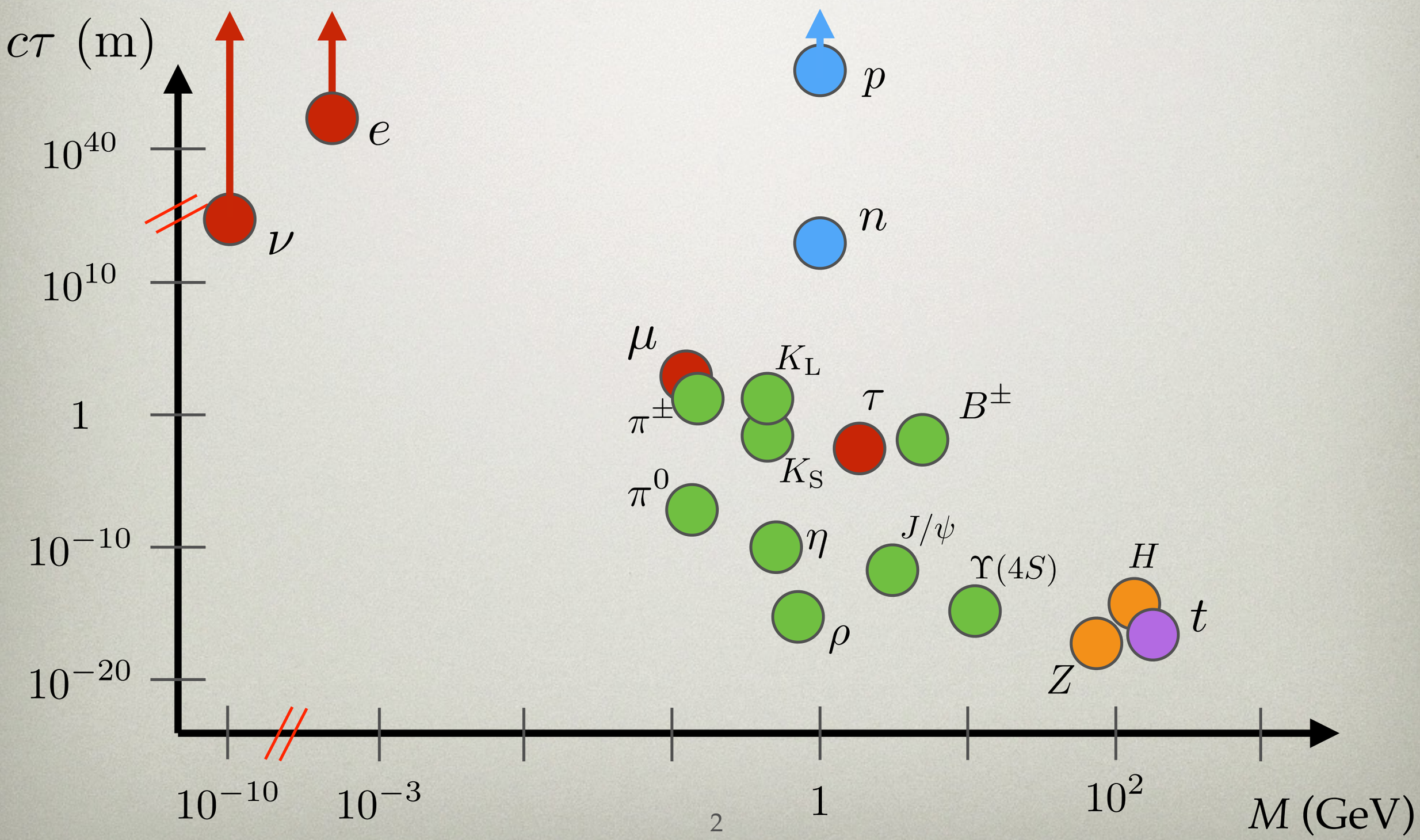
THEORY OVERVIEW OF **LONG-LIVED PARTICLES**

Brian Shuve — SLAC

LHC-LLP CERN Workshop — April 24, 2017

Long-Lived Particles in the SM

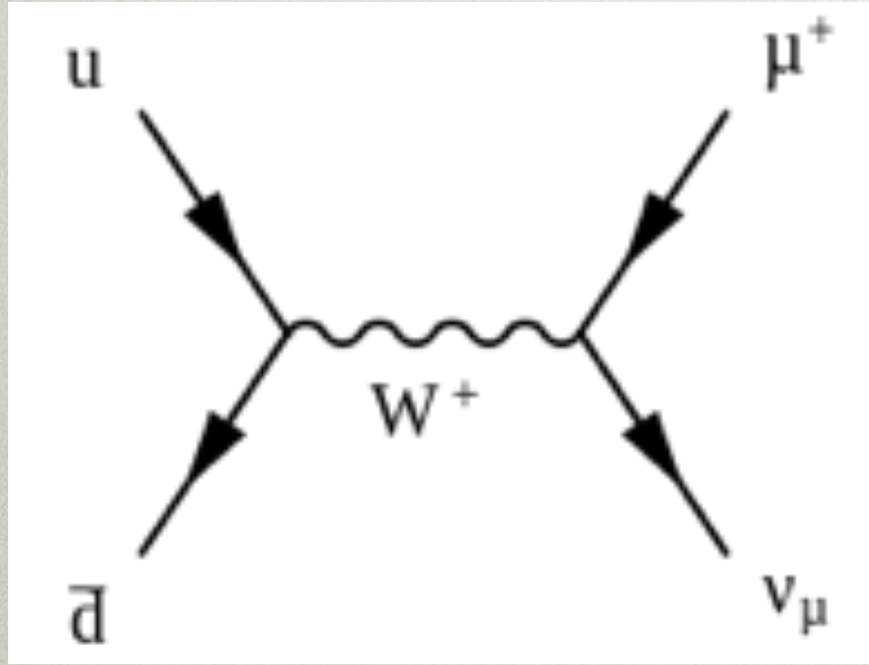
- The world is **full** of long-lived particles



Long-Lived Particles in the SM

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

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



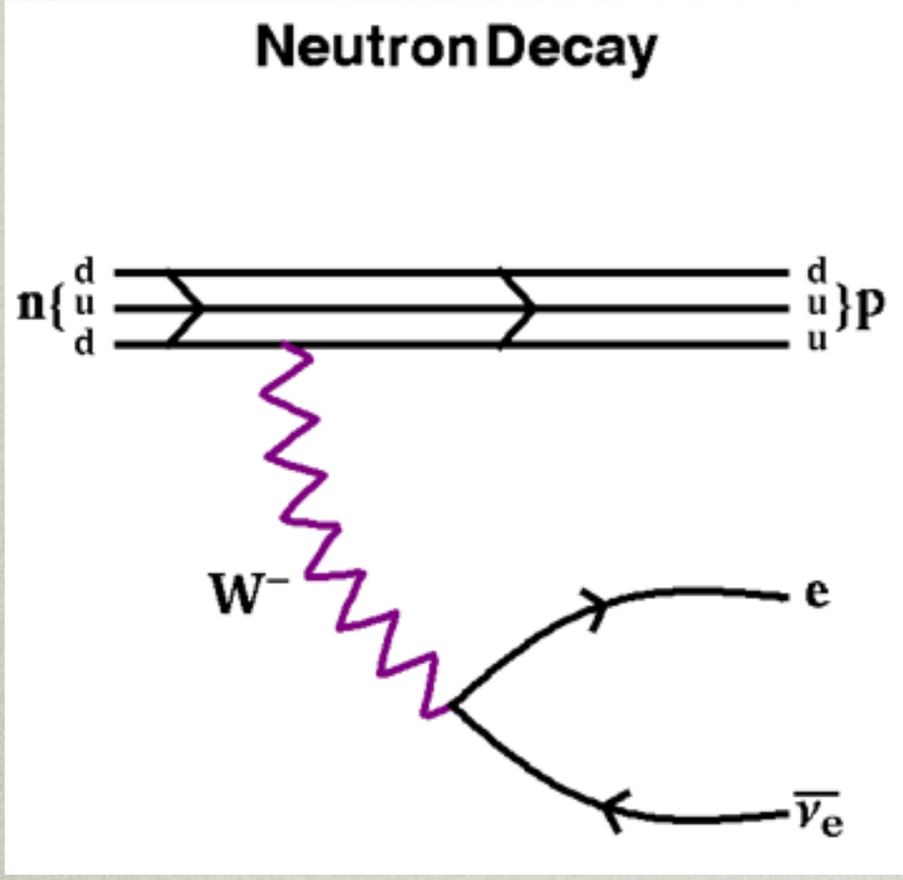
- Quark flavour conserved by all but weak interactions
- Decay highly off-shell:

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

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*

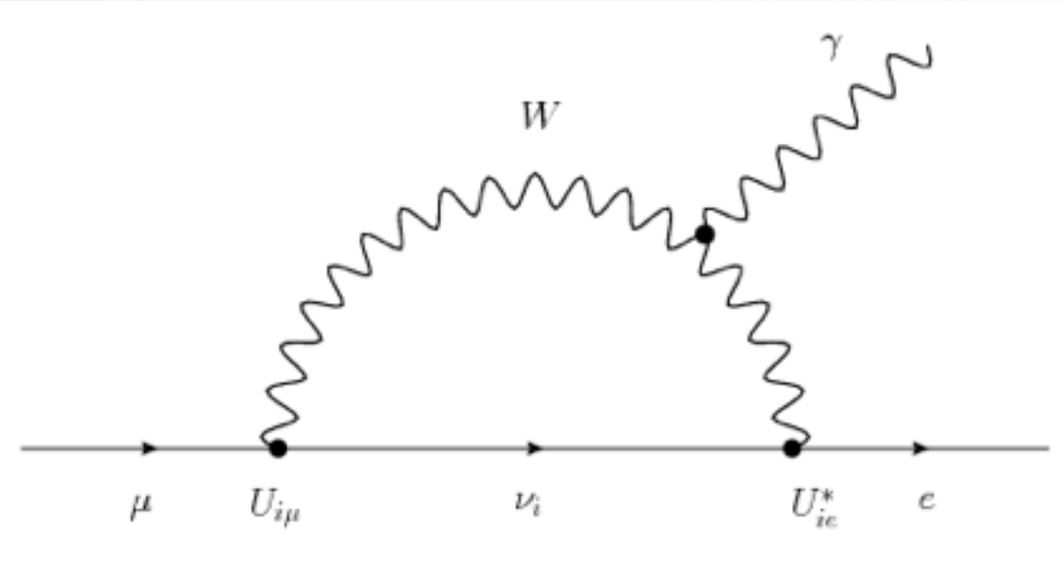


- Isospin ensures that proton and neutron are nearly degenerate
- Decay highly off-shell:

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

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

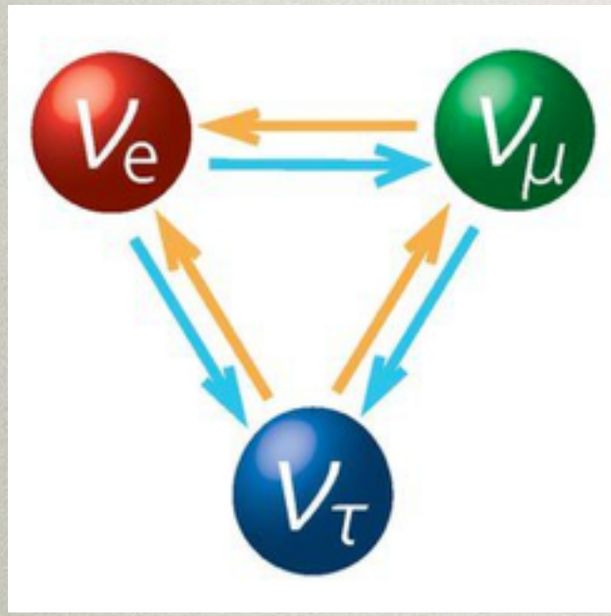
- SM particle lifetimes can be long if an **approximate symmetry** makes the particle stable
  - Typically has to do with "weakness" of weak interactions
  - This in turn arises from hierarchies of scale such as

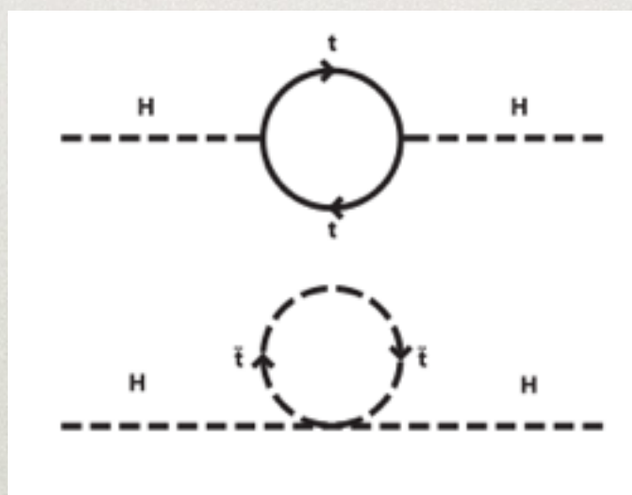
$$\Lambda_{\mathrm{QCD}} \ll M_W$$

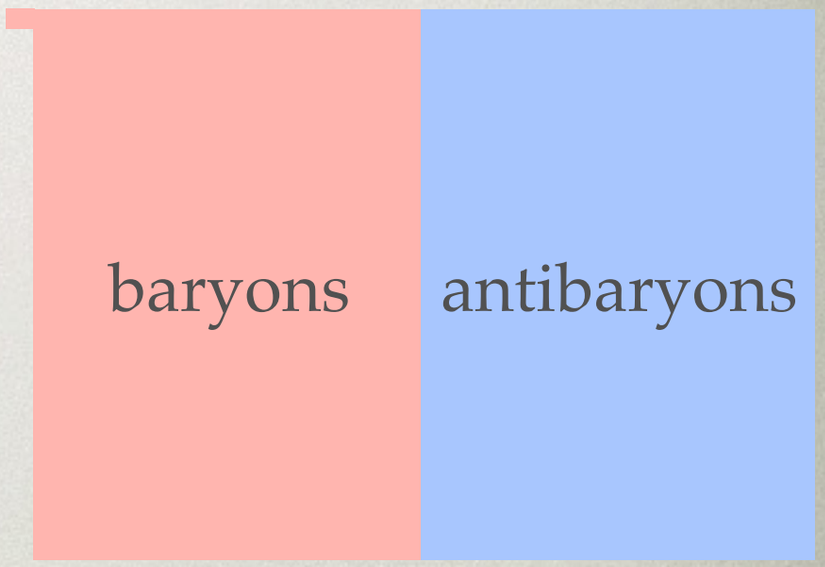
- Electroweak symmetry can lead to mass degeneracies, which suppress decay rates
- Small symmetry-breaking parameters can suppress decay rates

Long-Lived Particles Beyond the SM

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







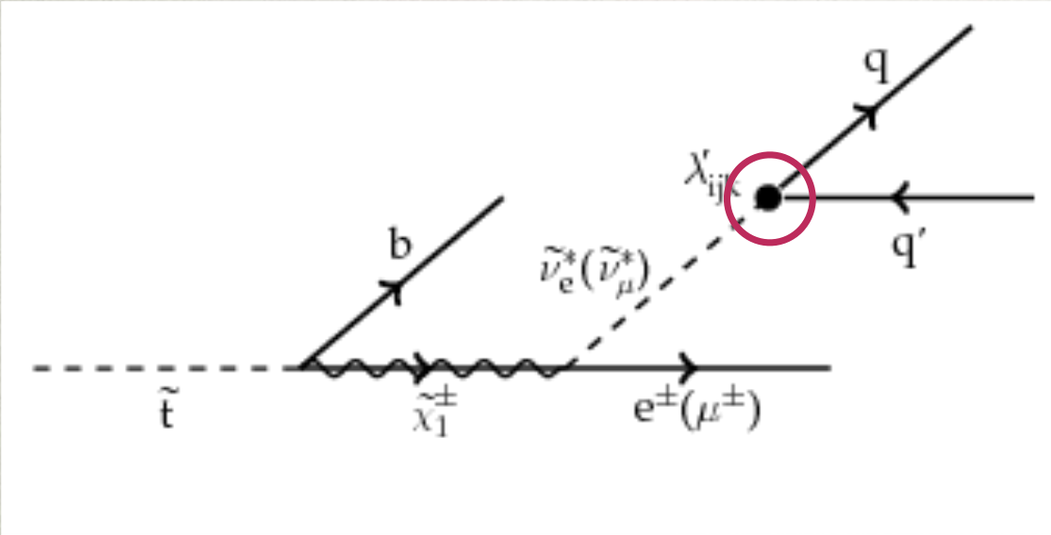
- Feeble couplings, no definite mass scale: easily get LLPs!

Outline of Talk

- Examples of Models with Long-Lived Particles
- A Theorist's Take on the Road Ahead
  - A Systematic Approach to Searches
  - Backgrounds at the LLP frontiers
  - Towards a comprehensive search strategy
  - Taming wild signatures

LLP Models: Supersymmetry

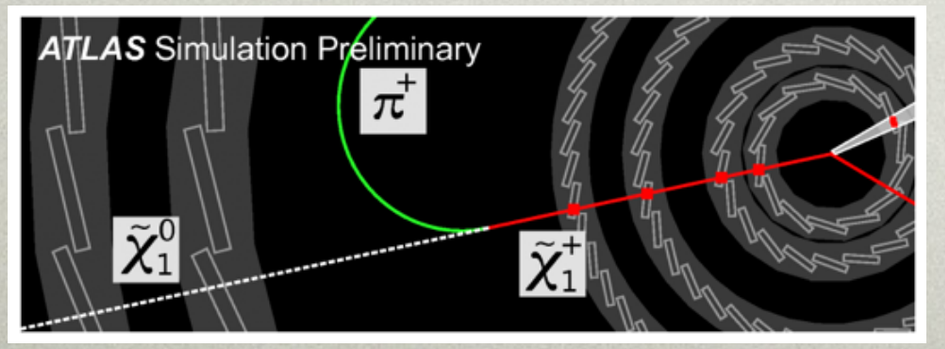
R-parity-violating SUSY:



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

Pure weak-ino states:

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

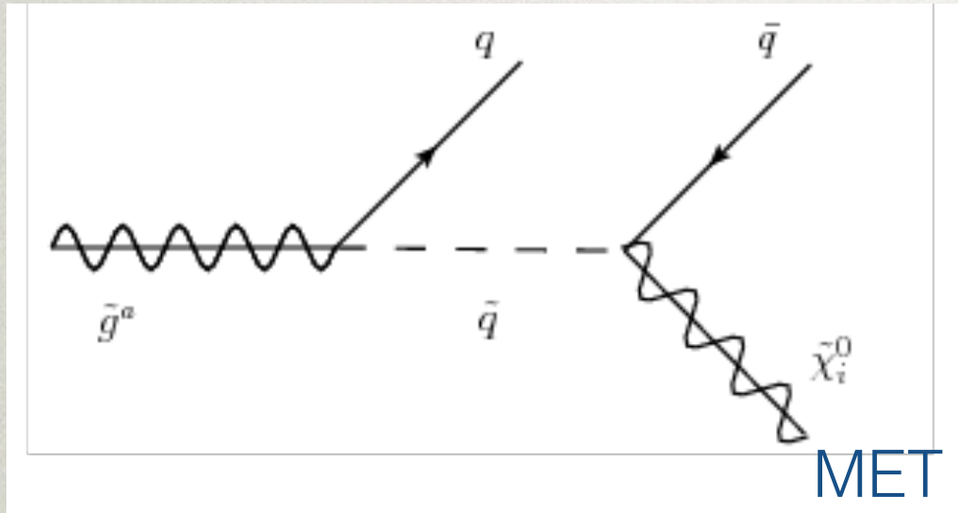


$$c\tau \approx 0.7\,\mathrm{cm} \times \left(\frac{\Delta m}{340\,\mathrm{MeV}}\right)^3$$

LLP Models: Supersymmetry

Split SUSY:

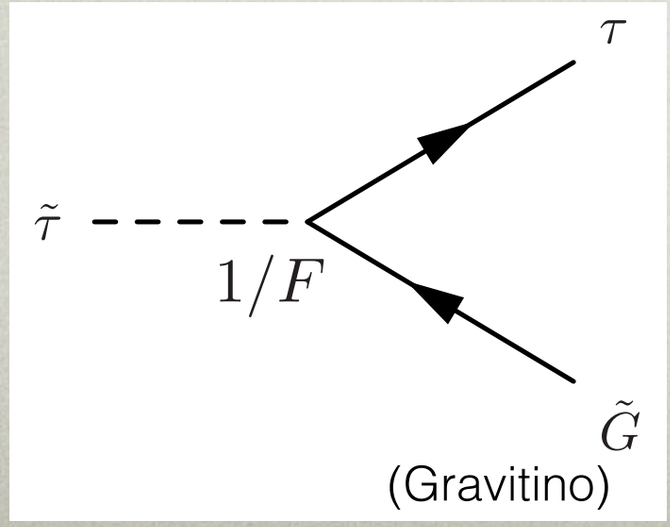
- Models with decoupled supersymmetric scalars



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

Gauge mediation:

- Decays to gravitino suppressed by SUSY-breaking scale



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

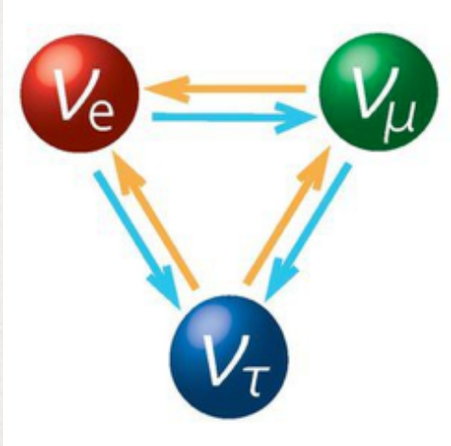
LLP Models: Supersymmetry

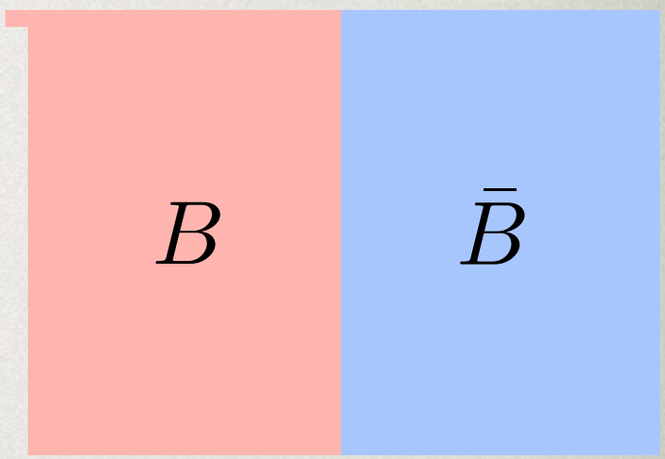
Lessons from SUSY:

- 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

Z. Liu *et al.*

LLP Models: Hidden Sectors





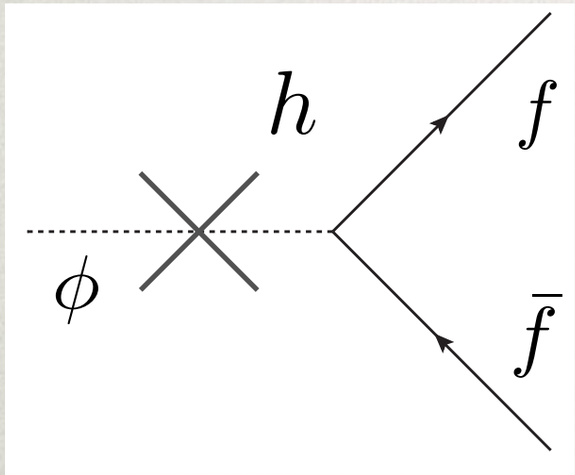
- New particles may (likely) be SM singlets
- Could be any mass! Want to look for low-mass LLPs in addition to > weak scale
- Could have own **hidden-sector** confinement, multiple states, …

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

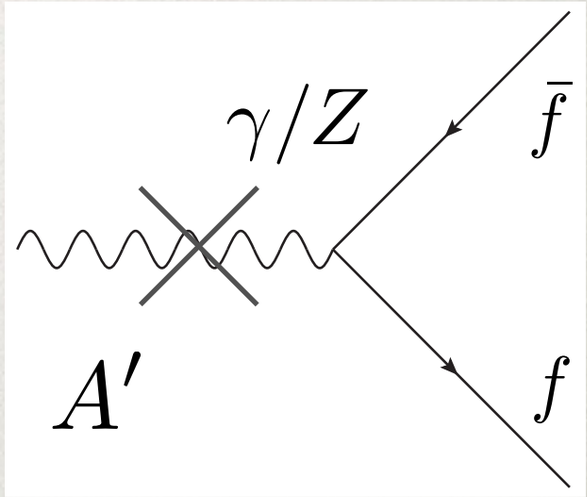
Hidden-Sector Portals

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

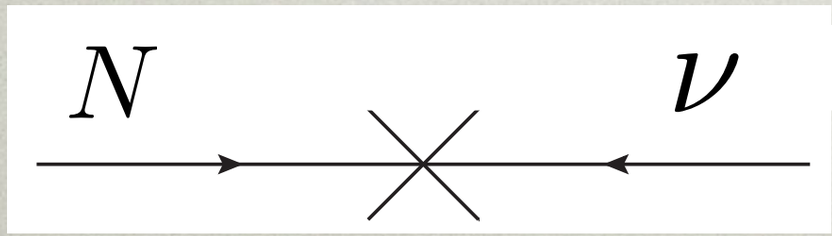
HIGGS PORTAL



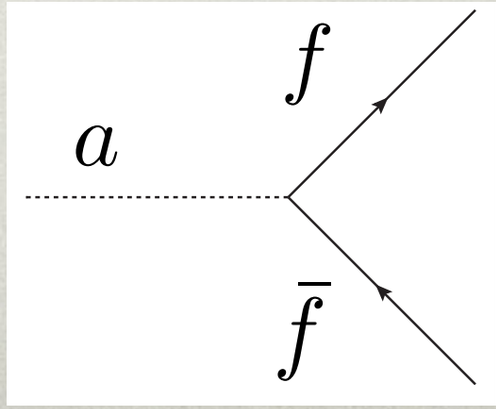
VECTOR PORTAL

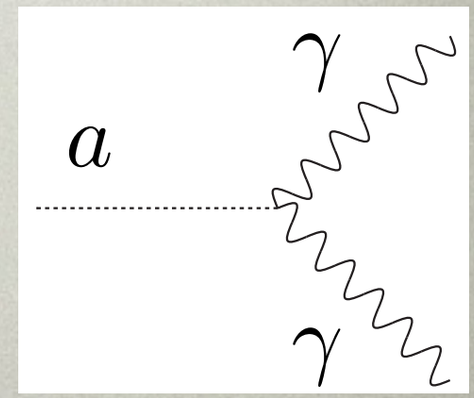


NEUTRINO PORTAL



AXION PORTAL



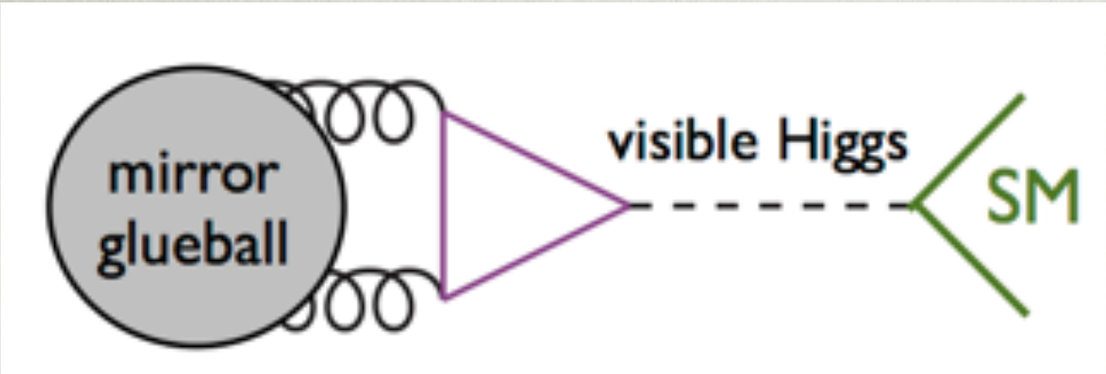


The Higgs Portal

- 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



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

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)

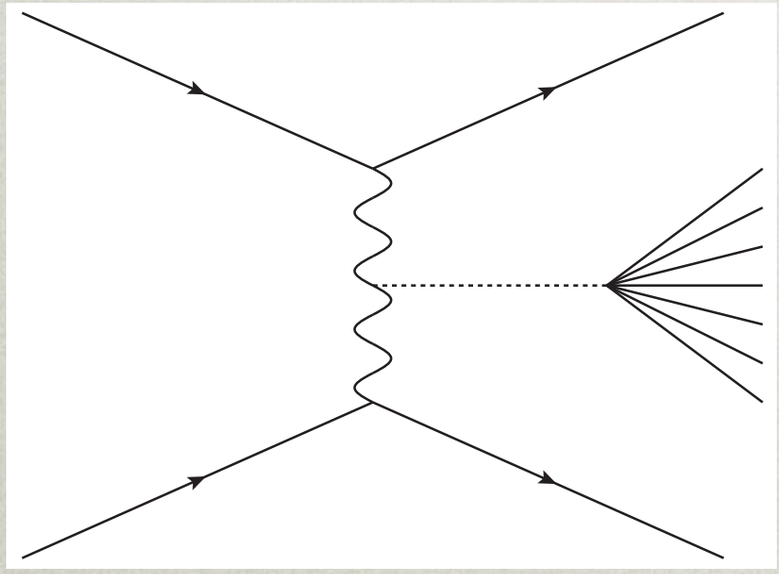
- Can also have mix of all of the above

e.g., "semi-visible jets", Cohen, Lisanti, Lou 2015

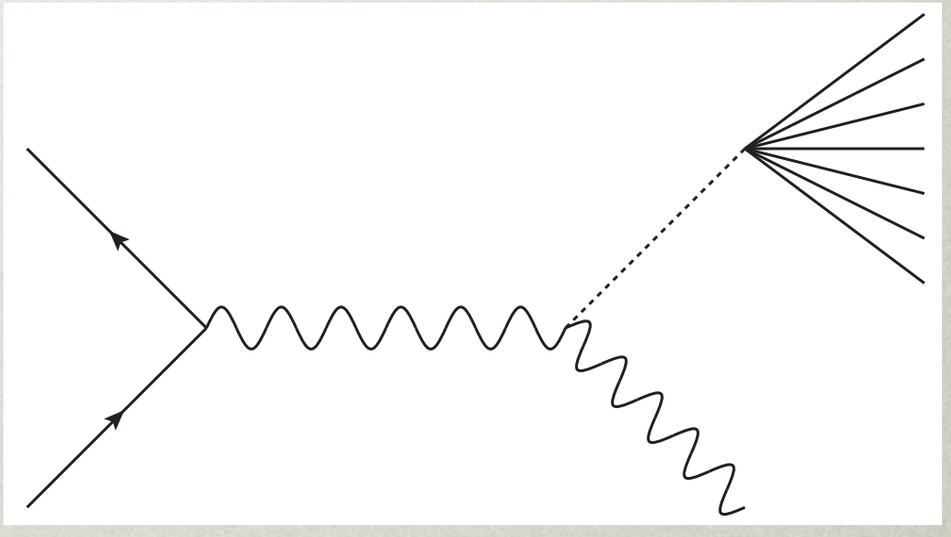
The Higgs Portal

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

VBF + LLP(s)



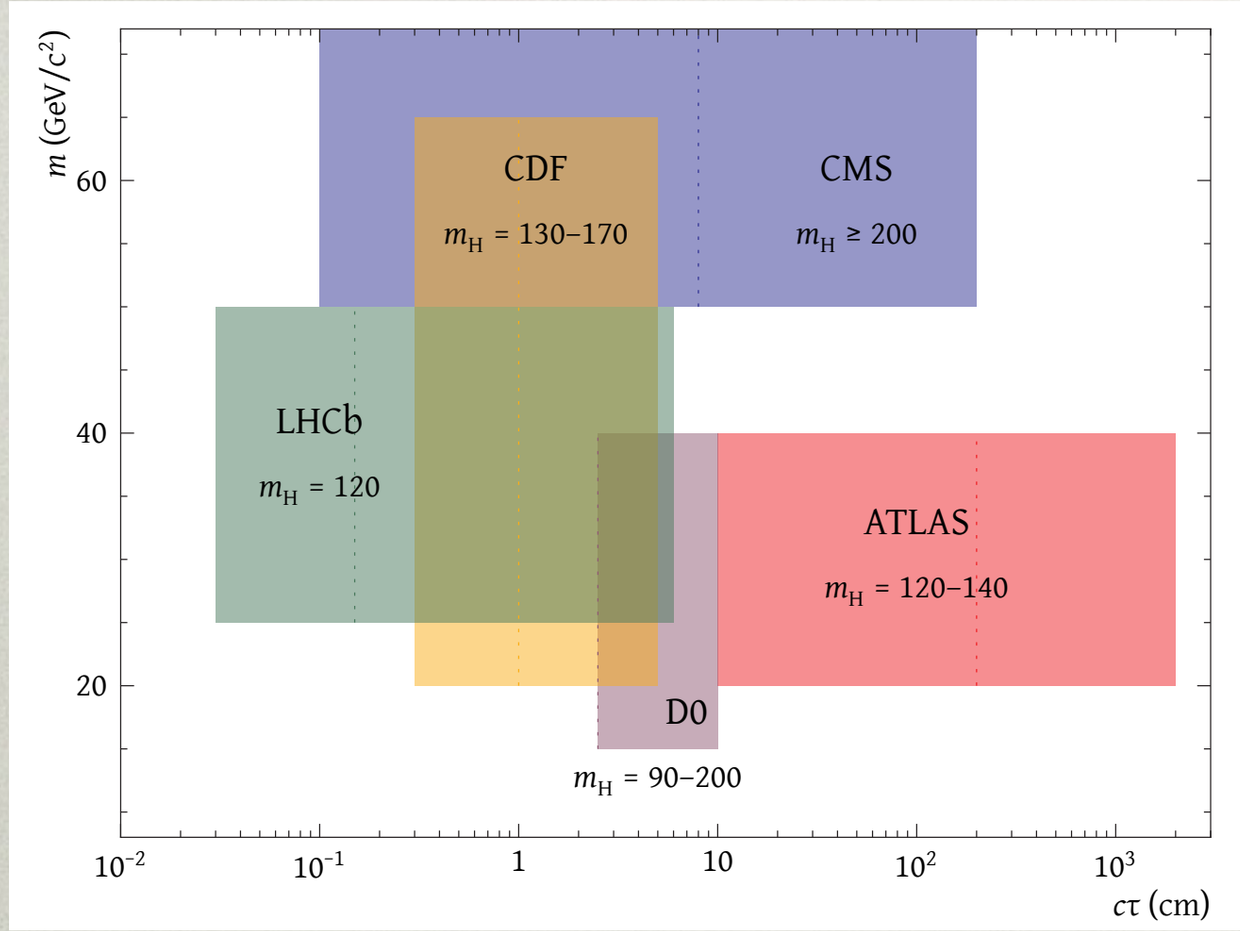
VH + LLP(s)



(jets, leptons, MET, …)

The Higgs Portal

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



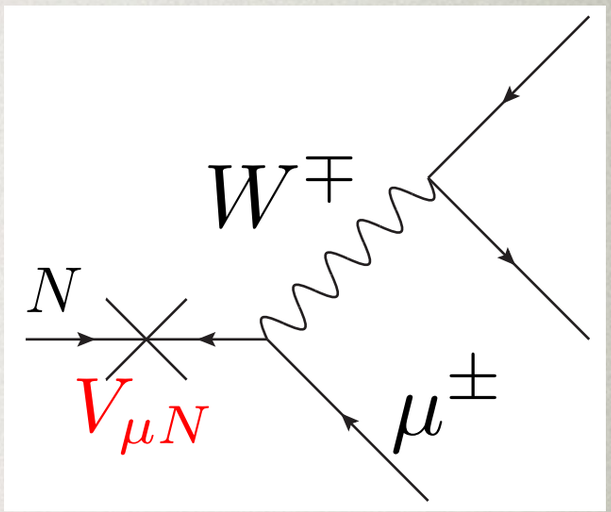
(assuming only pair production, hadronic decays)

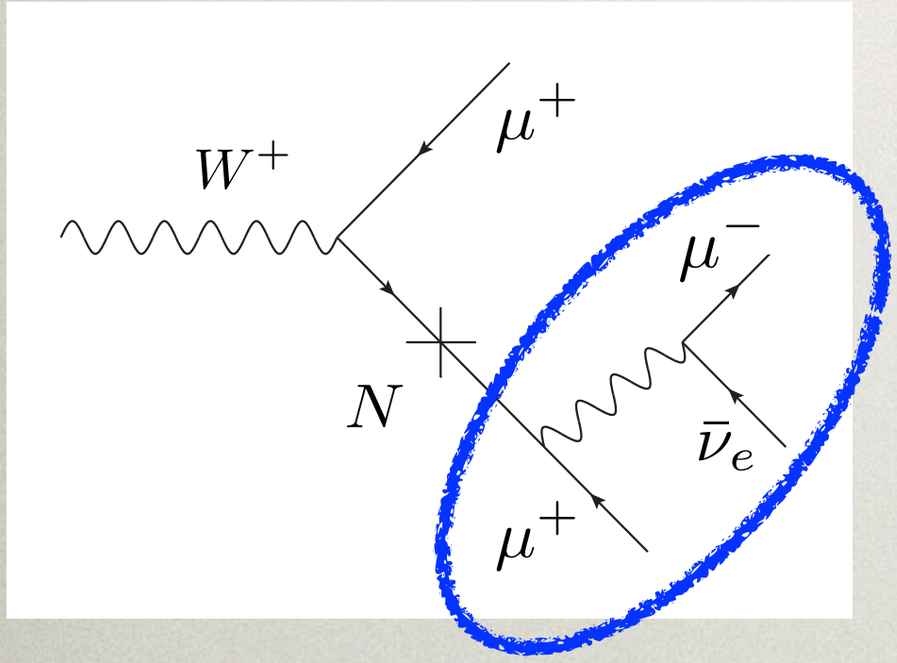
Pieter David thesis (LHCb), 2016

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

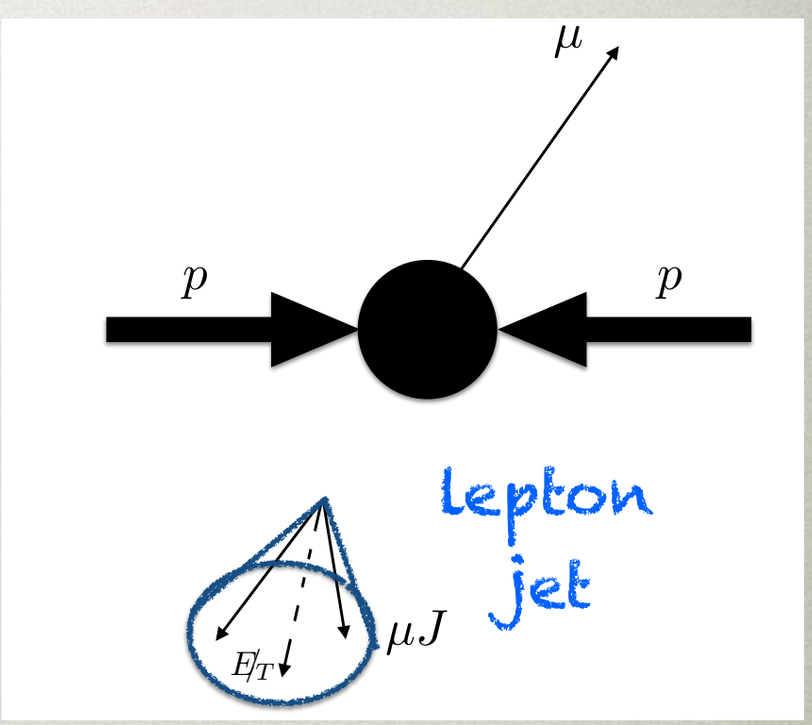
The Neutrino Portal

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





$M_N \ll M_W$



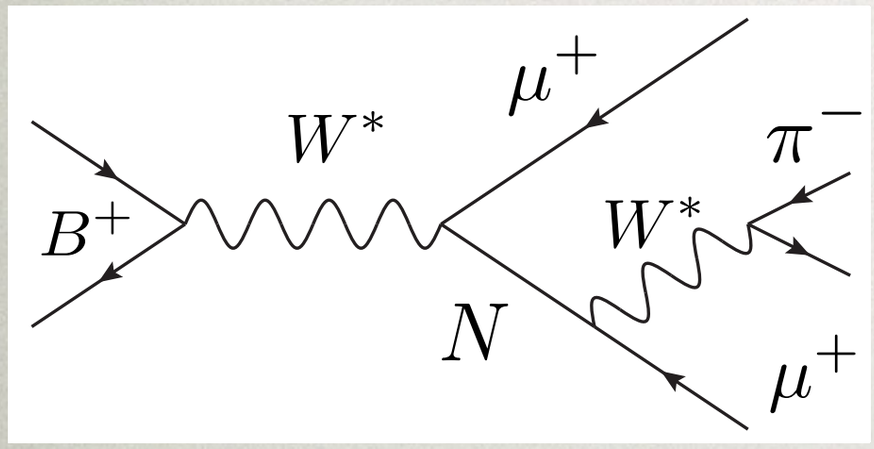
Arkani-Hamed, Weiner, 2008; …

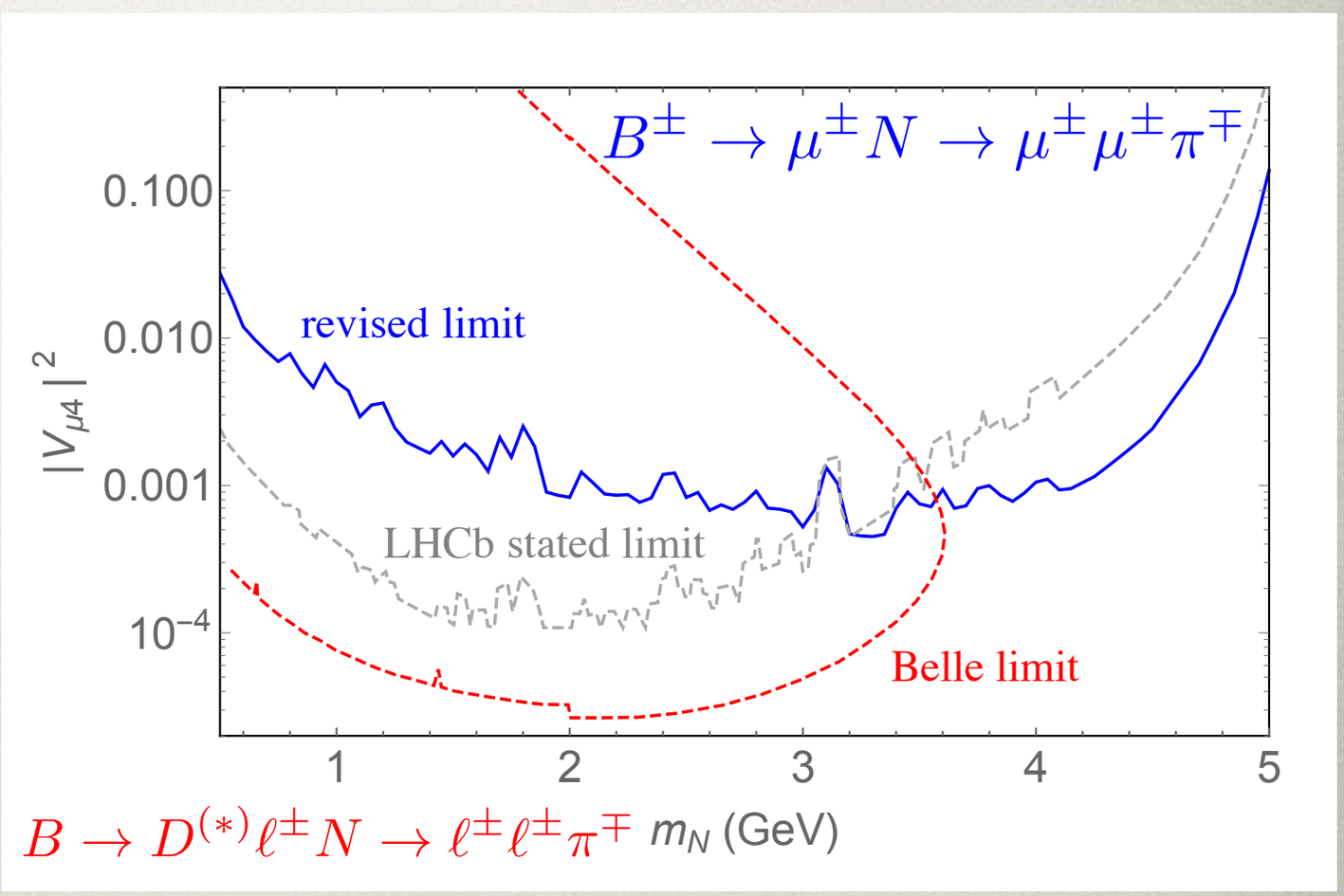
- Get 1 low mass LLP (lepton-only or semileptonic) from *W*/*Z* decay

Helo, Hirsch, Kovalenko 2013; Izaguirre, BS 2015

The Neutrino Portal

- Complementary forward/low-E experiments





LHCb: 1401.5361; Belle: 1301.1105

- Not yet leading constraint, more inclusive searches (including more initial states) could do better

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

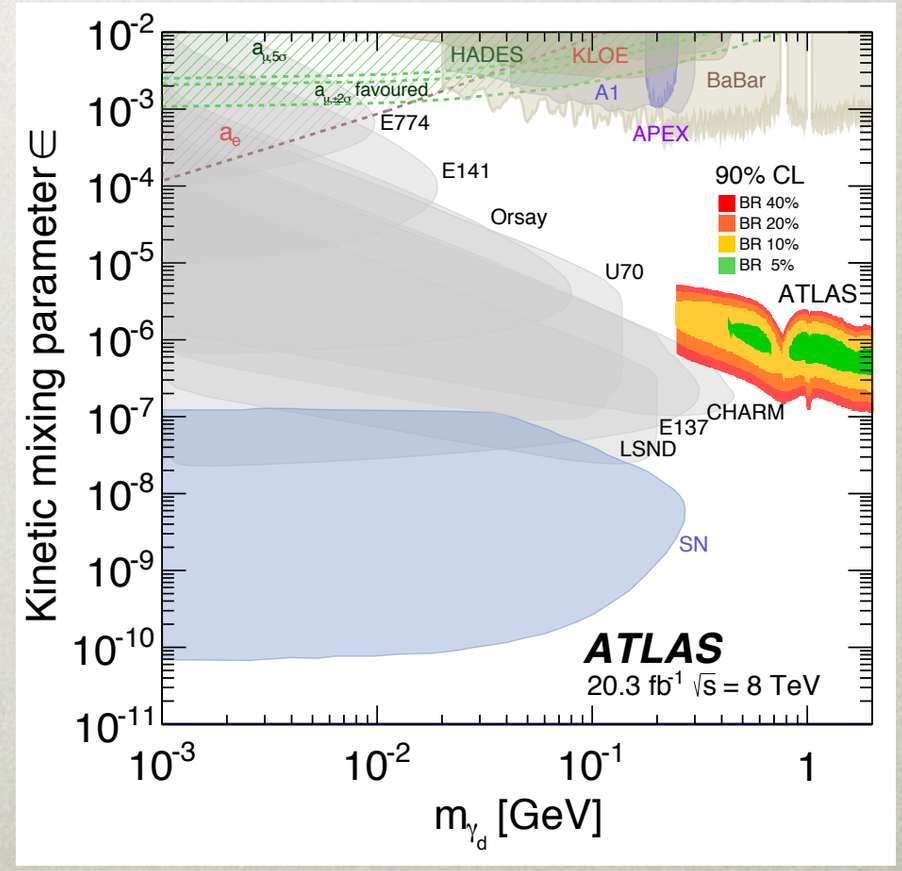
- From theory point of view, decays at different distances classified in same manner (hadrons, leptons,…) while *totally* different for experimental reconstruction

Summary of Hidden-Sector Portals

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

- When lifetime arises due to a hierarchy of scales, can get large boosts

  e.g., Falkowski *et al.*, 2010



ATLAS-CONF-2016-042

Outline of Talk

- Examples of Models with Long-Lived Particles
- A Theorist's Take on the Road Ahead
  - Developing a systematic approach to searches
  - Ensuring that needed searches can be done
  - Backgrounds at the LLP frontier
  - Taming wild signatures

A Systematic Approach to Searches

- Searches often target/are optimized for particular model

- However, LLP searches can be inclusive enough to have excellent sensitivity to a range of scenarios

  Liu, Tweedie 2015; CMS & ATLAS displaced jets; HSCP searches; ATLAS displaced multitrack; CMS "displaced SUSY"; …

- Want to identify a **minimal set** of motivated searches that covers as many scenarios as possible while being reasonably achievable

- Identify motivated, non-redundant list of simplified models
  - Searches should be (reasonably) easily re-interpretable

A Systematic Approach to Searches

WORKING GROUP: Simplified Models/Monte Carlo/ RECASTING and Reinterpretation

- Choose set of models, cross-reference to searches
    - Low-mass and/or high-multiplicity searches are most under-developed, need most work
- Ensure adequate tools exist for smooth interface between theory and experiment
- Recommendations for presentation of results so that searches can be easily applied to other models
    - Most important for signal efficiency?

Ensuring That Searches are Possible

- In order to do search, data must be on tape!
  - New triggers needed (especially for soft and/or high-multiplicity objects)?

- Can existing triggers be doing more?
  - Seeding LLP analyses with multiple triggers
  - Using associated objects where possible

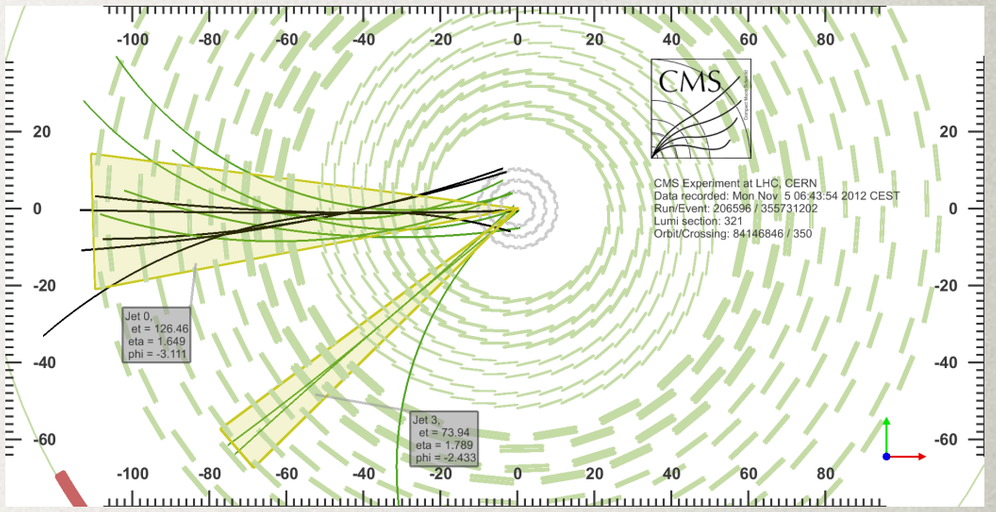
- As we head into Phase 2, concerned that trigger sensitivity to LLP will degrade
  - Strategies to mitigate pile-up? Best ways to use upgrades?

Ensuring That Searches are Possible

WORKING GROUP: Triggering Strategies and Recommended Studies for LLP Searches

- Discuss new uses of existing triggers, as well as brand new ideas
- Complementarity between ATLAS/CMS/LHCb/auxiliary detectors, especially for low-mass or unusual signatures
- Preparing for new challenges in future running
    - Soft displaced leptons (once iso/track requirements start coming in)
    - Ways to use FTK/track trigger technologies?
    - Impact of timing and other improvements on LLP reconstruction

Backgrounds for LLP Searches



- Unique non-prompt and non-collision backgrounds for LLPs
- Many searches are bkd-free
  - But, selections also limit sensitivity to low-mass regime
  - This may no longer be true as we push into low-mass regime or to other signatures *e.g.*, Coccaro *et al.*, 2016
- For theorists (and experimentalists on other expts), helpful to know where limitations are & what could be possible
- Connects with earlier discussion on upgrades

Backgrounds for LLP Searches

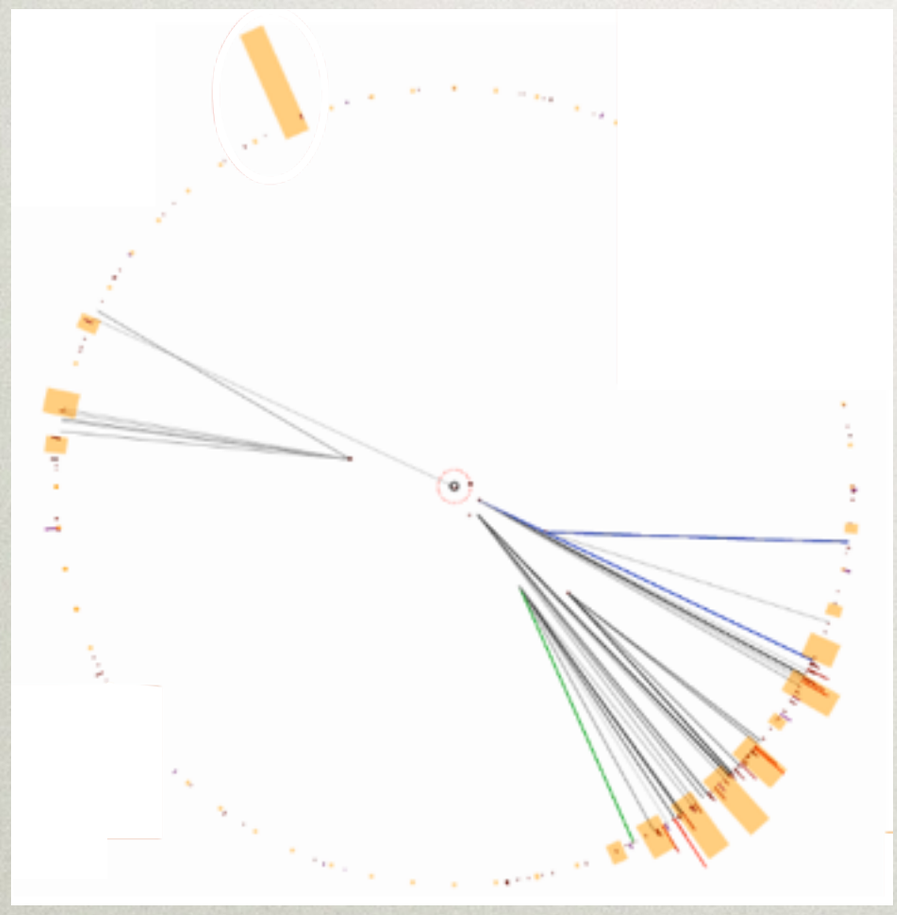
WORKING GROUP: Backgrounds for LLP Searches

- Summarize important backgrounds for LLP searches
- Better methods for characterizing such backgrounds and identifying signal vs. background
- Helps theorists (and others!) think of ideas to suppress backgrounds & models that give distinctive signatures

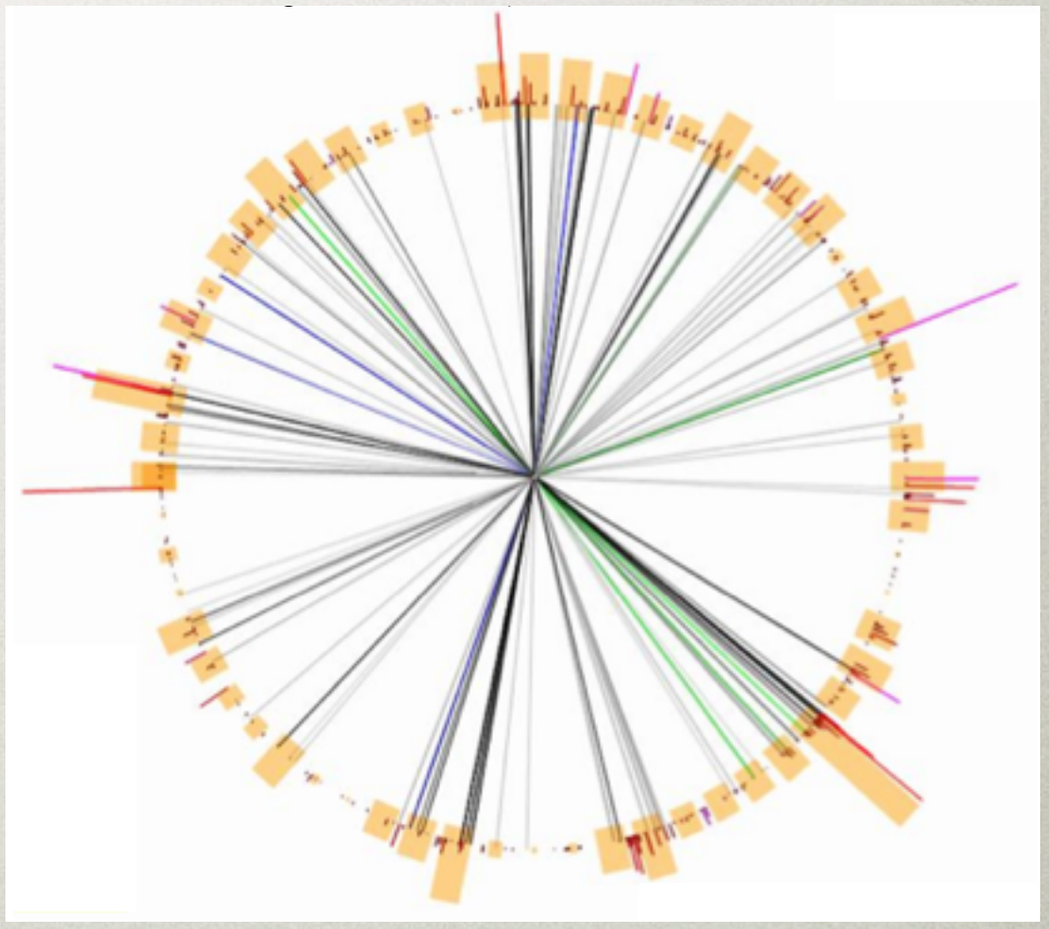
Taming Wild Signatures

- Showers can occur in hidden sectors with large couplings & hierarchies of scales

Schwaller, Stolarski, Weiler 2015



Knapen *et al.*, 2016



Event displays by M. Strassler

Taming Wild Signatures

- Ever more interest in these models thanks to neutral naturalness, Hidden Valleys, etc.

- But there are many unknowns:
  - Radiation patterns (details of shower)
  - Multiplicities (details of hadronization)
  - Fraction of visible vs. invisible particles
  - Fraction of particles with a given lifetime

- Not well covered by existing searches, in part because it's hard to design a search that isn't overly optimized to a particular model

Taming Wild Signatures

WORKING GROUP: Dark Showers

- Work systematically to identify most relevant parameters affecting the phenomenology (simplified model framework?)

- What are the challenges with robustly dealing with variable numbers of particles, overlapping states, etc.?

- Identify search strategies to fill the major gaps AND assure experimentalists that the searches are **broadly applicable**

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?