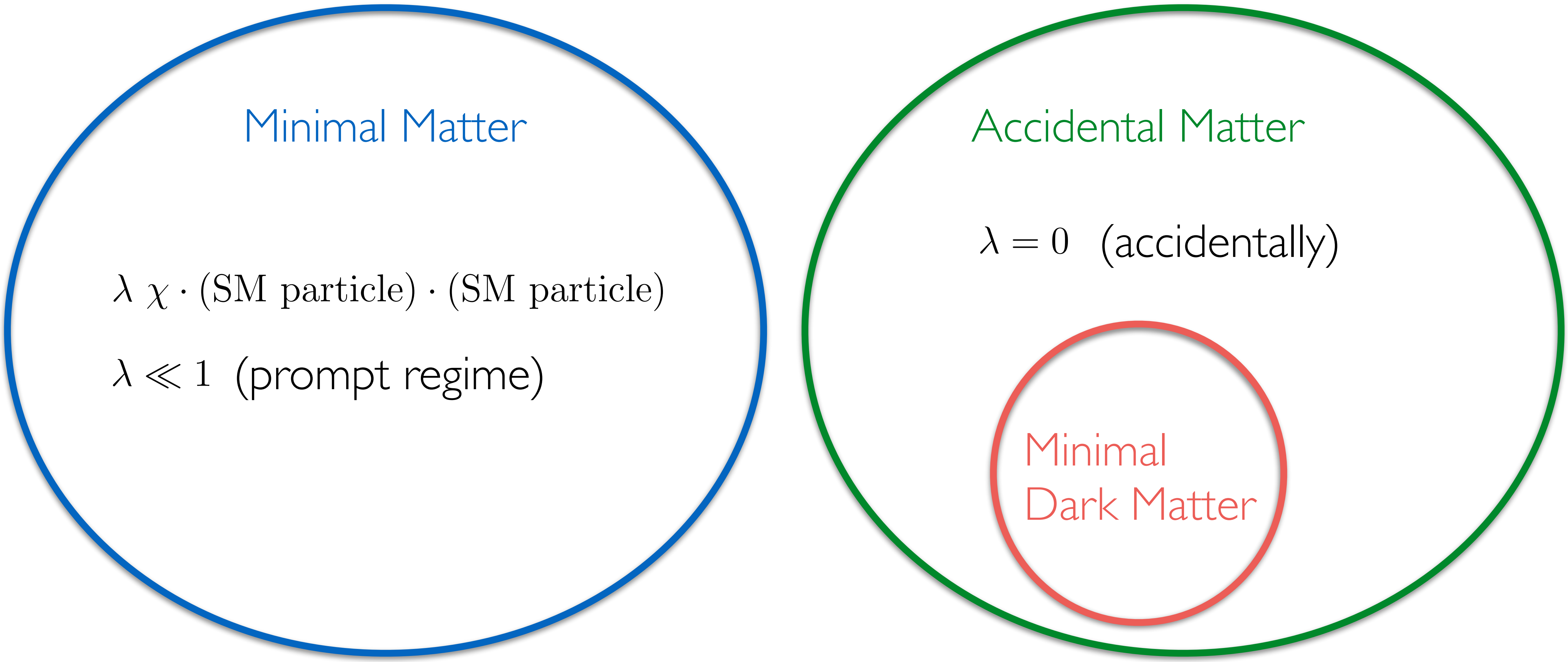
Accidental Matter

Physics at CLIC - CERN - 17 July 2017

Luca Di Luzio

Systematic approach to direct searches

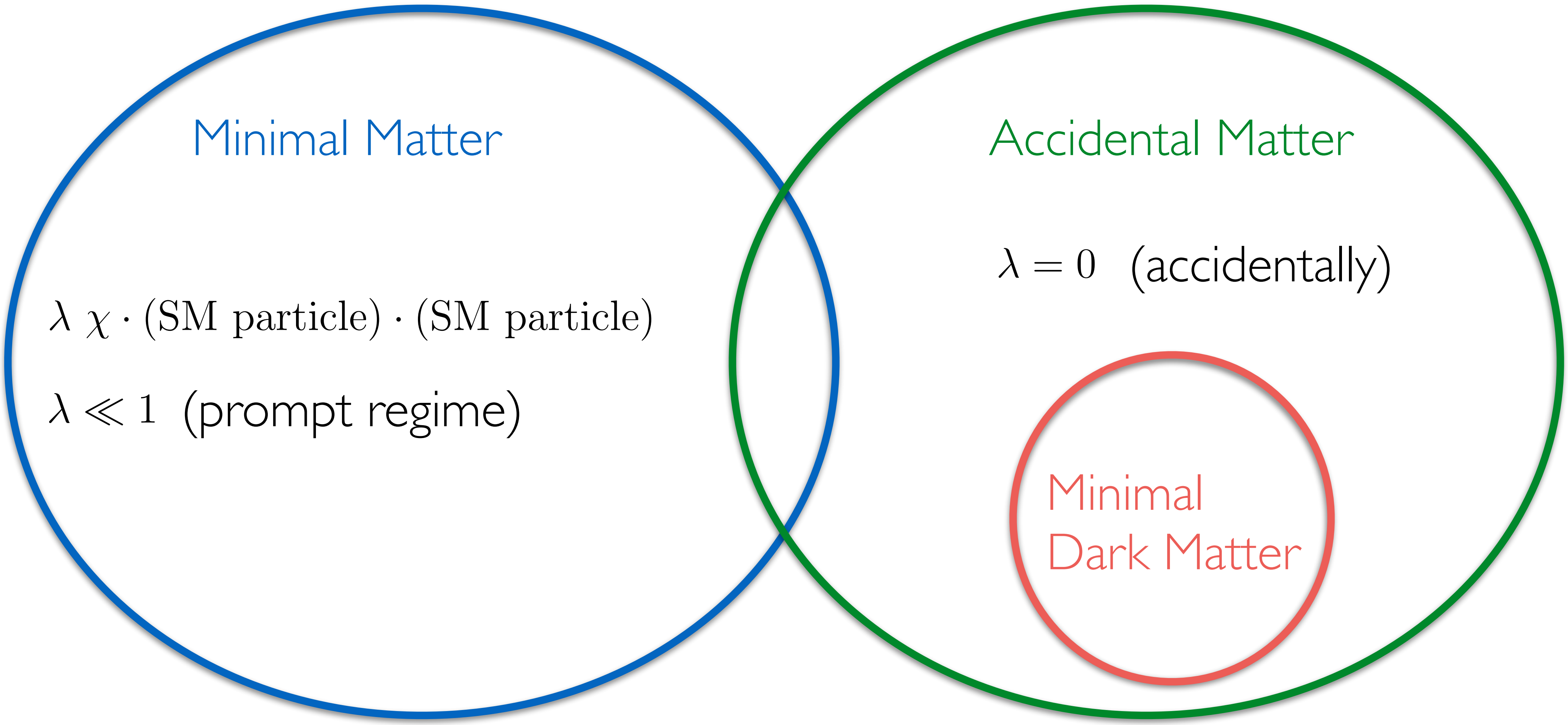


[“Minimal Matter at the Large Hadron Collider” Del Nobile, Franceschini, Pappadopulo, Strumia 0908.1567]

[“Accidental matter at the LHC”, Di Luzio, Gröber, Kamenik, Nardecchia 1504.00359]

[“Minimal Dark Matter” Cirelli, Fornengo, Strumia hep-ph/0512090]

Systematic approach to direct searches



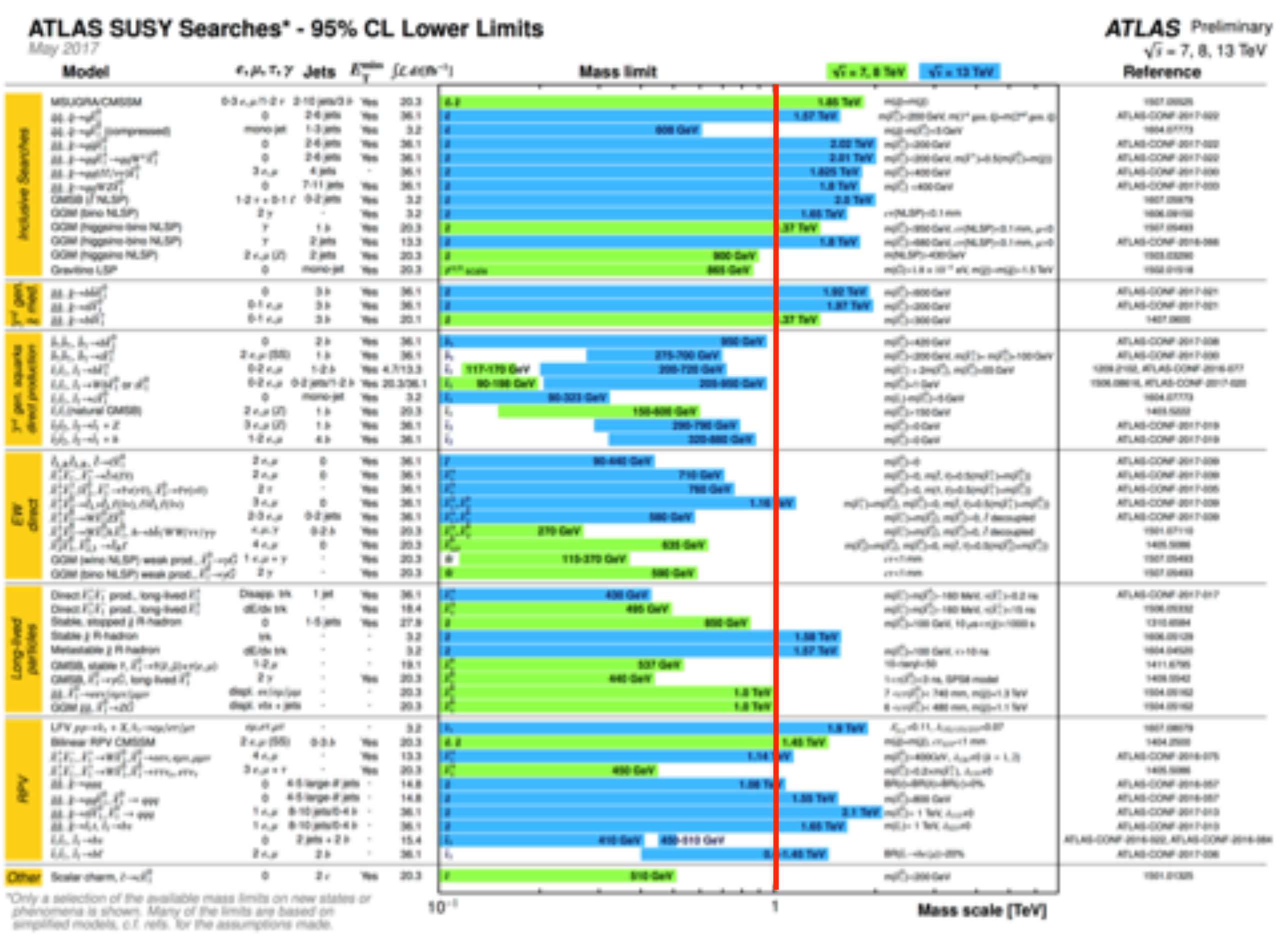
- blind to indirect searches, colliders as the main probes
- pair production via gauge interactions
- pheno: prompt decays vs. long-lived particles

Outline

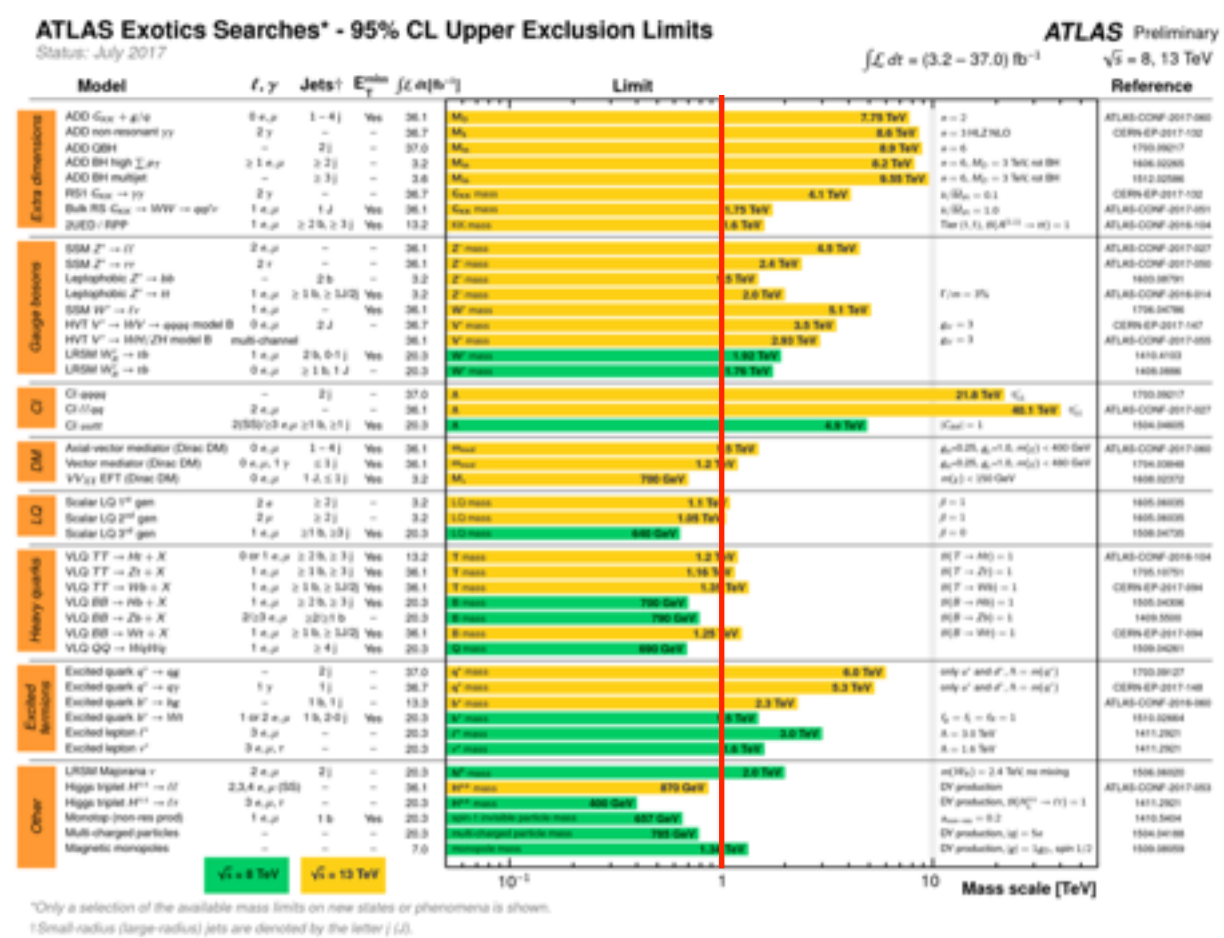
- The scale of new physics
- Accidental matter
- Collider pheno
- A physics case for CLIC

BSM status @ LHC

- SM-like Higgs
- No evidence of new physics beyond the SM → $\Lambda_{\rm SM} \gtrsim \rm TeV$ (<u>colored</u>)



SUSY



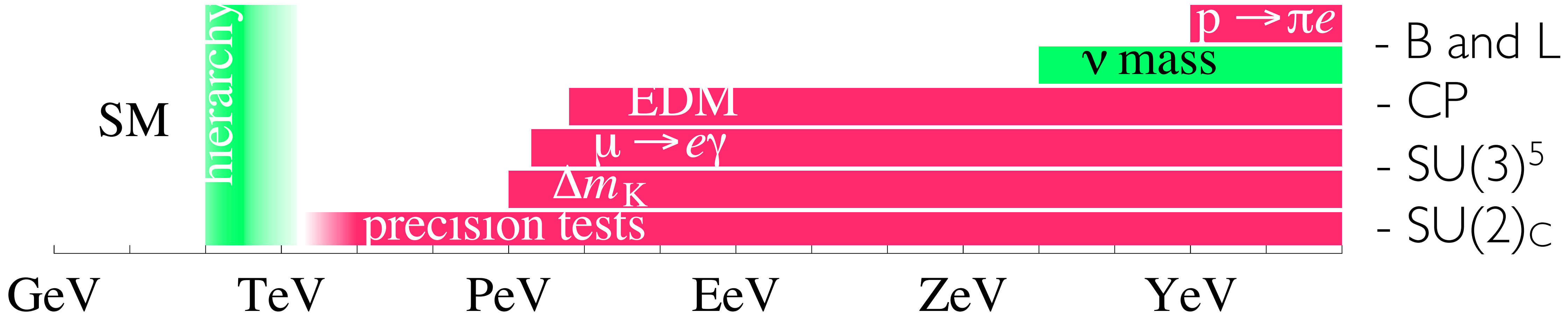
Exotics

Pre-LHC: indirect searches

- The SM as an effective field theory (EFT):

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(d\leq 4)} + \sum_{d>4} \frac{c^{(d)}}{\Lambda_{\rm eff}^{d-4}} \mathcal{O}^{(d)}(\text{SM fields})$$

- Bounds on $\Lambda_{\rm eff}$ (c ~ O(1))



[e.g. Strumia, Vissani, hep-ph/0606054]

$c \to 0$: accidental and approximate symmetry structure of the SM

Pre-LHC: indirect searches

- The SM as an effective field theory (EFT):

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(d\leq 4)} + \sum_{d>4} \frac{c^{(d)}}{\Lambda_{\rm eff}^{d-4}} \mathcal{O}^{(d)}(\text{SM fields})$$

- NP models at the EW scale need to be non-generic in order to comply with data

Traditional approach:

- impose extra symmetries protecting B, L, flavor, etc.

Alternative route:

- assume no extra symmetries (only Lorentz + SM gauge) and generic EFT

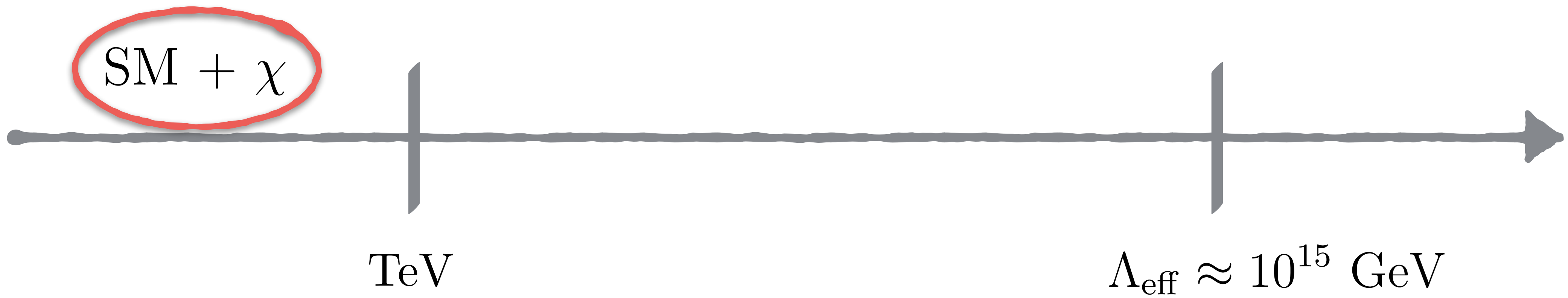
Accidental matter

- Which EW-scale extensions of the SM

  i) automatically preserve the accidental and approximate symmetries of the SM ?

  ii) are cosmologically viable ?

  iii) form a consistent EFT up to $\Lambda_{\text{eff}} \approx 10^{15}$ GeV (suggested by nu masses and p-decay) ?



Accidentally safe extensions

- Accidental symmetries in the SM

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm Yuk} - V(H)$$

- no extra symmetries imposed by hand, but extra accidental "gifts"

$\mathcal{L}_{\rm kin} \supset \psi^\dagger_{\rm SM} i \sigma^\mu D_\mu \psi_{\rm SM}$ $\longrightarrow$ invariant under $U(3)^5$

- Yukawa sector breaks this symmetry into

$$U(3)^5 \longrightarrow U(1)^5 = U(1)_Y \otimes U(1)_B \otimes U(1)_{L_e} \otimes U(1)_{L_\mu} \otimes U(1)_{L_\tau}$$

Accidentally safe extensions

- Add a single state χ (scalar or fermion)*

* massive vectors require an UV completion

Accidentally safe extensions

- Add a single state χ (scalar or fermion)
  - $U(3)^5$ automatically preserved if no ren. coupling of χ to SM fermions

	$\mathcal{O}_{\rm SM}$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$\psi_{\rm SM} H(H^\dagger)$	$qH(H^\dagger)$	3	$1\oplus 3$	$+2/3(-1/3)$
	$u^c H(H^\dagger)$	$\overline{3}$	2	$-1/6(-7/6)$
	$d^c H(H^\dagger)$	$\overline{3}$	2	$+5/6(-1/6)$
	$\ell H(H^\dagger)$	1	$1\oplus 3$	$0(-1)$
	$e^c H(H^\dagger)$	1	2	$+3/2(+1/2)$
$\psi_{\rm SM}\psi_{\rm SM}$	qq	$\overline{3}\oplus 6$	$1\oplus 3$	$+1/3$
	qu^c	$1\oplus 8$	2	$-1/2$
	qd^c	$1\oplus 8$	2	$+1/2$
	$q\ell$	3	$1\oplus 3$	$-1/3$
	qe^c	3	2	$+7/6$
	$u^c u^c$	$3\oplus\overline{6}$	1	$-4/3$
	$u^c d^c$	$3\oplus\overline{6}$	1	$-1/3$
	$u^c\ell$	$\overline{3}$	2	$-7/6$
	$u^c e^c$	$\overline{3}$	1	$+1/3$
	$d^c d^c$	$3\oplus\overline{6}$	1	$+2/3$
	$d^c\ell$	$\overline{3}$	2	$-1/6$
	$d^c e^c$	$\overline{3}$	1	$+4/3$
	$\ell\ell$	1	$1\oplus 3$	-1
	ℓe^c	1	2	$+1/2$
	$e^c e^c$	1	1	$+2$

$\rightarrow$ orthogonal choice or rep.'s w.r.t.

["Minimal Matter at the Large Hadron Collider", Del Nobile, Franceschini, Pappadopulo, Strumia 0908.1567]

$$\lambda\,\chi\cdot(\text{SM particle})\cdot(\text{SM particle})$$

Accidentally safe extensions

- Add a single state χ (scalar or fermion)
- New fermions: avoid the couplings $\chi\psi_{\rm SM}$ and $\chi\psi_{\rm SM}H(H^\dagger)$

- if $\chi \sim$ real rep. $$\mathcal{L} = \mathcal{L}_{\rm SM} + i\chi^\dagger\overline{\sigma}^\mu D_\mu\chi + \frac{1}{2}M(\chi^T\epsilon\chi + \text{h.c.})$$

Extra Z_2, $\chi \to -\chi$

- if $\chi \sim$ complex rep. introduce a vector-like copy χ^c

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\chi^\dagger\overline{\sigma}^\mu D_\mu\chi + i\chi^{c\dagger}\overline{\sigma}^\mu D_\mu\chi^c + M(\chi^T\epsilon\chi^c + \text{h.c.})$$

Extra $\text{U}(1)$, $\chi \to e^{i\theta}\chi$ and $\chi^c \to e^{-i\theta}\chi^c$

→ Extra accidental symmetry implies stability of χ at the ren. level

Accidentally safe extensions

- Add a single state χ (scalar or fermion)
- New fermions: avoid the couplings $\chi\psi_{\rm SM}$ and $\chi\psi_{\rm SM}H(H^\dagger)$
- New scalars: avoid the couplings $\chi\psi_{\rm SM}\psi_{\rm SM}$

  - Kinetic term of real or complex scalar invariant under extra Z_2 or $\mathrm{U}(1)$
  - Stability not guaranteed (depends on scalar potential interactions)

Cosmology

- If the lightest particle (LP) in the multiplet is <u>stable</u> at the ren. level
  - Colorless and EM neutral stable particles can be DM
  - Colored or charged stable particles are severely bounded

["Minimal Dark Matter", Cirelli, Fornengo, Strumia, hep-ph/0512090]

[See e.g. "Non-collider searches for stable massive particles", Burdin et al. 1410.1374]

→ implicit assumption: χ species are thermally produced ($T_{\rm RH} > m_\chi \sim \rm TeV$)

Cosmology

- If the lightest particle (LP) in the multiplet is stable at the ren. level
  - Colorless and EM neutral stable particles can be DM
  - Colored or charged stable particles are severely bounded
- Stability broken by non-renormalizable operators

$$\mathcal{L}_{\rm SM} + \mathcal{L}_\chi + \sum \frac{1}{\Lambda_{\rm eff}} O^{(5)} + \sum \frac{1}{\Lambda^2_{\rm eff}} O^{(6)} + \ldots$$

- Assuming $\Lambda_{\rm eff} \approx 10^{15}$ GeV and $m_\chi \approx 1$ TeV

$$\Gamma_5 \sim \frac{m_\chi^3}{\Lambda^2_{\rm eff}} \approx (0.1\ s)^{-1}$$ → BBN bounds [see backup slides]

$$\Gamma_6 \sim \frac{m_\chi^5}{\Lambda^4_{\rm eff}} \approx (10^{20}\ s)^{-1}$$ → Excluded by cosmic rays and heavy isotopes (if LP charged/colored)

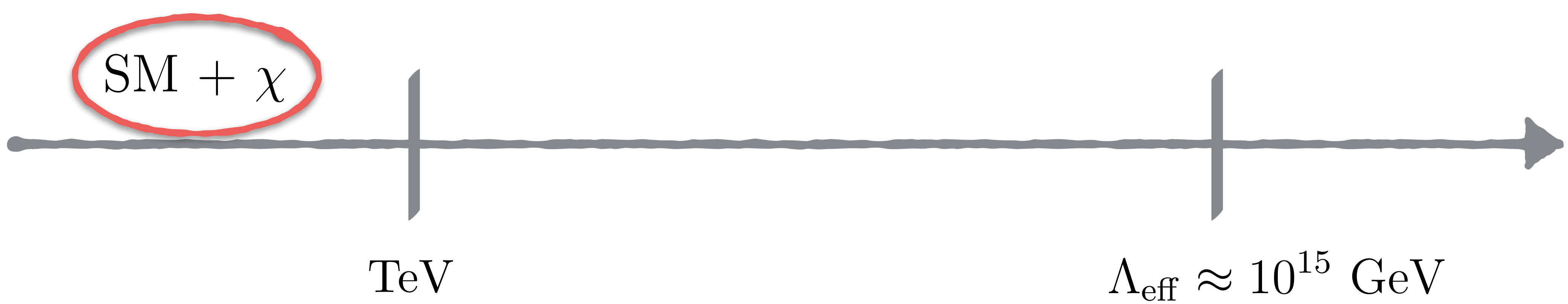
Accidental matter multiplets

- Selection criteria:

i) no ren. coupling of χ to SM fermions

ii) decay via dim < 6 op.'s (if LP colored/charged)

iii) no Landau poles below $\Lambda_{\text{eff}} \approx 10^{15}$ GeV



→ a finite set of possibilities

Accidental matter multiplets

Spin	χ	Q_{LP}	$\mathcal{O}_{\text{decay}}$	$\dim(\mathcal{O}_{\text{decay}})$	$\Lambda^{2-\text{loop}}_{\text{Landau}}$[GeV]
0	$(1,1,0)$	0	$\chi H H^\dagger$	3	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,3,0)^\ddagger$	0,1	$\chi H H^\dagger$	3	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,4,1/2)^\ddagger$	-1,0,1,2	$\chi H H^\dagger H^\dagger$	4	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,4,3/2)^\ddagger$	0,1,2,3	$\chi H^\dagger H^\dagger H^\dagger$	4	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,2,3/2)$	1,2	$\chi H^\dagger \ell\ell,\ \chi^\dagger H^\dagger e^c e^c,\ D^\mu \chi^\dagger \ell^\dagger \overline{\sigma}_\mu e^c$	5	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,2,5/2)$	2,3	$\chi^\dagger H e^c e^c$	5	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,5,0)$	0,1,2	$\chi H H H^\dagger H^\dagger,\ \chi W^{\mu\nu} W_{\mu\nu},\ \chi^3 H^\dagger H$	5	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,5,1)$	-1,0,1,2,3	$\chi^\dagger H H H H^\dagger,\ \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$\gg m_{\text{Pl}}$ (g_1)
0	$(1,5,2)$	0,1,2,3,4	$\chi^\dagger H H H H$	5	3.5×10^{18} (g_1)
0	$(1,7,0)^\star$	0,1,2,3	$\chi^3 H^\dagger H$	5	1.4×10^{16} (g_2)
1/2	$(1,4,1/2)$	-1	$\chi^c \ell H H,\ \chi \ell H^\dagger H,\ \chi \sigma^{\mu\nu} \ell W_{\mu\nu}$	5	8.1×10^{18} (g_2)
1/2	$(1,4,3/2)$	0	$\chi \ell H^\dagger H^\dagger$	5	2.7×10^{15} (g_1)
1/2	$(1,5,0)$	0	$\chi \ell H H H^\dagger,\ \chi \sigma^{\mu\nu} \ell H W_{\mu\nu}$	6	8.3×10^{17} (g_2)

+ 14 colored scalars and 3 colored fermions [see backup slides]

Accidental matter multiplets

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- Prompt decays, well-studied: constraints from Higgs couplings and EWPTs

Accidental matter multiplets

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- Minimal DM candidates (LP is neutral, no Z-boson coupling and sufficiently stable)

[Cirelli, Fornengo, Strumia, hep-ph/0512090]

Accidental matter multiplets

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- Scalar MDM: too fast loop-induced decay via d=5 op. [DL, Gröber, Kamenik, Nardecchia 1504.00359]

- Fermion MDM: constrained by gamma-ray searches (dependence on DM profile)

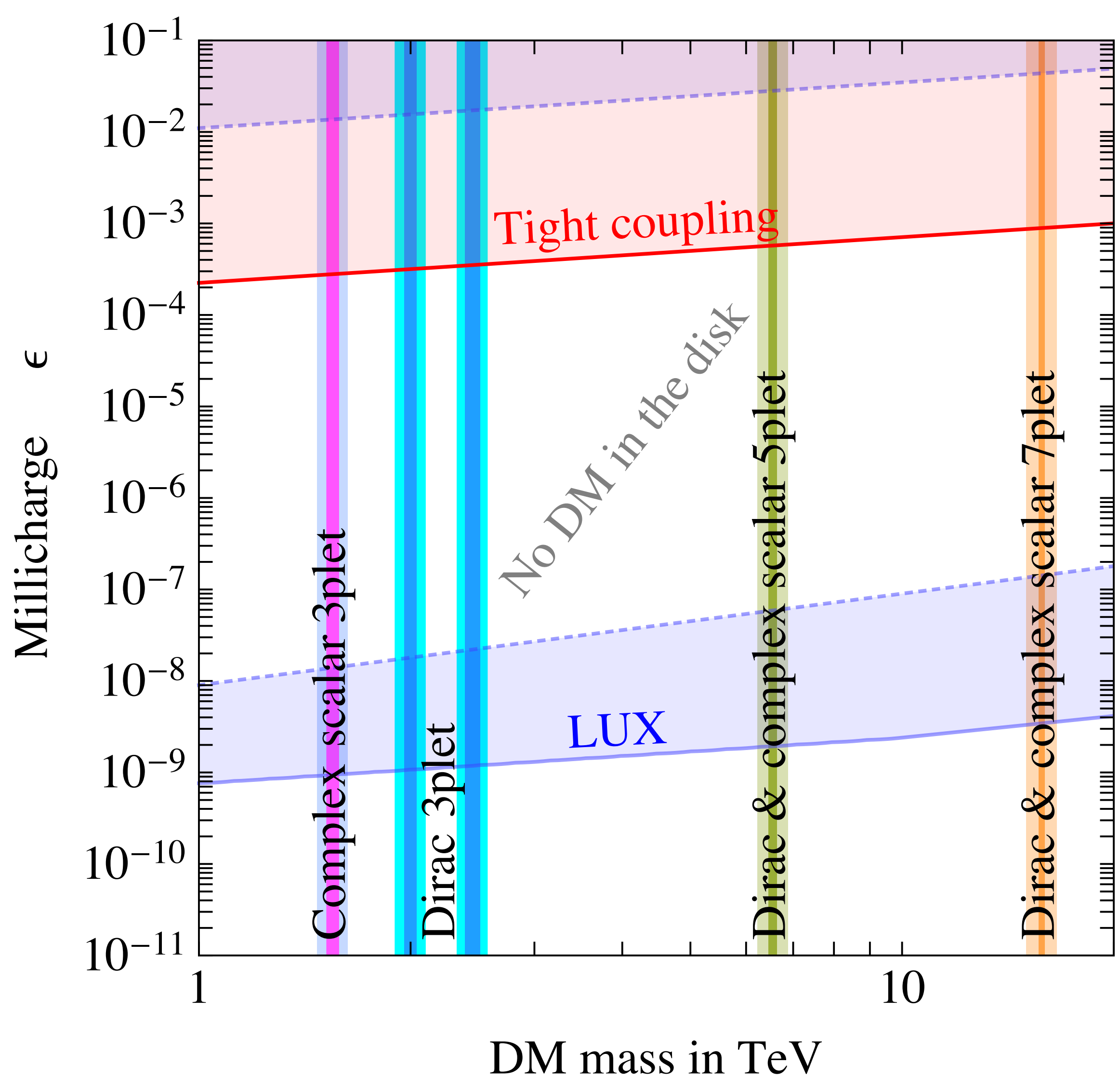
[Cirelli, Hambye, Panci, Sala, Taoso 1507.05519, Garcia-Cely, Ibarra, Lamperstorfer, Tytgat 1507.05536]

Beyond MDM

- A millicharge can effectively stabilise the DM: $\chi \sim (1, n, \epsilon)$

  - n = 3, 5, 7, … thermal production via gauge interactions (and suppressed Z couplings)

[Del Nobile, Nardecchia, Panci 1512.05353]

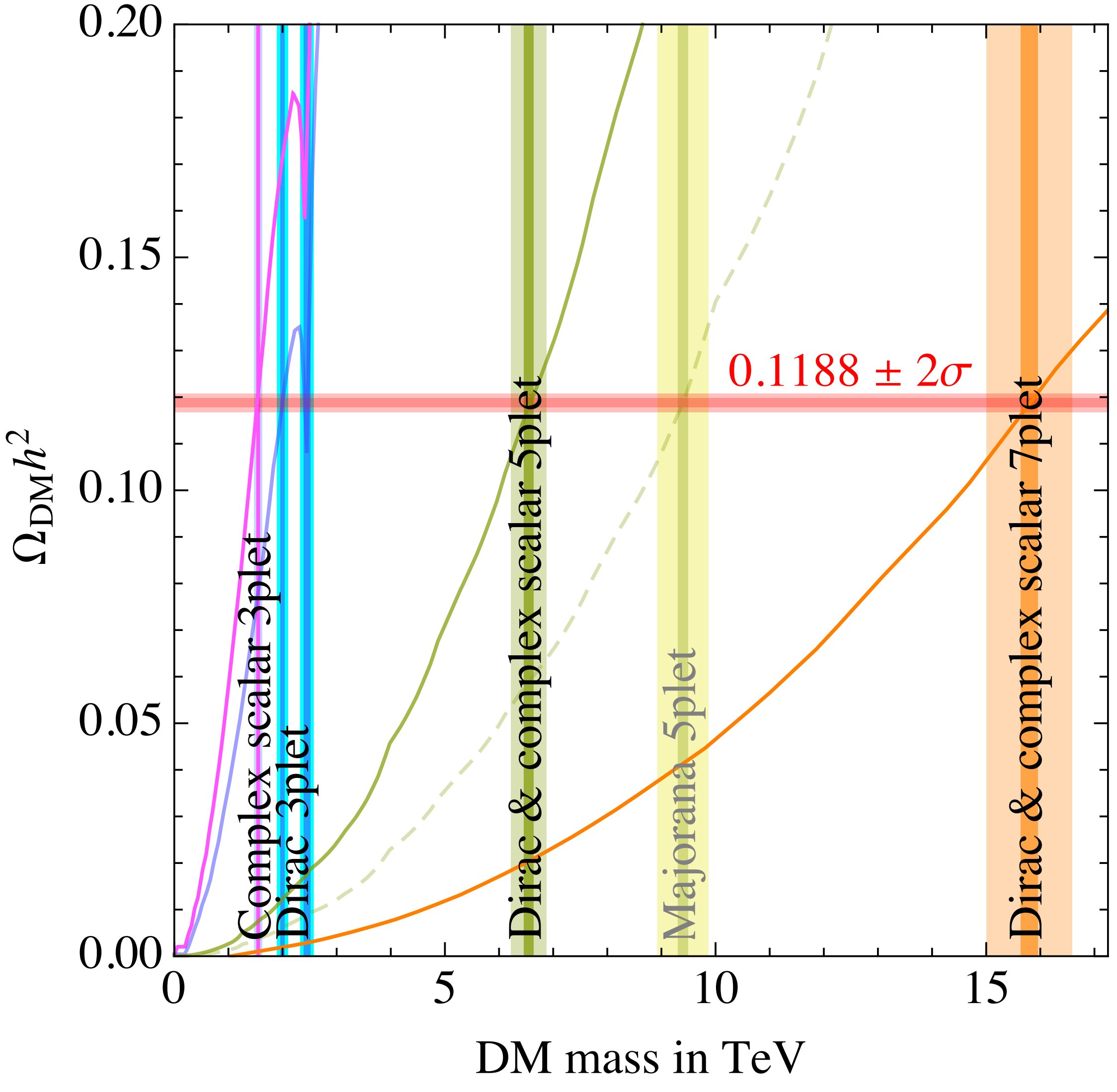


Beyond MDM

- A millicharge can effectively stabilise the DM: $\chi \sim (1, n, \epsilon)$
  - n = 3, 5, 7, … thermal production via gauge interactions (and suppressed Z couplings)
  - mass fixed by relic density

[Del Nobile, Nardecchia, Panci 1512.05353]

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$ *	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$ **	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



* wino-like MDM [Cirelli, Sala, Taoso 1407.7058]

** MDM [Cirelli, Fornengo, Strumia hep-ph/0512090]

Beyond MDM

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χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
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$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$	3.0
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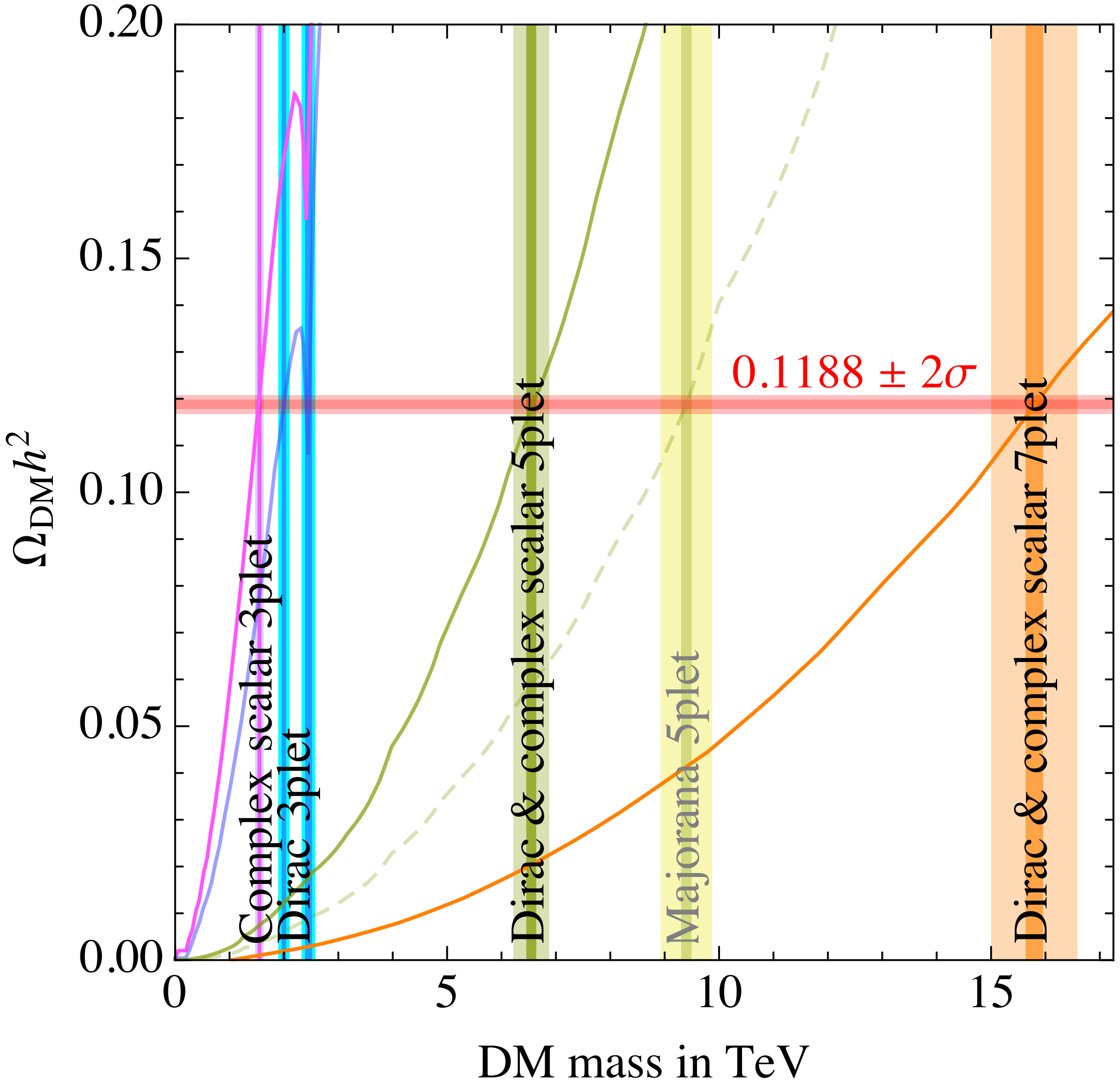
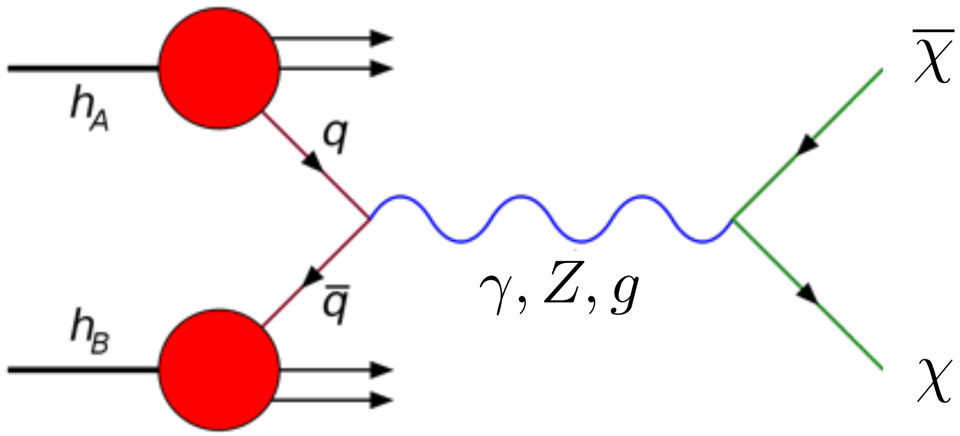


- discovery potential of "minimal" DM at $\sqrt{s} = 3$ TeV (3rd phase of CLIC)

Collider phenomenology

- Efficient production

  - Drell-Yan (for colorless) or QCD (for colored) χ pair production



Collider phenomenology

- Efficient production

  \- Drell-Yan (for colorless) or QCD (for colored) χ pair production

- Lightest state in the EW multiplet stable on detector size:

  \- Charged LP (charged tracks + …)

  \- Neutral LP (mono-x searches + disappearing tracks + …)

  \- Colored χ (R-hadrons + …)

Collider phenomenology

- Efficient production

  - Drell-Yan (for colorless) or QCD (for colored) χ pair production

- Lightest state in the EW multiplet stable on detector size:

  - Charged LP LHC bounds [400, 900] GeV [see backup slides]

  - Neutral LP → LHC bounds milder: a physics case for CLIC

  - Colored χ colored production [see backup slides]

Spectrum

- <u>Fermions</u>: mass splitting purely radiative

$$\Delta m_{\rm rad} = m_{Q+1} - m_Q \approx 166 \text{ MeV} \left(1 + 2\,Q + \frac{2\,Y}{\cos\theta_W}\right)$$

[Cirelli, Fornengo, Strumia hep-ph/0512090]

- LP can be charged for Y ≠ 0

- <u>Scalars</u>: radiative + tree-level splitting from potential term $\beta(\chi^\dagger T^a_\chi \chi)(H^\dagger T^a_H H)$

$$\Delta m_{\rm tree} = m_{I+1} - m_I \approx \frac{\beta v^2}{8 m_\chi} \approx \beta \times 7.6 \text{ GeV} \left(\frac{1 \text{ TeV}}{m_\chi}\right)$$

- the LP can be any for $\beta \in [10^{-3}, 1]$

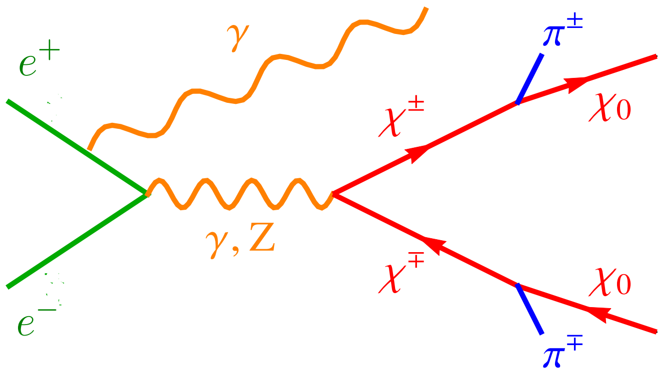
- next-to-lightest state (NLP) has $Q_{NLP} = Q_{LP} \pm 1$

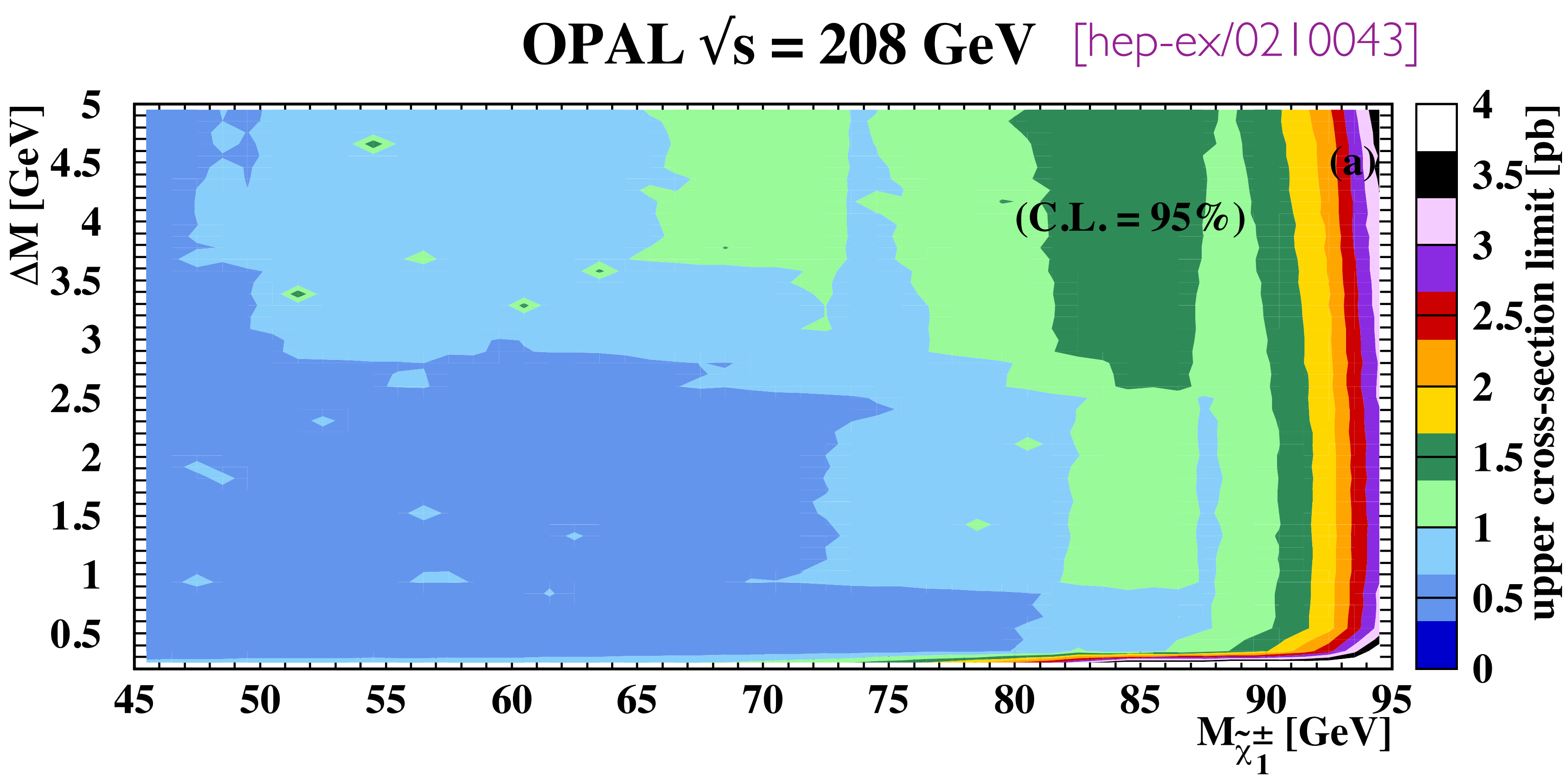
Colorless and neutral LP

- Z and H invisible widths
  - Z width: $m_\chi \gtrsim 45 \text{ GeV}$ for any EW multiplet
  - H width: only for scalars + model dependent

Colorless and neutral LP

- Z and H invisible widths
- Chargino searches at LEP
  - $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^+\gamma \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma + X$
  - Exclusions b/w 50-95 GeV for the |Q|=1 NLP

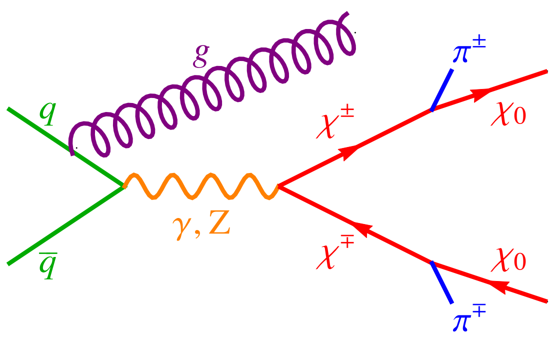


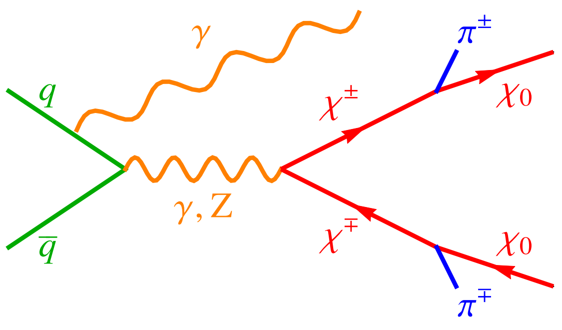


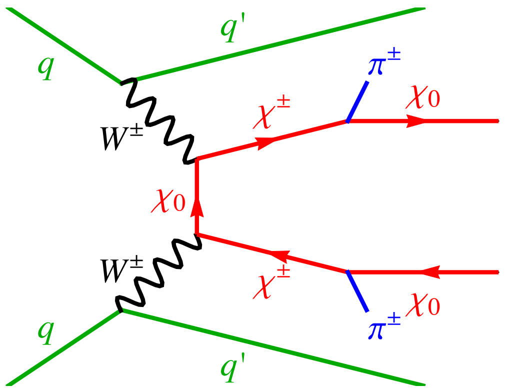
A useful benchmark: wino-like DM*

- Mono-x searches + VBF + disappearing tracks

[Cirelli, Sala, Taoso 1407.7058 + update from "Physics at a 100 TeV pp collider" 1606.00947]





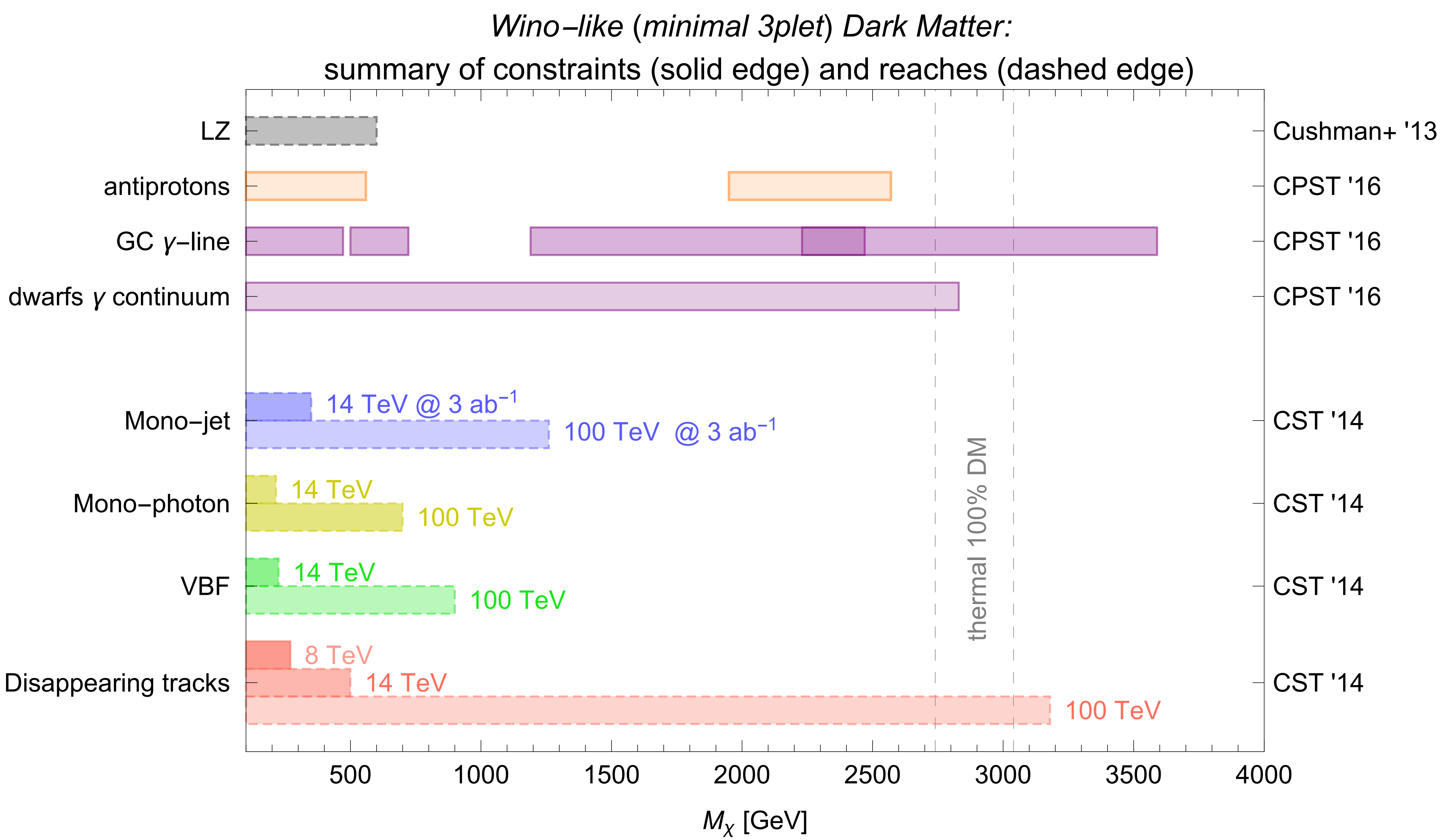


*requires an additional stabilizing symmetry

A useful benchmark: wino-like DM*

- Mono-x searches + VBF + disappearing tracks

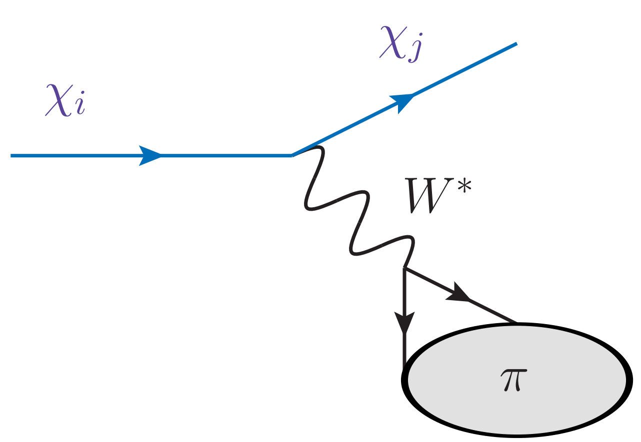
[Cirelli, Sala, Taoso 1407.7058 + update from "Physics at a 100 TeV pp collider" 1606.00947]



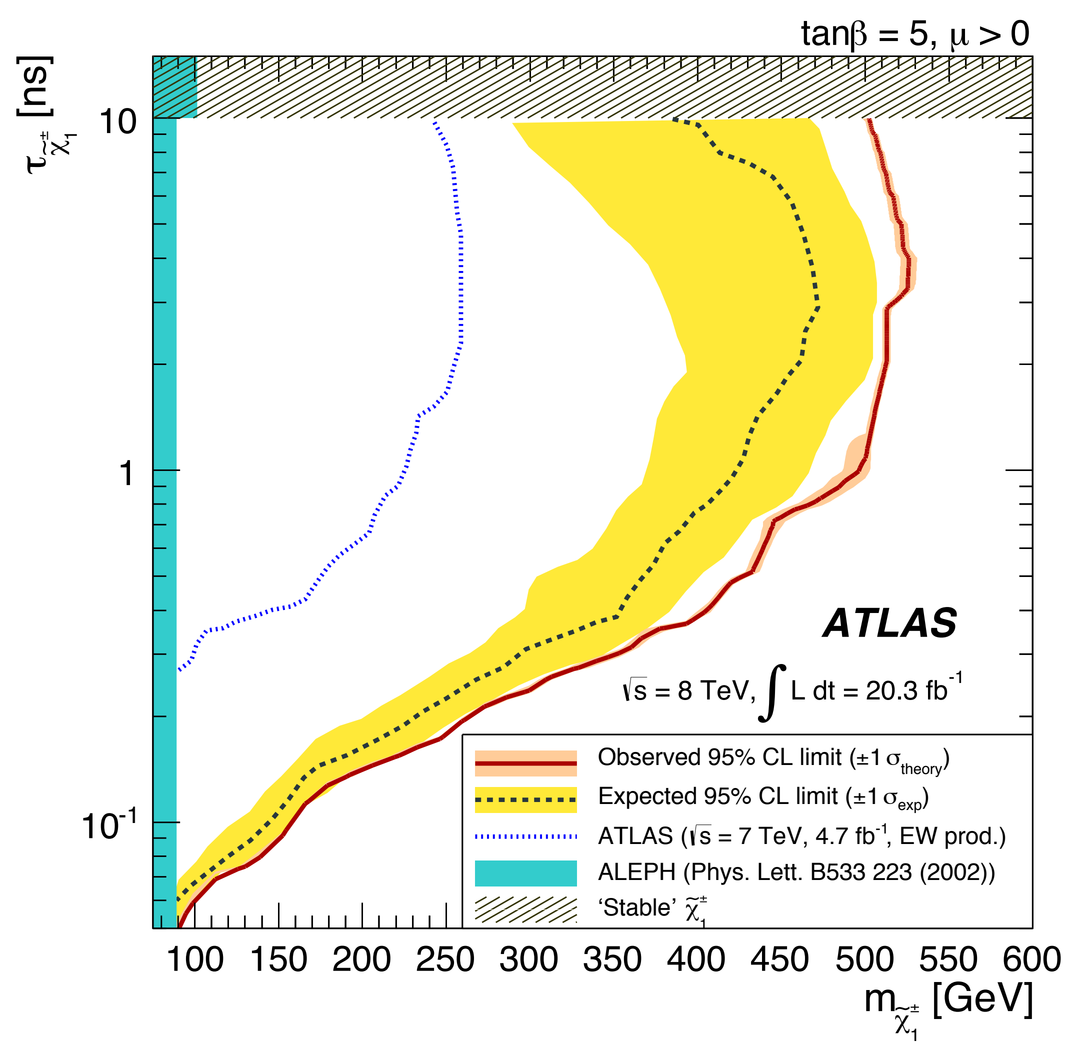
A closer look at disappearing tracks

- Accidental matter multiplets potentially bounded by DTs @ LHC
  - Naively, better sensitivity at LEP than LHC-I for lifetimes < 0.1 ns

χ	Δm [MeV]	$\tau(\chi^+ \to \chi^0 \pi^+)$ [ns]
$(1,3,0)$	166	0.10
$(1,5,0)$	166	0.034
$(1,7,0)$	166	0.017
$(1,4,3/2)$	734	0.00079



[ATLAS 1310.3675 + CMS 1411.6006]



A closer look at disappearing tracks

- Accidental matter multiplets potentially bounded by DTs @ LHC

  - Naively, better sensitivity at LEP than LHC-I for lifetimes < 0.1 ns

- Room for improvement

  - Installation of shorter tracks between Run-1 and Run-2 + new data at $\sqrt{s} = 13$ TeV (36.1 fb^{-1}) push sensitivity down to 10 ps

[ATLAS-CONF-2017-017]

  - Doubly charged states can help to extend the reach of DTs

$$\frac{\tau(\chi^{++} \to \chi^{+}\pi^{+})}{\tau(\chi^{+} \to \chi^{0}\pi^{+})} \simeq 1/20 \qquad m_{\chi^0_{(1,5,0)}} \gtrsim 270 \text{ GeV}$$

[Ostdiek 1506.03445]

→ [see talk by Pedro Schwaller for alternative strategies]

CLIC prospects - work to be done!

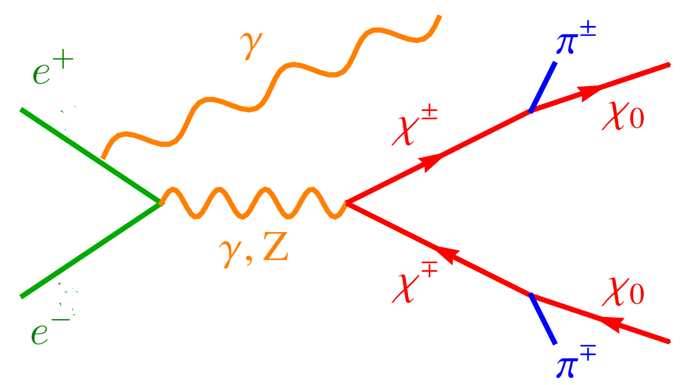
- Accidental EW multiplets with neutral LP

  - can be potentially probed at CLIC up to the kinematical limit $\sqrt{s}/2$ (pair production)

$$\sqrt{s} = \{380 \text{ GeV}, 1.5 \text{ TeV}, 3 \text{ TeV}\}$$

  - LEP-like chargino searches + disappearing tracks

    [Barklow, Münnich, Roloff, "Measurement of chargino and neutralino pair production at CLIC", LCD-Note-2011-037, 2012, focus on jet + MET final states (relevant for Δm >> 1 GeV)]



  - "Minimal" DM multiplet potentially testable

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16

Conclusions

- Accidental Matter

  the gauge quantum numbers of the NP states are such that the accidental and approximate symmetries of the SM are preserved at the ren. level

- Cosmology + consistency of the EFT up to $\Lambda_{\text{eff}} \approx 10^{15}\ \text{GeV}$ lead to a finite set of cases

- Pheno implications:

  - blind to indirect searches, colliders as the main probe of this scenario

  - most of the states are stable on the scale of the detectors

  - when the LP is colorless and neutral it can also be DM (a.k.a. Minimal DM)

Backup slides

Colored accidental matter multiplets

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}_{\rm decay}$	$\dim(\mathcal{O}_{\rm decay})$	$\Lambda^{\rm 2-loop}_{\rm Landau}$[GeV]
0	$(3,1,5/3)$	$5/3$	$\chi^\dagger H q e^c,\ \chi H^\dagger u^c \ell,\ D^\mu \chi^\dagger u^{c\dagger} \overline{\sigma}_\mu e^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(\overline{3},2,5/6)$	$1/3, 4/3$	$\chi^\dagger H q q,\ \chi^\dagger H u^c e^c,\ \chi H^\dagger q \ell,\ \chi H^\dagger u^c d^c,\ \chi H u^c u^c,\ \chi^\dagger H^\dagger d^c e^c,\ D^\mu \chi q^\dagger \overline{\sigma}_\mu u^c,\ D^\mu \chi^\dagger q^\dagger \overline{\sigma}_\mu e^c,\ D^\mu \chi d^{c\dagger} \overline{\sigma}_\mu \ell$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(\overline{3},2,11/6)$	$4/3, 7/3$	$\chi H^\dagger u^c u^c,\ \chi^\dagger H d^c e^c$	5	$5.5 \times 10^{19}\ (g_1)$
0	$(3,3,2/3)$	-1/3, 2/3, 5/3	$\chi^\dagger H^\dagger q e^c,\ \chi H u^c \ell,\ \chi H^\dagger d^c \ell,\ D^\mu \chi q^\dagger \overline{\sigma}_\mu \ell$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(3,3,5/3)$	$2/3, 5/3, 8/3$	$\chi^\dagger H q e^c,\ \chi H^\dagger u^c \ell$	5	$3.2 \times 10^{17}\ (g_1)$
0	$(3,4,1/6)$	$-4/3, -1/3, 2/3, 5/3$	$\chi H^\dagger q q,\ \chi^\dagger H q \ell$	5	$\gg m_{\rm Pl}\ (g_2)$
0	$(\overline{3},4,5/6)$	$-2/3, 1/3, 4/3, 7/3$	$\chi^\dagger H q q,\ \chi H^\dagger q \ell$	5	$\gg m_{\rm Pl}\ (g_2)$
0	$(\overline{6},2,1/6)$	-1/3, 2/3	$\chi H^\dagger q q,\ \chi^\dagger H u^c d^c,\ \chi^\dagger H^\dagger d^c d^c,\ D^\mu \chi^\dagger q^\dagger \overline{\sigma}_\mu d^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(6,2,5/6)$	$1/3, 4/3$	$\chi^\dagger H q q,\ \chi H u^c u^c,\ \chi H^\dagger u^c d^c,\ D^\mu \chi q^\dagger \overline{\sigma}_\mu u^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(\overline{6},2,7/6)$	$2/3, 5/3$	$\chi^\dagger H d^c d^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(8,1,0)$	0	$\chi H q u^c,\ \chi H^\dagger q d^c,\ D^\mu \chi D^\nu G_{\mu\nu},\ D^\mu \chi q^\dagger \overline{\sigma}_\mu q,\ D^\mu \chi u^{c\dagger} \overline{\sigma}_\mu u^c,\ D^\mu \chi d^{c\dagger} \overline{\sigma}_\mu d^c,\ \chi G^{\mu\nu} G_{\mu\nu},\ \chi G^{\mu\nu} B_{\mu\nu},\ \chi\chi\chi H^\dagger H$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(8,1,1)$	1	$\chi H^\dagger q u^c,\ \chi^\dagger H q d^c,\ D^\mu \chi^\dagger u^{c\dagger} \overline{\sigma}_\mu d^c,\ \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(8,3,0)$	0,1	$\chi H q u^c,\ \chi H^\dagger q d^c,\ \chi G^{\mu\nu} W_{\mu\nu},\ D^\mu \chi q^\dagger \overline{\sigma}_\mu q,\ \chi\chi\chi H^\dagger H$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(8,3,1)$	0,1,2	$\chi H^\dagger q u^c,\ \chi^\dagger H q d^c,\ \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$1.0 \times 10^{17}\ (g_1)$
1/2	$(6,1,1/3)$	$1/3$	$\chi^c \sigma^{\mu\nu} d^c G_{\mu\nu}$	5	$\gg m_{\rm Pl}\ (g_1)$
1/2	$(\overline{6},1,2/3)$	$2/3$	$\chi \sigma^{\mu\nu} u^c G_{\mu\nu}$	5	$\gg m_{\rm Pl}\ (g_1)$
1/2	$(8,1,1)$	1	$\chi^c \sigma^{\mu\nu} e^c G_{\mu\nu}$	5	$4.0 \times 10^{16}\ (g_1)$

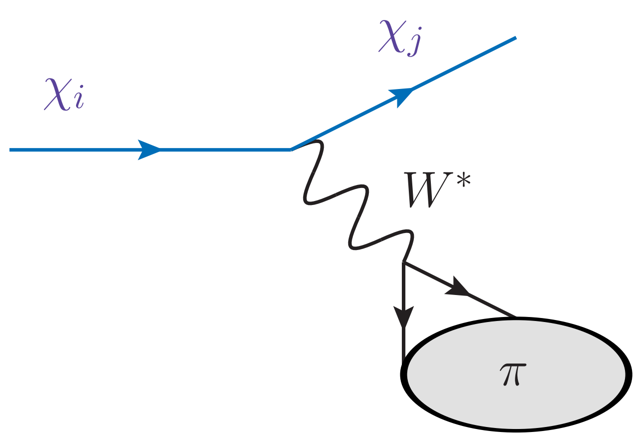
Lifetimes

- Inter-multiplet weak transitions to LP and pions

$$\Gamma(\chi^j_{I+1} \to \chi^j_I \, \pi^+) = \frac{T_+^2 G_F^2 V_{ud}^2 \Delta m^3 f_{\pi^+}^2}{\pi} \sqrt{1 - \frac{m_{\pi^+}^2}{\Delta m^2}} \approx \frac{T_+^2}{7.5 \times 10^{-12}\ \mathrm{s}} \left(\frac{\Delta m}{500\ \mathrm{MeV}} \right)^3$$

$$T_+ = \sqrt{j(j+1) - I(I+1)}$$

$$m_{\pi^+} \lesssim \Delta m \lesssim 1\ \mathrm{GeV}$$



Lifetimes

- Inter-multiplet weak transitions to LP and pions
- Decays via effective operators

$$\mathcal{L} \ni \frac{1}{\Lambda_{\text{eff}}} \mathcal{O}_{\text{decay}} + \text{h.c.}$$

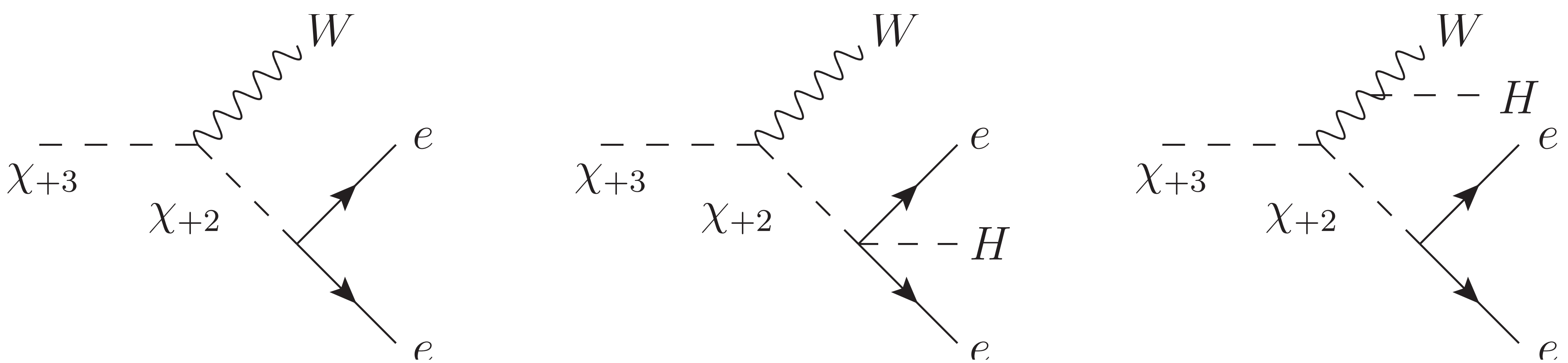
$$\Gamma_{\text{NDA}}(\chi \to \{p_f\}) = \frac{1}{4(4\pi)^{2n_f-3}} \frac{m_\chi^{3-2n_c}}{(n_f-1)!(n_f-2)!} \frac{\left(\frac{v}{\sqrt{2}}\right)^{2n_c}}{\Lambda_{\text{eff}}^2}$$

Lifetimes

- Inter-multiplet weak transitions to LP and pions
- Decays via effective operators

  - If LP cannot decay directly via effective operator: cascade decay

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}_{\rm decay}$
0	$(1,2,5/2)$	3	$\chi^\dagger H e^c e^c$
0	$(1,5,1)$	$-1,1,2,3$	$\chi^\dagger HHHH^\dagger$
0	$(1,5,2)$	$1,2,3,4$	$\chi^\dagger HHHH$



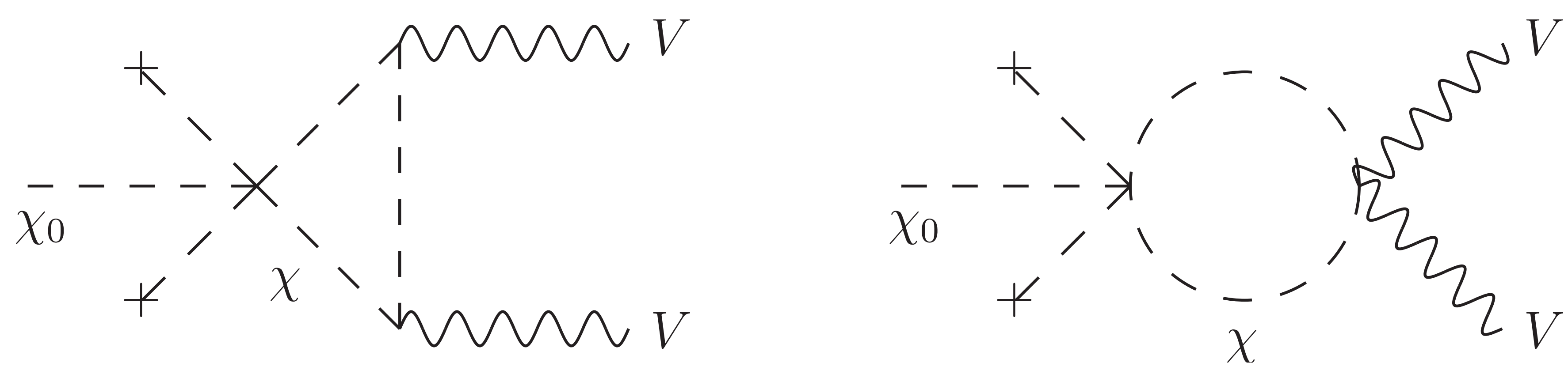
Lifetimes

- Inter-multiplet weak transitions
- Decays via effective operators

  - If LP cannot decay directly via effective operator: cascade decay

  - loop-induced decays

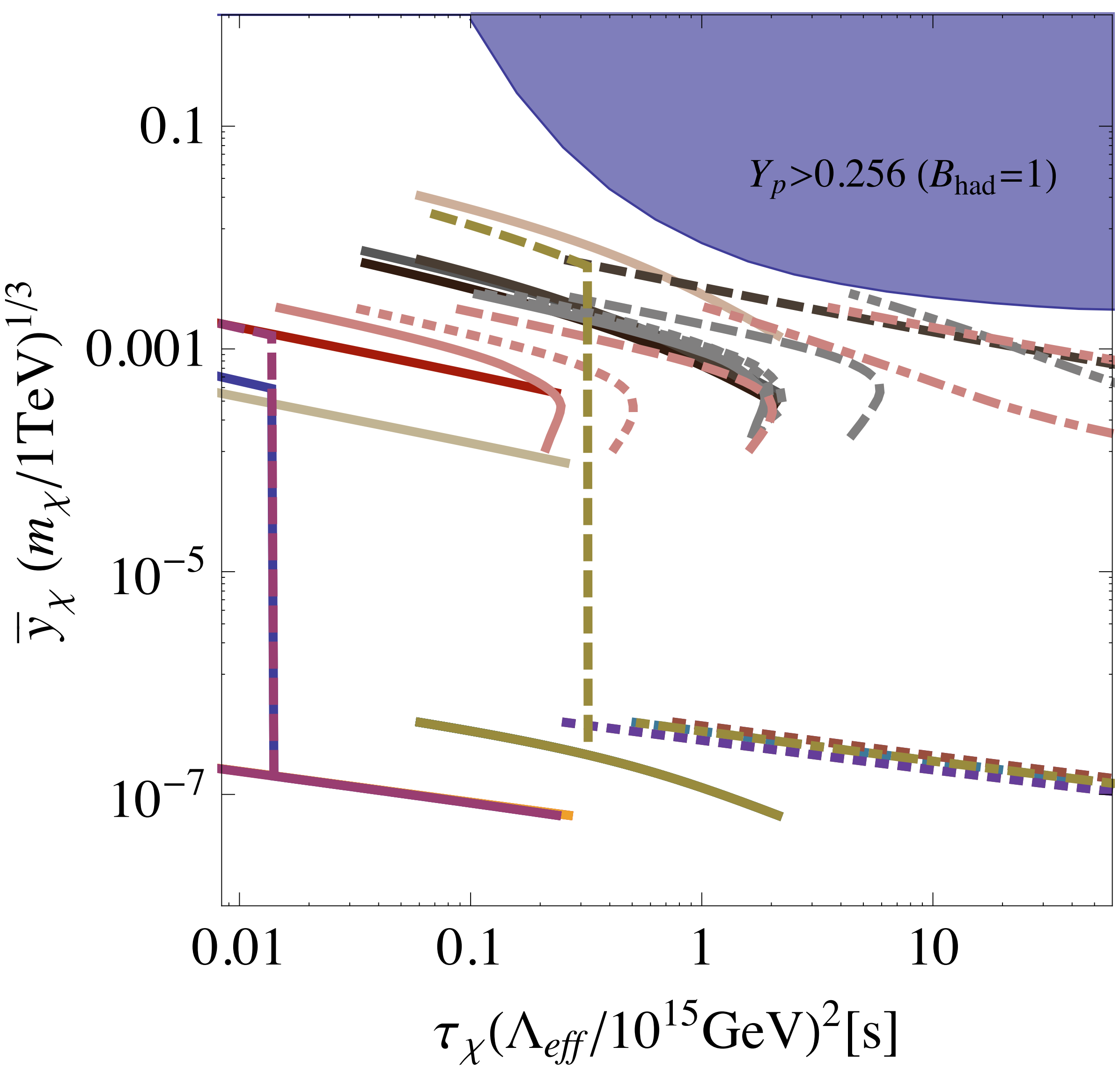
0	$(1,7,0)^\star$	0,1,2,3	$\chi^3 H^\dagger H$	5	1.4×10^{16} (g_2)

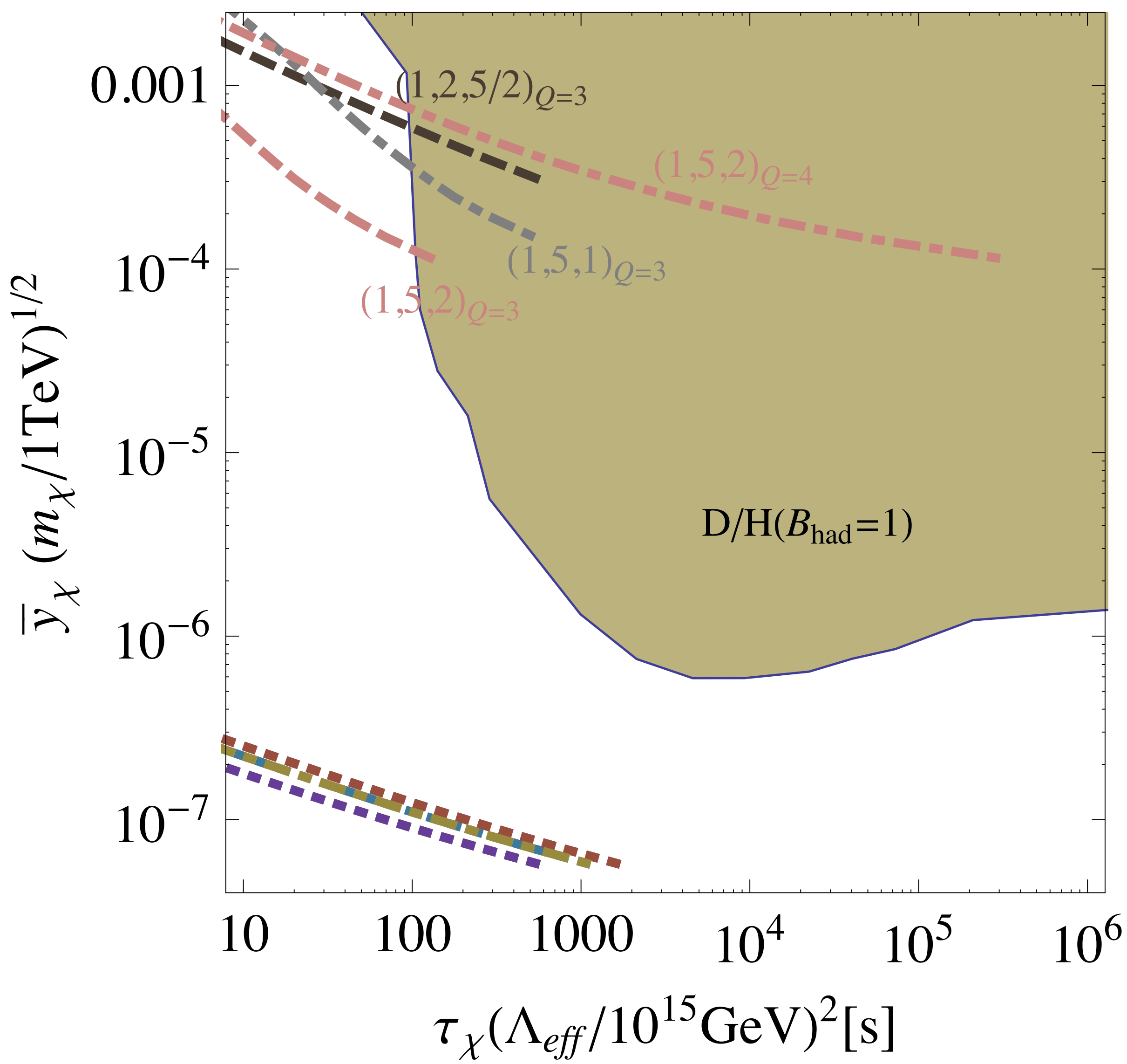


$$\Gamma_{\chi_0} = \frac{857 C_0^2}{441548\pi^5} \frac{g^4 v^4}{\Lambda_{\text{eff}}^2 m_\chi} = 5.9 \times 10^{-8}\ \text{s}^{-1} \left(\frac{10^{15}\,\text{GeV}}{\Lambda_{\text{eff}}}\right)^2 \left(\frac{1\,\text{TeV}}{m_\chi}\right)$$

BBN bounds

- Release of energy due to LP decay can alter BBN predictions



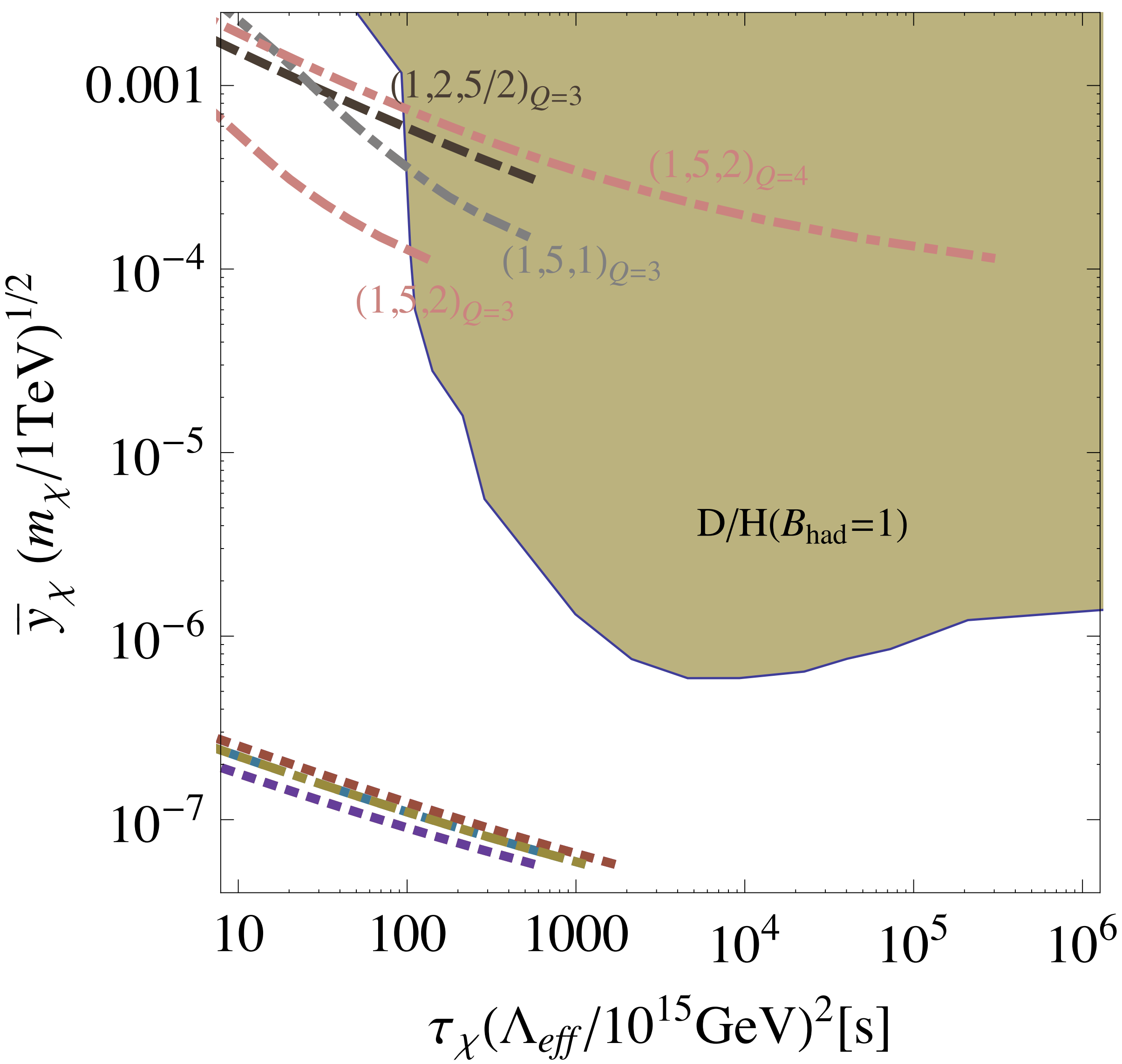


BBN bounds

- Release of energy due to LP decay can alter BBN predictions

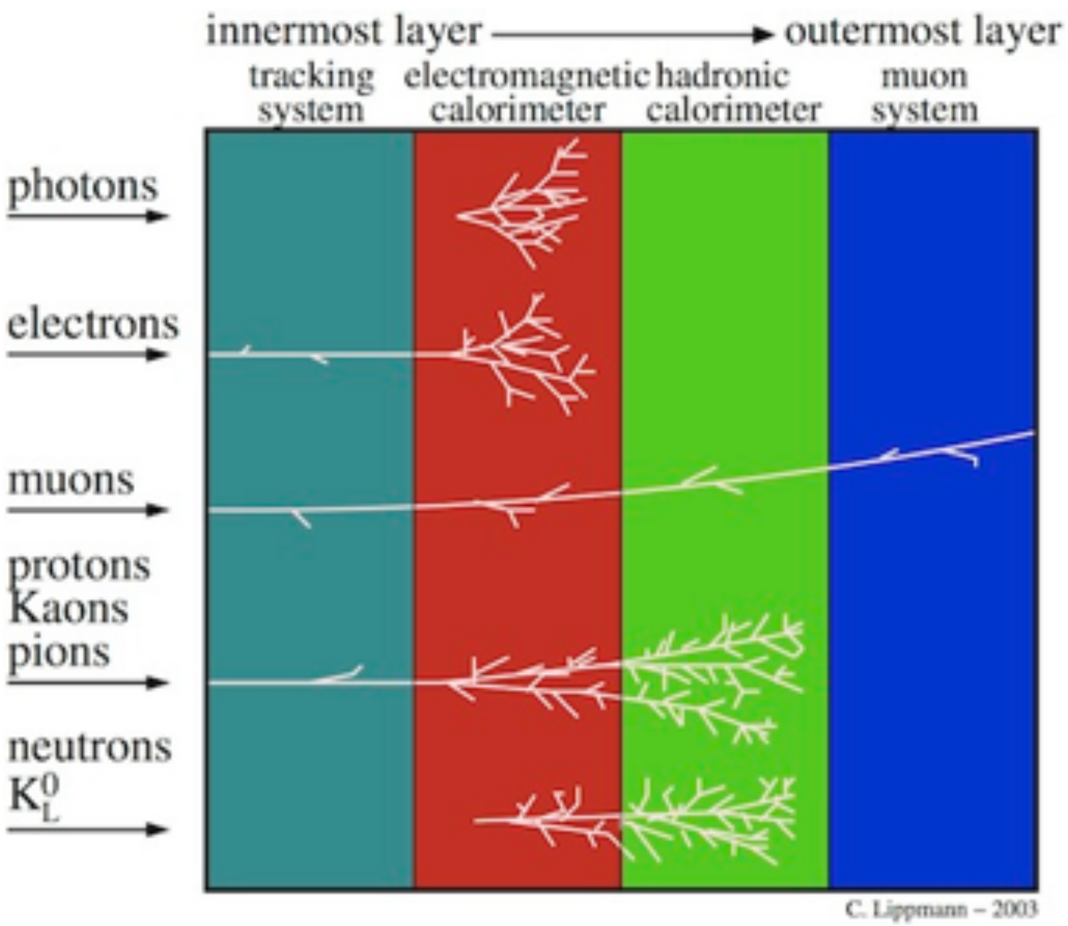
- bounds on uncoloured states decaying via loops or cascades

Spin	χ	$Q_{\rm LP}$	Mass bound [GeV]
0	$(1,2,5/2)$	3	790
0	$(1,5,1)$	3	920
0	$(1,5,2)$	3, 4	530, 1900
0	$(1,7,0)$	0, 1, 2, 3	$\gg 5000$



Colorless and charged LP

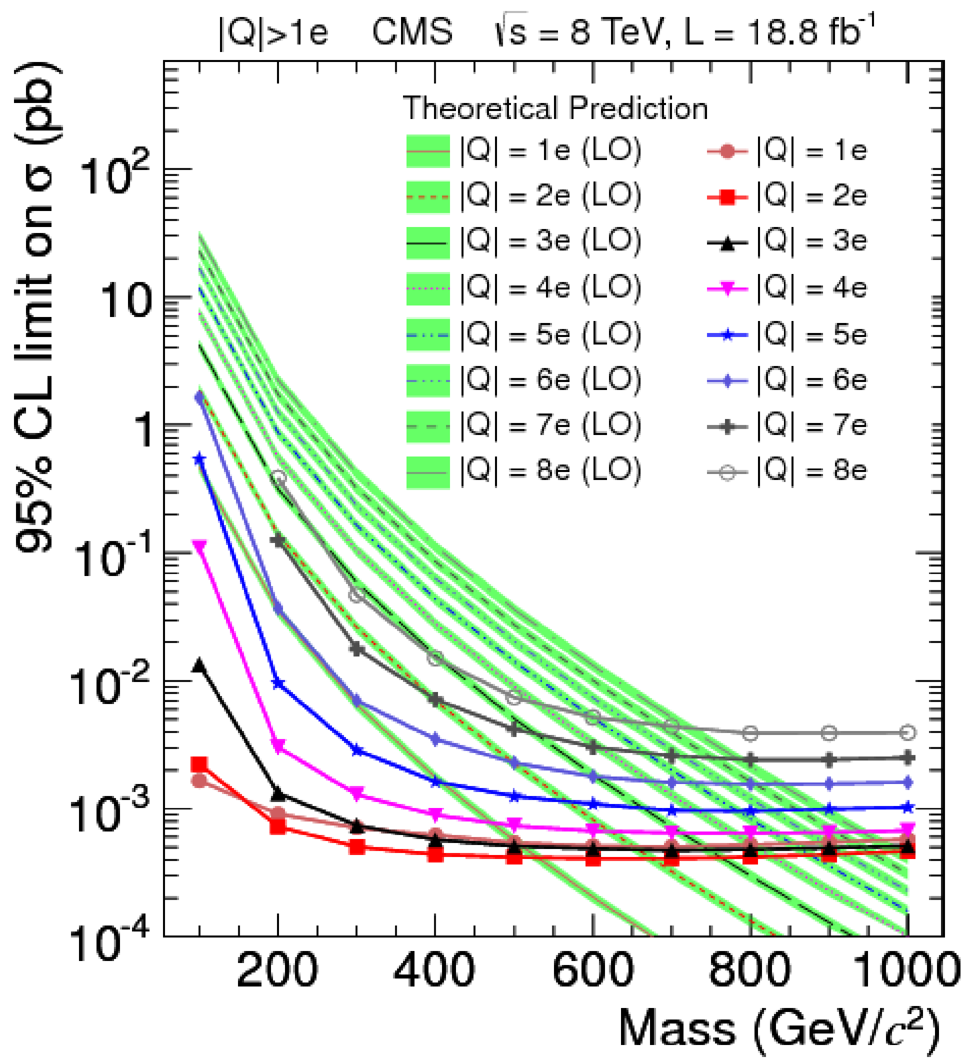
- Heavy (> 100 GeV) stable (> few ns) charged particles
  - Anomalous energy loss in the silicon tracker (*tracker-only analysis*)
  - Longer time of flight to the outer detector (*tracker+TOF analysis*)

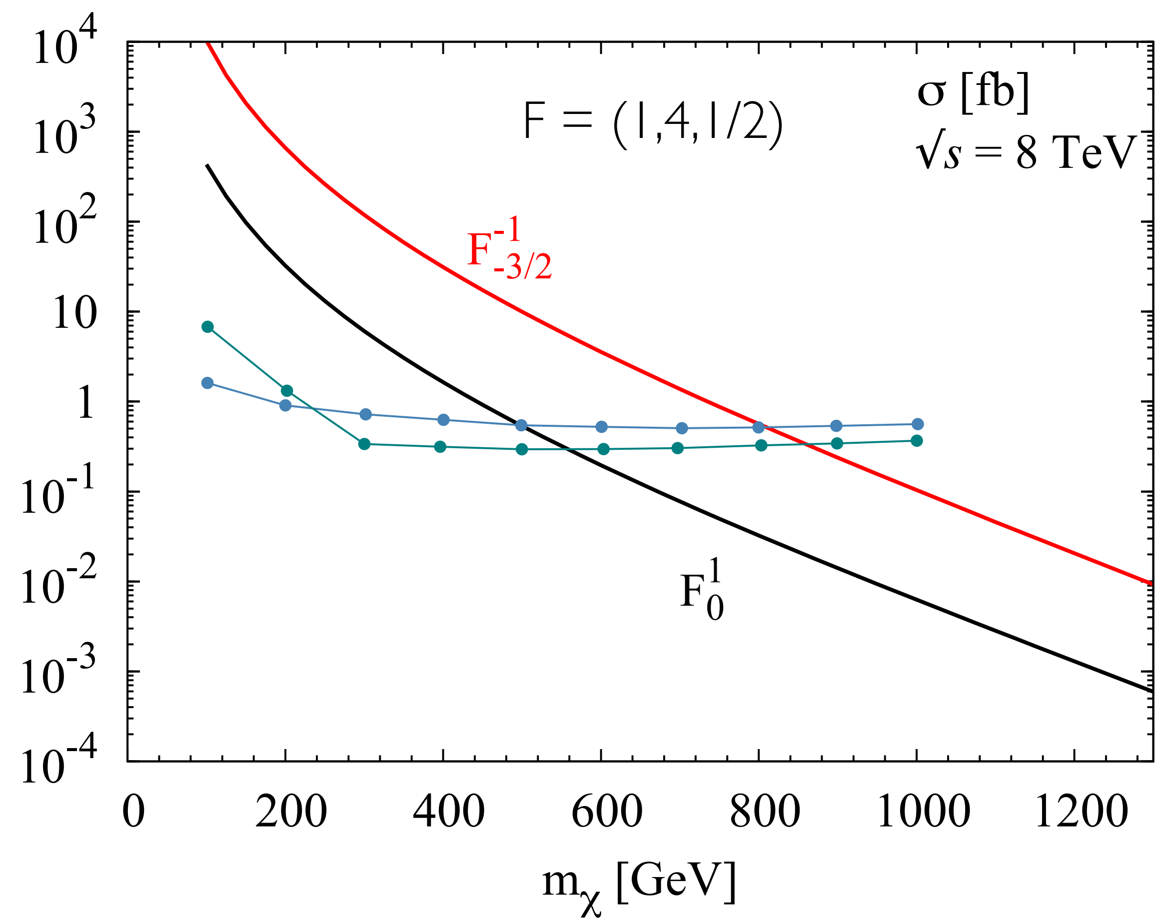


Colorless and charged LP

- Heavy (> 100 GeV) stable (> few ns) charged particles
  - Reinterpretation of the results for non-trivial SU(2) quantum numbers

[1305.0491 + CMS-PAS-EXO-13-006]





Colorless and charged LP

- Heavy (> 100 GeV) stable (> few ns) charged particles

  - Reinterpretation of the results for non-trivial SU(2) quantum numbers

Spin	χ	Q_{LP}	Mass bound [GeV]
0	$(1,2,3/2)$	1, 2	430, 420
0	$(1,2,5/2)$	2, 3	460, 460
0	(1, 5, 0)	0, 1, 2	75, 500, 600
0	(1, 5, 1)	-1, 0, 1, 2, 3	640, $50^\star$ (85), 320, 490, 600
0	(1, 5, 2)	0, 1, 2, 3, 4	85, 530, 410, 500, 570
0	(1, 7, 0)	0, 1, 2, 3	75, 500, 600, 670
1/2	$(1,4,1/2)$	-1	860
1/2	$(1,4,3/2)$	0	90
1/2	(1, 5, 0)	0	95

- $\sqrt{s} = 13$ TeV data do not change much the bounds (2.5 fb^{-1} integrated luminosity)

[CMS-EXO-15-010 1609.08382]

Colored multiplets

- Colored, long-lived particles → hadronize before decay
- Large theoretical uncertainties ! [See e.g. "Stable massive particles at colliders", Fairbairn et al. (2007)]
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stop & decay

Colored multiplets

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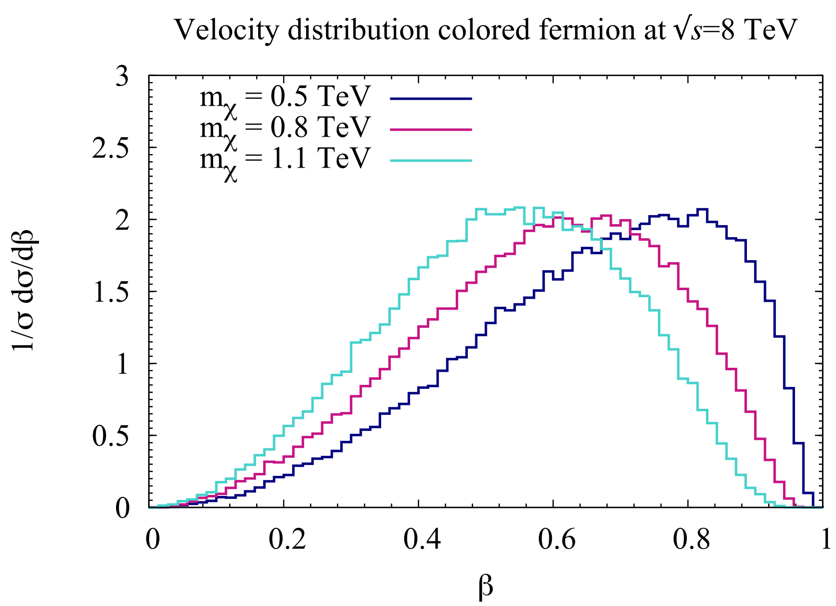
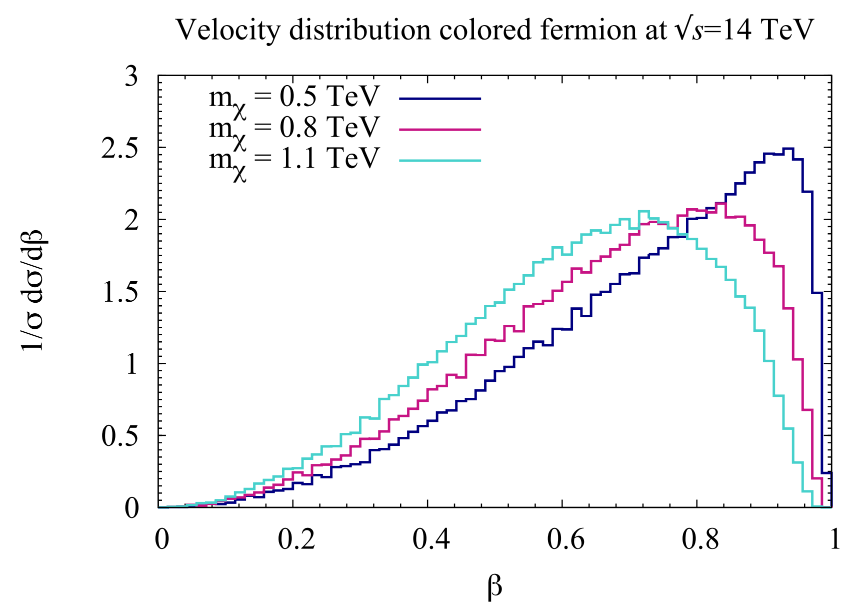
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stop & decay
- 1) Production

  - Large x-section (strong interactions)
  - Pair production (due to accidental symmetry)
  - Fate of the particle depends on velocity distribution





Colored multiplets

- Colored, long-lived particles $\longrightarrow$ hadronize before decay
- Large theoretical uncertainties ! [See e.g. "Stable massive particles at colliders", Fairbairn et al. (2007)]
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stop & decay
- 2) Hadronization

- Interest in triplets, sextects, octects, ... C_3, C_6, C_8
- Bound states

$$C_3\overline{q}, C_3 q_1 q_2, \ldots$$
$$C_6 qg, C_6 q\overline{q}q, C_6 \overline{qq}, \ldots$$
$$C_8\overline{q}q, C_8 q_1 q_2 q_3, C_8 g, \ldots$$

R-hadron	Pythia fraction (%)	Herwig fraction (%)
$R^+_{\tilde{g}u\bar{d}}$, $R^-_{\tilde{g}d\bar{u}}$	34.2	28.2
$R^0_{\tilde{g}u\bar{u}}$, $R^0_{\tilde{g}d\bar{d}}$	34.2	28.2
$R^+_{\tilde{g}u\bar{s}}$, $R^-_{\tilde{g}s\bar{u}}$	9.7	17.5
$R^0_{\tilde{g}d\bar{s}}$, $R^0_{\tilde{g}s\bar{d}}$, $R^0_{\tilde{g}s\bar{s}}$	10.4	26.1
$R^0_{\tilde{g}g}$	9.9	—
$R^{++}_{\tilde{g}}$, $R^-_{\tilde{g}}$ (anti)baryons	0.1	—
$R^+_{\tilde{g}}$, $R^-_{\tilde{g}}$ (anti)baryons	0.8	—
$R^0_{\tilde{g}}$ (anti)baryons	0.7	—

Colored multiplets

- Colored, long-lived particles → hadronize before decay
- Large theoretical uncertainties ! [See e.g. "Stable massive particles at colliders", Fairbairn et al. (2007)]
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stop & decay
- 3) Interactions with matter: e.m. and strong

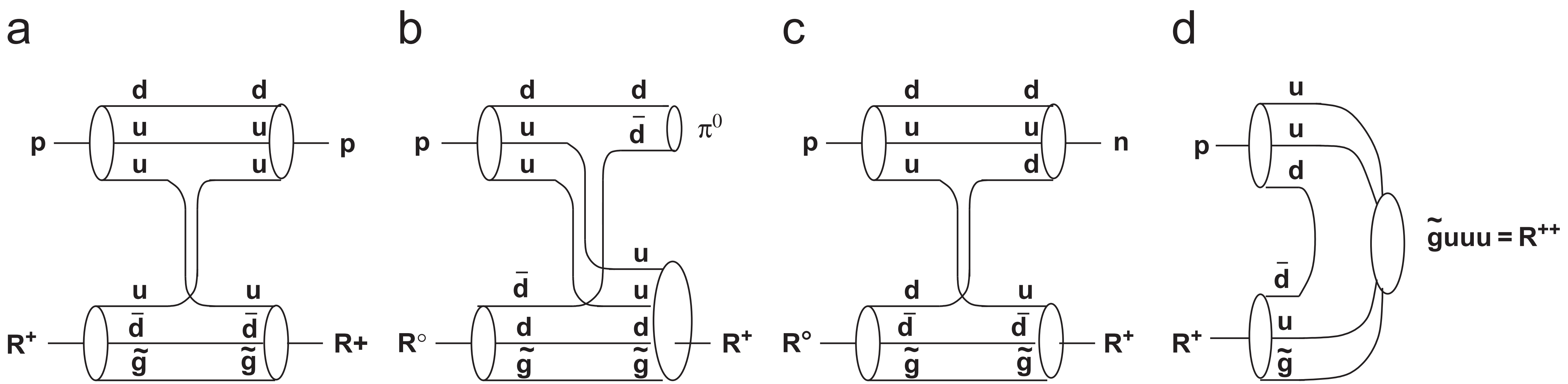


Fig. 13. *R*-hadron–proton scattering processes: (a) elastic scattering; (b) inelastic scattering leading to baryon and charge exchange; (c) inelastic scattering leading to charge exchange; (d) resonance formation.

Colored multiplets

- Colored, long-lived particles → hadronize before decay
- Large theoretical uncertainties ! [See e.g. "Stable massive particles at colliders", Fairbairn et al. (2007)]
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stop & decay
- 4) Stop & decay

  - Depending on the mass of the new state, new particle could stop and decay

Colored multiplets

- Colored, long-lived particles $\longrightarrow$ hadronize before decay
- @ LHC all searches made in the context of R-hadrons

  - Longer time of flight + anomalous energy loss [CMS 1305.0491, ATLAS 1411.6795]

$$m_{\tilde{g}} > 1250 \text{ GeV} \qquad\qquad m_{\tilde{t}} > 935 \text{ GeV}$$

  - Out-of-time decay [ATLAS 1310.6584]

$$m_{\tilde{g}} \gtrsim 900 \text{ GeV} \qquad\qquad m_{\tilde{t}}, m_{\tilde{b}} \gtrsim 350 \text{ GeV}$$