# Constraining simplified models of dark matter with searches for long-lived charged particles

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**with Valentin Khoze and Kazuki Sakurai**

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

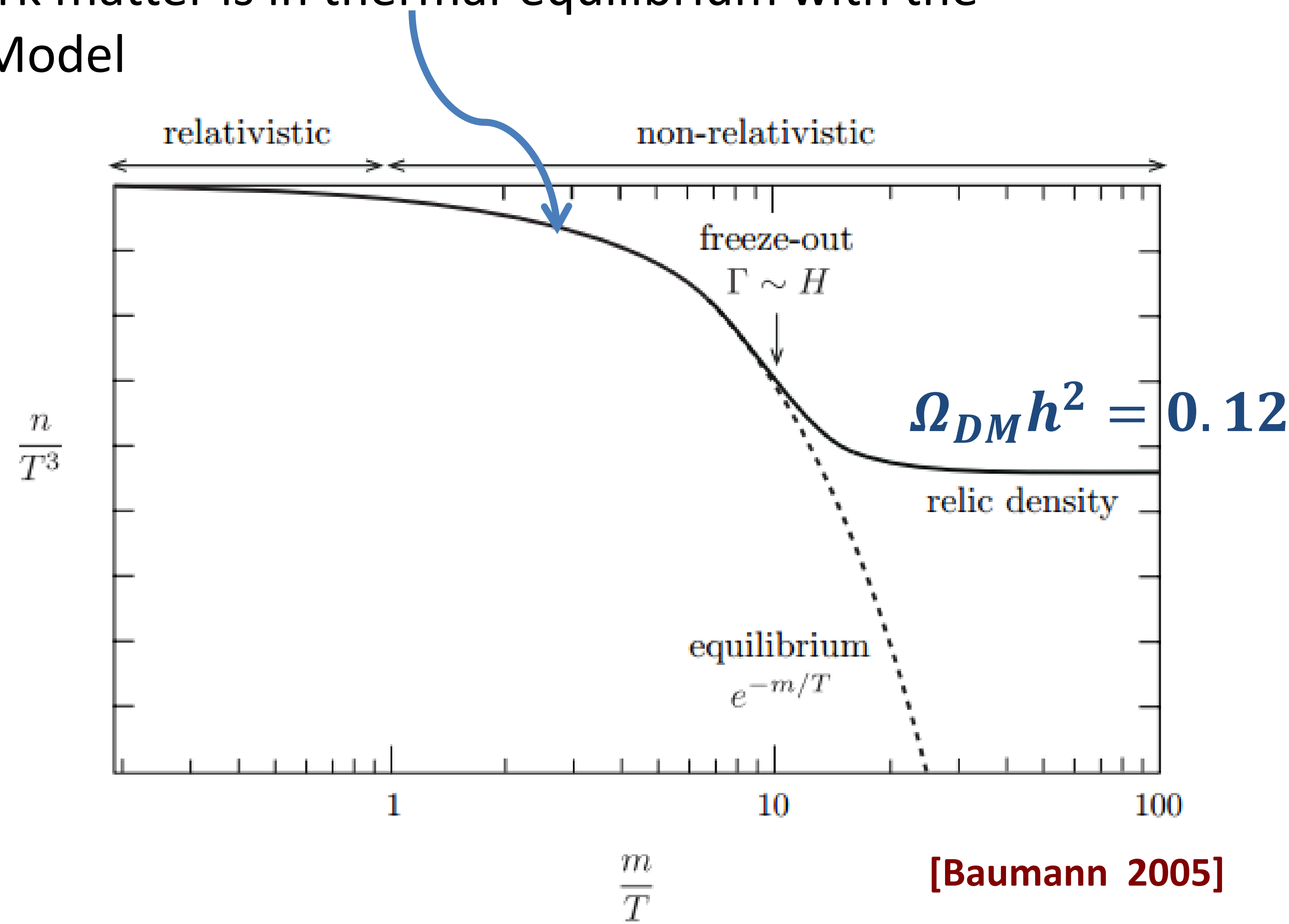
Durham University

IP3

DM@LHC Heidelberg 2018

# WIMP paradigm

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




[Baumann 2005]

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

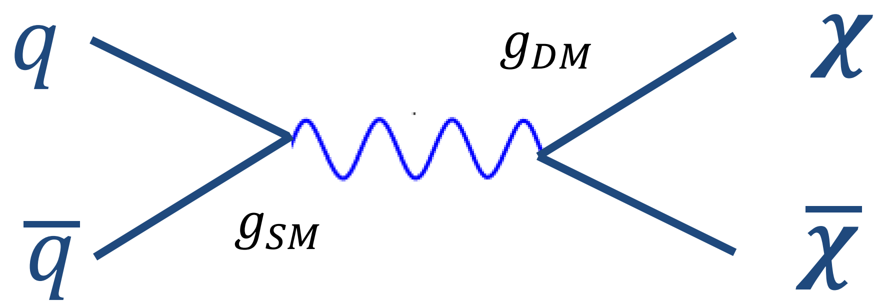
- An alternative and complementary search to Direct and Indirect detection experiments is the production of Dark Matter at colliders, such as the LHC

- 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 $\tau$ lepton

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

Co-annihilation partner (CAP)

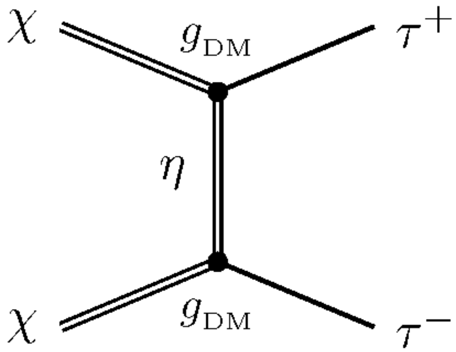
**Simplified models with only 3 free parameters:**

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

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

# 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

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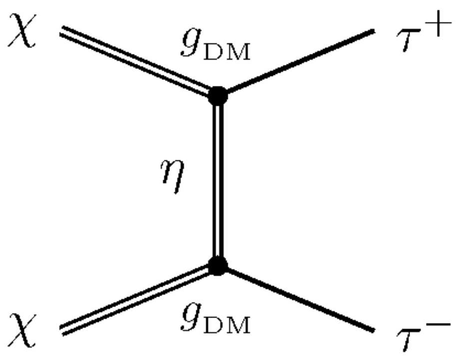


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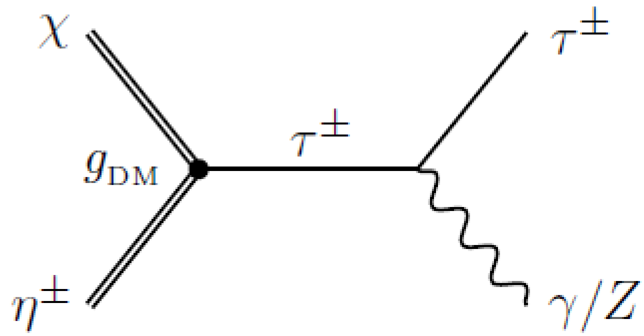
Co-annihilation:



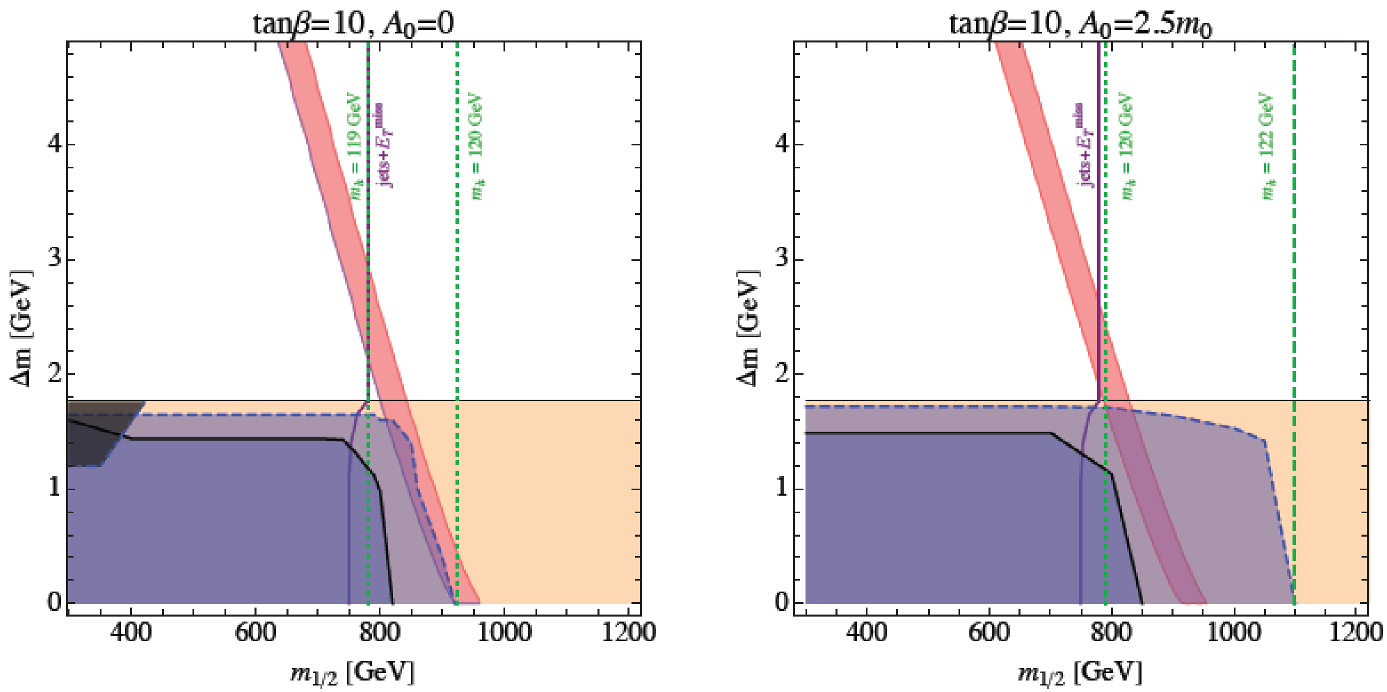

Freeze-out temperature $T_F \sim\ m_{DM}/25$

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)**

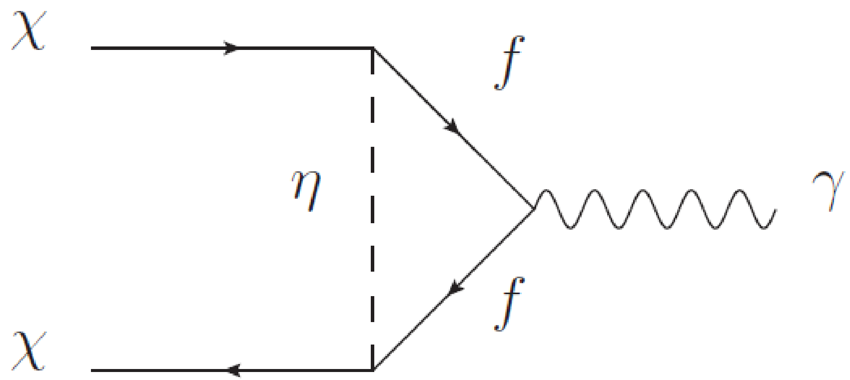



We want to generalize this.

[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 $A > 2 \times 10^{-5}\;[\mu_N\;\text{fm}]$

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

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

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

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

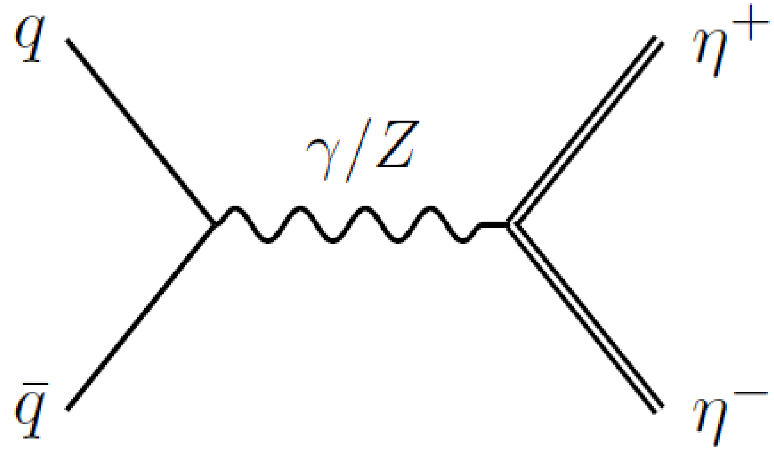
Nevertheless, the channel $S\,S \rightarrow l\,l\,\gamma$ can be relevant for future experiments for scalar DM

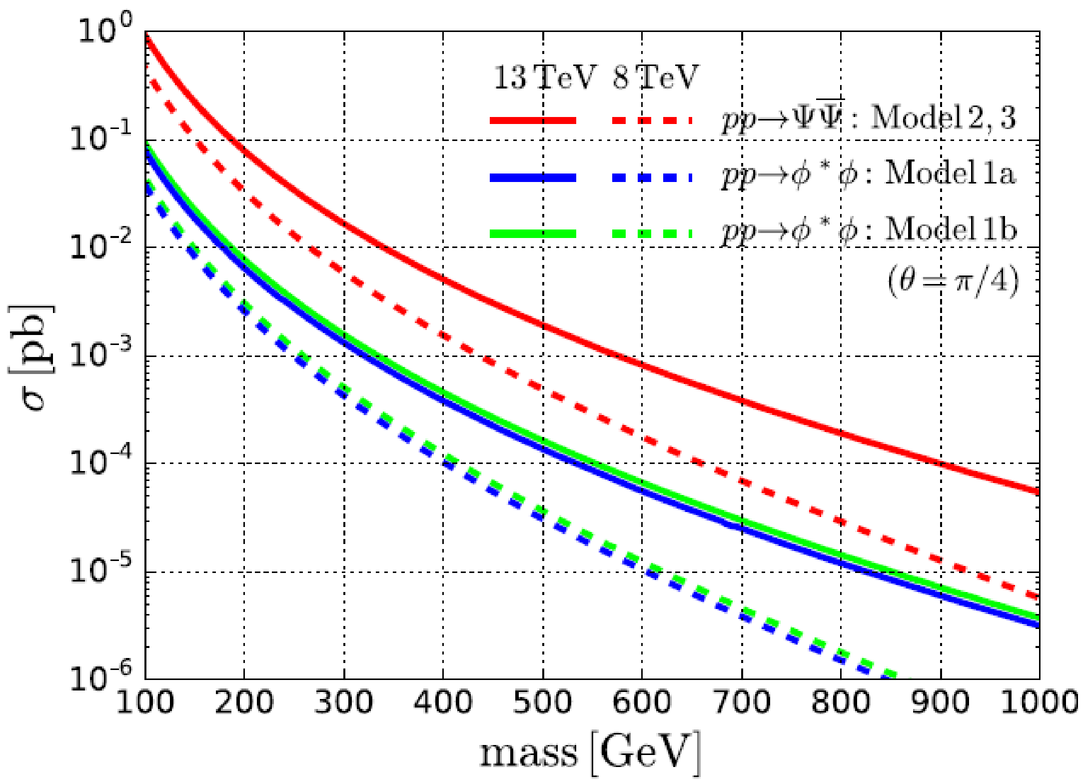
**For large $\Delta M$**

**[Giacchino, Lopez-Honorez, Tytgat 2013]**

# LHC production

- Drell-Yann pair production of co-annihilation partner

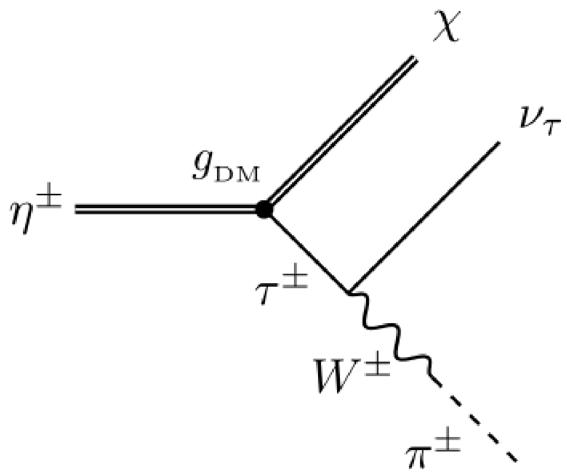


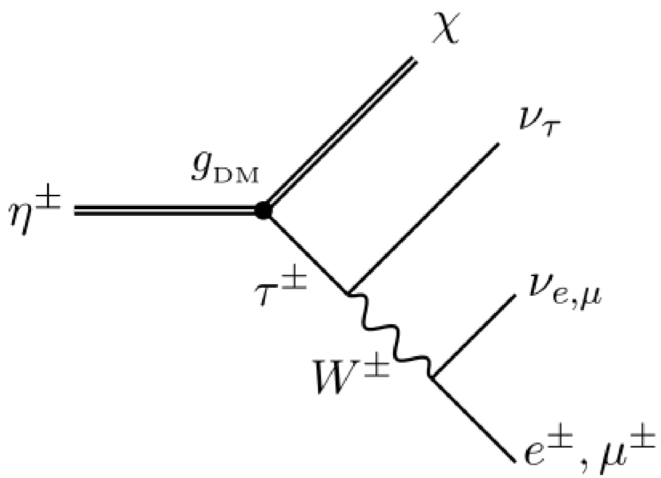

- We study Dirac fermion and complex scalar as co-annihilation partners

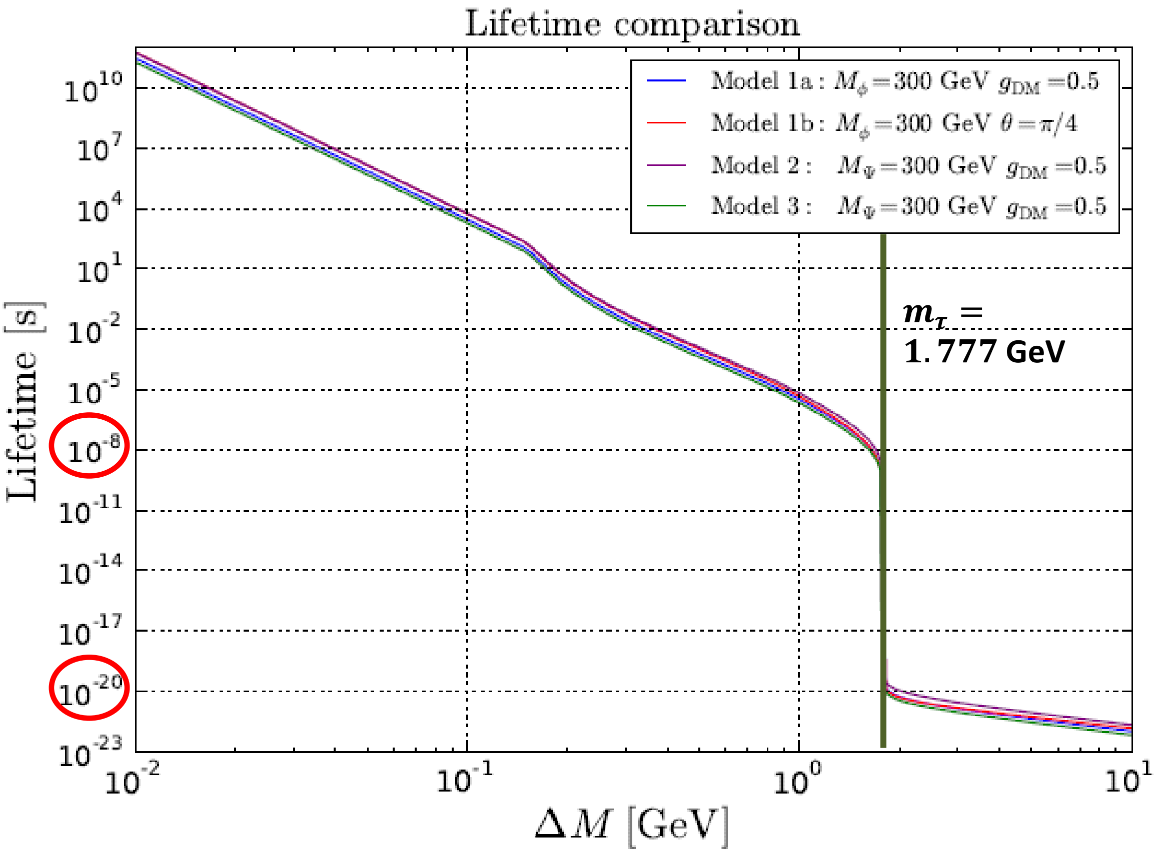
# Long-lived electrically charged particles

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

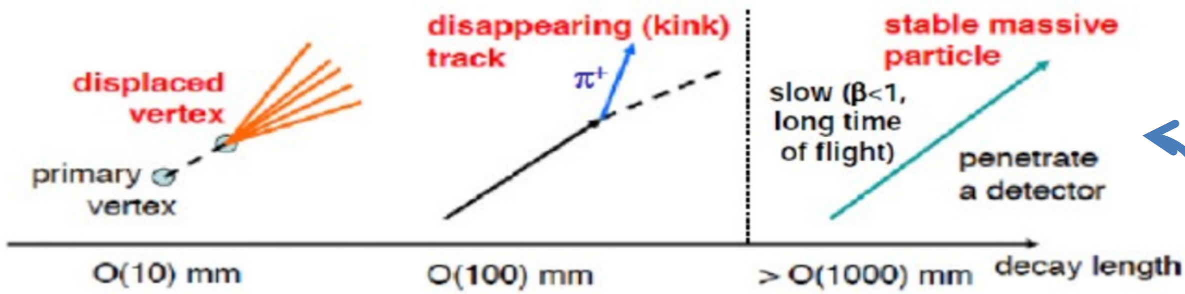



**Also ρ and $a_1$ mesons**



# Searching for long-lived charged particles



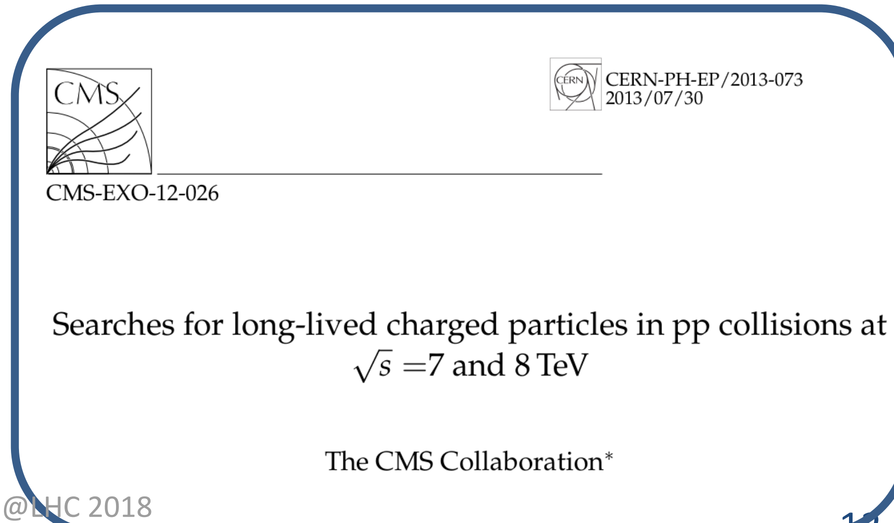

THIS TALK!

[Buchmuller et al, 2017]

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

$c\tau > 1\text{ m}$

- 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*

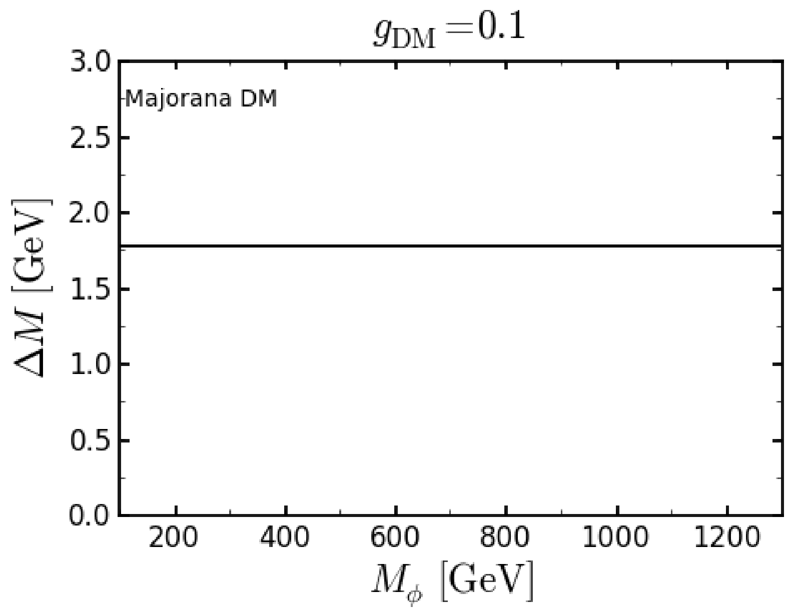
# Majorana Dark Matter

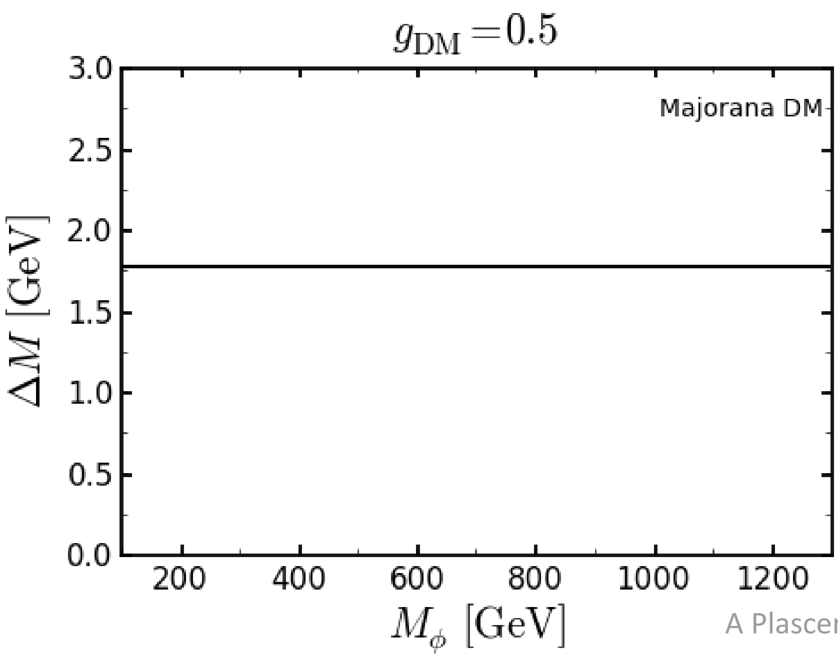
**DM** $\chi$

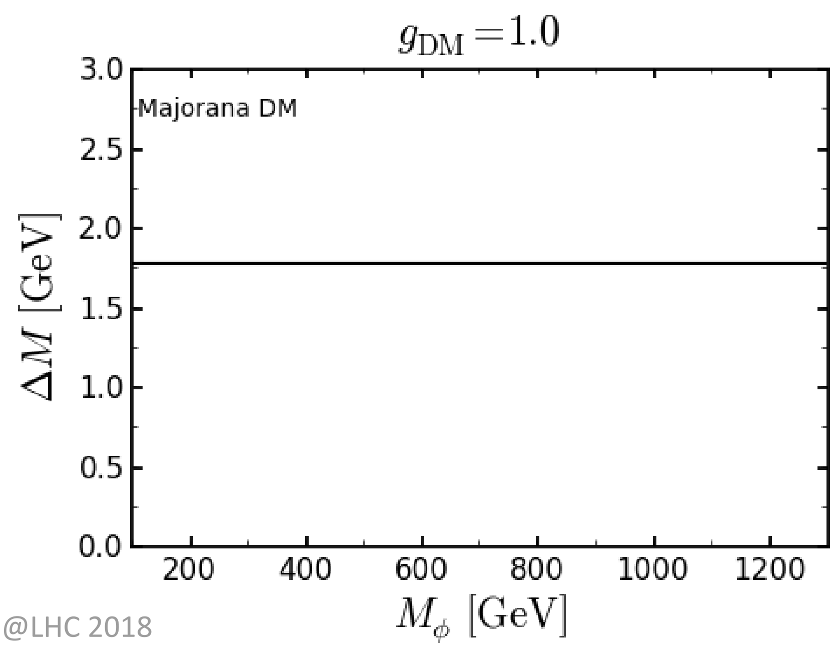
**CAP** $(Y = 1 \;\; L_\tau = 1)$ $\phi$

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

**Gauge-invariant and renormalizable, no problems of unitarity**



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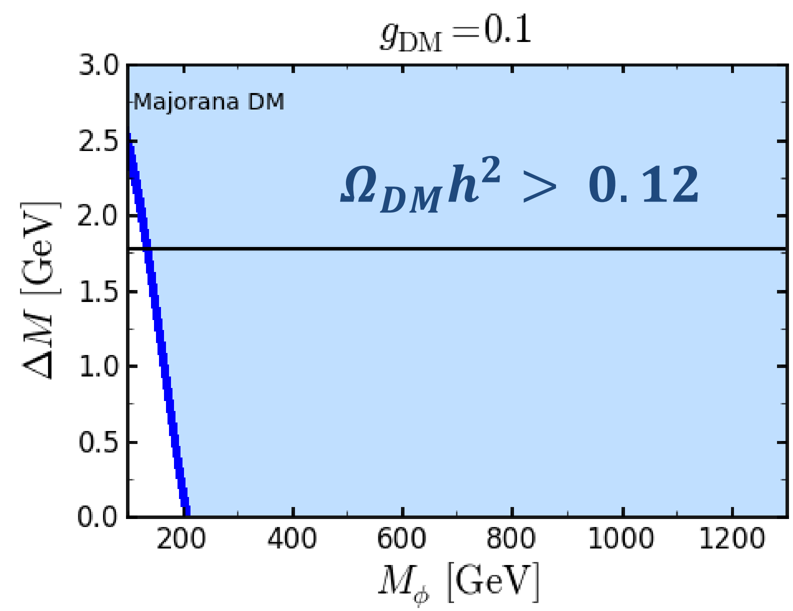


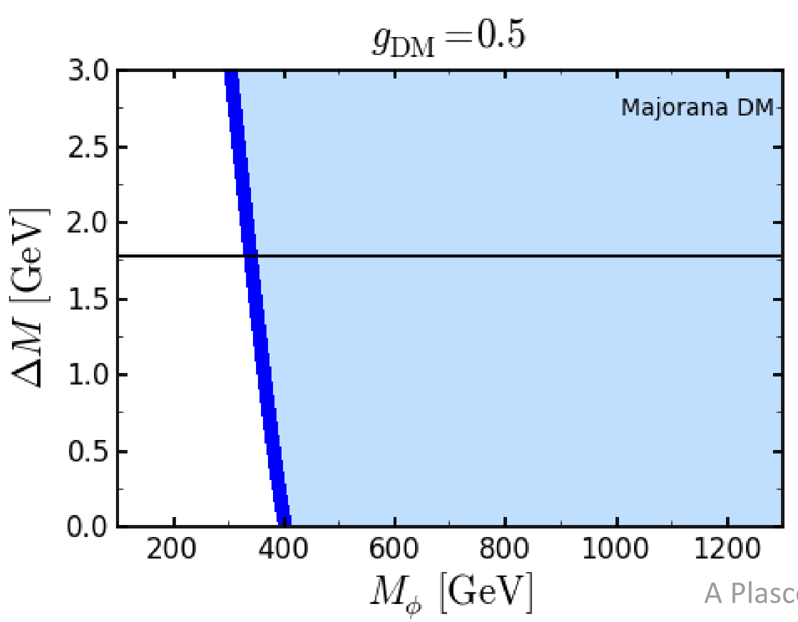


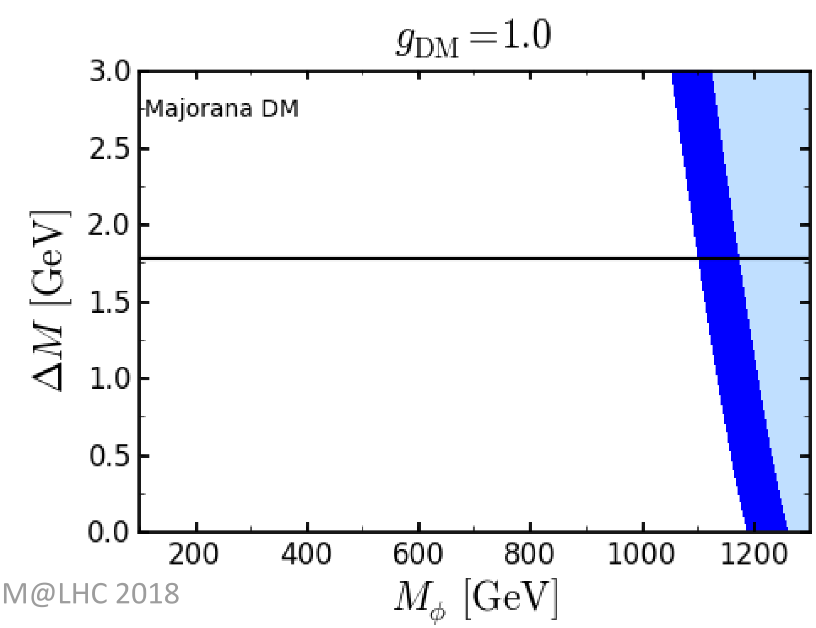

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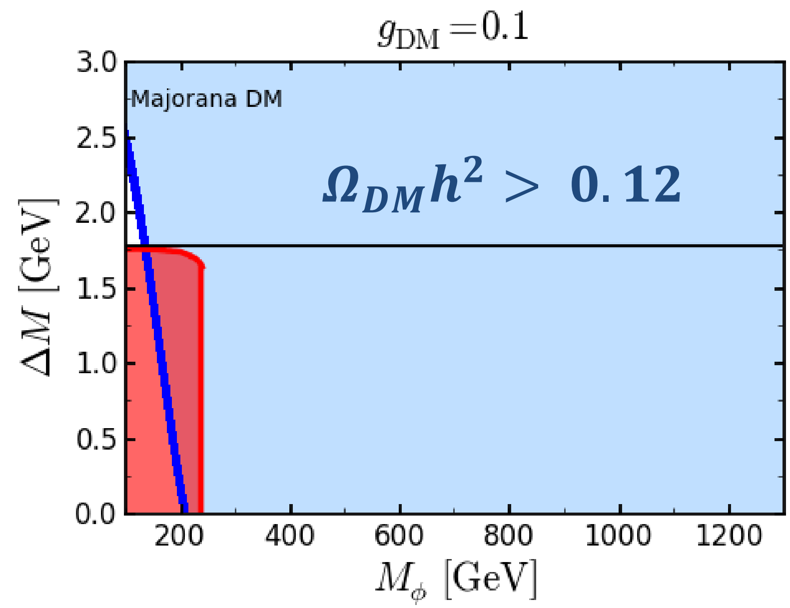
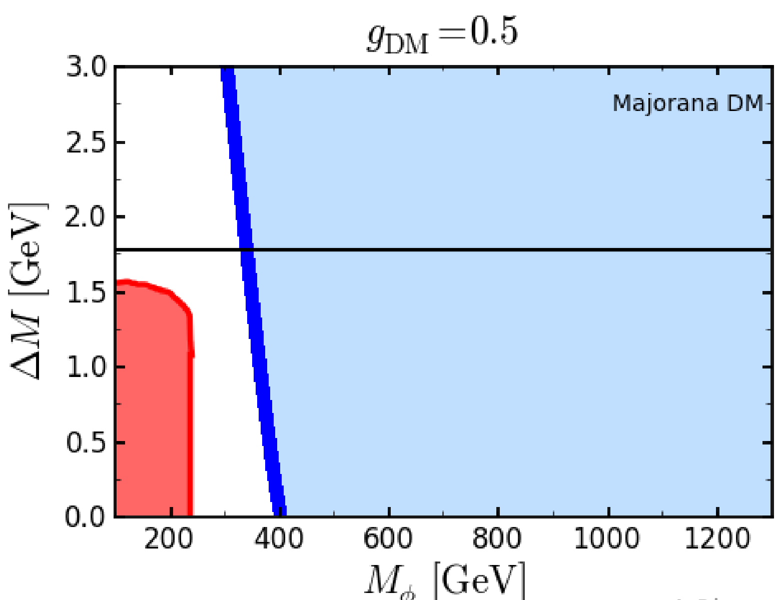
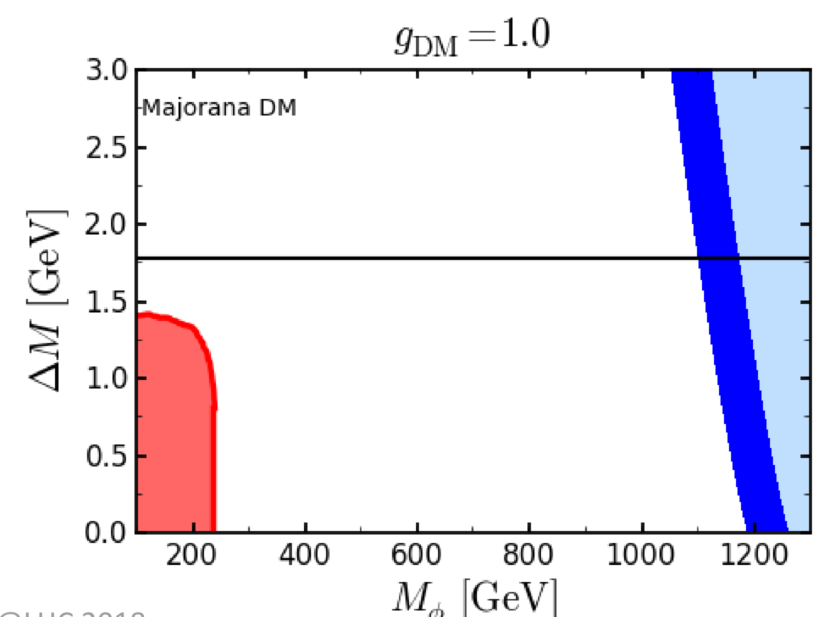
**CMS & ATLAS**
**8 TeV 18.8 fb $^{-1}$**



# Majorana Dark Matter

**DM** $\chi$

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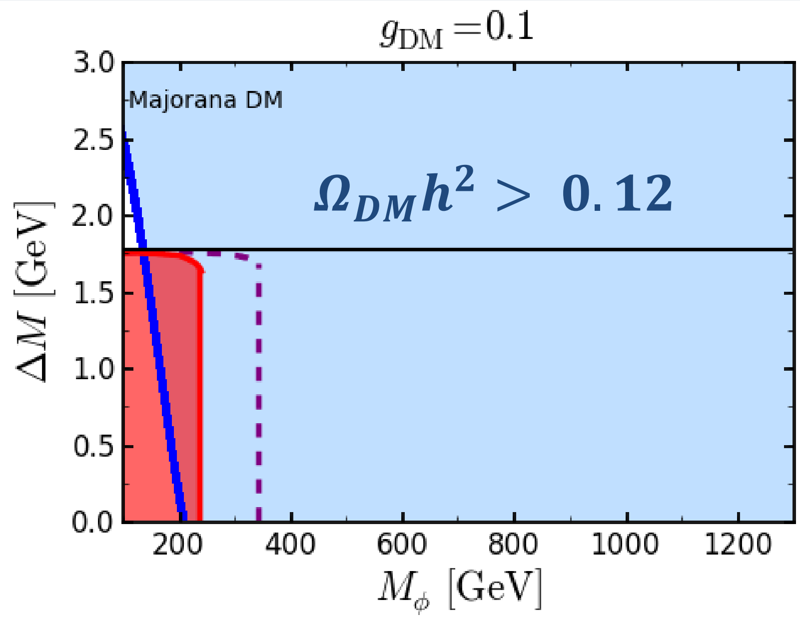
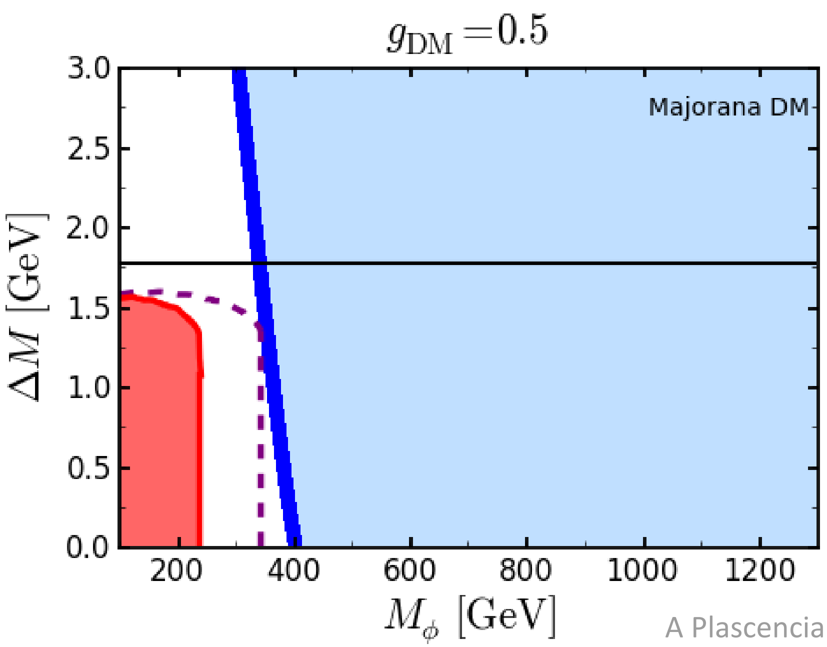
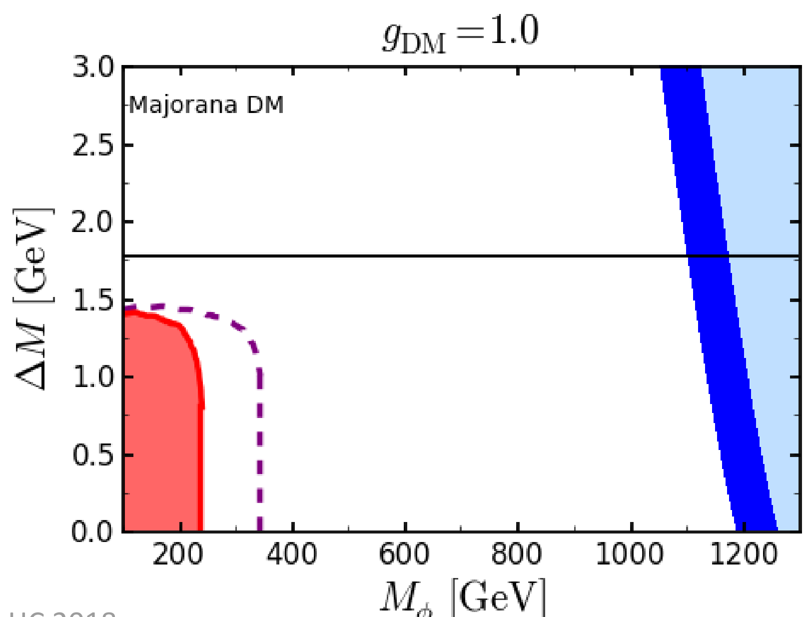
**13 TeV 30 fb$^{-1}$**



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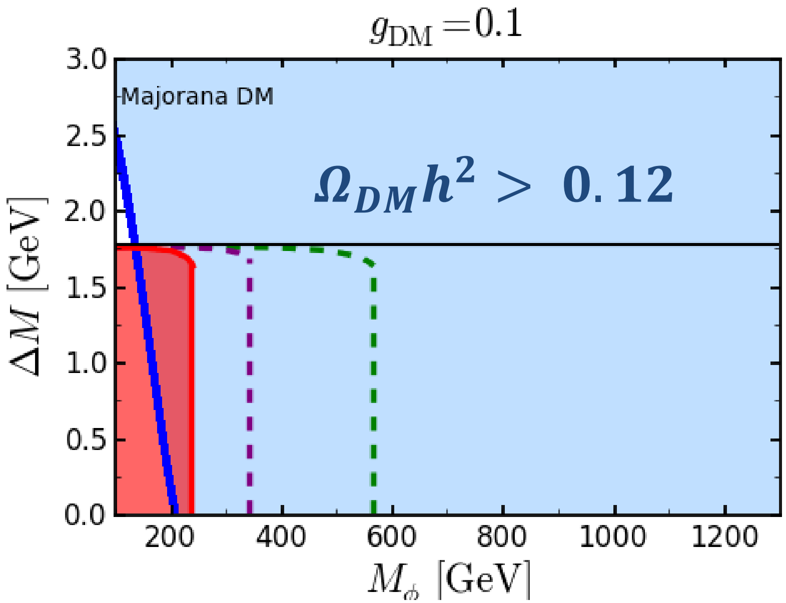
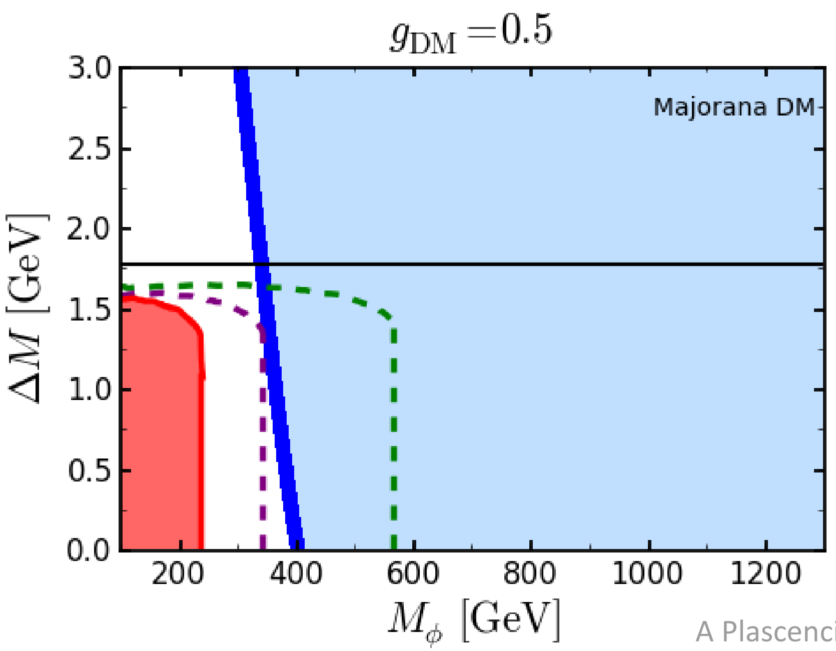
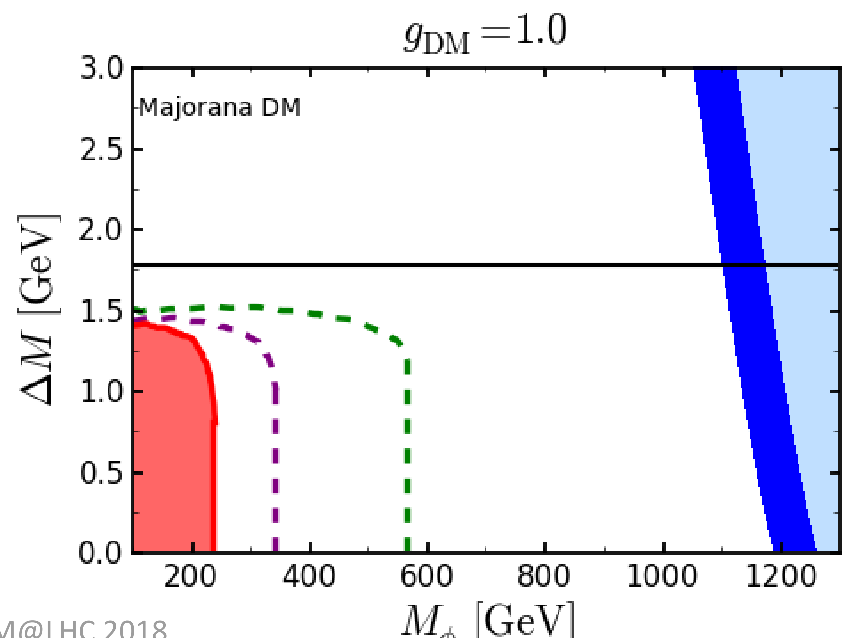


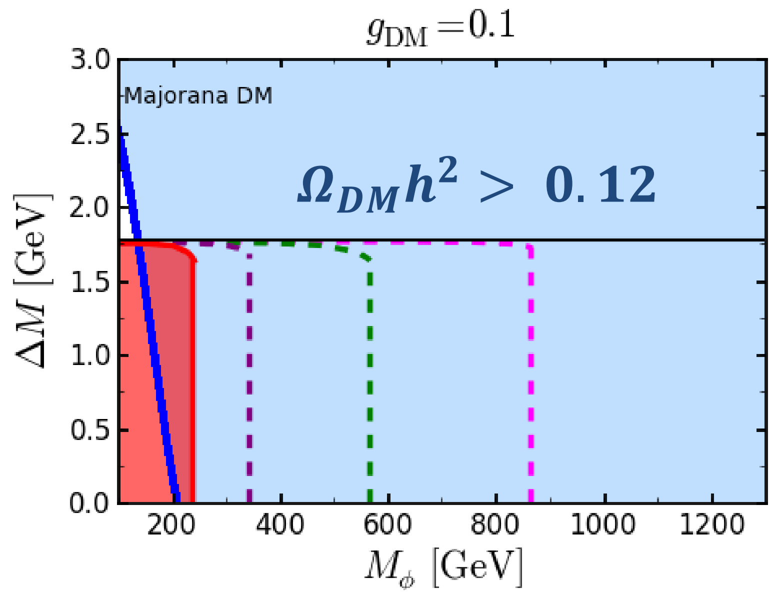



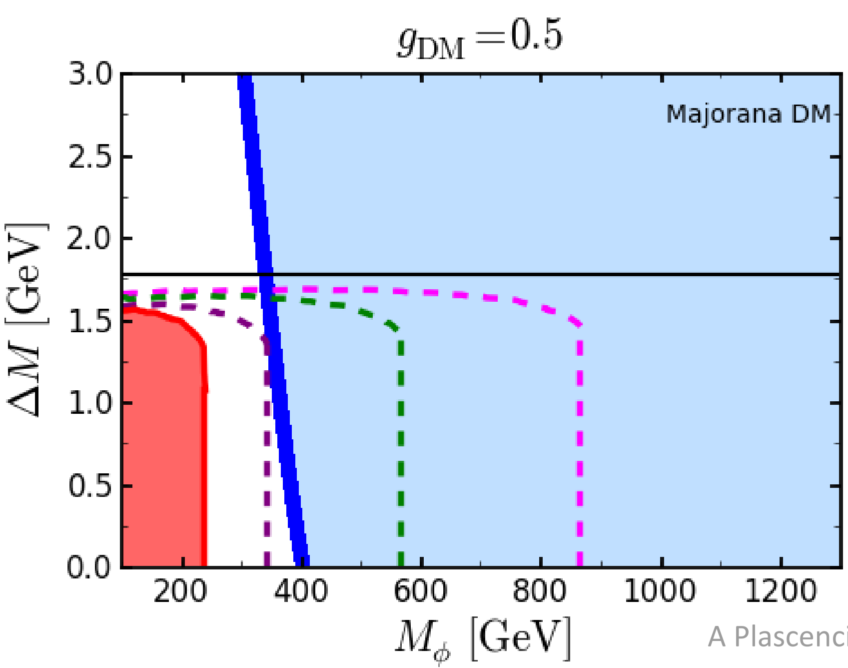
# Majorana Dark Matter

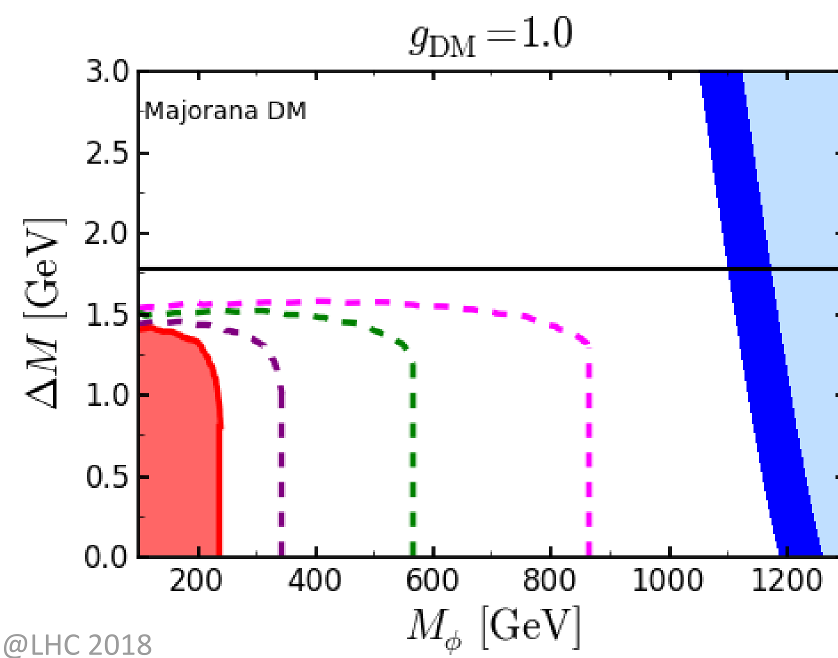
| DM | CAP $(Y = 1 \;\; L_\tau = 1)$ |
|---|---|
| $\chi$ | $\phi$ |

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

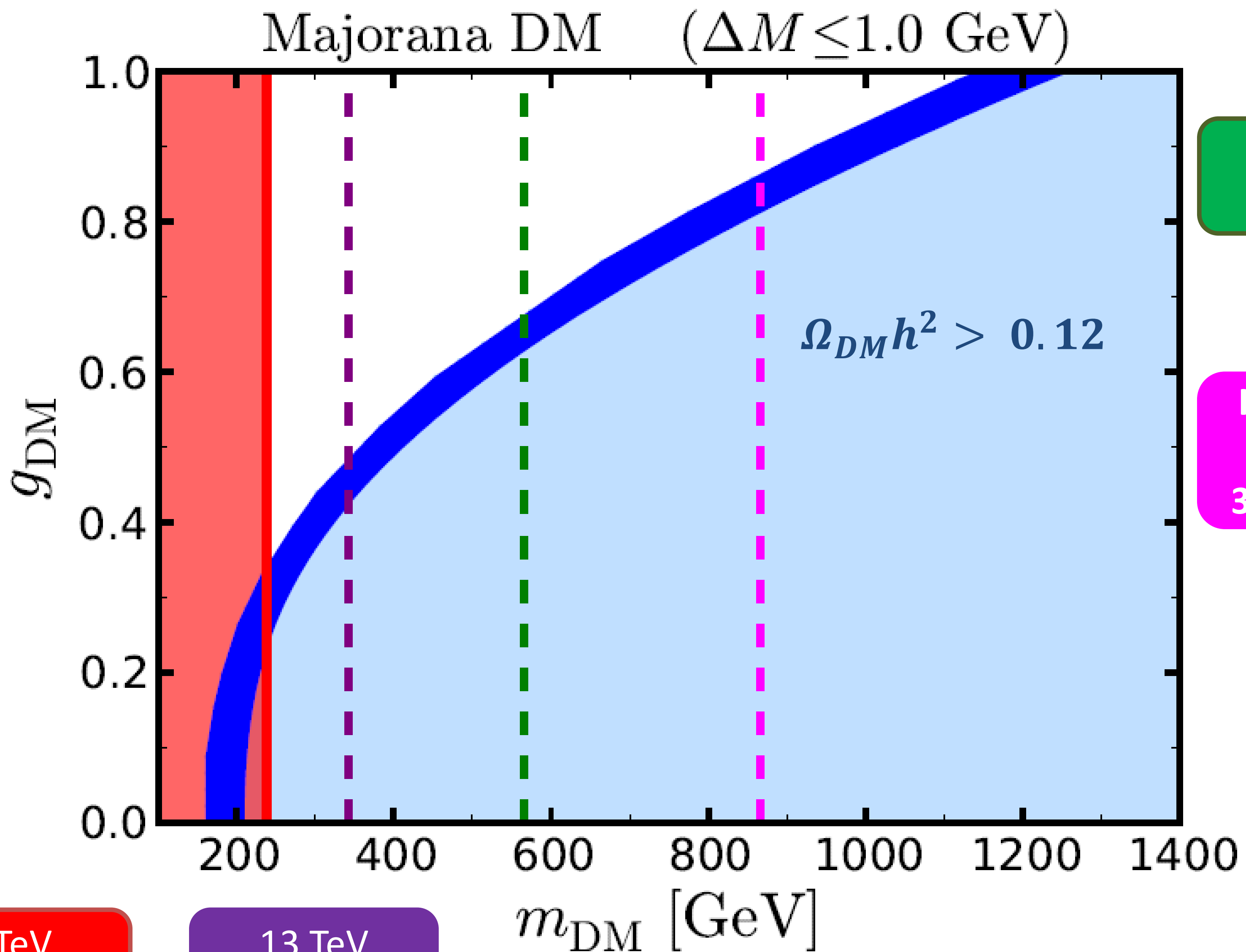
**High Lumi 13 TeV 3000 fb $^{-1}$**



# Majorana Dark Matter




13 TeV
300 fb $^{-1}$

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

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

A Plascencia DM@LHC 2018

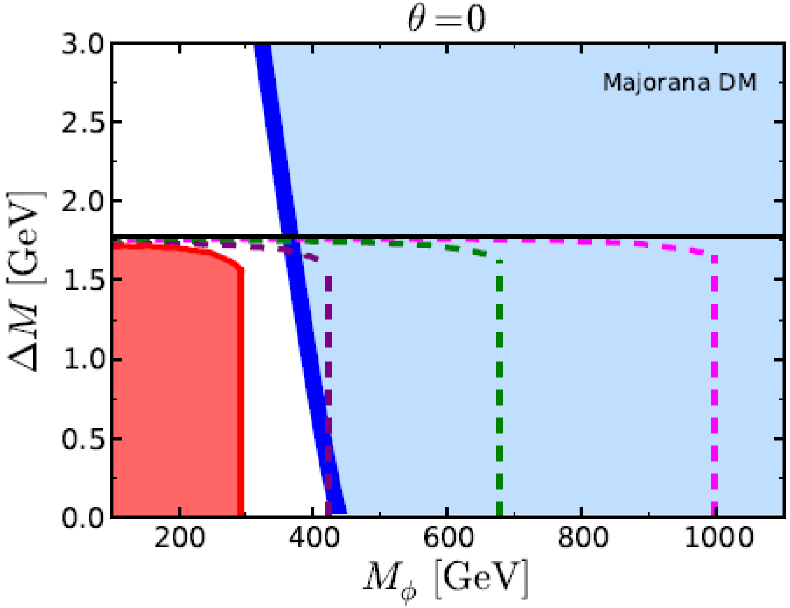
# Majorana Dark Matter (Model 1b)

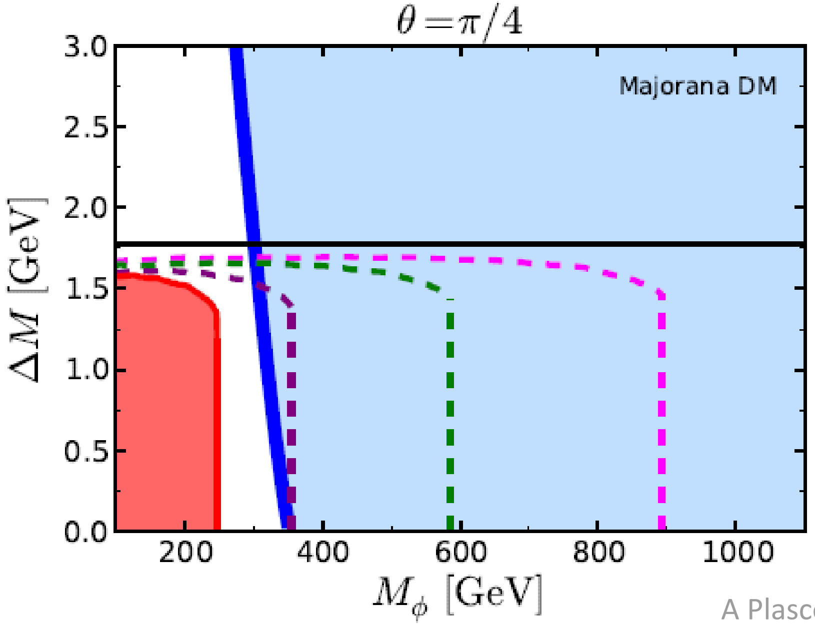
**DM** $\chi$ **CAP** $(Q = -1)$ $\phi$

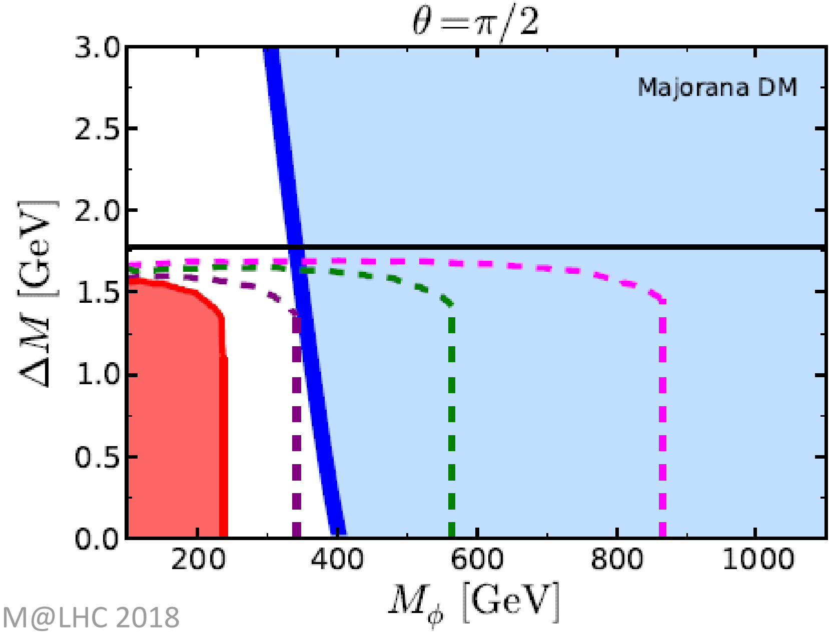
$$g_R\, \phi^* (\chi\, \tau_R) + g_L\, \phi^* (\chi\, \tau_L) \subset \mathcal{L}$$

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

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



# Majorana Dark Matter (Model 1b)

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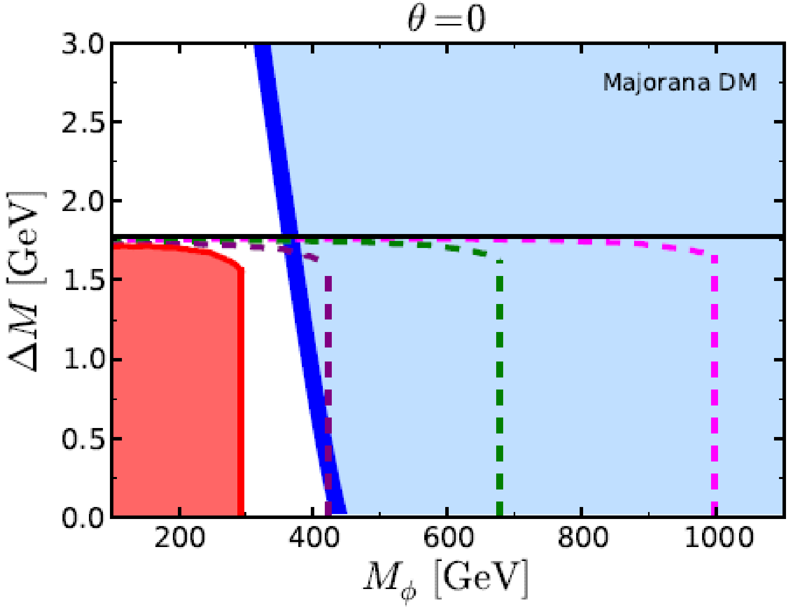
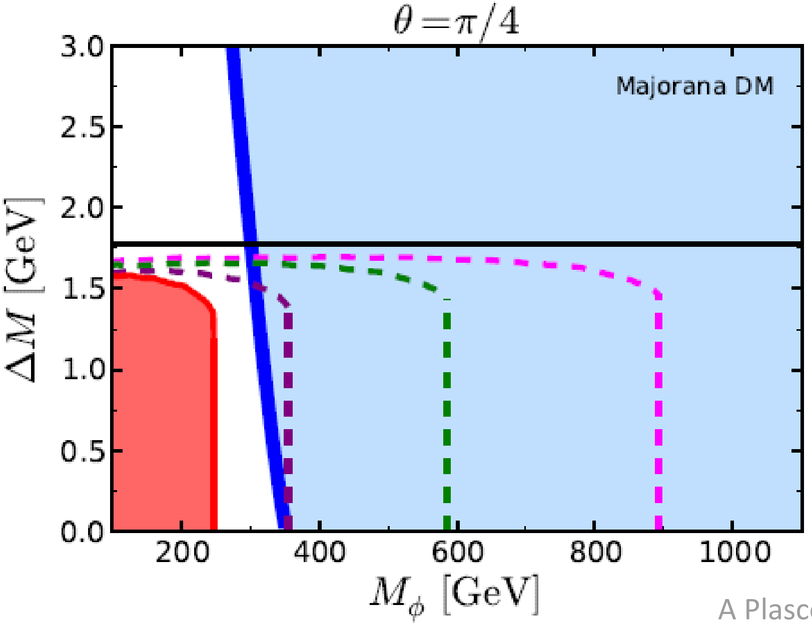
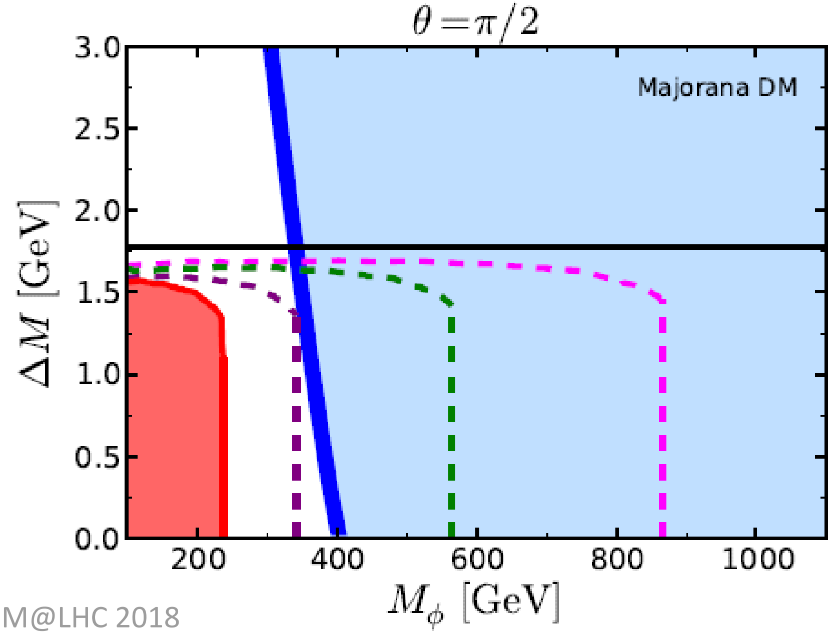
**CAP** $(Q = -1)$ $\phi$

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

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



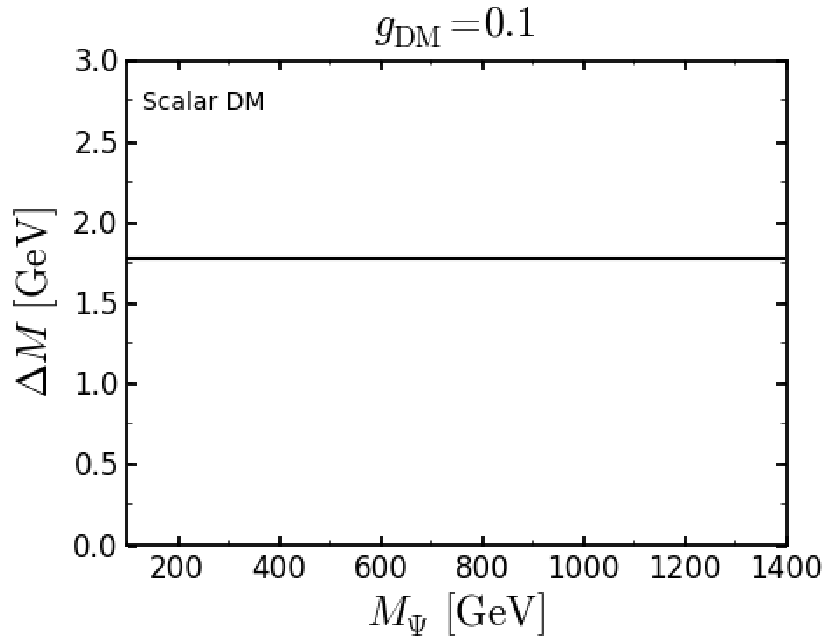
# Real scalar dark matter

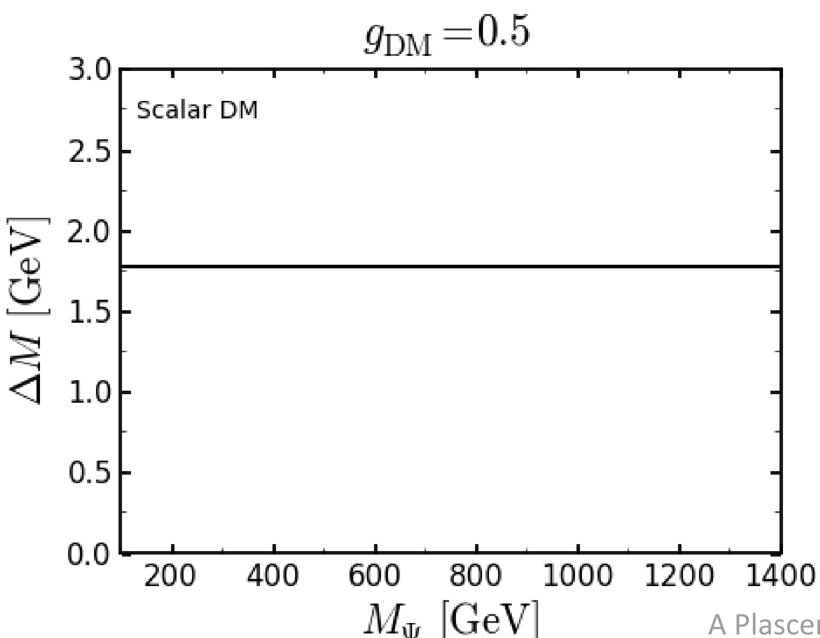
**DM** **CAP** $(Y = 1 \;\; L_\tau = 1)$

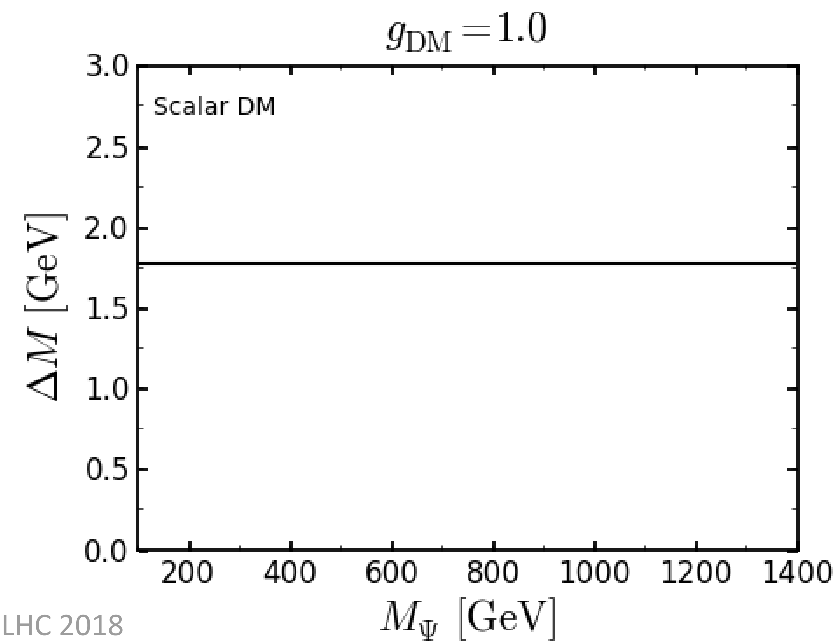
$S$ $\Psi$

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

**Gauge-invariant and renormalizable,**
**no problems of unitarity**



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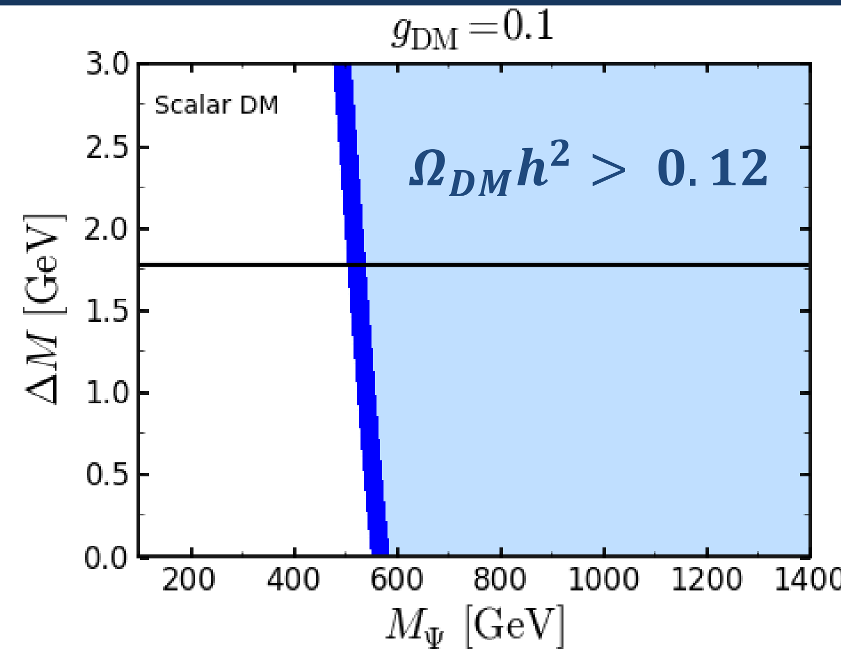


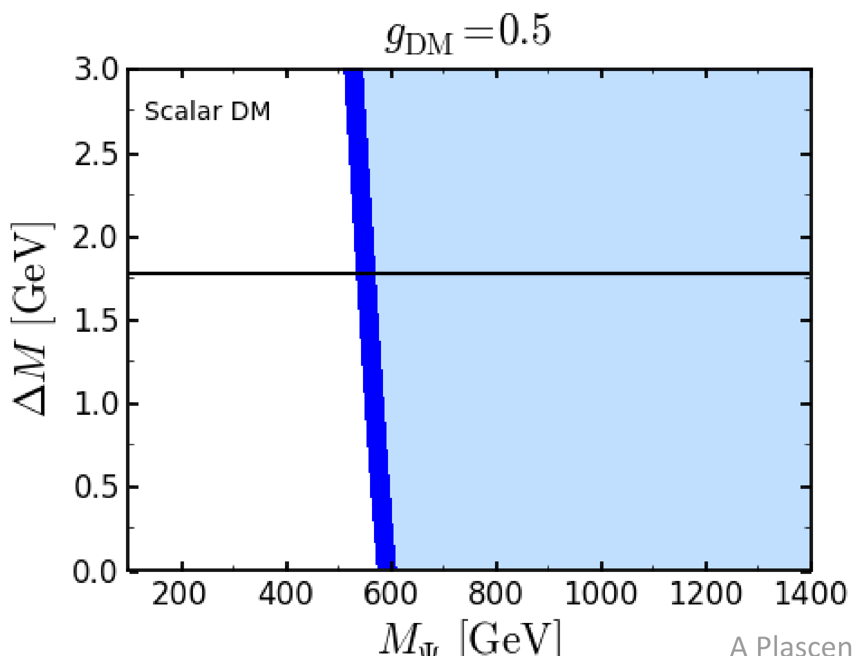


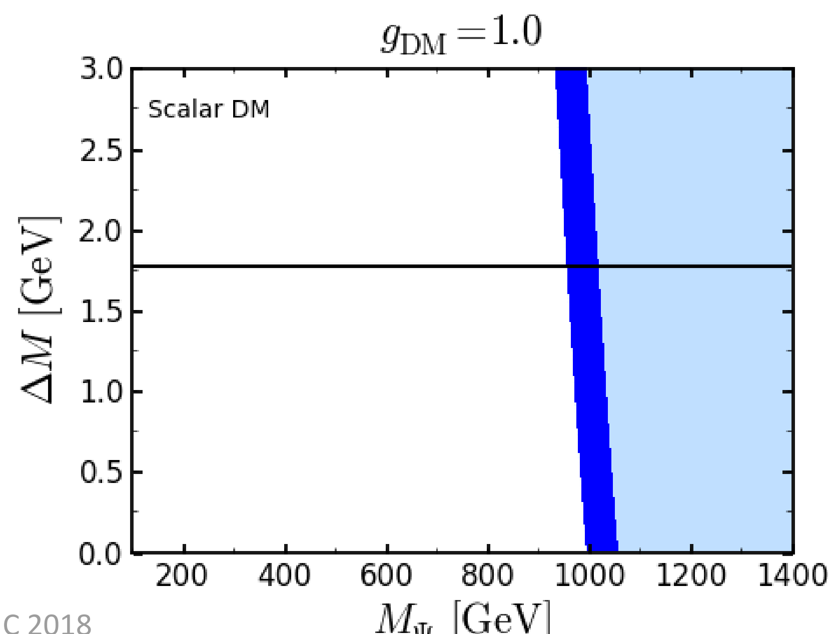

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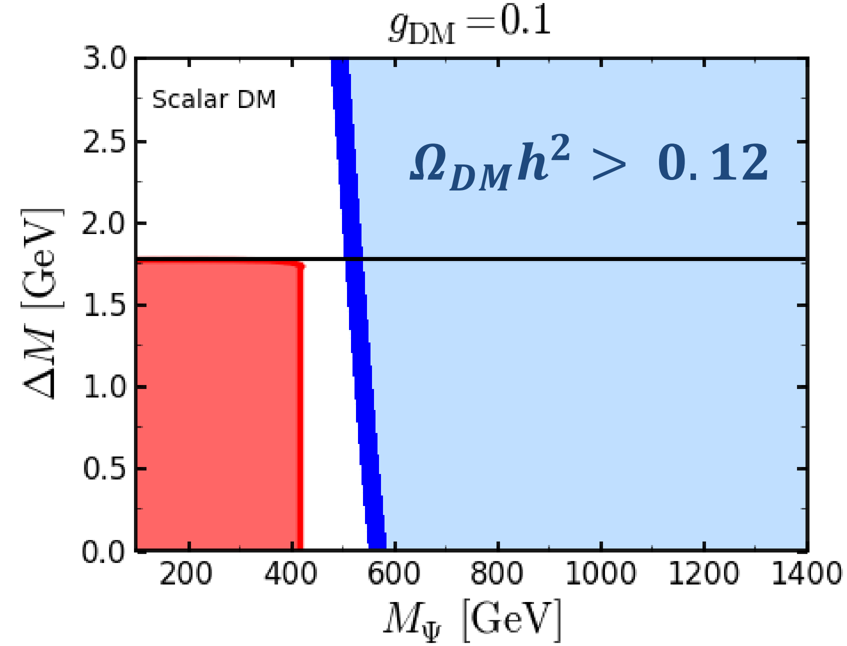
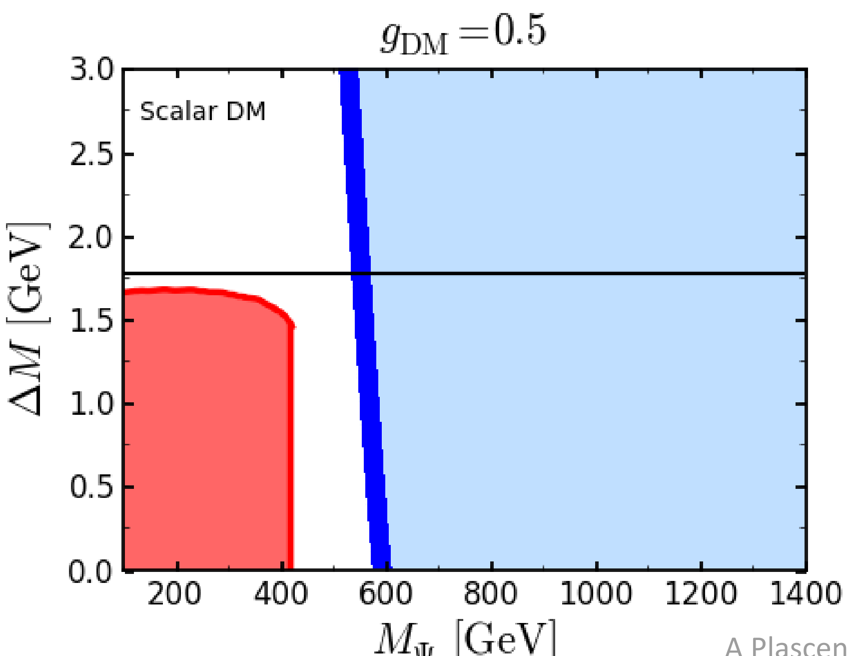
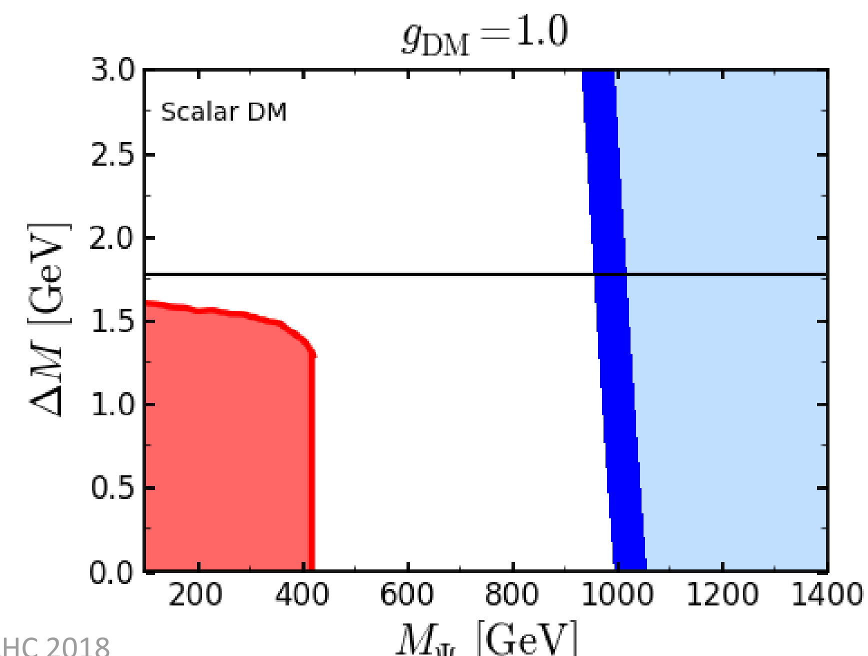
**8 TeV 18.8 fb $^{-1}$**



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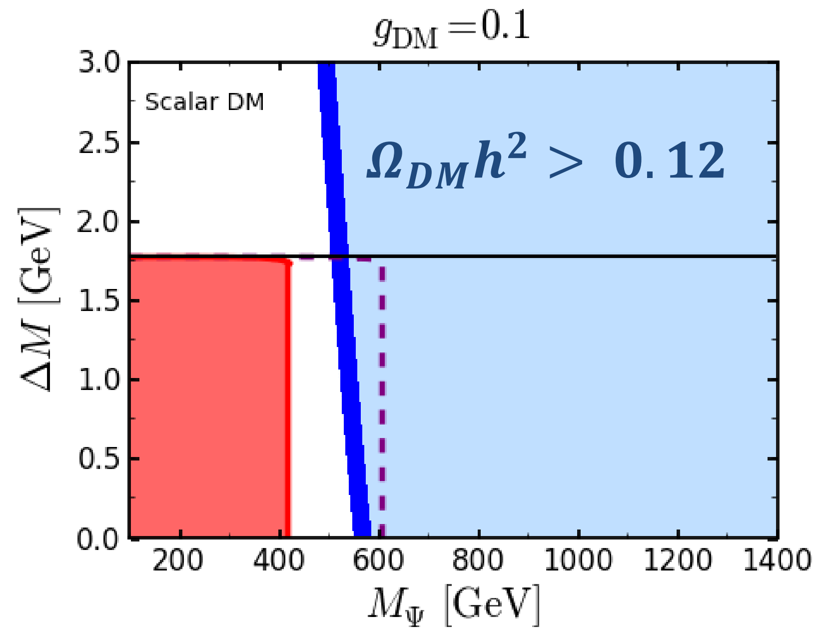


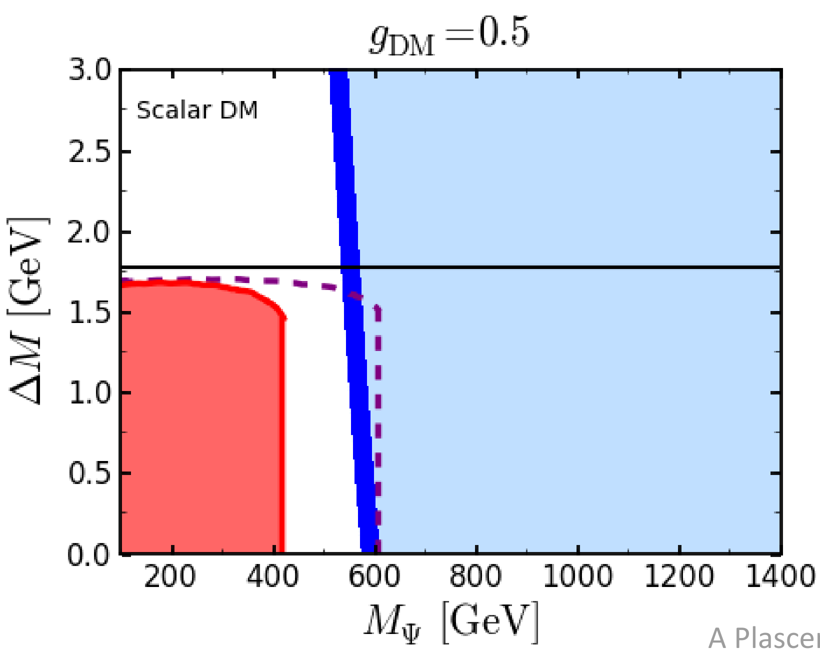


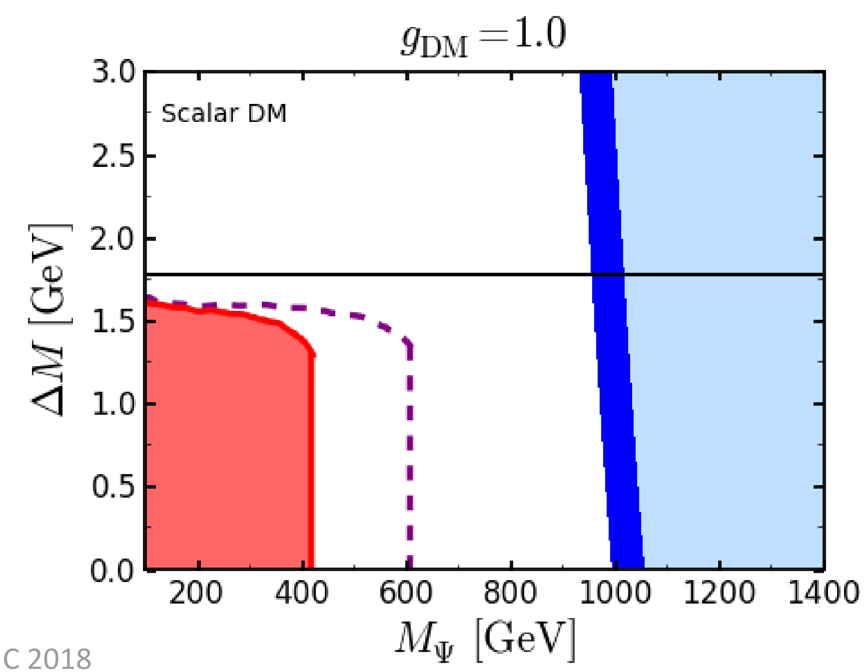

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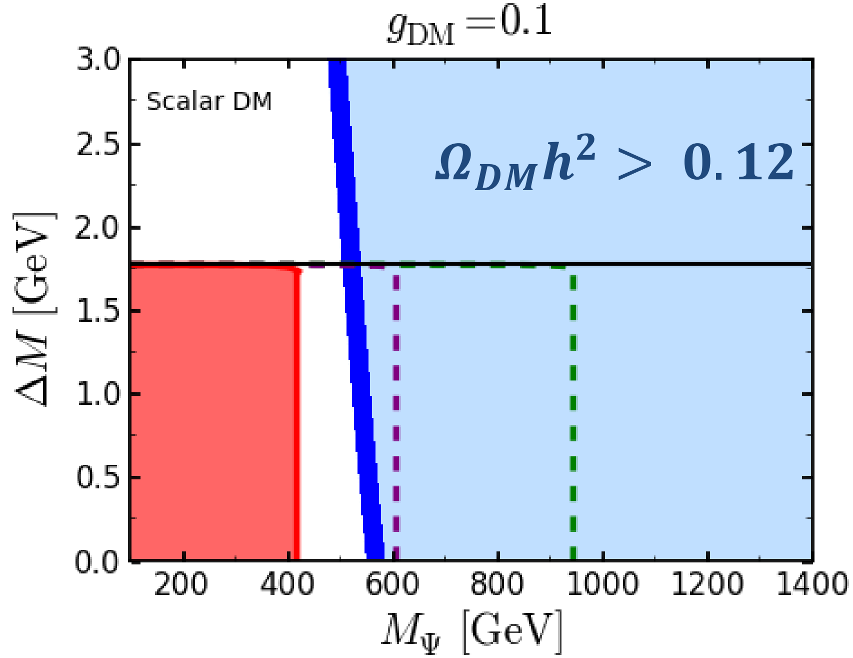
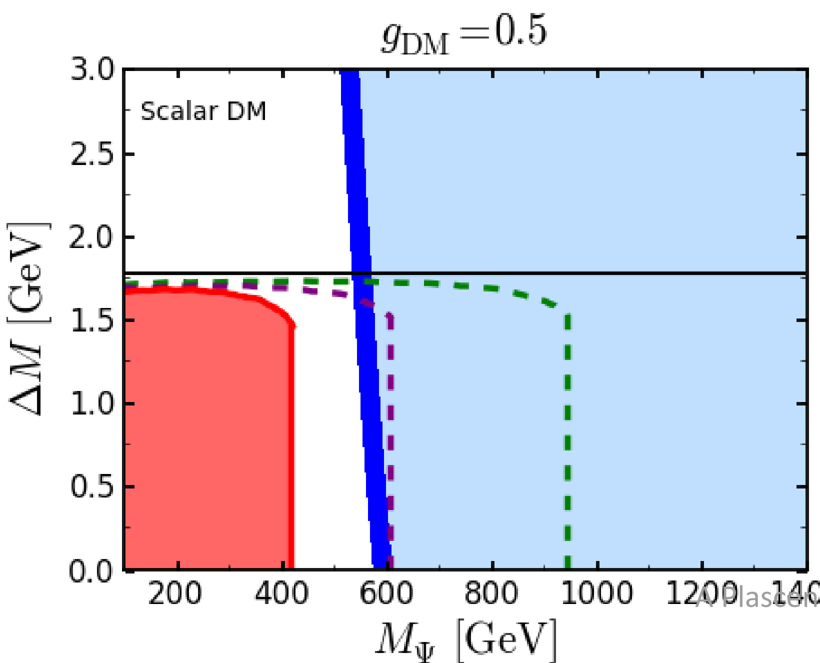
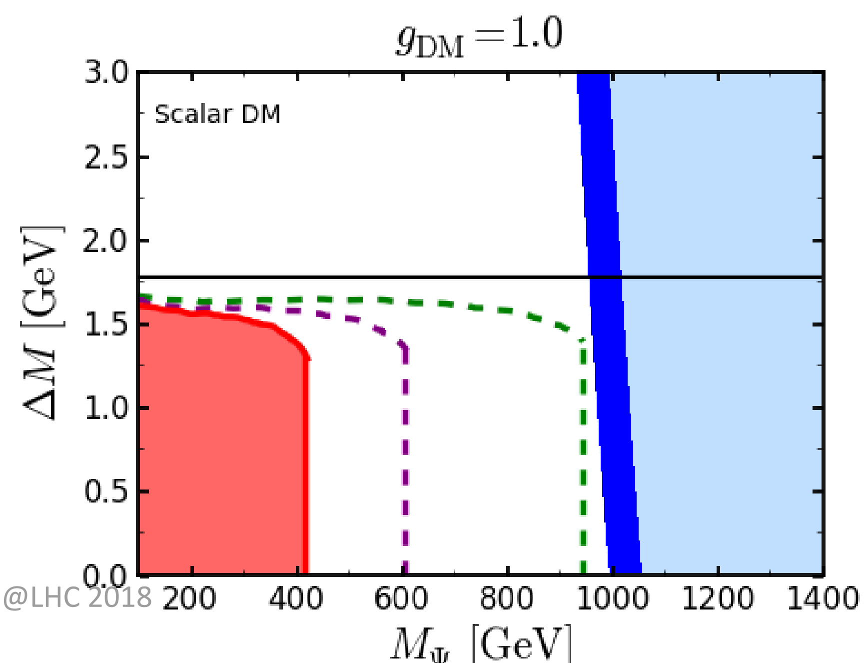


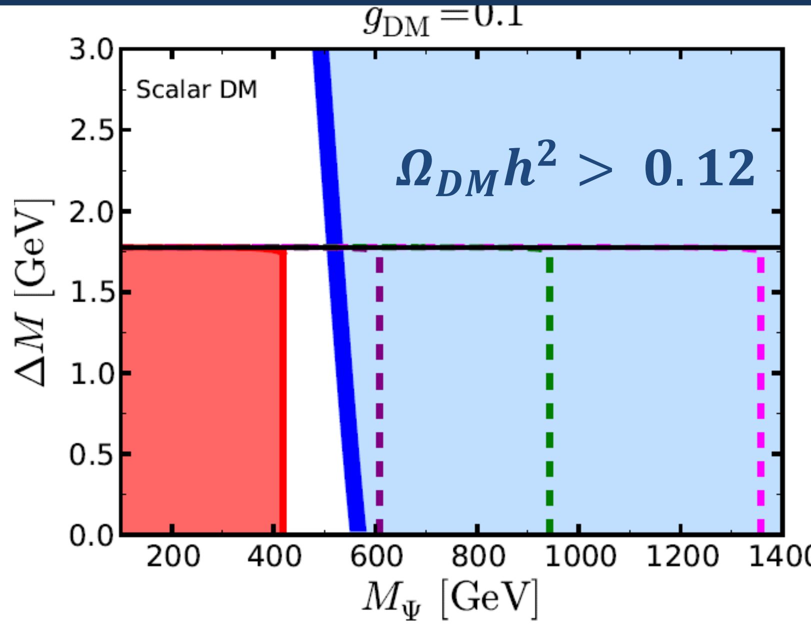
# Real scalar dark matter

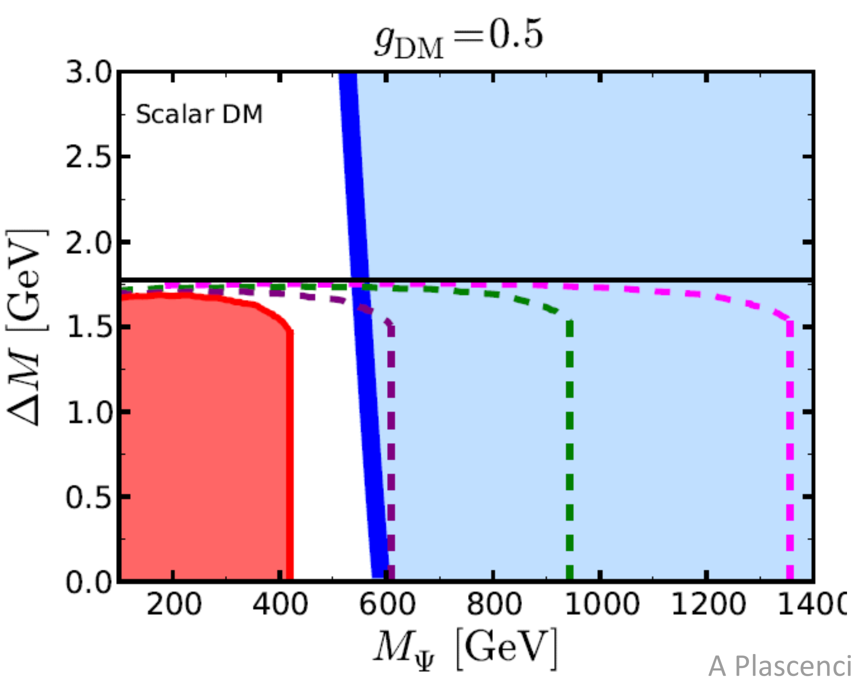
**DM** $S$

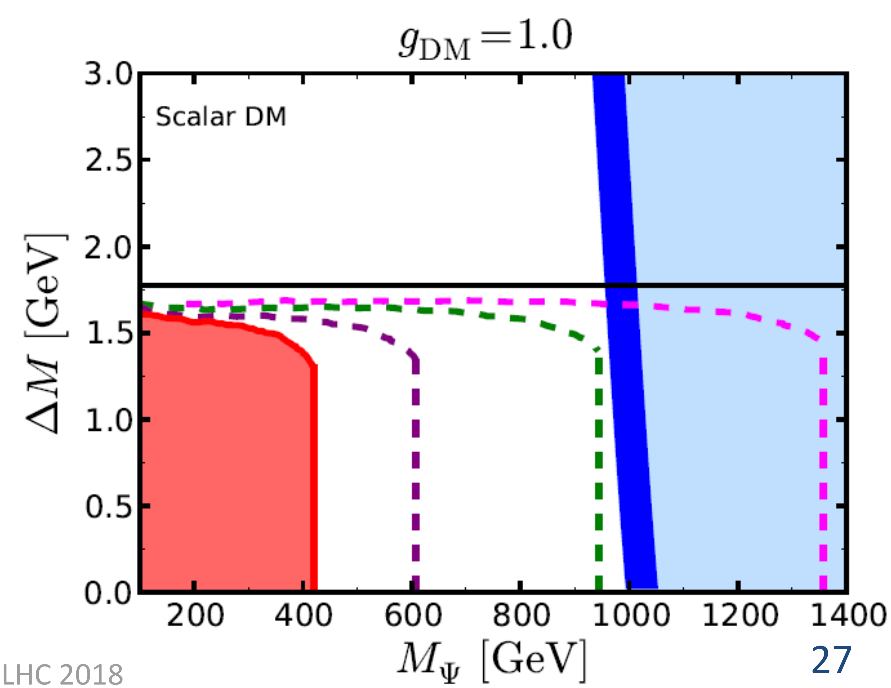
**CAP** $(Y = 1 \;\; L_\tau = 1)$ $\Psi$

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

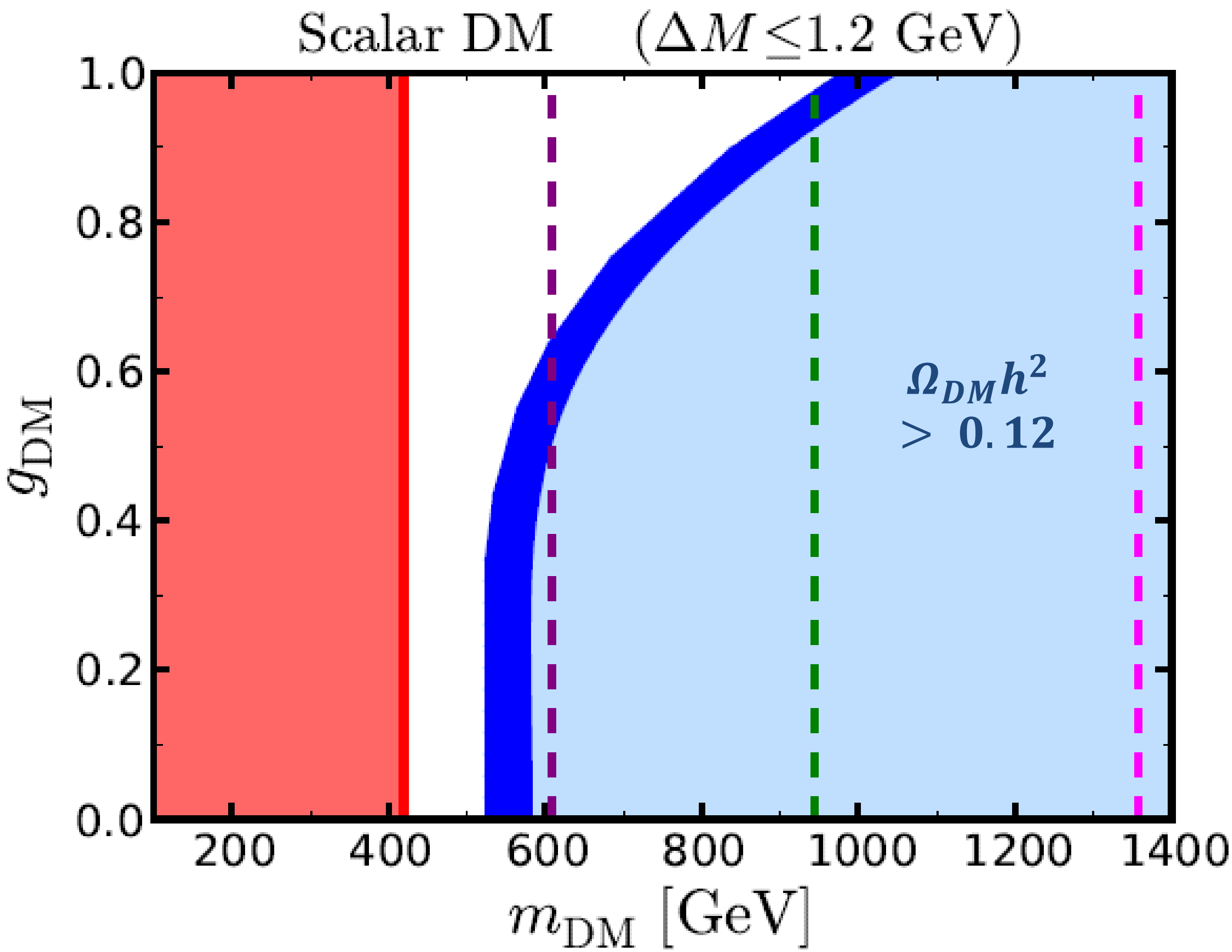
**High Lumi 13 TeV 3000 fb $^{-1}$**



# 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 $^{-1}$

A Plascencia DM@LHC 2018

# Vector dark matter (Model 3)

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

| DM | CAP $(Y = 1 \;\; L_\tau = 1)$ |
|---|---|
| $A_\mu$ | $\Psi$ |

**Kaluza-Klein photon $\gamma^1$**

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

**Kaluza-Klein $\tau^1$**

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

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

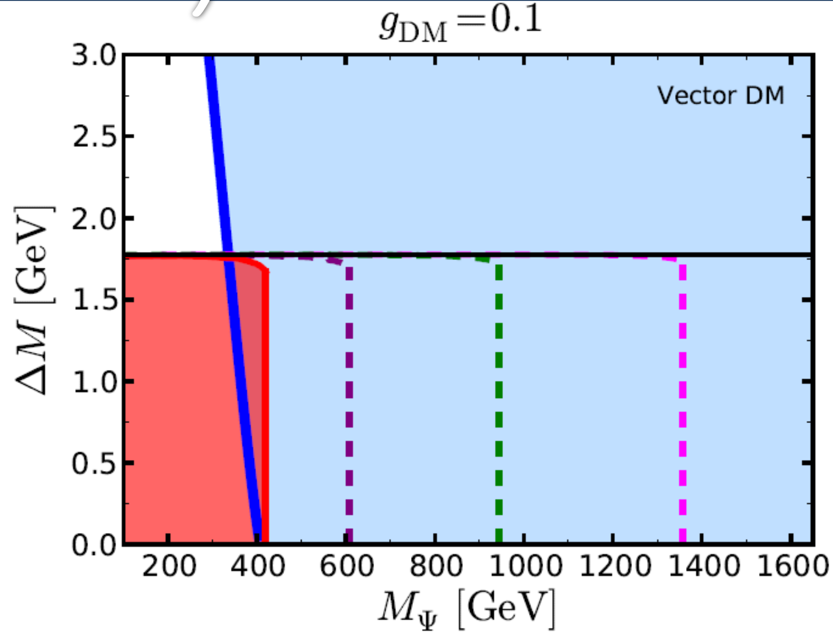
# Vector dark matter (Model 3)

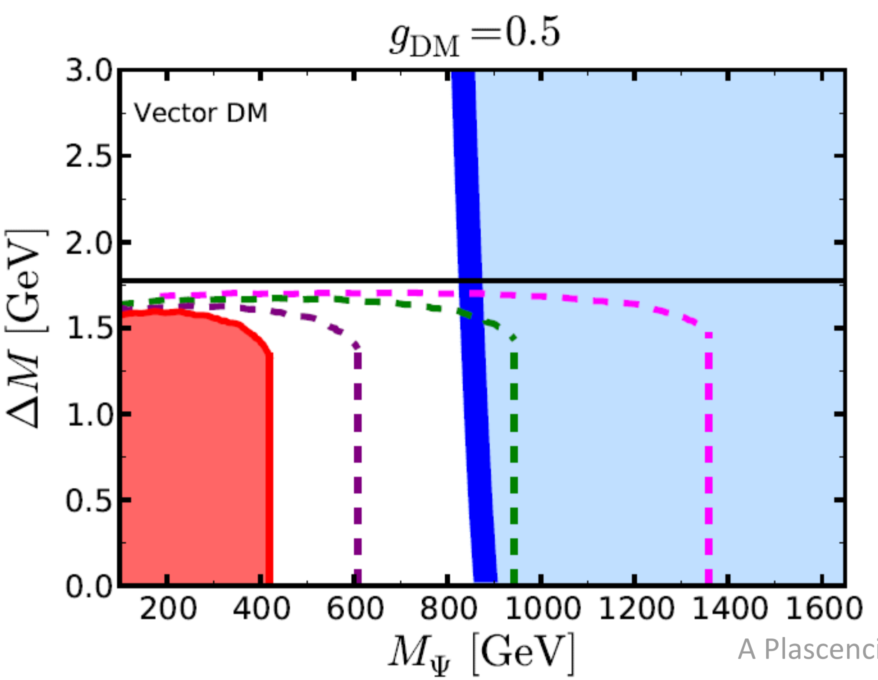
**DM** $A_\mu$

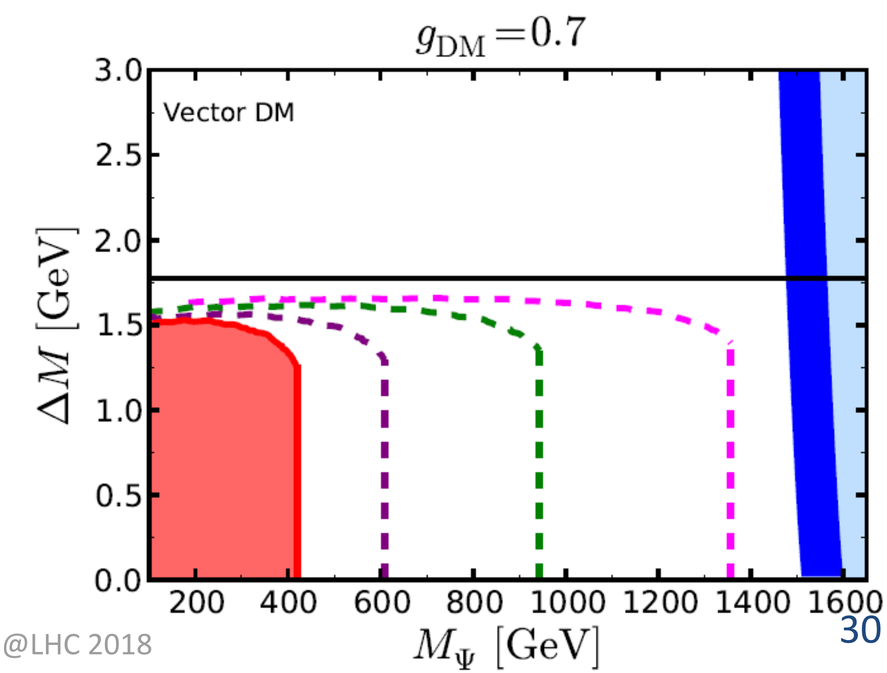
**CAP** $(Y = 1 \;\; L_\tau = 1)$ $\Psi$

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

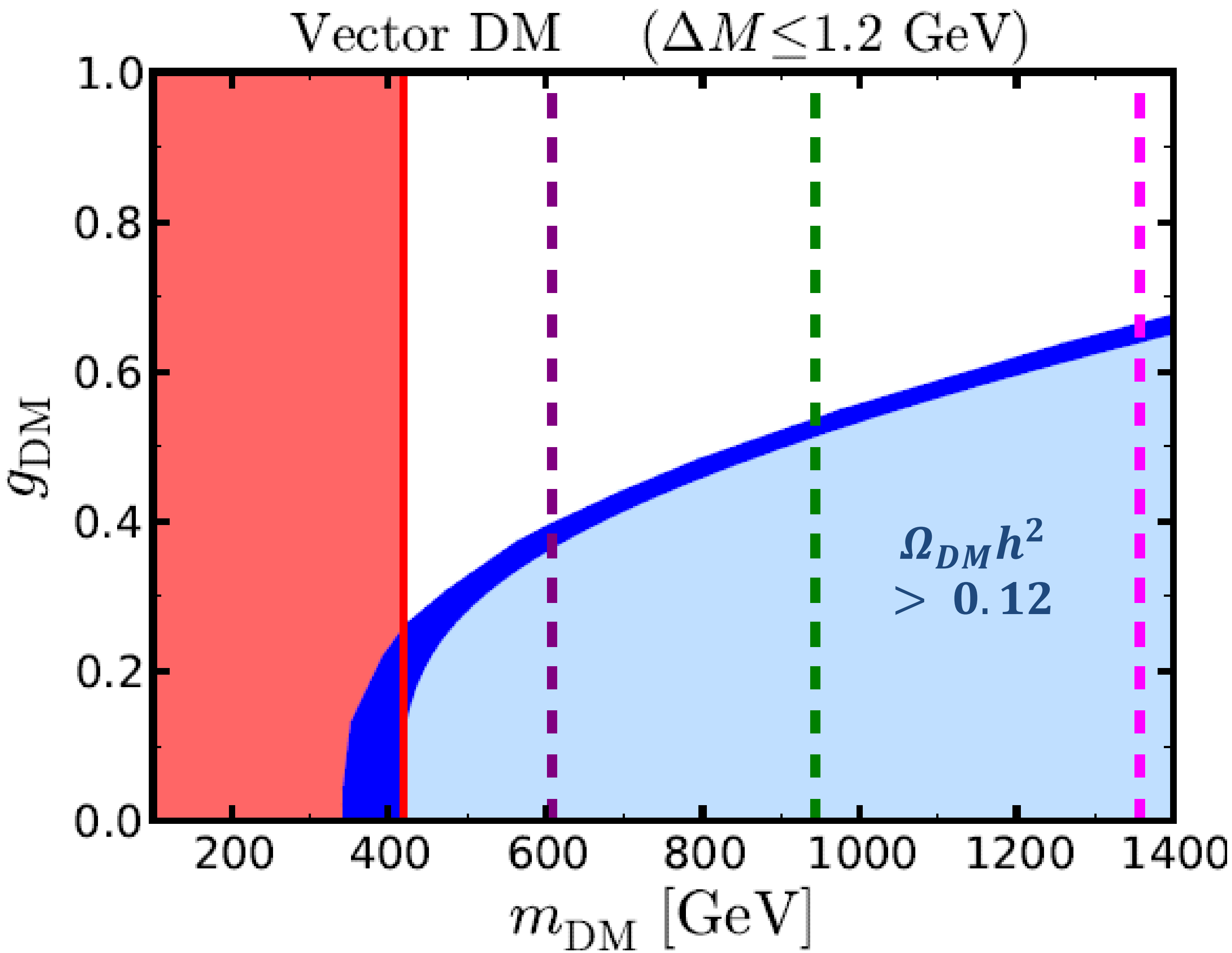
**NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions**



# Vector dark matter



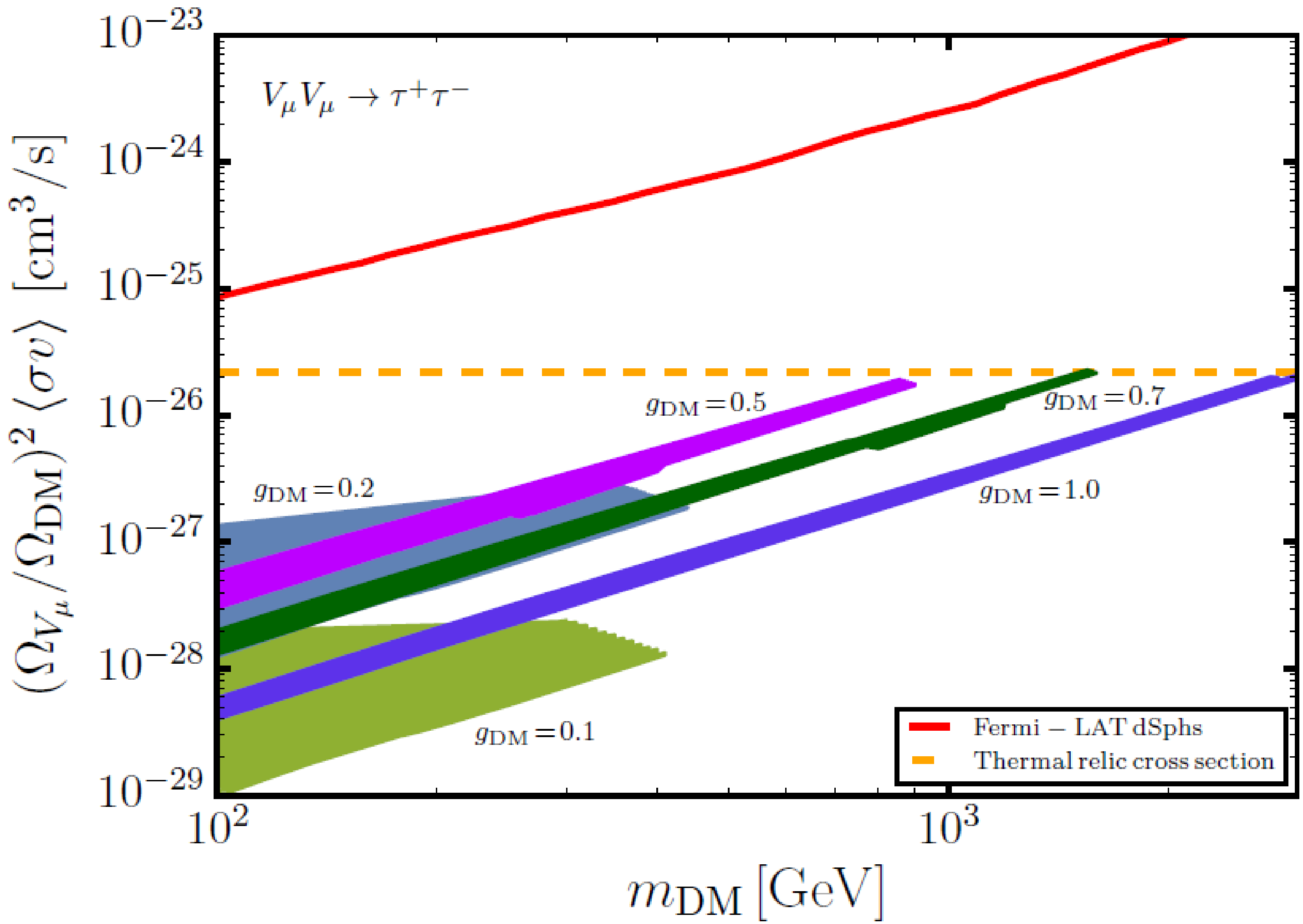

13 TeV
300 fb $^{-1}$

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

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

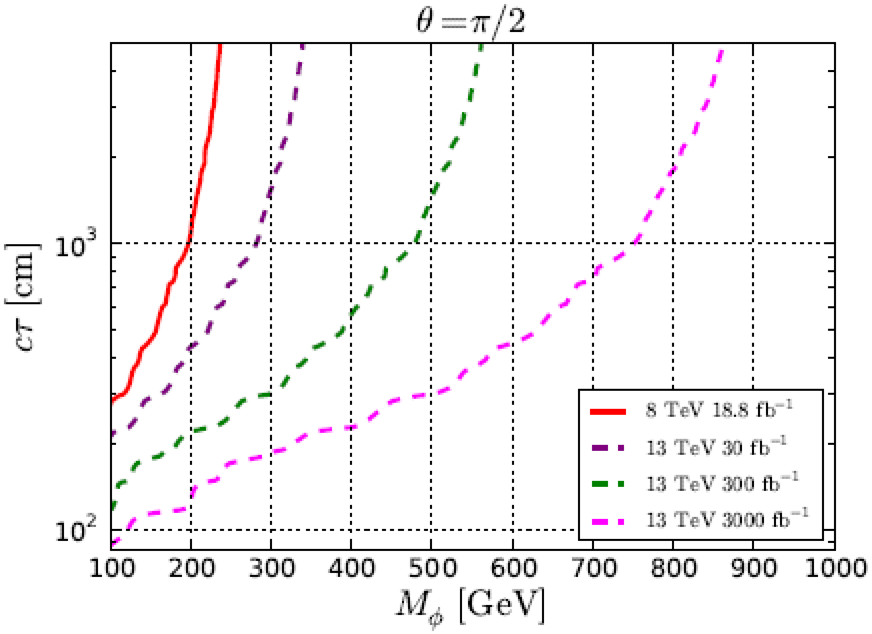
# Vector dark matter

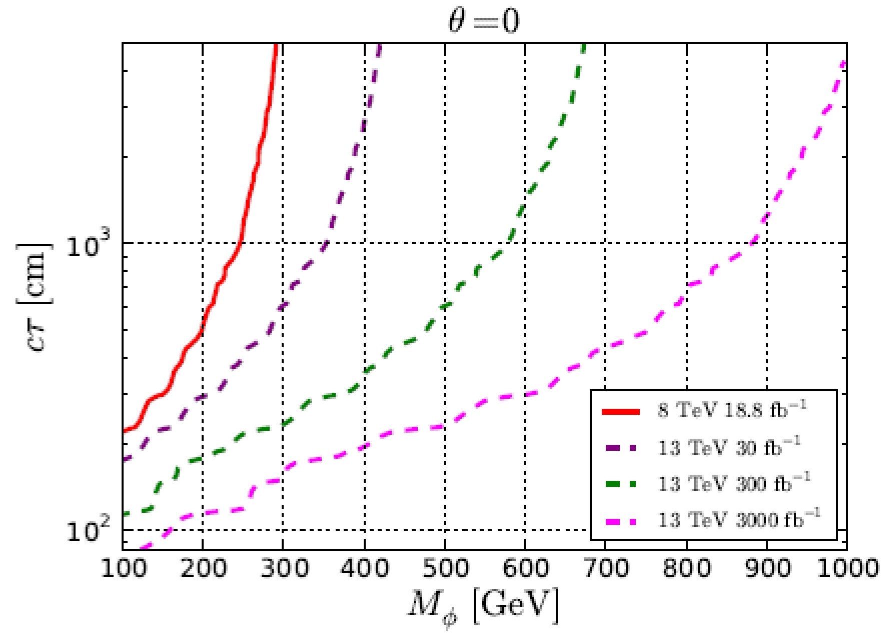


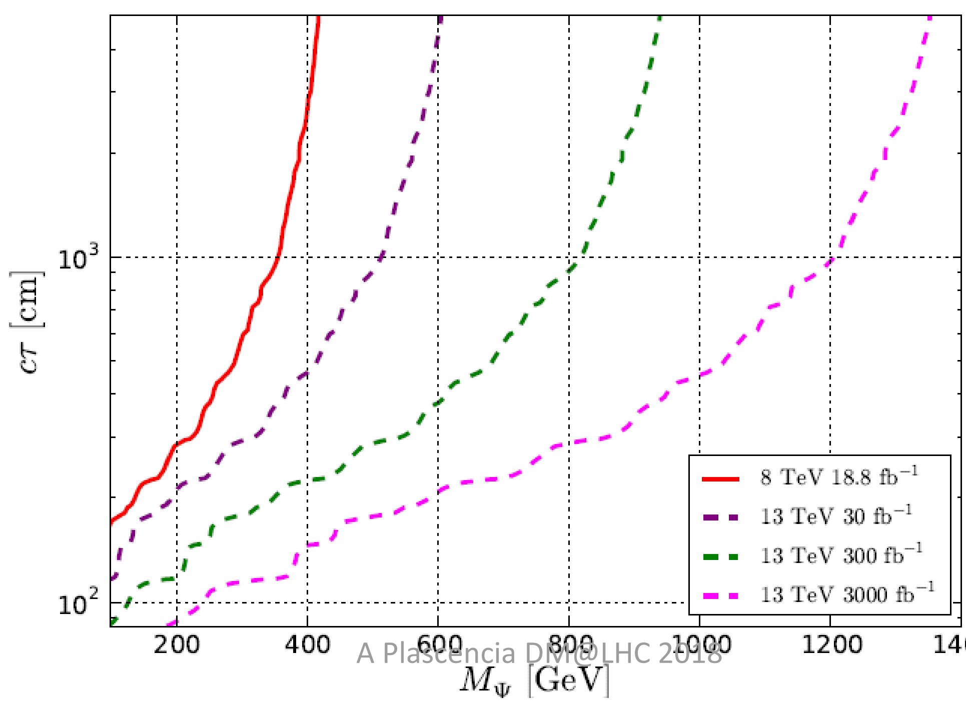
# Conclusions

- We have studied 4 classes of simplified models, that have 3-point interaction with **$\tau$-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

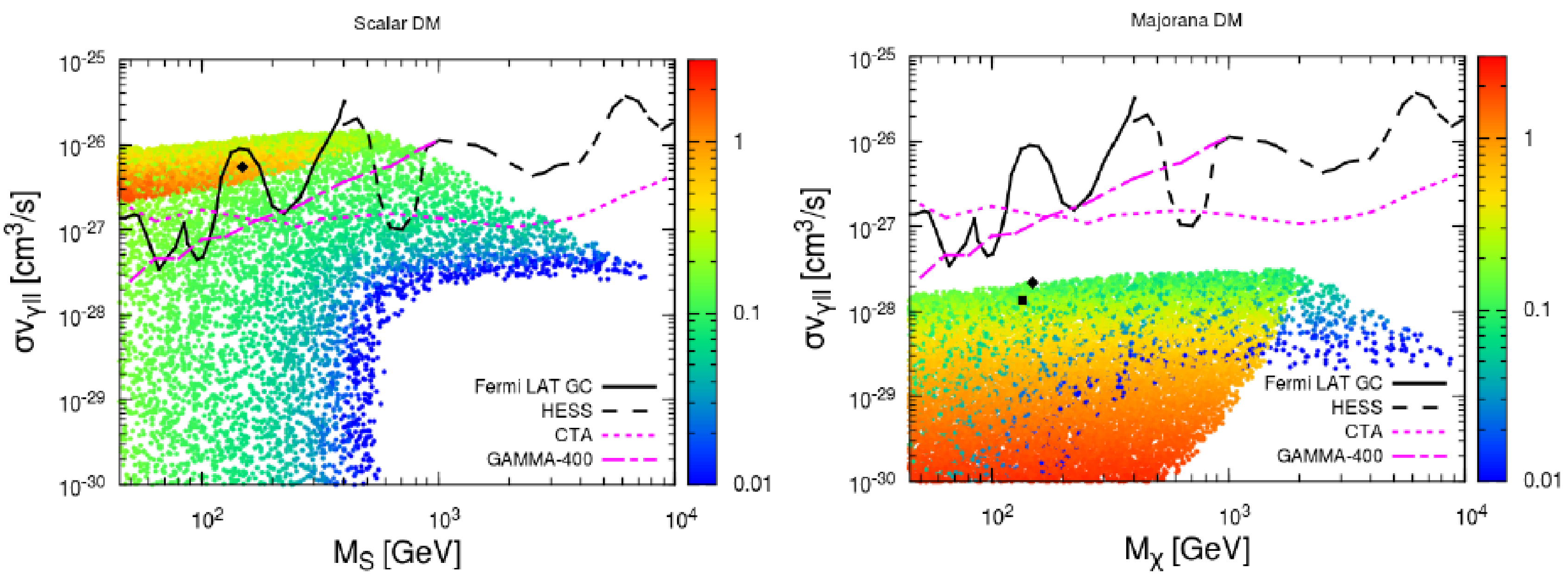
Thank you.


θ = π/2
cτ [cm]
M_φ [GeV]
8 TeV 18.8 fb⁻¹
13 TeV 30 fb⁻¹
13 TeV 300 fb⁻¹
13 TeV 3000 fb⁻¹


θ = 0
cτ [cm]
M_φ [GeV]
8 TeV 18.8 fb⁻¹
13 TeV 30 fb⁻¹
13 TeV 300 fb⁻¹
13 TeV 3000 fb⁻¹


cτ [cm]
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** $\frac{M_{CAP}}{M_{DM}} - 1$

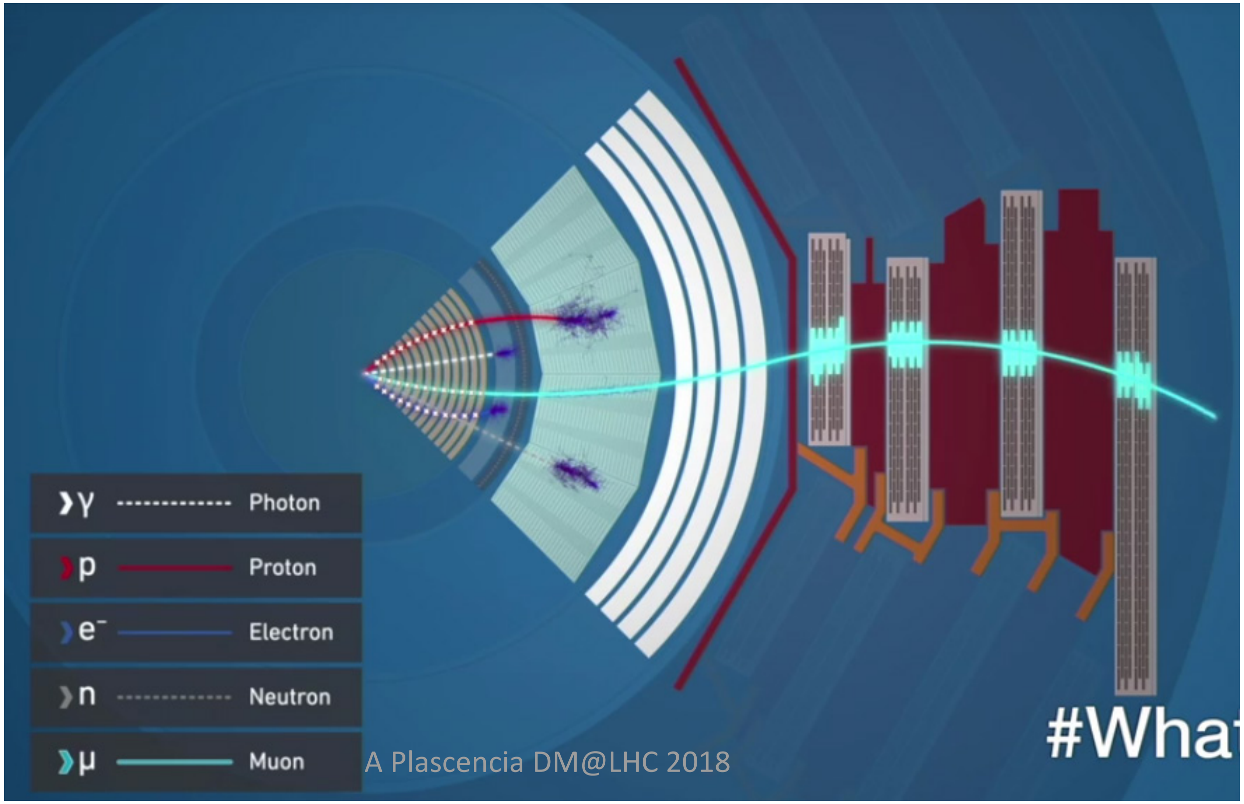
**Blue dots correspond to small mass splitting**

**[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]