

# Long-lived particles

## Lecture 1: why long-lived particles

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- 1 The Standard Model
- 2 New Physics & Long-lived particles
- 3 Conclusions

# The Standard Model of particle physics

- Particle physics: the study of fundamental particles and their interactions
- The **Standard Model**: the **ground stone** of particle physics
- Successful predictions:  $W$ ,  $Z$ ,  $h$ ,  $g$ ,  $c$ ,  $t$ ,  $\tau$ , ...

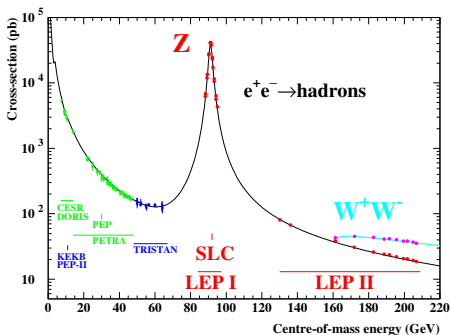
## Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			Interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	$-2/3$	$-2/3$	$-2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\bar{u}</math></b> antiup	<b><math>\bar{c}</math></b> anticharm	<b><math>\bar{t}</math></b> antitop	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\bar{d}</math></b> antidown	<b><math>\bar{s}</math></b> antistrange	<b><math>\bar{b}</math></b> antibottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>e^+</math></b> positron	<b><math>\bar{\mu}</math></b> antimuon	<b><math>\bar{\tau}</math></b> antitau	<b>Z<sup>0</sup></b> Z <sup>0</sup> boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b><math>\bar{\nu}_e</math></b> electron antineutrino	<b><math>\bar{\nu}_\mu</math></b> muon antineutrino	<b><math>\bar{\nu}_\tau</math></b> tau antineutrino	<b>W<sup>+</sup></b> W <sup>+</sup> boson	<b>W<sup>-</sup></b> W <sup>-</sup> boson

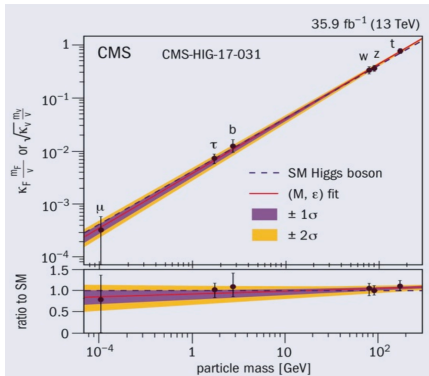
**QUARKS** (left side, purple text)  
**LEPTONS** (left side, green text)  
**GAUGE BOSONS** (right side, red text)  
**VECTOR BOSONS** (right side, red text)  
**SCALAR BOSONS** (right side, yellow text)

# Precision test in the SM

- Excellent performance in experimental tests (e.g. EW sector)
  - $m_Z$  measured at LEP:  $m_Z = 91.1876$  GeV, precision level  $\sim 10^{-5}$
  - $N_\nu \approx 3$  from Z-boson widths measurements and computation
  - QED, electron  $g - 2$ , precision level  $\sim 10^{-12}$ :
    - $(a_e)_{\text{exp}} = 1.15965218073(28) \times 10^{-3}$
    - $(a_e)_{\text{SM}} = 1.15965218188(78) \times 10^{-3}$
  - Higgs-boson coupling strengths



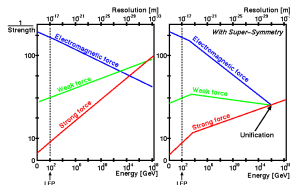
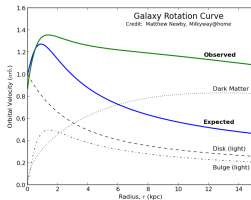
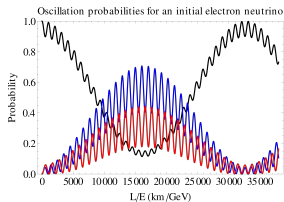
[hep-ex/0509008](http://hep-ex/0509008)



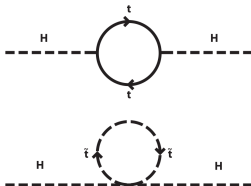
2003.05976

# Problems in the Standard Model

- neutrino masses
- dark matter
- non-unification of gauge couplings



- more: baryon asymmetry, strong CP problem, charge quantization. . .
- Hint at **GUT & NP**  $\Rightarrow$  the *hierarchy problem*: why  $m_h \ll M_{\text{Planck}}$ ?



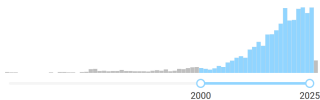
# New Physics (NP) & Long-lived particles (LLPs)

- NP models: SUSY, LRSM, Leptoquark,  $Z'$  (U(1) extensions) ...
- NP models often predict new heavy fields
- No new fundamental particles found yet at the LHC
- More stringent limits placed on NP models, e.g.  $m_{\tilde{q}, \tilde{g}} \gtrsim 2$  TeV
- LHC focus: **promptly decaying** NP particles

Perhaps this assumption is **wrong**

→ **Long-Lived Particles!**

Date of paper



'long-lived particle' on [INSPIRE](#)

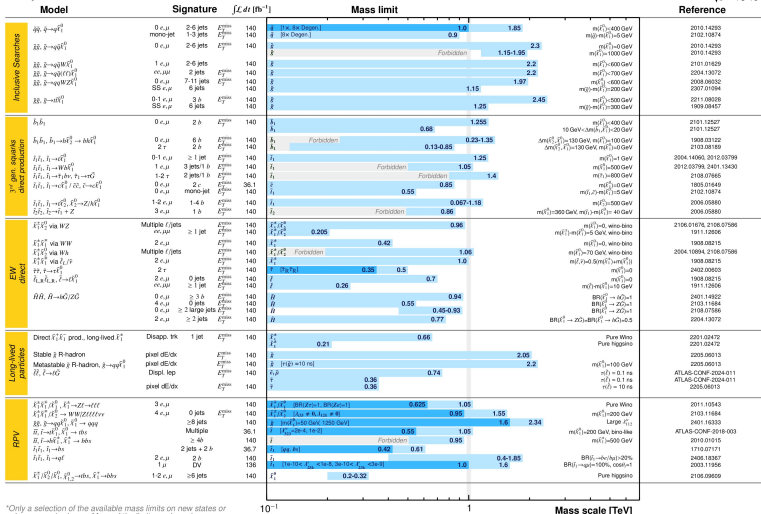
# ATLAS SUSY search summary plot 2024

ATLAS SUSY Searches\* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s} = 13$  TeV

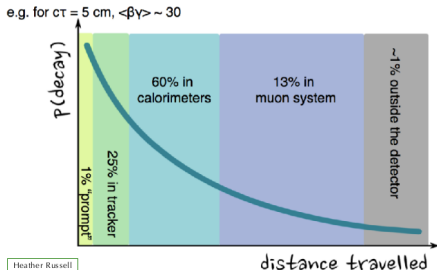
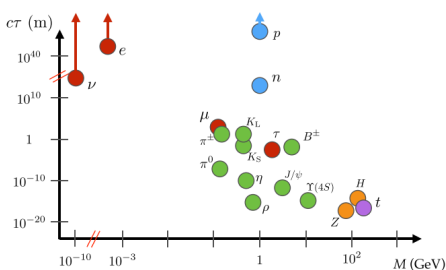


\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. the assumptions made.

## ATL-PHYS-PUB-2024-014

# LLPs in the SM

- **LLPs**: produced, travel a macroscopic distance, and then decay  
→ Displaced objects



LLPs in the SM, [B. Shuve's talk](#)

Exp. decay distribution [H. Russell's talk](#)

- Causes of the long lifetime:

- **Feeble** couplings:  $\Gamma \sim g^2$

- **Small** phase space:  $\Gamma \sim \left(\frac{m_1 - m_0}{m_0} \ll 1\right)^n$

- **Heavy** mediators:  $\Gamma \sim \frac{1}{M^4}$

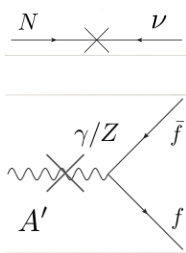
- ...

- Similarly applicable to BSM particles

# LLPs in BSM theories

Examples:

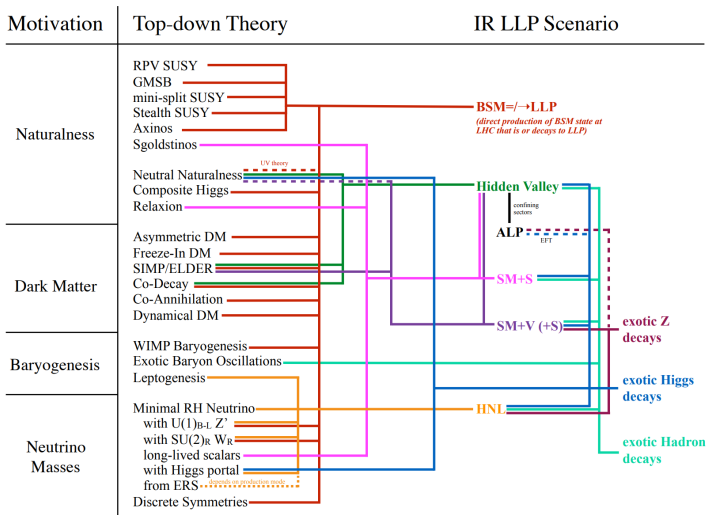
- Portal physics:  $\nu_s$ ,  $\gamma'$ ,  $s$ , and  $a$
- RPV/compressed SUSY
- Mirror glueballs
- .....
- See [1903.04497](#) for a review



Motivation:

- **Non-zero  $m_\nu$**
- **Dark matter**
- .....

# An incomplete list of theo. scenarios predicting LLPs

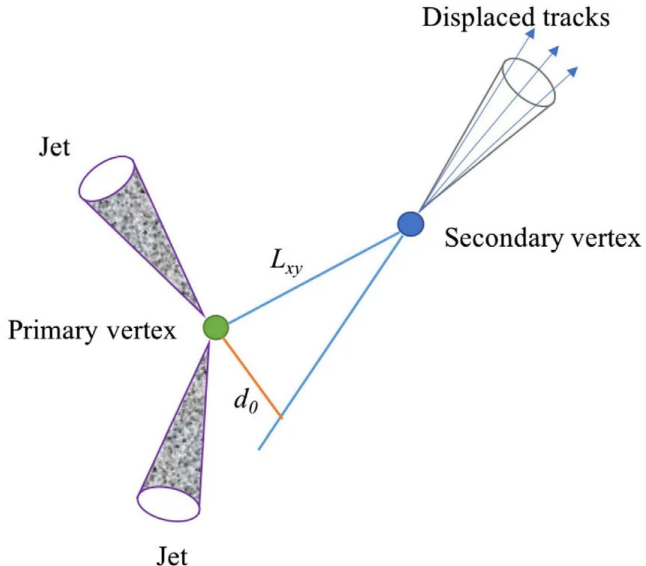


[1806.07396](https://arxiv.org/abs/1806.07396)

# Why conventional searches may miss LLPs

- Standard searches assume **prompt decays** near the interaction point
- Trigger and reconstruction optimized for:
  - **high- $p_T$**  objects or **large MET** from the primary vertex
  - tracks **pointing back to the IP**
- LLP signatures violate these assumptions:
  - displaced vertices
  - disappearing tracks
  - delayed signals
  - **See the next lecture...**
- $\Rightarrow$  signals may fail trigger or be rejected as background

# Primary vertex and Displaced vertex



# Conclusions

- SM: basis of modern understanding of particle physics
- Many **successes** but also **problems**:  $m_\nu \neq 0$ , DM, etc.
- Conventional NP searches vs. LLP signatures
- **LLPs widely predicted** in both the SM and BSM scenarios
- New signatures and new search strategies