Tau-philic dark matter co-annihilation at LHC and CLIC

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with Valentin Khoze and Kazuki Sakurai

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

Durham University

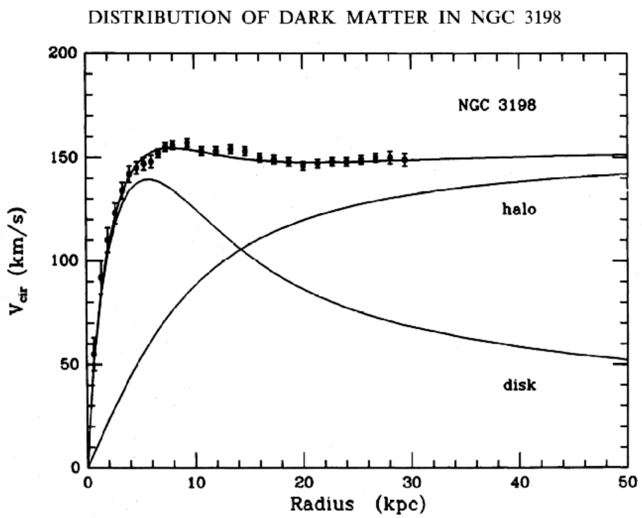
IP3

Outline

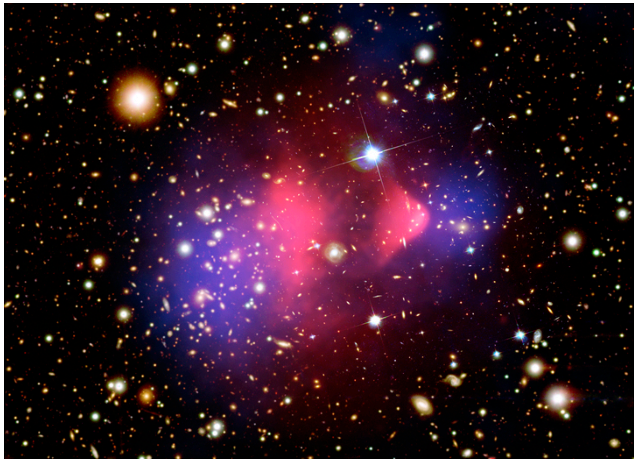
1. Dark Matter @ the LHC
2. Going Beyond EFT: ‘Simplified Models of DM’
3. Co-annihilation partner as the next-to-lightest state
4. Four different scenarios
5. Prospects at CLIC
6. Conclusions

Dark Matter

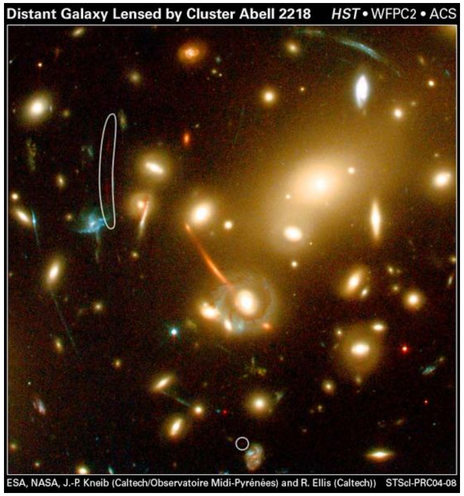
Galaxy rotation curves



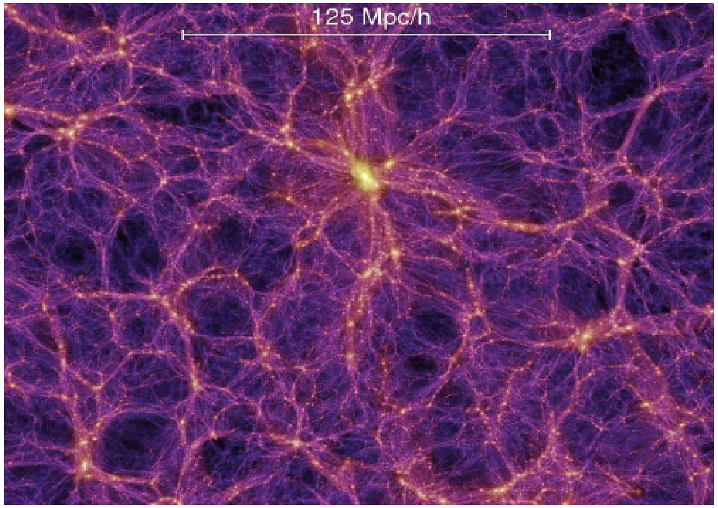
Bullet cluster

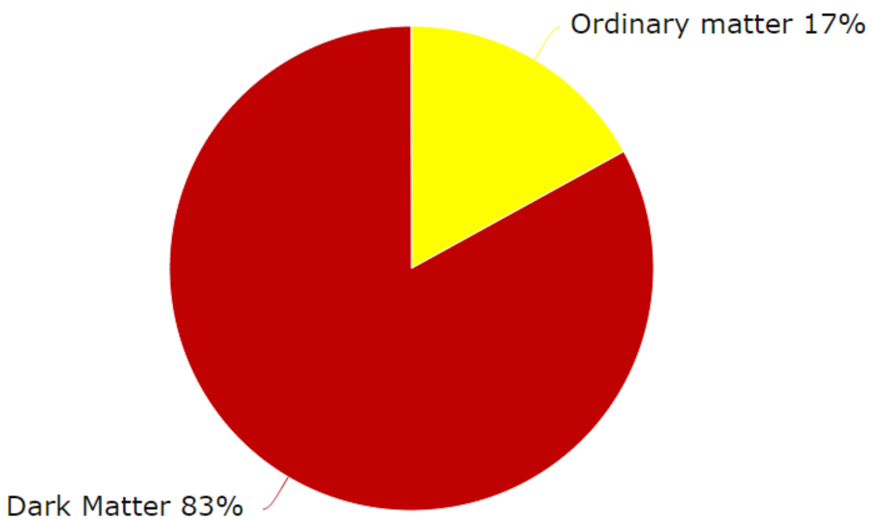


Gravitational lensing



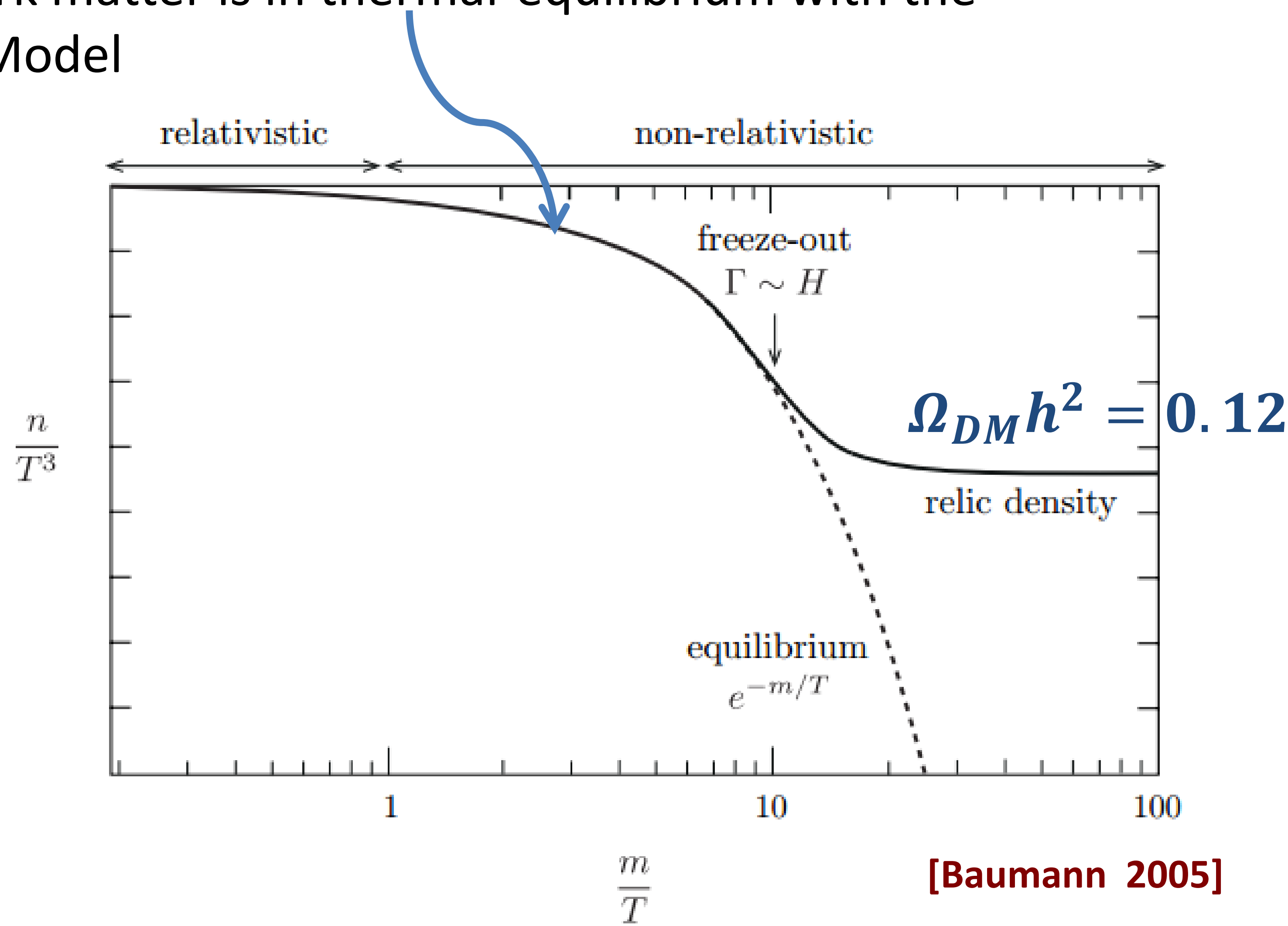
Structure formation





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

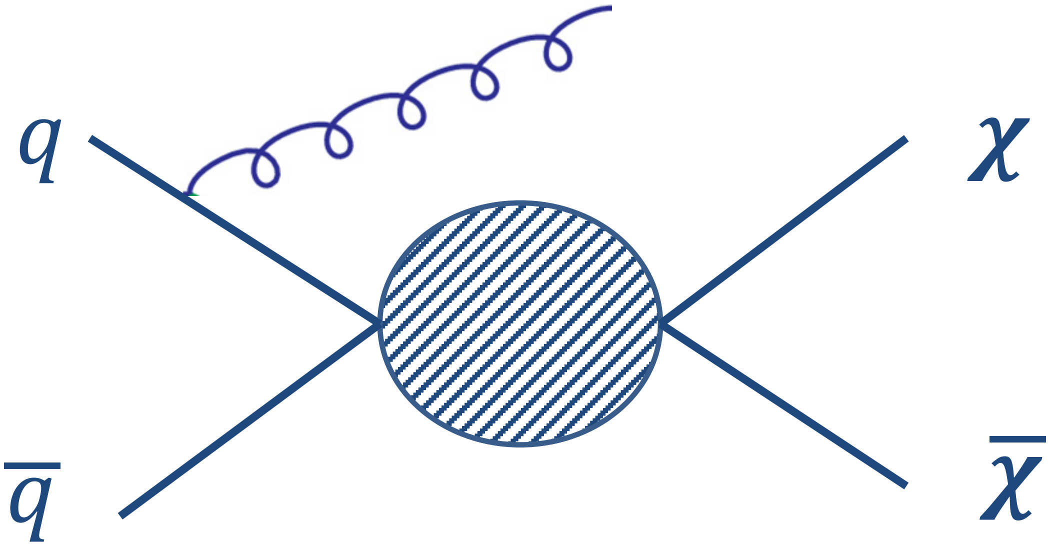
- In lack of a signal from DM experiments, we need to explore as much as we can of the WIMP's parameter space

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

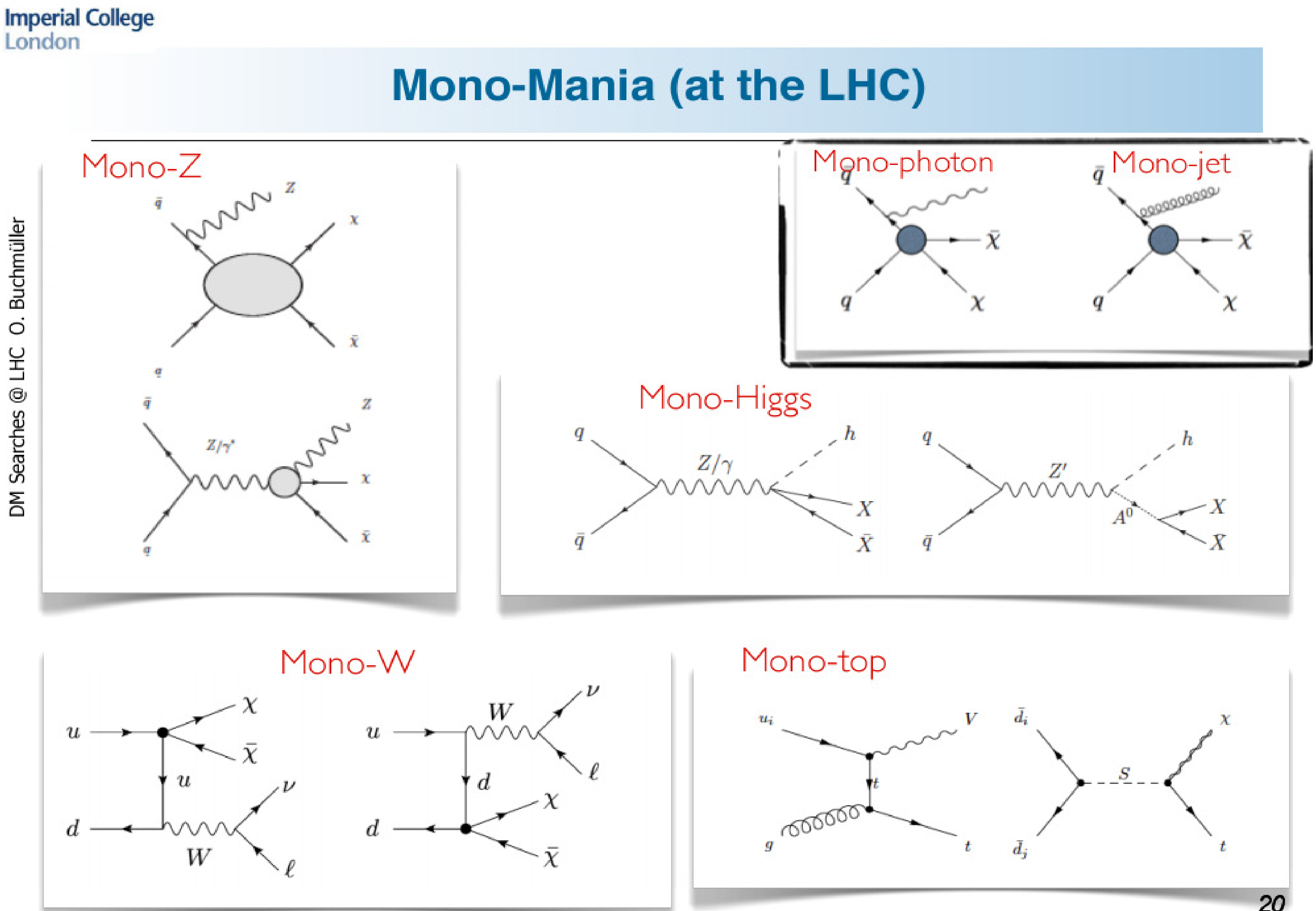
Dark Matter @ Colliders

- Pair-production of dark matter (missing energy)
- How do we detect DM pair-production? Consider extra visible emissions from the initial quarks



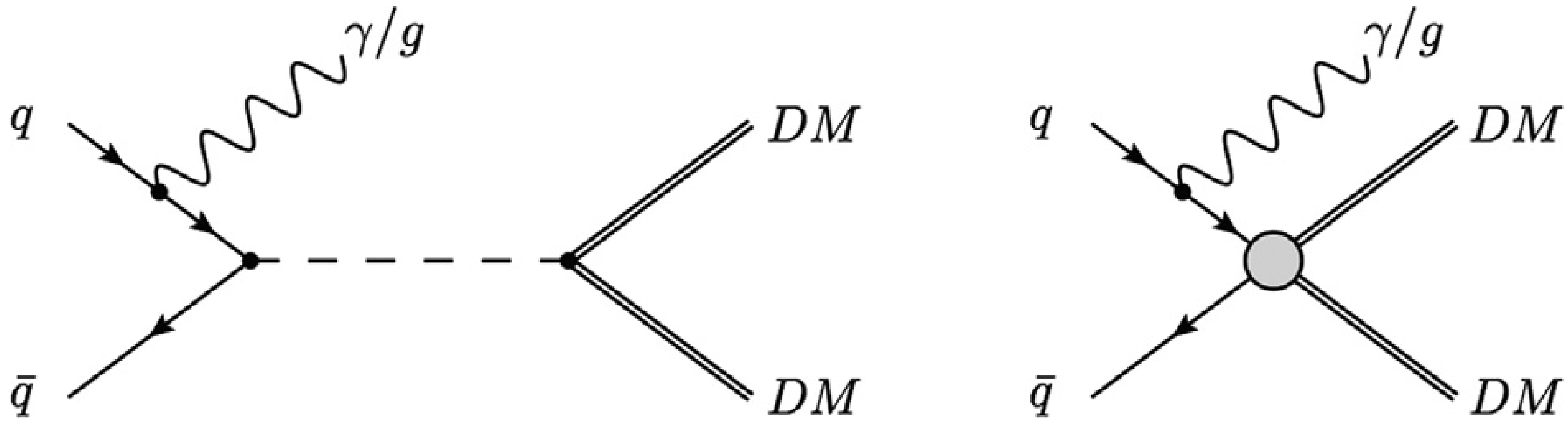
Mono-jet: $\not{E}_T + j$

There can also be visible emissions of other particles:



[Buchmuller 2015]

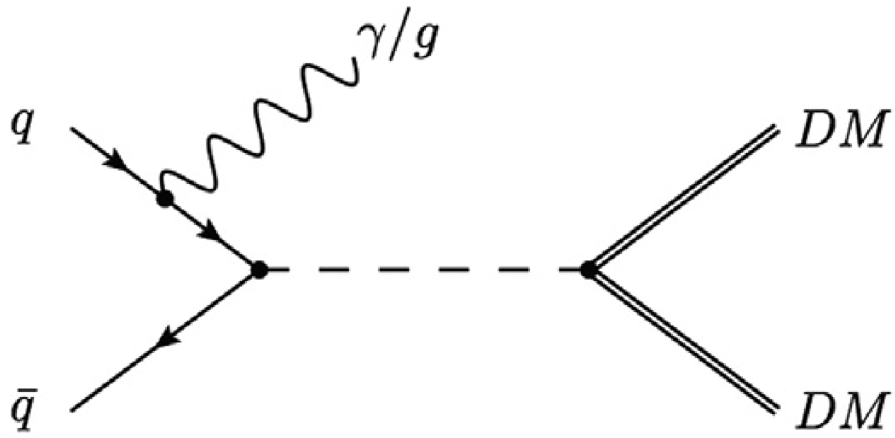
Model-independent approach

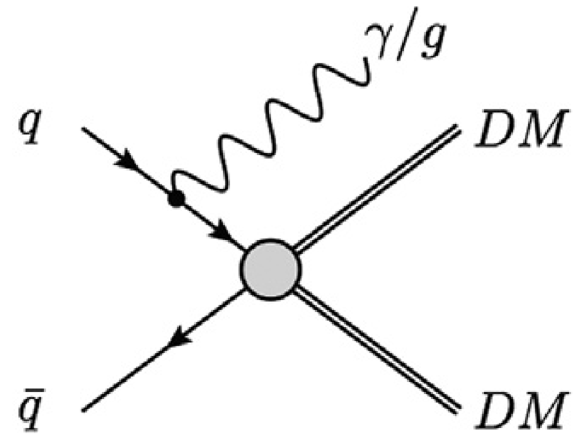


$$O_{EFT} = \frac{(\bar{\chi}\chi)\,(\bar{q}q)}{\Lambda^2}$$

EFT approach is powerful and model-independent

Model-independent approach





$$O_{EFT} = \frac{(\bar{\chi}\chi)\,(\bar{q}q)}{\Lambda^2}$$

$$\frac{1}{Q_{\rm tr}^2 - M^2} = -\frac{1}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right), \qquad Q_{\rm tr}^2 \ll M^2 \sim \Lambda^2.$$

$$O = \frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2}$$

LHC @ 14 TeV naive EFT valid for $M_{med} > 10$ TeV

This approach only works for very heavy mediator!

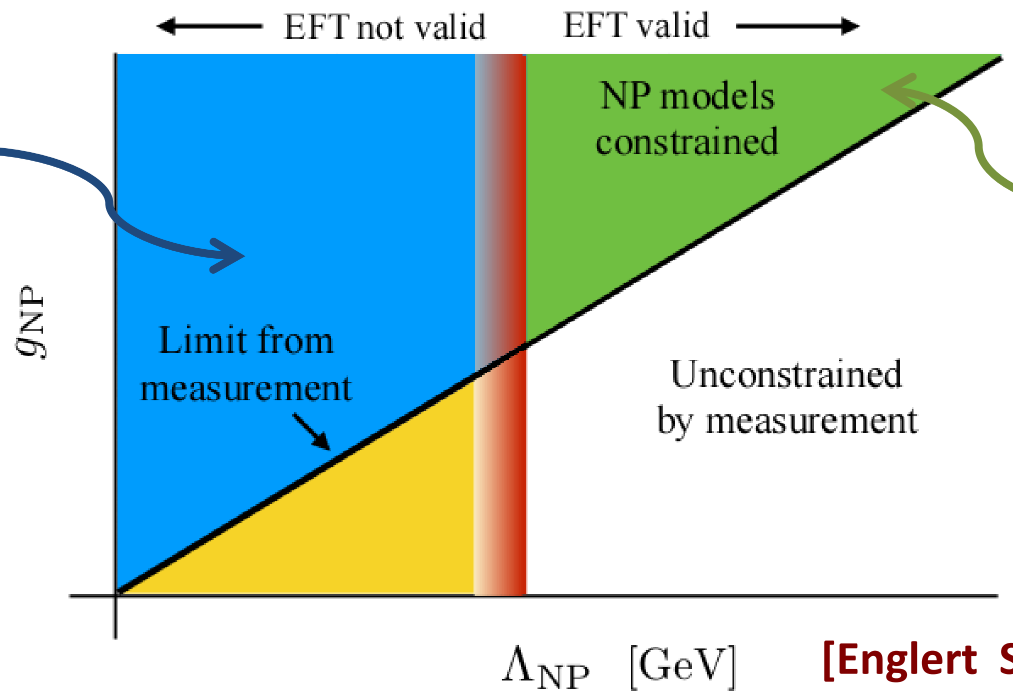
[Buchmueller, Dolan, McCabe 2013] **[Busoni, De Simone, Morgante, Riotto 2014]**

Model-independent approach

Experimental constraint on Wilson coefficient translates into diagonal black line

$C_i \approx g_{NP} / \Lambda_{NP}$

We cannot test this region using EFT approach



We can test region with large Λ_{NP} and large coupling g_{NP}

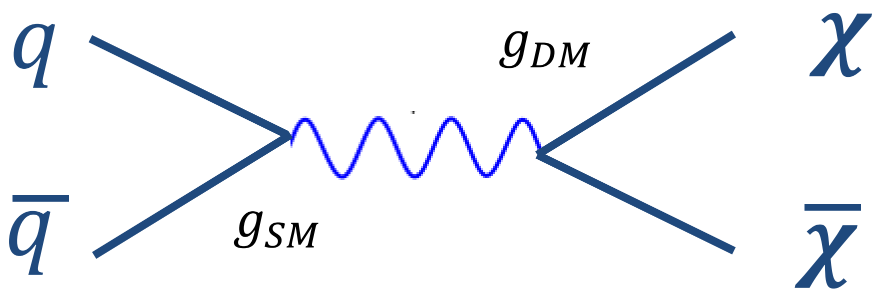
[Englert Spannowsky 2014]

- **EFT is consistent description if and only if energy of interaction** $E \ll M_{NP}$
- **EFT might not the best framework for Dark Matter searches at colliders**

Simplified models of dark matter

In the context of DM, there is no reason not to expect that $M_{MED} \approx m_{DM}$

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

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

Dark Matter candidate

Standard Model τ lepton

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

Co-annihilation partner (CAP)

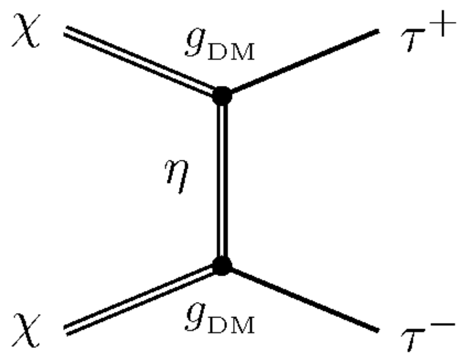
$\mathbb{Z}_2$: $\chi \rightarrow -\chi$ $\quad \eta \rightarrow -\eta$

Simplified models with only 3 free parameters:

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

Co-annihilation

Dark matter annihilation into pair of tau's



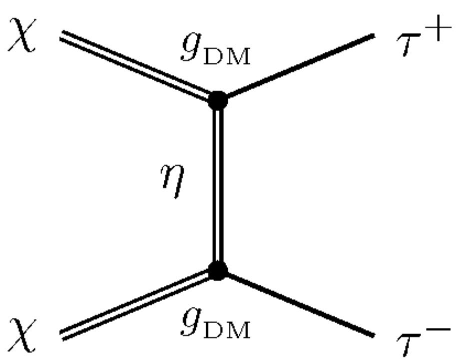
$$(\sigma v)^{\text{s-wave}}_{\text{ann}} = \frac{g_R^4\, m_\tau^2}{32\pi\, m_\chi^4} \frac{1}{(1+r^2)^2}$$

$\propto$ m_τ
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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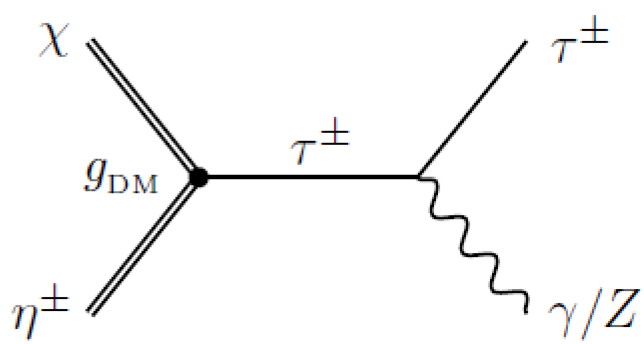
Co-annihilation:



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

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

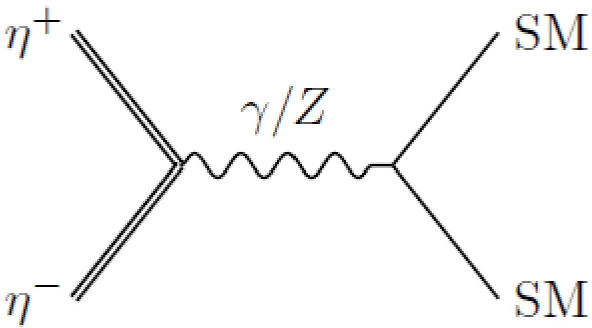
We need **mass splitting of 4% of m_{DM}**

Co-annihilation

$$\sigma_{\rm eff}\, v \;=\; \frac{1}{(g_\chi + \overline{g}_\eta)^2}\Big[\, g_\chi^2 \cdot \sigma(\chi\,\chi \to \tau^+\tau^-) + g_\chi \overline{g}_\eta \cdot \sigma(\chi\,\eta \to SM \text{ particles}) + \overline{g}_\eta^2 \cdot \sigma(\eta\,\eta \to SM \text{ particles}) \,\Big]\, v$$

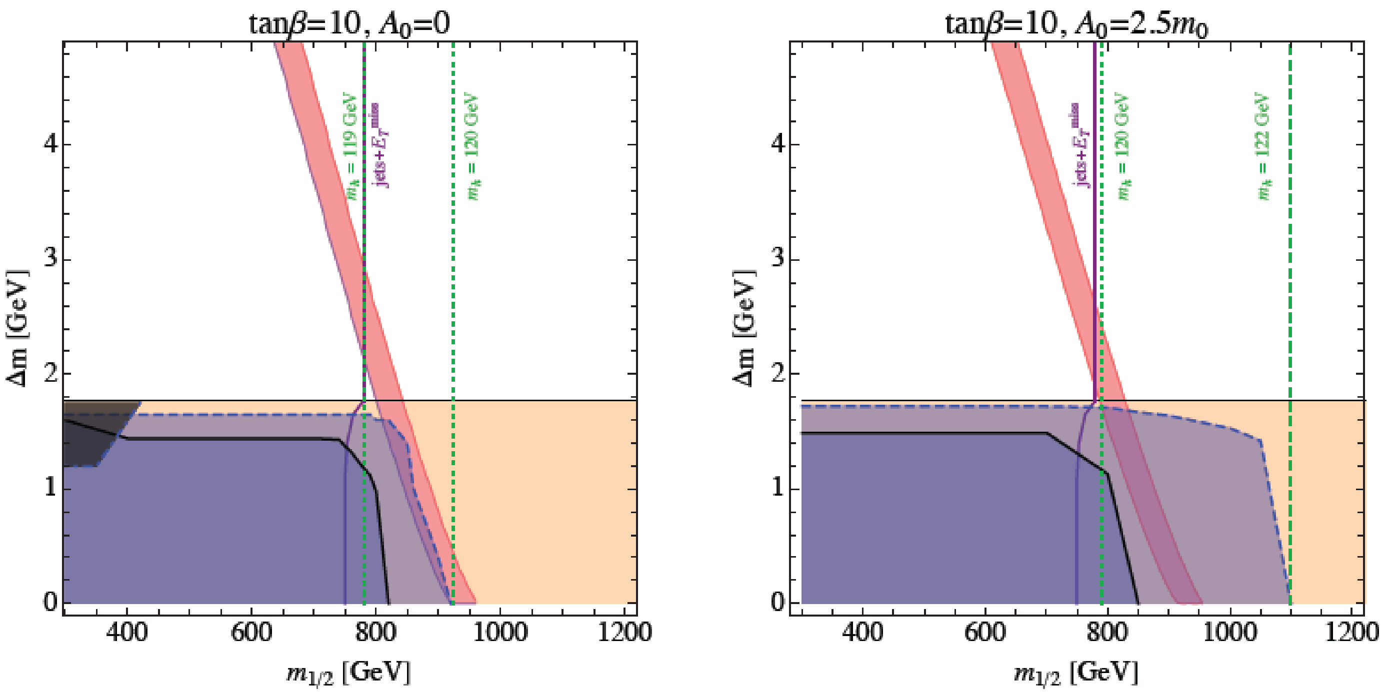
$$\overline{g}_\eta = g_\eta \left(\frac{M_\eta}{m_\chi}\right)^{3/2} \exp\left(-\frac{\Delta M}{T}\right)$$

Annihilation of co-annihilation partner can give large contribution to the relic density



Stau co-annihilation strip

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

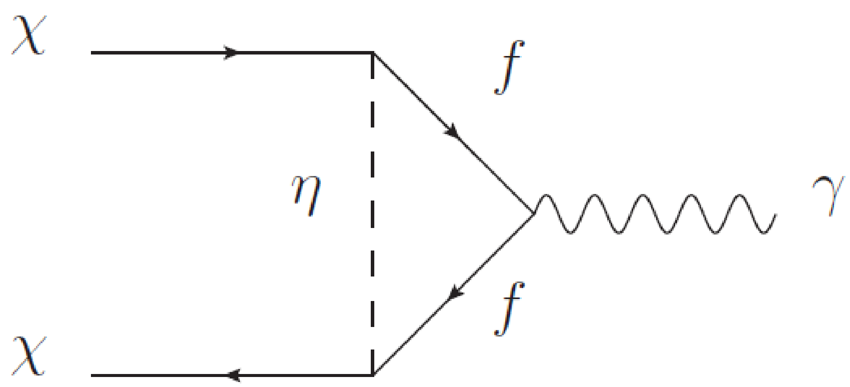


We want to generalize this.

[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

$$m_{\rm DM} \simeq 500\,{\rm GeV} \;\; {\rm and} \;\; \Delta M/m_\tau < 1$$

$$\mathcal{A}/g^2_{\rm DM} \sim 8 \cdot 10^{-7}\,[\mu_N {\cdot} {\rm fm}]$$

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 $\boldsymbol{m_{DM} \gg m_\tau}$:

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

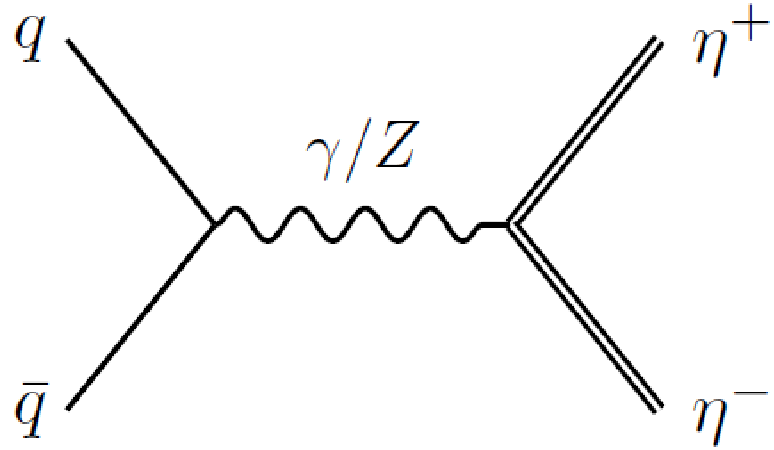
Nevertheless, the channel $S\,S \;\rightarrow\; l\;l\;\gamma$ can be relevant for future experiments for scalar DM

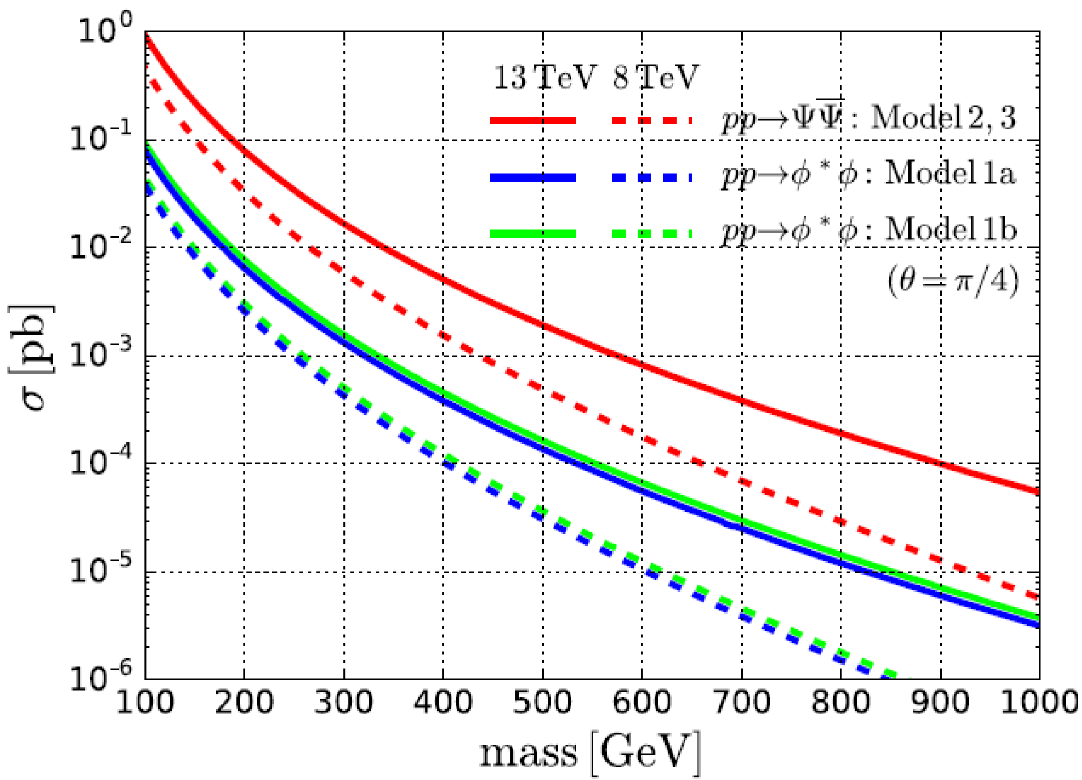
For large ΔM

[Giacchino, Lopez-Honorez, Tytgat 2013]

LHC production

- Drell-Yann pair production of co-annihilation partner

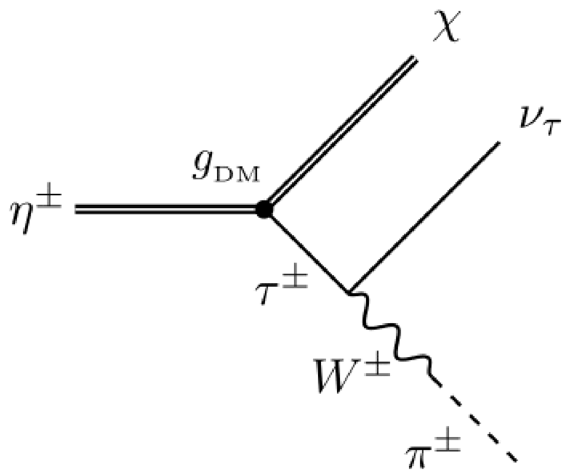




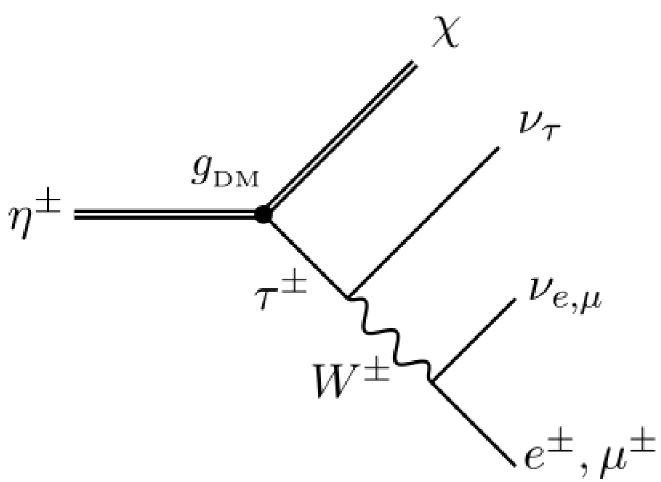
- We study Dirac fermion and complex scalar as co-annihilation partners

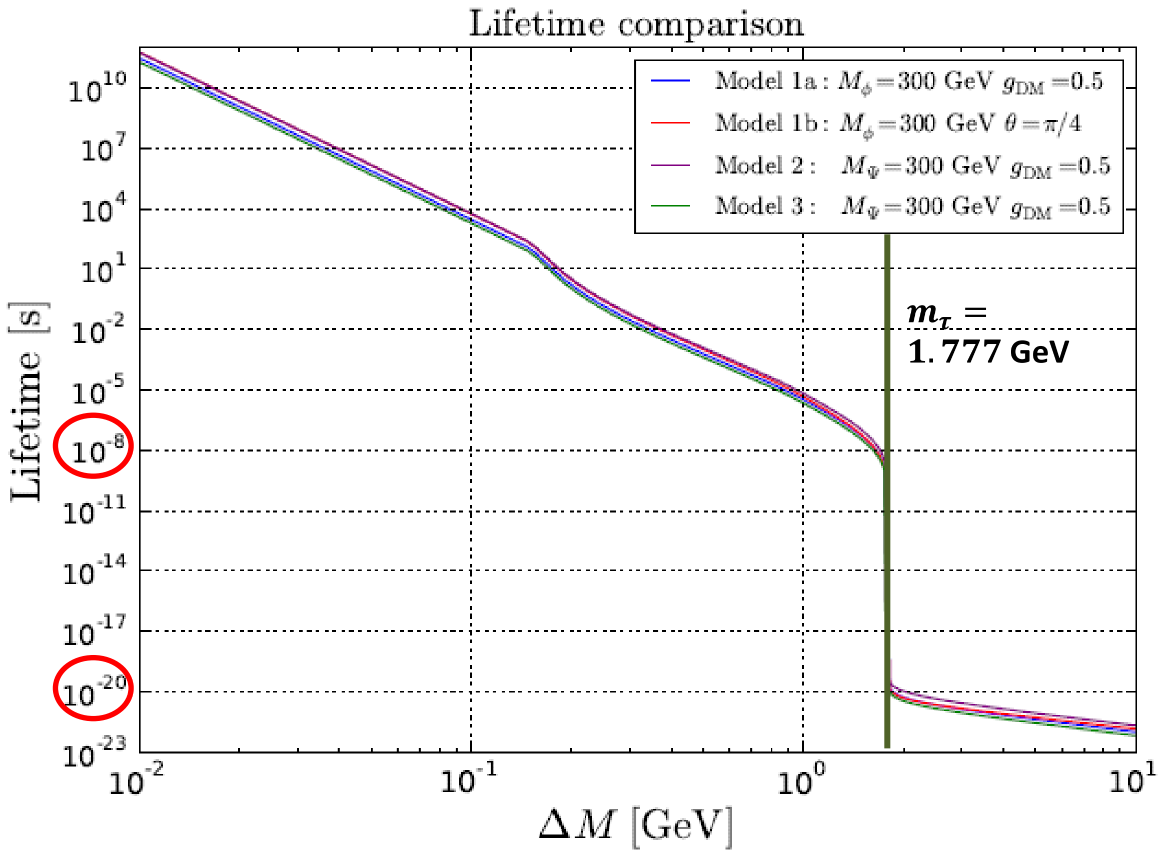
Long-lived electrically charged particles

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

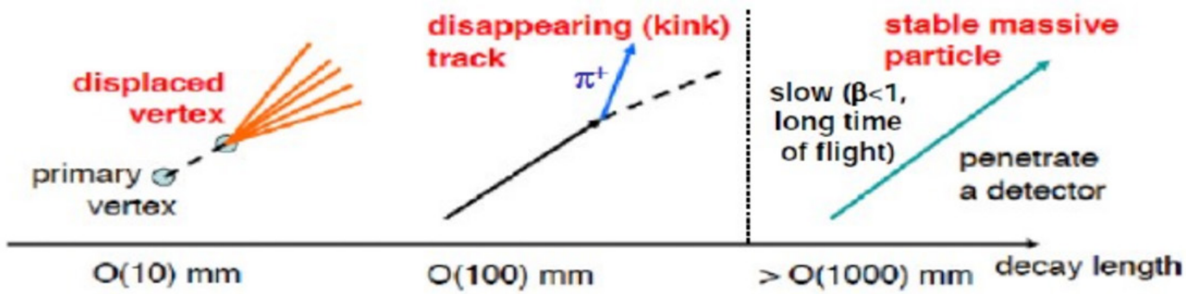


Also ρ and a_1 mesons





Searching for long-lived charged particles

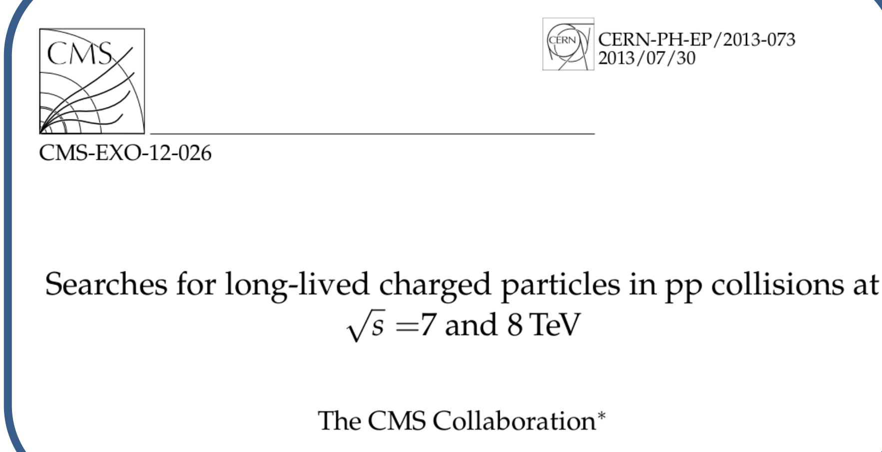


[Melzer-Pellmann, Pralavorio 2014]

- 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


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

CMS-EXO-12-026

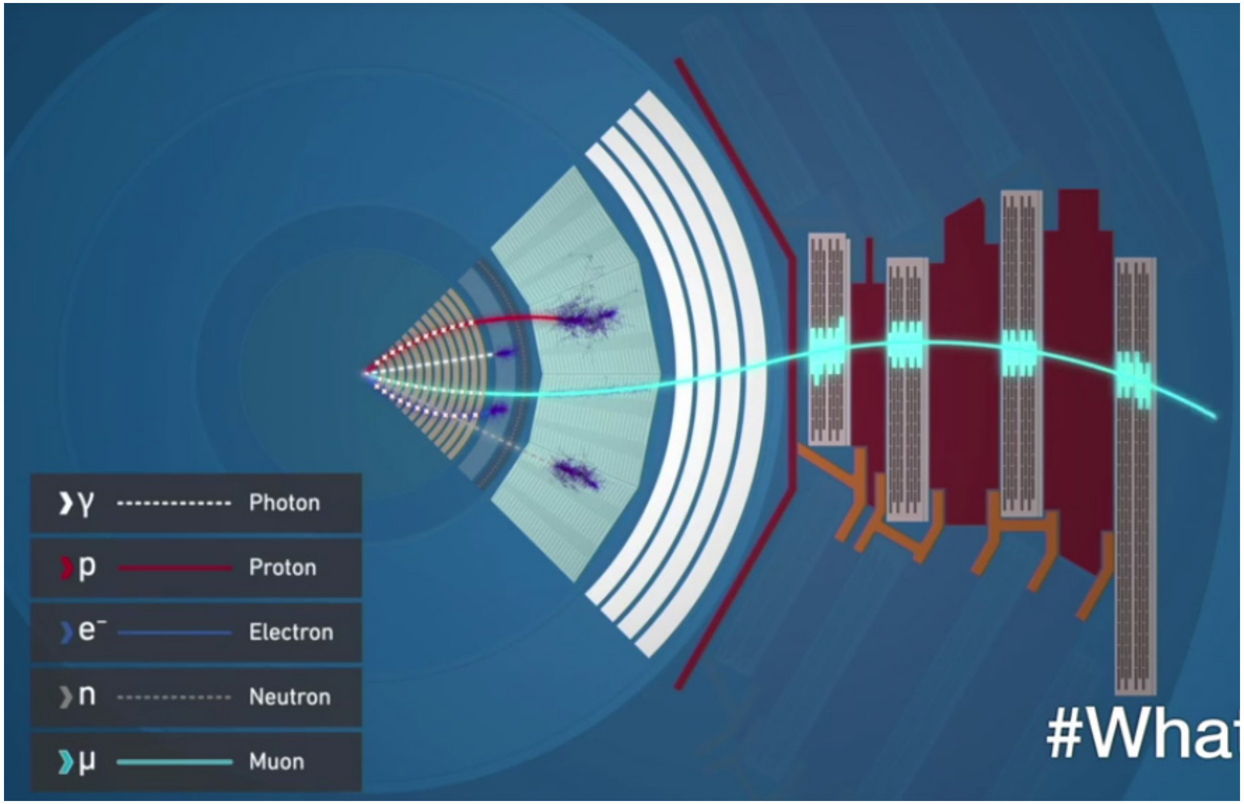
Searches for long-lived charged particles in pp collisions at $\sqrt{s}$ =7 and 8 TeV

The CMS Collaboration*

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]

Computational tools

DM relic density

[Belanger, Boudjema, Pukhov, Semenov 2002]

Production cross-sections

MADGRAPH 5

[Alwall, et al 2014]

Lifetimes

CalcHEP

[Belyaev, Christensen, Pukhov 2013]

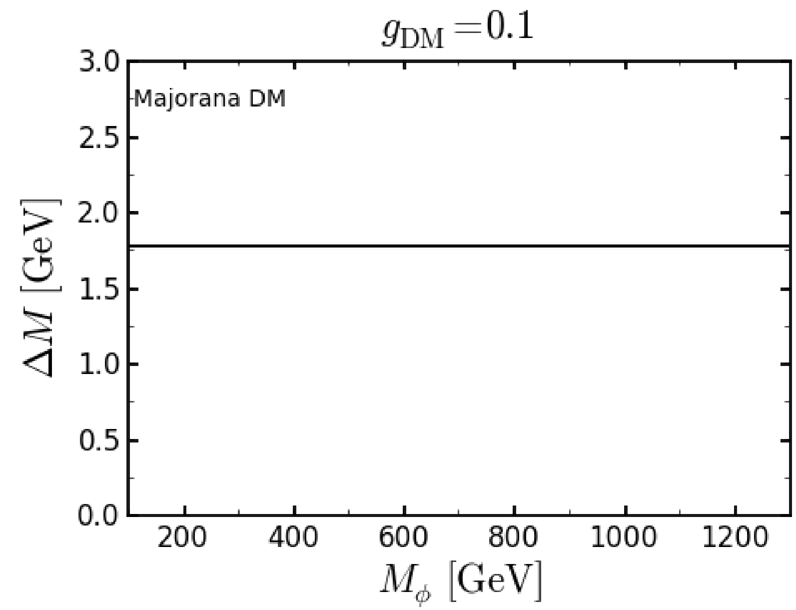
Majorana Dark Matter

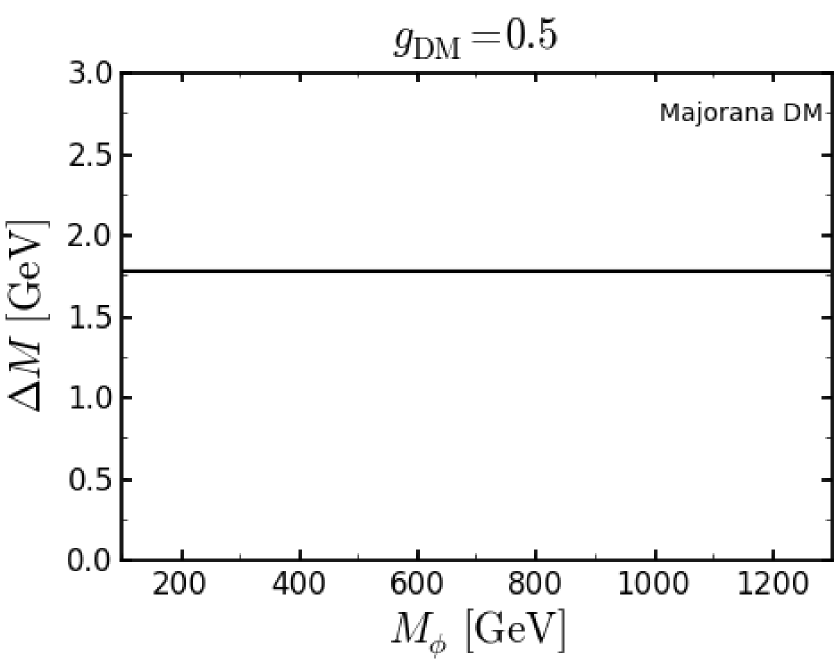
DM χ

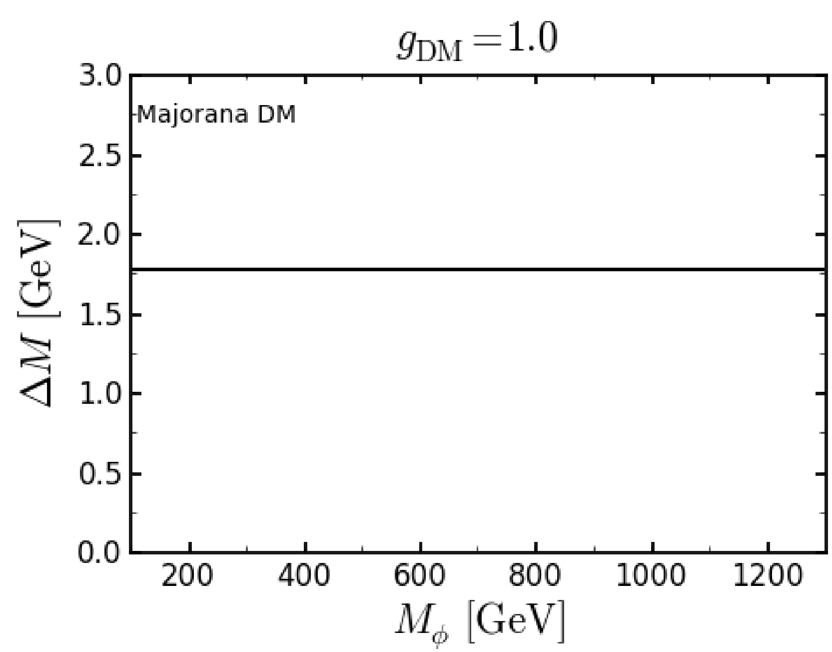
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

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

Gauge-invariant and renormalizable, no problems of unitarity







Majorana Dark Matter

DM	CAP (Y=-1)
χ	ϕ

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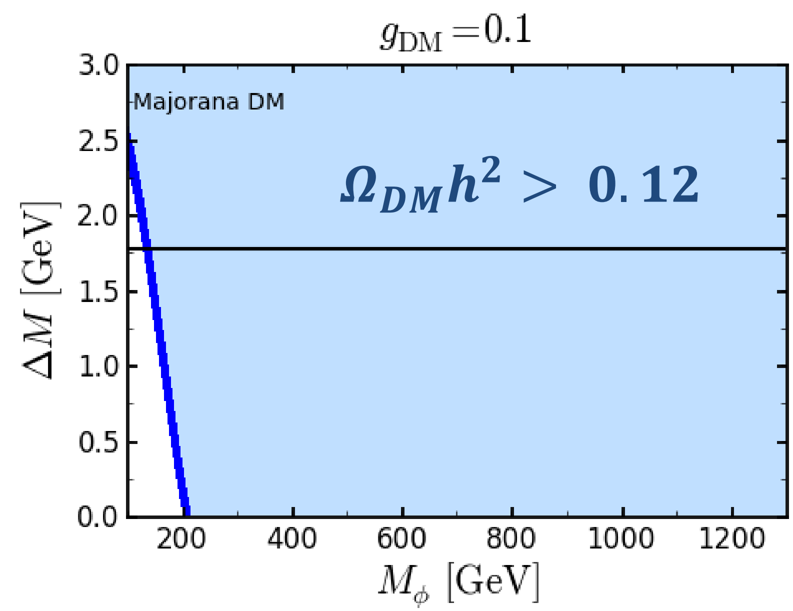
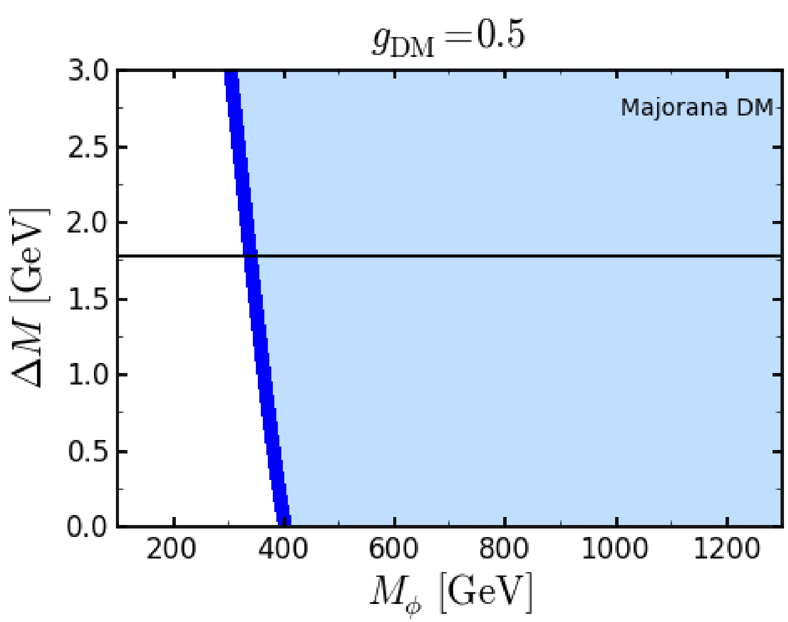
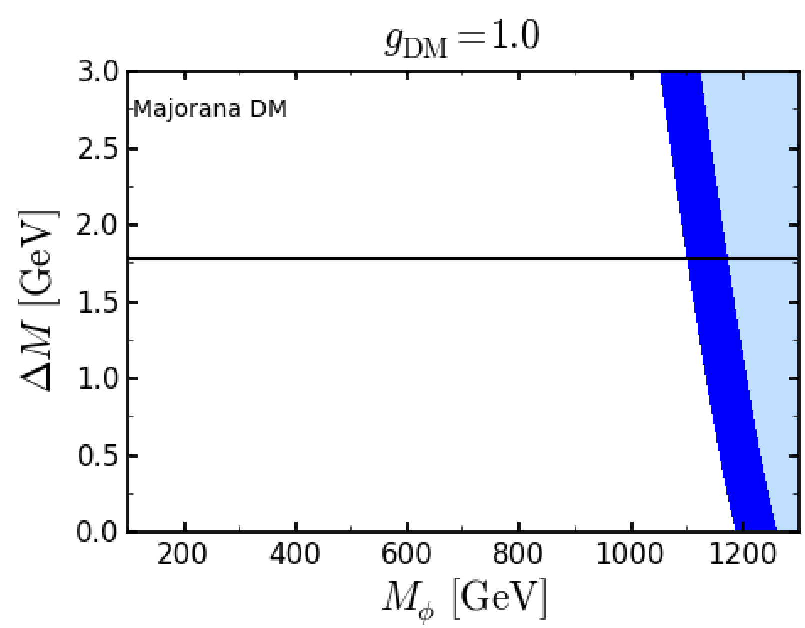
Gauge-invariant and renormalizable, no problems of unitarity







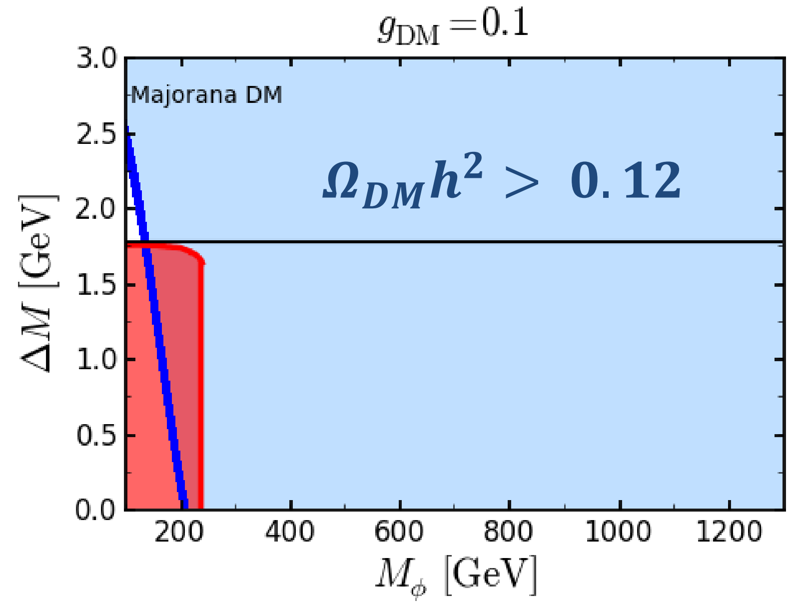
Majorana Dark Matter

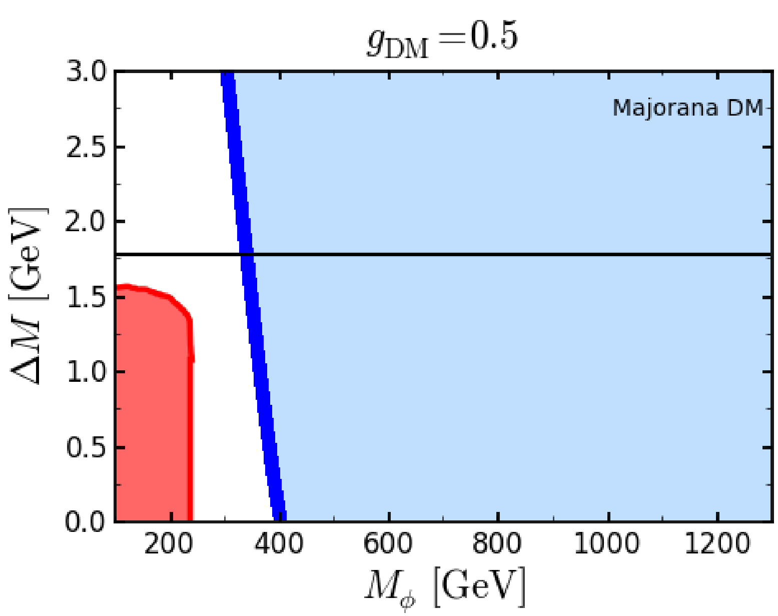
DM   **CAP** $(Y = 1 \;\; L_\tau = 1)$

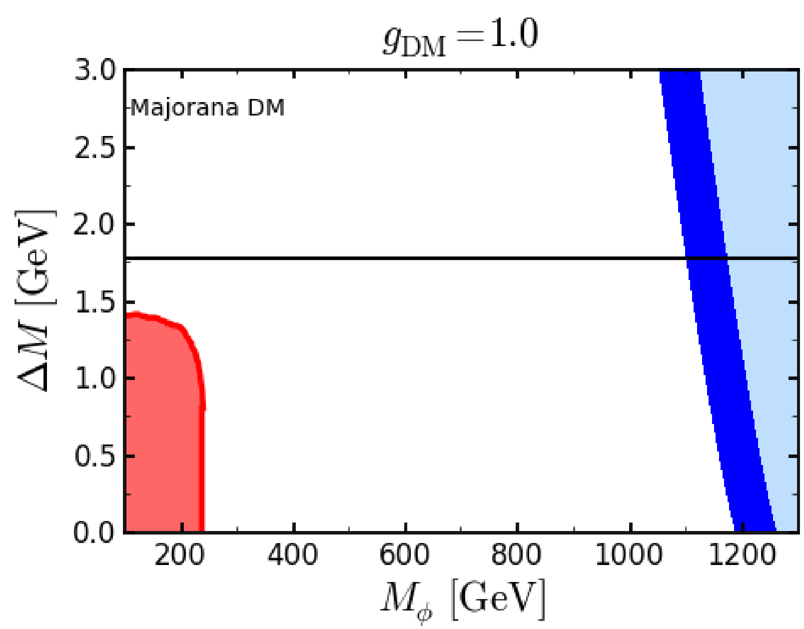
χ ϕ

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

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







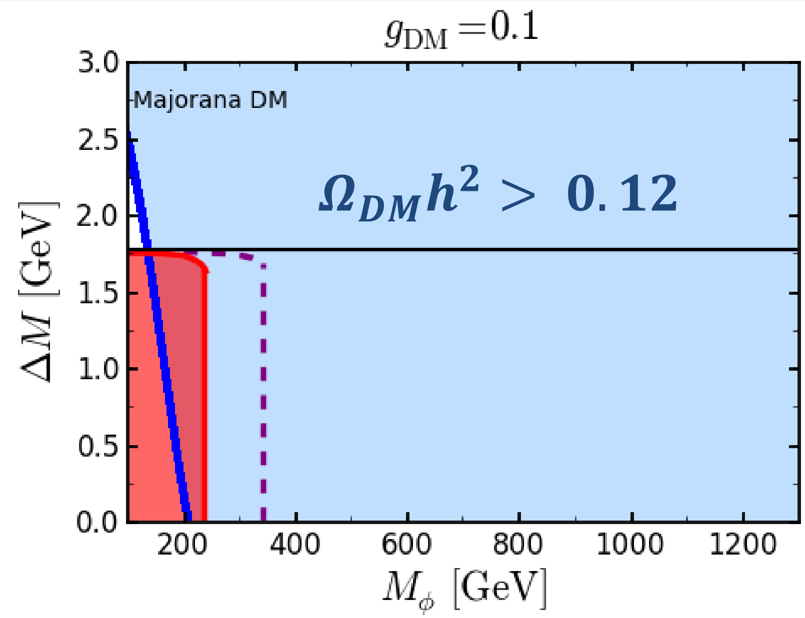
Majorana Dark Matter

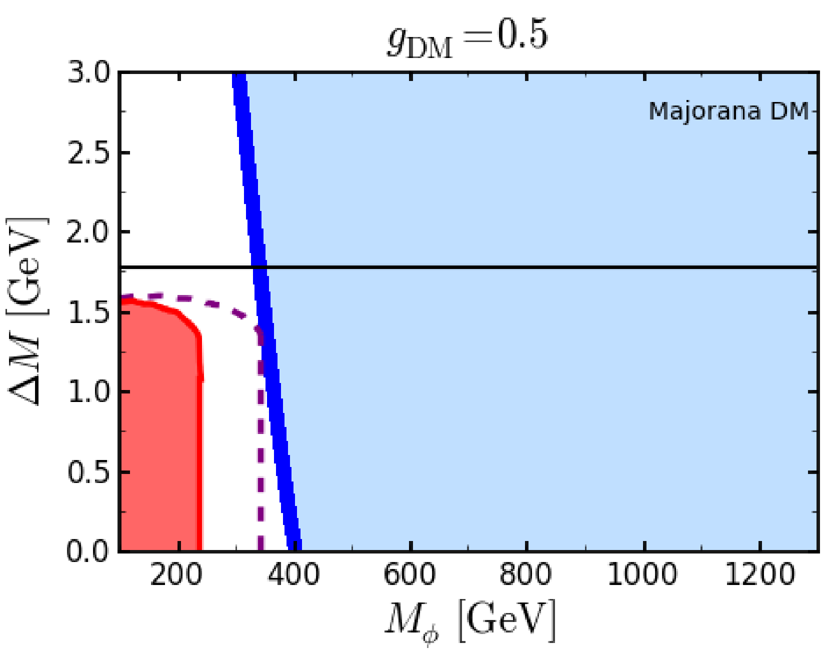
DM χ

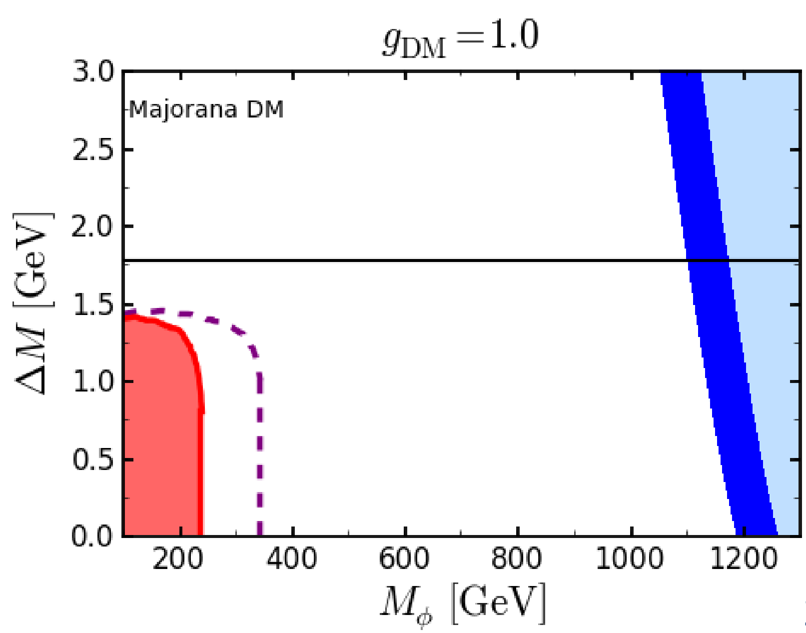
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

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

13 TeV 30 fb $^{-1}$







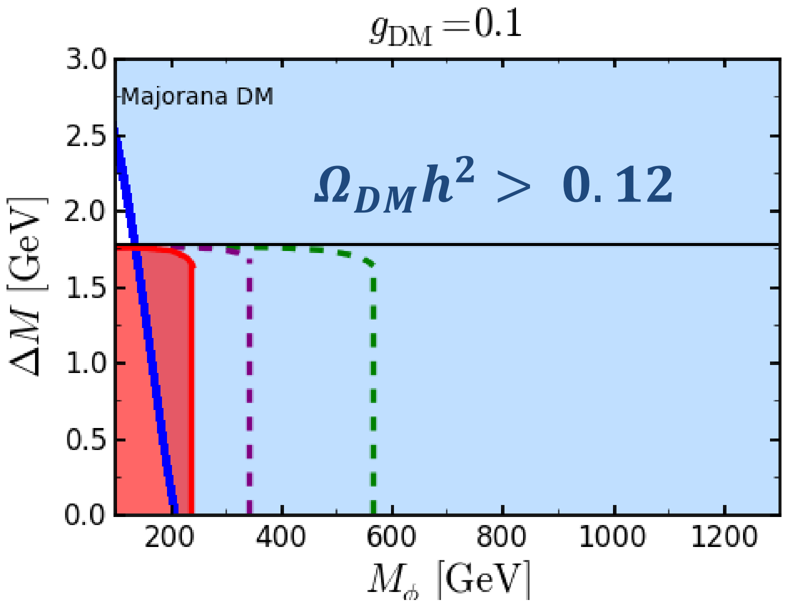
Majorana Dark Matter

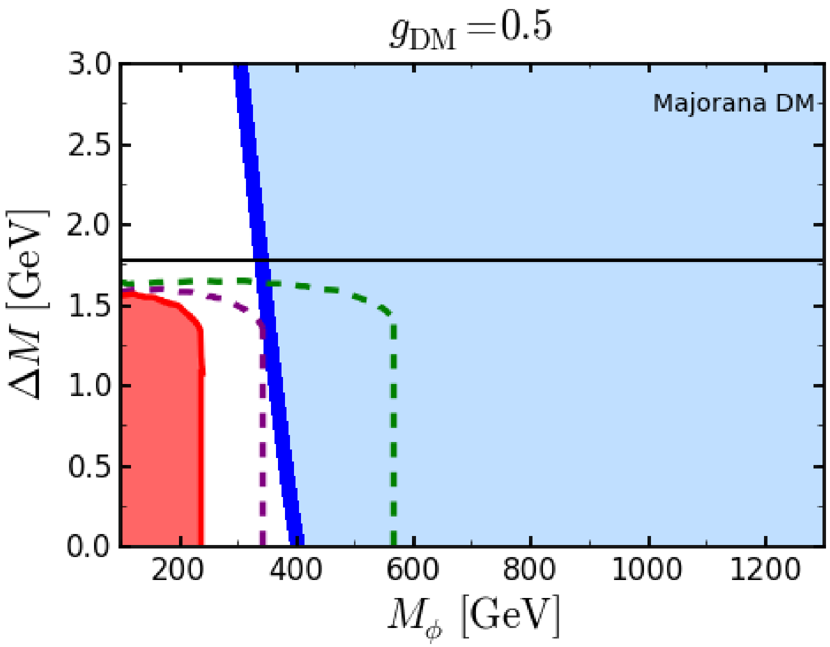
DM χ

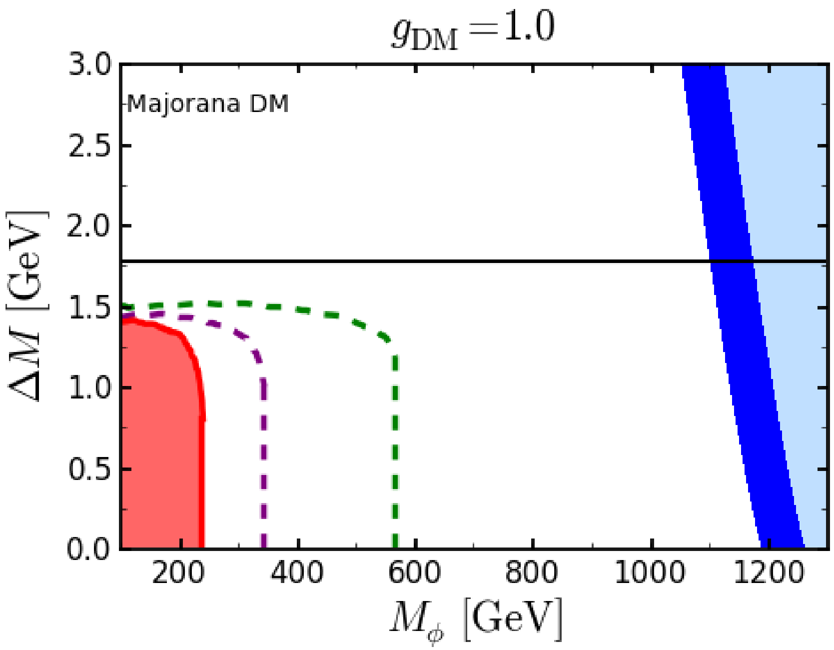
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

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

13 TeV 300 fb $^{-1}$







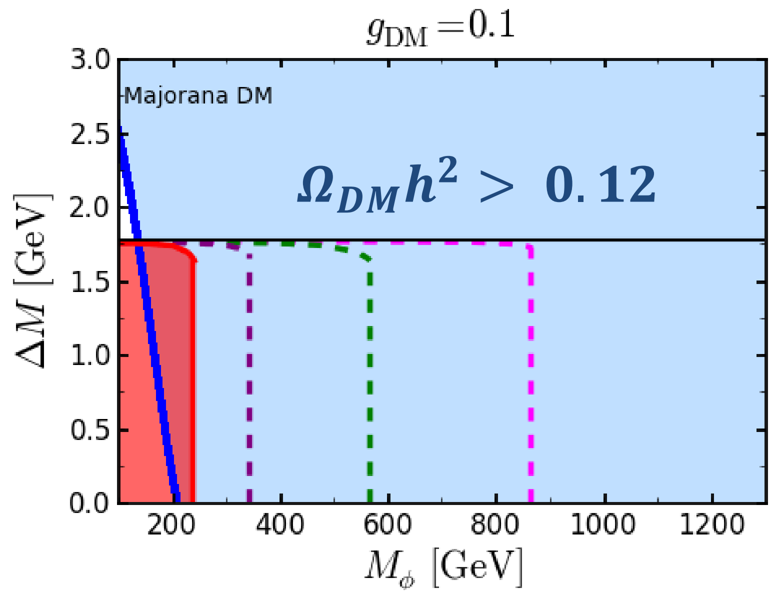
Majorana Dark Matter

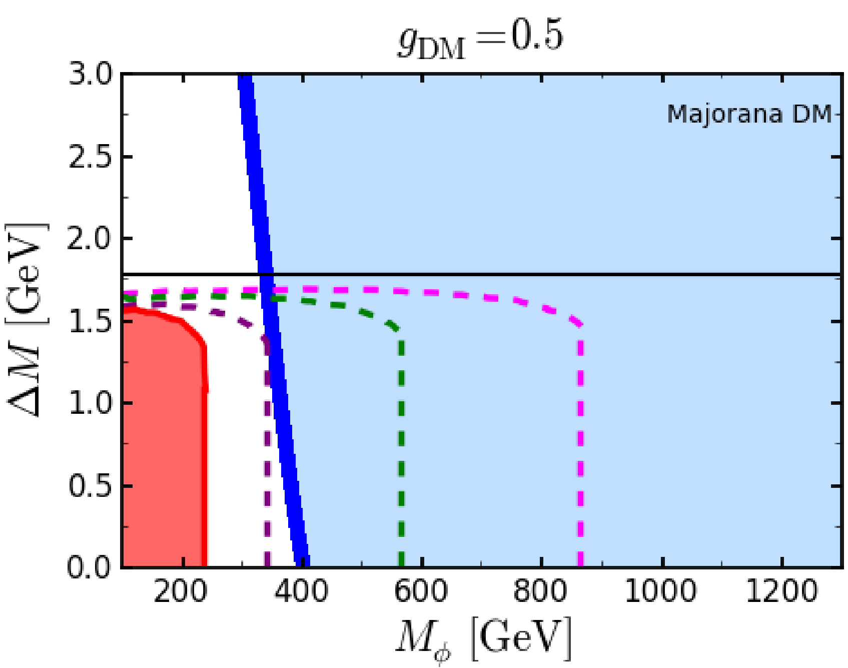
DM χ

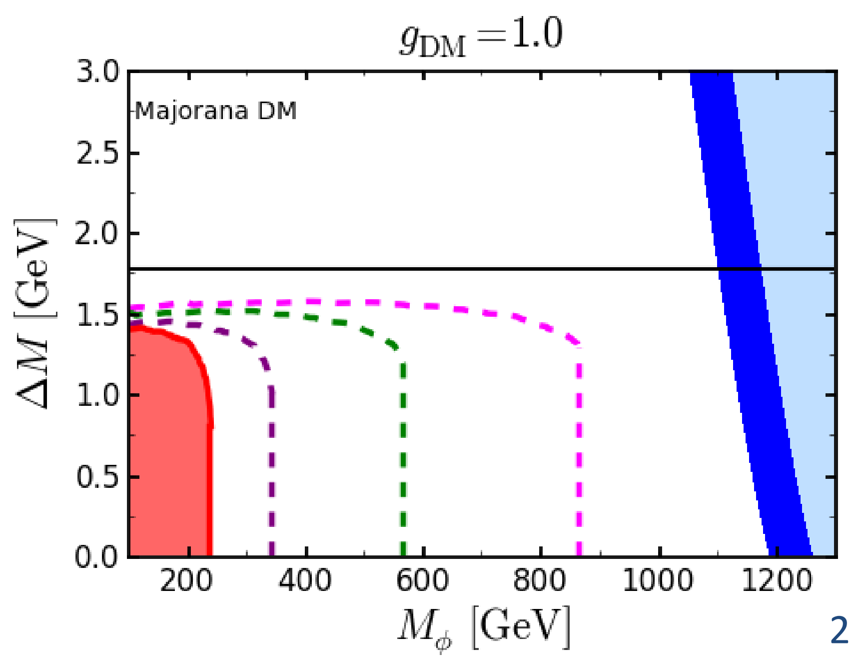
CAP $(Y = 1\ \ L_\tau = 1)$ ϕ

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

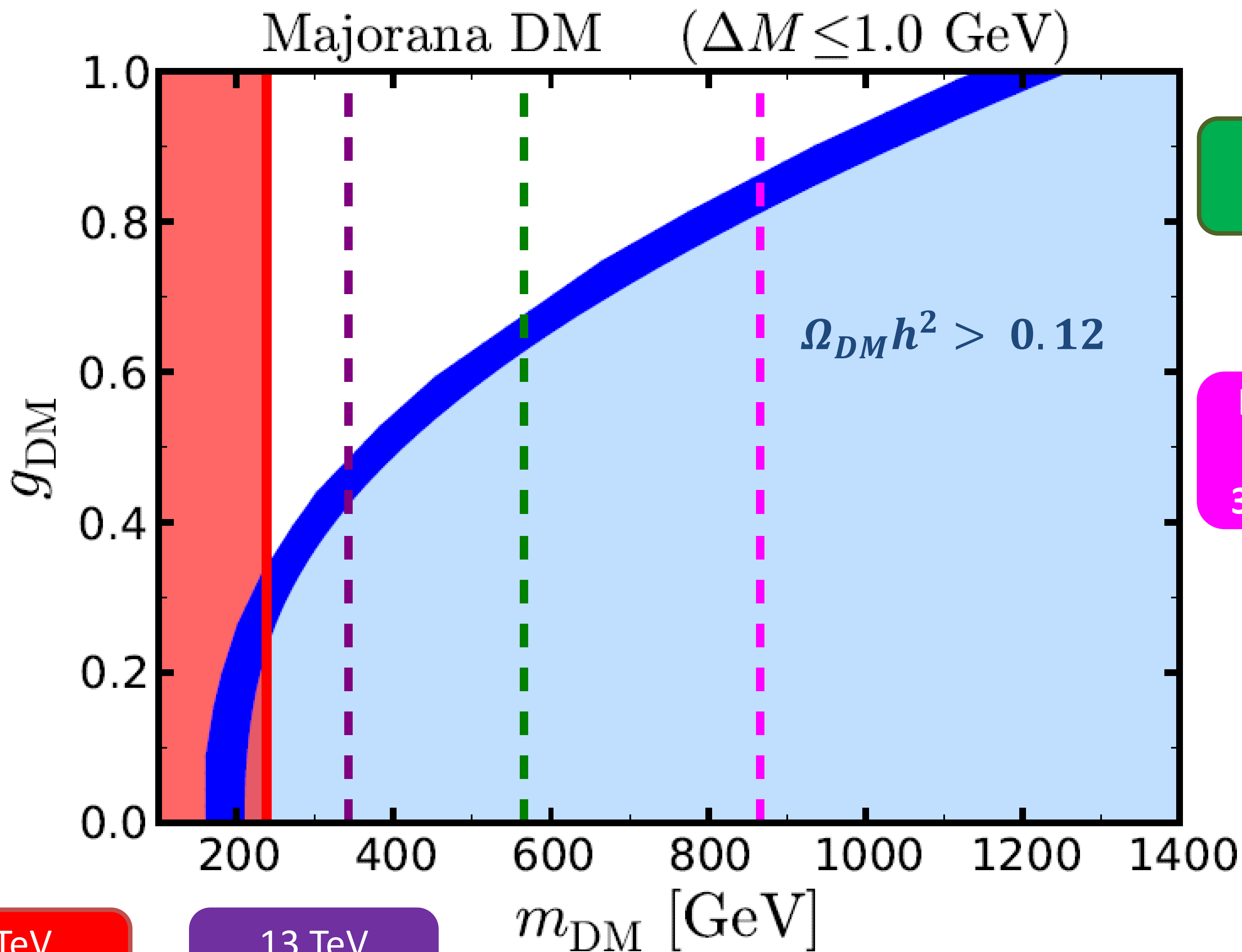
High Lumi 13 TeV 3000 fb $^{-1}$







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 $^{-1}$

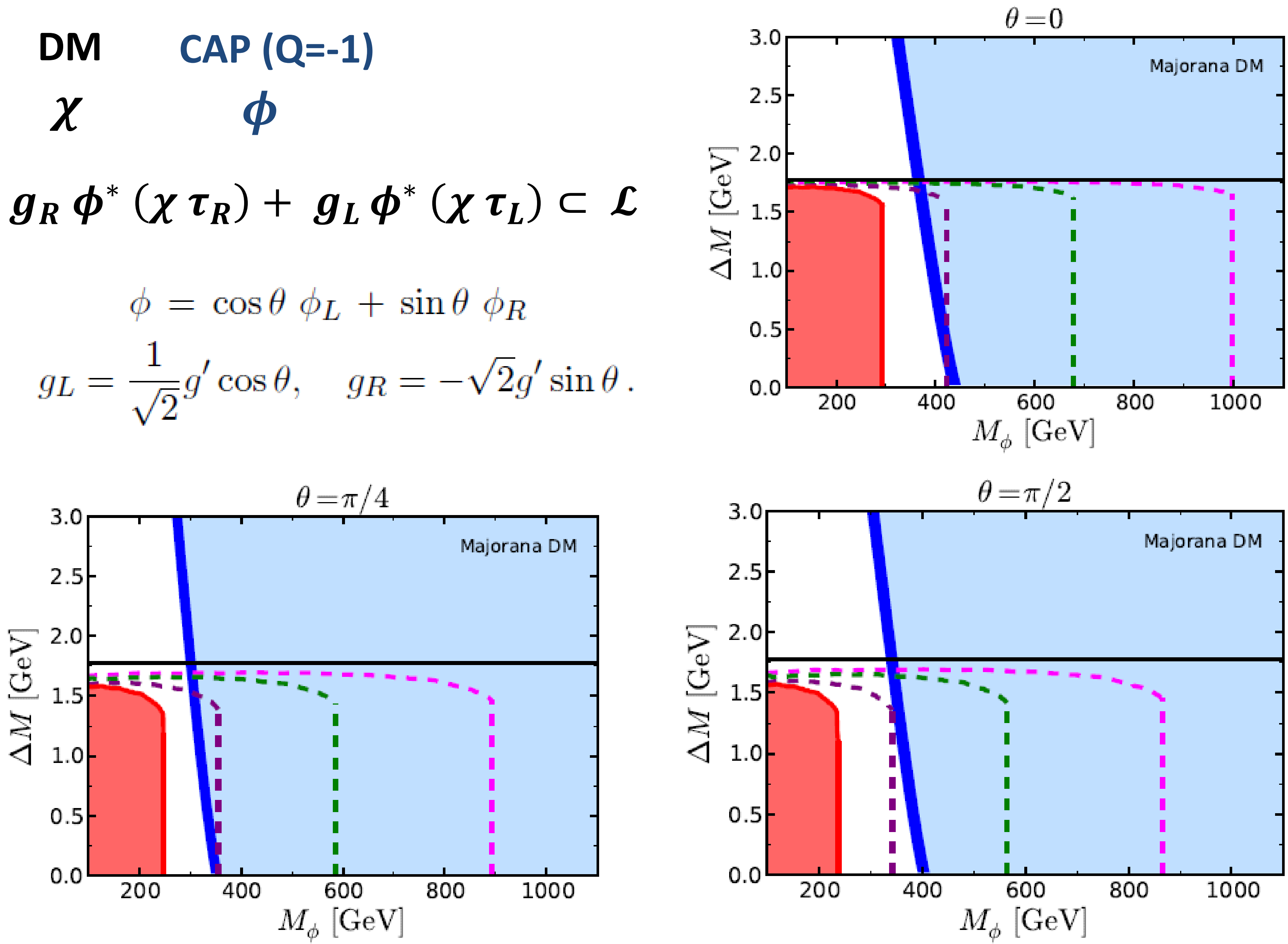
Majorana Dark Matter (Model 1b)

DM	CAP (Q=-1)
χ	ϕ

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

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

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



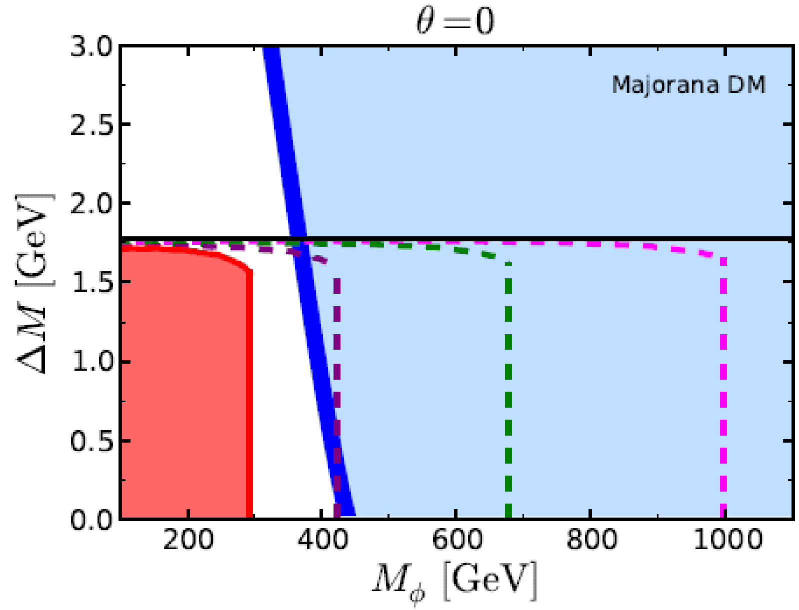
Majorana Dark Matter (Model 1b)

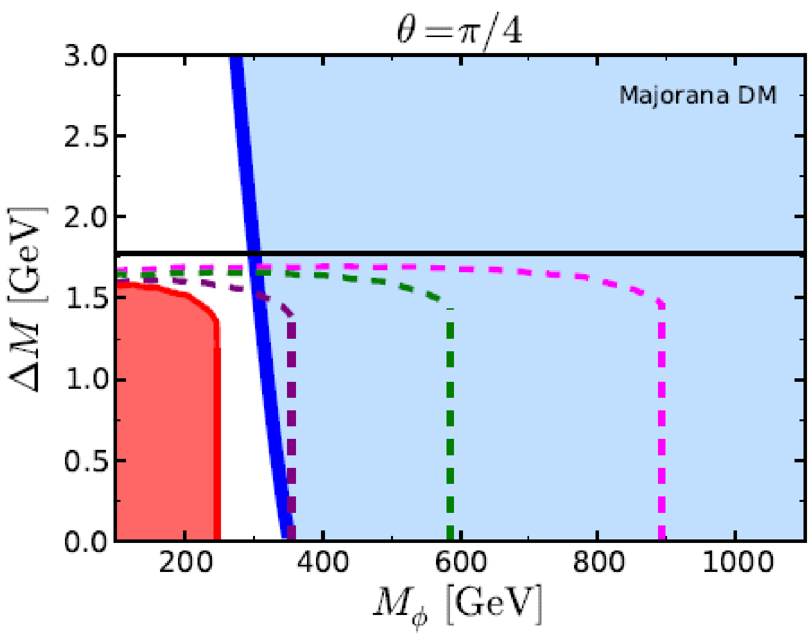
DM χ

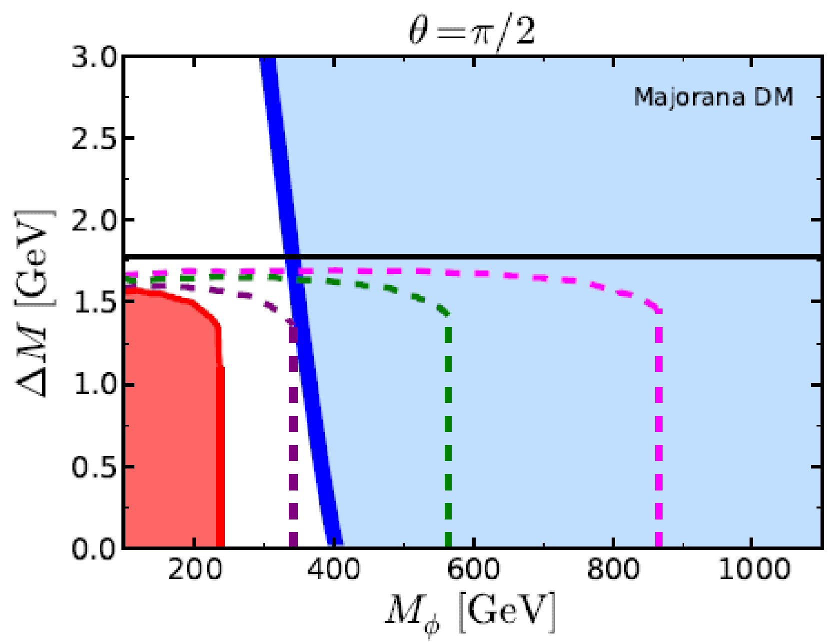
CAP (Q=-1) ϕ

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

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







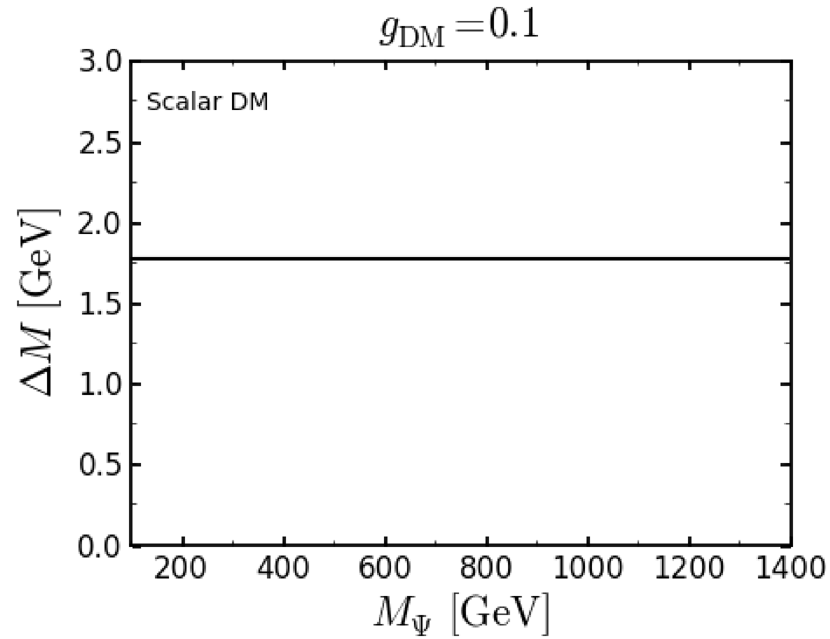
Real scalar dark matter

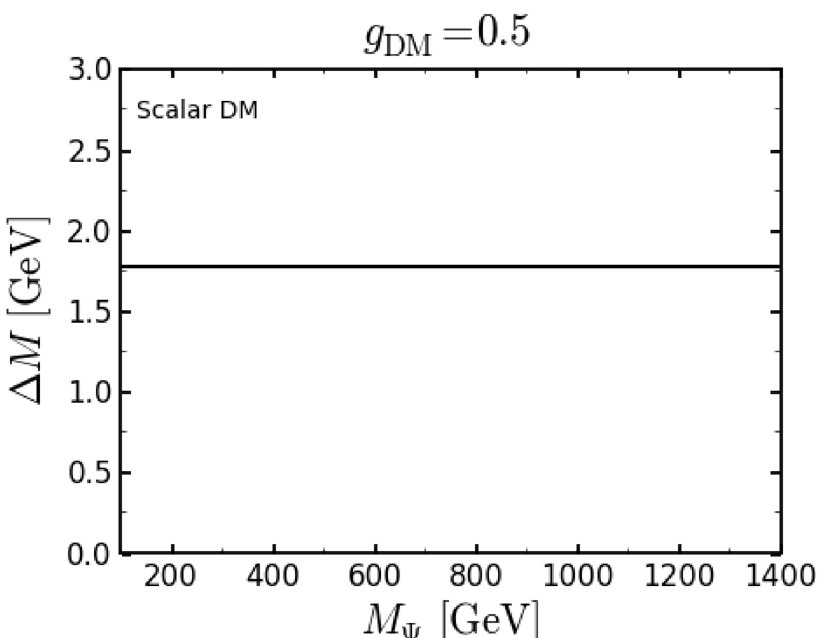
DM S

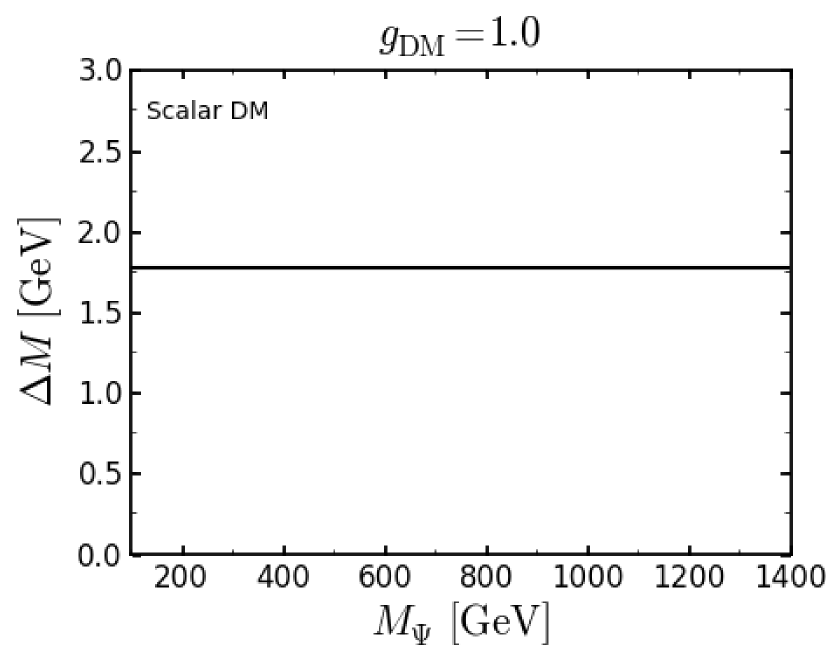
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

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

Gauge-invariant and renormalizable, no problems of unitarity







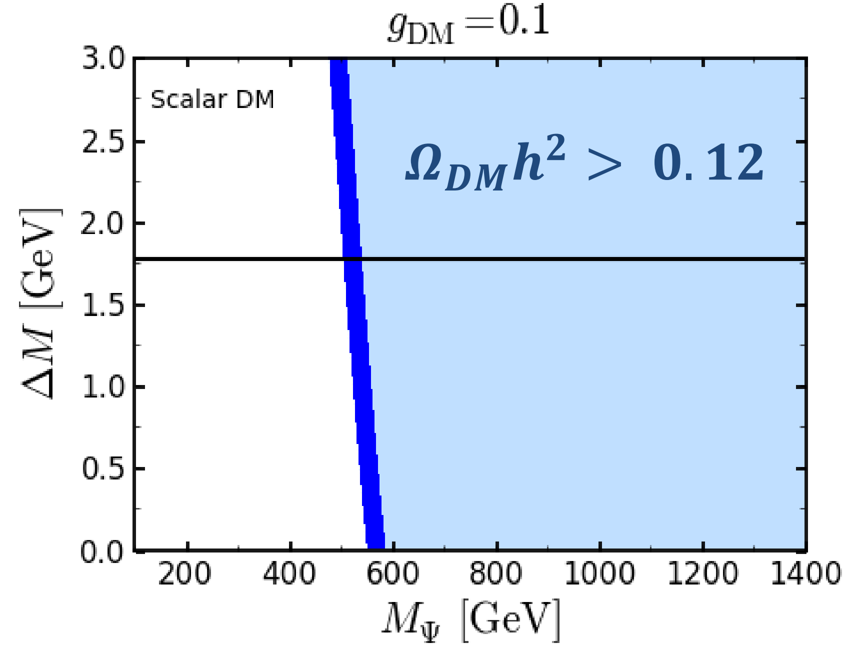
Real scalar dark matter

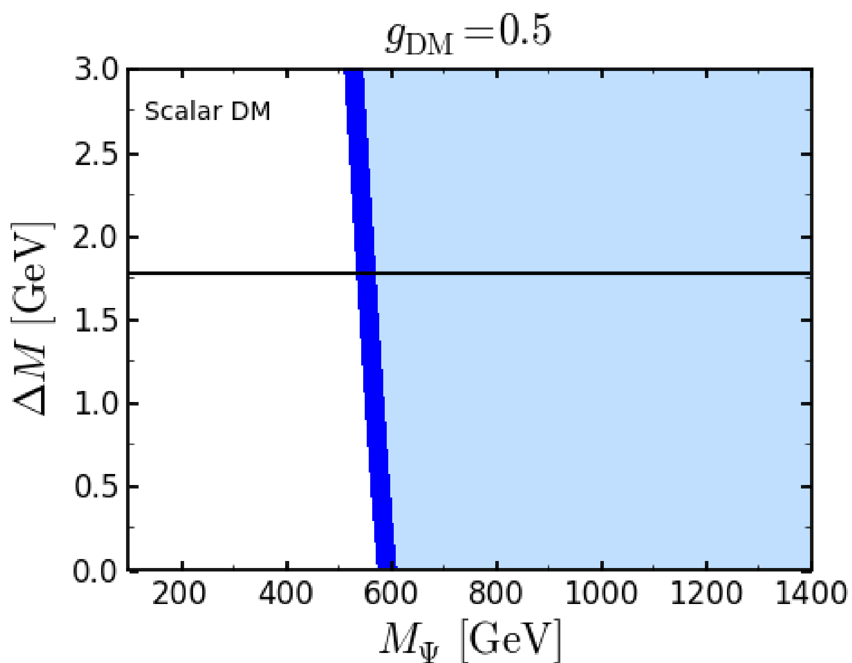
DM $\quad$ **CAP** $(Y = 1 \;\; L_\tau = 1)$

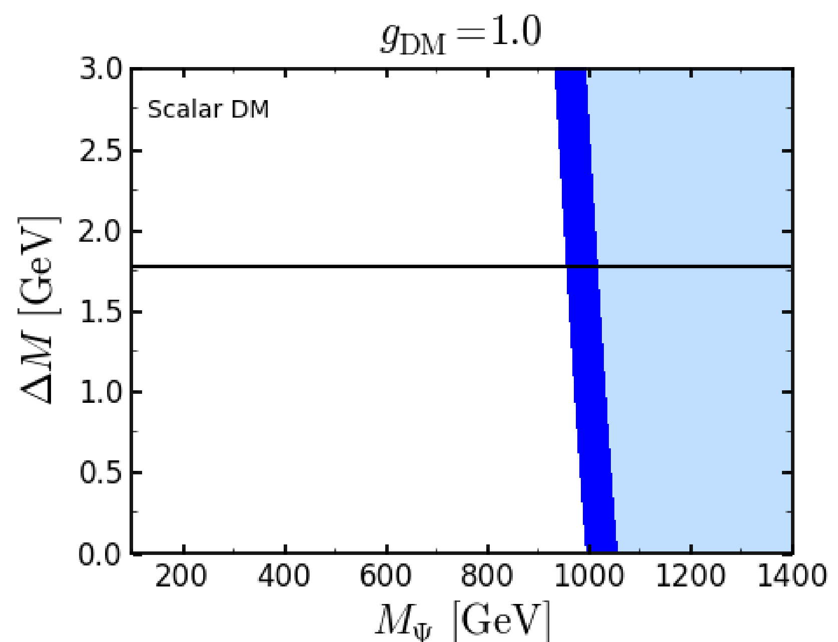
$S \quad \Psi$

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

Gauge-invariant and renormalizable,
no problems of unitarity





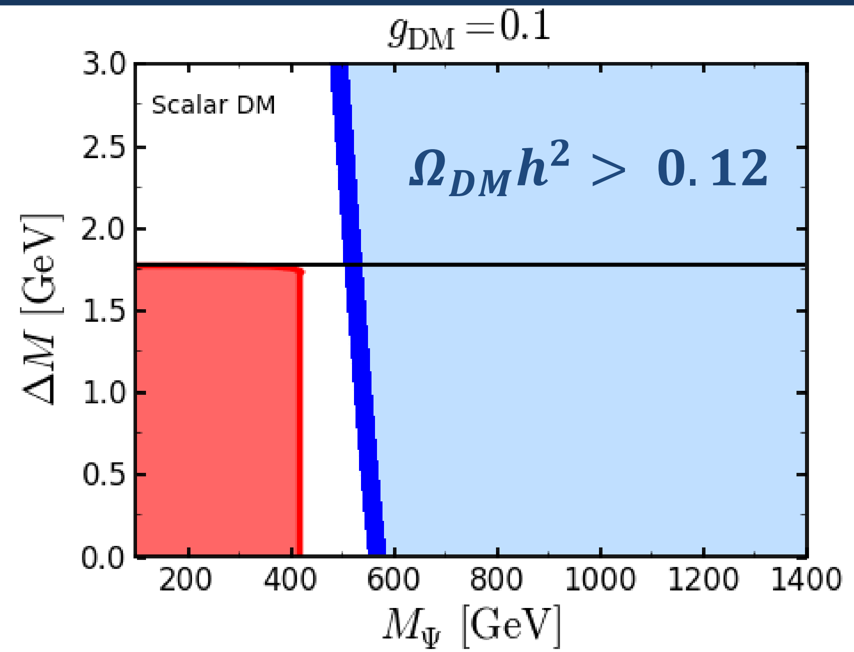


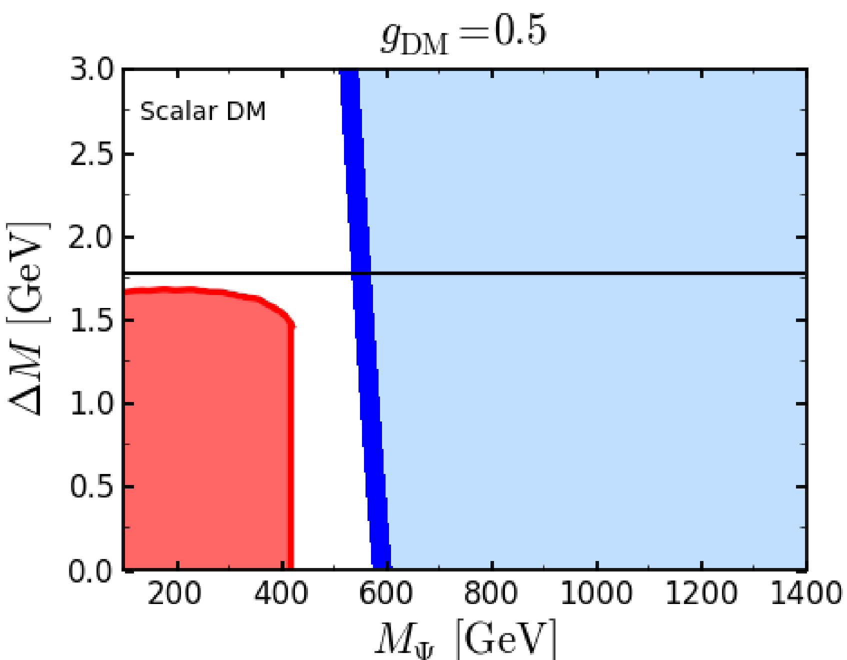
Real scalar dark matter

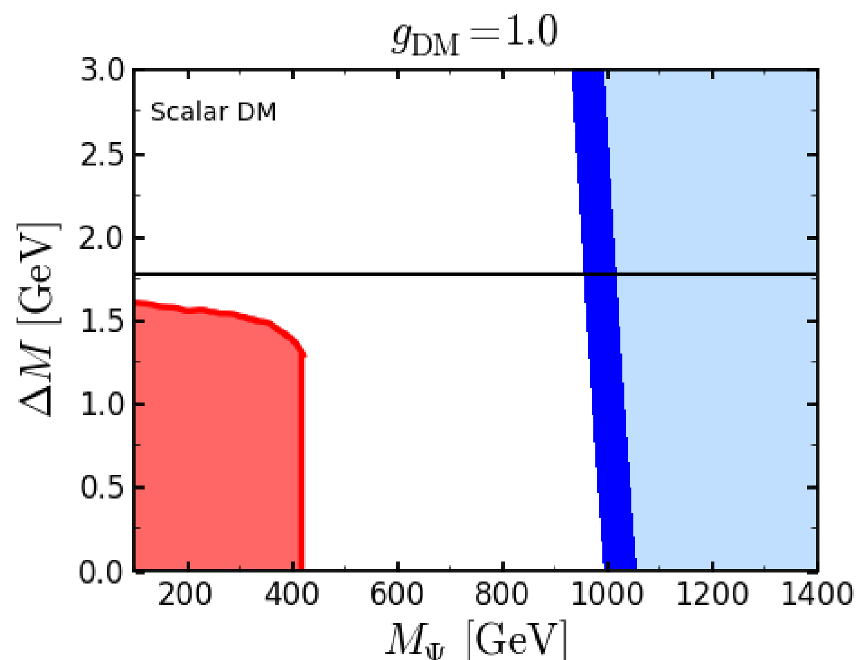
DM	CAP $(Y = 1\ \ L_\tau = 1)$
S	Ψ

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

CMS 8 TeV 18.8 fb^{-1}







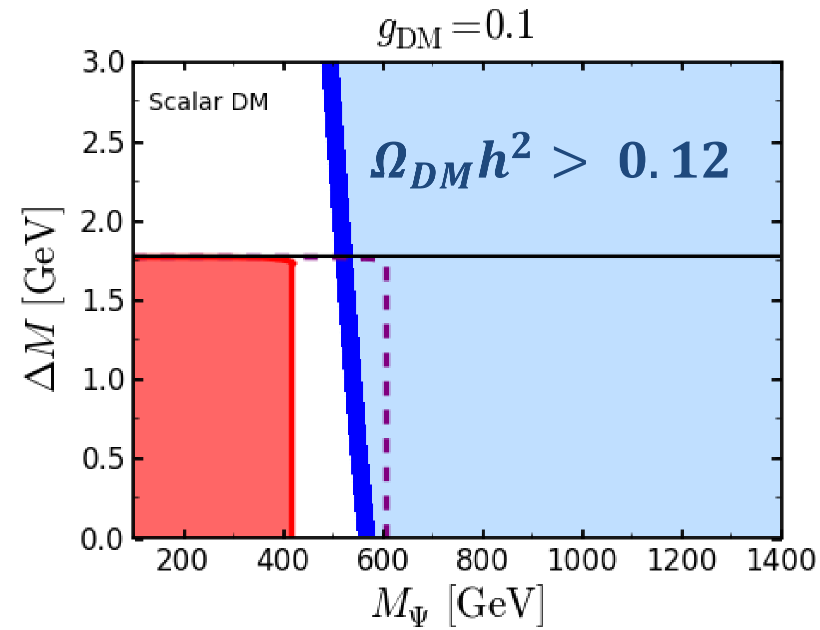
Real scalar dark matter

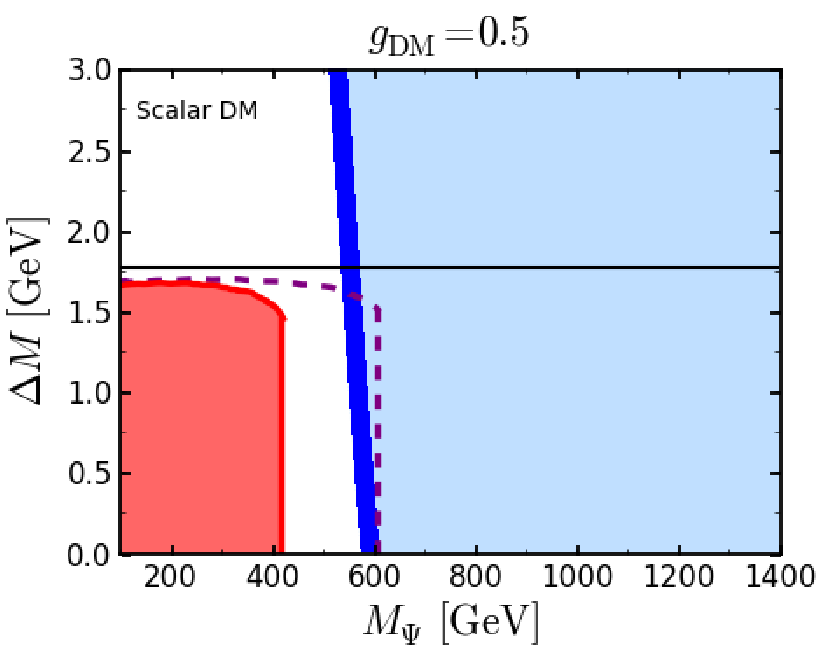
DM S

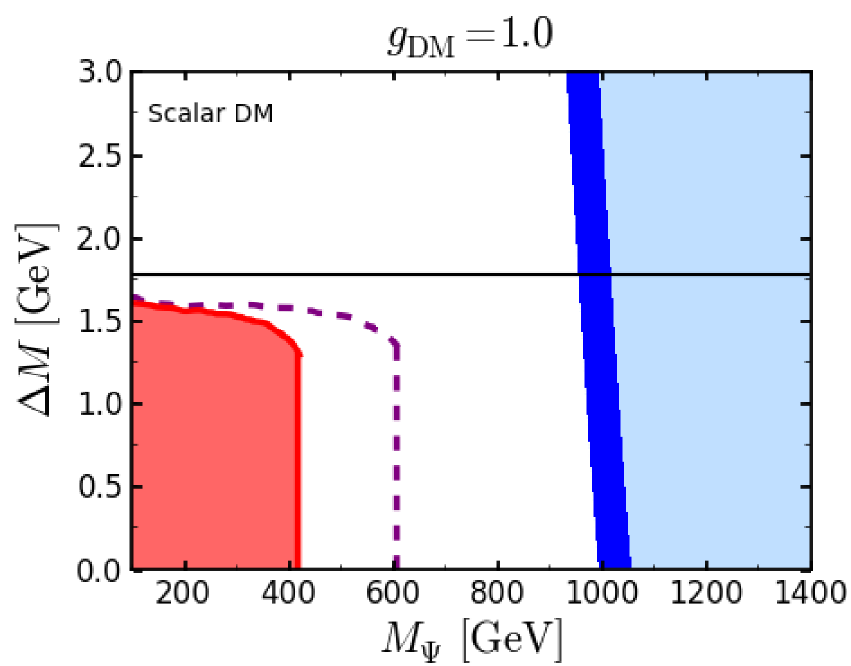
CAP $(Y = 1\ \ L_\tau = 1)$ Ψ

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

13 TeV 30 fb^{-1}







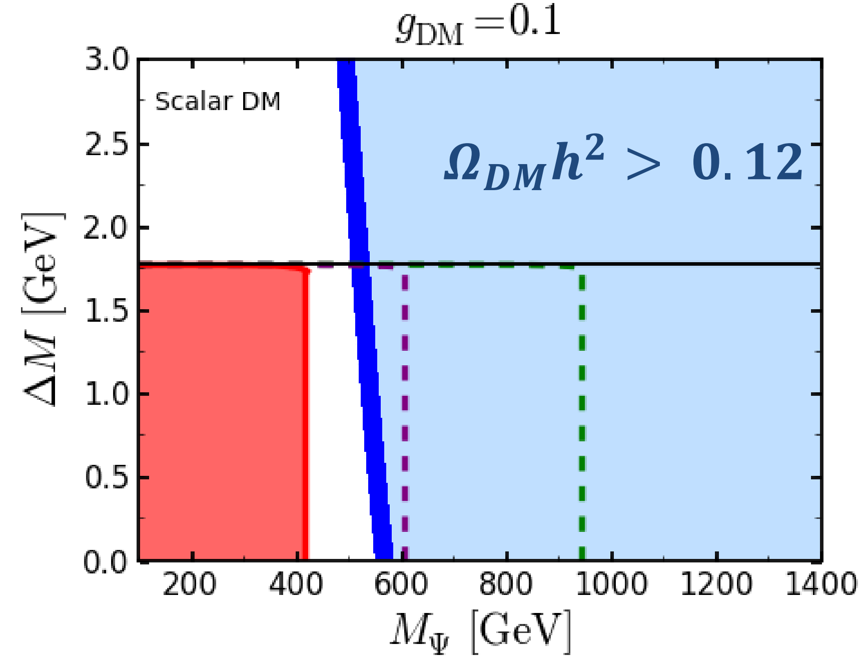
Real scalar dark matter

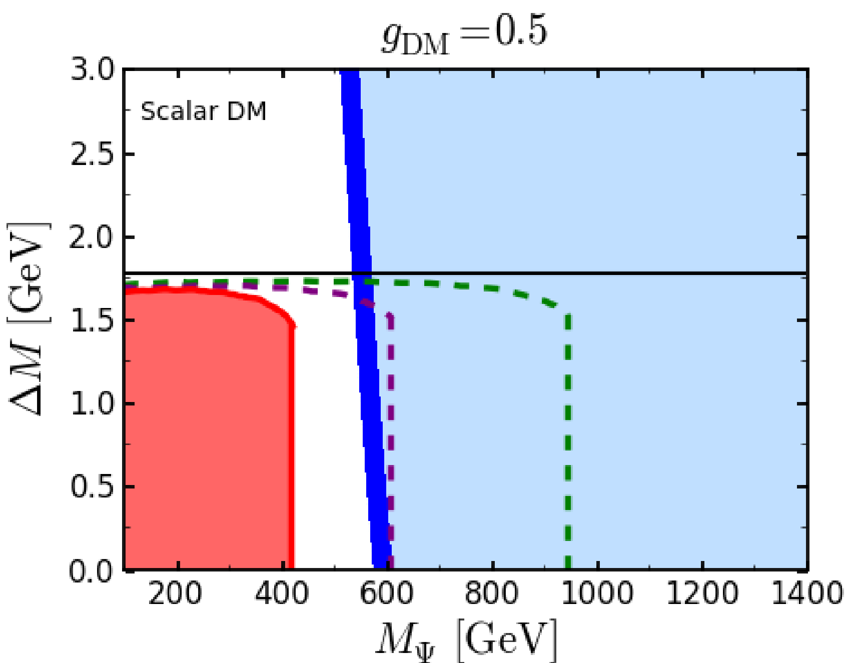
DM S

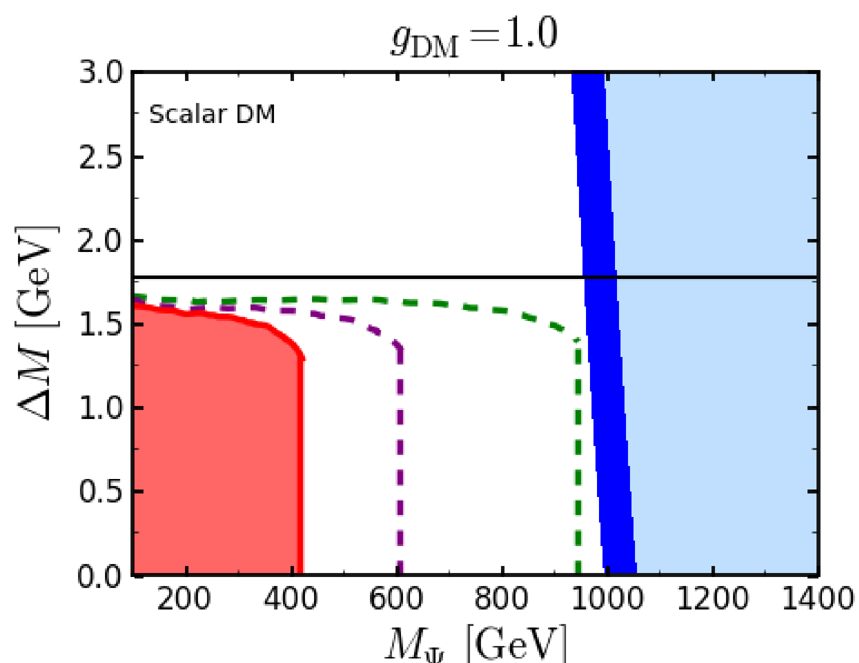
CAP $(Y = 1\ \ L_\tau = 1)$ Ψ

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

13 TeV 300 fb $^{-1}$







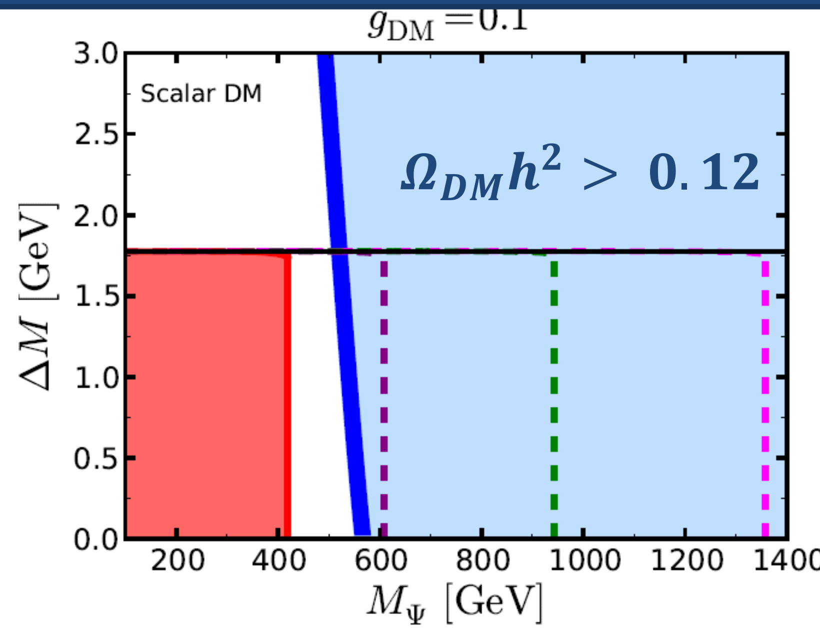
Real scalar dark matter

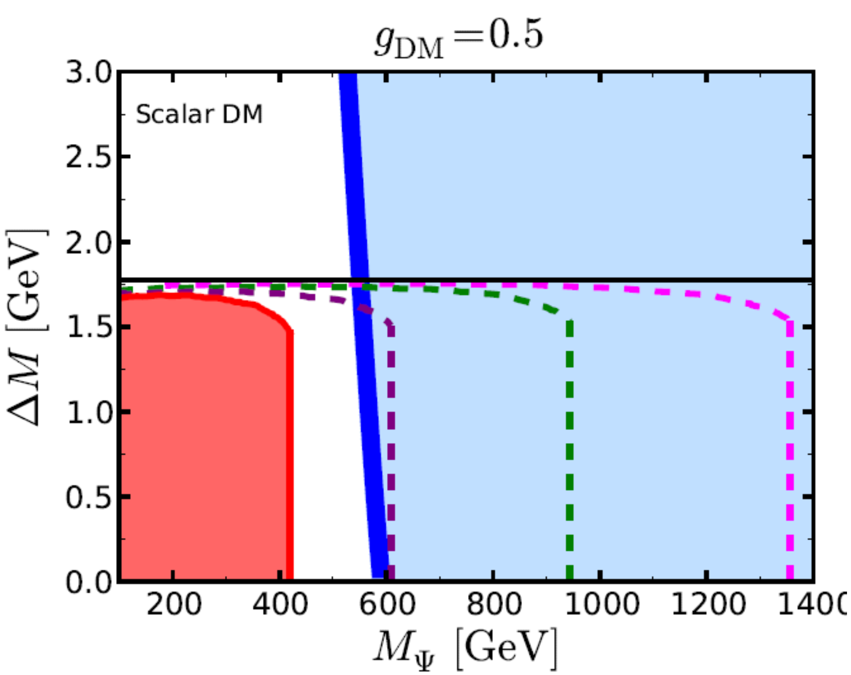
DM S

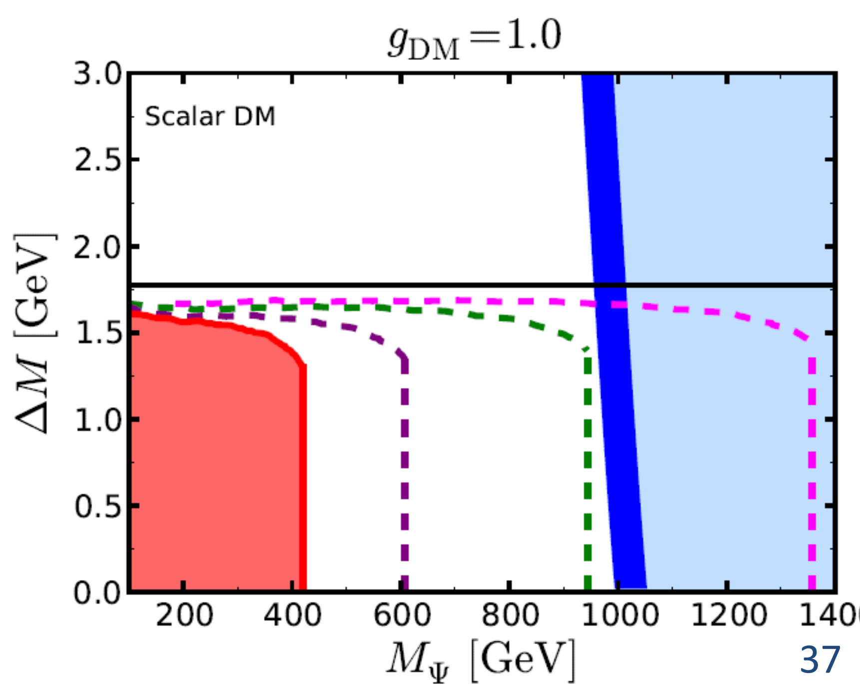
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

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

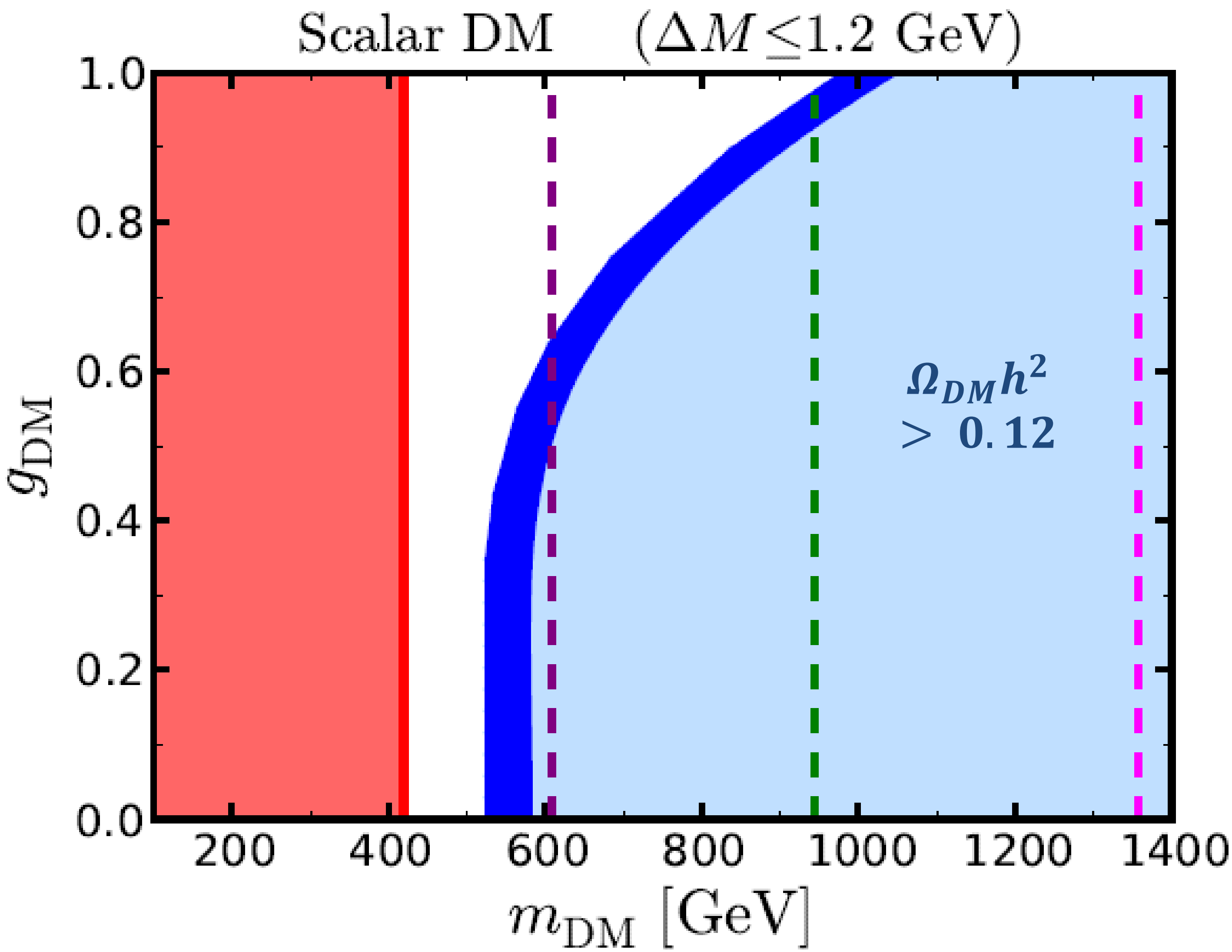
High Lumi 13 TeV 3000 fb^{-1}







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 $^{-1}$

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

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

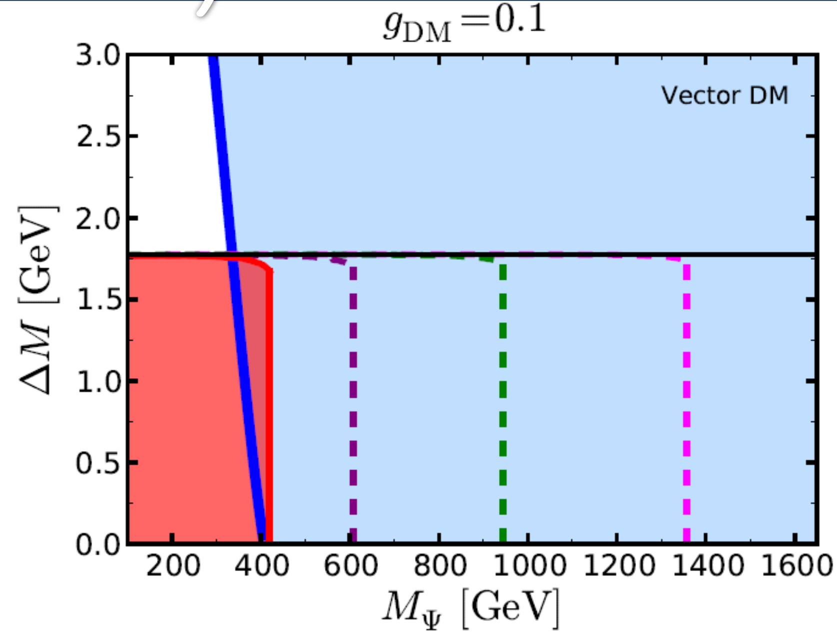
Vector dark matter (Model 3)

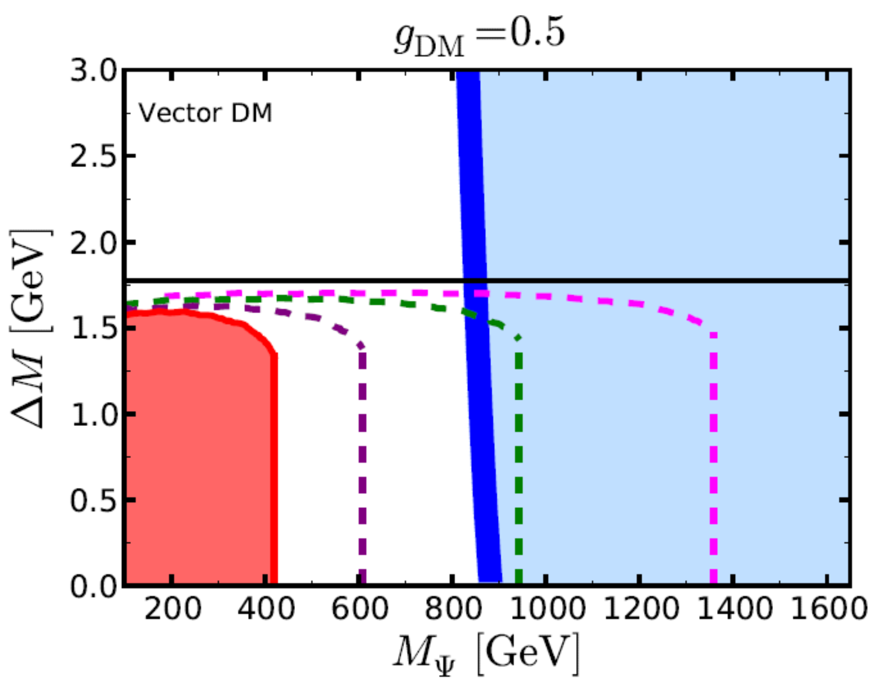
DM A_μ

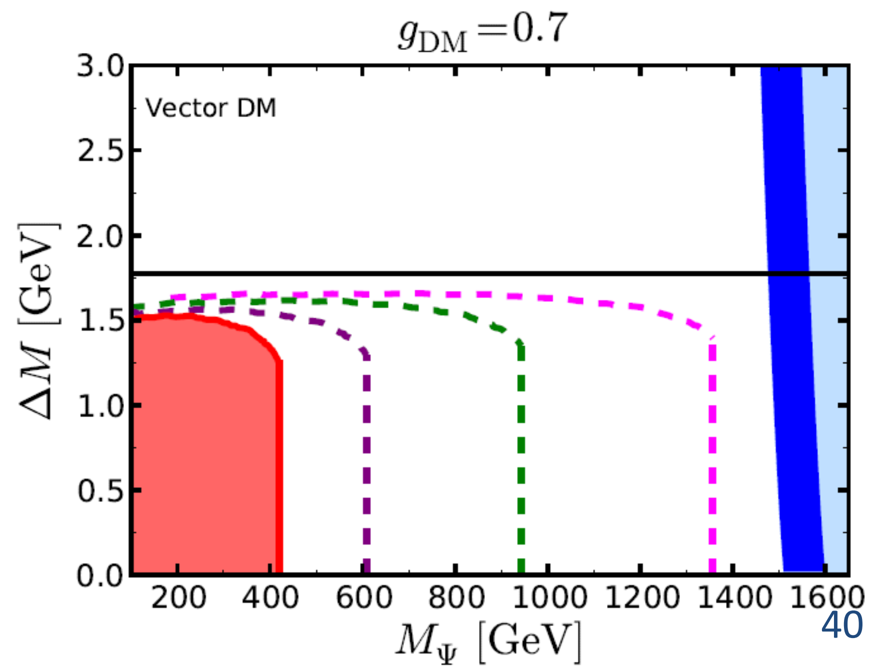
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

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

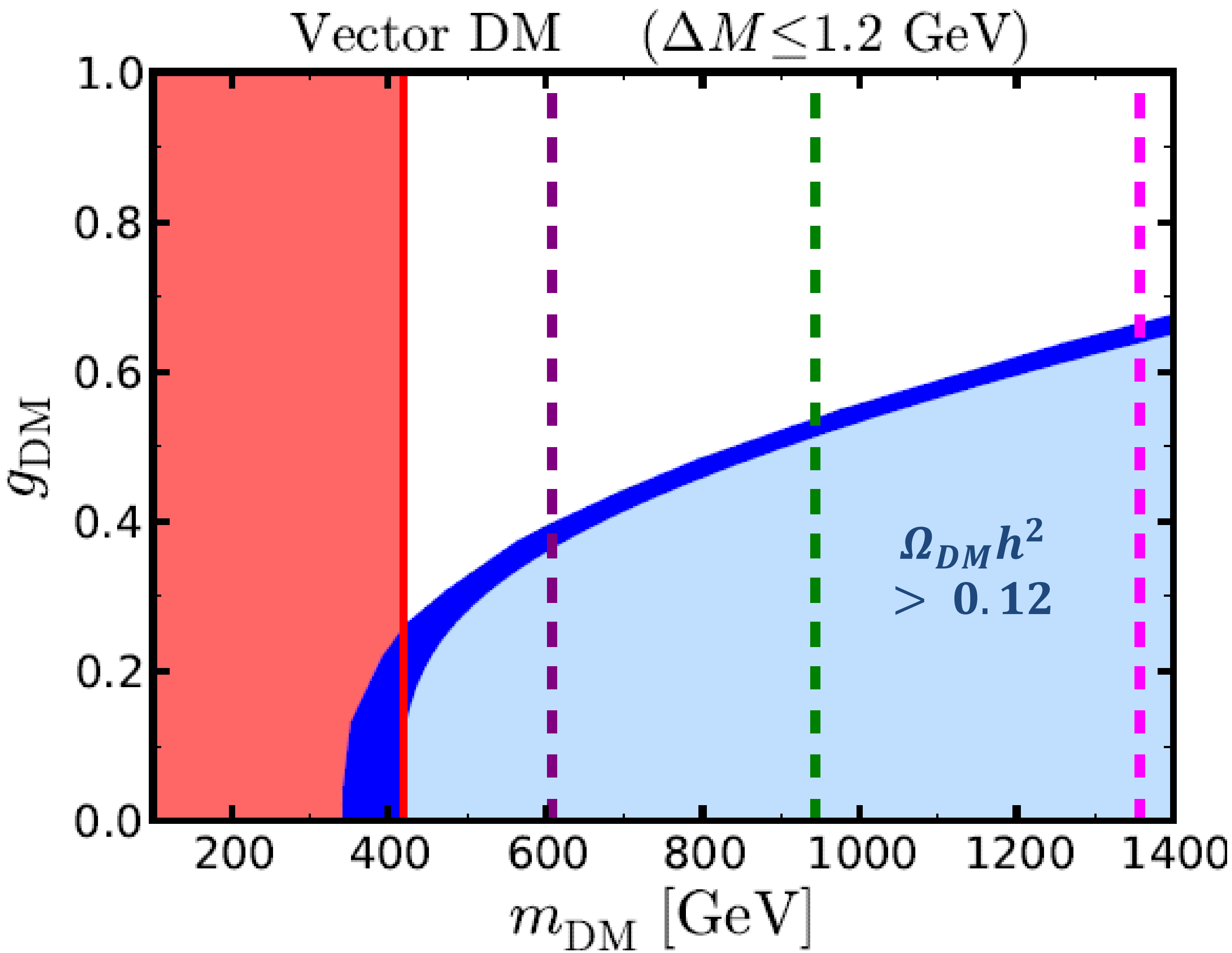
NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions







Vector dark matter



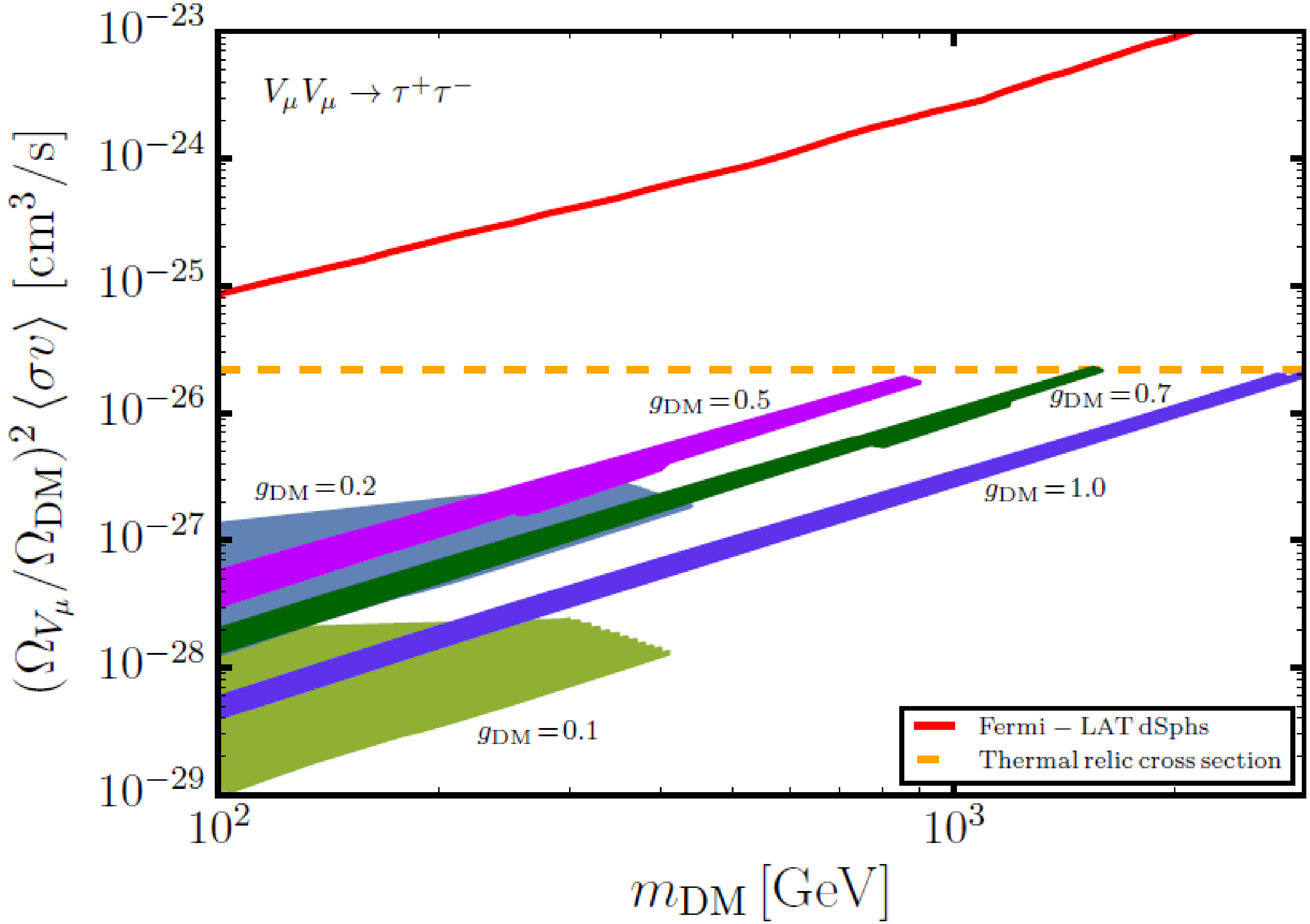
13 TeV
300 fb $^{-1}$

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

8 TeV
18.8 fb $^{-1}$

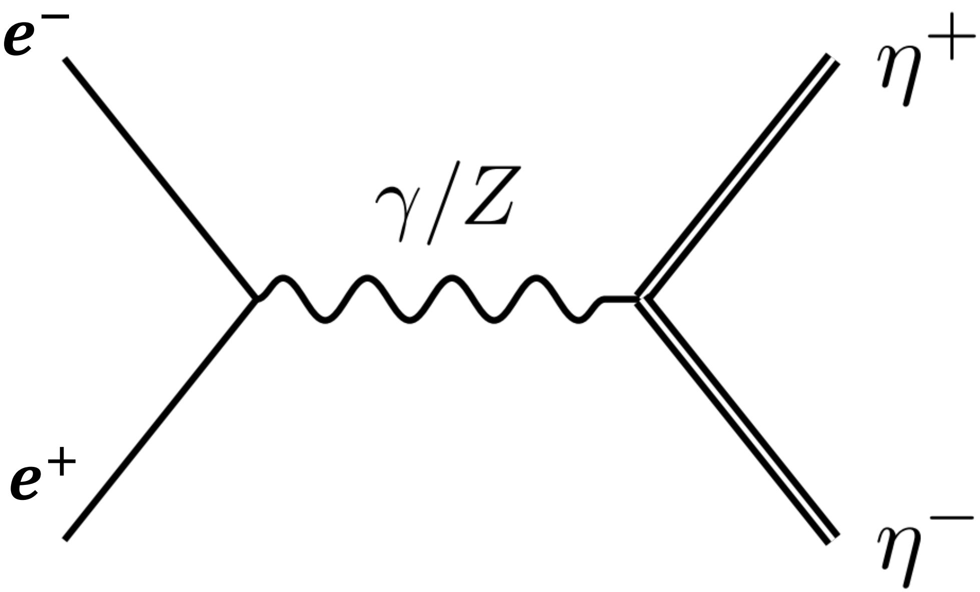
13 TeV
30 fb $^{-1}$

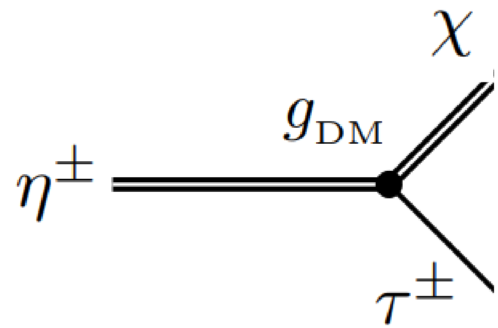
Vector dark matter



Prospects for CLIC

- Soft tau lepton is hard to reconstruct at the LHC
- The co-annihilation region $\Delta M > m_\tau$ is out of reach of LHC
- **CLIC can potentially test this region!**

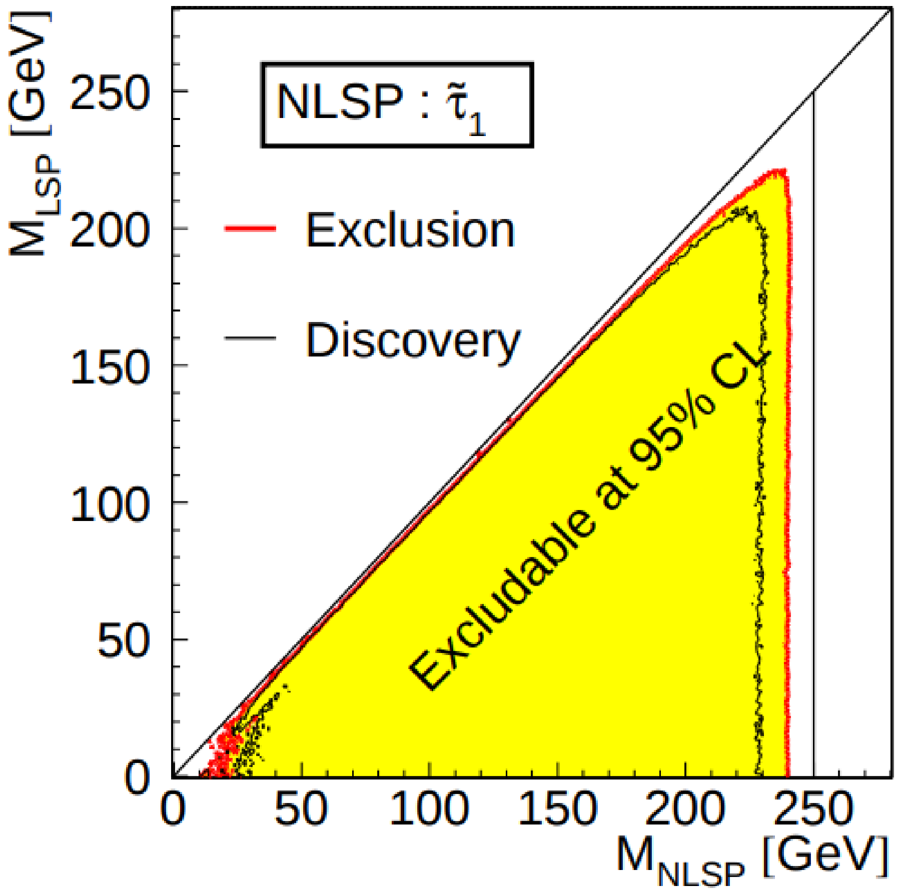




- Pair-production of co-annihilation partner from e+ e- initial state
- Cleaner experimental environment and one can fully reconstruct the missing energy

Prospects for CLIC

- **Example: Linear colliders can study compressed spectrum in SUSY**



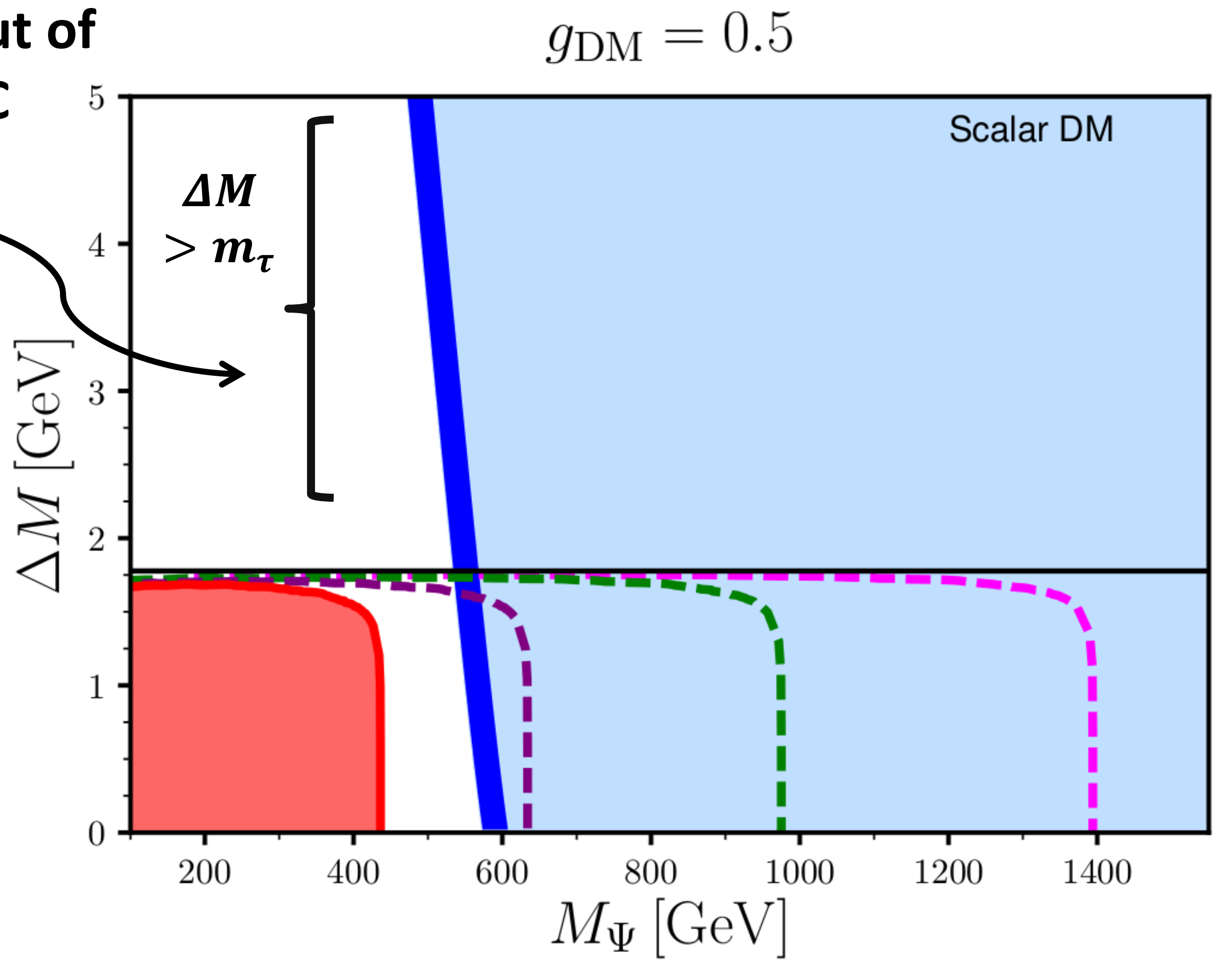
$\sqrt{s} = 500$ **GeV**

[Berggren 2013]

- Stau and neutralino, lightest supersymmetric states
- $\Delta M < 10$ GeV can be tested, virtual $\gamma\,\gamma$ becomes relevant background

Prospects for CLIC

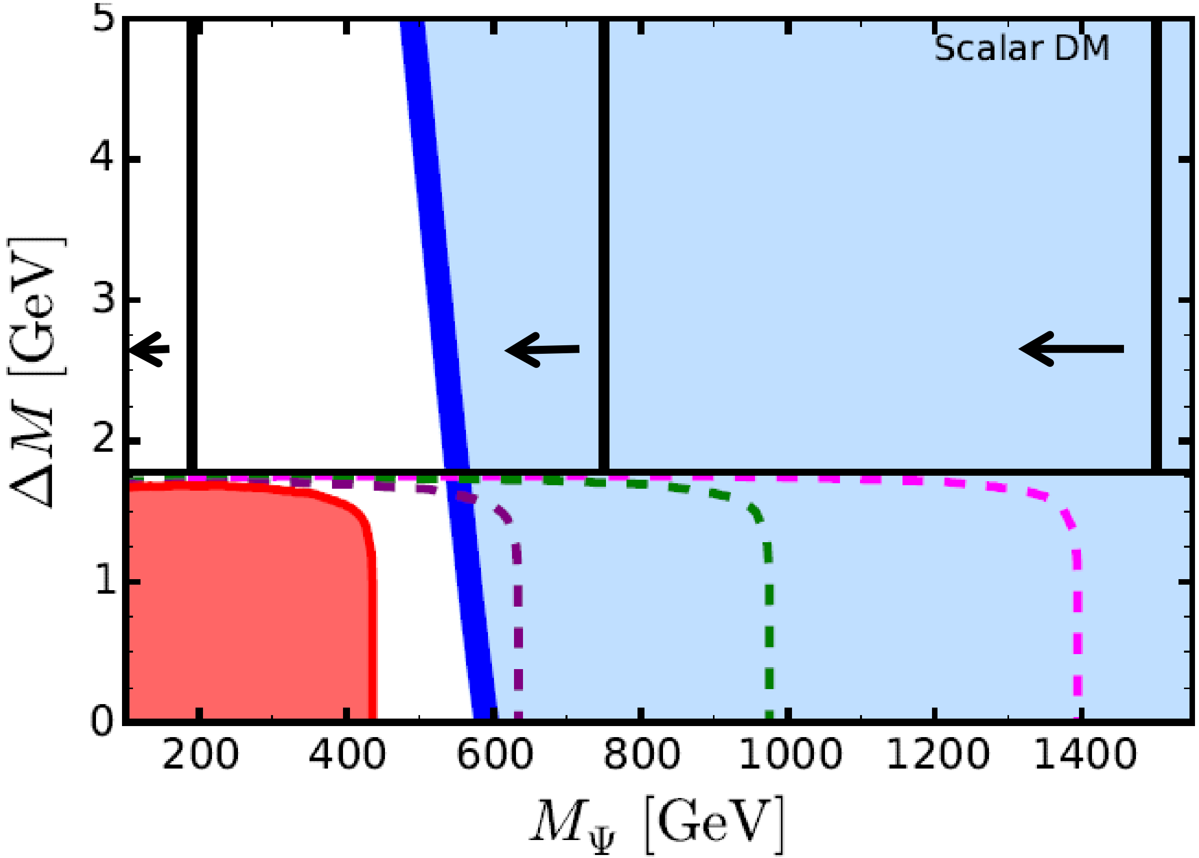
This region is out of reach of LHC



Prospects for CLIC

- Expected reach for electrically charged particles is $M < \frac{\sqrt{s}}{2}$

CLIC @ 380 GeV **CLIC @ 1.5TeV** **CLIC @ 3TeV**



- CLIC allows us to probe the co-annihilation strip for $\Delta M > m_\tau$

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**

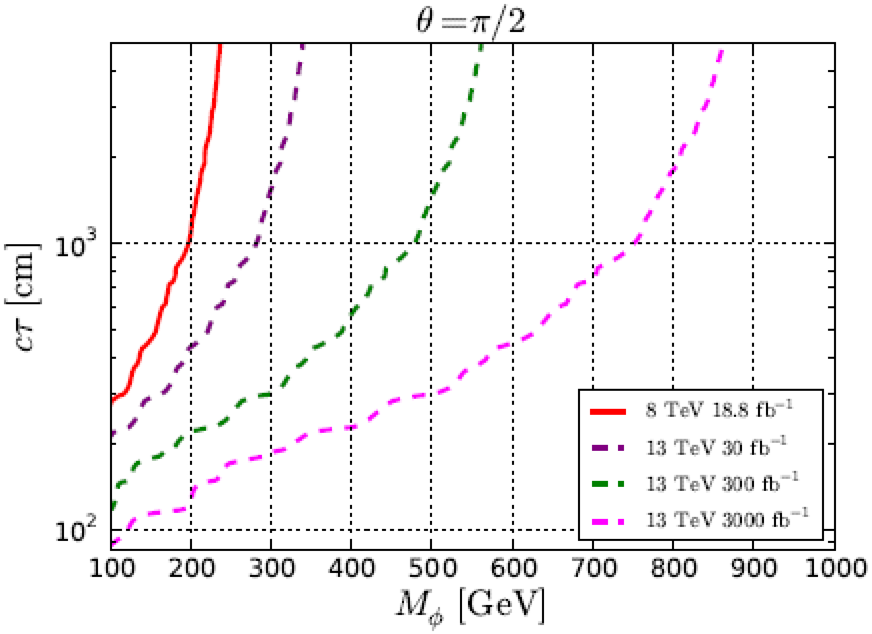
- The crucial signatures are **tracks of long-lived charged particles,** these searches had not been studied before in the context of simplified models of DM

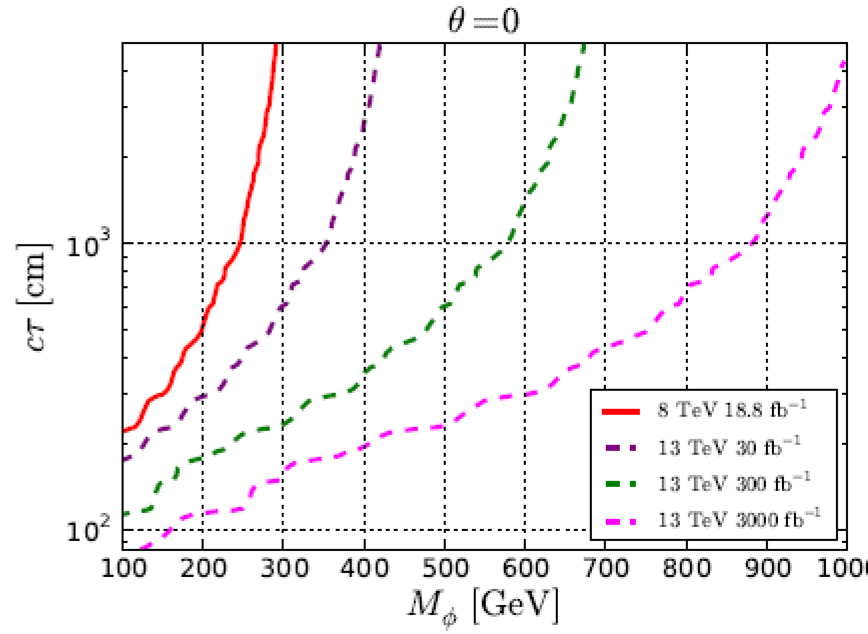
- In the four simplified models we have introduced there are only **3 free parameters**

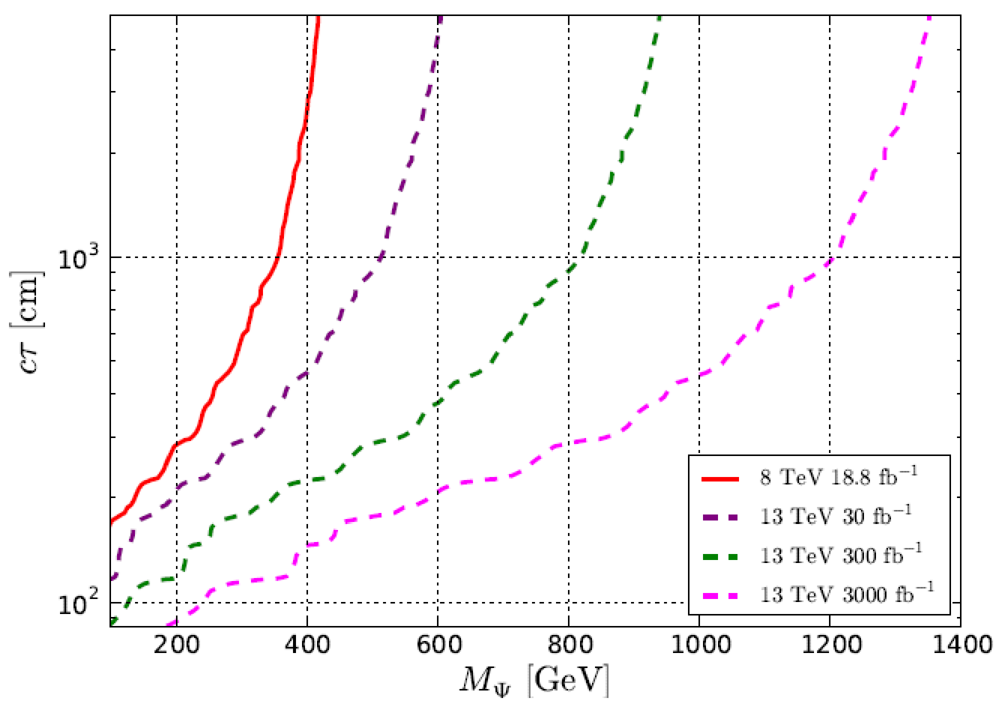
- Testing co-annihilation in dark matter models is one more motivation to build **CLIC**

- The possible **discovery** of a long-lived electrically charged particle could provide **an insight into the nature** of dark matter

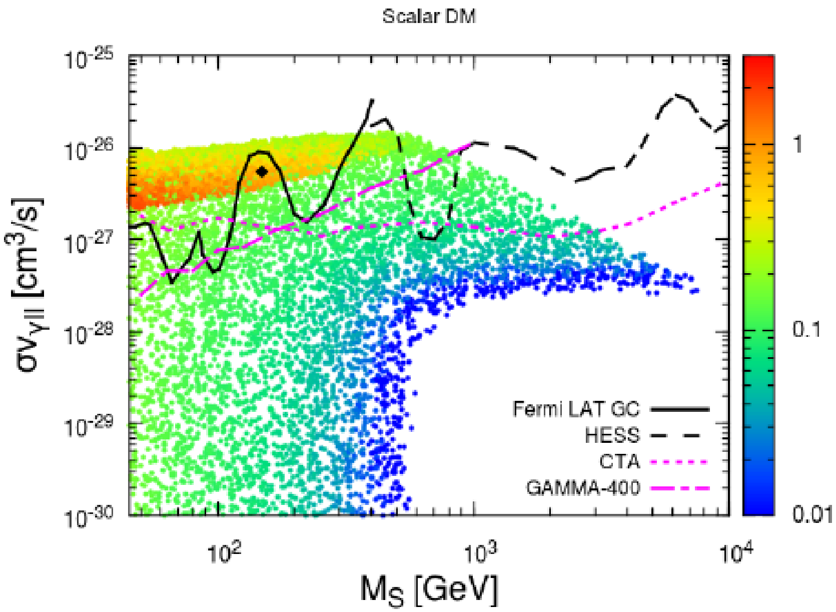
Thank you!

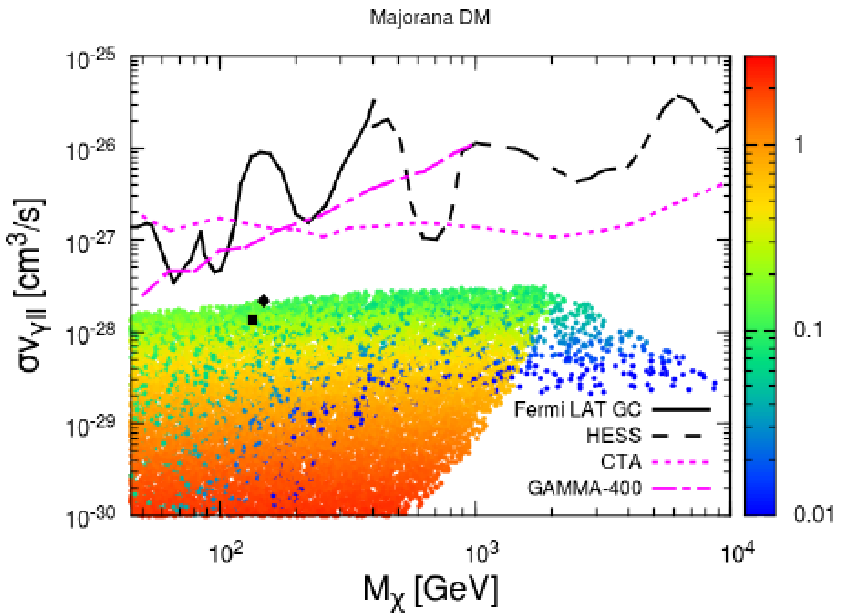

$\theta = \pi/2$
$c\tau$ [cm]
M_ϕ [GeV]
8 TeV 18.8 fb^{-1}
13 TeV 30 fb^{-1}
13 TeV 300 fb^{-1}
13 TeV 3000 fb^{-1}


$\theta = 0$
$c\tau$ [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}


$c\tau$ [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]