Probing tau-philic dark matter coannihilation at LHC and CLIC

Alexis Plascencia

with Valentin Khoze and Kazuki Sakurai

[arxiv:1702.00750] JHEP 06 (2017) 041
[arxiv:1812.02093] CERN YR - Section 5.4

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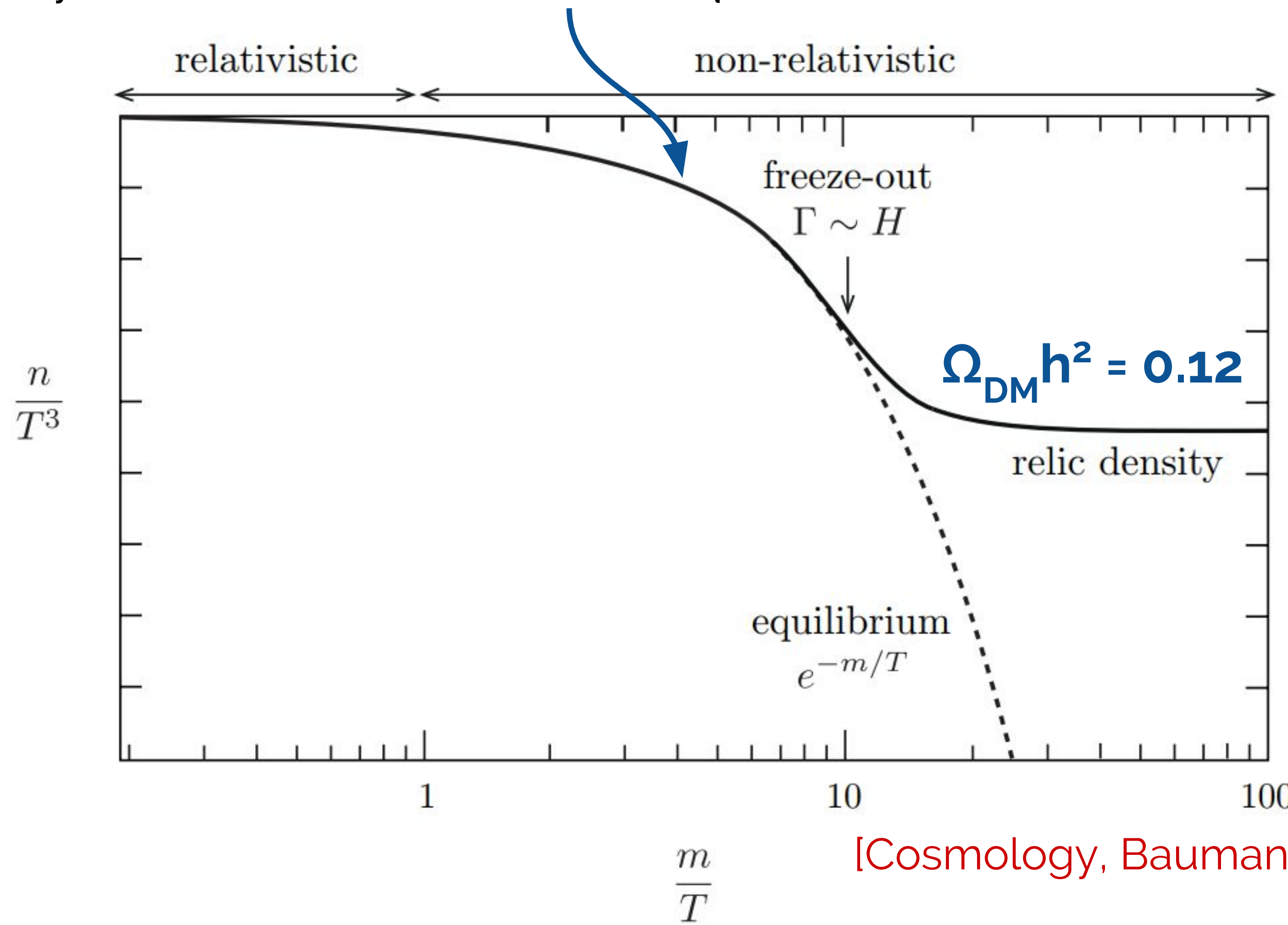
TRIUMF "Signals of Dark Matter in its Natural Habitat" 2019

Outline of the talk

1. Models with tau-philic dark matter coannihilation
2. Searches for long-lived charged particles at the LHC
3. Prospects for electron-positron linear colliders
4. Conclusions

WIMP paradigm

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



[Cosmology, Baumann 2015]

Later on, due to the weak interactions DM freezes out

WIMP paradigm

- Current experiments already impose 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 and CLIC

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

Tau-philic Yukawa interaction

Introduce a charged co-annihilation partner as the next-to-lightest BSM particle, instead of a mediator.

Dark matter candidate

SM τ lepton

$$g_{\mathrm{DM}}\, \chi\, \eta^{+}\, \tau^{-} \subset \mathcal{L}$$

Coannihilation partner (CAP)

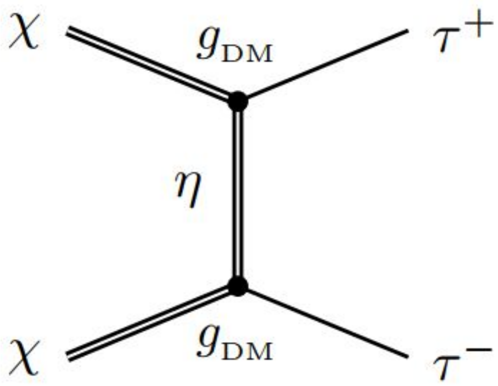
$$Z_2: \quad \begin{aligned} \chi &\to -\chi \\ \eta &\to -\eta \end{aligned}$$

Simplified models with only 3 free parameters:

$$g_{\mathrm{DM}} \qquad m_{\mathrm{DM}} \qquad M_{\mathrm{CAP}}$$

Coannihilation

Dark matter annihilates into a pair of τ-leptons



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

$\propto m_\tau^{\ 2}$
chiral suppression

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

Coannihilation

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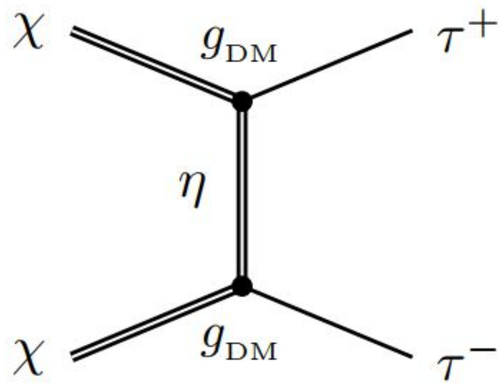

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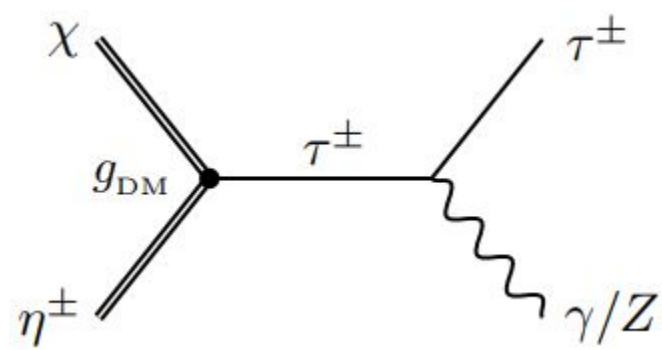
Coannihilation:



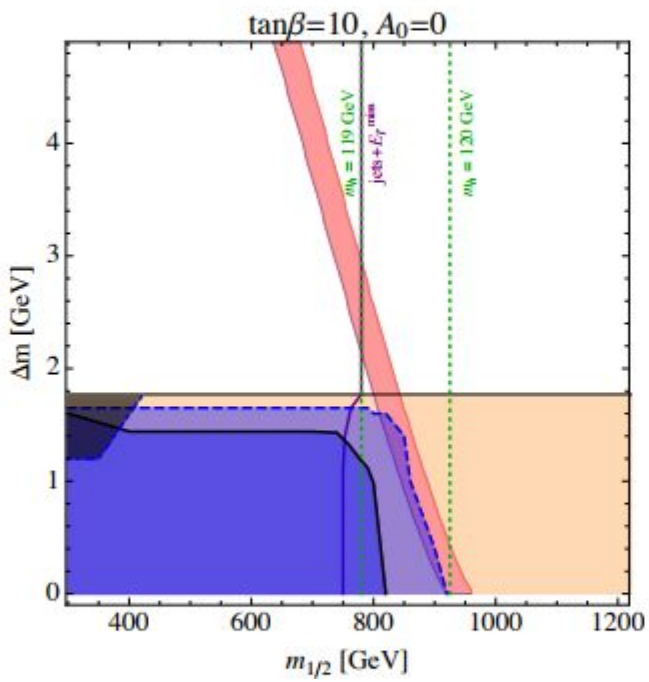
Freeze-out temperature $T_F \sim m_{DM}/25$

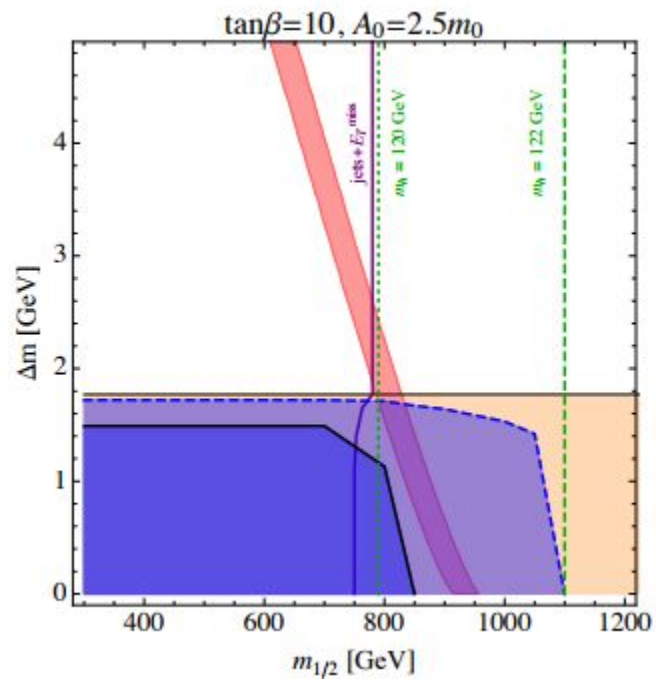
Boltzmann factor $\exp(-\Delta M/T)$ $\Longrightarrow$ $\Delta M \lesssim m_{DM}/25$

We need **mass splitting $< 4\%\ m_{DM}$**

Stau coannihilation strip

Inspired by the stau coannihilation strip in the CMSSM:
(stau and neutralino have very similar masses)



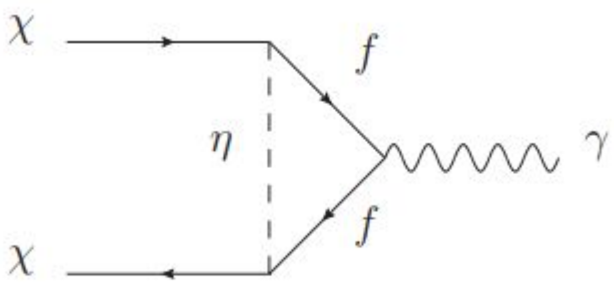


We want to generalize this.

[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

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

below projected sensitivity for Lux-Zeplin, even for g_{DM}=1.0

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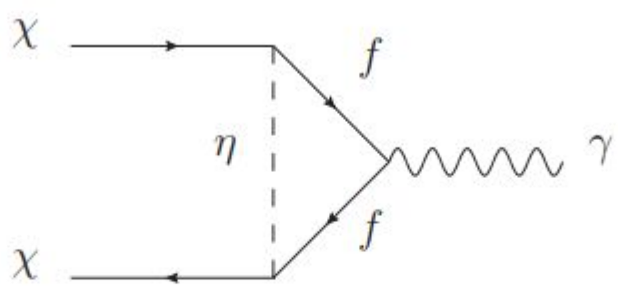

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- Indirect Detection: Due to chiral suppression, DM annihilation is velocity-suppressed

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

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

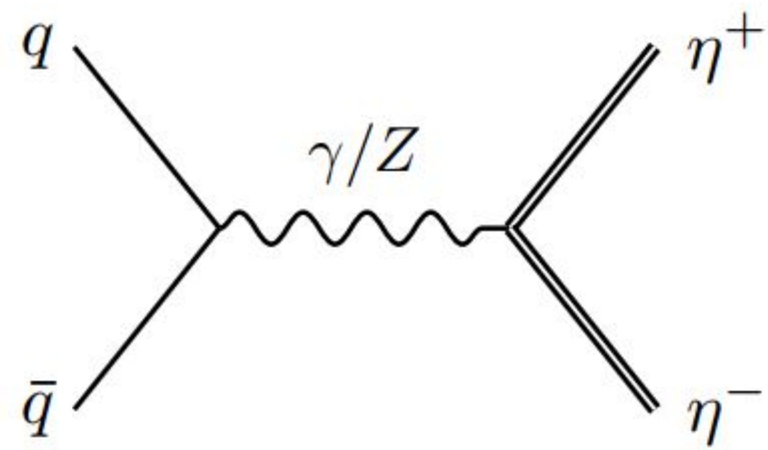
$\sigma v \propto v^2$	$\sigma v \propto v^4$
p-wave suppressed for Majorana DM	d-wave suppressed for scalar DM

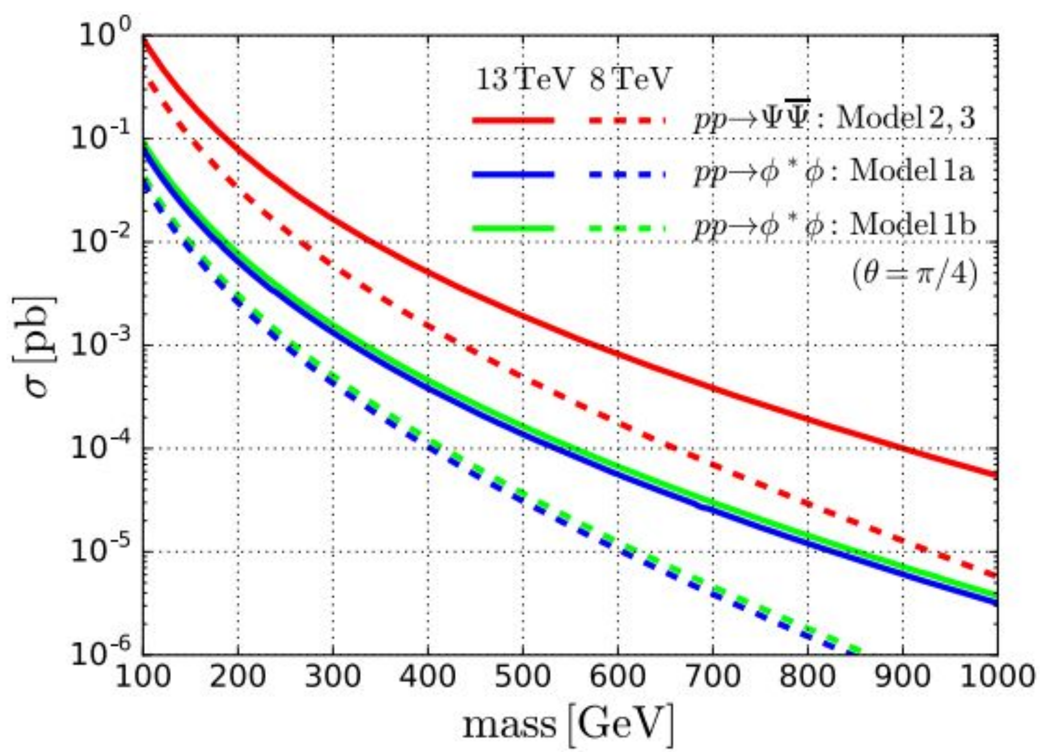
Nevertheless, for $\Delta M > m_{DM}/10$ the channel $S\,S \to l\,l\,\gamma$ can be relevant for future telescopes for scalar DM

[Giacchino, Lopez-Honorez, Tytgat 2013]

LHC production

- Drell-Yan pair production of coannihilation partner

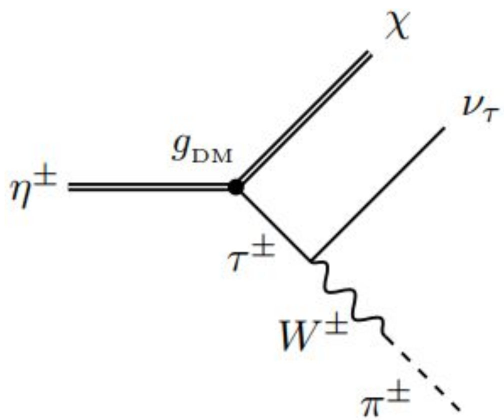




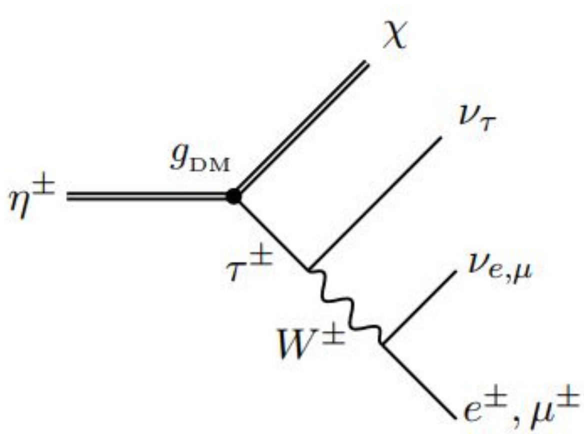
- We study Dirac fermion and complex scalar as coannihilation partners

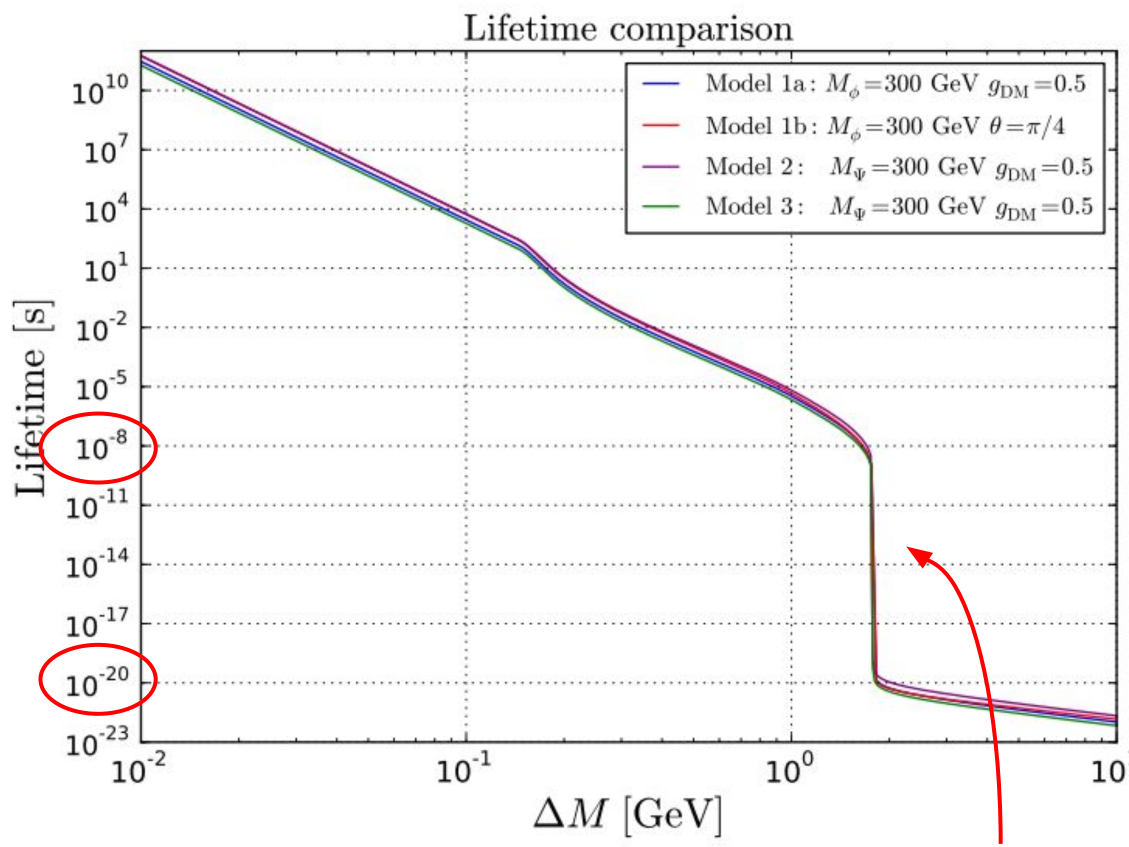
Long-lived charged particles

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



Also $\boldsymbol{\rho}$ and $\boldsymbol{a_1}$ mesons



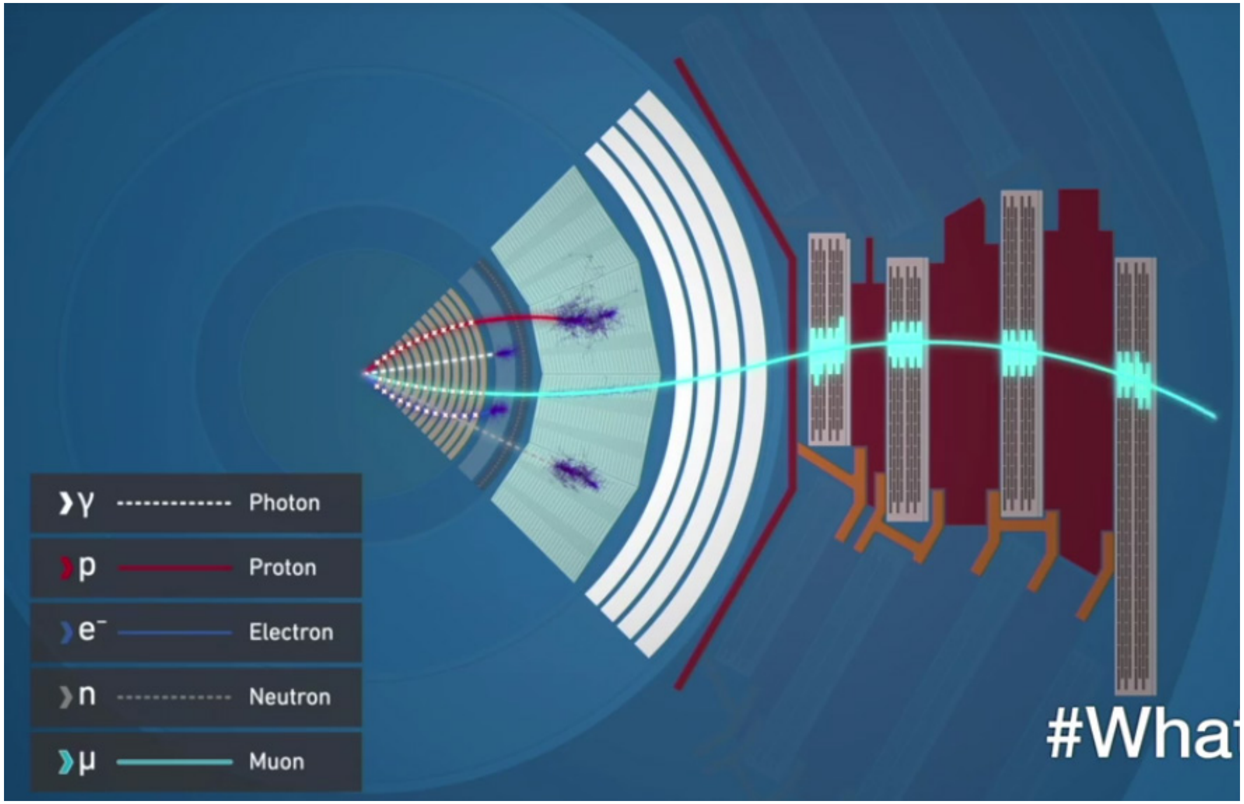


m_τ = 1.777 GeV

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]

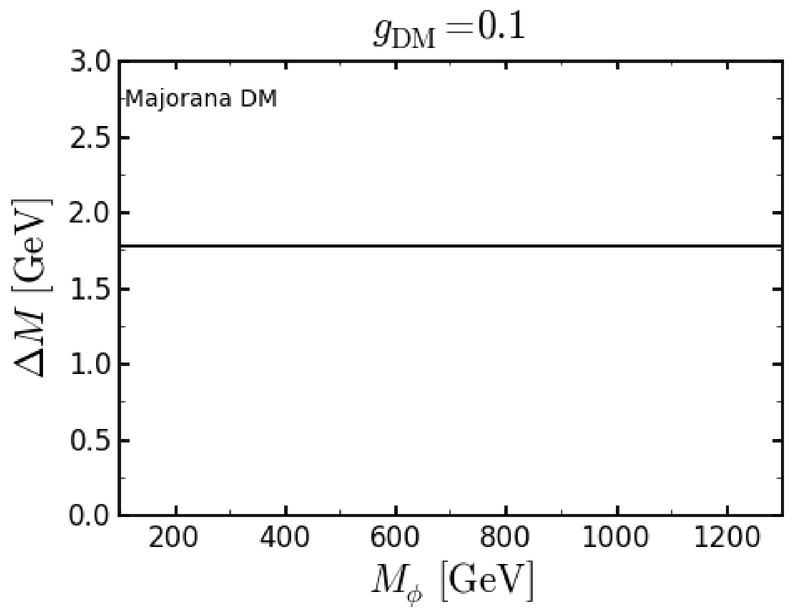
Majorana Dark Matter

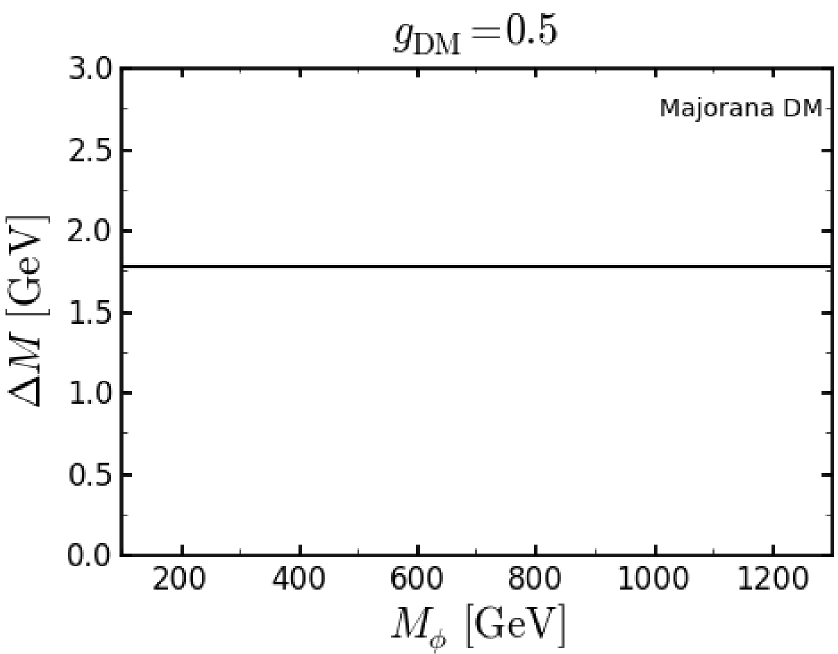
DM χ

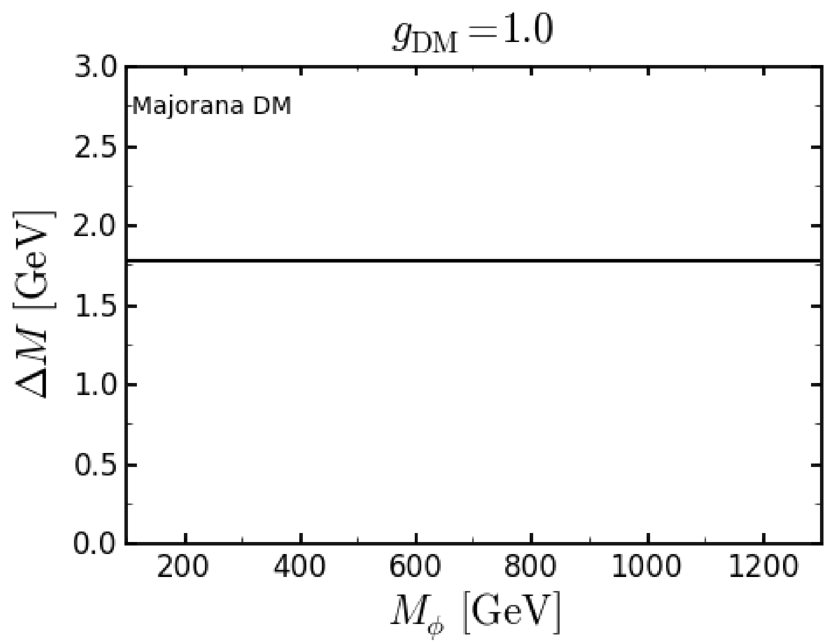
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

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

Gauge-invariant and renormalizable, no problems of unitarity







Majorana Dark Matter

DM | **CAP (Y=-1)**
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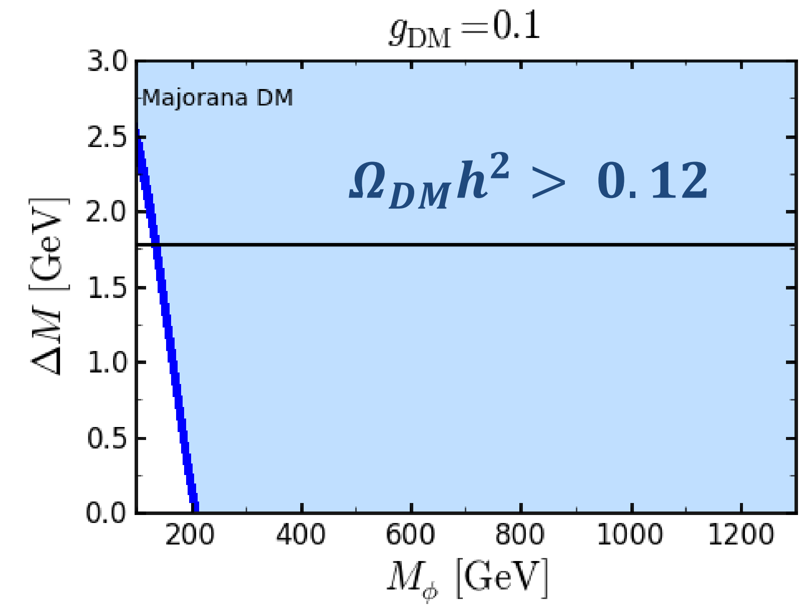

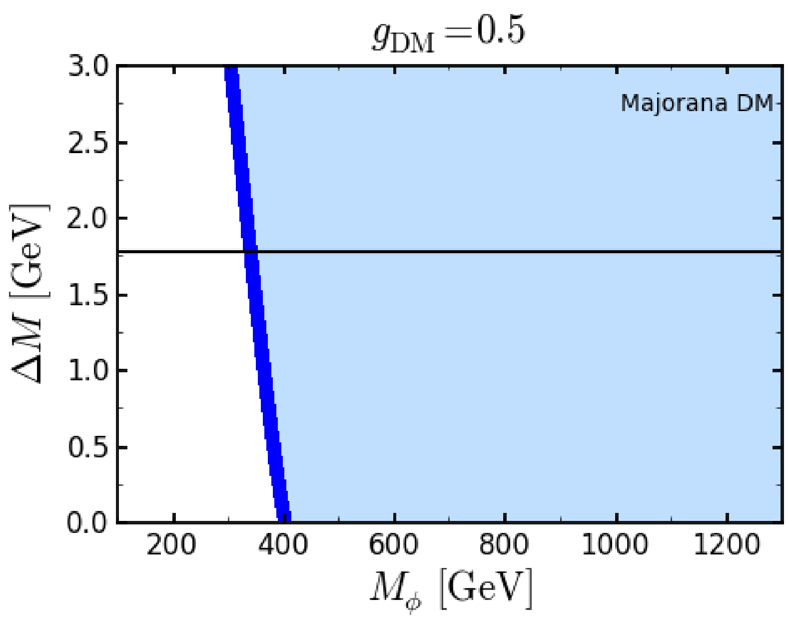

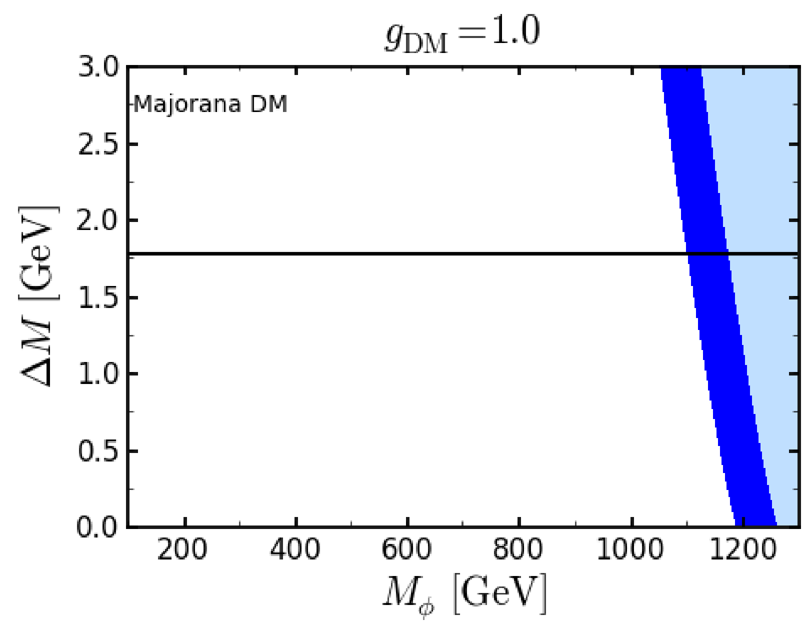

Majorana Dark Matter

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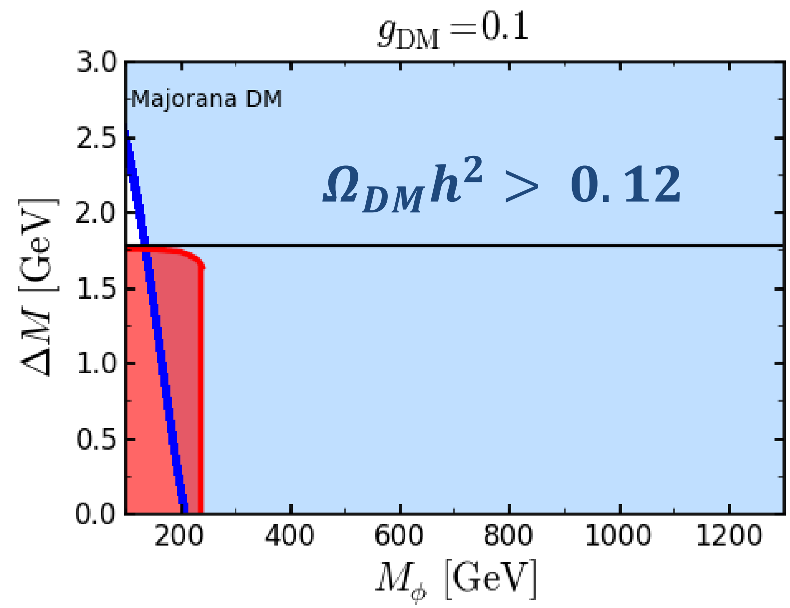
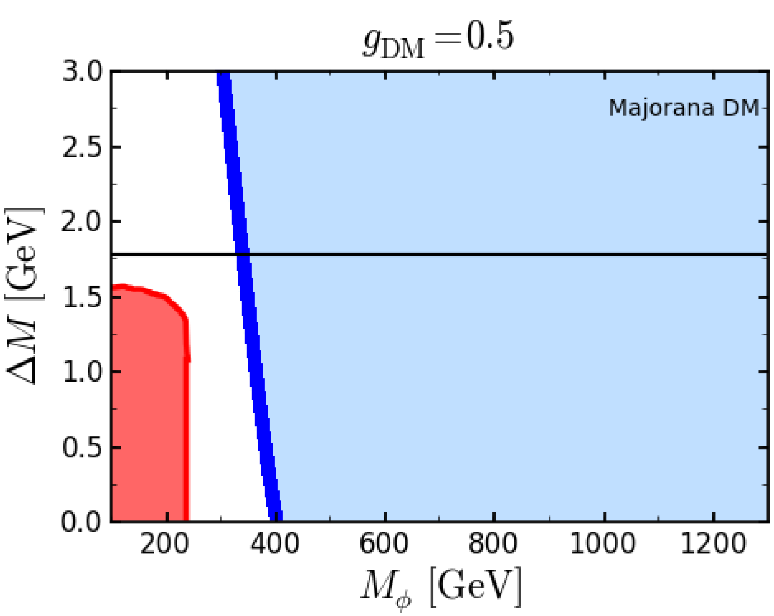
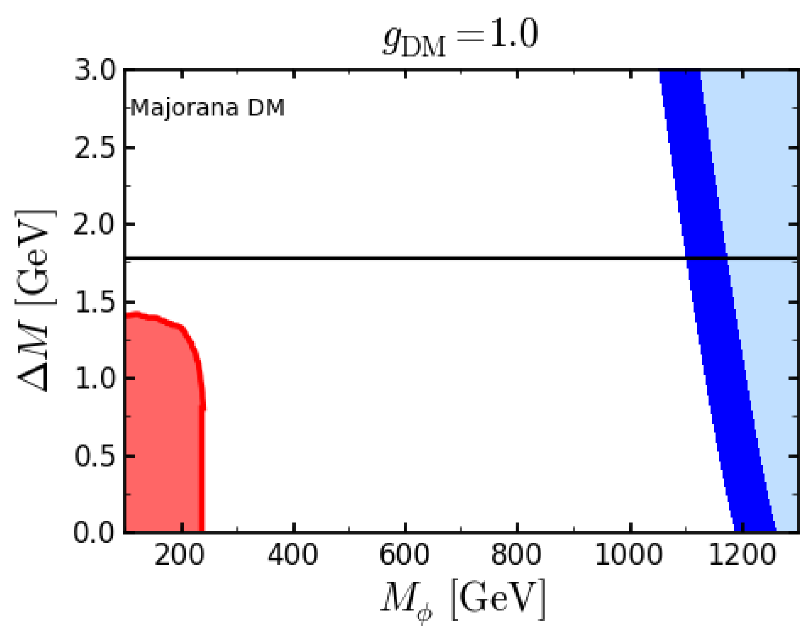
χ	ϕ

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

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







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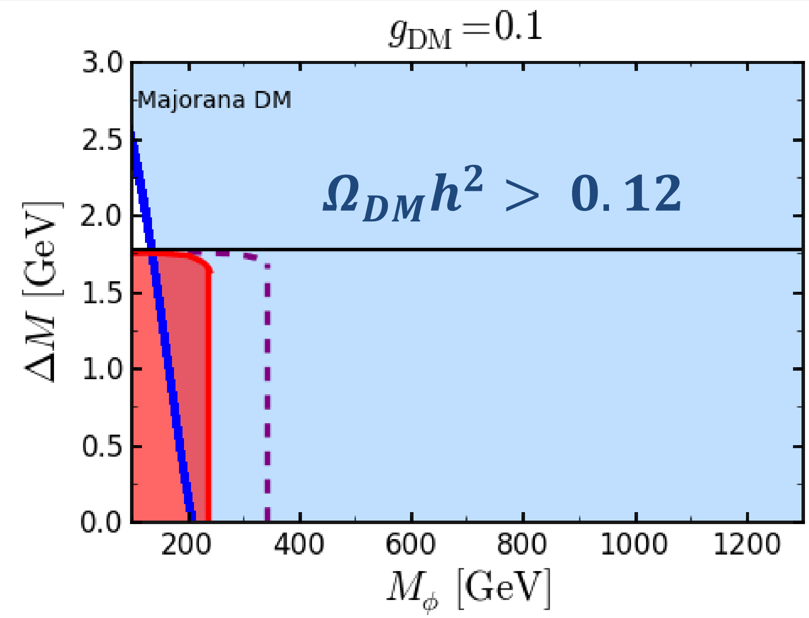

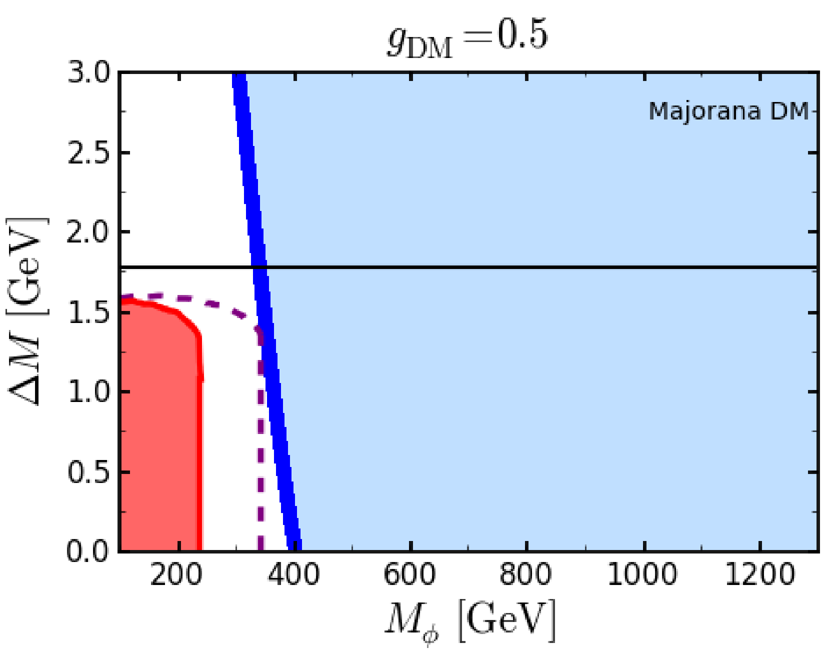

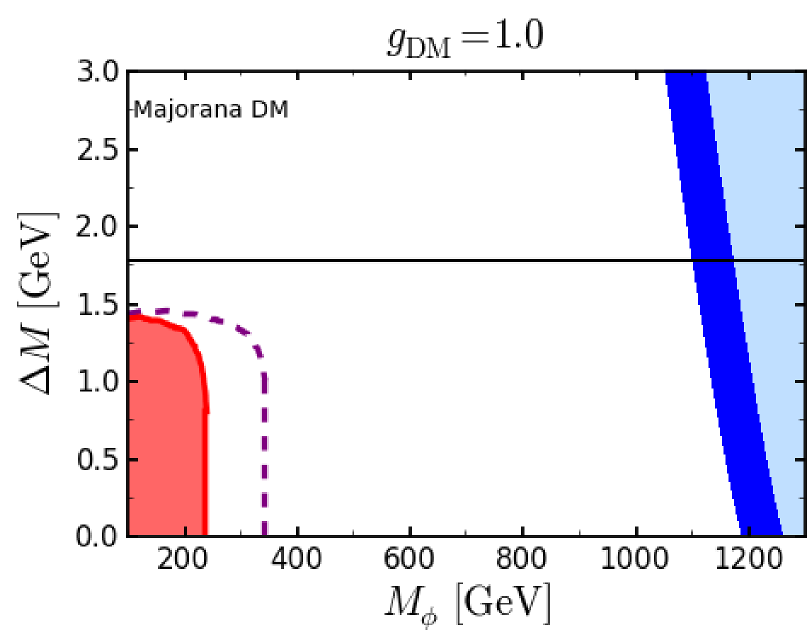

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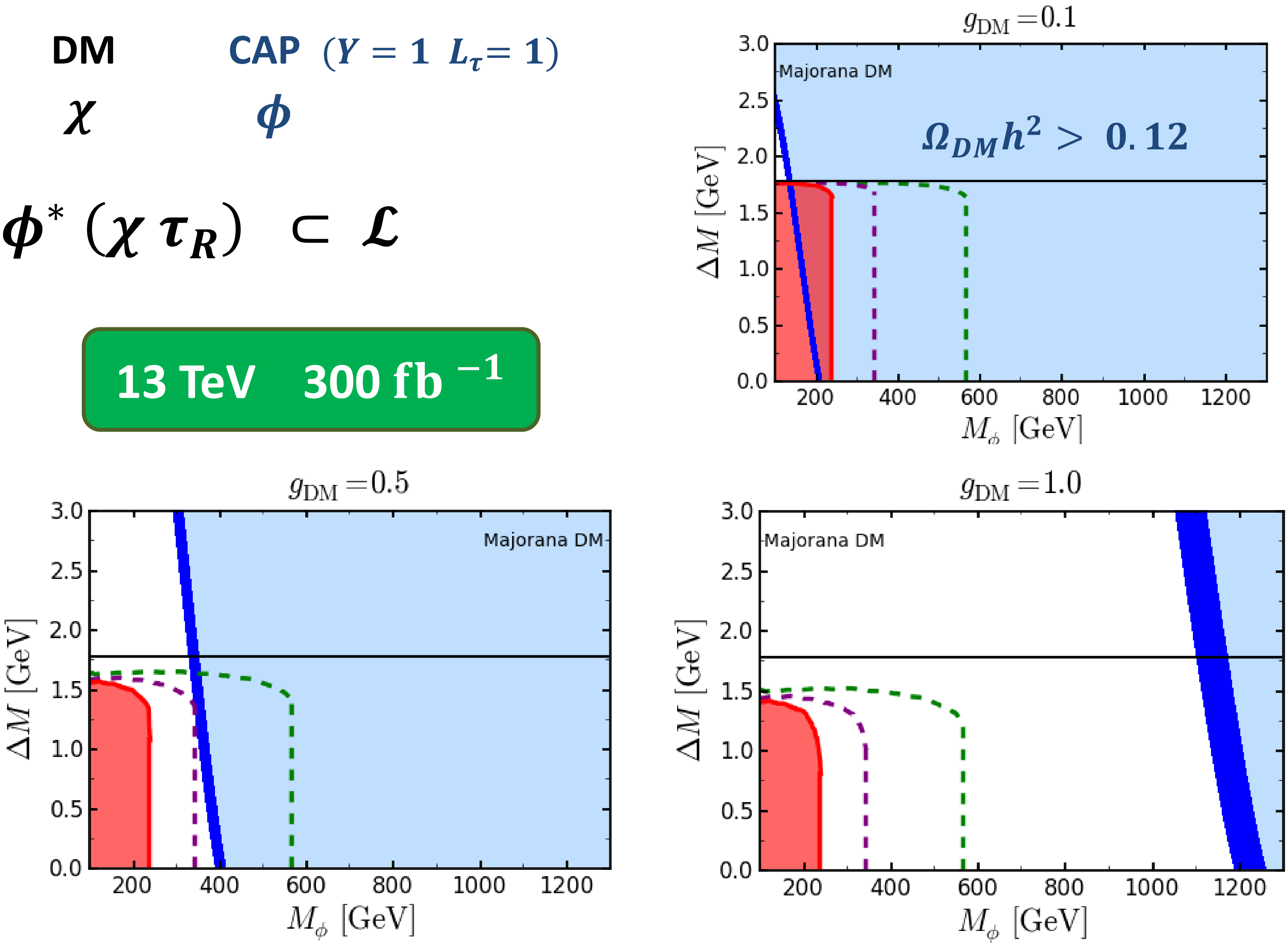

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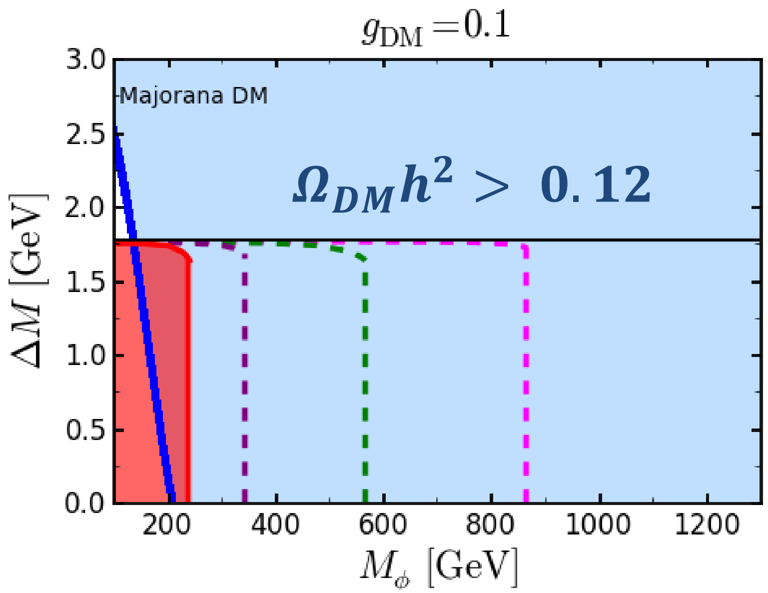

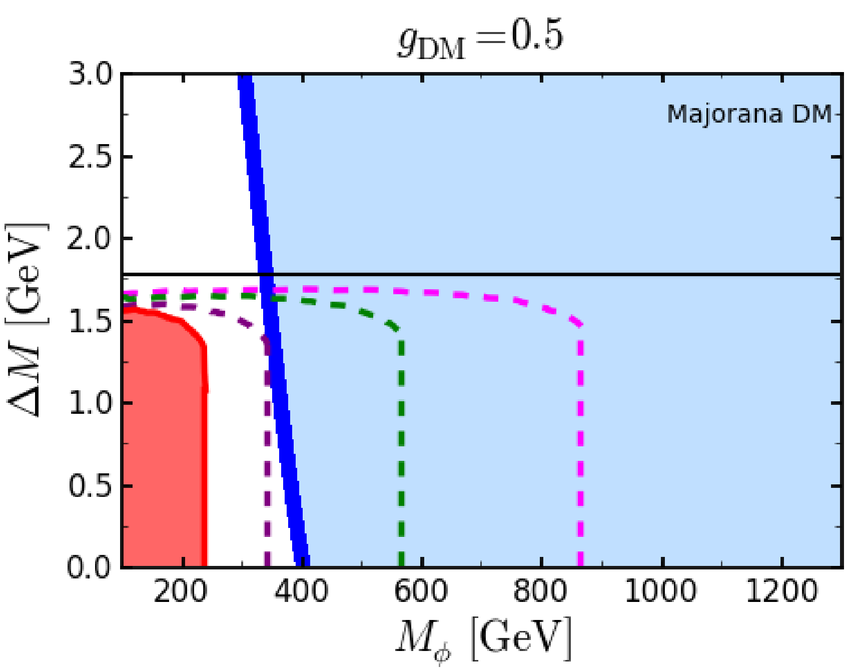

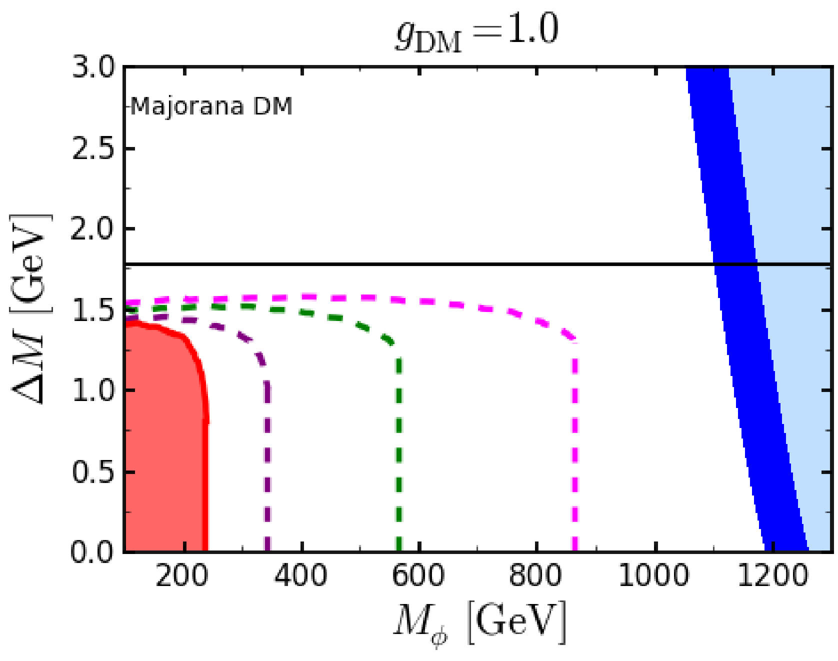

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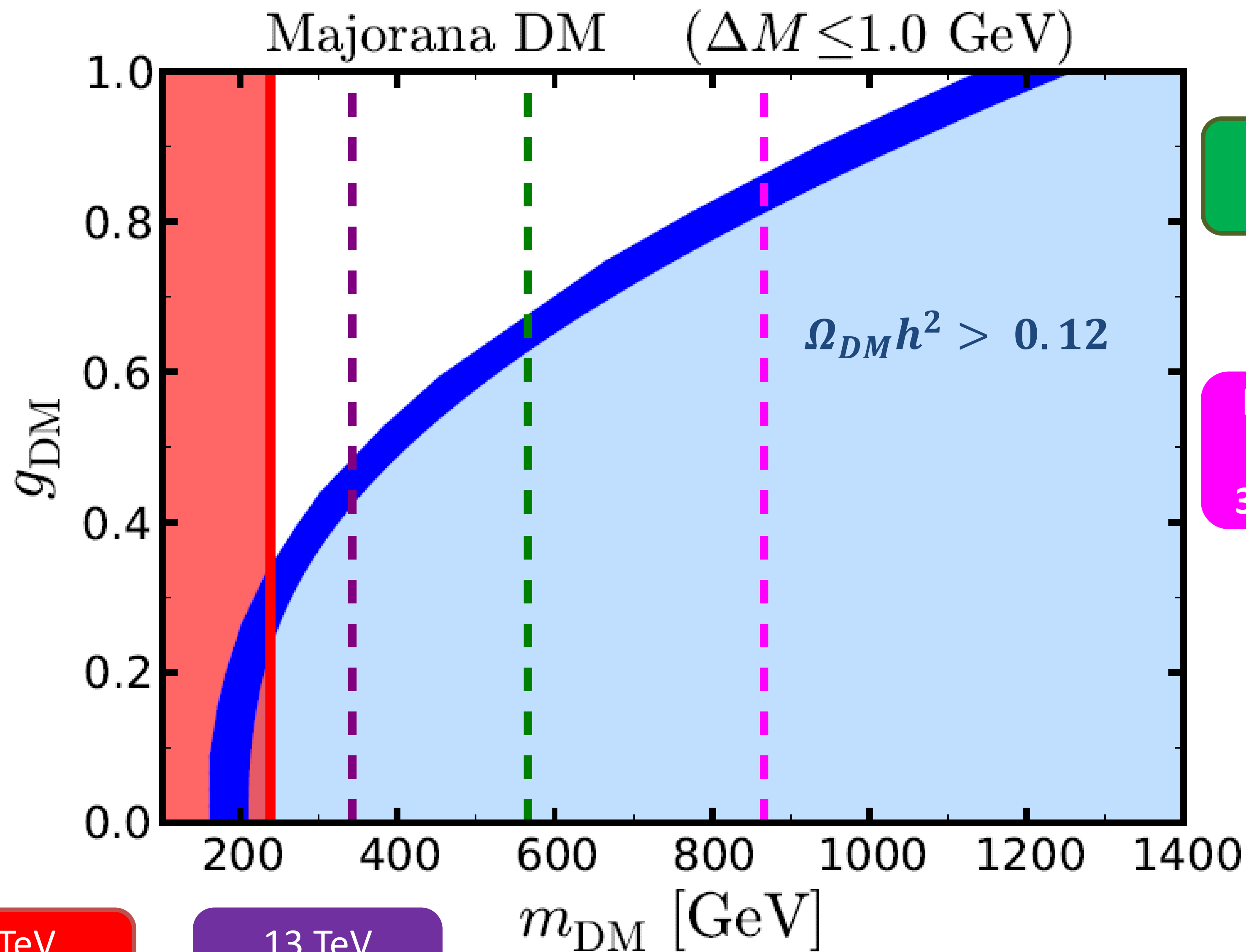


13 TeV
300 fb $^{-1}$

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

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

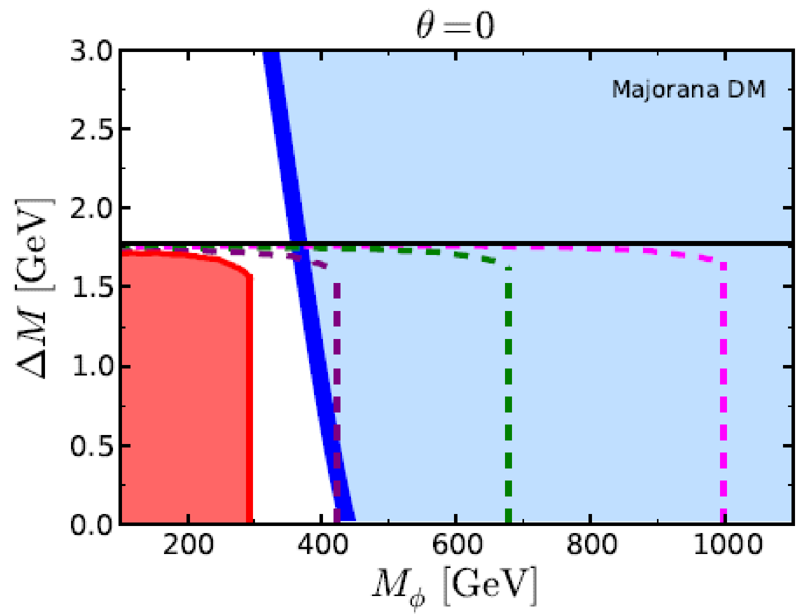
Majorana Dark Matter (Model 1b)

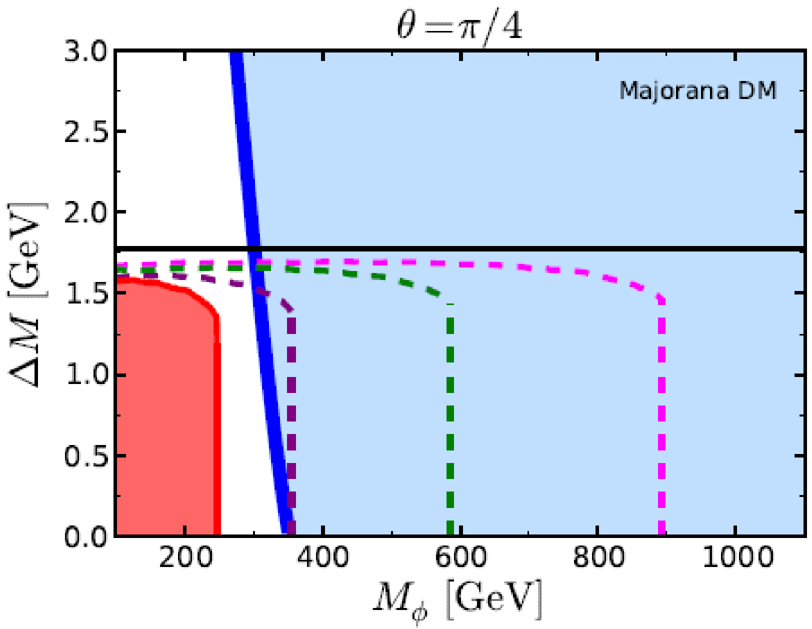
DM χ **CAP** $(Q = -1)$ ϕ

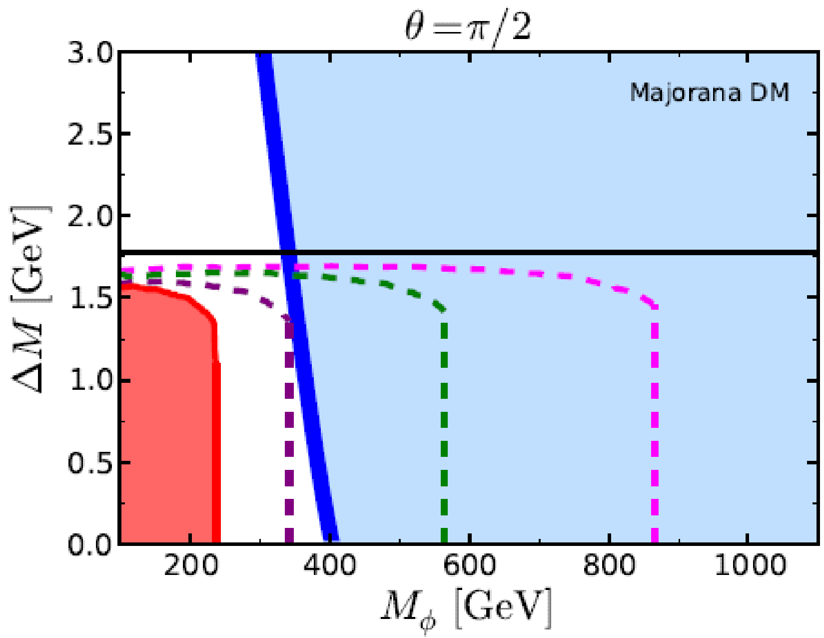
$$g_R\, \phi^* \,(\chi\, \tau_R) + g_L\, \phi^*\, (\chi\, \tau_L) \subset \mathcal{L}$$

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

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







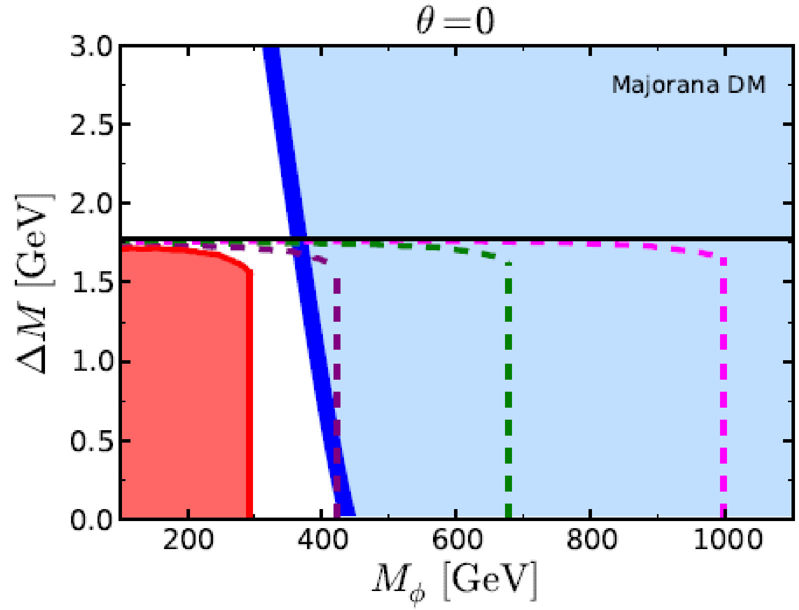
Majorana Dark Matter (Model 1b)

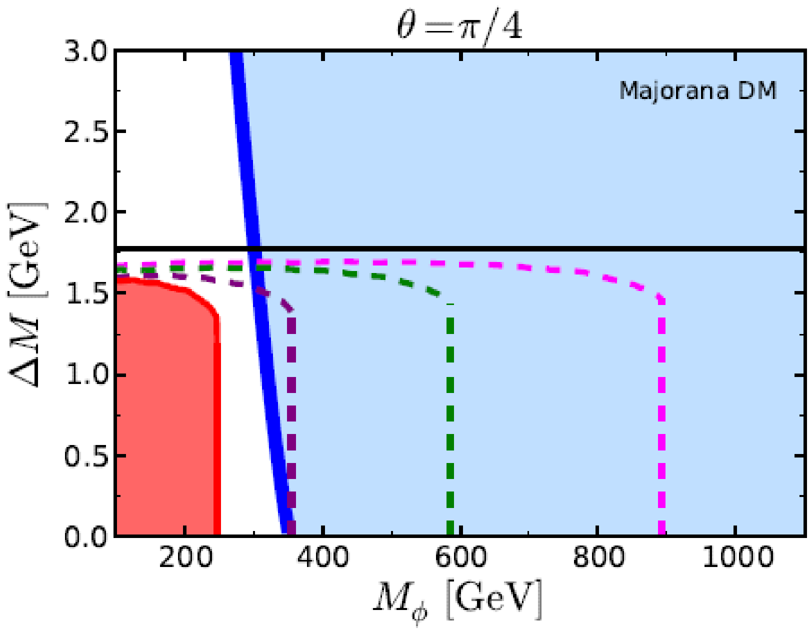
DM — **CAP** $(Q = -1)$

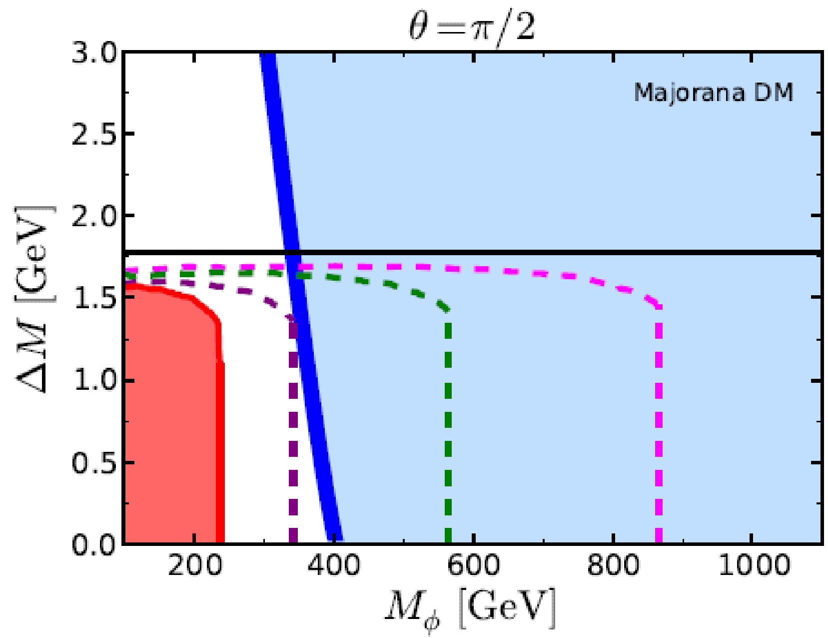
χ — ϕ

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

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







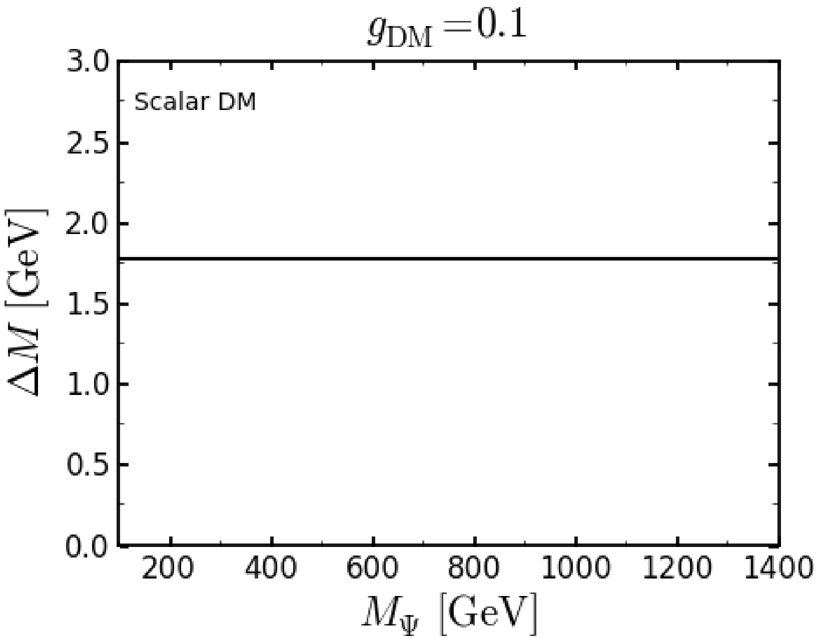
Real scalar dark matter

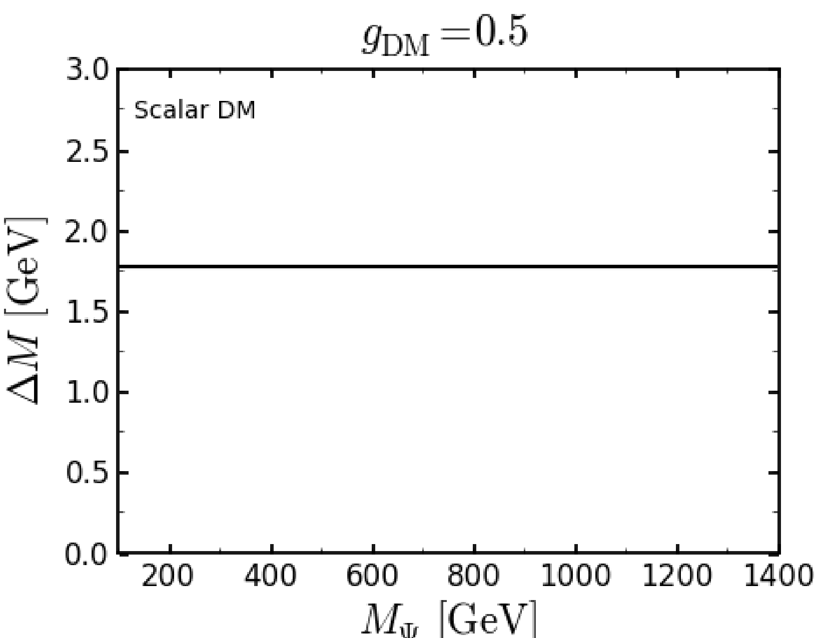
DM — S

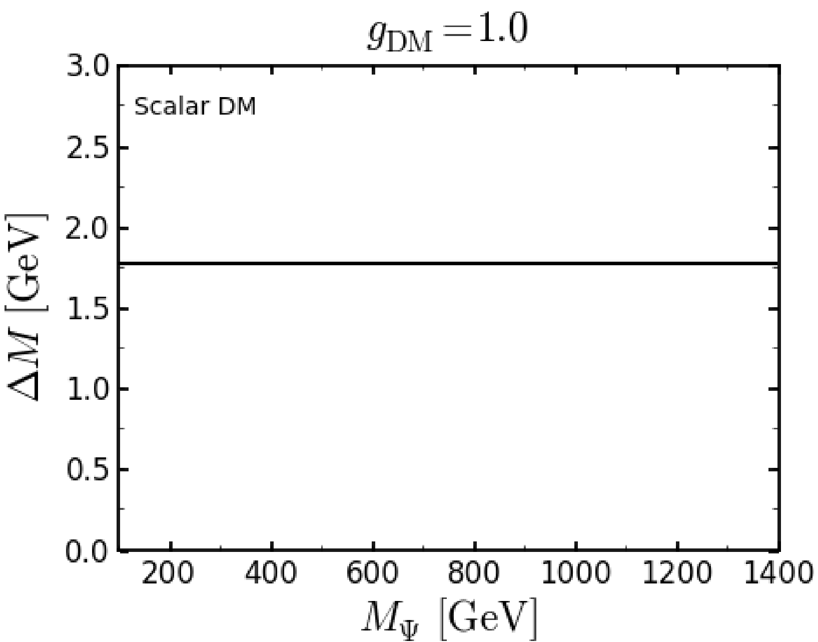
CAP $(Y = 1\ \ L_\tau = 1)$ — Ψ

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

Gauge-invariant and renormalizable, no problems of unitarity







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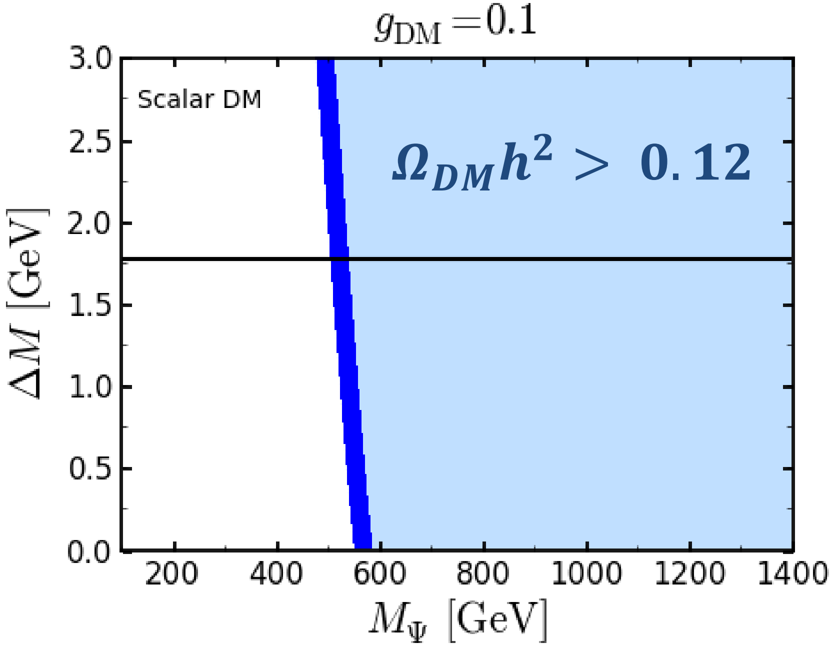

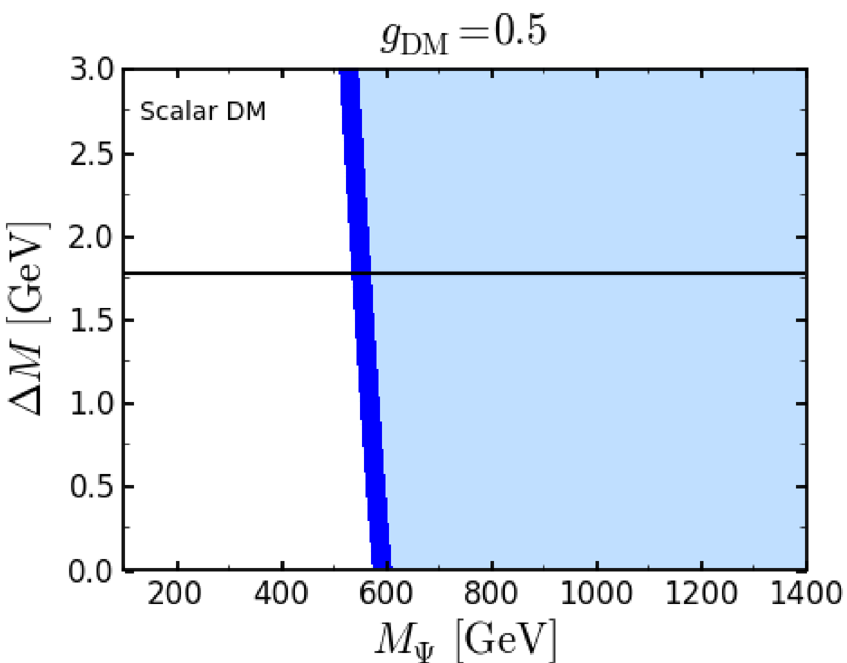

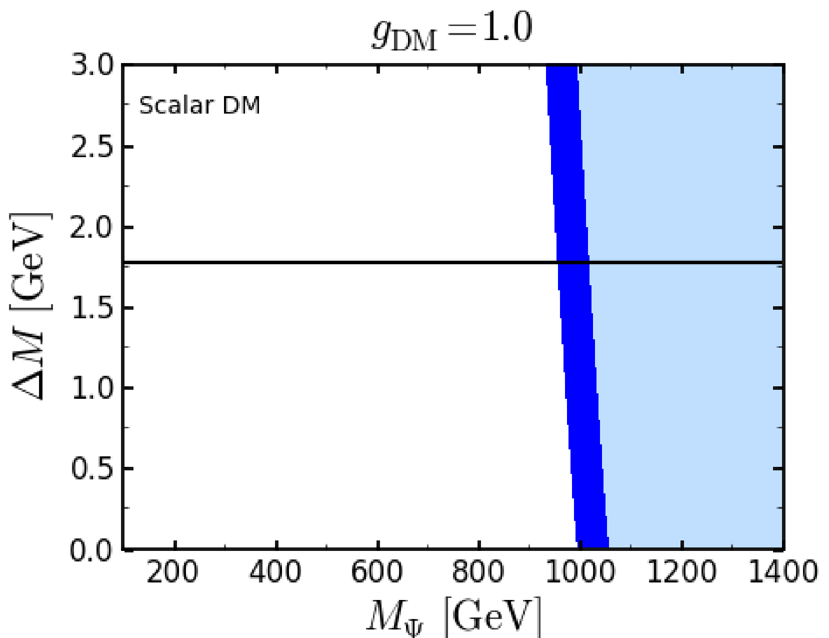

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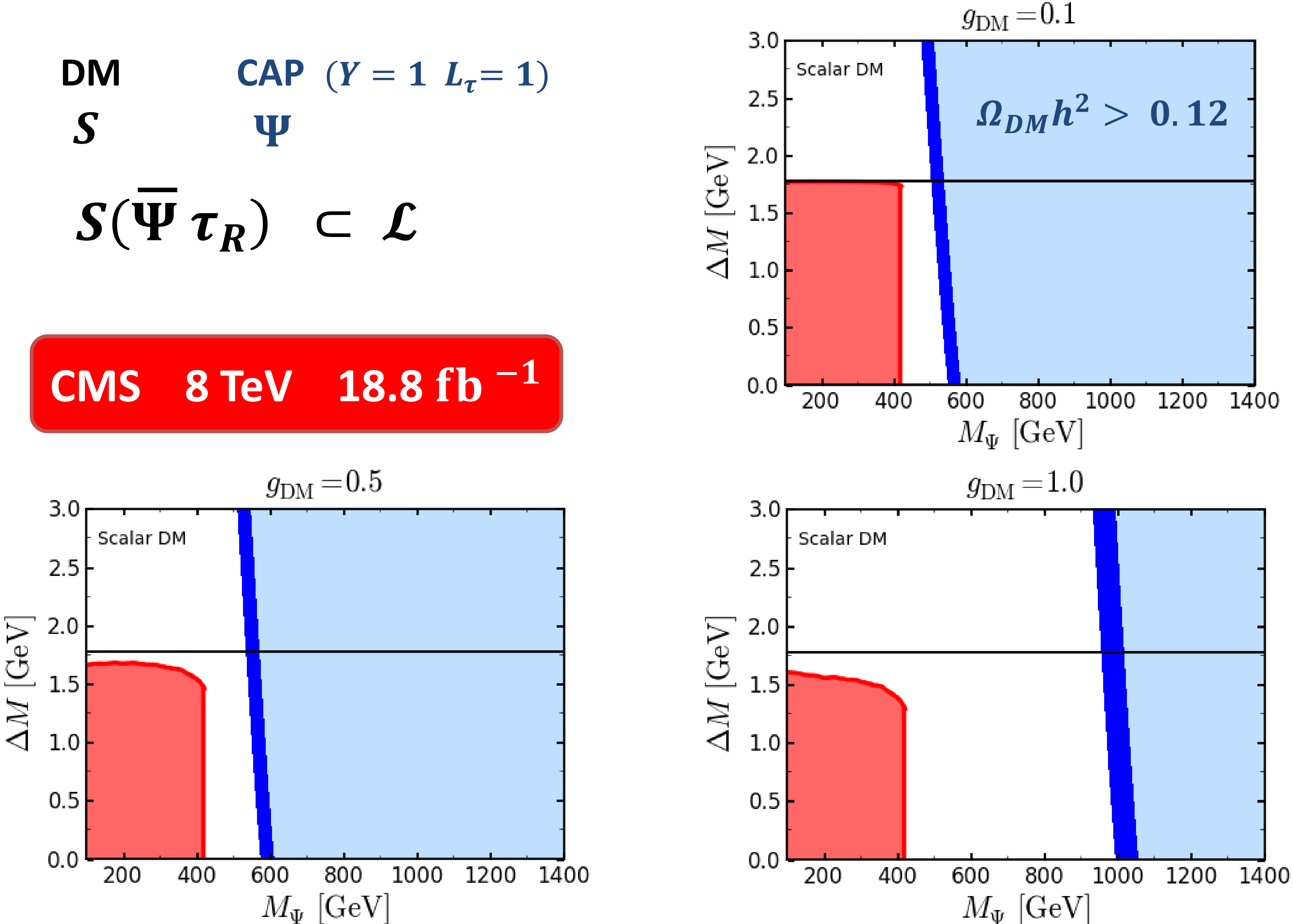

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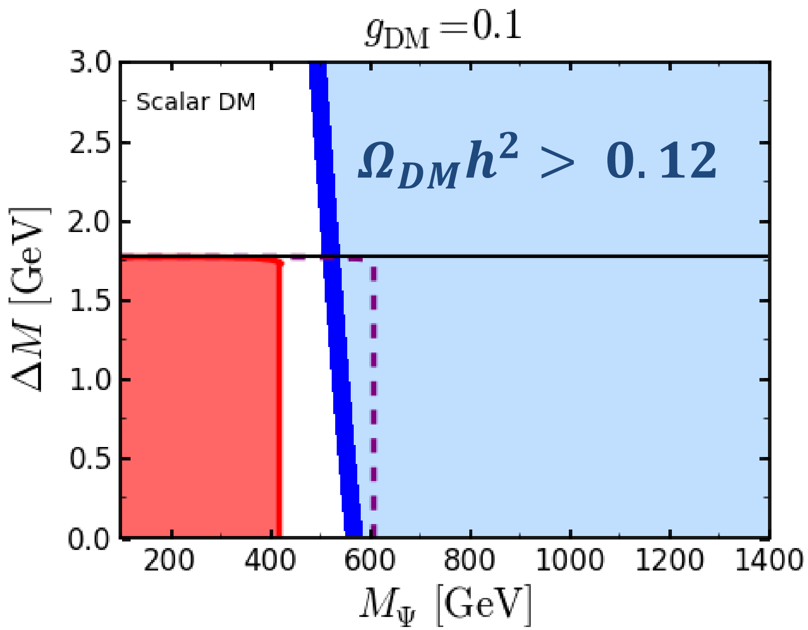

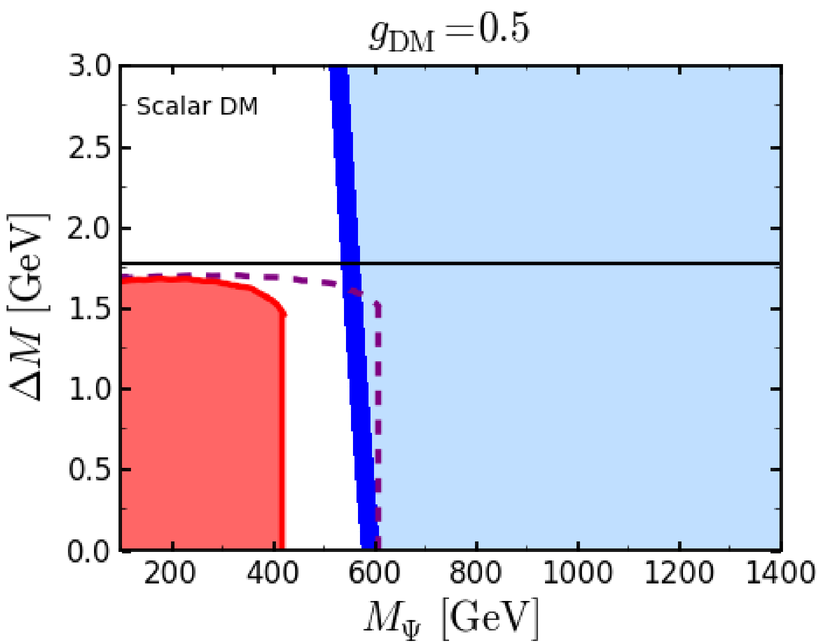

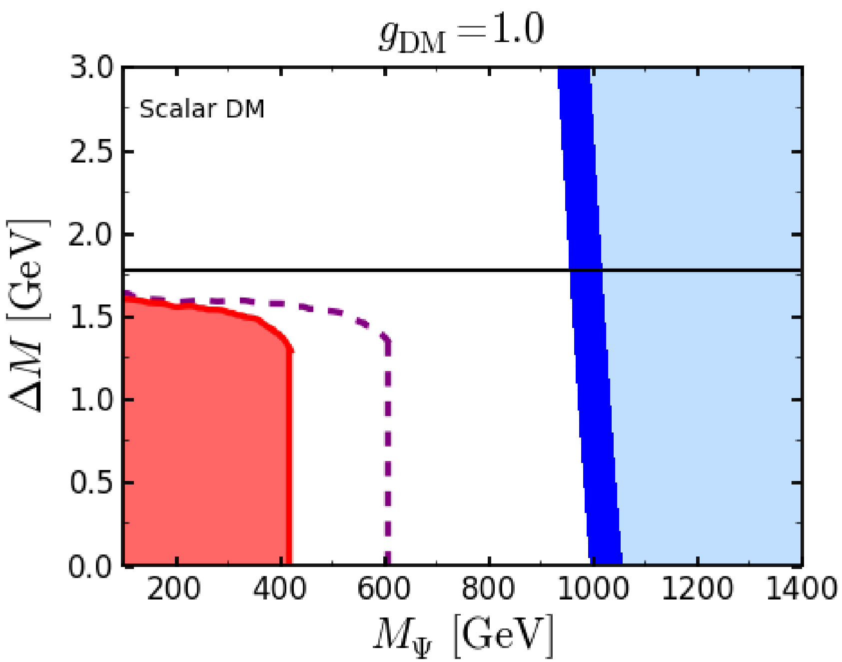

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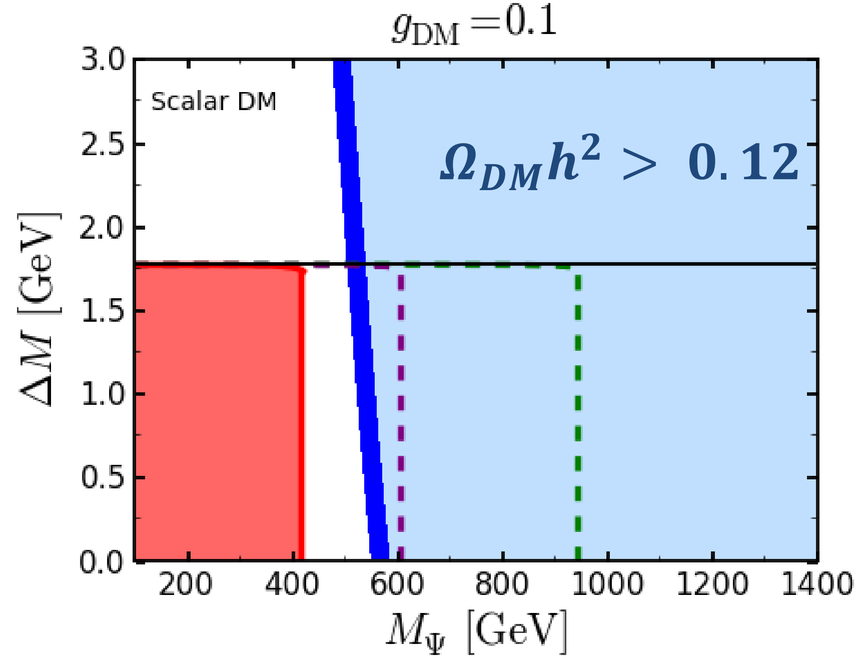

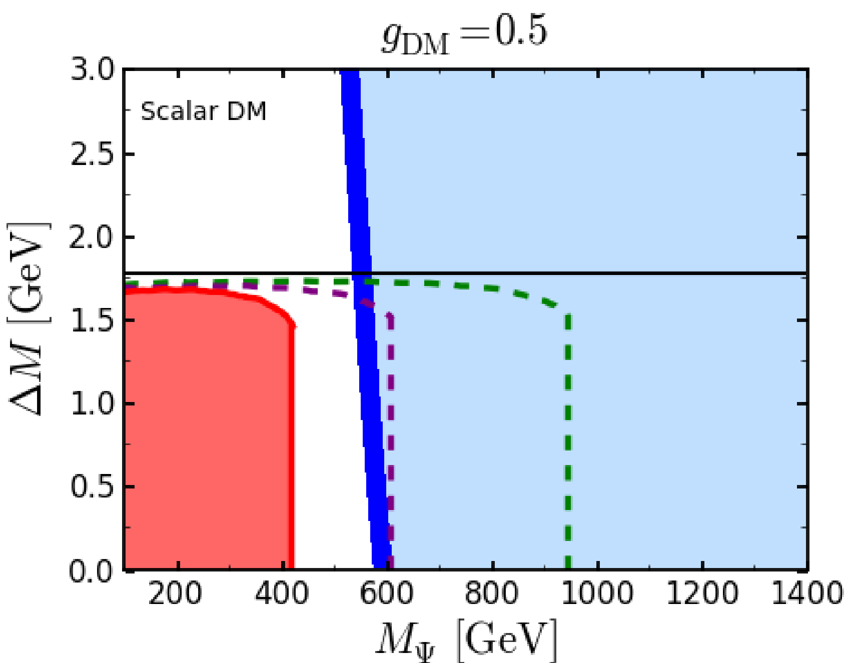

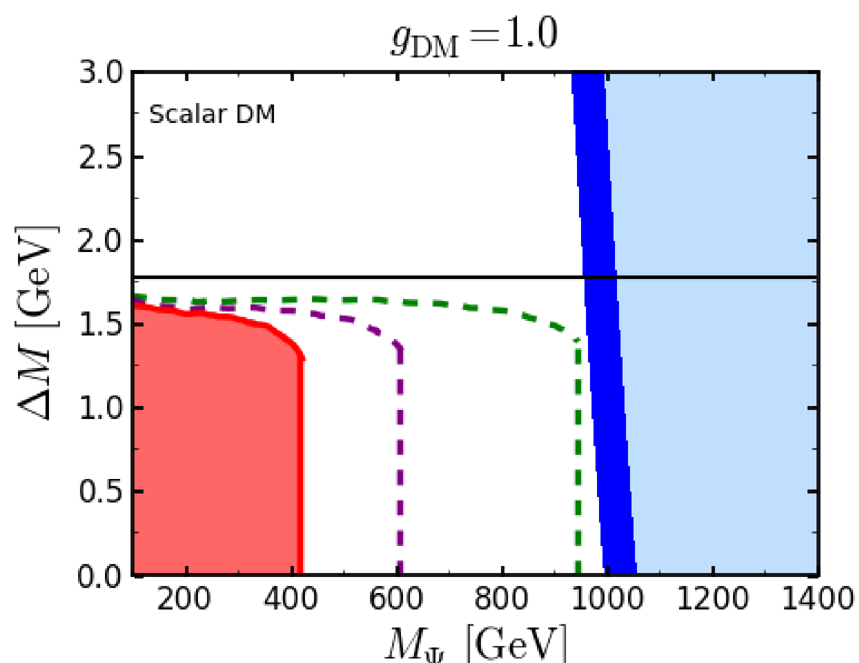

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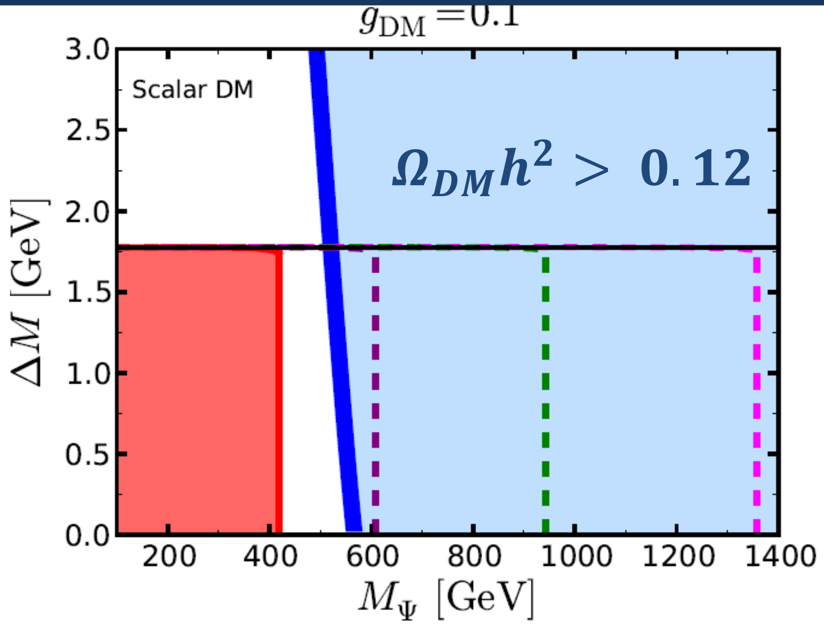

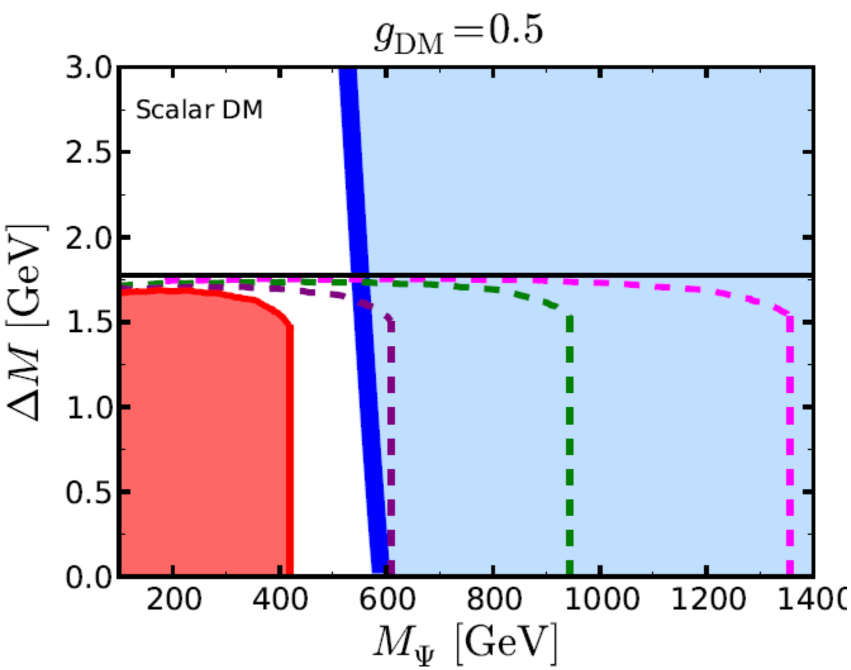

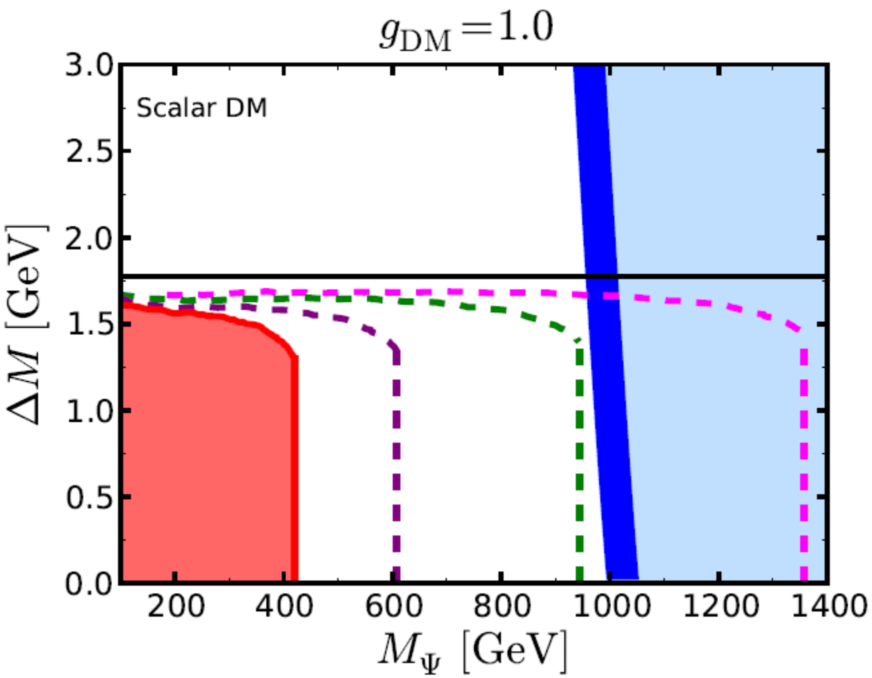

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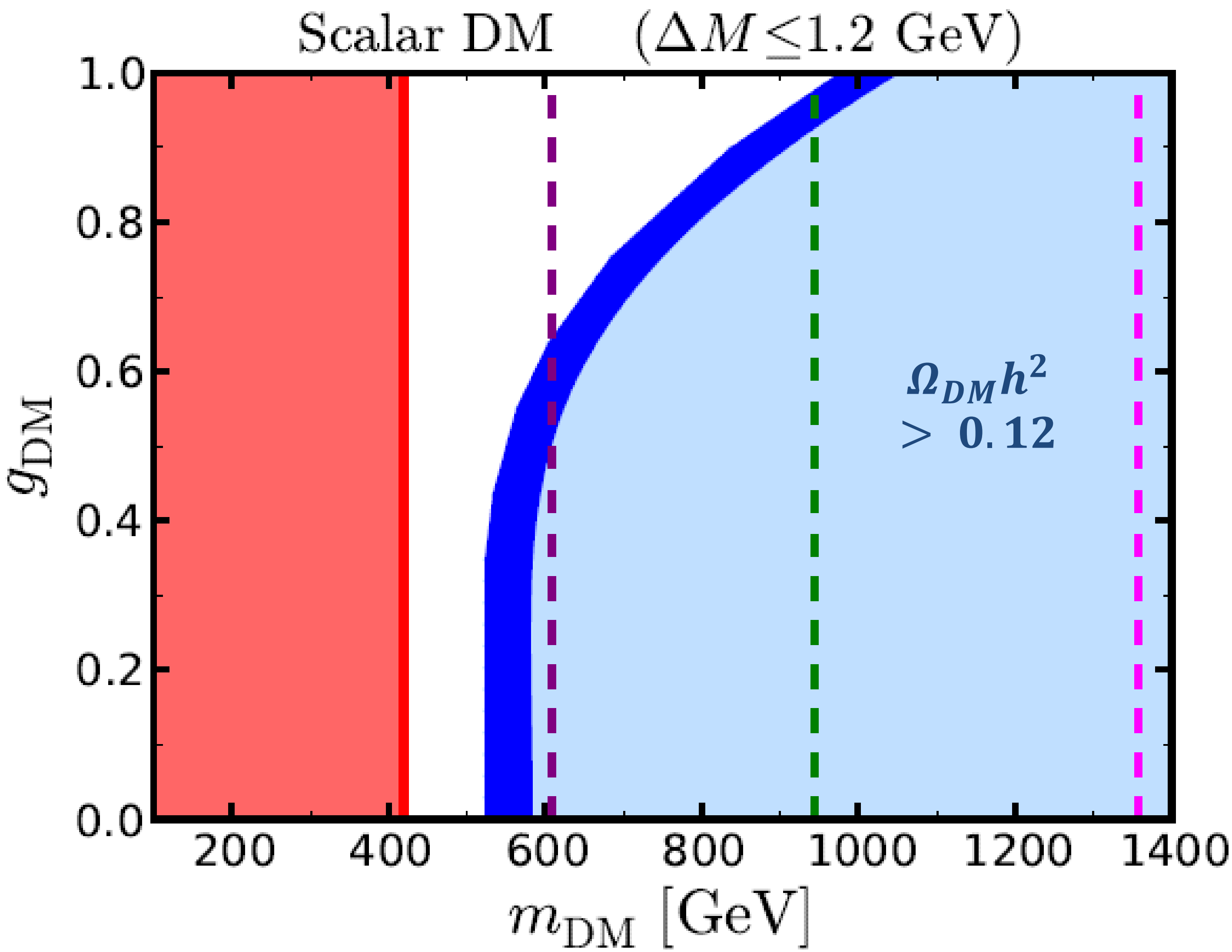

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13 TeV
30 fb $^{-1}$

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

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

- Theories with extra-dimensions, lightest KK excitation is usually the 1st excitation of the photon
- Stueckelberg mechanism and mixing between Ψ and τ_R
- Strong dynamics, composite spin-1 state
- DM spin=1 , so there is no chiral suppression

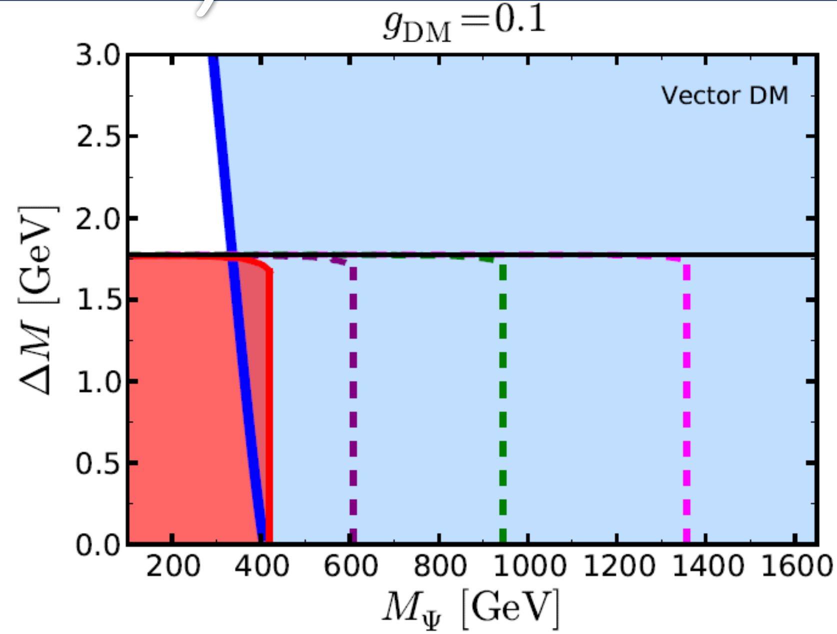
Vector dark matter (Model 3)

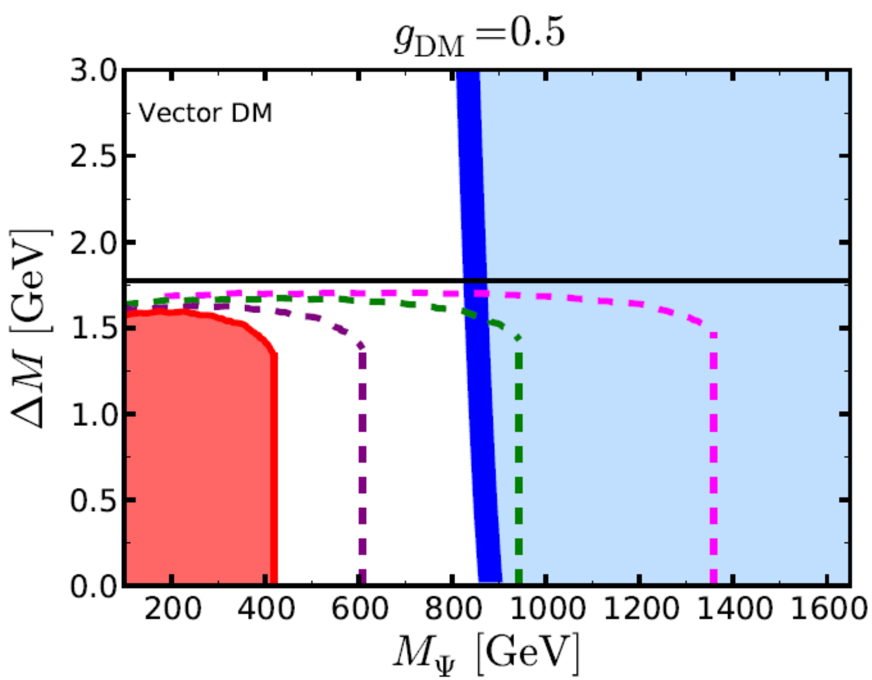
DM A_μ

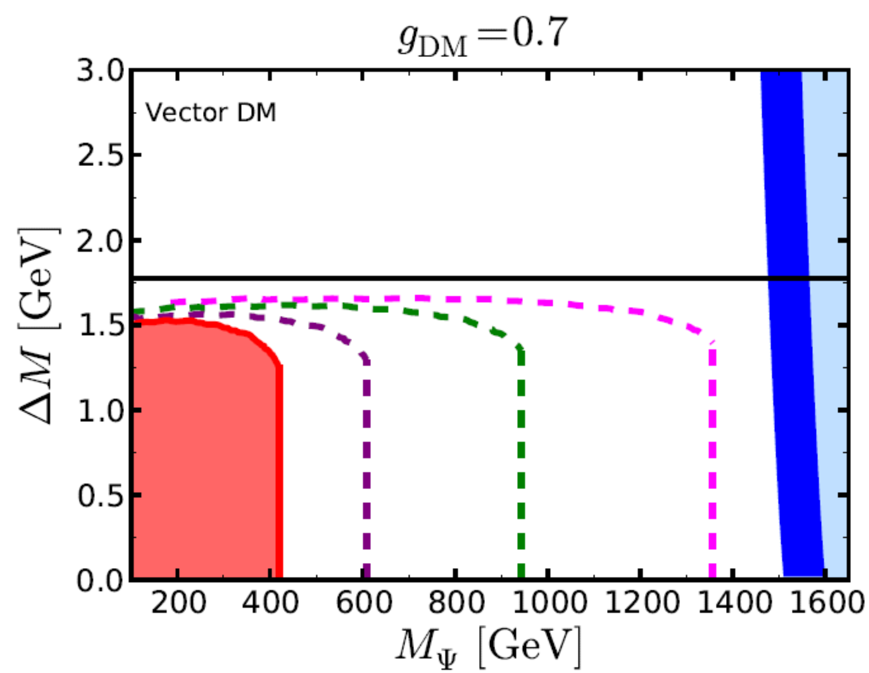
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

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

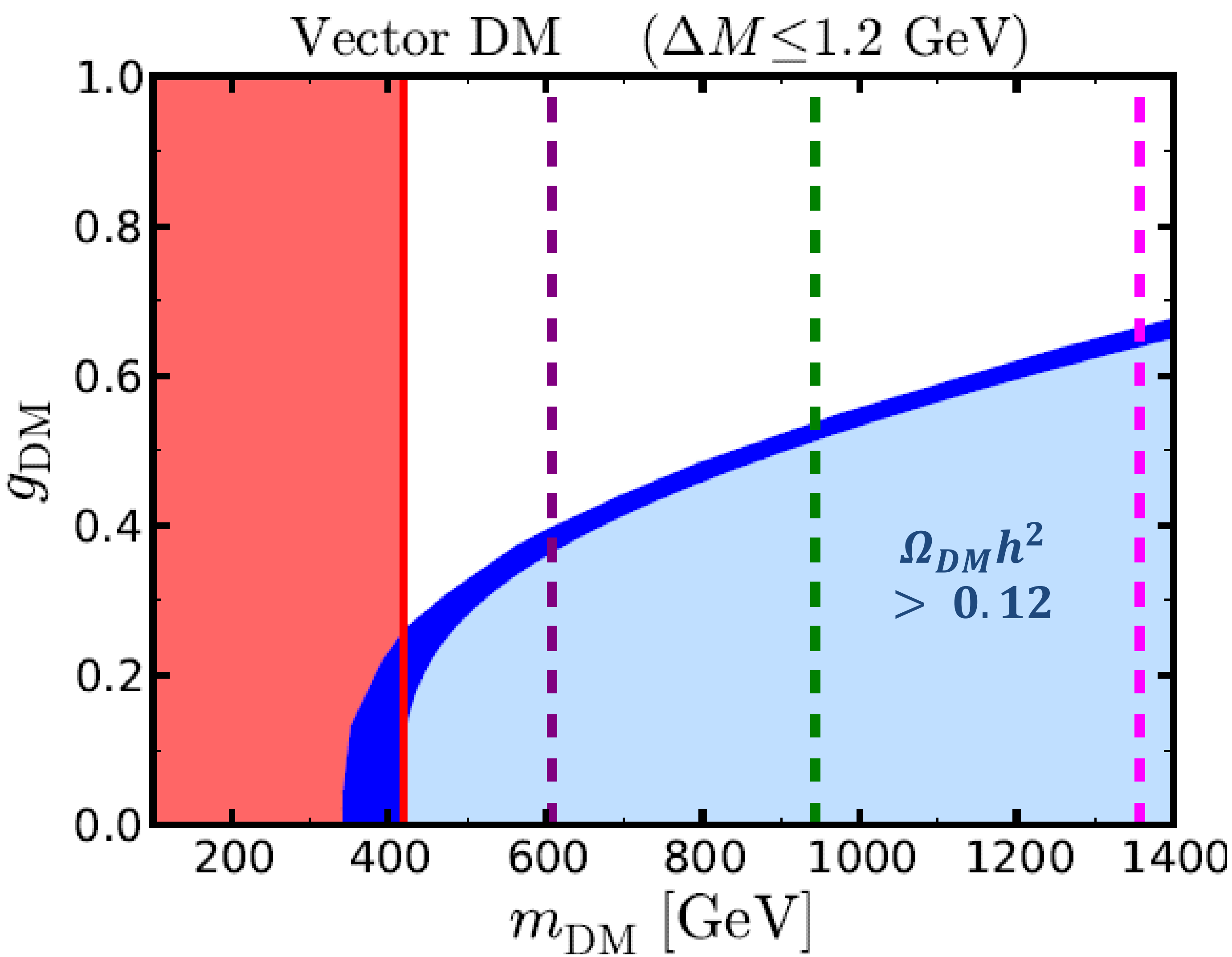
NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions







Vector dark matter



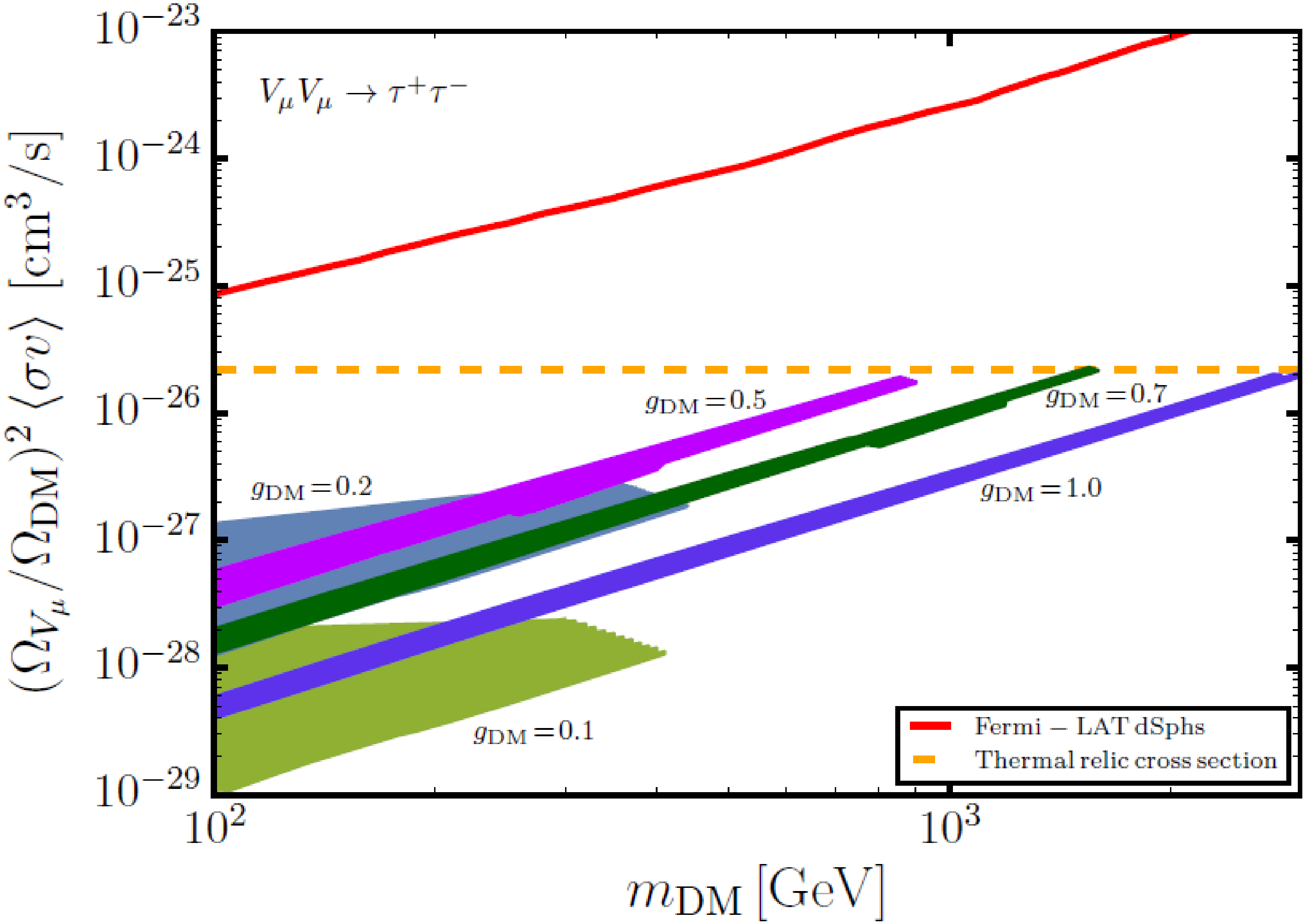
13 TeV
300 fb^{-1}

High Lumi
13 TeV
3000 fb^{-1}

8 TeV
18.8 fb^{-1}

13 TeV
30 fb^{-1}

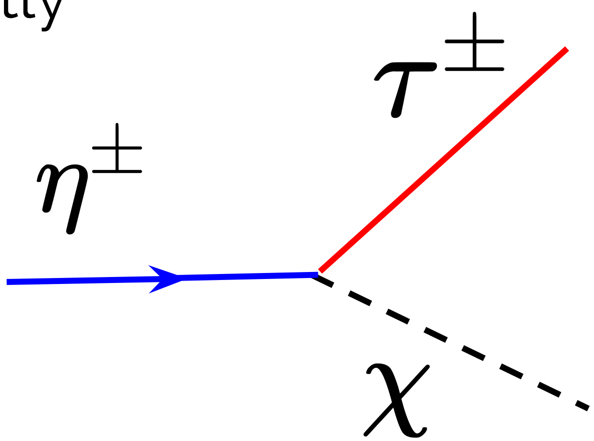
Vector dark matter



Large mass splitting?

- How can we probe the mass with large mass splitting?

- Two-body decay is open. Hence, coannihilation partner decays promptly



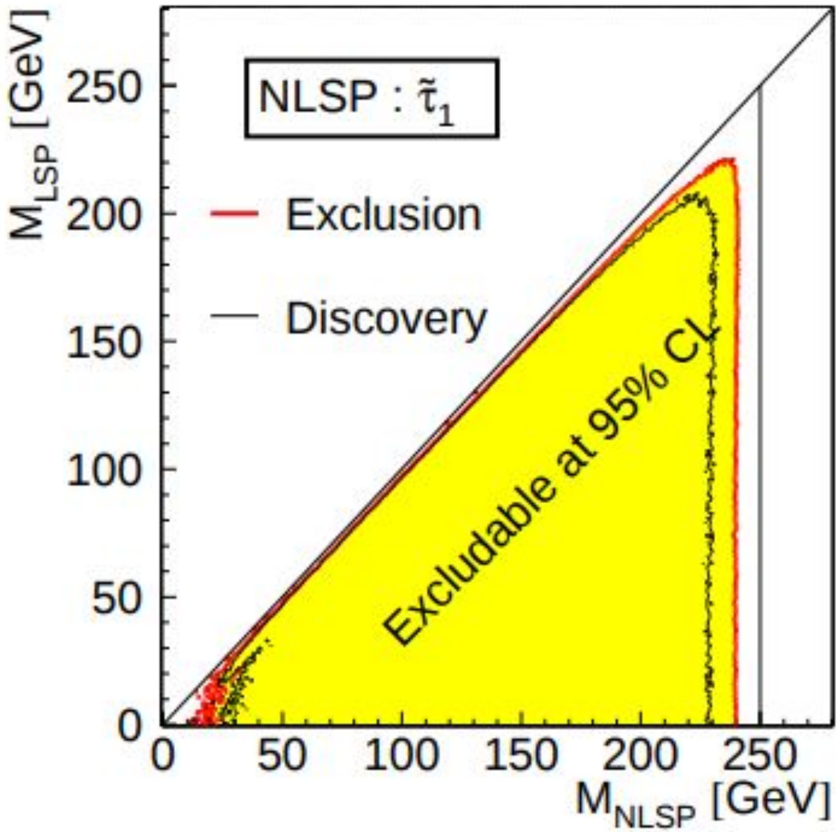
- At the LHC it is hard to reconstruct soft taus, coannihilation region $\boldsymbol{\Delta M > m_\tau}$ is out of reach. Could work for muons and electrons

Future proposed linear colliders

- Clean experimental environment and hence we can fully reconstruct the missing energy
- **ILC**: International Linear Collider concept in Japan. 20 km in length. First stage planned to have **sqrt(s) = 250 GeV**.
- **CLIC**: Compact Linear Collider concept at CERN. Between 11 - 50 km in length. First stage planned at **sqrt(s) = 380 GeV** (top quark factory), future stages will go up to **3 TeV.**
- We focus our study on CLIC, since it is planned to reach higher centre-of-mass energies

Neither collider has been approved yet

e+ e- linear colliders



[Berggren 2013]

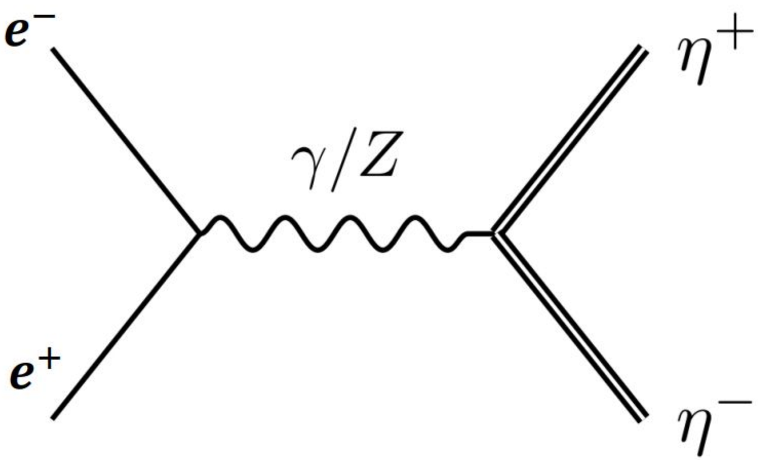
- Example: linear colliders can study compressed spectrum in SUSY
- Soft tau background from bremsstrahlung photon collisions, $\gamma\gamma \rightarrow \tau^+\tau^-$ can be large

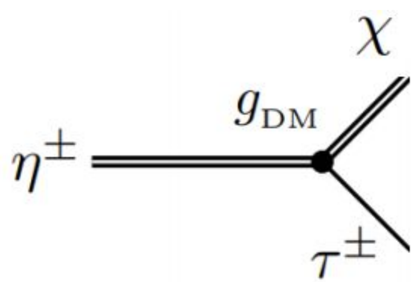
$e^+ e^-$ linear colliders

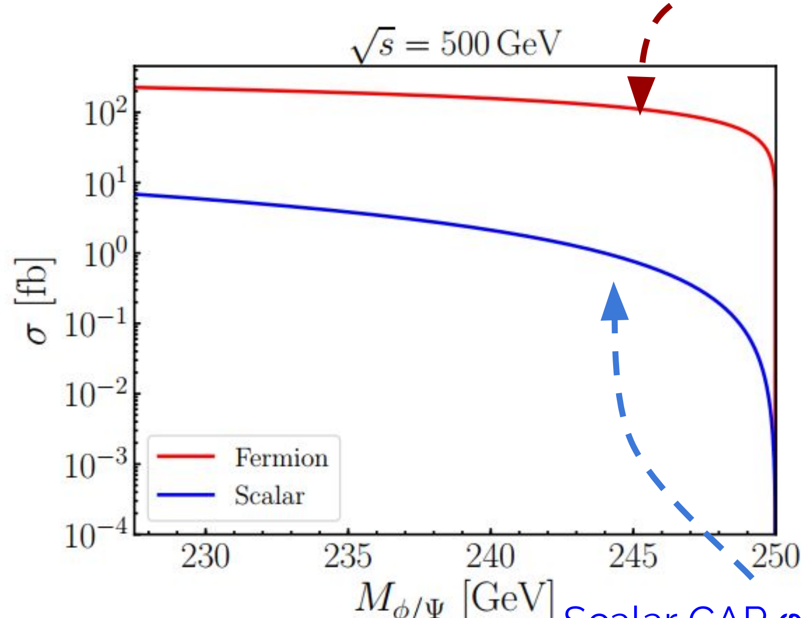
- Drell-Yan pair production of CAPs

$$e^+ e^- \rightarrow \psi^+ \psi^- \rightarrow \tau^+ \tau^- \chi \chi$$

Fermion CAP ψ^+





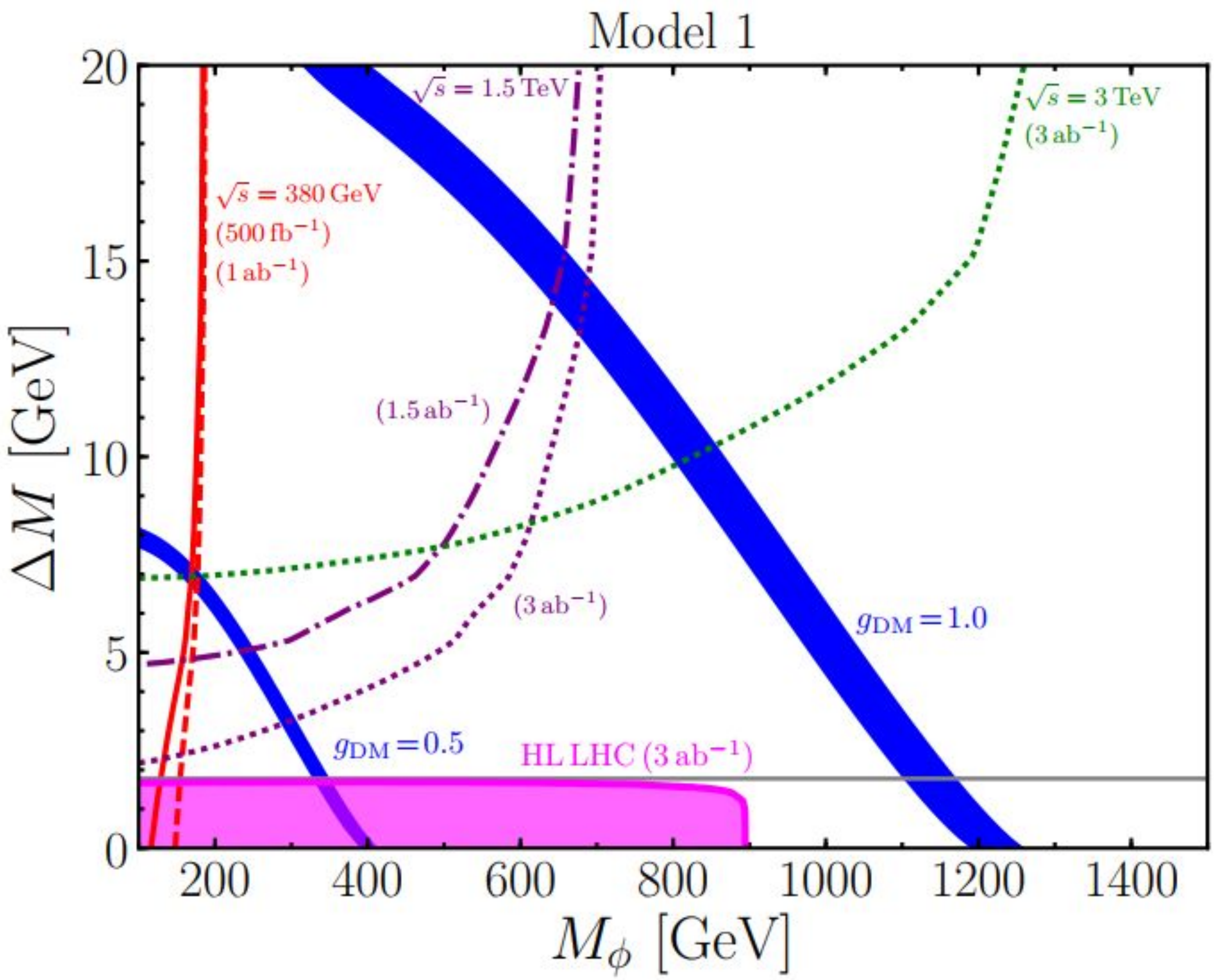


Scalar CAP φ^+
Cross-section decrease faster due to factor $\boldsymbol{\beta}^3$ in cross-section.

Majorana DM

$$g_{\mathrm{DM}}\ \phi^*\ \chi\ \tau_R \subset \mathcal{L}$$

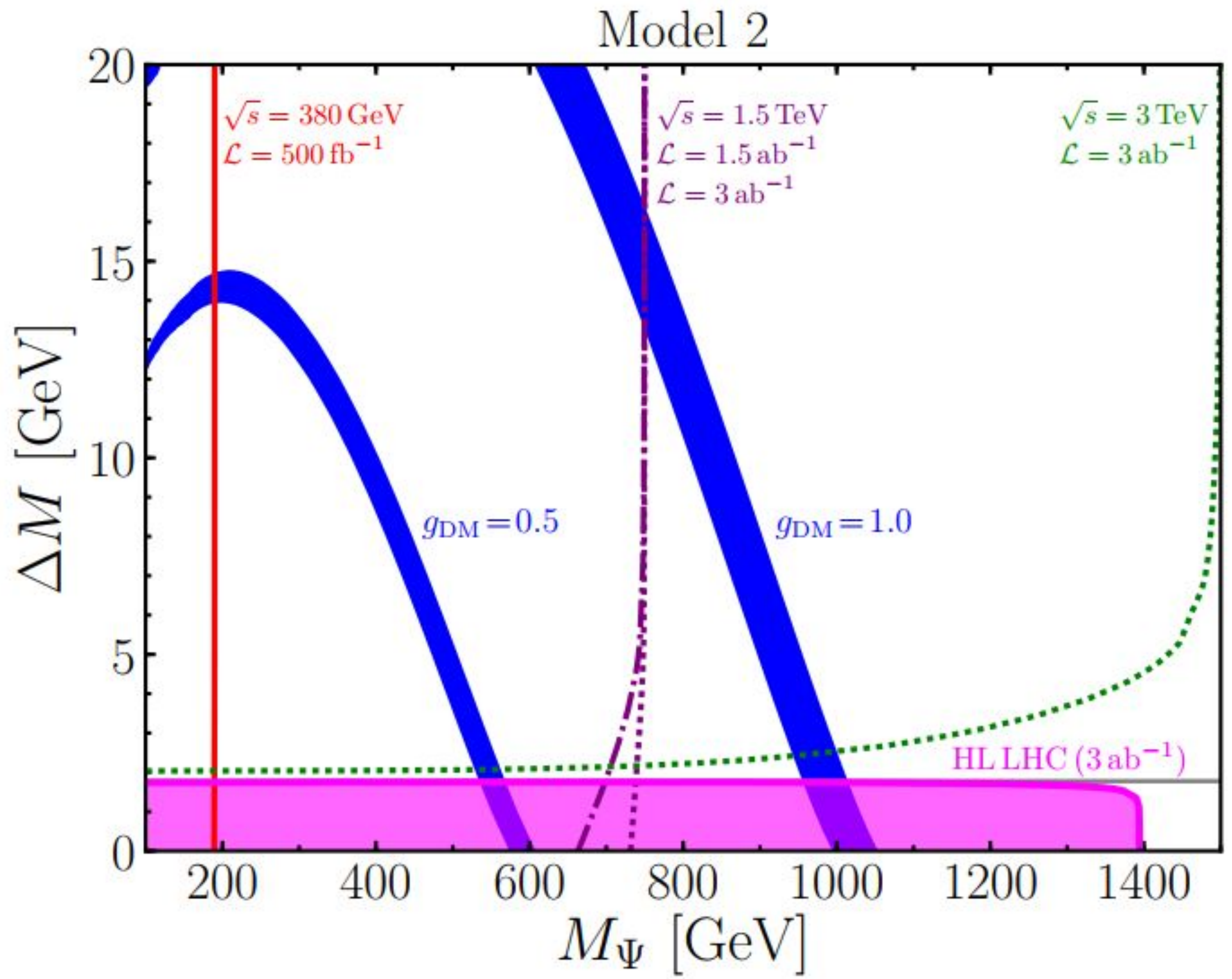
Blue bands correspond to correct relic abundance within 3σ for different couplings



Scalar DM

$$g_{\mathrm{DM}}\; S\,\overline{\Psi}\,\tau_R \subset \mathcal{L}$$

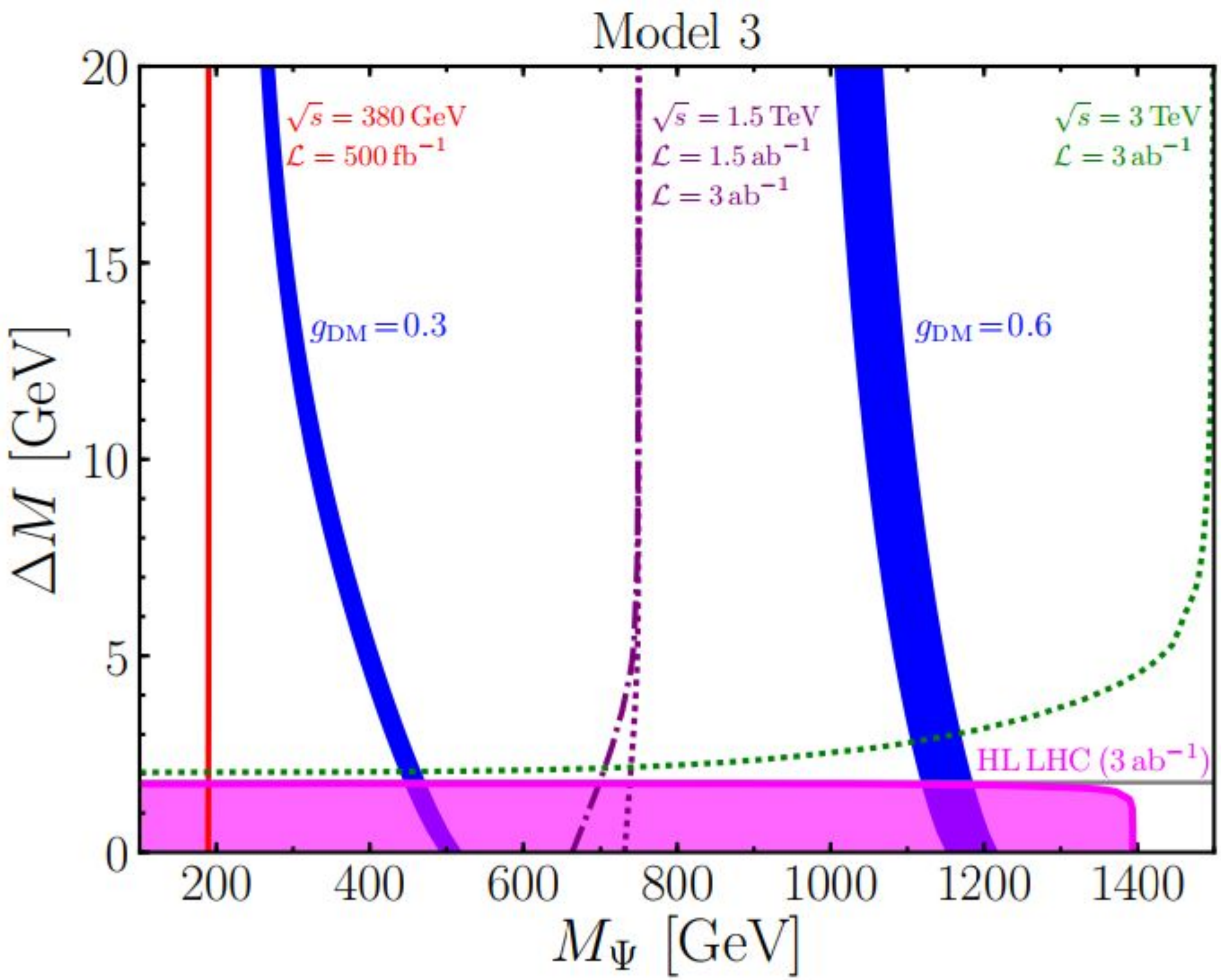
Blue bands correspond to correct relic abundance within 3σ for different couplings



Vector DM

$$g_{\rm DM}\, A_\mu\, \overline{\Psi}\, \gamma^\mu\, \tau_R \subset \mathcal{L}$$

Blue bands correspond to correct relic abundance within 3σ for different couplings

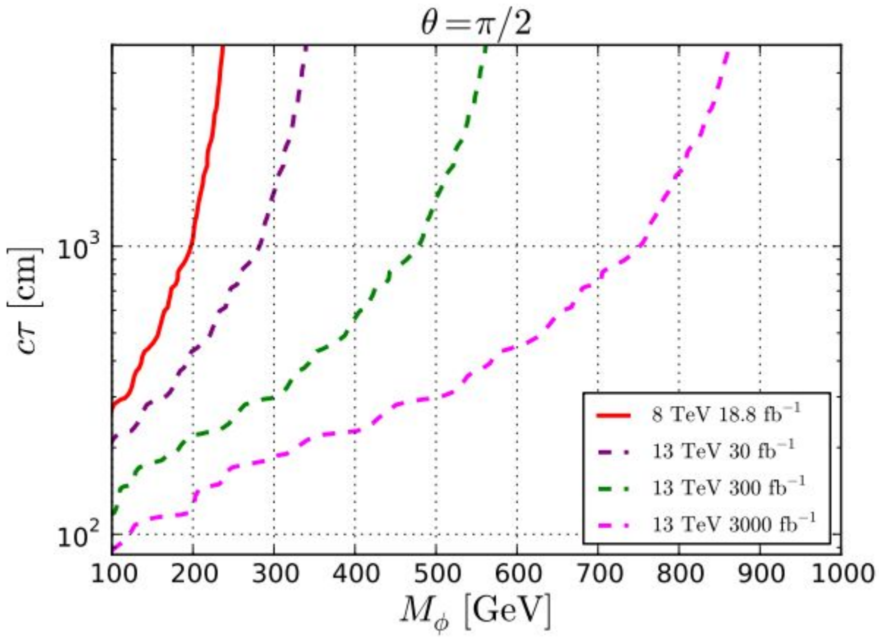


Conclusions

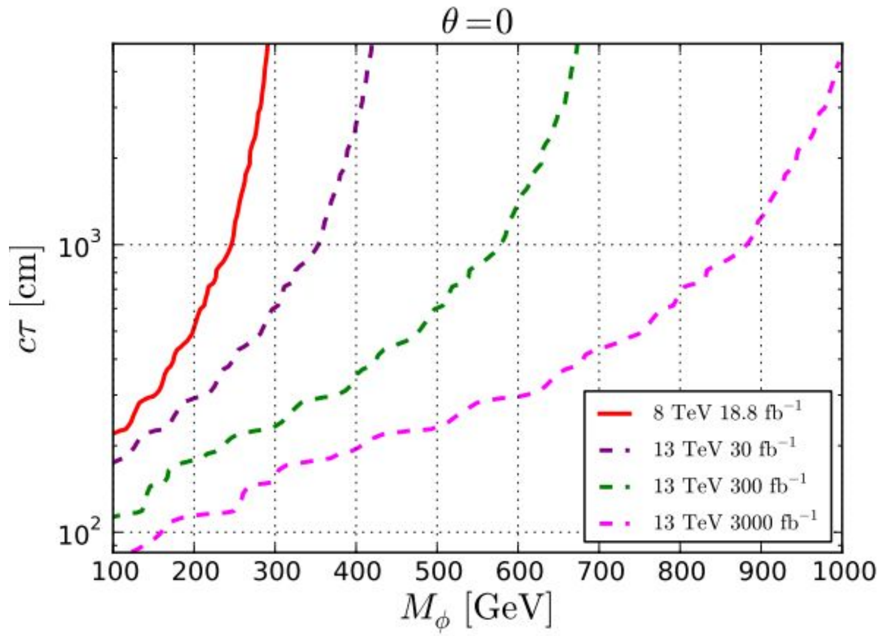
- We have studied 4-classes of simplified models of DM that have three-point interaction with τ-lepton
- Instead of a mediator, these models have a coannihilation partner that has non-zero hypercharge
- These models can hide from direct and indirect detection
- LHC + CLIC will probe almost the entire allowed region for scalar and vector DM and a large region of parameter space for Majorana DM

Thank you!

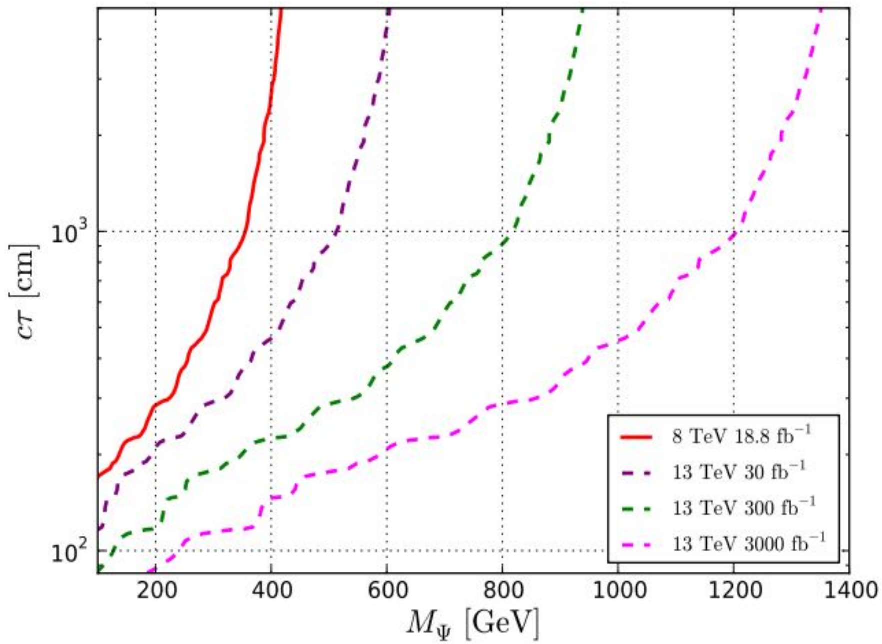
Back-up



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

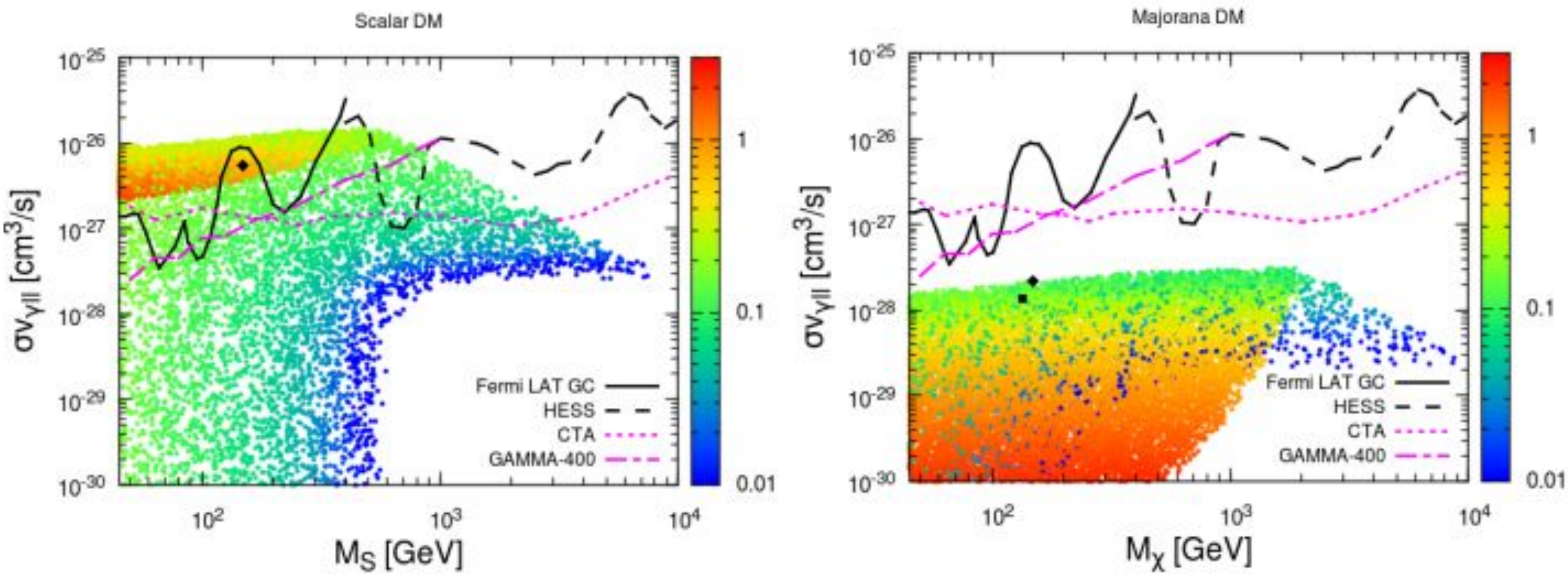


θ = 0
cτ [cm]
M_φ [GeV]
8 TeV 18.8 fb⁻¹
13 TeV 30 fb⁻¹
13 TeV 300 fb⁻¹
13 TeV 3000 fb⁻¹



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

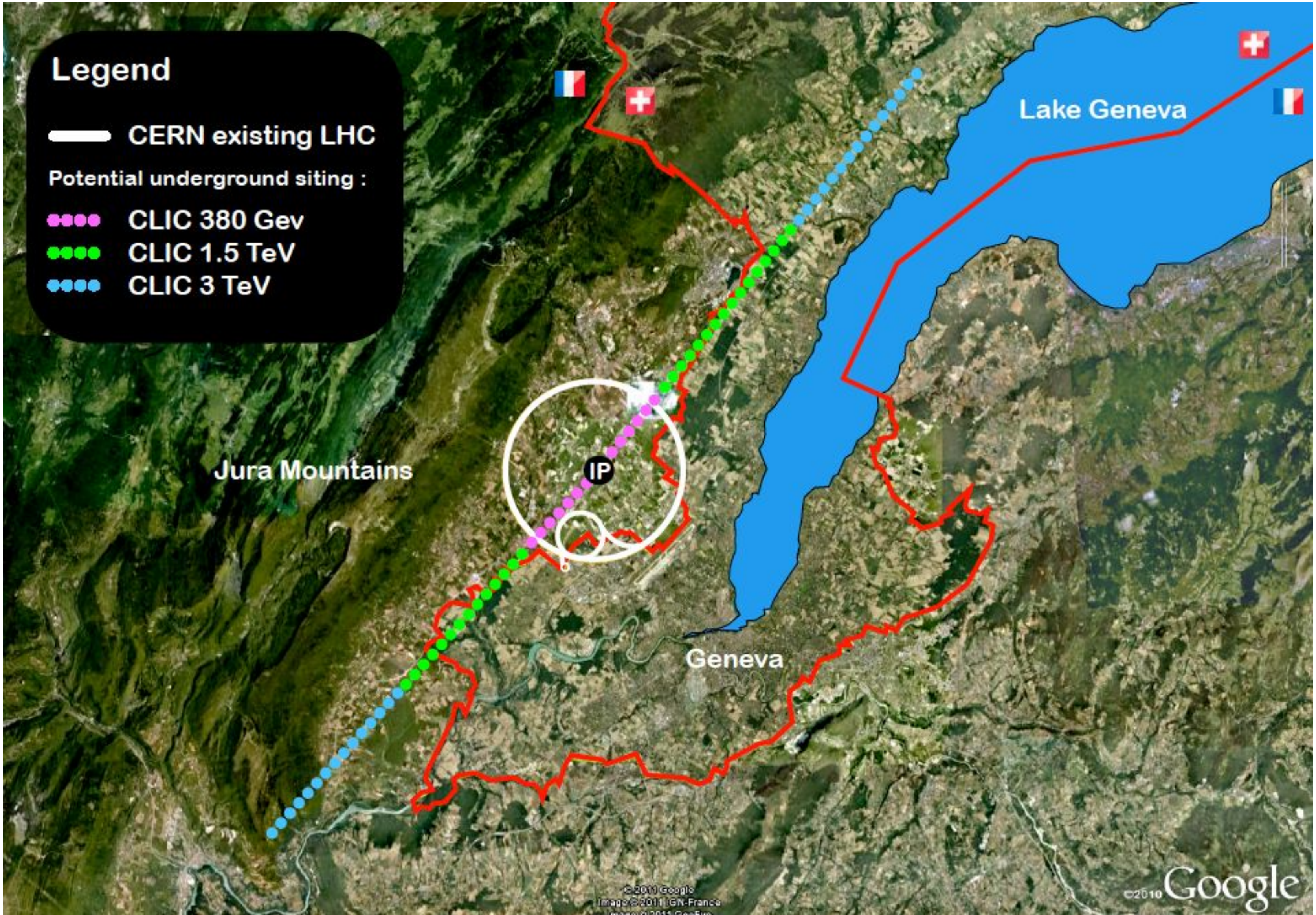


Color coding corresponds to parameter **M_{CAP}/M_{DM} - 1**

Blue dots correspond to small mass splitting

[Giacchino, Lopez-Honorez, Tytgat 2013]

CLIC


Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
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CLIC Timeline

- 2019 - Physicists will present the case for the CLIC concept in the Update for the European Strategy for Particle Physics

ILC

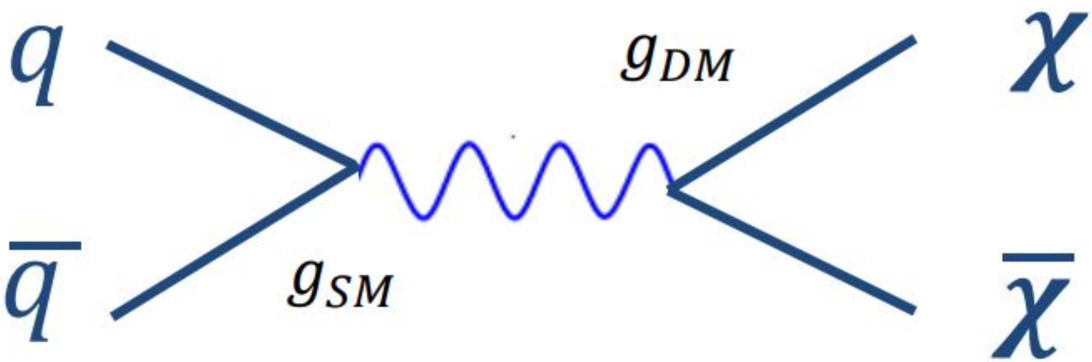
- Proposed to be built in the Kitakami site

- December 2018. Did not receive support from the Japanese Science Council:

  “The council says it recognizes the scientific significance of the project. But it says it has not reached the consensus that scientific achievements expected from the project will fully warrant its huge costs.” (US$7-billion)

Simplified models of dark matter

- EFT is a powerful and model-independent approach
- However, in the context of dark matter there is no reason to expect $M_{med} >> m_{DM}$
- Going beyond EFTs:



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

[Buchmueller, Dolan, McCabe 2013]
[Busoni, De Simone, Morgante, Riotto 2014]
Community reports: [1507.00966] [1506.03116]