Simplified models of dark matter with a long-lived co-annihilation partner

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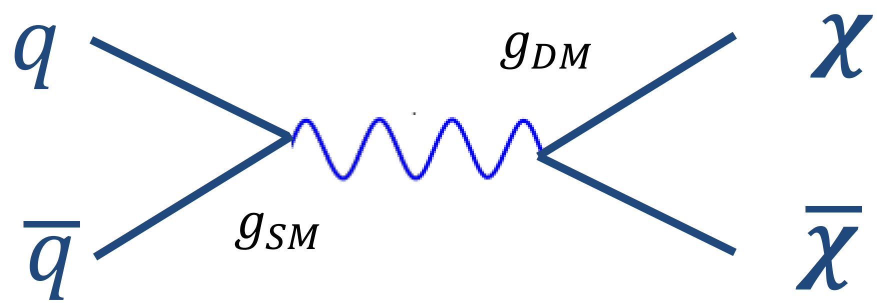
with Valentin Khoze and Kazuki Sakurai

[arxiv:1702.00750]

Simplified models of dark matter

- **EFT is a powerful and model independent approach**
- **Consistent description if and only if energy of interaction** $\boldsymbol{E \ll M_{NP}}$
- **In the context of DM, there is no reason not to expect that** $\boldsymbol{M_{MED} \approx m_{DM}}$
- **EFT might not the best framework for Dark Matter searches at colliders**

Going beyond EFTs:



4 free parameters g_{SM} g_{DM} m_{DM} M_{MED}

Dark Matter

- Dirac or Majorana fermion
- Complex or real scalar
- Vector?

Mediators

- Vector
- Axial-vector
- Scalar
- Pseudoscalar

3-point interaction

Dark Matter candidate

Standard Model τ lepton

$$\mathcal{L} \supset g_{\mathrm{DM}}\, \chi\, \eta\, \tau + \mathrm{h.c.}$$

Co-annihilation partner (CAP)

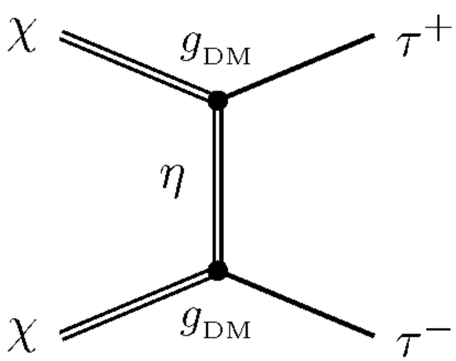
Simplified models with only 3 free parameters:

g_{DM} m_{DM} M_{CAP}

$\mathbb{Z}_2$: $\chi \rightarrow -\chi$ $\eta \rightarrow -\eta$

Co-annihilation

Dark matter annihilation into pair of tau's

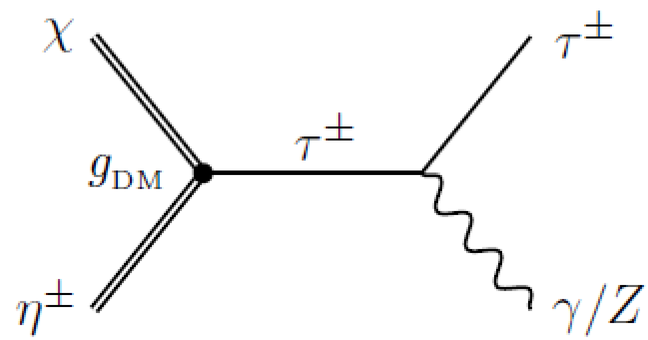


$$(\sigma v)^{\text{s-wave}}_{\text{ann}} = \frac{g_R^4\, m_\tau^2}{32\pi\, m_\chi^4} \frac{1}{(1+r^2)^2}$$

$\propto\ m_\tau$
Chiral suppression

- Overproduces dark matter (Unless large couplings)
- We need a mechanism to reduce the DM relic density

Co-annihilation:



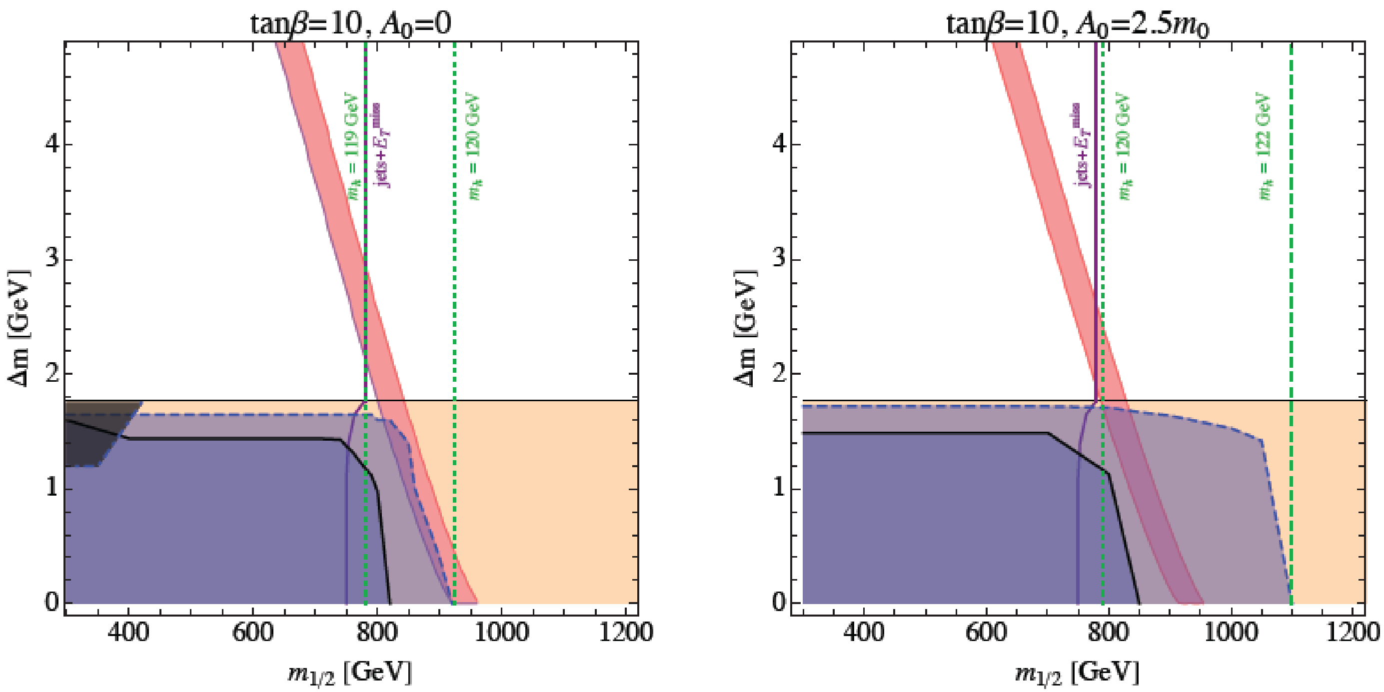
Freeze-out temperature $T_F \sim m_{DM}/25$

Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$ → $\Delta M \lesssim m_{DM}/25$

We need **mass splitting of 4% of m_{DM}**

Stau co-annihilation strip

Inspired by the stau co-annihilation strip in the CMSSM:
(stau and neutralino close in mass)

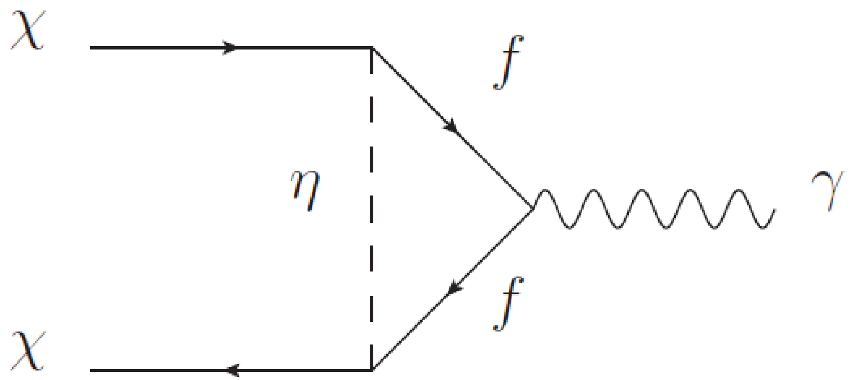


We want to generalize this.

[Citron, Ellis, Luo, Marrouche, Olive, Vries 2012]
[Desai, Ellis, Luo, Marrouche 2014]

LHC production is relevant

- Direct Detection: No tree-level interaction with quarks



One-loop suppressed
(Anapole moment)

[Kopp, Michaels, Smirnov 2014]

- Indirect Detection: Due to chiral suppression, DM annihilation is velocity-suppressed

In today's Universe, DM non-relativistic v/c << 1

In the limit $m_{DM} \gg m_\tau$:

$\sigma v \propto v^2$	$\sigma v \propto v^4$
p-wave suppressed for Majorana DM	d-wave suppressed for scalar DM

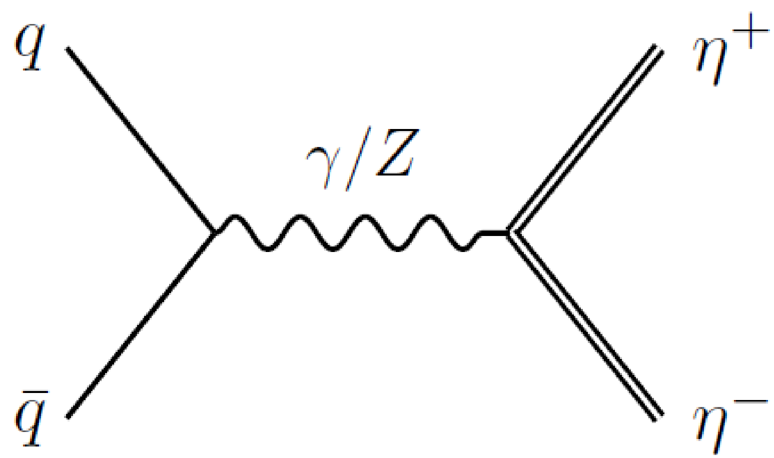
Nevertheless, the channel $S\,S \rightarrow l\,l\,\gamma$ can be relevant for future experiments for scalar DM

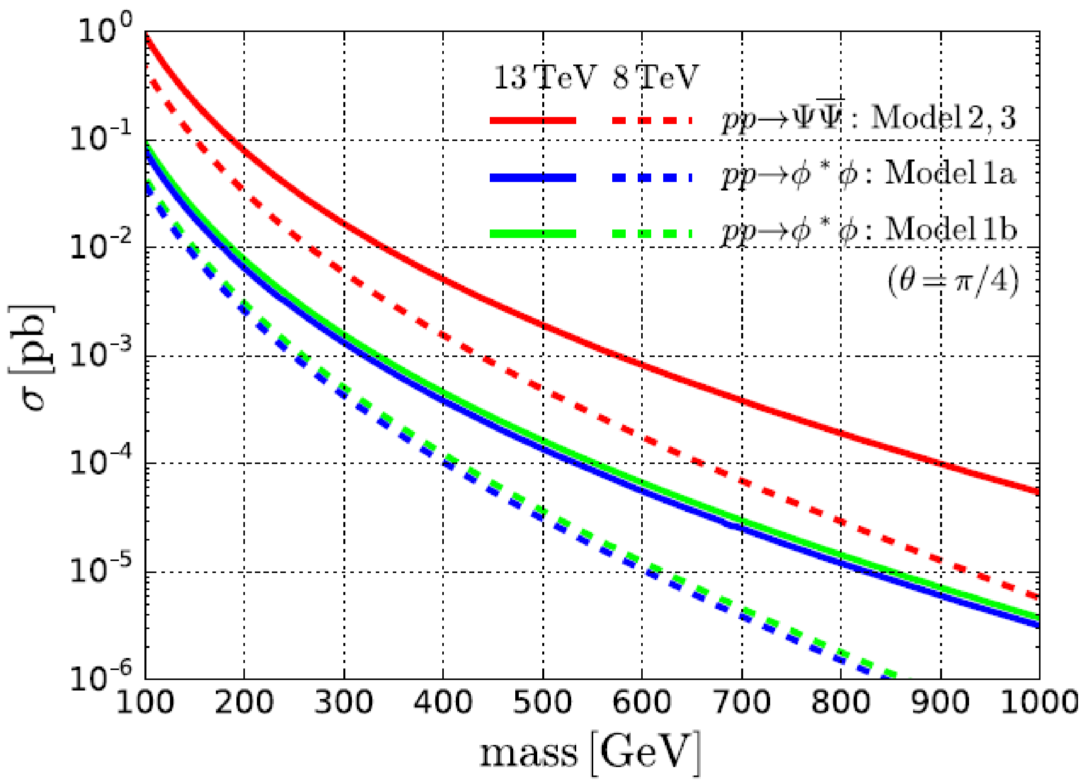
For large ΔM

[Giacchino, Lopez-Honorez, Tytgat 2013]

LHC production

- Drell-Yann pair production of co-annihilation partner

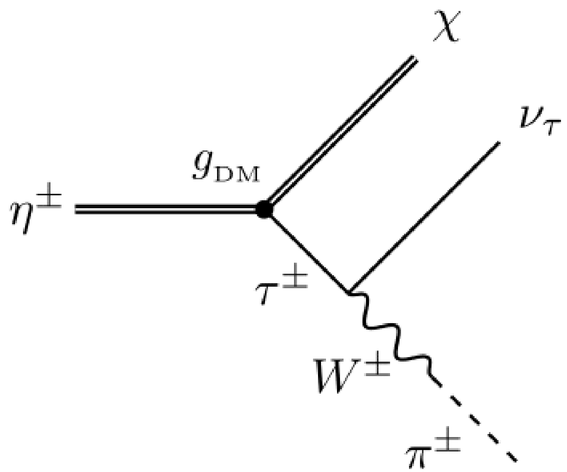




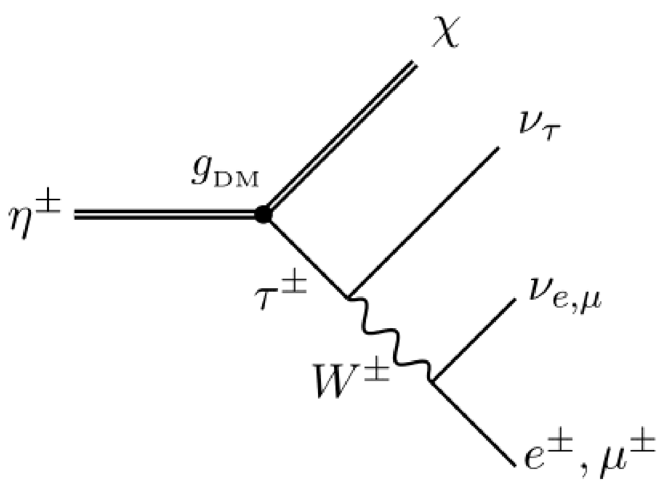
- We study Dirac fermion and complex scalar as co-annihilation partners

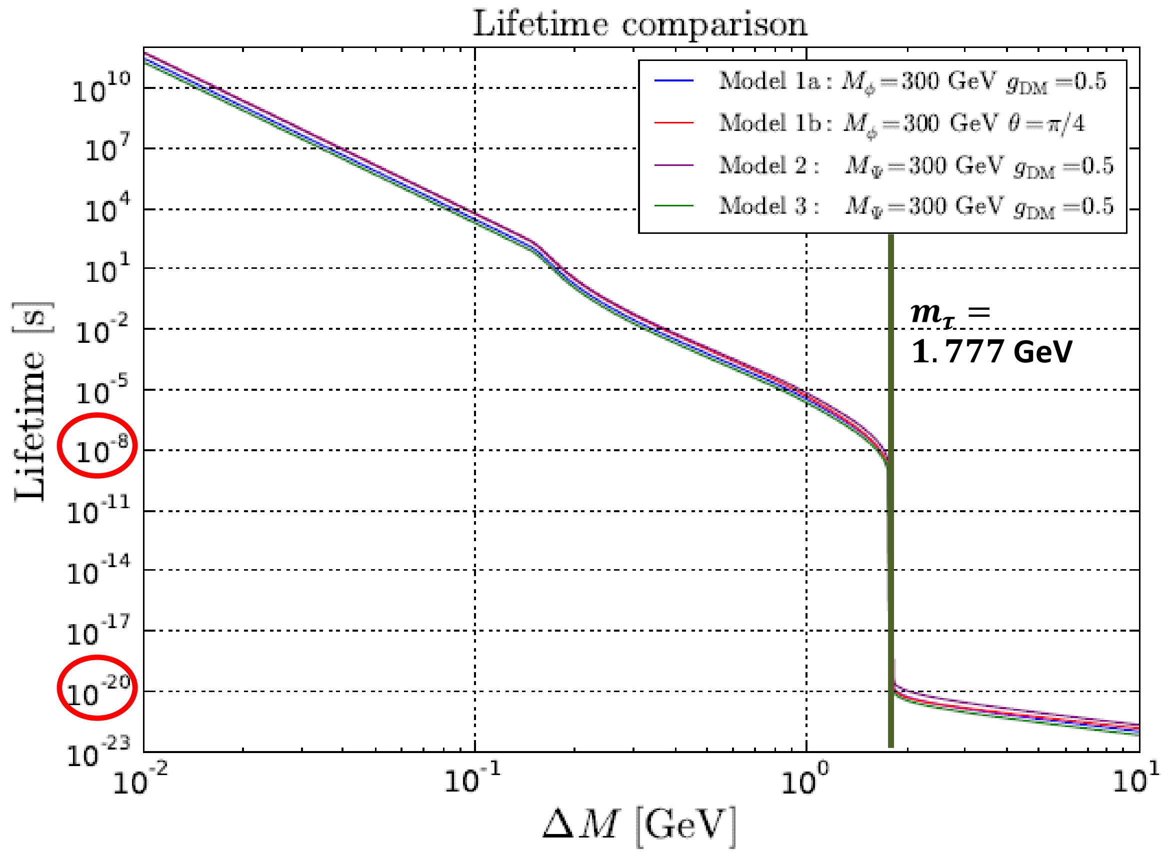
Long-lived electrically charged particles

If $\Delta M < m_\tau$ only 3-body and 4-body decays open:



Also ρ and a_1 mesons





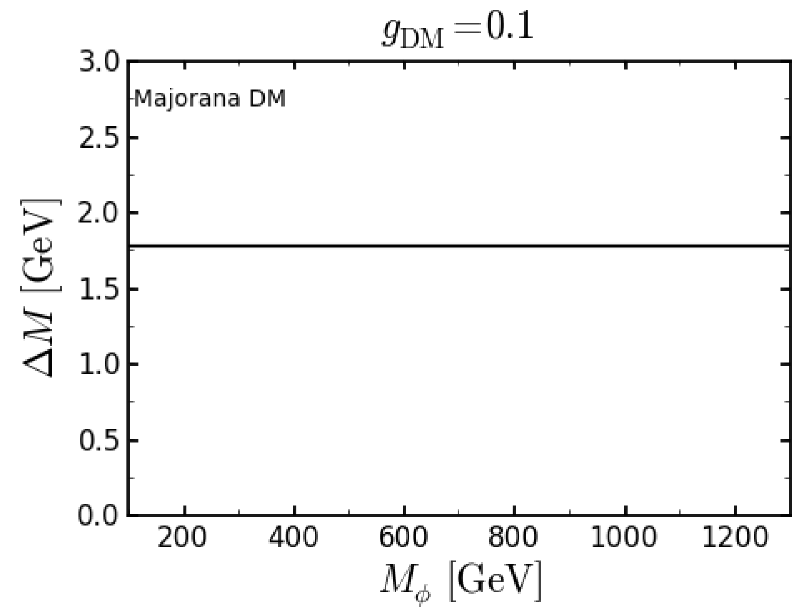
Majorana Dark Matter

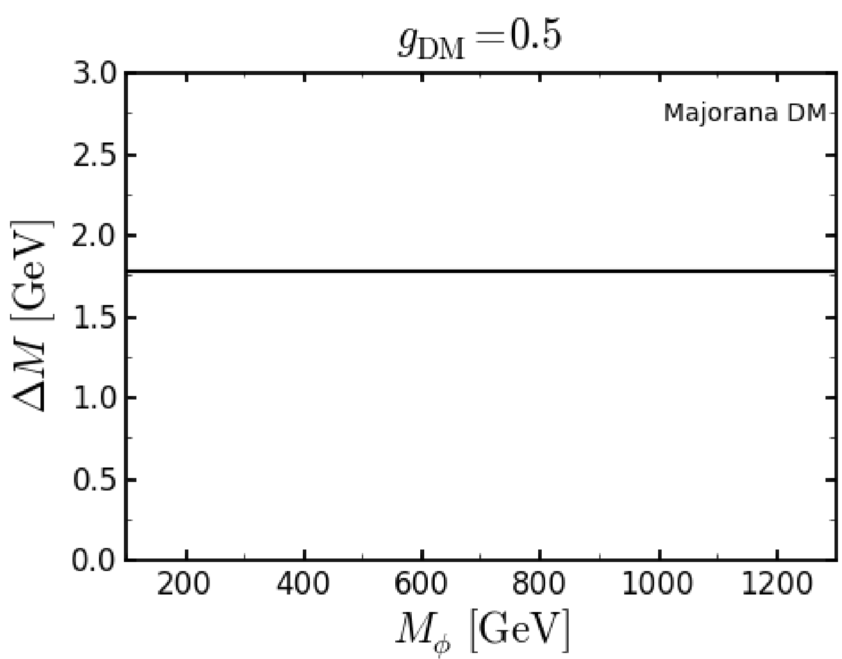
DM χ

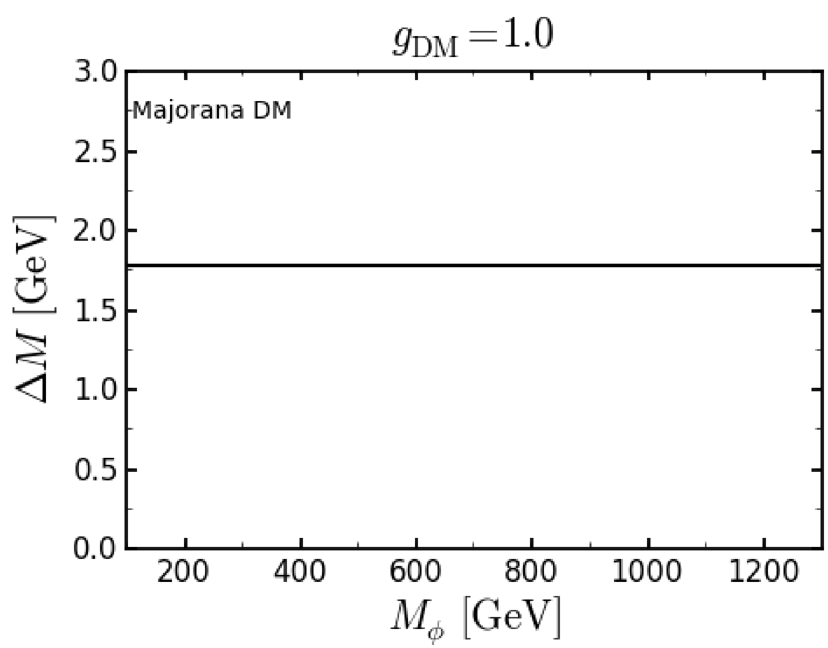
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

$$\phi^* \, (\chi \, \tau_R) \;\subset\; \mathcal{L}$$

Gauge-invariant and renormalizable, no problems of unitarity





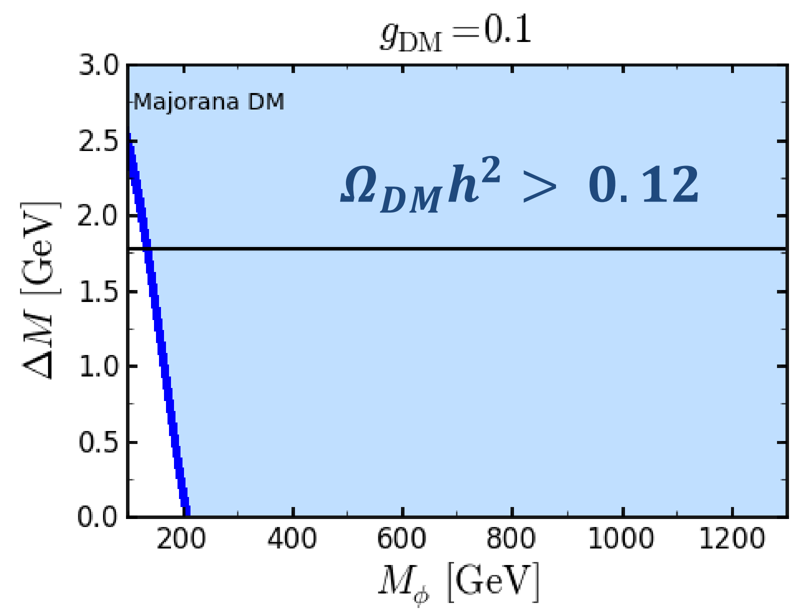


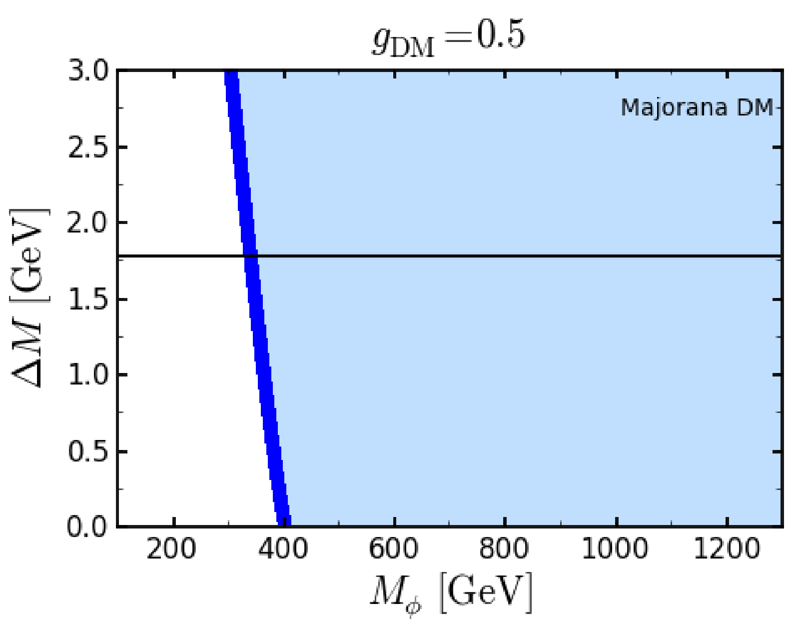
Majorana Dark Matter

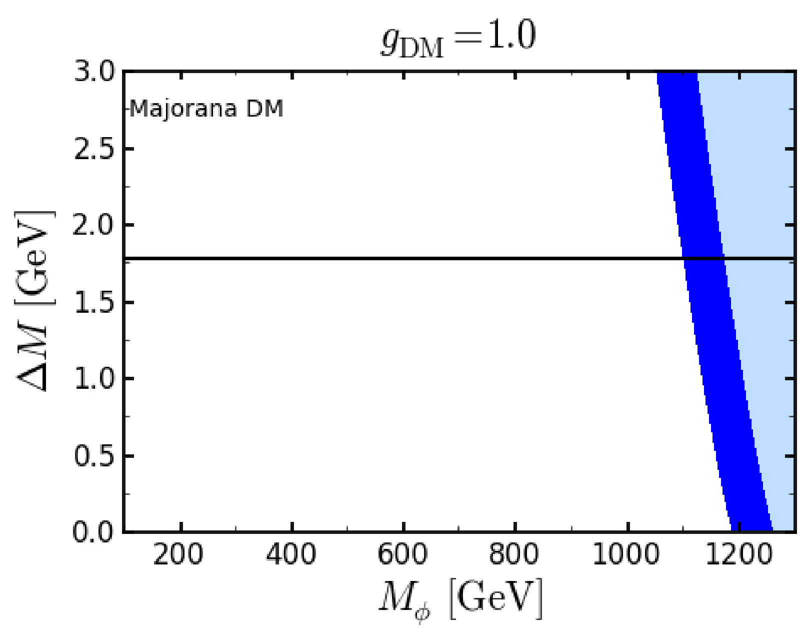
DM	**CAP (Y=-1)**
χ	ϕ

$$\phi^* \, (\chi \, \tau_R) \;\subset\; \mathcal{L}$$

Gauge-invariant and renormalizable, no problems of unitarity





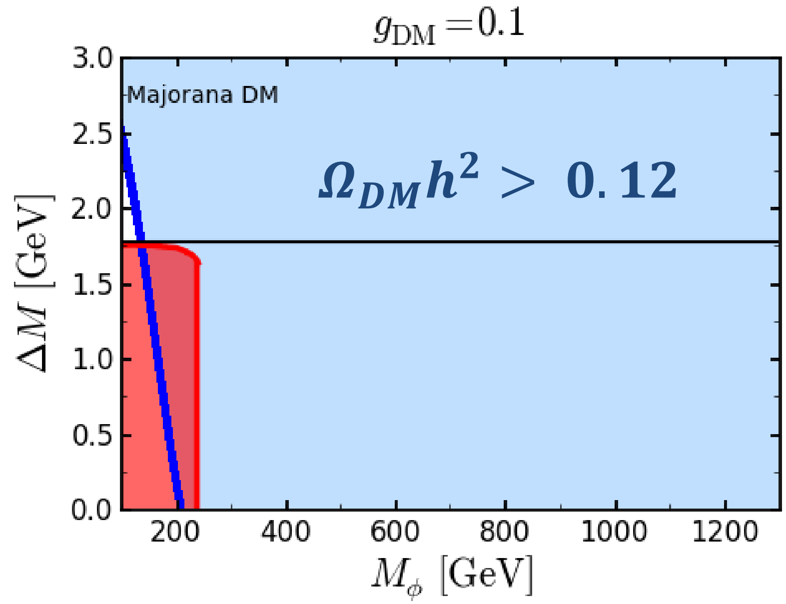


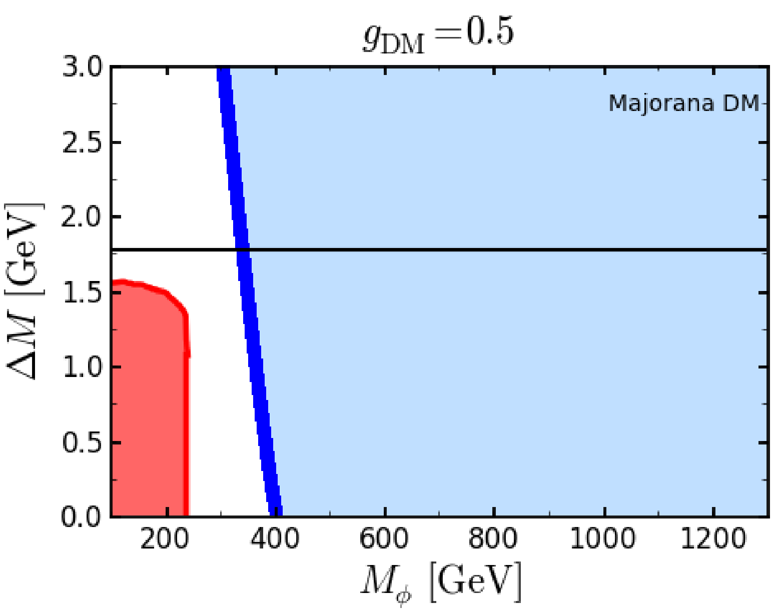
Majorana Dark Matter

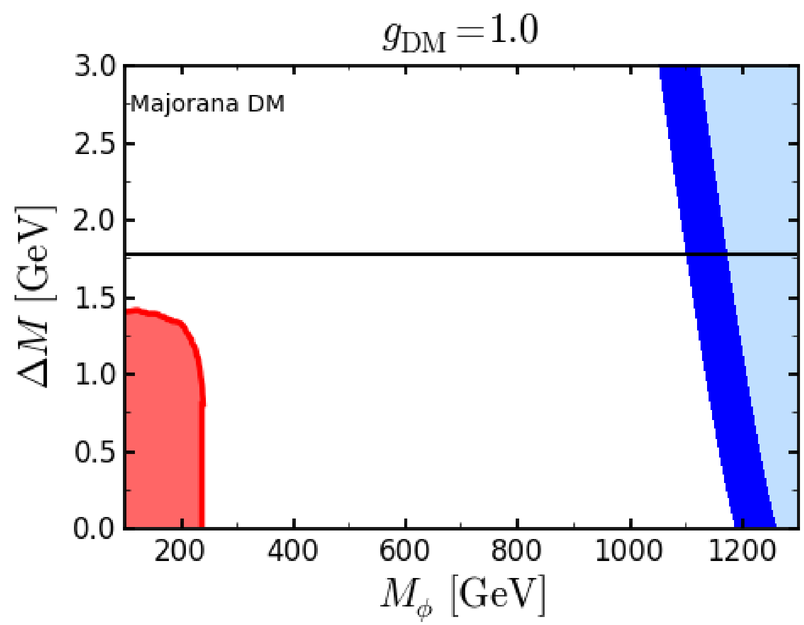
DM	CAP $(Y = 1 \;\; L_\tau = 1)$
χ	ϕ

$$\phi^* \, (\chi \, \tau_R) \;\; \subset \;\; \mathcal{L}$$

CMS and ATLAS
8 TeV 18.8 fb^{-1}







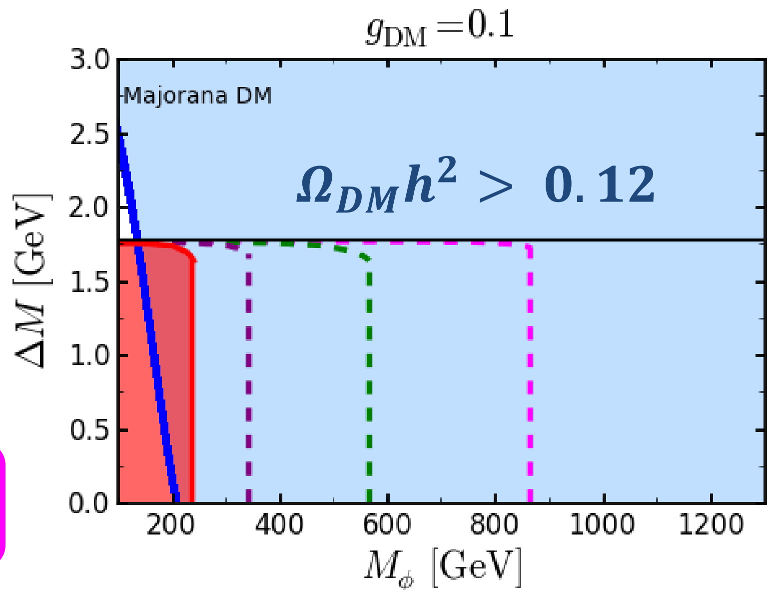
Majorana Dark Matter

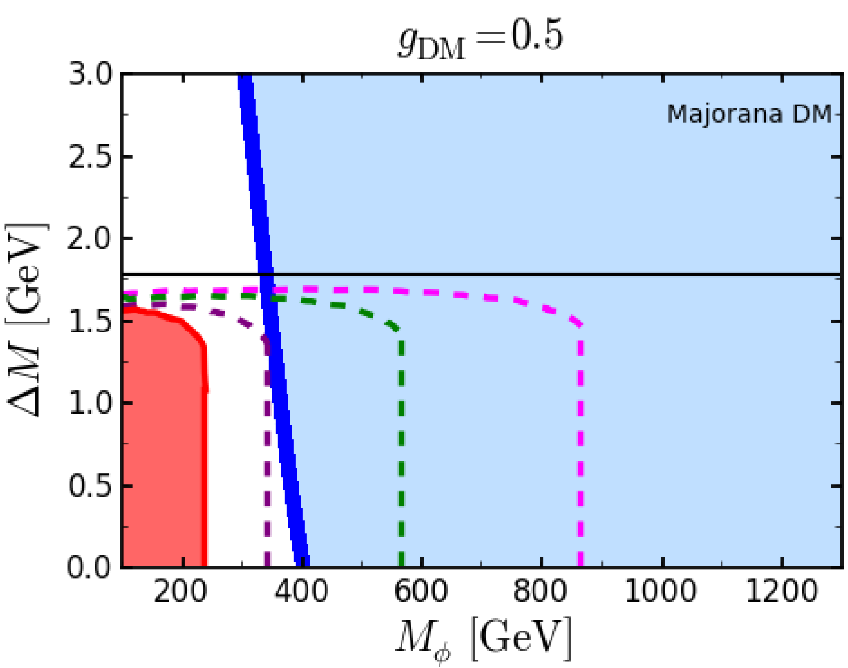
DM χ **CAP** $(Y = 1\ \ L_\tau = 1)$ ϕ

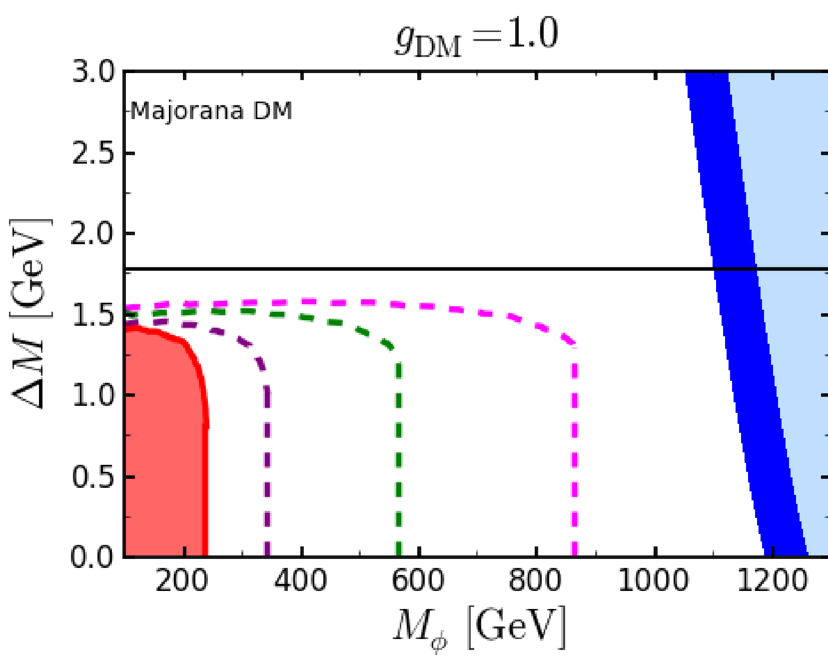
$$\phi^* (\chi\, \tau_R) \subset \mathcal{L}$$

13 TeV

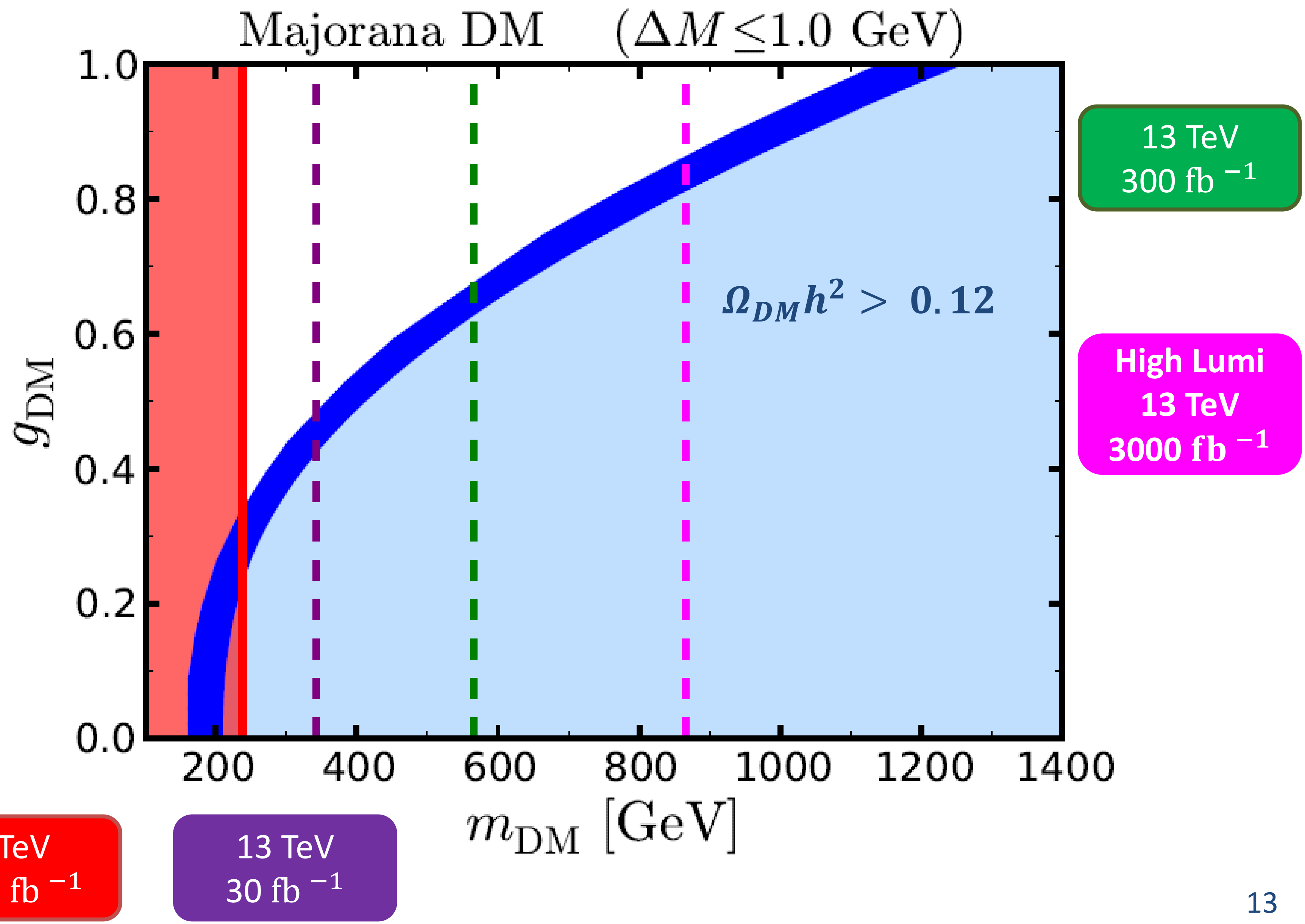
30 fb $^{-1}$ **300 fb $^{-1}$** **3000 fb $^{-1}$**







Majorana Dark Matter



Real scalar dark matter

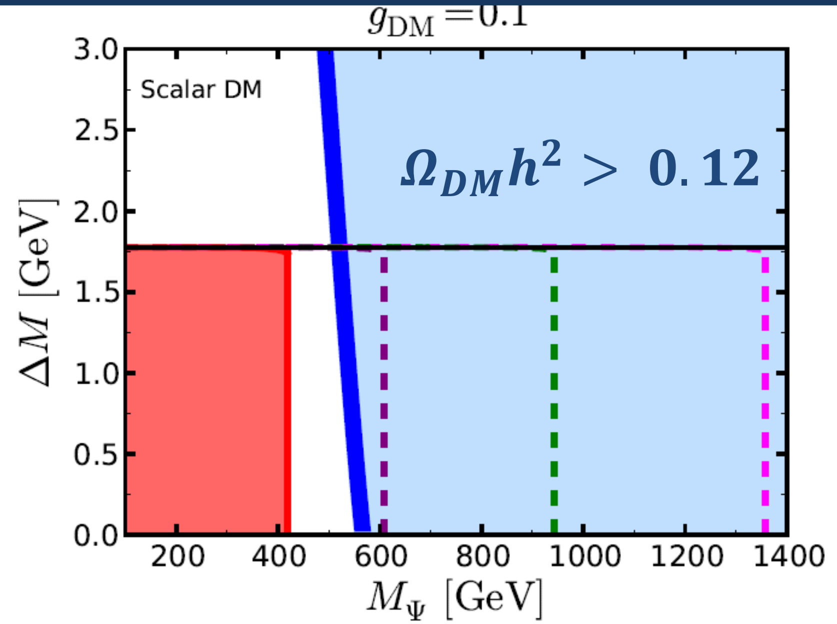
DM S

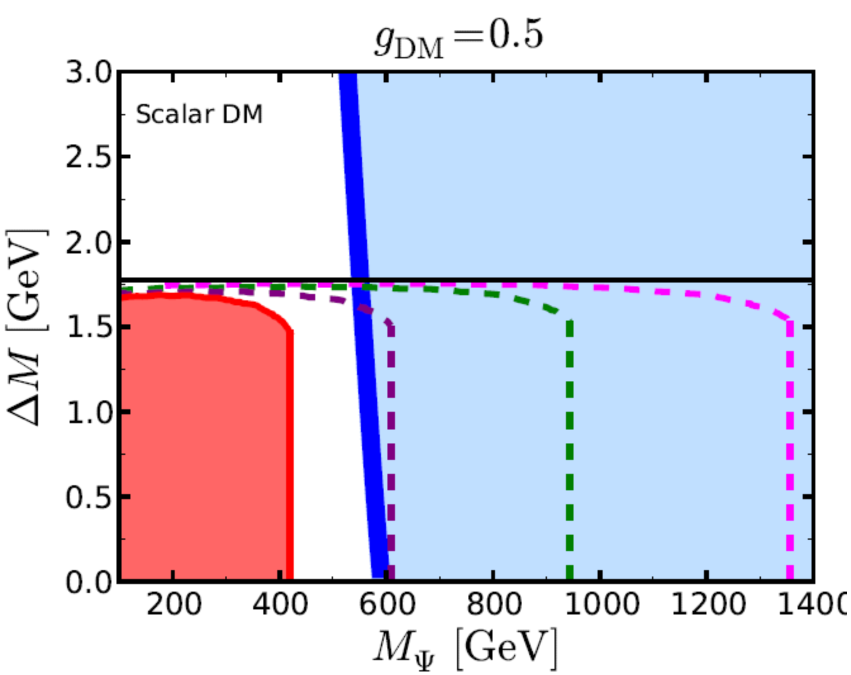
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

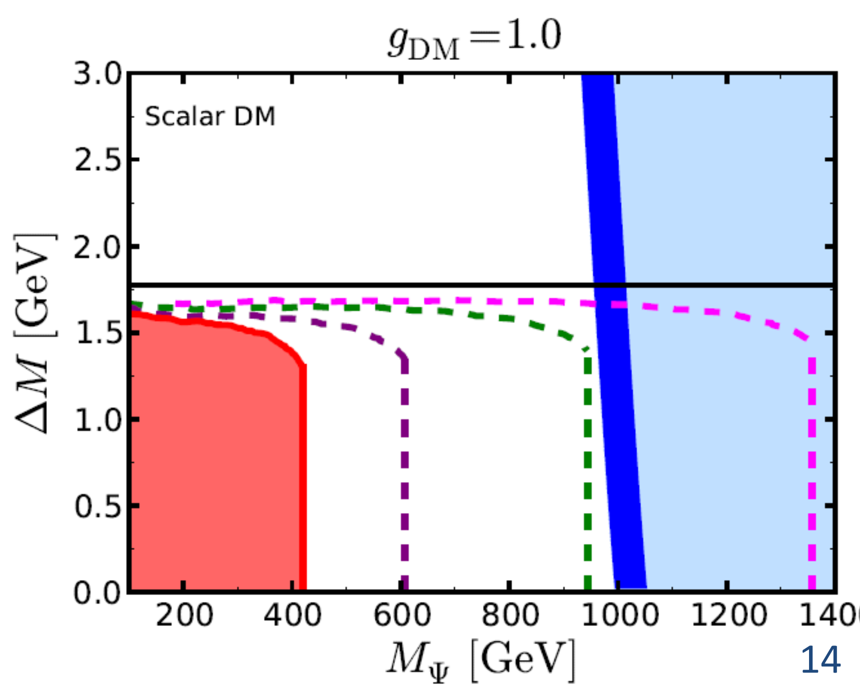
$$S(\overline{\Psi}\,\tau_R) \subset \mathcal{L}$$

13 TeV

30 fb $^{-1}$ **300 fb $^{-1}$** **3000 fb $^{-1}$**







Vector dark matter (Model 3)

NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions

DM	CAP $(Y = 1\ \ L_\tau = 1)$
A_μ	Ψ

Kaluza-Klein photon γ^1

$$A_\mu\,(\bar{\Psi}\,\gamma^\mu\,\tau_R)\ \subset\ \mathcal{L}$$

Kaluza-Klein τ^1

- The lightest KK excitation is usually the 1st excitation of the photon
- DM spin=1 , so there is no chiral suppression

$$m_n^2 = m_0^2 + \frac{n^2}{R^2}$$

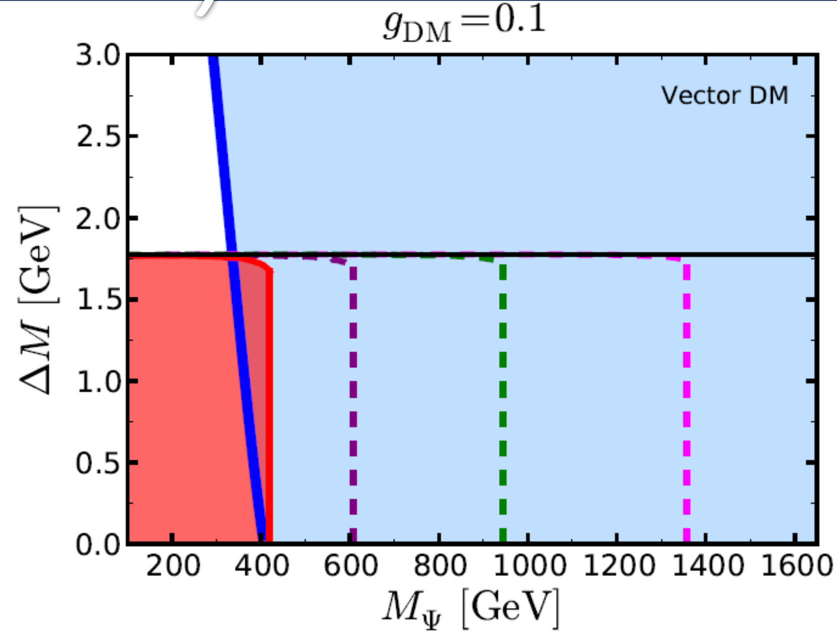
Vector dark matter (Model 3)

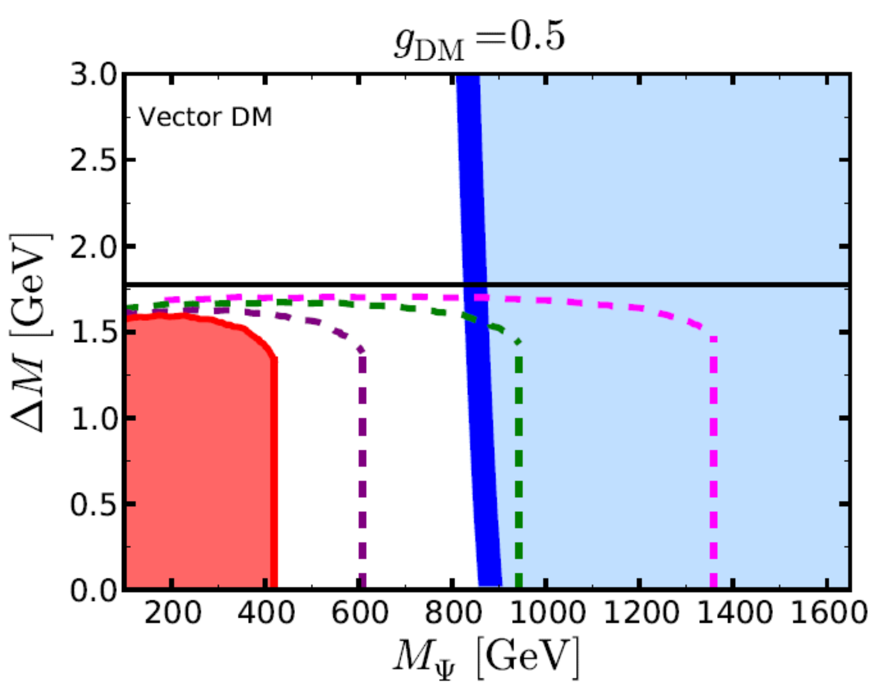
DM — A_μ

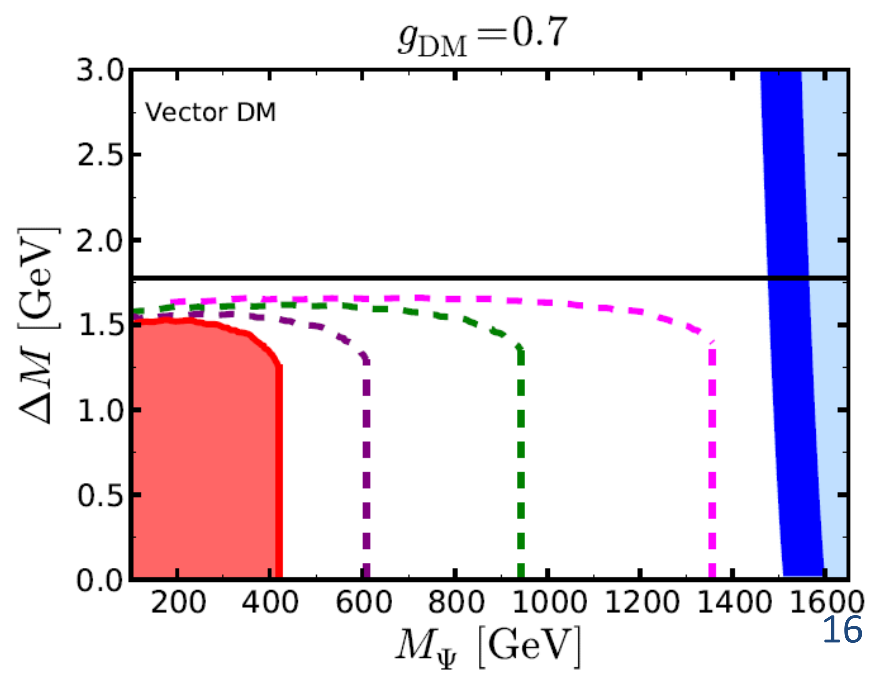
CAP $(Y = 1 \;\; L_\tau = 1)$ — Ψ

$$A_\mu \left(\bar{\Psi}\, \gamma^\mu\, \tau_R\right) \subset \mathcal{L}$$

30 fb $^{-1}$ **300 fb $^{-1}$** **3000 fb $^{-1}$**



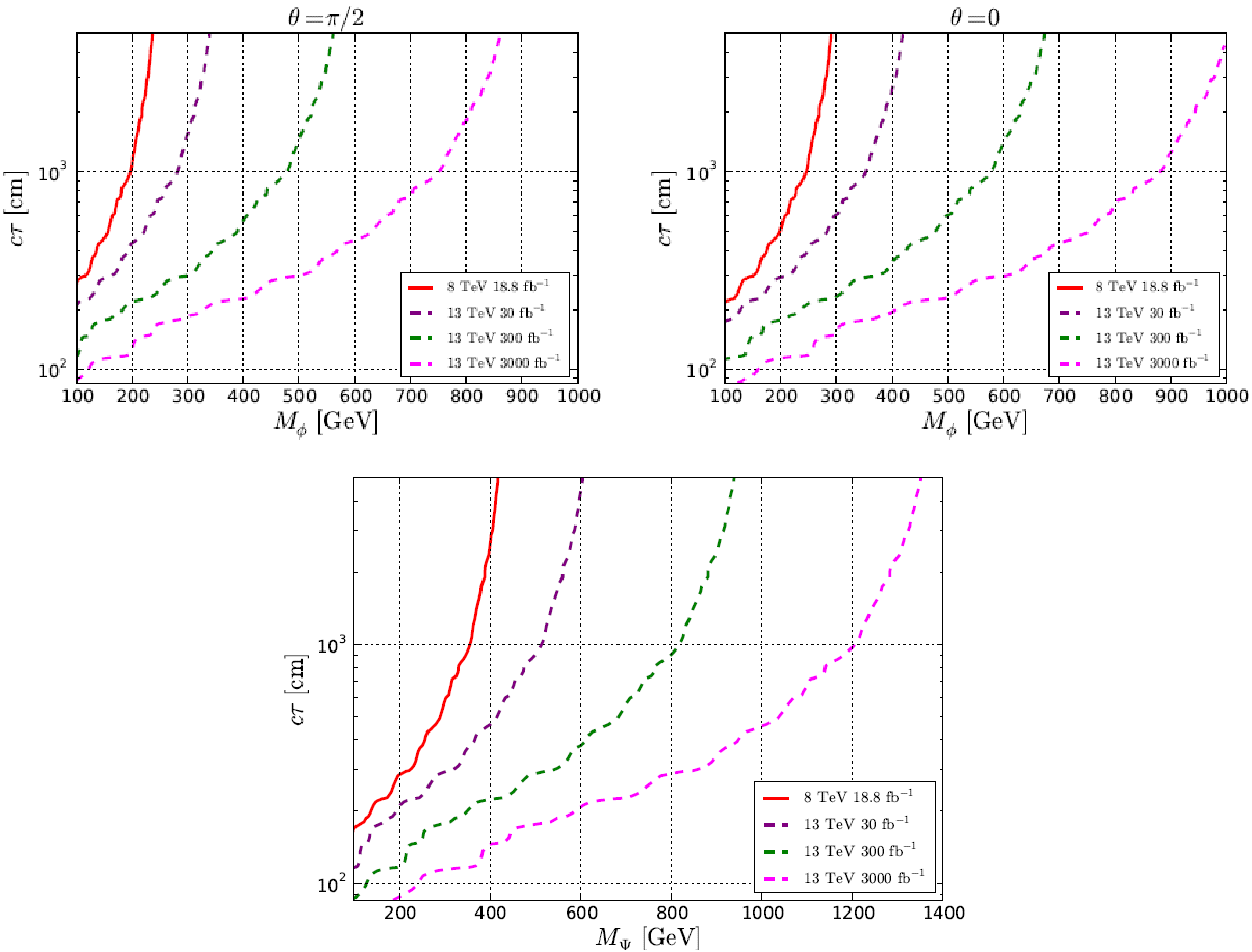




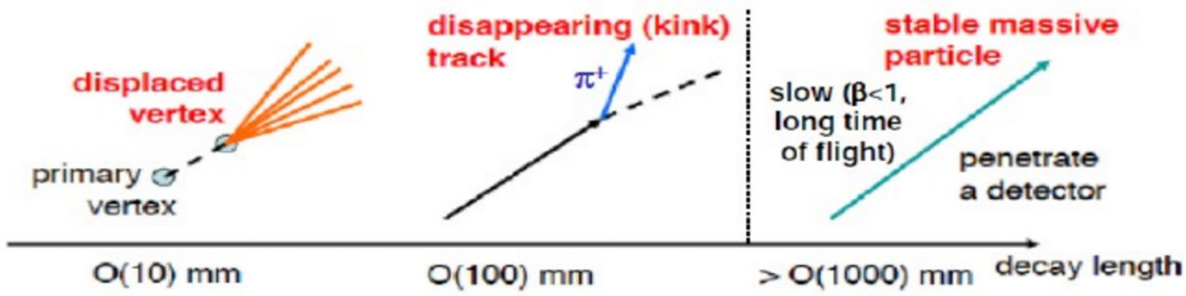
Conclusions

- We have studied 4 classes of simplified models, that have 3-point interaction with **τ-lepton**
- We have considered the case for **Majorana**, **real scalar** and **vector dark matter**
- Instead of a mediator, these simplified models have a **co-annihilation partner** that has **non-zero hypercharge** and the crucial signature are **tracks of long-lived charged particles.**
- In the four simplified models we have introduced there are only **3 free parameters**
- The possible **discovery** of a long-lived electrically charged particle could provide **an insight into the nature** of dark matter

Thank you.


θ = π/2
θ = 0
cτ [cm]
10^3
10^2
100 200 300 400 500 600 700 800 900 1000
M_ϕ [GeV]
200 400 600 800 1000 1200 1400
M_Ψ [GeV]
8 TeV 18.8 fb^{-1}
13 TeV 30 fb^{-1}
13 TeV 300 fb^{-1}
13 TeV 3000 fb^{-1}

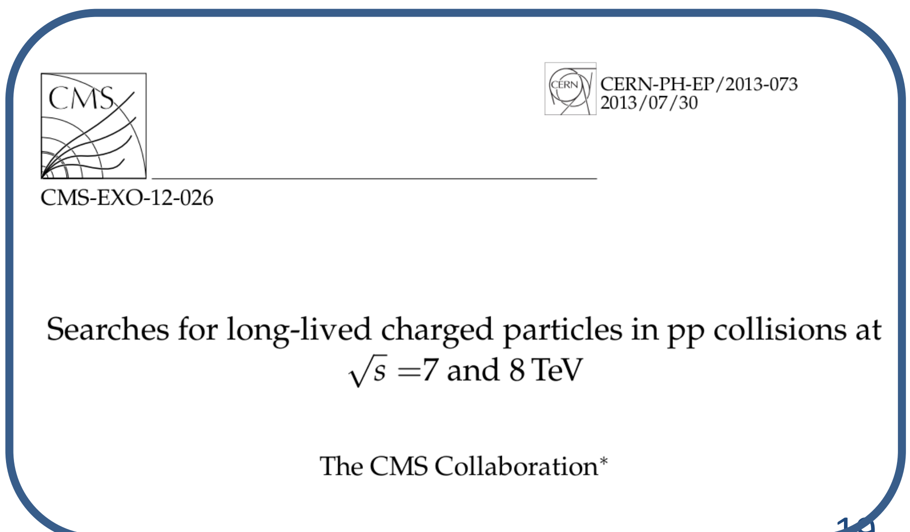
Searching for long-lived charged particles



[Melzer-Pellmann, Pralavorio 2014]

- A long-lived charged particle escapes inner detector, leaving a charged track from ionization energy loss

- Long-lived charged particles that have **lifetimes > 10^{-8} seconds**, leave anomalous charged track and ionize the muon chamber



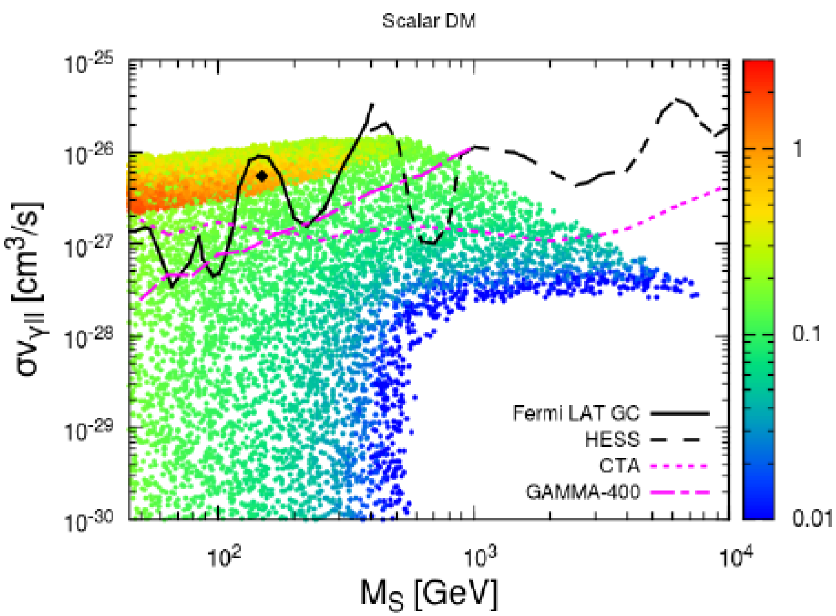
CERN-PH-EP/2013-073
2013/07/30

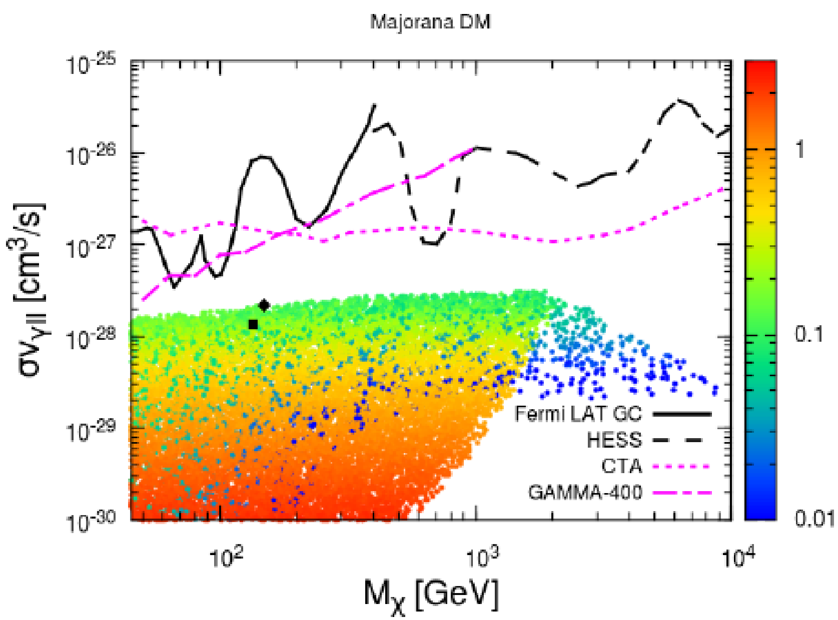
CMS-EXO-12-026

Searches for long-lived charged particles in pp collisions at $\sqrt{s}$ =7 and 8 TeV

The CMS Collaboration*

Indirect Detection





[Giacchino, Lopez-Honorez, Tytgat 2013]

Color coding corresponds to parameter $\frac{M_{CAP}}{M_{DM}} - 1$

Blue dots correspond to small mass splitting