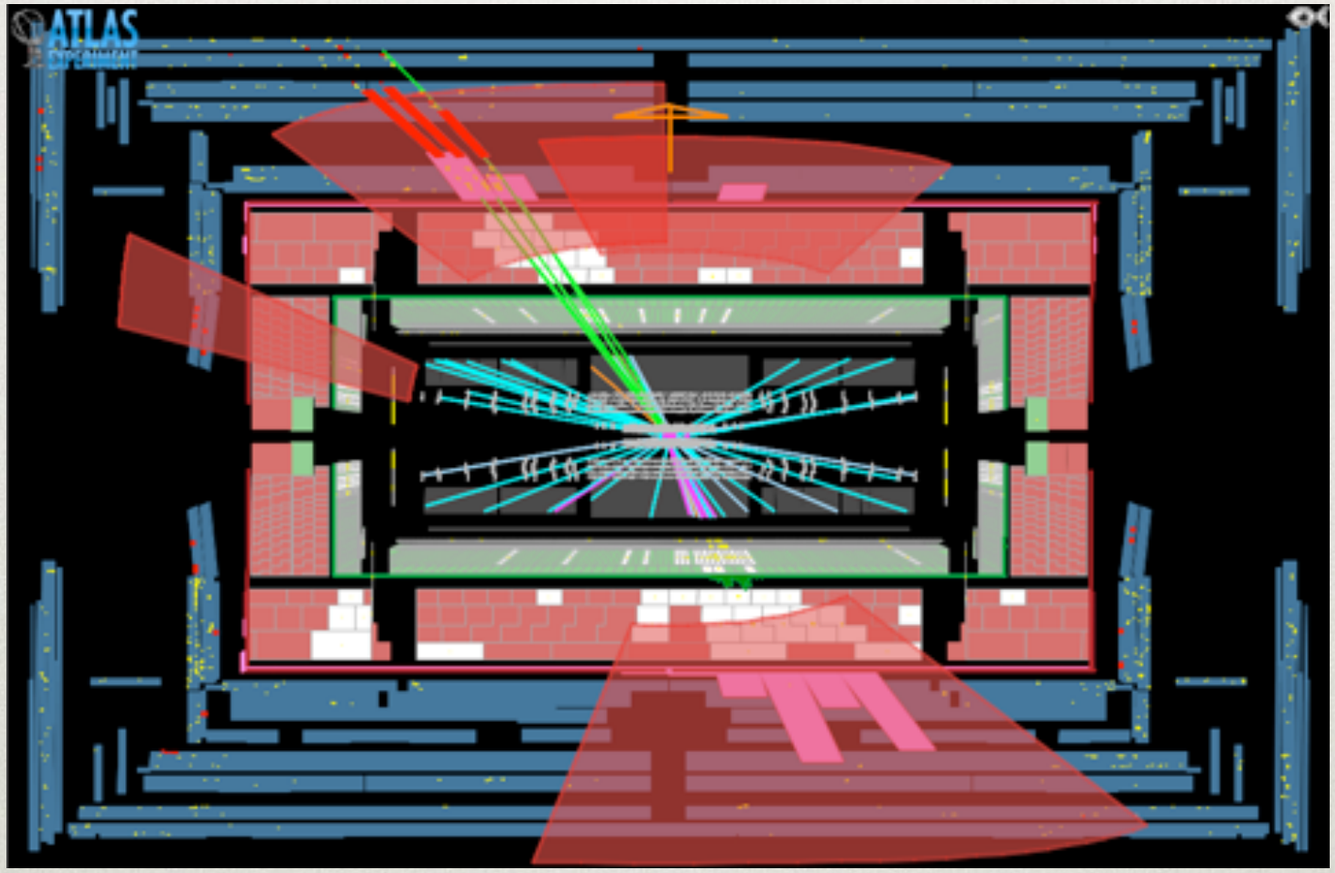
BEYOND WIMPS

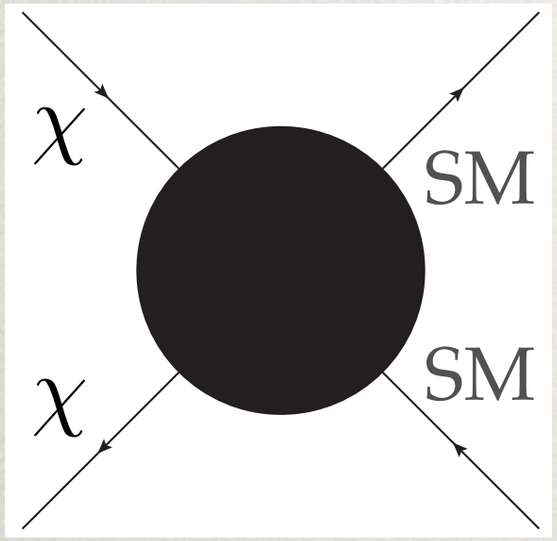


Brian Shuve — SLAC

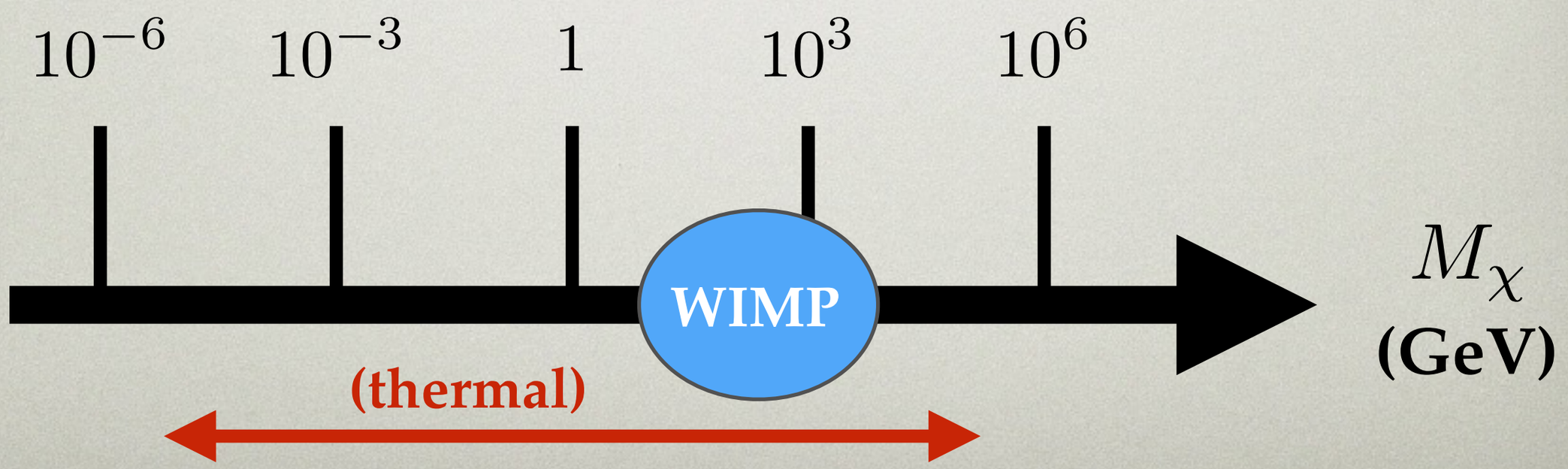
DM@LHC 2017 — UC Irvine

Thermal Dark Matter

- If we only **observe** DM gravitationally, why do we expect non-gravitational interactions?

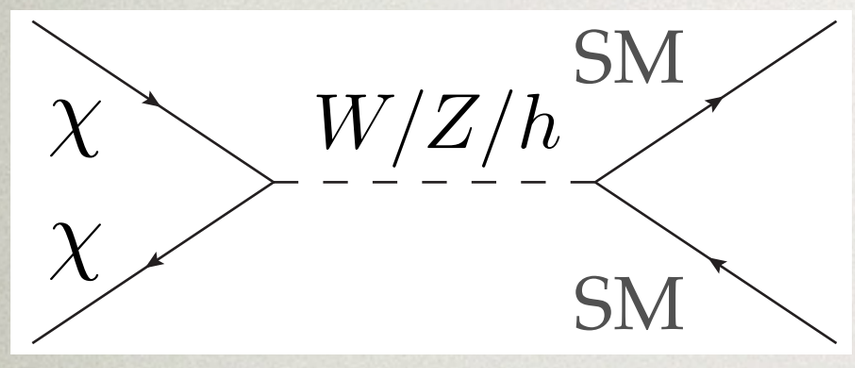


$$\sigma v \sim \left(3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\right) \sim \frac{\alpha_W^2}{\mathrm{TeV}^2}$$



Dark Matter & Dark Sectors

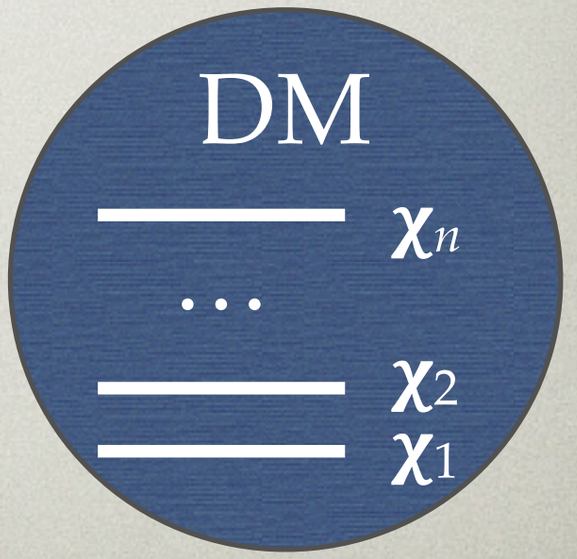
$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/s$$



$$M_\chi \ll M_W \quad \Rightarrow \quad M_\chi \gtrsim \text{few GeV}$$

Lee, Weinberg 1977

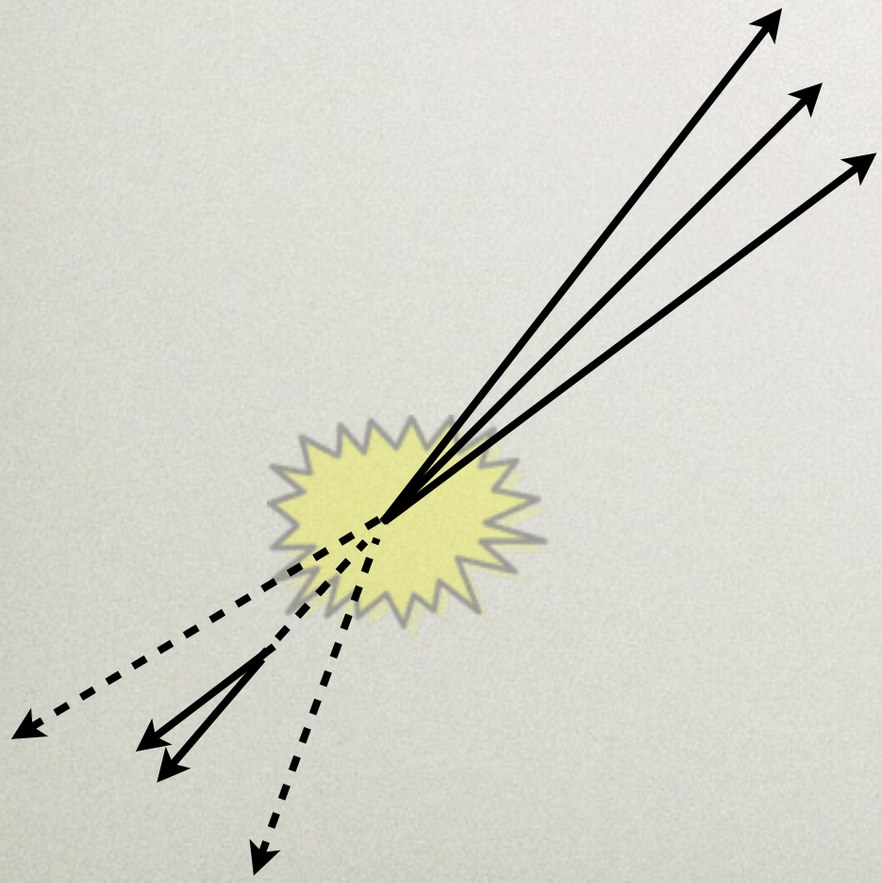
a



Dark Mediator Signatures

$$\frac{\alpha_{a\chi}\alpha_{a\mathrm{SM}}}{M_\chi^2} \sim \frac{10^{-9}}{\mathrm{GeV}^2} \sim \frac{10^{-3}}{\mathrm{TeV}^2}$$

Option 1:



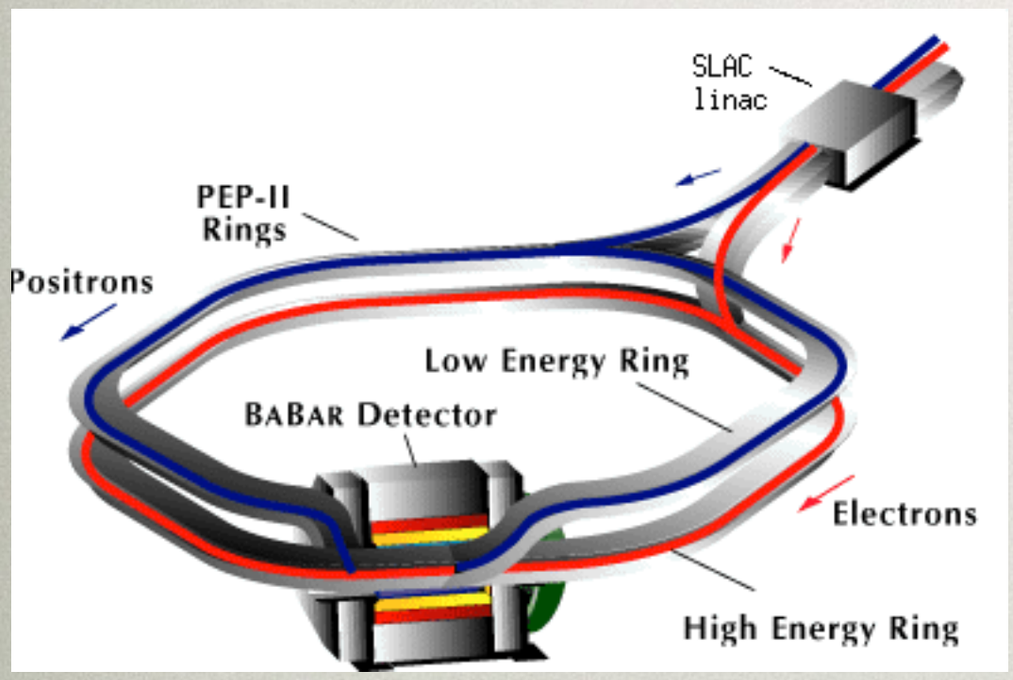
- Need high-energy particles in event to pass trigger
- Often get boosted, long-lived visible particles
- Associated prompt production

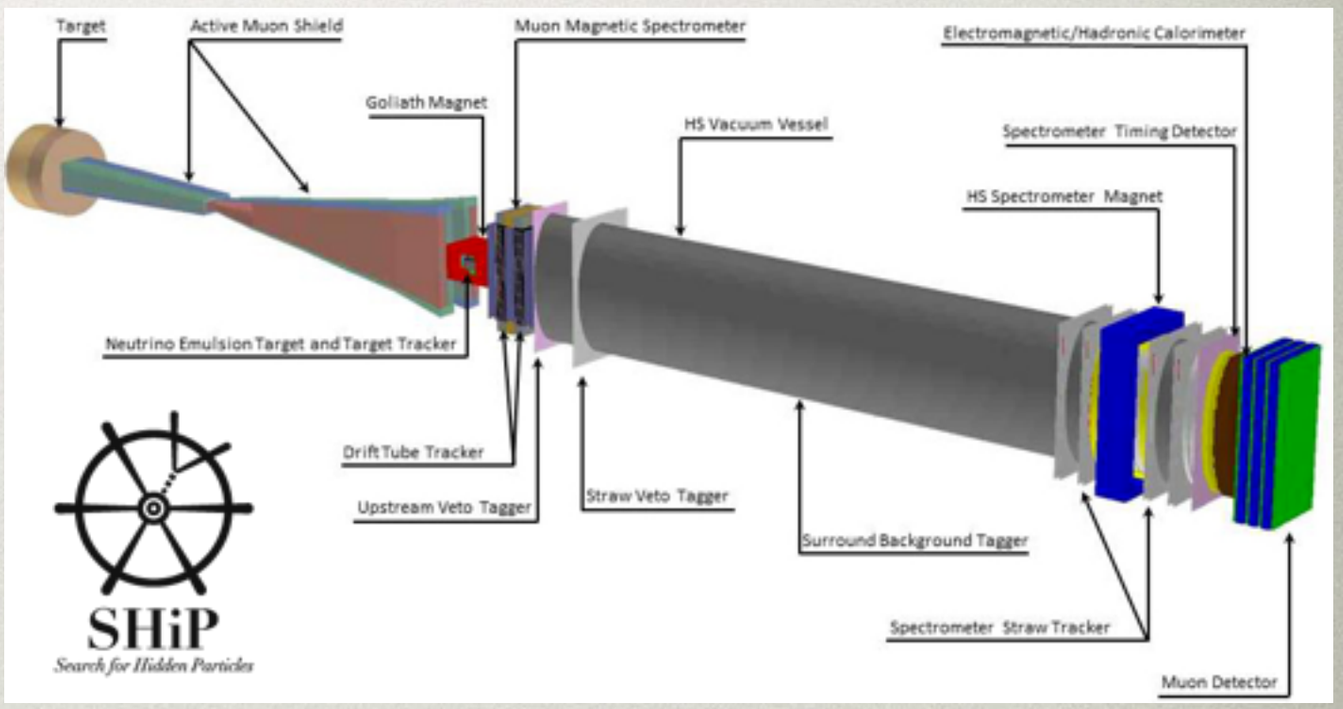
c.f. hidden valleys: Strassler, Zurek 2006

Dark Mediator Signatures

$$\frac{\alpha_{a\chi}\alpha_{a\mathrm{SM}}}{M_\chi^2} \sim \frac{10^{-9}}{\mathrm{GeV}^2} \sim \frac{10^{-3}}{\mathrm{TeV}^2}$$

Option 2:





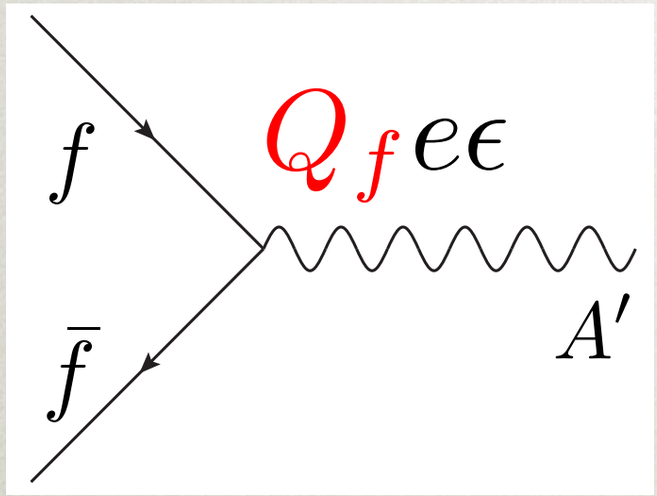
Options 3+: (In)direct detection, cosmology, …

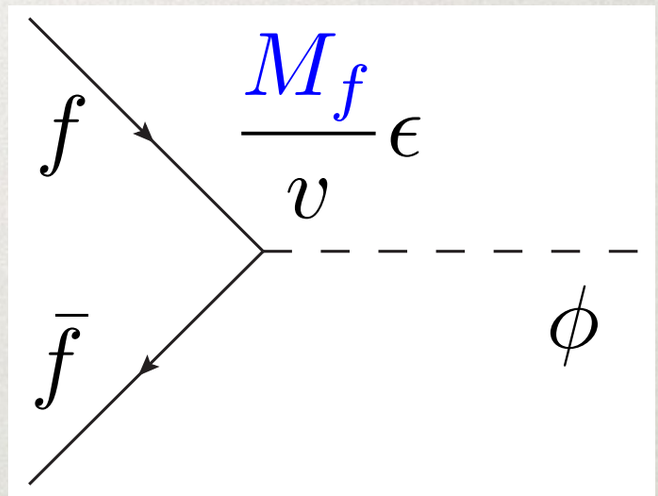
Outline for Rest of Talk

- Searches for New Mediators
- Multi-Particle Dark Sectors

Simple Portals

- In the simplest cases, the mediator acquires a coupling **proportional to SM coupling**

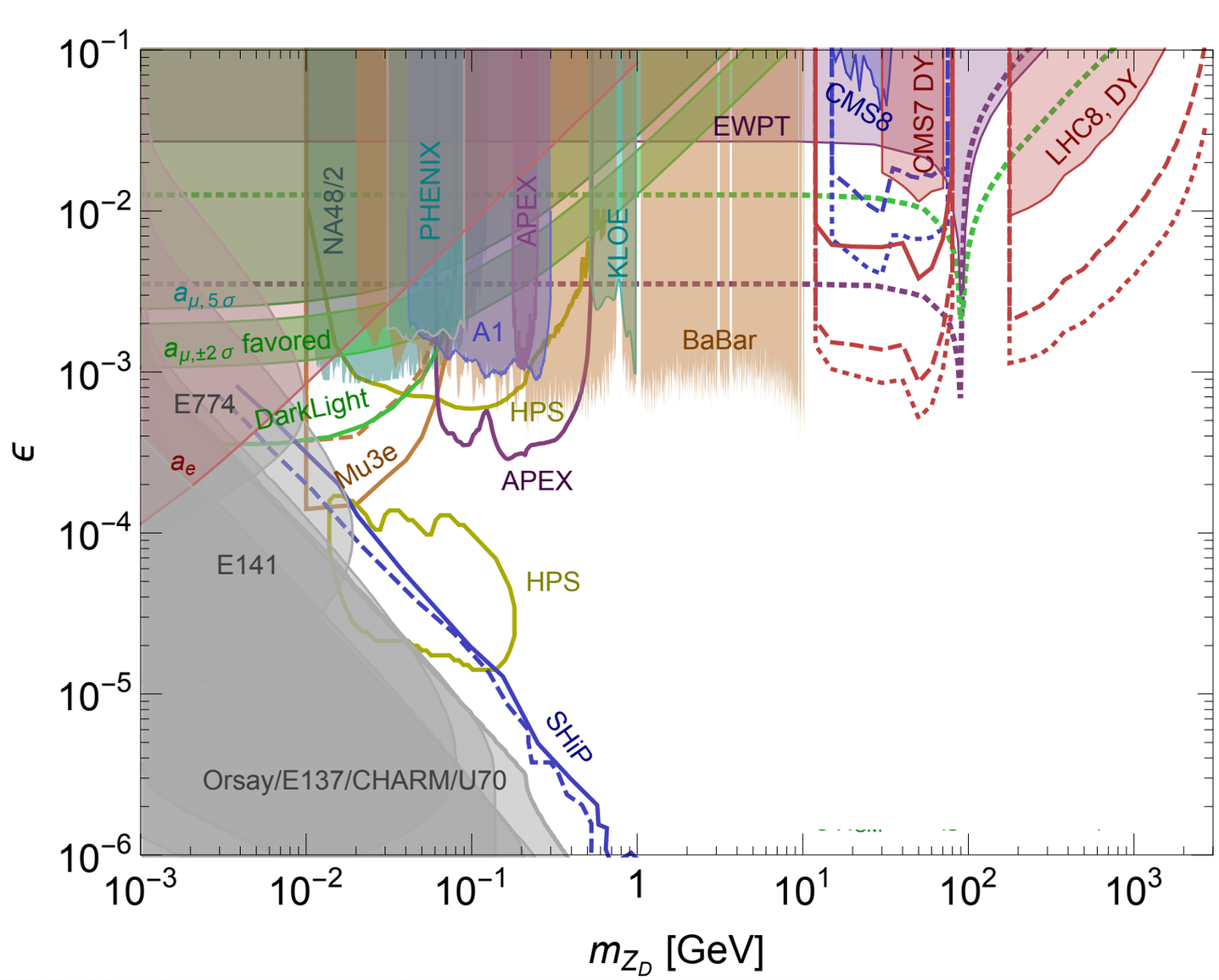




- Based on spectrum, can decay either visibly or invisibly

Dark Vector Signatures

- **Visible decays:** Strong limits (and stronger all the time!)
  - Prospects also good for future *ee* collider Karliner *et al.*, 2015



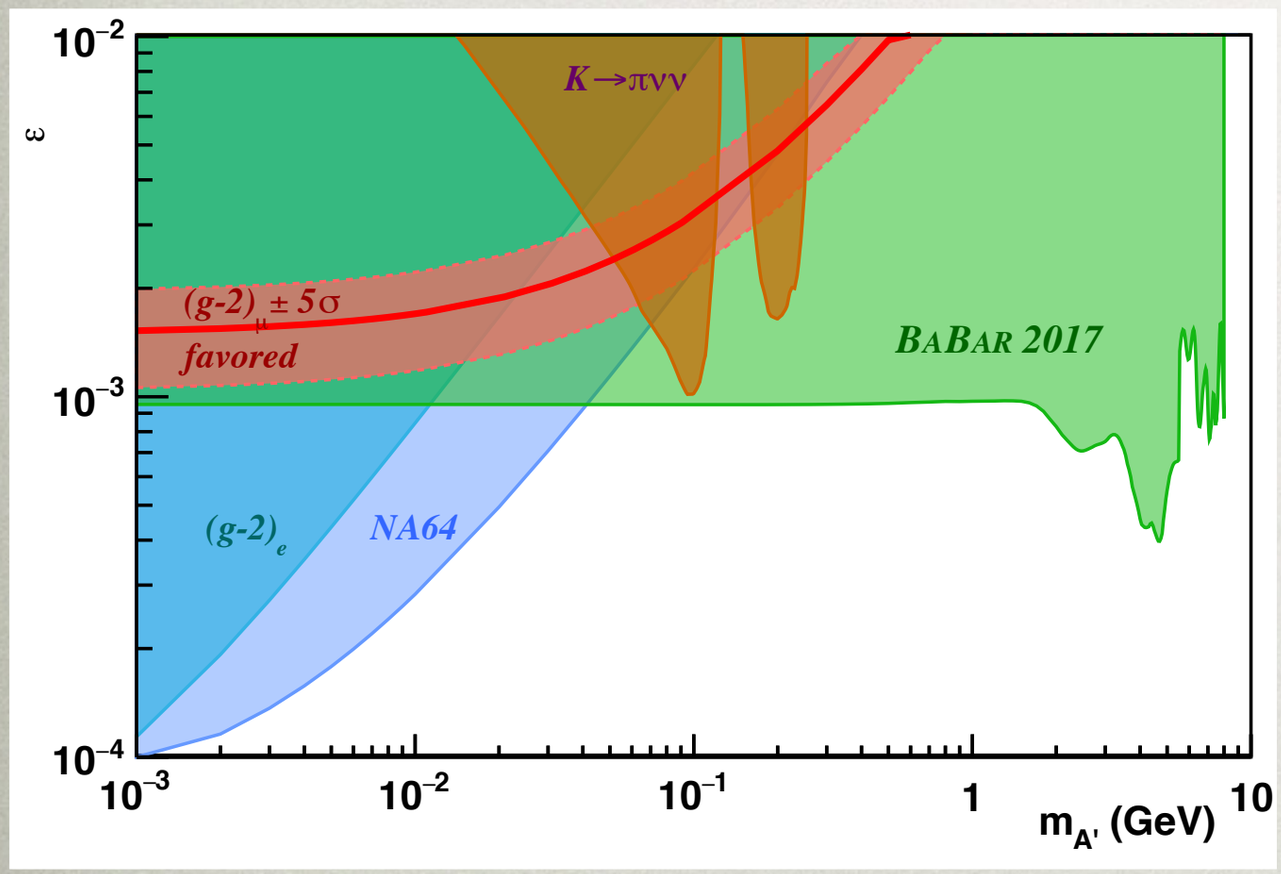
taken from Curtin *et al.*, 2014

- Also, new LHCb proposals:

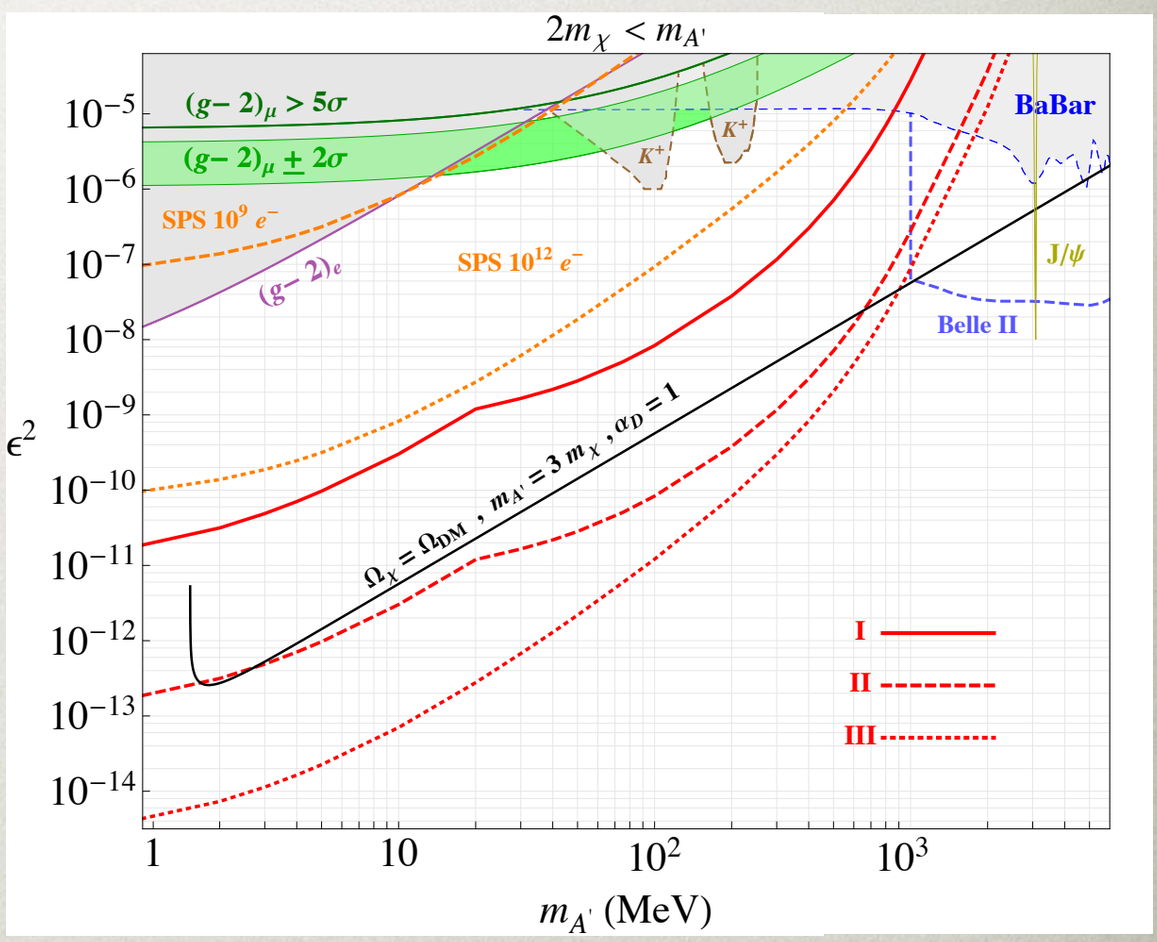
  Ilten *et al.*, 2015, 2016
  Haisch, Kamenik, 2016

Dark Vector Signatures

- **Invisible decays:** Look for missing momentum (also, production of DM + downstream decays)



BABAR, arXiv:1702.0332

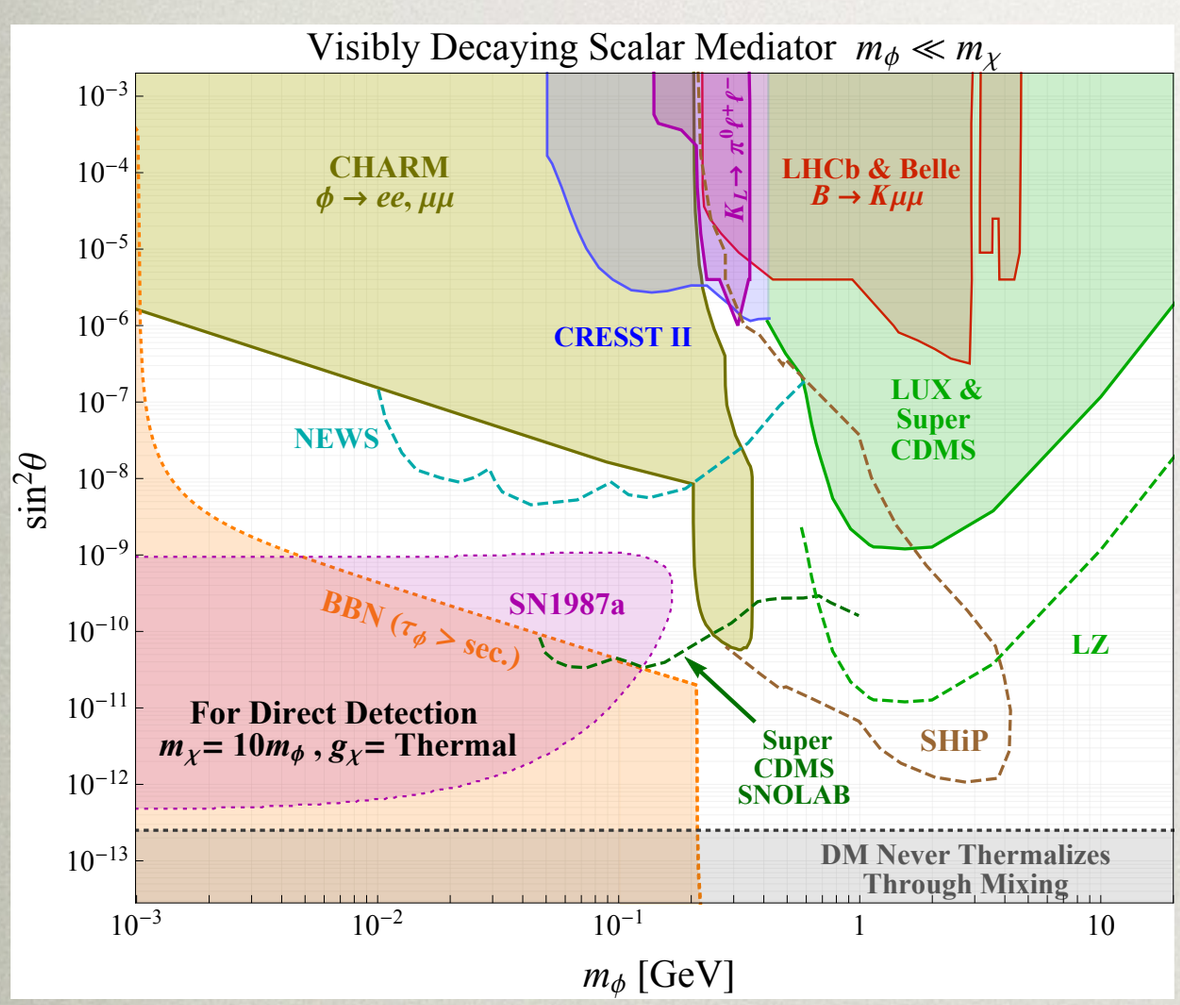


NA64: Andreas *et al.*, 2013
LDMX: Izaguirre *et al.*, 2014

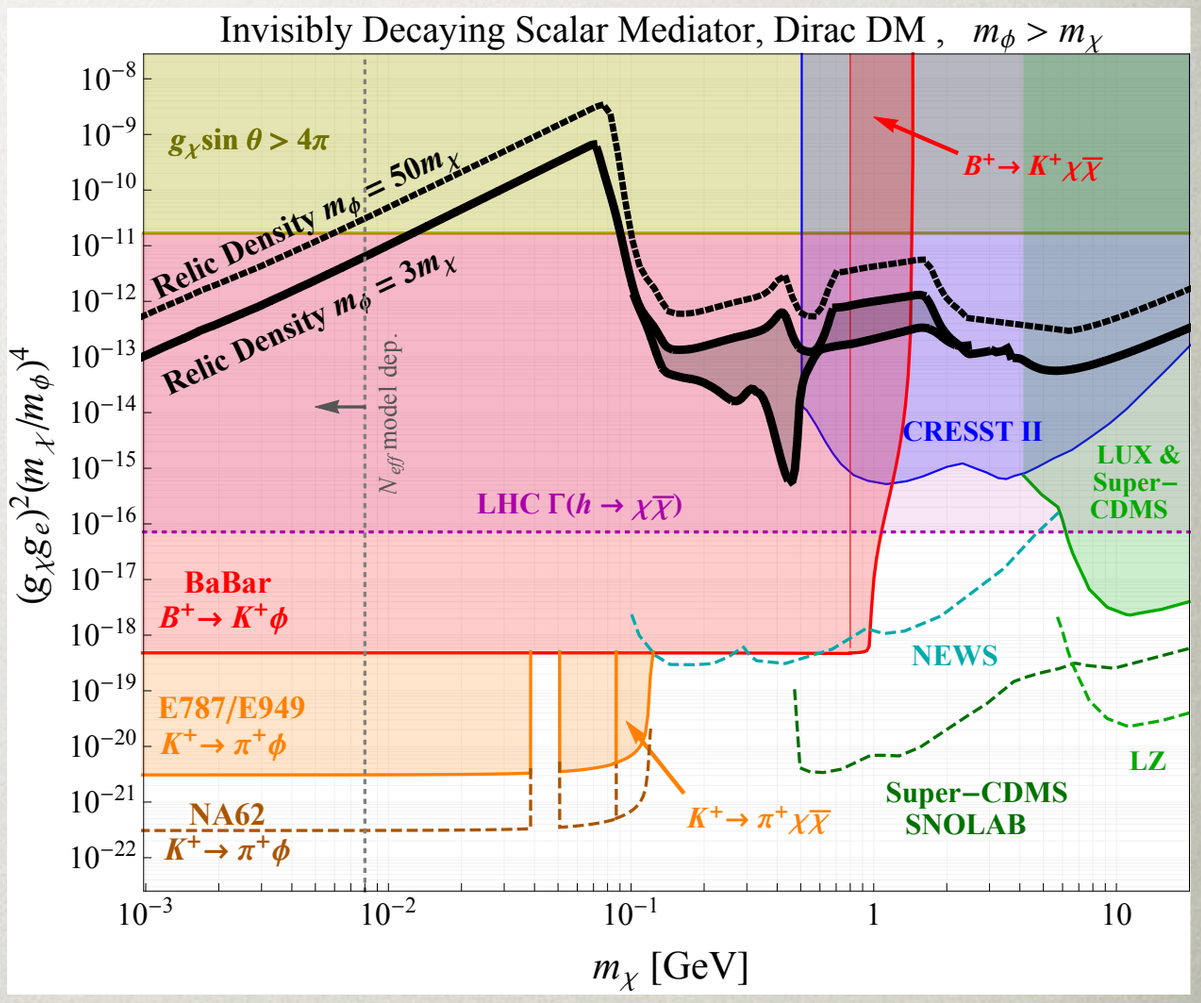
Essig *et al.*, 2013; Raggi *et al.*, 2015…

Dark Scalar Signatures

visible



invisible

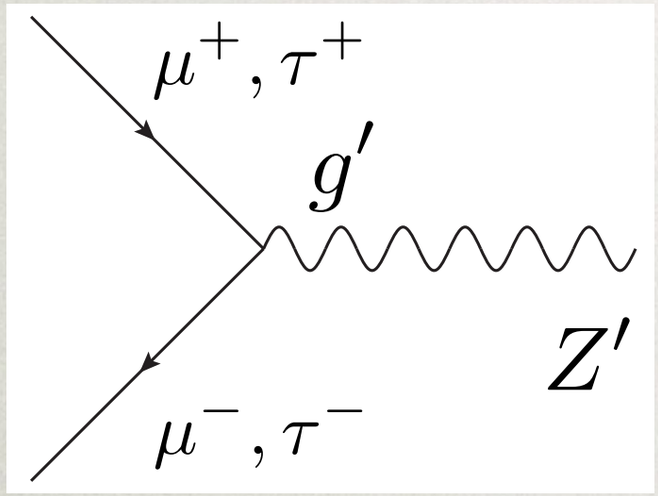


Krnjaic, 2015

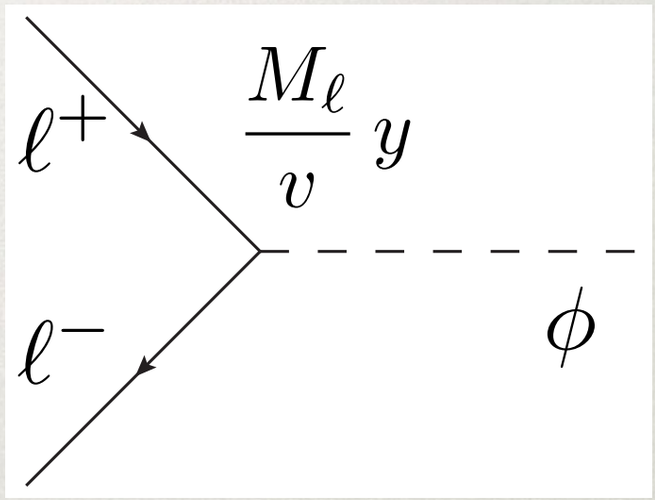
Variations on a Theme

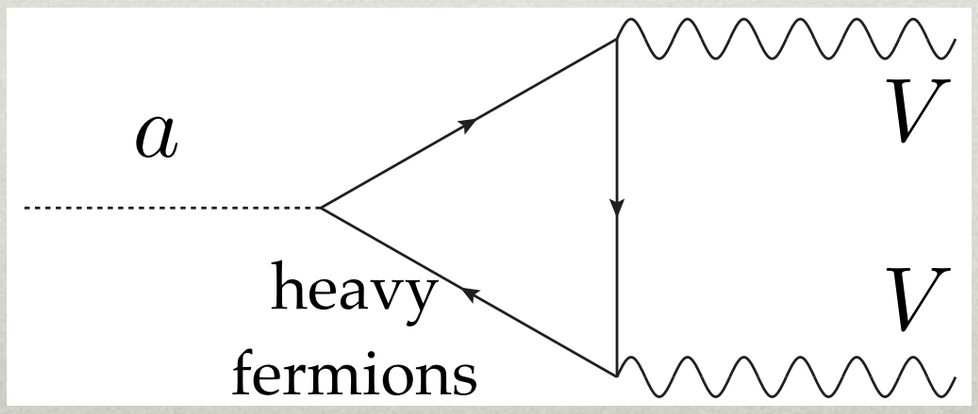
- Many of the constraints are due to **electron** and **quark** interactions

$L_\mu - L_\tau,\ \mu_{\rm R}, \ldots$



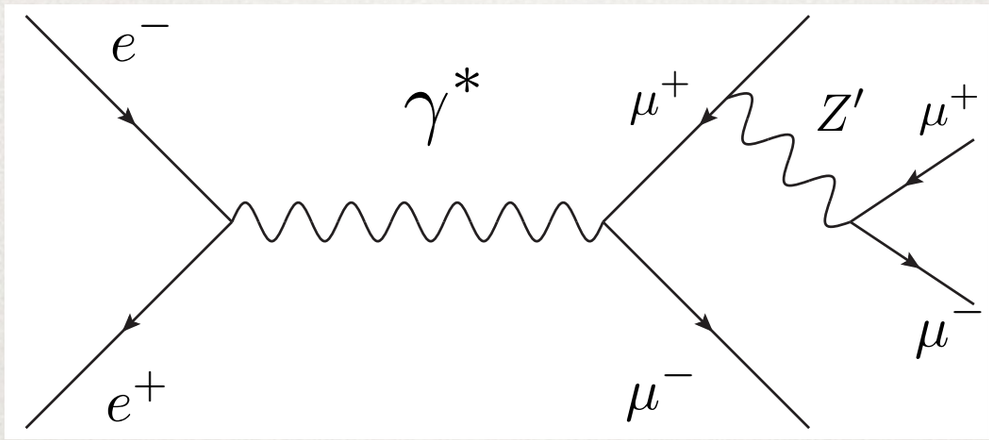
leptophilic scalar





New Leptonic Forces

- For muon/tau-philic interactions, can produce mediators via FSR



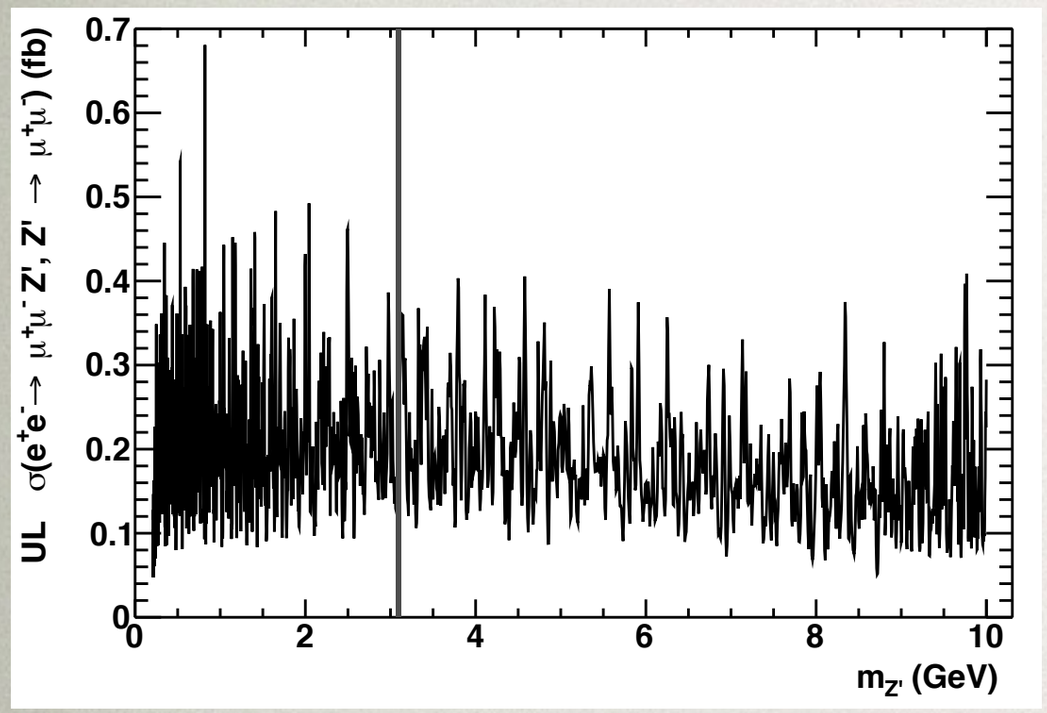
- Allows a more model-independent test of new couplings to muons

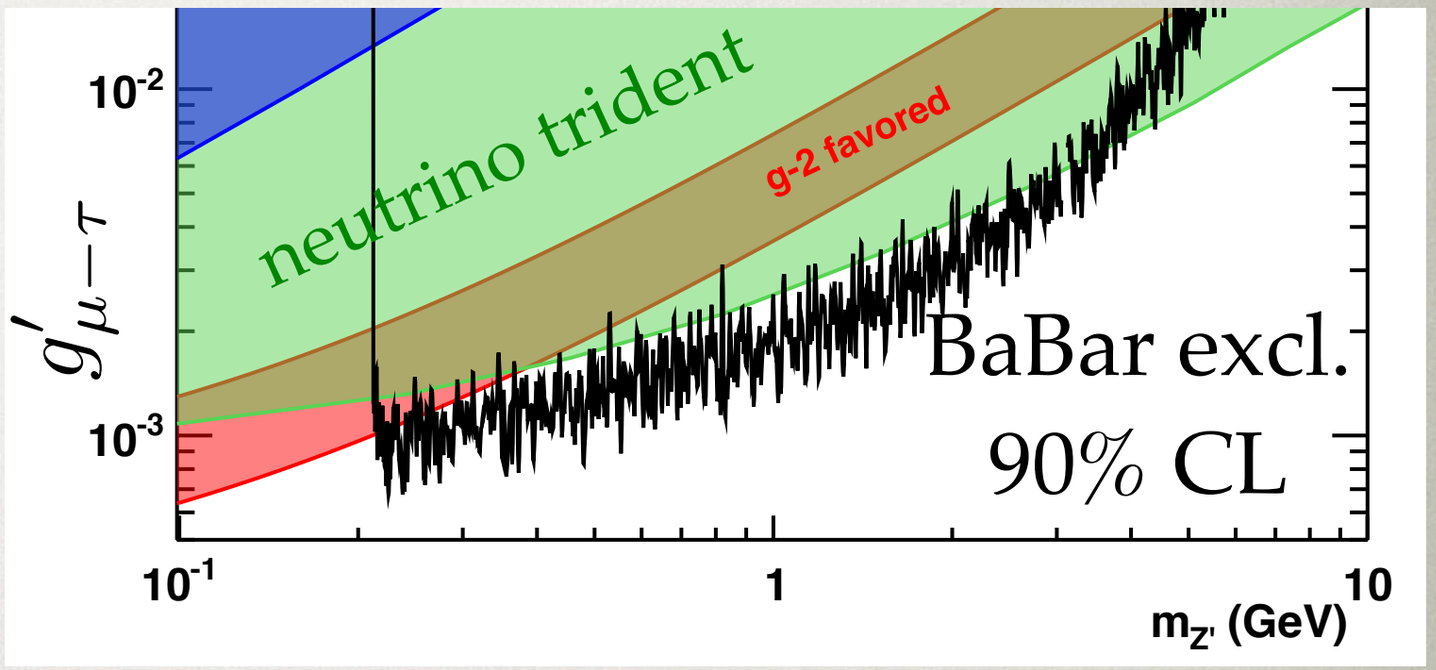
- Look for a bump in 4-muon events carrying full beam energy

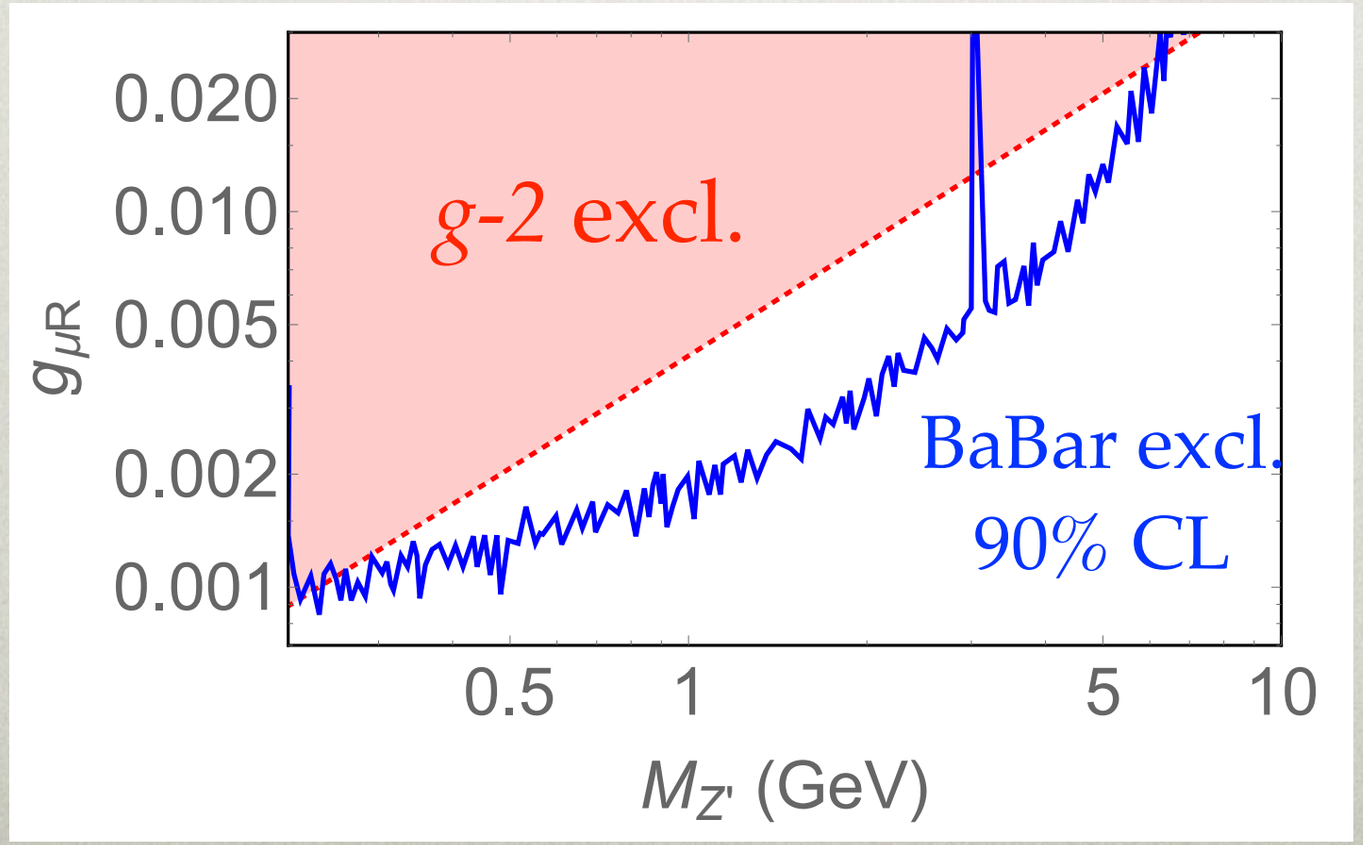
BS with *BABAR*, arXiv:1606.03501

BS w/*BABAR*, arXiv:1606.03501

New Leptonic Forces



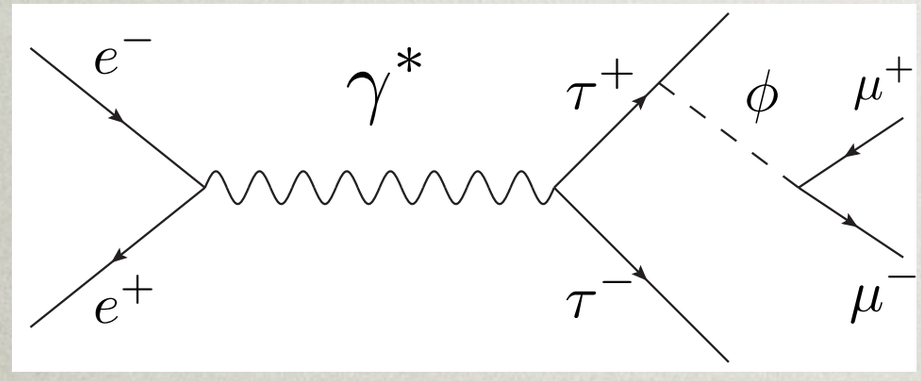




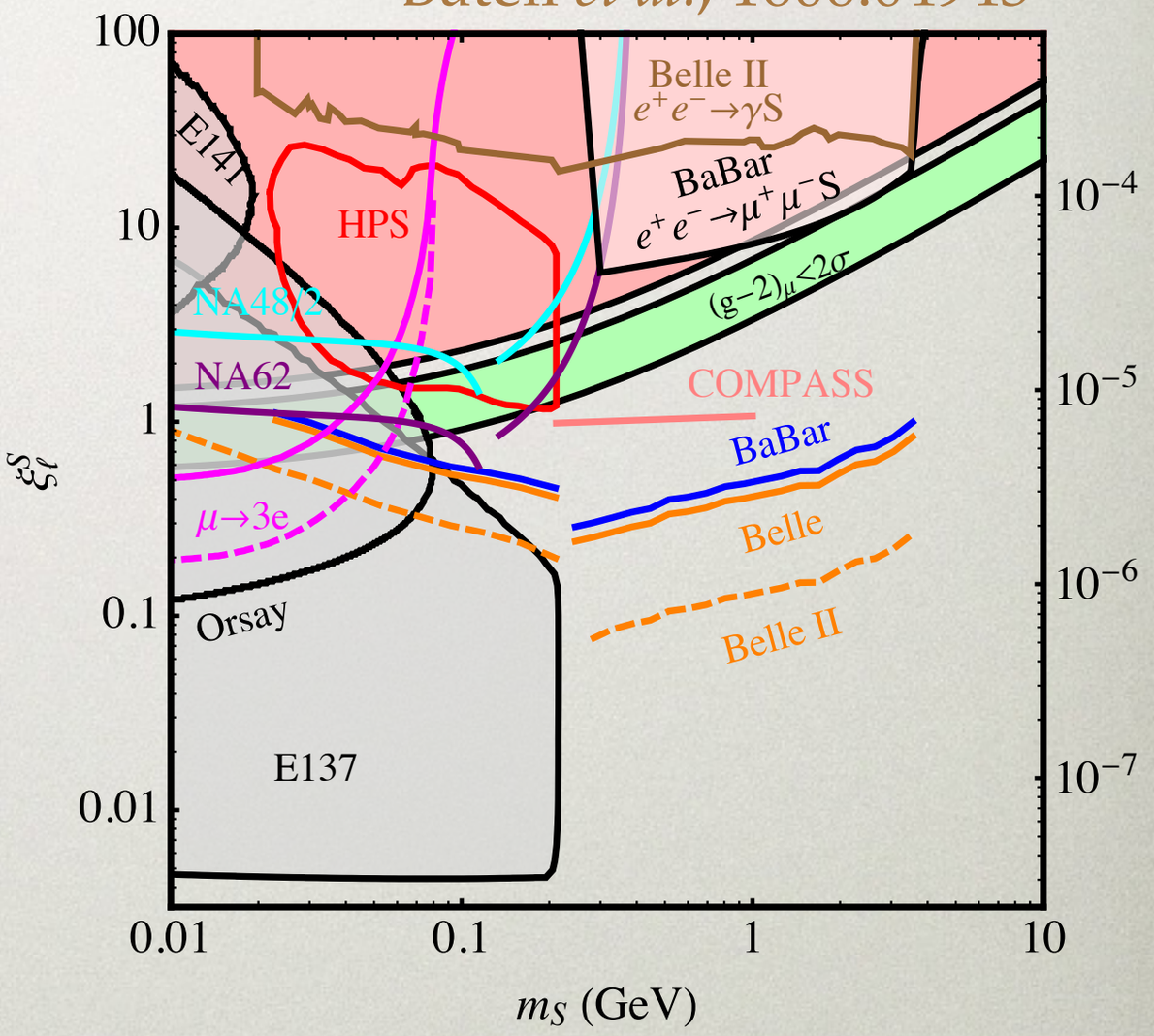
New Leptonic Scalars

Chen *et* al., 1511.004715; Batell *et al.*, 1606.04943

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

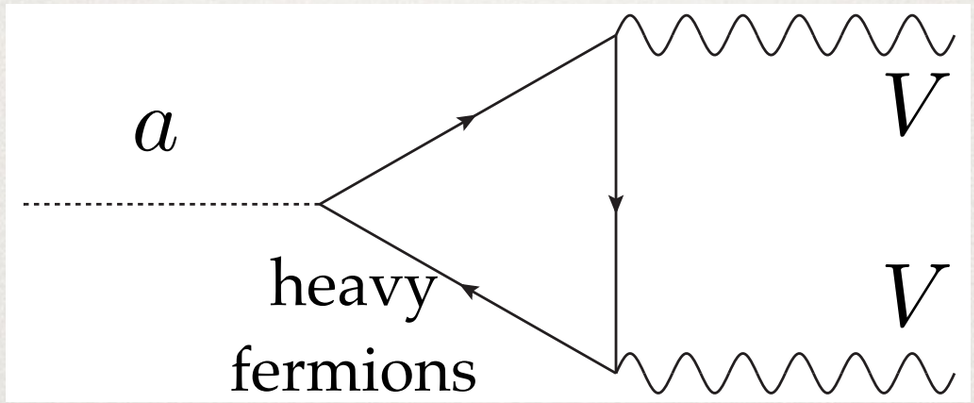


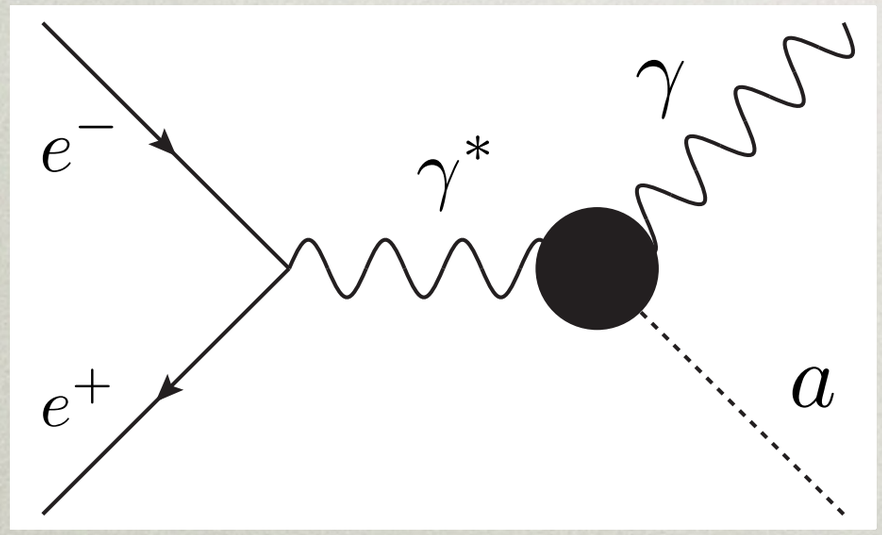
Batell *et al.*, 1606.04943



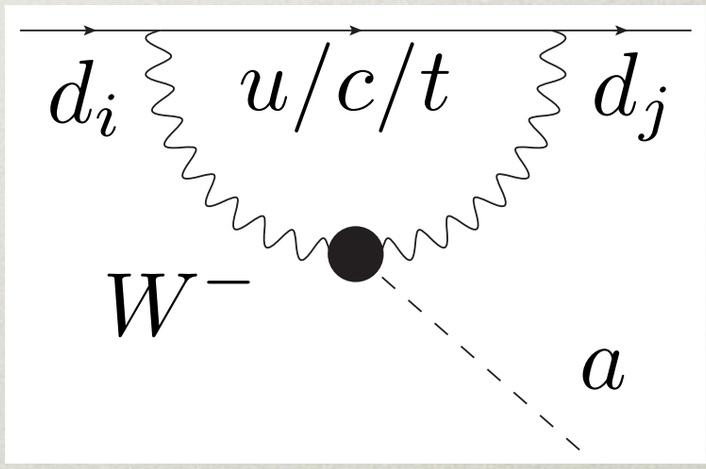
BS w/*BABAR*, in progress

Axion-like Particles





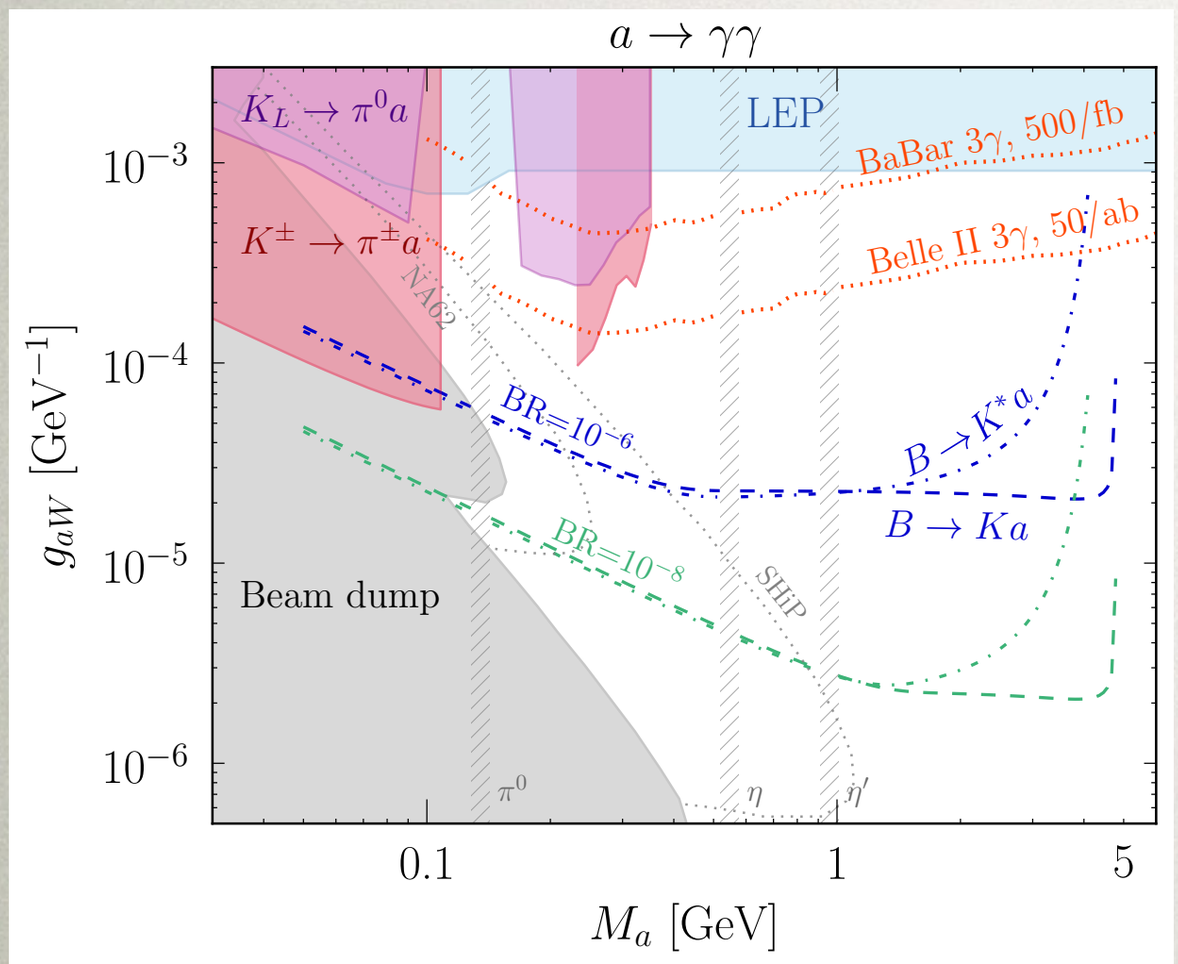
Mimasu, Sanz, 2014

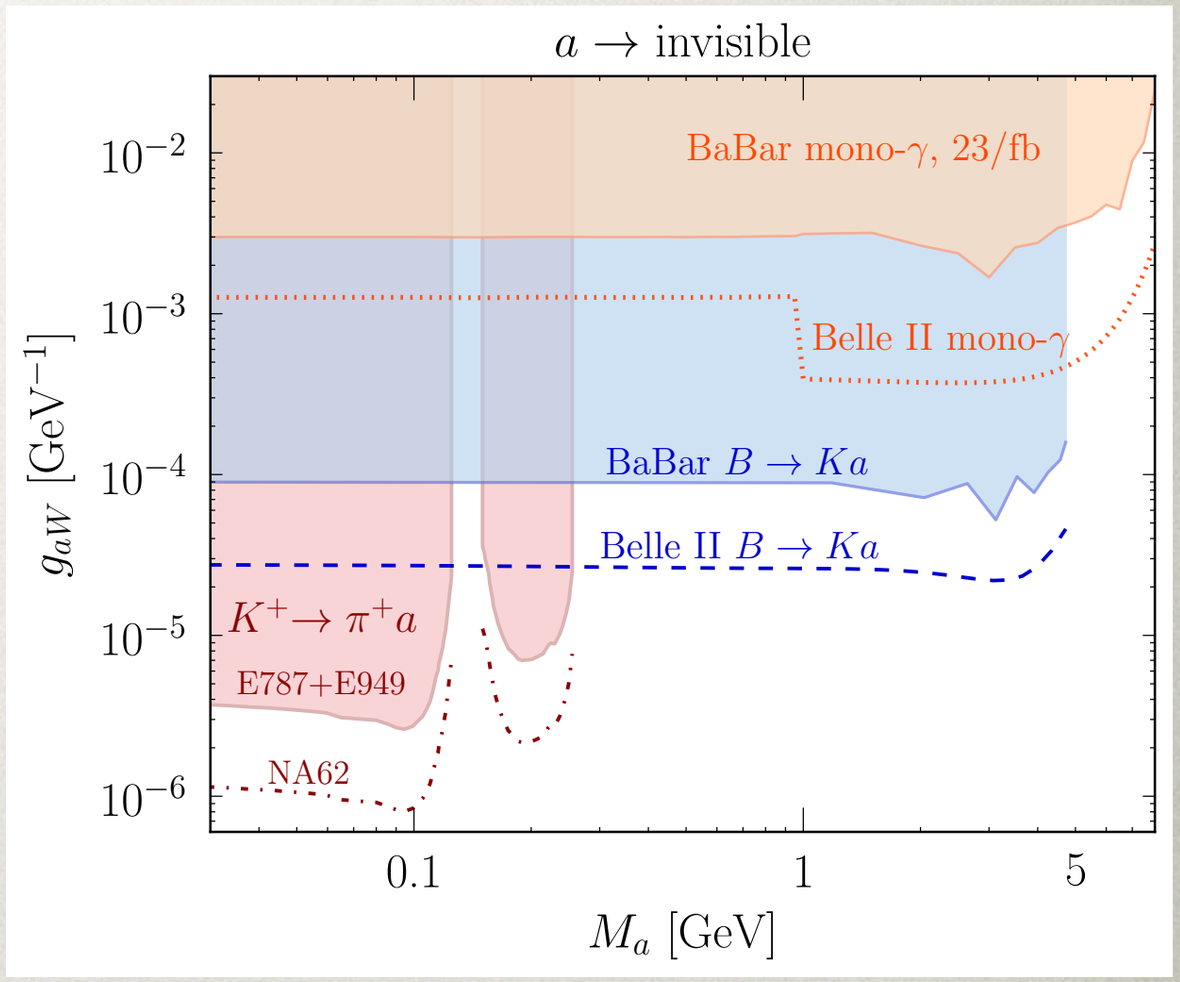


Izaguirre, Lin, and BS, 2016

Axion-like Particles

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

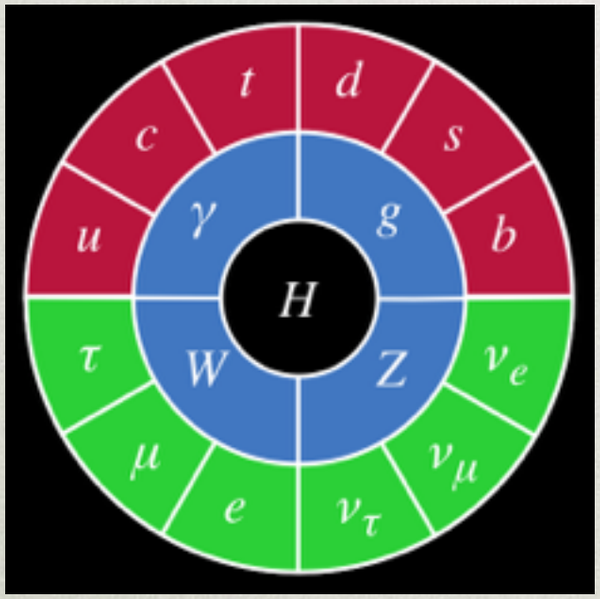




BS with *BABAR*, in progress

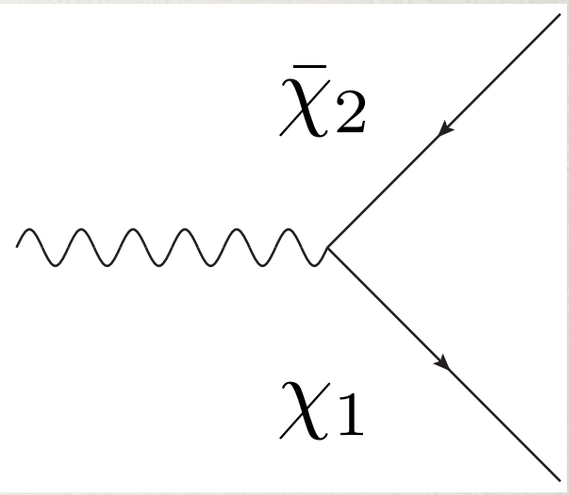
- Also can get similar signatures at LHC: (mono-W/Z+X)

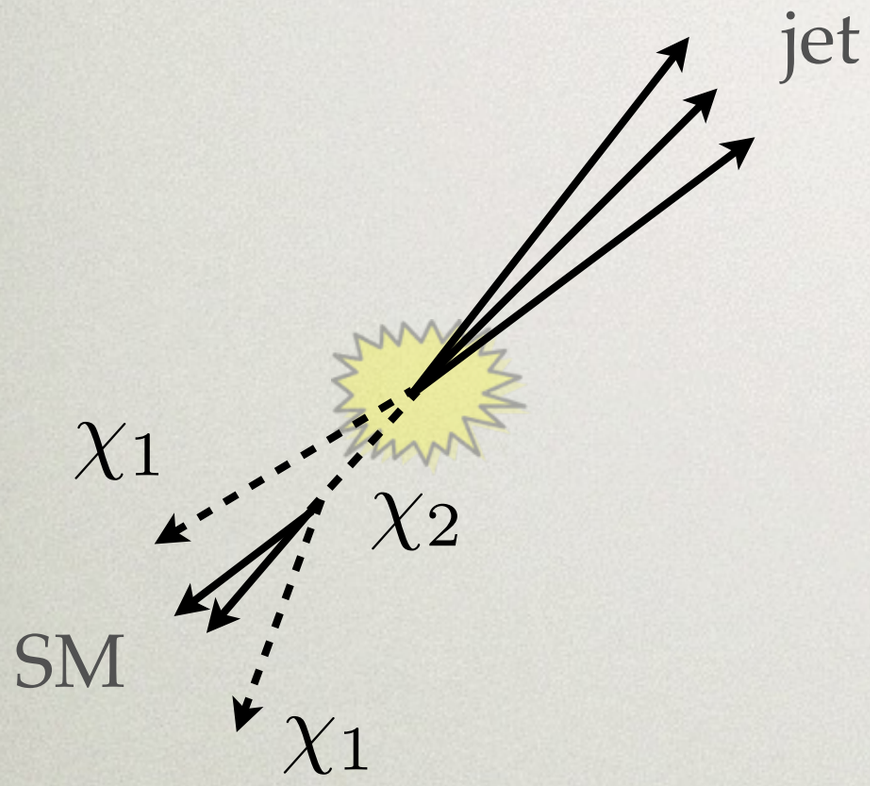
Multi-Particle Dark Sectors



Simple Example: Inelastic DM

- Two dark states that couple inelastically





- Looks like monojet + MET + (soft, collimated) SM particles

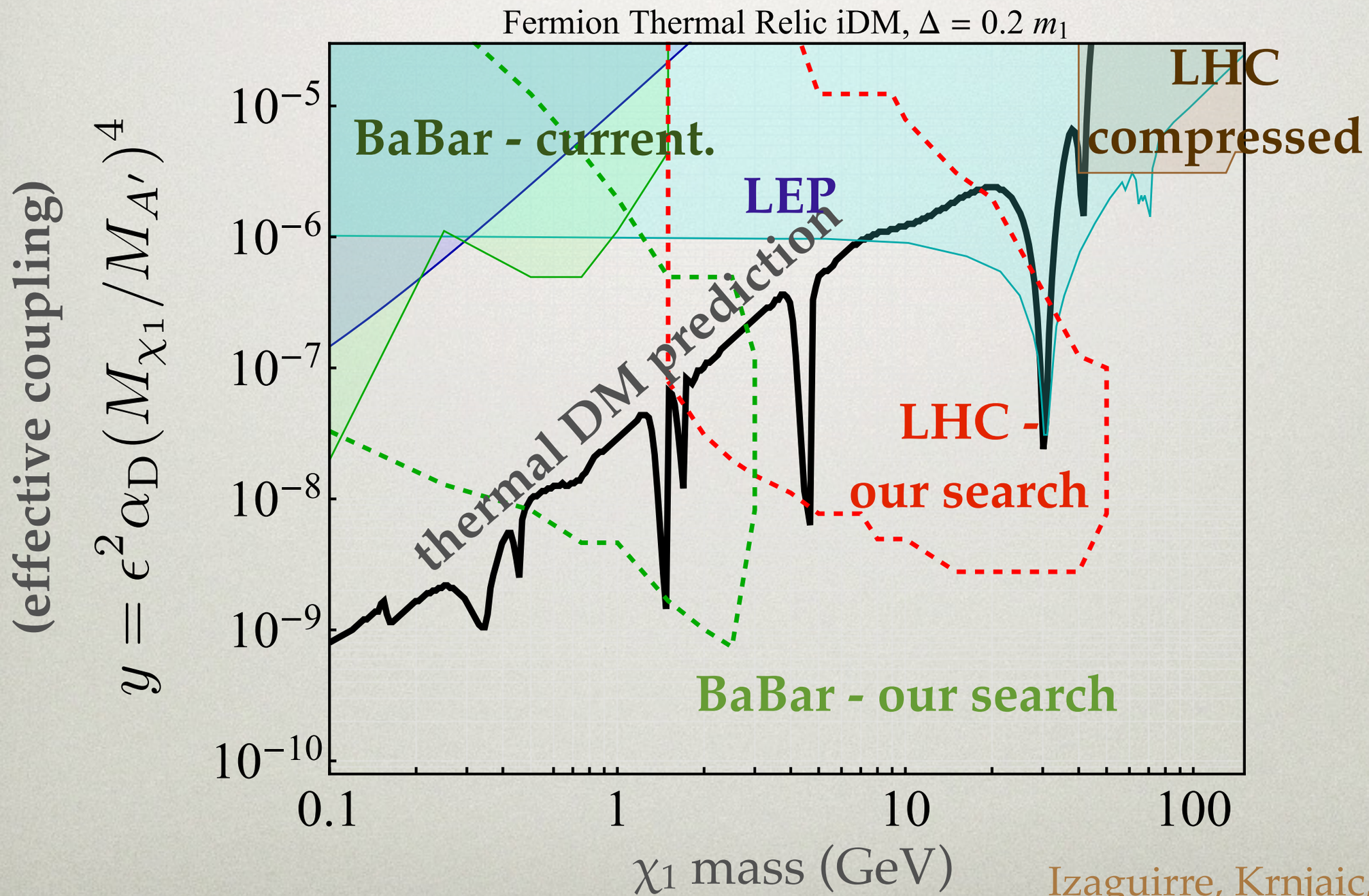
Bai, Tait, 2011; Izaguirre, Krnjaic, BS, 2015

- For large splitting, can trigger on decay products w/o monojet

Weiner, Yavin, 1206.2910; Primulando, Salvioni, Tsai, 2015; …

Simple Example: Inelastic DM

- Ex: dark photon model, monojet + MET + **displaced muon jet**



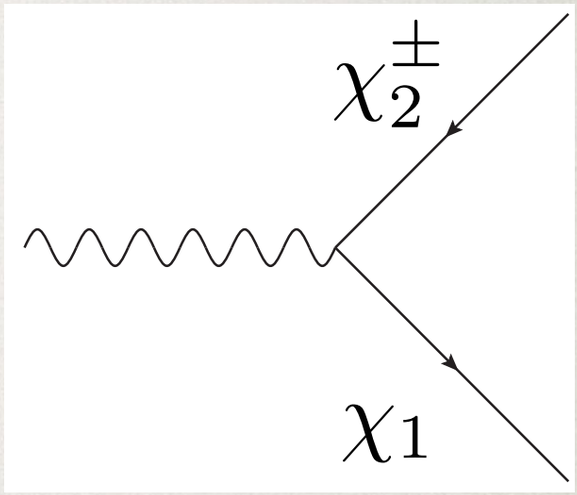
Izaguirre, Krnjaic, BS, 2015

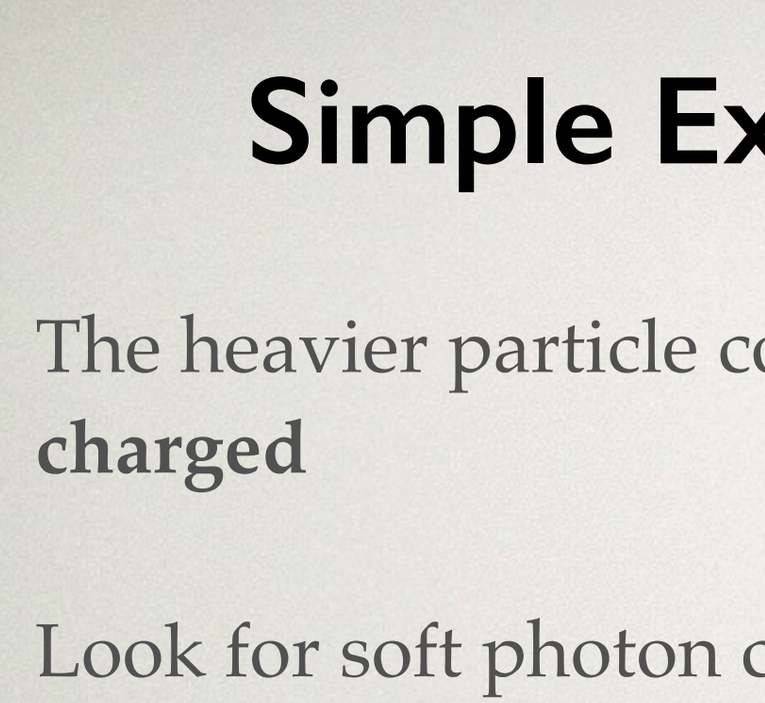
see also Izaguirre *et al.*, 2017

Simple Example: Inelastic DM

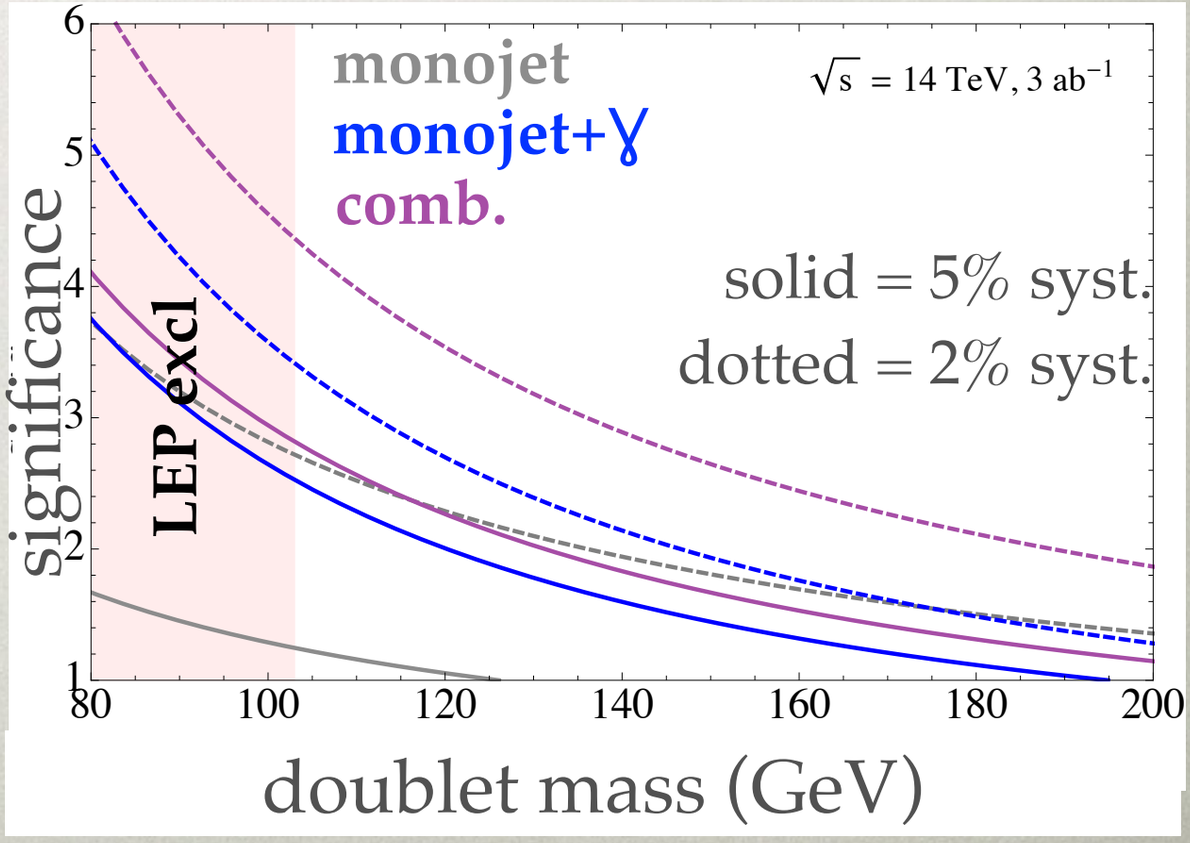
- The heavier particle could also be **charged**

- Look for soft photon collinear with MET (from FSR)



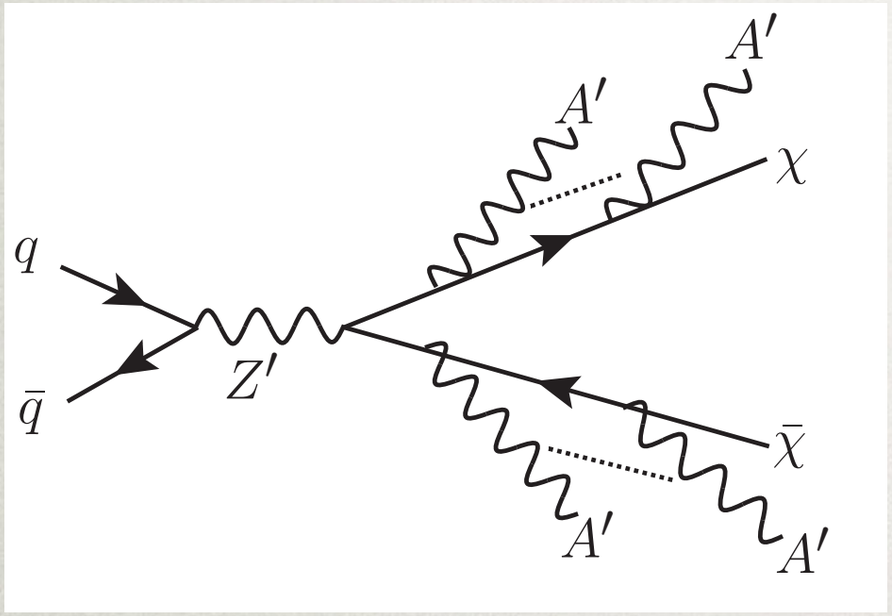


Ismail, Izaguirre, BS, 2016

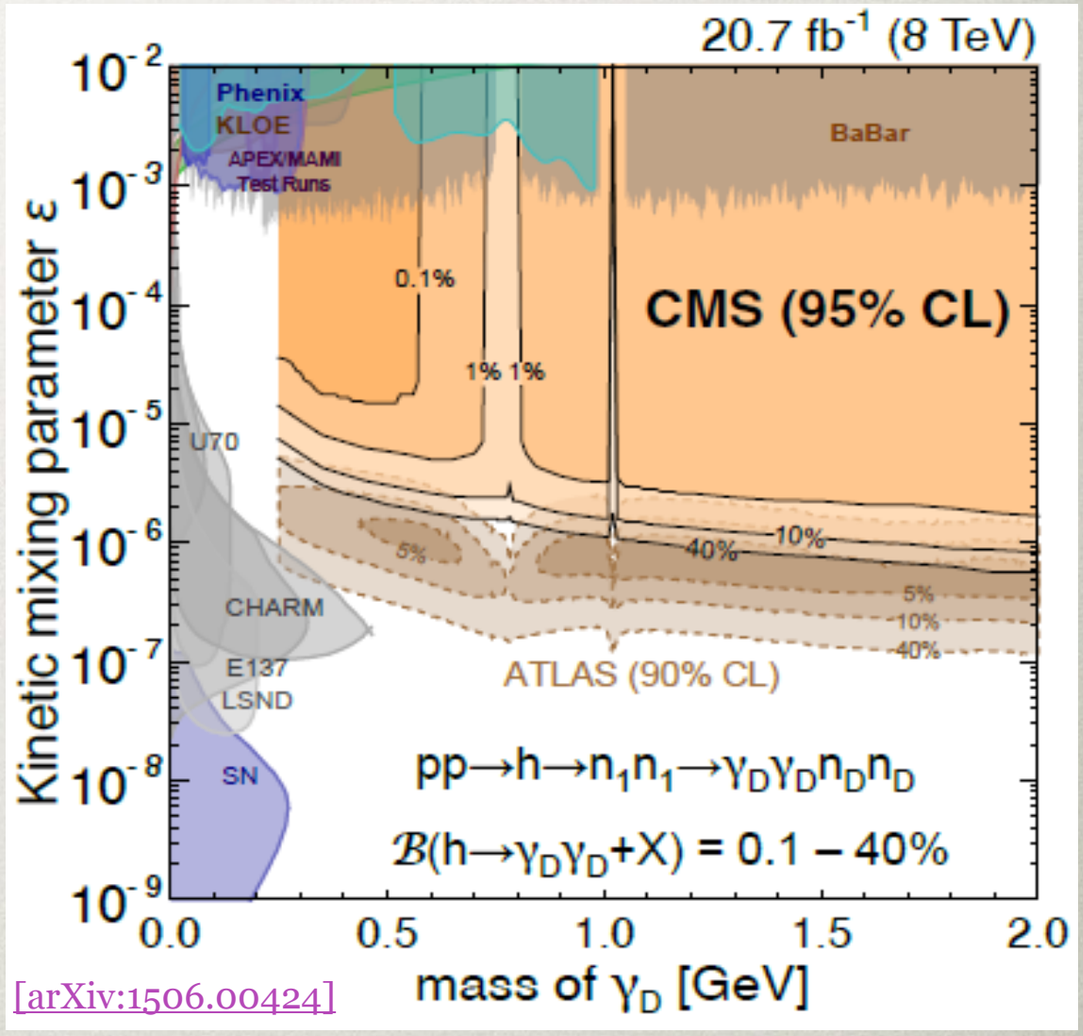


Dark Radiation

- As dark force coupling, can get more **dark radiation**



- For sufficiently strong force, get bound states and showers

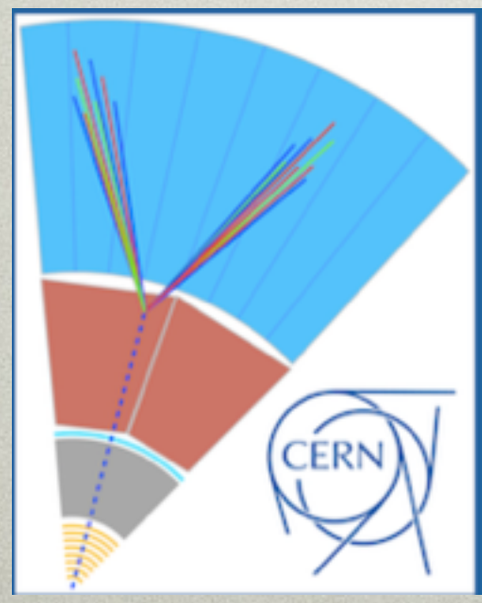


[arXiv:1506.00424]

Cheung *et al.*, 2009; recent works: Gupta, Primulando, Saraswat 2015; Bai, Borbeau, Lin 2015; Autran *et al.* 2015; Buschmann *et al.* 2015; Schwaller, Stolarski, Weiler 2015; Cohen, Lisanti, Lou 2015; Hochberg, Kuflik, Murayama, 2015; Knapen *et al.*, 2016; …

Long-Lived Particle Community

- Need whole community efforts to systematically cover gaps
- Already significant work towards a community document on proposing simplified models and searches
- Excellent response already 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

Summary

- Thermal dark matter can easily extend beyond WIMP models

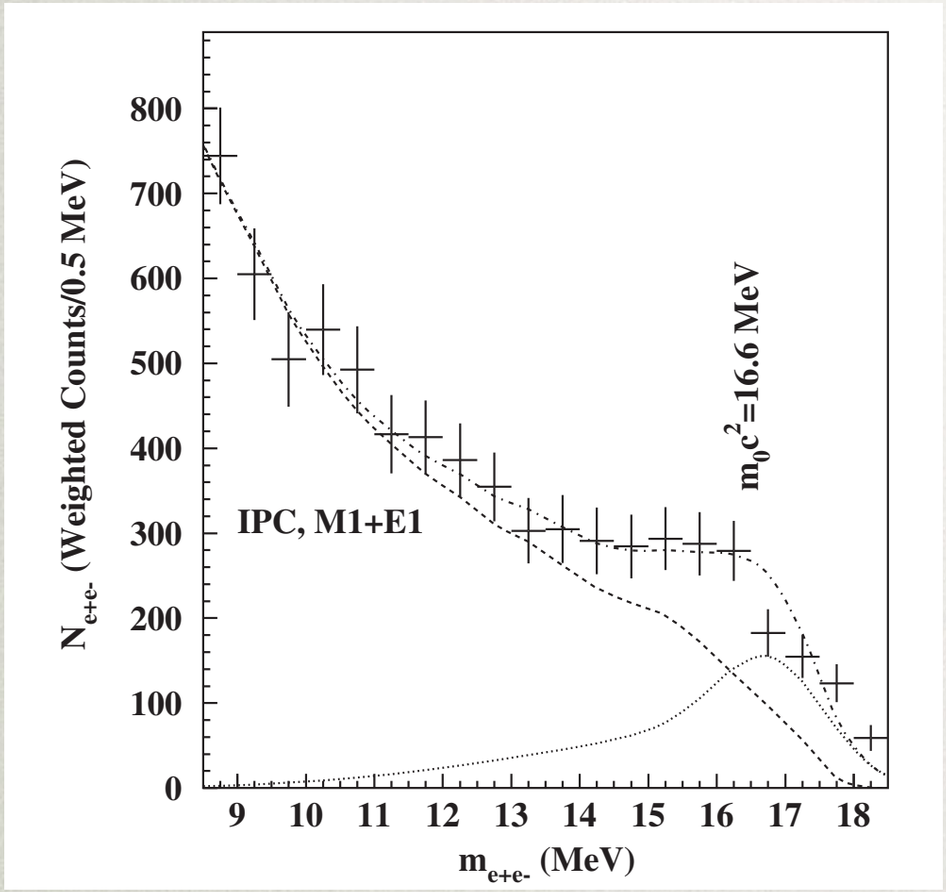
- Light dark matter is an exciting and relatively unconstrained possibility

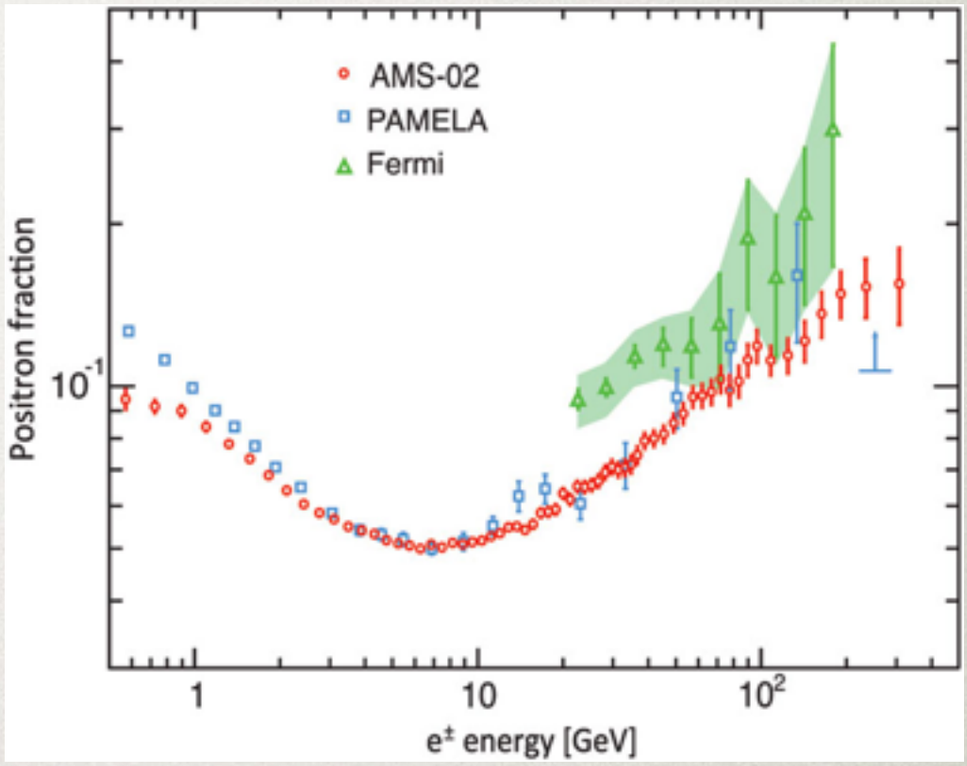
- New searches for mediators and dark-sector states at low-energy accelerators & high-energy colliders needed

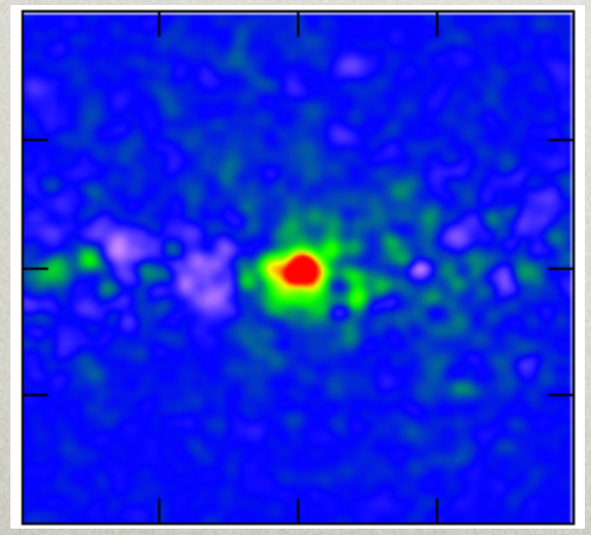
- Combination of collider, accelerator, direct/indirect detection, and cosmology needed to hone in on this hidden universe!

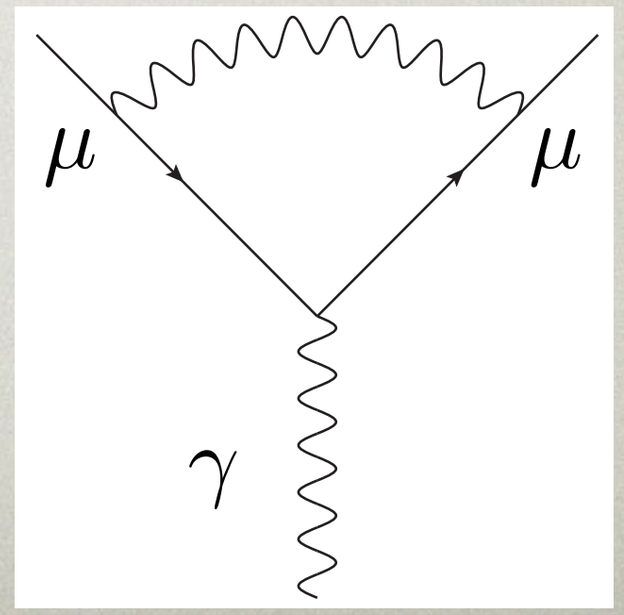
Back-up slides

Dark Matter & Dark Sectors



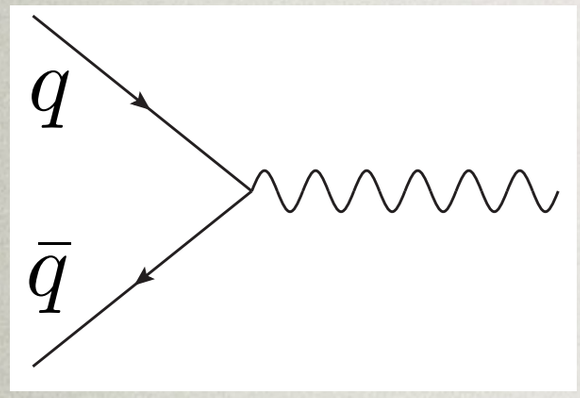


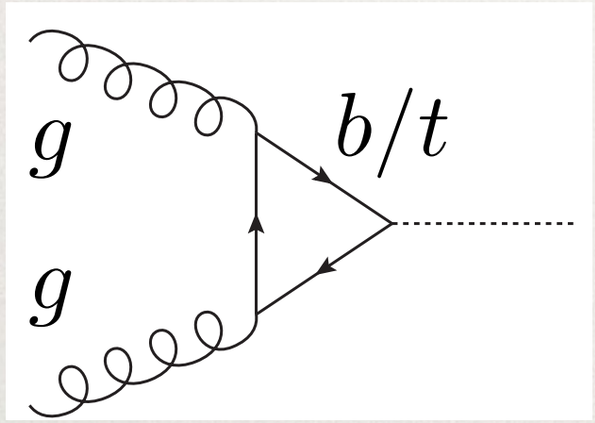




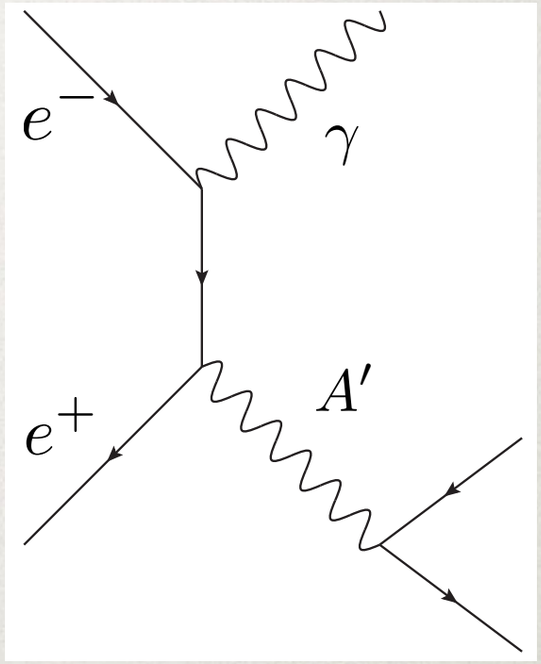
Dark Mediator Signatures

HADRON COLLIDERS

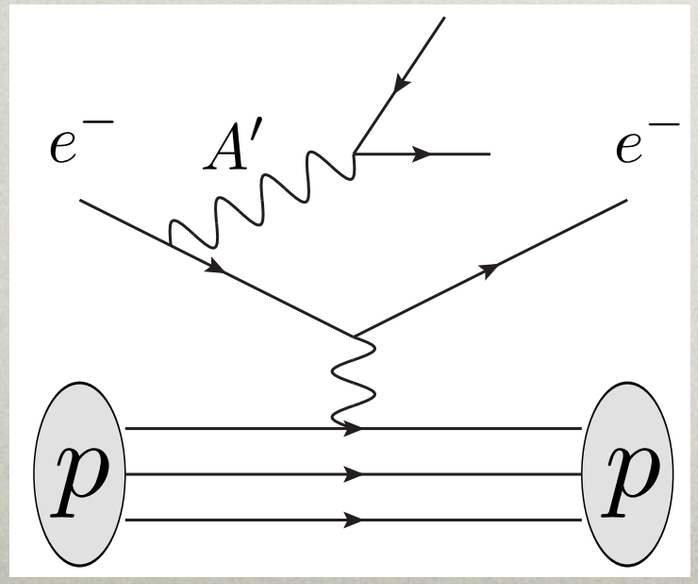




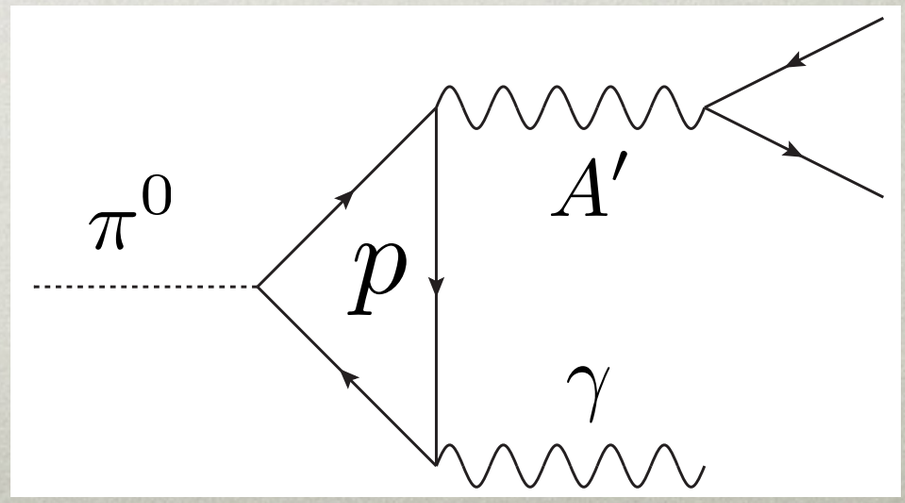
LEPTON COLLIDERS



FIXED TARGET/BEAM DUMP

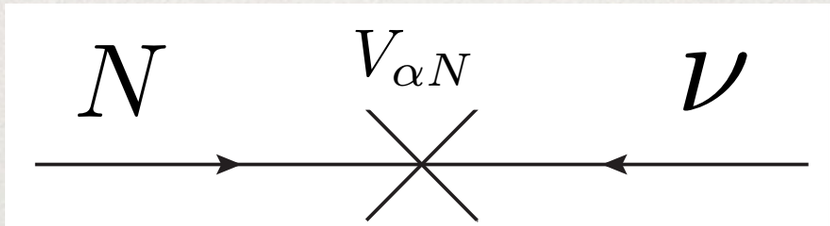


RARE MESON DECAYS



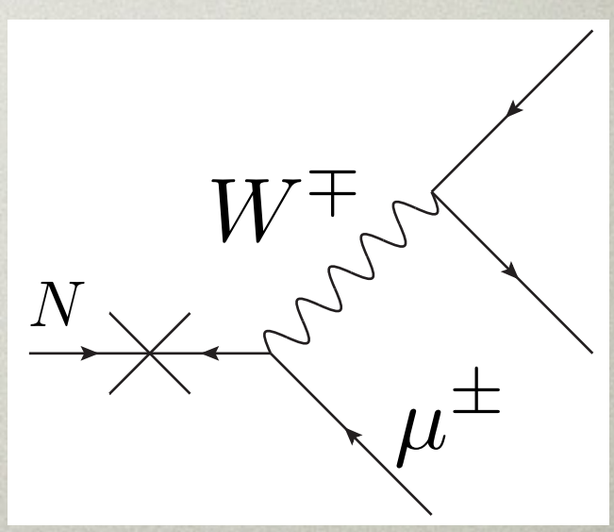
Dark Mediator Signatures

Neutrino Portal

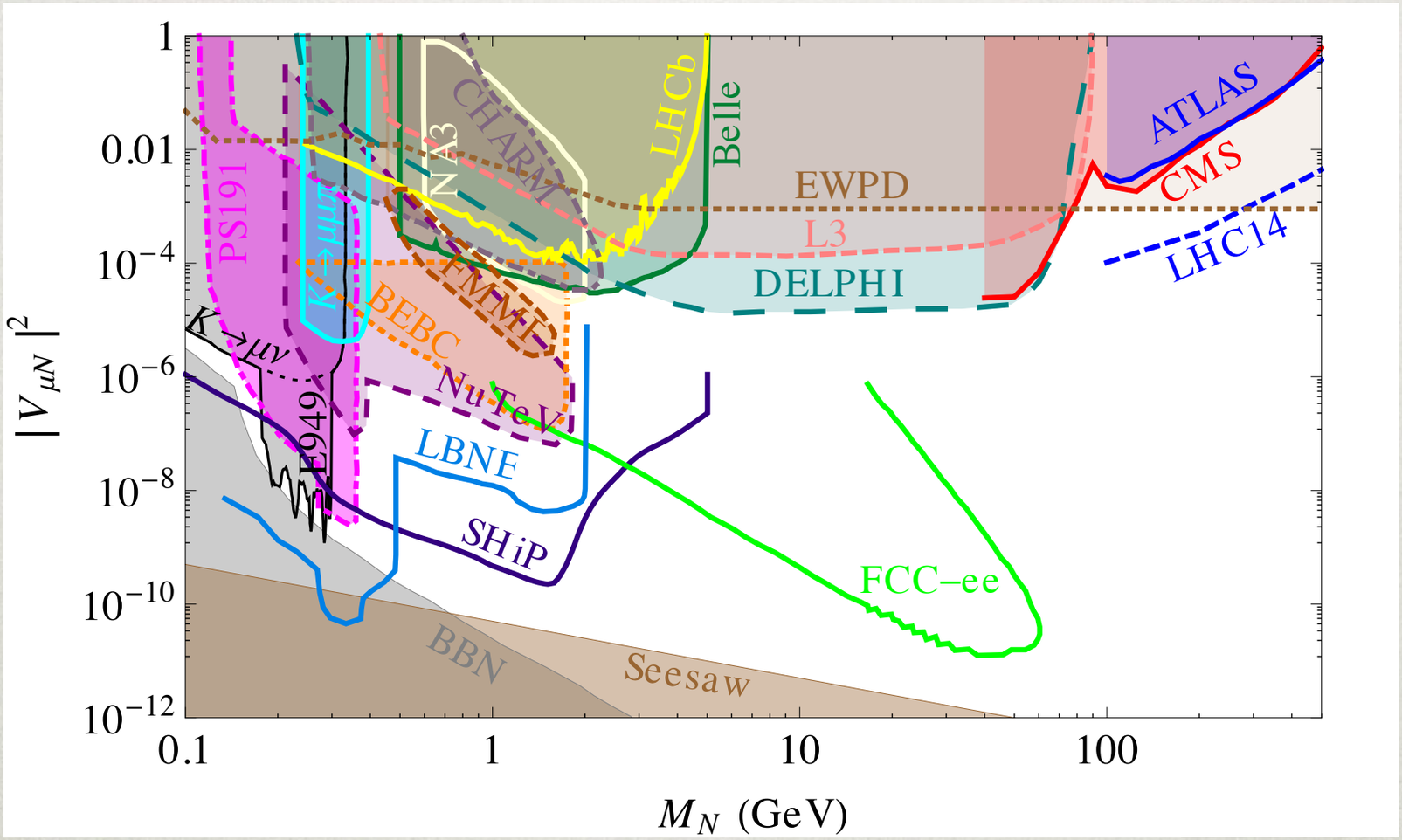


- Gives **mass** to SM neutrinos (also baryon asymmetry?)

- Majorana particle: violates lepton number



The Neutrino Portal



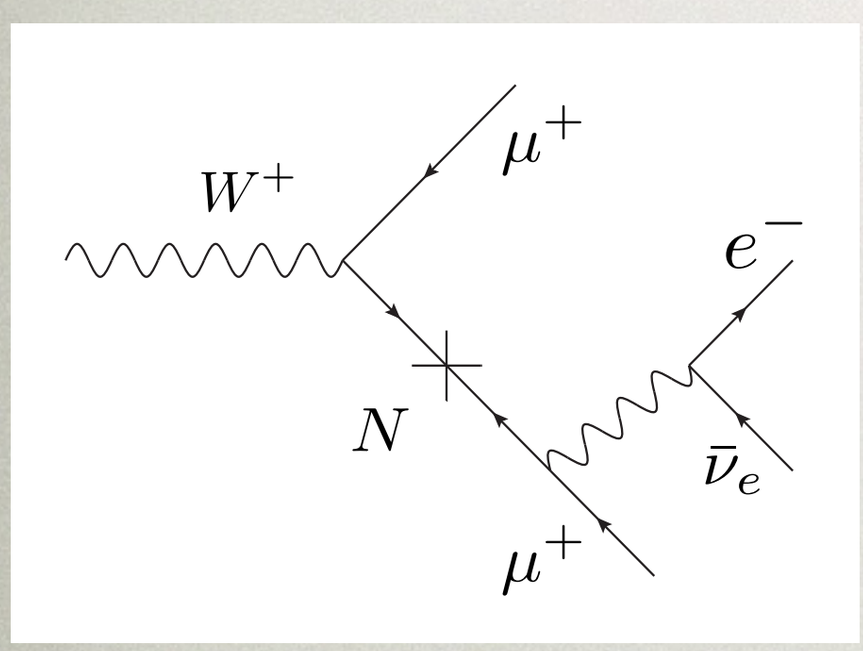
taken from Deppisch, Dev, Pilaftsis, 2015

- Best limits above b mass: LEP?!

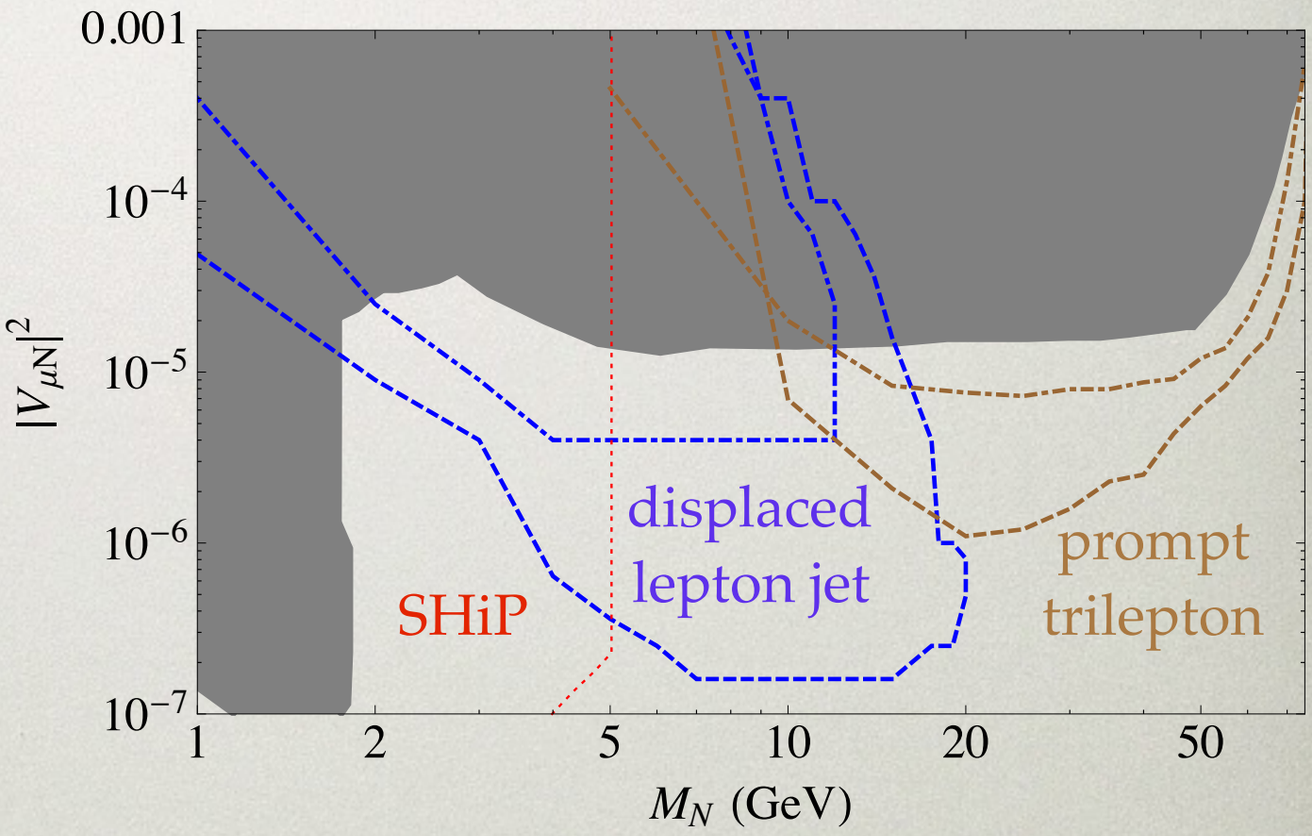
The Neutrino Portal

- The HL-LHC will make 0.7 trillion *W* bosons!

Izaguirre, BS, 2015



95% CL reach



dash-dot = 8 TeV
dashed = 13 TeV, 300/fb

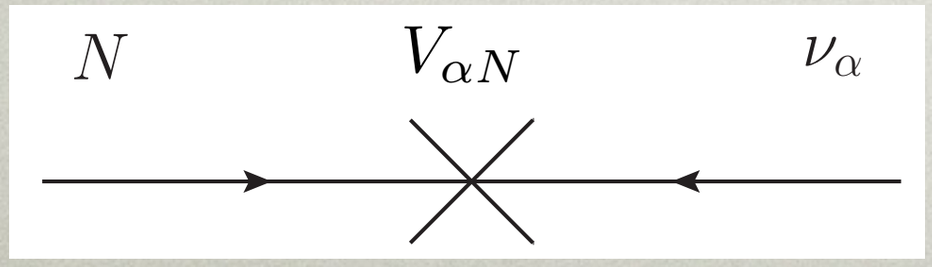
Neutrino Portal Signatures

- Simplest model for neutrino masses: **seesaw mechanism**

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

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

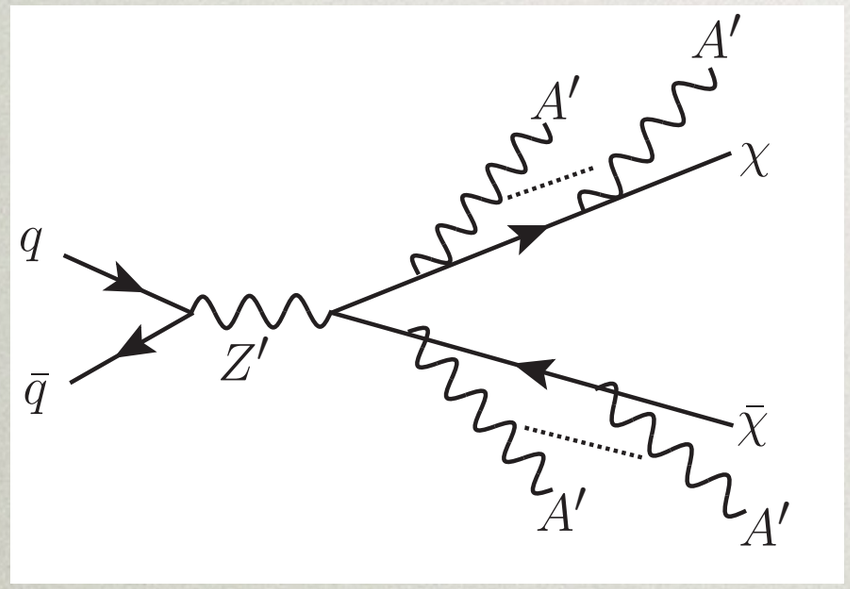
- After EWSB, the LH and RH neutrinos mix



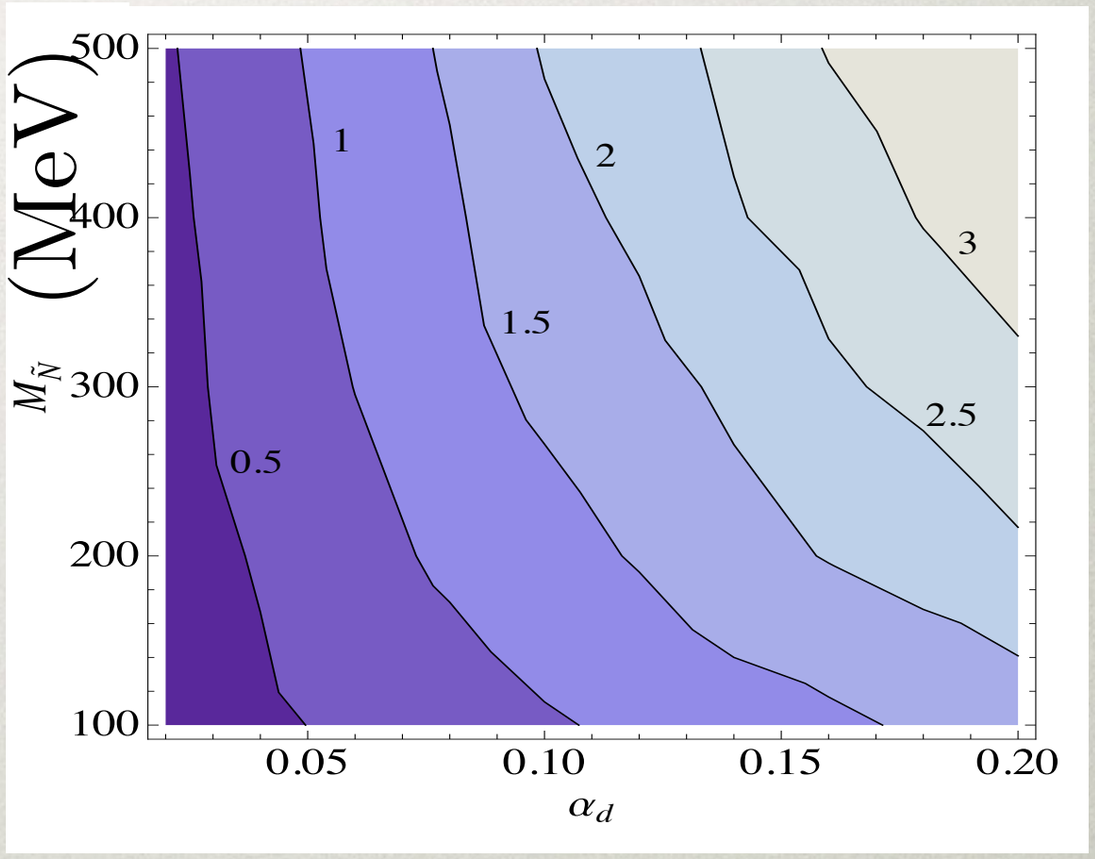
$$V_{\alpha N} \sim \frac{y_\alpha \langle H\rangle}{M_N}$$

Dark Radiation

- In models with large dark force coupling, can get **dark radiation**
  - Get mono-Z′ or multi-Z′ in association with MET, often boosted



$$Z \to \tilde{N}\tilde{N}$$



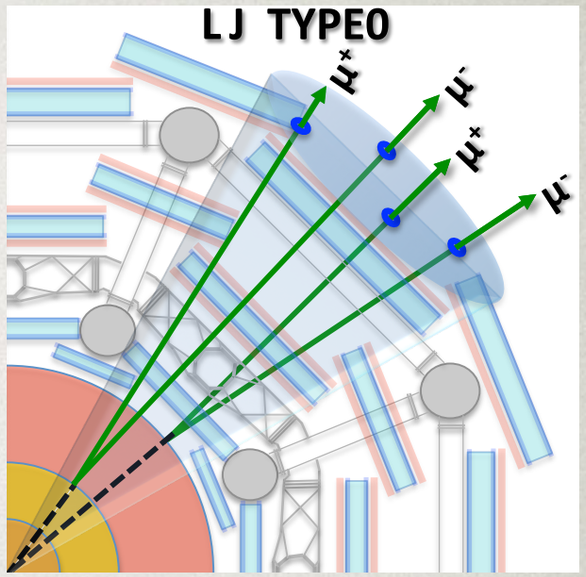
Cheung *et al.*, 2009

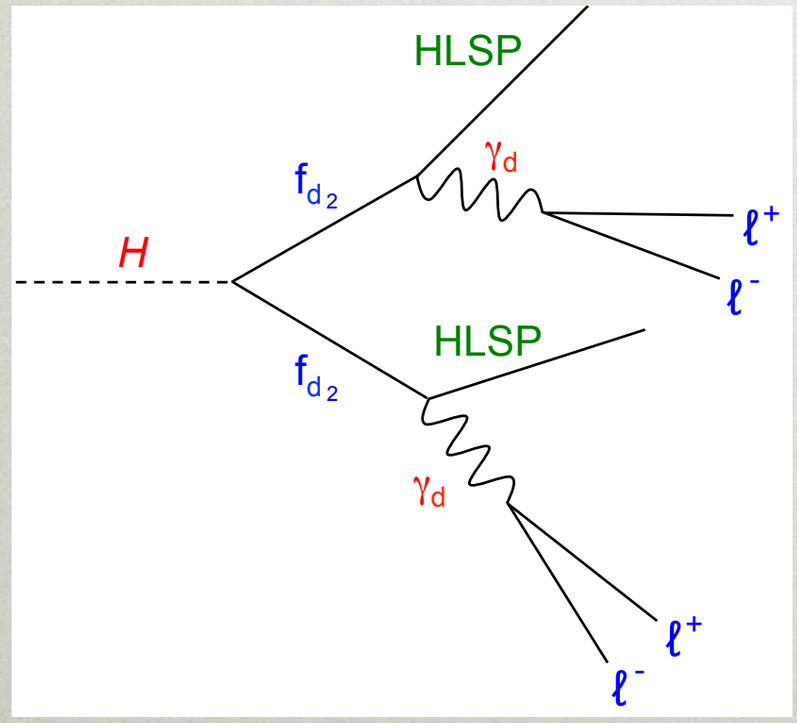
Cheung *et al.*, 2009; recent works: Gupta, Primulando, Saraswat 2015; Bai, Borbeau, Lin 2015; Autran *et al.* 2015; Buschmann *et al.* 2015; …

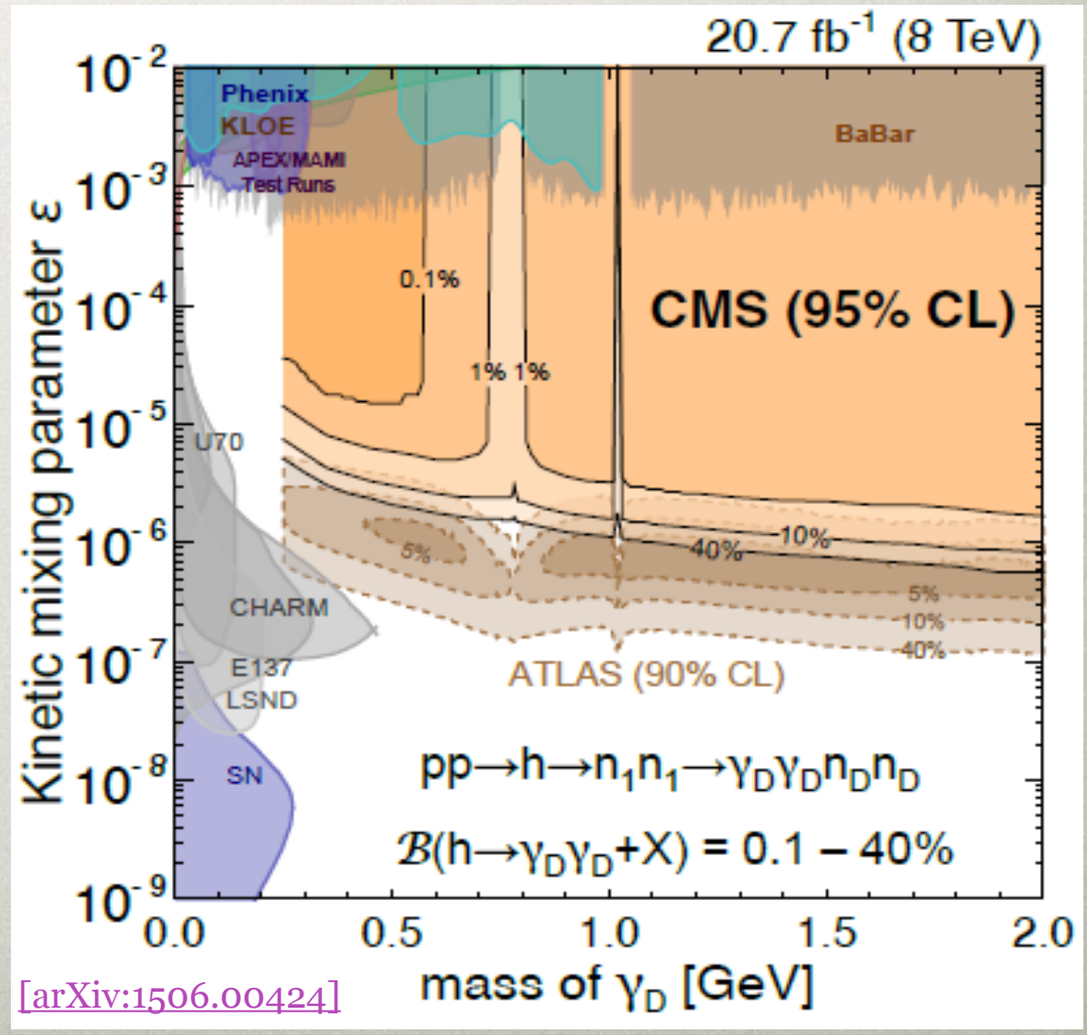
Dark Radiation

- Already nice results for multiple lepton jets
- "LJ gun" efficiencies for easy recasting

ATLAS, arXiv:1409.0746
CMS, arXiv:1506.00424



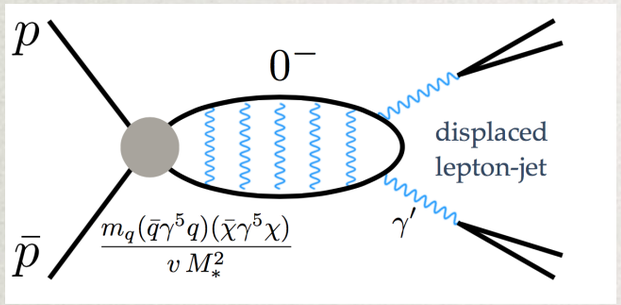


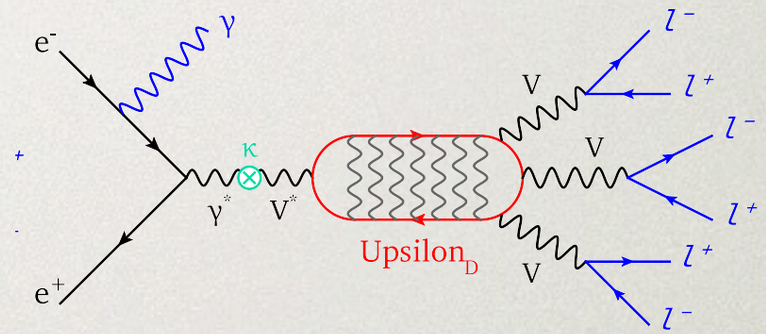


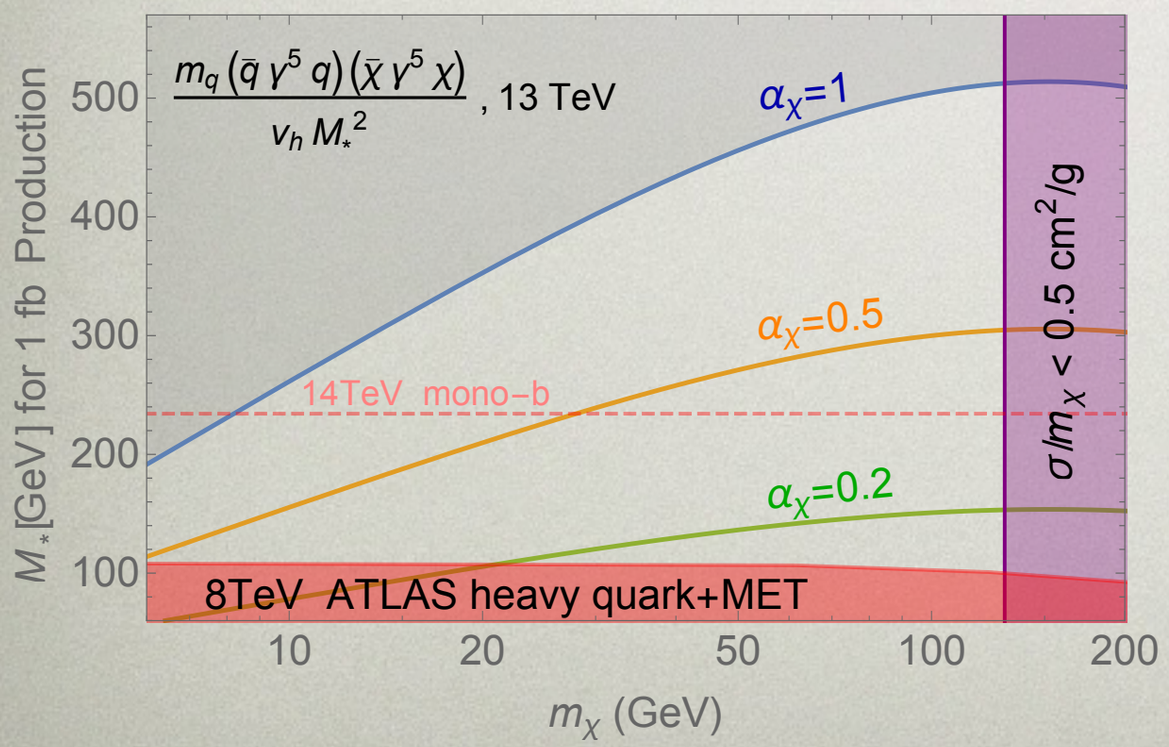
[arXiv:1506.00424]

Dark Radiation

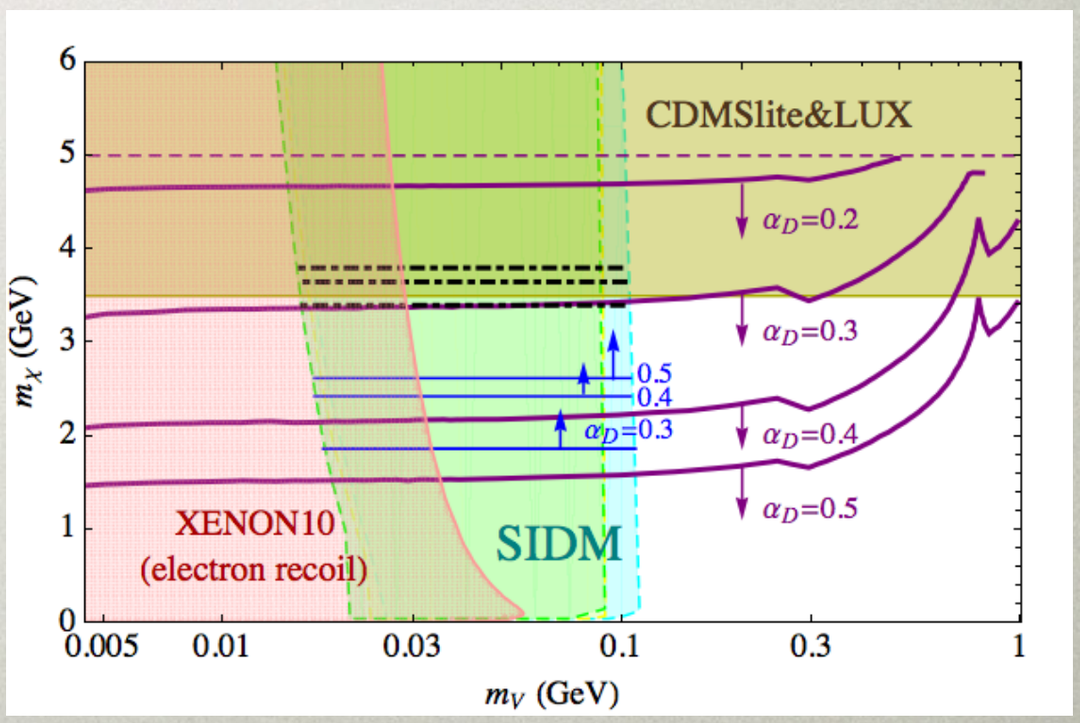
- As the coupling gets stronger, get **more radiation** and **bound state formation** Pospelov, Ritz 2008; March-Russell, West 2008; …
  - Sensitive to **self-interacting DM**







Tsai, Wang, Zhao, 2015



An *et al.*, 2015

Multi-Particle Sector Summary

- Signatures range from mostly-MET to mostly-visible
- Boosted, long-lived particles are common
- Many different strategies to look for these!
- Is there a good way to organize searches to ensure that we don't miss something?