THEORY OVERVIEW OF **LONG-LIVED PARTICLES**

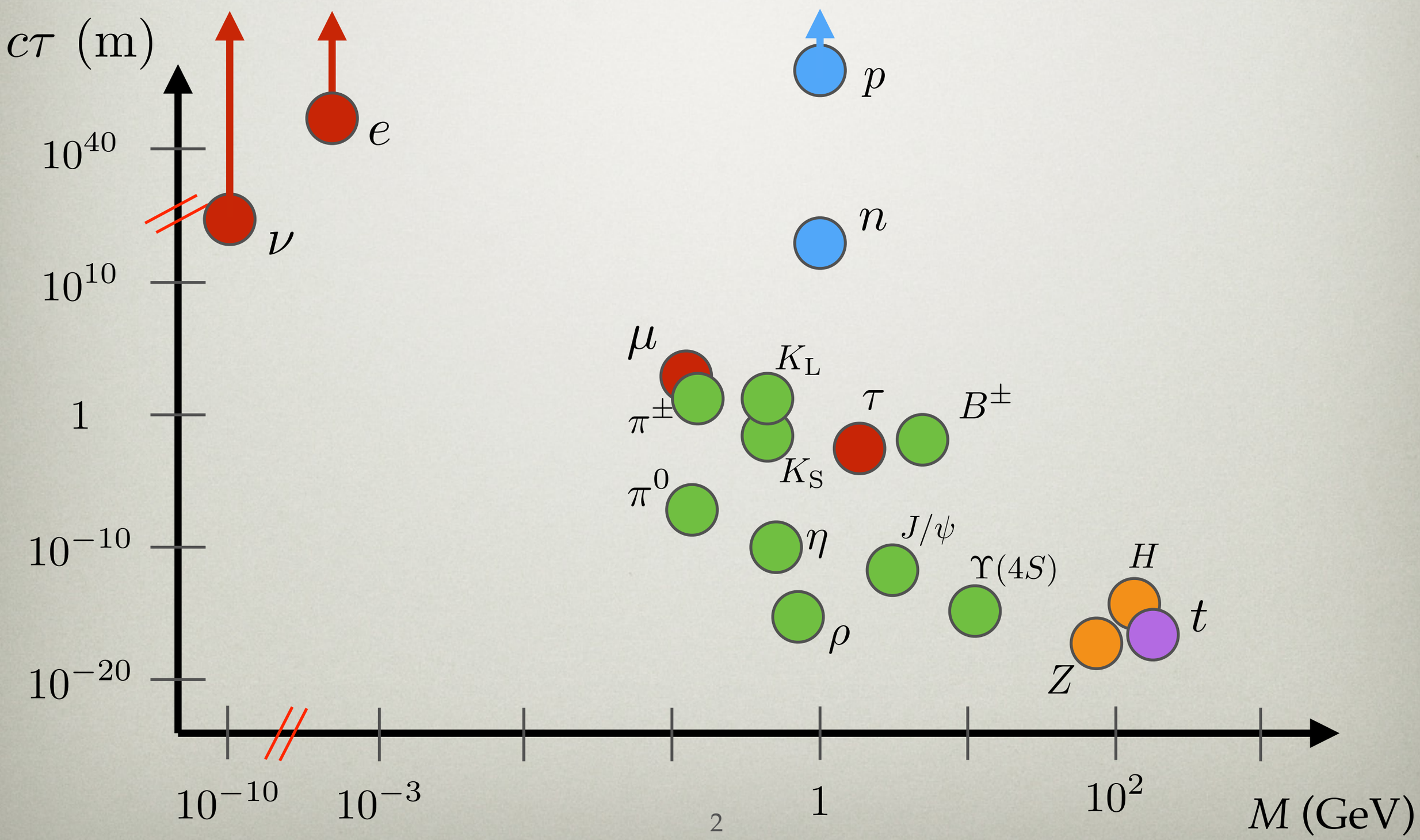
Brian Shuve

LHC-LLP Workshop

CERN 2018

Long-Lived Particles in the SM

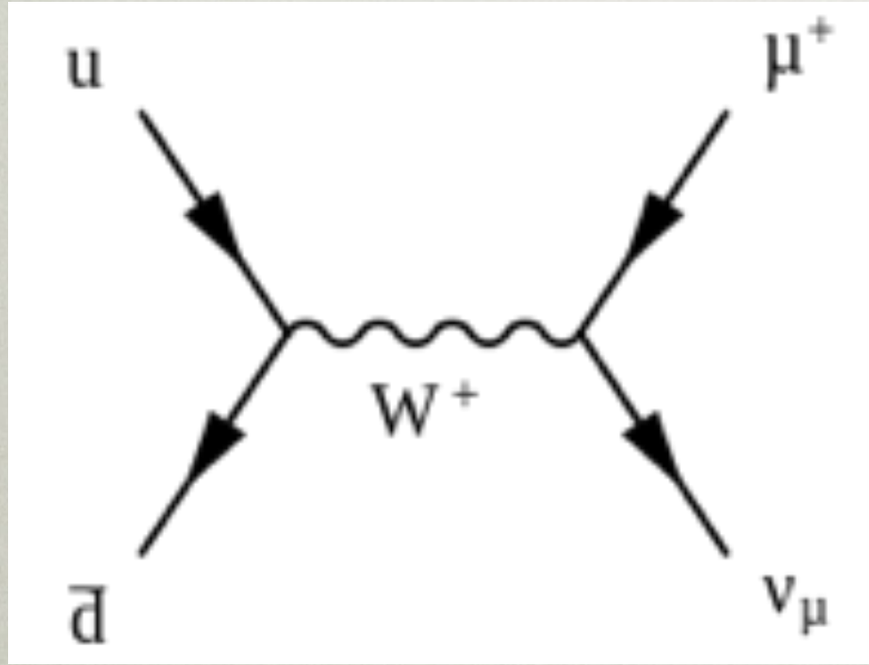
- The world is **full** of long-lived particles



Long-Lived Particles in the SM

- Why are SM particle lifetimes long?
- *Example 1: charged pion*

$$\pi^+ \to \mu^+ \nu_\mu$$



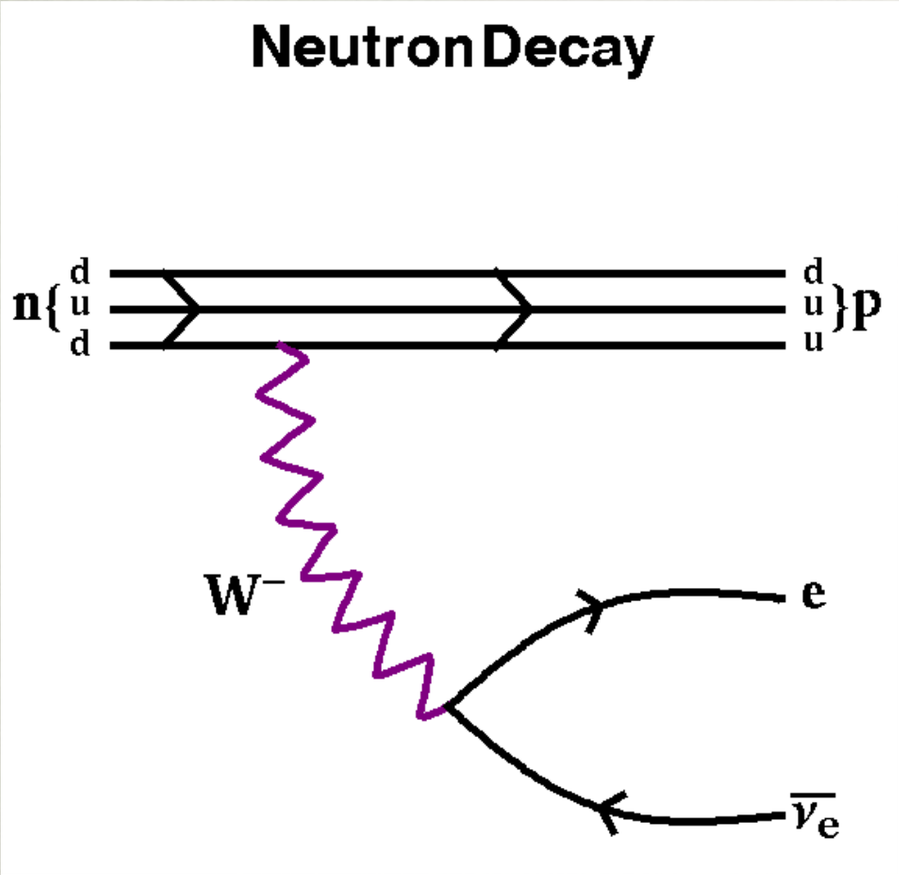
- Quark flavour conserved by all but weak interactions
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_\pi}{M_W} \right)^4 M_\pi$$

See M. Strassler, various talks;
S. Knapen, LBL ATLAS trigger workshop

Long-Lived Particles in the SM

- Why are SM particle lifetimes long?
- *Example 2: neutron*

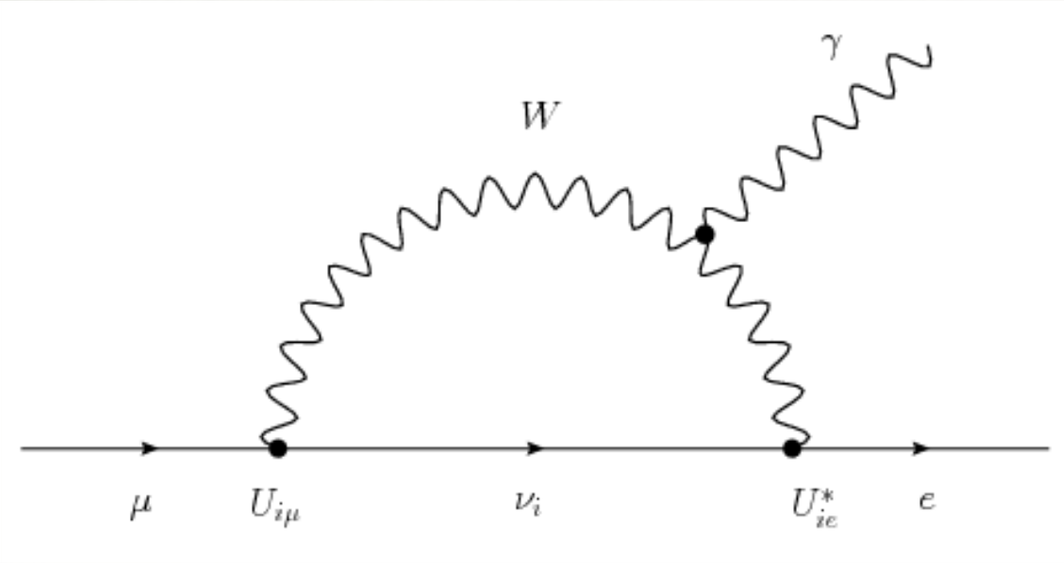


- Isospin ensures that proton and neutron are nearly degenerate
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_n - M_p}{M_W} \right)^4 (M_n - M_p)$$

Long-Lived Particles in the SM

- Why are SM particle lifetimes long?
- *Example 3: flavour-changing neutral currents*



- Lepton flavour only violated by tiny neutrino Yukawa couplings/ neutrino masses

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-54}$$

Long-Lived Particles in the SM

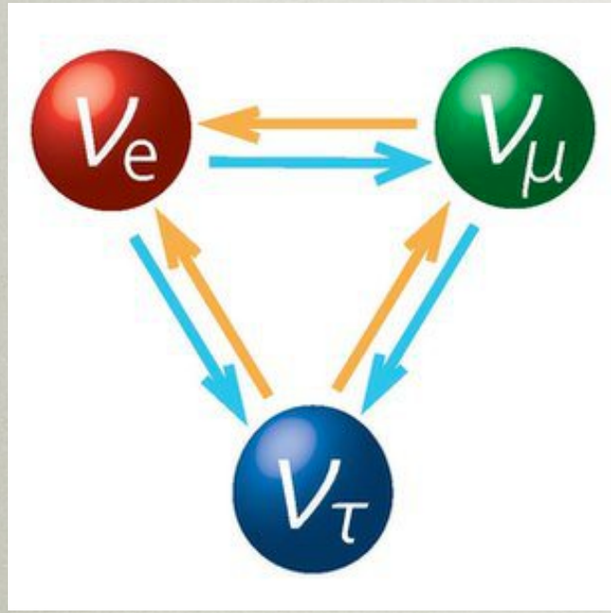
- SM particle lifetimes can be long if an **approximate symmetry** makes the particle stable
  - Typically has to do with "weakness" of weak interactions
  - This in turn arises from hierarchies of scale such as

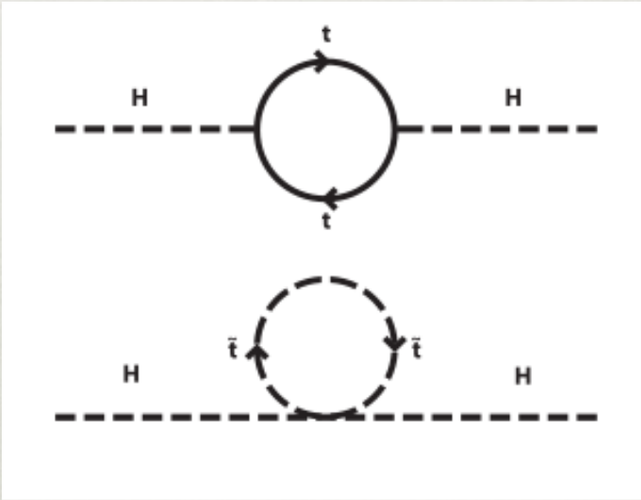
$$\Lambda_{\mathrm{QCD}} \ll M_W$$

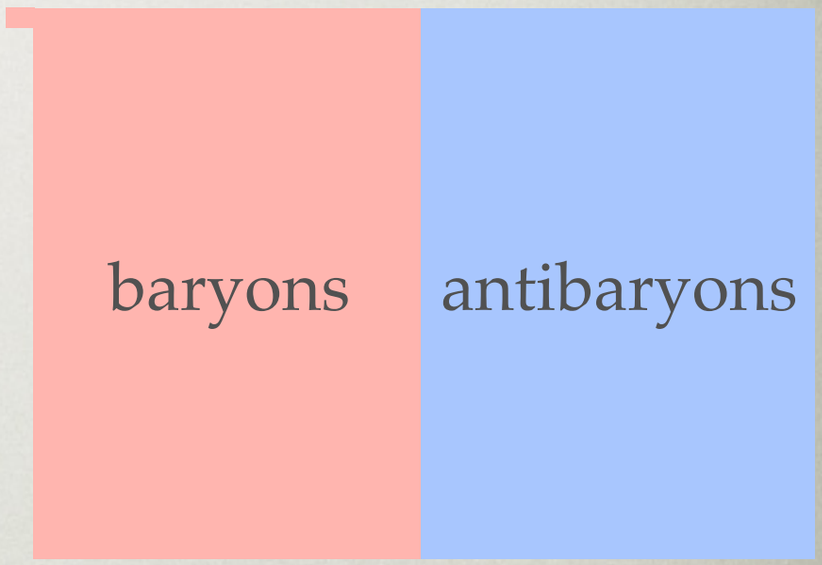
- Electroweak symmetry can lead to mass degeneracies, which suppress decay rates
- Small symmetry-breaking parameters can suppress decay rates

Long-Lived Particles Beyond the SM

- Same principles apply to **BSM** particles!







- Feeble couplings, no definite mass scale: easily get LLPs!

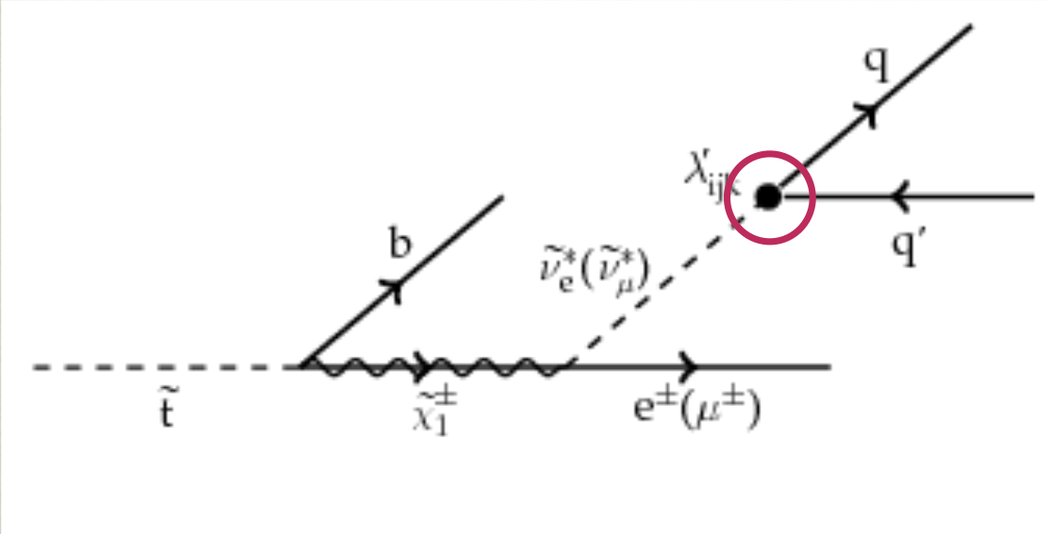
Outline of Talk

- Examples of Models with Long-Lived Particles

- Reinterpretation of LLP Searches

LLP Models: Supersymmetry

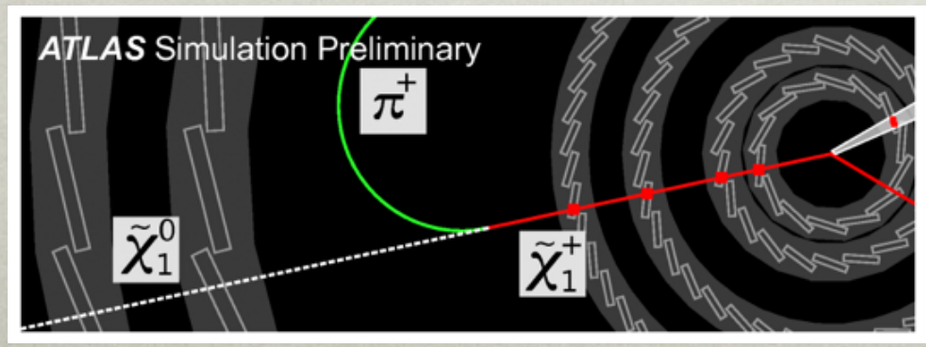
R-parity-violating SUSY:



$$|\lambda| \lesssim 10^{-8}$$

Pure weak-ino states:

- Electroweak symmetry gives degeneracy of NLSP-LSP masses if little mixing between Higgsino/gauginos

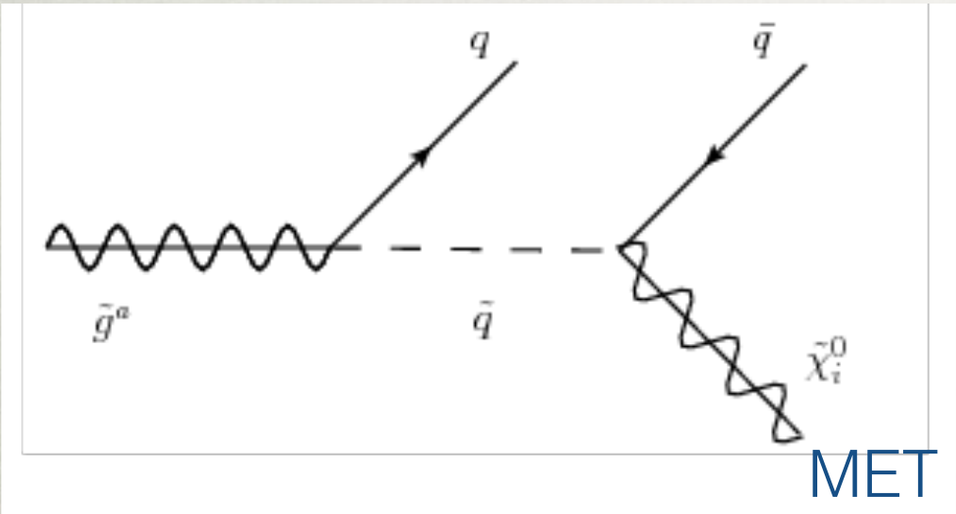


$$c\tau \approx 0.7\,\mathrm{cm} \times \left(\frac{\Delta m}{340\,\mathrm{MeV}}\right)^3$$

LLP Models: Supersymmetry

Split SUSY:

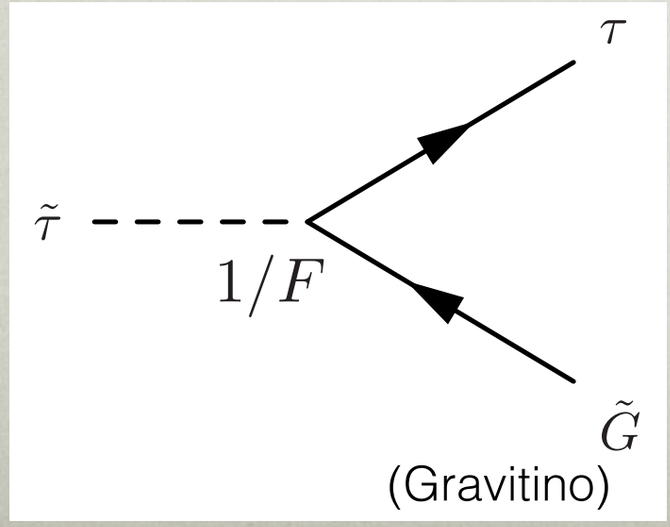
- Models with decoupled supersymmetric scalars



$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{10^3\,\mathrm{TeV}}\right)^4 \times \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

Gauge mediation:

- Decays to gravitino suppressed by SUSY-breaking scale



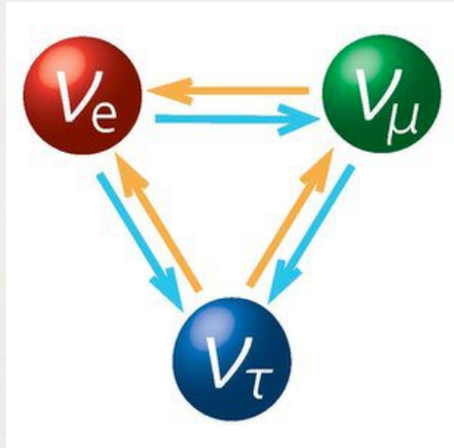
$$c\tau \approx 100\mu m \times \left(\frac{\sqrt{F}}{100\,\mathrm{TeV}}\right)^4 \times \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{\tau}}}\right)^5$$

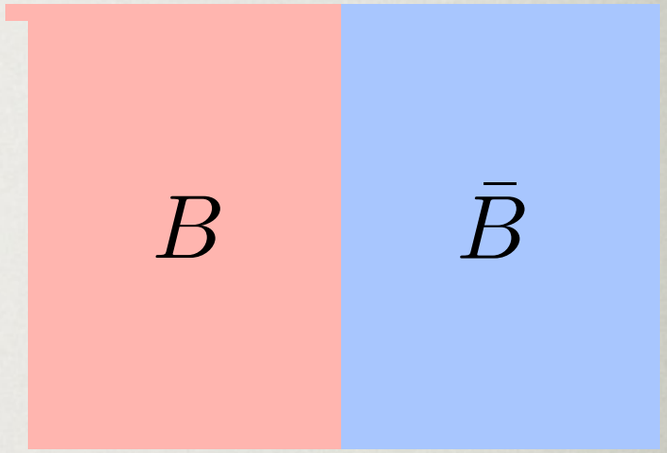
LLP Models: Supersymmetry

Lessons from SUSY:

- Production typically through new particles charged under SM gauge interactions (gluinos, stops, Higgsinos, etc.)
  - Some new, **heavy** particles in spectrum
  - Can have prompt production of jets, leptons, MET, …
  - Often LLP pairs
- LLP decays give jets, leptons, MET, or could be **stable & charged**
- Sometimes spectra are compressed, so there is still benefit in looking at searches for softer objects

LLP Models: Hidden Sectors





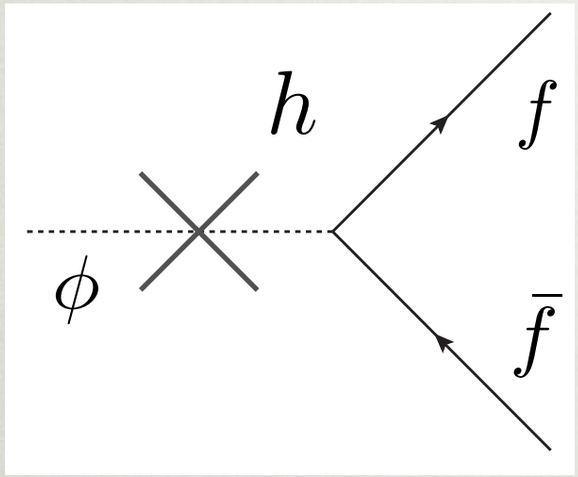
- New particles may (likely) be SM singlets
- Could be any mass! Want to look for low-mass LLPs in addition to > weak scale
- Could have own **hidden-sector** confinement, multiple states, …

  hidden valleys: Strassler, Zurek 2006
- Rich phenomenology, need comprehensive search strategies to cover all bases

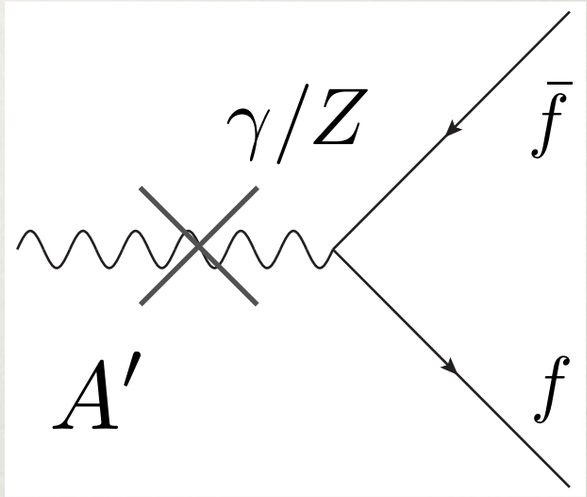
Hidden-Sector Portals

- Singlets dominantly couple to SM via **singlet portals**

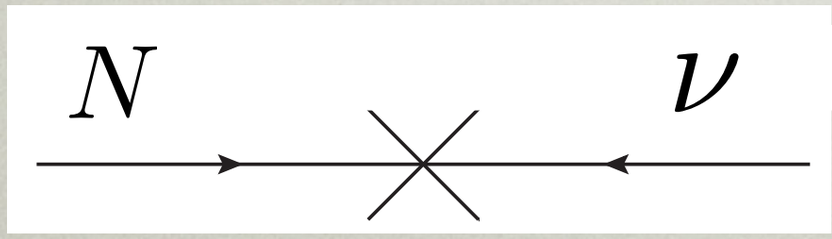
HIGGS PORTAL



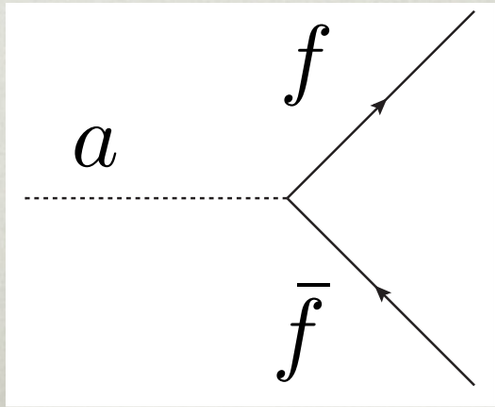
VECTOR PORTAL

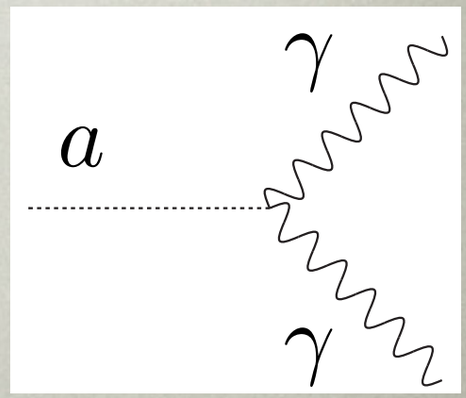


NEUTRINO PORTAL



AXION PORTAL



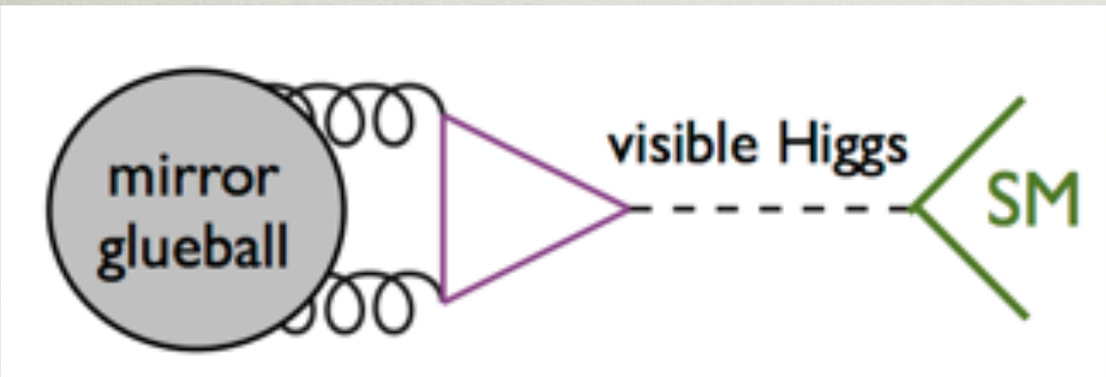


The Higgs Portal

- Probably the best motivated portal due to small Higgs width
  - Easy to have large beyond-SM branching fractions!

Example: Higgs portal to confining hidden sector

- Seen resurgence in interest due to connection w/ hierarchy problem in Twin Higgs models



$$c\tau \sim 18\ \mathrm{m} \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7$$

Craig *et al.*, arXiv:1501.05310; Curtin, Verhaaren, arXiv:1506.06141…

The Higgs Portal

- Can have variety of signatures based on whether pure-glue or quarks
- Different, long lifetimes for each type of hidden-sector particle
  - Scalar states can mix with SM Higgs, decay to bb, taus, etc
  - Vector mesons can mix with SM photon, decay to leptons
  - Some could be absolutely stable (giving rise to MET)
- Can also have mix of all of the above

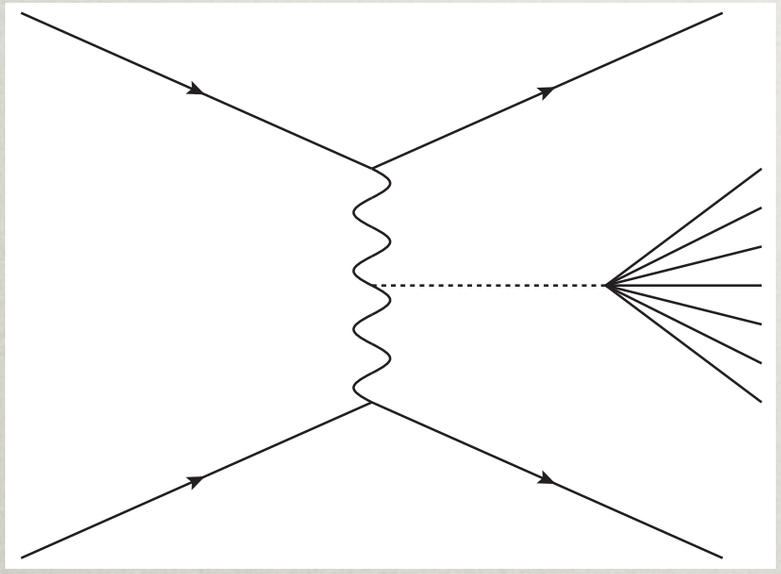
*** see Matt's talk; also dark showers breakout session! ***

e.g., Strassler, Zurek 2006; Han *et al.*, 2007; Juknevich, Melnikov, Strassler, 2009; Schwaller, Stolarski, Weiler 2015; Cohen, Lisanti, Lou 2015; Pierce *et al.*, 2017; ….

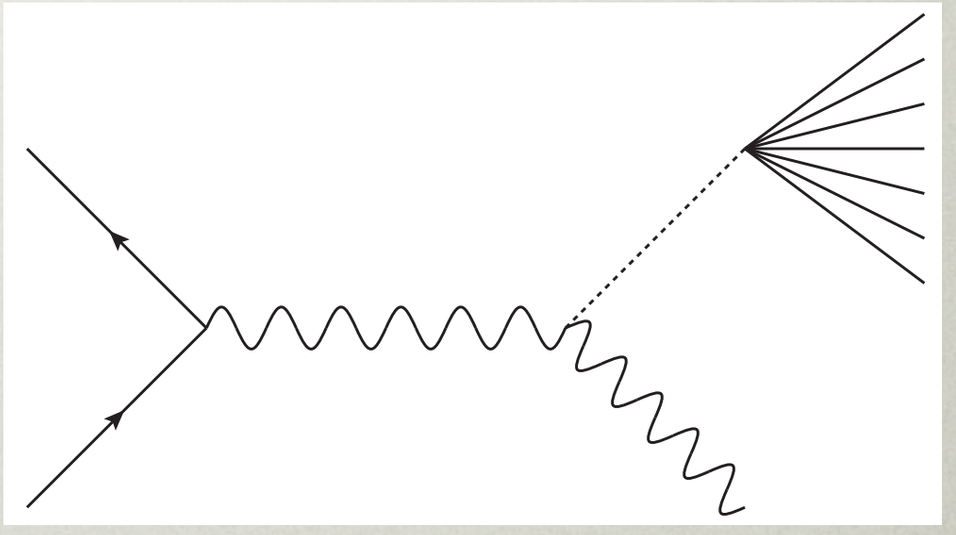
The Higgs Portal

- Higgs associated production mechanisms give additional prompt objects
- Can be useful for trigger and reconstruction

VBF + LLP(s)



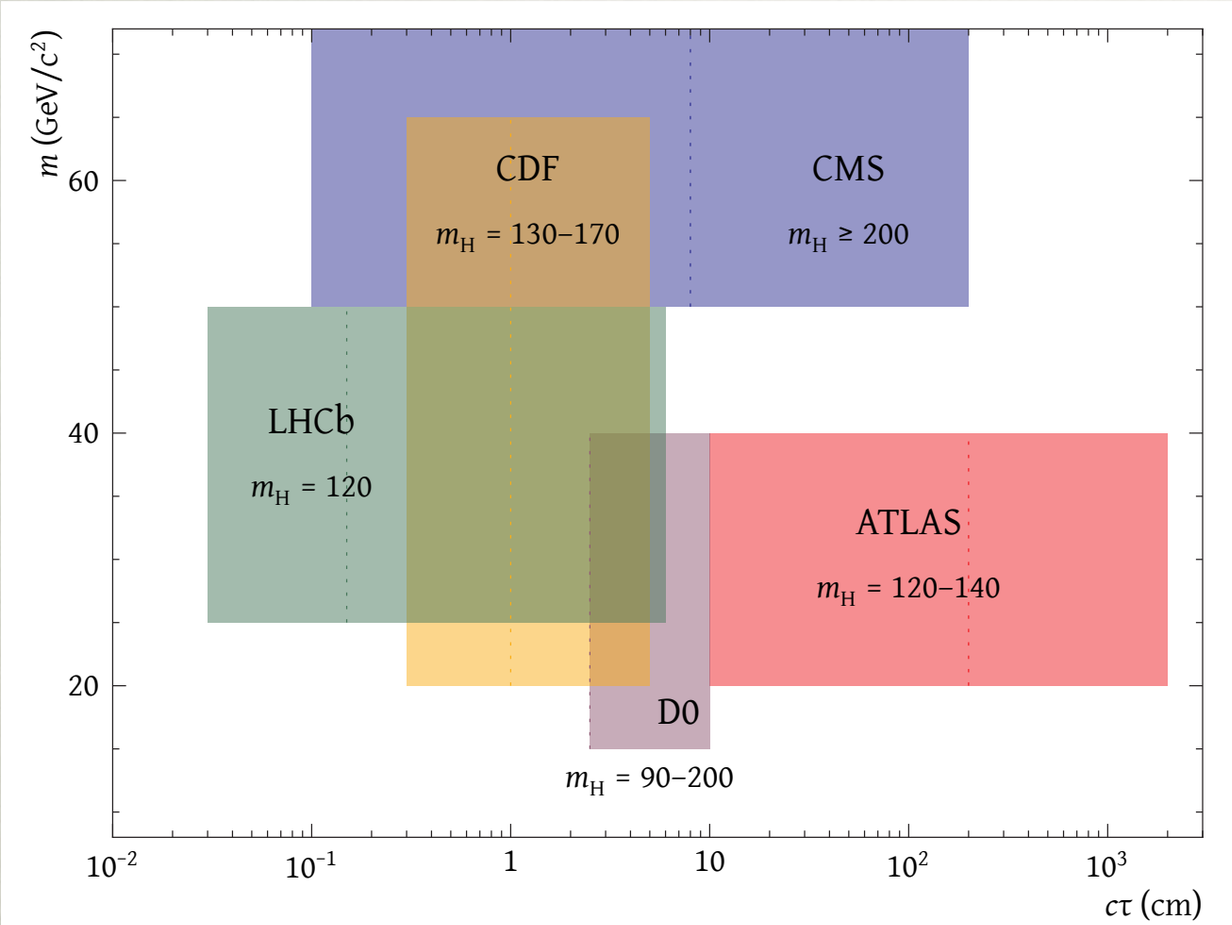
VH + LLP(s)



(jets, leptons, MET, …)

The Higgs Portal

- Complementarity between different experiments
- Particularly important for all-hadronic channels



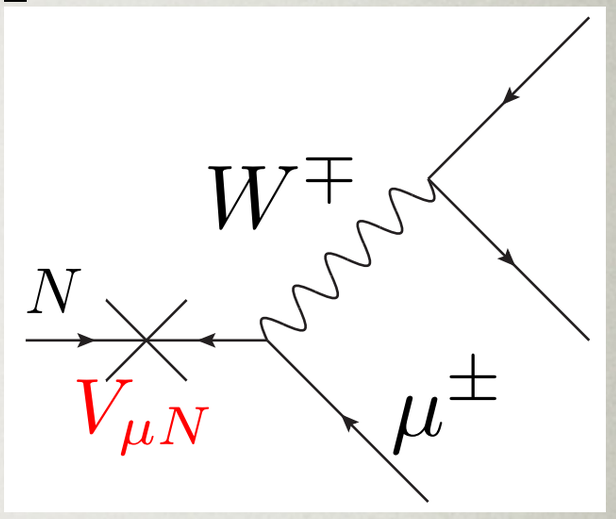
(assuming only pair production, hadronic decays)

Pieter David thesis (LHCb), 2016

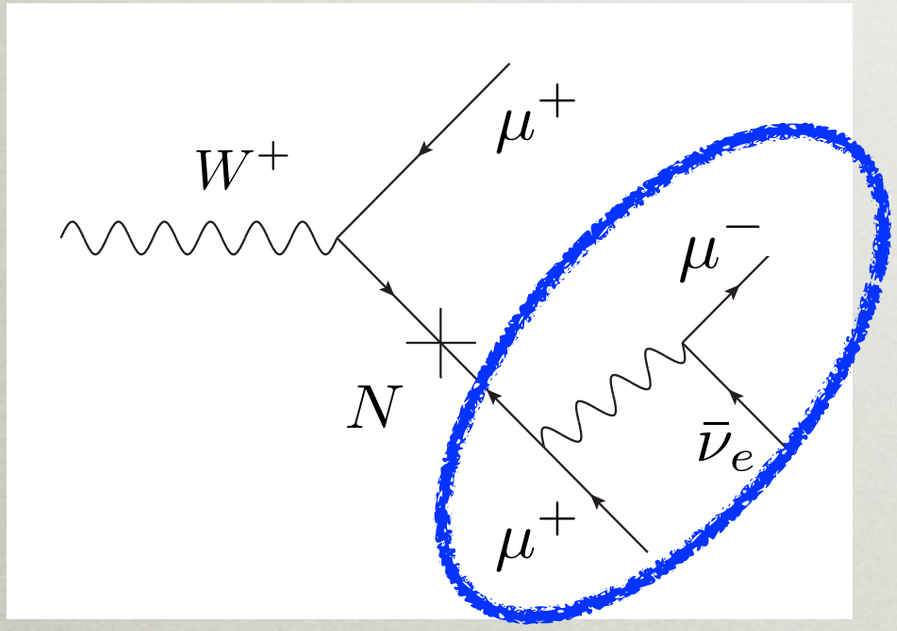
- In all cases, should push to more aggressive limits on Higgs mixing

The Neutrino Portal

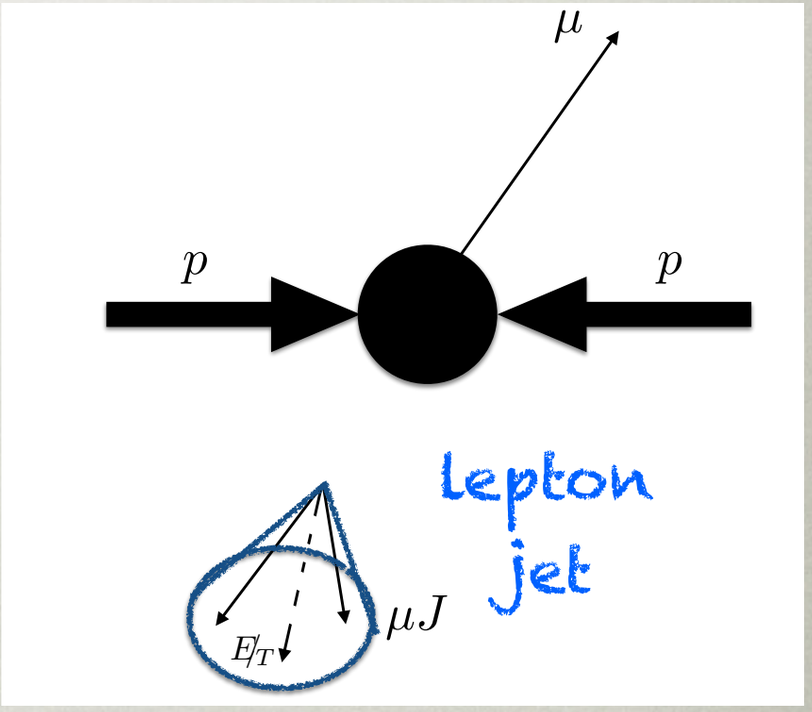
- Heavy, right-handed neutrino mixes with SM neutrino
- Naturally long lifetime due to off-shell decay



*** HNL Breakout Session!! ***



$M_N \ll M_W$



- Get 1 low mass LLP (lepton-only or semileptonic) from W/Z decay

Helo, Hirsch, Kovalenko 2013; Izaguirre, BS 2015; see talks by G. Popara, G. Cottin, O. Fischer

Decays of Hidden-Sector LLPs

- LLP widths are, by definition, small
  - Easily modified by new couplings
  - Usually, lifetime best treated as **free parameter**

- Decays often motivated by particular portal, but sometimes uncorrelated

- Can have many different:
  - Masses
  - Lifetimes
  - Associated objects
  - Decay modes/stable exotic particle states
  - LLP multiplicities

Outline of Talk

- Examples of Models with Long-Lived Particles

- Reinterpretation of LLP Searches

Reinterpretation Challenges

- One model can generate many different **signatures**
- One signature can come from many **models**

neutral LLP channels

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

Reinterpretation Challenges

- We want searches to cover as much phase space as possible
- We want results presented so they are as **broadly applicable** as possible
- LLP searches are challenging because:
  - "Standard" objects (electrons, muons, tracks) are not so standard if they come from LLP decay or stable LLP
  - Signal efficiencies hard to model with publicly available simulation
  - Efficiencies can have strong dependence on kinematics, LLP decay position, etc.

Reinterpretation Challenges

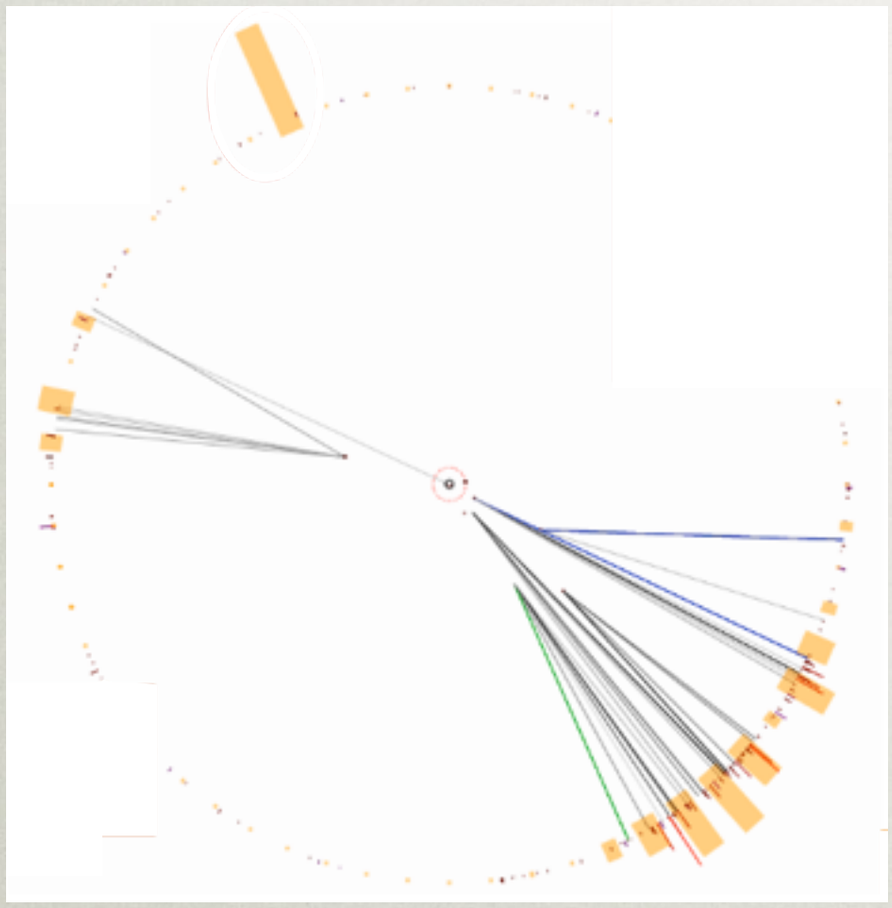
- **Some possible approaches:**
  - Cut flow efficiencies
    - But need reliable public tools to simulate signals!
  - Detailed efficiency maps
    - Huge effort to generate!
    - Efficiencies…of what? "Theory" object? "Detector" object?
  - Efficiencies for simplified models
    - Which simplified models? What parameter points?

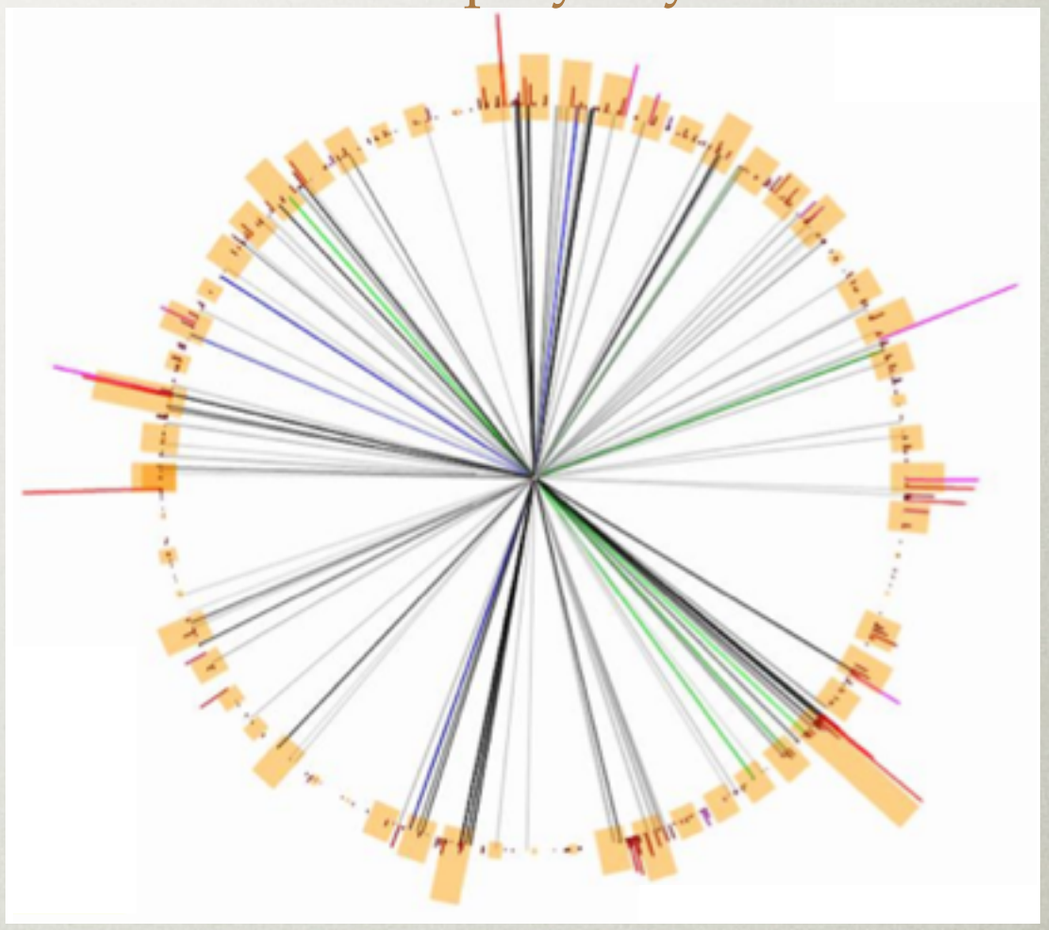
MUCH MORE on this in Nishita's reinterpretations overview and in every talk today!

Reinterpretation Challenges

- Challenges multiply for more exotic signatures, charged/color-charged LLPs, quirks, etc.!

Event displays by M. Strassler





*** Matt's talk, Dark Showers & G4 Breakout Sessions!! ***

Summary

- For decades, LLPs predicted in theoretical models & today receiving a resurgence in interest

- Amazing progress in the past few years on the theory & experiment fronts, but a long way to go

- One day, we hope to move from constraints to discovery. Are we ready for when that time comes?

Back-up slides