Accidental matter at the LHC

based on arXiv: 1504.00359

Ramona Gröber in coll. with Luca Di Luzio, Jernej Kamenik and Marco Nardecchia | 07.04.2015

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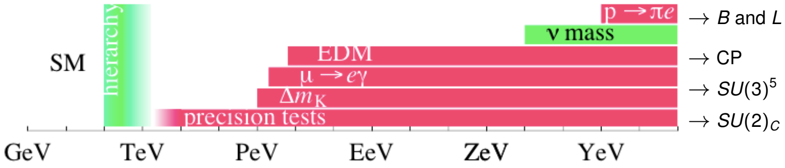
OUTLINE

Direct searches:
No evidence for new physics yet!

Indirect probes:
SM prediction fulfilled to high accuracy!
SM as EFT (with $\mathcal{O}(1)$ couplings)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c^d}{\Lambda^{d-4}} \mathcal{O}_{dim>4}$$



[Strumia, Vissani]

How can NP at EW scale be consistent with indirect bounds?

- Extra protection mechanism such as MFV, R-parity, ...
- Quantum numbers are such that states automatically perserve accidental/approximate symmetry structure of SM

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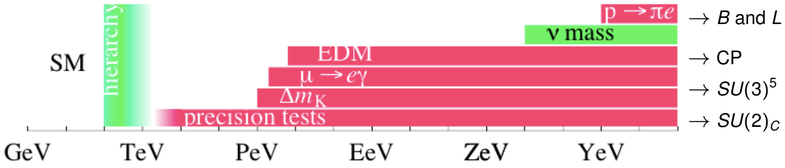

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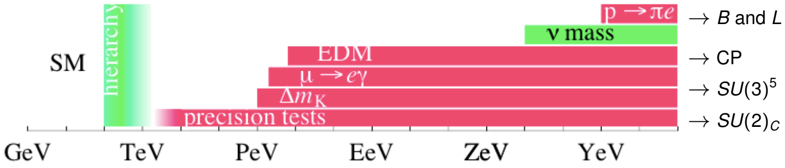

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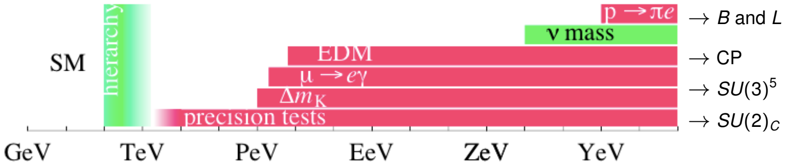

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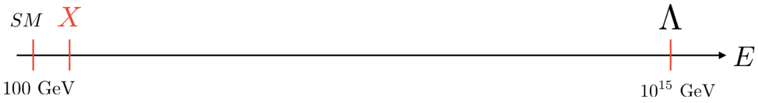
Which (single state) extensions of SM particle content with mass close to EW scale

- form consistent EFTs with cut-off
  $$\frac{HH\ell\ell}{\Lambda} \to m_\nu = \frac{v^2}{\Lambda} = \mathcal{O}(0.1\text{ eV}) \to \Lambda \sim 10^{15}\text{ GeV},$$
- are cosmologically viable
- automatically preserve accidental/approximate structure of SM?

automatically= without any additional protection mechanism

accidental/approximate= preservation of $U(3)^5$ is sufficient, custodial and CP not needed as requirements



- Automatical preservation of $U(3)^5$ approximate symmetry:
  Chose quantum numbers such that there are no couplings to SM fermions via operators $\Psi_{SM}\Psi_{SM}$, $\Psi_{SM}H$ and $\Psi_{SM}H^\dagger$
  - Fermion:
    $\chi \neq \Psi_{SM}, (1,1,0), (1,3,0), (1,3,1), \ldots$
    If χ Dirac

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

    $\mathcal{L}$ invariant under $\chi \to e^{i\theta}\chi\,, \chi^c \to e^{-i\theta}\chi^c \implies \chi$ stable on $d = 4$ operator level
  - Boson:
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- Cosmological viable:
  - Stable colorless and electrically neutral with $Y = 0$ can be dark matter candidate. [Minimal dark matter, Cirelli, Fornengo, Strumia]
  - Long-lived charged and colored relics are severly bound by BBN, thermalization of CMB before recombination, diffuse γ background, non-observation of anomolous isotopes. Need to decay sufficiently fast

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\chi} + \sum \frac{1}{\Lambda}\mathcal{O}_5(\phi_{SM}, \chi) + \sum \frac{1}{\Lambda^2}\mathcal{O}_6(\phi_{SM}, \chi)$$

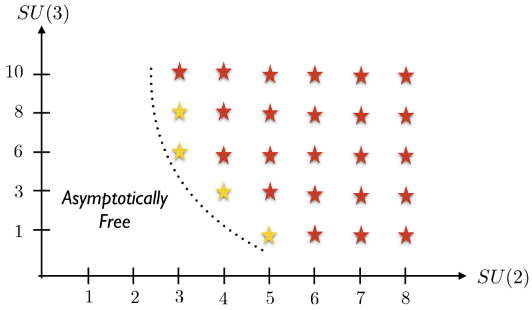
$$\Lambda = 10^{15}\ \text{GeV}, \qquad \underbrace{\Gamma_5 \sim \frac{m_\chi^3}{\Lambda^2}}_{\tau \lesssim 1\ \text{s}}, \qquad \underbrace{\Gamma_6 \sim \frac{m_\chi^5}{\Lambda^4}}_{\tau \sim 10^{20}\ \text{s}} \to \text{Too slow!}$$

$\Rightarrow$ New states have to decay via dim 5 operators if they cannot be a dark matter candidate.

- Consistent EFTs with cut-off $\Lambda = 10^{15}$ GeV:
  - No Landau pole before $\Lambda = 10^{15}$ GeV.
  - Extra matter changes running of gauge couplings

$$\mu \frac{d}{d\mu} g_i = -\beta_i g_i^3 \quad \text{with} \quad \beta_i = \text{gauge} - \text{matter}$$

  - Higher quantum numbers $\rightarrow$ lower Landau poles.
  - If there is an accidental cancellation in the one loop beta function, two-loop RGEs might even change the qualitative behaviour.



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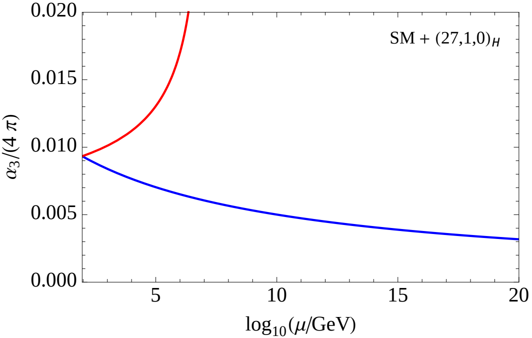


ACCIDENTAL MATTER MULTIPLES

Spin	χ	Q_{LP}	$\mathcal{O}_{\text{decay}}$	dim($\mathcal{O}$)	$\Lambda^{2-\text{loop}}_{\text{Landau}}$[GeV]
0	$(1, 1, 0)$	0	$\chi H H^\dagger$	3	$\gg m_{\text{Pl}}$ (g_1)
0	$(1, 3, 0)$	0,1	$\chi H H^\dagger$	3	$\gg m_{\text{Pl}}$ (g_1)
0	$(1, 4, 1/2)$	-1,0,1,2	$\chi H H^\dagger H^\dagger$	4	$\gg m_{\text{Pl}}$ (g_1)
0	$(1, 4, 3/2)$	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	$(1, 7, 0)$	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 scalar multiplets and 3 colored fermion multiplets

Spectrum for fermonic χ:

Mass splitting purely radiative

[Del Nobile, Franceschini, Pappadopulo, Strumia]

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

Y and T_3 fix LP.

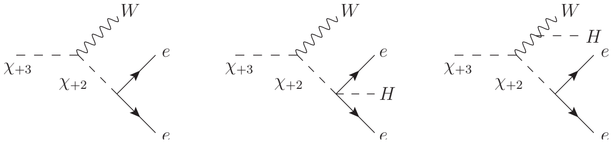
Spectrum for scalar χ:
Radiative and tree-level splitting from potential term

$$\beta(\chi^\dagger T^a_\chi \chi)(H^\dagger T^a_H H)$$

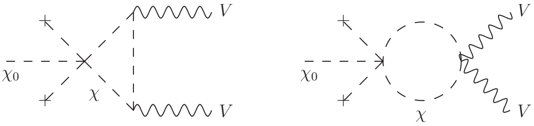
However, mass splitting restricted to be smaller than $\mathcal{O}$(20 GeV) by EWPTs.
All members of a multiplet can be LP.

DECAYS

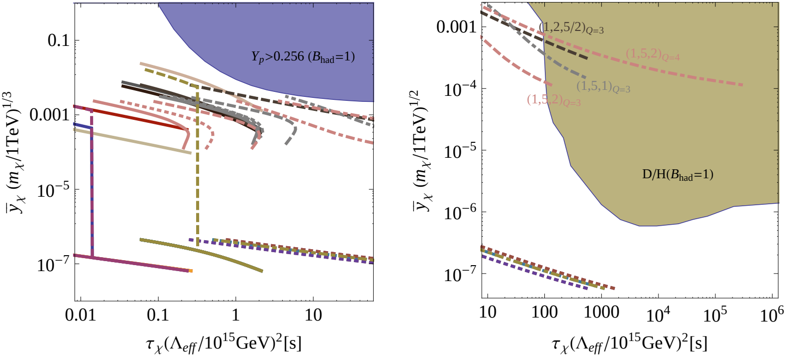
- Inter-multiplet decays to LP and pions
- Decays via effective operators
- If LP cannot directly decay via effective operator: Cascade decays



- $(1,7,0)_S$ can only decay at one-loop level



BBN BOUNDS

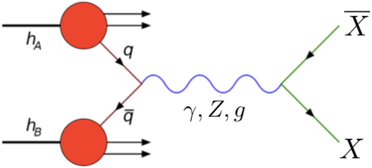


- Release of energy due to LP decay can alter BBN predictions
- Key quantities are relic density and the particles lifetime
- Bounds can be obtained on non-colored states which decay via loops or cascades

Spin	χ	Q_{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	$(1,7,0)$	$0,1,2,3$	$\gg 5000$

Collider phenomenology

- Non-renormalizable terms not relevant for collider phenomenology
- For most of the cases: Lightest particle inside an SU(2) multiplet is stable on detector scale
- New exotic fermions and scalars are pair produced



Collider phenomenology depends on whether

- Multiplet can decay via renomalizable interactions like $(1,1,0)_S$, $(1,3,0)_S$, $(1,4,1/2)_S$ and $(1,4,3/2)_S$
- LP is colorless and charged
- LP is colorless and neutral
- Multiplet is colored

Colorless and charged LP

- Stable massive charged particles can be detected by
  - Longer time of flight to outer detectors
  - Anomalous energy loss Depends on Q and β, described by Bethe-Bloch formula
- Various analyses by ATLAS and CMS, we used [CMS, 1305.0491]
- Reinterpretation of results for multiple charged fermions with non-trivial quantum numbers under SU(2) and scalars with [CMS-PAS-EXO-13-006]

  Bounds typically

$$m_\chi \gtrsim 500 \text{ GeV}$$

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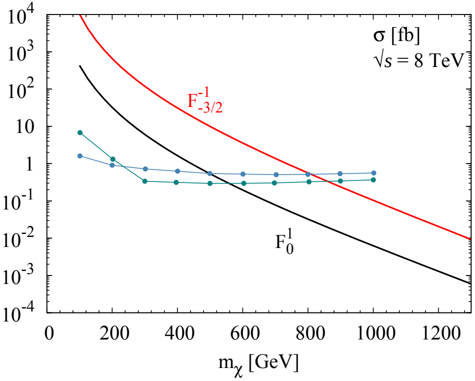

COLORLESS AND NEUTRAL LP

- Mono-x searches
  Not sensitive yet

see also [Cirelli, Sala, Taoso]

- Z boson width and invisible H boson width
  Z width: $m_\chi \gtrsim 45$ GeV for $Y \neq 0$
  H width: for scalars, depends on portal coupling $\alpha|\chi|^2|H|^2$
- Chargino searches at LEP
  Searches for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^+\gamma \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma + X$
  Leads to exclusion bounds between 50-95 GeV for the $|Q| = 1$ NLP state

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Spin	χ	$Q_{\rm LP}$	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, 590
0	(1, 5, 1)	-1, 0, 1, 2, 3	620, 50* (85), 320, 480, 590
0	(1, 5, 2)	0, 1, 2, 3, 4	85, 520, 400, 500, 560
0	(1, 7, 0)	0	75
1/2	(1, 4, 1/2)	-1	860
1/2	(1, 4, 3/2)	0	90
1/2	(1, 5, 0)	0	95

CONCLUSION

- Numerous indirect probes suggest that NP is highly non generic.
  - Extra protection mechanism for large contributions to indirect probes such as MFV, *R*-parity, ...
  - Quantum numbers of new states are such that accidental and approximate symmetries of SM are automatically perserved.
- Requiring also consistency with cosmology and validity up to $\Lambda = 10^{15}$ GeV, only a finite set of states remain.
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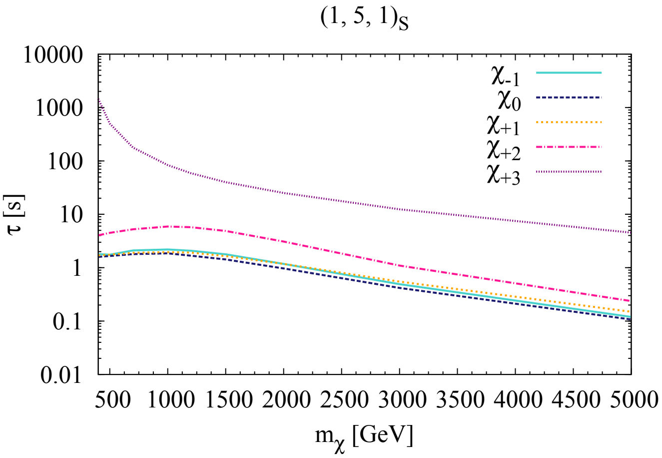
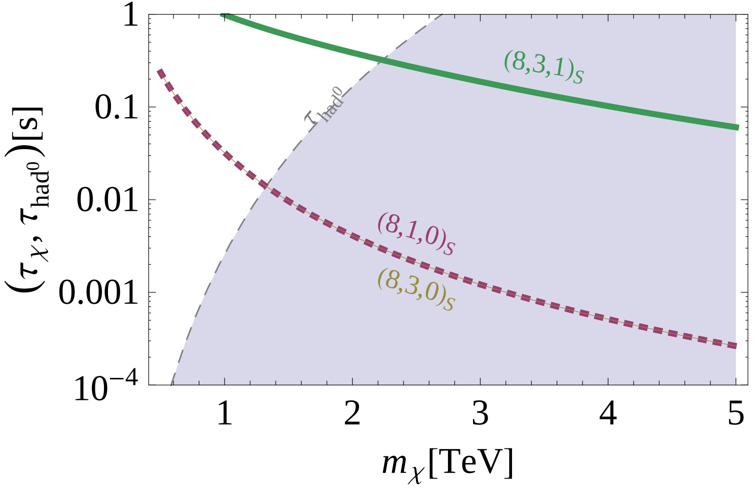
Thanks for your attention!

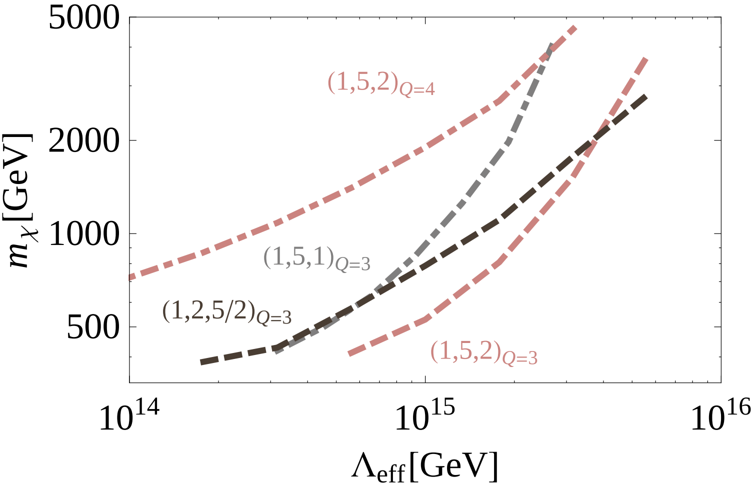
Cascade decays: Typical lifetimes



Hadronic lifetime for $Q = 0$ LP



SCALE DEPENDENCE BBN BOUNDS



- Colored long lived particles hadronize before decaying
- Form bound states

[Fairbairn, Kraan, Milstead, et al.]

$$C_3\bar{q},\ C_3 q_1 q_2,\ C_6 qg,\ C_6 q\bar{q}q,\ C_6 \bar{q}\bar{q},\ C_8 g,\ C_8 \bar{q}q \text{ and } C_8 q_1 q_2 q_3$$

  Hadronization process source of uncertainty.
- Nuclear and electromagnetic interactions with the detector material
  Bounds depend on nucelar scattering model.
- (Stopping and decay inside the outer detectors)

All experimental exclusion limits so far given in the context of SUSY!