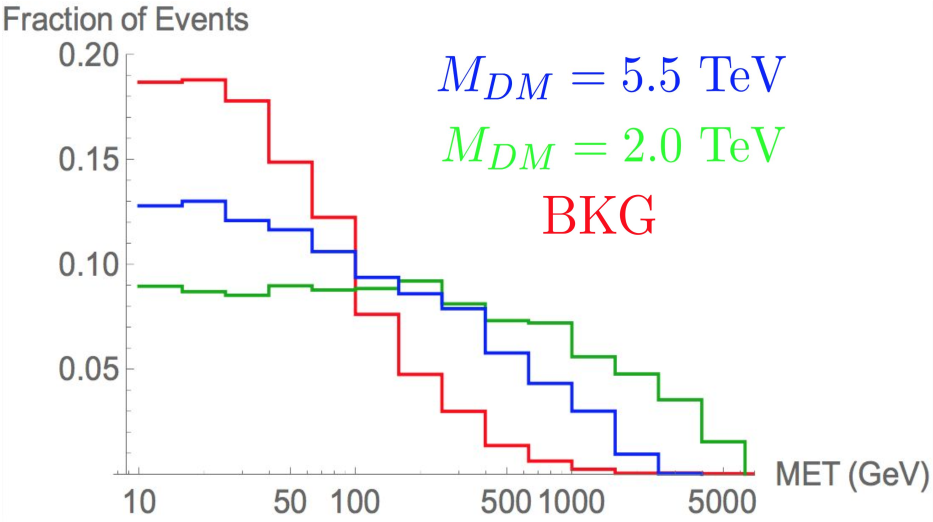
One detailed example: the mono-photon (7F)



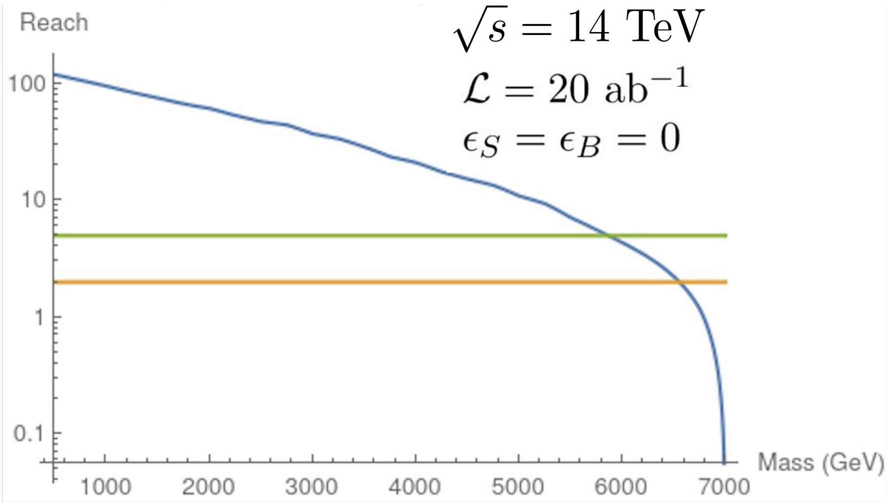
$\sqrt{s} = 14$ TeV



One detailed example: the mono-photon (7F)



$\sqrt{s} = 14$ TeV



To be repeated for all c.o.m. energies and **0.1% or 1%** of systematics

An extension: Di-X channels

The signal-to-noise ratio S/B results to be low for all the mono-X processes!!

An extension: Di-X channels

The signal-to-noise ratio S/B results to be low for all the mono-X processes!!

→

Bounds can be put only if systematic uncertainties are well under control

An extension: Di-X channels

The signal-to-noise ratio S/B results to be low for all the mono-X processes!!

Bounds can be put only if systematic uncertainties are well under control

Other possibility: **di-X channels ($X=\gamma,W$)**

An extension: Di-X channels

The signal-to-noise ratio S/B results to be low for all the mono-X processes!!

→ Bounds can be put only if systematic uncertainties are well under control

Other possibility: **di-X channels (X=γ,W)**

→ Two huge advantages:

1. higher S/B ratio
2. enhancement of the signals wrt bkg due to high charges in the multiplet (more evident for higher representations)

An extension: Di-X channels

The signal-to-noise ratio S/B results to be low for all the mono-X processes!!

→ Bounds can be put only if systematic uncertainties are well under control

Other possibility: **di-X channels (X=γ,W)**

→ Two huge advantages:

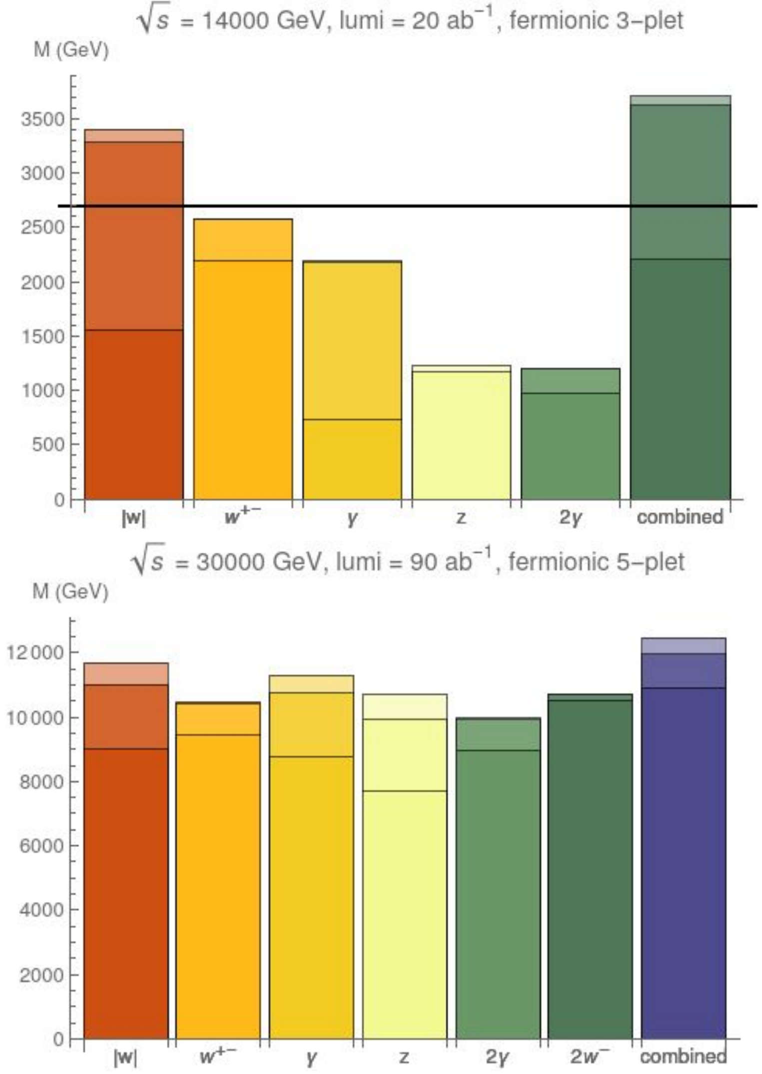
1. higher S/B ratio
2. enhancement of the signals wrt bkg due to high charges in the multiplet (more evident for higher representations)

Similar strategy for the analysis, for the same-sign di-W case the bkg comes from mistagging of charges

Thermal masses VS collider reaches

DM spin	Representation	M_{DM} [TeV]
Real scalar	3	2.53 ± 0.01
	5	15.4 ± 0.1
	7	54.2 ± 0.6
	9	120 ± 1
Majorana fermion	3	2.86 ± 0.01
	5	13.6 ± 0.3
	7	48.3 ± 0.5
	9	112 ± 1

See M. Costa talk, session B19

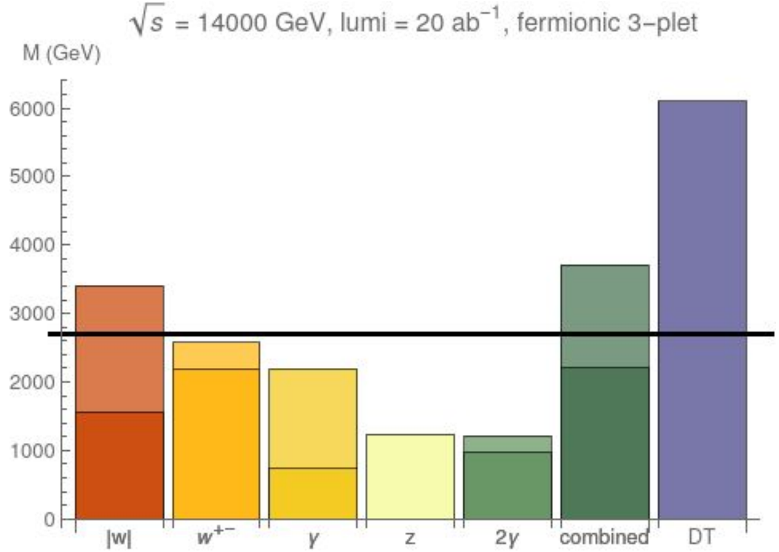


L. Vittorio (SNS & INFN, Pisa)

Thermal masses VS collider reaches

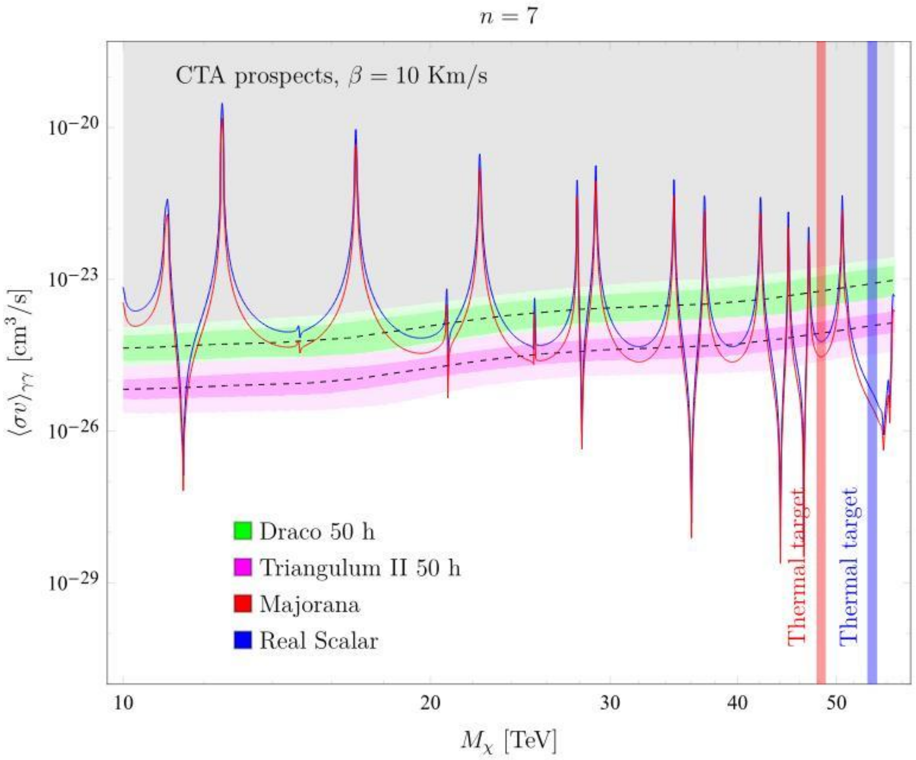
DM spin	Representation	M_{DM} [TeV]
Real scalar	3	2.53 ± 0.01
	5	15.4 ± 0.1
	7	54.2 ± 0.6
	9	120 ± 1
Majorana fermion	3	2.86 ± 0.01
	5	13.6 ± 0.3
	7	48.3 ± 0.5
	9	112 ± 1

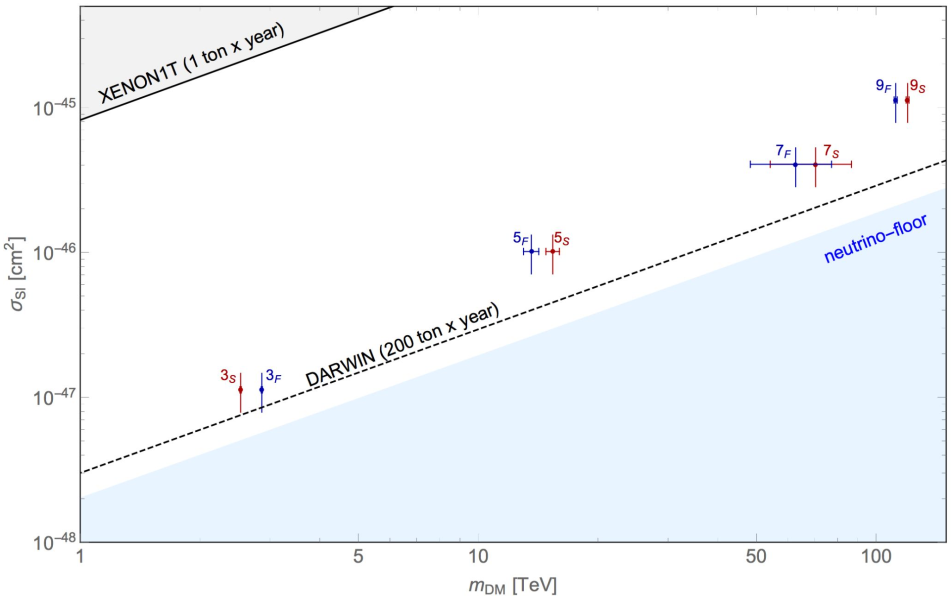
See M. Costa talk, session B19



2102.11292

Opportunities from Indirect/Direct Detection





Conclusions

- High-energy muon collider as a fundamental laboratory to put a final word on MDM candidates

Conclusions

- High-energy muon collider as a fundamental laboratory to put a final word on MDM candidates
- Analysis developed for various mono-X/di-X channels (different behaviour in function of systematics!!!)

Conclusions

- High-energy muon collider as a fundamental laboratory to put a final word on MDM candidates
- Analysis developed for various mono-X/di-X channels (different behaviour in function of systematics!!!)
- Results?
  - 3-plet @ 10/14 TeV with DT
  - 5-plet "almost" @ 30 TeV, low systematics (still missing DT)
  - 7-plet requires more than 100 TeV...

Conclusions

- High-energy muon collider as a fundamental laboratory to put a final word on MDM candidates
- Analysis developed for various mono-X/di-X channels (different behaviour in function of systematics!!!)
- Results?
  - 3-plet @ 10/14 TeV with DT
  - 5-plet "almost" @ 30 TeV, low systematics (still missing DT)
  - 7-plet requires more than 100 TeV...

- **Disappearing tracks** to be studied in detail for $n \geqslant 5$

Conclusions

- High-energy muon collider as a fundamental laboratory to put a final word on MDM candidates
- Analysis developed for various mono-X/di-X channels (different behaviour in function of systematics!!!)
- Results?
  - 3-plet @ 10/14 TeV with DT
  - 5-plet "almost" @ 30 TeV, low systematics (still missing DT)
  - 7-plet requires more than 100 TeV...

- **Disappearing tracks** to be studied in detail for n⩾5
- **ID/DD** are a good and independent opportunity to discover the heaviest n-plets

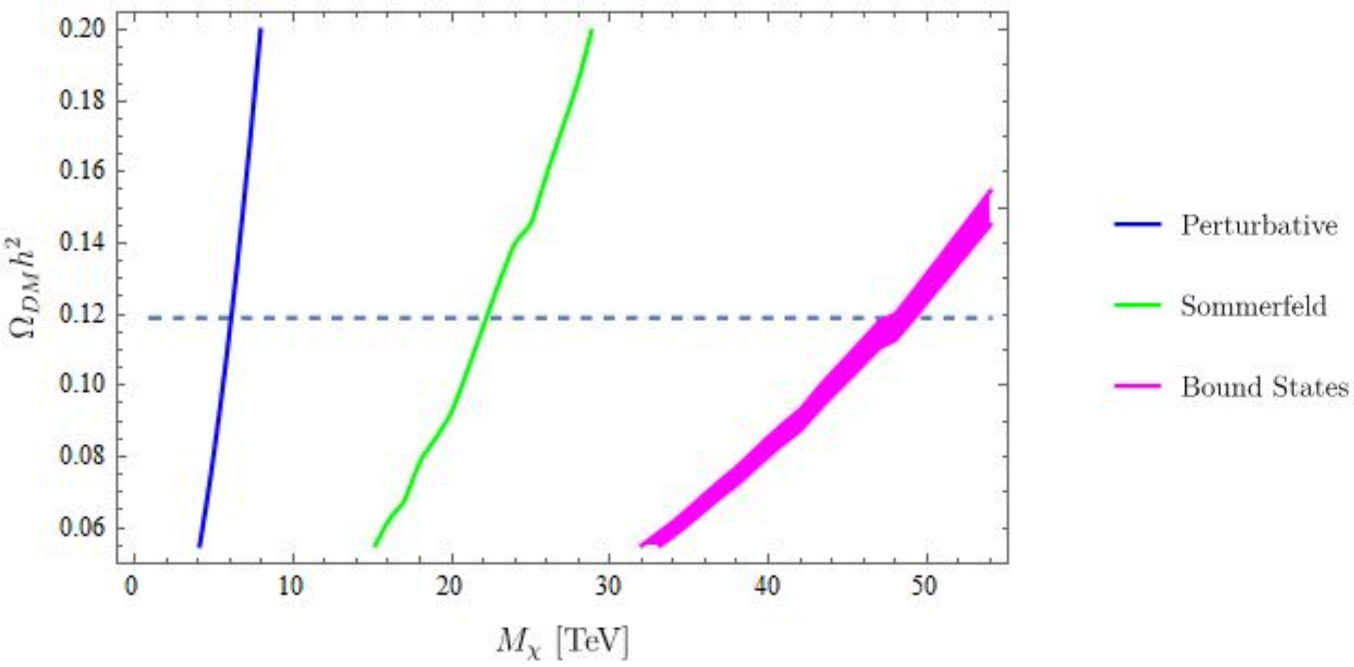
THANKS FOR THE ATTENTION!!!!

BACK-UP SLIDES

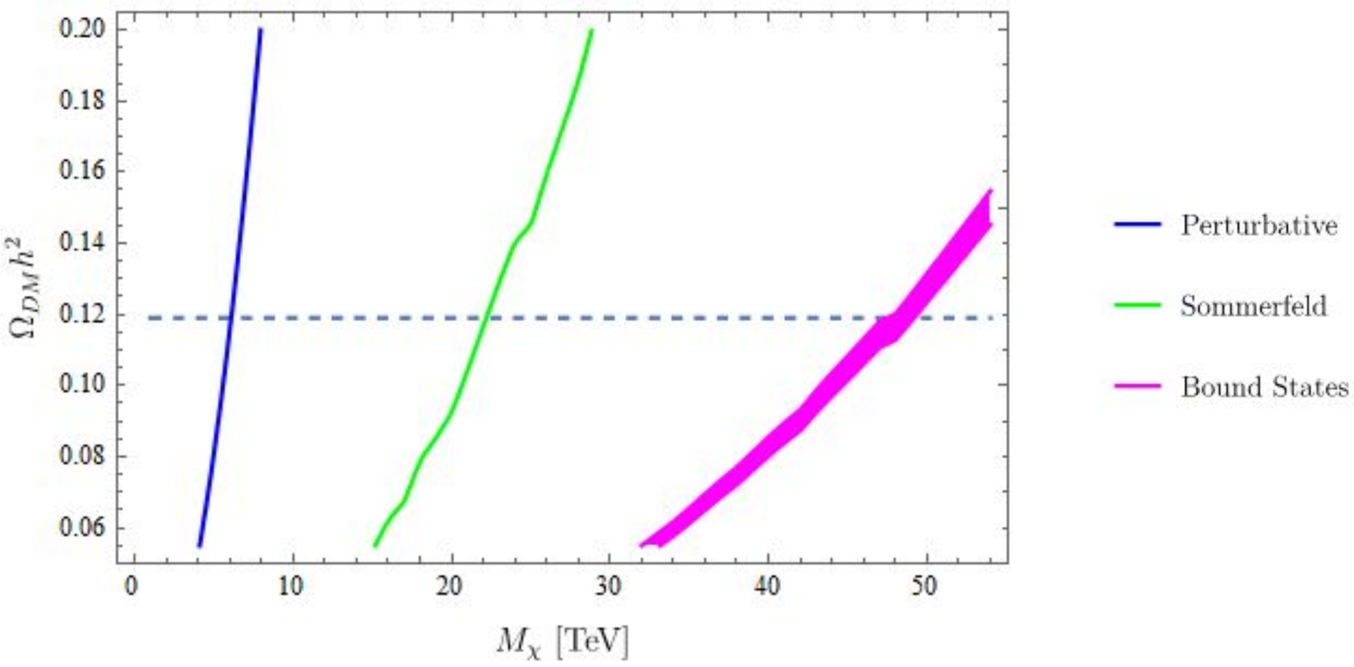
Landau Poles & Computability criterion for MDM scenarios

DM spin	Representation	Λ_{Landau}/M_{DM}
Real scalar	3	3×10^{37}
	5	5×10^{36}
	7	2×10^{19}
	9	3×10^{3}
	11	20
Majorana fermion	3	3×10^{37}
	5	3×10^{17}
	7	1×10^{4}
	9	30

Fermionic (Majorana) 7-plet - computation of the thermal mass



Fermionic (Majorana) 7-plet - computation of the thermal mass



Scalars: higher n, larger mass (because of larger xsec)

Other channels: Signals and Backgrounds

Mono-Z:

$$\mu^-\mu^+ \rightarrow Z\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \rightarrow Z\nu_l\bar{\nu}_l$$ bkg

Other channels: Signals and Backgrounds

Mono-Z:

$$\mu^-\mu^+ \to Z\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \to Z\nu_l\bar{\nu}_l$$ bkg

Mono-W:

$$\mu^-\mu^+ \to W^-\chi^k\chi^{-k+1}$$ signal

$$\mu^-\gamma \to W^-\nu_\mu$$ bkg 1

$$\mu^-\mu^+ \to W^-l^+\nu_l$$ bkg 2

Other channels: Signals and Backgrounds

Mono-Z:

$$\mu^-\mu^+ \to Z\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \to Z\nu_l\bar{\nu}_l$$ bkg

Mono-W:

$$\mu^-\mu^+ \to W^-\chi^k\chi^{-k+1}$$ signal

matching between the two bkgs:

$$\mu^-\gamma \to W^-\nu_\mu$$ bkg 1

$$\mu^-\mu^+ \to W^-l^+\nu_l$$ bkg 2

$$\eta_{\text{match}} = 5.4,\ 7,\ 7.5,\ 8.8 \quad \text{at} \quad \sqrt{s} = 3,\ 14,\ 30,\ 100\ \text{TeV}$$

Other channels: Signals and Backgrounds

Di-photon:

$$\mu^-\mu^+ \to \gamma\gamma\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \to \gamma\gamma\nu_l\bar{\nu}_l$$ bkg

Other channels: Signals and Backgrounds

Di-photon:

$$\mu^-\mu^+ \to \gamma\gamma\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \to \gamma\gamma\nu_l\bar{\nu}_l$$ bkg

Same-sign di-W:

$$\mu^-\mu^+ \to W^-W^-\chi^k\chi^{-k+2}$$ signal

$$\mu^-\mu^+ \to W^+W^-\nu_l\bar{\nu}_l$$ bkg

Other channels: Signals and Backgrounds

Di-photon:

$$\mu^-\mu^+ \to \gamma\gamma\chi^k\chi^{-k}$$ signal

$$\mu^-\mu^+ \to \gamma\gamma\nu_l\bar{\nu}_l$$ bkg

Same-sign di-W:

$$\mu^-\mu^+ \to W^-W^-\chi^k\chi^{-k+2}$$ signal

$$\boxed{\mu^-\mu^+ \to W^+W^-\nu_l\bar{\nu}_l}$$ bkg

mistagging of charges necessary to have a NON-ZERO BKG!!!