Accidental matter at the LHC

27th Rencontres de Blois

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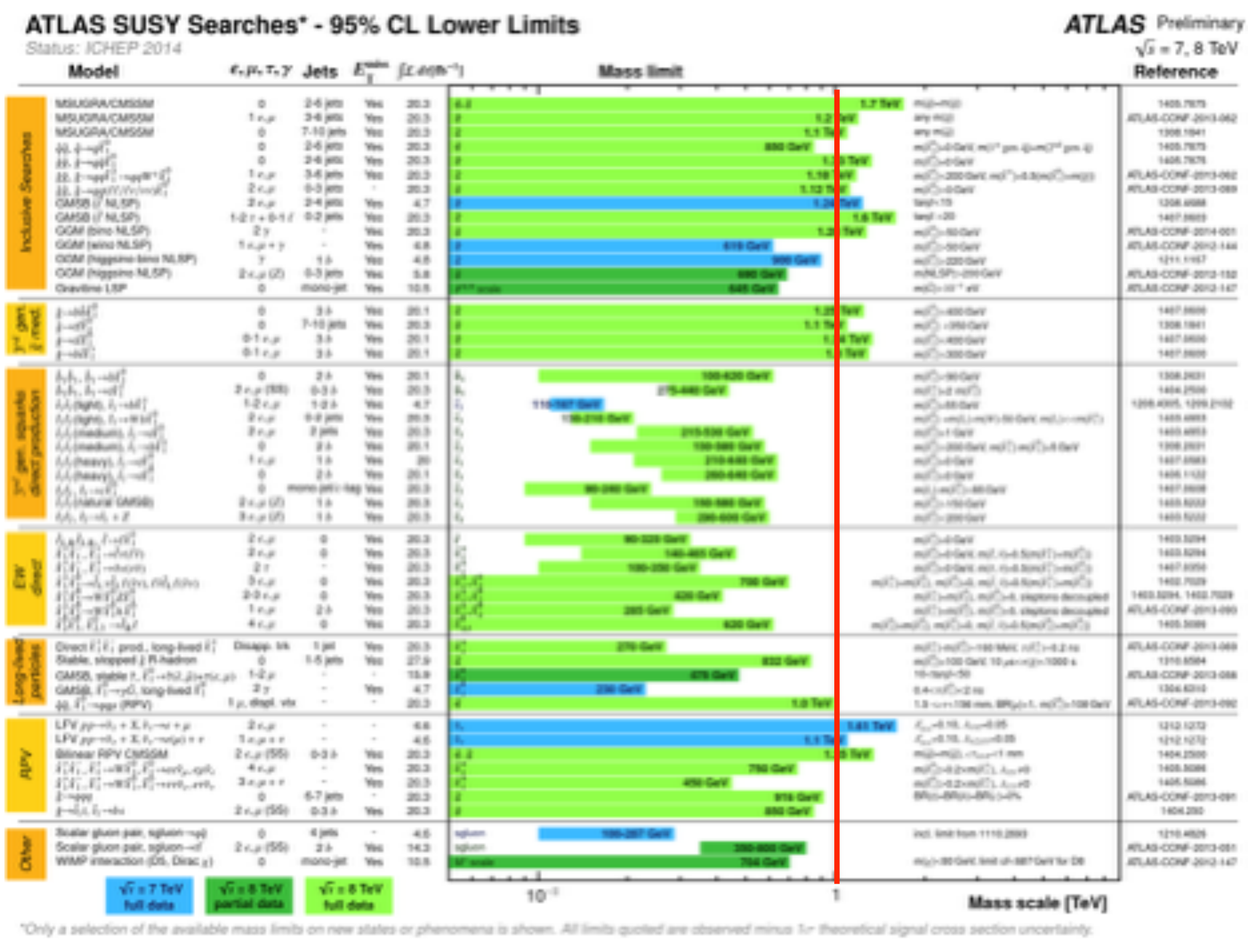
Outline

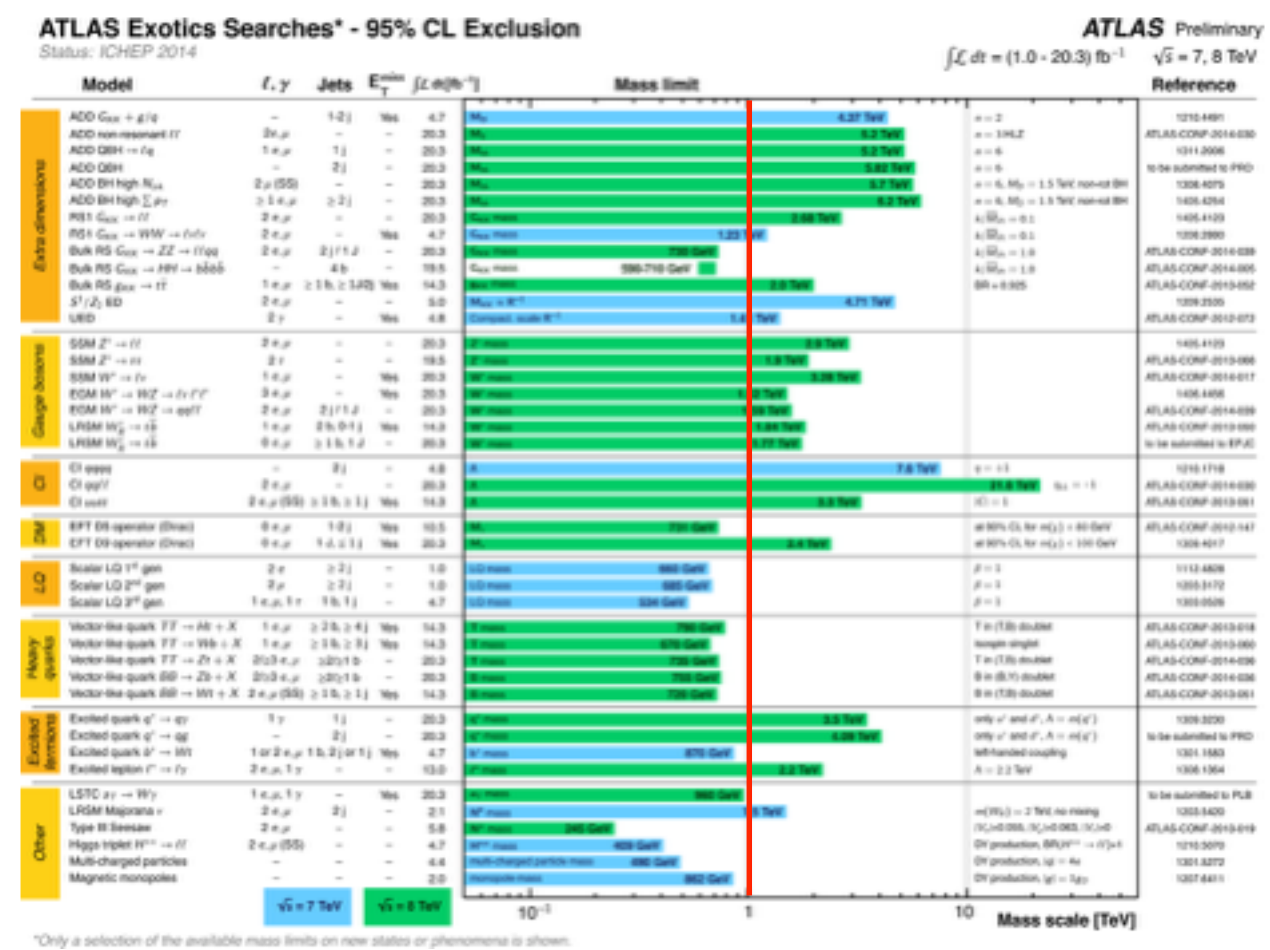
- Motivation
- Accidental matter
- Cosmology
- Collider pheno

The scale of new physics (NP)

- LHC-I: no deviations from the SM → $\Lambda_{\rm SM} \gtrsim {\rm TeV}$ (colored)



SUSY



Exotics

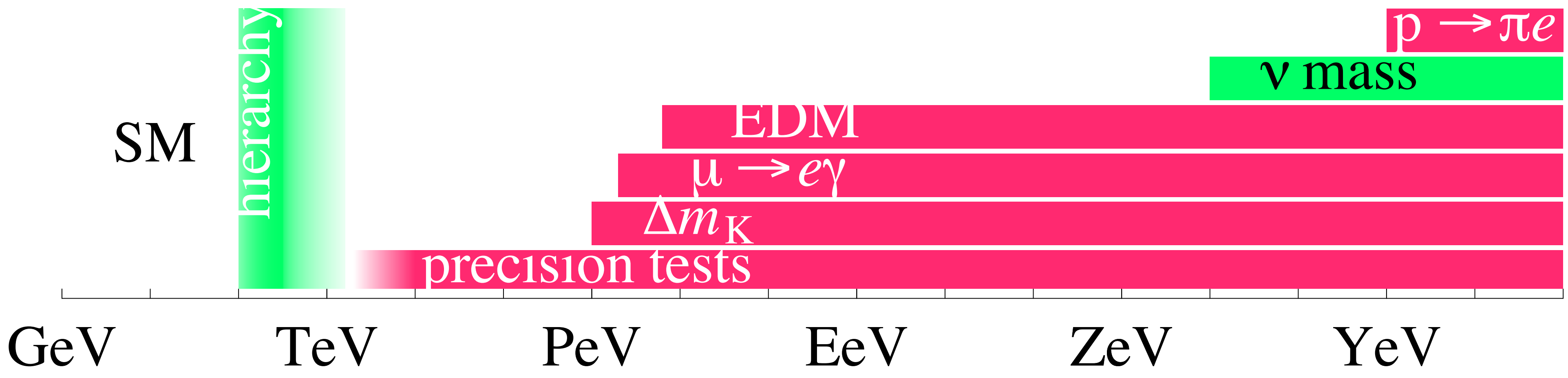
The scale of new physics (NP)

- LHC-I: no deviations from the SM
- Pre-LHC-I (indirect searches)

- The SM as an effective field theory (EFT)

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

- Bounds on Λ_{eff} (c ~ O(1))



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

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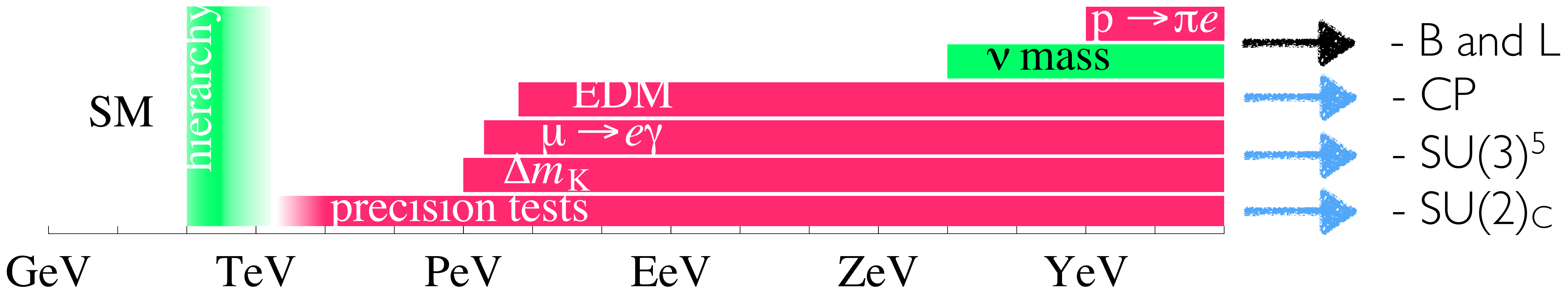
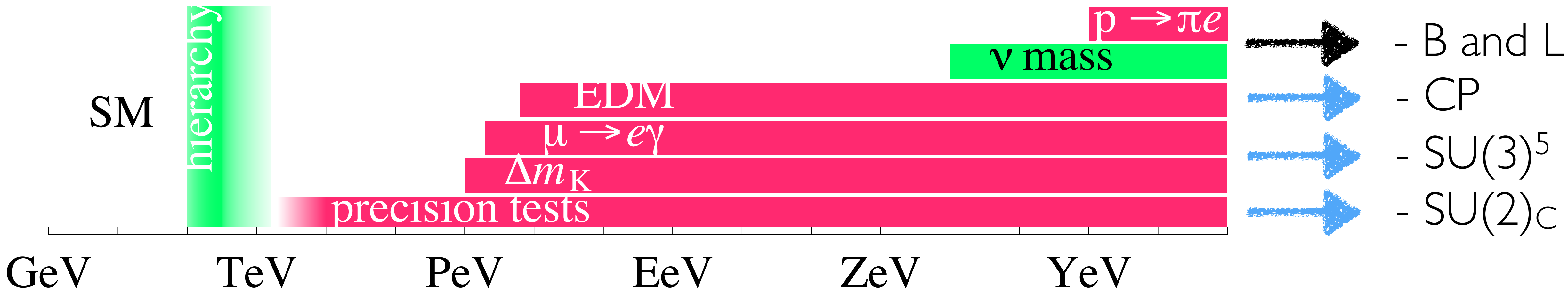


  - $c \to 0$: accidental and approximate symmetry structure of the SM

The scale of new physics (NP)

- How can NP at the electroweak (EW) scale be consistent with the indirect bounds ?
  - $c = 0$ due to an exact symmetry (e.g. B-L in LR-symmetric models)
  - $c \approx 0$ due to an approximate symmetry (e.g. minimal flavour violation)
  - yet another possibility …

  - Bounds on Λ_{eff} (c ~ O(1))



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

Accidental matter

- Which extensions of the SM particle content with masses close to the EW scale

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

close to the EW scale = LHC target

automatically = without any additional protection mechanism (Lorentz + SM gauge sym.)

approximate = only flavour is sufficient (custodial and CP not needed)

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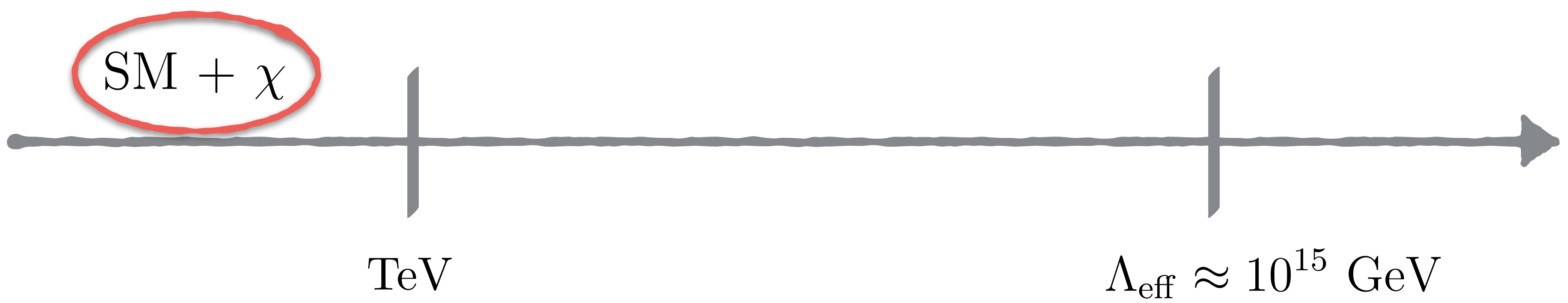
  iii) form consistent EFT's up to $\Lambda_{\rm eff} \approx 10^{15}$ GeV (suggested by nu masses and p-decay) ?



Accidental symmetries in the SM

- Fundamental symmetries: Lorentz + gauge
- Matter content
- Most general renormalizable lagrangian

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

- No extra symmetries imposed by hand, however we get 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) transforming under an IRR of the SM group
- No coupling of χ to SM fermions at the ren. level $\longrightarrow$ automatic $U(3)^5$ preservation

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$$\chi \neq \psi_{\rm SM}, (1,1,0), (1,3,0), (1,3,1), (1,2,3/2), (\overline{3},2,5/6), (3,2,7/6), (\overline{3},3,1/3), (3,3,2/3)$$

- if e.g. $\chi \sim$ 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 $(\chi \to -\chi)$ accidental symmetry implies stability of χ at the ren. level

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Extra Z_2 ($\chi \to -\chi$) accidental symmetry implies stability of χ at the ren. level

- New scalars: avoid the couplings $\chi\psi_{\rm SM}\psi_{\rm SM}$

- Gauge kinetic terms cannot lead to the decay of χ

- Stability depends on the interactions in the scalar potential [see backup slides]

Cosmology

- Barring few exceptions, the lightest particle (LP) in the multiplet is stable at the ren. level
- Colorless and electrically neutral stable particles can be DM ["Minimal Dark Matter", Cirelli, Fornengo, Strumia, (2005)]
- Colored or charged stable particles are severely bounded

[See e.g. "Non-collider searches for stable massive particles", Burdin et al. (2014)]

Cosmology

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

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

$$\begin{cases} \Lambda_{\rm eff} \approx 10^{15} \ \text{GeV} \\ m_\chi \approx 1 \ \text{TeV} \end{cases} \rightarrow \quad \Gamma_5 \sim \frac{m_\chi^3}{\Lambda_{\rm eff}^2} \approx (0.1 \ s)^{-1} \qquad \Gamma_6 \sim \frac{m_\chi^5}{\Lambda_{\rm eff}^4} \approx (10^{20} \ s)^{-1}$$

Γ_5 $\downarrow$ potential BBN bounds [see backup slides]

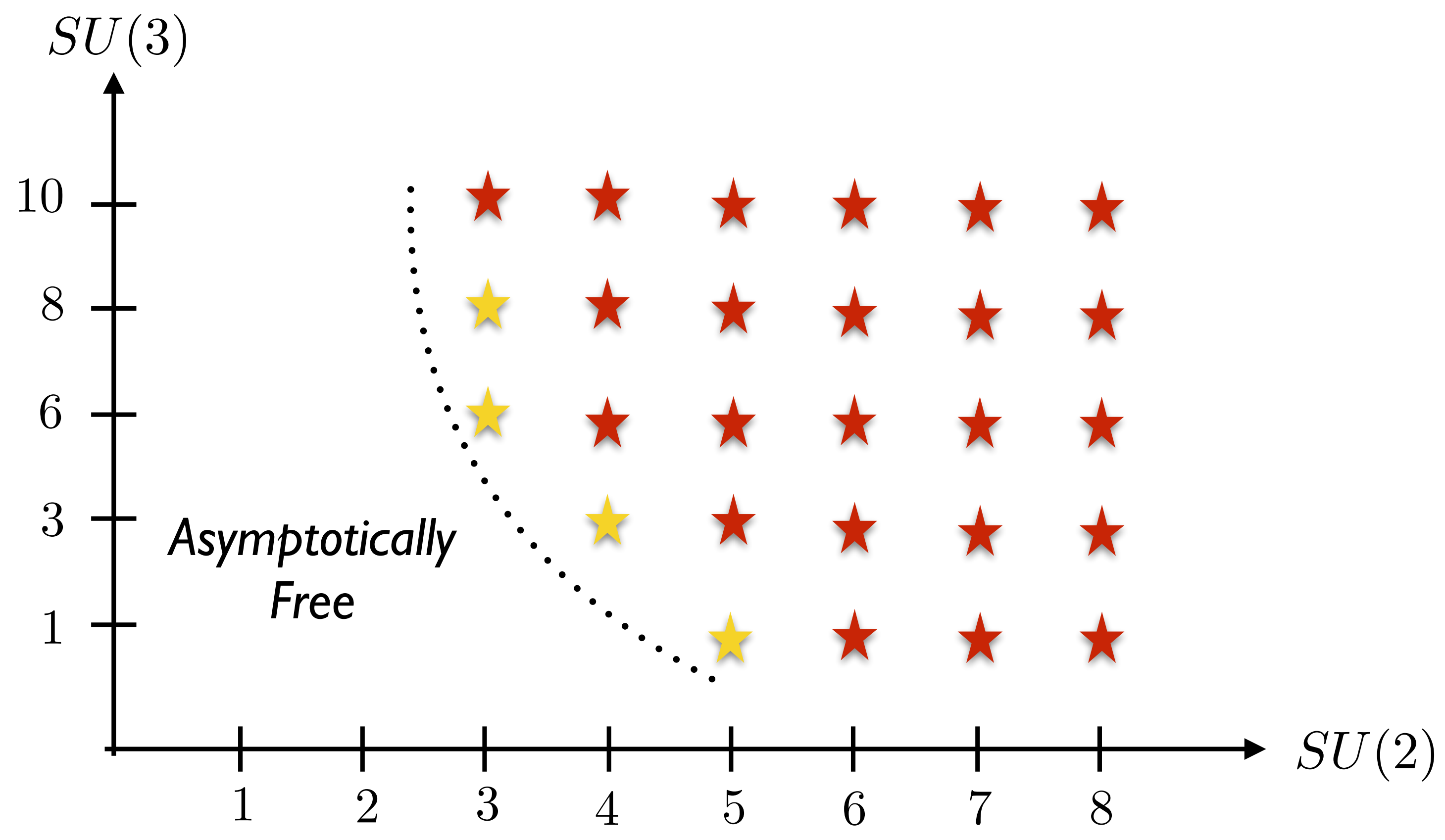
Γ_6 $\downarrow$ (if charged/colored) excluded by anomalously heavy isotopes

Landau poles

- Extra matter drives the gauge couplings towards the non-perturbative regime

$$\mu \frac{d}{d\mu} g_i = -b_i \, g_i^3 \qquad b_i = \text{gauge -matter}$$

- Bound on extra matter IRR by requiring no Landau poles below $\Lambda_{\text{eff}} \approx 10^{15}$ GeV



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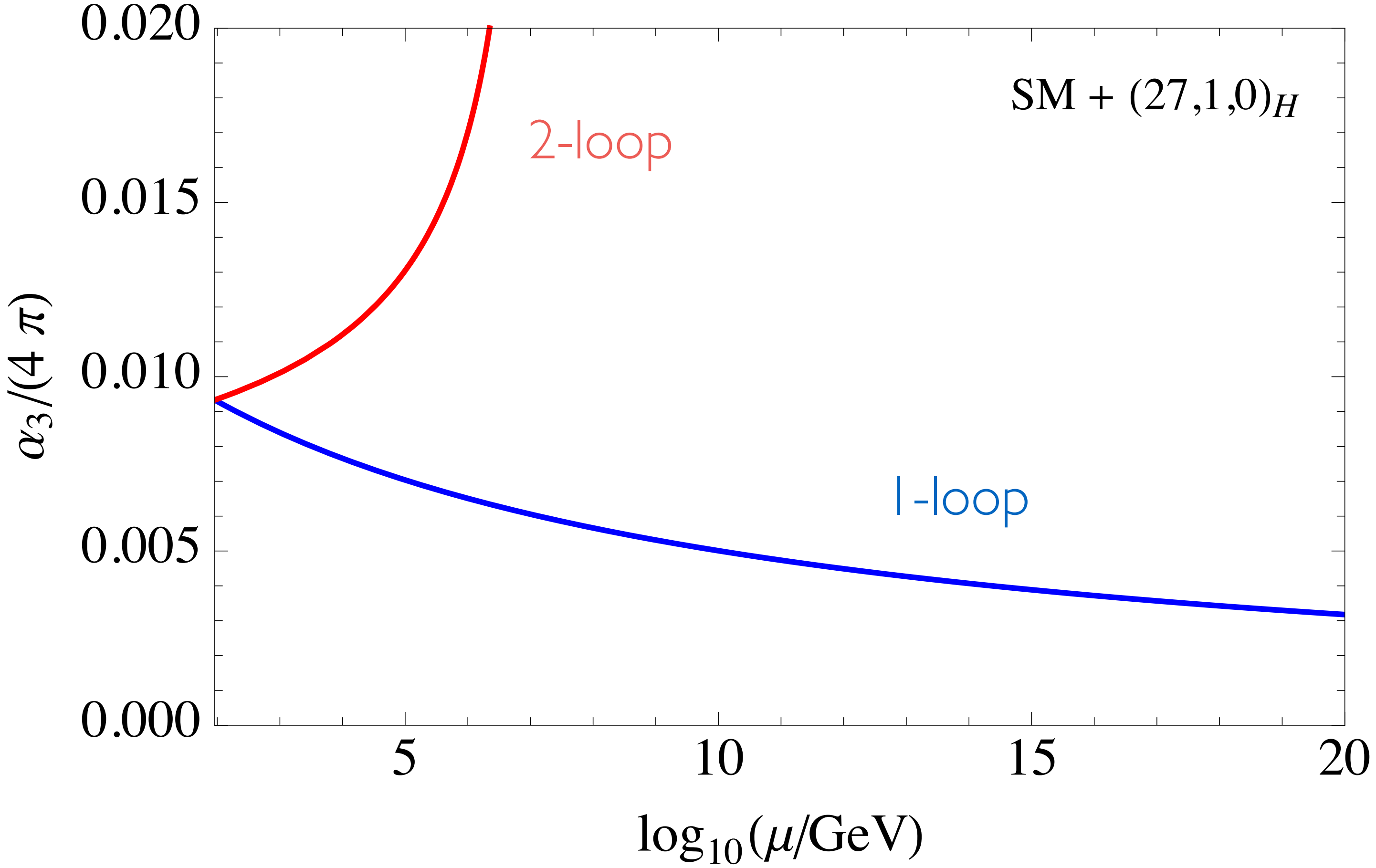
- N.B. two-loop effects might be crucial if there is an accidental cancellation in 1-loop b.f.



Accidental matter multiplets

- Which extensions of the SM particle content with masses close to the EW scale

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

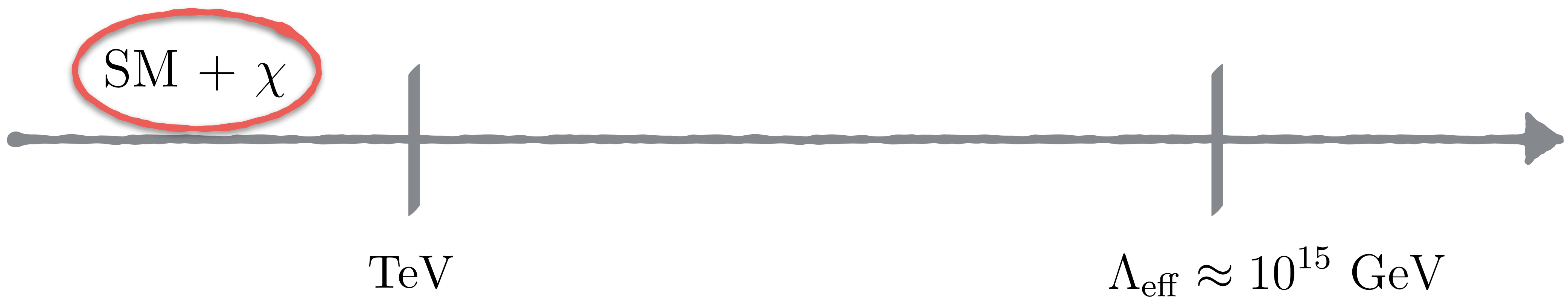
→ No couplings to SM fermions at the ren. level

ii) are cosmologically viable ?

→ Decay via dim ≤ 5 op.' s (if LP is charged or colored)

iii) form consistent EFT's up to $\Lambda_{\rm eff} \approx 10^{15}$ GeV ?

→ No Landau poles below 10^{15} GeV



Accidental matter multiplets

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}_{\rm decay}$	$\dim(\mathcal{O}_{\rm decay})$	$\Lambda^{2-\rm loop}_{\rm Landau}$[GeV]
0	$(1,1,0)$	0	$\chi H H^\dagger$	3	$\gg m_{\rm Pl}$ (g_1)
0	$(1,3,0)^\ddagger$	0,1	$\chi H H^\dagger$	3	$\gg m_{\rm Pl}$ (g_1)
0	$(1,4,1/2)^\ddagger$	-1,0,1,2	$\chi H H^\dagger H^\dagger$	4	$\gg m_{\rm Pl}$ (g_1)
0	$(1,4,3/2)^\ddagger$	0,1,2,3	$\chi H^\dagger H^\dagger H^\dagger$	4	$\gg m_{\rm Pl}$ (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	$\gg m_{\rm Pl}$ (g_1)
0	$(1,2,5/2)$	2,3	$\chi^\dagger H e^c e^c$	5	$\gg m_{\rm Pl}$ (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	$\gg m_{\rm Pl}$ (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	$\gg m_{\rm Pl}$ (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 (3) colored scalars (fermions) [see backup slides]

Accidental matter multiplets

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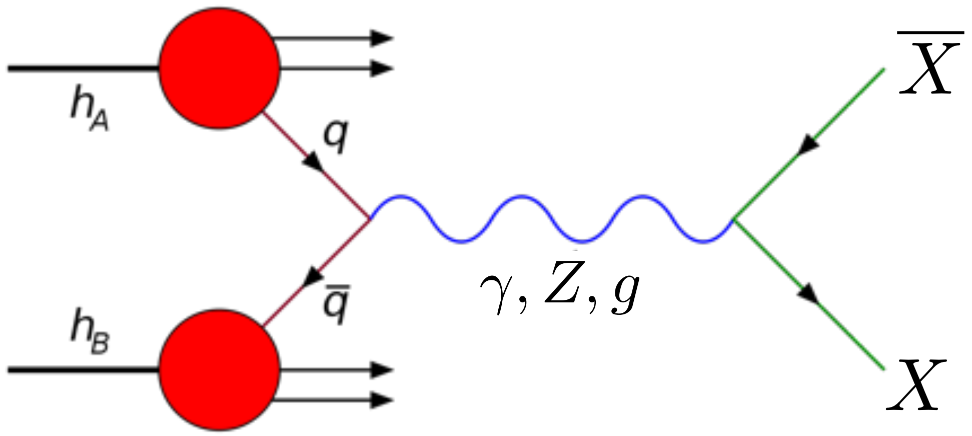
+ 14 (3) colored scalars (fermions) [see backup slides]

- Extra dim=5 op. rules out minimal scalar DM candidate (only spin=1/2 (1,5,0) left)

[Cirelli, Fornengo, Strumia, (2005)]

Collider phenomenology

- Non-renormalizable terms not relevant for collider pheno
- LP in the multiplet is stable (for most of the cases)
- New exotic fermions or scalars are pair produced



Collider phenomenology

- Non-renormalizable terms not relevant for collider pheno
- LP in the multiplet is stable (for most of the cases)
- New exotic fermions or scalars are pair produced
- Collider pheno depends on whether

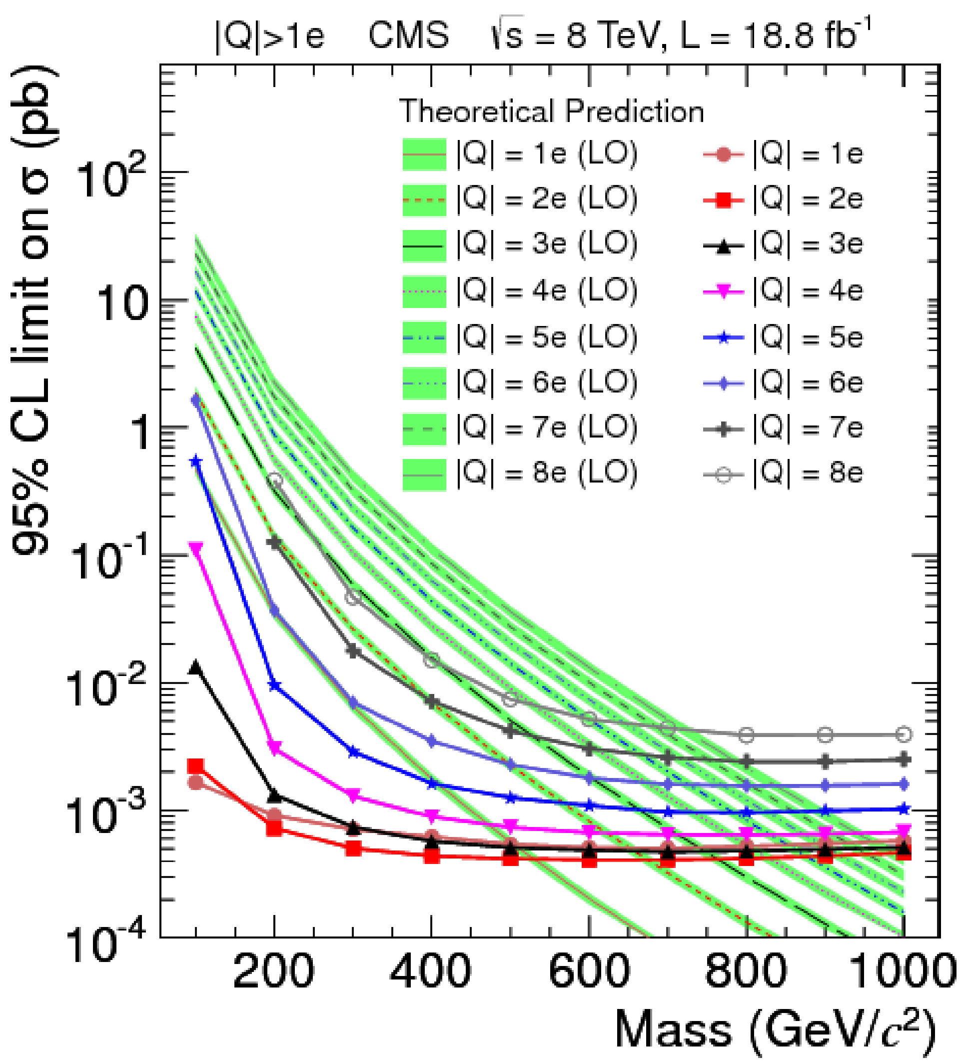
  - LP is colorless and charged

  - LP is colorless and neutral

  - Multiplet is colored [see backup slides]

Colorless and charged LP

- Stable massive charged particles will undergo charge exchange with the detector
  - Anomalous energy loss (Bethe-Bloch formula depends on Q and β)
  - Longer time of flight to the outer detector (muon tracks)



[CMS-PAS-EXO-13-006]

Colorless and neutral LP

- Mono-x searches

  - Not sensitive yet [See also Cirelli, Sala, Taoso (2014)

- Z and H invisible width

  - Z width: $m_\chi \gtrsim 45 \text{ GeV}$ for $Q \neq 0$ and $Y \neq 0$ multiplets

  - H width: only for scalars (model dependent)

- Chargino searches at LEP

  - Searches for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^+\gamma \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma + X$

  - Exclusions b/w 50-95 GeV for the |Q|=1 NLP

Collider bounds (uncolored)

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, 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

Conclusions

- Numerous indirect probes tell us that weak-scale NP (if there) is highly non-generic
  - Extra protection mechanisms like MFV, R-parity, … are required
  - Another possibility:

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

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- Cosmology + consistency of EFT up to 10^{15} GeV lead to a finite set of possibilities

- Phenomenological implications: most of the states are stable on the detector level

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- Cosmology + consistency of EFT up to 10^{15} GeV lead to a finite set of possibilities

- Phenomenological implications: most of the states are stable on the detector level

- Side products of this analysis:

  - We excluded the real scalar (1,7,0) as a minimal DM candidate [Cirelli, Fornengo, Strumia, (2005)]

  - Landau pole estimates of NP models might require two-loop accuracy

Backup slides

New scalars

- New scalars: avoid the couplings $\chi\psi_{\rm SM}\psi_{\rm SM}$

$$\chi \neq (1,1,1),(1,3,1),(1,1,2),(1,2,1/2),(\overline{3},1,1/3),(3,1,2/3),(\overline{3},1,4/3),(3,2,1/6),(3,2,7/6),$$
$$(\overline{3},3,1/3),(6,1,1/3),(\overline{6},1,2/3),(6,1,4/3),(6,3,1/3),(8,2,1/2)$$

- Kinetic term of real or complex IRR again invariant under extra Z_2 or $\mathrm{U}(1)$

- Stability depends on interactions in the scalar potential

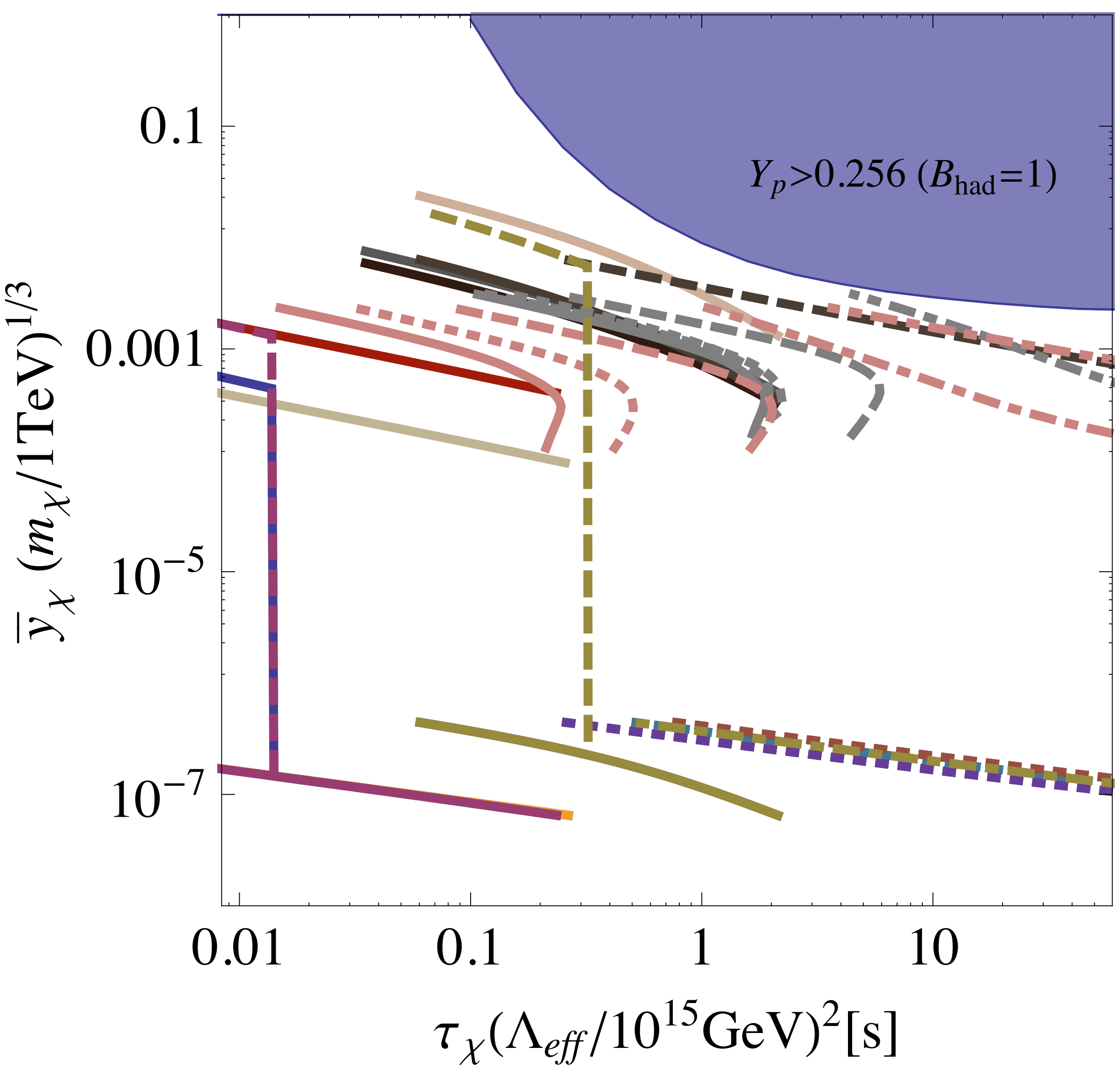
Spin	χ	$\mathcal{O}_{\rm decay}$	$\dim(\mathcal{O}_{\rm decay})$	Stability
0	$(1,1,0)$	$\chi H H^\dagger$	3	$\times$
0	$(1,3,0)$	$\chi H H^\dagger$	3	$\times$
0	$(1,4,1/2)$	$\chi H H^\dagger H^\dagger$	4	$\times$
0	$(1,4,3/2)$	$\chi H^\dagger H^\dagger H^\dagger$	4	$\times$
0	$(R,2k,1/2)$	$\chi\chi H^\dagger H^\dagger$	4	Z_2
0	$(R,n,0)$	$\chi\chi H H^\dagger$	4	Z_2
0	(C,n,Y)	$\chi\chi^\dagger H H^\dagger$	4	$\mathrm{U}(1)$
0	$(C,2k,1/6)$	$\chi\chi\chi H^\dagger$	4	Z_3
0	$(R,2k,1/2)$	$\chi\chi\chi^\dagger H^\dagger$	4	$\times$

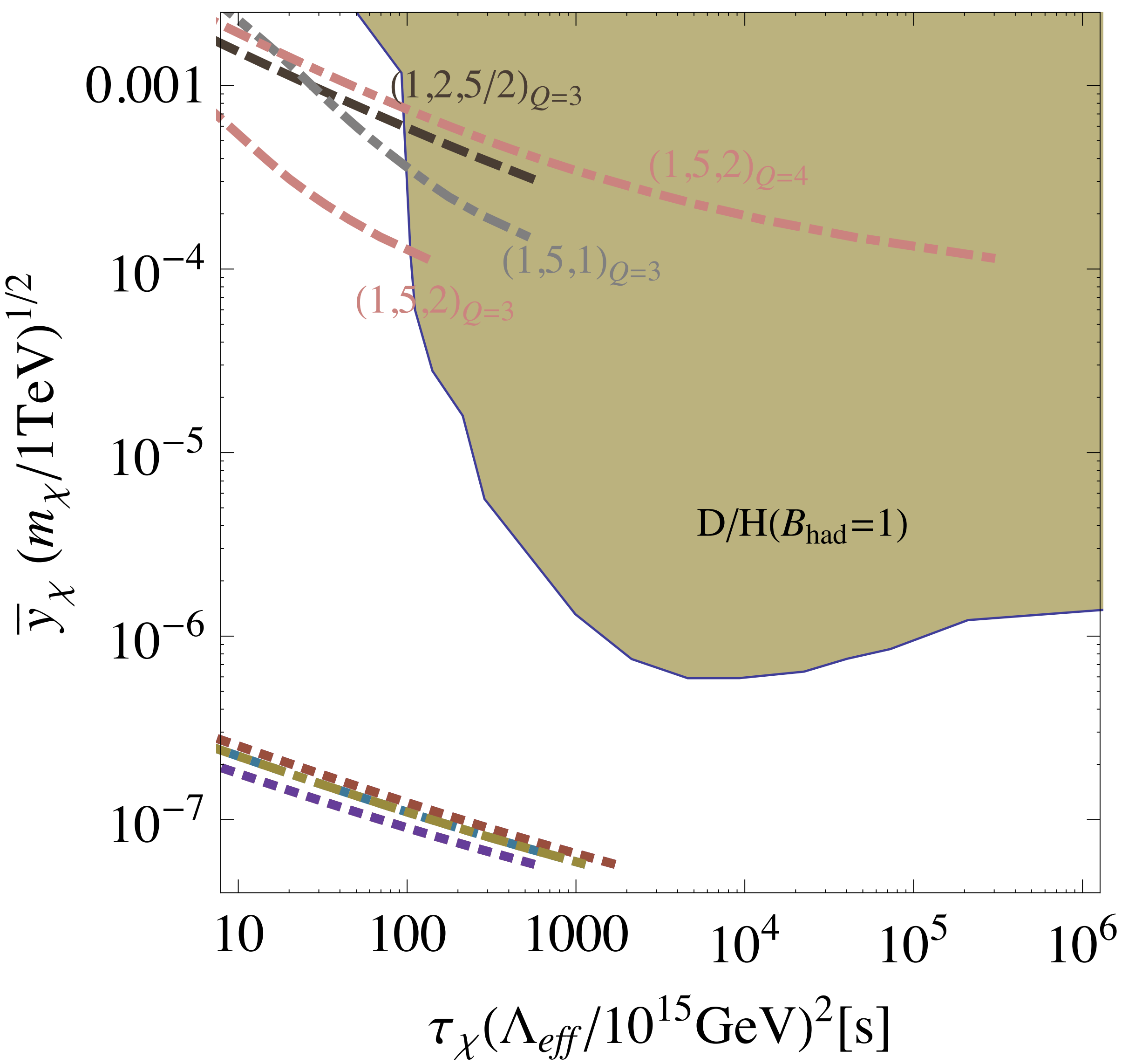
Colored accidental matter multiplets

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}_{\rm decay}$	$\dim(\mathcal{O}_{\rm decay})$	$\Lambda^{2-\rm loop}_{\rm Landau}$[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	$4.0 \times 10^{16}\ (g_1)$

BBN bounds

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



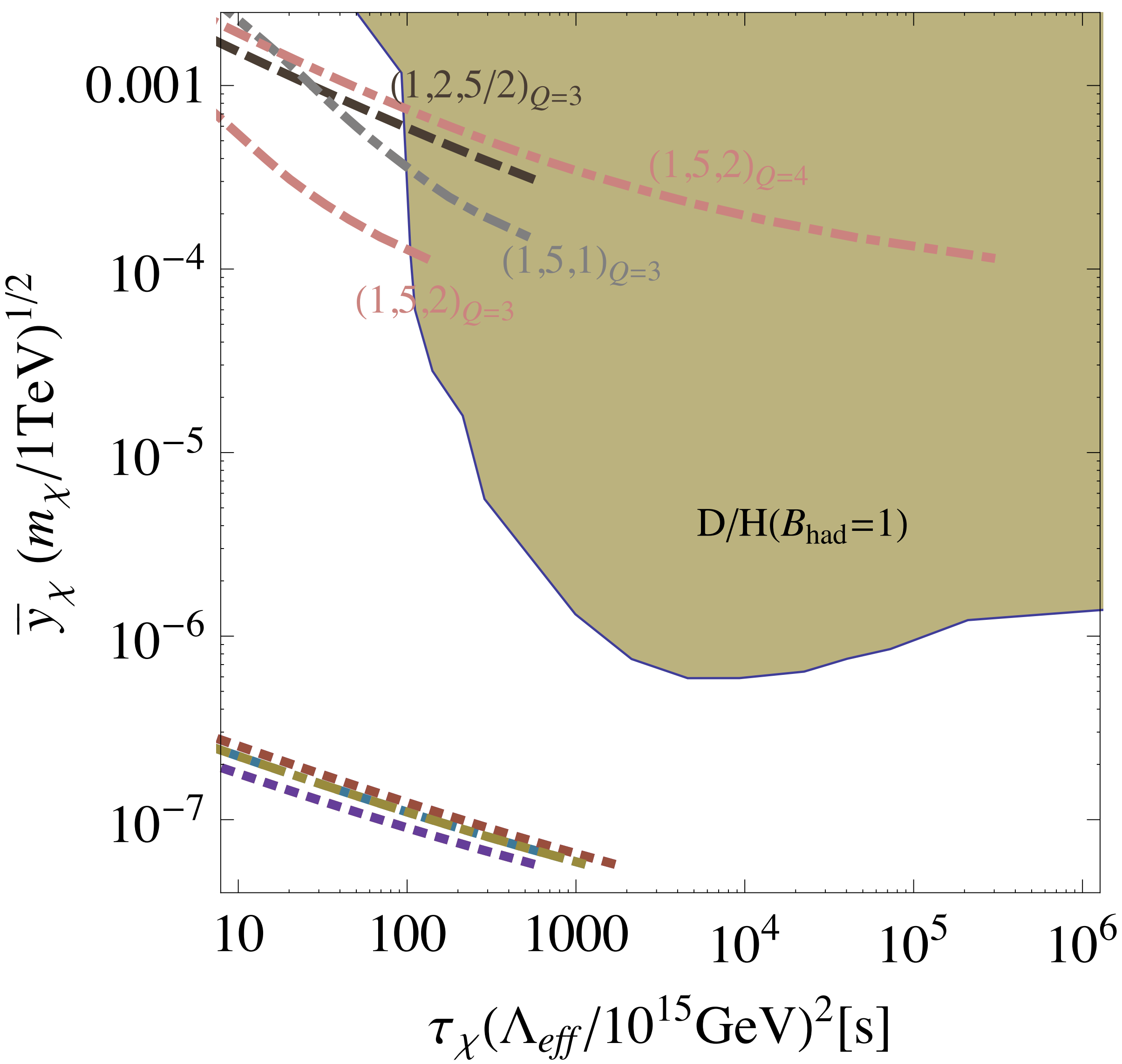


BBN bounds

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

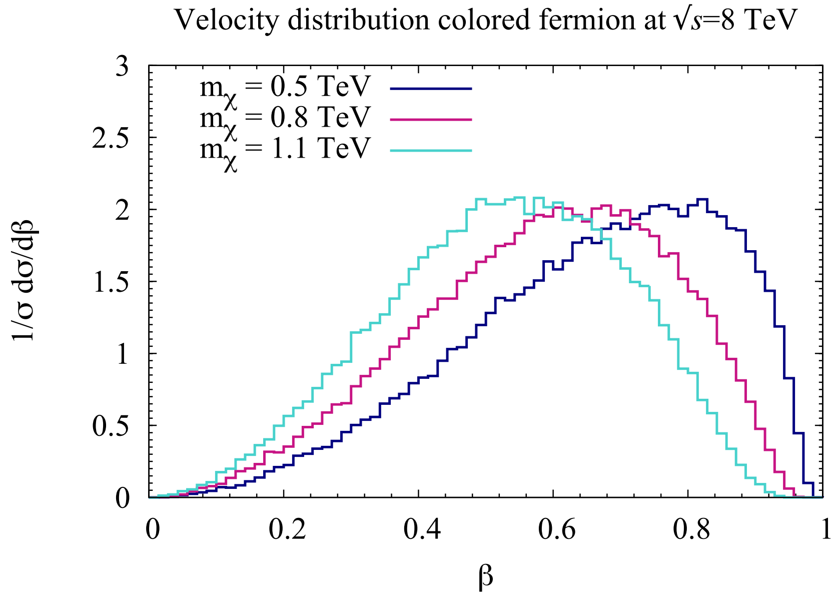
- bounds on uncoloured states (slowly) decaying via loops or cascades

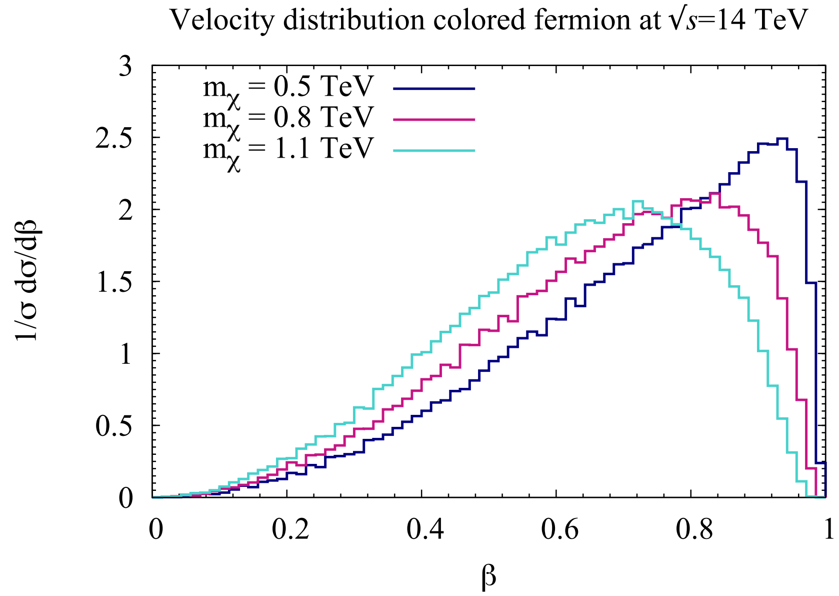
Spin	χ	$Q_{\rm LP}$	Mass bound [GeV]
0	$(1,2,5/2)$	3	790
0	$(1,5,1)$	3	920
0	$(1,5,2)$	3, 4	530, 1900
0	$(1,7,0)$	0, 1, 2, 3	$\gg 5000$



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
- 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

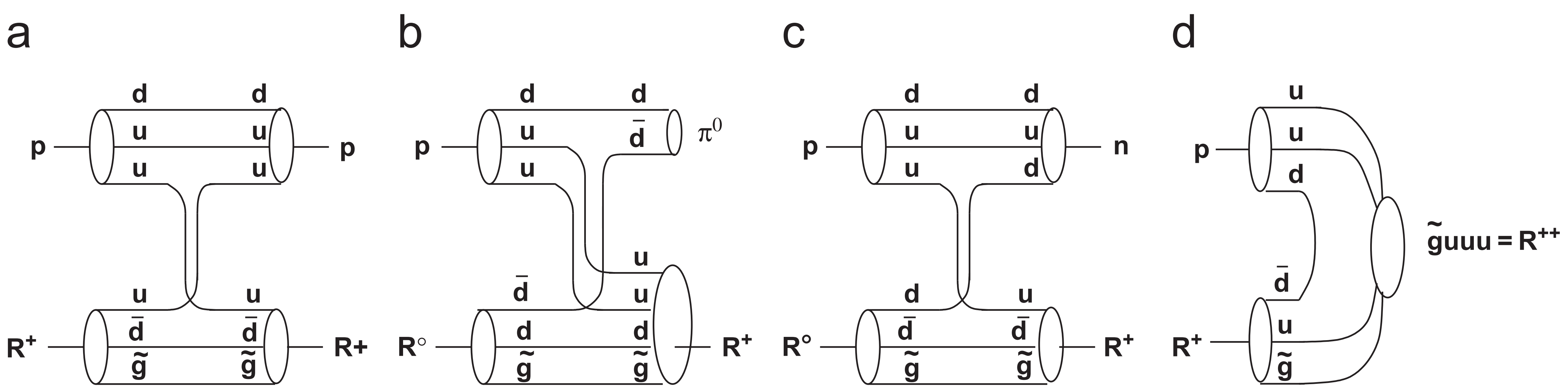


Fig. 13. *R*-hadron–proton scattering processes: (a) elastic scattering; (b) inelastic scattering leading to baryon and charge exchange; (c) inelastic scattering leading to charge exchange; (d) resonance formation.

Colored multiplets

- Colored, long-lived particles $\longrightarrow$ 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
- 4) Stop & decay

  - Depending on its mass, the new particle could stop and 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]

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

Spectrum

- Fermions: mass splitting is purely radiative [Cirelli, Fornengo, Strumia, (2005), Del Nobile, Franceschini, Pappadopulo, Strumia (2009)]

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

- the LP is fixed by Y and Q

- Scalars: radiative + tree-level splitting from the 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 $\beta \in [10^{-3}, 1]$, however $\Delta m \lesssim 20$ GeV by EW precision tests

Lifetimes

- Inter-multiplet weak transitions to LP and pions

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

Lifetimes

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

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

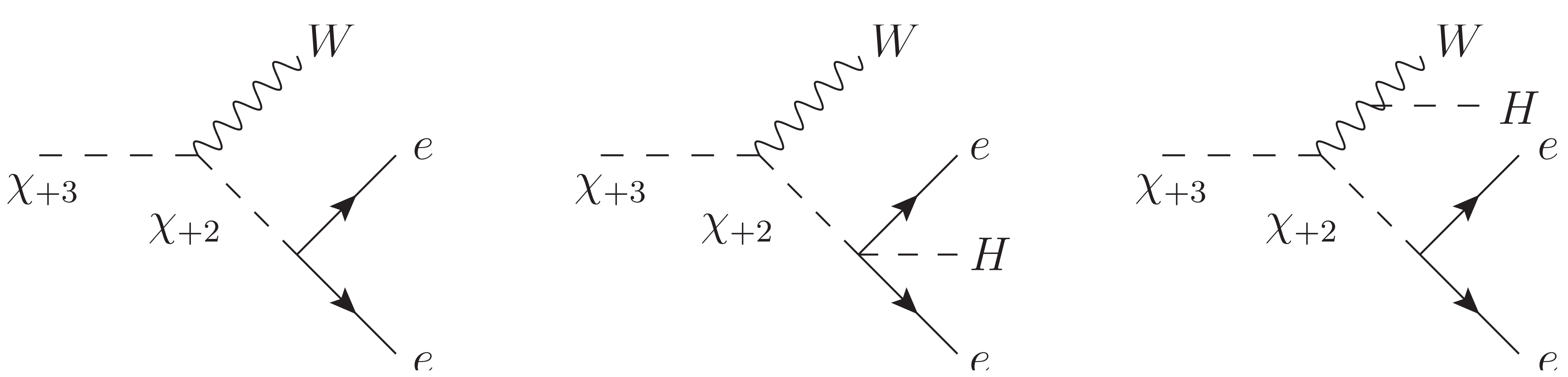
$$\Gamma_{\text{NDA}}(\chi \to \{p_f\}) = \frac{1}{4(4\pi)^{2n_f-3}} \frac{m_\chi^{3-2n_c}}{(n_f-1)!(n_f-2)!} \frac{\left(\frac{v}{\sqrt{2}}\right)^{2n_c}}{\Lambda_{\text{eff}}^2}$$

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	$(1,5,2)$	$1,2,3,4$	$\chi^\dagger HHHH$



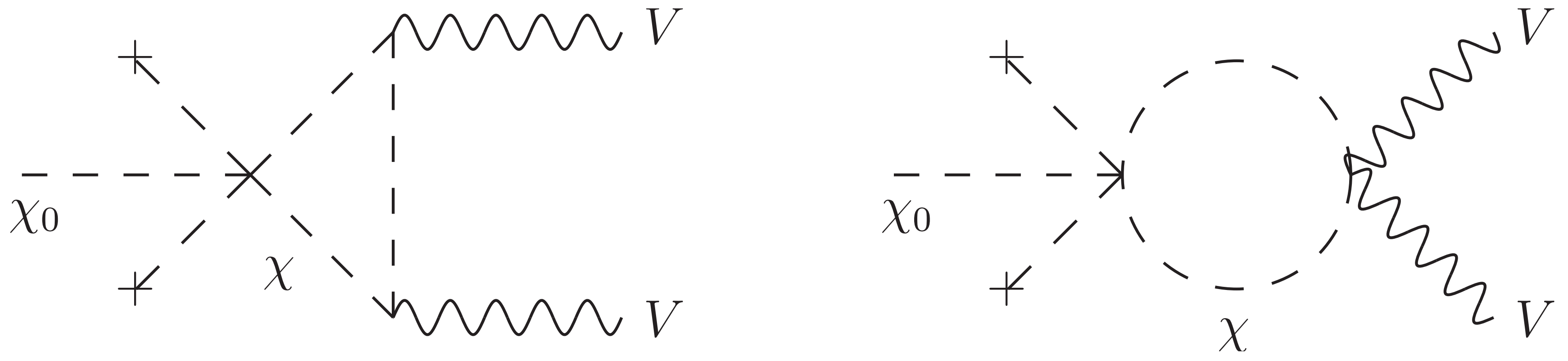
Lifetimes

- 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)



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