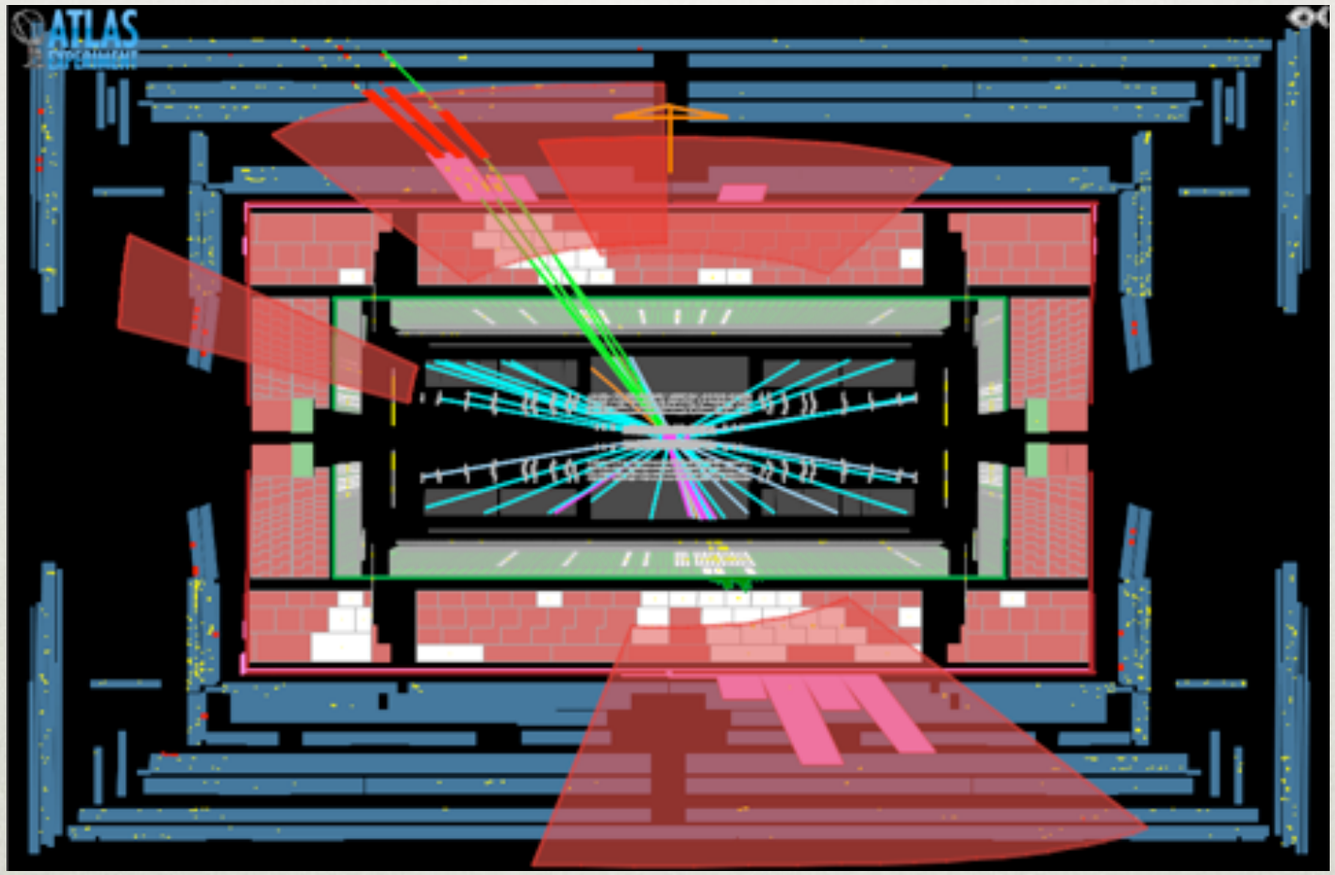
SEARCHING FOR SIMPLE HIDDEN SECTORS

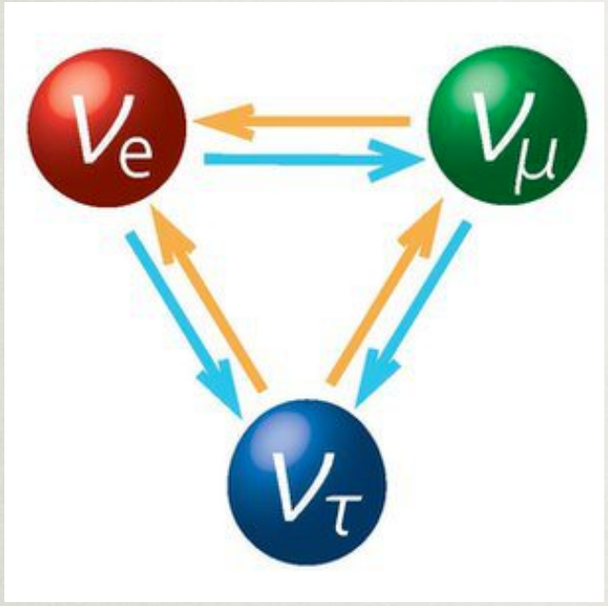


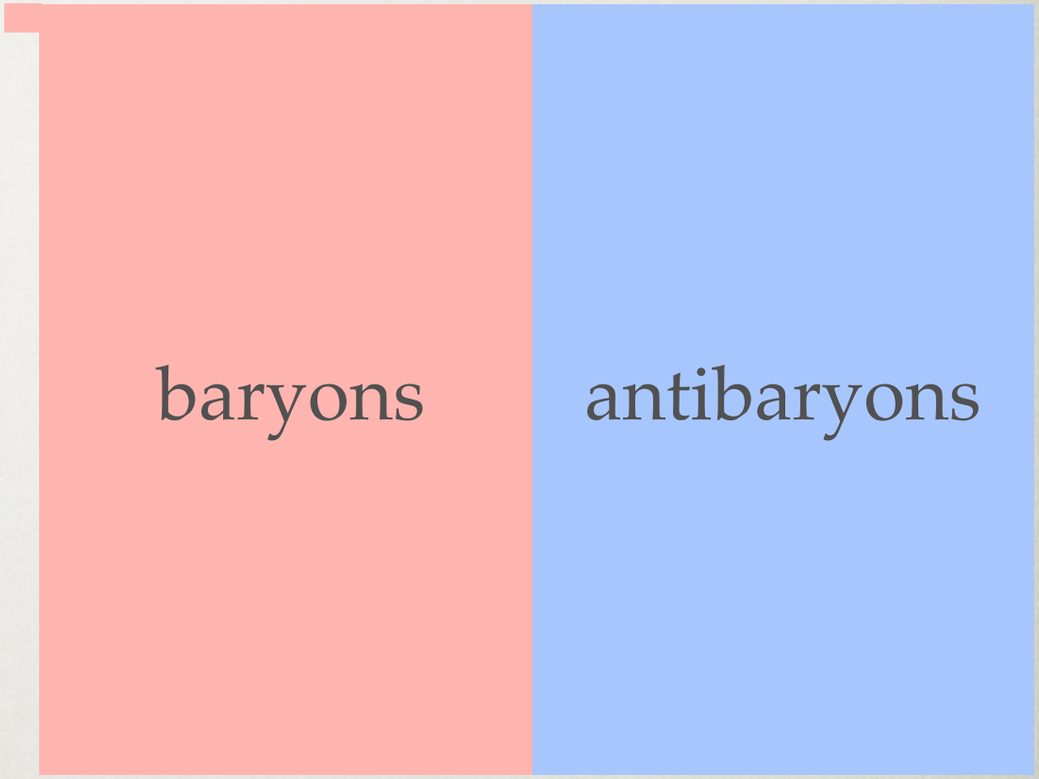
Brian Shuve

PCTS Trigger Workshop, 2018

HARVEY MUDD COLLEGE

Evidence for “Hidden Sector”



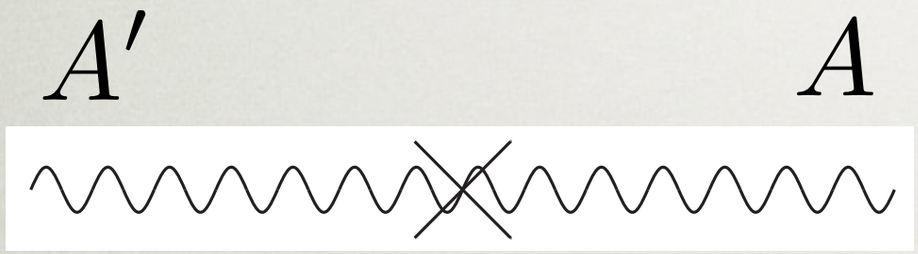


- In many well-motivated models, have new particles in **GeV** range
- No **definitive** mass scale for new physics

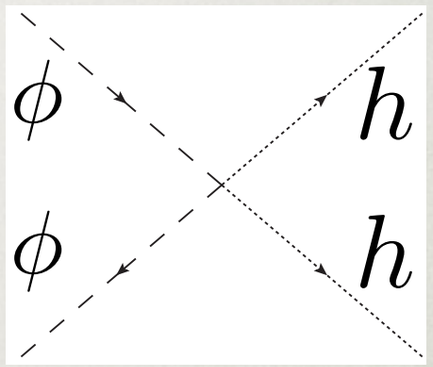
Dark Sector Portals

- Hidden sector singlets dominantly couple to SM via **portals**

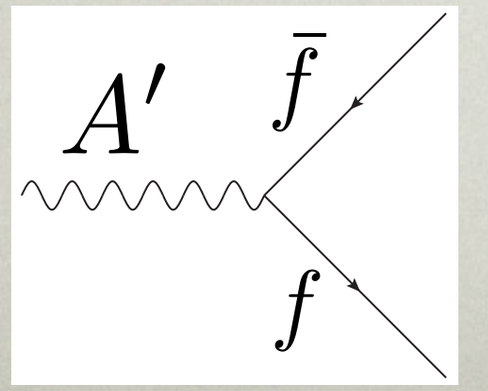
KINETIC MIXING PORTAL



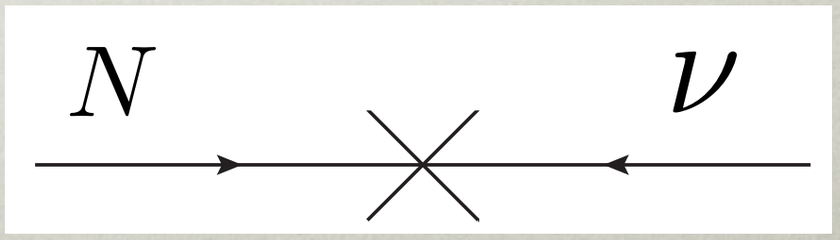
HIGGS PORTAL



GAUGE PORTAL

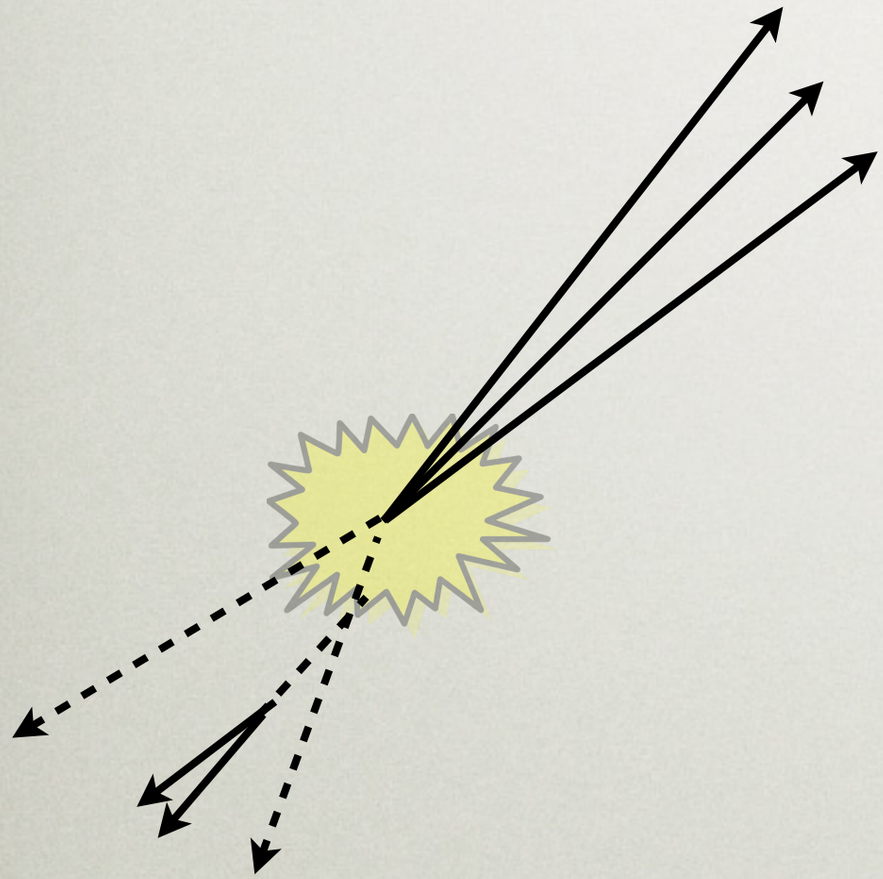


NEUTRINO PORTAL



Discovering Hidden Sectors @ LHC

- **Low-mass particles can be challenging!**



- How to trigger on ~1-100 GeV mass particles?

- Often have either **associated production** with SM objects *or* production of **multiple** hidden-sector particles

- Will focus on "simple" (non-shower) scenarios

This Talk

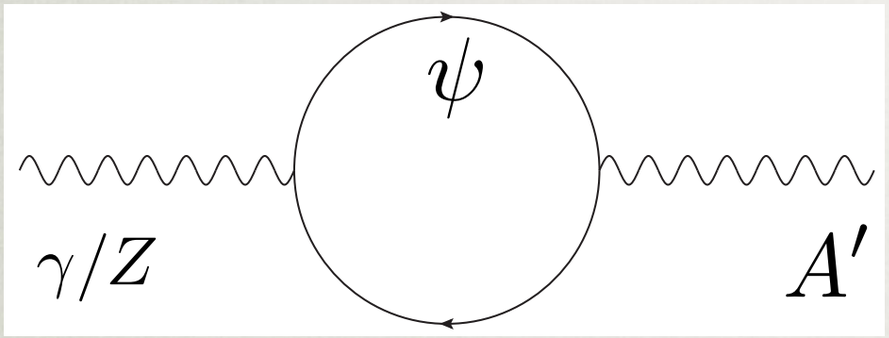
- Will look at a few example hidden sectors where triggering or reconstruction is challenging
    - Hidden U(1) model
    - Right-handed or sterile Majorana neutrinos
- Get both prompt and long-lived signatures
- Motivations to trigger on associated objects, and/or maintain low-threshold, high multiplicity triggers
- For signatures from exotic Higgs decays, see Jessie's talk tomorrow

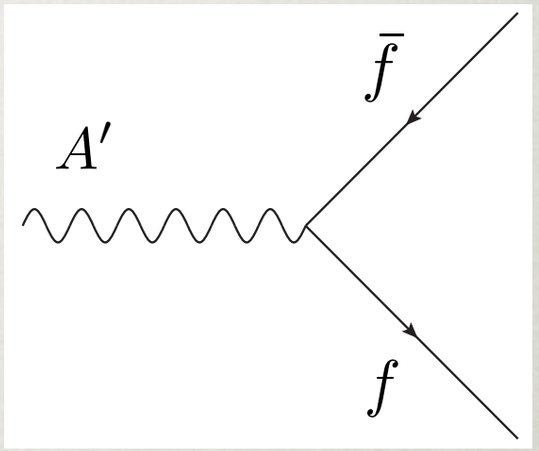
Hidden U(1) Model

- **Dark photon** *(A′)* couples to SM via kinetic mixing with the photon and *Z* boson

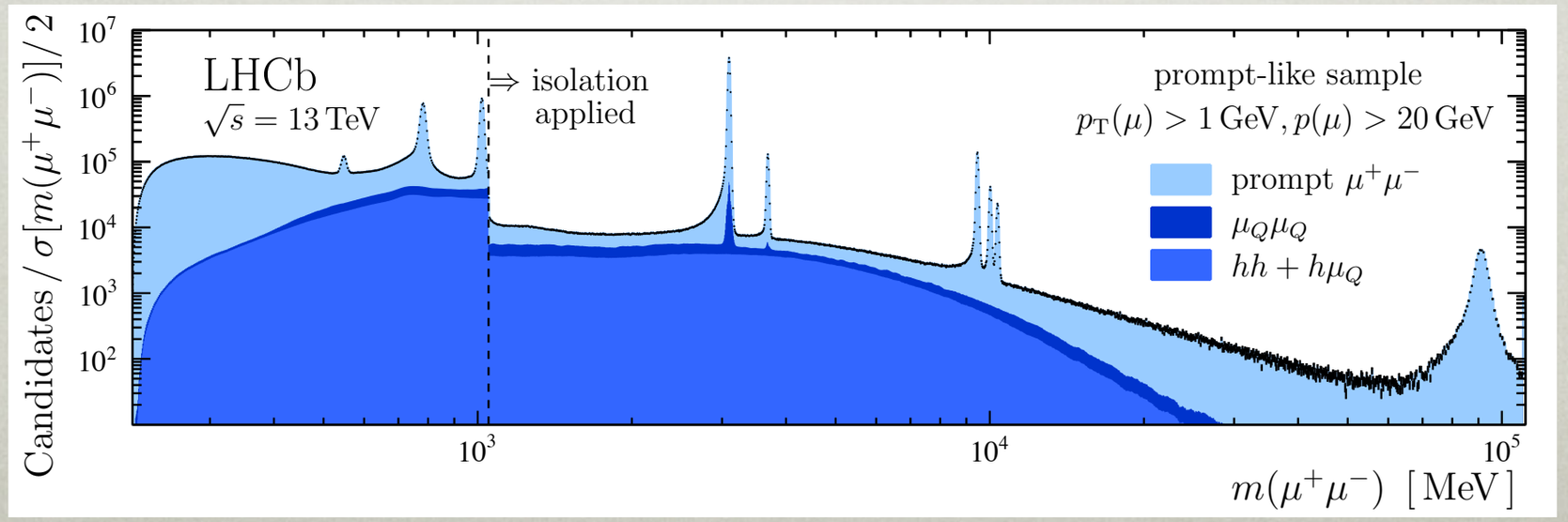
Holdom, Phys.Lett. 166B (1986) 196-198

- This couples the *A′* to the SM fermions





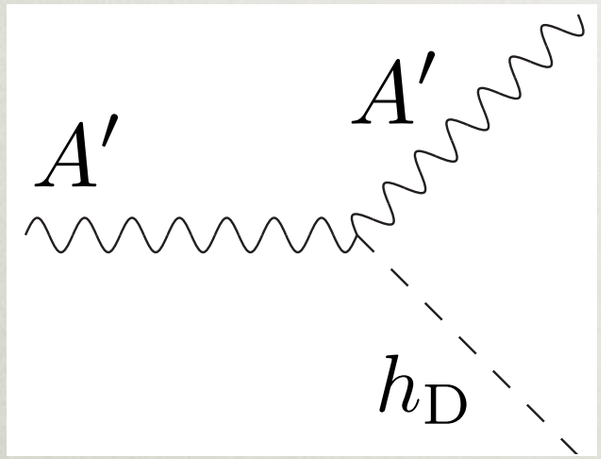
- Can search for dilepton resonances:

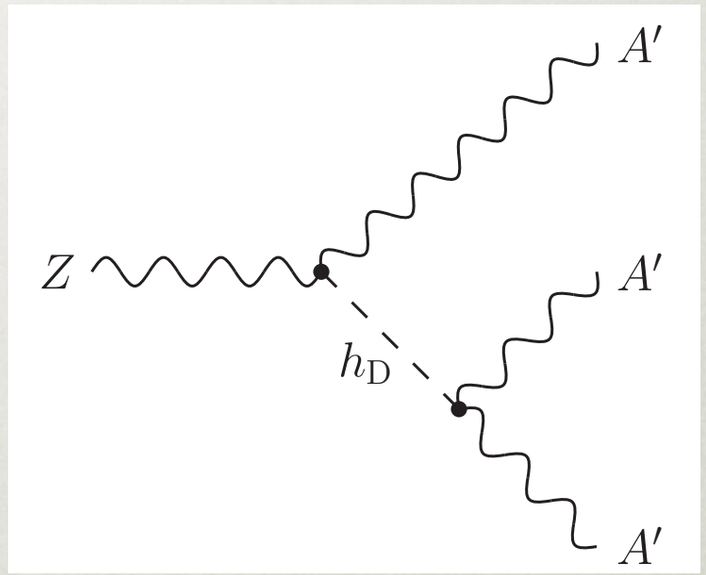


LHCb, arXiv:1710.02867

Hidden U(1) Model

- Spontaneous symmetry breaking in the hidden sector due to a **dark Higgs** can give rise to dark photon mass
- In this case, the same interaction that gives rise to *A'* mass also leads to new production mechanism





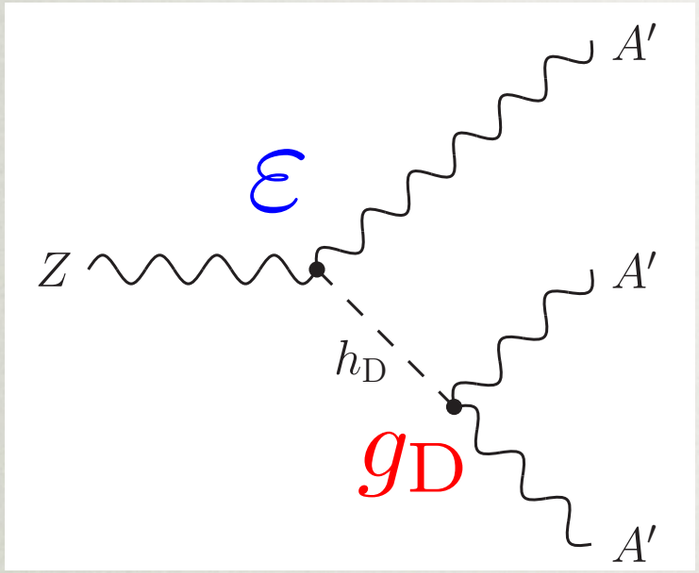
Blinov, Izaguirre, BS, arXiv:1710.07635

- The analogous process $e^+e^- \to A'h_{\rm D}$ has been searched for at *B*-factories (and can provide best limits on *A'*!)

Batell, Pospelov, Ritz, arXiv:0903.0363
BABAR, arXiv:1202.1313; Belle, 1502.00084

Hidden U(1) Model in Rare Z Decays

- Most interested in masses **above 10 GeV**, out of reach of *B*-factories



$$\Gamma(Z \to A' h_{\mathrm{D}}) \approx \frac{1}{12} \alpha_{\mathrm{D}} \, \varepsilon^2 \tan^2 \theta_{\mathrm{W}} \, m_Z$$

$$(m_{A'},\, m_{h_{\mathrm{D}}} \ll m_Z)$$

- Get up to **six** leptons, but they are very soft!

- Current best constraints come from low-MET SUSY search (Z to 6 leptons, 2 leptons not IDed so only 1 OSSF pair)

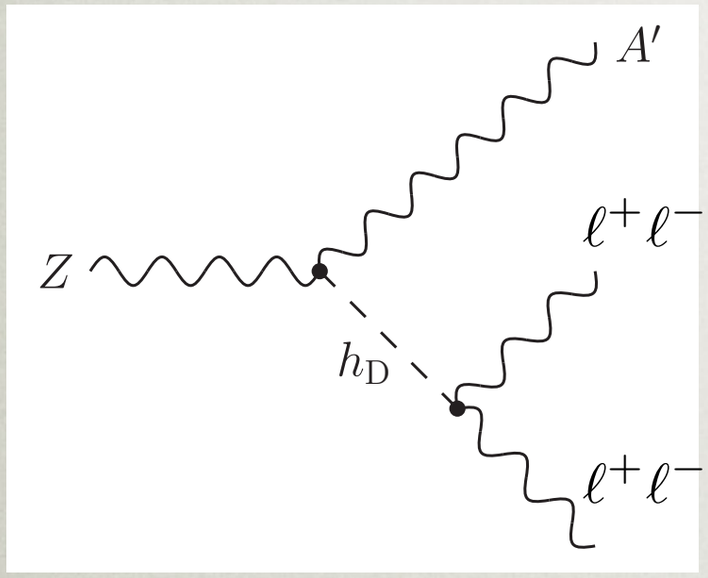
CMS, arXiv:1709.05406

- CMS search not optimized for hidden sector signal, but close to competitive with best direct limits on *A'*!

Hidden U(1) Model in Rare Z Decays

Blinov, Izaguirre, BS, arXiv:1710.07635

- For higher efficiency, we looked at events where the dark Higgs decays entirely leptonically, while other A' decays inclusively



- Four muons with pT > 7 GeV **or** four leptons with pT > 15, 8, 7, 5 GeV (consistent with current triggers)
- Veto 4-leptons reconstructing Z
- Pick A' candidates that are closest in mass

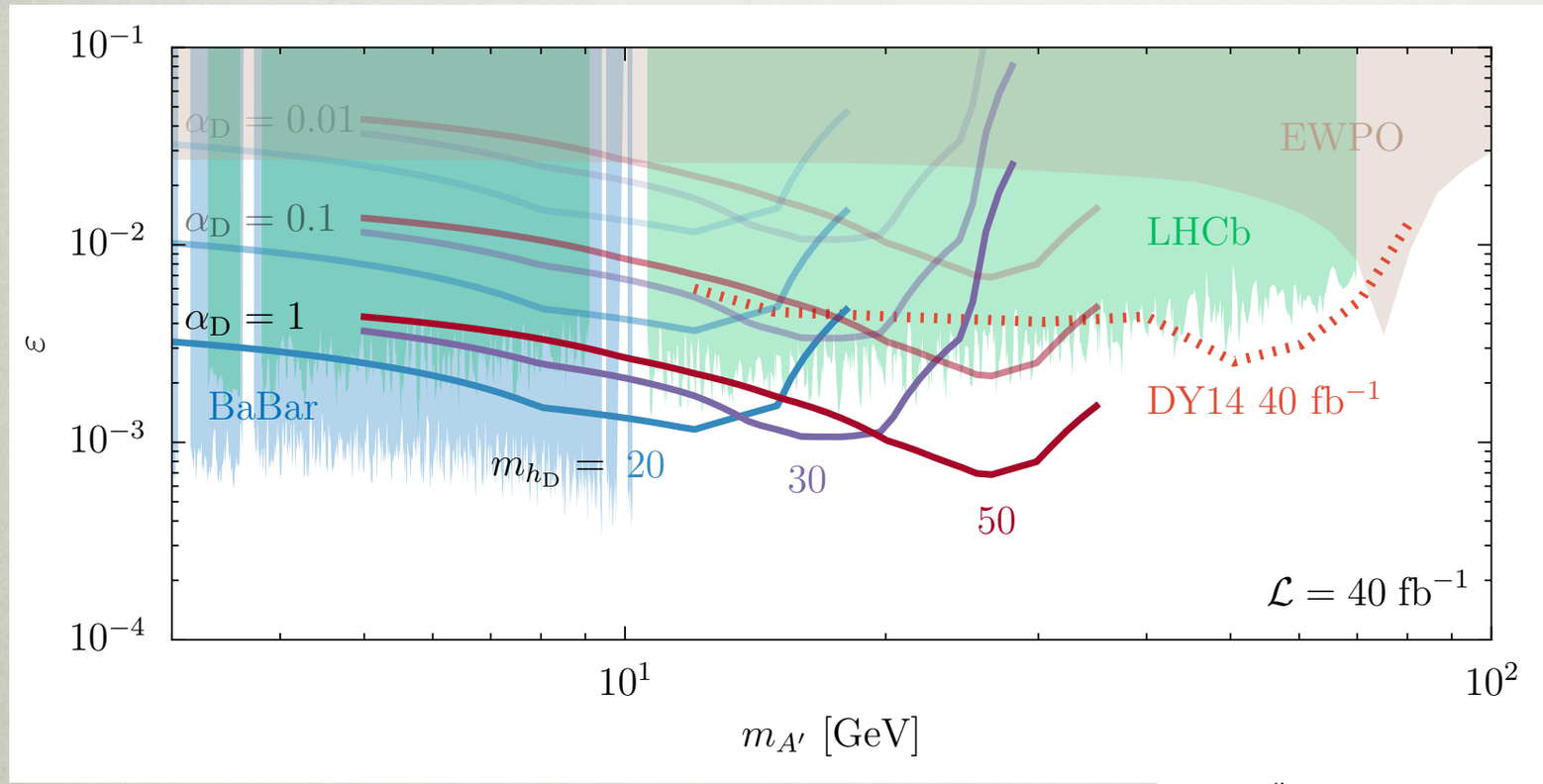
- Dominant background is p p > 4 leptons + X (validated in CMS SUSY signal region)
- Can perform resonance search in 4-lepton mass

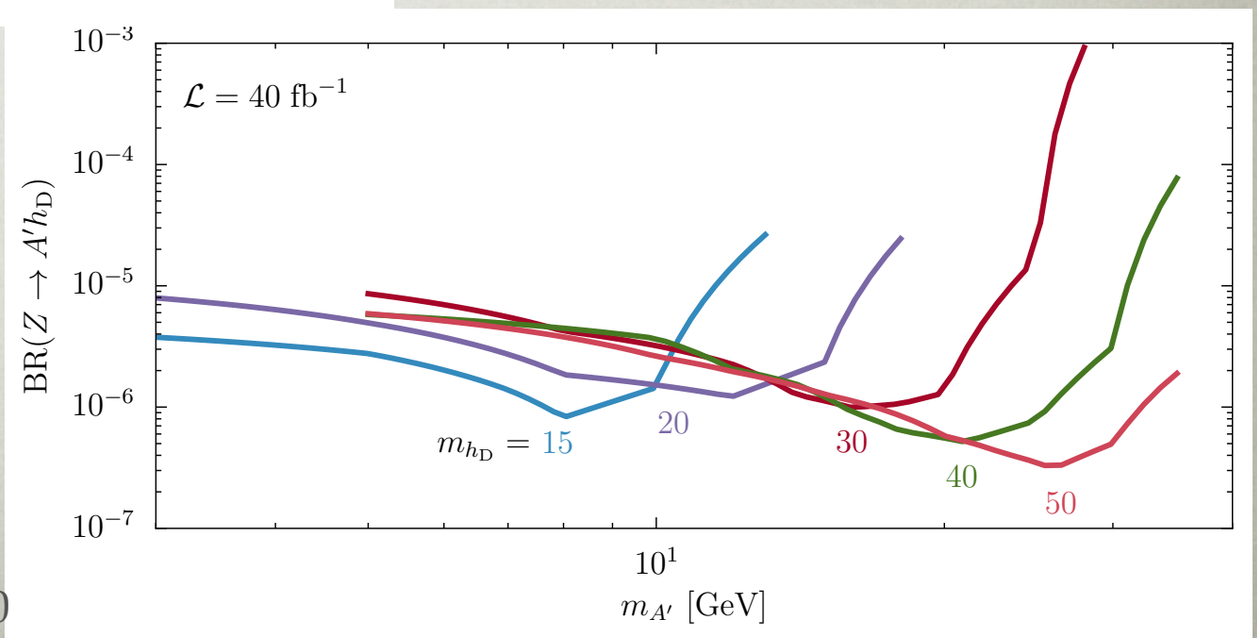
$$\Delta m_{4\ell} = 0.13\ \text{GeV} + 0.065 m_{4\ell}$$

CMS, arXiv:1210.7619

Rare Z Decays: 4-lepton Projections

- Projected 95% CL sensitivity with 40/fb luminosity, 13 TeV

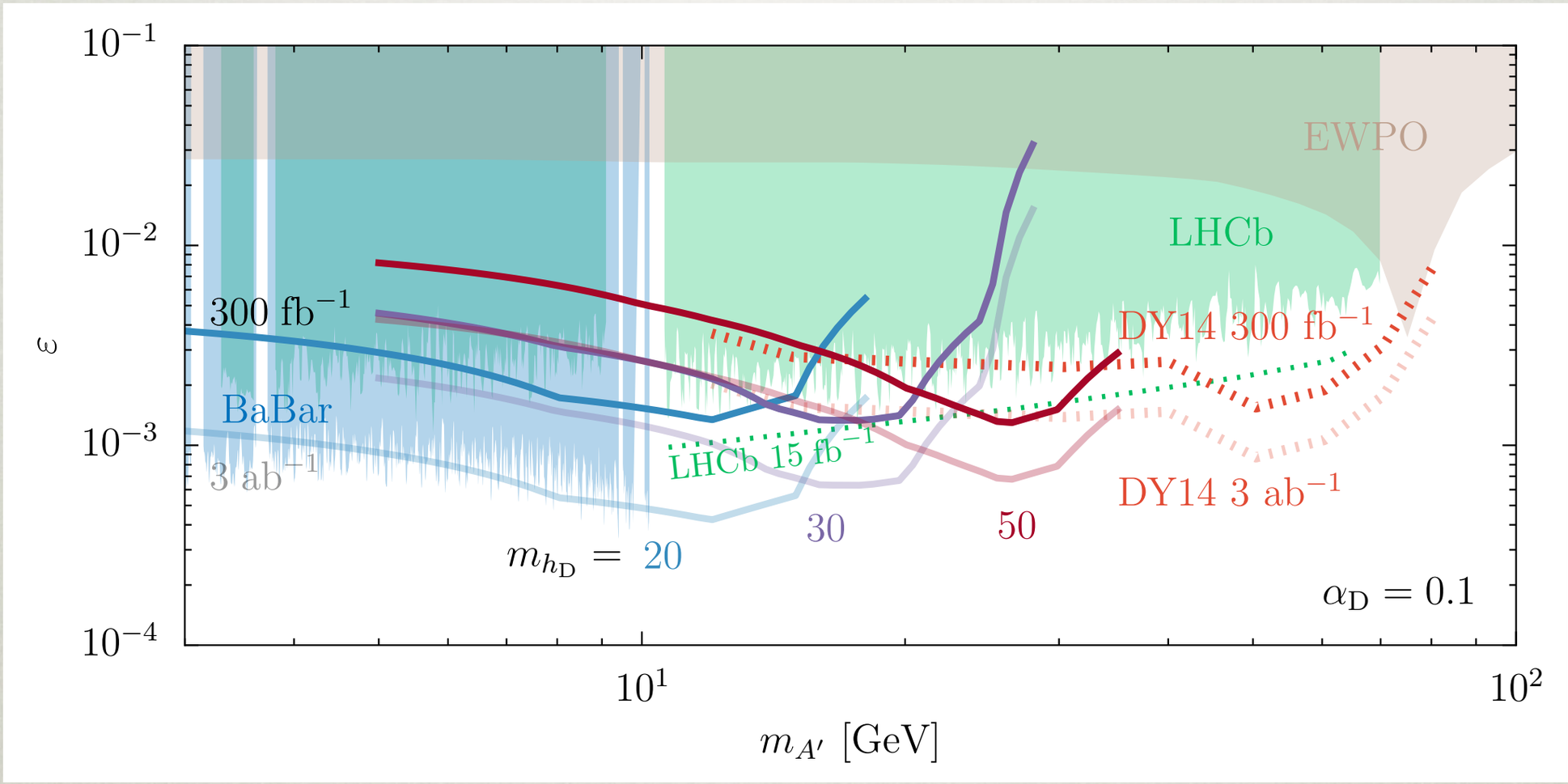




Blinov, Izaguirre, BS, arXiv:1710.07635

Rare Z Decays: 4-lepton Projections

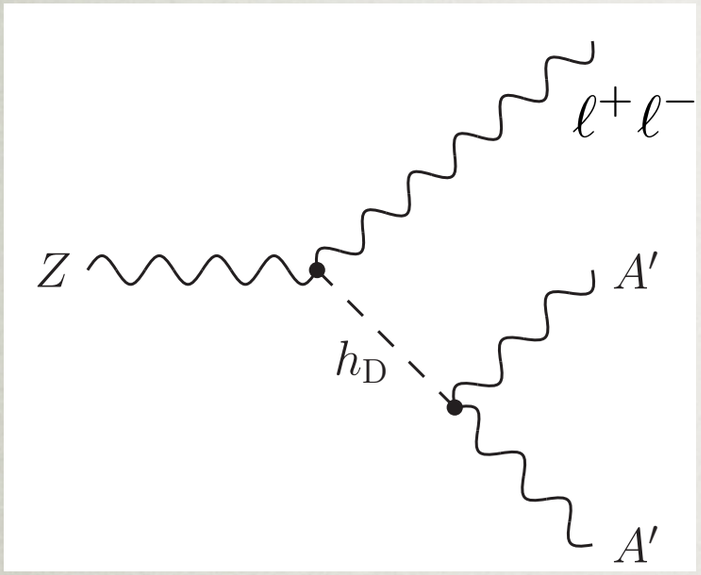
- For the future…



- But need to keep thresholds low enough!

Blinov, Izaguirre, BS, arXiv:1710.07635

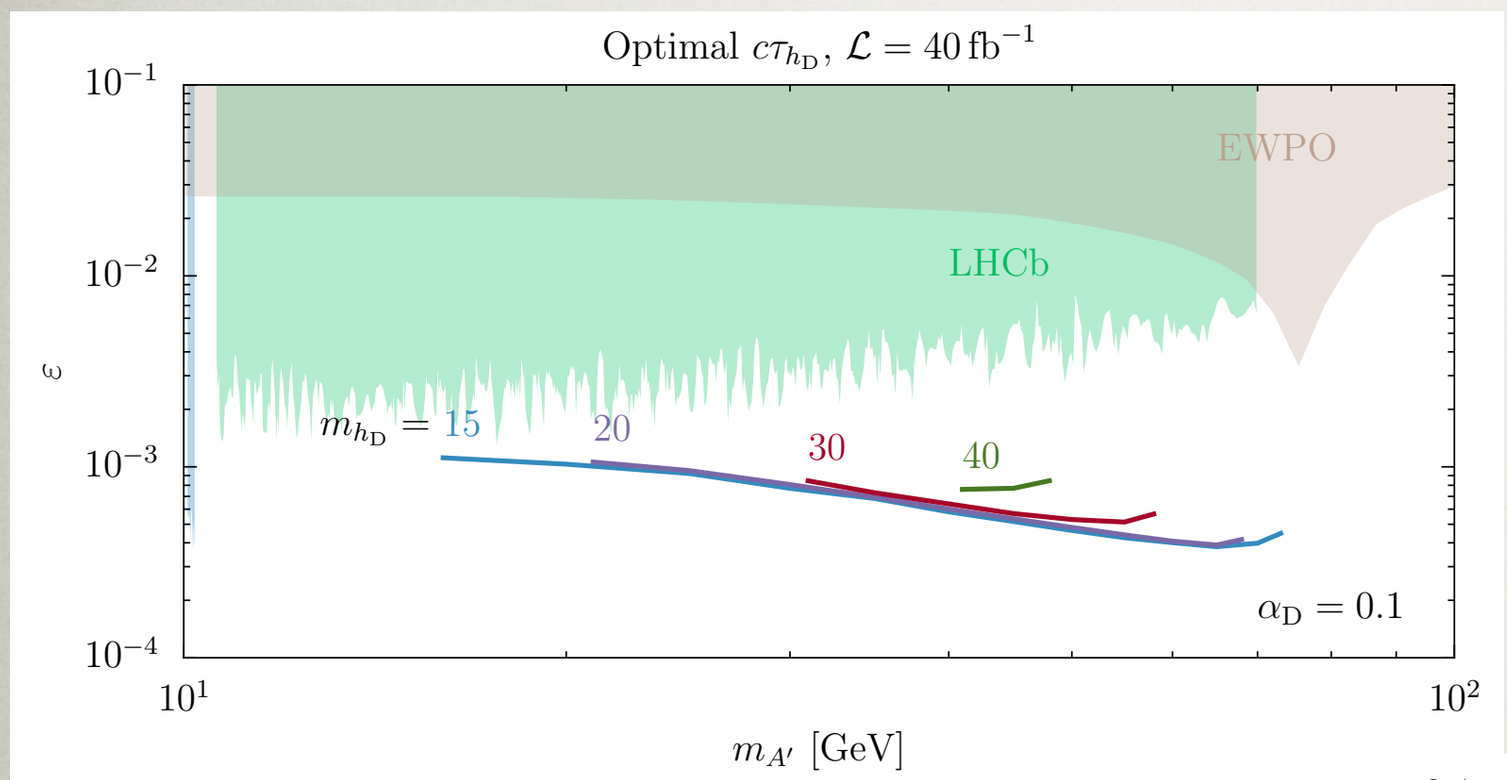
Rare Z Decays: Displaced Signatures



- So far, we have only looked at A' masses where at least one is on-shell
- What about for $m_{h_{\rm D}} < m_{A'}$?
- $h_{\rm D}$ lifetime tends to be very long

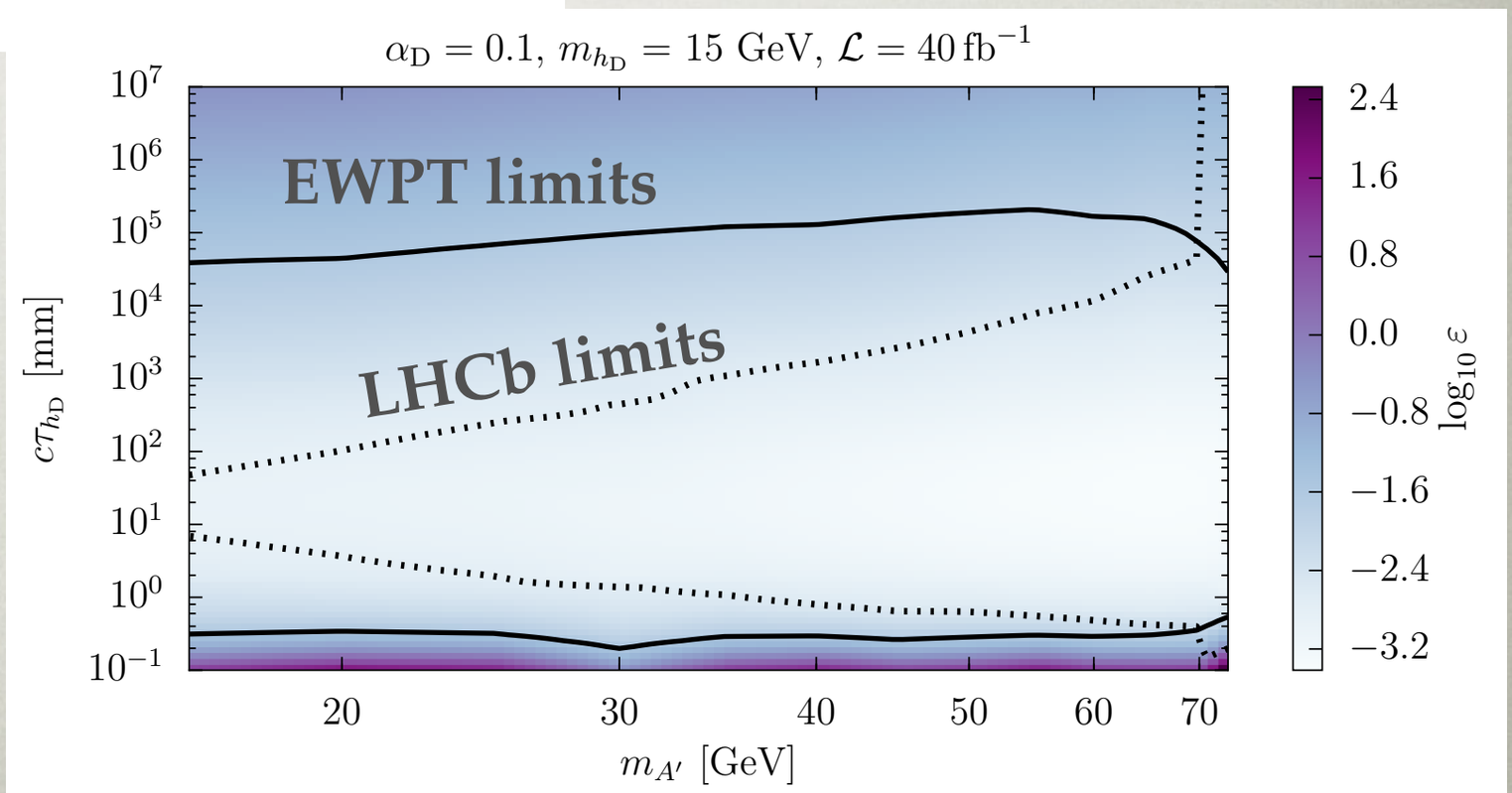
- Striking signature: prompt leptons from direct A' decay, displaced leptons and/or tracks from dark Higgs decay
- Dilepton trigger, assign 50% vertex efficiency
- Plot sensitivity to **10 signal events** (to suppress backgrounds, can do bump hunt *prompt* dilepton mass)

Rare Z Decays: Displaced Signatures



- Lifetime in to plot set to optimal value for sensitivity

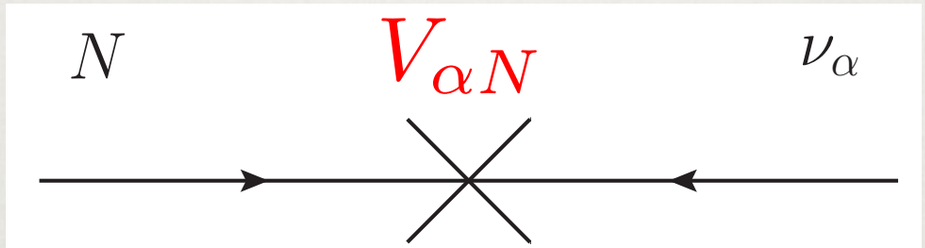
- Good sensitivity, but need to keep trigger thresholds low!

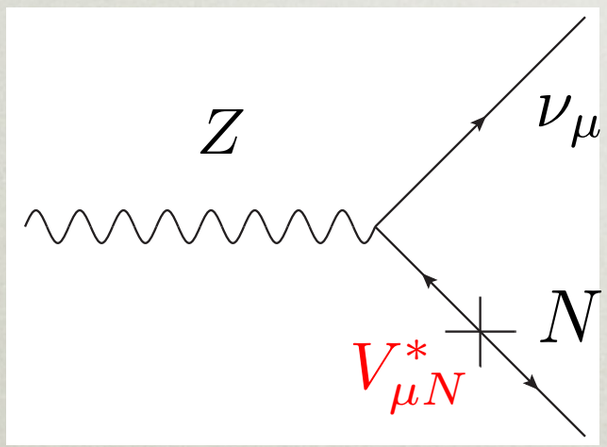


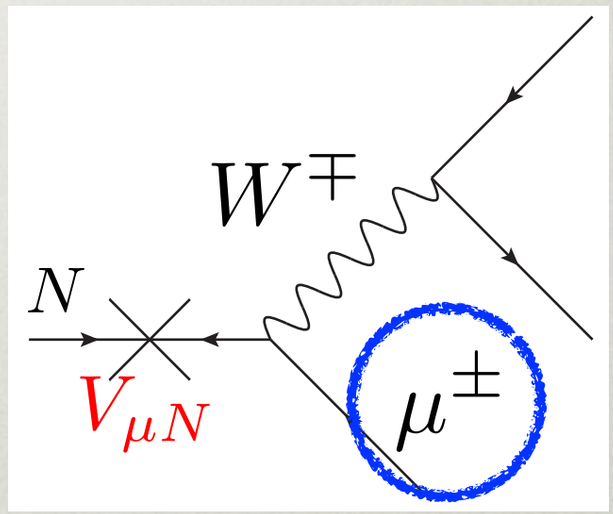
The Neutrino Portal

- Low-mass right-handed neutrinos could be responsible for neutrino masses, baryogenesis, etc.
    - Phenomenology arises from mixing with SM neutrino

e.g., Asaka, Shaposhnikov, hep-ph/0503065; hep-ph/0505013





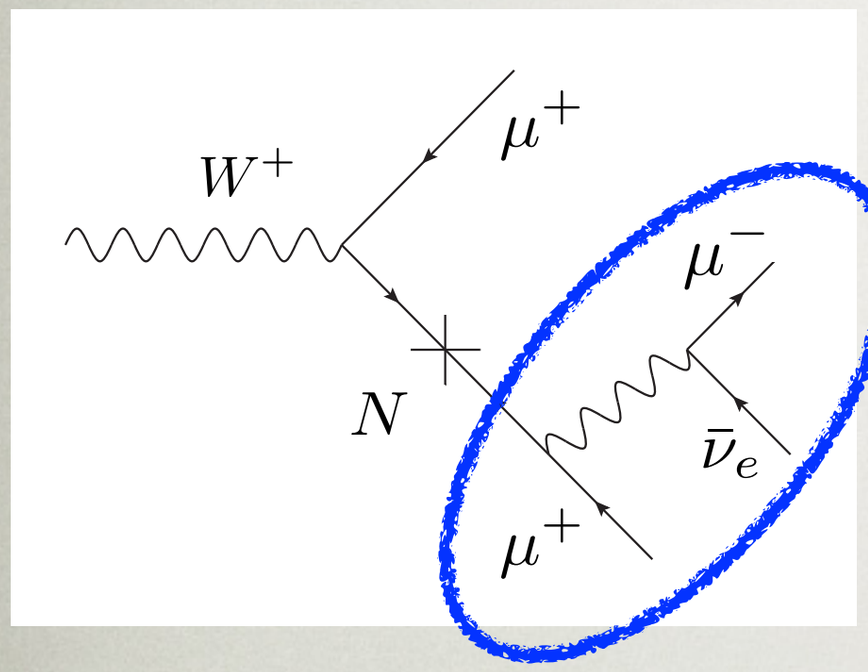


lepton-number violating!

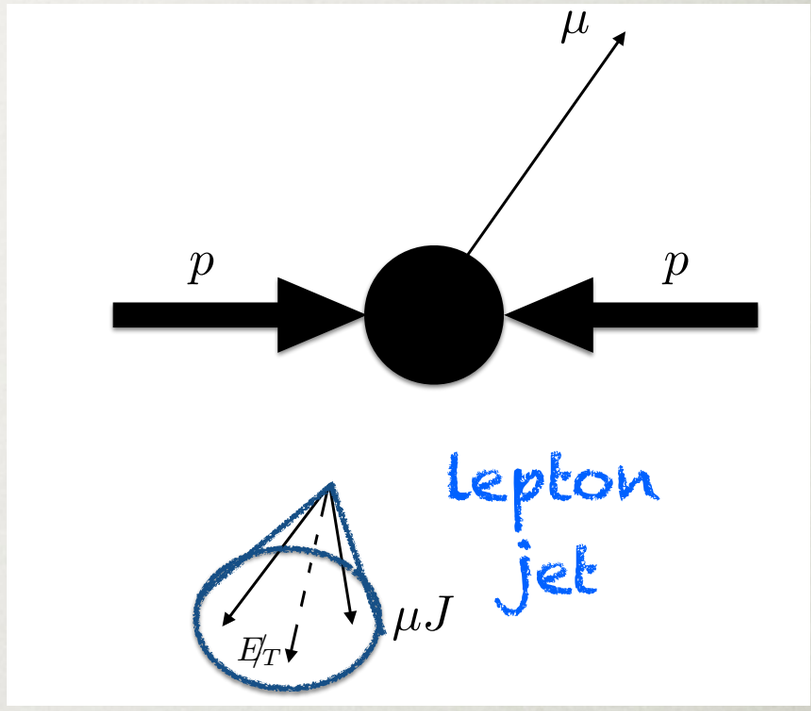
- Below weak scale, decay is through **off-shell gauge bosons**, often long-lived

Low-Mass Neutrino Signatures

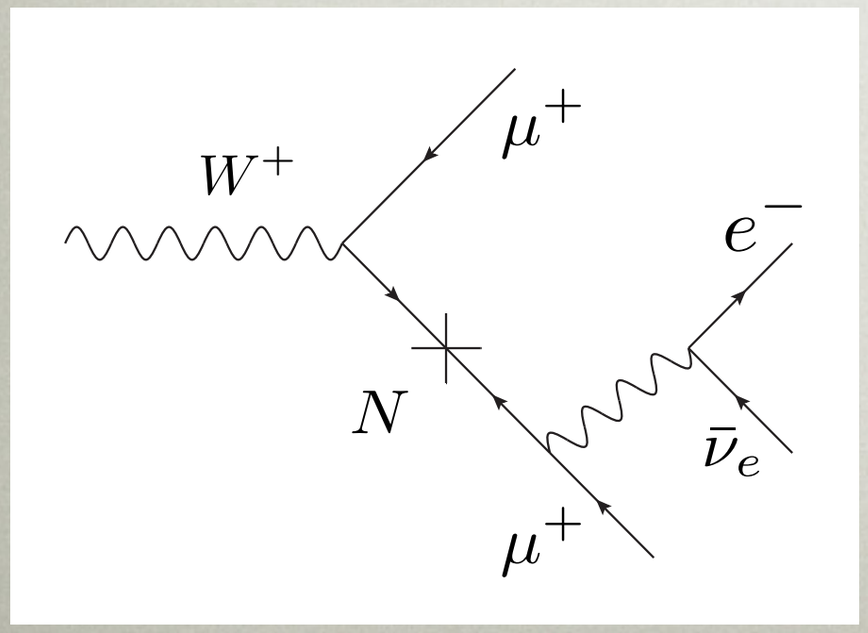
Izaguirre, BS, arXiv:1504.02470



$M_N \ll M_W$



e.g., Arkani-Hamed, Weiner, arXiv:0810.0714, …

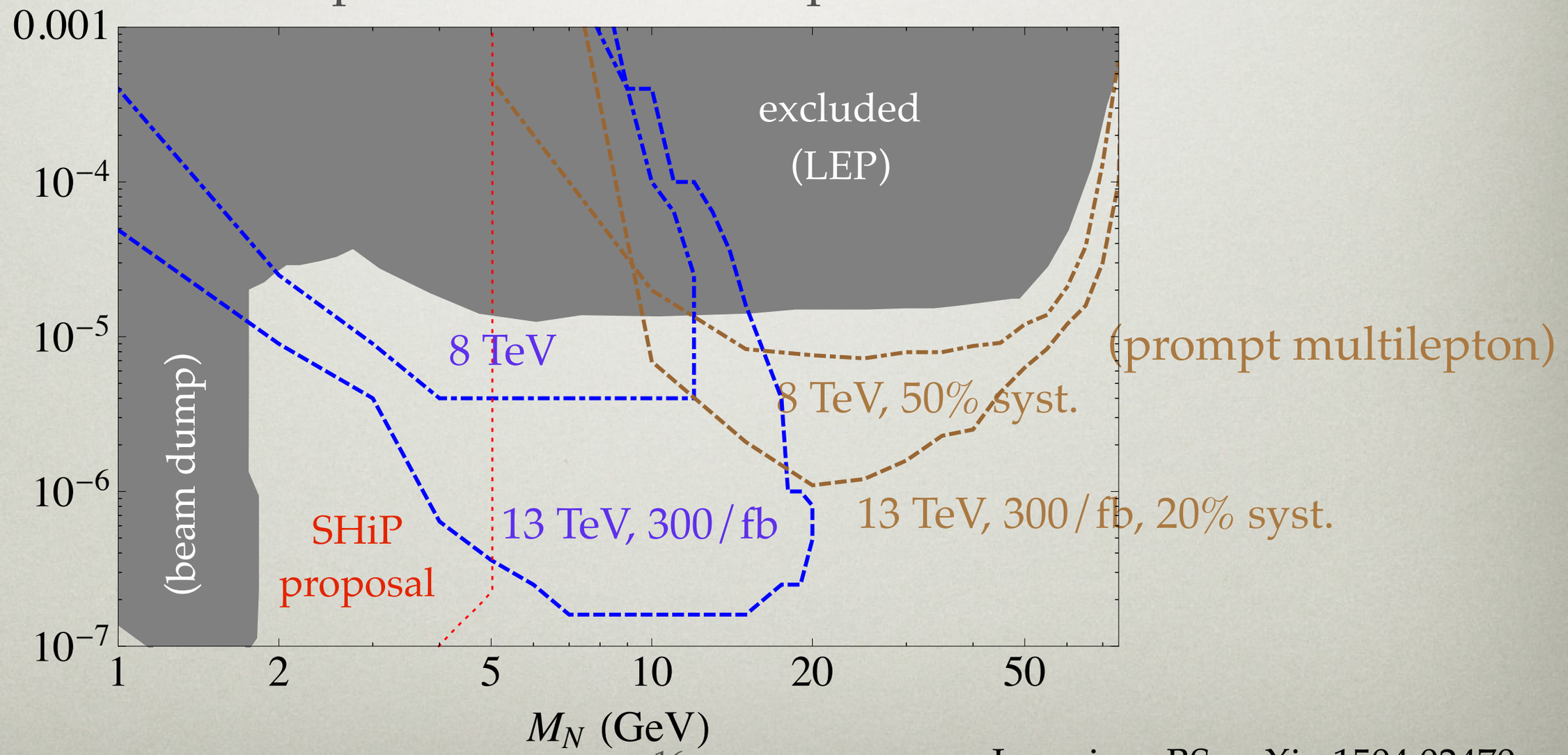


- In prompt regime, can also look for striking evidence for lepton number / flavour violation

(see also Helo, Hirsch, Kovalenko, arXiv:1312.2900)

Low-Mass Neutrino Signatures

- No current sensitivity, but dedicated searches could have good sensitivity to:
    - Single displaced lepton jet + prompt lepton
    - 3 soft leptons with no OSSF pairs

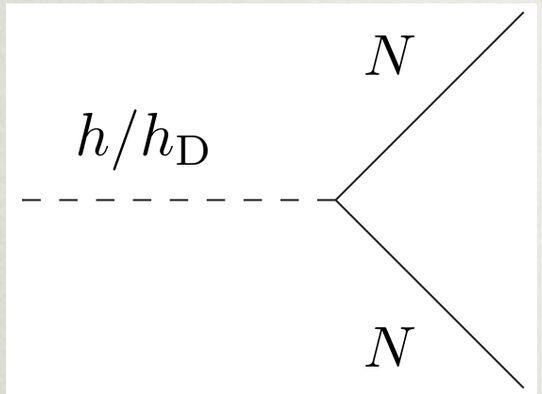


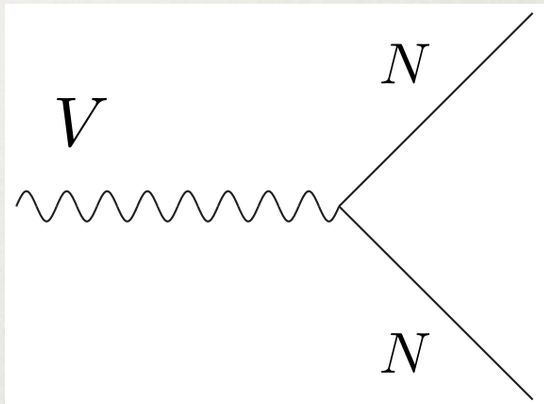
Izaguirre, BS, arXiv:1504.02470

Low-Mass Neutrino Signatures

- 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?

Batell, Pospelov, BS, arXiv:1604.06099 & work in progress

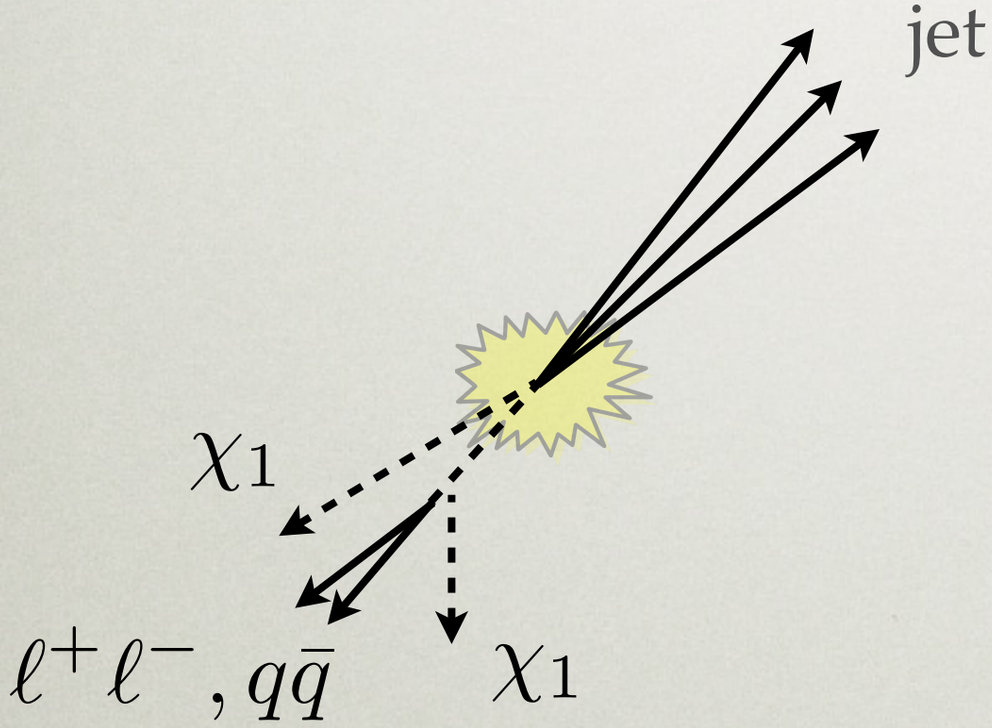
- In such models, can also have signatures like:

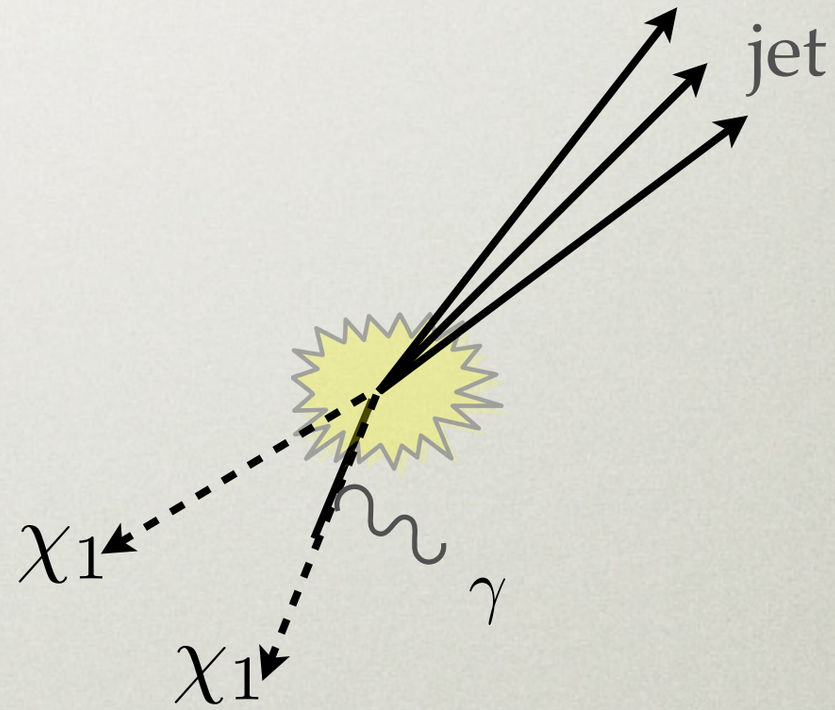
$$h \to h_{\rm D} h_{\rm D} \to 4N \to 12f \qquad\qquad h \to N_2 N_2,\ N_2 \to N_1 q\bar{q}$$

[17] *e.g.*, Nemevsek, Nesti, Vazques, arXiv:1612.06840

Other Possible Signatures

- Similar lessons from other simple hidden sectors, *e.g.*, many dark matter models with multiple DM states (EW multiplets or inelastic DM)
- Typically MET-rich signatures, so can use jet + MET trigger





Bai, Tait, 1109.4144; Weiner, Yavin, 1206.2910; Izaguirre, Krnjaic, BS, 1508.03050; Ismail, Izaguirre, BS, 1605.00658; Giudice *et al.*, 1004.4902; Schwaller, Zurita, 1312.7350; Han *et al.*, 1401.1235; Primulando, Salvioni, Tsai, 1503.04204; Bramante *et al.*, 1401.1235, 1412.4789, …

Bringing it all together…

- Hidden-sector particles can be produced copiously from decays of SM or other low-mass particles
    - Typically very soft! Need associated objects or exploit high multiplicities where possible
    - Use additional handles, like displacements or lepton number violation to suppress backgrounds, help with trigger?

- Long-lived particles offer particularly interesting opportunities + challenges
    - As tracking information moves to lower levels, need to retain efficiency to “weird” leptons and displaced objects, maybe can use to improve trigger efficiency for signals!
    - Maintain and develop triggers for LLP decays in MS and calorimeters

Bringing it all together…

- In the examples I've shown, there are often leptons or MET (produced either "promptly" or in hidden-sector cascade decays
    - Hardest situation is **all-hadronic** production + decay
    - Can rely on associated production, but take hit in signal efficiency

- Any interesting ideas for improvement, especially at low levels of trigger?

e.g., Bai, Bourbeau, Lin, arXiv:1504.01395; Trigger/Upgrade WG for LLPs

    - Very low-mass particles can look like taus; maybe more effective uses of tau triggers?
    - Track-based triggers for LLPs (*cf* Yuri's talk)
    - Any possibilities for trigger-level analysis?

Summary

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

- Examples shown here and throughout this workshop are representative of hidden-sector signals: can cover a lot of ground!

- Need to maintain as much sensitivity to soft, low-mass objects to improve coverage: use associated objects and/or high mult.

- Keeping sensitivity to low-mass hidden sectors is a big challenge in Phase II pile-up conditions, but the huge integrated luminosity could lead to a big payoff!

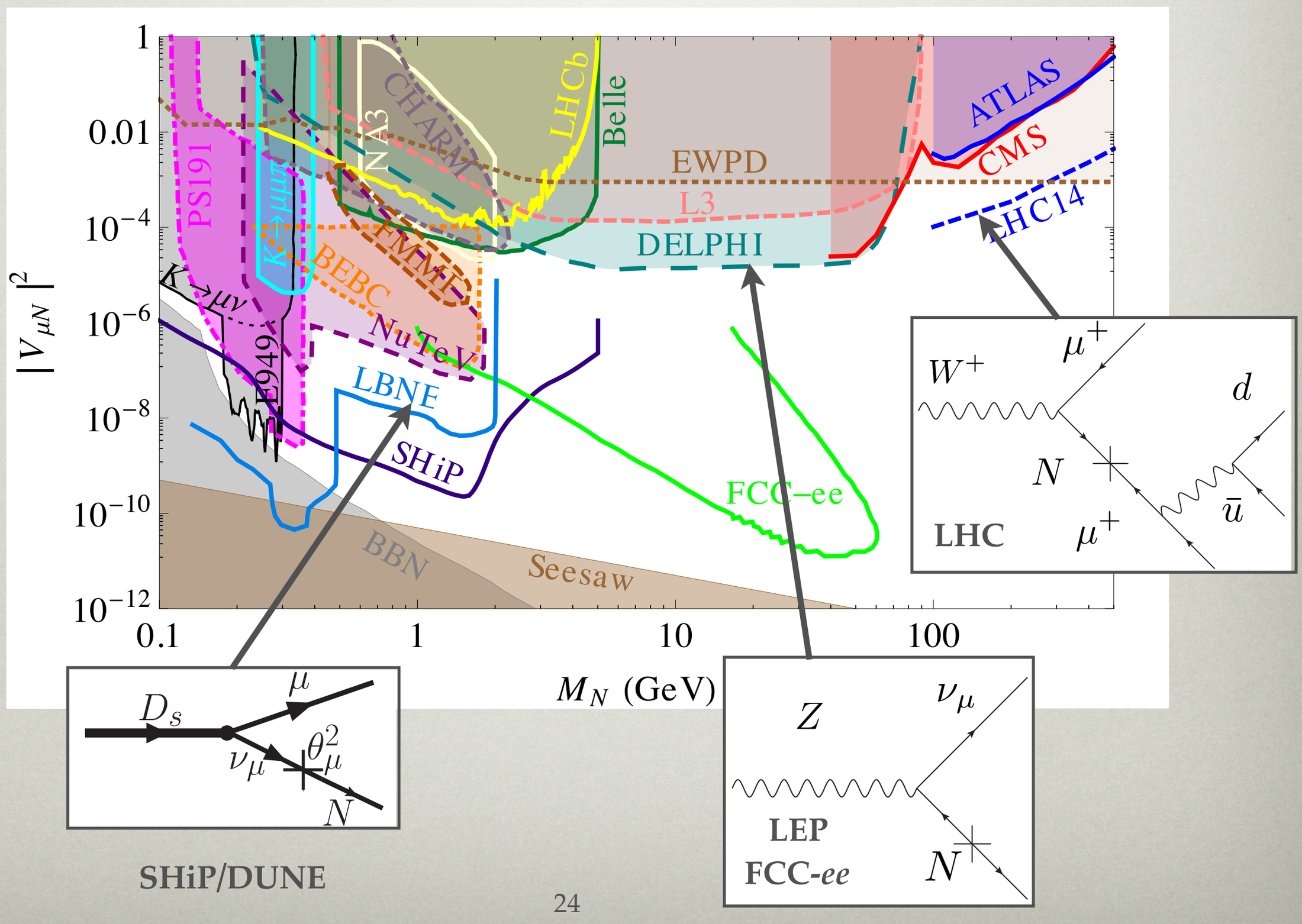
Back-up slides

Example: LLP Simplified Models

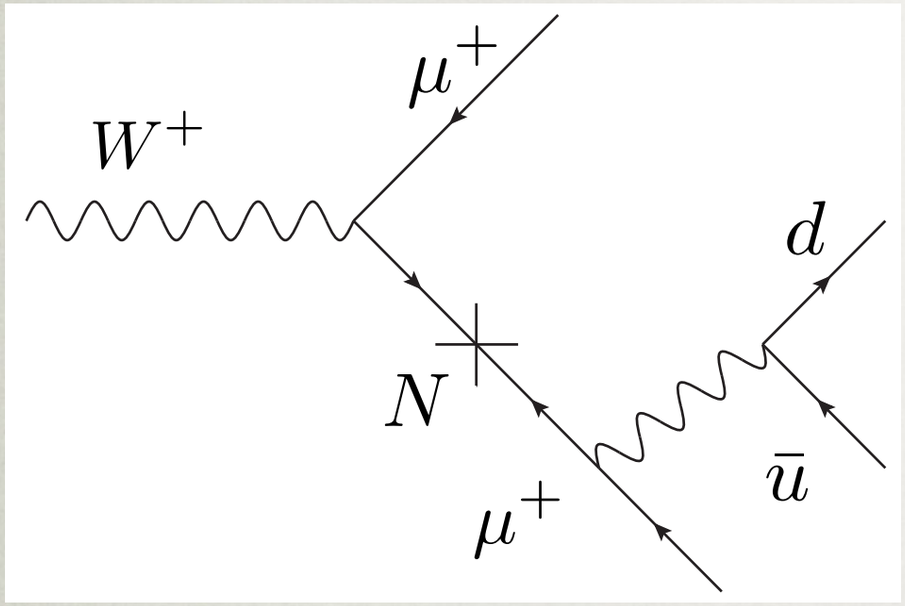
Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$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

Testing the See-Saw

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



Limitations of Current Searches

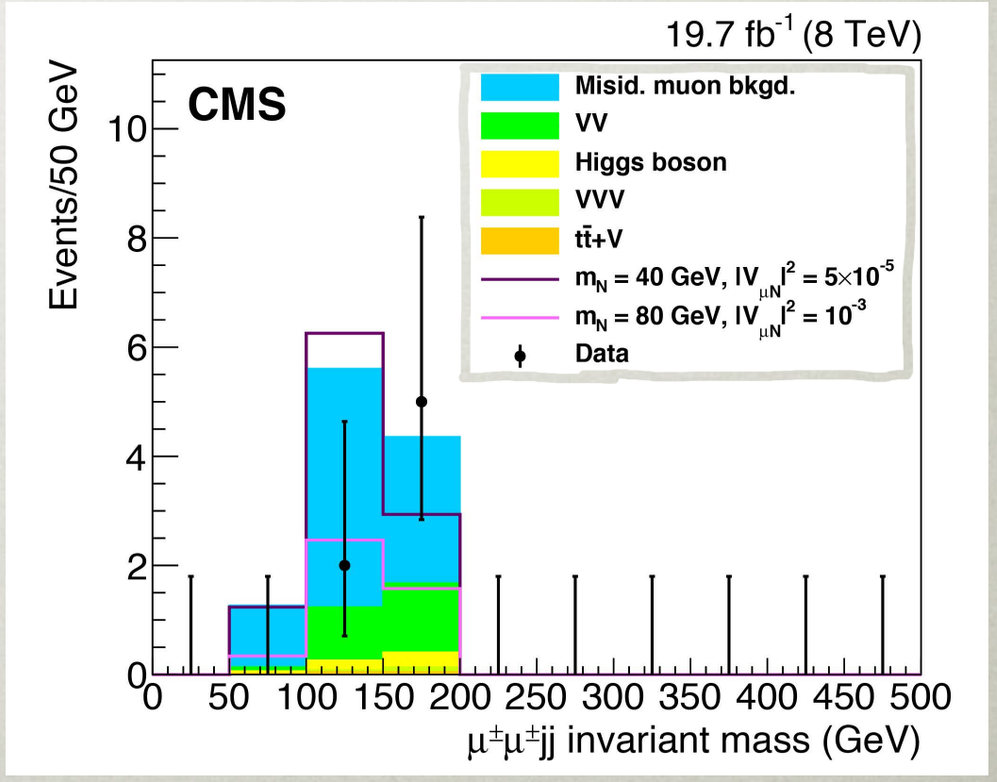


$$M_W \approx 80 \text{ GeV}$$

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

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

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

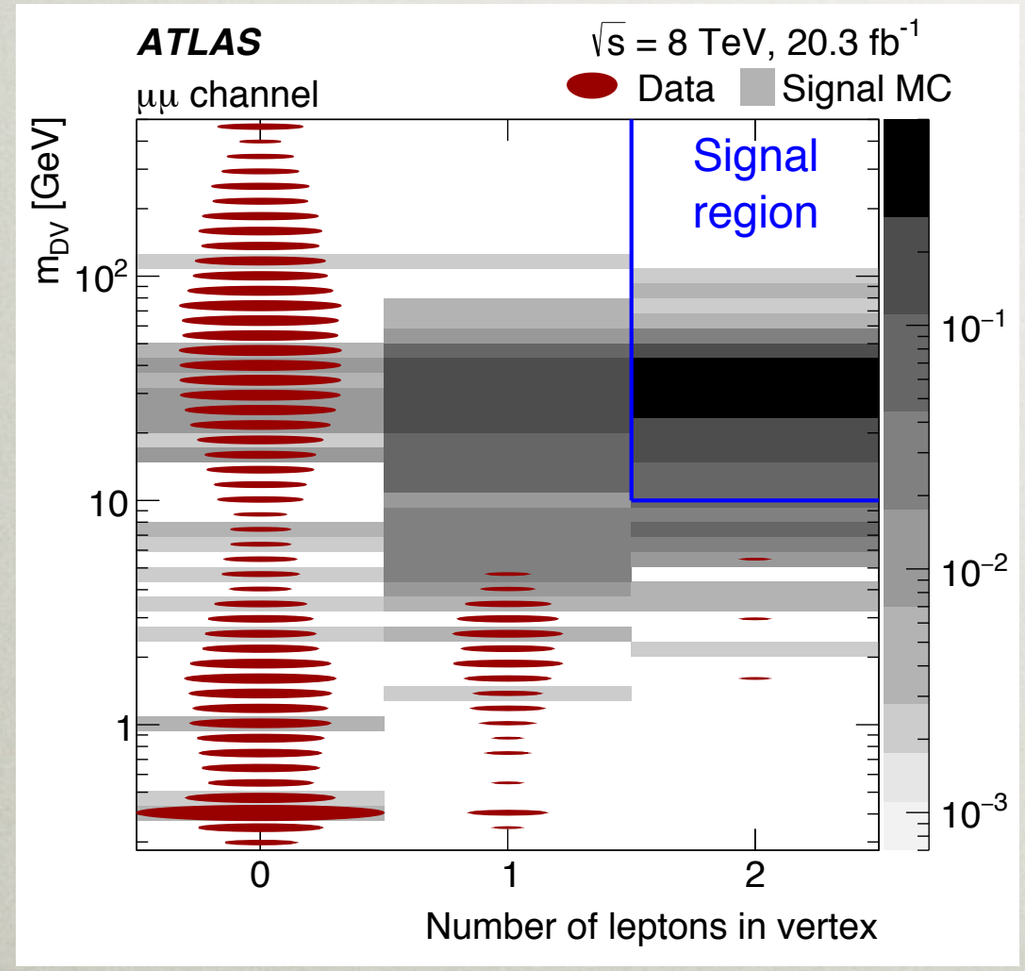


(from arXiv:1501.05566)

Low-Mass Neutrino Signatures

- Searches to date have no sensitivity to this final state

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



(a)

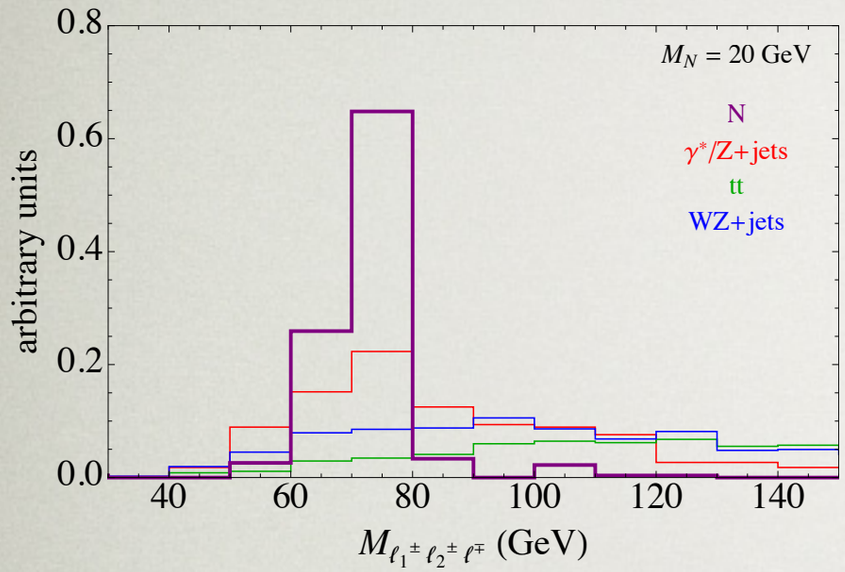
ATLAS, arXiv:1504.05162

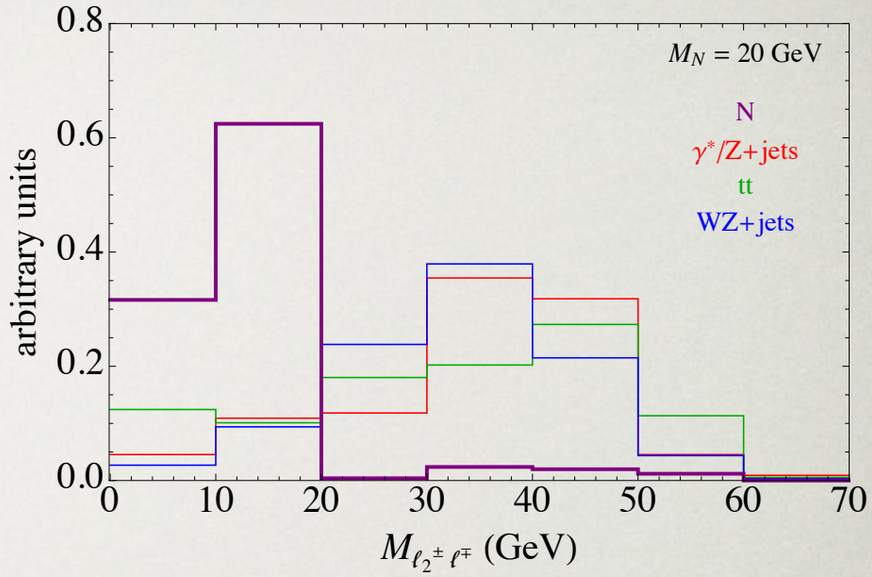
- Also, low-bkd found by extrapolation from existing 2-LJ searches

(ATLAS, arXiv:1409.0746)

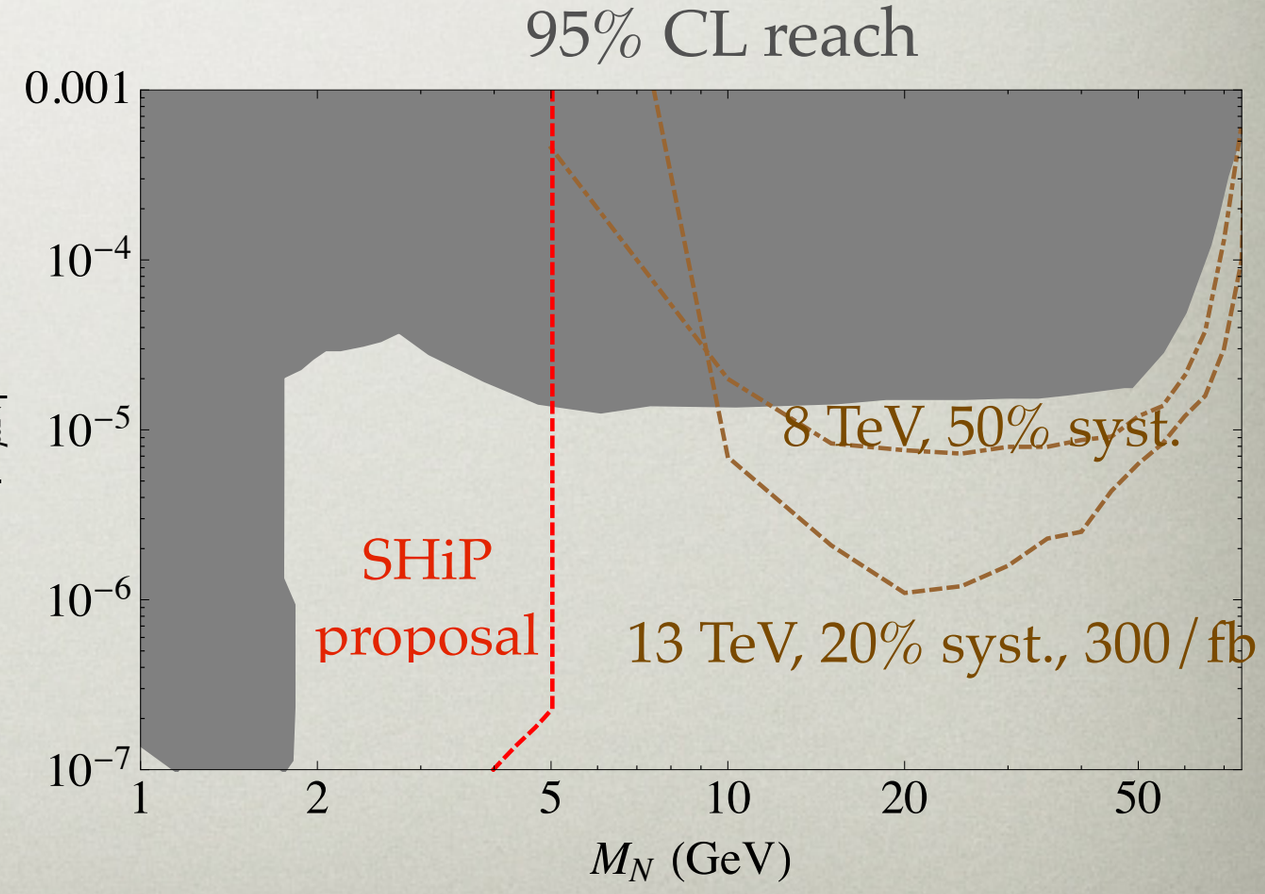
Izaguirre, BS, 2015

Prompt trilepton signatures

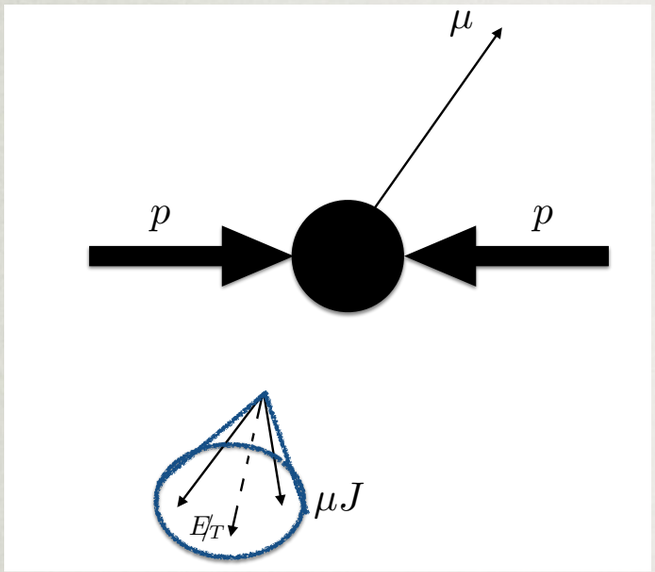




- Selections:
  - Three prompt, isolated leptons with $p_T > 10$ GeV, leading > 20 GeV
  - Two same-sign muons, opposite-sign electron
  - $H_T < 50$ GeV, MET < 40 GeV (suppresses top, tau backgrounds)
  - 80 GeV $> M_{3\ell} > 60$ GeV, mass-dependent cut on $M_{2\ell}$

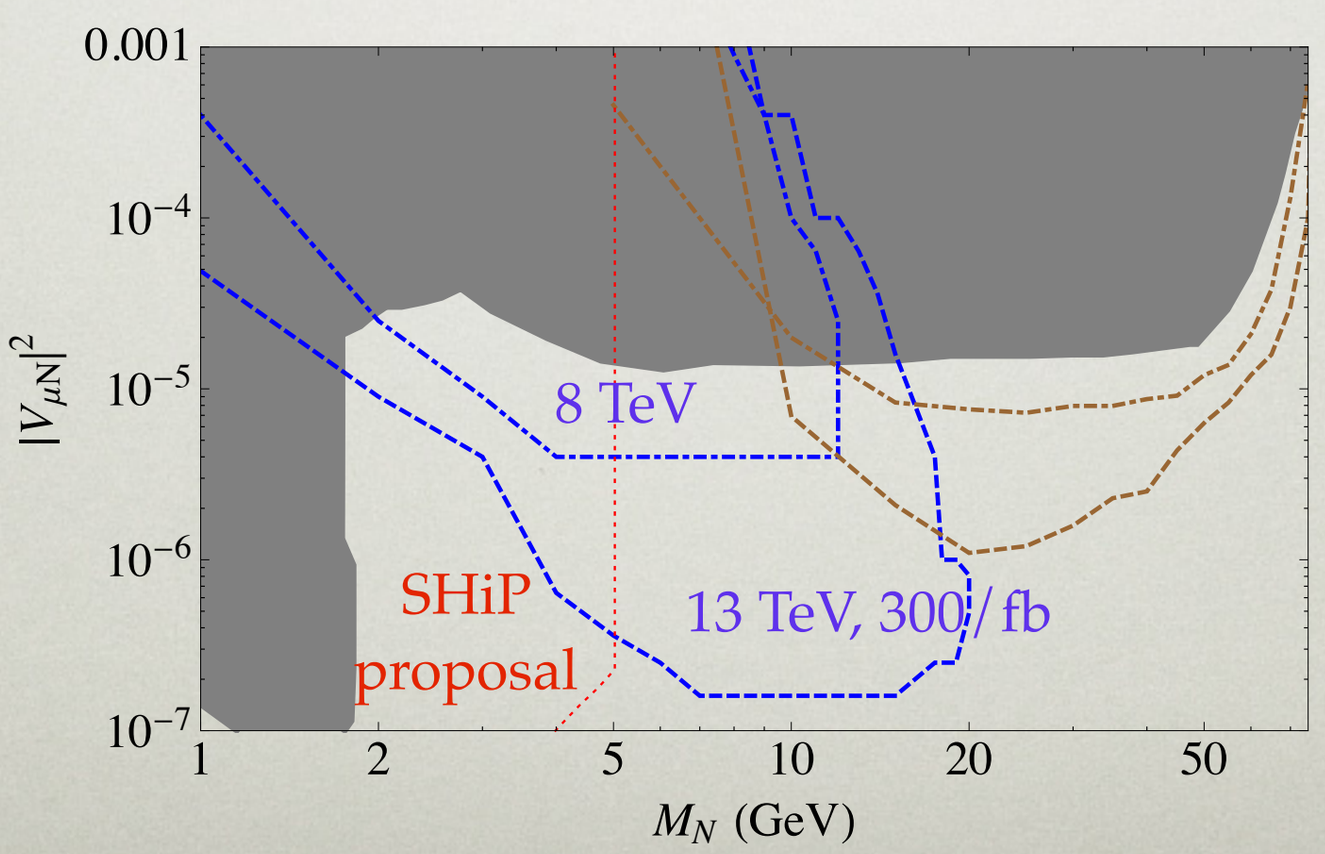


Displaced trilepton signatures



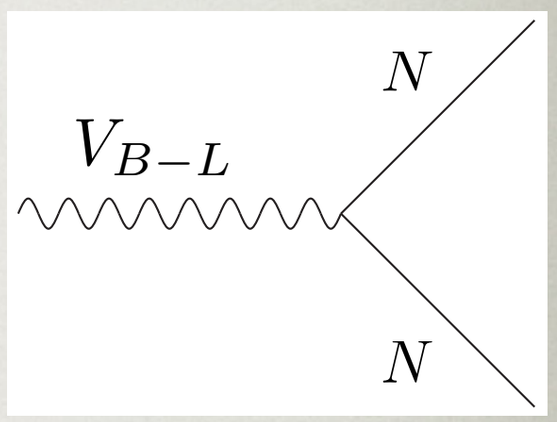
- We apply same LJ selections as ATLAS:
  - Prompt muon $p_T > 24$ GeV
  - Two muons in MS, $p_T > 6$ GeV
  - One muon jet ($\Delta R < 0.5$) with distance to PV between 1 mm and 1.2 m & displaced tracks
  - Veto back-to-back muons

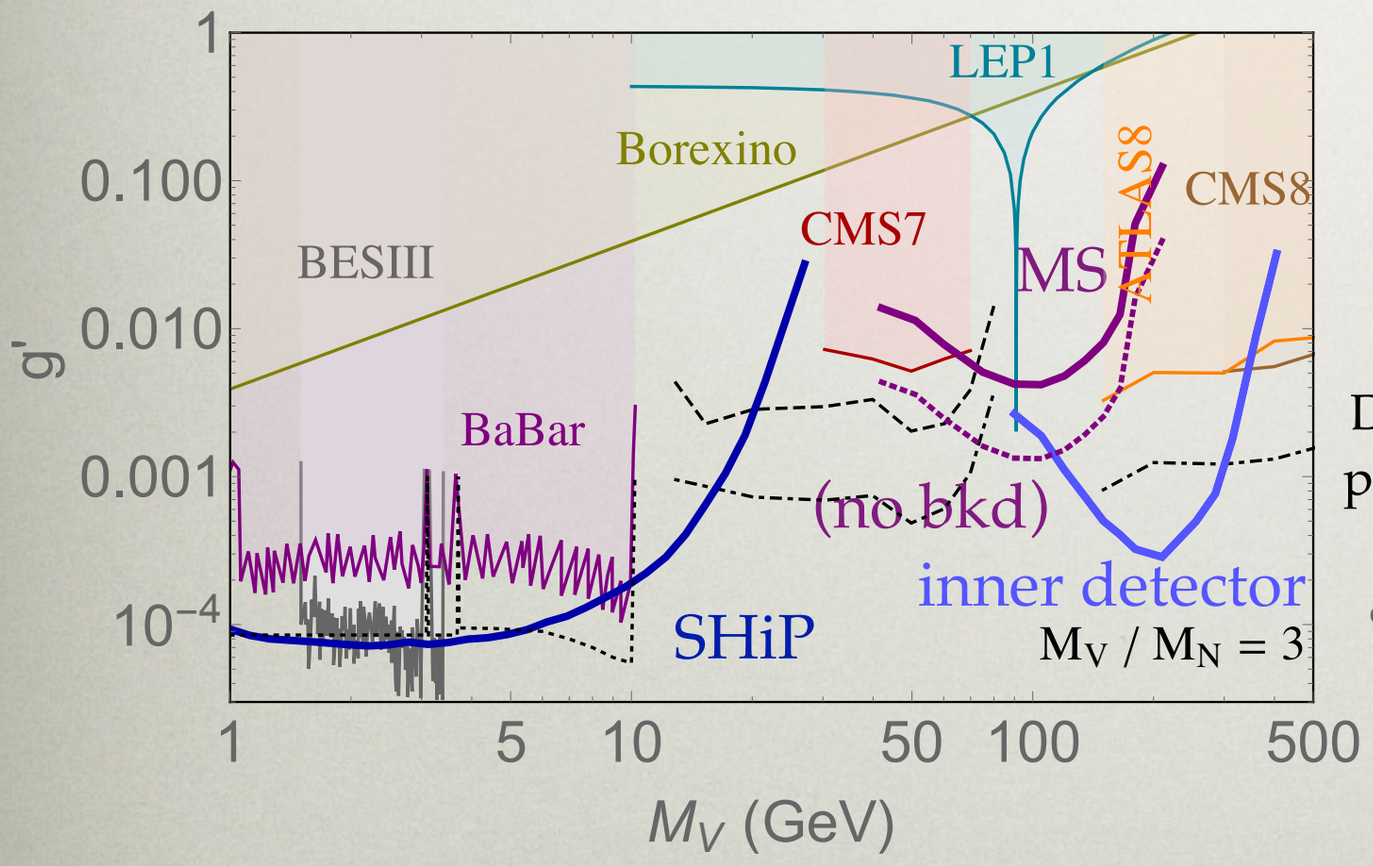
95% CL reach (signal yield ≥3)



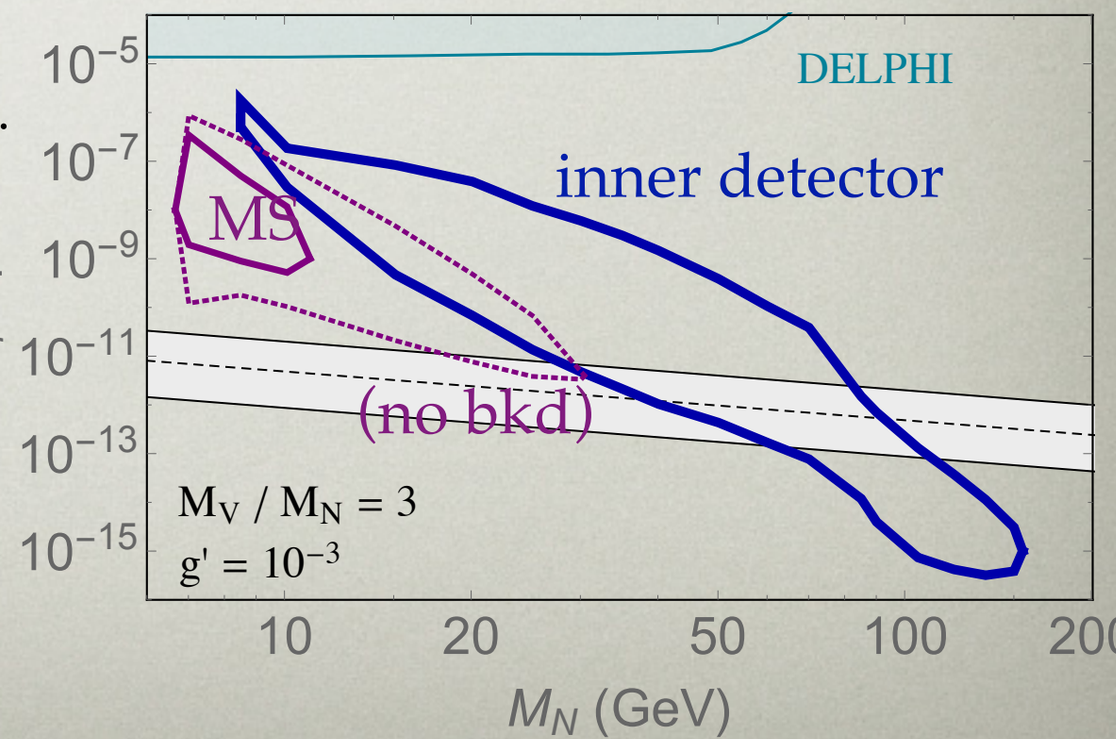
Direct Production of Low-Mass LLPs

- Can also have exotic, **low-mass** production modes
- Need to keep displaced, multilepton thresholds low to retain sensitivity
- Complementarity with *B*-factories, beam dumps





DY proj.



Batell, Pospelov, BS, arXiv:1604.06099