Title: Uncovering Hidden Sectors at Colliders

Speakers: Brian Shuve

Series: Colloquium

Date: April 04, 2019 - 10:30 AM

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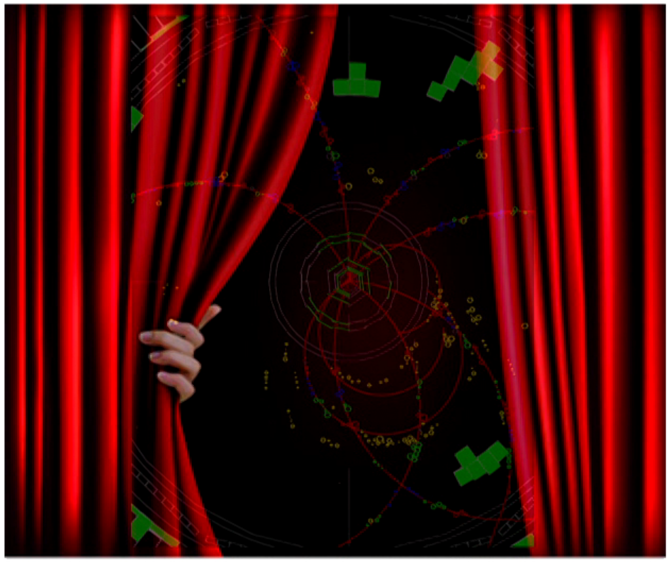
Abstract: Hidden sector particles, with masses and couplings below those of the weak interactions, can resolve many of the outstanding questions of the Standard Model, including the identity of dark matter, the origin of the baryon asymmetry, and the physics of neutrino masses. Existing searches at colliders such as the Large Hadron Collider are, however, often insensitive to signals of hidden sectors. Using the well-motivated example of low-scale leptogenesis and neutrino masses, I will demonstrate connections between the cosmology of hidden sectors and their signatures in experiments. I will then present new experimental ideas for how to uncover the existence of hidden sectors at the LHC, as well as my role in founding and leading a joint theory-experiment initiative working to greatly expand sensitivity to long-lived particles Finally, I will discuss my theoretical and experimental work on low-energy colliders such as B factories, which have an immense and under-utilized potential for discovering hidden particles. Given the many connections between colliders, astrophysics, cosmology, and other terrestrial experiments emerging from the study of hidden sectors, the future is bright for expanding our knowledge of the hidden universe.

UNCOVERING HIDDEN SECTORS AT COLLIDERS

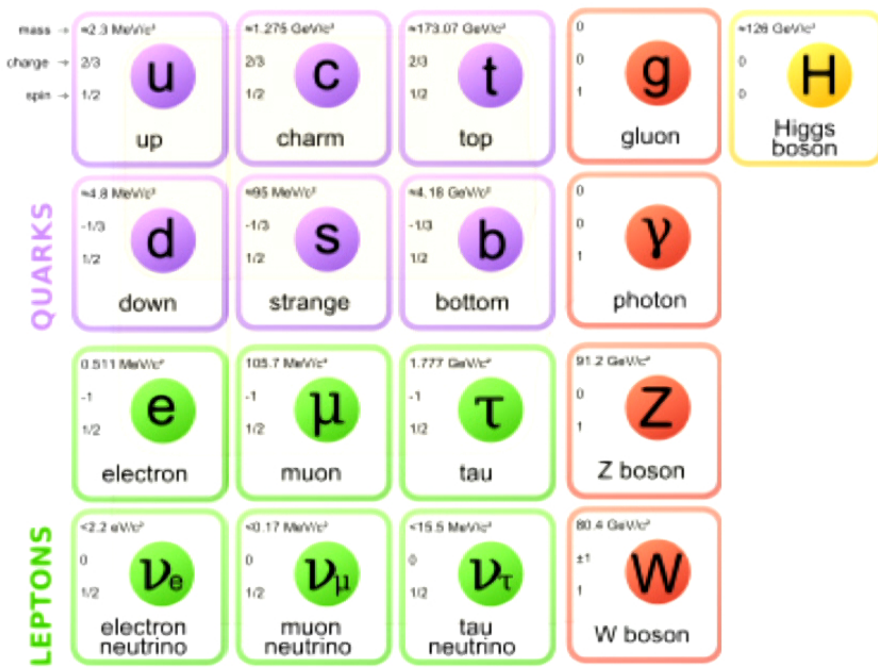


Brian Shuve

PI Colloquium

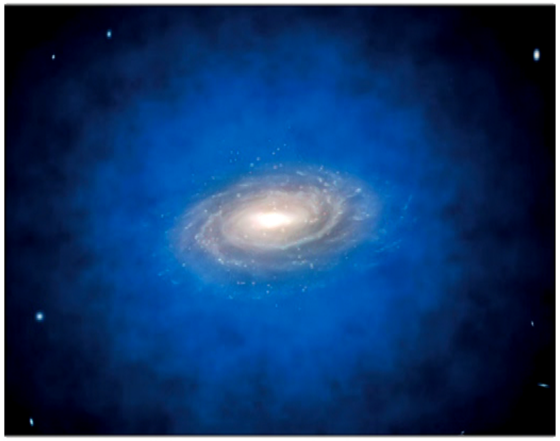
THE STANDARD MODEL

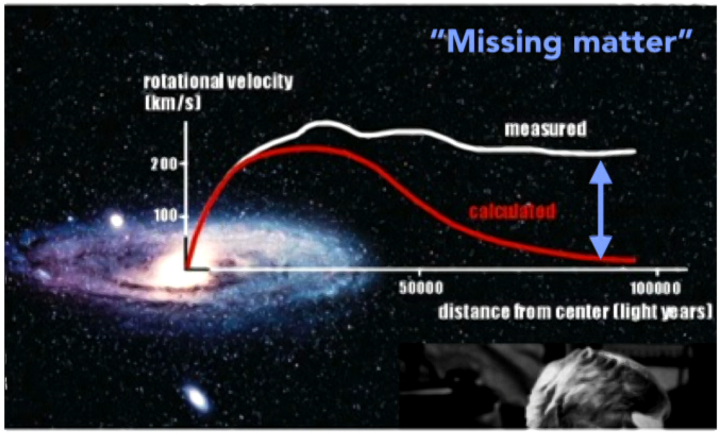
- Current understanding of particle physics: the **Standard Model**



- 3 forces with associated bosons
- 12 matter particles (fermions)
- 1 Higgs boson

THE HIDDEN UNIVERSE





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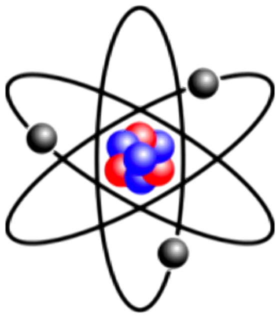

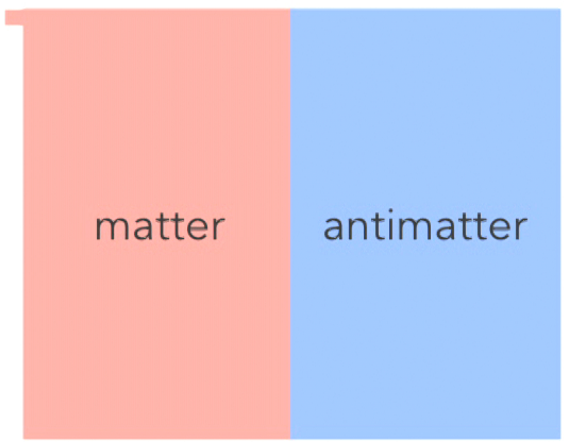

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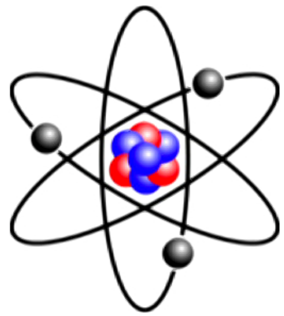
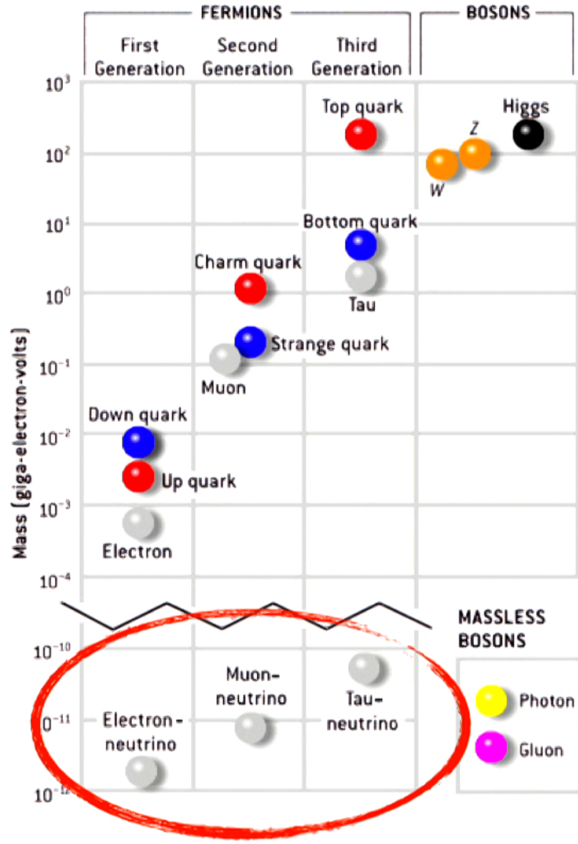
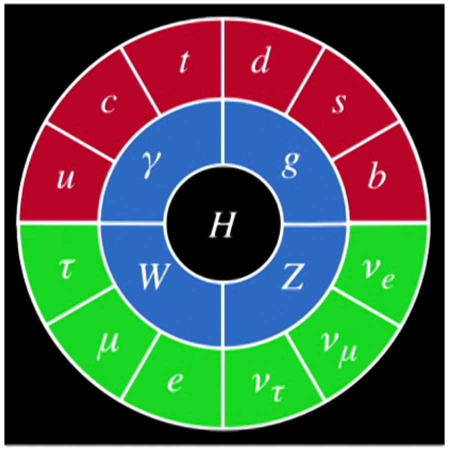


matter | antimatter



HIDDEN SECTORS

- All signs point to one (or many!) neutral particles: **hidden sectors**
- Masses of hidden sector particles relatively unconstrained. Could be **much lighter** than SM particle masses!



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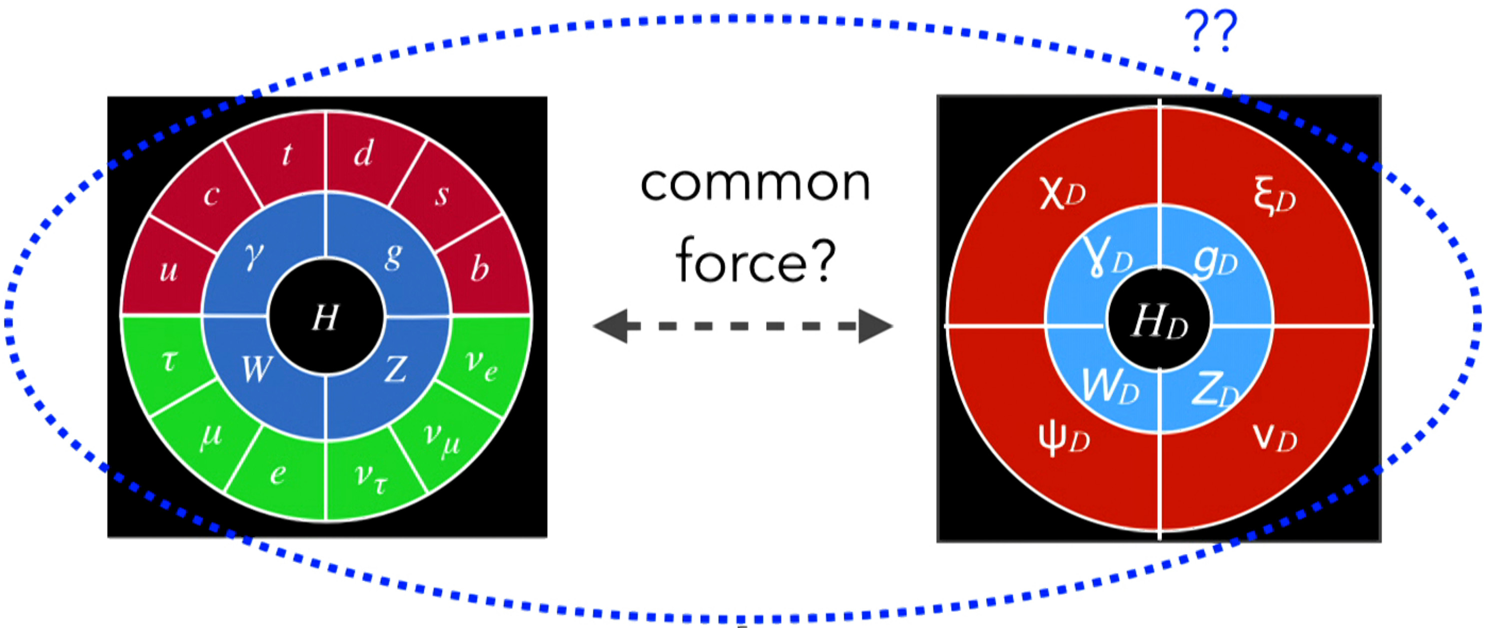

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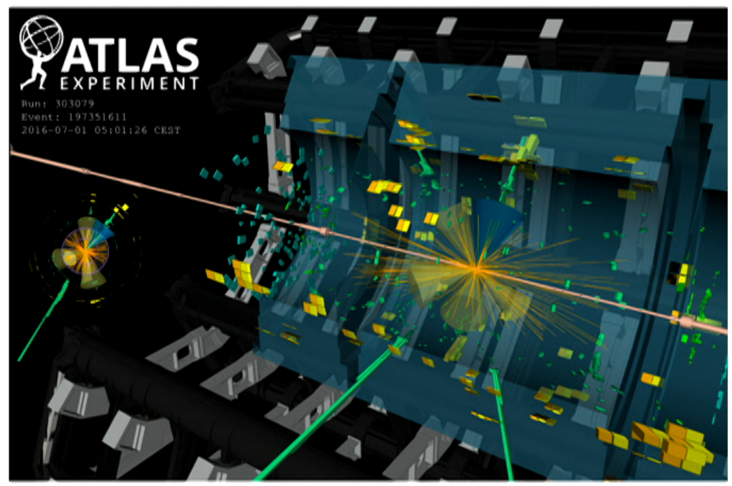
PARTICLE COLLIDERS

- As theorist, important to know how to make & test these particles!
- Colliders are machines built to create & study subatomic particles

<u>Proton-proton (LHC-ATLAS/CMS)</u>



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- Very messy collisions due to strong force between protons

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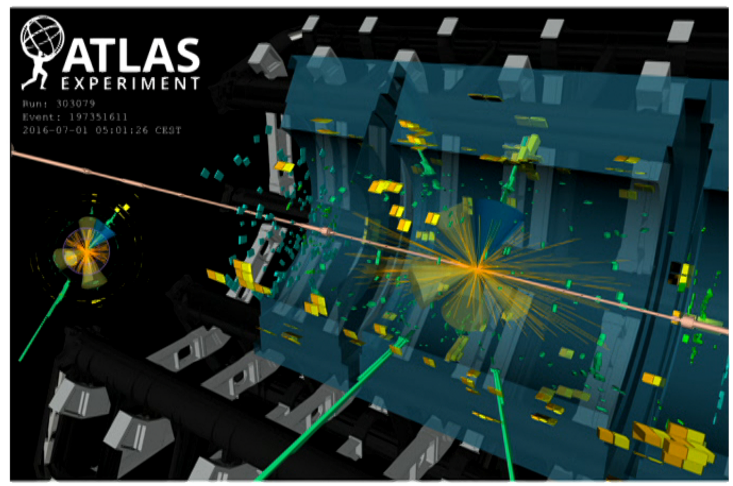

PARTICLE COLLIDERS

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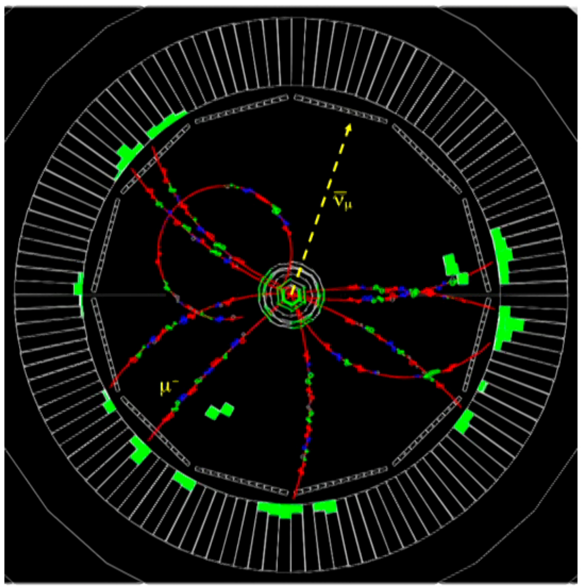
- Currently two main types of collider



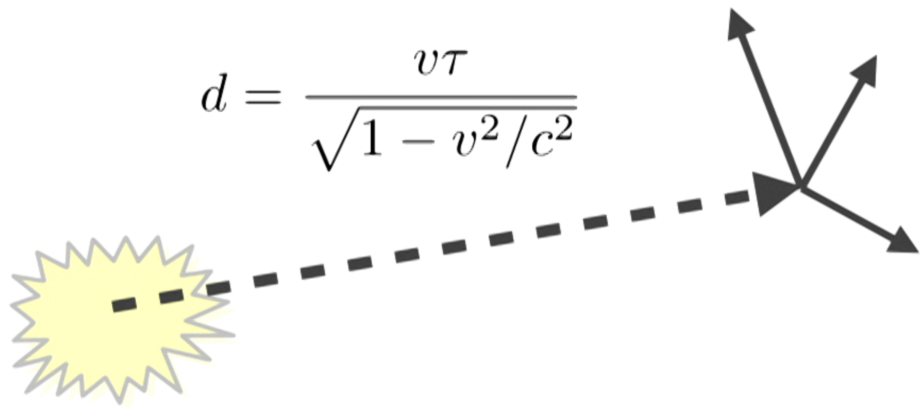
Electron-positron (BaBar, Belle II)

- Highest collision rate
- Very clean collisions
- Lower energy

TESTING HIDDEN SECTORS

- Many hidden sector particles are **long-lived particles (LLP)**
- Travels a macroscopic distance before decaying $(\gtrsim 0.01 \text{ mm})$

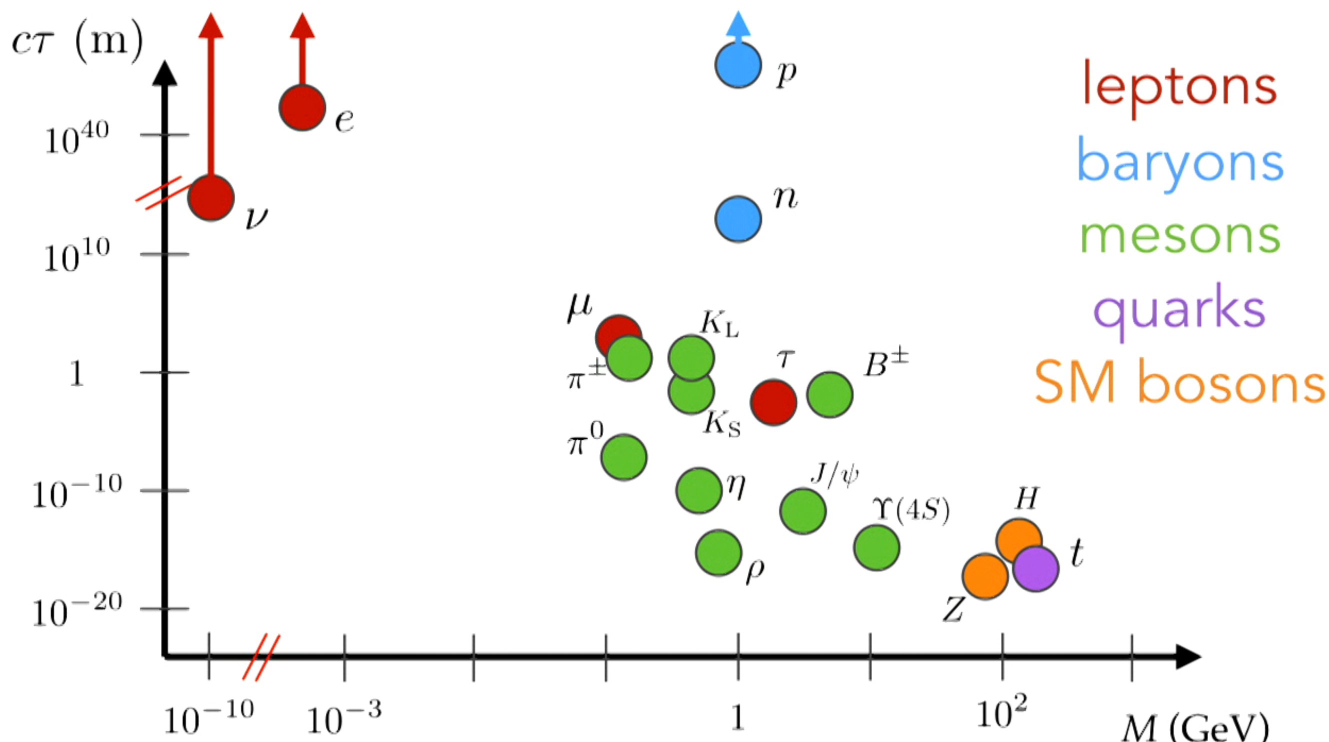
$$d = \frac{v\tau}{\sqrt{1 - v^2/c^2}}$$



- I will discuss why these particles are well motivated theoretically but difficult to see experimentally, and my role in founding & leading the community efforts to hunt for these hidden particles

WHY LONG-LIVED PARTICLES?

- The Standard Model has a lot of LLPs!



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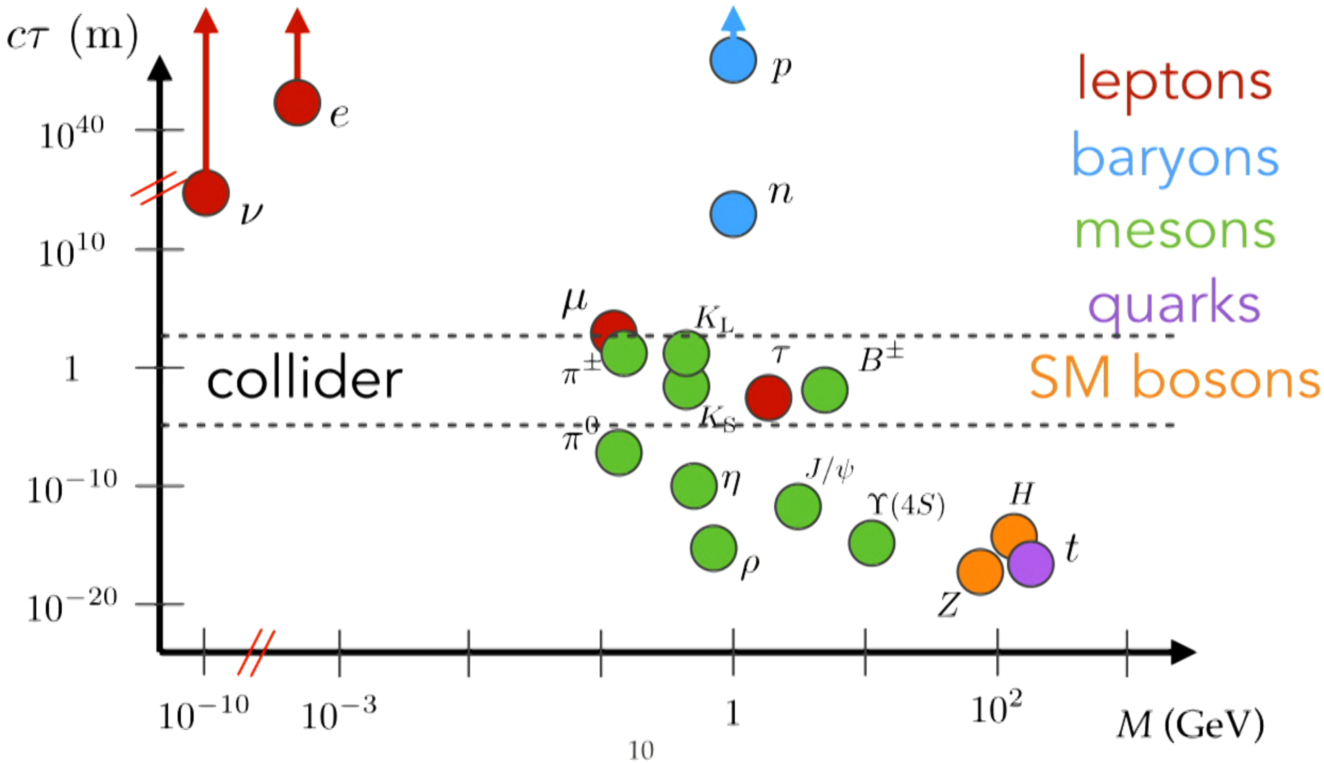
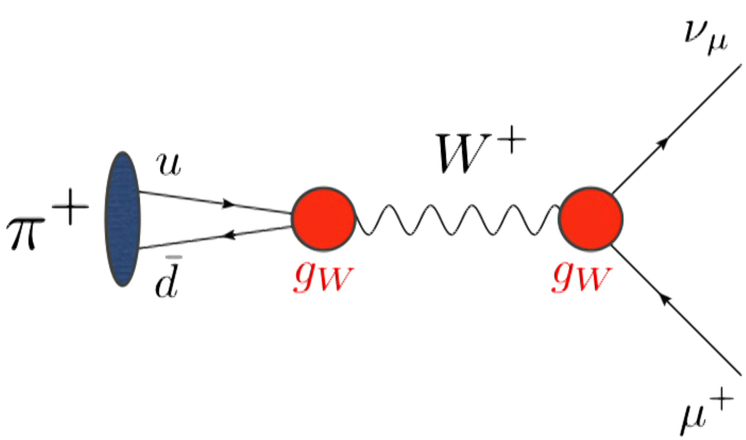


WHAT MAKES IT LONG LIVED?

Example: charged pion decay



decay rate: $\Gamma_{\pi^+} = \frac{1}{\tau_{\pi^+}}$

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

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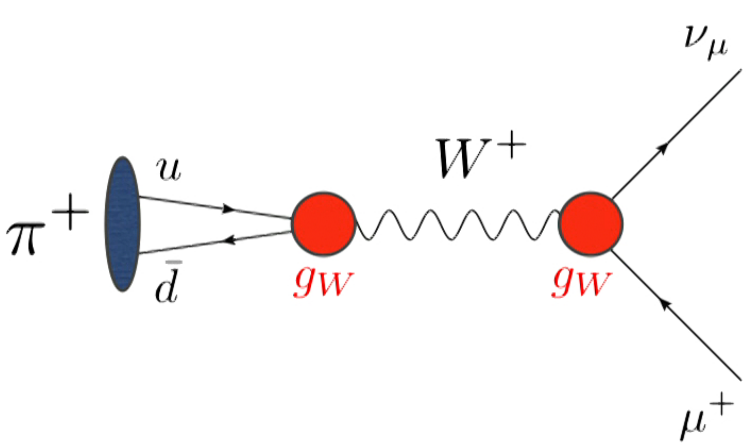

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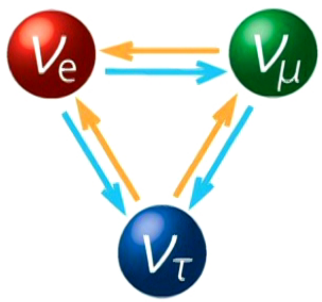
$$\Gamma_{\pi^+} \sim g_W^4 \left(\frac{M_{\pi^+}^2 M_\mu^2}{M_W^4} \right) M_{\pi^+}$$

~ 0.2

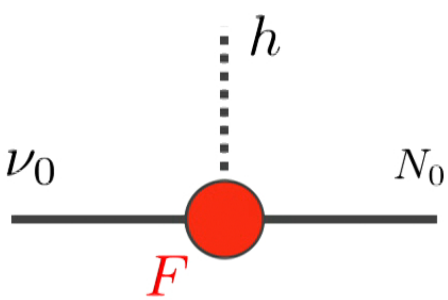
$\sim 5 \times 10^{-12}$

NEUTRINO HIDDEN SECTORS



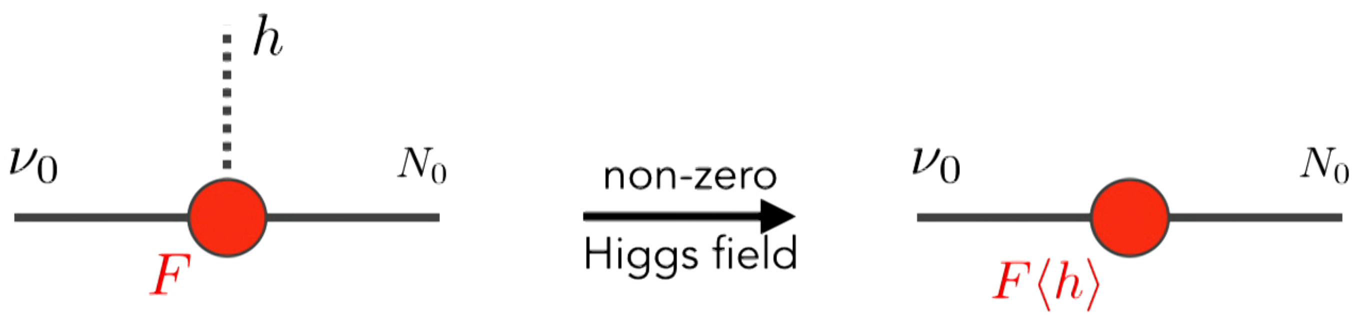
- How can SM neutrinos get mass? Through interacting with the Higgs field!
- However, no particles in SM have right weak charges to do this: introduce new **sterile neutrino** N_0

$$\mathcal{L} = F\, H\, \bar{L}_0 N_0$$



Minkowski, 1977; Yanagida, 1980; …

NEUTRINO HIDDEN SECTORS



- This leads to **mixing** of the SM and sterile neutrino states

feels weak force

$$|N\rangle \sim |N_0\rangle + \theta|\nu_0\rangle \qquad M_N \sim M_{N_0}$$

$$|\nu\rangle \sim -\theta|N_0\rangle + |\nu_0\rangle \qquad M_\nu \sim \frac{F^2\langle h\rangle^2}{M_N} \ll M_N$$

NEUTRINO MATTER ASYMMETRY

- If these sterile neutrinos have ~<300 GeV masses, they are long-lived particles!

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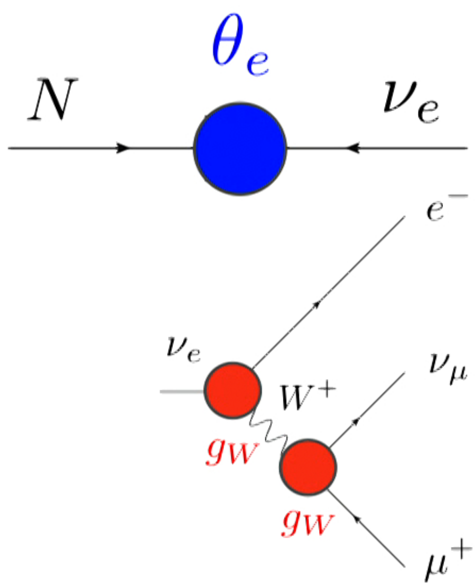

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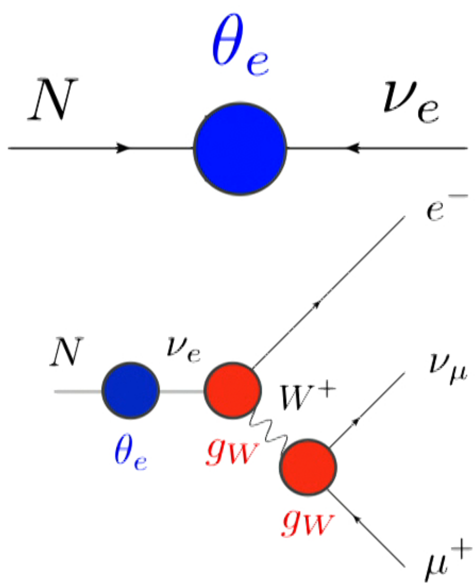
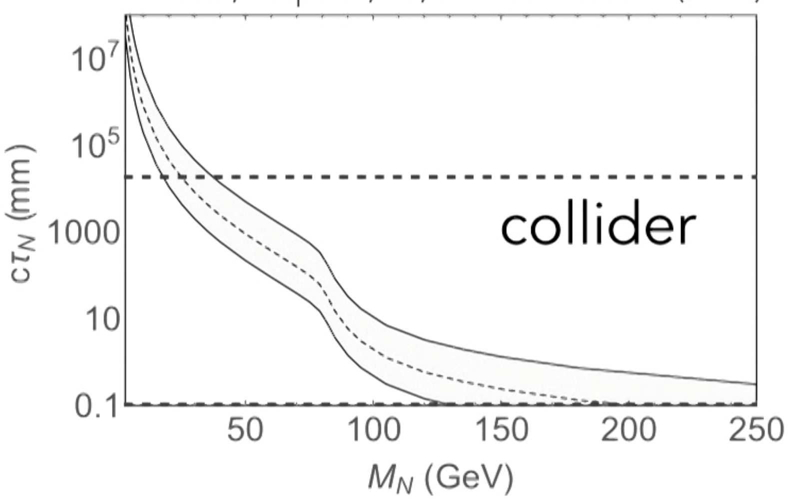


Batell, Pospelov, BS, arXiv:1604.06099 (JHEP)



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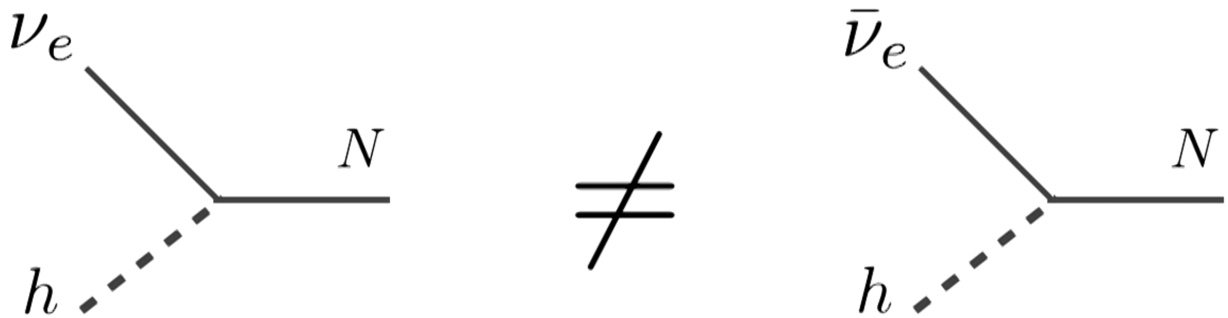
Akhmedov, Rubakov, Smirnov, 1998; Asaka, Shaposhnikov, 2005

NEUTRINO MATTER ASYMMETRY

- But why should they be in this mass range? Can explain matter-antimatter asymmetry!



ASYMMETRY -> LLPS!

- We need the scattering rates to be slow up until when Higgs field turns on (baryon-lepton asymmetries subsequently decouple)

$$\Gamma \sim |F|^2 T < H(T) \sim \left(\frac{T}{M_{\rm Pl}}\right) T \qquad |F| \lesssim 10^{-6} - 10^{-7}$$

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- But remember the neutrino mass requirement:

$$M_\nu \sim \frac{F^2 \langle h \rangle^2}{M_N} \qquad M_N \sim \text{GeV} \left(\frac{F}{10^{-7}}\right)^2 \left(\frac{0.1\ \text{eV}}{M_\nu}\right)$$

- The simultaneous requirements of neutrino mass + baryon asymmetry predict **testable** GeV-scale long-lived sterile neutrinos!!

ASYMMETRY -> LLPS!

- This is an example of **freeze-in cosmology**: there exist particles that never came into equilibrium over relevant epochs
- This makes the results particularly sensitive to new forces & particles: framework is predictive and constraining
- We are only now scratching the surface of models of hidden-sector baryogenesis! Many new scenarios to explore, including common explanations of baryon asymmetry + dark matter

Y. Cui, BS, 1409.6729 [JHEP]; see also BS, C. Tamarit, 1704.01979 [JHEP]

BEYOND NEUTRINO-GENESIS

- The LLP prediction follows from the out-of-equilibrium condition of many baryogenesis scenarios

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Out-of-equilibrium condition in early Universe gives prediction for LLPs in colliders! Universe's "size" was 1 cm at electroweak temperatures!

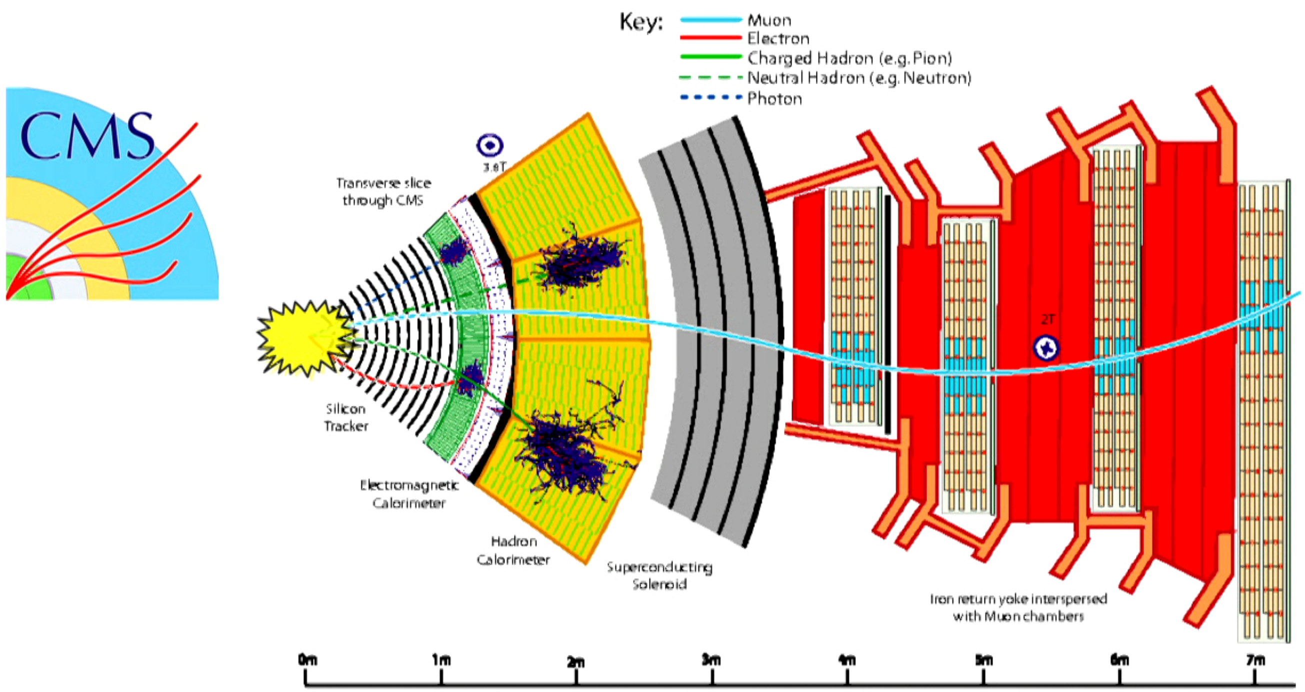
- Reverse processes suppressed if $T \ll M_\Phi$ at time of decay

$$\Gamma_\Phi < H(T = M_\Phi) \longrightarrow c\tau_\Phi \gtrsim 50 \text{ ps} \left(\frac{100 \text{ GeV}}{M_\Phi}\right)^2$$

~1 cm travel distance!

LARGE HADRON COLLIDER

- LLPs are super important! How can experimentalists look for them?



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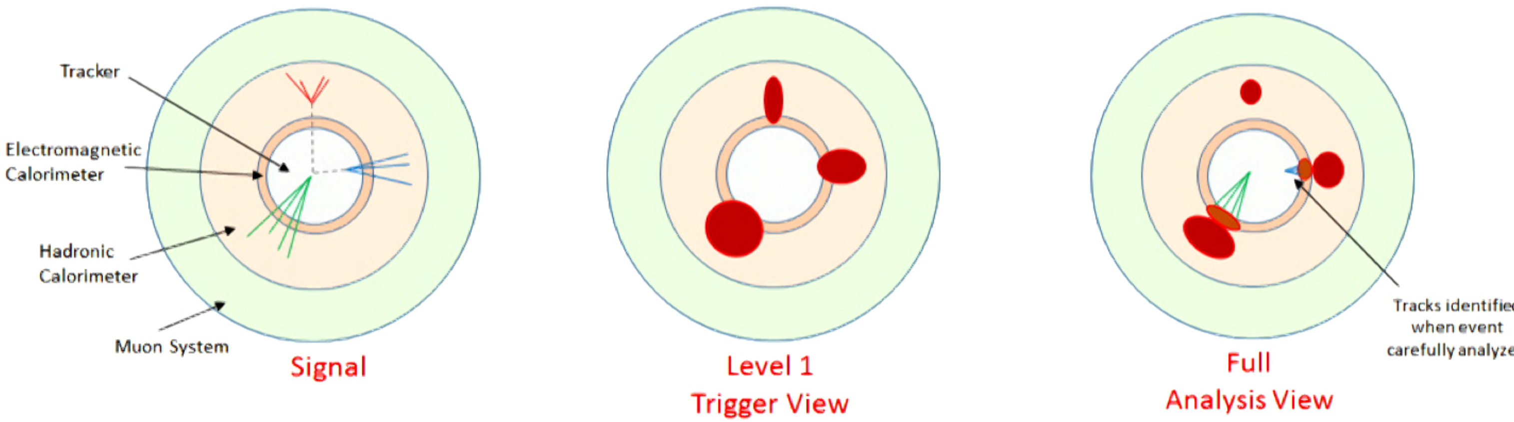
LLPS AND TRIGGERS

- Signals might not be recorded/reconstructed!
- ~30 million collisions per second, can only record **~1000-10000!**

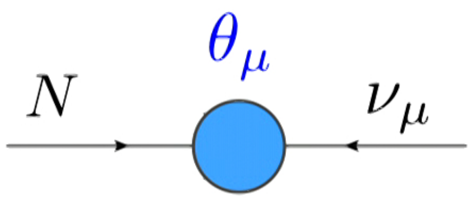


Matt Strassler, 2014

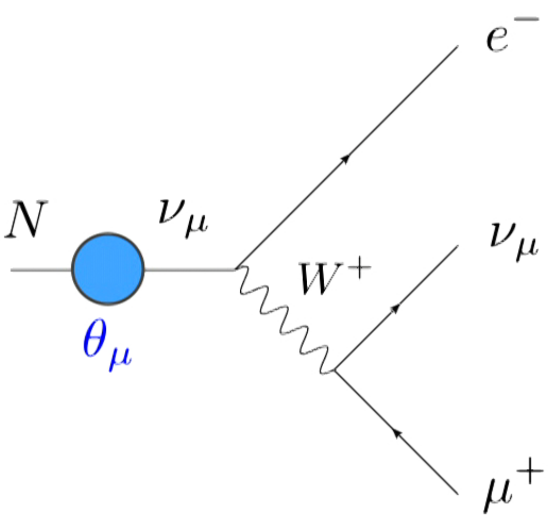
Izaguirre, BS, 1504.02470 [PRD]; see also Batell, Pospelov, BS, arXiv:1604.06099 (JHEP)

MISSING DISCOVERY POTENTIAL

- LLP searches at LHC are already happening, typically with large energy requirements on particles in detector
- Are they missing anything?



Example: dark neutrino



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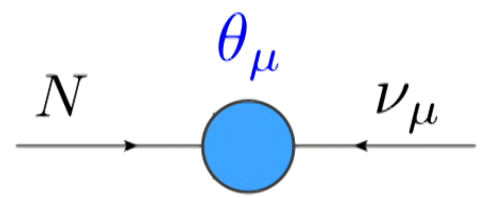

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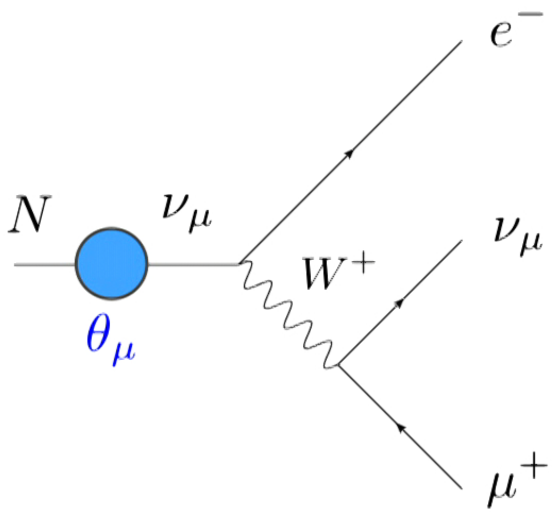

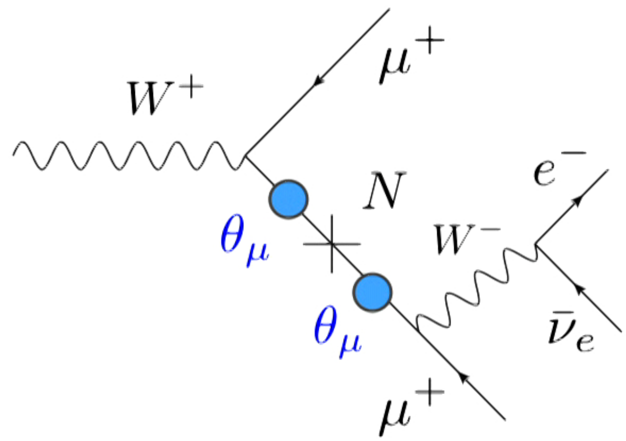

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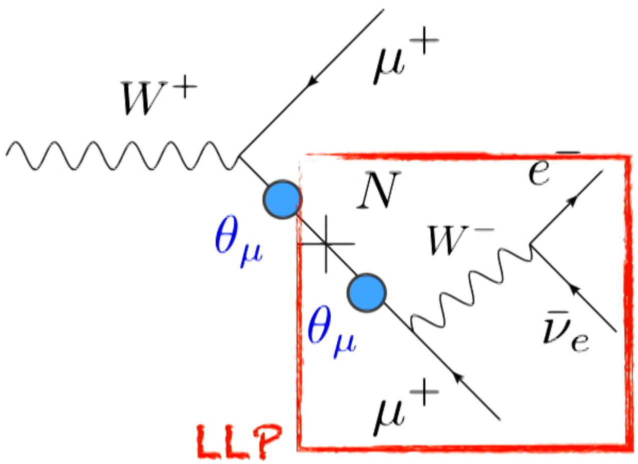

- Due to energy thresholds, LHC searches **not sensitive to this!!**
- No coverage for this important theory unless we try something new

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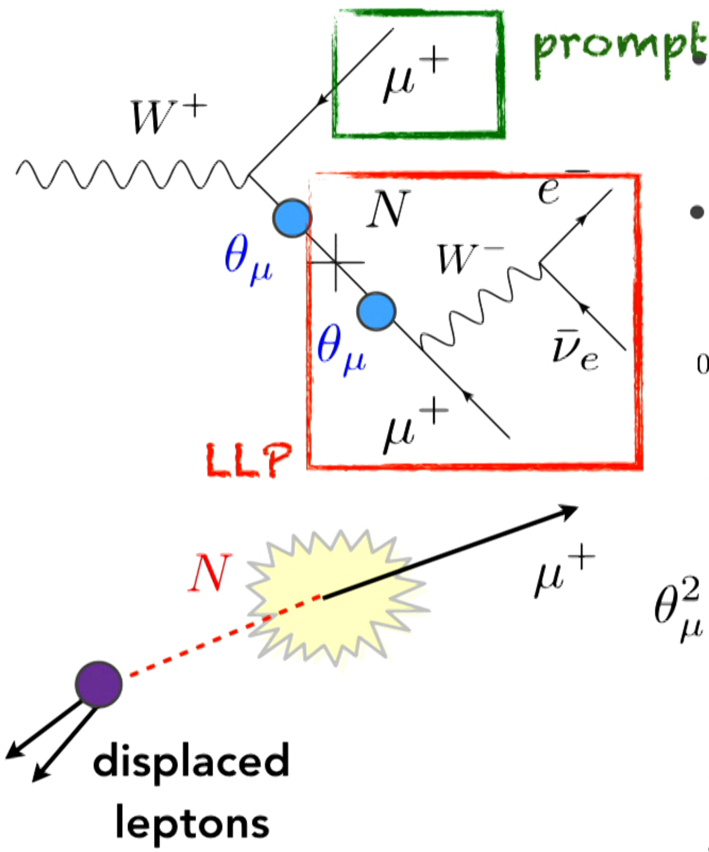

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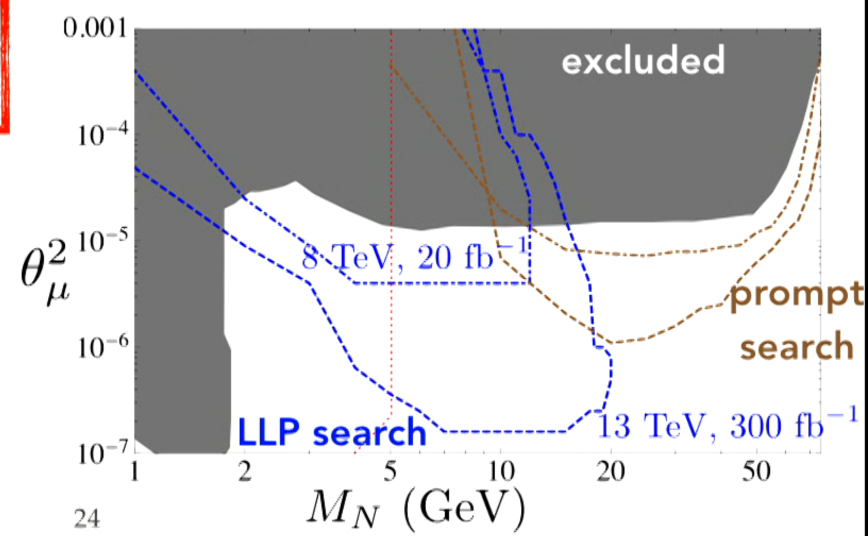

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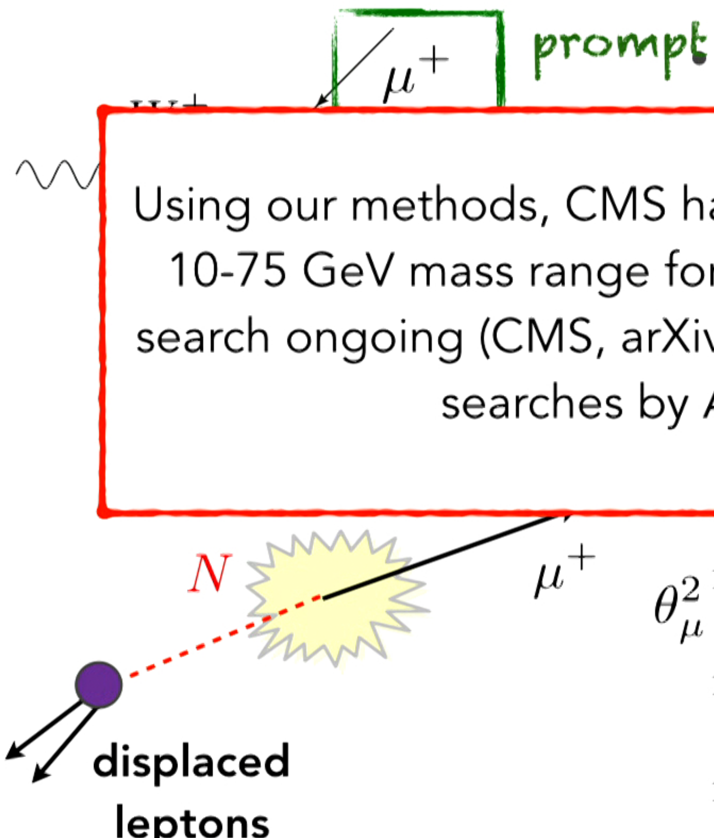
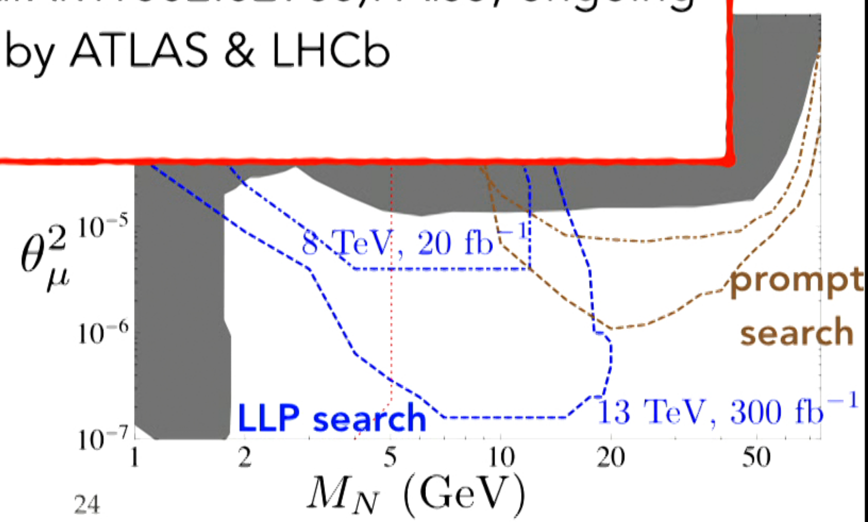


Due to energy thresholds, LHC

new

Using our methods, CMS has achieved best sensitivity in 10-75 GeV mass range for **prompt search**, long-lived search ongoing (CMS, arXiv:1802.02965). Also, ongoing searches by ATLAS & LHCb



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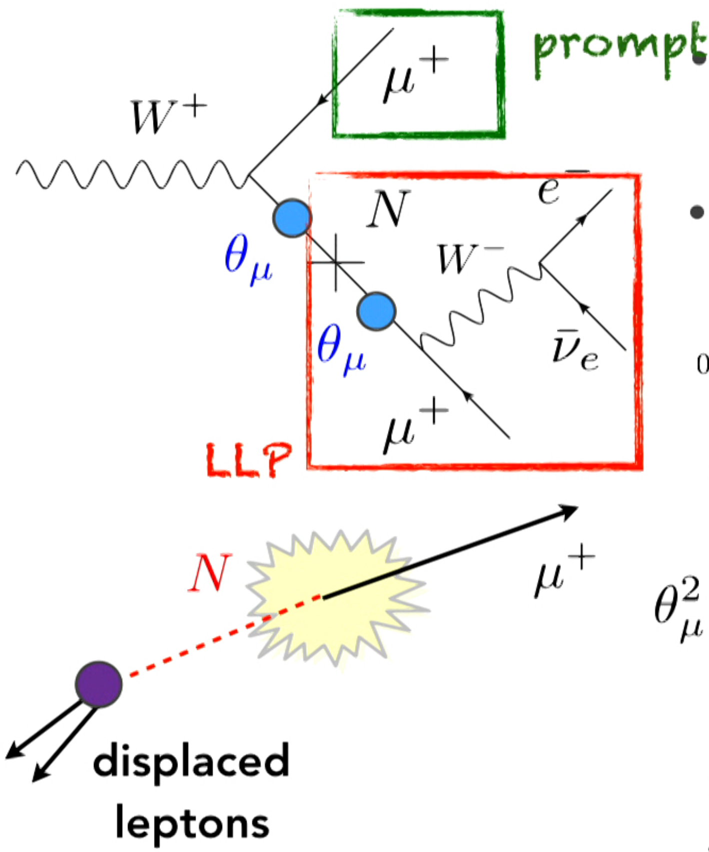

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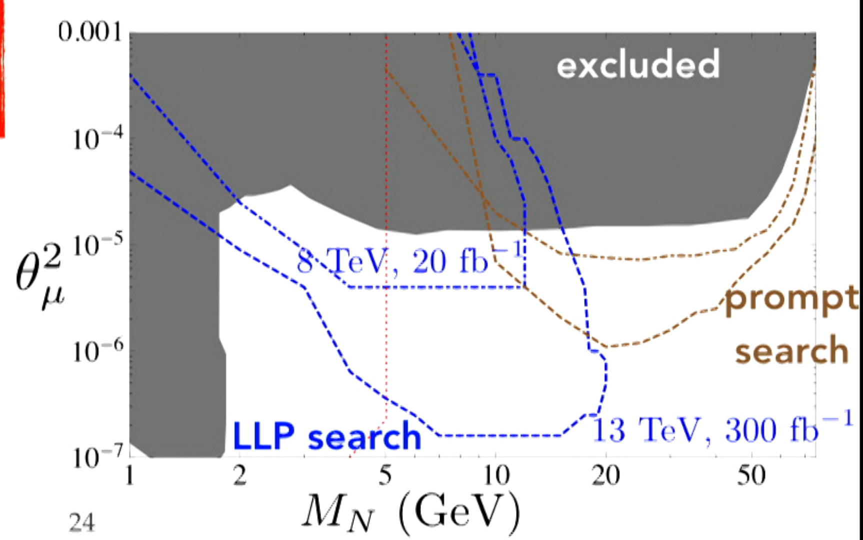

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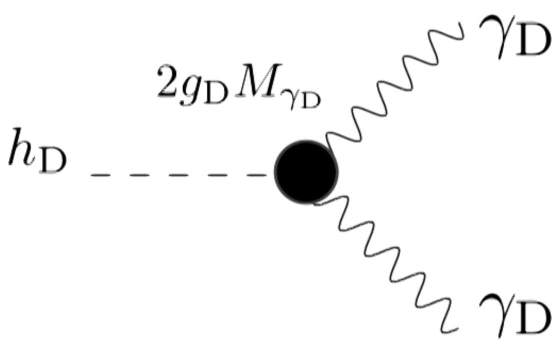
Example: dark forces

- Dark force with massive gauge boson in hidden sector

$$\mathcal{L} = \frac{\varepsilon}{2} F_{\mu\nu} F_{\mathrm{D}}^{\mu\nu}$$



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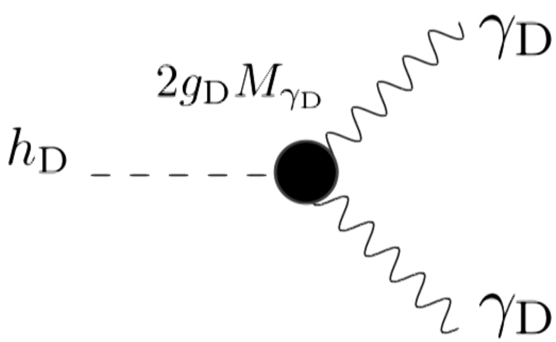

Blinov, Izaguirre, BS, arXiv:1710.07635 [PRD]

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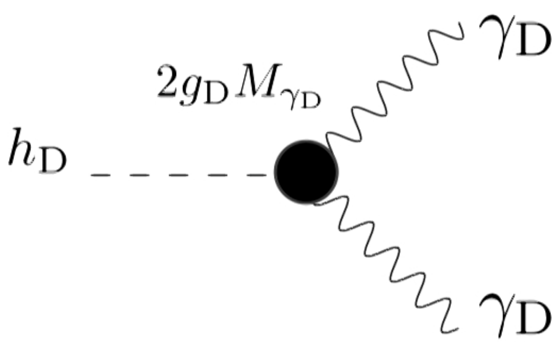

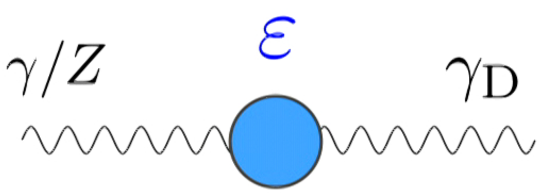

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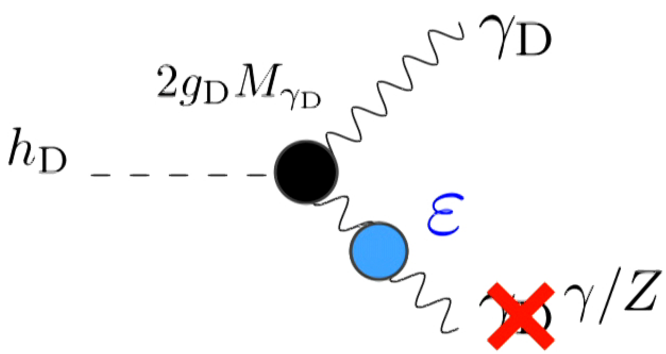

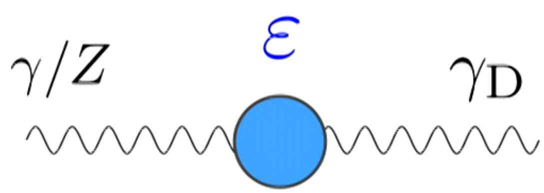

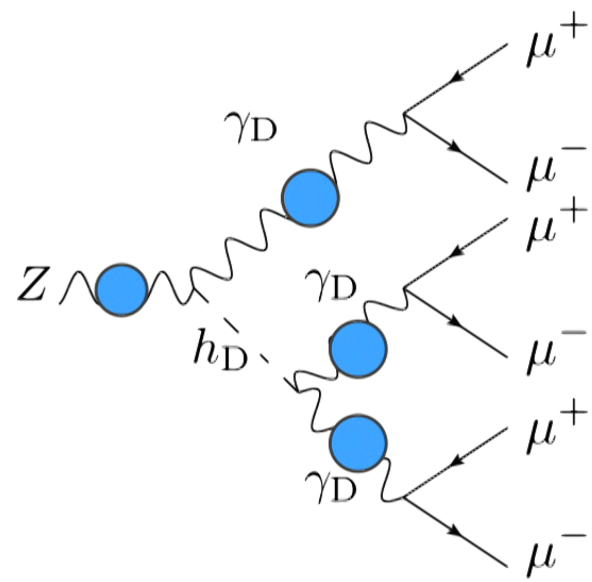

Y. Cui, BS, arXiv:1409.6729 [JHEP]; see also Z. Liu, B. Tweedie, arXiv:1503.05923 [JHEP]

ADDITIONAL CHALLENGES

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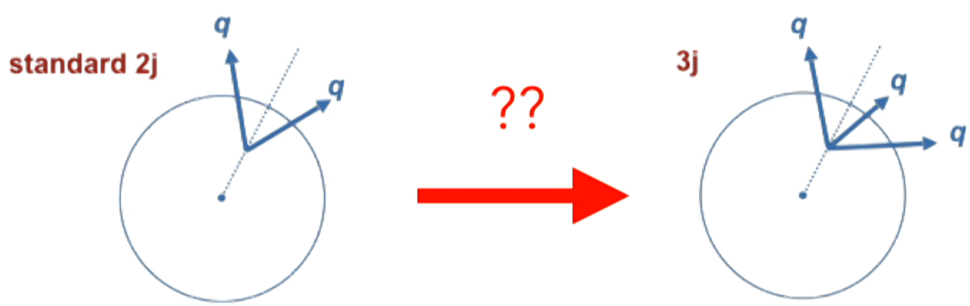
- Example: CMS had a search for a displaced pair of quarks. Does this cover other signatures, or are there gaps?



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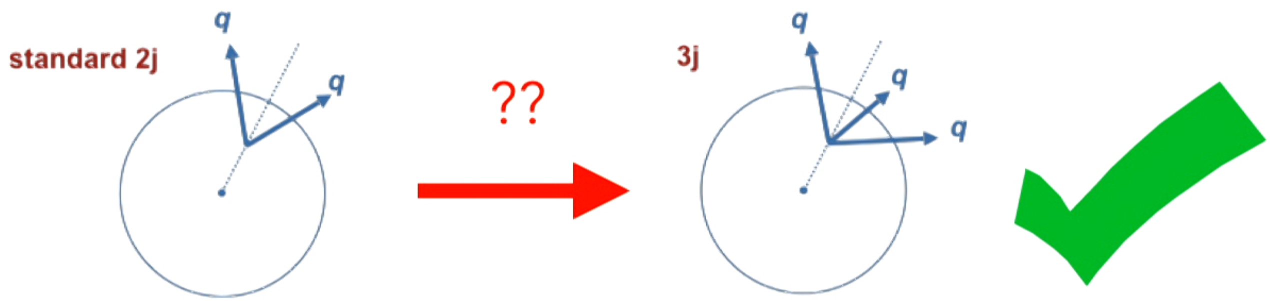


Cui, BS, arXiv:1409.6729 [JHEP]

- We had to work very hard for this result! How can we make search coverage apparent to reduce redundant efforts AND ensure no gaps?

J. Alimena *et al.* (ed. BS),1903.04497

LHC LLP COMMUNITY

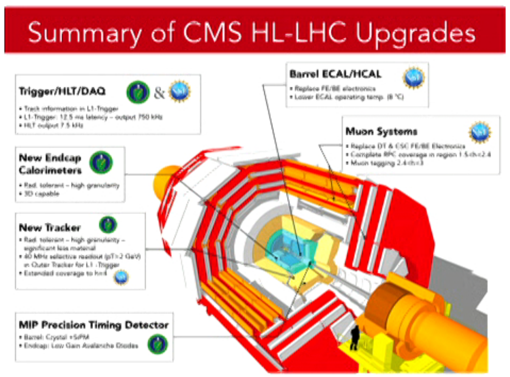
- The space of possible LLP models and signals is incredibly vast!
- Guidance from theory needed to:
  - Identify best motivated LLP signatures (production modes, decay modes) & kinematic regimes
  - Map signatures onto realistic experimental searches that take most advantage of incredible technology
  - Work with experimentalists to make sure searches are carried out, providing necessary tools (simulation frameworks, etc.), and make most efficient use of scant resources
- I co-founded and lead joint theory-experiment LHC LLP community to accomplish these goals

LHC LLP COMMUNITY

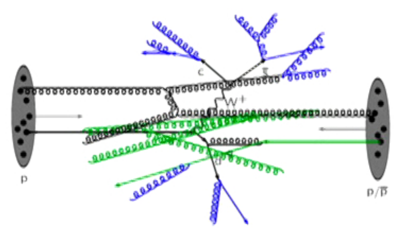
J. Alimena *et al.*, arXiv:1903.04497, submitted to J Phys G

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

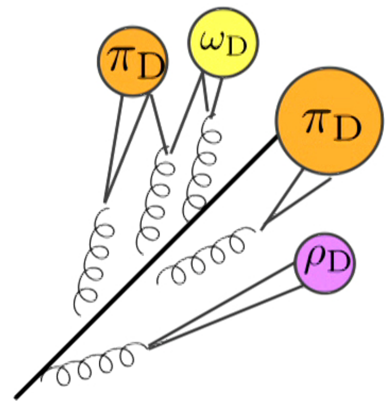
Document editors: James Beacham, Brian Shuve



LLP potential & studies with upgraded detectors



model library & simulation frameworks



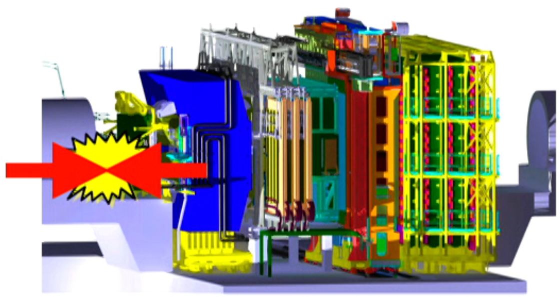
new frontier: high multiplicities of LLPs, dark showers

OUTLINE

- Why long-lived particles?
- Hunting for long-lived particles at the LHC
- Expanding the LLP frontier to LHCb
- Hidden sector archaeology with the BaBar Experiment

LLPS AT LHCB

- LHCb is an experiment designed to look for SM LLPs (*B* mesons), but so far has been under-studied for hidden sector LLPs

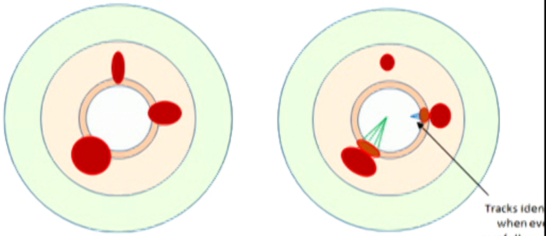


Challenges:

- Only covers 0.8-15° around beam
- Only ~5% of collision rate compared with ATLAS/CMS

Opportunities:

- Moving to **triggerless readout** in 2021!
- Full reconstruction of every collision

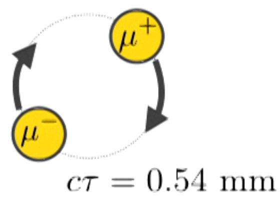


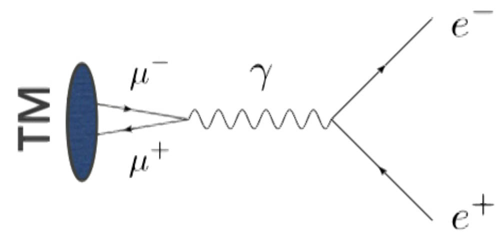
X. Cid Vidal, P. Ilten, J. Plews, BS, Y. Soreq, arXiv:1904.xxxxx; +work in progress

LLPS AT LHCB

Example: muon atom (true muonium)

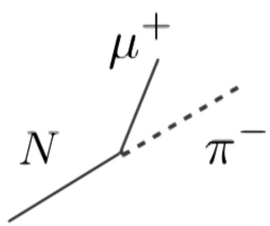
- Standard Model particle that has not yet been discovered! Produced in decays of η meson, can be discovered in next Run!





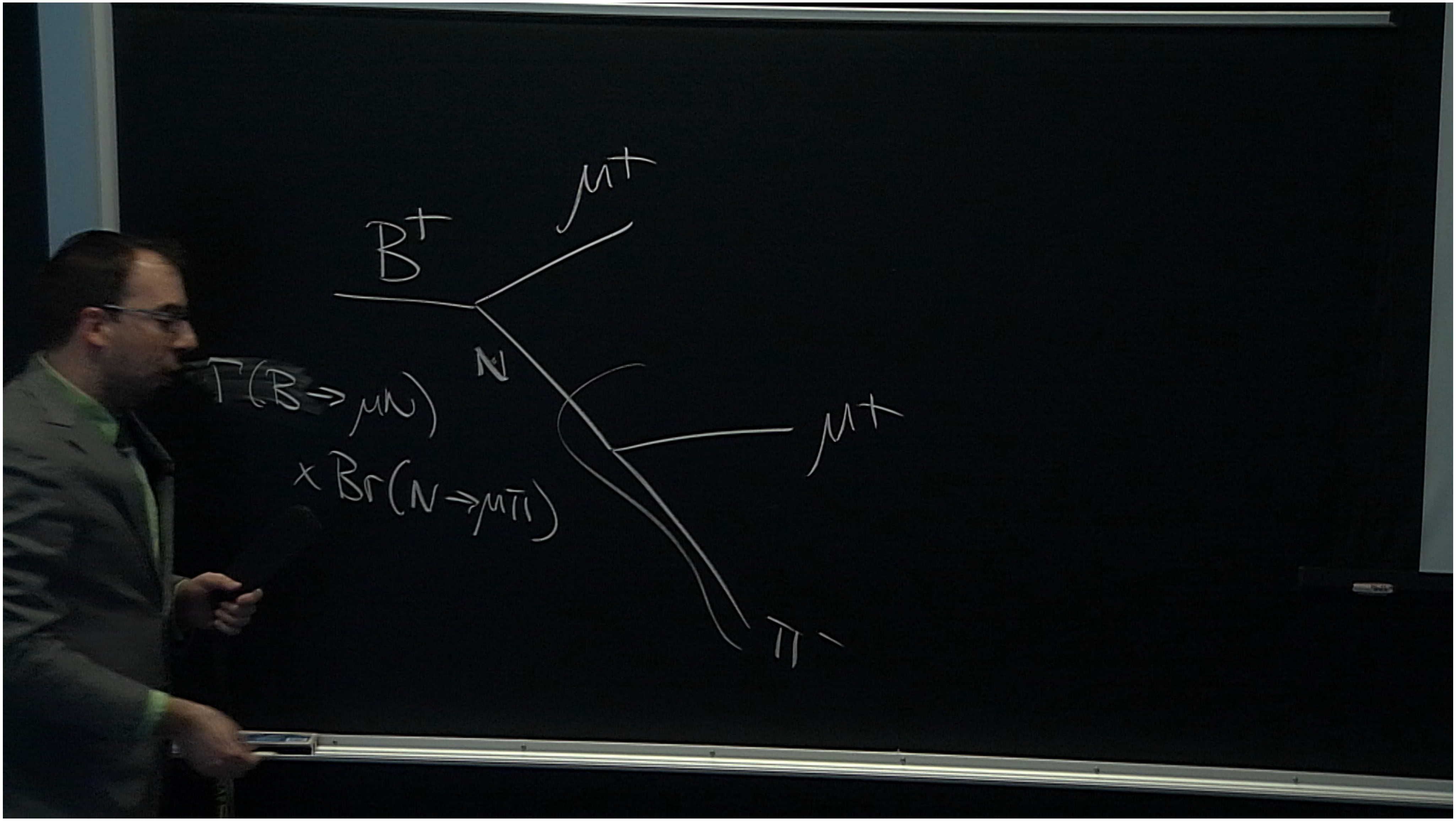
Example: exclusive decays

see also A. Pierce *et al.*, arXiv:1708.05389 [PRD]



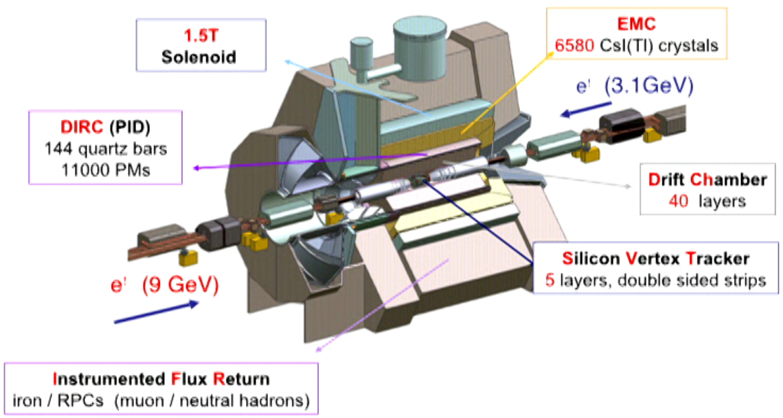
- Explicit reconstruction of weird LLP vertices ($\ell^+\pi^-$, K^+K^-, ...)
- But, have to do theory correctly!

BS, Peskin, arXiv: 1607.04258 [PRD]


B+
μ+
N
Γ(B→μN)
× Br(N→μπ)
μ+
π−

BABAR EXPERIMENT

- There is only so much the LHC can do!
- Consider BaBar: Electron-positron collider at SLAC from 1999-2008 to study *B* meson properties ($c\tau_B \sim 0.5$ mm)



- Compared to LHC, very few searches for new particle production
- Nevertheless, often has **world's best sensitivity**

- What else could be hiding? Opportunity for new and creative ideas!

BABAR (incl. BS), arXiv:1606.03501 [PRD]; BS, work in progress with B. Echenard

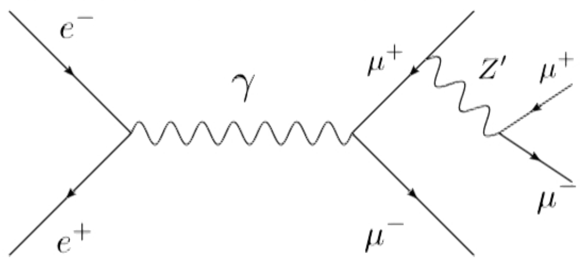
NEW SEARCHES AT BABAR

- Many opportunities for hidden sector archaeology!
- I joined BaBar to make sure we don't miss these well-motivated signatures, and build momentum for future studies at Belle II, …

Example: dark leptonic forces

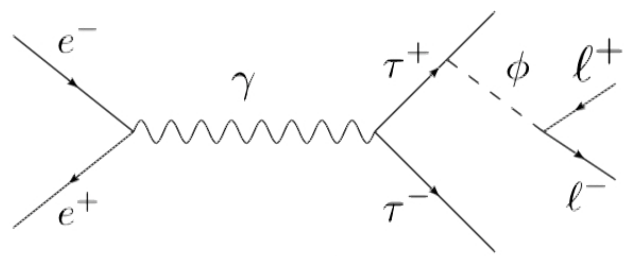
- New bosons that couple preferentially to heavy-flavour leptons

based on BS, I. Yavin, arXiv:1403.2727 [PRD]



$$\mathcal{L} = \bar{\mu}\gamma^\nu(g'_V + g'_A\gamma^5)Z'_\nu\mu$$

Batell *et al.*, arXiv:1606.06099 [PRD]



$$\mathcal{L} = g_\phi \frac{M_\ell}{\langle h \rangle}\bar{\ell}\phi\ell$$

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SUMMARY

- Deep theoretical motivations for hidden sectors, long lived particles
- Signals of are challenging and outside the scope of many collider searches: need out of the box thinking & theory guidance!
- LHC LLP community is major effort to leave no stone unturned for LLPs
- Archaeology could allow discovery of particles hiding in existing data!
- Comprehensively tackling hidden sectors means understanding complementarity of approaches & using every tool at our disposal