# COMPOSITE DARK MATTER AT COLLIDERS

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☞ Thanks to A. Mitridate, A. Podo, F. Revello for making many of the plots of this talk

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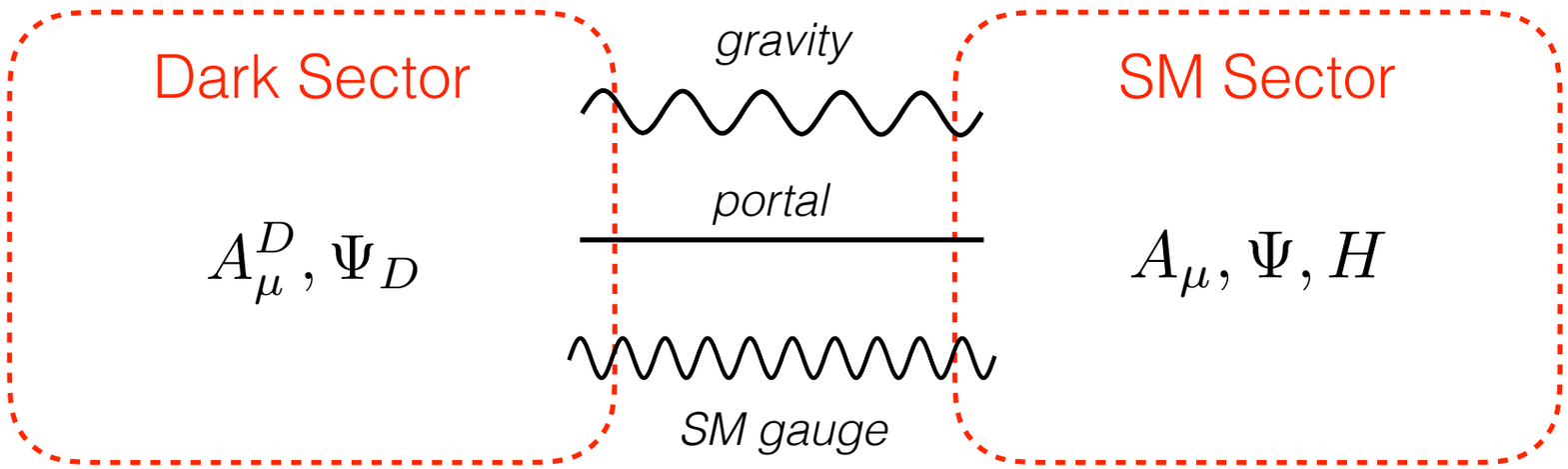
# Accidental Composite Dark Matter




- Postulate a ‘dark’ sector with new strongly-coupled gauge dynamics

- Dark matter candidate is a bound state stable on cosmological scales due to some accidental symmetry

☞ Analogy: *proton stable due to accidental baryon number*

# Types of accidental composite DM candidates

| Type | Accidental Symmetry | Breaking |
|---|---|---|
| Dark Baryons | dark baryon number $U(1)_{DB}$ | dim-6<br>(ex: $\psi\psi\psi\psi_{SM}$ for $N_{DC}$=3) |
| Dark Mesons<br>(pions, quarkonia) | species number $U(1)_i$<br>G-parity | dim-4 (Yukawas, hypercharge)<br>dim-5 ( $\bar{\psi}\psi HH$, $\bar{\psi}\sigma^{\mu\nu}\psi B_{\mu\nu}$) |
| Gluequarks<br>( $Qg$ bound states in theories with adjoint dark quarks) | $Z_2$ dark parity | dim-6 |
| $\vdots$ | | |

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See for example: Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039
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See: R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187

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# Vector-like theories

Dark fermions transform as vector-like representations under both $G_{DC}$ and $G_{DC} \times G_{SM}$

- mass terms allowed by gauge invariance
- dark condensate aligns in a $G_{SM}$-preserving direction

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Example #1

[ Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039 ]

| | $SU(N_{DC})$ | $SU(2)_{EW}$ | $U(1)_Y$ |
|---|---|---|---|
| $L$ | $\square$ | $2$ | $-1/2$ |
| $N$ | $\square$ | $1$ | $0$ |
| $L^c$ | $\bar{\square}$ | $\bar{2}$ | $+1/2$ |
| $N^c$ | $\bar{\square}$ | $1$ | $0$ |

$$\mathcal{L} = -\frac{1}{4g_{DC}^2} G_{\mu\nu}^2 + \bar{L}(i\not{D} - M_L)L + \bar{N}(i\not{\partial} - M_N)N + y\bar{N}LH + h.c.$$

Accidental symmetry: dark baryon number

DM candidate (ex for $N_{DC}=3$): $NNN$ baryon (spin 3/2) = $1_0$ of $G_{SM}$

# Vector-like theories

Dark fermions transform as vector-like representations under both $G_{DC}$ and $G_{DC} \times G_{SM}$

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Example #2

[ R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187 ]

| | $SU(N_{DC})$ | $SU(2)_{EW}$ | $U(1)_Y$ |
|---|---|---|---|
| $V$ | $adj$ | $3$ | $0$ |

$$\mathcal{L} = -\frac{1}{4g_{DC}^2} G_{\mu\nu}^2 + V^\dagger i\bar{\sigma}^\mu D_\mu V - \frac{M_V}{2}(VV + V^\dagger V^\dagger)$$

Accidental symmetry: dark parity ( $V \to -V$ )

DM candidate: (neutral component of) gluequark $Vg$ = $3_0$ of $G_{SM}$

# Chiral theories

Dark fermions transform as chiral representations under $G_{DC} \times G_D \times G_{SM}$

- no mass term allowed by gauge invariance
- representations vector-like under $G_{SM}$: condensate preserves $G_{SM}$
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Example [ Harigaya, Nomura PRD 94 (2016) 035013; R.C., Podo, Revello work in progress ]

| | $SU(N_{DC})$ | $U(1)_D$ | $SU(2)_{EW}$ | $U(1)_{3V}$ | $U(1)_V$ |
|---|---|---|---|---|---|
| $\psi_1$ | $\square$ | $+1$ | $\square$ | $+1$ | $+1$ |
| $\psi_2$ | $\square$ | $-1$ | $\square$ | $-1$ | $+1$ |
| $\chi_1$ | $\bar{\square}$ | $-a$ | $\bar{\square}$ | $-1$ | $-1$ |
| $\chi_2$ | $\bar{\square}$ | $+a$ | $\bar{\square}$ | $+1$ | $-1$ |

Free parameters:

dark dynamical scale: $\Lambda_D$

dark coupling: $e_D$

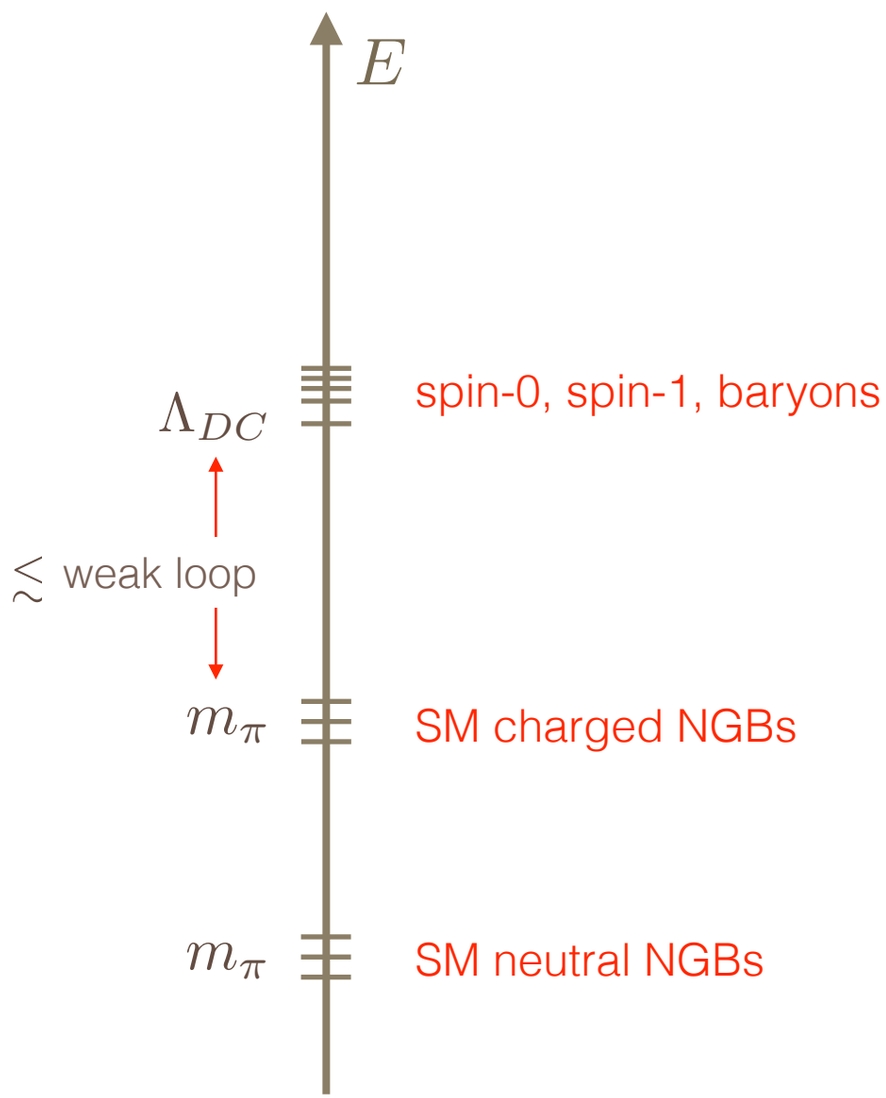
dark charge: $a$

hypercharge-dark photon mixing: $\varepsilon$

Accidental symmetries: $U(1)_{3V} \times U(1)_V$

DM candidates: i) dark pions $\pi^{\pm} \sim (\psi_1 \chi_2), (\psi_2 \chi_1)$ ii) lightest dark baryon

# Light quark regime $(m_\psi \ll \Lambda_{DC})$ - for vectorlike and chiral theories



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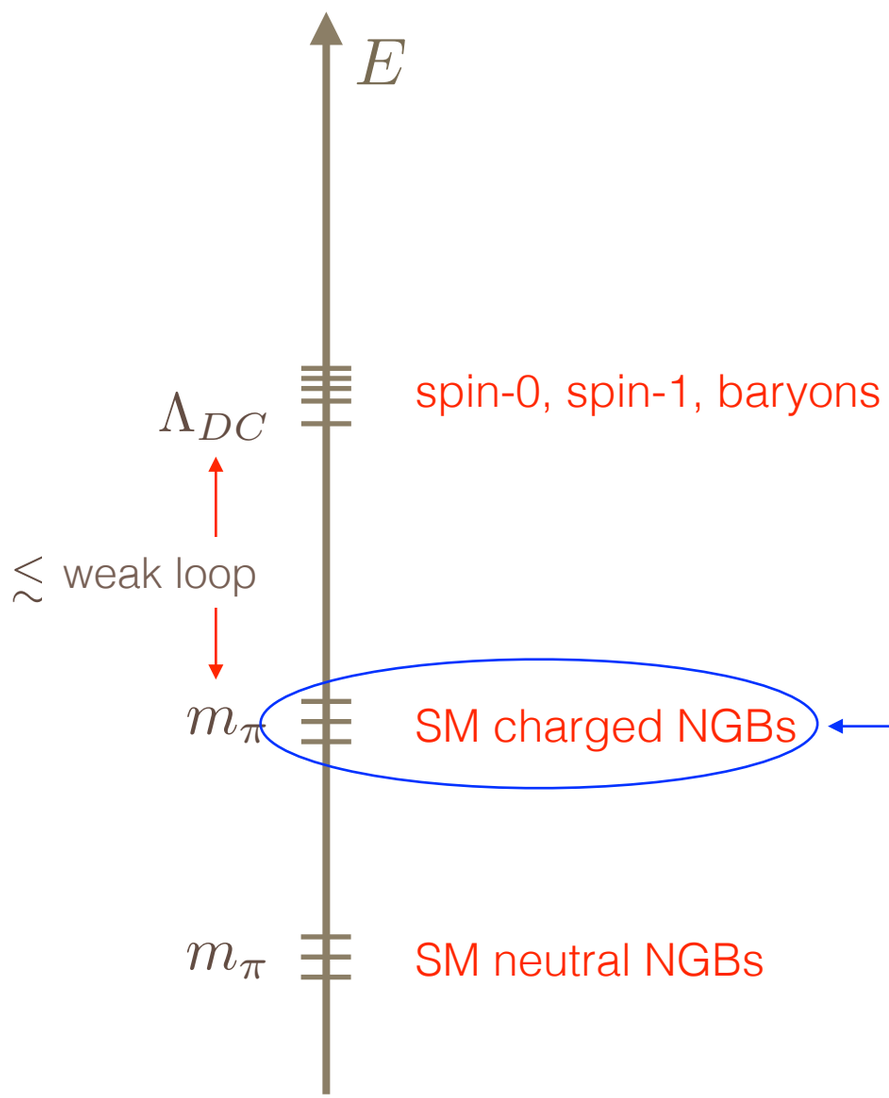



Dark pions charged under the SM

$$m_\pi^2 \sim \frac{g^2}{16\pi^2}\Lambda_{DC}^2 + m_\psi \Lambda_{DC}$$

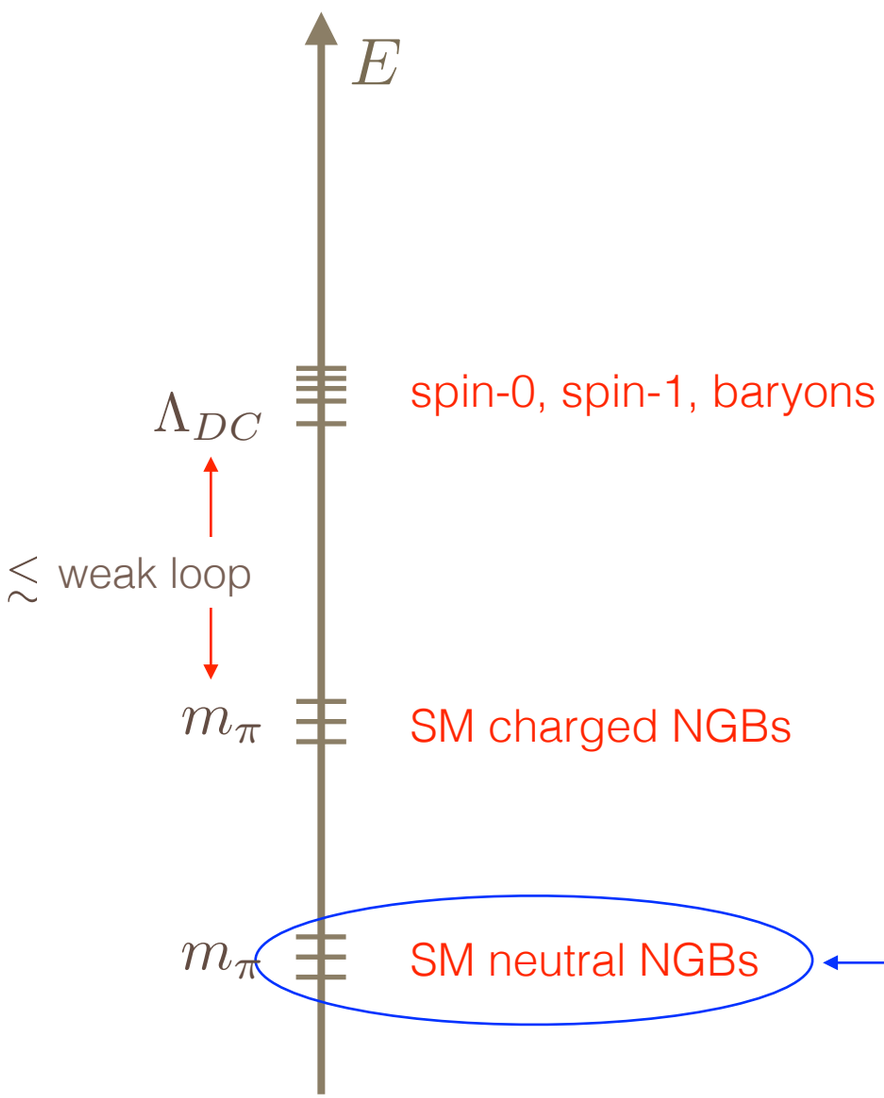
- pair produced via Drell-Yan

$$pp \to V \to \pi\pi \qquad (V = W, Z, \gamma)$$

- decay through anomalous/1-loop couplings or Yukawa couplings

$$\pi \to VV$$
$$\pi \to \pi' V \,/\, \pi' H \qquad (H = W_L, Z_L, h)$$

# Light quark regime $(m_\psi \ll \Lambda_{DC})$ - for vectorlike and chiral theories

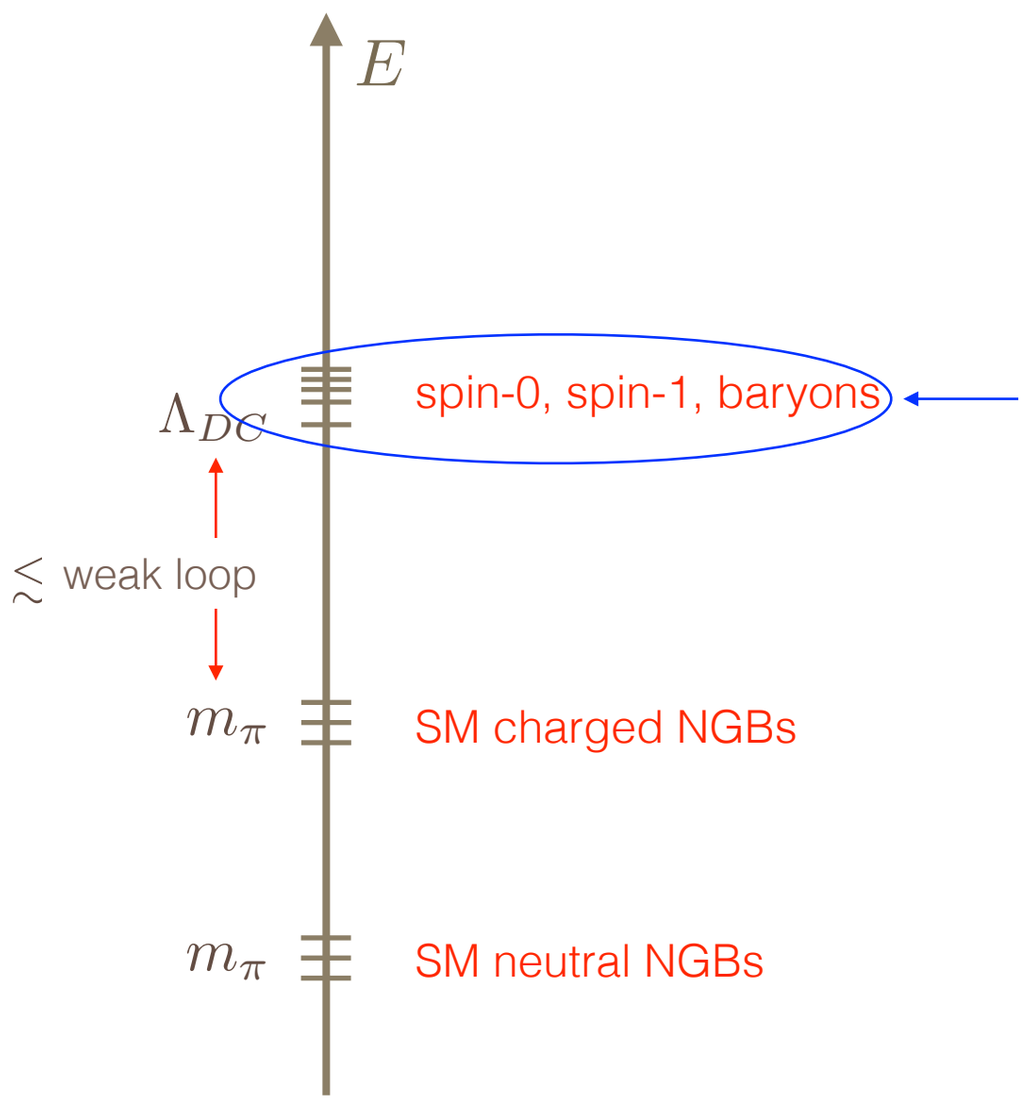



Dark pions neutral under the SM

$$m_\pi^2 \sim m_\psi \Lambda_{DC}$$

- singly produced via VBF, in association with a SM vector boson or from decays of heavier NGBs
- decay to $VV$ through anomalous couplings

# Light quark regime $(m_\psi \ll \Lambda_{DC})$ - for vectorlike and chiral theories




spin-1 resonances

- singly produced via Drell-Yan
- decay mostly to pairs of NGBs if kinematically allowed, decays to SM fermions parametrically suppressed

$$\Gamma(\rho \to \pi\pi) \sim \frac{g_\rho^2}{8\pi} m_\rho$$

$$\Gamma(\rho \to f\bar{f}) \sim \frac{1}{8\pi} \frac{g_{SM}^4}{g_\rho^2} m_\rho$$

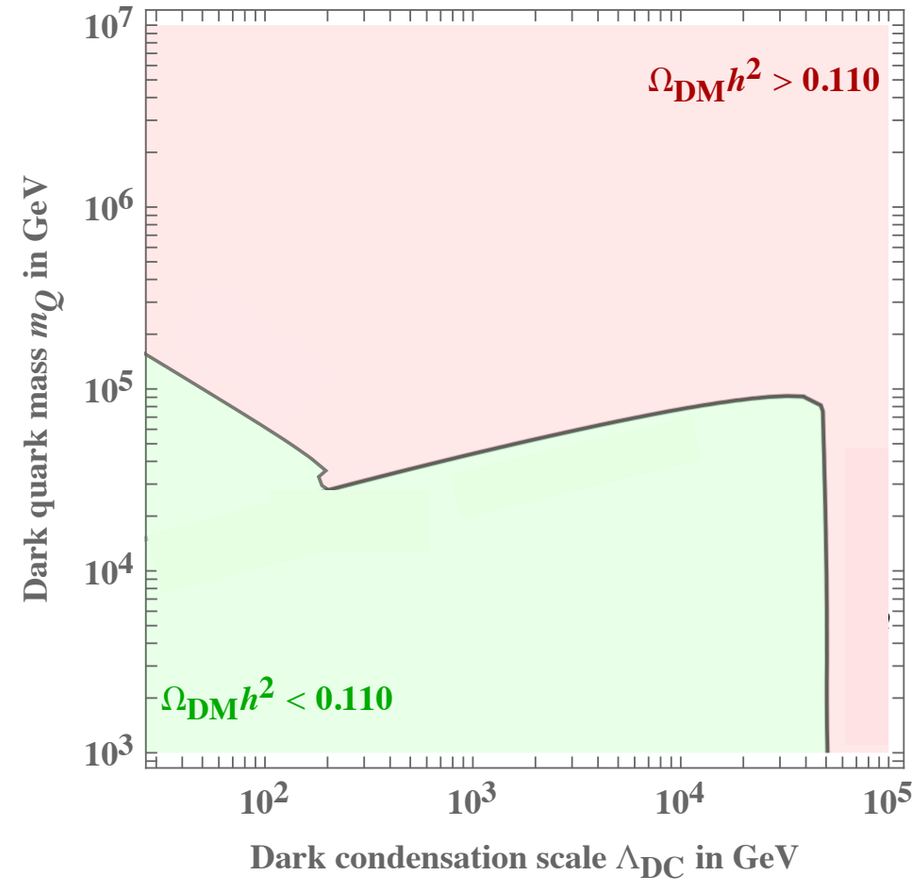
- <u>Benchmark</u>: L+N vectorlike model

$$SU(3)_L \times SU(3)_R \to SU(3)_V$$

$$8 \text{ NGBs} = 1_0(\eta) \oplus 2_\pm(K) \oplus 3_0(\pi)$$

$$\text{under } SU(2)_{EW} \times U(1)_Y$$

$$\frac{g}{4\pi}\Lambda_{DC} \lesssim m_\pi < \Lambda_{DC}$$



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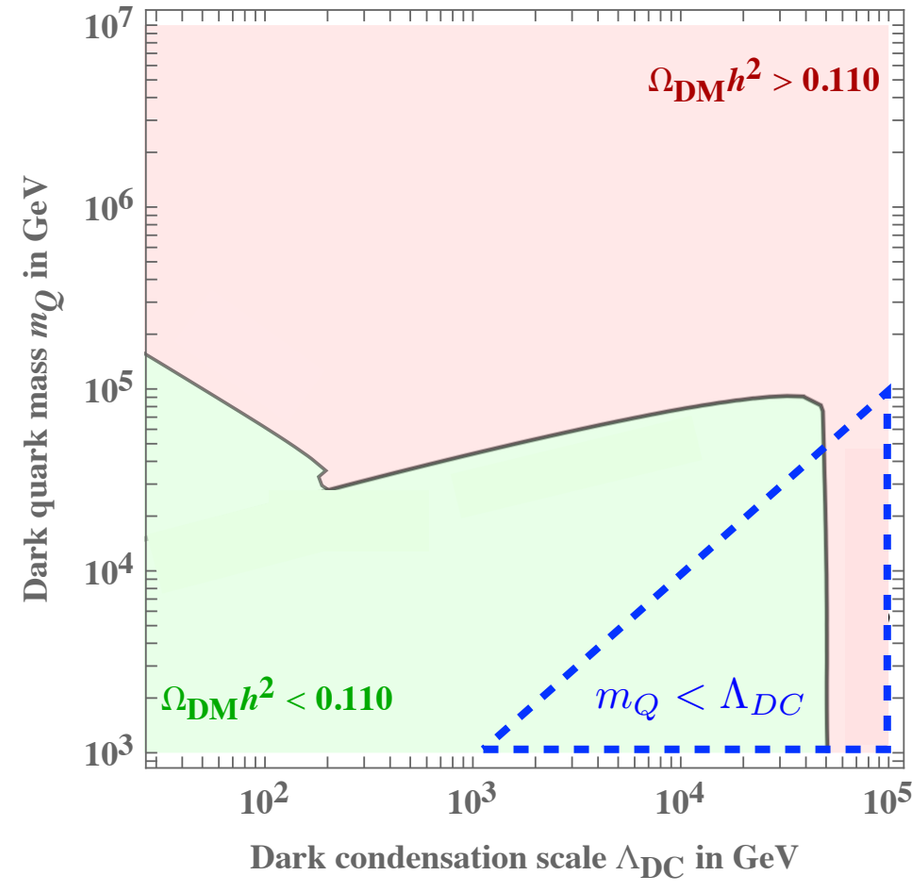

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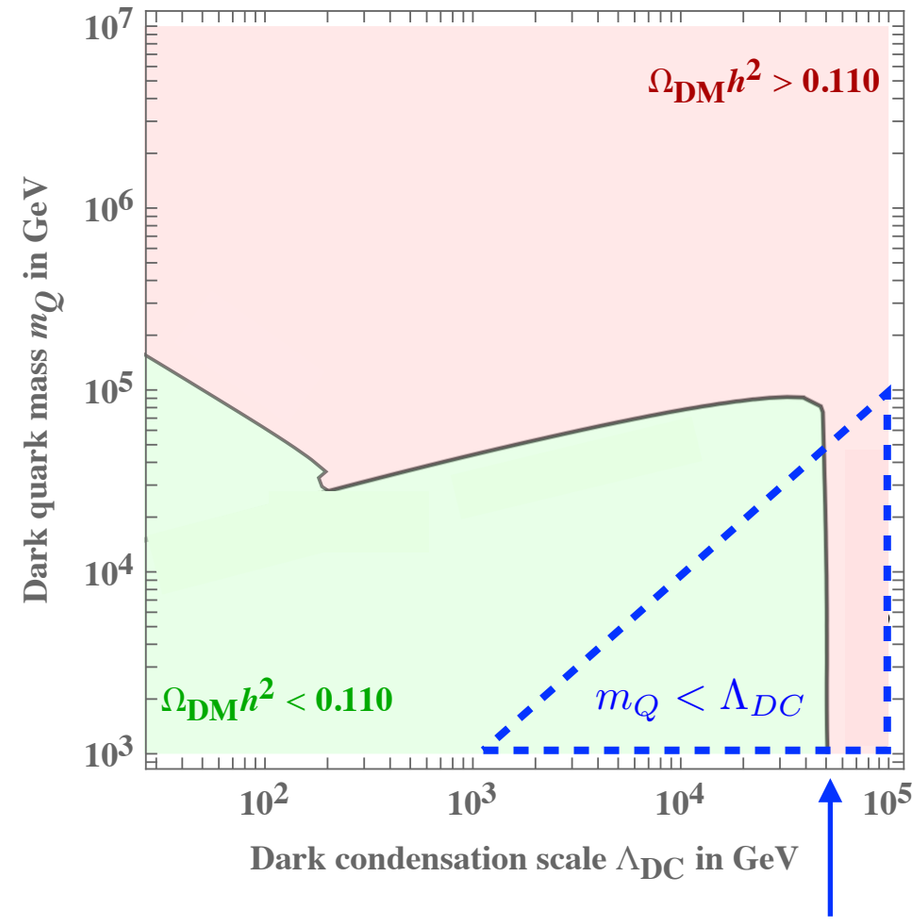


$\Lambda_{DC} \simeq 50\,\text{TeV}$

for thermal DM

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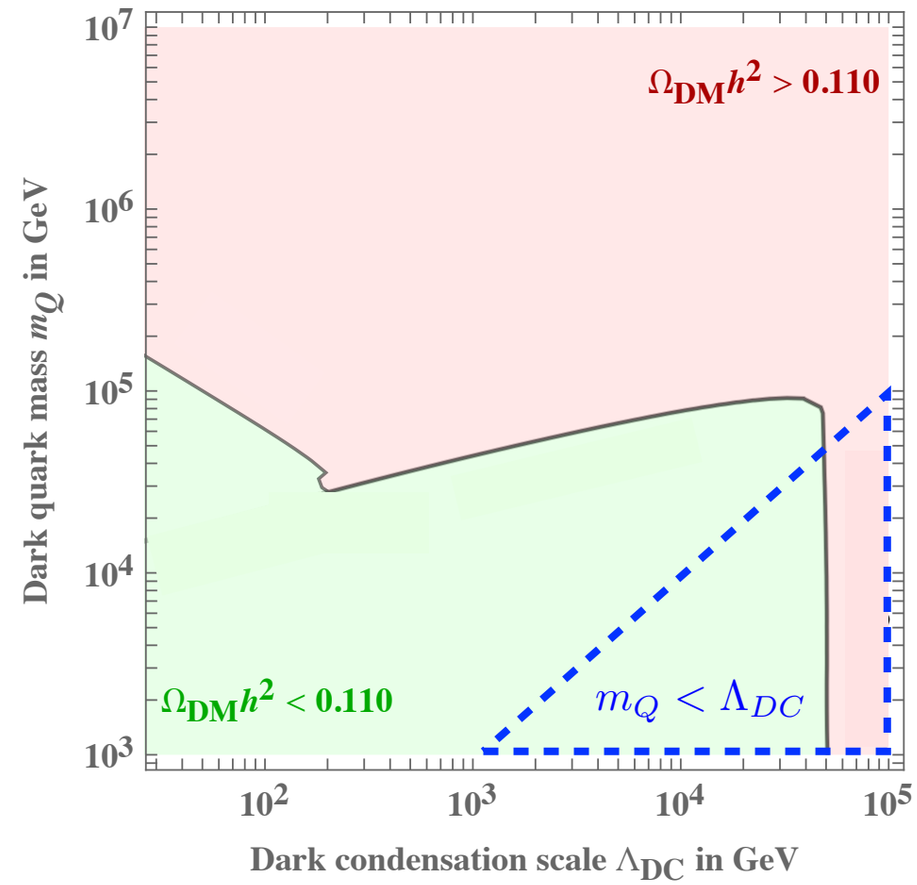
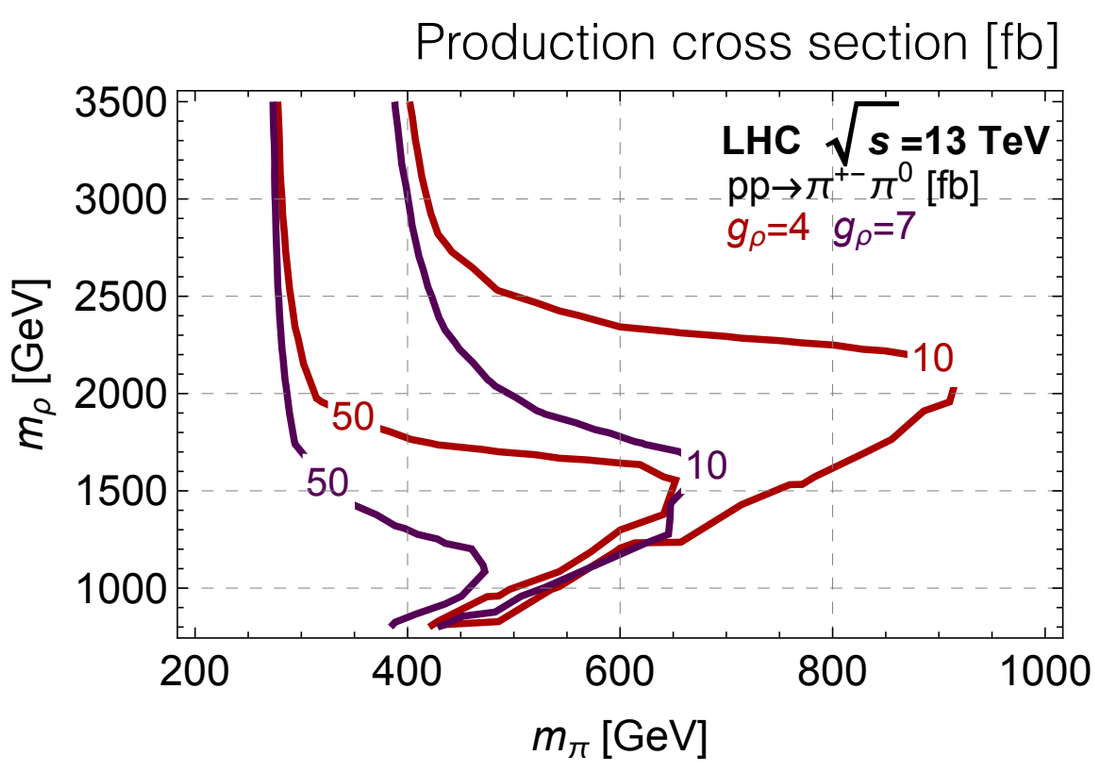
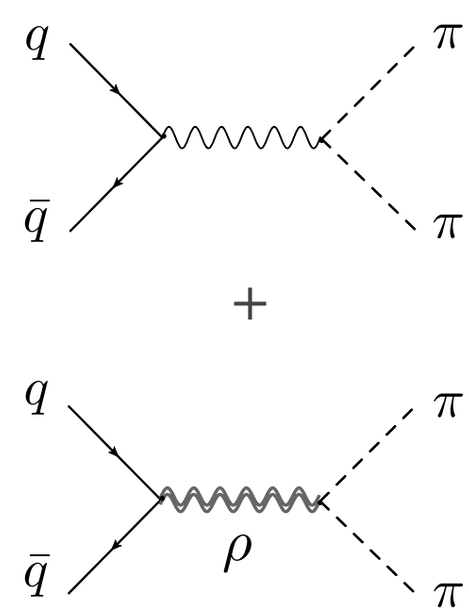



Reach on triplets at the LHC

[ from: Barducci et al. JHEP 1808 (2018) 017 ]



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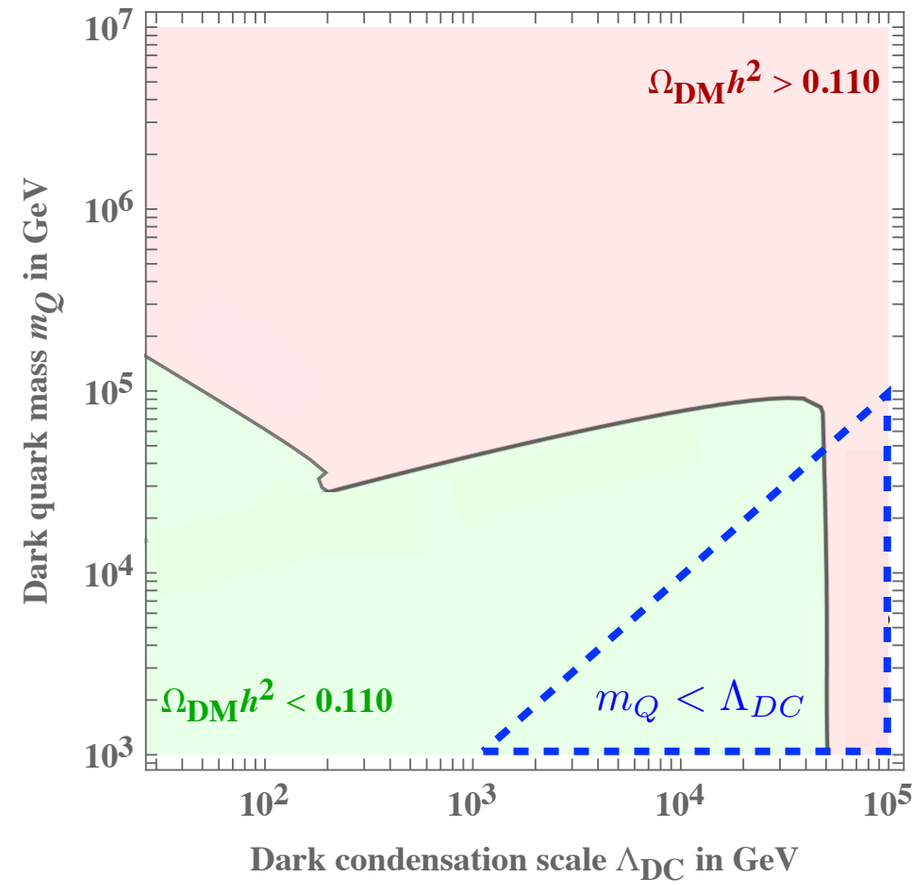


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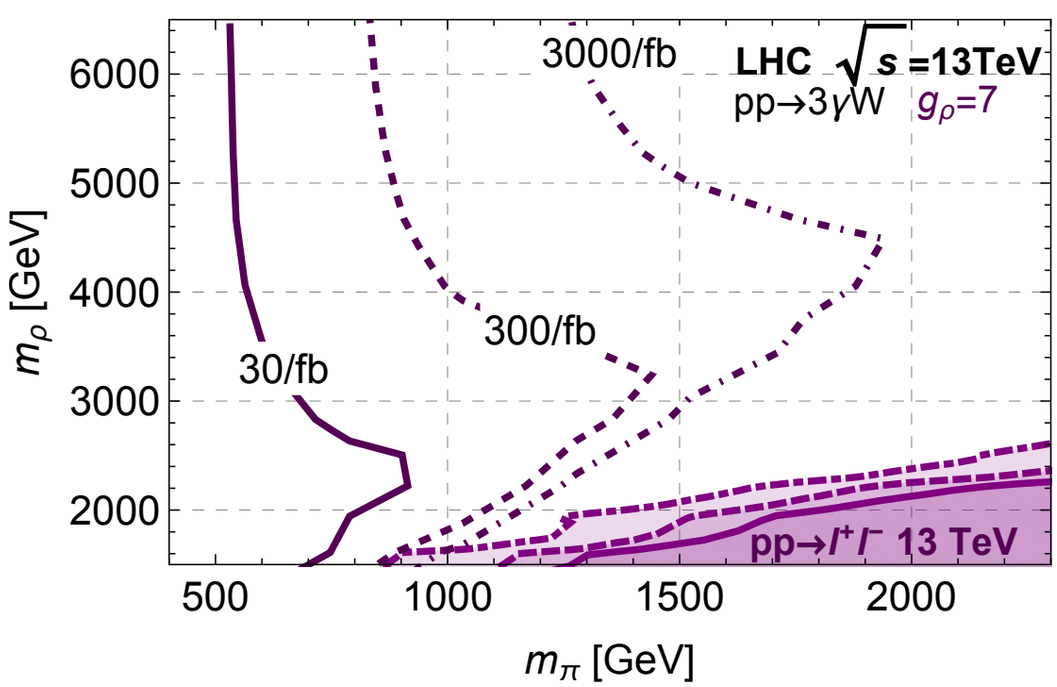
Estimated 95% exclusion from $3\gamma W$ final state




$$pp \to \pi^\pm \pi^0$$
$$\pi^0 \to \gamma\gamma$$
$$\pi^\pm \to W^\pm \gamma$$

- <u>Benchmark</u>: chiral model

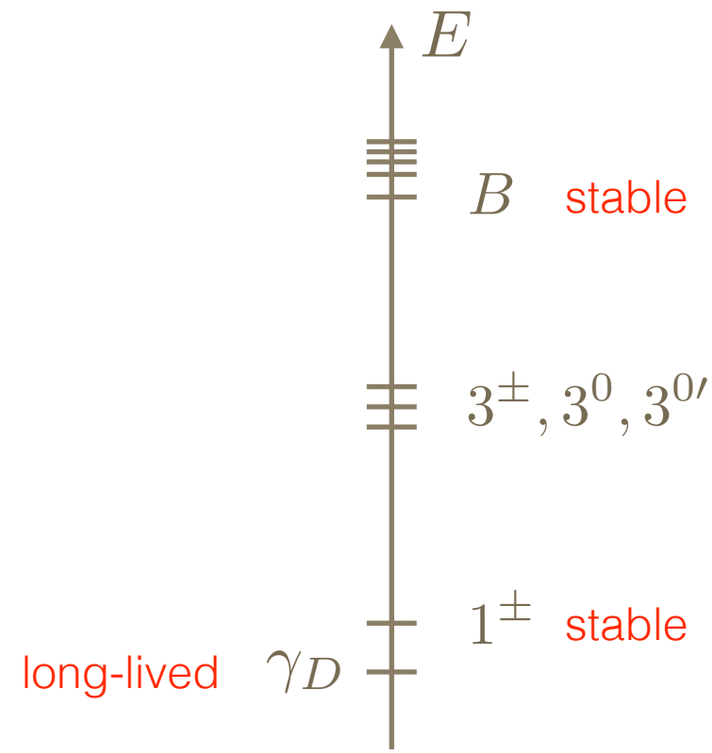
[ R.C., Podo, Revello work in progress ]

$$SU(4)_L \times SU(4)_R \to SU(4)_V$$

15 NGBs = $3^{\pm}$, $3^0$, $3^{0\prime}$, $1^{\pm}$, $1^0$

eaten by dark photon

stable (DM candidate)



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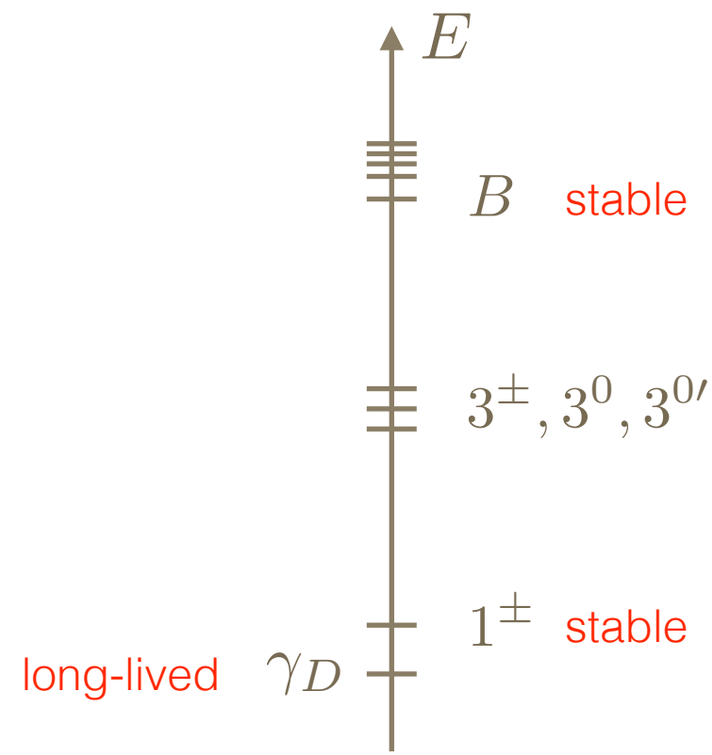


Reach on triplets at LHC and FCC-hh

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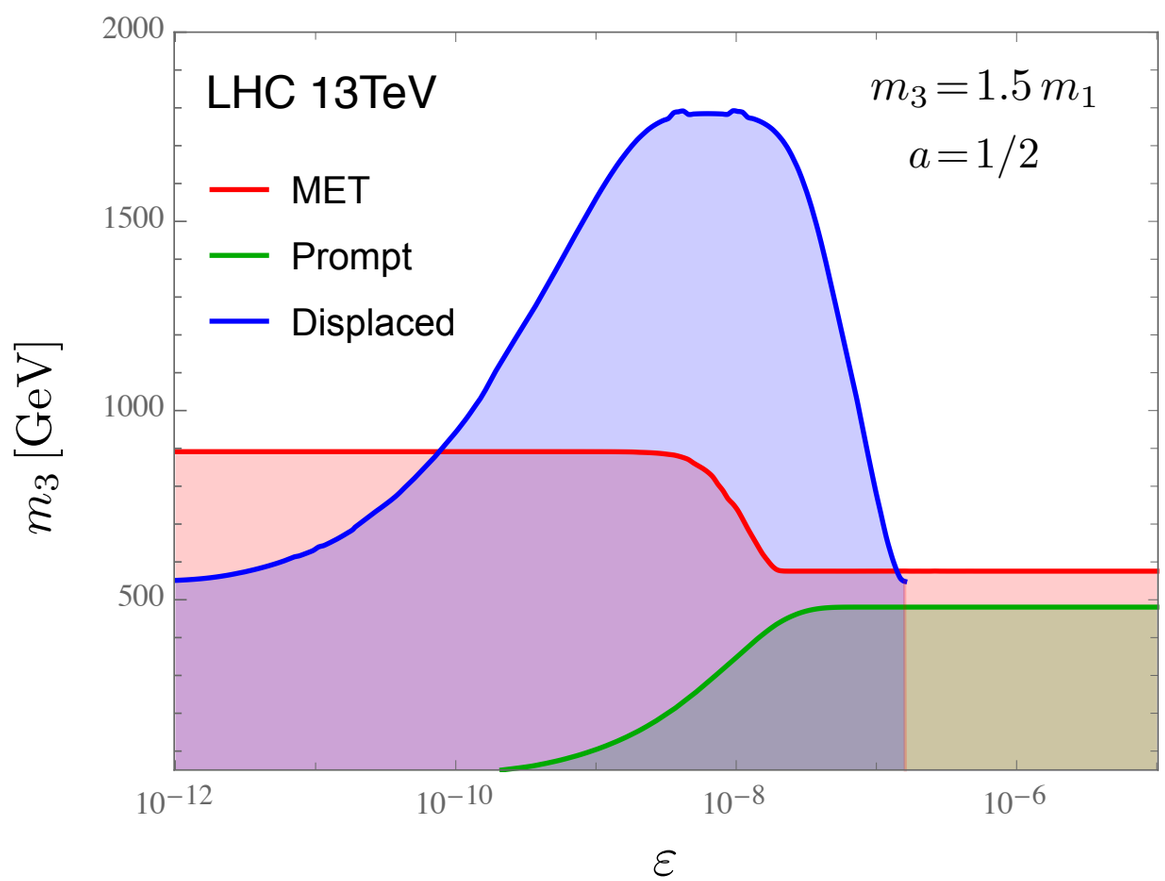

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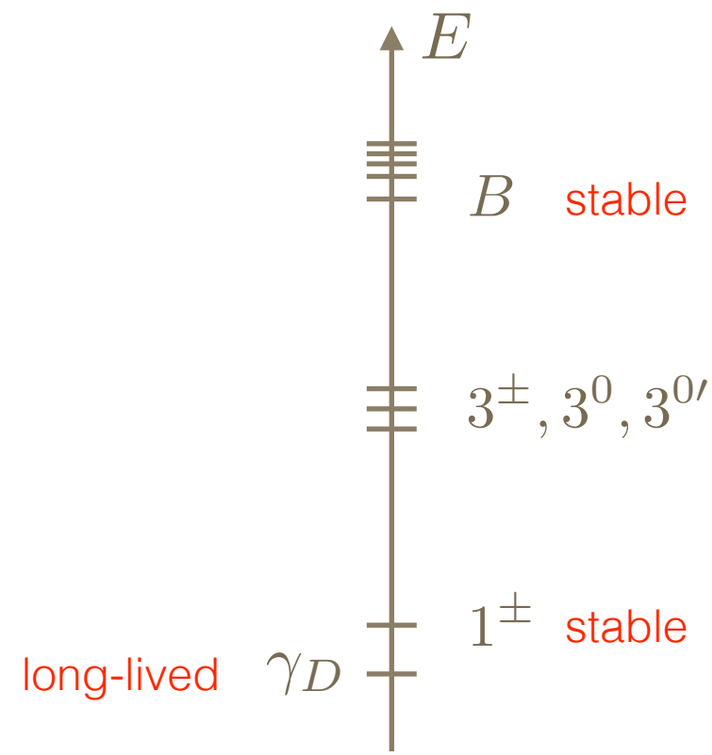


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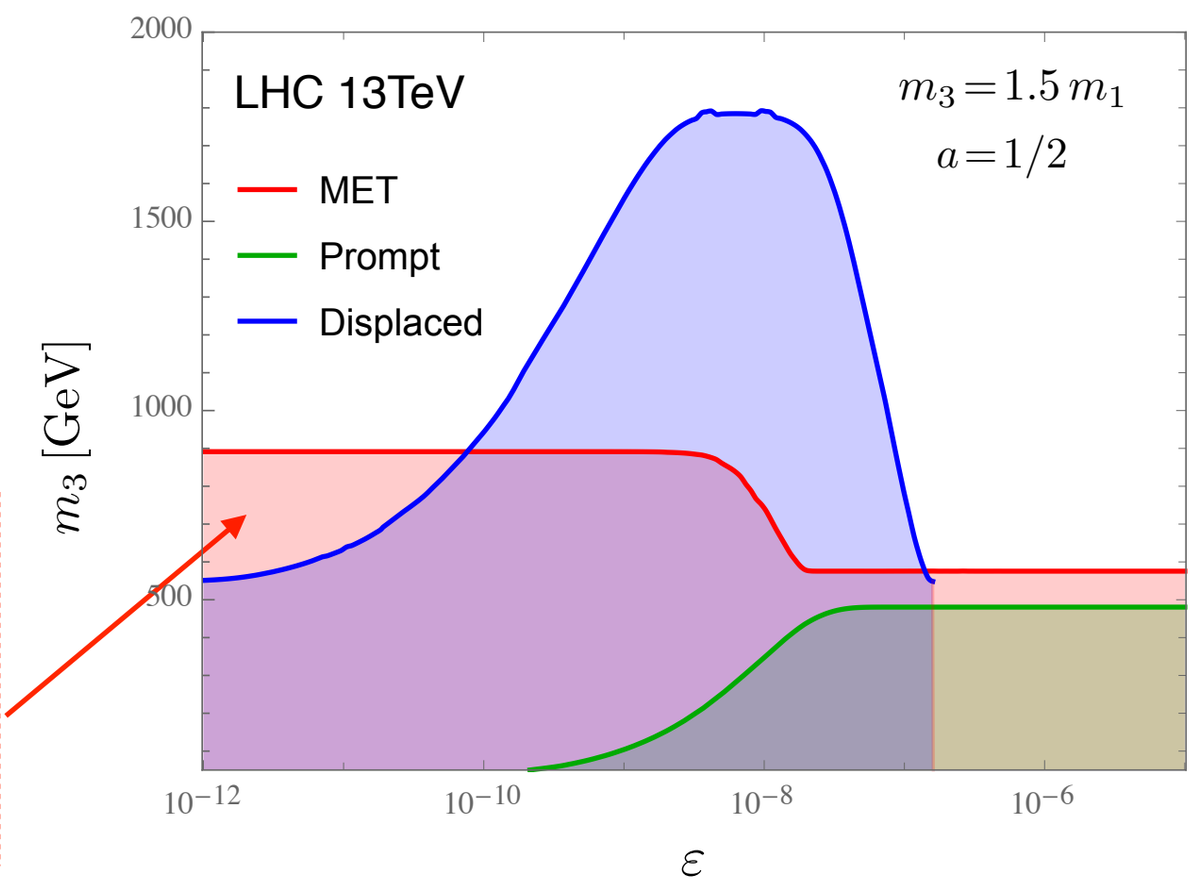
$\gamma_D$ 's decay outside the detector, final states with 1,2,3 leptons + $\not{E}_T$

Bounds from LHC searches of gauginos in SUSY



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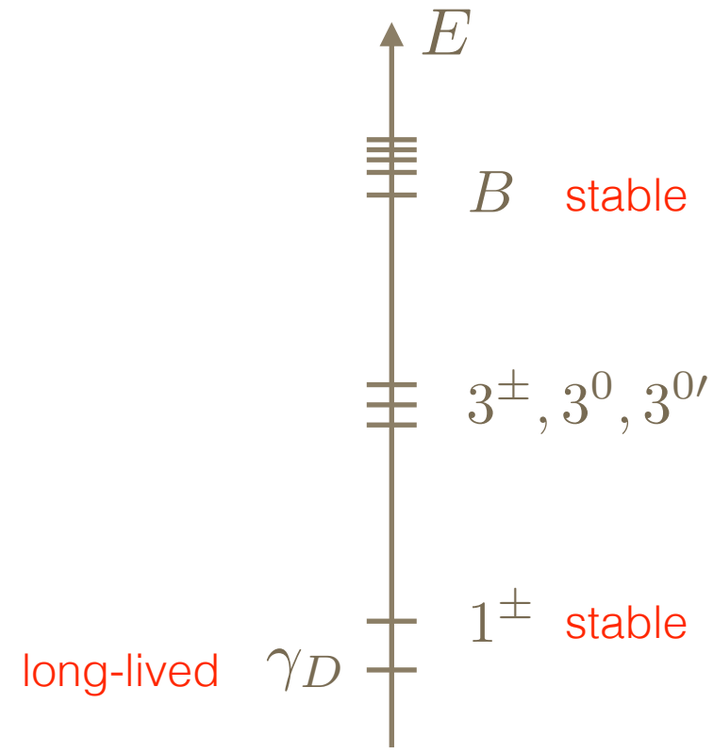


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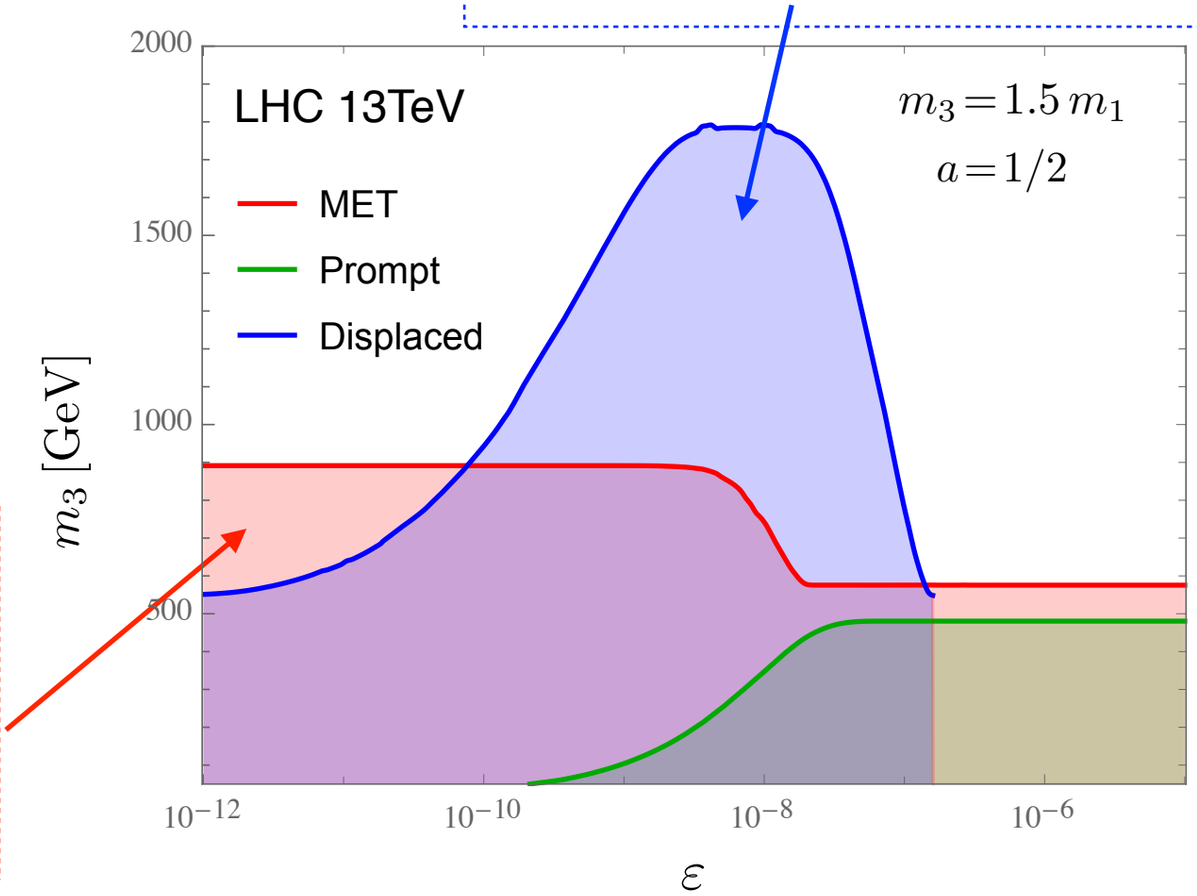
Displaced vertices from $\gamma_D$ decays

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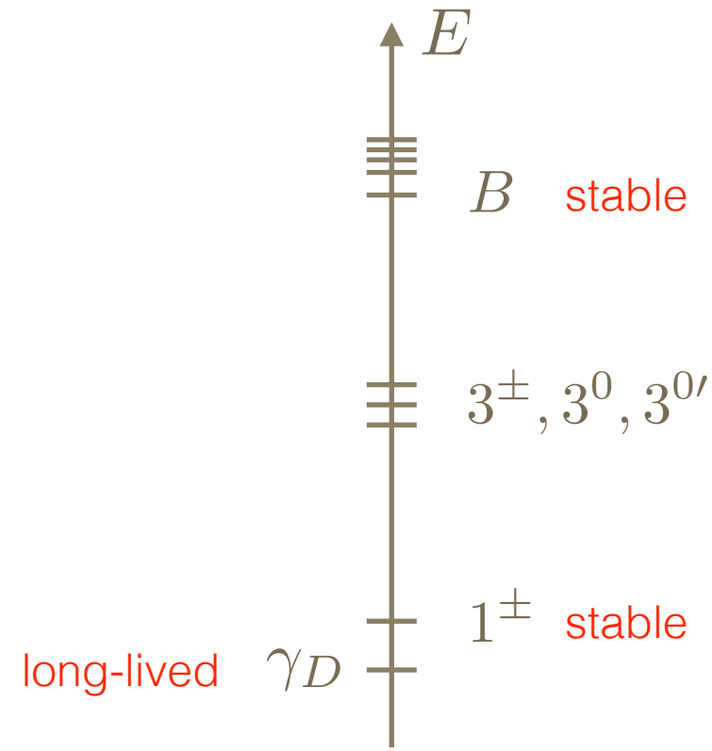


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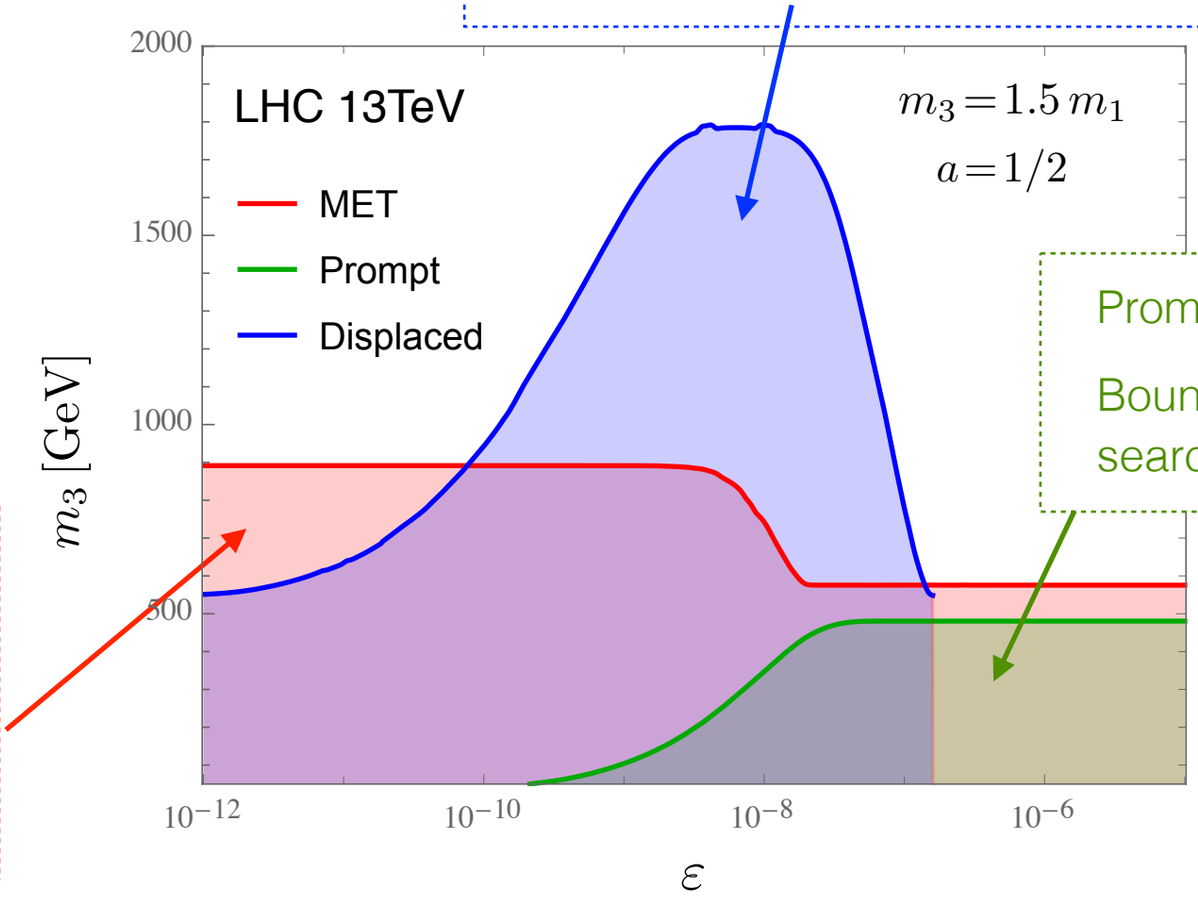


Prompt $\gamma_D$ decays

Bounds from Z' searches at the LHC

$\gamma_D$ 's decay outside the detector, final states with 1,2,3 leptons + $\not{E}_T$

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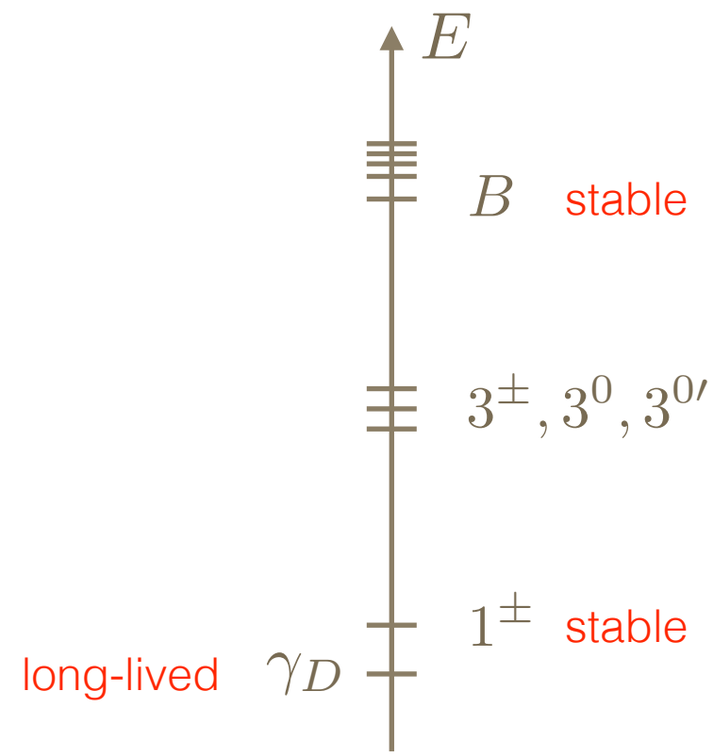


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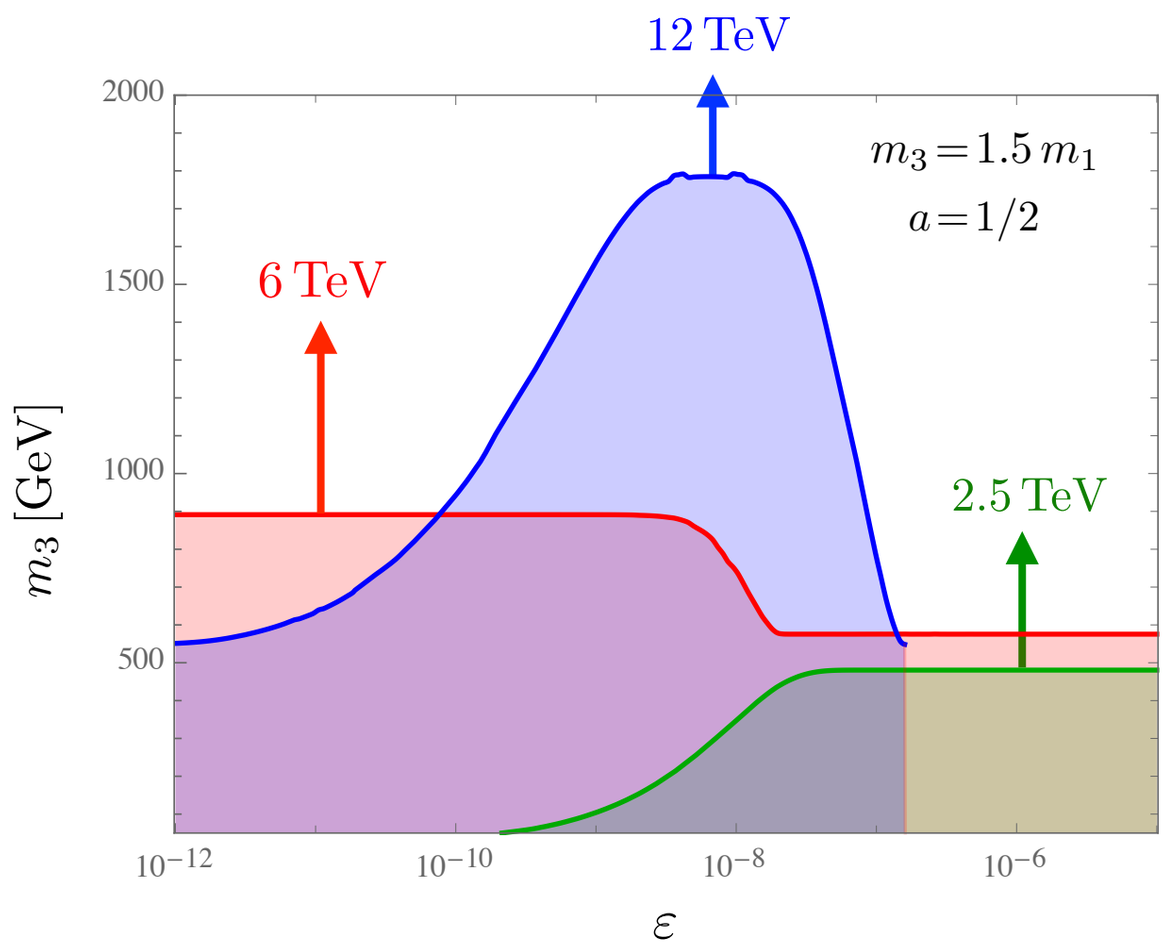
Naive extrapolation to FCC-hh with L=20ab$^{-1}$



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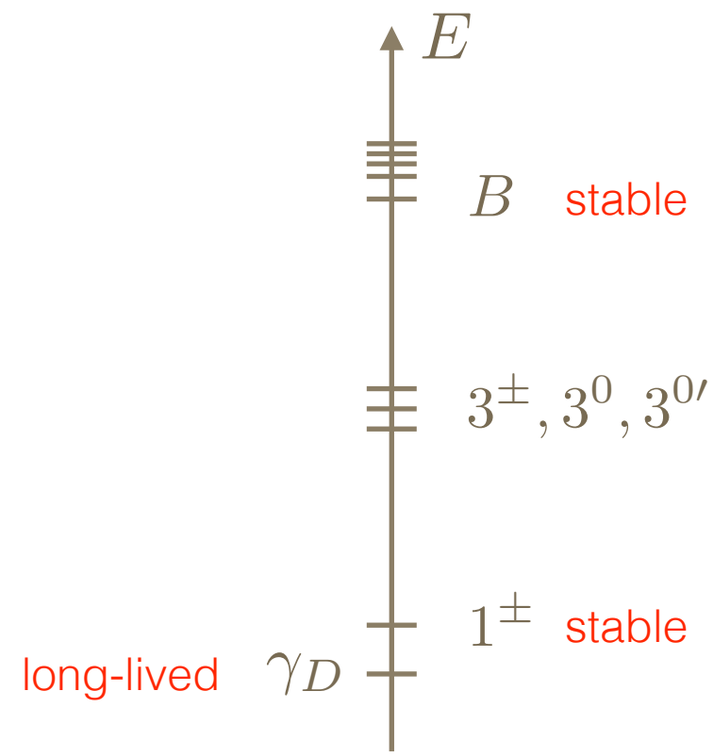
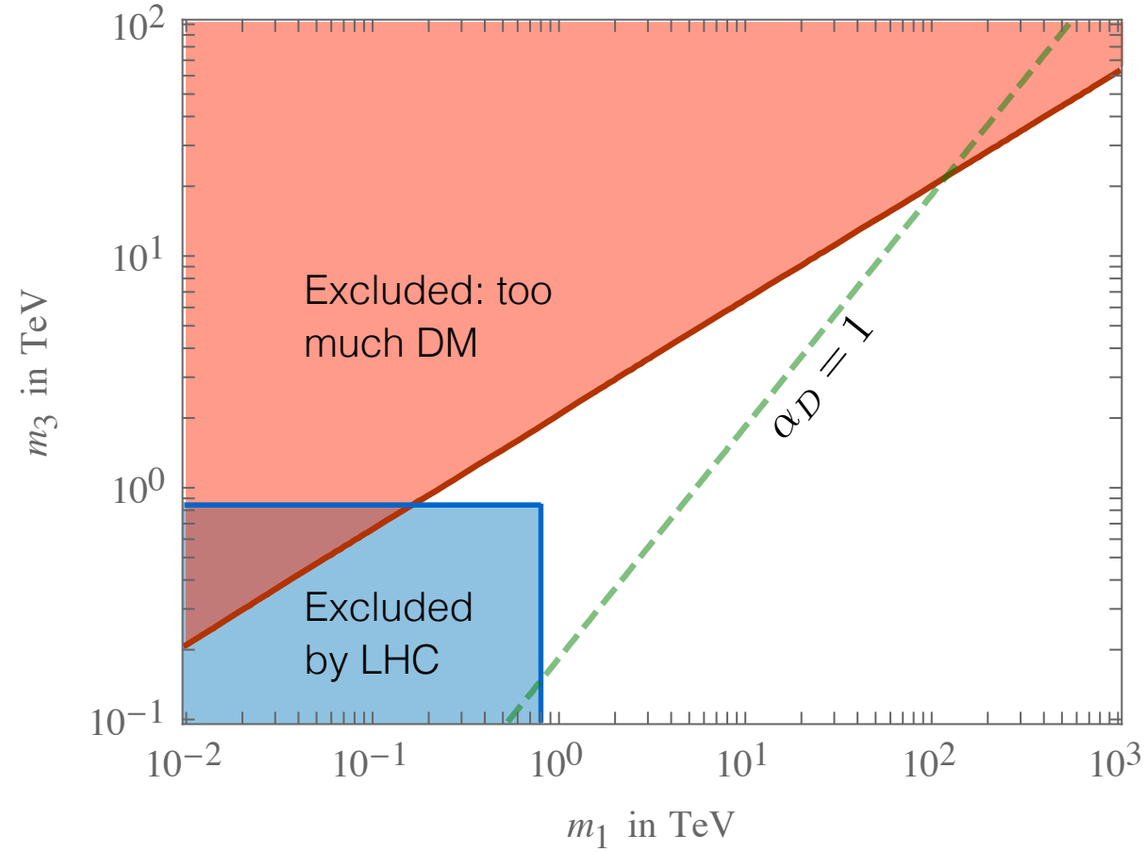



Reach on triplets at LHC and FCC-hh

Summary plot for long-lived dark photons

$\epsilon = 10^{-10}$ $\quad a = 1/2$



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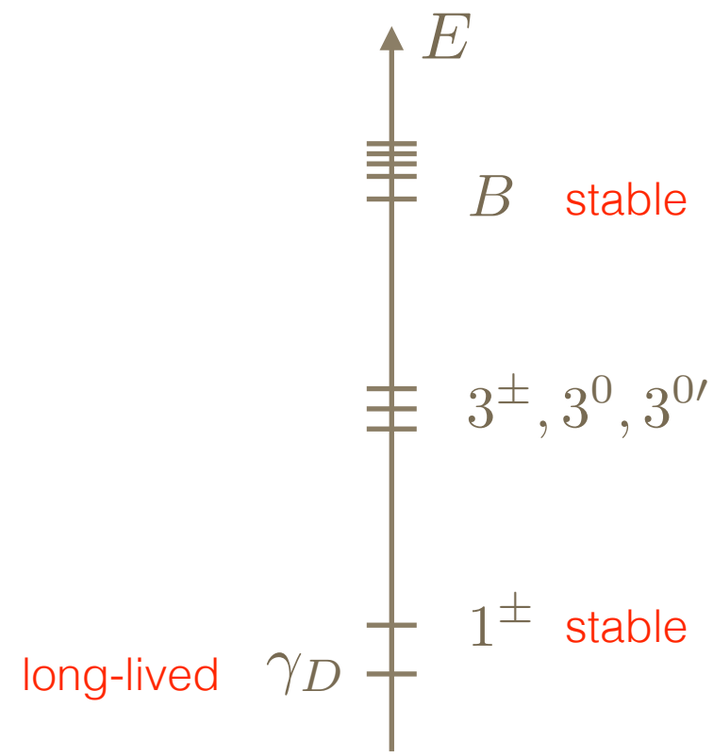
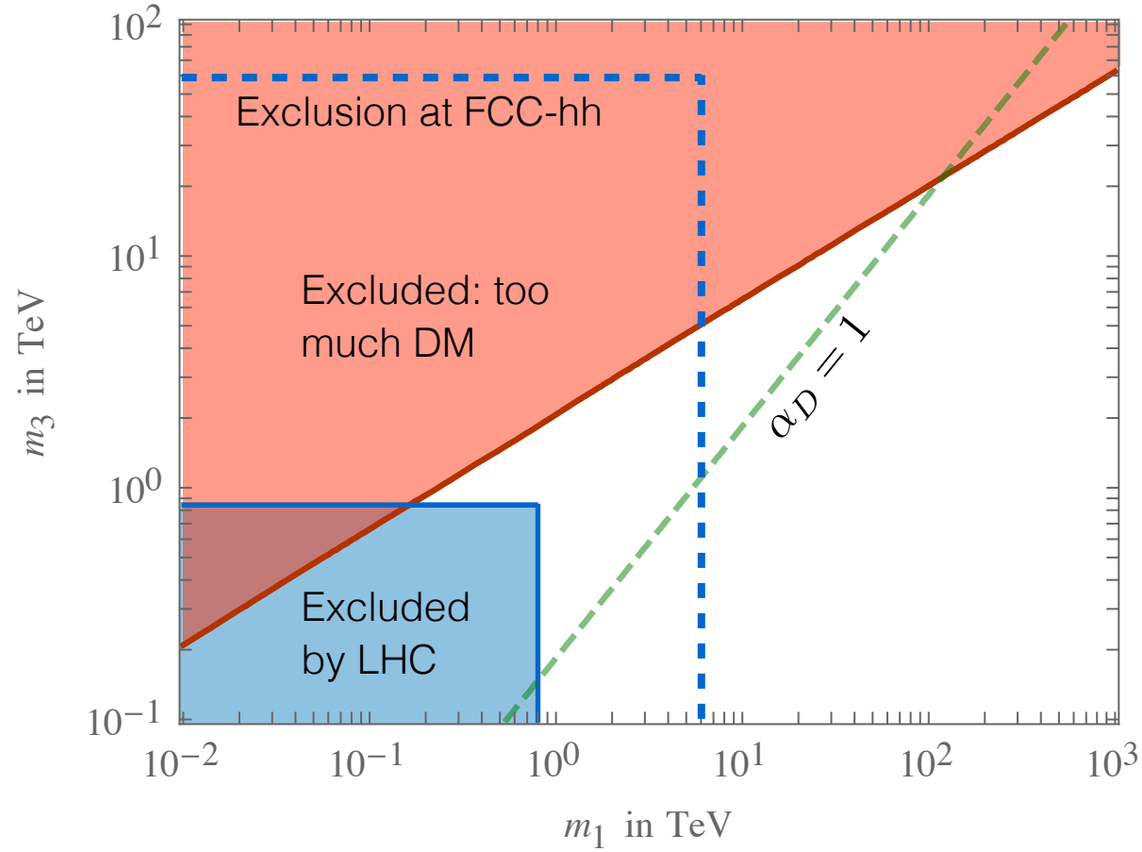


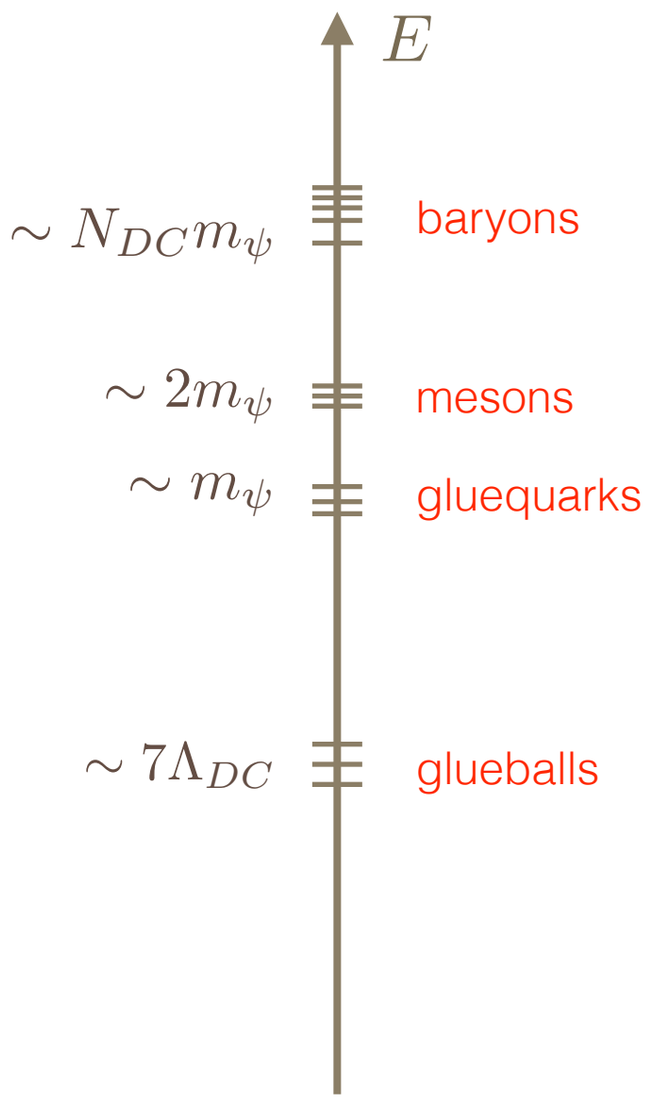

Reach on triplets at LHC and FCC-hh

Summary plot for long-lived dark photons

$\epsilon = 10^{-10}$ $\quad a = 1/2$



# Heavy quark regime ($m_\psi \gg \Lambda_{DC}$) - for vectorlike theories



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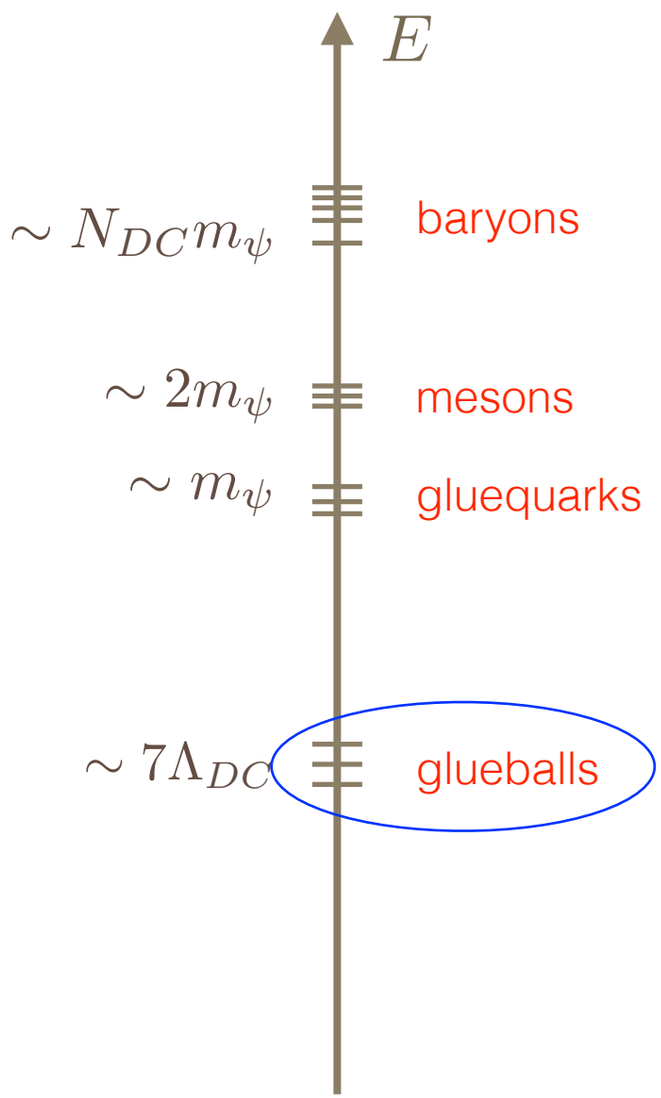
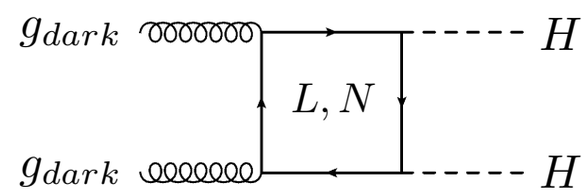



Glueballs couple to the SM only via loops of heavy fermions

Ex: in the L+N model




$$\frac{\alpha_{DC}}{4\pi}\frac{y^2}{M_L M_N} G^2_{\mu\nu} H^\dagger H$$

$$\Gamma[\Phi \to gg] \sim \frac{1}{8\pi}\left(\frac{\alpha_S}{4\pi}\right)^2 \frac{\alpha^2_{DC}(M_N)}{\alpha^2_{DC}(\Lambda_{DC})}\left(\frac{y^2}{16\pi^2}\right)^2 \frac{m^9_\Phi}{M^2_L M^2_N (m^2_h - m^2_\Phi)^2}$$

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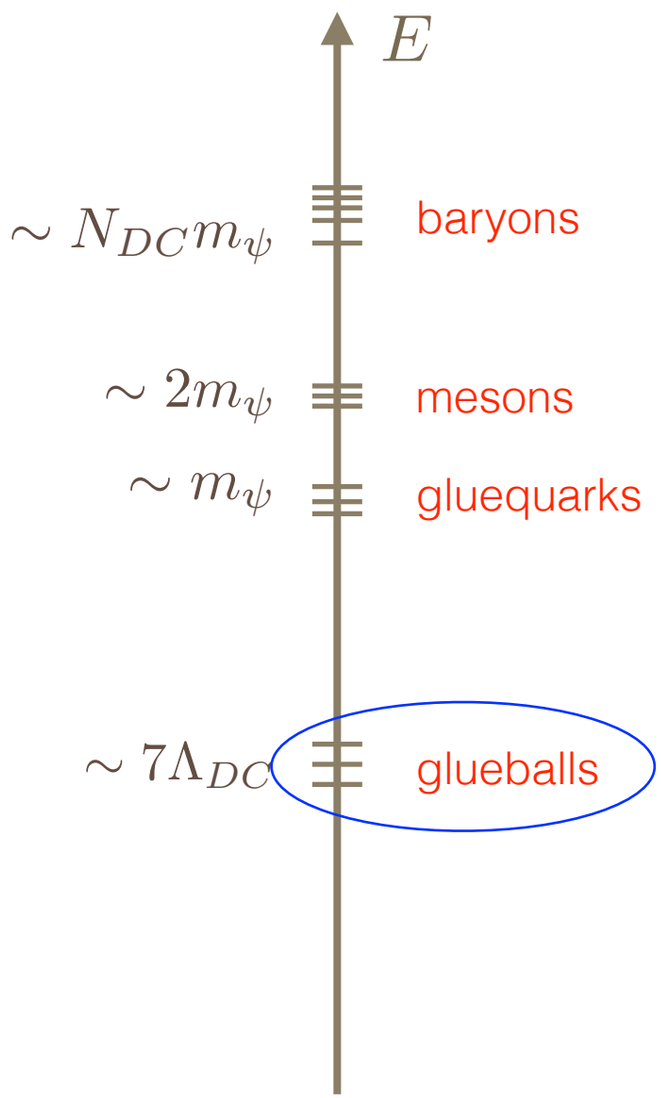


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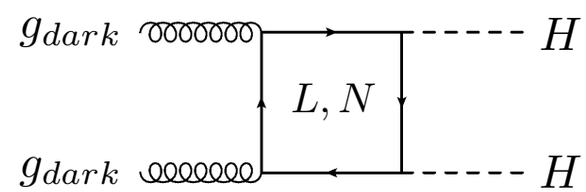


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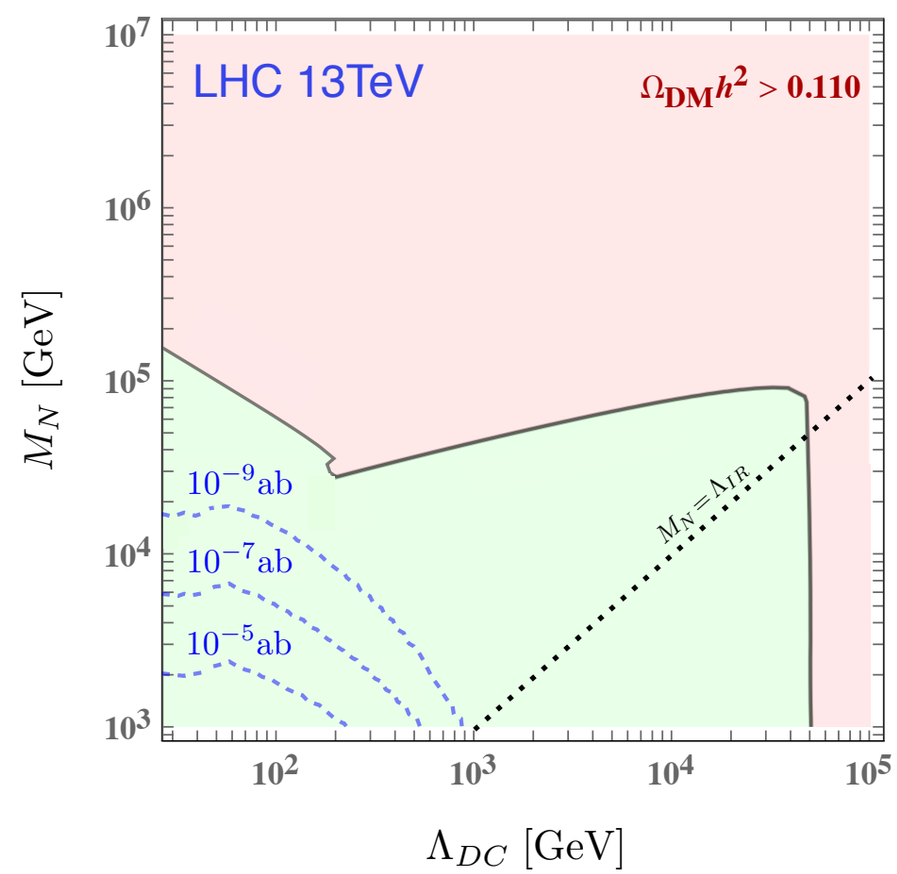


In blue:
isocurves of $\sigma(pp \to \Phi)$
for y=1, $M_L/M_N$=2

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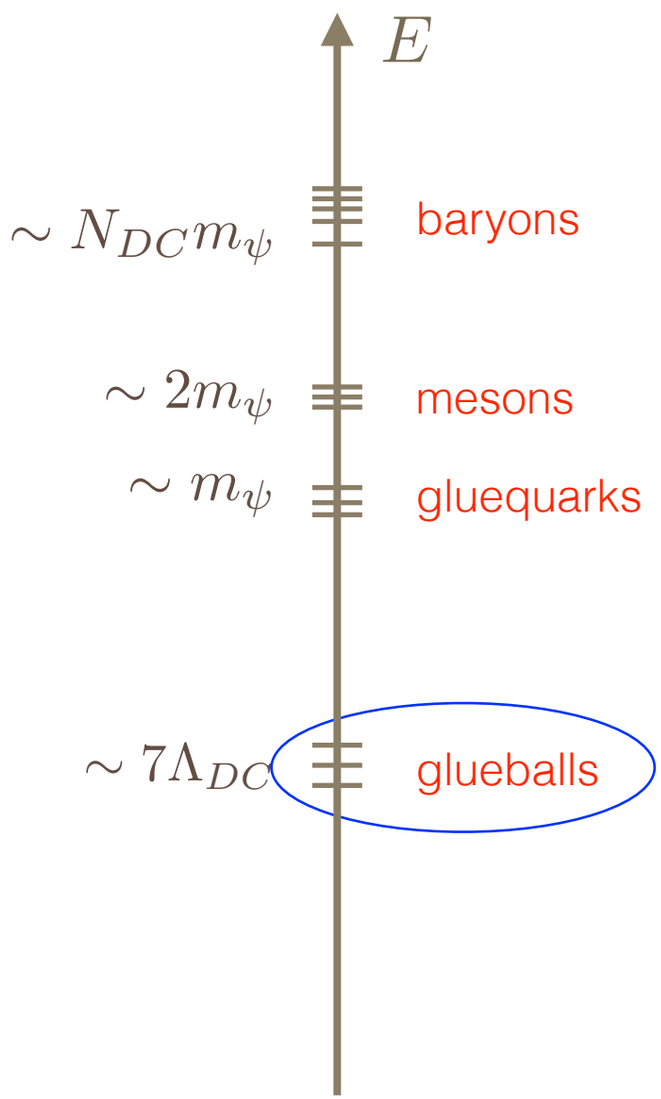


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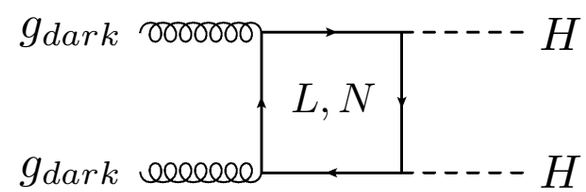


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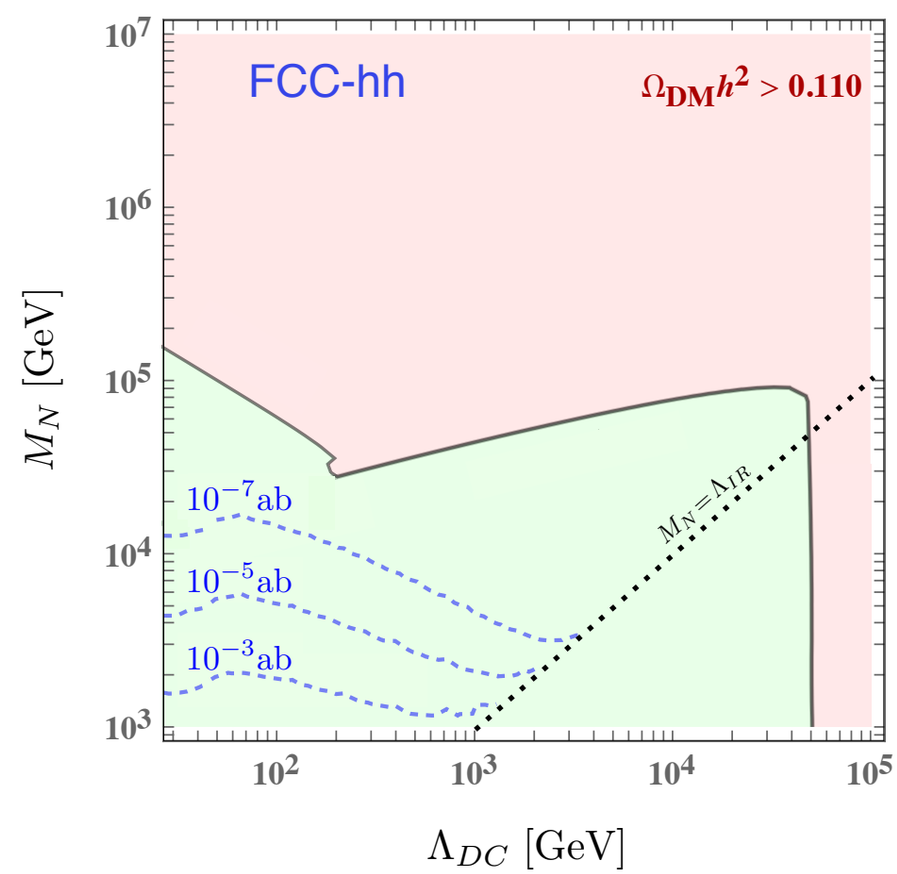


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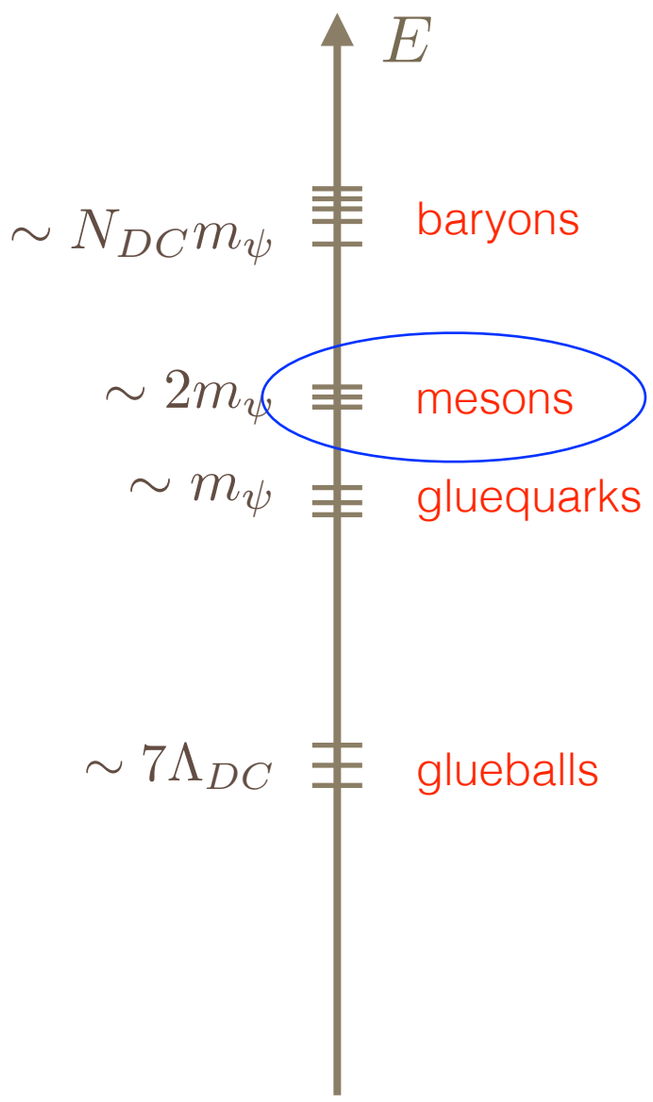
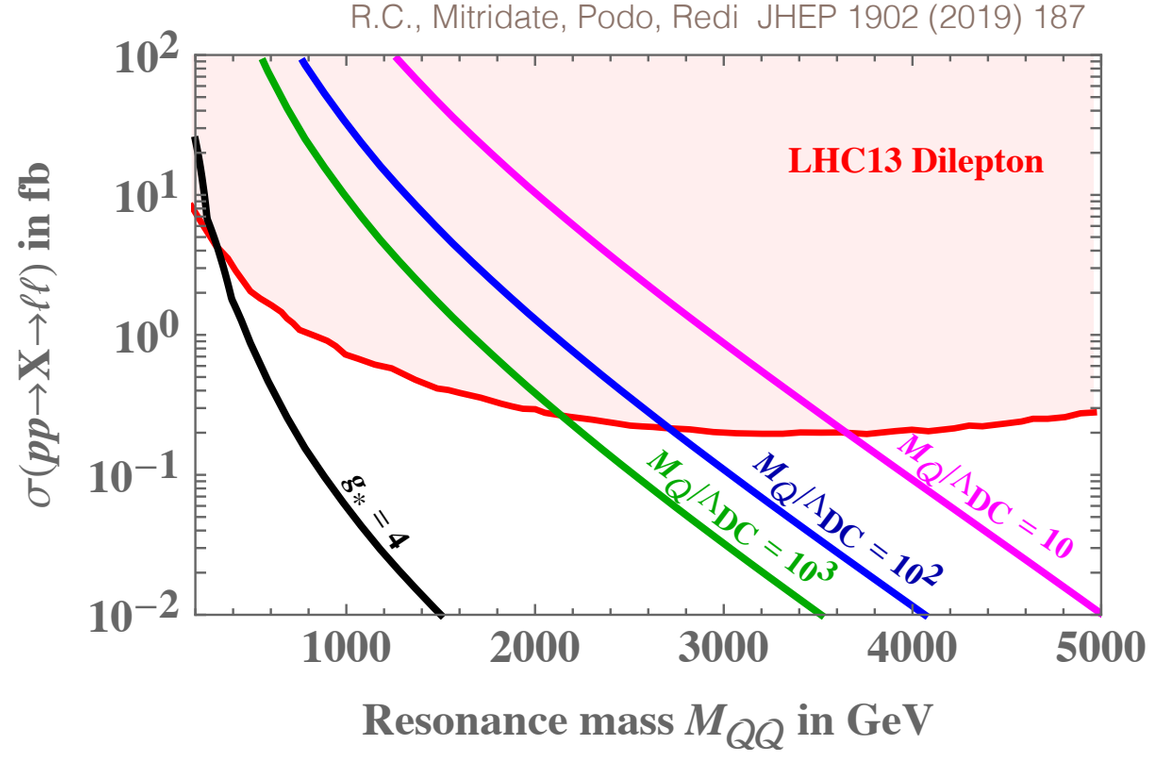



Heavy mesons are *perturbative* quarkonia bound states with calculable properties

- Spin-1 mesons are singly produced via Drell-Yan and have a sizeable (~7%) BR into SM leptons

Ex: in the V = adj model

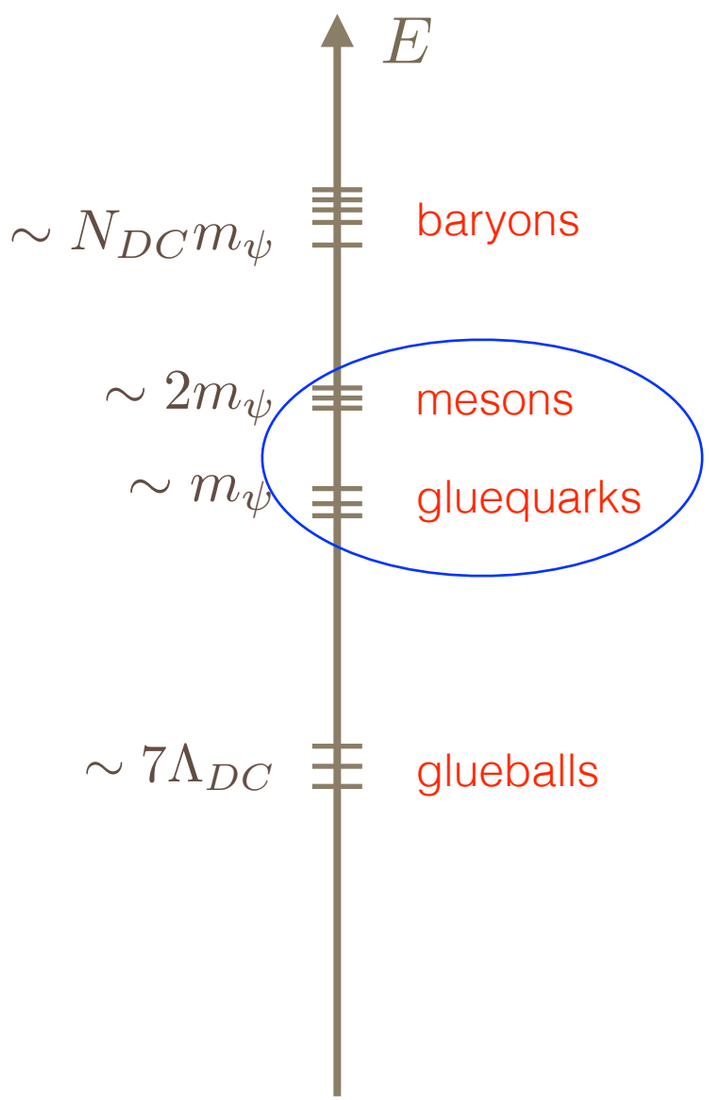
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187




Dilepton searches at the LHC exclude $m_\psi < 1.0 - 1.8\,\mathrm{TeV}$

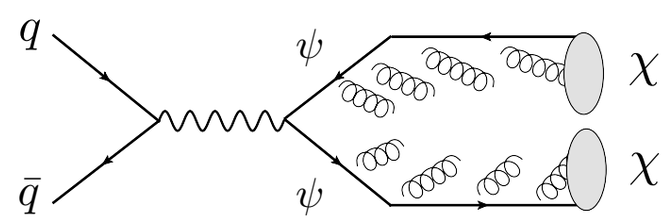
Naive exclusion at FCC-hh (20ab$^{-1}$): $m_\psi < 7 - 13\,\mathrm{TeV}$

# Heavy quark regime ( $m_\psi \gg \Lambda_{DC}$ ) - for vectorlike theories



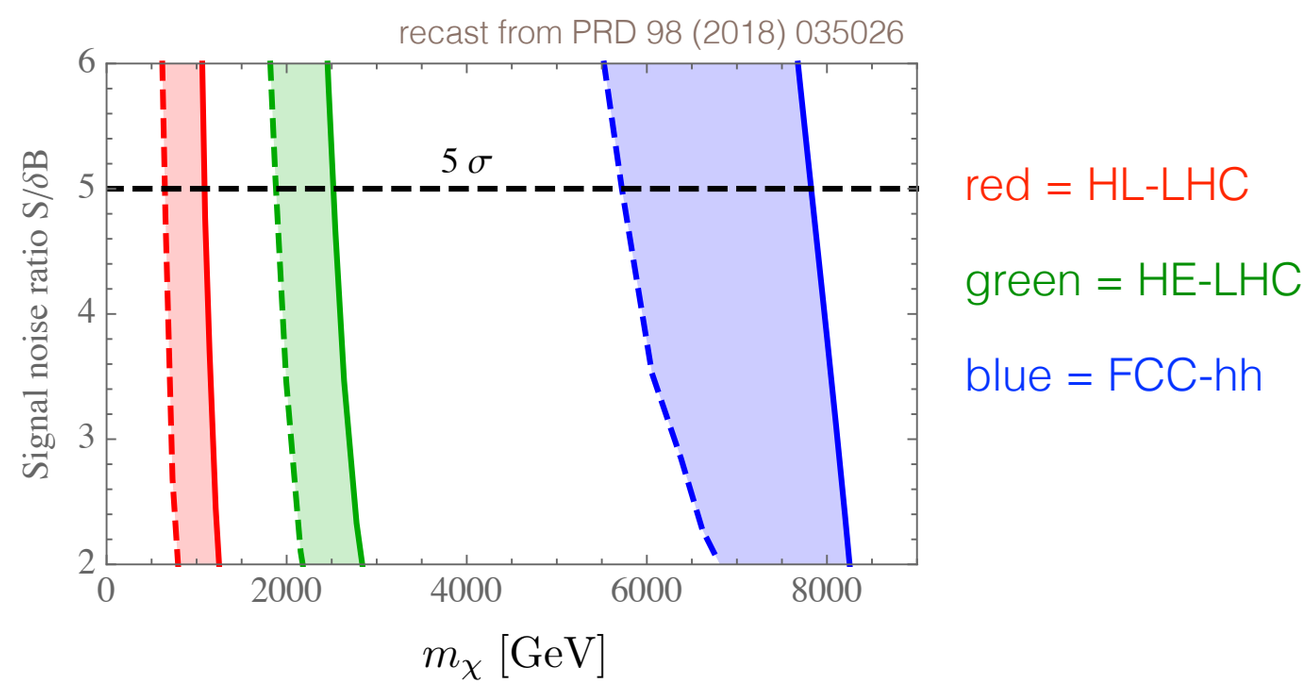

At $E \gtrsim 2m_\psi$ one has open production of $\bar{\psi}\psi$

- Heavy quarks in the fundamental lead to string formation and exotic (quirk) signatures
- Heavy quarks in the adjoint instead hadronize into dark color-singlet gluequarks




Ex: in the V = adj model $\quad m_{\chi^+} - m_{\chi^0} = 160\,\mathrm{MeV}$

$\chi^+$ long-lived gives disappearing track ( $\chi^+ \to \chi^0 + \pi^+$ )



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- DM candidate can easily be a SM singlet but may have charged partners within collider reach
- Classic DM searches like mono-X do *not* usually give the strongest bounds/reach
- More theoretical work needed to identify compelling models