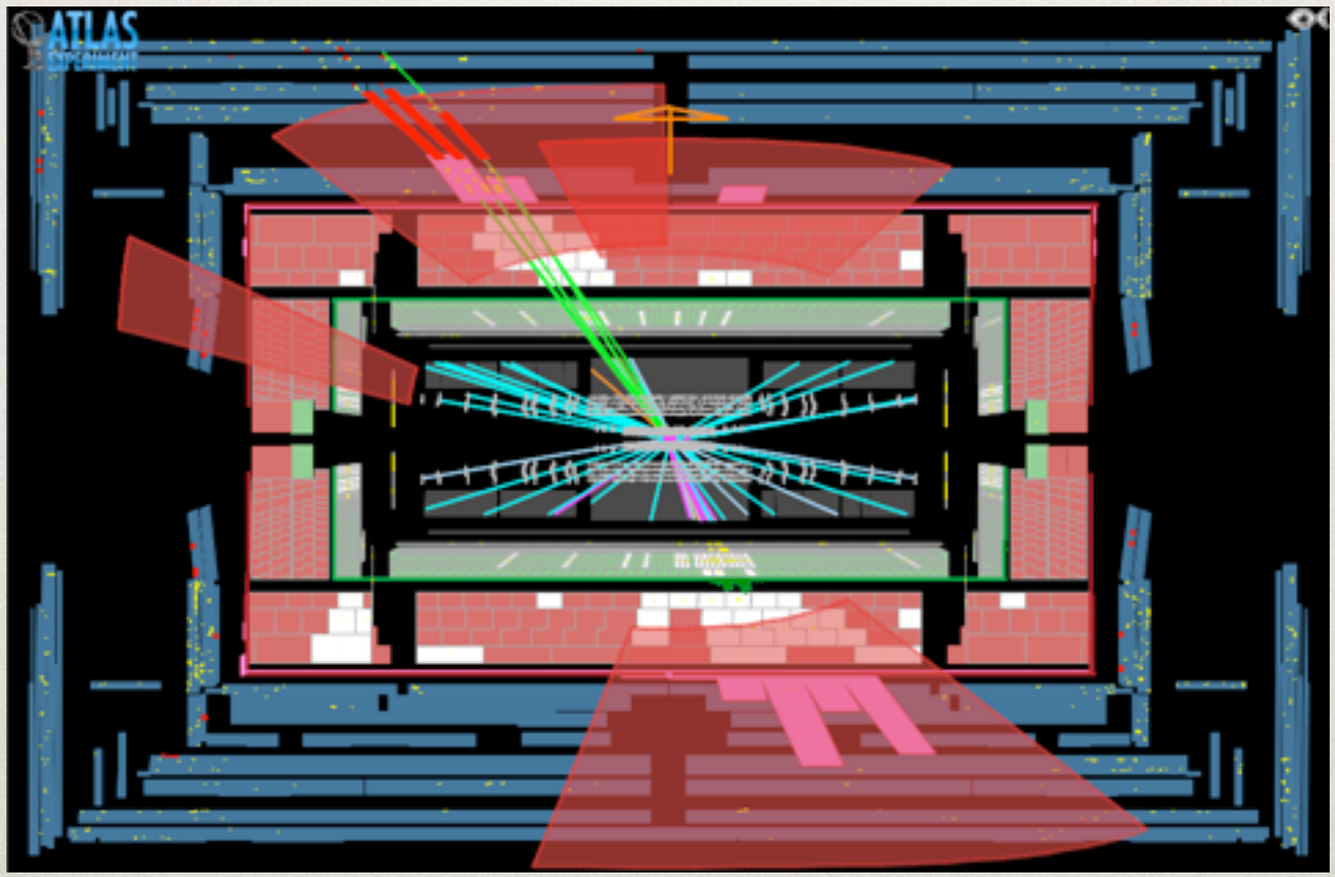
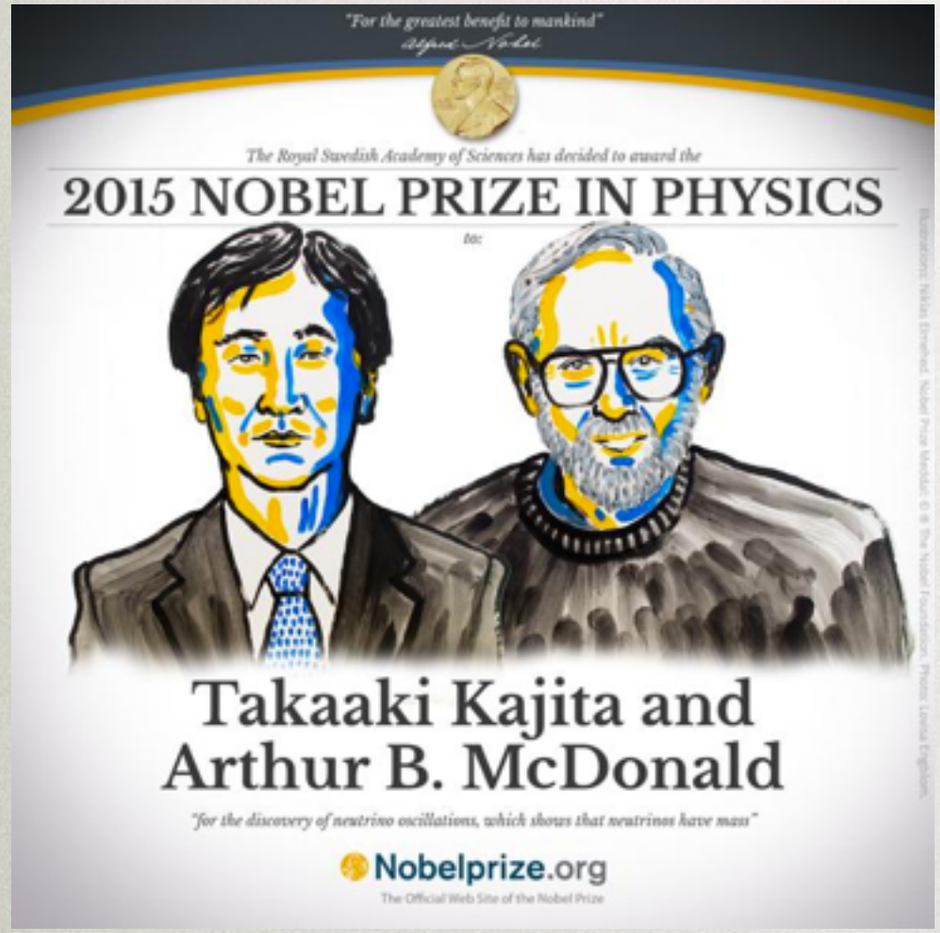
DISCOVERING HIDDEN SECTORS AT COLLIDERS

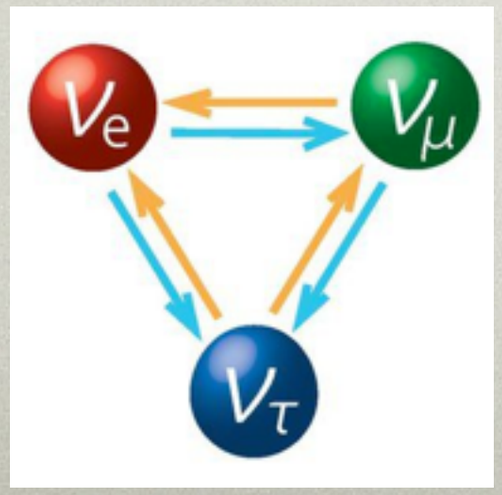


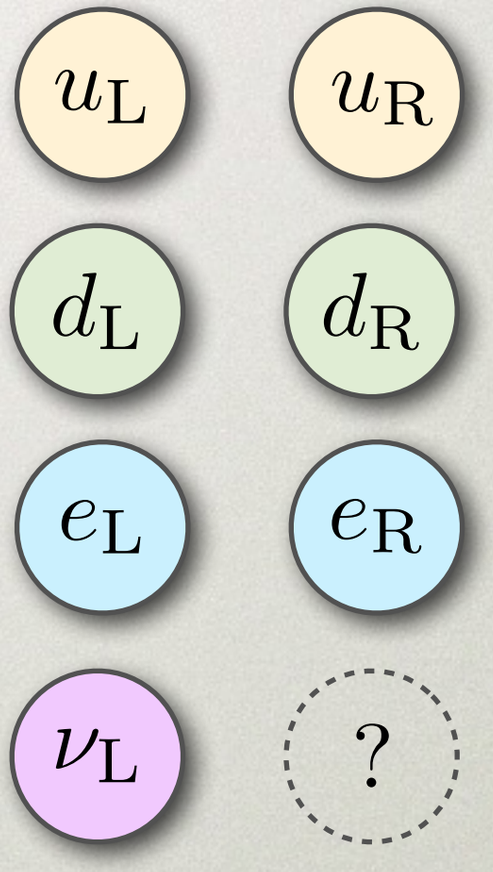
Brian Shuve — SLAC & Harvey Mudd College

SoCal BSM @ UCR, April 2, 2017

Evidence for “Hidden Sector”

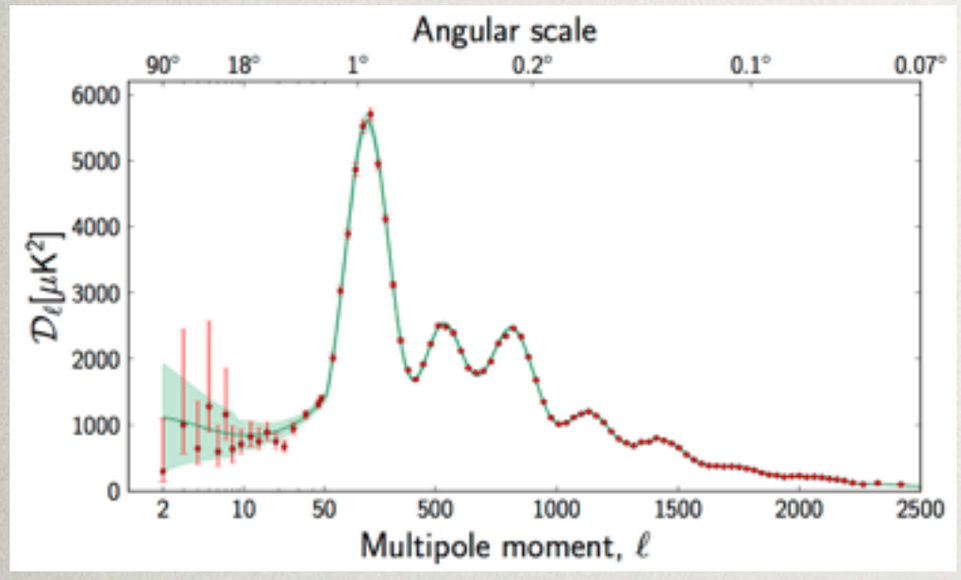




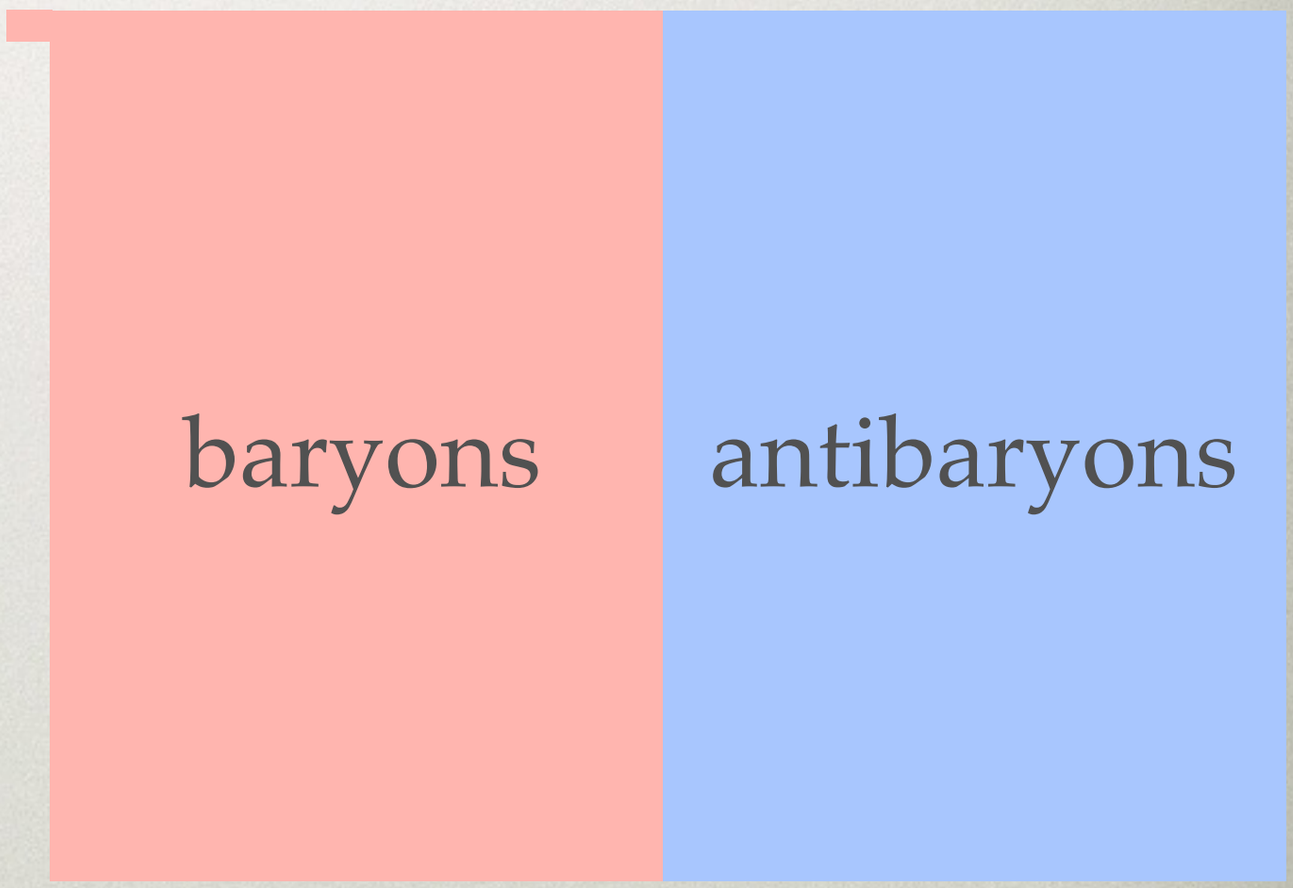


Evidence for “Hidden Sector”

Dark Matter



Matter-Antimatter Asymmetry



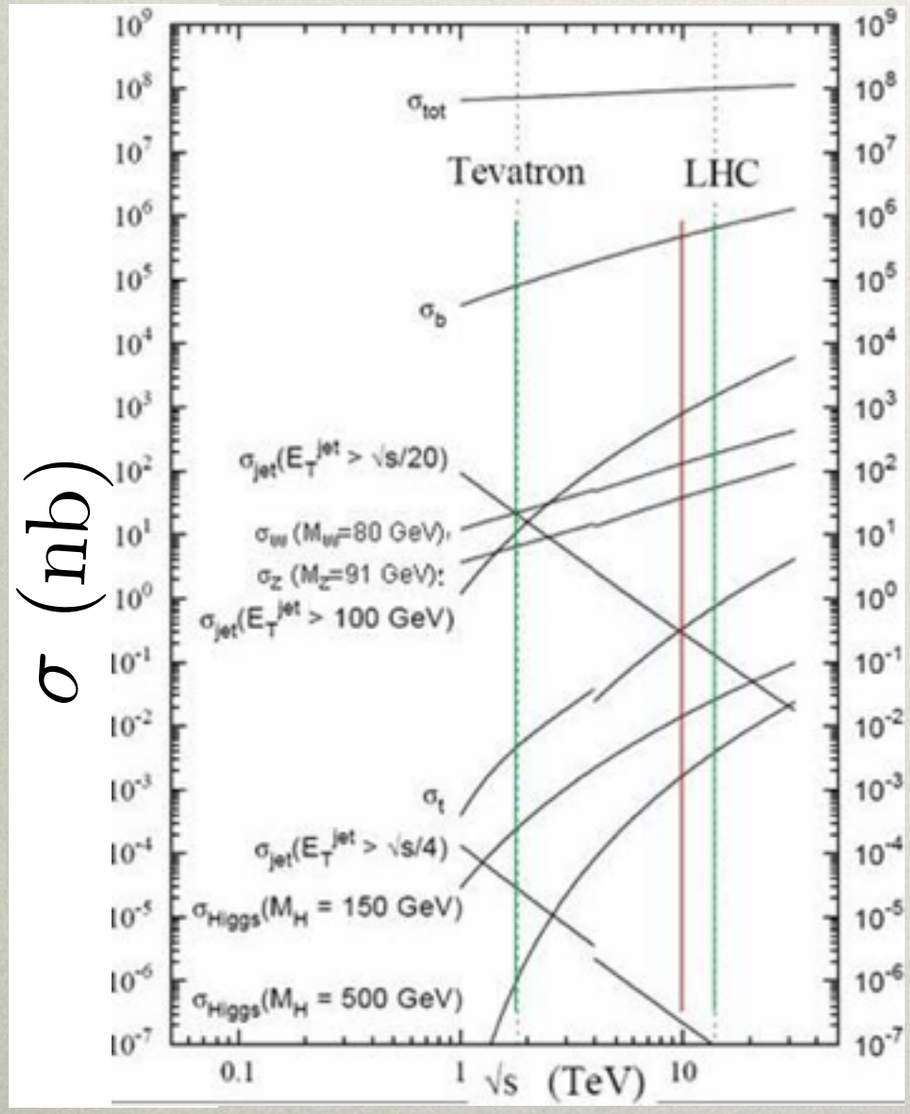
What Could We Be Missing?

- If some new, heavy particle responsible for these phenomena, a high-energy collider like the LHC is the best place to look

- After extensive searches, we have yet to see non-SM particles!

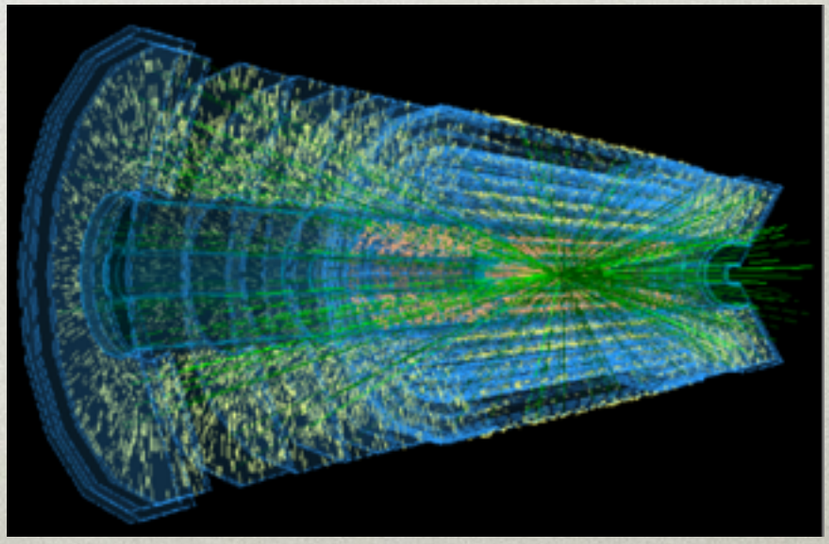
What Could We Be Missing?

- What about **lower mass** particles?



With 3000/fb @ 14 TeV:

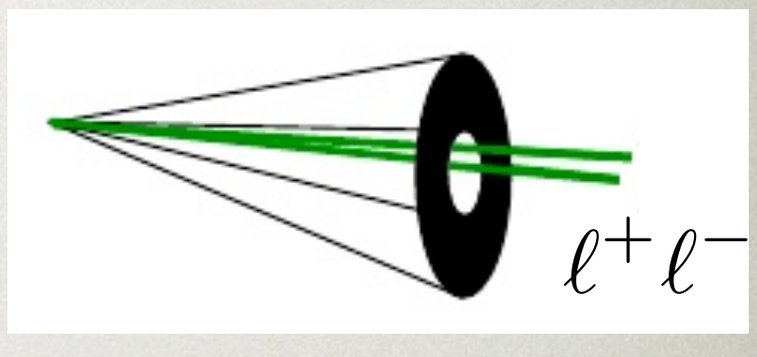
- 700 billion *W*
- 100 billion *Z*
- 200 million *H*
- 2000 trillion *B*



Signatures of Low-Mass Particles

- Need high-energy particles in event to pass trigger

- Suggests that new particles **boosted** and often come with friends



- Can often get **long lifetimes** & high boost

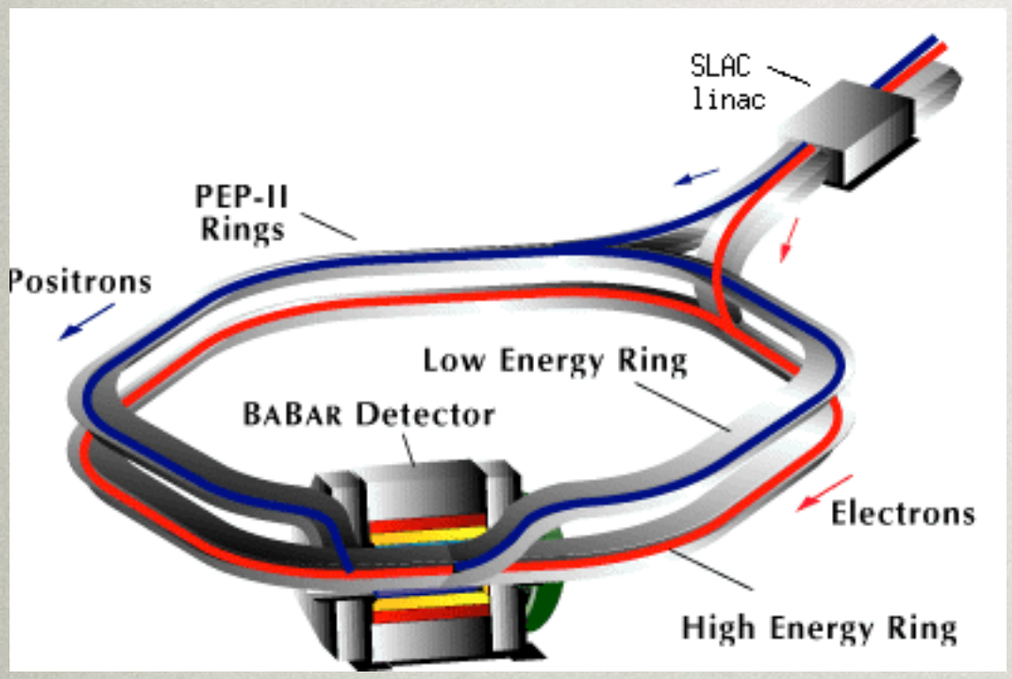
$$c\tau(\pi^{\pm}) \sim 10 \text{ m} \qquad c\tau(D^{\pm}) \sim 0.1 \text{ mm}$$

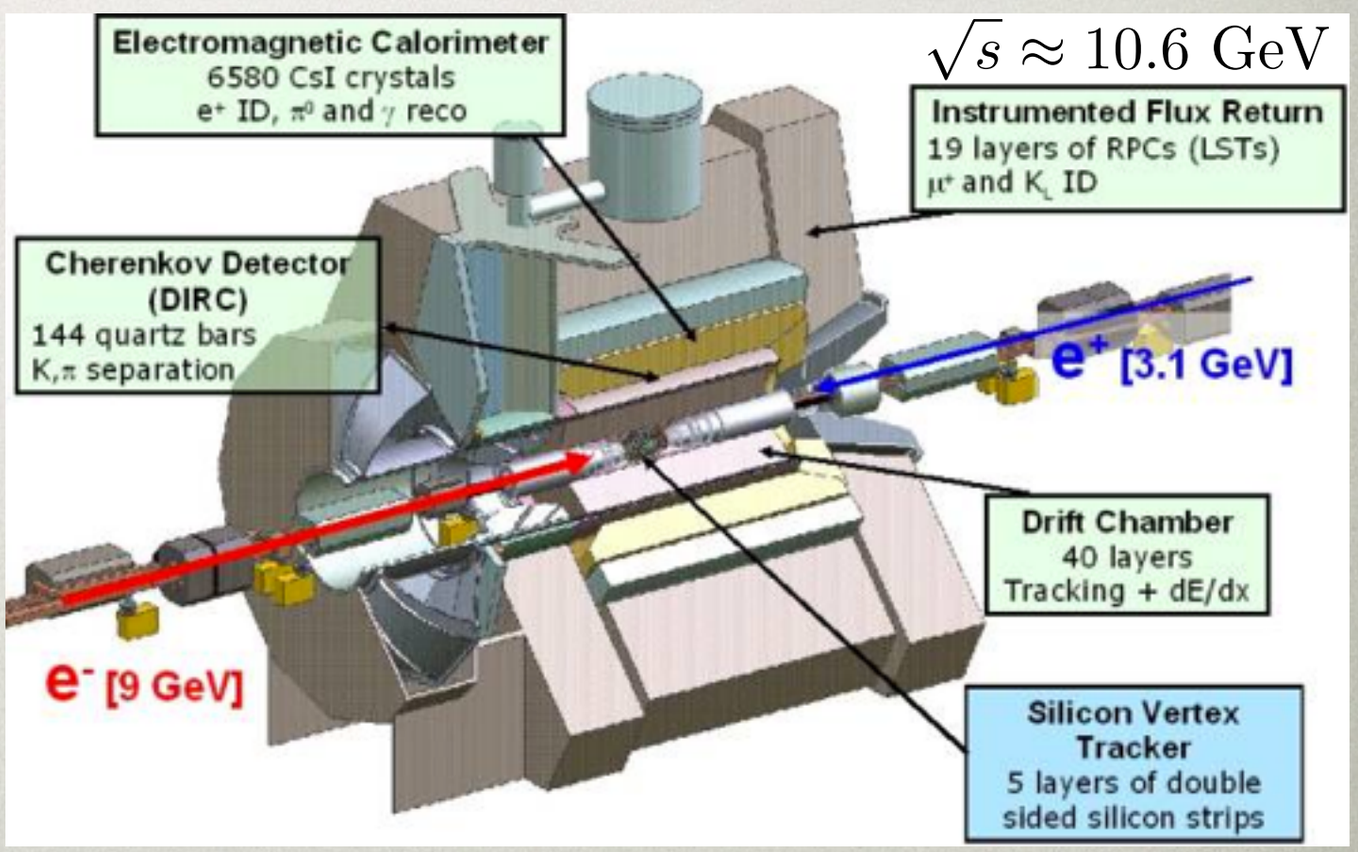
$$c\tau(K^0_{\rm S}) \sim 1 \text{ cm} \qquad c\tau(B^{\pm}) \sim 0.1 \text{ mm}$$

e.g., hidden valleys (Strassler, Zurek 2006)

Low-Mass Search Complementarity

- Low-mass particles could also be directly produced at lower-energy accelerators





Outline

- **New Searches for Long-Lived Hidden Sectors @ LHC**
    - Test case: right-handed neutrino
    - Towards closing the long-lived particle gaps at the LHC

- **New Searches for Hidden Sectors @ *B*-factories**
    - Search for leptophilic forces at *BABAR*
    - New ideas for *B*-factory searches

Neutrino Masses and New Light States

- SM neutrino masses can come from "sterile" neutrinos, N

Minkowski, 1977; Yanagida, 1979; Mohapatra and Senjanovic, 1980; …

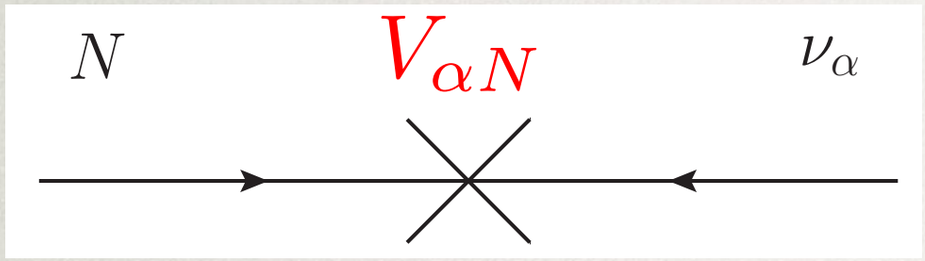
$$\mathcal{L} = y\,\bar{L}HN + \frac{M_N}{2}\bar{N}^{\rm c}N$$

$$m_{\nu\,\rm SM} = \frac{\langle H\rangle^2 y^2}{M_N}$$

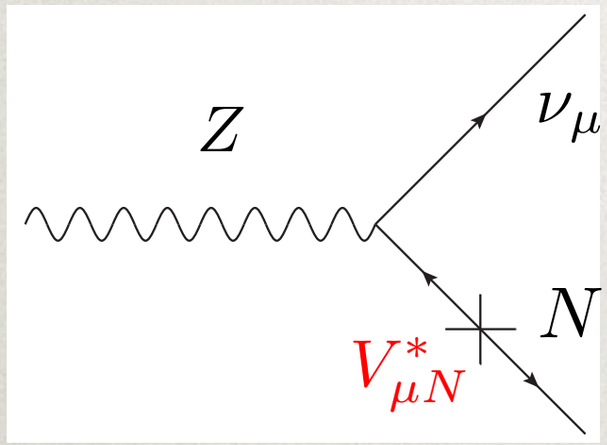
- For fixed $\langle H\rangle$ and $m_\nu \sim 0.1$ eV, we have GeV-scale N for $y \sim 10^{-7}$
  - With additional symmetries, coupling can be **much** larger
  - Viable matter-antimatter asymmetry in this mass range

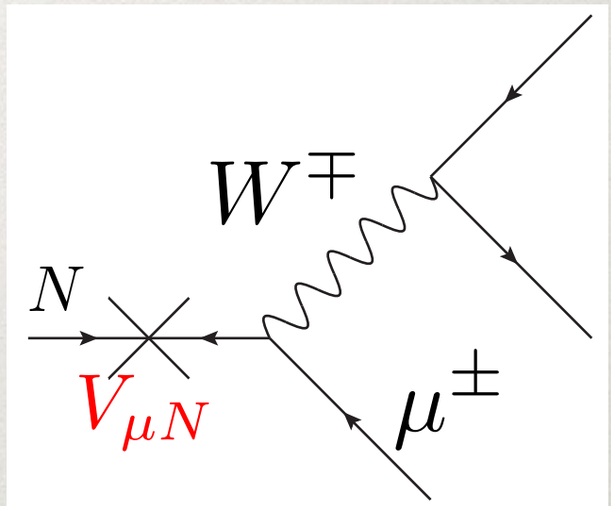
Mohapatra and Valle, 1986; Casas and Ibarra, 2001; Shaposhnikov, 2006; …

Testing the See-Saw



$$V_{\alpha N} \sim \frac{F_\alpha \langle \Phi \rangle}{M_N}$$



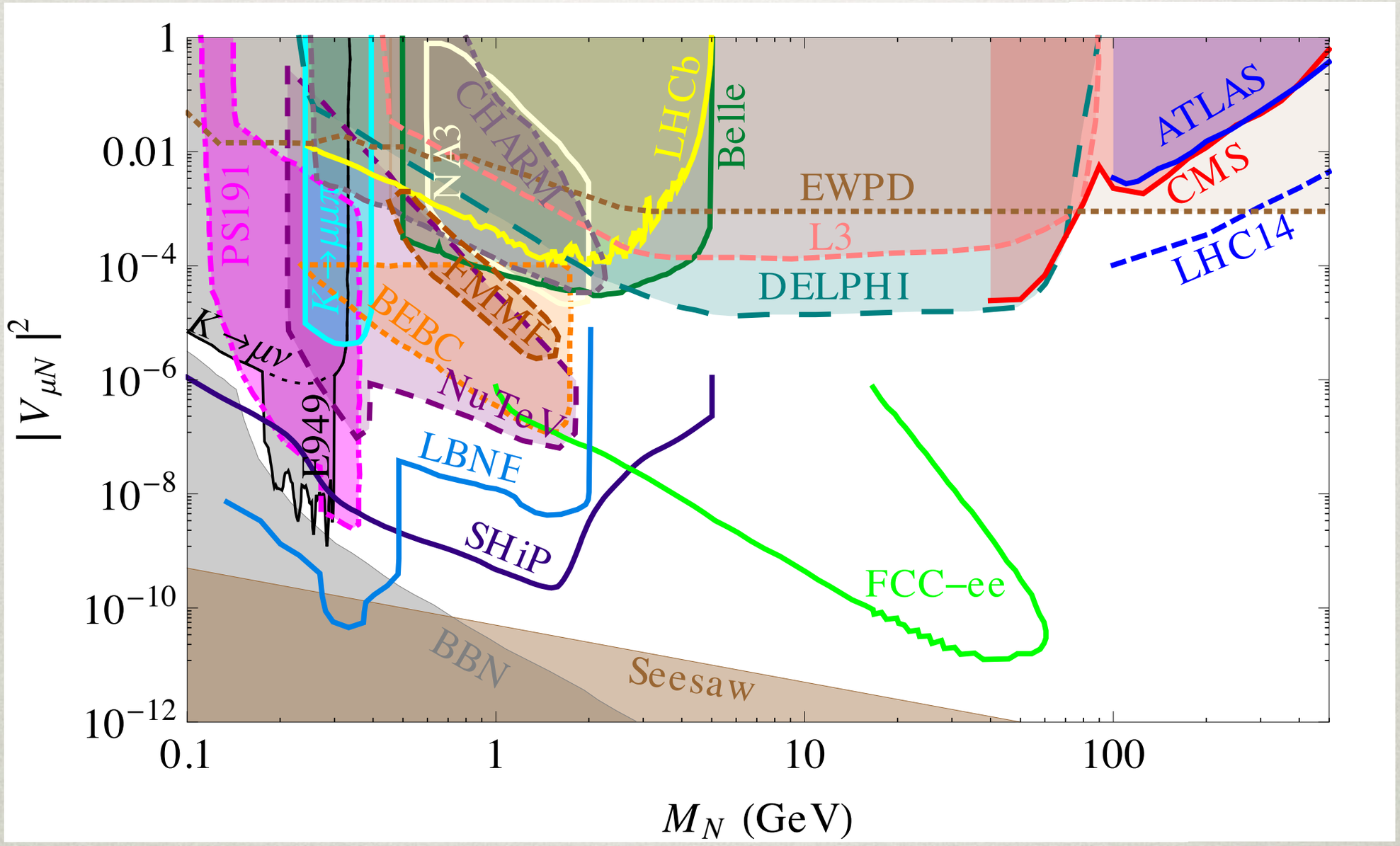


- Below weak scale, decay is through **off-shell gauge bosons**, often long-lived

- Consider a simplified model with M_N, $|V_{\mu N}|$ as free params.

Testing the See-Saw

plot taken from Deppisch, Dev, Pilaftsis, 2015
see also Gorbunov and Shaposhnikov, 2007; Atre, Han, Pascoli, Zhang, 2009; …



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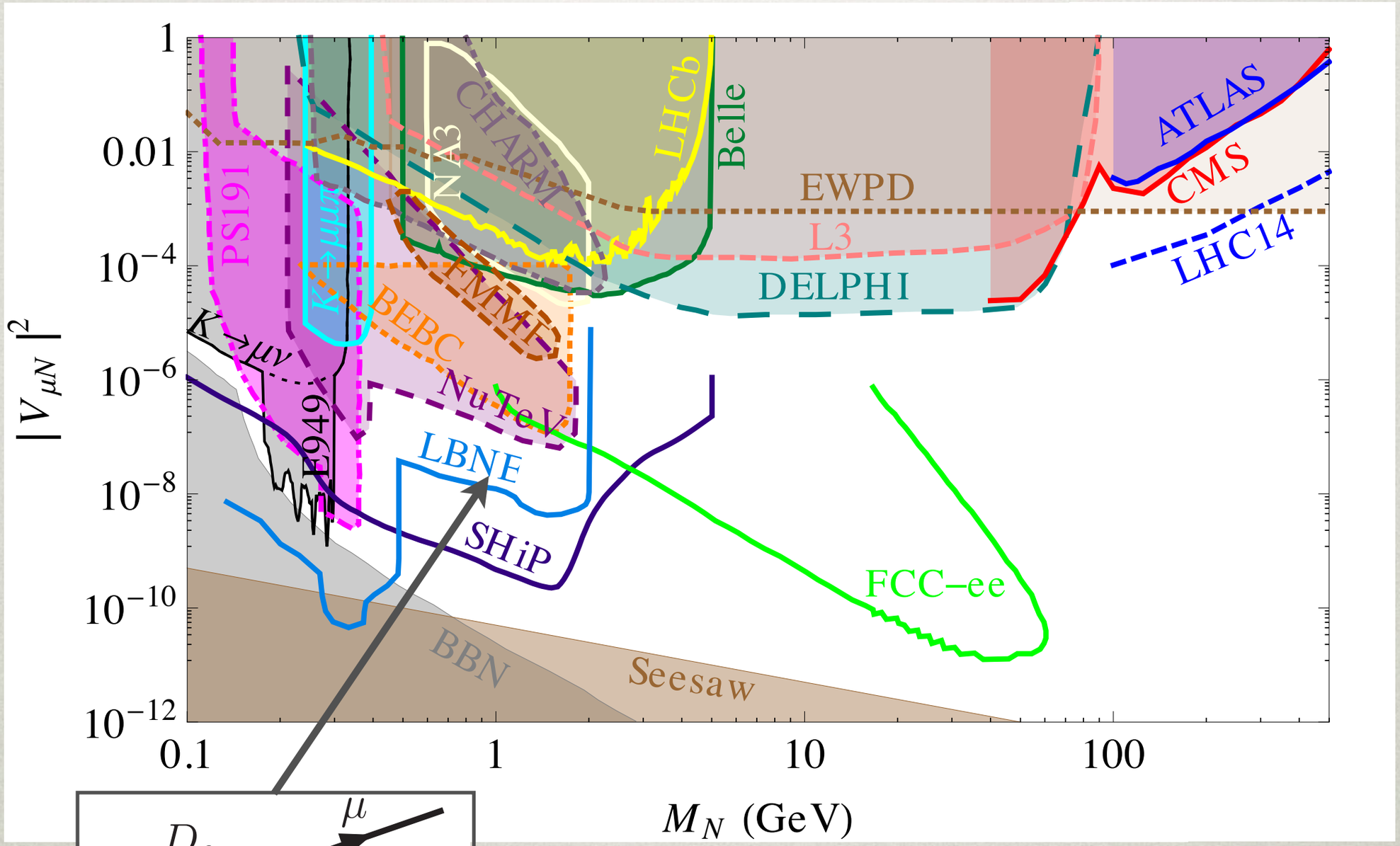

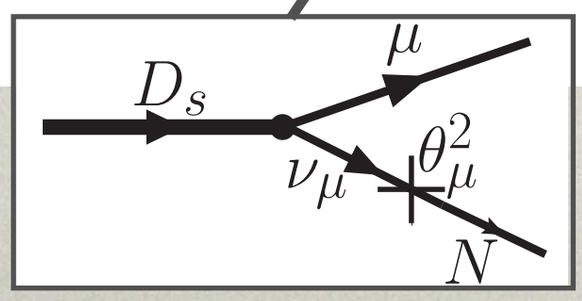

SHiP/DUNE

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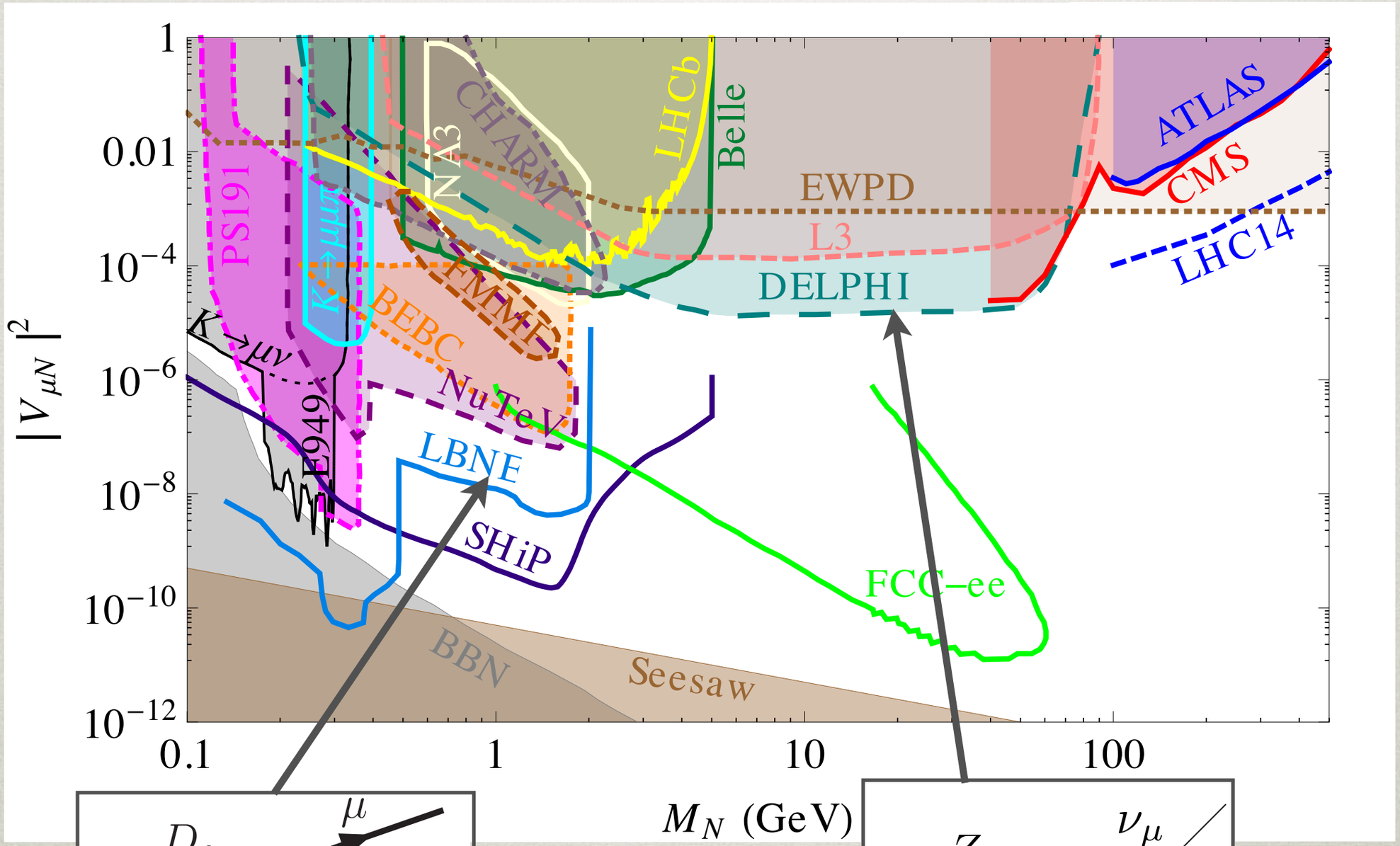

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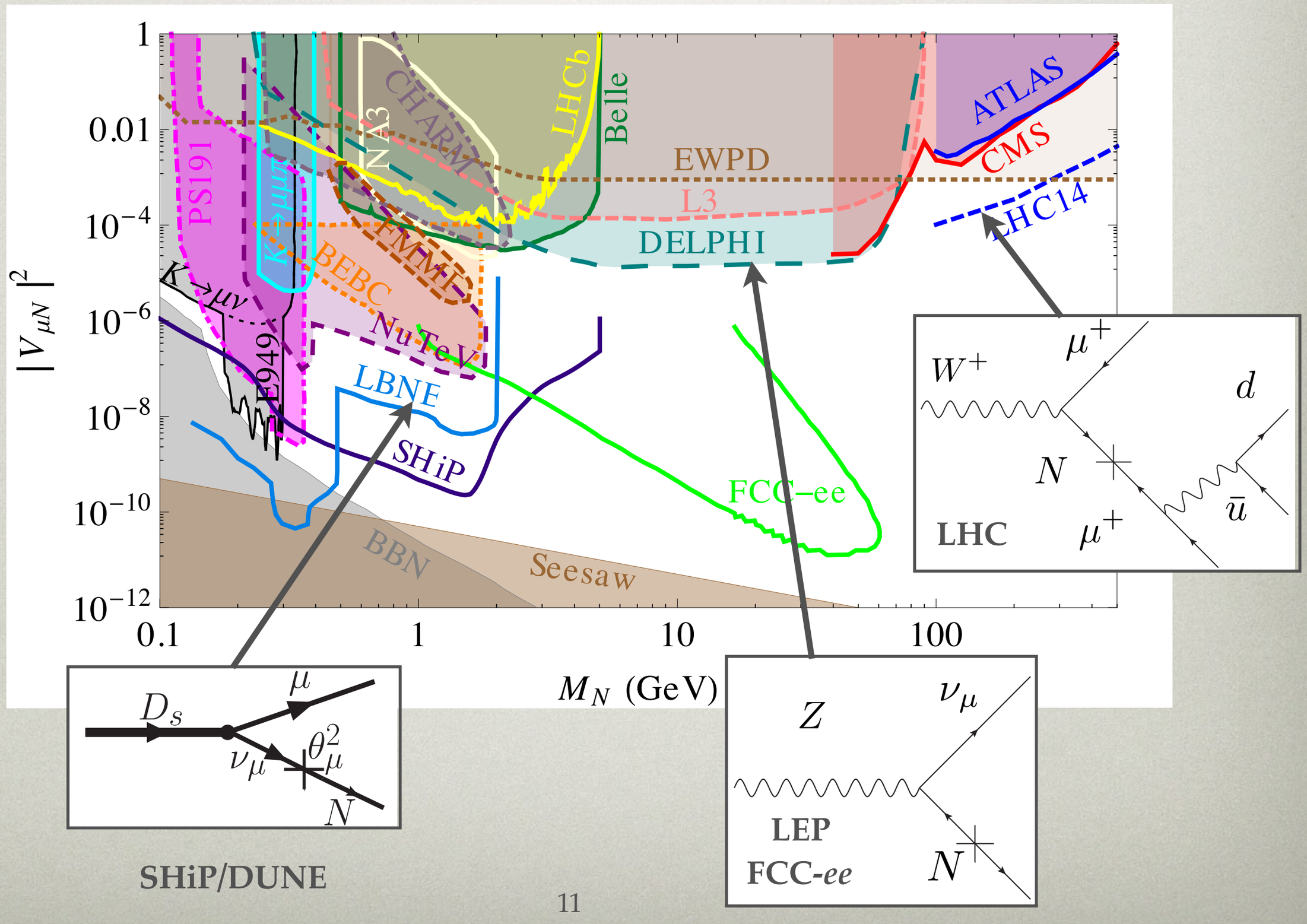
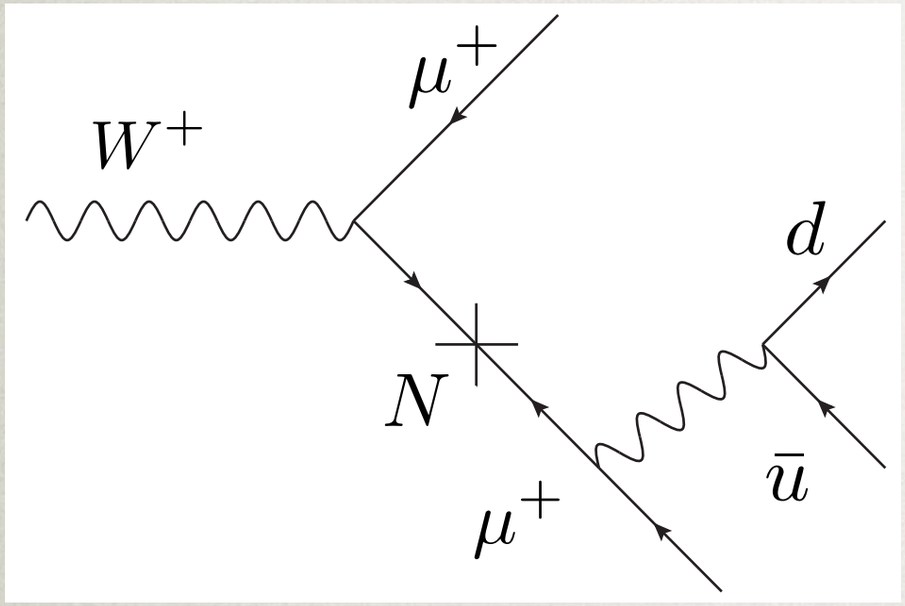


SHiP/DUNE

Limitations of Current Searches

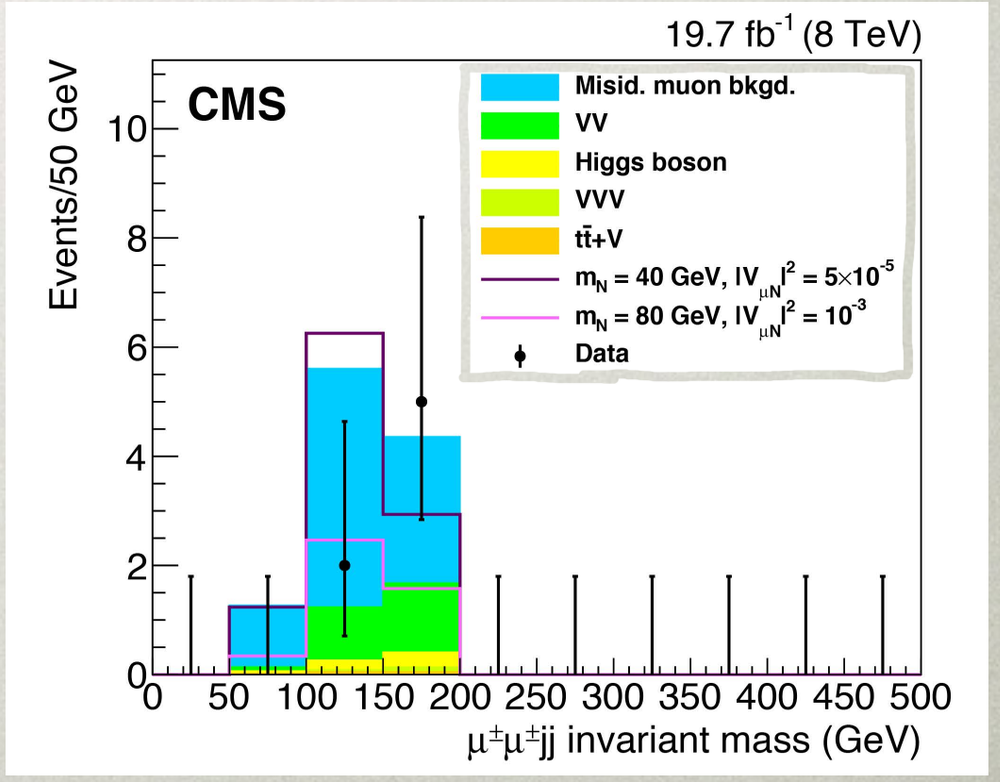


$$M_W \approx 80 \text{ GeV}$$

$$p_{\mathrm{T},\ell} \approx 20 \text{ GeV}$$

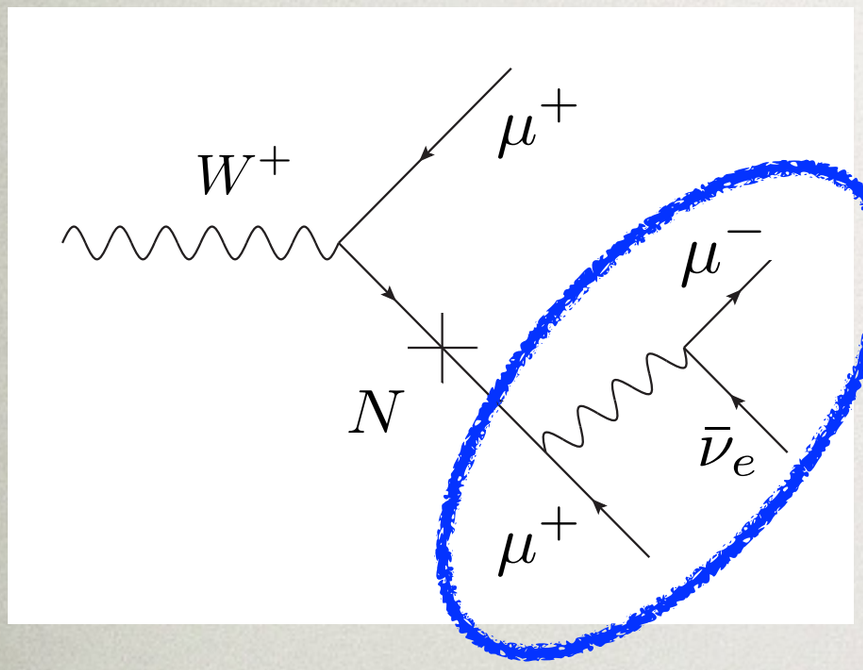
$$p_{\mathrm{T},j} \approx 30 \text{ GeV}$$

- At low mass, limits not improved over LEP
- Can cleaner, all-leptonic decays help?

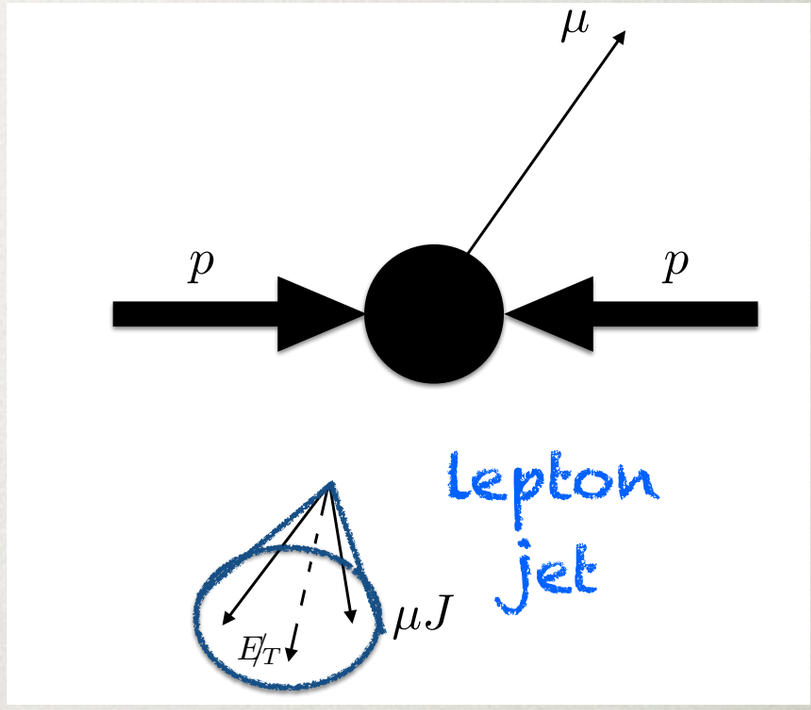


(from arXiv:1501.05566)

Low-Mass Neutrino Signature



$M_N \ll M_W$



Arkani-Hamed, Weiner, 2008; …

- Hadronic displaced vertices also possible, but backgrounds could be much larger

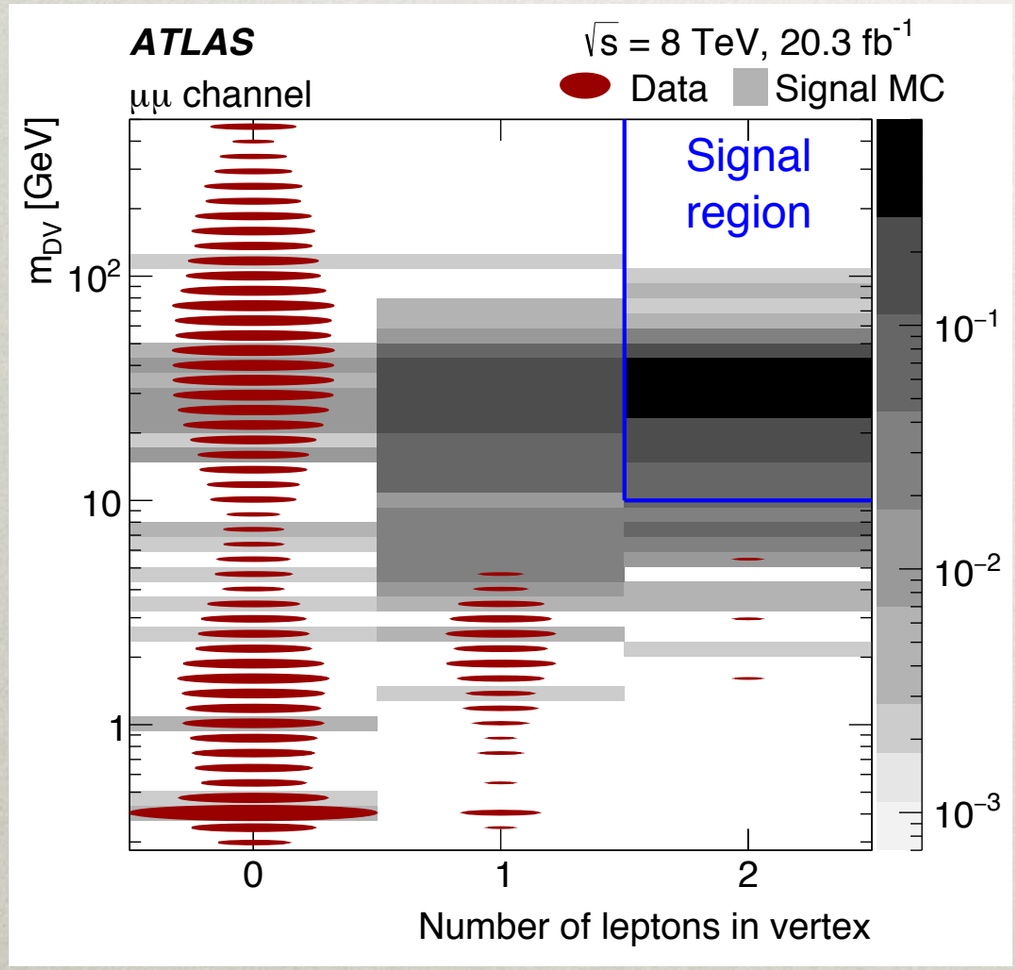
Helo, Hirsch, Kovalenko, 2013

Izaguirre, BS, 2015

Low-Mass Neutrino Signature

- Searches to date have no sensitivity to this final state

- We expect backgrounds to be very low for a dedicated search



(a)

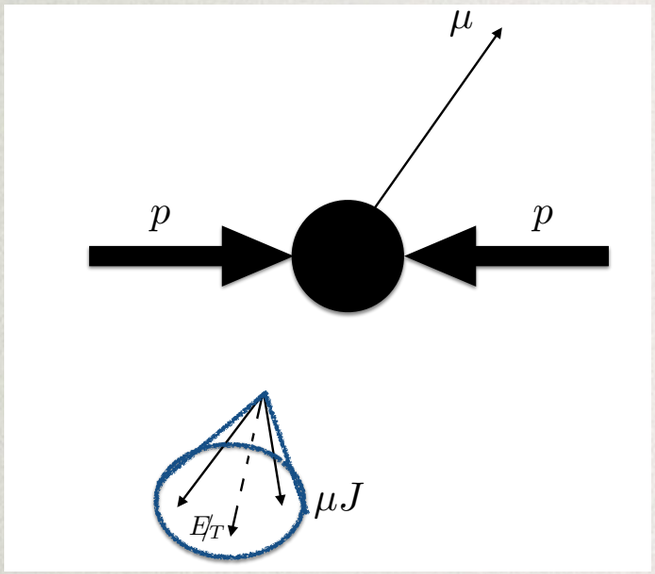
ATLAS, arXiv:1504.05162

- Also, low-bkd found by extrapolation from existing 2-LJ searches

  (ATLAS, arXiv:1409.0746)

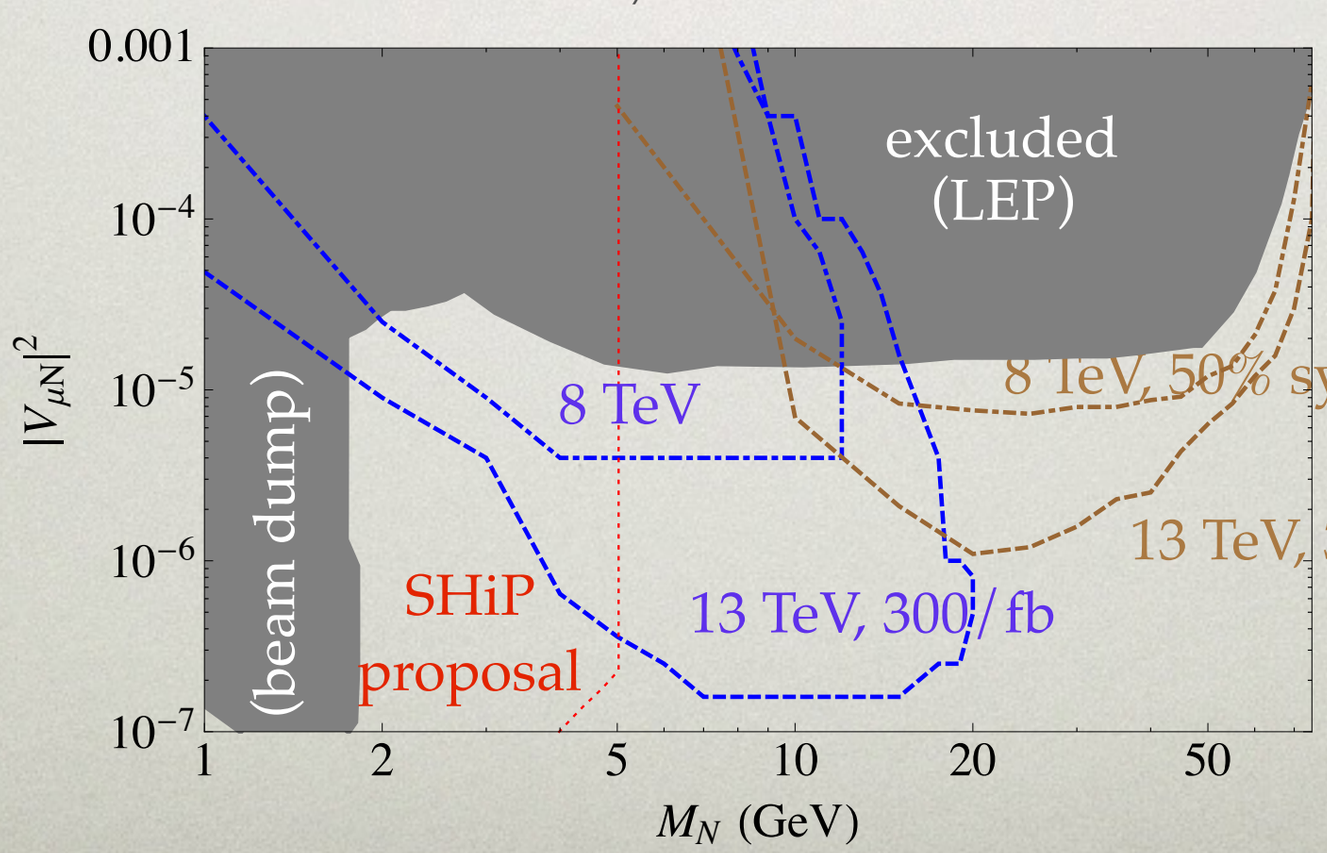
Izaguirre, BS, 2015

Low-Mass Neutrino Signature



- Good sensitivity for displaced search
- Also, good prospects for prompt decays as well!

95% CL reach



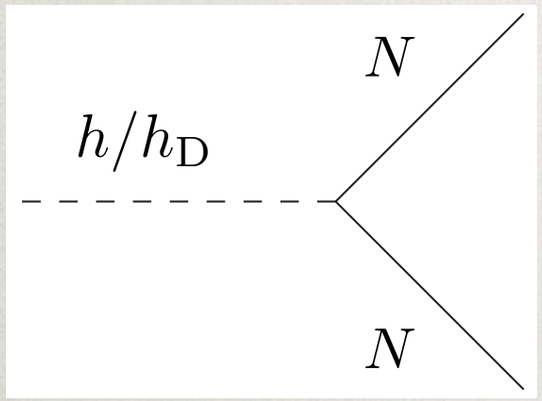
(prompt multilepton)

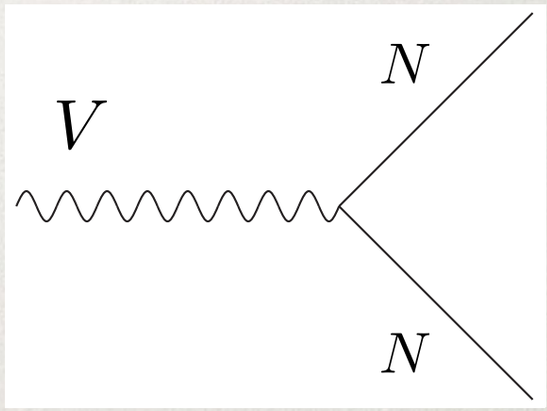
Izaguirre, BS, 2015

Low-Mass Neutrino Signature

- In other scenarios, N can be produced in decay of the Higgs boson or new gauge boson

Mohapatra, Marshak 1980; Huiti *et al.*, 2008; Aguilar-Saavedra, 2009; Basso *et al.*, 2009; Fileviez Perez, Han, Li 2009
Pilaftsis, 1999; Graesser, 2007; Shoemaker, Petraki, Kusenko, 2008; Garcia Cely *et al.*, 2012; Dev *et al.*, 2012; Gago *et* al., 2015; Accomando *et al.*, 2016





- *E.g.*, **current** unoptimized searches can be sensitive to gauge couplings and/or scalar mixing angles ~0.01, future ~10^{-4} level?

- Low-energy experiments should look for this too!

Batell, Pospelov, BS, 2016 & ongoing

Broadening the Scope

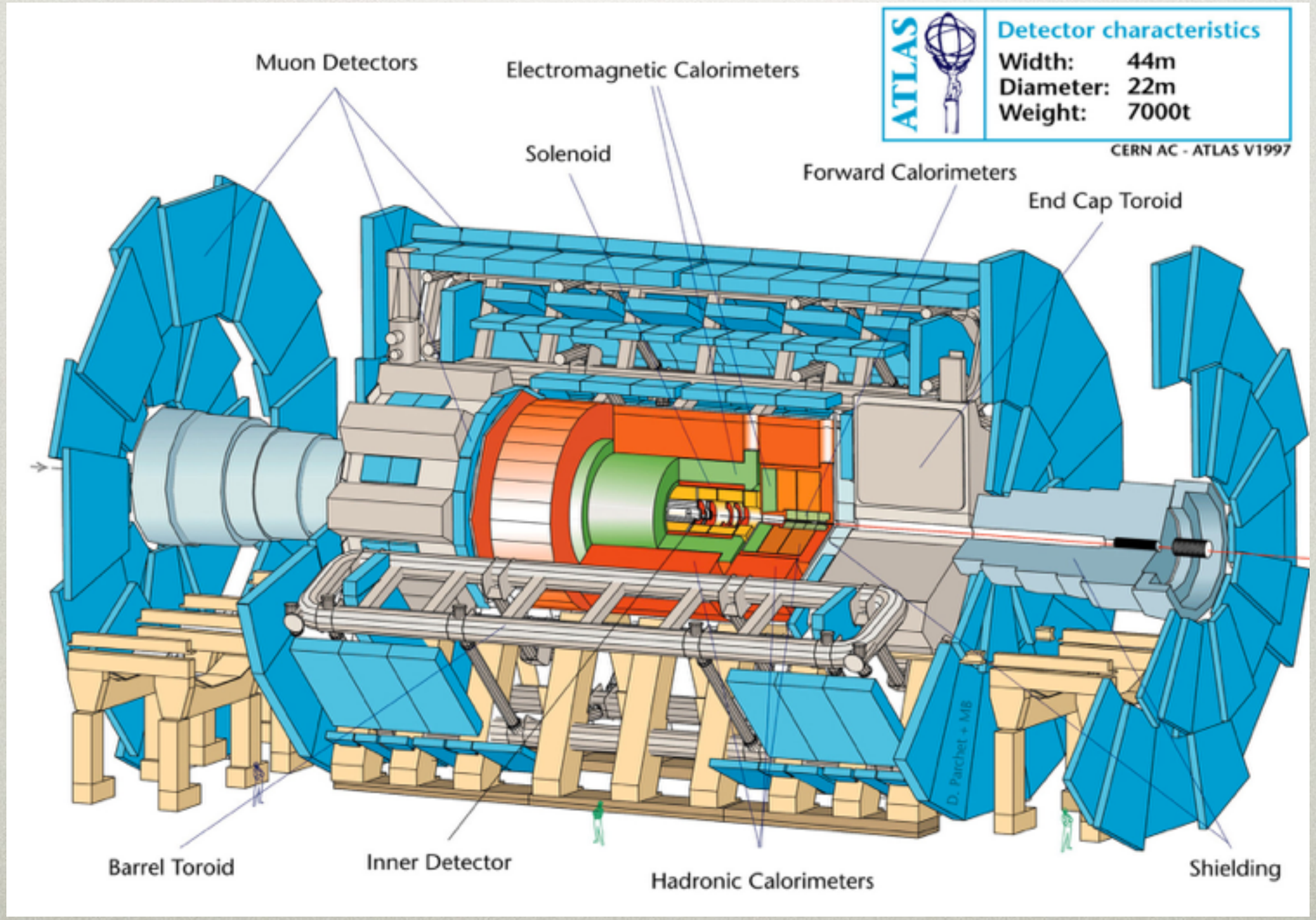
Thomas, Wells, 1998; Strassler, Zurek 2006; Bai, Tait, 2011; Curtin *et al.*, 2013;
Cui, BS, 2014; Izaguirre, Krnjaic, BS, 2015; Ismail, Izaguirre, BS, 2016
+ many, many more…

- Many of these lessons are generic
    - Use associated objects for trigger and background suppression
        - Also look for pairs of soft, long-lived objects

- Existing searches are a good start, but often lack sensitivity to low-mass final states in either single or pair production

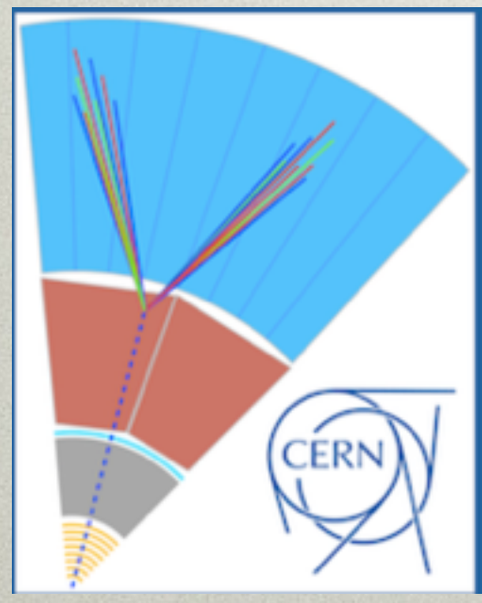
Barriers to a Comprehensive Strategy

- Decays can happen throughout detector, in various permutations of final states



Progress Requires Community Planning

- Need whole community efforts
- Already significant work towards a community document on proposing simplified models and searches
- Excellent response from theory community — let me know if you want to be involved!



Searches for long-lived particles at the LHC:
Workshop of the LHC LLP Community

Albert de Roeck (CMS)
James Beacham (ATLAS)
Xabier Cid Vidal (LHCb)
Brian Shuve (theory)

CERN
April 24-26, 2017

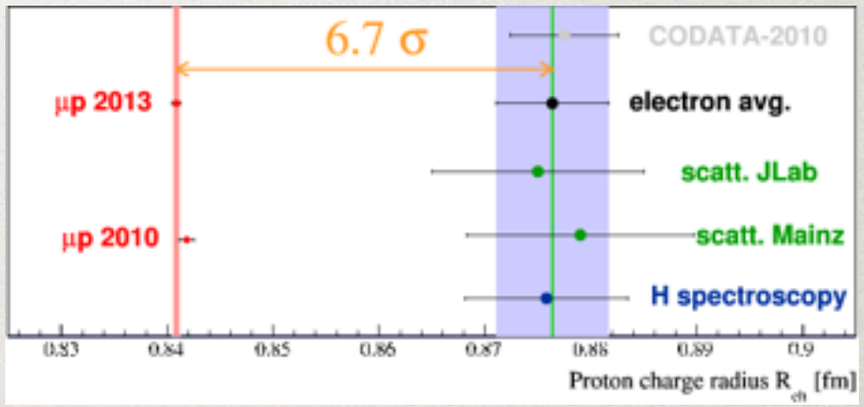
Outline

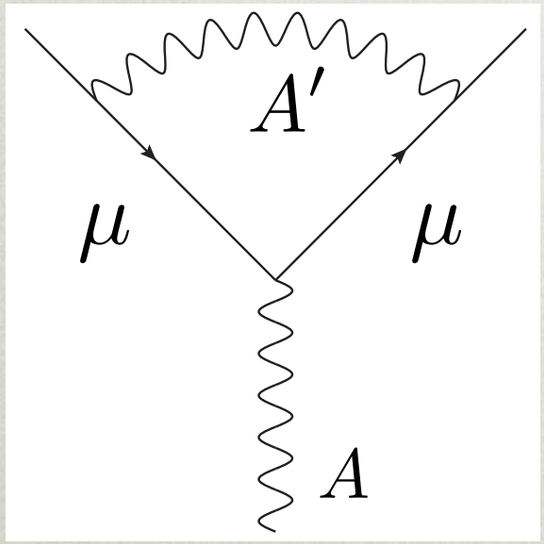
- **New Searches for Long-Lived Hidden Sectors @ LHC**
    - Test case: right-handed neutrino
    - Towards closing the long-lived particle gaps at the LHC

- **New Searches for Hidden Sectors @ *B*-factories**
    - Search for leptophilic forces at *BABAR*
    - New ideas for *B*-factory searches

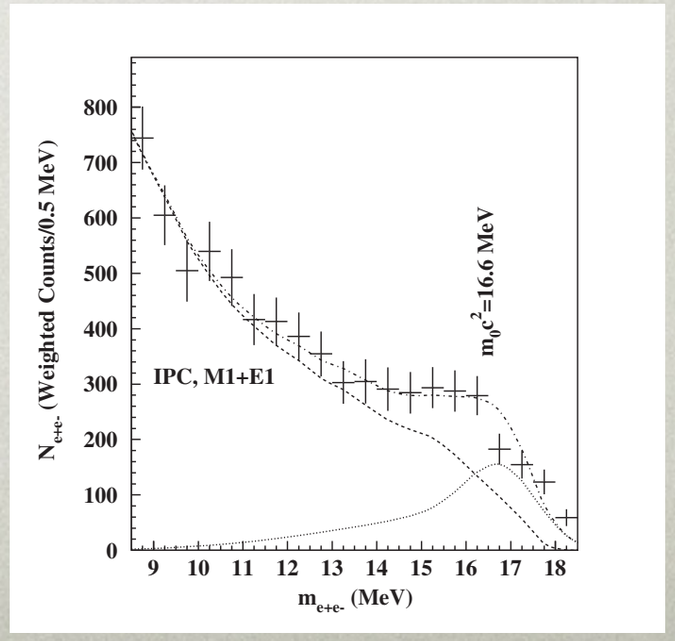
Low-Energy Searches

- If particles have low mass (<10 GeV), we could directly produce them in low-energy accelerator and collider experiments
- There are already some potential hints of new particle interactions in low-energy experiments



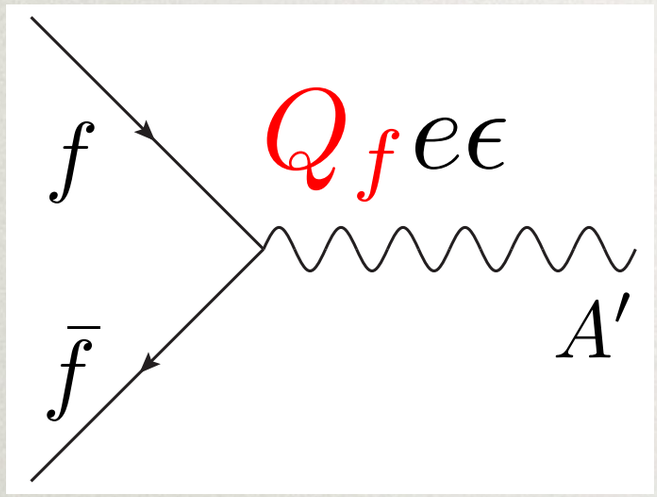


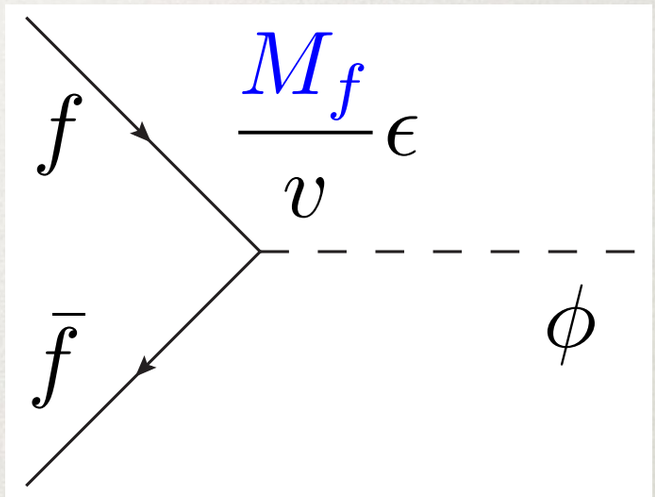
$$\Delta(g-2)_\mu \sim 3-4\sigma$$



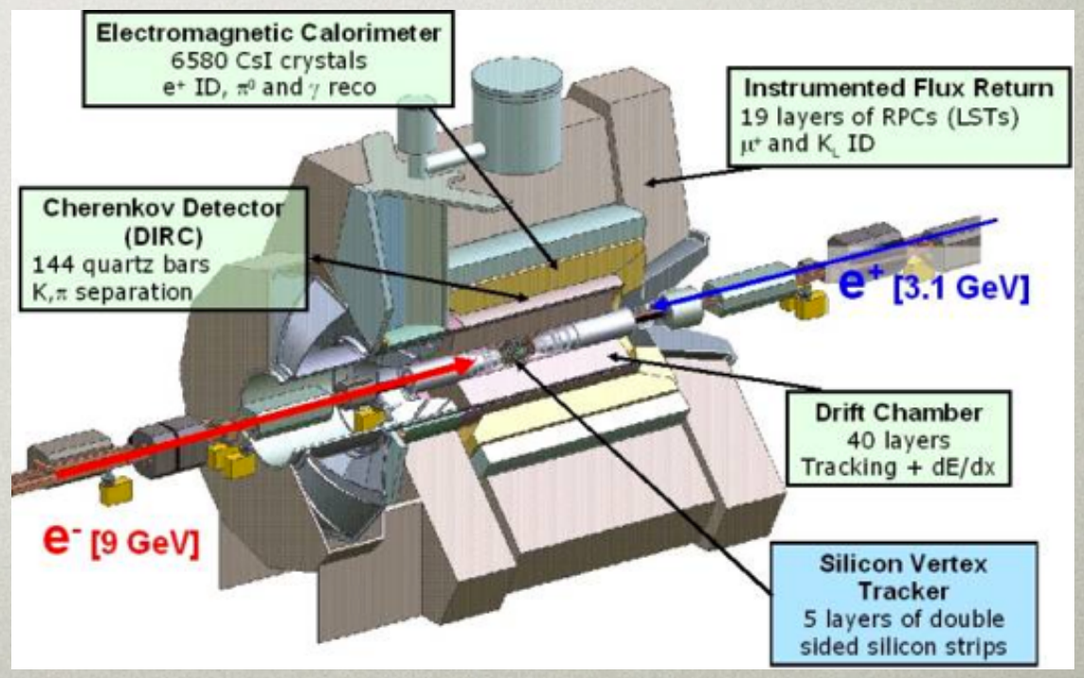
Low-Energy Searches

- Most existing searches for low-mass particles make simple assumptions, such as inheritance of couplings from SM





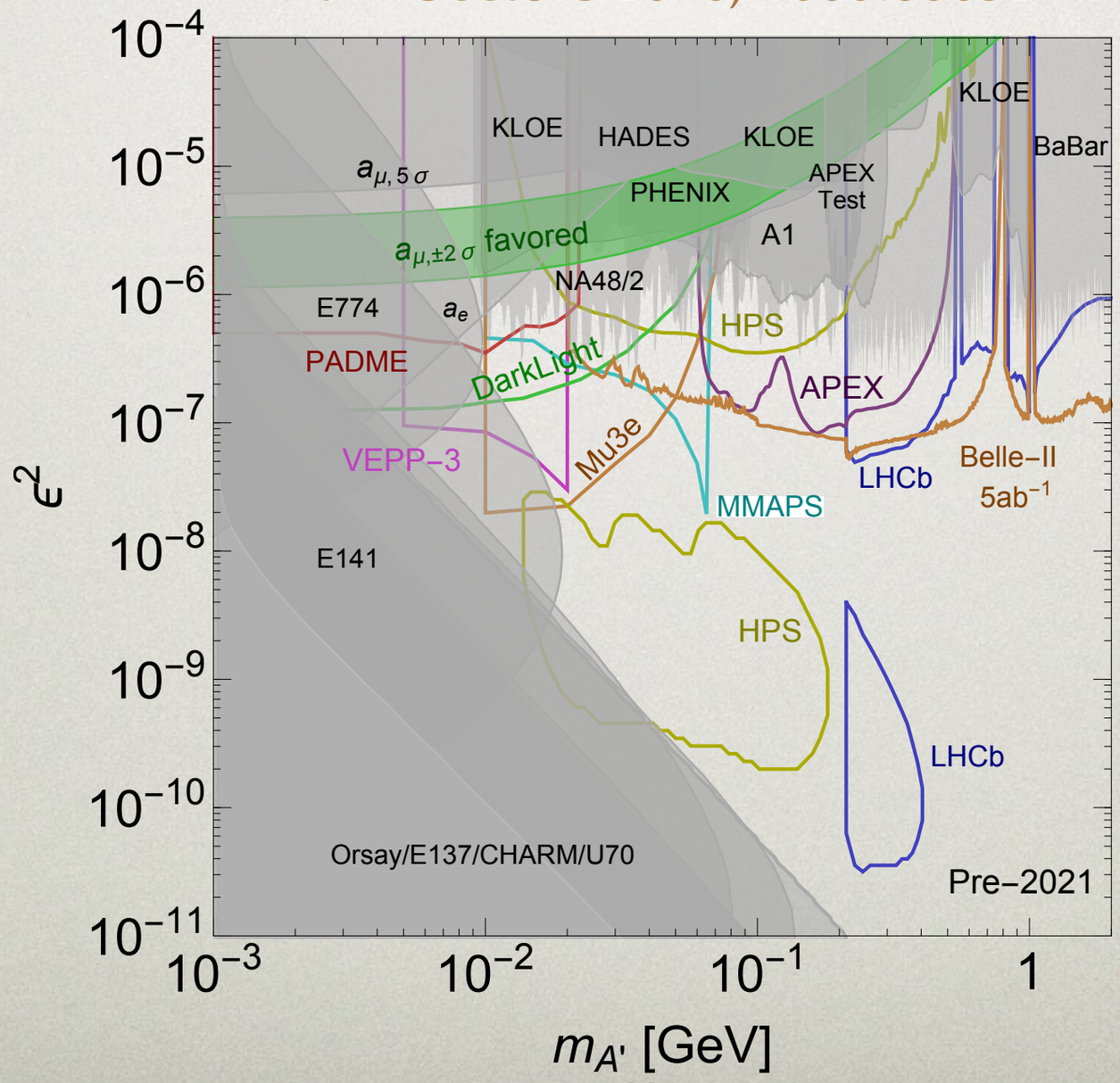
- Use of electron beams, meson factories to probe these



Low-Energy Searches

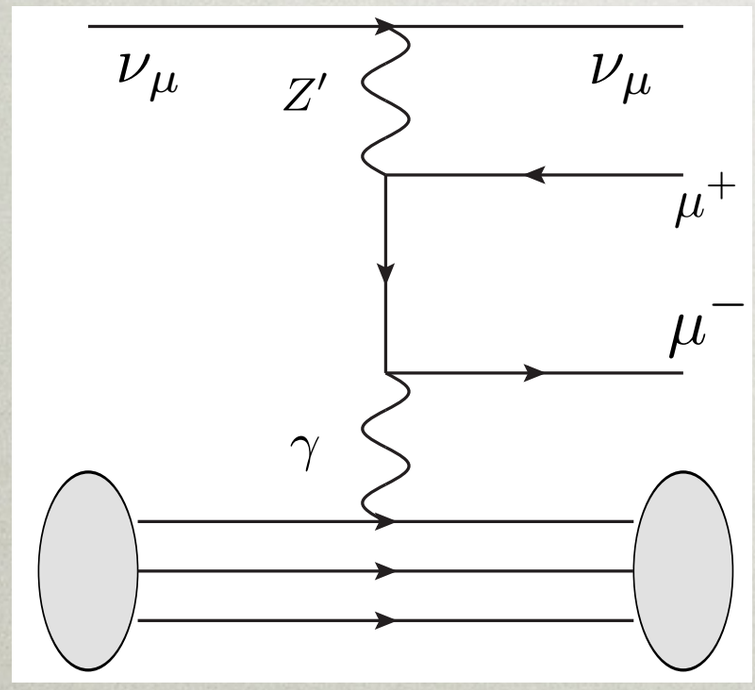
- So far…no luck
- Many of the constraints are due to **electron** and **quark** interactions

Dark Sectors 2016, 1608.08632

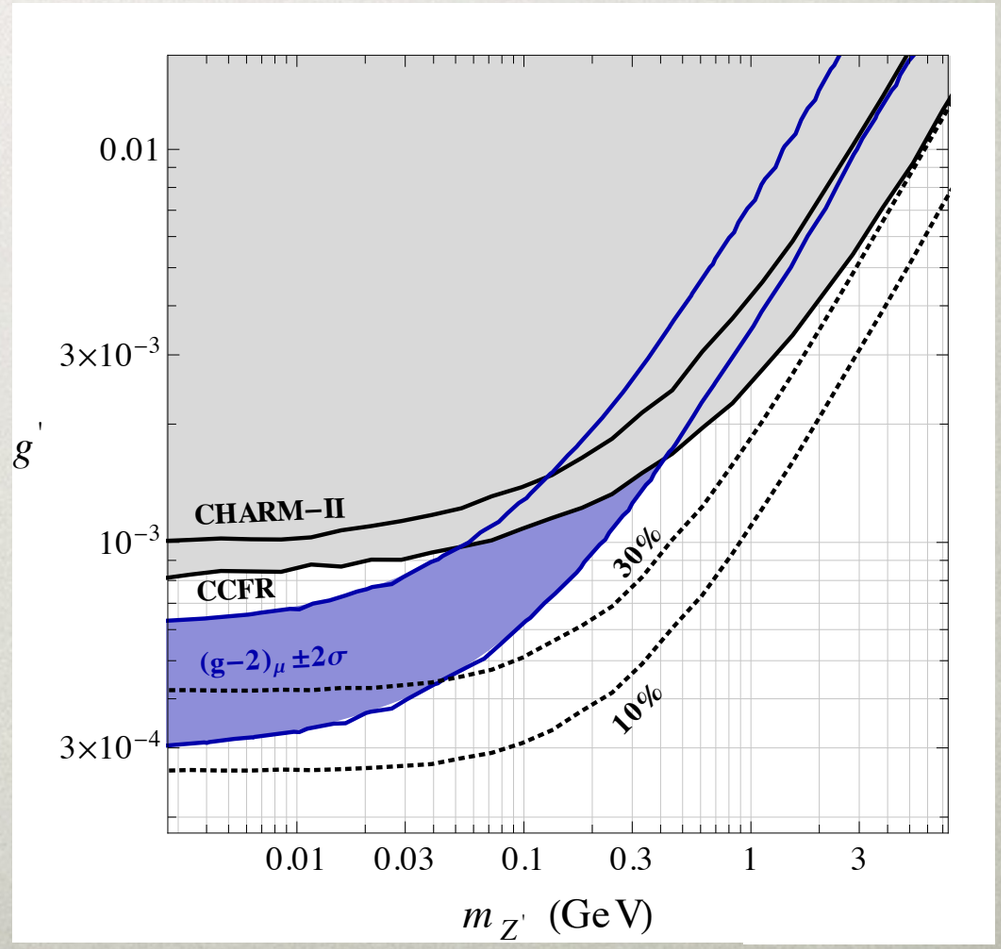


New Muonic Forces

- One possibility, consistent with lepton anomalies, is a new force coupled to muons but *not* electrons
- *E.g.*, gauged L_μ-L_τ with coupling to $\mu,\ \tau,\ \nu_\mu,\ \nu_\tau$



Altmannshofer *et al.*, 1406.2332



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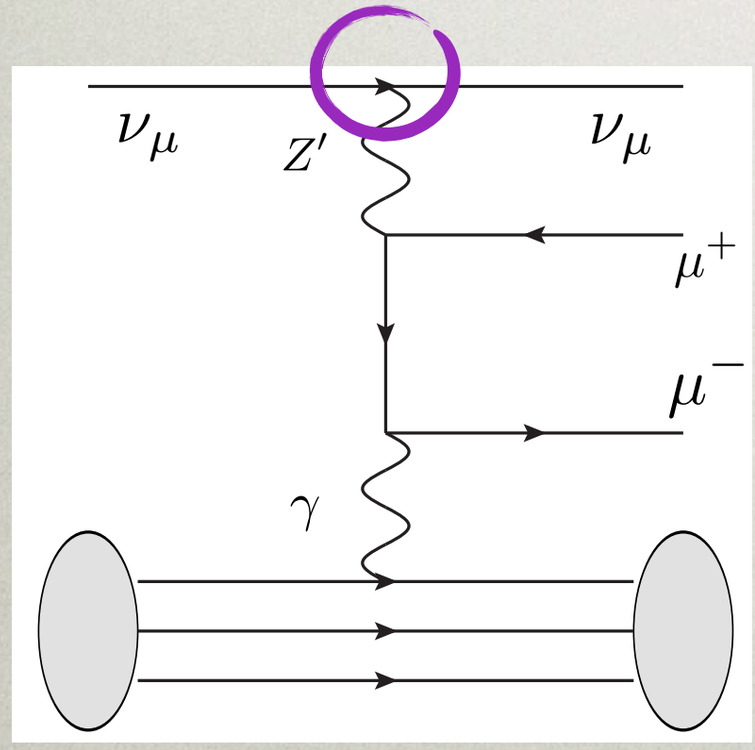
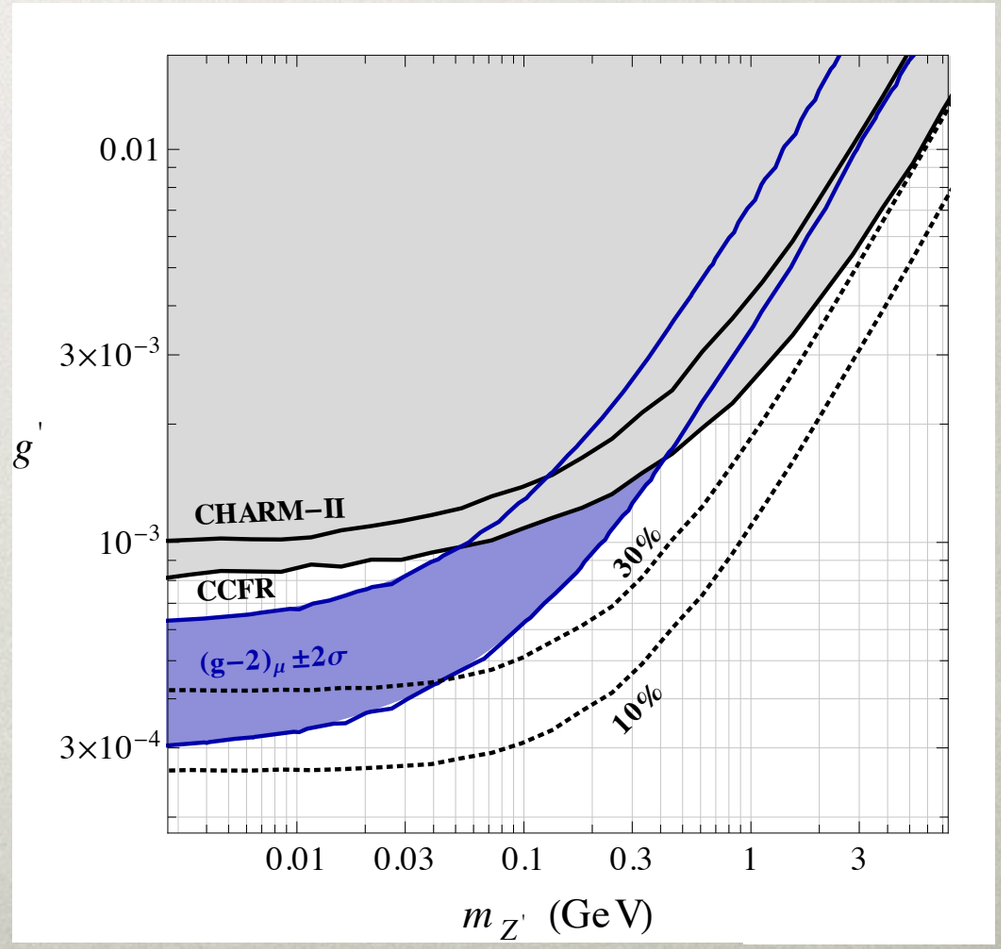
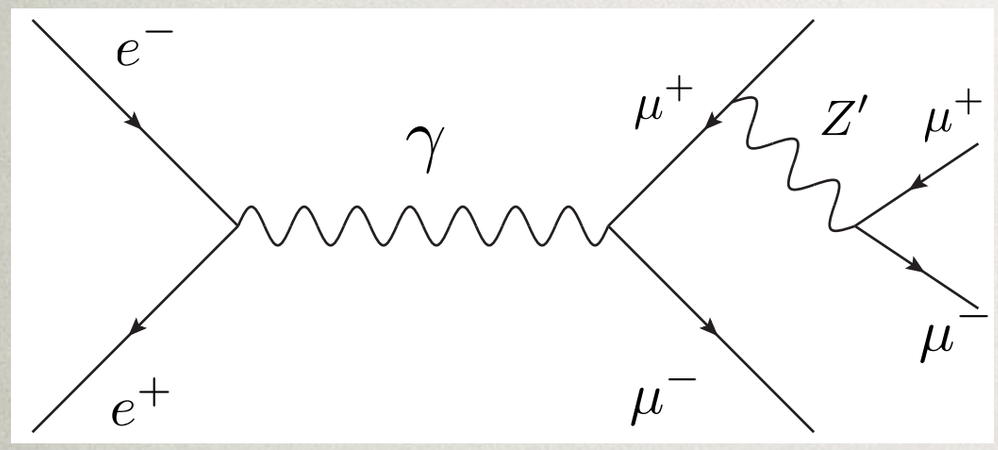


Altmannshofer *et al.*, 1406.2332

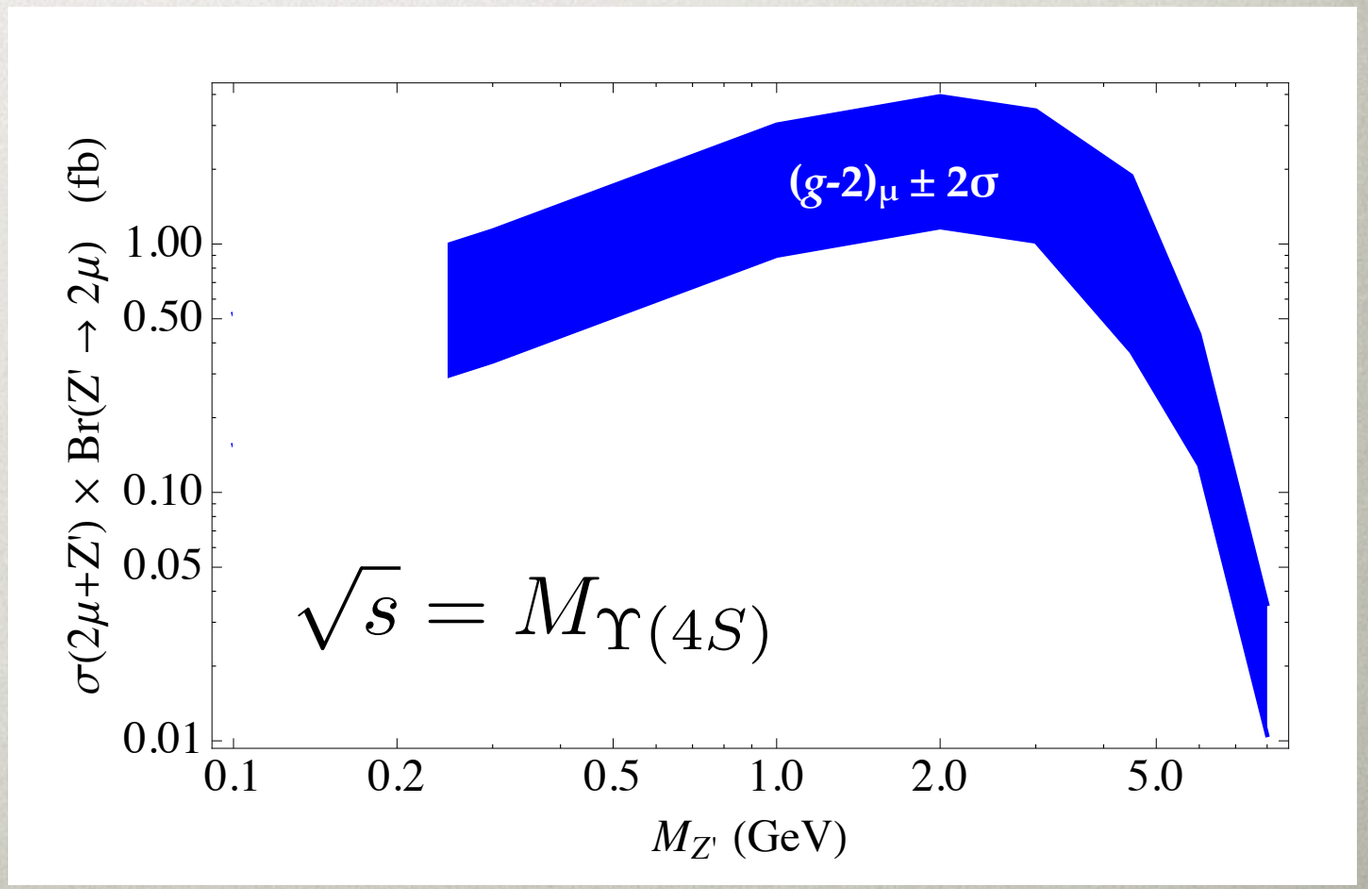


New Muonic Forces

- True **model-independent** test only exploits coupling to muons, but use L_μ-L_τ as a benchmark; complements indirect tests



BS with *BABAR*, arXiv:1606.03501

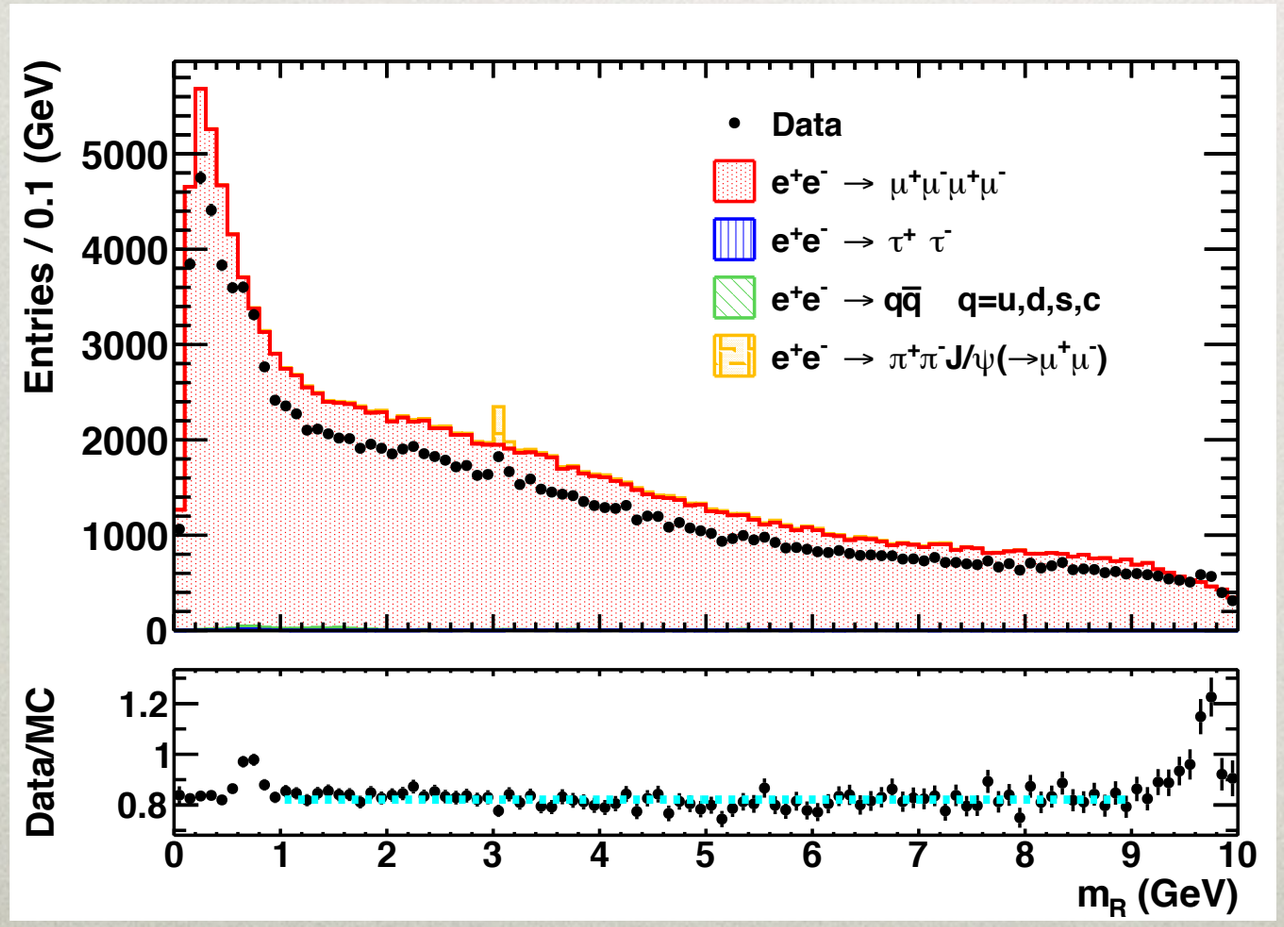


- BaBar: 514/fb total luminosity, mostly $\Upsilon(4S)$

Muonic Forces at *BABAR*

- Require 2 pos. and 2 neg. tracks that carry total beam energy

- Require same-sign tracks to pass muon ID (better efficiency than requiring 4 muons, 3% pion mis-ID rate)



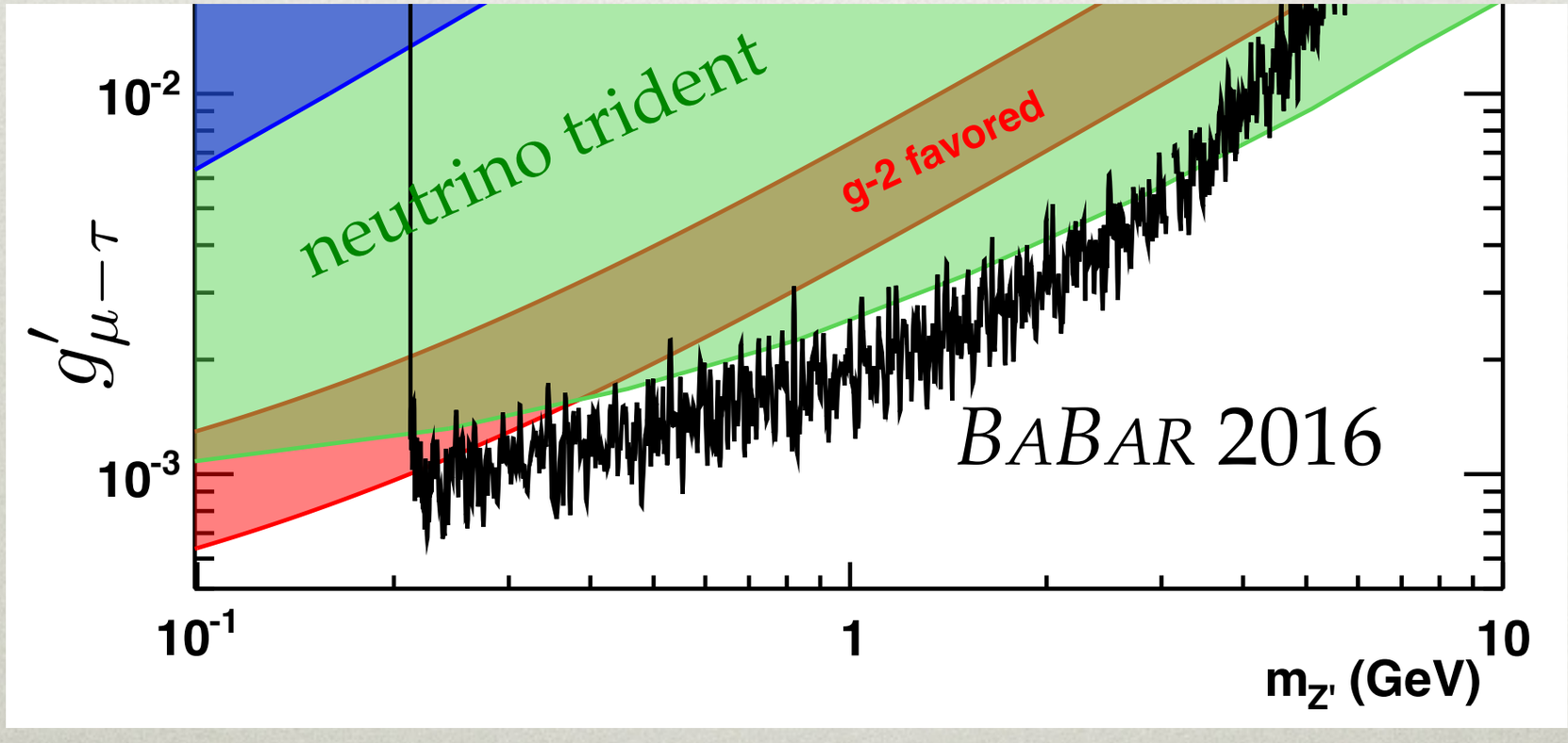
$$m_{\mathrm{R}} = \sqrt{M^2_{\mu\mu} - 4M^2_{\mu}}$$

BS with *BABAR*, arXiv:1606.03501

Muonic Forces at *BABAR*

- Do maximum likelihood fits of polynomial (bkd) vs. double Gaussian shape extracted from MC (signal)

- No significant excess observed, extract limits at 90% CL on model-independent cross section times branching fraction

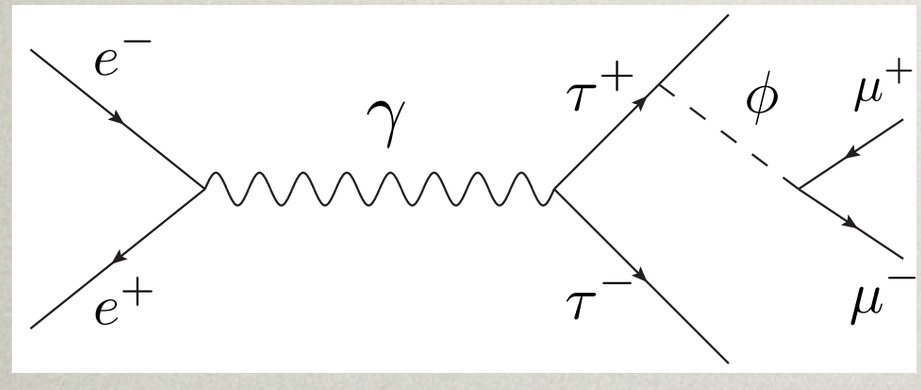


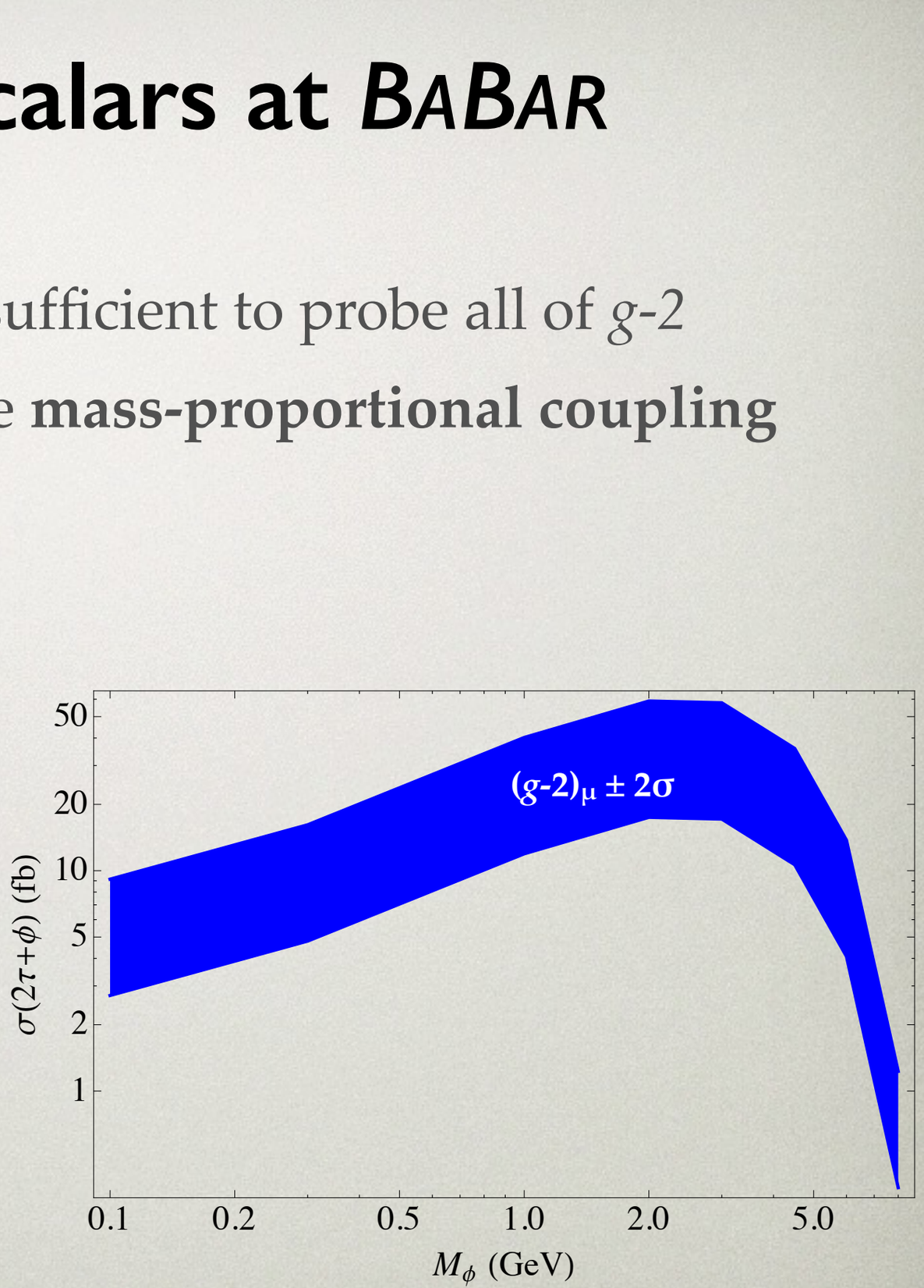
BS with *BABAR*, arXiv:1606.03501

Leptophilic Scalars at *BABAR*

- Muon-only coupling not (yet) sufficient to probe all of g-2
- However, scalars typically have **mass-proportional coupling**

$$\mathcal{L} = \frac{M_\ell}{v}\,\xi_\ell\,\phi\bar{\ell}\ell$$

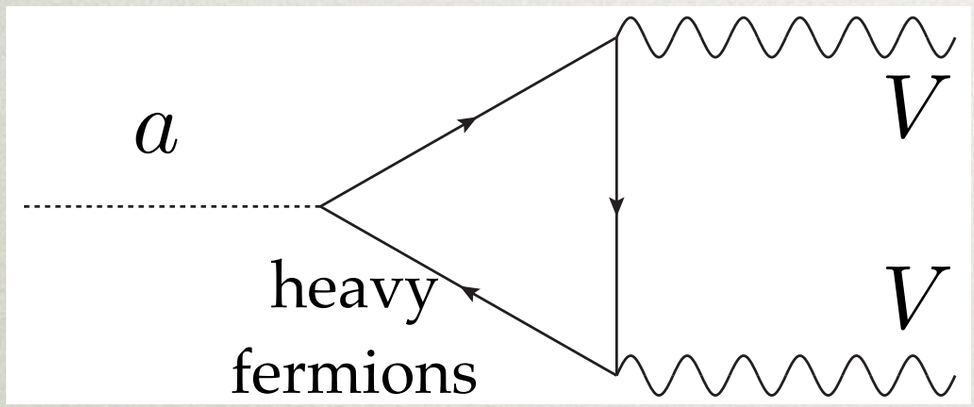


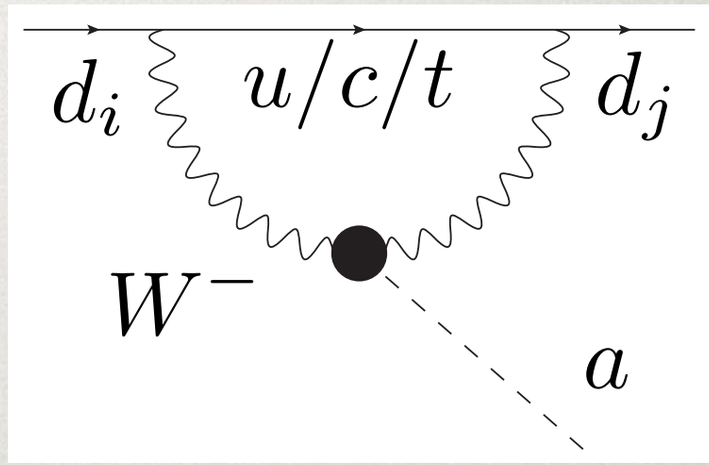


BS with *BABAR*, in progress

Axion-like Particles at *BABAR*

- Instead of preferential interaction with muons, could have preferential coupling of new particle with **gauge bosons**

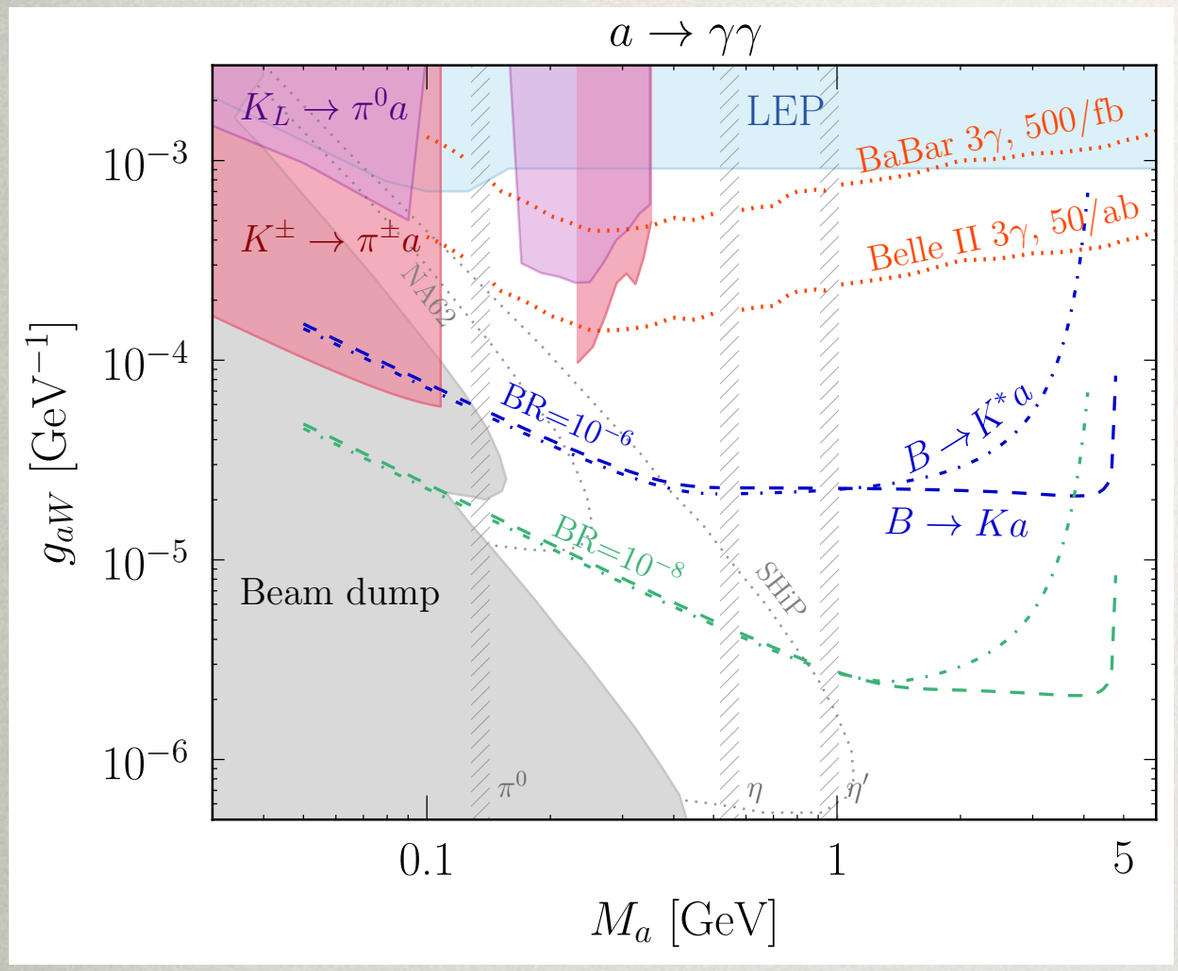


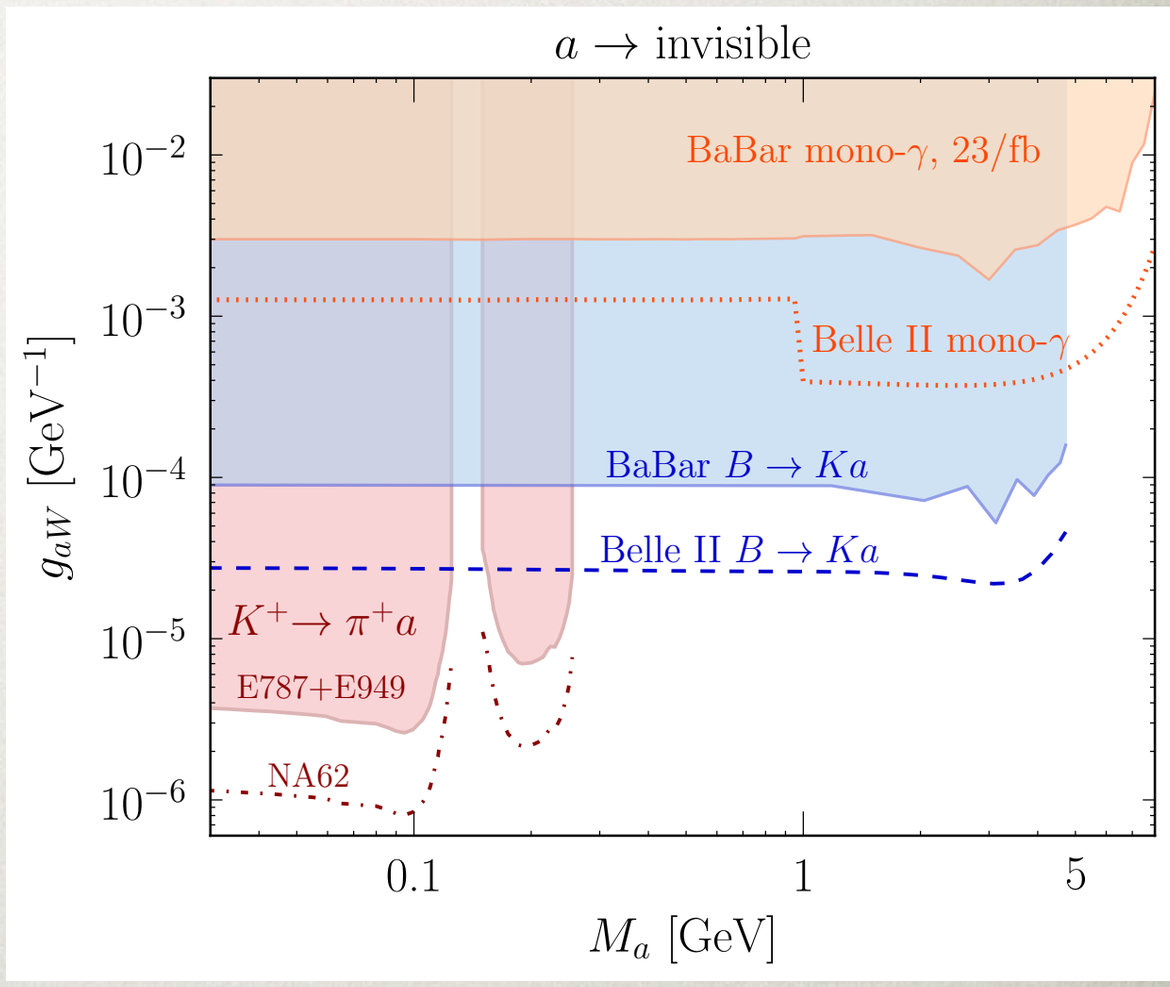


- Most commonly, ALP can be invisible or decay to photons

E. Izaguirre, T. Lin, and BS, arXiv:1611.09355

Axion-like Particles at *BABAR*





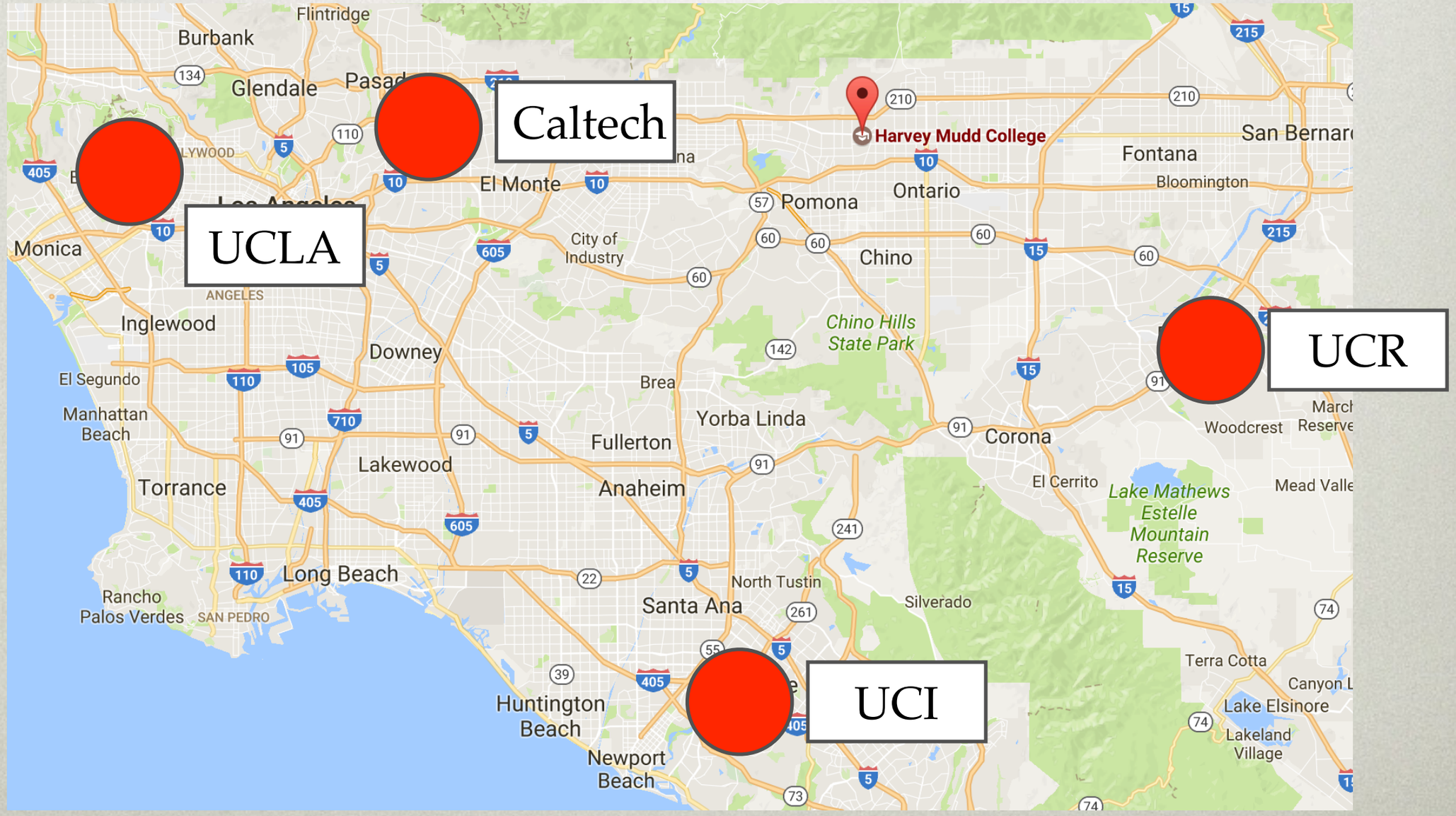
E. Izaguirre, T. Lin, and BS, arXiv:1611.09355

- New diphoton search ongoing

BS with *BABAR*, in progress

Harvey Mudd College

- College specializing in science, math & engineering w/ excellent students



Harvey Mudd College

- I will be building a research program there over the next few years

- Excellent students and educational/outreach possibilities, but more limited resources than in a research university

- Excited to get connected and build more collaborations with local physicists

- If you want more experience involving undergraduates or have ideas you want to try out, let me know!

Summary

- New hidden sectors are motivated by dark matter, neutrino masses, baryon asymmetry, etc.

- Excellent progress from colliders in last ~6 years for new heavy particle searches, but more work is needed for light states

- Combination of collider, accelerator, direct/indirect detection, and cosmology needed to hone in on this hidden universe!

Back-up slides

Hidden-Sector Connections?

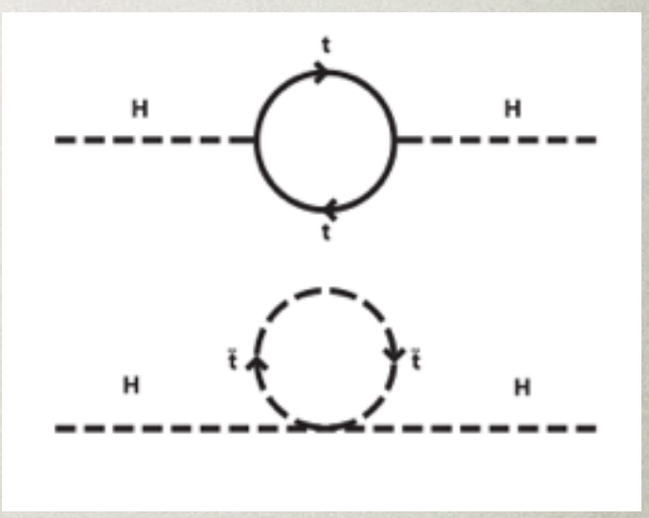
$\Omega_{DM} \sim 5\,\Omega_B$

baryons | antibaryons

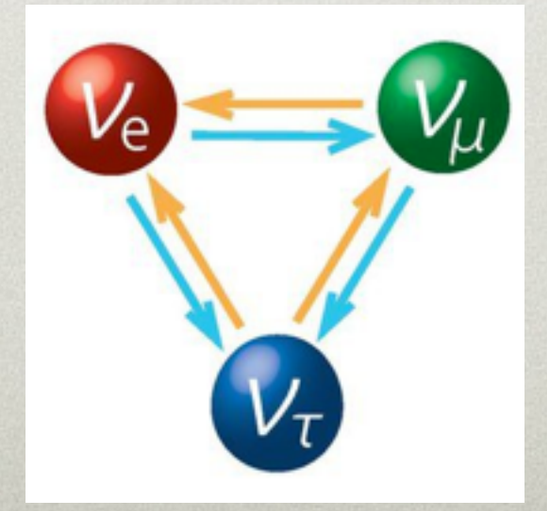
electroweak baryogenesis

leptogenesis

R-parity



sterile neutrino DM

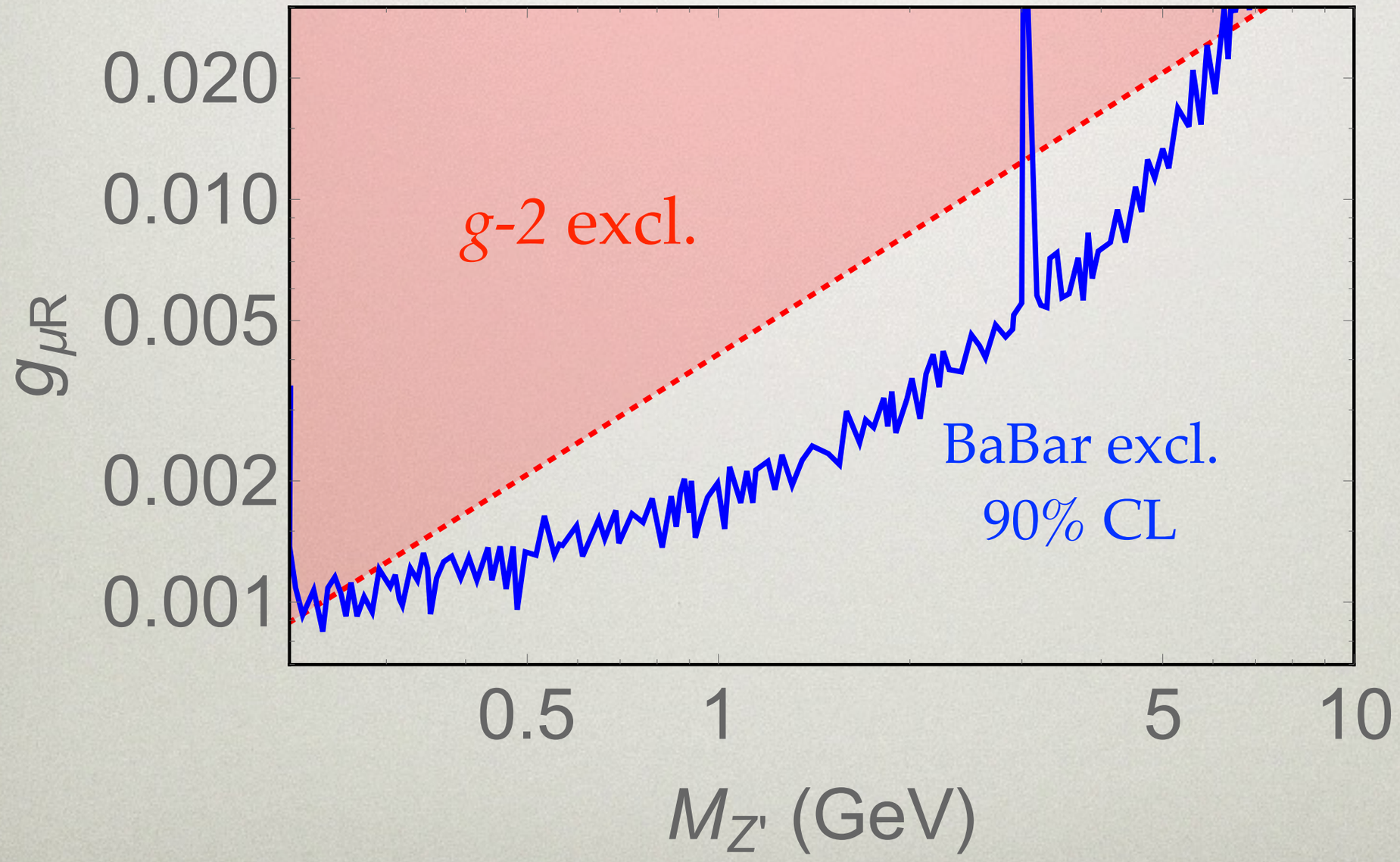


R-parity violation

.....

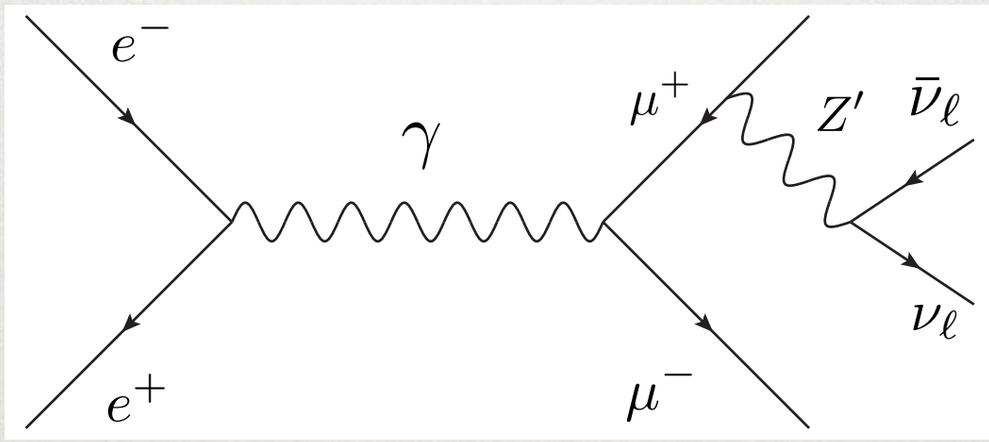
Dark Muonic Force - Limits

Model-independent limit: easily apply to other models



(Very) Dark Muonic Force

- What about below the muon threshold?



- Looks kind of like mis-reconstructed dimuon production…
- Work in progress, but may have to wait for Belle II/NA64
- Could be promising at BaBar for Z' decays to dark matter

The Leptonic Higgs Portal

- Example of UV complete model: leptophilic 2HDM+singlet
- Can separate IR and UV constraints, and UV constraints can be alleviated with more involved model

Batell *et al.*, 1606.04943