A new search for simplified models of dark matter at the LHC

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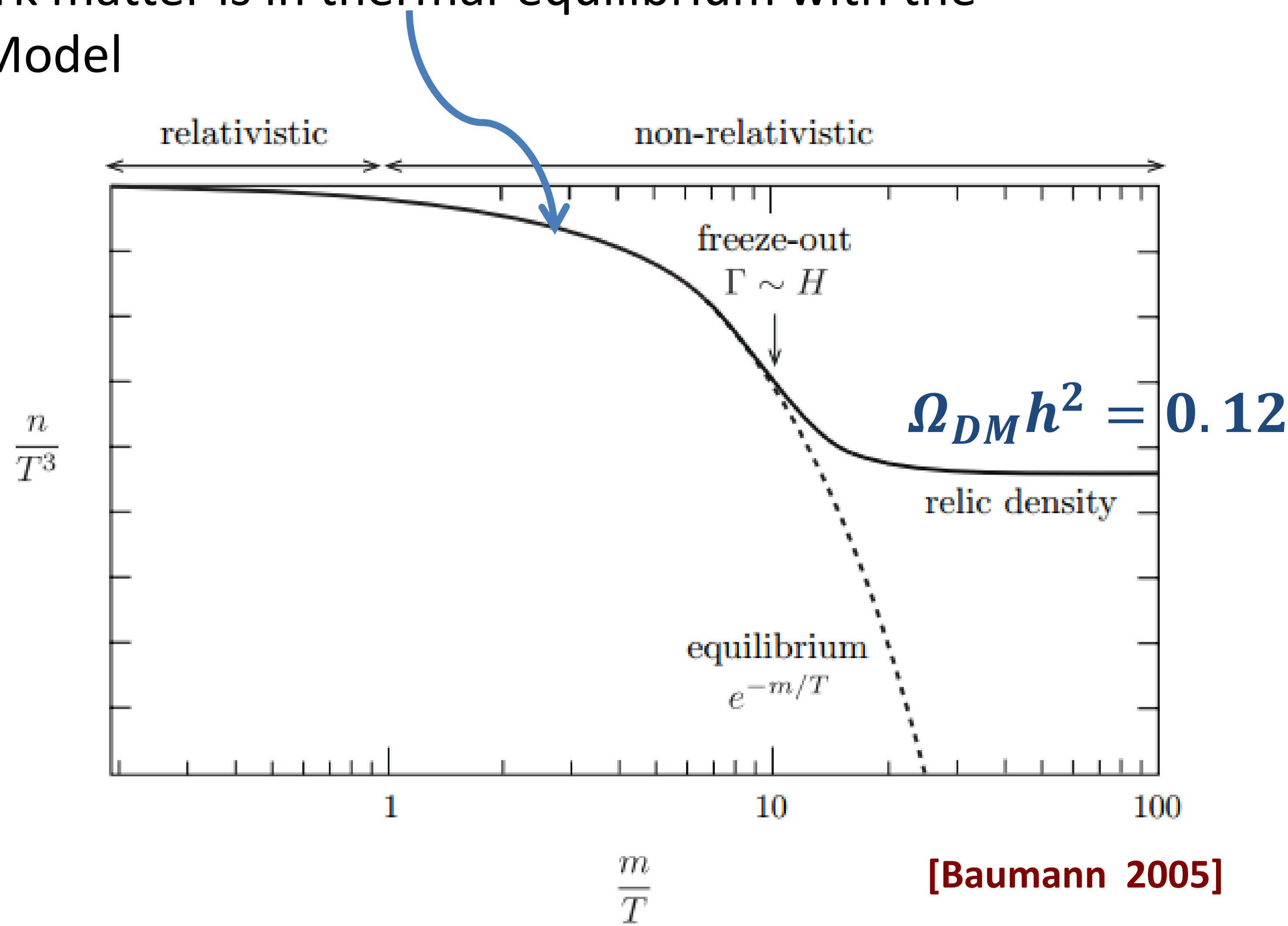
with Valentin Khoze and Kazuki Sakurai

[arxiv:1702.00750] [JHEP 06(2017)041]

WIMP paradigm

Initially dark matter is in thermal-equilibrium with the Standard Model



Later on, due to weak interactions DM freezes-out

WIMP paradigm

- Current experiments already have strong constraints on the simplest WIMPs scenarios, where Dark Matter is coupled to Standard Model gauge bosons or the Higgs

- In lack of a signal from DM experiments, we need to explore as much as we can of the WIMP's parameter space

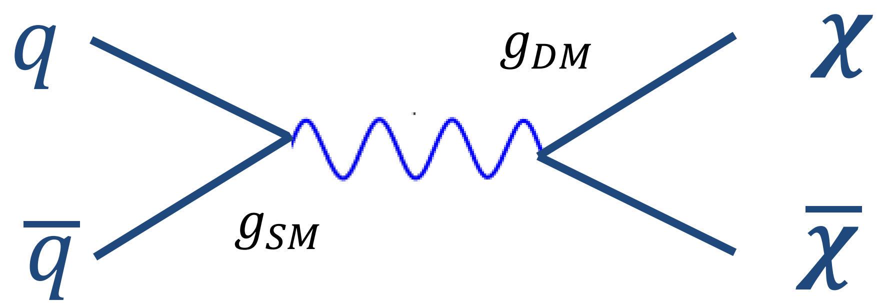
- An alternative and complementary search to Direct and Indirect detection experiments is the production of Dark Matter at colliders, such as the LHC

- There is a plethora of theories of Dark Matter, nevertheless in finding experimental constraints we would like to be as model-independent as possible

Simplified models of dark matter

- **EFT is a powerful and model independent approach**
- **Consistent description if and only if energy of interaction** $E \ll M_{NP}$
- **In the context of DM, there is no reason not to expect that** $M_{MED} \approx m_{DM}$
- **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)

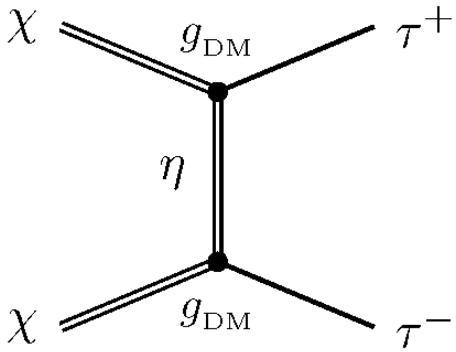
Simplified models with only 3 free parameters:

g_{DM} $\quad m_{DM}$ $\quad M_{CAP}$

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

Co-annihilation

Dark matter annihilation into pair of tau's



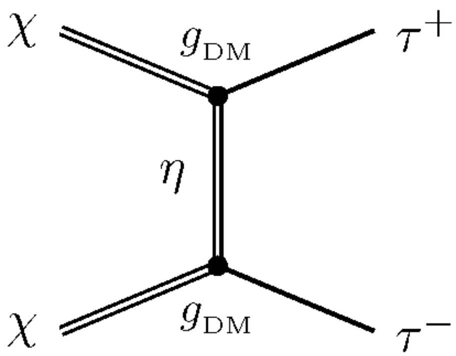
$$(\sigma v)^{\text{s-wave}}_{\text{ann}} = \frac{g_R^4\, m_\tau^2}{32\pi\, m_\chi^4} \frac{1}{(1+r^2)^2}$$

$\propto\ m_\tau$
Chiral suppression

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

Co-annihilation

Dark matter annihilation into pair of tau's



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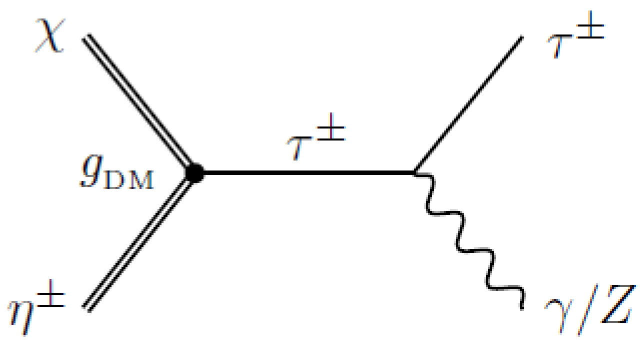
Co-annihilation:



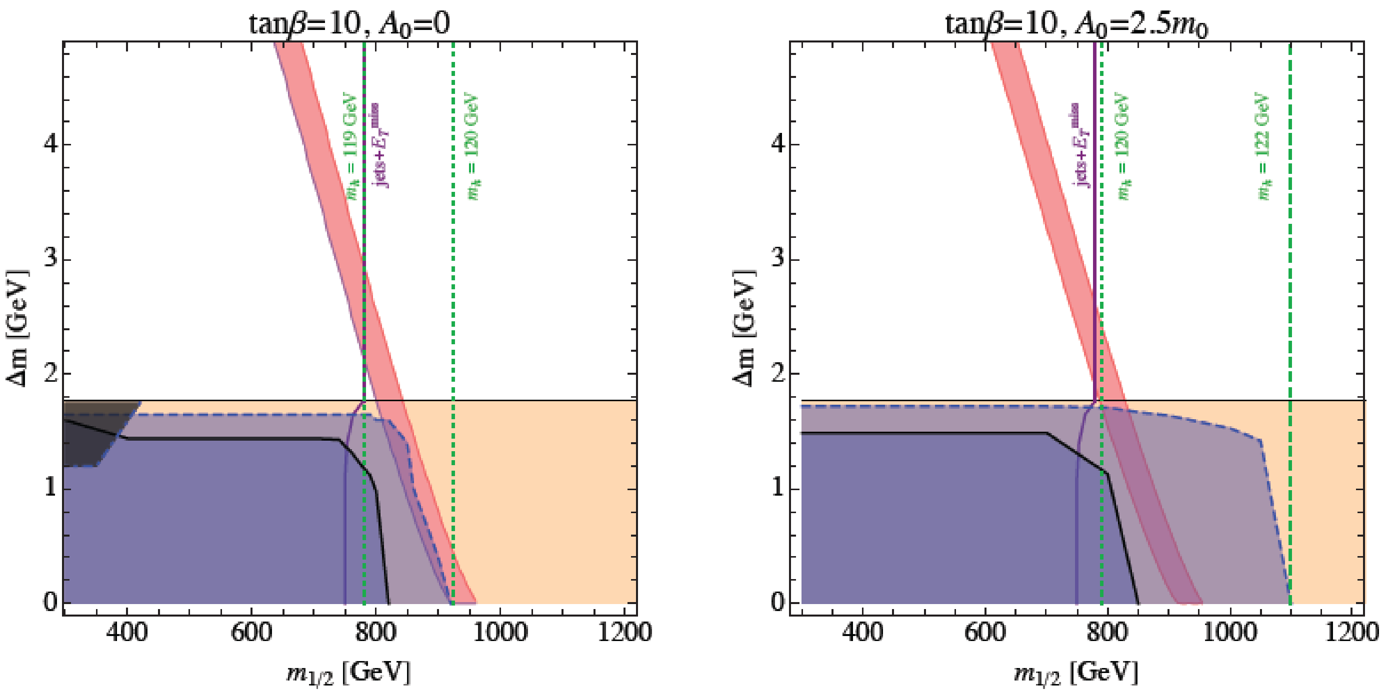
Freeze-out temperature $T_F \sim\ m_{DM}/25$

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)

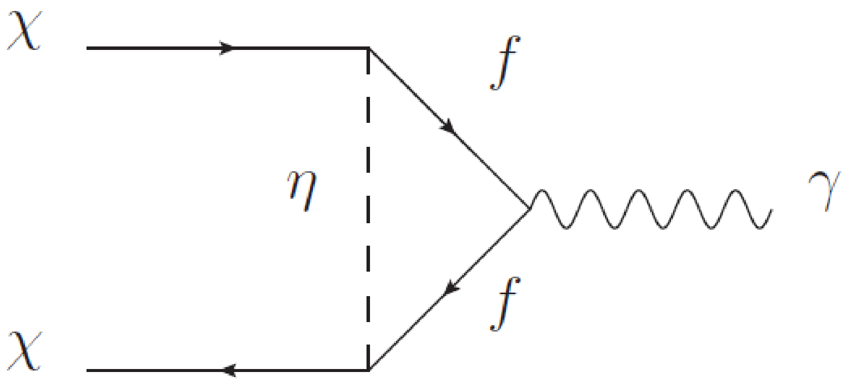


We want to generalize this.

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

LHC production is relevant

- Direct Detection: No tree-level interaction with quarks (anapole moment)



[Kopp, Michaels, Smirnov 2014]

One-loop suppressed

$$m_{\rm DM} \simeq 500\,{\rm GeV} \text{ and } \Delta M/m_\tau < 1$$
$$\mathcal{A}/g_{\rm DM}^2 \sim 8\cdot 10^{-7}\,[\mu_N\cdot{\rm fm}]$$

LUX $A > 2 \times 10^{-5}$ [μ_N fm]

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

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

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

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

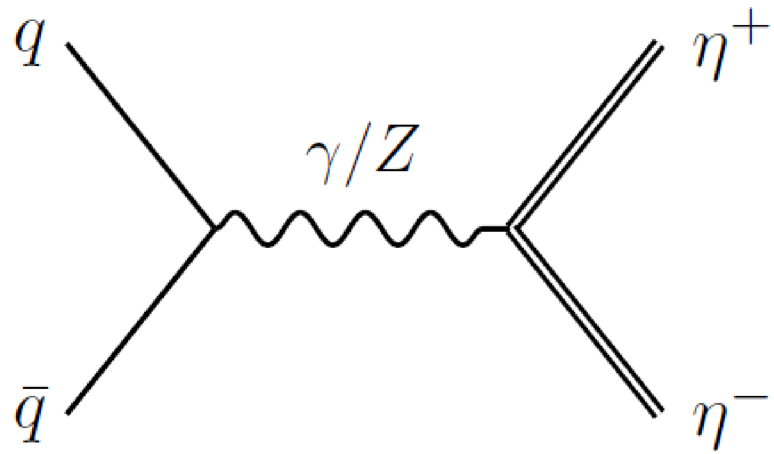
Nevertheless, the channel $S\,S \rightarrow l\,l\,\gamma$ can be relevant for future experiments for scalar DM

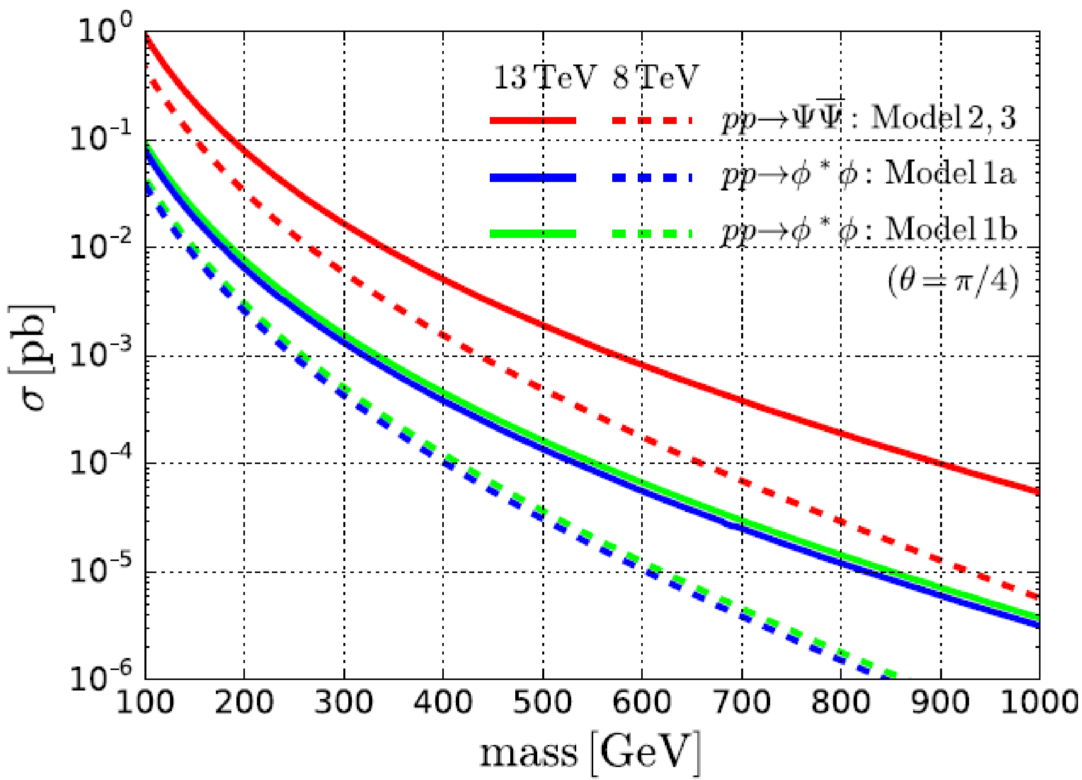
For large ΔM

[Giacchino, Lopez-Honorez, Tytgat 2013]

LHC production

- Drell-Yann pair production of co-annihilation partner

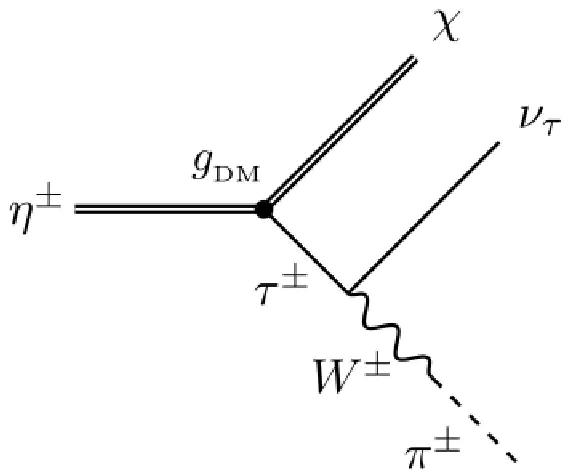




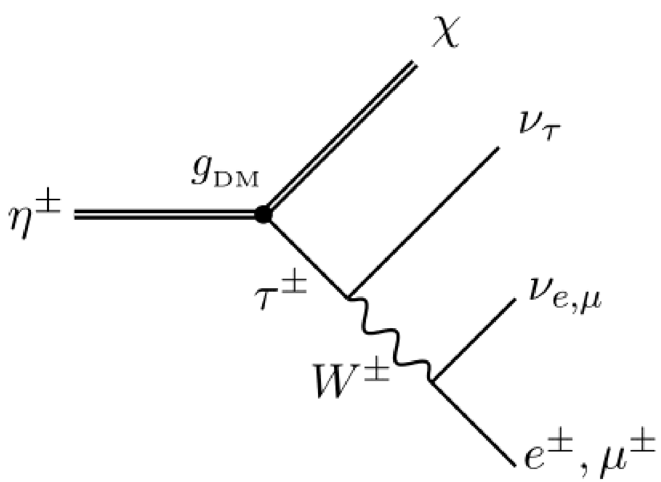
- We study Dirac fermion and complex scalar as co-annihilation partners

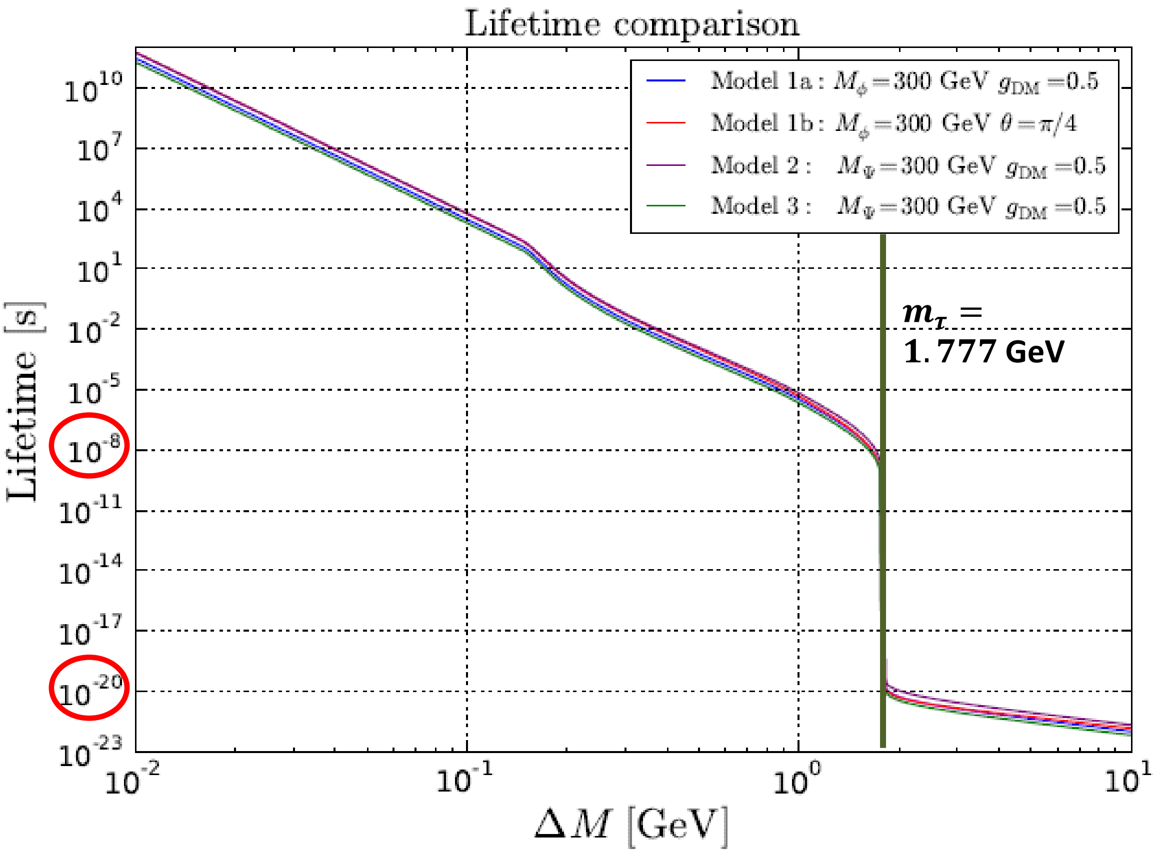
Long-lived electrically charged particles

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

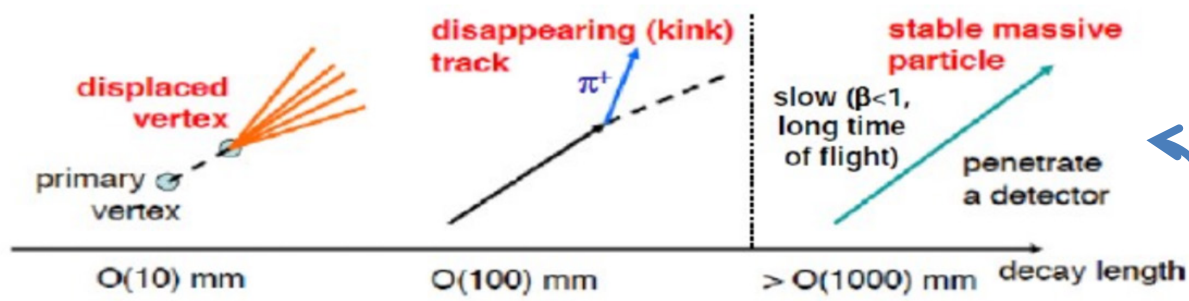


Also ρ and a_1 mesons





Searching for long-lived charged particles



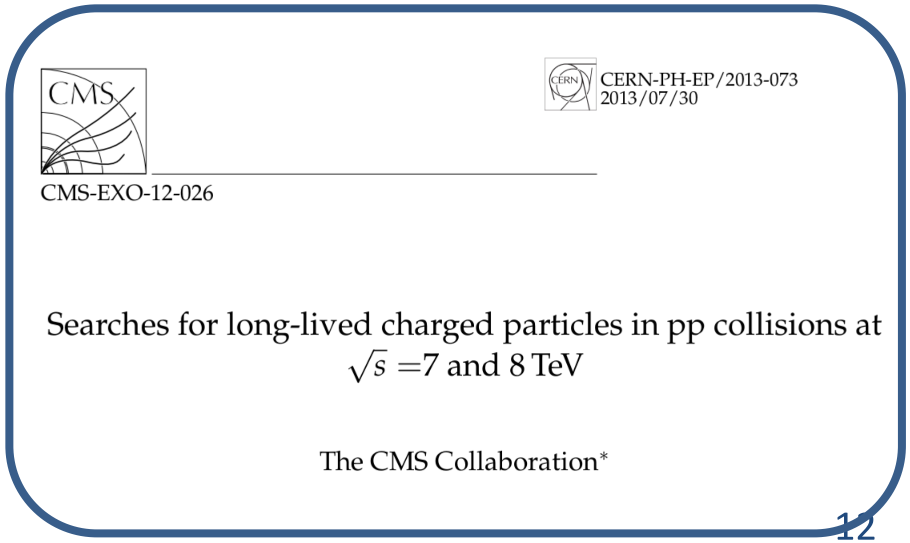
THIS TALK!

[Buchmuller et al, 2017]

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

$c\tau > 1$ m

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


CMS-EXO-12-026

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

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

The CMS Collaboration*

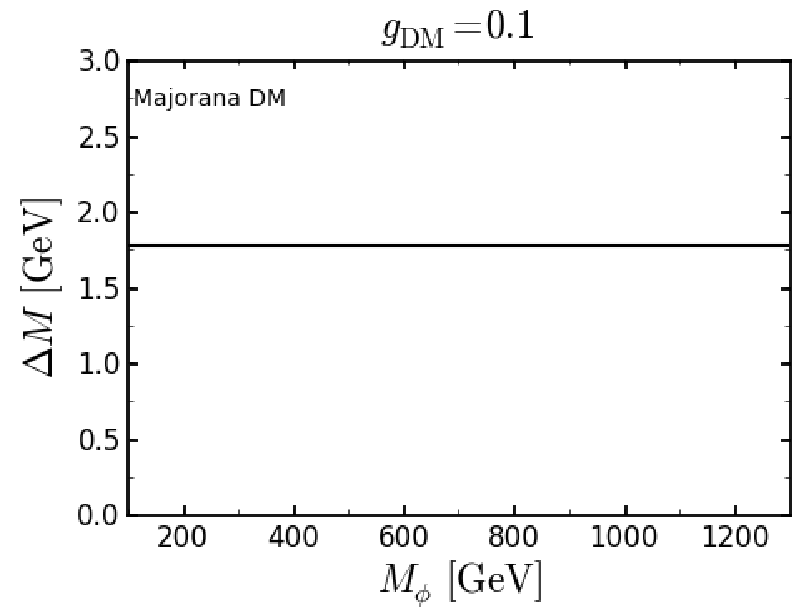
Majorana Dark Matter

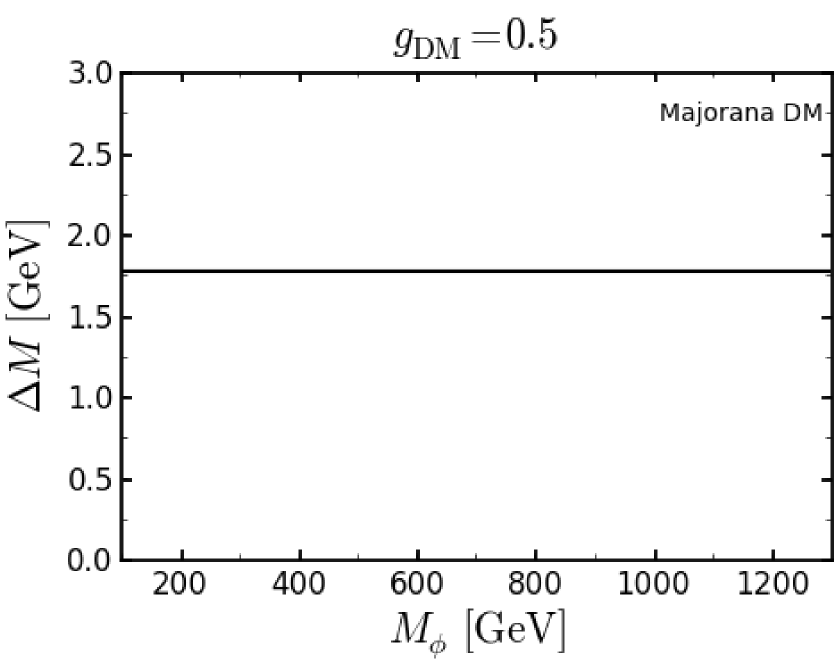
DM χ

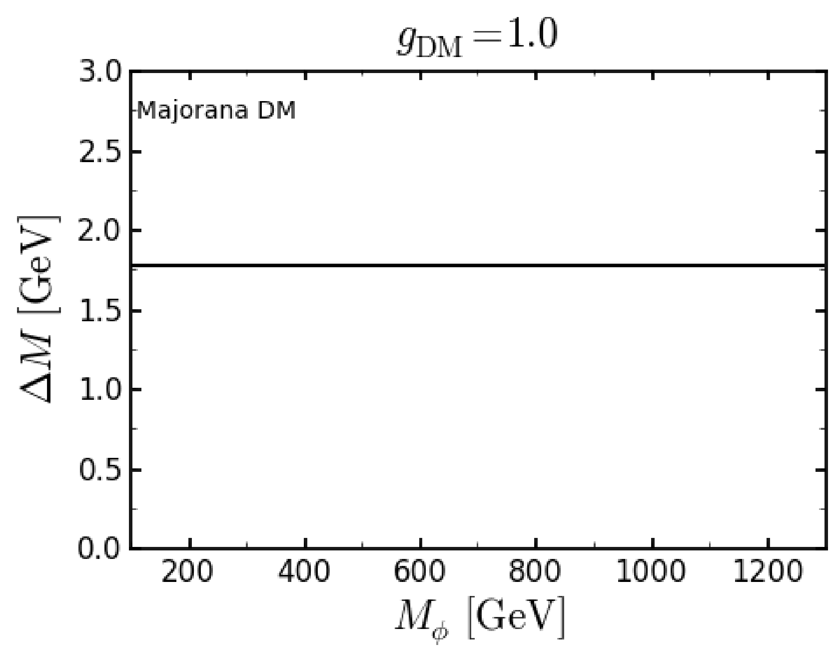
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

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

Gauge-invariant and renormalizable, no problems of unitarity







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DM — χ

CAP (Y=-1) — ϕ

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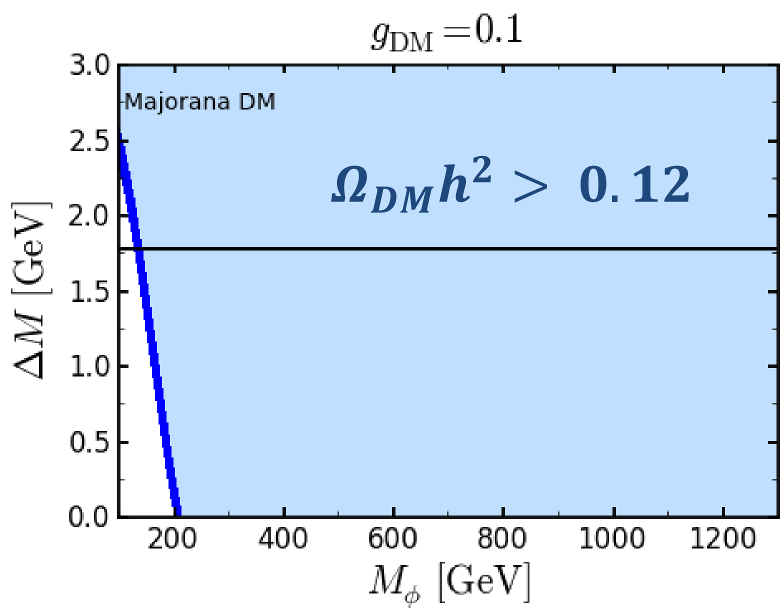

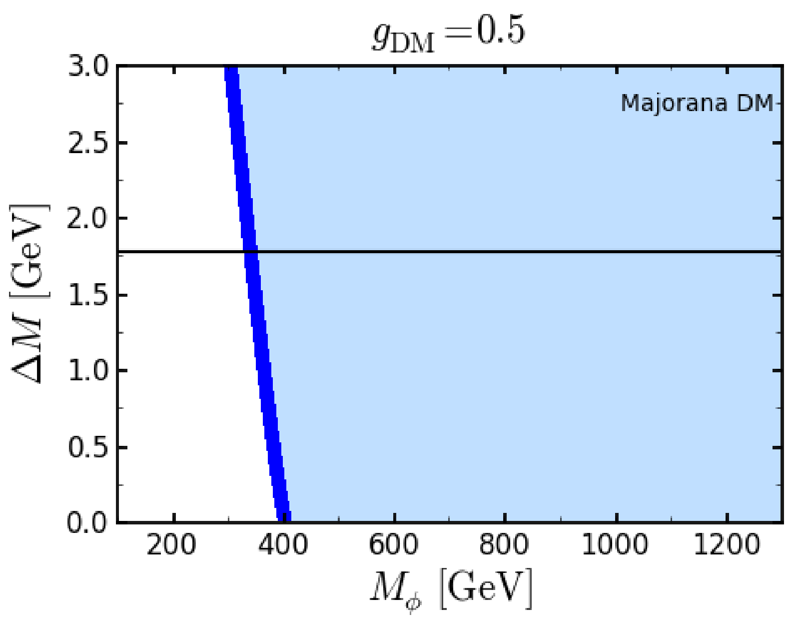

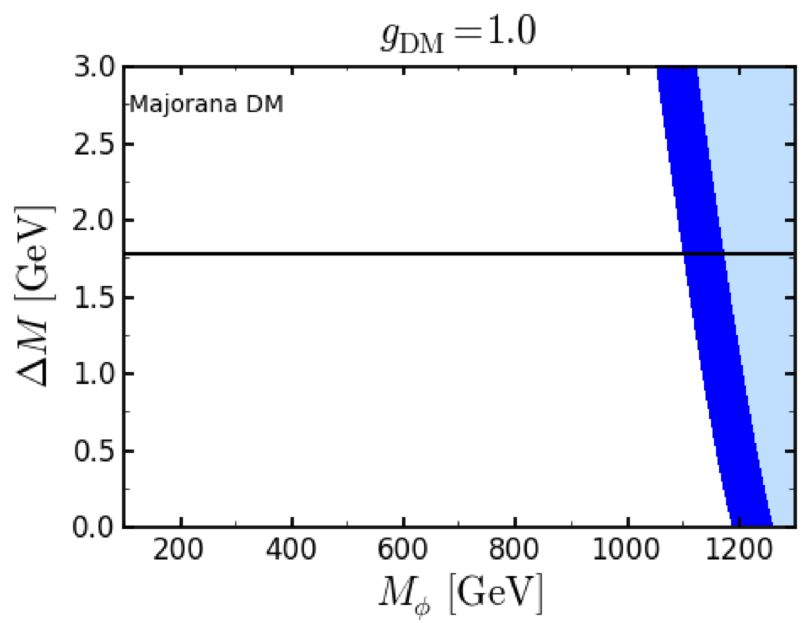

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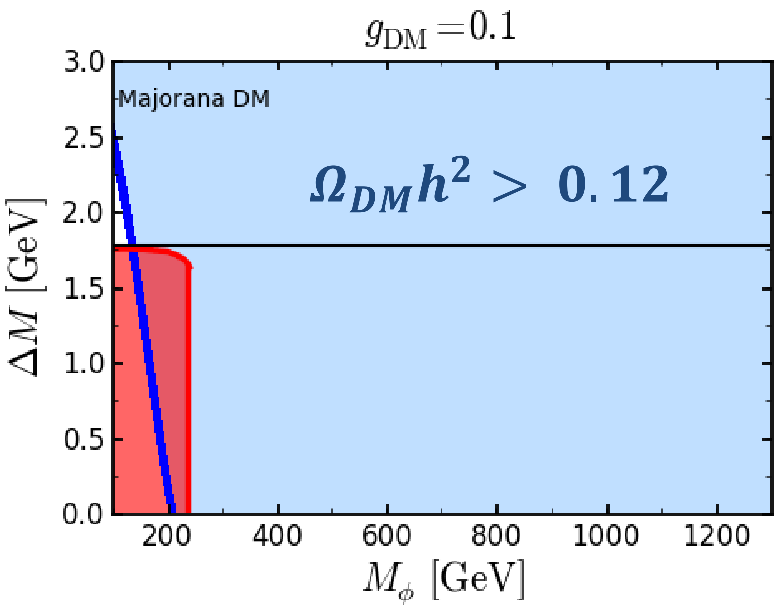
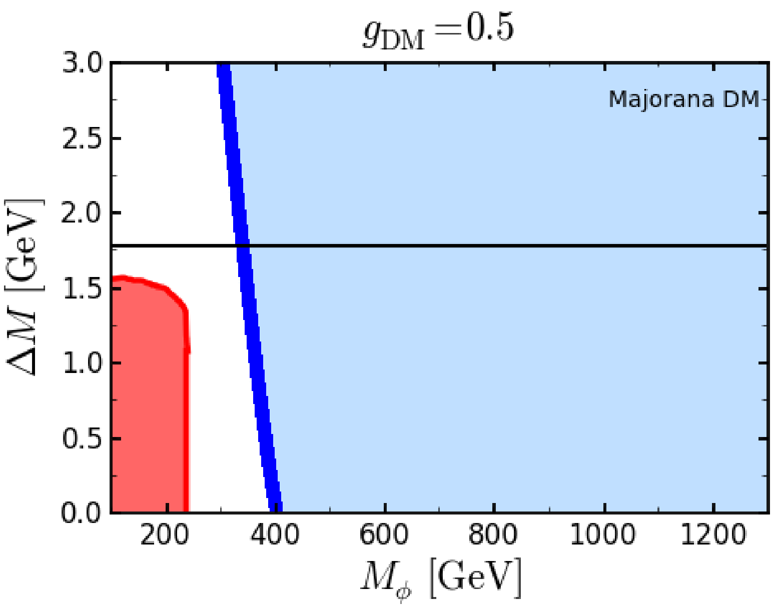
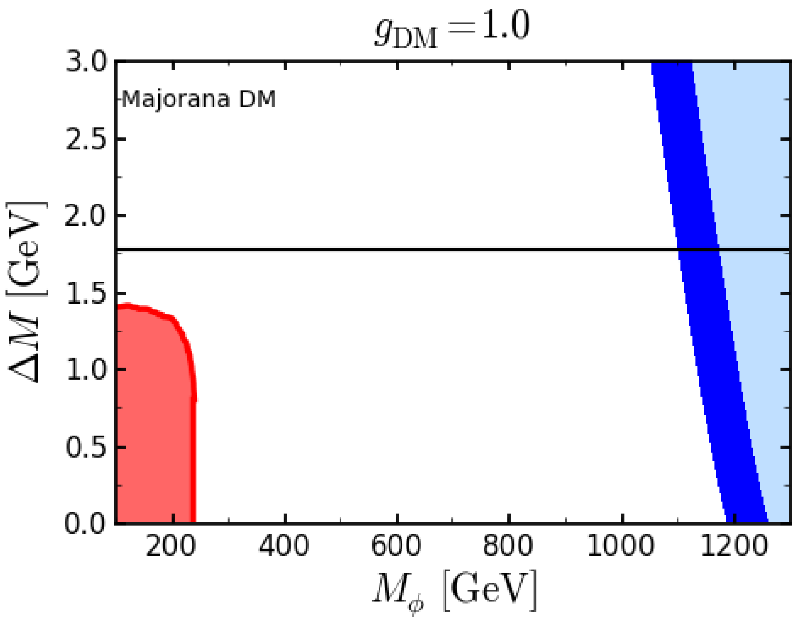
CMS 8 TeV 18.8 fb $^{-1}$







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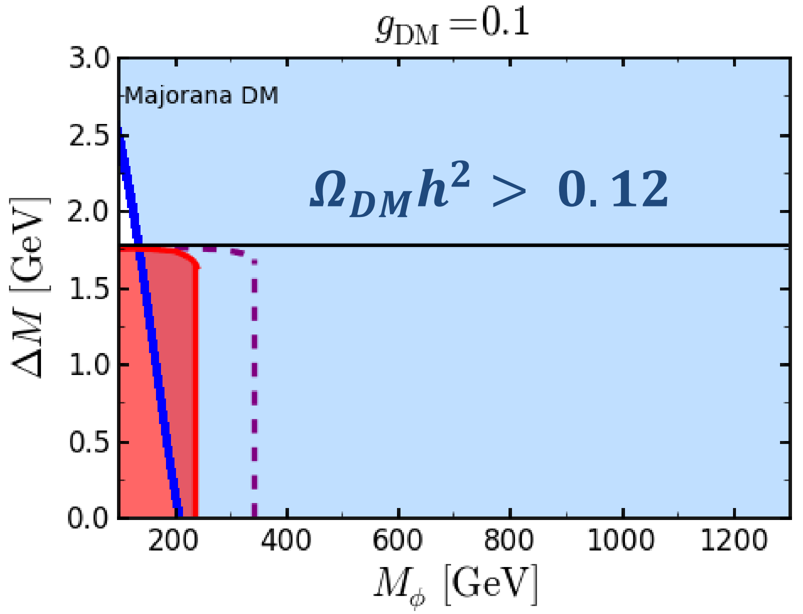

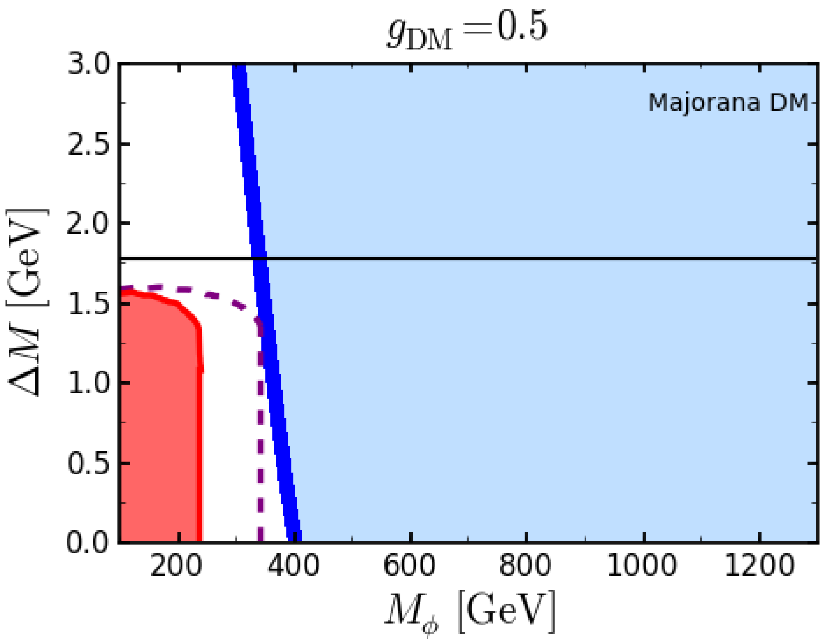

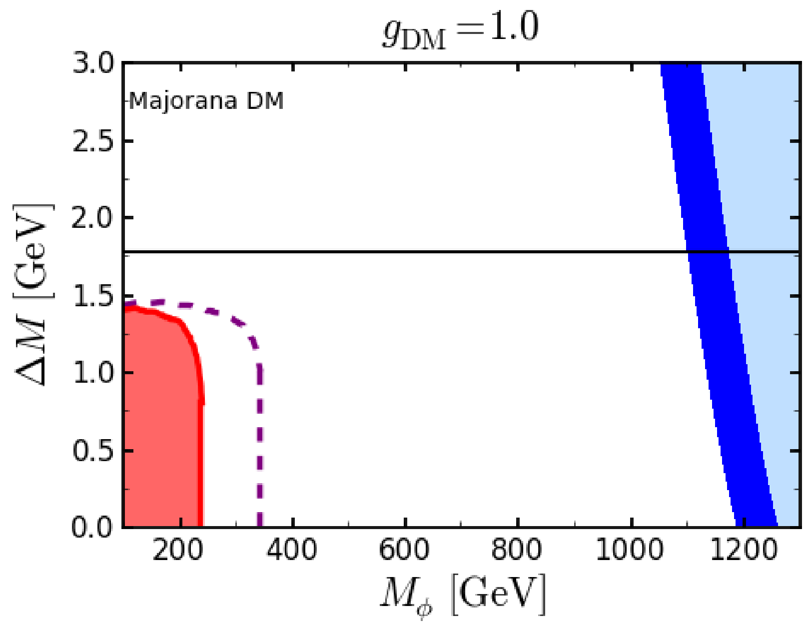

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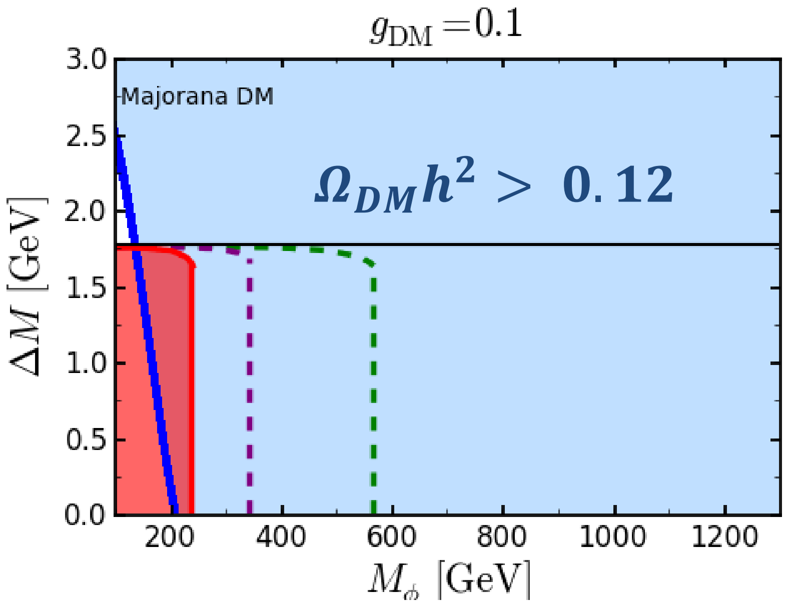

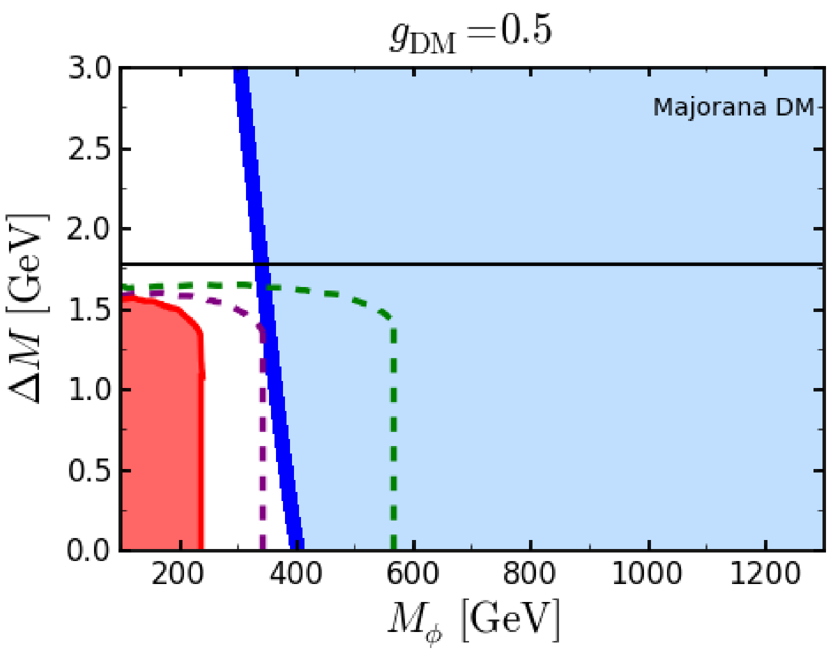

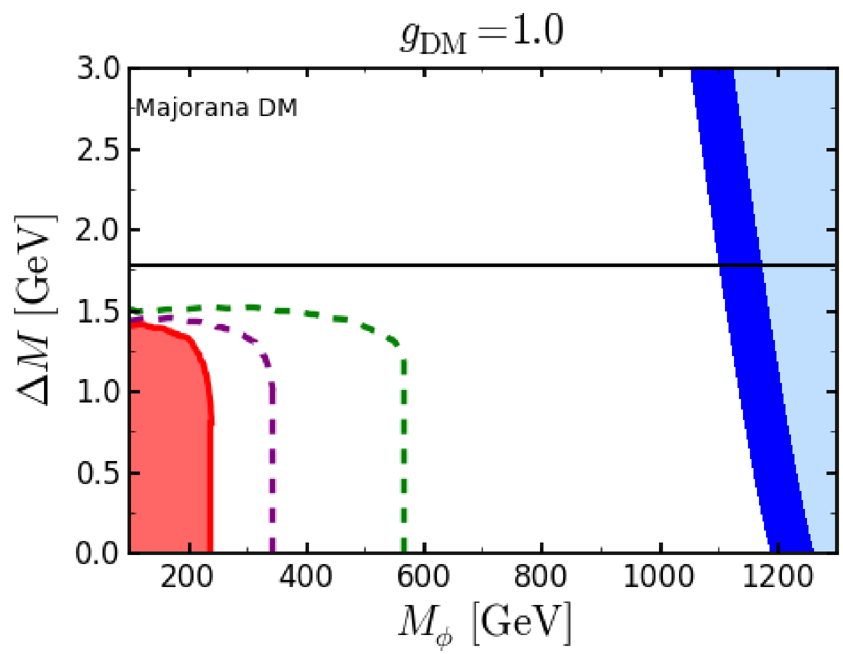

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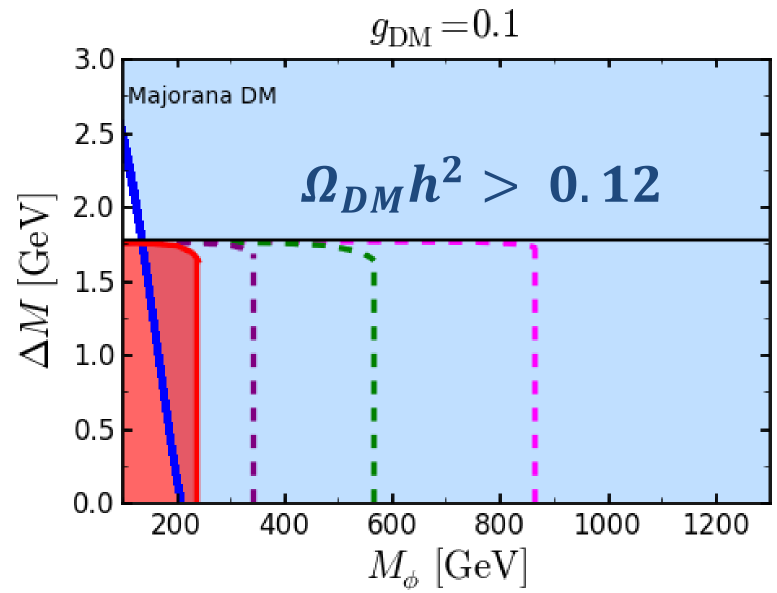
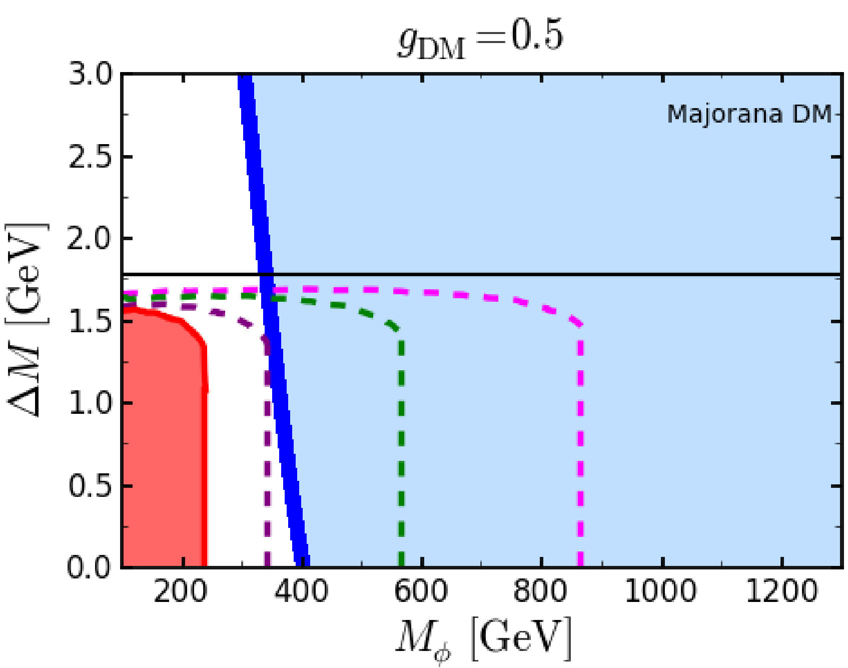
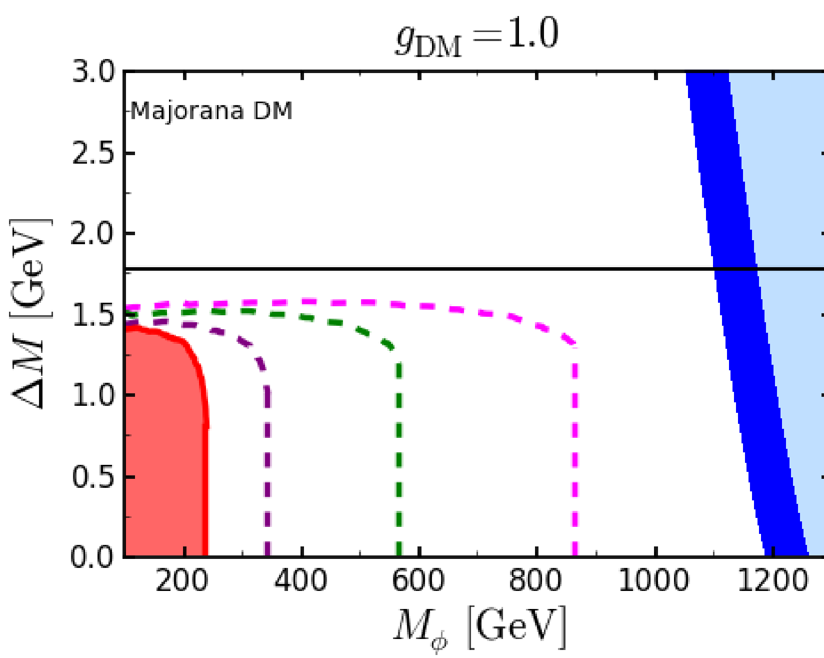
High Lumi 13 TeV 3000 fb $^{-1}$







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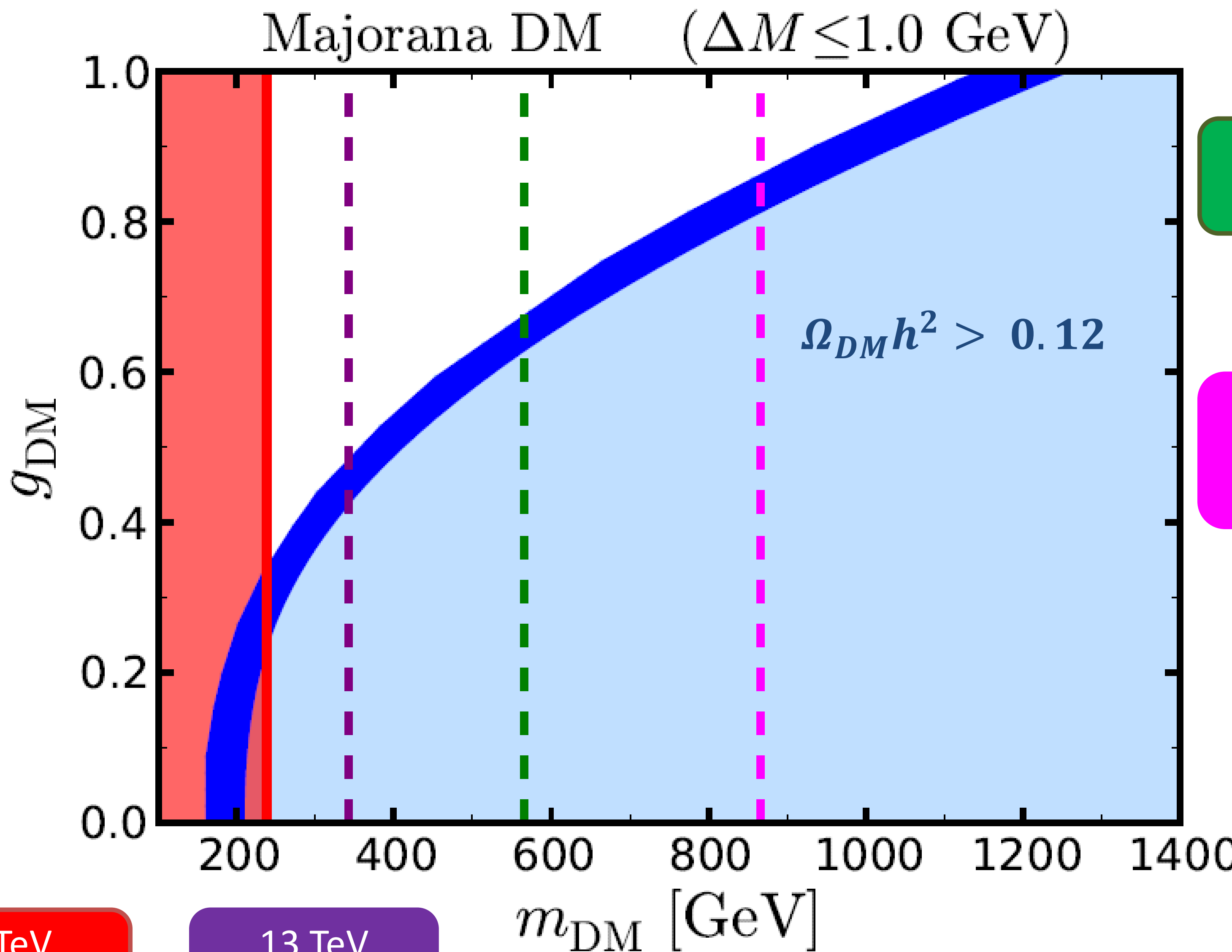


13 TeV
300 fb^{-1}

High Lumi
13 TeV
3000 fb^{-1}

8 TeV
18.8 fb^{-1}

13 TeV
30 fb^{-1}

Majorana Dark Matter (Model 1b)

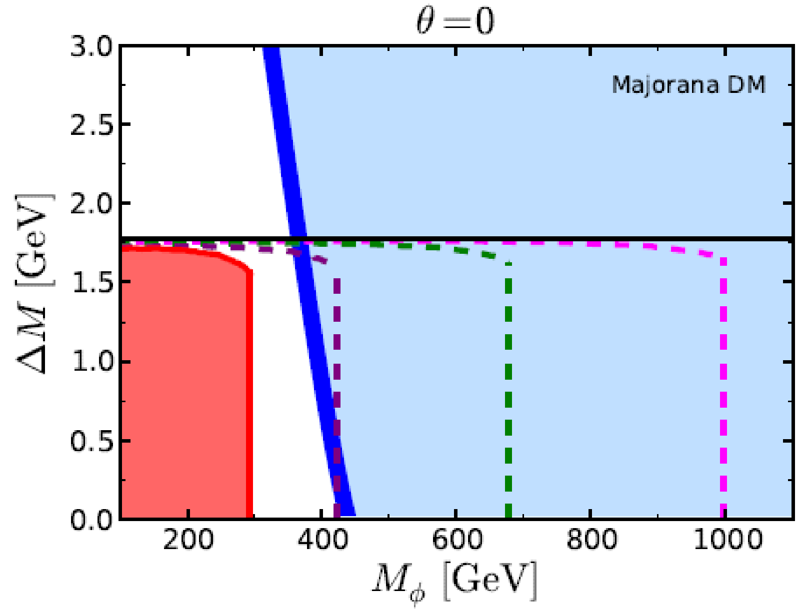
DM **CAP** $(Q = -1)$

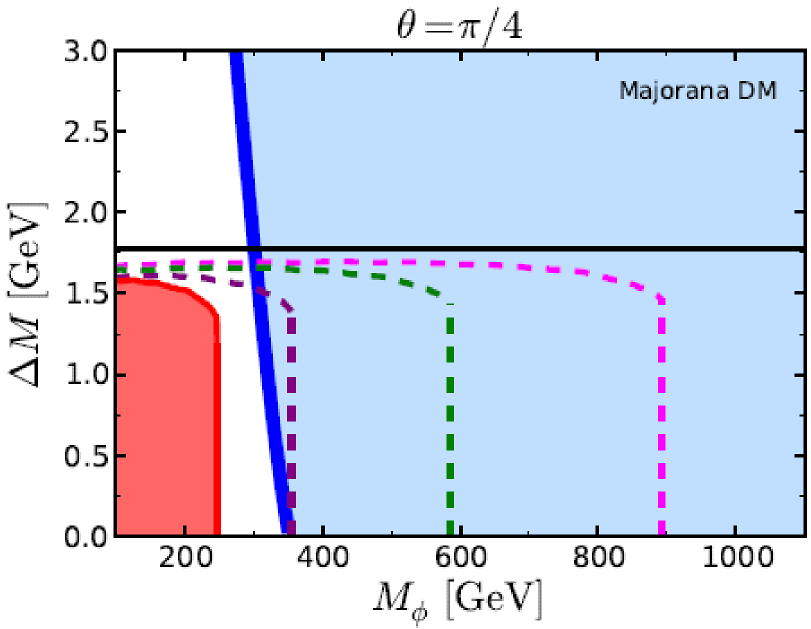
χ ϕ

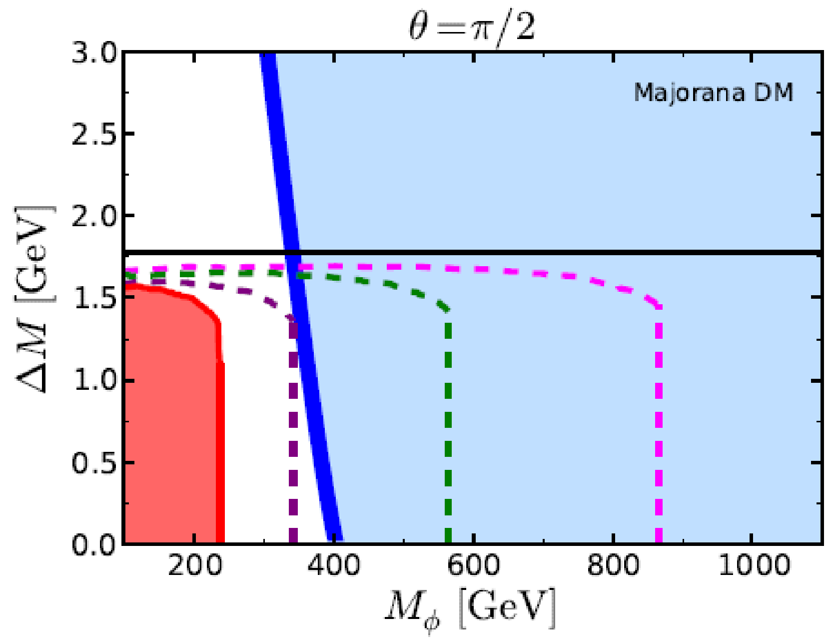
$$g_R\,\phi^*\,(\chi\,\tau_R) + g_L\,\phi^*\,(\chi\,\tau_L) \subset \mathcal{L}$$

$$\phi = \cos\theta\ \phi_L + \sin\theta\ \phi_R$$

$$g_L = \frac{1}{\sqrt{2}}g'\cos\theta, \quad g_R = -\sqrt{2}g'\sin\theta\,.$$







Majorana Dark Matter (Model 1b)

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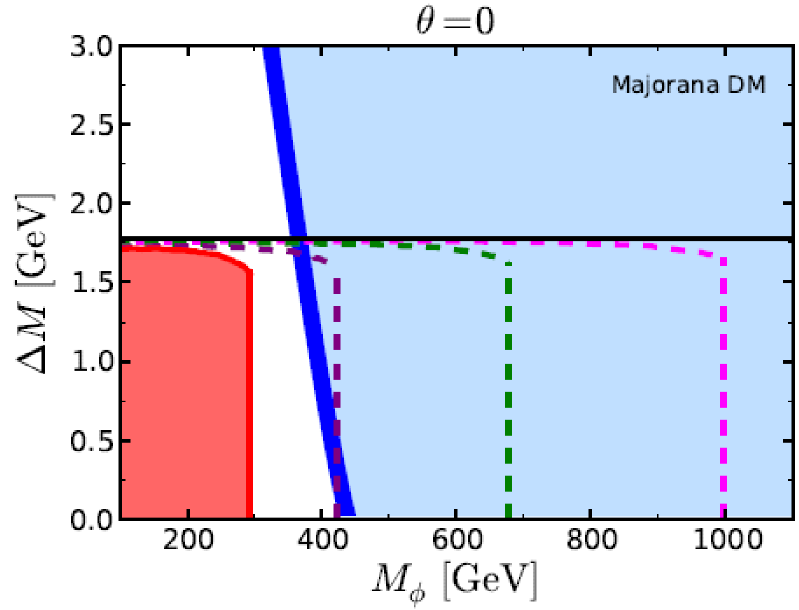
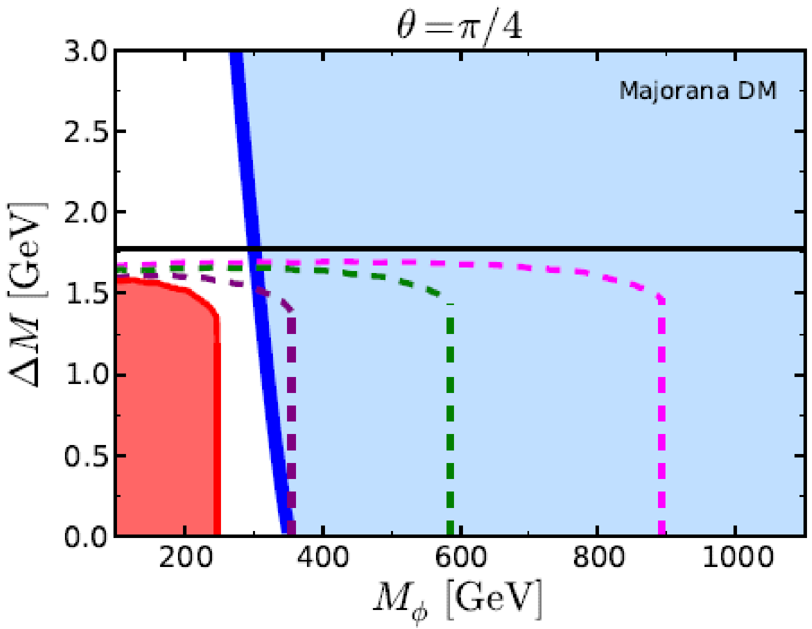
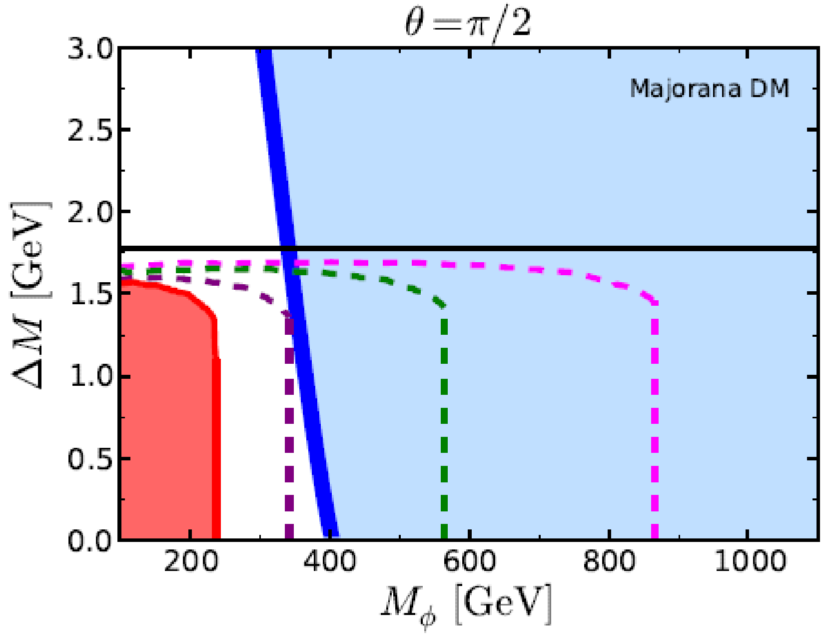
$$g_R\, \phi^* \, (\chi\, \tau_R) + g_L\, \phi^* \, (\chi\, \tau_L) \subset \mathcal{L}$$

NOT gauge-invariant, requires UV-completion, e.g. SUSY







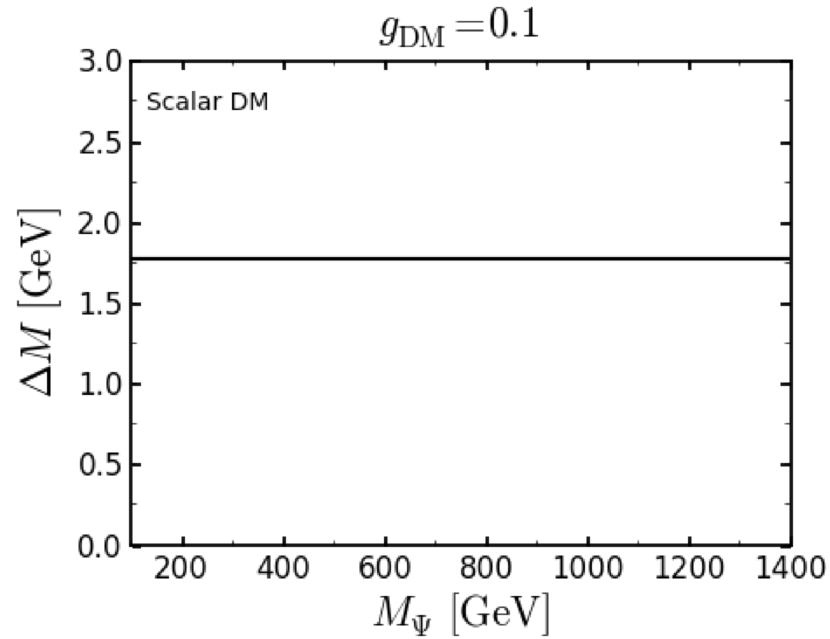
Real scalar dark matter

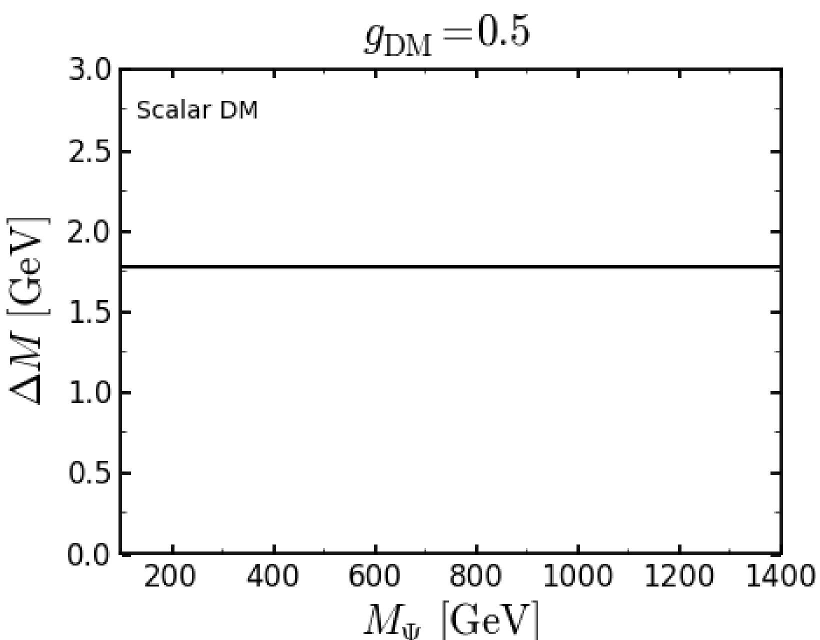
DM **CAP** $(Y = 1 \;\; L_\tau = 1)$

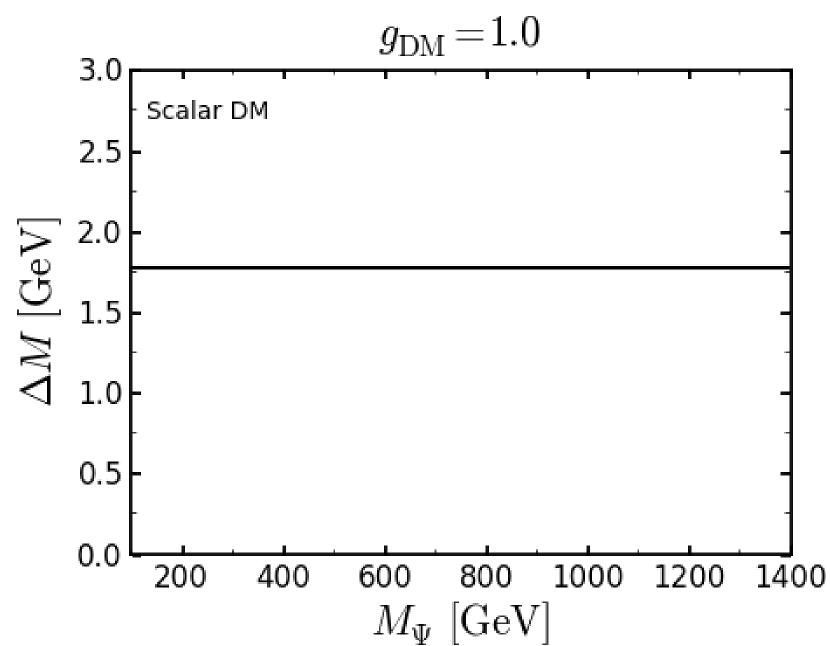
S Ψ

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

Gauge-invariant and renormalizable,
no problems of unitarity







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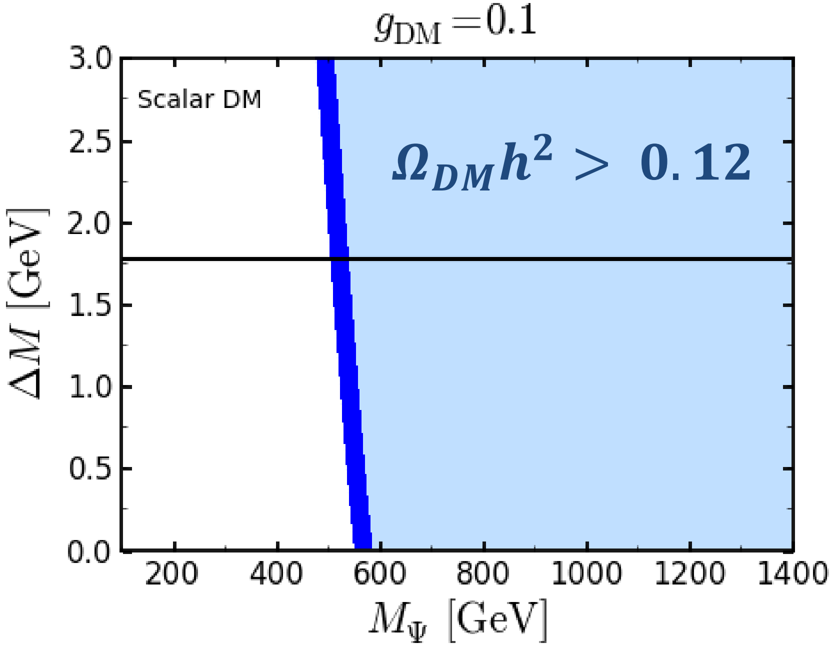

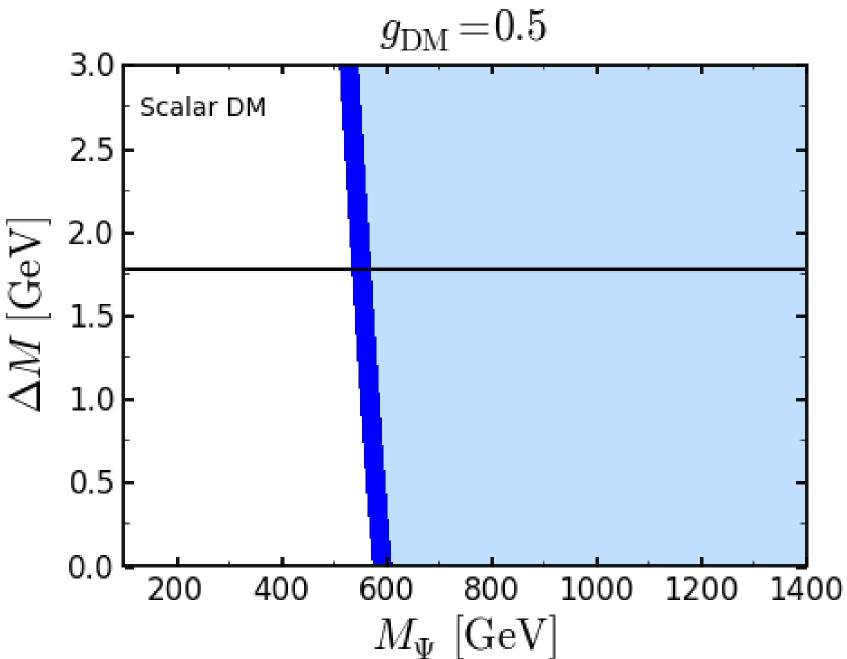

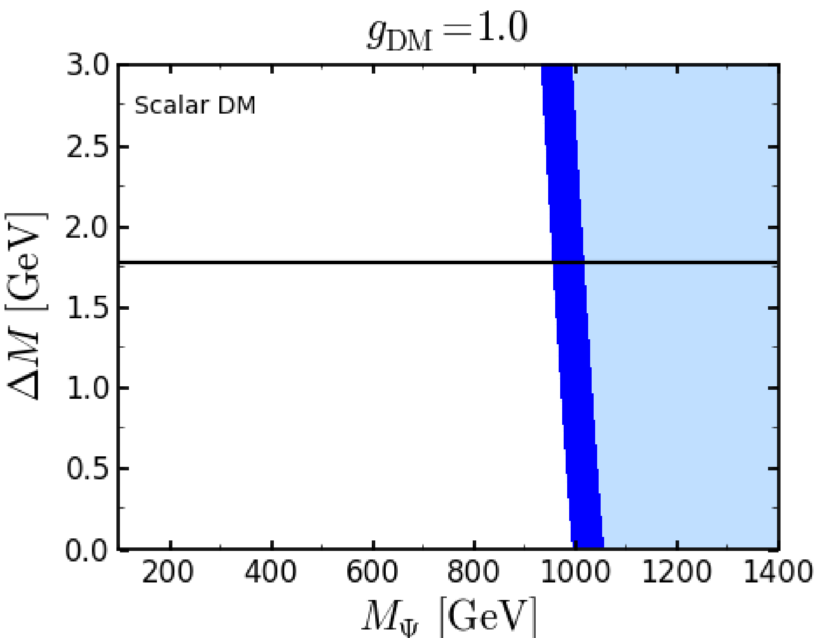

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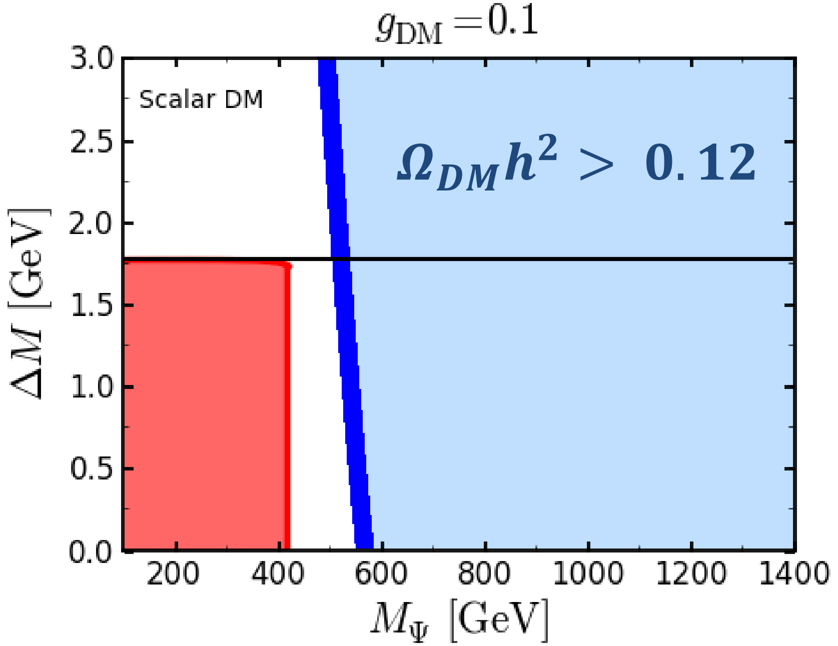

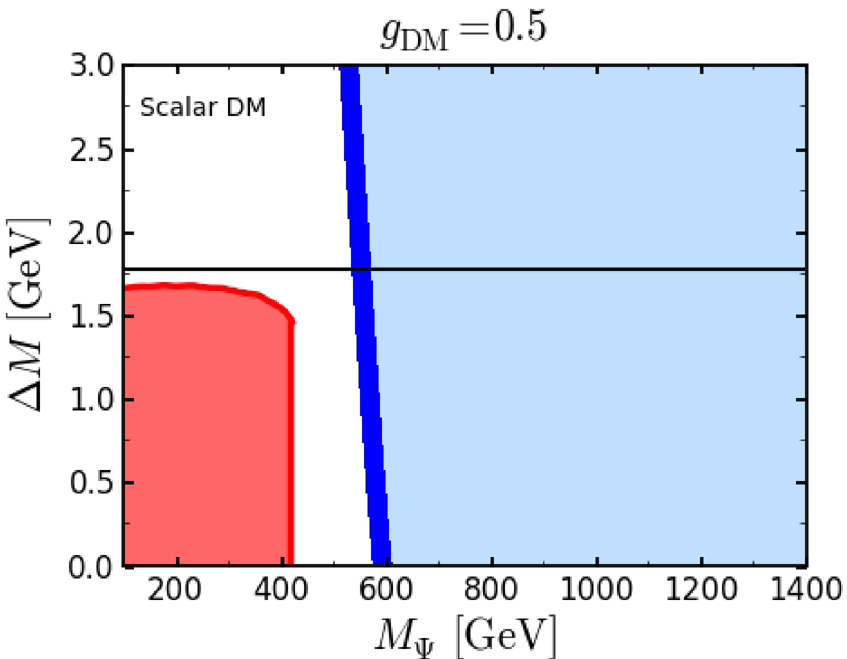

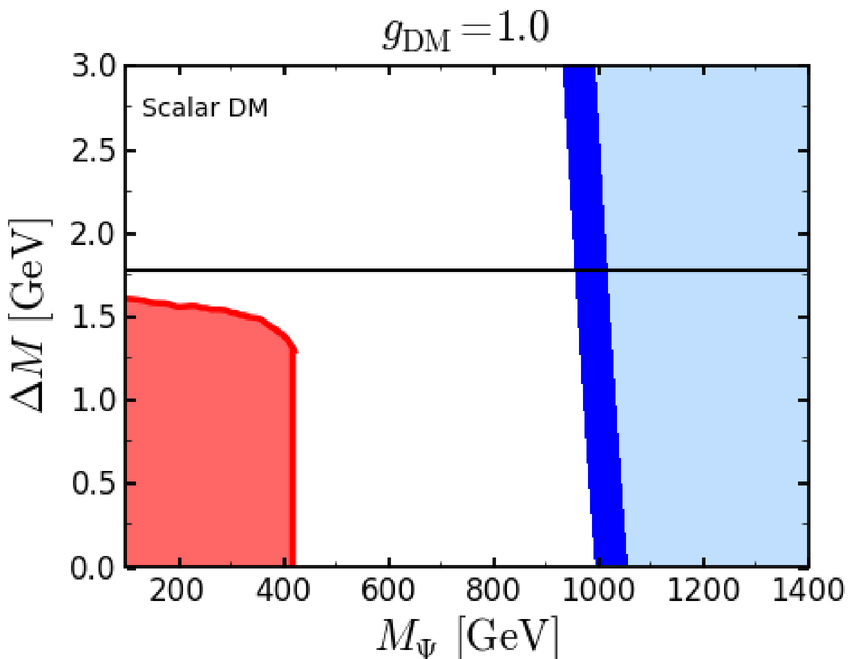

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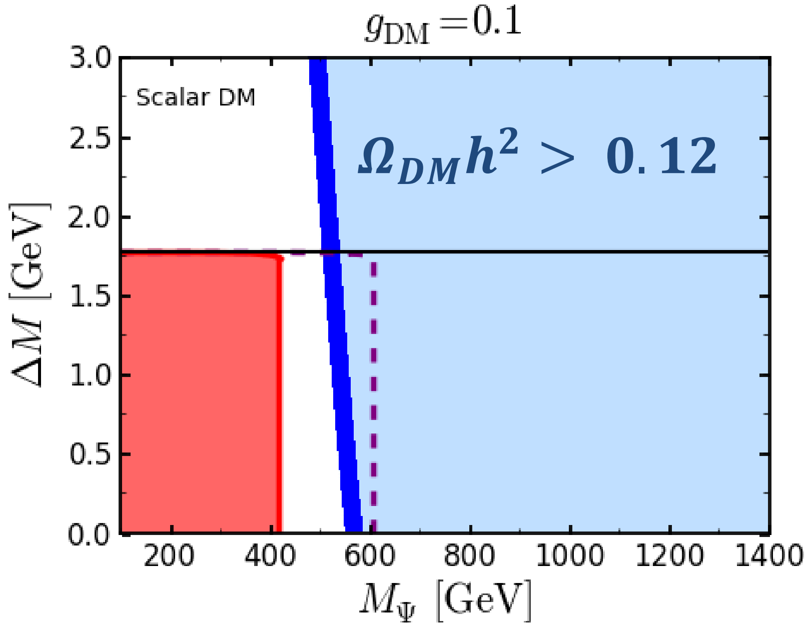

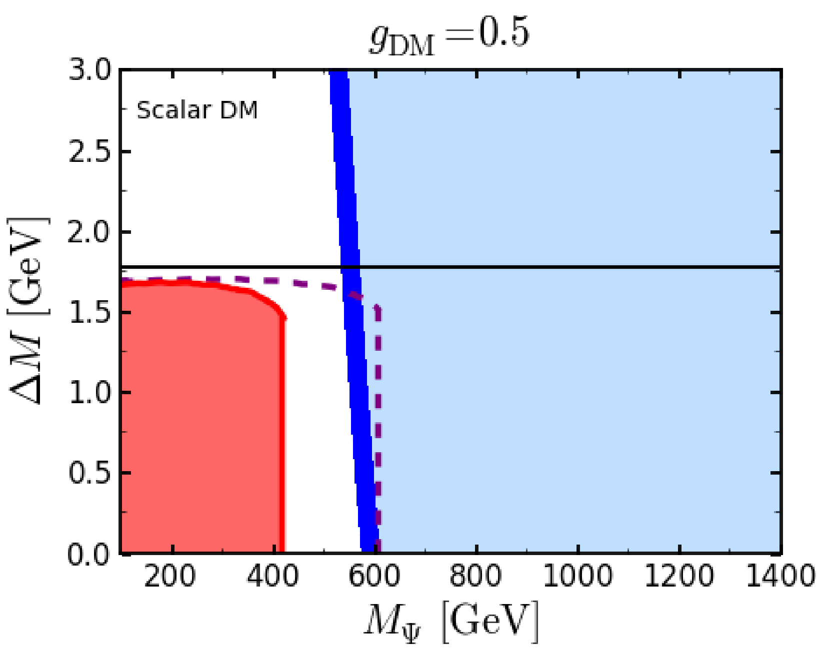

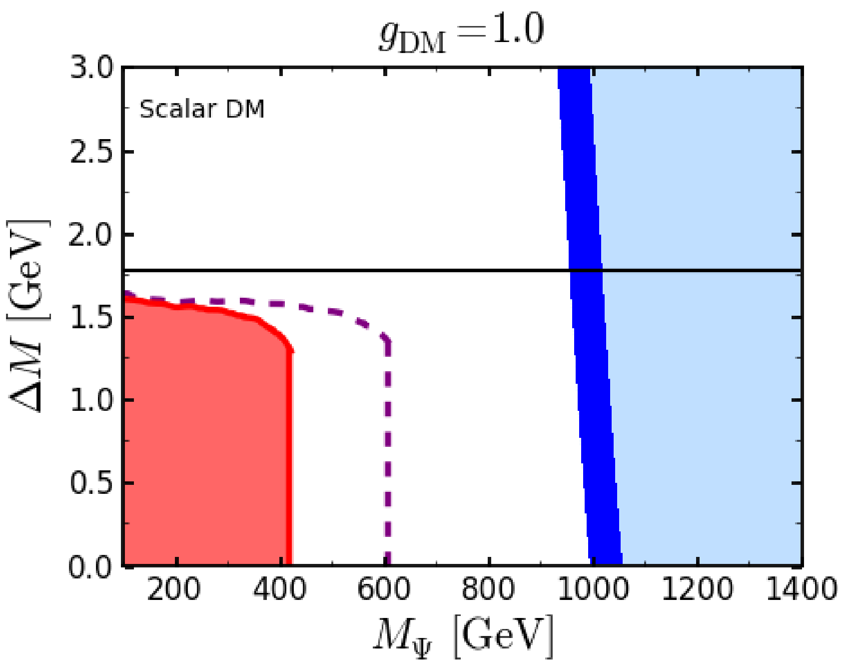

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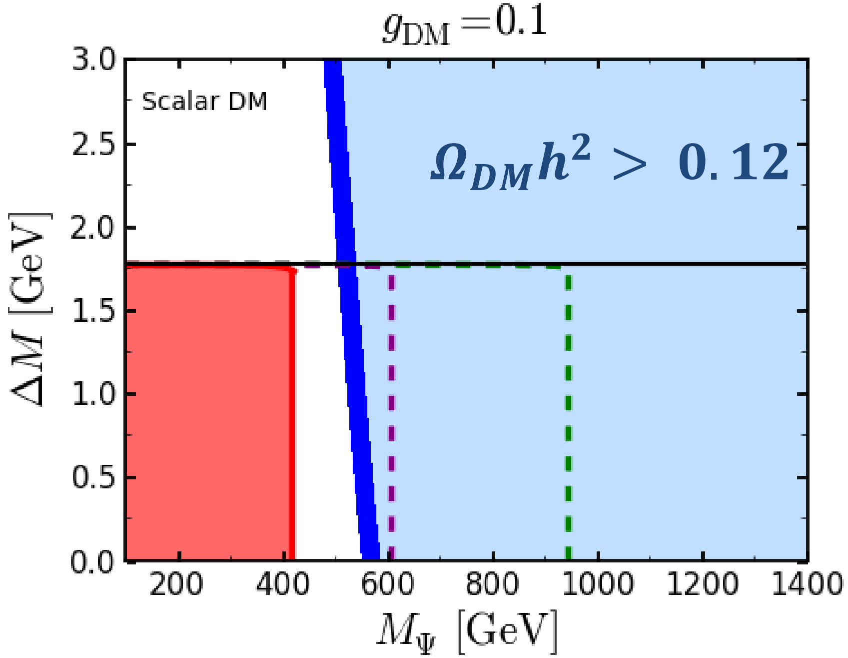

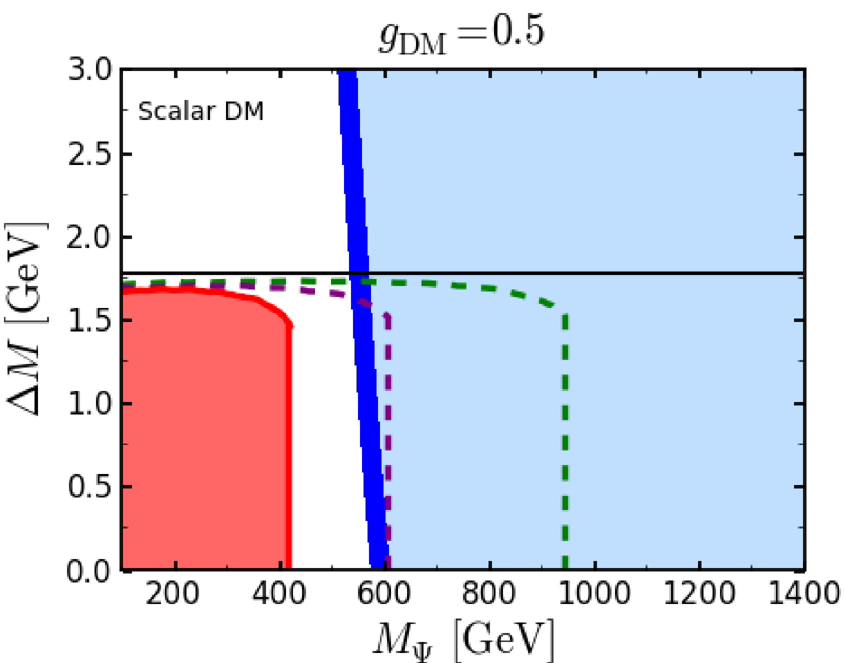

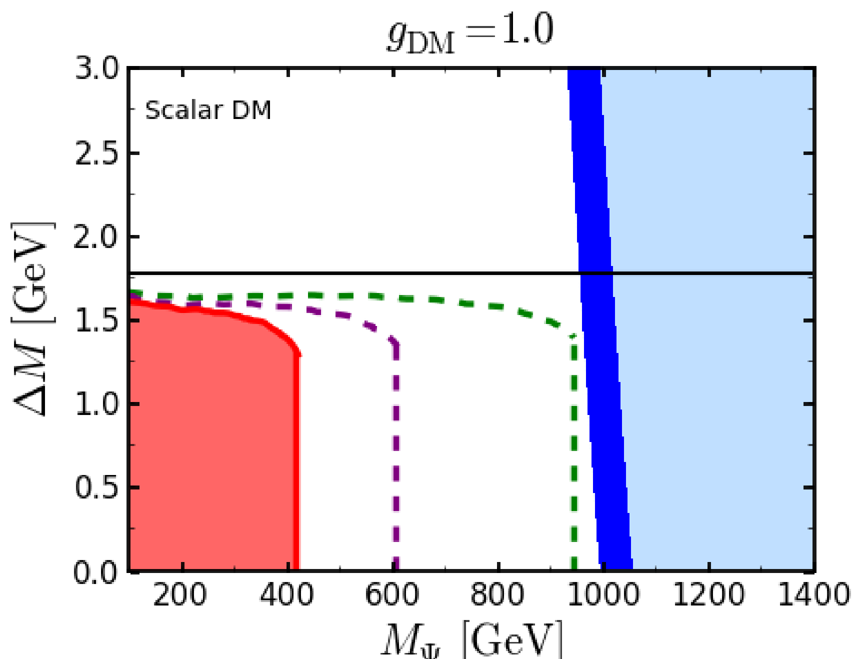

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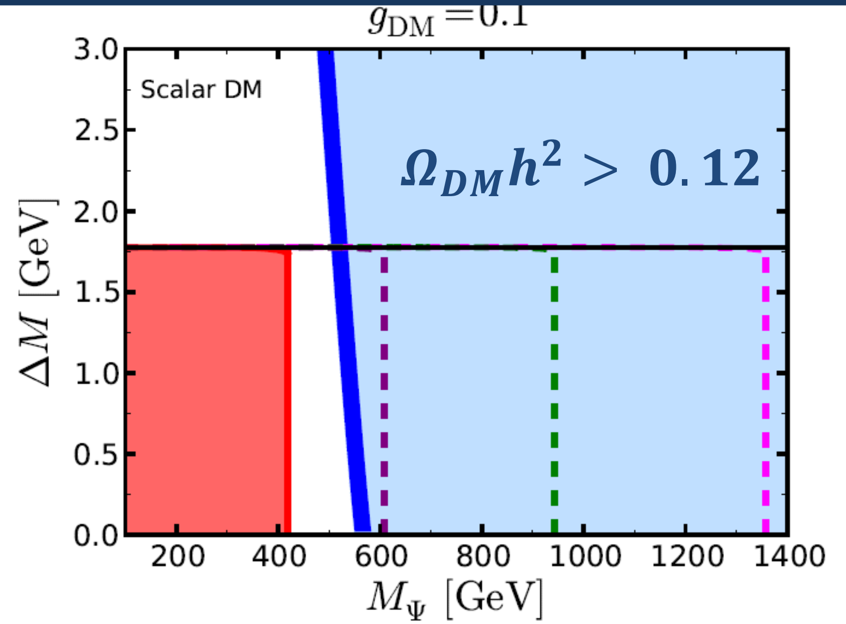
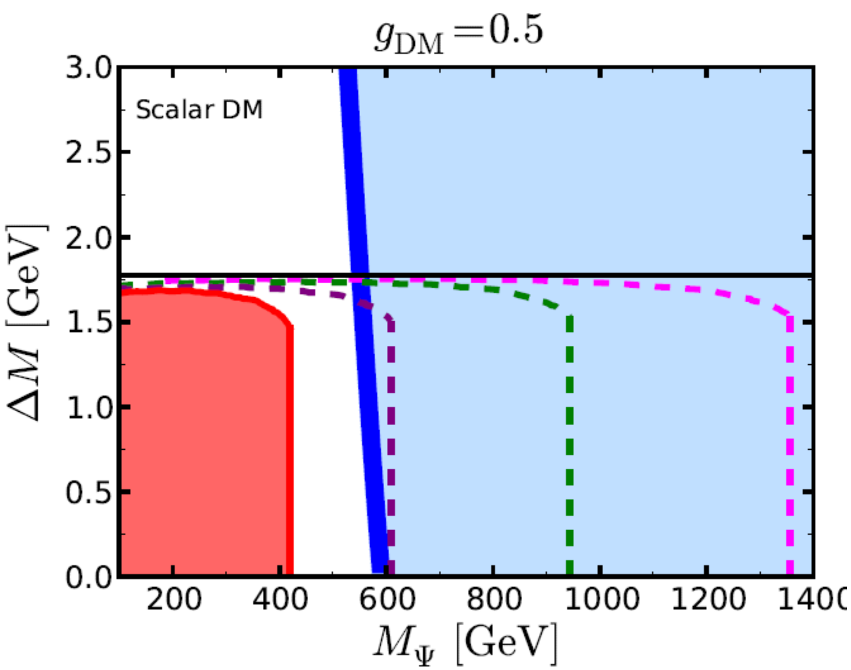
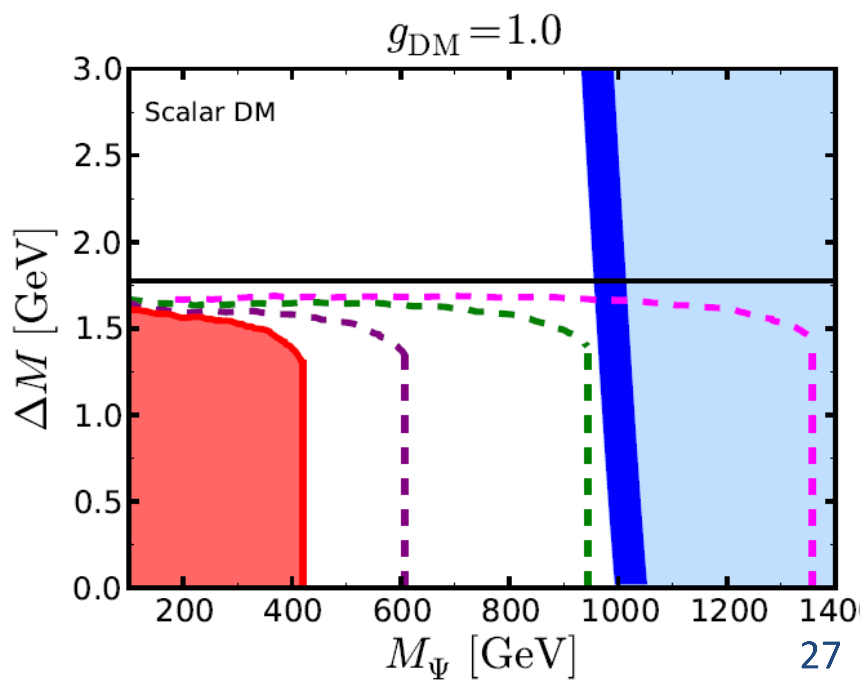
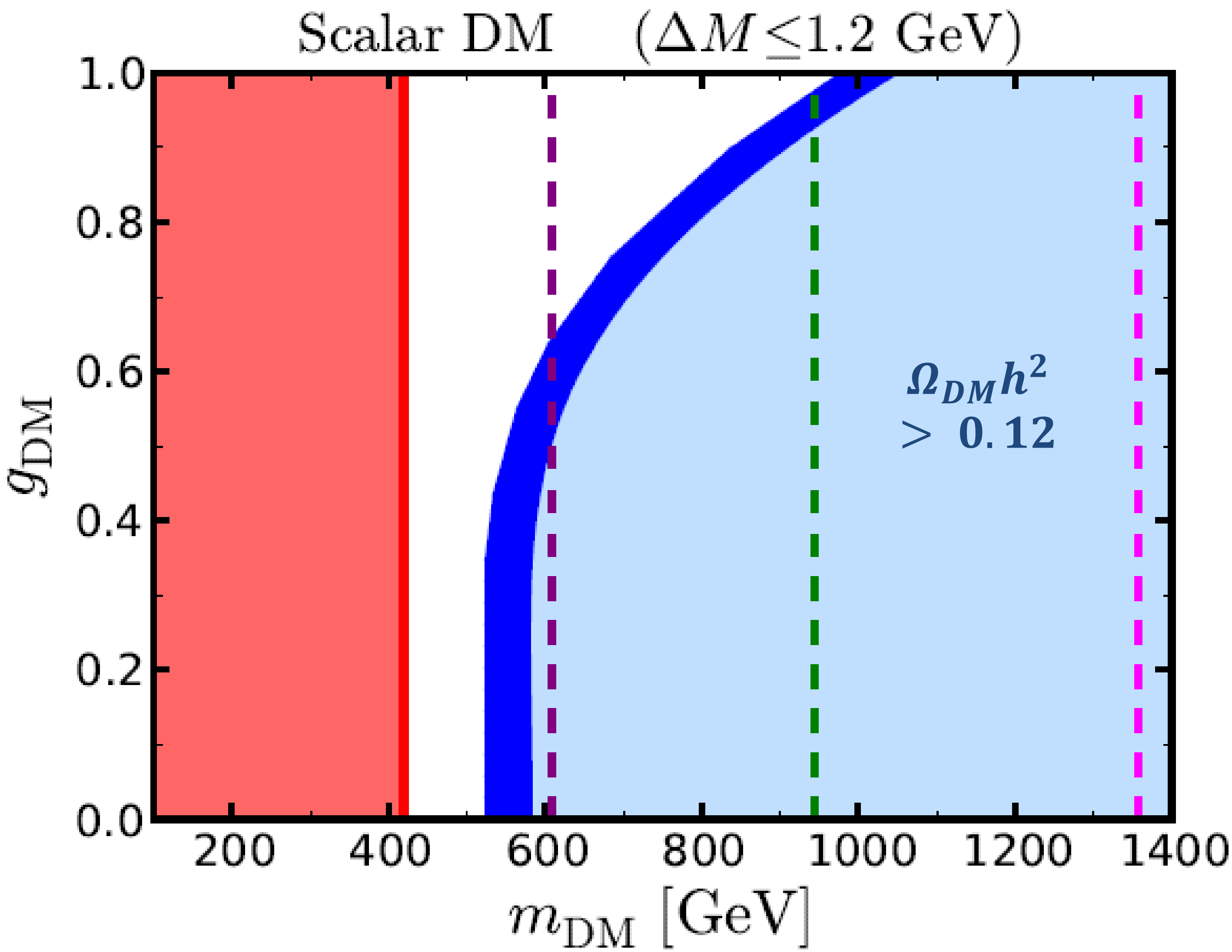
High Lumi 13 TeV 3000 fb $^{-1}$







Real scalar dark matter



13 TeV
300 fb $^{-1}$

High Lumi
13 TeV
3000 fb $^{-1}$

8 TeV
18.8 fb $^{-1}$

13 TeV
30 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

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

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

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

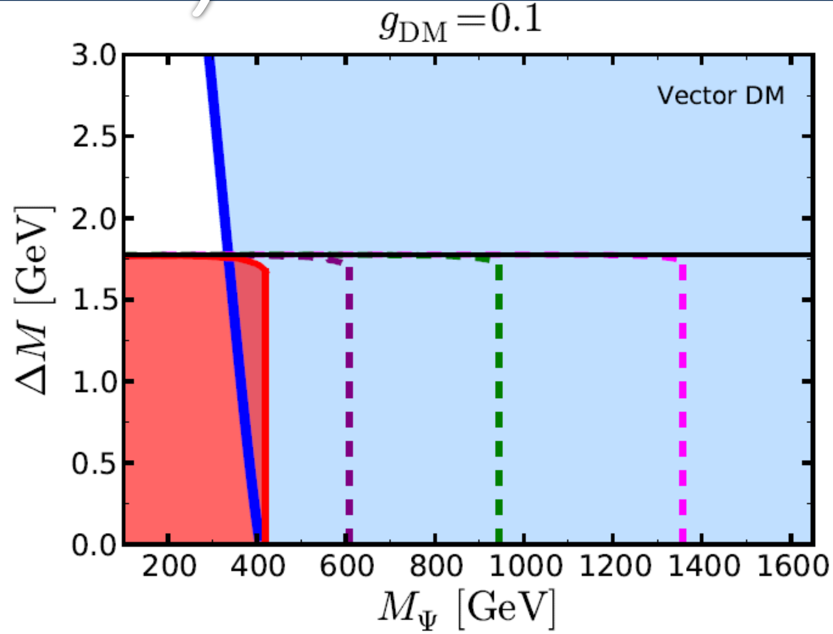
Vector dark matter (Model 3)

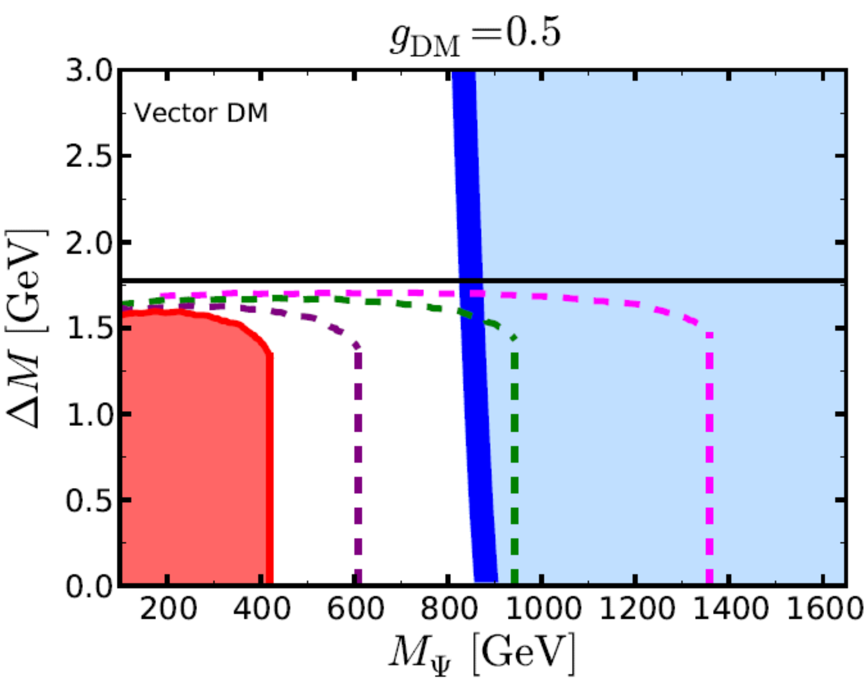
DM A_μ

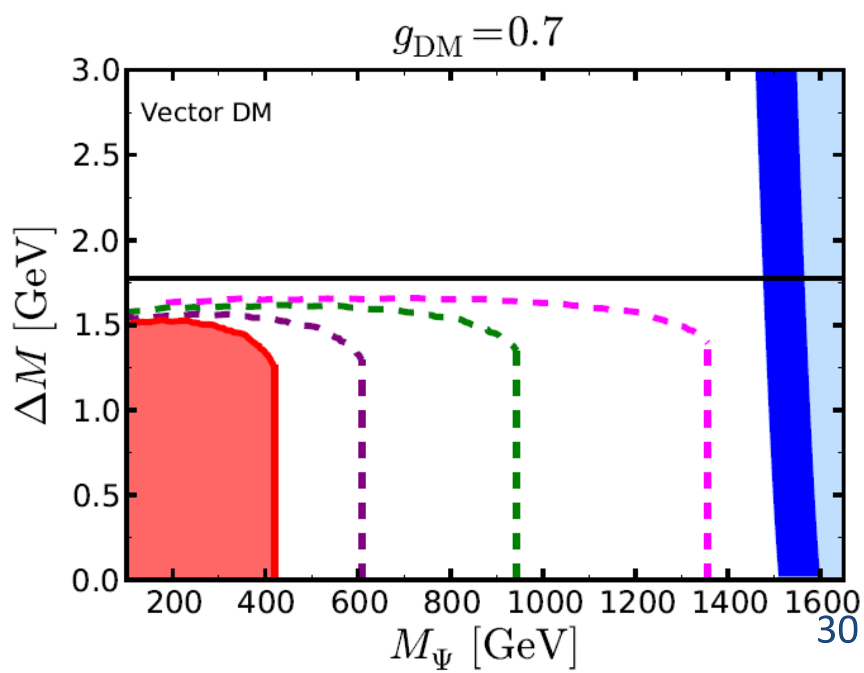
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

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

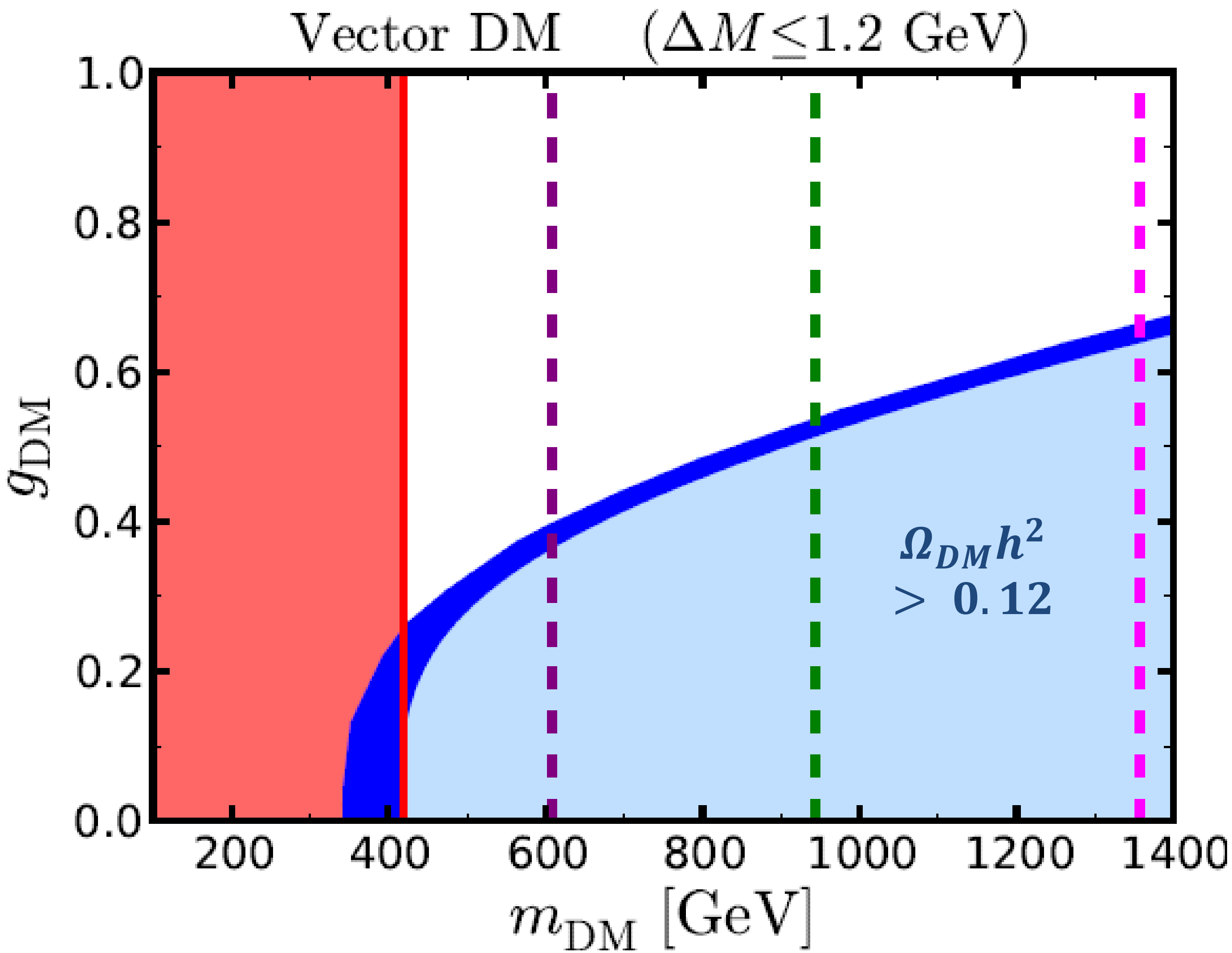
NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions







Vector dark matter



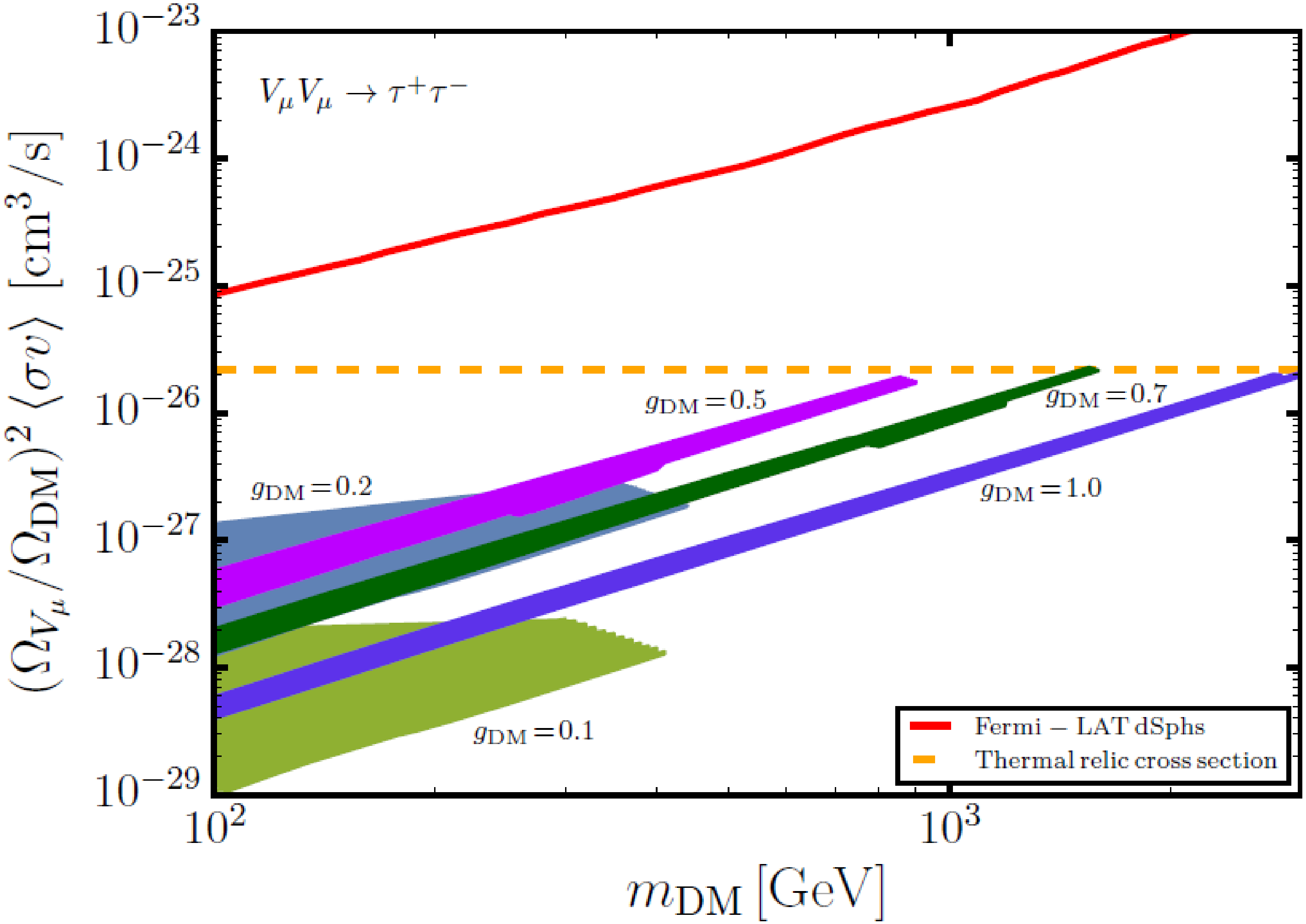
13 TeV
300 fb $^{-1}$

High Lumi
13 TeV
3000 fb $^{-1}$

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

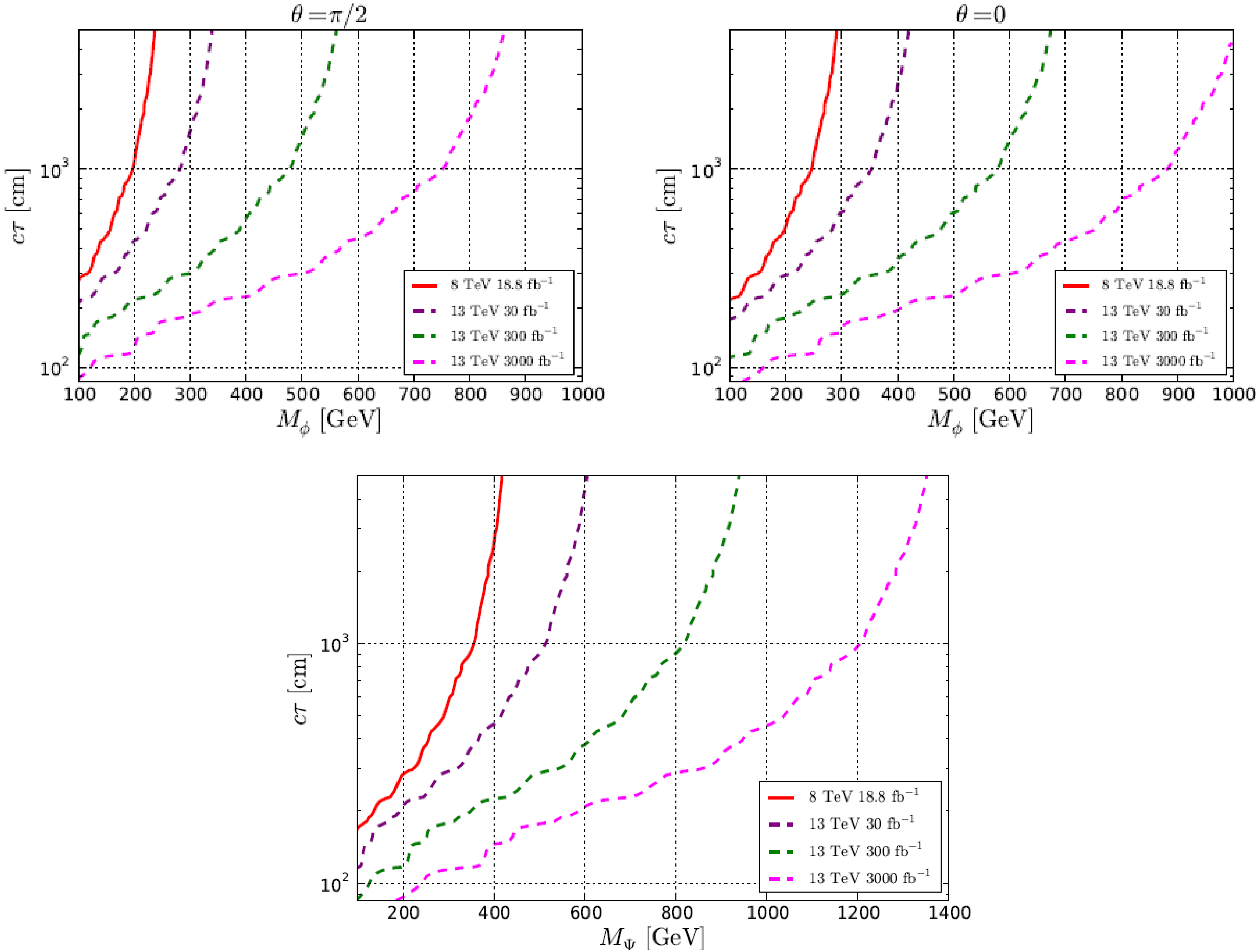
Vector dark matter



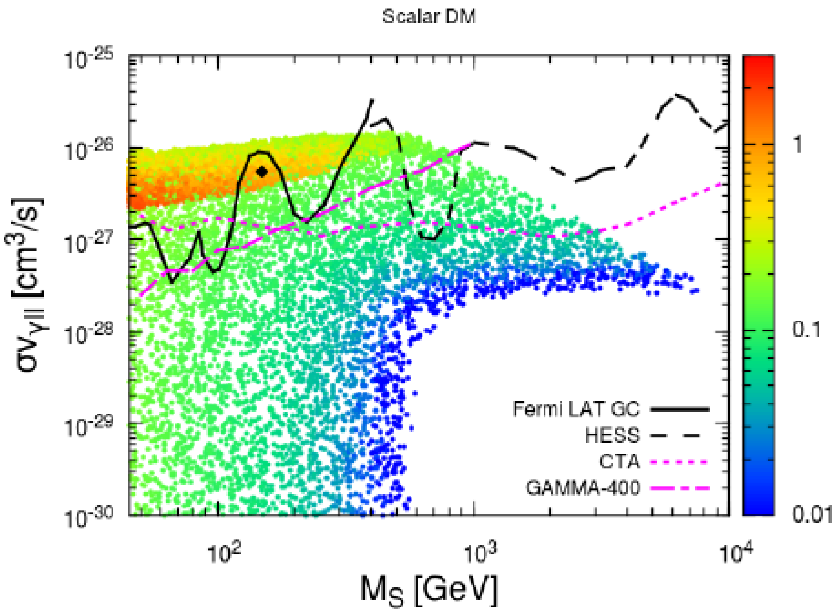
Conclusions

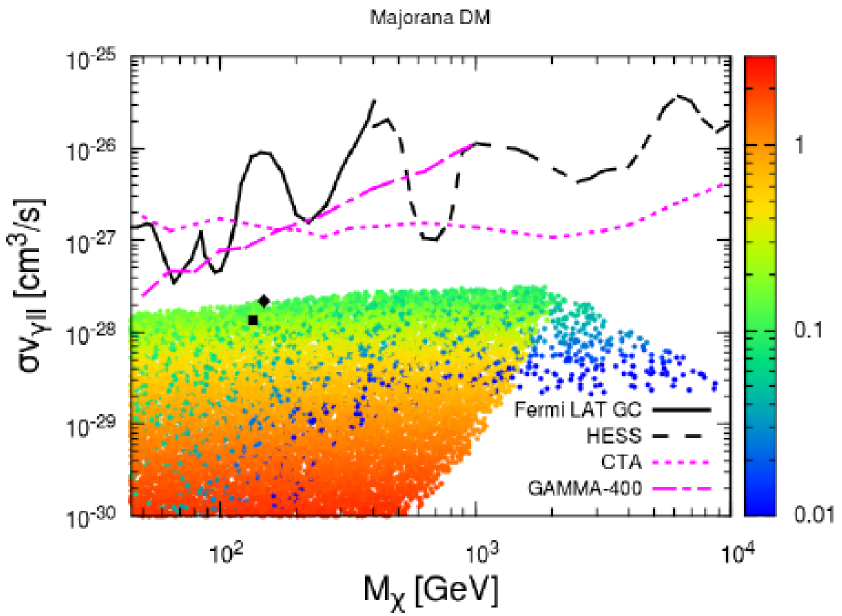
- We have studied 4 classes of simplified models, that have 3-point interaction with **τ-lepton**
- We have considered the case for **Majorana**, **real scalar** and **vector dark matter**
- Instead of a mediator, these simplified models have a **co-annihilation partner** that has **non-zero hypercharge**
- The crucial signatures are **tracks of long-lived charged particles,** these searches had not been studied before in the context of simplified models of DM
- 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.


$\theta = \pi/2$
$\theta = 0$
$c\tau$ [cm]
M_ϕ [GeV]
M_Ψ [GeV]
8 TeV 18.8 fb^{-1}
13 TeV 30 fb^{-1}
13 TeV 300 fb^{-1}
13 TeV 3000 fb^{-1}

Indirect Detection





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

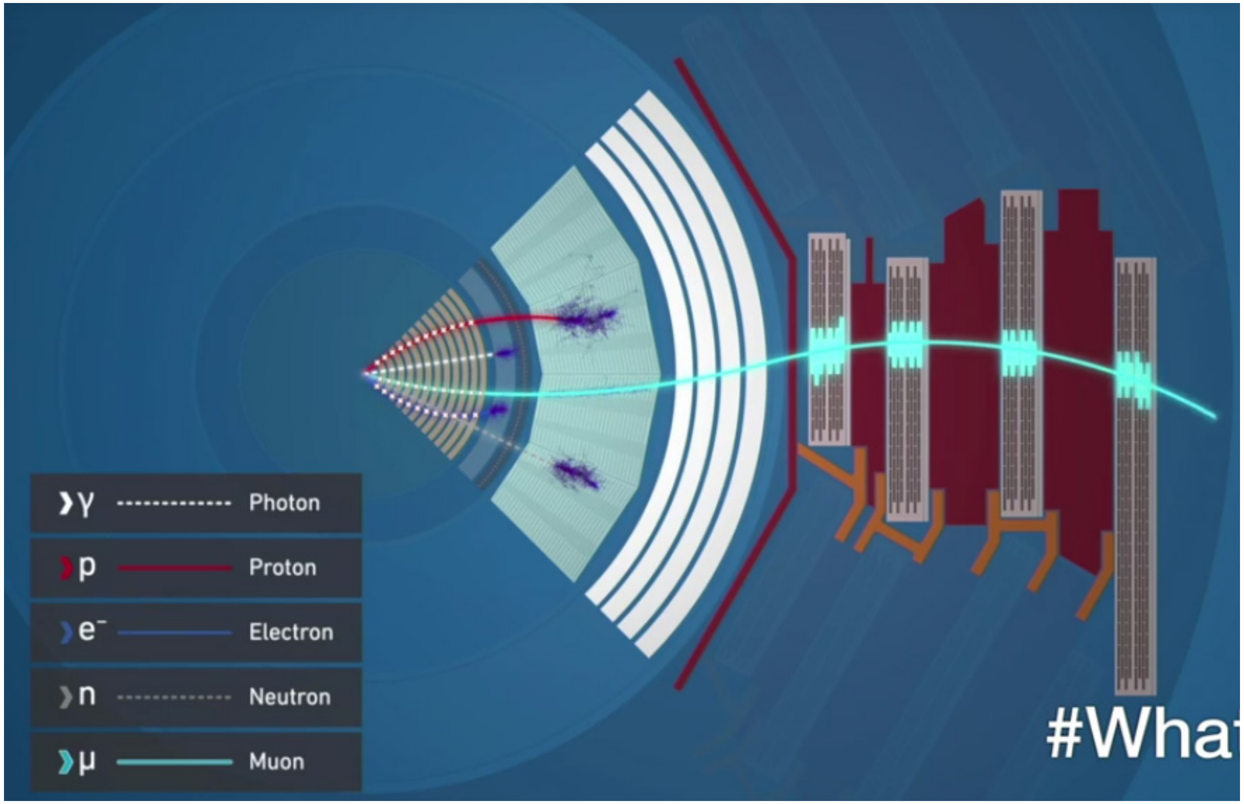
Blue dots correspond to small mass splitting

[Giacchino, Lopez-Honorez, Tytgat 2013]

Searching for long-lived charged particles

- To distinguish from muons experimentalists rely on energy loss and the time of flight (or bending from magnetic field to infer speed)

- **Anomalous charged tracks**: Heavier charged particles are slowly moving ($m > 100$ GeV $\Longrightarrow \beta = v/c < 0.9$) and have large energy loss through ionization dE/dx



[CERN Press Office]