ATLAS meeting

Simplified Dark Matter models with a long-lived co-annihilation partner

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based on arXiv:1702.00750

in collaboration with
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Introduction

- All evidence for the existence of Dark Matter is purely gravitational

- The particle physics nature of DM is unknown
  — is our main `new physics' challenge
  [pretty much main particle physics challenge at present]

- The current measured relic density of DM from cosmic microwave background $\Omega_{DM}\, h^2 = 0.1198 \pm 0.0026$

DM searches:

- Direct Detection (DD) experiments

- Indirect Detection (ID) experiments

- $\boxed{\text{Collider searches LHC}}$ (& future colliders 13-100 TeV)

Motivation

- A standard signature to search for dark matter at colliders is the mono-X (or multi-jets) plus missing energy.

- These searches are being exploited and interpreted in terms of simplified dark matter models with mediators.

$\boxed{\text{Dark Matter + mediator}}$ + $\boxed{\text{Standard Model particles}}$

- [A growing number of the analyses are also dedicated to the direct search of the mediators which can decay back to the SM.]

- We consider instead an alternative DM scenario characterised by simplified models without mediators.

$\boxed{\text{Dark Matter + co-annihilation partner}}$ + $\boxed{\text{Standard Model particles}}$

- Our dark sector includes a co-annihilation partner (CAP) particle instead of a mediator (in addition to the cosmologically stable DM).

Simplified Models without Mediators

$\boxed{\text{DM} + \text{CAP}} + \boxed{\text{SM particles}}$

- Co-annihilation partner (CAP) has an important role in lowering the relic density

- The signal we study for collider searches is the pair-production of CAPs that then ultimately decay into cosmologically stable dark matter

- Focus on the scenario where:

1. CAP is an SU(3)-singlet, charged under the EW sector

2. DM and CAP are nearly mass-degenerate (Delta M < tau mass ~1 GeV)

=> the CAP is long-lived

- Compared to simplified DM models that rely on signals with missing energy at colliders, in these models the crucial collider signature to look for are tracks of long-lived electrically charged particles

- We now introduce a set of simplified models which are distinct from and complimentary to the standard mediator-based simplified DM models set:

All models involve the 3-point interactions:

Dark Matter candidate

Standard Model τ lepton

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

Co-annihilation partner (CAP)

Will vary particle species of DM and CAP

Simplified models with only 3 free parameters:

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

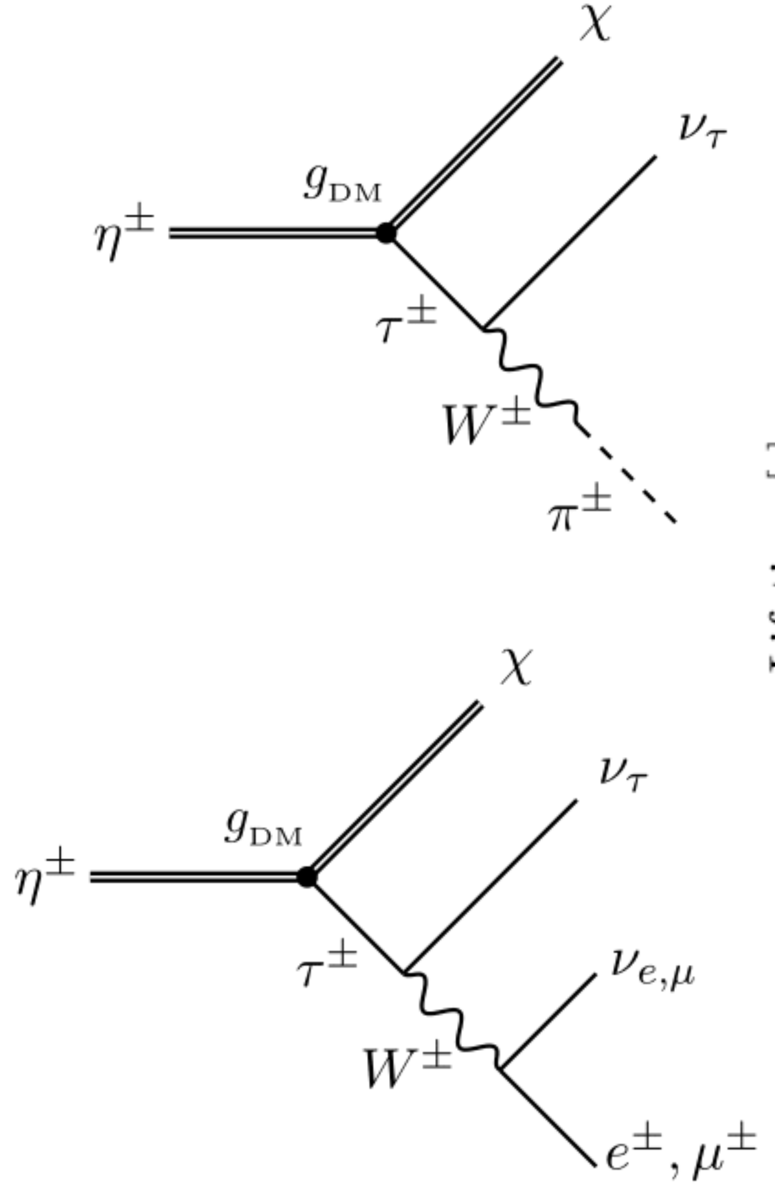
$$\mathbb{Z}_2: \quad \chi \rightarrow -\chi \qquad \eta \rightarrow -\eta$$

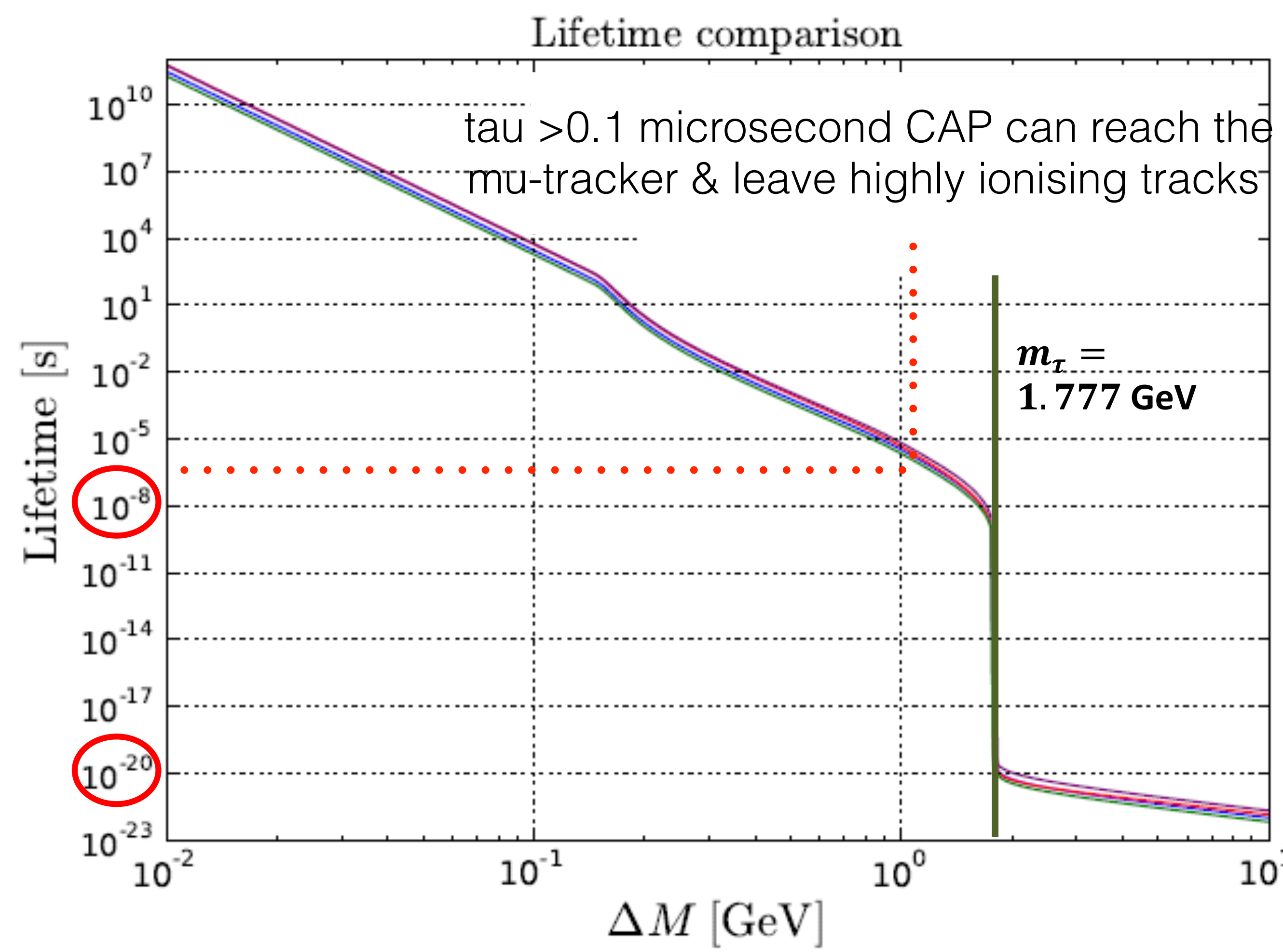
- These simplified modes can be used by ATLAS & CMS to interpret searches for long-lived charged particles to explore the new range of DM scenarios

- We now introduce a set of simplified models which are distinct from and complimentary to the standard mediator-based simplified DM models set:

+ Long-lived charged co-annihilation partners

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





- These simplified modes can be used by ATLAS & CMS to interpret searches for long-lived charged particles to explore the new range of DM scenarios

- We now introduce a set of simplified models which are distinct from and complimentary to the standard mediator-based simplified DM models set:

Fermion DM

Model-1a			
Component	Field	Charge	Interaction (5.1)
DM	Majorana fermion (χ)	$Y = 0$	$\phi^*(\chi\tau_R) + \text{h.c.}$
CAP	Complex scalar (ϕ)	$Y = -1$	

Model-1b			
Component	Field	Charge	Interaction (5.4)-(5.5)
DM	Majorana fermion (χ)	$Q = 0$	$\phi^*(\chi\tau_R) + \phi^*(\chi\tau_L) + \text{h.c.}$
CAP	Complex scalar (ϕ)	$Q = -1$	

Scalar DM

Model-2			
Component	Field	Charge	Interaction (5.6)
DM	Real scalar (S)	$Y = 0$	$S(\overline{\Psi}P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

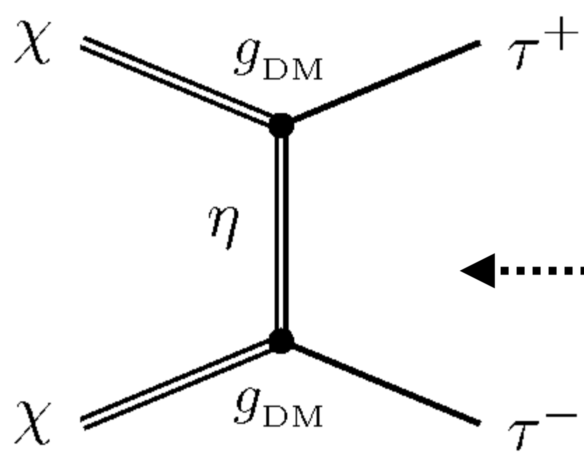
Vector DM

Model-3			
Component	Field	Charge	Interaction (5.7)
DM	Vector (V_μ)	$Y = 0$	$V_\mu(\overline{\Psi}\gamma^\mu P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

- These simplified modes can be used by ATLAS & CMS to interpret searches for long-lived charged particles to explore the new range of DM scenarios

Relic Density from annihilation & co-annihilation

Dark matter annihilation into pair of tau's



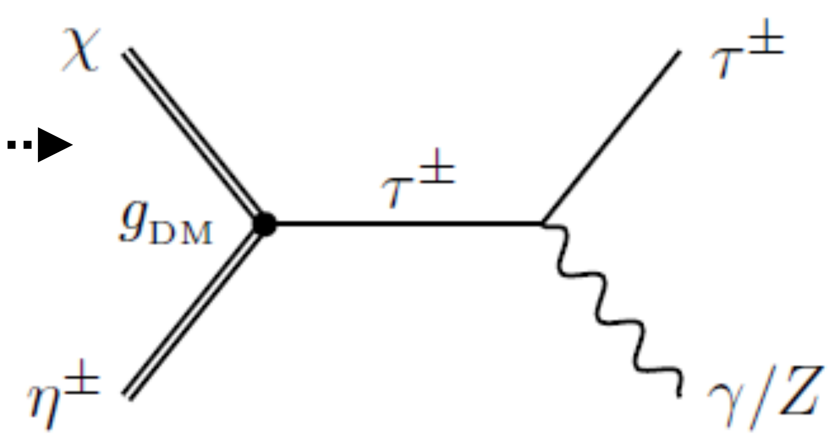
$$(\sigma v)^{\text{s-wave}}_{\text{ann}} = \frac{g_R^4\, m_\tau^2}{32\pi\, m_\chi^4} \frac{1}{(1+r^2)^2}$$

$\propto \boldsymbol{m_\tau}$

Chiral suppression

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

Co-annihilation:



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

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

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

Relic Density from annihilation & co-annihilation

DM
χ

CAP
ϕ

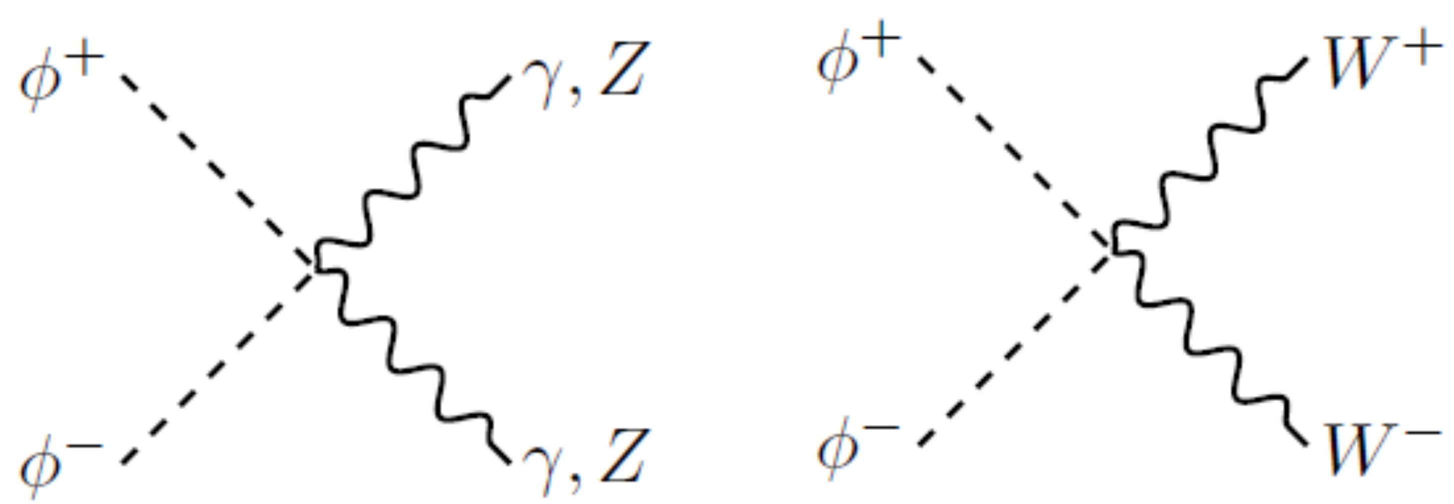
Using Majorana DM and scalar CAP as an example

$\boxed{\text{dependence on } g_{\rm DM} \text{ is weak if } g_{\rm DM} \ll 1}$

$\langle \sigma_{\rm eff} v \rangle$ dominated by $\boxed{\phi^+ \phi^- \to SM \text{ particles}}$

Dominant contributions come from:

CAP-CAP



SM-SM

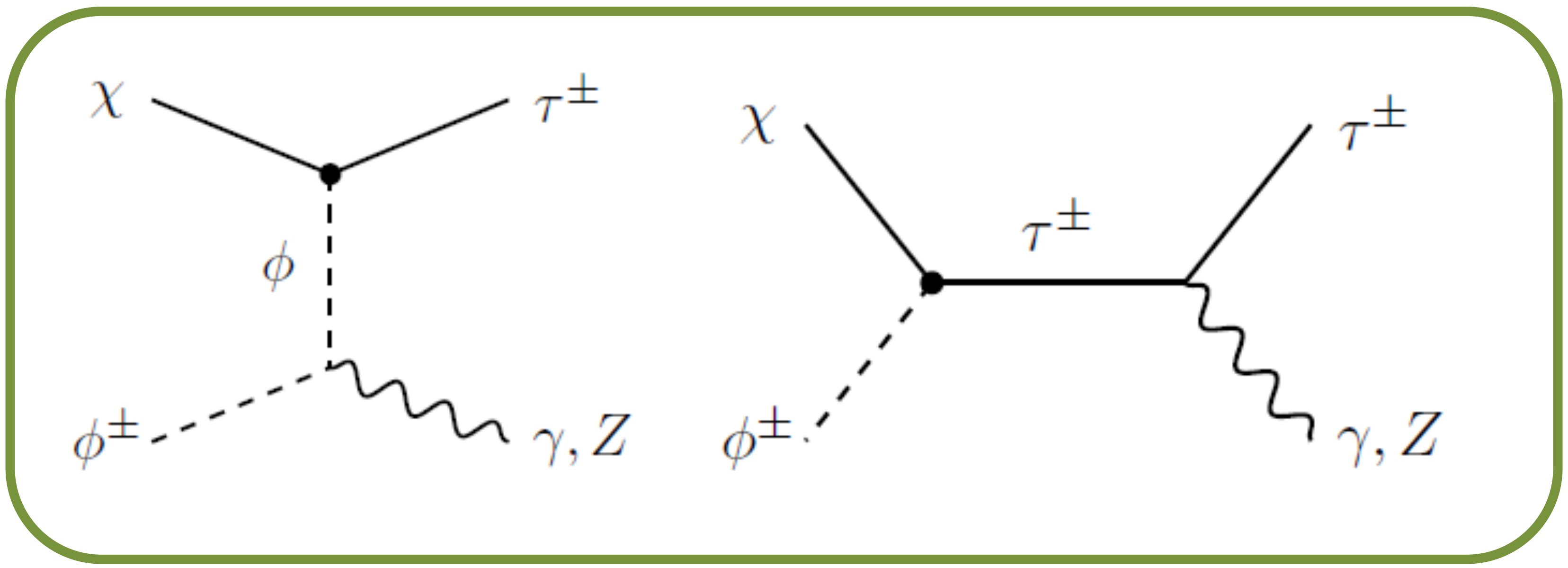
and that is why CAPs are important for cosmology

Relic Density from annihilation & co-annihilation

$g_{\mathrm{DM}} \gtrsim \mathbf{0.3}$ $\qquad \phi^{\pm}\chi \to SM \text{ particles}$

Becomes relevant
$g'^2 \; g_{DM}{}^2$

CAP-DM

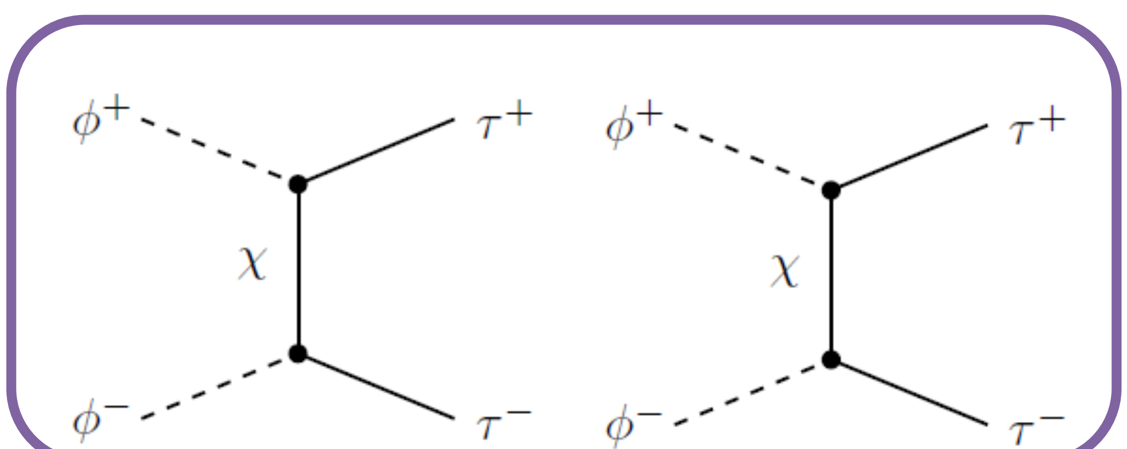


SM-SM

$g_{\mathrm{DM}} \gtrsim \mathbf{1.0}$ $\qquad \phi^{+}\phi^{+} \to \tau^{+}\tau^{+}$

Relevant
$g_{DM}{}^4$

CAP-CAP



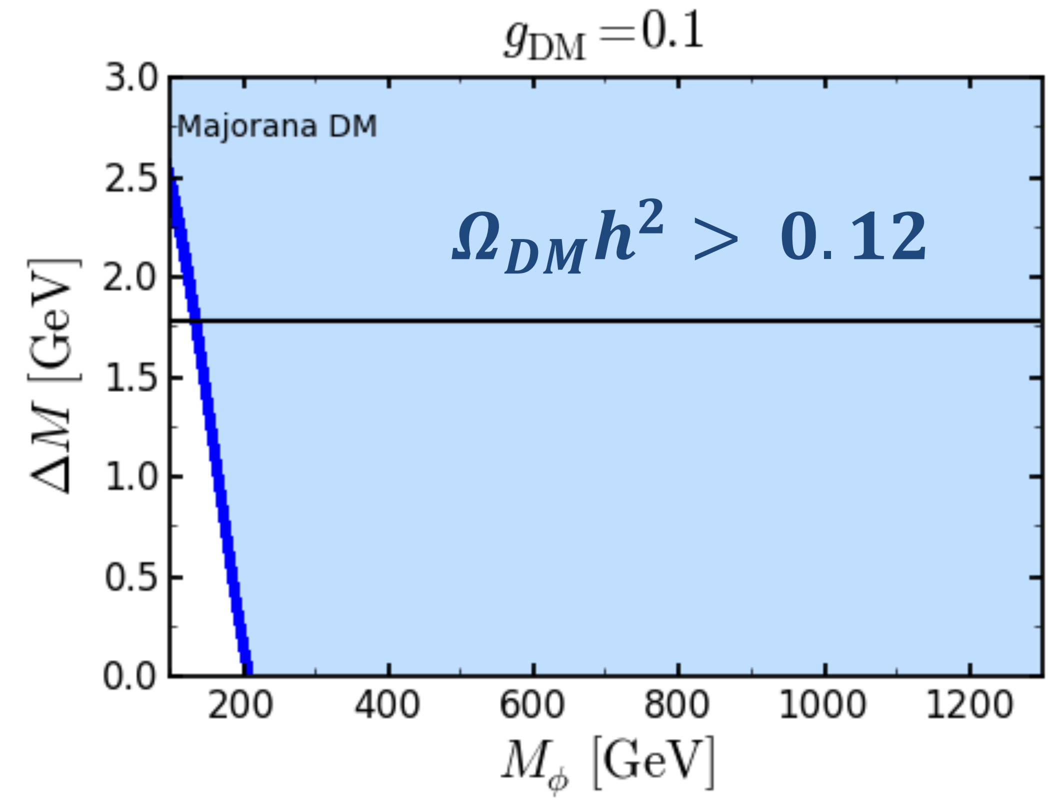
SM-SM

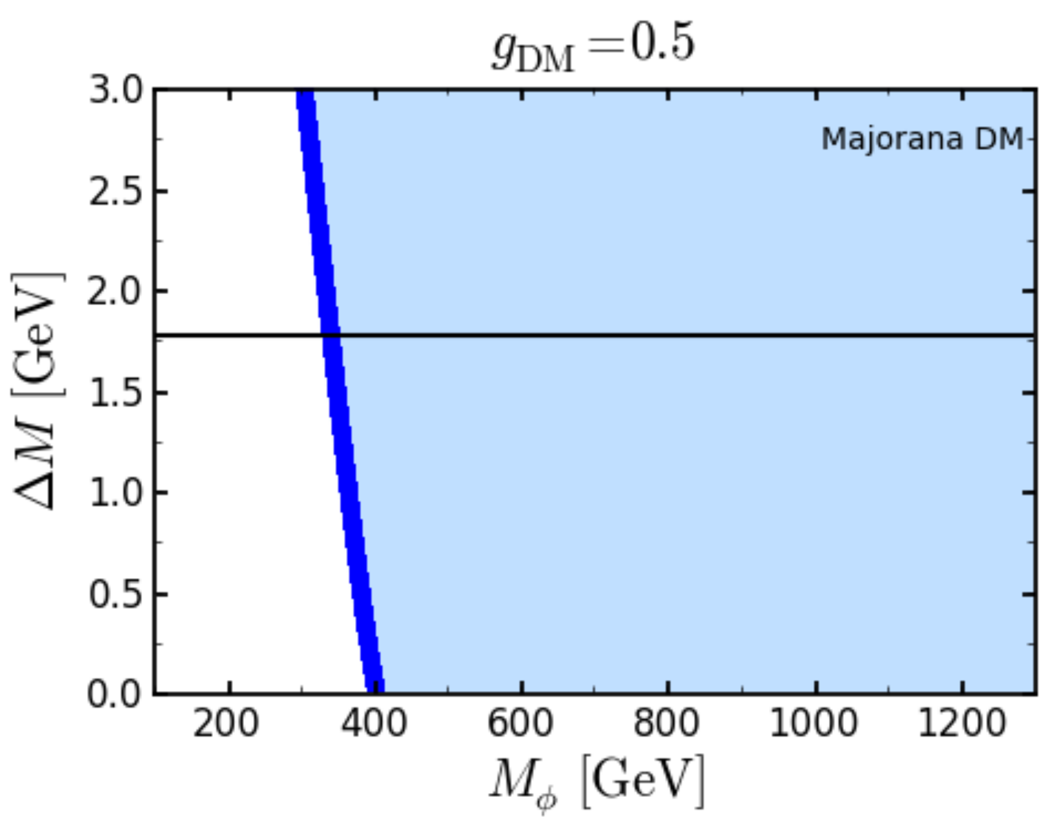
Relic Density from annihilation & co-annihilation

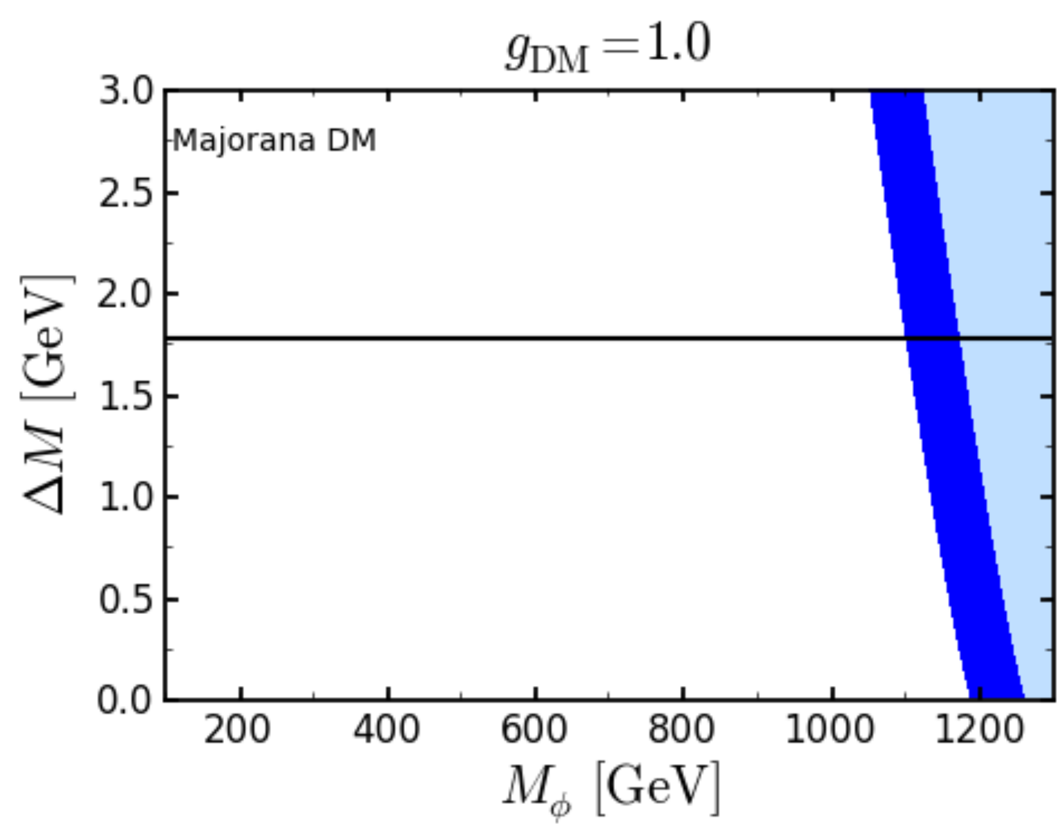
DM χ

CAP ϕ

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







Model 1a

- Dark Matter = Majorana fermion

- Co-annihilation Partner = complex scalar charged under U(1)_Y only
  $(\eta^+, \eta^-) = (\phi^*, \phi) = (\phi^+, \phi^-)$

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm CAP} + \mathcal{L}_{\rm int}\,, \\
\mathcal{L}_{\rm DM} &= \frac{1}{2}\chi(i\partial\!\!\!/ - m_{\rm DM})\chi\,, \\
\mathcal{L}_{\rm CAP} &= |D_\mu\phi|^2 - M_\phi^2\,|\phi|^2\,, \\
\mathcal{L}_{\rm int} &= g_{\rm DM}\,\phi^*\chi\tau_R + {\rm h.c.}\,,
\end{aligned}
$$

3 parameters:
gDM, mDM, $\Delta M < m_\tau$

- No SU(2) (and no SU(3)) interactions with the Dark Sector

- Can be the *Bino + right-handed Stau* co-annihilation strip in SUSY

- More importantly: this Simplified Model is interesting on its own right - it does not require a UV completion.

Model 1a

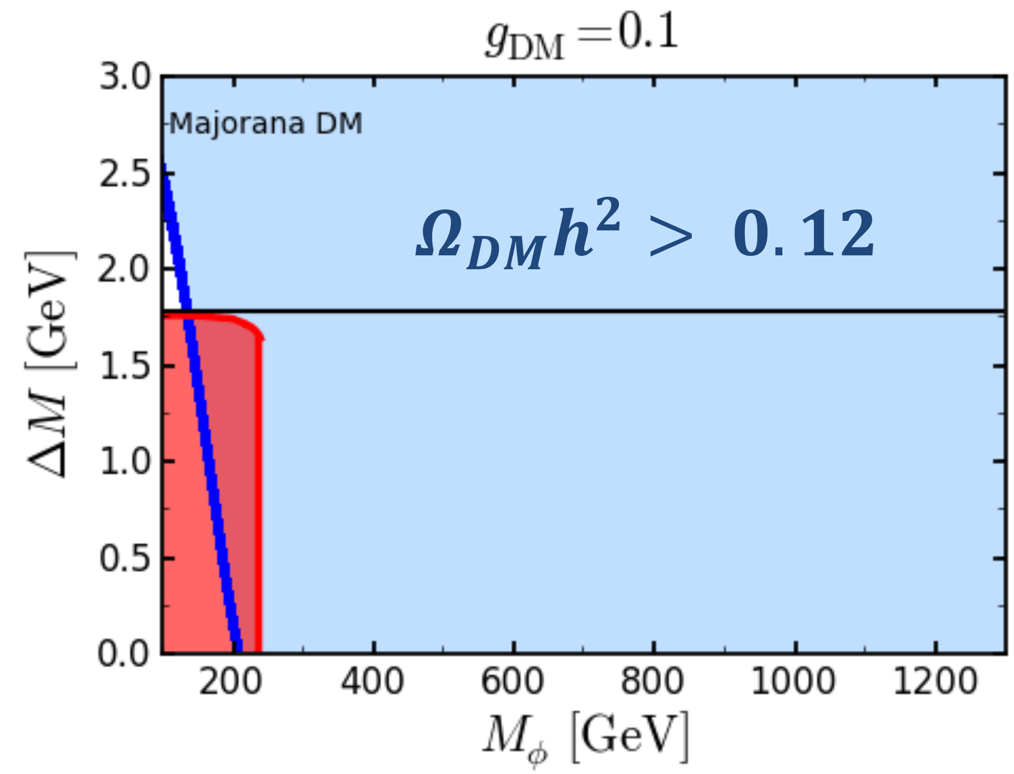
Majorana Scalar

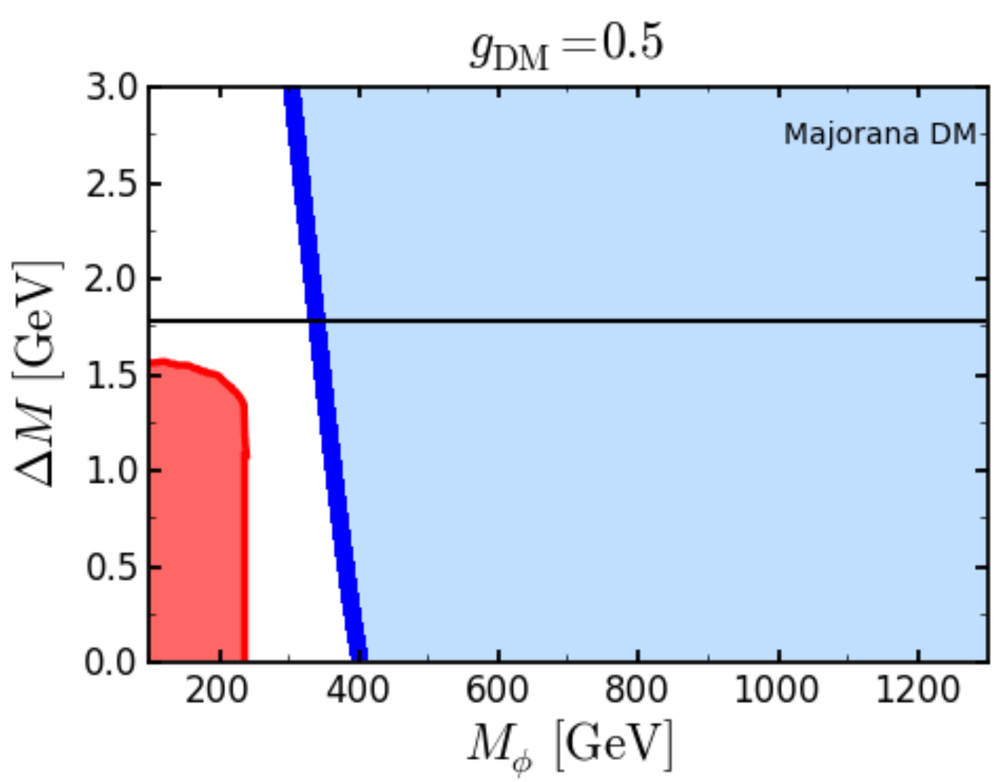
DM **CAP** $(Y = 1 \;\; L_\tau = 1)$

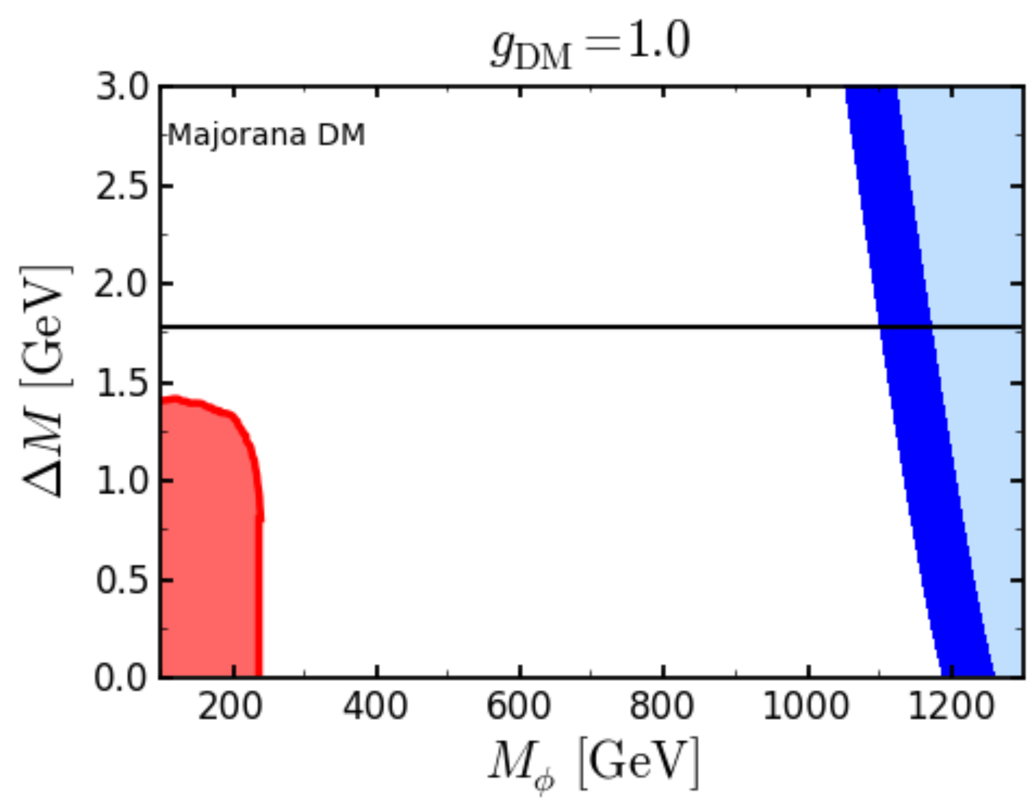
χ ϕ

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

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







Model 1a

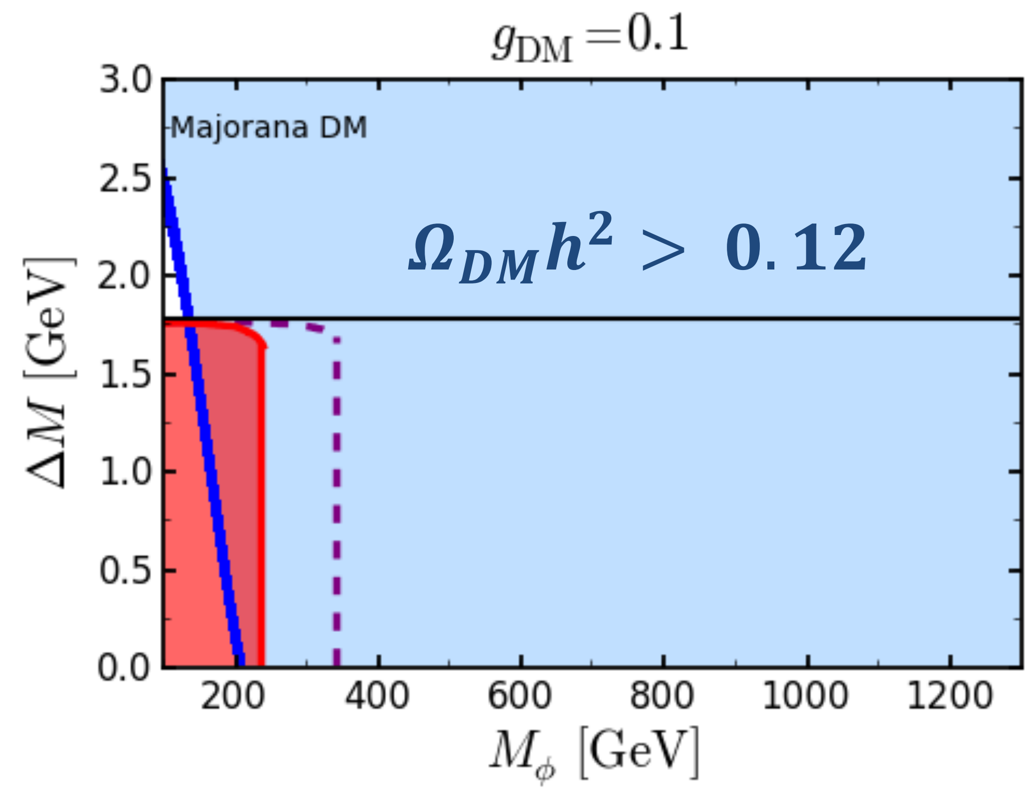
Majorana Scalar

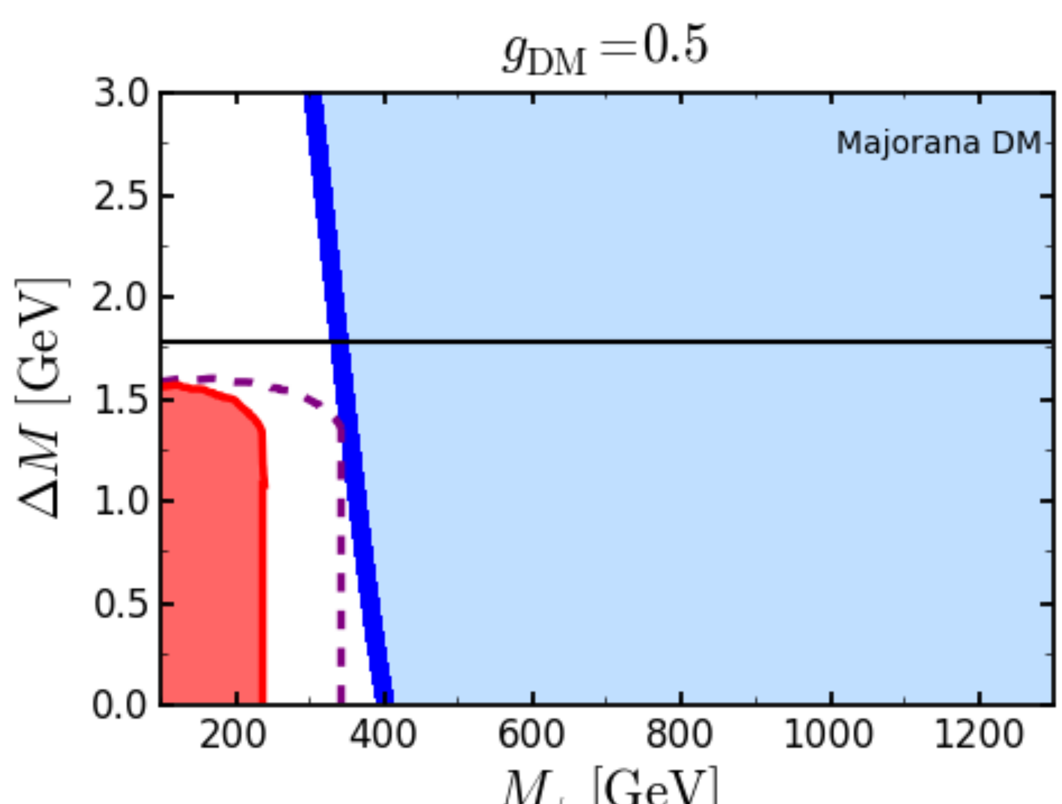
DM **CAP** $(Y = 1 \;\; L_\tau = 1)$

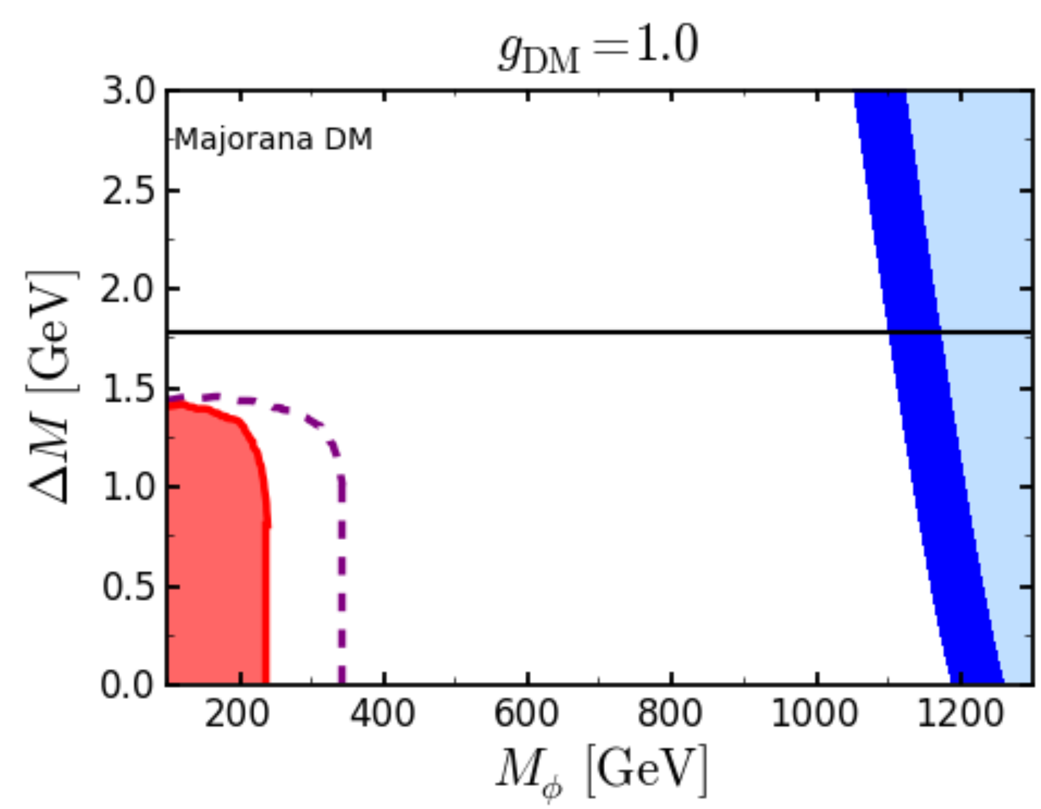
χ ϕ

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

13 TeV 30 fb $^{-1}$







Model 1a

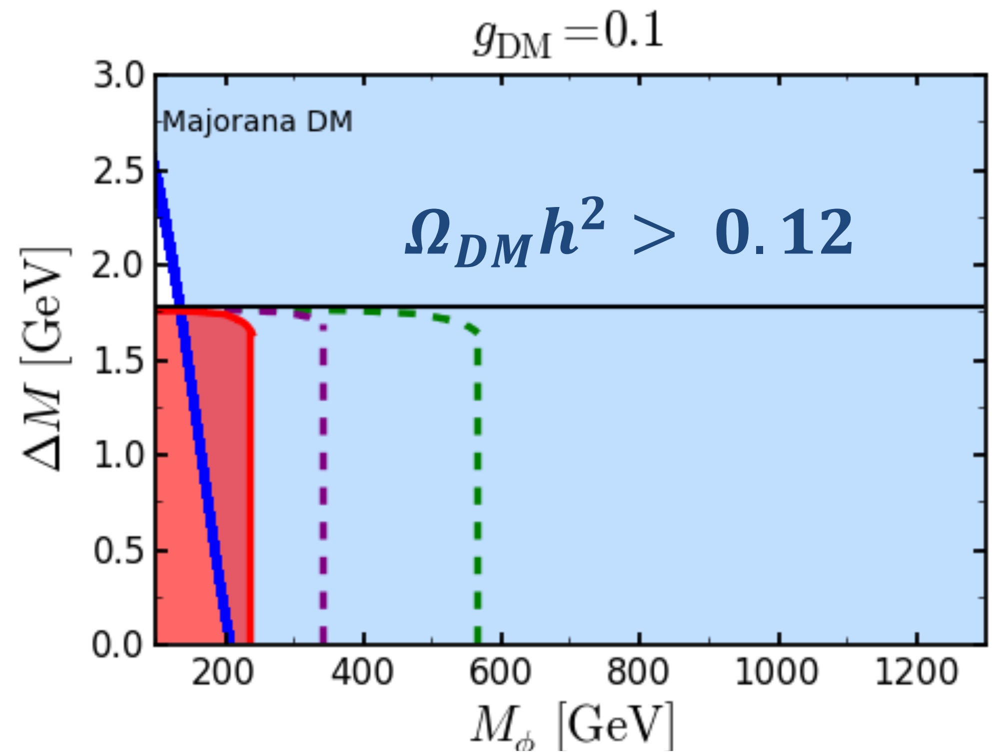
Majorana Scalar

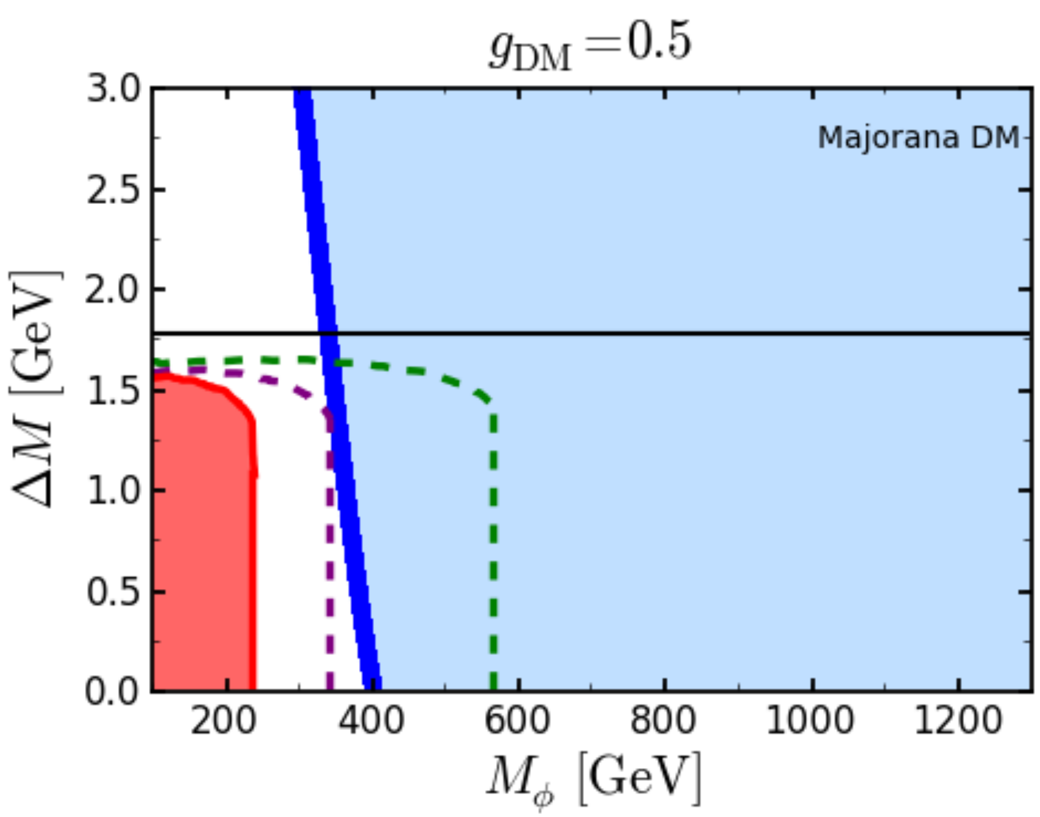
DM **CAP** $(Y = 1 \;\; L_\tau = 1)$

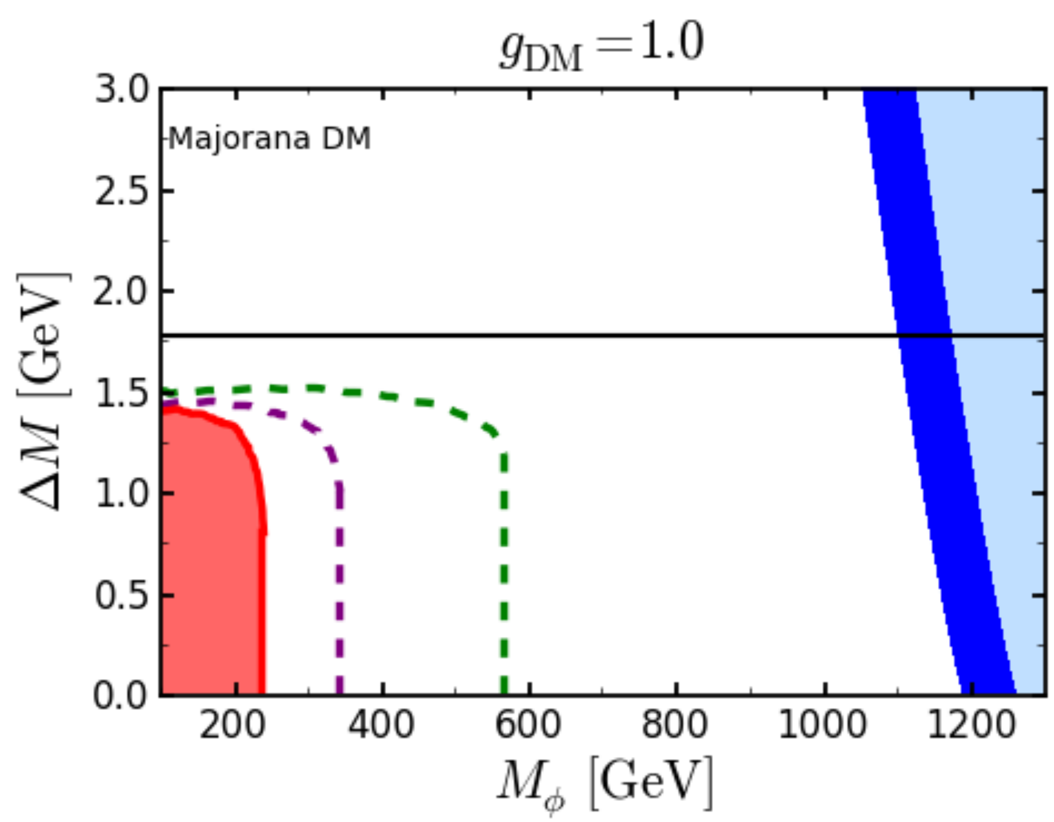
χ ϕ

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

13 TeV 300 fb^{-1}







Model 1a

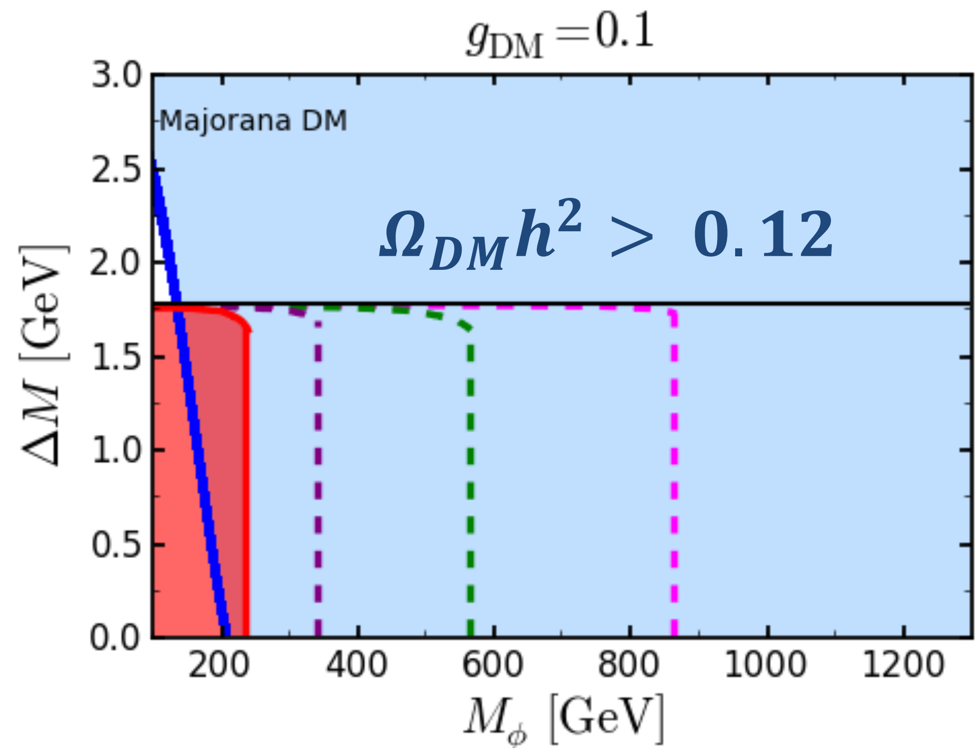
Majorana Scalar

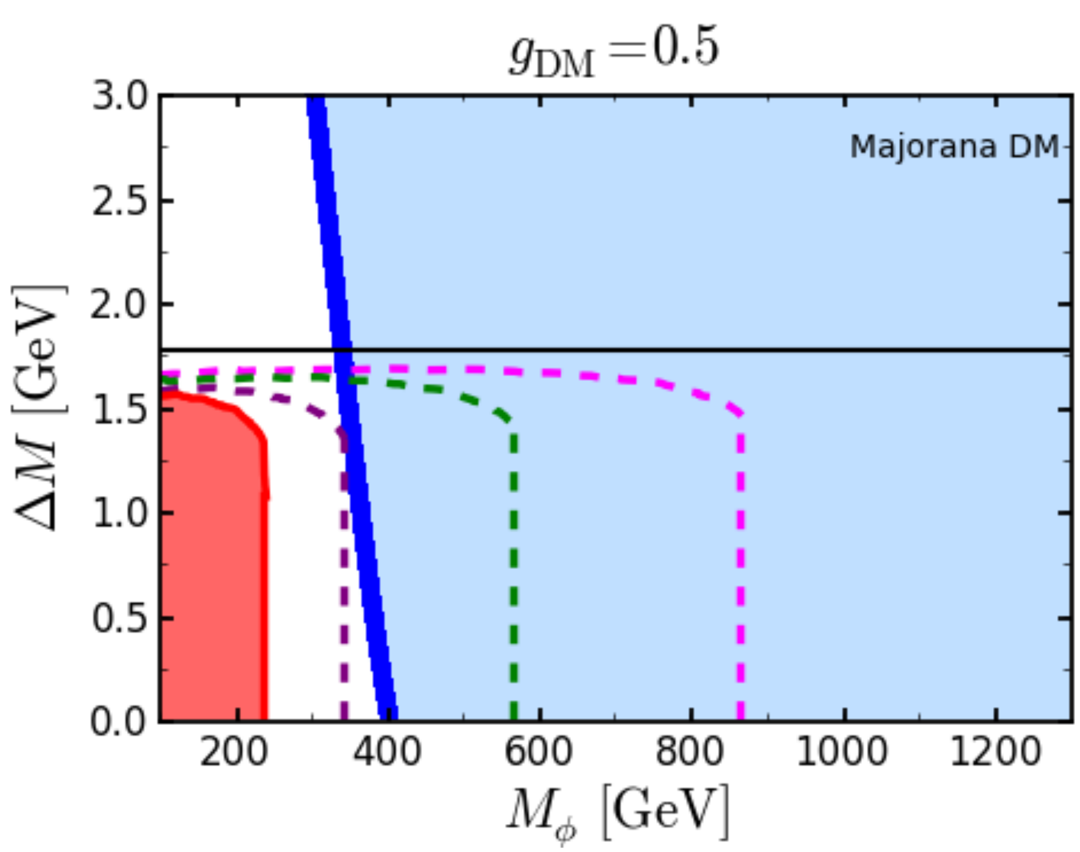
DM **CAP** $(Y = 1\ \ L_\tau = 1)$

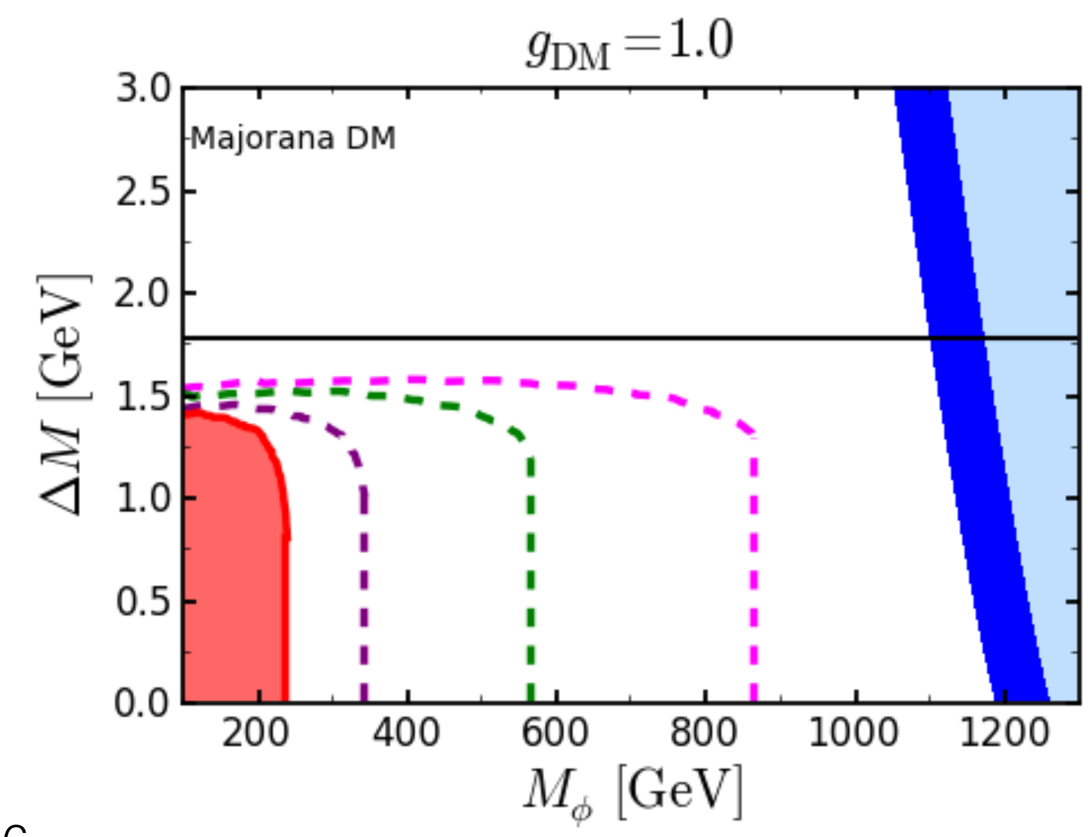
χ ϕ

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

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

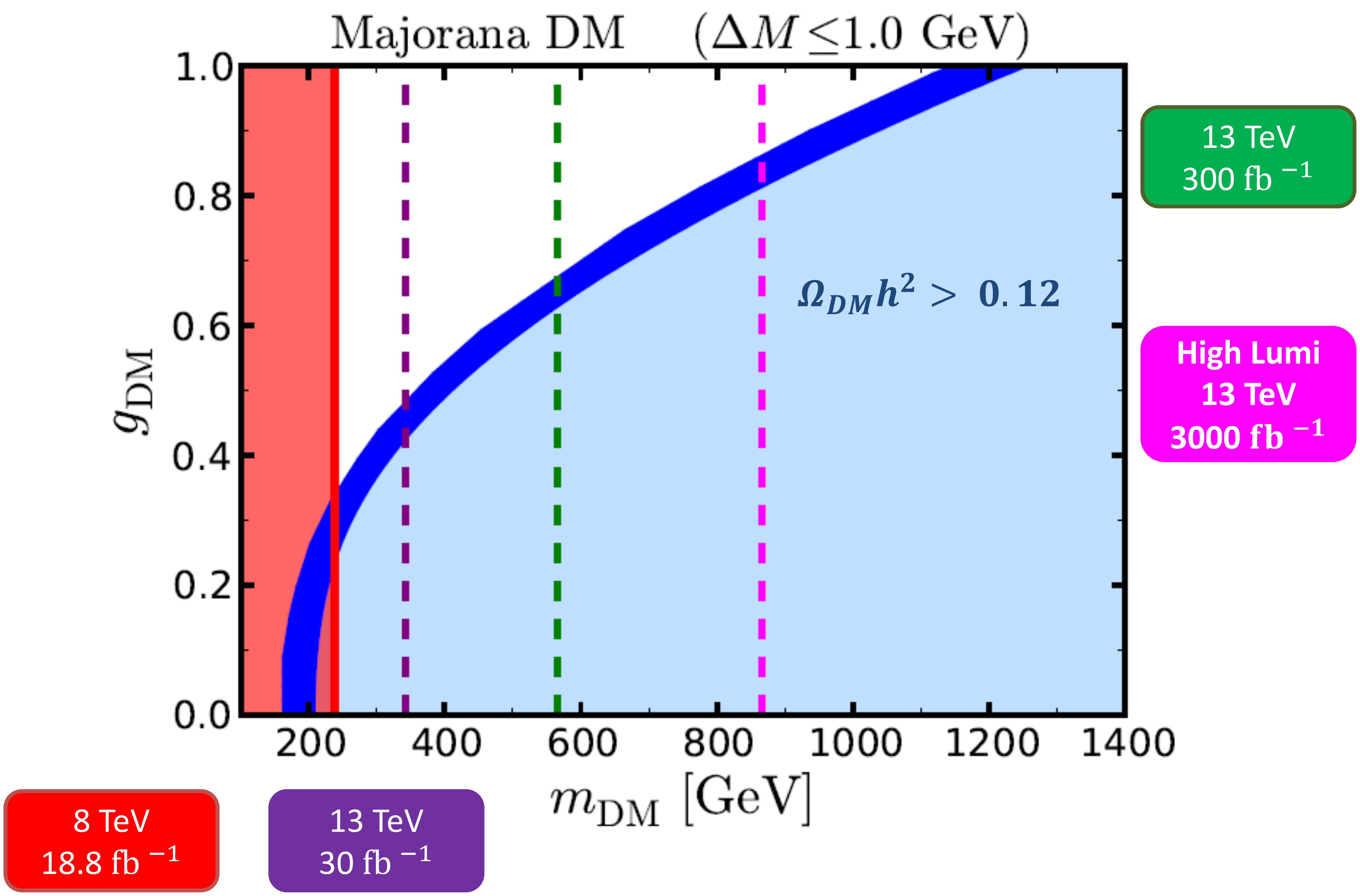






Model 1a

Now on the (gDM , mDM) plane:



Model 1b

Majorana Scalar

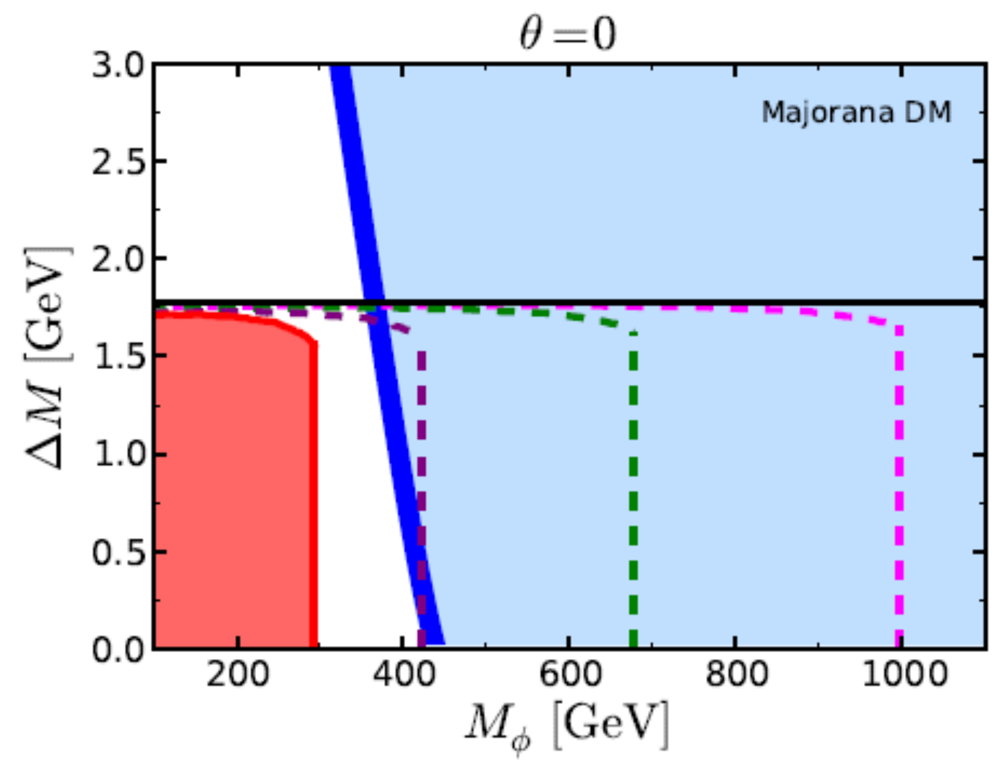
DM **CAP (Q=-1)**

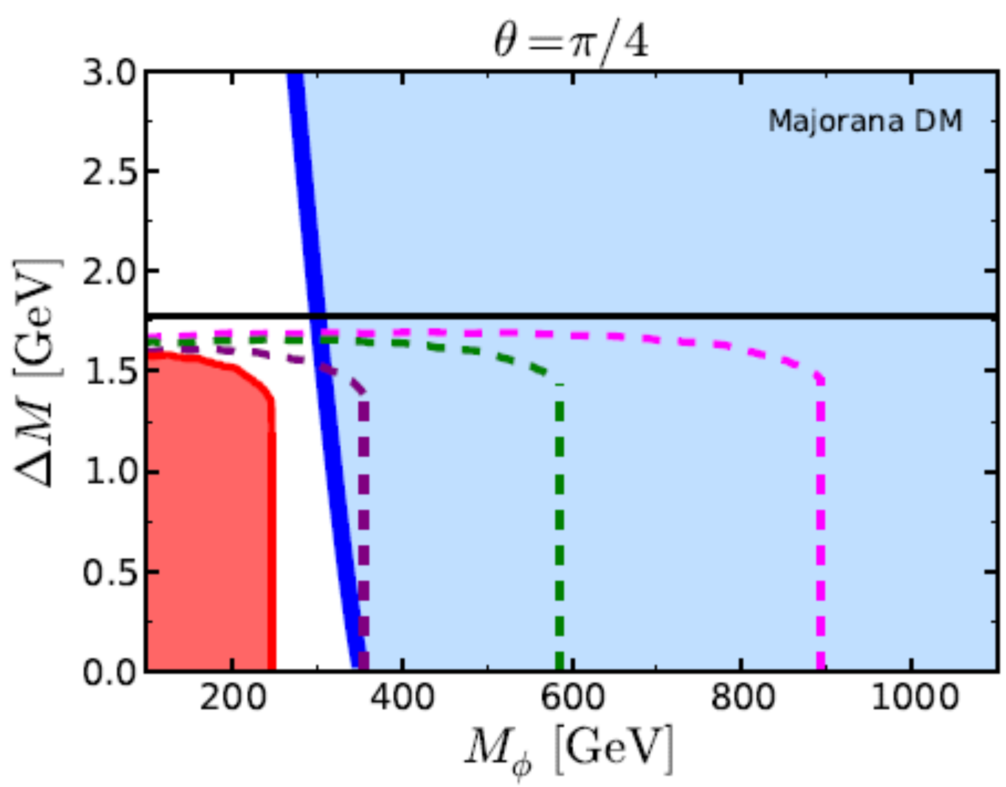
χ ϕ

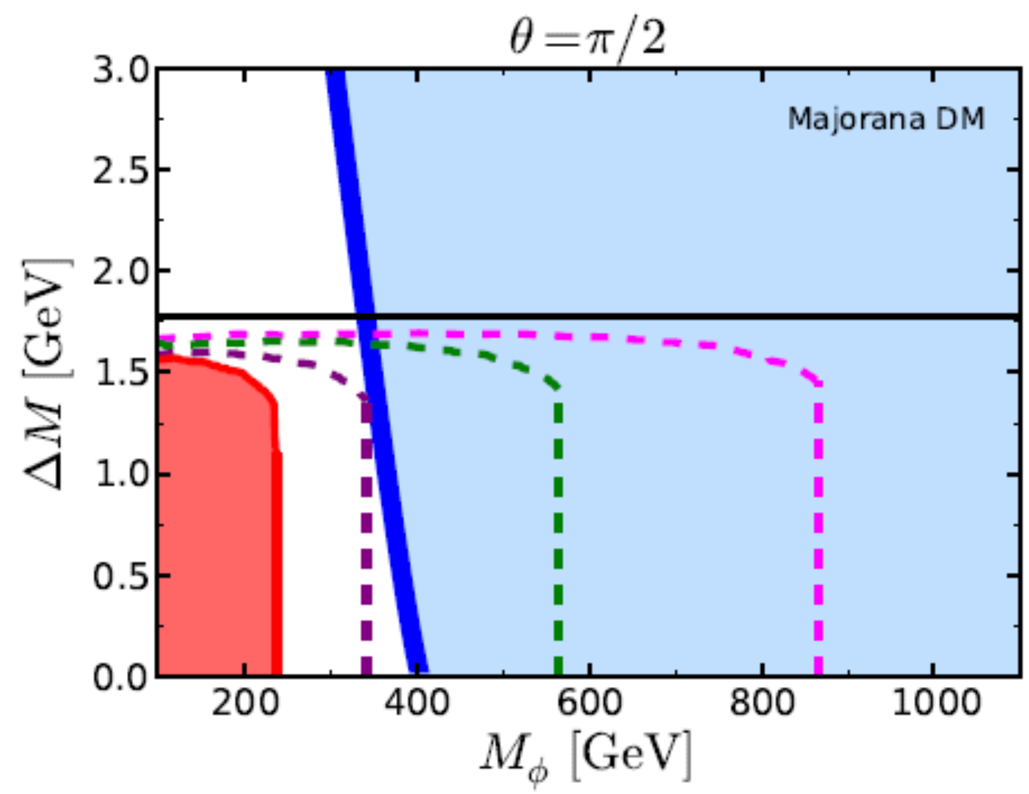
$$g_R\, \phi^* \,(\chi\, \tau_R) + g_L\, \phi^* \,(\chi\, \tau_L) \subset \mathcal{L}$$

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

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







Model 2

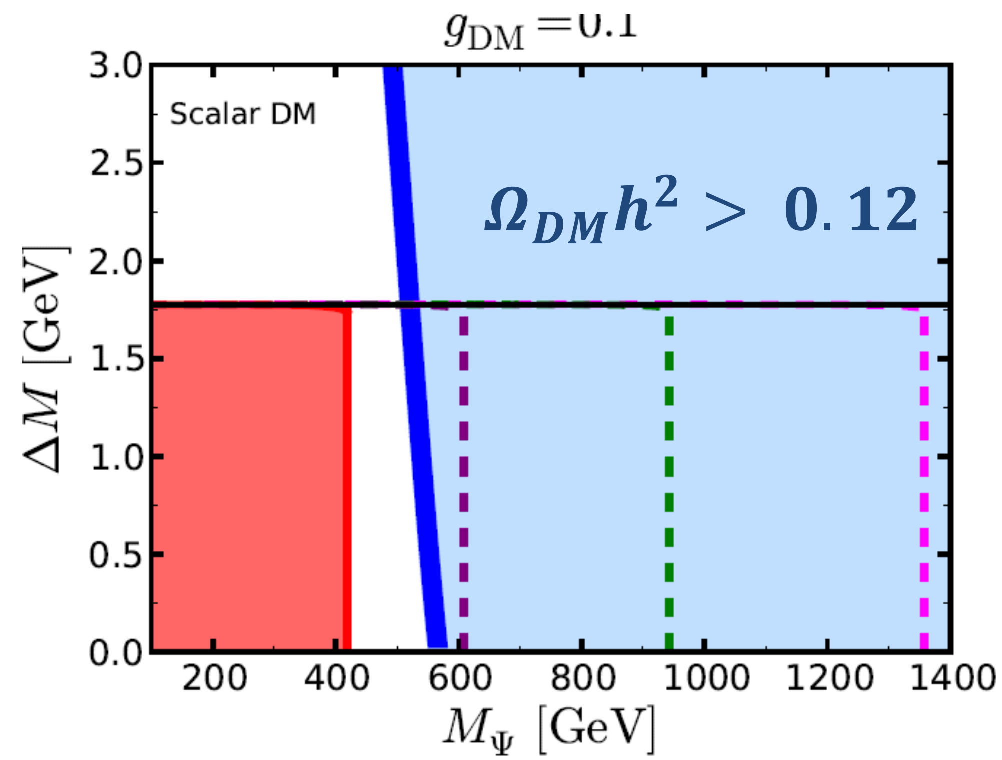
R Scalar   Dirac ferm

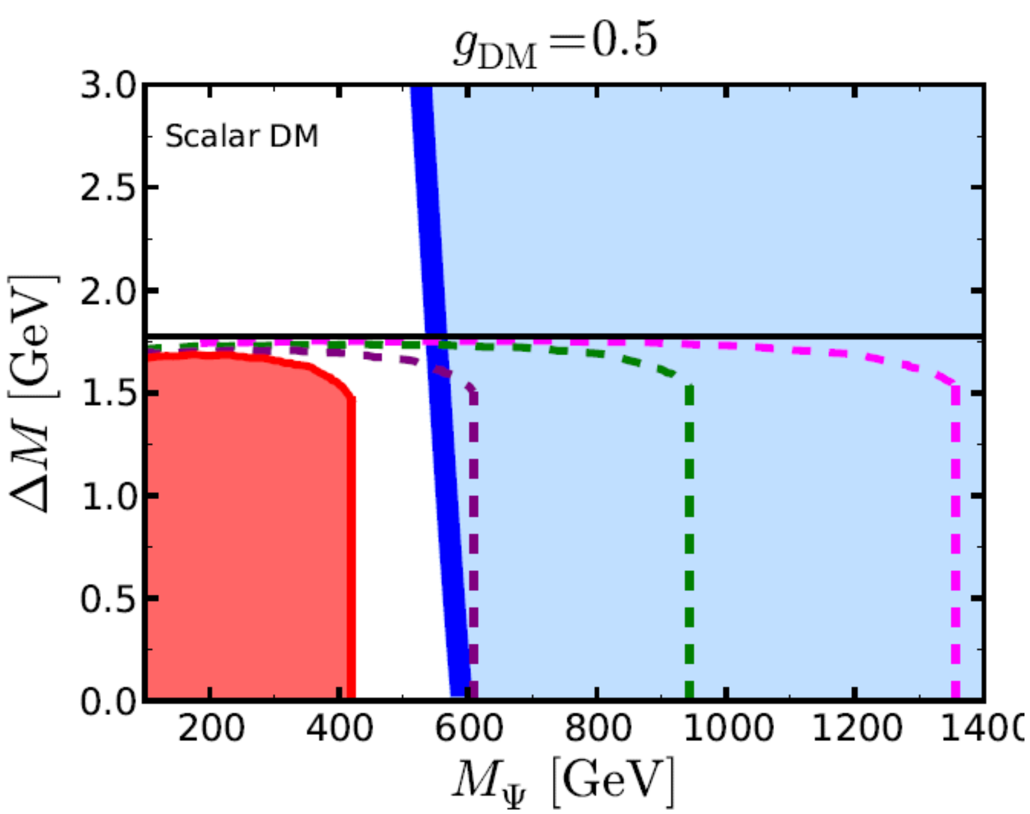
DM   **CAP** $(Y = 1 \;\; L_\tau = 1)$

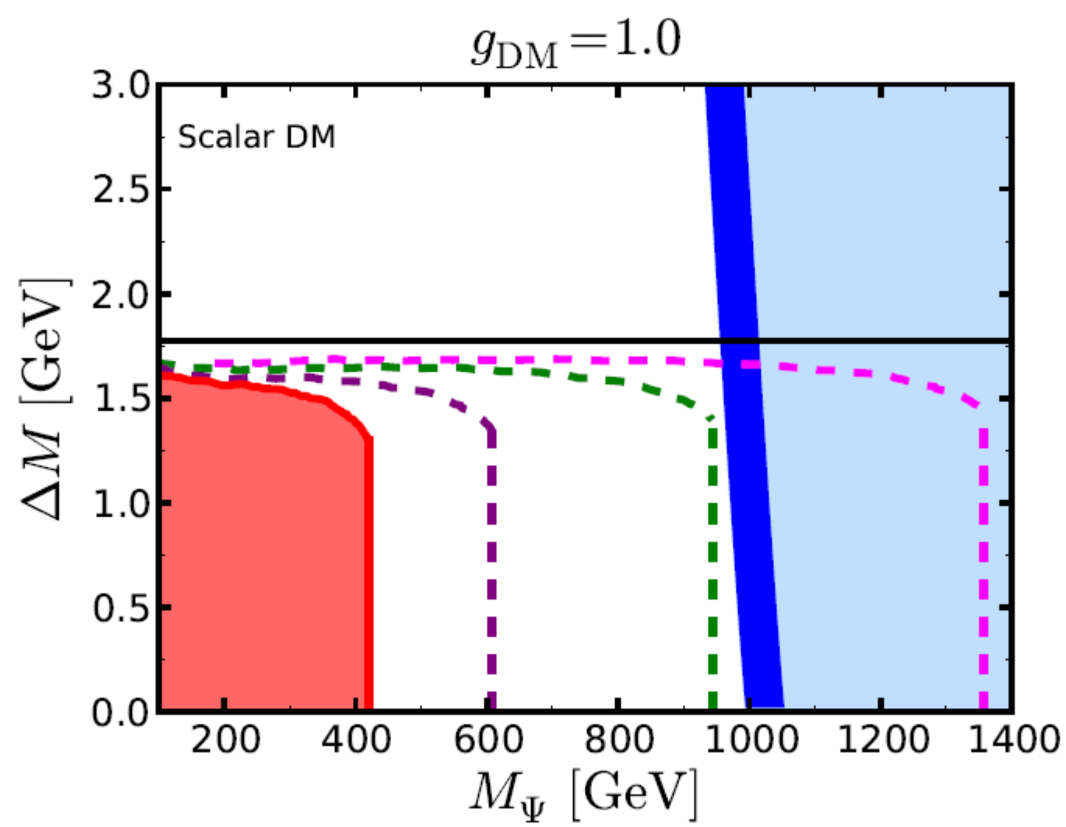
S Ψ

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

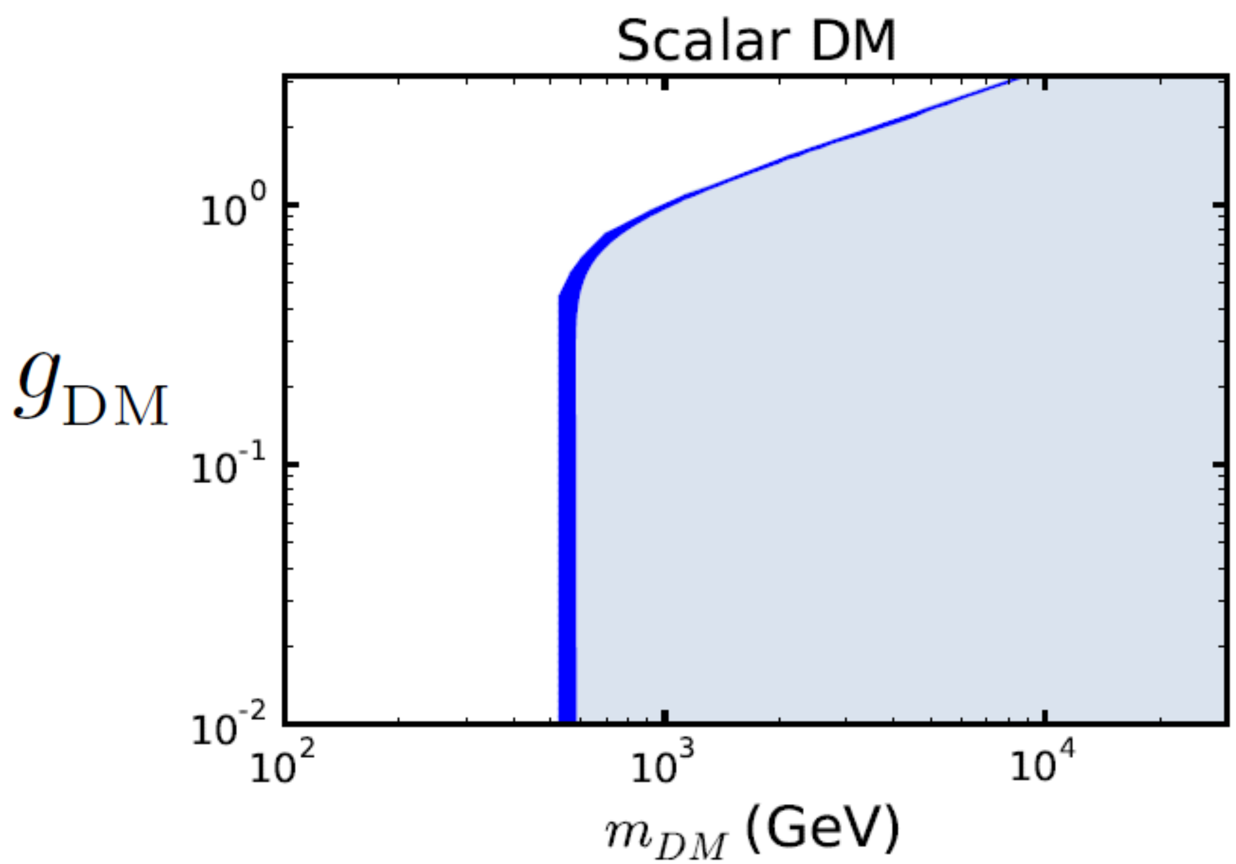
Gauge-invariant and renormalizable,
no problems of unitarity







Model 2

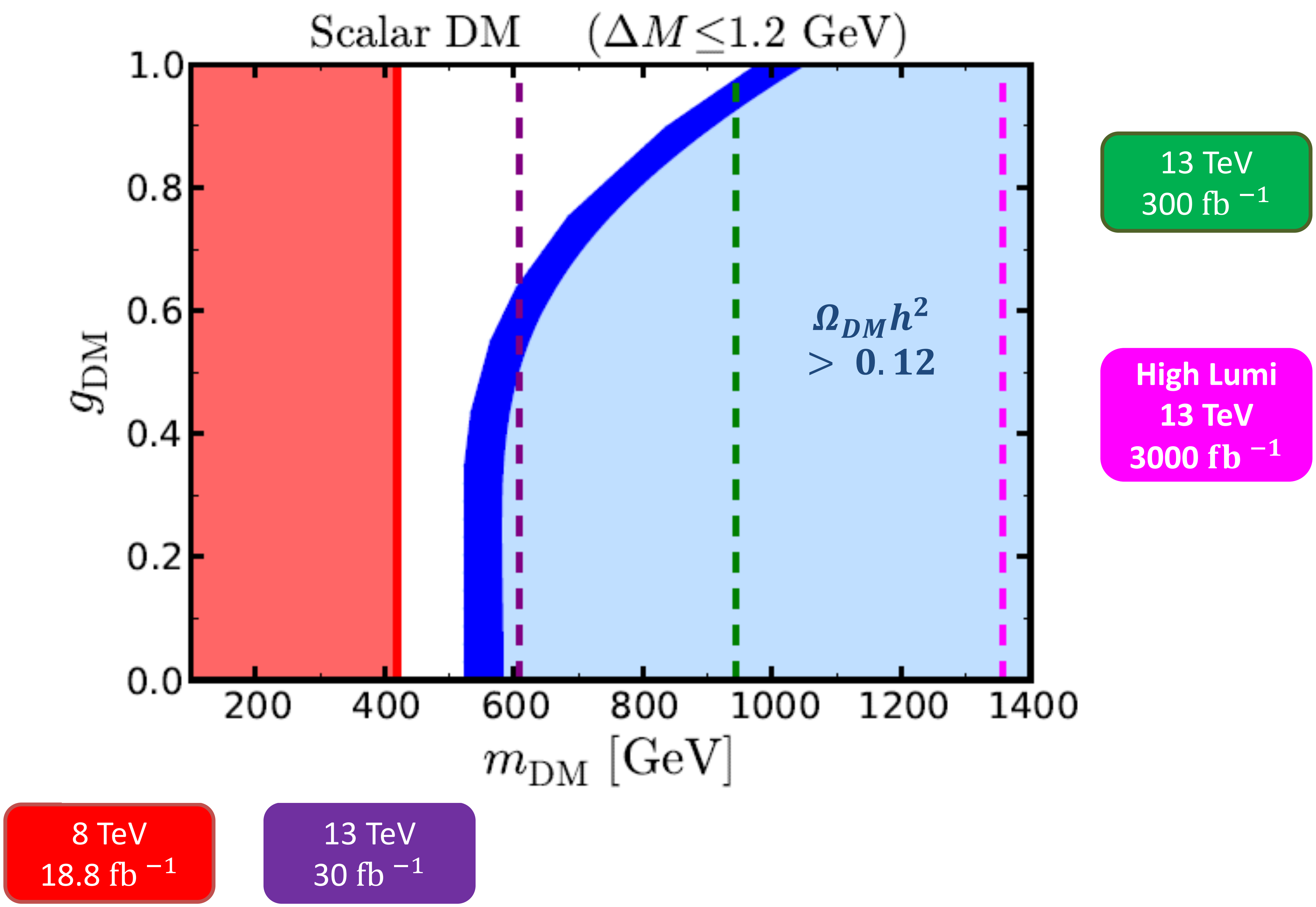


Intermediate region
$0.6 < g_{DM} < 0.8$
co-annihilations are relevant

$g_{\mathrm{DM}} \lesssim \mathbf{0.6}$ $\Psi\overline{\Psi}$ annihilation into SM final states is the dominant contribution to $\Omega_{DM}h^2$ — Independent of g_{DM}

$g_{\mathrm{DM}} \gtrsim \mathbf{0.8}$
$$\Psi\Psi \to \tau\tau$$
$$\Psi\overline{\Psi} \to \tau\overline{\tau}$$
Cross-section goes as $g_{DM}{}^4$

Model 2


Scalar DM ($\Delta M \leq 1.2$ GeV)
g_{DM}
0.0
0.2
0.4
0.6
0.8
1.0
200
400
600
800
1000
1200
1400
m_{DM} [GeV]
$\Omega_{DM}h^2$
> 0.12
13 TeV
300 fb $^{-1}$
High Lumi
13 TeV
3000 fb $^{-1}$
8 TeV
18.8 fb $^{-1}$
13 TeV
30 fb $^{-1}$

Model 3

Can be KK photon

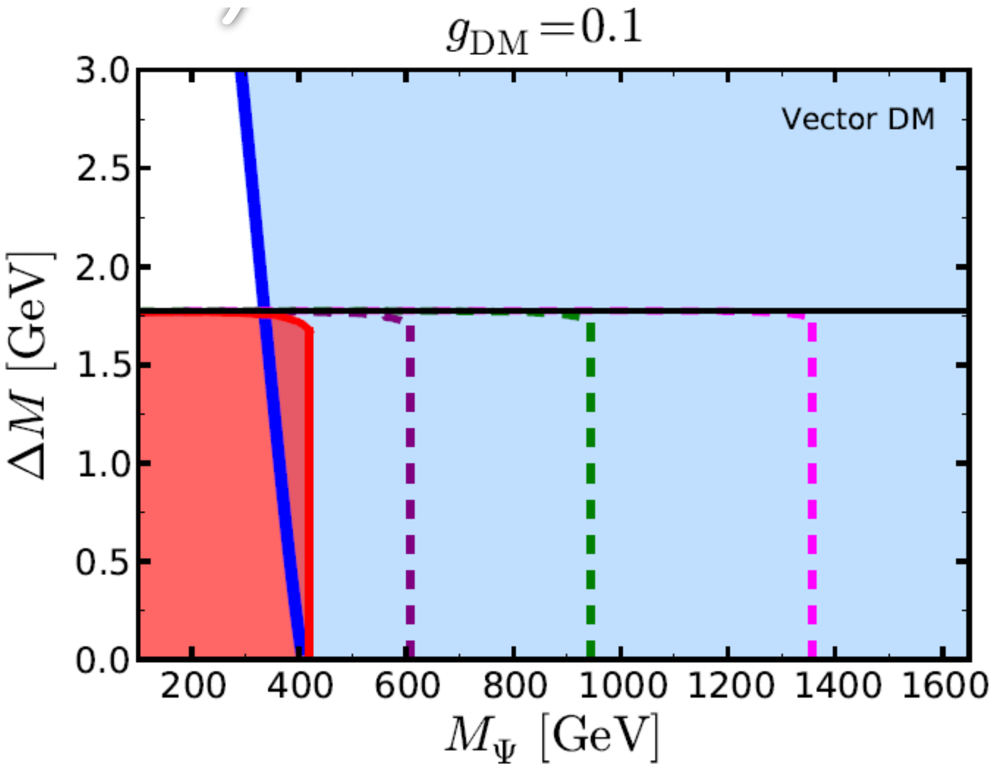
Vector Dirac ferm

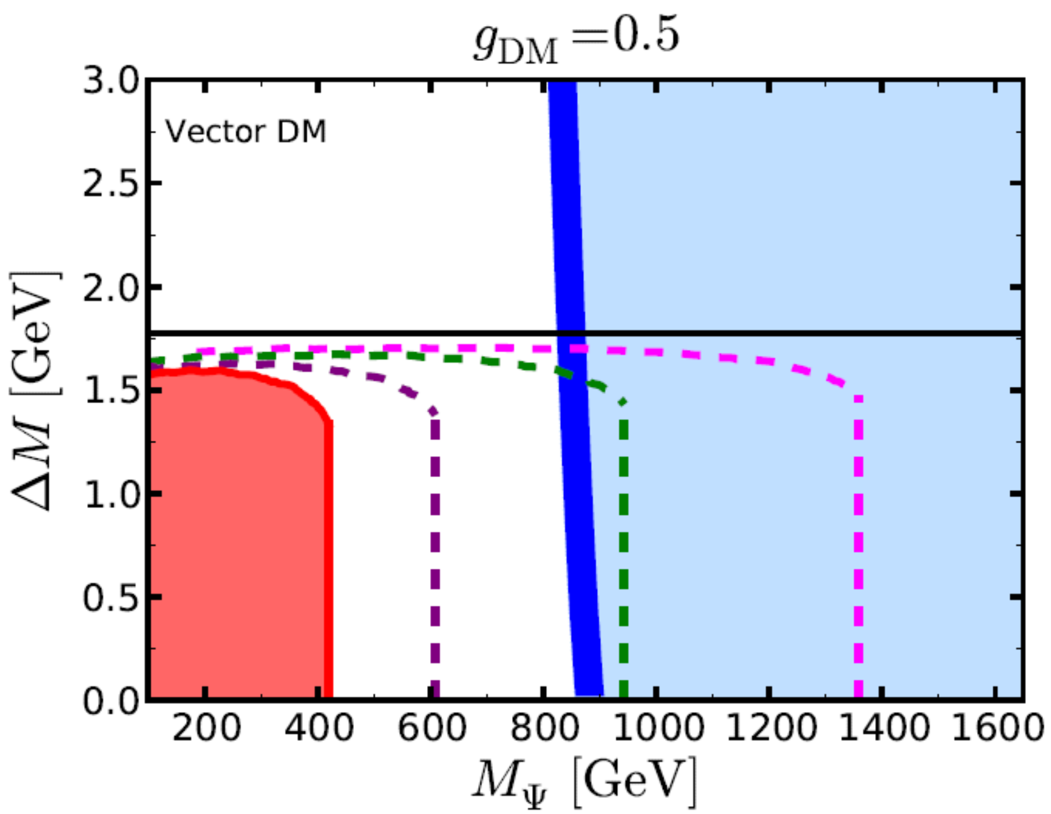
DM **CAP** $(Y = 1 \;\; L_\tau = 1)$

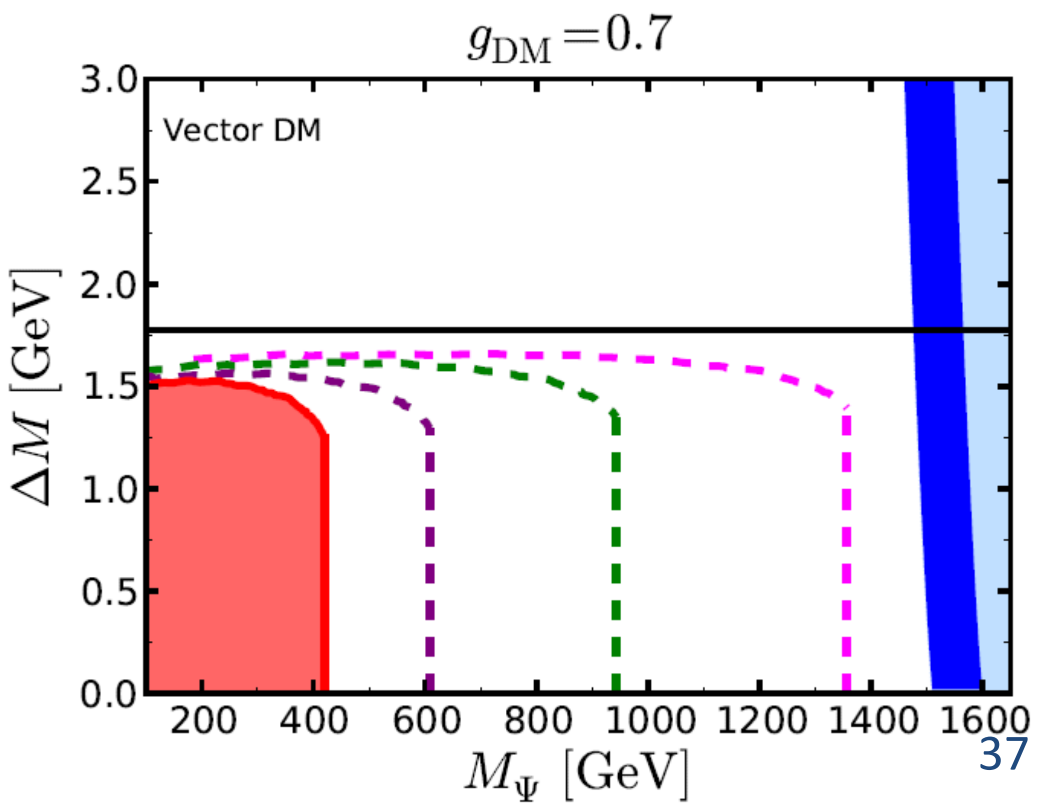
V_μ Ψ

$$V^\mu \, \overline{\Psi} \gamma_\mu P_R \, \tau \subset \mathcal{L}$$

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







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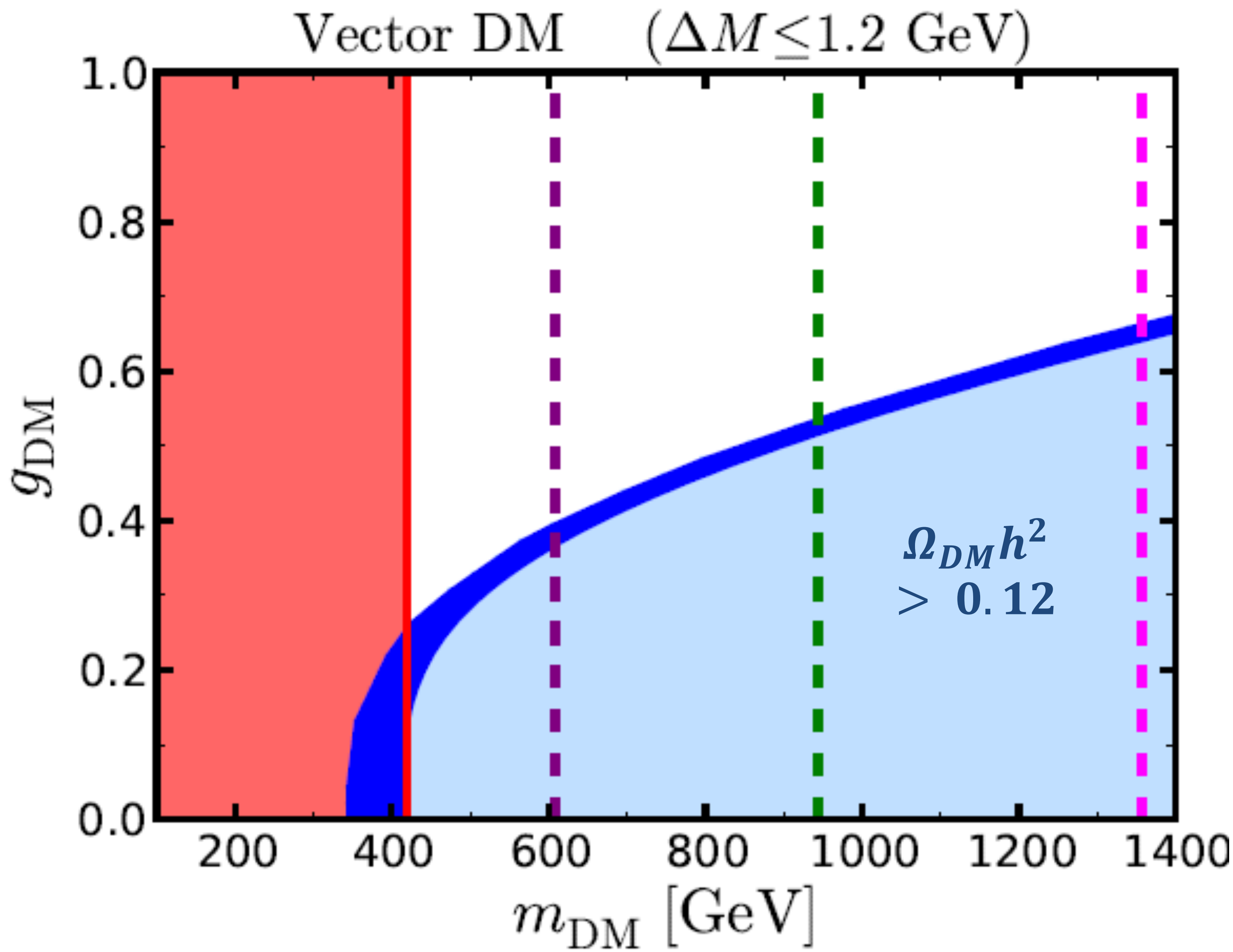
Model 3



13 TeV
300 fb $^{-1}$

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

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

Conclusions

- Presented a set of simplified models which are distinct from and complimentary to the standard mediator-based simplified DM models

  1a - Majorana DM & Complex scalar CAP: Gauge-invariant and renormalizable

  1b - Majorana DM L-R mixing & Complex scalar CAP: UV theory can include SUSY

  2 - Scalar DM & Dirac Fermion CAP: Gauge-invariant and renormalizable

  3 - Vector DM & Dirac Fermion CAP: UV theory can be a Kaluza-Klein model in extra dimensions

- The signal we study for collider searches is the pair-production of CAPs that then ultimately decay into cosmologically stable dark matter

- Collider strategy: long-lived charged particles; distinct from jets + MET

- Collider searches here are well ahead of DD (no tree-level ints. with quarks) and ID (velocity suppression)

- The only limitation for successful LHC searches is the requirement of ~1GeV compressed mass spectrum

- Co-annihilation partner plays an important role in lowering the relic density

- We presented a set of simplified models which are distinct from and complimentary to the standard mediator-based simplified DM models set:

Fermion DM

Model-1a			
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DM	Majorana fermion (χ)	$Y = 0$	$\phi^*(\chi\tau_R) + \text{h.c.}$
CAP	Complex scalar (ϕ)	$Y = -1$	

Model-1b			
Component	Field	Charge	Interaction (5.4)-(5.5)
DM	Majorana fermion (χ)	$Q = 0$	$\phi^*(\chi\tau_R) + \phi^*(\chi\tau_L) + \text{h.c.}$
CAP	Complex scalar (ϕ)	$Q = -1$	

Scalar DM

Model-2			
Component	Field	Charge	Interaction (5.6)
DM	Real scalar (S)	$Y = 0$	$S(\overline{\Psi}P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

Vector DM

Model-3			
Component	Field	Charge	Interaction (5.7)
DM	Vector (V_μ)	$Y = 0$	$V_\mu(\overline{\Psi}\gamma^\mu P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

- These simplified modes can be used by ATLAS & CMS to interpret searches for long-lived charged particles to explore the new range of DM scenarios

Back-up slides

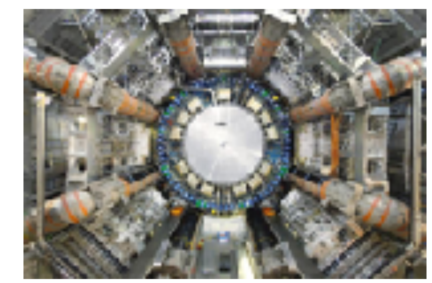
To draw simple collider reach projections (used above) for higher Energy and Luminosity:

- For a given theory model, e.g. Model 1a, compute the signal cross-section as a function of mDM (for a given Energy)
- Plot the predicted number of events = L x cross-section
- Plot the experimental exclusion curve = max number of allowed events (at a given confidence level) as a function of mDM
- The intersection of the theory and experimental excl. curves at mDM* gives the excluded region mDM < mDM*
- Assume that the experimental exclusion curve [excluded number of events] remains the same at higher E and higher L
- Theory curve is recomputed and the new bound found mDM < mDM*(E,L)

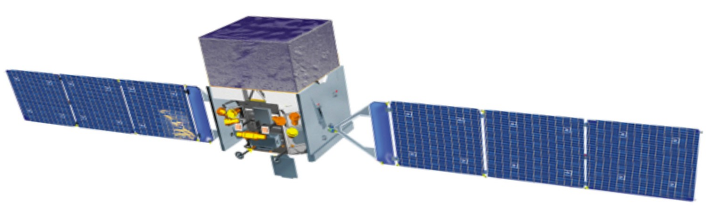
…this follows the `Collider Reach' philosophy…

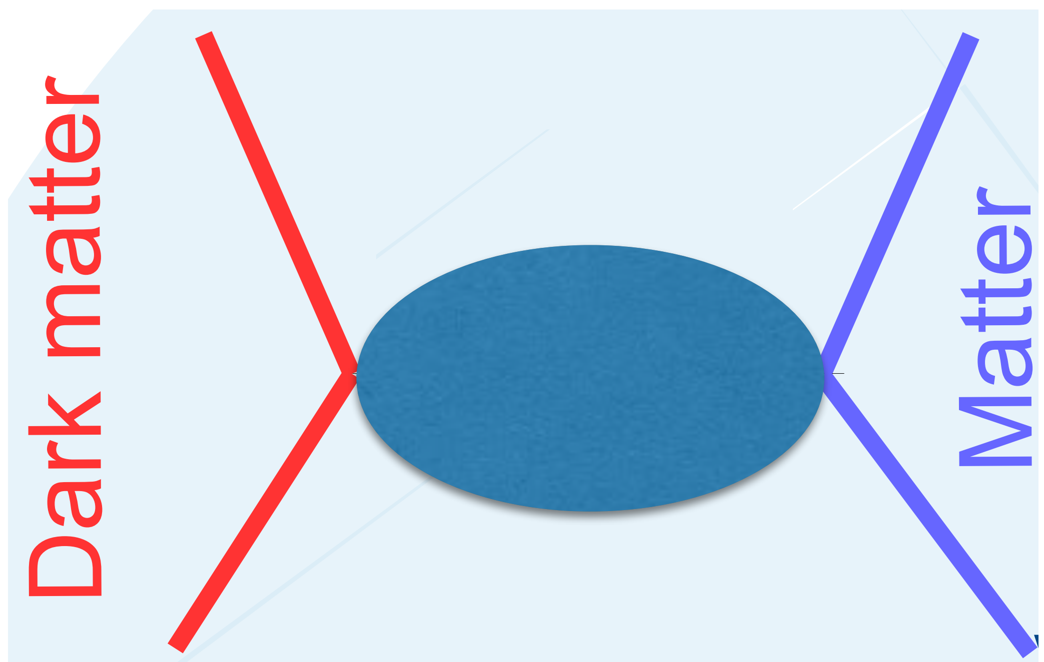
The same 2-to-2 cartoon involving DM and SM particles describes the DD, ID and Collider searches (only the initial state varies).

[One has to be extra careful with drawing conclusions from this in abridged theories - Simplified Models. The choice of the Dark sec & the SM particles involved in the dominant process in each case can be completely different.]



ID





Colliders

DD